Crypto Covered Interest Parity Deviations

Friedrich-Carl Franz[*] Alexander Valentin[†]

October 6, 2020

Abstract

Studying deviations from covered interest rate parity (CIP) in the Bitcoin/US-Dollar (BTC/USD) market, we find large CIP deviations of up to 15% until Q1/2018. Afterwards, CIP deviations have been subdued, which we attribute to the market entry of high-frequency traders (HFTs). We argue that these market entries have increased efficiency of cryptocurrency markets with respect to CIP as well as liquidity, volatility, and bid-ask spreads. Remarkably, these efficiency gains are larger for the less liquid cryptocurrency Litecoin. Employing a difference-in-differences design, we show that the launch of the BTC/USD future at the Chicago Mercantile Exchange (CME) did not affect market efficiency. Finally, remaining CIP deviations after Q1/2018 seem mostly related to increased credit risk of certain crypto exchanges.

Keywords: Cryptocurrencies, Bitcoin, Futures, Covered Interest Rate Parity, High-Frequency Trading

JEL Codes: E42, G12, G13, G14

[*]Goethe University Frankfurt, Theodor-W.-Adorno-Platz 3, 60323, Frankfurt am Main, Germany; franz@finance.uni-frankfurt.de

[†]Goethe University Frankfurt, Theodor-W.-Adorno-Platz 3, 60323, Frankfurt am Main, Germany; valentin@finance.uni-frankfurt.de

1 Introduction

The market for cryptocurrencies has evolved dramatically in recent years. Today many elements of traditional financial markets can be found in the crypto space. Market participants do not only face stronger market depth but also have access to a variety of financial instruments. For example, many crypto exchanges have extended their product offering beyond spot transactions, now offering futures, options, and credit against bitcoin (BTC) or U.S. Dollar (USD). Given the availability of these instruments and the evolution of new financial markets in the crypto space, an ideal laboratory arises to test for the effect of sophisticated arbitrageurs entering the market. Against this backdrop, we study a widely known parity relation, *Covered Interest Rate Parity (CIP)*, in the context of market-entries of high-frequency trading (HFT) firms. To the best of our knowledge, we are the first to study CIP deviations in the cryptocurrency market.

CIP can be described as the "closest thing to a physical law in international finance" (Borio et al. (2016)), as it dictates the relation between spot, futures or forward prices, and interest rate differentials. In an arbitrage-free market, two of these components must determine the third (for details see Figure 6). However, even in the long-existing conventional currency markets, such as EUR/USD, it does not hold. While Rime et al. (2017) argue that deviations from CIP occur due to funding constraints, Du et al. (2018) see regulatory constraints as a driving force of CIP deviations. Consequently, CIP deviations reveal a lot about market efficiency and frictions under which market participants operate.

In this paper, we show that there have been large CIP deviations especially in the early stages of the crypto market. Figure 1 shows that CIP deviations of BTC/USD have been large, e.g. up to 15% in mid-2017, pointing to inefficiencies that leave ample room for arbitrageurs. As crypto exchanges have not been subject to a strict regulatory regime and the size of CIP deviations in the crypto space cannot be rationalized by potential funding costs alone, we add to the existing literature by shedding light on the role of sophisticated arbitrageurs.

Insert Figure 1 here.

Specifically, we contribute three key insights: *First*, we provide a framework to calculate the cross-currency basis in the cryptocurrency space. Employing deviations from this cross-currency basis in a difference-in-differences design and in a panel regression, we rationalize the decline after Q1/2018 by the entrance of sophisticated arbitrageurs. Consequently, we demonstrate that professional arbitrageurs, such as HFT firms, are needed to make even basic arbitrage mechanisms hold. *Second*, the introduction of the Chicago Mercantile Exchange (CME) BTC/USD future in Q4/2017, i.e. the possibility to trade BTC outside the crypto space, which received much attention in the cryptocurrency literature, e.g. in Hale et al. (2018), only had a limited effect on market efficiency and did not provide a suitable tool for professional arbitrageurs. *Third*, we show that the presence of HFT firms is even more important for illiquid markets, such as LTC compared to BTC.

For our empirical analysis of CIP deviations, we collect interest rates for BTC and USD as well as future and spot prices from two major crypto exchanges, Bitfinex and OKEx. While CIP holds on average, large spikes occurred and persisted for several days before Q1/2018. During and after that, deviations have become much smaller. For example, a strategy that traded on these violations would have earned an annual excess return net of transaction costs of 44% (Sharpe Ratio of 2.23) before 03/2018 and just 1.24% (Sharpe Ratio of 0.2) after (Table 2 and Figure 7). Moreover, Figure 2 shows that the mean of absolute CIP has more than halved after entry of sophisticated arbitrageurs.

Insert Figure 2 here.

We employ a difference-in-differences design with another cryptocurrency, Litecoin (LTC), as control group to show that the launch of the CME future did not cause the structural change in CIP deviations (Table 3). The same is true for other measures of market efficiency, such as the half-life of CIP deviations, volatility, and bid-ask spreads. This is confirmed by a second difference-in-difference regression that differentiates between trading and non-trading hours of the CME. (Table 4). In our robustness section, we confirm that this is also true when we replace LTC with Ethereum (ETH).

Instead, a panel regression (Table 5) reveals that CIP deviations and the aforementioned additional market efficiency proxies have decreased due to the market entry of HFT firms, such as Jane Street (March 2018[1]) followed by Flow Traders (July 2018[2]). Two additional results support our claim. First, for volume-based liquidity proxies, such as the Amihud (2002) illiquidity measure, we find a similar but weaker result, i.e. liquidity has improved after Q1/2018 but not significantly. We argue that the market-entry of arbitrageurs should not affect trading volume as much as CIP deviations and bid-ask spreads. Second, deviations from uncovered interest rate parity (UIP) have also decreased after the market-entry of HFT arbitrageurs, but much less than CIP deviations. As CIP is bound by arbitrage (in contrast to UIP), it should be affected more.

Finally, we investigate the remaining (and economically small) CIP deviations that persisted after the HFT market-entry by limits to arbitrage arguments (Gromb and Vayanos (2010) and Gromb and Vayanos (2018)). Specifically, we relate these CIP deviations to increased counterparty risk of Bitfinex in 2019, following legal allegations regarding its stablecoin Tether (USDT) (Griffin and Shams (2020)). These allegations and a restriction on fiat[3] withdrawals have created a Bitfinex premium, i.e. BTC (USD) trades at a premium (discount) on Bitfinex compared to other exchanges. We find that this premium explains much of the remaining CIP deviations since the HFT market-entry (Figure 10 and Table 6).

The paper is structured as follows. First, we proceed with a brief literature review. Then, Section 2 provides an overview of the cryptocurrency market, i.e. characteristics of exchanges and their products, and introduces the data. Section 3 presents the theoretical background of the CIP paradigm, further economically motivates our analysis through profitable CIP ar-

[1]See pp. 108-109 of https://www.sec.gov/comments/sr-nysearca-2019-01/srnysearca201901-5164833-183434.pdf.

[2]https://www.bloomberg.com/news/articles/2018-07-05/dutch-speed-trader-jumps-into-crypto-bets-spurned-by-regulator

[3]In this paper, we will refer to conventional, government-issued currencies as fiat currencies.

bitrage trading strategies, and introduces our research design. Section 4 provides the results of our diff-in-diff analysis, which reveal that HFT-market entries changed the cryptocurrency market. The section proceeds by discussing short-sale constraints and counterparty risk as possible causes of the remaining CIP violations. Section 5 runs four robustness checks of our results and is followed by concluding remarks in Section 6.

Literature Review

Our findings are related to papers that show violations of CIP in conventional FX markets, such as Borio et al. (2016) and link them to funding constraints or credit risk, such as Ivashina et al. (2015), Du et al. (2018) and Du et al. (2019). For example, Rime et al. (2017) show that riskless CIP arbitrage in the USD market is available only to a subset of banks who have access to cheap funding as well as highly liquid investment assets. Such a segmentation does not exist for the CIP deviations in the cryptocurrency market. All required instruments for a risk-free arbitrage round-trip are publicly traded on a limit order book. Consequently, CIP arbitrage in cryptocurrencies is more a question of being "fast" enough, than being a member of a particular market segment. Our findings reveal that in a fragmented market, such as BTC/USD, regular market participants do not have the means to arbitrage CIP deviations. Instead, sophisticated arbitrageurs are required for CIP to hold.

Apart from the literature on CIP deviations, we contribute to research on the cryptocurrency market. For example, Griffin and Shams (2020) show that the Bitfinex-controlled stablecoin Tether[4] (USDT) has been used to manipulate the bitcoin market. In line with their results, we find that the default risk of Bitfinex increased in 2019 thereby creating violations from CIP. Alexander and Heck (2019) analyze jumps in the BTC market post-2018 and argue for the presence of high-frequency arbitrageurs. While this supports our results, we argue that CIP deviations allow for more direct evidence into the presence of sophisticated arbitrageurs and their influence on market efficiency. Makarov and Schoar (2019) document bitcoin spot market segmentation and large cross-exchange arbitrage profits until

[4]For more information see Section 2.1

03/2018. While we also find large arbitrage opportunities as represented by CIP violations before 03/2018, we show that market entries of HFT firms—exactly in 03/2018—have effectively alleviated these opportunities. This result is in line with studies of the fiat world that show that HFT trading improves market efficiency (Hendershott et al. (2011), Brogaard et al. (2014), and Brogaard et al. (2018)). Similar to our results, Menkveld (2013) finds that HFT-entry decreased bid-ask spreads on Chi-X.

While many papers study BTC futures and their impact on the cryptocurrency market, we are not aware of any paper that studies the effect of HFT market entries on the cryptocurrency market. For example, Hale et al. (2018) argue that the announcement of the CME BTC/USD future has increased volatility and that price formation is independent of it. This is in line with Alexander and Heck (2020) who show that price formation happens on the unregulated derivatives market, i.e. on exchanges, such as OKEx, and not on regulated exchanges, such as the CME. Other papers studying market microstructure topics, such as trading volume and lead-lag relationships concerning the CME BTC/USD future, include Hale et al. (2018), Corbet et al. (2018), Aleti and Mizrach (2019), and Akyildirim et al. (2020).

2 Cryptocurrency Market & Data

This section describes the cryptocurrency derivatives market and the data we use. It starts with an overview of the most popular exchanges and proceeds with an explanation of the instruments and their sources. The section concludes by discussing descriptive statistics of our data.

2.1 A Primer on the Cryptocurrency Derivatives Market

The cryptocurrency market is young—the infamous bitcoin whitepaper by Nakamoto (2008) is barely ten years old—and very fragmented. For example, Makarov and Schoar (2019) show large price deviations of BTC/USD across exchanges from 01/2017 to 03/2018. In contrast to the fragmented spot market, the derivatives market is centered around a few players. Figure 3 provides a brief timeline of its evolution.

Insert Figure 3 here.

The first exchange that offers derivatives has been the Bitcoin Mercantile Exchange (BitMEX), which was founded in 2014 and offers the most popular crypto derivative—a perpetual very short-term BTC/USD future called “swap”. In 2016, the OK Exchange (OKEx[5]) started to list more traditional futures with longer maturity. It is among the top three derivative exchanges with daily trading volumes above $2 billion at the time of writing.[6] Notably, the product specifications differ from that of fiat exchanges. For example, the low contract size of $100 in combination with a low margin-requirement of 1%, makes it accessible to retail traders. In general, OKEx accepts only cryptocurrencies as deposit and thus collateral and—in contrast to e.g. the CME which we address below—does not pay interest on the collateral.

Apart from future and spot trading, some cryptocurrency exchanges also offer lending rates (OKEx does not), which can be used to buy or sell on margin. One of the largest exchanges offering these rates is Bitfinex. Although Bitfinex did not introduce futures trading until late 2019, investors can—in contrast to OKEx—deposit both, crypto- and fiat currencies at Bitfinex. Consequently, there is a lending market, in the form of a limit order book (LOB), with interest rates for BTC and USD. These interest rates are used by other traders to borrow currency to trade on margin. Bitfinex tries to minimize counterparty risk, i.e. the loss of the margin before repaying the loan, by (i) requiring 1/3 of the outstanding loan as additional collateral on top of the loan position and (ii) pledging to cover losses due to a sudden price drop that could not be covered by the collateral. Consequently, any counterparty risk contained in the interest rates should be the default risk of Bitfinex itself.

[5]Until 2017, OKEx was a division of the Chinese crypto trading platform OKCoin

[6]See p.8 of https://downloads.coindesk.com/crypto-investing/crypto_derivatives.pdf

In addition to its lending market, Bitfinex also controls the stablecoin USD Tether (USDT). This stablecoin is supposed to trade at par to USD as it is backed by one USD per Tether. In April 2019 Bitfinex got sued by the New York Attorney General for using USDT to cover up a $850 million loss.[7] Furthermore, Griffin and Shams (2020) argue that USDT has been used to manipulate the BTC/USD price upwards. These alligations in combination with an introduction of withdrawal fees on fiat money in November 2018,[8] caused the BTC/USD spot price on Bitfinex to trade at a premium compared to other exchanges (see Subfigure II in Figure 10). This difference is also known as the Bitfinex Premium in the cryptocurrency community.[9] The mechanics behind this premium are straightforward. Due to the slow-moving nature of fiat money between crypto exchanges, traders tend to store their wealth in cryptocurrencies rather than fiat money in times of perceived elevated counterparty risk. Therefore, users are willing to pay a higher spot price to purchase bitcoins as moving bitcoins out of an exchange such as Bitfinex is relatively quicker and cheaper than moving out Dollar assets. At the time of writing, the premium has vanished and the BTC/USD spot price is again trading in line with the price on other exchanges.

Finally, Bitcoin futures can also be traded outside the crypto space on the CME in Chicago. The CME launched its BTC/USD future on the 17th December 2017. It has a relatively large contract size of 5 BTC and about 1/3 margin requirement. Similar to futures on OKEx, the CME future is cash-settled against a reference rate, which is an average of BTC/USD spot prices across various exchanges. Figure 4 shows that the trading volume of the CME contract never caught up to those of the other exchanges. Another example for this lack of demand can be found in the future launched by the Chicago Board Options Exchange (CBOE) which was similar to that of the CME and had been launched just seven days earlier, namely on the 10th December 2017. However, in March 2019 the CBOE had

[7] See https://iapps.courts.state.ny.us/fbem/DocumentDisplayServlet?documentId=vIexA1b0spKOnK_PLUS_ZUGTJ3A==&system=prod

[8] See https://www.bitfinex.com/posts/311

[9] https://www.bloomberg.com/news/articles/2019-04-30/bitcoin-trading-at-300-premium-on-exchange-accused-of-mischief

to discontinue its new product due to low demand.[10] One explanation for the low demand of these fiat futures might be the lack of 24/7 trading—in contrast to the underlying—as mentioned in a practitioner's comment:

> *"As a trader ... the problem you have with these futures exchanges is there's T+2 (settlement), weekends they are closed, bank holidays they're closed. We're all laughing at it because you have to send slow fiat to a futures exchange to post collateral on an asset that may move on a Sunday and margin-call you. It's slightly ludicrous."*[11]

2.2 Instruments & Data Sources

To calculate CIP deviations for BTC/USD, three components are required: interest rates, spot prices, and future or forward prices. Table A1 in the Appendix provides an overview of our data sources. Our interest rates are sourced from Bitfinex, because—to the best of our knowledge—Bitfinex is the largest exchange that offers interest rates in a LOB for BTC and USD. Reliable interest rate data on Bitfinex go back until 10/2016, which thus denotes the starting point of our sample, i.e. from October 2016 to October 2019. Since Bitfinex offers a spot market as well, we source our spot prices also from Bitfinex. This ensures that we take exactly that spot price, which an arbitrageur who is trading on Bitfinex, could have traded at. Unfortunately, Bitfinex offered no forwards or futures until late 2019 (see Figure 3). Therefore, we source our future prices from OKEx since arbitrageurs can make use of two exchanges simultaneously by holding collateral on both. Thus, we calculate CIP deviations by relying on future prices from OKEx, which offers the longest time-series of conventional bitcoin—and also altcoin[12]—futures. Because interest rates on Bitfinex are traded with 2 days to maturity, we focus on the weekly BTC/USD future from OKEx throughout our

[10] https://www.wsj.com/articles/cboe-abandons-bitcoin-futures-11552914001

[11] Alistair Milne, founder and manager of the Altana Digital Currency Fund., see https://www.reuters.com/article/us-bitcoin-futures/exchange-giant-cmes-bitcoin-futures-get-tepid-take-up-in-debut-idUSKBN1EB04N

[12] The term *altcoins* refers to all other cryptocurrencies besides bitcoin

paper thereby matching the maturity of the interest rates as closely as possible. It expires and is subsequently reissued every Friday at 8 AM UTC.

To reflect the aforementioned counterparty risk of Bitfinex, we compare its spot price to the index of *CryptoCompare*, which is a volume-weighted average across all major exchanges[13] and recommended by Alexander and Heck (2019). Table 1 shows that the average daily spot return in our sample is large, i.e. 24 basis points (bp) per day or more than 100% annually. These gains come with large swings, i.e. an annualized volatility of 82% with a minimum (maximum) one-day return of -23% (21%). Naturally, the future returns are very similar to spot returns.

Insert Table 1 here.

The minimum (maximum) basis for a weekly future contract, i.e. a contract with seven days to expiry, is -17.31% (+11.85%). Subfigure 1 and 2 in Figure 5 show that most of these extremes happened during 2017 and the early part of 2018. It also displays that large spot price movements oftentimes happen contemporaneously with large basis and interest rate moves.

