Pricing and Arbitrage Across 80 Cryptocurrency Exchanges

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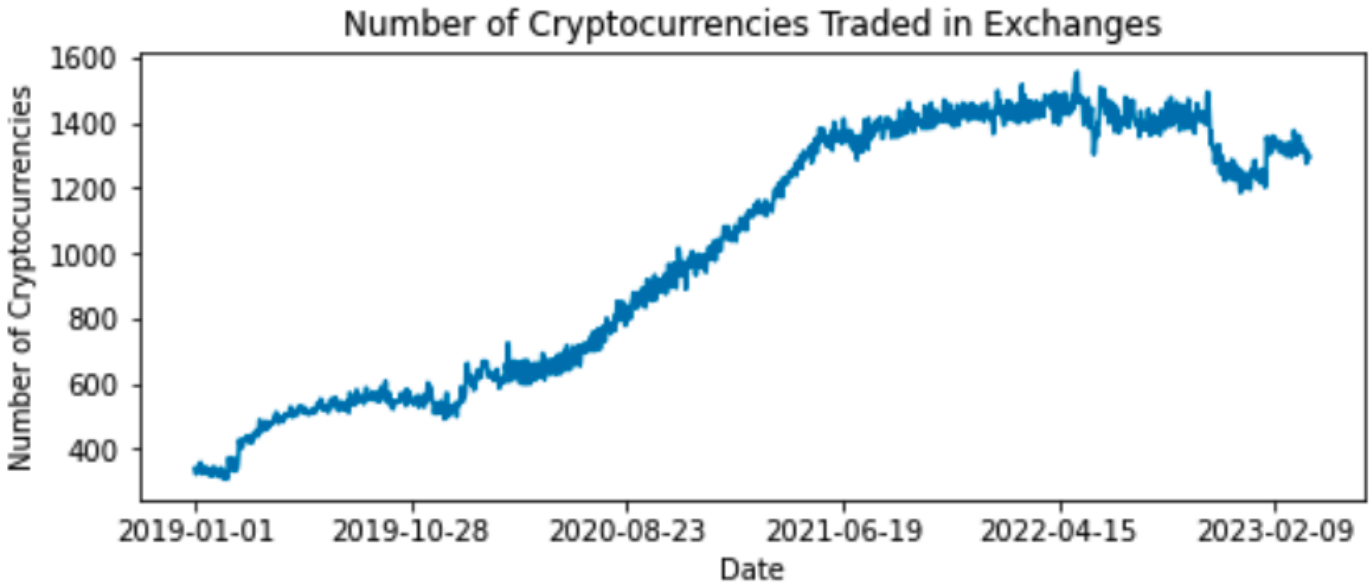
Crypto Market Overview

- Cryptocurrencies, worth over US$2 trillion, has emerged as a new asset class.
- Numerous ICO listings on exchanges contribute to the market's prosperity.



- Compared to equities, cryptocurrencies are easier to trade globally.
- How efficient is the pricing of cryptos?

Cryptocurrency Exchanges

- Cryptocurrency exchanges provide essential platforms for the buying, selling, or swapping of digital currencies with other digital (USDC) or traditional fiat currencies (USD).
- Crypto exchanges use traditional order book on centralized exchange (CEX) and automated market maker mechanism on decentralized exchange (DEX).
- The regulation of crypto exchanges remains an open question, as the collapse of FTX highlights the lack of oversight.
- What characteristics of exchange contribute to price synchronization across markets?

Motivation of Our Paper

- Makarov and Schoar (2020 JFE) explore bitcoin's price variation across 20 cryptocurrency exchanges and highlight the impact of the capital control of countries on these variations.
- Dimpfl and Pete (2021 JFM) analyze the price discovery contributions of cryptocurrency exchanges.
- Crépellière, Pelster, and Zeisberger (2022 JFM) suggest that geographic restrictions may partly explain price differences for Bitcoin.
- Wash trading of exchanges: Cong et al.(2023, MS)
- Transparency of exchanges: Griffin, and Shams (2020, JF)
- We employ a comparatively more extensive dataset that:
  1. Includes pricing data for over 200 cryptocurrencies.
  2. Contains daily pricing data from 80 cryptocurrency exchanges around the world, includes the data from both CEX and DEX.

