GMN/NTPE Analysis Update

Eric Fuchey

William & Mary

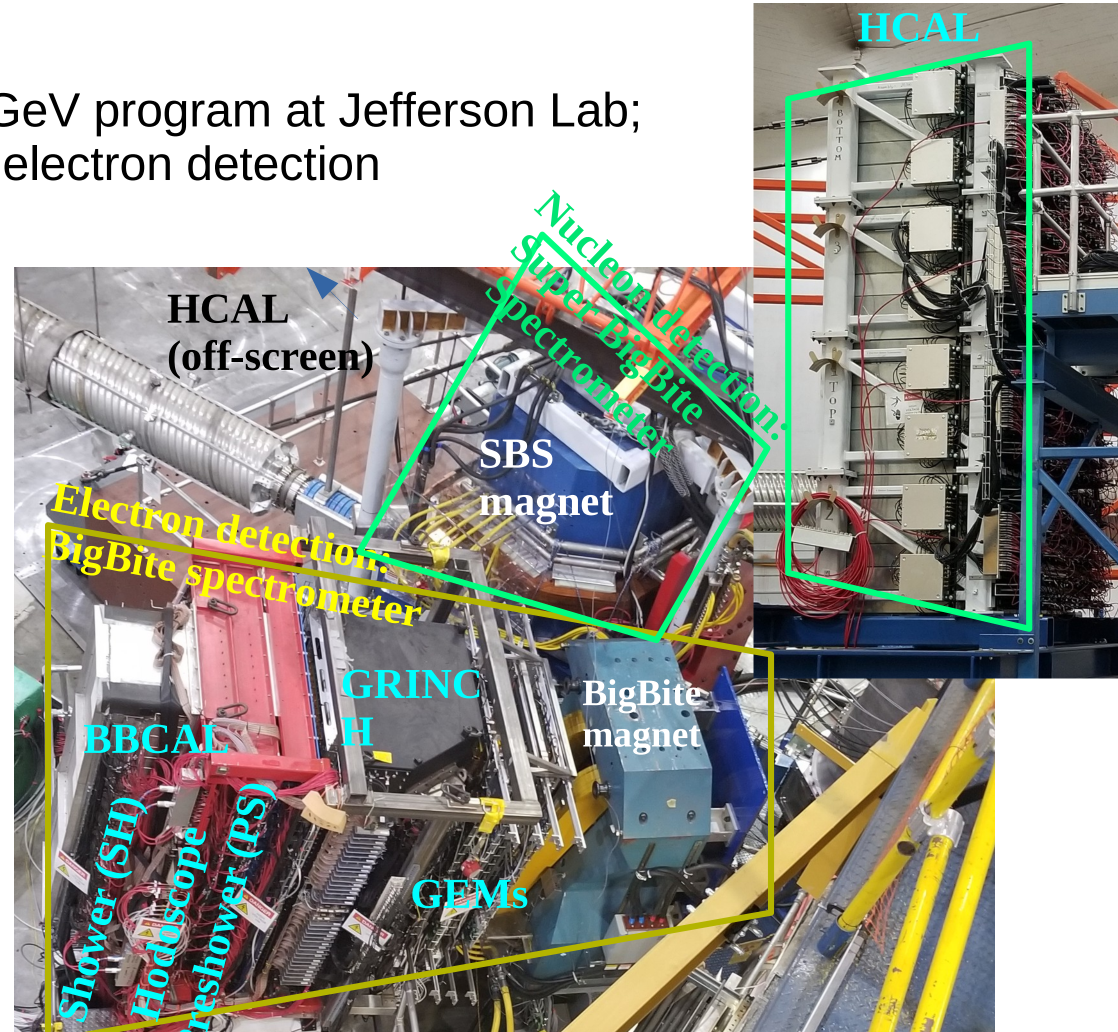
Hall A Collaboration Meeting, January 16th 2025

Reminder (Gordon’s talk): SBS

- **SBS:**
  - Major part of Hall A 12 GeV program at Jefferson Lab;
  - coupled with Bigbite for electron detection

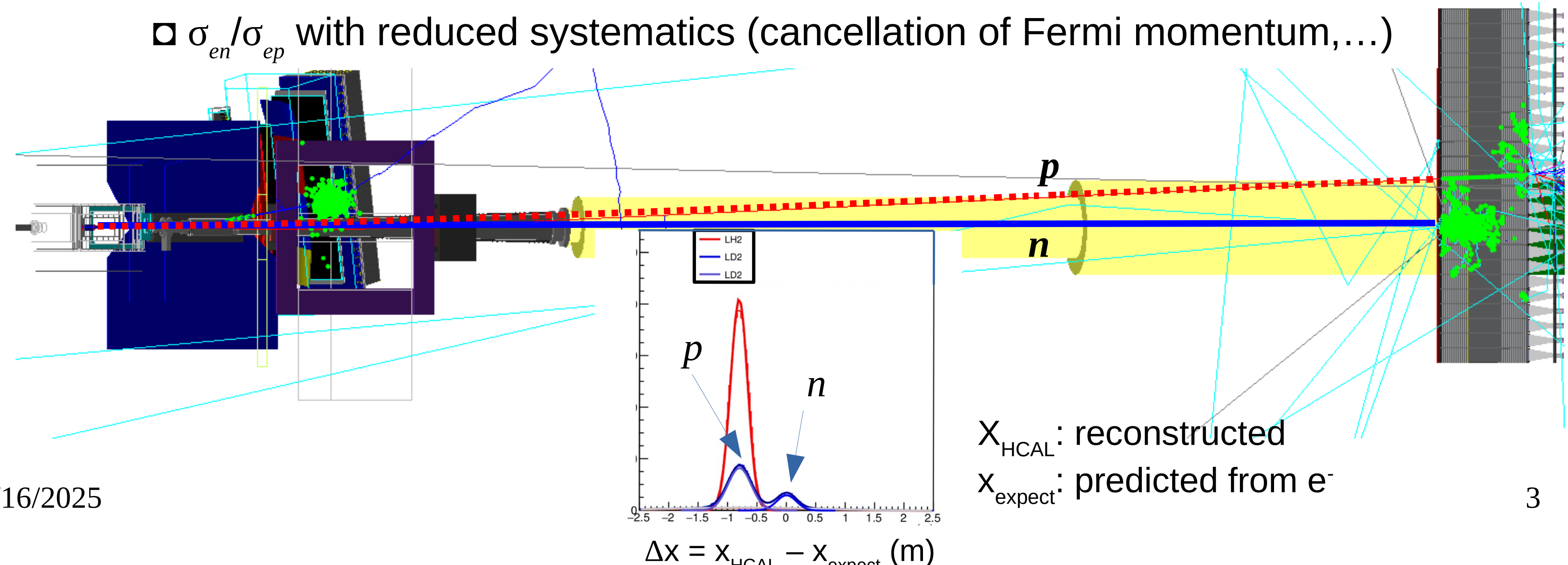
- **SBS form factor program**
  - GMN
  - **nTPE**
  - GEN
  - GEN-RP
  - GEP

- Focus on **nTPE**
  - Measurement;
  - Analysis status;
  - Next steps;



Reminder : GMN/NTPE

- GMN: E12-09-019 (A. Camsonne, B. Quinn, B. Wojteskhowski)
  - simultaneous *en*/*ep* measurement on D_2, Q^2 of 3, 4.5, 7.5, 10, 13.6 GeV^2
  - Separation of *p* and *n* with SBS
  - σ_{en}/σ_{ep} with reduced systematics (cancellation of Fermi momentum,…)



X_{HCAL}: reconstructed
x_{expect}: predicted from e^-

Reminder: GMN/NTPE

- GMN:

$$R' = \frac{N_{en,true}}{N_{ep,true}} = \frac{N_{en,gen,acc} f_{scale\,n}}{N_{ep\,gen,acc} f_{scale\,p}} \equiv \frac{\sigma_{en}}{\sigma_{ep}} = \underbrace{\frac{\sigma_{Mott}}{\sigma_{Mott}}}_{=1} \frac{(1+\tau_p)(\sigma_T^n + \epsilon \sigma_L^n)}{(1+\tau_n)(\sigma_T^p + \epsilon \sigma_L^p)} = \frac{(1+\tau_p)\left(\tau_n (G_M^n)^2 + \epsilon (G_E^n)^2\right)}{(1+\tau_n)\left(\tau_p (G_M^p)^2 + \epsilon (G_E^p)^2\right)}$$

- $\epsilon = \left[1 + 2(1+\tau)\tan^2(\theta/2)\right]^{-1}$
- $\tau_N = \frac{Q^2}{4 M_N^2}$
- $\sigma_{Mott} = \hbar c \alpha_{EM} \frac{1}{4E^2} \left(\frac{\cos\theta/2}{\sin\theta/2}\right)^2 \frac{E'}{E}$

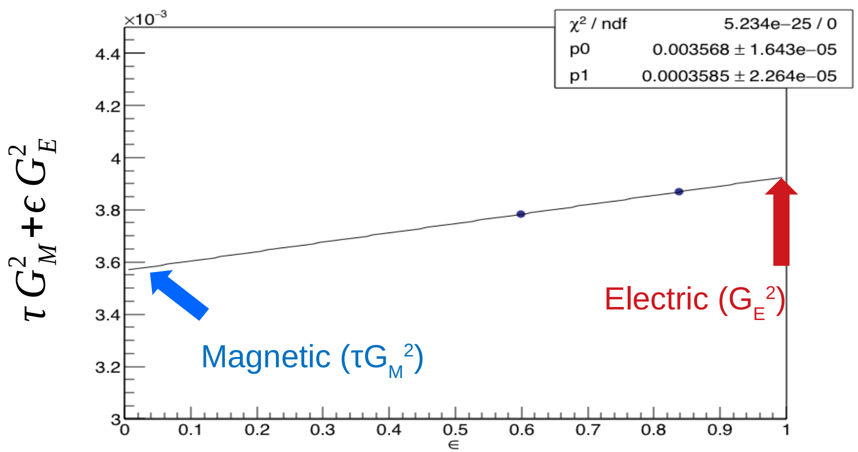
$$\tau_n (G_M^n)^2 + \epsilon (G_E^n)^2 = \frac{N_{en,gen,acc} f_{scale\,n}}{N_{ep\,gen,acc} f_{scale\,p}} \frac{(1+\tau_n)}{(1+\tau_p)} \boxed{\left(\tau_p (G_M^p)^2 + \epsilon (G_E^p)^2\right)}$$

