Hedge funds and the Treasury cash-futures disconnect*

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Abstract

We document the rise and fall of an arbitrage trade amongst hedge funds known as the Treasury cash-futures basis trade. This trade exploited a fundamental disconnect between cash and futures prices of Treasuries. We show that in recent years a replicating portfolio of Treasury bills and futures has been overvalued relative to Treasury coupons, creating an opportunity for arbitrageurs. Using regulatory datasets on hedge fund exposures and repo transactions, we are able to both identify these arbitrage positions and speak to their aggregate size. We show that the basis trade became popular among hedge funds following 2016, rising to make up as much as half of all hedge fund Treasury positions and around a quarter of dealers' repo lending. We present a model which illustrates the reasons for the rise in the basis trade, and shows how the trade could contribute to financial instability. In March of 2020, many of the risks of the trade materialized as Treasury market illiquidity associated with the COVID-19 epidemic led to large sales of these basis trade positions amongst hedge funds. Fast action by the Federal Reserve may have prevented broader instability. Our results underscore the importance of non-bank actors in the current structure of the Treasury market, and suggest this structure could create risks going forward.

Keywords: Treasuries, repo, futures, basis trade, hedge fund, securities dealers, liquidity
JEL Codes: E43, G12, G13, G23

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1 Introduction

During the first week of March 2020, the market for U.S. Treasury securities — the safest and most liquid asset market in the world — began to experience stress. By March 11^{th}, Treasury markets faced unprecedented disruptions: bid-ask spreads, particularly on longer maturity bonds such as the 30-year, widened to unseen levels; repo rates on Treasury collateral skyrocketed; and various arbitrage spreads diverged. It is difficult to overstate the importance of Treasury markets in the global financial system, and instability there would reverberate to every corner of financial markets. The Federal Reserve quickly stepped in, dramatically expanding purchases of Treasury securities from dealers and offering unlimited repo and reverse repo facilities on Treasury collateral.[1] By March 18^{th}, turmoil in Treasury markets had largely subsided and market functioning returned to normal.

The focus soon turned to a post-mortem on how the the U.S. Treasury market could have experienced such severe disruptions. One leading candidate was hedge funds exiting the Treasury cash-futures "basis trade."[2] The Treasury cash-futures basis represents an arbitrage relationship:

$$P_{t,\tau} = \sum_{s=t}^{T} B_{t,s} c_s + B_{t,T} F_{t,\tau,T}. \tag{1}$$

The price of the bond in the cash market ($P_{t,\tau}$) must be equal to the present values of the coupon payments ($B_{t,s}c_s$) plus the futures price ($B_{t,T}F_{t,\tau,T}$). When the futures price is too high relative to the cash price, arbitrageurs can go "long the basis" by buying the cash bond and shorting the futures. The trade profits from the convergence of the cash and futures prices at the delivery date. To establish a (nearly) zero net cash outlay, the purchase of the long position is financed in the repo market, usually short-term or overnight, with the bond as collateral.

In this paper, we study the implications of deviations from arbitrage in the Treasury cash and futures markets. We show that limits to arbitrage produce a disconnect between cash and futures prices. The disconnect is larger when financing costs are large, when volatility is high, and when dealer balance sheets have large exposures to Treasuries. Arbitrageurs who exploit this price

[1] While these weren't the only interventions, they were likely the most important. The Fed also excluded Treasuries from the Supplemental Leverage Ratio and Enhanced Supplementary Leverage Ratio.

[2] See Schrimpf et al. (2020) as one example.

difference by trading the basis, generally hedge funds, are exposed to financing risks in the form of rollover risk on their repo borrowing and margin risk on their futures positions. As stress unfolded in Treasury markets in March 2020, the risks associated with the basis trade materialized, and hedge fund sold Treasuries in order to unwind their positions. Timely intervention by the Federal Reserve relieved pressure on dealer balance sheets and likely prevented additional sell-offs, stabilizing the market and avoiding a potential liquidity spiral.

We begin with an analysis of the convergence between Treasury cash and futures prices. As a simple benchmark, we compare the futures price to the present value of the security to be delivered into the futures contract. In the absence of frictions the only difference in these prices is due to time; the cash price is in today's dollars and the futures price represents dollars on the delivery date. We examine the so-called "cheapest to deliver", the Treasury note that will be optimal to deliver into the futures contract. Indeed, as the delivery date approaches the price of the cash note converges to the futures price, with a vanishingly small variation in the price difference at the delivery date. This convergence only holds for the cheapest-to-deliver security; other Treasury notes that are eligible for delivery but are not the cheapest-to-deliver actually diverge as the delivery date nears.

While the convergence of the cash and futures price is required by the arbitrage pricing relation, the no-arbitrage condition places restrictions on the *rate* of convergence. In particular, in the absence of financing frictions and inventory costs, the cash note price must converge to the futures price at the risk-free rate. We show that this condition is frequently violated. Deviations from arbitrage are often large, and estimates from a GARCH(1,1) model with auto-regressive mean process show significant persistence in the disconnect between cash and futures prices. We also show that the size of the disconnect is substantial during two previous crisis events: the the Long Term Capital Management failure in 1998 and the Lehman Brothers bankruptcy in 2008. Interestingly, during these episodes the cash-futures disconnect is of opposite signs. The LTCM bailout was characterized by a flight to liquidity, with a high demand for cash and cash-like securities such as on-the-run Treasures. This is similar to the March 2020 Treasury event. In these, the cash bond because cheaper relative to the futures. The Lehman bankruptcy was instead categorized by a flight to safety, where counterparty uncertainty led to a demand for cash Treasuries. This led the

cash bond to be overvalued relative to the futures.

Beginning in early 2018, the cash futures basis began to widen. Demand from traditional asset managers for off balance sheet duration exposure pushed futures above their no-arbitrage prices, and hedge funds met this demand by shorting the futures and going long the cash note — a strategy referred to as "going long the basis." The dramatic increase in hedge fund Treasury activity directly associated with the cash-futures basis trade constitutes a major development in Treasury markets leading up to the March 2020 illiquidity crisis. From the end of 2017 through the end of 2019, total hedge fund Treasury exposure grew from $1.14 to $1.97 trillion, an increase of $830 billion, while total hedge fund short futures positions increased by $352 billion. From June 2018 to December 2019, total hedge fund repo (borrowing plus lending) increased by $476 billion. The magnitude of these changes are substantial. For instance, two-year short futures across all investor types grew by 113% between the end of 2017 and end of 2019, and hedge funds accounted for nearly 73% of this growth.

While these price deviations between Treasury cash securities and futures were sufficiently large to attract a significant influx of arbitrage capital, they do not reflect risk-free profits. In particular, hedge funds seeking to go long the basis are unable to borrow at the risk-free rate, and must instead finance the purchase of the note in the repo market. Further, the short futures position requires both initial margin and the potential for additional capital calls to meet maintenance margin requirements. These limits to arbitrage expose arbitrageur's to rollover risk on repo and margin risk on the futures, and prevent the basis trade from being true riskless arbitrage.

To further explore the consequences of the limits to arbitrage in the Treasury cash and futures markets, we develop an equilibrium model that explores both the size of the cash-futures disconnect and the risks the cash-futures basis trade poses for Treasury market liquidity. The model combines aspects of Greenwood and Vayanos (2014) and Brunnermeier and Pedersen (2008). As a result of limits to arbitrage on dealers and asset managers as well as shocks to preferred habitat investors, hedge funds play a role in the model as "warehouses" of Treasuries, holding them on their balance sheet for delivery to asset managers in the futures market, and funding them through repo. In the event of large sales by preferred habitat investors, hedge funds are forced by their margin constraints to unwind their trades, exacerbating the direct effects of these sales.

The risks of these margin-induced sales is compounded by rollover risk in the repo market. These risks, in combination with the difference in liquidity between repo and bills, leads to a disconnect in equilibrium between cash and futures prices of Treasuries.

We provide empirical evidence that supports the model's predictions. First, borrowing costs for hedge funds proxied by the spread between the GCF repo rate and IOER are positively associated with the Treasury cash-futures disconnect. When funding costs are high, arbitrage is costly, and the futures price strays further from the cash price. Next, we show that the amount of Treasuries held on dealer balance sheet, which is inversely related to dealer's willingness to supply funding with Treasury collateral, is also related to the cash-futures basis. Higher dealer Treasury exposure is associated with a higher arbitrage spread. Finally, conditional on dealer Treasury exposure and the VIX, maintenance margin on Treasury futures is positively associated with the basis for the 5-year, 10-year, and Treasury bond securities. The relationship is insignificant for the 2-year note, but this is likely due to much smaller initial margins on 2-year futures. These results point toward funding costs and margin risk as impediments to arbitrage in the Treasury cash and futures markets, and demonstrate that when funding costs and margin risk is high the disconnect between cash and futures prices is likely to be larger.

Finally, we turn to an evaluation of the stress in Treasury markets in March 2020 and the accompanying regulatory response. In early March 2020, Treasury market liquidity decreased. As yields fell, volatility spiked and bid-ask spreads increased, in particular for off-the-run Treasuries. Standard spreads associated with liquidity risk, such as the on-the-run off-the-run spread, also spiked. These indicators are consistent with a general flight to liquidity. Deteriorating liquidity seems to have been spurred by large sales from foreign and domestic real money investors, particularly foreign central banks and domestic mutual funds. As volatility increased and prices fell, margin requirements on short futures positions rose and the cash-futures basis widened. Repo rates, which represent the cost of funding the basis trade, soared.

The model we develop points to these factors as vulnerabilities inherent to the basis trade. In the extreme case, they could foretell a liquidity spiral. Indeed, hedge funds appear to have dramatically reduced their basis positions, reducing short futures positions from $774 billion to $684 billion between February 18 and March 17. The reduction in short futures would be accompanied

by sales of cash Treasuries held on the long side of the trade, and which could have accelerated Treasury market stress by further depreciating prices.

However, despite these sales, we provide evidence that hedge funds were unlikely to be the primary cause of stress in Treasury markets leading up to March 17. This isn't to say that hedge funds were not in a precarious position. Instead, timely intervention into repo and Treasury markets by the Fed likely stabilized markets and prevented further market deterioration. First, we note that hedge funds trading the basis appear to be largely concentrated in shorter maturity Treasuries, particularly the two- and five-year contracts. Yet, disruptions were largest in the longer maturity Treasuries. Next, the Treasury notes hedge funds most likely held in the basis trade were the cheapest to deliver notes, and during the height of the March stress episode, the prices of the cheapest to deliver actually *rose* relative to otherwise similar non-deliverable notes. This suggests the CTDs became more valuable during the period, likely due to their better liquidity compared to non-deliverable off-the-run notes. Finally, dealers sold very little of the cheapest to deliver notes to the Fed through the Fed's emergency purchase program prior to April, suggesting dealers were able to find buyers willing to pay a fair price for these securities. Together, these facts suggest that while hedge funds exiting the basis trade likely put additional strain on dealer balance sheets, they were probably not the primary source of stress leading up to the disruptions in the second week of March.

Instead, we argue that had regulators not intervened, hedge funds would have likely amplified stress through Treasury markets. The Fed's intervention in the repo market restored normal borrowing rates, and purchases of Treasuries for primary dealers relaxed constraints on balance sheets and allowed dealers to more efficiently intermediate markets. As a consequence, funding costs on the basis trade shrank and the basis narrowed, alleviating hedge fund losses and allowing them to remain in the trade. Had the Fed not intervened, our model suggests a Brunnermeier and Pedersen (2008) style liquidity spiral may have resulted, leading to unparalleled stress in the world's most important asset market.

Our empirical findings result from multiple regulatory and publicly available data sources. Our hedge fund data come from the SEC's Private Fund Statistics, which are derived from the SEC's Form PF. Form PF results from a mandate in the Dodd-Frank Wall Street Reform and Con-

sumer Protection Act that information on private funds be collected for the dual purposes of investor protection and systemic risk assessment. The data contain information on hedge fund activities, including size, asset class exposures, leverage and borrowing, and much more. Relevant to this study is information on hedge fund Treasury positions, both long and short, as well as repo borrowing and balance sheet leverage measured as the ratio of gross assets (balance sheet assets) to net assets (equity capital). Our information on hedge fund borrowing rates and volumes comes from the Office of Financial Research's Cleared Repo Collection. The collection of this data began in 2019, and the data provides transaction level coverage for all trades in the Fixed Income Clearing Corporation's bilateral DVP Service and their GCF Repo Service, the two cleared markets in the United States. We are the first research paper to use this data, which contains detail on borrowing rates, collateral, and counterparties in each trade. We have mapped these counterparties to hedge funds by hand, and use this data both for borrowing costs and to examine in detail hedge funds' positions in individual Treasuries. Before this data is available we proxy for hedge fund borrowing rates using the GCF Repo Index. We also use publicly available futures data from the CFTC's Commitment of Traders data. We use Bloomberg for Treasury futures prices, and CRSP for cash prices of Treasuries.

Our results contribute to a number of different literatures. First, relative to the post-mortem on March Treasury illiquidity, we provide evidence on the contribution of hedge fund basis trades to this stress event. Many previous studies have noted the importance of hedge fund Treasury sales in March, including Schrimpf et al. (2020). Estimates in the Office of Financial Research's 2020 Annual Report suggest that hedge fund Treasury positions decreased by $242 billion between the end of March and the beginning of February. He et al. (2020) presents a model, somewhat similar to our own, where hedge funds and dealers play a key role in episodes of illiquidity. However, in their model hedge funds participate in arbitrage between different Treasuries, with somewhat balanced short and long positions across maturities of cash Treasuries. We point out that much of hedge fund Treasury exposure can be attributed to the basis trade, in which hedge fund arbitrage is between cash Treasuries and Treasury futures. This highlights the importance of linkages across different markets in March Treasury illiquidity. We also expand on their model by including margin accounts and haircuts, which highlights the destabilizing role that hedge fund basis trades can play in times of stress. We estimate that about $90 billion in hedge fund Treasury

sales can be attributed to the basis trade. This matches Schrimpf et al. (2020) along with our own previous research in Barth and Kahn (2020) in highlighting the role of the basis trade in March Treasury sales among hedge funds. However, we show that Treasuries involved in the basis trade commanded a signficant liquidity premium in March, suggesting that the effect of these sales may have been limited. We suggest that the intervention of the Federal Reserve came at exactly the right time to avoid the amplifying effects the unwind of the basis trade may otherwise have had on Treasury market liquidity.

Second, our paper highlights the changing nature of the Treasury market, and particularly the increased importance of non-bank actors and repo markets in Treasury market functioning. The basis trade links Treasury cash markets, futures markets and repo markets. We show the arbitrageurs enforcing these links are almost entirely large relative value hedge funds. Hedge fund Treasury exposure associated with the basis trade made up roughly 25% of total Treasury exposure among hedge funds as of 2019, and repo balances made up roughly 25% of total primary dealer lending. While links between the Treasury market and repo market have been well established, for instance by DAmico et al. (2018), Correa et al. (2020) and Afonso et al. (2020), we contribute to this literature both by using more detailed data and data from a different segment of the market than has previously been explored. First, we examine the DVP repo market. This is the only segment of the market on which data is currently collected that hedge funds are large participants in. In contrast to papers relying on GCF or tri-party data, we are therefore able to examine hedge fund borrowing costs specifically, rather than costs in related markets. Using administrative data we are also able to link repo borrowing to the underlying Treasury collateral borrowed against, and therefore precisely identify positions related to the basis trade. This allows us to examine the role of hedge funds in general and the basis trade in particular in much more detail than previous papers. We show that hedge funds are major participants in the DVP repo market and that a disproportionate amount of their activity is associated with securities that are desirable for basis traders to hold.

Third, our paper documents a previously underexplored arbitrage opportunity that is central to the literature on the term-structure of interest rates, and our setting allows for us to identify both the participants in this arbitrage and its effects on individual securities and participants. We

highlight that the basis trade becomes profitable when the combination of cash Treasury notes or bonds and Treasury futures is overvalued relative to Treasury bills. Similar to Lenel et al. (2019), this highlights the importance of disconnects between Treasury bills and longer maturity Treasuries. In contrast to Lenel et al. (2019), we are able to demonstrate a specific tradeable opportunity related to this disconnect. Our measures of the returns on this arbitrage are not based on any particular model of the term structure of interest rates or of risk premia. Instead, for a large class of term structure models these arbitrage opportunities represent a puzzle. Our model explains this puzzle in an environment with limits to arbitrage and preferred-habitat investors that extends on Brunnermeier and Pedersen (2008) and Greenwood and Vayanos (2014). The focus of this paper on the consequences of limits to arbitrage for a specific arbitrage opportunity relates it to the literature on deviations from covered-interest-parity such as Du et al. (2018) and Avdjiev et al. (2019). One contrast to these papers is that we show that the majority of this arbitrage activity is concentrated in non-bank arbitrageurs. More importantly, however, we show the basis trade presents an arbitrage opportunity only for a specific and narrow set of Treasury securities. We are therefore able to precisely identify arbitrage positions, examine their funding in repo markets, and discuss the effects of arbitrage on the underlying securities relative to comparable securities for which the arbitrage is unavailable. This provides much more precise identification of the effects of arbitrage and limits to arbitrage on securities values than previous papers have been able to achieve. We show that securities that are not able included in arbitrage have prices below securities tied to the basis trade and that in times of financial stress the spread increases, suggesting the basis trade contributes to a substantial liquidity premium on the underlying Treasuries.

Finally, we contribute to the literature on hedge funds and systemic risk. Since the failure of LTCM, regulators have recognized the potential for stress at a large hedge fund to have consequences for financial stability. Chan et al. (2006) examine the implications of hedge fund illiquidity for systemic risk. Ang et al. (2011) shows that hedge fund leverage fell considerably in the wake of the 2008 financial crisis. Boyson et al. (2010) finds contagion in hedge fund returns, with excessive correlation in the tails the distribution of hedge fund returns. Aragon and Strahan (2012) show that shocks to traders' funding liquidity during the Lehman bankruptcy reduced the market liquidity of the assets that they traded. Brunnermeier and Nagel (2004) shows that hedge funds sold technology stock prior to the collapse of the dot come bubble.

The paper is organized as follows. Section 2 establishes the basic arbitrage relationship between Treasury cash and futures prices and examines the convergence in prices by the delivery date. Section 3 discusses the frictions that impose limits to arbitrage in the Treasury cash and futures markets and highlights potential risks associated with the trade. Section 4 describes hedge funds' dramatically expanded participation in the basis trade. Section 5 develops a model of limited arbitrage that provides economic content to these empirical findings, and formalizes the risks to Treasury market functioning that arise from cash-futures arbitrage. Section 6 provides empirical evidence in support of the model. Section 7 explores the disruptions in Treasury markets in March and examine what, if any, role the hedge fund basis trade had. Section 8 concludes.

2 The cash-futures disconnect

The cash-futures basis trade enforces a form of arbitrage between the spot price and futures price of Treasuries. When these prices diverge, hedge funds and other arbitrageur's can profit from this difference. In this section, we document the circumstances under which the spot and futures prices diverge, as well as describe the risks associated with trading the basis.

In the vast majority of term structure models, cash and futures prices are closely related. In particular, the value of a bond should be equal to the discounted value of coupons on that bond plus the value of a futures contract on that bond:

$$P_{t,\tau} = \sum_{s=t}^{T} B_{t,s} c_s + B_{t,T} F_{t,\tau,T}, \tag{2}$$

where $P_{t,\tau}$ is the price of a government coupon security at time t which matures at time τ, $B_{t,s}$ is the price of a zero-coupon government security maturing at time s, c_s are coupon rates at time s and $F_{t,\tau,T}$ is the invoice price for bond futures agreed to at time t and delivering at time T. Crucially, this equation does not depend on any assumptions about risk or preferences, in contrast to the expectations hypothesis, which would replace the futures price of the bond with the expected future price.[3] The only necessary assumptions for this equation are that agents are able to borrow and lend freely for any maturity at the same rate that the government borrows and that the futures

[3]The relationship between equation (2) and the expectations hypothesis is analogous to the relationship between covered and uncovered interest parity.

agreement does not require the posting of margin.

In practice, this no arbitrage condition is frequently violated. In recent years, the futures price has been above its no-arbitrage price, creating an opportunity for hedge funds to earn a profit by going short the futures contract and long the underlying bond. The model we present in section 5 formalizes the economic forces that may limit arbitrage between cash and futures prices. There are several. First, hedge funds cannot borrow at the Treasury bill rate, but must instead borrow at the repo rate, pledging the underlying bond as collateral. Second, both as a result of counterparty risk and due to regulatory costs on their lenders, hedge funds tend to borrow at overnight rates instead of securing financing for the full duration of the futures contract. This exposes hedge funds to rollover risk on their repo borrowing. Further, counterparties on futures contracts (in this case the Chicago Board of Trade) demand margin payments on futures contracts. This exposes arbitrageurs to further risks of margin calls which, when coupled with the high leverage involved in this arbitrage, can result in large cash outflows it is difficult for the trader to meet.

We review some of these risks in detail in section 5 and in section 7, where we discuss the Treasury market disruptions in March 2020. In this section, we focus on the returns to the trade itself. We begin by outlining the structure of the futures market. Only some Treasury securities are eligible for delivery into the futures contract, and in general only one of these securities, known as the "cheapest-to-deliver", will be optimal to deliver at any given time. We then discuss the disconnect between cash and futures prices of underlying cheapest-to-deliver Treasuries. We show that in recent years, futures have traded at a premium over cash Treasury prices, and that this premium has predictable time series variation. Moreover, the disconnect between cash and futures prices tends to be high in times of financial stress, and is highly correlated with measures of the disconnect between bill prices and coupon prices. Finally, examine how the futures market affects the prices of underlying Treasuries deliverable into the contract, showing that the prices of otherwise similar Treasuries are affected by their deliverability into the futures contract.

2.1 Structure of the futures market

The details of the basis trade are arcane in part because of the structure of the futures market, and the peculiar nature of delivery into this market as operated in the U.S. by the Chicago Board of

Treasury futures contract name	Original maturity restrictions	Residual maturity restrictions at delivery	Notional amount
2-year note	$\leq$ 5 years, 3 months	$\geq$ 1 year, 9-months $\leq$ 2 years	200,000
5-year note	$\leq$ 5 years, 3 months	$\geq$ 4 years, 2 months	100,000
10-year note	$\leq$ 10 years	$\geq$ 6 years, 6 months $\leq$ 10 years	100,000
10-year ultra note	$\leq$ 10 years	$\geq$ 9 years, 5-months $\leq$ 10 years	100,000
Bond		$\geq$ 15 years $\leq$ 25 years	100,000
Ultra bond		$\geq$ 25 years	100,000

Table 1: **Details of terms for different Treasury futures contracts.** This table provides details on the contract terms for Treasury futures traded at the Chicago Board of Trade, including the original and residual maturity required for cash Treasuries to be deliverable into the contract and notional amounts for each contract.

Trade. This structure affects not only the traders themselves, but also how an empirical counterpart to $F_{t,\tau,T}$ in equation (2) must be constructed. Since the structure of this market is not widely discussed in economics, we briefly review some of these details, though we also refer the reader to more in-depth treatments such as Burghardt and Belton (2005).

The CBOT offers Treasury futures contracts at various maturity points. These contracts, unlike other interest rate futures, require physical delivery of an underlying Treasury. Not all Treasuries are eligible for delivery into a Treasury futures. However, in order to keep the contract suitably liquid, these futures contracts allow for set of maturities among which any Treasury in that deliverable set can be used to fulfill a short-position's obligations to deliver. These maturity sets are based both on the Treasury's original maturity and its residual maturity on the last day of the delivery month. Despite the breadth of deliverable maturities, futures contracts are commonly referred to as 2-year notes, 5-year notes, 10-year notes, 10-year ultra note, and 30-year bonds. Table 1 provides details on the deliverable sets and terms for each of these Treasury futures.

In order to establish a means to deliver across different maturities, the CBOT establishes "conversion factors" for each Treasury in the deliverable set. These conversion factors are applied to the Treasury futures price, and are determined by the coupons and maturity of the Treasury

used. The invoice price (the price the seller in the contract receives for delivering a Treasury) for a particular Treasury futures agreed to at time t and delivering a τ maturity Treasury at time T is then:

$$F_{t,\tau,T} = \text{CF}_{\tau,\tilde{\tau}} \times \tilde{F}_{t,\tilde{\tau},T} + \text{AI}_{\tau,T} \tag{3}$$

where $\tilde{F}_{t,\tilde{\tau},T}$ is the traded price of a $\tilde{\tau}$ maturity futures contract at time t, $\text{CF}_{\tau,\tilde{\tau}}$ is the conversion factor between this futures price and the τ maturity bond, and $\text{AI}_{\tau,T}$ is accrued interest on the τ maturity Treasury at time T. In the appendix, we provide details on the calculation of accrued interest and conversion factors we use.

Conversion factors are not directly based on market prices. As a result, depending on the futures price, conversion factor, and other details of the underlying bond, at any given time some deliverable Treasuries will be more desirable to settle a short futures position than others. The most desirable Treasury is referred to as the "cheapest-to-deliver." As we show below, the cheapest-to-deliver is involved in much of the arbitrage activity in the basis trade, and will be the focus of much of our analysis in this paper. However, other Treasuries can be delivered and may be involved in the trade as well. However, these are less common since the delivery option is less likely to be relevant to these Treasury securities.

While the option to deliver disciplines the prices of Treasury futures, actual delivery is rare. Within the delivery month of the Treasury, several options are available for short positions regarding the timing of delivery and the exact Treasury delivered. These options are reviewed in Burghardt and Belton (2005). In part as a result of these options, which greatly complicate the trade and introduce other sources of risk, many traders in Treasury futures choose not to carry their positions into the delivery month. The CME reports that only 2.6% of Treasury futures open interest actually result in physical delivery. Figure 1 shows open interest in Treasury futures for 2019 by option maturity. By the beginning of the delivery month, most Treasury futures contracts are "rolled" into the next contract to deliver. This roll occurs generally before the last two business days of the month prior to the delivery month, which is referred to as the "first position day," and which is the first step in the Treasury futures delivery process. In the discussion below, we will generally focus only on the contract with the highest volume for a particular day, following traders in avoiding the complications of the delivery month. However, the option to carry these contracts

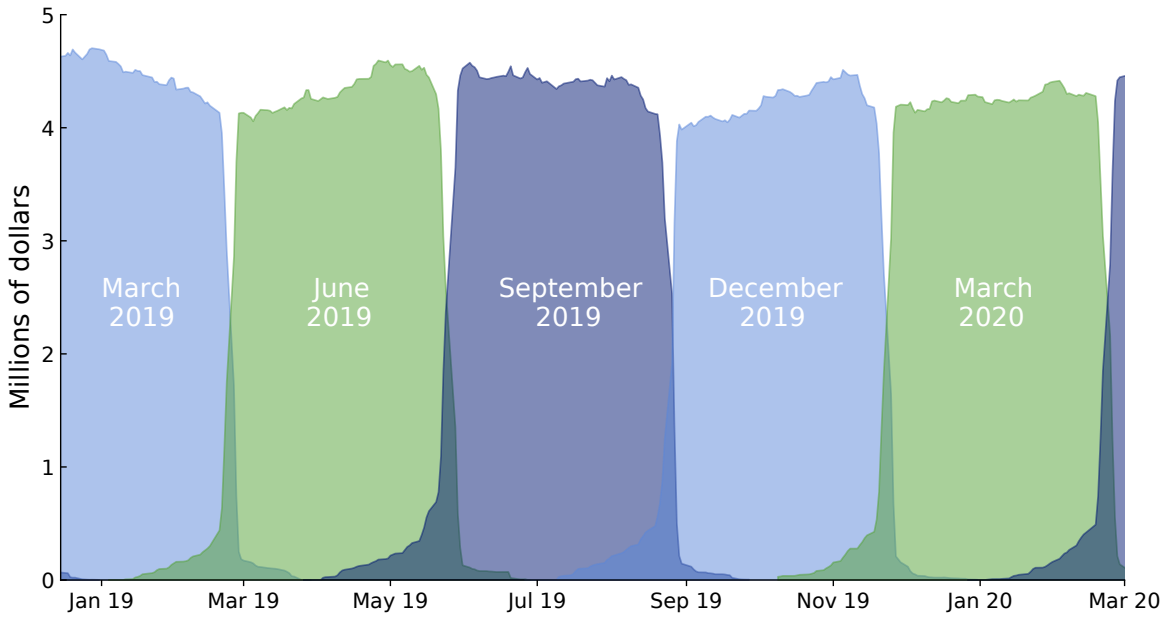


Figure 1: **Open interest in 5-year Treasury futures contract by delivery month.** Open interest in the 5-year Treasury futures contract by delivery month. The volumes suggest that most contracts tend to roll to the next delivery date just prior to the beginning of the current contract's delivery month.

into delivery is still what drives arbitrage returns, and ultimately determines the profitability of the basis trade. We therefore still employ the invoice price in our discussion of arbitrage trades and our reconstruction of equation (2).