Summary of Results

- Large arbitrage spread exists among various cryptocurrency exchanges. Even for Bitcoin, ranges from 8.67% to 15.69% .
- Arbitrage spreads are higher in non-US domiciled exchanges, decentralized exchanges, and non-trustworthy exchanges.
- Blockchain adoption improves price efficiency on DEXs.
- Some advanced protocols mitigate the arbitrage risks on blockchain.
- Blockchain latency and congestion increases arbitrage risks.
- Stablecoins with high transparency and sufficient collateral exist low arbitrage spread.

Cryptocurrency Exchanges Trading Data

- Our data is sourced from Kaiko, a premier[1] provider of cryptocurrency market data known for its extensive, real-time, and historical datasets that cover a wide range of cryptocurrencies.
- We obtain our study's data through the Kaiko API, specifically focusing on the daily OHLCV (Open, High, Low, Close, Volume) data for instruments listed across 80 exchanges. Data is aligned by GMT time zone.

- Blockchain-native data: Gas fee, total value locked.
- Stablecoin issuer: collaterals are collected from auditing files or Tether explorer.
- The capital control index is taken from Fernandez et al (2016).

[1] Schwenkler, Shah, and Yang (2023) suggests crypto data quality of lower liquidity cryptocurrencies from non-proprietary data providers can be unreliable

Daily Maximum Cross-Exchange Arbitrage Profit

- We report the **maximum** daily arbitrage profit for bitcoin across all exchanges:

BTC Percentage Value of Maximum Arbitrage Profit							
Year	**Mean**	**Std**	**Min**	**25%**	**50%**	**75%**	**Max**
2019	14.40%	12.58%	0.83%	4.94%	9.38%	19.84%	59.84%
2020	15.69%	13.02%	1.00%	5.84%	10.64%	22.20%	59.96%
2021	11.29%	9.50%	1.36%	5.54%	8.51%	13.56%	62.85%
2022	11.93%	9.90%	0.97%	5.39%	9.32%	15.00%	69.97%
2023	8.67%	9.09%	0.84%	2.81%	5.27%	11.37%	42.98%

- Even for Bitcoin, the most widely recognized cryptocurrency, ranges from 8.67% to 15.69%. And the market is becoming more efficient.

Daily Arbitrage Spread

- For a given cryptocurrency i traded on exchange j at date t, its price $P_{i,j,t}$ is defined as the average of closing prices quoted by USD stablecoins on exchange j at date t.
- Define the benchmark price of cryptocurrency i at date t as the median of prices across exchanges, denoted as $M_{i,t}$.
- The dollar value of arbitrage spread $S_{i,j,t,[\$]}$ and percentage value of arbitrage spread $S_{i,j,t,[\%]}$ for cryptocurrency i on exchange j at date t are calculated as follows:

$$S_{i,j,t,[\$]} = P_{i,j,t} - M_{i,t}$$

$$S_{i,j,t,[\%]} = S_{i,j,t,[\$]} / M_{i,t}$$

Bitcoin and Ethereum Arbitrage Spreads

- We report the bitcoin and Ethereum cross-exchange arbitrage spread $S_{BTC,j,t,[\%]}$ and $S_{ETH,j,t,[\%]}$ as follows:

Panel B. BTC Daily Percentage Value of Arbitrage Spread					
Year	**Mean**	**Std**	**Median**	**p5**	**p95**
2019	-0.05%	2.90%	0.00%	-1.31%	1.61%
2020	-0.15%	3.11%	0.00%	-0.98%	0.58%
2021	0.08%	2.14%	0.00%	-0.77%	1.04%
2022	0.16%	2.06%	0.00%	-0.41%	0.90%
2023	0.06%	1.71%	0.00%	-0.51%	0.62%

Panel D. ETH Daily Percentage Value of Arbitrage Spread					
Year	**Mean**	**Std**	**Median**	**p5**	**p95**
2019	0.07%	3.08%	0.00%	-1.19%	2.51%
2020	-0.02%	1.99%	0.00%	-1.03%	0.95%
2021	-0.10%	2.43%	0.00%	-0.94%	0.89%
2022	0.08%	1.31%	0.00%	-0.52%	0.82%
2023	0.08%	1.02%	0.00%	-0.64%	1.03%

- The transaction commission fee for most of exchanges is $0.1 \sim 0.2\%$. More than 10% of prices exist arbitrage opportunity compared with median price of the whole market.

