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Price discovery in the price disagreement between equity and option markets: Evidence from SSE ETF50 options of China

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ABSTRACT

We study the price discovery in price disagreement between the China ETF 50 index and option markets. The price disagreement is measured by upper and lower option boundary violations that are usually considered evidence of market inefficiency. We find that option boundary violations contain information about future returns and contribute to the price discovery process. Lower option boundary violations are more informative than upper boundary violations. Short-term at-the-money options contribute more to the price discover process than others. Pooling all the options together may introduce noise in the test of price discovery in the option market. These test results complement the mixed findings in literature regarding the price discovery in option markets.

1. Introduction

This paper examines price discovery in price disagreement between equity and option markets. The price disagreement is measured by upper and lower option boundary violations that are usually considered evidence of market inefficiency.

In this study, we employ China ETF50 index option, the first Chinese index option traded in Shanghai Security Exchange. It gives international market participants the ability to engage in anticipated market movements without having to buy or sell a large number of Chinese stocks. ETF 50 option market also permits portfolio managers to limit downside risk. Given its importance, however, the global investors still lack understanding of China ETF 50 options and Chinese investors' behavior in the derivatives market.[1] In an effort to improve our understanding of trading activity in the emerging option market, we examine the information content of China ETF 50 index options.

Many articles have documented the price disagreement between equity and option markets.[2] Literature also finds the information

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[1] The literature focusing on China's equity market is sparse. Only a handful of studies examine China's stock behavior. (See, for example, Liao, Liu, & Wang, 2014).

[2] See, for example, Bodurtha and Courtadon (1986), Gould and Galai (1974), Kamara and Miller (1995), Klemkosky and Resnik (1979, 1980), and Nisbet (1992), among others.

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content about future returns in derivative markets.[3] However, whether the price disagreement is purely random or information-driven is rarely analyzed. If option boundary violations are information-driven, they should contain information about the future return of the underlying assets. It is in our interest to analyze whether the inefficiency of emerging option markets contains any information for the future price movement.

Ofek, Richardson, and Whitelaw (2004) document the information content in violations of put-call parity according to stock option daily data from 1999 through 2001. Chakravarty, Gulen, and Mayhew (2004) show that stock options contribute to price discovery based on tick-by-tick option implied stock prices for 20 liquid stock options from 1988 through 1992. Cremers and Weinbaum (2010) employ the implied volatility difference between contract pairs in put-call parity to predict individual stock returns, finding statistically significant results according to end-of-day options data from 1996 to 2005.

In contrast, Muravyev, Pearson, and Broussard (2013) employ tick-by-tick quote data and find option market quotes adjust to eliminate the deviation between equity and option markets. They conclude no evidence of price discovery in equity options based on intraday high frequency quote data for 39 liquid at-the-money stock options with expirations between 10 and 70 days from 2003 through 2006. It is worth noting that Muravyev et al. (2013) use a matched sample method in their empirical design. They compare the change in both the actual and option-implied stock price quotes in the treatment sample of price disagreement events to the quote changes in a matched sample of otherwise similar observations for which no disagreement exists about the underlying stock prices.

Our paper shares some similarities with Muravyev et al. (2013), but is different in some other aspects. In this article, we also employ tick-by-tick quoted data and incorporate market frictions in our calculation. The way we compute the price disagreement is essentially the same. On the other hand, our paper traces the direction of the price disagreement according to upper boundary and lower boundary violations. Moreover, instead of pooling together all the options with expiration between 10 and 70 days, we categorize options into more refined categories according to five moneyness groups and four maturity classes. These differences may alter literature's findings and conclusions. Nevertheless, we do not conduct matched sample tests because China ETF 50 option is the only one equity index option available during our sample period.

To complement the mixed findings in current literature, this study segments options according to moneyness and time to expiration, separates option upper boundary violations from lower boundary violations, and utilizes high-frequency option data. We conduct three distinct test methods to examine whether option markets contain any information beyond equity markets. Each method examines a different aspect of price discovery and complements one another. Reversion-to-efficiency test scrutinizes how equity and option prices revert to price agreement once a price disagreement has been identified. Information transmission test examines the transmission of information between equity and option markets when price disagreements occur. Information share test analyzes how much the option market can contribute to price discovery when price disagreements happen.

This paper makes three major contributions. First, to the best of our knowledge, this is the first paper separating option boundary violations into upper and lower categories to examine the information content in option markets. We provide evidence of price discovery in the price disagreement between equity and option markets once we separate lower boundary violations from upper boundary violations. Pooling all the boundary violations together may affect the test results of the information content in the option markets.

Second, our study provides an approach to directly analyze the reverting process from inefficiency (price disagreement) back to efficiency (price agreement) in the equity and option markets when option boundaries are violated. We find that the equity market tends to move in tandem with the option market when lower boundary violations occur. For short-term at-the-money options, the equity market contributes 61.65% to the reversion to efficiency while the option market contributes 38.35%. This finding indicates that the option market leads the equity market when a lower boundary violation occurs.

Third, we show asymmetric price discovery in option boundary violations. The lower option boundary violations contain more information and contribute more to price discovery than the upper boundary violations. For short-term at-the-money options, when option boundaries are violated, the information transmission from the option to stock markets is 9.53% for the lower boundary violations, while it is 3.28% for the upper boundary violations. The lower boundary violations also show greater information shares than the upper boundary violations. This asymmetric information content may be attributed to short-sale constraints in the equity market.

The paper is organized as follows. Section 2 introduces the calculations of our option metrics. Section 3 describes our data. Section 4 discusses test methodologies and empirical results. Section 5 concludes the paper.

2. The estimation of option boundary violations (price disagreement)

Because China ETF50 options are European style, in the absence of arbitrage, put-call parity follows:

[3] The study on the information content of option markets can be classified into four major strands—information content in implied volatility skewness, option trading volume, option implied stock prices, and general option trading behavior. The literature on implied volatility includes Chang, Lin, and Yu (2018), Lin, Tsai, Zheng, Quia (2018), Gao and Yang (2017), An, Ang, Bali, and Cakici (2014), Bali and Murray (2013), Bollen and Whaley (2004), Conrad, Dittmar, and Ghysels (2013), Han (2008), Jin, Livnat, and Zhang (2012), Ni, Pan, and Poteshman (2008), Stilger, Kostakis, and Poon (2017), and Xing, Zhang, and Zhao (2010), among others. The studies on option trading volume include Bernile, Hu, and Tang (2016), Cao, Chen, and Griffin (2005), Chan, Ge, and Lin (2015), Easley, O'hara, and Srinivas (1998), Ge, Lin, and Pearson (2016), Hu (2014), Johnson and So (2012), Pan and Poteshman (2006), and Roll, Schwartz, Subrahmanyam (2010), among others. Manaster and Rendleman (1982) show information content in option implied stock prices. Augustin, Brenner, Grass, and Subrahmanyam (2017), Bates (1991), Cao, Ou-Yang (2009), Chakravarty et al. (2004), and Kumar, Sarin, and Shastri (1992) show the forecasting ability in general option trading behavior.

$$\mathrm{C} - \mathrm{P} = \mathrm{S}_0 - D - Ke^{-rT} \tag{1}$$

where S_O is the stock level,[4] C is the European call options price, P is the European put options price, K is the strike price, r is the continuously compounded risk-free rate, T is the time to maturity, and D is the present value of the dividends during the life of the option contract. It is worth noting that the equity price implied in the option market is $\mathrm{C} - \mathrm{P} + D + Ke^{-rT}$. According to Equation (1), if market frictions exist, the upper boundary condition for the stock price is:

$$\mathrm{S}_b \leq C_a - P_b + D + Ke^{-r_b T} + T_e + T_p + T_s \tag{2}$$

where S_b is the bid side of equity quote, $_{Ca}$ is the ask side of call option quote, $_{Pb}$ is the bid side of put option quote, and$r_b$is the bid side of interest rate quote. $_{Tc}$, $_{Tp}$, and T_s are the transaction fees for the call, put, and stock, respectively. Equation (2) indicates that buying a call, shorting a put, and lending the dollar amount of $Ke^{-r_b T}$ at r_b, plus transaction fees should have a value greater than or equal to the value of shorting the stock. An upper boundary condition is violated if the actual bid side of equity price S_b, is greater than the option implied equity price, $C_a - P_b + D + Ke^{-r_b T}$, plus transaction cost, $T_e + T_p + T_s$. In this situation, arbitrage opportunities exist. The arbitrage strategy consists of shorting the stock at a higher level in the equity market and constructing a synthetic long position in the option market. The difference, $S_b - (C_a - P_b + D + Ke^{-r_b T} + T_e + T_p + T_s)$, is the arbitrage profit. Therefore, the upper boundary violation or price disagreement between stock and option markets is specified as[5]:

$$\mathrm{S}_b - \left(C_a - P_b + D + Ke^{-r_b T} + T_e + T_p + T_s\right) = \mathrm{S}_b - (Option\_implied\_price + TC) > 0 \tag{3}$$

In Equation (3), $Option\_implied\_price = (C_a - P_b + D + Ke^{-r_b T})$ is the equity price implied in the option market and $T_C = (T_e + T_p + T_s)$ is the total transaction cost. Throughout this paper, the *Option_implied_price* is calculated in the same manner.