2.2 Treasury Cash and Futures Data

To our knowledge we assemble first comprehensive research data set compiled on returns to Treasuries and futures taking into account the full features of the delivery process. This allows us to construct an empirical counterpart to equation (2). The relationship in this equation need only hold for deliverable Treasuries, and among these may only hold for the cheapest-to-deliver, which is the Treasury most desirable for delivery by the short position. We establish the deliverable set using the rules above, and verify this set against Bloomberg. The rules for the deliverable set for Treasury bond futures changed in 2011 with the introduction of the ultra bond contract. Prior to 2011, Treasury bonds futures included all Treasury securities with residual maturities greater than 15 years. After 2011, bonds with residual maturities greater than 25 years were removed from the deliverable set for bond futures and moved into the deliverable set for ultra bond futures. For

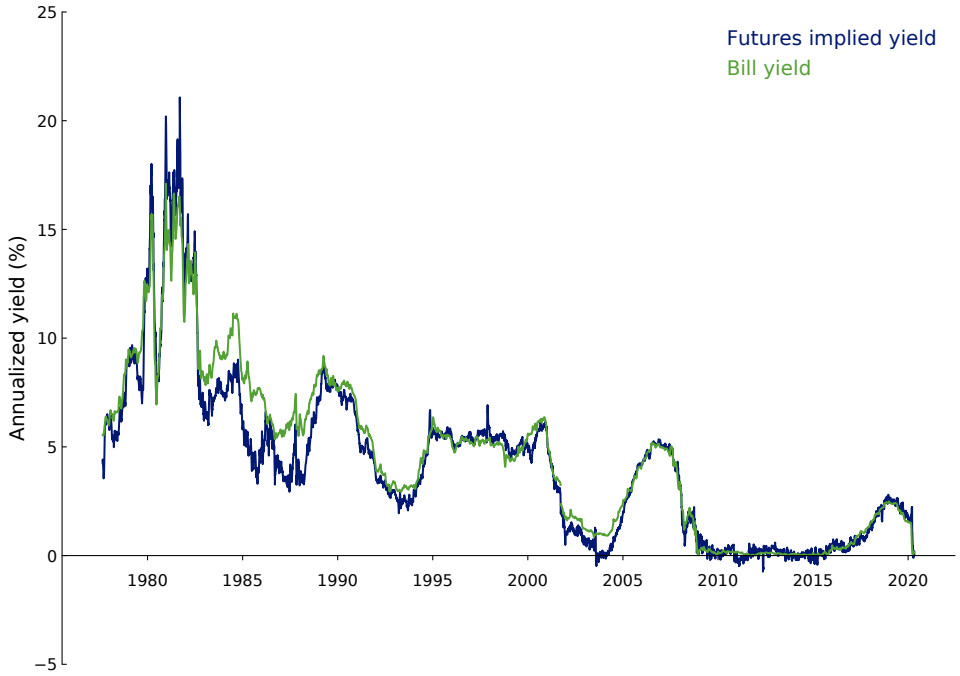


Figure 2: **Time series of the bond futures implied yield and bill yield.** Long time series of the annualized futures implied yield and the yield for an equivalent maturity bill. Uses the second-to-deliver futures contract.

callable Treasuries, the CBOT contract treats their residual maturity as determined by their first callable date. We establish conversion factors for these Treasuries from the formula used by the CME. This conversion factor formula changed in February of 2000, which we take account of in our estimates. For each deliverable Treasury, we use CRSP mid prices to measure $P_{t,\tau}$.

We must then account for coupon payments. Where possible, we use the realized coupon schedule recorded in CRSP for the calculation of $c_{t,s}$. For Treasuries which pay coupons past the end date of our CRSP sample, we use the coupon schedule of the Treasury and account for the fact that coupons are generally paid on business days following holidays or weekends. We discount these coupons using zero-coupon bill prices, $B_{t,s}$. We use the exact bill price paying off on the date of a coupon payment or on futures delivery whenever possible, and otherwise we interpolate existing bills. Since these coupon payments are all within a year, bill prices will generally cover the necessary period, and it is not necessary to rely on more complicated methods like spline interpolation, since there is always a bill of longer residual maturity than the delivery date trading. When no bill is trading of shorter maturity between the trade date and the date of the payment of the contract, we assume that a bill maturing today would trade at par, and use this

as the lower value in interpolation. As with the coupon security, we use the mid price for bills.

Finally, we must calculate the futures invoice price, $F_{t,\tau,T}$. To measure $\tilde{F}_{t,\tau,T}$ as in Equation (3) we use the last trade price for the futures contract in Bloomberg. Where possible we have verified our results against Bloomberg. We then apply the conversion factor for the particular Treasury to this futures contract. Finally, for the purposes of calculating accrued interest, we assume that the first delivery date is when the Treasury will be delivered. In reality, the exact delivery date is an option exercised by the seller. We have tried different delivery assumptions and found they do not have much affect on our results.

We also form our estimate for the cheapest-to-deliver Treasury in the deliverable basket. Formally, the definition of the cheapest-to-deliver is the Treasury most profitable for delivery into the short position, taking account of the repo rate, Treasury prices and cash prices. For our purposes we define the cheapest-to-deliver as:

$$\text{CTD}_{t,\tilde{\tau},T} = \underset{\tau \in \Omega(t,\tilde{\tau},T)}{\arg\min} \frac{F_{t,\tau,T}}{P_{t,\tau} - B_{t,s}c_s} \tag{4}$$

where $\Omega(t,T)$ includes all Treasuries in the delivery set $\tilde{\tau}$ futures delivering at time T which are available to traders as of time t. This approximates practice among many traders, who tend to form the cheapest-to-deliver using the futures price and cash price and assuming that and coupons are reinvested at a constant rate. However, it is important to note that this formulation implicitly assumes that repo rates across the deliverable basket are approximately equal. In the case of special collateral repo this may not be true, as the repo rate on the cheapest-to-deliver may differ from other repo rates. We discuss the validity of this assumption using our repo data below.

In all, we are able to form daily matched futures and Treasury data going back to 1977 for the Treasury bond futures contract, to 1982 for the 10-year contract, to 1988 for the 5-year contract, and to 1990 for the 2-year contract. These dates match the introduction for these futures contracts on the CBOT. We show 30-day rolling average futures implied yields and bill yields for the full sample for the bond contract in Figure 2. As can be seen we are able to establish a close match between bill yields and futures, suggesting our methodology is fairly accurate. However, the 5-year and 2-year were very thinly traded for the first part of the sample, and so for comparability we begin the sample we will use for analysis on January 1st, 1992.

2.3 Convergence of cash and futures prices

First, we examine the simplest form of convergence of cash and futures prices of Treasuries as the delivery date approaches. We construct a spot position equal to the present value of the Treasury to be delivered into the futures contract. To do so, we subtract from the price of the cash note the present value of coupon payments prior to the futures delivery:

$$\tilde{P}_{t,\tau,T} = P_{t,\tau} - \sum_{s=t}^{T} B_{t,s} c_s$$

Figure 3 plots $\tilde{P}_{t,\tau,T}$ against the futures price for the cheapest-to-deliver Treasury. Both converge to their values at the futures delivery date from below. Note that the updward drift of the futures price is a rejection of the expectations hypothesis; because the futures price represents the price of the same asset obtained in the same time period (T), the expectations hypothesis would imply the futures price should be a random walk around its last invoice price. The cheapest-to-deliver price is always below the futures price in expectation, but rises faster. It is unsurprising that in Figure 3 the cash price is below the futures price because the cash price is discounted to the present, whereas the futures price is dollars in period T. In a world without frictions or storage costs, the cash price should then converge to the futures price at a rate equal to risk-free rate. When the rate of convergence is faster, there is a potential arbitrage opportunity. We expand on these implications throughout the rest of the paper.

The convergence of the cheapest-to-deliver price to the note price is virtually guaranteed by the delivery date, since on that date the Treasury can be delivered essentially directly into the short contract, receiving the futures price. This bounds the futures price by the note price from below. Similarly, a long position in the futures contract is virtually guaranteed to receive the cheapest-to-deliver, which they could also purchase directly in the cash market. This bounds the futures price by the note price from above. As a result, cash and futures prices converge not only in expectation but also with near certainty. Figure 4 shows that the variation in the cash-futures disconnect falls to zero for the cheapest to deliver at the delivery date. The equality between futures prices and note prices at delivery underlies the arbitrage strategy we study in this paper.

Convergence to the futures price does not hold for all deliverable Treasuries. Figure 5 plots the

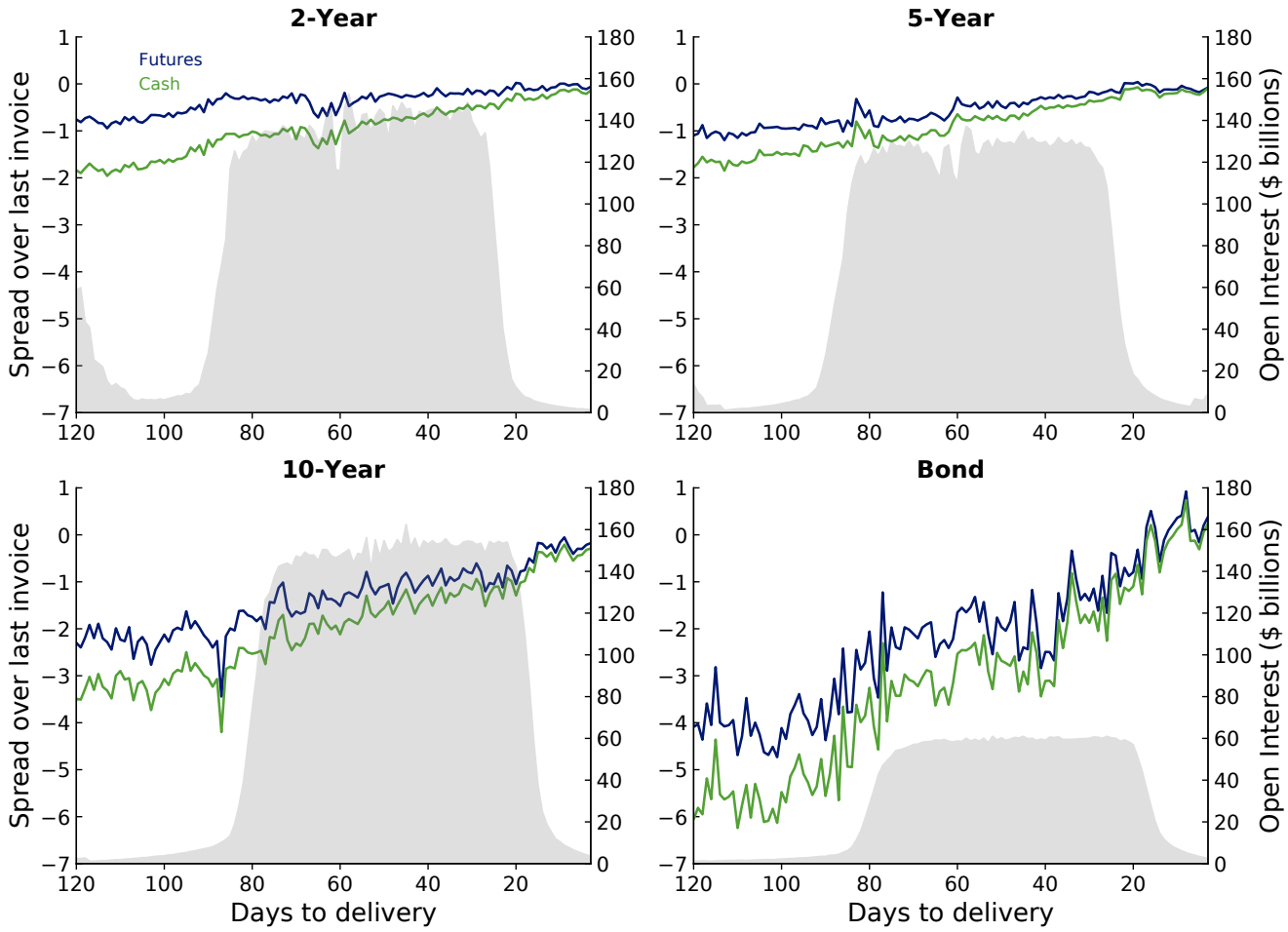


Figure 3: **Convergence of cash and Treasury prices for the cheapest-to-deliver (means).** Each series in this graph is the average deviation of the futures and cash Treasury from the last invoice price of the futures on the delivery date. The x-axis denotes days to delivery. The gray background denotes open interest in the contract, reported on the right axis.

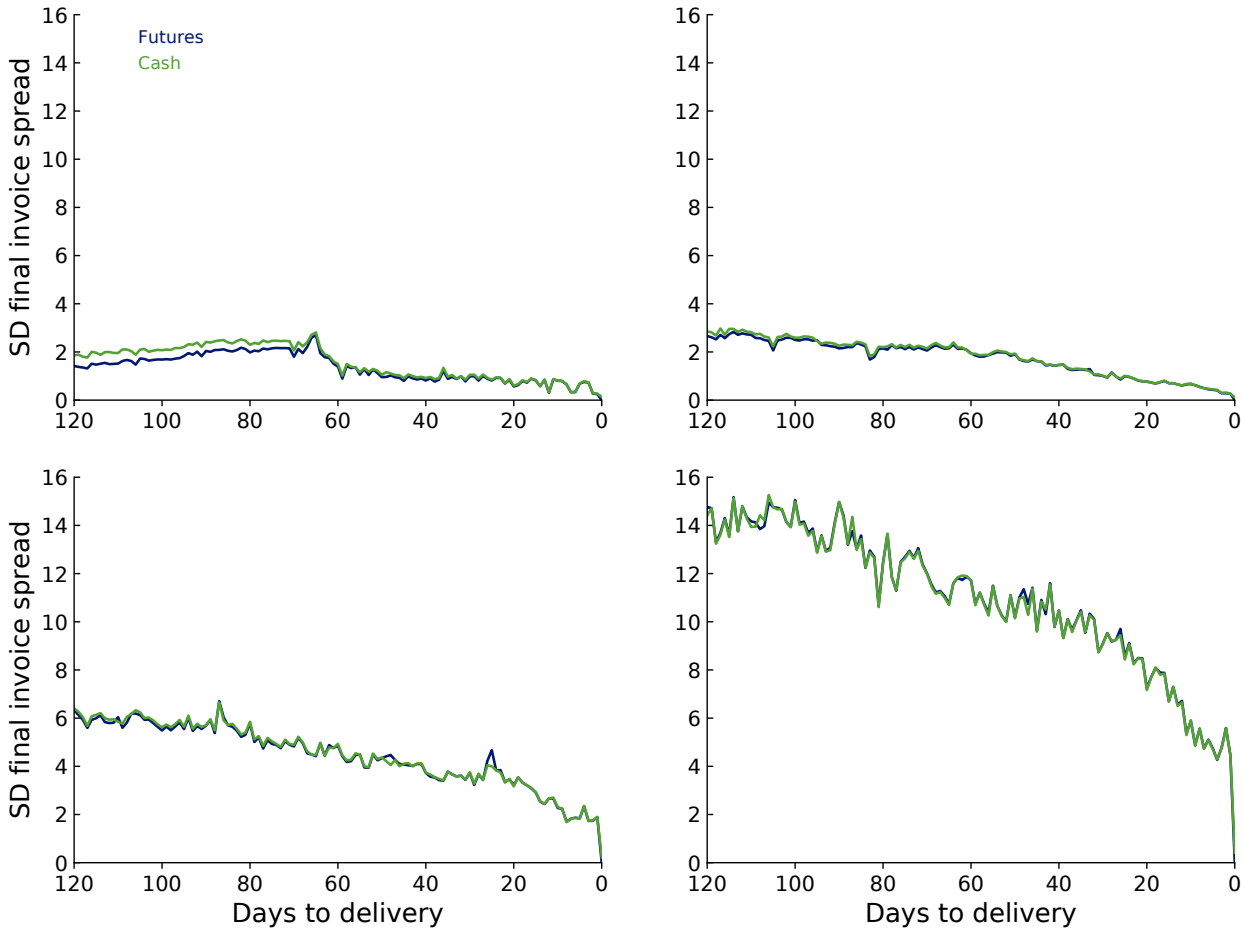


Figure 4: **Convergence of cash and Treasury prices for the cheapest-to-deliver (variance).** Each series in this graph is the average squared deviation of the futures and cash Treasury from the last invoice price of the futures on the delivery date. The x-axis denotes days to delivery. The gray background denotes open interest in the contract, reported on the right axis.

same series for Treasuries that are deliverable but are not the cheapest-to-deliver. In general, the Treasury cash price lies above the futures price even at delivery, and the two prices tend to diverge over time. This lack of convergence results because a long futures position is virtually guaranteed to *not* receive any bond other than the cheapest-to-deliver, meaning there is no upper bound on the futures contract from non-deliverable maturities.

Because of its convergence to the futures price, we restrict much of our analyses to the cheapest-to-deliver. However, throughout the lifetime of a futures a contract the cheapest-to-deliver may change. This can happen in two ways: either prices of one Treasury fall relative to the cheapest to deliver, or a new Treasury is issued which becomes the cheapest to deliver. While this mat-

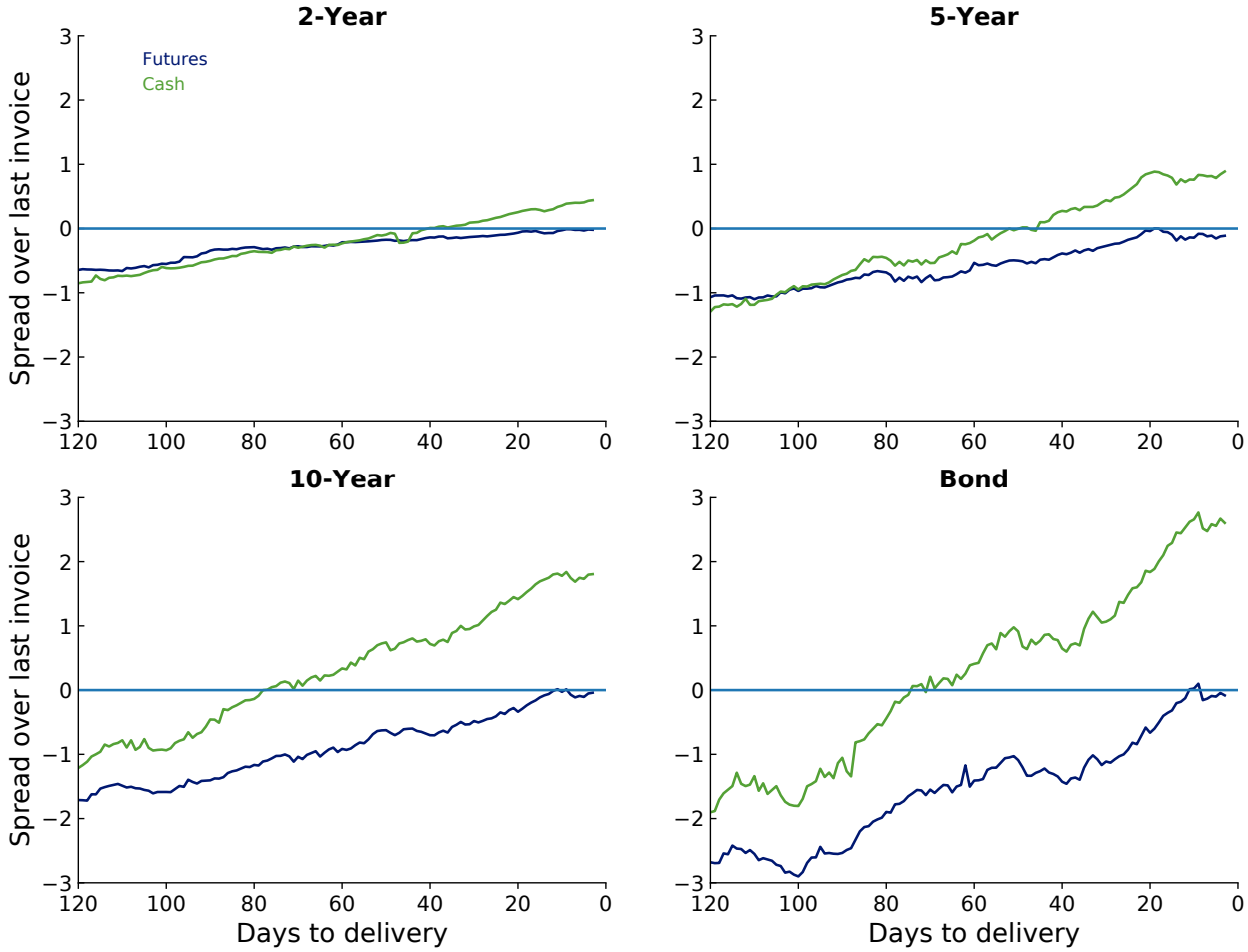


Figure 5: **Non-convergence of cash and futures prices for the non-cheapest-to-deliver (means).** Each series in this graph is the average deviation of the futures and cash Treasury from the last invoice price of the futures on the delivery date. In contrasat to the last figure, the average is taken over the invoice prices and Treasury prices for all Treasuries which are not the cheapest-to-deliver. The x-axis denotes days to delivery.

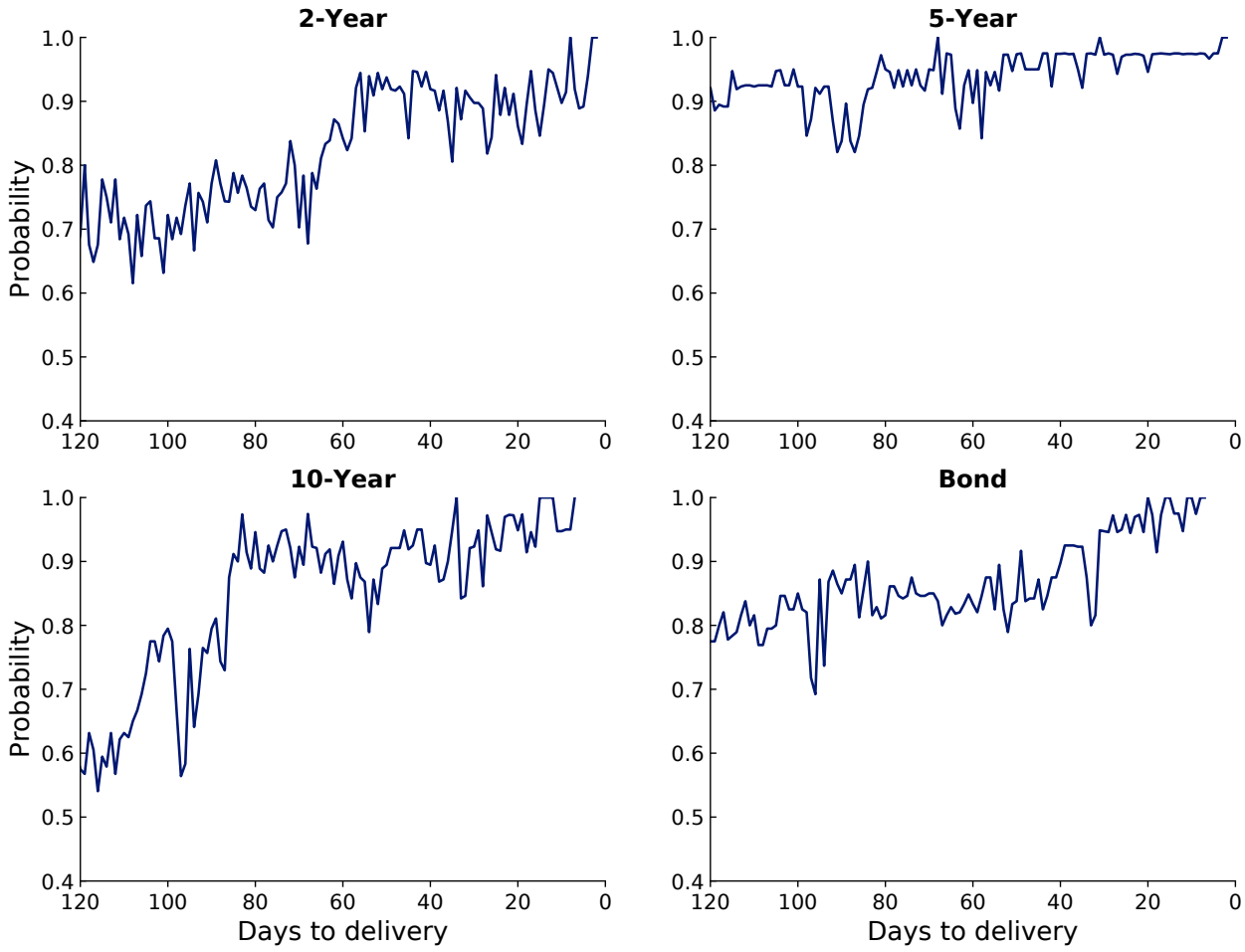


Figure 6: **Stability of the cheapest-to-deliver, 2010-2020.** Each series in this graph is the sample probability that the Treasury that is the cheapest-to-deliver on that day is the same as the Treasury which is cheapest-to-deliver at the delivery date.

ters for convergence, it is important to note that a short futures position with a Treasury that is no longer cheapest-to-deliver always preserves the option to hold until delivery and receive the fixed invoice price. As a result, arbitrage strategies are not directly affected by a change in the cheapest-to-deliver whenever a short futures position is advantageous.

Figure 6 shows the probability within sample that the cheapest-to-deliver on a particular date will be the cheapest-to-deliver on the last trade date for the decade prior to 2020. By 80 days prior to delivery, there is a more than 80% chance that the cheapest-to-deliver does not change across contracts, and the 2 and 5 year contracts are mostly above 90%. The stability in the cheapest-to-deliver in the last 10 years is somewhat higher than in previous periods. The increased stability of these futures may reflect lower variance in interest rates over this period. The increased stability of

cheapest-to-deliver bonds is likely to have reduced risks for long futures positions, but for reasons discussed earlier is less likely to be an issue for short Treasury futures positions.

2.4 The deliverability premium

The fact that only some Treasuries are deliverable into a futures contract, and that among those Treasuries the cheapest-to-deliver is the most desirable for a trader who is short a futures contract, creates a natural market for these Treasuries. In the presence of limits to arbitrage among Treasuries, a premium may result for deliverable Treasuries beyond the price of non-deliverable Treasuries. This premium can be thought of as comparable to the on-the-run/off-the-run premium, and captures the liquidity provided by the cash-futures arbitrage to the underlying Treasury.

