Arbitrage activity and price discovery across spot, futures and ETF markets

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Abstract

We examine how the introduction of exchange-traded fund (ETF) affects the arbitrage and price discovery mechanism between the China Securities Index (CSI)300 spot and futures markets. Utilizing a bivariate Smooth-Transition VECM (ST-VECM), we accommodate a two-speed error-correction mechanism to differentiate price discovery between no-arbitrage versus arbitrage states. Our analysis yields three main findings: i) Post-ETF trading, we see a substantial reduction in observed pricing errors. This is expected given a narrower no-arbitrage band due to lower transaction cost from trading ETF; ii) The futures market still contributes more price discovery than its spot index and ETF counterparts; iii) Arbitragers migrated from the CSI300 spot predominately to the ETF traded in Shanghai, seemingly ignoring the ETF traded in Shenzhen. When arbitragers are present, the Gonzalo and Granger (GG 1995) price discovery measure is noisy since the VECM averages the error-correction mechanism between no-arbitrage and arbitrage states. A modified GG measure from the ST-VECM addresses this issue. We explain why the price discovery bound that corresponds to the no-arbitrage state, provides a clearer indication of cross-market price discovery contribution.

JEL classification: G14, G15.

Keywords: Cost of carry; arbitrage; price discovery, index futures.

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1 Introduction

In April 2010, the China Financial Futures Exchange (CFFEX) launched the China Securities Index 300 (CSI300) futures contract. During its first three months of trading, average daily turnover volume reached RMB 230.8 billion (USD 40 billion), which exceeds the aggregate turnover volume of its constituent firms. In just its first year, CSI300 futures average trading volume has exceeded the KOSPI, Hang Seng and TAIEX futures markets. Compared to 2010, turnover volume increased by around 33% during the first half of 2012. More astoundingly, the second half of 2012 saw a further 60% increase in turnover volume over the first half. In less than three years after its launch, the CSI300 futures contract has grown to become one of the world's most actively traded equity index derivative. According to the 2013 survey by the Futures Industry Association, the CSI300 futures is ranked tenth globally among equity index derivative markets in terms of (contracts) trading volume. In May 2012, two fund management companies, Huatai-Pinebridge and Jiashi-Harvest, correspondingly launched CSI300 exchange traded funds (ETFs) on the Shanghai and Shenzhen stock exchange.

Our motivation is to acquire a better understanding of the arbitrage and price discovery mechanism among the CSI300 spot, futures and ETF markets. In developed countries, the introduction of ETF trading implies a straightforward migration by arbitragers from a non-tradable index to a tradable close-substitute. But in China, it is complicated. The CSI300 is designed to gauge the overall performance of the country's A-share market across both stock exchanges. The concurrent introduction of ETF trading on both exchanges raises an interesting question as to how arbitragers respond. Ex-ante, without limits to arbitrage, arbitragers will distribute themselves to equate the marginal net profit on both ETFs to zero. But if arbitragers persistently cluster on one ETF despite non-trivial carry-cost violation on the other ETF, this necessarily imply limits to arbitrage that somehow bind only one of the two exchanges e.g. trading rule, short-sale constraint, settlement procedure, liquidity etc.

Prior studies show that futures market leads the spot market in price discovery based on both U.S. [Kawaller et al. (1987), Edwards (1988), Stoll and Whaley (1990), Chan et al. (1991), Chan (1992), Hasbrouck (1995), Fleming et al. (1996)] and international evidence

[Ryoo and Smith (2004), Zhong et al. (2004) and Bose (2007)] for South Korean, Mexican and Indian markets respectively]. The greater price discovery contribution is commonly attributed to greater liquidity, more sophisticated investors [Chu et al. (1999)] and/or non-trading in constituent stocks [Miller et al. (1994)], which 'drags' the spot index price from adjusting to new information. However, these explanations do not readily apply to ETFs.

Booth et al. (1999) analyze price discovery across the German DAX index, futures and options markets. The authors find that the option market actually contributes less price discovery than the spot index, which they attribute to higher transaction cost in option markets. So and Tse (2004) find that Hang Seng futures contributes the most price discovery. But surprisingly, the Hang Seng tracker fund provides less price discovery than the spot index. Hasbrouck (2003) finds that most of the price discovery for the S&P500 and Nasdaq100 comes from the E-mini futures market. But for the S&P400 Midcap, price discovery is shared between the futures and ETF.

Spot-futures arbitrage violation is extensively studied for developed markets, including Yadav and Pope (1990) for the FTSE 100, Lim (1990) and Brenner et al. (1989) for the Nikkei 225. MacKinlay and Ramaswamy (1988) is one of the first papers to distinguish upper and versus lower arbitrage bound intra-day violations between the S&P500 spot and futures, which they associate with dissimilar transaction cost. Miller et al. (1994) attribute mean-reversion in the S&P500 basis to infrequent trading in constituent stocks, rather than arbitrage trading. Brennan and Schwartz (1990) highlight that the position limit of arbitragers provide a better understanding of fluctuations in the basis.

We have two related objectives. First, we utilize a bivariate Smooth Transition Vector Error-Correction Model (ST-VECM) to estimate non-linear return dynamics for four separate pairwise market analysis of the CSI300 futures against: i)+ii) CSI300 spot $r_{ft} \sim r_{st}$ in the pre- and post-ETF sample period, iii) Huatai-Pinebridge ETF (or SHETF) traded in Shanghai $r_{ft} \sim r_{SHt}$, and iv) Jiashi-Harvest ETF (or SZETF) traded in Shenzhen $r_{ft} \sim r_{SZt}$. We specify the error-correction variable in the ST-VECM as the carry-cost adjusted basis b_t. The ST-VECM allows the VECM's error-correction mechanism to take on a 'second-gear' in response to arbitrage activity. It is reasonable to assume that any adjustment in b_t will differ depending on whether b_t is fluctuating within or outside its no-arbitrage band. This implies that a VECM specification is sub-optimal.

The ST-VECM also has merit over regime-switching models that impose discrete transition processes. Such models assume an abrupt switch in the error-correction mechanism, which may be suitable for a matured market populated by savvy arbitragers ready to pounce at any mispricing opportunities. However, both CSI300 ETFs, and even the futures contract, were introduced less than six years ago. Furthermore, trading is dominated by individual investors[1]. Even if arbitragers are present, any mispricing adjustment back within the no-arbitrage band is likely to be gradual rather than abrupt, To address this issue, we specify a smooth transition function for the error-correction mechanism. Taylor et al. (2000) apply the ST-VECM to compare FTSE 100 spot and futures mispricing adjustments before and after electronic trading. Delatte et al. (2012) estimate information transmission between the sovereign CDS and bond markets for Euro-zone countries using an ST-VECM.

Our second objective is to apply the ST-VECM to compute a modified Gonzalo and Granger (1995) or GG measure of price discovery contribution for each of the four pairwise market estimations. If arbitrage trading generates a two-speed error-correction mechanism, this necessarily implies that the original GG (1995) measure is noisy. The VECM does not accommodate the impact of arbitrage activity on the error-correction mechanism between the two markets. Intuitively, when b_{t-d} becomes profitably non-trivial, arbitrage trading will force spot and futures prices towards each other. This causes the error-correction coefficients (λ_s, λ_f) to register a more comparable price impact between r_{st} and r_{ft}. But since arbitrage trading does not occur all the time, the VECM's estimated (λ_s, λ_f) reflect an 'average' error-correction mechanism between arbitrage and no-arbitrage states. Consequently, the GG (1995) measure, which is based on (λ_s, λ_f), is a noisy measure that encapsulates the price impact of both informed traders as well as arbitragers.

We show how a modified GG measure from the ST-VECM addresses the preceding issue. The modified measure consists of a pair of price discovery upper GG_0 and lower bound GG_1

[1]According to CFFEX market reports, individual investors constitute more than 80% of average daily trading volume.

that correspond to the no-arbitrage and arbitrage states. Hence, the *Gap* between GG_0 and GG_1 indicates the extent of arbitrage activity between two markets. Comparisons in *Gap* over time and/or across pairwise markets provide insights into the migration of arbitrager post ETF introduction. If arbitrage activity is weak or non-existent, this implies an insignificant two-speed error-correction, and consequently a trivial distinction between GG_0 and GG_1. Put simply, the ST-VECM reduces to a VECM.

In the pre-ETF sample, we document a significant two-speed error-correction mechanism in both spot r_{st} and futures r_{ft} return equations. The second-gear adjustment is delivered through $b_{t-d}F[b_{t-d}, \gamma]$, where $0 \leq F[b_{t-d}, \gamma] \leq 1$ is the transition function, γ is the transition speed coefficient, and b_{t-d} is the error-correction variable. Our result indicates the presence of arbitragers, whose trading activity in response to a non-trivial b_{t-d} affects both r_{st} and r_{ft}. The joint price impact exerted by b_{t-d} is larger on r_{st} than r_{ft}, which as expected, indicates that the futures market contributes more price discovery than the spot index. The average $F[b_{t-d}, \gamma]$ value, or F_{Avg} is 0.262, and $\gamma = 0.31$ is significant at the 1% level.

In the post-ETF sample, the two-speed error-correction mechanism remains significant in r_{st}, but not in r_{ft}. As such, only the spot price responds to a non-trivial b_{t-d}. This suggests that, post-ETF, arbitrage trading between the CSI300 spot and futures markets has either ceased, or it is substantially reduced. The joint price impact of b_{t-d} on r_{st} is now even larger than on r_{ft}, compared to the pre-ETF sample. $F_{Avg} = 0.636$ with $\gamma = 1.466$ that is significant at the 10% level.

It is in the SHETF and futures estimation that we find a significant two-speed error-correction mechanism in both r_{SHt} and r_{ft}. The joint price impact exerted by b_{t-d} remains larger on r_{SHt} than r_{ft}, but the difference is comparable to the pre-ETF sample. Furthermore, while $F_{Avg} = 0.633$ is comparable to the post-ETF $r_{st} \sim r_{ft}$ estimation, its speed of adjustment coefficient $\gamma = 2.594$ is larger and significant at the 1% level. A comparable F_{Avg} but a larger, more significant γ indicates that smaller pricing errors occur between the SHETF and futures markets. This is expected given a narrower no-arbitrage band for $r_{SHt} \sim r_{ft}$ compared to $r_{st} \sim r_{ft}$, due to lower transaction costs from trading an ETF compared to constituent stocks. The results also suggest that index arbitrager migrated from the

CSI300 spot to the SHETF, such that mispricing in b_{t-d} are traded away more rapidly. This is consistent with our finding that the significant two-speed error correction mechanism in the pre-ETF sample is found in $r_{SHt} \sim r_{ft}$, but not in $r_{st} \sim r_{ft}$, post-ETF.

In stark contrast, the $r_{SZt} \sim r_{ft}$ estimation reveals that neither r_{SZt} nor r_{ft} exhibit a two-speed error correction mechanism. More surprisingly, there is no significant error-correction mechanism in the SZETF and futures cross-market return dynamics. Out of the four pairwise market estimation, $r_{SZt} \sim r_{ft}$ yield the largest $F_{Avg} = 0.907$, which is near its maximum. To follow, its $\gamma = 1.174$ is the only speed of adjustment coefficient that is insignificant. These results strongly suggest that, after both CSI300 ETFs were simultaneously launched, index arbitragers migrated predominately to the SHETF traded in Shanghai, and seemingly ignored the ETF traded in Shenzhen.

Our paper proceeds as follow. The next section contains sample description and institutional background. The ST-VECM is outlined in section 3, and empirical results are reported in section 4. Section 5 concludes.