Insert Figure 5 here.

The interest rates are calculated as a 1-hour volume-weighted average price (VWAP). The given price states the daily rate, which is fixed for two days. To adjust for outliers, we replace negative rates and rates above 3% with the preceding value. Table 1 shows that the average daily lending rate is rather high with 2bp and 5bp for BTC and USD, respectively. Thus, the annualized yield on Bitfinex for BTC and USD has been 7.3% and 18.25%, respectively.[14] The mean 24-hour trading volume for the weekly OKEx future is close to $400 million. Credit volumes are much smaller, achieving $67 million and $85 million for BTC and USD, respectively.

[13] For the detailed methodology, see https://www.cryptocompare.com/media/12318004/cccagg.pdf

[14] Our findings are in line with rates from other platforms, see https://www.bloomberg.com/news/articles/2019-10-29/another-credit-bubble-grows-the-5-billion-crypto-loan-market

Using these three components described above—interest rates, spot prices, and futures—we calculate the CIP deviation by combining the interest rates and basis to calculate the BTC/USD cross-currency basis (see Equation 3). A deviation from zero equals a violation of the CIP condition and thus resembles an arbitrage opportunity. During our sample period, the mean and median CIP deviation was very close to zero but faced large deviations, such as -17.34% on the 16^{th} May, 2017. For our difference-in-differences setup, we use the same data as before but for the LTC/USD pair. Its descriptive statistics are shown in the Appendix, but it is noteworthy that LTC/USD is notably more illiquid. For example, the 24-hour trading volume in LTC futures (rates) even in the post-HFT-entry period has been $50 million ($3 million), which is 8.5 (28) times smaller than that of BTC.

3 Methodology and Research Design

This section lays out the foundations of CIP in general, i.e. an illustration of the arbitrage cycle, and its application in the cryptocurrency market. Next, we simulate the profits of an arbitrageur that exploits these deviations. For example, the Sharpe Ratio decreased from 2.23 in the period before the HFT market entry in 03/2018 to 0.20 after that. Finally, we discuss the market entry of HFTs in 03/2018 and our baseline research design to preclude the CME launch as the cause of the decrease in CIP deviations.

3.1 Definition of CIP Arbitrage in BTC/USD

We follow the literature and use the natural logarithm of future and spot prices, which we denote with lowercase letters f and s, respectively. Furthermore, we quote future prices denoted as USD per BTC. i refers to the interest rate of the USD on Bitfinex and i^* to the interest rate of the respective cryptocurrency, e.g. BTC, on Bitfinex.

CIP states that the basis of the future or forward must be equal to the interest rate differential (Equation 1). In contrast to the uncovered interest rate parity (UIP), CIP is bound by arbitrage. Figure 6 demonstrates the arbitrage flow. For example, if the basis were higher than the interest rate differential, an arbitrageur could sell the future, take a USD loan—with maturity equal to the expiry date of the future—to buy spot BTC—paying the USD interest rate—and invest the proceeds at the BTC interest rate. If the investor holds all positions until maturity, she makes a profit. Therefore, CIP must hold in an arbitrage-free market if frictions do not prevent arbitrage.

Insert Figure 6 here.

$$\underbrace{f_t - s_t}_{\text{basis}} \approx \underbrace{i_t - i_t^*}_{\text{rate differential}} \tag{1}$$

For pure CIP arbitrage, the maturity of the money market and futures contract must be equal. Otherwise, the presence of rollover-risk may impair the CIP condition. However, the credit market on cryptocurrencies is not mature enough that a whole term-structures is tradeable and thus, the (credit) rates from Bitfinex are fixed for just two days.[15] To mitigate rollover risk, we focus our analysis on short-term futures from OKEx that are reissued weekly and thus have only seven days to expiry. To approximate 7-day rates, we scale the daily interest rate differential, which is fixed for two days, to match the maturity of the futures contract by multiplying the daily interest with the time to maturity $T-t$. Thus, we rewrite CIP as:

$$\underbrace{f_t^T - s_t}_{\text{basis}} \approx \underbrace{(i_t - i_t^*) \times (T-t)}_{\text{rate differential}} \tag{2}$$

To visualize violations of CIP, we calculate the BTC/USD cross-currency basis by rearranging Equation 2 into Equation 3 whereby a deviation from zero resembles a violation of

[15]Rollover risk also applies to CIP arbitrage in the fiat world as explained by Du et al. (2018) for the short-sale of bonds.

the CIP.

$$\underbrace{(i_t^* - i_t) \times (T - t) + f_t^T - s_t}_{\text{cross-currency basis}} \approx \text{CIP Deviation} \tag{3}$$

To demonstrate the economic importance of CIP deviations, we calculate the profit of an arbitrageur who buys or sells the future and takes the counterposition on Bitfinex using its spot and interest rate market. Since there is no central counterparty, such as e.g. a broker in the fiat world, we assume that the arbitrageur contemporaneously holds collateral on both exchanges. However, trading BTC/USD is not cheap. In their presentation to the SEC, Bitwise Asset Management estimated the slippage to execute \$100,000 and \$1,000,000 in the BTC/USD spot market to be 4bp and 14bp, respectively.[16] While the futures market is likely to be more liquid, there are still commission costs charged by OKEx and Bitfinex, which are 3bp per side for OKEx[17] and 5bp per side on Bitfinex[18]. On top of that, Bitfinex charges 15% on every loan. Consequently, we calculate the gross return, i.e. before subtracting transaction costs, and the net return. The later is based upon the fees outlined above and should be closer to the true profitability of the arbitrage trade.

Table 2 shows the performance measures for the arbitrage strategy for different thresholds χ, i.e. for a strategy that only trades when the CIP violation is larger than $\chi = \{0, 1\%, ...10\%\}$. Figure 7 provides the visualization for the case when the threshold is zero, i.e. the strategy trades on every CIP deviation irrespective of its size. Naturally, an arbitrageur would only conduct arbitrage when the expected profits exceed the expected costs, such as fees. Consequently, the Sharpe Ratio improves when smaller deviations are neglected. Clearly, the CIP violations—at least in the earlier part of the sample—are not due to trading costs. For example, a strategy that traded according to the CIP condition and held the position until maturity—including the rollover of the interest rates—would have made an annualized mean return above the risk-free rate of almost 40% after accounting for transac-

[16]See pp. 108-109 of https://www.sec.gov/comments/sr-nysearca-2019-01/srnysearca201901-5164833-183434.pdf.

[17]https://www.okex.com/fees.html

[18]https://www.bitfinex.com/fees/

tion costs. Considering these large profits in combination with the trading volumes being in the millions, a market entry of a sophisticated arbitrageur, such as Jane Street, seems to be a logical consequence—as is the subsequent decline in profitability of the strategy.

Insert Table 2 here.

Insert Figure 7 here.

3.2 Market Efficiency after CME Future and HFT Market-Entry

Figures 1, 5, and 7 show a structural break in the data, which happened during the first quarter of 2018. The basis and the CIP violations have become visibly smaller in magnitude and less volatile. Figure A1 in the Appendix shows that the structural break is not exclusive to BTC/USD but occurred in LTC/USD, too. The comparison of the descriptive statistics between the pre- and post-HFT-entry period in Table A2 and Table A3 confirm this. We identify two events that might have caused this break. (I) The launch of the CME BTC/USD future on 17$^{\text{th}}$ December 2017 and (II) the market entry of HFT firms, such as Jane Street on 16$^{\text{th}}$ March 2018 and Flow Traders in July 2018.[19] We cannot rule out that other HFTs were already present in cryptocurrencies before Jane Street, but according to Bitwise Asset Management's presentation to the SEC, Jane Street was among the first and most major players only entered in the following months.

While the CME future launch coincided with the all-time high of BTC/USD and a subsequent crash in the hours after its go-live (Hale et al. (2018)), this does not automatically mean it has caused the decrease of BTC/USD CIP violations. For example, Figure 1 shows that large CIP violations occurred even months after the future had been launched. Moreover, in order to take advantage of CIP deviations, an arbitrageur must trade on (i) Bitfinex or any other exchange that offer interest rates and (ii) an exchange, which lists futures or

[19]See pp. 108-109 of https://www.sec.gov/comments/sr-nysearca-2019-01/srnysearca201901-5164833-183434.pdf

forwards, such as OKEx. While OKEx futures can be substituted through the CME future, the spot market cannot. Therefore, the introduction of the CME future is unlikely to open up CIP arbitrage in BTC/USD to arbitrageurs that do not want to enter the world of non-fiat exchanges.

3.3 Research Design

To rule out the launch of the CME future as the causing event of the improvement in market efficiency, we run the following difference-in-differences regression of the absolute CIP deviation between BTC/USD and LTC/USD of weekly future contracts on OKEx whereby D^{BTC} equals one if the currency pair (cc in Equation 3) is BTC/USD and D^{Post} equals one if day t is after the introduction of the CME future. CIP deviation is defined in Equation 3. Since both, a positive and negative CIP deviation resemble an arbitrage opportunity, we take the absolute value of the CIP deviation as the dependent variable.

$$|CIP\ Deviation_{cc,t}| = \alpha + D^{BTC}_{cc,t} + D^{Post}_{cc,t} + D^{BTC \times Post}_{cc,t} + \epsilon_{cc,t} \tag{4}$$

More importantly, the CME introduced only a BTC/USD future and not a future on altcoins. Hence, the altcoin market remains untreated throughout our sample period. We use LTC/USD as the control group because it was the first altcoin for which futures were launched on OKEx and thus provides the longest sample period for our regression analysis.

The intuition of our diff-and-diff design is that arbitrageurs using the CME future as a hedge would prefer to arbitrage BTC/USD instead of LTC/USD since hedging LTC/USD via the CME future leaves them exposed to the idiosyncratic risk of LTC. In contrast, a HFT firm, such as Jane Street, that is entering the cryptocurrency market might not need the CME future and would just trade the basis on OKEx against the interest rates on Bitfinex. Thus, there is no reason why they would prefer equally profitable arbitrage opportunities in BTC/USD to LTC/USD. Consequently, if the CME future launch caused the the decrease in CIP deviation, we would expect the decrease in CIP deviations in the BTC market to be stronger compared to the untreated LTC market.

In addition, we change the cutoff for the post-period dummy to the 16$^{\text{th}}$ March 2018, i.e. the date of the HFT-market entry, and run a panel regression similar to Equation 4. This allows us to examine whether the size of CIP deviations has changed significantly in response to the Jane Street entry in 03/2018. As the market entry of an HFT arbitrageur is likely to have affected both, LTC and BTC, we can not perform a classic diff-in-diff design due to the lack of a control group. Yet, as we will show in the next chapter, the diff-in-diff results in combination with our panel design strongly indicate that the Jane Street entry indeed was the structural change in the crypto market that led to increased market efficiency, especially with respect to CIP deviations. Moreover, the sign on the interaction dummy will allow us to draw conclusion on whether HFT-entry has a stronger impact on the market efficiency of more illiquid markets, such as LTC compared to BTC.

Apart from the CIP deviation, we also examine six other proxies for market efficiency, i.e. spot volatility, the half-life of CIP deviations, the Amihud (2002) illiquidity measure, the modified Pástor and Stambaugh (2003) illiquidity measure, the bid-ask spread as proxied by Abdi and Ranaldo (2017), and the returns of the CIP arbitrage trading strategy described in Section 3.1. Their exact calculations are described in the Appendix. The chosen proxies are also recommended by Brauneis et al. (2020) who show for cryptocurrencies that the bid-ask spread measure by Abdi and Ranaldo (2017) as well as the illiquidity ratio of Amihud (2002) can be successfully applied to low frequency data resembling results of high-frequency data.

4 Results

This section discusses the result of our baseline diff-and-diff analysis, which shows a stronger effect on CIP deviations for the untreated altcoin LTC compared to BTC. This result is irreconcilable with the notion that any arbitrageur would only use the CME future to enter the BTC market as it does not represent a suitable instrument to enter the LTC market. To support our hypothesis, we run a further diff-in-diff regression contrasting market efficiency within and outside of CME trading hours. We find that CIP deviations are not lower during trading hours which underlines that the CME Future does not represent the structural break in the data responsible for the improvement of market efficiency. Therefore, we run panel regressions which show that the entry of sophisticated arbitrageurs (Jane Street) appears to be the driving force in the decline of CIP deviations, confirming our hypothesis. Finally, we examine possible drivers of remaining CIP deviations such as short-sale constraints and default risk of crypto exchanges. While we find evidence in favor of short-sale constraints, we also show that distrust towards a crypto exchange can lead to a premium in the spot market resulting in larger CIP deviations.

4.1 Baseline Results

Figure 9 shows that the CIP deviations of BTC/USD and LTC/USD generally co-move and thus the common trend assumption inherent in our diff-and-diff design seems reasonable. While CIP deviations in the LTC/USD market were even higher than in the BTC/USD market in the pre-treatment period, they are much lower for both in the post-period. The other five proxies of market efficiency contained in Figure 9 display a similar movement and again indicate an even stronger relative impact on the LTC market compared to the BTC market.

Insert Figure 9 here.

The results in Table 3 confirm the evidence seen above. Performing a diff-in-diff regression using the CME BTC/USD launch in 12/2017, we find that the absolute value of CIP deviations decreases in the post-period. However, the interaction dummy for BTC in the post-period is positive in all settings and statistically significant for the CIP deviation, bid-ask spreads, and the returns of the arbitrage strategy. This means that the improvement of market efficiency has been more pronounced for the (structurally less liquid) LTC market. As argued above, any arbitrageur would rather use the CME Future to engage with the BTC market but would not use it to trade LTC. If the CME launch would have had an effect on BTC market quality, the coefficient of the interaction dummy should have been negative as the CME did not contemporaneously introduce a future on LTC. Therefore, this positive coefficient for the post-period-BTC dummy contradicts the hypothesis that the CME Future launch can be seen as causal for improved market efficiency.

Insert Table 3 here.

Although we have provided evidence that overall market conditions improved in response to the CME launch, we want to further rule out that the CME launch has been the driving force. Therefore, we run a second difference-in-differences regression in which we distinguish between trading and non-trading hours of the CME BTC future. While cryptocurrency exchanges trade 24/7, the CME is closed over the weekend. Hence, we would expect market efficiency to deteriorate on weekends if the CME future caused the improvement. Table 4 shows the results of the difference-in-differences regression of Equation 4 whereby we replace the post-period dummy with a dummy that is equal to one within the CME trading hours and zero otherwise. Furthermore, we drop those efficiency measures that resemble an average over a longer period than just a weekend, such as the Pástor and Stambaugh (2003) liquidity measure.

For CIP deviations, both $D^{Trading\ Hours}$ and $D^{BTC\times Trading\ Hours}$ are negative but statistically insignificant. That is, we do not find a significant difference in market efficiency with respect to CIP deviations between CME trading and non-trading hours. The results only indicate that the market is more liquid during trading hours, which is consistent with the results of Aleti and Mizrach (2019). Yet, the statistical significance is rather week being at the 10%-level and economically small. Therefore, we conclude that the CME future is not the primary driver of the structural break.

Insert Table 4 here.

Finally, Table 5 shows the results of a panel regression similar to the above diff-in-diff design in which we test how the Jane Street market entry has affected both markets, BTC and LTC. Since both cryptocurrencies can be traded on crypto exchanges, they are likely to be simultaneously influenced by any HFT arbitrageur entering the market. For each proxy of market efficiency we run two panel regressions, one controlling for the other proxies, i.e. illiquidity, volatility, and bid-ask spreads, and one in which we solely employ a BTC and a post-period as well as interaction dummy. We find that these dummies are highly statistically significant and economically relevant. For BTC and without controlling for proxies, they indicate a decrease of absolute CIP deviations by about 1.87 percentage points after the Jane Street entry, while the decrease for LTC is 4.1 percentage points. Given the absolute average CIP deviation of 2.71% for BTC and 5.08% for LTC before the Jane Street entry, our results indicate that absolute CIP deviations decreased by 69.0% in the BTC market and 80.7% in the LTC market.

Once we include proxies for volatility, illiquidity, and bid-ask spreads as control variables, we find that only the post-period dummy remains significant. Thus, we conclude that after the entry of HFT arbitrageur Jane Street, CIP deviations have significantly decreased. This finding of increased market efficiency also holds when looking at half-life, bid-ask spreads and the returns to our arbitrage strategy, irrespective of our specification, i.e. with or without controls. All coefficients yield a significantly negative impact of the HFT entry, indicating an increase in market efficiency.

We also find that the coefficient of the BTC-post-period interaction dummy has a significant positive impact on CIP deviations, bid-ask spreads, and the returns to the arbitrage strategy in our specification without control variables. When including controls, the statistical significance remains present for the bid-ask spread measure. As this positive coefficient indicates a stronger impact of the HFT entry on LTC, we infer that the less liquid market profits more from the entry of high-frequency arbitrageurs.

In conclusion, our results indicate that while the CME Future launch did not affect market quality with respect to CIP deviations as the stronger effect on LTC contradicts technical hedging arguments, the HFT entry in 03/2018 did. The lacking impact of the CME Future is in line with our economic argumentation that the CME brought no new arbitrageurs into the market because (i) very liquid futures were already in place and (ii) arbitrageurs using the CME futures to conduct CIP arbitrage, would still need to trade within the less regulated crypto market to conduct spot exchanges. Further evidence from our regression of inside vs. outside trading hours confirms this. Instead, we argue that HFT arbitrageurs have significantly and lastingly altered the cryptocurrency market and that this alteration has been even stronger for the more illiquid LTC market than for BTC.