In this study, we scale Equation (3) by the corresponding index level as the measure for the upper boundary condition. This European upper boundary metric ($_{EUB}$) is specified as:

$$\mathrm{EUB} = \frac{\mathrm{S}_b - \left(C_a - P_b + D + Ke^{-r_b T} + T_e + T_p + T_s\right)}{\mathrm{S}_b} \tag{4}$$

A European upper boundary violation occurs if $_{EUB} > 0$.

According to Equation (1), the lower boundary condition for European options is:

$$\mathrm{S}_a \geq C_b - P_a + D + Ke^{-r_a T} + T_e + T_p + T_s \tag{5}$$

In Equation (5), $C_b$is the bid side of European call option quote, $P_a$is the ask side of European put option quote, r_a is the ask side of interest rate, and S_a is the ask side of equity quote. It shows that buying a stock should have a value greater than or equal to that of shorting a call, longing a put, and borrowing dollar amount of $Ke^{-r_c T}$ at r_a, plus transaction fees. If this condition is violated, an arbitrage condition is present. The arbitrage strategy is to go long in a stock at a lower level in the equity market and then construct a synthetic short position in the option market. The difference, $(C_b - P_a + D + Ke^{-r_a T} + T_e + T_p + T_s) - S_a$, is the arbitrage profit. Therefore, the lower boundary violation or price disagreement between stock and option markets is:

$$\left(C_b - P_a + D + Ke^{-r_a T} + T_e + T_p + T_s\right) - \mathrm{S}_a > 0 \tag{6}$$

This paper scales Equation (6) by the corresponding index level and computes the European lower boundary metric (*ELB*) as:

$$\mathrm{ELB} = \frac{\left(C_b - P_a + D + Ke^{-r_a T} + T_e + T_p + T_s - \mathrm{S}_a\right)}{\mathrm{S}_a} \tag{7}$$

A European lower boundary is violated if $ELB > 0$.

3. Data

We obtain high frequency quote and trade data for ETF50 options and futures from the China Stock Market & Accounting Research Database (CSMAR) that is developed by GTA Information Technology, one of the major providers of Chinese financial data. Because China ETF50 index is not tradable in the arbitrage strategy, this paper derives the quasi-spot price quotes based on 1-month ETF 50 futures prices according to the futures pricing model:

$S_a = F_a \times e^{-r_b \times T} + D$ and $S_b = F_b \times e^{-r_a \times T} + D$, where F_a and F_b are the ask side and bid side of the futures quotes, respectively. r is the risk-free rate, T is time to maturity, and D is the present value of the dividends during the life of the futures. Because we cannot directly observe the actual spot price and do not arbitrage in real time, the boundary violations are in fact the price disagreement between equity

[4] Because China ETF50 index is not tradable, this paper derives the quasi-spot prices based on 1-month ETF50 futures prices according to $S = F \times e^{-r \times \tau} + D$. Please see Section 3 in detail.

[5] Because we cannot directly observe the actual spot price for ETF50 and do not arbitrage in real time, the boundary violations are in fact the price disagreement between equity and option markets.

and option markets.

The China ETF50 option market begins trading on February 02, 2015 while the China ETF50 futures inception date is April 16, 2015. Our sample begins from the ETF50 futures inception date, April 16, 2015 through June 30, 2016.[6] The CSMAR data provides high frequency options and futures trading volume, side of trade, bid price, ask price, open or close positions, and trading time.

Table 1 reports basic statistics for ETF50 index options. We classify the options according to five moneyness and four time-to-maturity categories. Deep-out-the-money (DOTM), out-of-the-money (OTM), at-the-money (ATM), in-the-money (ITM), and deep-in-the-money (DITM) are the options with deltas between 0.02 and 0.2, 0.2–0.4, 0.4–0.6, 0.6–0.8, and 0.8–0.98, respectively. 1-month, 3-month, 6-month, and >6-month are the time to expirations shorter than 1 month, between 1 and 3 months, 3–6 months, and longer than 6 months, respectively. We discard the option pairs with call delta smaller than 0.02 and greater than 0.98 for thin trading problem and remove the option pairs with time to maturity shorter than 5 trading days because of option squaring activity.

Panel 1.A summarizes the option daily trading volume and U.S. dollar amount. ETF50 call volume (79,033) is higher than ETF 50 put volume (61,163), indicating the hedging may not be active in the emerging option market. Short-term ATM and DOTM options are more heavily traded than other options.

Panel 1.B shows option bid-ask spreads (Spread $= \frac{Ask-Bid}{(Ask+Bid)/2}$) and buyer-initiated trade ratios (Buyer Initiated Trade Trade Ratio $= \frac{Number\ of\ Buyer\ Initial\ Trade}{Total\ Number\ of\ Trade}$).[7] The overall spread for ETF50 calls (11.27%) is higher than that of ETF50 puts (8.38%). Across different moneyness categories, we find DITM options have the narrowest bid-ask spreads because their option prices are higher than others. On the other hand, DOTM options have the widest spread because their option prices are much lower than others in spite of high trading volume as shown in Panel 1.A. The buyer-initiated trade ratio is 51.88% for call options and 47.78%, for put options, suggesting ETF50 option investors are more likely to buy call options. This finding, again, indicates that hedgers may not be active in the ETF50 option market, because hedgers tend to use out-of-the-money put options to hedge (see Bollen & Whaley, 2004).

Volatility and boundary measures are presented in Panel 1.C. The realized volatility for China ETF50 index (27.23%) is lower than the implied volatility of call options (28.36%), indicating a trivial risk premium in ETF50 option market. Panel 1.C also summarizes the boundary measures. The average of the upper boundary metrics (*EUB*) is 0.61% and the average of lower boundary measures (*ELB*) is −0.86%. This finding indicates that the upper boundaries are more likely to be violated than the lower boundaries.

Fig. 1 shows option daily trading activity during our sample period. We find ETF50 option trading volume increases over time.

4. Empirical results

In this section, we present preliminary results on the tests of the price disagreement between equity and option markets in Section 4.1 and analyze the information content in the price disagreement in Section 4.2.

4.1. Preliminary results on the price disagreement between equity and option markets

We begin with the preliminary test results on the price disagreement between equity and option markets. We estimate the upper boundary violations according to Equation (4) and the lower boundary violations are computed from Equation (7). Table 2 presents the percentage (%) of boundary violations and the magnitude of violation segmented by moneyness and time to maturity. Moneyness is based on call option deltas. For example, DOTM indicates a pair of DOTM call and DITM put. The violation percentage is calculated as Violation% $= \frac{Number\ of\ Boundary\ Violations}{Total\ Number\ of\ Observations}$. The magnitude of violations is calculated as the price disagreement divided by the corresponding underlying equity value.

Table 2 shows that the ETF50 upper boundary violations occur frequently. For example, the violation percentage for 1-month DITM options is 85.25% and the magnitude of violations is 2.26%. The violation percentage for the lower boundaries in the ETF50 option market is smaller than the violation percentage for the upper boundaries. For instance, the violation ratio of the lower boundaries for 1-month ATM options in ETF50 market is 10.32% while it is 79.24% for the upper boundaries.