2 Institutional background

2.1 The CSI300 spot, futures and ETF markets

Driven by over 15 years of economic expansion, China's financial markets are receiving increasing attention from both the investment and academic communities. The two main stock exchanges, located in Shanghai and Shenzhen, were established in 1990 and 1991 respectively. From inception, both stock exchanges maintain their own broad-based market indices, namely, the Shanghai Composite Index and the Shenzhen Composite Index. On 8-April-2005, the China Securities Index (CSI) Company Ltd launched the CSI300 with the aim to provide a comprehensive indicator of the A-share market's overall performance across the two stock exchanges. The index comprises 300 of the largest and most actively traded A-shares that are listed in either Shanghai or Shenzhen, and represents around 70% of total market capitalization of both stock exchanges[2].

Five years after the CSI300 was introduced, CFFEX launched the CSI300 futures in April 2010. We outline key contractual specifications in Table 1. Each CSI300 futures contract has a RMB300 contract multiplier, and is governed by a tick size of 0.2 index point, or RMB60. The contract expires on the third Friday of the delivery month. There are four available delivery months: current month, next month, and the next two quarter-months i.e. final months of the next two quarters[3]. As with many other futures markets around the world, CSI300 futures trading volume is concentrated on the front contract, which accounts for more than 95% of aggregate trading volume. On average, three days before expiry, traders roll-over from the current to the next delivery month. Accordingly, our time-series data is constructed using the front contract. On the third Tuesday of every month, we switch over from the current to the next contract month. This allows us to construct a continuous time series of futures data over the relevant sample periods.

INSERT TABLE 1

Since it is a relatively new market, the CSI300 futures contract is closely regulated. To open a margin account, an individual investor is required pass a compulsory qualifications exam, and deposit a minimum RMB 0.5 million (m) into a trading account[4]. The RMB 0.5m deposit is non-trivial given that domestic institutional investors are only required to deposit RMB 1m[5]. Qualified Foreign Institutional Investors (QFII) are not allow to trade CSI300 futures. The CFFEX clearing house imposes a 15% (18%) initial margin for the current and next month (next two quarter month) contracts[6]. From 29-June-2012, the margin

[2]The CSI300 base value is set to 1000 on 31-Dec-2004. Every six months, firms are sorted by market capitalization and turnover volume, and the index is updated for new constituent firms. The value of the index is computed every second and published every 5 seconds.

[3]For example, if we are in early January, the delivery months are January, February, March and June. If we are in March, the delivery months are March, April, June and September, and so forth.

[4]To note, this is not a margin requirement, since the trading account needs to be established before undertaking any futures trading.

[5]It is explicitly mentioned in various regulatory documents issued by the China Securities Regulatory Commission that index futures is not suited for individual investors.

[6]Margin accounts can only be maintained with cash. Other liquid assets, such as stocks and bonds, are not recognized as collateral for satisfying margin requirements.

requirement is adjusted to 12% for all four contract cycles. The balance in the margin account earns a risk-free rate that is based on the Shanghai Interbank Offer Rate (SHIBOR)[7].

The first two CSI300 ETFs were launched in China on 28-May-2012. The Huatai-PineBridge ETF (Stock Code 510300), or SHETF, is listed on the Shanghai Stock Exchange, while the Jiashi-Harvest ETF (Stock Code 159919), or SZETF, is launched on the Shenzhen Stock Exchange. Our analysis is based on synchronized one-minute observations over a three months pre-ETF and post-ETF sample. The pre-ETF sample period runs from 27-February to 28-May 2012, and covers both CSI300 spot and futures market. The post-ETF sample period runs from 01-December-2012 to 28-February-2013, and covers data for all four CSI300 markets. We skip the first six months after ETF launch to avoid any trading anomalies associated a newly introduced market from contaminating our results[8].

Both stock exchanges trade four hours a day between 09:30 to 11:30, and from 13:00 to 15:00. The CSI300 futures market opens 15 minutes earlier and closes 15 minutes later than the stock markets, but shares the same lunch-break from 11:30 to 13:00. Our analysis is based on overlapping trading hours across the four CSI300 markets, which gives a total of 240 one-minute observations per trading day for around 65 trading days in each of the pre-ETF and post-ETF samples.

CSI300 constituent firms pay dividends throughout the year. However, dividend payouts are clustered mainly during the high earnings reporting season from May to September. In 2013, we compute the monthly annualized dividend yield, and find that it ranges from 1.21%pa in May to 2.3%pa in September. For other months, the dividend yield is around 0.8%pa for 2013, and even lower for 2012. Indeed, firms in China typically pay much lower dividends compared to similar firms in Western economies. Furthermore, since both pre- and post-ETF sample periods are from the low earnings reporting season, we assume $q = 0\%$[9]. Our main focus is on the comparison among the four pairwise market estimations. The level

[7]In our analysis, we also use the 3-month Treasury yield and the RMB prime rate. Both rates are very similar to SHIBOR, and so are our main results.

[8]Furthermore, during the first six months, the data format and structure for the SZETF is different from the other three CSI300 markets.

[9]We can confirm that the dynamics of b_t over time is unaffected by whether we use $q = 0$ or $0.8\%pa$.

of q cannot explain dissimilar findings across the various pairwise estimations.

2.2 Prior studies on derivative markets in China

The majority of studies on derivative markets in China examine industrial commodity futures of the Shanghai Futures Exchange (SHFE) and/or agricultural futures traded either the Dalian or Zhengzhou Futures Exchange. Fung et al. (2010) study the information flow in copper and aluminum futures markets between China and U.S., while Fung et al. (2003) conducts a similar study that focuses on agricultural commodity futures. Liu and An (2011) analyze cross-market price discovery between U.S. and China for the copper and soybean futures markets. Hua and Chen (2007) examines information flow in industrial metal futures traded between SHFE and the London Metal Exchange, as well as agricultural futures traded between Dalian Exchange and CBOT. Lee et al. (2009) compares day-of-the-week effects between U.S. and Chinese commodity futures. Chan et al. (2004) analyze the determinants of daily volatility behavior in the soybean contract in Dalian, and the mungbean and wheat contracts traded in Zhenzhou.

The introduction of the CSI300 futures contract in 2010 opened up new avenues of derivative research on China's first stock index futures market. Yang et al. (2012) find that price discovery in the newly launched contract did not function well, which they attribute to high barriers to entry for informed foreign investors. Chen et al. (2012) report that stock market volatility has decreased significantly after the introduction of CSI300 futures trading. Zhuo et al. (2012) analyze arbitrage violation and mean-reversion in the CSI300 futures market over a six months period. Their mean-reverting model contains dummy variables to indicate arbitrage violation. However, this imposes a rapid shift in the mean-reverting process when an arbitrage violation occurs. This assumes that the supply of arbitrage activity is highly elastic, which is not appropriate for a newly launched market dominated by poorly capitalized individual investors.

3 ST-VECM estimation and modified GG measure

In equation (1), an arbitrage violation occurs when the carry-cost adjusted basis b_t exceeds either its lower TC_L or upper TC_U arbitrage bound. These bounds normally reflect the applicable round-trip transaction cost associated with index arbitrage. Denote S_t and F_t as spot and futures prices, r and q respectively as the continuously compounded annualized risk-free rate and dividend yield on the CSI300 index. In equilibrium, the pricing error $b_t \sim (0, \sigma_b)$ fluctuates within its bounds over the life of the contract $T - t$. Setting $TC_U \neq TC_L$ allows for dissimilar transaction cost associated with short and long arbitrage[10].

$$b_t = F_t - S_t e^{(r-q)(T-t)}$$

$$TC_U \geq b_t \geq -TC_L, \text{where } TC_U \neq TC_L \tag{1}$$

The widely used Gonzalo-Granger (1995) (GG) common-factor weights measure of cross-market price discovery is based on a VECM specification. Since the VECM assumes a linear error-correction mechanism, the GG measure imposes a single-speed adjustment by b_t, regardless of whether b_t triggers an arbitrage violation. Intuitively, we expect b_t to deliver more price impact on both r_{st} and r_{ft} equations when arbitrage trading is taking place between the two markets. This implies that a non-linear error-correction mechanism, which facilitates a two-speed adjustment, is a more appropriate empirical specification. Furthermore, since trading in CSI300 markets is dominated by smaller retail investors, the adjustment by b_t back within its arbitrage-free bounds is likely to occur gradually over time. As such, a discrete regime-switching model would not be appropriate.

We elaborate on how the ST-VECM in equation (2) addresses the above concerns. Bounded between [0,1], the transition function $F[b_{t-d}, \gamma]$ is determined by the speed of adjustment parameter γ, the magnitude of b_{t-d} and its variability $\sigma_{b_{t-d}}$. Since our analysis

[10]When $b_t > TC_U$, this triggers short arbitrage i.e. short-futures, long-spot, and reversing later on. When $b_t < -TC_L$, this triggers long arbitrage i.e. going long-futures and short-spot. Normally, we expect $TC_U < TC_L$, since it is more expensive to go short rather than long in the underlying index.

covers newly launched CSI300 ETF markets, we allow illiquidity variables $ILLQ_{st} = \frac{r_{st}}{Size_{st}}$ and $ILLQ_{ft} = \frac{r_{ft}}{Size_{ft}}$ from both markets to enter the ST-VECM as exogenous variables. Chakravarty et al. (2004) find that liquidity help explains lead-lag effects. We construct the illiquidity variables as price impact conditional on trade size, in the spirit of Amihud (2002).

$$
\begin{aligned}
r_{ft} = \alpha_0^f + \sum_{i=1}^{T}(\alpha_{1i}^s r_{st-i} + \alpha_{1i}^f r_{ft-i} + [\beta_0^f + \beta_{1i}^s r_{st-i} + \beta_{1i}^f r_{ft-i}] \cdot F[b_{t-d},\gamma]) \\
+ (\lambda_1^f + \lambda_2^f \cdot F[b_{t-d},\gamma])b_{t-d} + \delta_1^s ILLQ_{st-1} + \delta_1^f ILLQ_{ft-1} + \varepsilon_{ft}
\end{aligned}
$$

$$
\begin{aligned}
r_{st} = \alpha_0^s + \sum_{i=1}^{T}(\alpha_{2i}^s r_{st-i} + \alpha_{2i}^f r_{ft-i}) + [\beta_0^s + \beta_{2i}^s r_{st-i} + \beta_{2i}^f r_{ft-i}] \cdot F[b_{t-d},\gamma]) \\
+ (\lambda_1^s + \lambda_2^s \cdot F[b_{t-d},\gamma])b_{t-d} + \delta_2^s ILLQ_{st-1} + \delta_2^f ILLQ_{ft-1} + \varepsilon_{st}
\end{aligned}
$$

$$
F[b_{t-d},\gamma] = 1 - exp^{-\gamma(\frac{b_{t-d}}{\sigma_{t-d}})^2} \in [0,1] \tag{2}
$$

Consider when there is no significant two-speed error-correction, such that $\gamma = 0$. This implies $F[b_{t-d},\gamma] = 0$, and the ST-VECM reduces to a VECM. Conversely, if a non-linear error-correction mechanism is inherent in the data i.e. $\gamma > 0$, a statistically non-trivial pricing error $\frac{b_{t-d}}{\sigma_{b_{t-d}}}$ will cause $F[b_{t-d},\gamma]$ to increase. When this happens, a second set of error-correction coefficients $(\lambda_2^s, \lambda_2^f)$ is introduced into the VECM. Accordingly, the $F[b_{t-d},\gamma]$ in the ST-VECM allows the error-correction mechanism between two markets to shift between first-gear $(\lambda_1^s, \lambda_1^f)$ and second-gear $(\lambda_1^s + \lambda_2^s, \lambda_1^f + \lambda_2^f)$ in response to a non-trivial b_{t-d}.

