The GameStop Short Squeeze: Put-Call Parity and the Effect of Frictions Before, During and After the Squeeze

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Abstract

The short squeeze in GameStop attracted worldwide attention and resulted in congnressional hearings. The increase in price from $21 to $483 over a short period of time was not the result of obvious fundamental earnings prospects. Buying pressure from investors on a social media site accompanied by short covering, resulted in the stratospheric ascent of stock price. We use put-call parity to investigate the related issue of the no-arbitrage violations before, during, and after the squeeze. We do not find evidence of abundant free money after accounting for short selling frictions.

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1 Background

The short squeeze on GameStop stock (GME) attracted worldwide attention and resulted in hearings in the US Congress. The hearings focused on the role of short-selling, payment for order-flow, and the suspension of trading in GameStop stock on January 28. The increase in price from \$21 to \$483 over a short period of time was not the result of obvious fundamental earnings prospects. Buying pressure was created by an orchestrated effort dominated by small investors on a social media site[1]. Their demand, accompanied by short covering, resulted in a rapid and large (24 fold) increase in stock price. According to IHS Markit (ihsmarkit.com), GameStop short interest was 114 percent of free floating shares in mid-January, falling to 39 percent on February 1.

How well did the market function during this crisis period? Jones, Reed, and Waller (2021) examined the effect of brokerage restrictions on stock returns and market quality for GameStop and 37 other heavily shorted firms. They found significant negative stock returns and spikes in implied volatility when trading was restricted. Equity bid-ask spreads were not adversely affected by the restrictions. There was some transfer of volume from the equity markets to option markets.

We use Put-call parity (PCP) to investigate the related issue of the arbitrage efficiency in GameStop trading before, during, and after the squeeze periods. Violations of put-call parity is frequently attributed to short selling constraints. See, for example, Battalio and Schultz (2011), Grundy, Lim and Verwijmeren (2012) and

[1] The social media site was Reddit and the buying hype came from users in the WallStreetBets subgroup.

Ofek, Richardson, and Whitelaw (2004). Hendershott, Namvar and Phillips (2013) review the literature on short-sale bans and report that their effect is pervasive in financial markets. In contrast to these studies we look at the possible failure of put-call parity *because* of short selling excesses. The GameStop short squeeze represents in microcosm many of the issues now confronting regulators, such as the gamification of investing, new technologies, and investor protection. Examination of market efficiency in the turbulent short squeeze regime therefore provides a useful benchmark for regulators.

1.1 Preview

We use stock price/volume and stock price/option volume, Figures 1 and 2 respectively, to focus the analysis on pre-squeeze, squeeze and post-squeeze periods. We define periods as follows: pre-squeeze - January 4 to January 21, squeeze - January 22 to February 10, and post-squeeze - February 11 to February 26. Breakpoints were defined by significant changes in the volume of trades and stock prices. Violations are recorded when PCP strategies have positive returns after adjusting for bid-ask spreads. There are relatively more violations in the pre-squeeze and squeeze periods. The greatest number of violations are found in the PCP branch that requires stocks to be sold or shorted. There is a greater percentage of violations in long maturities. We also model errors as a mean regressive process and find that the speed of adjustment to the long term mean (a proxy for equilibrium), is higher during the squeeze period, presumably because of the high volume of trades and smaller bid-ask spreads.

There are well known frictions incurred in selling short. These include failure to deliver, stock borrowing rates, and stock availability. Using regression models, we find that these frictions largely explain deviations from PCP predictions. Our takeaway is that the market was largely rational with respect to friction adjusted no-arbitrage conditions during the GameStop short squeeze. However, we find implied volatility was approximately 65 percent higher during the days when trading was restricted (January 27 and 28, 2021) compared to the day when restrictions were eased (January 29). However, implied volatility also increased several days before restrictions were in place.

2 Put-Call Parity

We test arbitrage efficiency using put-call parity (PCP). Put-call parity is a useful relationship that enables market participants to efficiently employ their preferred strategies. Put-call parity was introduced in the finance literature by Stoll (1969). Common strategies based on PCP include the protective put, covered call, stock short-sales, leveraged stock positions and dividend purchase.

Absent market frictions, the PCP relationship between European puts and calls with common strike and maturity, the underlying non-dividend paying stock, and a default-free bond is written

$$C = P + S - K/(1+r)^T,$$

where:

$C =$ European call price,

$P =$ European put price,

$S =$ underlying stock price,

$K =$ strike price,

$r =$ the risk-free rate of interest, and

$T =$ the time to option maturity.

We employ the Ofek, et al (2004) approach to the American version of PCP and write the relationship for a non-dividend paying stock as

$$C = (P_A - EEP) + S - K/(1 + r)^T,$$

where EEP is the non-zero early exercise premium on the American put (P_A) and $P_A - EEP \approx P$ approximates the European put. We estimate this premium using a binomial tree assuming that stock returns follow geometric Brownian motion. The implicit assumption is that the early exercise premium when the underlying follows gBm closely approximates the early exercise premium under the true but unknown stochastic process or processes. We note, however, that the estimated PCP relationship is no longer a true no-arbitrage relationship. The European/American dichotomy, however, should have minimal effect on the GameStop PCP. We observe that the overwhelming majority of trades on GameStop during our sample period were short term ($<$ 10 days), minimizing the effect of early exercise.

Another friction arises from bid-ask spreads. We use the standard assumption that buys are executed at ask prices and sells at the bid. In reality this is the worst case assumption since many transactions are executed inside these limits. We first cast PCP in terms of the *cash* position from selling the synthetic stock (S_b^*) as

$$S_b^* = C_b - P_a + K/(1+r)^T, \tag{1}$$

where the cash position arises from selling a call at the bid, buying a put at the ask, and borrowing $K/(1+r)^T$. Calls and puts are European and have common time-to-maturity (T) and exercise price K. Subscripts b and a denote bid and ask, respectively. To evaluate potential arbitrage, buy the stock in the market at ask price, S_a, and sell the synthetic stock, S_b^*. There is an arbitrage opportunity if

$$\begin{aligned} & S_b^* - S_a \\ = \quad & C_b - P_a + K/(1+r)^T - S_a > 0. \end{aligned}$$

The market participant pockets immediate cash $S_b^* - S_a$ and there is no future outflow if positions are maintained until option expiration at time-T. Absent large violations, $S_b^* - S_a$ will be negative since buys are made at the ask and sells at the bid.

Positions are reversed if the synthetic stock is bought and the stock sold. In this case the cash *outlay* is

$$S_a^* = C_a - P_b + K/(1+r)^T.$$

There is an arbitrage opportunity if

$$\begin{aligned} & S_b - S_a^* \\ = \quad & S_b - (C_a - P_b + K/(1+r)^T) > 0. \end{aligned}$$

If either branch is positive, an arbitrage opportunity exists. We norm deviations and compute

$$
\begin{aligned}
e_L &= \frac{S_b^* - S_a}{S_a} \\
e_S &= \frac{S_b - S_a^*}{S_b}
\end{aligned}
$$

where e_L (e_S) corresponds to proportional deviations in the strategy that buys (sells) stock.[2]

3 Data

We obtained tick data from iVolatility (ivolatility.com) for the period January 4, 2021 through February 28, 2021. Option trading was extremely heavy during this period, resulting in a dataset in excess of 1 terabyte. We applied a number of data screens. Given available data precise to the second, we retained only observations where all pairs were recorded as simultaneous. For example, if the stock traded at 10:02:40, only puts and calls with common strike and maturity that traded at 10:02:40 were included in the dataset. Observations were also deleted if: option price < 0.25, bid on the call $\geq$ ask on the underlying, if bid on put $\geq$ ask on the underlying, the transaction option price is outside of the bid-ask spread, and bid or ask < 0. Other

[2]Early empirical studies of put-call parity include those of Klemkosky and Resnick (1979) and Kamera and Miller (1995). Klemkosky and Resnick tused the inequality form of put-call parity for Ameican options (Merton, 1973). Their results were generally consistent with put-call parity. Kamera and Miller test PCP for European options on the S&P 500 index using daily and intraday time-stamped data. They found smaller and less frequent violations than those found in earlier studies using American options.

screens were applied to eliminate observations when implied volatility calculations failed. When time to expiration was zero days, American option values were assumed to be equal to European option values. Thus, implied volatilities used in estimating early exercise was only computed for observations with one or more days to maturity.

We summarize the total GME dataset in Table 1 and the GME PCP dataset in Table 2. Table 1 includes information on all tick-by-tick option trades on all US exchanges while Table 2 includes information on matched option trades in the PCP dataset. The number of call (put) observations recorded in Table 1 are 544,136 (347,237), 1,426,421 (2,103,643), and 654,826 (542,802) in the pre-squeeze, squeeze, and post-squeeze periods. Average maturities were 19.07 days for calls and 36.14 days for puts.

