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LIMITS TO ARBITRAGE DURING THE CRISIS: FUNDING LIQUIDITY CONSTRAINTS AND COVERED INTEREST PARITY

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Limits to arbitrage during the crisis: funding liquidity constraints and covered interest parity*

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Abstract

Arbitrage ensures that covered interest parity holds. The condition is central to price foreign exchange forwards and interbank lending rates, and reflects the efficient functioning of markets. Normally, deviations from arbitrage, if any, last seconds and reach a few basis points. But after the Lehman bankruptcy, arbitrage broke down. By replicating exactly two major arbitrage strategies and using high frequency prices from novel datasets, this paper shows that arbitrage profits were large, persisted for months and involved borrowing in dollars. Empirical analysis suggests that insufficient funding liquidity in dollars kept traders from arbitraging away excess profits.

JEL classification: F31, G01, G14

Keywords: limits to arbitrage, covered interest parity, funding liquidity, financial crisis, slow moving capital, market freeze, unconventional monetary policy.

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Arbitrage is the glue of financial markets. It links securities through pricing relationships, and allows for the smooth and efficient functioning of markets. But under sufficient pressure, arbitrage can break down. That this glue can, and does, snap underscores the fragility of the financial system and potentially calls for policy action. A proper understanding of when and why arbitrage breaks down is therefore fundamental.

Arbitrage needs capital to operate properly and may be disrupted by lack of it. That is the main suggestion of a vibrant literature currently emerging under the heading of slow moving capital, captured with eloquence in Duffie (2010). But earlier writings already suggest these frictions are of first order importance. That is the case in Shleifer and Vishny (1997) and notably Keynes who remarked, as early as 1923, that "speculation [in the foreign exchange market may be] exceptionally active and all one way. It must be remembered that the floating capital normally available... for the purpose of taking advantage of moderate arbitrage... is by no means unlimited in amount" and thus excess profits, when they arise, persist until "fresh capital [is drawn] into the arbitrage business" (Keynes, 1923, pp. 129-130).

This paper revisits the above insights and contributes to the literature on slow moving capital in two ways: by providing a concrete example for large and persistent deviations from arbitrage, and by testing empirically the relevance of specific factors brought up in the literature to explain enduring arbitrage opportunities.

This paper's first goal is thus to measure deviations from arbitrage. The focus is on arbitrage between national money markets – borrowing in one currency and lending in another, while hedging foreign exchange risk – usually

ensuring that the covered interest parity (CIP) condition holds. This condition is essential to price foreign exchange forwards and short term money market or cash interest rates.

Measuring deviations from arbitrage entails specifying the arbitrage strategy as a trader would actually implement it. In many ways, this goes beyond the textbook CIP condition. Specifically, arbitrage can be undertaken by borrowing and lending funds on secured terms, as would a hedge fund, or on unsecured terms, as would a bank's proprietary trading desk (prop desk). We call the first secured and the second unsecured arbitrage. The distinction draws on that made in Brunnermeier and Pedersen (2009).

Both arbitrage strategies – actually quite different in practice – yield very similar results. Excess profits from CIP arbitrage were negligible or negative prior to the financial crisis, as expected. And while profits rose at the onset of the financial crisis, in August 2007, they remained small. However, when Lehman collapsed, excess profits spiked to nearly 400 basis points and lasted almost three months. Moreover, profits arose only when attempting to borrow in dollars. These findings represent a clear rupture from earlier papers which find excess profits, if any, to reach a few basis points during merely seconds, over different currency pairs indistinguishably.

A new dataset allows us to obtain these results with precision. Data replicate very accurately the profits a trader could have realized by engaging in either secured or unsecured arbitrage. Data reflect traded prices selected from several daily snaps synchronous across securities, covering several years and currency pairs, and including transaction costs. Data for secured arbitrage include interbank repo rates in different currencies, used, to our knowledge,

for the first time in this literature.

This paper's second goal is to investigate why arbitrage broke down. Did specific transactions necessary for CIP arbitrage become overly risky, as in a classical risk premium or asset pricing story? Or was there too little funding liquidity available to carry out arbitrage in sufficient volume, as suggested by the slow moving capital literature?

This paper's empirical section finds that funding liquidity constraints predominantly explain deviations from arbitrage. Risk factors, instead, are mostly insignificant. Liquidity factors involve intermediaries cutting back loans to arbitrageurs in order to shrink their balance sheet, and hoarding liquidity to cover their own funding strains, as summarized in Duffie (2010) or captured in Brunnermeier and Pedersen (2009). In addition, it seems that arbitrageurs themselves had insufficient pledge-able capital to fund their arbitrage trades, as surveyed in Gromb and Vayanos (2010).

The predominance of liquidity factors matches the stylized facts of arbitrage deviations. First, liquidity – as opposed to risk – can be currency specific, thus explaining that arbitrage profits only arise when attempting to borrow dollars. Second, liquidity factors are common to both secured and unsecured arbitrage strategies, thus accounting for these strategies' very similar returns. Risk factors are instead mostly specific to unsecured arbitrage. And third, as central banks significantly ramped up their dollar swaps with the US Federal Reserve to offer dollar funding liquidity domestically, CIP arbitrage profits diminished noticeably.

This paper therefore has two policy implications. First, unconventional monetary policy seems to have been successful. Specifically, central bank

swap lines were effective at providing the necessary funding liquidity in dollars and re-establishing arbitrage across money markets. Second, looking forward, regulation should emphasize the importance of maintaining liquidity, and not only capital, buffers. Moreover, liquidity requirements should be aligned with the foreign exchange composition of an institution's balance sheet. Some of these recommendations echo those made elsewhere, as in Kashyap, Berner, and Goodhart (2011).

In the largely theoretical literature on slow moving capital and market freezes, some papers stand out as providing concrete evidence on deviations from arbitrage. These are Mitchell, Pedersen, and Pulvino (2007) focusing on the convertible bond market, and, during the recent financial crisis, Mitchell and Pulvino (2009) and Garleanu and Pedersen (2011), both addressing the CDS and bond yield spread. More generally, Brunnermeier (2009) and Pedersen (2009) illustrate the role of insufficient liquidity in aggravating of the financial crisis.

Other papers have centered specifically on deviations from CIP arbitrage. The first is Frenkel and Levich (1975, 1977), followed more recently by papers focusing on the financial crisis such as Baba, Packer, and Nagano (2008), Baba and Packer (2009b, 2009a), as well as Coffey, Hrung, Nguyen, and Sarkar (2009), Genberg, Hui, Wong, and Chung (2009) and Jones (2009). Yet, all approach the question of CIP deviations using Libor rates as a measure of funding costs.

There are several drawbacks from using Libor rates. First, they can be mis-representative of actual trading rates as they are indicative and only denote borrowing rates (i.e. ask and not bid quotes), void of transaction

costs. McAndrews (2009) emphasizes potential distortions in Libor rates during the crisis. Second, while the Libor survey is undertaken at 11 am London time, it is unclear if reported rates represent borrowing costs at any specific time snap. In addition, the survey is undertaken when US and Asian markets are closed. Together, these factors limit the extent to which price data can be synchronized to replicate actual trading profits. Finally, Libor rates do not reflect the possibility of engaging in arbitrage on secured terms.

The papers on CIP arbitrage that have used finer data are few, predate the crisis and mostly use data spanning a few months. The four that stand out are Taylor (1989), Rhee and Chang (1992), Akram, Rime, and Sarno (2008) and Fong, Valente, and Fung (2010). These papers all use high frequency data, synchronous among the various markets under study, and inclusive of bid-ask spreads as a measure of transaction costs.

In the remainder of this paper we first outline the structure of CIP arbitrage and specify the payoffs and strategies used for secured and unsecured arbitrage. We then summarize our data and illustrate the size and duration of the break-down of CIP arbitrage. Finally, we try to explain this phenomenon by regressing CIP profits on specific measures of either risk or liquidity factors, each drawn from theory and tied to specific papers in the literature.

1 The structure of CIP arbitrage

This section first introduces the basics of CIP arbitrage, but argues these are insufficient to properly measure CIP deviations. In practice, traders use two major arbitrage strategies. Each is presented along with its respective payoff

function.

1.1 Basics of CIP arbitrage

CIP arbitrage entails borrowing in one currency and lending in another to take advantage of interest rate differentials while avoiding exchange rate risk. The trade is usually described as borrowing in currency k at an interest cost $r_{k,t}$, exchanging the sum to currency j using the spot forex market, lending the proceeds in currency j at rate $r_{j,t}$, and exchanging the principal and accrued interest back to currency k at maturity to reimburse the original loan with interest. The last transaction is undertaken using a forex forward contract thereby eliminating exchange rate risk.

Profits from CIP arbitrage are often expressed as,

$$z_{1,t} = \frac{F_{t\cdots T}}{S_t}(1 + r_{j,t}) - (1 + r_{k,t}) \tag{1}$$

where the spot exchange rate S_t is expressed as the price in currency k of one unit of currency j. The same is true of the forward exchange rate, $F_{t\cdots T}$, where the subscript captures the time the contract is written and its maturity.