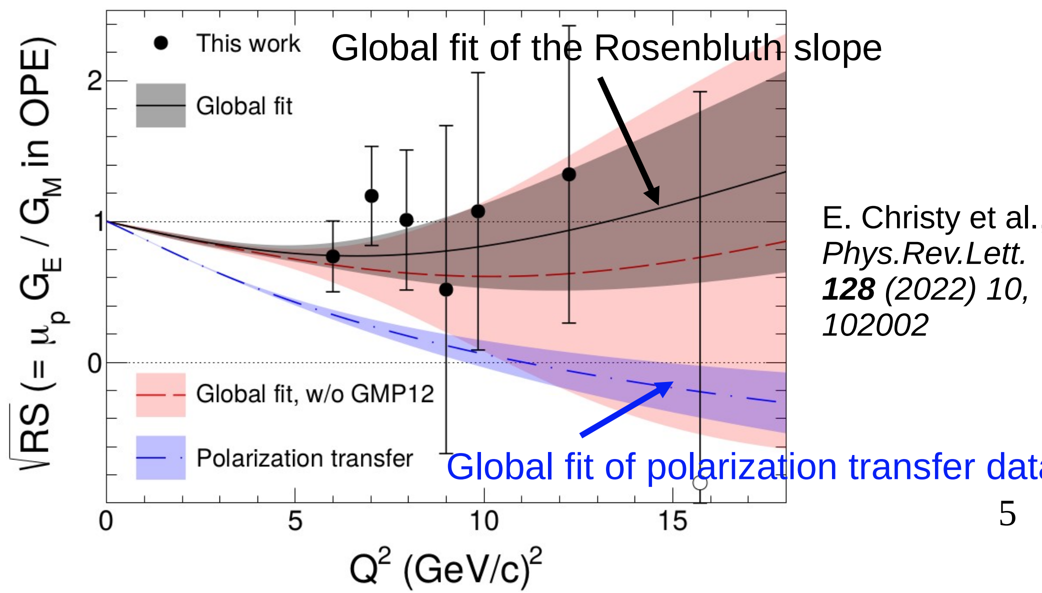
From proton data

$$\boxed{(G_M^n)^2 = \frac{1}{\tau_n} \left(\frac{N_{en,gen,acc} f_{scale\,n}}{N_{ep\,gen,acc} f_{scale\,p}} \times \frac{1+\tau_n}{1+\tau_p} \left(\tau_p (G_M^p)^2 + \epsilon (G_E^p)^2\right) - \epsilon (G_E^n)^2 \right)}$$

Reminder: GMN/NTPE

- NTPE: E12-20-010 (E.F., S. Alsalmi, B. Wojteskhowski)
  - measurement of σ_{en}/σ_{ep} at two beam energies, Q^2 = 4.5 GeV^2
  - neutron Rosenbluth slope;
  - NTPE = Discrepancy neutron Rosenbluth slope <=> polarization data





E. Christy et al., *Phys.Rev.Lett.* ***128*** *(2022) 10, 102002*

Reminder: GMN/NTPE

- **E12-20-010:** E. F., S. Alsalmi, B. Wojteskhowski
  - **Rosenbluth separation of σ_{en}/σ_{ep} at Q^2 = 4.5 GeV^2**
  - Neutron Rosenbluth slope extracted from proton data

$$R=\frac{N_{en\to en}}{N_{ep\to ep}} \qquad R'=\frac{\sigma_{en}}{\sigma_{ep}}=R\,f_{corr}$$

$$f_{corr}=\frac{\eta_{en}(t)}{\eta_{ep}(t)}\times\eta_{RC}(v,Q2,\ldots)\times\ldots$$

Radiative corrections (radiative corrections at vertex, energy loss, ...)

neutron/proton detection efficiency

$$R'_{\epsilon_{1/2}}=R_{Mott,\epsilon_{1/2}}\frac{\sigma_T^n(1+\epsilon_{1/2}S^n)}{\sigma_T^p(1+\epsilon_{1/2}S^p)} \qquad A=\frac{R'_{\epsilon_1}}{R'_{\epsilon_2}}\simeq B(S^p)\times(1+S^n\Delta\epsilon) \qquad B=\frac{R_{Mott,\epsilon_1}}{R_{Mott,\epsilon_2}}\frac{1+\epsilon_2 S^p}{1+\epsilon_1 S^p}$$

proton data

$$\Delta\epsilon=\epsilon_1-\epsilon_2$$

$$S^n=\frac{A-B}{B\Delta\epsilon} \qquad nTPE=S^n-(G_E^n)^2/\tau(G_M^n)^2$$

GEN fits and *GEN-RP measurement at* **Q^2 = 4.5 GeV^2**

Reminder: Kinematic tables

Kin	Q^2 (GeV/c)^2	E (GeV)	E' (GeV)	θ_{BB} (deg)	θ_{SBS} (deg)	ε
SBS4	3.01	3.728	2.129	36.0	31.9	0.721
SBS7	10.0	7.906	2.588	40.9	15.9	0.492
SBS11	13.50	9.860	2.676	41.9	12.8	0.437
SBS14	7.52	5.965	1.965	47.2	17.3	0.456
SBS8	4.51	5.965	3.565	26.5	29.9	0.797
SBS9	4.50	4.015	1.618	49.0	22.5	0.512

NTPE

GMN/NTPE Analysis Steps

- Elastic en, ep selection (done as of last update);

- Evaluation of en, ep cross section ratios from en, ep measured counts using data/Monte Carlo comparison (done as of last update);

- Subtraction of inelastic background;

- Evaluation of systematics;

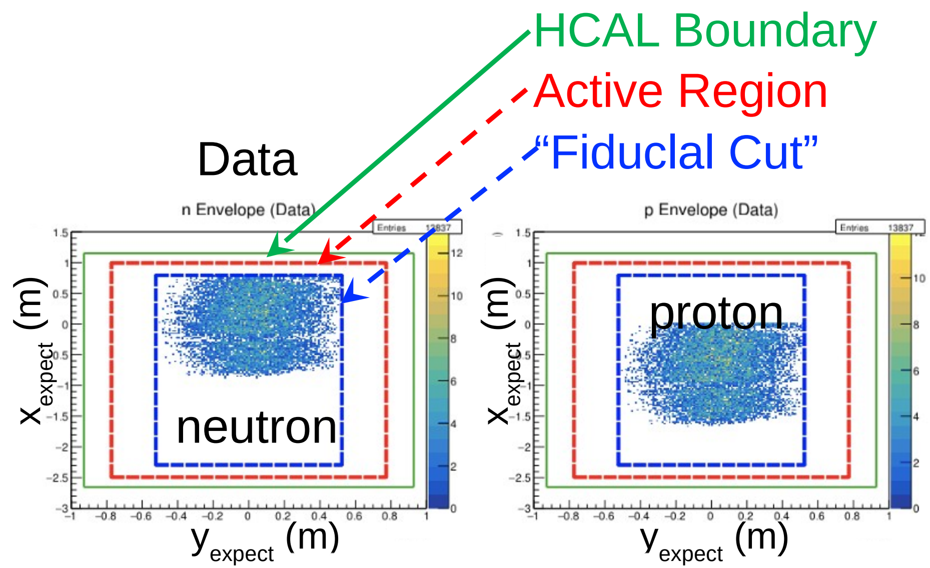
    - Inelastic background subtraction;

    - HCal detection efficiency;

- Extraction of observables;

Elastic Selection

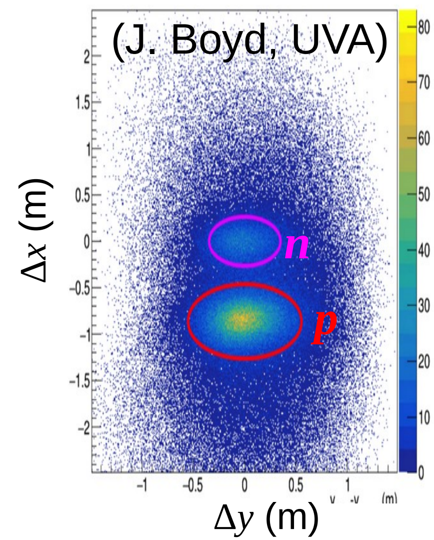
- Electron track and electron ID:
  - $z_{vertex} < \pm 8$cm
  - electron track with ≥ 3/5 hits
  - $E_{PS} > 0.2$
  - *"Fiducial Cut": events with projected* **n** *and* **p** *position within active HCal region*



- Exclusivity cut:
  - *W^2 within elastic nucleon peak;*

- Nucleon selection:
  - $E_{HCAL} > 0.1$

  of HCAL active region;
  - selection on x_{HCAL}-x_{expect}, y_{HCAL}-y_{expect} < 3σ (spot cuts)
  - $|t_{HCAL}-t_{BBCAL}| < 3\sigma$