Insert Table 5 here.

4.2 Short-Sale Constraints

As we have demonstrated in the previous chapter, CIP deviations have been subdued after the market entry of HFT arbitrageurs in Q1/2028. However, they have not been eradicated and continue to occur although in smaller magnitude. We argue that short-sale constraints explain part of these remaining deviations. In order to profit from a CIP violation (Equation 3), investors must buy the future and sell the spot when the basis is negative and vice versa when the basis is positive. Trivially, going short in the future poses no problem. However, shorting bitcoin in the spot market might. As shown in Figure 4 future volumes can easily be larger than spot volumes and hence arbitrage could be difficult to implement when the basis is negative. Consequently, short-sale constraints can cause CIP violations. For example, Du et al. (2018) find that cross-country differences in liquidity between bonds might explain some violations of the CIP.

We find evidence in favor of short-sale constraints as a meaningful limit of arbitrage for CIP arbitrageurs. Figures 1 and 5 show that in the recent past, i.e. the time period after the market entry of Jane Street, CIP violations and the basis are one-sided and negative.

While the basis has also been positive at times since the market entry, it did not lead to a CIP violation. Hence, arbitrageurs nowadays might take advantage of a positive basis by simply buying BTC in the spot market and selling the future but have more troubles doing the trade the other way around. Additionally, Figure 8 shows the historic profit of the arbitrage strategy split by the sign of the basis. Most of the arbitrage profits were made when the basis has been negative, i.e. when the arbitrageur needs to sell the BTC in the spot market. Consequently, even before the HFT market entry, short-sale constraints might—at least partly—explain the CIP violations.

Insert Figure 8 here.

4.3 Default Risk of Crypto Exchanges

Besides short-sale constraints as a potential explanation for the observed CIP deviations, we also take a closer look at the risk of default which can vary between exchanges. To illustrate this, we go back to our CIP condition and rewrite Equation 3 as follows:

$$\underbrace{f_0 - s_0}_{\text{basis}} \approx \underbrace{i_0 - i_0^*}_{\text{rate differential}} \tag{5}$$

This is the covered interest parity with zero default risk, neither from the credit nor from the future or spot markets. However, while zero default risk seems reasonable for mature exchanges, such as the CME, cryptocurrency exchanges might be subject to larger default risk, i.e. the collateral posted on these exchanges is lost if they default. Thus, we replace the risk-free rate with the observable rates and subtract a risk premium τ, which compensates for the default risk and write Equation 5 as:

$$\begin{aligned} f_0 - s_0 &\approx \underbrace{(i_{Bitfinex} - \tau_{Bitfinex})}_{i_0} - \underbrace{(i^*_{Bitfinex} - \tau_{Bitfinex})}_{i_0^*} \\ \Leftrightarrow f_0 - s_0 &\approx i_{Bitfinex} - \tau_{Bitfinex} - i^*_{Bitfinex} + \tau_{Bitfinex} \end{aligned} \tag{6}$$

Trivially, τ cancels out because the arbitrageur lends money on Bitfinex, i.e. receives the risk premium for default risk, but also borrows money, i.e. pays the risk premium. In the next step, we consider the risk of the spot and futures exchange because the arbitrageur is holding the future contracts on e.g. OKEx and the spot market on Bitfinex. Importantly, the arbitrageur cannot withdraw their collateral while having a position. Therefore, we write:

$$f_{OKEx} - s_{Bitfinex} + \tau_{OKEx} - \tau_{Bitfinex} \approx i_{Bitfinex} - i^*_{Bitfinex} \tag{7}$$

Hence, a CIP violation might just signal a large spread between the credit risk of Bitfinex and OKEx:

$$f_{OKEx} - s_{Bitfinex} + i^*_{Bitfinex} - i_{Bitfinex} \approx \tau_{Bitfinex} - \tau_{OKEx} \tag{8}$$

While we do not easily observe the counterparty risk of neither OKEx nor Bitfinex, it seems reasonable to assume that the spread of the two counterparty risks is measured by the difference between the Bitfinex spot price and the spot price on OKEx. However, because OKEx does not have a fiat market, we take the spot index from *CryptoCompare*, which is an index that aggregates the spot price over the most liquid cryptocurrency exchanges. Because—to our knowledge—there are no allegations regarding OKEx's solvency, it seems reasonable that the average exchange in the CryptoCompare index has very similar counterparty risk as OKEx. Therefore, we write the spread between the two counterparty risks as:

$$\underbrace{s_{Bitfinex} - s_{CryptoCompare}}_{\text{Bitfinex Premium}} \approx \tau_{Bitfinex} - \tau_{OKEx} \tag{9}$$

This spread is essentially the Bitfinex Premium described in Section 2.1 and the higher the spread, the higher the counterparty risk of Bitinex compared to OKEx.

Subfigure I in Figure 10 shows that CIP deviations are strongly related to the spread and hence counterparty risk of Bitfinex whereby a higher spread leads to a negative CIP deviation. This makes sense because a negative CIP deviation usually occurs when the basis is negative and investors would need to sell BTC in the spot market in order to take advantage of the arbitrage opportunity. Short-selling the spot is not possible on most exchanges and hence investors turn to Bitfinex, which allows short-selling due to its lending market. However, if the counterparty risk of Bitfinex is too high, investors might forgo a seemingly profitable arbitrage opportunity. Subfigure II displays the residuals of a regression of CIP deviations on the Bitfinex premium. We call this "adjusted" CIP deviation because it is adjusted for the credit risk of Bitfinex. Once that is controlled for, we see that CIP deviations are much lower after the HFT-entry. For example, while before HFT-entry we find a maximum absolute CIP deviation of over 10%, it is well below 3% in the period after the entry.

Insert Figure 10 here.

To test that conclusion further, we regress the first difference of CIP deviations on the spread and several controls. Particularly, we also test for price pressure as a cause of CIP violations. If arbitrageurs are capital constrained, price pressure can cause the price to temporarily deviate from fundamental values (see e.g. Scholes (1972) and Harris and Gurel (1986)). CIP violations in the fiat world are also linked to funding constraints (Du et al. (2018) or Du et al. (2019)) and price pressure might be especially strong in cryptocurrencies since it is a very fragmented market (Makarov and Schoar (2019)). That is, arbitrageurs must split up their capital to several exchanges in order to keep prices in sync. Apart from our two illiquidity proxies and the proxy for the bid-ask spread, we include the Tether (USDT) deviation from unity (remember that 1 USDT should always be equal to 1 USD) as a proxy for price pressure. This price pressure stems from investors rushing for the exit of their crypto position who might be forced to sell it for stablecoins such as Tether, when they cannot trade their position on the exchange's fiat spot market.

Insert Table 6 here.

Table 6 shows the regressions of CIP deviation (Panel A) and absolute CIP deviation (Panel B) on several explanatory variables which proxy for the aforementioned drivers of

CIP deviations. As expected and argued earlier, the Bitfinex premium is highly significant with a t-stat of up to 10. All other coefficients in Regressions 2 to 5 are insignificant (except for lagged CIP deviation). However, small CIP deviations might not be arbitrable due to trading costs and therefore would not resemble a true inefficiency. In order to focus on deviations that could actually be traded against, we estimate their conditional 90$^{\text{th}}$ quantile via a quantile regression.

Regression 6 displays the results and shows that the coefficients for spot volatility, bid-ask spread measure of Abdi and Ranaldo (2017), and the VIX become significant while the Bitfinex Premium remains the dominant driver of CIP violations. A 1 percentage point increase in the Bitfinex Premium — defined as the log difference between the Bitfinex spot price and the CryptoCompare spot price — directly translates to a 1 percentage point increase in the absolute CIP deviation (Regression 6b in Panel B). From Panel A we can infer that this increase in the Bitfinex Premium is associated to a negative CIP deviation.

5 Robustness

This section runs four robustness checks. First, we use the most popular altcoin Ethereum instead of Litecoin as a control group and obtain similar results. Second, we use quarterly instead of 7-day futures to show that our results are neither due to some market microstructure issues near expiry nor due to rollover risk introduced by the scaling of the interest rate differential. Third, we show (i) that UIP deviations for BTC and LTC are smaller after the HFT-entry and (ii) that the decrease is larger for LTC than for BTC. Finally, we employ data from another crypto exchange—Bitstamp—to show that classical triangle arbitrage opportunities between BTC/USD, BTC/EUR, and EUR/USD also decreased after Q1/2018. Consequently, we argue that our results are robust to intra-exchange arbitrage opportunities.

5.1 Ethereum as control group instead of Litecoin

We are using the LTC/USD future in our main specification because it was the first cryptocurrency apart from BTC for which OKEx launched futures. However, in December 2017 OKEx introduced futures on the popular altcoin Ethereum (ETH). Because the trading volume in these new contracts was subdued until mid-January 2018, we simply do not have enough data to obtain meaningful results in our main difference-in-differences design with ETH instead of LTC. However, the results in Table 7 show that our result of BTC not behaving differently compared to altcoins in trading vs. non-trading hours is robust to the choice of the altcoin. CIP deviations of BTC are only marginally smaller compared to ETH in trading hours (t-stat: 1.67) while results for volatility and bid-ask spreads are insignificant.

Insert Table 7 here.

We also show that the results of the arbitrage strategy are qualitatively very similar to our main results when replacing the BTC with LTC or ETH. Subfigure I in Figure 11 shows for LTC/USD that just as in the BTC/USD strategy (i) the gross return was much higher in the pre-HFT area and (ii) the net return has become almost flat after the HFT-entry. The latter result is also true for ETH.

Insert Figure 11 here.

5.2 Rollover Distortions and Rollover Risk

Because we did not find any longer-term interest rates, we focused our analysis on the short-term future with just seven days to expiry. However, the frequent rollovers might distort our results.[20] To show the influence of these rollover distortions, we use quarterly futures on OKEx, which expire at the end of every quarter instead of every week. The quarterly future also has higher trading volume and is thus more liquid than the weekly future.

[20]See e.g. Szymanowska et al. (2014) who show that open interest in commodity futures becomes low near rollover.

Insert Figure 12 here.

Figure 12 shows that although the short-term interest rates do not match the maturity schedule that well, we still see a sizeable decrease in violations of CIP after HFT-entry. Although the magnitude of CIP deviations of down to -20% even in the post-HFT-entry period is larger than for weekly futures, the frequency and magnitude of the spikes are much smaller compared to the pre-HFT-entry period. This holds for BTC, LTC, and ETH. Because this is identical to our main findings using short-term futures, we conclude that our results are not due to market microstructure distortions around rollovers.

If the deviations are caused by rollover risk, we would expect CIP deviations to be the strongest when the maturity of the future contract is the longest. If CIP deviations were due to rollover risk for arbitrageurs, they should disappear when the maturity of the futures contract approaches 2 days given that interest rates at Bitfinex are valid for two days. However, Table 8 shows that the largest CIP deviations occurred with just three days to expiry. Moreover, the next largest deviations have no particularly large or short time to maturity, either. Instead, they are much more clustered around a time-period, e.g. the largest CIP deviations to the downside occurred end of April to the beginning of May 2017. This shows that the general circumstances around that time and not rollover risk were the dominant driver of CIP deviations. Consequently, our scaling of the interest rate differential in 2 does not seem to impair our conclusions.

Insert Table 8 here.

5.3 UIP Deviations

Apart from CIP deviations, which are bound by arbitrage, there is also the unbiased expectation hypothesis, which states that the future or forward equals the future spot price and thus predicts future price movements (Equation 10, for a futures contract F with corresponding spot price S). If CIP holds, the unbiased expectation hypothesis would become identical to uncovered interest rate parity (UIP), i.e. the future exchange rate movement is similar to the current interest rate differential (Fama (1984)).

$$f_t - s_t = \mathbb{E}_t[\Delta s_{t+1}] \tag{10}$$

In contrast to CIP, UIP is not bound by arbitrage. Consequently, CIP deviations in fiat markets are minor (see Borio et al. (2016), Rime et al. (2017), and Du et al. (2019)) compared to the profits of the popular carry traded caused by deviations of UIP.[21] While we have shown that CIP deviations have been subdued due to the entry of HFT firms, we have not performed our diff-in-diff analysis with respect to uncovered interest rate parity. As HFT is already well established in fiat markets and UIP still does not hold (see e.g. Lustig et al. (2019)), it seems likely that UIP in the cryptocurrency markets should not be affected to the same extent as CIP by the market entries of HFT. To test that hypothesis, we use weekly BTC/USD and LTC/USD futures contracts and run the same panel regression as in Table 5 but take the difference between the weekly spot and future return as the dependent variable. Table 9 shows the results. The coefficient of interest here is the post-period dummy, which is negative and significant with a small t-stat of -1.83. That is, deviations from UIP are smaller after the HFT-entry than before. However, the t-stat (-1.83) is smaller than that of CIP deviations (2.85) and the interaction dummy is insignificant for UIP while highly significant for CIP. Hence, there is no stronger effect on BTC or LTC compared to each other. Therefore, the cryptocurrency market—in general—has become more efficient not only with respect to CIP, but also to UIP. Yet, the effect seems to be more pronounced for CIP than UIP.

[21] See e.g. Brunnermeier et al. (2008), Lustig et al. (2011), or Menkhoff et al. (2012) for papers on UIP and the carry trade.

5.4 Triangle Arbitrage

Due to the lack of derivatives on Bitfinex, we calculated CIP deviations by combining interest and spot rates from Bitfinex, and futures contracts from OKEx. Thus, an arbitrageur would need to trade on both exchanges simultaneously. To make sure that the change in Q1/2018 is not due to some changes in the intra-exchange space, e.g. country-specific regulations, we test a classic triangle arbitrage (see Grimberg et al. (2020) for triangle arbitrage in cryptocurrencies) within just one exchange. Specifically, we use daily data from Bitstamp[22] to calculate the triangle arbitrage ratio as follows where a deviation from one resembles a profitable triangle arbitrage trade :

$$\frac{BTC/USD \times EUR/USD}{BTC/EUR} - 1 \tag{11}$$

Similar to the results of Makarov and Schoar (2019), Figure 13 shows that large arbitrage opportunities have been present until Q1/2018. However, after the HFT-entry date these opportunities diminished drastically. Therefore, we argue that the HFT-entry did not only change intra-exchange arbitrage mechanisms, such as our CIP deviations, but also opportunities within the same exchange.

Insert Figure 13 here.

6 Conclusion

We show that CIP deviations in BTC/USD have been large in 2016 and 2017 but have been subdued since Q1/2018 due to professional arbitrageurs stepping in. Market efficiency has also improved with respect to liquidity, volatility, and bid-ask spreads. Our results are in line with other studies such as Menkveld (2013) that find improved market conditions after the entry of HFT firms. Moreover, the importance of HFT seems to be even larger in

[22] Bitstamp is a major player among the exchanges that allow fiat deposits and withdrawal.

more illiquid markets as the improvements of market efficiency are not exclusive to BTC but appear to be even stronger for the more illiquid altcoin LTC.

Additionally, our results demonstrate that the crypto ecosystem seems to be relatively independent of the fiat world. For example, the introduction of the CME future faced little demand and does not seem to be required upon by HFT firms. This view supports studies such as Baur et al. (2018), that struggle to find a common driver in crypto and fiat returns.

Finally, we open up several avenues for future research as the crypto ecosystem continues to evolve. While we tested CIP arbitrage across two exchanges, new products will allow for cleaner identification. For example, Bitfinex recently announced the introduction of futures trading, which can be used to test CIP within one exchange instead of across exchanges. Another avenue for further research is the role of counterparty risk and its influence on prices. Counterparty risk of Bitfinex seems to have vanished, but the rumors and allegations regarding its reputation and that of Tether remain. Future research should extend our analysis by evaluating the impact of physically-settled futures and options in the fiat world, such the recently introduced bitcoin future by Bakkt.

References

Abdi, F., & Ranaldo, A. (2017). A simple estimation of bid-ask spreads from daily close, high, and low prices. *Review of Financial Studies*, *30*(12), 4437–4480.

Akyildirim, E., Corbet, S., Katsiampa, P., Kellard, N., & Sensoy, A. (2020). The development of bitcoin futures: Exploring the interactions between cryptocurrency derivatives. *Finance Research Letters*, *34*, 101234.

Aleti, S., & Mizrach, B. (2019). Bitcoin spot and futures market microstructure. *Available at SSRN 3459111*.

Alexander, C., & Heck, D. (2019). Price discovery, high–frequency trading and jumps in bitcoin markets. *Available at SSRN*.

Alexander, C., & Heck, D. F. (2020). Price discovery in bitcoin: The impact of unregulated markets. *Available at SSRN 3583843*.

Amihud, Y. (2002). Illiquidity and stock returns: Cross-section and time-series effects. *Journal of Financial Markets*, *5*(1), 31–56.

Baur, D. G., Dimpfl, T., & Kuck, K. (2018). Bitcoin, gold and the us dollar – a replication and extension. *Finance Research Letters*, *25*, 103–110.

Borio, C., McCauley, R., McGuire, P., & Sushko, V. (2016). Covered interest parity lost: Understanding the cross-currency basis. *BIS Quarterly Review*.

Brauneis, A., Mestel, R., Riordan, R., & Theissen, E. (2020). How to measure the liquidity of cryptocurrencies? *SSRN Working Paper Series*.

