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Crypto Carry*

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Abstract

We document that the carry of crypto futures, i.e. the difference between futures and spot prices, can become very large (up to 60% p.a.) and varies strongly over time. This behavior is most consistent with the existence of a highly volatile crypto convenience yield that stems from two main forces: (i) trend-chasing and attention by smaller investors seeking leveraged upside exposure to crypto assets in boom periods, and (ii) the relative scarcity of "arbitrage" capital taking the other side through a cash and carry position. Engaging in the latter is risky due to spikes in margins and liquidations amid drawdowns. The interplay between these two forces, and the involved high leverage, may help explain why severe market crashes are a frequent feature of crypto markets.

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The 'Risk-Free' Crypto Trade Is Back In a Big Way [Bloomberg, 8 October 2021]

"The closest thing to a risk-free bet has reemerged in the cryptocurrency market as traders [...] bid up the price of futures."

1. Introduction

Digital assets such as Bitcoin (BTC) and Ether (ETH) have gained significant attention from market practitioners, academics, and policymakers in recent years due to their extreme growth in market capitalization, trading volume, and the rise of products and applications based on these crypto assets. This digital ecosystem has matured to a point where cash and derivative instruments are now actively traded both on native crypto exchanges as well as on traditional exchanges, i.e. the Chicago Mercantile Exchange (CME).

Against this background, the main purpose of our paper is to study one of the most salient features of these instruments in recent years – the large difference between spot and futures prices, the so-called *futures basis* or "crypto carry".[1] Crypto carry encapsulates the return on a simple "cash and carry" strategy: going long in the spot market, while selling forward the same amount forward via a futures contract. If carry is positive, locking in the higher futures price while holding the spot until expiration of the futures contract generates profit (loss if carry is negative). We analyze crypto carry observed for the two major digital assets, Bitcoin and Ethereum, shed light on its economic drivers, and study how these are connected to the boom-and-bust dynamics commonly observed in crypto markets.

The first contribution of our paper is to provide stylized facts about crypto carry, characterizing its variation over time and across various crypto platforms and traditional exchanges. A striking feature of crypto carry is its size, averaging about 10% p.a. across exchanges from April 2019 to January 2022. A simple cash and carry trade would thus have yielded about 10% p.a. while at the same time being hedged against price swings in the underlying asset. The carry for BTC and ETH is overall quite similar in terms of its level and is highly correlated across the two assets over time. Carry is also highly correlated across exchanges, with correlations typically exceeding 90%. That said, there is some evidence on market segmentation between crypto exchanges and the traditional financial system (CME), with correlations of carry on the

[1] We use the terms crypto carry and basis interchangeably in this paper.

former and that on the CME being much weaker (only about 60-70%), see, e.g. Makarov and Schoar (2020) for an empirical analysis of price inefficiencies in crypto markets. Crypto carry is also very volatile at low frequencies with maximum (minimum) values above 40% p.a. (below -20%) over the longer run, while it is quite persistent at higher frequencies (such as daily).

Based on these facts, we seek to provide a deeper understanding of the economic forces driving crypto carry. As an organizing framework, we rely on the basic futures pricing equation, slightly adapted to digital asset markets (see Section 2.3 for further details):

$$f^i_{t,T} - s^i_t = r_{t,T} - r^\star_{t,T} + \delta_{t,T} + \varepsilon^i_t,$$

where $f = \log F$ and $s = \log S$ denote log futures and spot prices, respectively, T is the maturity of the futures contract, and i indexes exchanges. $r_{t,T}$ and $r^\star_{t,T}$ denote short-term interest rates for US dollars (USD) and for crypto assets, respectively. The part unexplained by the interest differential conceptually consists of two parts: ε^i_t denotes an idiosyncratic (exchange-specific) pricing error, while δ in turn can be thought of as an aggregate crypto *convenience yield*. More specifically, we denote by $\delta_{t,T}$ the net (of storage) convenience yield of *holding the futures contract*.[2]

This basic pricing equation tells us that the variation in carry that we observe in the data must stem from: (i) interest rate differentials between the crypto world and the fiat world, (ii) idiosyncratic variation in pricing errors specific to exchanges (ε^i_t), (iii) the convenience yield of holding the future versus the spot (δ).

Dissecting these different channels, we first document that interest rate differentials only capture 2% of carry's total variation. Likewise, variation in exchange fixed effects only captures about 1% of changes in carry. These facts suggest that neither interest rates nor idiosyncratic pricing errors drive a significant share of crypto carry. Hence, variation in carry must stem from fluctuations in convenience yields.

Going a step further, we run regressions to dissect movements in carry into changes in spot

[2] We depart from the standard convention of defining the convenience yield as referring to holding spot (e.g., Gorton and Rouwenhorst, 2006) for reasons that will become clear later: namely, the convenience of futures as a tool to engage in levered crypto trading. Convenience yields are shown to be important drivers of prices also in assets other than commodities: e.g., Jiang et al. (2021) use currency forwards to show that foreign investors derive a convenience yield from holding U.S. Treasuries.

rates and the futures premium. We do so by regressing realized spot and futures price changes on the current carry ($F_t - S_t$) in the spirit of Fama (1984) and Fama and French (1987). The logic of this regression is based on the fact that carry at time t has to mechanically predict either changes in spot prices or changes in the futures price from t to maturity of the contract T, or both, since the futures price has to converge to the spot price at T.[3]

The results for these regressions are striking in that a positive carry predicts *both* a decline in the spot as well as in the futures price, albeit to different degrees. Specifically, our estimates for 1-month BTC futures imply that a rise in absolute carry by one dollar predicts a five dollar *decline* in spot prices which is overcompensated by a six dollar *decline* in futures prices. These results indicate that a high carry predicts future crypto price crashes. They further imply that there is "excess volatility" of crypto futures relative to spot prices, i.e. our estimates imply that changes in futures prices are about *ten times more volatile* than changes in spot prices when measured in units of the variance of carry.[4]

In the second part of the paper we then seek to establish a better understanding of the economic forces that shape crypto convenience yields. Two main questions guide our work: why do prices in the futures market decouple so strongly from spot prices? And, what prevents "arbitrageurs" – that is, cash and carry traders who are short (long) the futures when carry is positive (negative) – to lean against these extreme price dislocations?[5]

We look at investor positioning to shed light on the types of market participants that are on different sides of the trade in crypto futures. Based on the commitment of traders (COT) data of the Commodity Futures Trading Commission (CFTC) for the CME, we establish that a rise in net long positions by "nonreportable" traders (and "other reportables") tends to be associated with an increase in crypto carry. These nonreportables typically comprise smaller players such as family offices, proprietary trading shops that run commodity trend-following strategies, and/or wealthy individuals. Empirically, dealer intermediaries and leveraged funds tend to take the

[3] In a similar vein, a long literature on uncovered interest parity (UIP) in foreign exchange (FX) markets has tested for the ability of FX carry (also often labelled forward discount in that literature) to predict spot exchange rates (see, e.g., Hassan and Mano, 2019, for a recent contribution).

[4] These results are qualitatively similar – albeit more extreme – to earlier results for commodities markets by Fama and French (1987), notably for precious metals, and suggest a strong role for time-variation in convenience yields in driving carry.

[5] We put arbitrageurs deliberately into inverted commas here, as we will argue later on that the cash and carry strategy cannot be regarded as a riskless trade in the sense of a "free lunch".

opposite position by being short in crypto futures. These results square well with the notion that the crypto futures basis tends to be elevated when smaller entities seek leveraged upside exposure.[6]

This bird's eye perspective suggests that two lines of inquiry are important to understand fluctuations in crypto convenience yields. The first one is the pressure created by smaller, trend-chasing investors to gain leveraged upside exposure to crypto-assets, which would likely increase carry. We call these investors "trend-followers". The second one is factors that prevent a larger deployment of capital to the cash and carry strategy, which, in turn, by being on the other side through short futures positions, should dampen the upside pressure on the basis. We label the investors who are on the other side of the trend-followers as "carry traders".

To investigate the first channel empirically, we study the actions of trend followers. Our main hypothesis is that when there are strong price trends and heightened media attention, more of these investors rush into levered crypto futures positions. Consistent with this narrative, we find that crypto carry is positively correlated with social media metrics such as Reddit followers (attention) and with past crypto returns (trend chasing or momentum).[7] If this class of investors has a preference for leveraged products (cf. Asness et al., 2012; Frazzini and Pedersen, 2014), a rise in their demand would go hand in hand with a rise in carry and a convenience yield on leveraged futures over spot, i.e., $\delta > 0$ in the equation above.

Regarding the second channel, the key question is why capital devoted by carry traders – who effectively take the other side of trend followers – is scarce and slow-moving? To answer this question, it is essential to examine the risk and return profile of the crypto cash and carry strategy. Cash and carry can be seen as a trade on the convergence of spot and futures prices (i.e., long spot, short futures or vice versa). However, despite being often portrayed as "risk-free" in the financial media (as evidenced by the quote at the start of the introduction), such trades are risky in practice due to frictions in how collateral is handled on traditional and crypto exchanges. Implementing such long-short carry position exposes a trader to the risk of spikes

[6]See Makarov and Schoar (2021) for an in-depth analysis of the bitcoin ecosystem, disaggregated by individual wallets, and the different types of uses over time and Kose et al. (2021) for a recent overview of papers studying the economics of blockchain fundamentals.

[7]Liu and Tsyvinski (2021) in a recent paper also find that attention is useful for predicting cryptocurrency returns. Kogan et al. (2023) study retail traders and show that these investors tend to be trend-followers in crypto assets.

in margins (Brunnermeier and Pedersen, 2009), e.g. when the basis moves against the trader before maturity of the contract. As such, there is a risk that such a trade cannot be funded until convergence. This risk is exacerbated by the fact that the long spot position cannot be used as collateral for the futures position on traditional exchanges such as the CME to which larger institutions have direct access.

We then investigate factors limiting the deployment of capital to the crypto cash and carry strategy. First, we study the basic return characteristics of the strategy. We construct cash and carry returns by shorting the futures contract and going long spot at time t when carry is positive (or doing the opposite when it is negative), and holding this position until expiration at T. The Sharpe Ratio of this strategy (before transaction costs) is about 0.59 p.a. for 1-month futures traded on the CME, when financing the position at LIBOR. Yet, we also find that the returns on the futures leg of this strategy exhibit severe drawdowns. Such drawdowns can lead to contract liquidations of the carry traders' positions if margin calls cannot be met. In line with this, we find that, in practice, carry is a significant predictor of liquidations in futures positions. For example, an increase of carry by 10% predicts that liquidations of short futures positions rise by 44% of total open interest over the next month. These findings indicate that the strategy exposes patient carry traders to significant risk as the absence of cross-margining, or other margin frictions could lead to forced liquidations before maturity. These frictions also explain why arbitrageurs oftentimes may not deploy enough capital to lean against a carry widening during crypto price booms.

Finally, we study the link between carry and crypto crash risk discussed above in more detail by analysing the data on contract liquidations together with (option-implied) return moments. Empirically, we find that carry emerges as a strong predictor of realized and implied skewness such that a higher carry predicts lower (more negative) skew of BTC, and ETH returns. The latter suggests that a rise in carry typically goes hand in hand with a rise in the price of crash risk insurance in option markets (as captured by risk reversals, which measure risk-neutral skew). We attribute the increased cost in relative downside protection to the reluctance by intermediaries (and other more patient market participants) to write puts in crypto boom periods that come alongside a rise in carry.

Overall, our results suggest that fluctuations in crypto carry largely owe to time variation in convenience yields. Empirically, these swings are accompanied by heightened social media attention and an influx of smaller, impatient, trend-chasing investors. During such episodes, these trend-followers with a high appetite for leverage pour into crypto markets, thereby driving up crypto carry via long futures positions. As "arbitrage" capital by more patient carry traders is scarce and slow-moving, these episodes go hand in hand with a rise in carry - and for the most part, crypto convenience yields. At the same time, crash risk as captured via the prices of downside protection in option markets increases. In turn, these boom periods of exuberance in crypto markets tend to be followed by bursts in volatility and the liquidation of leveraged positions. The interplay between these forces and the involved high leverage both of those seeking upside exposure and of those taking the other side, help explain why severe price run-ups and market crashes are a frequent feature of crypto markets.

2. Stylized facts about crypto carry

This section starts with a brief description of the data sources and construction of the crypto futures basis. We then present some stylized facts about crypto carry, examining its time-series and cross-sectional (across exchanges) characteristics. Finally, we use simple regressions known from the commodities futures literature to assess if the crypto futures basis anticipates future spot price moves or changes in the futures premium.

2.1. Data sources

We collect daily data from March 2019 to January 2022 on BTC and ETH spot prices as well as futures and options market characteristics from the data provider 'Skew'. The data on futures contracts contain futures basis, trading volume, open interest, buy and sell liquidations. The data on options include open interest, the ratio of put-to-call open interest, and realized 1-month volatility. In addition, the dataset also contains the 1-month at-the-money (ATM) implied volatility, and 25-delta risk reversal: the difference between a 25-delta put's implied volatility and a 25-delta call's implied volatility, normalized by the ATM implied volatility. Skew also provides social media metrics, most notably, the number of Reddit subscribers to groups dedicated to topics about BTC and ETH, but these time series are only available for a shorter sample period (starting in February 2021).