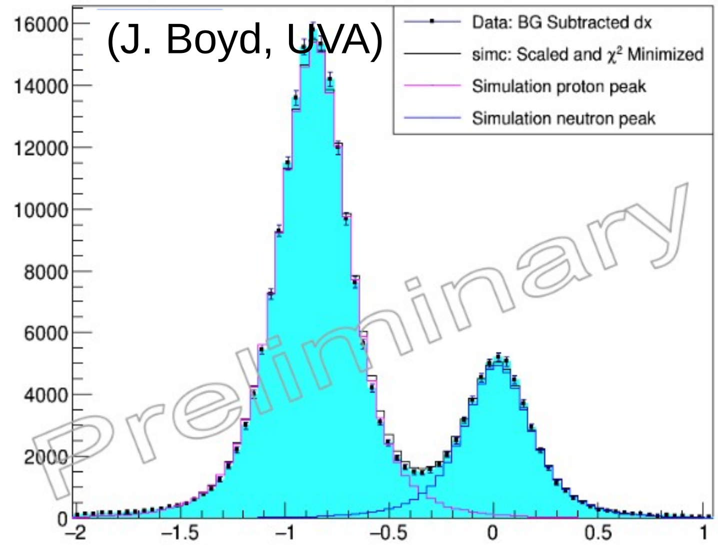


MC/Data Comparison

- Comparison between data and MC *including radiative corrections* (SIMC):

  - ◘ provides correction term: $R' = \frac{\sigma_{en}}{\sigma_{ep}} = \frac{(N_{en \to en})_{meas}}{(N_{ep \to ep})_{meas}} f_{corr}$

  - ◘ MC/data yield comparison, SBS8 (high ε):

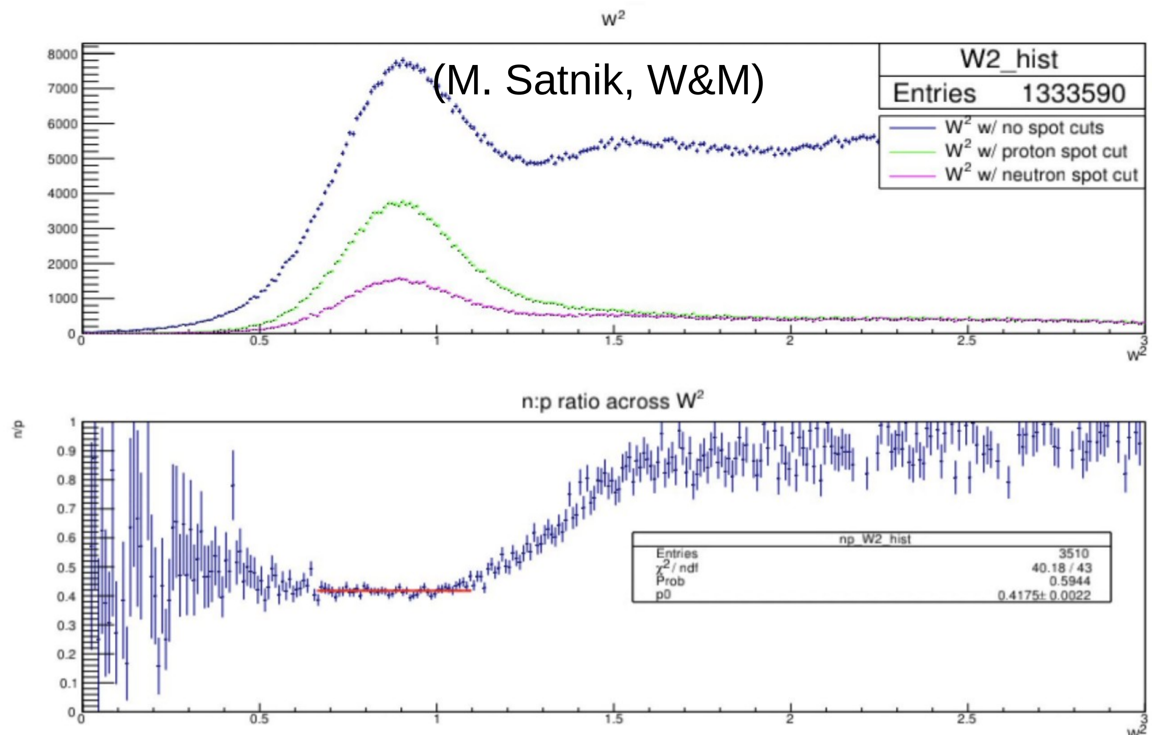


$x_{HCAL} - x_{expect}$ (m)

x_{HCAL}: reconstructed
x_{expect}: predicted from e^-

Selection Optimization

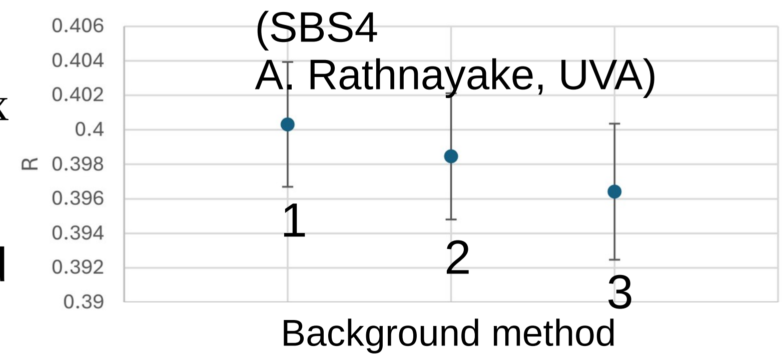
- ***n/p* stability over selection cuts:**
  - W^2;
  - E_{PS}, E_{SH}, E_{HCAL};
  - t_{HCAL}-t_{Shower};
  - Δx, Δy, fiducial cuts;



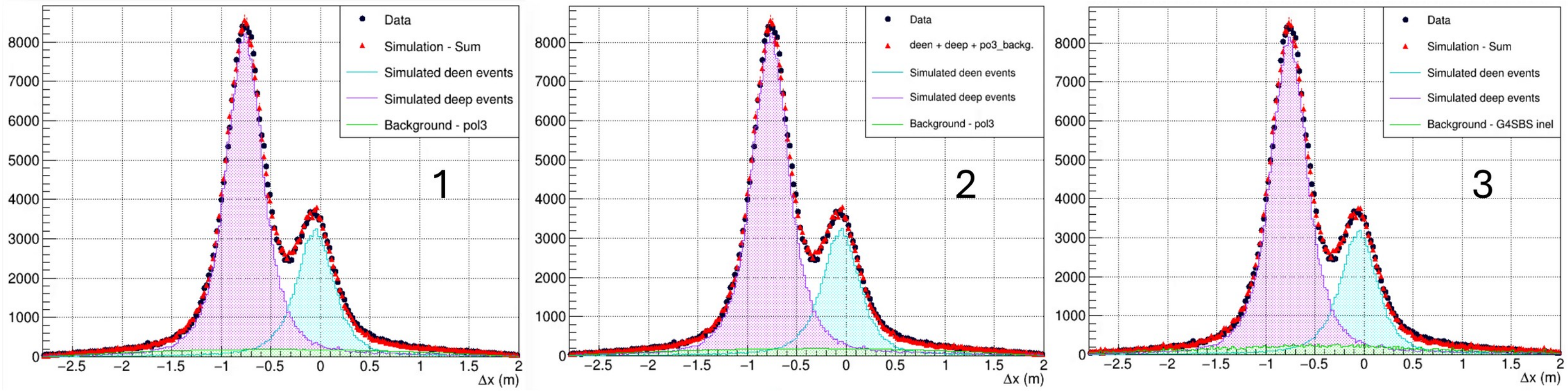
W^2 (GeV^2)

Inelastic Background Subtraction

- **Inelastic background subtraction:**
  - ◘ 1: Combined fit $en+ep$ +background of data Δx
  - ◘ 2: Data background (HCal “antiselection”);
  - ◘ 3: MC (Christy-Bosted) generated background