In Table 2, it is worth noting that the magnitudes of violation for the lower boundaries tend to be greater than those for the upper boundaries in the ETF50 option market. For example, the magnitude of violation for 1-month DITM options is 5.82% for the lower boundaries, while it is 0.86% for the upper boundaries. Although the lower boundaries are less likely to be violated than the upper boundaries, the magnitude of the lower boundary violations is much bigger than that of the upper boundary violations. If the lower boundary violations are uninformative and purely driven by random noise, their violation magnitude should not be consistently higher than that for the upper boundary violations across most of the option categories. Overall, Table 2 shows that price disagreement exists in terms of option boundary violations in the option market.

4.2. Information content in the price disagreement between equity and option markets

To thoroughly examine the information content in option markets, we conduct three tests to examine whether the price

[6] This paper does not omit the first two weeks of trade to avoid possible initial trading inefficiencies, as documented by Figlewski and Webb (1993) and Yang et al. (2012), because our test focuses on the price disagreement (inefficiencies).

[7] Because CSMAR option data provide the side of each trade for ETF50 options, the buyer initiated trade is identified if the trade is from the buy side.

Table 1
Basic statistics. This table reports basic statistics for ETF50 index options. The sample period is from April 16, 2015 through June 30, 2016. We classify the options according to five moneyness and four time-to-maturity categories. Deep-out-the-money (DOTM), out-of-the-money (OTM), at-the-money (ATM), in-the-money (ITM), and deep-in-the-money (DITM) are those options with deltas between 0.02 and 0.2, 0.2–0.4, 0.4–0.6, 0.6–0.8, and 0.8–0.98, respectively. 1-month, 3-month, 6-month, and >6-month are the time to maturity shorter than 1 month, between 1 and 3 months, 3–6 months, and longer than 6 months, respectively. Panel 1.A presents option daily trading volume and U.S. dollar amount. Panel 1.B shows options bid-ask spreads and buyer-initiated trades. Panel 1.C presents the realized and implied volatility of all options and the average upper and lower boundary measures as described in equations (4) and (7).

Panel 1.A Option trading volume

Moneyness	Maturity	Call		Put	
		Volume	($1000)	Volume	($1000)
TOTAL		79,033	63.77	61,163	64.84
DOTM	1-month	19,808	7.73	15,833	13.22
	3-month	2317	0.47	1458	0.23
	6-month	975	0.24	524	0.11
	>6-month	390	0.1	305	0.06
OTM	1-month	11,128	6.95	9437	6.16
	3-month	701	0.43	1002	0.76
	6-month	393	0.44	435	0.62
	>6-month	273	0.24	1127	2.01
ATM	1-month	13,817	10.02	11,945	11.06
	3-month	717	0.54	1089	1.32
	6-month	502	0.81	512	1.8
	>6-month	610	2.03	453	1.43
ITM	1-month	12,024	12.66	9236	13.91
	3-month	628	0.6	359	0.3
	6-month	382	0.65	305	0.97
	>6-month	460	2.03	211	0.74
DITM	1-month	12,493	16.79	6138	9.73
	3-month	819	0.78	447	0.13
	6-month	306	0.17	210	0.13
	>6-month	290	0.09	137	0.14

Panel 1.B: Option bid-ask spreads and buyer-initiated ratios

Moneyness	**Maturity**	**Call**		**Put**	
		Spread	**Buyer-initiated trade**	**Spread**	**Buyer-initiated trade**
TOTAL		**11.27%**	**51.88%**	**8.38%**	**47.78%**
DOTM	1-month	36.17%	48.41%	24.64%	46.59%
	3-month	8.19%	48.35%	6.19%	45.45%
	6-month	6.41%	47.43%	5.32%	44.81%
	>6-month	7.63%	46.72%	2.72%	47.93%
OTM	1-month	2.56%	50.68%	2.76%	45.33%
	3-month	4.33%	50.94%	5.28%	44.92%
	6-month	5.64%	53.30%	5.46%	44.29%
	>6-month	6.53%	50.53%	4.36%	43.07%
ATM	1-month	2.20%	53.79%	2.31%	51.32%
	3-month	4.58%	54.69%	4.50%	51.39%
	6-month	5.42%	53.21%	5.12%	52.82%
	>6-month	5.34%	51.29%	5.02%	50.24%
ITM	1-month	2.40%	50.13%	2.23%	47.88%
	3-month	4.94%	50.74%	3.51%	48.30%
	6-month	4.74%	50.17%	4.13%	46.74%
	>6-month	4.30%	47.67%	4.23%	45.37%
DITM	1-month	2.11%	47.52%	1.29%	48.66%
	3-month	3.97%	48.87%	2.22%	47.15%
	6-month	3.60%	46.56%	1.87%	47.81%
	>6-month	2.94%	45.34%	3.11%	45.01%

Panel 1. C: Basic option metric statistics

Realized Volatility	27.23%
IVC (Implied Volatility for Call)	28.36%
IVP (Implied Volatility for Put)	29.45%
Average Upper Boundary Measure (*EUB*)	0.61%
Average Lower Boundary Measure (*ELB*)	−0.86%

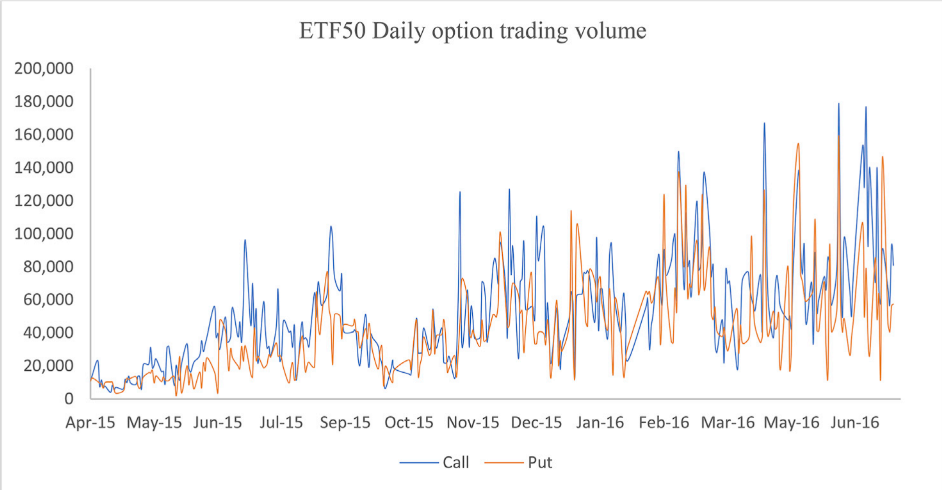


Fig. 1. Option trading volume and ETF returns over time. This figure shows option daily trading activity for call options and put options for Chinese ETF50 options. The sample period is from April 16, 2015 through June 30, 2016.

Table 2

Boundary Violations. This table reports the boundary violation ratio and the magnitude of violation. The upper boundary violations are calculated according to Equation (4) and the lower boundary violations are computed from Equation (7). Table 2 presents the percentage (%) of boundary violations and the magnitude of violation. Moneyness is based on call option deltas. The violation percentage is calculated as $\text{Violation\%} = \frac{\textit{Number of Boundary Violations}}{\textit{Total Number of Observations}}$. The magnitude of violation is calculated as quasi arbitrage profits divided by the corresponding equity price. Deep-out-the-money (DOTM), out-of-the-money (OTM), at-the-money (ATM), in-the-money (ITM), and deep-in-the-money (DITM) are those options with deltas between 0.02 and 0.2, 0.2–0.4, 0.4–0.6, 0.6–0.8, and 0.8–0.98, respectively. 1-month, 3-month, 6-month, and >6-month are the time to maturity shorter than 1 month, between 1 and 3 months, 3–6 months, and longer than 6 months, respectively.