The futures basis data from Skew are annualized and refer to a constant maturities of 1- and 3-months from a set of crypto trading platforms: Binance, OKEx, FTX, Huobi, BitMEX, Deribit, and CME. The data for some exchanges is shorter (e.g., the CME basis starts in August 2020). From these data, we calculate constant-maturity 1- and 3-month futures prices $F_{t,T}$, where T is the expiration date of the futures. We complement these data with daily borrowing and lending rates from Aave (one of the largest decentralized finance (DeFi) lending platforms) and Binance (one of the largest crypto-native exchanges), and with weekly net trader futures positions from the CFTC's Commitments of Traders Reports.

2.2. Crypto carry over time and across exchanges

A notable feature of crypto markets is that futures trade on a range of crypto-native exchanges such as OKEx and Binance, and more recently, also on regulated exchanges such as the CME. These venues operate in markedly different ways. Futures contract specifications differ across exchanges, both within the crypto system as well as between crypto-native exchanges and the CME. For example, futures on the CME settle in cash against US dollars (USD) and have to be collateralized by high-quality assets in USD. Crypto exchanges, by contrast, allow traders to post spot BTC (or other crypto assets) as collateral when opening a futures position.

Attainable leverage on native-crypto exchanges is very high and significantly exceeds that on the CME. The initial margin on crypto-native exchanges is several orders of magnitude smaller than that on CME: less than 2% compared to 50% at CME (as seen from Table A.1 in the Internet Appendix, which reports the maximum attainable leverage during our sample period).[8] As a result, the maximum leverage on crypto-native exchanges is significantly higher, which might attract more speculative traders to these venues.

[Figure 1 about here]

Bearing these differences in mind, Figure 1 shows that Binance has the largest dollar open interest on average for both BTC and ETH. The total dollar open interest on all BTC exchanges

[8] That said, maximum leverage has come down on many of these exchanges as well more recently. For example, Binance reduced maximum leverage on its platform to $\times 20$ (from $> \times 100$ before) in July 2021.

in our sample was USD 13.3 billion as of January 2022.[9] The bulk of BTC futures contracts' open interest (81%) is traded on crypto-native exchanges, with the regulated CME accounting for the residual 19%. In terms of trading volume, crypto-native exchanges account for an even larger share: 97% of the total.

[Table 1 about here]

Table 1 shows summary statistics for crypto carry for a representative crypto-native exchange (OKEx) and the only regulated one in our sample (CME). We chose OKEx here and in other parts of the paper as a representative non-regulated exchange, because it has complete data for both 1-month and 3-month carry, for BTC and ETH.[10] Table A.1 shows the cross-sectional summary statistics on how carry differs across exchanges. Carry is very persistent at the first lag (daily frequency) with autoregressive coefficients only slightly below one, especially for the 3-months contracts. The volatility of carry tends to decline in the maturity of the contract, with 1-month carry being more volatile than 3-months carry. Interestingly, carry is right-skewed for both BTC and ETH and for both maturities, i.e. the distribution of carry features a long tail of large positive observations. For cash and carry arbitrageurs, which typically are long spot and short futures, this asymmetry in the distribution of carry implies a high risk of large drawdowns, an issue to which we return to below. In addition, carry on OKEx and other crypto-native exchanges is much more volatile than on the CME, possibly driven by the higher maximum leverage of non-regulated crypto exchanges.

[Figure 2 about here]

Figure 2 shows the evolution of carry for OKEx and CME. The figure illustrates the high average level of crypto carry of about 10-11% p.a., which is larger than the carry of other assets such as equities, fixed income, currencies, and commodities (see Koijen et al. (2018)). The figure also illustrates the large, sudden spikes in crypto carry that occur several times during our sample period. For example, there are three periods for the 1-month BTC futures on OKEx (early 2019,

[9]Together with CoinFlex, ByBit and Bitfinex, which are not in our sample, the total open interest is around USD 15.6 billion. For Ether (ETH), Binance, Huobi and OKEx have the largest dollar open interest. The total dollar open interest in all exchanges in our sample was USD 8.5 billion as of January 2022.

[10]The other such exchange is Huobi but it has fewer observations.

early 2020, and March 2021), during which crypto carry reached or exceeded 40% p.a. before declining significantly in a short period of time. By contrast, CME carry shows a more muted behavior with the highest values reaching 30% in early 2021 and somewhat less abrupt declines.

[Table 2 about here]

The upper two panels in Figure 2 illustrate another striking feature, namely that carry for BTC and ETH are similar in magnitude and highly correlated on a given exchange for both the one- and three-months maturities. Table 2 expands on this observation and reports correlation coefficients for the carry of BTC and ETH and for both maturities on OKEx (Panel A), as well as correlations of 1-month BTC carry across different exchanges (Panel B). The table shows that carry is highly correlated across non-regulated exchanges with correlation coefficients well in excess of 90%. That said, it is especially noteworthy that CME carry is the *least correlated* with that of other crypto exchanges, which indicates some degree of market segmentation. Possible explanations include differences in contract specifications, differences in trading hours, and the difference in settlement currency between unregulated exchanges and the CME discussed above.

Finally, we also compare crypto carry to that of commodity and VIX futures (Table A.2 in the Internet Appendix). We find that BTC carry is by and large uncorrelated with the carry of commodities and the VIX. This fact suggests that the economic forces affecting pricing in traditional futures markets have little in common with those affecting crypto carry.

2.3. The crypto convenience yield

How can we understand the magnitude and large swings in crypto carry? For a simple framework guiding our subsequent analysis, consider the following equation

$$f^i_{t,T} - s_t = r_{t,T} - r^\star_{t,T} + \delta_{t,T} + \varepsilon^i_t, \tag{1}$$

where $f_{t,T}$ denotes the log futures price for a crypto asset from t to T, s denotes the log spot price, $r_{t,T}$ ($r^\star_{t,T}$) denotes the USD (crypto) risk-free rate, and ε^i_t is a (potentially exchange-specific) pricing error where i denotes different exchanges.[11] We denote by $\delta_{t,T}$ a systematic, non-exchange-specific residual, which we label the *crypto convenience yield*. For simplicity, $\delta_{t,T}$ is the *convenience yield on holding the futures contract* over the spot contract and net of any storage costs.[12]

As Eq. (1) makes clear, the observed dynamics in carry could stem from (i) variation in interest rate differentials, (ii) variation in pricing errors across exchanges i, or (iii) variation in convenience yields. As a special case of this equation, the classic covered interest parity (CIP) condition in FX would tell us that arbitrage would wipe out any differences across exchanges i, abstracts from convenience yields, and predicts a carry equal to the interest rate differential.

Guided by the above equation, we run several simple tests. First, we dissect the contribution of time-specific (t) and exchange-specific (i) variation to the total variability of carry in a panel of all exchanges in our sample. Table 3 shows results for panel regressions in which one month carry is the dependent variable. The first two specifications simply regress carry on exchange fixed effects (FEs) or time FEs, respectively. The R^2 with exchange FEs is only 1% whereas the R^2 with time FEs is 88%. We find similar results for ETH, where exchange-specific factors capture less than 0.2% of the variation, whereas time-specific factors capture 93% (these results are unreported for brevity). These results are well in line with the visual impression from Figure 2 above and show that exchange-specific factors do not explain significant share of the variation of crypto carry.[13]

Second, according to Eq. (1), a "fundamental" driver of crypto carry is the interest rate

[11] To see this, note that *in the absence of pricing errors and convenience yields*, a trader could borrow the present value of one dollar $(1/(1+r_{t,T}))$, buy bitcoin at the spot rate (which results in $1/S_t$ BTC per dollar invested), lend out the BTC at gross rate $1+r^\star_{t,T}$ and then sell the BTC forward at $F_{t,T}$ for delivery in T in the futures market to hedge her price risk. Since this round-trip carries no price risk, it must be true that

$$\frac{F_{t,T}}{S_t} \times \frac{1+r^\star_{t,T}}{1+r_{t,T}} = 1$$

in the absence of arbitrage. Taking logs and re-arranging gives the equation above (assuming that risk-free rates are relatively low), to which we have added terms to account for the possibility of convenience yields (δ) and idiosyncratic price differentials across exchanges (ε^i).

[12] Implicitly, we thus disregard costs associated with protecting the asset from cyber security risks associated with the crypto trading platforms, as these costs are unlikely to be strongly time-varying.

[13] In column (3) of the Table, we also include contemporaneous changes in VIX to proxy for potential pricing errors due to (time-varying) financial constraints that may affect arbitrageurs who operate also in the traditional financial system. Such constraints could drive variation in $\delta_{t,T}$ and explain the (co-)variation in carry observed in the data. However, the results in column (3) do not suggest an important role of such constraints for explaining crypto carry.

differential. There are two types of crypto interest rates that can matter for carry. First, if we take the perspective of an investor in the crypto world, the appropriate risk-free rate depends on whether the investor already has an endowment of spot BTC or not. If the investor has the asset, then the opportunity cost of deploying it in a cash and carry arbitrage is to stake that asset in a liquidity pool and earn rewards (sometimes also referred to as yield farming). As a rough approximation for that rate, we use 1-month BTC lending rates on the DeFi platform Aave.[14] Second, in case the investor does not have the spot asset, she can borrow it either from the same pool (if she has some other crypto-asset to pledge as collateral), or she can source the asset from other platforms, paying larger rates. To proxy for these larger rates, we use Binance borrow rates for the top client ("VIP") category (assuming carry traders are able to borrow at the most attractive rates).[15] Finally, one can also take the prospective of an investor without any prior endowment of crypto assets who can use funding in fiat currency to finance the collateral pledged on a regulated exchange such as the CME. The appropriate interest rate can be approximated by LIBOR (likely plus some funding spread depending on the creditworthiness of the investor).

The plot of these interest rates in the third panel of Figure 2 shows that they are not variable enough to explain the more volatile carry of crypto futures – regardless of whether we take interest rates in the crypto or in the fiat world.[16] In addition, even the riskiest borrowing rate from Binance is still too low compared to the one implied by crypto carry, on average. Any funding spreads on top of LIBOR, which would have to be paid by arbitrageurs depending on their credit risk, are unlikely to be large enough to account for the difference between carry and LIBOR. Overall, the evidence from the plots suggests that interest rate differentials are unable to explain the variation in carry observed in the data.

[Table 3 about here]

To test more formally whether interest rate differentials span carry, we also regress carry on the two measures of interest rate differentials described above, in columns (4) and (5) of Table 3. Interestingly, while the R^2 is low in both regressions, the two interest rate spreads are negative and statistically significant in each case. While the benchmark futures pricing equation in (1)

[14] Aave is a large decentralized finance protocol that allows users to lend and borrow several crypto-assets at variable and fixed interest rates.

[15] The results with the rate for the lowest client category are similar.

[16] Also see Franz and Valentin (2020) for an analysis of covered interest parity deviations in the crypto space.

would prescribe a coefficient of minus one in these regressions in the absence of frictions (also see footnote 11 above), both coefficients are far from this predicted theoretical value and confirm that carry cannot be explained by interest rate differentials alone. The time-variation in crypto carry thus must come from fluctuations in crypto convenience yields.

2.4. Decomposing crypto carry: Spot versus futures premium

To understand the drivers of crypto carry better, we now turn to a decomposition time t carry into (expected) changes in future spot rates and the futures premium (Section 2.4.1). We then link these results to the variance of carry and show that crypto futures exhibit excessive volatility (Section 2.4.2) before comparing our results to those for other commodities (Section 2.4.3).

2.4.1. Fama regressions

Based on the insights in Fama (1984) and Fama and French (1987), we can use the identity

$$\underbrace{F_{t,T} - S_t}_{\text{Carry}} = \underbrace{F_{t,T} - F_{T,T}}_{\text{Futures premium}} + \underbrace{S_T - S_t}_{\text{Spot change}} \tag{2}$$

to show that, by definition, time t's basis $F_{t,T} - S_t$ should predict subsequent changes of the spot price S_t until maturity T or the futures $F_{t,T}$ (premium), or both. Note that this decomposition is true without making any assumptions.

To test whether the basis $F_{t,T} - S_t$ predicts subsequent changes of the spot price S_t, we run a simple predictive regression:

$$S_T - S_t = \alpha_1 + \beta_1 \cdot (F_{t,T} - S_t) + \epsilon_{1,t}. \tag{3}$$

Similarly, for the futures $F_{t,T}$ (premium), we run:

$$F_{t,T} - F_{T,T} = \alpha_2 + \beta_2 \cdot (F_{t,T} - S_t) + \epsilon_{2,t}. \tag{4}$$

By adding eq. (3) and eq. (4) , we see that $\beta_1 + \beta_2$ should be equal to one. The closer β_1 is to

1, the more predictive power the basis has for the spot price change to maturity, and the less it is related to the futures premium. These two regressions are classic ones from the commodity futures literature (Fama and French, 1987).