BTC Daily Arbitrage Spread by Regions

Panel A. BTC Daily Percentage Value of Arbitrage Spread (North America)					
Year	**Mean**	**Std**	**Median**	**p5**	**p95**
2019	-0.42%	3.83%	0.00%	-0.80%	0.41%
2020	-0.39%	3.52%	0.01%	-0.27%	0.22%
2021	0.05%	1.65%	0.01%	-0.14%	0.26%
2022	0.00%	0.21%	0.00%	-0.10%	0.11%
2023	0.00%	0.18%	0.00%	-0.16%	0.15%

Panel B. BTC Daily Percentage Value of Arbitrage Spread (Europe)					
Year	**Mean**	**Std**	**Median**	**p5**	**p95**
2019	-0.01%	2.23%	0.00%	-1.67%	2.03%
2020	0.26%	2.99%	0.00%	-1.40%	2.00%
2021	0.22%	2.56%	0.00%	-1.66%	2.40%
2022	0.63%	3.26%	0.01%	-0.58%	5.35%
2023	0.49%	2.96%	0.01%	-0.39%	1.78%

Panel C. BTC Daily Percentage Value of Arbitrage Spread (Asia-Pacific)					
Year	**Mean**	**Std**	**Median**	**p5**	**p95**
2019	0.17%	2.47%	0.00%	-0.93%	1.51%
2020	-0.32%	3.15%	-0.01%	-0.89%	0.45%
2021	-0.13%	2.04%	-0.01%	-0.42%	0.25%
2022	0.00%	1.46%	0.00%	-0.22%	0.25%
2023	-0.04%	1.25%	0.00%	-0.43%	0.29%

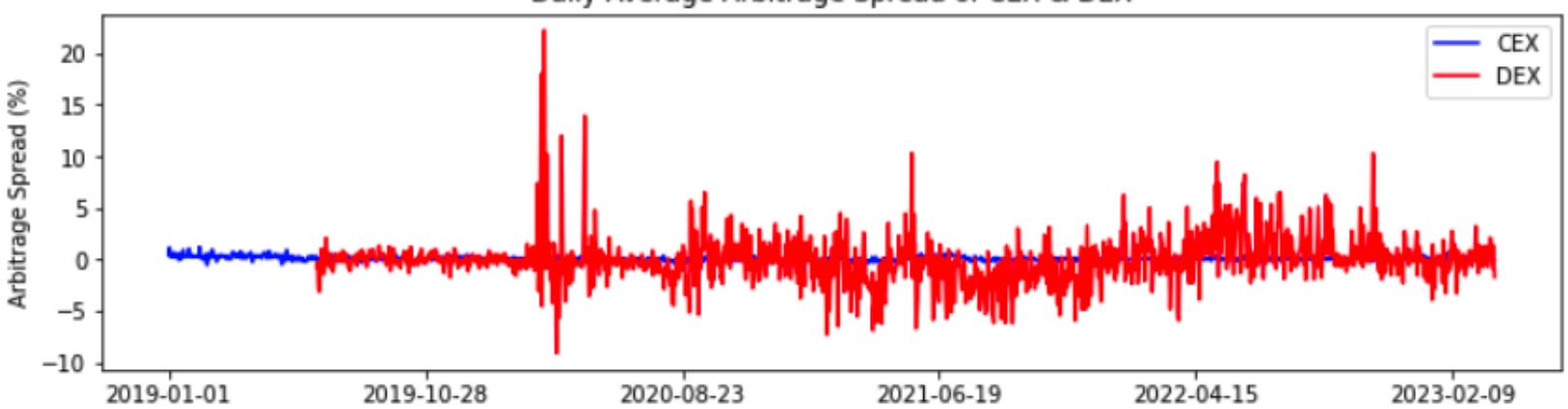
BTC Daily Arbitrage Spread by Regions Conti.