Put-call parity raw statistics are given in Table 2. Synchronous trades in the stock, put, and call contracts constitute one observation. There were 26,017, 136,076, and 22,826 observations during the pre-squeeze, squeeze, post-squeeze periods, respectively. The average maturity was 8.345 days, less than half that of the full dataset (19.07 days). Proportion bid-ask spreads for calls (puts) were 0.0606 (0.0690) for the full period. During the squeeze there was a fivefold increase in volume and the call (put) proportional spreads were marginally less at 0.0551 (0.0618).

4 Results

We first present results with frictions limited to bid-ask spreads. Frictions related to short sales are addressed later. We define errors for the short stock strategy as

$e_S = \frac{S_b - S_a^*}{S_b}$ and errors from the long stock strategy as $e_L = \frac{S_b^* - S_a}{S_a}$, where S is stock price and S^* is synthetic stock price. Subscripts a and b denote ask and bid prices. Positive errors indicate potential arbitrage opportunities.

Histograms for errors in the short and long stock branches of PCP are given in Figures 3 and 4. Histograms are notably different but not unexpected because of short sale frictions. The short stock branch is more are symmetric with error means near zero. The long stock branch is strongly negatively skewed with very few positive errors. Errors and percent violations during different periods are presented as bar graphs in Figure 5. Average errors are positive in pre-squeeze and squeeze periods for the short stock PCP strategy and negative for all periods under the long stock PCP strategy.

Detailed results for the pre-squeeze, squeeze, and post-squeeze periods are given in Table 3. Panel A shows statistics for the entire two-month period. Panels B, C, and D show statistics for the pre-squeeze, squeeze, and post-squeeze periods, respectively. For the 2-month period, PCP was violated ($e > 0$) for the short stock strategy on 48.72% of the 184,922 observations. For the same period and same number of observations, PCP was violated in 3.8% of the observations for the long stock strategy. The same pattern is observed in all squeeze periods. Violations for the short (long) strategy were 52.29% (1.81%), 53.11% (3.01%) and 18.48% (5.45%) in the pre-squeeze, squeeze, and post-squeeze periods, respectively. Violations for the short strategy were noticeably less in the post-squeeze period than other periods, however.

We also examine the mean level of errors ($\bar{e}$) and the mean level of violations.

The mean level of violations is the mean level of errors, given that $e > 0$ ($\bar{e}|e_i > 0$). For the short stock strategy, mean errors are positive in the pre- and squeeze periods and negative post-squeeze. Mean errors are negative for the long stock strategy in all periods. Mean violations are necessarily positive and slightly larger in the squeeze period.

The main takeaways are: 1) PCP violations are due primarily to short-selling frictions and 2) PCP violations in the pre-squeeze and squeeze periods were similar, but larger and much more frequent than in the post-squeeze period.

4.1 Errors by Moneyness and Maturity

Maturity and moneyness breakpoints were defined to give a balanced number of observations in each cell. The greatest number of observations were in maturities less than or equal to 10 days. Maturity categories were τ ϵ [0,2], (2,10], (10,45], and $(45, \theta 360]$ where τ is option maturity in days. We use call moneyness $\equiv \frac{S}{K}$ to define PCP moneyness. The moneyness categories are $\frac{S}{K}$ ϵ $[0, 0.80]$, $(80, 0.97]$, $(0.97, 1.03]$, $(1.03, 1.10]$, and (> 1.10). As structured, this means the high (low) call moneyness results in low (high) put moneyness and a PCP equation where option values are dominated by either the put or call. Puts and call contribute almost equally for at-the-money observations. Frequencies are given in Table 4. The squeeze period has the most observations and maturities between 2 and 10 days dominate the number of observations in that period.

Table 5 gives the percent of violations and the mean level of violations for the short stock PCP strategy. Rows and columns are not exhaustive (do not sum to

100%). For example, the 10.35% in Panel A (All data), maturity less than 2 days, and call moneyness $\leq$ 0.80 means that 10.35% of all observations in that cell were violations of PCP. The largest percent of violations, by far, occurred in long maturity options. For example, averaged over moneyness, there were violations in almost 90% of observations in the longest maturity. This holds for all data, pre-squeeze, and squeeze periods. The post-squeeze period (Panel D) had violations in about 55% of long maturity observations. The lowest percentage of violations was at the shortest maturity ($\leq$2 days) for all periods. With the exception of the post-squeeze period, violation percentages by moneyness did not vary in a consistent and remarkable way.

The mean level of *violations* followed the same pattern. That is, cells with a higher percentage of violations also had higher mean errors. Positive (negative) means signal apparent arbitrage (no-arbitrage) opportunities. Over all data (Panel A), mean errors were negative at the shortest maturity for all but the highest moneyness level. And all mean errors were positive at the two longest maturities. Errors at the longest maturity averaged about 6% (Panel A). Results for the pre-squeeze and squeeze periods (Panels B and C) were very similar to those in Panel A. The post- squeeze means were considerably different. Means were negative for all but two long maturity cells (Panel D).

Table 6 gives the percent of violations and the mean level of violations for the long stock PCP strategy. The percent of violations and size of violations is smaller for this strategy. The largest percentage of violations was 12.5% for the shortest maturity option in the squeeze period. Almost one third of cell entries for percent violations were zero in the three periods (Panels B, C, and D). And these were all in the longest two maturities. Mean *errors* tell the same story. Mean errors were negative for all periods except in two cells.

We summarize as follows: There were more frequent and larger arbitrage opportunities in the short PCP strategy and in long maturity options. It is not surprising that arbitrageurs would opt for short maturity options since the GME American options behave like European options at short maturities. Moneyness is not especially informative nor well defined in PCP strategies since the arbitrage position requires both puts and calls.

4.2 Mean Regressive PCP errors

Under PCP, deviations should move toward a negative equilibrium when spreads are non-zero. Define the change in PCP deviations as $de_t = e_t - e_{t-1}$. To study this aspect of market efficiency we propose a mean-regressive error process of the form:

$$de_t = \kappa(\theta - e_t)dt + \sigma dZ_t, \tag{2}$$

commonly referred to as the Ornstein-Uhlenbeck (1930) process (when $\theta = 0$) or, in the financial economics literature, as the Vasicek model (1977). The intuition is that errors move toward a long term mean θ. Innovations are introduced by the usual σdZ_t term, where Z_t is zero-mean Brownian motion.

If $e_t < \theta$, the drift component is negative and the change in the next instant tends to be negative, moving the process toward the long-term mean θ. A symmetric argument follows when $e_t > \theta$. The process is also referred to as an elastic random walk since the movement toward the mean is stronger when e_t is further displaced from θ. The speed of adjustment is faster with increasing κ and therefore movements toward no-arbitrage is relatively stronger for large κ. We transform κ to half-life time units to give a more intuitive interpretation of efficiency.

To estimate parameters, we Euler discretize the process so that

$$\begin{aligned} e_t - e_{t-1} &= \kappa(\theta - e_{t-1})dt_i + \epsilon_t \\ &= \gamma dt_i - \kappa e_{t-1} dt_i + \epsilon_t, \end{aligned} \tag{3}$$

where $\gamma = \kappa\theta$ and $dt_i = t_i - t_{i-1}$. The time increment is variable and differs from the usual construct $dt_i =$ constant. We use the Newy-West (1987) covariance matrix estimator to determine significance levels. The long term mean is estimated as $\hat{\theta} = \frac{\hat{\gamma}}{\hat{\kappa}}$. To form the dataset we sort contracts by time, maturity, and moneyness. All consecutive pairs of observations on the same contract are included in the dataset.

To determine half-life we express the solution to the diffusion equation (2) as

$$\begin{aligned} e_t &= e_0 e^{-\kappa t} + \theta\left(1 - e^{-\kappa t}\right) + \sigma e^{-\kappa t} \int_0^t e^{\kappa s} dZ(s), \\ E[e_t] &= \theta + e^{-\kappa t}\left(e_0 - \theta\right). \end{aligned}$$

We define the half-life as the time required to move to an expected displacement $E[e_t] - \theta = e^{-\kappa t}(e_0 - \theta)$ from $\frac{1}{2}$ of the current displacement, or

$$\begin{aligned} e^{-\kappa t}\left(e_0 - \theta\right) &= 0.5\left(e_0 - \theta\right), \\ t &= -\frac{\ln(0.5)}{\kappa}. \end{aligned}$$

Results are given in Table 7. Regression estimates are given in Panel A and half-life calculations in Panel B. For the short-sales strategy, the speed-of-adjustment estimate ($\kappa = 15.56$) is largest in the squeeze period. The half-life of excursions from the mean in this period is therefore shortest and equal to 1.0691 hours or 64.15 minutes. The estimate of the long term mean is positive for both the pre-squeeze and squeeze periods. Volume was higher and bid-ask spreads lower in the squeeze period. In the pre-squeeze, **squeeze** and post-squeeze periods volume was 25,235, **133,395**, 21,748 and bid-ask spreads were 0.0145, **0.0138**,0.024 for calls and 0.0198, **0.0154**, 0.0251 for puts. Presumably, larger volumes and tighter bid-ask spreads during the squeeze period led to faster convergence toward the long term mean.