The construction of this premium is non-trivial: Treasuries are distinguished by unique coupon and maturity dates, so it is necessary to establish a benchmark for comparison. In particular, a synthetic price for deliverable Treasuries based on prices of comparable non-deliverable Treasuries. To establish this benchmark, we follow Fisher et al. (1995) in using flexible basis splines to capture a yield curve. In particular we model a Treasury's price as:

$$P_{t,\tau} = \sum_{s=t}^{\tau} \exp(-f(s|\theta))c_s + 100 \times \exp(-f(\tau|\theta))$$

where $f(s|\theta)$ is a quadratic basis spline with parameters θ, fitted to minimize the least-squares error between model and actual prices. We fit these curves using only coupon Treasuries, excluding Treasuries with less than 30 days to maturity and Treasuries with optionality such as callable bonds. For this approach, our focus is on the closest fit to prices possible and not on a reliable set of zero-coupon bonds. As a result, we do not employ methods that have recently been more popular such as the method in Nelson and Siegel (1987) and Svensson (1994), which provides advantages in Monte-Carlo simulations for zero-coupon prices. We also do not employ the smoothing penalty in Fisher et al. (1995). Finally, our estimation includes on-the-run and deliverable Treasuries. As a result, the error from this excercise is, if anything, likely to understate the true premium on deliverable Treasuries.

Maturity	Cheapest-to-deliver		On-the-run	
	Mean	Std. Dev	Mean	Std. Dev
2-year	1.09	6.70	1.17	5.86
5-year	0.85	2.49	2.09	4.38
10-year	0.53	2.65	6.08	6.10
30-year	0.34	2.24	2.28	2.87

Table 2: **Fitted yield spreads for cheapest-to-deliver and on-the-run Treasuries.** For the right two columns, we show the average pricing error from our spline model as well as the standard deviation for Treasuries which are cheapest-to-deliver in each category. For the left two columns, we show the same statistics for on-the-run Treasuries in that maturity category.

For each deliverable Treasury we then calculate the deliverability premium as:

$$\hat{y}_{t,\tau} - y_{t,\tau}$$

where $y_{t,\tau}$ is the actual yield on the deliverable Treasury, and $\hat{y}t, \tau$ is the fitted yield on the deliverable Treasury from our spline yield-curve. A postive value of this premium then indicates that the Treasury is overvalued relative to the benchmark from our estimation. We also calculate standard errors for this premium based on the delta method and the standard error for non-linear least squares. This standard error is:

$$\text{SE}(\hat{y}_{t,\tau}) = \frac{1}{\hat{D}(t,\tau)\hat{P}_{t,\tau}} \times \sqrt{\frac{\partial \hat{P}_{t,\tau}}{\partial \hat{\theta}}' \text{Var}(\hat{\theta}) \frac{\partial \hat{P}_{t,\tau}}{\partial \hat{\theta}}}$$

where $\hat{D}(t,\tau)$ is the duration of the Treasury, and $\text{SE}(\hat{\theta})$ is derived using the asymptotic properties of non-linear least squared estimators.

In Table 2 we present the average premia on cheapest-to-deliver Treasuries. All premia are on average larger than zero, and decline for longer maturities. For comparison, we also present those premia for on-the-run Treasuries. It is well known that on-the-run Treasuries recieve a liquidity premium relative to off-the-run Treasuries (see for instace Krishnamurthy (2002) and Adrian et al. (2017)), and the trade between on-the-run and off-the-run Treasuries is another popular relative value trade among hedge funds. The on-the-run premium is therefore a good basis for comparison to the cheapest-to-deliver. For 2-year deliverables, premia are similar in size to the on-the-run 2-year. At higher maturities, on-the-run Treasuries tend to receive significantly higher premia.

In Figure 7 we show the premia that emerges for the cheapest-to-deliver and on-the-run Treasuries from our estimation. Note that the patterns for the premium both for cheapest-to-deliver and on-the-run Treasuries differ by maturity. This is consistent with previous studies that have looked at the premium for on-the-run Treasuries, in particular Fleming (2005). For 2-year and 10-year Treasuries, the premia are highly correlated with the premia for the cheapest-to-deliver, rising dramatically during periods of stress. Correlations are much lower for the 5-year and 30-year. This may be in part because of differences in timing - for an on-the-run Treasury, at a high frequency premia will respond to the regular Treasury issuance and reopening schedule, while the cheapest-to-deliver will respond to delivery and roll dates. For Treasury bond futures in particular the instability of the cheapest to deliver is likely to dilute any liquidity premium, and the long delivery windows for this contract means that the cheapest-to-deliver usually differs in maturity from the on-the-run bond by the order of a decade. Table 3 formalizes this logic by regressing the premia on the cheapest-to-deliver on the premia for on-the-run Treasuries. The on-the-run premium is significant and positive for all but the bond cheapest-to-deliver, where the securities may have very different maturities, and higher delivery risk may interfere with the liquidity value of the underlying bond. The premium on the cheapest-to-deliver also explains a substantial amount of the variation of both the 2-year and 10-year cheapest-to-deliver premium on a daily basis.

	Dependent-variable: Cheapest-to-deliver premium			
	2-Year	5-Year	10-Year	Bond
On-the-run premium	0.727^{***}	0.135^{***}	0.187^{***}	-0.127^{*}
	(0.104)	(0.041)	(0.054)	(0.074)
R^2	0.403	0.052	0.175	0.021
Note:				$^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$

Table 3: **Yield spread for cheapest-to-deliver regressed on the on-the-run spread.** This graph shows a regression of the cheapest-to-deliver premium, obtained as the residual from a spline curve, against a similar premium calculated for the on-the-run premium.

These results suggest Treasuries which are tied to futures earn liquidity premia with comparable size and properties to on-the-run Treasuries. The premium afforded by this link is a result of large trading between Treasury cash and futures prices, which we discuss below. We now turn to the source of these trades, the disconnect between cash and futures prices.

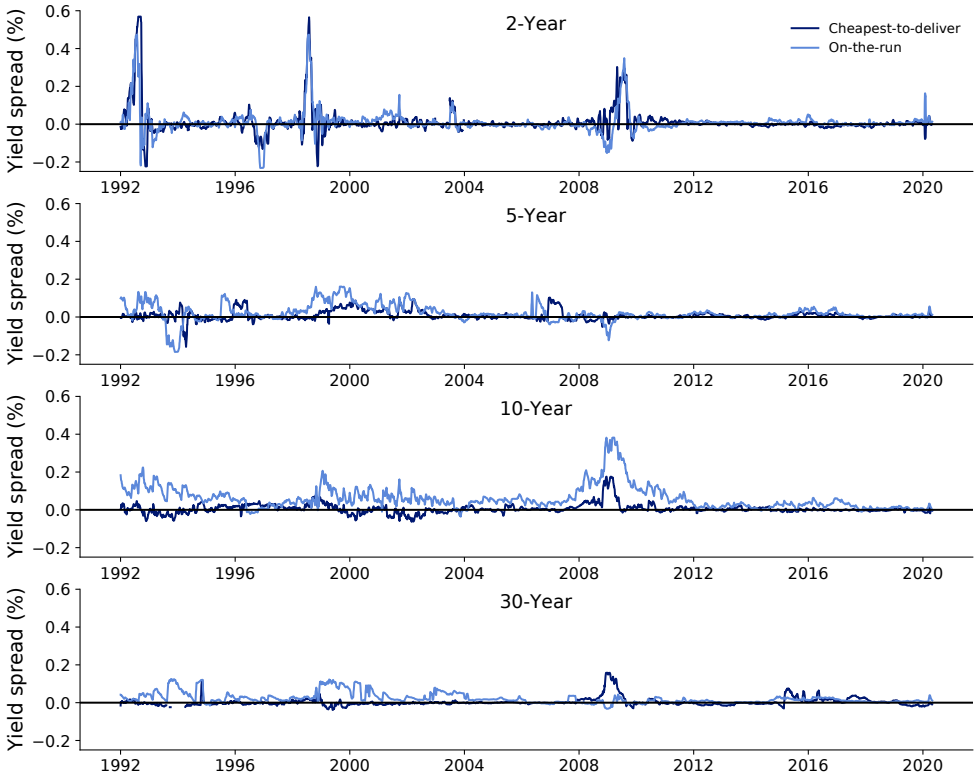


Figure 7: **Time series of premia on on-the-run and cheapest-to-deliver Treasuries.** Each series is the pricing error from our spline model for cheapest-to-deliver Treasuries and on-the-run Treasuries in a given maturity bin, over time.

	Buy τ-maturity note	Sell $F_{t,\tau,T}$ of T-maturity bill	Short τ futures delivering at T	Net cash flow
Time 0	$-P_{0,\tau}$	$F_{0,\tau,T}B_{0,T}$	0	$F_{0,\tau,T}B_{0,T} - P_{0,\tau}$
Time T	0	$-F_{0,\tau,T}$	$F_{0,\tau,T}$	0
Time τ	1	0	-1	0

Table 4: **Cash flows from arbitrage strategy with a short bills position.**

2.5 The Treasury cash-futures disconnect

In previous sections we documented the convergence of cash and futures prices of Treasuries at the delivery date. Equation (2) imposes the additional restriction that convergence for the cheapest-to-deliver occurs at the same rate as the Treasury bill rate; that is, the difference between the cash and futures price is solely compensation (at the risk-free rate) for the time difference between today and the future delivery date. In this section we explore this arbitrage condition and show that in general there are large and predictable deviations from the neo-classical benchmark.

Table 4 describes the strategy one would take if the relationship in Equation (2) did not hold (we focus on the most common case where the futures is overvalued relative to the Treasury note). For simplicity, the note is assumed to have zero coupons. First, the arbitrageur buys the underlying note and takes a short position in the futures contract, promising delivery of that note at time T at a fixed price $F_{0,\tau,T}$. The price agreed to today will be paid to the long futures position in the future, so in order to guarantee the price today the trader also sells $F_{0,\tau,T}$ of bills. Cash flows at time τ, the maturity of the note, are zero since the note has been delivered to the long futures position. Cash flows at time T are zero since the cash from the short futures position pays off the short bill position. Cash flows today are zero if and only if:

$$P_{0,\tau} = F_{0,\tau,T}B_{0,T}$$

which is the zero-coupon equivalent of equation (2). Note that this expression requires that agents be able to freely short bills. In following sections we will discuss how realistic this assumption is, and discuss the basis trade, which uses repo to fund the Treasury position instead. However, in the majority of term-structure models this trade would be pure arbitrage.

Because differences in dollar prices can be difficult to interpret, we instead convert our prices

into futures implied yields and bill yields. The futures implied yield is defined as:

$$y^F_{t,\tau,T} = \left(\frac{F_{t,\tau,T}}{P_{t,\tau} - B_{t,s} c_s} \right)^{\frac{252}{T-t}} \tag{5}$$

With this yield in hand, the no-arbitrage condition given by equation (2) can be restated as the condition:

$$y^F_{t,\tau,T} = r_{t,T} \equiv \left(\frac{1}{B_{t,T}} \right)^{\frac{252}{T-t}} \tag{6}$$

or in other words, the yield to delivery on a portfolio long the cash bond and short the futures must be the same as the yield on a bill maturing on the delivery day.

Figure 8 shows that the underlying cash Treasury bond displays large and persistent deviations from the arbitrage portfolio formed using futures. In particular, from 2015–2020 the cash-futures disconnect was large and positive. Table 5 shows that these price deviations are also highly statistically significant during this period. For both the second and third to deliver contracts and for the 2-year, 5-year, and 10-year contracts, t-statistic exceed eight in almost every case, and often exceed 20 for the periods 2010-2015 and 2015-2020. Coefficient estimates often exceed 0.10, indicating a difference of ten basis points between between the bill yield and futures implied yield. However, the cash-futures disconnect is not always positive; going back to the 1990's, the disconnect is frequently negative. This is shown in Figure 37 in the Appendix which plots a significantly longer time-series for the Treasury cash-futures disconnect. Table 5 confirms this observation.

Table 6 shows that the persistence of price deviations is also statistically significant using a GARCH(1,1) with an auto-regressive term for the mean process. The model shows that the means are highly persistent, nearing a random-walk, though predictability declines for longer tenors. The variance of the arbitrage spreads are also highly predictable across contracts over time. Not only are these deviations predictable, they are also highly correlated across different Treasury contracts: the first principal component explains 65% of the daily variation across the first and second to deliver contracts for all maturities. This is despite the fact that the construction of each portfolio of futures and notes is essentially independent, and in principle these securities are linked only by having similar classes of assets and similar (although not identical) delivery dates.

The time-series of deviations in Figure 8 suggests that the link between cash and futures values

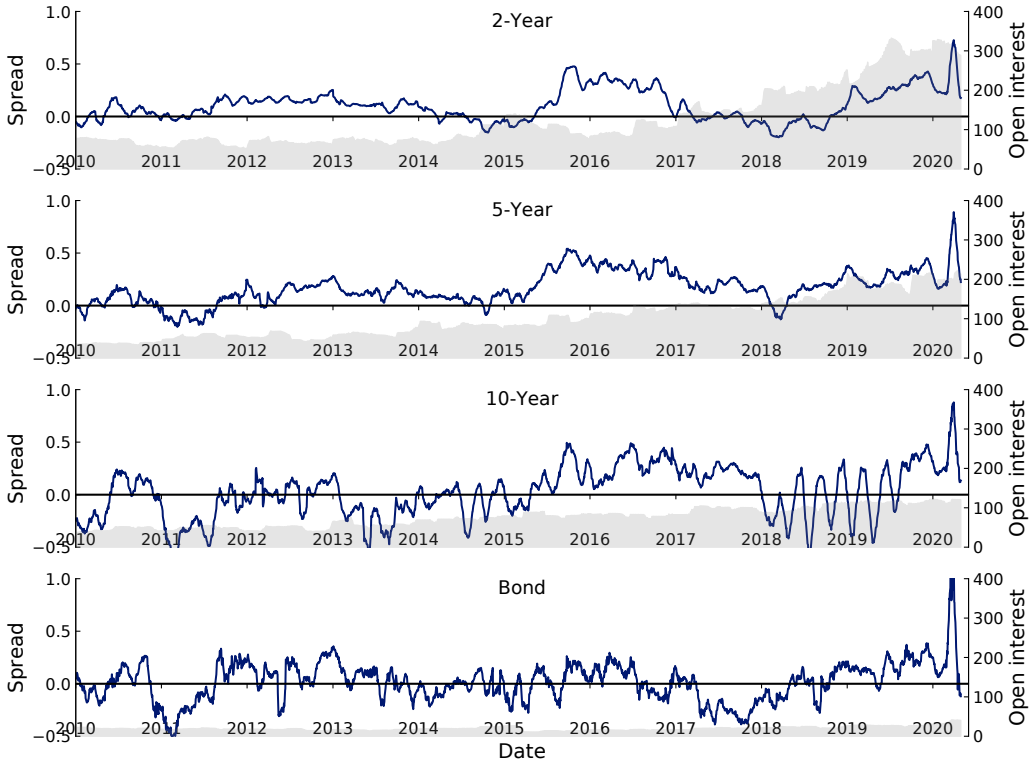


Figure 8: **Deviations of Treasury prices from the replicating portfolio.** Each series graph shows the deviation of the futures-implied yield from the yield on a similar maturity bill and the open interest in that contract. Values above zero imply the replicating portfolio is overvalued relative to the cheapest-to-deliver. These series use the second-to-deliver contract.

Contract	Roll	1992-1995	1995-2000	2000-2005	2005-2010	2010-2015	2015-2020	1992-2020
2-Year	**1st**	-0.097	0.318	-0.024	0.193	0.211	0.246	0.138
		(-2.6)	(9.87)	(-0.84)	(7.19)	(20.65)	(18.83)	(13.01)
	2nd	-0.194	0.111	-0.612	-0.51	0.07	0.13	-0.206
		(-20.76)	(9.6)	(-26.07)	(-36.96)	(19.84)	(23.61)	(-33.16)
	3rd	-0.116	0.255	-0.398	-0.305	0.042	0.227	-0.13
		(-0.68)	(2.97)	(-3.78)	(-22.54)	(4.5)	(42.11)	(-12.14)
5-Year	**1st**	-0.264	0.753	-1.324	-0.152	0.122	0.327	-0.165
		(-7.61)	(14.91)	(-29.15)	(-3.34)	(5.21)	(14.96)	(-9.18)
	2nd	-0.508	0.295	-0.932	-0.326	0.072	0.254	-0.257
		(-48.11)	(19.22)	(-65.2)	(-18.09)	(13.34)	(44.61)	(-34.07)
	3rd	-0.567	0.144	-1.066	-0.074	0.212	0.281	-0.097
		(-30.25)	(8.76)	(-12.0)	(-4.85)	(12.03)	(29.35)	(-9.18)
10-Year	**1st**	-0.536	0.093	-0.729	-0.235	0.098	0.209	-0.239
		(-11.84)	(1.82)	(-19.68)	(-5.05)	(2.61)	(6.6)	(-13.48)
	2nd	-0.721	-0.084	-0.845	-0.631	-0.095	0.128	-0.454
		(-58.93)	(-6.65)	(-54.47)	(-35.57)	(-9.04)	(13.65)	(-63.48)
	3rd	-0.749	-0.044	-0.959	-0.511	0.207	0.098	-0.368
		(-60.8)	(-2.7)	(-25.84)	(-13.71)	(11.89)	(8.53)	(-31.48)
Bond	**1st**	-0.243	0.346	-0.655	0.209	0.054	0.04	-0.043
		(-3.69)	(4.86)	(-12.79)	(3.23)	(0.92)	(0.73)	(-1.71)
	2nd	-0.425	0.182	-0.57	0.012	0.004	0.006	-0.135
		(-30.12)	(15.38)	(-38.17)	(0.81)	(0.35)	(0.48)	(-20.98)
	3rd	-0.465	0.039	-0.555	-0.15	0.137	0.341	-0.176
		(-54.16)	(4.26)	(-48.62)	(-4.11)	(3.32)	(22.29)	(-15.61)

Table 5: **Difference between futures implied yields and bill yields.** This table displays the difference between the cheapest-to-deliver price and the replicating portfolio of Treasury bills and futures by sample. In parentheses, t-statistics test the hypothesis that the average difference between these yields is zero.

	Dependent variable: Arbitrage Spread			
	2-Year	5-Year	10-Year	Bond
		Mean model		
Constant	0.001^{***}	-0.011^{***}	-0.035^{***}	-0.03^{**}
	(0.002)	(0.003)	(0.005)	(0.012)
Lagged arbitrage spread	0.943^{***}	0.93^{***}	0.884^{***}	0.527^{***}
	(0.02)	(0.013)	(0.01)	(0.071)
		Variance model		
Constant	0.002^{***}	0.005^{***}	0.031^{***}	0.006^{**}
	(0.001)	(0.002)	(0.007)	(0.003)
Auto-regressive term	0.419^{***}	0.36^{***}	0.34^{***}	0.182^{***}
	(0.061)	(0.078)	(0.07)	(0.03)
Moving average term	0.581^{***}	0.631^{***}	0.434^{***}	0.818^{***}
	(0.07)	(0.072)	(0.075)	(0.033)
Observations	$6,061$	$6,826$	$6,857$	$6,873$
R^2	0.774	0.815	0.623	0.17
Adjusted R^2	0.774	0.815	0.622	0.17
Note:				*p<0.1; **p<0.05; ***p<0.01

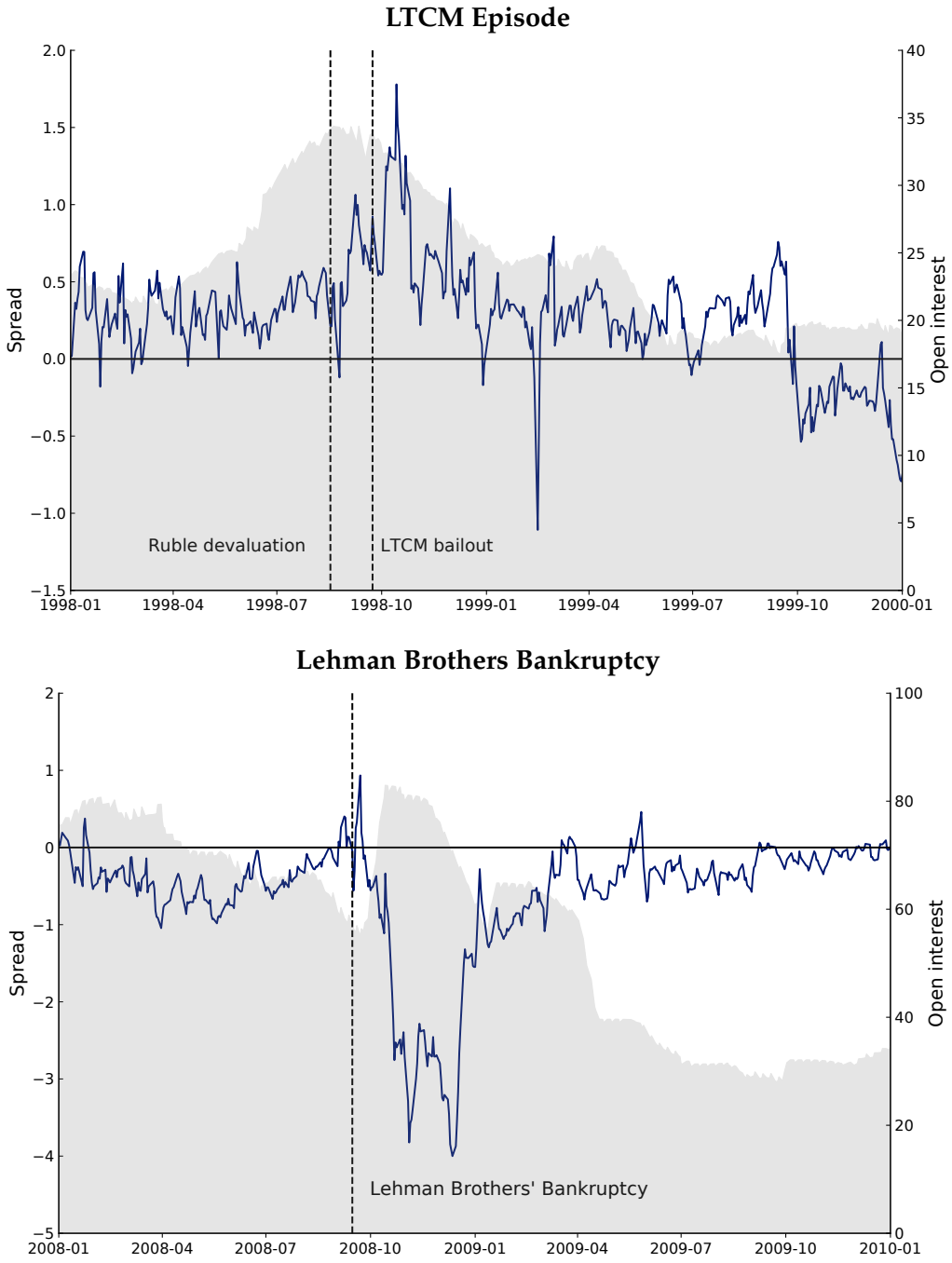
Table 6: **GARCH estimates of the cash-futures arbitrage spread.** This table shows the results of a GARCH(1,1) process estimated on the arbitrage spread: the difference between the futures implied yield and the yield on a similar maturity bill. In the top panel, we show our estimates for the AR-1 process for means, while in the bottom panel we show our GARCH process estimates for variances.

of Treasuries has changed over time. Table 5 shows that from 1992-2020 on average futures have been under-valued relative to the underlying Treasuries. However, in the last decade, futures have become over-valued. The most relevant line for each Treasury is the second roll date, where most basis trading activity seems to be concentrated, and where there is less interference from the delivery month. Here, we can see that across note contracts, futures have been significantly over-priced relative to underlying bonds, with t-statistics regularly well above significance. These t-statistics are also particularly large in 2-year and 5-year futures, due primarily to lower volatility in mispricings at shorter maturities, and are much smaller for bond futures.

Examining the time-series of the price deviations from the no-arbitrage condition around episodes of financial stress suggests a relationship between the arbitrage spread and financial stability. The clearest evidence of this relationship may be events in March of 2020. However, even prior to March 2020 stress, the spread between the futures implied yield and the bill yield seems to be associated with financial stress. One example is the deviation of the bond futures implied yield from the bill yield around the Long Term Capital Management (LTCM) crisis. The bond contract is of particular interest for two reasons. First, the bond contract was much more popular at this time than note contracts which were still being slowly adopted. Second, from The President's Working Group on Financial Markets (1999) we know that LTCM had large Treasury bond positions, but know little about their other positions. The top panel of Figure 2.5 shows that immediately prior to the ruble devaluation, Treasury bond open interest (the grey-shaded area) had been rising. After the ruble devaluation, this open interest began to fall, and at the same time the difference between implied yields and bill rates spiked. The decline in note positions accelerated following LTCM's bankruptcy, and yields spiked even higher. While the available data for this crisis is not nearly as complete as the data we avaiable for the March 2020 crisis, Figure 2.5 is suggestive of the role arbitrageurs like LTCM may have played in the futures market even during previous bouts of instability. The President's Working Group on Financial Markets (1999) suggests that futures positions were not a crucial cause of LTCM's bankruptcy. However, the resolution and unwinding of positions from LTCM may have nonetheless destabilized the Treasury cash and futures markets.

The Lehman Brothers' bankruptcy provides another illustrative example of the relationship between arbitrageur activity and Treasury cash and futures spreads. As with the March 2020

Figure 9: **Treasury bond and note deviations around LTCM's Bailout and the Lehman Brothers Bankruptcy.** The top panel shows the deviation of the futures implied yield of the bond futures as a spread over the bill yield in the period surrounding the LTCM bailout. In gray, we show open interest in the futures contract, with values on the right axis. The bottom panel shows the deviations of the 2-year note yield from the bill yield around Lehman Brothers' bankruptcy. Again, in gray we show open interest in the futures contract, with values on the right axis.

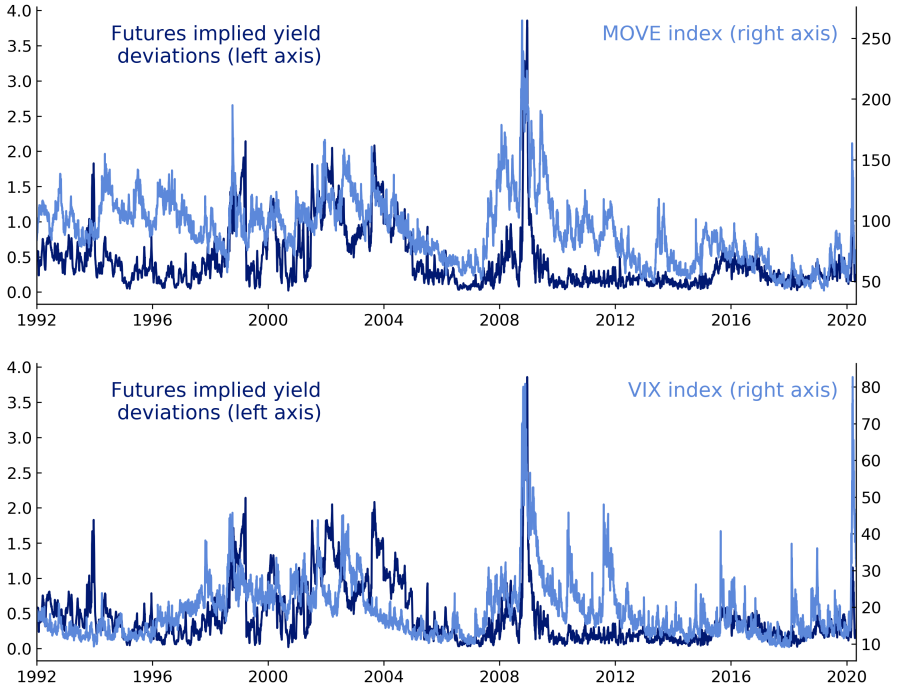


episode and LTCM's default, following Lehman Brothers' bankruptcy, across note contracts futures implied yields deviated sharply from bill yields. In contrast to these other two episodes, however, the Lehman Brothers' bankruptcy was followed by a significant *under*valuation of futures prices relative to cash prices. This is shown in the bottom panel of Figure 2.5. This may have reflected a difference in the nature of the financial crisis. While the LTCM crisis and the March episode were characterized by a flight to liquidity in the form of cash and cash-like securities such as on-the-run Treasuries, the 2008 financial crisis was arguably more of a flight to safety. Counterparty concerns in both the repo market and the futures market may have led investors to generally prefer cash Treasuries where the counterparty was the U.S. government to futures and repo where the counterparties were other financial institutions. The general decline in the availability of repo financing may also have contributed to the undervaluation of futures.