- This observation aligns with Makarov and Schoar's (2019) finding, which underscores the importance of U.S. exchanges in price discovery.
- Exchanges in the Asia-Pacific area have shown increasing efficiency from 2019 to 2023, with the 95th percentile of arbitrage spread narrowing from 1.51% to 0.29%
- In contrast, the arbitrage spreads on European exchanges remain notably high.

Arbitrage Spread by Exchange Type (CEX vs DEX)

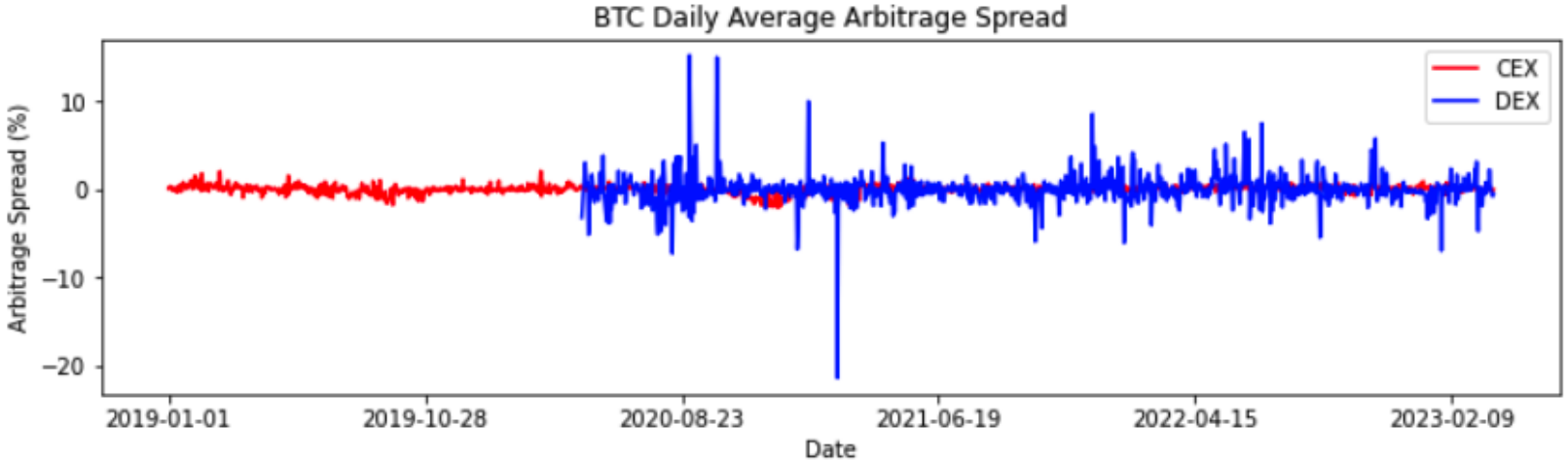
- CEX: Centralized Cryptocurrency Exchanges. E.g., Binance, Coinbase, ...
- DEX: Decentralized Cryptocurrency Exchanges. E.g., Uniswap, dYdX, ...

Panel A. Average Arbitrage Spread on CEX vs DEX.