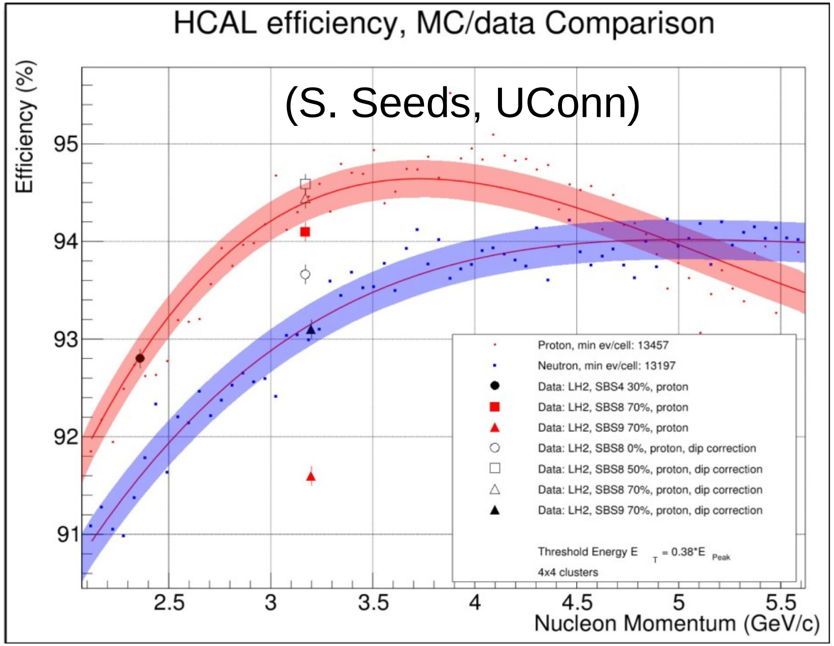


- $R_{n/p}$ consistent within 1% => **systematics**



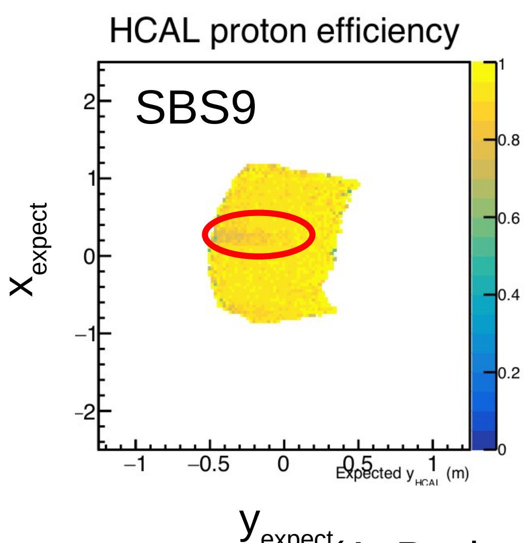
HCAL Detection Efficiency

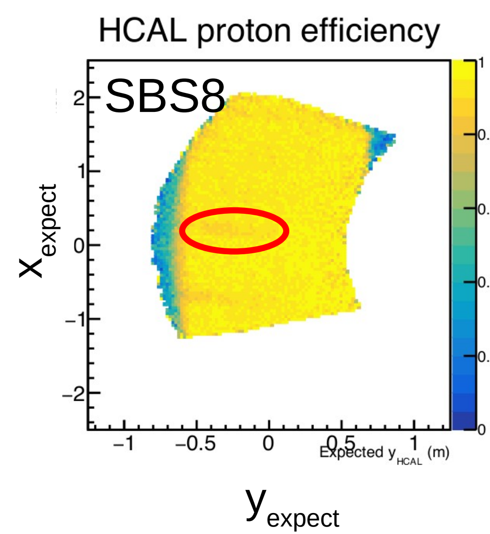
- HCal detection efficiency major source of systematic (especially for nTPE):
  - n and p detection efficiency expected to be similar, but not identical;
  - MC detection efficiency different for n, p, and varies with energy;



HCAL Detection Efficiency Non-Uniformity

- HCal detection efficiency major source of systematic (especially for nTPE):
  - ◘ HCal efficiency from LH2 data shows non-uniformity of HCAL efficiency:
  - ◘ Larger nucleon projection footprint on HCal for higher ε kinematic:
    - ♦ non-uniformity has more impact on low ε kinematic;
    - ♦ *n/p* cross section ratio biased for both, more biased for low ε;





(A. Puckett, Uconn, EF, W&M)

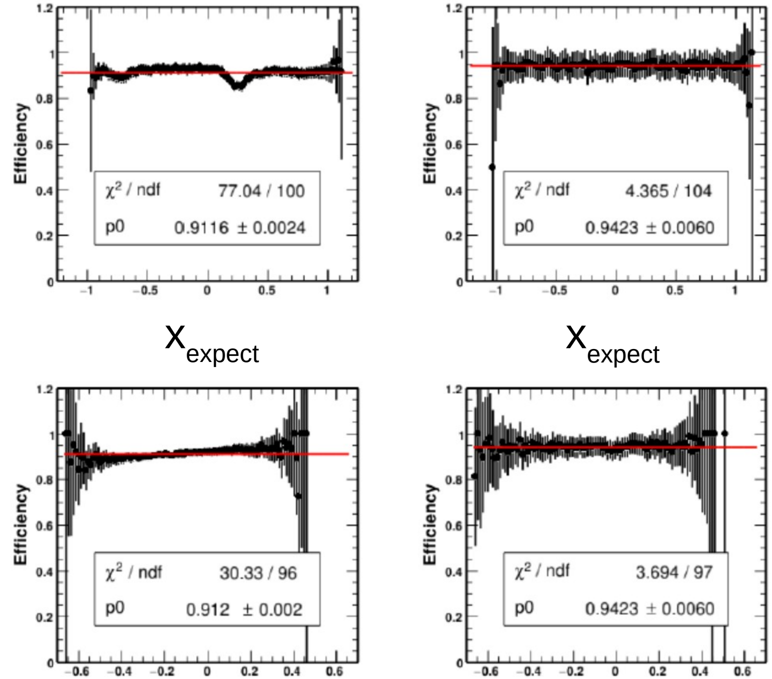
HCAL Non-Uniformity:

- Mmethod to work around HCal efficiency non-uniformity:
  Reweight MC events with HCal non-uniformity map;

  - Map efficiency along x_{expect}, y_{expect};
  - weight MC with relative efficiency variation;
  - Improvement:
    - ♦ Apply same efficiency analysis for data, MC;
    - ♦ use ratio of η_{data}/η_{MC};
    - ♦ deployed in analysis;

Analysis credit: P. Datta

Data SBS9 LH2 MC SBS9 LH2



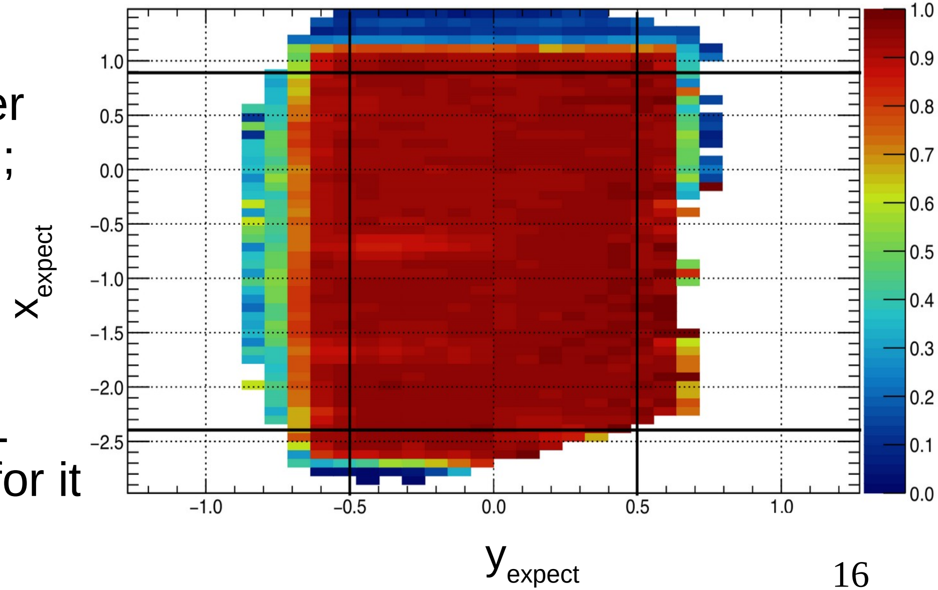
x_{expect} x_{expect}

y_{expect} y_{expect}

HCAL Non-Uniformity:

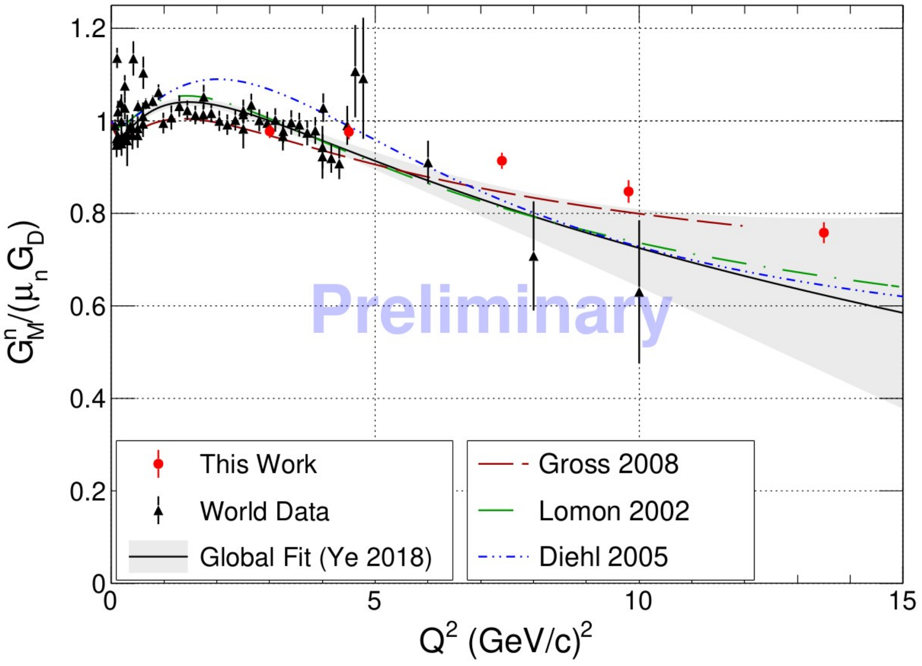
- Reweight MC events with HCal non-uniformity map:
  - Analysis of all combined SBS8 LH2 settings for map efficiency:
  - Accurate for protons, not necessarily for neutrons:
    - ♦ proton and neutron detection efficiency not exactly equal;
    - ♦ Still working to determine a better estimation of correction for neutron;
    - ♦ “Good enough” for GMN ***preliminary*** results;
    - ♦ NTPE sensitive enough to HCAL efficiency that it is not satisfactory for it
    - ♦ HCal efficiency stability between SBS8 and SBS9 to be verified

