^{36}Ar 0ν2EC Search

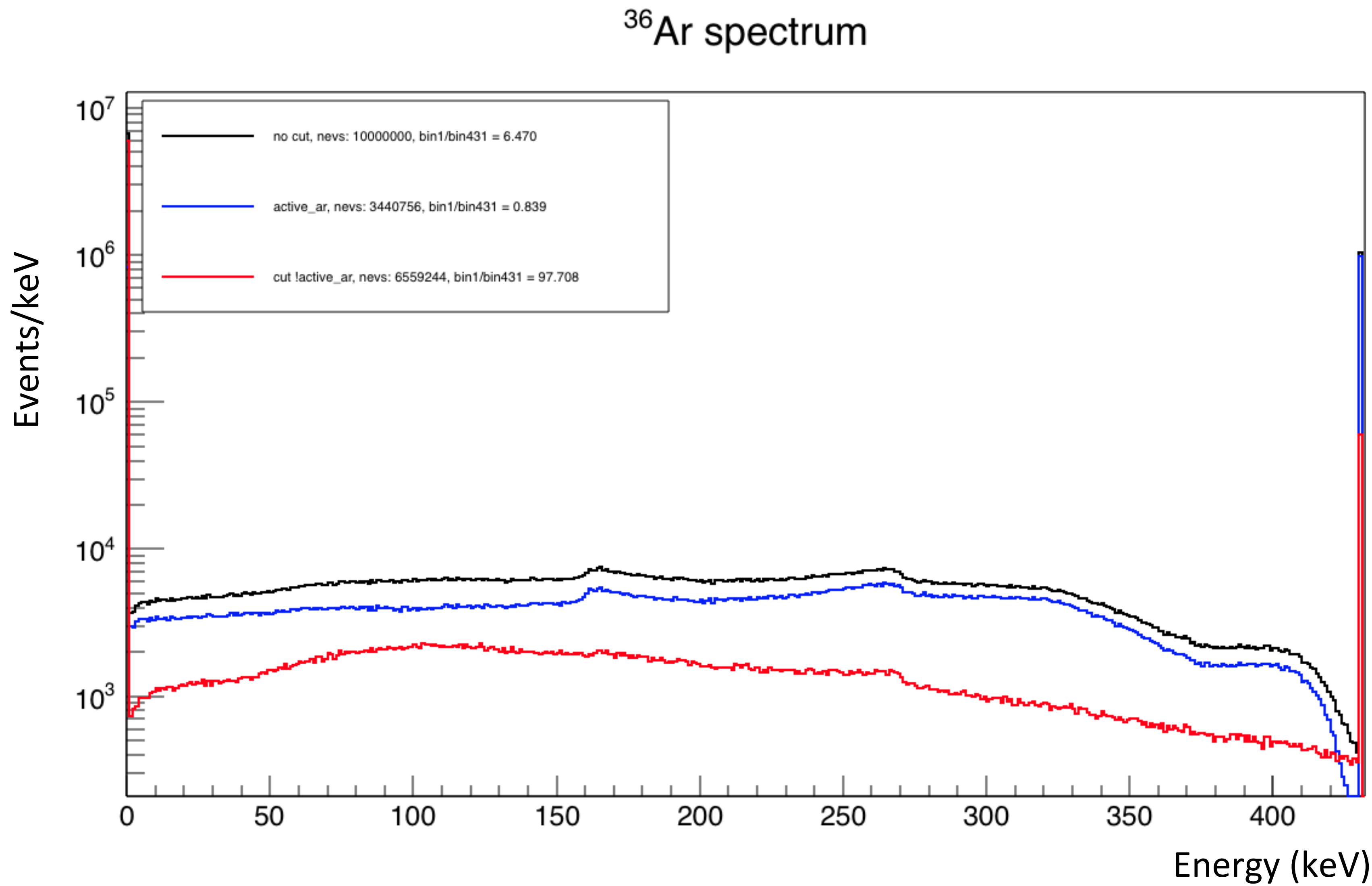
A. Renshaw, Y. Guardincerri, L. Pagani, H. O. Back, S. Norris, J. Martoff

January 29, 2015

Introduction

- $^{36}Ar + 2e^- \rightarrow {}^{36}S + 0\nu$ is energetically allowed, but hindered by linear and angular momentum conservation
- Both 2ν and 0ν emit 2 x-rays
- 0ν case must also emit 431 keV gamma to conserve linear momentum – this is the signal (with field off, S1=~3500 PE and S1_late=~2600 PE)
- Search requires good energy resolution, linearity, background model
  - using S1_late avoids linearity issues coming from saturation
  - z-dependent S1 correction necessary for resolution
  - ^{39}Ar background spectral fit becomes poor below ~1000 PE

Expected Signal (From Geant4 MC)

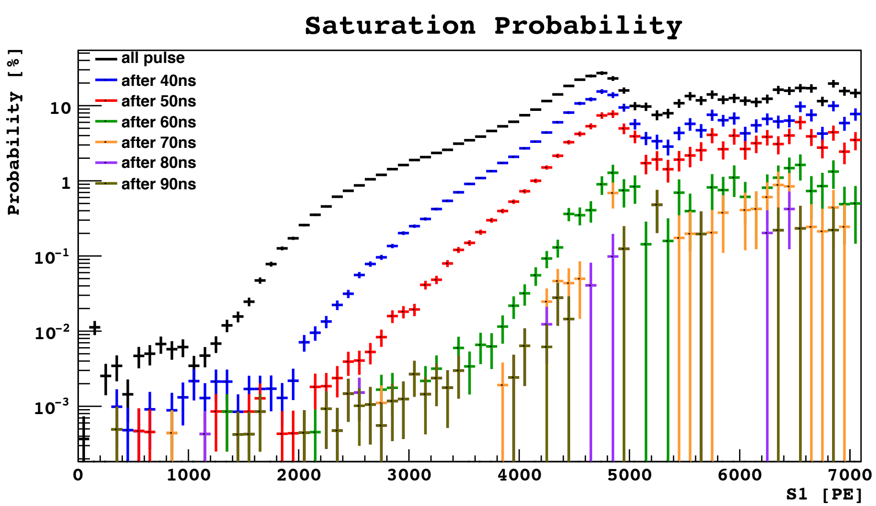


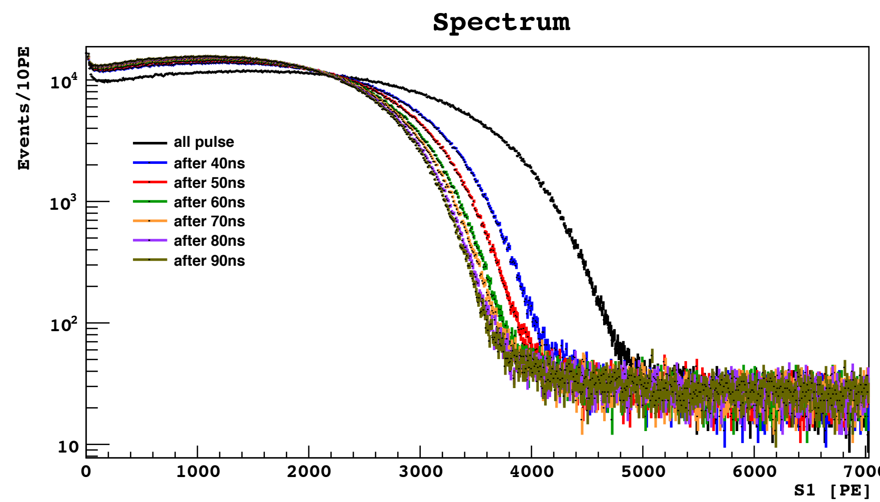
Field-Off Data (First Campaign)

- Data taken with field off and prescale 1
- Trigger:
  - spec_g2_inh810
  - normal_g70000
  - V1724 present (but not used)
- Cuts:
  - found_baseline == true
  - channels.size() == 38
  - S1 dependent f90 cut
  - n_phys_pulses == 1
  - -6.09 < s1_start_time < -6.02
  - max_s1_late/total_s1_late < 0.4

Saturation and S1_late

- The saturation probability has a strong energy dependence, should not cut on this
- Will have an important effect on background estimations





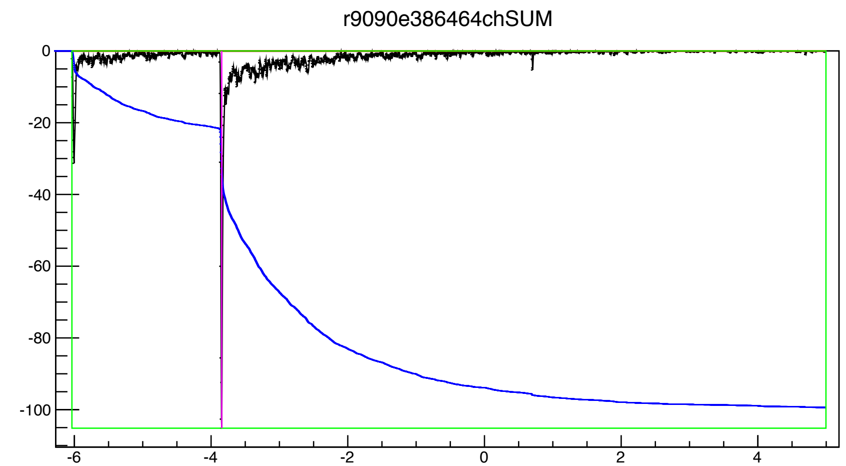
To remove the strong energy dependence of the saturation probability (1000 PE to 5400 PE), define variables S1_fromX, which is the integrated S1 starting X ns after the pulse start time

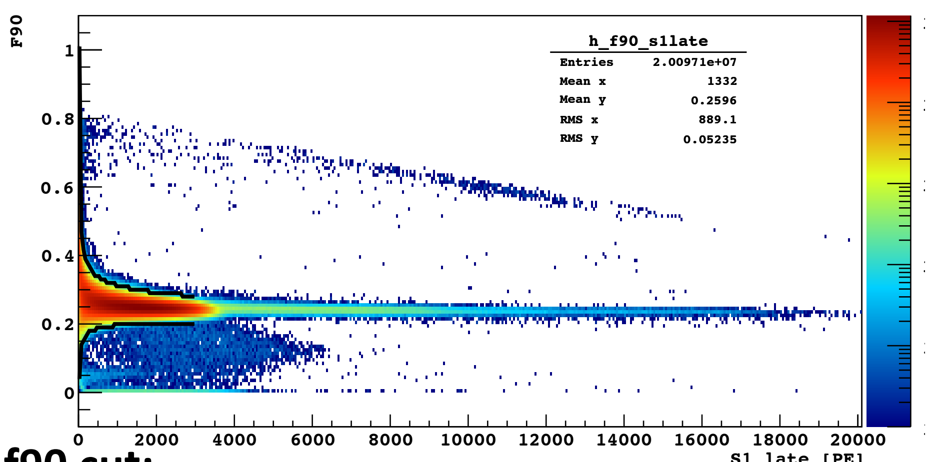
Saturation below 4000 PE is basically removed when X=80 ns, with a smooth transition beyond this energy to a higher probability

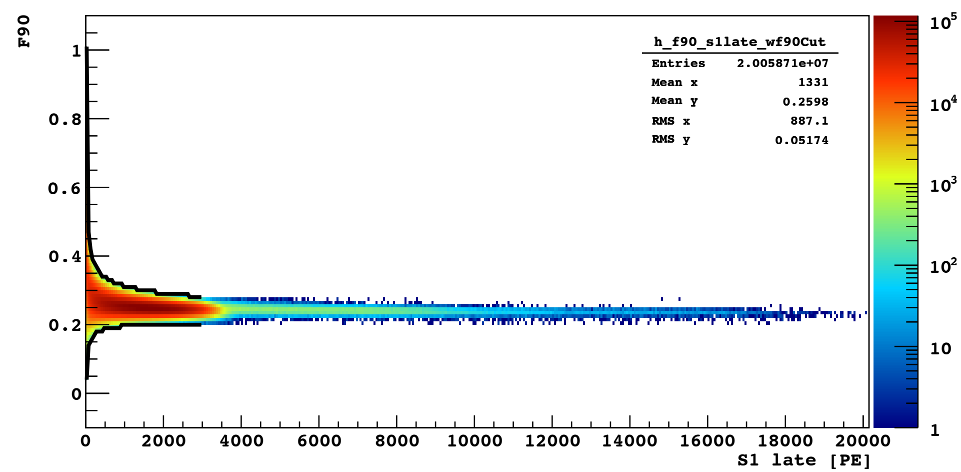
Choose to use S1_from90, which is equivalent to (1-f90)*S1, and define this as S1_late

F90 Cut to Kill Multiple Pulses

- When two peaks are close in time, the pulse finder fails, and only finds one peak
- This will induce small values of f90, this motivates an f90 cut



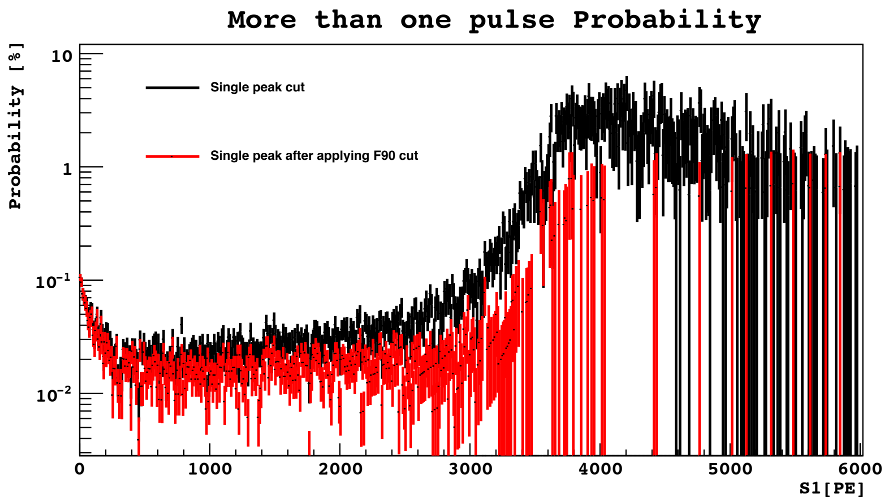




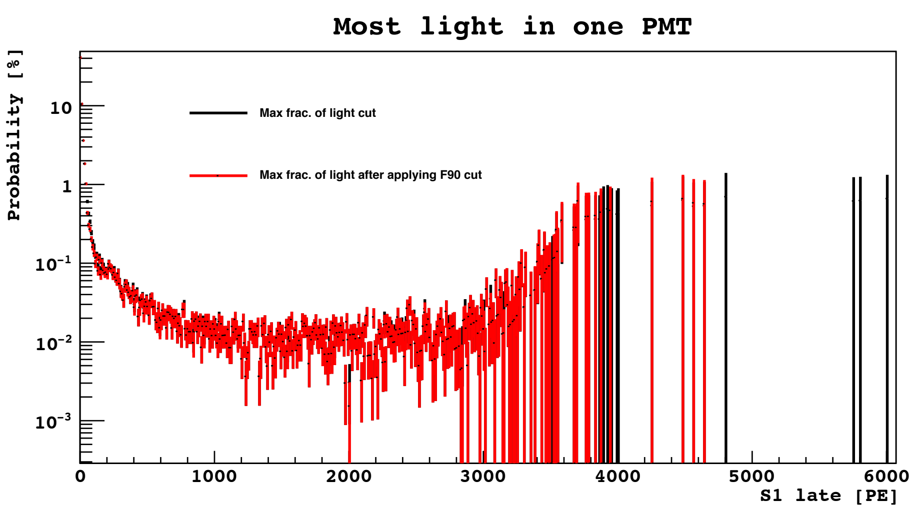
f90 cut:

- for each bin of 50 PE in s1_late look for f90 bin with highest content
- move high/low in f90 and stop when the content is less than 1% of highest content (or first bin with 0 content).
- After 3000 PE the range in f90 is constant [0.2,0.28]

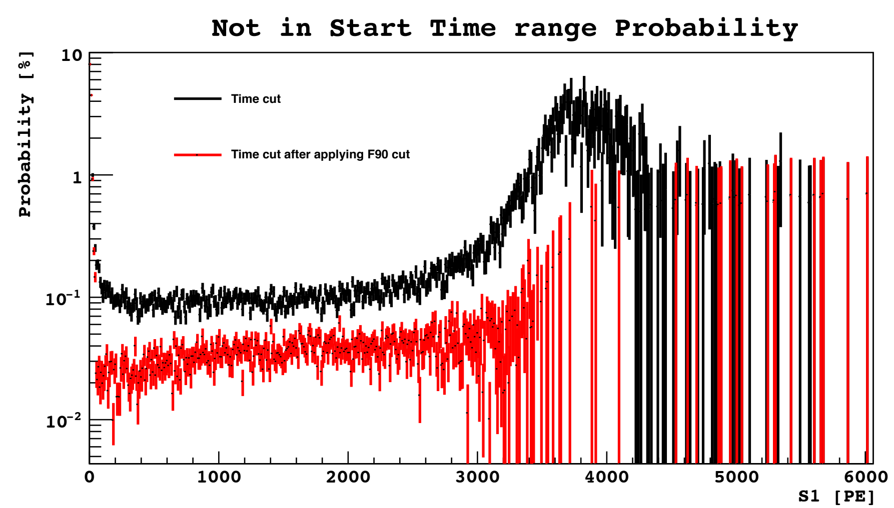
F90 Cut Effectiveness



After applying f90 cut, essentially nothing left to cut
(most bins contain either 0 or 1 events)