Because all variables are known at time t, as emphasized by the shared subscripts, textbooks normally suggest CIP arbitrage is riskless and should yield zero profits. When re-arranged with $z_{1,t} = 0$, the above equation is often referred to as the "CIP no-arbitrage condition", or the "CIP condition" for short.

1.2 CIP arbitrage in practice, two types of traders

Replicating actual arbitrage profits brings up several questions. Relative to the above characterization of CIP arbitrage, what instruments are used to

borrow and lend? What transactions are undertaken? Are there hidden costs? Over what term should CIP arbitrage hold?

There are typically two ways to implement CIP arbitrage. Each is loosely representative of a kind of trader, either a hedge fund or a bank's proprietary (prop) desk. The distinction is the same as that in Brunnermeier and Pedersen (2009). Each trader typically operates on different funding markets using different strategies. Hedge funds tend to borrow and lend on secured terms, while banks tend to tap the unsecured interbank market. Thus, each strategy involves different interest rates and maturities, has different risk and liquidity implications, and potentially different payoffs.

1.3 Payoffs from secured CIP arbitrage

Secured arbitrage is the most straightforward to implement. The trader (a hedge fund) pledges capital to obtain a secured loan from Lender L, as illustrated in Figure 1. The trader then turns around and offers cash to Borrower B against collateral. In market jargon, the hedge fund carries out a "repo" transaction with Lender L and a "reverse repo" with Borrower B, thus paying and receiving respective interbank "repo" rates.[1] These trades are of the term over which the trader wishes to carry out arbitrage.

The resulting payoff is given by,

$$z_{2,t} = \frac{F^B_{t\cdots T}}{S^A_t}(1 + r^{R,B}_{j,t\cdots T}) - (1 + r^{R,A}_{k,t\cdots T}) \tag{2}$$

where r^R are repo rates in currency j or k, set in time t up to maturity T, thus of term $(T - t)$. Also, the B and A superscripts denote bid and ask quotes to incorporate transaction costs related to arbitrage. We follow

[1]The term "repo" refers to selling a security as collateral against cash and repurchasing back the security at maturity.

standard convention in assuming the trader pays the ask quotes on what she acquires and the bid quotes on what she sells.[2]

1.4 Payoffs from unsecured CIP arbitrage

Unsecured CIP arbitrage is slightly more complex. Because this strategy uses unsecured loans, traders will usually avoid long-term loans in order to minimize counterparty default risk. Thus, in order to implement arbitrage over a desired period, traders roll over short term – typically overnight – money market positions. In doing so, traders also benefit from the usually very liquid overnight market for funds. This strategy therefore stacks the cards against finding CIP deviations, as risk is minimized while liquidity is maximized.

The expected (ex-ante) payoff from such a strategy is given by,

$$z_{3,t} = \frac{F^B_{t\cdots T}}{S^A_t}(1 + r^{C,B}_{j,t\cdots T}) - (1 + r^{C,A}_{k,t\cdots T}) \tag{3}$$

where $r^C_{t\cdots T}$ are the cumulative interest rates given by rolling over overnight loans from t to T. More explicitly, these are given by,

$$\begin{aligned} 1 + r^{C,A}_{k,t\cdots T} &= \mathbb{E}_t\left[\prod_{s=t}^{T-1}(1 + r^A_{k,s\cdots s+1})\right] \\ 1 + r^{C,B}_{j,t\cdots T} &= \mathbb{E}_t\left[\prod_{s=t}^{T-1}(1 + r^B_{j,s\cdots s+1})\right] \end{aligned} \tag{4}$$

where r in the square bracket captures overnight lending rates.

An immediate drawback from the unsecured arbitrage strategy as described here is interest rate risk. At time t, $r^C_{t\cdots T}$ merely reflects the expectation of the overnight interest rates' future path. In practice, of course, actual

[2]When a trader buys currency j while selling currency k in the spot market, she pays the *ask* price for the jk exchange rate, where, by convention, the exchange rate is the price of the currency cited first in units of that cited second (such as for EURUSD, where the exchange rate is the price in dollars of one euro).

rates may vary substantially from this path. Thus, traders typically complement an unsecured arbitrage strategy by hedging interest rate risk with overnight index swaps, or OIS.

An OIS is an instrument allowing traders to swap a floating income stream (where floating means time varying and unknown ex-ante) with a fixed rate established ex-ante. The floating leg of an OIS is indexed on an interbank overnight unsecured rate, such as the Federal Funds rate in the US, EONIA in the euroarea, or SONIA in the UK. A long position in an OIS contract allows one to receive this floating income stream against a fixed payment agreed up-front. Just the opposite is true for a short position in an OIS contract. Importantly, though, an OIS contract involves no exchange of notional upon initiation, but just the settlement at maturity of the net difference between the accrued interest on the floating leg and the fixed rate. Engaging in an OIS contract therefore adds very little risk to the basic arbitrage strategy of rolling over overnight money market or cash positions.

An OIS contract is therefore a convenient and popular instrument to hedge interest rate risk on a cash position, such as in CIP arbitrage. To illustrate, take the arbitrageur's short cash position in currency k, requiring her to make floating overnight interest payments. By taking, in addition, a long position in an OIS contract denominated in currency k, the trader will receive the same floating overnight interest payments. Indeed, the floating leg of the OIS contract and her cash position will be indexed on the same interbank, unsecured, overnight money market rates. Thus, intuitively, these two floating income streams will cancel out, leaving the trader to pay only the fixed OIS rate known ex-ante, at time t. The same goes for the trader's

long money market position in currency j, to be combined with a short OIS position denominated in that currency.

To summarize, the trader rolls over overnight cash or money market positions, short in currency k and long in currency j until maturity T. In addition, at time t, she hedges interest rate risk by engaging in a long OIS position in currency k and a short position in currency j. As a result, the trader's expected payoff from CIP arbitrage is given by,

$$\begin{aligned} z_{4,t} &= \frac{F^B_{t\cdots T}}{S^A_t}\left[(1+r^{C,B}_{j,t\cdots T})-(1+r^{C}_{j,t\cdots T})+(1+r^{O,B}_{j,t\cdots T})\right]+ \\ &\quad \left[(1+r^{C}_{k,t\cdots T})-(1+r^{C,A}_{k,t\cdots T})-(1+r^{O,A}_{k,t\cdots T})\right] \end{aligned} \tag{5}$$

where, in the first square bracket, the first term is the floating income from lending cash in currency j, the last term is the fixed ex-ante OIS rate and the middle term captures the floating payment liabilities of the OIS contract, given by,

$$1+r^{C}_{j,t\cdots T}=\mathbb{E}_t\left[\prod_{s=t}^{T-1}(1+r_{j,s\cdots s+1})\right] \tag{6}$$

where the absence of bid or ask quotes on the right hand side captures the fact that the flexible leg of the OIS is technically indexed on an effective rate.

2 Measuring excess profits from CIP arbitrage

The crux of this section is its third part, showing evidence of substantial and persistent deviations from CIP arbitrage. To get to these results, though, we first review data sources.

2.1 Data for secured CIP arbitrage

Secured CIP arbitrage involves borrowing and lending on the interbank repo market against collateral. It therefore requires interbank repo rates which are notoriously difficult to obtain. Data on USD interbank repo rates were acquired from ICAP whose BrokerTec trading platform accounts for over half the interbank repo market in USD. Data for comparable rates in EUR and CHF come from Eurex AG, whose platform is the dominant trading venue for both ECB and SNB GC repos.[3]

All repo rates represent actually traded prices and include bid-ask spreads for the EUR and CHF. While the data cover several daily snaps, we focus on the 1:45 pm snap (London time), corresponding to market opening in the US, thus ensuring maximum liquidity. For the same reason, we only extract repo rates for one week terms, discarding longer terms.

In all cases, we use repo rates from GC collateral (ECB GC for EUR repos and SNB GC for CHF repos). This ensures maximum liquidity and minimal risk, and makes data more closely comparable across currency markets. Note that while the risk profile of a GC collateral pool may have varied over time, along with its repo rate, it should not have affected the CIP condition. The arbitrage condition, after all, should hold given any interest rate differential, irrespective of the source of fluctuations.

Finally, synchronous spot foreign exchange data, along with bid and ask quotes, come from ICAP's Electronic Brokering Services (EBS) and forward rates from Tullet Prebon (TP), a leading intermediary in wholesale financial markets which facilitates the trading activities of its large client base, includ-

[3]Data for both EUR and CHF were graciously shared with us on the basis of the close working relationship between Eurex AG and the Swiss National Bank.

ing financial institutions, brokers, market makers and hedge funds.[4] All data go from March 2006 to April 2009.