Brogaard, J., Carrion, A., Moyaert, T., Riordan, R., Shkilko, A., & Sokolov, K. (2018). High frequency trading and extreme price movements. *Journal of Financial Economics*, *128*(2), 253–265.

Brogaard, J., Hendershott, T., & Riordan, R. (2014). High-frequency trading and price discovery. *Review of Financial Studies*, *27*(8), 2267–2306.

Brunnermeier, M. K., Nagel, S., Pedersen, L. H., Rogoff, K., Woodford, M., & Acemoglu, D. (2008). Carry trades and currency crashes. *NBER Macroeconomics Annual 2008*, *23*, 313–347.

Corbet, S., Lucey, B. M., Peat, M., & Vigne, S. (2018). Bitcoin futures - what use are they? *SSRN Electronic Journal*.

Driscoll, J. C., & Kraay, A. C. (1998). Consistent covariance matrix estimation with spatially dependent panel data. *The Review of Economics and Statistics*, *80*(4), 549–560.

Du, W., Hébert, B., & Huber, A. W. (2019). Are intermediary constraints priced? *Cambridge, MA*, National Bureau of Economic Research.

Du, W., Tepper, A., & Verdelhan, A. (2018). Deviations from covered interest rate parity. *The Journal of Finance*, *73*(3), 915–957.

Fama, E. F. (1984). Forward and spot exchange rates. *Journal of Monetary Economics*, *14*(3), 319–338.

Griffin, J. M., & Shams, A. (2020). Is bitcoin really untethered? *The Journal of Finance*, *75*(4), 1913–1964.

Grimberg, P., Lauinger, T., & McCoy, D. (2020). Empirical analysis of indirect internal conversions in cryptocurrency exchanges. *arXiv preprint arXiv:2002.12274*.

Gromb, D., & Vayanos, D. (2010). Limits of arbitrage. *Annual Review of Financial Economics*, *2*(1), 251–275.

Gromb, D., & Vayanos, D. (2018). The dynamics of financially constrained arbitrage. *The Journal of Finance*, *73*(4), 1713–1750.

Hale, G., Krishnamurthy, A., Kudlyak, M., & Shultz, P. (2018). How futures trading changed bitcoin prices. *FRBSF Economic Letter*.

Harris, L., & Gurel, E. (1986). Price and volume effects associated with changes in the s&p 500 list: New evidence for the existence of price pressures. *The Journal of Finance*, *41*(4), 815–829.

Hendershott, T., Jones, C. M., & Menkveld, A. J. (2011). Does algorithmic trading improve liquidity? *The Journal of Finance*, *66*(1), 1–33.

Ivashina, V., Scharfstein, D. S., & Stein, J. C. (2015). Dollar funding and the lending behavior of global banks*. *The Quarterly Journal of Economics*, *130*(3), 1241–1281.

Koenker, R., & Bassett Jr, G. (1978). Regression quantiles. *Econometrica: journal of the Econometric Society*, 33–50.

Lustig, H., Roussanov, N., & Verdelhan, A. (2011). Common risk factors in currency markets. *Review of Financial Studies*, *24*(11), 3731–3777.

Lustig, H., Stathopoulos, A., & Verdelhan, A. (2019). The term structure of currency carry trade risk premia. *American Economic Review*, *109*(12), 4142–77.

Makarov, I., & Schoar, A. (2019). Trading and arbitrage in cryptocurrency markets. *Journal of Financial Economics*.

Menkhoff, L., Sarno, L., Schmeling, M., & Schrimpf, A. (2012). Carry trades and global foreign exchange volatility. *The Journal of Finance*, *67*(2), 681–718.

Menkveld, A. J. (2013). High frequency trading and the new market makers. *Journal of financial Markets*, *16*(4), 712–740.

Nakamoto, S. (2008). Bitcoin: A peer-to-peer electronic cash system. *Cryptography Mailing list at https://metzdowd.com*.

Pástor, Ľ., & Stambaugh, R. F. (2003). Liquidity risk and expected stock returns. *Journal of Political Economy*, *111*(3), 642–685.

Rime, D., Schrimpf, A., & Syrstad, O. (2017). Segmented money markets and covered interest parity arbitrage.

Scholes, M. S. (1972). The market for securities: Substitution versus price pressure and the effects of information on share prices. *The Journal of Business*, *45*(2), 179–211.

Szymanowska, M., de Roon, F., Nijman, T., & van den Goorbergh, R. O. (2014). An anatomy of commodity futures risk premia. *The Journal of Finance*, *69*(1), 453–482.

Tables

Table 1: Descriptive Statistics

This table provides descriptive statistics for BTC/USD at daily frequency. Spot returns are based on the last traded spot price on Bitfinex. Future returns and volume refer to the short-term (7 days) BTC/USD future on OKEx. Rates refer to the daily lending rate, which is used for margin trading on Bitfinex and fixed for two days. They are aggregated as a 1-hour VWAP. The CIP deviation combines lending rates with the basis on OKEx to calculate the cross-currency basis and is defined in Equation 3. A deviation from zero is a deviation from covered interest parity. The sample period is 10/2016 - 10/2019.

	Return Spot %	Return Future %	Basis Future %	Rate BTC %	Rate USD %	CIP Dev. %	Volume Future mm \$	Volume Rate BTC mm \$	Volume Rate USD mm \$
count	1,095.00	938.00	1,095.00	1,094.00	1,094.00	1,094.00	1,095.00	1,095.00	1,094.00
mean	0.24	0.27	-0.78	0.02	0.05	-0.88	398.60	66.77	85.48
std	4.34	4.67	3.53	0.05	0.05	3.44	520.14	52.75	69.77
min	-23.00	-23.61	-17.31	0.00	0.00	-17.34	2.87	0.20	0.66
25%	-1.47	-1.54	-2.06	0.01	0.02	-2.13	71.83	12.65	17.52
50%	0.25	0.17	-0.25	0.01	0.04	-0.34	191.44	60.39	78.03
75%	2.42	2.54	0.59	0.03	0.07	0.49	526.98	107.45	129.37
max	21.28	20.45	11.85	1.11	0.62	11.45	5,088.58	269.02	469.25
Skewness	-0.32	-0.30	-1.30	14.27	3.55	-1.35	2.93	0.47	1.00
Kurtosis	3.22	3.48	4.85	301.02	21.31	5.03	13.81	-0.57	2.00

Table 2: CIP Arbitrage Trading Strategy: Performance Measures

This table shows the performance of a trading strategy that takes advantage of CIP violations between interest rates, spot rates at Bitfinex and weekly futures contracts on OKEx (see Figure 6). Threshold refers to a deviation larger in magnitude than the CIP deviation, i.e. the strategy only takes advantage of CIP violations above the threshold. The CIP deviation combines lending rates with the basis on OKEx to calculate the cross-currency basis and is defined in Equation 3. Specifically, if the basis is greater (smaller) than the interest rate differential, the strategy sells (buys) the future at OKEx, buys spot BTC (USD) at Bitfinex, finances the spot buy with a USD (BTC) loan and earning the BTC (USD) interest rate by lending out the bought BTC (USD). Gross Return refers to the return before trading cost and net return after costs (for details, see Section 3.1). The risk-free rate is the USD rate taken from French's website and the sample period is 10/2016 - 10/2019 whereby pre (post) marks the period before (after) the Market Entry of the HFT firm Jane Street in 03/2018.

Threshold in %:	0	1	2	3	5	7.5	10
Full Sample							
Cum. gross return	225.40%	254.10%	210.01%	173.06%	110.88%	54.62%	26.62%
Cum. net return	95.70%	147.13%	145.54%	132.02%	92.74%	47.61%	23.72%
Ann. mean net excess return	22.01%	29.75%	29.40%	27.46%	21.14%	11.95%	5.93%
Ann. volatility	14.49%	14.07%	13.10%	12.78%	11.77%	8.99%	7.48%
Sharpe ratio	1.52	2.11	2.24	2.15	1.80	1.33	0.79
Pre Jane Street Market Entry							
Cum. gross return	140.33%	169.17%	151.90%	134.61%	101.25%	52.03%	26.62%
Cum. net return	86.80%	115.83%	119.35%	109.09%	85.74%	45.58%	23.72%
Ann. mean net excess return	44.10%	53.95%	54.82%	51.48%	43.13%	25.83%	14.40%
Ann. volatility	19.75%	19.28%	17.97%	17.77%	16.60%	12.80%	10.72%
Sharpe ratio	2.23	2.80	3.05	2.90	2.60	2.02	1.34
Post Jane Street Market Entry							
Cum. gross return	35.40%	31.55%	23.07%	16.39%	4.79%	1.71%	0.00%
Cum. net return	4.92%	14.50%	11.94%	10.97%	3.77%	1.39%	0.00%
Ann. mean net excess return	1.24%	6.88%	5.38%	4.77%	0.37%	-1.17%	-2.07%
Ann. volatility	6.16%	5.62%	5.06%	4.08%	2.65%	1.29%	0.02%
Sharpe ratio	0.20	1.22	1.06	1.17	0.14	-0.91	-

Table 3: Difference-in-Differences BTC vs. LTC: Before and After CME Launch

This table shows the results of the difference-in-differences regression described in Equation 4. The CIP deviation combines lending rates with the basis on OKEx to calculate the cross-currency basis in percent and is defined in Equation 3. A deviation from zero is a deviation from covered interest parity. Half-Life measures the half-life of the CIP deviation in days, i.e. $-\frac{ln(2)}{|\beta|}$ whereby β is the coefficient of a regression with a constant of the CIP deviation on day t on the deviation on day t-1. Volatility is the annualized 10-day spot volatility. $ILLIQ_{Amihud}$ refers to the daily Amihud (2002) illiquidity measure averaged over 14 days whereby the future trading volume is given in \$100,000. $ILLIQ_{P\&S}$ refers to the illiquidity measure of Pástor and Stambaugh (2003) averaged over 14 days using rolling regressions with 30 daily data points. The excess return is given by the future minus the spot return. We multiply it by (-1) so that a higher measure signals lower liquidity. $Spread_{A\&R}$ refers to the 14-day averaged bid-ask spread measure by Abdi and Ranaldo (2017) using daily high and low prices. Arbitrage-Strat refers to the daily returns of the trading strategy, which takes advantage of CIP violations (see Section 3.1). D^{BTC} equals 1 if the cryptocurrency is BTC and 0 if it is LTC. D^{Post} is 1 if the day is after the CME launch on the 17$^{\text{th}}$ December 2017 and 0 otherwise. Adj. R^2 refers to the between Adj. R^2. Standard Errors are estimated using the Driscoll and Kraay (1998) covariance matrix and * refers to significance at the 10%-level, ** at the 5%-level, and *** at the 1%-level. The sample period is 04/2017 - 10/2019.

	$\|CIPDev.\|$	$Half-Life$	$Volatility$	$ILLIQ_{P\&S}$	$ILLIQ_{Amihud}$	$Spread_{A\&R}$	$Arbitrage-Strat$
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
constant	6.43***	3.91***	1.44***	8.79	0.04***	1.85***	1.47***
	(3.96)	(2.79)	(8.59)	(1.59)	(3.13)	(9.31)	(7.39)
D^{BTC}	-3.08***	-1.39	-0.61***	-8.64	-0.04***	-0.71***	-0.62***
	(-3.04)	(-0.79)	(-2.95)	(-1.45)	(-2.98)	(-3.98)	(-3.76)
D^{Post}	-5.42***	-3.48**	-0.41**	-8.65	-0.02	-0.88***	-1.14***
	(-3.31)	(-2.45)	(-2.35)	(-1.57)	(-1.18)	(-4.14)	(-5.73)
$D^{\text{BTC x Post}}$	2.92***	1.39	0.29	8.80	0.01	0.46***	0.55***
	(2.86)	(0.79)	(1.41)	(1.48)	(1.02)	(2.59)	(3.31)
N	1558	1558	1558	1558	1558	1558	1558
F-Stat	4.92	2.43	23.58	1.83	18.15	13.20	19.91
Adj. R^2	35.63%	9.05%	16.90%	18.82%	27.54%	21.24%	19.18%

Table 4: Difference-in-Differences BTC vs. LTC: Inside CME Trading Hours

This table shows the results of the difference-in-differences regression described in Equation 4. The CIP deviation is in percent and combines lending rates with the basis on OKEx to calculate the cross-currency basis and is defined in Equation 3. A deviation from zero is a deviation from covered interest parity. *Volatility* is the squared daily spot return. $ILLIQ_{Amihud}$ refers to the daily Amihud (2002) illiquidity measure whereby the future trading volume is given in \$100,000. $Spread_{A\&R}$ refers to the bid-ask spread measure by Abdi and Ranaldo (2017) using daily high and low prices. *Arbitrage-Strat* refers to the daily returns of the trading strategy, which takes advantage of CIP violations (see Section 3.1). D^{BTC} equals 1 if the cryptocurrency is BTC and 0 if it is LTC. $D^{Trading\ Hours}$ is 1 if t is within the CME bitcoin future trading hours and 0 otherwise. Adj. R^2 refers to the between Adj. R^2. Standard Errors are estimated using the Driscoll and Kraay (1998) covariance matrix and * refers to significance at the 10%-level, ** at the 5%-level, and *** at the 1%-level. The sample period is 12/2017 - 10/2019.

	$\|CIPDev.\|$ (1)	$Volatility$ (2)	$ILLIQ_{Amihud}$ (3)	$Spread_{A\&R}$ (4)	$Arbitrage - Strat$ (5)
constant	1.06***	0.26***	2.97***	1.02***	0.03
	(6.41)	(4.79)	(5.69)	(7.03)	(0.84)
D^{BTC}	-0.12	-0.11***	-2.83***	-0.23*	0.01
	(-1.26)	(-3.84)	(-5.53)	(-1.96)	(0.68)
$D^{Trading\ Hours}$	-0.08	0.13	-0.51*	-0.08	0.06
	(-1.35)	(1.48)	(-1.87)	(-0.51)	(1.28)
$D^{BTC\ x\ Trading\ Hours}$	-0.06	-0.07	0.48*	-0.06	-0.05*
	(-1.10)	(-1.22)	(1.83)	(-0.50)	(-1.79)
N	1116	1116	1116	1116	1116
F-Stat	2.10	10.76	17.43	8.20	1.13
Adj. R^2	0.97%	1.05%	28.94%	0.23%	-0.05%

Table 5: Panel Regression BTC vs. LTC: Before and After Jane Street

This table shows the results of the panel regression described in Equation 4. The CIP deviation combines lending rates with the basis on OKEx to calculate the cross-currency basis in percent and is defined in Equation 3. A deviation from zero is a deviation from covered interest parity. Half-Life measures the half-life of the CIP deviation in days, i.e. $-\frac{ln(2)}{|\beta|}$ whereby β is the coefficient of a regression with a constant of the CIP deviation on day t on the deviation on day t-1. Volatility is the annualized 10-day spot volatility. $ILLIQ_{Amihud}$ refers to the daily Amihud (2002) illiquidity measure averaged over 14 days whereby the future trading volume is given in $100,000. $ILLIQ_{P\&S}$ refers to the illiquidity measure of Pástor and Stambaugh (2003) averaged over 14 days using rolling regressions with 30 daily data points. The excess return is given by the future minus the spot return. We multiply it by (-1) so that a higher measure signals lower liquidity. $Spread_{A\&R}$ refers to the 14-day averaged bid-ask spread measure by Abdi and Ranaldo (2017) using daily high and low prices. Arbitrage-Strat refers to the daily returns of the trading strategy, which takes advantage of CIP violations (see Section 3.1). $\mathrm{D}^{\mathrm{BTC}}$ equals 1 if the cryptocurrency is BTC and 0 if it is LTC. $\mathrm{D}^{\mathrm{Post}}$ is 1 if the day is after the Market Entry of the HFT firm Jane Street on the 16$^{\mathrm{th}}$ March 2018 and 0 otherwise. The control variables refer to the referenced volatility, illiquidity, and bid-ask spread measures. The respective measure is left out of the controls if the dependent variable is one of them. Standard Errors are estimated using the Driscoll and Kraay (1998) covariance matrix and * refers to significance at the 10%-level, ** at the 5%-level, and *** at the 1%-level. The sample period is 04/2017 - 10/2019.

