Real-Time Implied Volatility Surfaces:

A Practitioner's View of the Black Arts

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Introduction

- The listed options market has grown dramatically over the last two decades.
  - In US alone: circa 1,600,000 options on 5,600 underliers (OPRA, Oct 2023)
  - SPX has about 20,000 options (calls and puts) and about 60 expiries these days!
  - Daily ODTEs, retail trading, meme stocks and many other new market “features”...
- Prop shops and hedge funds are much more important players now. OTC flow and exotics markets can’t ignore the listed (vanilla) market (but still try?).
  - Prop shops trade autocallables & hedge funds have HFT teams !?
- Vanilla valuation is complicated due to divs, borrow costs, rate term-structure, events, settlement details, Berm/Amer, vol-time, and “funky” vol curve shapes.
  - American “vanillas” are really path-dependent exotics — getting EEP right is hard!

Introduction (cont'd)

- These problems are hard at any time scale — but especially if all possible corner cases have to be handled in real time!
- The two main threads of this talk are:
  a. The listed options market has become very "sophisticated and opinionated". It contains a lot of useful information.
  b. The many modeling and algorithmic details one has to get right to create and maintain a large-scale, real-time valuation & risk (+ margin, PnL decomp, etc) infrastructure.
- Can only give a flavor of the myriad of details one has to deal with…
  but it's a 2-day conference and I have a lot of (extra) slides we can discuss.

Implied Vol Surfaces

- Implied volatility surfaces & borrow/forward curves are the standard approach to summarizing the vanilla options market in an intuitive and compact manner.
- They provide the fundamental building block for the trading of vanillas (listed and OTC), as well as flow derivatives and exotics.
- There are many quant problems facing options and derivatives trading desks, and the problem of constructing sensible, arbitrage-free volatility surfaces from options market prices (bids and asks) is one of the hardest.
- This issue already exist for European-style options (SPX, VIX, SX5E, DAX, etc).

Implied Vols and (American) Pricing

- For European options (without divs) only integrated rates and variances matter.
  - Cash dividend modeling is relatively minor issue for Euro options (unless stochastic divs...).
- But American options are really path-dependent exotics and a lot of extra complications arise (esp. for ETFs, stocks, esp. with dividends):
  - Need to choose proper cash dividend and borrow cost modeling. Then:
  - Even in BS: Rate term-structure, proper choice of "vol time" (including events), and details like settlement, Bermudan vs American all significantly affect early exercise premia (EEP).
  - Beyond BS: Local vol? Stochastic LV? (Look at volga, vanna...)
  - Approxs/hacks to adjust ITM relative to OTM vol to still price call & put of same strike in BSM.
- There are subtleties in "De-Americanization" (see above and at the end...), but if in doubt think of "implied vol surfaces" as summarizing European options prices in a convenient and intuitive manner (whether they are listed/traded or not).

Vol Curve/Surface Parametrizations

- There are advantages to having a good vol curve parametrization (by strike).
- For current purposes all we have to know is:
  - There are various curves in the public domain, e.g. **S* curves**:
    1. SVI / S5 (5 params per term)
    2. SSVI / S3 (3 params per term)
    3. SABR (3 params per term; name is overloaded: model and curve...)
  - The S* curves do not have much shape flexibility, e.g. they do not allow W-shapes as required around events.
  - Hence there are many proprietary curves out there... Vola has **C* curves**.
  - First 3 params: vol0 (=ATF vol) and s2, c2 (dimensionless slope & curvature...).

Other Inputs for Pricing: Forwards, Rates, Divs

- To price European options of any expiry and payoff we need:
  - A discount rate curve: Term rates r(T)
  - A forward curve: F(T) (also divs in some models of pricing Euros…)
  - An implied vol surface (IVS aka VS).
- Convenient to think of the **forward curve** in terms of **rates** and **divs** (0 if Fut, FX)
  - In the **American** case, the **rates are primary**, i.e. needed for proper EEP calculation.
  - The forward grows with the "drift" between divs, and jumps down by the div amount at ex-div dates. "drift" = fundingRate – borrowRate = b – q:

$$F_T = f_p(T)\left(S_0 - \sum_{i:t_i \le T} \frac{d_i}{f_p(t_i)}\right) \qquad f_p(t) := \exp\left(\int_0^t (b(t') - q(t'))\, dt'\right)$$

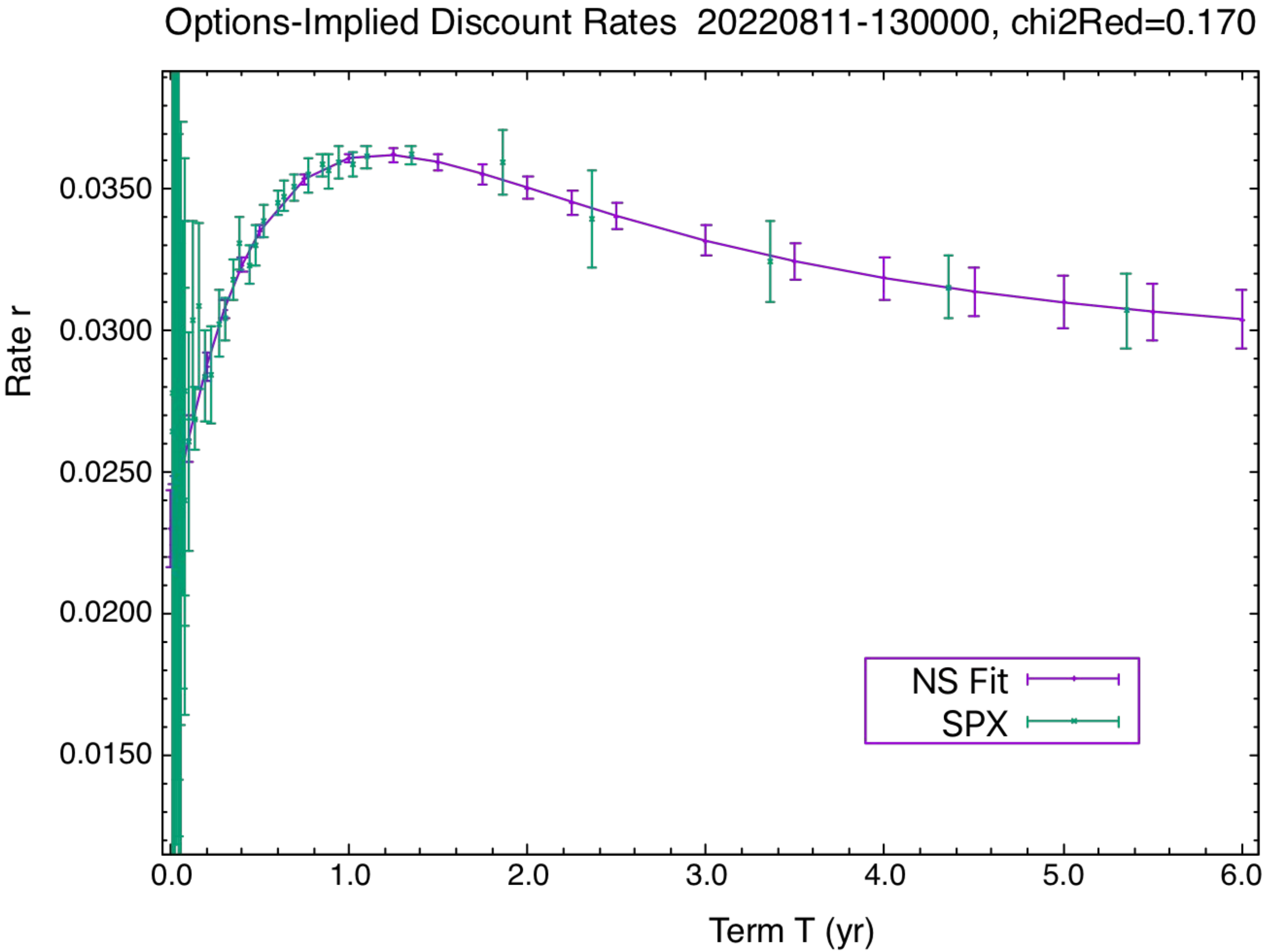
NB: Sometimes b=r is used, since the difference can be absorbed into the (implied) borrow rate q.

“SPIBOR” — SPX Implied Discount Rates

- What discount curve should one use for options pricing and trading?
    - Depends... but for implying borrows, vols, etc, use market consensus.
- European put-call-parity (PCP) for a given term:
    - $$C - P = DF \cdot F - DF \cdot K$$
- To imply the discount factor for a given term T, DF = DF(T), we need a robust linear regression across many strikes K.
- For further robustness, can smooth rates across T via a term-structure fit.

SPIBOR — Even the Fed cares now!

- Fed (-associated) economists have written a number of papers about SPIBOR in the last few years.
- Why does the Fed care?
  - The Fed needs to know what's going on...
  - **Treasury, SOFR, etc rates are NOT risk-free rates!**
  - They can be lower than risk-free ("convenience yield"), or higher ("default risk").
  - Usually they are a bit lower, by 20 – 40 bps (almost flat).
  - SPX options market makers should be using close to risk-free rates ("box rates") due to margin requirements at exchange and OCC level.

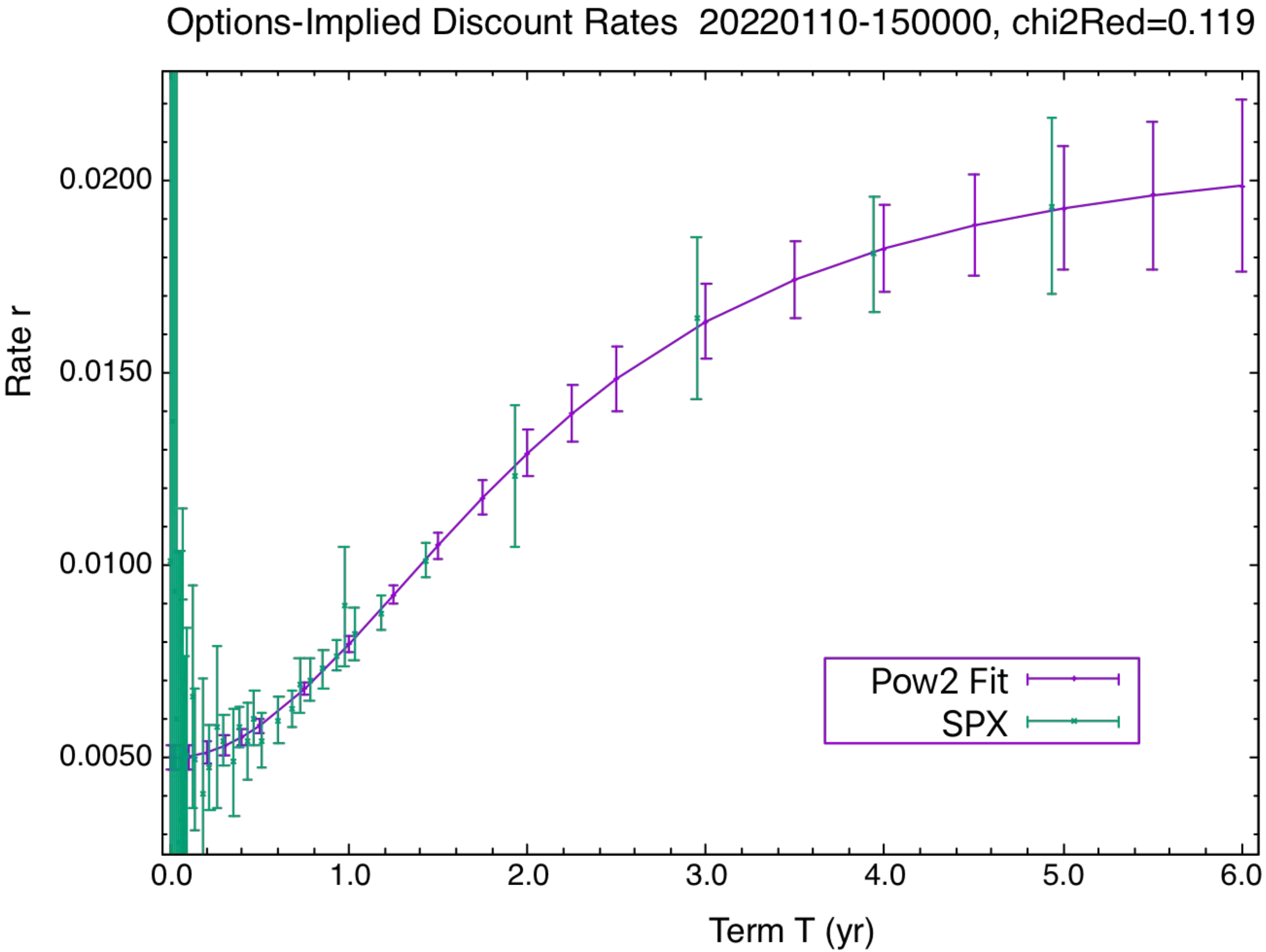


What discount rates should I use?

SPIBOR

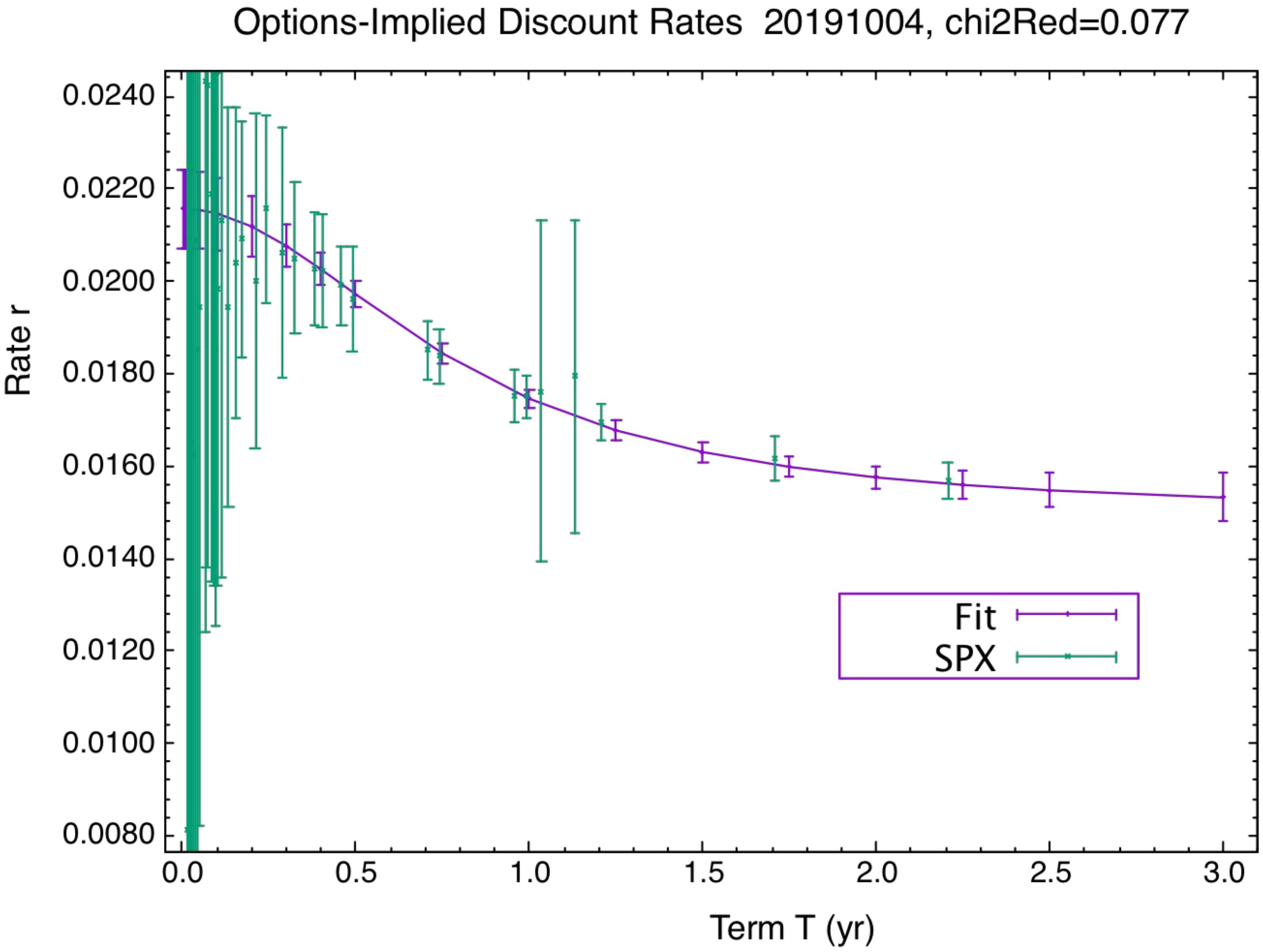
Just one snapshot!

Nelson-Siegel TS fit



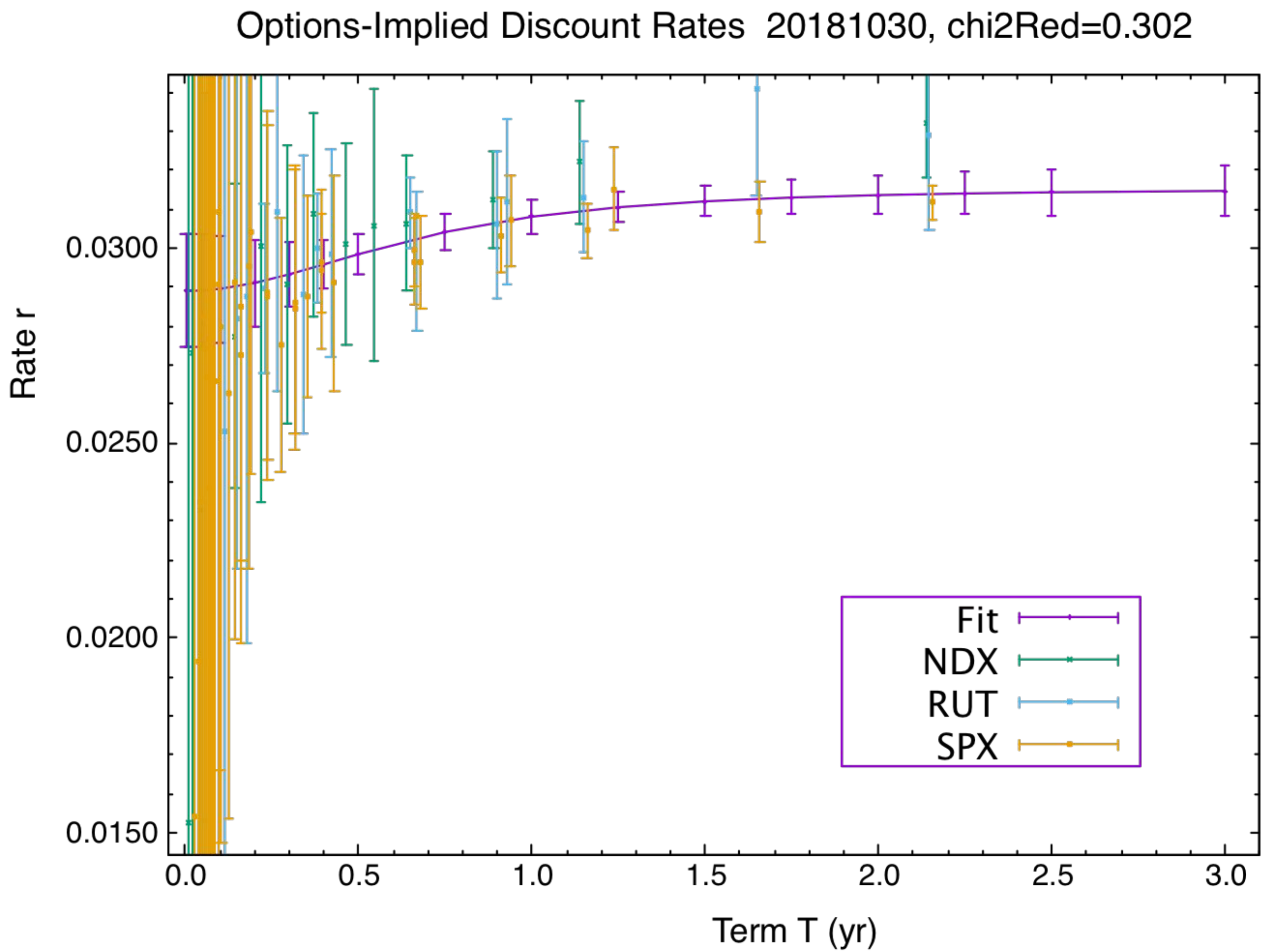
What discount rates should I use?

SPIBOR



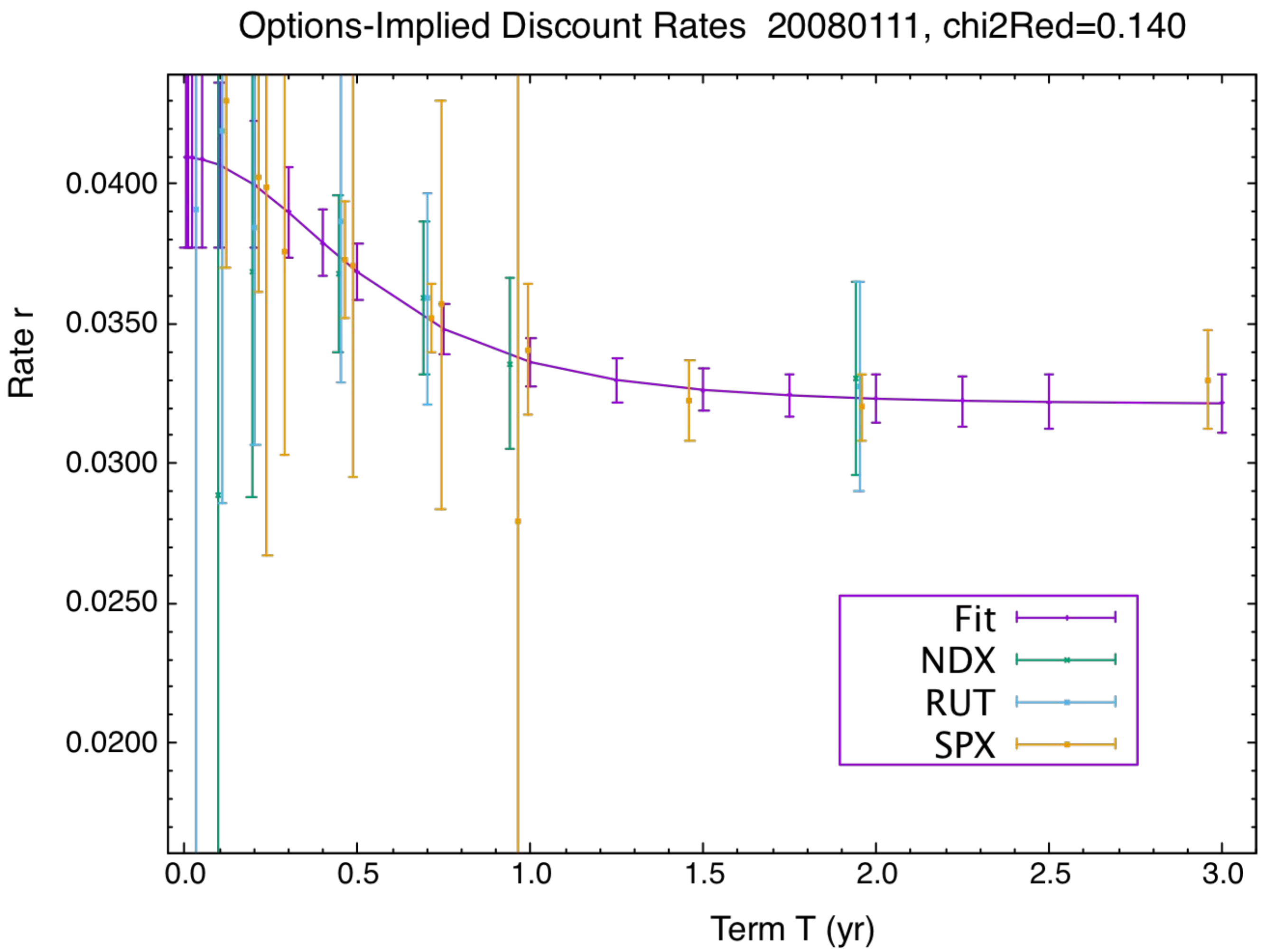
What discount rates should I use?

SPIBOR



What discount rates should I use?

Maybe they are underlier/ sector dependent?



What discount rates should I use in **2008** ??

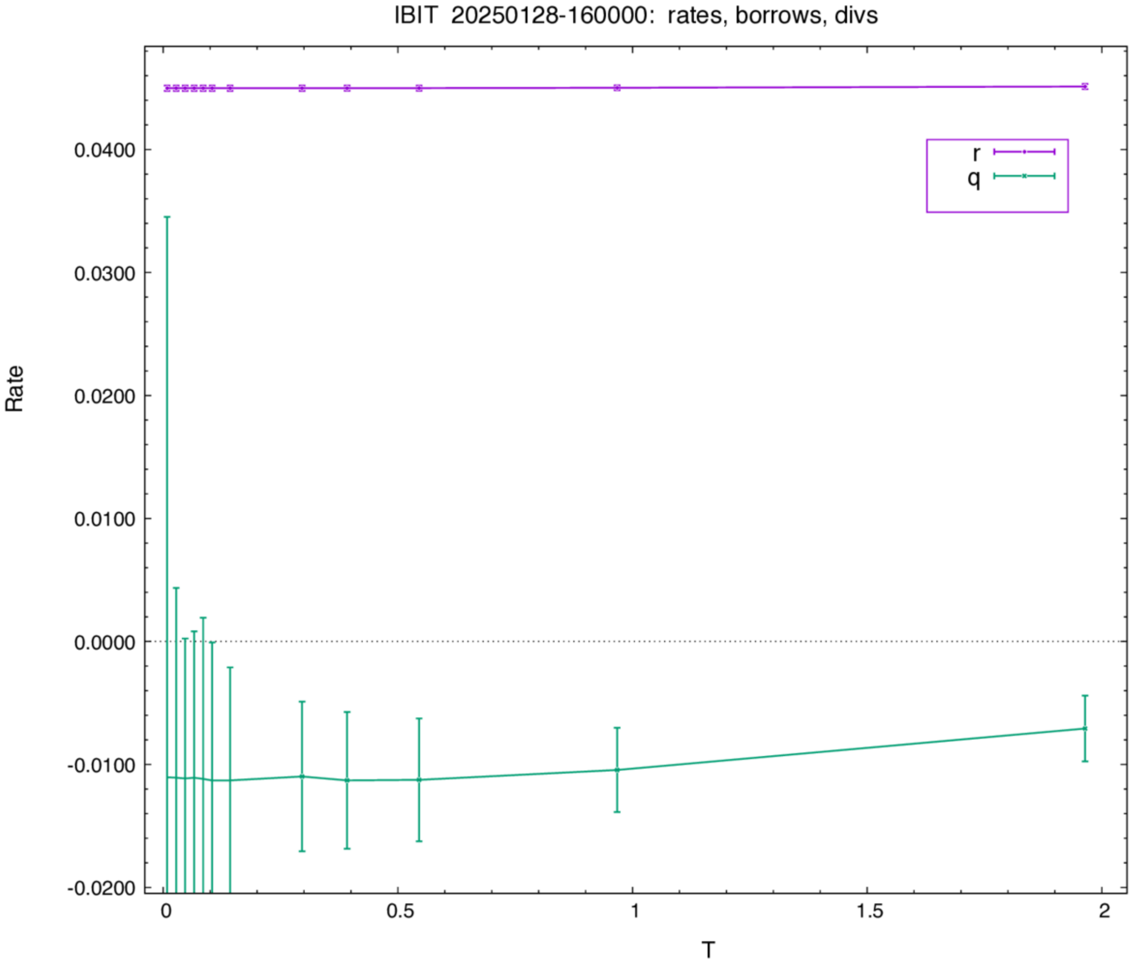
SPIBOR

Example: IBIT options

- IBIT = iShares Bitcoin ETF, launched 2024-02-15.
- One of the most successful ETF launches in decades: ~$80bn AUM (Sep 2025)
- Options started trading 2024-11-19: Very quickly became very liquid.
- We will show:
  - Implied borrow costs q(T).
  - Vol fits: SVI vs C9W, with metrics like chi2Reds, avE5 (avgErrors5)
  - Theoretical prices (“theos”) vs market prices
  - No arbitrage: Densities, total variances

How to imply the borrow cost q(T)?

- For European-style options we could use PCP to imply the forward for each expiry, and then q(T) from the forwards.
- For American-style options PCP does not hold. Call and/or put prices could have an early-exercise premium (EEP), even around ATM.
- Time-honored tradition is to use **"American PCP"** as:
  - For strikes K around ATM demand: volPut(K) = volCall(K)
- This is not really true! One can check this in any real model, like LV, SLV.
- It holds "well enough" if EEP are small-ish compared to spreads for some strikes around ATM — OR if this is what "the market" does!
- For now, imply the borrow such that American PCP holds.
  - If pricing with rate term-structure, bootstrapping from small to large T is needed.



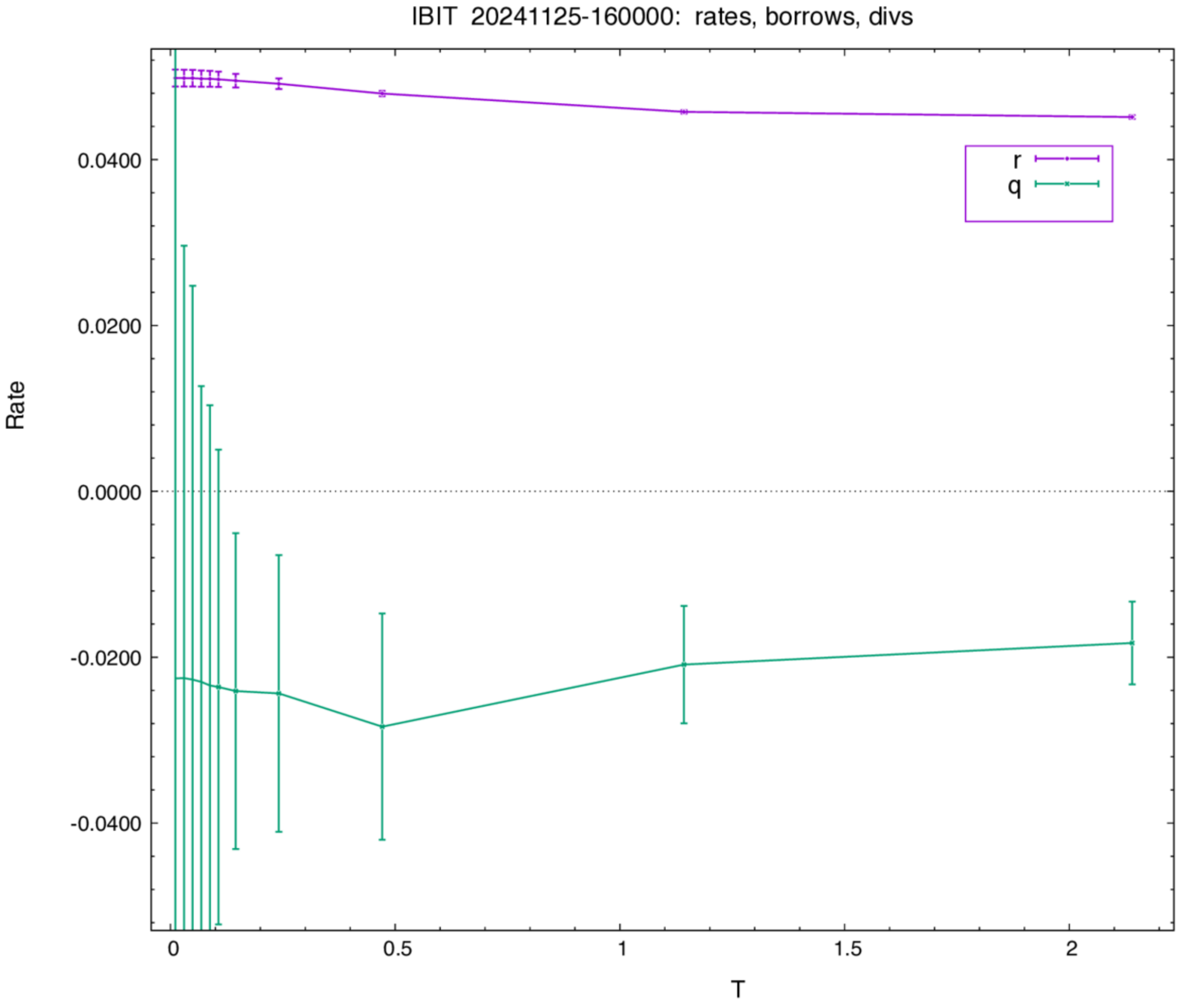
IBIT 2025-01-28

Implied borrow cost by term q(T)

The actual borrow cost is +1.2%

Massive demand for upside leverage leads to much smaller implied q(T) !

We also implied the spot here.



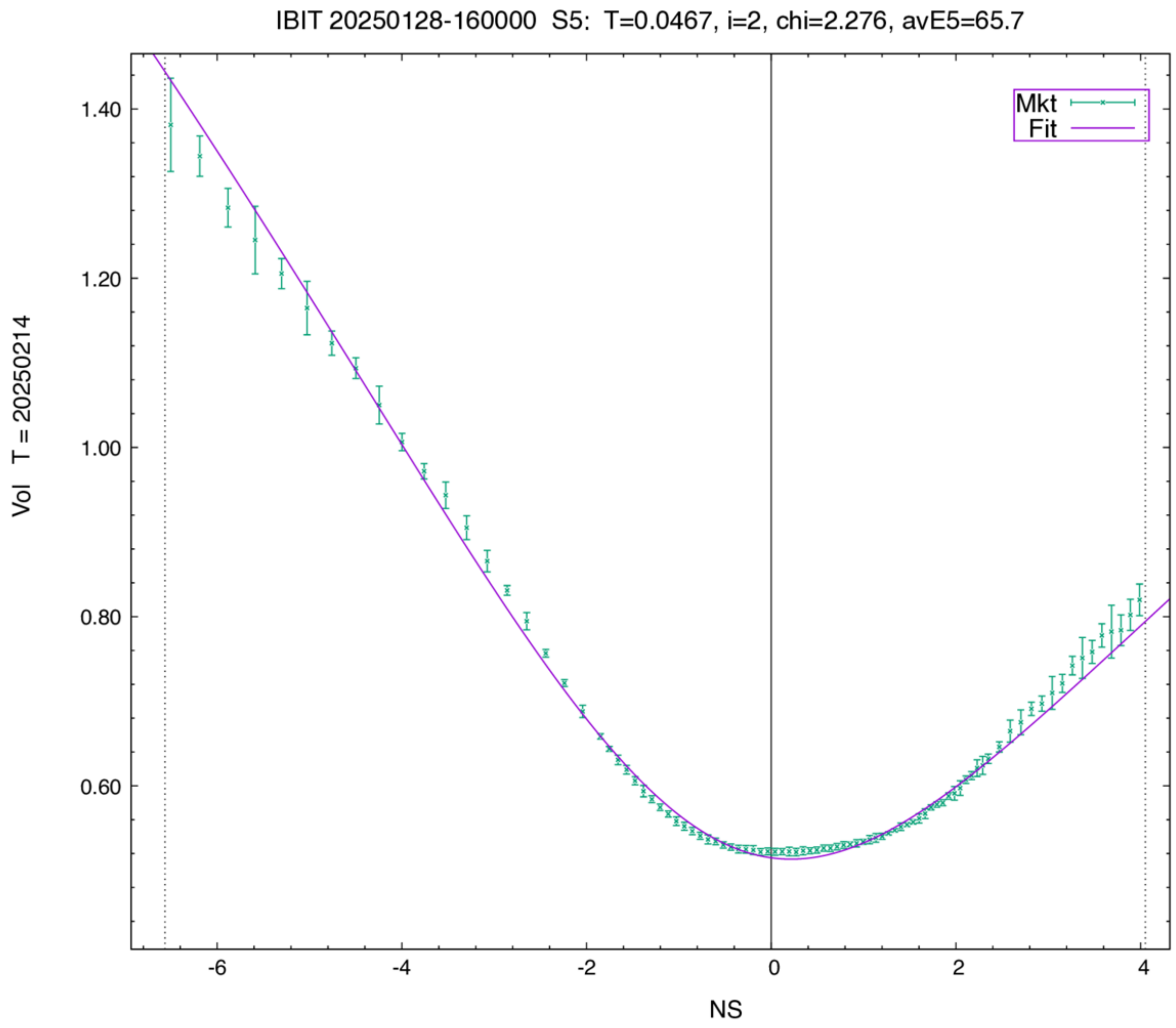
IBIT 2024-11-25

A few days after options trading started

Implied borrow cost by term q(T)

Massive demand for (upside leverage) leads to much smaller implied q(T) !

We also implied the spot here.