[Figure 3 about here]

Figure 3 shows the results for regressions eq. (3) and eq. (4). The estimates illustrate that a higher carry (higher futures compared to spot price) predicts a *negative* change for the spot *and* the futures price, i.e., both the futures and the spot price will be lower at expiration. The figure also shows that $|\beta_2| > |\beta_1|$, which means that the decline in the futures is larger than the decline in spot prices. The estimates are larger in absolute value for longer maturities: the coefficients for $T = 3$ months are above ten (for all exchanges), whereas the coefficients for $T = 1$ month are below seven, except for 1-month ETH on CME (Figure A.4). The estimates for 3-month futures show that a one-dollar increase in the basis roughly predicts an eleven-dollars drop in the futures premium and a ten-dollars drop in the spot at expiration–rather extreme moves from an economic perspective. Estimates for 1-month futures generally have lower degree of statistical significance than those for 3-month but are similarly large from an economic standpoint.[17] The estimates for 1-months OKEx futures, for example, show that a one-dollar increase in the basis roughly predicts a six-dollars drop in the futures premium and five-dollars drop in the spot at expiration.

We also repeat the analysis using the longest available data for each individual exchange in the right panels of Figure 3 and Figure A.4. The estimates are only marginally significant for 3-month ETH for this sample, which might be due to larger volatility in the longer time period. However, also for this sample, the large economic magnitude of the estimates indicates that the basis is too persistent to capture the volatile changes in the spot and the futures as we explain next.

[17] There is some heterogeneity across exchanges with Huobi and Deribit having the largest coefficients in absolute value among non-regulated exchanges. CME has the largest coefficients in absolute value for 3-month BTC, and is the only exchange with insignificant 1-month estimates. This fact might be driven by CME-specific effects that are different to non-regulated trading platforms. For example, an important factor is that CME does not have trading on weekends and has limited trading hours. Therefore, prices on CME might react more discontinuously to shocks compared to prices on non-regulated exchanges, which have trading 24/7.

2.4.2. *Crypto futures prices exhibit excessive volatility*

The fact that $\beta_2 >> 0.5$ implies that futures price changes are excessively volatile compared to spot price changes, in units of crypto carry variance. To see this, let us define $F_{t,T} - S_t = \text{Carry}$, $S_T - S_t = dS$, $F_{T,T} - F_{t,T} = dF$ and by taking conditional variances of both sides of eq. (2), we can write:

$$\begin{aligned} &\text{Var}_t(\text{Carry}) = \text{Var}_t(-dF) + \text{Var}_t(dS) + 2\text{Cov}_t(-dF, dS) \\ \iff &\text{Var}_t(dF) = \text{Var}_t(dS) + (2\beta_2 - 1)\text{Var}_t(\text{Carry}). \end{aligned} \tag{5}$$

Since $\text{Var}_t(\text{Carry}) \geq 0$, the last equation shows that if $\beta_2 > 0.5$, $\text{Var}_t(dF) \geq \text{Var}_t(dS)$, i.e., the change in the futures prices is more volatile than the change in the spot price. Given that our estimates of β_2 are close to 6 for 1-month maturity, eq. (5) implies that the variance of the futures change is *at least* 11 times larger than the variance of the spot change in units of the variance of carry.[18]

This observation suggests that crypto futures price changes exhibit *excessive volatility* relative to spot prices (expressed in units of carry variance). Put differently, the carry is too persistent to account for the larger volatility of futures and spot price changes to maturity. One possible reason for the finding that futures are more volatile than spot is that a large share of crypto trading takes place in leveraged products, such as futures, which creates "excessive" volatility of futures prices, e.g., when levered positions are forced to be liquidated on margin calls. We come back to this potential explanation below when studying the drivers of crypto carry.

2.4.3. *Comparison to commodity markets*

It is also instructive to compare our results for BTC and ETH to traditional commodities such as gold, silver, oil and gas. In these markets, β_1 and β_2 are much closer to 1 for 1-month and 3-months futures (see Figure A.1 in the Internet Appendix). At 3-months maturity, the regression estimates for BTC and ETH resemble those for gold in that $\beta_2 > 1$ and $\beta_1 < 0$. Gold is the

[18] This finding is not an artifact of using constant-maturity futures, but also obtains when using raw future prices and simply calculating $[\text{Var}(dF) - \text{Var}(dS)]/\text{Var}(Carry)]$.

only commodity in our sample with $\beta_2 > 1$. In a sense, these results show that the predictive behavior of crypto carry is similar to that for gold futures, albeit with a much larger magnitude of the estimates.

Interestingly, our results are similar to the findings of Fama and French (1987), who show that $\beta_1 < -1$, $\beta_2 > 1$ for silver and gold. For example, they find that $\beta_1 = -8.56$, $\beta_2 = 9.56$ for silver and write that "the regressions ... are puzzling ... the coefficients seem bizarre". The similarity between the carry of crypto assets and that of precious metals may be interesting since BTC is frequently referred to as "digital gold" in the media and some authors (e.g. Selgin, 2015) suggest to classify these crypto assets as "synthetic commodities".

3. Understanding crypto carry

Our results so far indicate that fluctuations in crypto carry largely owe to movements in convenience yields and that a positive carry predicts large drops in crypto prices. We now go a step further to provide a deeper understanding of the *economic drivers* of crypto carry. In particular, we explore why convenience yields fluctuate so strongly, and why smart capital does not take full advantage of the high yields implied by crypto carry.

We first study the investor composition of crypto futures markets and the positioning of different classes of investors. This allows us to get a better sense of the different counterparties trading crypto futures and their likely motives. We then analyse the role of smaller, potentially less sophisticated, investors that seek leveraged exposure to crypto, before turning to factors that might limit the deployment of capital leaning against the trades of such investors. Finally, we describe how these forces shape the dynamics of crypto prices and potentially lead to prolonged booms followed by severe crashes.

3.1. Positioning of different types of investors

To study how the trading actions of different investors impact crypto carry, we run regressions of carry on net CME futures positions of various trader groups. We identify those positions based on the COT reports by the CFTC and run:

$$\text{Carry}_t = \alpha + \beta_D X_{D,t} + \beta_L X_{L,t} + \beta_N X_{N,t} + \beta_O X_{O,t} + \epsilon_t, \tag{6}$$

where $X_{D,t}, X_{L,t}, X_{N,t}, X_{O,t}$ are the positions of 'dealer intermediaries', 'leveraged funds', 'nonreportables' and 'other reportables', respectively, in week t. The group of 'institutional investors' is left out and thus serves as a reference category, since net futures positions sum to zero across all investor groups. In these regressions, we use 1-month BTC carry (the results for ETH and 3-month carry are similar) at a weekly frequency to match the CME positions data.

[Figure 4 about here]

The left panel of Figure 4 illustrates how the positions of different investor types evolve over the sample period. Nonreportable positions are on average net long futures, whereas leveraged funds and dealers are on average net short. Other reportables have been net long since late 2020, whereas institutional investors have on average been net short. Note that institutional investors' positions are flat and close to zero for most of the sample period. The spike in institutional investor positions towards the end of 2021 might be related to the launch of the first US Bitcoin exchange-traded fund (ETF) in October 2021 (Todorov, 2021).

The right panel of Figure 4 reports the estimates of regression Eq. (6) above, all of which are significant at the 5% level. More interestingly, we find that increases in net long positions by nonreportables are associated with a larger basis, whereas dealer intermediaries' net long positions are negatively correlated with crypto carry. The coefficients for leveraged funds (negative) and other reportables (positive) are smaller in magnitude.

Since the group of nonreportables in the COT data captures the activity of smaller investors (e.g., family offices, smaller trading shops and proprietary traders), these initial results square well with the notion that a high carry, and thus convenience yield, typically comes alongside with a rise in positions of smaller investors. By contrast, larger institutions typically take the opposite side, effectively providing liquidity. Aside from outright short futures positions, such liquidity provision could take the form of collecting the returns on a cash and carry trade.

3.2. Demand for leveraged upside exposure by small and trend-chasing investors

We now try to establish more formally the link between the demand for futures by smaller, trend-following investors, and increases in crypto carry. We do so by running regressions of the carry on potential drivers of the convenience yield. To keep the presentation concise, and given the high correlation of carry across non-regulated exchanges (Deribit, OKEx, FTX, Huobi and Binance), for simplicity we present the regression of carry using OKEx as a representative crypto exchange in our results below.[19] In addition, we also present results for carry on the only regulated exchange (CME).

[Table 4 about here]

In the first column of Table 4 we regress 1-month crypto carry on changes in social media users on Reddit. The main motivation behind the Reddit variable is to capture trading interest by smaller, potentially less sophisticated traders that coordinate on social media platforms. For carry on OKEx, we find a strong and positive link between changes in the number of Reddit subscribers to topics relating to Bitcoin and crypto carry, with a relatively large R^2 of 23%.[20] The explanatory power of the Reddit variable for CME basis is smaller, and the estimate is more than twice smaller compared to OKEx as seen from column (6) of Table 4. The differences between the two exchange could be explained by prices on non-regulated exchanges being more heavily influenced by retail traders who are more likely to coordinate using platforms like Reddit. By contrast, on regulated exchanges such as the CME, which are populated by a relatively larger share of institutional investors, the impact of changes in the attention by retail investors seems to be less pronounced.

In the specifications of columns (2), (3), (8) and (9) of Table 4, we include BTC returns over the past week and month. The idea here is to analyse how possible trend-following behavior – due to investors chasing past price moves – is related to crypto carry. Consistent with a trend-chasing argument, the estimates in the table show that higher past crypto returns are typically associated with a larger crypto carry.

[19] OKEx is the exchange with one of the largest open interest and the longest data available in our sample. The regressions for other non-regulated exchanges share similar patterns with OKEx.

[20] Note that the Reddit data is not available for the full sample period, which explains the drop in the number of observations.

Price pressure. To address the concern that the trend-chasing variables do not simply capture general price pressure effects, we add measures of price pressure to the regression. The specifications in columns (4) and (9) regress crypto carry on two measures that capture possible price pressure effects. The first measure is signed trading volume (futures trading volume multiplied with +1 for positive futures returns, and -1 for negative ones), and the second is futures open interest. We find a positive and significant effect of both measures for OKEx and CME, with a large R^2. However, in the richer specifications (columns (5), and (10)), only open interest remains statistically significant. These results support the idea that price pressure effects (or "downward sloping demand curves") have a bearing on crypto carry.

More importantly, the effects of the Reddit variable and trend-chasing variables remain significant and positive also after controlling for the price pressure variables in columns (5) and (10). The estimates for short-term returns (one week) are more robust than those for long-term returns (one month) for OKEx, suggesting that shorter-term trend-following investors have larger impact on crypto carry on this non-regulated crypto platform.

3.3. Limits to the deployment of carry trade capital

After establishing that demand for leveraged upside via crypto futures by trend-followers is positively correlated with crypto carry, we now turn to the factors that limit the deployment of capital to take the other side of such trades. One can think of these factors as "limits to the supply of arbitrage capital". By engaging in a cash and carry trade that is long the spot and short the futures, carry traders would lean against the demand side pressure from smaller investors, which would presumably lead to a tightening of the basis.

The cash and carry strategy, and limits to arbitrage. To understand the incentives of the arbitrageurs, we first study the risk-return characteristics of the cash and carry strategy. At time t, this strategy assumes going long spot and selling forward BTC (or ETH) via a futures contract if the carry is positive (and vice versa if the carry is negative). Hence, if the carry at time t is positive ($F_{t,T} > S_t$), the payoff for the cash and carry trader is positive at t and zero at maturity T since $F_{t,T} - S_T = 0$. Conversely, the trader earns a positive payoff of $S_t - F_{t,T}$ at t if the current carry is negative ($F_{t,T} < S_t$), and does not have to pay anything at T. This simple setup allows for convergence trades in both directions, depending on the sign of the carry when the trade is initiated. We report separately the characteristics of the futures and the spot legs of the strategy since otherwise we run into an infinite Sharpe Ratio problem because at expiration, $F_{t,T} = S_T$.

Importantly, while this basis trade is "risk-free" in the sense that the futures and spot price will converge at maturity of the contract, it is not risk-free during the lifetime of the trade. The reason is that the basis can widen, e.g. when trend-followers increase their long futures position when carry is positive, thereby triggering margin calls and possibly contract liquidations of arbitrageurs before convergence actually takes place at maturity. This risk is more pronounced for trades on the CME, since traders cannot hold the spot at the exchange (but rather need to pledge liquid assets in fiat currency as collateral) and hence, there is no way of *cross-margining* between the spot and the futures position. This is a crucial friction that could prevent more sophisticated carry traders in traditional finance from shorting futures when carry is positive: losses on the short futures position are not automatically offset by gains in the long spot position because the spot asset cannot not held with the CME.

The absence of cross-margining and the opacity of margining rules on several key non-regulated exchanges can also act as a deterrent for the carry traders to deploy more capital. For example, some exchanges specify a maximum loss on a futures position, which limits the amount of capital that could be devoted to the cash and carry strategy.[21] Other exchanges also use USD as the numeraire when calculating margin balances, similar to CME, and thus require liquidations of the spot asset to meet margin calls. This liquidation, however, removes the hedge asset used in the cash and carry strategy, and could also lead to premature liquidation of the whole position. Overall, the absence of cross-margining, as well as other margin frictions could lead to forced liquidations before maturity and make the cash and carry strategy risky. The fact that rises in carry predict significant liquidations of existing short futures positions as we report below, is consistent with this conjecture.