Analysis credit: P. Datta, A Puckett;
Z Wertz has made similar analysis



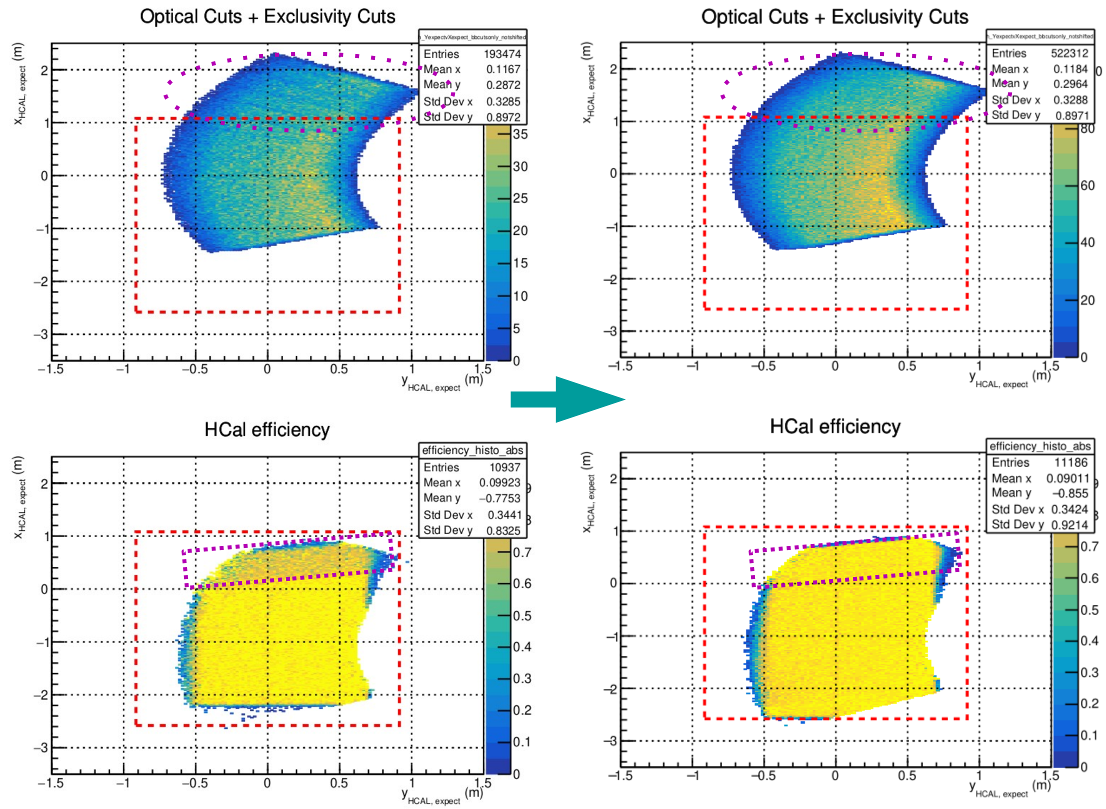
GMN/NTPE results

- GMN latest **preliminary** results (Plot Credit ***P. Datta***)
  - ◘ does include **preliminary** estimation of HCal detection efficiency uncertainty;
  - ◘ includes charge exchange/FSI effect (0.5% uncertainty)
  - ◘ will still benefit from a refined correction of HCal non-uniformity;
  - ◘ Does include recent MC updates yet



Monte-Carlo Fixes: G4SBS Geometry

- G4SBS geometry bugs fixes:
  - ◘ Dimensions of PS block (8.5 mm) not matched with block center-to-center distance (9mm) => “ribs” in X_{expect} Vs Y_{expect}
  - ◘ PS block material density out-of-date
  - ◘ Scattering chamber right beam window vertical aperture too small => HCAL MC efficiency degraded in a fraction of acceptance;

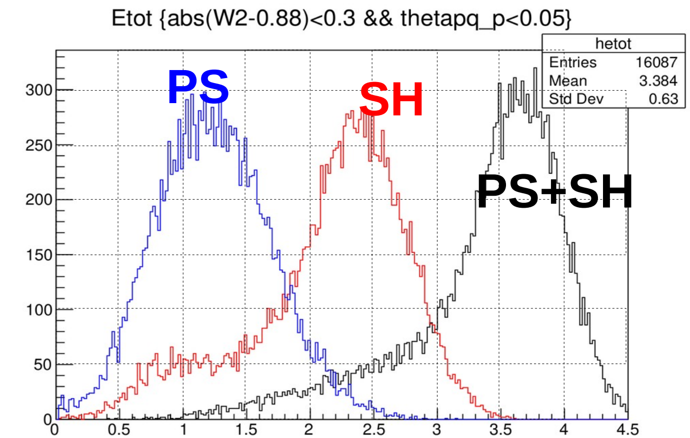


Before fixes

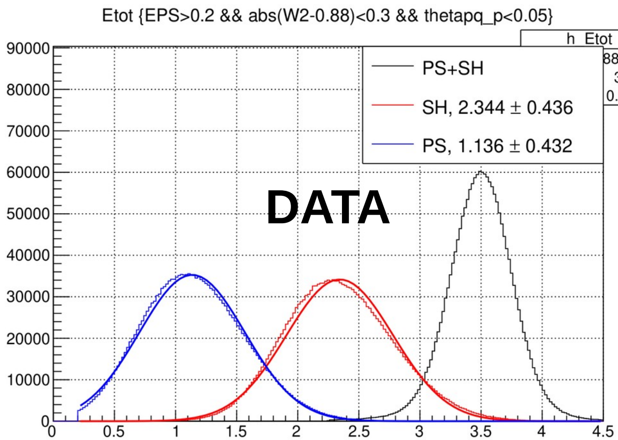
After fixes

Monte-Carlo Fixes: Digitization

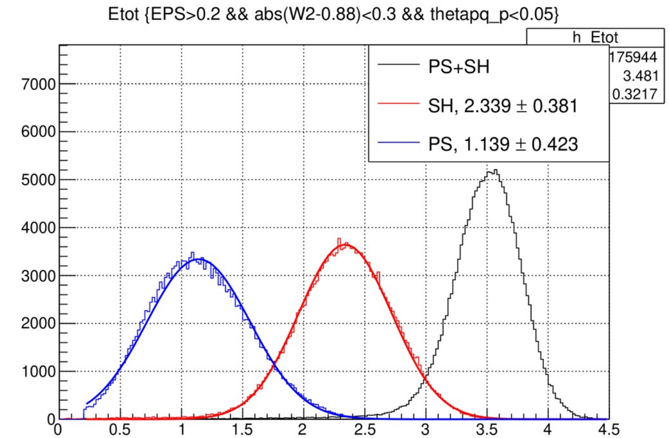
- Digitization parameters for BBCal readjusted to fit the data better (e.g. SBS8)
- *HCal gain adjustments underway*



PS gain: 2.e6
PS pedestal noise 3.0
SH gain: 7.5e5
SH pedestal noise 4.5



PS gain: 1.84e6
PS pedestal noise 3.0
SH gain: 8.03e5
SH pedestal noise 3.0



Summary

- **GMN preliminary results!**

- Integration of HCal non-uniformity:
  - current correction sufficient for GMN **preliminary** results;
  - more work needed for NTPE;

- Monte Carlo fixes
  - BB Cal and Scattering chamber geometry fixes;
  - SIMC fix (slightly insufficient angle aperture)
  - Digitization parameter adjustements
    - BBCal gains adjusted for all kinematics
    - HCal gains to be adjusted.

- Next steps:
  - **3rd pass** of calibration for optimization of HCal and hodoscope timing;
  - **“2nd pass”** of MC D(*ee’n*), D(*ee’p*), H(*ee’p*) samples;
  - start to draft publication for PRL for GMN;

Thank you to all the students!

J. Boyd (UVA), P. Datta (UConn), N. Lashley (Hampton U), R. Marinaro (Glasgow), A. Rathnayake (UVA), M. Satnik (W&M), S. Seeds (Uconn), Z. Wertz (W&M)

… and all other people actively participating to the analysis! (A. Puckett, E.F.)

- Ralph, Nathaniel, John, Sebastian, Provakar, Anu graduated (Congrats!);
- Maria, Zeke to graduate within the next 3 months;
- Anu, Provakar, Nathaniel continue analysis as post-docs;

Back up

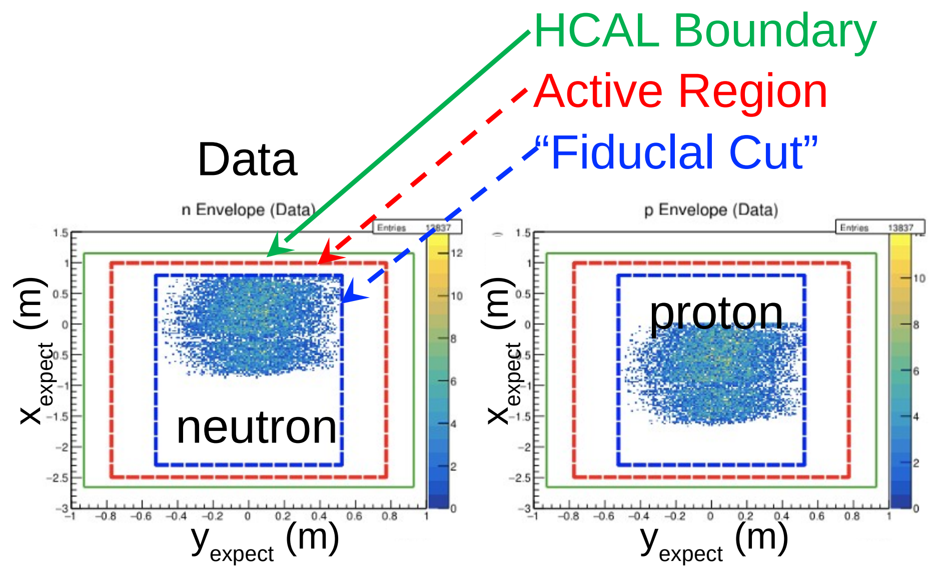
Elastic Selection

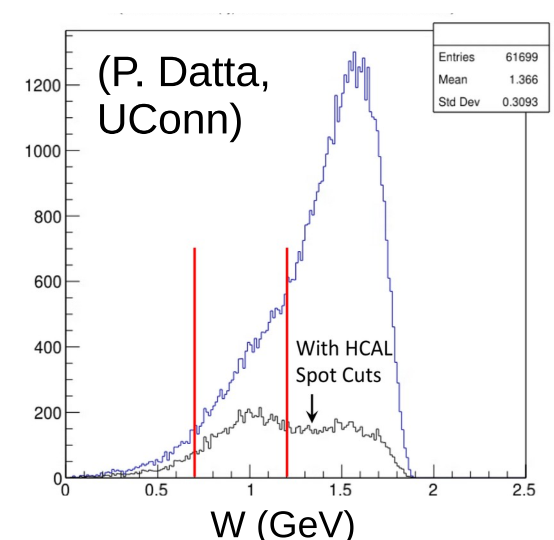
- Electron track and electron ID:
  - $z_{vertex} < \pm 8$cm
  - electron track with ≥ 3/5 hits
  - $E_{PS} > 0.2$
  - *"Fiducial Cut": events with projected **n** and **p** position within active HCal region*