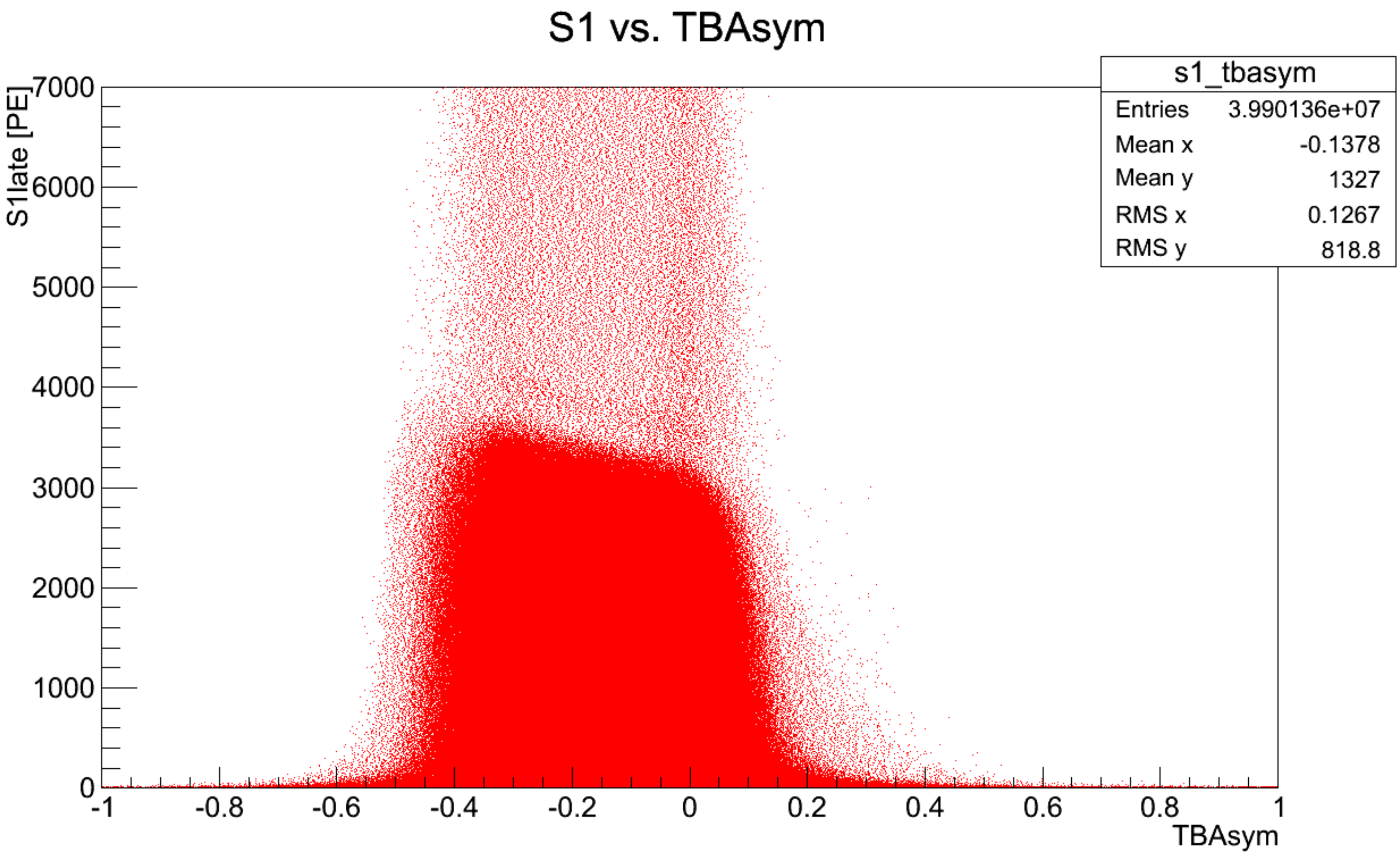


max_s1_late/s1_late < 0.4



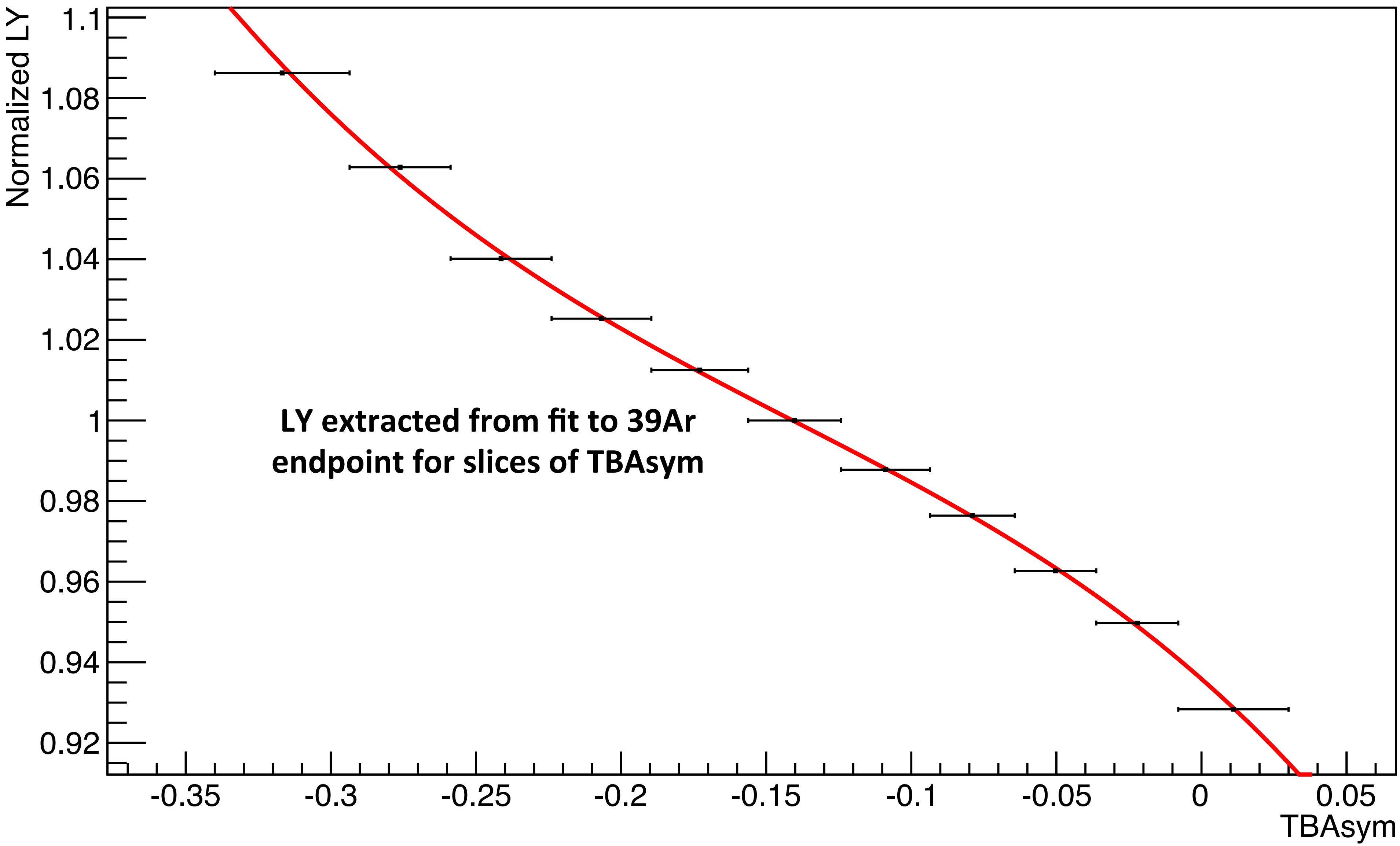
-6.09μs<pulse[0].pulse.start_time < -6.02μs

S1_late vs. TBAsym

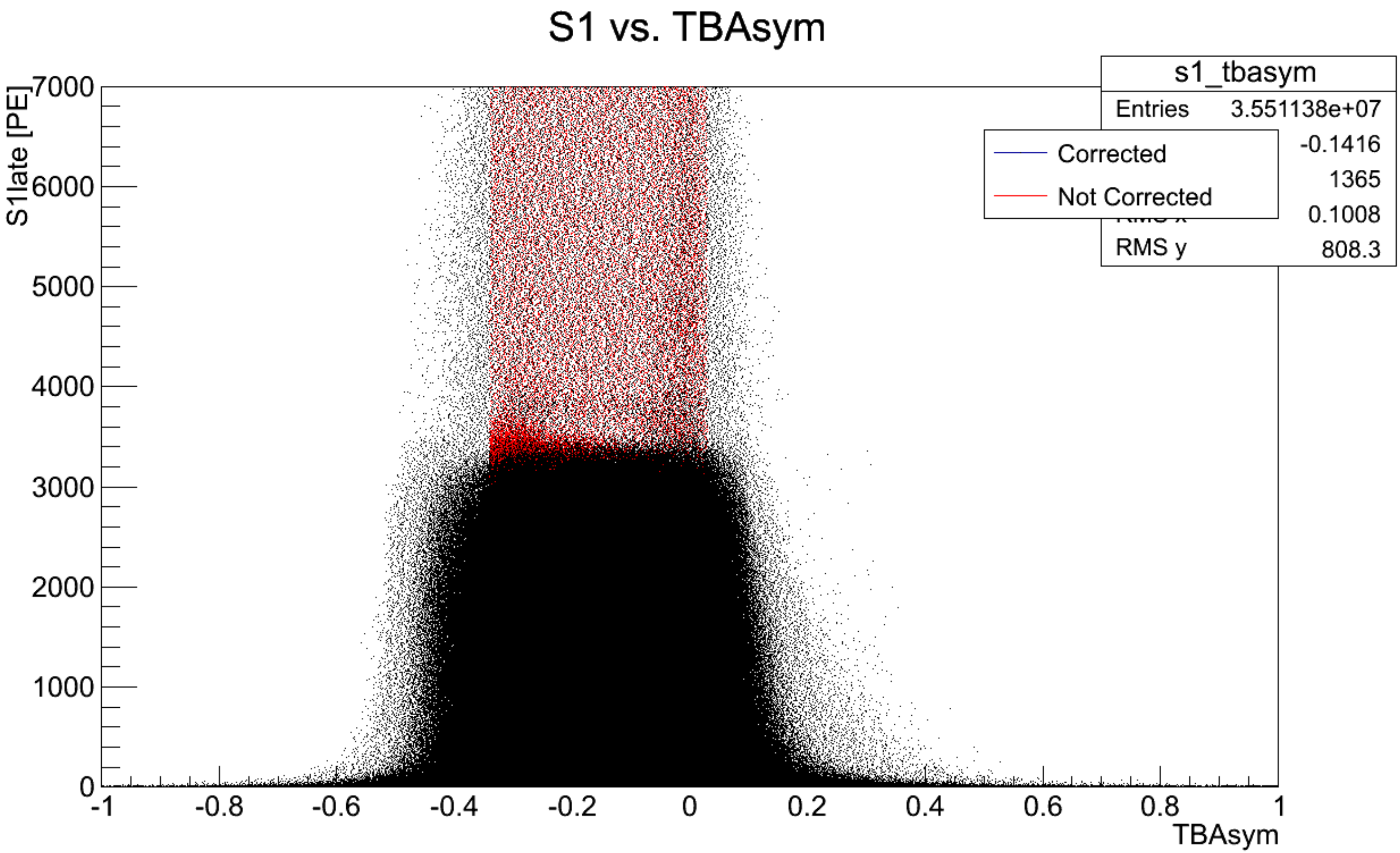


TBAsym defined as (S1_late_top-S1_late_bot)/(S1_late_top+S1_late_bot)

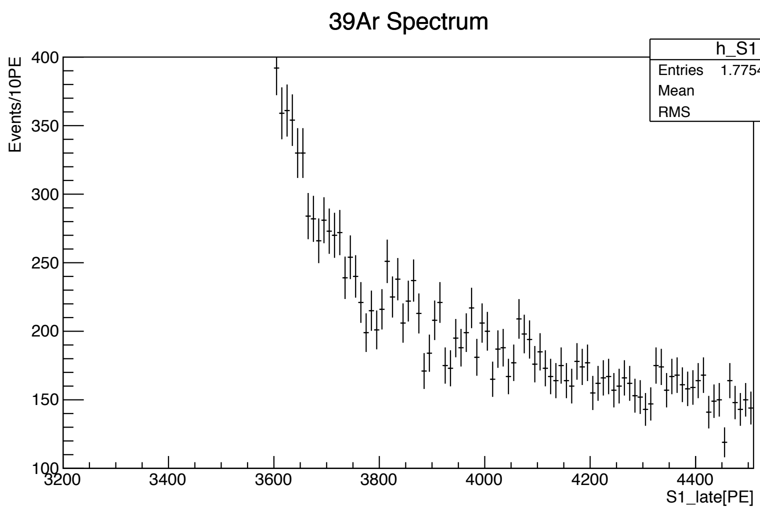
Normalized LY vs. TBAsym

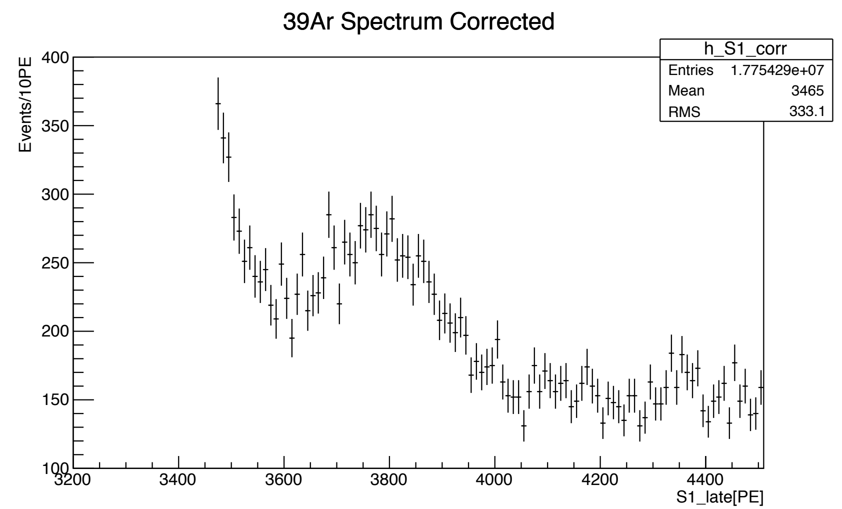


Depth Dependent (TBAsym) S1_late Correction



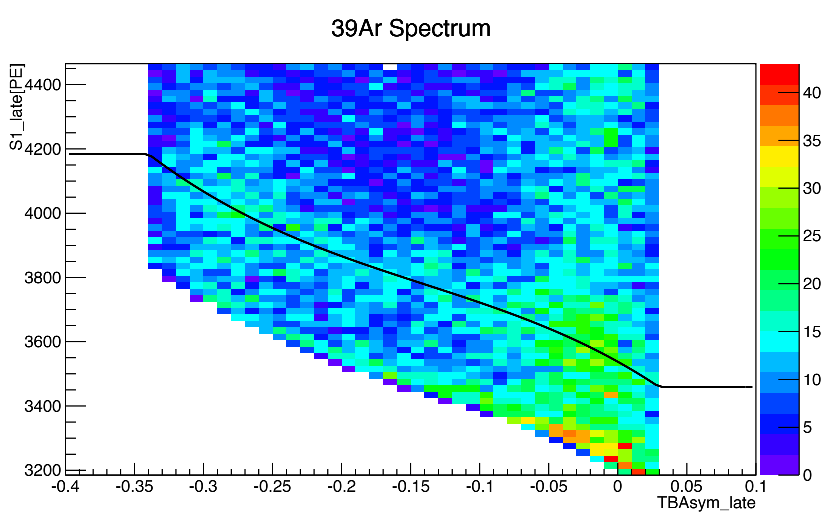
Effect of S1_late Correction





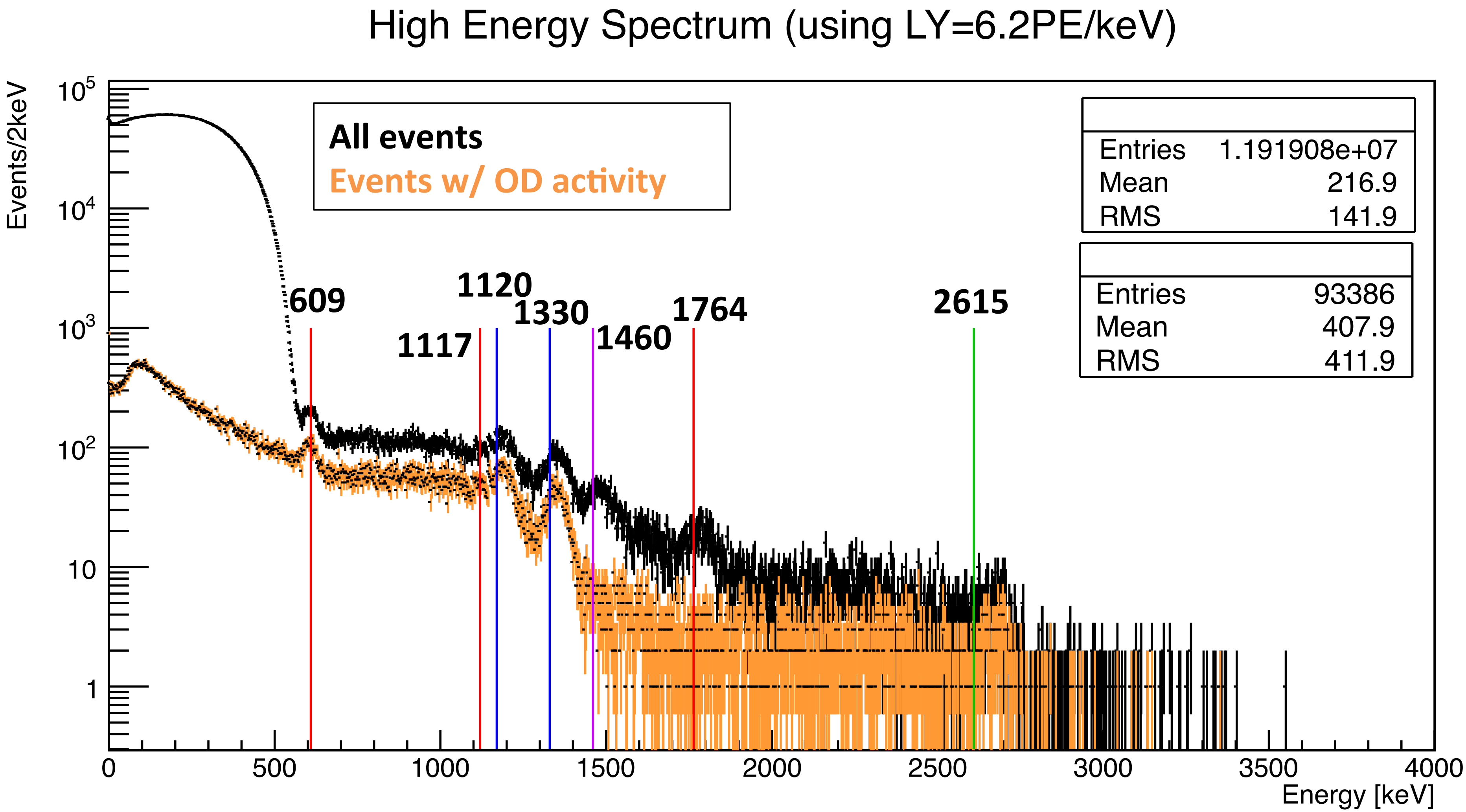
Left: Spectrum at 39Ar endpoint, before correction

Right: With correction, the excess has become a clear peak



S1_late (corrected) vs. TBAsym shows events in the peak are located at bottom of TPC

Effect of S1_late Correction



- **Bi214 609 keV peak has OD signal as it is always accompanied by another γ**
- **Co60 peaks have OD signal as "back" γ can trigger it.**
- **K40 peak has no OD signal as there is no other γ involved**
- **Bi214 1764 keV has no OD signal as there is no other γ involved**

