



**Price Discovery In The Modern Bitcoin Market:
Examining Lead-Lag Relationships Between The Bitcoin Spot
And Bitcoin Futures Market**

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I. Introduction

In 2008, the online posting of a technical white paper—*Bitcoin: A Peer-to-Peer Cash Electronic Cash System*¹—envisioned a new way to store and transfer value on the internet. In the ensuing years, bitcoin has grown from a niche asset embraced by retail investors into an increasingly mainstream allocation held by a wide variety of market participants, from individual investors to financial advisors, hedge funds, corporations, institutions, endowments, insurance companies, and more. As of September 30, 2020, the end of this study, bitcoin was valued at \$200 billion.²

As the market has grown, so too has the trading ecosystem that allows for the efficient transfer of bitcoin from one market participant to another. This ecosystem today includes both large spot trading platforms (e.g., Coinbase³) and a large, regulated futures market run by the CME Group.⁴

This paper builds on a growing library of academic and practitioner research that aims to determine whether price discovery in the bitcoin market primarily takes place on spot trading platforms or on the regulated CME bitcoin futures market. This paper extends the existing literature in four primary ways:

1. **Time Period:** This paper uses available trade data on the CME bitcoin futures market, from its inception in December 2017 through the end of the study on September 30, 2020.
2. **Academic Survey:** This paper includes a detailed survey of existing academic and practitioner research, examining papers that have evaluated where price discovery occurs between spot trading platforms and the regulated bitcoin futures market.
3. **Diversity of Statistical Approaches:** This paper takes a broad approach to its analysis, using two distinct and well-established statistical methods to evaluate the lead-lag relationship between the spot and futures markets.
4. **Data Quality and Replicability:** This paper uses professionally developed data feeds in its analysis, as well as commonly available statistical software tools, so that the study can be replicated by other researchers.

Using this multifaceted and replicable approach, the paper finds that the CME bitcoin futures market leads the bitcoin spot market in a consistent and statistically significant manner.

¹ <https://bitcoin.org/bitcoin.pdf>

² Bitcoin's market cap as of September 30, 2020 was \$200.75B. Source: Blockchain.com.

³ Q3 2020 ADV for Coinbase was \$194M. Source: Coin Metrics.

⁴ Q3 2020 ADV of the CME bitcoin futures market was \$365M. Source: CME Group.

II. Data Sourcing

Bitcoin trading platforms exist in multiple countries and operate under a variety of regulatory regimes. There are generally no requirements for these platforms to provide data on their trading activity in a uniform fashion to a centralized database. As a result, there is no equivalent to the Consolidated Tape System in the U.S., which offers a single source of universally agreed-upon trading data for publicly traded equities in the U.S.

Over the years, however, a variety of private data providers have emerged that consolidate trading data from large numbers of bitcoin trading platforms. In preparing to evaluate price discovery in the bitcoin markets, we engaged in a detailed survey of these data providers in May 2020, evaluating them on metrics including data quality, trading platform coverage, cost, service quality, and other corporate factors. The goal of this survey was to determine which provider or set of providers could supply the highest quality data.

We began by cataloging bitcoin data providers commonly referenced in the industry. We then supplemented this list by conducting broad web searches to identify additional bitcoin data providers and by consulting a third-party survey titled, “The State of the Digital Asset Data and Infrastructure,” published by The Block on May 14, 2020.⁵

Aggregating these steps resulted in a total of 29 firms, 14 of which offered bitcoin tick data, the specific type of data needed to conduct lead-lag analysis. We evaluated these 14 firms on four separate criteria:

- **Data coverage:** All else equal, more trading platforms are better than fewer.
- **Data quality:** Data gathered by third-party providers should match the actual activity that takes place on each trading platform, with as few errors as possible.
- **Cost:** The cost of licensing the data from a given provider should be reasonable.
- **Corporate factors:** Available facts should give confidence that the provider in question will continue to operate in a robust manner over a meaningful period of time.

Data quality was weighted heavily in the analysis, as it has a direct impact on the output of price discovery research. Still, the other three factors were important as well.

Based on this analysis, we elected to use Coin Metrics as the lead data provider for our analysis.

⁵<https://www.tbstat.com/wp/uploads/2020/05/The-State-of-the-Digital-Asset-Data-and-Infrastructure-Landscape-1.pdf>

At the time, Coin Metrics offered coverage of 26 exchanges, and had exceptionally high data quality. For instance, in one portion of our analysis, we downloaded the full record of BTC/USD trades (2,523,481 trades) directly from Bitfinex, a spot bitcoin trading platform, for the month of March 2020. We compared these trades with data from participating data providers, looking for three types of errors: duplicated trades, erroneous trades, and missing trades. Coin Metrics had zero data errors, while its competitors had between two and 4,929 errors. We repeated this analysis using trades at Coinbase and LBank, two additional bitcoin trading platforms, and found similar results.

To supplement Coin Metrics' data, we evaluated data providers that covered a large number (>100) of crypto trading platforms. Of these providers, CoinAPI scored the best on our four factors, including scoring well on data quality. We elected to use CoinAPI data to supplement Coin Metrics data where necessary to conduct our analysis.

Using Coin Metrics and CoinAPI data, we focused our analysis on 10 bitcoin trading platforms: the five trading platforms that contribute to the price used to settle the CME CF Bitcoin Reference Rate⁶ (Bitstamp, Coinbase, Gemini, itBit, and Kraken), and five additional trading platforms with large reported trading volumes that do not contribute to the CME CF Bitcoin Reference Rate (Binance, Bitfinex, Huobi, LBank, and OKEx).

Data on CME bitcoin futures was taken directly from the CME Group.

⁶ The price used to settle bitcoin futures contracts on the CME.
<https://www.cmegroup.com/trading/cryptocurrency-indices/cf-bitcoin-reference-rate.html>

III. Analytical Framework: Two Approaches To Evaluating Price Discovery And Lead-Lag Relationships

We began this analysis by reviewing relevant academic and practitioner papers. This included papers broadly related to the topic of price discovery and lead-lag analysis in financial markets, and papers that specifically evaluated these concepts vis-à-vis the bitcoin spot market and the regulated bitcoin futures market.

This survey revealed two major categories of price discovery analysis in the general financial market literature:

i) Information Share (IS)/Component Share (CS) Price Discovery Analysis: This type of analysis is based on the principle that there is a common “efficient” price for any asset being traded on multiple platforms. It allows you to construct a model of the relationship between different platforms by comparing their price series against this common efficient price, and testing which price series is faster to incorporate new information. Markets that are faster to incorporate new information are considered to have a “higher share” of price discovery; and

ii) Time-Shift Lead-Lag Analysis (TSLL): TSLL is a more intuitive approach to evaluating lead-lag relationships between markets. It involves taking two time series of price data and offsetting (or “shifting”) them against each other to determine what offset, or “lag,” produces the highest cross-correlation between the two series.

Both IS/CS price discovery analysis and TSLL have an extensive history in the financial literature, and each comes with its own strengths and weaknesses.

We evaluate each approach separately in this paper and discuss the holistic result in our conclusion.

IV. Information Share (IS) And Component Share (CS) Price Discovery Analysis

Information share (IS) and component share (CS) are two variants of a core analytical approach to price discovery research that traces its roots back to the 1990s. It is sometimes referred to in the literature as “common efficient price”-based analysis, “fundamental price”-based analysis, or simply “price discovery” analysis.

Price discovery analysis is based on the idea that, in a perfectly efficient market, new information should be reflected simultaneously in the price of an asset as it trades on different platforms. In practice, however, this is not the case; some platforms move before others. In addition, some market moves are simply noise that do not reflect a change in the fundamental price at all. Price discovery analysis attempts to measure the speed and accuracy with which each platform incorporates new information into its price. Platforms that are faster to incorporate new information while being better at avoiding noise are considered to have a “higher share” of price discovery.

Specific approaches to this type of price discovery analysis have evolved over time.

A. Academic Overview

In 1995, Hasbrouck⁷ proposed the information share (IS) metric, describing his new metric as measuring “‘who moves first’ in the process of price adjustment.” He used it to compare price discovery for equities on the New York Stock Exchange with those on regional stock exchanges. Hasbrouck’s work built on early advances of Garbade and Silber (1983),⁸ and is considered a foundational paper in price discovery research.

In the same year, Gonzalo and Granger (1995)⁹ discussed a method of modeling a common time series by composing each individual series based on its “component weight,” or contribution to the common price. Gonzalo and Granger’s work was extended by many others, including Booth, So, and Tse (1999),¹⁰ Chu, Hsieh, and Tse (1999),¹¹ and Harris, McNish, and Wood (2002).¹² It

⁷ Hasbrouck, J. (1995). One security, many markets: Determining the contributions to price discovery. *The Journal of Finance*, 50(4), 1175-1199.

⁸ Garbade, K.D., and Silber, W.L. (1983). Price movements and price discovery in futures and cash markets, *Review of Economics and Statistics* 65(2), 289-297.

⁹ Gonzalo, J., and Granger, C. (1995). Estimation of common long-memory components in cointegrated systems. *Journal of Business & Economic Statistics*, 13(1), 27-35.

¹⁰ Booth G., So R., Tse Y. (1999). Price discovery in the German equity index derivatives markets. *Journal of Futures Markets*, 19(6), 619-643.

¹¹ Chu QC, Hsieh WG, Tse Y (1999). Price discovery on the S&P 500 index markets: An analysis of spot index, index futures and SPDRs. *International Review of Financial Analysis*, 8(1), 21-34.

¹² Harris F., McNish T., Wood R. (2002). Security price adjustment across exchanges: An investigation of common factor components for Dow stocks. *Journal of Financial Markets*, 5(3), 277-308.

was labeled with the name Component Share (CS) by Yan and Zivot (2010).¹³

It is fairly standard in academic analyses of price discovery to present both IS and CS statistics, since they have slightly different statistical characteristics. We have followed that standard in our own analysis.

Importantly, as the name suggests, IS and CS are presented as “shares” in the literature. When comparing two markets, the IS (CS) assigned to the two markets must sum to 100%. A market is considered to lead price discovery if it has a majority share (>50%) of IS (CS).

Despite the paired nature of IS (CS) values, the convention in the literature is to present only one value in the results tables, leaving the other implied. For instance, a paper examining price discovery between Market A and Market B would only report the IS (CS) share of Market A.

We have followed that convention, only reporting the IS (CS) value of the CME bitcoin futures market, as it is compared to each spot bitcoin trading platform. Therefore, in this document, an IS (CS) value above 50% indicates that the CME bitcoin futures market leads price discovery compared with the bitcoin spot trading platform in question.

B. Bitcoin Markets Literature Review

We conducted a broad literature survey and identified 10 academic and practitioner studies that use IS and/or CS to compare the bitcoin spot market with the CME bitcoin futures market. These papers and core findings are summarized in the table below (a single long horizontal table has been divided here into two parts).

#	Title	Year	Authors
1	Bitcoin futures—What use are they?	2018	Corbet, Lucey, et al.
2	Price discovery in bitcoin spot or futures?	2019	Baur and Dimpfl
3	An analysis of price discovery between bitcoin futures and spot markets	2019	Kapar and Olmo
4	Price discovery, high-frequency trading and jumps in bitcoin markets	2019	Alexander and Heck
5	What role do futures markets play in bitcoin pricing? Causality, cointegration and price discovery from a time-varying perspective	2019	Hu, Hou, and Oxley
6	The development of bitcoin futures: Exploring the interactions between cryptocurrency derivatives	2019	Akyildirim, Corbet, et al.
7	Price discovery in bitcoin futures	2020	Fassas, Papadamou, and Koulis

¹³ Yan, B., and Zivot, E. (2010). A structural analysis of price discovery measures. *Journal of Financial Markets*, 13(1) 1-19.

8	The determinants of price discovery on bitcoin markets	2020	Entrop, Frijns, and Seruset
9	Bitcoin spot and futures market microstructure	2020	Aleti and Mizrach
10	Efficient price discovery in the bitcoin markets	2020	Chang, Herrmann, and Cai

#	Authors	CME IS	CME CS	Intervals	Time Period	Result
1	Corbet, Lucey, et al.	15%	18%	1 min	--	Spot leads
2	Baur and Dimpfl	14%	14%	15 min	12/18/2017 - 10/18/2018	Spot leads
3	Kapar and Olmo	89%	--	1 day	12/18/2017 - 05/16/2018	Futures lead
4	Alexander and Heck	66%	73%	30 min	12/18/2017 - 06/30/2019	Futures lead
5	Hu, Hou, and Oxley	55%	--	1 day	12/18/2017 - 06/16/2019	Futures lead
6	Akyildirim, Corbet, et al.	91-97%	67-87%	1/5/10/15/30/60 min	12/18/2017 - 02/26/2018	Futures lead
7	Fassas, Papadamou, and Koulis	97%	77%	1 hour	01/01/2018 - 12/31/2018	Futures lead
8	Entrop, Frijns, and Seruset	50%	53%	1 min	12/18/2017 - 03/31/2019	Mixed
9	Aleti and Mizrach	53-55%	68-91%	5 min	01/02/2019 - 02/28/2019	Futures lead
10	Chang, Herrmann, and Cai	--	63%	1 min	07/01/2019 - 12/31/2019	Futures lead

As the table indicates, a majority of papers support the notion that the CME bitcoin futures market leads price discovery using IS and/or CS when compared to the bitcoin spot market.

Because the methodologies and findings of each paper are nuanced, it is worth examining each paper in detail.

We begin with papers aligned with the majority opinion that the CME bitcoin futures market leads the bitcoin spot market:

- Kapar and Olmo (2019)¹⁴ was the first paper to assert that, contrary to the two studies that came before it (Corbet et al. (2018)¹⁵ and Baur and Dimpfl (2019)¹⁶), the data “clearly reflect the leadership of the Bitcoin futures markets with respect to the spot market.” The paper attributed 89% of IS to the futures market.

Kapar and Olmo (2019) relies on daily price data, which means the study may not capture intraday information flow. Still, long-run relationships are relevant in holistically describing the relative strength one market has compared with another.

The authors illustrated the importance of long-run relationships, saying, “when the market is in contango we can expect increases in the spot price in the next period. In contrast, when the market is in backwardation, the VECM suggests a fall in spot prices to correct departures from equilibrium.” In other words, the authors found that if there is a gap between the spot and futures price on a given day, the spot price is more likely to correct toward the futures price than vice versa.

- Alexander and Heck (2019)¹⁷ similarly found that there was “strong evidence that both CME and CBOE futures have played the leading role in price discovery.” Unlike Kapar and Olmo (2019), Alexander and Heck (2019) used intraday data with a 30-minute timing interval. Their analysis ran from December 18, 2017 to June 30, 2019, the longest time period among the 10 studies we discovered. It showed that the CME bitcoin futures market led the bitcoin spot market with 66% of IS and 73% of CS during that time.

Interestingly, the authors noted strong price leadership from CME futures during Q2 2019, the last quarter they studied. In fact, Q2 2019 boosted the overall IS from the study from 57% to 66%, and CS from 50% to 73%. This increase in the CME’s contribution to price discovery aligned with significant growth in volume on the CME bitcoin futures market after Q1 2019.¹⁸

¹⁴ Kapar, B., and Olmo, J. (2019) An analysis of price discovery between Bitcoin futures and spot markets. *Economics Letters* (174), 62-64.

¹⁵ Corbet, S., Lucey, B., Peat, M., and Vigne, S. (2018) Bitcoin futures—What use are they? *Economics Letters* (172), 23-27.

¹⁶ Baur, D.G., and Dimpfl, T. (2019) Price discovery in bitcoin spot or futures? *Journal of Futures Markets* (39)7, 803-817.

¹⁷ Alexander, C., and Heck, D. (2019) Price Discovery, High-Frequency Trading and Jumps in Bitcoin Markets. *SSRN Electronic Journal*. <https://doi.org/10.2139/ssrn.3383147>.

¹⁸ The monthly ADV in the CME Bitcoin Futures Market grew from \$60 million in March 2019 to \$230 million in April 2019, according to data from the CME Group. In Q3 2020, the CME Bitcoin Futures market had a \$365 million ADV.

Of note, Alexander and Heck published a second paper, in 2020, titled “Price discovery in bitcoin: The impact of unregulated markets”¹⁹ where the authors highlight the role unregulated futures and perpetual swaps from trading platforms such as Bitmex, Huobi, and OKEx play in the bitcoin market. The analysis involves a complex, multidimensional approach to price discovery analysis conducted across eight different markets and four different exposure types (unregulated futures, regulated futures, perpetual swaps, and spot markets), each with different levels of microstructure friction and data integrity. These complications make it difficult to draw a direct comparison of this paper’s results with the 10 studies included in the table above.

The direct question around whether the CME bitcoin futures market leads or lags price discovery compared to unregulated bitcoin futures trading platforms is explored in detail in Appendix A.

- Hu et al. (2020)²⁰ added to the literature, saying, “What we contribute to this literature here, especially compared to Alexander & Heck (2019), is that we consider price discovery in the Bitcoin futures markets that allow for time-varying approaches,” noting that cointegrating relationships can be interrogated more comprehensively using time-varying approaches.

The authors conclude that, “Bitcoin futures markets dominate the price discovery process using a time-varying version of an information share measure of both the IS and GIS types.” This finding provides additional clarity around the time-dependency of other price discovery analytical results.

- Akyildirim, Corbet, et al. (2019)²¹ conducted its analysis in 5-, 10-, 15-, 30-, and 60-min price data intervals to reach a range of IS and CS outcomes in order to test robustness across different data time intervals. The finding that the CME bitcoin futures market led the bitcoin spot market was consistent across all studied intervals.
- Fassas et al. (2020)²² added another record to the body of literature, finding that CME futures lead the bitcoin spot market, saying, “Our study confirms [the] Akyildirim et al. (2019), Alexander et al. (2019) and Kapar and Olmo (2019) conclusion that bitcoin futures markets, while in their relative youth, have portrayed evidence of price discovery leadership compared to the spot market.” Fassas et al. (2020) arrives at this conclusion

¹⁹ Alexander, C., and Heck, D. (2020). Price Discovery in Bitcoin: The Impact of Unregulated Markets. *Journal of Financial Stability* (50), Article Number 100776.

²⁰ Hu et al. (2020) What role do futures markets play in bitcoin pricing? Causality, cointegration and price discovery from a time-varying perspective. *International Review of Financial Analysis* (72).

²¹ Akyildirim, Corbet, et al. (2020). The development of bitcoin futures: Exploring the interactions between cryptocurrency derivatives. *Finance Research Letters* (34).

²² Fassas et al. (2020) Price discovery in bitcoin futures. *Research in International Business and Finance* (52).

after applying price discovery measures to the entire year of 2018 with hourly price data.

- Aleti and Mizrach (2020)²³ explore the market microstructure of four spot trading platforms (Bitstamp, Coinbase, Kraken, and itBit) and the CME bitcoin futures market over a relatively narrow two-month time period (January 2, 2019 to February 28, 2019). The paper reports separate CME IS values for each of the four spot trading platforms, ranging from 53% versus itBit to 55% versus Bitstamp, and four CME CS values ranging from 68% versus itBit to 91% versus Kraken. All of these tests find that the CME futures led price discovery against each of the spot trading platforms.
- Chang et al. (2020)²⁴ explored a more recent time period (the “second half of 2019”) and found that CME futures led the spot market in price discovery with a CS of 63%.

Of course, we should address the three studies where the authors noted that the spot market led the CME futures market or had mixed results:

- Corbet et al. (2018) is the earliest study examining whether the futures or spot market led in the bitcoin marketplace. It reached the conclusion that the spot market led, with IS and CS values assigned to the futures market of just 15% and 18%, respectively. The time period of the price discovery analysis is not clear from the paper, and it is possible that, being the earliest paper, the period was very short. Akyildirim, Corbet, et al. (2019), a study that shares the same co-author (Corbet) but examines different data sets, arrived at the opposite conclusion, as noted above, determining that the futures market had the dominant share of price discovery. Discussing the difference between the two papers, Akyildirim, Corbet, et al. (2019) notes that Corbet et al. (2018) was based on a shorter time period, and for that reason, could have found a relationship that has since reversed.²⁵
- Baur and Dimpfl (2019) is the other study that found the bitcoin spot markets led the bitcoin futures market. This paper, however, has an important methodological flaw that led the the CME futures contribution to appear artificially low: The authors conducted their price discovery analysis on a per-lifetime-of-each-contract basis, rather than a standard rolling-contract basis.

²³ Aleti, S., and Mizrach, B. (2021) Bitcoin spot and futures market microstructure. *Journal of Futures Markets* (41)2, 194-225.

²⁴ Chang et al. (2020) Efficient price discovery in the bitcoin markets. *Wilshire Phoenix*.

²⁵ Akyildirim, Corbet, et al. (2019) notes that “in contrast to results based on a shorter period as in Corbet et al. (2018a), it appears that as the new cryptocurrency futures markets developed, they presented substantial leadership in price discovery over spot Bitcoin markets.” The view is repeated in the conclusion, which says, “while earlier research found that information flows and price discovery were transmitted from spot to futures markets, this research verifies that this relationship has since reversed, most likely explained by the influx of institutional and sophisticated investors.”

Alexander and Heck (2019) explore this issue extensively, going as far as running a similar per-lifetime-of-each-contract analysis to observe how much lower the futures market contribution can appear, and concluded that, “This apparently leading role of the spot market is not surprising since, during the first few months after the introduction of a contract, there is always another contract with a nearer maturity where almost all trading activity occurs. So any finding that the spot market dominates the price discovery process is merely an artefact of very low trading volumes when the contract is first issued.”

Baur and Dimpfl (2019) acknowledge this issue in their own paper, and run a rolling-futures model of the same analysis for contracts traded on the Cboe, using a fairly standard methodology where the studied contract is rolled over one day prior to maturity. This led to a significantly higher share of price discovery for the Cboe contract, albeit one that still did not dominate the bitcoin spot market. Unfortunately, the authors were not able to do the same analysis for CME futures, noting that the continuous price data approach was “only feasible for the CBOE futures as there are short gaps in our CME data.”

It is not clear why such data gaps existed, as CME data is readily available. Additionally, it is not appropriate to assume that, if the authors had studied a rolling-futures version of the CME analysis, the result would also have aligned with the findings of the rolling-futures version of the Cboe analysis. There were fewer CME bitcoin futures contracts in the data set than in the Cboe data set (four versus seven), and each of the CME contracts had a longer lifetime (or “Sample Period,” as shown in Table 1 of the paper), likely leading to a stronger bias from this methodological flaw.

Therefore, this paper does not actually address the question at hand: whether the CME bitcoin futures market (as a whole) leads price discovery versus the bitcoin spot market.

- Entrop et al. (2020)²⁶ arrives at a mixed result. In aggregate, the paper finds that the CME leads, noting that the futures exchange has an average IS value of 50% and average CS value of 53%. The paper also finds that the CME led price discovery in a majority of months studied, noting, “We find that, on average, the futures market leads the price formation process in 9 (contract) months, while the spot market is the leader in the remaining (6) months.”

The paper, however, does note that the spot market led the CME market in a statistically significant way in the last two months of the study (February and March 2019), and in nonsignificant ways in select other months. These findings led the authors to the claim

²⁶ Entrop, O., Frijns B., Seruset, M. (2020) The determinants of price discovery on bitcoin markets, *The Journal of Futures Markets*, (40)5, 816-837.

that “the leading market has changed.”

It is worth noting that Aleti et al. (2020) and Alexander and Heck (2019) explored price discovery in overlapping time periods and reached a different conclusion.

In summary, the majority of academic and practitioner papers support the view that the CME bitcoin futures market leads price discovery as compared with the bitcoin spot market. Of the 10 papers available in the literature, seven clearly find that the CME leads, and an eighth (Entrop et al. (2020)) has aggregate results in favor of CME leading. Of the two papers that conclude that the spot market leads, one was an early paper that potentially studied a very limited time period (Corbet et al. (2018)) and the other (Baur and Dimpfl (2019)) has an important methodological flaw that limits its applicability to the question at hand.

C. Analytical Methodology

We looked to extend and expand upon the academic literature by conducting a broad analysis of IS/CS price discovery between the CME bitcoin futures market and 10 bitcoin spot trading platforms, including all five trading platforms that contribute prices to the CME CF Bitcoin Reference Rate and five additional trading platforms with significant reported trading volume.

These 10 spot trading platforms were:

- Binance
- Bitfinex
- Bitstamp
- Coinbase
- Gemini
- Huobi
- itBit
- Kraken
- LBank
- OKEEx

We used available trade data, from the inception of the CME bitcoin futures contract on December 18, 2017 through the end of the study on September 30, 2020. Data on spot trading platforms was downloaded from Coin Metrics and CoinAPI.²⁷ Data on CME bitcoin futures was acquired directly from the CME Group.

²⁷ Coin Metrics data was used as the primary data source for all 10 spot trading platforms. CoinAPI data was used only to extend the time period back to December 18, 2017 for four trading platforms (Gemini, Huobi, itBit, and OKEEx) that Coin Metrics did not have full time period coverage for.

We ran our IS/CS analysis using “pdshare,”²⁸ a publicly available software package written in the programming language R, that includes an implementation of IS and CS based on Hasbrouck (1995) and Gonzalo and Granger (1995). We chose to use a publicly available software package to increase the replicability of our research.

We took the following steps to run our analysis:

- Remove trades during non-CME trading hours. This includes removing holidays and weekends.
- For each pair of spot trading platform and CME bitcoin futures, align the price series into 1-second intervals where both platforms have a trade, taking the last traded price of the interval.
- Run pdshare’s IS/CS analysis on each pair of price series, outputting an IS and CS value for each spot platform/futures pair for each day (i.e., the CME bitcoin futures market’s percentage share of IS or CS versus the given spot trading platform for each day).
- Average the daily IS/CS values across the time periods, while running statistical significance tests with a 95% confidence interval.

D. Results

The results of our analysis align with the majority of academic and practitioner research in finding that the CME bitcoin futures market leads all evaluated bitcoin spot trading platforms over the duration of the study. These results are statistically significant for all 10 trading platforms when evaluated from both an IS and a CS perspective.

Here, we present the results in both full time period and monthly formats. The full time period results are commonly how results are presented in academic literature. However, shorter time periods such as the monthly results may be more appropriate given the potential for time variation in the cryptomarket.

Full Period Analysis

The table below shows the IS and CS for the CME versus each of the 10 spot trading platforms averaged across the entire time period of this study (December 18, 2017 to September 30, 2020), along with a 95% confidence interval for those results. The * indicates that the results are statistically significant ($p\text{-value} < 0.05$). Note that all of the IS and CS values and their confidence intervals are above the 50% mark, indicating that CME led all of the 10 spot trading platforms across this time period.

²⁸ <https://rdrr.io/rforge/ifrogs/man/pdshare.html>. More details about the implementation including validation of accuracy can be found here: <https://rdrr.io/rforge/ifrogs/f/inst/doc/pdshare.pdf>.

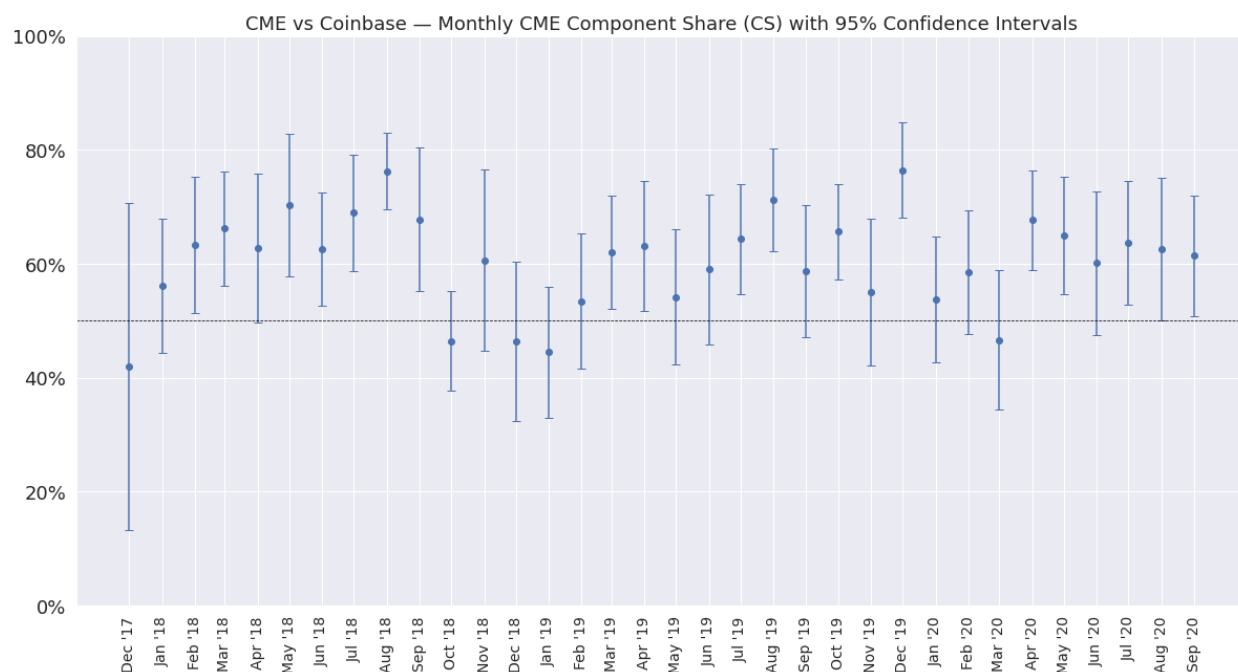
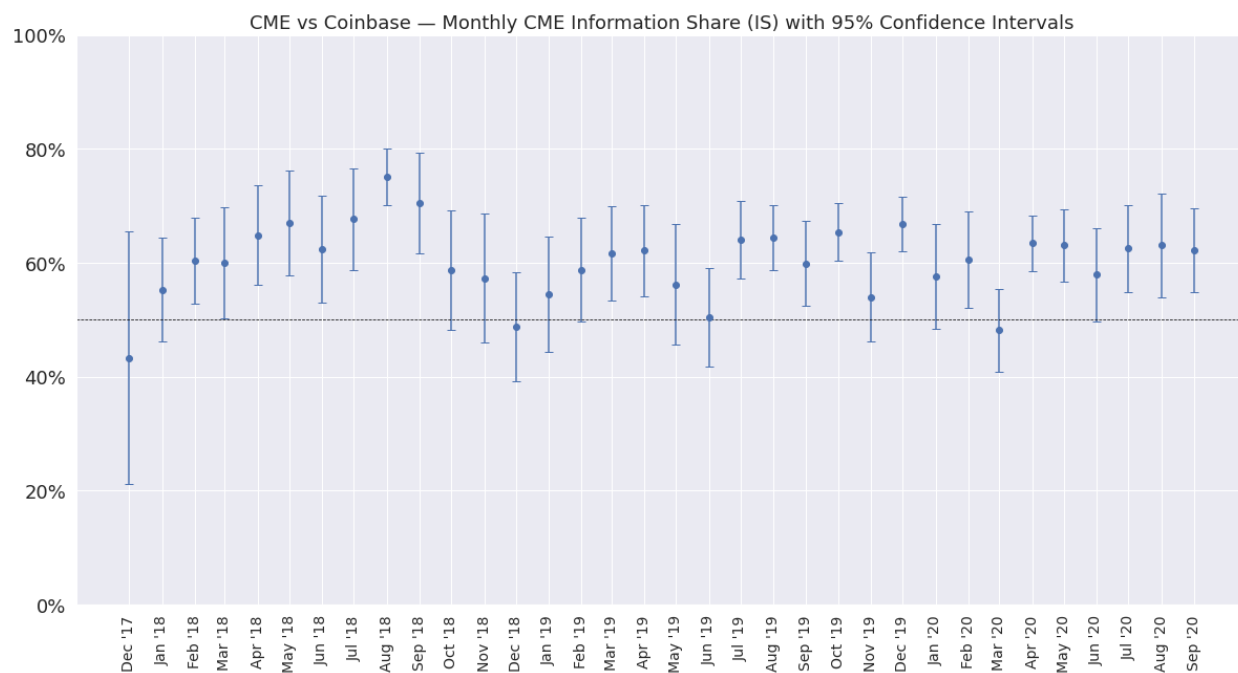
	CME IS	Confidence Interval	CME CS	Confidence Interval
Binance	58.32%*	56.78% - 59.86%	57.38%*	55.45% - 59.32%
Bitfinex	65.75%*	64.22% - 67.29%	65.08%*	63.28% - 66.89%
Bitstamp	64.10%*	62.74% - 65.47%	68.03%*	66.21% - 69.86%
Coinbase	60.60%*	59.20% - 62.00%	60.88%*	58.99% - 62.77%
Gemini	56.44%*	55.03% - 57.84%	56.73%*	54.73% - 58.72%
Huobi	60.91%*	59.34% - 62.49%	58.97%*	56.96% - 60.98%
itBit	53.33%*	51.91% - 54.75%	52.97%*	50.93% - 55.00%
Kraken	63.17%*	61.58% - 64.76%	63.24%*	61.29% - 65.19%
LBank	66.03%*	63.95% - 68.11%	63.51%*	61.34% - 65.68%
OKEx	56.19%*	54.74% - 57.64%	53.60%*	51.73% - 55.47%

Monthly Period Analysis

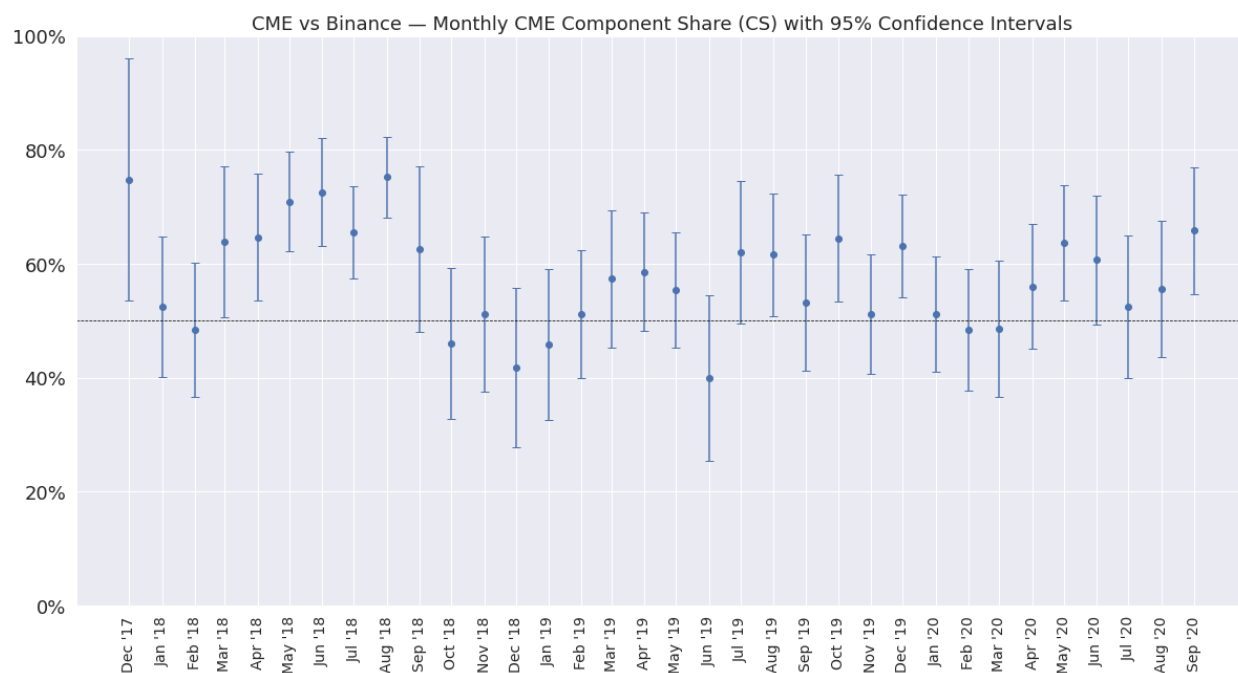
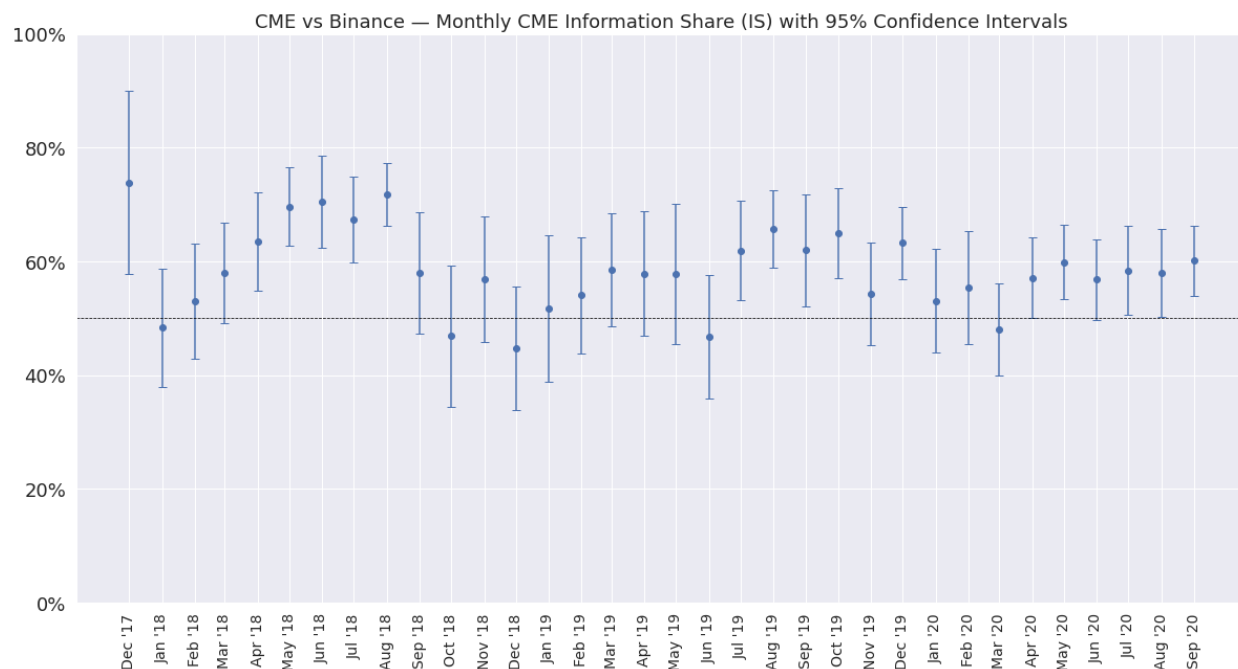
To provide additional context to this finding, we also examined each market on a calendar-month-by-calendar-month basis, as discussed. This calendar-month-segmented approach allows us to evaluate the potential for time variation in price discovery leadership between the CME bitcoin futures market and the bitcoin spot market over shorter periods.