- Exclusivity cut:
  - *W^2 within elastic nucleon peak;*

- Nucleon selection:
  - $E_{HCAL} > 0.1$

  of HCAL active region;
  - selection on x_{HCAL}-x_{expect}, y_{HCAL}-y_{expect} < 3σ (spot cuts)
  - $|t_{HCAL}-t_{BBCAL}| < 3\sigma$





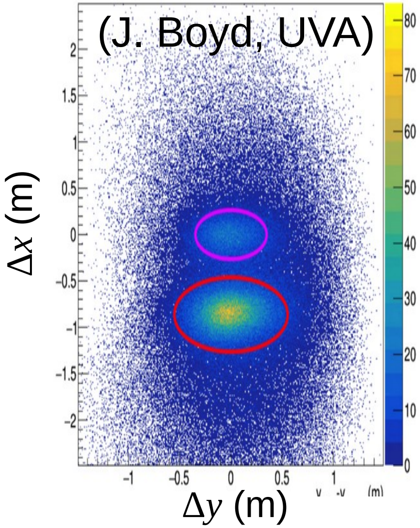
Elastic Selection (2)

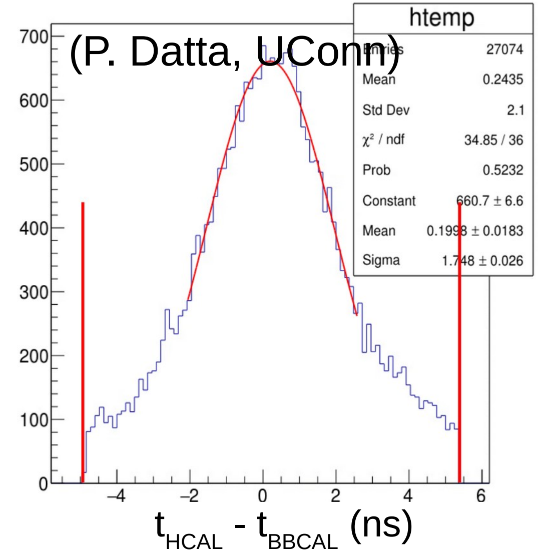
- Electron track and electron ID:
  - $z_{vertex} < \pm$ 8cm
  - electron track with ≥ 3/5 hits
  - $E_{PS} > 0.2$
  - *"Fiducial Cut": events with projected* ***n*** *and* ***p*** *position within active HCal region*

- Exclusivity cut:
  - *W^2 within elastic nucleon peak;*

- Nucleon selection:
  - $E_{HCAL} > 0.1$

  of HCAL active region;
  - selection on x_{HCAL}-x_{expect}, y_{HCAL}-y_{expect} < 3σ (spot cuts)
  - $|t_{HCAL}-t_{BBCAL}| < 3\sigma$

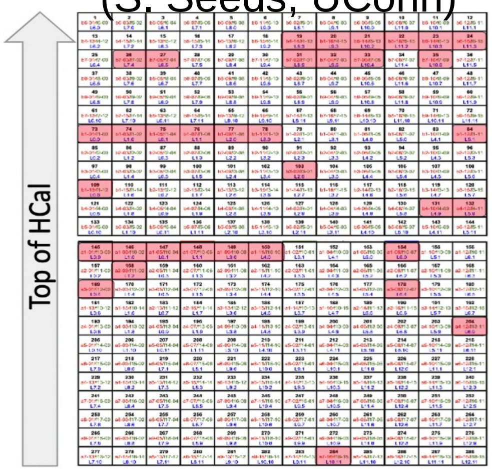




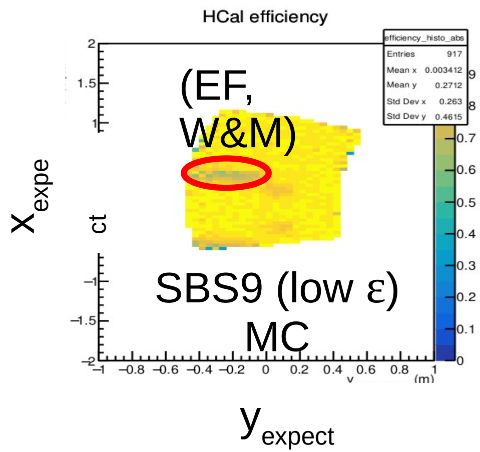
HCAL efficiency non-uniformity

- Addressing HCal non-uniformity:
  - Adjust HCal gain in MC to reproduce data non-uniformity;
  - Analysis with new Vs old HCal MC gain:
  - issue: effect on n/p ratios unexpectedly large => to be understood!

(S. Seeds, UConn)



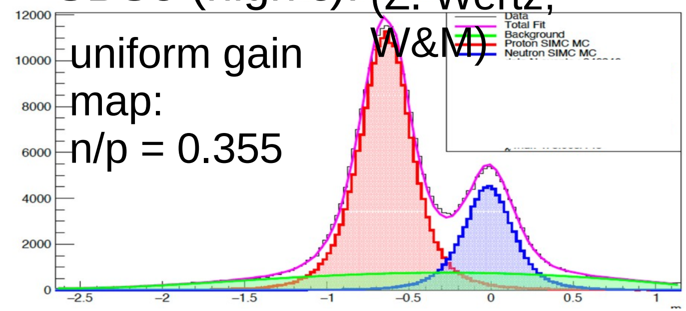
(EF, W&M)



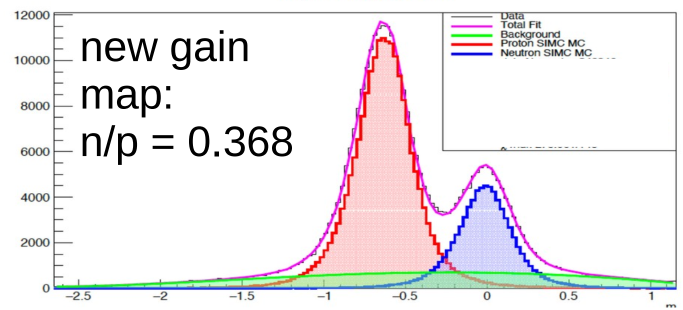
SBS9 (low ε) MC

SBS8 (high ε): (Z. Wertz, W&M)

