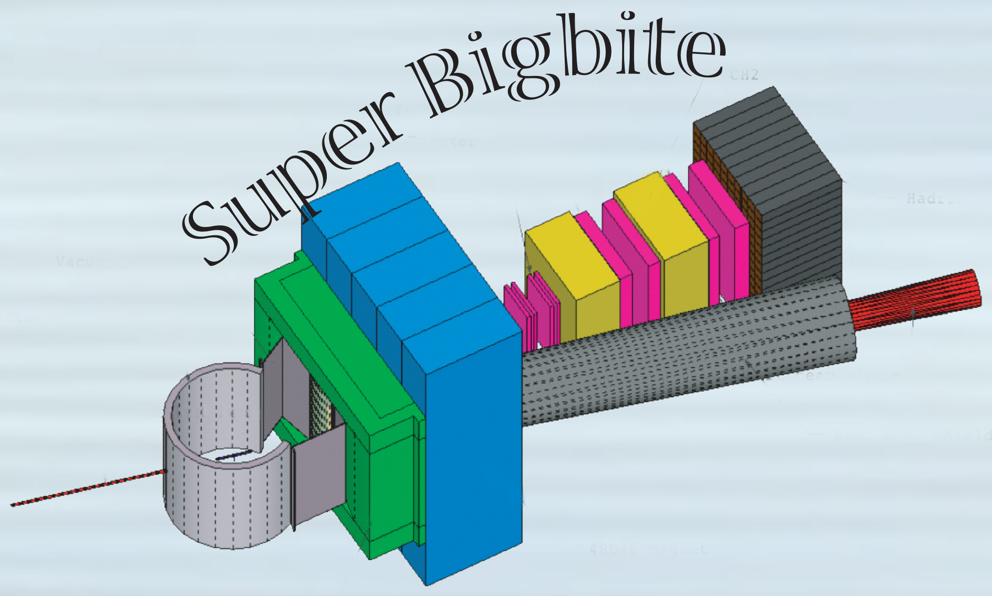
GEn-II analysis update

- Quick overview of the experiment
- Pass-1 results: thesis of Sean Jeffas
- Pass-2 results: thesis of Hunter Presley
- Preparation for Pass-3
- Pass-4 and beyond



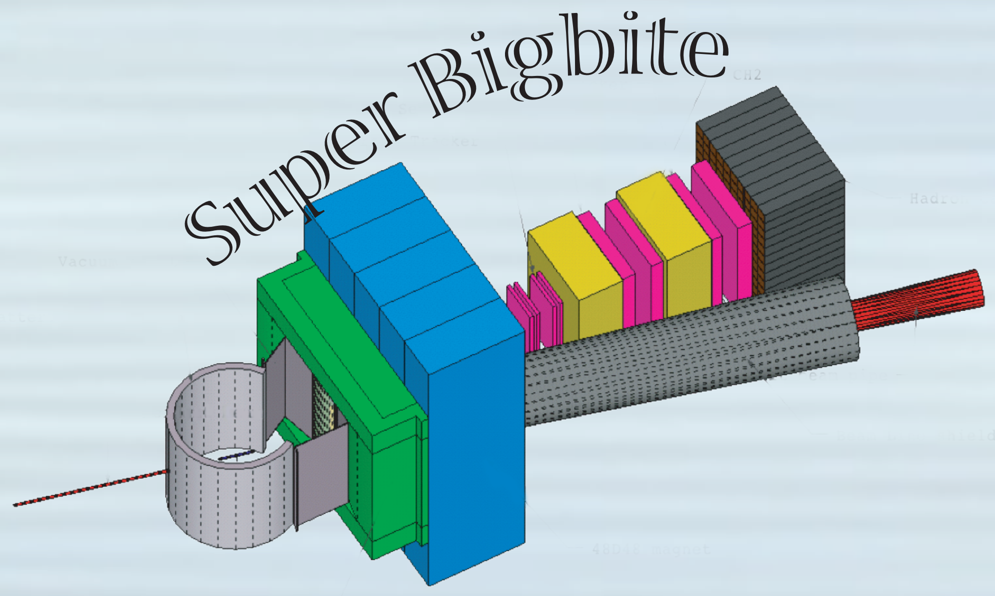
Gordon D. Cates
March 2, 2026

University of Virginia

Jefferson Lab
EXPLORING THE NATURE OF MATTER

GEn-II analysis update

- Quick overview of the experiment
- Where did we start?
- Where are we now?
- Where will be soon?
- How well might we do ultimately?



Gordon D. Cates
March 2, 2026

University of Virginia

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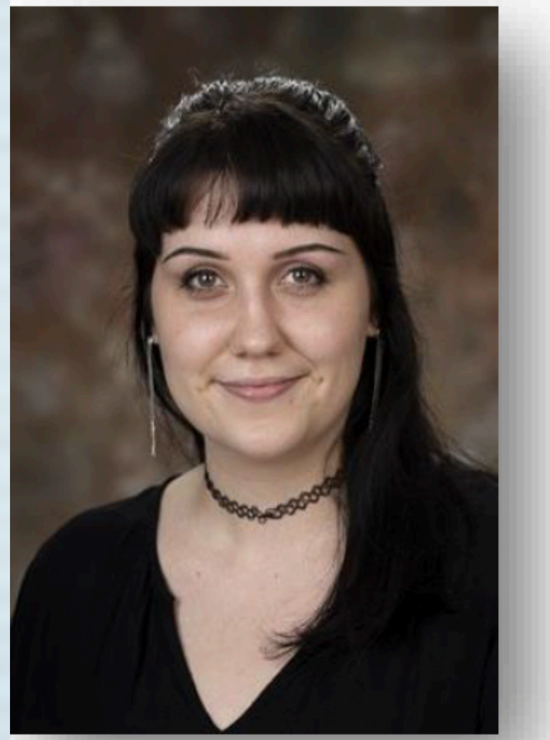
EXPLORING THE NATURE OF MATTER

GEn-II students and spokespeaple

Kate Evans



Jack Jackson

Faraz Chahili

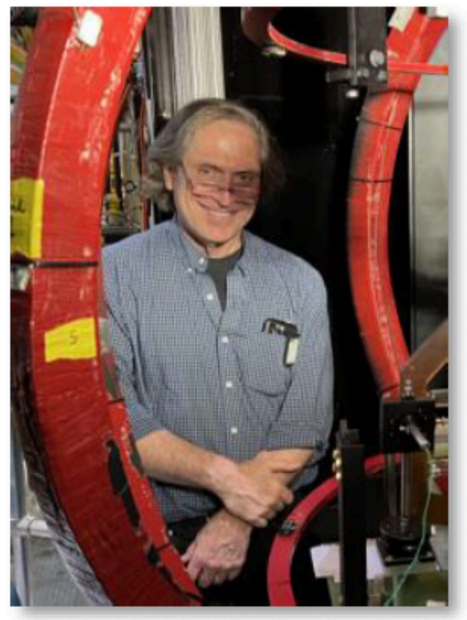
Hunter Presley

Vimukthi Gamage

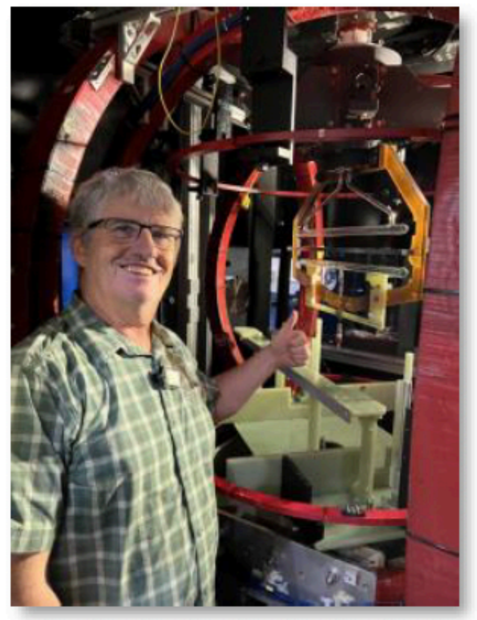
Jacob Koenemann

Braiain Mederos

Gordon Cates



Todd Averett



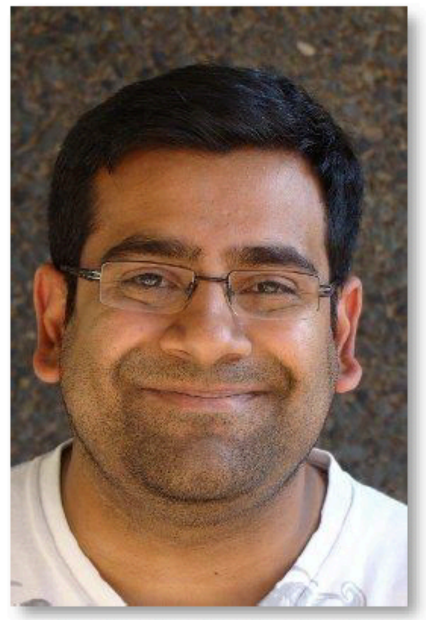
Bogdan Wojtsekhowski

Spokespeople!

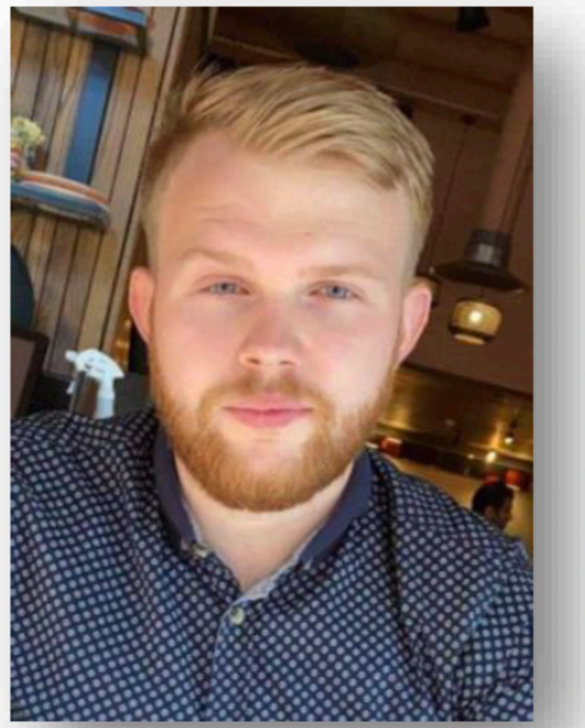
Special Thanks!

Andrew Puckett

Arun Tadepalli

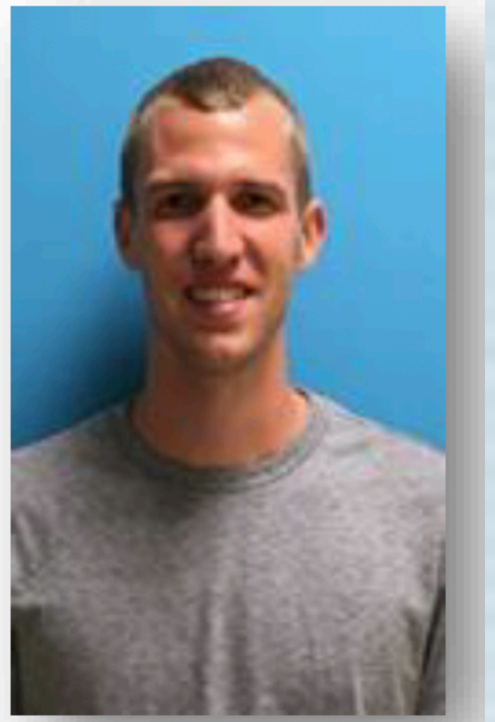


Gary Penman



Graduated March 2025

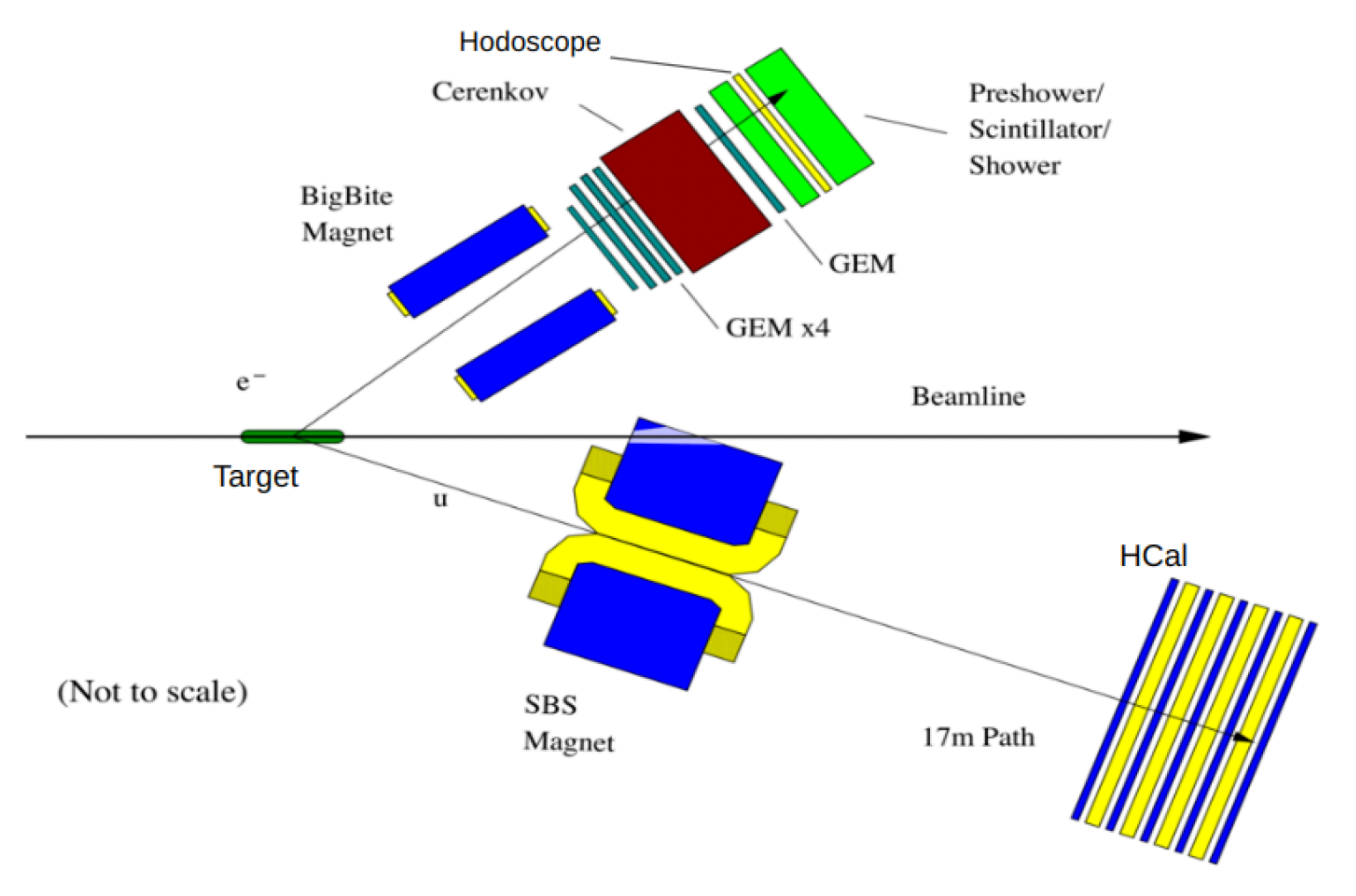
Sean Jeffas

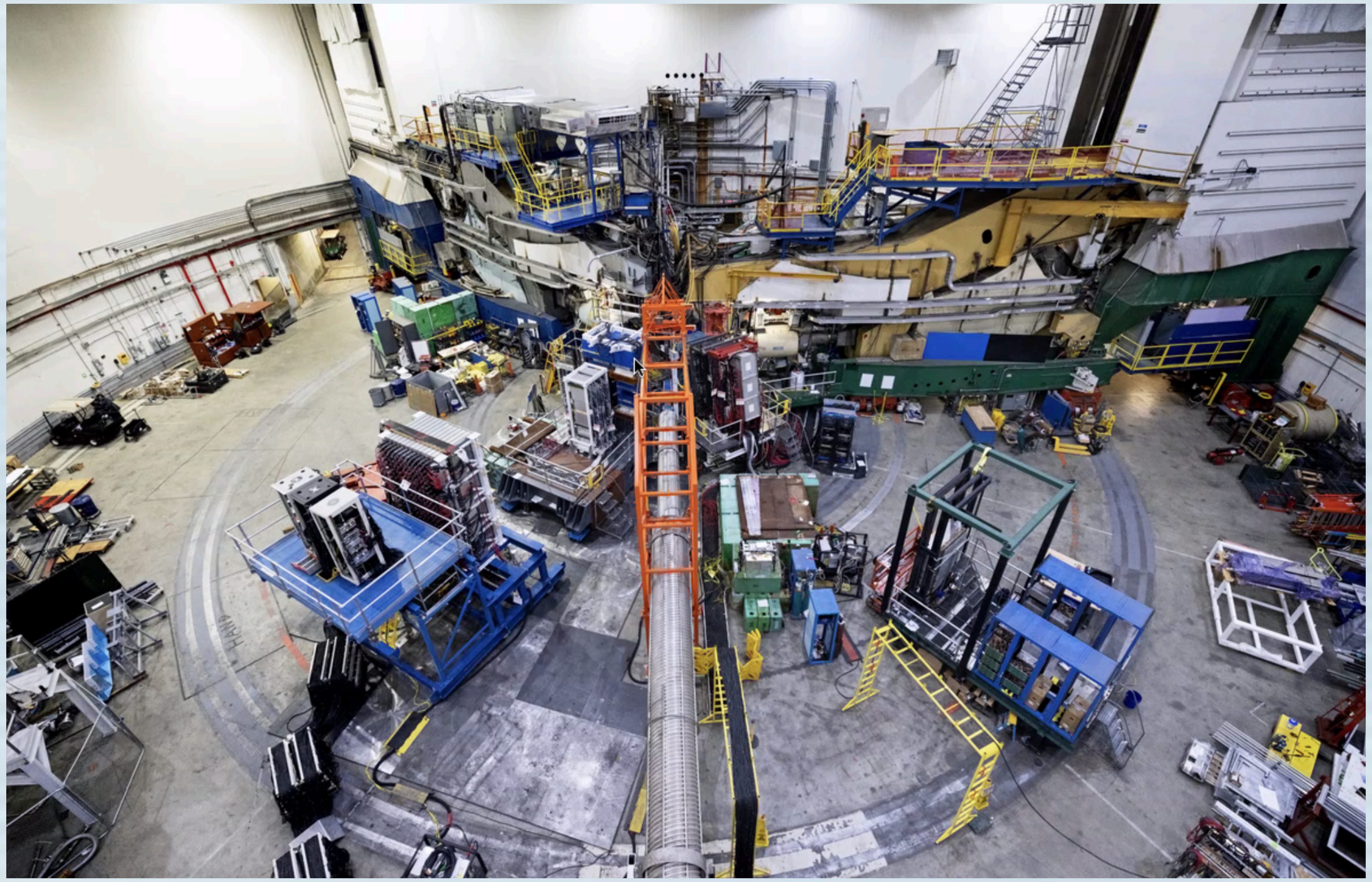


Graduated July 2024

The GEn-II experiment

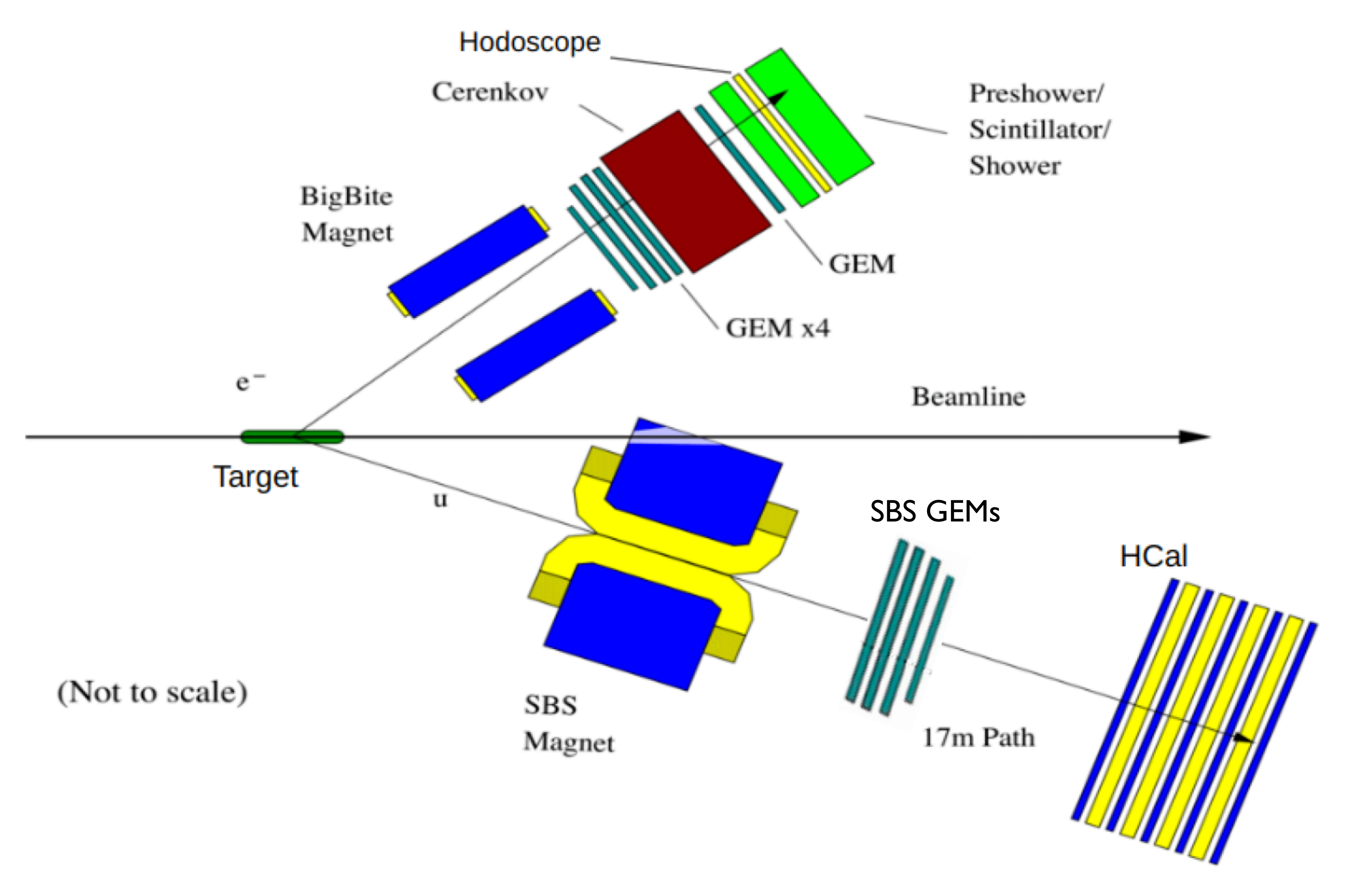
Kin	Q^2(GeV^2)	E_{beam}(GeV)	E arm angle (deg)	H arm angle (deg)	Run time (days)
1	1.79	2.206	29.5	34.7	1
2	3.00	4.291	29.5	34.7	13
3	6.83	6.373	36.5	22.1	33
4	9.82	8.448	35.0	18.0	86