Just as the GG (1995) measure is based on the VECM's error-correction coefficients (ECC), the modified measure GG_t in equation (3) is calculated from the ECC_t^s and ECC_t^f of the ST-VECM. Functional forms aside, the intuitive interpretation of the original GG (1995) measure flows directly onto the modified version. Specifically, the magnitude of the ECCs indicate each market's reliance on the error-correction variable for their price formation over time. If $ECC_t^s > ECC_t^f$, this implies that r_{st} is affected more by deviations between S_t and F_t, compared to r_{ft}. The modified GG_t is based on the spot market. Hence, a larger (smaller) GG_t implies that the spot market performs less (more) price discovery, relative to the futures market.

$$ECC_t^s = \lambda_1^s + \lambda_2^s F[b_{t-d}, \gamma] \qquad\qquad ECC_t^f = \lambda_1^f + \lambda_2^f F[b_{t-d}, \gamma]$$

$$GG_t = \frac{ECC_t^s}{ECC_t^s - ECC_t^f} \tag{3}$$

The transition function $F[b_{t-d}, \gamma]$ induces fluctuation in ECC_t^s between λ_1^s and $(\lambda_1^s + \lambda_2^s)$, and in ECC_t^f between λ_1^f and $(\lambda_1^f + \lambda_2^f)$. As such, equation (4) shows that GG_t is bounded between GG_0 when $F[b_{t-d}, \gamma] = 0$, and GG_1 when $F[b_{t-d}, \gamma] = 1$. Whether GG_0 (or GG_1) is the upper or lower bound depends on the estimated λs. It is easy to show[11] that if $\frac{\lambda_1^s}{\lambda_2^s} < \frac{\lambda_1^f}{\lambda_2^f}$, then GG_0 and GG_1 are the upper and lower bounds respectively, and vice versa.

$$GG_0 = \frac{\lambda_1^s}{\lambda_1^s - \lambda_1^f} \qquad\qquad GG_1 = \frac{\lambda_1^s + \lambda_2^s}{(\lambda_1^s + \lambda_2^s) - (\lambda_1^f + \lambda_2^f)}$$

$$GG_0 > GG_1 \text{ if } \frac{\lambda_1^s}{\lambda_2^s} < \frac{\lambda_1^f}{\lambda_2^f} \qquad\qquad GG_1 > GG_0 \text{ if } \frac{\lambda_1^s}{\lambda_2^s} > \frac{\lambda_1^f}{\lambda_2^f} \tag{4}$$

The original GG (1995) measure, which has the same functional form as GG_0, is bounded between 0 and 1. This is because the estimated λ^s and λ^f from the VECM have opposite signs, such that 0.5 is the threshold value to determine which market possesses the price leadership role i.e. contributes more price discovery. Equation (4) shows that this is not the case for GG_t, since λ_1^s and λ_1^f can have the same sign. Furthermore, the values of GG_0 and GG_1 can differ across pairwise markets, since the estimated $\{\lambda_1^s, \lambda_2^s, \lambda_1^f, \lambda_2^f\}$ are likely to be different.

[11]The condition $GG_0 > GG_1$ corresponds to $\lambda_1^s(\lambda_1^s + \lambda_2^s - \lambda_1^f - \lambda_2^f) > \lambda_1^s(\lambda_1^s + \lambda_2^s - \lambda_1^f) - \lambda_1^f \lambda_2^s$, or $\frac{\lambda_1^s}{\lambda_2^s} < \frac{\lambda_1^f}{\lambda_2^f}$

4 Discussion of empirical results

4.1 Basic features of the sample and diagnostic test

We present preliminary results to reveal some basic features of the sample. Figures 1A∼D plot the price series for each of the four pairwise market estimations. Given that they are all closely-related securities, it is not surprising to observe evident price co-movements over time. However, we notice that in Figure 1D, SZETF and futures prices seems to exhibit greater discrepancy over time compared to its two spot market counterparts in Figures 1B and 1C.

INSERT FIGURE 1

Next, we compare the return series of the four pairwise markets in Figures 2A∼D. For the post-ETF sample, r_{ft} is the same across Figures 2B∼D. Using r_{ft} as a visual benchmark, we can see that the relevant spot market return becomes increasing volatile as we move from r_{st} in Figure 2B to r_{SHt} in Figure 2C, and again to r_{SZt} in Figure 2D. Based on the descriptive statistics[12], we can confirm that: r_{st} is less volatile than r_{ft}; r_{SHt} has comparable volatility to r_{ft}; r_{SZt} is more volatile than r_{ft}.

INSERT FIGURE 2

To follow, we plot the carry-cost adjusted basis b_t corresponding to the four pairwise markets in Figures 3A∼D. Consistent with the two previous figures, Figure 3 shows that the b_t between the SZETF and futures market exhibits the largest mean and volatility compared to the other two pairwise markets. These visual plots provide some early indication that the trading link between SZETF and the futures market seems to be weaker compared to either the SHETF or the spot index.

INSERT FIGURE 3

[12]The descriptive statistics on the key variables pre- and post-ETF are not included due to space constraint. They are readily available upon request.

Lastly, we conduct Augmented Dickey-Fuller (ADF) tests to confirm the stationarity of the key variables that are used in the ST-VECM[13]. We use the Schwarz Information Criterion to determine the optimal lag specification for the ADF test on each variable. At the 1% significance level, we can confirm that all the price series are non-stationary, but the log difference in prices are all stationary. Furthermore, b_{t-d} and the illiquidity variables for all four pairwise markets are stationary as well.

4.2 Estimation results from the ST-VECM

The ST-VECM estimation requires a lag specification for the spot and futures return dynamics, as well as the error-correction variable b_{t-d}. An analysis of the auto- and cross-auto correlation functions indicate that all return series exhibit lag-1 dynamics. However, b_{t-d} is the key variable in the ST-VECM that affects both the transition function $F[b_{t-d}, \gamma]$, and the relative movements in spot and futures prices over time. Furthermore, since the estimation is conducted using 1-minute observations, the error-correction mechanism inherent in the data may be occurring at longer lags i.e. $d > 1$. Hence, we conduct a formal test to determine an optimal d for b_{t-d}, which is then apply to all four pairwise market estimations.

Swanson (1999) proposes a Lagrange-Multiplier (LM) test for non-linear error-correction mechanism, which the ST-VECM is intended to capture. Following Swanson (1999), we perform a third-order Taylor-Series expansion on each return series around b_{t-d}, and test for the joint significance of higher-order terms. Equation (5) outlines the LM test on r_{ft}. If the higher-order terms are jointly insignificant i.e. $H_0 : \phi_1 = \phi_2 = \phi_3 = 0$, then we fail to reject the null hypothesis of no significant non-linear dynamics in r_{ft}. The LM-test is repeated for $d = 1, 2, ...$ to ascertain the optimal d for which most of not all of the return series exhibit non-linear dynamics. Intuitively, the LM-test allows us to determine an optimal d that allows the ST-VECM to bring out non-linear interactions in return dynamics between markets.

[13] Due to space constraint, and since these are standard results, we do not report them in the paper. The ADF test statistics are readily available upon request.

$$
\begin{aligned}
r_{ft} =& \phi_0(f_{t-1} + s_{t-1} + b_{t-d}) \\
&+ \phi_1(f_{t-1} + s_{t-1} + b_{t-d})b_{t-d} + \phi_2(f_{t-1} + s_{t-1} + b_{t-d})b_{t-d}^2 + \phi_3(f_{t-1} + s_{t-1} + b_{t-d})b_{t-d}^3
\end{aligned} \tag{5}
$$

We report the LM-test statistics in Table 2 for $d = 1, 2..., 5$. For the pre-ETF sample, r_{ft} exhibits non-linear dynamics up to b_{t-3}, whereas r_{st} displays non-linear dynamics up to b_{t-5}. These results are also documented in the post-ETS sample. In contrast, both r_{SHt} and r_{SZt} exhibit non-linear effect only for $d = 4$, for which there is no significance for r_{ft}. Since the futures market is involved in all four pairwise estimation, we do not consider $d = 4$. In addition, among $d = 1, 2, 3$, the test statistics for the various markets are the highest for $d = 3$. Hence we specify $d = 3$ for b_{t-d} and $F[b_{t-d}, \gamma]$ in the ST-VECM estimation.

INSERT TABLE 2

We present the estimation results in Table 3 Panels A and B for the pre- and post-ETF sample. In Panel A, $r_{st-1} \cdot F[b_{t-d}, \gamma]$ and $r_{ft-1} \cdot F[b_{t-d}, \gamma]$ are significant in both r_{ft} and r_{st} equations. This indicates substantial non-linear own- and cross-market return dynamics between the spot and futures markets, even after controlling for illiquidity effects across both markets. There is also an evident two-speed error-correction mechanism, with $b_{t-d} \cdot F[b_{t-d}, \gamma]$ significant in both r_{ft} and r_{st} equations. For the error-correction coefficients, we find that $|\lambda_1^s| > |\lambda_1^f|$ and $|\lambda_1^s + \lambda_2^s| > |\lambda_1^f + \lambda_2^f|$. This indicates that b_{t-d} exerts a larger price impact on r_{st} compared to r_{ft}. The estimated λs imply that the modified GG measure assigns the price leadership role to the futures market. For $F[b_{t-d}, \gamma]$, the speed of adjustment coefficient $\gamma = 0.31$ is also significant at the 1% level. In sum, these results indicate the presence of arbitrage activity between the CSI300 spot and futures market in the pre-ETF sample.

INSERT TABLE 3

In the post-ETF sample, the $r_{st} \sim r_{ft}$ estimation results in Panel B are generally consistent with Panel A, but with two exceptions. The two-speed error-correction mechanism is no longer significant in r_{ft}, although it remains significant in r_{st}. Interestingly, $\gamma = 1.466$ indicates a faster speed of adjustment in b_{t-d} compared to pre-ETF γ, albeit less significant at the 10% level.

The $r_{SHt} \sim r_{ft}$ estimation reveals significant cross-market non-linear return interactions, with $r_{ft-1} \cdot F[b_{t-d}, \gamma]$ and $r_{SHt-1} \cdot F[b_{t-d}, \gamma]$ correspondingly significant in r_{SHt} and r_{ft}. However, own-market non-linear return dynamics are insignificant. A two-speed error-correction mechanism is significant in both r_{SHt} and r_{ft}, with the estimated coefficients also having larger magnitudes in the r_{SHt} equation. Lastly, the speed of adjustment $\gamma = 2.594$ is larger and highly significant, compared to the $r_{st} \sim r_{ft}$ estimation.

Lastly, the $r_{SZt} \sim r_{ft}$ estimation reveals starkly dissimilar findings. Only $r_{SZt-1} \cdot F[b_{t-d}, \gamma]$ is significant in r_{ft}. There are no significant two-gear error-correction mechanisms in either r_{SZt} or r_{ft}, although, consistent with the other three pairwise estimations, the magnitude of error-correction coefficients are larger for r_{SZt} compared to r_{ft}. More surprisingly, even b_{t-d} is insignificant in both equations. The speed of adjustment $g = 1.174$ is also insignificant. One could associate these findings to the diagnostic results in Table 2, which indicate that r_{SZt} does not exhibit non-linear effects at b_{t-3}. However, this is also the case for r_{SHt}. Hence, a potentially sub-optimal lag specification for b_{t-d} cannot explain the dissimilar results between r_{SZt} and r_{SHt}.

4.3 Price discovery over time

4.3.1 Price impact and error-correction mechanism

To facilitate a more comprehensive discussion of findings across the four pairwise market estimations, we provide a summary of key results in Table 4. Our focus is on ST-VECM estimates that provide insights into the impact of ETF trading on price discovery across CSI300 markets. In Table 3, the ST-VECM consistently yields $|\lambda_1^s| > |\lambda_1^f|$ and $|\lambda_1^s + \lambda_2^s| > |\lambda_1^f + \lambda_2^f|$ across all four pairwise market estimations. This strongly indicates that the CSI300 futures market contributes more price discovery than its three spot market counterparts.