Money	Maturity	Upper Boundary Violations		Lower Boundary Violations	
		%	Magnitude of Violation	%	Magnitude of Violation
Total		17.57%	3.30%	10.19%	1.82%
DOTM	1-month	13.35%	2.55%	6.98%	0.93%
	3-month	14.32%	2.90%	6.43%	1.77%
	6-month	14.97%	2.16%	7.09%	0.99%
	>6-month	16.24%	2.28%	7.42%	0.85%
OTM	1-month	13.43%	1.79%	7.92%	0.63%
	3-month	14.67%	2.91%	7.22%	1.45%
	6-month	16.18%	2.90%	8.37%	1.37%
	>6-month	17.53%	2.89%	9.15%	1.15%
ATM	1-month	17.13%	1.88%	9.38%	0.70%
	3-month	17.15%	3.38%	9.85%	2.18%
	6-month	16.69%	4.50%	10.68%	2.90%
	>6-month	20.51%	4.50%	11.14%	2.71%
ITM	1-month	19.29%	1.88%	10.93%	0.73%
	3-month	21.58%	3.60%	12.30%	1.92%
	6-month	19.91%	4.78%	11.89%	2.55%
	>6-month	22.67%	5.55%	14.82%	3.11%
DITM	1-month	17.05%	2.02%	11.57%	0.66%
	3-month	18.54%	3.45%	11.95%	1.92%
	6-month	19.34%	3.69%	13.39%	2.31%
	>6-month	20.80%	4.19%	15.25%	2.80%

disagreement between equity and option markets contains any information in price discovery. These three test methods are distinct and complement one another. Section 4.2.1 scrutinizes how equity and option prices revert to no-arbitrage values once a violation has been identified. Section 4.2.2 examines the information transmission between equity and option markets when boundary violations occur. Section 4.2.3 analyzes the information share attributed to the option market according to the frequency of boundary violations.

4.2.1. Reversion to efficiency test

As pointed out in Chordia, Roll, and Subrahmanyam (2001), efficiency does not just congeal from spontaneous combustion; rather, it is a process that depends on individual actions and, as a result, takes time. To analyze how equity and option prices revert to no-arbitrage values after boundary violations occur, we match pairs of synchronous transactions of calls and put with the same strike and time to maturity. This paper computes the initial (ex post) quasi-profit using Equations (4) and (7) for ETF50 options.[8] Each time a new market value is recorded for one of the components in the arbitrage portfolio, its price is updated. The quasi-profit resulting from the construction of the arbitrage portfolio is then computed with this new set of prices. The updating process stops as soon as the quasi-profit vanishes. The reversion to efficiency is the price evolution under which the arbitrage profit disappears.

To examine how the equity and option markets contribute to the reverting process, we break the boundary into two parts: a) the reversion from the option market, and b) the reversion from the equity market. For instance, for the *EUB* (European upper boundary metric), these decompositions are specified as:

$$\text{Option}_{reversion_{t+1}} = \frac{(C_{a,t+1} - CP_{b,t+1} + D + Ke^{-r_b \times T})}{S_{b,t}} - \frac{(C_{a,t} - CP_{b,t} + D + Ke^{-r_b \times T})}{S_{b,t}}, \tag{8}$$

$$\text{Equity\_}reversion_{t+1} = \frac{S_{b,t+1} - S_{b,t}}{S_{b,t}},$$

where Option_$reversion_{t+1}$ is the reversion from the option market at time t+1, and Equity_$reversion_{t+1}$ is the reversion from the equity market at time t+1. The time interval is in seconds. We use the prices in the end of each second in the test. The entire reversion for an *EUB* (European upper boundary) violation becomes:

$$\text{EUB\_Violation}_t = \sum_{p=1}^{N} Option\_reversion_{t+p} + \sum_{p=1}^{N} Equity\_reversion_{t+p} \tag{9}$$

where EUB_$Violation_t$ indicates $EUB > 0$ and is the proxy for the magnitude of the boundary violation at time t. N is the number of reverting periods (in seconds) to eliminate all the quasi arbitrage profits. If salient information is revealed in the equity market first and diffused gradually into the option market, Option_*reversion* should contribute more to the reverting process. On the other hand, if material information is revealed in the option market first and diffused into the stock market, Equity_*reversion* should contribute more to the reverting process.

According to Equation (9), the proportions from these two markets to restore efficiency are:

$$\text{Option\_}reversion\_proportion = \frac{\left|\sum_{p=1}^{N} Option\_reversion_{t+p}\right|}{\left|\sum_{p=1}^{N} Option\_reversion_{t+p}\right| + \left|\sum_{p=1}^{N} Equity\_reversion_{t+p}\right|} \tag{10}$$

$$\text{Equity\_}reversion\_proportion = 1 - Option\_reversion\_proportion$$

Table 3 reports the test results for reversion to efficiency. For upper boundary violations, the reversion to efficiency takes up to 27 s to restore the option market efficiency. The overall ETF50 Option_*reversion_proportion* is 69.35% and Equity_*reversion_proportion* is 30.65%, indicating that the option market contributes 69.35% in the price reverting process. This finding suggests that the option market moves toward the equity market after upper boundaries are violated. The difference, 38.69% (= 69.35%–30.65%), is significant at less than the five percent level. Therefore, the option market in general does not reveal much information beyond the equity market when the ETF50 upper boundaries are violated. The overall upper boundary violations tend to be random and uninformative in the ETF50 option market.

As we segment options in terms of moneyness and time to maturity, most of the results are consistent with the overall finding. However, short-term ATM options behave differently. The 1-month ATM options, for instance, show an Option_*reversion_proportion* of 46.71% and an Equity_*reversion_proportion* of 53.29%. The difference, −6.58%, is statistically significant, showing that the equity price moves in the direction toward the option implied price after the short-term ATM boundaries are violated. Thus, when upper boundary violations occur in the short-term ATM category, the ETF50 option market reveals information beyond the equity market. These boundary violations do not appear to be random and may play a non-trivial role in the price discovery process.

Table 3 also shows that Option_*reversion_proportion* increases as time to maturity increases and when moneyness moves away from ATM. For instance, for DITM options with time to maturity greater than 6 months, the Option_*reversion_proportion* is 82.55%. This finding suggests that the boundary violations for long-term DITM and DOTM options are random. These test results suggest that the price discovery for different option categories varies over a wide range. Pooling all the options together may introduce noise in the test of price discovery in the option market.

For the lower boundary violations, the reversion to efficiency in the ETF50 option market is 21 s. The overall

[8] Because multiple boundary violations may happen in succession, we begin our analysis from the time of the first boundary violation in the time series as our initial time point. The initial boundary violation is the one that occurs directly after a boundary pair without violation.

Table 3

The reversion to efficiency test. This table reports the test results for reversion to efficiency. To measure informational efficiency of option markets, we match pairs of synchronous transactions of calls and puts with the same strike and time to maturity. This paper computes the initial (ex post) quasi-profit using Equations (4) and (7). Each time a new market value is recorded for one of the components in the arbitrage portfolio, its price is updated. The quasi-profit resulting from the construction of the arbitrage portfolio is then computed with this new set of prices. The updating process stops as soon as the quasi-profit vanishes. The reversion to efficiency is the process for the arbitrage profit to disappear. The proportions from the option and equity markets to restore efficiency are specified in Equation (10). "*" indicates the significance at less than the five percent level.