Energy Resolution

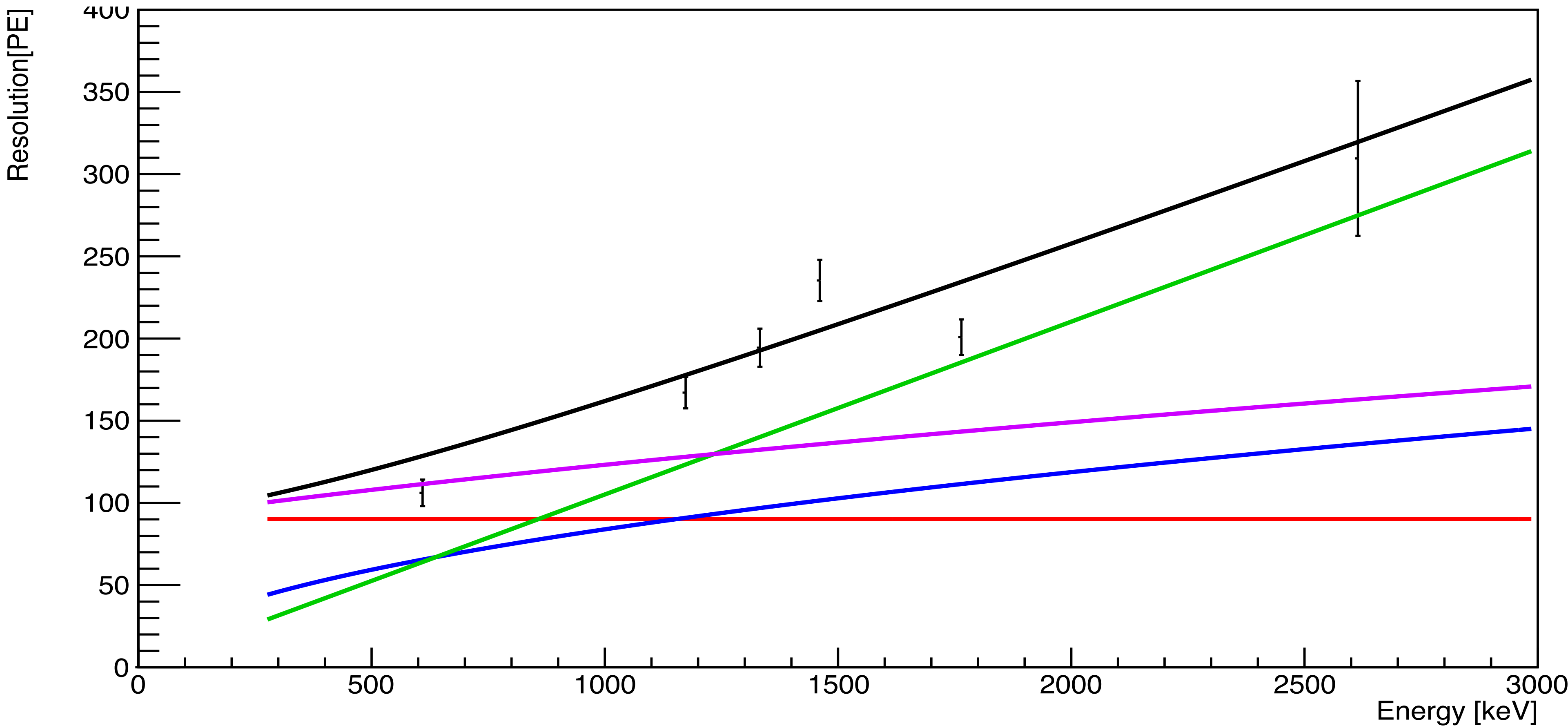
Every line is converted into a measured spectrum by scaling it with LY=6.2PE/keV and $\sigma(LY \times E) = \sqrt{(a + b * (LY \times E) + c \times (LY \times E)^2)}$

a=8133 PE^2 $\Rightarrow \sqrt{(a)} = 90$PE

b=1.161 PE $\Rightarrow \sqrt{(b * (LY \times E))} = 2.7\sqrt{(E/keV)}$PE

c=3×10^{-4} $\Rightarrow \sqrt{(c * (LY \times E)^2)} = 0.11(E/keV)$PE

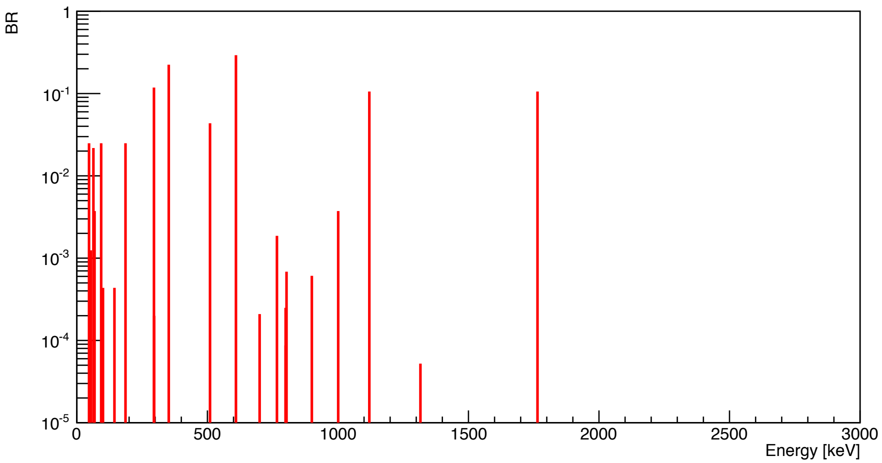
In purple only terms “a” and “b” are considered because the “c” term is not picked by a fit to the Ar39 (it is too small in that range).



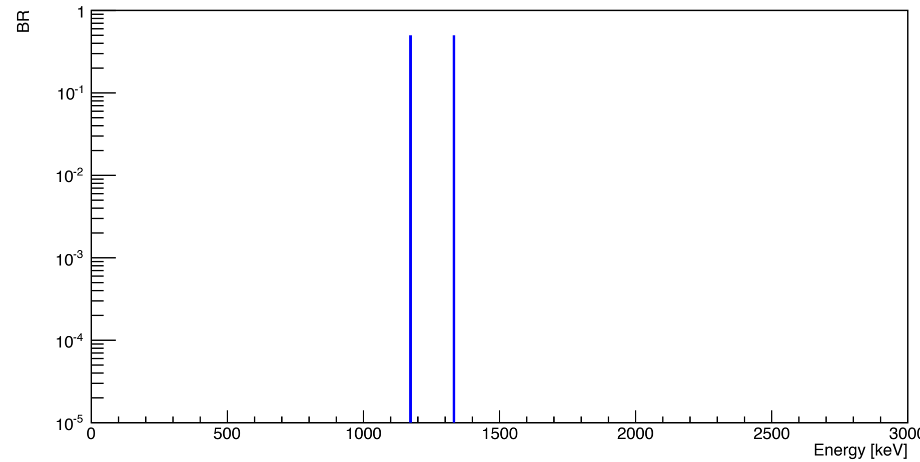
Background Lines

Lines provided by Jeff

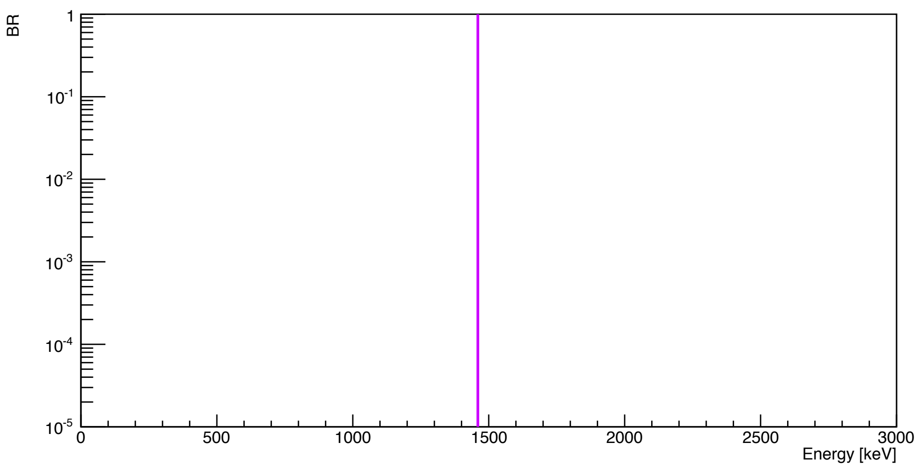
^{238}U



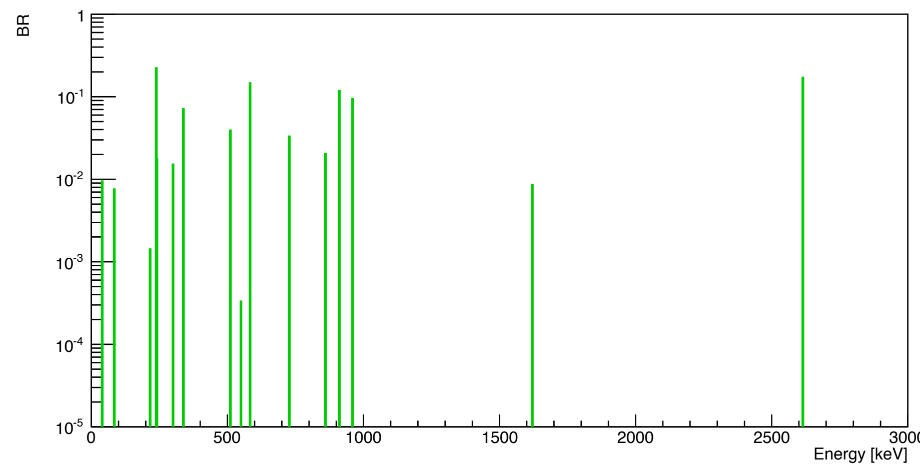
^{60}Co



^{40}K

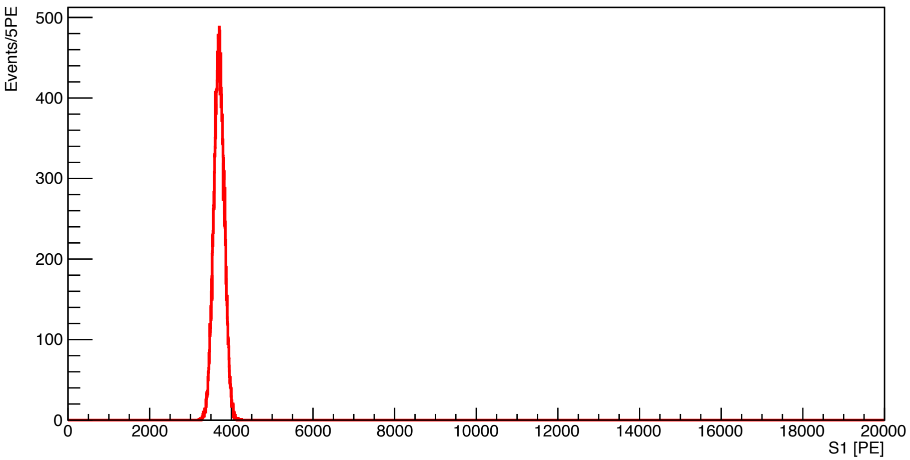


^{232}Th



Also considering ^{235}U, but the effect seems to be negligible

Add in Detector Resolution and Compton Shoulder

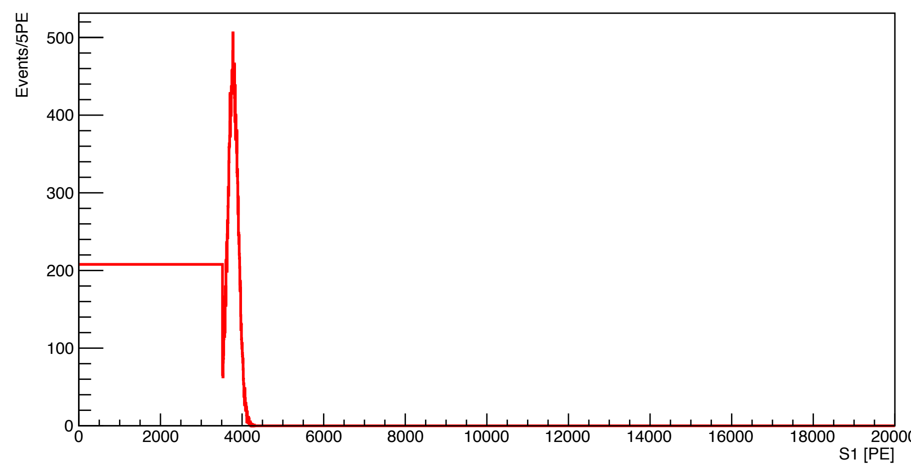


Apply detector resolution, form previous slide, for the ^{214}Bi 609 keV line, assuming 6.2 PE/keV

Method to add in simple model of the Compton shoulder:

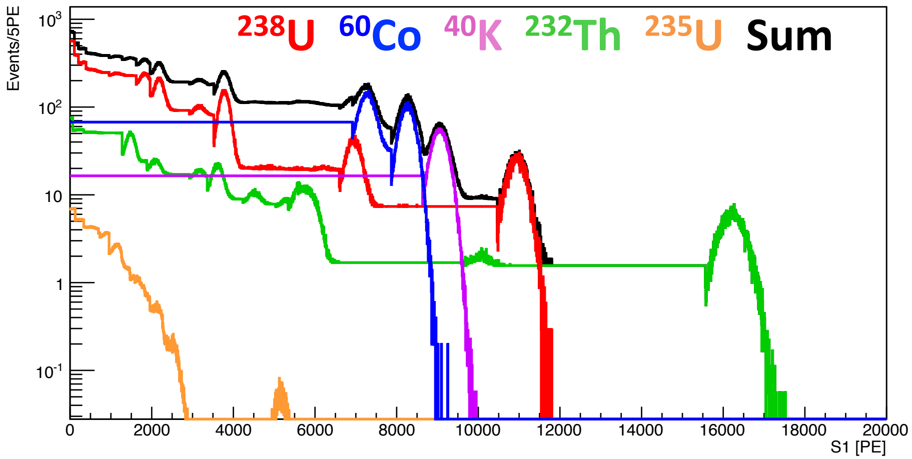
1. **Calculate integral of peak (I)**

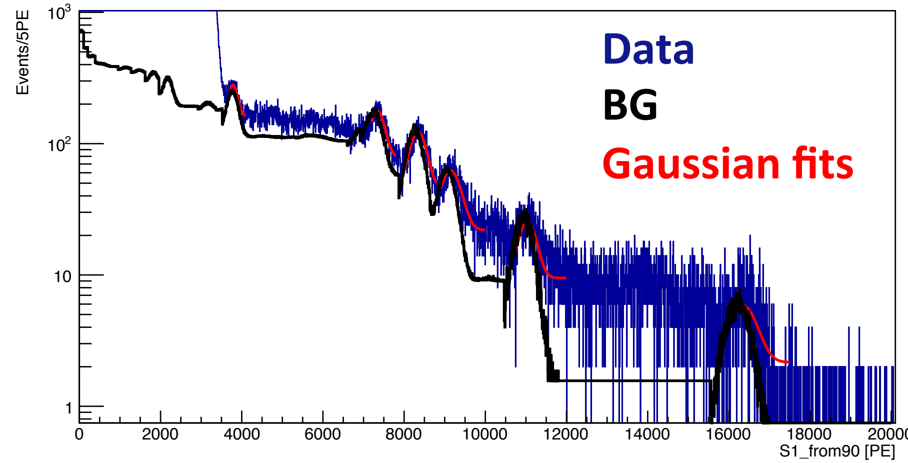
2. **Add a uniform distribution between 0 and LY x E – 2 x σ(LY x E), with an area of 5*I**



Note: This model is very simple and not meant to be the final answer, just used to identify the decay chains we see in the data

High Energy Spectrum

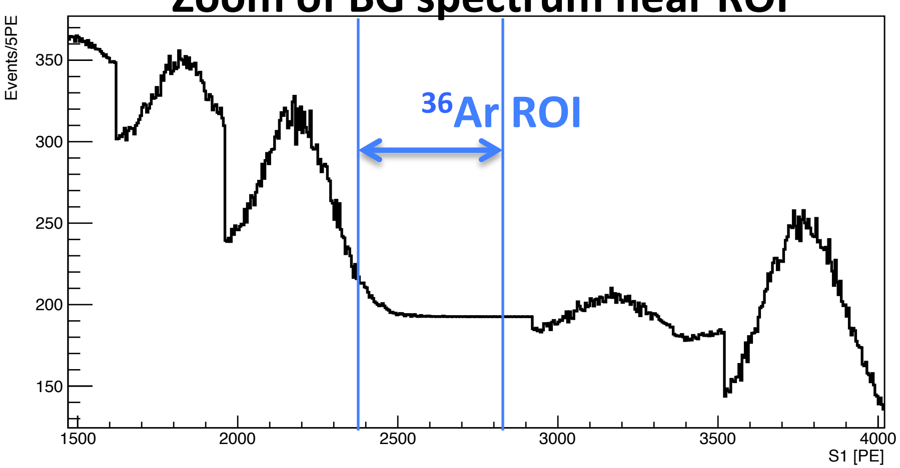




Each of the decay chain spectra are normalized to the data, using Yann's eyes

The gamma peaks agree with the data well, but not perfect→Energy dependence of the LY

Zoom of BG spectrum near ROI

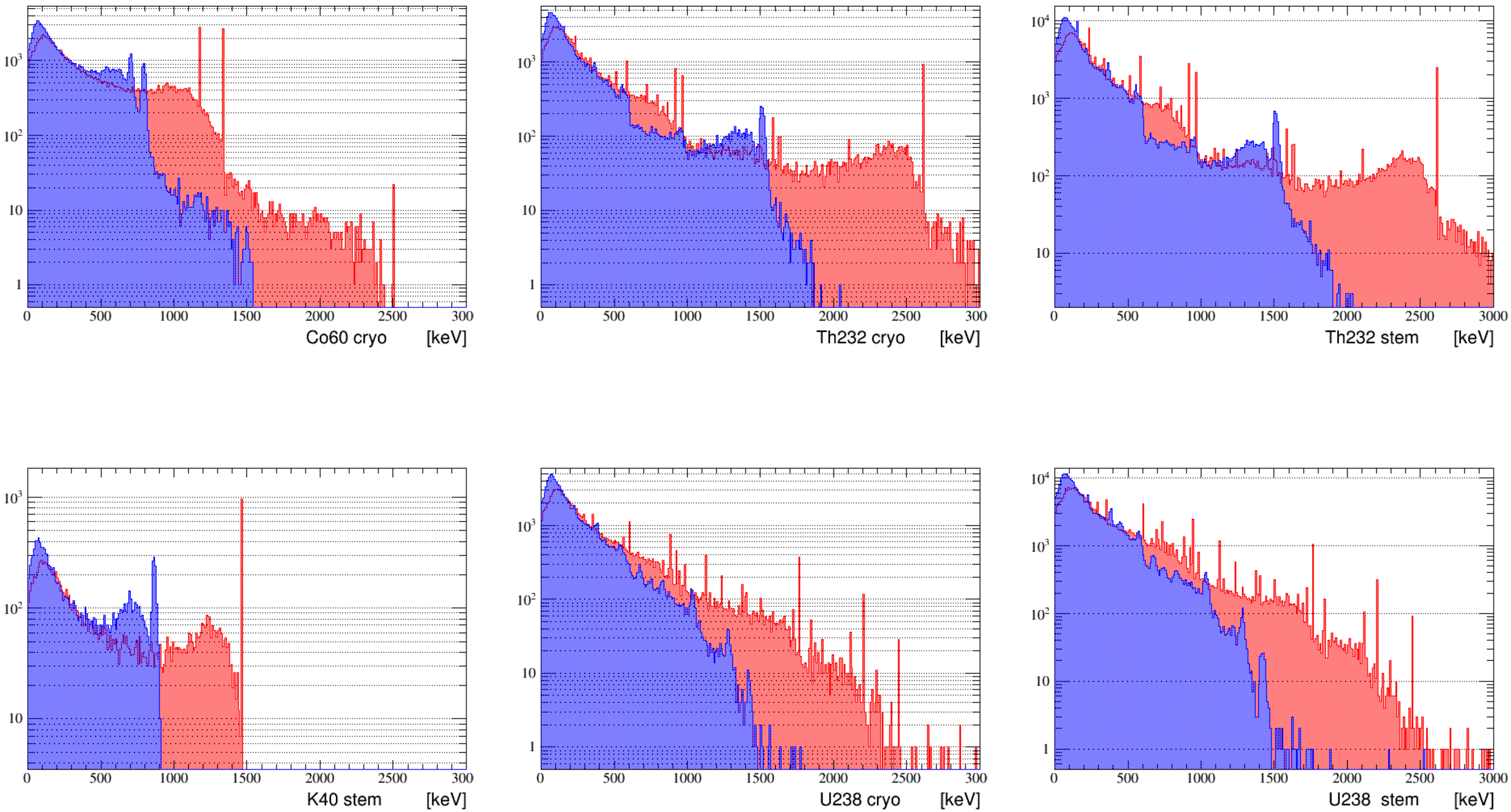


The Compton shoulders do not match well, not surprising considering the model

There are no gamma peaks within the ROI, coming from the identified decay chains, quite lucky!