In Table 4, we report the joint price impact of lag-1 returns and b_{t-3} on the corresponding markets of each pairwise estimation. This includes the second-gear price impact that is delivered through $F[b_{t-d}, \gamma]$ on the estimated coefficients for each variable. However, since $F[b_{t-d}, \gamma]$ varies over time, we compute the associated price impact based on the average $F[b_{t-d}, \gamma]$, or F_{Avg}, over the sample period, corresponding to each pairwise market. For example, consider the $r_{SHt} \sim r_{ft}$ estimation. In the r_{SHt} equation, the joint price imposed by b_{t-d} is $[\lambda_1^{sh} + \lambda_2^{sh} \cdot F_{Avg}]$. This corresponds to 0.046 in the last column of Table 4, where (**/**) indicates that both λ_1^{sh} and λ_2^{sh} are significant at the 5% level.

INSERT TABLE 4

The pre-ETF $r_{st} \sim r_{ft}$ estimation reveals that the joint price impact on r_{st} is larger than r_{ft}, and this is consistently delivered by r_{ft-1} (0.4113 vs. 0.0138), r_{st-1} (0.399 vs. 0.0008) as well as b_{t-d} (0.0057 vs. 0.0021). All coefficients are significant at the 1% level except λ_2^s, which is significant at the 10% level. These results strongly suggest that the futures market contributes more price discovery than the spot index, which is expected. The finding is consistent and slightly stronger in the post-ETF estimation. We find that r_{ft-1} (0.4530 vs. 0.0586), r_{st-1} (0.3560 vs. 0.0017) and b_{t-d} (0.0203 vs. 0.0028) still deliver larger price impacts on r_{st} compared to r_{ft}. More interestingly, the second-gear error-correction mechanism λ_2^f is no longer significant in r_{ft}, which implies that only r_{st} responses to non-trivial pricing errors. This suggests that, post-ETF trading, arbitrage activity between the CSI300 spot and futures market has declined.

The $r_{SHt} \sim r_{ft}$ estimation results complement the preceding discussion. Consistent with the pre- and post-ETF $r_{st} \sim r_{ft}$ estimations, we find that r_{SHt} receives a heavier joint price impact from all three variables r_{ft-1} (0.549 vs. 0.046), r_{st-1} (-0.2485 vs. 0.0215) and b_{t-d} (0.0046 vs. 0.0008). The latter also confirms that the futures market retains its price leadership over the SHETF. Both r_{SHt} and r_{ft} equations exhibit a significant two-speed error correction mechanism. This indicates the presence of arbitrage activity between the SHETF and futures market, since both r_{SHt} and r_{ft} respond to a non-trivial b_{t-d}. In conjunction with earlier findings that the two-speed error-correction mechanism in the $r_{st} \sim r_{ft}$ estimation has disappeared when we move from the pre- to post-ETF sample, the results strongly suggest that arbitrage activity has migrated from the CSI300 spot to the SHETF.

Is this also the case for the ETF traded in Shenzhen? Ex-ante, we expect some arbitragers to migrate to the SZETF. In the pre-ETF days, arbitragers trade in CSI300 replicating portfolios. As a number of large constituent firms are listed in Shenzhen, we expect a substantial portion of arbitragers to have trading accounts with the Shenzhen Exchange. We document starkly dissimilar findings from the $r_{SZt} \sim r_{ft}$ estimation. The results are consistent in showing that, relative to futures return, r_{SZt} experiences more price impact from r_{ft-1} (0.4014 vs. 0.0554), r_{st-1} (-0.0552 vs. -0.0056) and b_{t-d} (0.0082 vs. -0.0022). But surprisingly, not only is there an insignificant two-speed error correction mechanism, b_{t-d} itself is also insignificant i.e. no error-correction mechanism between the SZETF and futures markets. This implies a lack of arbitrage activity to enforce the pricing link between r_{SZt} and r_{ft}.

To complement the discussions thus far, we plot the estimated $F[b_{t-d}, \gamma]$ against b_{t-d} to acquire a sense of the range of pricing error that is associated with a second-gear error correction mechanism. In Figures 4A$\sim$C, the outer (blue) graph is based on the pre-ETF estimation, which is identical across the three figures. The inner (green) graphs correspond to the three post-ETF pairwise market estimations. Figure 4 shows that all three post-ETF graphs are subsumed by the pre-ETF graph. This implies that full adjustments in pricing errors occur within narrower bands post-ETF trading. This is not surprising given that the arbitrage bounds that govern the carry-cost adjusted basis is expected to narrow substantially post-ETF trading, due to lower transaction cost with trading ETFs.

INSERT FIGURE 4

Interestingly, the $r_{st} \sim r_{ft}$ estimation exhibits the narrowest range of pricing errors in Figure 4A. But according to Table 3, only r_{st} exhibits a significant two-speed error-correction. In contrast, although the $r_{SHt} \sim r_{ft}$ estimation yields a significant two-speed error-correction across both markets, Figure 4B shows the least narrowing in the range of pricing errors. We elaborate on this in the next section. As a preview, if arbitragers migrate from the CSI300 spot market post-ETF, the index simply becomes a 'follower' market. When a non-trivial b_{t-d} occurs, r_{st} will simply respond to r_{ft} and move towards the new futures price.

Furthermore, if arbitragers migrate predominately to the SHETF market, this can also explain why Figure 4B shows the least narrowing in the range of pricing errors. Consider when pricing errors are induced by informed futures traders attempting to discover a new price for the CSI300. When the pricing error become profitably non-trivial, arbitragers step in. Their trading activity by default will slow down informed traders from discovering the new futures price. This interaction between informed traders and arbitragers can result in a wider range of observed pricing errors compared to the CSI300 spot, where arbitragers are absent. We formally examine this issue by analyzing and comparing the price discovery mechanism among the four pairwise markets in the next section.

4.3.2 Modified Gonzalo-Granger measures over time

The estimated λs in Table 3 allow us to compute modified Gonzalo-Granger measures GG_t for each of the four pairwise markets. To reiterate, all four estimations yield $\frac{\lambda_1^f}{\lambda_2^f} > \frac{\lambda_1^s}{\lambda_2^s}$. According to equation (4), this implies $GG_0 > GG_1$ i.e. GG_0 is the upper bound for which the spot market price discovery GG_t hits when $F[b_{t-d}, \gamma] = 0$. And GG_1 is the lower bound for GG_t corresponding to $F[b_{t-d}, \gamma] = 1$. When the no-arbitrage condition holds for a pair of CSI300 markets, $F[b_{t-d}, \gamma]$ is trivial, and GG_t will fluctuate near its upper bound GG_0. In this case, the spot index or ETF performs the least price discovery. When an arbitrage violation occurs, a non-trivial b_{t-d} will cause $F[b_{t-d}, \gamma]$ to increase. This allows the error-correction mechanism in the ST-VECM to shift into 'second gear' in response to arbitrage activity. The increase in $F[b_{t-d}, \gamma]$ will also cause GG_t to decline towards its lower bound GG_1.

The above discussion seems to suggest that the spot market's price discovery is enhanced by arbitrage activity. Such an interpretation is misguided. Index arbitragers per se do not conduct informed trading in either the spot or futures market. Rather, they profit from misalignments between S_t and F_t, regardlessly of which price is more informed. When b_{t-d} becomes profitably non-trivial, arbitrage trading will force S_t and F_t towards each other. Even if F_t is the more informed price moving in the right direction, arbitrage activity will drag it partially back towards S_t. This effect is captured by GG_t declining from GG_0 to GG_1.

In equation (3), the difference between ECC_t^s and ECC_t^f reflects the differential price impact exerted by b_{t-d} on r_{st} (or r_{SHt}, r_{SZt}) and r_{ft}. Arbitrage activity in response to a non-trivial b_{t-d} will generate more comparable price impact on both S_t and F_t. In the post-ETF $r_{st} \sim r_{ft}$ estimation, when $F[b_{t-d}, \gamma] = 0$, the differential price impact is $|\lambda_1^s| - |\lambda_1^f| = 0.033$. This drops to $|\lambda_1^s + \lambda_2^s| - |\lambda_1^f + \lambda_2^f| = 0.0086$, or 26%, when $F[b_{t-d}, \gamma] = 1$. We observe similar declines in the differential price impact to 17.3% for $r_{SHt} \sim r_{ft}$, and 16.7% for $r_{SZt} \sim r_{ft}$, when $F[b_{t-d}, \gamma]$ increases from 0 to 1. It is noteworthy that, across all four pairwise estimations, both GG_0 and GG_1 indicate that the CSI300 futures market contributes more price discovery than each of its three spot market counterpart. This is indicated by the magnitude of the λs from each pairwise estimation. Fluctuations in GG_t between GG_0 and GG_1 only reflect the extent of the futures market's price leadership role[14].

In Figure 5, we plot GG_t for $r_{st} \sim r_{ft}$ based on the pre-ETF estimation, and separately compare it against the post-ETF GG_t between $r_{st} \sim r_{ft}$ in Figure 5A, $r_{SHt} \sim r_{ft}$ in Figure 5B and $r_{SZt} \sim r_{ft}$ in Figure 5C[15]. For the pre-ETF sample, $|\lambda_1^s| > |\lambda_1^f|$ and $|\lambda_1^s + \lambda_2^s| > |\lambda_1^f + \lambda_2^f|$, which correspond to an upper bound of $GG_0 = 2.435$, and a lower bound of $GG_1 = 0.833$. Regardless of whether GG_t is near GG_0 or GG_1, r_{ft} contributes more price discovery than r_{st}. As previously explained, when the no-arbitrage condition holds between the spot and futures markets, GG_t fluctuates near GG_0. In Figure 5A, this corresponds to the upper, near-flat segments of the GG_t graph. When non-trivial pricing errors occur, $F[b_{t-d}, \gamma]$ increases, causing GG_t to decline towards GG_1. As arbitrage trading force F_t and S_t towards each other, the mispricing dissipates, and GG_t gradually fluctuates back towards GG_0.

INSERT FIGURE 5

Figures 5A to 5C provide an interesting comparison of the gap, or *Gap*, between GG_0 and GG_1. Compared to the pre-ETF *Gap* of 2.435 - 0.833 = 1.602, Figure 5A shows that *Gap* is almost non-existent in the post-ETF sample. In Table 3, $|\lambda_1^s| - |\lambda_1^f| = 0.033$, and $|\lambda_1^s + \lambda_2^s| - |\lambda_1^f + \lambda_2^f| = 0.0086$. As a result, $GG_0 = 1.182$ and $GG_1 = 1.116$, such that GG_t fluctuates within a much narrower *Gap* of 0.066. For the $r_{SZt} \sim r_{ft}$ estimation, Figure 5C also

[14]For example, if GG_0 refers to the futures market contributing 80% of price discovery, then GG_1 could correspond to the futures market contributing 65% price discovery.

[15]The pre-ETF time-series plots for GG_t are the same across the three figures.

reveals a comparatively narrower *Gap* of 0.526 associated with $GG_0 = 1.214$, $GG_1 = 0.688$, $|\lambda_1^s| - |\lambda_1^f| = 0.021$ and $|\lambda_1^s + \lambda_2^s| - |\lambda_1^f + \lambda_2^f| = 0.0035$. In stark contrast, Figure 5B shows that the $r_{SHt} \sim r_{ft}$ estimation yields a wider *Gap* of 2.204, with $|\lambda_1^s| - |\lambda_1^f| = 0.0081$, $|\lambda_1^s + \lambda_2^s| - |\lambda_1^f + \lambda_2^f| = 0.0014$, $GG_0 = 1.704$ and $GG_1 = -0.5$.