2.2 Data for unsecured CIP arbitrage

Moving from theory to data, we make one simplification. Equation (5) requires data on OIS rates in two currency markets as well as half spreads on future overnight money market rates. But these spreads are not known to the trader at time t, nor are they available to us. More importantly, these spreads are likely to be very small, especially compared to the size of deviations from CIP. For estimation purposes and in the spirit of replicating traders' expected arbitrage profits, we therefore ignore this half spread, thereby allowing us to simplify equation (5) to,

$$z_{4,t}^{'} = \frac{F_{t\cdots T}^{B}}{S_t^A}(1 + r_{j,t\cdots T}^{O,B}) - (1 + r_{k,t\cdots T}^{O,A}) \tag{7}$$

OIS, spot and forward data span the same 2006-2009 time period and are perfectly synchronous across the forex and money markets considered, coming from four daily snaps at 9 am, 11 am, 4 pm and 11 pm, London time. The first snap captures the trading hours of European and Asian markets, the third of European and US, the fourth of US and Asian markets and the second coincides with the Libor fixing.

Data cover EURUSD, USDCHF, USDJPY, GBPUSD, as well as EURCHF, the last serving as a control not involving the dollar. In each case, data cover relevant OIS and forward contracts of one week as well as 1, 3, 6,

[4]Whereas spot rates are perfectly synchronous with the repo rates, taken at 1:45 pm London time, we use forward rates with time snaps at both 11 am and 4 pm London time as data collection was optimized for exact synchronization first and foremost among the richer dataset used in unsecured arbitrage. But results for secured arbitrage are not sensitive to the use of either forward market snap.

8, 12 and 24 month maturities.[5]

The OIS and forward data from Tullet Prebon are technically indicative, although very close to binding bid and ask prices. This is because TP clients emitting quotes most often use the TP platform for actual trading. Indeed, there are few alternative platforms to trade these instruments.

Figure 2 shows the bid-ask spreads related to unsecured CIP arbitrage. Average spreads in the forex market, both spot and forward, became more volatile after the start of the crisis in August 2007, and increased substantially after the Lehman bankruptcy. Only in April 2009 were spreads back to pre-crisis levels. Average OIS spreads followed forex spreads in a stunning jump in September 2008, but remained elevated at end of sample.

2.3 Actual CIP profits

In the case of secured arbitrage, CIP arbitrage profits are generally negligible or negative, as expected, up to the first signs of the crisis, in August 2007. Profits then increase somewhat, suggesting growing tensions in arbitrage, although levels remain relatively small. The spike coinciding with the Lehman bankruptcy is instead a very clear indication of a break-down of arbitrage.

At their peak, profits – as measured by $z_{2,t}$ – reach nearly 400 bps on an annualized basis; a very substantial amount. Moreover, they remain high for about two months. These dynamics are visible in Figure 3 which plots CIP profits for EURUSD and USDCHF trades. In both cases, trades represent short dollar positions in the spot market. We thus refer to these as long

[5]Forward rates are expressed in "pips" to be divided by 10^4 and added to the spot rate. Note also that OIS rates are annualized and thus needed to be adjusted by a multiplier in order to be consistent with their maturity. The multiplier is $\mu = T/360$ where T is maturity in days, except for sterling and yen for which the denominator is 365.

EURUSD and short USDCHF trades.

As a comparison, Akram, Rime, and Sarno (2008) study CIP profits from tick-by-tick data in 2004 over various currency pairs. They find that annualized mean returns from CIP arbitrage, when they occur, range from 2 to 15 pips and last between 2 to 16 seconds.

Two other results emerge. First, the reverse of these trades, involving long dollar positions on the spot market, yield negative returns, as shown in Figure 4. And second, CIP profits over EURCHF yields negative returns independently of the direction of the trade, as plotted in Figure 5. These results suggest that the very unusual arbitrage profits derived from CIP trades are (i) currency specific (involving the dollar) and (ii) directional (involving short dollar spot positions). Both these take-aways will inspire our explanations for the break-down of arbitrage.

These stylized facts are strongly corroborated by results for unsecured arbitrage profits – as measured by $z'_{4,t}$. Indeed, the extent and duration of CIP profits from secured and unsecured strategies over one week terms are nearly the same for EURUSD and USDCHF, as plotted in Figures 6 and 7.

Data for unsecured arbitrage allow us to explore the robustness of results along two further dimensions: more currency pairs and longer terms of arbitrage. Results are very similar to those described above. Figure 8 plots CIP profits for short dollar trades against the euro, yen, sterling and Swiss franc, over a one month term. As above, CIP profits increase in August 2007 and spike at the time of the Lehman bankruptcy, reaching nearly 400 bps annualized. Returns remain persistent to year end. The second spike, not visible in either secured or unsecured arbitrage over one week, most likely

comes from end-of-year window dressing effects; this is the only noticeable difference from extending the term of arbitrage. As before, CIP returns are negative when spot positions are long in dollars, as shown in Figure 9. And finally, returns on EURCHF unsecured arbitrage over a one month term remain negative throughout the sample, irrespective of which currency is used for financing, as illustrated in Figure 10.

To summarize, all measures show that CIP profits appear to be dollar specific and directional, as well as persistent and closely tied to the Lehman event. Profits seem to be insensitive to the arbitrage strategy.

3 Explaining excess profits from CIP arbitrage

This section first reviews the possible factors explaining the break-down of CIP arbitrage. These stem from two camps: risk and liquidity factors. Second, we suggest that liquidity factors seem to play the predominant role. Third, we test this hypothesis empirically. We first link each factor to a specific proxy or measurable, then include these in a regression of CIP profits. Results consistently show the predominance of the liquidity factors.

3.1 Risk and liquidity factors

We isolate three possible causes of risk specific to the arbitrage trade. The first, contract risk, involves default of the trader's FX forward counterparty during the term of arbitrage. Both Duffie and Huang (1996) and Melvin and Taylor (2009) emphasize this risk. Clearly, contract risk is common to both secured and unsecured arbitrage.

Second, the trader is exposed to rollover risk, but only when engaging in

unsecured arbitrage. Indeed, her unsecured trading strategy involves rolling over overnight money market positions. At any point, though, Lender L (referring back to Figure 1) may stop rolling over the trader's debt, or the trader may do the same to Borrower B. Acharya, Gale, and Yorulmazer (2011), among others, suggest that rollover risk may lead to market freezes when investor sentiment turns negative.[6]

Third, the trader engaged in unsecured arbitrage faces counterparty default risk, as recently emphasized in Taylor and Williams (2009). Specifically, the risk is that Borrow B default. Of course, this risk is typically small for overnight loans, but exists none-the-less and is potentially dissuasive of lending at times of extreme crisis.

We also identify three potential causes of liquidity constraints. The first comes from Lender L's pressure to deleverage, or reduce its balance sheet size, and thus cut funding, albeit lucrative, to the arbitrage trader. This is common to both secured and unsecured arbitrage strategies and reflects the notion in Duffie (2010) of intermediaries' "balance sheet capacity." The impressive extent to which financial institutions deleveraged during the recent crisis is documented and discussed in Adrian and Shin (2008b) and McCauley and McGuire (2009), among others. Garleanu and Pedersen (2011) also focus on deleveraging and suggest a model in which assets with lower margin requirements – with less impact on the balance sheet – can trade at lower prices.[7]

[6]Other papers emphasize sentiment shocks, as Shleifer and Vishny (1997) which brings up the prospects of self fulfilling prophecies. The availability of information also plays a central role, as in Hombert and Thesmar (2009) and Morris and Shin (2010), where imperfect knowledge of aggregate losses is paramount.

[7]Other papers also emphasize feedback from balance sheets to asset prices, as Acharya and Viswanathan (2011) and Benmelech and Bergman (2009). Other papers emphasize

The second cause of liquidity constraint is prudential, involving Lender L hoarding liquidity away from the arbitrage trader to address its own funding strains. Again, this phenomenon affects both secured and unsecured arbitrage. McGuire and von Peter (2009) clearly document the importance of this channel during the financial crisis. By 2008, banks had accumulated substantial dollar assets, funded mostly on a very short term basis on unsecured terms. On net, McGuire and von Peter (2009) estimate that Canadian, Dutch, German, Swiss, UK and Japanese banks required an aggregate of USD 1.2 trillion (net) in USD to fund their assets. When funding markets dried up and when the assets in question became illiquid, banks faced a severe funding strain. The situation was exacerbated by signaling dynamics: banks didn't want to be caught by their peers scrambling for liquidity and they knew that posting sufficient liquidity was essential to maintaining their credit rating. As a result, banks sacrificed lending profits to rebuild their liquidity pools, mostly in USD. These dynamics emphasizing the vicious circle between market and funding liquidity, as well as cross market contagion, are modeled more explicitly in Brunnermeier and Pedersen (2009), Adrian and Shin (2008a) and Gromb and Vayanos (2009), and eloquently discussed in Brunnermeier (2009) and Pedersen (2009).