[Table 5 about here]

[21]For example, as of 2021, FTX specified a maximum loss of USD 30,000 on a futures position. This means that a 1 million USD short futures position would be liquidated after a 3% rise in BTC.

Properties of the cash and carry strategy. Table 5 reports results for the cash and carry strategy, implemented for CME 1-month futures contracts on BTC.[22] We report mean returns, Sharpe Ratios, and drawdowns for two periods: 2018-2022 (longest available CME sample) and 2019-2022 (our main sample used in the rest of the paper). Table 5 shows that mean excess returns on the futures leg of the basis trade is sizeable at 3-4% *per month*, which is several orders of magnitude larger than the returns on futures in traditional asset classes like equities, fixed income, currencies and commodities (see Heston and Todorov (2023)). Crypto futures returns are also highly volatile (about 25% per month) and exhibit strong negative skewness. The latter indicates that, as the basis can widen significantly before maturity, large losses for carry traders can occur. Further corroborating the point that crypto carry trades are risky, we find that the futures leg of the strategy would have been liquidated in more than half of the months in our sample in the case where we assume a leverage of 10, as shown in Figure 5. The Figure illustrates several profit and loss (PnL) paths for the futures leg of the strategy before maturity.

In the fourth column of Table 5, we report the return properties of the cash and carry strategy.[23] The annualized Sharpe Ratio of this strategy is about 0.6 (before transaction costs and financing spreads). Such a Sharpe Ratio is roughly in the same ballpark as that for the aggregate stock market. However, a simple buy-and hold spot bitcoin position over the same sample period has a twice lower Sharpe Ratio but a higher mean return. The "opportunity cost" of earning lower average return in the cash and carry strategy compared to simply holding the spot asset may also partly explain the reluctance of some traders to lean against carry widening. If crypto traders pay more attention to average returns rather than Sharpe Ratios, they would find it more attractive to simply hold the spot asset instead of implementing a cash and carry trade.

[Figure 5 about here]

The facts from this section indicate that rather than being a risk-free arbitrage trade (as it is commonly portrayed in the financial press), the crypto carry trade exposes arbitrageurs to significant risks. These risks might loom large if noise traders push up the futures price prior

[22] We only report results for BTC here since we have to use non-overlapping 1-month intervals but the sample period for ETH CME futures is too short. We assume the collateral has been financed at LIBOR.

[23] This strategy assumes the investor keeps equal portfolio weights in the futures and the spot legs on a monthly basis. We construct this strategy to avoid the infinite Sharpe Ratio problem highlighted before.

to the futures' maturity date, thereby generating mark-to-market losses for the carry trader who is short the futures. In addition, these results already tentatively suggest that, from the viewpoint of a potential arbitrageur, deploying capital in a cash and carry crypto trade may not be attractive enough compared to other investment opportunities.[24]

Contract liquidations and carry trade risks. To investigate the risks to the cash and carry strategy further, we also regress the amount of 'buy and sell liquidations" in futures contracts, i.e. the forced closing of open contracts, as well as implied and realized volatility, on the lagged crypto basis.

We present the regression results in Table 6. Sell (buy) liquidations is the cumulative amount of short (long) futures positions that were liquidated over a given month (expressed as percent of open interest). These measures capture both forced liquidations by the exchange due to missed margin calls, as well as voluntary liquidations by the trader.

[Table 6 about here]

Interestingly, Table 6 shows that crypto carry predicts significantly only sell liquidations: a rise in carry by 10% predicts 44% increase in total sell liquidations (relative to total open interest) over the next month. Hence, while a high carry predicts overall greater risk (as both future realized and implied volatility go up when carry rises as indicated in columns 3-6), it only forecasts contract liquidations of short positions, but not of long positions. The latter fact is consistent with contract liquidations of cash and carry trades as these trades involve short futures positions (for most of the sample).

Taken together, these results support our argument above that crypto carry does not represent a "risk-free" arbitrage trade. Instead, it exposes traders to the risk of sharp price moves that could lead to liquidations of positions. A key implication is that carry traders, despite seemingly earning risk-free arbitrage returns, could only deploy capital cautiously. The cash and carry trade essentially boils down to liquidity provision by the carry traders as they are the counterparties to trend-followers who seek leveraged upside exposure via futures. Thus, a natural

[24]For example, based on anecdotal evidence from currency carry traders at banks and hedge funds, Lyons (2001) reports that Sharpe Ratios have to exceed a certain threshold (somewhere in the range of 0.5-1.0 p.a.) in order for arbitrageurs to commit capital to such a trade. Crypto cash and carry trades hardly pass this hurdle as documented in Table 5.

explanation for why crypto carry is persistent and large, is that such type of liquidity provision may not be attractive enough for most market participants given the involved risks. Hence, capital that "leans against" a widening of the basis might be relatively scarce and slow-moving.

3.4. Crypto carry and crash risk

A salient feature of crypto markets is their high volatility and propensity of price crashes. In the following, we take a closer look at the link between crypto carry and crash risk.

Recall from the results in Section 2.4.1 that a higher carry today predicts a (large) drop in BTC and ETH prices at maturity. This fact could have implications also for options markets and particularly for put options, since those contracts will be in the money when prices fall. Anticipating that a higher basis is associated with low returns in the future, sellers of put options (liquidity providers in option markets) would presumably charge a higher premium at times of an elevated basis.[25]

[Table 7 about here]

To test this hypothesis, we regress crypto carry on several risk measures from the option and spot markets, in Table 7. The variables we select include proxies for implied skewness (25-Delta risk reversal), open interest of puts relative to calls, 1-month at the money (ATM) implied volatility, and 1-month realized volatility.

Columns (1) and (4) of Table 7 show that crypto carry is strongly contemporaneously correlated with implied skew for non-regulated and regulated exchanges. The negative sign of this correlation illustrates that a higher carry typically goes hand in hand with larger put prices relative to call prices (for the same level of moneyness). In other words, insuring against crashes becomes more expensive when carry widens. Moreover, we find that a larger carry is associated with a higher ratio of puts versus calls as measured via their open interest. Similarly, a rising basis goes hand in hand with a higher implied volatility.

To the extent that past realized volatility is the expectation of future realized volatility and ATM volatility captures risk-neutral expected volatility, the results from column (1) show that

[25] For a study on demand pressure in BTC option prices and option market makers' inventory management see e.g., Alexander et al. (2022).

basis is positively related to the variance risk premium (VRP) – the difference between expected risk-neutral and expected realized volatility. This fact is illustrated by the positive estimates on 1-month ATM Vol and the negative coefficients on 1-month Realized Vol. The positive exposure to the VRP is therefore consistent with option sellers charging larger premiums when the basis increases.

Taken together, these findings suggest that option sellers charge higher premiums when the basis is high and particularly so for downside protection (put options). The option measures alone capture 42–44% of the variation in crypto carry, as indicated by R^2. According to that criterion, they turn out to be the strongest variables that help explain fluctuations in carry. Among these option measures, the 25-delta skew and put-call open interest stand out, illustrating the importance of crash risk. When we include additional variables as controls to the regression, i.e. the variables considered in the previous regression tables, the link with crash risk remains robust (see columns (2) and (5) of Table 7). That said, the regression coefficients tend to shrink and significance is reduced when we add the lagged basis itself to the regression, as columns (3) and (6) indicate. Put-call open interest (and 25 delta skew in case of OKEx), however, remain(s) significant in explaining movements in the basis.

In addition, the measures of trend-chasing behavior considered in Section 3.2 remain significant for OKEx, but the Reddit variable becomes insignificant for CME after controlling for option measures. These results may indicate that trend-followers might play a less significant role in explaining carry on regulated exchanges.[26] Alternatively, option variables might subsume some of the explanatory power from the Reddit-based measure, especially if an increase in Reddit users coincides with an increasing activity in crypto options.

Carry as a crash risk predictor. As discussed above, we observe some very large swings in crypto carry during our sample period (see Figure 2). These periods in turn are often followed by sharp declines in the spot price of BTC and ETH as well as the respective futures premiums. Such price behavior is reminiscent of the Wall Street adage of “going up the stairs and down the elevator”.

This observation indicates that variations in crypto carry might also predict future price

[26]The results are robust to using the same period for OKEx and CME in the regressions.

crashes, akin to the crash risk observed in carry trades in other markets like foreign exchange (e.g. Brunnermeier et al., 2008). To test this link, we next run regressions of measures of crash risk on lagged carry:

$$y_{t+1\ month} = \alpha + \beta \times \text{Carry}_t + \varepsilon_{t+1}, \tag{7}$$

where y denotes a proxy for asymmetries in returns (implied based on options or realized based on spot prices) or volumes.

[Table 8 about here]

Table 8 reports the results of these regressions. We only report the results for the 1-month BTC basis as independent variable, for brevity. We find a strong negative relationship between implied skewness and carry for both exchanges, implying that a larger carry is associated with a higher price of crash risk over the next one to three months. The relationship between realized skew (measured from daily spot returns over the following month) and carry is also negative but only statistically significant for OKEx, for which we have a longer sample period. These findings confirm the notion that a high basis tends to be followed by price crashes in the spot price of BTC, which is consistent with the results of Borri and de Magistris (2021) who find that the premium of crypto assets is largely driven by higher-order moments risk.[27]

Consistent with our previous results (in Section 2.4.1), we also find that a higher basis predicts lower realized spot returns. This effect is especially pronounced at longer horizons (3 months). In other words, carry also predicts the first moment of the return distribution, in addition to higher moments (skew).

4. Conclusion

We study the carry of crypto futures on Bitcoin and Ether, i.e. the difference between futures and spot prices. Crypto carry is large (up to 60% p.a.), strongly time-varying, and is most compatible with the existence of a highly volatile crypto futures convenience yield, i.e. investors

[27]Borri et al. (2022) study the risk premium in crypto assets and find that macroeconomic risk is priced in cryptocurrency. Borri and Shakhnov (2019) propose a risk-based explanation for bitcoin price differences across currencies and countries.

are willing to pay more for the convenience of a levered futures contract relative to buying spot crypto. This convenience yield stems from two main forces: (i) trend-chasing and attention by smaller investors seeking leveraged upside exposure to crypto assets, and (ii) the relative scarcity of "arbitrage" capital taking the other side through a cash and carry position. Engaging in such an arbitrage trade is risky due to spikes in margins when carry widens before maturity of the futures contract, which leads to early liquidation of positions.

Our results have a number of implications, more narrowly for the understanding of crypto markets and associated derivatives, but also more broadly, for understanding economic drivers of convenience yields and limits to arbitrage in segmented markets. Our findings suggest that the carry of futures contracts has a strong common component across exchanges and shows few exchange-specific price discrepancies. Most of the large swings in carry instead seem to be driven by aggregate forces, which we trace back to a large and time-varying crypto convenience yield that cannot be easily arbitraged away. Moreover, our results suggest that crash risk in crypto markets and liquidations of futures positions are closely linked to, and partly predictable, by crypto carry. In other words, one of the most salient features of crypto markets over the past years, namely rapid price booms followed by large busts, seem to be linked to the drivers of the crypto convenience yields. These drivers are investor attention and momentum trading by smaller investors on the one hand, versus limited deployment of arbitrage capital by large and presumably more sophisticated investors, on the other hand. At a broader level, our findings underscore the importance of investor heterogeneity for understanding asset pricing phenomena.

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5. Figures and Tables

Figure 1: Size of the crypto futures market.
The figure shows the average daily dollar open interest (number of contracts times futures price) across exchanges. Sample: September 2019 to January 2022. The data on crypto derivatives comes from Skew.