	$\|CIPDev.\|$		$Half-Life$		$Volatility$		$ILLIQ_{P\&S}$		$ILLIQ_{Amihud}$		$Spread_{A\&R}$		$Arbitrage-Strat$	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
constant	5.08***	2.44**	2.95**	3.48	1.53***	0.59***	6.48	4.56	0.03***	0.03***	1.88***	0.83***	1.25***	0.46***
	(3.55)	(2.35)	(2.47)	(1.40)	(8.61)	(4.12)	(1.50)	(1.23)	(2.94)	(3.77)	(10.26)	(5.08)	(7.52)	(3.06)
$\mathrm{D}^{\mathrm{BTC}}$	-2.37***	-0.27	-1.00	-0.28	-0.58***	-0.20*	-6.21	-5.40	-0.03***	-0.03***	-0.62***	-0.22**	-0.49***	-0.03
	(-2.76)	(-0.36)	(-0.74)	(-0.15)	(-3.52)	(-1.66)	(-1.33)	(-1.34)	(-2.82)	(-4.18)	(-3.74)	(-2.02)	(-3.78)	(-0.37)
$\mathrm{D}^{\mathrm{Post}}$	-4.10***	-2.23***	-2.48**	-3.66*	-0.63***	-0.12	-6.28	-5.76	-0.00	-0.00	-1.08***	-0.64***	-0.97***	-0.52***
	(-2.85)	(-3.05)	(-2.04)	(-1.96)	(-3.40)	(-0.93)	(-1.45)	(-1.41)	(-0.35)	(-0.25)	(-5.44)	(-4.96)	(-5.79)	(-5.58)
$\mathrm{D}^{\mathrm{BTC\ x\ Post}}$	2.23***	0.65	0.98	1.66	0.29*	0.08	6.25	5.92	0.00	0.00	0.39**	0.20*	0.43***	0.12
	(2.58)	(0.80)	(0.72)	(1.00)	(1.71)	(0.65)	(1.34)	(1.39)	(0.20)	(0.11)	(2.25)	(1.66)	(3.27)	(1.33)
N	1558	1558	1558	1558	1558	1558	1558	1558	1558	1558	1558	1558	1558	1558
F-Stat	3.33	41.87	1.60	14.10	26.93	66.11	0.92	0.53	20.64	20.64	19.38	56.83	19.52	21.63
R^2	24.20%	50.20%	5.34%	18.19%	29.17%	52.46%	12.59%	14.53%	24.47%	27.29%	36.83%	55.69%	16.66%	25.77%
Controls	NO	YES	NO	YES	NO	YES	NO	YES	NO	YES	NO	YES	NO	YES

Table 6: Drivers of CIP Violations

This table shows the results of time-series regressions of the form $y_t = \alpha + \boldsymbol{\beta' X_t} + \epsilon_t$. y_t is the first difference of a CIP deviation in percent. The CIP deviation is in percent and combines lending rates with the basis on OKEx to calculate the cross-currency basis and is defined in Equation 3. A deviation from zero is a deviation from covered interest parity. Ret_S refers to the daily log spot return. The *Bitfinex Premium* is defined as the difference between the Bitfinex BTC/USD spot price and the spot index of CryptoCompare, which is a volume-weighted average across the major exchanges. A higher premium means higher counterparty risk of Bitfinex. $\frac{USDT}{USD} - 1$ measures the deviation from unity of Tether against USD at day t. $ILLIQ_{Amihud}$ refers to the daily Amihud (2002) illiquidity measure averaged over 14 days whereby the future trading volume is given in \$100,000. $ILLIQ_{P\&S}$ refers to the illiquidity measure of Pástor and Stambaugh (2003) averaged over 14 days using rolling regressions with 30 daily data points. The excess return is given by the future minus the spot return. We multiply it by (-1) so that a higher measure signals lower liquidity. $Spread_{A\&R}$ refers to the 14-day average bid-ask spread measure by Abdi and Ranaldo (2017) using daily high and low prices. Standard Errors are calculated using bootstrapping with blocks and * refers to significance at the 10%-level, ** at the 5%-level, and *** at the 1%-level. The sample period is 03/2018 - 10/2019. Models 1-5 refer to OLS and model 6 to a 90$^{\text{th}}$ quantile regression (Koenker and Bassett Jr (1978)).

	Panel A: $y_t := \Delta\left[i_t^* - i_t + f_t - s_t\right] \times 100$							Panel B: $y_t := \Delta\left\|[i_t^* - i_t + f_t - s_t]\right\| \times 100$					
	(1a)	(2a)	(3a)	(4a)	(5a)	(6a)		(1b)	(2b)	(3b)	(4b)	(5b)	(6b)
Intercept	-0.00	-0.00	-0.01	-0.01	-0.01	0.35***		-0.01	0.00	-0.01	-0.01	-0.00	0.33***
	(-0.12)	(-0.15)	(-0.42)	(-0.45)	(-0.56)	(10.26)		(-0.59)	(0.18)	(-0.43)	(-0.40)	(-0.36)	(8.96)
y_{t-1}	-0.27***		-0.14***	-0.14***	-0.14***	-0.13*		-0.22***		-0.10**	-0.10**	-0.11**	0.00
	(-5.42)		(-2.69)	(-2.65)	(-2.69)	(-1.81)		(-3.73)		(-2.26)	(-2.20)	(-2.39)	(0.01)
Ret_S	0.04***		0.02**	0.02**	0.02**	0.05*		-0.01		-0.00	-0.00	-0.00	0.01
	(3.22)		(2.47)	(2.48)	(2.53)	(1.92)		(-1.25)		(-0.27)	(-0.28)	(-0.22)	(0.54)
Ret_S^2	-0.00		0.00	0.00	0.00	0.01**		0.00		0.00	0.00	0.00	0.01***
	(-0.10)		(0.34)	(0.35)	(0.39)	(2.14)		(0.95)		(0.67)	(0.66)	(0.66)	(3.17)
Δ Bitfinex Premium		-1.16***	-1.07***	-1.07***	-1.06***	-0.96***			0.93***	0.90***	0.90***	0.89***	1.06***
		(-10.30)	(-8.76)	(-8.81)	(-8.58)	(-6.84)			(6.53)	(6.20)	(6.07)	(6.11)	(5.10)
$\Delta \frac{USDT}{USD} - 1$		0.00	-0.00	-0.00	-0.00	0.05			0.11	0.11	0.11	0.11	0.07
		(-0.02)	(-0.14)	(-0.12)	(-0.09)	(-0.01)			(1.55)	(1.57)	(1.55)	(1.56)	(0.94)
$\Delta\ ILLIQ_{Amihud}$			-168.90	-167.86	-184.92	-132.96				-172.70	-173.04	-191.38	-342.77
			(-0.99)	(-1.00)	(-1.07)	(-0.89)				(-1.32)	(-1.36)	(-1.42)	(-1.61)
$\Delta\ ILLIQ_{P\&S}$				-45607	-41772	0.04					14676	14097	-0.63
				(-1.06)	(-0.95)	(-0.10)					(0.35)	(0.32)	(-0.19)
$\Delta\ Spread_{A\&S}$					3.10	30.75						23.34	58.95**
					(0.34)	(1.17)						(1.27)	(2.11)
ΔTED					0.00	0.00						-0.00	-0.01
					(0.63)	(0.26)						(-0.15)	(-0.42)
ΔVIX					-0.01	-0.05**						0.00	-0.05***
					(-0.94)	(-2.30)						(0.12)	(-3.13)
N	558	558	558	558	558	558		558	558	558	558	558	558
Durbin-Watson	2.037	2.467	2.278	2.281	2.281	1.219		1.969	2.435	2.232	2.232	2.237	1.22
Adj. R^2	11.24%	40.68%	43.71%	43.65%	43.46%	-	Adj. R^2	5.56%	39.90%	40.89%	40.78%	40.78%	-

Table 7: Difference-in-Differences BTC vs. ETH: Inside CME Trading Hours

This table shows the results of the difference-in-differences regression described in Equation 4. The CIP deviation is in percent and combines lending rates with the basis on OKEx to calculate the cross-currency basis and is defined in Equation 3. A deviation from zero is a deviation from covered interest parity. *Volatility* is the squared daily spot return. $ILLIQ_{Amihud}$ refers to the daily Amihud (2002) illiquidity measure whereby the future trading volume is given in \$100,000. $Spread_{A\&R}$ refers to the bid-ask spread measure by Abdi and Ranaldo (2017) using daily high and low prices. *Arbitrage-Strat* refers to the daily returns of the trading strategy, which takes advantage of CIP violations (see Section 3.1). D^{BTC} equals 1 if the cryptocurrency is BTC and 0 if it is ETH. $D^{\text{Trading Hours}}$ is 1 if t is within the CME bitcoin future trading hours and 0 otherwise. Standard Errors are estimated using the Driscoll and Kraay (1998) covariance matrix and * refers to significance at the 10%-level, ** at the 5%-level, and *** at the 1%-level. The sample period is 12/2017 - 10/2019.

	$\lvert CIPDev.\rvert$ (1)	$Volatility$ (2)	$ILLIQ_{Amihud}$ (3)	$Spread_{A\&R}$ (4)	$Arbitrage-Strat$ (5)
constant	1.01***	0.25***	0.81***	1.03***	0.06*
	(6.57)	(4.98)	(7.31)	(5.28)	(1.87)
D^{BTC}	-0.08	-0.10***	-0.67***	-0.23*	-0.01
	(-1.06)	(-3.42)	(-6.53)	(-1.84)	(-0.40)
$D^{\text{Trading Hours}}$	-0.04	0.11	-0.21***	-0.12	-0.05
	(-0.55)	(1.59)	(-3.18)	(-0.65)	(-1.22)
$D^{\text{BTC x Trading Hours}}$	-0.10*	-0.05	0.18***	-0.02	0.06***
	(-1.67)	(-1.05)	(3.18)	(-0.12)	(3.00)
N	1116	1116	1116	1116	1116
F-Stat	2.74	7.92	18.82	5.88	3.16
Adj. R^2	0.82%	0.94%	21.49%	0.17%	-0.05%

Table 8: Top 10 CIP Deviations

This table shows CIP deviations by days to expiry of the corresponding futures contract. The CIP deviation combines lending rates with the basis on OKEx to calculate the cross-currency basis and is defined in Equation 3. A deviation from zero is a deviation from covered interest parity. The sample period is 12/2017 - 10/2019.

Pre Jane-Street Entry					
Lowest 10			Highest 10		
Date	Days to Expiry	CIP Deviation	Date	Days to Expiry	CIP Deviation
16/05/2017	3.17	-17.34%	26/06/2017	4.17	11.45%
05/05/2017	0.17	-16.78%	05/01/2017	1.17	10.90%
27/04/2017	1.17	-16.19%	27/06/2017	3.17	9.20%
24/04/2017	4.17	-16.14%	25/06/2017	5.17	8.60%
26/04/2017	2.17	-15.86%	20/06/2017	3.17	8.50%
28/04/2017	0.17	-15.44%	16/06/2017	0.17	8.45%
25/04/2017	3.17	-15.40%	22/06/2017	1.17	7.58%
08/05/2017	4.17	-15.36%	13/06/2017	3.17	7.57%
04/05/2017	1.17	-15.11%	24/06/2017	6.17	7.50%
Post Jane-Street Entry					
Lowest 10			Highest 10		
Date	Days to Expiry	CIP Deviation	Date	Days to Expiry	CIP Deviation
02/05/2019	0.67	-8.02%	27/05/2019	3.67	2.92%
30/04/2019	2.67	-7.72%	24/07/2018	2.67	2.21%
01/05/2019	1.67	-7.55%	31/07/2018	2.67	2.20%
04/05/2019	5.67	-7.39%	28/05/2019	2.67	2.15%
28/04/2019	4.67	-7.29%	01/08/2018	1.67	1.93%
06/05/2019	3.67	-6.98%	26/07/2018	0.67	1.82%
15/10/2018	3.67	-6.87%	29/07/2018	4.67	1.69%
03/05/2019	6.67	-6.60%	23/07/2018	3.67	1.67%
29/04/2019	3.67	-6.59%	02/08/2018	0.67	1.61%
07/05/2019	2.67	-6.40%	20/05/2019	3.67	1.59%

Table 9: Panel Regression BTC vs. LTC: UIP

This table shows the results of a panel regression similar to the one in Table 5. The UIP deviation is in percent and combines lending rates with the basis on OKEx to calculate the difference between the weekly spot and future return. D^{BTC} equals 1 if the cryptocurrency is BTC and 0 if it is LTC. D^{Post} is 1 if the day is after the Market Entry of the HFT firm Jane Street on the 16^{th} March 2018 and 0 otherwise. Standard Errors are estimated using the Driscoll and Kraay (1998) covariance matrix and * refers to significance at the 10%-level, ** at the 5%-level, and *** at the 1%-level. The sample period is 12/2017 - 10/2019.

	UIP Deviation
constant	4.11
	(1.19)
D^{BTC}	-1.30
	(-0.53)
D^{Post}	-6.57*
	(-1.83)
$D^{BTC\ x\ Post}$	3.87
	(1.52)
N	299
F-Stat	4.91
Adj. R^2	2.61%

Figures

Figure 1: CIP Deviations

This figure shows CIP deviations of BTC/USD. The CIP deviation combines lending rates from Bitfinex with the basis on OKEx to calculate the cross-currency basis and is defined in Equation 3. A deviation from zero is a deviation from covered interest parity. Adjusted CIP deviation refers to the residuals of a regression of CIP deviations on the so-called "Bitfinex Premium", which is the deviation of the Bitfinex BTC/USD spot price from the broad market index. CME Future Launch refers to the launch of the BTC/USD future on the CME Exchange on the 17$^{\text{th}}$ December 2017 and HFT Market Entry denoted the market entry of the HFT firm Jane Street on the 16$^{\text{th}}$ March 2018.

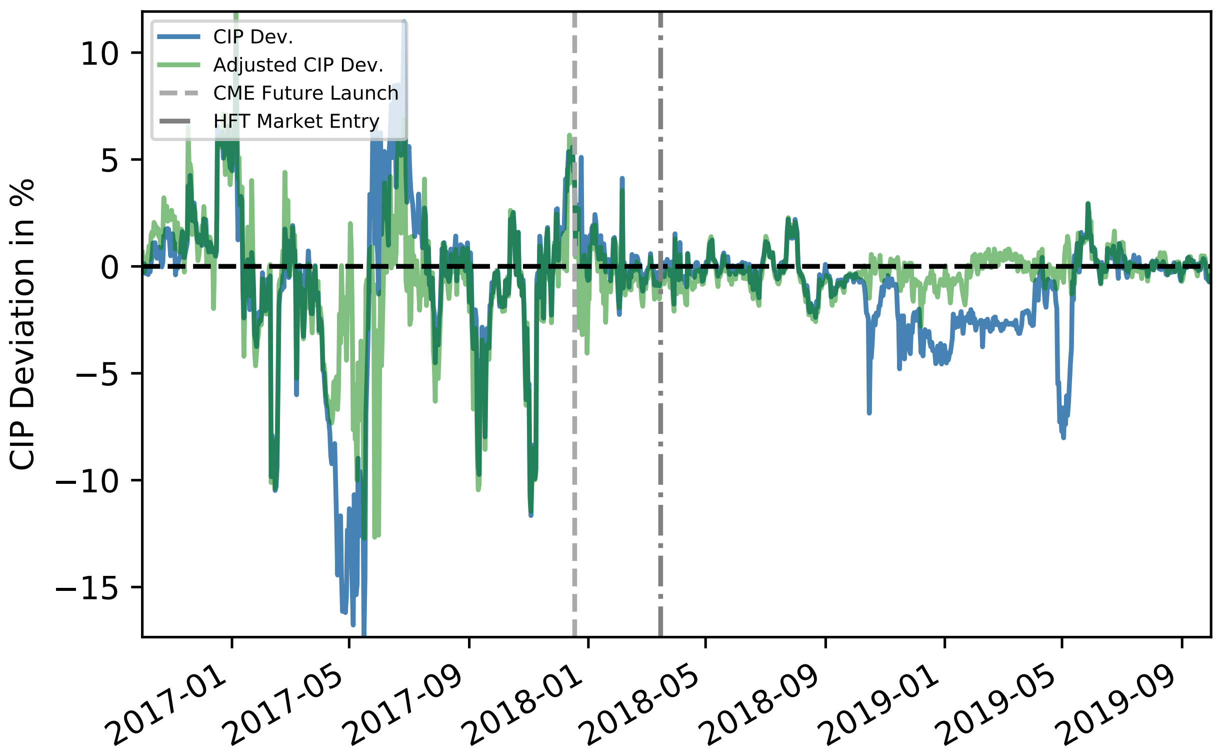
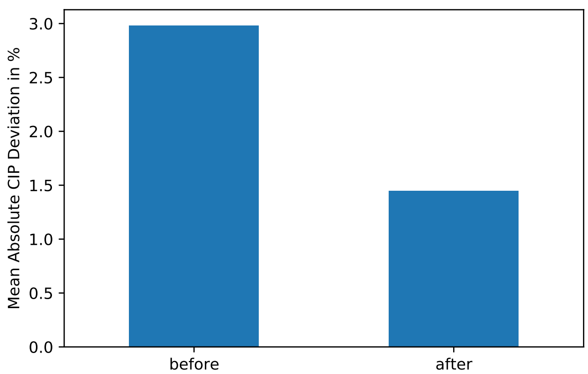


Figure 2: Absolute CIP Deviations before and after HFT Entry

Subfigure I shows the mean of absolute CIP deviations for a symmetric window of 531 days before and after the entry of HFT arbitrageur Jane Street on March 16, 2018. Subfigure II shows the mean of absolute adjusted CIP deviations for a symmetric window of 531 days before and after the entry of HFT arbitrageur Jane Street on March 16, 2018. The adjusted CIP deviation is based on the residuals of a regression of CIP deviations on the *Bitfinex Premium* (for details see Figure 1).