The charts below present this month-by-month data in a graphical format for the CME-Coinbase pair, as one example of the output of this analysis. For each month, the large dot represents the midpoint finding of the analysis (averaged across the findings for each day of the month), or what the literature would generally refer to as the CME's IS or CS value for a given time period (in this case, a month). The confidence bars capture the values contained within a 95% confidence interval.

The results show that the CME has led price discovery versus Coinbase in 31 of 34 months studied (91% of all months) from an IS perspective, and in 29 of 34 months studied (85% of all months) from a CS perspective. The wider confidence intervals versus the full-duration analysis is a matter of statistical power: Monthly analysis incorporates significantly fewer data points than longer periods, and therefore has lower levels of statistical strength. It is worth noting that the month of December 2017 only has nine trading days worth of data, since the CME bitcoin futures market launched on December 18, 2017.



As one would expect, each trading platform generates a slightly different profile and has slightly different results. For instance, the CME versus Binance pair shows that CME led price discovery in 29 of 34 months studied (85% of all months) from an IS perspective, and 27 of 34 months studied (79% of all months) from a CS perspective.



The table below displays the percentage of months that the CME has led price discovery versus each of the 10 evaluated spot trading platforms since the launch of the CME bitcoin futures contract in December 2017. The exact numbers vary by exchange, but on average, CME has led spot trading platforms from an IS perspective in 90% of evaluated months, and from a CS perspective in 81% of evaluated months. Month-by-month IS and CS charts are available for

each of the 10 trading platforms versus the CME in Appendix B.

	% of Months CME Led IS	% of Months CME Led CS
Binance	85%	79%
Bitfinex	94%	91%
Bitstamp	94%	91%
Coinbase	91%	85%
Gemini	82%	76%
Huobi	94%	84%
itBit	79%	62%
Kraken	94%	91%
LBank	90%	80%
OKEX	85%	65%
Average	89%	80%

Taken together, these findings support the notion that the CME leads price discovery compared with the bitcoin spot market, and that leadership is generally persistent across the full time period.

V. Time-Shift Lead-Lag Analysis

The other popular academic approach to investigating market leadership is time-shift lead-lag analysis (TSLL). Time-shift lead-lag analysis is an attempt to find the direction and length of the lead-lag relationship between two price series that maximizes the predictive strength of one price series against another.

The analysis is performed by shifting one price series forward or backward in time relative to another series and calculating the cross-correlation between the two series. This shifting is repeated for many different lag periods to see which amount of lag of one price series results in the highest cross-correlation between the two price series. The amount of lead or lag that results in the highest cross-correlation is referred to as “lead-lag time” in the literature.

A. Academic Overview

The literature on how to conduct lead-lag analysis has evolved over time. Initially, cross-correlations were calculated based on time series with price observations made at specific intervals. This is called the “synchronous” approach. Later, a “non-synchronous” approach was developed. The non-synchronous approach does not use fixed sampling intervals; rather, it uses all tick-by-tick price observations from each time series without matching up intervals in a time-rigid fashion.

Early research using time-shift lead-lag analysis, such as de Jong and Nijman (1997),²⁹ described the synchronous approach, using fixed sampling intervals (such as one price every 10 minutes). The paper was one of the first to extensively explore lead-lag relationships between financial markets by calculating synchronous cross-correlations on leads and lags of different time series. It focused on the relationship between the S&P 500 Index and S&P 500 futures. The paper determined that, at all chosen intervals (10 minutes, 5 minutes, and 1 minute), futures returns led index returns.

The non-synchronous approach was proposed in Hayashi and Yoshida (2005)³⁰ to address concerns that “the choice of regular interval size and data interpolation scheme (in the synchronous approach) may lead to unreliable estimation ... and bias...” Hayashi-Yoshida has become the dominant (but not exclusive) paradigm for conducting this type of analysis.

²⁹ de Jong, F., and Nijman, T. (1997) High frequency analysis of lead-lag relationships between financial markets. *Journal of Empirical Finance* (4)2-3, 259-277.

³⁰ Hayashi, T., and Yoshida, N. (2005) On covariance estimation of non-synchronously observed diffusion processes. *Bernoulli* 11(2), 359-379.

Hoffmann, Rosenbaum, and Yoshida (2013)³¹ extended the Hayashi-Yoshida cross-correlation function by describing how to apply it to leads and lags of one time series against another to determine the lead-lag time between the two time series.

Alsayed and McGroarty (2014)³² applied the Hayashi-Yoshida cross-correlation function to identify lead-lag relationships between S&P 500, FTSE 100, and DAX futures contracts. They also confirmed that the non-synchronous approach was more robust in avoiding data errors compared with the synchronous approach.

B. Bitcoin Markets Literature Review

Schei (2019)³³ applied the Hayashi-Yoshida cross-correlation function to determine the lead-lag relationship between various spot trading platforms. Schei looked at trades on Binance, Bitfinex, Bitstamp, Coinbase, HitBTC, Poloniex, and Kraken during 2018. He found that low-volume exchanges (Poloniex and Kraken) tended to lag higher-volume exchanges (Bitfinex, Binance, Bitstamp, and Coinbase). Schei also found that similar volume exchanges showed weaker lead-lag relationships, such as between Bitstamp and Bitfinex.

Schei did not evaluate the lead-lag relationship between the bitcoin spot and bitcoin futures markets. In fact, while the TSSL technique has been used to compare spot and futures relationships in multiple asset classes, as discussed above, this study is the first to apply this technique to the bitcoin spot and bitcoin futures markets.

C. Analytical Methodology

We analyzed the TSSL relationship between the CME bitcoin futures market and the same 10 bitcoin spot trading platforms we evaluated using IS/CS price discovery analysis, including all five trading platforms that contribute prices to the CME CF Bitcoin Reference Rate and five additional trading platforms with significant reported trading volume.

We used available trade data from the inception of the CME bitcoin futures contract on December 18, 2017 through the end of the study on September 30, 2020. Data on spot trading

³¹ Hoffmann, M., Rosenbaum, M., Yoshida, N. (2013) Estimation of the lead-lag parameter from non-synchronous data. *Bernoulli*, 19(2), 426-461.

³² Alsayed, H., and McGroarty, F. (2014) Ultra-high-frequency algorithmic arbitrage across international index futures. *Journal of Forecasting*, 33(6), 391-408.

³³ Schei, B. (2019) High frequency lead-lag relationships in the bitcoin market (unpublished master's thesis). Copenhagen Business School, Copenhagen, Denmark.

platforms were downloaded from Coin Metrics and CoinAPI.³⁴ Data on CME bitcoin futures was acquired directly from the CME Group.

We ran our TSLL analysis using “lead-lag,”³⁵ a publicly available open source implementation of TSLL written in the programming language Python based on Hoffmann, Rosenbaum, and Yoshida (2013).

We took the following steps to run our analysis:

- Remove trades during non-CME trading days. This includes removing holidays and weekends.
- Remove zero-return trades (trades with the same price as the previous trade) from the price series, consistent with the procedure used by Huth and Abergel (2014)³⁶ and Alysayed and McGroarty (2014).
- For each pair of spot trading platform and CME bitcoin futures, run TSLL analysis for each day, shifting the lag time from -60 seconds to +60 seconds in 0.2 second increments. Find the lead-lag time (LLT) that produces the highest cross-correlation.
- Average the daily lead-lag time across the full time period, while running statistical significance tests with a 95% confidence interval.

D. Results

The results of our TSLL analysis align with the results of our IS/CS analysis and demonstrate that the CME bitcoin futures market leads all evaluated spot trading platforms over the duration of the study.

Here, again, we present the results in both full time period and monthly formats. The full time period results are commonly how results are presented in academic literature. However, shorter time periods such as the monthly results may be more appropriate given the potential for time variation in the cryptomarket.

Full Period Analysis

The table below shows the lead-lag time (the amount of lead or lag that results in the highest cross-correlation between two price series) for the CME versus each of the 10 spot trading platforms, calculated daily, and averaged across the entire time period of this study (December

³⁴ Coin Metrics data was used primarily for all 10 spot trading platforms. CoinAPI data was used only to extend the time period back to December 18, 2017 for four trading platforms (Gemini, Huobi, itBit, and OKEx) that Coin Metrics did not have full time period coverage for.

³⁵ <https://github.com/philipperemy/lead-lag>.

³⁶ Huth, N., and Abergel, F. (2014) High frequency lead/lag relationships: Empirical facts. *Journal of Empirical Finance* (26), 41-58.

18, 2017 to September 30, 2020). It also shows the 95% confidence interval for those results. A positive value indicates the CME leading by that amount of seconds. A negative value would indicate CME lagging. The * indicates the result being statistically significant (p-value < 0.05), meaning the lead-lag time for the entire time period lies squarely within the positive (or negative) value territory.

	Lead-Lag Time (seconds)	Confidence Interval (seconds)
Binance	7.28*	6.53 - 8.03
Bitfinex	9.03*	8.33 - 9.73
Bitstamp	6.52*	5.96 - 7.08
Coinbase	8.42*	7.65 - 9.18
Gemini	6.51*	5.91 - 7.11
Huobi	7.57*	6.96 - 8.18
itBit	8.63*	7.89 - 9.37
Kraken	17.19*	16.00 - 18.38
LBank	16.62*	15.37 - 17.87
OKEx	8.27*	7.41 - 9.13

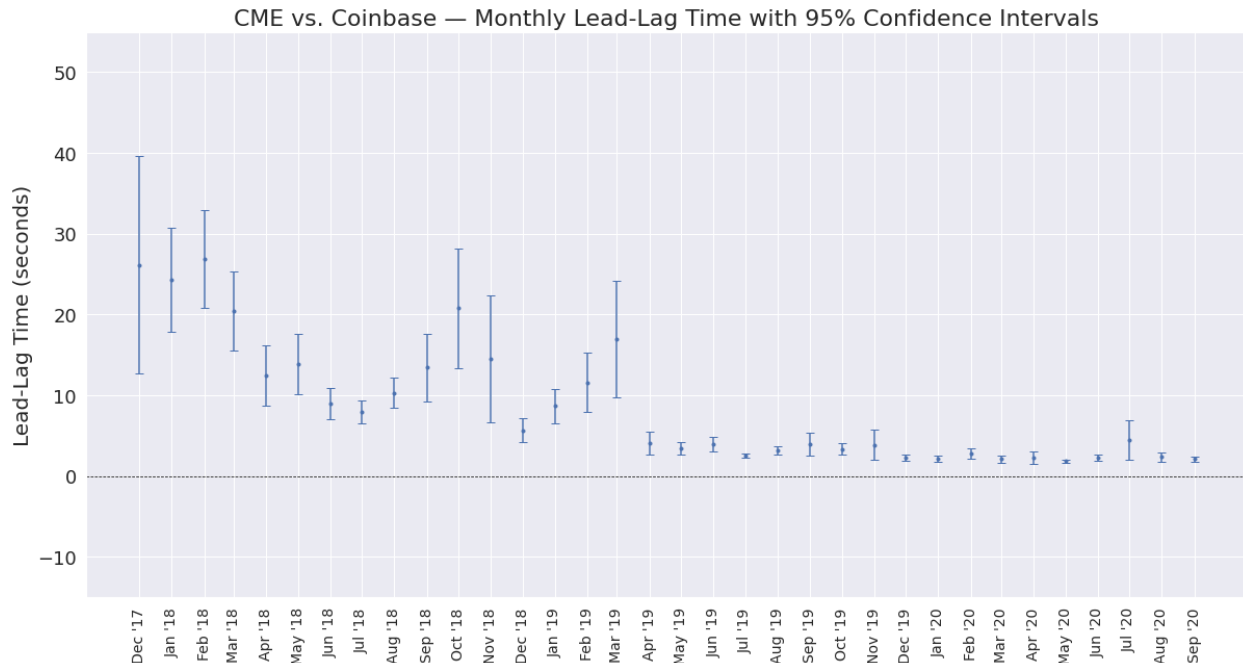
The lead-lag times vary slightly by platform, but are all contained within a positive value band of 6.51 - 17.19 seconds, indicating CME leading. All results are statistically significant.

Monthly Period Analysis

To provide additional context to this finding, we also examined each market on a calendar-month-by-calendar-month basis, as we did with our IS/CS analysis. This calendar-month-segmented approach allows us to evaluate the potential for time variation in price leadership between the CME bitcoin futures market and the bitcoin spot market over shorter periods, using the TSSL approach.

The chart below presents this month-by-month data in a graphical format for the CME-Coinbase pair, as one example of the output of this analysis. For each month, the dot represents the midpoint finding of the analysis (averaged across the findings for each day of the month), or what literature would generally refer to as the lead-lag time value for a given time period. The confidence bars capture the values contained within a 95% confidence interval.

The results show that the CME led Coinbase from a TSSL perspective in all 34 of the 34 months studied (100% of all months). Additionally, the results were statistically significant for all 34 of 34 months studied (100% of all months).

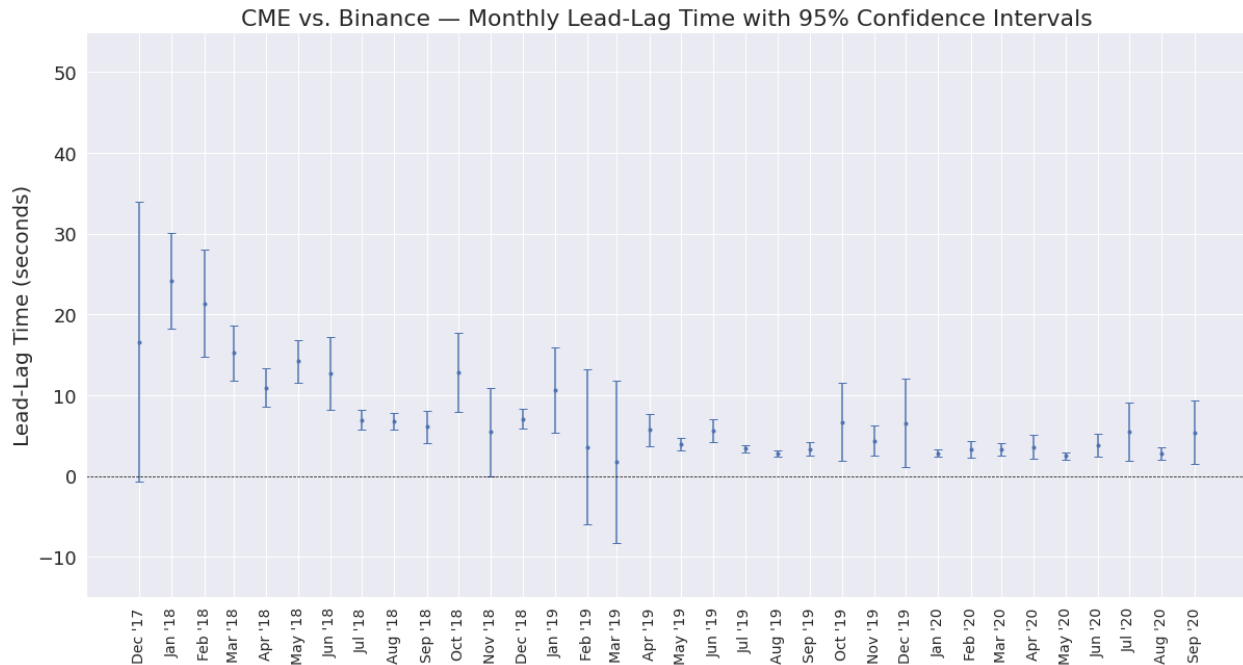


The chart displays a notable pattern, which is repeated in other trading platform pairs: The CME’s “lead” versus Coinbase starts out long, with wide confidence bands, and then tightens over time and becomes more consistent.

For instance, the average monthly lead-lag time for CME versus Coinbase from December 2017 through March 2019 is 15.18 seconds, and the confidence interval span is from 2.84 seconds to 26.87 seconds. By comparison, from April 2019 through September 2020, the average monthly lead-lag time is 2.94 seconds, and the confidence interval span is from 0.27 seconds to 4.85 seconds.

As one would expect, each trading platform generates a slightly different profile and has slightly different results. For instance, the CME versus Binance pair also shows the CME has led price discovery in all 34 of 34 months studied (100% of all months), but with different exact lead times. The result is statistically significant in 30 of 34 months studied (88% of all months).

The results show the same general trend as the CME versus Coinbase pair, although in a more muted fashion: starting wide, with the relationship tightening and becoming more consistent over time.



Month-by-month TSLL analysis results for the remaining eight evaluated spot trading platforms are available in Appendix C. They share Coinbase’s and Binance’s results in that the CME leads consistently across an overwhelming majority of months.

Taken together, the results of our TSLL analysis support the conclusion of our IS/CS analysis, showing that the CME bitcoin futures market leads each of the 10 evaluated spot trading platforms in a statistically significant manner over the duration of the study.

VI. Conclusion

This study extends and improves upon prior literature by conducting a detailed survey and analysis of academic and practitioner papers in the space, running a validation of the data feeds, incorporating a longer period of time, and using multiple statistical techniques to evaluate the relationship between the CME bitcoin futures market and the bitcoin spot market.

The results show that the CME bitcoin futures market leads the bitcoin spot market in a significant fashion:

1. **Academic and Practitioner Literature:** The majority of academic and practitioner studies conclude that the CME bitcoin futures market leads the bitcoin spot market.
2. **IS/CS Price Discovery Analysis:** The CME bitcoin futures market has the dominant share of price discovery when compared with each of the 10 evaluated bitcoin spot trading platforms using both information share (IS) and component share (CS).
3. **TSSL Analysis:** The CME bitcoin futures market has led each of the 10 evaluated bitcoin spot trading platforms using time-shift lead-lag analysis over the duration of the study.

We therefore conclude that the CME bitcoin futures market is the dominant source of price discovery when compared with the bitcoin spot market, and that prices on the CME bitcoin futures market lead prices on bitcoin spot markets.

These findings are, perhaps, unsurprising. Futures markets often lead price discovery when compared to spot markets. As described in papers like Garbade and Silber (1983),³⁷ Chan (1992),³⁸ and Fleming et al. (1996),³⁹ futures benefit from leverage, lower transaction costs, and access to short exposure. In addition, in the bitcoin market, the regulated nature of the CME bitcoin futures market may attract more professional investors than unregulated spot markets. These professional investors may have advantages over retail investors from an available capital, technology, information flow, and trading speed perspective. Such conditions may be expected to continue into the future, particularly as we see continued and expanded adoption of bitcoin as an investable asset by professional and institutional investors.

³⁷ Garbade, K. and Silber, W. (1983). Price movements and price discovery in futures and cash markets. *The Review of Economics and Statistics* 65(2), 289-297.

³⁸ Chan, K. (1992). A further analysis of the lead-lag relationship between the cash market and stock index futures market. *The Review of Financial Studies* (5)1, 123-152.

³⁹ Fleming et al. (1996). Trading costs and the relative rates of price discovery in stock, futures, and option markets. *Journal of Futures Markets* 16(4), 353-387.

Appendix A. Examining Lead-Lag Relationships Between The Unregulated Bitcoin Futures Trading Platforms And The CME Bitcoin Futures Market

Introduction

Investors and traders have multiple ways of accessing the bitcoin market, including spot trading platforms like Coinbase, regulated futures markets like the CME bitcoin futures market, and unregulated futures trading platforms like BitMEX.

In the main body of this paper, we demonstrated that the regulated CME bitcoin futures market leads price discovery compared to the largest bitcoin spot trading platforms. In this Appendix, we turn our attention to unregulated bitcoin futures trading platforms, and determine where price discovery occurs between those platforms and the CME.

Getting Started: The Selection of Unregulated Futures Trading Platforms And Contracts For Analysis

The goal of our analysis was to determine whether price discovery on the CME bitcoin futures market leads or lags relative to unregulated bitcoin futures trading platforms. We began our analysis by gathering general market data on unregulated futures trading platforms from CoinGecko, a popular crypto data provider that maintains an extensive list of unregulated bitcoin futures trading platforms and their futures contracts⁴⁰.

The site tracks two categories of contracts: perpetual futures and quarterly futures. Perpetual futures are cash-settled futures that do not have an expiration date, while quarterly futures settle on a calendar basis and must be rolled forward to maintain exposure. Aggregating these two categories generated a list of 33 unregulated bitcoin futures trading platforms. We elected to evaluate the seven largest markets, which accounted for approximately 80% of all open interest and included the most recognized names in the unregulated bitcoin futures market: Binance, BitMEX, Bybit, Deribit, FTX, Huobi, and OKEx.⁴¹

Because some platforms offer both perpetual and quarterly contracts, on each platform, we selected the contract type with the highest level of open interest: Perpetuals for Binance, BitMEX, Bybit, Deribit, and FTX, and quarterlies for Huobi and OKEx.

We pulled data on these contracts from CoinMetrics and CoinAPI, the same data providers used in our spot market analysis. Data on the CME bitcoin futures contract was pulled directly from the CME.

⁴⁰ <https://www.coingecko.com/en/coins/bitcoin#markets>. Navigate to the “Perpetuals” (perpetual futures) and “Futures” (predominantly quarterly futures) sub tabs within the “Markets” tab.

⁴¹ Data as of May 4, 2021.

We used the full period of data available for each unregulated trading platform. The data start month for each trading platform was:

- Binance: September 2019
- BitMEX: December 2017⁴²
- Bybit: October 2019
- Deribit: August 2018
- FTX: July 2019
- Huobi: August 2019
- OKEEx: October 2018

The study ran through the end of Q1 2021.

For both CME's monthly contract and the Huobi and OKEEx's quarterly contracts, we followed the same technique used in our spot market analysis to create a continuous price series for analysis, rolling contracts one day prior to expiration.

Important Context Regarding The Unregulated Bitcoin Futures Trading Platforms

Unregulated bitcoin futures trading platforms may be less familiar to casual market observers than either the spot bitcoin trading platforms or the regulated CME bitcoin futures market. It may be helpful, therefore, to provide context on the relative size, volume, and functioning of these markets before we proceed to our statistical analysis.

The table below highlights three key statistics for the highest open interest contract on each of the evaluated trading platforms for the month of May 2021: Open Interest, Trading Volume, and Required Margin. The CME row is highlighted in light blue.

	Open Interest	Trading Volume	Required Margin
Bybit	\$1,666,878,515	\$7,438,356,443	1%
Binance	\$1,575,326,903	\$21,718,058,270	<1%
CME	\$1,404,125,298	\$1,840,129,468	33%
FTX	\$1,232,139,553	\$4,423,394,792	1%
OKEEx	\$842,460,775	\$2,112,965,793	<1%
Huobi	\$680,431,607	\$5,823,998,157	<1%

⁴² BitMEX was the only platform that existed and has data available from the inception of the CME bitcoin futures market on December 17, 2017. OKEEx claims to have launched bitcoin futures trading as early as June 2013, but historical data for OKEEx is not available before October 2018. Binance, Bybit, Deribit, FTX, and Huobi all launched bitcoin futures trading after the inception of the CME bitcoin futures market, between 2018 and 2019.

BitMEX	\$664,421,615	\$2,656,967,907	1%
Deribit	\$599,004,598	\$1,264,134,910	1%

Three factors jump out from the table:

1. **Open Interest:** Open interest reflects the notional value of outstanding contracts and is a common way to judge the size of a futures market. In this table, open interest at the end of each trading day was averaged across the month of May 2021. The largest contract (Bybit's perpetuals) had \$1.67 billion in average open interest in May, while the smallest contract (Deribit's perpetuals) had \$600 million. The CME contract ranked third in this list, with \$1.40 billion in average open interest.
2. **Trading Volume:** Trading volume reflects the notional value traded in a given contract on each trading day averaged across the month of May 2021. The dispersion of trading volume statistics here is much wider than the dispersion of open interest: The most traded contract (Binance's perpetuals) reported \$21.72 billion in average daily trading volume in May, while the least traded contract (Deribit's perpetuals) reported \$1.26 billion. The CME contract ranked seventh by trading volume, at \$1.84 billion.⁴³
3. **Required Margin:** The required margin statistic highlights the major difference in potential leverage between the regulated CME market and the unregulated bitcoin futures trading platforms. The evaluated unregulated bitcoin futures trading platforms offer clients leverage at ratios ranging from 100-to-1 to 125-to-1⁴⁴, meaning required margin is 1% or less of the notional value of open contract positions. By comparison, the maximum leverage ratio on the CME bitcoin futures market is 3-to-1, meaning a 33% required margin ratio.⁴⁵

The last point is of particular interest. While traders on a given platform do not always make use of the full amount of potential leverage, industry reports suggest that the level of realized leverage on unregulated futures trading platforms is high. For instance, a 2019 report from BitMEX found that the average level of realized leverage on that platform for the year ending April 2019 was approximately 27-to-1, meaning an average maintained margin of less than 4%.⁴⁶

⁴³ Note that both trading volume and open interest statistics are self-reported. While most observers have a high degree of confidence in the data reported by regulated exchanges like the CME, the same cannot be said for market statistics self-reported by unregulated futures trading platforms.

⁴⁴ As of May 31, 2021, BitMEX, Bybit, Deribit offered 100-to-1 leverage, FTX offered 101-to-1 leverage, and Binance, Huobi and OKEx offered 125-to-1 leverage, according to each trading platform's website.

⁴⁵ <https://www.cmegroup.com/trading/equity-index/us-index/bitcoin.html>.

⁴⁶ <https://blog.bitmex.com/bitmex-leverage-statistics-april-2019/>

The high leverage ratios offered by unregulated bitcoin futures trading platforms mean that, at any given moment, the amount of capital committed to any one of these unregulated futures contracts is likely significantly lower than the amount of capital committed to the CME bitcoin futures contract.

As a hypothetical example, assuming an average margin of 4% (i.e., 25-to-1 leverage), the amount of capital backing the \$7.26 billion in aggregate open interest across the seven unregulated futures contracts can be estimated at \$363 million. By comparison, assuming a 33% margin (the minimum required), the capital backing the \$1.40 billion of open interest on the CME bitcoin futures contract is at least \$462 million. In other words, it is very possible that the amount of capital committed to the CME bitcoin futures contract is larger than the capital committed to all of the evaluated unregulated futures contracts, combined.

It is also worth noting that all evaluated unregulated bitcoin futures contracts have a higher ratio of trading volume to open interest than the CME bitcoin futures contract. This difference could be indicative of different styles of trading: highly levered short-term trades with frequent opening and closing of positions versus less levered longer-term trades with lower turnover.

The question of which style of trading and/or which features of a market are more important for price leadership is interesting. In the following section, we examine whether the CME bitcoin futures market or the unregulated bitcoin futures trading platforms leads price discovery using established statistical techniques..

Methodology and Results

To determine whether the CME bitcoin futures market leads or lags price discovery compared to unregulated bitcoin futures trading platforms, we applied the same statistical tests that we did when comparing the CME to bitcoin spot trading platforms: Information Share/Component Share analysis (IS/CS) and Time-Shift Lead-Lag analysis (TSLL).

IS/CS Analysis

The table below shows the results of our IS and CS analysis comparing the CME with each of the seven unregulated bitcoin futures trading platforms over the duration of our study. Each unregulated futures trading platform evaluation has its own date range, based on the length of data available for each trading platform.

IS and CS values above 50% indicate that the CME led price discovery against a given unregulated futures trading platform over the duration of the study period. A * indicates that the results are statistically significant (p-value < 0.05). We have also included a 95% confidence

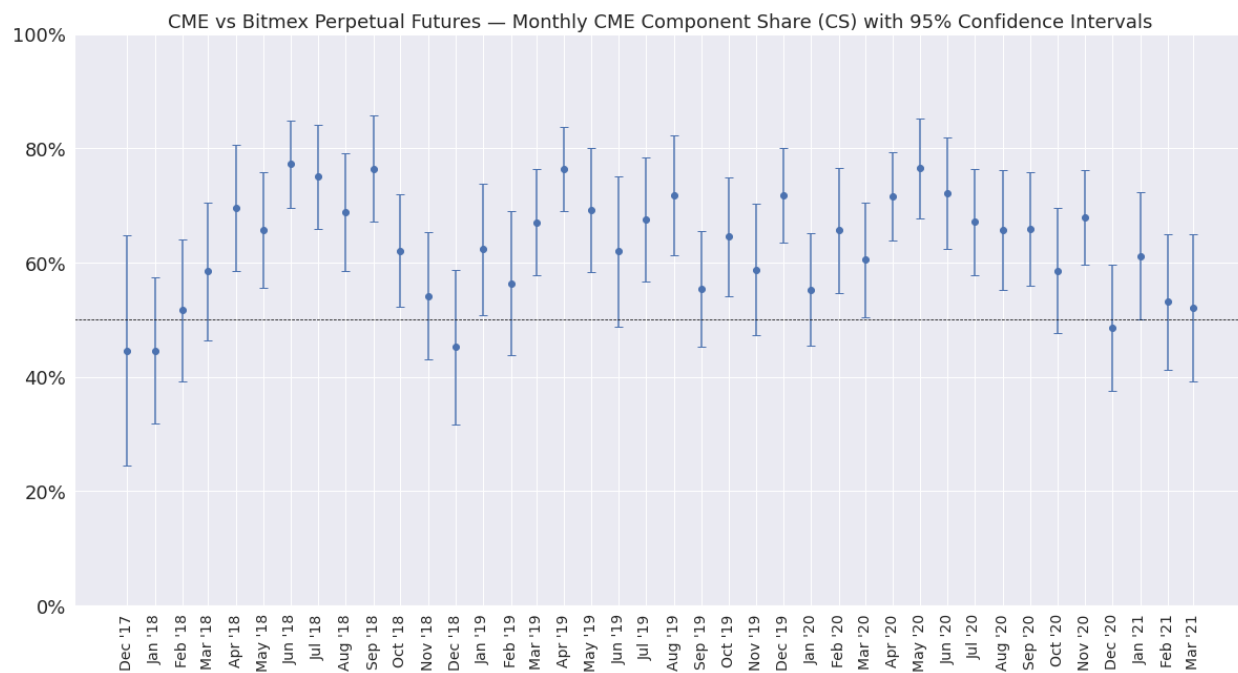
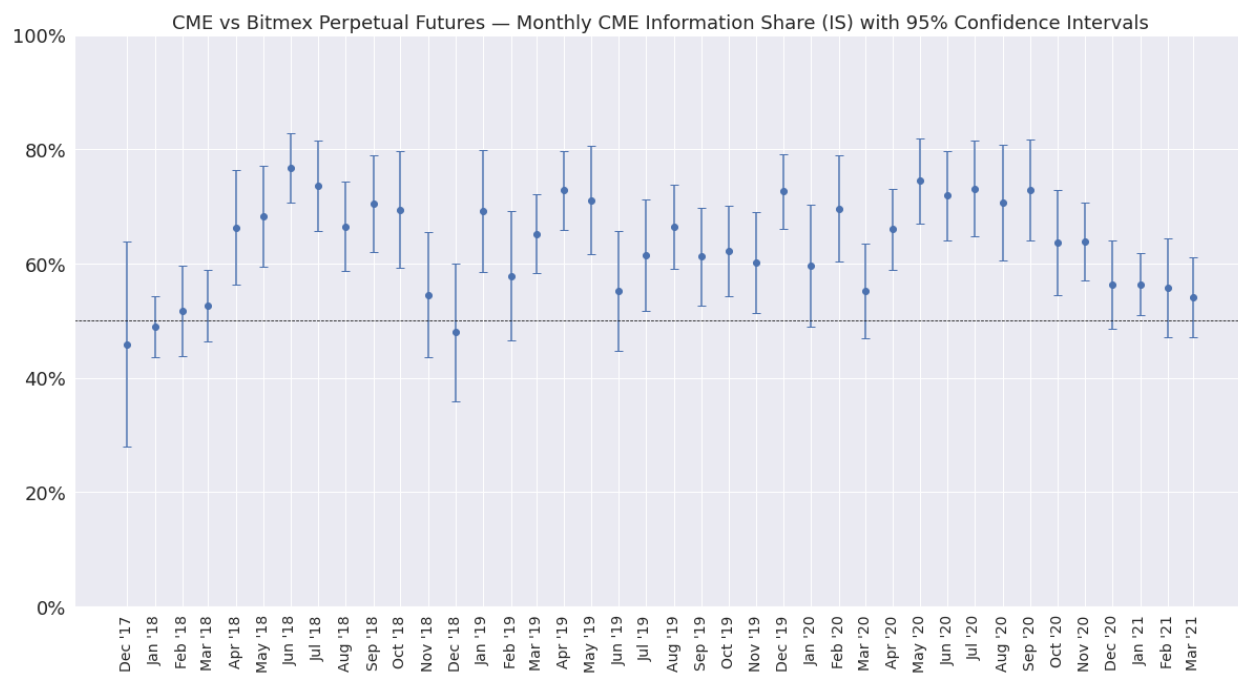
interval for the results to provide further context.