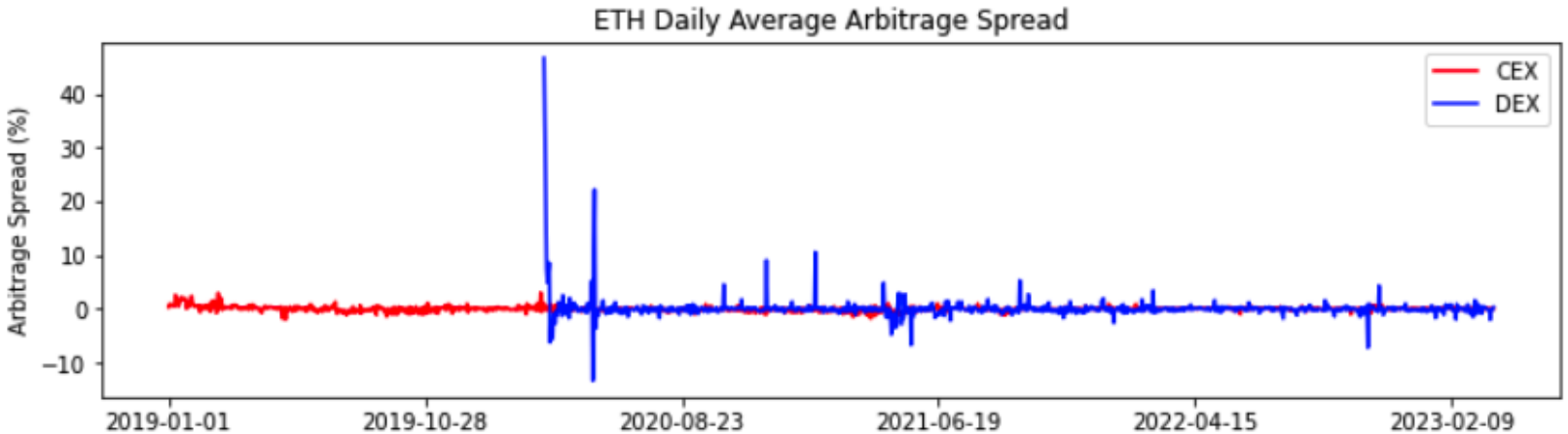


BTC and ETH Arbitrage Spread by Exchange Type

Panel B. Bitcion Arbitrage Spread on CEX vs DEX.

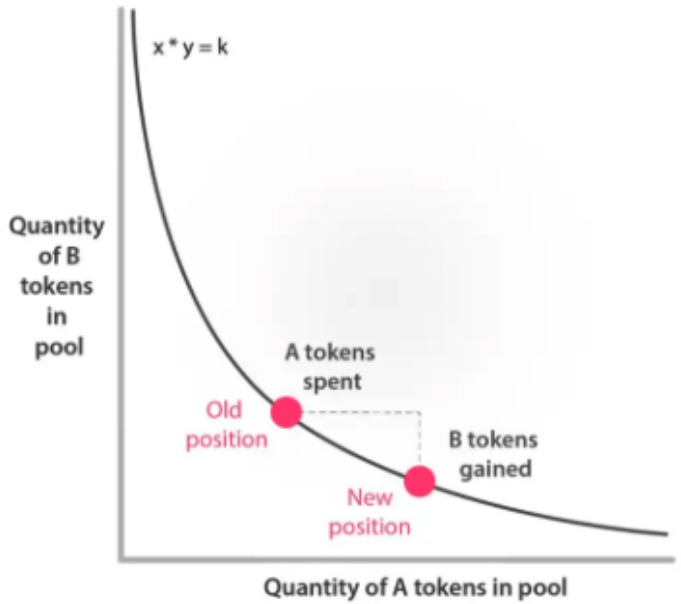


Panel C. Ethereum Arbitrage Spread on CEX vs DEX.



Arbitrage Risks in DEXs

- Arbitrage risks on DEXs:
- Complexity of automated market maker.
- Non-native assets require cross-blockchain trading.
- Front-running and arm races on public blockchains.



Identification of Arbitrage Risks in DEXs

- We examine two significant technological innovations as treatments in DiD.
- Flashbots protocol and the growing adoption of decentralized finance, commonly known as "DeFi Summer."

$$\begin{aligned}|S_{i,j,t,[\%]}| =& \alpha_0 + \alpha_1 \text{Treatment}_{j \in DEX} \times \text{Post}_{Innovation} + \\ & \alpha_2 \text{Treatment}_{j \in DEX} \\ & + \alpha_3 \text{Post}_{Innovation} + \eta_i + \gamma_t + \epsilon_{i,j,t}\end{aligned}$$

- Flashbots provide off-chain private channels that allow traders to send their orders directly to miners, thus avoiding the risk of being front-run in the mempool.
- During the summer of 2020, the growing popularity of this sophisticated technology drew an increasing number of participants to DEXs.

DiD results of Arbitrage Risks in DEXs

- Flashbot: Jan - Mar 2021.
- DeFi Summer: May - Jul 2020.