uniform gain map: n/p = 0.355



new gain map: n/p = 0.368

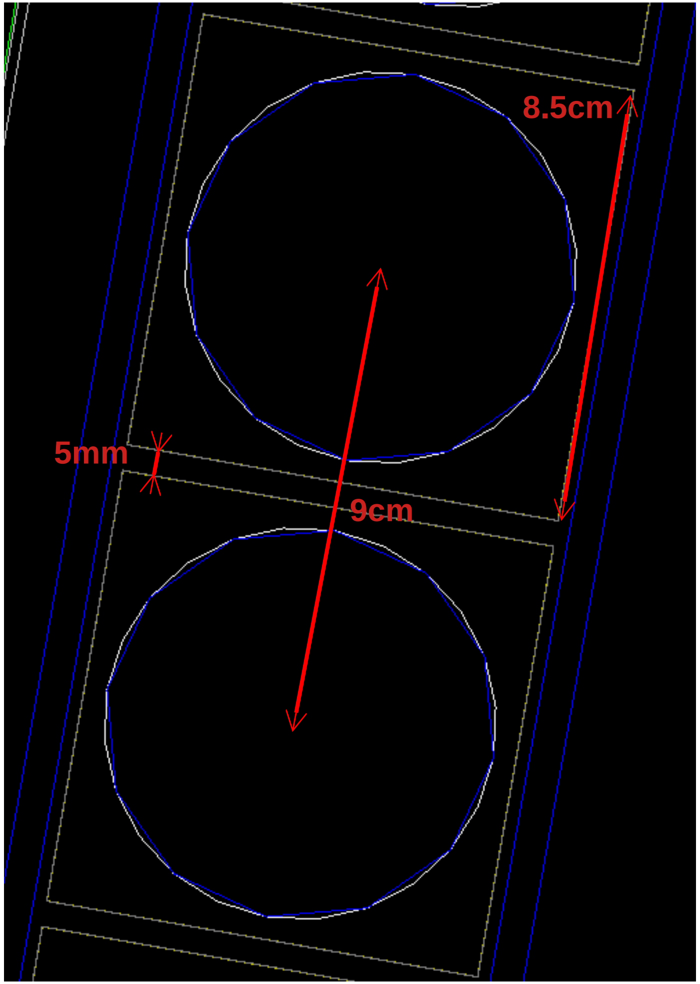


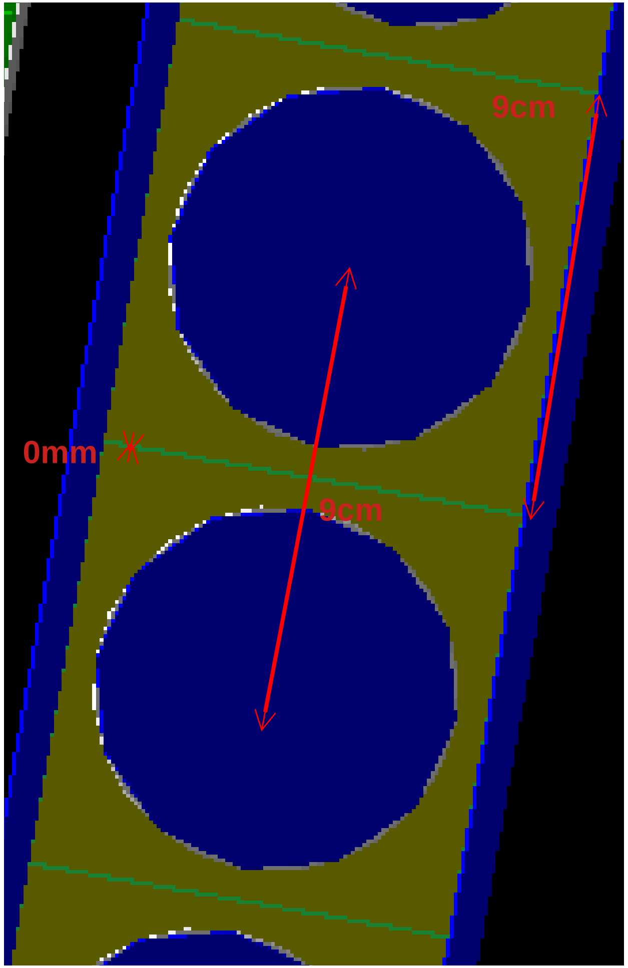
GMN/NTPE results

- NTPE: (John, Sebastian, Zeke)
  - Existing analyses very preliminary and need independent cross checks
  - Result featured in John Boyd’s thesis may change with a more refined correction of HCal non-uniformity;
  - Regardless, the existing results are still too premature to be unveiled

BBCal geometry fix in G4SBS

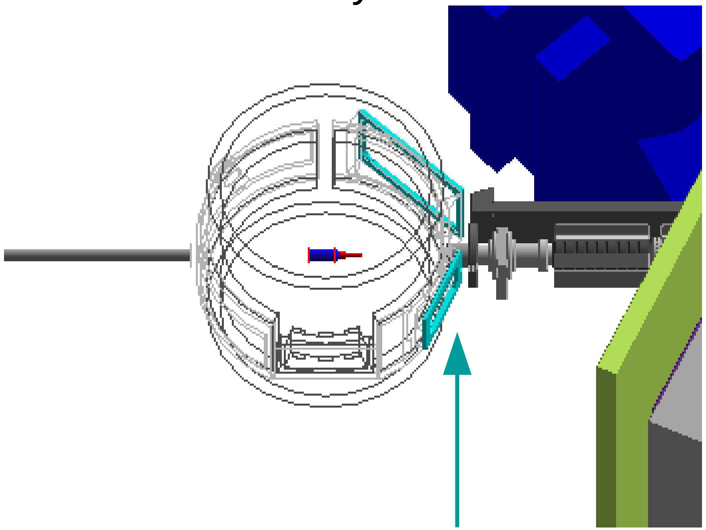
- BBCal geometry bugs
  - Dimensions of old PS block (8.5 mm) had been accidentally kept while center-to-center block distance was set at 9mm => "ribs" in X_{expect} Vs Y_{expect}
  - PS block material density incorrect



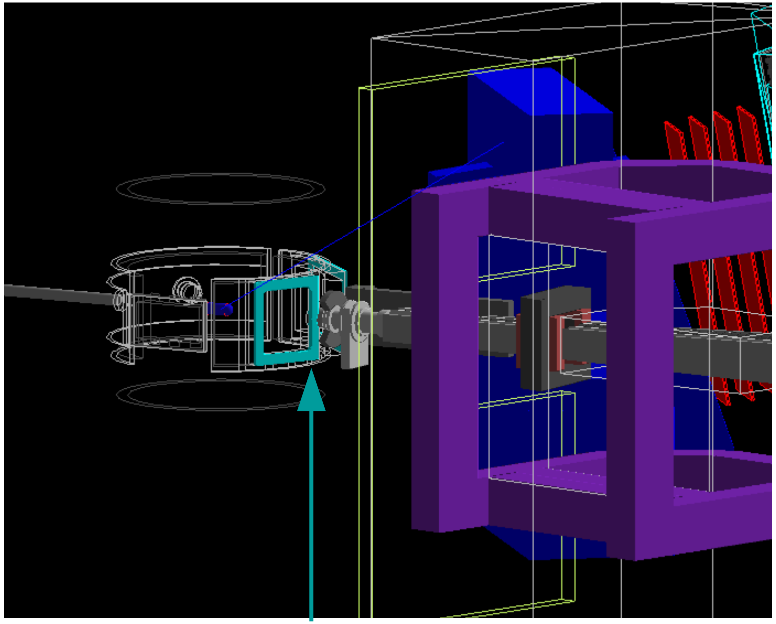


Scattering chamber geometry fix in G4SBS

- Scattering chamber right beam window issue:
  - old design that never got updated
  - affected HCAL MC efficiency in a fraction of



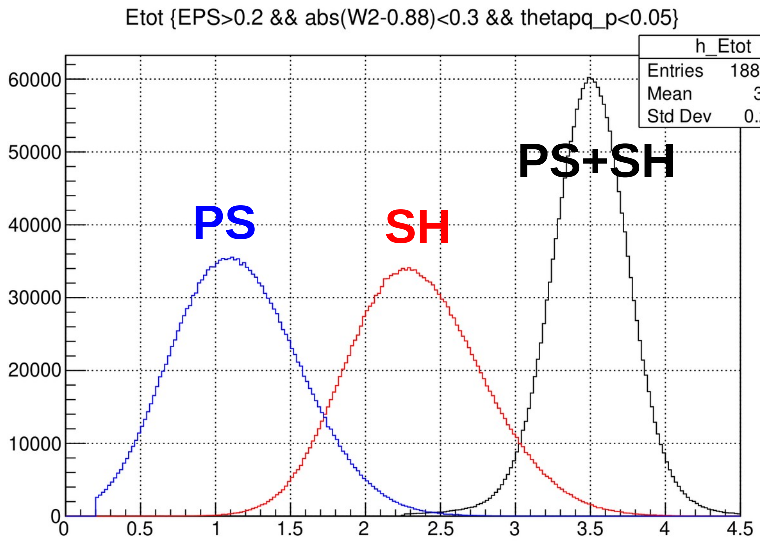
7’’ vertical clearance



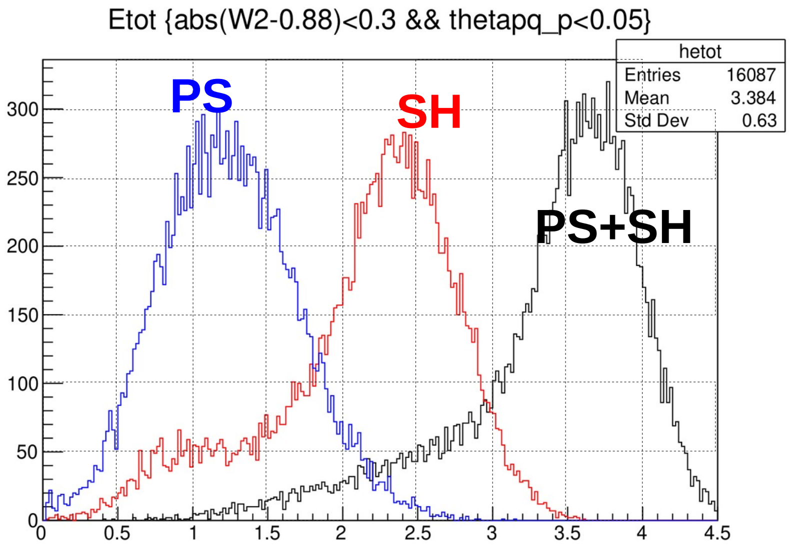
14’’ vertical clearance

BBCal response: SBS8

Data



MC after digitization, analysis

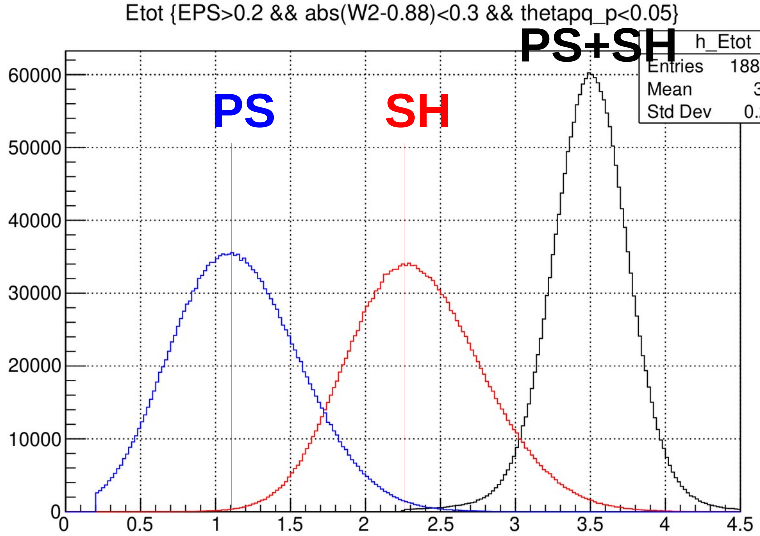


NChan_bbps 52
gatewidth_bbps 200
gain_bbps 2.e6
ped_bbps 300.0
pedsigma_bbps 3.0
...