Finally, the third cause of liquidity constraint builds on the theory of

related frictions also leading to capital constraints and market freezes, such as the structure of financial institutions, as in Diamond and Rajan (2005), He and Krishnamurthy (2008b) and Duffie (2009), the structure of markets, as in Acharya and Pedersen (2005), Allen and Gale (2003), Allen, Carletti, and Gale (2009) and Lagos, Rocheteau, and Weill (2009), or adverse selection or investor sentiment as in Malliaris and Yan (2010), Mancini Griffoli (2009), Heider, Hoerova, and Holthausen (2009), and Bolton, Santos, and Scheinkman (2008). Finally, Cornett, McNutt, Strahan, and Tehranian (2010) suggests that during the crisis the pressure to deleverage was exacerbated by having to honor prior commitments to credit lines, mostly in USD; the paper documents the sharp drop in new loans emanating especially from banks needing to deleverage.

limited capital and is specific to secured arbitrage. According to this theory, reviewed with particular clarity in Gromb and Vayanos (2010),[8] capital to pledge in exchange for cash can be insufficient in times of crisis. Indeed, borrowing on secured terms requires capital to cover margins or haircuts. Following the Lehman bankruptcy, hedge funds faced increasing redemptions and incurred heavy losses on their portfolios. In a time when raising equity was nearly impossible, available capital became scarce. As a result, hedge funds were curtailed in their ability to engage in lucrative arbitrage trades.

3.2 Is it risk or liquidity? Two hints

Before jumping into the more rigorous empirical analysis, earlier results provide two strong hints suggesting that funding liquidity, rather than risk, mostly explains the break-down of CIP arbitrage. First, CIP profits were currency specific and directional in the sense that they emerged when borrowing dollars. While funding constraints can affect a single currency and make it harder to borrow than lend that currency, risk factors would more likely affect all currencies and trades equally.

Second, CIP profits were nearly the same for both secured and unsecured arbitrage. Common results imply a common cause and indeed, liquidity factors affect both arbitrage strategies. Instead, contract risk is the only risk factor common to both strategies; secured arbitrage being mostly void of risk.

[8]But also at the heart of models in Acharya, Shin, and Yorulmazer (2009), Brunnermeier and Pedersen (2009), Kondor (2009), He and Krishnamurthy (2008b,a), Liu and Longstaff (2004), Gromb and Vayanos (2002), Rinne and Suominen (2009) and Shleifer and Vishny (1997)

3.3 Variables, specification and methodology

The basic methodology involves regressing CIP profits on specific measures of the risk and liquidity factors discussed earlier. The measures are presented below and summarized in Table I.

Contract risk involves the early termination of arbitrage, and thus exposes the trader to exchange rate risk by having to close her positions using a reverse spot transaction (or renew her forward contract). We thus capture exchange rate risk with one month forex option implied volatility.

Rollover risk – specific to unsecured arbitrage – entails foregone profits from having to close arbitrage positions early. Foregone profits depend on the maturity structure of current and expected short term interest rate differentials (losses increase when this differential rises in time, since profits are made on the differential). We therefore include the one week to one month OIS spread in currency j relative to that in currency k. This corresponds to potentially lost profits from closing positions after one week instead of the planned one month (unsecured CIP profits are taken over one month terms in our regressions).

We capture counterparty default risk with the CDS index of US financial institutions (results are unchanged with CDS of European banks). And finally, as a control variable, we add a more general measure of risk which could affect any of the above three factors, in the form of the VIX index for equities, such as in Brunnermeier, Nagel, and Pedersen (2009).

On the side of liquidity, we capture the impetus to deleverage using the measure of balance sheet size of financial intermediaries developed in Adrian

and Shin (2008a).[9]

Second, we track prudential hoarding of USD liquidity with cash deposits at Federal Reserve Banks in excess of reserve balances. These represented safe liquidity pools for banks, held at significant opportunity costs.

Third, we had raised the prospects of capital constraints to obtain secured funding. While the literature offers little guidance as to an appropriate measure, we draw inspiration from Coffey, Hrung, Nguyen, and Sarkar (2009) as well as Gorton and Metrick (2009) in using the spread between Agency MBS and GC repo rates. The idea is that as capital becomes scarce, lenders are in a position to extract higher rents from borrowers in the form of higher repo rates. This is all the more true on riskier collateral, such as MBS.

To these, we add two control variables in the form of more general liquidity measures which could be related to any of the factors above. The first are TED spreads, as in Brunnermeier (2009) and Brunnermeier, Nagel, and Pedersen (2009), implying that liquid capital is withdrawn from markets when it flies to high quality government bonds. The second are Libor-OIS spreads. We orthogonalize these variables relative to their risk components by always including the earlier mentioned risk variables in the regression. This is as in Taylor and Williams (2009).

While liquidity was drying up, policy was working to facilitate borrowing conditions. We therefore add two policy measures which represent exogenous sources of liquidity fluctuations.[10] The first of these is USD swap lines extended by the Fed to other central banks (BOE, BOJ, BOC, ECB and SNB), and the second is the Fed's "Reserve Bank Credits". Reserve bank credits

[9]We thank the authors for kindly sharing their data with us.

[10]Papers studying the policy responses to liquidity constraints are Cecchetti and Disyatat (2009), Drehmann and Nikolaou (2009) and Sarkar (2009).

include securities held outright, but more importantly repos, term auction credits, other loans, as well as credit extended through the commercial paper funding facility and the money market investor funding facility.[11] While these measures had the goal of improving funding liquidity issues generally, FX swaps were more precisely targeted at solving the shortage of dollar funding abroad.

A final two variables are considered, intended to capture market liquidity more generally, as opposed to funding liquidity measures. We do this following Brunnermeier and Pedersen (2009) who emphasize the link between market and funding liquidity. We capture market liquidity with the first principal component across currencies (or currency pairs) of bid-ask spreads in the OIS and forex market. This is as in Korajczyk and Sadka (2008) and yields two latent liquidity variables.[12]

In the end, we estimate the following equation,

$$\Delta z_t = \alpha + \gamma \Delta z_{t-1} + \beta_1' \Delta \Sigma_t + \beta_2' \Delta \Psi_t + \beta_3' \ \Delta \Theta_t + \epsilon_t \tag{8}$$

where Σ_t is a matrix of variables capturing "risk", Ψ_t is a matrix of "funding liquidity" variables and Θ_t is a matrix including the "market liquidity" variables. Note that all variables are taken in first differences, as it is primarily the impact of the tightening of funding liquidity on the growth of excess CIP

[11] Weekly data is available on the Federal Reserve Bank of New York's website www.federalreserve.gov/releases/h41/

[12] The FX latent liquidity variable is defined as the first principle component (FPC) of the bid-ask spreads of the exchange rates (both spot and forward rates) against the USD. The FPC accounts for more than 80% of the overall liquidity and the loadings are extremely similar across exchange rates. We also tried using a straight average and found, as expected, very similar results. The OIS latent liquidity variable is defined as the FPC that accounts for 60% of the total volatility and the loadings are very similar across currencies (i.e. between 0.42 and 0.54), except for the JPY which has a loading of -0.14. The exclusion of the latter leaves the results essentially unchanged.

profits that interests us. Estimation is carried out for both EURUSD and a panel including EURUSD, USDJPY, GBPUSD, and USDCHF, all over a one month term for unsecured arbitrage. Shorter and longer terms are explored in the robustness tests. For secured arbitrage, results are shown only for EURUSD over a one week term. Time series regressions are estimated using OLS with Newey-West standard errors, and panel regressions using Seemingly Unrelated Regression with fixed effects, exchange rate specific constants and autoregressive coefficients. The identification strategy entails testing the significance of each funding liquidity variable separately, while, controlling for risk as well as market liquidity factors. The only funding liquidity variable included in all regressions due to its exogeneity is FX swaps. This method entails running seven regressions for unsecured arbitrage and eight for secured arbitrage. Other variants are instead explored in the robustness tests.

3.4 Estimation results

Market liquidity variables are highly significant across the various specifications in the panel case (Table III). In the EURUSD time series case (Table II), market liquidity variables are less often significant, probably because of the more liquid forex and money markets. In all cases the coefficient on forex market liquidity is negative, suggesting higher bid-ask spreads erode excess returns. But the positive coefficient on the OIS latent liquidity variable suggests another interpretation: that OIS bid-ask spreads are also a measure of funding liquidity. Results suggest that as liquidity becomes depressed on funding markets – or as spreads increase – excess returns grow. Results do not change if each variable is taken separately.

Funding liquidity variables – TED spreads, Libor-OIS spreads, as well as central bank deposits – are all highly significant across both panel and time series (Tables III and II). Their positive coefficients indicate that as funding liquidity worsens (an increase in these variables), excess profits from CIP arbitrage increase. The Adrian and Shin measure of balance sheet size, though, is not significant. It does gain significance and appears with the expected negative sign when all variables are taken in levels (included in robustness tests). The balance sheet measure may be tainted by banks having to absorb formerly off-balance sheet vehicles or other pre-committed credit lines, while wanting to deleverage on other fronts none-the-less.