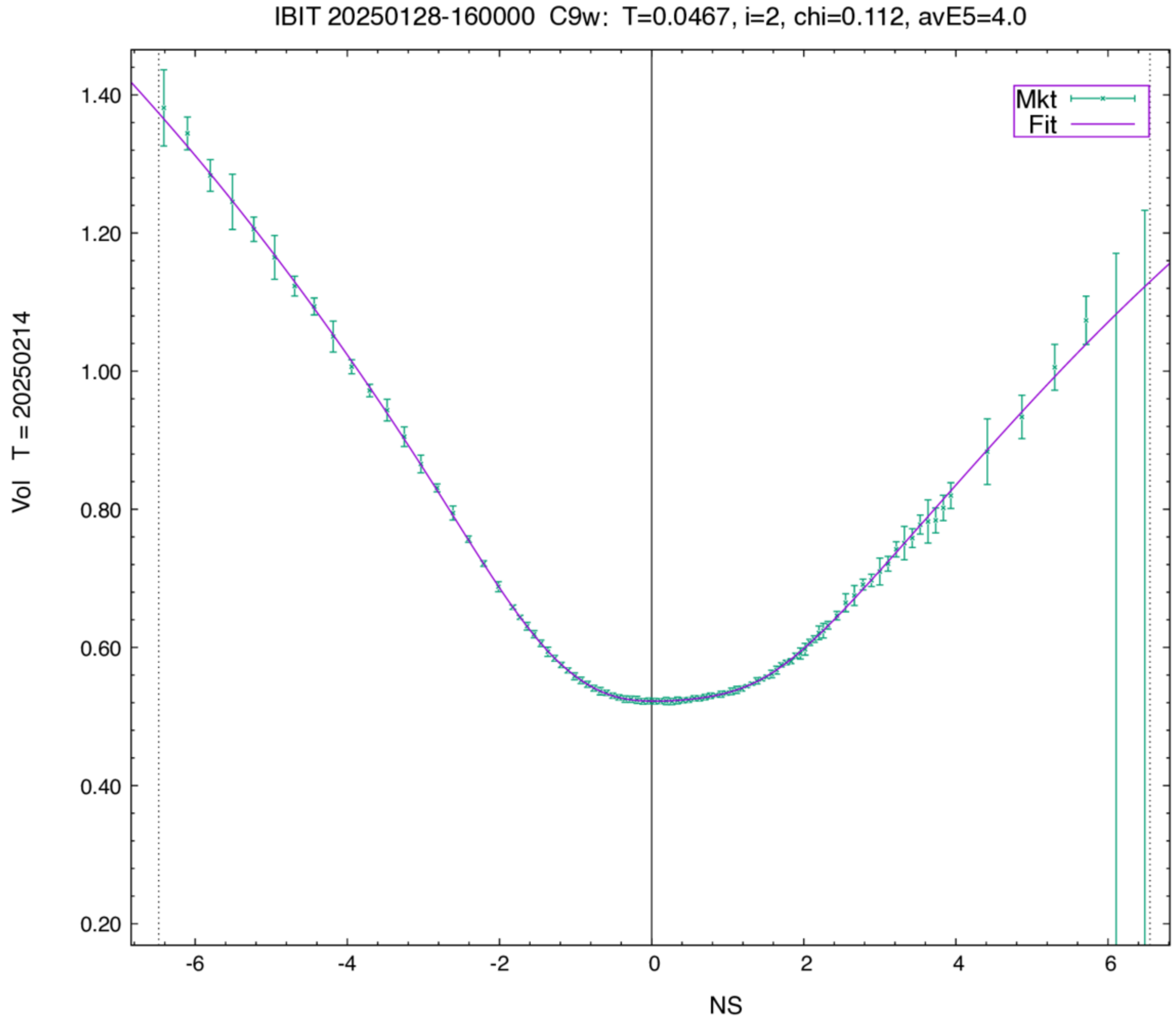


IBIT 20250128 16:00

S5, T = 2w, NS space

S5 = **SVI**

$$z := \mathrm{NS} := \frac{\ln(K/F)}{\sigma_0\sqrt{T}}$$



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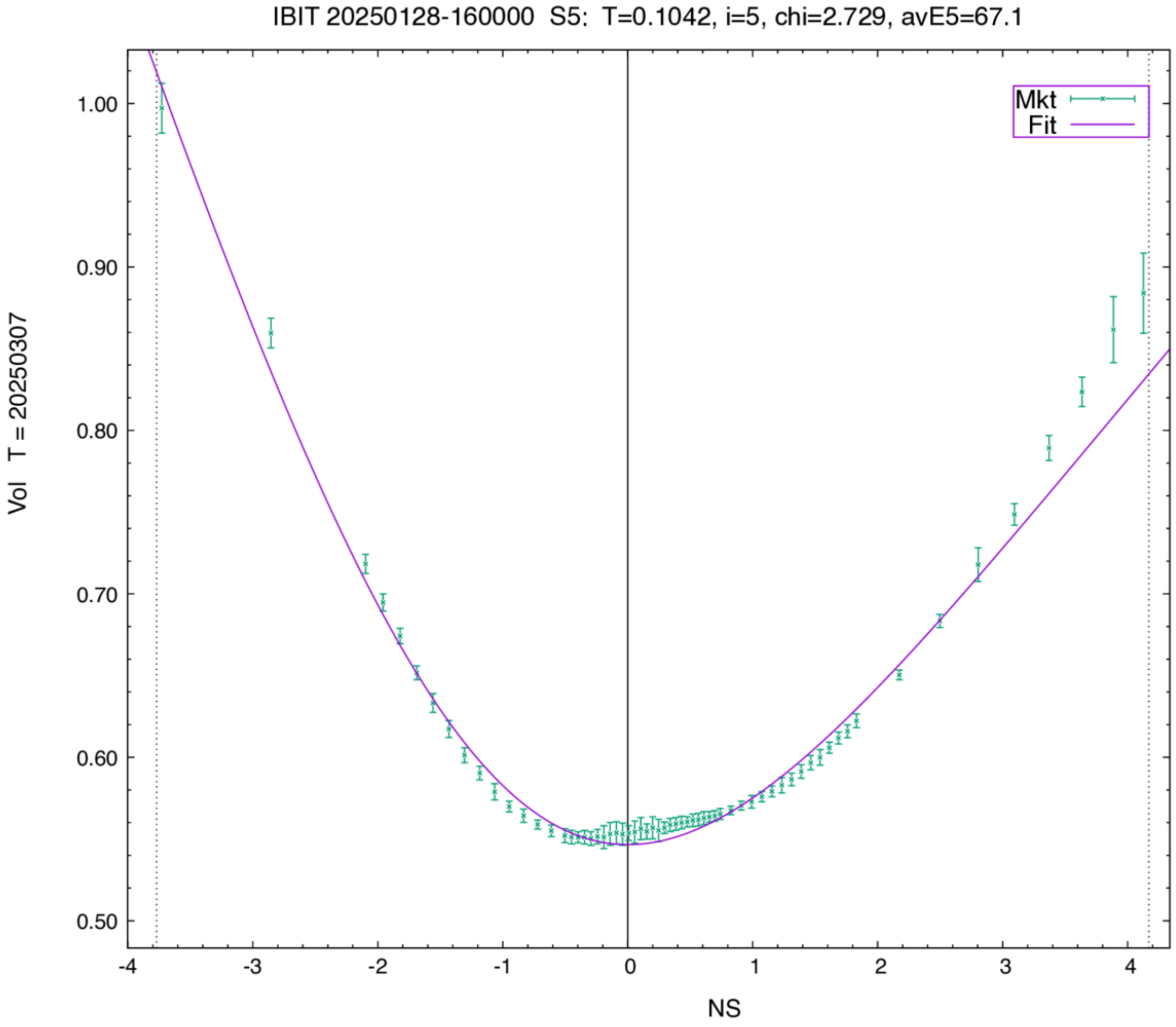
C9w, T = 2w, NS space

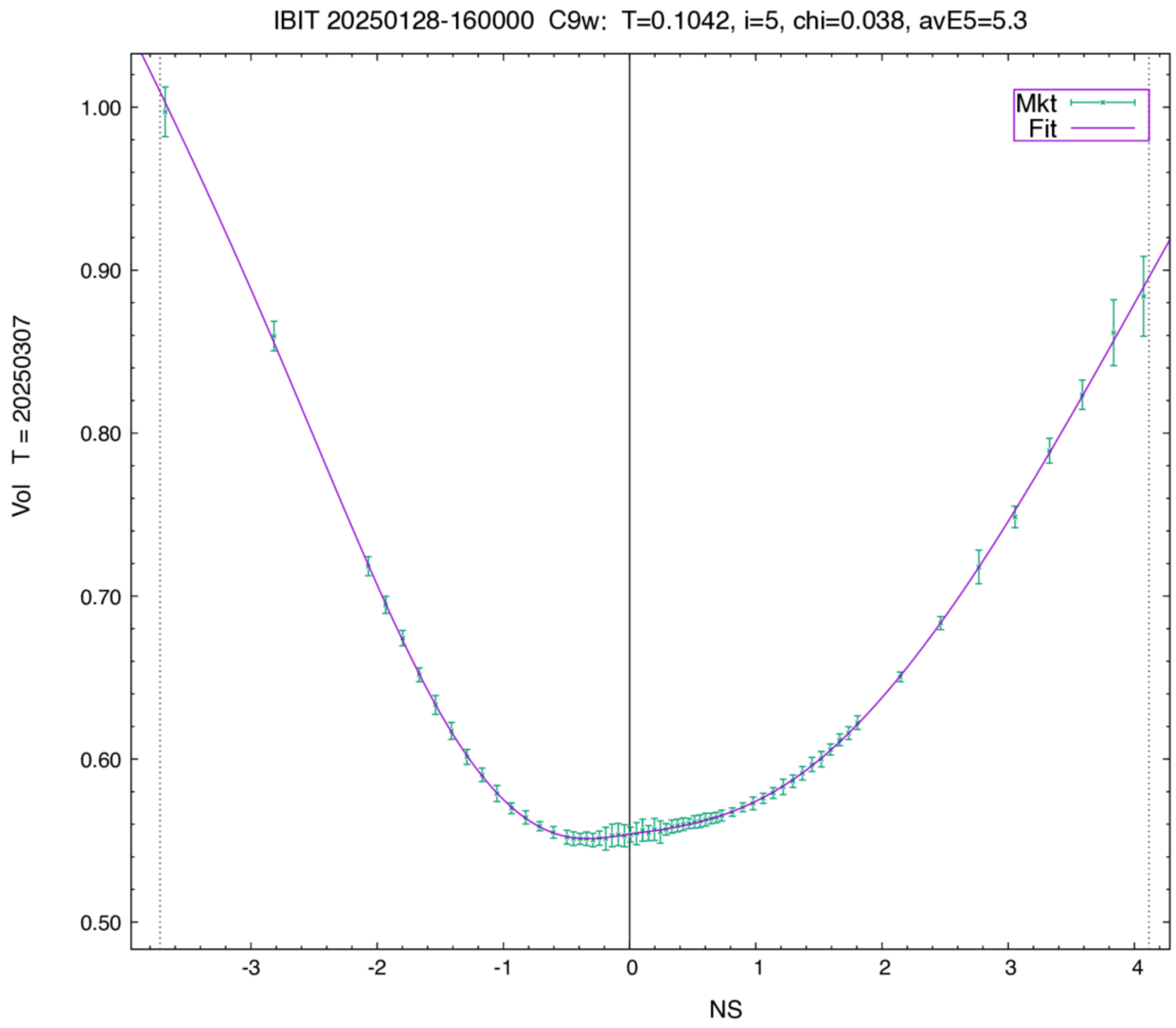
Fit is 15-20x better than SVI



IBIT 20250128 16:00

S5 T = 5w, NS space

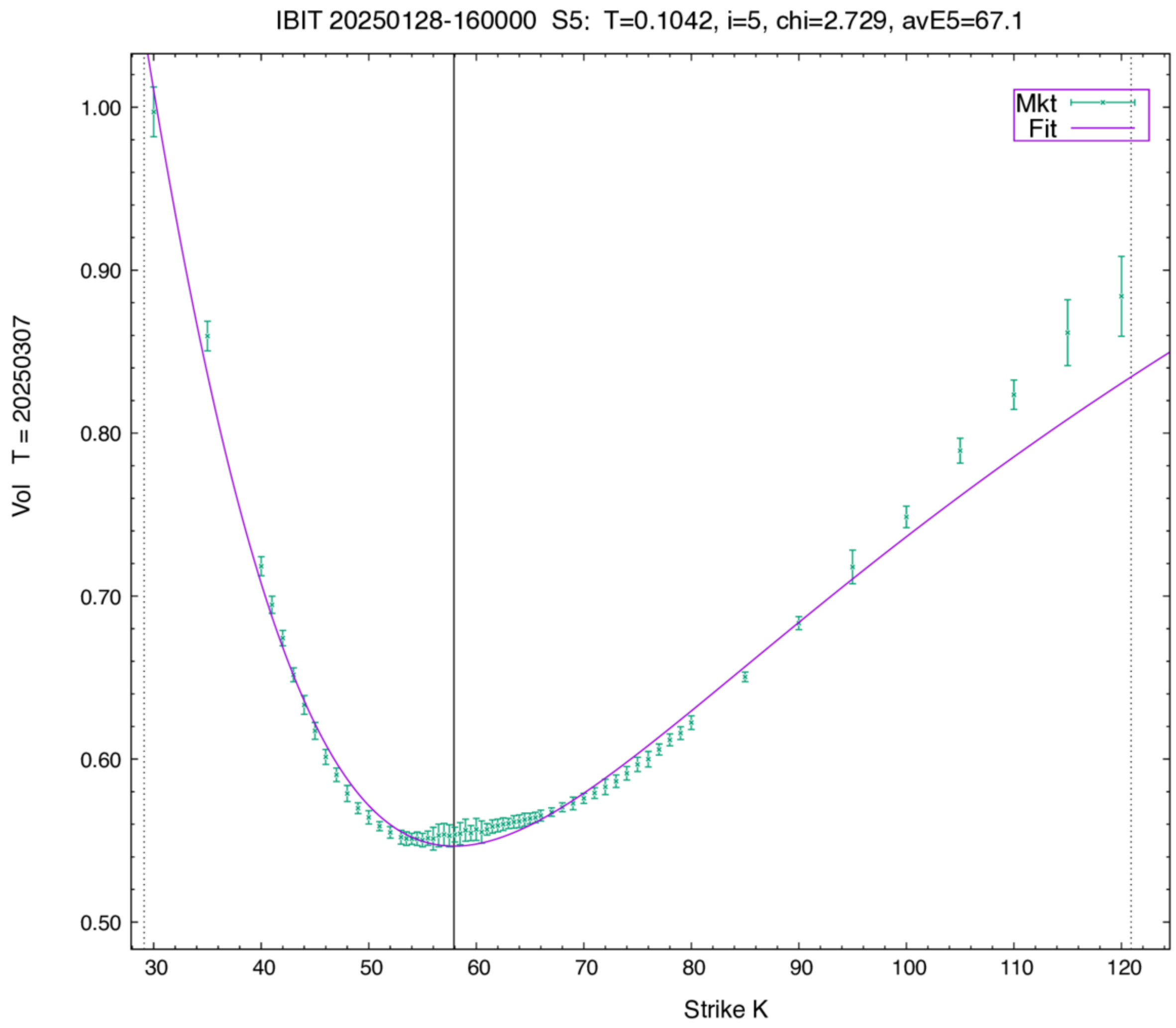
$$z := \text{NS} := \frac{\ln(K/F)}{\sigma_0\sqrt{T}}$$



IBIT 20250128 16:00

C9w, T = 5w, NS space

Fit is 13-70x better than SVI



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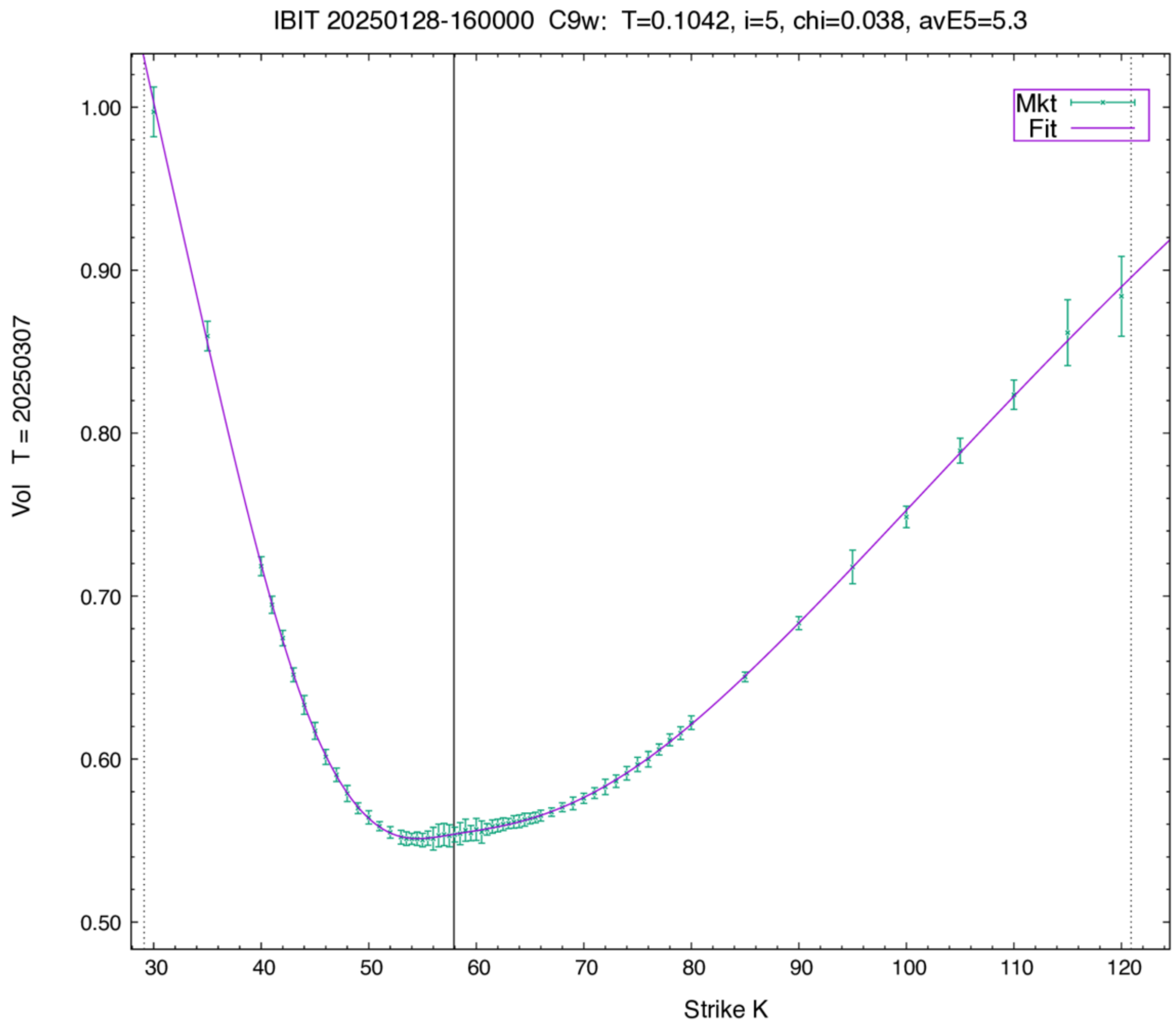
S5 T = 5w, K space



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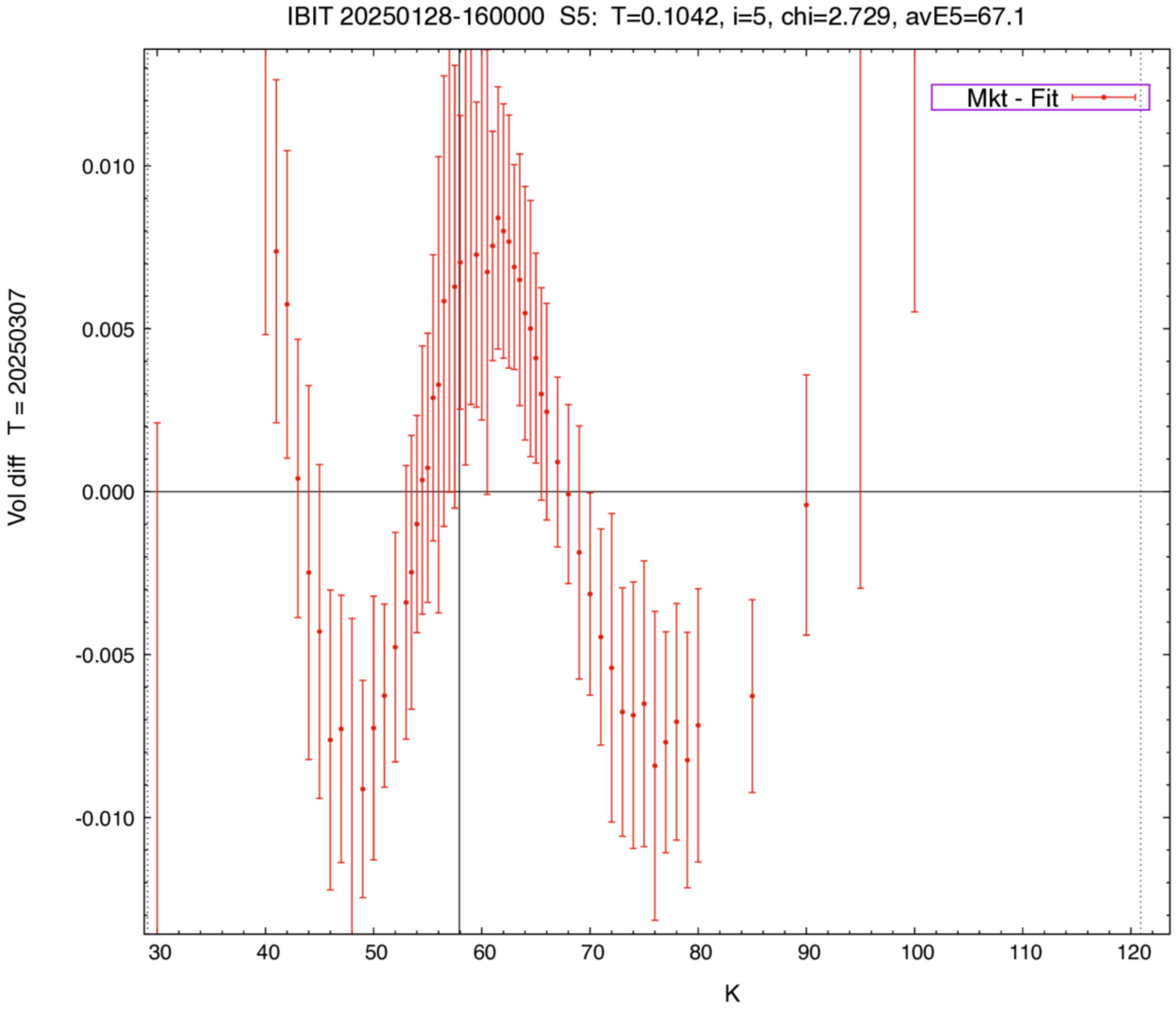

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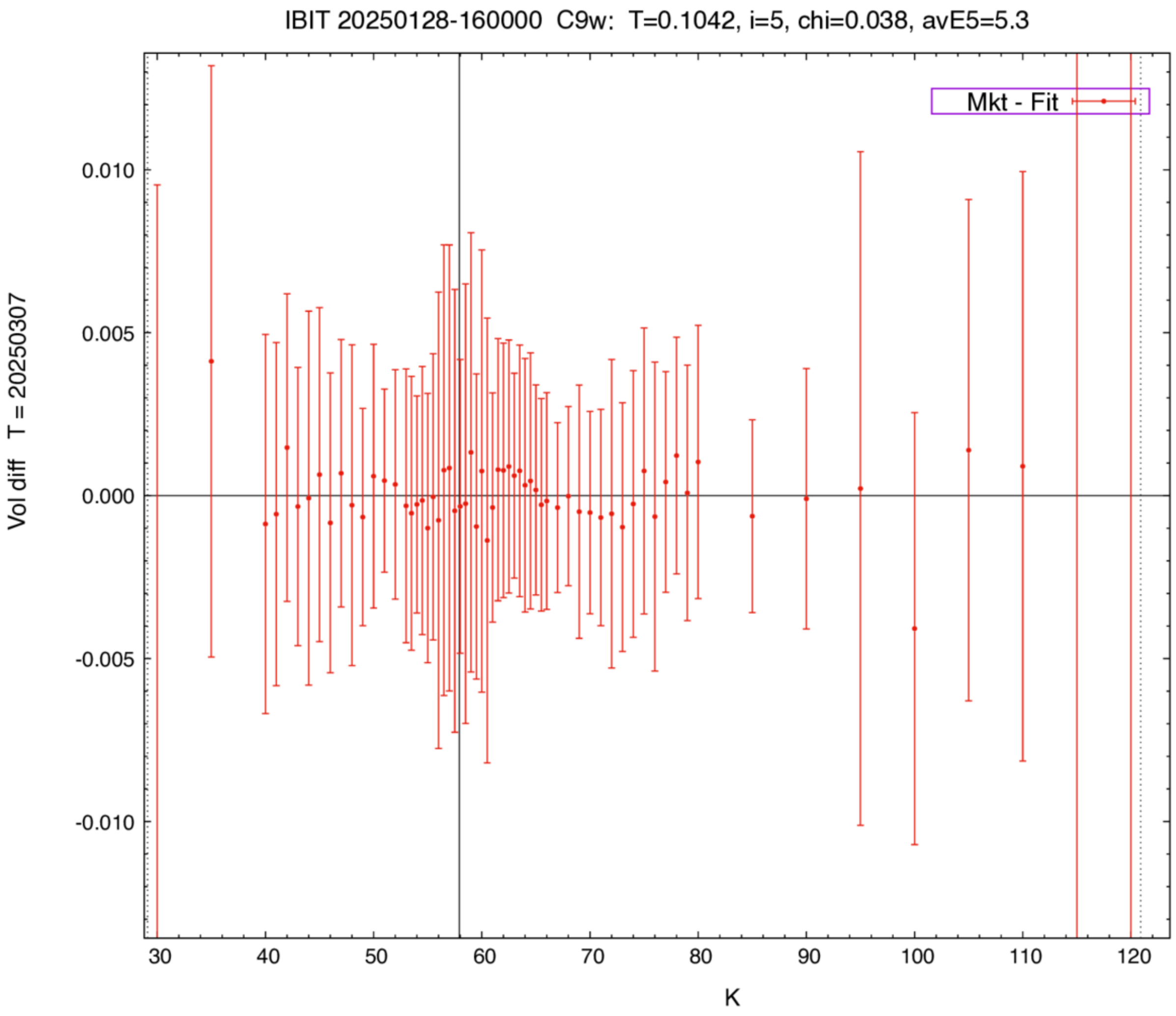
S5 T = 5w, K space

"Vol diff" plot



IBIT 20250128 16:00

C9w, T = 5w, K space

“Vol diff” plot

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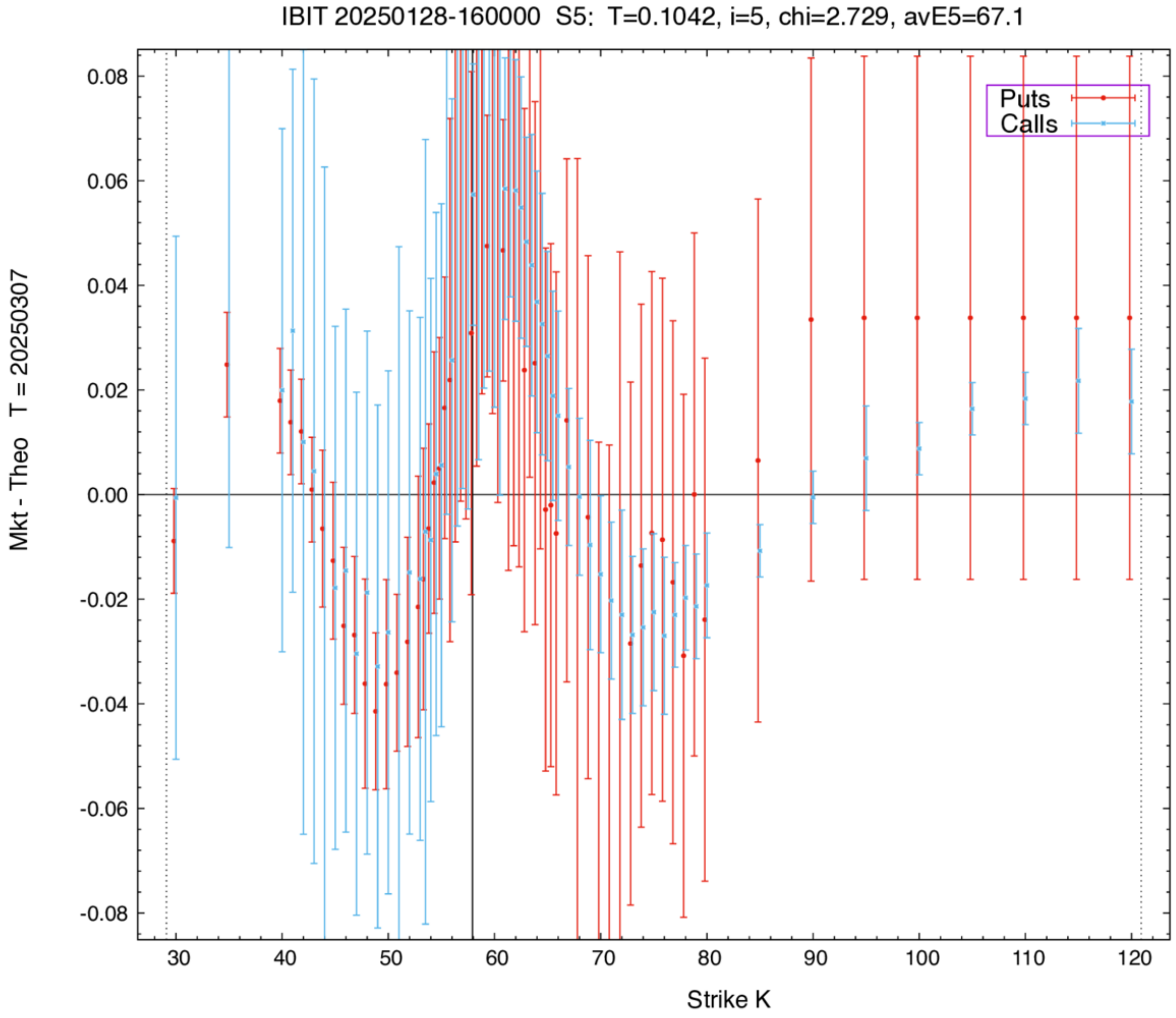

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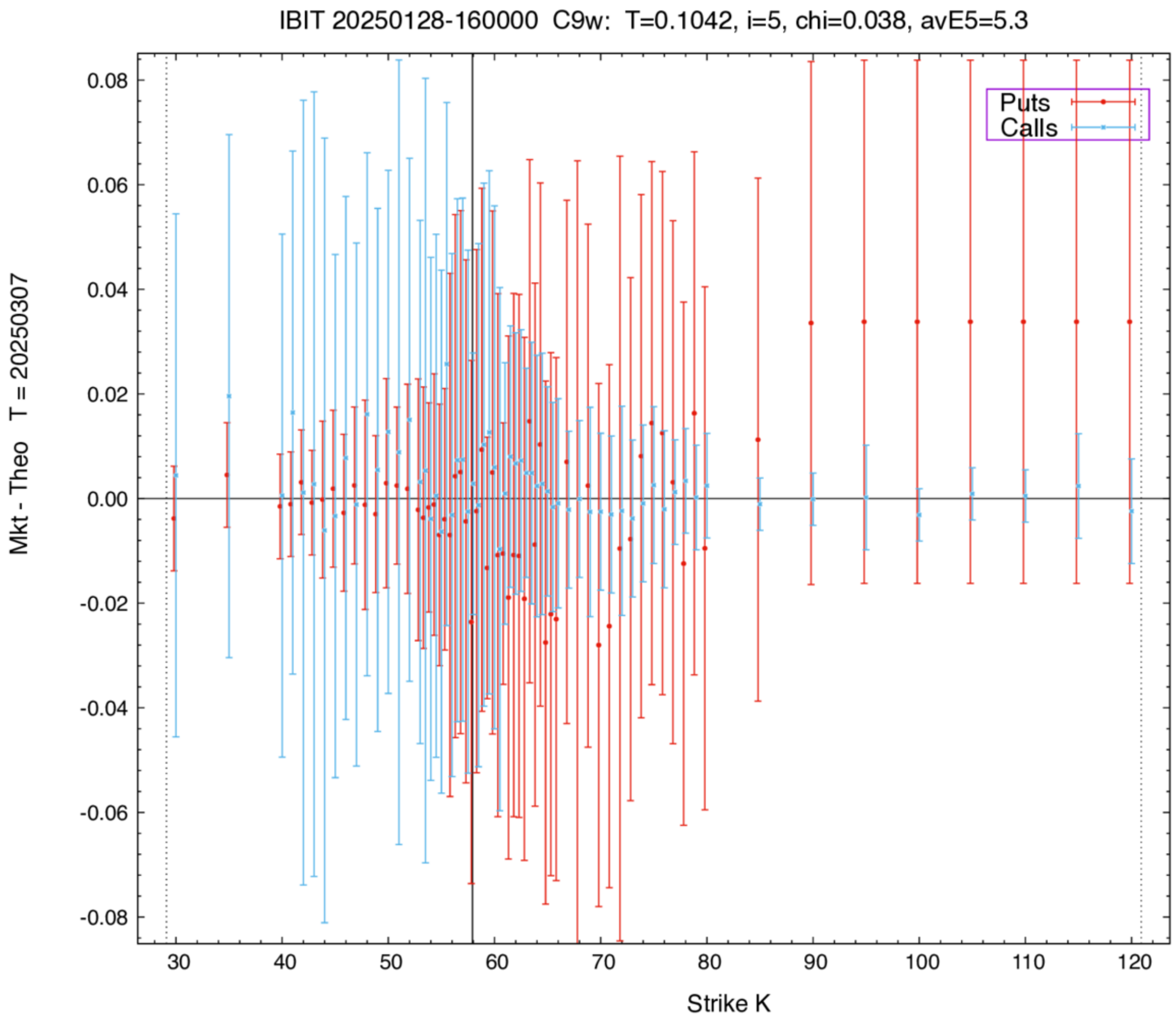
S5 T = 5w, K space

“Price diff” plot: The ultimate test!

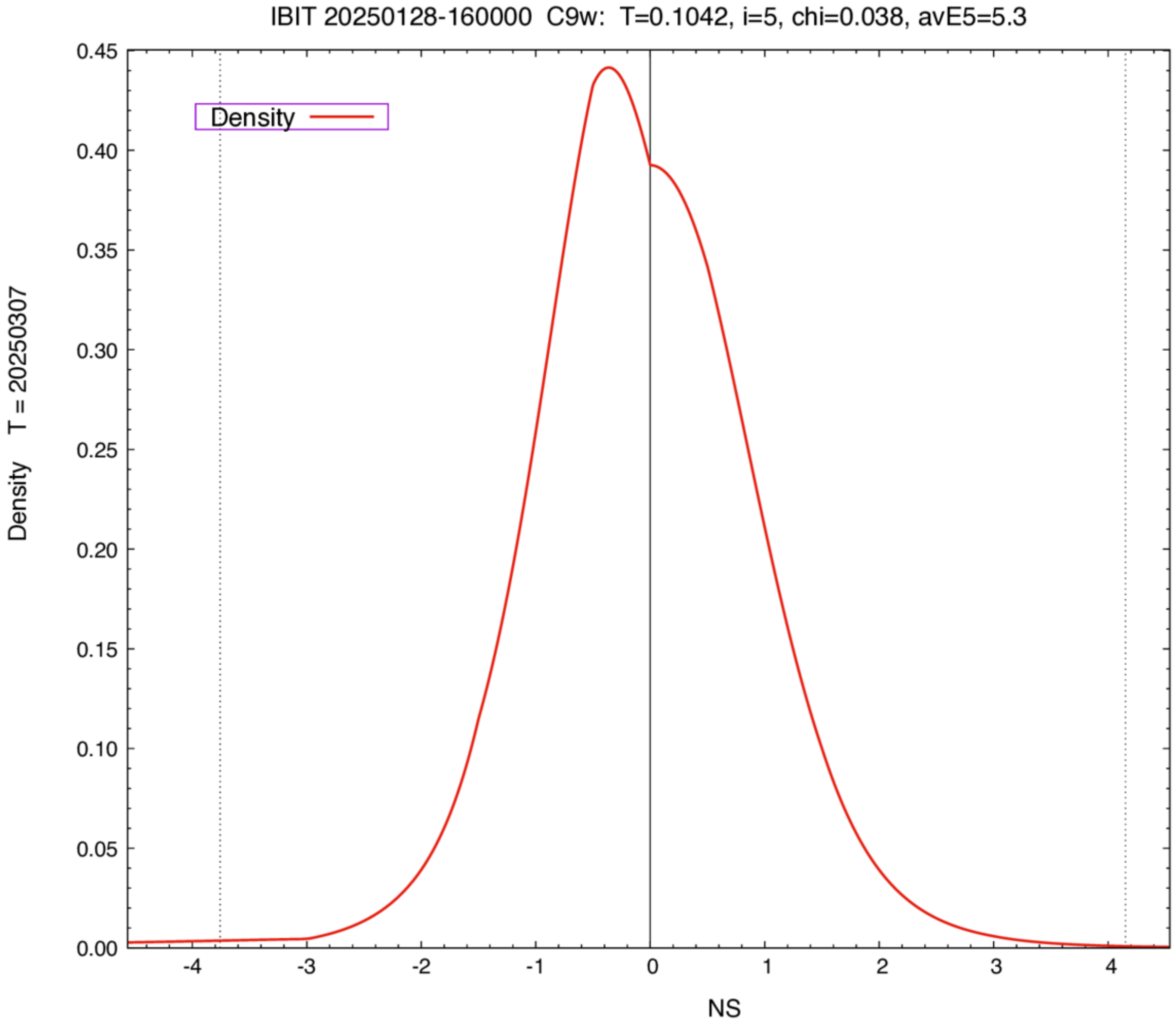


IBIT 20250128 16:00

C9w, T = 5w, K space

“Price diff” plot: The ultimate test!