For the long stock strategy, long term mean estimates were negative in each period, consistent with no-arbitrage. The shortest half-life for this strategy was in the post-squeeze period, anomalous to the results for the short stock strategy. The longest half-life for both strategies was in the pre-squeeze period.

5 Frictions in the PCP short stock strategy

Several short selling restrictions have been investigated in the literature but the most prominent are borrowing fees, rebate rates, failures to deliver, and the availability of shares to short. When shares are shorted, they must be borrowed (with some exceptions) and a fee paid to the lender. The short-seller may be paid a rate on cash collateral and the net of these two rates is the rebate rate. When fees are high on hard to deliver stocks, the net rebate may be negative. Stocks with negative rebate rates are said to be "on special."

Ofek, et al., (2004) use data from OptionMetrics and end-of-day prices to study PCP in US stocks trading between July 1999 and November 2001. They use proprietary data to compute the spread between the rebate rate for a stock and the "cold rate" for a majority of traded stocks. Using regressions, they show a significant relationship between a measure of PCP deviations and the rebate rate spread.

Evans, et al. (2009) study failures to deliver. For the retail buyer, shares must be located prior to the sale. Absent accounting missteps or operational difficulties, failures do not occur. Market makers, however, need not locate shares and may engage in naked shorting. Moreover, they may suffer little or no penalty when they fail to deliver. Evans, et al. find that market makers will not deliver when the rebate rate is negative. This possibility can attenuate the effect of high borrowing rates.

Why is not failure more costly for market makers? Boni (2006) focuses on strategic delivery and the role of the National Securities Clearing Corporation (NSCC), regulation SHO, and threshold securities. She provides evidence that many firms allow others to fail strategically "...because they are unwilling to earn a reputation for forcing delivery and hope to receive quid pro quo for their own strategic fails." Her findings support the argument that inability to strategically fail to deliver after regulation SHO will reduce liquidity and increase short-sale constraints.

We investigate these frictions using regressions and find support for the findings of Ofek, et al. with respect to PCP errors. Our data on fees, failure to deliver, and stock availability are from iBorrow (iborrowDesk.com) whose data is sourced from Interactive Brokers (IB). We use borrowing fees as a proxy for the rebate rate in our regressions since IB calculates the rebate rate as borrowing fees minus the Fed Funds Overnight rate. The Fed Funds rate is small and relatively constant for the squeeze periods.

Frictions are depicted in Figure 6. Borrowing fees are high (20 to 40 percent per annum) in the pre-squeeze period, highest in the squeeze period (up to 90 percent) and lowest in the post-squeeze period (about 1 percent). Fails to deliver are high during the pre-squeeze period and highest during the first part of the squeeze period. Share availability is typically high (1/availability near zero) except near the pre-squeeze and squeeze breakpoint. We conclude that frictions were impactful during pre-squeeze and squeeze periods and not remarkable during the post-squeeze period.

We test several models. One class of models is of the form

$$e_t = \alpha + \sum_{i=1}^{3} \beta_i f_{it} + \epsilon_t, \tag{4}$$

where e_t is the proportional price error (deviation) in PCP observation-t for the short stock strategy and f_i is a market friction. We expect that β_i coefficients will be positive since an increase in the friction should increase deviations. Frictions include daily fails-to-deliver, borrowing fees, and the inverse of available shares. We also look at a number of controls such as option volume, stock volume, call bid-ask spread, put bid-ask spread, moneyness, and time to expiration.

Results for the complete put-call dataset (184,921 observations) are given in Table 8. All frictions are significant and have positive coefficients. Moreover, we note that the intercept is negative and significant. The easy interpretation is that average deviations would be negative and consistent with no-arbitrage (on average) if these frictions were zero. That is $E[e|f_i = 0,\ i = 1,2,3] < 0$ A cautionary note is that $R^2 = 0.0384$. Though not a friction, we also include time-to-expiration in Model 3. The coefficient is positive, significant and increases R^2 to 0.1092. This result agrees with Evans et al. who find significant regression coefficients on time-to-maturity when regressed on an equivalent error measure. Presumably, this is because arbitrageurs are more active in short maturity option markets. We also provide regressions with controls and find consistency in sign and magnitude for fail-to-deliver, availability inverse and time-to expiration.

Regressions for the squeeze periods are given in Panels B, C, and D of Table 8. Results for Model 2 (with frictions regressors) are generally consistent. A notable exception is that intercepts are positive for the pre-squeeze period (Panel B). This suggests that arbitrage strategies would remain profitable on average pre-squeeze even when these frictions are accounted for. Frictions contribute as expected during the squeeze period. The intercept is negative and friction coefficients are positive and significant (Panel C). The post-squeeze period was least sensitive to frictions with $R^2 = 0.0045$ being the lowest among all periods. In a general sense we conclude that, given frictions, there was more non-equilibrium behavior in the pre-squeeze period and that frictions were uninformative post-squeeze.

5.1 Brokerage Trading Restrictions

Selected brokerages restricted stock buys and option trades on GameStop and heavily shorted stocks on Wednesday, January 27 and Thursday, January 28. Some margin requirements were also increased. BusinessWire (businesswire.com) reported that Interactive Brokerage restricted option trading on selected stocks, including GameStop, at mid-day on Wednesday. Charles Schwab and TD Ameritrade imposed margin restrictions on Thursday. Robinhood froze buys and restricted option trades on Thursday morning. According to the Robinhood CEO, restrictions were necessary due to increased collateral requirements imposed by the National Securities Clearing Corporation. Robinhood reported that their restrictions were eased on Friday, January 29[3]. We expect negative PCP and option pricing effects on Wednesday and Thursday, returning to normal levels on Friday.

A close examination of observations on Wednesday reveals large violations in both branches of PCP near mid-day. We aggregated data over 15 minute intervals. The average number of observations over these 15 minute periods (280) was lower than that for the day (338). On the short stock side, PCP was violated in 91.3 percent of the observations in the interval between 12:45 and 13:00 and in 92.4 percent of the observations in the interval between 13:00 and 13:15. The violation percentage for the day was 78.9. On the long stock side, PCP was violated in 2.73 percent of the observations between 12:15 and 12:30 and in 2.9 percent of the observations between 13:00 and 13:25. While low, these percentages are high relative to the percentage for the day (0.72 percent). In summary, there were fewer transactions and more violations of PCP on Wednesday. January 27 when restrictions were in place.

Robinhood and other app based brokerages either froze or restricted trading on Thursday morning. For the day, short stock PCP violations were lower than usual

[3]More detail on restrictions and their effect on market quality is provided by Jones, Reed, and Waller (2021).

(30.6 percent) and long stock violations were much higher than usual (11.6 percent). While the low number of violations for the short stock side of PCP is anomalous, the relatively high number of violations on the buy stock side is consistent with restrictions on stock buys. Volume was down. The total number of PCP observations was 8782 on January 27 and 3056 on January 28.

Violations were lower when restrictions were eased on Friday. Short (long) stock PCP violations were 23 (0.03) percent. The number of PCP observations remained low, however (2640). Put (call) average volatility was 7.95 (6.82) on Wednesday and 8.59 (8.51) on Thursday. When restrictions were eased on Friday, put (call) average implied volatility eased slightly to 6.04 (5.64). Jones et al. (2021) find similar numbers and suggest that option positions were used as substitutes for stock positions when stock trading was restricted. They used data from five minute intervals to compute realized volatility and note that option prices could be regarded as actuarially unfair since implied volatilities were much higher than realized volatility during periods of restricted traded. Furthermore, they suggest that overpriced options during restricted trading resulted in a transfer of wealth from retail to institutional participants.[4] Their arguments can be questioned on several fronts. First, implied volatilities are averages of forward volatilities over the life of the option. Volatilities computed over five minute intervals are akin to spot volatility measures and need not proxy for implied volatilities. Second, even though implied volatilities were higher during periods of restricted retail trading, they were elevated in days before trading

[4] Our GameStop dataset includes options all options while Jones et al do not include options with maturities less than 7 days. But these options constitute 77 percent of the 3384 options in our GameStop dataset on January 27, 28, and 29.

was restricted. For example, On January 21, GME implied put (call) volatility was 2.86 (2.47) jumping to 5.96 (5.41) on the next trading day (January 25). While implied volatilities were slightly higher on restricted trading days, one could argue that expectations of greater forward stock volatility was primarily responsible for the increase in IVs.