In fact, deviations from arbitrage are highly correlated with volatility in financial markets. Figure 10 shows a time-series plot of the absolute value of the futures implied yield deviations along with two measures of financial market volatility. The top panel shows deviations along with the MOVE index, which is a volatility measure specific to Treasury markets. This index is based off of the implied volatility of Treasury options. As can be seen, the correlation is quite close following the year 2000. However, since the Treasury option market is based off of the price of Treasury futures, it is concievable that this relationship is purely the result of mispricing in Treasury futures impacting the price of Treasury options. The bottom panel shows the same futures implied yield deviations along with the VIX index, which being based off of equity options should not be subject to be any direct relationship through Treasury futures pricing. Again, we see that periods of high volatility coincide with large deviations from arbitrage between Treasury cash and futures markets.

Again, we emphasize that in theory there should be no difference between these two portfolios. Equation (2) should, in the absence of margins on futures contracts, hold exactly. Any regular deviations from this equation imply an apparent deviation from arbitrage. The fact that these deviations are large relative to the underlying variation in Treasury prices is therefore notable, as is the fact that they are sustained and predictable. That these deviations grow larger in times of stress and high volatility in financial markets further suggests the importance of arbitrage activity.

Figure 10: **Absolute value of 5-year note deviations and measures of financial market volatility.** In the top panel, we plot absolute values of the deviation between the 5-year note futures implied yield and the yield on an equivalent maturity bill as well as the MOVE index, with values in light blue recorded on the right axis. The bottom panel has the same values for the futures implied yield, but displays the VIX index in light blue with values on the right axis.



We now turn to how arbitrageurs actually exploit this opportunity in practice, which builds a relationship between the cash-futures disconnect, margins on futures contracts, and the rate at which arbitrageurs can fund their trades in the repo market.

3 Limits to Arbitrage and the Cash-Futures Basis Trade

In the previous section we introduced the disconnect between cash and futures prices of Treasuries, showing that in recent years cash Treasuries have traded at a discount to the prices implied by their discounted coupons and futures prices. We presented an idealized model of arbitrage where agents borrow at the bill rate in order to arbitrage the difference between these two prices. In this section, we explore how arbitrage in this market takes place when agents cannot borrow at the bill rate, and instead must borrow at the repo rate and face margin requirements on short positions. When cash-futures arbitrage is funded in the repo market, it is known as the Treasury cash-futures "basis trade". We will discuss in the next section the explosion in popularity of the trade among hedge funds, and then present a model examines the consequences of the trade for market functioning and systemic risk. Here, we describe the frictions that prevent the basis trade from being true riskless arbitrage.

The first friction is that short bill positions do not represent the funding costs of arbitrageurs who span the cash and futures markets. Shorting Treasury bills is expensive. Actual arbitrage between cash and futures prices therefore uses repo borrowing. Table 7 describes how the arbitrage trade is constructed when repo financing is part of the trade. This is a modified version of Table 4, which described the idealized form of the basis trade. In order to borrow to pay for the long note position, traders borrow in the repo market with the Treasury the note as collateral, ideally matching the tenor of the repo contract to the delivery date of the futures. This results in zero cash flows today. At the delivery date, traders receive the note back from their repo lender, and in return pay back the repo loan plus interest. The note is delivered to meet the short obligation in the futures contract. Any residual cash from the short position above the repo balance is then pure profit for the trader. Using repo borrowing has an additional advantage over short Treasury bills in that if futures prices and note prices increase in tandem, any increase in margin balances can be met with an increase in the value of the underlying collateral. As well as matching common

	Buy τ-maturity note	Borrow against note in repo market	Short τ futures delivering at T	Net cash flow
Time 0	$-P_{0,\tau}$	$P_{0,\tau}$	0	0
Time T	0	$-P_{0,\tau}(1+r)^T$	$F_{0,\tau,T}$	$F_{0,\tau,T} - P_{0,\tau}(1+r)^T$
Time τ	1	0	-1	0

Table 7: **Cash flows from arbitrage strategy with repo.**

practice (see Burghardt and Belton (2005)), this description of using repo borrowing to fund basis positions rather than shorting Treasury bills matches both the formulation of our model and the evidence we present on hedge fund balance sheets.

For the arbitrage relationship between cash and futures prices of Treasuries, the important aspect of the reliance of the basis trade on repo financing is that the rate on repo financing may differ from the yield on a Treasury bill. There are several reasons these two returns may differ. The first is that repo financing has counterparty risk: whether the counterparty in repo is a bank or dealer in the case of uncleared bilateral repo or a central counterparty with a clearing fund in the case of cleared repo, the risk of these private counterparties defaulting is likely to be substantially higher than the risk of U.S. government default on bills. The second is that repo financing uses up the balance sheet capacity of entities like dealers who provide cash to the basis trader, as has been emphasized by He et al. (2020). Finally, in part because repo uses up balance sheet capacity, bills are generally considered to be more liquid than repo, commanding their own premium (see Lenel et al. (2019)).

While the structure of the trade described above assumes the repo tenor is matched to the term of the futures contract, much of the repo financing of the basis trade is likely to be of a shorter tenor. Repo financing is more likely to be overnight than term, and in fact, because of the rarity of term repo trades, reliable sources on term repo rates are difficult to find. One reason that term repo funding may be difficult to obtain is that dealers bear a higher regulatory burden for term repo funding than for overnight funding. As a result, term repo is generally more expensive than overnight repo, and basis traders appear to rely on this overnight funding. This means that for the lifetime of the repo contract, funding must be rolled over on a daily basis, as show in Figure 11. This figure shows the movement of the cash Treasury in a basis trade rolled over nightly across markets and over time. The Treasury is initially received by the basis trader and offered

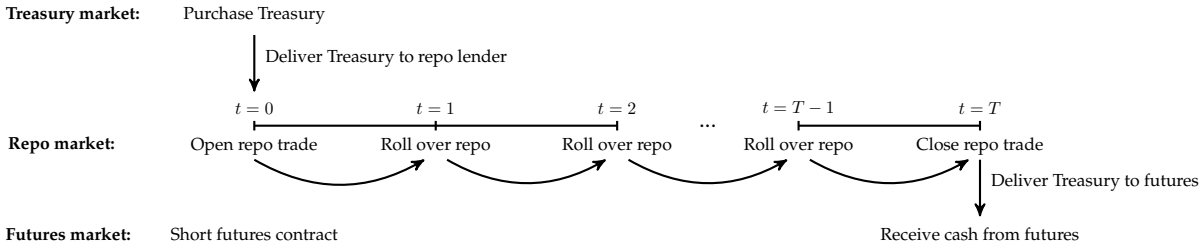


Figure 11: **Diagram of a Basis Trade.** Carrying a Treasury security to delivery to the futures market through the repurchase agreement (repo) market. Arrows denote flow of Treasury security; cash moves in the opposite direction.

as collateral in order to secure a loan to pay for its purchase. The next day, when the loan comes due, the hedge fund rolls over its financing, again pledging the Treasury as collateral against its borrowing. This continues until the delivery data of the Treasury futures, at which point the hedge fund pays off its repo borrowing with the cash from the long futures position. The final amount the hedge fund will have to repay will depend on the repo rate at each intervening day, which is not known in advance. This exposes the basis trade to the risk that the repo rate appreciates over the trade horizon, increasing the principal they have to repay on the delivery date.

Another important limit to arbitrage in the basis trade is the margin requirements on futures contracts. Futures margins are set by the Chicago Board of Trade (CBOT), and require that positions in the futures market are backed by cash in the event of an agent's default. The importance of margin requirements as a limit to arbitrage is underscored by (Brunnermeier and Pedersen, 2008). Margin requirements in futures markets differ somewhat from margins in equity trading or the treatment of haircuts on repo. The first component of futures margin requirements is the value that agents have in their accounts, which is the cash in the margin account plus the value of their open futures positions. The second component is the maintenance margin, which is set by the CBOT. The maintenance margin marks the lower bound on the value of the margin account. Whenever the value of an agent's margin account is less than the maintenance margin, a margin call is made, and agents must top off their margin account or be in default. The amount they must add is the difference between the value of their margin account and the final component of margin requirements for futures contracts, which is the initial margin. The CBOT sets initial margins to 110% of the maintenance margin. In our model, we simplify this setting by assuming that maintenance margins are equal to initial margins, and by exploring a setting where agents do not have an

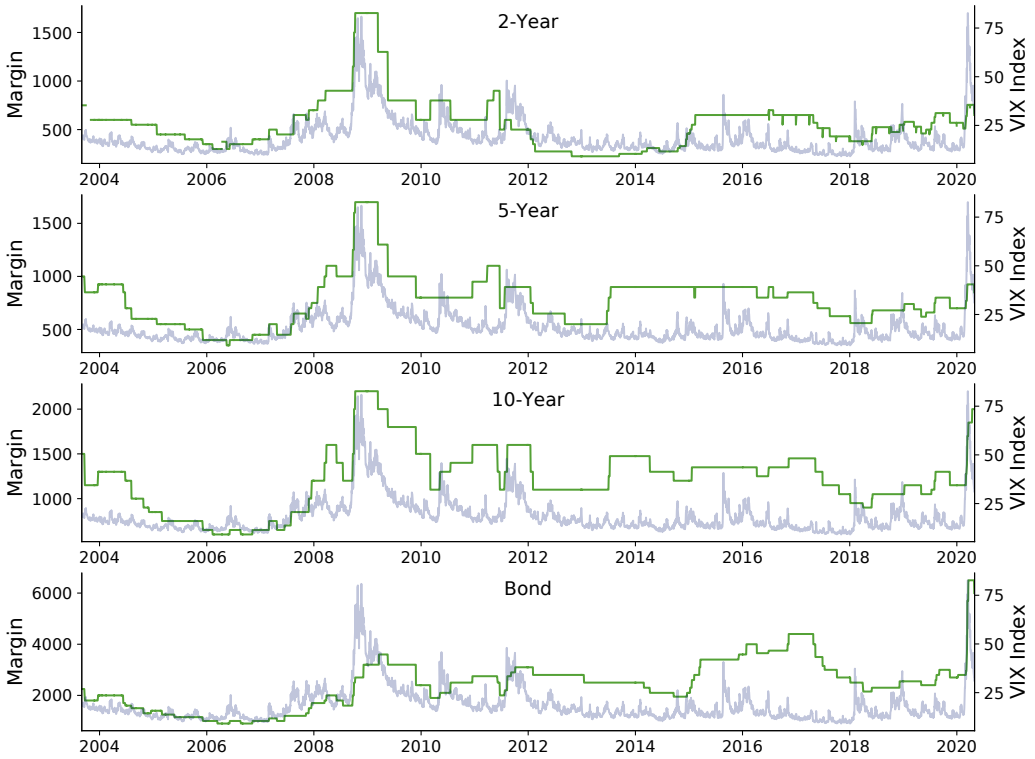


Figure 12: **Margins on futures contracts and the MOVE index.** In green, for each contract, we show the initial margin for the second-to-deliver futures contract, which are recorded on the left axis. In light blue we show the value of the VIX, which are recorded on the right axis.

incentive to keep cash in their margin accounts in excess of the maintenance margin, meaning that any change in the value of the account is either a cash increase or decrease. However, anecdotally traders appear to keep excess cash in their margin accounts in order to avoid margin calls.

The rules for margin setting by the CBOT are somewhat opaque, and give the central counterparty some leeway in the determination of margins, however margins are well correlated with volatility in futures markets. Figure 12 shows the level of variation margins along with the MOVE index. As can be seen, the two are highly correlated, with margins increasing in high volatility times. The highest margin periods have been the 2008 financial crisis and March of 2020. However, with Treasury bonds futures, March of 2020 was the highest margin period, with the second highest in 2017. These particularly high margins on Treasury Bond futures may help to explain why the bond futures contract has been relatively unpopular in recent years. However, in interpreting the relationship between margin on Treasury futures and the MOVE index, it once again important to recognize that the MOVE index is ultimately based on the Treasury futures to which

the margins apply. In Table 8 we show regressions of the maintenance margin on the MOVE index as well as the VIX index. While the MOVE index explains more of the movements in maintenance margins, the VIX index is also significant for all but the bond contract, and the explanatory power of the MOVE and VIX models are roughly similar.

	Dependent variable: Maintenance Margin							
Index	2-Year		5-Year		10-Year		Bond	
MOVE	6.446^{***}		5.084^{***}		6.609^{***}		0.680	
	(1.119)		(0.977)		(1.167)		(2.826)	
VIX		20.745^{***}		16.936^{***}		24.895^{***}		28.149^{**}
		(4.947)		(4.015)		(3.358)		(12.864)
Observations	3,464	3,464	3,268	3,268	3,681	3,681	4,272	4,272
R^2	0.540	0.485	0.435	0.420	0.332	0.418	0.001	0.076
Note:								*p<0.1; **p<0.05; ***p<0.01

Table 8: **Maintenance margins and volatility indexes.** This table reports results for a regression of margins on the second-to-deliver Treasury futures contract on the values of the VIX and MOVE indexes.

It is important to be clear about how margin requirements are likely to affect basis traders. A trader long the basis has a long position in the underlying Treasury in addition to their short position in futures markets. In the absence of haircuts on repo, if Treasury prices move together with futures prices, a margin call on short futures contracts will occur at the same time that the value of long cash Treasuries increases. This increase in the value of Treasuries means that the basis trader can borrow more against their Treasury collateral. It is therefore ambiguous how much of a direct role margin requirements themselves will play for basis traders. In principal, the rise in Treasury prices could exactly offset the rise in the futures price. However, the because the counterparty on the futures contract and the repo contract are generally two different agents, margin requirements may still impact the basis trader, especially when futures and Treasury prices diverge. For a trader long the basis, when the price of the underlying falls relative to the price of the futures contract, the basis trader may have to supply additional cash while their ability to borrow has decreased, requiring them to raise additional funds.

In our model we incorporate both these elements as important drivers of the cash-futures basis. First, liquidity and balance sheet space drive a difference in returns between bills and repo financing. This difference is compounded by the fact that repo financing is of a shorter tenor

than the maturity of the futures contract. Second, margins on futures contracts play an important role both in driving the cash-futures disconnect and in possibly exacerbating the effects of sales of Treasuries to dealers on cash prices. These effects occur through the constraints placed on the major arbitrageurs in the model: hedge funds. We now cover evidence of the extent of hedge fund participation in the basis trade.

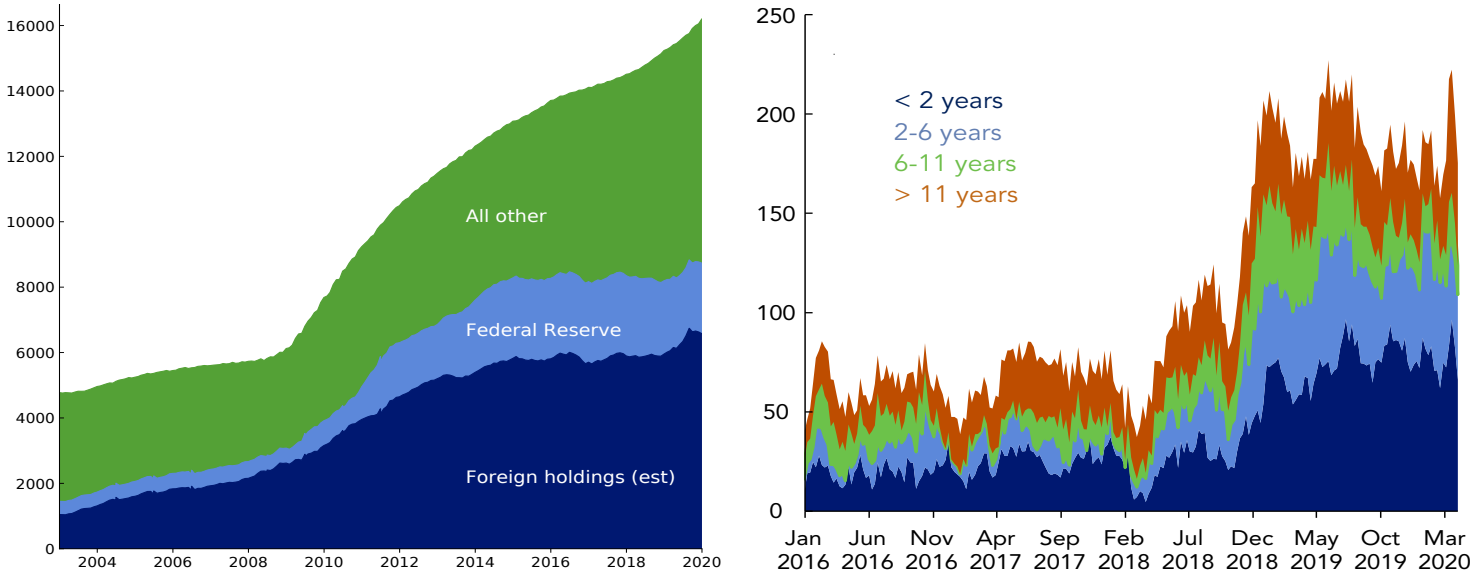
4 Hedge funds and the cash-futures basis trade

In this section, we document the dramatic rise in hedge fund cash-futures arbitrage trading in Treasury markets that began in early 2018. By late 2019, the magnitude of hedge fund basis trade positions were substantial, and constituted not only a significant development in Treasury markets over the previous two years, but also a build-up of vulnerabilities that would prove important for understanding the March 2020 episode and the corresponding regulatory response.

At least two important developments affected Treasury market functioning beginning in 2018. First, in the wake of the Tax Cuts and Jobs Act passed at the end of 2017, Treasury issuance grew significantly, as shown in the left panel of Figure 13. Around this time, the amount of Treasury securities held on dealer balance sheets also rose significantly, as shown in the right panel of Figure 13. Also at the beginning of 2018, restrictions on bank leverage, specifically the Supplementary Leverage Ratio (SLR) and Enhanced Supplementary Leverage Ratio, came into effect. The SLR and eSLR set a minimum value for the ratio of bank equity capital to leverage exposure, and included Treasury securities and net repo exposures in the denominator without any adjustments for the safety of those activities. These simultaneous developments may have affected the elasticity of repo rates with Treasury collateral, which had important implications for the stress in Treasury markets in March 2020, as discussed below.

These market developments coincided with an increased demand for long Treasury futures positions by traditional asset managers such as pension funds and mutual funds, possibly as a cheap way to get duration exposure without holding Treasuries on balance sheet. Figure 14 shows the increase in long futures positions held by traditional asset managers in the 2, 5, and 10 year contracts. Between December 2017 and December 2019, long Treasury futures positions held by asset managers grew from $396 billion to $732 billion, an increase of 85%. The corresponding

Figure 13: **Holdings of Treasuries over time ($ billions).** The left panel of this figure shows outstanding Treasury holdings by category of holder, specifically foreign holdings, Federal Reserve holdings, and holdings by all other investors. The right panel shows primary dealer net Treasury exposures broken out by maturity.



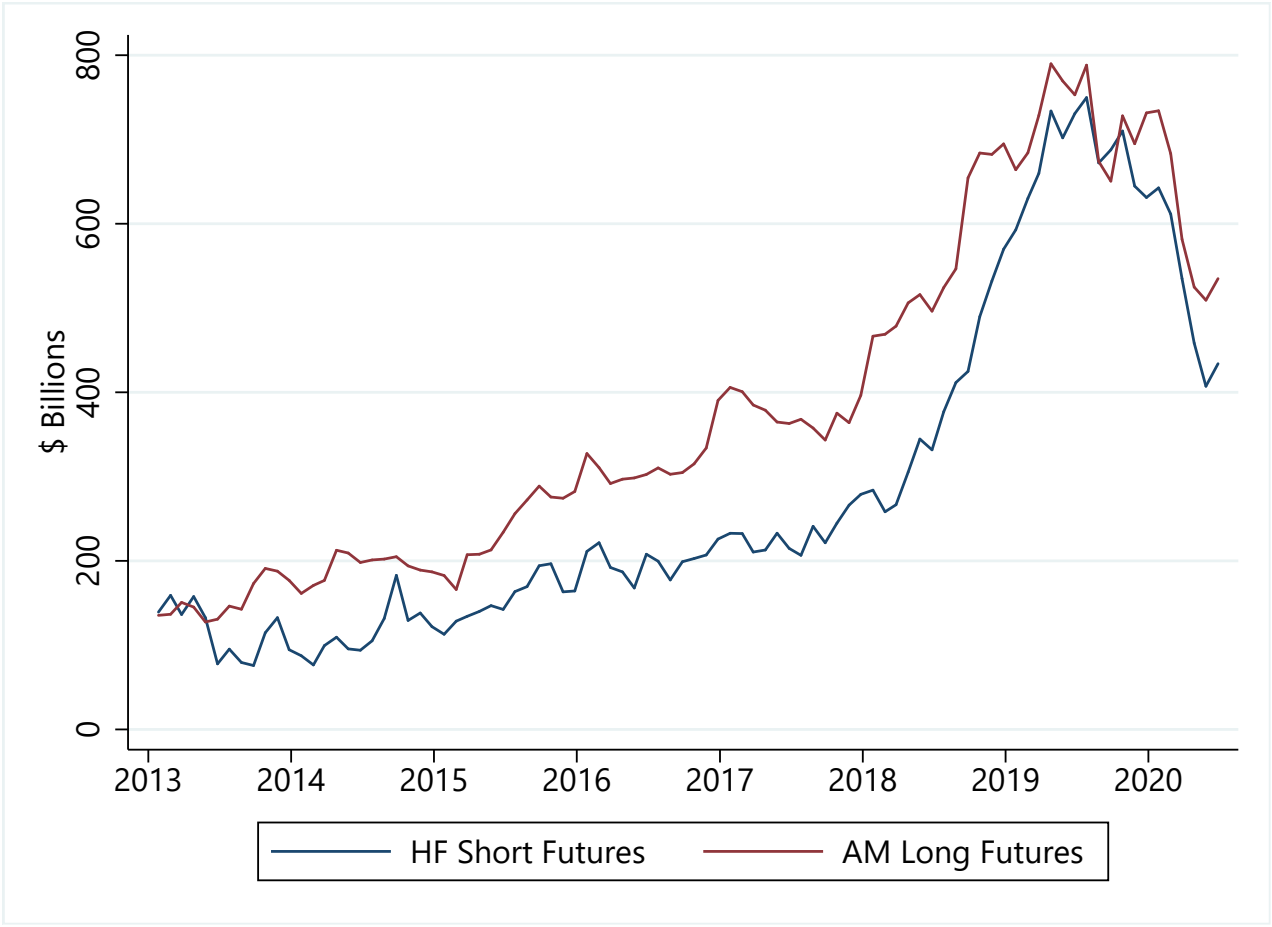
short positions appear to have been taken up predominately by hedge funds. Over the same period, hedge fund short futures positions grew from $279 billion to $631 billion, an increase of 126%.

During this same period total hedge fund Treasury exposure also increased. Using data from the SEC's Private Fund Statistics, the top panel of Figure 15 shows a dramatic increase in Treasury exposure beginning in 2018. We define Treasury exposure as the sum of long and short Treasury positions, which in the Form PF data includes both cash holdings and derivatives.[4] In December 2014, total hedge fund Treasury exposure was $927 billion. By the end of 2017, this exposure was $1.14 trillion, and by the September 2019 had grown to $1.97 trillion.

Form PF also asks funds to report separately their long and short asset class exposures. Com-

[4]Form PF instructs the reporting of derivatives as follows: "for derivatives (other than options), "value" means gross notional value; for options, "value" means delta adjusted notional value; for all other investments and for all borrowings where the reporting fund is the creditor, "value" means market value or, where there is not a readily available market value, fair value; for borrowings where the reporting fund is the debtor, "value" means the value you report internally and to current and prospective investors; and Form PF: General Instructions Page 10 for questions 20, 21, 25, 28, and 35, the numerator you use to determine the percentage of net asset value should be measured on the same basis as gross asset value and may result in responses that total more than 100%."

Figure 14: **Futures contracts of hedge funds and asset managers.** This figure shows total hedge fund short Treasury futures positions and asset manager long positions in notional dollars across all Treasury futures contracts.



bining Form PF short and long Treasury exposures with CFTC data provides evidence that much of the growth in hedge fund Treasury positions was the direct result of the basis trade. This is shown in the bottom panel of Figure 15, which comes from the OFR's 2020 Annual Report and was calculated from the underlying Form PF data. The growth in short Treasury exposure reported in Form PF aligns closely with the increase in short futures positions from CFTC data. However, the increase in the long Treasury exposure comes almost exclusively from cash securities; while long Treasury exposures were growing quickly on Form PF, long futures positions remained relatively flat.[5] Because the basis trade comprises a long cash position and a short futures position, the com-

[5]This takes a small leap of faith. Because the Traders of Financial Futures data reports gross long positions as the

bination of Form PF and CFTC data suggest much of the Treasury exposure growth on hedge fund balance sheets is directly attributable to an increase in the basis trade. In fact, if we assume that every dollar of short futures has a corresponding long position in a cash Treasury note, then 85% of the $830 billion dollar increase in hedge fund Treasury exposures between December 2017 and December 2019 would be attributable to the basis trade.

Additional evidence of a large increase in hedge fund basis trading can be found in the repo positions reported on Form PF, as aggregated in the Private Fund Statistics. Figure 16 shows that prior to 2018 hedge fund repo borrowing and lending were largely matched, and in the second half of 2017 and first quarter of 2018, repo lending was actually larger than repo borrowing. However, beginning in the second quarter of 2018, repo borrowing increased sharply, from $676 billion to $1.18 trillion in September 2019. In contrast, repo lending barely changed, from $690 billion in June 2018 to $662 billion in September 2019. Because the cash-futures basis trade requires only the long note position be financed in the repo market with no corresponding repo lending piece associated with the short leg of the trade (unlike the one-the-run/off-the-run trade that would contain both a repo and a reverse repo for instance), the substantial divergence in repo borrowing and lending offers even more evidence that much of the increase in hedge fund Treasury positions resulted from the basis trade. That this repo divergence corresponds exactly with the total increase in Treasury exposure and the ramp-up in short futures positions further strengthens this interpretation.

The difference in repo and reverse repo also offers a method for estimating the total size of the hedge fund basis trade. If we assume that the entirety of the dollar difference in repo borrowing and lending in September 2019 results from the cash-futures basis trade, this would imply a total basis position of $519 billion for the hedge fund industry as a whole. Of course, this ignores repo haircuts and the price differences between the cash note and the futures contract, which my complicate this estimate. Alternatively, if we assume the total increase in hedge fund short futures positions from December 2017 to December 2019 (combining the 2-year, 5-year, and 10-year contracts) is due to the basis trade, this would imply a total basis trade size of $352 billion by the end of 2019. This lower value is almost surely an under-estimate. CFTC data first nets long

total net long positions (long minus short) of net-long traders, we can't see the true long versus short mix for hedge funds and therefore can't back out the true total cash Treasury positions held on hedge fund balance sheets.

and short futures positions, then reports values in aggregate for funds that are net short and net long. The true gross value of hedge fund short futures positions are not available, which makes estimates based on Form PF data particularly informative.

Even the lower bound estimate of more than $350 billion, accumulated over a less than a two year period, highlights just how important this trade was for Treasury market functioning between 2018 and 2020. It also foreshadows the building possible vulnerabilities in Treasury markets leading into the disruptions in March 2020.

4.1 Evidence from the repo market

The basis trade links hedge funds' cash-futures arbitrage to their borrowing in the repo market. In the preceeding section we used aggregated data to show that hedge fund positions in the aggregate are consistent with a sizeable Treasury cash-futures basis trade. However, this data is limited both in the details it provides on positions and the frequency with which it is updated. In this section, we use data from the OFR's collection of cleared repo data, which allows for a daily, security-specific view of hedge funds' trades. Since the basis trade involves heavy leverage through repo borrowing, this data provides insight on hedge funds' Treasury positions and on their borrowing costs that would otherwise be unavailable.