Fit is 13-70x better than SVI



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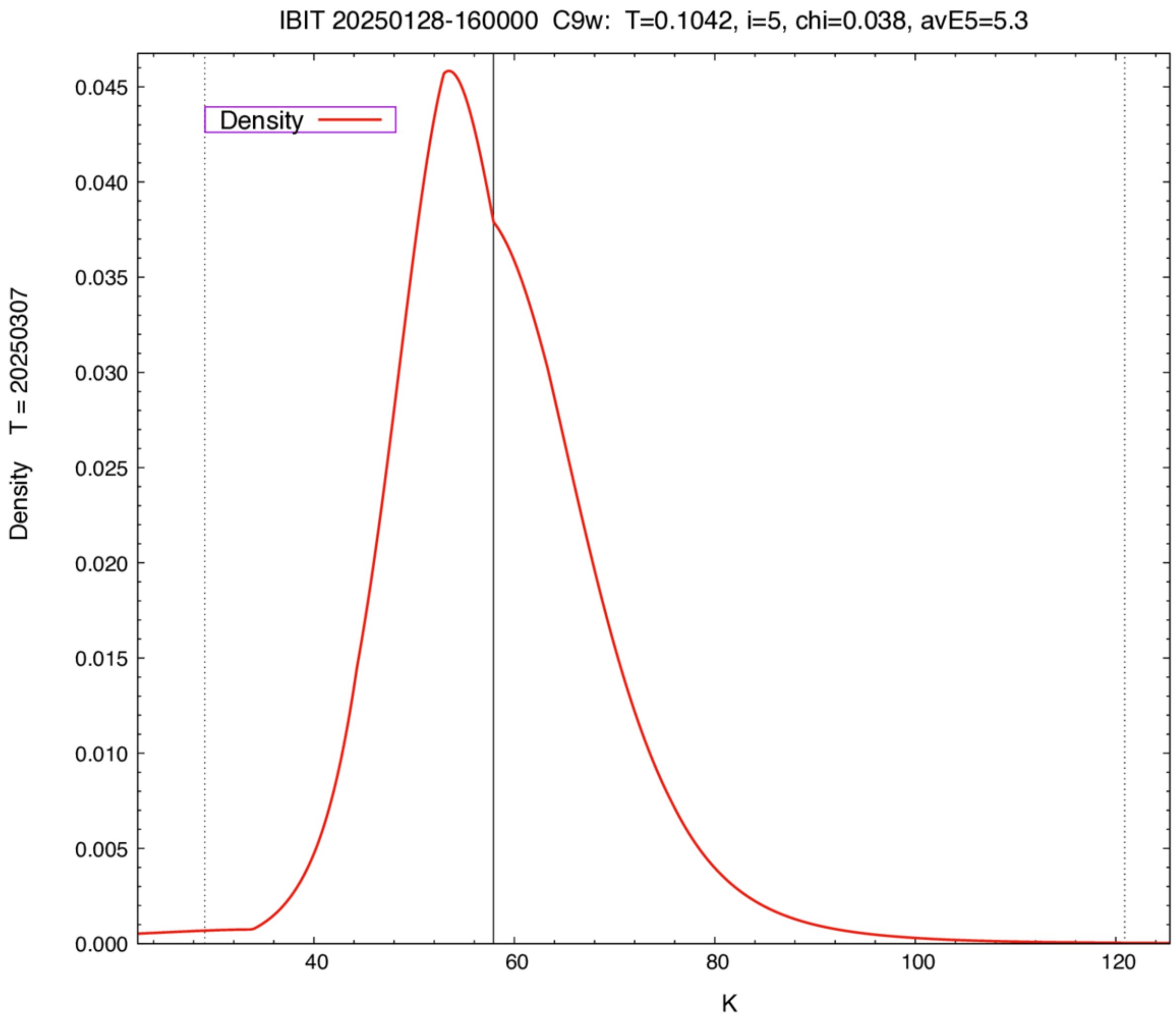
C9w, T = 5w, NS space

Implied density

A pretty fat put wing…



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C9w, T = 5w, K space

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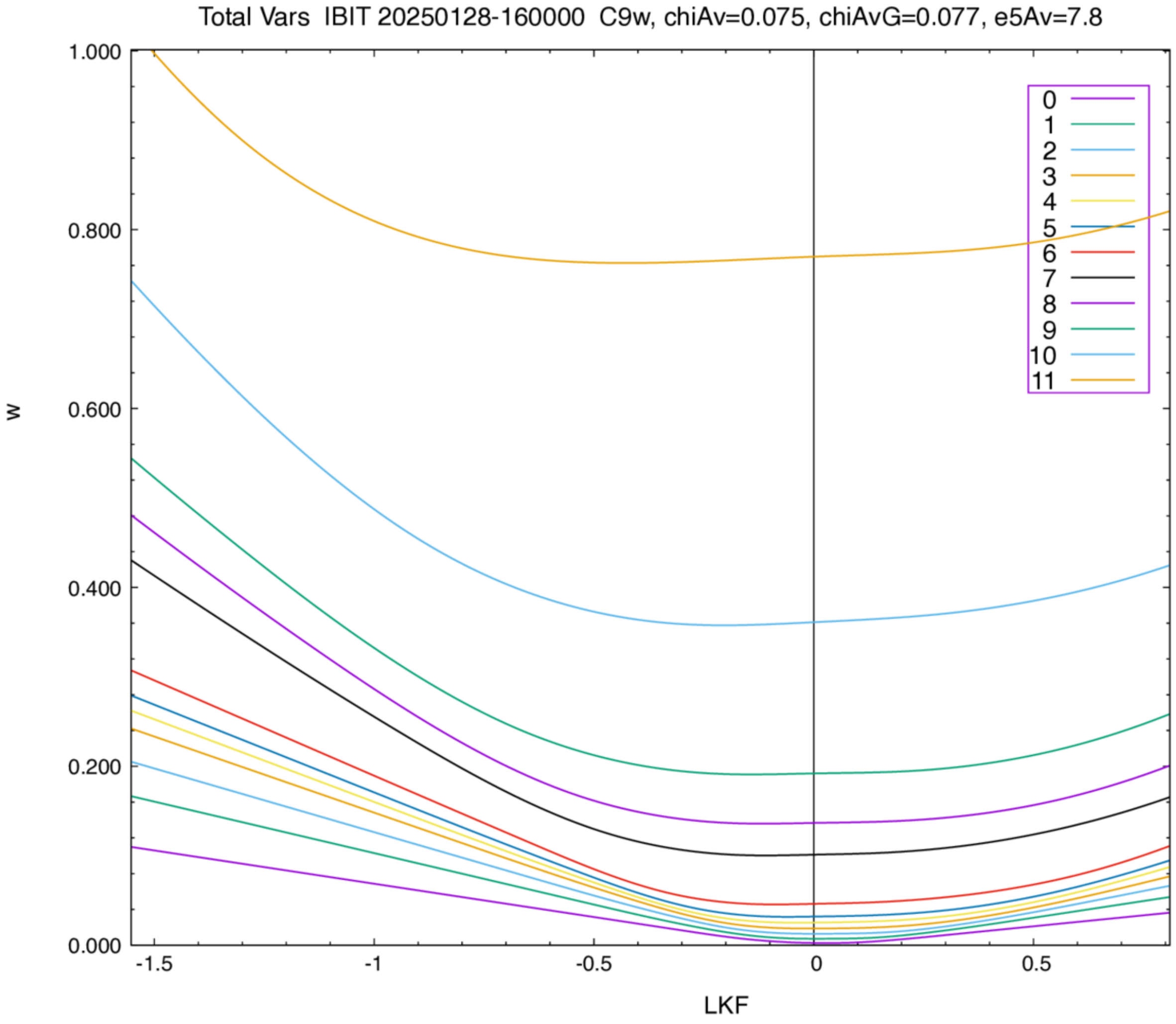
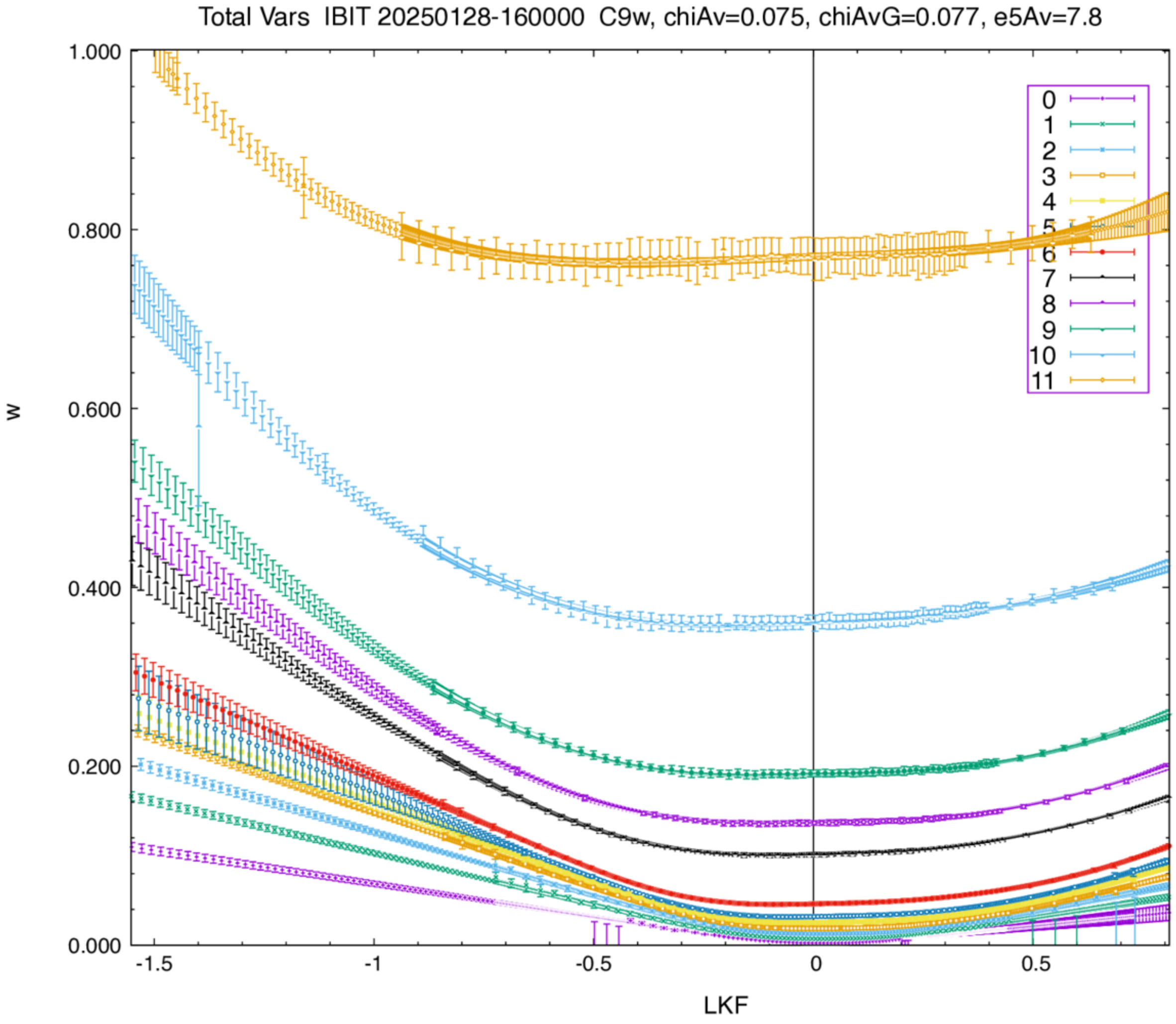


IBIT 20250128 16:00

Total Variance plot

No calendar arbitrage!

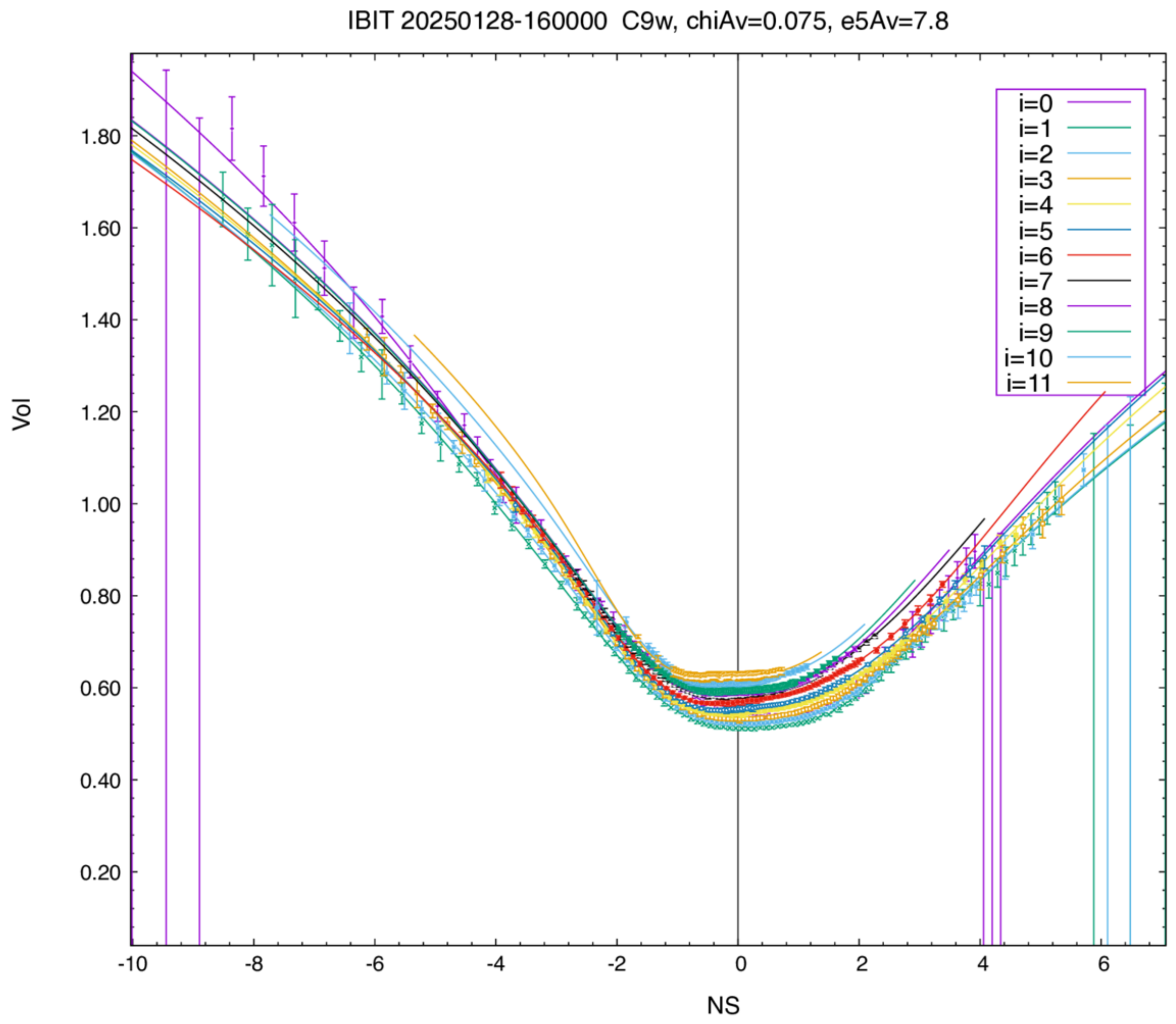
$$w(T,K) := \sigma(T,K)^2 \ T$$



IBIT 20250128 16:00

Total Variance plot

With error bars!

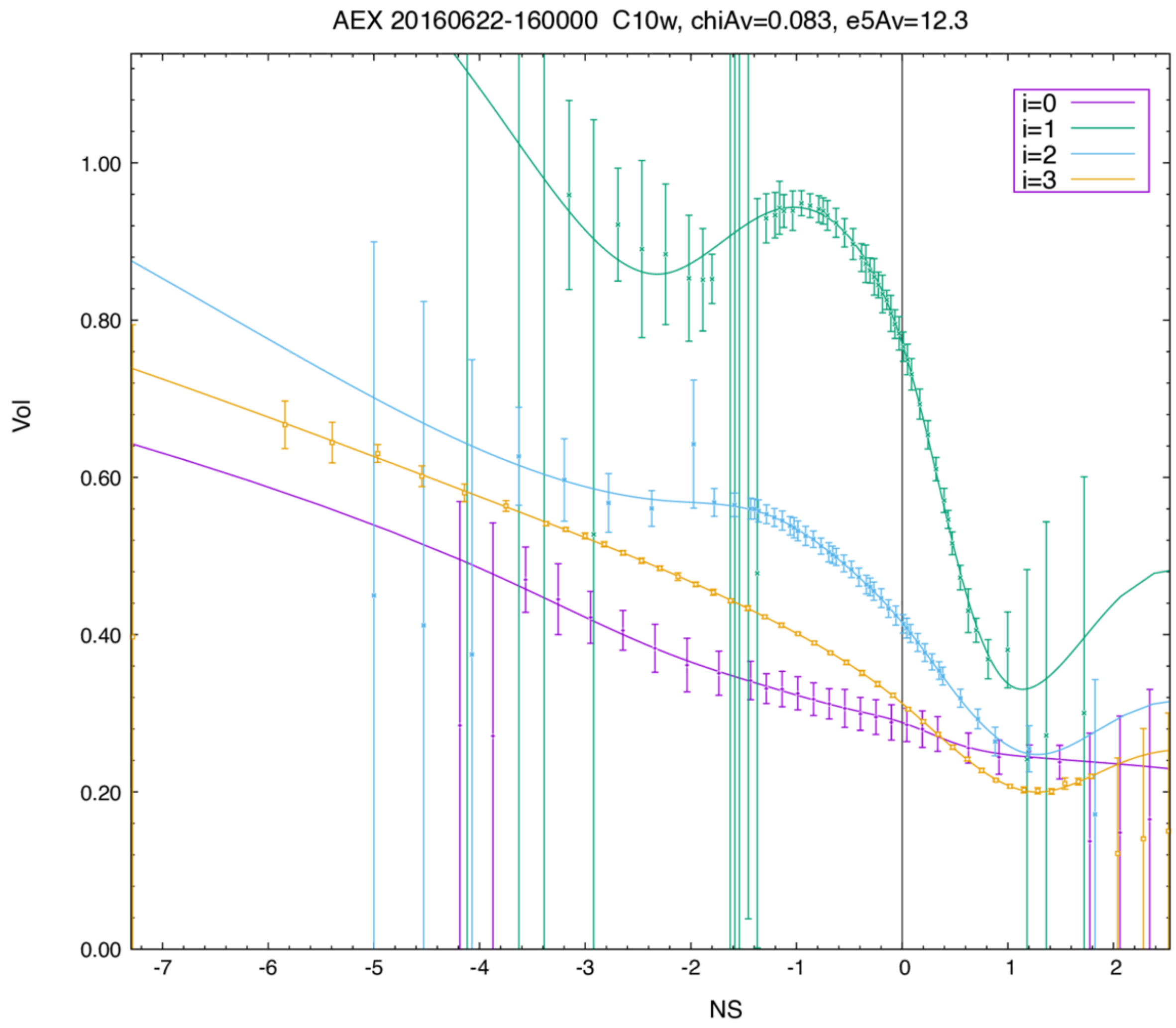


IBIT 20250128 16:00

All vols by NS

IBIT options: Conclusions

- Implied borrows can be very different from actual (overnight) borrow fees charged by agent banks/prime brokers.
- As an options market becomes liquid, SVI or other simple curves will very quickly not be flexible enough to match the market in a bias-free manner.

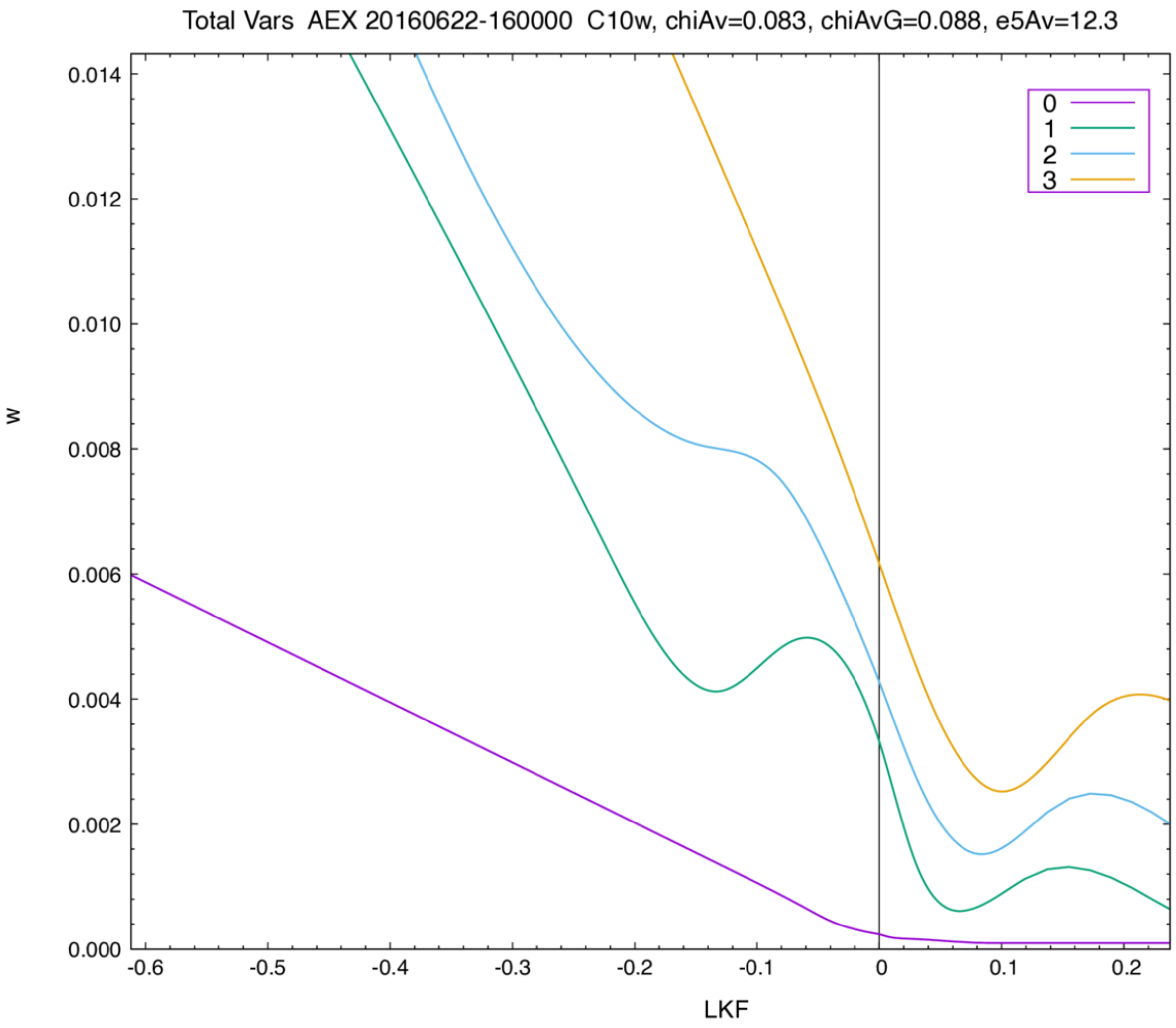


AEX 2016-06-22

Day before Brexit!

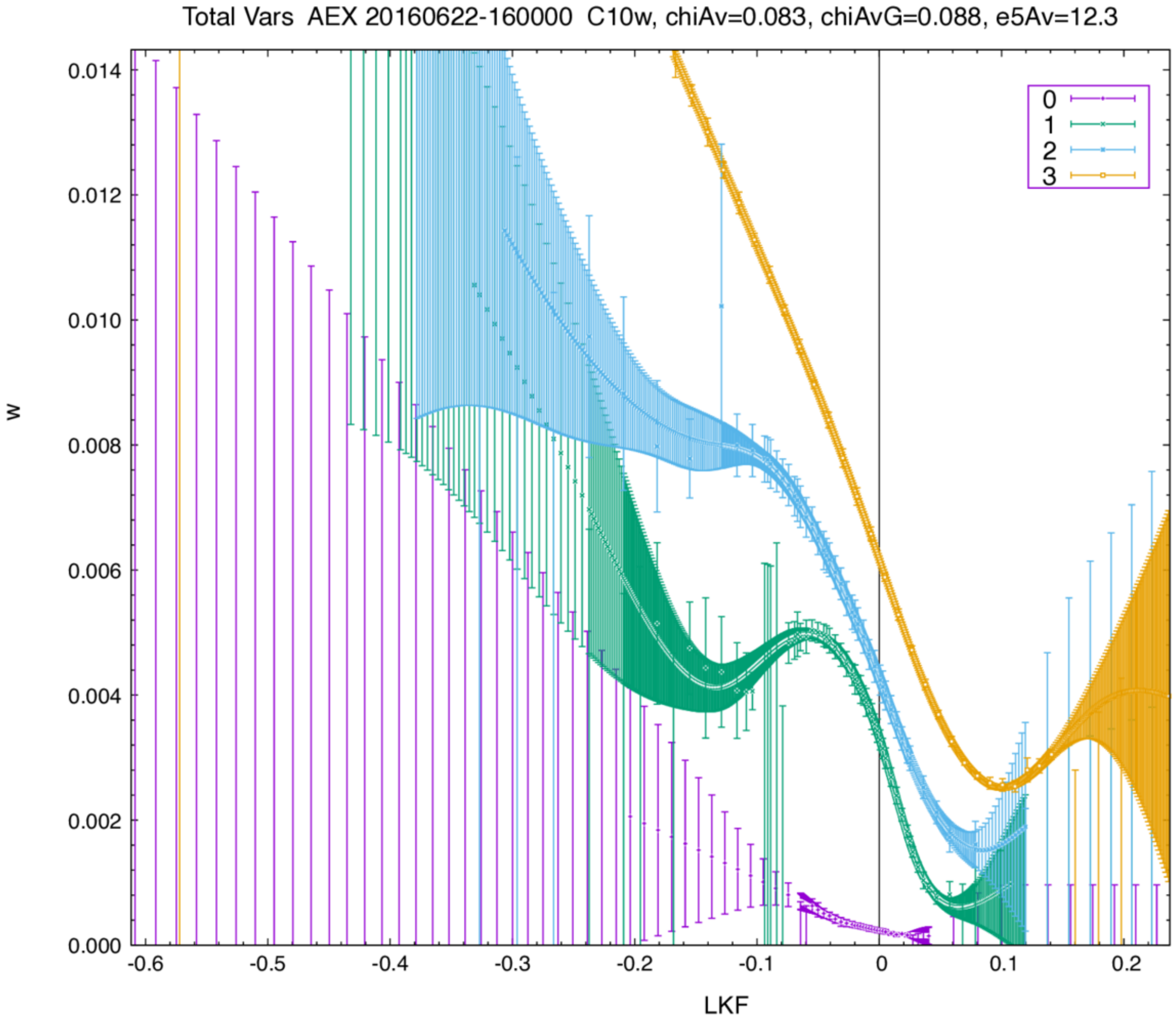
Vol vs NS

$$z := \mathrm{NS} := \frac{\ln(K/F)}{\sigma_0\sqrt{T}}$$



Fitting **AEX** on day before Brexit

Total Var plot



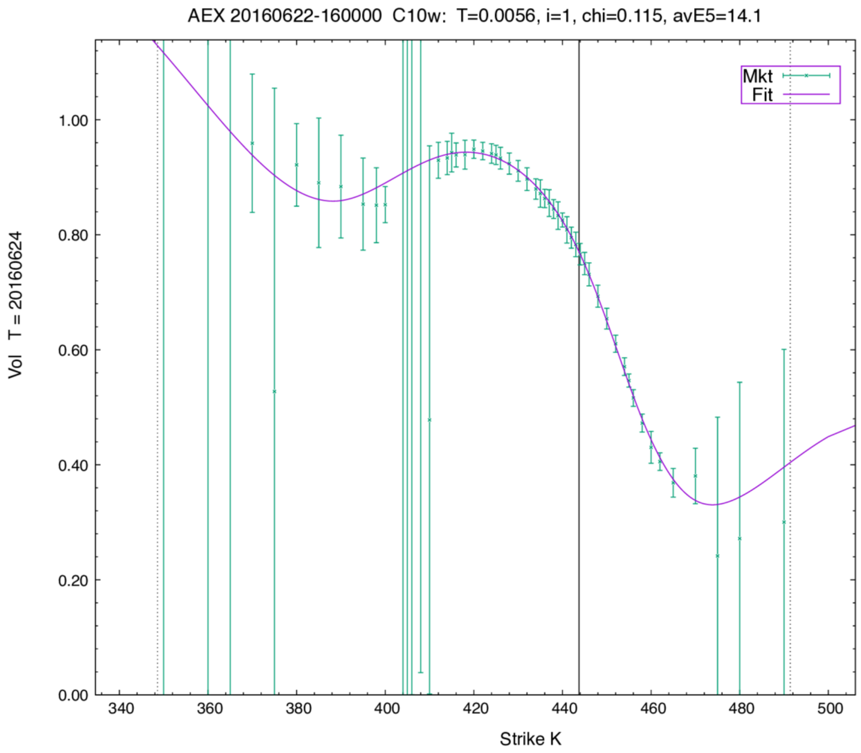
Fitting **AEX** on day before Brexit

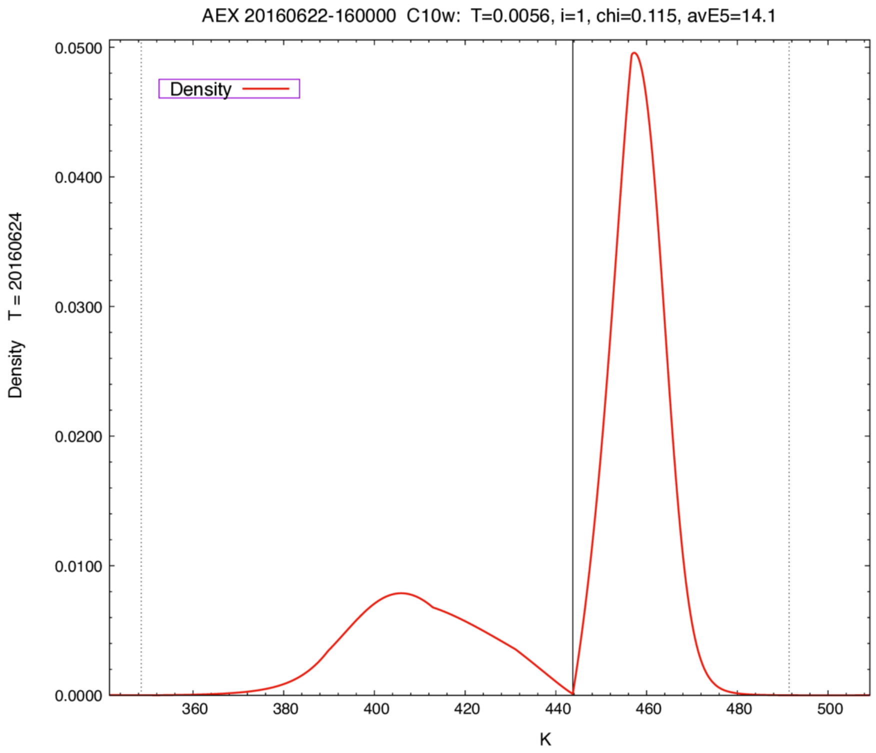
Total Var plot

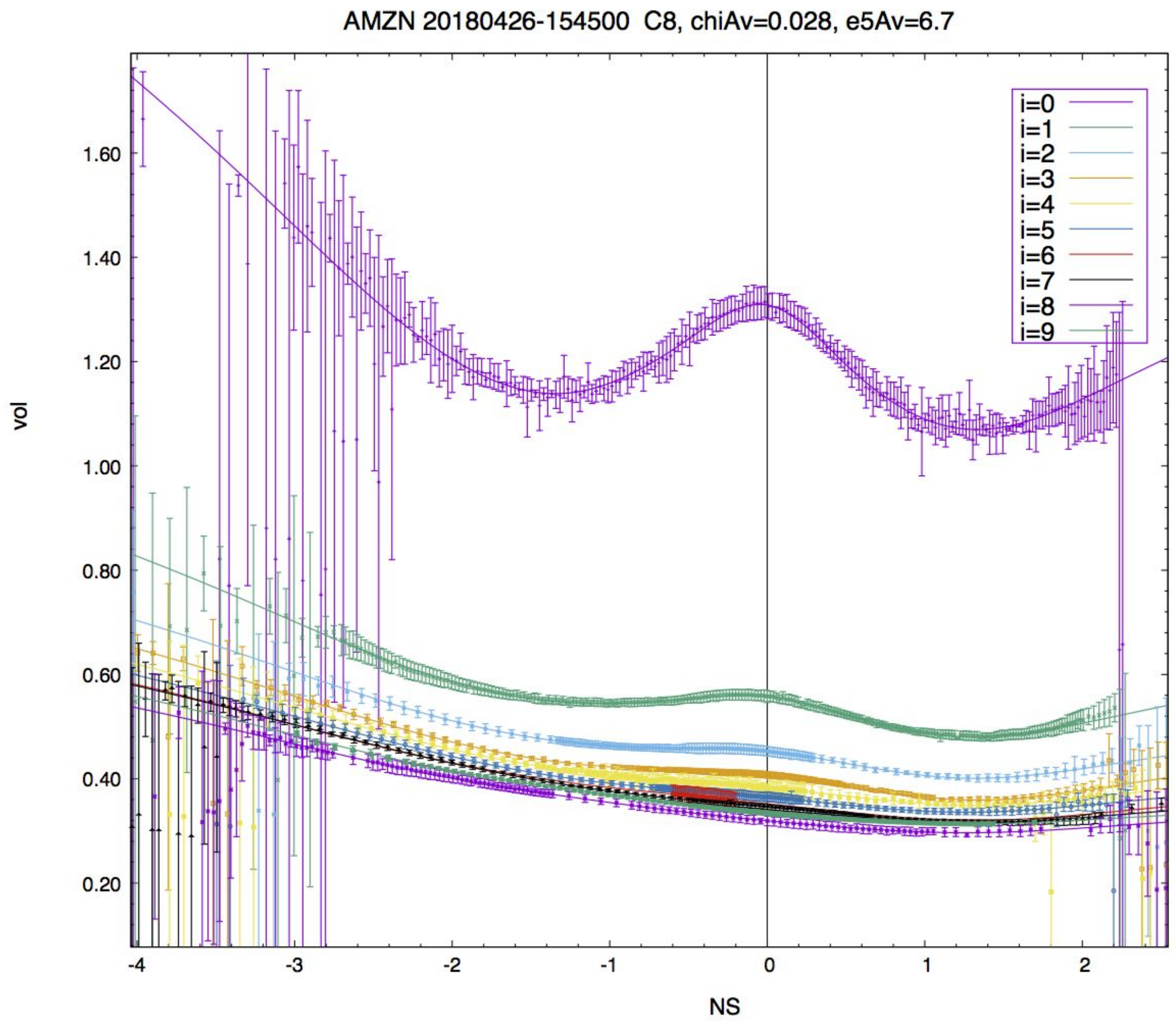
with error bars

AEX on day before Brexit vote:

T=2d, vols and implied density (AEX dropped 5.9%)







AMZN 2018-04-26 earnings day

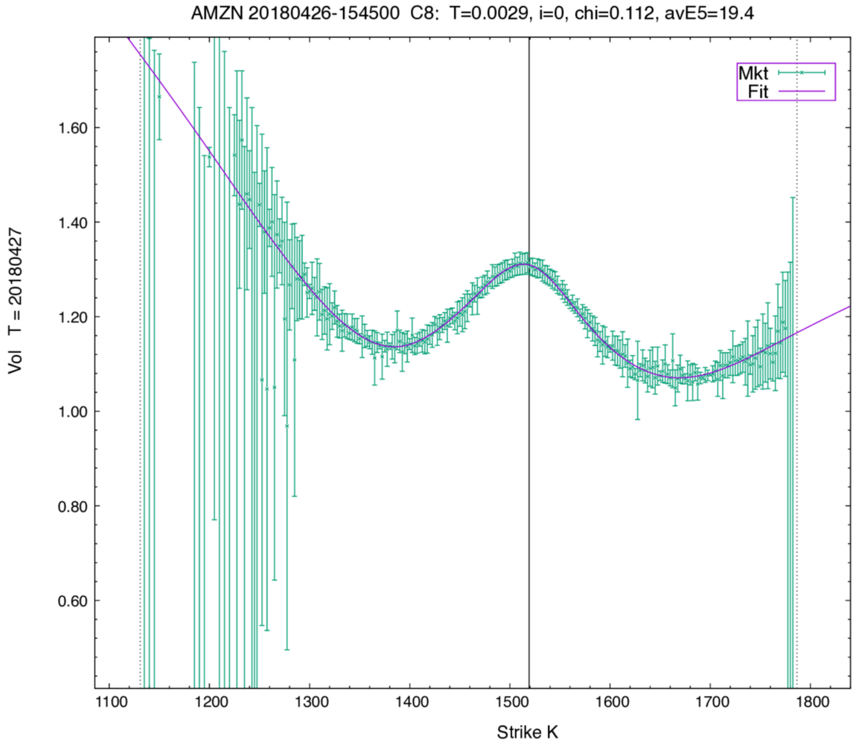
C8 Vol vs NS

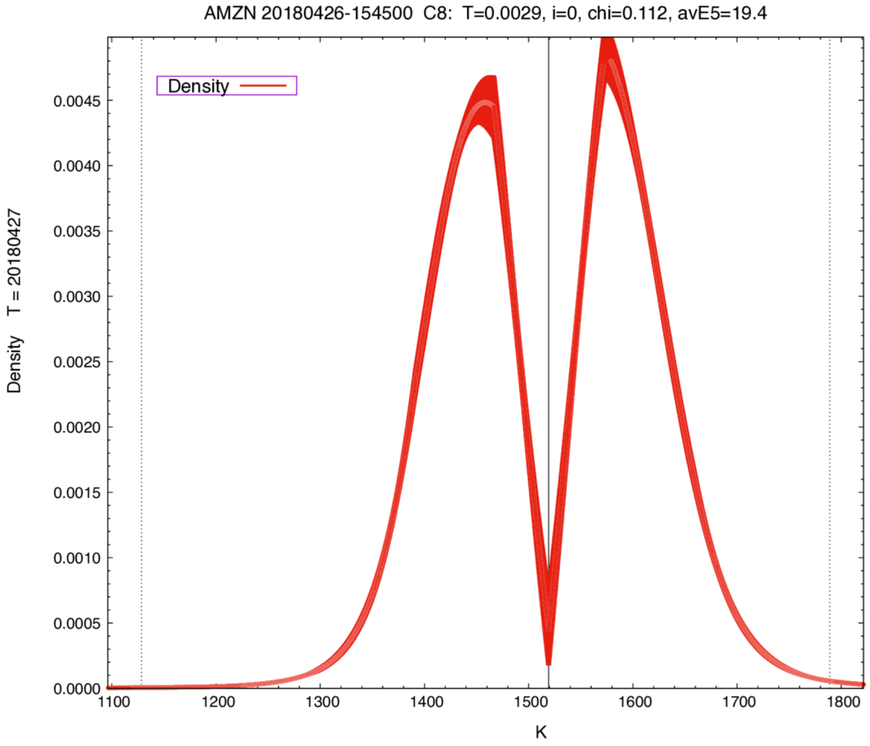
Interesting Thursday: Earnings, new weekly listed (only a few strikes in PW)

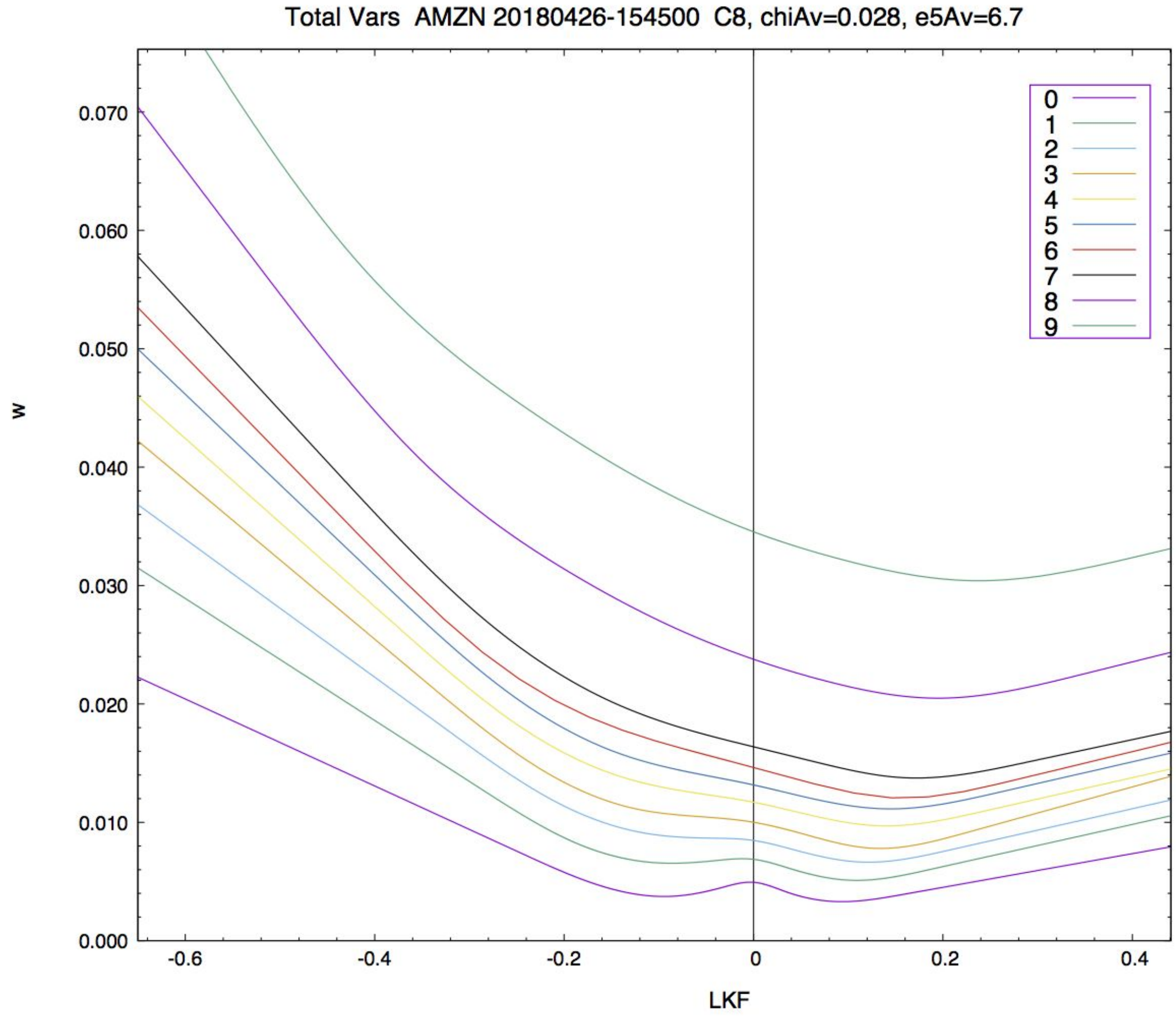
$$z := \mathrm{NS} := \frac{\ln(K/F)}{\sigma_0\sqrt{T}}$$

AMZN 2018-04-26 earnings day:

T=1d, vols and implied density — most bimodal density ever!