We prefer an alternative interpretation of market action that does not suggest mispricing nor transfer of wealth. Instead, we focus on the likelihood of a segmented market. We argue that, especially in the pre-squeeze and squeeze periods, risk averse investors with long positions bought puts for insurance while bearish participants bought puts as a substitute for shorting the stock. These investors sought long maturity puts while arbitrageurs were more active in short maturity (American) puts and calls. The result was relatively higher buying pressure for long term puts and thus the implied put-call volatility spread is positive and increases with maturity. Since arbitrageurs are operating in short maturities, we also expect that PCP errors are an increasing function of maturity. Our regressions are consistent with this argument.

5.2 Implied Volatility Effect On PCP

The overwhelming majority of PCP violations occurs in the short stock strategy and in long maturities. In this strategy, shares are sold, calls are bought, and puts are sold. We expect that PCP deviations will increase with increases in the volatility spread ($\delta = IV_{put} - IV_{call}$) as risk averse investors demand put insurance while bearish speculators demand put exposure. The result is that cash inflow from expensive puts increase relative to the cash outflow required to buy cheaper calls. Buying pressure arguments in the context of PCP have been documented by Bollen and Whaley (2004). Furthermore, arbitrageurs operate in short maturity options and should have less effect on long maturity buying pressures.

We do a direct test by regressing errors from the short stock PCP strategy (e_1) on the put-call volatility spread, frictions, and controls. The GameStop implied volatility dataset consists of 130,483 observations. The dataset for this regression is smaller since implied volatilities were not computed for PCP observations with expiring options (zero days to maturity). The model is

$$e_{1t} = \alpha + \beta\delta_t + \text{frictions}_t \ + \ \text{controls}_t \ + \ \epsilon_t. \tag{5}$$

Results in Table 9 are consistent with our hypothesis.. The βs are positive and significant at the 0.01 level for All Data and for all periods. The All Data β coefficient is 0.0154 and 0.0185, 0.0169, and 0.0095 for the pre-squeeze, squeeze, and post-squeeze periods, respectively. Other friction and control coefficients are similar in sign, significance and magnitude to those found in the larger dataset displayed in Table 8.

We also argue that the volatility spread should be an increasing function of time since the maturity domain of the buying pressure participants is relatively longer than that of arbitrageurs.. We test this proposition over all periods with the regression of the volatility spread on maturity,

$$\delta = \alpha + \beta\tau + \epsilon, \tag{6}$$

where τ is the time-to maturity. We expect that α and β will be positive. Results are given in Table 10. The intercept and slope coefficients are positive and significant at 0.01 for all periods. Slope coefficients were significant and largest in the squeeze period. The values for the pre-squeeze, squeeze and post-squeeze periods were 0.2360, 0.5818, and 0.3050, respectively.

To further document our findings we display volatility spreads by moneyness and maturity in Table 11. Average IV The IV spread and percentage IV spread are given side-by-side. In every case, the overall IV spread is positive, consistent with the regressions. Moreover, the IV spread over all periods increases with maturity, implying that cash flows and therefore violations from the short side of the PCP strategy increase with maturity. IV spread and percentage IV spread is largest during the squeeze period and smallest during the post-squeeze period. Anomalies are noted during the squeeze period and post-squeeze period for deep in-the-money calls (out-of-the money puts). In these periods IVs are not positively monotonic with maturity.

For completeness, we document implied volatilities and volatility spreads by moneyness and maturity in Tables 12 Implied volatilities decrease monotonically with maturity during all periods generally ranging from about 6 at the shortest maturity (one day) to about 1.5 at the longest maturity (45 to 360 days). There was no systematic variation noted over moneyness levels. The average volatility during the squeeze (post-squeeze) was 5.20 (5.18) for puts and the corresponding IVs for calls were 4.74 (4.90). Higher volatility in short maturities is consistent with participants substituting short maturity calls and puts for longs and shorts in the spot.

6 Conclusions

Despite the near hysteria during the GameStop short squeeze, the market generally operated rationally with respect to a no-arbitrage equilibrium. There did not appear to be an abundance of available "free money." While there were a significant number of no-arbitrage violations in the short sales side of the PCP equilibrium, these can be largely accounted for by proxies for market frictions, such as borrowing fees, stock availability, and failure to deliver. Because of frictions, PCP errors in the pre-squeeze period were similar to those found during the squeeze period. Errors were significantly smaller post-squeeze.

Taken as a whole, the evidence is consistent with market segmentation, also noted by Evans, et al. (2009). Put-call parity arbitrageurs prefer the short end of the maturity spectrum. The intuition is simple. When options are American, PCP prices are bounded but there is no longer an arbitrage relationship. But the difference between an American and European option is negligible when maturity is short. Other participants appear to have operated in the options market in a way that allowed prices to drift away from no-arbitrage values while frictions prevented their correction.

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Table 1: Description statistics of the original data

The data are tick-by-tick option trades across all exchanges on GME from January 4, 2021 to February 26, 2021. The pre-squeeze period refers to days from January 4 to January 21, the squeeze period from January 22 to February 10, and the post-squeeze period from February 11 to February 26. Moneyness is calculated as S/K. At-the-money options refers to options with moneyness between 0.97 and 1.03.

	Calls					Puts				
	Number of observations	Mean	Std. dev.	Min	Max	Number of observations	Mean	Std. dev.	Min	Max
Panel A: All data										
Option price ($)	2,625,383	26.33	48.79	0.01	475.00	2,993,682	11.83	30.99	0.01	2999.95
Trade size (contracts)	2,625,383	3.71	17.15	1.00	3400.00	2,993,682	4.16	19.27	1.00	9455.00
Maturity (days)	2,625,383	19.07	61.08	0.00	746.00	2,993,682	36.14	92.04	0.00	746.00
Moneyness	2,625,383	1.21	8.96	0.04	840.50	2,993,682	13.02	56.57	0.05	962.36
At-the-money option (%)	2,625,383	12.10%				2,993,682	6.10%			
Panel B: Pre-squeeze period										
Option price ($)	544,136	4.34	4.45	0.01	43.30	347,237	2.75	3.36	0.01	40.41
Trade size (contracts)	544,136	4.64	16.99	1.00	3400.00	347,237	4.84	28.10	1.00	9455.00
Maturity (days)	544,136	21.94	65.01	0.00	746.00	347,237	19.13	53.72	0.00	746.00
Moneyness	544,136	0.99	0.76	0.43	86.64	347,237	1.45	2.21	0.43	88.50
At-the-money option (%)	544,136	18.08%				347,237	14.14%			
Panel C: Squeeze period										
Option price ($)	1,426,421	40.17	61.04	0.01	475.00	2,103,643	13.48	32.74	0.01	2999.95
Trade size (contracts)	1,426,421	3.41	17.64	1.00	2700.00	2,103,643	4.05	18.00	1.00	4000.00
Maturity (days)	1,426,421	19.15	62.09	0.00	728.00	2,103,643	41.40	99.96	0.00	728.00
Moneyness	1,426,421	1.50	12.09	0.05	840.50	2,103,643	17.21	66.49	0.05	962.36
At-the-money option (%)	1,426,421	12.44%				2,103,643	5.51%			
Panel D: Post-squeeze period										
Option price ($)	654,826	14.46	21.21	0.01	170.00	542,802	11.28	32.75	0.01	875.00
Trade size (contracts)	654,826	3.61	16.14	1.00	2000.00	542,802	4.17	16.96	1.00	2174.00
Maturity (days)	654,826	16.53	55.08	0.00	708.00	542,802	26.64	75.95	0.00	708.00
Moneyness	654,826	0.75	1.46	0.04	303.22	542,802	4.19	16.81	0.05	367.38
At-the-money option (%)	654,826	6.40%				542,802	3.22%			

Table 2: Description statistics of matched sample

Data are matched pairs of calls and puts with the same expiration and strike price trading at the same time. Moneyness is calculated as S/K. The relative bid-ask spread is calculated as $\frac{P_{ask}-P_{bid}}{0.5(P_{ask}+P_{bid})}$. Pre-squeeze, squeeze, and post-squeeze periods refer to trades between January 4 and January 21, January 22 and February 10, and February 11 and February 26, resp.