Interestingly, results suggest the policy responses during the crisis were quite effective at alleviating the constraint on funding liquidity, and thus contributing to restoring the CIP condition. Coefficients on the reserve credits as well as forex swap lines, in both the time series and panel regressions, are all highly significant. Their negative sign suggests that as policy injected greater dollar funding liquidity, excess CIP profits decreased. Note that both variables are taken with a one week lag, to allow for the transmission of policy. This is when significance is highest, although coefficients remain significant when policy variables are included with a two week lag, or contemporaneously.

Next, we move to the risk variables. The implied volatility (IV) variable is always positive and significant in the EURUSD time series regressions (Table II), although the picture is less clear in the more representative panel case (Table III). Generally, though, it would seem that exchange rate risk did play some role in propping up excess arbitrage profits.

Results are quite weak for the other risk factors. The CDS and VIX variables are never significant and the interest rate differential is only significant in half the panel regressions, while it is never so in the time series regressions. Thus, counterparty, rollover and more general risk do not seem to have played a direct role in dissuading arbitrage.

We end with a closer look at regression results from secured arbitrage over a one week term, presented in Table IV. As expected, results change only very little with respect to the case of unsecured arbitrage, even if the term of arbitrage is different. This is certainly the case for the market and funding liquidity variables. The CDS and VIX variables also remain insignificant, as expected from an arbitrage strategy mostly void of risk. And the implied volatility variable loses significance in two of the eight cases, although retains the approximate size of its coefficient. Finally, the repo spread variable (Agency MBS to GC repo spreads) is significant, supporting the hypothesis that capital was insufficient to pledge as collateral.

Generally, then, the above results suggest that CIP deviations can be explained mostly by funding liquidity constraints in dollars, as well as generally tighter market liquidity, and, in part, from the risk of default of the forward counterparty. But the riskiness of the arbitrage trade does not seem to have played a major role in dissuading arbitrage.

3.5 Additional robustness tests

Results from additional robustness tests are described verbally for the sake of brevity. None-the-less, any specific result is available upon request.

- Time of day does not seem to affect CIP profits. Results are unchanged

when using a 4 pm snap relative to the baseline 11 am snap for unsecured arbitrage (all times are London time).

- Considering unsecured arbitrage over a six month or a one week term, instead of one month, does not affect results.

- Results over sub-samples support our main findings: liquidity variables are insignificant prior to August 2007, become significant between August 2007 and the Lehman bankruptcy, and grow substantially thereafter. Risk related variables instead remain mostly insignificant throughout each period.

- Results are robust to different regression specifications. Results are nearly unchanged when considering all variables in levels instead of first differences (except for the significance of the balance sheet variable as discussed earlier) and when including each variable separately, while still controlling for a constant and an autoregressive term. An encompassing regression that includes all variables together delivers consistent results, except that TED spreads lose significance most probably due to their collinearity with Libor-OIS spreads. Finally, accounting for ARCH effects leaves all findings essentially unchanged.

4 Conclusion

This paper provides empirical evidence for the theory of slow moving capital and limits to arbitrage, and adds to recent studies on the effects of the financial crisis. This paper focused on measuring precisely, and explaining, deviations from covered interest parity (CIP) arbitrage. The paper described

how such arbitrage strategies are actually implemented in practice, using either secured or unsecured money market transactions. Especially after the Lehman bankruptcy, excess profits from CIP arbitrage were substantial and persistent, involved borrowing dollars and did not depend on whether borrowing was secured. These results were found with data which closely match those a trader would have used to undertake arbitrage. Data are intra-daily, synchronized across markets and inclusive of transaction costs. Results implied that it was especially the lack of dollar funding liquidity – due to deleveraging imperatives, prudential hoarding and limited capital to pledge in exchange for liqudity – that hindered arbitrage and thus failed to balance the CIP condition. These results suggested that policy aimed at avoiding future crises, or at least at containing their effects on the proper functioning of markets, should also take into consideration the role of liquidity and possibly require liquidity buffers reflecting the currency composition of financial institutions' balance sheets.

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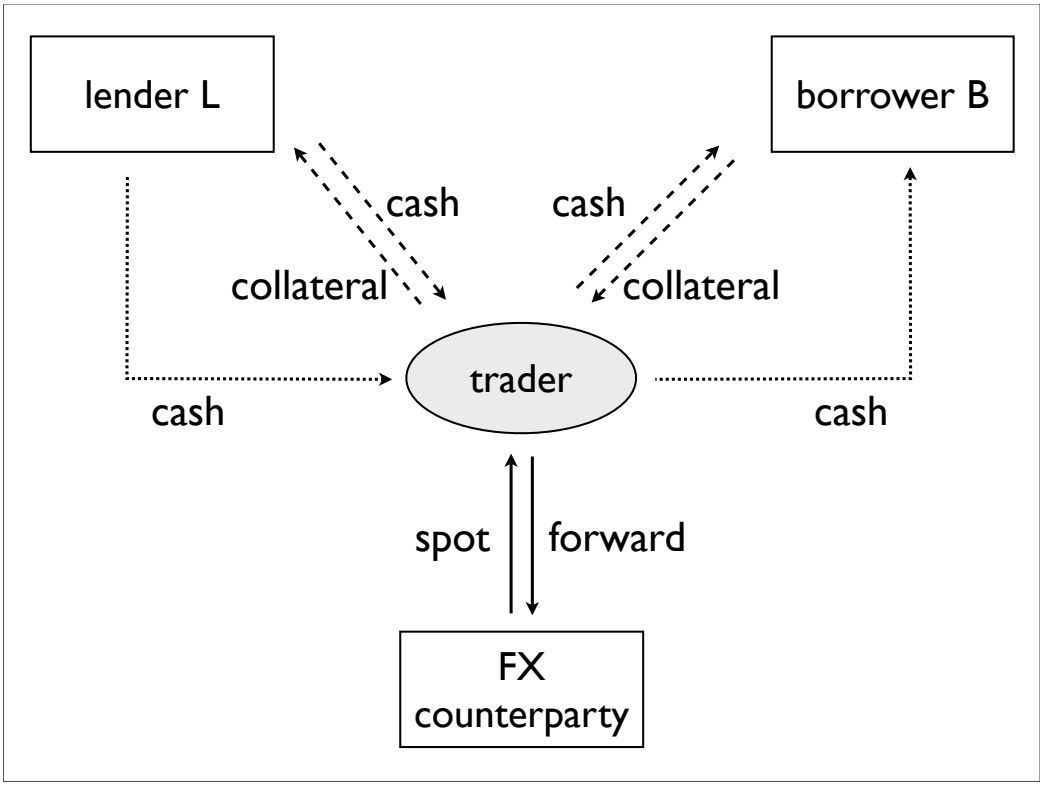

Figure 1: *An illustration of CIP arbitrage: the trader can be thought of as either a hedge fund or the prop desk of a large financial institution. Typically, the former borrows and lends on secured terms by exchanging cash against collateral (hashed lines), and the latter does so on unsecured terms (dotted lines). Both are money market transactions. The trader also engages in two forex transactions with appropriate counterparties, one spot and one forward. In all, CIP arbitrage involves four transactions.*

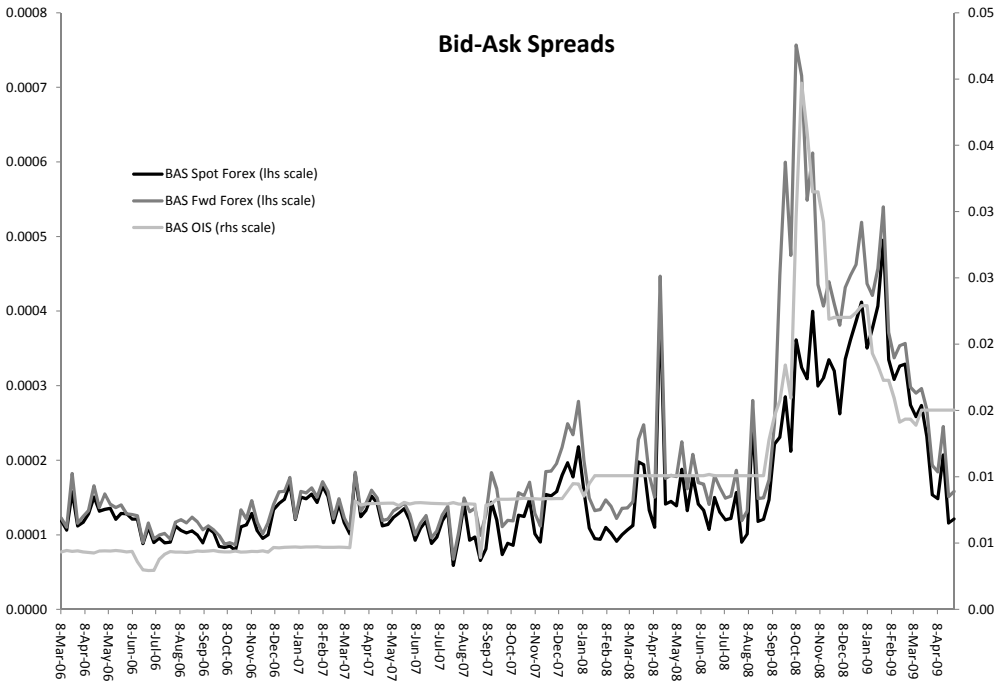

Figure 2: *Average bid–ask spreads across currency pairs in the forex spot and forward markets, as well as OIS market. Bid–ask spreads are calculated as* $(Ask - Bid)/C$ *where* C *is the average midquote.*