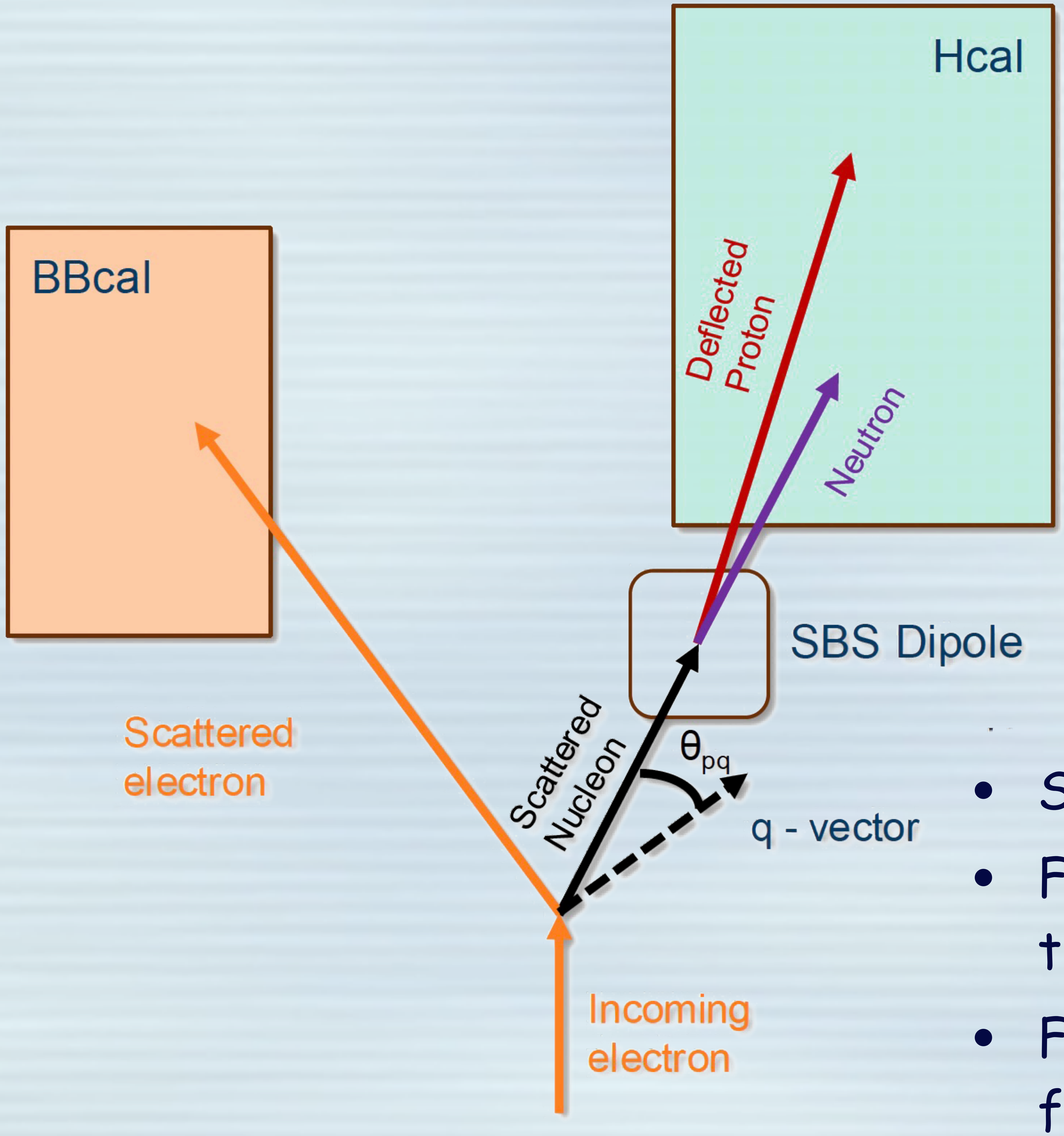
The GEn-II experiment

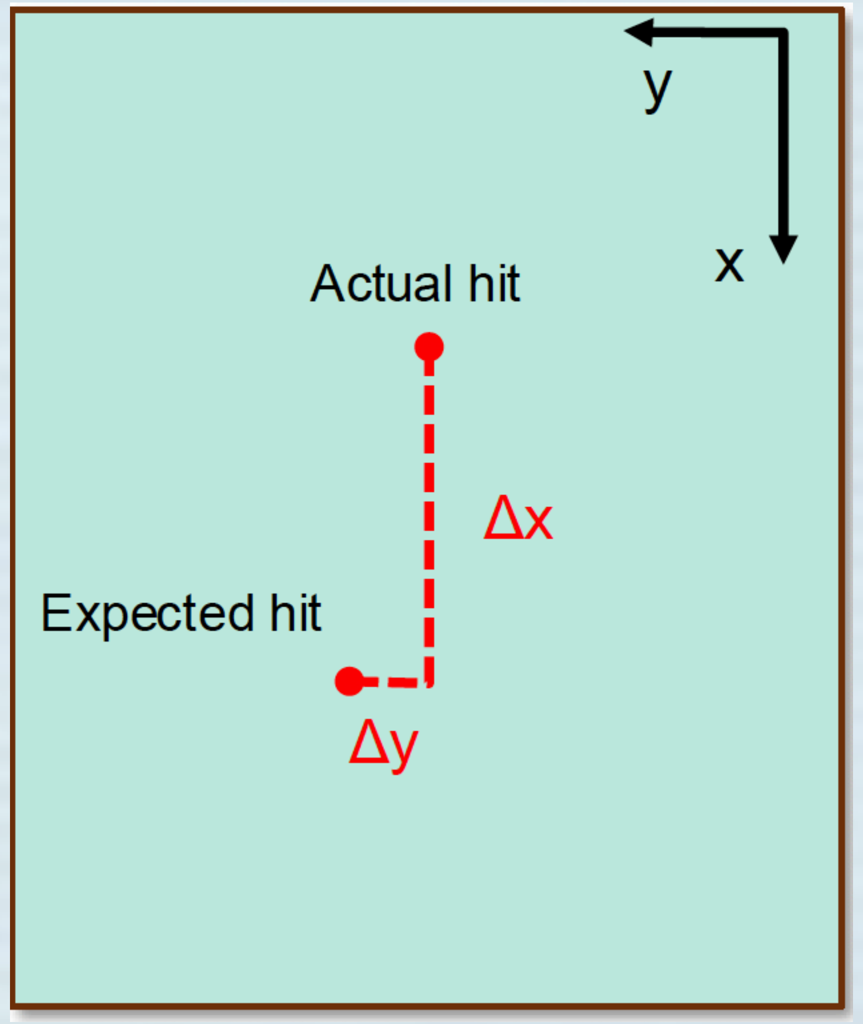
- Electrons are detected in the BiBite Spectrometer
- BigBite dipole provides momentum analysis
- Tracking is done with GEMs
- BBCal, with both the shower and pre shower, provides electron trigger and aids in particle ID
- GRINCH will also aid in particle ID
- Hodoscope provides timing information (along with BBCal)



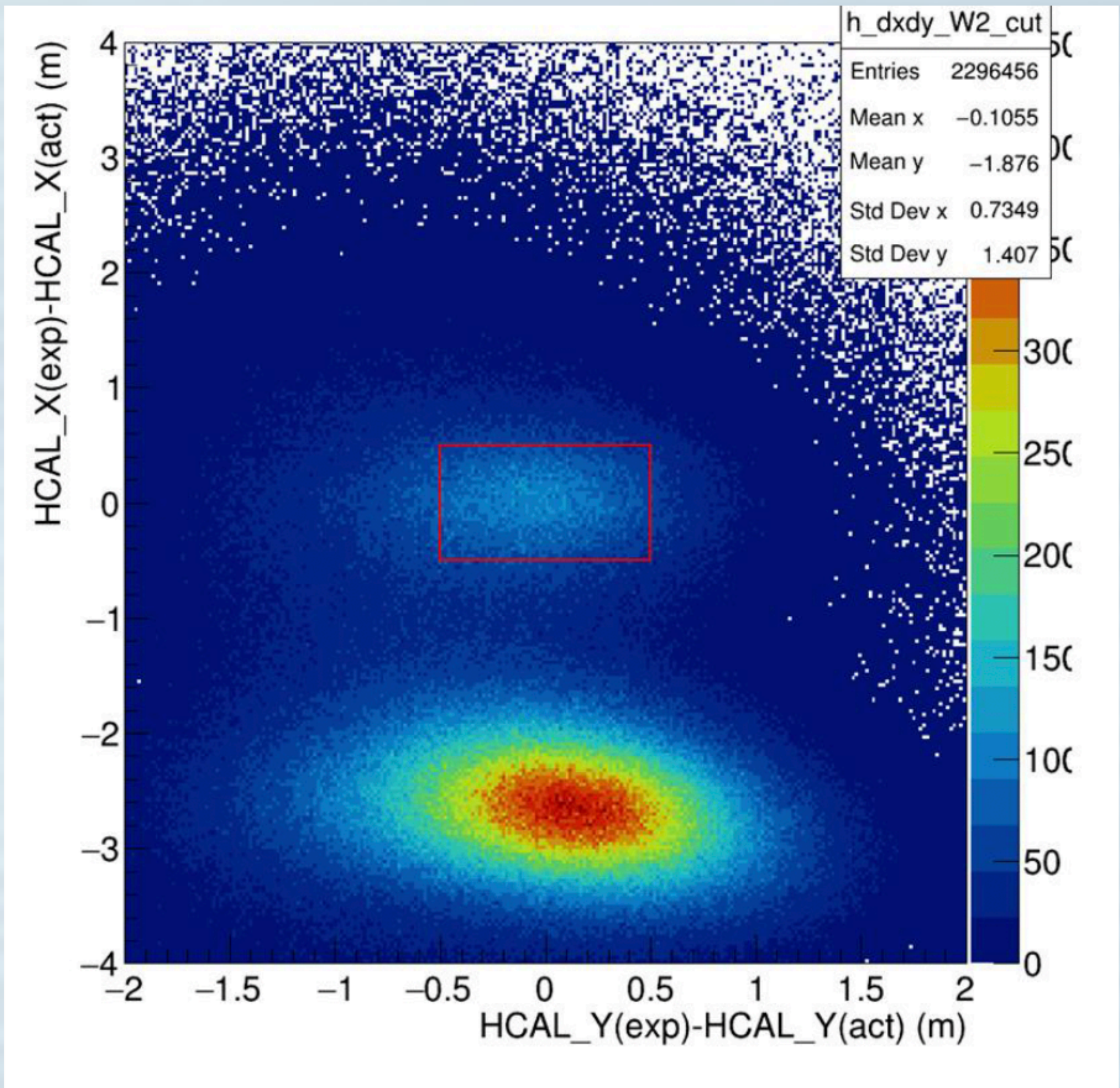
- Neutrons are detected in HCal with (relatively) high threshold but coarse timing
- SBS magnet provides separation of protons and neutrons (or more accurately, charged and uncharged particles).
- SBS GEMs, not formally part of GEn-II, provide tracking information for roughly 1/3 of the GEn-II data

PID in the hadron arm





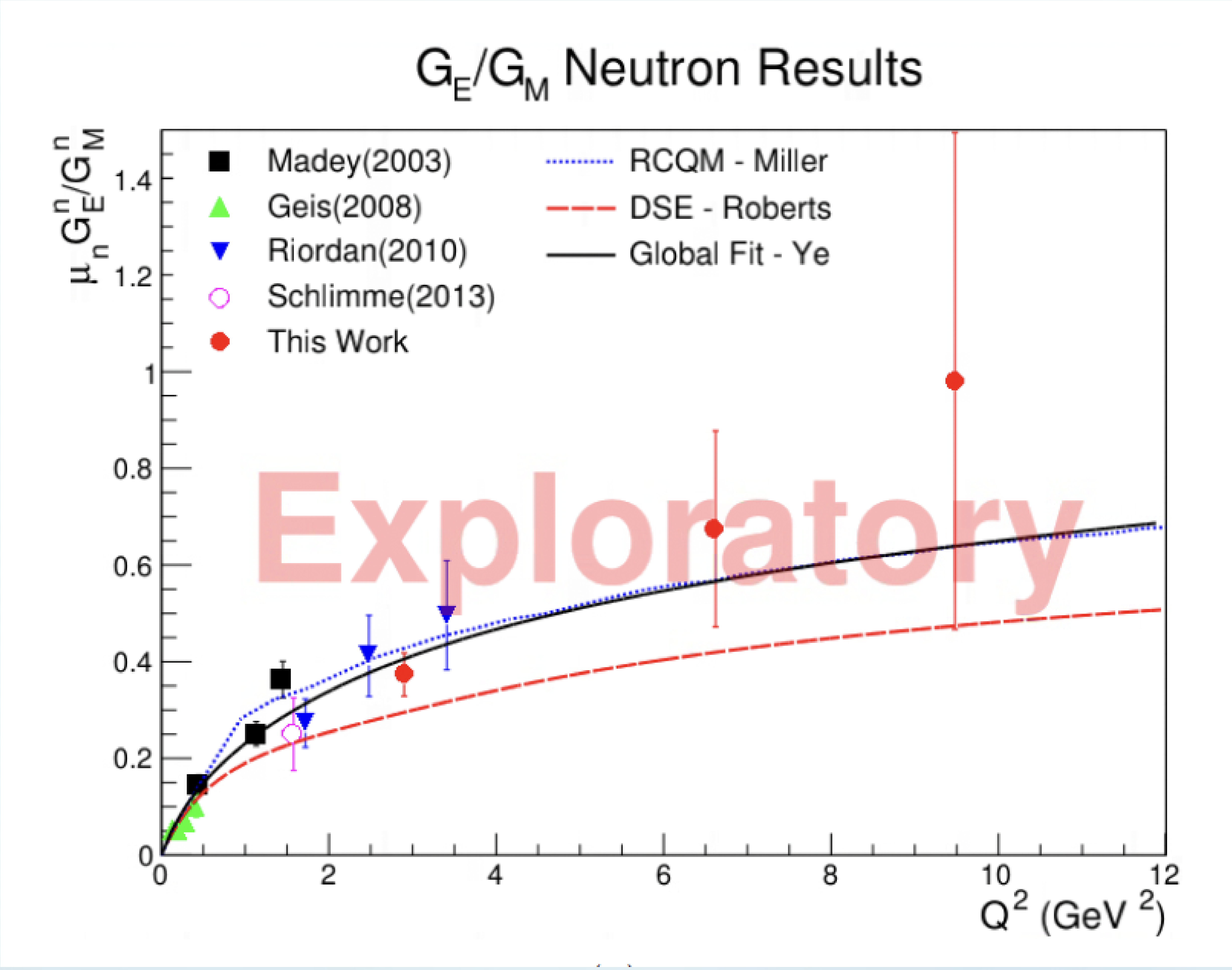
Face of HCal



- SBS magnet deflects charged particles
- For true elastic events, the track from BigBite determines where the hadron should hit HCal
- Fermi smearing spreads the hit in HCal around the point expected for an elastic event.
- The deviation from the elastic position is described by Δx and Δy.

Results from Sean Jeffas' thesis

First-pass analysis



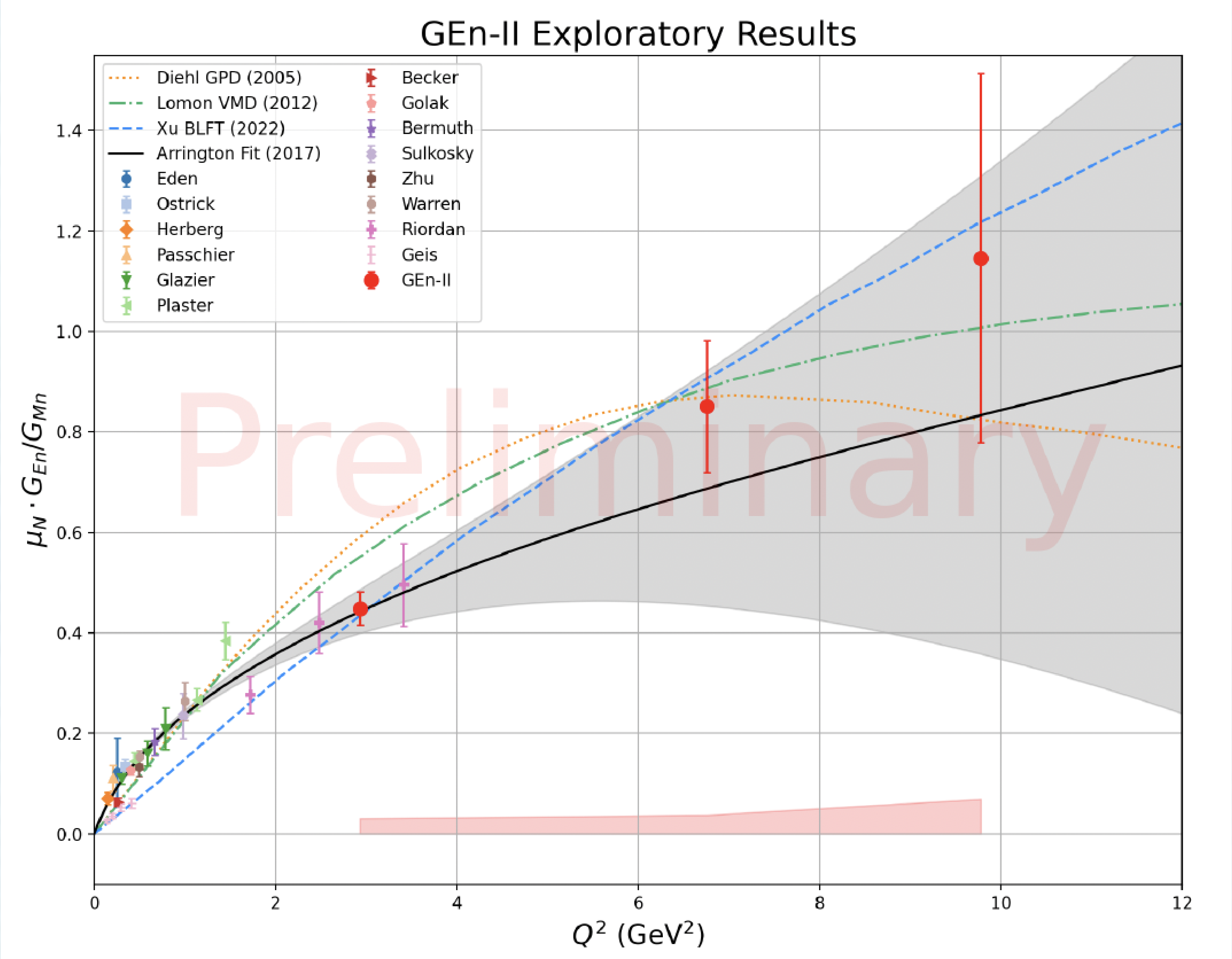
July 2024

- The first GEn-II analysis to yield values for GEn/GMn.
- Sean defended in July 2024, roughly ~nine months after the end of the experiment.
- Detector calibrations were rough, at best, depending heavily on the GMn analysis.
- Kin4 point did not include the Kin4b data.

Pass-2 analysis

Results from Hunter Presley's thesis

Second-pass analysis



- First analysis with nominal calibrations for all detectors.
- Kin3 improved by a factor of 1.6 compared with the results from Sean's thesis.
- Kin4 improved by a factor of 1.3 compared with the results from Sean's thesis.