$$\text{Option\_}reversion\_proportion = \frac{\left|\sum_{p=1}^{N} Option\_reversion_{t+p}\right|}{\left|\sum_{p=1}^{N} Option\_reversion_{t+p}\right| + \left|\sum_{p=1}^{N} Equity\_reversion_{t+p}\right|} \quad (10)$$

$$\text{Equity\_}reversion\_proportion = 1 - Option\_reversion\_proportion$$

Moneyness	Maturity	Upper boundary violations				Lower boundary violations			
		Reversion proportions				Reversion proportions			
		N (00″)	Options	Equity	Diff.	N (00′)	Options	Equity	Diff.
Total		27	69.35%	30.65%	38.69%*	21	54.89%	45.11%	9.78%*
DOTM	1-month	18	69.74%	30.26%	39.48%*	23	53.00%	47.00%	6.00%*
	3-month	22	67.50%	32.50%	35.00%*	22	61.31%	38.69%	22.62%*
	6-month	30	72.32%	27.68%	44.64%*	23	64.80%	35.20%	29.60%*
	>6-month	32	81.69%	18.31%	63.38%*	19	73.14%	26.86%	46.28%*
OTM	1-month	17	48.92%	51.08%	−2.16%	21	37.49%	62.51%	−25.02%*
	3-month	22	49.51%	50.49%	−0.98%	20	44.01%	55.99%	−11.98%*
	6-month	29	63.18%	36.82%	26.36%*	21	50.39%	49.61%	0.78%*
	>6-month	31	74.12%	25.88%	48.24%*	18	58.31%	41.69%	16.62%*
ATM	1-month	19	46.71%	53.29%	−6.58%*	16	38.35%	61.65%	−23.30%*
	3-month	23	48.18%	51.82%	−3.64%	20	45.13%	54.87%	−9.74%*
	6-month	23	65.17%	34.83%	30.34%*	21	51.17%	48.83%	2.66%*
	>6-month	28	69.26%	30.74%	38.52%*	18	53.62%	46.38%	7.24%*
ITM	1-month	27	64.86%	35.14%	29.72%*	21	40.71%	59.29%	−18.58%*
	3-month	24	66.49%	33.51%	32.98%*	20	46.11%	53.89%	−7.78%*
	6-month	24	78.67%	21.33%	57.34%*	23	55.09%	44.91%	10.18%*
	>6-month	31	83.16%	16.84%	66.32%*	18	59.81%	40.19%	19.62%*
DITM	1-month	25	73.89%	26.11%	47.78%*	23	53.58%	46.42%	7.16%*
	3-month	32	76.65%	23.35%	53.30%*	20	64.69%	35.31%	29.38%*
	6-month	30	79.04%	20.96%	58.08%*	26	70.86%	29.14%	41.72%*
	>6-month	34	82.55%	17.45%	65.10%*	20	73.08%	26.92%	46.16%*

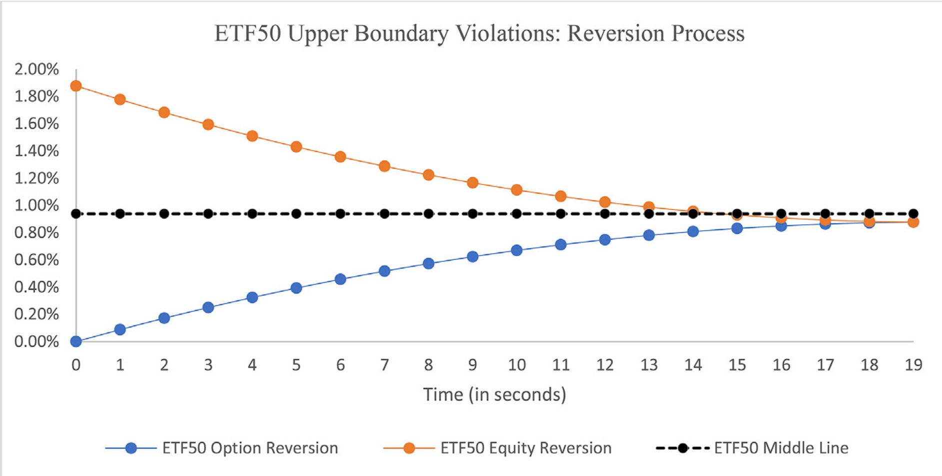
Option_*reversion_proportion* is 54.89% and Equity_*reversion_proportion* is 45.11%. This finding indicates the option market, in general, moves toward the equity market after the lower boundaries are violated. The difference, 9.78%, is significant at less than the five percent level. Therefore, the option market does not contribute much to price discovery when we pool all the ETF50 option data together.

After segmenting options according to moneyness and time to maturity, we find that short-term lower boundary violations are informative. For instance, the 1-month ATM options shows a Option_*reversion_proportion* of 38.35% and Equity_*reversion_proportion*, 61.65%. The difference, −23.30%, is statistically significant, suggesting that the equity market moves toward the option market after 1-month ATM lower boundaries are violated. A similar pattern is also found in short-term OTM and ITM categories. These results indicate that the lower boundary violations are informative and contribute to price discovery in the ETF50 option market. The price disagreement between option and stock markets contains information about the future equity price movement in China ETF50 market.

Comparing upper boundaries and lower boundaries, we find that the lower option boundary violations are more informative than the upper option boundary violations. For example, according to the 1-month ATM ETF50 options, the difference of reversion proportions between option and equity market is −23.30% for lower boundary violations and −6.58% for upper boundary violations.

Fig. 2 displays the process of reversion to efficiency for the 1-month ATM boundary violations. Fig. 2a presents the reversion process for the upper boundary violations. It takes 19 s for the ETF50 to restore to efficiency when the upper boundary is violated. It is worth noting that the black dash line is in the middle between the equity and option markets. If the information contents in equity and option markets are equal, equity market should move down to the middle line and the option market should move up to the middle line. These two markets should converge to the middle line. On the other hand, if the option market contains more information than the equity market, the equity market should move down more toward the option market. Therefore, these two markets should converge below the middle line, and vice versa. Fig. 2a shows that the equity and option markets converge below the middle line, indicating that the equity price moves in the direction toward the option implied price after the short-term ATM boundaries are violated. This finding suggests that the option market contains more information than the equity market. We also find that the reversion in the early stage (within the first few seconds) is much larger than in the later stage. This result suggests that as the arbitrage profits are relatively high, the arbitrage activity is relatively more active, resulting in a quicker speed than the later stage.

Fig. 2b depicts the reversion process for the lower boundary violations. It takes 16 s for the ETF50 to restore to efficiency if the lower boundary is violated. Similar to the discussion for Fig. 2a, if the equity and option markets have the same information content, equity



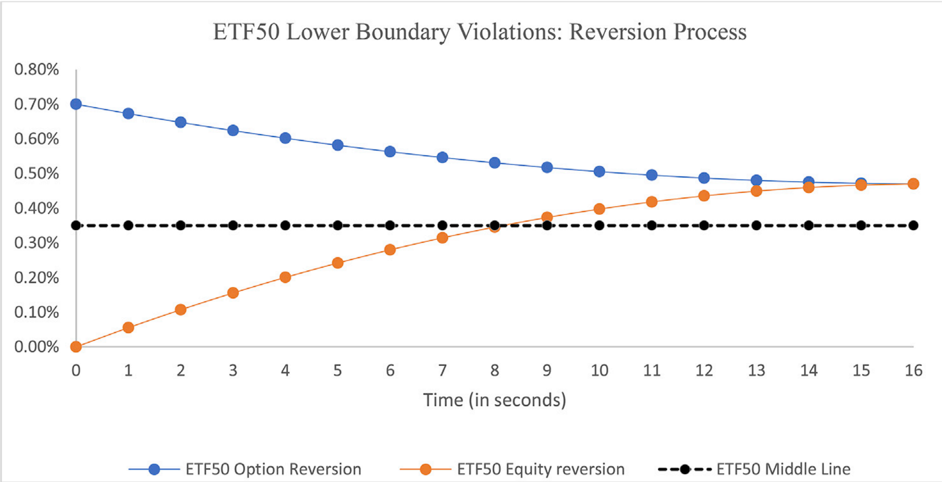


Fig. 2. Reversion to efficiency. Fig. 2 displays the process of reversion to efficiency for the 1-month ATM boundary violations. Fig. 2 a presents the reversion process for the upper boundary violations. Fig. 2 b depicts the reversion process for the lower boundary violations. The sample period is from April 16, 2015 through June 30, 2016.

market should move up and the option market should move down. These two markets will converge to the middle line. Alternatively, if the option market contains information beyond the equity market, the equity market should move up more toward the option market. Eventually these two markets should converge above the middle line, and vice versa. We find that these two markets converge above the middle line, suggesting that the option market contains more information than the equity market. This figure also shows the reversion in the early stage (within the first few seconds) is much larger than in the later stage. Once again, this finding indicates that when the arbitrage profits are relatively high, the arbitrage activity is relatively more active.