Hedge fund repo borrowing is highly concetrated in the two bilateral repo markets in the U.S., FICC's DVP Service, which is a cleared bilateral market, and the uncleared bilateral repo market. In these markets, lenders know the exact collateral they are promised by borrowers, and unlike in tri-party markets, there is no custodian bank which locks up collateral in its own account. This allows the collateral to circulate easily, and for dealers to source particularly valuable securities. Hedge funds are a primary source of collateral for dealers in these markets, and the large volumes involved in the basis trade makes this supply crucial.

While the majority of hedge fund repo borrowing likely occurs through bilateral uncleared trades, the sponsored DVP market offers insights not available in the bilateral market. Sponsored DVP is also increasingly important in its own right. At present, hedge funds make up the vast majority of sponsored borrowing (see Figure 17). The Depository Trust & Clearing Corporation first allowed hedge fund participation in sponsored repo in 2017. Such participation increased dramat-

ically after the expansion of sponsorship in April 2019. Recent repo data show that cash provided by money market funds is mostly passed on to hedge funds, so the expansion of sponsored lending provides a hint to the pace of growth in sponsored borrowing. Following the expansion of sponsorship, participation of money market funds in sponsored repo increased dramatically (see Figure 18). This may be associated with increased cash demand by hedge funds in DVP.

In general, rates in the sponsored market for cash borrowers are higher than interdealer rates, which are again higher than the sponsored market for cash lenders. There are two primary reasons for this. First, sponsors are required to guarantee the trades of the entities they sponsor. This means that hedge funds that trade in sponsored markets represent relatively high risk for their counterparties. Second, sponsored borrowers generally borrow early in the day relative to sponsored lenders. Because much of sponsored borrowing uses cash from sponsored lenders, sponsored borrowing creates additional liquidity risk for sponsors. The fact that sponsored borrowing rates are in general above interdealer rates highlights a potential for imperfect pass-through of liquidity-boosting interventions by the Federal Reserve to the borrowing rates of hedge funds, adding an additional layer of liquidity risk to hedge fund basis trades.

If hedge funds were actively basis trading, we would expect them to disproportionately hold the cheapest-to-deliver Treasury notes. Figure 19 shows hedge fund positions in repo by security CUSIP prior to the Dec. 1, 2019, futures delivery date and following that delivery date. The shaded windows in the top panel are the maturity dates of notes eligible for delivery into the December futures contract. Securities just inside this delivery window had significantly more hedge fund repo volume than securities just outside this window. The largest position prior to December 1 was in the two-year window and was for the Treasury security that was cheapest-to-deliver for this contract. After December 1, the position in the cheapest-to-deliver for the two-year December contract had diminished considerably, while positions had expanded for deliverables for the March contract, highlighted in gray in the bottom panel. This is consistent with hedge funds maintaining positions in the cheapest-to-deliver for contracts near to delivery.

5 A limits to arbitrage model of the cash-futures basis

The previous sections have presented a picture of the returns to the cash-futures basis trade, the size of this trade and its particpants. We have shown that Treasury futures prices have been persistently overvalued relative to cash prices in recent years. We have also shown large partipation of hedge funds in the basis trade. This illuminates a part of a larger structure of the basis trade and its role in the structure of Treasury markets, repo markets and futures markets. This role is displayed in Figure 20, which gives a stylized description of how the basis trade functions, with hedge funds purchasing cash Treasuries through dealers in the Treasury market with cash provided to them by money market funds through dealers the repo market. These hedge funds then deliver the Treasury to the futures market on the delivery date, where they are passed on to asset managers, and repay their repo borrowing with cash from the long position. In this structure, hedge funds act as a temporary warehouse for Treasuries, holding them on their balance sheets for other agents in the economy.

Using this general structure of the trade in recent years as a baseline, we now present an equilibrium model of the basis trade. The model focuses on limits to arbitrage across the three markets the basis trade relies on. The model combines aspects of liquidity spirals driven by margins on hedge funds as in Brunnermeier and Pedersen (2008) with preferred habitats and limits to arbitrage on dealers as in Greenwood and Vayanos (2014). The model three purposes: first, to explain the existence of an equilibrium futures implied yield that is higher than the bill rate, second to examine the determinants of hedge funds role as warehouses of Treasuries as in Figure 20, and finally to assess how the basis trade may exacerbate financial instability.

The model delivers three predictions. First, as a result of constraints on dealers and limits to arbitrage, an equilibrium basis can emerge in which the return on holding a Treasury note to delivery in the futures market is higher than the bill rate. Second, the size of hedge fund or levered participation in the basis trade is increasing in the extent of constraints on dealers, and in the demand for futures contracts. Third, basis traders are exposed to margin and rollover risks, which in times of large Treasury sales can exacerbate pressure on dealers. This pressure can be directly counteracted through asset purchases by central banks.

5.1 Environment

There are four periods, $t = 0, 1, 2, 3$. There are two financial assets in fixed supply, a quantity of notes S_N which mature at time 3 and pay off \$1, and bills S_C, each of which last for one period and payoff the next period. The price of a note today which pays off at time 3 is $P_{N,t}$. The price of a note today which will pay one dollar next period is $P_{C,t}$. As in Greenwood and Vayanos (2014), Treasury notes are subject to stochastic demand from habitat investors, $x_{N,t}$. Bill prices follow an exogenous stochastic process where:

$$\log(P_{C,t+1}) = \log(P_{C,t}) - r - \frac{\sigma}{2} + \sigma\epsilon_{t+1} \tag{7}$$

with $\epsilon_{t+1} \sim \mathcal{N}(0, 1)$. This process reflects underlying uncertainty about the short rate.

In addition to these Treasury assets, there are two financial assets in zero net supply: repo and futures. Futures contracts for the Treasury note struck at time $t < 2$ guarantee a price for the delivery of a Treasury note at time 2 of F_t. They come with a margin requirement, m_t. Repo markets are open in each period, where agents can borrow at a price $B_{R,t}$ to repay \$1 repay next period, provide they post Treasury notes as collateral.[6] A haircut of h is applied to these Treasuries.

There are four particpants in these markets. The first are dealers, who are meant to specifically capture dealers in Treasury markets from whom basis traders purchase cash Treasuries. The second are money market funds, who are meant to capture the source of repo loans to basis traders. The third are speculators, who are meant to capture the demands of asset managers for futures contracts. Finally, hedge funds in the model span these three markets and arbitrage differences between them. We now describe each of these particpants in detail.

5.2 Dealers

Dealers follow a form similar to that in Greenwood and Vayanos (2014). They are born at time t with an initial wealth W_t^D, and die at time $t + 1$. They invest in notes in quantity $q_{N,t}^D$ and bills in

[6] Bills are not allowed to be posted as collateral for repo in the model, which matches their low usage as collateral in the data.

quantity $q^D_{C,t}$, in order to solve the mean-variance maximization problem:

$$\mathrm{E}_t\left[P^D_{N,t+1}q^D_{N,t} + q^D_{C,t}\right] - \phi_D \mathrm{Var}_t(P_{N,t+1}){q^D_{N,t}}^2 \tag{8}$$

where ϕ_D is a preference parameter reflecting the disutility of high-variance assets. The set-up of dealers as living for only one period suppresses any possible precautionary motives which would emerge were they truly dynamic. However, it also serves to keep the dealer's problem simple, while preserving the general intuition that high dealer holdings of Treasuries tend to push prices up.

5.3 Speculators

Speculators take a long position in futures in a quantity $q_{F,t}$, and then sell the notes they are delivered once the futures comes due. Like dealers, they are mean-variance optimizers, solving:

$$\mathrm{E}_t\left[P_{N,2} - F_{N,2}\right] q^D_{F,t} - \phi_S \mathrm{Var}_t(P_{N,2}) q^2_{F,t} \tag{9}$$

Note that this objective function implies that expectations hypothesis will not hold, and futures prices will on average converge to spot prices from below.

5.4 Money market funds

Money market funds follow a standard model of liquidity demand. They are restricted to investing in repo, quantity $q^M_{R,0}$, and bills, $q^M_{C,0}$. This restriction follows the actual regulation of money market funds which restricts them to investing in short-term instruments. Therefore the entirety of their wealth is split between these two investments:

$$W^M_t = P_{C,t}q^M_{C,t} + B_{RR,t}q^M_{RR,t} \tag{10}$$

Money market funds act to maximize their end of period wealth plus utility value of repo holdings:

$$\max_{q^M_{C,t}, q^M_{RR,t}} \log(q^M_{C,t} + q^M_{RR,t}) + \omega \log(q^M_{RR,t}) \tag{11}$$

A value of $\omega > 0$ reflects a reduced form version of the liquidity management problem money market funds face. This form is common in the literature on the return to near-money assets (see for instance Krishnamurthy and Vissing-Jorgensen (2012) and Nagel (2016)).

5.5 Hedge funds

A hedge fund has access to notes, maturing in period 3 and paying \$1 with a price $P_{N,t}$ at time t, which it buys in quantity $q^H_{N,t}$. These notes are deliverable into a futures contract at time 2, with price F_t. We will focus on the situation where the hedge fund desires to go short the futures contract, in which case every Treasury they purchase will be delivered into the futures contract. The hedge fund can borrow in the repo market at a price of $B_{R,t}$, promising to repay \$1 in the next period. Repo borrowing faces a time-invariant haircut, h, and futures positions face a margin requirement m_t.

The cash flows to the hedge fund at time 2 are:

$$W_2 = F_0 q_{N,0} - q^H_{R,1} + F_1(q^H_{N,1} - q^H_{N,0}) \tag{12}$$

The first term reflects the futures contract agreed to at time 0. All Treasuries purchased at time 0 must be delivered to the long position in the futures market, and will receive the futures price agreed to at time 0. The second term reflects the repayment of repo balances the hedge fund has accumulated over time 0 and 1. The final term reflects any additional or offsetting contracts agreed to at time 1, which will recieve the price agreed to at time 1.

As in Brunnermier-Pedersen, margin requirements for futures and haircuts for repo limit the extent to which wealth can be used to purchase Treasuries, imposing the constraint:

$$W_t \geq (m_t + h) P_{C,t} q^H_{N,t} \tag{13}$$

This constraint reflects that repo lenders and the long futures position will both require a portion of Treasuries held as equity by the fund against the possibility of the fund's default. At $t = 1$, any margin risk has been realized and there will never be a need for precautionary savings, so in this

case we have:

$$\frac{W_1}{m_1+h} = P_{C,1}q^H_{N,1} = \frac{B_{R,1}q^H_{R,1}}{P_{N,1}-(m_1+h)P_{C,1}}$$

In period 1, we assume that wealth includes not only the price of the Treasury net of repo borrowing, but also the appreciation of the futures' price, which we also assume is discounted to the present at the bill rate

$$W_1 = P_{N,1}q^H_{N,0} - P_{C,1}(F_{N,1}-F_{N,0})q^H_{N,0} - q^H_{R,0}$$

Note that the inclusion of the appreciation of the futures price in wealth reflects the structure of futures margining at the CBOT. For a short futures position, increases in the futures price amount to a decrease in the value of the commitment to sell at that price, and thereby mean a decrease in the equity in the trader's margin account. However, in reality the value of the futures contracts are not discounted. Discounting by the bill rate is a simplification that allows for a simpler solution to the model, but does not qualitatively affect our results.

Assume that the margin constraint is binding at $t = 0$, as will be justified later. Then:

$$W_1 = \left(P_{N,1} + P_{C,1}(F_0 - F_1) - \frac{P_{N,0}-(m_0-h)P_{C,1}}{B_{R,0}}\right) q^H_{N,0}$$

Total dollar purchases (sales) at time 1 will be:

$$q^H_{N,1} - q^H_{N,0} = \frac{1}{m_1+h}\left(F_0 - F_1 + \frac{P_{N,1}}{P_{C,1}} - m_1 - h - \frac{1}{B_{R,0}}\frac{P_{C,0}}{P_{C,1}}\left[\frac{P_{N,0}}{P_{C,0}} - m_0 - h_0\right]\right) q^H_{N,0} \qquad (14)$$

which represents the appreciation in the value of the short futures claims plus the change in the margin requirements due to changes in margins and in the value of the underlying collateral.

The gross return on the original wealth invested by the hedge fund will be the net basis at time 0 multiplied by the leverage achievable on this trade, plus the time 1 net basis multiplied by the

the change in positions at time 1:

$$\frac{W_2}{q_{N,0}} = \left(F_0 - \frac{P_{N,0} - \mu_0}{B_{R,0}B_{R,1}}\right) + \left(F_1 - \frac{P_{N,1} - \mu_1}{B_{R,1}}\right)\frac{1}{\mu_1}\left(P_{N,1} - \mu_1 + P_{C,1}\Delta F_1 - \frac{P_{N,0} - \mu_0}{B_{R,0}}\right) - \frac{P_{N,1}B_{R,0} - P_{N,0} - (\mu_1 - \mu_0)}{B_{R,0}B_{R,1}} \tag{15}$$

Assuming the time 1 net basis remains positive, losses (relative to initial basis) will occur whenever there are sales:

$$\left(\frac{1}{\mu_1} - 1\right)\frac{P_{N,1}}{P_{N,0}} - \frac{1}{\mu_1}\frac{1 - \mu_0}{B_{RR,0}} \leq 0 \tag{16}$$

$$\frac{1 - \mu_1}{1 - \mu_0}\frac{P_{N,1}}{P_{N,0}} \leq \frac{1}{B_{RR,0}} \tag{17}$$

5.6 Market clearing

For the two assets in positive supply, bills and notes, total quantities outstanding must equal quantities held by agents, including the habitat investors:

$$S_N = q^D_{N,t} + q^H_{N,t} + x_{N,t} \tag{18}$$

$$S_C = q^D_{C,t} + q^M_{C,t} \tag{19}$$

For the two assets in zero net supply, quantity demanded must equal quantity supplied:

$$q_{F,t} = q^H_{N,t} \tag{20}$$

$$q^H_{R,t} = q^M_{R,t} \tag{21}$$

As (20) reflects, all hedge fund Treasury note holdings are assumed to be delivered into the futures market.

5.7 Properties of equilibrium

The equilibrium must be derived by working backwards. At time 3, notes and bills both pay off 1 with certainty. Therefore, at time 2, according to the dealers' problem, $P_{C,2} = P_{N,2}$. With this

constraint, all markets will close at time 2. We begin by discussing the behavior of prices at time 1, when hedge funds are constrained by their margin requirements and cannot issue additional equity to meet these demands.

5.7.1 Margin constraints and illiquidity

We begin by discussing the behavior of prices at time 1, when hedge funds are constrained by their margin requirements and cannot issue additional equity to meet these demands. Dealers' Treasury note holdings are determined by their first order condition:

$$q_{N,1}^{D} = \frac{\mathrm{E}\left[P_{N,2}\right] - \dfrac{P_{N,1}}{P_{C,1}}}{\phi_D \sigma_1} \tag{22}$$

For dealers to hold more Treasury notes prices must fall to compensate them for the short-rate risk they are taking on above the one-period bills. The more risk-averse dealers are, the more prices must fall.

Hedge fund holdings are determined by their margin constraints and wealth, which in turn are a function of the basis at time 1. We consider the joint demand for Treasury notes from hedge funds and the speculators they hold notes for. This leads to the expression:

$$q_{N,1}^{H} = \left(\frac{F_0 - E[P_{N,1}] - \dfrac{P_{N,0} - P_{C,0}(m_0 + h)}{P_{C,1} B_{R,0}} + \dfrac{P_{N,1}}{P_{C,1}}}{m_1 + h - \phi_S \sigma_1 q_{N,0}^{H}} \right) q_{N,0}^{H} \tag{23}$$

Note that the sign of the effect of Treasury note prices on hedge fund holdings depends on the sign of $m + h - \phi_S \sigma_1 q_{N,0}^{H}$. This is due to the effect of Treasury cash prices on futures prices. If $m + h < \phi_S \sigma_1 q_{N,0}^{H}$, then along this curve Treasury note prices falling lead to the basis tightening, and hedge fund holdings must increase. If $m + h > \phi_S \sigma_1 q_{N,0}^{H}$, then along this curve Treasury note prices falling leads to the basis widening, and hedge fund holdings must decline.

Theorem 5.1. *For small enough initial holdings of Treasury notes by hedge funds, in particular if* $q_{N,0}^{H} < \frac{m_1 + h}{\phi_S \sigma_1}$*, then: :*

1. *Hedge fund holdings are increasing in the price of notes,* $P_{N,1}$.

2. *The ratio of hedge fund holdings to dealer holdings is increasing in the price of notes.*

Equilibrium in the notes market requires that the demand from hedge funds and dealers equal the supply of notes S_N less the exogenous demand from habitat investors $x_{N,1}$. The net demand curve will be:

$$S_N - x_{N,1} = \left(\frac{F_0 - \frac{P_{N,0} - (m_0 + h)P_{C,0}}{B_{R,0}P_{C,1}}}{m_1 + h - \phi_S q^H_{N,0}\sigma_1} \right) q^H_{N,0} + \frac{m_1 + h - (\psi_D + \psi_S)\sigma_1 q^H_{N,0}}{\phi_D \sigma_1 \left(m_1 + h - \phi_S \sigma_1 q^H_{N,0} \right)} \left(\mathrm{E}_1[P_{N,2}] - \frac{P_{N,1}}{P_{C,1}} \right) \tag{24}$$

The first term reflects the value of wealth hedge funds take on, the second term reflects the relative cost of hedge funds and dealers for taking on Treasuries in order to close the gap between their expected future price and their price today.

The corresponding equilibrium dealer and hedge fund holdings of notes are:

$$q^D_{N,1} = (1 - a)(S_N - x_N) - b q^H_{N,0} \tag{25}$$

$$q^H_{N,1} = a(S_N - x_N) + b q^H_{N,0} \tag{26}$$

where:

$$a = \frac{\phi_D \sigma_1 q^H_{N,0}}{m_1 + h - (\phi_D + \phi_S)\sigma_1 q^H_{N,0}} \qquad \text{and} \qquad b = \frac{F_0 - \frac{P_{N,0} - (m_0 + h)P_{C,0}}{B_{R,0}P_{C,1}}}{m_1 + h - (\phi_D + \phi_S)\sigma_1 q^H_{N,0}} \tag{27}$$

Note that a represents the ratio of the marginal cost of dealers for hedge fund balances, divided by the marginal cost of hedge fund balances in the basis trade and marginal cost of dealers. It therefore represents the relative ability of dealers and hedge funds to take on Treasury notes. Meanwhile, b represents the sensitivity of hedge fund wealth to note prices.

With these equilibrium quantities in hand, as well as the first order conditions for dealers and speculators, we can derive a statement of the equilibrium size of the basis at time 1:

$$\frac{F_1 - \frac{P_{N,1}}{P_{C,1}}}{\sigma_1} = \left(\frac{(m_1 + h)\phi_D}{m_1 + h - (\phi_D + \phi_S)\sigma_1 q^H_{N,0}} \right) (S_N - x_{N,1}) - (\phi_D + \phi_S) b q^H_{N,0} \tag{28}$$

Note again the central role of the spread of the margin over the marginal disutility of another

Treasury for dealers and speculators.

Theorem 5.2. *For small enough initial holdings of Treasury notes by hedge funds, in particular if* $q^H_{N,0} < \frac{m+h}{\sigma_1(\phi_S+\phi_D)P_{C,1}}$*, then:*

1. *Equilibrium dealer holdings,* $q^D_{N,0}$*, are* ***increasing*** *in sales by habitat investors.*
2. *The basis,* $F_1 - \dfrac{P_{N,1}}{P_{C,1}}$*, is* ***increasing*** *in sales by habitat investors.*
3. *Price sensitivity to sales is larger with hedge fund trades than if dealers took on Treasuries alone.*

In this case, sales of the basis by hedge funds exacerbate sales by preferred habitat investors. The exacerbating role is the result of the margin constraints on hedge funds. As dealers take on more Treasuries, the price of Treasuries falls. As a result, the basis widens, reducing hedge funds wealth. Hedge funds are then forced to sell Treasuries to meet their margins, amplifying the effect of sales on prices. This amplification is of a similar form as the doom-loop in Brunnermeier and Pedersen (2008).

6 Empirical evidence of limits to cash-futures arbitrage

In this section we test some of the equilibrium relationships predicted by our model. These statistics illustrate how limits to arbitrage affect the cash-futures disconnect. In particular, consistent with our model, we show 1) funding costs of arbitraguers are correlated with the cash-futures disconnect, 2) measures of Treasury volatility are associated with larger deviations from arbitrage, and 3) the quantity of Treasuries on dealer balance sheets are associated with the cash-futures disconnect. All three of these facts illustrate not only the direct role of limits to arbitrage, but also the central role that the balance sheet costs of Treasuries play in the trade. As we will discuss in the next section, in March of 2020, repo markets saw simultaneously high funding costs, volatility, and a surge of Treasuries on dealer balance sheets, leading to a breakdown in the trade.

One of the main mechanisms of the model in generating the cash-futures disconnect is the difference between bills and repo financing. To examine this, in Figure 22 we show the arbitrage spread along with the spread between the GCF Treasury Index and the interest rate on excess

reserves. The GCF Treasury index is not ideal for this exercise since it is an inter-dealer rate: most hedge funds either borrow in DVP sponsored repo or in uncleared bilateral repo markets. While we use data from DVP repo for some sections of this paper, our sample is limited to the beginning of the OFR's collection in 2019. GCF is therefore the closest available rate for which we have a long time-series. We take the spread over the IOER as an example of an overnight unsecured rate. While few agents have direct access to the IOER, it is a safe overnight and unsecured rate. It is therefore comparable to GCF rates.

Even with these caveats, the relationship between repo rates and futures implied yields is strong. The 2-year and 5-year implied yields are the clearest correlation, particularly during the period between 2015 and 2020, with both repo rates and futures implied yields relatively high between 2015 and 2017, low from 2017 to 2018, and rising again after 2019, peaking in March of 2020. Similar, although more noisy patterns can be seen for the 10-year note contract and the bond contract. In the first row of Table 9, we show a regression of the arbitrage spread on the spread of repo rates over the IOER from 2010 to 2020. In order to control for any term premia in the arbitrage spread, we include fixed effects for the distance to delivery of the contract, allowing for an arbitrary pattern over the life of the contract. For all contracts, the GCF spread is a highly significant predictor of the arbitrage spread, with higher GCF rates predicting higher arbitrage spreads. This is in line with the importance of arbitrageur's funding costs in driving the overvaluation of futures relative to cash Treasury prices.

One simple interpretation of these results is that arbitrage between futures positions and cash positions require that the cash position must be carried to delivery. In the simplest model of this arbitrage, the spread between the futures and cash position is made up entirely of the cost of carry. While the bill rate represents a portion of this cost of carry, bills differ from Treasury notes in two related respects. First, bills are generally considered to be more liquid than Treasury notes, leading to a liquidity premium for bills. Second, the owners of bills tend to be different from the owners of notes: most bills are held by short-horizon investors such as money-market funds. Most notes are held by pension funds, insurance funds, and longer-term investors. If these two markets are segmented, and arbitrage between bills and notes is limited, the cost of carry for notes will deviate from the bill yield, and will reflect in part the funding costs of arbitrageurs in the form of the repo

	Dependent variable: Arbitrage Spread							
	2-Year		5-Year		10-Year		Bond	
GCF - IOER	0.299***		0.355***		0.524***		0.296**	
	(0.092)		(0.122)		(0.196)		(0.122)	
Dealer exposure		1.127***		1.737***		2.233***		1.444***
		(0.298)		(0.361)		(0.374)		(0.332)
Observations	2,154	446	2,001	416	2,014	422	2,582	535
R^2	0.136	0.353	0.119	0.323	0.141	0.319	0.078	0.245
Adjusted R^2	0.081	0.158	0.071	0.156	0.089	0.118	0.031	0.067
Note:				*p<0.1; **p<0.05; ***p<0.01				

Table 9: **Regression of arbitrage spreads on the repo rate.** This table shows results of a regression of the spread between futures implied yields and equivalent maturity bill yields on either the spread of the GCF repo index over the interest rate on excess reserves or dealer Treasury exposures. Fixed effects are included to account for the days to deliver of the futures contract. Errors are calculated using Newey-West with a 14-day lag.

rate.

The model we present highlights that an important driver of both arbitrage spreads and spreads between unsecured and secured financing can be the exposure of dealers to Treasuries. When dealers carry large amounts of Treasuries on their balance sheets, they demand extra compensation to carry more. In the second row of Table 9, we replace the spread of GCF over the IOER with the net coupon Treasury exposure of primary dealers, which we take from the Federal Reserve Bank of New York's Primary Dealer Statistics. This data is available bi-weekly, so we have far fewer observations. However, Table 9 shows a consistent effect across contracts of dealer Treasury exposure on the cash-futures disconnect. Higher dealer exposure leads to cash Treasuries being discounted relative to futures. This is consistent with the mechanism in the model where rising dealer carry costs cause a greater spread between cash and futures prices. This second column is arguably more directly relevant to our model, since the relationship between dealer Treasury exposure and the cash-futures disconnect is a direct prediction of the model, whereas the focus of the model is on hedge fund repo rather than inter-dealer repo.

Next, we examine the effects of margins and volatility on the cash-futures disconnect. The effect of the repo rate on short and long positions is symmetric. If repo borrowing is expensive, shorting the basis is cheap as lending will command higher returns. However, if repo borrowing is expensive, going long the basis is expensive, since there will be more compensation for borrowing

against the cheapest-to-deliver. Repo borrowing costs should therefore not only predict the size of any deviations of cash prices from futures prices but also their size. On the other hand, margin requirements apply equally to long and short Treasury futures positions, making both more expensive. Therefore, high margins are likely to predict high deviations from arbitrage, but not their sign. Indeed, if we include margins in the regression in Table 9, they are not regularly statistically significant nor do they have a consistent sign across contracts.

	Dependent variable: |Arbitrage Spread |			
	2-Year	5-Year	10-Year	Bond
Maitenance margins	0.051	0.450***	0.214**	0.070***
	(0.075)	(0.127)	(0.103)	(0.024)
Dealer exposure	0.897***	1.192***	0.556***	0.733***
	(0.200)	(0.262)	(0.211)	(0.281)
VIX	0.665***	0.271	0.640***	1.555***
	(0.155)	(0.225)	(0.242)	(0.396)
Quarter end	−0.030	0.018	0.042	−0.014
	(0.038)	(0.051)	(0.063)	(0.067)
Observations	446	416	422	535
R^2	0.423	0.292	0.247	0.365
Adjusted R^2	0.243	0.109	0.015	0.210
Note:				*p<0.1; **p<0.05; ***p<0.01

Table 10: **Arbitrage deviations, margins and the VIX.** This table shows results of a regression of the absolute value of the spread of futures implied yields over equivalent maturity bill yields on maintenance margins for the contract as well as dealer Treasury exposure, the VIX and a dummy for quarter ends. Fixed effects are included to control for the distance to delivery of the futures contract. Errors are calculated using Newey-West with a 14-day lag.

On the other hand, margin requirements do seem to affect deviations from arbitrage - that is the absolute value of the spread between futures implied yields and the bill yield. Table 10 shows the results of regressions of the deviations from arbitrage on the level of maintenance margins, the VIX index, dealer Treasury exposures, a quarter end dummy, and a set of fixed effects for days to delivery. Maintenance margins are significant for all contracts except the 2-year, where margins are generally significantly smaller, and across these contracts higher margins are associated with higher deviations from arbitrage. This is suggestive that margin requirements play a role in deviations from arbitrage.

Independently from margins, the VIX index also appears to affect arbitrage spreads. There

are two possibilities for this association. First, the current level of margins is not a basis traders' primary concern. Instead, their concern is over futures margins and any margin calls that may result. The VIX index may capture both some of these future margins and also some underlying Treasury volatility, which makes margin calls more likely. Second, the VIX index may capture limits to arbitrage on other participants in cash Treasury and futures markets. In our model of the basis trade, the sources of arbitrage spreads are a function of limits to arbitrage on dealers and asset managers who affect segmentation across these markets. In many models of limits to arbitrage, including our own, volatility also impacts the ability of these agents to close spreads among these assets in addition its affect on margins.