August 2025

Highlights of the Pass-2 analysis

- Careful calibration of BBCal (using precise momentum determination from tracking).
- Better pion rejection using 2D histograms with both pre-shower and E/p.
- Calibration of HCal using protons from both elastic and inelastic ^{3}He collisions with momentum determined using the SBS GEMs.
- Significantly improved timing calibration for both BigBite and HCal for tighter coincidence distribution.
- Improved fitting using simulations.
- Optimization of cuts to minimize final errors.

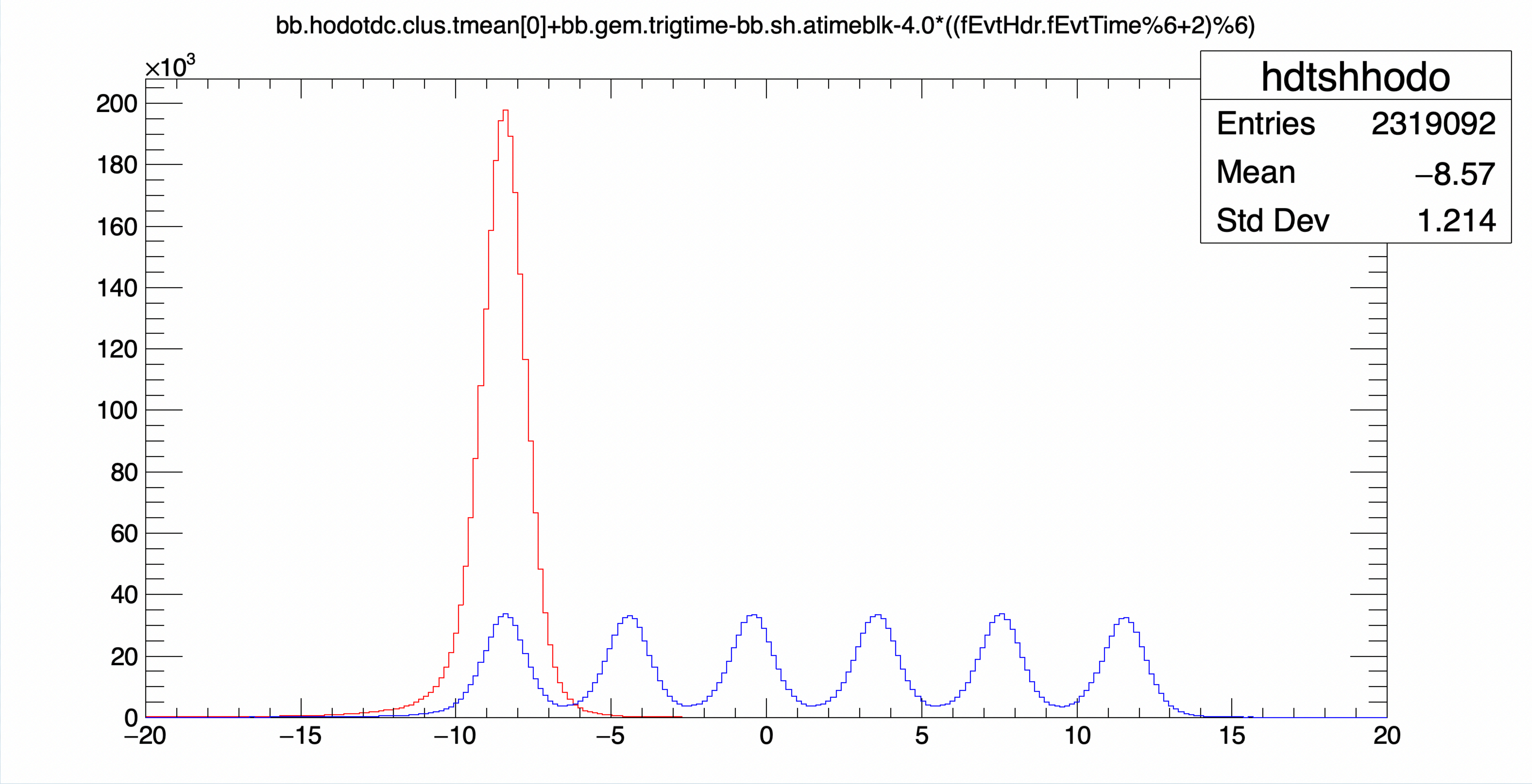
Progress toward the Pass-3 analysis

(which is imminent)

Improvements for pass 3 compared to pass 2

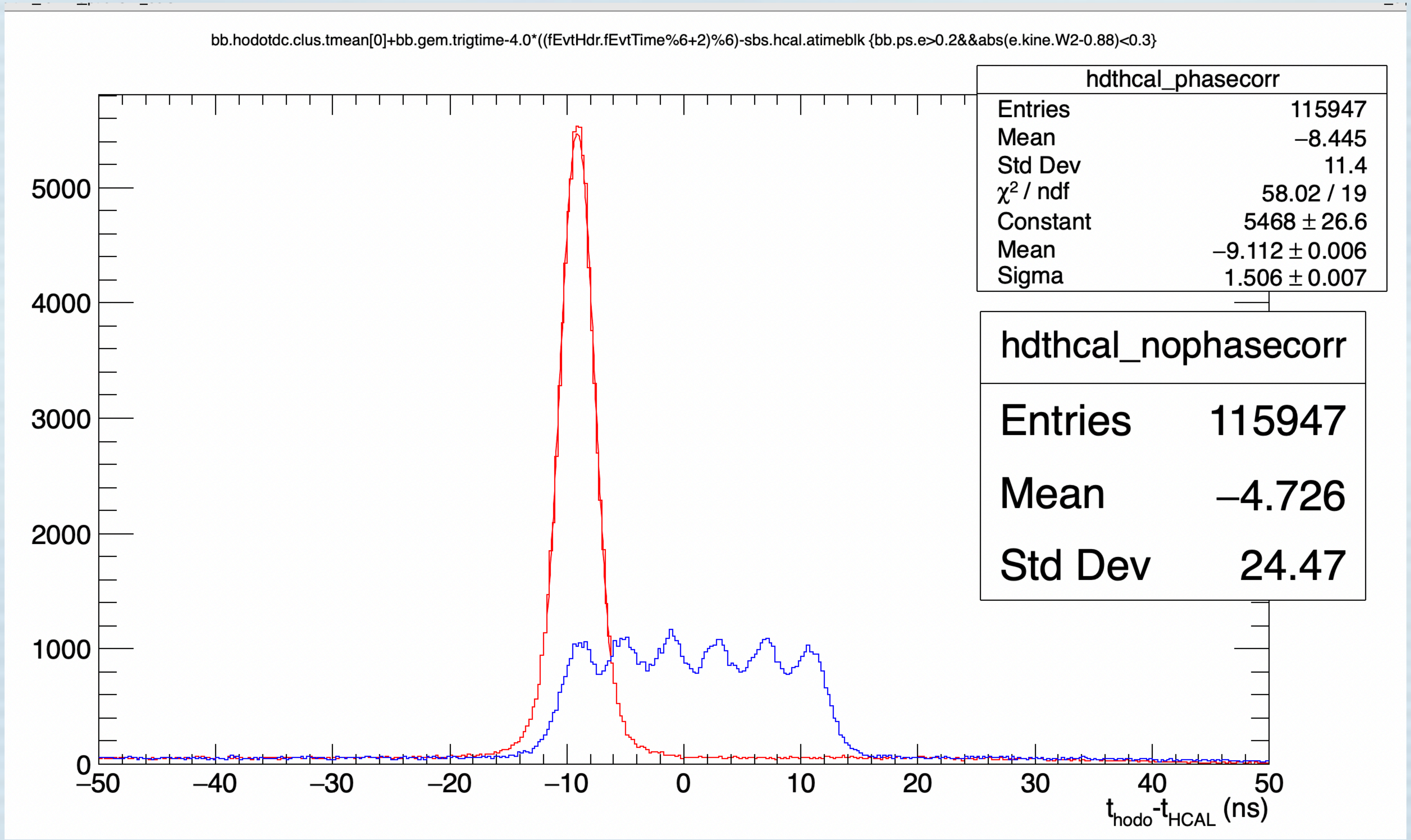
- Significantly improved timing that, for the first time, is at the level where we can identify the specific rf bucket responsible for the event.
- Better understanding of background-fitting methods.
- Improved optics calibrations for BigBite.
- New algorithm (Andrew calls it the in-time highest-energy technique) for matching up the correct cluster in HCal with the detected electron.
- Also … output of information that will inform and help guide pass 4.

Deciphering the trigger supervisor phase



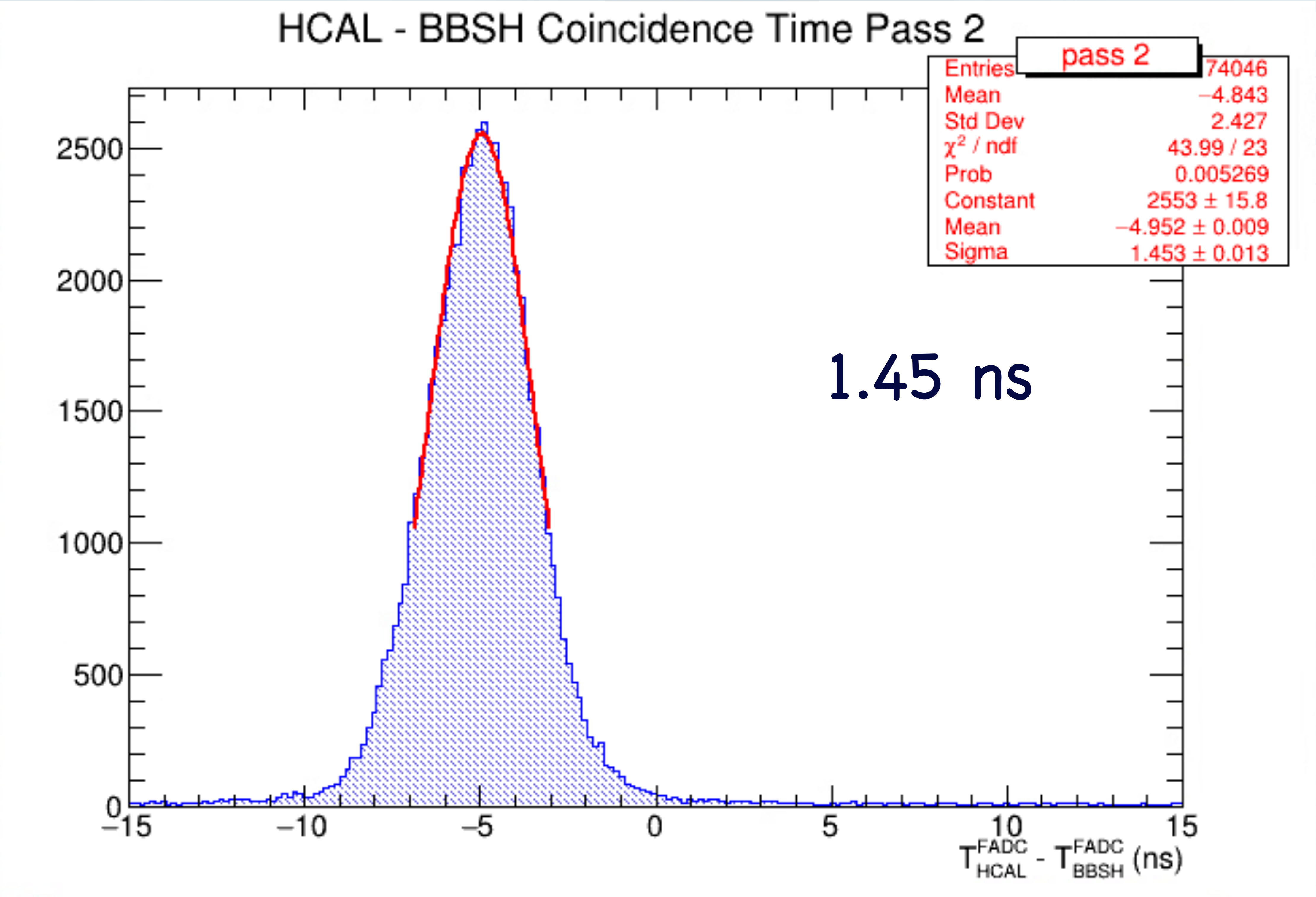
Hodoscope TDC time - shower ADC time with and without trigger phase correction from a randomly chosen run from GMn

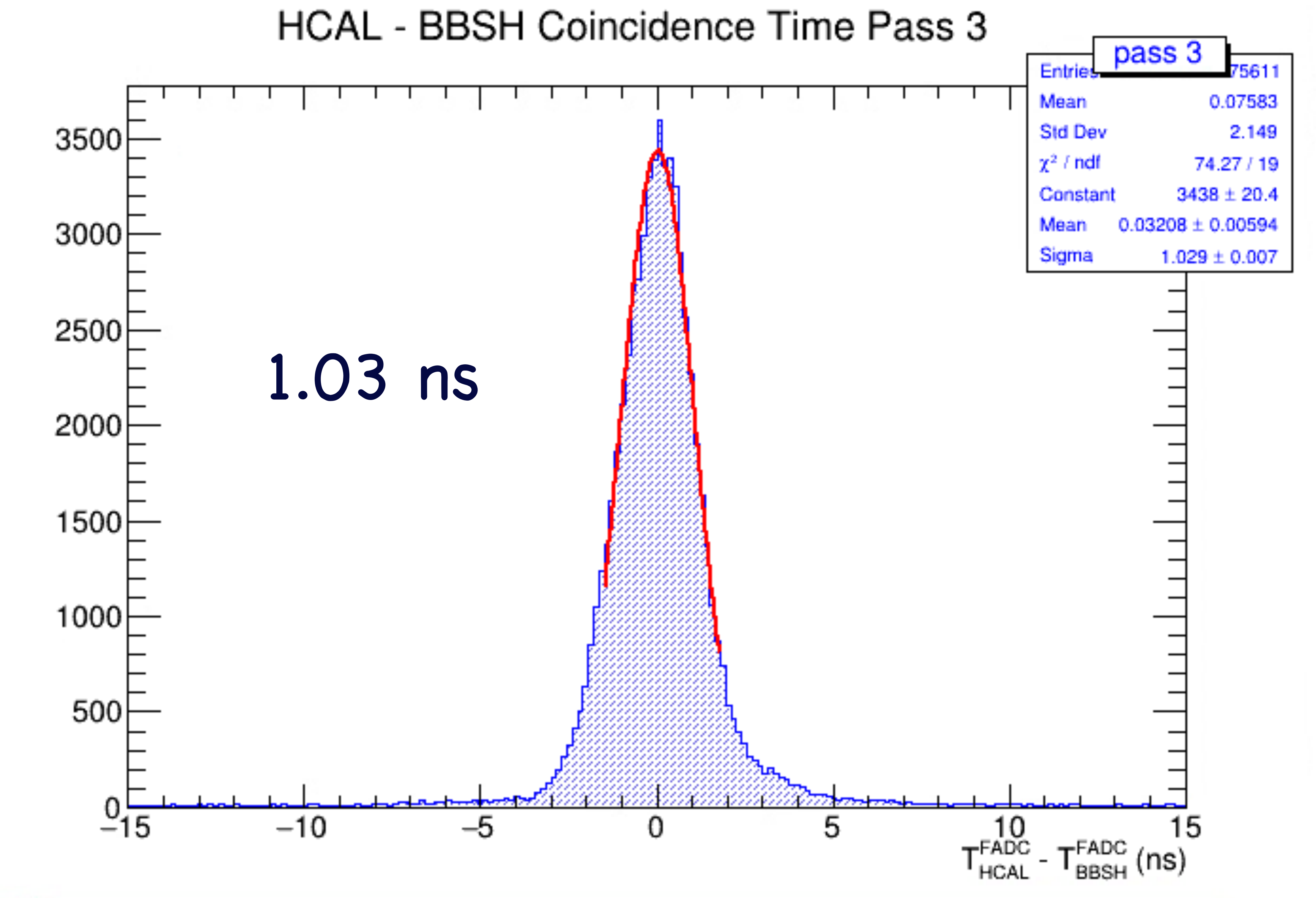
Deciphering the trigger supervisor phase



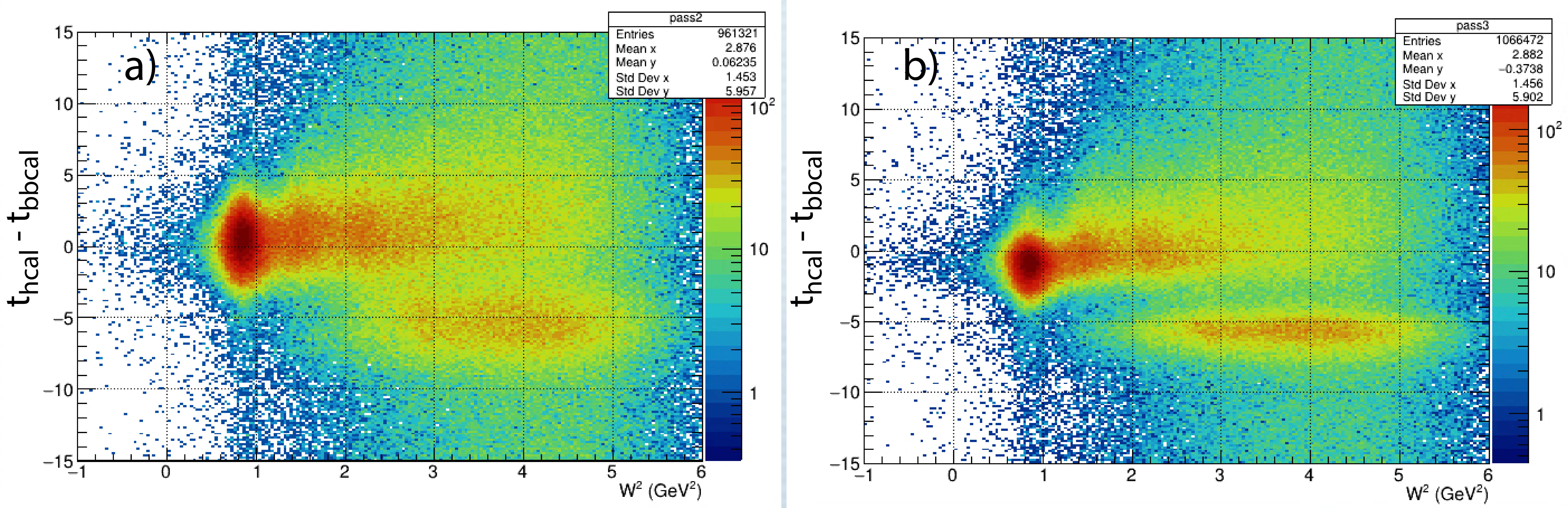
Hodoscope TDC time - HCal ADC time with and without trigger phase correction from the same run from GMn

Comparison of pass-2 and pass-3 coincidence time distributions for hydrogen (GEn-II Kin2)