The results show that the CME has led price discovery against each of the seven unregulated trading platforms across the duration of the study. The results are statistically significant for all platforms when evaluated from an IS perspective, and for six of seven platforms from a CS perspective.

	CME IS	Confidence Interval	CME CS	Confidence Interval	Data Range
Binance	55.30%*	53.64% - 56.96%	54.01%*	51.41% - 56.61%	Sept 2019 - Mar 2021
BitMEX	63.67%*	62.30% - 65.04%	63.33%*	61.68% - 64.99%	Dec 2017 - Mar 2021
Bybit	61.50%*	59.69% - 63.30%	60.26%*	57.75% - 62.77%	Oct 2019 - Mar 2021
Deribit	56.91%*	55.56% - 58.26%	56.20%*	54.23% - 58.17%	Aug 2018 - Mar 2021
FTX	56.73%*	55.13% - 58.32%	58.72%*	56.33% - 61.10%	July 2019 - Mar 2021
Huobi	55.25%*	53.33% - 57.17%	53.85%*	51.36% - 56.33%	Aug 2019 - Mar 2021
OKEx	53.04%*	51.45% - 54.63%	51.22%	49.14% - 53.31%	Oct 2018 - Mar 2021

To add greater context to this full duration analysis, we also examined the results for each unregulated futures trading platform on a month-by-month basis. The chart below showcases those findings for the CME-BitMEX pair, as the longest data range example; the IS/CS results for all other unregulated futures trading platforms are available at the end of Appendix B.

For each month, the dot represents the midpoint finding averaged across the findings for each day of the month, or what the literature would generally refer to as the CME's IS or CS value for the given month. Dots that appear above the black horizontal line at the 50% mark show that the CME led price discovery for that month, while dots below the 50% mark show that BitMEX led. Confidence bars capture a 95% confidence interval.



The results show that the CME led price discovery versus BitMEX in 37 of 40 months studied (93% of all months) from an IS perspective, and 36 of 40 months (90%) from a CS perspective. The results are statistically significant in a majority of months.

The wider confidence intervals versus the full duration analysis is a matter of statistical power: Monthly analysis incorporates significantly fewer data points than the full study period, and therefore has lower levels of statistical strength.

Other trading platform pairs show similar results. The table below shows the percentage of months that the CME led IS/CS price discovery against each trading platform:

	% of Months CME Led IS	% of Months CME Led CS	Data Range
Binance	84%	74%	Sept 2019 - Mar 2021
BitMEX	93%	90%	Dec 2017 - Mar 2021
Bybit	100%	94%	Oct 2019 - Mar 2021
Deribit	88%	78%	Aug 2018 - Mar 2021
FTX	90%	95%	July 2019 - Mar 2021
Huobi	85%	70%	Aug 2019 - Mar 2021
OKEx	73%	60%	Oct 2018 - Mar 2021

These monthly results support the conclusion of our full duration analysis in finding that the CME bitcoin futures market leads each of the seven unregulated bitcoin futures trading platforms from an IS and CS perspective.

TSSL Analysis

In addition to our IS/CS analysis, we also examined the CME bitcoin futures market versus the unregulated bitcoin futures trading platforms using Time-Shift Lead-Lag (TSSL) analysis. TSSL analysis is a more intuitive approach to analyzing price discovery, using cross-correlation measures to determine which of two price series “leads” the other from a time-ordered perspective: i.e., are the prices on one platform ahead or behind prices on the other platform more frequently.

The results of our TSSL analysis align with the results of our IS/CS analysis in finding that the CME bitcoin futures market leads all evaluated unregulated bitcoin futures trading platforms over the duration of the study. The results are statistically significant for all seven evaluated trading platforms.

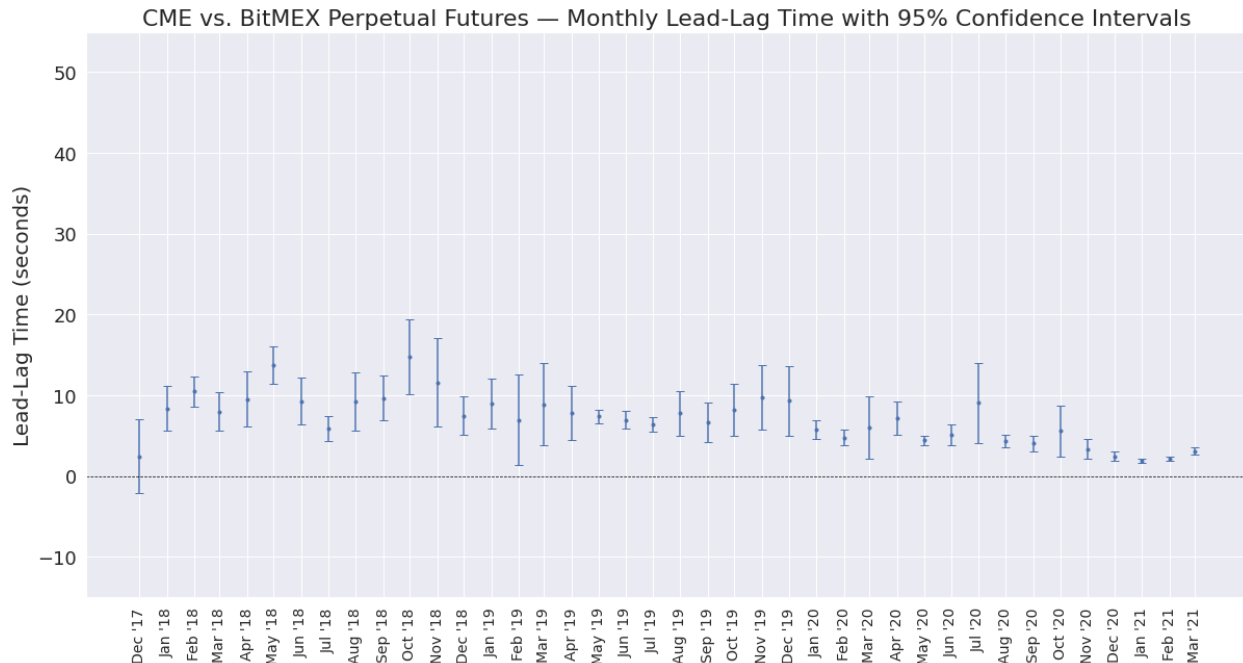
The table below shows the lead-lag time (the amount of lead or lag that results in the highest cross-correlation between two price series) for the CME versus each of the seven unregulated bitcoin futures trading platforms, calculated daily and averaged across the entire time period. The table also shows the 95% confidence interval for those results.

A positive value indicates the CME leading by that amount of seconds. A negative value would indicate CME lagging. The * indicates the result being statistically significant (p-value < 0.05), meaning the lead-lag time for the entire time period lies squarely within the positive (or negative) value territory.

	Lead-Lag Time (seconds)	Confidence Interval (seconds)	Data Range
Binance	3.07*	2.50 - 3.65	Sept 2019 - Mar 2021
BitMEX	7.23*	6.76 - 7.70	Dec 2017 - Mar 2021
Bybit	5.13*	4.56 - 5.70	Oct 2019 - Mar 2021
Deribit	4.98*	4.47 - 5.49	Aug 2018 - Mar 2021
FTX	2.27*	2.08 - 2.46	July 2019 - Mar 2021
Huobi	2.34*	2.21 - 2.47	Aug 2019 - Mar 2021
OKEx	3.47*	2.94 - 4.00	Oct 2018 - Mar 2021

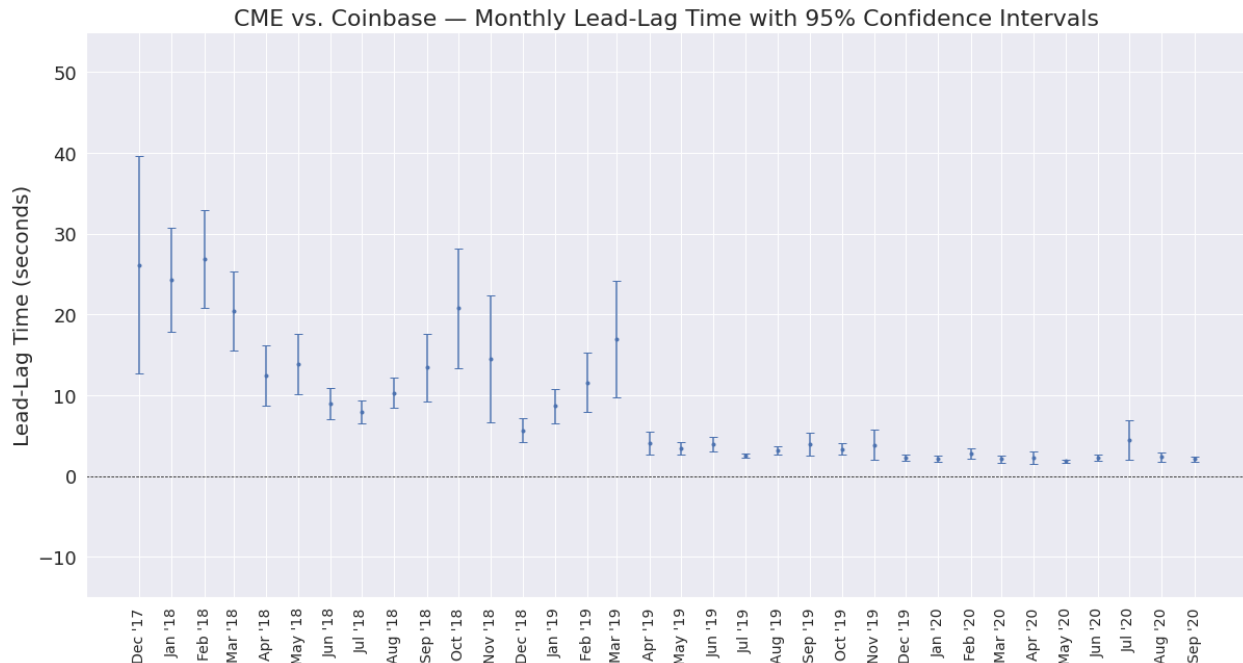
The results show that prices on the CME generally led prices on unregulated bitcoin futures trading platforms by 2-7 seconds.

To add context, we also evaluated each platform on a month-by-month basis, as we did with IS/CS. The chart below shows the results for the CME-BitMEX pair, as the longest data range example; the TSLR results for all other unregulated futures trading platforms are available at the end of Appendix C.



The results show that the CME led BitMEX from a TSSL perspective in all 40 of 40 months studied (100% of all months). The results were statistically significant for 39 of 40 months studied (98% of all months).

The lead-lag relationship between the CME and BitMEX does not follow the pattern seen in TSSL charts between the CME and spot platforms where the CME leads by a large number of seconds in the early part of the study, with that lead time shortening substantially after Q1 2019. You can see that pattern, for instance, in the chart below comparing the CME and Coinbase.



The CME-BitMEX chart does not follow this pattern. This may be related to the prolonged bear market that occurred during the early period of our study, ending in Q1 2019. After all, spot trading platforms like Coinbase and futures trading platforms like BitMEX differ in the types of exposure they provide: Spot trading platforms primarily facilitate long exposure, while futures trading platforms allow traders to go both long and short. This difference could be the reason why BitMEX diverged and lagged from the CME less compared to spot trading platforms such as Coinbase during the prolonged bear market.

Regardless, however, in both CME-BitMEX and CME-Coinbase, the CME bitcoin futures market consistently leads price discovery throughout the study period, and does so in a statistically significant manner.

Conclusion

In this appendix, we used established statistical techniques also used in the main body of the paper to determine where price discovery occurs between seven unregulated bitcoin futures trading platforms and the regulated CME bitcoin futures market. The results demonstrate that the CME has led each of the seven unregulated futures trading platforms over the duration of our study, and has done so in most instances in a statistically significant manner.

These results may surprise some observers given the high notional trading volume statistics reported by unregulated entities. These volume statistics, however, must be understood in the context of other important measures of market size, including open interest and capital-at-risk.

Viewed from these perspectives, unregulated bitcoin futures markets appear similar or smaller than the regulated CME bitcoin futures market.

The question this study answered is an interesting one: Whether highly leveraged, unregulated platforms dominated by day-traders can lead price discovery against a regulated platform with long-term oriented investors and more capital-at-risk. In this instance, the data lands in favor of the regulated market.

Appendix B: List Of IS/CS Price Discovery Analysis Monthly Results

CME vs. Binance (Chart)



CME vs. Binance (Table)

Month	CME IS	Confidence Interval	CME CS	Confidence Interval
Dec '17	73.88%*	57.83% - 89.92%	74.77%*	53.55% - 95.98%
Jan '18	48.38%	37.98% - 58.78%	52.54%	40.20% - 64.87%
Feb '18	53.00%	42.85% - 63.15%	48.38%	36.61% - 60.16%
Mar '18	58.03%	49.23% - 66.83%	63.90%*	50.70% - 77.09%
Apr '18	63.50%*	54.80% - 72.19%	64.66%*	53.48% - 75.83%
May '18	69.62%*	62.67% - 76.56%	70.95%*	62.13% - 79.76%
Jun '18	70.50%*	62.43% - 78.56%	72.58%*	63.06% - 82.10%
Jul '18	67.42%*	59.90% - 74.94%	65.54%*	57.43% - 73.64%
Aug '18	71.78%*	66.23% - 77.33%	75.22%*	68.13% - 82.31%
Sep '18	57.98%	47.31% - 68.64%	62.61%	48.13% - 77.09%
Oct '18	46.86%	34.51% - 59.20%	45.99%	32.76% - 59.22%
Nov '18	56.87%	45.85% - 67.88%	51.20%	37.57% - 64.83%
Dec '18	44.76%	33.85% - 55.68%	41.87%	27.89% - 55.85%
Jan '19	51.76%	38.93% - 64.60%	45.85%	32.54% - 59.16%
Feb '19	54.06%	43.89% - 64.22%	51.20%	40.02% - 62.37%
Mar '19	58.55%	48.62% - 68.48%	57.34%	45.26% - 69.42%
Apr '19	57.86%	46.88% - 68.84%	58.56%	48.18% - 68.94%
May '19	57.84%	45.51% - 70.18%	55.37%	45.25% - 65.49%
Jun '19	46.78%	35.95% - 57.62%	39.94%	25.34% - 54.55%
Jul '19	61.92%*	53.21% - 70.62%	62.06%	49.53% - 74.60%
Aug '19	65.71%*	58.85% - 72.57%	61.61%*	50.82% - 72.39%
Sep '19	61.95%*	52.07% - 71.82%	53.23%	41.30% - 65.17%
Oct '19	64.98%*	57.10% - 72.86%	64.49%*	53.32% - 75.66%
Nov '19	54.33%	45.37% - 63.29%	51.09%	40.60% - 61.57%
Dec '19	63.24%*	56.91% - 69.57%	63.09%*	54.13% - 72.06%
Jan '20	53.07%	44.00% - 62.13%	51.12%	41.00% - 61.24%
Feb '20	55.37%	45.41% - 65.33%	48.39%	37.76% - 59.02%
Mar '20	48.10%	39.99% - 56.21%	48.61%	36.71% - 60.50%
Apr '20	57.08%*	50.01% - 64.15%	56.04%	45.03% - 67.05%
May '20	59.90%*	53.37% - 66.42%	63.65%*	53.58% - 73.73%
Jun '20	56.85%	49.76% - 63.93%	60.70%	49.37% - 72.02%
Jul '20	58.40%*	50.55% - 66.24%	52.52%	39.98% - 65.06%
Aug '20	57.97%*	50.19% - 65.76%	55.63%	43.66% - 67.60%
Sep '20	60.11%*	54.02% - 66.19%	65.87%*	54.73% - 77.02%
2017-12-18 - 2020-09-30	58.32%*	56.78% - 59.86%	57.38%*	55.45% - 59.32%

CME vs. Bitfinex (Chart)



CME vs. Bitfinex (Table)

Month	CME IS	Confidence Interval	CME CS	Confidence Interval
Dec '17	49.44%	34.75% - 64.13%	51.78%	33.83% - 69.73%
Jan '18	52.12%	43.86% - 60.37%	52.57%	38.27% - 66.87%
Feb '18	54.82%	45.82% - 63.82%	48.82%	34.04% - 63.60%
Mar '18	60.22%*	53.88% - 66.56%	67.73%*	58.60% - 76.87%
Apr '18	64.47%*	56.08% - 72.85%	64.84%*	53.46% - 76.21%
May '18	76.94%*	71.66% - 82.22%	76.97%*	69.55% - 84.40%
Jun '18	72.50%*	66.05% - 78.95%	72.27%*	64.66% - 79.89%
Jul '18	76.62%*	70.09% - 83.15%	76.26%*	66.99% - 85.53%
Aug '18	75.55%*	69.77% - 81.32%	76.74%*	68.91% - 84.56%
Sep '18	77.13%*	68.98% - 85.29%	75.63%*	64.73% - 86.54%
Oct '18	45.08%	30.12% - 60.03%	44.99%	32.76% - 57.23%
Nov '18	51.30%	38.00% - 64.60%	47.82%	37.65% - 57.99%
Dec '18	55.81%	44.77% - 66.84%	53.80%	42.80% - 64.81%
Jan '19	65.40%*	53.33% - 77.46%	61.22%	49.55% - 72.88%
Feb '19	60.07%	48.18% - 71.96%	59.19%	45.37% - 73.01%
Mar '19	61.84%	46.94% - 76.75%	57.56%	44.71% - 70.40%
Apr '19	70.92%*	59.27% - 82.56%	68.74%*	55.88% - 81.60%
May '19	69.17%*	58.93% - 79.40%	67.67%*	56.57% - 78.78%
Jun '19	58.38%	47.95% - 68.81%	62.62%	49.82% - 75.42%
Jul '19	67.83%*	61.32% - 74.33%	69.52%*	60.28% - 78.76%
Aug '19	73.42%*	67.87% - 78.97%	75.99%*	66.84% - 85.14%
Sep '19	64.12%*	55.73% - 72.52%	62.21%*	52.69% - 71.73%
Oct '19	75.64%*	70.21% - 81.07%	76.37%*	70.08% - 82.66%
Nov '19	64.53%*	56.82% - 72.25%	62.11%*	51.43% - 72.80%
Dec '19	67.56%*	60.44% - 74.68%	63.12%*	52.96% - 73.27%
Jan '20	74.29%*	66.65% - 81.93%	64.12%*	55.48% - 72.76%
Feb '20	68.90%*	62.02% - 75.77%	66.73%*	57.34% - 76.12%
Mar '20	63.19%*	58.64% - 67.75%	67.27%*	58.92% - 75.62%
Apr '20	69.09%*	62.34% - 75.83%	70.71%*	62.11% - 79.31%
May '20	67.11%*	58.52% - 75.71%	65.24%*	54.36% - 76.12%
Jun '20	73.99%*	66.21% - 81.78%	73.83%*	62.44% - 85.22%
Jul '20	67.84%*	58.73% - 76.95%	63.50%*	52.24% - 74.77%
Aug '20	62.91%*	53.48% - 72.34%	62.67%*	51.49% - 73.86%
Sep '20	67.29%*	61.10% - 73.48%	71.74%*	60.62% - 82.87%
2017-12-18 - 2020-09-30	65.75%*	64.22% - 67.29%	65.08%*	63.28% - 66.89%

CME vs. Bitstamp (Chart)



CME vs. Bitstamp (Table)

Month	CME IS	Confidence Interval	CME CS	Confidence Interval
Dec '17	41.39%	19.72% - 63.05%	40.57%	17.33% - 63.82%
Jan '18	46.93%	38.42% - 55.43%	42.49%	31.06% - 53.91%
Feb '18	58.16%*	50.73% - 65.60%	54.52%	41.89% - 67.15%
Mar '18	61.80%*	55.78% - 67.81%	73.16%*	63.14% - 83.17%
Apr '18	68.67%*	62.45% - 74.90%	72.98%*	63.09% - 82.87%
May '18	69.66%*	61.96% - 77.36%	74.39%*	66.05% - 82.74%
Jun '18	72.13%*	64.37% - 79.89%	79.61%*	69.49% - 89.73%
Jul '18	76.50%*	71.35% - 81.65%	80.49%*	73.68% - 87.30%
Aug '18	78.01%*	73.85% - 82.18%	84.35%*	80.37% - 88.34%
Sep '18	67.85%*	57.83% - 77.86%	68.18%*	53.24% - 83.13%
Oct '18	52.84%	41.36% - 64.31%	49.48%	38.42% - 60.54%
Nov '18	62.57%*	52.92% - 72.22%	72.67%*	59.92% - 85.41%
Dec '18	57.05%	48.06% - 66.05%	63.52%*	50.88% - 76.16%
Jan '19	68.15%*	57.05% - 79.25%	62.81%	49.61% - 76.02%
Feb '19	66.53%*	59.58% - 73.48%	69.92%*	61.58% - 78.27%
Mar '19	59.56%*	50.18% - 68.93%	60.71%	48.40% - 73.02%
Apr '19	74.16%*	67.58% - 80.74%	80.55%*	73.93% - 87.17%
May '19	65.72%*	56.56% - 74.88%	70.38%*	58.61% - 82.14%
Jun '19	57.60%	47.54% - 67.66%	67.27%*	53.86% - 80.67%
Jul '19	72.58%*	68.42% - 76.75%	80.08%*	72.91% - 87.24%
Aug '19	66.48%*	58.78% - 74.17%	75.64%*	64.20% - 87.08%
Sep '19	68.96%*	62.35% - 75.57%	70.45%*	62.31% - 78.60%
Oct '19	71.24%*	65.87% - 76.60%	73.86%*	65.66% - 82.06%
Nov '19	64.77%*	56.12% - 73.43%	72.17%*	61.82% - 82.53%
Dec '19	73.52%*	68.55% - 78.48%	80.80%*	74.03% - 87.57%
Jan '20	61.80%*	52.42% - 71.17%	64.13%*	53.11% - 75.16%
Feb '20	63.47%*	53.98% - 72.96%	66.85%*	55.15% - 78.56%
Mar '20	53.01%	46.55% - 59.47%	55.52%	43.41% - 67.63%
Apr '20	61.12%*	54.97% - 67.28%	72.05%*	63.85% - 80.25%
May '20	65.27%*	58.99% - 71.56%	68.66%*	60.07% - 77.25%
Jun '20	58.02%*	50.65% - 65.40%	62.67%*	52.80% - 72.54%
Jul '20	56.27%	47.74% - 64.81%	57.57%	45.94% - 69.20%
Aug '20	60.97%*	51.70% - 70.25%	63.01%	48.90% - 77.12%
Sep '20	60.74%*	54.37% - 67.11%	61.44%*	50.30% - 72.57%
2017-12-18 - 2020-09-30	64.10%*	62.74% - 65.47%	68.03%*	66.21% - 69.86%

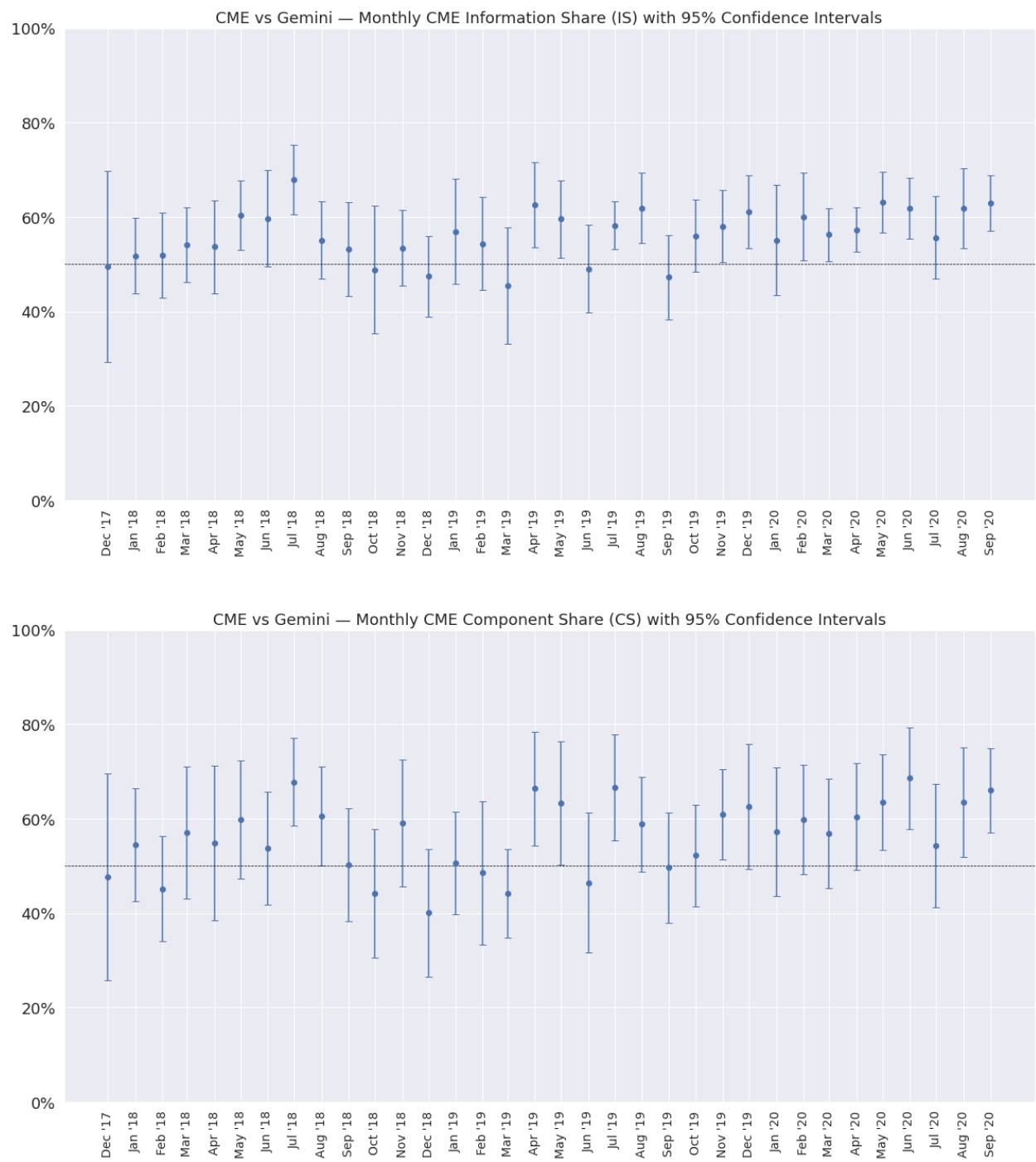
CME vs. Coinbase (Chart)



CME vs. Coinbase (Table)

Month	CME IS	Confidence Interval	CME CS	Confidence Interval
Dec '17	43.35%	21.24% - 65.47%	42.04%	13.35% - 70.73%
Jan '18	55.27%	46.14% - 64.40%	56.14%	44.35% - 67.94%
Feb '18	60.41%*	52.87% - 67.95%	63.39%*	51.42% - 75.36%
Mar '18	60.01%*	50.30% - 69.72%	66.22%*	56.22% - 76.22%
Apr '18	64.85%*	56.14% - 73.57%	62.74%	49.71% - 75.77%
May '18	66.99%*	57.75% - 76.22%	70.27%*	57.75% - 82.79%
Jun '18	62.44%*	53.09% - 71.80%	62.58%*	52.60% - 72.56%
Jul '18	67.66%*	58.67% - 76.64%	68.96%*	58.77% - 79.14%
Aug '18	75.08%*	70.12% - 80.04%	76.25%*	69.57% - 82.93%
Sep '18	70.47%*	61.62% - 79.32%	67.79%*	55.18% - 80.40%
Oct '18	58.67%	48.22% - 69.13%	46.47%	37.75% - 55.18%
Nov '18	57.32%	45.93% - 68.70%	60.57%	44.65% - 76.49%
Dec '18	48.71%	39.14% - 58.28%	46.33%	32.35% - 60.30%
Jan '19	54.51%	44.37% - 64.65%	44.48%	32.99% - 55.97%
Feb '19	58.78%	49.75% - 67.82%	53.44%	41.60% - 65.28%
Mar '19	61.65%*	53.36% - 69.93%	62.09%*	52.16% - 72.02%
Apr '19	62.15%*	54.11% - 70.20%	63.08%*	51.70% - 74.46%
May '19	56.17%	45.58% - 66.76%	54.16%	42.30% - 66.02%
Jun '19	50.37%	41.74% - 58.99%	59.07%	45.93% - 72.20%
Jul '19	64.11%*	57.28% - 70.93%	64.35%*	54.72% - 73.98%
Aug '19	64.46%*	58.71% - 70.20%	71.30%*	62.28% - 80.31%
Sep '19	59.90%*	52.40% - 67.39%	58.73%	47.13% - 70.32%
Oct '19	65.40%*	60.40% - 70.41%	65.62%*	57.33% - 73.90%
Nov '19	53.97%	46.13% - 61.81%	55.05%	42.19% - 67.92%
Dec '19	66.79%*	61.94% - 71.63%	76.40%*	68.06% - 84.75%
Jan '20	57.65%	48.46% - 66.85%	53.68%	42.62% - 64.74%
Feb '20	60.62%*	52.16% - 69.08%	58.53%	47.69% - 69.37%
Mar '20	48.14%	40.83% - 55.45%	46.63%	34.36% - 58.90%
Apr '20	63.43%*	58.53% - 68.32%	67.69%*	58.99% - 76.39%
May '20	63.06%*	56.76% - 69.35%	65.05%*	54.74% - 75.35%
Jun '20	57.92%	49.73% - 66.11%	60.11%	47.53% - 72.70%
Jul '20	62.50%*	54.88% - 70.12%	63.65%*	52.76% - 74.53%
Aug '20	63.04%*	53.97% - 72.12%	62.53%*	50.01% - 75.05%
Sep '20	62.16%*	54.77% - 69.54%	61.43%*	50.84% - 72.01%
2017-12-18 - 2020-09-30	60.60%*	59.20% - 62.00%	60.88%*	58.99% - 62.77%

CME vs. Gemini (Chart)



CME vs. Gemini (Table)

Month	CME IS	Confidence Interval	CME CS	Confidence Interval
Dec '17	49.51%	29.28% - 69.74%	47.63%	25.70% - 69.57%
Jan '18	51.75%	43.74% - 59.77%	54.46%	42.45% - 66.48%
Feb '18	51.88%	42.91% - 60.85%	45.18%	34.04% - 56.32%
Mar '18	54.11%	46.21% - 62.00%	57.06%	43.00% - 71.12%
Apr '18	53.69%	43.81% - 63.58%	54.81%	38.40% - 71.21%
May '18	60.37%*	52.95% - 67.80%	59.83%	47.29% - 72.36%
Jun '18	59.72%	49.55% - 69.88%	53.73%	41.81% - 65.65%
Jul '18	67.94%*	60.52% - 75.36%	67.80%*	58.52% - 77.09%
Aug '18	55.11%	47.00% - 63.22%	60.59%*	50.15% - 71.03%
Sep '18	53.18%	43.22% - 63.14%	50.22%	38.31% - 62.12%
Oct '18	48.84%	35.30% - 62.38%	44.20%	30.61% - 57.79%
Nov '18	53.41%	45.40% - 61.41%	59.07%	45.66% - 72.47%
Dec '18	47.44%	38.87% - 56.01%	40.08%	26.60% - 53.56%
Jan '19	56.96%	45.88% - 68.03%	50.63%	39.72% - 61.53%
Feb '19	54.32%	44.47% - 64.17%	48.56%	33.36% - 63.76%
Mar '19	45.40%	33.10% - 57.70%	44.14%	34.80% - 53.48%
Apr '19	62.51%*	53.49% - 71.53%	66.39%*	54.39% - 78.39%
May '19	59.55%*	51.42% - 67.69%	63.26%*	50.18% - 76.34%
Jun '19	48.97%	39.68% - 58.26%	46.42%	31.63% - 61.21%
Jul '19	58.24%*	53.20% - 63.29%	66.62%*	55.34% - 77.89%
Aug '19	61.93%*	54.42% - 69.44%	58.82%	48.75% - 68.90%
Sep '19	47.24%	38.36% - 56.13%	49.61%	38.02% - 61.21%
Oct '19	56.04%	48.47% - 63.61%	52.20%	41.40% - 63.00%
Nov '19	58.03%*	50.36% - 65.70%	60.91%*	51.42% - 70.40%
Dec '19	61.10%*	53.37% - 68.82%	62.63%	49.35% - 75.91%
Jan '20	55.08%	43.44% - 66.72%	57.20%	43.57% - 70.83%
Feb '20	60.05%*	50.81% - 69.29%	59.75%	48.15% - 71.36%
Mar '20	56.31%*	50.71% - 61.90%	56.89%	45.27% - 68.51%
Apr '20	57.31%*	52.65% - 61.97%	60.43%	49.07% - 71.79%
May '20	63.18%*	56.71% - 69.65%	63.51%*	53.45% - 73.57%
Jun '20	61.83%*	55.42% - 68.23%	68.58%*	57.76% - 79.39%
Jul '20	55.66%	46.90% - 64.43%	54.34%	41.31% - 67.37%
Aug '20	61.81%*	53.40% - 70.22%	63.45%*	51.87% - 75.03%
Sep '20	62.98%*	57.07% - 68.88%	66.02%*	57.08% - 74.96%
2017-12-18 - 2020-09-30	56.44%*	55.03% - 57.84%	56.73%*	54.73% - 58.72%