	Number of observations	Mean	Std. dev.	Min	Max
Panel A: All data					
Moneyness	184,922	1.1997	1.4472	0.0735	365.7950
Maturity (days)	184,922	8.3367	32.2663	0.0000	737.0000
At-the-money option (%)	184,922	26.33%			
Relative bid-ask spread for calls	184,922	0.0606	0.0766	0.0000	1.9998
Relative bid-ask spread for puts	184,922	0.0690	0.0974	0.0000	1.9980
Panel B: Pre-squeeze period					
Moneyness	26,017	1.0506	0.2118	0.5857	9.5000
Maturity (days)	26,017	10.0229	34.7268	0.0000	737.0000
At-the-money option (%)	26,017	30.78%			
Relative bid-ask spread for calls	26,017	0.0582	0.0594	0.0000	1.0201
Relative bid-ask spread for puts	26,017	0.0794	0.1040	0.0000	1.9344
Panel C: Squeeze period					
Moneyness	136,076	1.2306	1.6625	0.0882	365.7950
Maturity (days)	136,076	8.5974	33.7144	0.0000	728.0000
At-the-money option (%)	136,076	25.59%			
Relative bid-ask spread for calls	136,076	0.0551	0.0735	0.0000	1.9998
Relative bid-ask spread for puts	136,076	0.0618	0.0873	0.0000	1.9841
Panel D: Post-squeeze period					
Moneyness	22,829	1.1855	0.6388	0.0735	42.6900
Maturity (days)	22,829	4.8609	16.3740	0.0000	697.0000
At-the-money option (%)	22,829	25.68%			
Relative bid-ask spread for calls	22,829	0.0964	0.0992	0.0000	1.9996
Relative bid-ask spread for puts	22,829	0.1003	0.1334	0.0000	1.9980

Table 3: Put-call parity before, during, and after the short squeeze

Violation metrics from put-call parity. When the stock is shorted, the error is calculated as $e_S = \frac{S-S^*}{S}$, where *S* is the price of GME, *S** is the synthetic stock price calculated as $S^* = C - P + \frac{K}{(1+r)^T}$, *C* (*P*) is the traded call (put) price, *K* the strike price, *r* the risk free rate, and *T* is time-to-maturity. Corresponding PCP metrics are calculated when the stock is bought. All buys (sells) for the stock are assumed to be at the ask (bid) price. American option prices are converted to European option prices by estimating early exercise premium by a binomial tree assuming prices are geometric Brownian motion.

	Stock Shorted	Stock Bought
Panel A: All data		
Number of observations	184,922	184,922
Violations	48.72%	3.80%
Mean errors	0.0026	-0.0071
Mean violation	0.0186	0.0071
Maximum violation	0.5087	0.2180
Panel B: Pre-squeeze period		
Number of observations	26,017	26,017
Violations	52.29%	1.81%
Mean errors	0.0021	-0.0214
Mean violation	0.0120	0.0029
Maximum violation	0.2494	0.0235
Panel C: Squeeze period		
Number of observations	136,076	136,076
Violations	53.11%	3.91%
Mean errors	0.0048	-0.0294
Mean violation	0.0207	0.0084
Maximum violation	0.5087	0.3474
Panel D: Post-squeeze period		
Number of observations	22,829	22,829
Violations	18.48%	5.45%
Mean errors	-0.0103	-0.0214
Mean violation	0.0108	0.0034
Maximum violation	0.2261	0.0745

Table 4: Number of observations by moneyness and maturity

Moneyness is calculated as S/K. Moneyness category 1 refers to moneyness less than 0.80, category 2 denotes moneyness between 0.80 and 0.97, category 3 denotes moneyness between 0,97 and 1.03, category 4 denotes moneyness between 1.03 and 1.10, and category 5 denotes moneyness greater than or equal to 1.10.

	Moneyness category				
Maturity	1	2	3	4	5
All data					
Less than 2 days	2,590	8,047	10,219	6,850	14,315
2 to 10 days	6,127	11,191	17,035	11,614	25,298
11 to 45 days	1,854	2,270	2,185	1,655	7,061
46 to 360 days	639	804	490	434	2,752
Pre-squeeze period					
Less than 2 days	170	3,000	5,098	3,624	3,795
2 to 10 days	172	1,146	1,855	958	1,302
11 to 45 days	289	711	314	193	614
46 to 360 days	291	527	61	35	176
Squeeze period					
Less than 2 days	1,658	2,909	2,614	2,065	6,405
2 to 10 days	5,558	9,079	13,860	10,091	22,946
11 to 45 days	1,324	1,286	1,598	1,334	5,644
46 to 360 days	307	220	382	383	2,368
Post-squeeze period					
Less than 2 days	762	2,138	2,507	1,161	4,115
2 to 10 days	397	966	1,320	565	1,050
11 to 45 days	241	273	273	128	803
46 to 360 days	41	57	47	16	208

Table 5: Put-call parity violations in the short stock branch by moneyness and maturity

Moneyness is calculated as S/K. Category 1 refers to moneyness less than 0.80, category 2 to moneyness between 0.80 and 0.97, category 3 between 0.97 and 1.03, category 4 between 1.03 and 1.10, and category 5 greater than or equal to 1.10.

	Percent of violations					Mean violation				
	1	2	3	4	5	1	2	3	4	5
Full Time Period										
Less than 2 days	10.35%	21.73%	32.00%	46.70%	45.62%	0.0041	0.0054	0.0050	0.0063	0.0228
2 to 10 days	42.42%	51.89%	73.60%	80.75%	73.33%	0.0110	0.0114	0.0138	0.0157	0.0168
11 to 45 days	76.70%	79.52%	89.38%	90.76%	80.82%	0.0251	0.0261	0.0306	0.0375	0.0314
46 to 360 days	81.53%	88.18%	97.14%	96.31%	86.48%	0.0782	0.0580	0.0784	0.0973	0.0591
Pre-squeeze period										
Less than 2 days	41.18%	38.70%	45.49%	54.83%	44.85%	0.0064	0.0055	0.0050	0.0056	0.0068
2 to 10 days	54.65%	60.03%	65.71%	72.44%	54.53%	0.0063	0.0053	0.0050	0.0064	0.0080
11 to 45 days	87.20%	86.08%	87.90%	89.12%	78.34%	0.0226	0.0221	0.0228	0.0201	0.0197
46 to 360 days	87.97%	86.15%	98.36%	85.71%	94.32%	0.0493	0.0500	0.0472	0.0445	0.0379
Squeeze period										
Less than 2 days	7.24%	16.19%	26.70%	47.51%	58.86%	0.0040	0.0059	0.0060	0.0081	0.0315
2 to 10 days	43.16%	54.80%	79.32%	84.46%	76.21%	0.0114	0.0125	0.0151	0.0167	0.0172
11 to 45 days	79.46%	84.91%	94.49%	95.28%	85.99%	0.0265	0.0299	0.0346	0.0409	0.0337
46 to 360 days	81.11%	98.64%	99.48%	98.69%	90.33%	0.1113	0.0823	0.0886	0.1031	0.0619
Post-squeeze period										
Less than 2 days	10.24%	5.47%	10.09%	19.90%	25.71%	0.0023	0.0028	0.0024	0.0050	0.0177
2 to 10 days	26.70%	14.91%	24.62%	28.50%	33.90%	0.0048	0.0034	0.0040	0.0047	0.0139
11 to 45 days	48.96%	37.00%	61.17%	46.09%	46.45%	0.0172	0.0090	0.0081	0.0131	0.0163
46 to 360 days	39.02%	66.67%	76.60%	62.50%	36.06%	0.0263	0.0153	0.0224	0.0330	0.0273

Table 6: Put-call parity violations of the long stock branch by moneyness and maturity

Moneyness is calculated as S/K. Category 1 refers to moneyness less than 0.80, category 2refers to moneyness between 0.80 and 0.97, category 3 denotes moneyness between 0.97 and 1.03, category 4 denotes moneyness between 1.03 and 1.10, and category 5 denotes moneyness greater than or equal to 1.10.