True background distribution will not be flat here, this is an artifact of the simple model

Geant4 MC Gamma Simulations

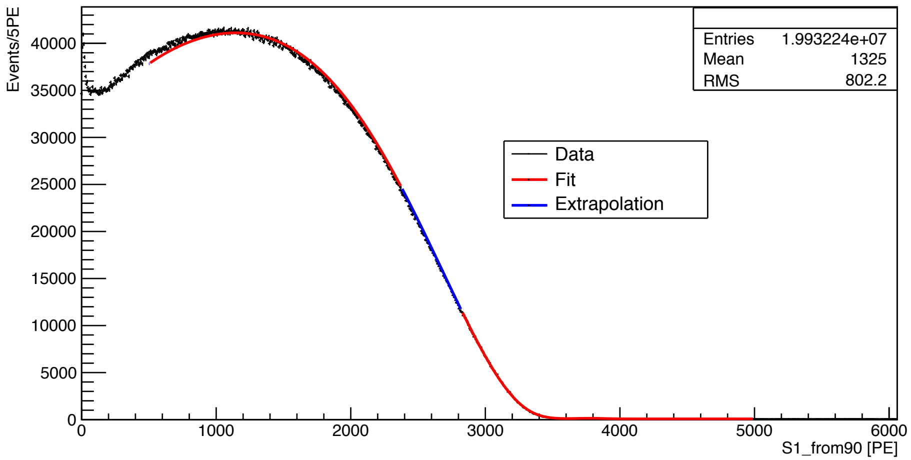


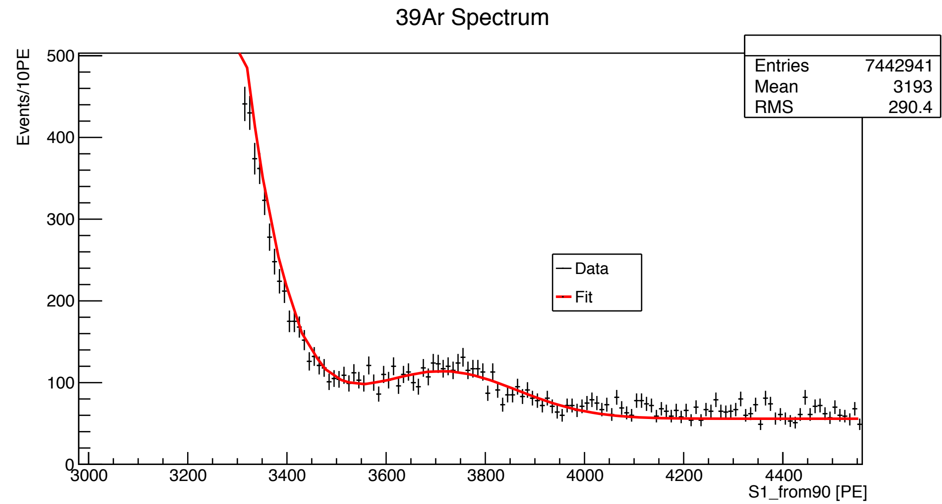
Thank you to Davide Franco for providing these spectra

^{39}Ar+Gaus+Const fit to S1_late

- **Fit the ^{39}Ar spectrum + Gaussian (centered @ 609 keV) + constant**
- **Fit goes from 500 PE to 5000 PE, excluding the ROI**
- **ROI = 2380 PE to 2820 PE, range centered at the 431.8 keV gamma peak (assuming ~6 PE/keV, typical value from ^{39}Ar fit), with a ±2 σ width (based on the measured detector resolution)**

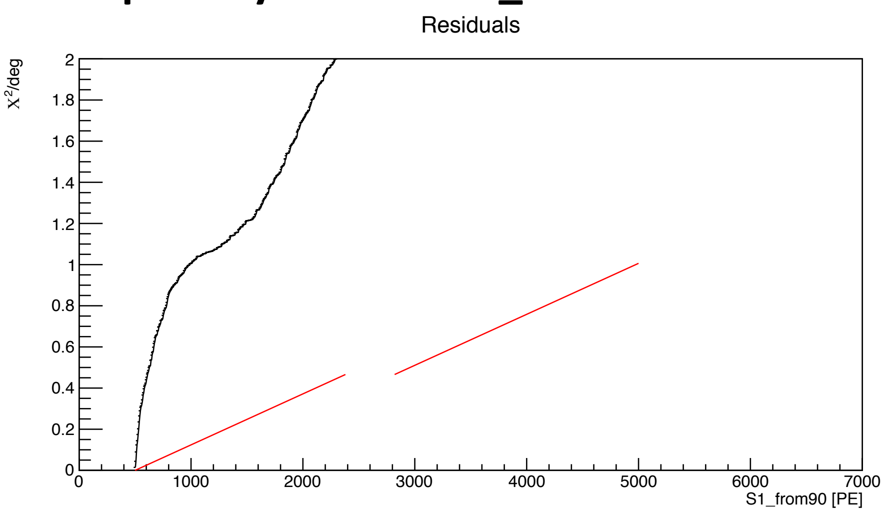
^{39}Ar fit to S1_late

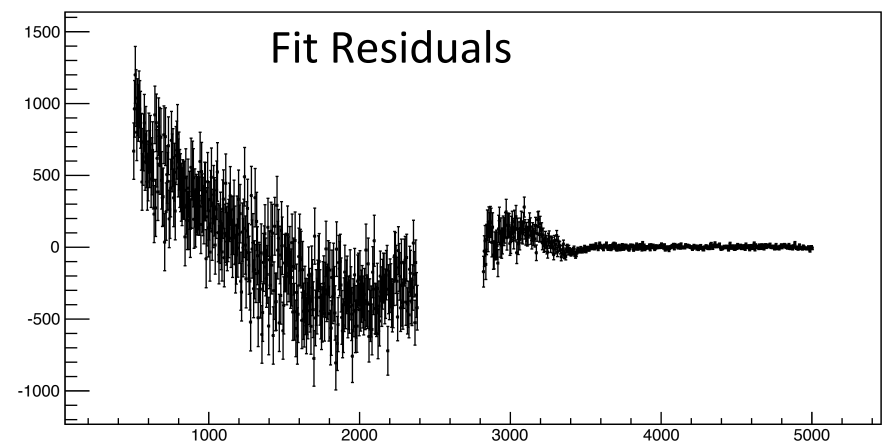




The fit does not follow the data well, especially at small S1_late

Fitting a Gaussian to the 609 keV peak describes the data well

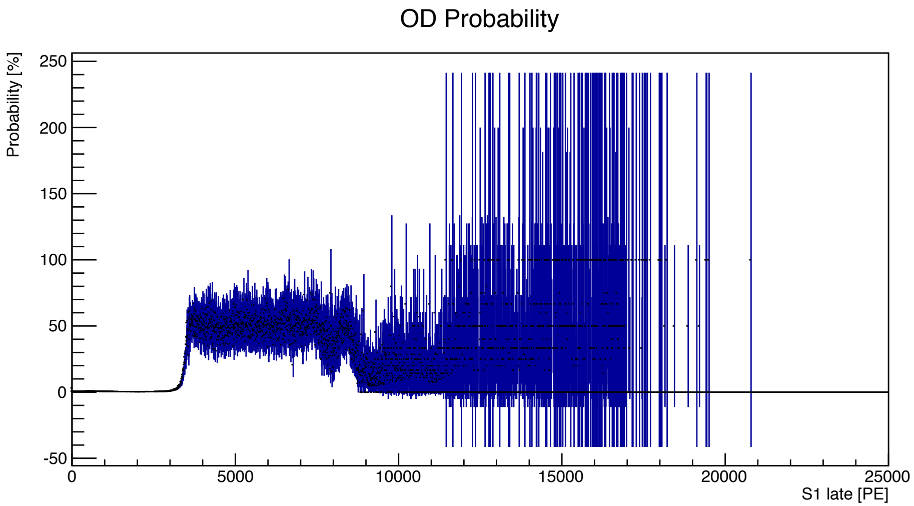




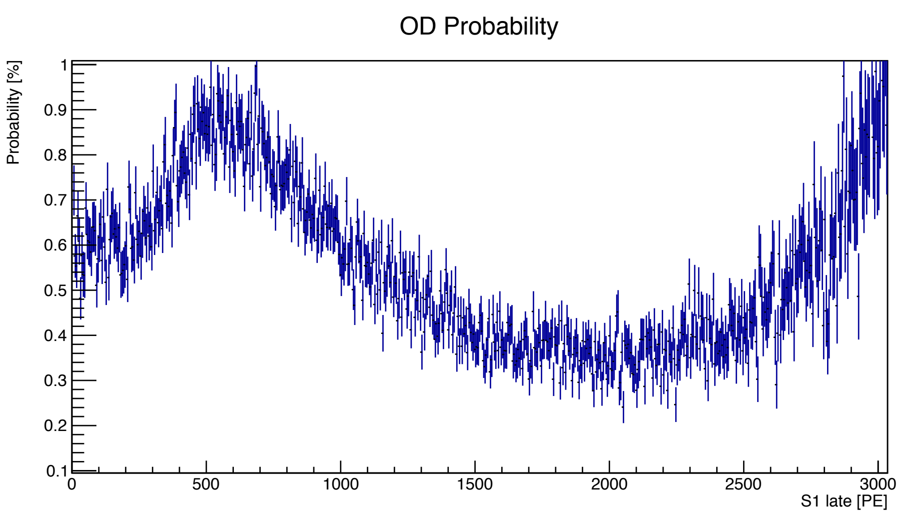
With the large number of statistics and a poor fit, the X^2/(degrees of freedom) blows up

At 500 PE there is a difference of 900 events out of ~37000 (2.4%)

^{39}Ar fit to S1_late



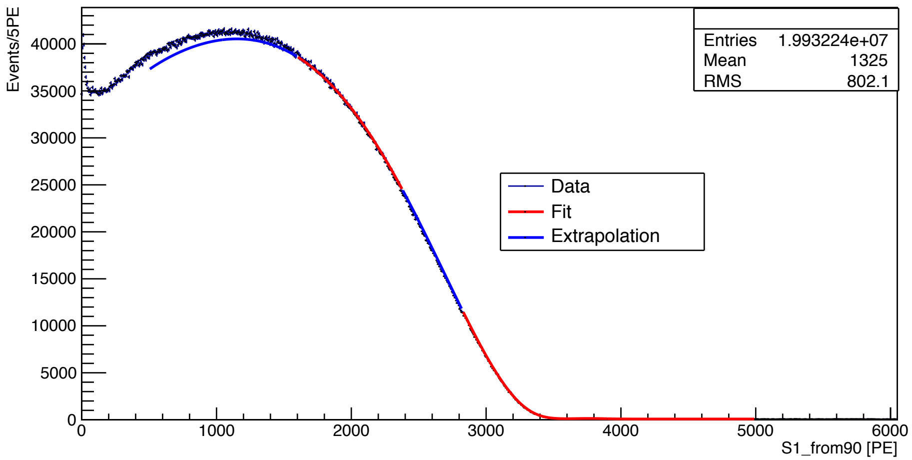
Big jump when the Ar39 ends and the γ start to dominate. Around 50% of the high energy events are seen in the OD with more than 5PE



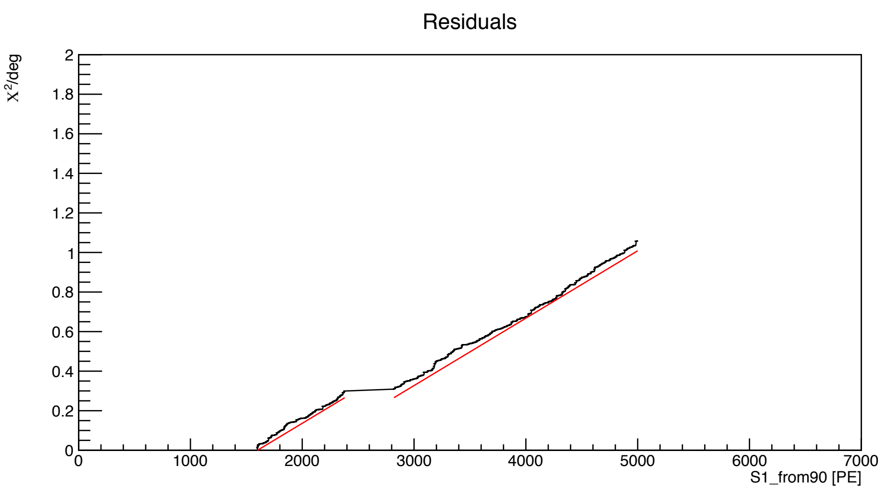
- At low energies there is an excess
- However prob. (500 PE) 0.9% while the floor is at 0.3%. 0.6% difference compared to 2.4% seen in previous slide ⇒ OD is not enough to make a good fit
- We have two hypothesis:
  - The efficiency of the OD is low
  - The Ar39 true spectrum used in the fit is underestimating the low energies

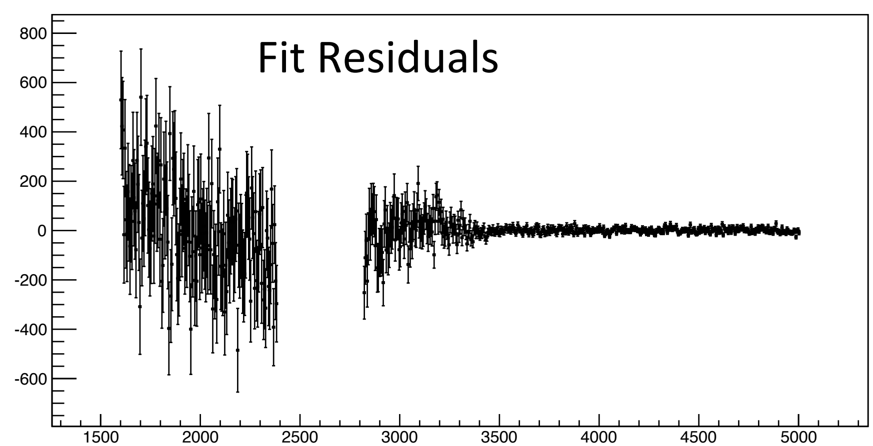
****This motivates starting the fit to the ^{39}Ar spectrum at 1600 PE**

^{39}Ar fit to S1_late Starting at 1600 PE



- The fit now does a nice job within the range of fitting, but large discrepancy at lower values
- We cut the fit at 5000 PE, as a constant function beyond this does not describe the data well (we begin to be sensitive to the structure of the high energy spectrum
- The fit gives LY=6.07 PE/keV, lower than the 6.2 PE/keV attained from the high energy peaks → S1 dependence of the light yield





Even with the large number of statistics, the fit performs very well, with X2/(dof)=621.5/(594-7)

Fit Results

- **The expected number of background (^{39}Ar) events, coming from the extrapolation of the fit into the ROI is 8011310, with a Poissonian fluctuation of 2830 events**

- **The observed number of events in the ROI is 8010195, this is $-0.4\sigma_b$**

- **The number of signal events is given by**

$$n_s = \frac{\ln(2) \cdot N \cdot \epsilon \cdot \Delta T}{T_{1/2}} \text{ with } N = N_A \cdot \frac{a \cdot M}{A}$$

- **Use Feldman-Cousins to place upper limit on number of signal events:**

$$n_s \leq FC_{90\%} \cdot \sigma_b$$

$$FC_{90\%} = 1.27 \text{ and } \sigma_b = 2830 \text{ events}$$

- **This returns a lower limit on the half-life of**

$$T_{1/2} \geq 3 \times 10^{19} \text{ years}$$

Unpublished GERDA limit is 1.85×10^{18} years

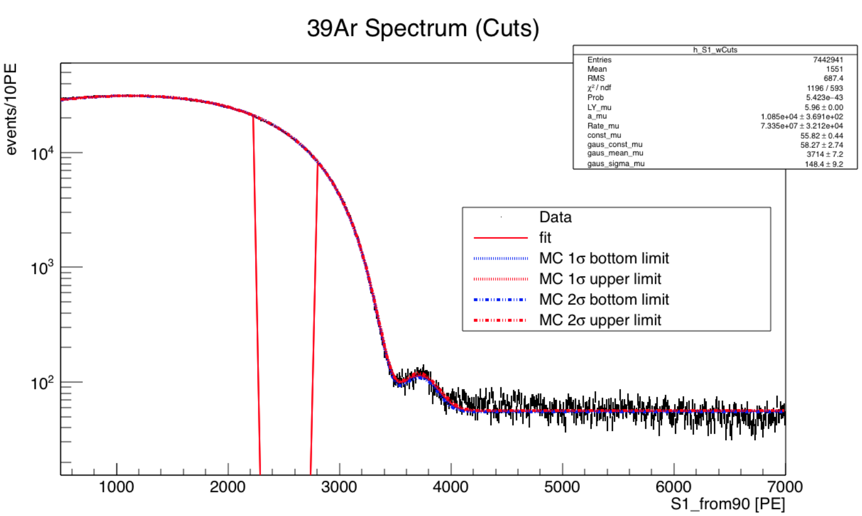
Note: We have not added the uncertainties here yet

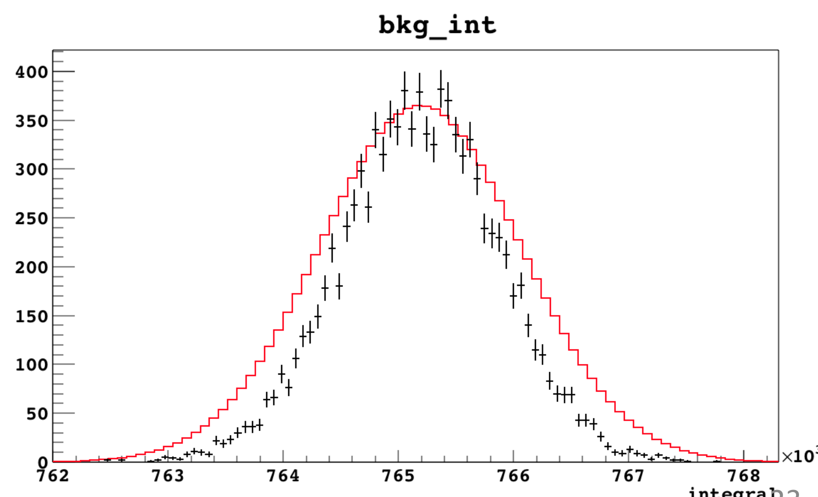
Current Fit Method Uncertainties

There are two sources of uncertainties that come from fitting the background

1. **Truly statistical uncertainty, coming from the number of events**

2. **Uncertainty coming from the predictions, this is more like a systematic uncertainty of the fit**
   - **To extract this Luca has used a multivariate PDF derived from the fit to the ^{39}Ar spectrum and the covariance matrix from the fit**
   - **Toy MC is then thrown, and an envelope constructed to symmetrically enclose 68% of the MC fitted values**