Coincidence time versus W² for hydrogen data

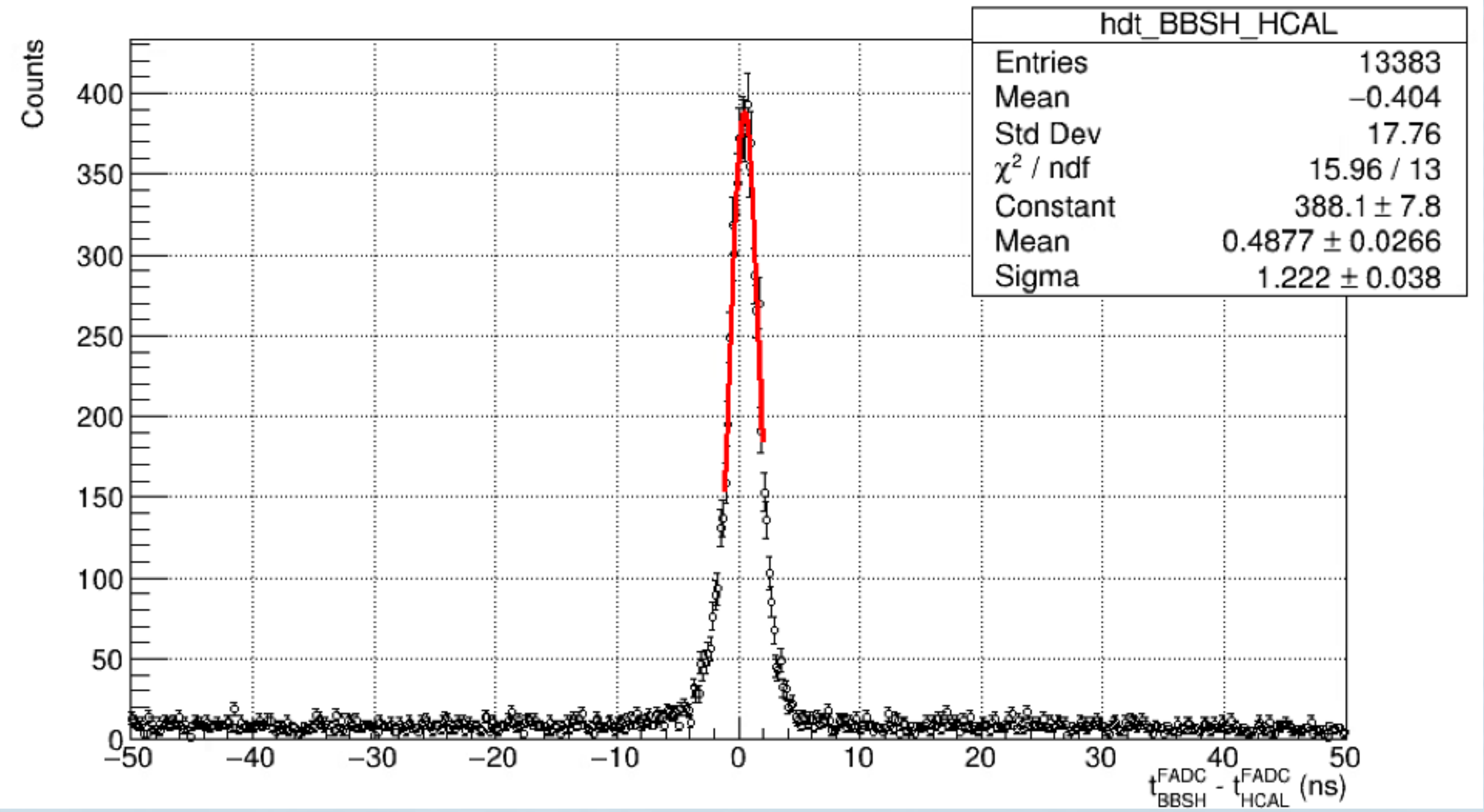


Pass 2 timing

Pass 3 timing

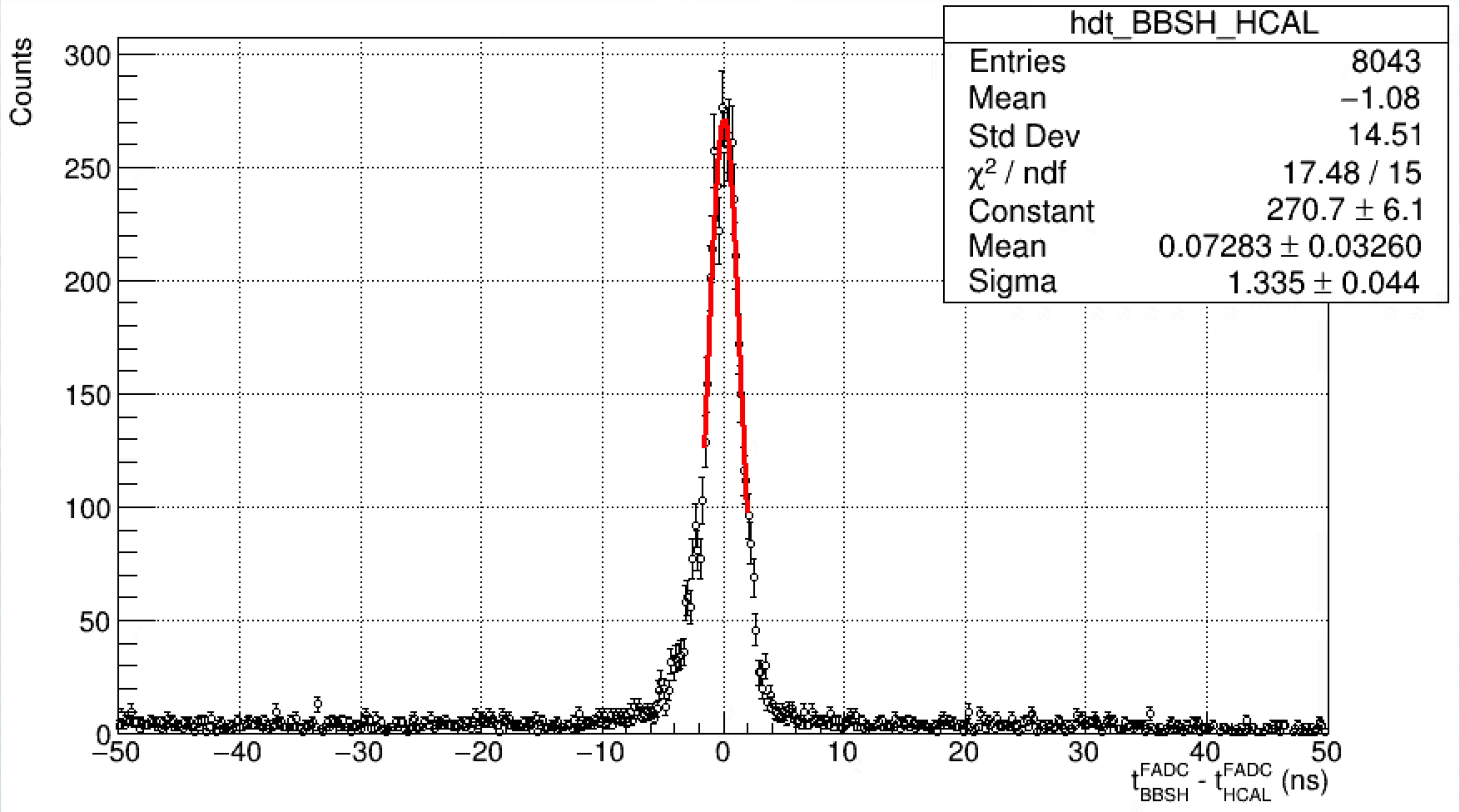
Kin4b coincidence time distribution for ^{3}He

- Cuts used
  - E_PS > 0.2
  - 0.7 < (E_PS + E_SH)/P_tr < 1.3
  - -0.27 < Z_target < 0.27
  - E_HCAL > 0.02
  - 0.0 < W2 < 1.6
  - -0.5 < dx < 0.5
  - -0.5 < dy < 0.5
- Fit is a gaussian fit of the peak



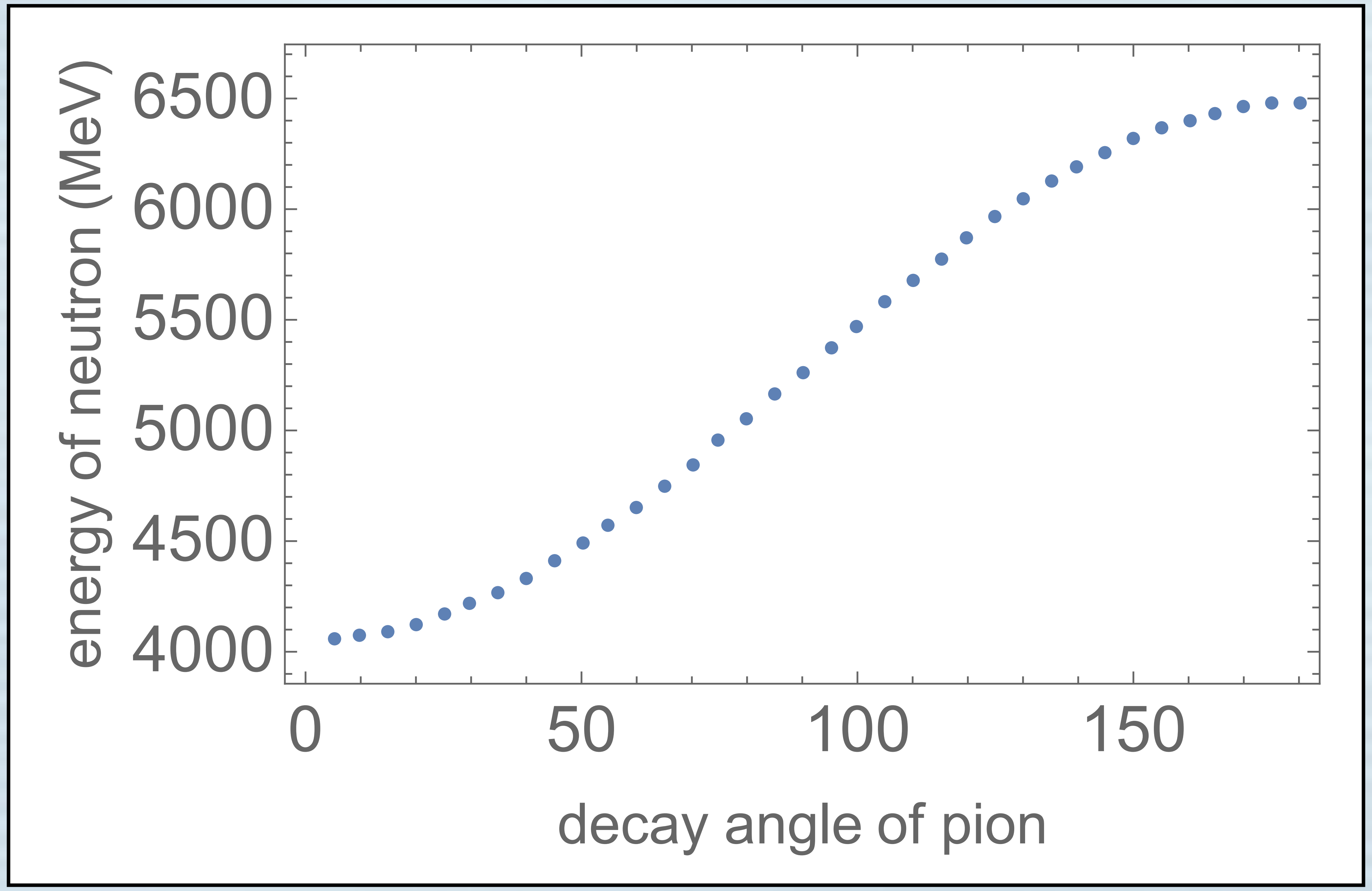
Kin3 coincidence time distribution for ^3He

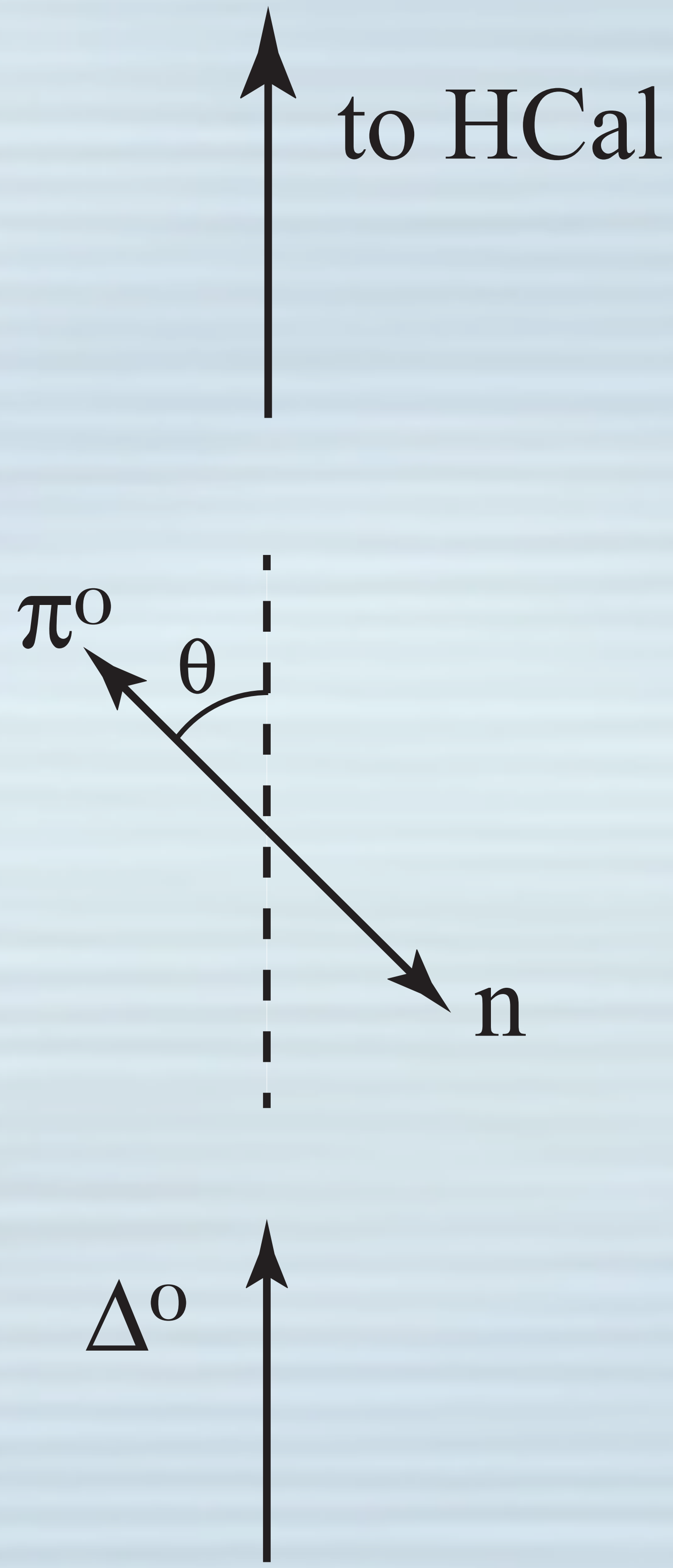
- Cuts used
  - E_PS > 0.2
  - 0.7 < (E_PS + E_SH)/P_tr < 1.3
  - -0.27 < Z_target < 0.27
  - E_HCAL > 0.02
  - 0.0 < W2 < 1.6
  - -0.5 < dx < 0.5
  - -0.5 < dy < 0.5
- Fit is a gaussian fit of the peak



Timing of inelastic events

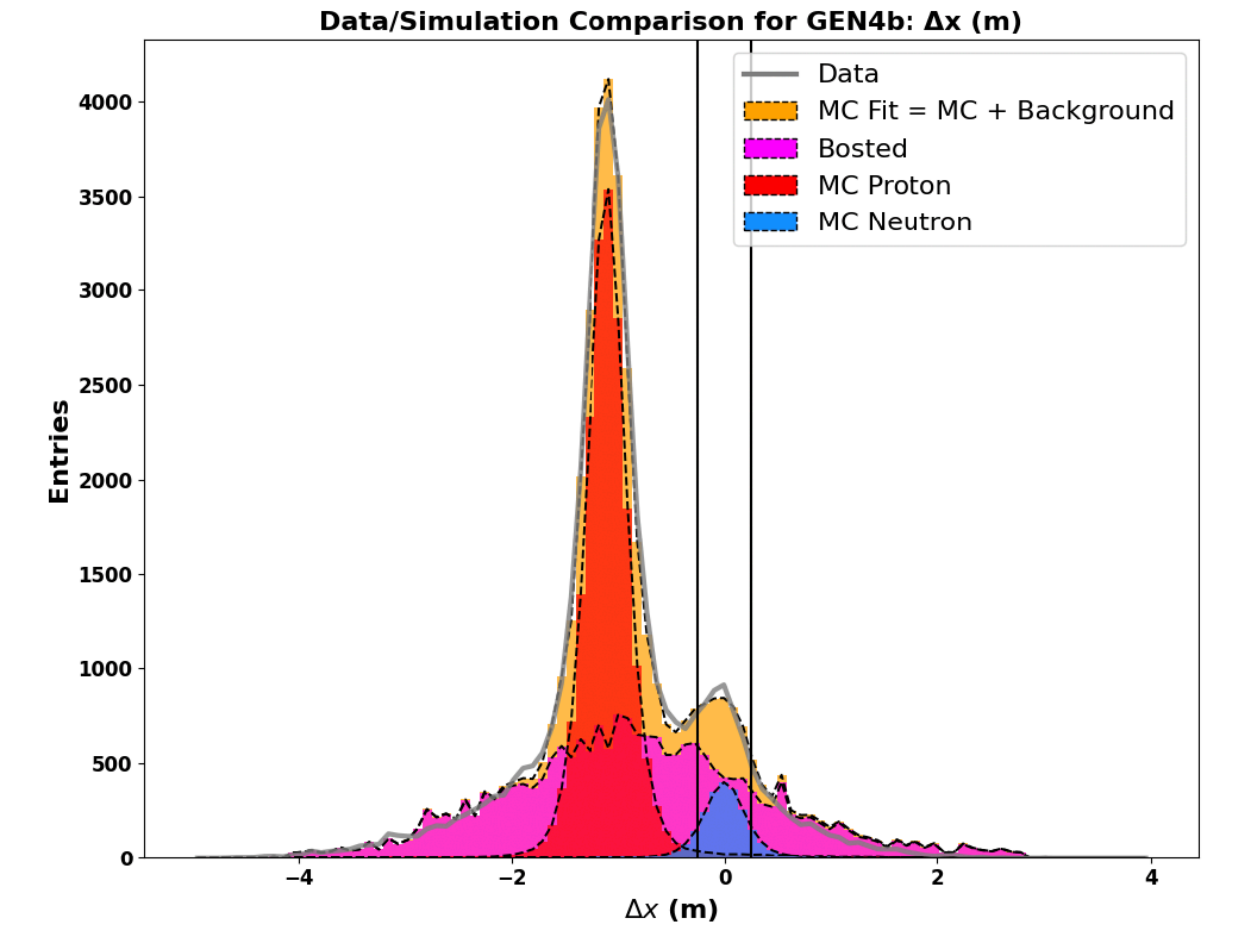
example: Δ^0





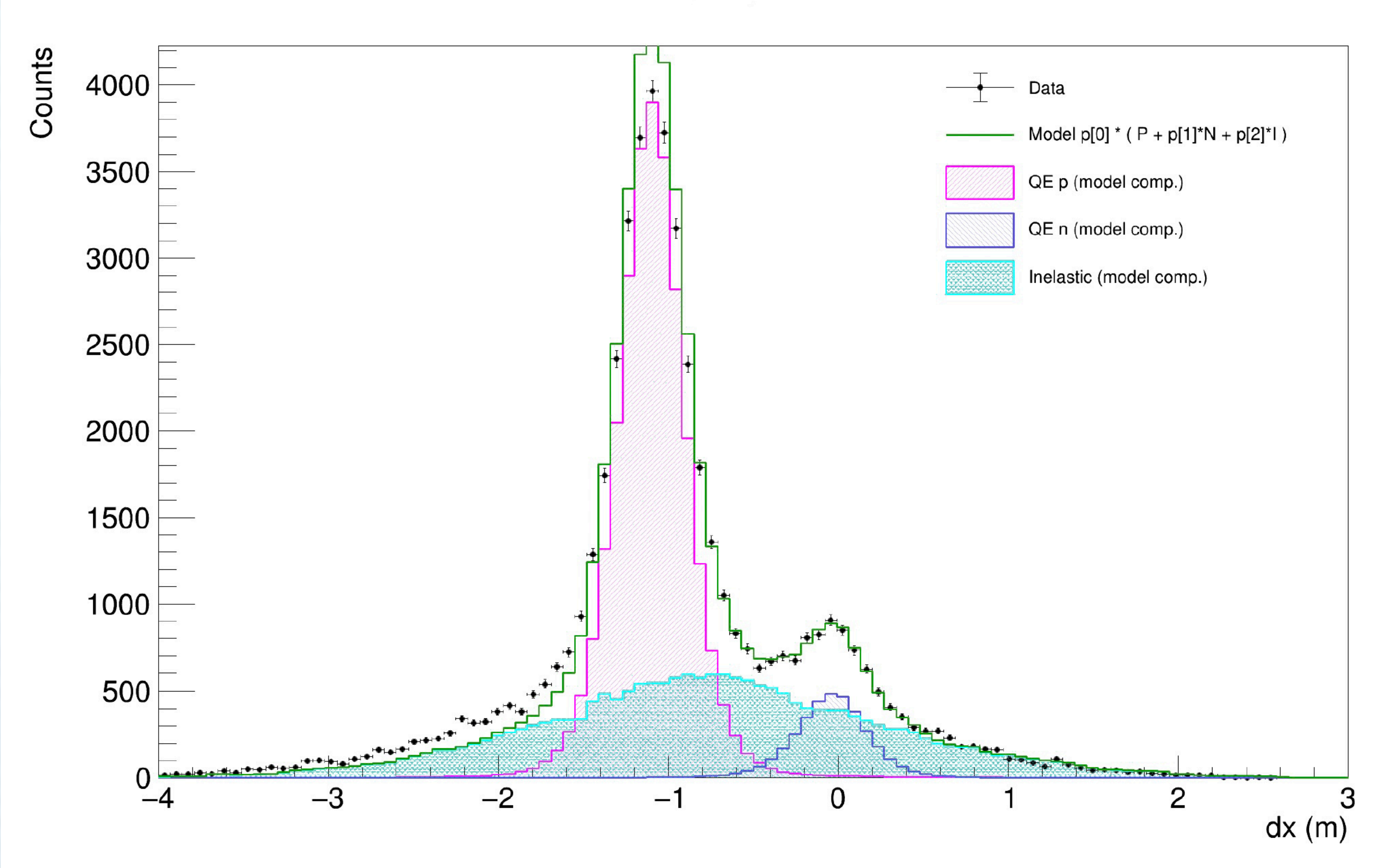
- A 6.5 GeV neutron takes 57.3 ns to reach HCal
- A 4.0 GeV neutron takes 58.3 ns to reach HCal
- So, even for a Δ^0, good timing resolution will help suppress background.