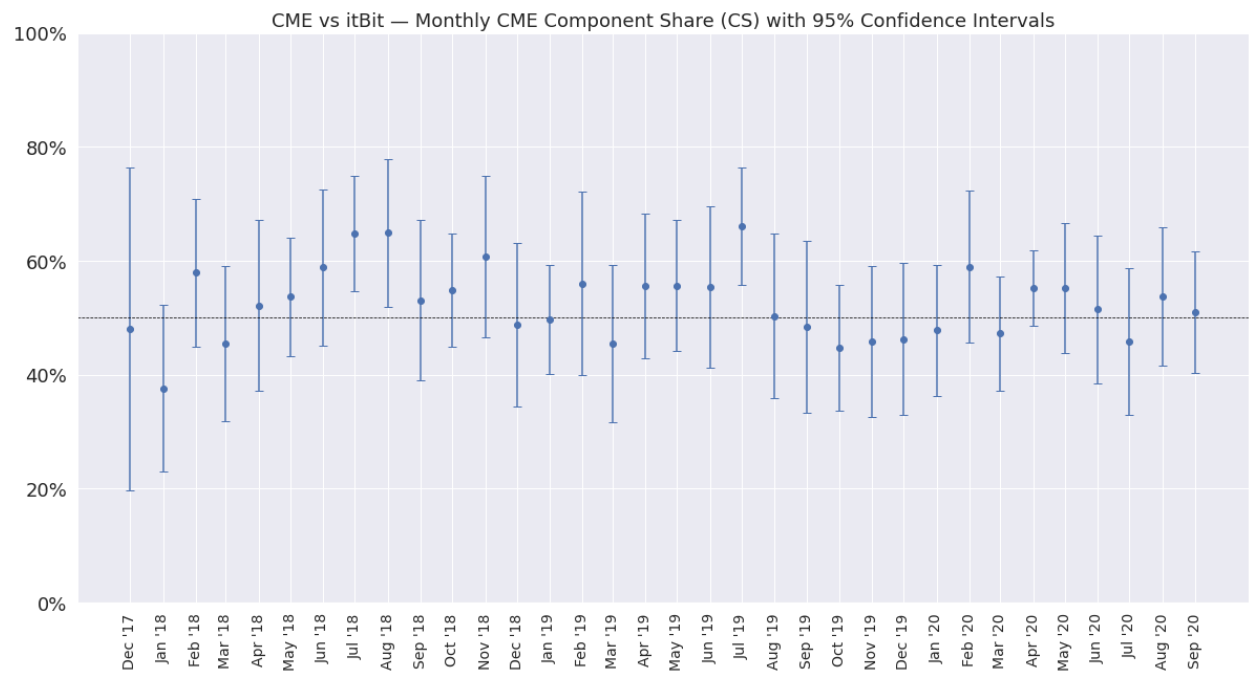
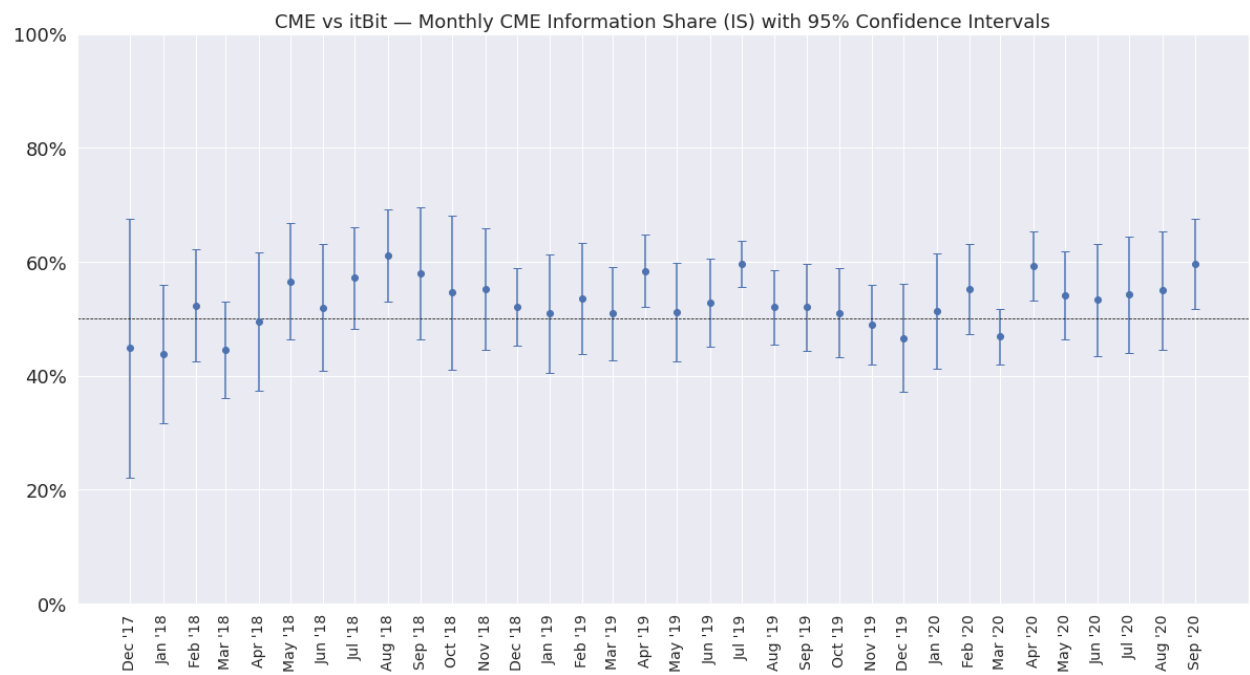
CME vs. Huobi (Chart)



CME vs. Huobi (Table)

Month	CME IS	Confidence Interval	CME CS	Confidence Interval
Mar '18	66.17%*	57.72% - 74.62%	67.72%*	57.64% - 77.79%
Apr '18	71.96%*	65.56% - 78.37%	72.53%*	62.80% - 82.25%
May '18	77.35%*	71.04% - 83.66%	77.14%*	68.84% - 85.45%
Jun '18	76.84%*	68.75% - 84.92%	77.30%*	67.23% - 87.37%
Jul '18	72.59%*	65.28% - 79.90%	68.88%*	59.58% - 78.18%
Aug '18	76.21%*	70.24% - 82.19%	80.93%*	72.70% - 89.15%
Sep '18	66.04%*	60.30% - 71.78%	76.70%*	68.07% - 85.33%
Oct '18	45.26%	31.92% - 58.59%	39.42%	26.82% - 52.01%
Nov '18	57.49%	45.51% - 69.46%	52.16%	39.80% - 64.52%
Dec '18	51.64%	40.90% - 62.38%	45.47%	32.15% - 58.79%
Jan '19	57.58%	46.33% - 68.84%	50.48%	39.74% - 61.23%
Feb '19	61.48%*	50.84% - 72.12%	59.33%	49.04% - 69.61%
Mar '19	60.41%*	50.36% - 70.45%	54.27%	42.20% - 66.33%
Apr '19	59.15%	46.41% - 71.89%	60.74%	49.54% - 71.94%
May '19	56.79%	43.38% - 70.20%	55.45%	43.49% - 67.40%
Jun '19	50.71%	40.85% - 60.57%	43.93%	29.91% - 57.95%
Jul '19	64.42%*	55.80% - 73.04%	63.51%*	51.96% - 75.05%
Aug '19	63.04%*	56.18% - 69.91%	60.41%	49.40% - 71.41%
Sep '19	62.43%*	53.62% - 71.24%	52.40%	39.04% - 65.77%
Oct '19	63.86%*	57.33% - 70.40%	60.04%	49.19% - 70.88%
Nov '19	55.56%	47.98% - 63.14%	56.59%	44.66% - 68.51%
Dec '19	63.88%*	57.76% - 70.00%	64.41%*	55.42% - 73.40%
Jan '20	53.46%	44.72% - 62.21%	53.35%	42.05% - 64.65%
Feb '20	55.27%	45.18% - 65.36%	45.44%	35.54% - 55.35%
Mar '20	48.81%	40.58% - 57.04%	45.94%	33.22% - 58.66%
Apr '20	57.88%*	51.21% - 64.55%	54.09%	42.78% - 65.39%
May '20	61.55%*	55.05% - 68.05%	62.69%*	52.65% - 72.73%
Jun '20	56.51%	49.45% - 63.57%	57.71%	46.60% - 68.82%
Jul '20	55.99%	48.12% - 63.87%	52.40%	39.67% - 65.14%
Aug '20	58.05%*	50.43% - 65.68%	54.64%	43.71% - 65.57%
Sep '20	59.24%*	52.83% - 65.65%	60.74%	48.22% - 73.25%
2018-03-01 - 2020-09-30	60.91%*	59.34% - 62.49%	58.97%*	56.96% - 60.98%

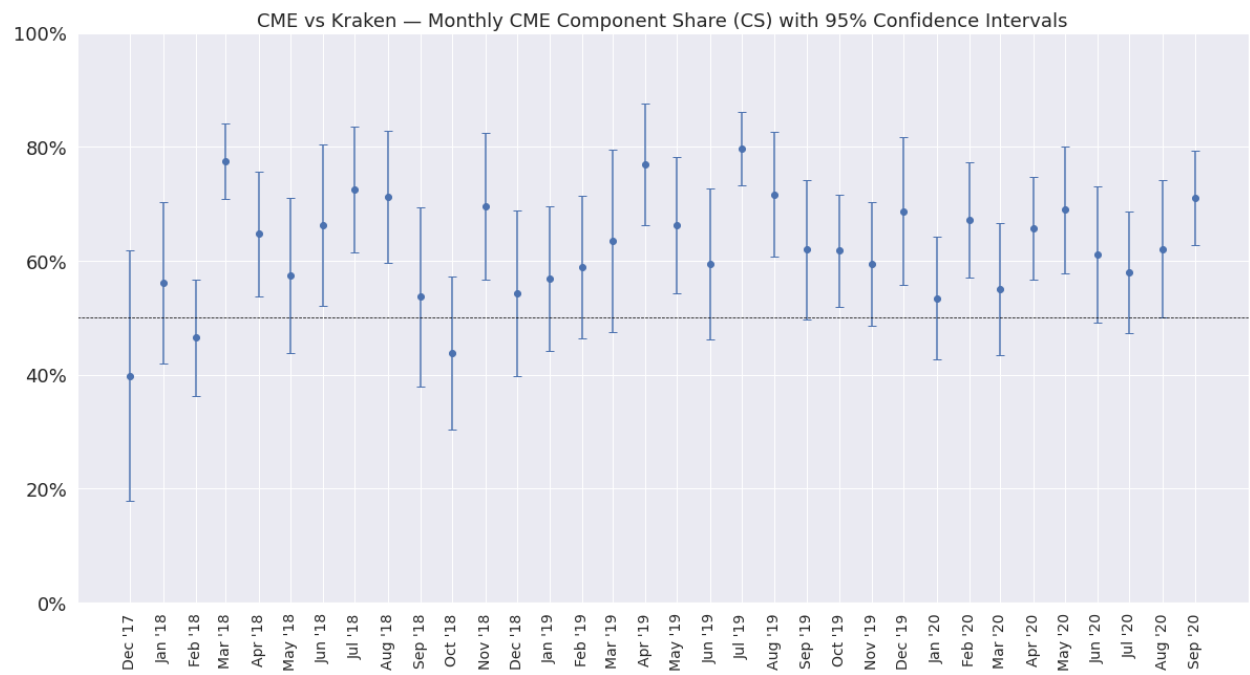
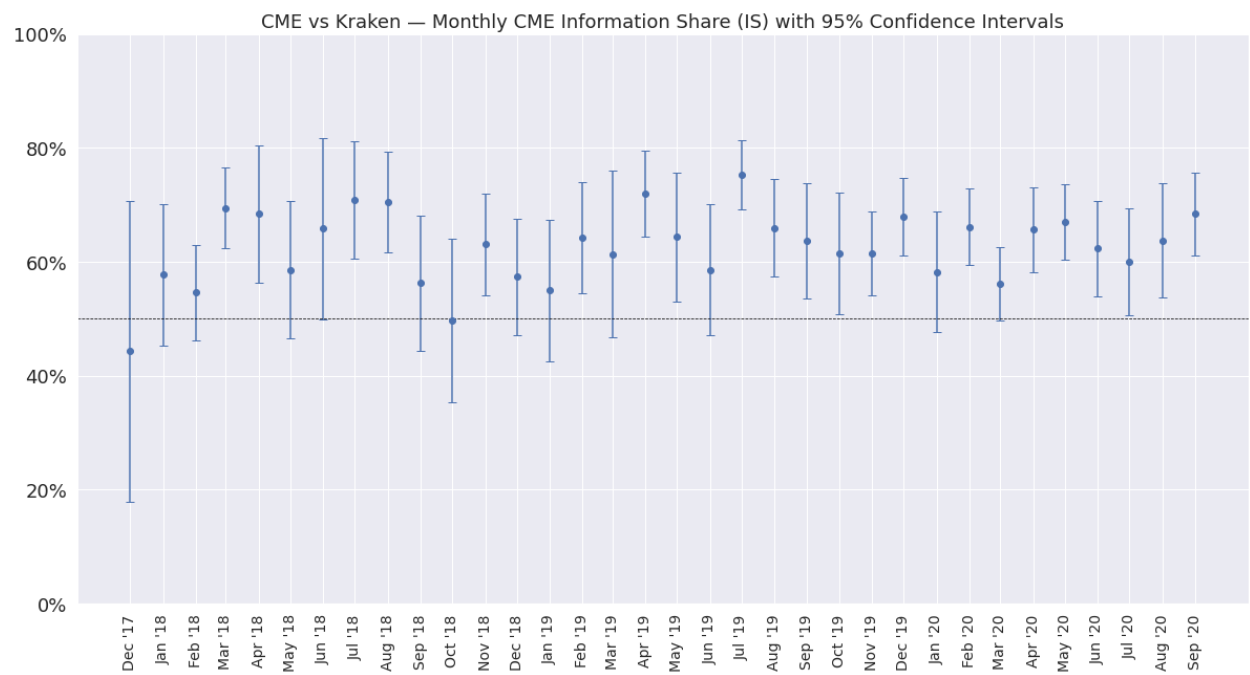
CME vs. itBit (Chart)



CME vs. itBit (Table)

Month	CME IS	Confidence Interval	CME CS	Confidence Interval
Dec '17	44.83%	22.06% - 67.60%	48.07%	19.80% - 76.34%
Jan '18	43.81%	31.60% - 56.02%	37.59%	22.97% - 52.22%
Feb '18	52.34%	42.47% - 62.22%	57.90%	44.94% - 70.86%
Mar '18	44.58%	36.07% - 53.09%	45.48%	31.89% - 59.08%
Apr '18	49.45%	37.29% - 61.61%	52.17%	37.12% - 67.22%
May '18	56.59%	46.39% - 66.80%	53.66%	43.23% - 64.09%
Jun '18	51.92%	40.81% - 63.04%	58.86%	45.12% - 72.59%
Jul '18	57.16%	48.30% - 66.02%	64.78%*	54.73% - 74.83%
Aug '18	61.13%*	53.03% - 69.23%	64.89%*	51.88% - 77.90%
Sep '18	57.99%	46.37% - 69.61%	53.08%	38.97% - 67.18%
Oct '18	54.59%	41.03% - 68.14%	54.88%	45.00% - 64.77%
Nov '18	55.19%	44.54% - 65.85%	60.70%	46.54% - 74.86%
Dec '18	52.04%	45.22% - 58.87%	48.78%	34.43% - 63.14%
Jan '19	50.93%	40.54% - 61.33%	49.66%	40.13% - 59.20%
Feb '19	53.53%	43.74% - 63.33%	56.04%	39.96% - 72.12%
Mar '19	50.92%	42.78% - 59.07%	45.50%	31.74% - 59.26%
Apr '19	58.38%*	52.03% - 64.73%	55.63%	42.95% - 68.31%
May '19	51.24%	42.61% - 59.87%	55.63%	44.13% - 67.13%
Jun '19	52.85%	45.08% - 60.63%	55.33%	41.16% - 69.51%
Jul '19	59.71%*	55.68% - 63.75%	65.99%*	55.69% - 76.30%
Aug '19	52.06%	45.52% - 58.61%	50.34%	35.83% - 64.84%
Sep '19	52.01%	44.32% - 59.70%	48.43%	33.34% - 63.52%
Oct '19	51.03%	43.23% - 58.83%	44.71%	33.67% - 55.75%
Nov '19	48.99%	42.06% - 55.92%	45.81%	32.52% - 59.10%
Dec '19	46.61%	37.11% - 56.11%	46.30%	33.02% - 59.58%
Jan '20	51.36%	41.28% - 61.43%	47.78%	36.24% - 59.32%
Feb '20	55.26%	47.32% - 63.19%	58.97%	45.57% - 72.37%
Mar '20	46.90%	42.00% - 51.80%	47.23%	37.19% - 57.26%
Apr '20	59.25%*	53.21% - 65.28%	55.19%	48.55% - 61.83%
May '20	54.13%	46.39% - 61.87%	55.21%	43.82% - 66.61%
Jun '20	53.33%	43.51% - 63.15%	51.48%	38.54% - 64.43%
Jul '20	54.25%	44.08% - 64.43%	45.87%	32.97% - 58.78%
Aug '20	55.00%	44.64% - 65.36%	53.75%	41.54% - 65.97%
Sep '20	59.68%*	51.79% - 67.56%	50.98%	40.36% - 61.59%
2017-12-18 - 2020-09-30	53.33%*	51.91% - 54.75%	52.97%*	50.93% - 55.00%

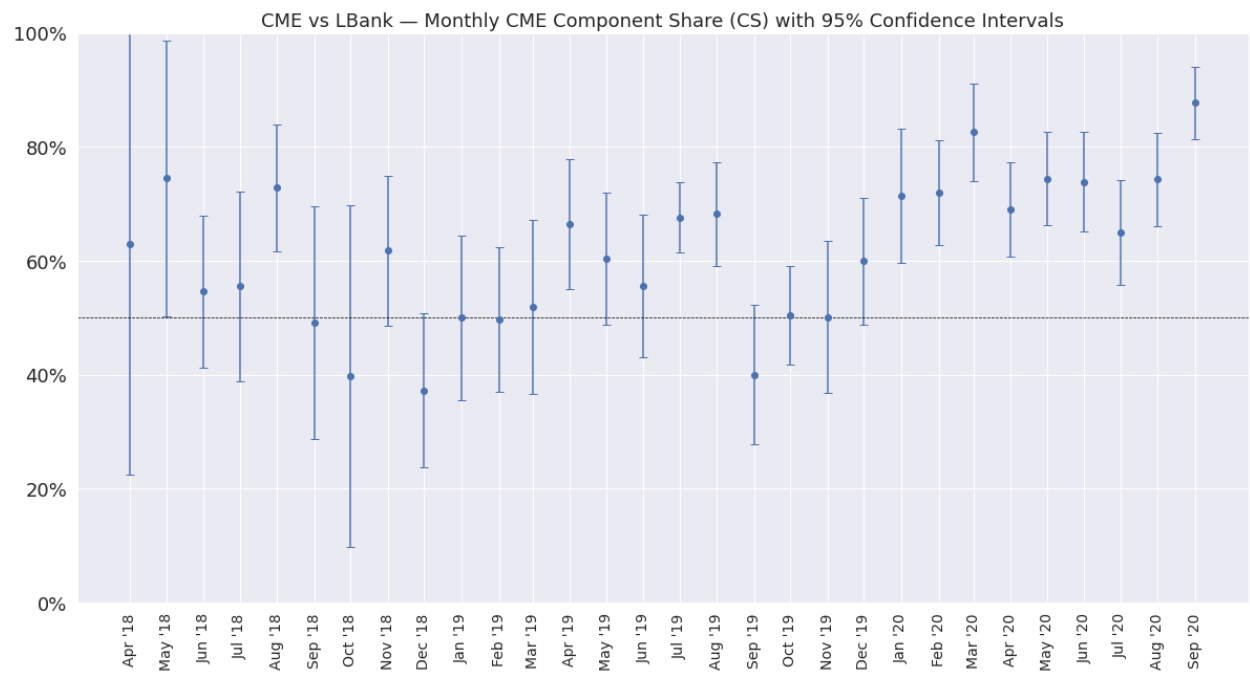
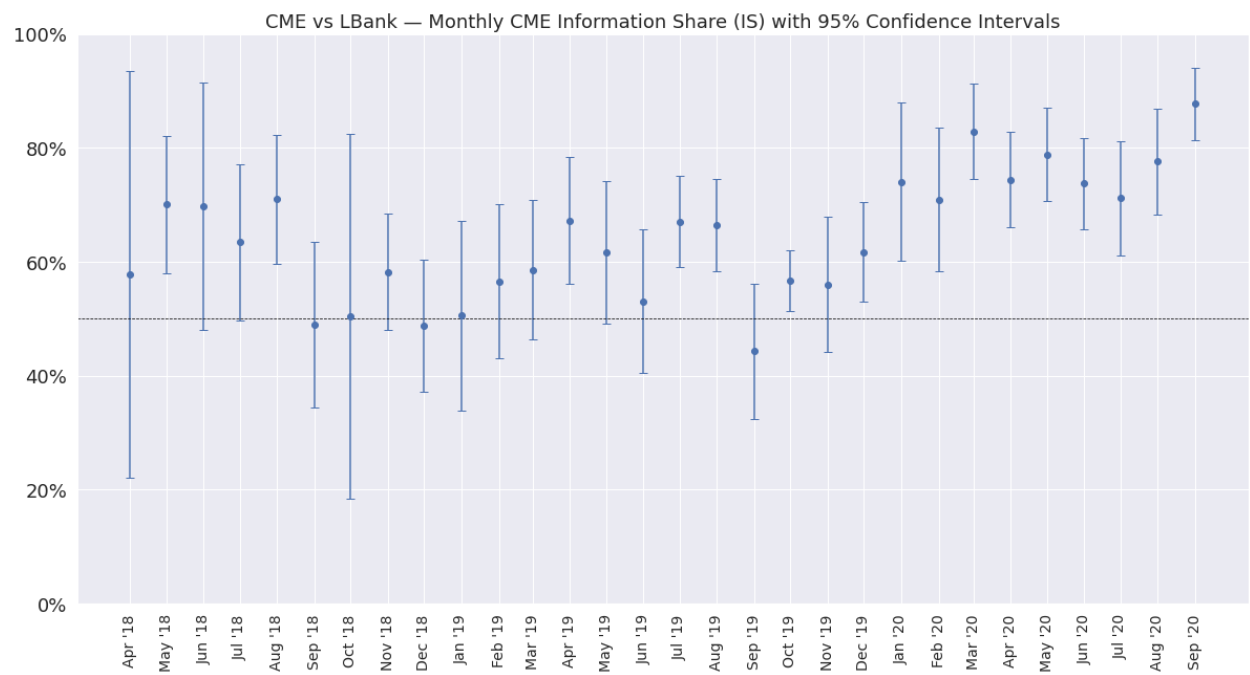
CME vs. Kraken (Chart)



CME vs. Kraken (Table)

Month	CME IS	Confidence Interval	CME CS	Confidence Interval
Dec '17	44.29%	17.93% - 70.64%	39.83%	17.90% - 61.75%
Jan '18	57.74%	45.33% - 70.15%	56.19%	42.04% - 70.33%
Feb '18	54.59%	46.24% - 62.95%	46.51%	36.25% - 56.77%
Mar '18	69.46%*	62.36% - 76.55%	77.45%*	70.81% - 84.10%
Apr '18	68.42%*	56.37% - 80.46%	64.73%*	53.81% - 75.66%
May '18	58.56%	46.50% - 70.63%	57.41%	43.86% - 70.96%
Jun '18	65.83%	49.91% - 81.75%	66.25%*	52.04% - 80.45%
Jul '18	70.81%*	60.49% - 81.13%	72.48%*	61.41% - 83.54%
Aug '18	70.52%*	61.70% - 79.33%	71.16%*	59.58% - 82.74%
Sep '18	56.26%	44.40% - 68.11%	53.70%	37.96% - 69.45%
Oct '18	49.77%	35.44% - 64.10%	43.74%	30.31% - 57.17%
Nov '18	63.05%*	54.18% - 71.92%	69.62%*	56.76% - 82.49%
Dec '18	57.40%	47.22% - 67.58%	54.29%	39.79% - 68.79%
Jan '19	54.97%	42.53% - 67.41%	56.85%	44.14% - 69.56%
Feb '19	64.26%*	54.50% - 74.02%	58.89%	46.36% - 71.43%
Mar '19	61.37%	46.73% - 76.01%	63.48%	47.54% - 79.42%
Apr '19	72.02%*	64.46% - 79.58%	76.92%*	66.26% - 87.58%
May '19	64.33%*	52.94% - 75.71%	66.35%*	54.39% - 78.31%
Jun '19	58.56%	47.04% - 70.08%	59.46%	46.19% - 72.73%
Jul '19	75.22%*	69.12% - 81.33%	79.66%*	73.23% - 86.09%
Aug '19	65.97%*	57.49% - 74.45%	71.62%*	60.68% - 82.55%
Sep '19	63.67%*	53.47% - 73.87%	61.96%	49.68% - 74.24%
Oct '19	61.50%*	50.89% - 72.11%	61.77%*	51.98% - 71.56%
Nov '19	61.42%*	54.11% - 68.74%	59.48%	48.67% - 70.28%
Dec '19	67.95%*	61.17% - 74.73%	68.73%*	55.70% - 81.75%
Jan '20	58.23%	47.69% - 68.77%	53.39%	42.64% - 64.15%
Feb '20	66.15%*	59.41% - 72.89%	67.20%*	57.02% - 77.37%
Mar '20	56.18%	49.78% - 62.58%	55.11%	43.52% - 66.69%
Apr '20	65.64%*	58.14% - 73.14%	65.72%*	56.76% - 74.69%
May '20	67.04%*	60.40% - 73.67%	68.96%*	57.88% - 80.04%
Jun '20	62.35%*	53.94% - 70.75%	61.04%	49.11% - 72.98%
Jul '20	60.01%*	50.64% - 69.39%	57.99%	47.34% - 68.65%
Aug '20	63.71%*	53.69% - 73.73%	62.07%*	50.01% - 74.12%
Sep '20	68.42%*	61.13% - 75.71%	71.02%*	62.68% - 79.37%
2017-12-18 - 2020-09-30	63.17%*	61.58% - 64.76%	63.24%*	61.29% - 65.19%

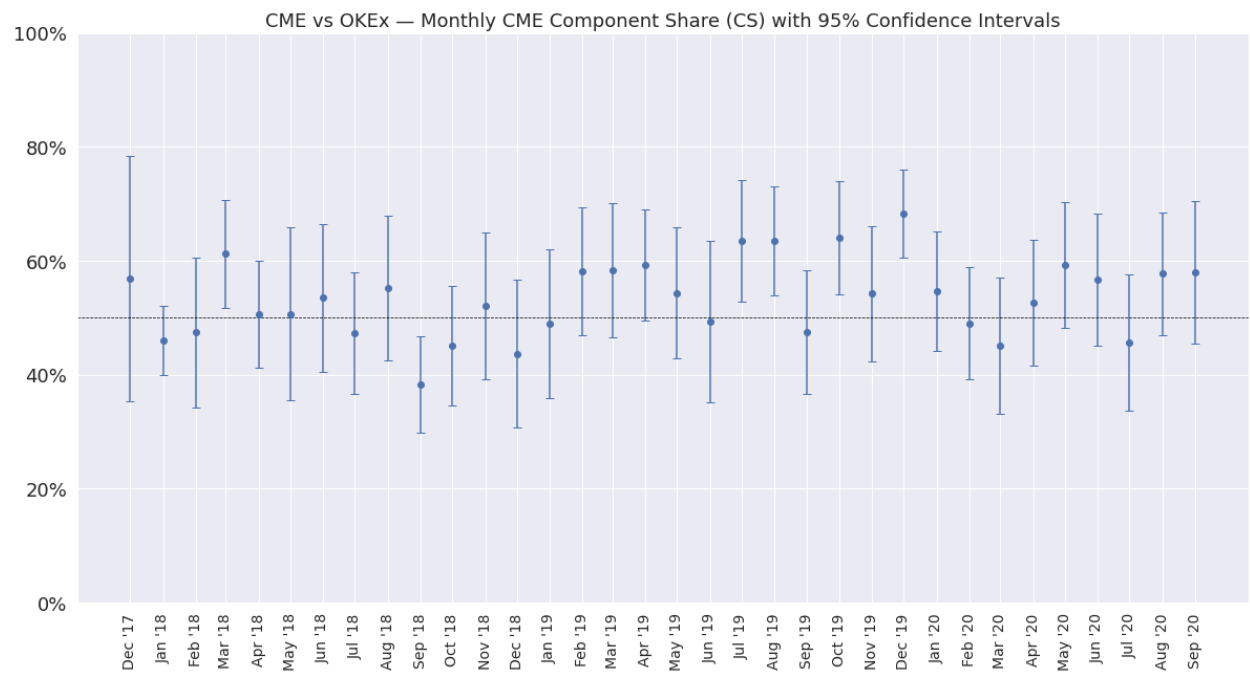
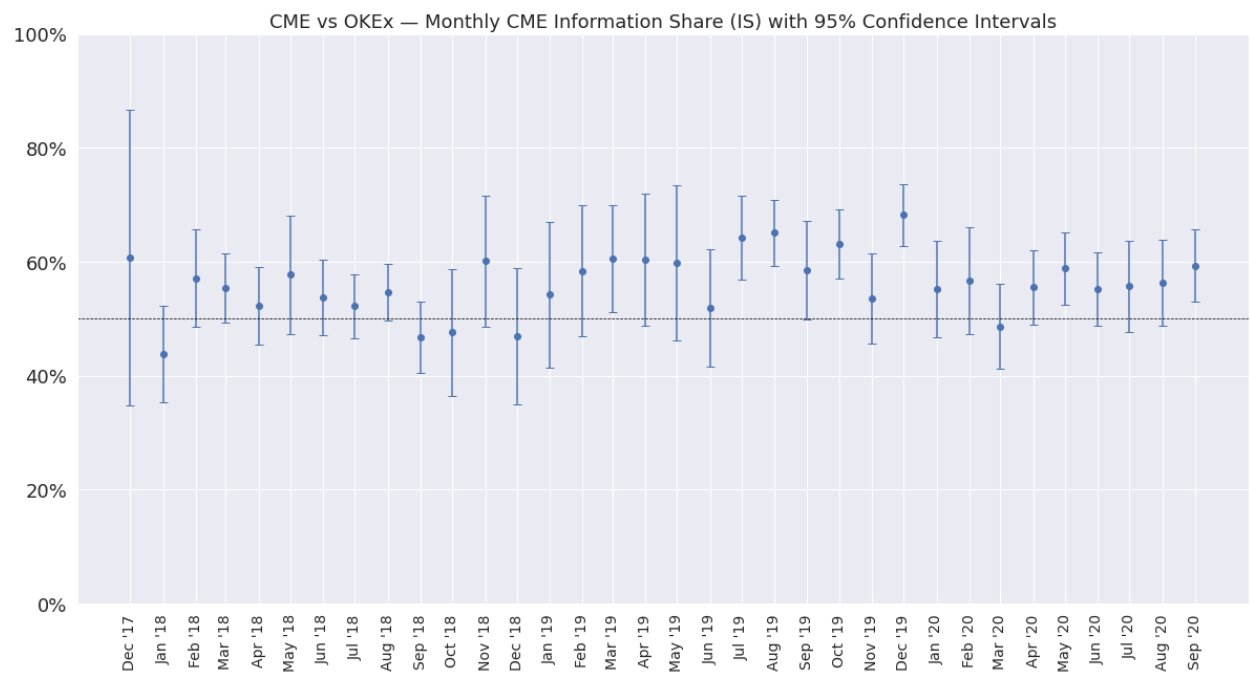
CME vs. LBank (Chart)



CME vs. LBank (Table)