Conclusions

- High energy spectrum (peaks)
  - Now understood
  - Good motivation to include Gaussian at 609 keV
  - Peaks not currently seen with Field-ON due to larger poorer S1 resolution
- Low energy discrepancy
  - The OD removes part of the excess, but not all
  - Currently excluding low energy region from fit
- Fit
  - Need to reconcile the 6.07 PE/keV resulting from the fit and the 6.2 PE/keV used to match the gamma peaks
  - Using simple counting method yields a lower limit on the half-life of 3×10^{19} years

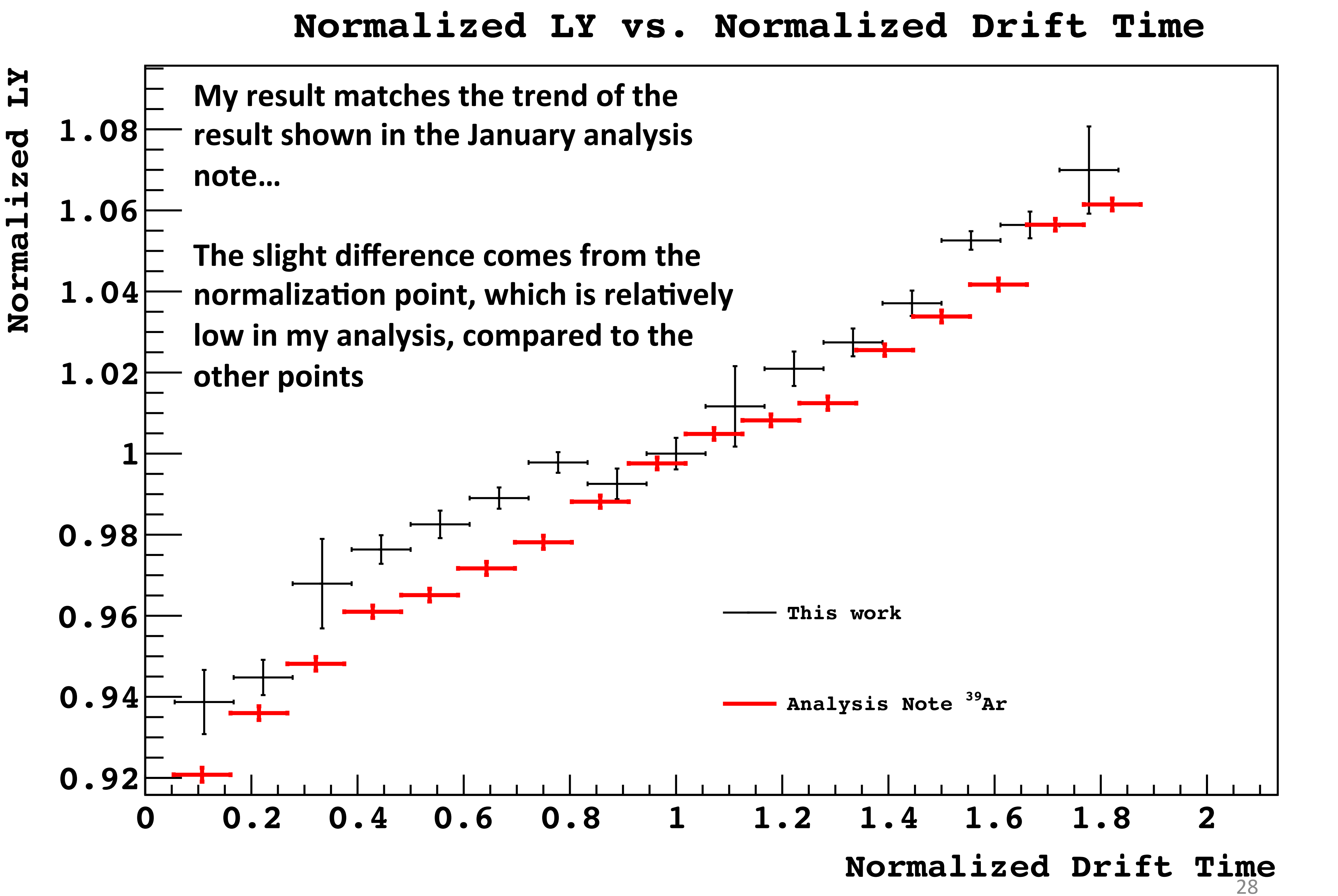
Future Plans

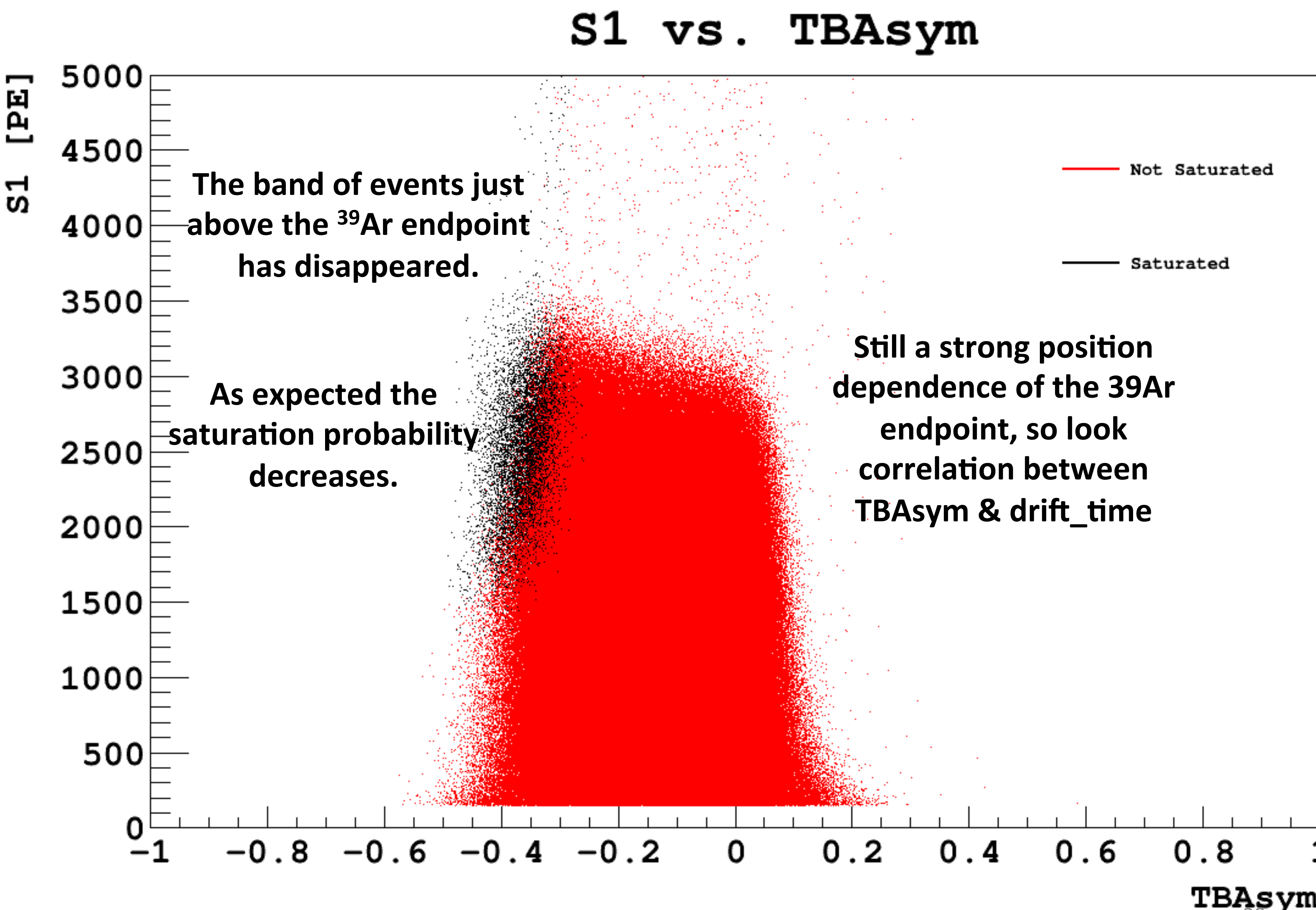
- Data: Add in the data from the second campaign, will approximately double the current data set
- Operations: Remember to keep a sample of the current Atm Ar to measure the ^{36}Ar content
- Systematics: We still nee to formulate a complete list and begin the full study
- Work on the maximum likelihood ratio method, instead of event counting on a fixed range
- Work on the full detector MC to get efficiency and signal and background PDFs to be used in a maximum likelihood method

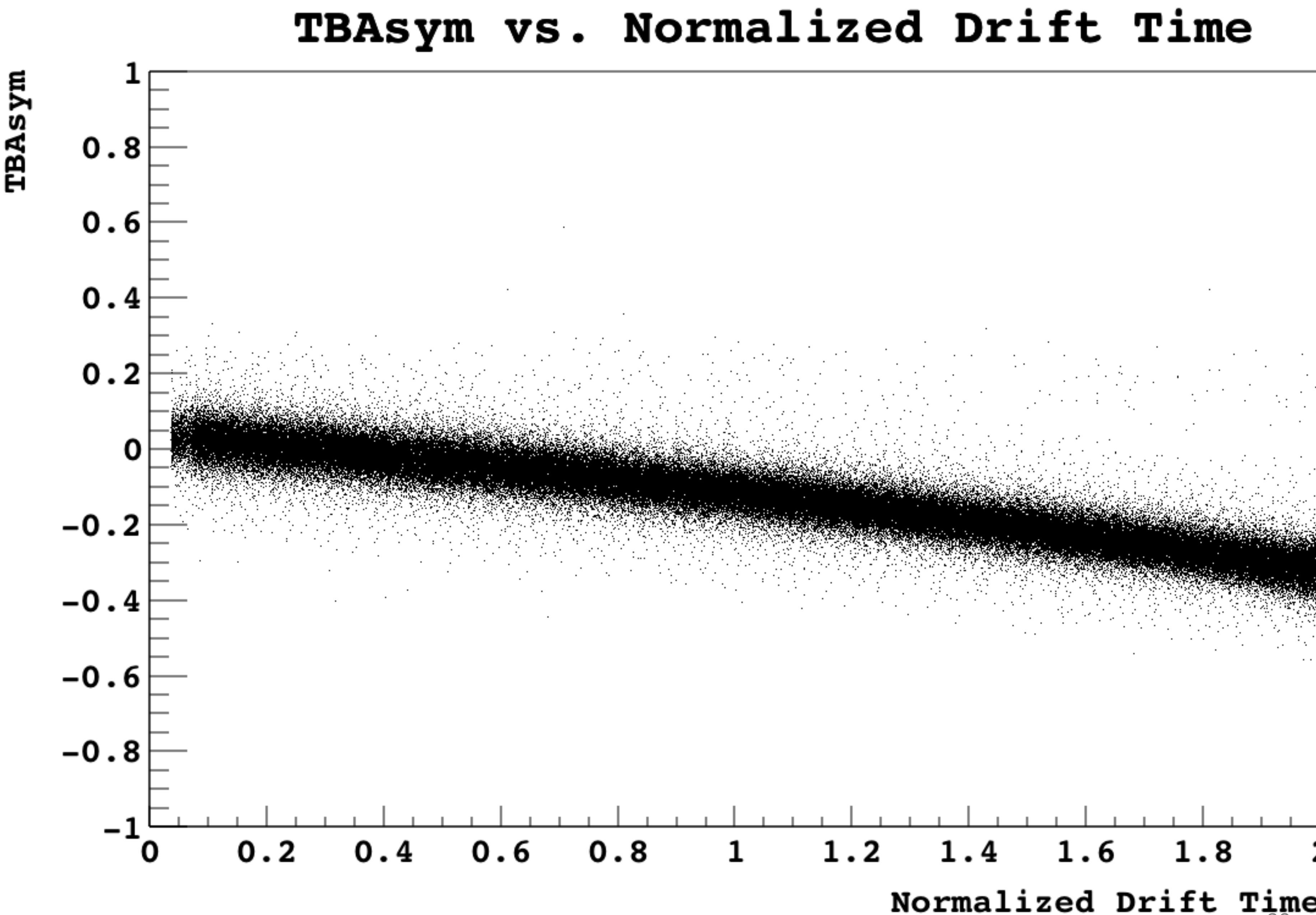
Backup Slides

Field-On Data Set

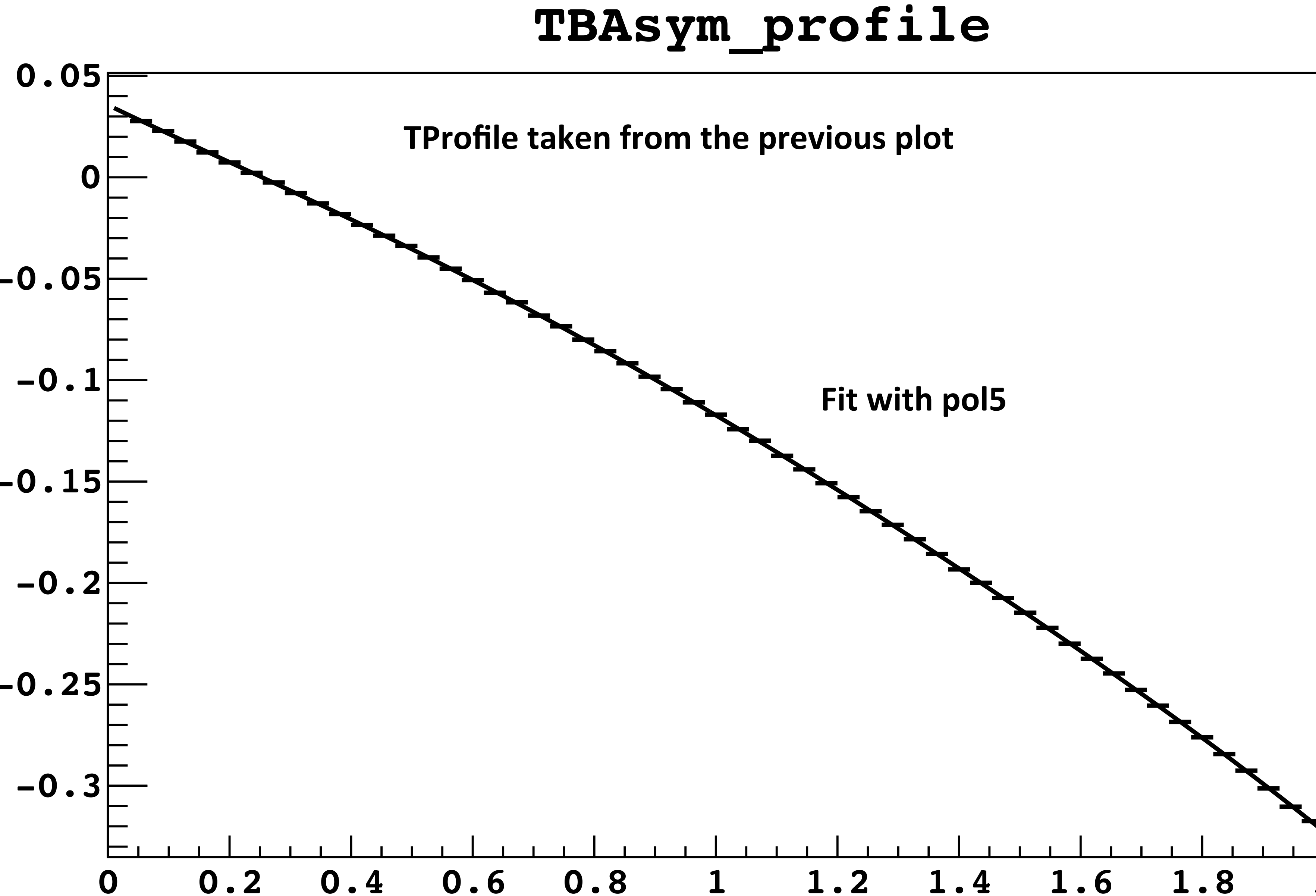
- Data taken with field off and prescale 1
- Trigger:
  - spec_g2_inh810
  - normal_g70000
  - V1724 present (but not used)
- Cuts:
  - found_baseline == true
  - channels.size() == 38
  - isSaturate == 0
  - 150 < S1 < 7000
  - n_phys_pulses == 2
  - -0.25 < s1_start_time < -0.18
  - max_s1/total_s1 < 0.4
  - 10 <= drift_time <= 370

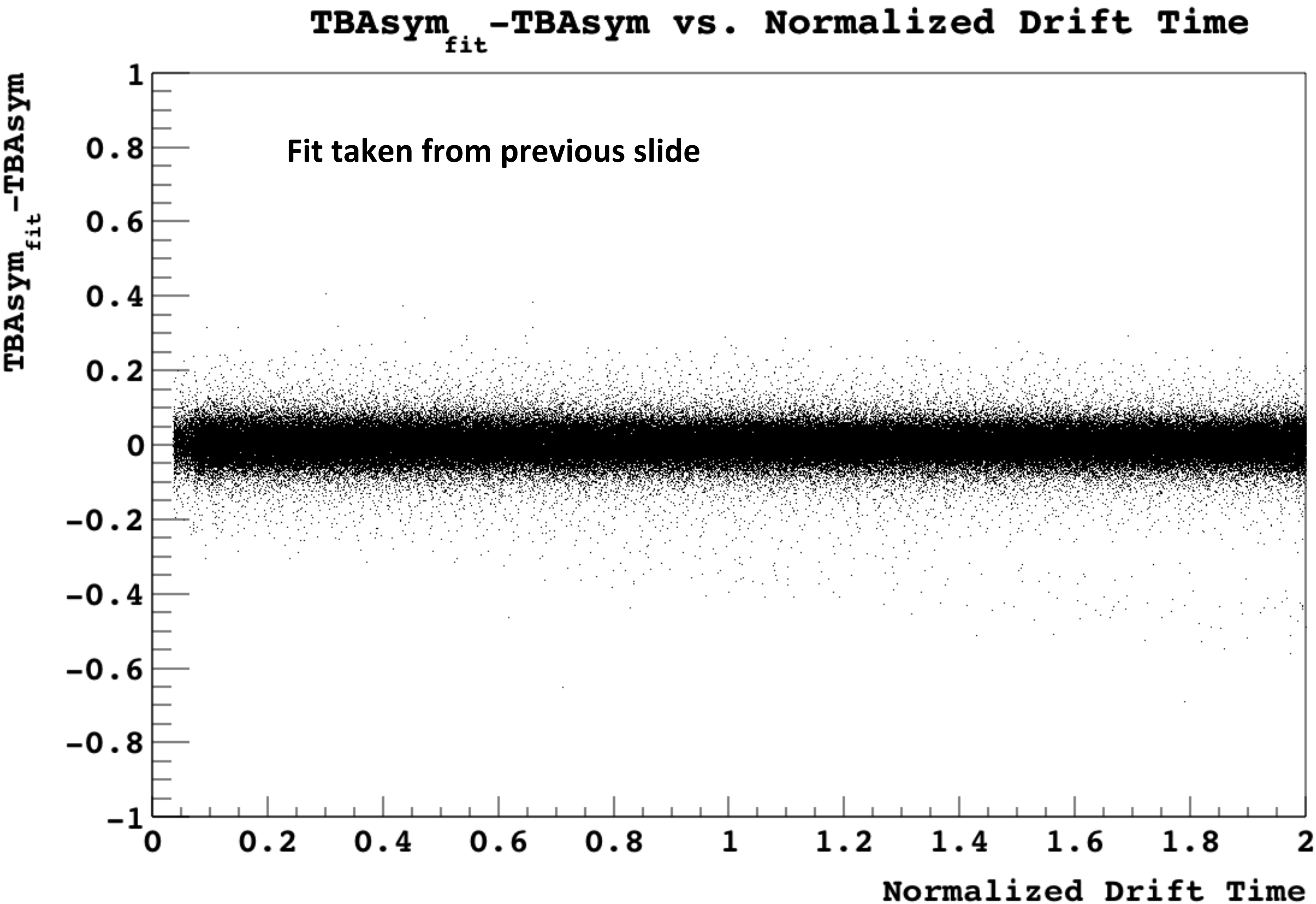

Normalized LY vs. Normalized Drift Time
My result matches the trend of the result shown in the January analysis note…
The slight difference comes from the normalization point, which is relatively low in my analysis, compared to the other points
This work
Analysis Note ^{39}Ar
Normalized LY
Normalized Drift Time
0.92
0.94
0.96
0.98
1
1.02
1.04
1.06
1.08
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2