Table 10 also presents an interesting contrast between the arbitrage trade we study and other studies of arbitrage deviations and the repo market. Many of these papers have focused on quarter end deviations from arbitrage. For instance, Du et al. (2018) highlights the effects of quarter ends in increasing the level of CIP deviations, and He et al. (2020) focuses on the effects of quarter ends on repo rates. We do not find similar affects for the cash-futures arbitrage spread, even when including interaction terms for different periods. We believe this represents the specific factors affecting the cash-futures basis. Quarter end periods are a focus because they tend to feature a pull-back of arbitrage capital from foreign banks concerned about their quarterly filing deadlines. The fact that quarter ends do not appear to have a consistent affect on arbitrage spreads across contracts highlights the roles of the specific arbitrageurs involved in a trade on the pattern of deviations from arbitrage. In contrast to CIP deviations, we show that the arbitrageurs in the cash-futures basis are largely hedge funds, who are not likely to face these quarter end incentives.

7 Cash-Futures Basis Trades and March Treasury Illiquidity

A key prediction of the model is that during times of stress, hedge fund basis trades can amplify stress that results from sales of Treasuries by other investors. In March of 2020, selling pressure by real money investors in the Treasury market brought on by the COVID-19 pandemic led to pressure on dealers' balance sheets, increasing Treasury volailitiy while decreasing prices. In addition to the direct margin requirements for hedge funds that were caused by these decreasing prices, the CBOT also increased maintenance margins on Treasury futures in response to rising volatility.

Due either to margin calls or prudential risk management by hedge funds, sales of the basis trade resulted, with hedge fund futures positions declining sharply by mid-March. Simultaneously, repo rates increased, and arbitrage deviations between cash and futures prices widened.

These developments were consistent with the amplification mechanism outlined in our model, suggesting hedge funds' sales of the basis may have exacerbated stress in the Treasury market. However, we present suggestive evidence that well-timed actions by the Federal Reserve were essential to minimizing the amplification of Treasury market stress through sales of the basis. Purchases of Treasuries by the Federal Reserve and expansions of their repo facilities eased the impact of sales on dealers, and provided a guarantee of a buyer for cheapest-to-deliver securities. This is consistent with our model, where repo facilities and purchases by the Federal Reserve can directly offset selling pressure from preferred habitat investors, short-circuiting margin spirals. The mechanism in our model is then suggestive both of the importance of these Federal Reserve actions and the possibility that, absent these actions, the impact on Treasury markets might have been much worse.

7.1 Onset of Treasury market illiquidity

In early March 2020, Treasury market liquidity decreased. As yields fell, volatility spiked, according to multiple option-implied indexes (see Figure 23). At the same time, bid-ask spreads began to increase, concentrated in off-the-run Treasuries (see Figure 24). Standard spreads associated with liquidity risk, such as the on-the-run off-the-run spread, also spiked. These indicators are consistent with a general flight to liquidity, with investors selling off-the-run Treasuries and either holding the proceeds as cash or purchasing more-liquid on-the-run Treasuries that could be more readily converted into cash.

The illiquidity in Treasury markets seems to have been spurred by large sales from foreign and domestic real money investors, particularly foreign central banks and domestic mutual funds. Sales by domestic mutual funds have been highlighted by Pastor and Vorsatz (2020). Less attention has been paid to foreign official accounts. Treasury International Capital System data show that net decreases in foreign Treasury positions were around $257 billion in the month of March,

with a decrease of $147 in foreign official accounts.[7] Data from the Federal Reserve's Factors Affecting Reserves, which provide a higher-frequency view of foreign official custody holdings with the Federal Reserve, suggest these sales began in the last weeks of February, as shown in Figure 25. These sales were likely made in order to build up dollar buffers for foreign central banks for currency interventions as well as spending. The later addition of swap lines by the Federal Reserve allowed foreign official accounts to build these buffers without the need for greater selling of Treasuries.

Sales from these foreign official accounts may have had particular importance for Treasury market illiquidity. Primary dealers are required to make "reasonable" markets for sales of Treasuries by these accounts. Additionally, as Figure 25 shows, the funds from these sales seem to have been invested in significant part in the Federal Reserves foreign repo pool. This effect is outlined in Figure 26. When a domestic agent sells Treasuries to a dealer and invests the proceeds in a domestic bank account, these funds can still be made available to the dealer to fund the Treasury purchase through the repo market. When a foreign seller invests the proceeds of a sale into the foreign repo pool, reserves are effectively removed from the system, potentially making repo financing of Treasuries more expensive. While large increases in reserves provided by the Federal Reserve may have blunted the impact of the pool on the availability of funding, on the margin the foreign repo pool may still have had a deleterious impact on Treasury liquidity by making repo balances more expensive.

As our model highlights, the immediate effect of these sales by real money investors on Treasury prices occurred because they increased the Treasury exposure of dealers. In our model, even without hedge funds to amplify Treasury market stress, a sudden increase in Treasury sales will cause Treasury prices to decrease. Making markets requires dealers to hold inventories of the Treasuries in which they make those markets, with accompanying regulatory and balance sheet costs. As Figure 27 shows, leading into March, primary dealers already had elevated exposure to Treasuries, which had begun to rise in late 2018. Sales in the Treasury market increased this exposure, especially to the shortest and longest residual maturity Treasuries. Without immediate buyers, these Treasuries remained on dealers' balance sheets and made the dealers hesitant to

[7] Unlike other figures from TIC, these figures, which come from the Major Foreign Holders of Treasuries data are likely to exclude hedge funds domiciled abroad.

create markets in these off-the-run Treasuries.

7.2 Stress in hedge fund basis trades

Treasury market illiquidity had an immediate effect on basis trades. One feature our model highlights is the importance of margins in the amplification of Treasury market stress. This was mirrored in events in March. The price movements and volatility induced by Treasury sales led to increases in maitenance margins on Treasury futures. Figure 28 examines these increases in maitenance margins around March stresss. The figure is created from the point of view of a trader short the Treasury futures contract. The gray area represents the size of margins, while the blue line is the change in price of a $200,000 notional 2-year contract. When the blue line goes beyond the gray area below zero, the increase in Treasury price exceeds the maitenance margin for the short-position. A trader short the futures contract who held no cash in their margin accounts beyond the maitenance margin would then face a margin call. When the blue line goes beyond the gray area above zero, the decrease in Treasury price exceeds the maitenance margin for the long-position. A trader *long* the futures contract who held no cash in their margin accounts beyond the maitenance margin would then be faced with a margin call.

Leading into March, volatility increased in Treasury prices, matched by volatility in futures prices. Just prior to the beginning of March, price movements were large enough that maintenance margins were breached, meaning that the single day price movement was larger than the maintenance margin set by the CBOT. To give a sense of the surprise of these price movements, the green area denotes the range of 95% of the daily price movements in 2019, the price movements which breached these margins were far larger than those bounds. As a result, the CBOT began increasing margins. On March 9th, margins were again breached, leading to an additional increase in maitenance margins. During the peak of stress in Treasury markets, these margins also reached their peak, and remained high through early May. This pattern held across Treasury futures contracts. From February 28 to March 16, across Treasury note futures contracts margins rose by more than 30 percent, while margins on bond futures more than doubled, corresponding to their longer duration.

It is important to note that these breaches of maintenance margins do not necessarily corre-

spond to margin calls on positions. In general, hedge funds keep funds in their margin accounts in excess of maintenance margins as a matter of risk management. It is therefore difficult to assess the probability that hedge funds faced margin calls or the size of any margin call they may have faced. However, even when hedge funds do not face margin calls directly, increases in maintenance margins increase the effective cost of positions in Treasury futures, and will therefore still lead to hedge funds being less likely to take on basis positions all else being equal.

The imperfect nature of pass-through within repo markets may also have contributed to the losses on basis positions. Figure 29 illustrates the pass-through of federal funds rate target changes onto the repo rates for sections of the DVP market. In the top panel, we present the spread of DVP rates over the federal fund's target rate. We have split these rates into three segments, the sponsored lending segment, which is largely money market funds lending to banks and dealers, the inter-member market, which is dealers and banks borrowing from and lending to each other, and the sponsored borrowing market, which as we have shown is largely hedge fund borrowing from dealers and banks. The two black lines show the rates on the Federal Reserve's repo (RP) and overnight reverse-repo facilities (ON-RRP), which since September 2019 the Fed uses to control rates in the repo market and to enact monetary policy. In the bottom panel, we show volumes in these facilities. As we discuss, volumes in these facilities effectively controlled rates up until March.

Prior to March, these facilities provided tight control over rates in the inter-dealer and sponsored lending sections of the market. The repo facility gives dealers an outside option from which to borrow. When this ceiling is effective, dealers in the interdealer market will not be willing to accept rates higher than the RP facility. Indeed, the interdealer rate prior to March stays near the ceiling set by this facility. At the same time, the ON-RRP facility gives an outside option to money-market funds. Funds can lend to the Federal Reserve overnight and receive the ON-RRP rate, and will therefore be unwilling to accept lower rates. Since the majority of sponsored lenders are money-market funds, rates in this market stay near the floor set by the ON-RRP facility. This is true even as the facility rates were adjusted in late February. Repo rates rise nearly one-for-one with the increase in these rates relative to the Federal Funds target at this date.

At the beginning of March, two vulnerabilities of this system were exposed. The first is that the

RP facility had limited volume. As liquidity became scarce, volume in the RP facility increased, as can be seen in the shaded areas of Figure 29. This resulted in the weighted average rate on the repo facility being driven up beyond the minimum in auctions, which can be seen in the periods in which the black RP facility line spikes up. During these periods, interdealer rates in DVP also rose beyond the upper bound, as dealers who did not recieve funding from the RP facility had to fund themselves at higher rates. In the brief period during which the RP facility was not breached, rates fell low enough that they were below the floor set by the RRP facility, and money-market funds instead turned to the Fed facility.

The second vulnerability was that there is no direct means for hedge funds to access liquidity provided by the Federal Reserve. Instead, they must recieve their funding through dealers and banks, and so are only indirectly supplied with liquidity by the Fed. Prior to March, the premia hedge funds were charged was relatively constant over interdealer rates. Entering March, these premia increased, reaching a peak around the peak of Treasury illiquidity on the 17th. Hedge funds borrowing in DVP were therefore exposed both to the increase in the cost of funding for dealers and also to increases in the spreads charged over that financing cost. On the 17th in particular many hedge funds in DVP recieved extremely high rates for their repo funding, therefore making it costlier to carry the basis trade through this period of illiquidity.

In March, the two primary risks of the basis trade were realized. Margins increased, at a minimum increasing the costs of maintaining basis positions, and possibly causing margin calls, while funding through the repo market became more volatile, increasing rollover risk for trades funded in the repo market. As a result, it seems, hedge funds began to unwind their basis trade positions.

7.3 The unwind of hedge fund basis trades

Margin calls and repo rate uncertainty may have forced an accelerated decline of hedge fund short futures positions (see Figure 30). In particular, total hedge fund shorts declined from $774 billion in face value to $684 billion between February 18 and March 17, with particularly large declines of around $71 billion in the 2-year contract.[8] Some portion of this decline preceded March, with total

[8]There are two ways to reduce futures exposure: for contracts maturing in March, hedge funds may have simply not rolled over into the June contract. For contracts maturing after March, hedge funds would have to take on offsetting

shorts declining by $25 billion between February 18 and March 3, which may have represented some foresight of the stress that potential spread of COVID-19 to the United States could put on Treasury markets.

The variation margin payments on the futures contract were not fully offset by the increase in prices in the long note position. Futures prices rose more quickly than cash prices and remained elevated relative to recent history (see Figure 31). This also served to increase the cash-futures basis, leading to losses for basis traders who were long the basis.

In combination, Treasury illiquidity and imperfect repo pass-through led to a large disconnect between the implied repo rate and Treasury bill yields across contracts. The IRR followed the bill rate until early March, but then quickly diverged as the two-month Treasury yield fell while the IRR rose (see Figure 32). This departure began as the bill rate rapidly moved below the DVP sponsored borrowing rate and these trades became less profitable. The spread between the IRR and bill yields then increased, rising well above the average over the last two years, and falling around two percent per annum (see Figure 33). This disconnect peaked around March 17 when the Fed intervened (see discussion below), and then began to normalize with the IRR falling back into line with both the bill rate and actual repo rate.

While we are unaware of any hedge fund defaults associated with the basis trade during this illiquidity episode, many of the risks of the basis trade appear to have materialized during March. Large sales from foreign central banks and asset managers put pressure on dealer balance sheets, raising Treasury price volatility, margins on Treasury futures, and increasing uncertainty on repo rates with Treasury collateral. In response, hedge funds appear to have reduced their basis positions, selling cash Treasuries and purchasing offsetting long futures contracts. These facts suggest that the Treasury market may have been on the precipice of even greater disruptions. However, in the next section we show that the security most heavily connected to the basis trade continued to show signs of liquidity during the period, suggesting that while hedge fund sales may have contributed to stress, they were unlike to be the proximate cause of instability leading up to the March 17 intervention.

long positions.

7.4 Signs of liquidity in the cheapest-to-deliver

The large size of the basis unwind does not in itself indicate the effect of these trades on Treasury liquidity. Rather, there is evidence that the basis trade continued to provide liquidity through March.

In particular, the deliverability premium increased dramatically in the stress period of March. Figure 35 shows the premium of the June cheapest-to-deliver for all Treasury contracts over 2020. These deliverable spread increases coincided with increases in bid-ask spreads across Treasuries. THey reached their peak during the height of Treasury market stress, between March 11 and March 17. The spreads were highest on the Treasuries most popular in the basis trade, the 2-year, 5-year and to a lesser extent the 10-year, and had generally decreased by the beginning of April as stress in the Treasury market fell.

Moreover, this liquidity premia was tightly concentrated in the cheapest-to-deliver Treasuries. Figure 34 shows the fitted and actual yields across Treasuries on March 11, the height of the illiquidity. Deliverable maturities are highlighted in gray, while deliverable Treasuries are shown in green, and non-deliverable Treasuries in light blue. The dark blue line shows the fitted values from the spline model for each maturity, and the shaded blue area denotes the 95% confidence interval for the fitted curve. For the 2-year and 5-year the cheapest to deliver are the lowest maturity of the green dots, which are both well outside the confidence interval for the fitted curve. suggesting their price is significantly different from what would be expected given the prices of similar Treasuries. While the second-cheapest to deliver for the 2-year also has a significant error, the prices of other deliverable Treasuries generally fall within the standard error bounds. This is consistent with the importance of the cheapest-to-deliver in the trade during this month.

That the deliverability premium increased during March runs counter to the narrative that sales of the basis directly harmed Treasury liquidity. If selling pressure from hedge funds exiting the basis trade had significantly harmed Treasury liquidity, we would expect the price of the cheapest-to-deliver securities to have fallen relative to comparable securities as dealers accumulated large net exposure to these specific Treasuries. That the premium rose suggests that any selling pressure was offset by the liquidity that the basis trade provides and the link it establishes

to futures markets.[9] This link may have become particularly valuable during the general flight to liquidity during March, and reduced pressure on dealers purchasing the cheapest-to-deliver.

As a result, while the general evidence points to sales of the basis by hedge funds during March, we do not find evidence that these sales in turn caused greater illiquidity in the Treasury market. While many of the risks of this trade seem to have materialized, evidence of spillovers into Treasury liquidity and short-term funding disruptions are limited. Yet, had liquidity not returned to the Treasury market when it did, and had repo rates not fallen, the consequences for relative value hedge funds likely would have been much worse. With this in mind, we turn next to the impotance of the Fed's actions to restore normal Treasury market functioning.

7.5 Effect of Federal Reserve actions

Timely intervention by the Federal Reserve may have been crucial for limiting the extent of hedge fund losses in the basis trade and in preventing broader spillovers. Following March 16, returns on the basis trade began to move back into line with the returns on Treasury bills, and came closer to the cost of borrowing in the sponsored repo market. Several Fed actions on March 16 and 17 may have contributed to this easing of pressure on hedge funds. In particular, Federal Reserve expansions of Treasury purchases provided an additional source of demand for off-the-run Treasuries, while expansions of the central banks repo facility reduced financing risks associated with providing liquidity to Treasury markets. It is difficult to know exactly which of these actions was most important, in particular because they were mutually reinforcing.

The Federal Reserve took the unusual action of including the cheapest-to-deliver Treasury across contracts in its purchases. The direct effect of these purchases may have been limited. Purchases of deliverables for longer duration securities picked up almost immediately after March 15 (see Figure 36). However, these longer-duration securities seem to have made up a relatively small portion of hedge fund short futures positions. Alternatively, Fed purchases of the most popular two-year and five-year cheapest-to-deliver Treasuries were negligible until April. This is

[9]It is possible that in order to keep basis trades open while meeting margin calls, hedge funds may have sold Treasuries other than the cheapest-to-deliver, thus contributing to the lower price of other securities. It is difficult to reject this possibility without more detailed data on hedge funds' Treasury holdings. However, even in this case the willingness of hedge funds to sell other Treasuries to keep their basis trades open would still indicate excess demand for the trade.

consistent with the basis trade still providing liquidity to the market, as dealers may have been more comfortable holding Treasuries for which they had a natural source of demand from basis traders.

However, the indirect effect of including cheapest-to-deliver Treasuries in Federal Reserve purchases may have been substantial. Even if purchases of shorter-maturity cheapest-to-deliver Treasuries on March 16 were small, the knowledge that the Treasuries could be sold to the Federal Reserve in the future may have made dealers more willing to hold these Treasuries, allowing hedge funds to gradually reduce their exposure to the basis trade. The increase in Federal Reserve purchases in April may then represent concerns over the longer-term profitability of basis trades. Without these actions, dealers may not have been willing to hold the cheapest-to-deliver securities in order to accommodate a gradual withdrawal from the basis trade.

As these purchases may have made dealers more willing to accept cheapest-to-deliver Treasuries, the Fed also lowered the costs of funding these Treasury holdings for hedge funds. Fed actions succeeded in lowering the DVP repo rate across segments of the market, including in the sponsored borrowing segment. Expansion of the repo facility likely reduced these rates by relieving liquidity concerns among dealers. Following this expansion on March 16, the sponsored lending rate fell to the zero lower bound defined by the Feds overnight reverse repurchase (ON-RRP) facility (see Figure 29). The rate on sponsored borrowing largely fell in lockstep, reducing the cost of funding these Treasury positions for hedge funds. The relatively calm state of the repo market following this expansion of the RP facility on the 17th is a testament to the strength of these facilities in controlling rates.

In total, the large and timely intervention by the Fed into both Treasury and repo markets eased building pressure in the system. While impossible to know, without these steps the unwinding of the basis trade may have further destabilized markets and could have sparked a liquidity spiral as in Brunnermeier and Pedersen (2008). Nonetheless, we offer evidence that contrary to much of the coverage in the financial media and popular press, hedge fund stress in the basis trade was unlikely to be the primary cause of stress leading to the events in mid March. While hedge funds were vulnerable to worsening illiquidity, they appear to have sold the securities that dealers were most willing to accept, suggesting sales from other market participants may have contributed

more to balance sheet constraints on dealers, price volatility, and widening bid-ask spreads.

8 Conclusion

The stress in Treasury markets in March of 2020 has led to an evaluation of the structure of Treasury markets and their exposure to sudden bouts of illiquidity. Regardless of their direct impact during March, the involvement of hedge funds in the basis trade is a key feature of Treasury markets in recent years, with hedge funds involved playing a role both as a major holder of Treasuries and as a major supplier of collateral to repo markets. The sheer quantity of Treasury securities involved makes understanding the trade important to our picture of Treasury markets, especially as the trade drives a substantial proportion of holdings of Treasuries by hedge funds, a key non-bank actor in Treasury markets.

We show the basis trade became popular in part as a result of a fundamental disconnect between the prices of cash Treasuries and Treasury futures, one that has grown larger in recent years. In a frictionless market, the spreads we demonstrate would not exist. Yet we show these spreads in reality are both fairly large and relatively persistent. Further, we show the size of these spreads are associated with measures of volatility, disconnects between bills and repo, and the Treasury exposure of primary dealers. These facts suggest the importance of limits to arbitrage in cash and futures markets for Treasuries.

The popularity of this trade, as well as the persistent disconnect between cash Treasuries and a replicating portfolio of futures and bills, serves to illustrate more general issues affecting Treasury markets. The role that hedge funds involved in the trade played as a warehouse for Treasuries suggests substantial costs to other actors for holding Treasuries on their balance sheet. Our model illustrates the circumstances under which hedge funds end up playing this role, but also suggests the risks this role could play when margin constraints lead to hedge fund which amplify pressure on dealer balance sheets in a flight to liquidity.

In March of 2020, sales by real money investors led to rising volatility in Treasury markets, and corresponding increases in margins and volatility in repo markets. Large sales from hedge funds trading the basis seem to have followed this event. We show some evidence that these sales may have had a smaller effect on dealer balance sheets than might otherwise have been expected, and

in fact that dealers attached particular value to these Treasuries during the peak of March stress. However, these facts must be interpreted in the context of a timely and large intervention of the Federal Reserve into Treasury and repo markets. Without that intervention, our model suggests that the amplifying role of hedge fund sales could have exacerbated illiquidity in the Treasury market.

In the context of on-going discussions of Treasury market reform, policy makers should therefore consider both the potential impact of the basis trade on Treasury market liquidity, and the broader context that allowed these trades to be profitable in the first place. While this broader research project is only at its beginning, our paper points to important links between repo markets, Treasury markets and futures markets spanned by hedge funds.

Figure 15: **Hedge fund Treasury exposures ($ billions).** The top panel shows hedge funds' total Treasury exposures taken from the SEC's Private Fund Statistics. The bottom panel is taken from the OFR's 2020 Annual Report and shows hedge fund long and short Treasury exposure along with their notional long and short futures exposure.

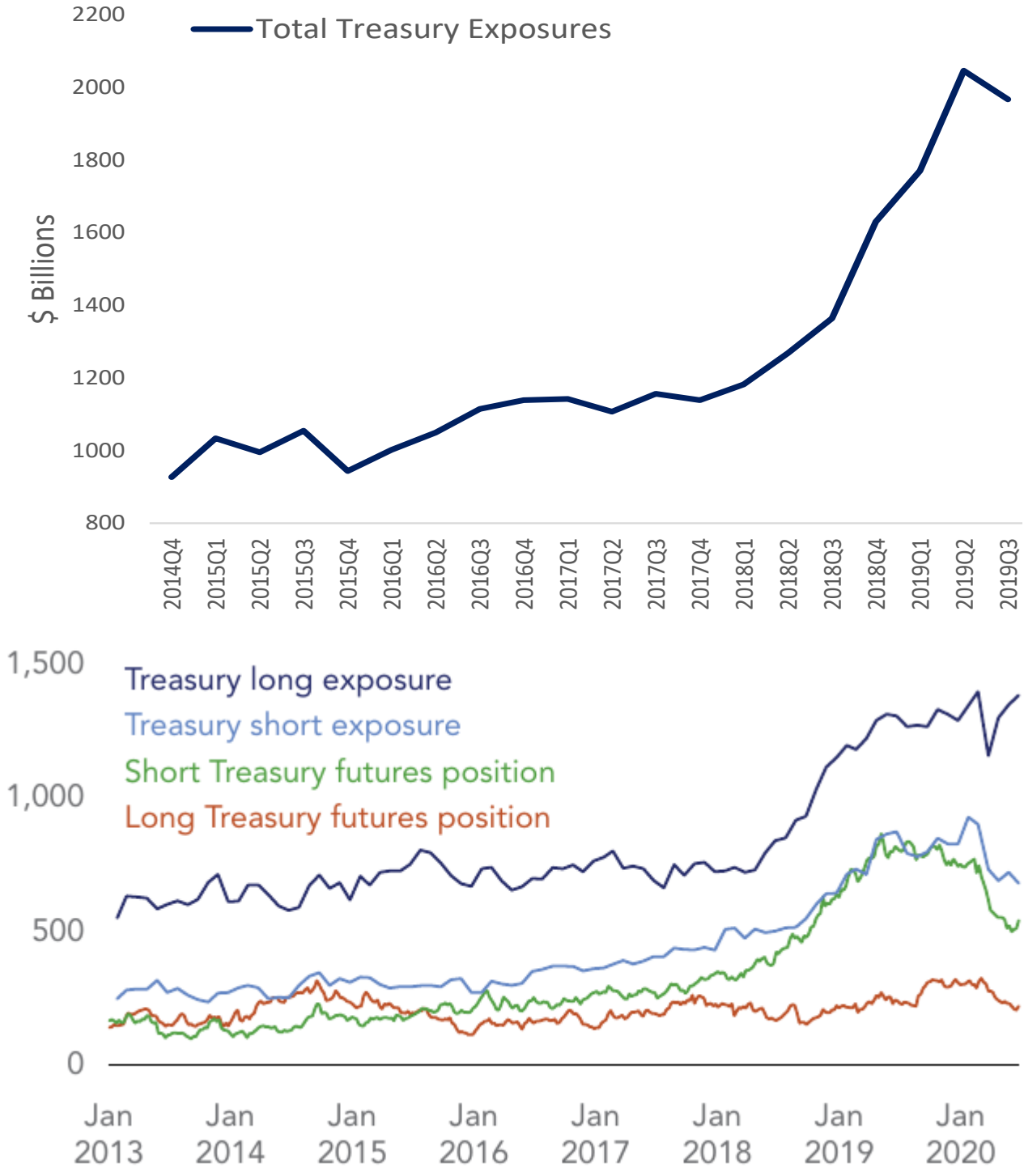
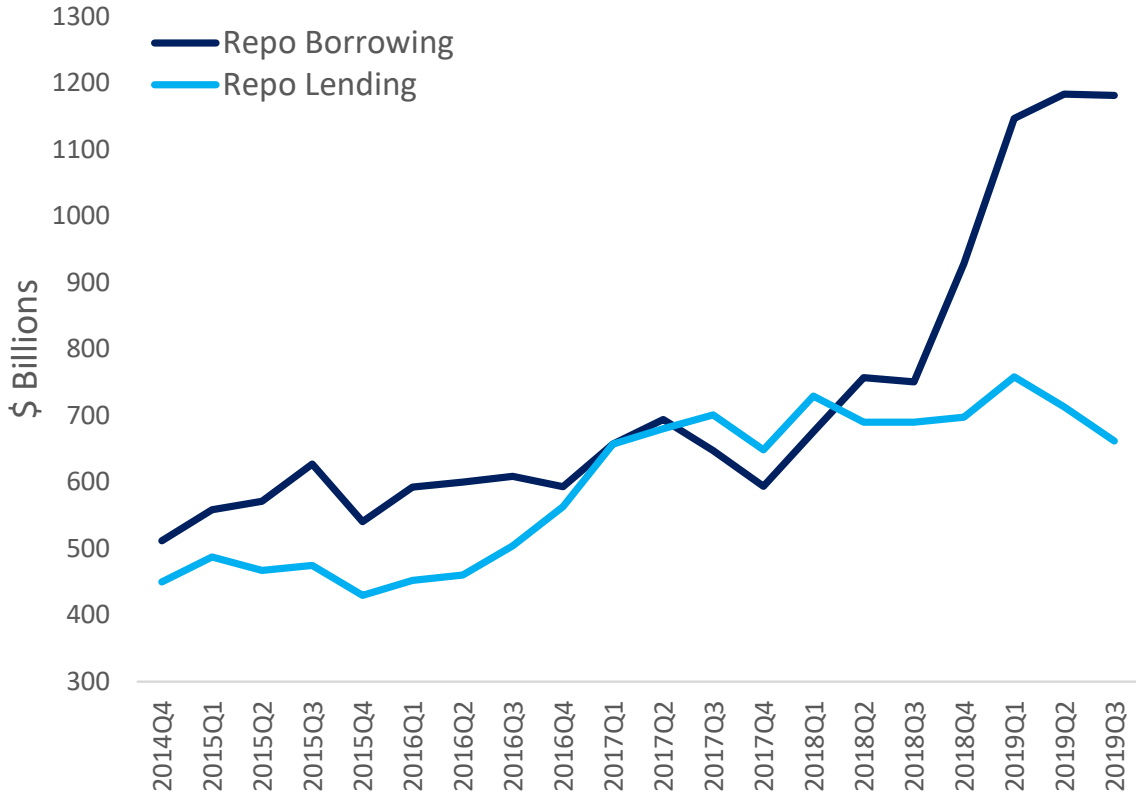


Figure 16: **Hedge fund repo borrowing and lending.** This figure shows hedge fund repo borrowing and lending as reported in the SEC's Private Fund Statistics.