	Percent of violations					Mean violation				
	1	2	3	4	5	1	2	3	4	5
All data										
Less than 2 days	11.27%	5.70%	2.24%	1.77%	3.33%	0.0379	0.0046	0.0045	0.0079	0.0073
2 to 10 days	2.58%	2.42%	0.50%	0.22%	0.90%	0.0164	0.0152	0.0076	0.0079	0.0210
11 to 45 days	0.11%	0.18%	0.09%	0.00%	0.35%	0.0088	0.0234	0.0079	N/A	0.0144
46 to 360 days	0.16%	0.00%	0.00%	0.00%	0.25%	0.0021	N/A	N/A	N/A	0.0159
Pre-squeeze period										
Less than 2 days	1.18%	3.57%	1.16%	1.08%	2.27%	0.0048	0.0053	0.0018	0.0019	0.0037
2 to 10 days	2.33%	0.35%	0.11%	0.31%	0.31%	0.0025	0.0063	0.0037	0.0013	0.0078
11 to 45 days	0.00%	0.00%	0.00%	0.00%	0.16%	N/A	N/A	N/A	N/A	0.0002
46 to 360 days	0.00%	0.00%	0.00%	0.00%	0.00%	N/A	N/A	N/A	N/A	N/A
Squeeze period										
Less than 2 days	12.85%	5.16%	2.60%	1.94%	3.12%	0.0509	0.0061	0.0103	0.0192	0.0106
2 to 10 days	2.57%	2.65%	0.40%	0.21%	0.94%	0.0175	0.0168	0.0087	0.0092	0.0219
11 to 45 days	0.00%	0.31%	0.00%	0.00%	0.30%	N/A	0.0234	N/A	N/A	0.0171
46 to 360 days	0.00%	0.00%	0.00%	0.00%	0.17%	N/A	N/A	N/A	N/A	0.0199
Post-squeeze period										
Less than 2 days	10.10%	9.45%	4.07%	3.62%	4.64%	0.0027	0.0030	0.0022	0.0027	0.0054
2 to 10 days	2.77%	2.69%	2.05%	0.18%	0.76%	0.0065	0.0012	0.0056	0.0015	0.0025
11 to 45 days	0.83%	0.00%	0.73%	0.00%	0.87%	0.0088	N/A	0.0079	N/A	0.0097
46 to 360 days	2.44%	0.00%	0.00%	0.00%	1.44%	0.0021	N/A	N/A	N/A	0.0106

Table 7: Speed of adjustment

The speed of adjustment and long term means are estimated by the regression: $d\pi_t = \kappa\theta dt - \kappa\pi_{t-1}dt + \varepsilon_t$, where π_t is a change in error: $d\pi_t = \pi_{t-1} - \pi_{t-1}$, κ is the speed of adjustment, and θ is the long-term mean of π . Standard errors are reported in parenthesis. *** refers to significance at the 0.01 level. The half-life $t_{1/2}$ is calculated as $t_{1,2} = \frac{\ln(2)}{\kappa}$.

Panel A: Regression results

	Error 1			Error 2		
	Pre-squeeze	Squeeze	Post-squeeze	Pre-squeeze	Squeeze	Post-squeeze
κ (day^{-1})	5.428***	15.56***	6.861***	3.148***	4.666***	9.233***
	(0.129)	(0.169)	(0.179)	(0.073)	(0.075)	(0.209)
κ θ (day^{-1})	-0.054***	-0.055***	0.075***	0.041***	0.183***	0.185***
	(0.004)	(0.008)	(0.007)	(0.004)	(0.006)	(0.009)
Adj R-squared	0.076	0.060	0.066	0.089	0.029	0.084
Number of observations	25,235	133,395	21,748	25,235	133,395	21,748

Panel B: Speed of adjustment, long-term mean, and half-life

	Error 1			Error 2		
	Pre-squeeze	Squeeze	Post-squeeze	Pre-squeeze	Squeeze	Post-squeeze
κ ($hours^{-1}$)	0.2262	0.6483	0.2859	0.1312	0.1944	0.3847
θ	0.0099	0.0035	-0.0109	-0.0130	-0.0392	-0.0200
Half-life (hours)	3.0648	1.0691	2.4247	5.2845	3.5653	1.8017

Table 8: Regressions of the Error (e_s) on market frictions using the full dataset

	Model 1	Model 2	Model 3	Model 4	Model 1	Model 2	Model 3	Model 4
	Panel A: All dataset				Panel B: Pre-squeeze period			
Constant	0.0026***	-0.0088***	-0.0114***	0.0055***	0.0021***	0.0065***	0.0033***	0.0042***
Fail-to-deliver (million shares)		0.0096***	0.0095***	0.0098***		0.0073***	0.0051***	0.0018***
Fee		0.0039***	0.0029***	-0.0015***		-0.0397***	-0.0301***	0.0283***
1/Available shares		20.19***	20.17***	22.17***		111.54**	-123.79***	77.18***
Expiration (days)			0.0004***	0.0004***			0.0003***	0.0003***
At-the-money				-0.0003***				-0.0006***
Call spread				-0.1227***				-0.0742***
Put spread				-0.0299***				-0.0414***
Option volume (million shares)				0.0039***				-0.0477***
Stock volume (million shares)				-0.0001***				0.0003***
R-square	*0*	*0.0384*	*0.1297*	*0.2081*	0	*0.0120*	*0.4348*	*0.6082*
Number of observations	184,921	184,921	184,921	184,921	26,017	26,017	26,017	26,017
	Panel C: Squeeze period				Panel D: Post-squeeze period			
Constant	0.0048***	-0.0077***	-0.0108***	0.0142***	-0.0103***	-0.0116***	-0.0118***	0.0015
Fail-to-deliver (million shares)		0.0094***	0.0095***	0.0199***		-0.0028	-0.0051*	-0.0730***
Fee		0.0026***	0.0021***	-0.00003		-0.0460***	-0.0391***	0.0560***
1/Available shares		18.71***	19.36***	66.14***		4683***	4168***	-12120***
Expiration (days)			0.0004***	0.0004***			0.0001***	0.0001***
At-the-money				-0.0006***				0.0020***
Call spread				-0.1445***				-0.0606***
Put spread				-0.0328***				-0.0241***
Option volume (million shares)				0.0042***				0.0350***
Stock volume (million shares)				-0.0003***				-0.0001***
R-squared	*0*	*0.0262*	*0.1114*	*0.1963*	0	*0.0045*	*0.0116*	*0.1362*
Number of observations	136,076	136,076	136,076	136,076	22,828	22,828	22,828	22,828

Table 9: Regressions of the Error 1 on market frictions using the dataset without options with zero days to expiration

The IV difference is calculated as $IV\ dif = IV_{put} - IV_{call}$

	Model 1	Model 2	Model 3	Model 4	Model 1	Model 2	Model 3	Model 4
	Panel A: All dataset				Panel B: Pre-squeeze period			
Constant	0.0056***	-0.0074***	-0.0114***	0.0089***	0.0028***	-0.0040***	-0.0031***	0.0054***
Fail-to-deliver (million)		0.0086***	0.0091***	0.0057***		0.0065***	0.0042***	0.0002
Fee		0.0035***	0.0024***	-0.0036**		0.0045	-0.0033	0.0150**
1/Available shares		52.48***	47.21***	38.38***		180.12***	-134.66***	-5.8647
Expiration (days)			0.0004***	0.0005***			0.0004***	0.0004***
At-the-money				0.0010***				0.0001
Call spread				-0.2128***				-0.0911***
Put spread				-0.0492***				-0.0442***
Option volume (million)				-0.0009***				-0.0283***
Stock volume (million)				-0.00005***				0.0001***
IV difference				0.0154***				0.0185***
R-square	*0*	*0.0560*	*0.1597*	*0.3275*	*0*	*0.0076*	*0.5194*	*0.7402*
Number of observations	130,483	130,483	130,483	130,483	24,162	24,162	24,162	24,162
	Panel C: Squeeze period				Panel D: Post-squeeze period			
Constant	0.0093***	-0.0051***	-0.0104***	0.0099***	-0.0104***	-0.0097***	-0.0098***	0.0080***
Fail-to-deliver (million)		0.0081***	0.0088***	0.0076**		-0.0277***	-0.02808***	-0.0174***
Fee		0.0009	0.0007	-0.0014		0.0564***	0.0560***	0.0542**
1/Available shares		49.35***	45.05***	45.17***		1285.0	552.9	-3491.7
Expiration (days)			0.0005***	0.0005***			0.0001***	0.0002***
At-the-money				0.0008**				0.0006***
Call spread				-0.2488***				-0.1262***
Put spread				-0.0841***				-0.0365***
Option volume (million)				0.0010				-0.0050*
Stock volume (million)				-0.0001***				-0.00002*
IV difference				0.0169***				0.0095***
R-squared	*0*	*0.0378*	*0.1340*	*0.3119*	*0*	0.018	*0.0261*	*0.3821*
Number of observations	89,898	89,898	89,898	89,898	16,423	16,423	16,423	16,423

Table 10. Regression of difference of put and call implied volatilities on time to maturity

The volatility difference is calculated as $\delta = IV_{put} - IV_{call}$

	All Data	Pre-Squeeze	Squeeze	Post Squeeze
Constant	0.3492	0.2150	0.4224	0.1559
	(<0.0001)	(<0.0001)	(<0.0001)	(<0.0001)
Time to maturity (days)	0.5264	0.2360	0.5818	0.3050
	(<0.0001)	(<0.0001)	(<0.0001)	(0.0010)
R-squared	0.010	0.017	0.013	0.001
Number of observations	130,484	24,162	89,898	16,424

Table 11: Differences in implied volatilities between puts and calls

The spread in volatilities is calculated as $\delta = IV_{put} - IV_{call}$, where IV_{call} and IV_{put} are average implied volatilities of calls and puts. The percentage IV spread is calculated as $\frac{(IV_{put} - IV_{call})}{\left(\frac{IV_{put}+IV_{call}}{2}\right)} * 100\%$.