(I) Mean of abs. CIP Deviations



(II) Mean of abs. adjusted CIP Deviations

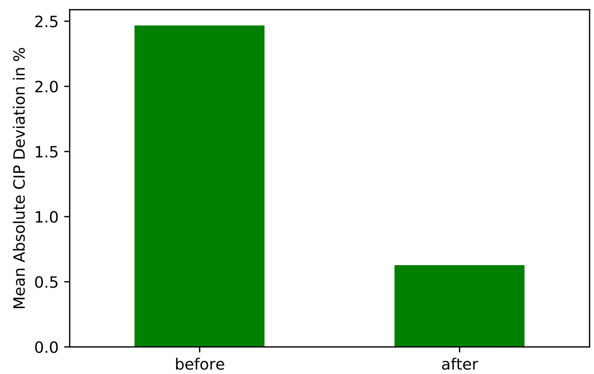


Figure 3: Timeline of Important Events

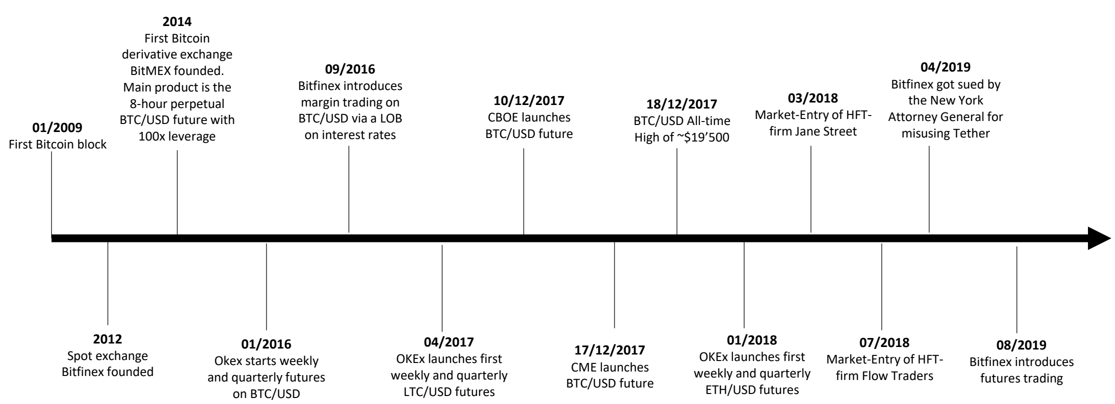


Figure 4: Trading Volume in BTC/USD

This figure shows the 30-day average 24-hour trading volume in USD of BTC/USD markets. Spot volumes are taken from the CryptoCompare index, which includes all major exchanges. OKEx future volume is the aggregated volume of the weekly and quarterly futures contracts. BitMEX Swap is the perpetual swap on BitMEX. For BitMEX and CME the volume is calculated using the front month.

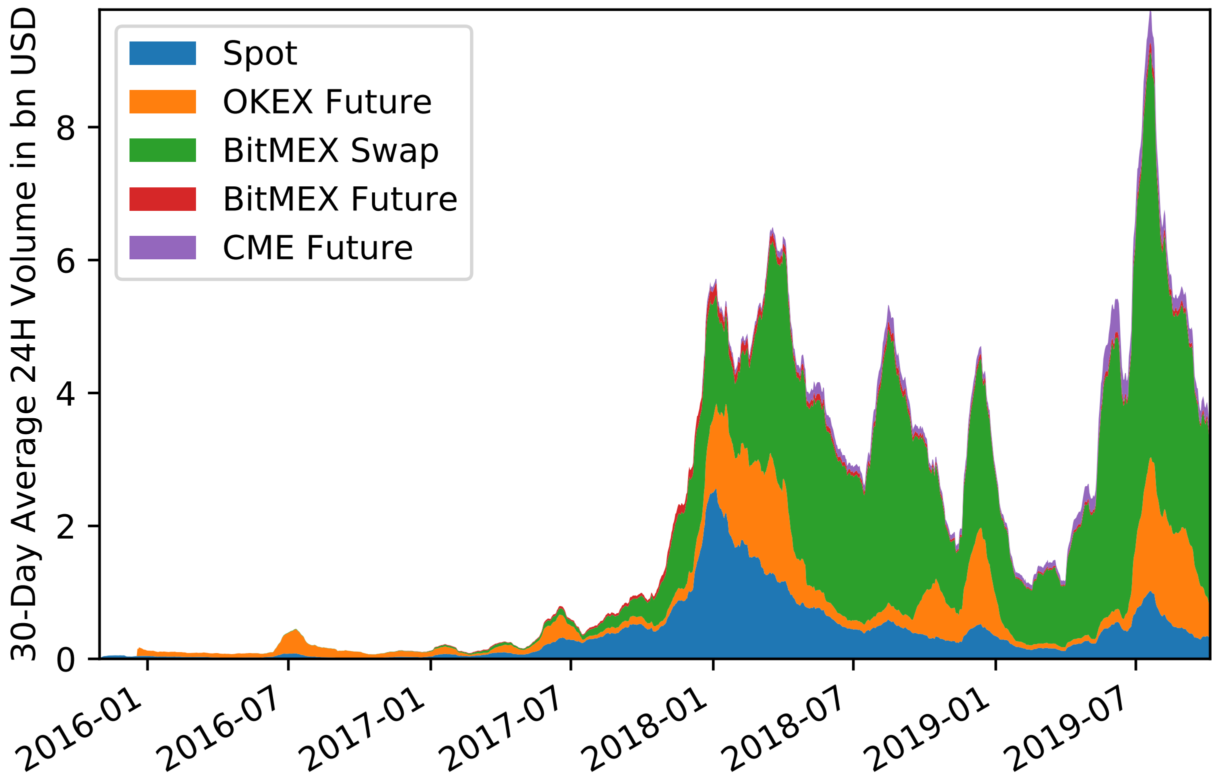
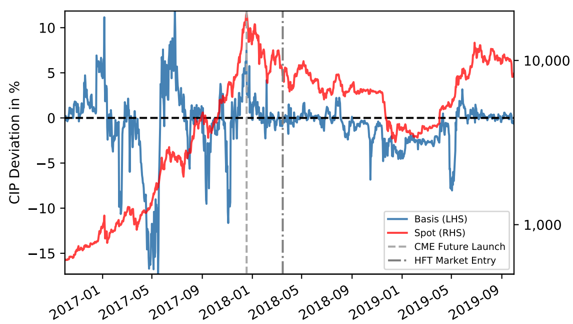


Figure 5: BTC/USD Basis and Lending Rates

Subfigure I shows the basis using the weekly BTC/USD futures contract on OKEx. The basis is calculated as the log of the future minus the log of the spot price. Subfigure II shows daily lending rates of BTC and USD. The rates are aggregated using 1-hour VWAP of 2-day contract trades on Bitfinex. CME Future launch refers to the launch of the BTC/USD future on the CME Exchange on the 17^{th} December 2017 and HFT Market Entry denoted the market entry of the HFT firm Jane Street on the 16^{th} March 2018.

(I) Basis of weekly Futures on OKEx



(II) Bitfinex Lending Rates

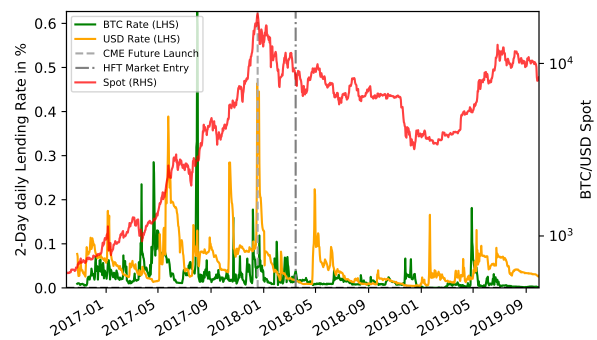


Figure 6: Flowchart of Trading Strategy

This figure illustrates the capital flows of an arbitrageur who trades on Bitfinex and OKEx to take advantage of CIP deviations. The BTC/USD spot and interest rates (i) at day t are traded on Bitfinex and the BTC/USD future at day t with maturity T is traded on OKEx. The arbitrageur would need to hold collateral on both exchanges separately.

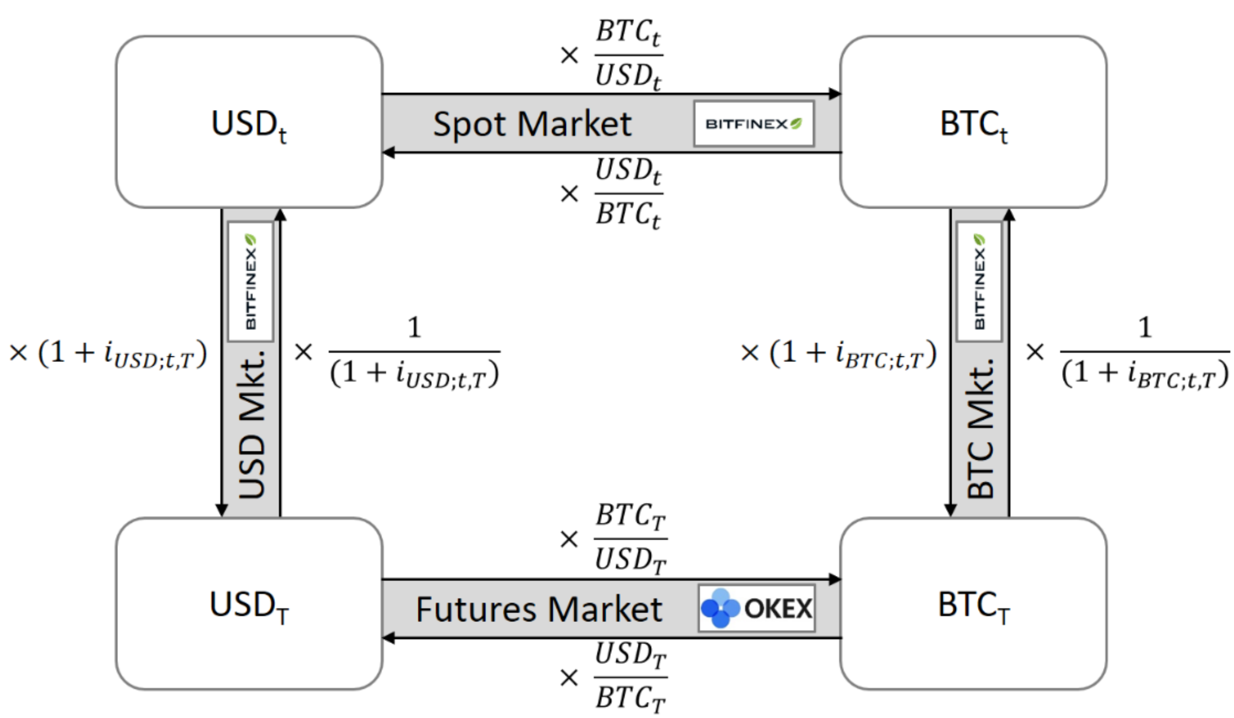


Figure 7: CIP Arbitrage Strategy

This figure shows the performance of a trading strategy that takes advantage of CIP violations between interest rates, spot rates at Bitfinex and weekly futures contracts on OKEx (see Figure 6). Specifically, if the basis is greater (smaller) than the interest rate differential, the strategy sells (buys) the future at OKEx, buys spot BTC (USD) at Bitfinex, finances the spot purchase with a USD (BTC) loan and earning the BTC (USD) interest rate by lending out the purchased BTC (USD). Positions are held until expiry of the futures contract. Gross refers to the return before trading costs and net return after costs (for details see Section 3.1). CME Future Launch refers to the launch of the BTC/USD future on the CME Exchange on the 17$^{\text{th}}$ December 2017 and HFT Market Entry denoted the market entry of the HFT firm Jane Street on the 16$^{\text{th}}$ March 2018.

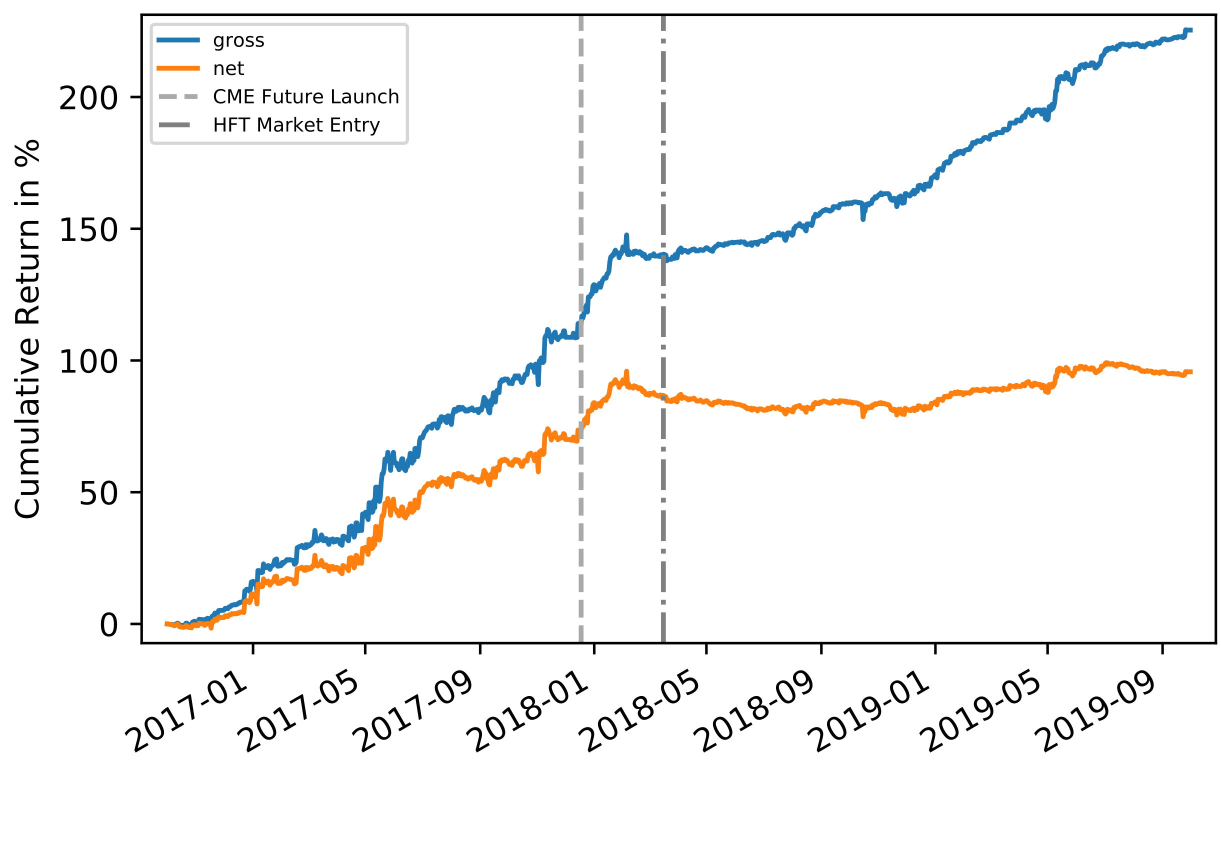
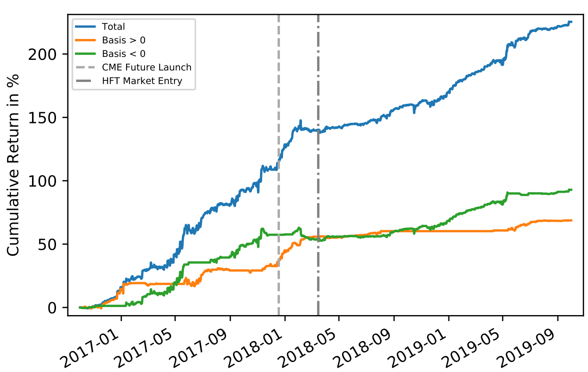


Figure 8: Long-Short Legs of CIP Arbitrage Strategy

This figure shows the performance of a trading strategy that takes advantage of CIP violations between interest rates, spot rates at Bitfinex and weekly futures contracts on OKEx (see Figure 6). Specifically, if the basis is greater (smaller) than the interest rate differential, the strategy sells (buys) the future at OKEx, buys spot BTC (USD) at Bitfinex, finances the spot purchase with a USD (BTC) loan and earning the BTC (USD) interest rate by lending out the purchased BTC (USD). Positions are held until expiry of the futures contract. Gross refers to the return before trading cost and net return after costs (for details see Section 3.1). Basis>0 (Basis<0) measures the returns of the strategy when the future price is greater (lower) than the spot price. CME Future Launch refers to the launch of the BTC/USD future on the CME Exchange on the 17$^{\text{th}}$ December 2017 and HFT Market Entry denoted the market entry of the HFT firm Jane Street on the 16$^{\text{th}}$ March 2018.

(I) Gross



(II) Net

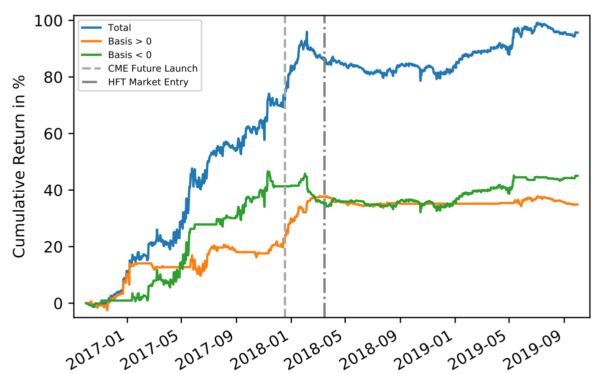
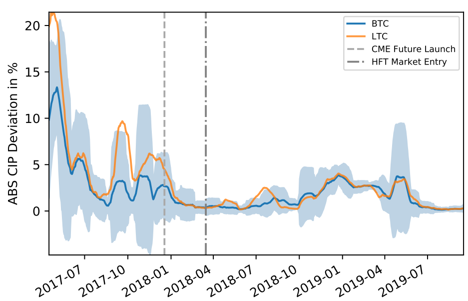


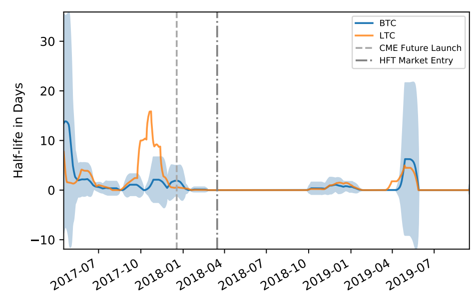
Figure 9: BTC vs. LTC

This figure shows several measures of BTC and LTC market efficiency averaged over a 30-day window. The CIP deviation combines lending rates from Bitfinex with the basis on OKEx to calculate the cross-currency basis and is defined in Equation 3. A deviation from zero is a deviation from covered interest parity. Half-Life measures the half-life of the CIP deviation, i.e. $-\frac{ln(2)}{|\beta|}$ whereby β is the coefficient of a regression with a constant of the CIP deviation on day t on the deviation on day t-1. Volatility is the annualized 10-day spot volatility. $ILLIQ_{Amihud}$ refers to the daily Amihud (2002) illiquidity measure averaged over 14 days whereby the future trading volume is given in \$100,000. $ILLIQ_{P\&S}$ refers to the illiquidity measure of Pástor and Stambaugh (2003) averaged over 14 days using rolling regressions with 30 daily data points. The excess return is given by the future minus the spot return. We multiply it by (-1) so that a higher measure signals lower liquidity. $Spread_{A\&R}$ refers to the 14-day averaged bid-ask spread measure by Abdi and Ranaldo (2017) using daily high and low prices. The shaded blue area is a 2-standard deviation confidence interval for the BTC value.