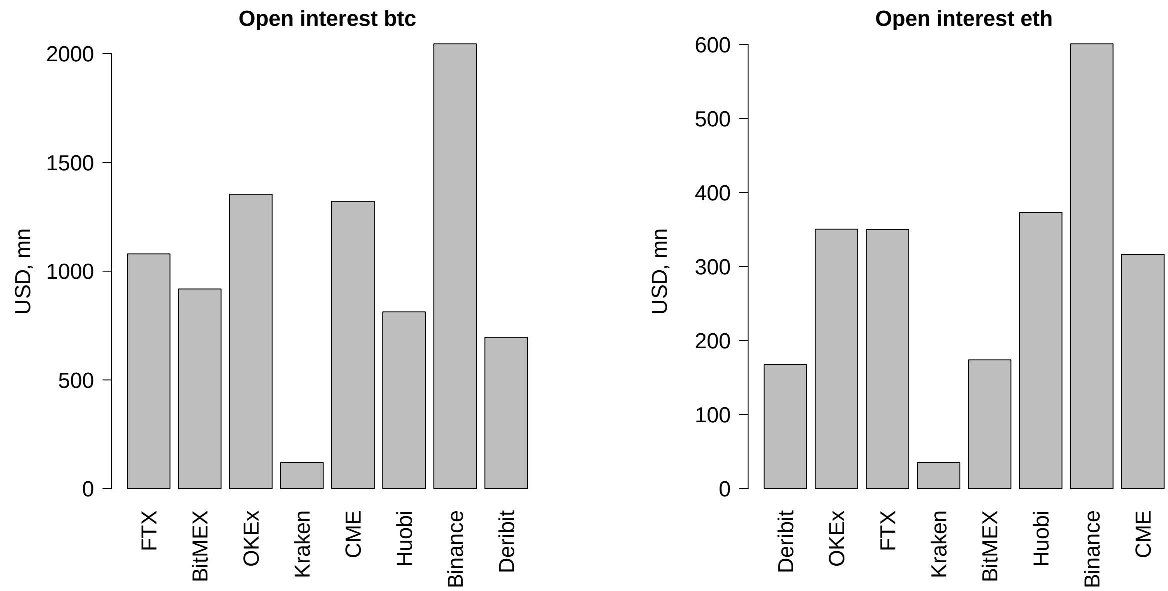


Figure 2: Dynamics of crypto carry.
The figure shows the dynamics of crypto carry for OKEx (top left panel) and CME (top right panel). The bottom panel shows also the dynamics of interest rates from Binance, Aave, and 1-month USD LIBOR. The lower right-hand panel depicts fluctuations in the 1-month BTC basis on OKEx and the spot price of bitcoin. Sample: March 2019 to January 2022 for OKEx, August 2020 to January 2022 for CME. The data on crypto derivatives comes from Skew.

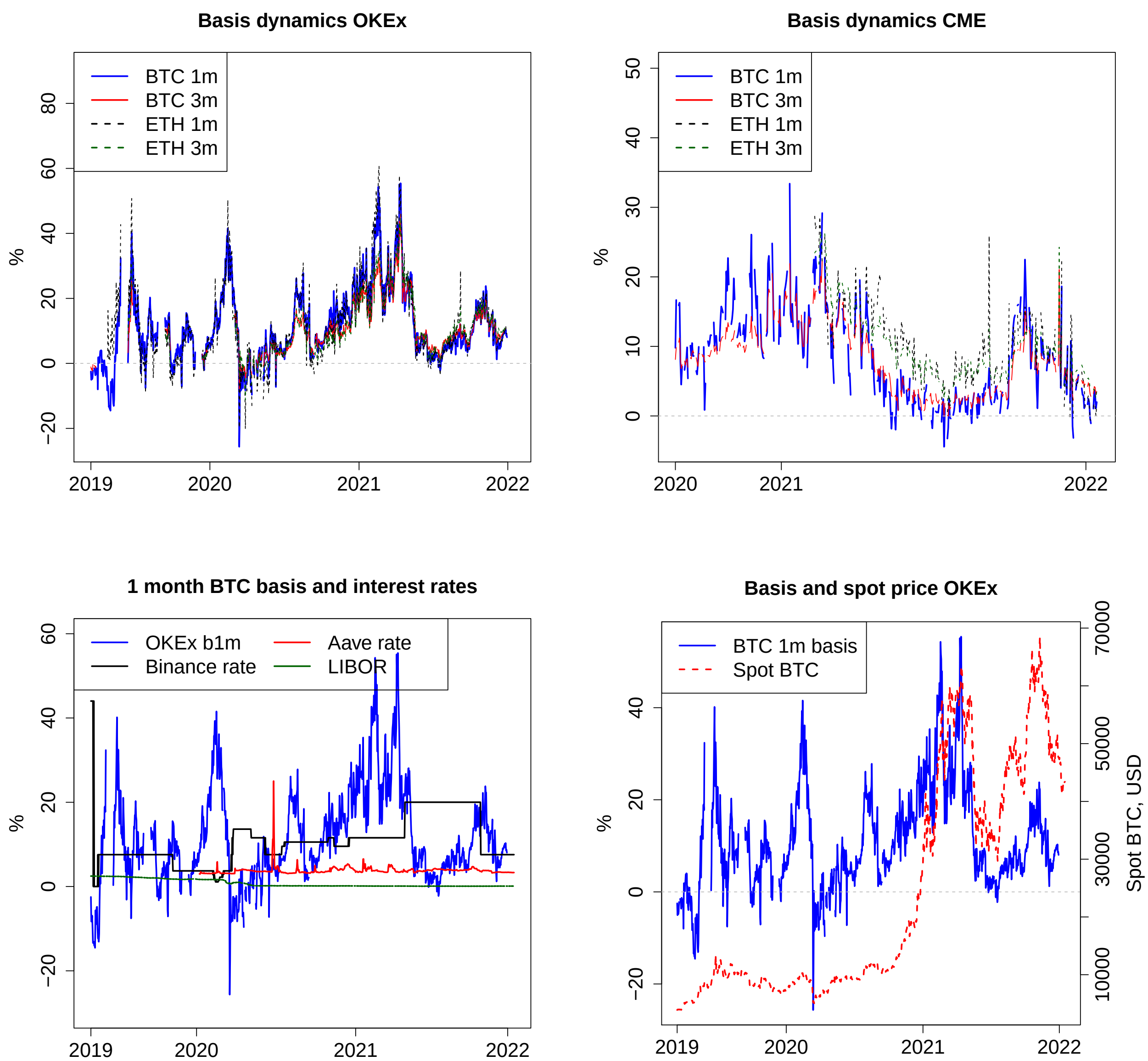


Figure 3: Predictive power of crypto carry.
The figure depicts β_1 and β_2 from regressions (3): $S_T - S_t = \alpha_1 + \beta_1 \cdot (F_{t,T} - S_t) + \epsilon_{1,t}$ and (4): $F_{t,T} - F_{T,T} = \alpha_2 + \beta_2 \cdot (F_{t,T} - S_t) + \epsilon_{2,t}$ for 1-month (upper panels) and 3-month (lower panels) BTC. The left panels use the same sample period for all exchanges (August 2020 to January 2022), the right use the longest period for each exchange (Deribit is the longest, from March 2019 to January 2022). Insignificant coefficients at the 5% level are with dashed filling. Interpretation of the estimates: e.g., for Deribit, same period, 1-month: 1% increase in basis predicts 6% drop in the spot, and 7% drop in the futures until expiration of the futures contract. Here and in all subsequent regression figures and tables standard errors are computed using the Newey-West method with automatic bandwidth selection). The data on crypto derivatives comes from Skew.

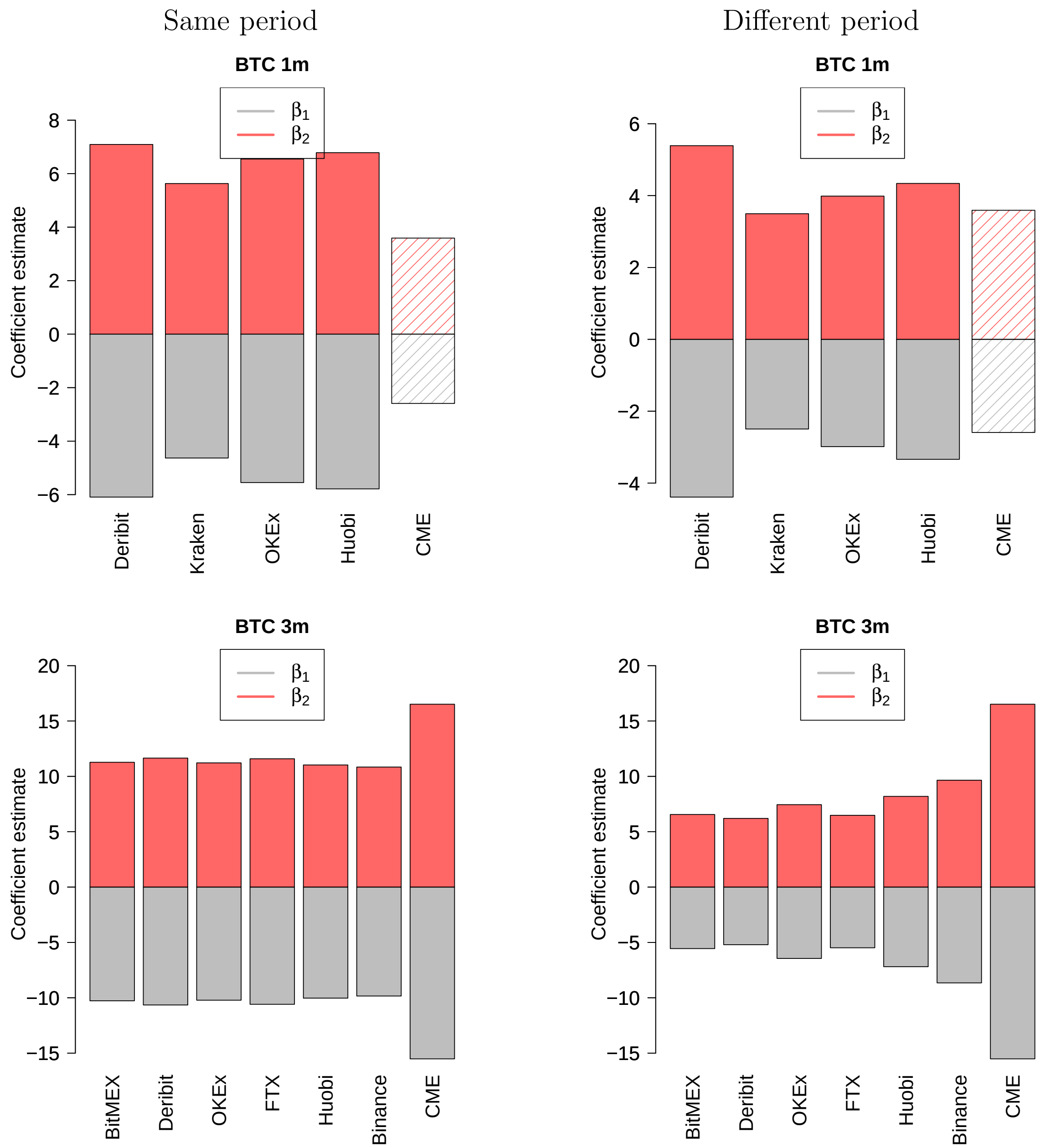


Figure 4: CME positions and regressions.

The left panel shows the dynamics of positions from different types of investors. The right panel shows the estimates of the following regression at the weekly frequency: basis 1-month$_t$ = $\alpha + \beta_D X_{D,t} + \beta_L X_{L,t} + \beta_N X_{N,t} + \beta_O X_{O,t} + \epsilon_t$, where basis 1-month$_t$ is 1 month futures basis, $X_{D,t}, X_{L,t}, X_{N,t}, X_{O,t}$ are the positions of dealer intermediaries, leveraged funds, nonreportables and other reportables, respectively. All β-s are significant at the 5% level. Reference category is institutional investors. The estimate of β_N ("Nonreportable") for instance shows that an increase in nonreportable positions by 1,000 contracts is correlated with 0.9% increase in basis. Sample: March 2019 to January 2022. The data on crypto derivatives comes from Skew.

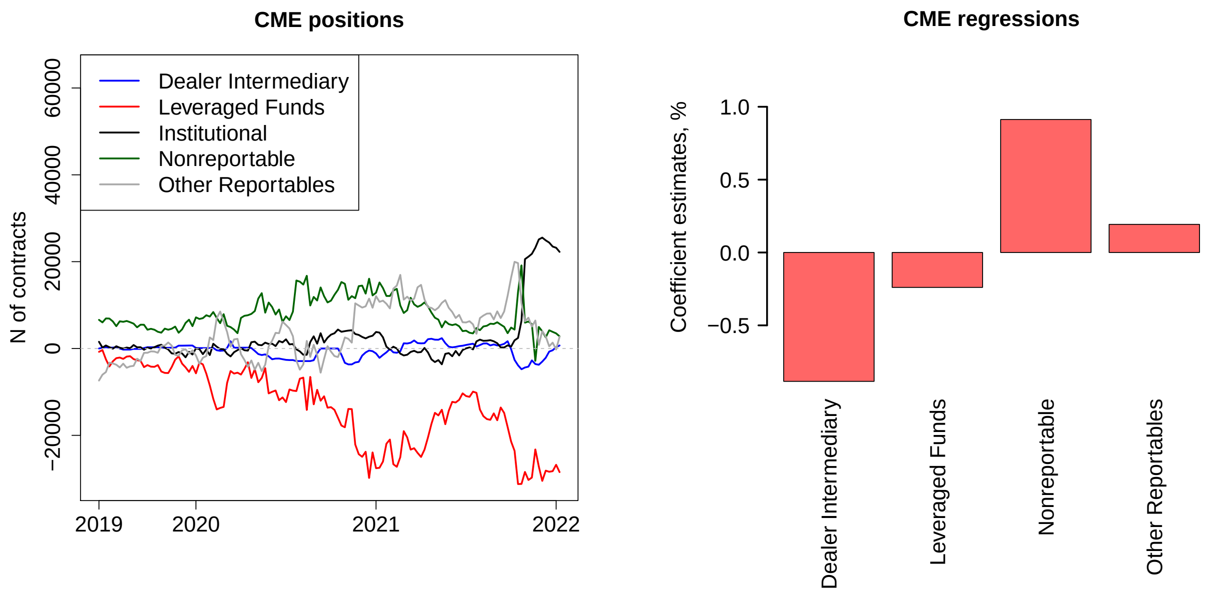


Figure 5: Trading strategy: futures leg.
The figure shows the cumulative returns on the strategy of selling (buying) CME BTC futures when basis is positive (negative) 19 trading days before expiration. 19 trading days capture most of the months in our sample since 28 days before expiration corresponds to 19-22 trading days. The lines correspond to several paths, the dashed horizontal lines illustrate several levels of leverage (L). E.g., with a leverage of 5, the position is bankrupt if the cumulative return before maturity is below -0.2. Sample: August 2020 to January 2022.