S1 vs. TBAsym
S1 [PE]
TBAsym
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1
Not Saturated
Saturated
The band of events just above the ^{39}Ar endpoint has disappeared.
As expected the saturation probability decreases.
Still a strong position dependence of the 39Ar endpoint, so look correlation between TBAsym & drift_time

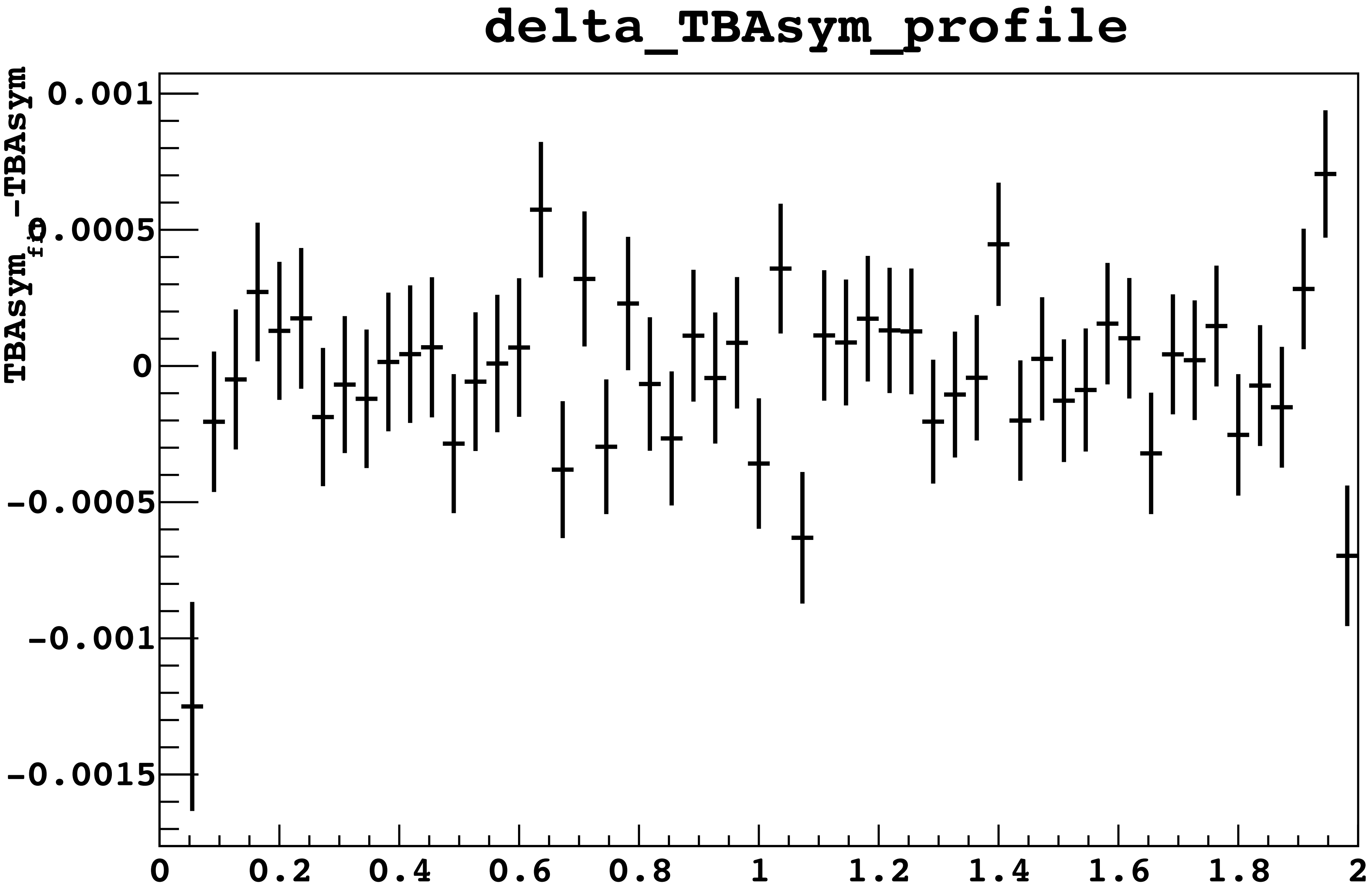


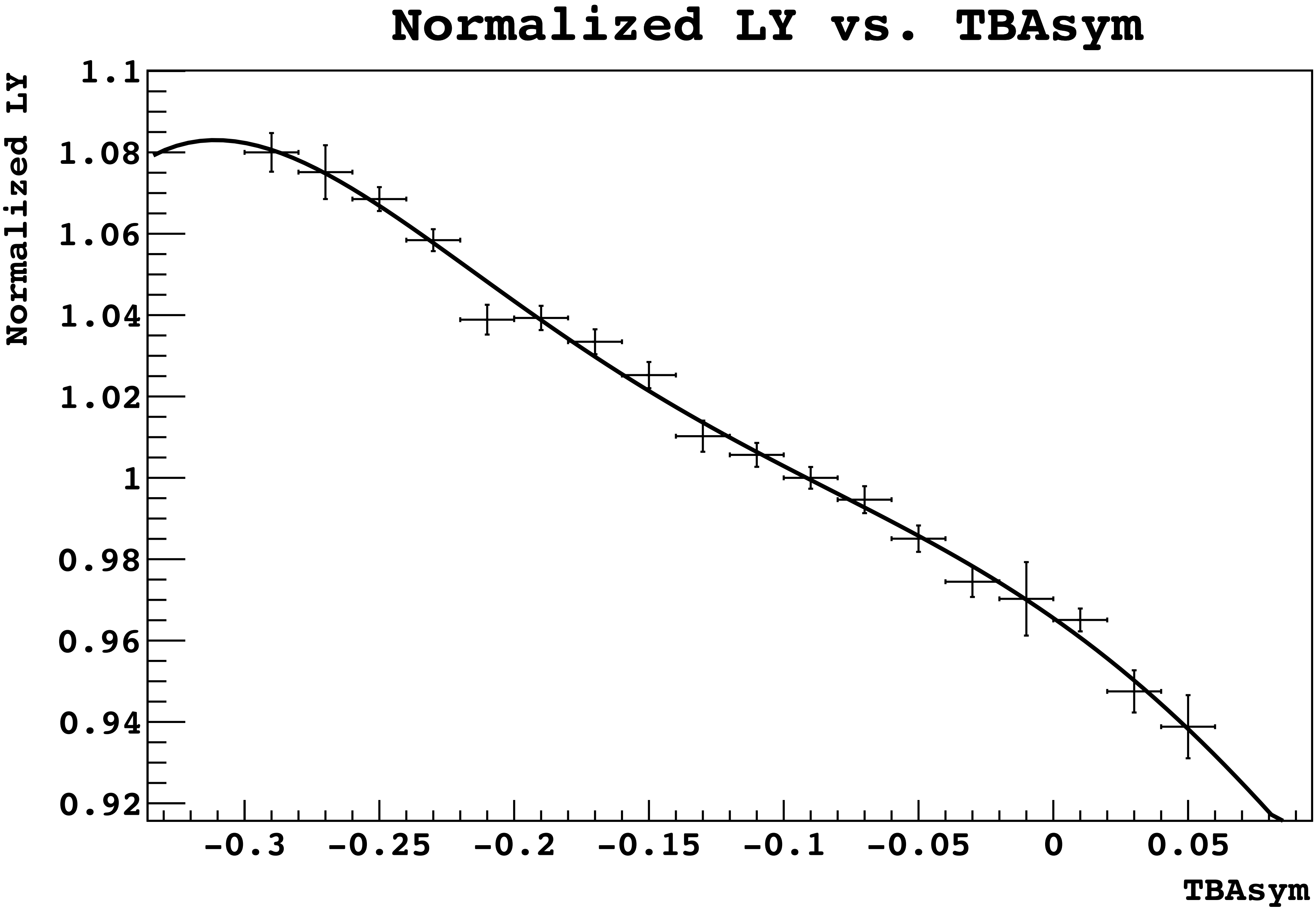
TBAsym vs. Normalized Drift Time
TBAsym
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Normalized Drift Time

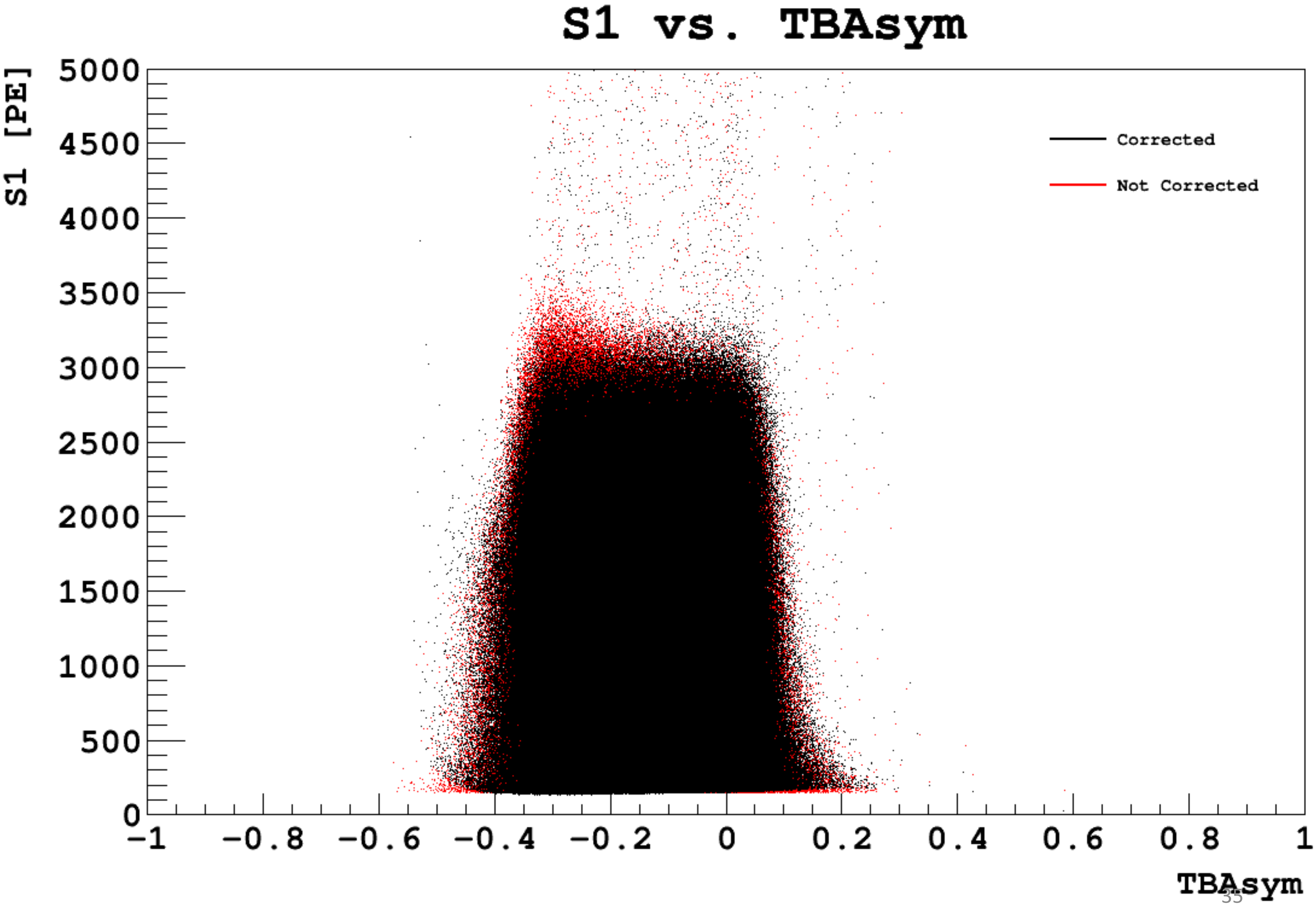

TBAsym_profile
TProfile taken from the previous plot
Fit with pol5
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2



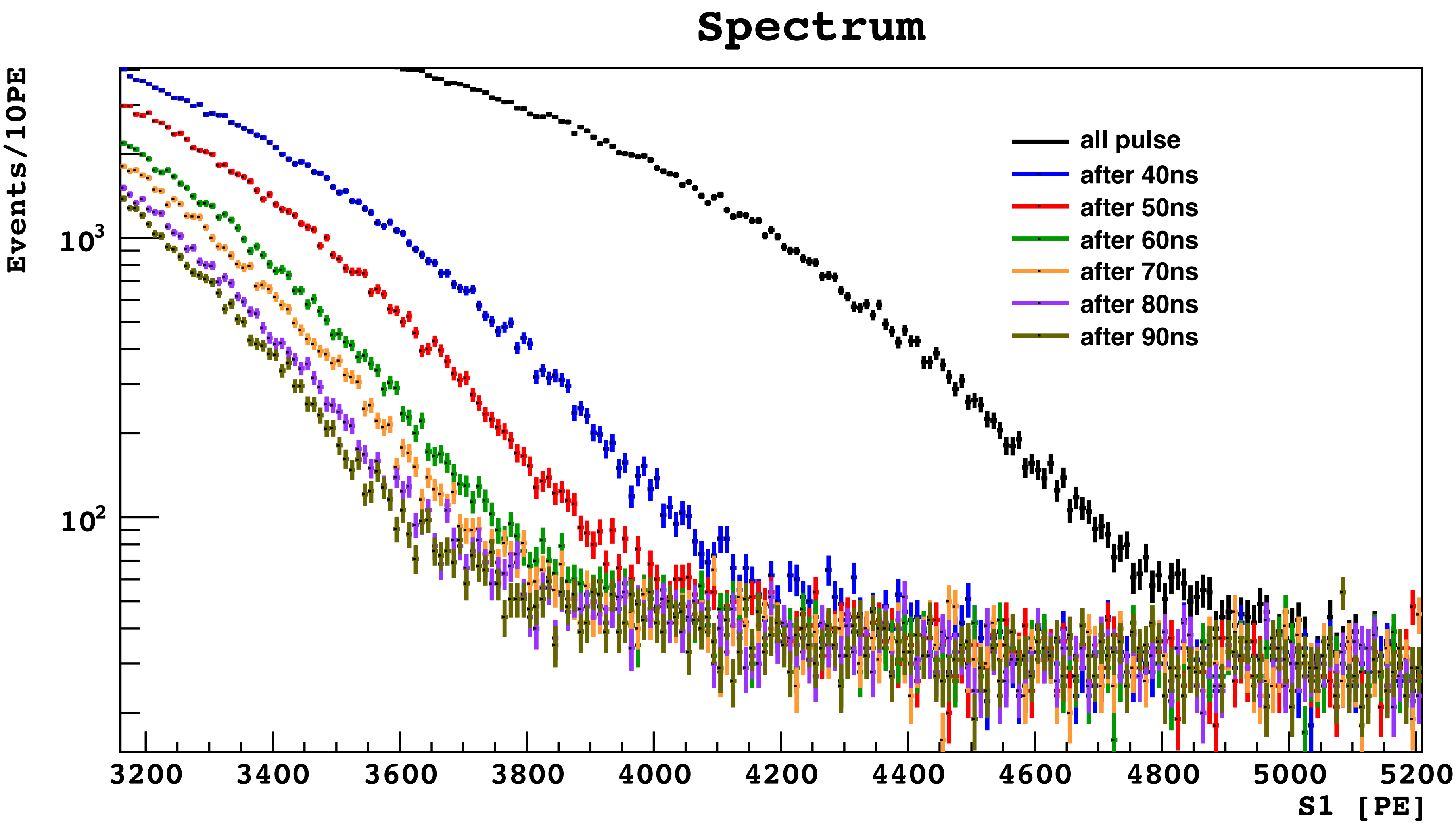
Fit taken from previous slide


delta_TBAsym_profile
TBAsym_fit -TBAsym
0.001
0.0005
0
−0.0005
−0.001
−0.0015
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

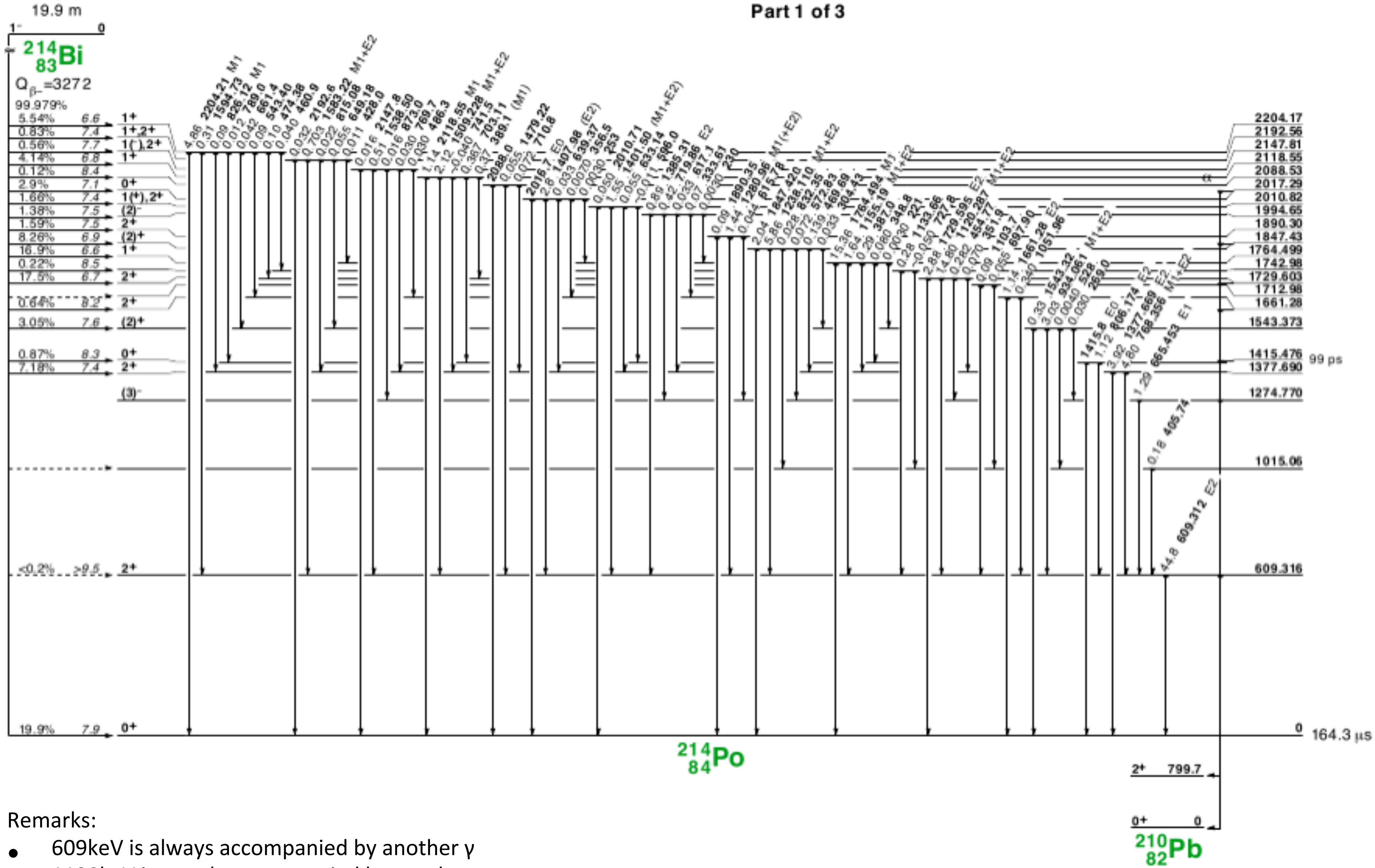

Normalized LY vs. TBAsym
Normalized LY
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
-0.3
-0.25
-0.2
-0.15
-0.1
-0.05
0
0.05
TBAsym