Better understanding of background fitting
(Kin4b shown)



From Hunter's pass-2 analysis

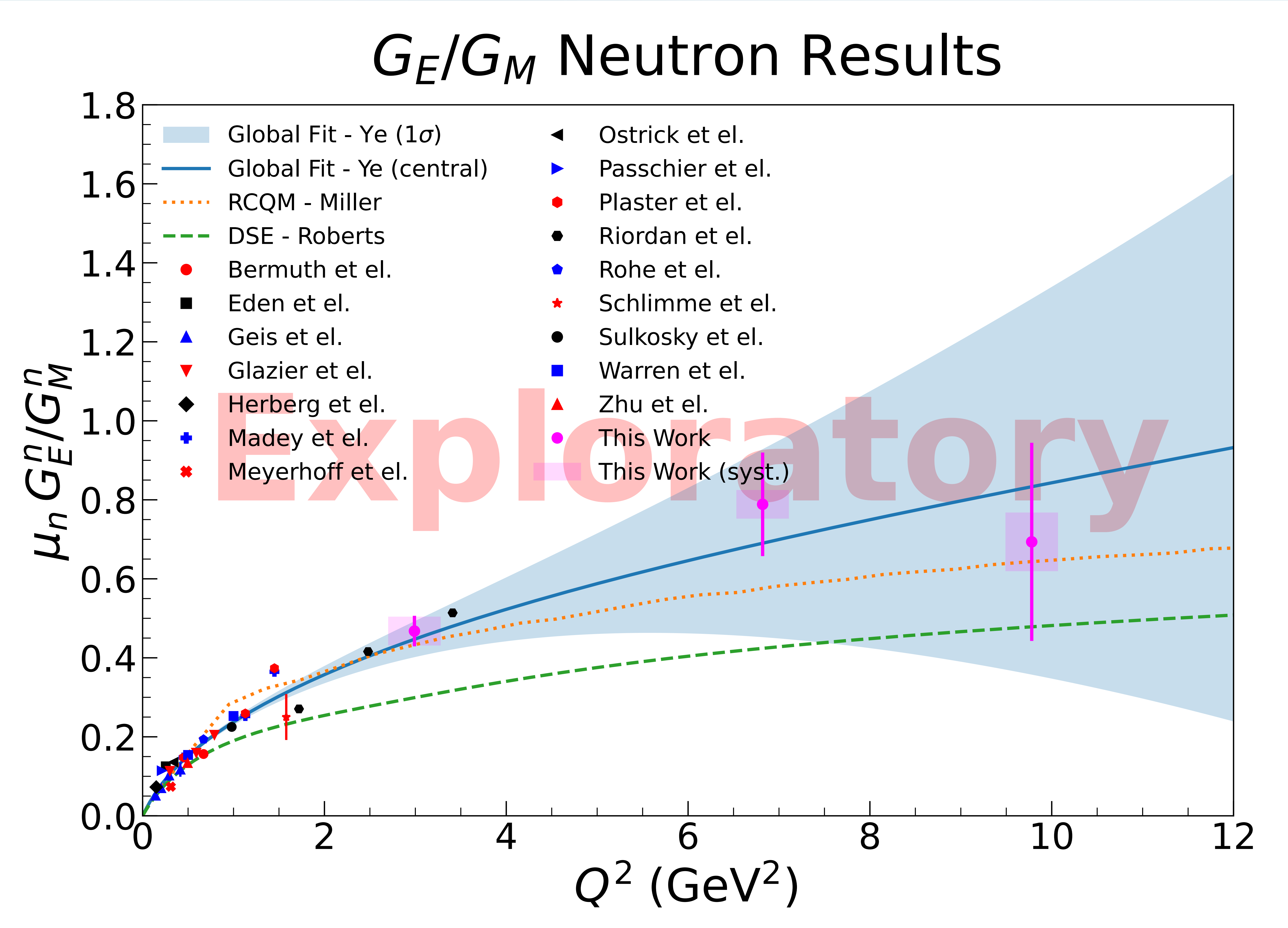
Events vs. Δx with fits for quasi-elastic protons and neutrons and background



From Vimukthi's recent replay of Kin4b using some (but not all!) of what will go into pass-3

Re-visiting pass 2 - Vimukthi Gamage

Second-pass analysis



- VERY Exploratory! Vimukthi's thesis will be based on pass 3.
- Biggest difference here is in the fitting procedure.
- Kin4 improved by a factor of 1.5 compared to Hunter's result, and a factor of 1.9 compared to Sean's result.

February 2026

Looking toward the Pass-4 analysis

Possibled areas of improvement for the Pass-4 analysis

- Better tracking/event reconstruction to recover more events?
- More refined simulations
- Adding the GRINCH in particle ID
- Using multiple hits on HCal to identify background events
- Using the shapes of signals on HCal to identify background events

Some ultimate goals for the final analysis

Fraction of expected events reconstructed in the pass-2 analysis

Estimates of expected and observed # of neutrons for each kinematic setting							
1	2	3	4	5	6	7	8
Kin. setting	Act. Q^2 (GeV^2)	Est. rate (Hz)	Accum. charge (C)	Seconds at 60μA (K)	Est. of expected #n	Est. of observed #n	Percentage of expected neutrons
Kin2	2.93	2.36 †	13.5	225	531,000	161,928*	30.5%
Kin3	6.76	0.061 ††	48.6	810	49,410	15,907*	32.2%
Kin4	9.78	0.013 ††	97.7	1,628	21,164	3,459*	16.3%

† Rate calculated by Andrew for the August 15, 2022 report for the ERR
†† Rate calculated by Andrew for the August 9, 2023 SBS weekly meeting
* As reported in Ph.D.thesis of Hunter Presley

What is the very best we might achieve?

	Pass-1	Pass-2	70% recon. efficiency	w 50% less background	ERR adjusted	ERR
kin3 error is	0.205	0.132	0.090	0.080	0.084	0.077
kin4 error is	0.483	0.368	0.178	0.145	0.121	0.095

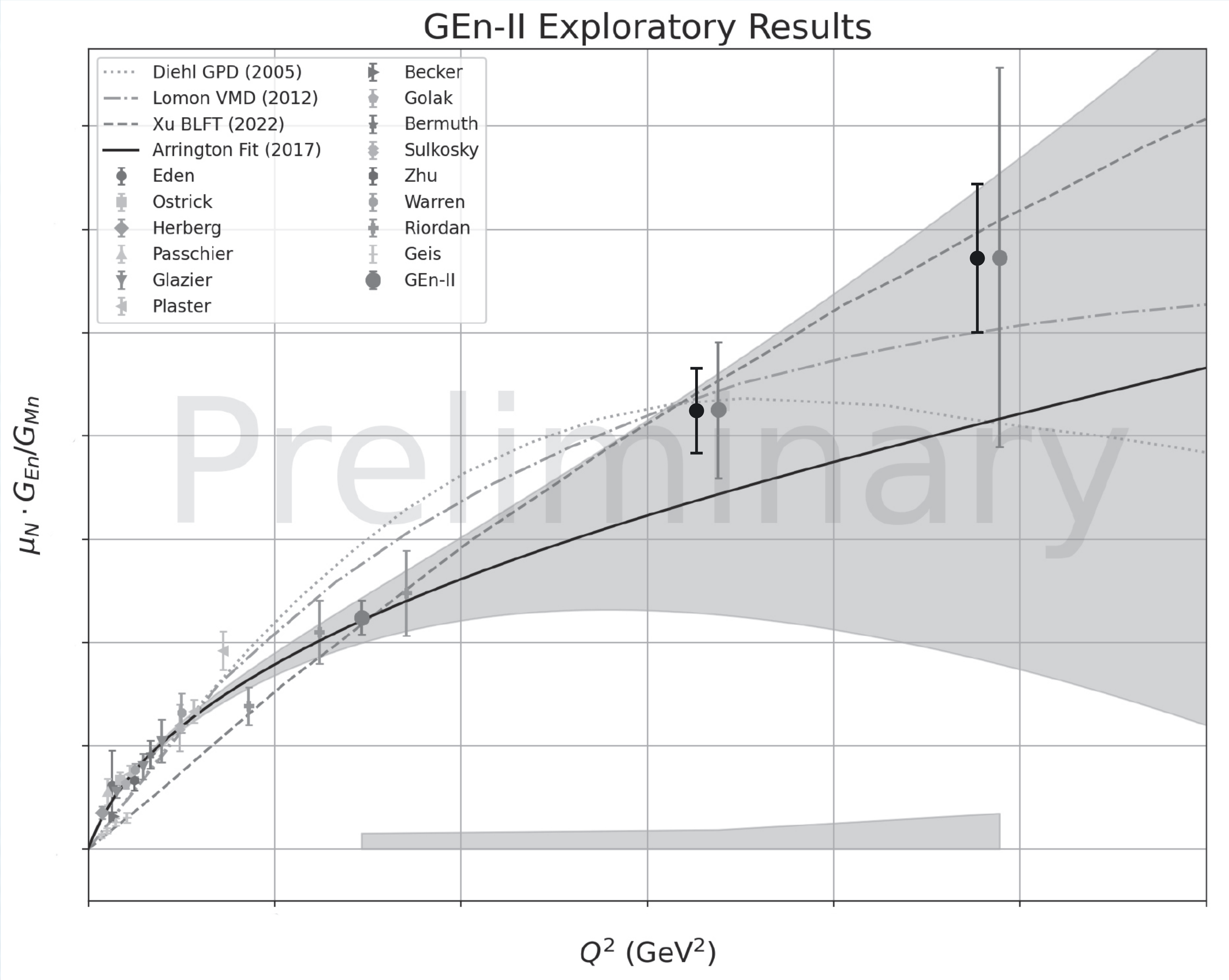
Vimukthi's recent Kin4 error: 0.268
(somewhere between pass-2 and pass3).

Best case scenario?
(however unlikely)

972 hours at 45 uA is 157.5 C	we received 97.7 C
360 hours at 45 uA is 58.3 C	we received 48.6 C

What is the very best we might achieve?

- The best-case scenario assumes 70% reconstruction efficiency and a 50% reduction in background. Better refined simulations
- The projections are scaled from Hunter's thesis (pass-2 analysis)
- These best-case projections will be considerably refined with pass 3.
- Whether we reach these goals or not, it is important to understand what is limiting us.



Potential limitations on our statistics

- We could be losing events at the trigger level (if so, these are not recoverable).
- We might not always be matching the correct cluster in HCal with the electrons (the correct cluster might not be the highest energy cluster).
- It might be that lowering the energy cut on HCal to allow more good events will be limited by the increase in background.
- Finding ways to reduce background could be enormously useful!

Expected yield of quasi-elastic protons from H_2

Summary	GEN-2	GEN-3	GEN-4
N_{tries}	10^6	10^6	10^6
$\Delta \sum \sigma_i(\mathrm{cm}^2)$	1.1262×10^{-30}	5.5489×10^{-32}	1.1106×10^{-32}
$\sigma_{avg}(\mathrm{cm}^2)$	2.9×10^{-34}	3.7×10^{-36}	5.5×10^{-37}
Luminosity ($\mathrm{s}^{-1}\mathrm{cm}^{-2}$)	1.1543×10^{37}	1.1543×10^{37}	1.1543×10^{37}
I_{beam}(A)	60×10^{-6}	60×10^{-6}	60×10^{-6}
Yield (events/C)	2.1666×10^5	1.0675×10^4	2.1366×10^3
Charge collected (C)	0.813		0.720
Elastic proton yield	176122		1538
Actual proton yield (corrected for livetime)			1061

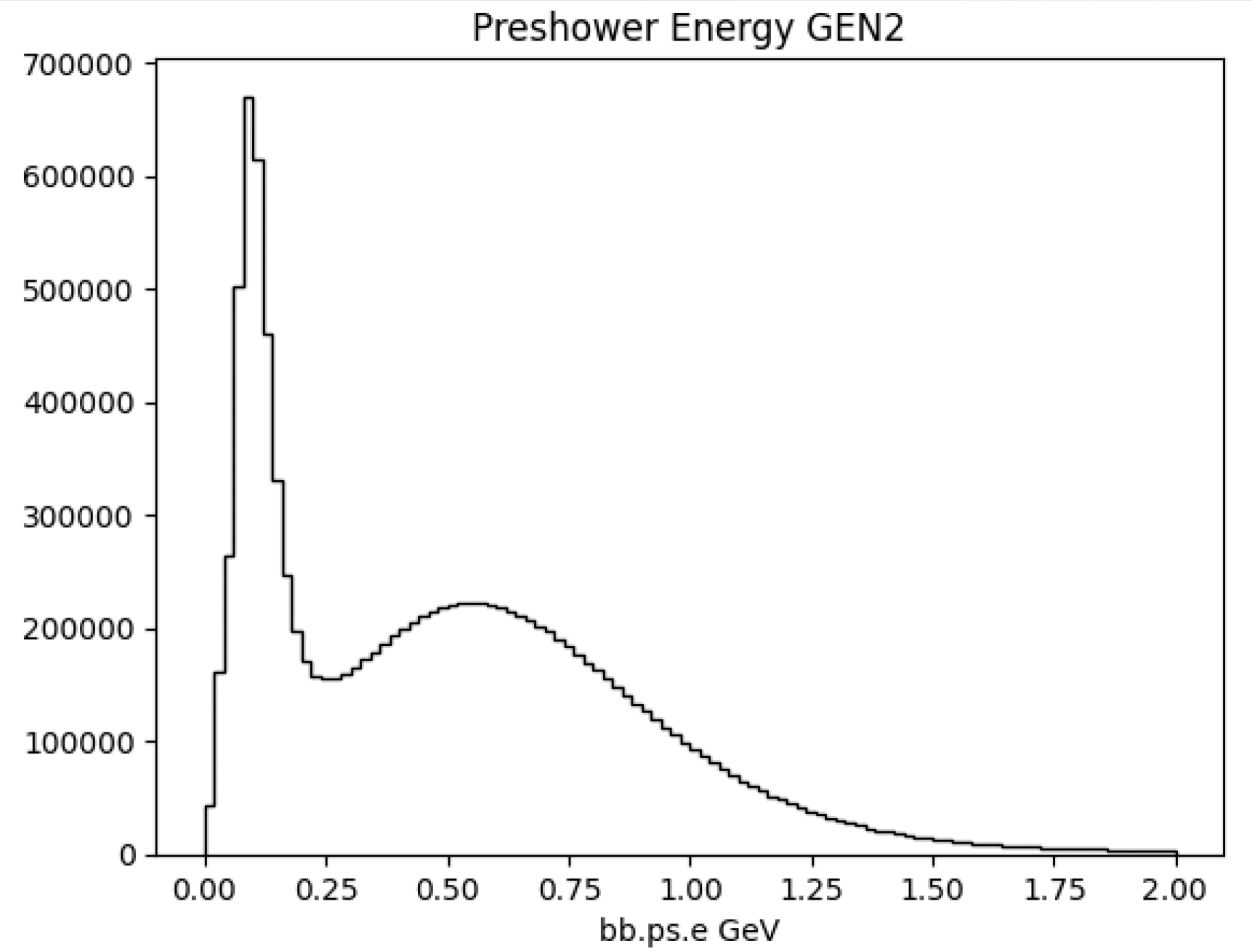
- Actual yield was between 60-70% of expected yield
- These hydrogen runs were with what was essentially a singles trigger.
- There is good news and bad news here …

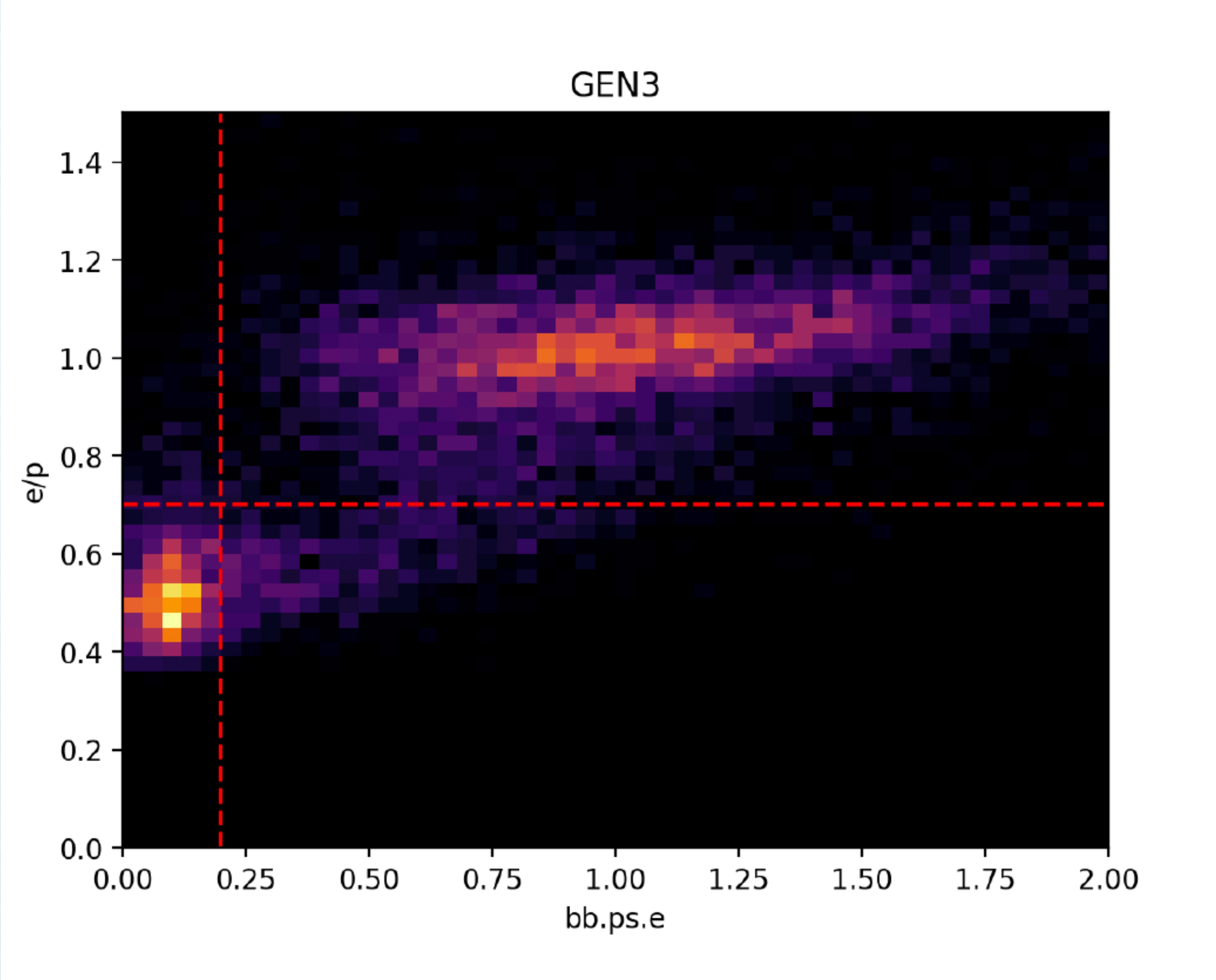
There are clearly substantial improvements that are possible