More importantly, the preceding results indicate a migration of arbitrage activity from the spot index predominately to the CSI300 ETF traded in Shanghai. To reiterate, arbitrage trading causes the error-correction variable in the ST-VECM to impose similar price impact on r_{st} and r_{ft}, resulting in a decline in GG_t from GG_0 to GG_1. Accordingly, *Gap* reflects the extent of arbitrage activity across a given pair of markets. A decline in *Gap* for $r_{st} \sim r_{ft}$ over time, as shown in Figure 5A, indicates that arbitrage activity has either ceased or had declined substantially between the CSI300 spot and futures market in the post-ETF sample. The ST-VECM makes only a trivial distinction in GG_t between no-arbitrage (GG_0) versus arbitrage (GG_1) states. Put simply, the magnitude of pricing errors no longer affects the price discovery mechanism between CSI300 spot and futures markets, due to the lack of arbitrage activity between the two markets.

Figures 5A∼5C also reveals an interesting difference in *Gap* across the three pairwise markets in the post-ETF sample. While *Gap* has narrowed for $r_{st} \sim r_{ft}$, but Figure 5B shows that *Gap* has instead widened to 2.204 for $r_{SHt} \sim r_{ft}$. While Figure 5A indicates a migration of arbitrage activity away from $r_{st} \sim r_{ft}$, Figure 5B shows the 'other side of the story', with substantial arbitrage activity taking place between the CSI300 ETF and futures markets. The ST-VECM clearly distinguishes between two price discovery mechanisms for GG_t that are associated with no-arbitrage G_0, and arbitrage violation G_1.

Figure 5C reveals a slightly different story. Table 4 shows that the $r_{SZt} \sim r_{ft}$ estimation yields the lowest speed of adjustment coefficient $\gamma = 1.174$ that is insignificantly different from zero. Furthermore, all interacting variables with $F[b_{t-d}, \gamma]$ are statistically insignificant as well. However, its F_{Avg} of 0.907 is substantially larger than for the other pairwise markets. These results jointly suggest that the pricing error between the SZETF and futures market is substantial. This is consistent with our preliminary analysis and what is shown in Figures 1 to 3. And there is a lack of arbitrage activity to trade away these pricing errors. This explains both a low and insignificant γ, and a high F_{Avg}.

Indeed, compared to Figure 5B, we notice that Figure 5C reveals a somewhat opposite pattern in the post-ETF GG_t over time. A persistently non-trivial b_{t-d} generates a large $F[b_{t-d}, \gamma]$. As a result, we find that GG_t fluctuates close to its lower bound GG_1. During times when arbitragers are able to reduce b_{t-d}, this allows GG_t to fluctuate upwards to GG_0 i.e. no-arbitrage state. In the post-ETF sample, the lack of arbitrage activity explains both a low speed of adjustment coefficient, and why the flat segments of GG_t in Figure 5C are observed along GG_1 rather than GG_0, as with the $r_{SHt} \sim r_{ft}$ estimation in Figure 5B.

4.4 Arbitrage activity and price discovery contribution

In this section, we raise a methodological issue regarding the computation and interpretation of cross-market price discovery measures when pairwise markets differ in the extent of arbitrage activity. Consider Markets A and B that share a common stochastic factor, but the limits to arbitrage are binding. One example is cross-listed stocks, where currency risk, non-overlapping trading hour and differential tax treatment deter arbitrage activity. Another example is ownership restriction on a firm's stocks, which are listed on the local and foreign boards of the same stock exchange. For such pairwise markets, it is less likely for r_{At}, r_{Bt} to exhibit a two-speed error-correction mechanism. If $F[b_{t-d}, \gamma]$ is insignificant, this implies that the VECM suffices to model cross-market return dynamics, and the GG (1995) price discovery measure can be applied in the usual fashion.

The presence of arbitrage activity is likely to induce a two-speed error-correction mechanism in cross-market return dynamics. We document this in both the pre-ETF $r_{st} \sim r_{ft}$ as well as $r_{SHt} \sim r_{ft}$ estimations. This implies that a VECM is misspecified since it does not differentiate the error-correction mechanisms between no-arbitrage and arbitrage states. Specifically, its estimated λ_s, λ_f, hence the GG (1995) measure, captures the price impact that is jointly imposed by informed traders and arbitragers.

In the previous section, we explain how arbitrage trading, by definition, drags the more informed F_t back towards the less informed S_t. Consequently, arbitrager partially negates the price discovery contribution made by informed futures traders. This effect is manifested in GG_t declining from GG_0 to GG_1 when b_{t-d} becomes non-trivial. Arbitrage trading, which induces price impact on both S_t and F_t, cause GG_t to give given an indication that price discovery contribution by the spot (futures) market has increased (decreased). Figure 5 shows that, while this effect is consistently being observed across all four pairwise market estimations, it is most prevalent in the pre-ETF $r_{st} \sim r_{ft}$ and $r_{SHt} \sim r_{ft}$ estimations. Both estimations yield a significant two-speed error-correction mechanism in both markets, which indicates the presence of arbitrage activity.

This raises an interesting methodological implication when using the ST-VECM's modified GG measure to infer cross-market price discovery contribution. Put simply, it is in the absence of arbitrage activity when we can acquire a better picture of cross-market price discovery. In equation (3), GG_0, which corresponds to $F[b_{t-d}, \gamma] = 0$, reflects price discovery contribution in the absence of arbitrage. To follow, GG_1, which is associated with arbitrage trading, provides a less accurate indication of cross-market price discovery.

In the context of CSI300 pairwise markets that we examined, the above distinction is moot. This is because both GG_0 and GG_1 values for various pairwise markets all correspond to the futures market contributing more price discovery than its spot market counterpart. The magnitude of λs are consistently larger for r_{st}, r_{SHt}, r_{SZt} compared to r_{ft}, regardless of whether $F[b_{t-d}, \gamma] = 0$ or 1. In all four pairwise estimations, *Gap* simply reflects the degree of price leadership that the futures market exert on its spot market counterpart, associated with varying degrees of arbitrage activity.

Now, let us assume a pair of markets in which the price impact by b_{t-d} is larger for one market when $F[b_{t-d}, \gamma] = 0$, but it is larger for the other market when $F[b_{t-d}, \gamma] = 1$. Intuitively, this suggests that the 'borderline' GG_t value[16], which indicates a tie in price discovery contribution, is straddled between GG_0 and GG_1. Fluctuation in GG_t between GG_0 and GG_1 appears to indicate an oscillation in the price leadership role between the two markets. In fact, the price leadership role remains with the market that is indicated by GG_0. Arbitrage trading causes GG_t to move from GG_0 to GG_1, thus giving an appearance that

[16]The original GG (1995) measure ranges from 0 to 1, and the borderline GG value is 0.5.

the other market has taken over the price leadership role.

A numerical example: To motivate the above discussion, we provide a simple numerical example based on the λ coefficients from the pre-ETF $r_{st} \sim r_{ft}$ estimation. We assume that the estimated λ_2^f is -0.0103 instead of -0.0045, while the other three λs remain unchanged: $\lambda_1^s = 0.0056$, $\lambda_1^f = 0.0033$ and $\lambda_2^s = 0.0004$. Based on these λ estimates, when $F[b_{t-d}, \gamma] = 0$, the incremental price impact on r_{st} over r_{ft} is $|\lambda_1^s| - |\lambda_1^f| = 0.0056 - 0.0033 = 0.0023$. However, when $F[b_{t-d}, \gamma] = 1$, the incremental price impact becomes $|\lambda_1^s + \lambda_2^s| - |\lambda_1^f + \lambda_2^f| = 0.006 - 0.007 = -0.001$ i.e. it is the futures market that received a larger price impact from b_{t-d}. Since $(\lambda_1^s, \lambda_1^f)$ are unchanged, GG_0 remains at 2.4348. But GG_1 has decreased from 0.8333 to 0.006/(0.006+0.007)=0.4762.

More importantly, if GG_t drops to $GG_1 = 0.8333$ with $\lambda_2^f = -0.0045$, the futures market still retains its price leadership role. But if GG_t drops to $GG_1 = 0.4762$, which corresponds to a hypothetical $\lambda_2^f = -0.0103$, it appears that the spot index has taken over the price leadership role. We exlain earlier that, when GG_0 and GG_1 give different indications on the market that exhibits price leadership, it is GG_0 that depicts a more accurate price discovery picture. This is because GG_1 incorporates the price impact of arbitrage trading.

5 Conclusion

In this paper, we find that the introduction of ETF trading does not dilute the price leadership role of the CSI300 future market. CFFEX's flagship contract still contributes more price discovery than its three spot market counterparts. Results from the ST-VECM also reveals that the significant two-speed error-correction mechanism in the pre-ETF $r_{st} \sim r_{ft}$ estimation is also documented in the post-ETF sample period, but only for the $r_{SHt} \sim r_{ft}$ estimation. This strongly suggests that arbitragers migrate predominately to the Huatai-Pinebridge ETF that is traded in Shanghai.

We explain why the original GG (1995) cross-market price discovery contribution is a noisy measure in the presence of arbitrage activity. The VECM does not formally acknowledge the impact of arbitrage trading on the error-correction mechanism. Intuitively, when

b_{t-d} becomes profitably non-trivial, arbitrage trading will force spot and futures prices towards each other. This causes the error-correction coefficients (λ_s, λ_f) to register comparable price impact on r_{st} and r_{ft}. But since arbitrage trading does not always occur, the estimated (λ_s, λ_f) from the VECM reflect an 'average' error-correction mechanism between arbitrage and no-arbitrage states over a given sample period. Consequently, the GG (1995) measure, which is based on (λ_s, λ_f), is a noisy measure that encapsulates the price impact of both informed traders as well as arbitragers.

We apply the ST-VECM to compute a modified GG measure for each of the four pairwise market estimations. We observe that the *Gap* for $r_{st} \sim r_{ft}$ narrows substantially when we move from the pre-ETF to post-ETF sample. In contrast, the *Gap* for $r_{SHt} \sim r_{ft}$ is wider than the pre-ETF *Gap* for $r_{st} \sim r_{ft}$. We do not find a significant two-speed error-correction mechanism for $r_{SZt} \sim r_{ft}$. This is consistent with earlier findings that arbitragers migrate predominately to the SHETF. A potential mis-specification in the optimal lag dynamics for b_{t-d} cannot explain the dissimilar findings between SHETF and SZETF. Our diagnostic tests confirm that both ETFs exhibit similar optimal lag structures. Furthermore, estimating a highly non-linear ST-VECM using intraday data makes it near-infeasible to conduct a joint estimation that encompasses all four CSI300 markets.

Indeed, we are more interested in the specific nature of the limits to arbitrage that bind the SZETF market, but not the SHETF market. These are electronically traded close-substitute securities, so the geographical proximity between CFFEX and Shanghai Stock Exchange is not a satisfying explanation for why arbitragers ignore the SZETF. Understanding the dissimilar arbitrage situations between the two ETFs require a detailed comparison of arbitrage violation characteristics, conditional on dissimilar trading or settlement features e.g. short-interest, tracking error etc, that imposes a binding limit to arbitrage only on SZETF. We are pursuing this direction in an on-going project.