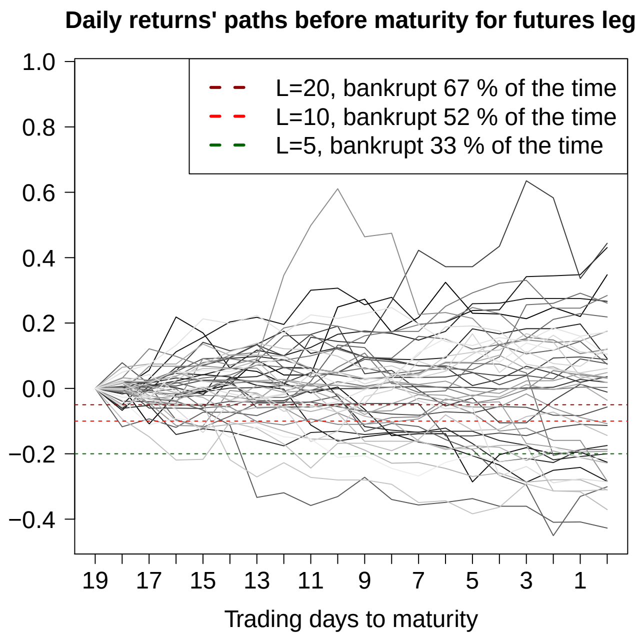


Table 1: Summary statistics for crypto carry.

The table shows the average basis (crypto carry), constant maturity of 1 month or 3 months and in annualized %. For BTC, the sample starts in March 2019 for OKEx and in August 2020 for CME. For ETH, it starts in April 2019 for OKEx and in February 2021 for CME. The final date is January 2022 for all time series. Frequency is daily. The data on crypto derivatives comes from Skew.

Panel A: BTC crypto carry				
	OKEx	CME	OKEx	CME
	1 month		3 months	
Mean	11.10	8.69	10.84	8.22
Median	8.77	8.29	9.21	8.23
Std	11.21	6.78	8.32	4.93
Skewness	0.86	0.52	0.97	0.43
Min	-25.65	-4.43	-7.87	-0.10
Max	55.42	33.40	45.93	22.33
AR(1)	0.93	1.00	1.00	0.94
Observations	958	340	707	354
Panel B: ETH crypto carry				
	OKEx	CME	OKEx	CME
	1 month		3 months	
Mean	12.09	10.34	11.17	9.85
Median	9.55	9.69	9.54	8.60
Std	12.10	6.05	8.93	5.13
Skewness	0.99	0.69	0.87	1.20
Min	-20.14	-0.62	-11.21	2.01
Max	60.69	28.72	44.98	26.42
AR(1)	0.92	0.83	1.00	0.93
Observations	932	232	696	237

Table 2: Correlations of crypto carry.
Panel A of the table shows daily correlations of the basis within exchange. Panel B reports correlations across exchanges for the 1-month BTC basis. The data on crypto derivatives comes from Skew.

Panel A: OKEx correlations

	BTC, 1 month	BTC, 3 months	ETH, 1 month
BTC, 3 months	0.96		
ETH, 1 month	0.94	0.93	
ETH, 3 months	0.93	0.98	0.96

Panel B: BTC, 1 month correlations

	Deribit	Kraken	OKEx	Huobi
Kraken	0.95			
OKEx	0.97	0.95		
Huobi	0.97	0.95	0.99	
CME	0.70	0.74	0.68	0.66

Table 3: Crypto carry and interest rate differentials.
The table shows pooled regressions of 1-month BTC basis for all exchanges on exchange fixed effects, time fixed effects, the change in VIX (proxy for risk constraints), and interest rate spreads. The data on crypto derivatives comes from Skew. Here and in all subsequent regression tables *,**, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

	Basis, 1 month				
	(1)	(2)	(3)	(4)	(5)
ΔVIX			0.001		
			(0.001)		
Binance-LIBOR spread				-0.24***	
				(0.03)	
Aave-LIBOR spread					-0.33*
					(0.18)
Exchange FEs	Yes	No	No	No	No
Time FEs	No	Yes	No	No	No
Observations	3,683	3,683	2,588	2,573	2,093
Adjusted R^2	0.01	0.88	0.001	0.02	0.005

Table 4: Crypto carry, investor attention and trend-chasing.
The table shows daily regressions of 1-month BTC basis on measures of investor attention and trend-chasing. All independent variables are standardized. The first five columns are for OKEx, the last five for CME. "Reddit" is the daily change in number of Reddit subscribers to groups dedicated to BTC. "$r^{spot}_{t-1w,t}$" is one-week spot BTC return, "$r^{spot}_{t-1m,t}$" is 1-month spot BTC return. In columns (4), (5), (9) and (10), we add variables capturing price pressure. "Signed volume" refers to futures trading volume multiplied with the sign of the contemporaneous return (-1 for negative return, +1 for positive), "OI" is open interest in the futures market. The data on crypto derivatives comes from Skew. Here and in all subsequent regression tables standard errors are computed using the Newey-West method with automatic bandwidth selection.

	Basis, 1 month$_t$									
	OKEx					CME				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Reddit$_t$	5.88***				3.05***	2.30***				1.94***
	(0.98)				(0.58)	(0.65)				(0.25)
$r^{spot}_{t-1w,t}$		2.67***			1.77***		2.59***			1.19***
		(0.76)			(0.46)		(0.55)			(0.34)
$r^{spot}_{t-1m,t}$			4.45***		0.50			3.80***		3.09***
			(0.89)		(1.38)			(0.49)		(0.76)
Signed volume$_t$				2.54***	0.33				2.28***	−0.52
				(0.59)	(0.60)				(0.42)	(0.41)
OI$_t$				7.07***	11.38***				0.17	2.87***
				(0.64)	(0.97)				(0.54)	(0.33)
Intercept	14.39***	10.91***	10.56***	11.64***	3.80***	6.33***	8.55***	8.20***	8.54***	3.76***
	(1.10)	(1.10)	(1.04)	(0.76)	(0.98)	(0.64)	(0.70)	(0.56)	(0.90)	(0.45)
Observations	325	956	956	812	325	230	340	339	340	230
Adjusted R^2	0.23	0.06	0.16	0.54	0.86	0.14	0.14	0.36	0.25	0.60

Table 5: Strategy characteristics.
The table shows characteristics of the strategy that sells (buys) CME BTC futures and buys (sells) spot BTC when basis is positive (negative) 28 days before expiration. The first column shows the futures leg of the strategy for January 2018–January 2022 since this is the longest available sample for CME BTC futures. The second column is March 2019–January 2022 (our main sample). The third column shows the spot leg of the strategy for March 2019–January 2022, and the fourth presents the "combined cash and carry strategy" by adding the monthly returns on the futures and the spot legs. The last column shows the returns on holding the spot until expiration. The returns are monthly. Max drawdown is the maximum value drop after the peak of the variable (e.g., for spot 2019-2022, the return drops from 62% to -40%).

	Fut. 2018–2022 (1)	Fut. 2019–2022 (2)	Spot 2019–2022 (3)	Strat. 2019–2022 (4)	Spot long 2019–2022 (5)
Mean	0.04	0.03	-0.02	0.01	0.10
Std	0.23	0.25	0.24	0.02	0.23
Sharpe	0.54	0.51	0.27	0.59	0.32
Skewness	-0.77	-0.86	0.87	2.89	0.27
Max drawdown	0.95	0.87	1.02	0.08	0.97
Observations	40	30	30	30	30

Table 6: Crypto carry, contract liquidations and volatility.
The table shows predictive regressions of crypto carry for cumulative buy or sell liquidations, ATM implied volatility and realized volatility for OKEx. The predictive horizon is either 1-month or 3-months. The data on crypto derivatives comes from Skew. All independent variables are standardized. "Buy liq" are cumulative buy liquidations of futures contracts, scaled by open interest, whereas "Sell liq" are sell liquidations, also scaled by open interest. "Ivol" is 1-month implied volatility, "Rvol" is 1-month realized volatility. "Risk rev" is 25 delta, 1-month risk-reversal, which proxies risk-neutral skew, "Skew re" is realized 1-month skew.

	Buy liq$_{t+1m}$	Sell liq$_{t+1m}$	Ivol$_{t+1m}$	Rvol$_{t+1m}$	Ivol$_{t+3m}$	Rvol$_{t+3m}$
	(1)	(2)	(3)	(4)	(5)	(6)
Basis, 1m$_t$	−0.80	4.40**	5.09***	3.57	2.88***	5.31***
	(0.66)	(2.03)	(1.52)	(2.91)	(0.87)	(1.60)
Risk rev$_t$	−0.57	0.83				
	(0.67)	(1.06)				
Skew re$_t$	0.05	0.21				
	(0.60)	(0.76)				
OI$_{t+1m}$	3.44***	2.62*				
	(0.72)	(1.36)				
Intercept	8.18***	11.63***	76.85***	74.54***	81.84***	76.62***
	(0.60)	(1.04)	(1.43)	(2.86)	(1.03)	(1.57)
Observations	818	818	953	953	912	912
Adjusted R^2	0.20	0.20	0.07	0.01	0.04	0.06

Table 7: Crypto carry and option-based crash risk indicators.
The table shows daily regressions of 1-month BTC basis on a range of variables. The setup is akin to that of Table 4, but adds option-based variables that capture crash risk. The first three columns are for OKEx, the last three for CME. The data on crypto derivatives comes from Skew. All independent variables are standardized. "Reddit" is the daily change in number of Reddit subscribers to groups dedicated to BTC. "$r^{spot}_{t-1w,t}$" is 1-week spot BTC return, "$r^{spot}_{t-1m,t}$" is 1-month spot BTC return. "Volume" is total trading volume in the futures market, "Signed volume" is total trading volume in the futures market multiplied with the sign of the contemporaneous return (-1 for negative return, +1 for positive), "OI, fu" is open interest in the futures market. "1-month ATM Vol" is at-the-money (ATM) volatility for maturity 1 month, "1-month 25D skew" is the difference between a 25-delta put's implied volatility and a 25-delta call's implied volatility, normalized by the ATM implied volatility, for maturity 1 month. "1-month Realized Vol" is the realized volatility of the spot over the past 1 month. "Putcall OI" is the ratio of open interest of puts to that of calls.

	Basis, 1 month_t					
	OKEx			CME		
	(1)	(2)	(3)	(4)	(5)	(6)
Reddit_t		3.76***	0.64*		0.02	−0.02
		(0.76)	(0.37)		(0.35)	(0.22)
$r^{spot}_{t-1w,t}$		1.10*	0.72***		1.16***	0.84***
		(0.63)	(0.23)		(0.42)	(0.24)
$r^{spot}_{t-1m,t}$		−0.78	−0.14		1.07	0.52
		(1.58)	(0.67)		(0.84)	(0.66)
Signed volume_t		1.78**	0.09		0.43	0.18
		(0.76)	(0.32)		(0.40)	(0.28)
Volume_t		−2.10*	−0.91		0.04	0.09
		(1.15)	(0.55)		(0.37)	(0.33)
OI, fu_t		−2.52	0.40		2.84***	1.07***
		(3.71)	(1.57)		(0.36)	(0.34)
1-month ATM Vol_t	2.72***	2.56**	0.70	1.02	2.43***	0.86
	(0.66)	(1.06)	(0.51)	(0.65)	(0.81)	(0.73)
1-month 25D skew_t	−4.44***	−4.30***	−1.32***	−3.11***	−1.14**	−0.39
	(0.38)	(1.08)	(0.47)	(0.37)	(0.53)	(0.38)
1-month Realized Vol_t	−2.53***	−3.53***	−0.34	−0.75	0.12	0.28
	(0.56)	(1.06)	(0.52)	(0.82)	(0.90)	(0.65)
Putcall OI_t	3.63***	5.63***	0.96**	1.53***	2.17***	0.63**
	(0.55)	(0.81)	(0.39)	(0.45)	(0.35)	(0.28)
Basis, 1 month_{t-1}			8.79***			3.98***
			(0.49)			(0.49)
Intercept	11.51***	13.88***	11.84***	8.07***	6.38***	7.73***
	(0.48)	(2.24)	(0.98)	(0.42)	(0.43)	(0.33)
Observations	932	323	322	338	228	227
Adjusted R^2	0.44	0.78	0.92	0.42	0.70	0.79

Table 8: Crypto carry and subsequent crashes.