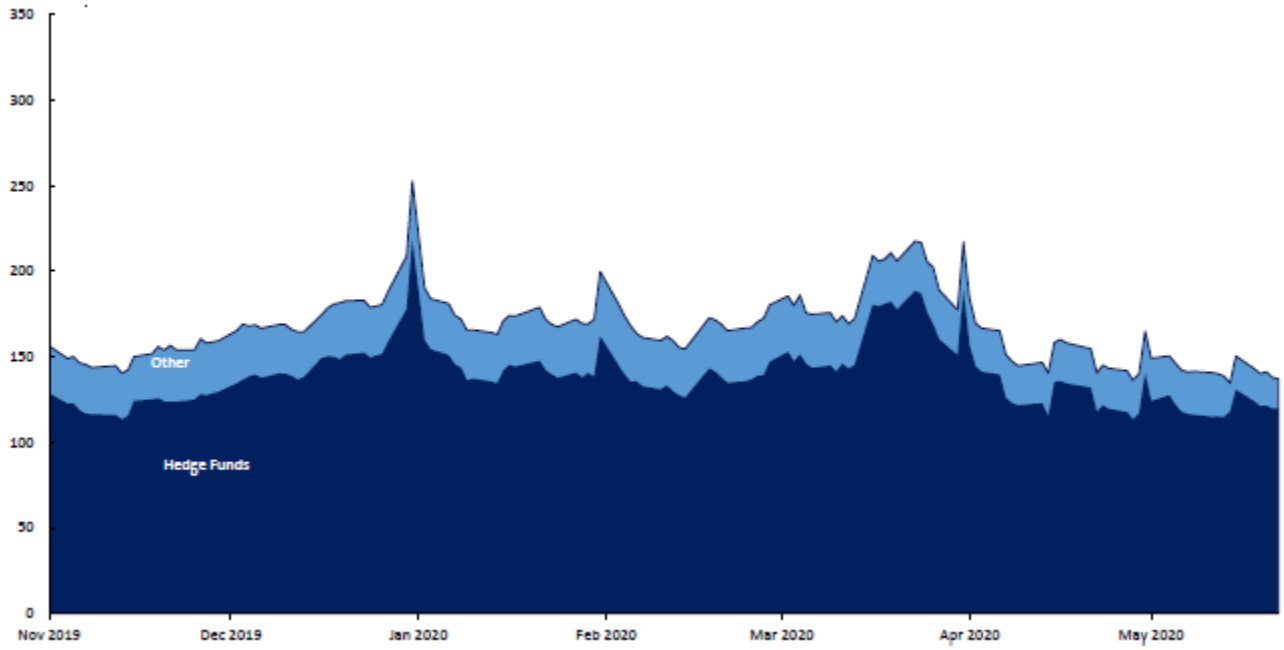


Figure 17: **DVP Sponsored Reverse Repo by Participant Type ($ billions).** Data are aggregate daily transaction volumes.

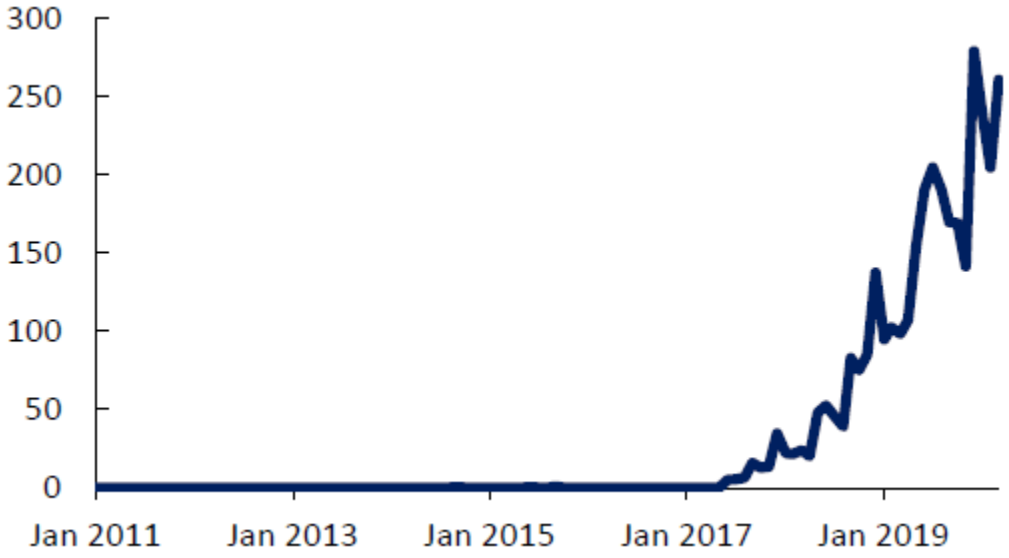


Figure 18: **Money Market Fund Repo with FICC ($ billions).** Aggregate repo volume outstanding. FICC stands for Fixed Income Clearing Corporation.

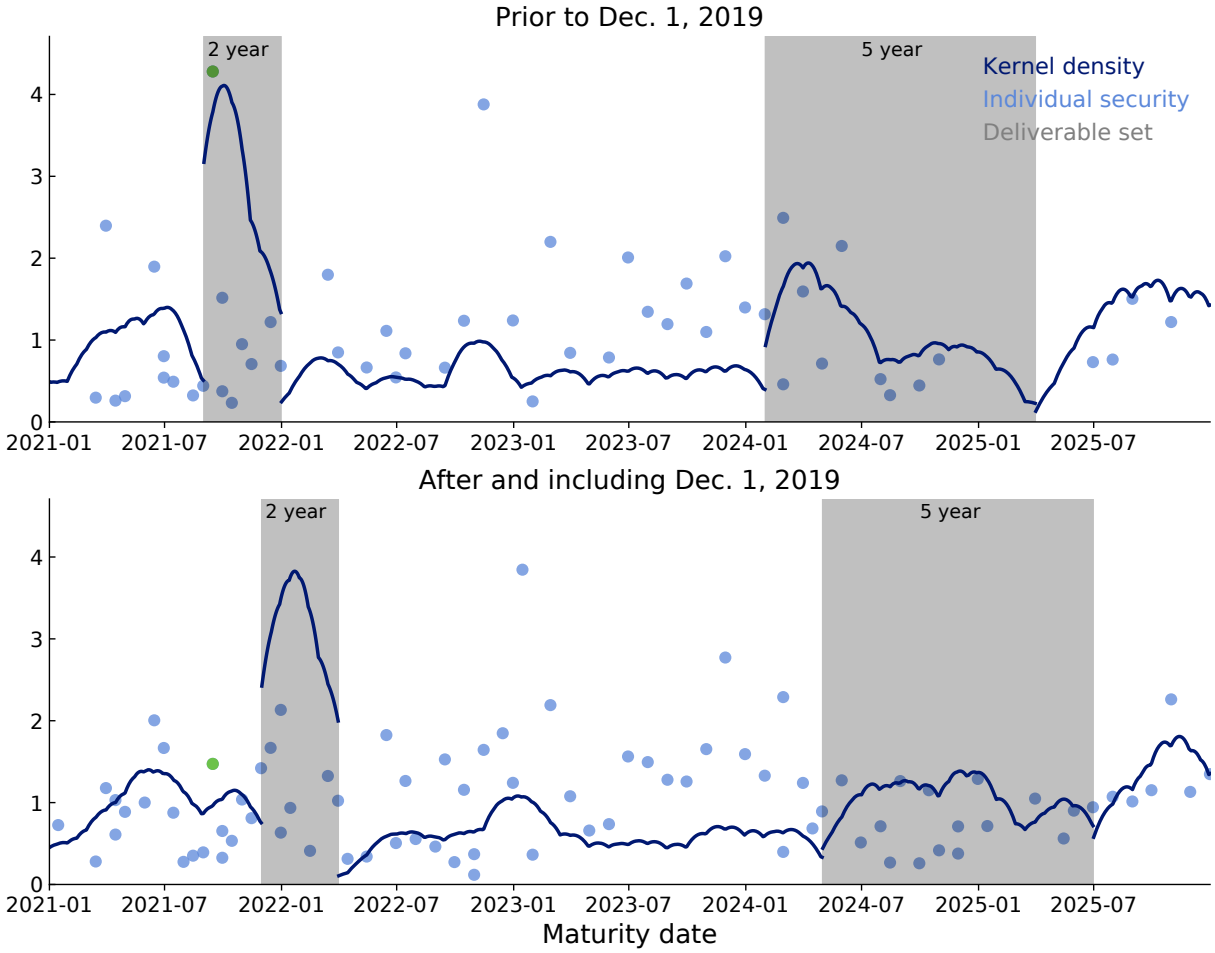


Figure 19: **Hedge Fund DVP Repo in Treasuries by Maturity Date ($ billions, average daily transaction value).** Dots are average daily outstanding positions in individual Treasuries; solid lines are smoothed fitted sums within maturity windows. Above, gray areas are deliverables for December 2019, below for March 2020. The green dot denotes positions in the cheapest-to-delivery for the two-year December contract.

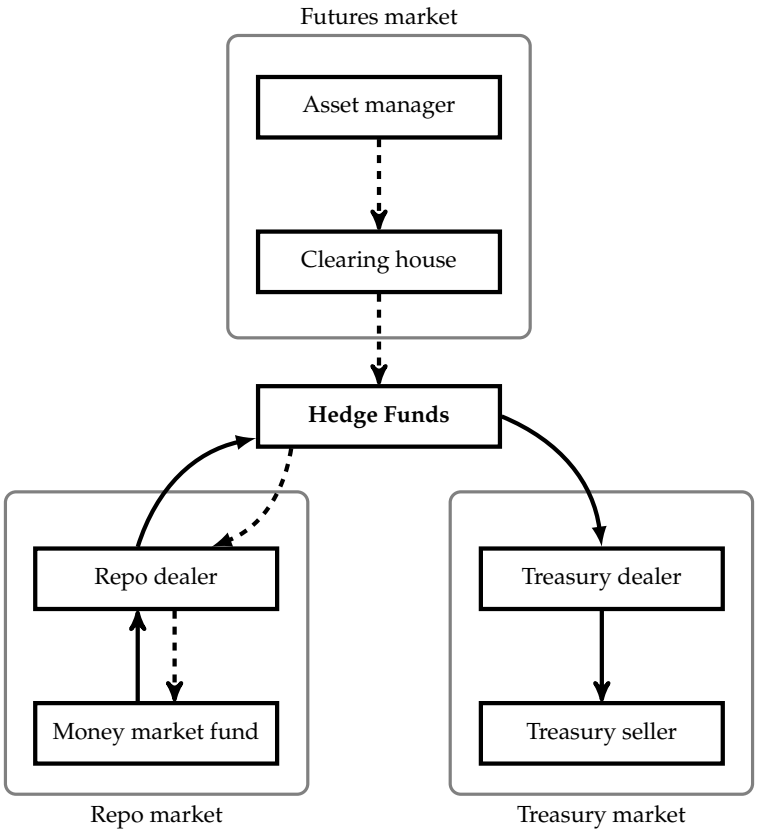


Figure 20: **Struture of the basis trade in recent years.** This figure shows the structure of the basis trade in recent years. Arrows denote the flow of cash, from cash lenders or from purchasers, to cash borrowers or to sellers. The solid arrows denote the flows at the beginning of the trade, while the dashed arrows denote the flows on the unwind of the trade at delivery.

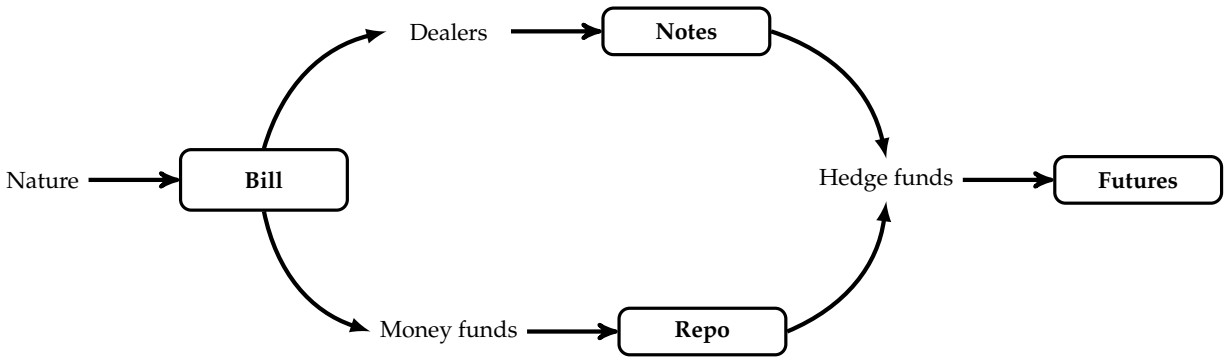


Figure 21: **Struture of the model.** Short-rates for bills are transmitted to note prices and repo prices, and from there determine futures prices. Arrows denote the structure of this transmission, from bill prices to futures prices. Transmission is determined by agents who are indifferent between two assets. Dealers are indifferent on the margin between notes and bills, while money funds are indifferent between bills and repo lending. Hedge funds are indifferent between notes, repo and futures positions.

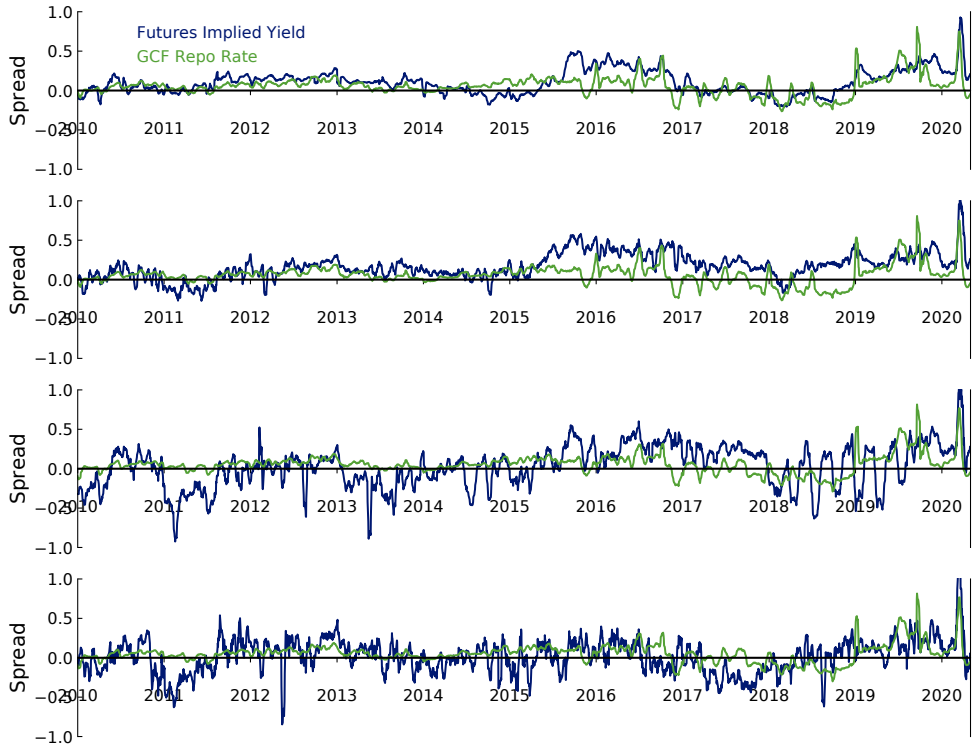


Figure 22: **Futures implied yields and the GCF repo spread.** Each panel in this figure shows the spread of futures implied yields over equivalent maturity bill yields in blue, and the spread of the GCF repo rate over the bill rate in green.

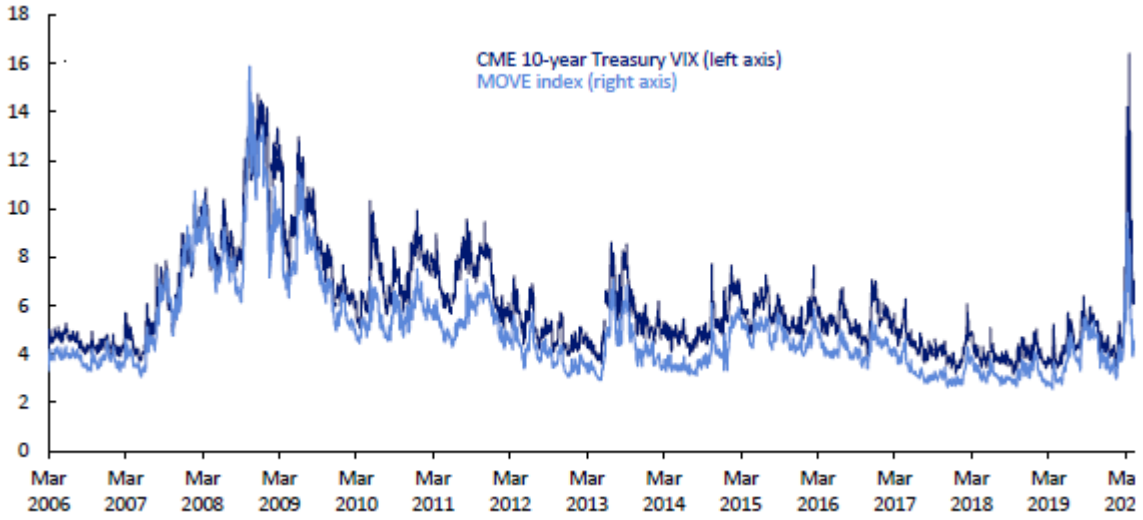


Figure 23: **Treasury volatility indexes.** CME 10-year Treasury VIX and the MOVE Index are option implied Treasury volatility indexes.

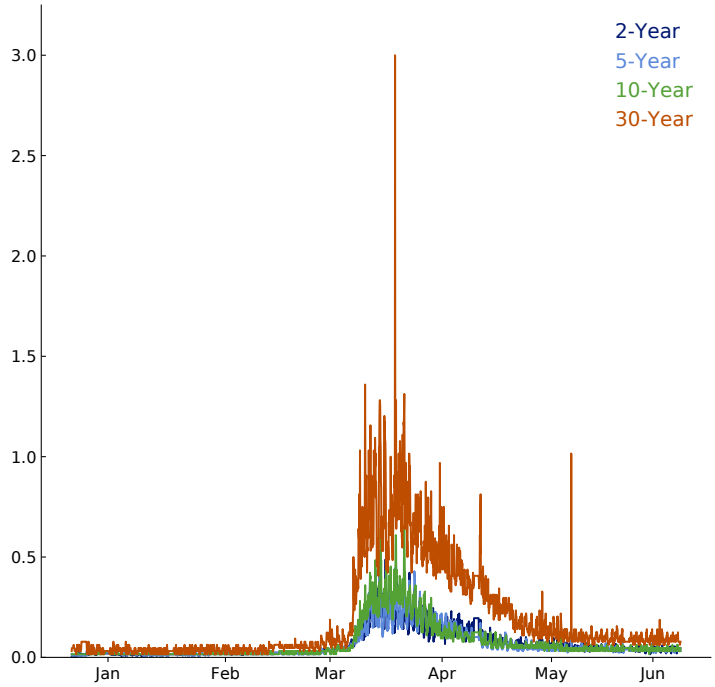


Figure 24: **Bid-Ask Spreads for Off-the-run Treasuries ($).** March illiquidity was concentrated in off-the-run securities.Spreads are the difference between bid and ask prices for $100 notional in the fourth-from-most-recent Treasury issuance as of January 2020.

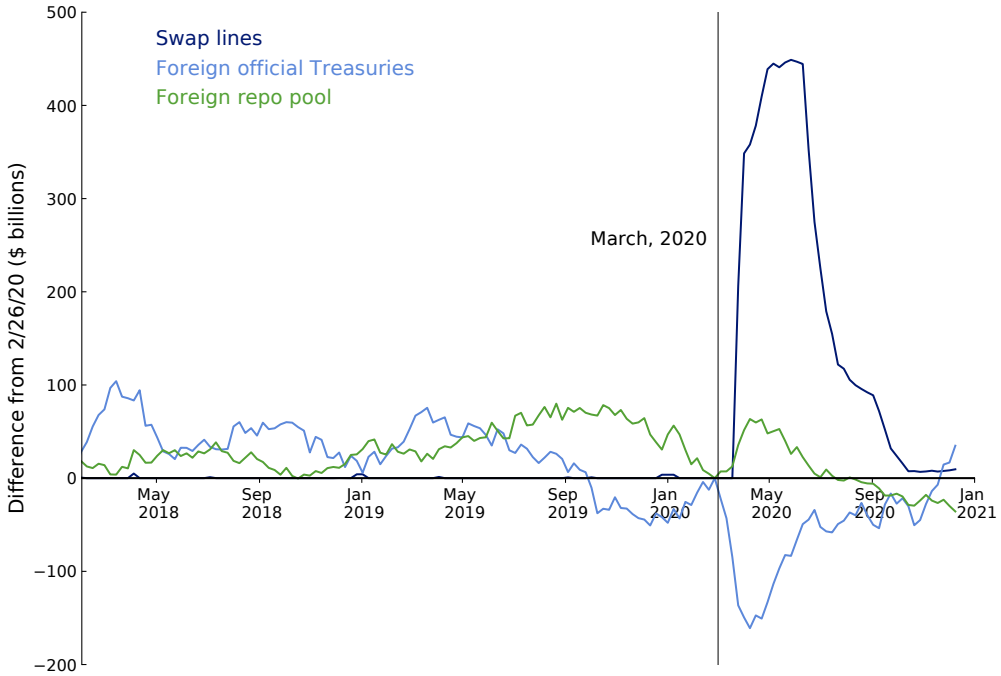


Figure 25: **Foreign official sales and dollar liquidity.** This figure shows foreign official Treasury holdings, swap lines and investments into the foreign repo pool as reported in the Federal Reserve's Factors Affecting Reserves release. All values are differences from their values as of March 1st, 2020.

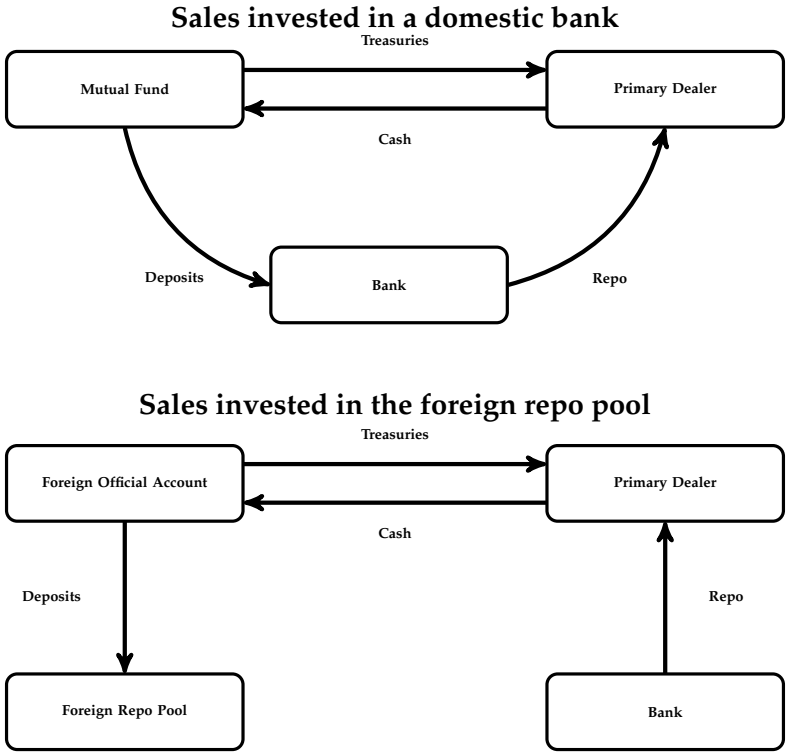


Figure 26: **The effect of the foreign repo pool on reserves.** Two stylized figures, in which arrows denote the flow of different assets. In the top figure, a domestic mutual fund sells a Treasury to a dealer, receiving cash in return. The cash is invested in a bank deposit, which lends into the repo market, funds which are used by the dealer to finance their purchase of the Treasury. In the bottom figure, sales by a foreign official account are invested in the foreign repo pool. No new reserves are made available to the bank which funds the primary dealer's repo borrowing, meaning that repo financing may become more expensive.

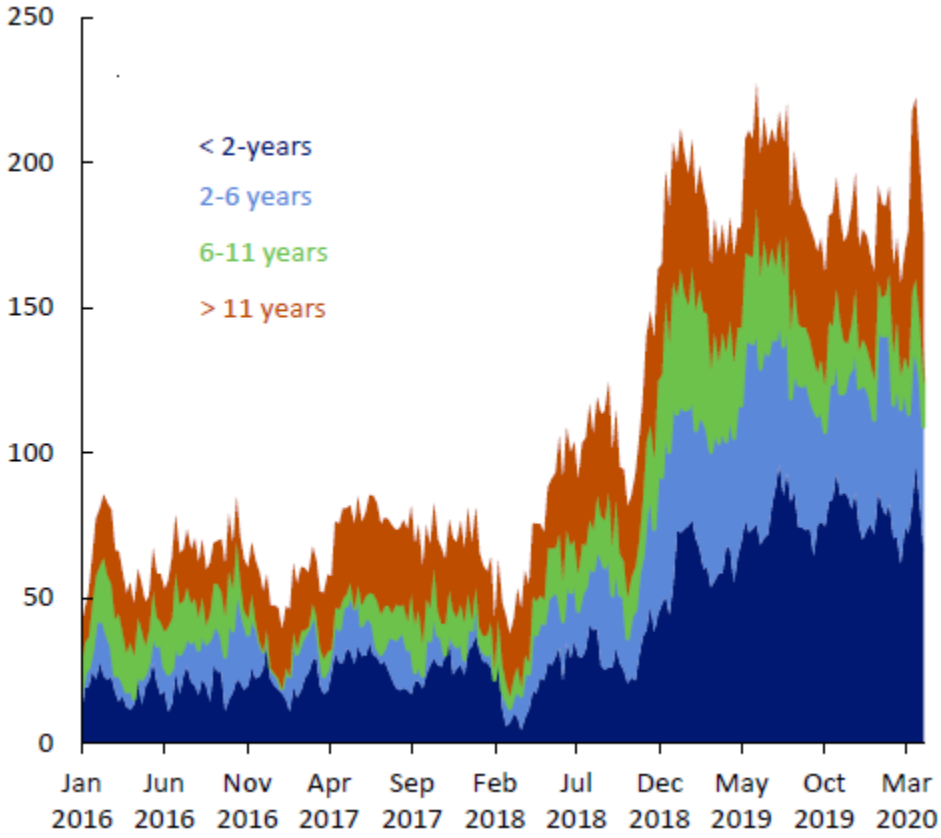


Figure 27: **Primary Dealer Treasury Net Exposure ($ billions).** Data are net exposures by maturity.