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Figure 1: Price series for the CSI300 spot, futures and ETF markets

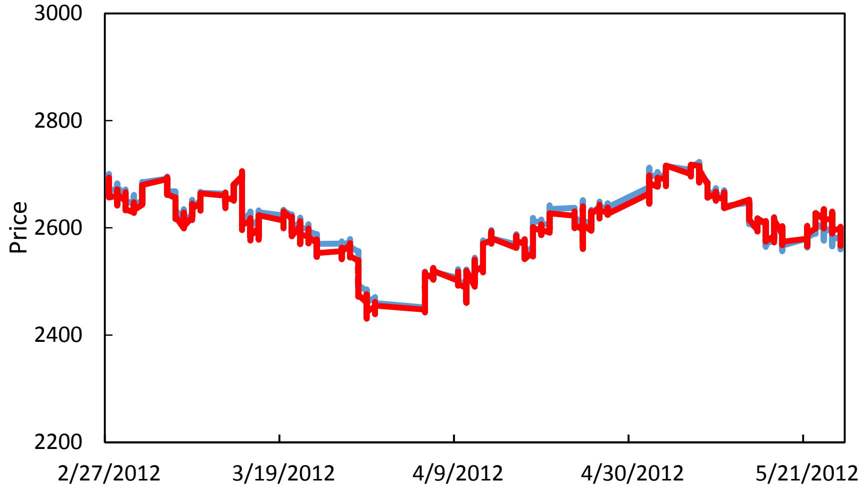

Figure 1A: CSI300 spot and futures prices in Pre-ETF sample period

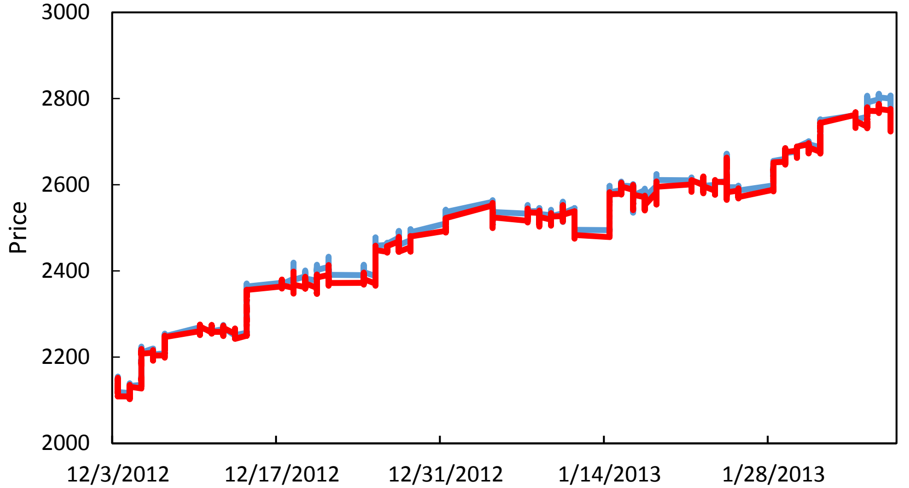

Figure 1B: CSI300 spot and futures prices in Post-ETF sample period

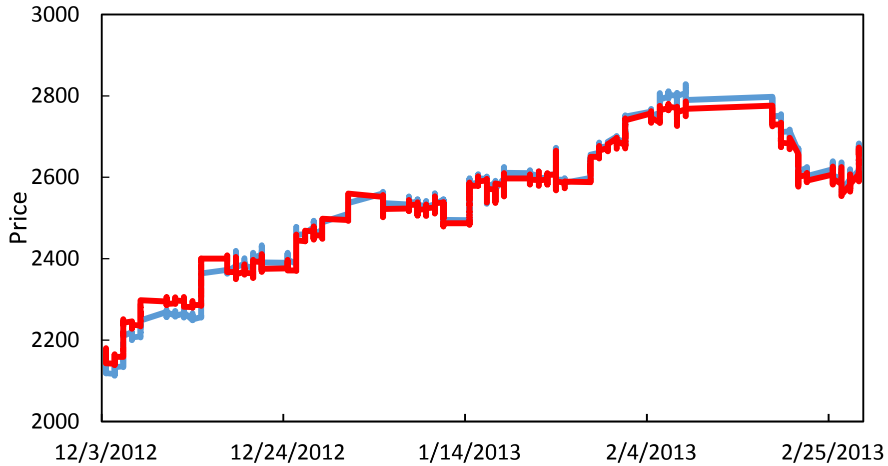

Figure 1C: SHETF and futures prices in Post-ETF sample period

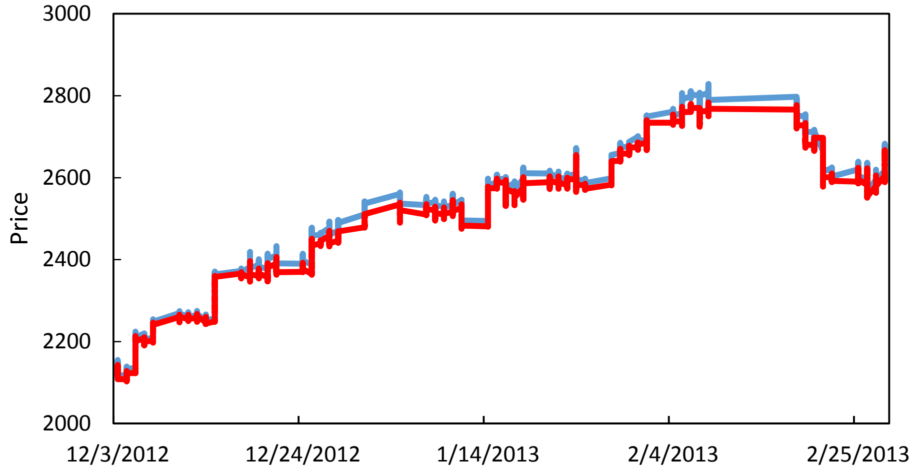

Figure 1D: SZETF and futures prices in Post-ETF sample period

Figure 2: Return series for the CSI300 spot, futures and ETF markets

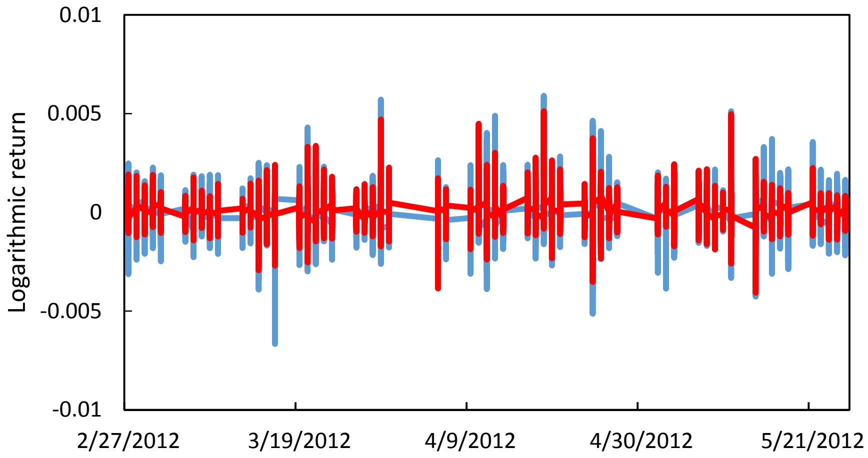

Figure 2A: CSI300 spot and futures return in pre-ETF sample period

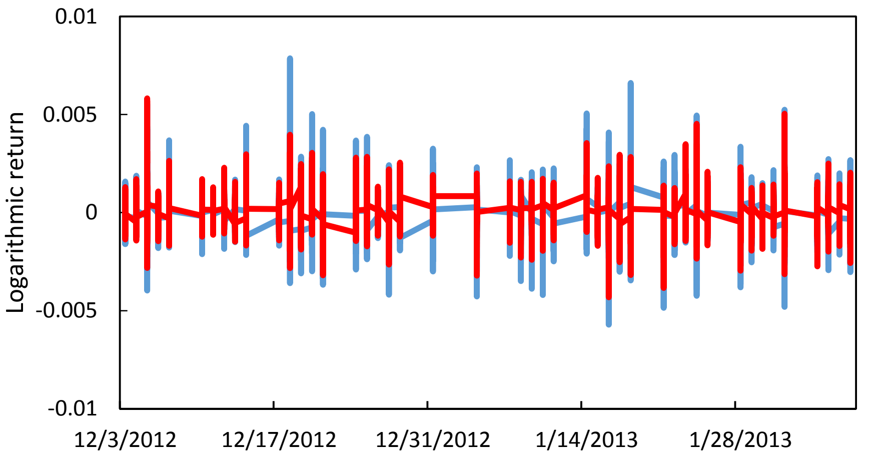

Figure 2B: CSI300 spot and futures return in post-ETF sample period

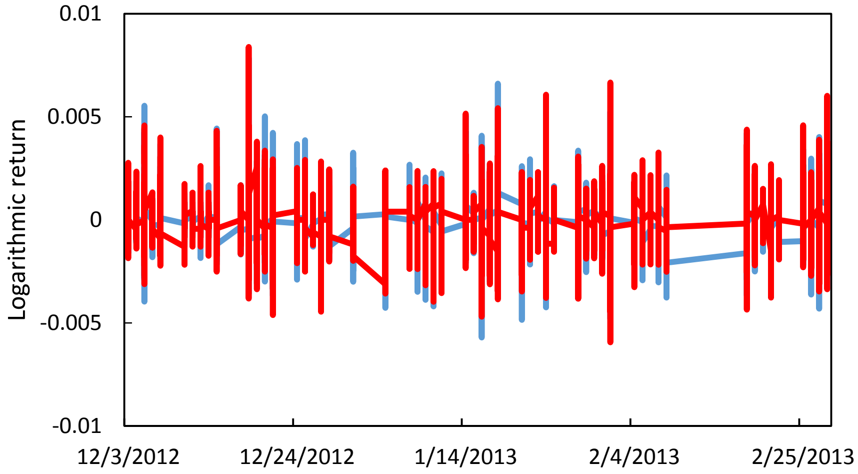

Figure 2C: SHETF and futures return in post-ETF sample period

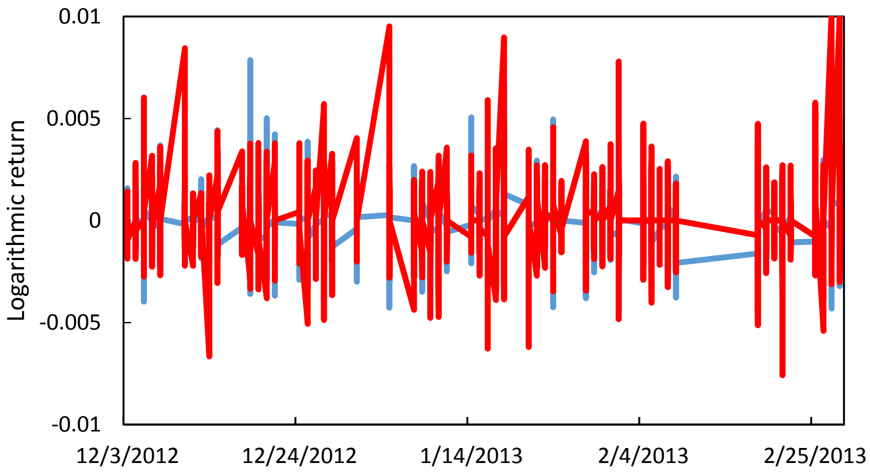

Figure 2D: SZETF and futures return in post-ETF sample period

Figure 3: Pricing error (carry-cost adjusted basis) between CSI300 futures and each of the three spot markets