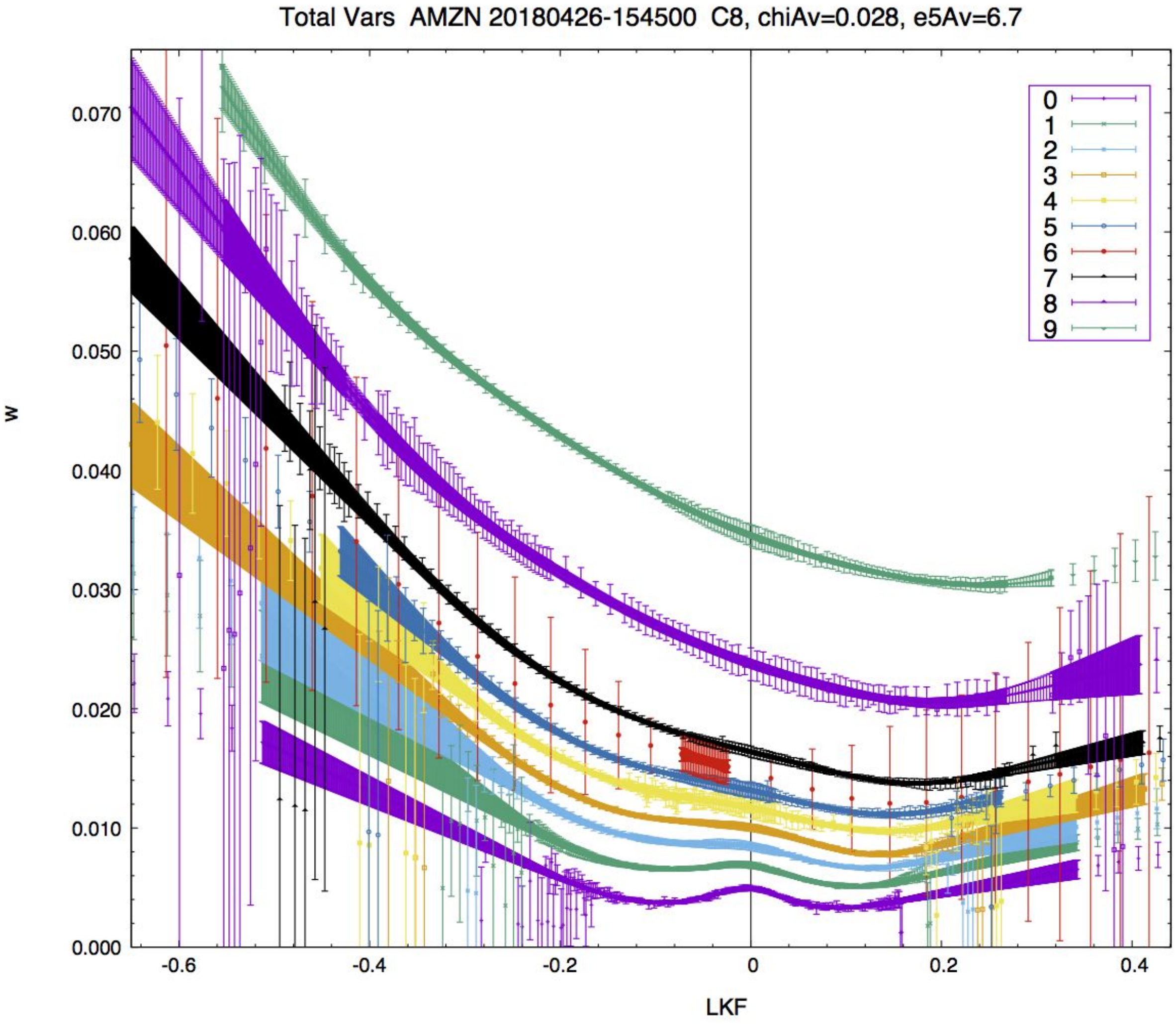
AMZN 2018-04-26 earnings day

C8 total variance plot

First 10 terms

No calendar arbitrage! (Or butterfly…)

Interesting Thursday: Earnings, new weekly listed (**i=6**), etc.

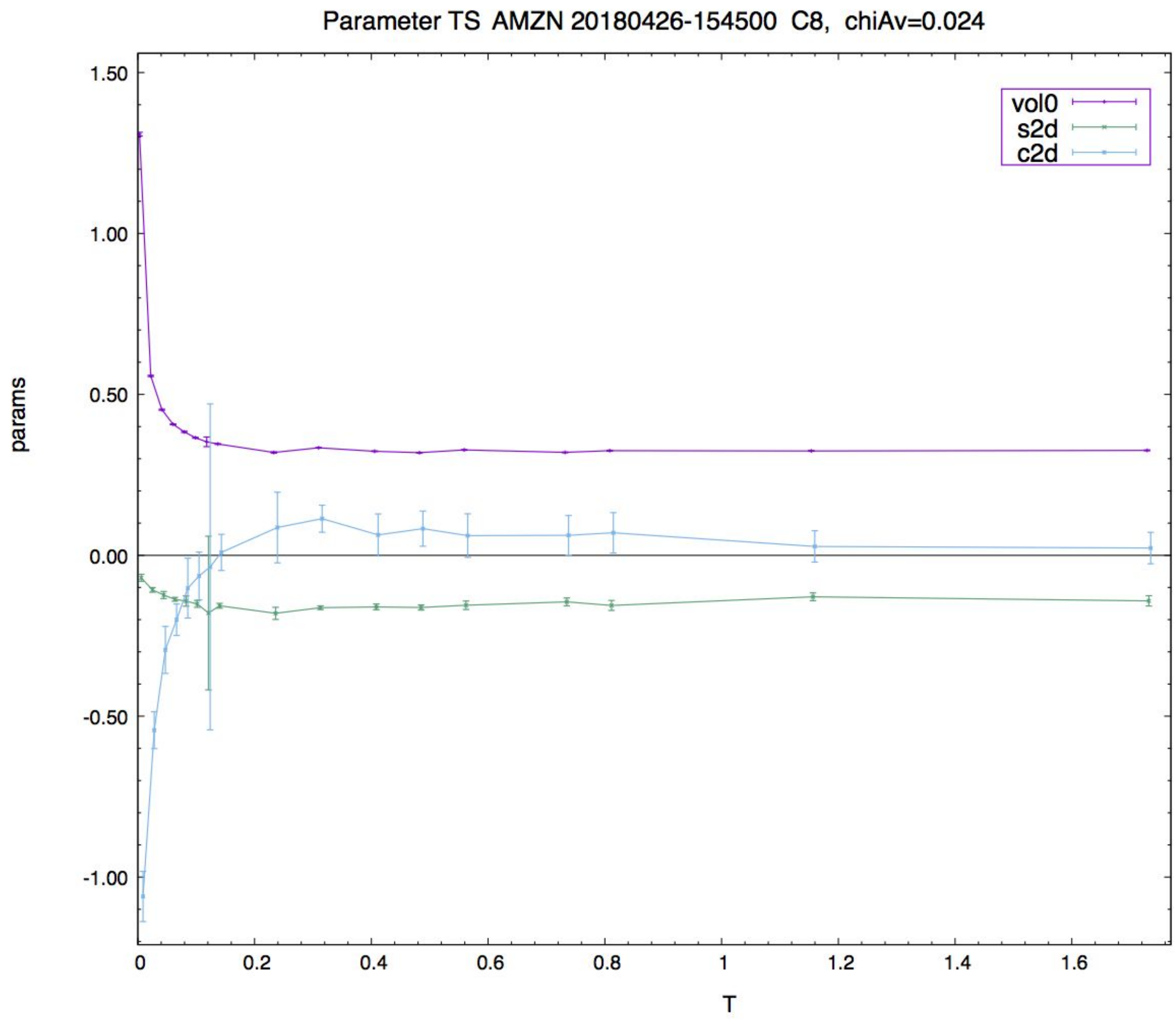


AMZN 2018-04-26 earnings day

C8 total variance plot

First 10 terms, with errors bars

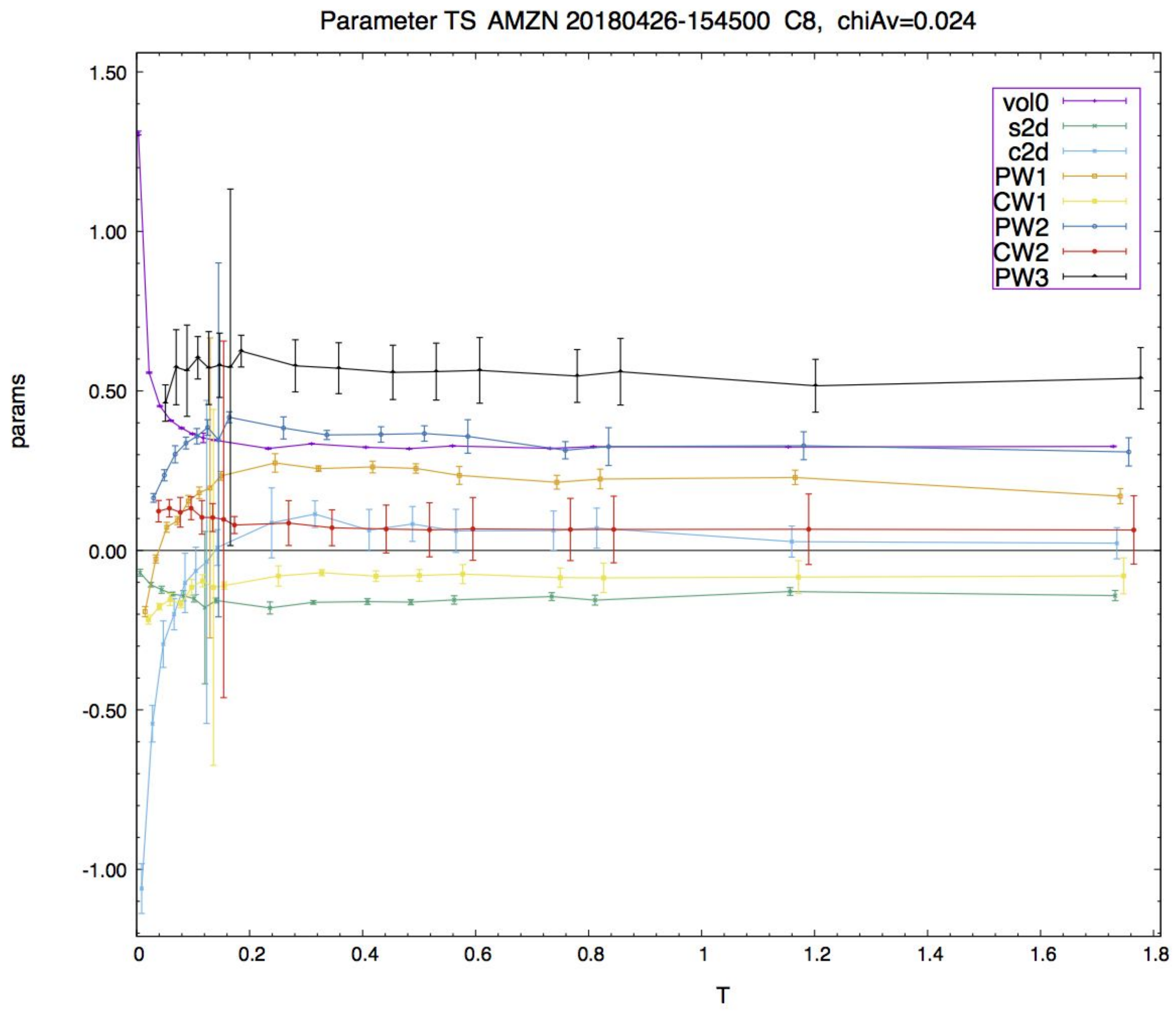
Interesting Thursday: Earnings, new weekly listed (i=6), etc.



AMZN 2018-04-26 earnings day

C8 parameter term-structure
First 3: vol0, s2, c2

Essentially flat shape params after 3m



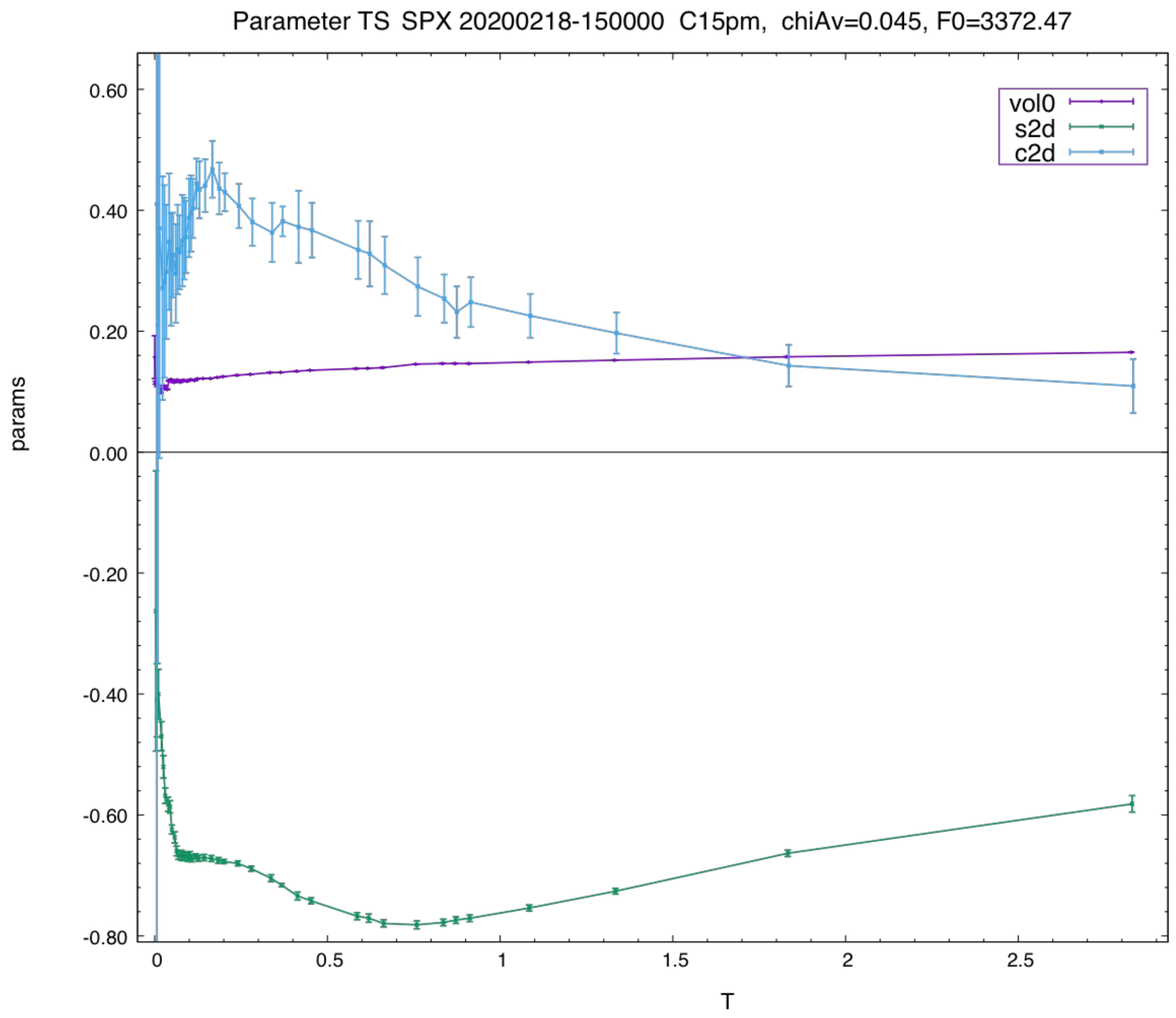
AMZN 2018-04-26 earnings day

C8 parameter term-structure

Essentially flat shape params after 3m

SPX during the covid crash of March 2020

- SPX vol curves and surfaces had unprecedented shapes.
- Supposedly even some Tier 1 bank(s) didn't manage to produce a tradable SPX surface for 2 days (e.g. arbitrage-free).
- But the options market functioned perfectly fine at all times and those "funky" shapes reflected quite precise & consistent forward-looking views.



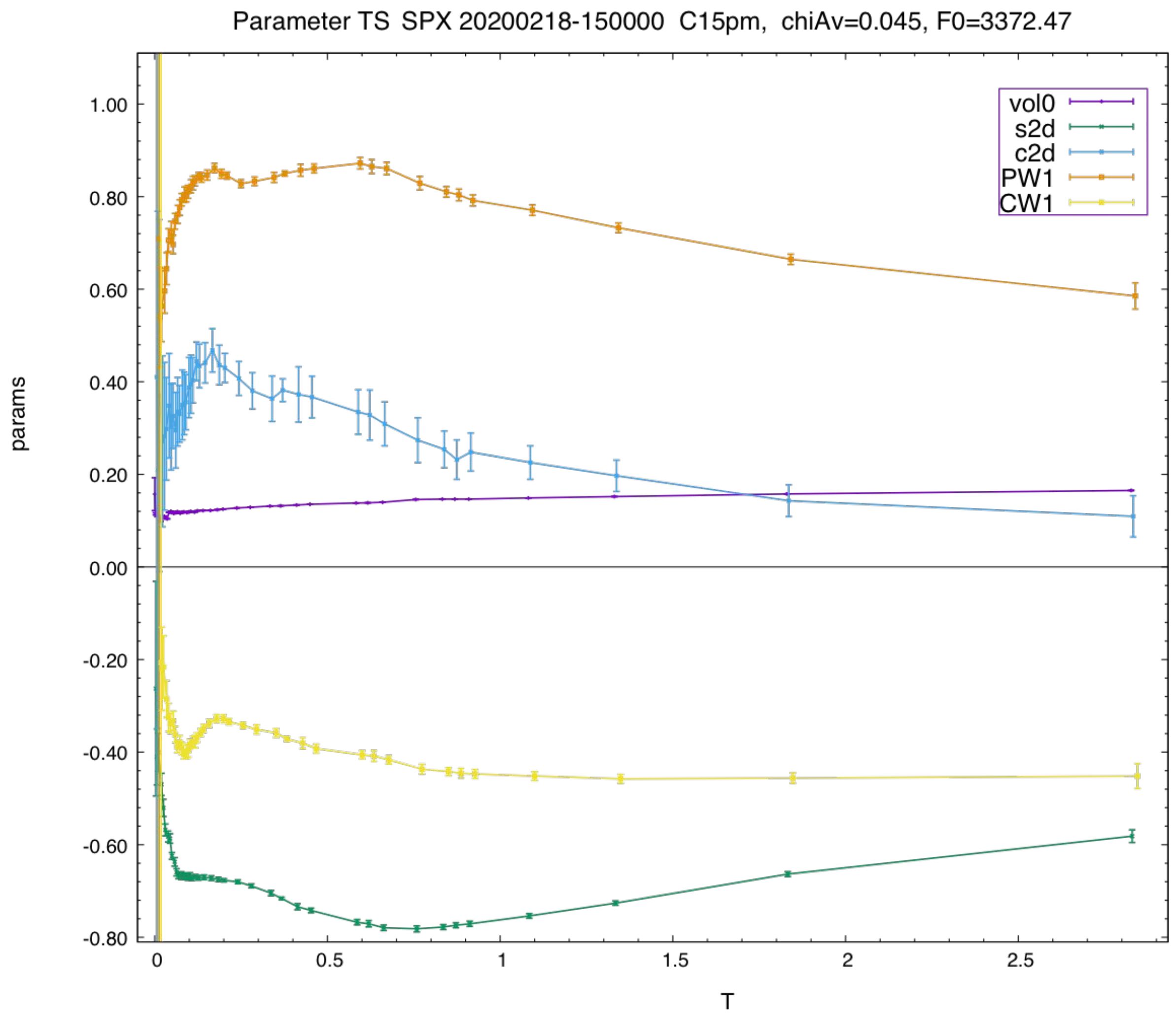
For reference: 3w before big covid crash…

SPX 20200218 15:00

C15PM Param Term-Structure

First 3 params…

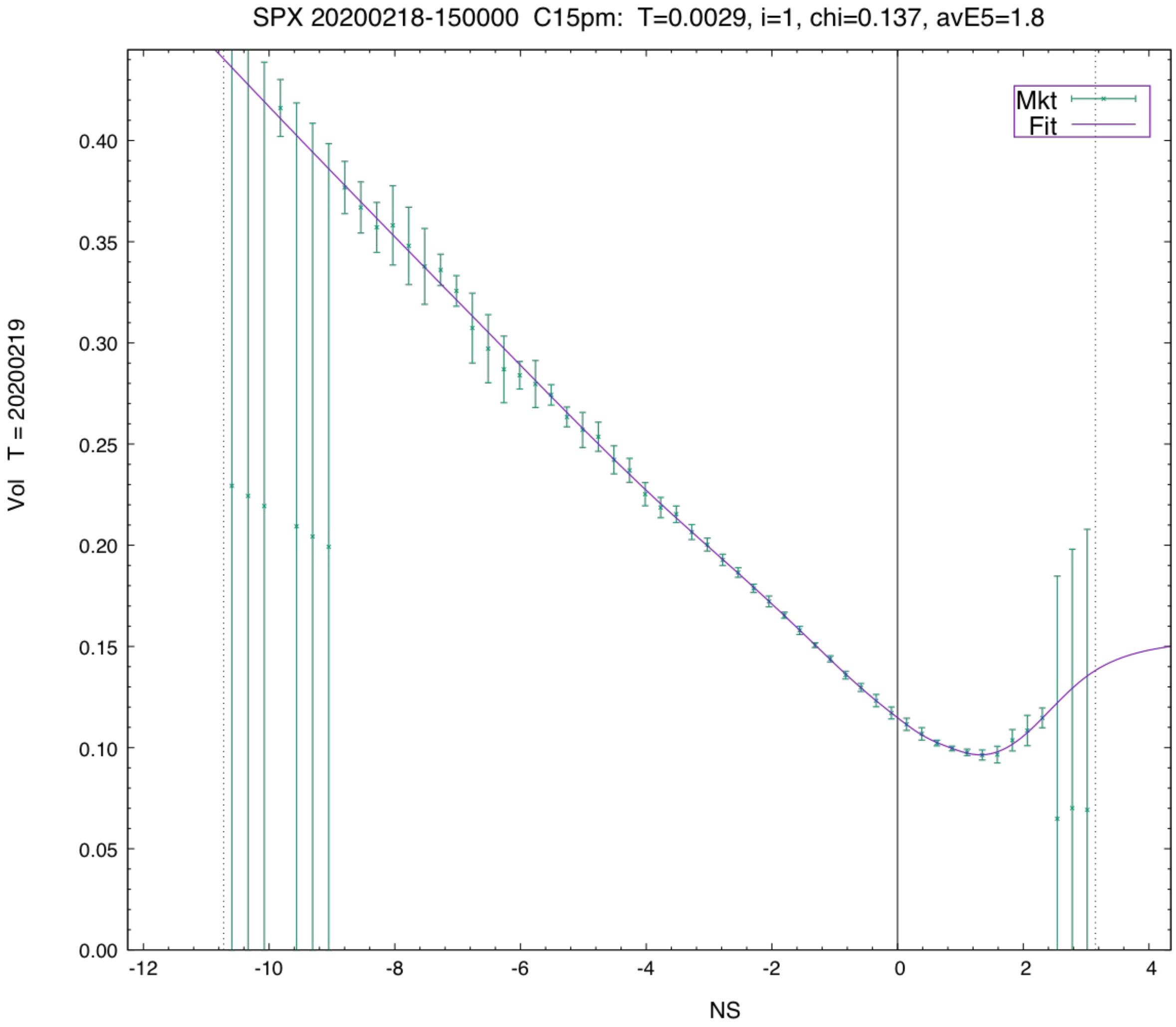
s2(T) a bit unusual…



SPX 20200218 15:00

C15PM Param Term-Structure

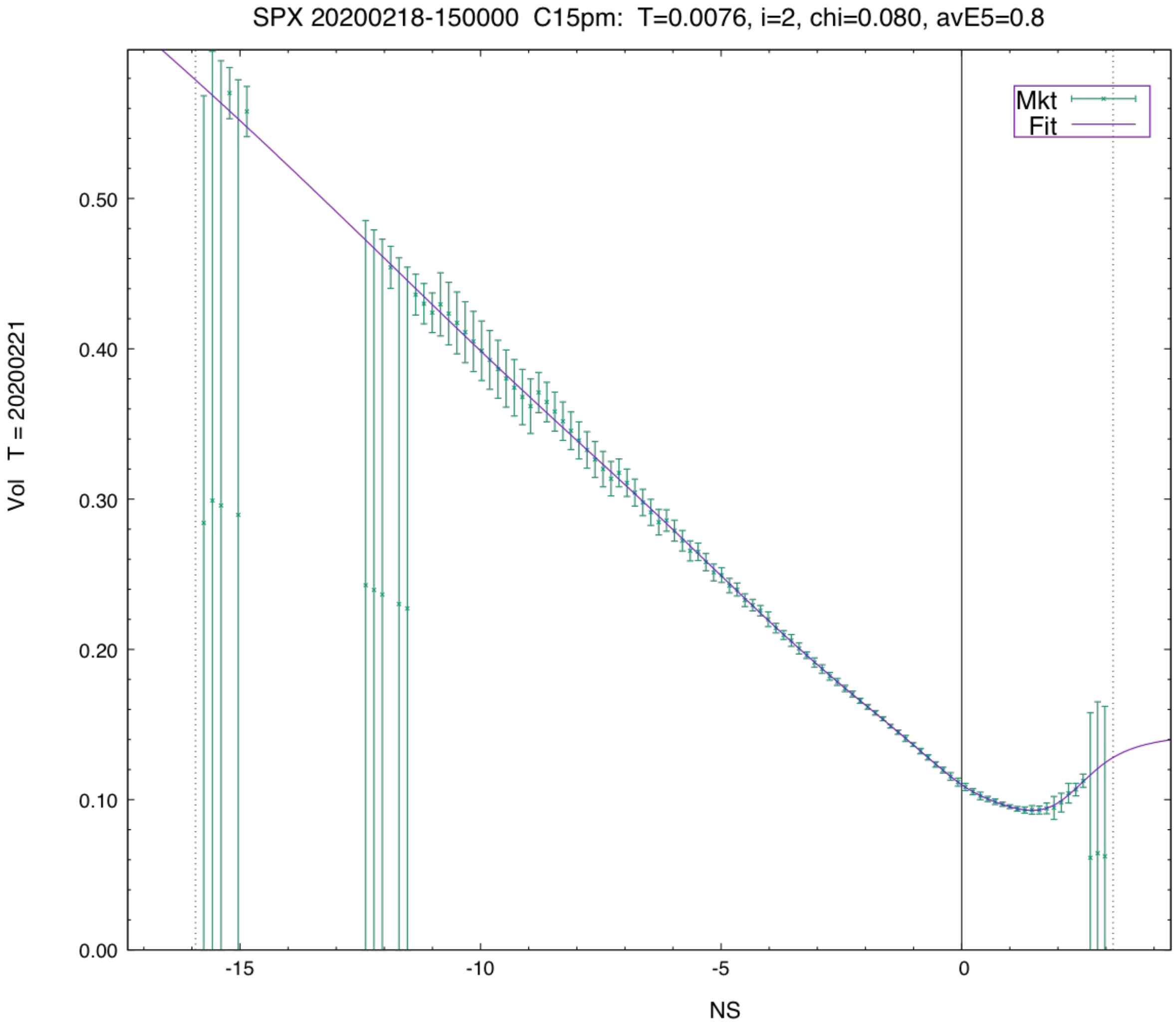
First 5 params… meaning?