	$\lvert S_{i,j,t,[\%]} \rvert$	
Event	(Flashbots)	(DeFi Summer)
Treatment	1.9654***	1.2334***
	(0.103)	(0.166)
Post	0.0699***	-0.0129
	(0.005)	(0.009)
Treatment × Post	-0.1904***	-0.6400***
	(0.081)	(0.169)
Year-Month Fixed Effects	Yes	Yes
Cryptocurrency Fixed Effects	Yes	Yes
R^2	0.023	0.017
# of Observations	20315	15618

Measures of Arbitrage Risks in DEXs

- Front-running risk: $\rightarrow \mathbb{I}(\text{After Flashbots})_t$
- DeFi adoption risk: $\rightarrow \text{TVL}_{j,t}$
- Latency and congestion of blockchain: $\rightarrow \text{Gas}_t$ (Hautsch, Scheuch, and Voigt (2024, RF))
- Cross chain risks: $\rightarrow \mathbb{I}(\text{1 if Native})_i$

$$
\begin{aligned}
|S_{i,j,t,[\%]}|_{j \in DEX} =& \alpha_0 + \eta_i + \delta_j + \gamma_t + \epsilon_{i,j,t} \\
&+ \alpha_1 \mathbb{I}(\text{After Flashbots})_t / \text{TVL}_{j,t} / \text{Gas}_t / \mathbb{I}(\text{1 if Native})_i
\end{aligned}
$$

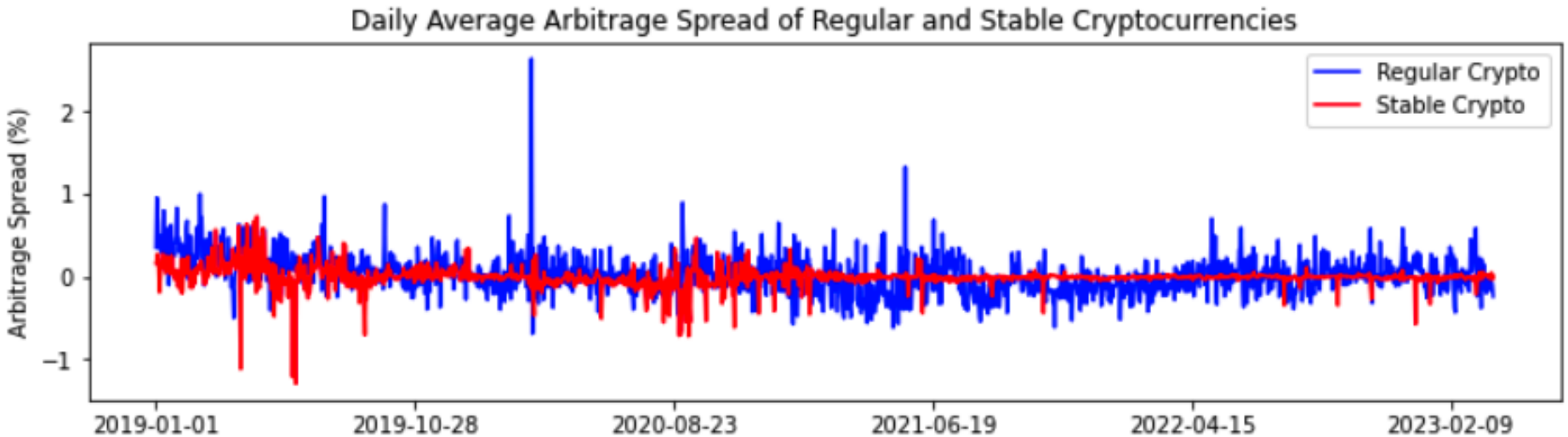
Arbitrage Spreads in DEXs

Panel A. Regression of Arbitrage Spread in DEXs (I)

	$\lvert S_{i,j,t,[\%]}\rvert_{j \in DEX}$				
	(1)	(2)	(3)	(4)	(5)
$\mathbb{I}(\text{After Flashbots})_t$	-0.3895***				-0.2819***
	(0.013)				(0.018)
$\text{TVL}_{j,t}$		-0.5583**			-0.3886***
		(0.245)			(0.064)
Gas_t			0.0028***		0.0031***
			(0.001)		(0.001)
$\mathbb{I}(\text{1 if Native})_i$				-1.4214***	
				(0.216)	
Year-Month Fixed Effects	Yes	Yes	Yes	Yes	Yes
Exchange Fixed Effects		Yes			
Cryptocurrency Fixed Effects	Yes		Yes		Yes
R^2	0.001	0.009	0.001	0.015	0.021
# of Observations	34693	34693	34693	34693	34693

Arbitrage Spread by Token Types (Stable vs Other Tokens)

- Stablecoins tend to exhibit narrower, downward arbitrage spreads.