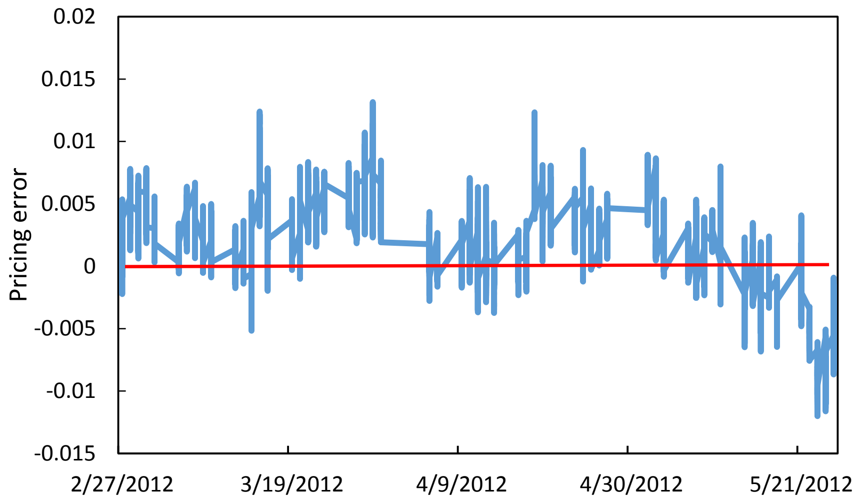

Figure 3A: CSI300 spot and futures in pre-ETF sample period

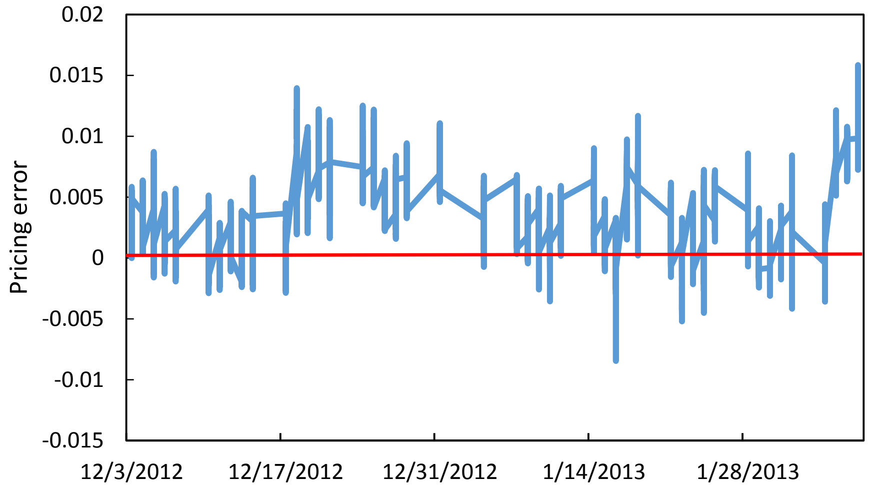

Figure 3B: CSI300 spot and futures in post-ETF sample period

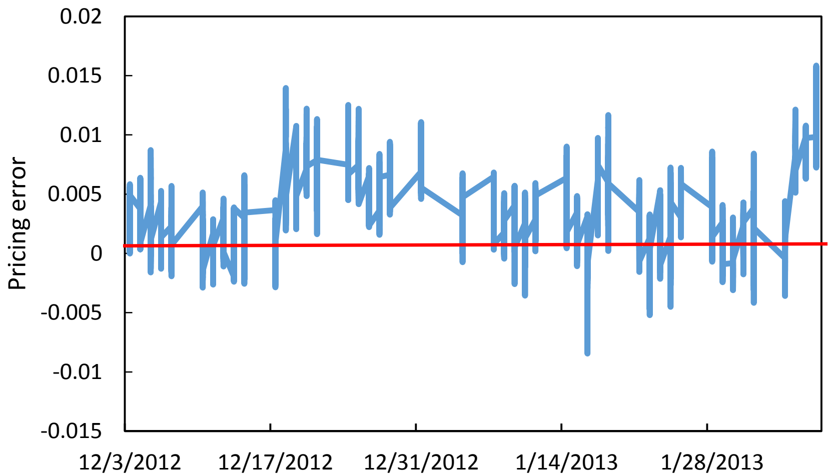

Figure 3C: SHETF and futures in post-ETF sample period

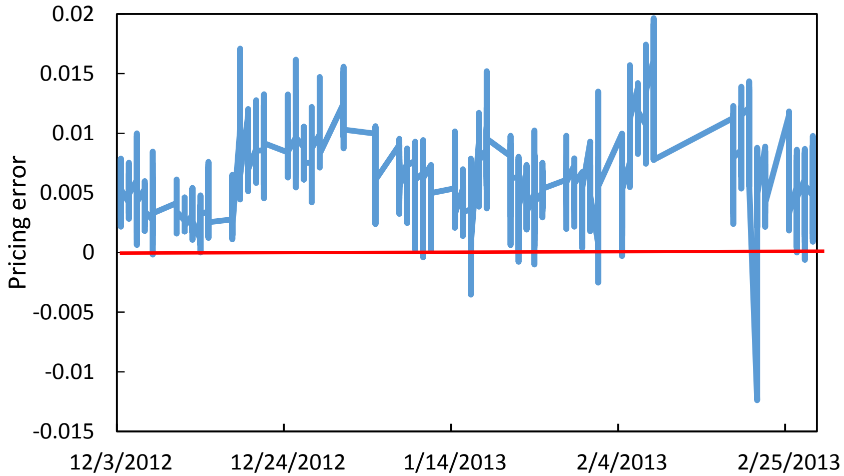

Figure 3D: SZETF and futures in post-ETF sample period

Figure 4: Transition functions of ST-VECM estimation between CSI300 futures and each of the three spot markets

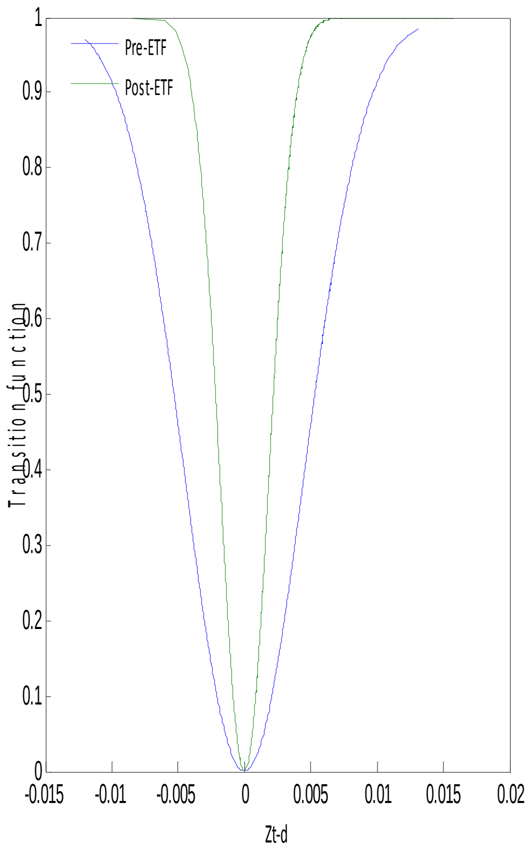

Figure 4A: CSI300 spot and futures

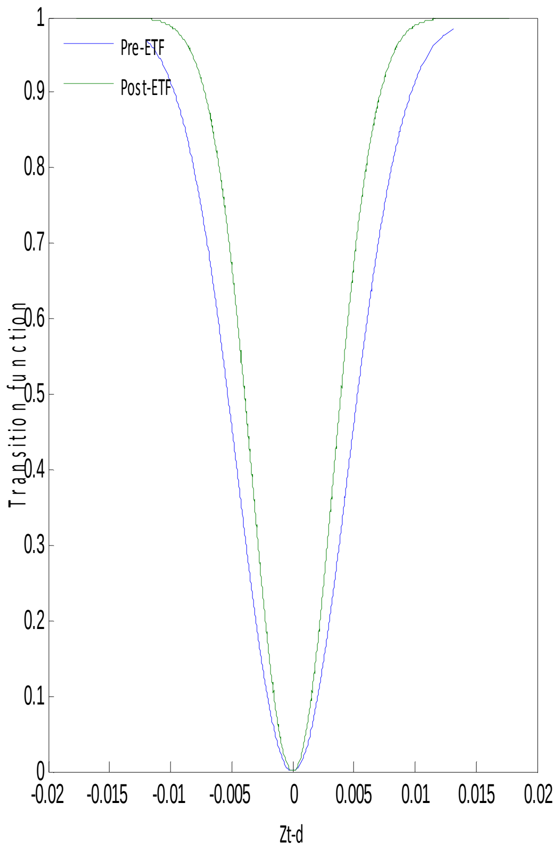

Figure 4B: SHETF and futures

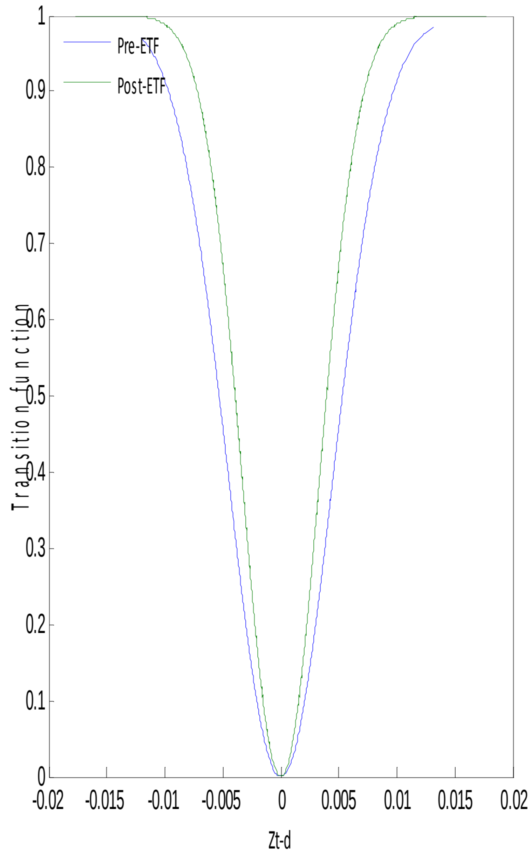

Figure 4C: SZETF and futures

Figure 5: Time-varying modified Gonzalo-Granger price discovery measure between pre- and post-ETF sample period