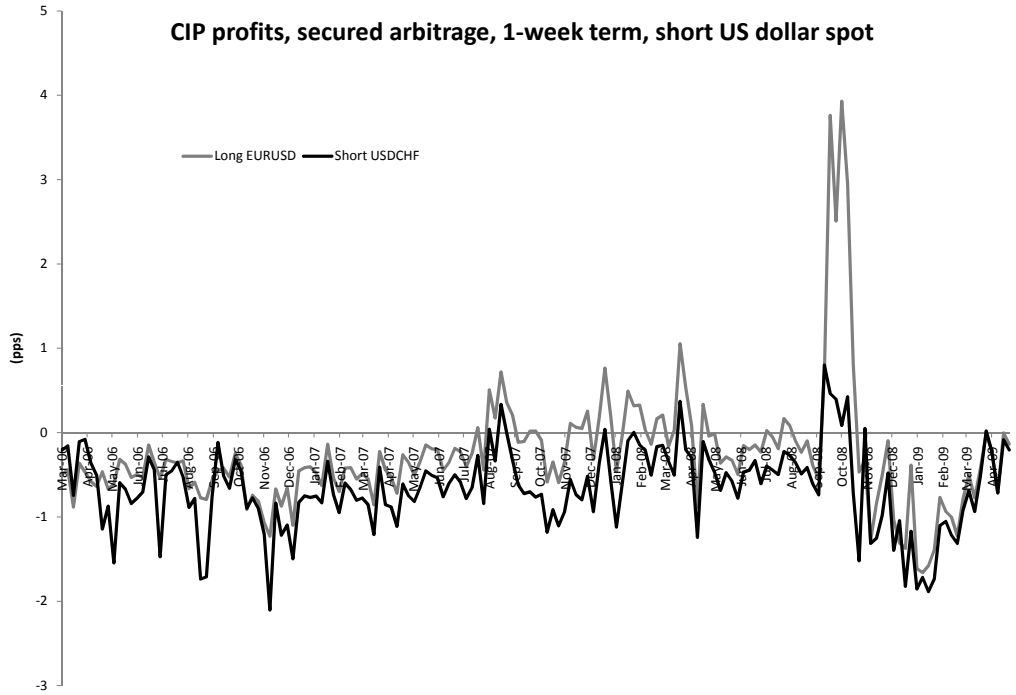

Figure 3: *Excess profits are large and persistent from secured CIP arbitrage on trades involving a short USD spot position, over a 1 week term.*

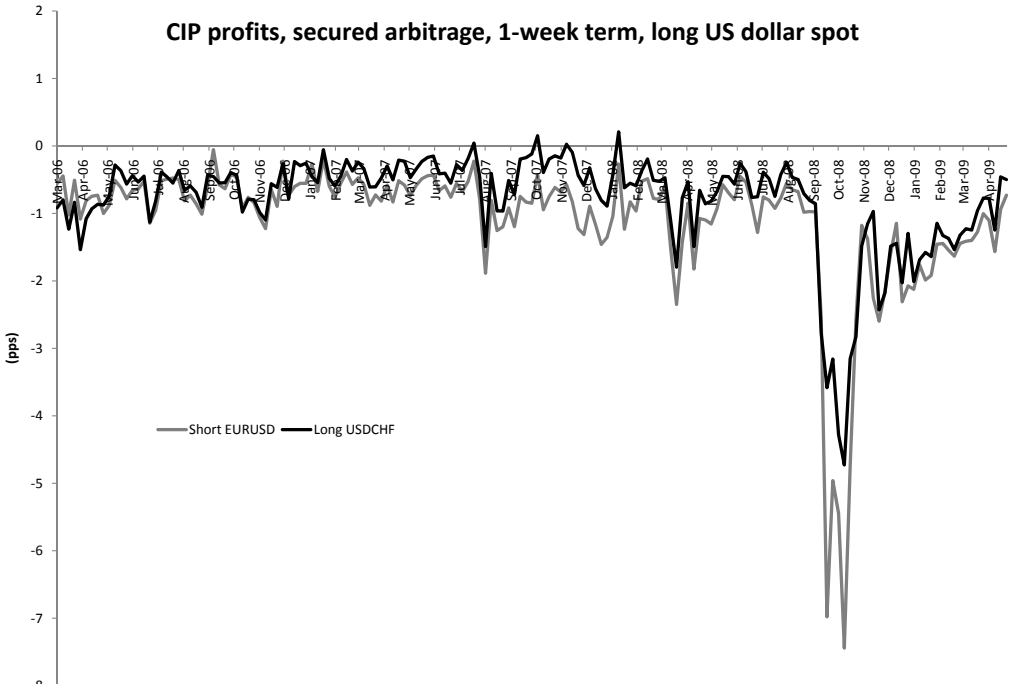

Figure 4: *Excess profits are negative from secured CIP arbitrage on trades involving a long USD spot position, over a 1 week term.*

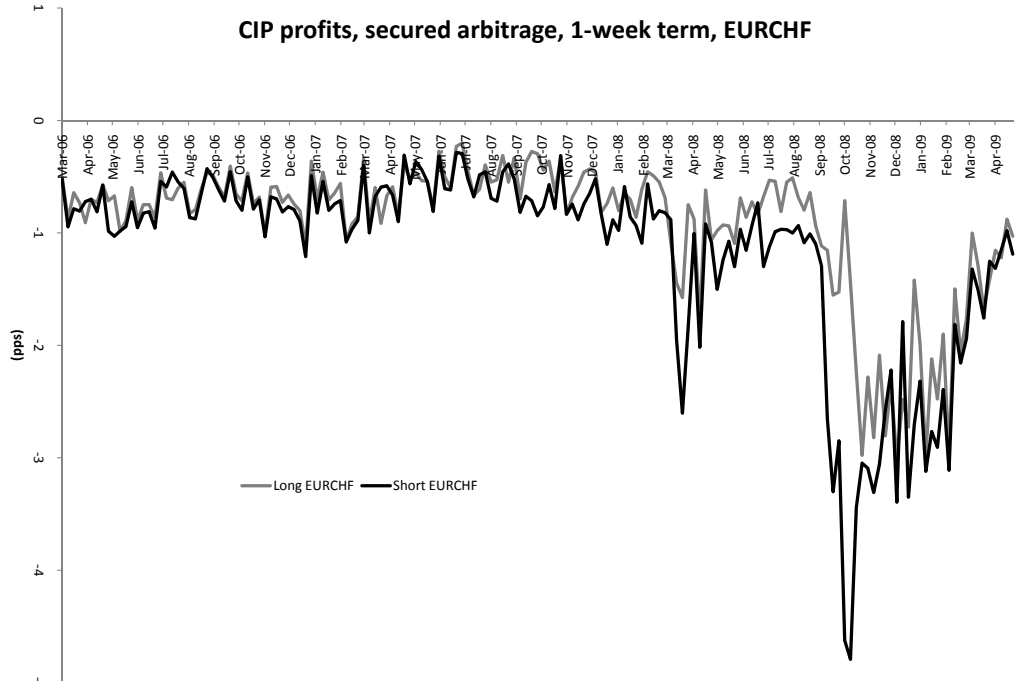

Figure 5: *Excess profits are negative from secured CIP arbitrage over a 1 week term on trades in EURCHF, irrespective of the currency used for financing.*

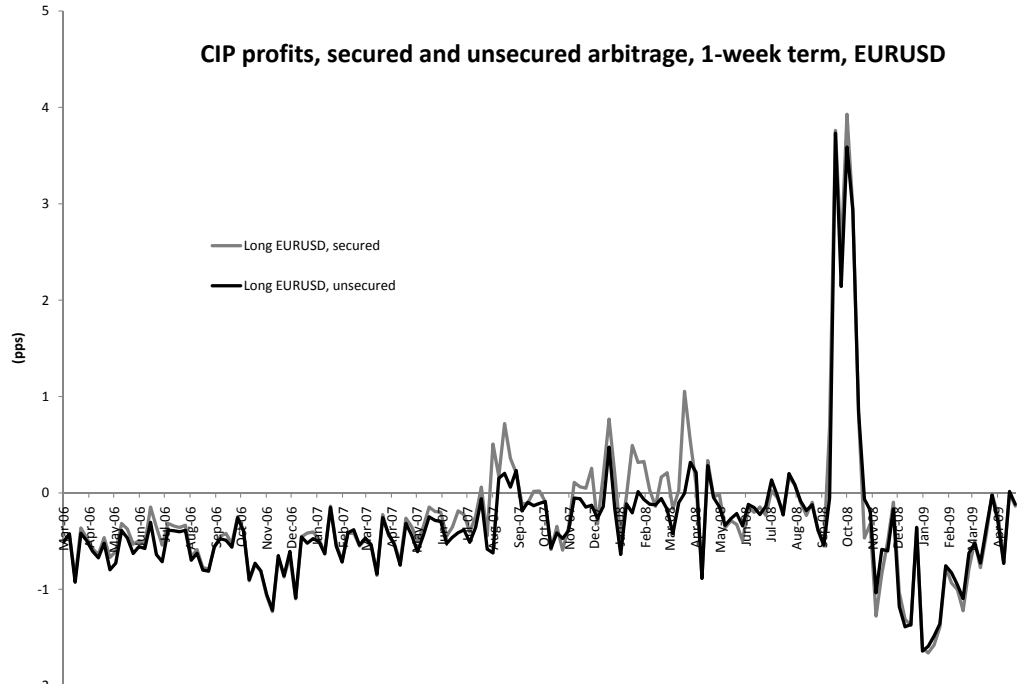

Figure 6: *Excess profits are exactly the same on secured and unsecured CIP arbitrage over a 1 week term on trades involving a short USD spot position.*