Month	CME IS	Confidence Interval	CME CS	Confidence Interval
Apr '18	57.83%	22.09% - 93.57%	63.03%	22.42% - 100.00%
May '18	70.04%*	58.06% - 82.02%	74.46%*	50.33% - 98.60%
Jun '18	69.76%	48.11% - 91.41%	54.64%	41.29% - 67.99%
Jul '18	63.43%	49.76% - 77.10%	55.50%	38.86% - 72.14%
Aug '18	71.01%*	59.68% - 82.33%	72.84%*	61.74% - 83.95%
Sep '18	49.00%	34.44% - 63.55%	49.12%	28.68% - 69.56%
Oct '18	50.51%	18.48% - 82.54%	39.74%	9.72% - 69.76%
Nov '18	58.21%	47.99% - 68.42%	61.78%	48.66% - 74.90%
Dec '18	48.84%	37.23% - 60.45%	37.26%	23.74% - 50.78%
Jan '19	50.57%	33.95% - 67.20%	49.99%	35.49% - 64.49%
Feb '19	56.52%	43.00% - 70.04%	49.73%	36.98% - 62.48%
Mar '19	58.61%	46.43% - 70.78%	51.95%	36.68% - 67.22%
Apr '19	67.27%*	56.20% - 78.34%	66.46%*	55.12% - 77.80%
May '19	61.60%	49.10% - 74.11%	60.30%	48.73% - 71.87%
Jun '19	53.08%	40.44% - 65.72%	55.55%	43.09% - 68.01%
Jul '19	67.06%*	59.02% - 75.10%	67.61%*	61.44% - 73.79%
Aug '19	66.47%*	58.37% - 74.58%	68.23%*	59.07% - 77.39%
Sep '19	44.33%	32.48% - 56.17%	40.01%	27.73% - 52.29%
Oct '19	56.64%*	51.27% - 62.01%	50.37%	41.71% - 59.02%
Nov '19	56.03%	44.12% - 67.94%	50.12%	36.81% - 63.43%
Dec '19	61.73%*	53.00% - 70.46%	59.91%	48.80% - 71.03%
Jan '20	74.07%*	60.21% - 87.93%	71.33%*	59.55% - 83.11%
Feb '20	70.92%*	58.33% - 83.51%	71.94%*	62.78% - 81.11%
Mar '20	82.90%*	74.52% - 91.28%	82.54%*	73.99% - 91.10%
Apr '20	74.42%*	66.11% - 82.72%	69.07%*	60.79% - 77.34%
May '20	78.85%*	70.62% - 87.09%	74.41%*	66.23% - 82.59%
Jun '20	73.73%*	65.78% - 81.69%	73.88%*	65.10% - 82.66%
Jul '20	71.17%*	61.18% - 81.15%	64.98%*	55.75% - 74.22%
Aug '20	77.58%*	68.24% - 86.92%	74.31%*	66.15% - 82.47%
Sep '20	87.70%*	81.30% - 94.10%	87.71%*	81.36% - 94.06%
2018-04-05 - 2020-09-30	66.03%*	63.95% - 68.11%	63.51%*	61.34% - 65.68%

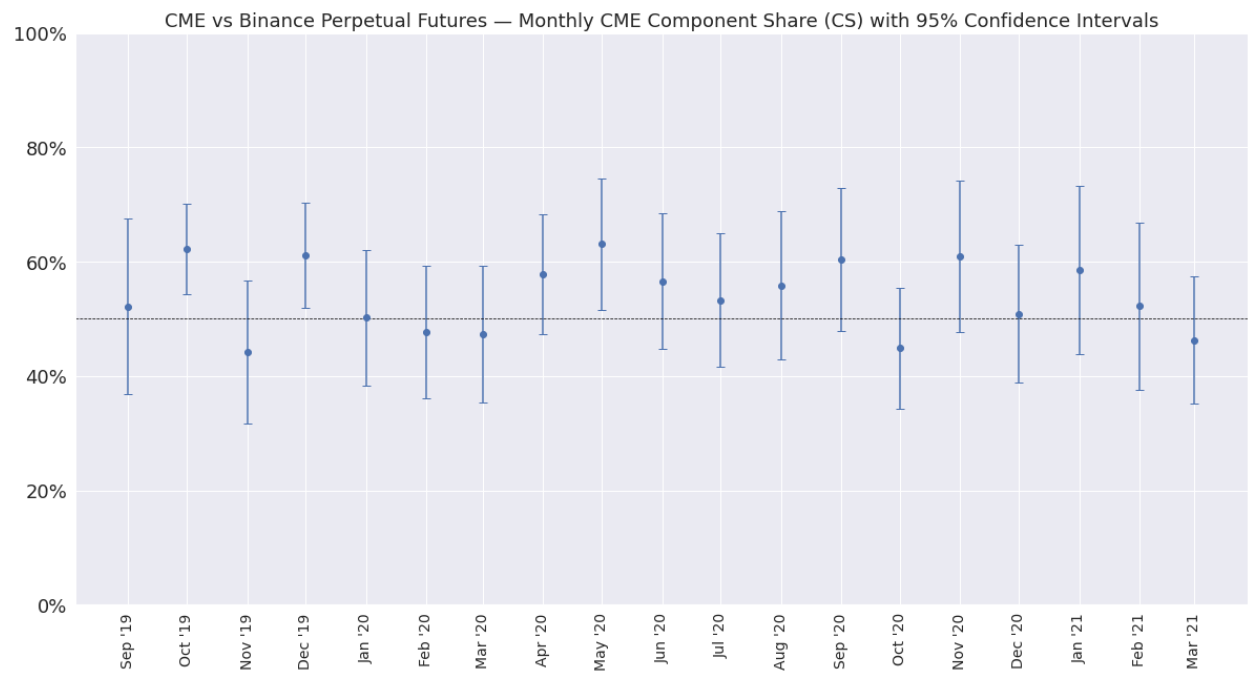
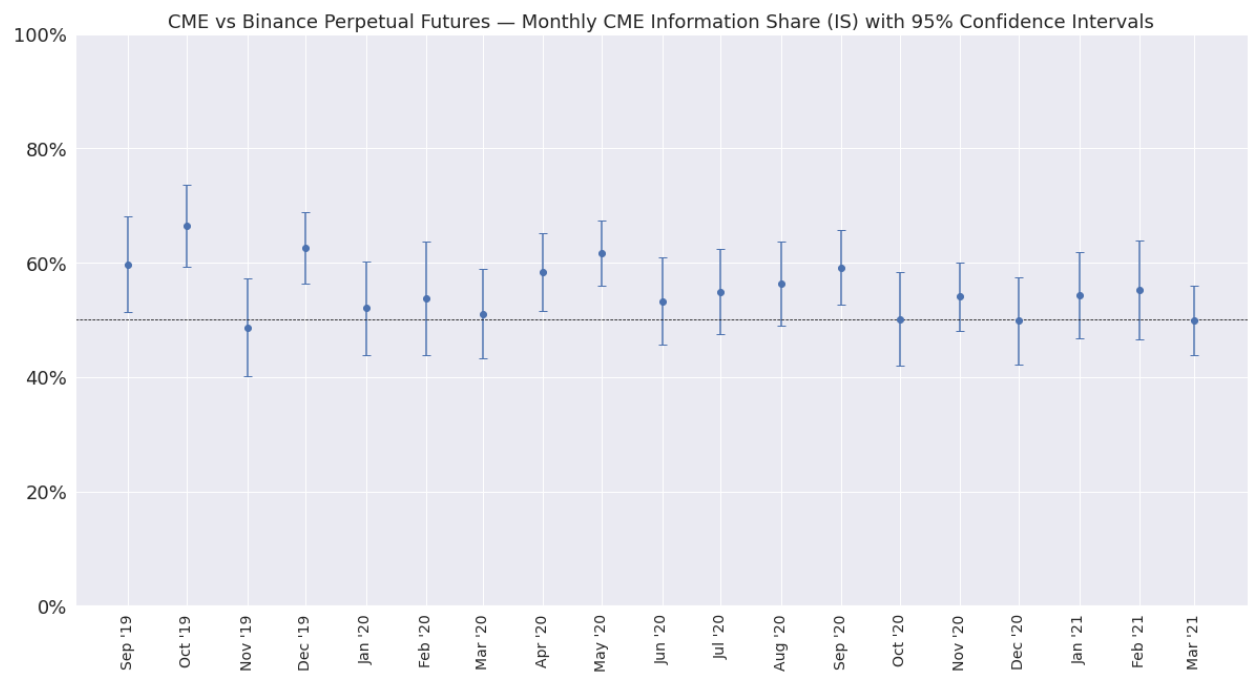
CME vs. OKEEx (Chart)



CME vs. OKEEx (Table)

Month	CME IS	Confidence Interval	CME CS	Confidence Interval
Dec '17	60.69%	34.76% - 86.62%	56.88%	35.39% - 78.37%
Jan '18	43.77%	35.33% - 52.21%	46.03%	39.93% - 52.12%
Feb '18	57.14%	48.66% - 65.62%	47.43%	34.29% - 60.57%
Mar '18	55.36%	49.34% - 61.39%	61.20%*	51.79% - 70.61%
Apr '18	52.26%	45.49% - 59.03%	50.68%	41.26% - 60.09%
May '18	57.72%	47.34% - 68.10%	50.67%	35.46% - 65.88%
Jun '18	53.80%	47.17% - 60.43%	53.50%	40.47% - 66.53%
Jul '18	52.19%	46.60% - 57.79%	47.32%	36.68% - 57.96%
Aug '18	54.66%	49.63% - 59.70%	55.22%	42.45% - 67.99%
Sep '18	46.76%	40.42% - 53.10%	38.31%*	29.91% - 46.71%
Oct '18	47.59%	36.46% - 58.72%	45.09%	34.53% - 55.64%
Nov '18	60.12%	48.61% - 71.62%	52.16%	39.30% - 65.03%
Dec '18	46.87%	34.90% - 58.85%	43.68%	30.70% - 56.65%
Jan '19	54.28%	41.49% - 67.08%	48.89%	35.83% - 61.95%
Feb '19	58.41%	46.93% - 69.89%	58.17%	46.94% - 69.39%
Mar '19	60.57%*	51.12% - 70.02%	58.34%	46.55% - 70.14%
Apr '19	60.41%	48.80% - 72.03%	59.27%	49.52% - 69.01%
May '19	59.84%	46.25% - 73.42%	54.39%	42.96% - 65.81%
Jun '19	51.93%	41.59% - 62.27%	49.34%	35.19% - 63.49%
Jul '19	64.22%*	56.85% - 71.60%	63.56%*	52.90% - 74.22%
Aug '19	65.14%*	59.34% - 70.94%	63.51%*	53.90% - 73.13%
Sep '19	58.56%	49.90% - 67.22%	47.42%	36.56% - 58.28%
Oct '19	63.16%*	57.12% - 69.19%	64.07%*	54.10% - 74.03%
Nov '19	53.53%	45.58% - 61.49%	54.27%	42.43% - 66.10%
Dec '19	68.21%*	62.71% - 73.70%	68.32%*	60.55% - 76.10%
Jan '20	55.30%	46.83% - 63.77%	54.66%	44.15% - 65.18%
Feb '20	56.71%	47.34% - 66.07%	49.04%	39.17% - 58.90%
Mar '20	48.68%	41.20% - 56.16%	45.06%	33.15% - 56.97%
Apr '20	55.51%	48.97% - 62.05%	52.67%	41.67% - 63.67%
May '20	58.81%*	52.46% - 65.16%	59.26%	48.18% - 70.34%
Jun '20	55.22%	48.78% - 61.67%	56.69%	45.17% - 68.21%
Jul '20	55.70%	47.74% - 63.66%	45.71%	33.76% - 57.66%
Aug '20	56.31%	48.85% - 63.78%	57.72%	46.96% - 68.47%
Sep '20	59.35%*	53.03% - 65.68%	58.01%	45.53% - 70.49%
2017-12-18 - 2020-09-30	56.19%*	54.74% - 57.64%	53.60%*	51.73% - 55.47%

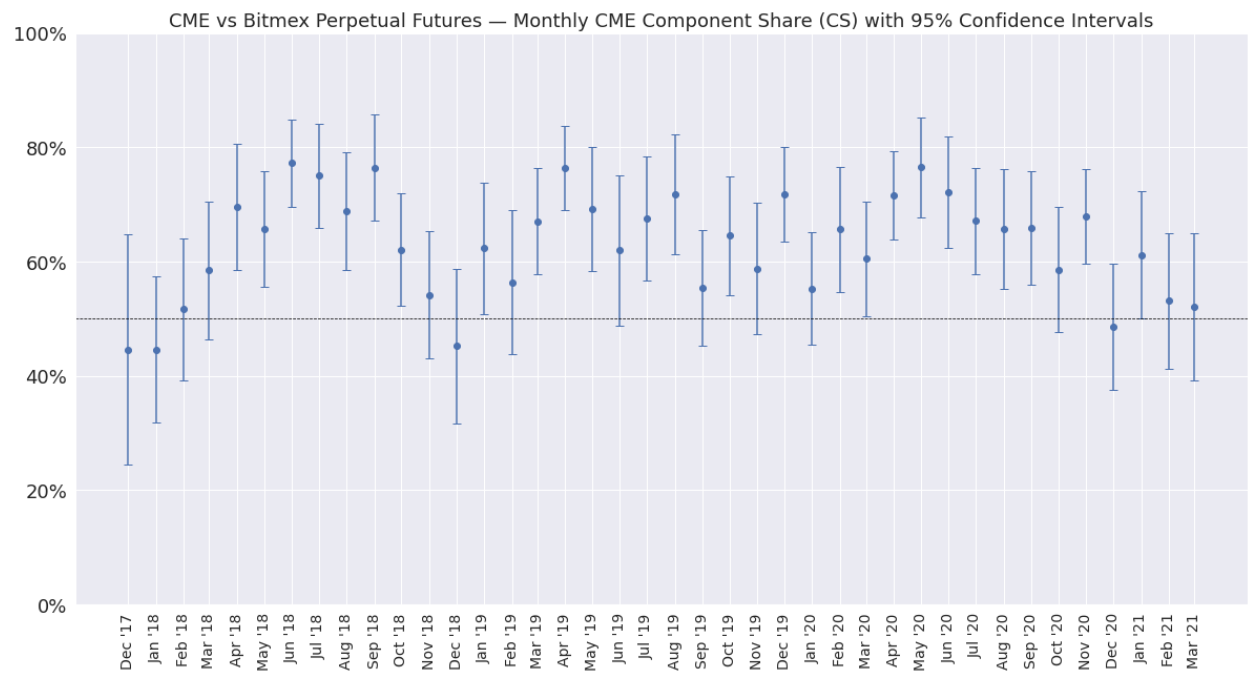
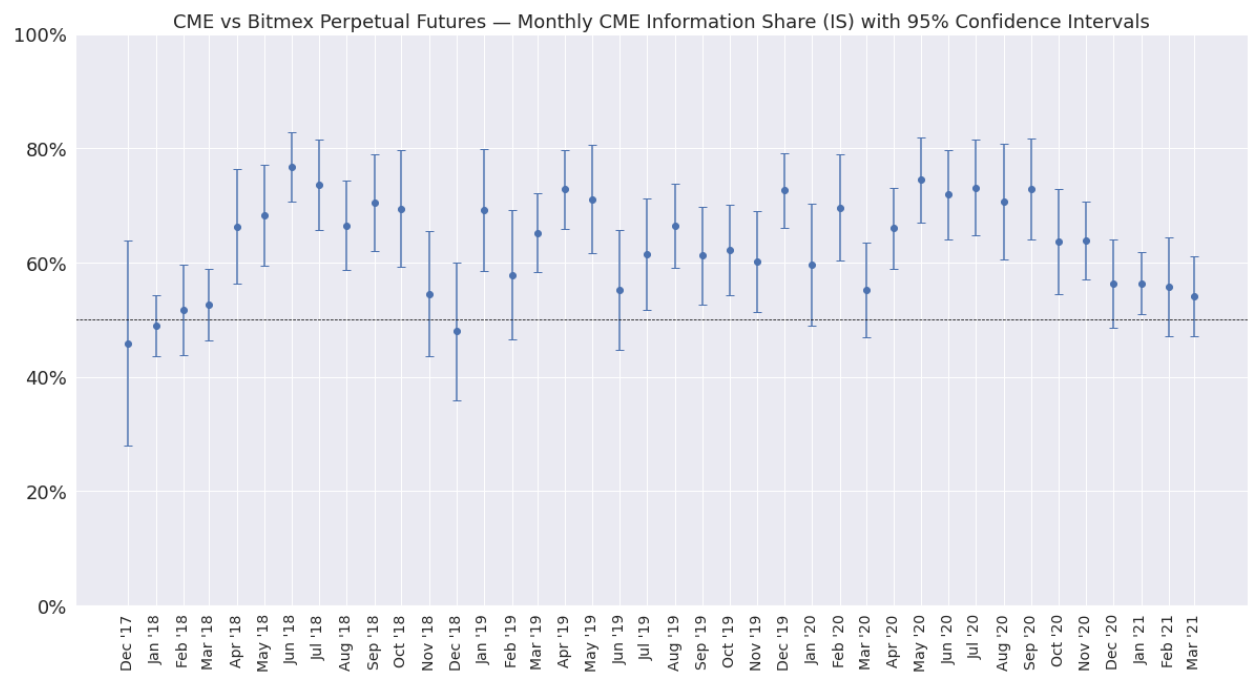
CME vs. Binance Perpetual Futures (Chart)



CME vs. Binance Perpetual Futures (Table)

Month	CME IS	Confidence Interval	CME CS	Confidence Interval
Sep '19	59.69%*	51.29% - 68.09%	52.15%	36.80% - 67.50%
Oct '19	66.52%*	59.33% - 73.71%	62.19%*	54.26% - 70.12%
Nov '19	48.70%	40.17% - 57.22%	44.21%	31.75% - 56.67%
Dec '19	62.65%*	56.37% - 68.92%	61.10%*	51.93% - 70.27%
Jan '20	52.08%	43.89% - 60.27%	50.20%	38.35% - 62.04%
Feb '20	53.77%	43.78% - 63.75%	47.68%	36.04% - 59.33%
Mar '20	51.04%	43.22% - 58.86%	47.39%	35.41% - 59.36%
Apr '20	58.35%*	51.60% - 65.10%	57.84%	47.31% - 68.37%
May '20	61.66%*	55.89% - 67.44%	63.14%*	51.65% - 74.63%
Jun '20	53.27%	45.65% - 60.89%	56.58%	44.72% - 68.43%
Jul '20	54.90%	47.42% - 62.37%	53.31%	41.57% - 65.04%
Aug '20	56.36%	48.93% - 63.78%	55.83%	42.84% - 68.82%
Sep '20	59.16%*	52.59% - 65.72%	60.41%	47.88% - 72.95%
Oct '20	50.16%	41.92% - 58.40%	44.90%	34.35% - 55.45%
Nov '20	54.06%	48.06% - 60.07%	61.01%	47.79% - 74.23%
Dec '20	49.87%	42.23% - 57.52%	50.91%	38.93% - 62.89%
Jan '21	54.31%	46.75% - 61.87%	58.55%	43.82% - 73.29%
Feb '21	55.25%	46.67% - 63.82%	52.30%	37.67% - 66.92%
Mar '21	49.93%	43.86% - 56.00%	46.30%	35.12% - 57.48%
2019-09-10 - 2021-03-31	55.30%*	53.64% - 56.96%	54.01%*	51.41% - 56.61%

CME vs. BitMEX Perpetual Futures (Chart)



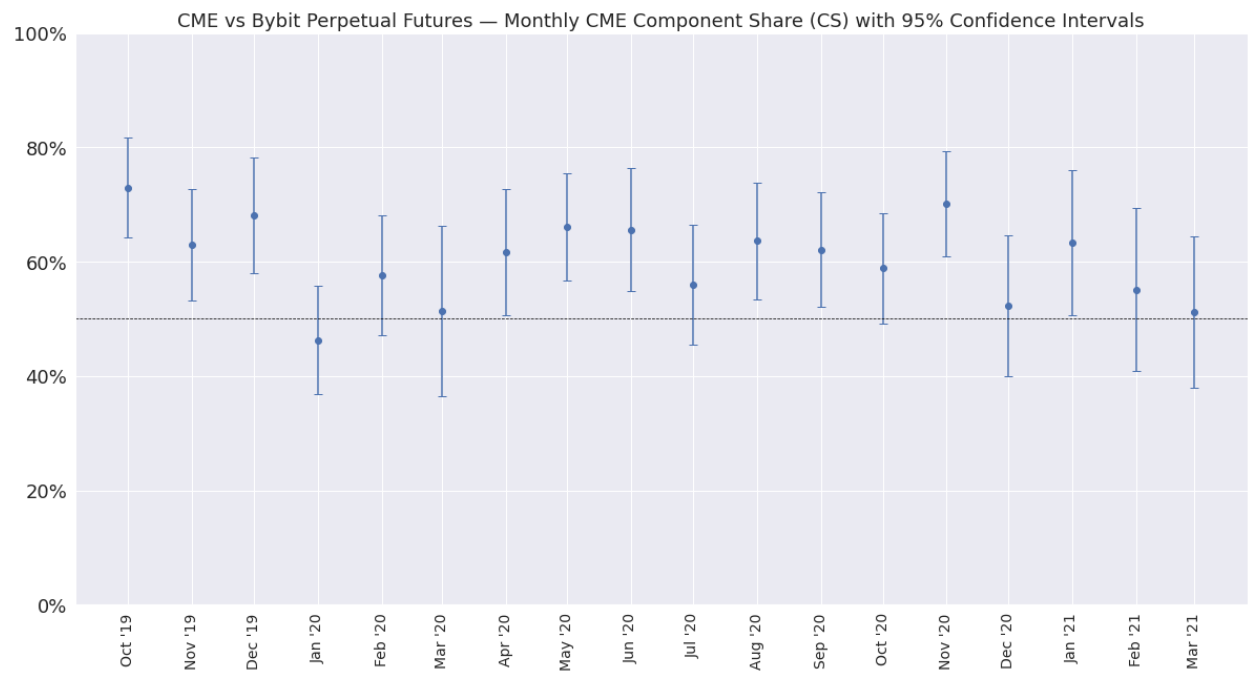
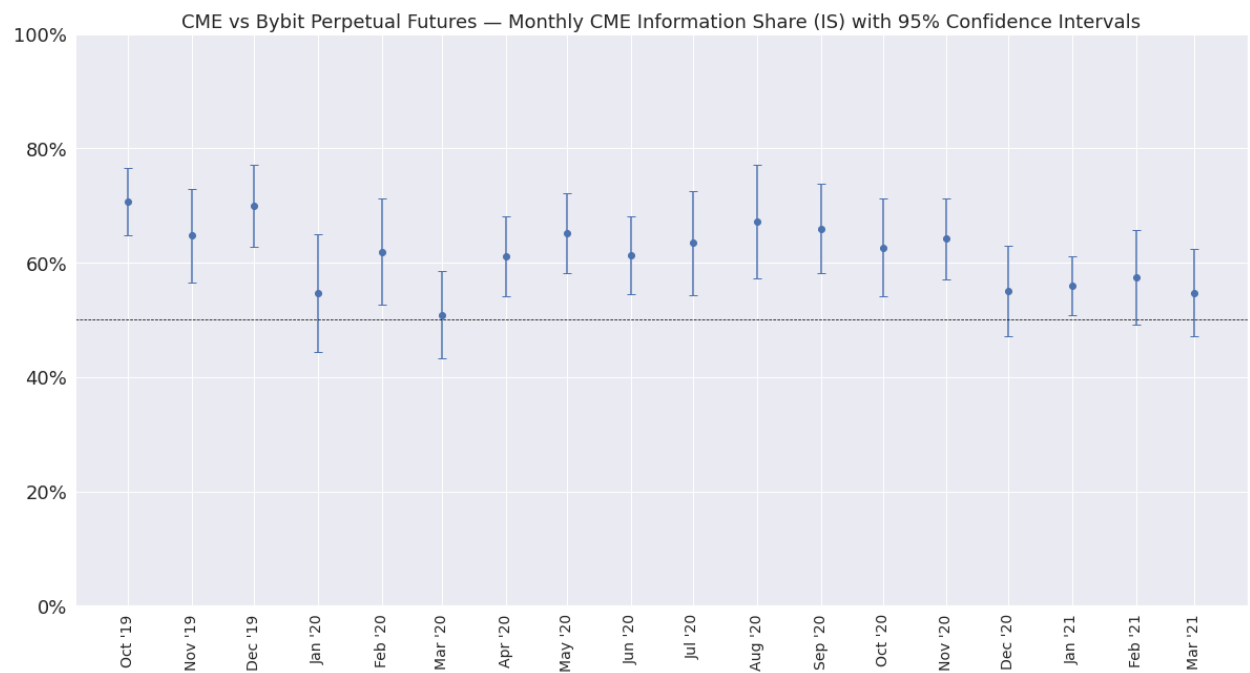
CME vs. BitMEX Perpetual Futures (Table)

Month	CME IS	Confidence Interval	CME CS	Confidence Interval
Dec '17	45.88%	27.96% - 63.80%	44.61%	24.45% - 64.78%
Jan '18	48.95%	43.55% - 54.36%	44.64%	31.83% - 57.45%
Feb '18	51.78%	43.83% - 59.73%	51.66%	39.22% - 64.10%
Mar '18	52.66%	46.35% - 58.98%	58.47%	46.45% - 70.49%
Apr '18	66.32%*	56.29% - 76.36%	69.58%*	58.62% - 80.53%
May '18	68.32%*	59.52% - 77.11%	65.62%*	55.51% - 75.73%
Jun '18	76.72%*	70.58% - 82.86%	77.21%*	69.63% - 84.78%
Jul '18	73.58%*	65.67% - 81.49%	75.07%*	65.96% - 84.18%
Aug '18	66.49%*	58.69% - 74.29%	68.85%*	58.52% - 79.18%
Sep '18	70.49%*	62.11% - 78.87%	76.45%*	67.23% - 85.68%
Oct '18	69.40%*	59.19% - 79.62%	62.08%*	52.24% - 71.93%
Nov '18	54.57%	43.56% - 65.57%	54.17%	43.07% - 65.27%
Dec '18	48.00%	35.93% - 60.07%	45.20%	31.61% - 58.78%
Jan '19	69.22%*	58.49% - 79.94%	62.34%*	50.82% - 73.87%
Feb '19	57.87%	46.60% - 69.14%	56.39%	43.86% - 68.93%
Mar '19	65.19%*	58.27% - 72.11%	67.07%*	57.81% - 76.33%
Apr '19	72.84%*	65.93% - 79.74%	76.40%*	69.10% - 83.70%
May '19	71.09%*	61.61% - 80.57%	69.16%*	58.36% - 79.97%
Jun '19	55.28%	44.79% - 65.76%	61.96%	48.76% - 75.15%
Jul '19	61.46%*	51.65% - 71.28%	67.54%*	56.67% - 78.41%
Aug '19	66.44%*	58.99% - 73.88%	71.76%*	61.26% - 82.27%
Sep '19	61.21%*	52.70% - 69.71%	55.46%	45.35% - 65.58%
Oct '19	62.23%*	54.30% - 70.17%	64.54%*	54.09% - 74.99%
Nov '19	60.16%*	51.35% - 68.97%	58.79%	47.33% - 70.25%
Dec '19	72.62%*	66.11% - 79.12%	71.78%*	63.58% - 79.98%
Jan '20	59.64%	49.03% - 70.26%	55.30%	45.47% - 65.13%
Feb '20	69.59%*	60.29% - 78.89%	65.69%*	54.74% - 76.64%
Mar '20	55.27%	46.95% - 63.58%	60.46%*	50.38% - 70.55%
Apr '20	66.04%*	58.99% - 73.09%	71.67%*	63.94% - 79.40%
May '20	74.48%*	67.01% - 81.95%	76.47%*	67.80% - 85.13%
Jun '20	71.90%*	64.07% - 79.73%	72.17%*	62.42% - 81.91%
Jul '20	73.12%*	64.76% - 81.49%	67.16%*	57.87% - 76.45%
Aug '20	70.67%*	60.63% - 80.71%	65.75%*	55.27% - 76.23%
Sep '20	72.84%*	64.03% - 81.66%	65.98%*	56.05% - 75.91%
Oct '20	63.65%*	54.47% - 72.82%	58.57%	47.59% - 69.55%
Nov '20	63.87%*	57.02% - 70.71%	67.95%*	59.63% - 76.27%
Dec '20	56.34%	48.56% - 64.13%	48.65%	37.59% - 59.71%

Jan '21	56.40%*	50.96% - 61.85%	61.18%*	50.01% - 72.36%
Feb '21	55.76%	47.12% - 64.39%	53.13%	41.24% - 65.01%
Mar '21	54.11%	47.04% - 61.18%	52.08%	39.13% - 65.03%

2017-12-18 - 2021-03-31	63.67%*	62.30% - 65.04%	63.33%*	61.68% - 64.99%
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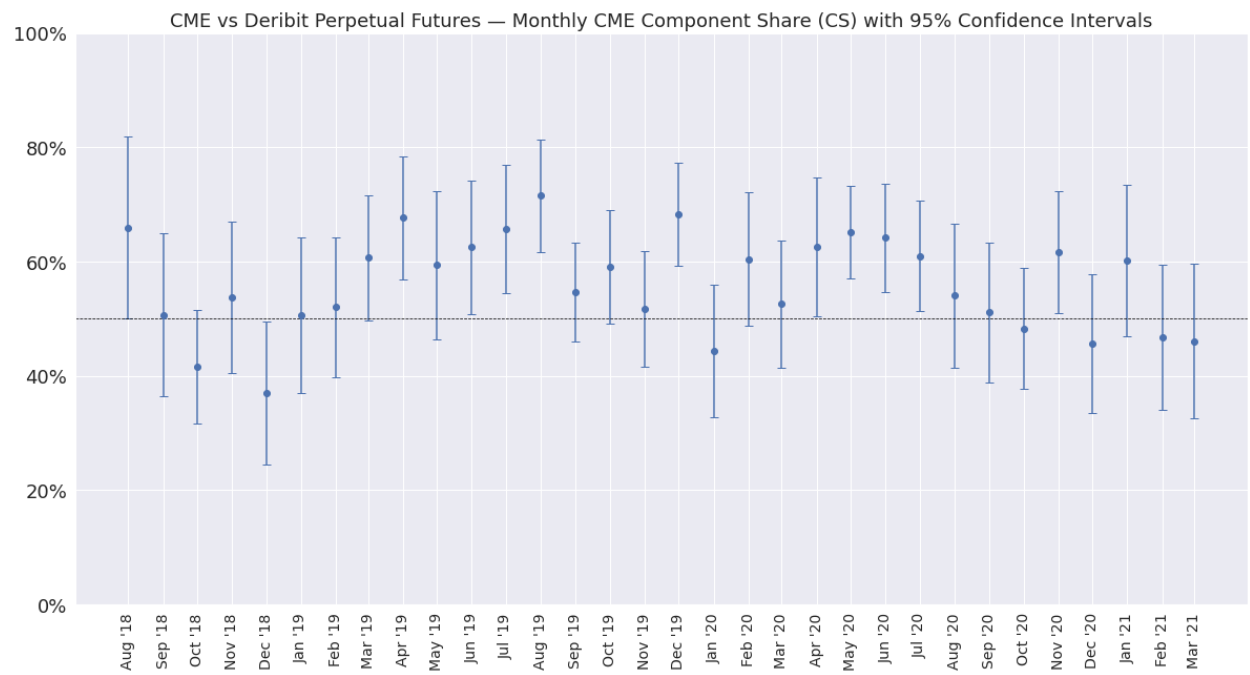
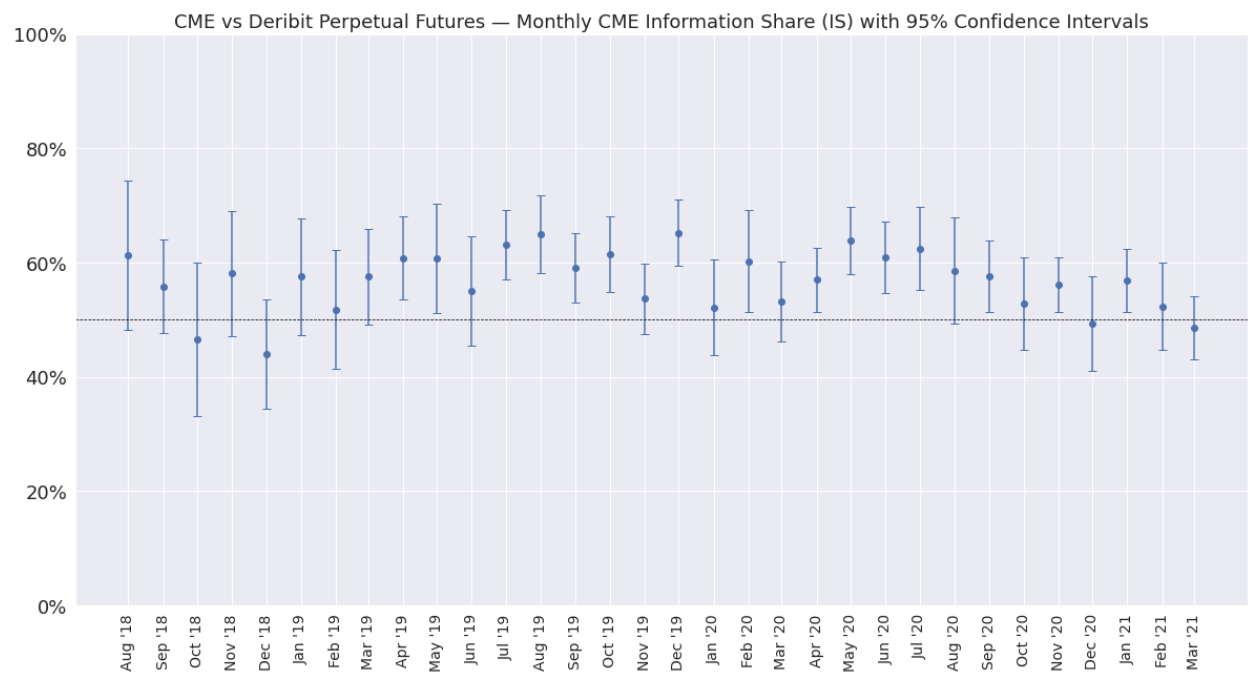
CME vs. Bybit Perpetual Futures (Chart)



CME vs. Bybit Perpetual Futures (Table)

Month	CME IS	Confidence Interval	CME CS	Confidence Interval
Oct '19	70.72%*	64.78% - 76.66%	72.99%*	64.26% - 81.72%
Nov '19	64.73%*	56.52% - 72.94%	62.95%*	53.13% - 72.76%
Dec '19	70.03%*	62.83% - 77.22%	68.10%*	57.96% - 78.24%
Jan '20	54.68%	44.39% - 64.96%	46.28%	36.83% - 55.72%
Feb '20	61.92%*	52.64% - 71.21%	57.58%	47.07% - 68.09%
Mar '20	50.85%	43.24% - 58.47%	51.33%	36.43% - 66.24%
Apr '20	61.13%*	54.12% - 68.14%	61.64%*	50.60% - 72.68%
May '20	65.19%*	58.17% - 72.21%	66.06%*	56.64% - 75.49%
Jun '20	61.27%*	54.50% - 68.04%	65.61%*	54.84% - 76.38%
Jul '20	63.47%*	54.41% - 72.53%	56.03%	45.53% - 66.53%
Aug '20	67.12%*	57.19% - 77.05%	63.64%*	53.48% - 73.80%
Sep '20	65.97%*	58.19% - 73.75%	62.13%*	52.11% - 72.15%
Oct '20	62.63%*	54.10% - 71.16%	58.88%	49.20% - 68.56%
Nov '20	64.19%*	57.07% - 71.30%	70.14%*	61.02% - 79.26%
Dec '20	55.07%	47.23% - 62.91%	52.37%	40.03% - 64.70%
Jan '21	55.96%*	50.75% - 61.16%	63.33%*	50.61% - 76.04%
Feb '21	57.39%	49.14% - 65.64%	55.12%	40.84% - 69.39%
Mar '21	54.77%	47.19% - 62.35%	51.20%	38.01% - 64.39%
2019-10-01 - 2021-03-31	61.50%*	59.69% - 63.30%	60.26%*	57.75% - 62.77%