4.2.2. Information transmission between equity and option markets

After analyzing the reversion to efficiency for the option boundary violations, we examine how information is transmitted between equity and option markets. To abstract and disentangle information flows from the option market, we use a two-stage specification similar to Hou and Moskowitz (2005) and Acharya and Johnson (2007), and Hayunga and Lung (2014).

This study regresses option boundary metrics on a constant, the contemporaneous and lags of the stock market returns, as well as lags of the options metric we are examining. For instance, with the *EUB* (European upper boundary metric) as the dependent variable, the specification is:

$$\text{EUB}_t = \alpha + \sum_{k=0}^{13} \beta_{t-k} R_{t-k} + \sum_{k=1}^{13} \delta_{t-k} (EUB)_{t-k} + u_{EUB,t} \tag{11}$$

R is the equity index return. Any remaining information content in the residuals $U_{EUB,t}$, is independent news arriving in the option market for the European upper boundary that is neither pertinent nor appreciated by the equity market. Thus, $U_{EUB,t}$ represents innovation in the option market. Because the choice of number of lags could be arbitrary, we select thirteen lags for ETF50 according to the

Akaike information criterion (AIC). The time interval is in seconds.

In the second stage, we compute a model examining the equity index change at the time when option boundaries are violated. In this model, the index return is regressed against the option market innovation from the first stage as well as from lagged index returns. The specification is:

$$R_t = \alpha + \sum_{k=1}^{13}\left[b_k + b_k^D\left(D\right)_t\right]u_{EUB_{t-k}} + \sum_{k=1}^{13}\left[c_k + c_k^D\left(D\right) \tag{12}$$

D is a dummy variable representing the occurrence of an option boundary violation. It is unity if the option boundary is violated and zero otherwise. $u_{EUB,t}$ is the option market innovation from Equation (11). b_k measures the unconditional information flow from the option market to the equity market not specific to option boundary violations. b_k^D is the information from the option market to the equity market conditioned on the occurrence of option boundary violations. The parameter c_k measures general price discovery in the stock market that is unconditional while c_k^D measures any information flow in the equity market conditioned on the boundary violations.

Table 4 presents the test results for the conditional information flow from options to equity markets, $\sum_{k=1}^{13} b_k^D$, for ETF50 options. Because the choice of number of lags could be arbitrary, we select thirteen lags for ETF50 according to the Akaike information criterion (AIC). The time interval is in seconds.

For the upper boundary metrics, if we aggregate all the options together, we find no information transmission from the option market to the equity market. In the ETF50 option market, the total information flow measure for the upper boundary violation, $\sum_{k=1}^{13} b_k^D$, is 0.0045, which is essentially zero and not statistically significant. These results indicate that, in general when we consider all options, the upper boundary violations are random and uninformative.

After analyzing the options according to moneyness and time to maturity, we find the estimates for information transmission are not significant in most of the option categories, with the exception of short-term ATM options. This result is consistent with the findings in Table 3. For example, 1-month ATM options have a measure of −0.0328 (t-stat = −3.26). This measure represents that upper boundary violations transmit 3.28% of information in the innovation of the ETF50 option market to the equity market, showing price discovery in the upper option boundary violations.

Note that the sign of $\sum_{k=1}^{13} b_k^D$ is negative, indicating that the equity price will drop and move closer to the option implied price if 1-month ATM upper boundaries are violated in the ETF50 option market. This reasoning can be seen according to the calculation for *EUB* in Equation (4) and Fig. 2 a. When *EUB* is greater than zero, the actual price in the equity market (S_b) is greater than the option implied price ($C_a - P_b + D + Ke^{-r_b T}$), showing that S_b is relatively expensive in comparison with $C_a - P_b + D + Ke^{-r_b T}$. In order to restore market

Table 4

The information transmission test. Table 4 presents the test results for the conditional information flow from options to equity markets, $\sum_{k=1}^{13} b_k^D$, for ETF50 options. Because the choice of number of lags could be arbitrary, we select thirteen lags for ETF50 according to the Akaike information criterion (AIC). The time interval is in seconds. The conditional information flow from options to equity markets is estimated based on Equation (12). "*" indicates the significance at less than the five percent level.

$$R_t = \alpha + \sum_{k=1}^{13}[b_k + b_k^D(D)_t]u_{EUB_{t-k}} + \sum_{k=1}^{13}[c_k + c_k^D(D)_t]R_{t-k} + \varepsilon_t \quad (12)$$

Money	Maturity	Upper boundary		Lower boundary	
		$\sum_{k=1}^{13} b_k^D$	t-stat.	$\sum_{k=1}^{13} b_k^D$	t-stat
Total		0.0045	0.76	0.0323*	2.09
DOTM	1-month	0.0485	0.17	0.0123	0.07
	3-month	0.0021	0.04	0.0142	0.69
	6-month	0.0099	0.48	−0.0003	−0.01
	>6-month	0.0041	0.02	0.0087	0.41
OTM	1-month	−0.0240	−1.14	0.0681*	5.24
	3-month	−0.0049	−0.11	0.0461*	3.15
	6-month	0.0086	0.08	0.0313	1.79
	>6-month	0.0099	0.21	0.0171	0.45
ATM	1-month	−0.0328*	−3.26	0.0953*	4.11
	3-month	−0.0257*	−2.12	0.0878*	2.91
	6-month	−0.0167	−0.14	0.0465	1.51
	>6-month	0.0064	0.03	0.0195	0.59
ITM	1-month	−0.0197	−1.79	0.0407*	3.20
	3-month	−0.0163	−0.18	0.0256*	2.14
	6-month	0.0089	0.25	0.0391	1.91
	>6-month	0.0074	0.32	0.0117	0.28
DITM	1-month	0.0015	1.34	−0.0011	−0.05
	3-month	0.0023	0.34	0.0218	0.87
	6-month	0.0068	0.07	−0.0224	−0.63
	>6-month	0.0099	0.27	0.0021	0.09

efficiency, the equity market needs to move down and/or the option market needs to move up. With a negative sign of the information flow measure, $\sum_{k=1}^{13} b_k^D$, we assert the equity market moves down to be closer to the option market, showing that upper boundary violations are informative and contain information relevant to the future equity price. This result confirms the findings from Table 3.

For the lower boundary violations, when considering all options in the ETF50, we find that the total information flow measure, $\sum_{k=1}^{13} b_k^D$, is 0.0323 (t-stat = −2.09), which is statistically significant, indicating the lower boundary violations are informative and should not be purely random. This measure shows 3.23% transmission of information in the innovation of the ETF50 option market to the equity market, which is greater in magnitude and more significant than the measure of the upper boundary violations.

Note that the sign of $\sum_{k=1}^{13} b_k^D$ is positive. This positive sign suggests that the equity price will increase and move closer to the option implied price when the lower boundaries are violated. According to *EUB* in Equation (7), if the European lower boundary is violated, the stock price in the equity market (S_a) is relatively low compared to the option implied price ($C_a - P_b + D + Ke^{-r_a T}$). To revert to efficiency, the equity market needs to move up and/or the option market needs to move down. With a positive sign of the information flow measure, $\sum_{k=1}^{13} b_k^D$, the result suggests that the equity market moves up to be closer to the option market and, accordingly, market efficiency is restored. Our finding indicates that the lower boundary violations in ETF50 option market are not random and contain information about future equity price movement. This result is consistent with the findings from Table 3.

As we divide the options into different categories according to moneyness and time to maturity, we note that the measures of conditional information transmission are not all statistically significant. The statistically significant measures concentrate around short-term ATM, OTM, and ITM options. For example, as the lower boundaries are violated at the 1-month ATM in the ETF50 market, the information transmission is 0.0953 (t-stat = 4.11) from the option to the equity market, while it is essentially none for 1-month DITM options. This finding could be attributed to liquidity and option returns.[9] As informed investors trade on their information, they are more likely to trade on the options with higher liquidity and the options generating greater returns for each dollar they invest. Both ATM and OTM satisfy these criteria. Although the delta-to-option-premium ratio ($\frac{option\_premium}{|delta|}$) is generally high for DOTM, the liquidity for DOTM is low in terms of bid-ask spreads as shown in Panel 1.b. These reasons could partially explain why the information transmission are mostly from short-term ATM, ITM, and OTM options.