We will have a much better sense of the "end game" after pass-3 is complete

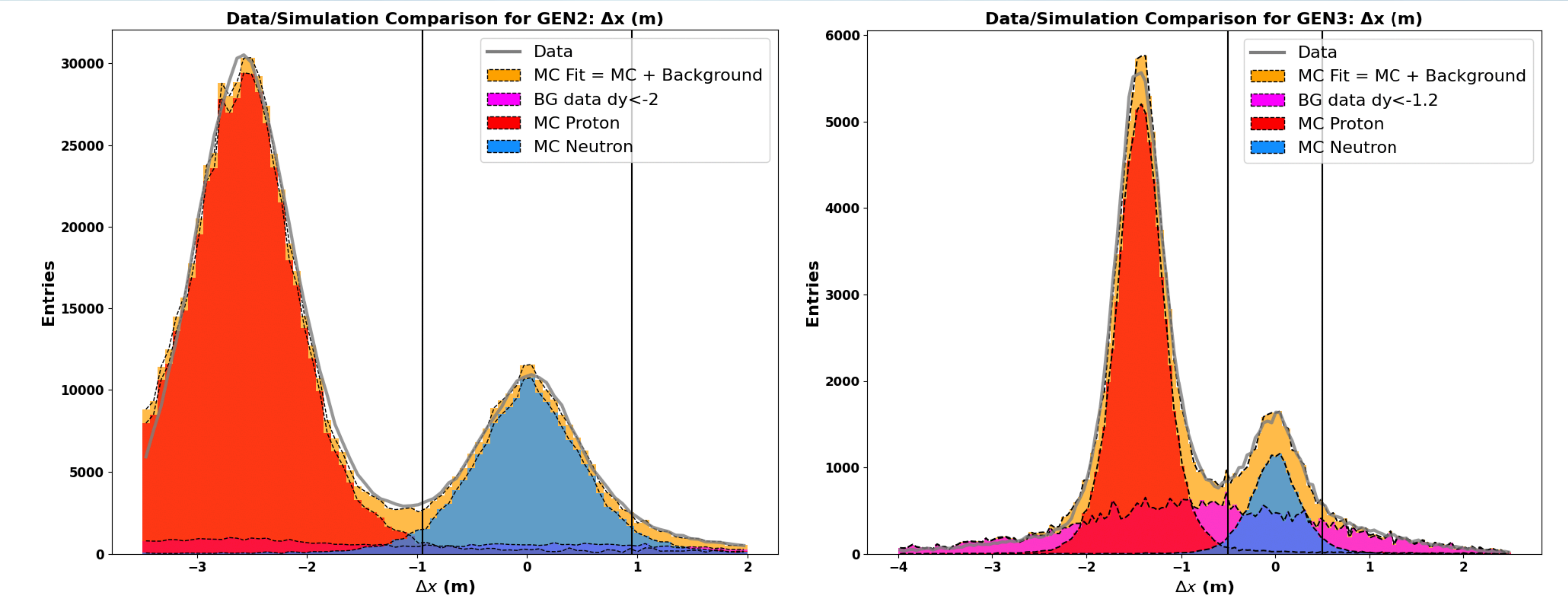
Backup slides

Pion rejection in BigBite





Fitting Δx plots with simulations



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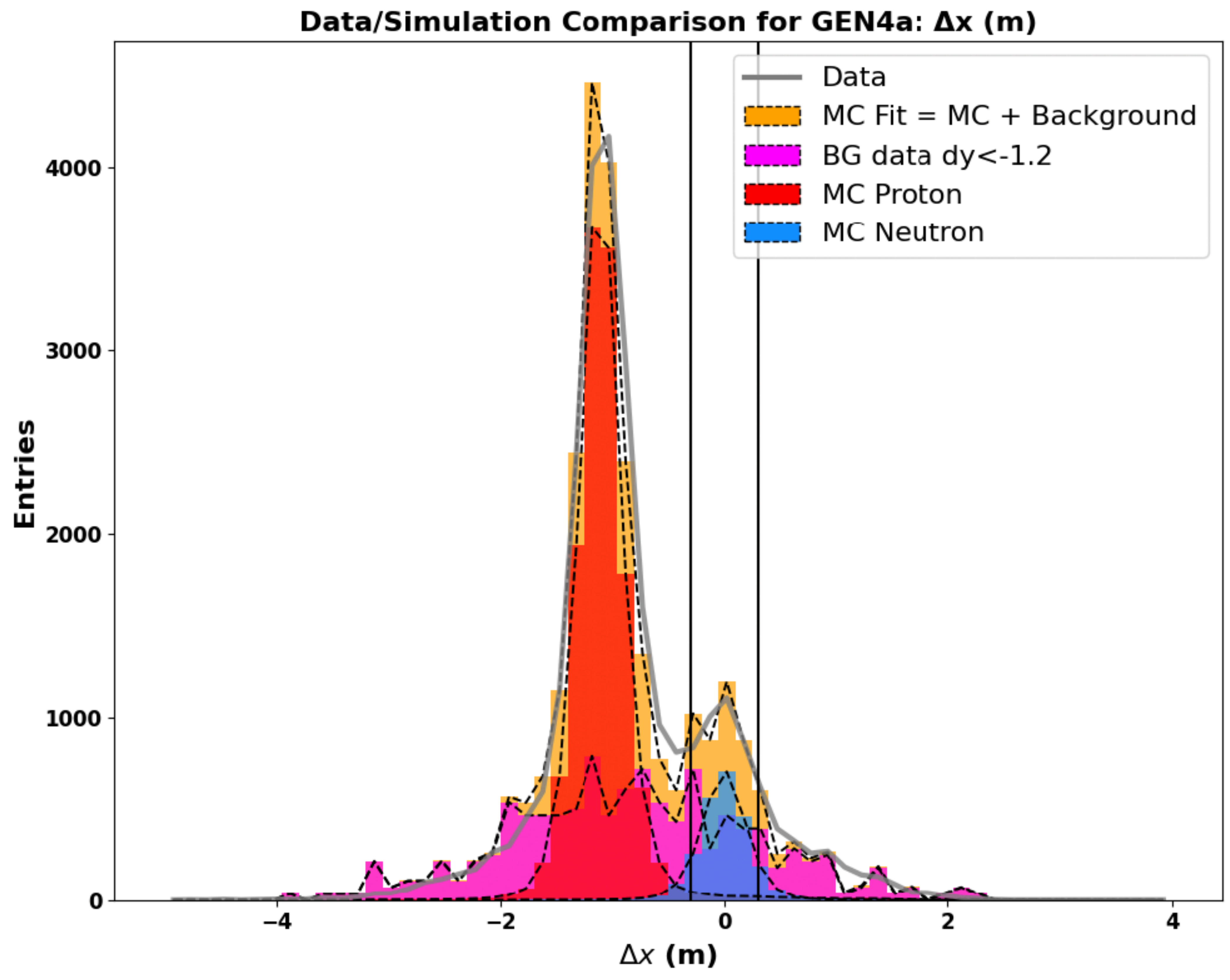
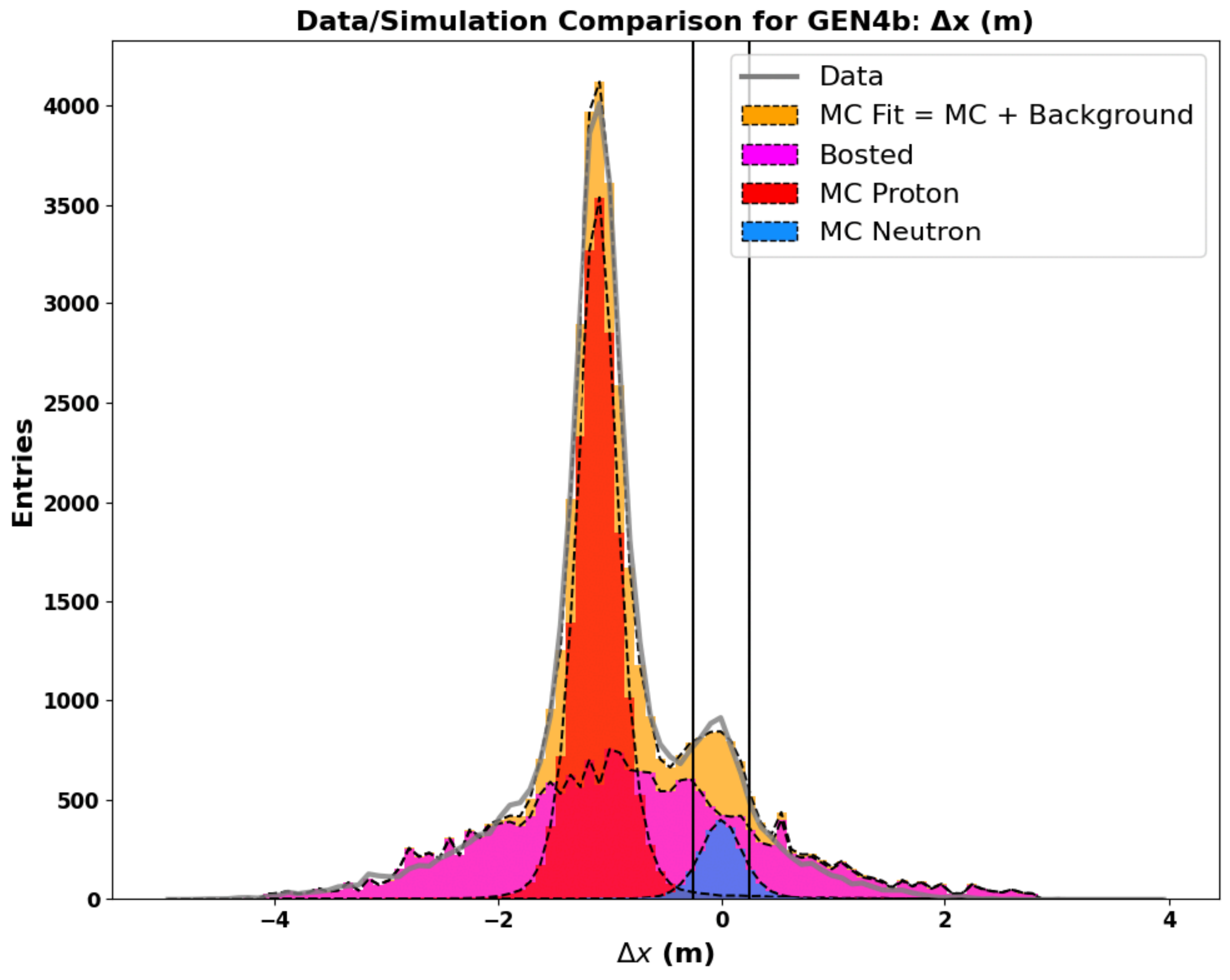




Pass-one (Jeffas) coincidence time distributions

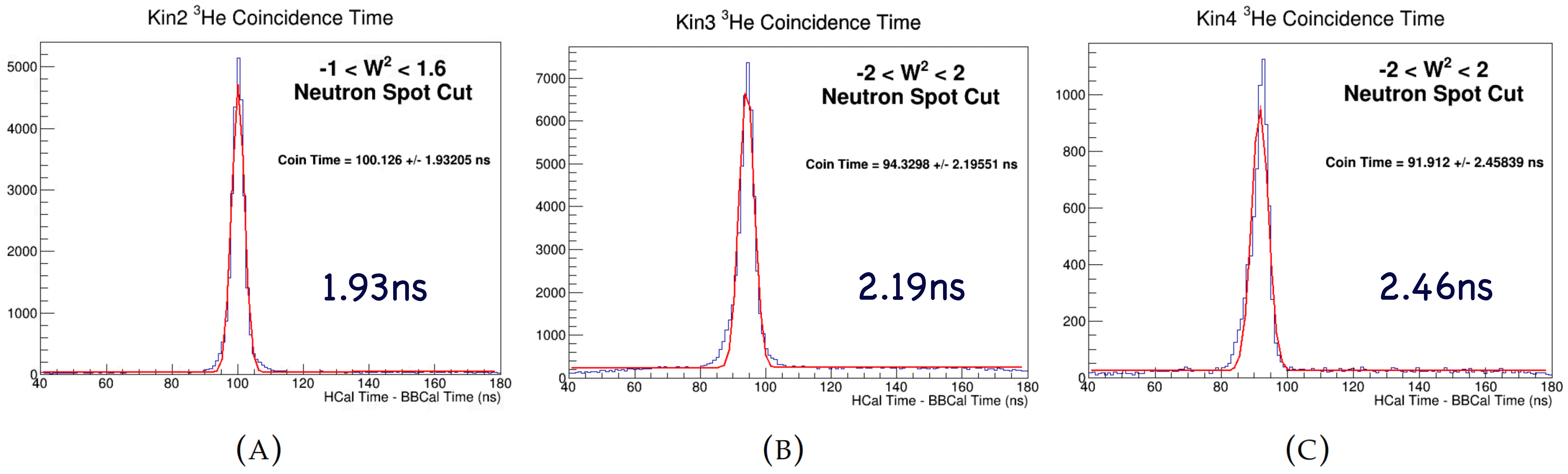
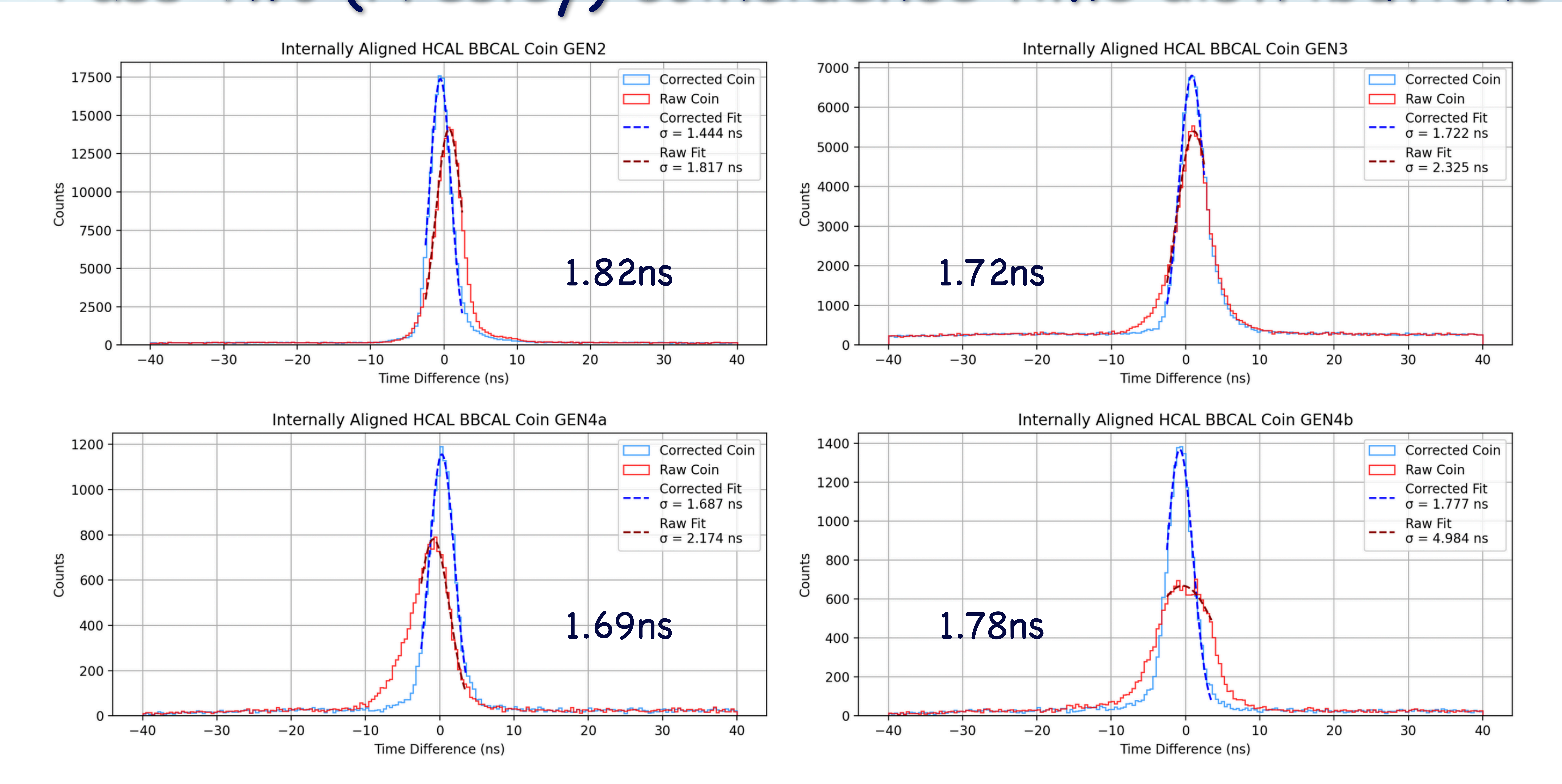
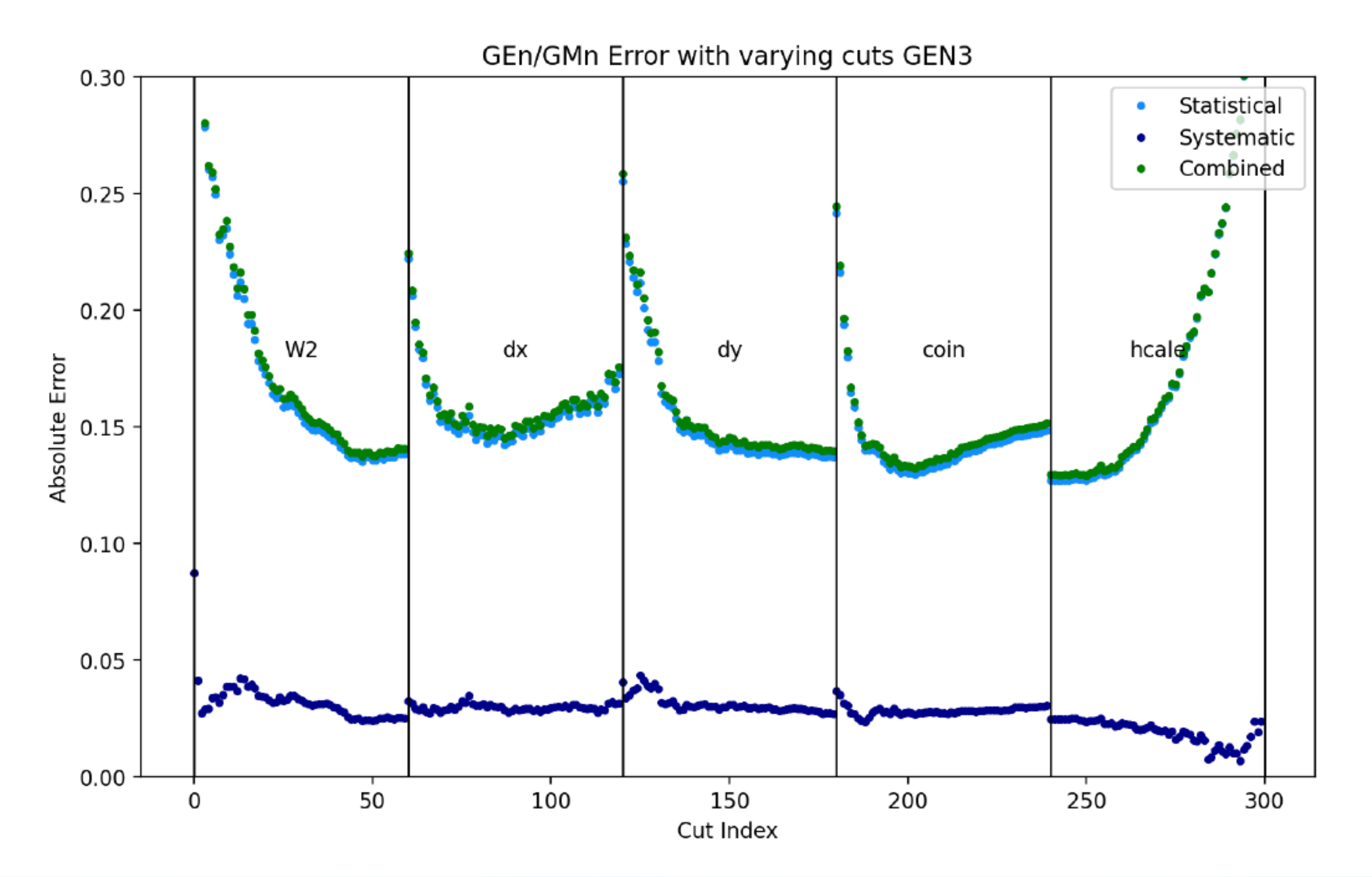


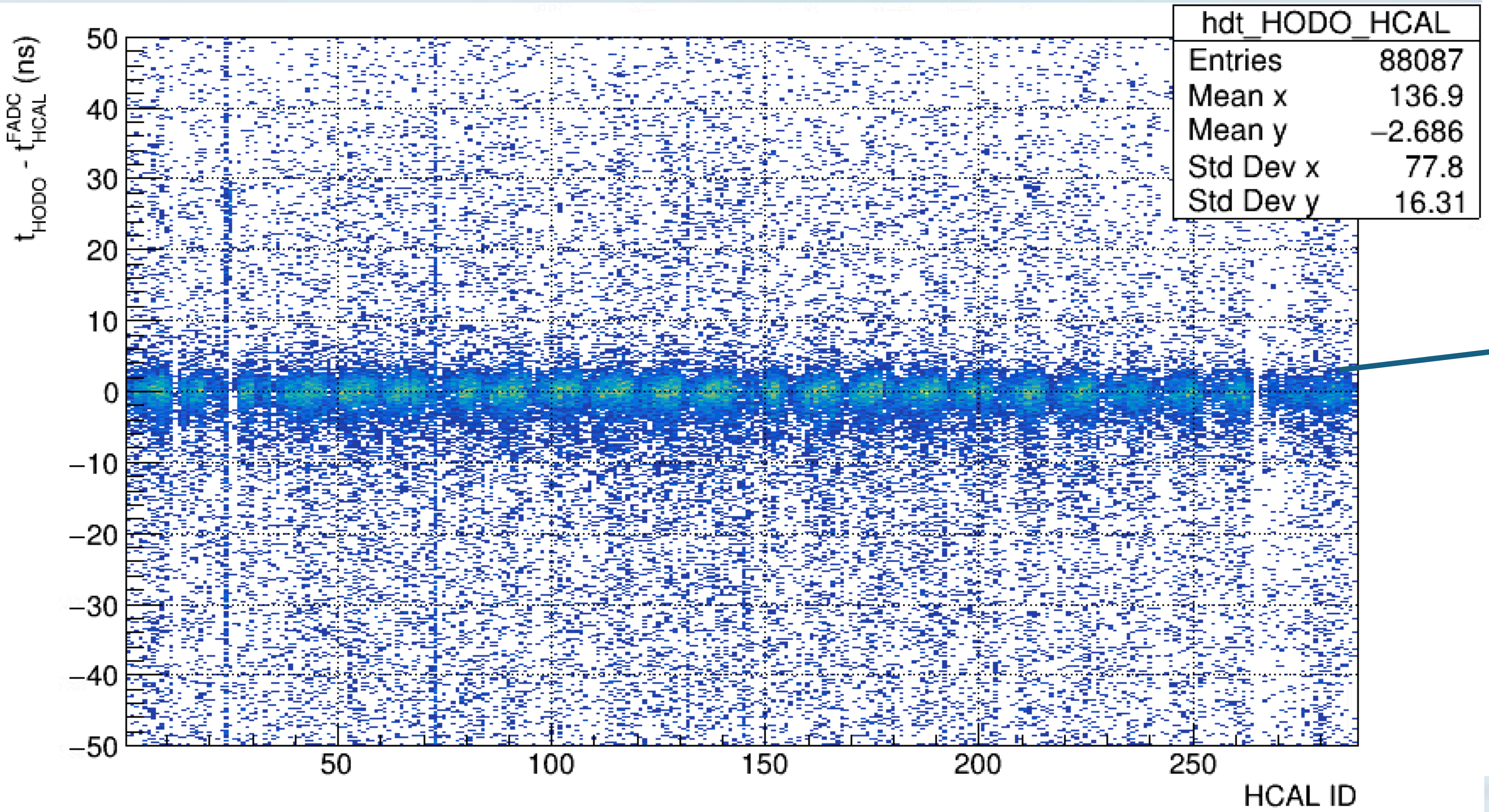
FIGURE 7.9: Coincidence time distributions for all three kinematics. A Gaussian + linear fit is used for the histogram. The resulting Gaussian fit is printed on each plot.