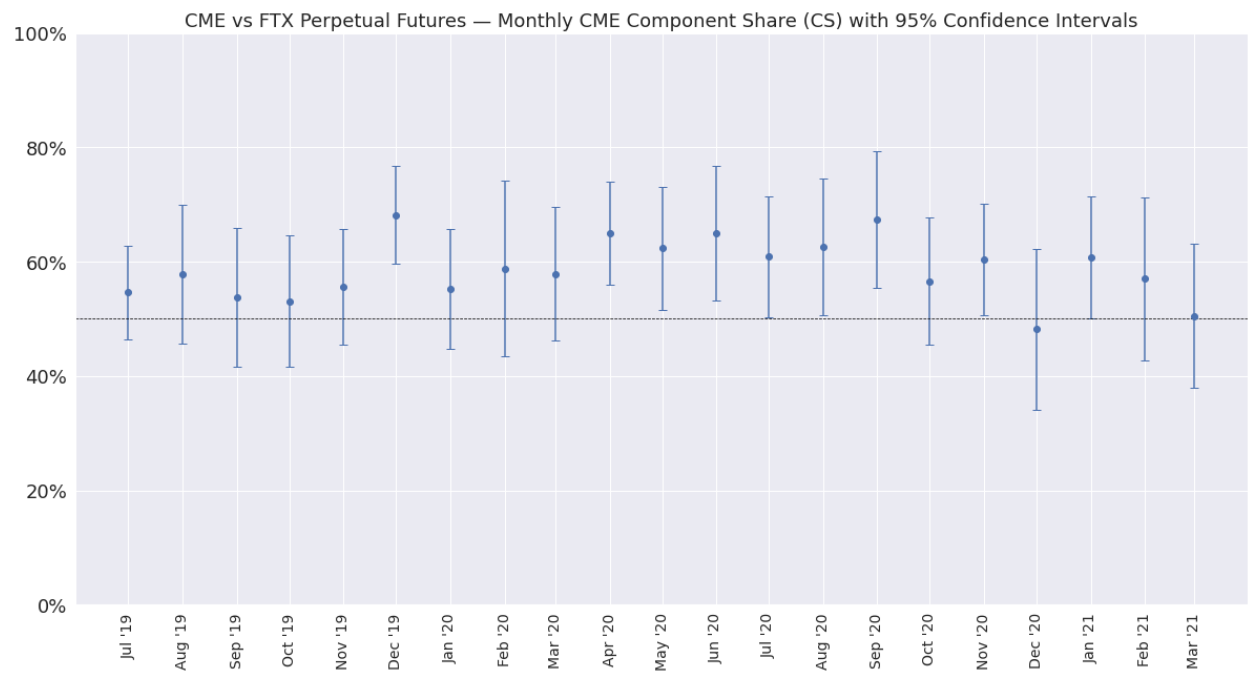
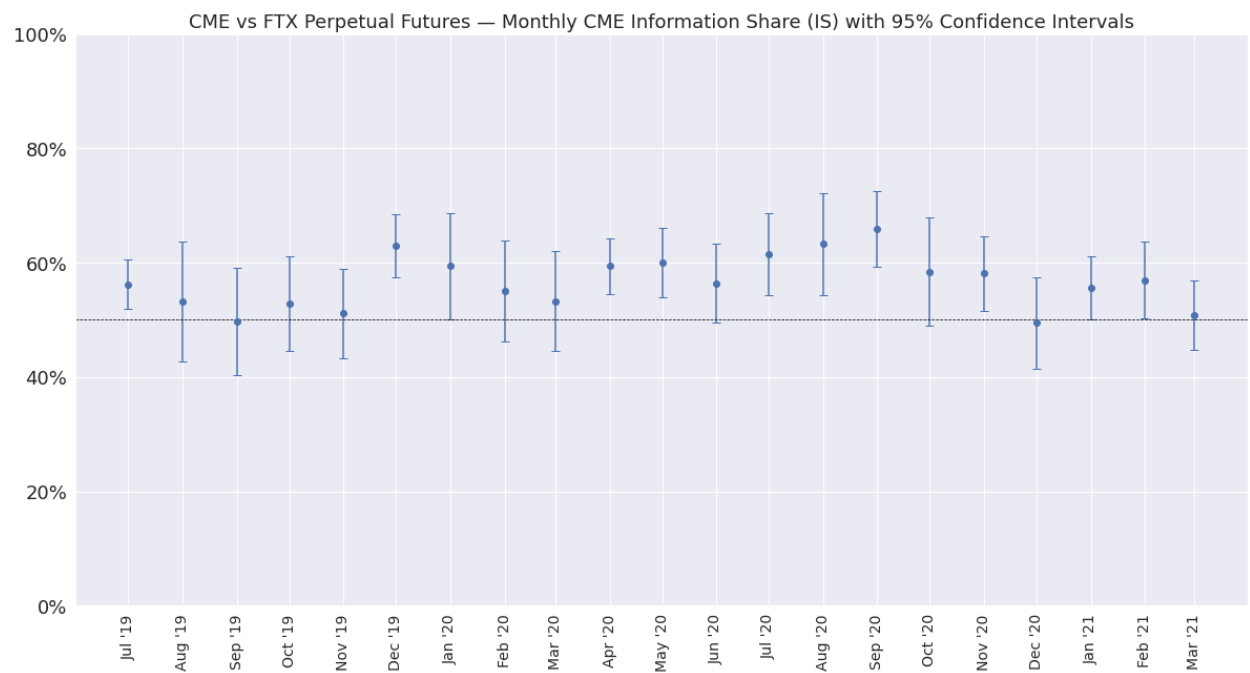
CME vs. Deribit Perpetual Futures (Chart)



CME vs. Deribit Perpetual Futures (Table)

Month	CME IS	Confidence Interval	CME CS	Confidence Interval
Aug '18	61.28%	48.19% - 74.38%	65.98%*	50.08% - 81.87%
Sep '18	55.84%	47.69% - 63.99%	50.64%	36.37% - 64.91%
Oct '18	46.58%	33.08% - 60.08%	41.62%	31.66% - 51.59%
Nov '18	58.09%	47.16% - 69.02%	53.79%	40.59% - 66.99%
Dec '18	43.94%	34.39% - 53.50%	37.03%*	24.45% - 49.61%
Jan '19	57.53%	47.24% - 67.82%	50.61%	37.06% - 64.17%
Feb '19	51.80%	41.34% - 62.26%	52.01%	39.76% - 64.27%
Mar '19	57.55%	49.20% - 65.89%	60.70%	49.79% - 71.61%
Apr '19	60.77%*	53.51% - 68.04%	67.66%*	56.92% - 78.39%
May '19	60.67%*	51.10% - 70.24%	59.40%	46.41% - 72.40%
Jun '19	55.07%	45.51% - 64.63%	62.55%*	50.89% - 74.22%
Jul '19	63.16%*	57.07% - 69.25%	65.70%*	54.52% - 76.88%
Aug '19	65.04%*	58.24% - 71.84%	71.53%*	61.69% - 81.38%
Sep '19	59.07%*	53.04% - 65.10%	54.61%	45.99% - 63.23%
Oct '19	61.49%*	54.81% - 68.17%	59.07%	49.08% - 69.06%
Nov '19	53.70%	47.51% - 59.89%	51.73%	41.54% - 61.92%
Dec '19	65.24%*	59.47% - 71.00%	68.34%*	59.34% - 77.35%
Jan '20	52.13%	43.76% - 60.49%	44.35%	32.74% - 55.95%
Feb '20	60.22%*	51.29% - 69.16%	60.38%	48.70% - 72.06%
Mar '20	53.20%	46.13% - 60.26%	52.59%	41.50% - 63.69%
Apr '20	57.02%*	51.38% - 62.65%	62.60%*	50.40% - 74.80%
May '20	63.87%*	57.95% - 69.79%	65.08%*	56.99% - 73.17%
Jun '20	60.97%*	54.73% - 67.21%	64.16%*	54.69% - 73.64%
Jul '20	62.44%*	55.18% - 69.71%	60.97%*	51.28% - 70.67%
Aug '20	58.57%	49.26% - 67.87%	54.05%	41.49% - 66.61%
Sep '20	57.66%*	51.43% - 63.88%	51.12%	38.88% - 63.37%
Oct '20	52.81%	44.79% - 60.83%	48.25%	37.68% - 58.82%
Nov '20	56.14%*	51.43% - 60.86%	61.68%*	50.97% - 72.38%
Dec '20	49.31%	41.06% - 57.56%	45.64%	33.47% - 57.82%
Jan '21	56.91%*	51.43% - 62.39%	60.18%	46.90% - 73.45%
Feb '21	52.34%	44.71% - 59.98%	46.79%	34.07% - 59.51%
Mar '21	48.59%	43.03% - 54.14%	46.04%	32.52% - 59.56%
2018-08-14 - 2021-03-31	56.91%*	55.56% - 58.26%	56.20%*	54.23% - 58.17%

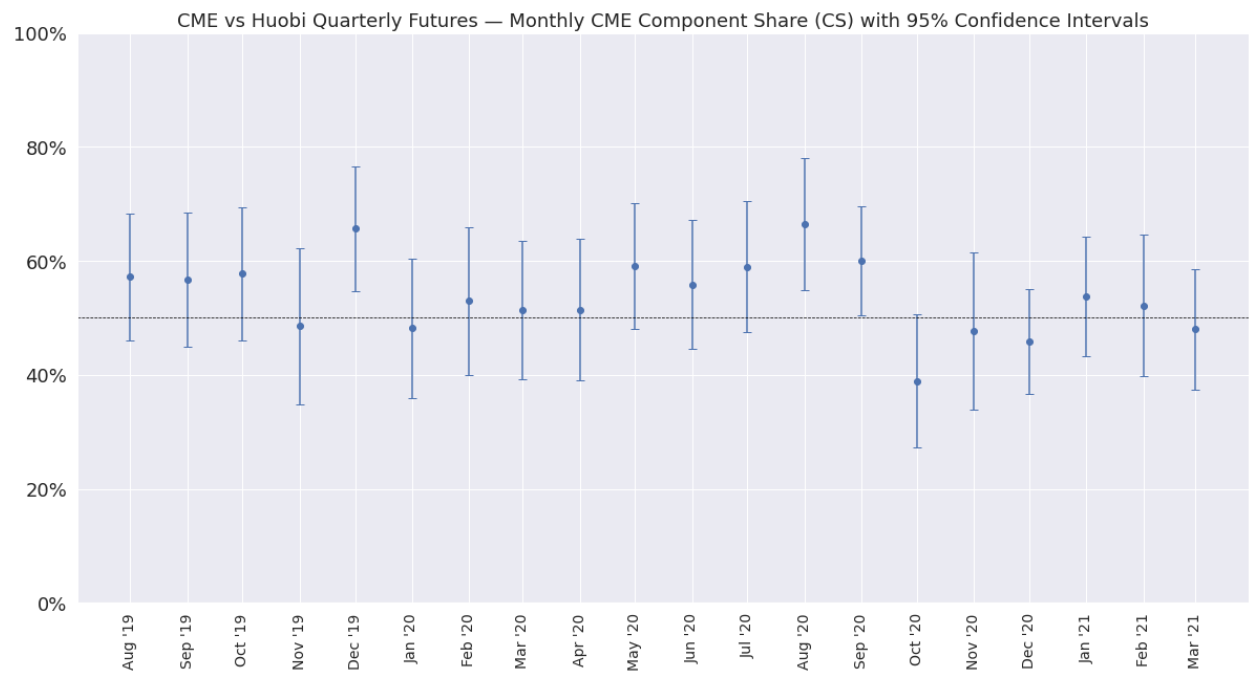
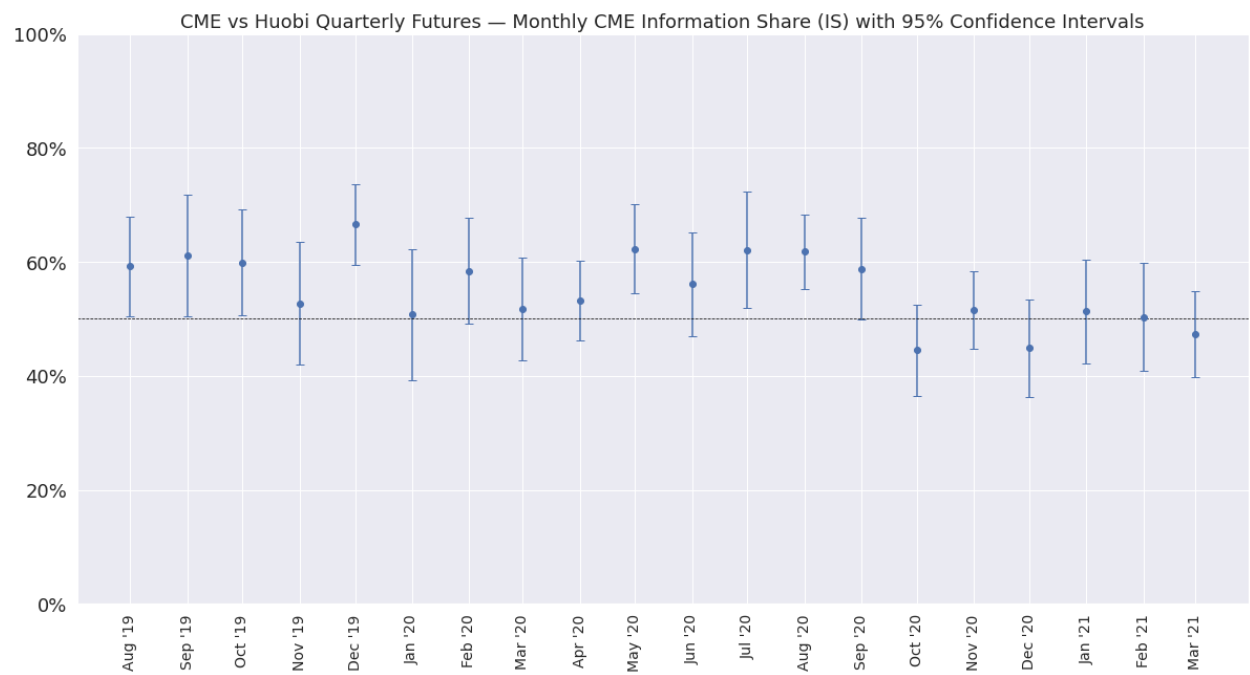
CME vs. FTX Perpetual Futures (Chart)



CME vs. FTX Perpetual Futures (Table)

Month	CME IS	Confidence Interval	CME CS	Confidence Interval
Jul '19	56.20%*	51.89% - 60.50%	54.61%	46.46% - 62.76%
Aug '19	53.27%	42.81% - 63.74%	57.90%	45.76% - 70.04%
Sep '19	49.65%	40.26% - 59.03%	53.79%	41.62% - 65.97%
Oct '19	52.86%	44.58% - 61.13%	53.12%	41.66% - 64.58%
Nov '19	51.15%	43.36% - 58.93%	55.66%	45.52% - 65.81%
Dec '19	62.96%*	57.42% - 68.49%	68.15%*	59.59% - 76.70%
Jan '20	59.39%*	50.09% - 68.69%	55.18%	44.72% - 65.64%
Feb '20	55.02%	46.16% - 63.88%	58.78%	43.40% - 74.16%
Mar '20	53.29%	44.61% - 61.98%	57.91%	46.31% - 69.51%
Apr '20	59.38%*	54.43% - 64.34%	64.94%*	55.91% - 73.98%
May '20	60.01%*	53.93% - 66.10%	62.34%*	51.64% - 73.04%
Jun '20	56.43%	49.58% - 63.27%	65.03%*	53.25% - 76.80%
Jul '20	61.48%*	54.36% - 68.60%	60.89%*	50.33% - 71.45%
Aug '20	63.27%*	54.41% - 72.13%	62.62%*	50.66% - 74.58%
Sep '20	65.94%*	59.27% - 72.61%	67.35%*	55.45% - 79.25%
Oct '20	58.44%	48.91% - 67.97%	56.62%	45.55% - 67.68%
Nov '20	58.18%*	51.65% - 64.72%	60.40%*	50.66% - 70.13%
Dec '20	49.47%	41.42% - 57.52%	48.17%	34.06% - 62.28%
Jan '21	55.62%*	50.12% - 61.12%	60.72%*	50.03% - 71.41%
Feb '21	56.97%*	50.21% - 63.74%	56.99%	42.69% - 71.29%
Mar '21	50.83%	44.75% - 56.91%	50.53%	37.88% - 63.18%
2019-07-01 - 2021-03-31	56.73%*	55.13% - 58.32%	58.72%*	56.33% - 61.10%

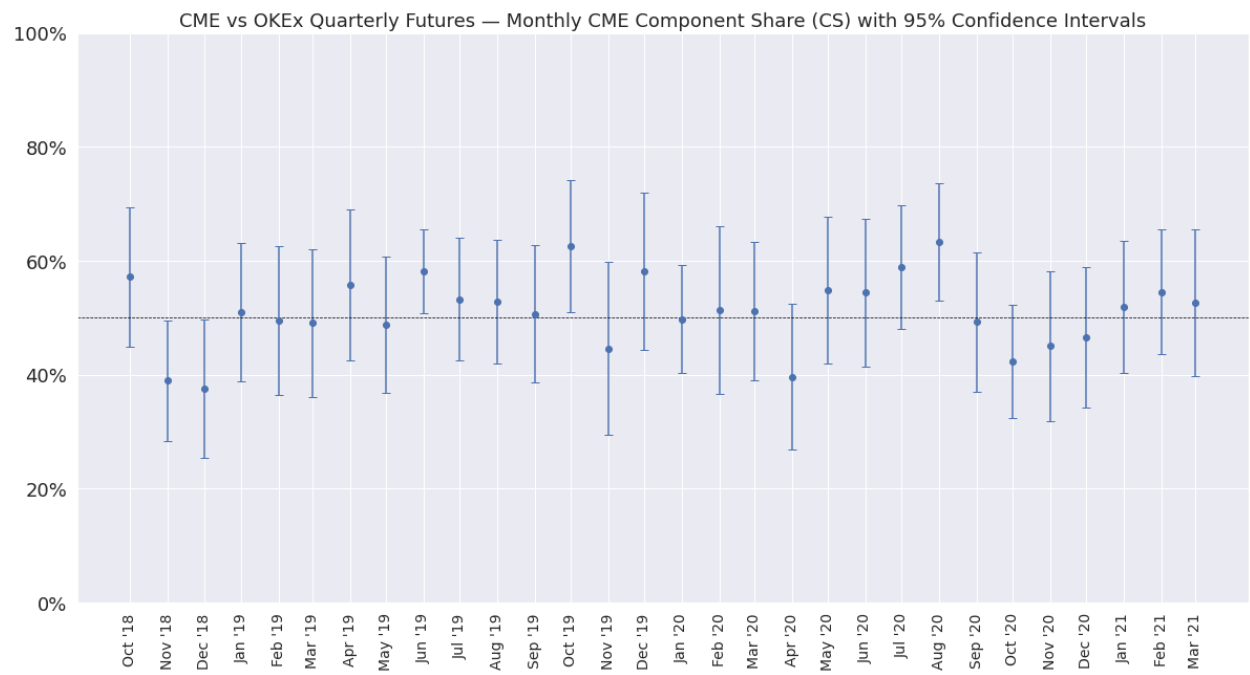
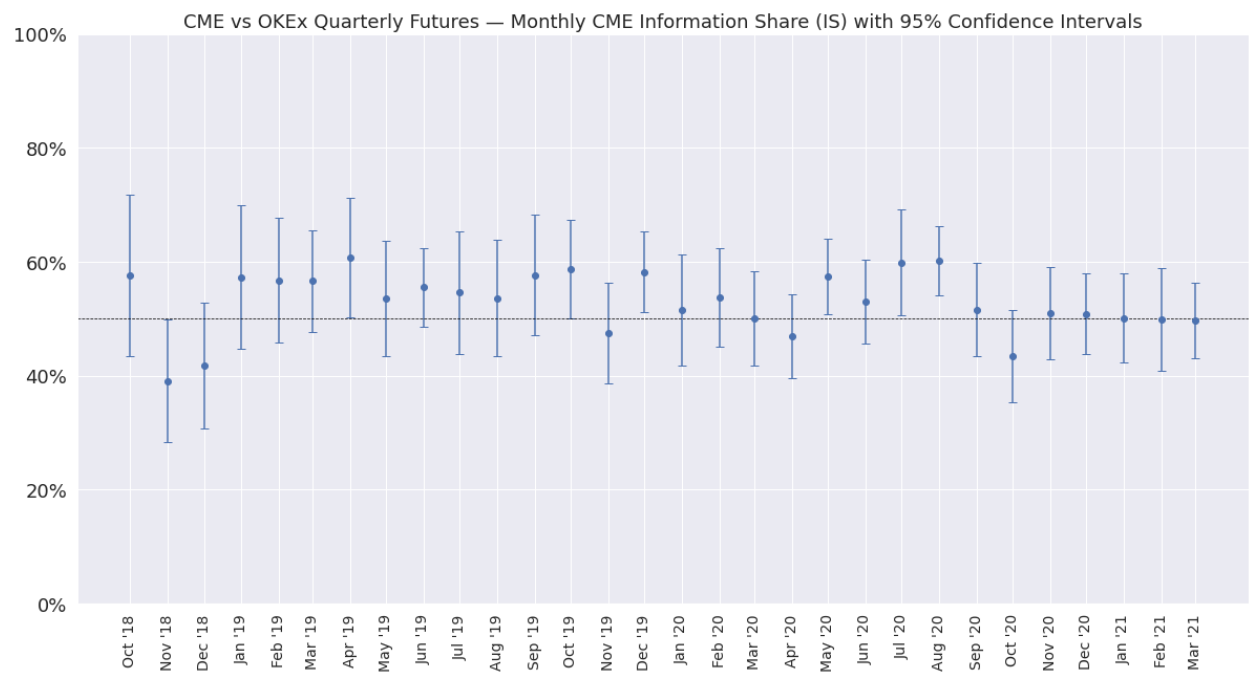
CME vs. Huobi Quarterly Futures (Chart)



CME vs. Huobi Quarterly Futures (Table)

Month	CME IS	Confidence Interval	CME CS	Confidence Interval
Aug '19	59.26%*	50.51% - 68.01%	57.18%	46.00% - 68.36%
Sep '19	61.11%*	50.50% - 71.73%	56.69%	44.90% - 68.49%
Oct '19	59.93%*	50.62% - 69.23%	57.76%	46.12% - 69.40%
Nov '19	52.74%	41.92% - 63.56%	48.58%	34.86% - 62.31%
Dec '19	66.59%*	59.53% - 73.65%	65.67%*	54.67% - 76.67%
Jan '20	50.80%	39.32% - 62.28%	48.19%	35.93% - 60.46%
Feb '20	58.46%	49.13% - 67.79%	52.99%	40.04% - 65.94%
Mar '20	51.83%	42.81% - 60.84%	51.37%	39.30% - 63.44%
Apr '20	53.23%	46.28% - 60.17%	51.40%	38.97% - 63.83%
May '20	62.29%*	54.49% - 70.09%	59.10%	48.14% - 70.06%
Jun '20	56.07%	46.94% - 65.20%	55.88%	44.49% - 67.26%
Jul '20	62.10%*	51.86% - 72.35%	58.99%	47.46% - 70.51%
Aug '20	61.82%*	55.32% - 68.32%	66.42%*	54.80% - 78.04%
Sep '20	58.81%	49.90% - 67.73%	60.03%*	50.48% - 69.57%
Oct '20	44.52%	36.53% - 52.51%	38.91%	27.20% - 50.62%
Nov '20	51.51%	44.68% - 58.33%	47.78%	33.99% - 61.58%
Dec '20	44.86%	36.33% - 53.40%	45.93%	36.74% - 55.12%
Jan '21	51.31%	42.25% - 60.37%	53.78%	43.30% - 64.26%
Feb '21	50.35%	40.93% - 59.77%	52.16%	39.77% - 64.55%
Mar '21	47.34%	39.83% - 54.84%	48.01%	37.40% - 58.62%
2019-08-01 - 2021-03-31	55.25%*	53.33% - 57.17%	53.85%*	51.36% - 56.33%

CME vs. OKEEx Quarterly Futures (Chart)

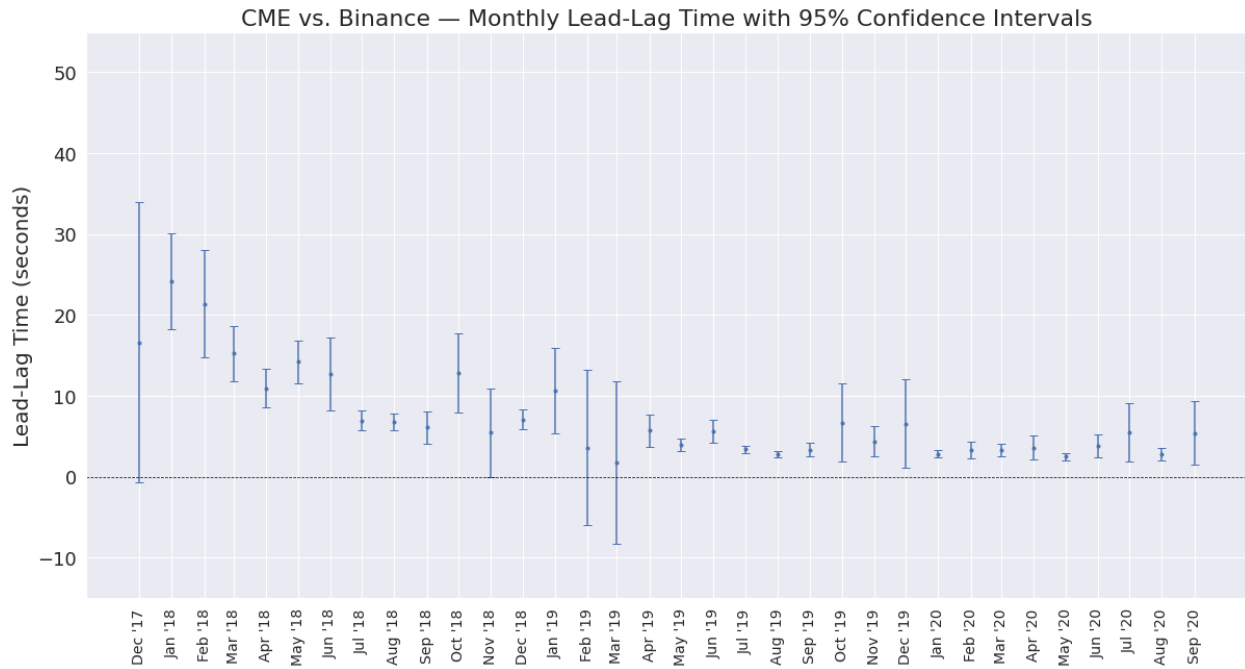


CME vs. OKEEx Quarterly Futures (Table)

Month	CME IS	Confidence Interval	CME CS	Confidence Interval
Oct '18	57.57%	43.38% - 71.76%	57.20%	44.97% - 69.43%
Nov '18	39.06%*	28.29% - 49.84%	38.94%*	28.32% - 49.57%
Dec '18	41.80%	30.72% - 52.88%	37.58%*	25.48% - 49.67%
Jan '19	57.28%	44.70% - 69.87%	50.95%	38.77% - 63.14%
Feb '19	56.77%	45.78% - 67.77%	49.54%	36.46% - 62.62%
Mar '19	56.63%	47.74% - 65.51%	49.10%	36.09% - 62.10%
Apr '19	60.75%*	50.24% - 71.27%	55.78%	42.55% - 69.01%
May '19	53.63%	43.54% - 63.73%	48.78%	36.89% - 60.66%
Jun '19	55.51%	48.60% - 62.42%	58.15%*	50.82% - 65.47%
Jul '19	54.64%	43.89% - 65.39%	53.26%	42.51% - 64.01%
Aug '19	53.63%	43.47% - 63.78%	52.86%	42.02% - 63.71%
Sep '19	57.66%	47.06% - 68.25%	50.70%	38.69% - 62.72%
Oct '19	58.75%*	50.13% - 67.38%	62.58%*	51.03% - 74.13%
Nov '19	47.52%	38.75% - 56.29%	44.62%	29.40% - 59.84%
Dec '19	58.20%*	51.15% - 65.26%	58.16%	44.40% - 71.91%
Jan '20	51.61%	41.84% - 61.37%	49.79%	40.25% - 59.33%
Feb '20	53.77%	45.17% - 62.36%	51.43%	36.71% - 66.14%
Mar '20	50.08%	41.87% - 58.29%	51.18%	39.02% - 63.34%
Apr '20	46.90%	39.53% - 54.27%	39.67%	26.92% - 52.41%
May '20	57.45%*	50.84% - 64.06%	54.88%	41.96% - 67.80%
Jun '20	53.02%	45.62% - 60.43%	54.44%	41.44% - 67.44%
Jul '20	59.85%*	50.53% - 69.17%	58.92%	48.01% - 69.84%
Aug '20	60.21%*	54.11% - 66.30%	63.33%*	53.10% - 73.56%
Sep '20	51.62%	43.40% - 59.85%	49.27%	37.06% - 61.47%
Oct '20	43.50%	35.44% - 51.56%	42.26%	32.32% - 52.19%
Nov '20	51.00%	42.86% - 59.14%	45.03%	31.94% - 58.12%
Dec '20	50.85%	43.75% - 57.96%	46.57%	34.26% - 58.87%
Jan '21	50.14%	42.27% - 58.01%	51.95%	40.36% - 63.54%
Feb '21	49.91%	40.85% - 58.96%	54.53%	43.62% - 65.44%
Mar '21	49.72%	43.08% - 56.36%	52.63%	39.75% - 65.51%
2018-10-03 - 2021-03-31	53.04%*	51.45% - 54.63%	51.22%	49.14% - 53.31%

Appendix C: List Of Time-Shift Lead-Lag Analysis Monthly Results

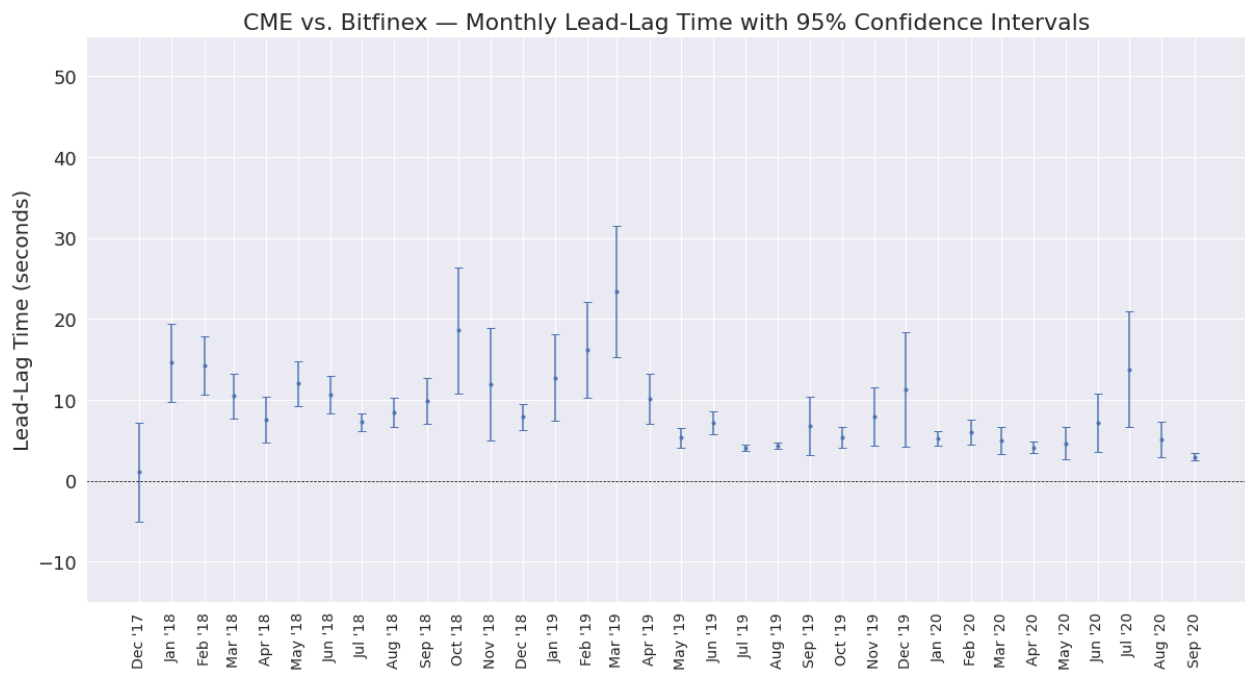
CME vs. Binance (Chart)



CME vs. Binance (Table)

Month	Lead-Lag Time (seconds)	Confidence Interval (seconds)
Dec '17	16.58	-0.74 - 33.90
Jan '18	24.16*	18.24 - 30.09
Feb '18	21.38*	14.71 - 28.05
Mar '18	15.23*	11.83 - 18.62
Apr '18	10.94*	8.55 - 13.34
May '18	14.19*	11.61 - 16.77
Jun '18	12.76*	8.26 - 17.27
Jul '18	6.97*	5.80 - 8.14
Aug '18	6.76*	5.71 - 7.80
Sep '18	6.08*	4.07 - 8.09
Oct '18	12.85*	8.00 - 17.70
Nov '18	5.47	-0.01 - 10.94
Dec '18	7.10*	5.83 - 8.37
Jan '19	10.65*	5.42 - 15.87
Feb '19	3.6	-5.97 - 13.17
Mar '19	1.76	-8.27 - 11.79
Apr '19	5.70*	3.69 - 7.72
May '19	3.95*	3.18 - 4.71
Jun '19	5.64*	4.24 - 7.04
Jul '19	3.37*	2.92 - 3.83
Aug '19	2.81*	2.40 - 3.22
Sep '19	3.36*	2.58 - 4.15
Oct '19	6.70*	1.84 - 11.55
Nov '19	4.38*	2.48 - 6.28
Dec '19	6.58*	1.14 - 12.03
Jan '20	2.81*	2.34 - 3.28
Feb '20	3.28*	2.22 - 4.35
Mar '20	3.28*	2.47 - 4.09
Apr '20	3.63*	2.20 - 5.05
May '20	2.49*	2.02 - 2.95
Jun '20	3.86*	2.45 - 5.28
Jul '20	5.48*	1.92 - 9.04
Aug '20	2.77*	2.04 - 3.50
Sep '20	5.39*	1.47 - 9.31
2017-12-18 - 2020-09-30	7.28*	6.53 - 8.03