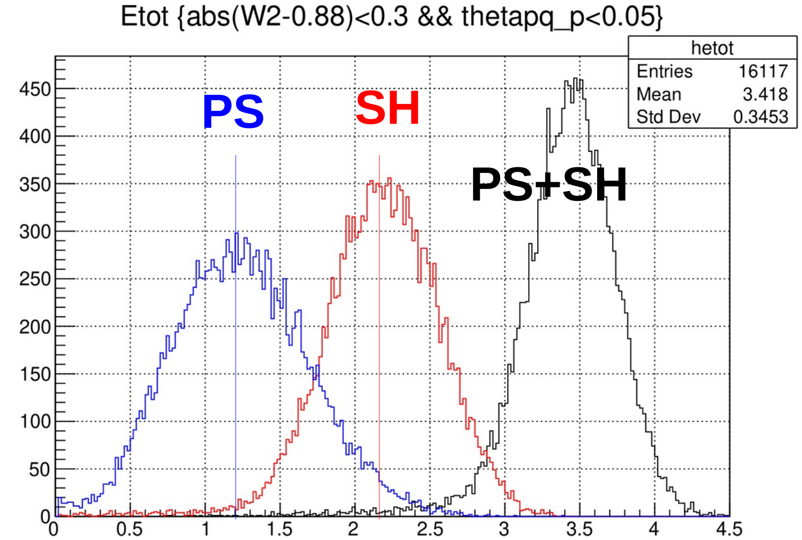
NChan_bbsh 189
gatewidth_bbsh 200
gain_bbsh 7.5e5
ped_bbsh 300.0
pedsigma_bbsh 4.5
...

BBCal response: SBS8 MC: SH σ_{ped} 4.5 → 3.0

Data



MC after digitization, analysis



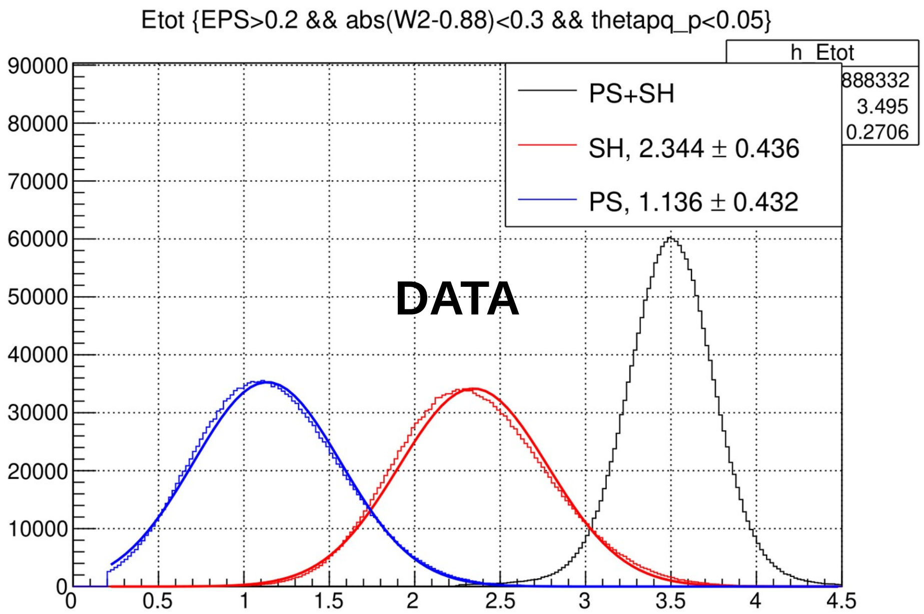
NChan_bbps 52
gatewidth_bbps 200
gain_bbps 2.e6
ped_bbps 300.0
pedsigma_bbps 3.0
...

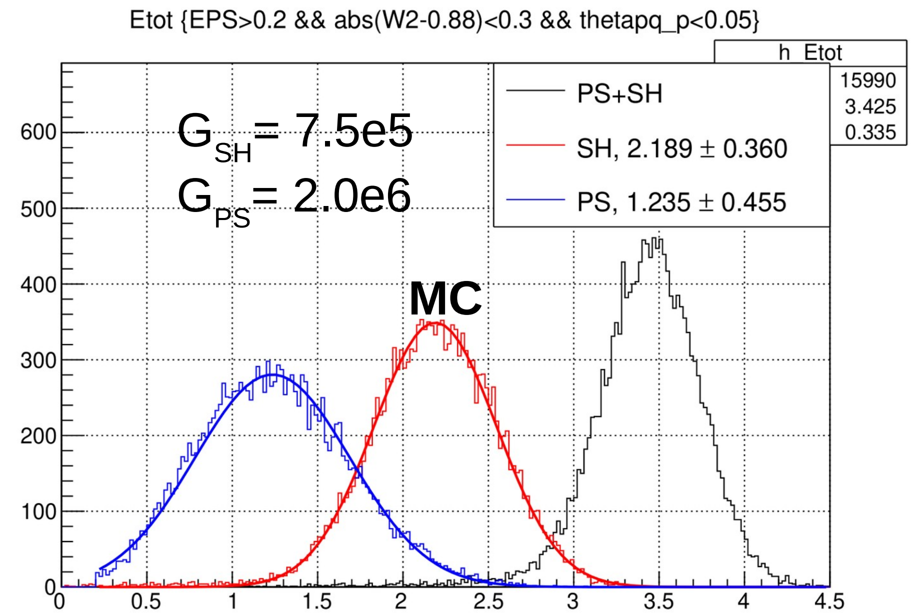
NChan_bbsh 189
gatewidth_bbsh 200
gain_bbsh 7.5e5
ped_bbsh 300.0
pedsigma_bbsh 3.0
...

SH tail disappeared!

Gain Adjustment

* Done for SBS9, **SBS8**:

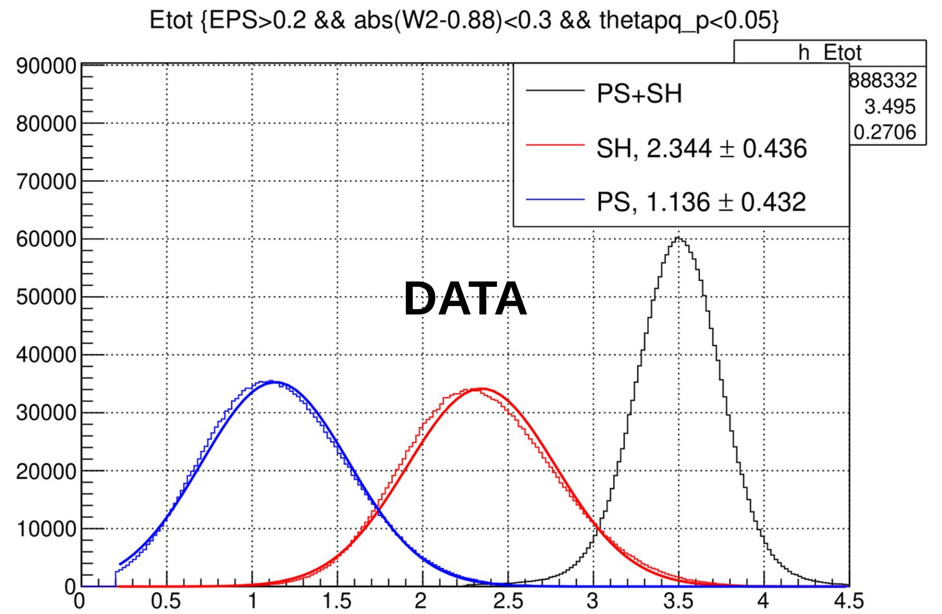


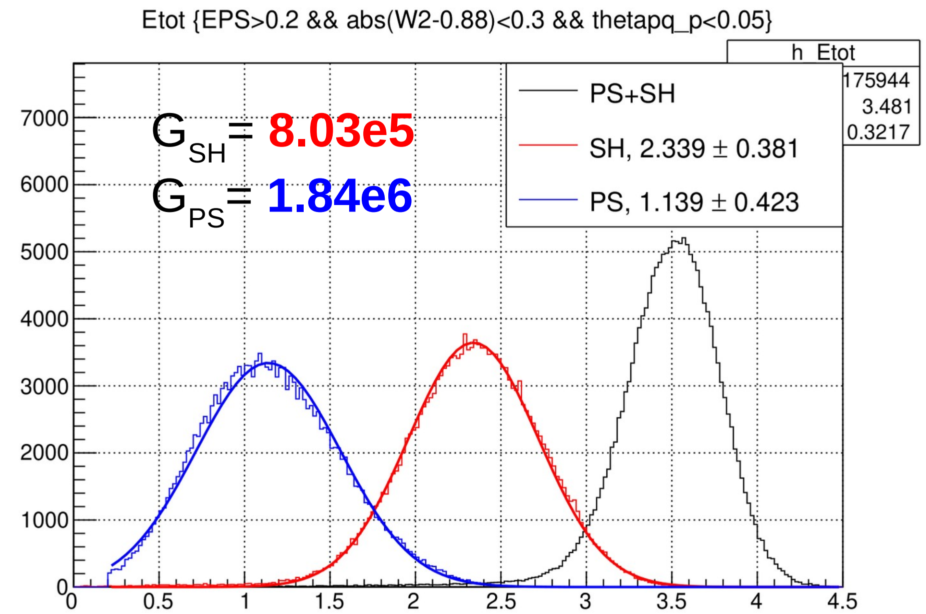


SH: 7.5e5 * 2.344/2.189 = **8.03e5**
PS: 2.0e6 * 1.136/1.235 = **1.84e6**
(Resolutions in rough agreement for PS)

Gain Adjustment

* Done for SBS9, **SBS8**:





SH: 7.5e5 * 2.344/2.189 = **8.03e5**
PS: 2.0e6 * 1.136/1.235 = **1.84e6**
(Resolutions in rough agreement for PS)