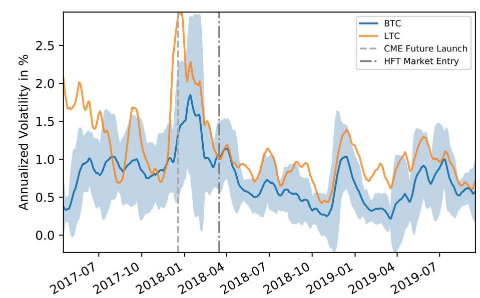
(I) CIP Deviations



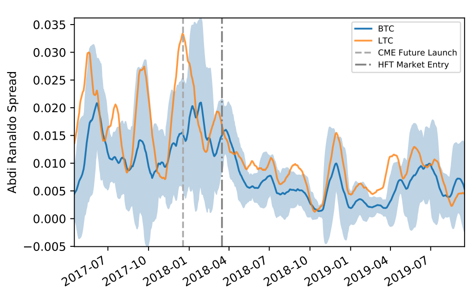
(II) Half-Life



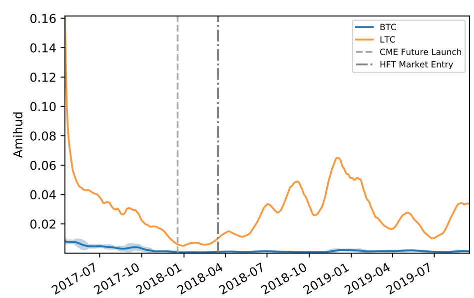
(III) Volatility



(IV) $Spread_{A\&S}$



(V) $ILLIQ_{Amihud}$



(VI) $ILLIQ_{P\&S}$

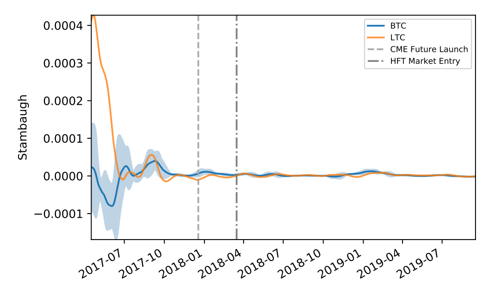
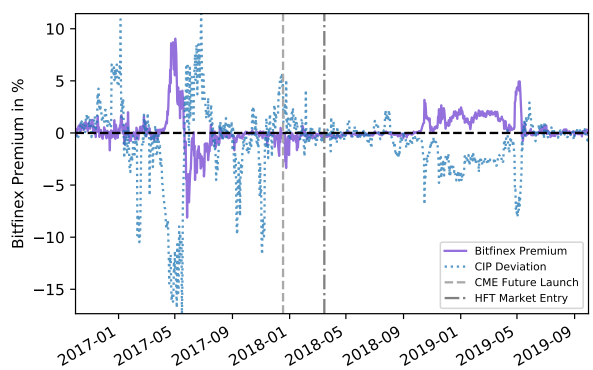


Figure 10: Counterparty Risk

Subfigure I compares CIP deviations and the Bitfinex Premium. The CIP deviation combines lending rates from Bitfinex with the basis on OKEx to calculate the cross-currency basis and is defined in Equation 3. A deviation from zero is a deviation from covered interest parity. The Bitfinex Premium is defined as the difference between the Bitfinex BTC/USD spot price and the spot index of CryptoCompare, which is a volume-weighted average across the major exchanges. A higher premium means higher counterparty risk of Bitfinex (see Section 4.3). In Subfigure II, we plot the residuals of a regression of CIP deviations on the Bitfinex Premium. This adjusted CIP deviation resembles deviation from CIP after accounting for the Bitfinex Premium. The sample period is 10/2016 - 10/2019 whereby pre (post) marks the period before (after) the Market Entry of the HFT firm Jane Street in 03/2018. CME Future Launch refers to the launch of the BTC/USD future on the CME Exchange on the 17$^{\text{th}}$ December 2017 and HFT Market Entry denoted the market entry of the HFT firm Jane Street on the 16$^{\text{th}}$ March 2018.

(I) Bitfinex Premium vs. CIP Deviation



(II) Adjusted CIP Ratio

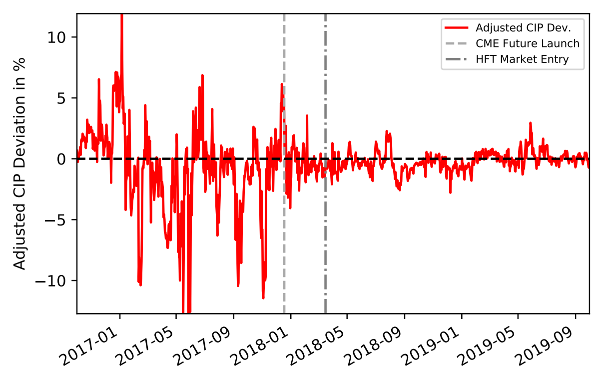


Figure 11: CIP Arbitrage Strategy in Altcoins

This figure shows the performance of a trading strategy that takes advantage of CIP violations between interest rates, spot rates at Bitfinex and weekly futures contracts on OKEx (see Figure 6). Specifically, if the basis is greater (smaller) than the interest rate differential, the strategy sells (buys) the future at OKEx, buys spot LTC (USD) at Bitfinex, finances the spot purchase with a USD (LTC) loan and earning the LTC (USD) interest rate by lending out the purchased LTC (USD). Positions are held until expiry of the futures contract. Gross refers to the return before trading costs and net return after costs (for details see Section 3.1). CME Future Launch refers to the launch of the BTC/USD future on the CME Exchange on the 17$^{\text{th}}$ December 2017 and HFT Market Entry denoted the market entry of the HFT firm Jane Street on the 16$^{\text{th}}$ March 2018.

(I) LTC/USD **(II) ETH/USD**

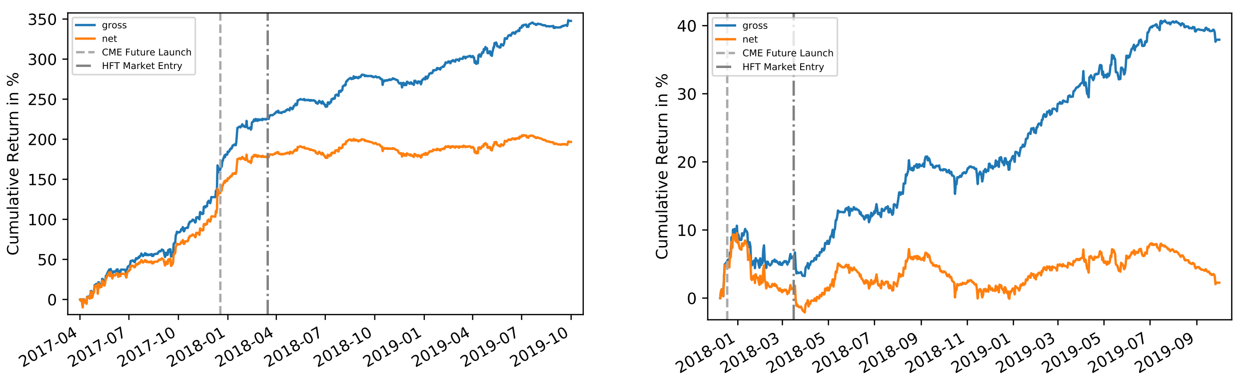


Figure 12: CIP Deviations in Quarterly Futures

This figure shows the CIP deviation and its components. The CIP deviation combines lending rates from Bitfinex with the basis on OKEx to calculate the cross-currency basis and is defined in Equation 3. A deviation from zero is a deviation from covered interest parity. The basis is calculated as the log of the future minus the log of the spot price and the rate differential as the USD minus the cryptocurrency interest rate. CME Future Launch refers to the launch of the BTC/USD future on the CME Exchange on the 17$^{\text{th}}$ December 2017 and HFT Market Entry denoted the market entry of the HFT firm Jane Street on the 16$^{\text{th}}$ March 2018.

(I) Quarterly BTC/USD **(II) Quarterly LTC/USD** **(III) Quarterly ETH/USD**

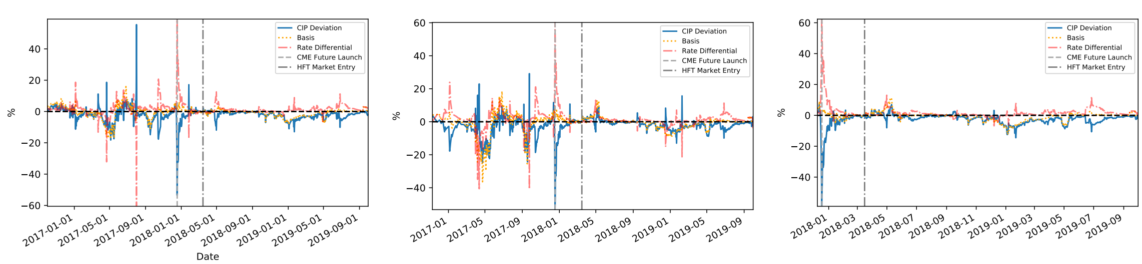
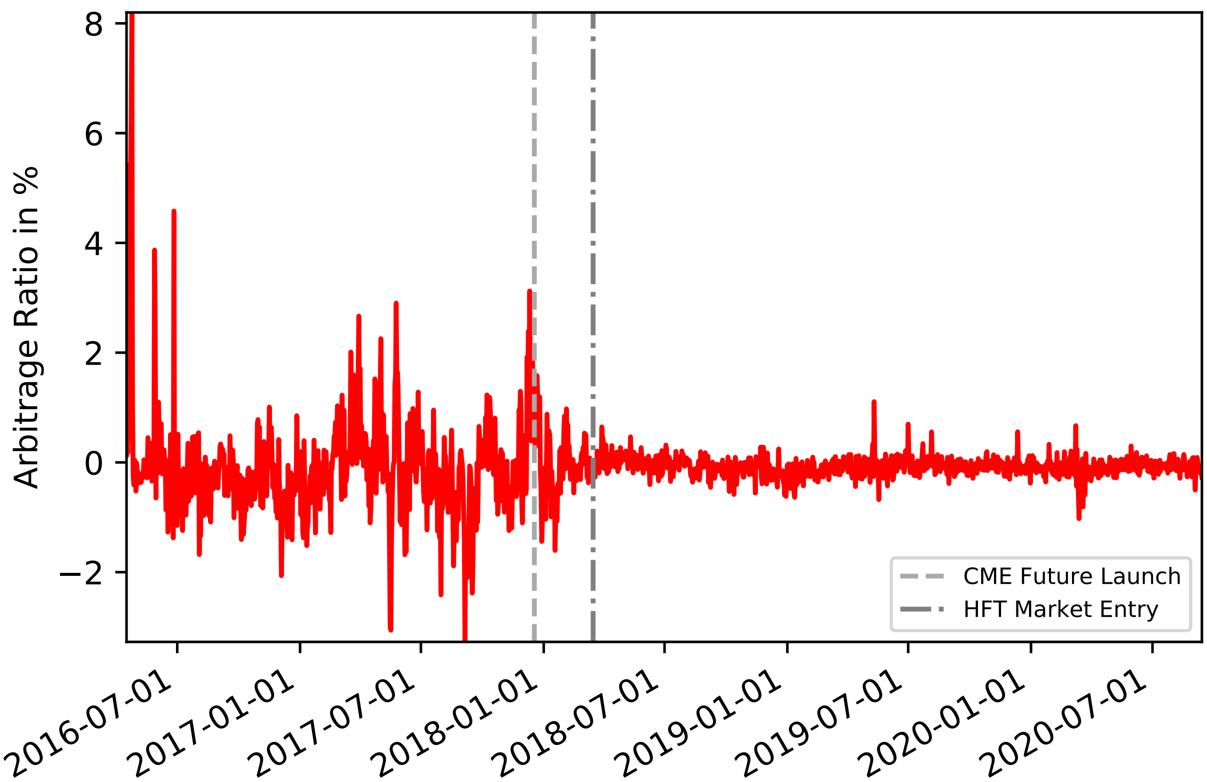


Figure 13: Triangle Arbitrage on Bitstamp

This figure shows daily arbitrage opportunity from a triangle arbitrage in BTC/USD, BTC/EUR, and EUR/USD. Arbitrage ratio refers to the ratio of $(\frac{BTC/USD \times EUR/USD}{BTC/EUR} - 1) \times 100$ A deviation from zero is an arbitrage opportunity. The spot rates are from Bitstamp. CME Future Launch refers to the launch of the BTC/USD future on the CME Exchange on the 17$^{\text{th}}$ December 2017 and HFT Market Entry denoted the market entry of the HFT firm Jane Street on the 16$^{\text{th}}$ March 2018.



Appendix

- Additional Tables and Figures in Appendix A
- Construction of illiquidity Proxies in Appendix B

A Additional Tables and Figures

Table A1: Data Sources

Name	Used Frequency	Source	From	To
		Baseline Data		
Weekly BTC/USD Future	Daily	OKEx	10/2016	10/2019
BTC/USD Spot	Daily	Bitfinex	10/2016	10/2019
BTC Interest Rate	Daily	Bitfinex	10/2016	10/2019
USD Interest Rate	Daily	Bitfinex	10/2016	10/2019
		Additional Data: Diff-and-Diff (Section 4.1)		
Weekly LTC/USD Future	Daily	OKEx	04/2017	10/2019
LTC Interest Rate	Daily	Bitfinex	04/2017	10/2019
LTC/USD Spot	Daily	Bitfinex	04/2017	10/2019
LTC/USD Aggregated Spot Volume	Daily	CryptoCompare	04/2017	10/2019
		Additional Data: Counterparty Risk (Section 4.3)		
BTC/USD Spot Index	Daily	CryptoCompare	10/2018	10/2019
BTC/USD Aggregated Spot Volume	Daily	CryptoCompare	10/2016	10/2019
VIX Index	Daily	Eikon	12/2017	10/2019
TED Spread	Daily	Eikon	12/2017	10/2019
USDT/USD Spot Index	Daily	CryptoCompare	12/2017	10/2019

Figure A1: CIP Deviations in LTC

This figure shows CIP deviations of LTC/USD. The CIP deviation combines lending rates from Bitfinex with the basis on OKEx to calculate the cross-currency basis and is defined in Equation 3. A deviation from zero is a deviation from covered interest parity. CME Future Launch refers to the launch of the BTC/USD future on the CME Exchange on the 17^{th} December 2017 and HFT Market Entry denoted the market entry of the HFT firm Jane Street on the 16^{th} March 2018.