S1 vs. TBAsym
S1 [PE]
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1
TBAsym
Corrected
Not Corrected



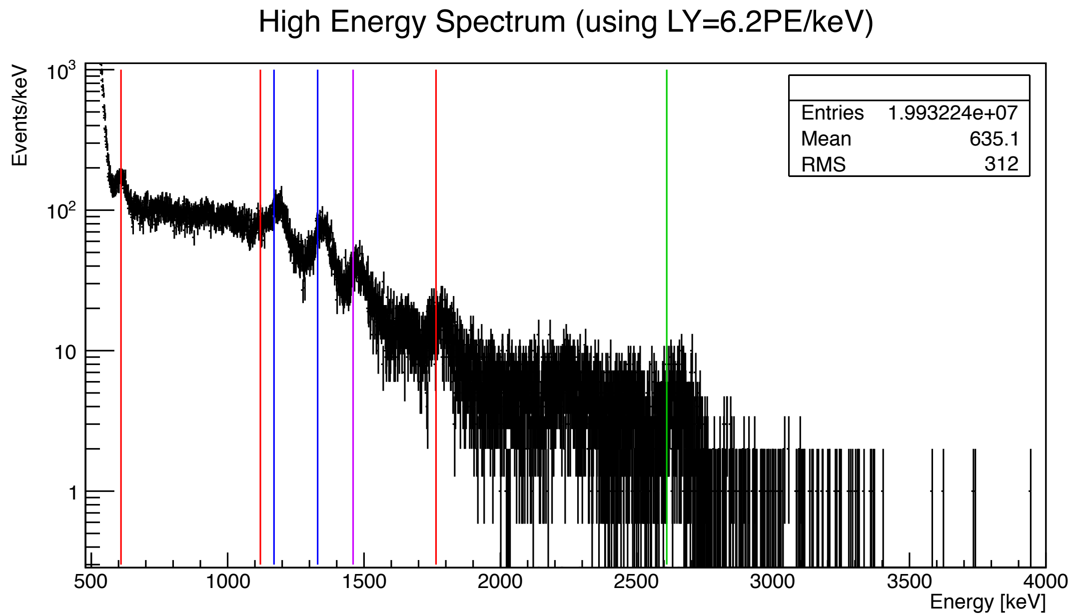
Spectrum
Events/10PE
10^3
10^2
3200
3400
3600
3800
4000
4200
4400
4600
4800
5000
5200
S1 [PE]
all pulse
after 40ns
after 50ns
after 60ns
after 70ns
after 80ns
after 90ns



Remarks:

- 609keV is always accompanied by another γ
- 1120keV is mostly accompanied by another γ
- 1764keV goes directly to ground state (no other γ)
- The double peaks (removed by F90 cut) could be a coincidence of two decays.
    - Need to check the decay times of each state and perform careful study

Complete High Energy Spectrum



Bi214:

- Produced by Rn222 which is in turn produced by U238.
- Very complicated decay chain (see later).
- Most important gammas:
  - 45% BR: 609keV
  - 15% BR: 1120keV
  - 15% BR: 1764keV

Co60:

- Most important gammas:
  - 1170keV
  - 1330keV

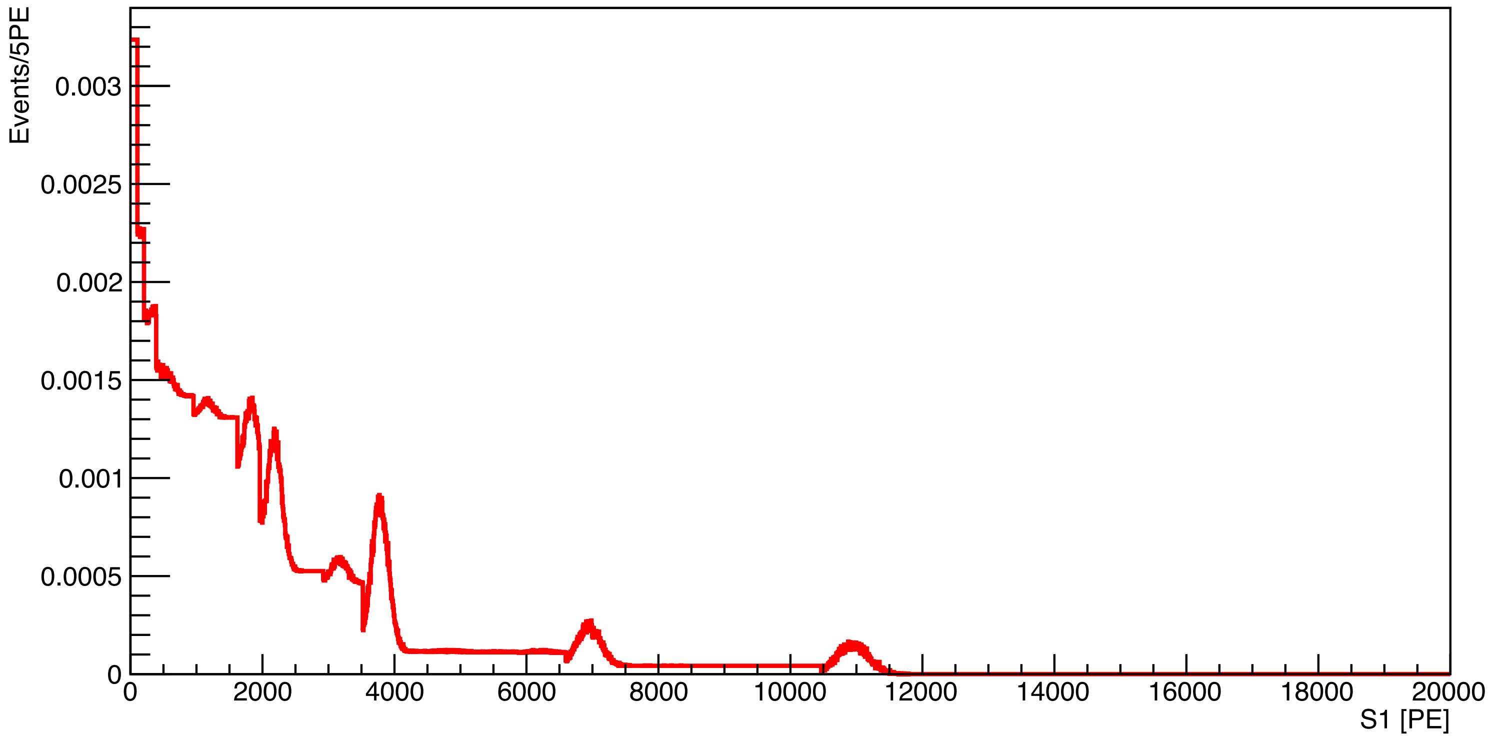
K40:

- 10% of the time β^+ decay with a γ 1460keV

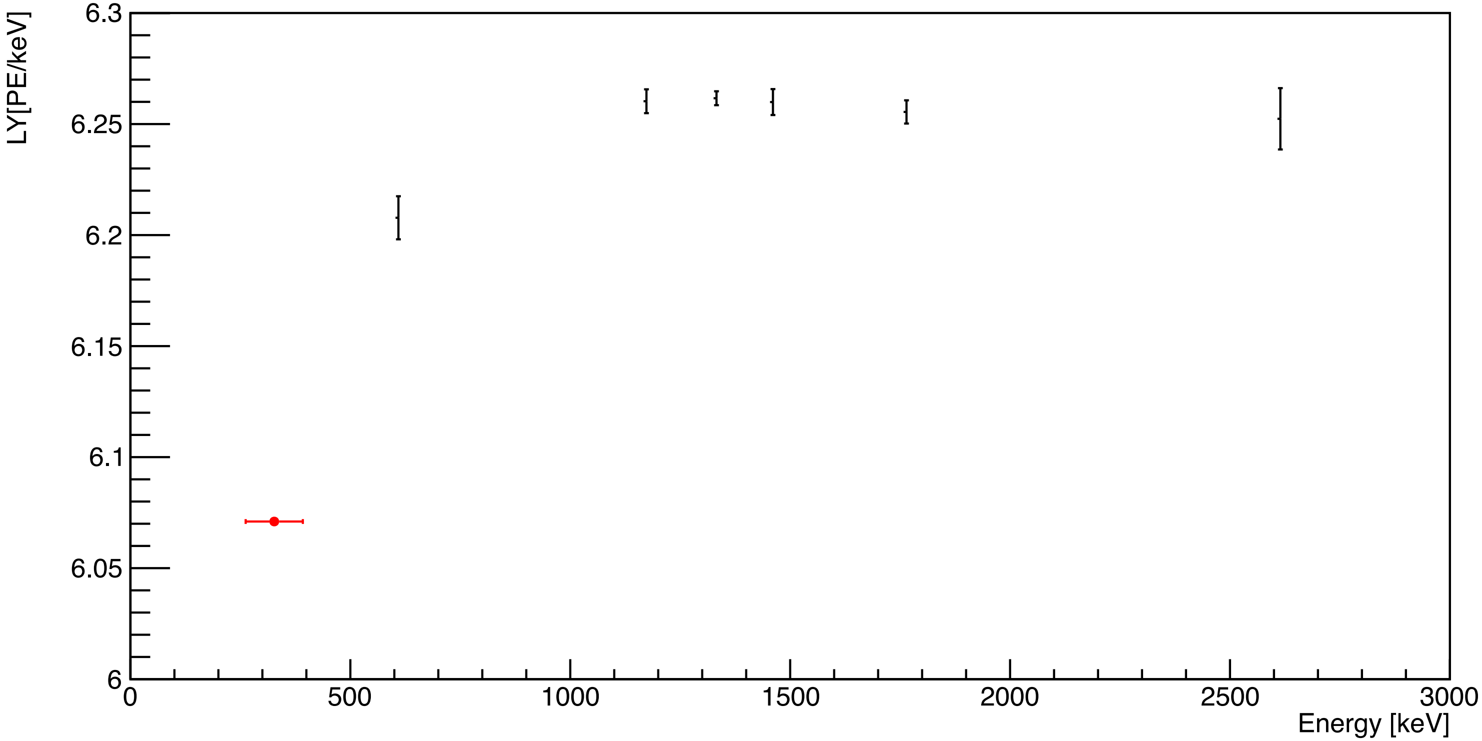
Tl208:

- Produced in the decay chain of Th232
- γ of 1460keV

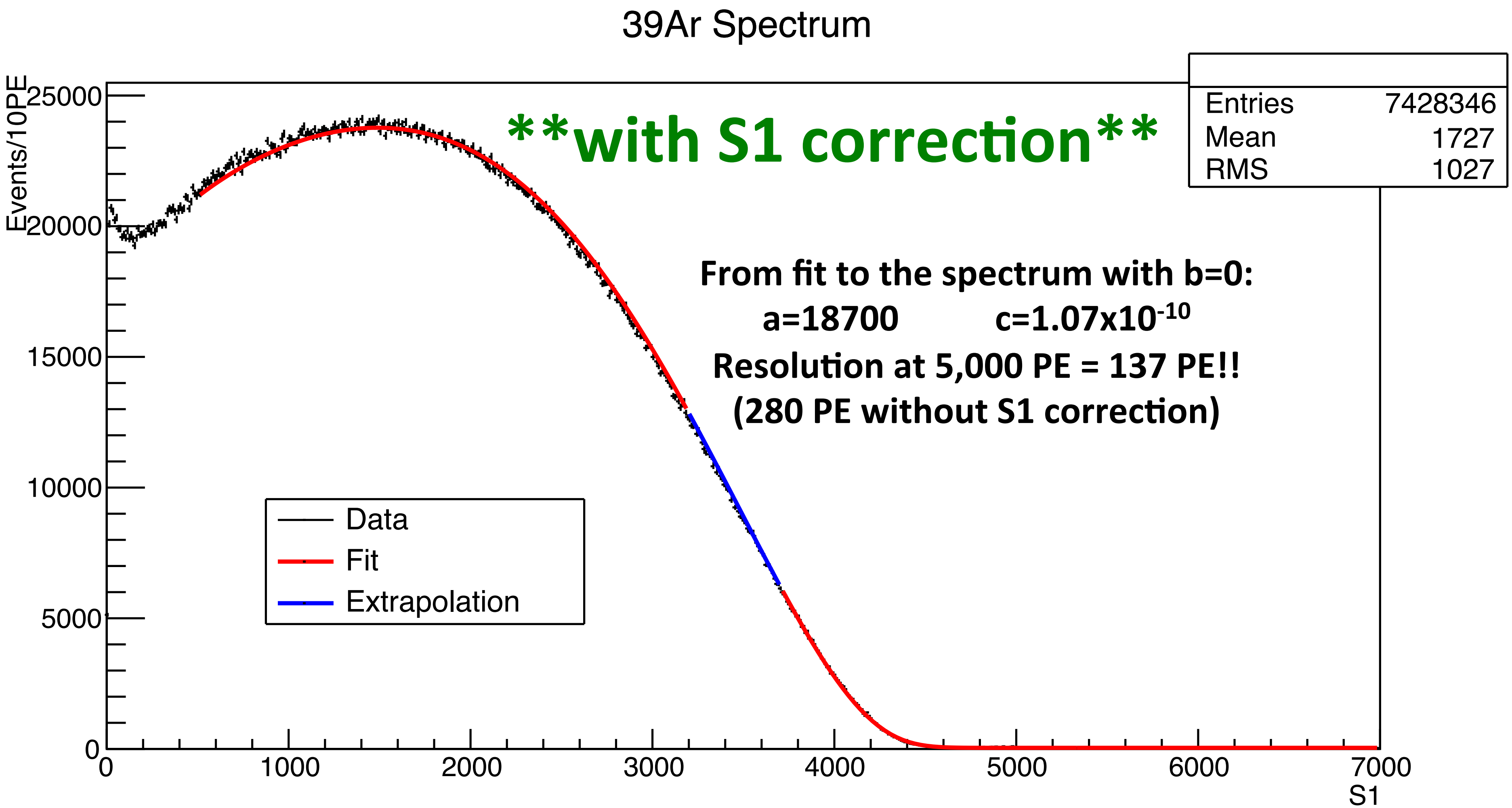
In this example we add all the lines from U238 already smeared and having added the continum.