Aribitrage Spread of Stablecoins

- Tether (USDT), a centralized stablecoin backed by fiat reserves, is widely utilized for its liquidity but has encountered transparency issues. (Griffin, and Shams (2020, JF))
- USDC, developed by Circle and Coinbase, is a fiat-backed stablecoin noted for its strong regulatory compliance and transparency.
- DAI, engineered by MakerDAO, is a decentralized stablecoin backed by cryptocurrency collateral, which maintains its peg through automated smart contracts.

Panel A. USD Stable Cryptocurrencies Arbitrage Spreads Statistics

Cryptocurrency	Start	End	N	Mean	Std	p5	p95	Skew	Kurt
DAI	1/1/19	3/30/23	31312	-0.01%	1.21%	-0.55%	0.49%	-8.64	630.65
USD	1/1/19	3/30/23	18660	-0.07%	1.37%	-1.18%	0.61%	-3.51	321.81
USDC	1/1/19	3/30/23	33114	-0.05%	1.17%	-0.58%	0.43%	-3.31	390.04
USDT	1/1/19	3/30/23	40113	0.07%	1.44%	-0.39%	0.49%	0.7	389.17

Collateral of Stablecoins

- $41 million fine to Tether imposed by the CFTC in October 2021 for misleading investors about always being fully backed.
- In March 2023, SVB collapse sparks Stablecoin turmoil as USDC Loses Dollar Peg.
- DAI is backed by Ethereum which is non-stable.

- Arbitrage spreads are likely influenced by the transparency, stability, and security of the collateral.

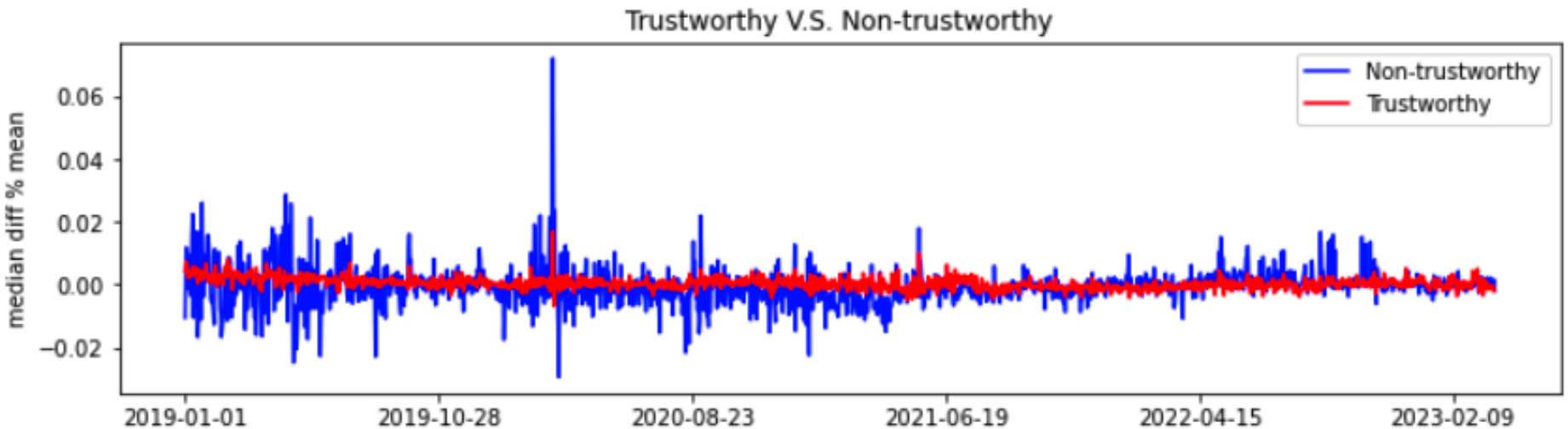
Arbitrage Spread of Stablecoins, and Collaterals

- Daily newly issued USDT is collected from Tether Explorer
- Over-collateralization of USDC is calculated from auditing of Deloitte.