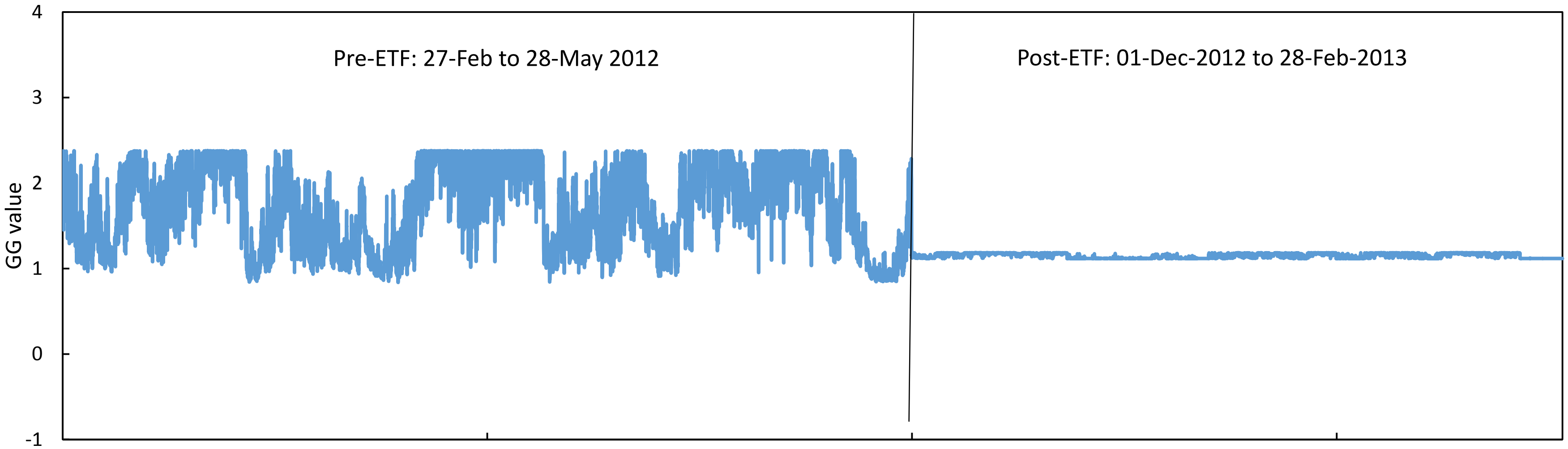

Figure 5A: GG measurement between CSI300 spot and futures markets

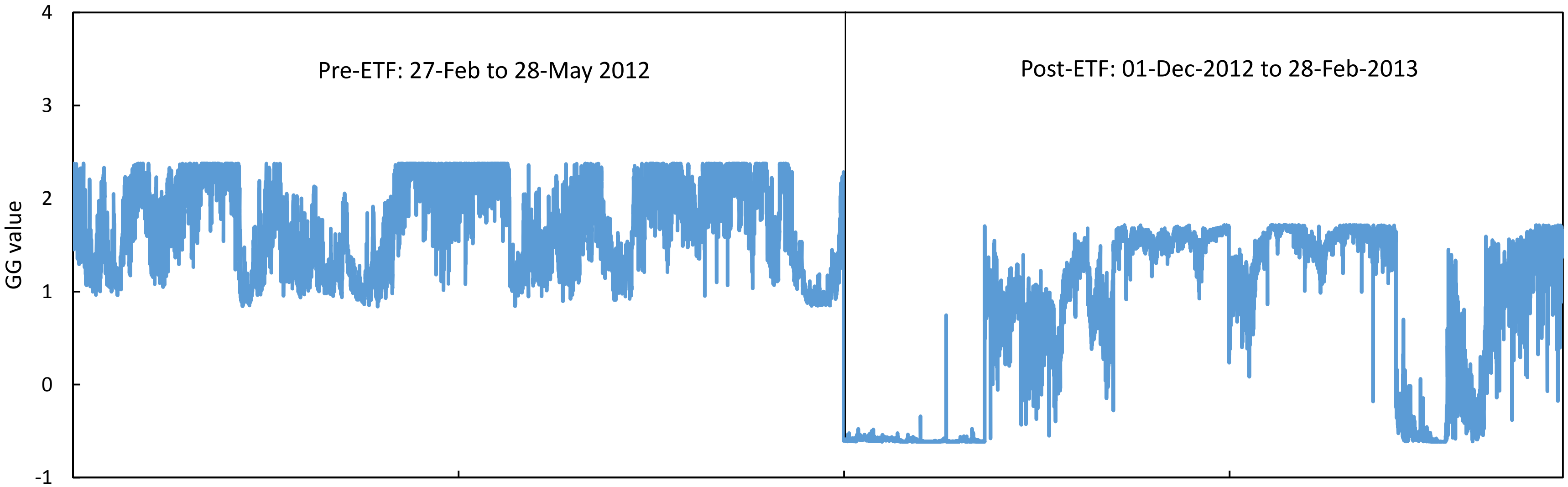

Figure 5B: GG measurement between SHETF and futures markets

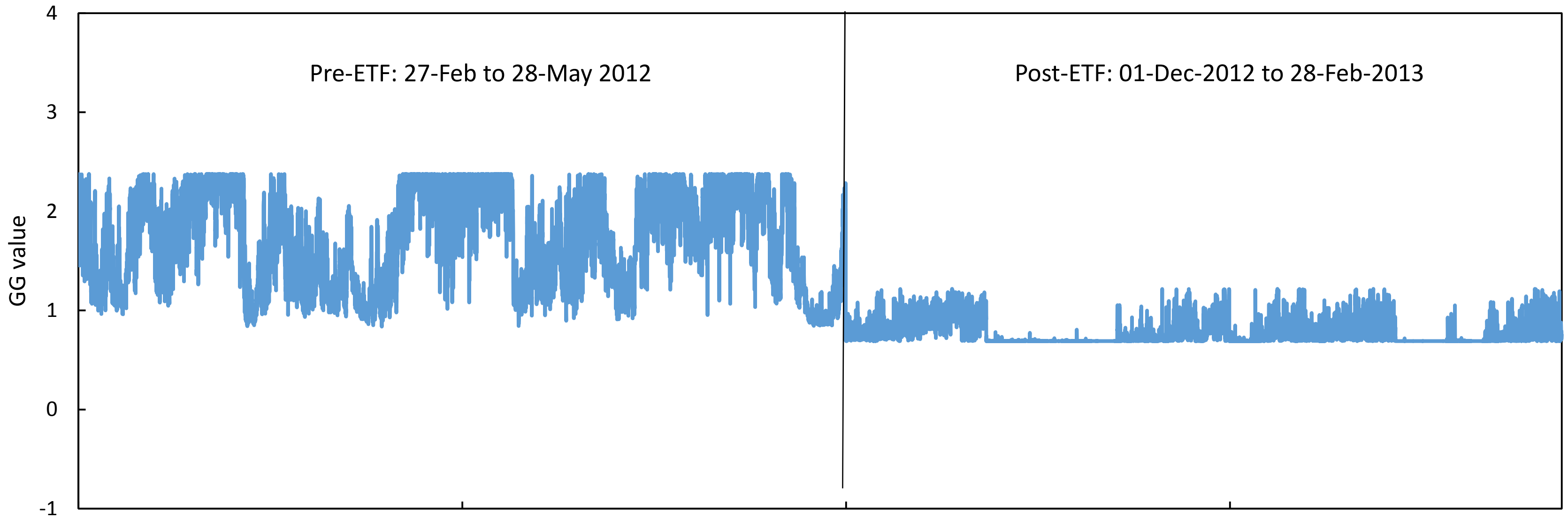

Figure 5C: GG measurement between SZETF and futures markets

Table 1: Contractual specifications for CSI300 futures

Introduction	16th April 2010
Underlying Index	China Securities Index (CSI) 300 (www.csindex.com.cn has more details)
Trading Hours	SHSE and SZSE Morning: 09:30-11:30 Afternoon: 13:00-15:00 CFFEX 09:15-11:30 13:00-15:15 (15:00 on last trading day)
Delivery Months and Expiry Day	Current month; Next month; Next two quarter months; Third Friday of a given delivery month
Contract and Tick Size	300 RMB per index point; 0.2 index point or 60 RMB tick
Price Limits	±10% on the previous trading day's settlement price
Daily Settlement Price	Positions are cash-settled. The settlement price is calculated as the volume-weighted average price (VWAP) for a given contract over a certain period of time for that trading day.
Trading Platform	Double-auction electronic limit order book

Table 2: Non-linearity LM test statistics for various return series pre- and post-ETF.

Sample period	Variable	d=1	d=2	d=3	d=4	d=5
Pre-ETF	r_{ft}	32.64 (0.000)**	163.49 (0.000)**	559.42 (0.000)**	0.780 (0.941)	0.660 (0.985)
	r_{st}	50.45 (0.000)**	12.90 (0.002)**	57.41 (0.000)**	645.84 (0.000)**	317.87 (0.000)**
Post-ETF	r_{ft}	48.74 (0.000)**	232.32 (0.002)**	692.54 (0.000)**	4.68 (0.322)	0.822 (0.976)
	r_{st}	4.102 (0.043)*	4.73 (0.094)	103.54 (0.000)**	757.89 (0.000)**	363.89 (0.000)**
	r_{SHt}	2.554 (0.110)	2.68 (0.262)	2.63 (0.453)	106.03 (0.000)**	4.95 (0.422)
	r_{SZt}	1.661 (0.197)	2.266 (0.322)	3.389 (0.336)	1609.03 (0.000)**	281.06 (0.875)

Table 3: Coefficient estimates from a ST-VECM (1, 1, 3) specification

Market	α_0	r_{ft-1}	r_{st-1}	β_0	$r_{ft-1}F[.]$	$r_{st-1}F[.]$	b_{t-3}	$b_{t-3}F[.]$	$ILLQ_{ft-1}$	$ILLQ_{st-1}$	γ	AIC
Panel A: Pre-ETF sample period from 27-Feb to 28-May 2012												
r_{ft}	0.000***	0.020***	-0.007***	0.000***	-0.024***	0.028***	0.0033***	-0.0045***	3.35E+06***	2.87E+06***	0.310***	-25.89
r_{st}	0.000***	0.402***	0.415***	0.000***	0.036***	-0.060***	0.0056***	0.0004*	-1.9E+05***	1.09E+07***		-24.81
Panel B: Post-ETF sample period from 01-Dec 2012 to 28-Feb 2013												
r_{ft}	0.000***	0.072***	0.040***	0.000*	-0.021***	-0.060***	0.006*	-0.005	6.81E+07***	1.23E+07***	1.466*	-30.360
r_{st}	-0.000***	0.460***	0.371***	0.000***	-0.010***	-0.023***	0.039***	-0.0294***	-5.2E+07***	2.17E+07***		-31.16
r_{ft}	0.000**	0.039***	0.012***	0.000	0.011	0.015*	0.0057*	-0.0078*	5.55E+07***	4.03E+03***	2.594***	-33.54
r_{SHt}	0.000**	0.518***	-0.261***	0.000	0.050*	0.020	0.0138**	-0.0145**	4.86E+06***	4.92E+02***		-34.72
r_{ft}	0.000	0.062	0.084*	0.000	-0.007	-0.099**	0.0045	-0.0074	5.52E+07***	2.84E+00***	1.174	-18.10
r_{SZt}	-0.000***	0.454***	-0.050***	0.000***	-0.058	-0.005	0.0255	-0.0191	-5.1E+07***	-4.53E+01***		-20.69

***: 1% significance level; **: 5% significance level; *: 10% significance level

We use the Akaiki Information Criterion (AIC) to determine the lag dynamics (T) for the VECM. Following Swanson (1999), we compute the non-linear LM test statistics to specify d=3 for the error correction variable b_{t-d} and the transition function G[.]. Hence the estimation results are based on a ST-VECM (1, 1, 3) specification.

Table 4: Summary of variable significance and transition parameters from a ST-VECM (1, 1, 3) estimation

	Market	F_{Avg}	γ	r_{ft-1}	$r_{ft-1}F[.]$	r_{st-1}	$r_{st-1}F[.]$	b_{t-3}	$b_{t-3}F[.]$	$\alpha^f + \beta^f F_{Avg}$	$\alpha^s + \beta^s F_{Avg}$	$\lambda_1 + \lambda_2 F_{Avg}$
Pre-ETF	r_{ft}	0.262	0.310***	***	***	***	***	***	***	0.0138 (***/***)	0.0008 (***/***)	0.0021 (***/***)
	r_{st}			***	***	***	***	***	*	0.4113 (***/***)	0.3990 (***/***)	0.0057 (***/*)
Post-ETF	r_{ft}	0.636	1.466*	***		***	***	*		0.0586 (***/***)	0.0017 (***/***)	0.0028 (*/~)
	r_{st}			***	***	***	***	***	***	0.4530 (***/***)	0.3560 (***/***)	0.0203 (***/***)
	r_{ft}	0.633	2.594***	***		***	*	*	*	0.0460 (***/~)	0.0215 (***/*)	0.0008 (*/*)
	r_{SHt}			***	*	***		**	**	0.5491 (***/*)	-0.2485 (***/~)	0.0046 (**/**)
	r_{ft}	0.907	1.174			*	**			0.0554 (~/~)	-0.0056 (*/**)	-0.0022 (~/~)
	r_{SZt}			***		***				0.4014 (***/~)	-0.0552 (***/~)	0.0082 (~/~)

***: 1% significance level; **: 5% significance level; *: 10% significance level

The last three columns indicate the joint price impact of lagged futures return, spot return and pricing error on the spot and futures return. The price impact is calculated based on the average value of the estimated transition function F_{Avg}.