4.2.3. information shares from option markets

This section utilizes the methodology of Hasbrouck (1995) to examine whether the option boundary violations contribute to price discovery. Our hypothesis is:

If the option boundary violations contribute to price discovery, the days with few or without boundary violations should contribute less information than those days with more boundary violations.

According to Hasbrouck (1995) and Chakravarty et al. (2004), the information share approach of Hasbrouck (1995) is suitable to estimate each market's relative contribution to price discovery because the option-implied price in the option markets and the observed price in the equity markets are cointegrated. Hasbrouck's information share model assumes that the prices from both markets share a common random walk component referred to as the efficient price. The information share of a market is measured as that market's contribution to the total variance of this random-walk efficient price.

We denote a price vector V that includes both the option-implied and observed price:

$$V_t = \begin{bmatrix} S_t \\ O_t \end{bmatrix} \tag{13}$$

where S_t is the observed price that equals the efficient price, E_t, plus a random noise in the equity market. O_t is the option-implied price that equals the efficient price, E_t, plus a random noise in the option market. For example, based on the upper boundary condition in the ETF50 option market, O_t is specified as $C_b - P_a + D + Ke^{-r_a T}$ according to Equation (6). The efficient price is assumed to follow random walk process. It is

$$E_t = E_{t-1} + \mu_t \tag{14}$$

where μ_t is a latent random shock to the efficient price at time t. In this model, we assume the expected value of the random shock is zero, the expected variance of the random shock at any point in time is constant, and μ follows an identical and independent distribution.

Thus, by the Granger Representation Theorem (Engle and Granger (1987)), these cointegrated prices can be formulated as a vector error correction model of order P:

$$\Delta V_t = m_1 \Delta V_{t-1} + m_2 \Delta V_{t-2} + \ldots + m_p \Delta V_{t-p} + \beta(X_{t-1} - \mu) + \varepsilon_t \tag{15}$$

where m is a 2 × 2 matrix of autoregressive coefficients, and $\beta(X_{t-1} - \mu)$ is the error correction term with $X_{t-1} = V_{t-1} - V_{t-2}$ and μ is the expected value of X_t. Therefore, the price vector can be written as a vector moving average model:

$$\Delta V_{t=} \varepsilon_t + \theta_1 \varepsilon_{t-1} + \theta_2 \varepsilon_{t-2} + \ldots \tag{16}$$

[9] See Chakravarty et al. (2004).

ε_t in Equation (16) is a $_2\times{}_1$vector of innovations with mean of zero and variance matrix of Ω. From the above formulation, the sum of all the moving average coefficient matrices $\theta=\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}+\theta_1+\theta_2+\ldots$has identical rows θ. Since θ reflects the impact on innovations on the permanent price component rather than transitory components, the total variance of implicit efficient price changes can be calculated as θΩθ'.

Following Hasbrouck (1995), the contribution to price discovery by each market is measured as each market's contribution to this total innovation variance. If price innovations across markets are uncorrelated (or if the innovation covariance matrix is diagonal), the information share of market j is given by

$$\mathrm{IS}_j=\frac{\theta_j^2\Omega_{jj}}{\theta\Omega\theta'} \tag{17}$$

where $\theta_j$is the j-th element of θ and Ω_{jj} is the j-th element of Ω. If the price innovations across markets are correlated, as is usually the case, then the information share is not uniquely defined. In this case, we only compute a range of information shares instead of a point estimate. The high and low bounds of this range can be computed by orthogonalizing covariance matrix and trying all alternative rotations.

To minimize the impact of time aggregation on the correlation of price innovations and to better reflect the price updating sequence between the markets, the models are estimated with one-second sampling intervals. In all the specifications, lags up to 300 s are used. To keep the estimations manageable, polynomial distributed lags are employed, as in Hasbrouck (1995). Information share bounds are computed each day using intraday transactions data.

To examine information share in option boundary violations, we classify our sample into quartiles. Quartile 1 shows the days with the least option boundary violations and Quartile 4 shows the days with the most option boundary violations. Previously we demonstrated statistically significant information transmission from 1-month OTM, ATM, and ITM options in the ETF50 option market while other options show no significant information flow. We therefore focus on these informative boundary conditions in the information share tests.[10]

Table 5 presents the test results on information shares. For the upper boundary violations, the average shares show a monotonic relationship with the frequency of the upper boundary violations for 1-month ATM options. The Low-Bound information share for 1-month ATM options is 2.08%, 2.81%, 3.08%, and 4.14% for Quartiles 1, 2, 3, and 4, respectively. The difference between Quartile 4 and Quartile 1 is 3.17% (t-stat = 9.55) and statistically significant. This finding suggests that the upper boundary violation affects the information share of the option market in the price discovery process. Information share increases with the frequency of the boundary violations in the ETF50 option market. However, the information shares for OTM and ITM are not monotonic. These test results for the upper boundary violations are mixed.

For the lower boundary violations, it shows a monotonic pattern for OTM, ATM, and ITM options. The differences between Quartile 4 and Quartile 1 are statistically significant across all ranges of moneyness. In addition, we find the information shares for the lower boundary violations are greater than those for the upper boundary violations. For instance, for China ETF50 1-month OTM options, the information share bounds are from 6.73% to 7.21% for the lower boundary violations, while they are from 4.01% to 4.59% for the upper boundary violations. These results suggest that the lower boundary violations contain more information shares than the upper boundary violations.

In Table 5, we also find that the average information shares across OTM, ATM, and ITM are close to one another, indicating that those boundary violations may happen in clusters. For instance, for Quartile 4 in the ETF50 market, the High-Bound information share is 7.21%, 6.98%, and 6.80% for OTM, ATM and ITM options, respectively. These information-share measures are close to one another, suggesting that the option boundary violations in these categories tend to happen at the same time when influential news arrives at the market.

Fig. 3 displays the average daily information share for the 1-month ATM lower boundary violations during our sample period. The daily information shares increase over time from around 1%–10%. It is worth noting that the information shares spike in June 2015 and January 2016. These spikes correspond to the Chinese equity market turmoil, indicating that the option market contribute more to the price discovery process during financial crises.

In sum, the information share tests show that the option boundary violations affect the price discovery in the option markets.

4.3. Robustness

In our main analyses, the sample period is from April 16, 2015, through June 30, 2016. The test results may be time varying if the emerging option market improves its efficiency over time. In this robust test, we rerun the reversion-to-efficiency test, information transmission test, and information share test based on 1-month ATM lower boundary violations in three subperiods—April 2015 ~ August 2015, September 2015 ~ January 2016, and February 2016 ~ June 2016.[11]

Table 6 reports the robustness test results. Panel 6.A displays the reversion to efficiency test results by the three subperiods. We find that 50.33% of the reversion portions are from the option market and 46.97% from the equity market for the first subperiod. This

[10] The information test results for all the boundary conditions across the moneyness and maturity are available upon request.

[11] The test results for short-term ITM and OTM are qualitatively similar for both of the upper and lower boundaries.

Table 5

Information share tests by moneyness and time to maturity. This table presents the test results on information shares. To minimize the impact of time aggregation on the correlation of price innovations and to better reflect the price updating sequence between the markets, the models are estimated with one-second sampling intervals. In all the specifications, lags up to 300 s are used. To keep the estimations manageable, polynomial distributed lags are employed, as in Hasbrouck (1995). Information share (IS) bounds are computed each day using intraday transactions data. To examine information shares in option boundary violations, we classify our sample into quartiles. Quartile 1 shows the days with the least option boundary violations and Quartile 4 shows the days with the most option boundary violations. Because we have found statistically significant information transmission from 1-month OTM, ATM, and ITM options in the ETF50 option market while other options show no significant information flow, we will focus on these informative boundary violations in the information share tests. The information share is calculated based on Equation (17). "*" indicates the significance at less than the five percent level $IS_j = \frac{\theta_j^2 \Omega_{jj}}{\theta \Omega \theta'}$ (17).