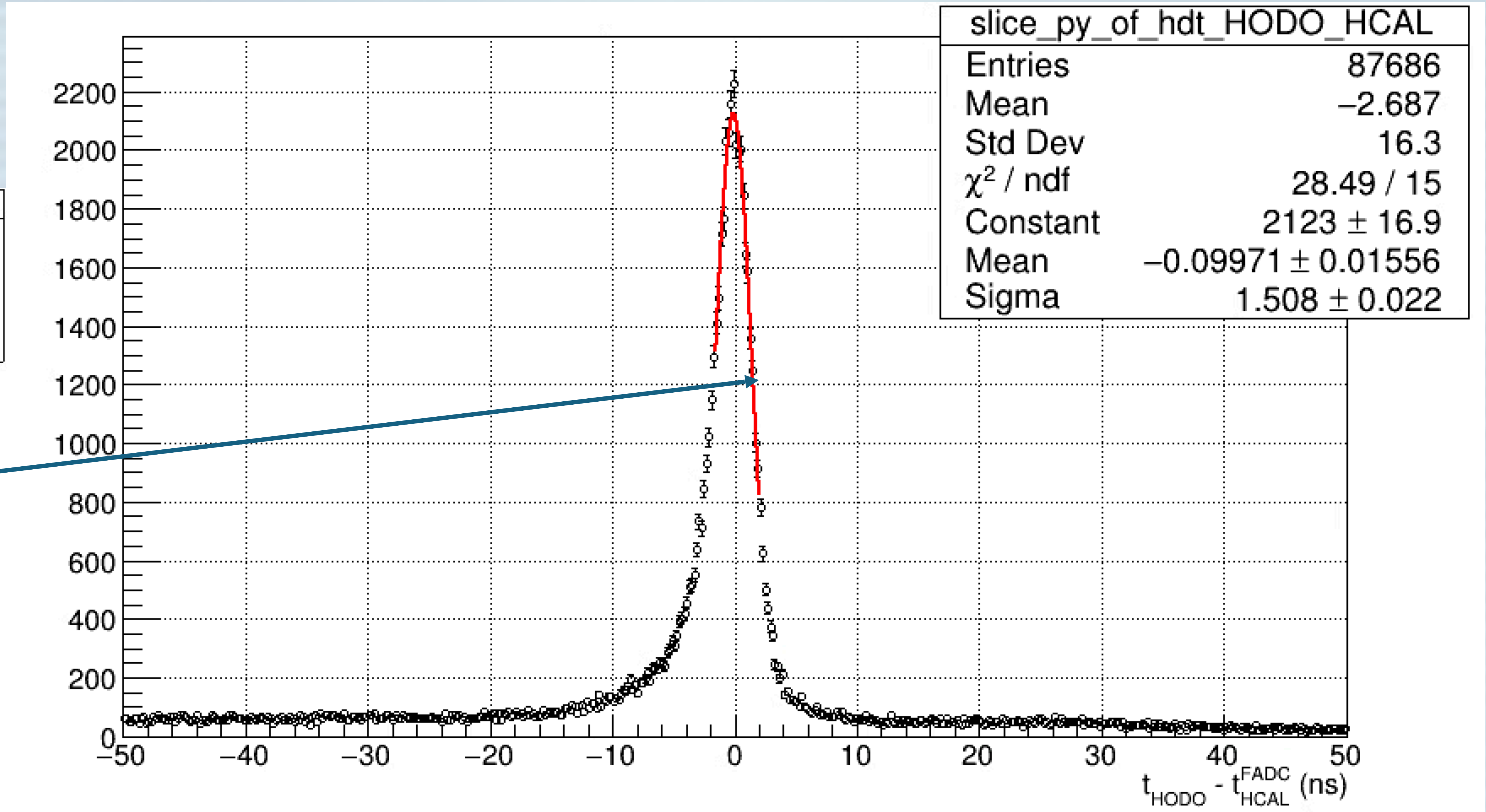
Pass-two (Presley) coincidence time distributions

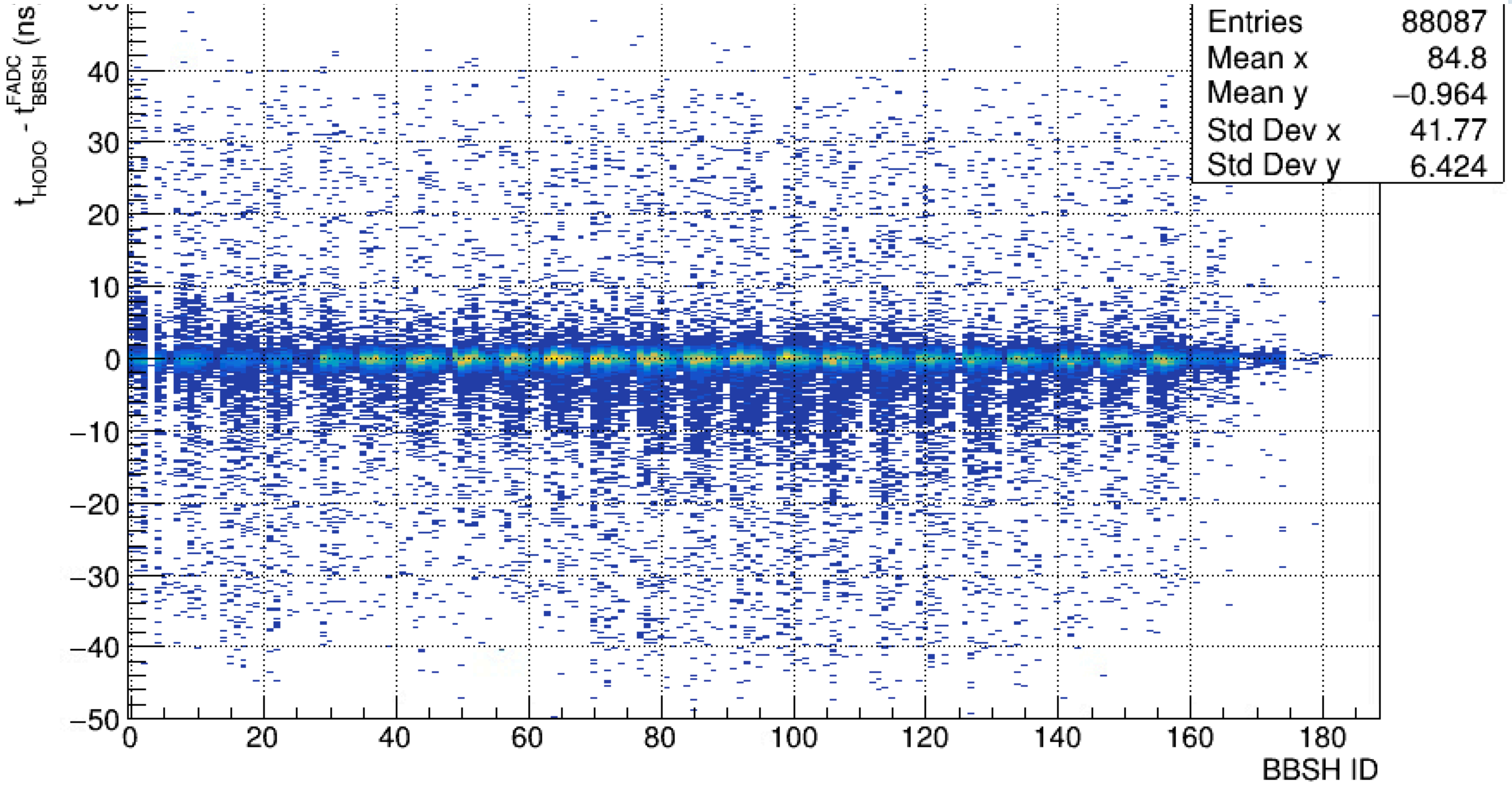


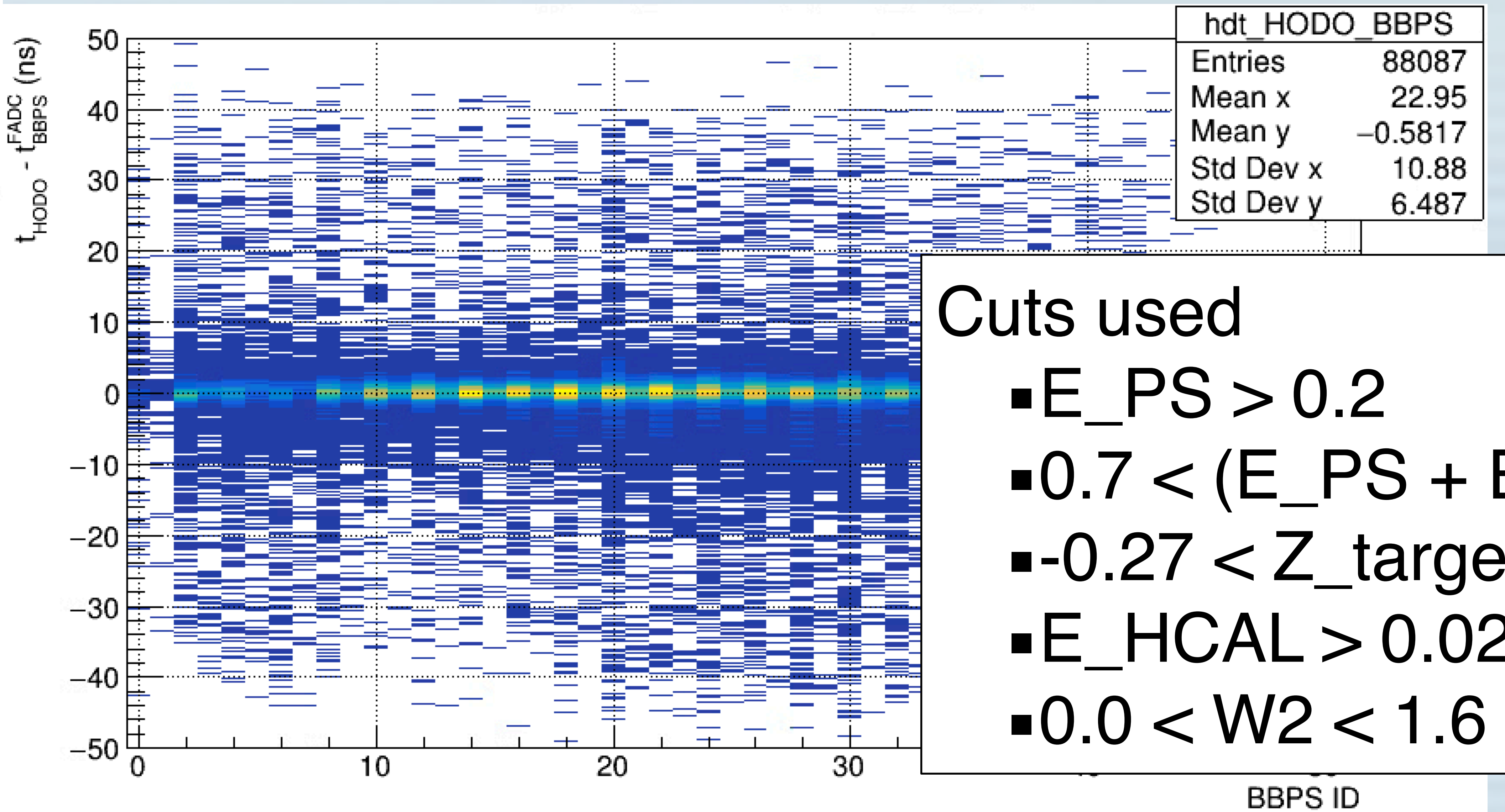
Optimizing cuts to minimize final errors











Cuts used

- E_PS > 0.2
- 0.7 < (E_PS + E_SH)/P_tr < 1.3
- -0.27 < Z_target < 0.27
- E_HCAL > 0.02
- 0.0 < W2 < 1.6

- Cuts used
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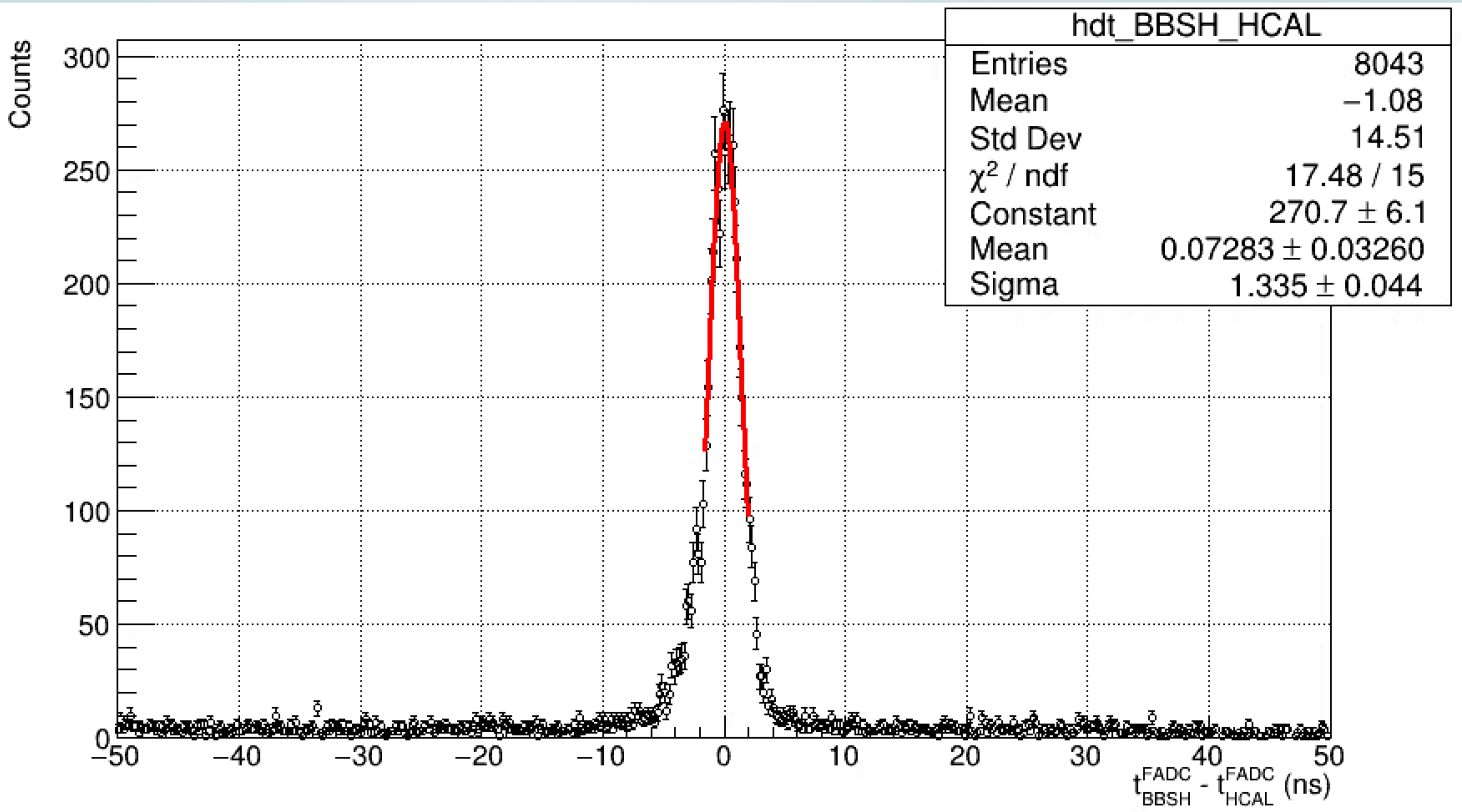
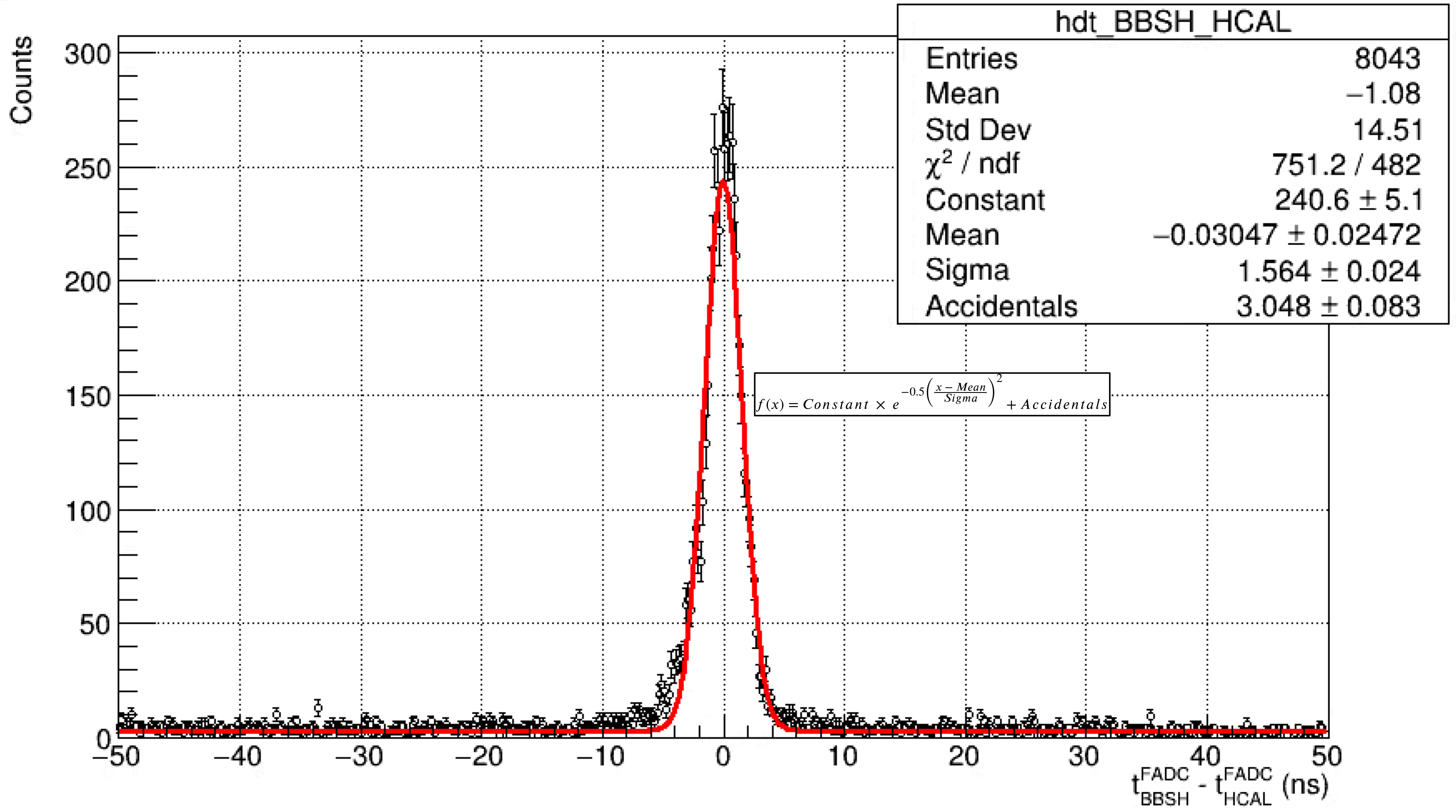
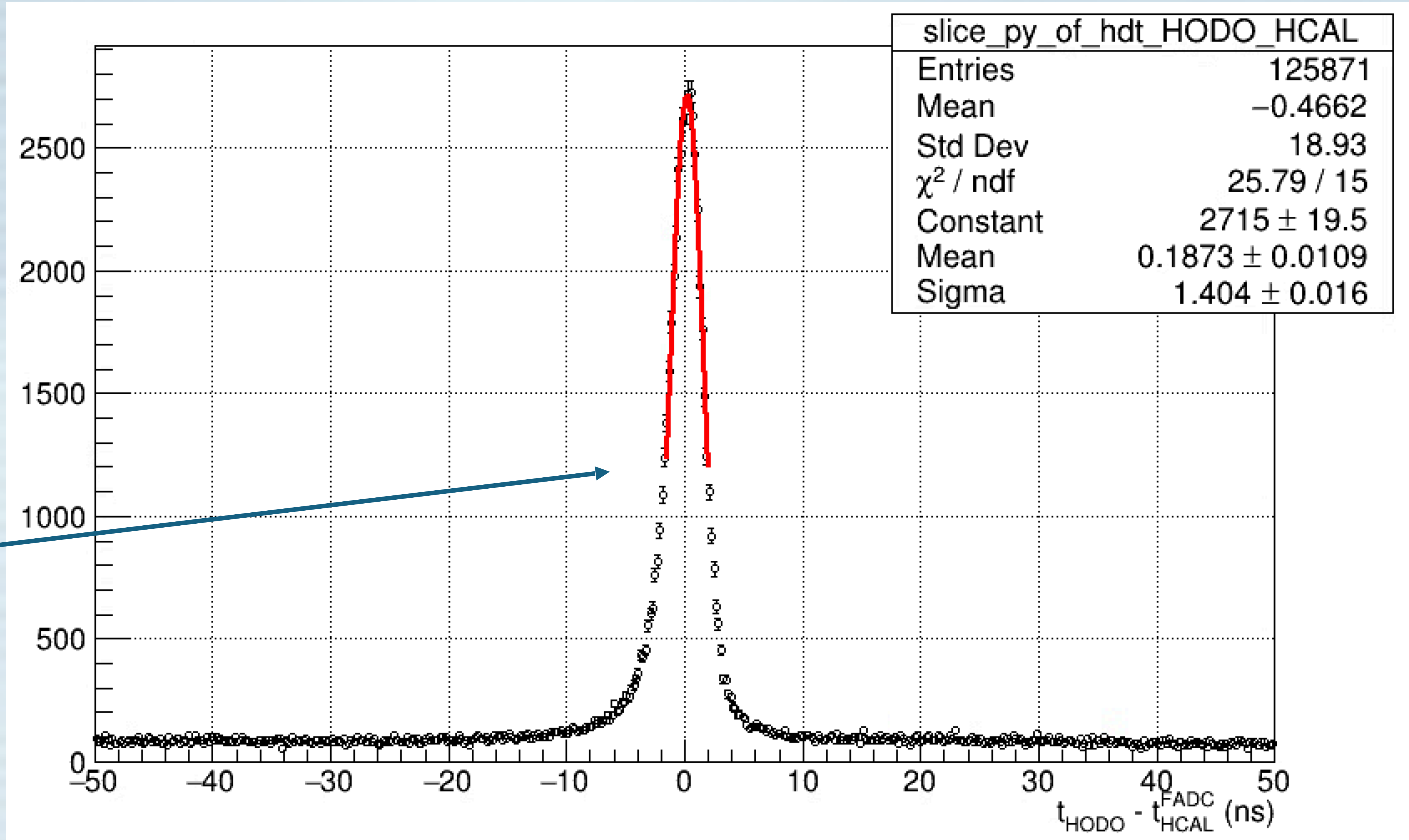
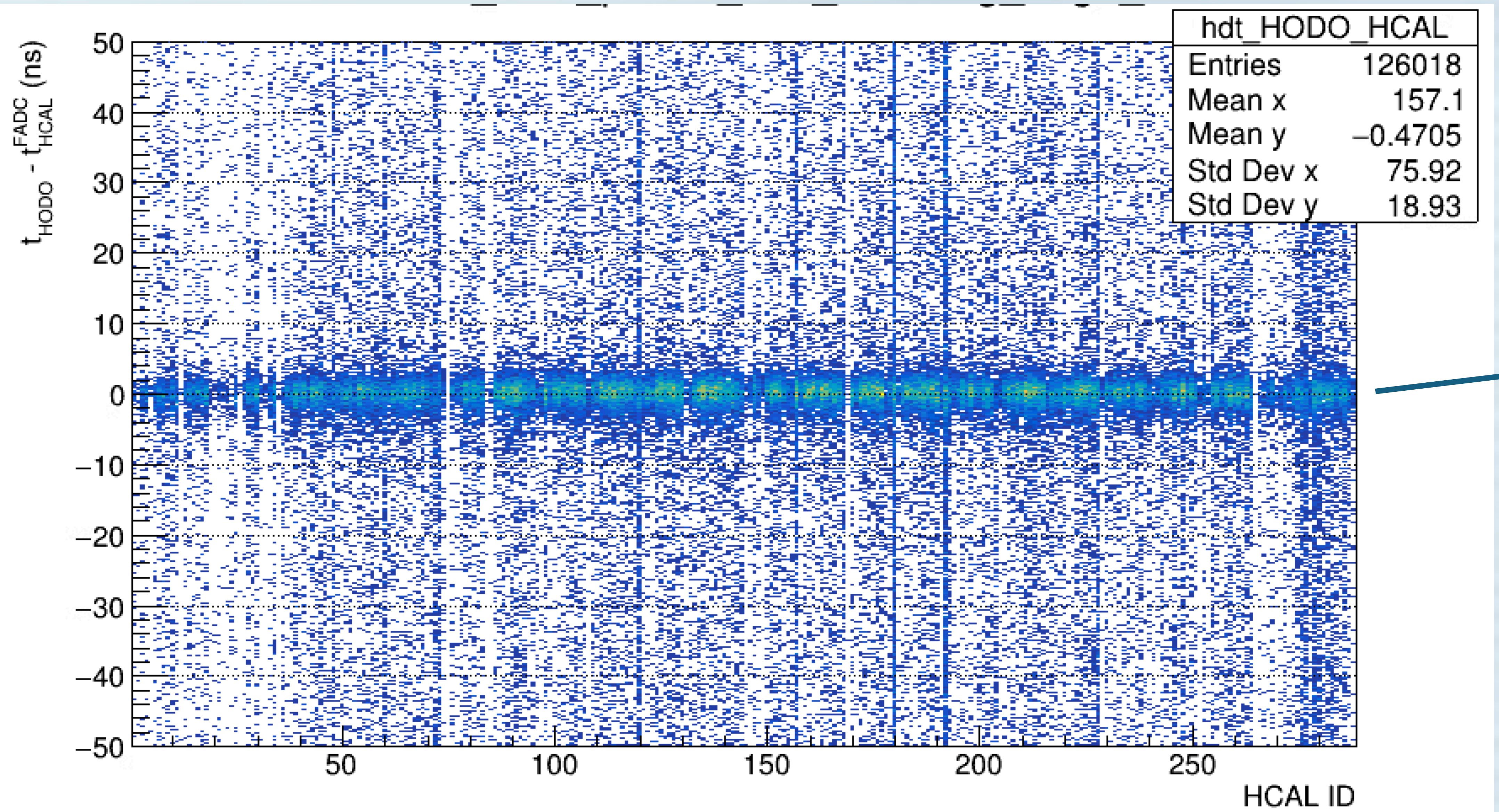
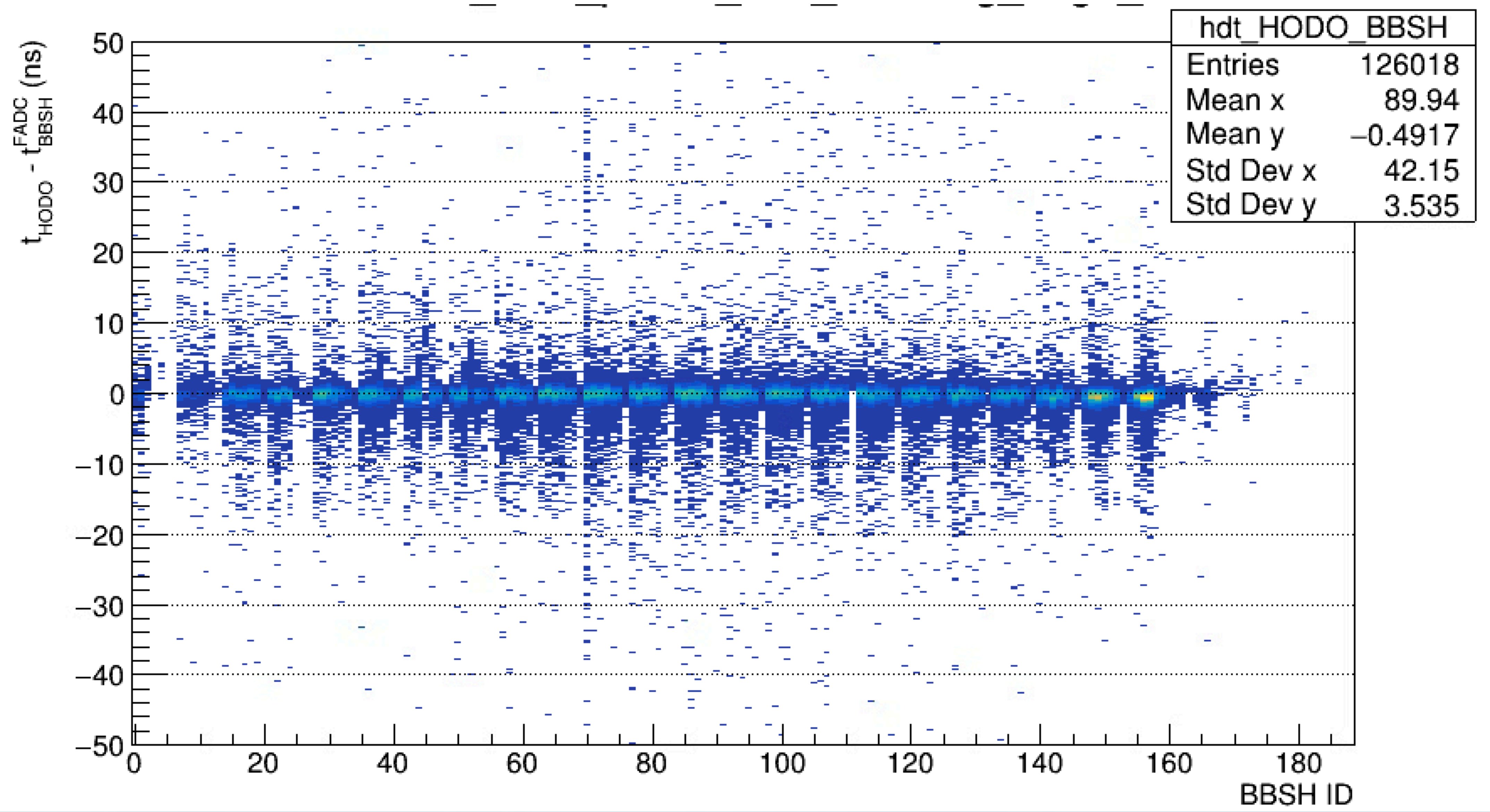
  - E_HCAL > 0.02
  - 0.0 < W2 < 1.6
  - -0.5 < dx < 0.5
  - -0.5 < dy < 0.5\
- Top figure is doing just a gaussian fit of the peak
- Bottom figure is doing a gaussian fit + a constant I'm calling "Accidentals" for the whole domain