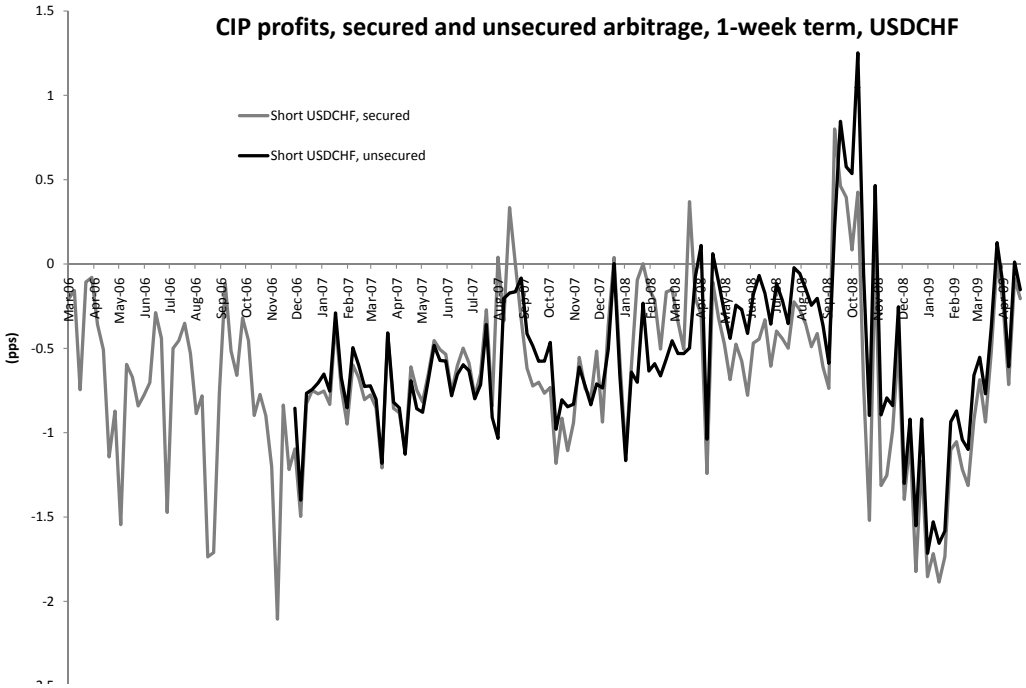

Figure 7: *Excess profits are nearly the same on secured and unsecured CIP arbitrage over a 1 week term on trades involving a short USD spot position.*

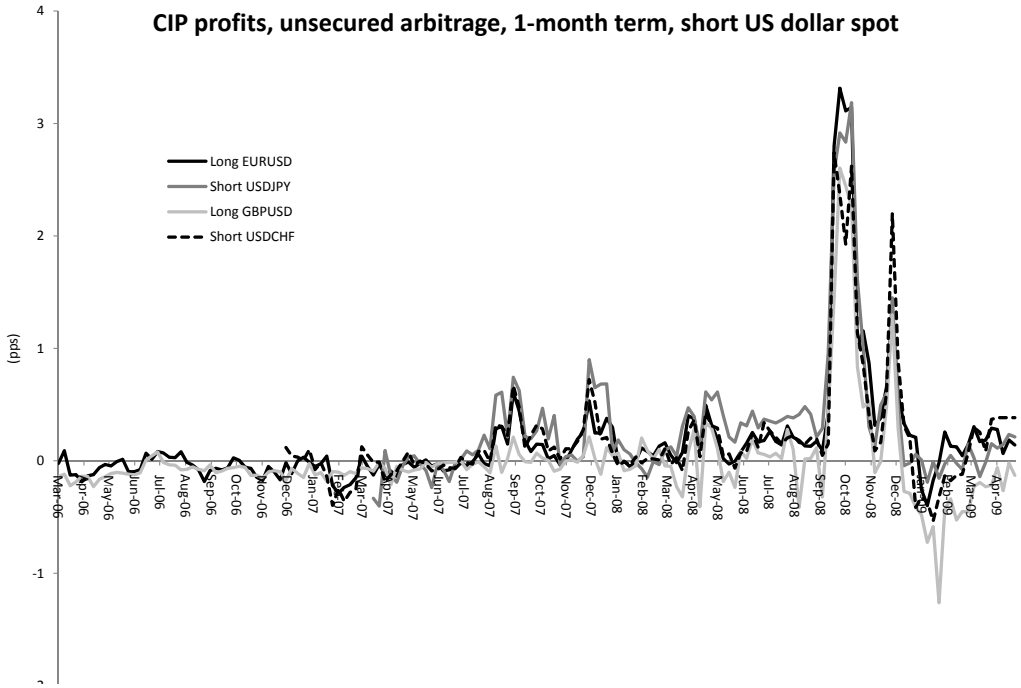

Figure 8: *Excess profits are large and persistent from unsecured CIP arbitrage on trades involving a short USD spot position, over a 1 month term.*

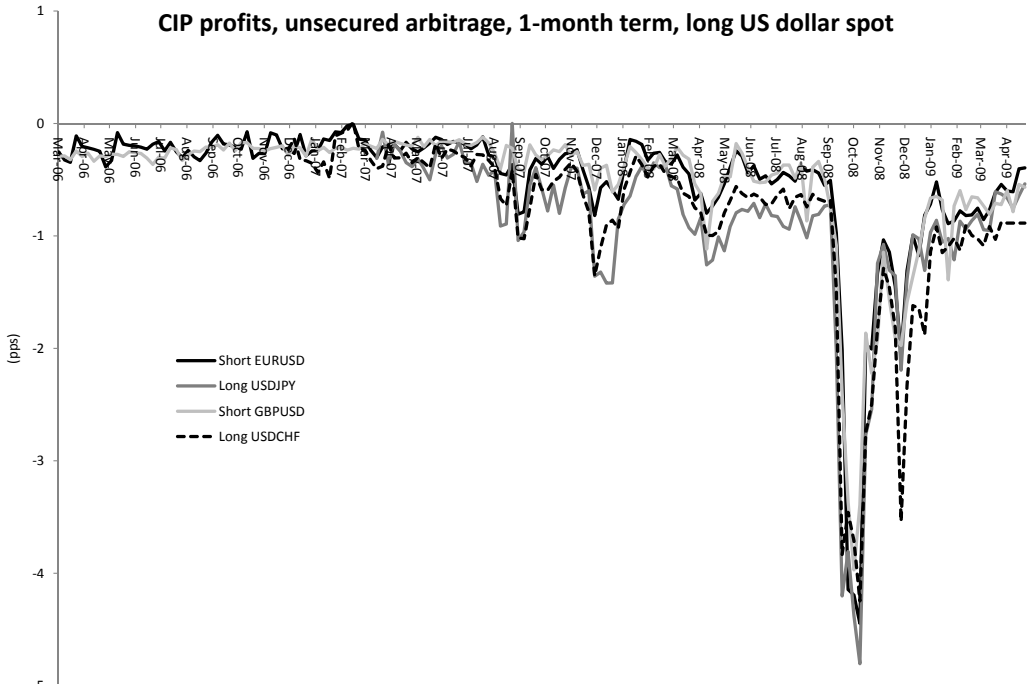

Figure 9: *Excess profits are negative from unsecured CIP arbitrage on trades involving a long USD spot position, over a 1 month term.*