	Calls All	1	2	3	4	5	Puts All	1	2	3	4	5
All data												
1 to 360 days	0.3836						13.38%					
1 day		-0.1916	0.0817	0.1267	0.2109	0.7569		-2.81%	1.75%	2.94%	4.43%	10.92%
2 to 10 days		0.26	0.2662	0.3175	0.3845	0.5538		4.74%	5.58%	7.53%	8.91%	11.35%
11 to 45 days		0.3135	0.3162	0.3642	0.4637	0.6203		9.89%	11.13%	13.18%	15.53%	19.93%
46 to 360 days		0.46	0.363	0.5235	0.6722	0.8094		25.50%	21.85%	26.80%	30.69%	37.86%
Pre-squeeze												
1 to 360 days	0.2538						13.76%					
1 day		0.3018	0.1776	0.1707	0.2277	0.314		8.27%	4.90%	5.06%	6.57%	8.58%
2 to 10 days		0.2068	0.175	0.1621	0.1985	0.2602		6.84%	6.49%	6.30%	8.18%	10.87%
11 to 45 days		0.2393	0.2192	0.233	0.2444	0.3058		14.86%	13.35%	14.54%	15.68%	20.53%
46 to 360 days		0.2799	0.293	0.3084	0.3159	0.4437		21.55%	20.05%	22.72%	23.92%	35.89%
Squeeze												
1 to 360 days	0.4398						14.33%					
1 day		-0.3224	0.0553	0.1277	0.2382	0.9248		-4.85%	0.99%	2.15%	3.65%	10.94%
2 to 10 days		0.2713	0.2997	0.3614	0.4183	0.5806		4.80%	5.73%	7.89%	9.11%	11.47%
11 to 45 days		0.3532	0.4064	0.4271	0.5247	0.6969		10.15%	11.79%	14.71%	16.67%	21.37%
46 to 360 days		0.6683	0.5593	0.5914	0.7215	0.8924		29.92%	27.56%	29.37%	31.89%	41.33%
Post-squeeze												
1 to 360 days	0.1780						5.58%					
1 day		-0.0097	-0.0168	0.0362	0.1098	0.5705		-0.97%	-1.68%	3.62%	10.98%	57.05%
2 to 10 days		0.1251	0.059	0.0745	0.0952	0.3526		12.51%	5.90%	7.45%	9.52%	35.26%
11 to 45 days		0.1854	0.1435	0.1466	0.1593	0.3216		18.54%	14.35%	14.66%	15.93%	32.16%
46 to 360 days		0.1788	0.2532	0.2508	0.271	0.254		17.88%	25.32%	25.08%	27.10%	25.40%

Table 12: Average volatilities for calls and puts by moneyness and maturity

Average implied volatilities by moneyness and maturity. Moneyness is calculated as S/K for both calls and puts. Moneyness category 1 refers to moneyness less than 0.80, category 2 refers to moneyness between 0.80 and 0.97, category 3 refers to moneyness between 0,97 and 1.03, category 4 refers to moneyness between 1.03 and 1.10, and category 5 refers to moneyness greater or equal to 1.10.

	Moneyness category											
	All	1	2	3	4	5	All	1	2	3	4	5
	Calls						Puts					
All data												
1 to 360 days	4.4193						4.8213					
1 day		6.9092	4.6371	4.2461	4.6546	6.5536		6.7176	4.7188	4.3728	4.8655	7.3105
2 to 10 days		5.3591	4.6409	4.0594	4.1231	4.6022		5.619	4.907	4.3769	4.5076	5.156
11 to 45 days		3.0124	2.683	2.5809	2.7548	2.8022		3.3259	2.9992	2.9451	3.2186	3.4224
46 to 360 days		1.574	1.48	1.6913	1.854	1.7332		2.034	1.8431	2.2148	2.5261	2.5426
Pre-squeeze												
1 to 360 days	2.9102						3.1342					
1 day		3.4988	3.5358	3.2852	3.3528	3.5037		3.8006	3.7134	3.4559	3.5806	3.8177
2 to 10 days		2.9187	2.6082	2.4921	2.3262	2.2639		3.1255	2.7833	2.6542	2.5247	2.5241
11 to 45 days		1.4908	1.5319	1.4862	1.4371	1.3367		1.7302	1.7511	1.7192	1.6815	1.6425
46 to 360 days		1.1588	1.3146	1.2028	1.1624	1.0144		1.4387	1.6076	1.5112	1.4783	1.4582
Squeeze												
1 to 360 days	4.7367						5.2007					
1 day		6.8106	5.556	5.8665	6.4102	7.9904		6.4882	5.6113	5.9942	6.6484	8.9151
2 to 10 days		5.512	5.0778	4.3974	4.3814	4.7731		5.7832	5.3775	4.7588	4.7997	5.3537
11 to 45 days		3.3046	3.2445	2.6896	2.8849	2.9124		3.6578	3.651	3.1167	3.4096	3.6094
46 to 360 days		1.8994	1.7496	1.7182	1.9015	1.713		2.5677	2.3088	2.3096	2.623	2.6054
Post-squeeze												
1 to 360 days	4.9017						5.1824					
1 day		7.8845	4.932	4.5106	5.5954	7.4637		7.8748	4.9152	4.5467	5.7053	8.0342
2 to 10 days		4.2757	2.9459	2.7132	2.557	3.7462		4.4008	3.0049	2.7877	2.6523	4.0989
11 to 45 days		3.2318	3.0362	3.2037	3.3855	3.1478		3.4172	3.1796	3.3502	3.5448	3.4695
46 to 360 days		2.0842	1.9693	2.1073	2.229	2.4915		2.263	2.2225	2.3582	2.4999	2.7455

Figure 1: Stock volume and stock price before, during and after the short squeeze

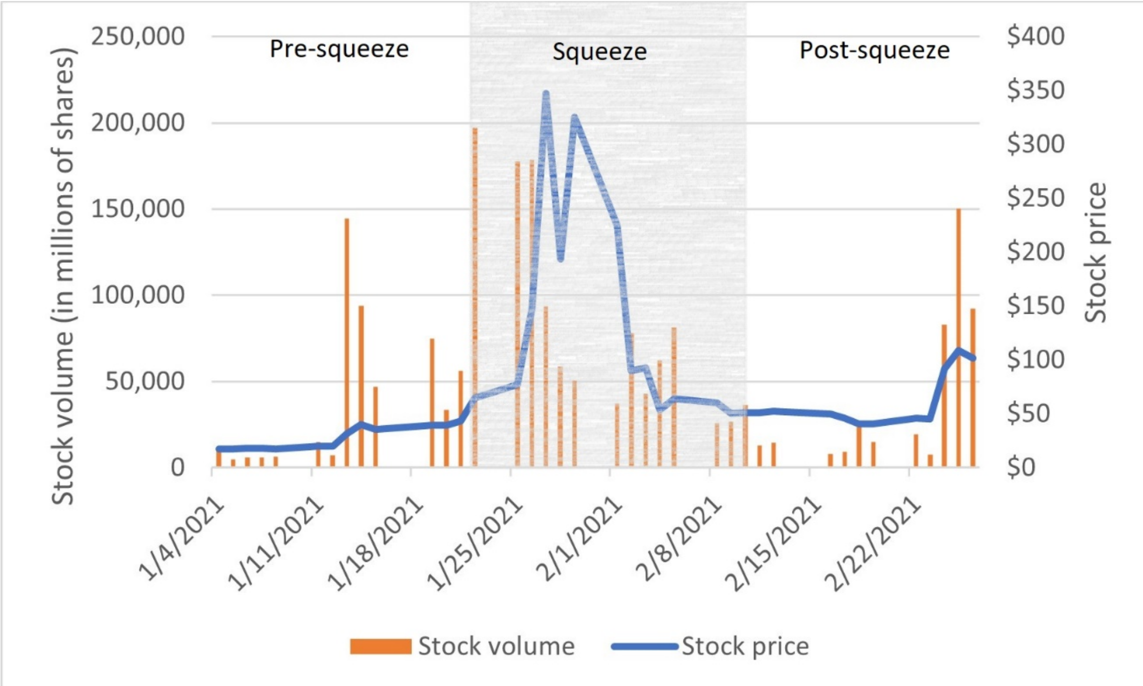

Figure 2: Option volume and stock price before, during and after the short squeeze