SPX 20200218 15:00

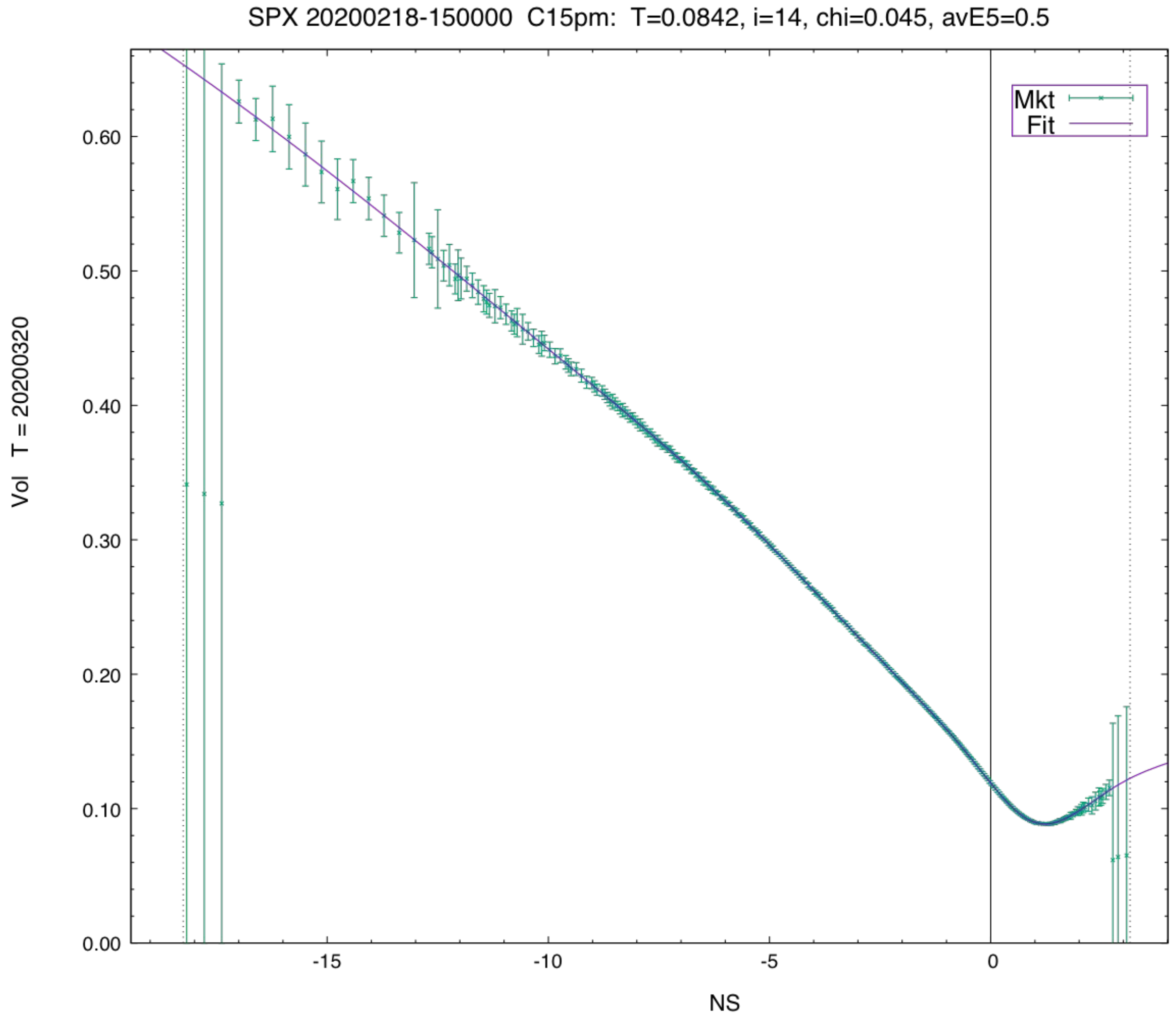
C15PM T = 1d

$$z := \mathrm{NS} := \frac{\ln(K/F)}{\sigma_0\sqrt{T}}$$



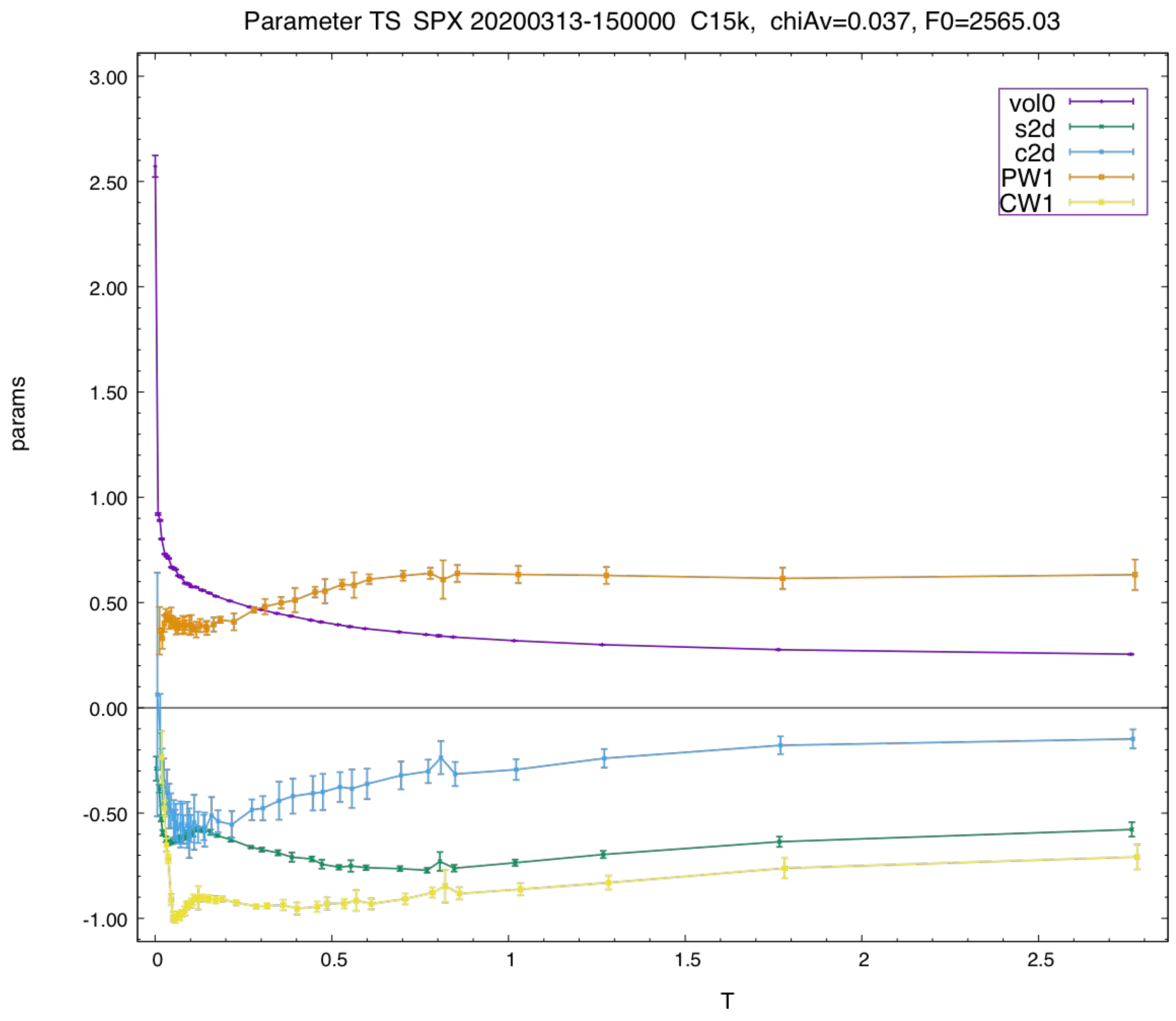
SPX 20200218 15:00

C15PM T = 3d



SPX 20200218 15:00

C15PM T = 1m



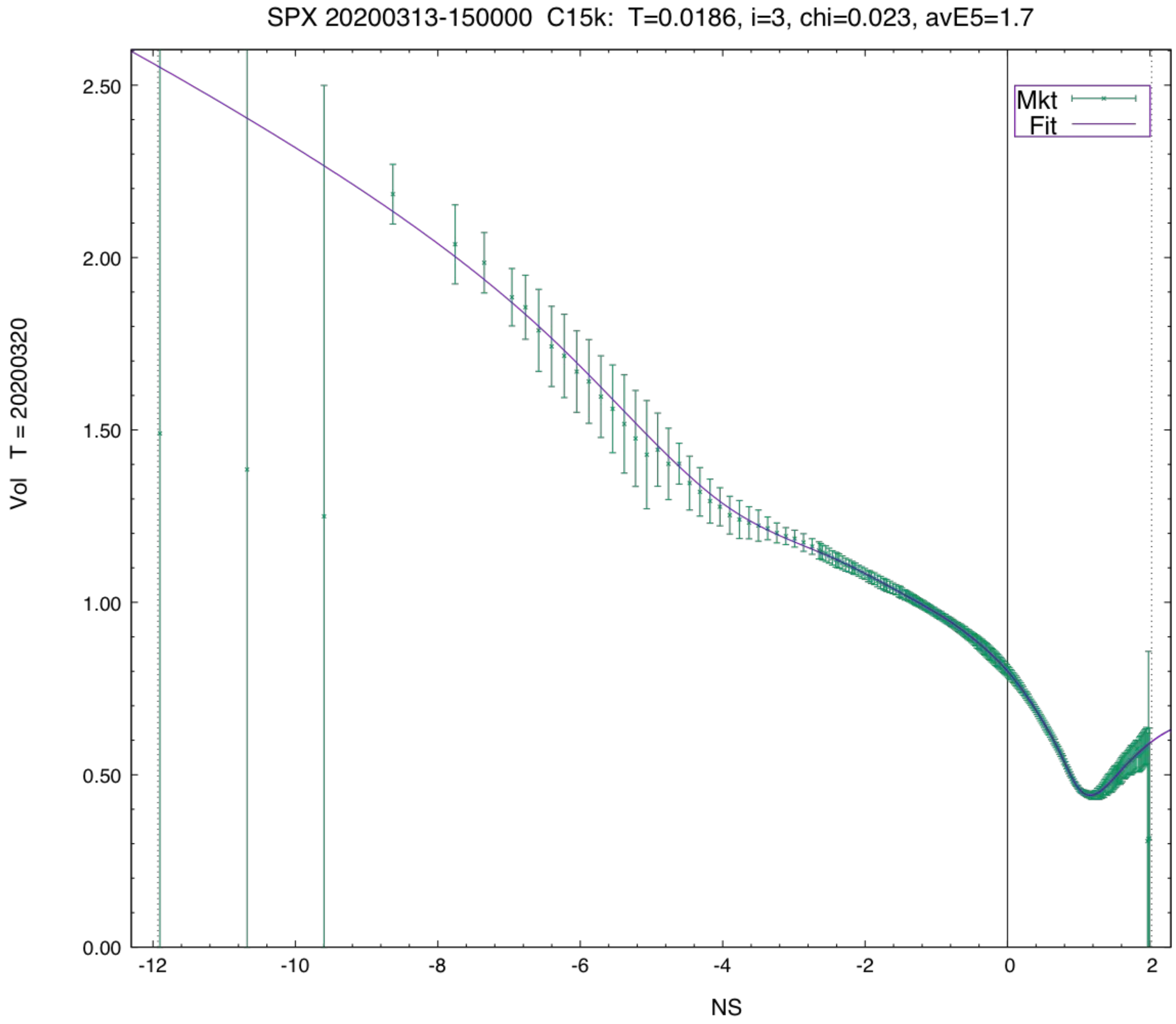
SPX 20200313 15:00

C15K Param Term-Structure during the **covid crash**

First 5 params…

All **c2** < 0 !!

Super-steep near call wing: **CW1**

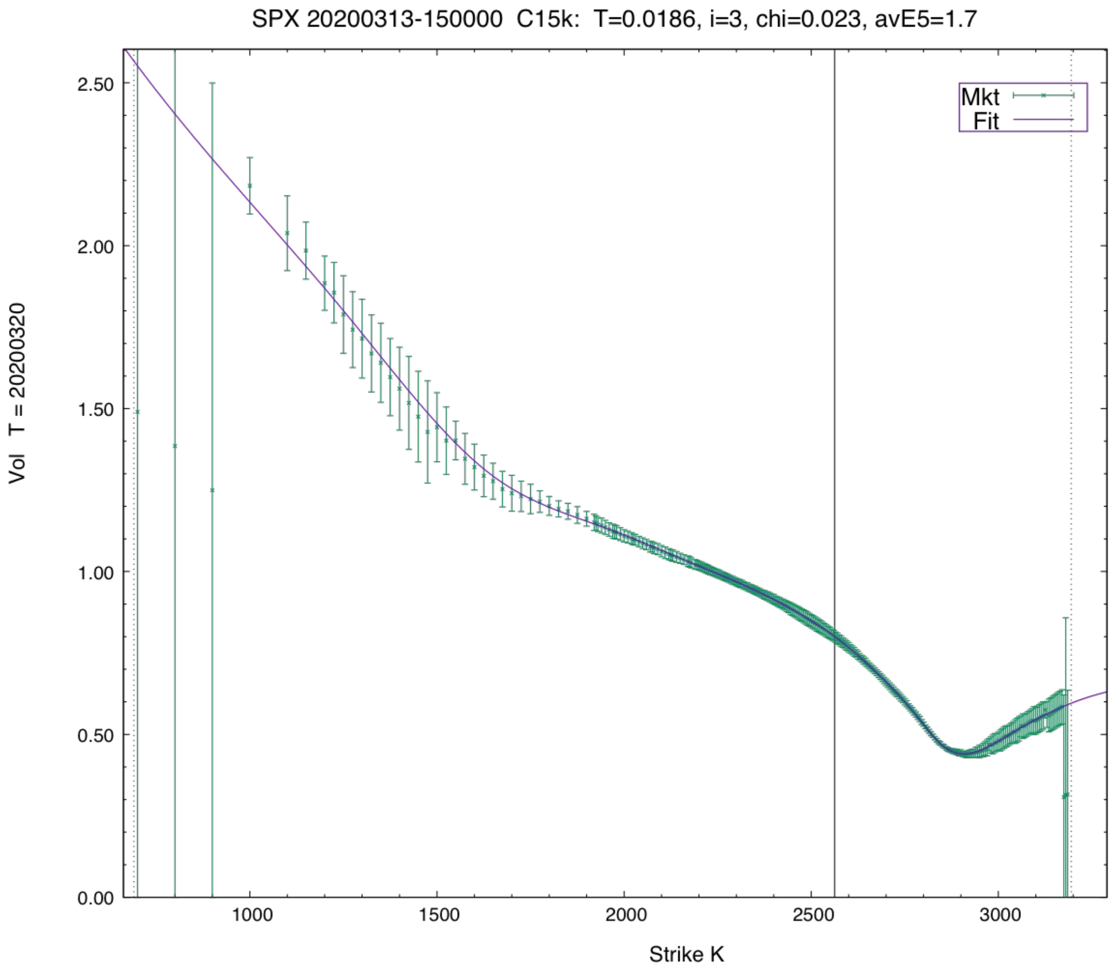


SPX 20200313 15:00

C15K T = 1w, in NS-space

Very compressed CW.

If fit followed PW more closely there would be fly arb…



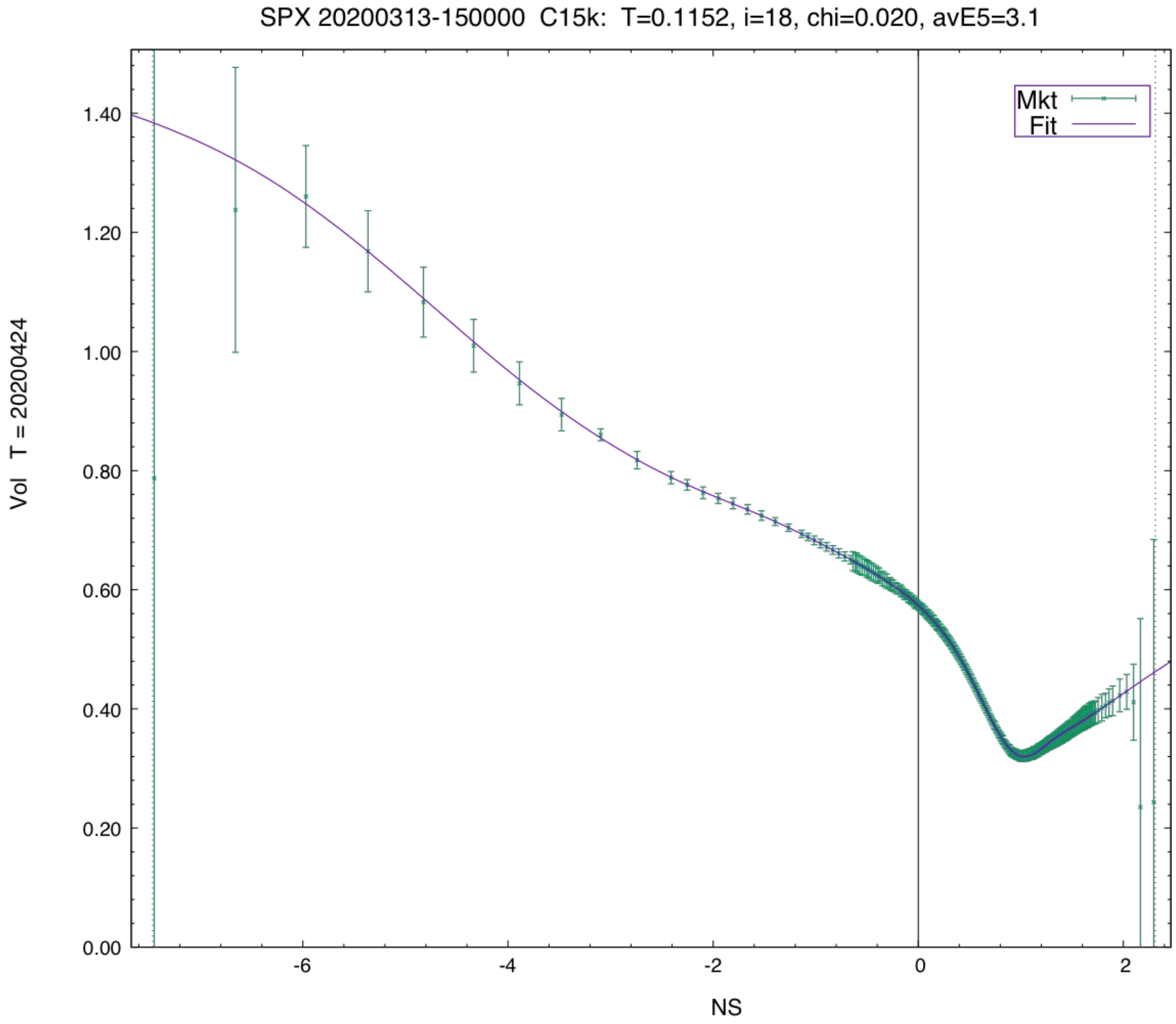
SPX 20200313 15:00

C15K T = 1w, in K-space

Very compressed CW.

If fit followed PW more closely there would be fly arb…

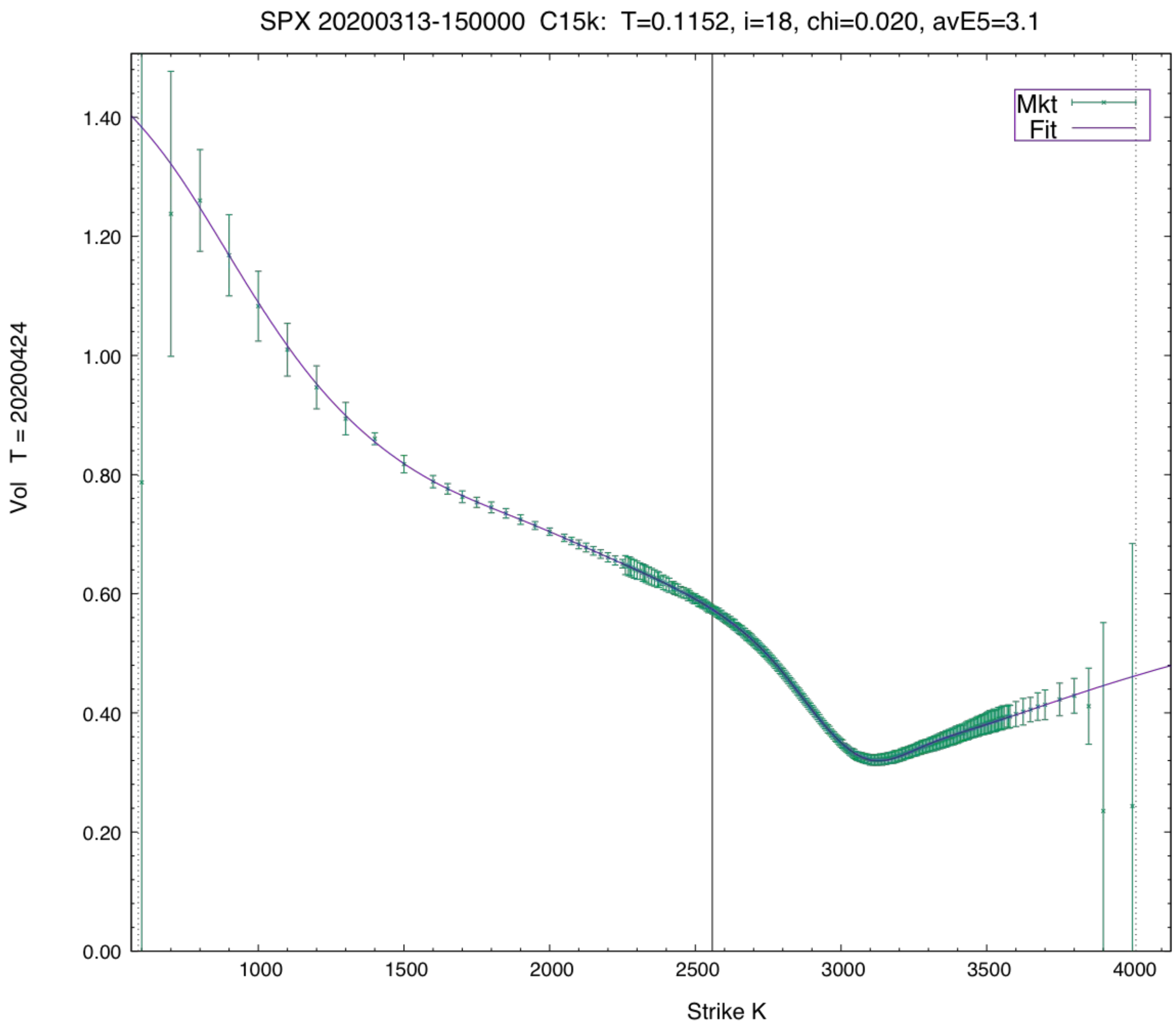
(Pretty well-functioning market over nK=379 strikes here…)



SPX 20200313 15:00

C15K T = 6w, in NS-space

Very compressed CW, very sharp knee…

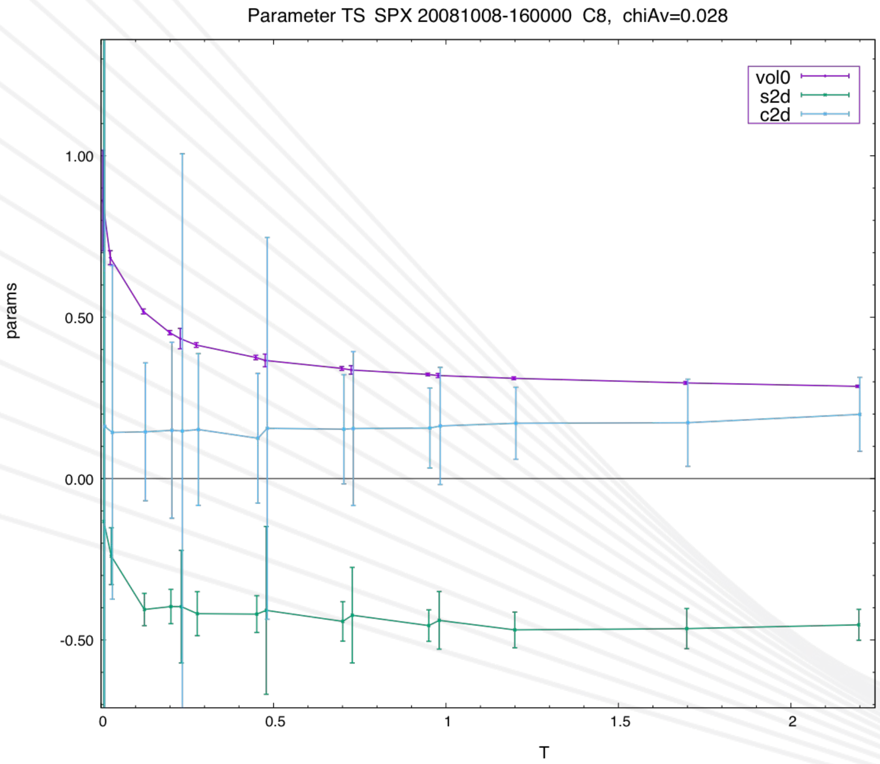


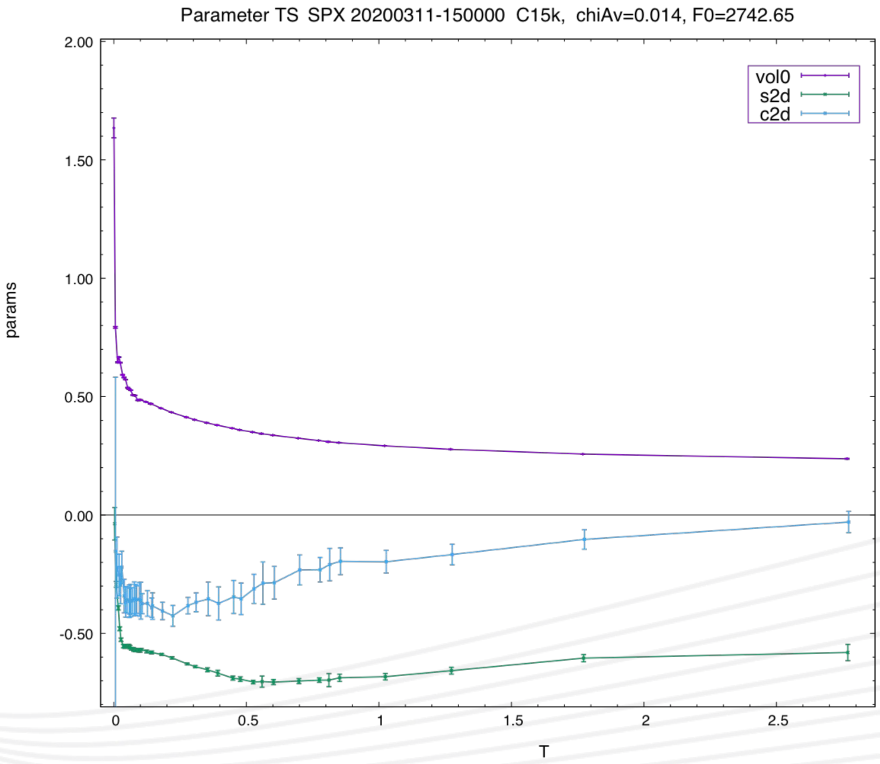
SPX 20200313 15:00

C15K T = 6w, in K-space

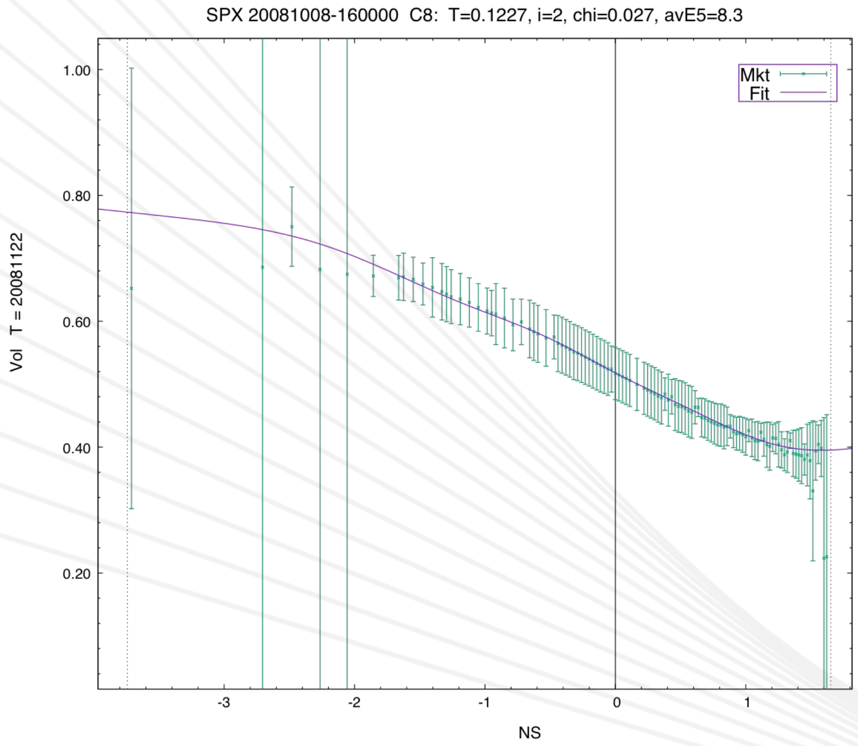
Very compressed CW, very sharp knee…

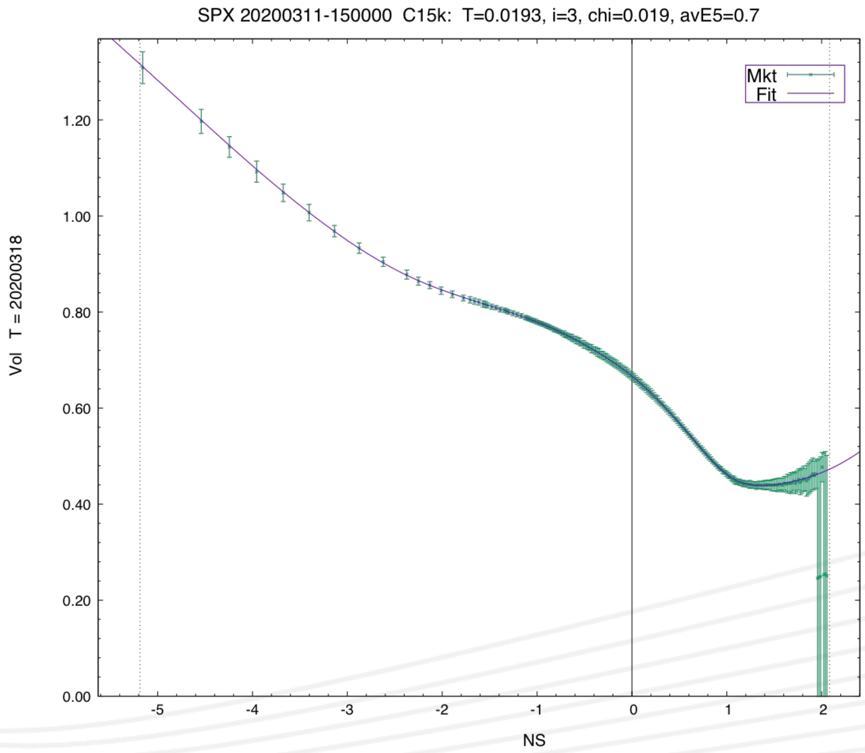
Parameter TS: 2008 versus 2020





Vol Skews: 2008 versus 2020





Vol Curve Statistics

- There are ~5630 names in OPRA (Oct 2023). We find, roughly, for bias-free fits:
  - 4100 (73%) can be fit with S3/SSVI. (S5/SVI: 70 or 1.2%)
  - 650 (11.5%) can be fit with C5.
  - 700 (12.4%) can be fit with C6, C7*, C8* C9*.
  - There are a 70 inverse curves (C6C+) for VIX, VXX, (inverse) leveraged ETFs, low-priced stocks.
  - The remaining 50 (0.9%) names require higher C10 – C16 curves – the most liquid names!
- SPX/SPY/ES require ~16-18 parameters (for some terms) to get bias-free fits of all options down to zero-bids. Some OMMs use ~25 params for SPX.
- Big tech names and (other) global indices require 9 –15 params per term.
- There has been a relentless drive towards higher curves, to fit tighter spreads and wider (normalized) strikes ranges.
  - Empirically, roughly (for OPRA universe): $nParams \approx (nOptions / 5)^{1/3}$

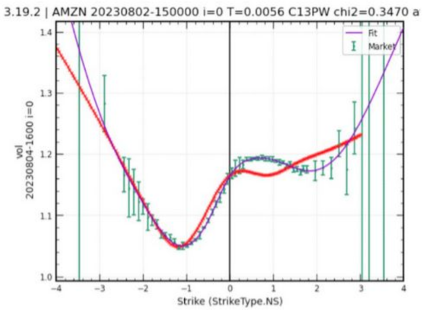
Event Modeling

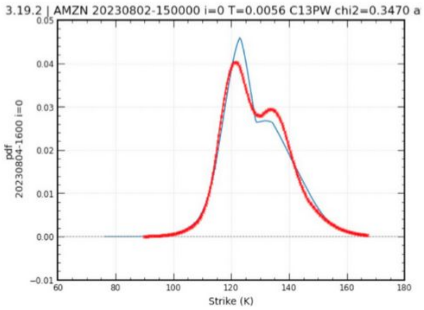
- Modeling an event like earnings properly requires a jump model.
  - With events at specific, non-random time(s).
- Minimal proper model: Two "**Merton Event Jumps**", on top of a diffusive process, described by a "clean" aka "background" vol surface.
  - Various assumptions are possible about how to combine the clean surface with jumps.
  - Pricing: sum of Black formulas with an integral over jump sizes.
  - This is a ~proper model, unlike just describing the pdf of some expiry with a sum of log-normals, aka the Log-Normal Mixture "Model".
  - So, one can ask if different expiries are **consistent with the same jumps**, and similar non-trivial questions.

AMZN 2023-08-02 earnings

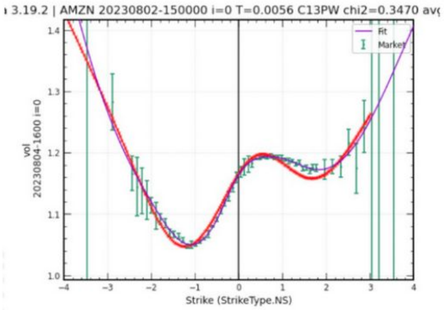
Calibrating three 2-jump models, with 2,3,4 parameters:

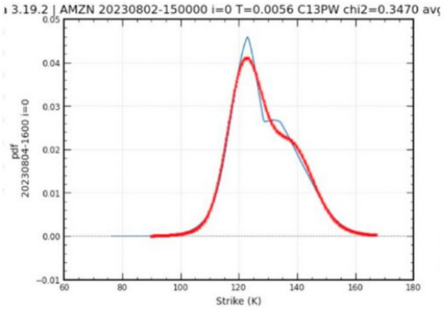
```
ASYMMETRIC_DISCRETE_JUMP
J = [0.955, 1.071]
p = [0.613, 0.387]
s = [0.000, 0.000]
```



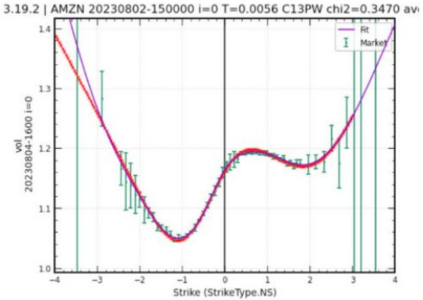


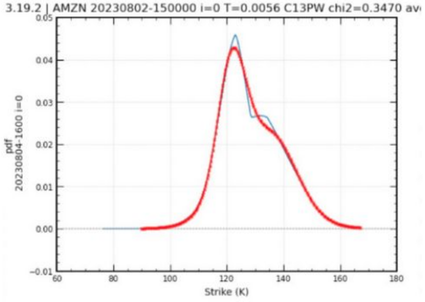

```
ASYMMETRIC_MERTON_JUMP
J = [0.956, 1.084]
p = [0.654, 0.346]
s = [0.045, 0.045]
```






```
ASYMMETRIC_MERTON_JUMPS
J = [0.944, 1.059]
p = [0.516, 0.484]
s = [0.037, 0.059]
```

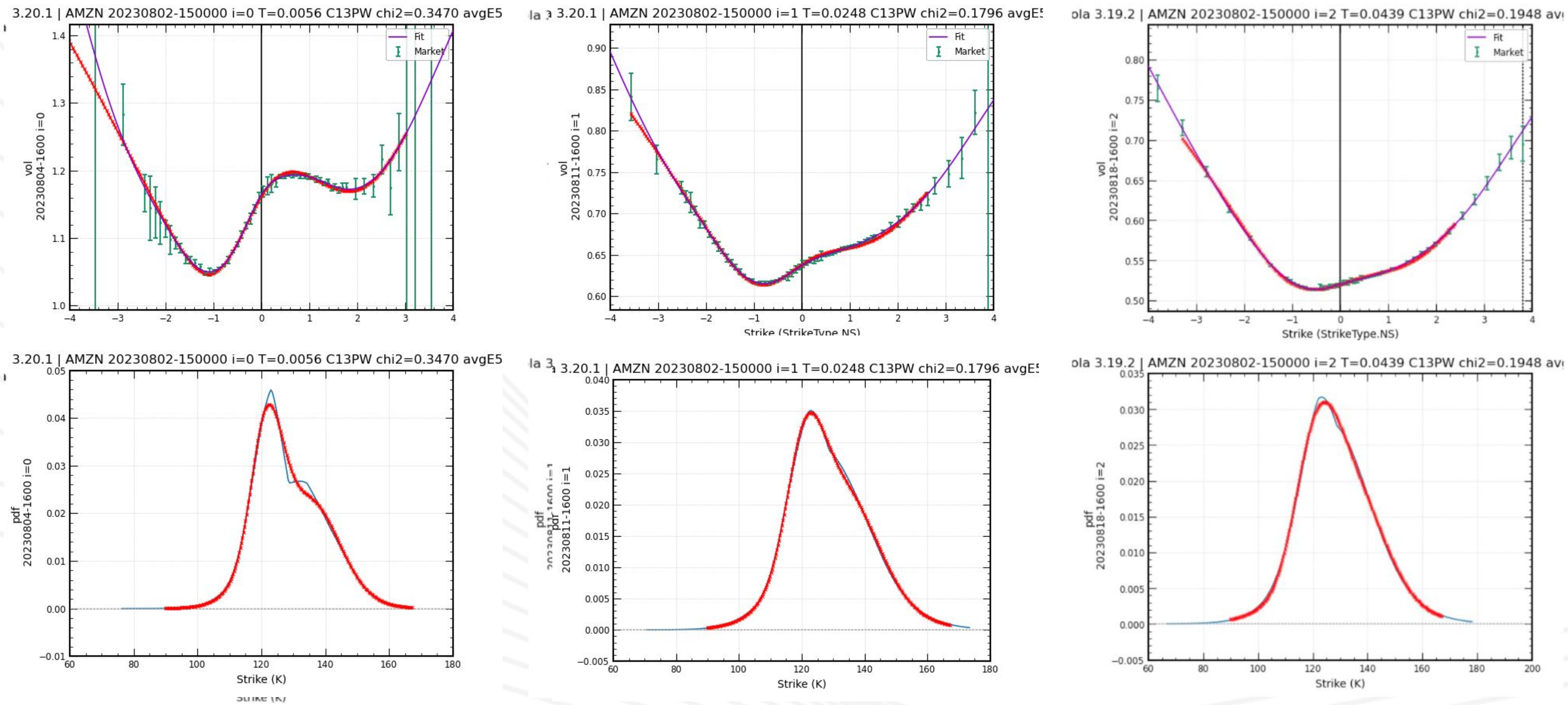





```
vctClean = C5
nAfter   = 3
```

AMZN 2023-08-02 earnings

The best 2-jump model works for three expiries after earnings:

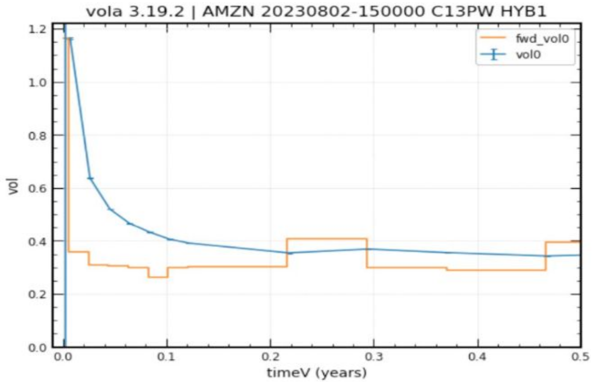


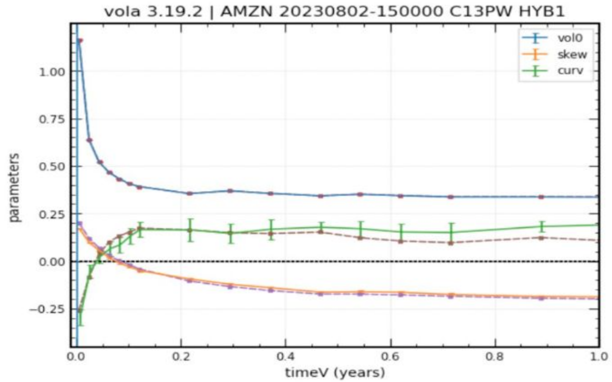
AMZN 2023-08-02 earnings

Though the clean VS is not quite as clean as we would like:

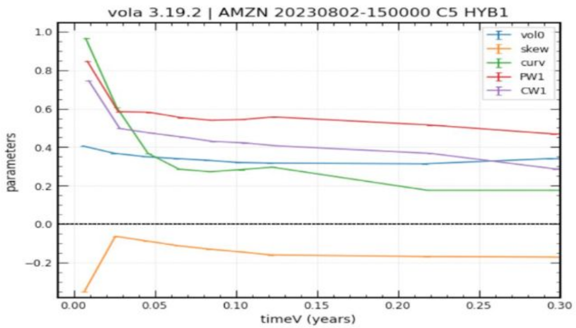
Analytics for Options Trading

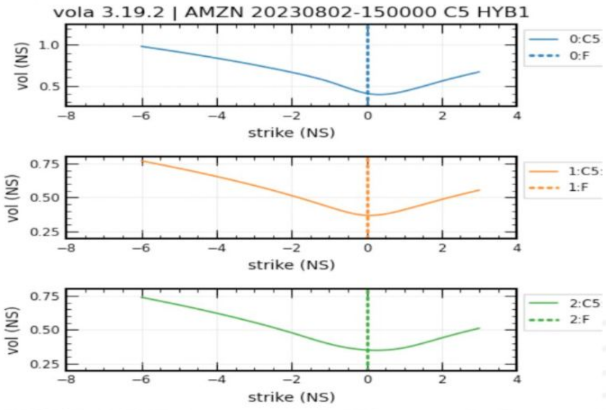
Dirty





Clean



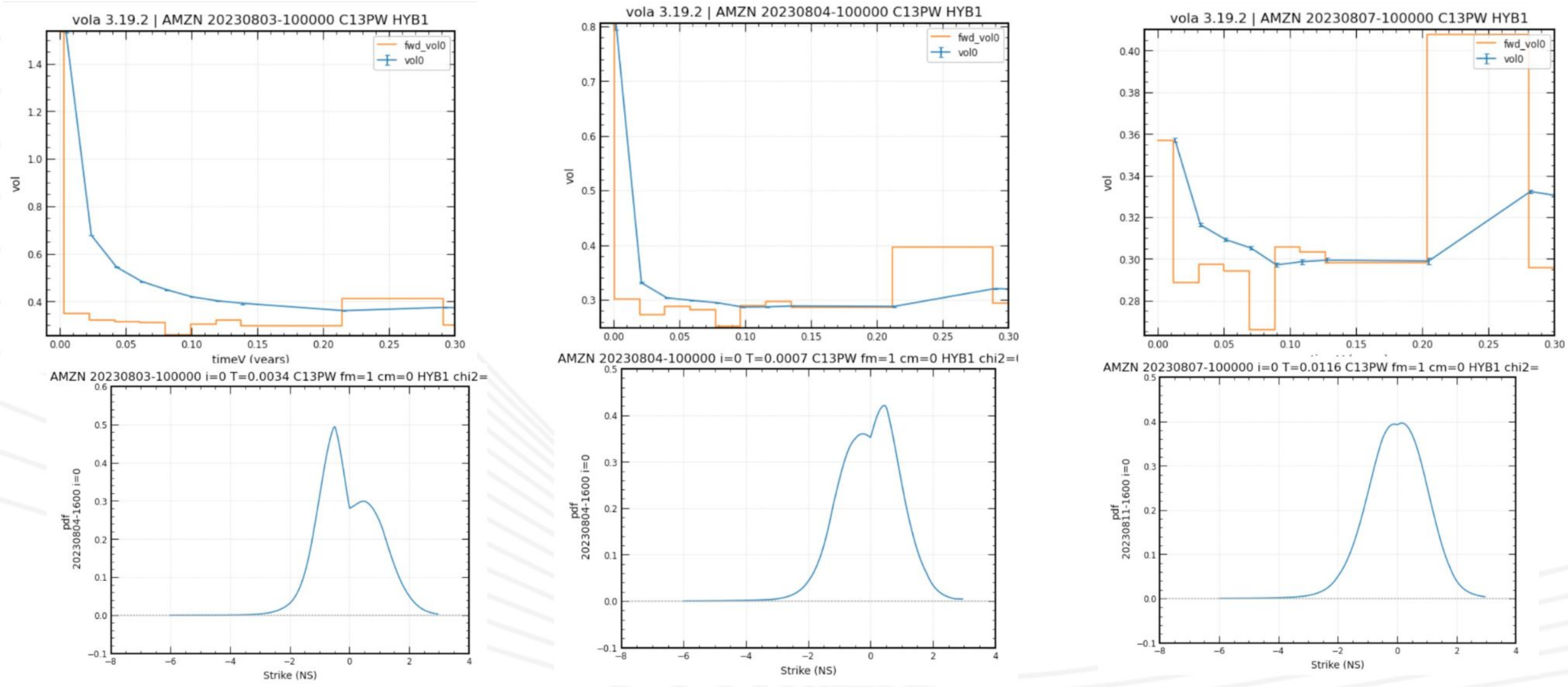


nAfter=3
vctC = C5
MertonJumps

```
J= [1.0594025258161424, 0.9441995069221296]
p= [0.48436658703542335, 0.5156334129645767]
s= [0.0588065555709617, 0.03688014214112789]
```

AMZN 2023-08-02 earnings

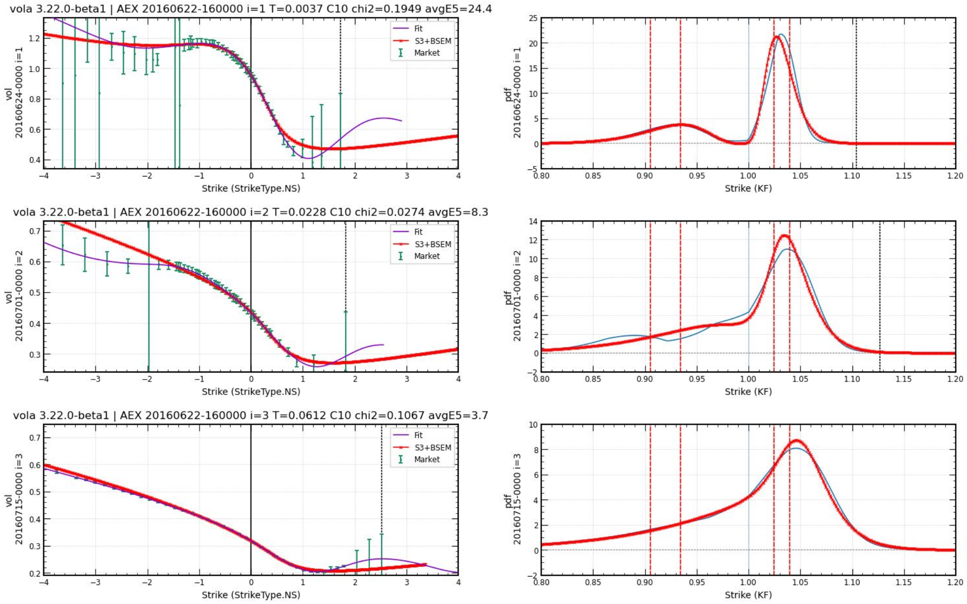
The event is not quite discrete in time, there are “**aftershocks**”:

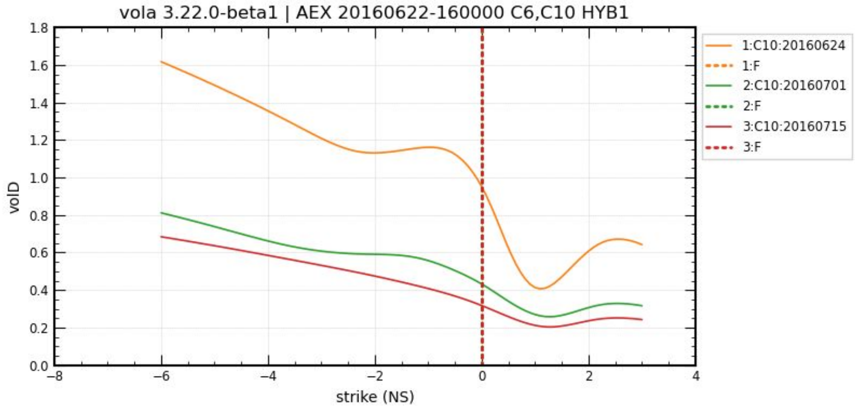


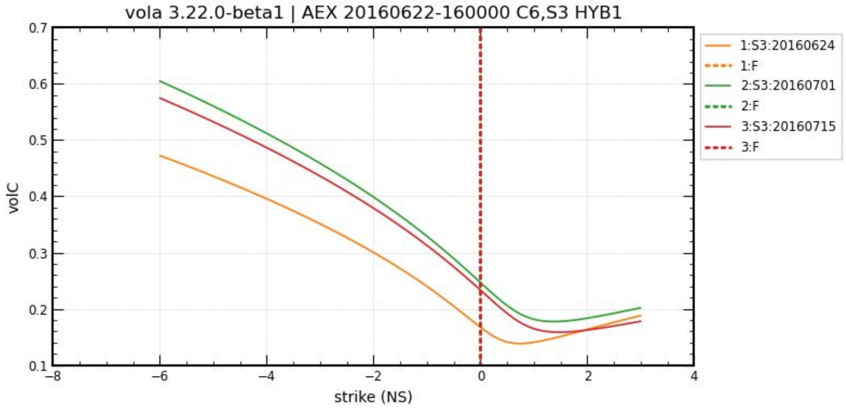
AEX before Brexit

Calibrated jump params:

```
J = [0.9201, 1.0322]
p = [0.2870, 0.7130]
s = [0.0146, 0.0076]
```





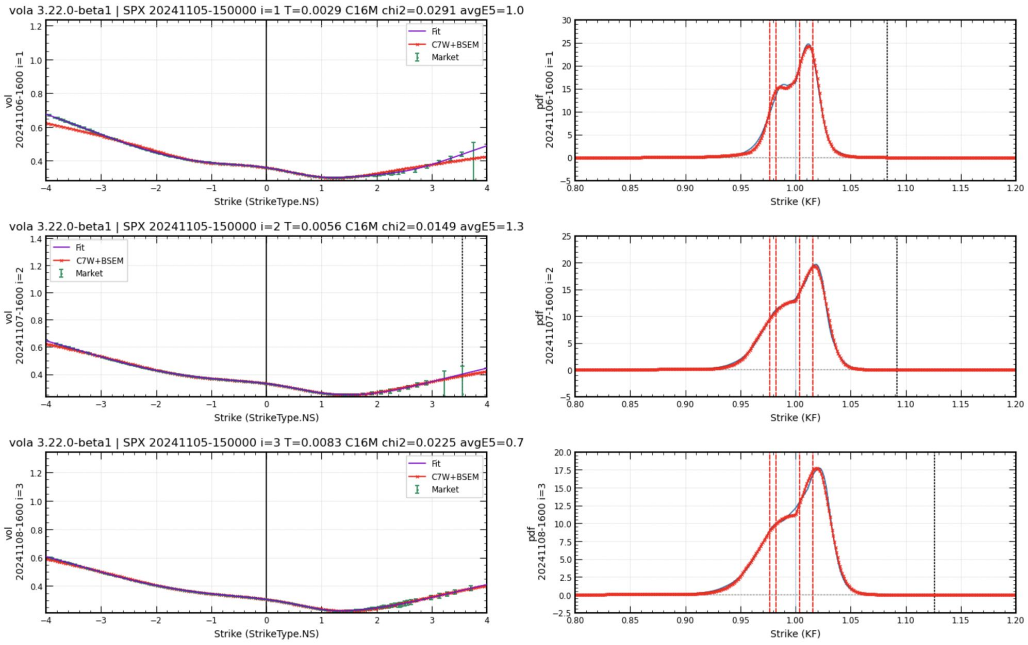


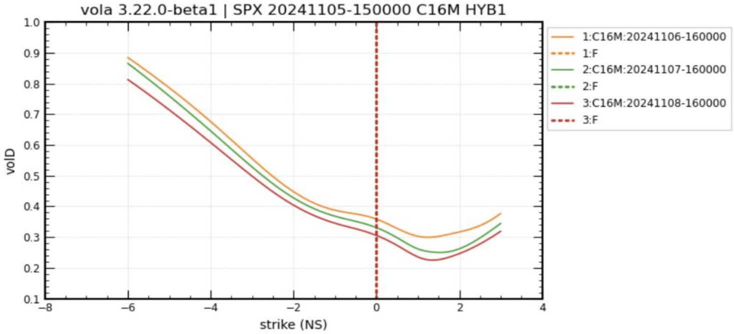
SPX before 2024 election

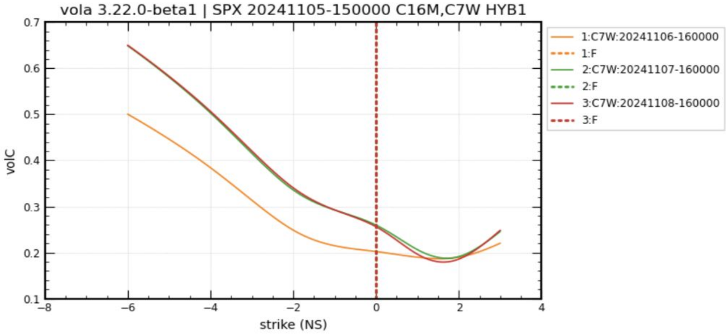
Calibrated jump params:

J = [0.9795, 1.0096]
p = [0.3183, 0.6817]
s = [0.0028, 0.0061]

- Calibration performed with just the i=1 expiry, followed by dirty → clean Vol surface conversion performed with the calibrated event shown above.
- The calibrated clean Vol Surface exhibits the presence of an aftershock.

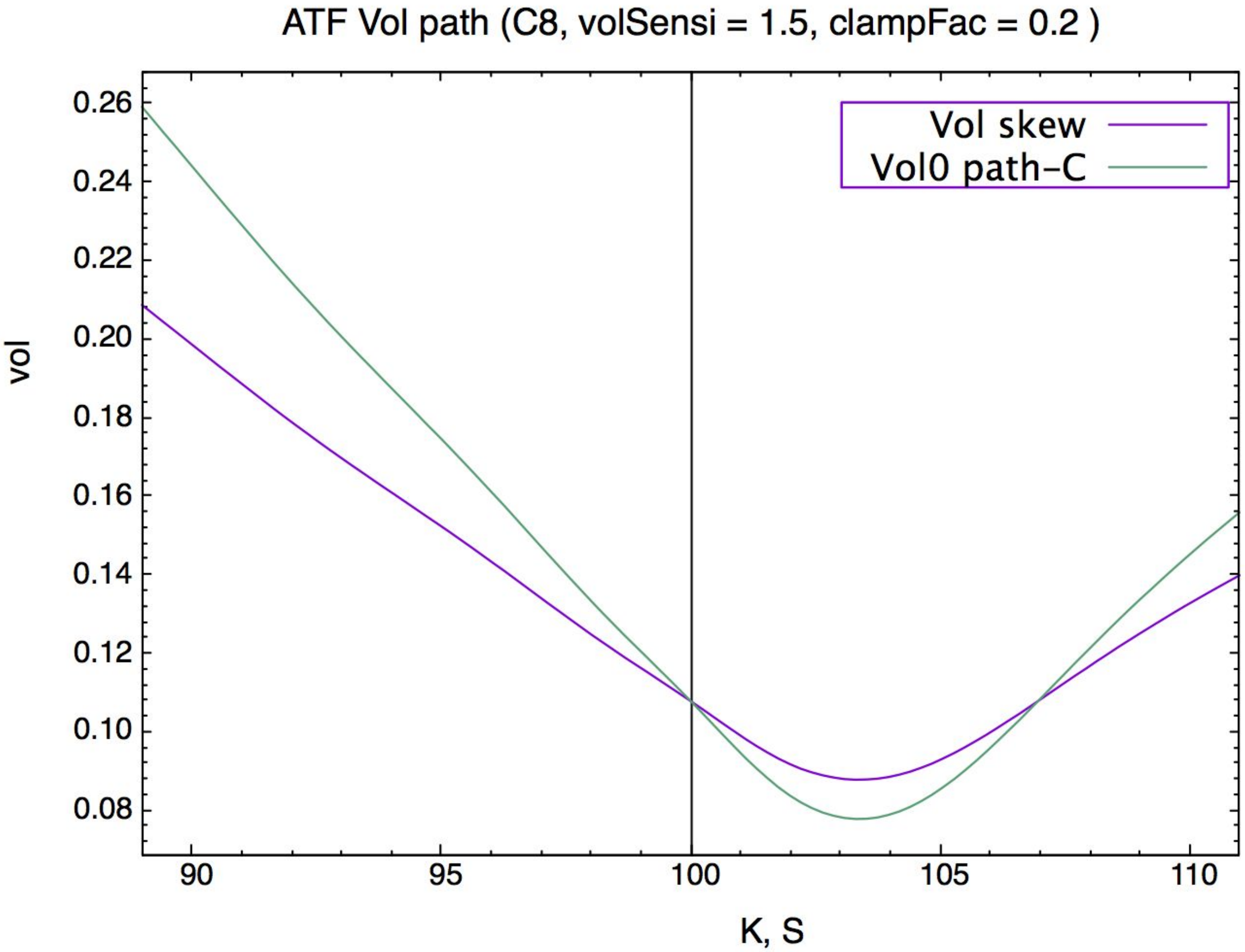






Spot-Vol Dynamics: Basics

- **Shape** (by NS or Δ) is much more **stable** than overall vol level (vol0 aka ATF vol).
- **ATF vol dynamics** is very well described by one dimensionless number, **SSR** aka vol sensitivity aka super-skew, which is the ratio of vol0-path & skew slopes.
- Very **simple dynamics** in terms of NS **vol parameters** (e.g. just ATF vol), gives **complicated vol-by-strike dynamics**, that actually describes market moves.
  - It also gives the correct adjusted (aka smart aka **skew**) **delta** and gamma (see LinkedIn article).
- We will illustrate each of these points.



Spot-Vol Dynamics

ATF “vol path”

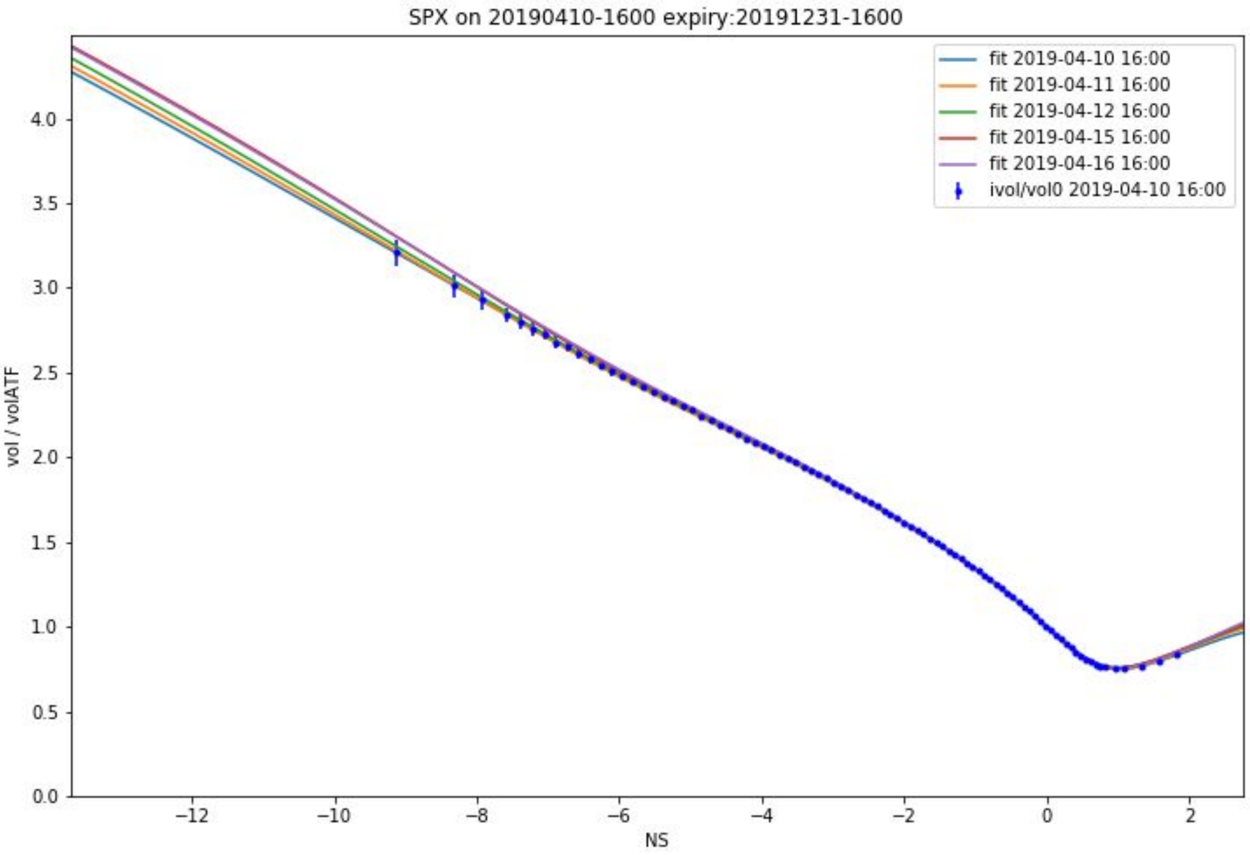
SSR = 1.5

“Along curve”

No clamps

SPX Spot-Vol Dynamics: Then and Now

- In the olden days:
  - Virtually no shape dynamics.
  - Overall vol level dynamics described very well by one SSR with little term-structure (TS).
  - 1 < SSR < 2, with 2 reached only on big down days. Typical value SSR=1.3.
- Nowadays:
  - There is often **term-structure** in SSR, with SSR(T > 1y) closer to typical values.
  - There is occasionally, e.g. on some big down days, **shape dynamics**, eg in c2.
  - **SSR > 2 and SSR < 1** can happen, on short end.
  - Some horizon dependence (1min, 5min, etc), including intraday vs overnight differences.
  - More “fluctuations”, in **path-dependent** manner (cf. Guyon), around typical values.
  - Open Q: How strong is path-dependency effect relative to levels set by “SSR regime” ?

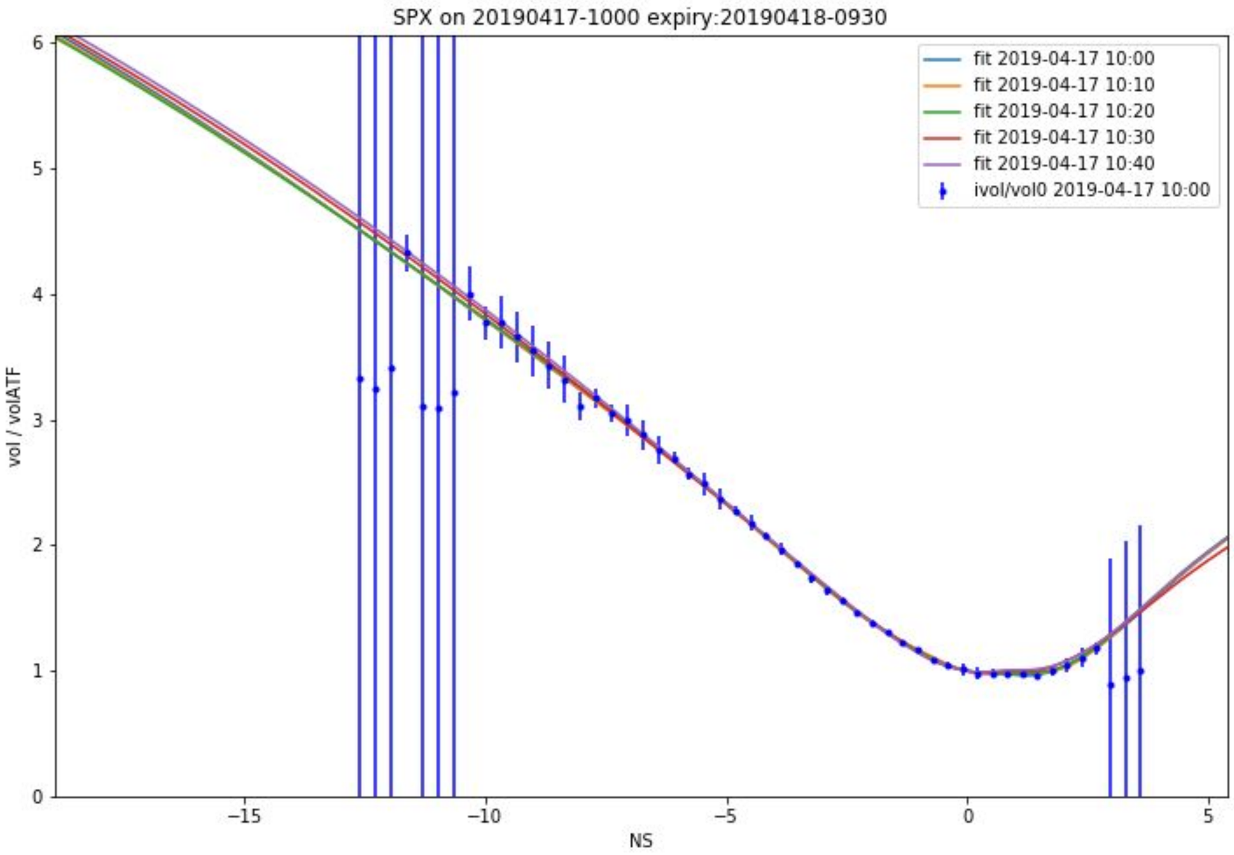


Stability of NS Shape

SPX 20190410 T = 9m

Shape stable over many days, while underlier moves around.

Also, no floppy wings!

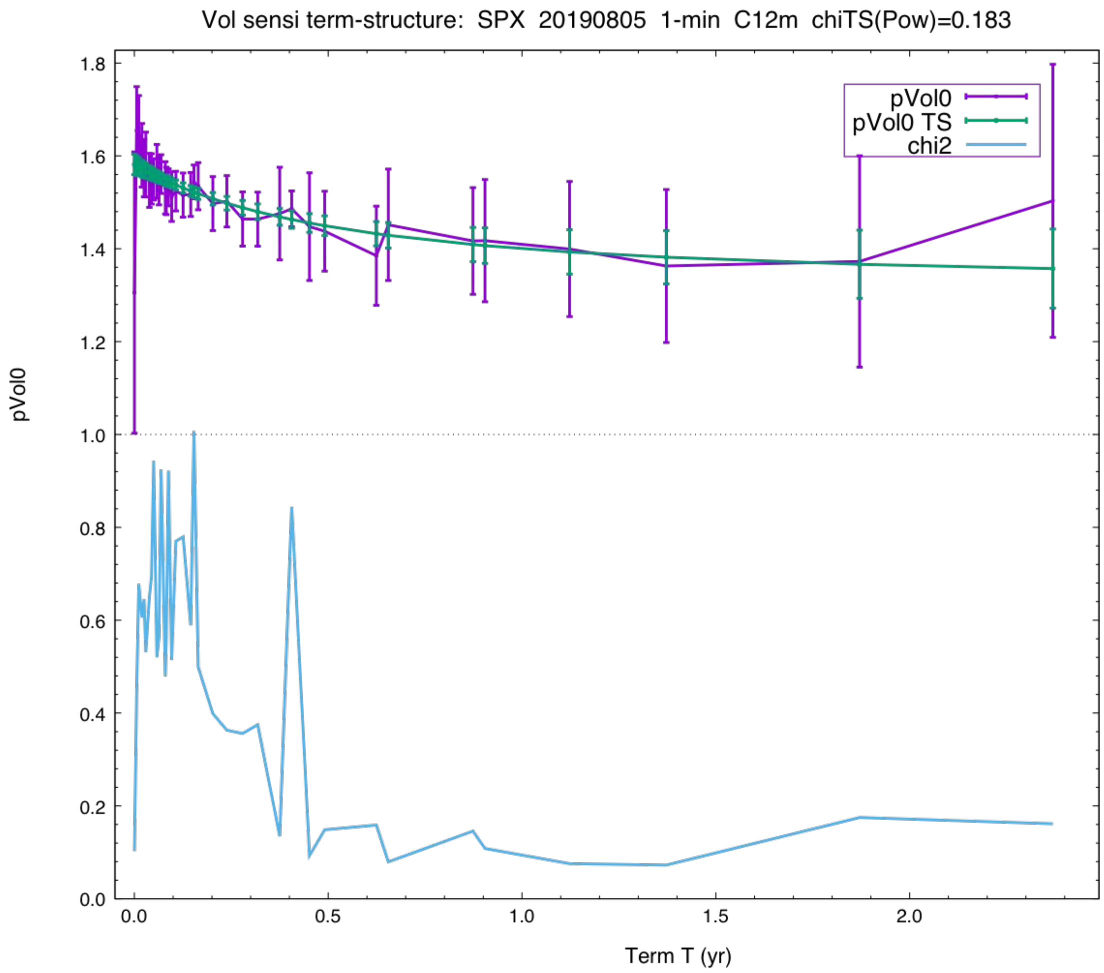


Stability of NS Shape

SPX 20190410 T = 1d

Shape stable even on last day

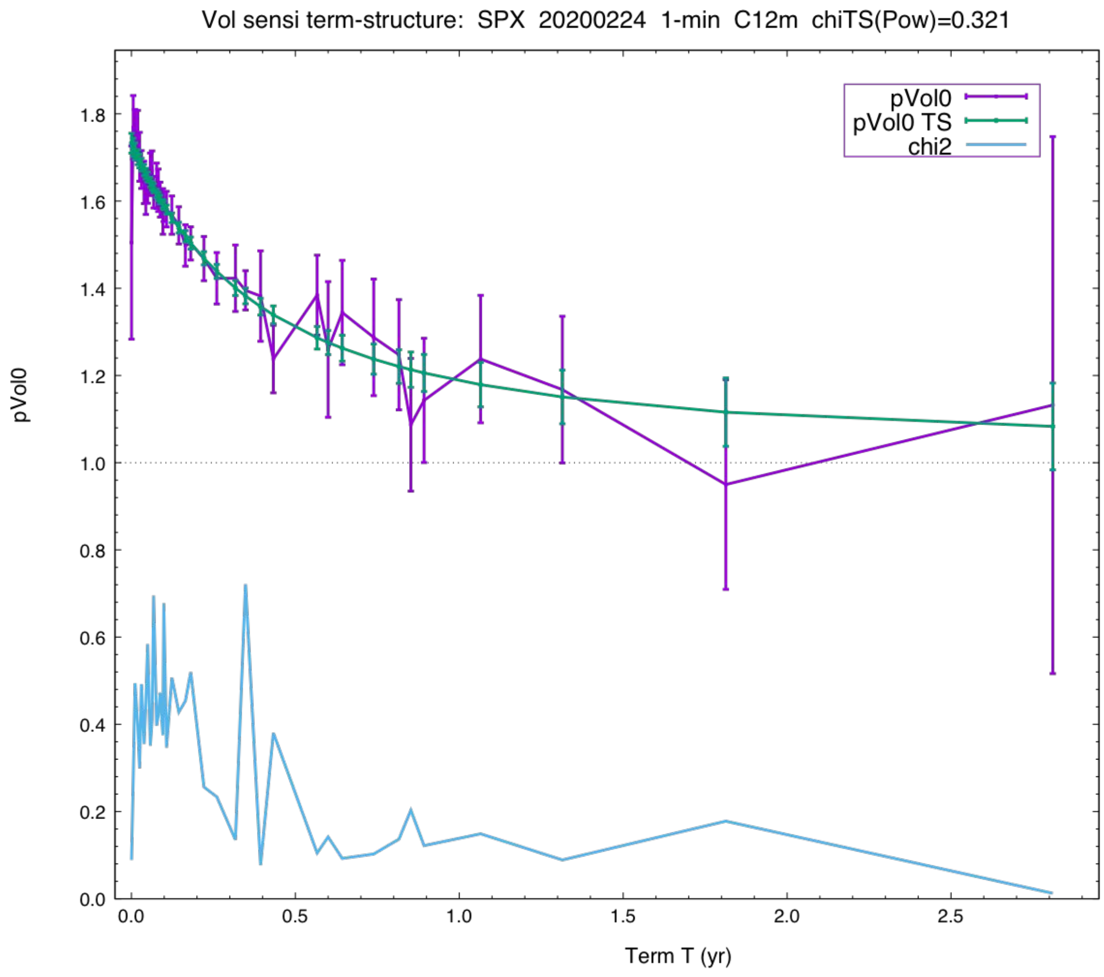
Also, no floppy wings!



SPX 20190805

Vol sensitivity (SSR) term-structure

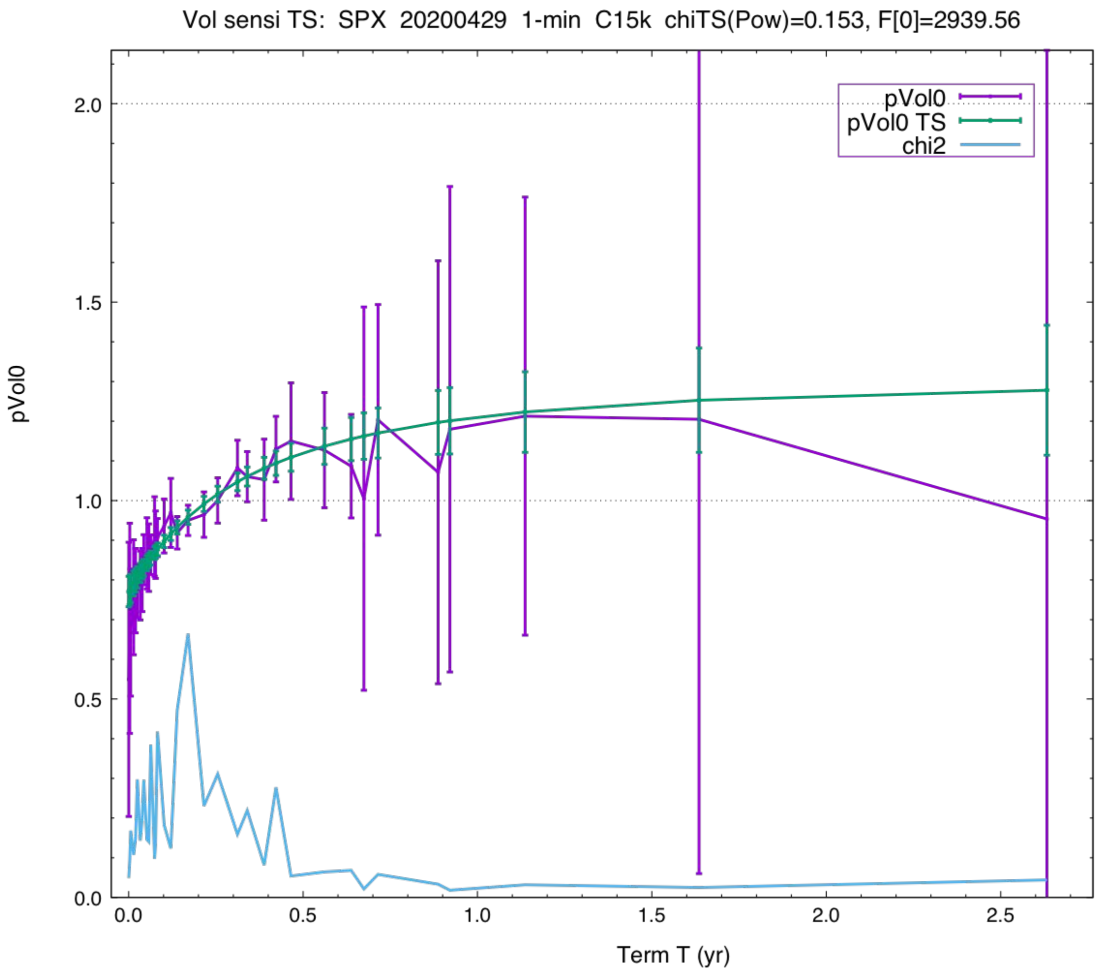
Parametric fit for robustness on small data sets (can be done intra-day)



SPX 20200224

Vol sensitivity (SSR) term-structure

Parametric fit for robustness on small data sets



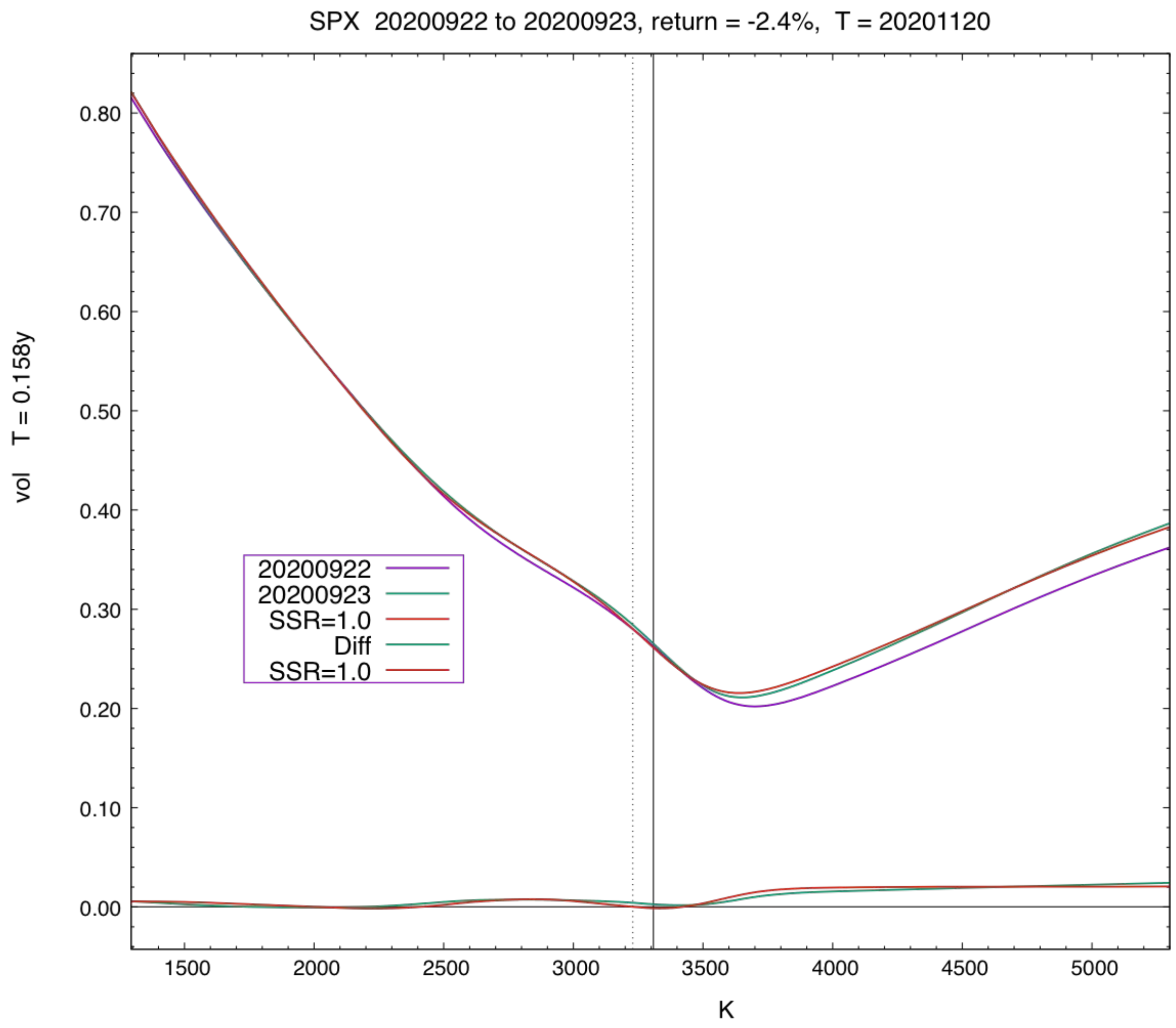
SPX 20200429

Vol sensitivity (SSR) term-structure

On up-days can be upward-sloping, and SSR < 1 at least for some terms

Spot-Vol Dynamics Myths

- **Myth: Common "vol regimes" are "sticky-by-strike" or "sticky-by-delta"**
  - Sticky-strike scenarios are still commonly used by risk departments.
- In equities, at least, **neither has happened for 20y+**.
- Sticky-delta implies SSR=0 for all terms. Never happens.
- Sticky-strike implies SSR=1 (i.e. sticky-strike around ATM).
  - Even when vols are sticky-by-strike around ATM, they never are in the wings.
  - There are many examples. Let's look at some.