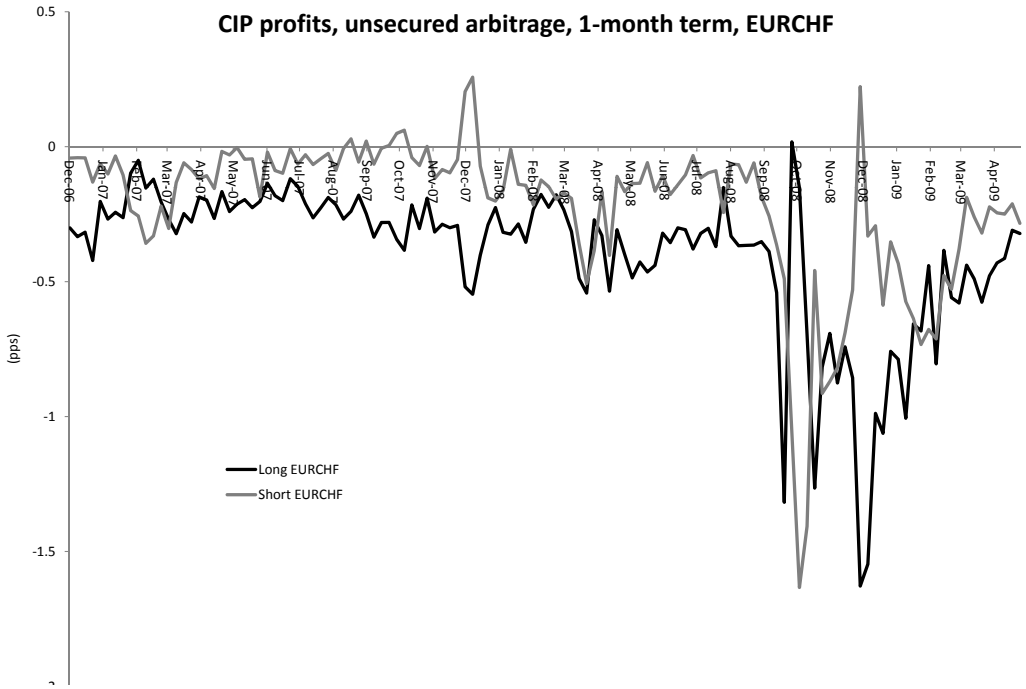

Figure 10: *Excess profits are negative from secured CIP arbitrage over a 1 month term on trades in EURCHF, irrespective of the currency used for financing.*

	Factor	Unsecured arbitrage proxy	Secured arbitrage proxy
Risks			
	Contract	Implied volatility (IV)	Implied volatility (IV)
	Rollover	Interest differential	NA
	Counterparty default	CDS	NA
	General/ controls	VIX, CDS	VIX, CDS
Funding liquidity			
	Deleveraging	Balance sheet (CPG)	Balance sheet (CPG)
	Prudential hoarding	CB deposits	CB deposits
	Limited capital	NA	MBS-GC repo spreads
	Policy measures	CB swaps,	CB swaps,
		Reserve credits	Reserve credits
	General/ controls	TED, Libor-OIS	TED, Libor-OIS
Market liquidity			
	Transaction costs	OIS & FX BAS spreads	OIS & FX BAS spreads

Table I: *Summary of various explanatory factors for excess profits from CIP arbitrage, categorized according to risk, funding liquidity and market liquidity. Each factor is intended to be captured by a corresponding "proxy" or variable. Since some factors are not relevant to both unsecured and secured arbitrage strategies, some proxies are market as not applicable (NA).*

Time series, long EURUSD unsecured CIP arbitrage (1M)

	Specification						
	1	2	3	4	5	6	7
Market Liquidity							
FX liquidity	-0.021	**-0.039**	**-0.039**	-0.032	-0.026	-0.040	**-0.041**
	-0.906	-1.671	-1.747	-1.331	-1.153	-1.573	-2.171
OIS liquidity	**0.302**	**0.321**	**0.374**	0.089	0.129	**0.330**	**0.237**
	2.661	2.741	3.150	0.740	1.139	2.666	2.924
Funding Liquidity							
CB swap		**-6.704**		**-4.618**	**-4.721**	**-6.743**	**-7.537**
		-4.498		-3.303	-3.468	-4.120	-8.198
Reserve credits			**-4.289**				
			-3.300				
TED Spread				**0.655**			
				4.032			
Libor-OIS					**0.765**		
					4.426		
Adrian-Shin CPG						1.433	
						0.661	
Deposit							**1.009**
							10.649
Risks							
IV		**1.697**	**1.581**	**0.967**	**1.397**	**1.853**	**1.074**
		3.104	2.920	1.796	2.763	3.050	2.802
Interest Diff.		-0.246	-0.293	-0.205	-0.154	-0.291	-0.124
		-1.219	-1.415	-1.102	-0.840	-1.317	-0.939
CDS		-0.305	-0.270	-0.477	-0.243	-0.335	0.118
		-0.808	-0.704	-1.329	-0.695	-0.776	0.475
VIX		0.446	0.257	0.179	0.075	0.358	-0.191
		0.968	0.564	0.393	0.166	0.701	-0.565
Adj. R2	0.040	0.237	0.185	0.345	0.380	0.223	0.637

Table II: *Time series results for long EURUSD spot positions. For each variable, estimated coefficients appear above corresponding t-statistics. Numbers in bold represent significance at least at the 10% level. AR(1) coefficients are always significant, while the constant is never so; neither are shown to simplify the table.*

Panel, short USD unsecured CIP arbitrage (1M)

	Specification						
	1	2	3	4	5	6	7
Market Liquidity							
FX liquidity	**-0.073**	**-0.077**	**-0.083**	**-0.075**	**-0.072**	**-0.079**	**-0.065**
	-3.838	-4.014	-4.281	-4.195	-4.455	-3.792	-4.029
OIS liquidity	**0.349**	**0.350**	**0.387**	0.134	**0.161**	**0.354**	**0.271**
	3.949	4.050	4.270	1.606	2.216	3.955	4.037
Funding Liquidity							
CB swap		**-5.741**		**-3.494**	**-3.854**	**-5.945**	**-7.184**
		-5.648		-3.759	-4.658	-5.456	-9.676
Reserve credits			**-2.417**				
			-3.133				
TED Spread				**0.739**			
				6.985			
Libor-OIS					**0.850**		
					8.505		
Adrian-Shin CPG						0.171	
						0.119	
Deposit							**0.898**
							11.641
Risks							
IV		**0.856**	0.587	0.194	**0.671**	**0.929**	**0.832**
		2.112	1.406	0.529	2.073	2.081	2.658
Interest Diff.		-0.091	-0.072	**-0.172**	**-0.157**	-0.103	**-0.149**
		-0.951	-0.712	-2.002	-1.851	-1.002	-1.908
CDS		0.155	0.383	-0.214	0.053	0.221	0.044
		0.575	1.354	-0.898	0.245	0.720	0.214
VIX		0.576	0.346	0.182	0.003	0.522	-0.042
		1.634	0.952	0.564	0.009	1.365	-0.149
Adj. R2							
EURUSD	-0.045	0.124	0.012	0.281	0.298	0.101	0.614
USDJPY	0.006	0.246	0.098	0.446	0.514	0.253	0.436
GBPUSD	0.127	0.171	0.128	0.295	0.381	0.142	0.402
USDCHF	-0.061	0.133	-0.033	0.306	0.404	0.115	0.528

Table III: *Panel results for USD group exchange rates, involving short USD spot positions. For each variable, estimated coefficients appear above corresponding t-statistics. Numbers in bold represent significance at least at the 10% level. AR(1) coefficients are always significant, while the constant is never so; neither are shown to simplify the table.*

Time series, long EURUSD secured CIP arbitrage (1W)

	Model							
	1	2	3	4	5	6	7	8
Market Liquidity								
FX liquidity	-0.062	-0.065	-0.067	**-0.080**	**-0.068**	-0.053	**-0.086**	**-0.092**
	-1.539	-1.626	-1.609	-2.072	-1.714	-1.222	-2.639	-2.433
OIS liquidity	**0.746**	**0.776**	**0.854**	**0.491**	**0.658**	**0.765**	**0.738**	**0.483**
	4.166	4.568	4.536	2.899	3.857	4.369	5.673	2.976
Funding Liquidity								
CB swap		**-10.413**		**-8.128**	**-9.371**	**-9.860**	**-12.529**	**-7.637**
		-5.448		-4.440	-4.949	-4.846	-8.586	-4.352
Reserve credits			**-4.374**					
			-2.968					
TED Spread				**0.819**				
				4.055				
Libor-OIS					**0.529**			
					2.348			
Adrian-Shin CPG						2.713		
						1.060		
Deposit							**1.109**	
							7.643	
Repo spread								**0.612**
								2.685
Risks								
IV		**1.521**	0.803	1.013	**1.515**	**1.611**	**1.379**	0.887
		1.983	0.977	1.419	2.043	1.909	2.372	1.291
CDS		0.099	0.264	-0.003	0.166	0.239	0.284	-0.114
		0.205	0.494	-0.007	0.357	0.438	0.778	-0.191
VIX		0.379	0.011	-0.167	-0.022	0.087	-0.300	-0.138
		0.579	0.015	-0.268	-0.033	0.123	-0.581	-0.325
Adj. R2	0.159	0.267	0.156	0.357	0.298	0.260	0.528	0.396

Table IV: *Time series results for long EURUSD spot positions. For each variable, estimated coefficients appear above corresponding t-statistics. Numbers in bold represent significance at least at the 10% level. AR(1) coefficients are always significant, while the constant is never so; neither are shown to simplify the table.*