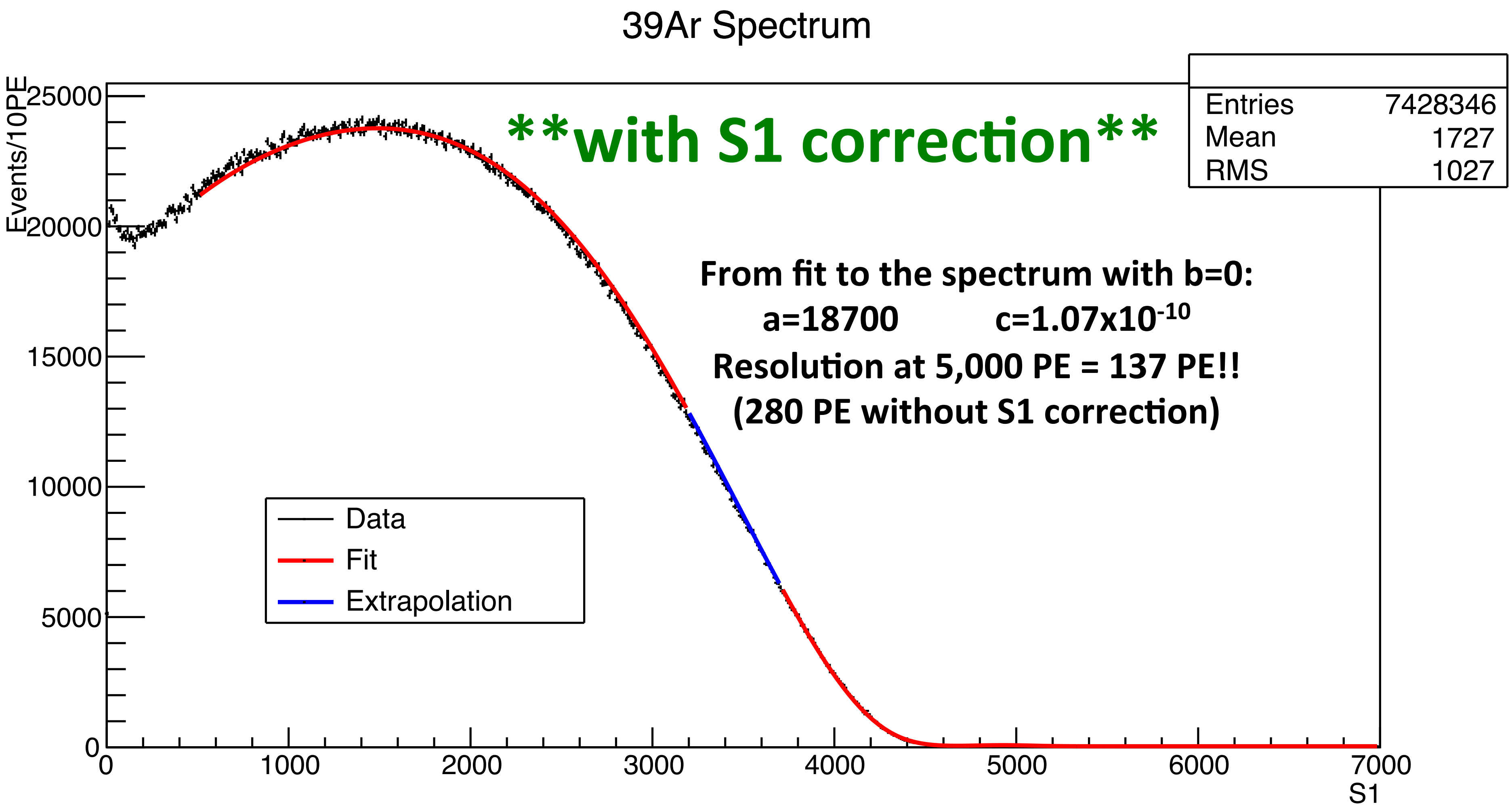
Variation on the Light Yield

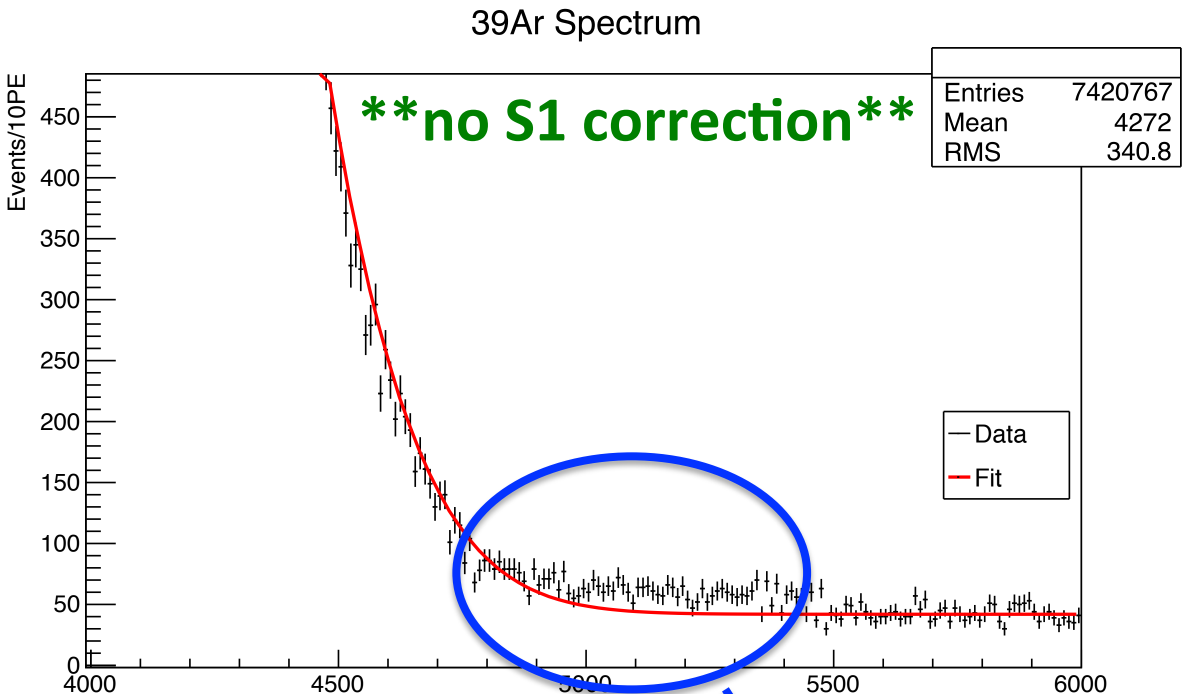


S1 Correction

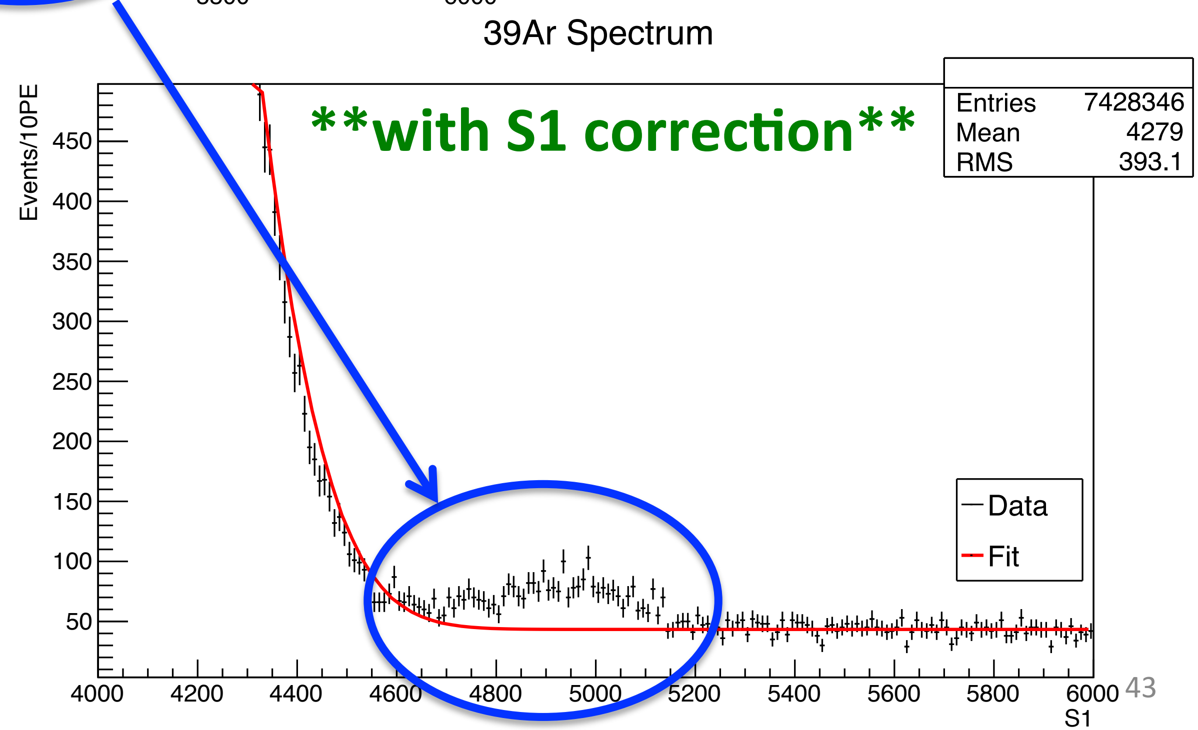


Add a gaussian background to the fit of the 39Ar spectrum…



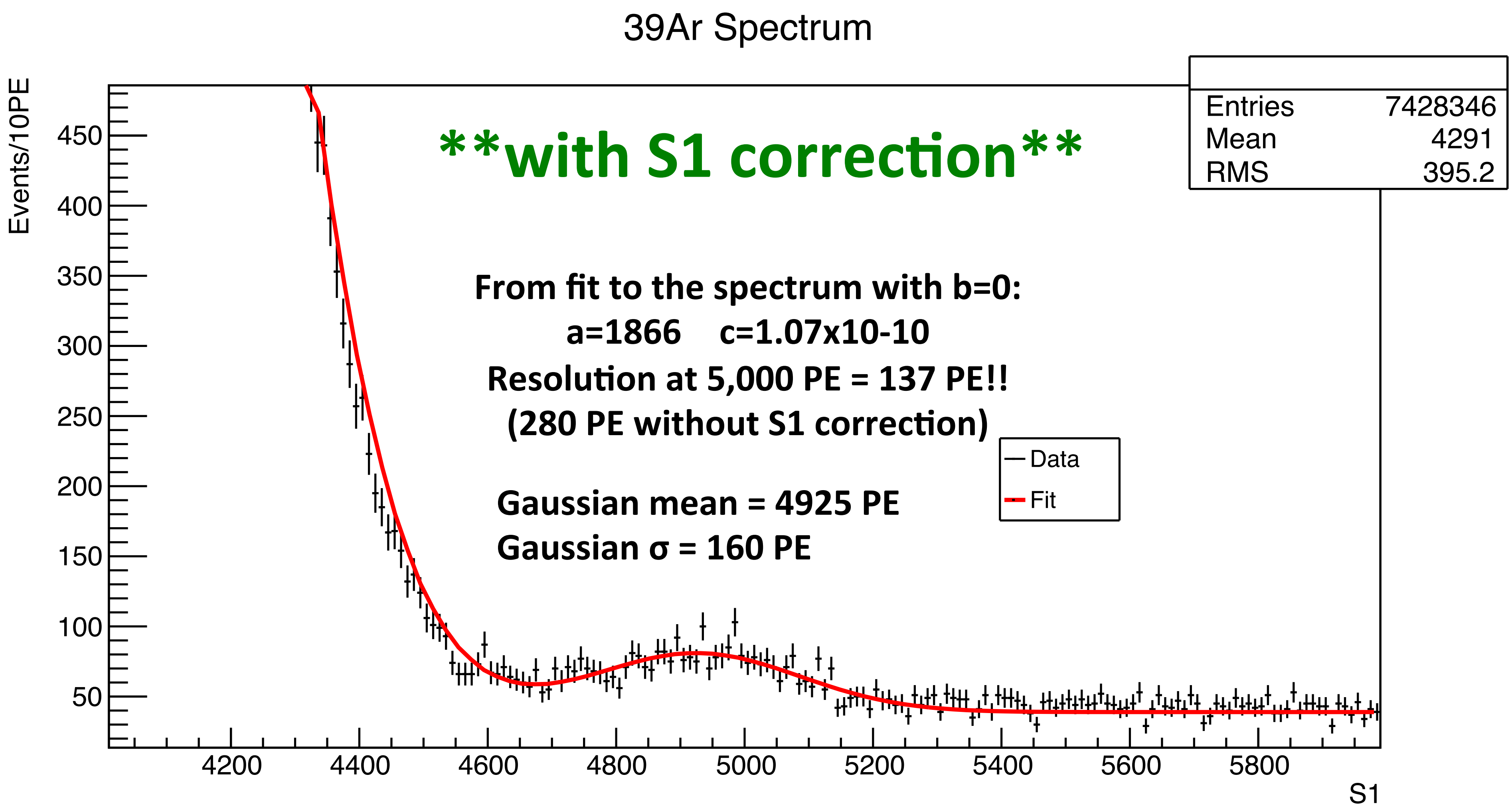


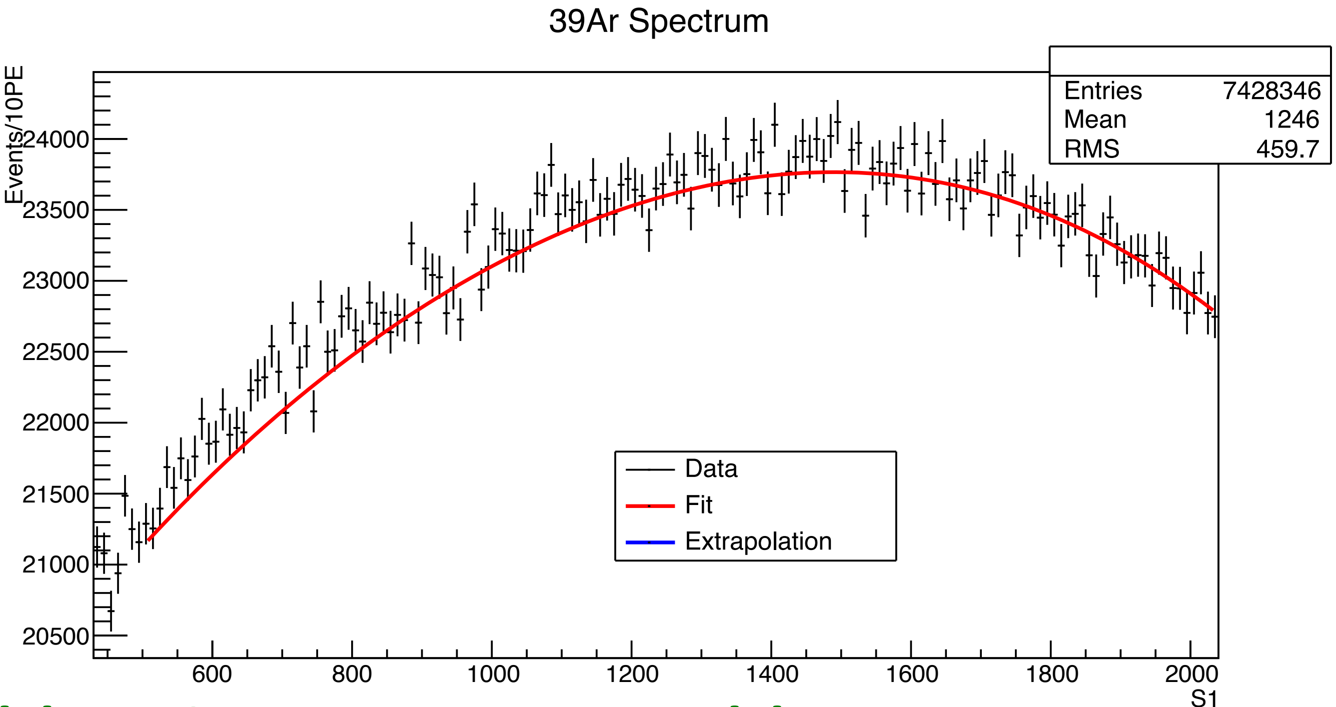
Excess near ~5000 PE is seen, could affect the background (^{39}Ar) fit



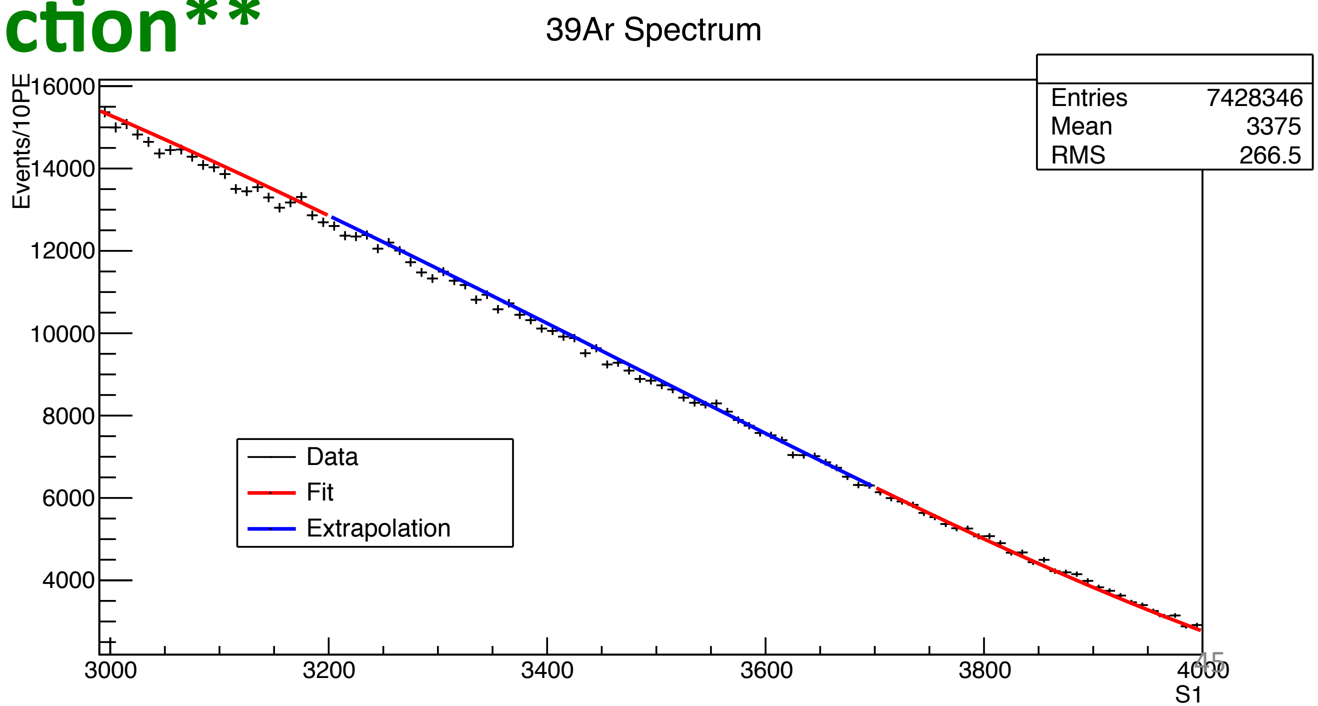
Once S1 is corrected based on the LY as a function of TBAsym, the excess becomes more concentrated and starts to look even more like a peak, what are these events???

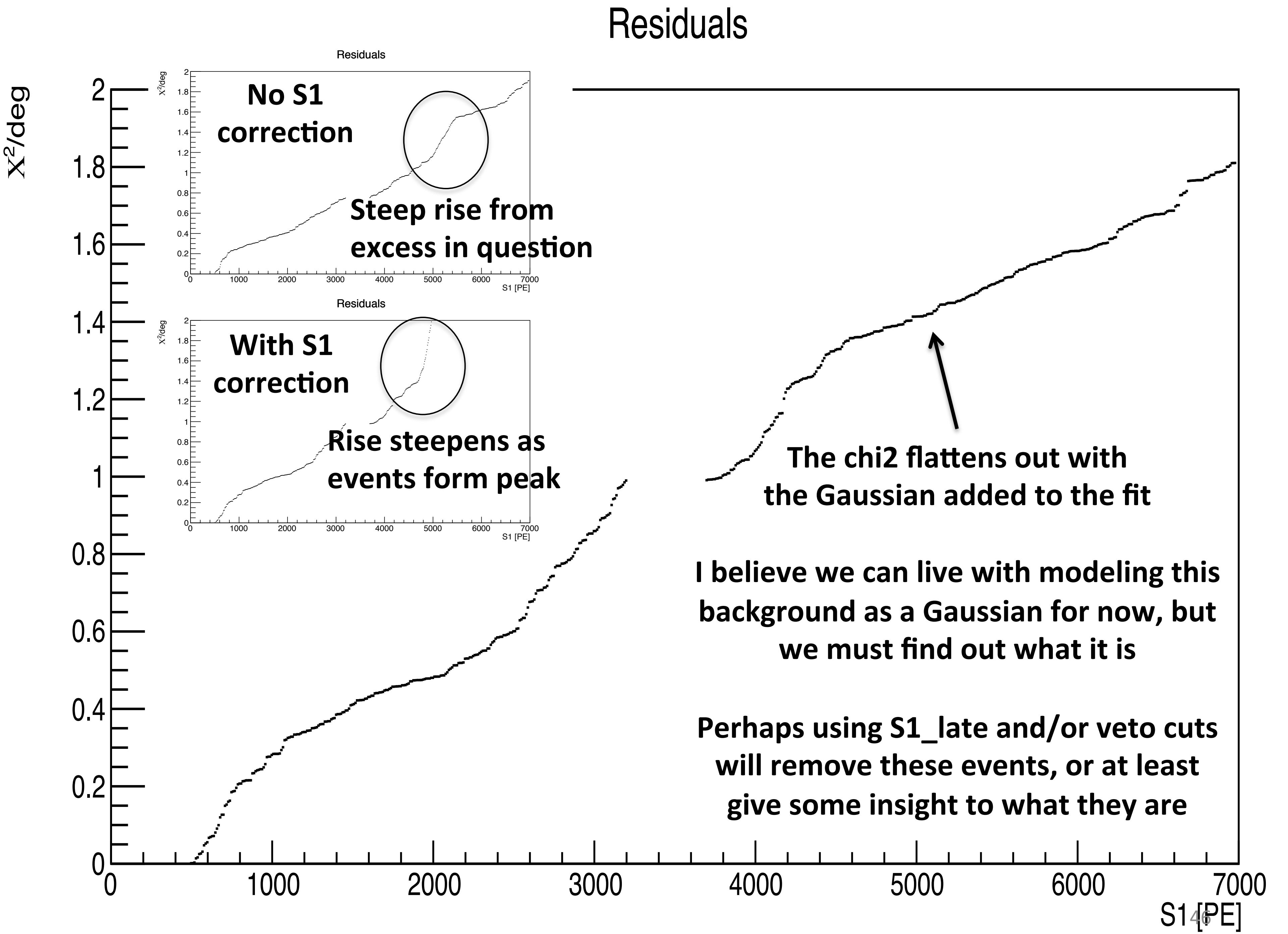
Add a gaussian background to the fit of the 39Ar spectrum…





with S1 correction




Residuals
X²/deg
S1 [PE]
Residuals
No S1 correction
Steep rise from excess in question
Residuals
With S1 correction
Rise steepens as events form peak
The chi2 flattens out with the Gaussian added to the fit
I believe we can live with modeling this background as a Gaussian for now, but we must find out what it is
Perhaps using S1_late and/or veto cuts will remove these events, or at least give some insight to what they are