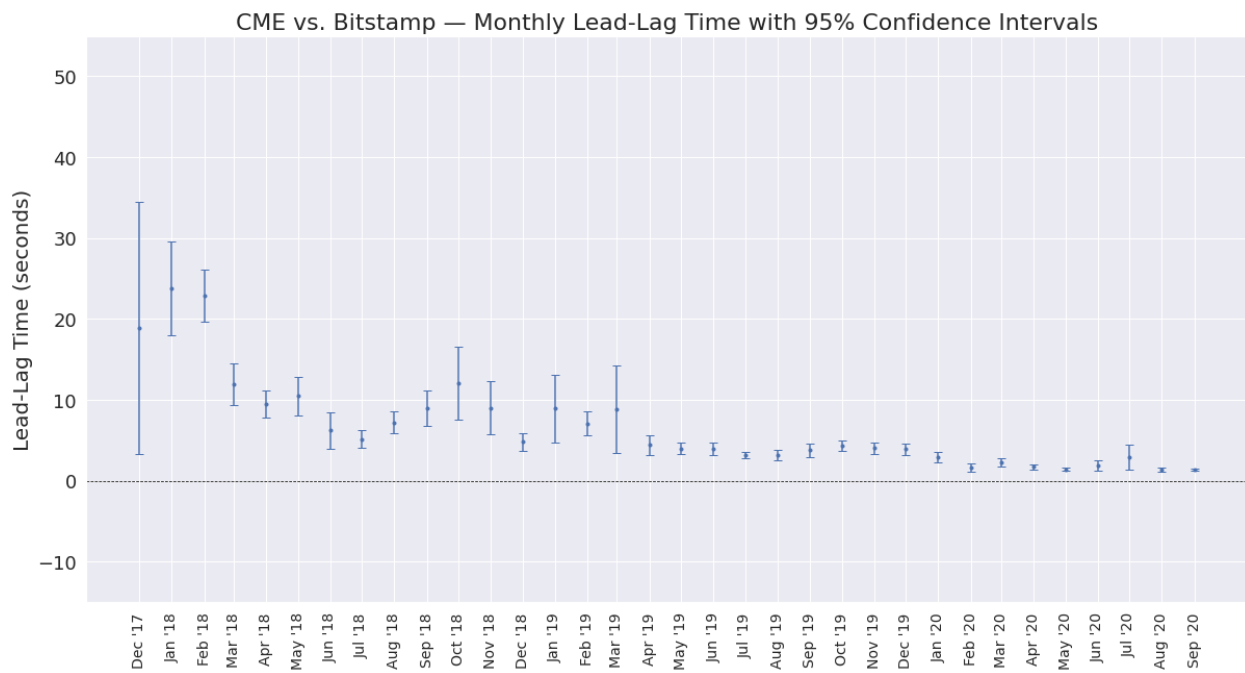
CME vs. Bitfinex (Chart)



CME vs. Bitfinex (Table)

Month	Lead-Lag Time (seconds)	Confidence Interval (seconds)
Dec '17	1.09	-5.05 - 7.23
Jan '18	14.59*	9.79 - 19.40
Feb '18	14.29*	10.70 - 17.88
Mar '18	10.48*	7.70 - 13.25
Apr '18	7.58*	4.73 - 10.43
May '18	12.03*	9.23 - 14.82
Jun '18	10.62*	8.31 - 12.93
Jul '18	7.25*	6.11 - 8.38
Aug '18	8.46*	6.65 - 10.27
Sep '18	9.90*	7.05 - 12.75
Oct '18	18.61*	10.84 - 26.38
Nov '18	11.96*	4.97 - 18.95
Dec '18	7.89*	6.26 - 9.52
Jan '19	12.77*	7.42 - 18.12
Feb '19	16.14*	10.20 - 22.08
Mar '19	23.33*	15.22 - 31.45
Apr '19	10.11*	6.99 - 13.24
May '19	5.35*	4.14 - 6.57
Jun '19	7.14*	5.74 - 8.54
Jul '19	4.11*	3.72 - 4.51
Aug '19	4.34*	3.91 - 4.77
Sep '19	6.81*	3.22 - 10.40
Oct '19	5.35*	4.10 - 6.60
Nov '19	7.96*	4.35 - 11.57
Dec '19	11.28*	4.18 - 18.37
Jan '20	5.23*	4.31 - 6.15
Feb '20	6.03*	4.52 - 7.54
Mar '20	4.95*	3.30 - 6.61
Apr '20	4.12*	3.38 - 4.87
May '20	4.66*	2.64 - 6.68
Jun '20	7.16*	3.53 - 10.79
Jul '20	13.80*	6.64 - 20.96
Aug '20	5.10*	2.95 - 7.24
Sep '20	2.95*	2.52 - 3.38
2017-12-18 - 2020-09-30	9.03*	8.33 - 9.73

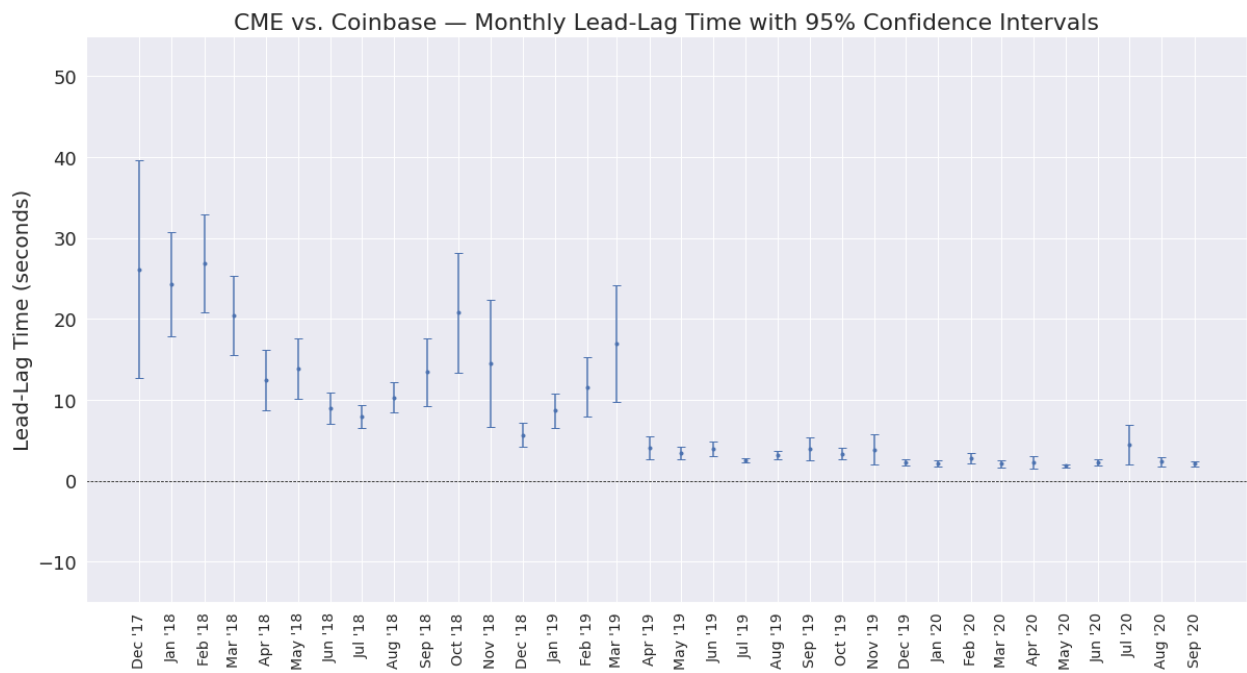
CME vs. Bitstamp (Chart)



CME vs. Bitstamp (Table)

Month	Lead-Lag Time (seconds)	Confidence Interval (seconds)
Dec '17	18.87*	3.31 - 34.43
Jan '18	23.77*	17.94 - 29.61
Feb '18	22.90*	19.72 - 26.08
Mar '18	11.96*	9.37 - 14.56
Apr '18	9.50*	7.82 - 11.19
May '18	10.46*	8.08 - 12.84
Jun '18	6.23*	3.94 - 8.51
Jul '18	5.14*	4.05 - 6.22
Aug '18	7.23*	5.88 - 8.59
Sep '18	8.98*	6.83 - 11.13
Oct '18	12.04*	7.55 - 16.54
Nov '18	9.04*	5.81 - 12.27
Dec '18	4.80*	3.74 - 5.86
Jan '19	8.92*	4.76 - 13.09
Feb '19	7.10*	5.63 - 8.57
Mar '19	8.86*	3.40 - 14.32
Apr '19	4.46*	3.24 - 5.68
May '19	3.98*	3.30 - 4.66
Jun '19	4.00*	3.22 - 4.78
Jul '19	3.16*	2.81 - 3.51
Aug '19	3.15*	2.49 - 3.80
Sep '19	3.79*	2.95 - 4.63
Oct '19	4.30*	3.68 - 4.93
Nov '19	4.02*	3.28 - 4.76
Dec '19	3.93*	3.22 - 4.64
Jan '20	2.95*	2.31 - 3.59
Feb '20	1.65*	1.10 - 2.21
Mar '20	2.31*	1.81 - 2.81
Apr '20	1.71*	1.36 - 2.07
May '20	1.43*	1.26 - 1.60
Jun '20	1.87*	1.27 - 2.48
Jul '20	2.94*	1.44 - 4.44
Aug '20	1.42*	1.18 - 1.66
Sep '20	1.38*	1.22 - 1.54
2017-12-18 - 2020-09-30	6.52*	5.96 - 7.08

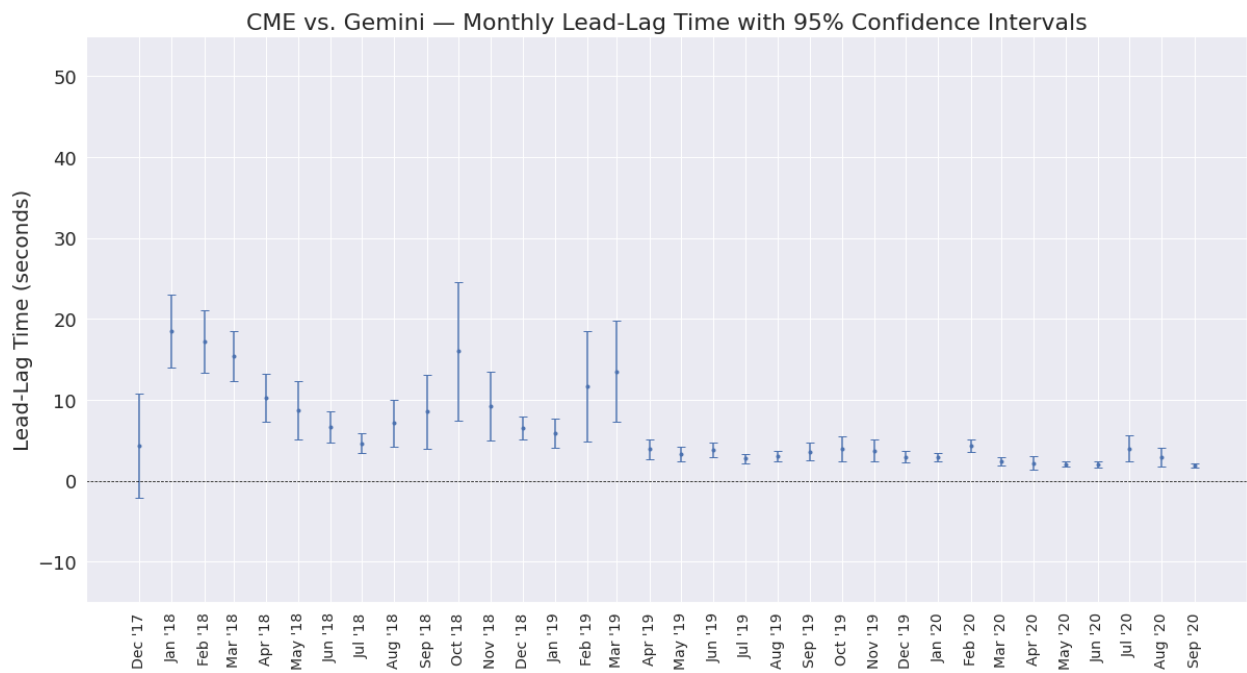
CME vs. Coinbase (Chart)



CME vs. Coinbase (Table)

Month	Lead-Lag Time (seconds)	Confidence Interval (seconds)
Dec '17	26.16*	12.72 - 39.59
Jan '18	24.31*	17.89 - 30.73
Feb '18	26.91*	20.86 - 32.96
Mar '18	20.43*	15.52 - 25.34
Apr '18	12.46*	8.74 - 16.17
May '18	13.85*	10.11 - 17.59
Jun '18	8.92*	7.00 - 10.85
Jul '18	7.91*	6.49 - 9.33
Aug '18	10.30*	8.47 - 12.14
Sep '18	13.42*	9.22 - 17.62
Oct '18	20.79*	13.38 - 28.20
Nov '18	14.52*	6.63 - 22.42
Dec '18	5.67*	4.22 - 7.12
Jan '19	8.66*	6.48 - 10.83
Feb '19	11.58*	7.90 - 15.26
Mar '19	16.95*	9.75 - 24.16
Apr '19	4.07*	2.65 - 5.48
May '19	3.39*	2.62 - 4.16
Jun '19	3.93*	3.03 - 4.83
Jul '19	2.49*	2.23 - 2.75
Aug '19	3.17*	2.70 - 3.64
Sep '19	3.96*	2.58 - 5.35
Oct '19	3.37*	2.67 - 4.06
Nov '19	3.88*	2.00 - 5.75
Dec '19	2.32*	1.94 - 2.70
Jan '20	2.17*	1.79 - 2.55
Feb '20	2.80*	2.11 - 3.49
Mar '20	2.12*	1.65 - 2.58
Apr '20	2.26*	1.51 - 3.01
May '20	1.83*	1.69 - 1.96
Jun '20	2.26*	1.85 - 2.68
Jul '20	4.51*	2.08 - 6.93
Aug '20	2.36*	1.77 - 2.96
Sep '20	2.11*	1.77 - 2.46
2017-12-18 - 2020-09-30	8.42*	7.65 - 9.18

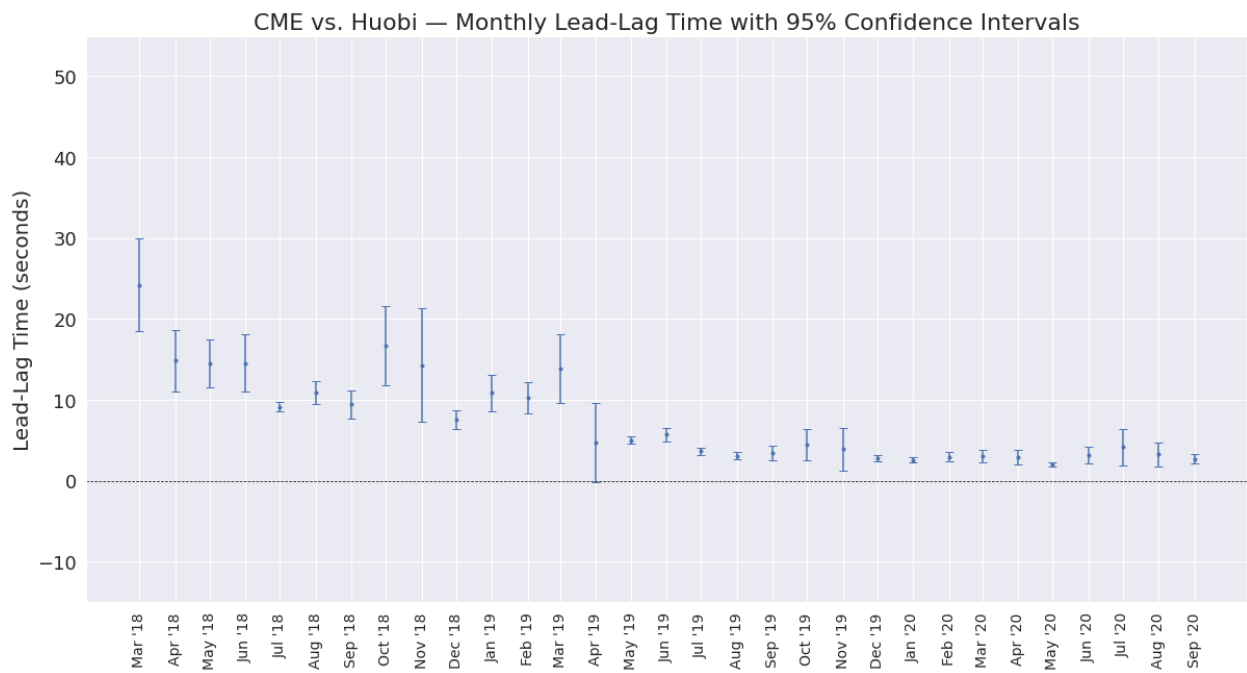
CME vs. Gemini (Chart)



CME vs. Gemini (Table)

Month	Lead-Lag Time (seconds)	Confidence Interval (seconds)
Dec '17	4.36	-2.08 - 10.80
Jan '18	18.52*	14.00 - 23.04
Feb '18	17.22*	13.38 - 21.06
Mar '18	15.40*	12.35 - 18.45
Apr '18	10.29*	7.29 - 13.28
May '18	8.71*	5.07 - 12.36
Jun '18	6.70*	4.75 - 8.64
Jul '18	4.65*	3.46 - 5.85
Aug '18	7.11*	4.17 - 10.06
Sep '18	8.54*	3.93 - 13.15
Oct '18	16.00*	7.40 - 24.60
Nov '18	9.21*	4.93 - 13.49
Dec '18	6.51*	5.09 - 7.93
Jan '19	5.90*	4.07 - 7.72
Feb '19	11.64*	4.81 - 18.47
Mar '19	13.49*	7.24 - 19.74
Apr '19	3.93*	2.72 - 5.14
May '19	3.28*	2.40 - 4.16
Jun '19	3.87*	2.97 - 4.77
Jul '19	2.75*	2.17 - 3.32
Aug '19	3.04*	2.41 - 3.66
Sep '19	3.63*	2.55 - 4.71
Oct '19	3.90*	2.34 - 5.45
Nov '19	3.75*	2.42 - 5.09
Dec '19	2.97*	2.30 - 3.64
Jan '20	2.92*	2.41 - 3.44
Feb '20	4.37*	3.58 - 5.16
Mar '20	2.37*	1.88 - 2.87
Apr '20	2.20*	1.41 - 2.99
May '20	2.06*	1.77 - 2.35
Jun '20	2.00*	1.62 - 2.38
Jul '20	3.97*	2.34 - 5.59
Aug '20	2.91*	1.74 - 4.08
Sep '20	1.86*	1.59 - 2.12
2017-12-18 - 2020-09-30	6.51*	5.91 - 7.11

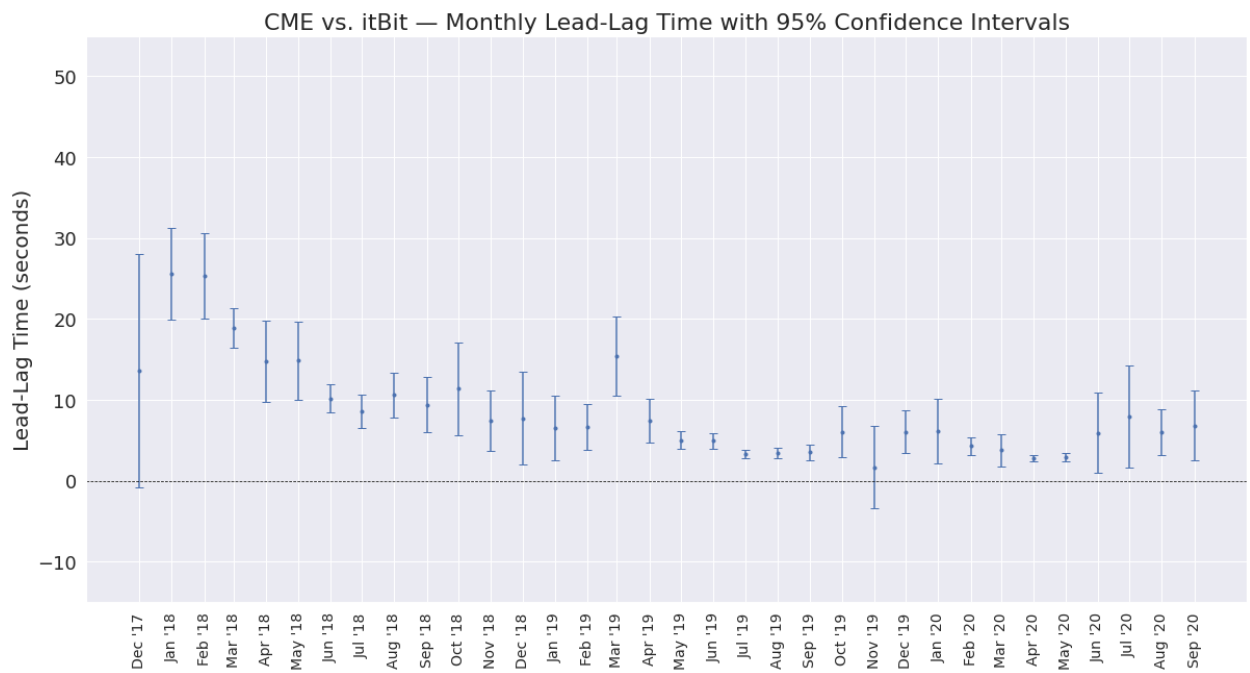
CME vs. Huobi (Chart)



CME vs. Huobi (Table)

Month	Lead-Lag Time (seconds)	Confidence Interval (seconds)
Mar '18	24.21*	18.46 - 29.95
Apr '18	14.86*	11.03 - 18.69
May '18	14.50*	11.59 - 17.41
Jun '18	14.56*	11.00 - 18.13
Jul '18	9.14*	8.54 - 9.73
Aug '18	10.92*	9.49 - 12.36
Sep '18	9.44*	7.68 - 11.20
Oct '18	16.70*	11.80 - 21.59
Nov '18	14.30*	7.24 - 21.35
Dec '18	7.57*	6.43 - 8.71
Jan '19	10.87*	8.62 - 13.12
Feb '19	10.28*	8.32 - 12.24
Mar '19	13.88*	9.65 - 18.11
Apr '19	4.78	-0.11 - 9.67
May '19	5.02*	4.58 - 5.46
Jun '19	5.75*	4.91 - 6.59
Jul '19	3.64*	3.18 - 4.11
Aug '19	3.10*	2.62 - 3.58
Sep '19	3.46*	2.55 - 4.36
Oct '19	4.43*	2.48 - 6.37
Nov '19	3.94*	1.31 - 6.57
Dec '19	2.76*	2.37 - 3.16
Jan '20	2.56*	2.26 - 2.86
Feb '20	2.96*	2.38 - 3.54
Mar '20	3.07*	2.34 - 3.81
Apr '20	2.91*	2.03 - 3.80
May '20	2.02*	1.72 - 2.32
Jun '20	3.15*	2.14 - 4.17
Jul '20	4.15*	1.90 - 6.39
Aug '20	3.25*	1.77 - 4.73
Sep '20	2.70*	2.13 - 3.26
2018-03-01 - 2020-09-30	7.57*	6.96 - 8.18

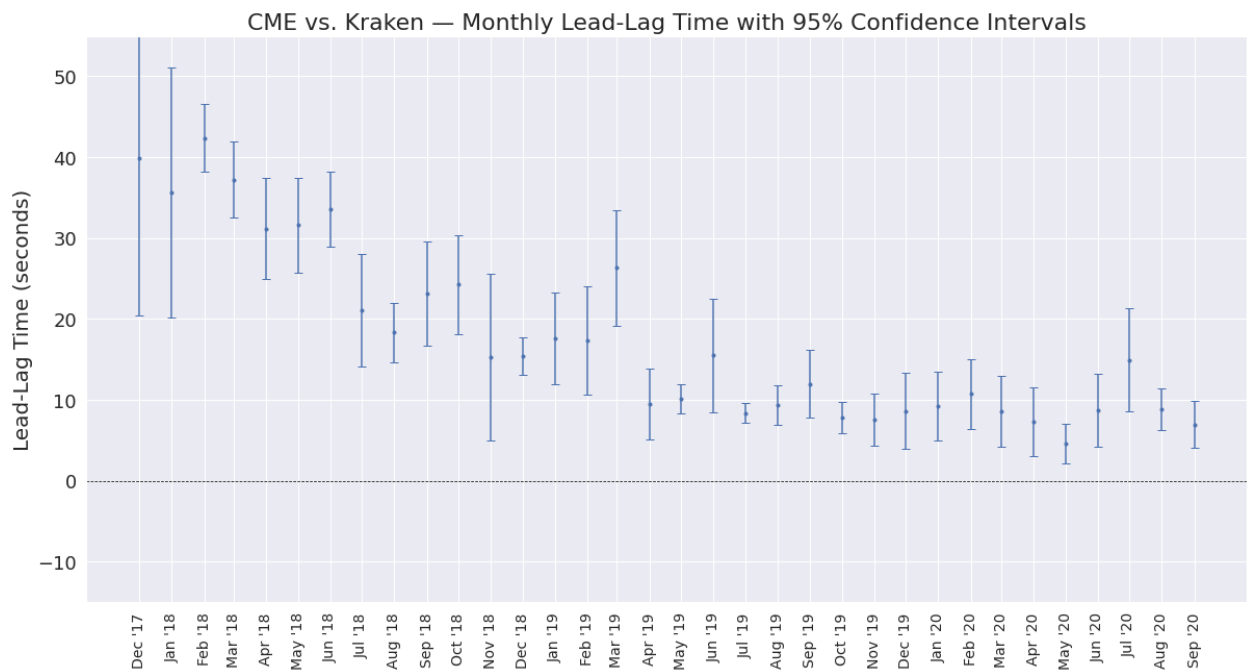
CME vs. itBit (Chart)



CME vs. itBit (Table)

Month	Lead-Lag Time (seconds)	Confidence Interval (seconds)
Dec '17	13.58	-0.86 - 28.01
Jan '18	25.57*	19.88 - 31.27
Feb '18	25.33*	20.01 - 30.65
Mar '18	18.86*	16.42 - 21.29
Apr '18	14.77*	9.81 - 19.73
May '18	14.83*	10.00 - 19.67
Jun '18	10.15*	8.40 - 11.90
Jul '18	8.56*	6.53 - 10.60
Aug '18	10.59*	7.84 - 13.34
Sep '18	9.42*	6.02 - 12.82
Oct '18	11.40*	5.65 - 17.15
Nov '18	7.43*	3.66 - 11.20
Dec '18	7.72*	1.97 - 13.47
Jan '19	6.54*	2.53 - 10.56
Feb '19	6.67*	3.83 - 9.52
Mar '19	15.44*	10.54 - 20.34
Apr '19	7.38*	4.69 - 10.07
May '19	5.03*	3.96 - 6.10
Jun '19	4.95*	3.99 - 5.91
Jul '19	3.30*	2.75 - 3.85
Aug '19	3.49*	2.84 - 4.14
Sep '19	3.51*	2.52 - 4.51
Oct '19	6.02*	2.87 - 9.17
Nov '19	1.66	-3.45 - 6.76
Dec '19	6.08*	3.47 - 8.68
Jan '20	6.10*	2.09 - 10.12
Feb '20	4.33*	3.22 - 5.43
Mar '20	3.76*	1.75 - 5.78
Apr '20	2.76*	2.36 - 3.16
May '20	2.89*	2.36 - 3.41
Jun '20	5.92*	0.96 - 10.88
Jul '20	7.97*	1.65 - 14.28
Aug '20	5.97*	3.14 - 8.80
Sep '20	6.84*	2.49 - 11.19
2017-12-18 - 2020-09-30	8.63*	7.89 - 9.37

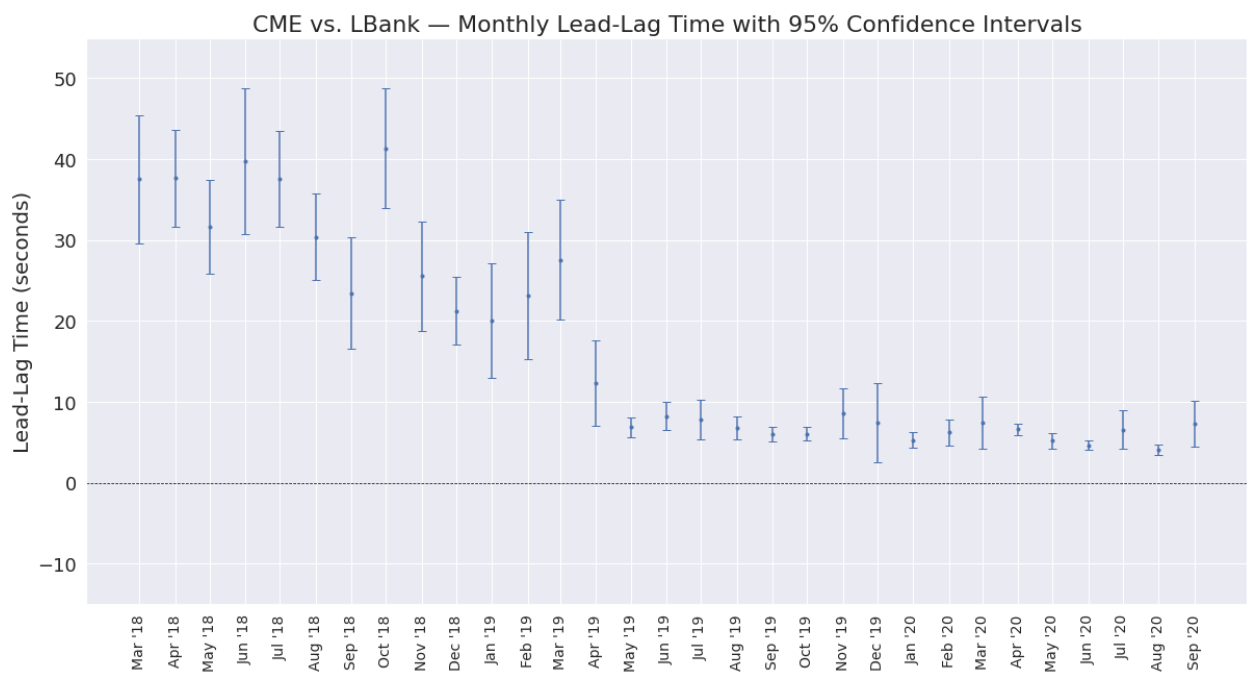
CME vs. Kraken (Chart)



CME vs. Kraken (Table)

Month	Lead-Lag Time (seconds)	Confidence Interval (seconds)
Dec '17	39.91*	20.45 - 59.38
Jan '18	35.66*	20.18 - 51.13
Feb '18	42.38*	38.21 - 46.55
Mar '18	37.23*	32.49 - 41.97
Apr '18	31.17*	24.90 - 37.45
May '18	31.59*	25.75 - 37.43
Jun '18	33.53*	28.91 - 38.16
Jul '18	21.09*	14.18 - 28.00
Aug '18	18.33*	14.62 - 22.04
Sep '18	23.13*	16.66 - 29.60
Oct '18	24.24*	18.12 - 30.37
Nov '18	15.29*	5.03 - 25.54
Dec '18	15.35*	13.03 - 17.67
Jan '19	17.63*	11.96 - 23.30
Feb '19	17.34*	10.70 - 23.98
Mar '19	26.30*	19.11 - 33.48
Apr '19	9.49*	5.13 - 13.85
May '19	10.15*	8.35 - 11.96
Jun '19	15.48*	8.50 - 22.46
Jul '19	8.37*	7.17 - 9.56
Aug '19	9.35*	6.97 - 11.74
Sep '19	11.97*	7.77 - 16.18
Oct '19	7.82*	5.87 - 9.77
Nov '19	7.52*	4.32 - 10.73
Dec '19	8.65*	3.93 - 13.37
Jan '20	9.24*	5.02 - 13.46
Feb '20	10.76*	6.43 - 15.09
Mar '20	8.62*	4.26 - 12.98
Apr '20	7.30*	3.02 - 11.57
May '20	4.57*	2.12 - 7.02
Jun '20	8.73*	4.22 - 13.23
Jul '20	14.94*	8.56 - 21.31
Aug '20	8.82*	6.23 - 11.41
Sep '20	6.96*	4.04 - 9.88
2017-12-18 - 2020-09-30	17.19*	16.00 - 18.38

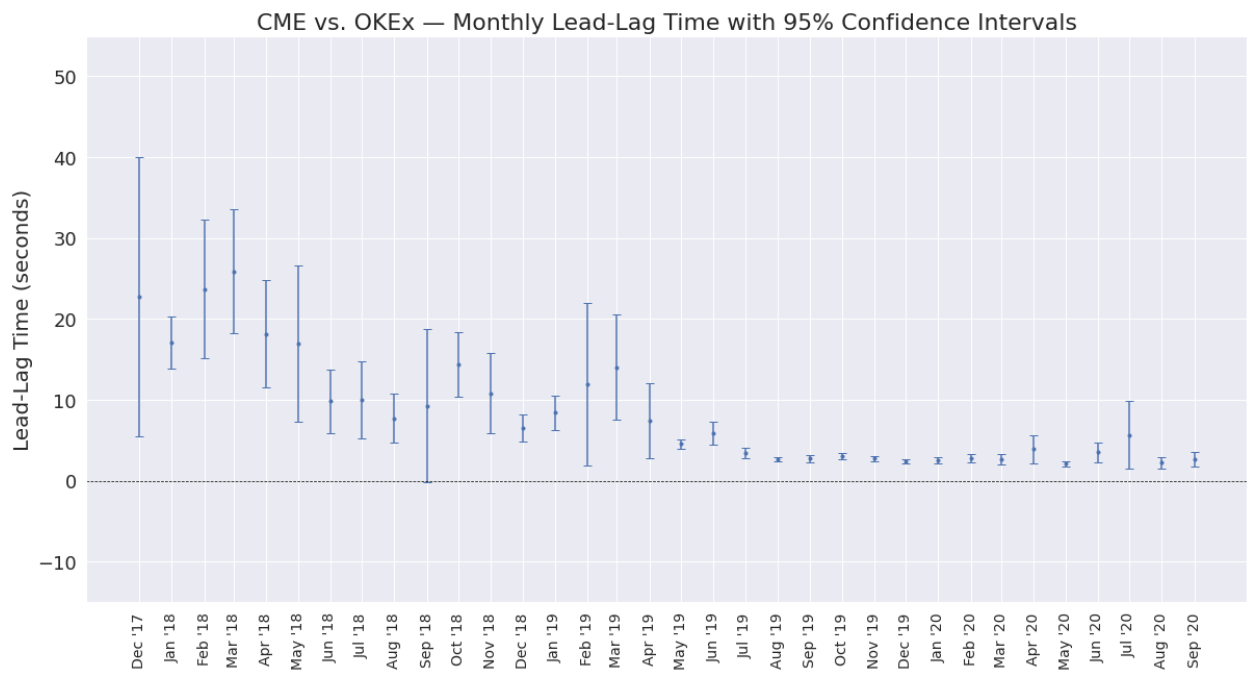
CME vs. LBank (Chart)