	$\lvert S_{i,j,t,[\%]}\rvert_{i \in Stablecoins}$		
	(USDT)	(USDC)	(DAI)
New Issued Tether$_t$	1.2620**		
	(0.558)		
New Issued Tether$_t$ × 𝕀(After CFTC Orders)$_t$	0.0150***		
	(0.003)		
OC of Circle$_t$		-11.864**	
		(2.402)	
Past Volatility$_{ETH,j,t}$			0.0466***
			(0.018)
Year-Month Fixed Effects	Yes		Yes
Exchange Fixed Effects	Yes	Yes	Yes
# of Observations	40112	18667	30367

Arbitrage Spread by Exchange Trustworthiness

- Trustworthy exchanges with longer operational time tend to exhibit narrower spreads.
- Hautsch, Scheuch, and Voigt (2024, RF): price differences are smaller across exchanges with low default risk.
- Cong, Li, Tang, and Yang (2023, MS) find that exchanges with a longer operating history tend to experience fewer wash trades, which leads to reduced price deviations.



Other Contributing Factors to Arbitrage Spread

- Capital Controls index measured by Fernandez et al (2016). Investors may pay a premium for cryptocurrencies as a hedge against local financial restrictions.
- Derivative trading (Augustin, Rubtsov, and Shin (2023, MS)). Exchanges that offer perpetual futures trading enable investors to short overpriced cryptocurrencies or hedge the risk associated with arbitrage trades.
- Transfer latency (Number of confirmation block). It's a proxy for the 'leg risk' in arbitrage trading, with fewer confirmation blocks potentially reducing this risk.

Arbitrage Spread-Crypto Characteristics

- Buying pressure denotes the deviation from the actual log price to this smoothed log price.

	$\lvert S_{i,j,t,[\%]} \rvert$			
	(1)	(2)	(3)	(4)
$\text{Volume}_{i,t}$	-0.0280***			-0.0507***
	(0.002)			(0.003)
$\lvert\text{Crypto Buying Pressure}\rvert_{i,t} \times \mathbb{I}(\text{1 if not in U.S})_j$		0.3098***		0.1335***
		(0.026)		(0.031)
$\mathbb{I}(\text{1 if stable})_i$			-0.3996***	-0.4826***
			(0.025)	(0.027)
$\text{Past Volatility}_{i,j,t}$				0.0256***
				(0.006)

Arbitrage Spread-Exchange Characteristics

	$\lvert S_{i,j,t,[\%]} \rvert$			
	(1)	(2)	(3)	(4)
$\mathbb{I}(\text{1 if DEX})_j$	1.2634***			1.3805***
	(0.072)			(0.073)
$\mathbb{I}(\text{1 if in U.S})_j$		-0.1096***		-0.1595***
		(0.026)		(0.028)
$\mathbb{I}(\text{1 if trustworthy})_j \times \mathbb{I}(\text{Before June 2021})_t$			-0.6098***	-0.3280***
			(0.065)	(0.067)
$\text{Past Volatility}_{i,j,t}$				0.1745***
				(0.022)
$\text{Capital Control}_{j,t}$				1.0503***
				(0.137)
$\mathbb{I}(\text{1 if has futures})_j$				-0.6092***
				(0.034)
$\#\text{ of Confirmation Blocks}_j$				0.0188***
				(0.003)

Conclusions

- Arbitrage spread regressions on both crypto and exchange characteristics are not shown in this slide but consistent with previous results.
- Our findings highlight the impact of market liquidity, exchange reputation, regulatory constraints, and geographical locations on pricing variations.
- Blockchain innovation and DeFi adoption improves price efficiency on DEXs.
- Stablecoins with high transparency and sufficient collateral exist low arbitrage spread.

Thank you!