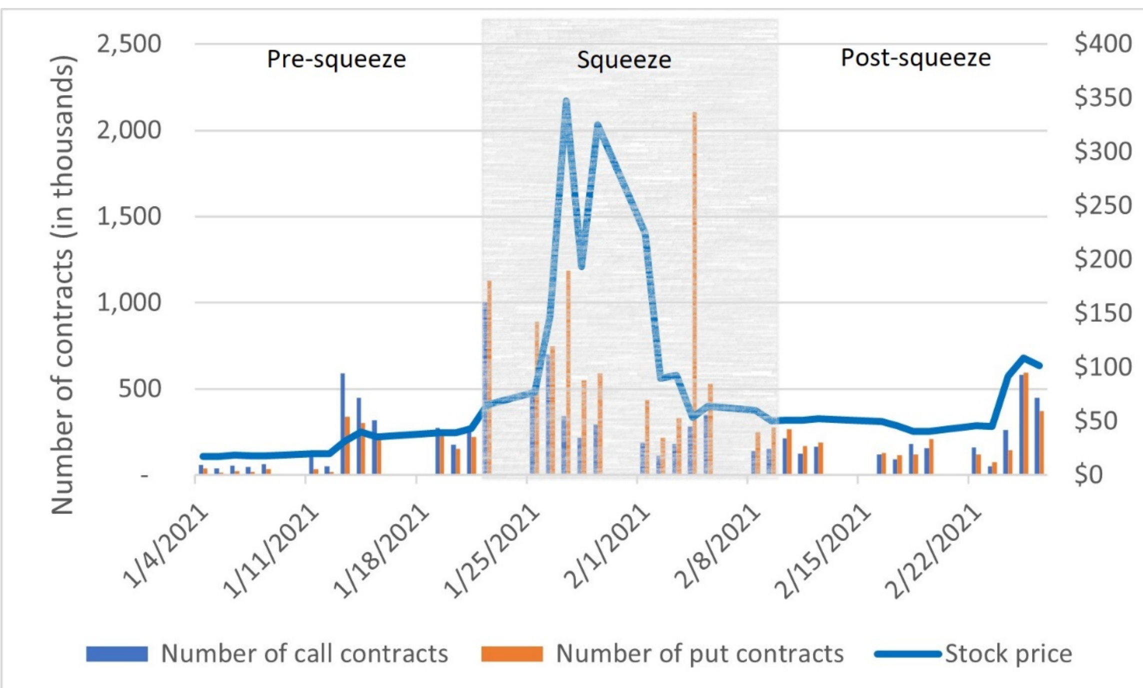

Figure 3: Histogram of PCP Error (e_S), shares shorted

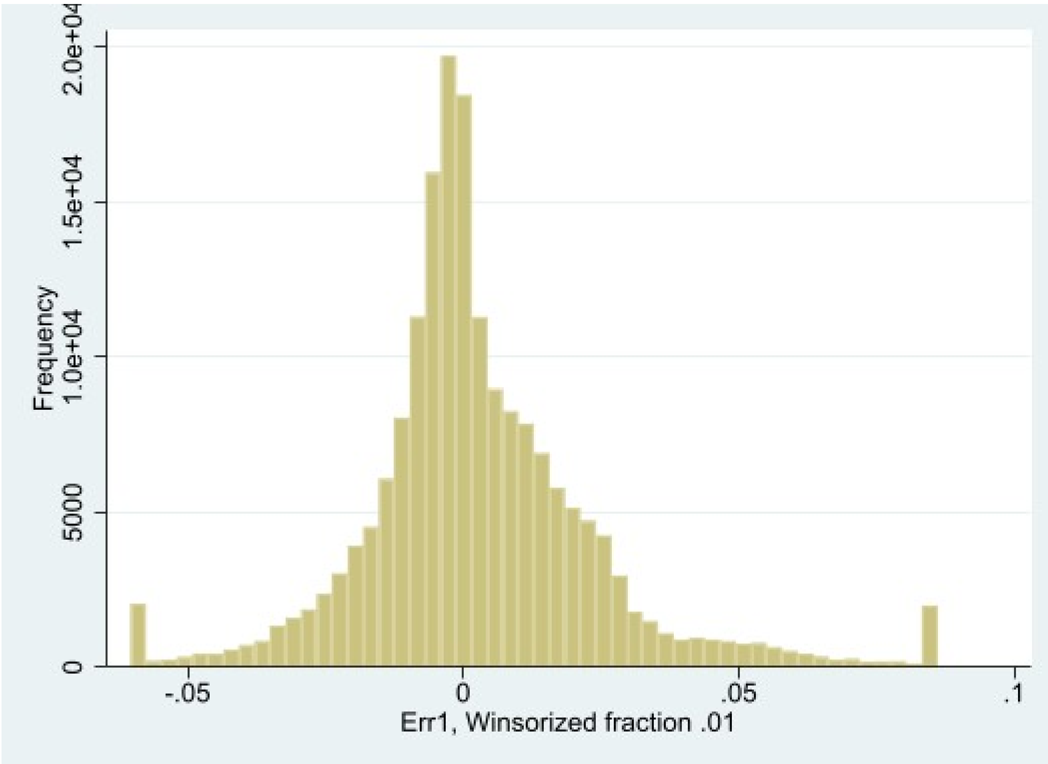

Figure 4: Histogram of PCP Error (e_L), shares bought

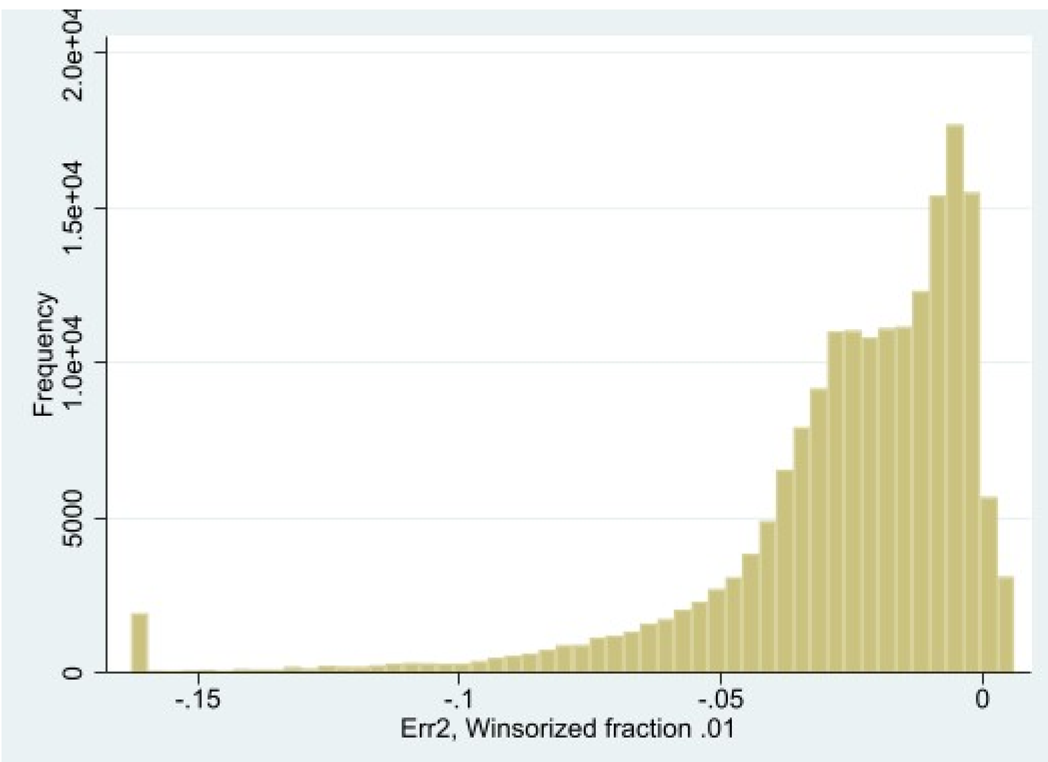

Figure 5: Market frictions before, during and after the short squeeze