The table shows predictive regressions of 1-month BTC basis for risk-neutral 1-month skew (measured by risk reversal), realized skew of crypto asset returns, and realized returns. The predictive horizon is either 1-month and 3-month. The top panel is for OKEx, the bottom one for CME. All independent variables are standardized. "Risk rev" is 25 delta, 1 month risk-reversal, which proxies risk-neutral skew over the next month, "Skew re" is realized skew and "r^{spot}" is realized BTC spot return. The data on crypto derivatives comes from Skew.

	Panel A: OKEx				
	Risk rev, t	Skew re, t+1m	Skew re, t+3m	$r^{spot}_{t,t+1m}$	$r^{spot}_{t,t+3m}$
	(1)	(2)	(3)	(4)	(5)
Basis, $1m_t$	-4.44^{***}	-0.21^{***}	-0.14^{***}	-0.05^{***}	-0.14^{***}
	(0.61)	(0.06)	(0.04)	(0.01)	(0.02)
Intercept	-0.75	-0.01	-0.06	0.07^{***}	0.23^{***}
	(0.55)	(0.07)	(0.05)	(0.01)	(0.03)
Observations	940	952	912	952	912
Adjusted R^2	0.30	0.07	0.05	0.07	0.10

	Panel B: CME				
	Risk rev, t	Skew re, t+1m	Skew re, t+3m	$r^{spot}_{t,t+1m}$	$r^{spot}_{t,t+3m}$
	(1)	(2)	(3)	(4)	(5)
Basis, $1m_t$	-5.48^{***}	-0.09	-0.12^{**}	-0.05	-0.12^{**}
	(0.65)	(0.08)	(0.05)	(0.03)	(0.05)
Intercept	-1.57^{**}	-0.01	-0.004	0.08^{***}	0.33^{***}
	(0.64)	(0.09)	(0.06)	(0.03)	(0.06)
Observations	340	325	286	325	286
Adjusted R^2	0.37	0.01	0.05	0.04	0.05

6. Appendix

A.1. Summary stats for basis across exchanges

Table A.1 shows that Huobi, Binance, and FTX have the largest average bases. Basis is very persistent at the first lag with AR(1) coefficients close to 1, especially for 3 months maturity. Basis for 1 month is more volatile than that for 3 months. OKEx and Huobi have the most volatile bases, on average.

A.2. Additional figures and tables

Figure A.1: Predictive power of carry in commodity markets.
The figure depicts β_1 and β_2 from regressions (3): $S_T - S_t = \alpha_1 + \beta_1 \cdot (F_{t,T} - S_t) + \epsilon_{1,t}$ and (4): $F_{t,T} - F_{T,T} = \alpha_2 + \beta_2 \cdot (F_{t,T} - S_t) + \epsilon_{2,t}$ for gold, silver, oil and gas. Insignificant coefficients at the 5% level are with dashed filling.

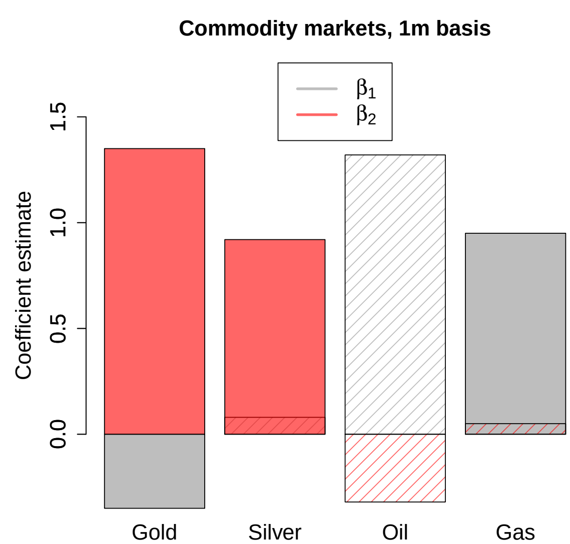


Table A.1: Summary stats for basis across exchanges.
The table shows crypto basis with constant maturity of 1 month (Panels A and C) or 3 months (B and D). The table also shows the max leverage for exchanges. Huobi had a max leverage of 125 before June 2021 but then changed it to 5 reportedly. Source: Skew, exchanges websites.

Panel A: BTC, 1 month

	Deribit	Kraken	OKEx	Huobi	CME
Mean	10.86	9.37	11.1	11.48	8.69
Median	8.34	7.47	8.77	8.48	8.29
Std	10.98	9.39	11.21	11.06	6.78
Skewness	1.24	1.11	0.86	0.97	0.52
Min	-28.72	-23.87	-25.65	-33.22	-4.43
Max	59.89	50.4	55.42	54.28	33.4
AR(1)	0.94	0.92	0.93	0.99	1
Observations	576	977	958	832	340
Max leverage	100	50	125	5-125	2

Panel B: BTC, 3 months

	BitMEX	Deribit	OKEx	FTX	Huobi	Binance	CME
Mean	7.7	8.88	10.84	10.66	12.35	13.39	8.22
Median	6.41	7.88	9.21	9.24	9.8	10.73	8.23
Std	7.69	7.4	8.32	7.55	8.25	8.21	4.93
Skewness	1.31	1.12	0.97	1.27	0.95	1.21	0.43
Min	-11.34	-6.55	-7.87	-6.88	-9.39	1.12	-0.1
Max	45.6	45.63	45.93	45.59	44.85	46.76	22.33
AR(1)	1	1	1	1	1	1	0.94
Observations	1044	1042	707	861	528	548	354
Max leverage	285	100	125	20	5-125	50-125	2

Panel C: ETH, 1 month

	Kraken	OKEx	Deribit	Huobi	CME
Mean	11.16	12.09	10.68	11.83	10.34
Median	8.61	9.55	7.55	8.41	9.69
Std	11.44	12.1	11.18	11.99	6.05
Skewness	1.15	0.99	1.47	1.06	0.69
Min	-22.1	-20.14	-22.72	-19.57	-0.62
Max	58.81	60.69	64.98	57.98	28.72
AR(1)	0.93	0.92	0.93	0.93	0.83
Observations	934	932	536	832	232

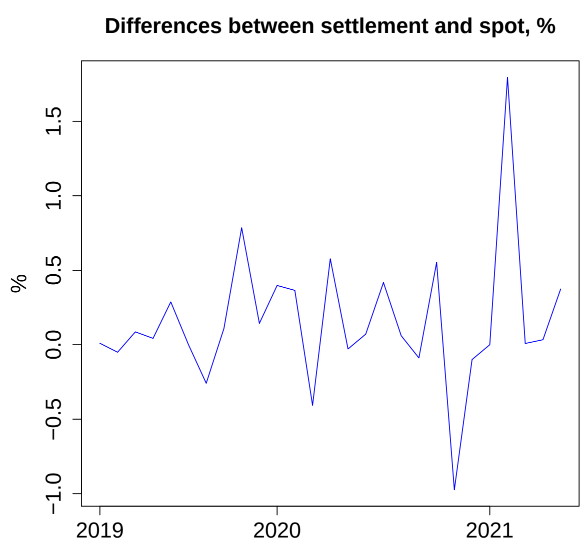
Panel D: ETH, 3 months

	Deribit	BitMEX	OKEx	FTX	Huobi	Binance	CME
Mean	9.57	8.42	11.17	13.85	12.54	13.96	9.85
Median	7.84	6.65	9.54	10.82	9.64	11.42	8.6
Std	7.86	10.6	8.93	9.86	8.72	8.48	5.13
Skewness	1.15	1.12	0.87	0.98	1	1.07	1.2
Min	-10.66	-15.01	-11.21	-7.88	-4.04	0.79	2.01
Max	44.7	49.22	44.98	50.19	44.82	46.97	26.42
AR(1)	1	0.92	1	1	1	1	0.93
Observations	994	128	696	474	528	513	237

Table A.2: Correlations of crypto and commodities carry.
The table shows correlations of CME 1-month BTC basis with that of VIX and commodities. All correlations are insignificant at the 5% level. Source: Bloomberg, CME. Sample is from February 2018 to January 2022.

	VIX b1-month	oil b1-month	gas b1-month	gold b1-month
daily	0.04	0.02	0.02	-0.04
monthly	-0.08	-0.05	-0.05	0.10

Figure A.2: Settlement prices differences.
The figure shows percentage differences between the settlement price of the futures contract based on the CME settlement procedure, and the price at the moment of expiration. Source: Cryptocompare.



A.3. Robustness analysis: using raw futures prices for Fama regressions

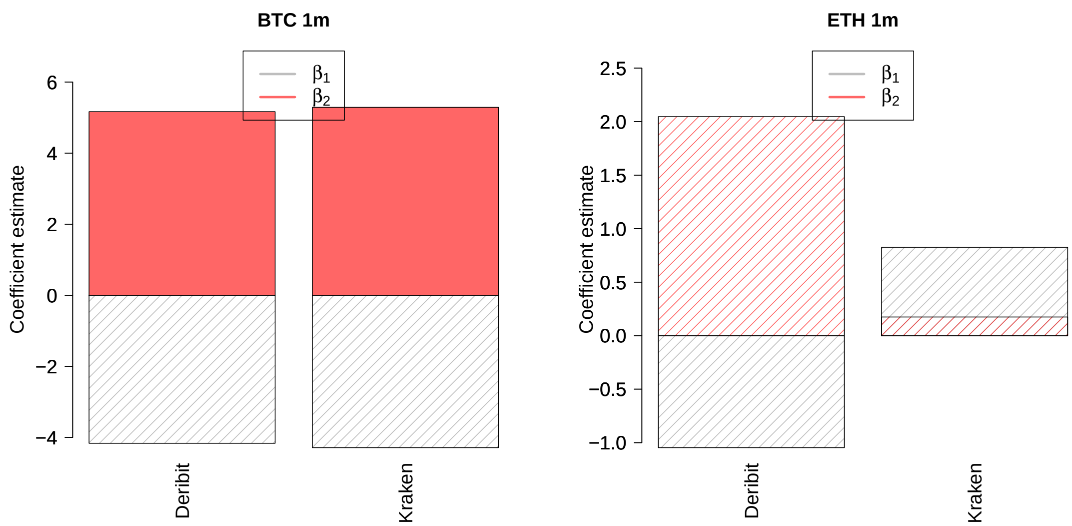
For robustness, we repeat the Fama regressions from Section 2.4.1 using raw futures prices. A limitation of this robustness check is that the data is only available after April 2020 for non-regulated exchanges. Due to the shorter time period and the non-overlapping nature of the analysis, these regressions have fewer data points. Figure A.3 shows that for BTC, β_2 for Deribit is of similar magnitude and of the same sign as in the main regression from Figure 3, whereas the estimate for β_1 is now insignificant. For ETH, the estimates at the monthly frequency for Kraken are of the opposite sign relative to the interpolated sample, which indicates that the spot is more volatile than the futures for that exchange based on Equation 5. These results should be taken with a grain of salt, however, given that there are fewer data points with non-overlapping observations, and that the estimates are insignificant at the 5% level for BTC.

We also download data on raw CME futures prices from Bloomberg from December 2017 to January 2022. The estimates for 1 months are significant, in contrast to the ones with interpolated futures, whereas the ones for 3 months are insignificant as shown in Table A.3. $\beta_2 > 1$ for 1-month, which is consistent with the main intuition from Figure 3.

Table A.3: Robustness: CME raw futures regressions.
The table reports the coefficient estimates β_1 and β_2 from regressions (3): $S_T - S_t = \alpha_1 + \beta_1 \cdot (F_{t,T} - S_t) + \epsilon_{1,t}$ and (4): $F_{t,T} - F_{T,T} = \alpha_2 + \beta_2 \cdot (F_{t,T} - S_t) + \epsilon_{2,t}$. The sample period is December 2017 to January 2022 and we filter out for futures with exactly 28 days until expiration (one of the most popular maturities around 1-month). Non-overlapping observations.

	1-month	3-month
β_1	-16.55**	-0.74
	(6.59)	(3.16)
β_2	17.55**	1.74
	(6.59)	(3.16)

Figure A.3: Robustness: predictive power of crypto carry using raw futures prices.
The figure depicts β_1 (S on basis) and β_2 (F on basis) from regressions (3): $S_T - S_t = \alpha_1 + \beta_1 \cdot (F_{t,T} - S_t) + \epsilon_{1,t}$ and (4): $F_{t,T} - F_{T,T} = \alpha_2 + \beta_2 \cdot (F_{t,T} - S_t) + \epsilon_{2,t}$ significant at the 10% level for 1-month BTC and at the 5% level for 1-month ETH. The sample period is April 2020 to January 2022 and we filter out for futures with exactly 28 days until expiration (one of the most popular maturities around 1-month).



A.4. ETH regressions

Figure A.4: Predictive power of crypto carry for ETH.
The figure depicts β_1 and β_2 from regressions (3): $S_T - S_t = \alpha_1 + \beta_1 \cdot (F_{t,T} - S_t) + \epsilon_{1,t}$ and (4): $F_{t,T} - F_{T,T} = \alpha_2 + \beta_2 \cdot (F_{t,T} - S_t) + \epsilon_{2,t}$ for 1-month ETH. Overlapping observations. The left panel uses the same sample period for all exchanges (August 2020 to January 2022), the right uses the longest period for each exchange (Deribit is the longest, from March 2019 to January 2022). The data on crypto derivatives comes from Skew. Insignificant coefficients at the 5% level are with dashed filling.