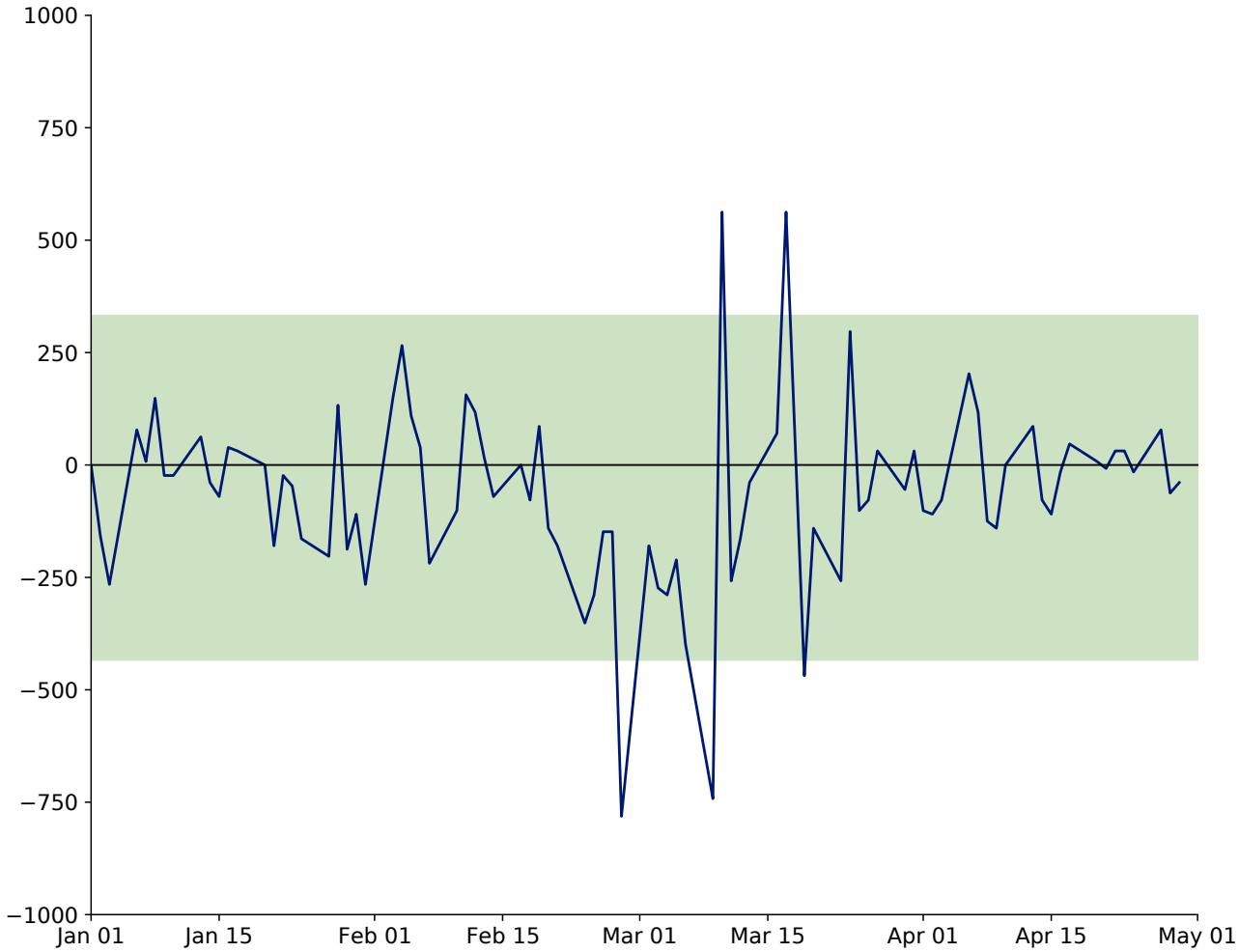


Figure 28: **Maintenance Margins for Treasury Futures ($).** Data are for maintenance margins on $200,000 notional in two-year Treasury futures contracts, and price movements in normalized to changes in those notional values.

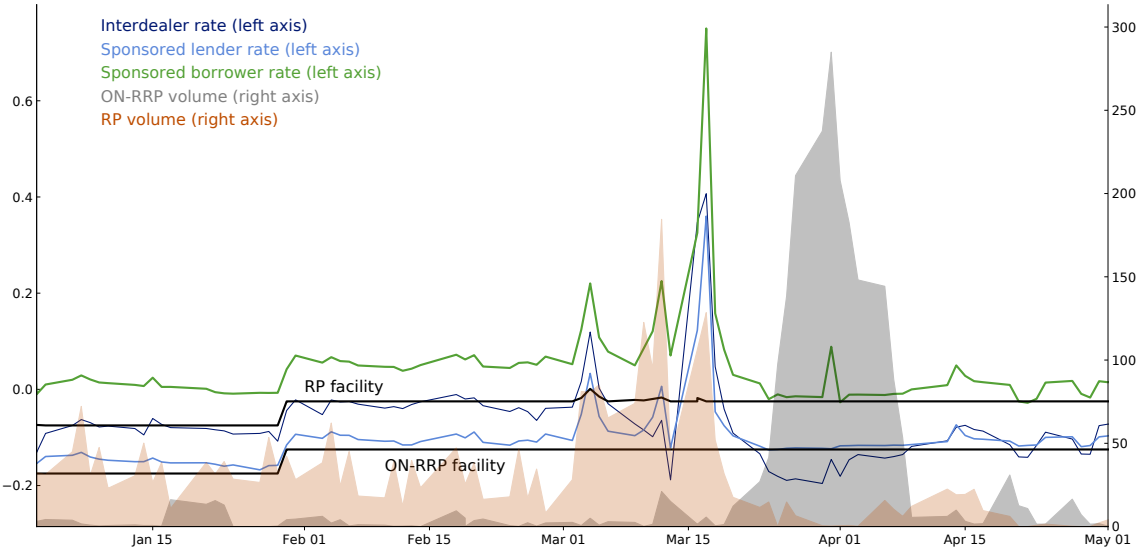


Figure 29: **DVP Repo Rates (left axis, percentage point spread over fed funds target midpoint) and Federal Reserve Facility Participation (right axis, $ billions).** Repo rates are average overnight Treasury rates for each market segment.. The two black lines represent the average rate offered by the Federal Reserves Overnight Reverse-Repurchase Facility (ON-RRP) and Repo Facility (RP). The two shaded areas are daily transaction volumes in these facilities.

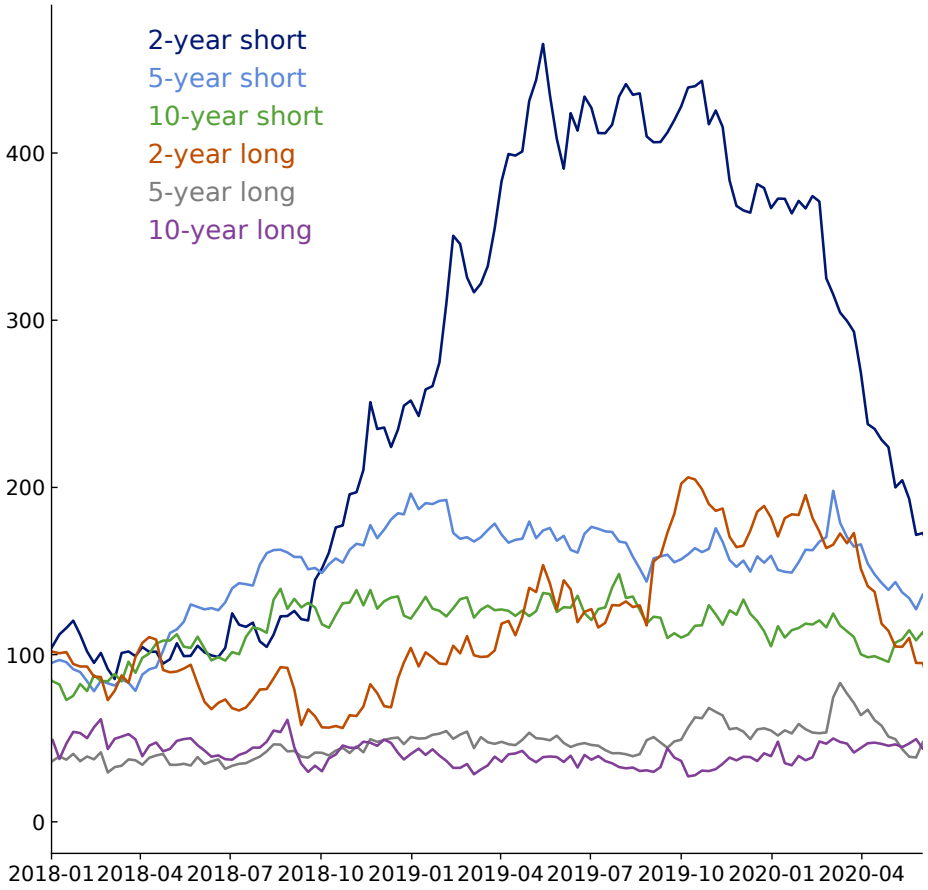


Figure 30: **Hedge Fund Treasury Note Futures Position ($ billions).** Data are leveraged fund short and long positions in dollars of face value.

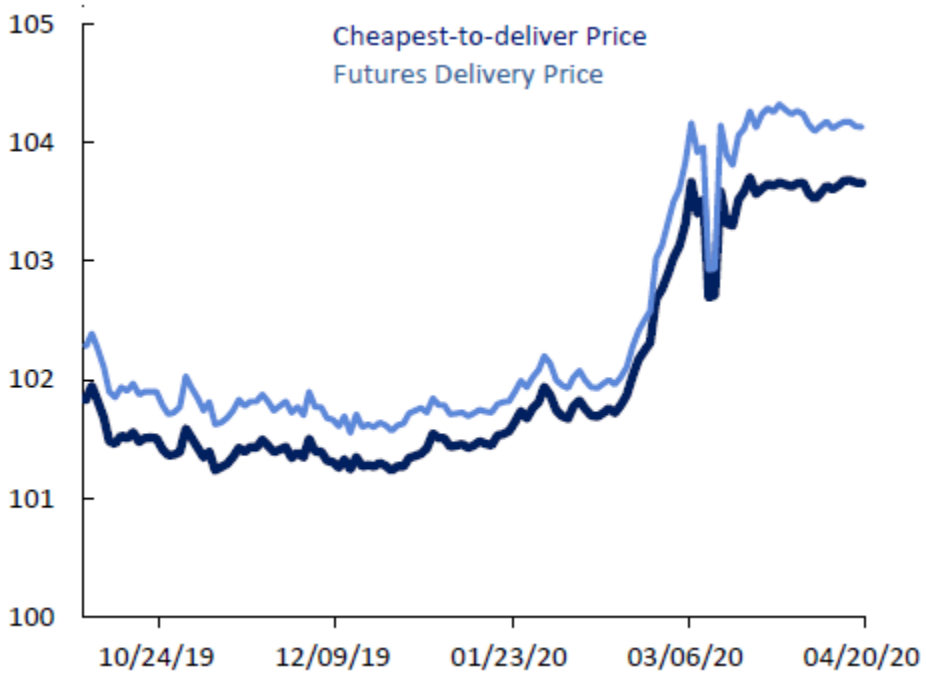


Figure 31: **Futures and Cash Prices for the Two-Year June 2020 Contract ($).** Delivery price is futures price multiplied by the conversion factor for the cheapest-to-deliver. Prices are for $100 notional.

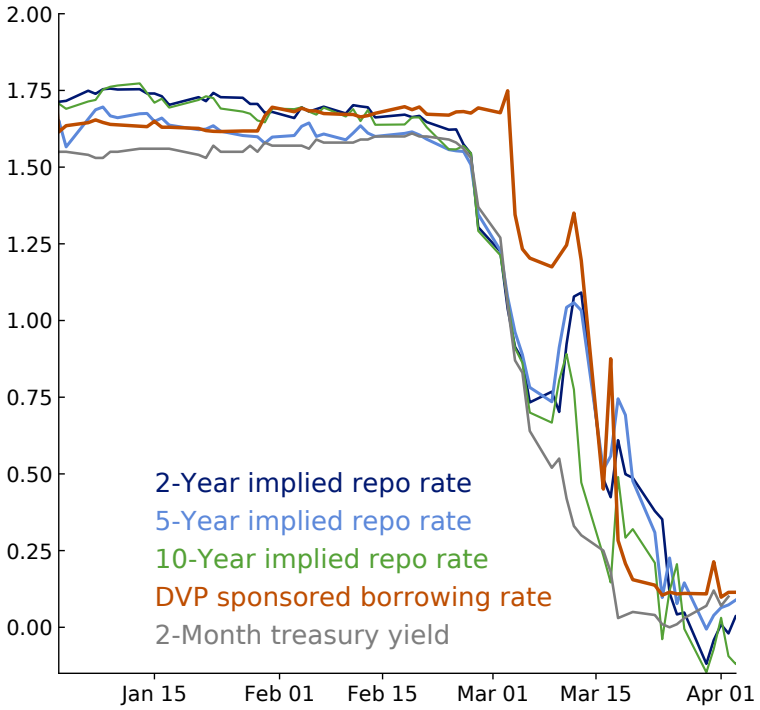


Figure 32: **Basis Trade Return, Bills Rate, and DVP Repo Rate (percent).** DVP Repo rate is the average overnight rate for sponsored borrowers with Treasury collateral. Implied repo rates are for July contracts.

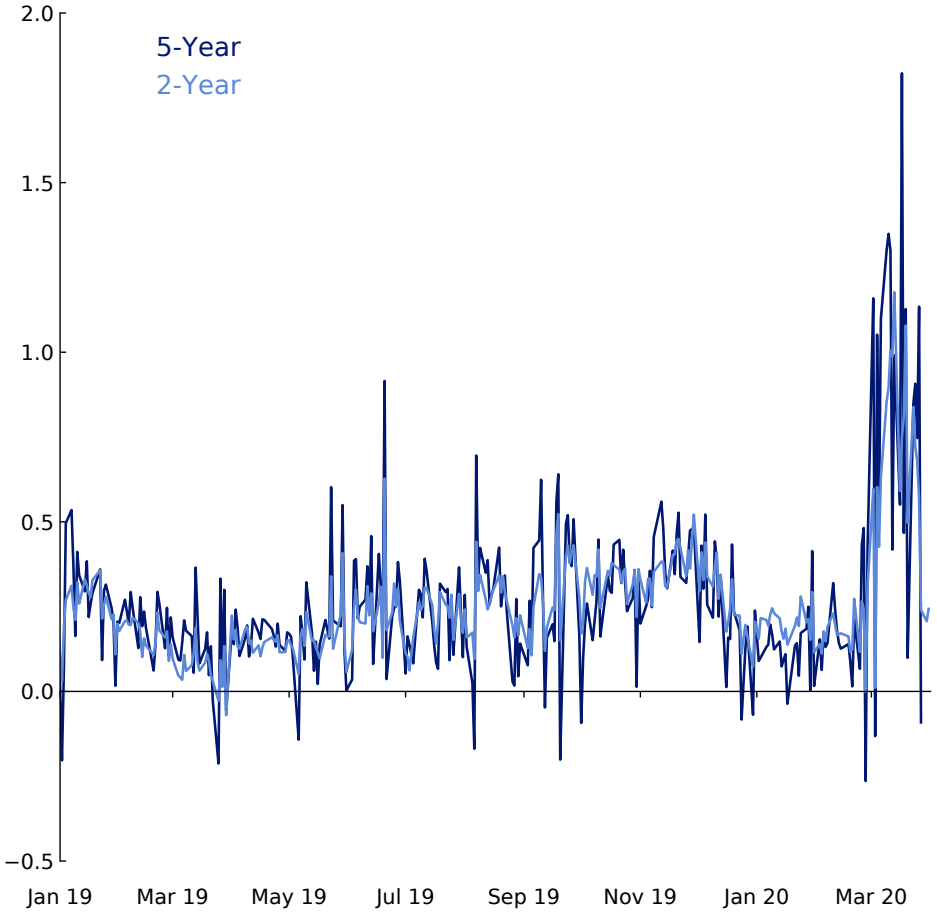


Figure 33: **Basis Trade Return, Bills Rate, and DVP Repo Rate (percent).** DVP Repo rate is the average overnight rate for sponsored borrowers with Treasury collateral. Implied repo rates are for July contracts.

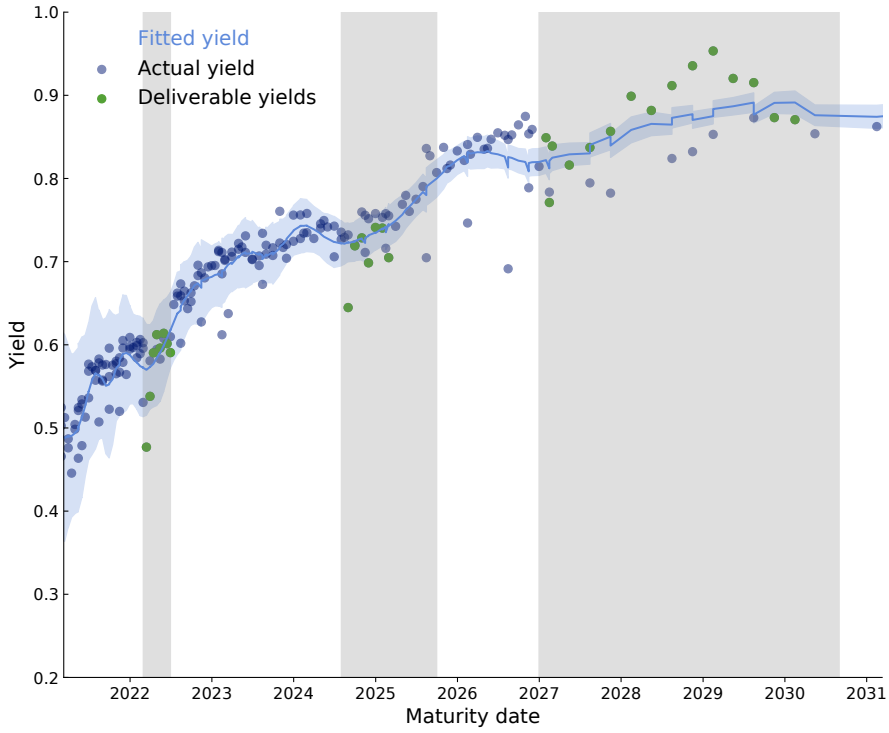


Figure 34: **Fitted and actual yields on March 11, 2020.** This figure shows fitted and actual yields of Treasuries on March 11, 2020. The actual values are shown as dots, with blue dots denoting non-deliverable Treasuries and green dots denoting deliverable Treasuries. The fitted spline yield curve is the line in blue, and the blue area around it denotes the 95% confidence interval for these yields. The gray areas denote the bounds of deliverable Treasuries for the 2-year, 5-year and 10-year contracts deliverable in June of 2020.

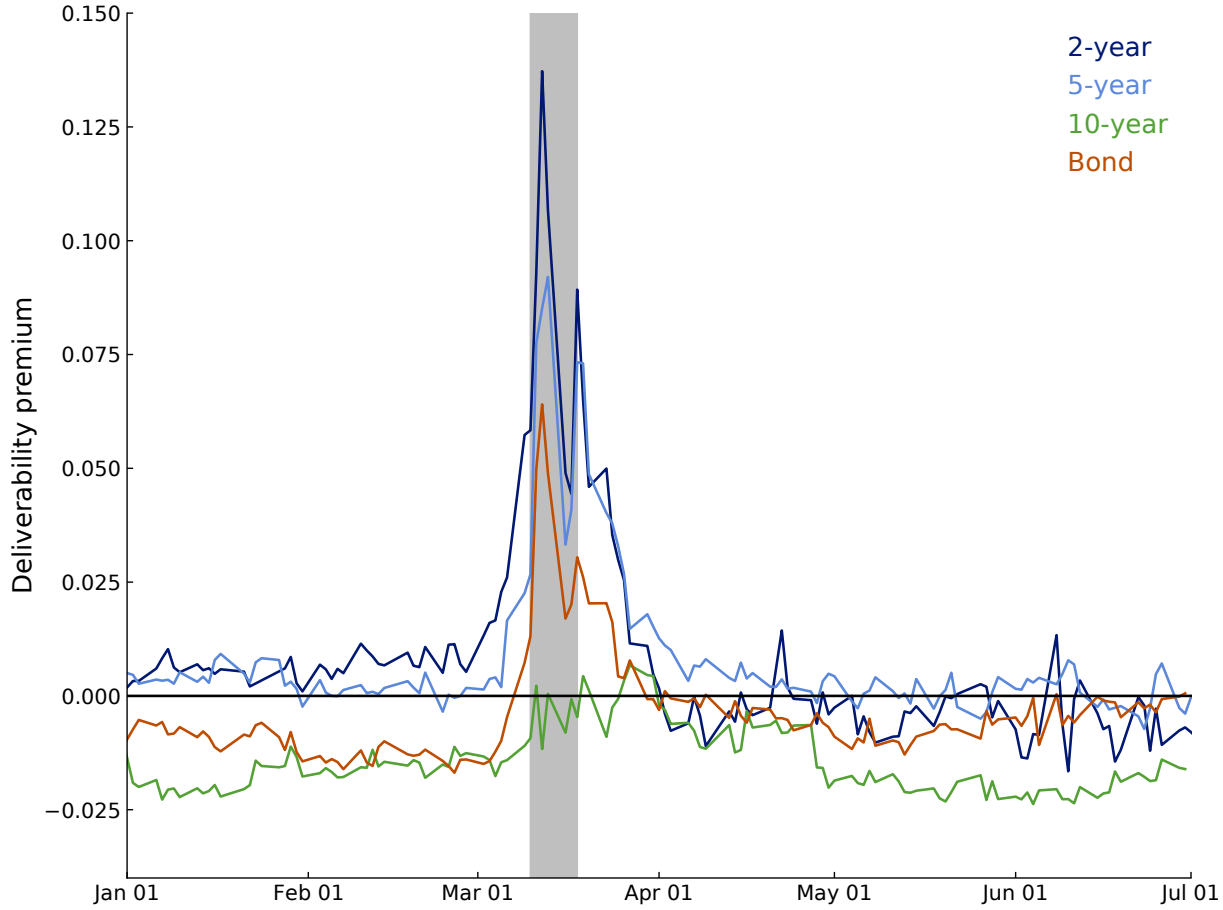


Figure 35: **Spread on the Cheapest-to-Deliver Treasury (percentage points).** Wider spreads show deliverable Treasuries were more valuable during March. Spread is the fitted spline yield minus the yield on the cheapest-to-deliver. Cheapest-to-deliver is for June futures contracts.

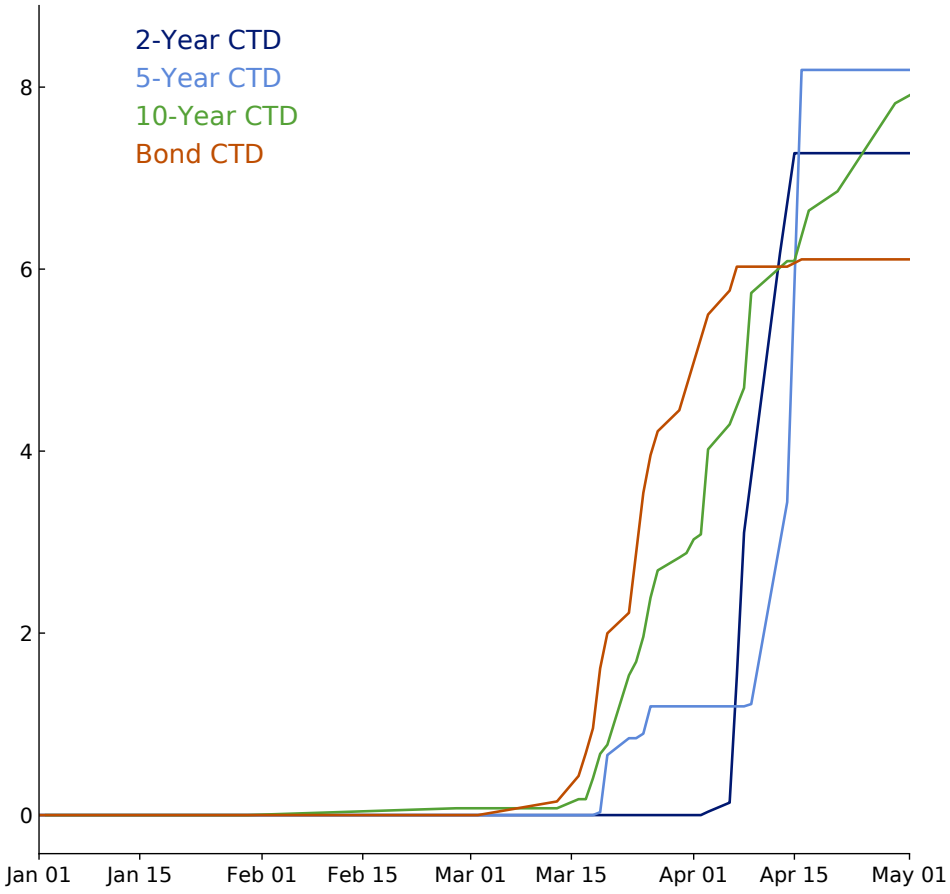


Figure 36: **Cumulative Federal Reserve Purchases of the Cheapest-to-Deliver Securities ($ billions).**Cumulative purchases of the cheapest-to-deliver (CTD) Treasuries for June delivery.

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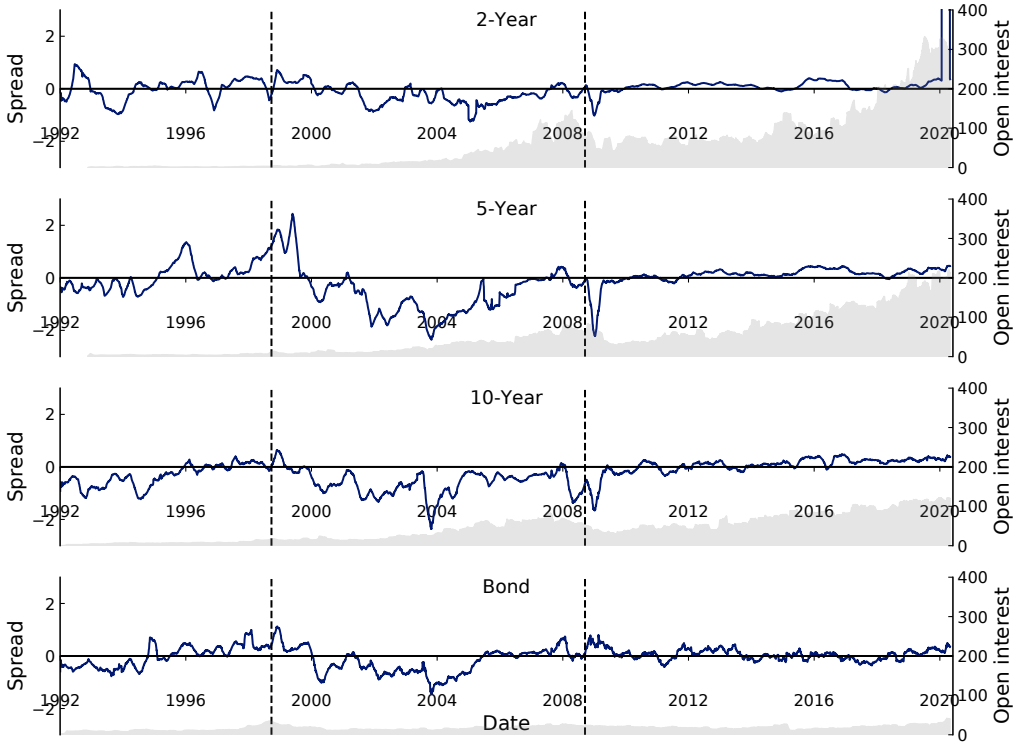


Figure 37: **Deviations of Treasury prices from the replicating portfolio.** Each series graph shows the deviation of the futures-implied yield from the yield on a similar maturity bill and the open interest in that contract. Values above zero imply the replicating portfolio is overvalued relative to the cheapest-to-deliver. These series use the second-to-deliver contract.

A Appendix

Figure 37 shows a longer time-series for the plot in Figure 8. The link between cash and futures values of Treasuries has changed over time. From 1992-2020 on average futures have been under-valued relative to the underlying Treasuries. However, in the last decade, futures have become over-valued.