Close-to-close spot vol dynamics

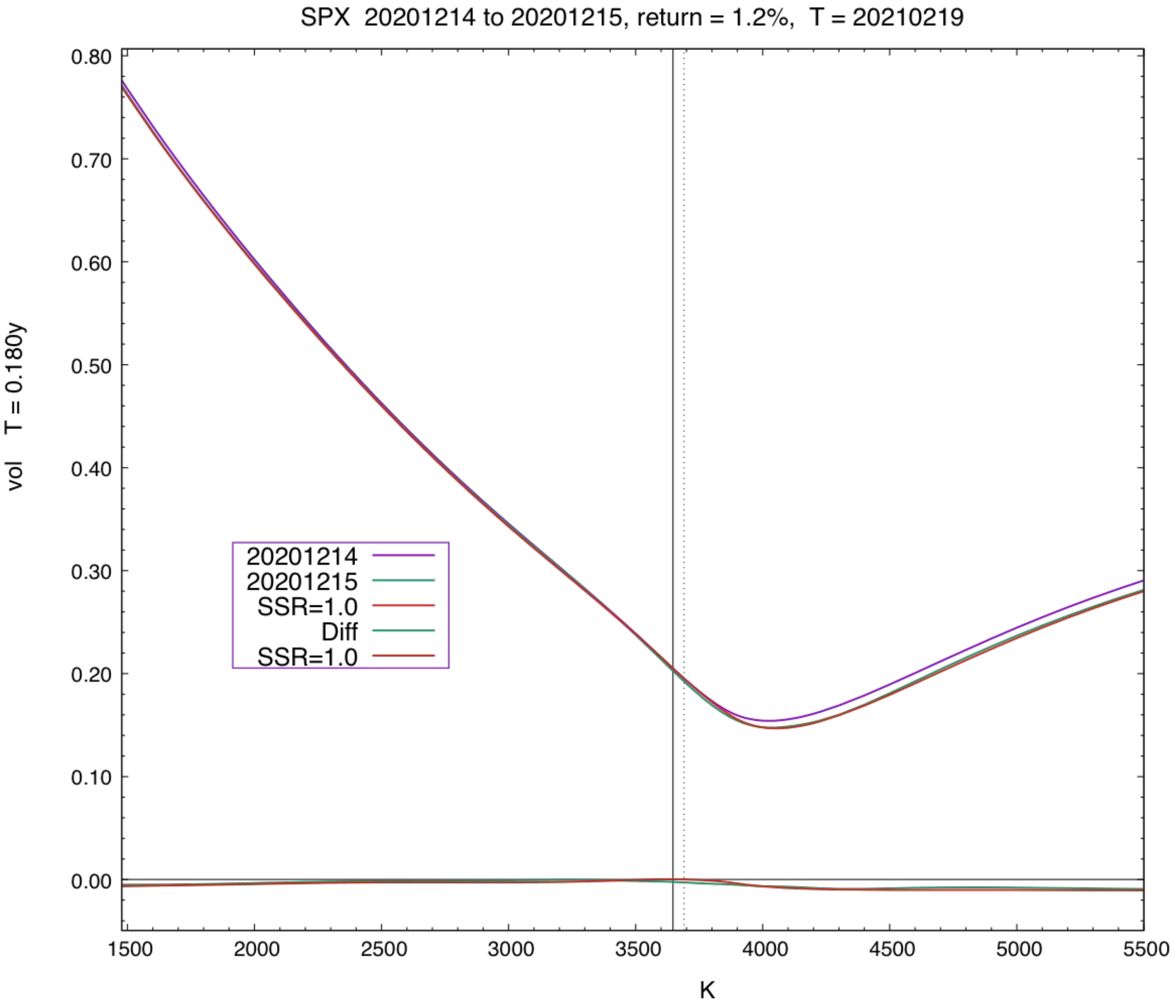
SPX 2020-09-22 to 2020-09-23

SSR=1, but NO sticky strike in the wings.

Instead: Shapes are sticky-by-NS!

Non-trivially so in the call and put wing!

This down-day comes after a sequence of (minor) down days, and SSR has mean-reverted to 1.0

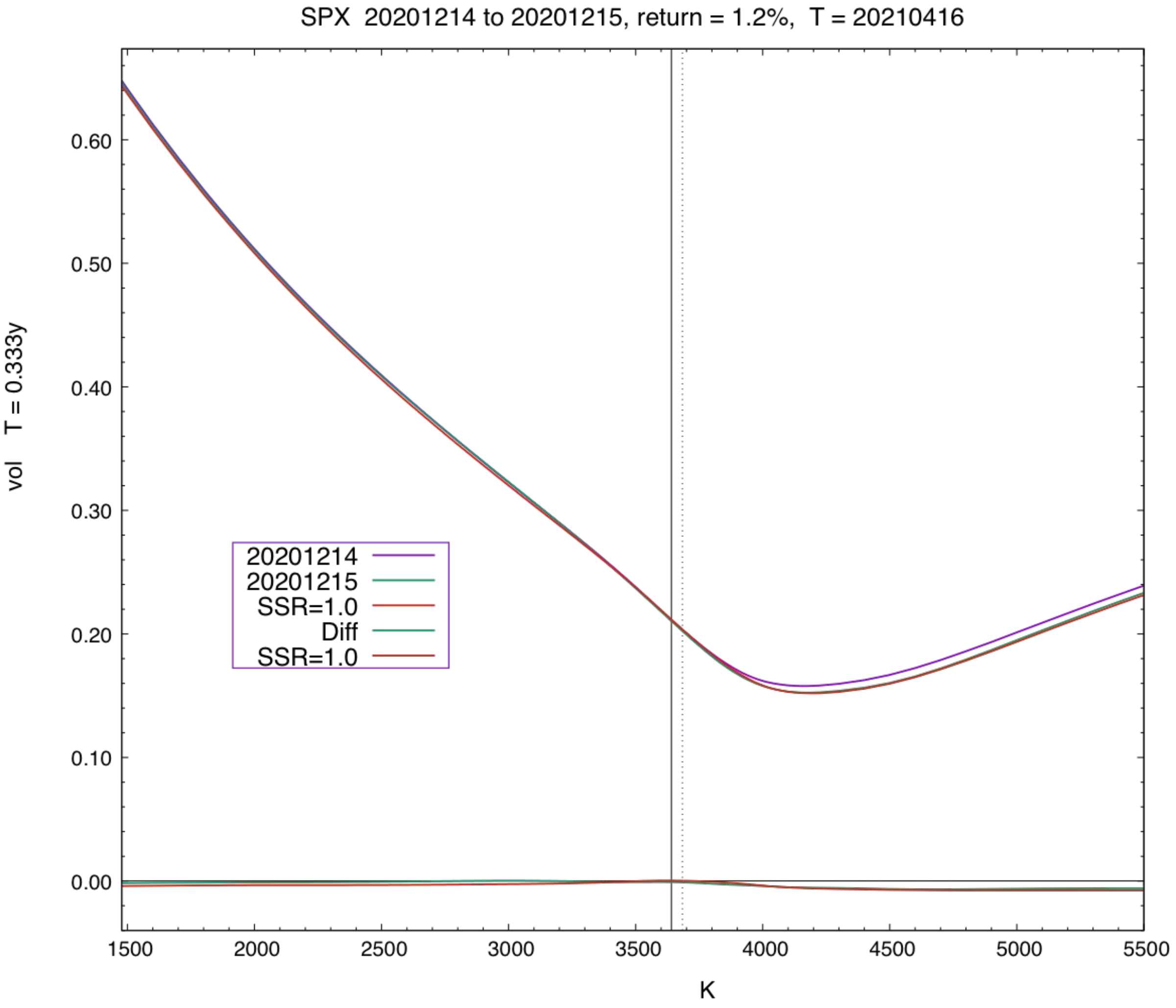


Close-to-close spot vol dynamics

SPX 2020-12-14 to 2020-12-15

T = 9w, SSR = 1

Fixed NS shape assumption works **amazingly** well!

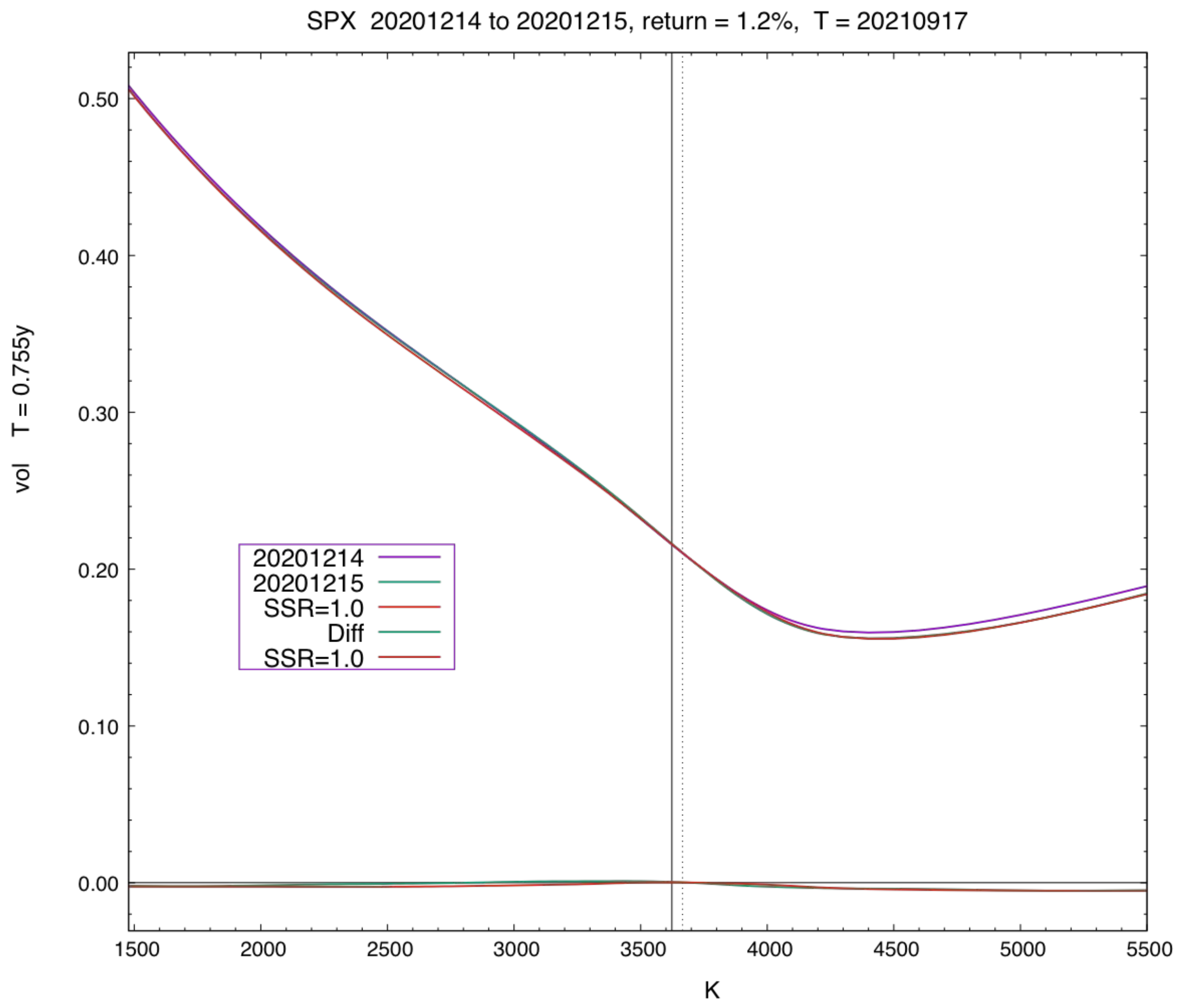


Close-to-close spot vol dynamics

SPX 2020-12-14 to 2020-12-15

T = 4m, SSR = 1

Fixed NS shape assumption works **amazingly** well!

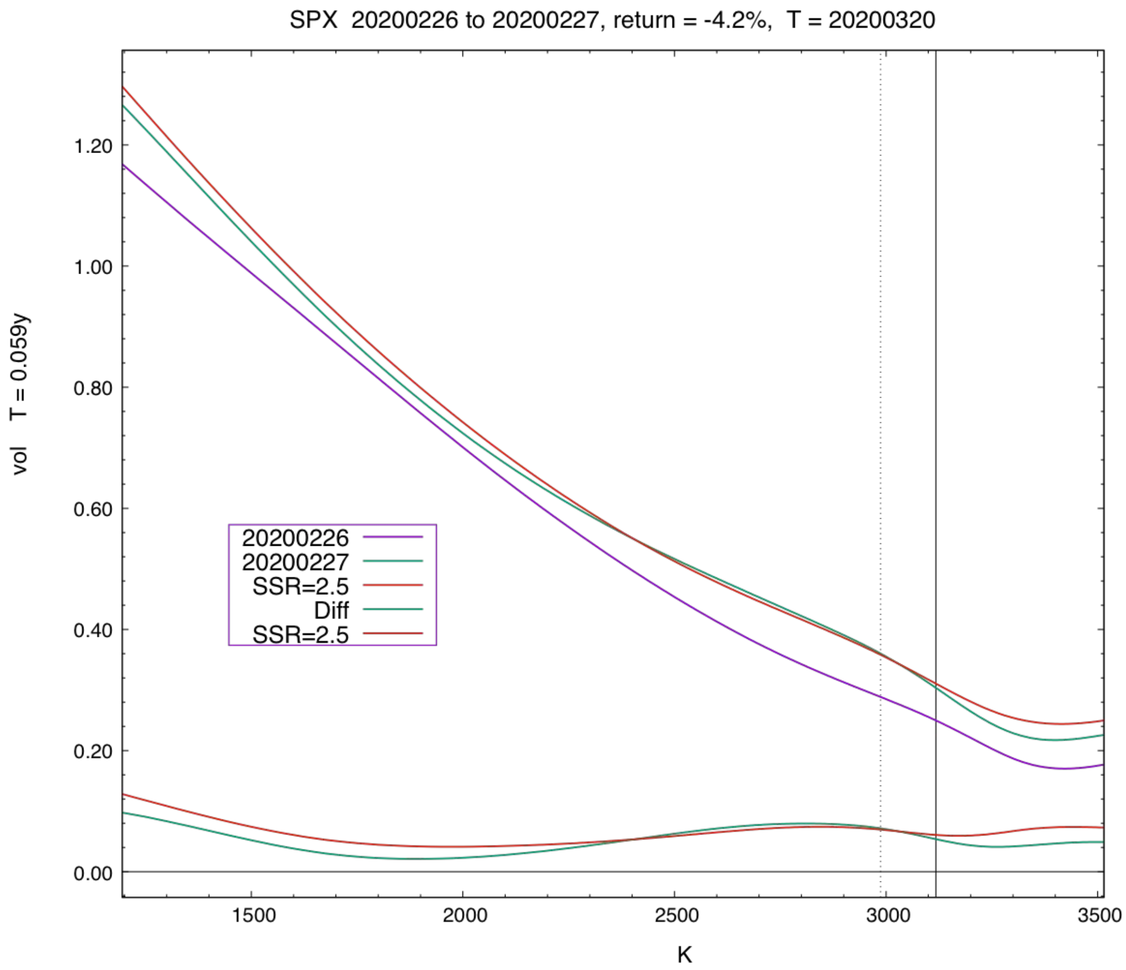


Close-to-close spot vol dynamics

SPX 2020-12-14 to 2020-12-15

T = 9m, SSR = 1

Fixed NS shape assumption works **amazingly** well!



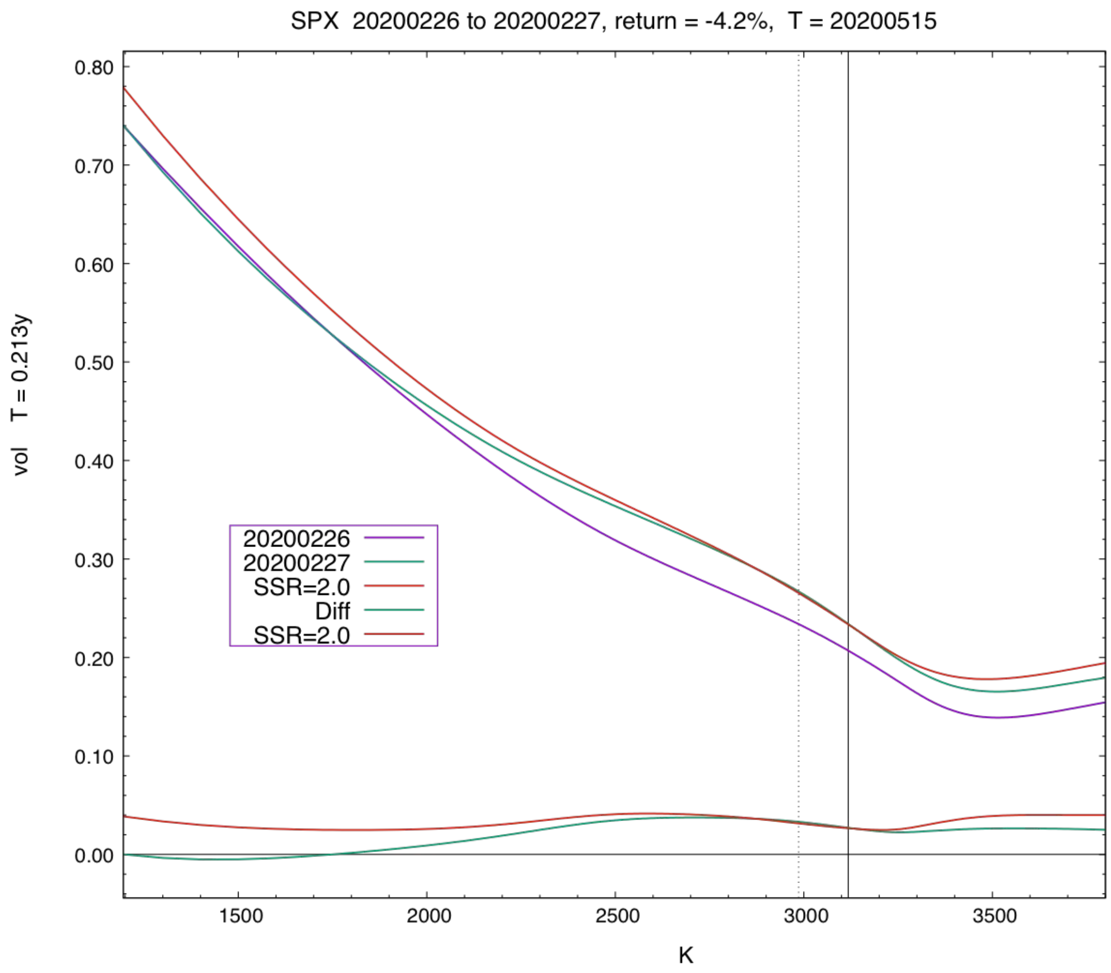
Close-to-close spot vol dynamics

SPX 2020-02-26 to 2020-02-27

Covid crash!

T = 3w, SSR = 2.5

Evidence for c2-spot-sensitivity > 0



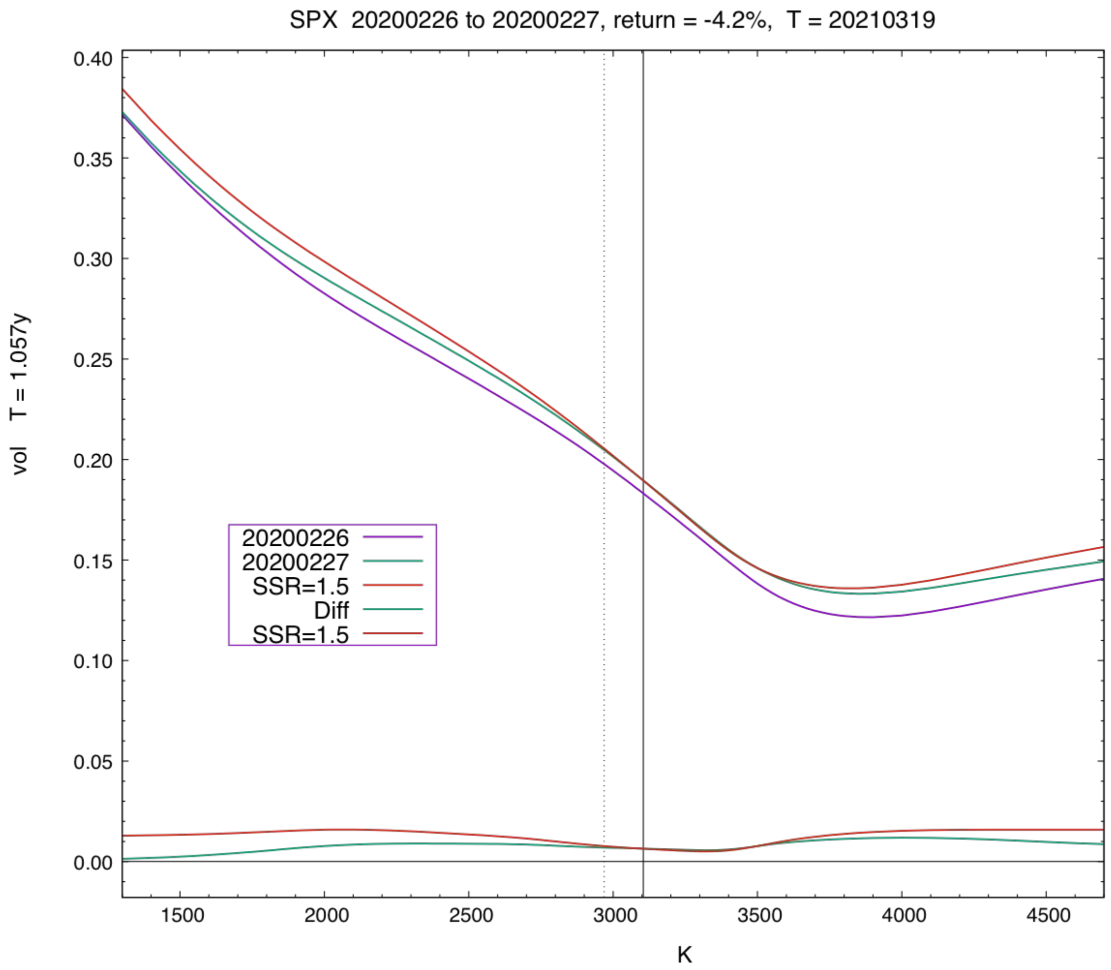
Close-to-close spot vol dynamics

SPX 2020-02-26 to 2020-02-27

Covid crash!

T = 2.5m, SSR = 2.0

Evidence for c2-spot-sensitivity > 0



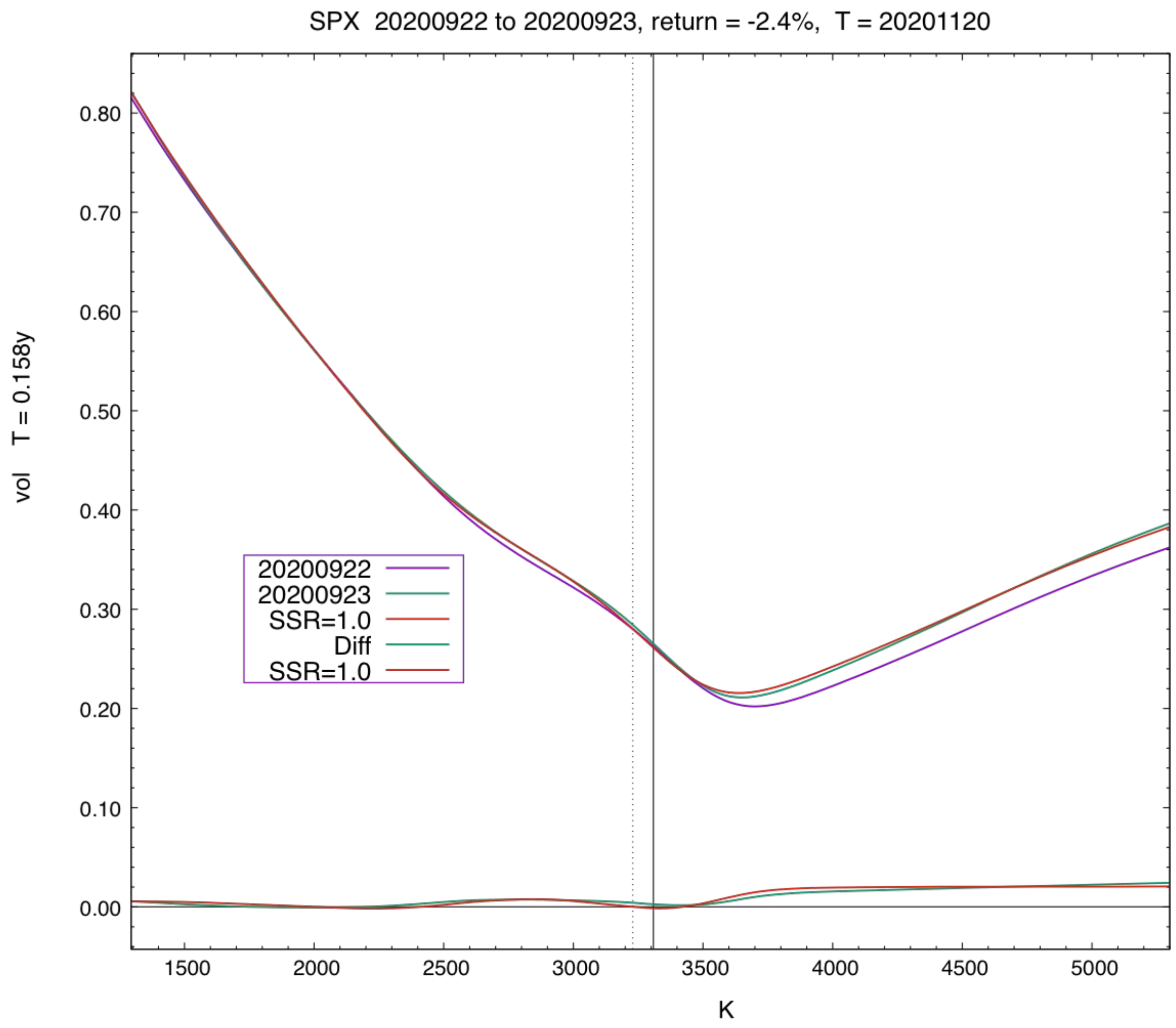
Close-to-close spot vol dynamics

SPX 2020-02-26 to 2020-02-27

Covid crash!

T = 1y, SSR = 1.5

Evidence for c2-spot-sensitivity > 0



Close-to-close spot vol dynamics

SPX 2020-09-22 to 2020-09-23

SSR=1, but NO sticky strike in the wings.

Instead: Shapes are sticky-by-NS!

Non-trivially so in the call and put wing!

This down-day comes after a sequence of (minor) down days, and SSR has mean-reverted to 1.0

Subtleties of Pricing American “vanillas”

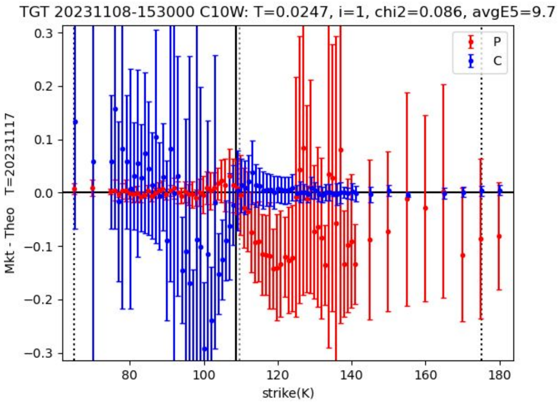
- For European options (without divs) only integrated rates and variances matter.
  - Cash dividend modeling is relatively minor issue for Euro options (unless stochastic divs…).
- But American options are really path-dependent exotics and a lot of extra complications arise (esp. for ETFs, stocks, esp. with dividends):
- Empirically, in the olden days:
  - Could price every vanilla, European of American, with one flat r, q, and vol.
  - The same vol would work (well enough…) for call and put at same T,K.
- Already pretty hard, especially in real time. One needs:
  - A proper **cash dividend model** (no consensus even for vanilla…).
  - Handle **settlement** effects (incl. exchange and bank holidays).
  - A good choice of “**vol time**” (aka “trading/business time”), including “**events**”.
  - Then: imply “SPIBOR” (~daily), borrows (~real time), and vol surfaces (real time).
  - “American PCP” condition to imply borrow: Demand volP(K) = volC(K) around ATM

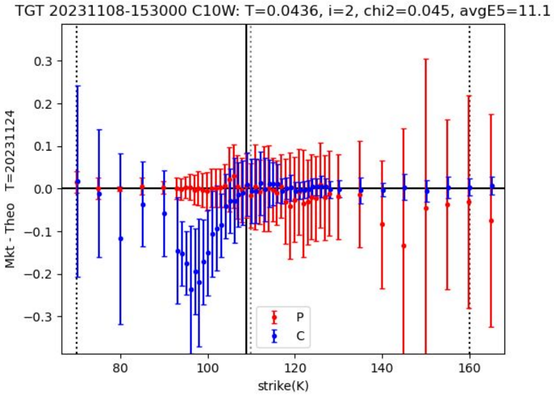
Subtleties of Pricing American “vanillas” 2

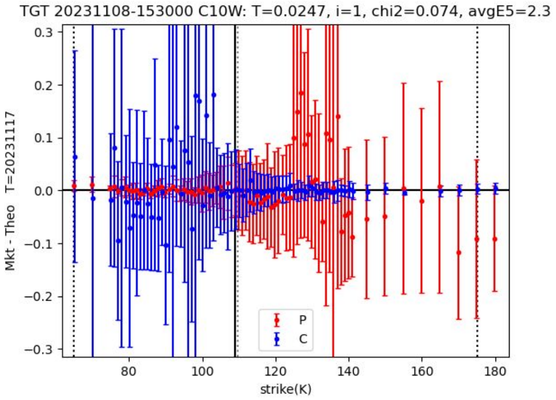
- Now: How fancy does modeling have to be?

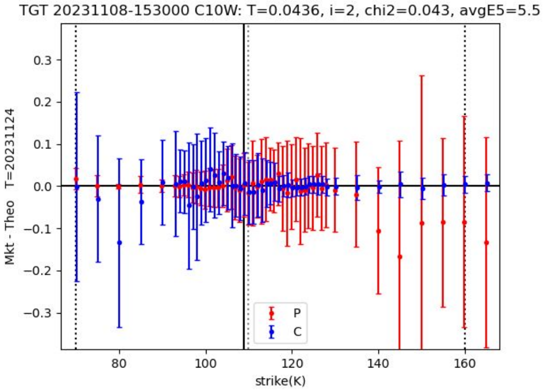
  OR: What is the “Market Model” for American options (going to be…)?
  - BS: (1) Flat r,q, vol (2) r(t), q(t), vol (3) r(t), q(t), vol(t) for each K(?)
  - Beyond-BS: (4) r(t), q(t), LV, (5) r(t), q(t), SLV, (6) Other (approx/hacks…)
- Empirically in US: One definitely needs rate TS, vol-time incl. events, settlement, Berm (not Amer) exercise, proper dividend modeling, and “some” vol TS pricing.
- In Europe: Some evidence that LVs (or roughly equiv approx’s) are being used.
- Let’s look at some (more) examples:
  - Rate TS and event effects: TGT, MSFT, TSLA, CRWV
  - Settlement effects (+more): SPX
  - Settlement + vol TS: SPY

Event Time Effect on Pricing American Vanillas









TGT 2023-11-08

Target has a dividend and earnings call just before expiry T=2023-11-17 (i=1).

Top row: Without an “event time” an implied borrow allows (OTM and ITM) market prices to be matched at a few strikes, but not all.

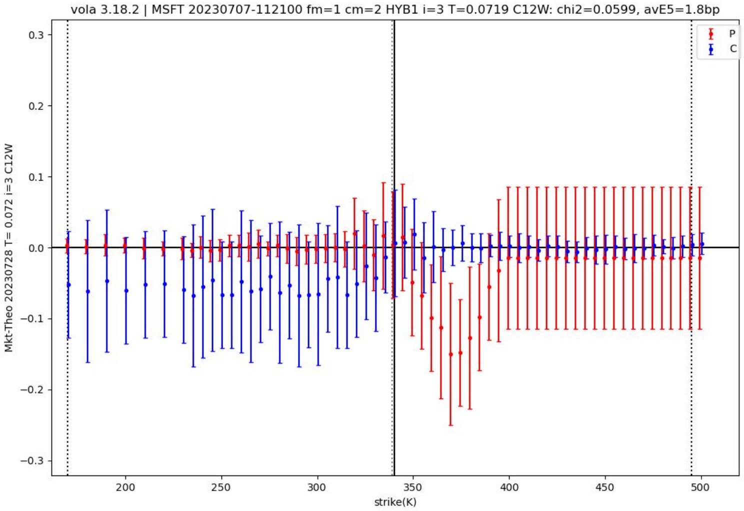
Bottom row: With an event time of 0.09y all prices can be matched, in all expiries!