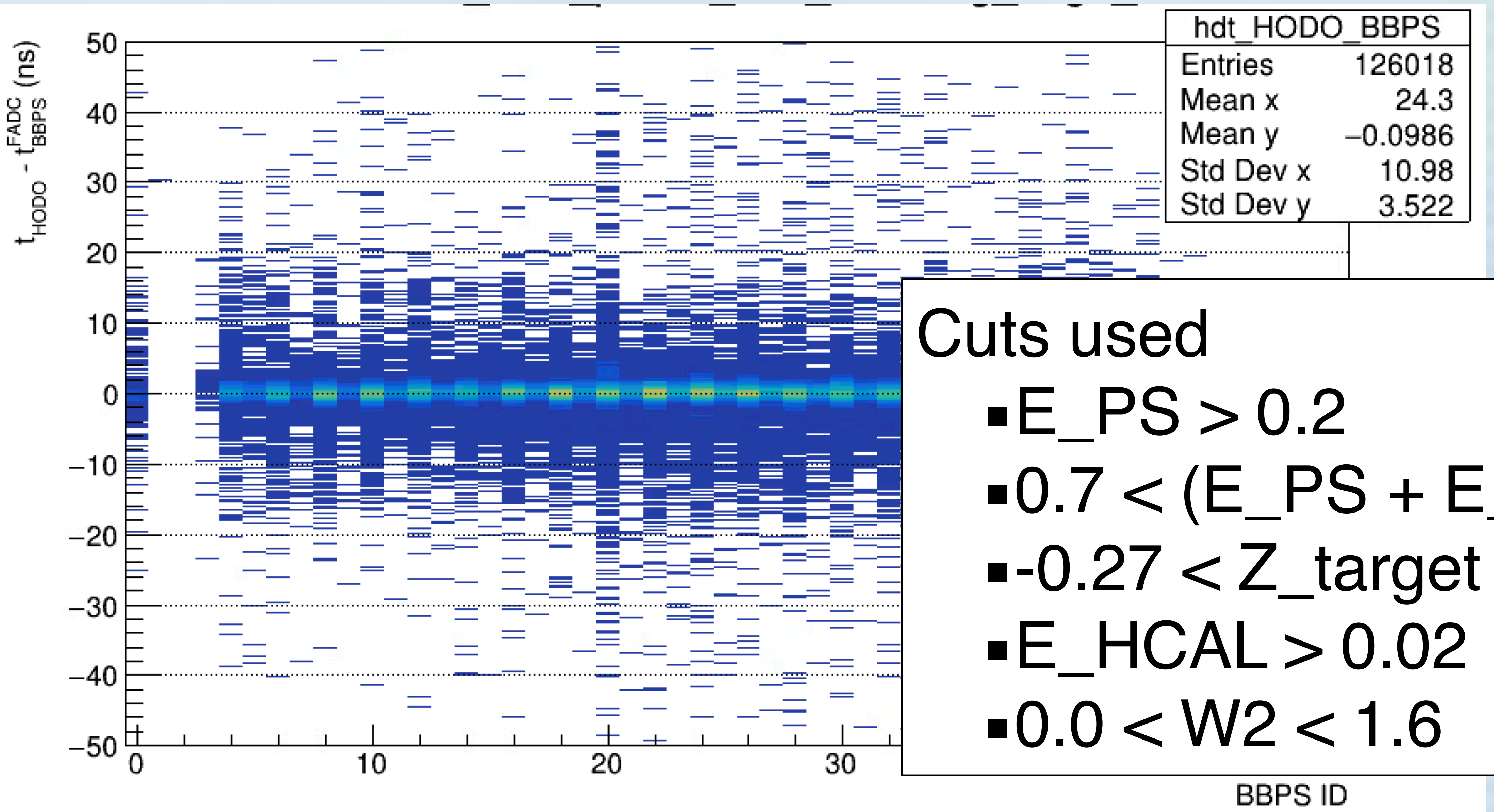












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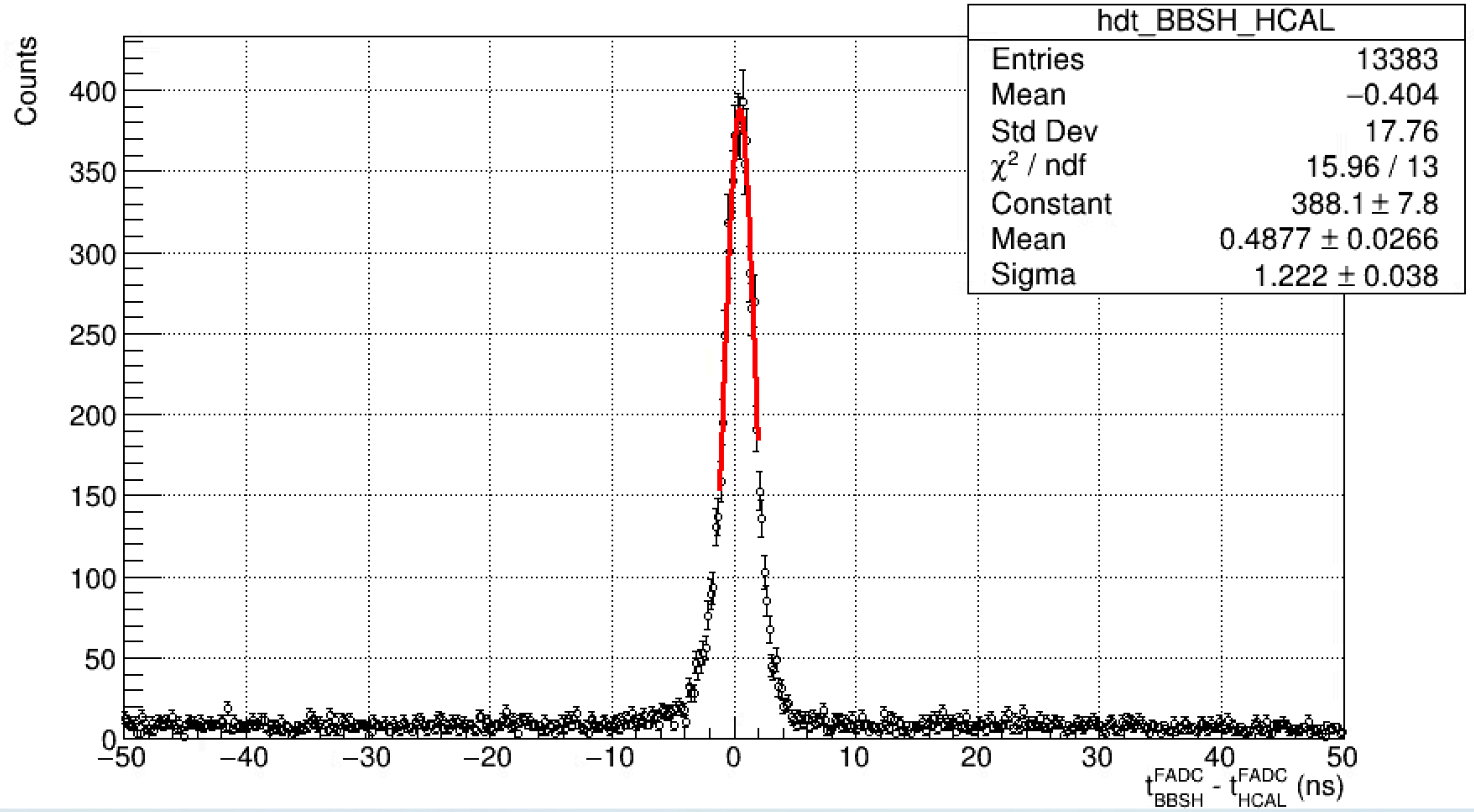
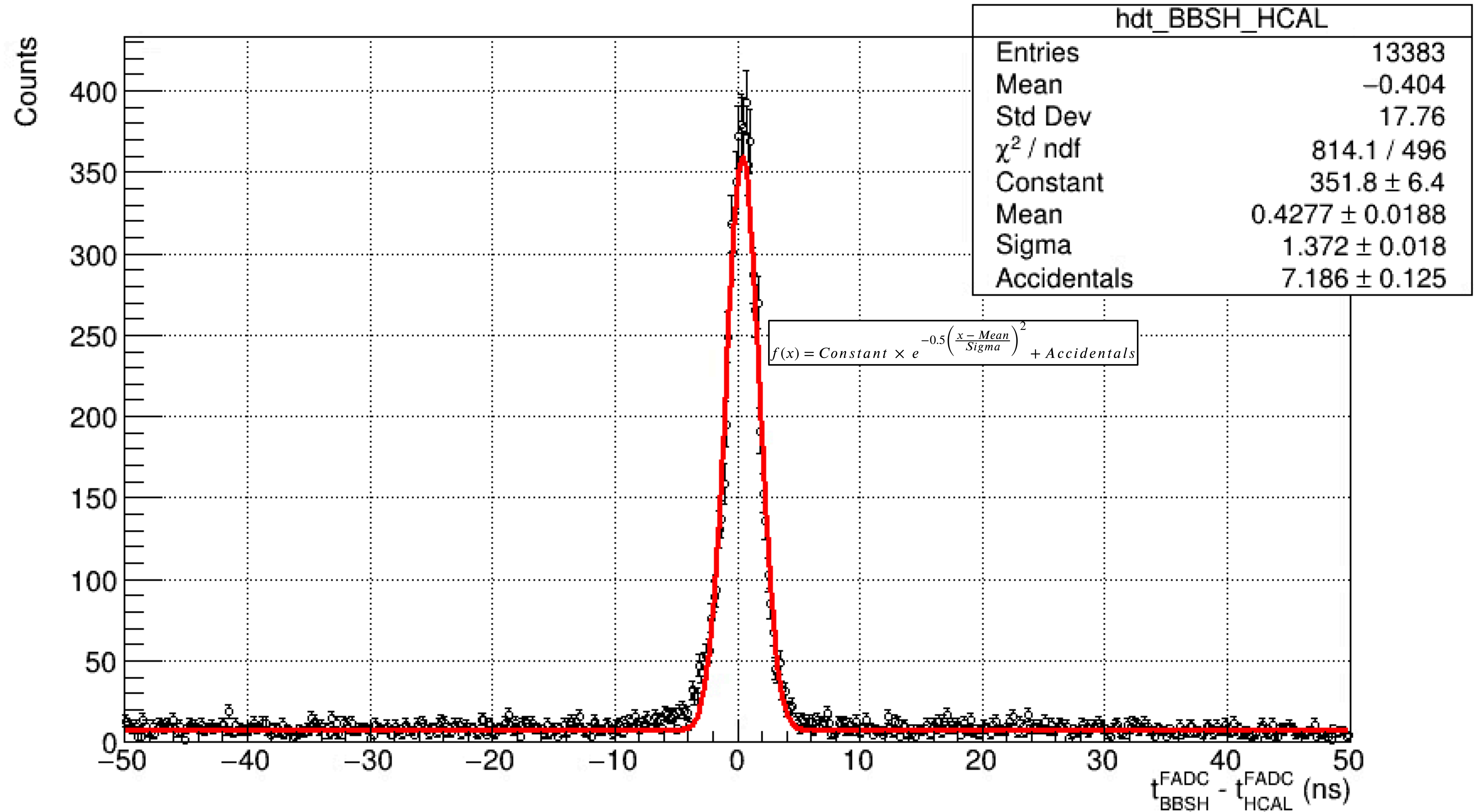
- E_HCAL > 0.02
- 0.0 < W2 < 1.6


hdt_BBSH_HCAL
Entries 13383
Mean −0.404
Std Dev 17.76
χ^2 / ndf 15.96 / 13
Constant 388.1 ± 7.8
Mean 0.4877 ± 0.0266
Sigma 1.222 ± 0.038
Counts
$t^{FADC}_{BBSH} - t^{FADC}_{HCAL}$ (ns)


hdt_BBSH_HCAL
Entries 13383
Mean −0.404
Std Dev 17.76
χ^2 / ndf 814.1 / 496
Constant 351.8 ± 6.4
Mean 0.4277 ± 0.0188
Sigma 1.372 ± 0.018
Accidentals 7.186 ± 0.125
$f(x) = Constant \times e^{-0.5\left(\frac{x-Mean}{Sigma}\right)^2} + Accidentals$
Counts
$t^{FADC}_{BBSH} - t^{FADC}_{HCAL}$ (ns)