	Upper boundary violations			Lower boundary violations		
	OTM	ATM	ITM	OTM	ATM	ITM
	1-month	1-month	1-month	1-month	1-month	1-month
Quartile 1						
IS Low-Bound	2.10%	2.08%	1.71%	1.68%	2.06%	2.26%
IS High Bound	2.26%	2.53%	2.36%	1.84%	2.50%	2.65%
Quartile 2						
IS Low-Bound	1.96%	2.81%	1.30%	3.00%	2.62%	3.55%
IS High Bound	2.30%	3.06%	1.54%	3.64%	3.29%	3.95%
Quartile 3						
IS Low-Bound	2.74%	3.08%	2.26%	4.46%	4.44%	3.88%
IS High Bound	3.14%	3.18%	2.58%	5.11%	4.96%	5.35%
Quartile 14						
IS Low-Bound	4.01%	4.14%	4.00%	6.73%	6.44%	6.30%
IS High Bound	4.59%	4.52%	4.08%	7.21%	6.98%	6.80%
The information share difference between Quartile 4 and Quartile 1						
IS Low-Bound	2.92%*	3.17%*	2.99%*	5.06%*	4.38%*	4.03%*
t-stat	3.89	9.55	3.12	5.68	10.42	4.03
IS High Bound	3.33%*	3.18%*	2.72%*	5.38%*	4.48%*	4.15%*
t-stat	5.08	8.21	4.86	6.59	11.48	5.37

indicates the lower boundary violations are not informative and tend to be random. On the other hand, the equity market tends to move in tandem with the option market in the second and third subperiods. For example, in the third subperiod, the equity market contributes 68.35% to the reversion and the option market, 31.65%. The difference, −36.70%, is significant at less than the five percent level. This finding suggests that the lower boundary violations in the ETF50 option market become more informative over time.

Panel 6.B presents the information transmission by subperiods. For ETF50, the conditional information flow from ETF50 options is only 2.15% and not statistically significant in the first subperiod, but it is significant at less than the five percent level for the following two subperiods. This result, again, shows that the information content in the ETF50 option market is improving.

Panel 6.C reports the information share tests by subperiods. The information share difference between Quartile 4 and Quartile 1 is 1.18% and not statistically significant in the first subperiod, suggesting that lower boundary violations are not informative. In the second and third subperiods, we find the difference in information share becomes significant at less than the five percent level. Again, this finding confirms the test results from Panels 6.A and 6.B.

Overall, Table 6 shows that the test results vary over time in the emerging option market. The lower boundary violations may be random and not informative in the first several trading months, but become more informative over time.

5. Conclusion

This paper examines the price discovery in price disagreement between equity and option markets for China ETF50. The price disagreement is proxied by upper and lower option boundary violations that are usually considered as evidence of market inefficiency. We show that option boundary violations in short-term ATM options are informative and not purely driven by noise in the emerging option market.

We examine the price discovery evolution in the price disagreement based on three distinct approaches—the reversion-to-efficiency test, information transmission test, and the information share test. Each approach examines a different aspect of price discovery and complements one another.

The reversion-to-efficiency test studies how the equity price and option-implied price reverse to price agreement once an option boundary violation has been identified. We find that the equity market contributes more to the reversion process than the option market for short-term ATM and OTM options, indicating that the option boundary violations are informative. As the boundary violations occur, equity markets tend to move toward option. In addition, lower option boundary violations contain more information than upper option

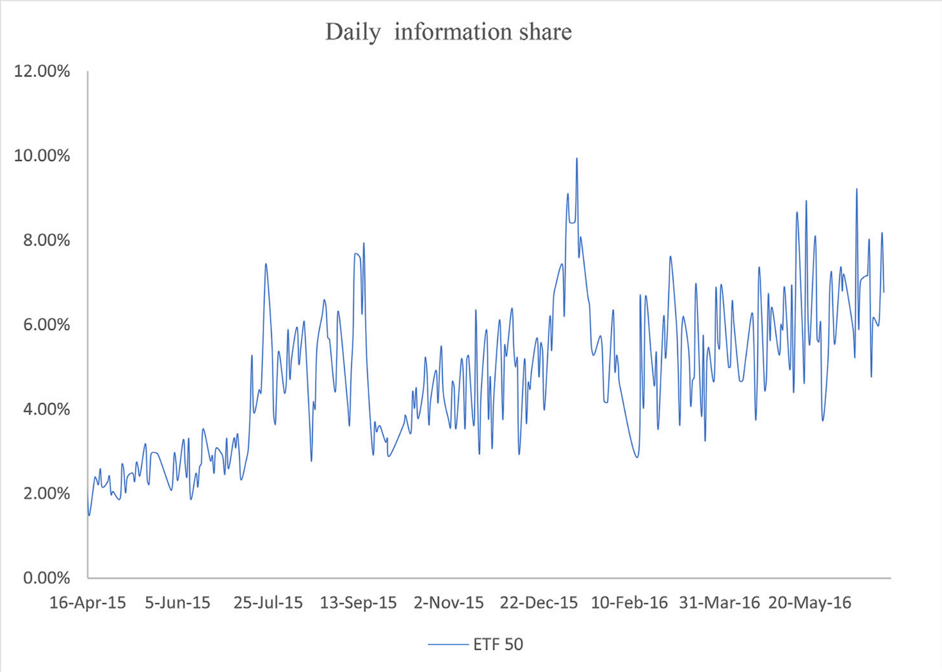


Fig. 3. Information share. This figure displays the average daily information share for the 1-month ATM lower boundaries over time. The sample period is from April 16, 2015 through June 30, 2016. The information share is calculated based on Equation (17). "*" indicates the significance at less than the five percent level. .(17) $IS_j = \frac{\theta_j^2 \Omega_{jj}}{\theta \Omega \theta}$

Table 6
Information contents by subperiods. This table reports the robustness test results. In this robust test, we rerun the reversion-to-efficiency test, information transmission test, and information share test based on 1-month ATM lower boundaries in three subperiods—April 2015 ~ August 2015, September 2015 ~ January 2016, and February 2016 ~ June 2016. "*" indicates the significance at less than the five percent level.

Panel 6.A: Reversion to efficiency by subperiods				
	N (00′)	Reversion proportions		
		Options	Equity	Difference
Subperiod 1	24	50.33%	49.67%	0.66%*
Subperiod 2	13	33.07%	66.93%	−33.86%*
Subperiod 3	11	31.65%	68.35%	−36.70%*

Panel 6.B: Information transmission by subperiods		
		t-statistic
Subperiod 1	0.0215	0.93
Subperiod 2	0.0396*	3.76
Subperiod 3	0.0496*	5.01

Panel 6.C: Information share by subperiods				
	The information share difference (Quartile 4 — Quartile 1)			
	Low-bound difference (t-stat)		High-bound difference (t-stat)	
Subperiod 1	1.18%	(1.45)	2.05%	(0.93)
Subperiod 2	5.37%*	(8.19)	5.49%*	(9.95)
Subperiod 3	6.59%*	(12.47)	5.90%*	(10.72)

boundary violations.

The information transmission test scrutinizes the information flow between the equity and option markets. We find that conditional information flow from the option to equity market is statistically significant when the option boundaries are violated for the short-term ATM, OTM, and ITM options. The conditional information transmission from the option market to the equity market is 9.53% for ETF50 when the short-term ATM lower boundaries are violated.

The information share test analyzes the contribution of the option market in the price discovery process. In this test, we group the trading days into four categories according to the frequency of the option boundary violations. The test results show a monotonic relation between the frequency of the boundary violations and information shares. The information share from the option market increases with the frequency of the option boundary violations. The difference of information shares between high-violation days and low-violation days is statistically significant. Moreover, lower option boundary violations have more information shares than upper option boundary violations.

Collectively, this paper complements the mixed findings in current literature regarding the information content in the option market. According to the three test methods in this paper, we find that pooling all the option data together may contaminate our test results. As we segment options according to moneyness and time to expiration and separate option lower boundary violations from higher boundary violations, we find statistically significant information content in short-term OTM and ATM options for lower boundary violations. These test results are robust according to different test methods and sample periods.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.iref.2019.04.005.

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