Rate TS and Event Time for American Vanillas

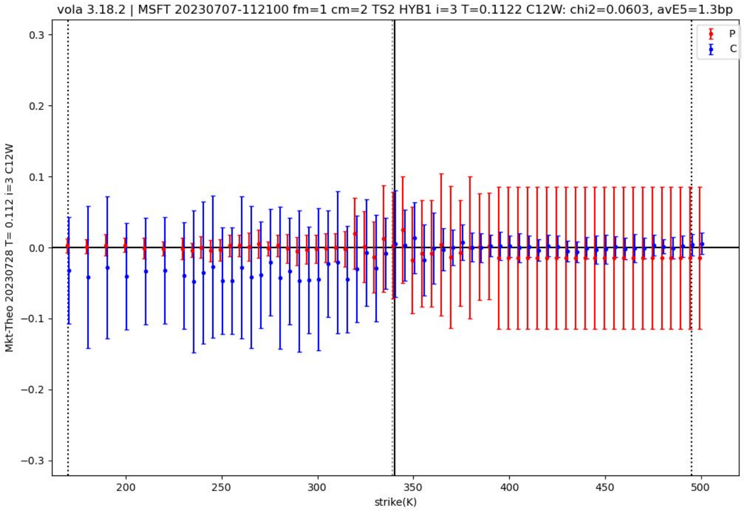
MSFT 2023-07-07

The ultimate test of a valuation approach is always the **price-difference plot**: Mkt - Theo

Flat term rates r(T), q(T)



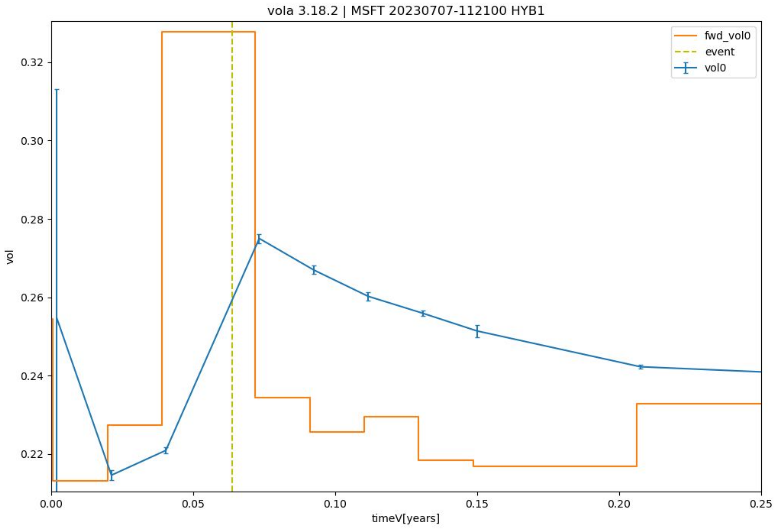
Local r(t),q(t) and $\Delta T_E = 0.04y$



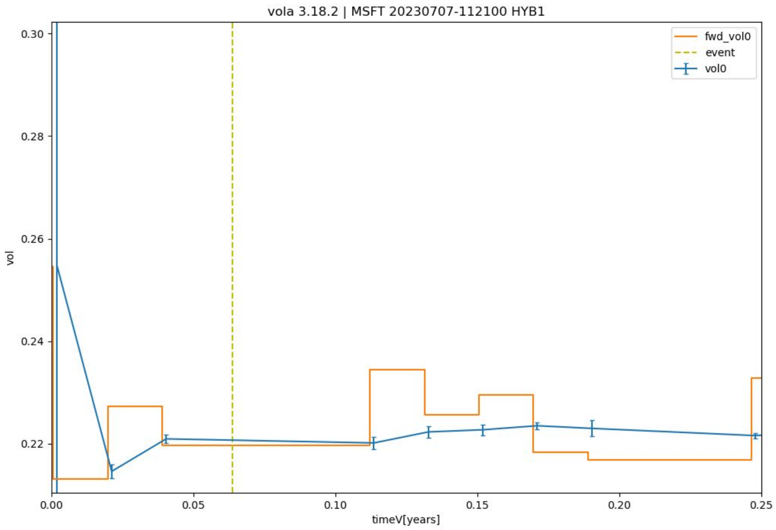
Rate TS and Event Time for American Vanillas

MSFT 2023-07-07

“Dirty” ATF vols

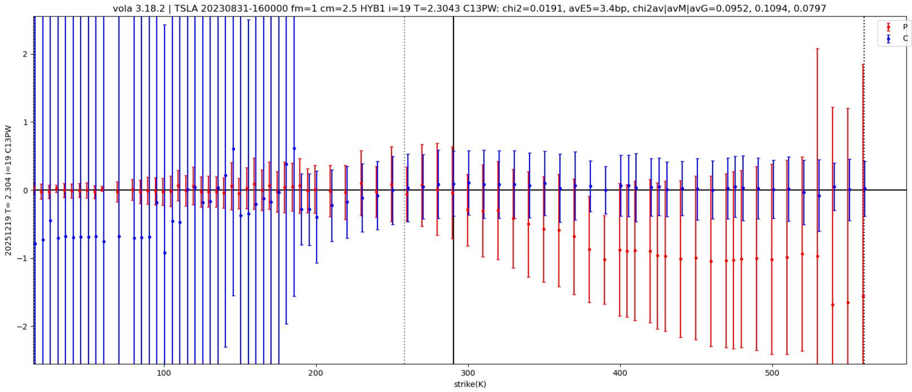


“Clean” ATF vols, $\Delta T_E = 0.04y$



Rate Term-Structure Effect on Pricing American Vanillas

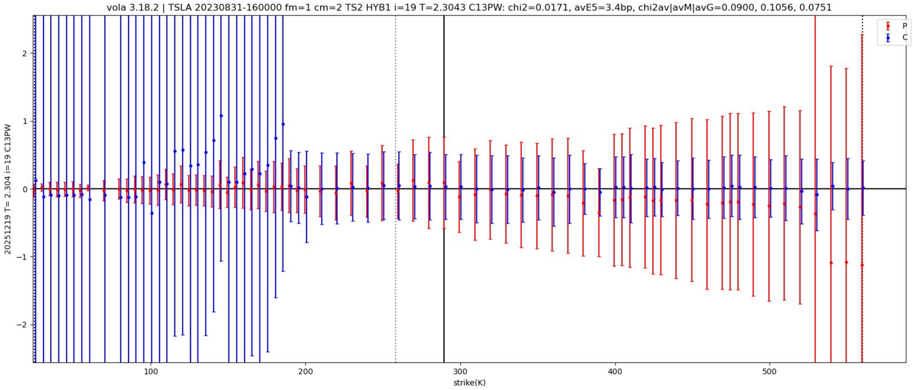
TSLA 2023-08-31



Price-Difference plot: Mkt - Theo

← Pricing with flat term r,q

T = 2.4y



← Pricing with local r(t),q(t)

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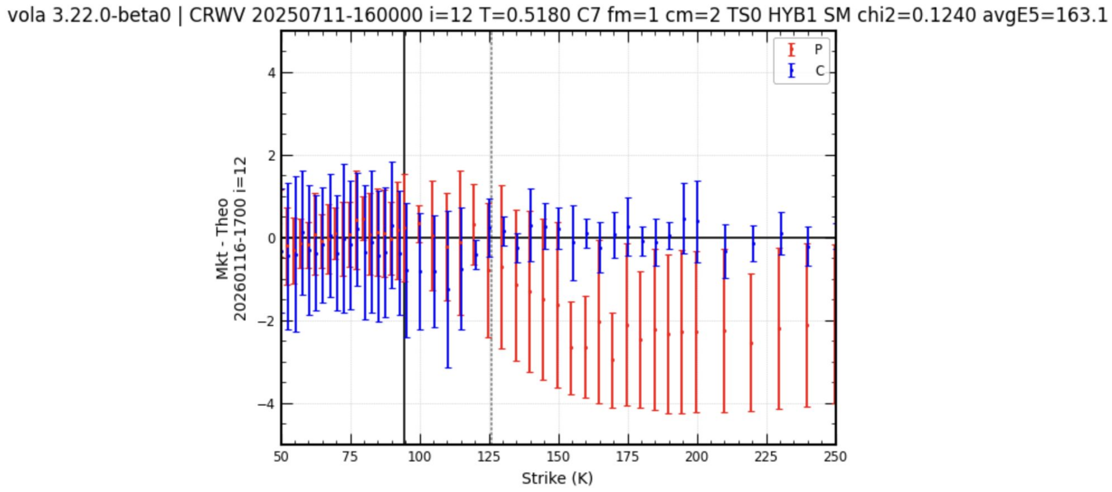
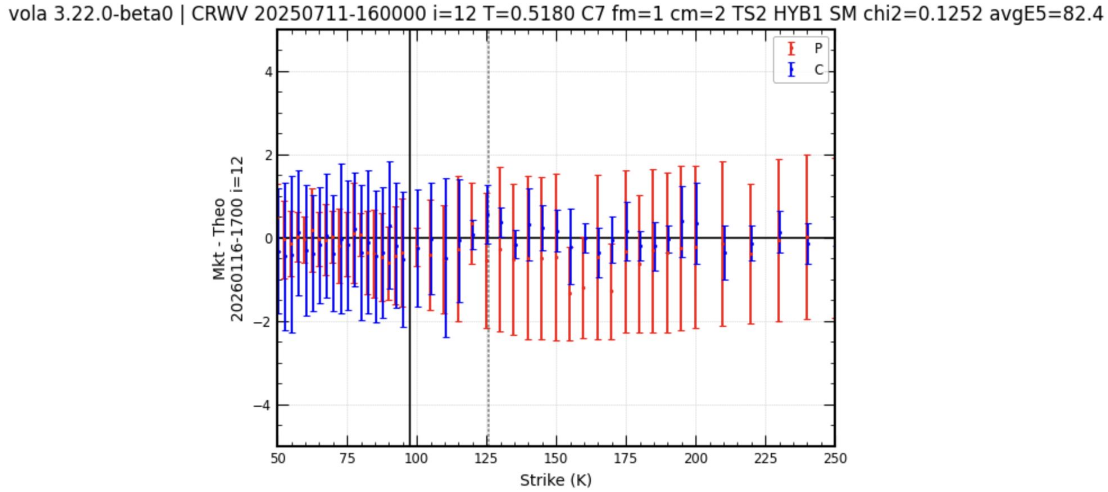


←TS0 priceDiff(K), T = 0.52y

Flat rate pricing



←TS2 priceDiff(K), T = 0.52y

Local rate pricing

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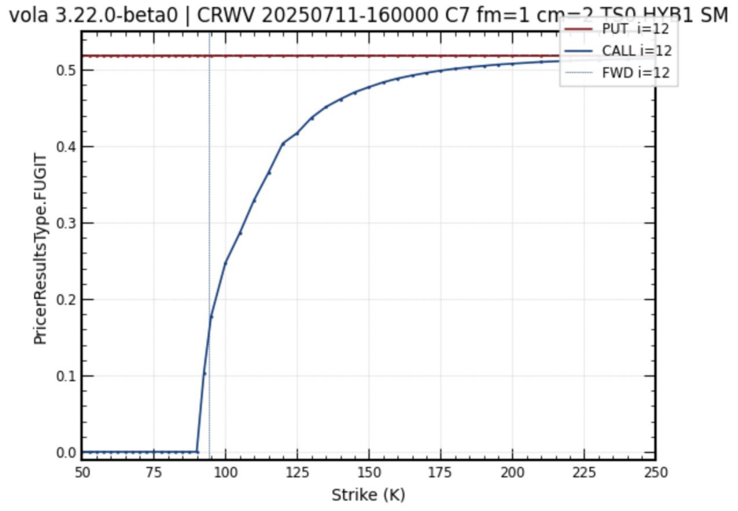
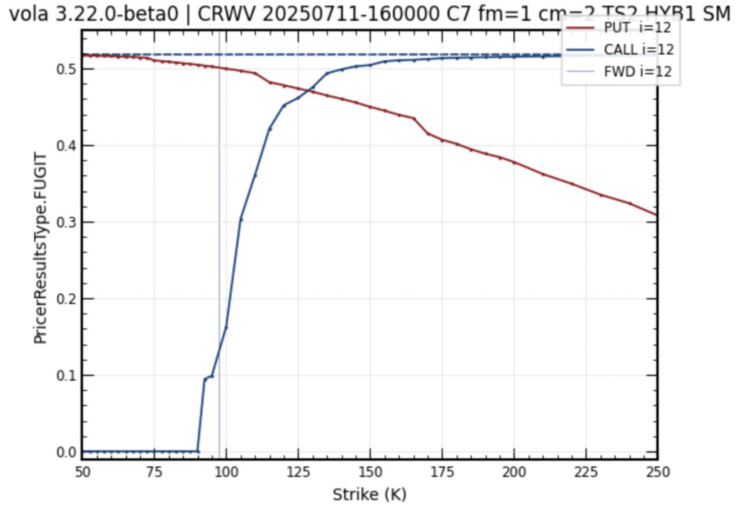


←TS0 fugit, T = 0.52y



←TS2 fugit, T = 0.52y

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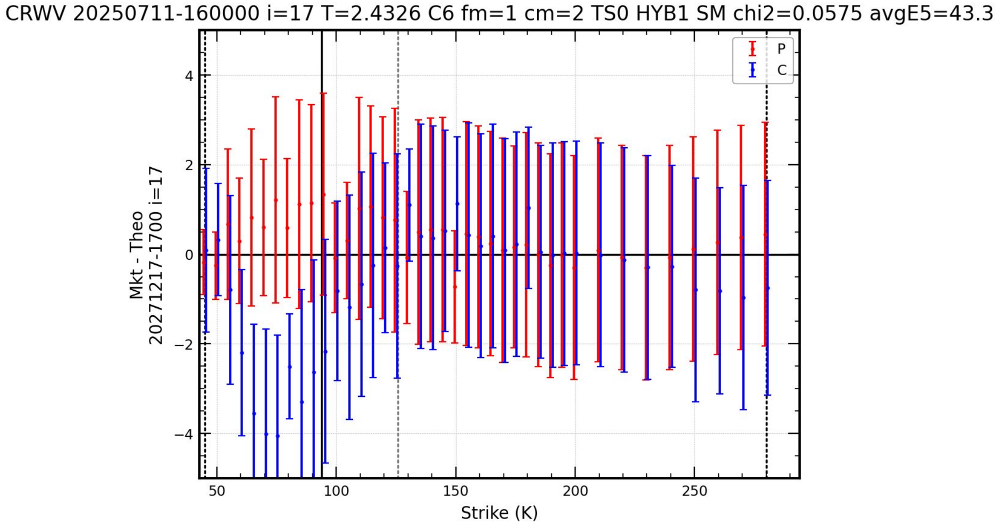
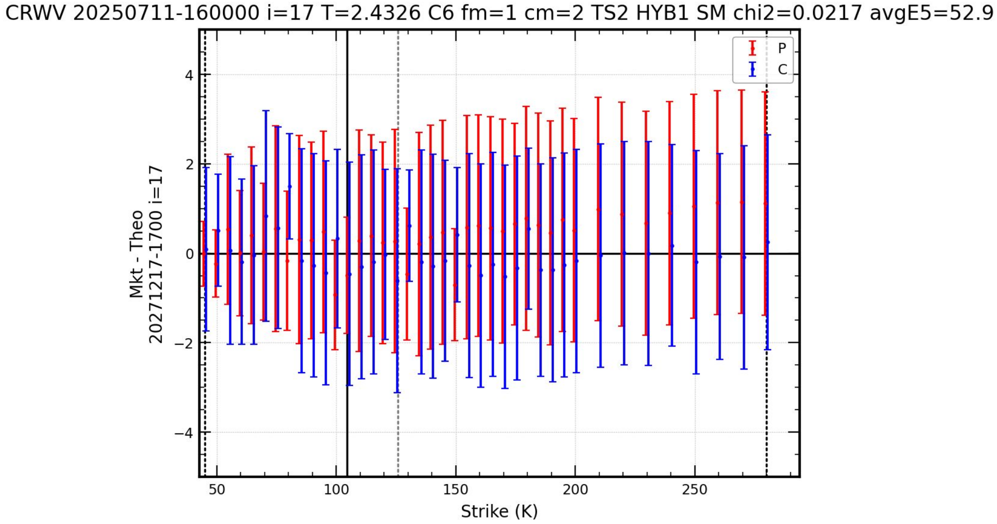
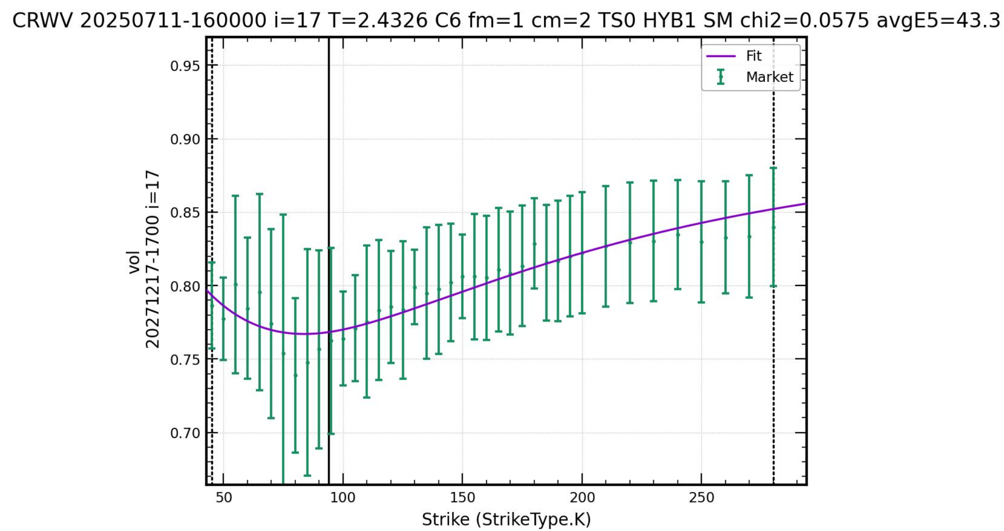
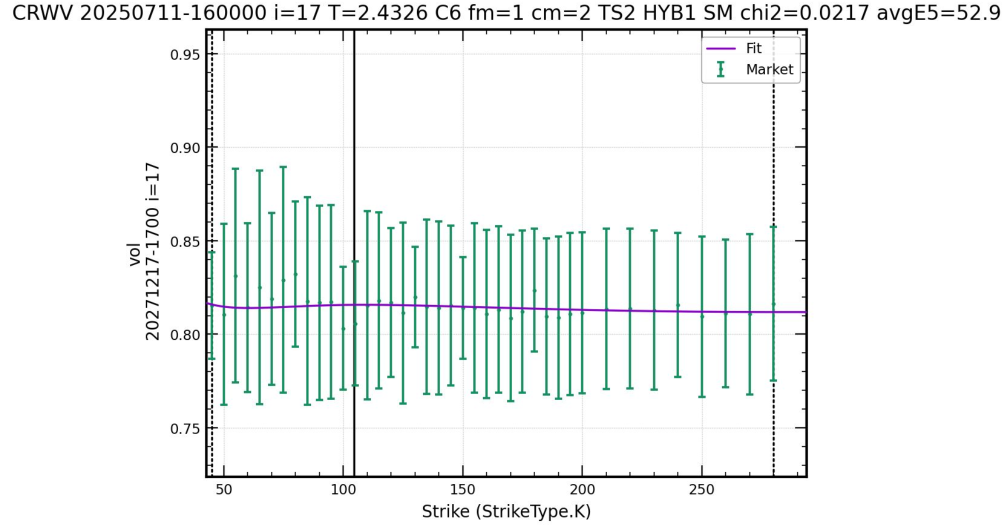


←TS0 priceDiff(K), T = 2.4y



←TS2 priceDiff(K), T = 2.4y





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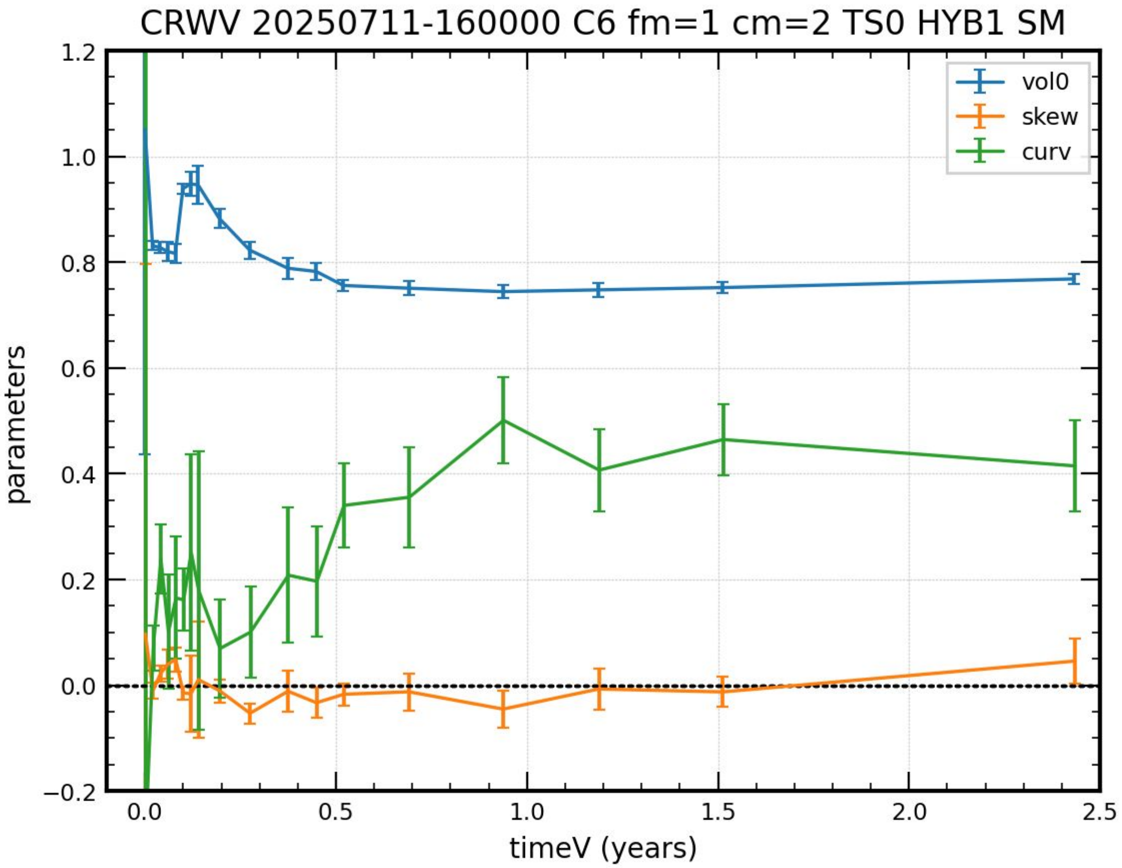
←TS0 fitted vol(K), T = 2.4y

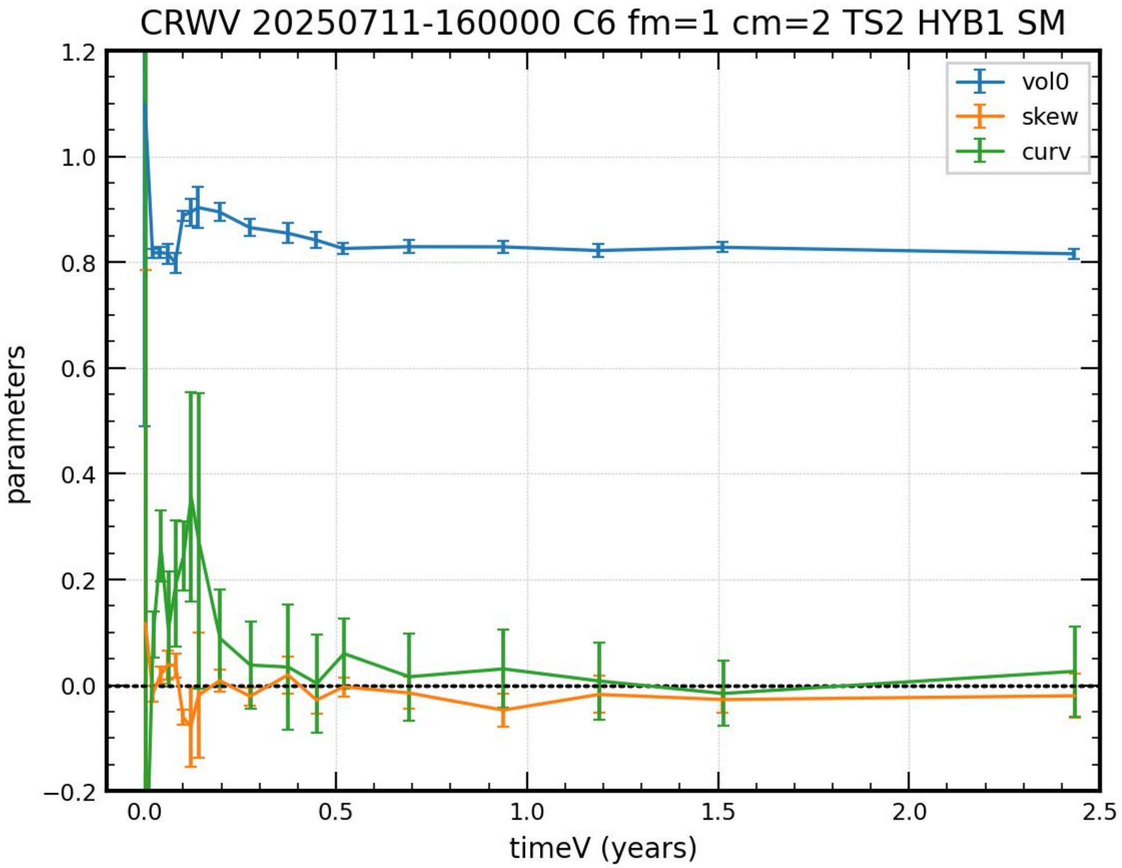
Note that implied forward is quite different with TS0 and TS2!

←TS2 fitted vol(K), T = 2.4y



CRWV 2025-07-11

Param TS (first 3) with **TS0**



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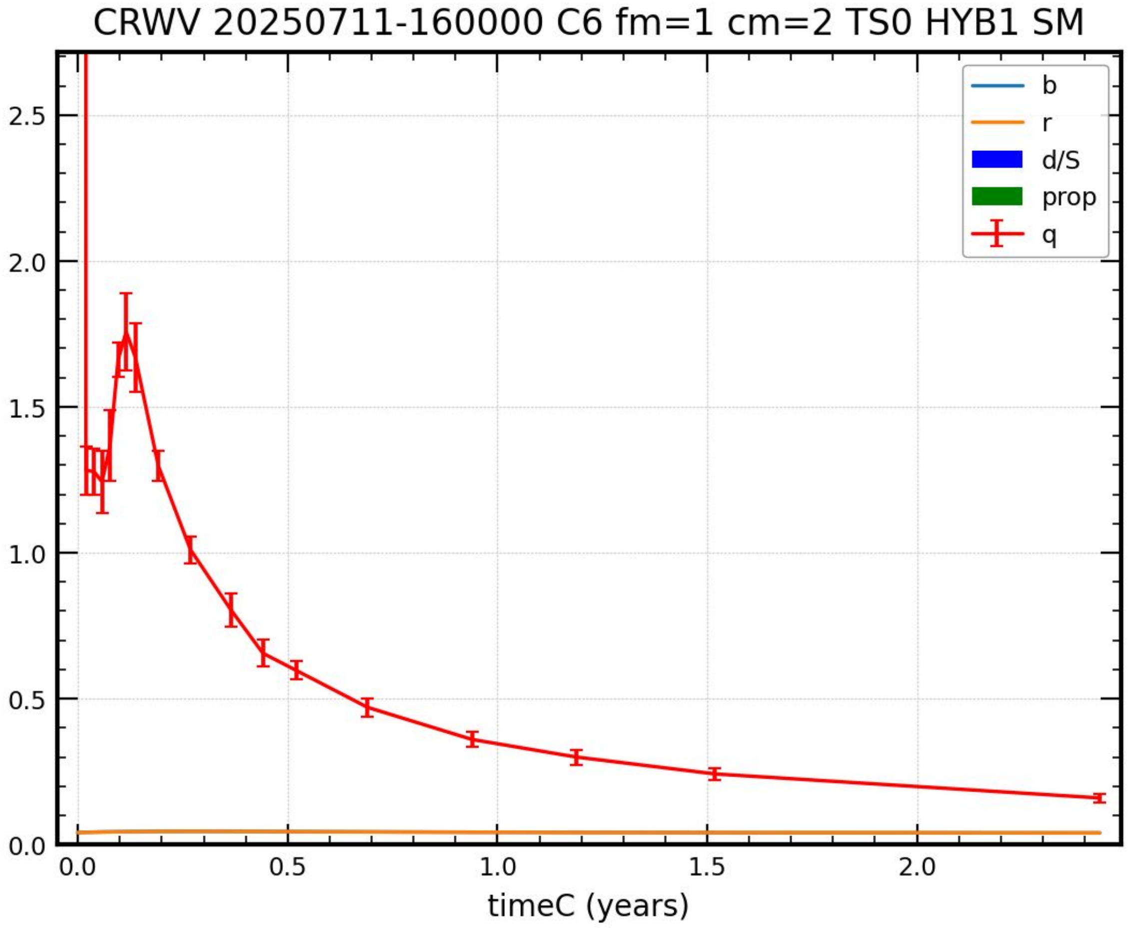
Param TS (first 3) with **TS2**

Very different from TS0 params, eps. vol0 and c2.



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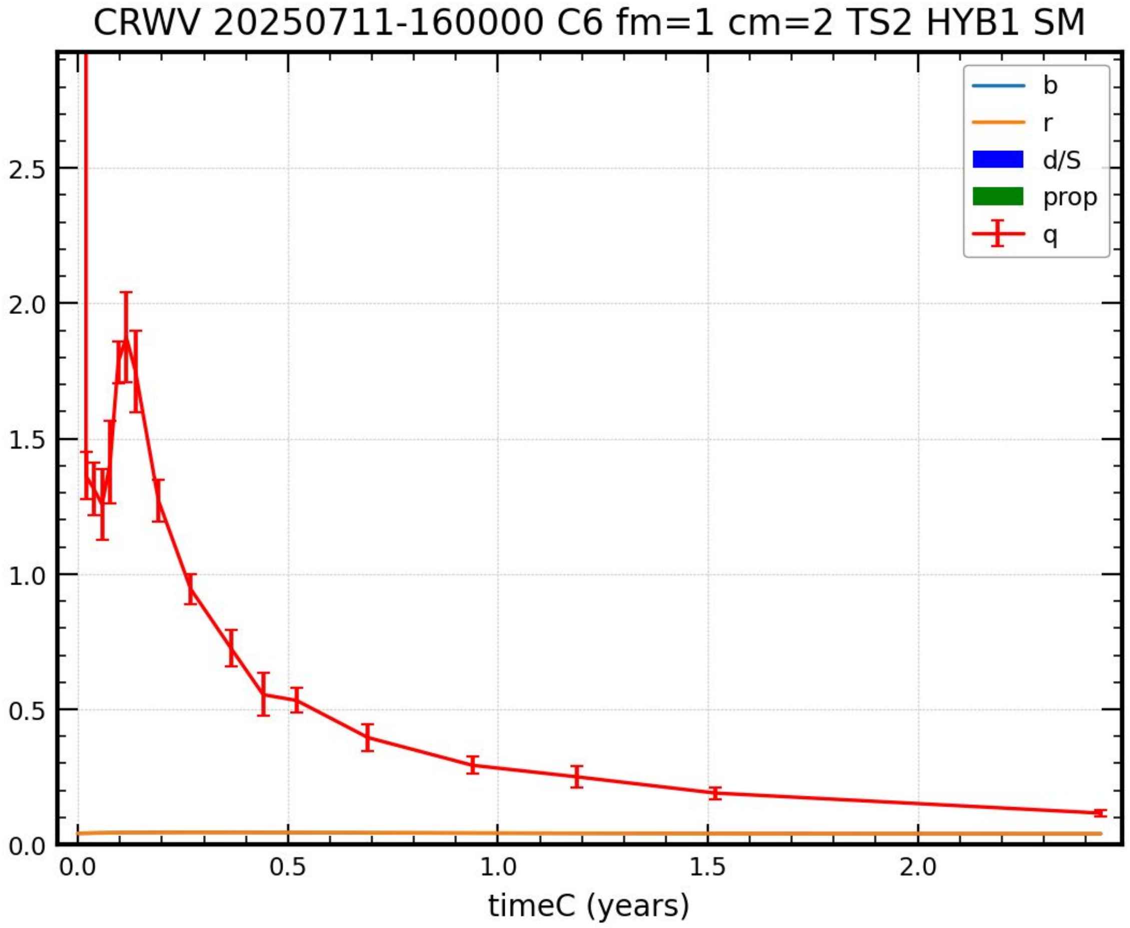
TS0 implied borrow q(T)

Non-monotonic !?



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TS2 implied borrow q(T)

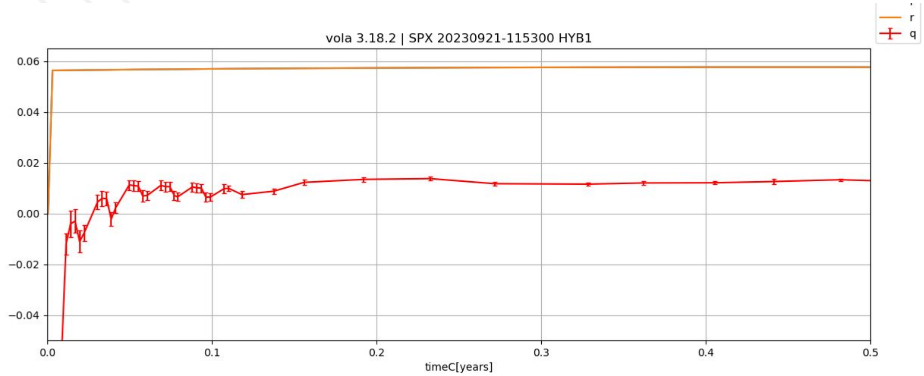
Also non-monotonic, but otherwise similar to TS0 q(T).

Lockup period ended 2025-08-14.

This q(T) is really needed to match market!

Settlement Effects for SPX options

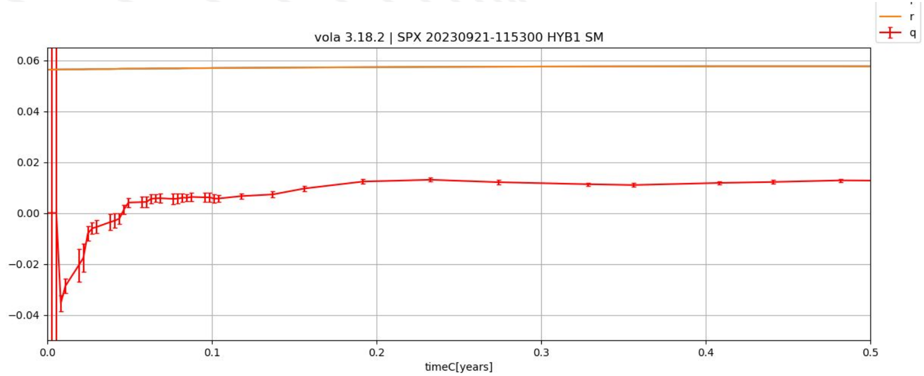
Let's treat SPX like an equity with a "spot", borrow cost, and (perhaps) cash dividends.



Implied borrow cost term structure

← Ignoring settlement, wrong spot

Wrong spot shows up as 1/T term in the borrow TS (made up wrong spot for illustration here…).

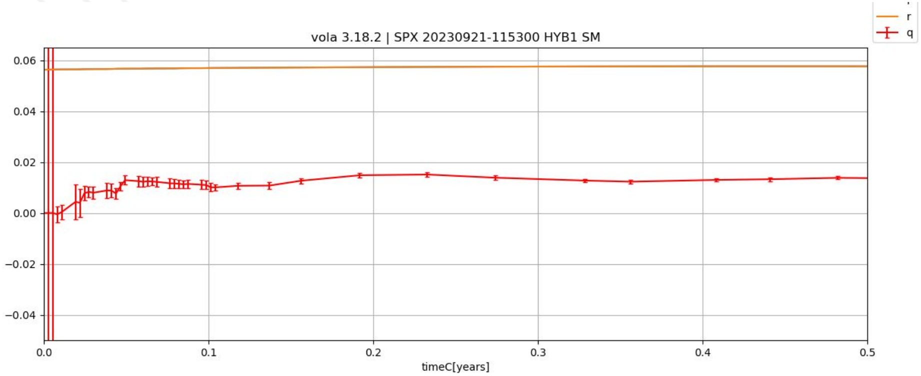


← With settlement, wrong spot

Now short-term borrow TS is smooth.

Settlement Effects for SPX options

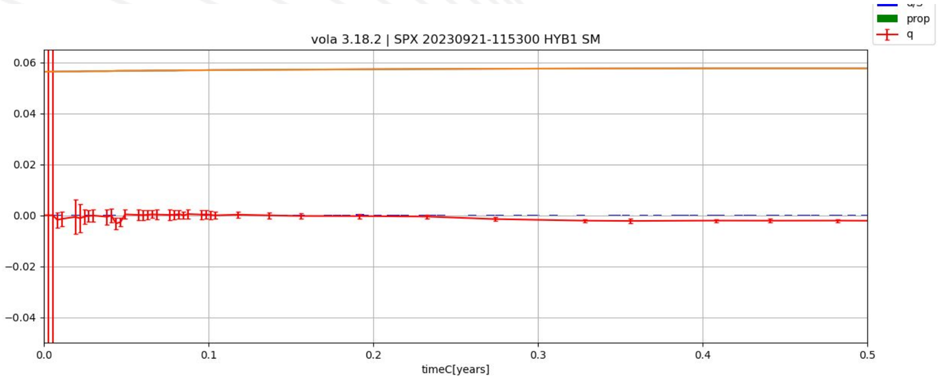
Let's treat SPX like an equity with a "spot", borrow cost, and (perhaps) cash dividends.



Implied borrow cost term structure

← With settlement, implied spot

No divs, so borrow includes div yield

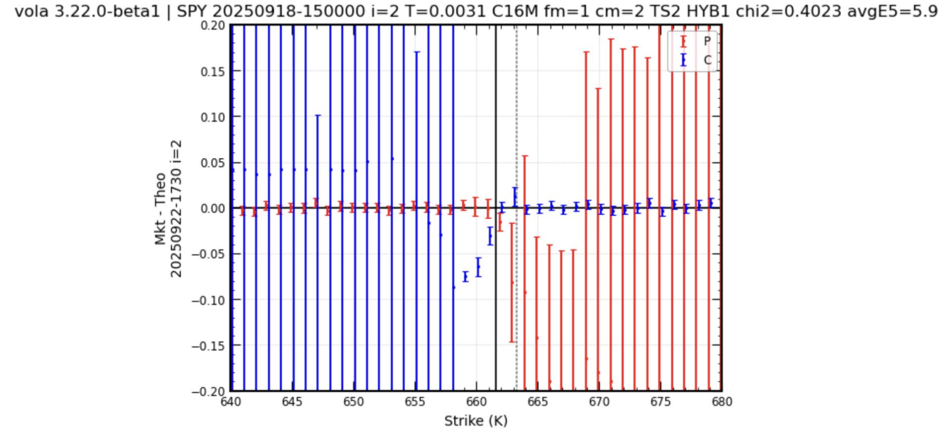


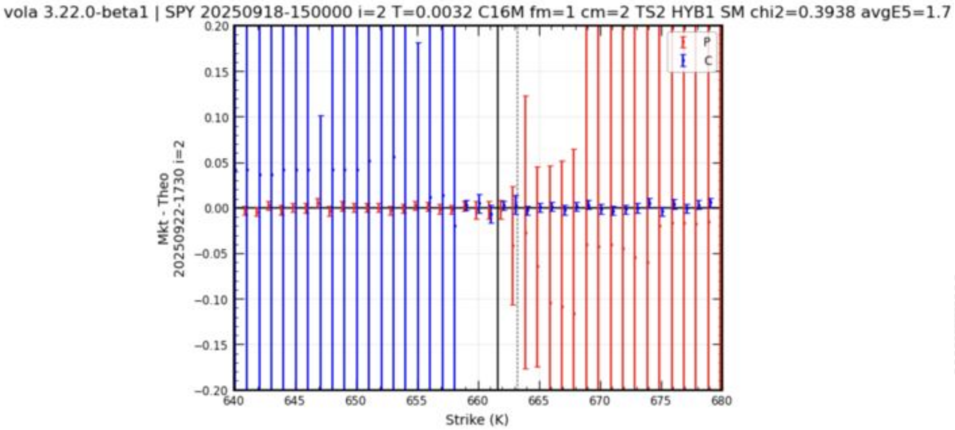
← With settlement, implied spot

With divs, so borrow is "pure" and very flat close to 0

Settlement + Vol Term-Structure Effects for SPY options

American options expiries right after dividends are hard:





Price Difference plots:

← With vol TS, ignoring settlement

← With vol TS, and **settlement**

THE END

Questions?