CME vs. LBank (Table)

Month	Lead-Lag Time (seconds)	Confidence Interval (seconds)
Mar '18	37.55*	29.64 - 45.46
Apr '18	37.64*	31.68 - 43.59
May '18	31.65*	25.83 - 37.47
Jun '18	39.79*	30.78 - 48.80
Jul '18	37.56*	31.61 - 43.52
Aug '18	30.40*	25.05 - 35.75
Sep '18	23.45*	16.56 - 30.34
Oct '18	41.35*	33.97 - 48.73
Nov '18	25.55*	18.79 - 32.32
Dec '18	21.23*	17.05 - 25.41
Jan '19	20.04*	12.93 - 27.15
Feb '19	23.18*	15.32 - 31.04
Mar '19	27.57*	20.13 - 35.01
Apr '19	12.37*	7.10 - 17.64
May '19	6.86*	5.61 - 8.12
Jun '19	8.22*	6.47 - 9.97
Jul '19	7.83*	5.42 - 10.23
Aug '19	6.76*	5.36 - 8.17
Sep '19	5.99*	5.08 - 6.90
Oct '19	6.07*	5.18 - 6.96
Nov '19	8.62*	5.51 - 11.73
Dec '19	7.42*	2.47 - 12.37
Jan '20	5.29*	4.34 - 6.23
Feb '20	6.21*	4.60 - 7.82
Mar '20	7.42*	4.16 - 10.68
Apr '20	6.65*	5.95 - 7.35
May '20	5.21*	4.25 - 6.17
Jun '20	4.61*	4.02 - 5.20
Jul '20	6.54*	4.15 - 8.93
Aug '20	4.04*	3.41 - 4.67
Sep '20	7.32*	4.52 - 10.13
2018-03-14 - 2020-09-30	16.62*	15.37 - 17.87

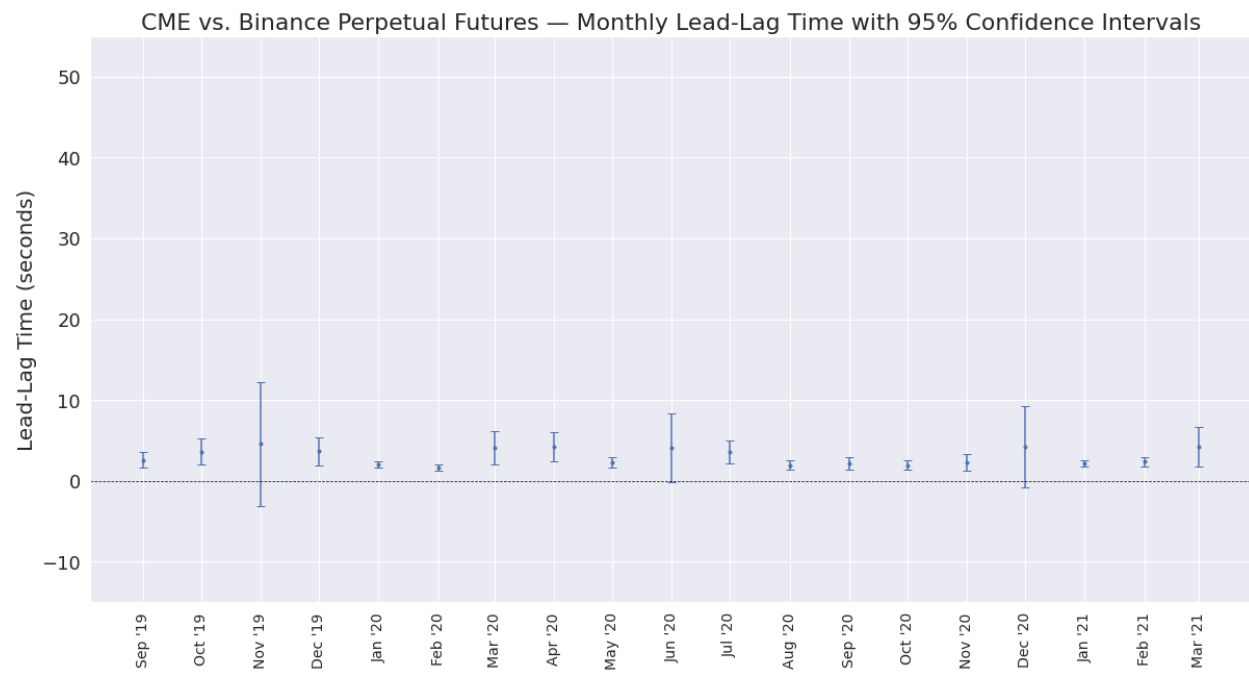
CME vs. OKEx (Chart)



CME vs. OKEEx (Table)

Month	Lead-Lag Time (seconds)	Confidence Interval (seconds)
Dec '17	22.71*	5.45 - 39.97
Jan '18	17.06*	13.82 - 20.30
Feb '18	23.70*	15.14 - 32.26
Mar '18	25.89*	18.20 - 33.58
Apr '18	18.18*	11.57 - 24.79
May '18	16.97*	7.33 - 26.61
Jun '18	9.83*	5.90 - 13.77
Jul '18	9.99*	5.24 - 14.74
Aug '18	7.73*	4.68 - 10.78
Sep '18	9.28	-0.23 - 18.79
Oct '18	14.37*	10.34 - 18.41
Nov '18	10.79*	5.82 - 15.76
Dec '18	6.57*	4.88 - 8.26
Jan '19	8.41*	6.29 - 10.53
Feb '19	11.96*	1.94 - 21.98
Mar '19	14.02*	7.52 - 20.52
Apr '19	7.43*	2.86 - 12.00
May '19	4.56*	3.98 - 5.15
Jun '19	5.84*	4.43 - 7.25
Jul '19	3.41*	2.73 - 4.09
Aug '19	2.63*	2.38 - 2.88
Sep '19	2.73*	2.32 - 3.14
Oct '19	3.02*	2.64 - 3.39
Nov '19	2.75*	2.46 - 3.04
Dec '19	2.41*	2.20 - 2.62
Jan '20	2.51*	2.10 - 2.92
Feb '20	2.76*	2.23 - 3.29
Mar '20	2.65*	2.00 - 3.30
Apr '20	3.90*	2.19 - 5.60
May '20	2.11*	1.78 - 2.45
Jun '20	3.52*	2.32 - 4.72
Jul '20	5.65*	1.49 - 9.82
Aug '20	2.24*	1.53 - 2.95
Sep '20	2.62*	1.73 - 3.51
2017-12-18 - 2020-09-30	8.27*	7.41 - 9.13

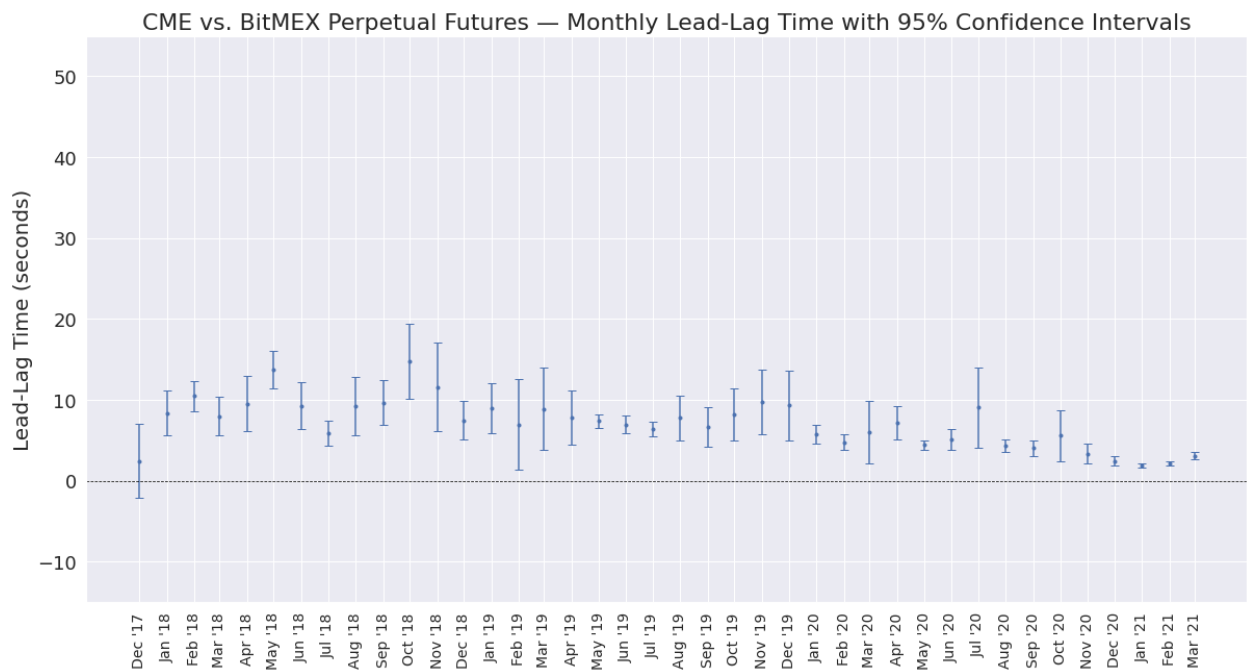
CME vs. Binance Perpetual Futures (Chart)



CME vs. Binance Perpetual Futures (Table)

Month	Lead-Lag Time (seconds)	Confidence Interval (seconds)
Sep '19	2.60*	1.64 - 3.56
Oct '19	3.63*	2.03 - 5.24
Nov '19	4.56	-3.10 - 12.22
Dec '19	3.70*	1.97 - 5.42
Jan '20	2.03*	1.64 - 2.42
Feb '20	1.64*	1.21 - 2.07
Mar '20	4.12*	2.03 - 6.20
Apr '20	4.21*	2.41 - 6.00
May '20	2.32*	1.66 - 2.99
Jun '20	4.08	-0.20 - 8.36
Jul '20	3.59*	2.14 - 5.04
Aug '20	1.94*	1.38 - 2.51
Sep '20	2.19*	1.41 - 2.97
Oct '20	1.95*	1.41 - 2.50
Nov '20	2.29*	1.29 - 3.29
Dec '20	4.21	-0.80 - 9.22
Jan '21	2.19*	1.84 - 2.54
Feb '21	2.41*	1.84 - 2.98
Mar '21	4.28*	1.83 - 6.73
2019-09-09 - 2021-03-31	3.07*	2.50 - 3.65

CME vs. BitMEX Perpetual Futures (Chart)



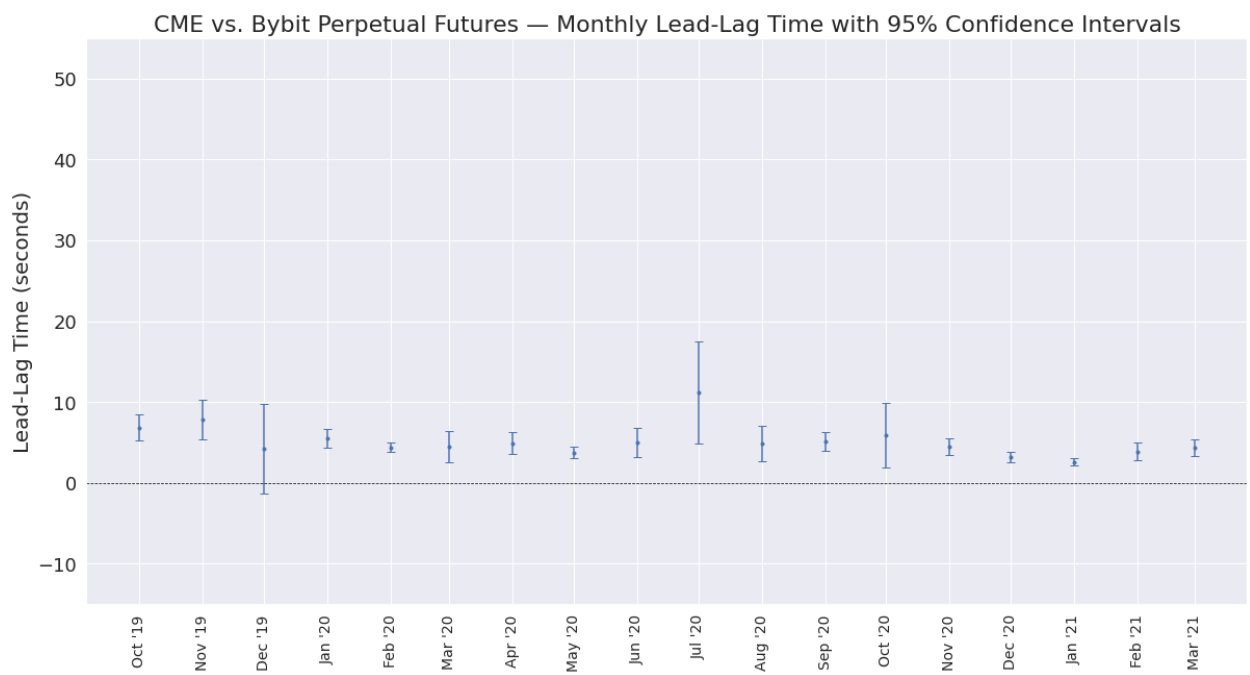
CME vs. BitMEX Perpetual Futures (Table)

Month	Lead-Lag Time (seconds)	Confidence Interval (seconds)
Dec '17	2.47	-2.12 - 7.06
Jan '18	8.39*	5.57 - 11.21
Feb '18	10.47*	8.60 - 12.34
Mar '18	8.00*	5.56 - 10.44
Apr '18	9.52*	6.09 - 12.96
May '18	13.73*	11.42 - 16.04
Jun '18	9.29*	6.35 - 12.23
Jul '18	5.85*	4.31 - 7.40
Aug '18	9.24*	5.67 - 12.82
Sep '18	9.66*	6.87 - 12.45
Oct '18	14.77*	10.09 - 19.46
Nov '18	11.61*	6.14 - 17.08
Dec '18	7.47*	5.07 - 9.87
Jan '19	8.98*	5.87 - 12.09
Feb '19	6.96*	1.38 - 12.54
Mar '19	8.90*	3.76 - 14.05
Apr '19	7.84*	4.52 - 11.15
May '19	7.38*	6.58 - 8.18
Jun '19	6.95*	5.86 - 8.04
Jul '19	6.42*	5.49 - 7.35
Aug '19	7.78*	4.98 - 10.58
Sep '19	6.69*	4.23 - 9.14
Oct '19	8.18*	4.96 - 11.41
Nov '19	9.74*	5.69 - 13.80
Dec '19	9.34*	5.01 - 13.67
Jan '20	5.79*	4.62 - 6.96
Feb '20	4.76*	3.79 - 5.72
Mar '20	6.00*	2.15 - 9.85
Apr '20	7.17*	5.09 - 9.25
May '20	4.42*	3.85 - 4.99
Jun '20	5.09*	3.84 - 6.34
Jul '20	9.04*	4.10 - 13.98
Aug '20	4.33*	3.60 - 5.06
Sep '20	4.02*	3.03 - 5.00
Oct '20	5.57*	2.38 - 8.77
Nov '20	3.36*	2.09 - 4.63
Dec '20	2.42*	1.85 - 2.99

Jan '21	1.87*	1.61 - 2.13
Feb '21	2.17*	1.94 - 2.40
Mar '21	3.11*	2.61 - 3.61

2017-12-18 - 2021-03-31	7.23*	6.76 - 7.70
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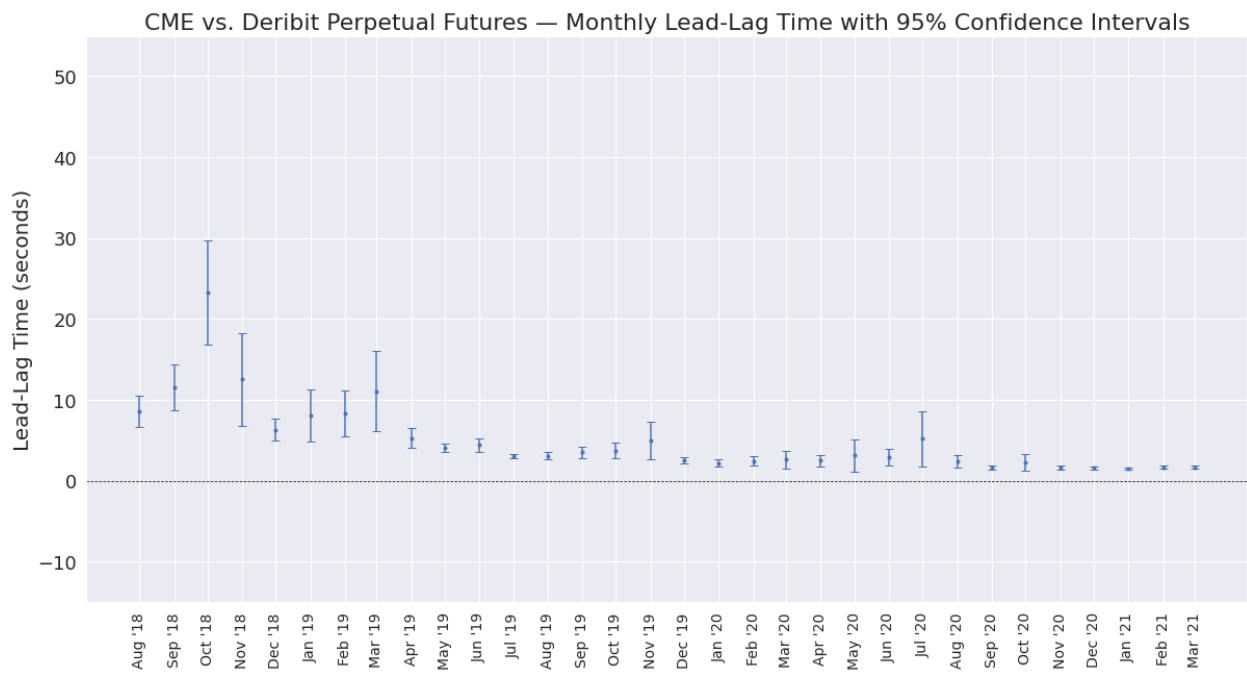
CME vs. Bybit Perpetual Futures (Chart)



CME vs. Bybit Perpetual Futures (Table)

Month	Lead-Lag Time (seconds)	Confidence Interval (seconds)
Oct '19	6.82*	5.20 - 8.43
Nov '19	7.82*	5.36 - 10.28
Dec '19	4.25	-1.30 - 9.80
Jan '20	5.51*	4.36 - 6.67
Feb '20	4.40*	3.81 - 4.99
Mar '20	4.46*	2.53 - 6.40
Apr '20	4.91*	3.55 - 6.27
May '20	3.75*	3.01 - 4.49
Jun '20	4.99*	3.18 - 6.80
Jul '20	11.15*	4.87 - 17.43
Aug '20	4.86*	2.70 - 7.01
Sep '20	5.12*	3.99 - 6.26
Oct '20	5.95*	1.97 - 9.92
Nov '20	4.44*	3.39 - 5.49
Dec '20	3.23*	2.59 - 3.87
Jan '21	2.59*	2.12 - 3.06
Feb '21	3.89*	2.83 - 4.95
Mar '21	4.38*	3.34 - 5.43
2019-10-01 - 2021-03-31	5.13*	4.56 - 5.70

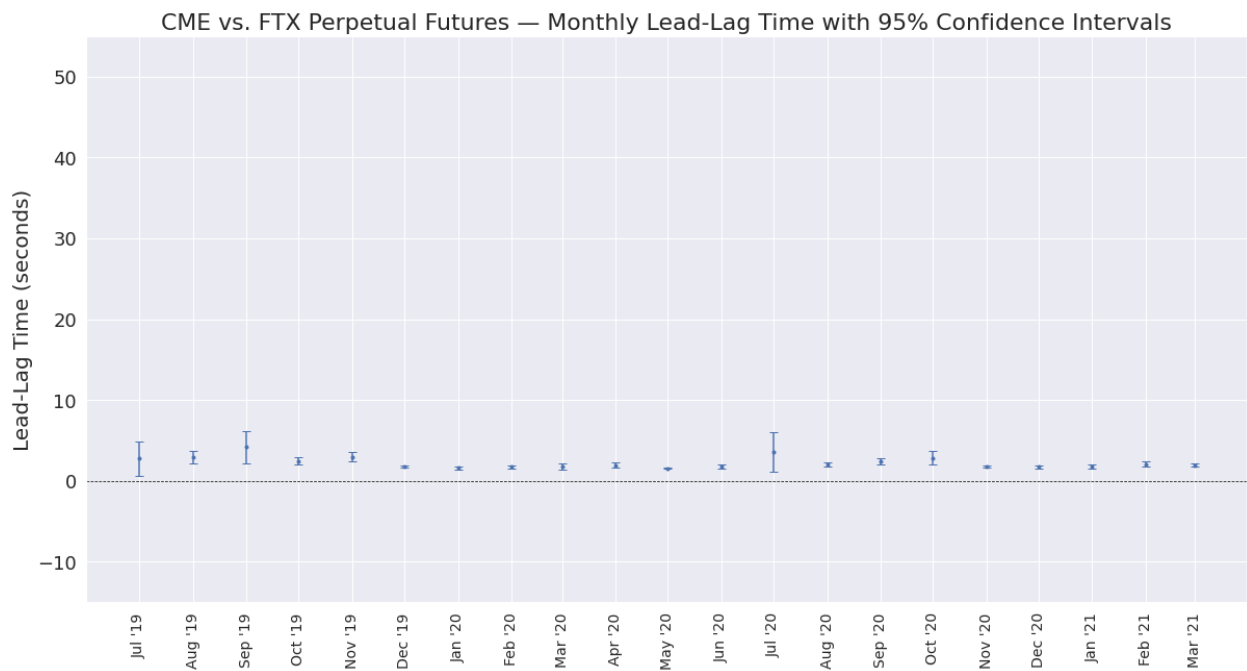
CME vs. Deribit Perpetual Futures (Chart)



CME vs. Deribit Perpetual Futures (Table)

Month	Lead-Lag Time (seconds)	Confidence Interval (seconds)
Aug '18	8.59*	6.69 - 10.48
Sep '18	11.50*	8.67 - 14.33
Oct '18	23.22*	16.78 - 29.66
Nov '18	12.56*	6.82 - 18.30
Dec '18	6.30*	4.93 - 7.67
Jan '19	8.10*	4.87 - 11.32
Feb '19	8.36*	5.56 - 11.16
Mar '19	11.06*	6.11 - 16.01
Apr '19	5.30*	4.03 - 6.56
May '19	4.08*	3.52 - 4.64
Jun '19	4.43*	3.62 - 5.24
Jul '19	3.09*	2.84 - 3.34
Aug '19	3.06*	2.61 - 3.52
Sep '19	3.56*	2.85 - 4.27
Oct '19	3.73*	2.77 - 4.69
Nov '19	4.97*	2.70 - 7.24
Dec '19	2.50*	2.10 - 2.91
Jan '20	2.17*	1.73 - 2.62
Feb '20	2.46*	1.92 - 3.01
Mar '20	2.61*	1.52 - 3.70
Apr '20	2.50*	1.79 - 3.20
May '20	3.13*	1.14 - 5.12
Jun '20	2.94*	1.91 - 3.96
Jul '20	5.20*	1.80 - 8.60
Aug '20	2.37*	1.60 - 3.14
Sep '20	1.64*	1.40 - 1.88
Oct '20	2.26*	1.27 - 3.26
Nov '20	1.64*	1.41 - 1.87
Dec '20	1.62*	1.42 - 1.82
Jan '21	1.47*	1.34 - 1.60
Feb '21	1.67*	1.44 - 1.90
Mar '21	1.65*	1.46 - 1.84
2018-08-14 - 2021-03-31	4.98*	4.47 - 5.49

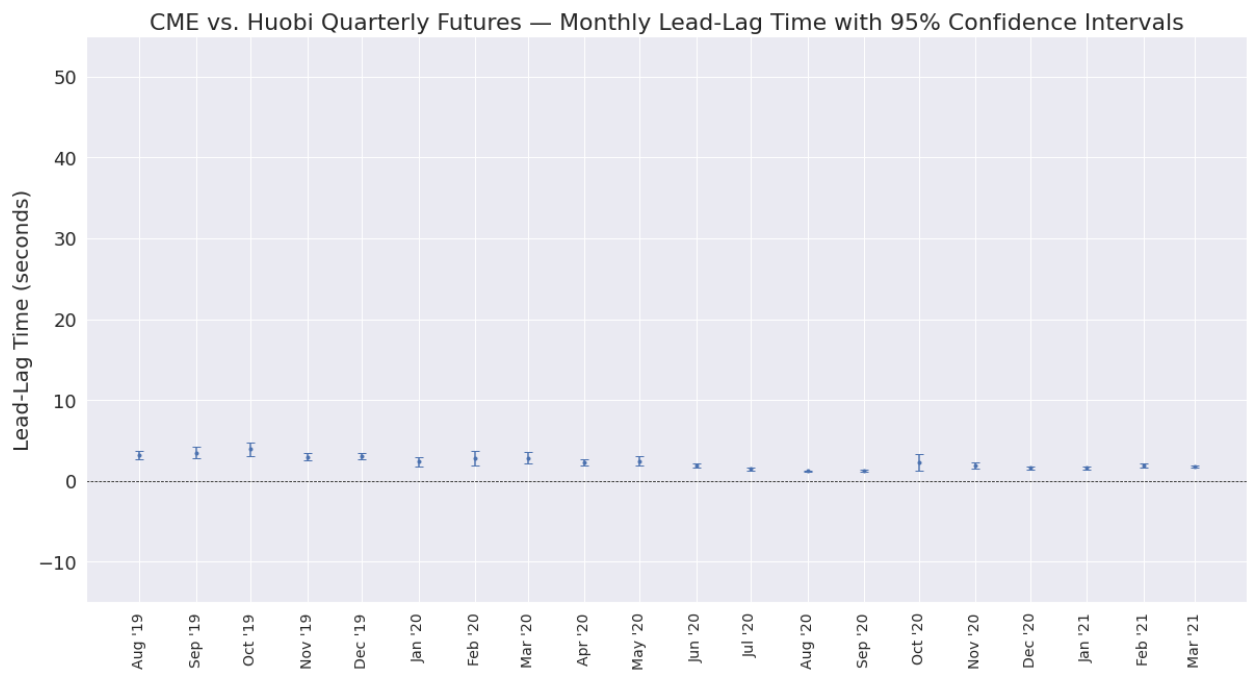
CME vs. FTX Perpetual Futures (Chart)



CME vs. FTX Perpetual Futures (Table)

Month	Lead-Lag Time (seconds)	Confidence Interval (seconds)
Jul '19	2.76*	0.59 - 4.92
Aug '19	2.92*	2.16 - 3.67
Sep '19	4.16*	2.22 - 6.10
Oct '19	2.48*	2.06 - 2.90
Nov '19	3.00*	2.38 - 3.62
Dec '19	1.77*	1.60 - 1.95
Jan '20	1.59*	1.43 - 1.75
Feb '20	1.72*	1.51 - 1.92
Mar '20	1.75*	1.36 - 2.13
Apr '20	1.97*	1.70 - 2.24
May '20	1.58*	1.47 - 1.69
Jun '20	1.76*	1.55 - 1.97
Jul '20	3.56*	1.11 - 6.00
Aug '20	2.04*	1.83 - 2.25
Sep '20	2.39*	1.98 - 2.81
Oct '20	2.87*	2.00 - 3.74
Nov '20	1.78*	1.61 - 1.95
Dec '20	1.72*	1.50 - 1.95
Jan '21	1.78*	1.56 - 2.00
Feb '21	2.09*	1.77 - 2.41
Mar '21	1.96*	1.77 - 2.15
2019-07-01 - 2021-03-31	2.27*	2.08 - 2.46

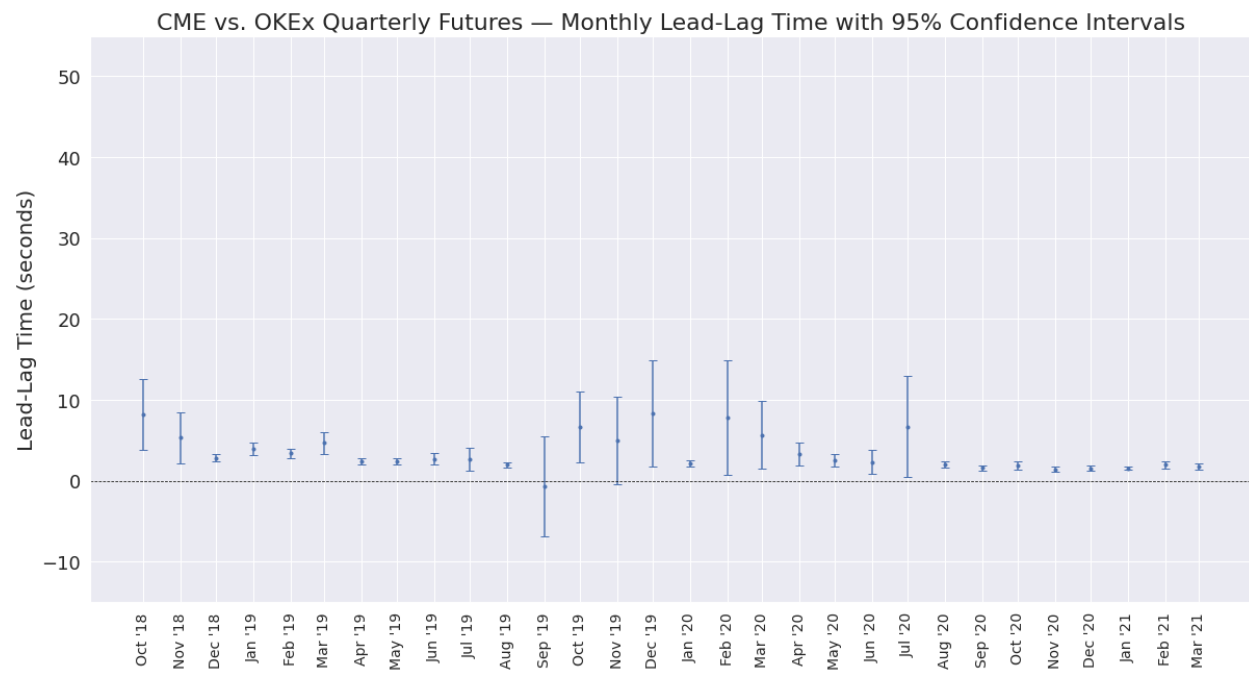
CME vs. Huobi Quarterly Futures (Chart)



CME vs. Huobi Quarterly Futures (Table)

Month	Lead-Lag Time (seconds)	Confidence Interval (seconds)
Aug '19	3.20*	2.73 - 3.67
Sep '19	3.50*	2.76 - 4.23
Oct '19	3.91*	3.12 - 4.70
Nov '19	2.95*	2.49 - 3.42
Dec '19	3.05*	2.65 - 3.45
Jan '20	2.40*	1.84 - 2.96
Feb '20	2.81*	1.95 - 3.67
Mar '20	2.85*	2.17 - 3.52
Apr '20	2.29*	1.92 - 2.66
May '20	2.47*	1.93 - 3.00
Jun '20	1.92*	1.63 - 2.20
Jul '20	1.51*	1.33 - 1.69
Aug '20	1.26*	1.20 - 1.32
Sep '20	1.24*	1.14 - 1.33
Oct '20	2.31*	1.31 - 3.31
Nov '20	1.86*	1.48 - 2.24
Dec '20	1.64*	1.45 - 1.83
Jan '21	1.64*	1.45 - 1.83
Feb '21	1.96*	1.69 - 2.23
Mar '21	1.77*	1.61 - 1.94
2019-08-01 - 2021-03-31	2.34*	2.21 - 2.47

CME vs. OKEEx Quarterly Futures (Chart)



CME vs. OKEEx Quarterly Futures (Table)

Month	Lead-Lag Time (seconds)	Confidence Interval (seconds)
Oct '18	8.20*	3.80 - 12.60
Nov '18	5.32*	2.20 - 8.44
Dec '18	2.83*	2.39 - 3.27
Jan '19	3.98*	3.19 - 4.77
Feb '19	3.38*	2.82 - 3.94
Mar '19	4.70*	3.34 - 6.05
Apr '19	2.36*	1.98 - 2.75
May '19	2.44*	2.08 - 2.79
Jun '19	2.69*	1.96 - 3.42
Jul '19	2.69*	1.27 - 4.11
Aug '19	1.96*	1.62 - 2.31
Sep '19	-0.73	-6.92 - 5.46
Oct '19	6.63*	2.29 - 10.98
Nov '19	5.01	-0.40 - 10.42
Dec '19	8.30*	1.70 - 14.89
Jan '20	2.13*	1.74 - 2.53
Feb '20	7.85*	0.78 - 14.92
Mar '20	5.66*	1.49 - 9.83
Apr '20	3.30*	1.85 - 4.74
May '20	2.57*	1.81 - 3.34
Jun '20	2.33*	0.80 - 3.85
Jul '20	6.69*	0.42 - 12.97
Aug '20	2.01*	1.59 - 2.43
Sep '20	1.61*	1.30 - 1.91
Oct '20	1.88*	1.35 - 2.41
Nov '20	1.44*	1.16 - 1.72
Dec '20	1.51*	1.19 - 1.83
Jan '21	1.55*	1.38 - 1.72
Feb '21	1.96*	1.55 - 2.37
Mar '21	1.82*	1.42 - 2.21
2018-10-01 - 2021-03-31	3.47*	2.94 - 4.00