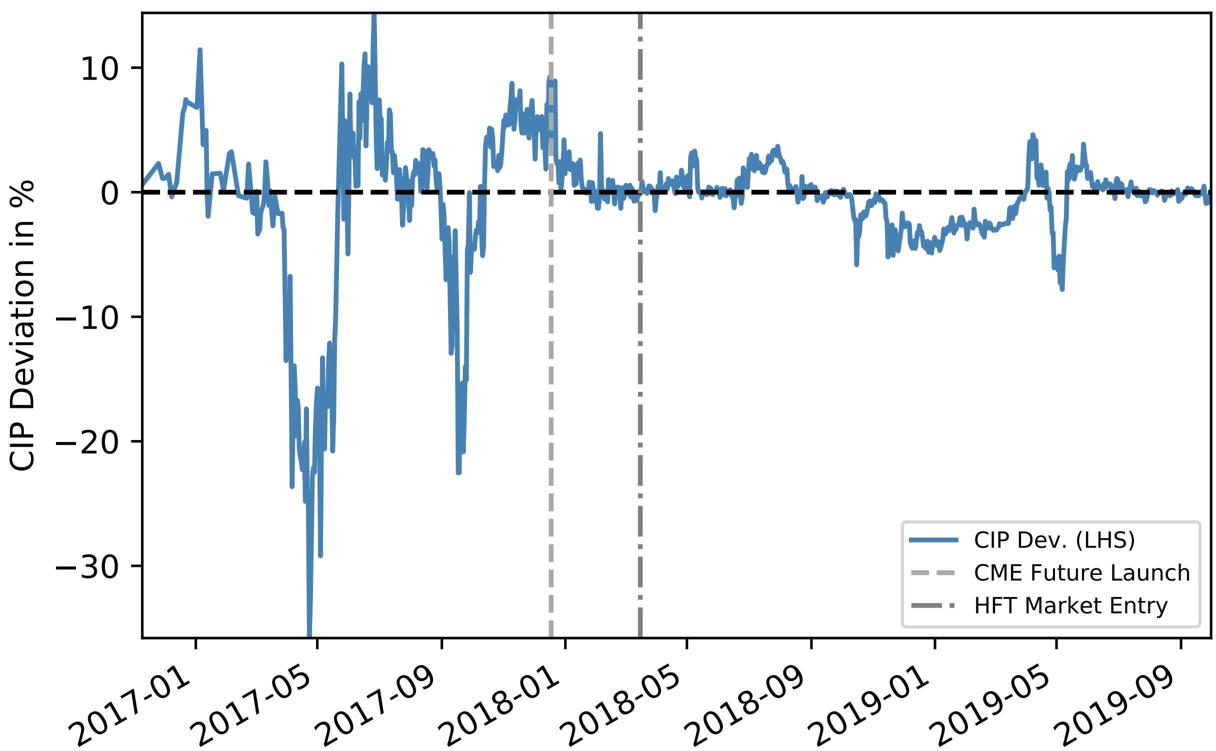


Table A2: Descriptive Statistics in BTC

This table provides descriptive statistics for BTC/USD at daily frequency. Spot returns are based on the Bitfinex last traded spot price. Future returns and volume refer to the short-term (7 days) BTC/USD future on OKEx. Rates refer to the daily lending rate, which is used for margin trading on Bitfinex and fixed for two days. They are aggregated as a 1-hour VWAP. The CIP deviation combines lending rates with the basis on OKEx to calculate the cross-currency basis and is defined in Equation 3. A deviation from zero is a deviation from covered interest parity. The sample period is 10/2016 - 10/2019.

	Return Spot %	Return Future %	Basis Future %	Rate BTC %	Rate USD %	CIP Dev. %	Volume Future mm \$	Volume Rate BTC mm \$	Volume Rate USD mm \$
Pre 03/2018									
count	1,095.00	938.00	1,095.00	1,094.00	1,094.00	1,094.00	1,095.00	1,095.00	1,094.00
mean	0.24	0.27	-0.78	0.02	0.05	-0.88	398.60	66.77	85.48
std	4.34	4.67	3.53	0.05	0.05	3.44	520.14	52.75	69.77
min	-23.00	-23.61	-17.31	0.00	0.00	-17.34	2.87	0.20	0.66
25%	-1.47	-1.54	-2.06	0.01	0.02	-2.13	71.83	12.65	17.52
50%	0.25	0.17	-0.25	0.01	0.04	-0.34	191.44	60.39	78.03
75%	2.42	2.54	0.59	0.03	0.07	0.49	526.98	107.45	129.37
max	21.28	20.45	11.85	1.11	0.62	11.45	5,088.58	269.02	469.25
Skewness	-0.32	-0.30	-1.30	14.27	3.55	-1.35	2.93	0.47	1.00
Kurtosis	3.22	3.48	4.85	301.02	21.31	5.03	13.81	-0.57	2.00
Post 03/2018									
count	564.00	483.00	564.00	563.00	563.00	563.00	564.00	564.00	563.00
mean	0.01	0.02	-1.01	0.01	0.03	-1.09	457.09	84.49	110.36
std	3.53	3.67	1.75	0.01	0.03	1.70	506.64	37.86	43.97
min	-13.38	-14.12	-8.04	0.00	0.00	-8.02	14.93	14.39	26.11
25%	-1.40	-1.31	-2.34	0.00	0.01	-2.33	107.45	54.17	75.89
50%	-0.05	-0.07	-0.51	0.01	0.02	-0.55	294.92	81.65	108.43
75%	1.50	1.40	0.17	0.01	0.04	0.04	646.20	112.20	137.43
max	14.80	14.98	3.17	0.13	0.22	2.92	4,016.30	224.04	340.20
Skewness	0.07	0.25	-1.08	3.93	1.99	-1.11	2.39	0.43	0.72
Kurtosis	2.34	2.70	1.64	27.60	7.09	1.69	8.64	-0.38	0.89

Table A3: Descriptive Statistics in LTC

This table provides descriptive statistics for BTC/USD at daily frequency. Spot returns are based on the Bitfinex last traded spot price. Future returns and volume refer to the short-term (7 days) BTC/USD future on OKEx. Rates refer to the daily lending rate, which is used for margin trading on Bitfinex and fixed for two days. They are aggregated as a 1-hour VWAP. The CIP deviation combines lending rates with the basis on OKEx to calculate the cross-currency basis and is defined in Equation 3. A deviation from zero is a deviation from covered interest parity. The sample period is 04/2017 - 10/2019.

	Return Spot %	Return Future %	Basis Future %	Rate LTC %	Rate USD %	CIP Dev. %	Volume Future mm $	Volume Rate LTC mm $	Volume Rate USD mm $
Pre 03/2018									
count	457.00	390.00	457.00	384.00	457.00	384.00	457.00	457.00	457.00
mean	0.77	0.77	-0.73	0.04	0.08	-1.33	44.20	3.62	68.30
std	8.35	8.57	8.10	0.08	0.07	8.45	77.05	4.81	84.26
min	-35.25	-35.96	-36.68	0.00	0.01	-35.80	0.08	0.00	0.66
25%	-2.79	-2.94	-1.43	0.01	0.04	-2.30	3.60	0.23	7.70
50%	-0.00	0.30	0.89	0.01	0.07	0.74	17.60	1.32	27.16
75%	3.60	3.94	3.84	0.03	0.09	3.45	55.53	5.59	119.56
max	56.67	52.74	14.79	0.83	0.62	14.40	935.19	27.34	469.25
Skewness	1.39	0.84	-1.66	5.39	2.88	-1.50	5.29	1.88	1.68
Kurtosis	8.56	6.10	2.73	37.66	13.01	1.89	45.22	3.92	2.94
Post 03/2018									
count	562.00	481.00	562.00	562.00	562.00	562.00	562.00	562.00	562.00
mean	-0.19	-0.21	-0.46	0.02	0.03	-0.51	53.15	3.23	110.64
std	5.08	5.25	2.08	0.03	0.03	2.01	74.92	1.77	43.80
min	-17.22	-17.99	-7.67	0.00	0.00	-7.81	1.57	0.66	30.02
25%	-2.63	-2.75	-2.00	0.00	0.01	-2.02	10.65	1.87	75.98
50%	-0.24	-0.28	-0.01	0.01	0.02	-0.10	27.43	2.85	108.50
75%	2.17	2.06	0.53	0.02	0.04	0.46	54.39	4.08	137.49
max	20.33	22.74	4.71	0.48	0.22	4.62	482.69	14.61	340.20
Skewness	0.20	0.21	-0.51	10.62	1.99	-0.51	2.88	1.70	0.73
Kurtosis	1.78	2.01	0.21	171.43	7.07	0.37	9.41	5.14	0.91

Table A4: Drivers of CIP Violations

This table shows the results of time-series regressions of the form $y_t = \alpha + \boldsymbol{\beta}'\mathbf{X_t} + \epsilon_t$. y_t is the first difference of a CIP deviation in percent. The CIP deviation is in percent and combines lending rates with the basis on OKEx to calculate the cross-currency basis and is defined in Equation 3. A deviation from zero is a deviation from covered interest parity. Ret_S refers to the daily log spot return. The *Bitfinex Premium* is defined as the difference between the Bitfinex BTC/USD spot price and the spot index of CryptoCompare, which is a volume-weighted average across the major exchanges. A higher premium means higher counterparty risk of Bitfinex. $\frac{USDT}{USD} - 1$ measures the deviation from unity of Tether against USD at day t. $ILLIQ_{Amihud}$ refers to the daily Amihud (2002) illiquidity measure averaged over 14 days whereby the future trading volume is given in $100,000. $ILLIQ_{P\&S}$ refers to the illiquidity measure of Pástor and Stambaugh (2003) averaged over 14 days using rolling regressions with 30 daily data points. The excess return is given by the future minus the spot return. We multiply it by (-1) so that a higher measure signals lower liquidity. $Spread_{A\&R}$ refers to the 14-day average bid-ask spread measure by Abdi and Ranaldo (2017) using daily high and low prices. Standard Errors are calculated using bootstrapping with blocks and * refers to significance at the 10%-level, ** at the 5%-level, and *** at the 1%-level. The sample period is 10/2016 - 03/2018. Models 1-5 refer to OLS and model 6 to a 90$^{\text{th}}$ quantile regression (Koenker and Bassett Jr (1978)).

	Panel A: $y_t := \Delta\left[i_t^* - i_t + f_t - s_t\right] \times 100$							Panel B: $y_t := \Delta\left\|\left[i_t^* - i_t + f_t - s_t\right]\right\| \times 100$					
	(1a)	(2a)	(3a)	(4a)	(5a)	(6a)		(1b)	(2b)	(3b)	(4b)	(5b)	(6b)
Intercept	0.03	0.01	0.01	0.02	0.01	1.68***		-0.14	-0.08	-0.13	-0.14	-0.16	1.50***
	(0.27)	(0.10)	(0.13)	(0.15)	(0.14)	(5.30)		(-1.55)	(-1.07)	(-1.43)	(-1.53)	(-1.61)	(4.81)
y_{t-1}	-0.15**		-0.14**	-0.15**	-0.14**	-0.14*		-0.18**		-0.18**	-0.19**	-0.18**	-0.16
	(-2.20)		(-2.29)	(-2.34)	(-2.31)	(-1.93)		(-2.37)		(-2.36)	(-2.44)	(-2.35)	(-1.47)
Ret_S	0.03*		0.04**	0.04**	0.03*	0.07		-0.01		-0.01	-0.01	-0.01	-0.03
	(1.76)		(2.00)	(1.98)	(1.76)	(0.67)		(-0.70)		(-0.55)	(-0.55)	(-0.60)	(-0.39)
Ret_S^2	-0.00		-0.00	-0.00	-0.00	0.00		0.00		0.00	0.00	0.00	0.00
	(-0.30)		(-0.73)	(-0.74)	(-0.55)	(0.60)		(1.35)		(1.27)	(1.30)	(1.31)	(0.67)
Δ Bitfinex Premium		-0.35*	-0.36*	-0.35*	-0.34*	-0.49**			-0.01	-0.03	-0.05	-0.04	-0.14
		(-1.77)	(-1.95)	(-1.90)	(-1.91)	(-2.41)			(-0.05)	(-0.24)	(-0.31)	(-0.28)	(-0.72)
$\Delta\frac{USDT}{USD} - 1$		0.06	0.06	0.06	0.06	0.13			0.00	-0.02	-0.02	-0.02	-0.10
		(0.90)	(1.07)	(1.03)	(1.04)	(0.54)			(-0.05)	(-0.45)	(-0.46)	(-0.48)	(-0.19)
$\Delta\, ILLIQ_{Amihud}$			-375.32	-355.12	-373.41	-1011.92				243.18	193.34	183.38	-46.79
			(-0.90)	(-0.84)	(-0.87)	(-0.48)				(0.71)	(0.55)	(0.52)	(0.32)
$\Delta\, ILLIQ_{P\&S}$				-13966.25	-11906.05	-6.74					35918.83*	36918.75*	-0.34
				(-0.51)	(-0.43)	(-0.20)					(1.91)	(1.95)	(-0.06)
$\Delta\, Spread_{A\&S}$					-8.88	44.27						20.26	-4.17
					(-0.49)	(0.61)						(0.77)	(0.08)
ΔTED					-0.03	-0.08						0.03	-0.07
					(-0.88)	(-0.91)						(0.74)	(-0.18)
ΔVIX					-0.07	0.16						-0.04	0.23
					(-0.95)	(0.52)						(-0.67)	(0.71)
N	311	311	311	311	311	311		311	311	311	311	311	311
Durbin-Watson	2.057	2.335	2.079	2.082	2.077	1.06		2.081	2.401	2.074	2.077	2.083	1.088
Adj. R^2	2.86%	2.31%	5.90%	5.70%	5.40%	-	Adj. R^2	2.86%	-0.65%	2.17%	2.64%	2.05%	-

Table A5: CIP and UIP Tests

Motivated by Fama (1984), this table shows results of time-series regressions of the form $y_t = \alpha + \boldsymbol{\beta}'\mathbf{X_t} + \epsilon_t$ to test for covered and uncovered interest rate parity. s denotes the log spot BTC/USD price of Bitfinex and f the log BTC/USD price of weekly BTC/USD futures contracts on OKEx. The futures expire and are reissued 15 minutes later every Friday at 8 AM UTC. t resembles the first trading day of a new contract, i.e. with six days to expiry. Therefore, the model is estimated using only the first trading day of each new contract. i^* and i denote the USD and BTC interest rates, respectively. Interest rates are from Bitfinex, aggregated as a 1-hour VWAP, fixed for two days, and scaled to match the time to maturity of the futures contract. *Cursive* t-statistics are against the null hypothesis that the coefficient is 1 and t-statistics in normal font against 0. Standard Errors are calculated using bootstrapping with blocks and * refers to significance at the 10%-level, ** at the 5%-level, and *** at the 1%-level. The sample period is 10/2016 - 10/2019 whereby pre (post) marks the period before (after) the HFT Market Entry in 03/2018.

	Pre				Post				Full Sample			
	(1a) $s_{t+1} - s_t$	(2a) $f_t - s_{t+1}$	(3a) $f_2 - s_2$	(4a) $f_t - s_t$	(1b) $s_{t+1} - s_t$	(2b) $f_t - s_{t+1}$	(3b) $f_2 - s_2$	(4b) $f_t - s_t$	(1c) $s_{t+1} - s_t$	(2c) $f_t - s_{t+1}$	(3c) $f_2 - s_2$	(4c) $f_t - s_t$
Intercept	0.02*	-0.02*	-0.02*	-0.02	-0.01	0.01	-0.02***	-0.02***	0.01	-0.01	-0.02***	-0.02***
	(1.89)	(-1.87)	(-1.86)	(-1.48)	(-1.45)	(1.45)	(-4.26)	(-3.98)	(0.80)	(-0.79)	(-3.25)	(-2.91)
$f_t - s_t$	-0.11***	1.11***			-0.33***	1.33***			-0.09***	1.09***		
	(-4.24)	(4.23)			*(-2.92)*	(2.99)			*(-4.88)*	(4.80)		
$i_2 - i_2^*$			16.27**				14.51***				15.65***	
			(2.16)				*(3.48)*				*(2.95)*	
$i_t - i_t^*$				6.00**				4.94**				5.84***
				(2.30)				*(2.24)*				*(2.92)*
N	75	75	75	75	80	80	80	80	155	155	155	155
F-Stat	0.27	27.65	7.29	10.49	0.81	13.19	15.72	10.79	0.20	28.04	12.23	16.64
Durbin-Watson	1.991	1.991	0.674	0.641	1.836	1.836	0.636	0.788	1.911	1.911	0.663	0.661
Adj. R^2	-1.15%	17.16%	21.75%	22.96%	-0.82%	5.81%	32.66%	23.31%	-0.54%	12.53%	23.47%	24.01%

B Construction of illiquidity Proxies

The Amihud (2002) illiquidity measure is defined as follows, whereby S refers to the spot price at at trading day t and V to the spot volume in million USD.

$$Amihud_t = \frac{1}{14}\sum_{t=-7}^{6}\frac{|ln(S_t) - ln(S_{t-1})|}{V_t} \tag{12}$$

The modified Pástor and Stambaugh (2003) illiquidity measure is defined as follows.

$$P\&S_t = \frac{1}{14}\sum_{t=-7}^{6}\gamma_t \tag{13}$$

with γ being the coefficient from the following regression whereby r_t^e refers to the excess return at trading day t, i.e. the future minus the spot return, $r_t^f - r_t^s$. V^f refers to the trading volume of the future in million USD. The regression is estimated using a rolling centered window of 30 days. Finally, we multiply the γ_t by (-1) so that a higher modified Pástor and Stambaugh (2003) illiquidity measure signals lower liquidity.

$$r_{t+1}^e = \alpha + \phi r_t^f + \gamma sign(r_t^e) \times V_t^f + \epsilon_t \tag{14}$$

The Abdi and Ranaldo (2017) bid-ask spread measure is defined as follows whereby C_t, H_t, L_t refer to the daily closing, high, and low price, respectively.

$$Spread_t = \frac{1}{14}\sum_{t=-7}^{6}\eta_t \tag{15}$$

with η_t defined as follows

$$\eta_t = 4 \times \sqrt{\left[ln(C_t) - \frac{ln(H_t) + ln(L_t)}{2}\right] \times \left[ln(C_t) - \frac{ln(H_{t+1}) + ln(L_{t+1})}{2}\right]} \tag{16}$$

We replace instances of $ln(C) - \frac{ln(H)+ln(L)}{2}$ that are negative with zero.

The half-life of CIP deviation is calculated as follows.

$$Half - Life_t = \frac{1}{7}\sum_{t=-3}^{3} -\frac{ln(2)}{|\kappa_t|} \tag{17}$$

whereby κ_t is the coefficient of the following regression, which is estimated with a rolling 20-day centered window.

$$y_t = \alpha + \kappa \times y_{t-1} + \epsilon_t \tag{18}$$

y_t is the CIP deviation at day t. The CIP deviation combines lending rates from Bitfinex with the basis on OKEx to calculate the cross-currency basis and is defined in Equation 3.