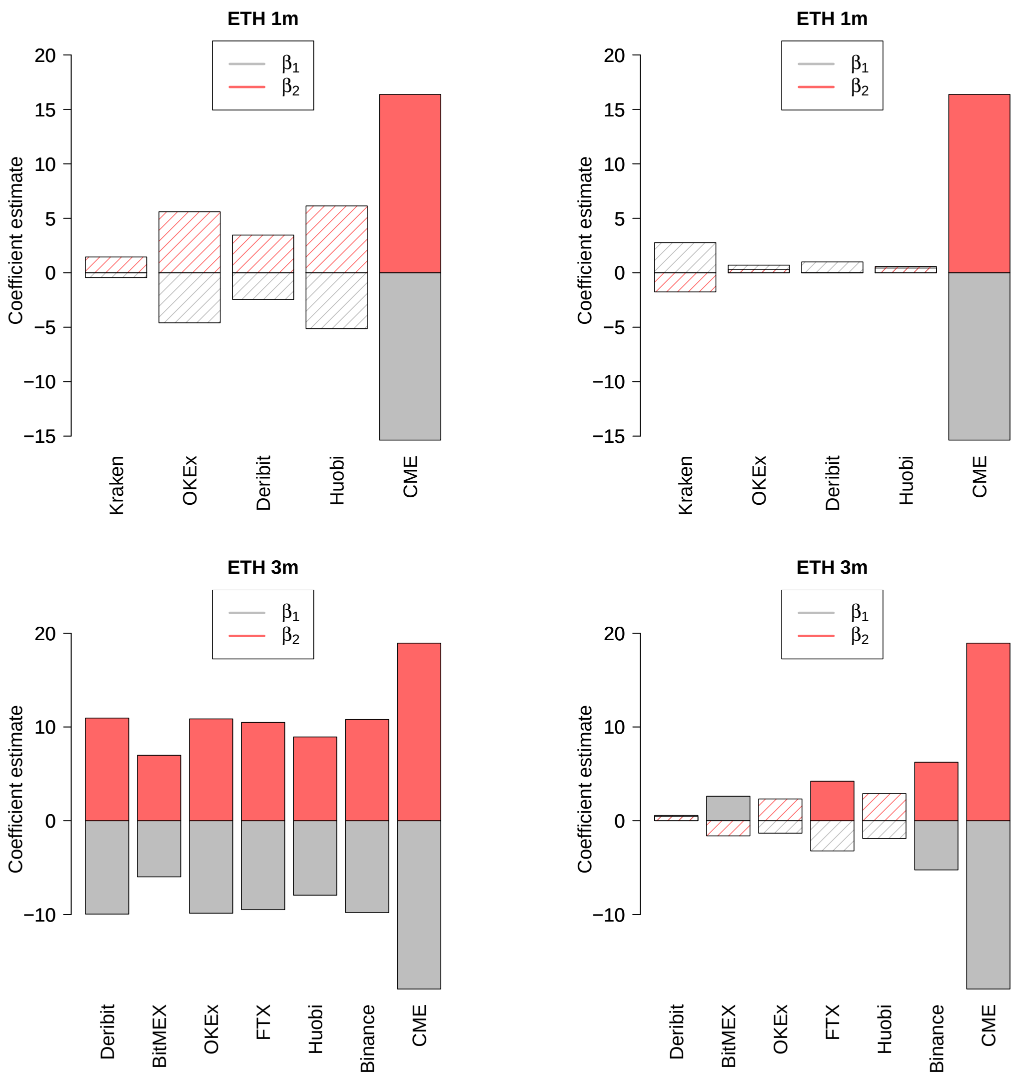


Table A.4: Crypto carry, investor attention and trend-chasing for ETH.
The table shows daily regressions of 1-month ETH basis on measures of investor attention and trend-chasing. All independent variables are standardized. The first five columns are for OKEx, the last five for CME. "Reddit" is the daily change in number of Reddit subscribers to groups dedicated to ETH. "$r^{spot}_{t-1w,t}$" is one-week spot ETH return, "$r^{spot}_{t-1m,t}$" is 1-month spot ETH return. In columns (4), (5), (9) and (10), we add variables capturing price pressure. "Signed volume" refers to futures trading volume multiplied with the sign of the contemporaneous return (-1 for negative return, +1 for positive), "OI" is open interest in the futures market. Standard errors are computed using the Newey-West method with automatic bandwidth selection. The data on crypto derivatives comes from Skew.

	Basis, 1 month$_t$									
	OKEx					CME				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Reddit	6.89***				6.20***	2.85***				2.58***
	(1.26)				(0.97)	(0.72)				(0.62)
$r^{spot}_{t-1w,t}$		3.89***			0.57		1.58***			0.43
		(0.60)			(1.05)		(0.45)			(0.50)
$r^{spot}_{t-1m,t}$			6.34***		9.12***			2.66***		4.17***
			(0.77)		(2.42)			(0.66)		(1.24)
Signed volume$_t$				3.73***	−3.85***				0.99***	−1.71**
				(1.25)	(1.21)				(0.25)	(0.68)
OI$_t$	3.41***	4.46***	3.69***	4.07***	1.95**	−1.09	−1.92**	−1.91***	−1.93***	−1.14**
	(1.06)	(0.97)	(0.77)	(1.02)	(0.86)	(0.71)	(0.76)	(0.63)	(0.67)	(0.51)
Intercept	11.91***	11.72***	11.23***	11.69***	13.19***	10.28***	10.33***	10.25***	10.32***	10.18***
	(1.76)	(0.96)	(0.74)	(1.02)	(1.58)	(0.69)	(0.69)	(0.61)	(0.64)	(0.49)
Observations	328	821	821	823	328	230	232	232	232	230
Adjusted R^2	0.33	0.25	0.39	0.26	0.42	0.28	0.16	0.25	0.17	0.39

Table A.5: Crypto carry, contract liquidations and volatility for ETH.
The table shows predictive regressions of crypto carry for cumulative buy or sell liquidations, ATM implied volatility and realized volatility for OKEx, ETH. The predictive horizon is either 1-month or 3-months. All independent variables are standardized. "Buy liq" are cumulative buy liquidations of futures contracts, scaled by open interest, whereas "Sell liq" are sell liquidations, also scaled by open interest. "Ivol" is 1-month implied volatility, "Rvol" is 1-month realized volatility. "Risk rev" is 25 delta, 1-month risk-reversal, which proxies risk-neutral skew, "Skew re" is realized 1-month skew. The data on crypto derivatives comes from Skew.

	Buy liq_{t+1m}	Sell liq_{t+1m}	Ivol_{t+1m}	Rvol_{t+1m}	Ivol_{t+3m}	Rvol_{t+3m}
	(1)	(2)	(3)	(4)	(5)	(6)
Basis, 1m_t	-1.51	2.63^{*}	9.15^{***}	2.56	6.68^{***}	5.39^{***}
	(1.36)	(1.54)	(1.26)	(1.86)	(1.35)	(1.01)
Risk rev_t	1.28	0.23				
	(1.69)	(3.09)				
Skew re_t	1.69	1.22				
	(1.66)	(3.31)				
OI_{t+1m}	7.99^{***}	8.23^{***}				
	(1.89)	(2.60)				
Intercept	14.33^{***}	22.58^{***}	92.39^{***}	74.55^{***}	97.14^{***}	76.52^{***}
	(1.73)	(3.18)	(1.19)	(1.66)	(1.51)	(0.92)
Observations	829	829	911	911	886	886
Adjusted R^2	0.20	0.10	0.14	0.01	0.11	0.06

Table A.6: Crypto carry and option-based crash risk indicators for ETH.
The table shows daily regressions of 1-month ETH basis on a range of variables. The setup is akin to that of Table A.4, but adds option-based variables that capture crash risk. The first three columns are for OKEx, the last three for CME. All independent variables are standardized. "Reddit" is the daily change in number of Reddit subscribers to groups dedicated to ETH. "$r^{spot}_{t-1w,t}$" is 1-week spot ETH return, "$r^{spot}_{t-1m,t}$" is 1-month spot ETH return. "Volume" is total trading volume in the futures market, "Signed volume" is total trading volume in the futures market multiplied with the sign of the contemporaneous return (-1 for negative return, +1 for positive), "OI, fu" is open interest in the futures market. "1-month ATM Vol" is at-the-money (ATM) volatility for maturity 1 month, "1-month 25D skew" is the difference between a 25-delta put's implied volatility and a 25-delta call's implied volatility, normalized by the ATM implied volatility, for maturity 1 month. "1-month Realized Vol" is the realized volatility of the spot over the past 1 month. "Putcall OI" is the ratio of open interest of puts to that of calls. The data on crypto derivatives comes from Skew.

	Basis, 1 month$_t$					
	OKEx			CME		
	(1)	(2)	(3)	(4)	(5)	(6)
Reddit$_t$		3.25***	1.27**		1.04	0.17
		(1.01)	(0.60)		(0.68)	(0.33)
$r^{spot}_{t-1w,t}$		−0.20	0.28		0.60	0.65**
		(0.71)	(0.20)		(0.37)	(0.26)
$r^{spot}_{t-1m,t}$		4.65**	1.12		4.32***	2.03***
		(1.97)	(0.75)		(1.09)	(0.65)
Signed volume$_t$		−4.88***	−1.00***		−3.48***	−1.56***
		(1.06)	(0.39)		(0.56)	(0.38)
Volume$_t$		−2.77***	−1.17***		0.05	0.57
		(0.70)	(0.31)		(0.60)	(0.60)
OI$_t$		6.70***	1.72***		1.97**	0.77
		(1.73)	(0.61)		(0.90)	(0.66)
1-month ATM Vol$_t$	4.92***	2.55*	0.44	2.82**	3.36***	0.94*
	(1.24)	(1.49)	(0.41)	(1.30)	(0.95)	(0.54)
1m 25D skew$_t$	−5.81***	−2.65*	−0.44	−1.94**	−0.57	0.17
	(0.58)	(1.55)	(0.50)	(0.81)	(0.64)	(0.42)
1-month Realized Vol$_t$	−3.07***	−5.83***	−0.76*	−1.36*	−3.40***	−1.34***
	(1.08)	(1.38)	(0.42)	(0.82)	(0.77)	(0.46)
Putcall OI$_t$	0.78	22.55***	3.96**	6.21***	13.62***	6.19***
	(0.78)	(4.90)	(1.65)	(2.30)	(3.07)	(1.93)
Basis, 1 month$_{t-1}$			9.70***			3.58***
			(0.51)			(0.53)
Intercept	11.69***	21.82***	13.85***	12.72***	15.51***	12.52***
	(0.61)	(1.77)	(0.60)	(1.26)	(1.43)	(0.89)
Observations	932	328	327	232	230	229
Adjusted R^2	0.33	0.73	0.91	0.40	0.55	0.67

Table A.7: Crypto carry and subsequent crashes for ETH.
The table shows predictive regressions of 1-month ETH basis for risk-neutral 1-month skew (measured by risk reversal), realized skew of crypto asset returns, and realized returns. The predictive horizon is either 1-month and 3-month. The top panel is for OKEx, the bottom one for CME. All independent variables are standardized. "Risk rev" is 25 delta, 1 month risk-reversal, which proxies risk-neutral skew over the next month, "Skew re" is realized skew and "r^{spot}" is realized ETH spot return. The data on crypto derivatives comes from Skew.

	Panel A: OKEx				
	Risk rev, t	Skew re, t+1m	Skew re, t+3m	$r^{spot}_{t,t+1m}$	$r^{spot}_{t,t+3m}$
	(1)	(2)	(3)	(4)	(5)
Basis, $1m_t$	-4.22^{***}	-0.14^{***}	-0.05	-0.01	-0.07^{***}
	(0.67)	(0.05)	(0.05)	(0.01)	(0.02)
Intercept	-2.50^{***}	0.06	-0.09	0.10^{***}	0.32^{***}
	(0.65)	(0.06)	(0.06)	(0.01)	(0.03)
Observations	932	928	886	928	886
Adjusted R^2	0.26	0.03	0.004	-0.0000	0.01

	Panel B: CME				
	Risk rev, t	Skew re, t+1m	Skew re, t+3m	$r^{spot}_{t,t+1m}$	$r^{spot}_{t,t+3m}$
	(1)	(2)	(3)	(4)	(5)
Basis, $1m_t$	-3.11^{***}	-0.08	-0.16^{***}	-0.00	-0.04^{*}
	(0.86)	(0.07)	(0.02)	(0.02)	(0.02)
Intercept	0.43	0.12	0.15^{***}	0.07^{***}	0.25^{***}
	(1.06)	(0.08)	(0.03)	(0.02)	(0.05)
Observations	232	217	191	217	191
Adjusted R^2	0.16	0.02	0.21	-0.005	0.01

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