GMn/nTPE Analysis Update

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College of William & Mary
(On behalf of the nTPE collaboration)

Hall A/C Summer Collaboration Meeting,
June 18th 2025

WILLIAM & MARY
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Jefferson Lab

Elastic *e-N* scattering: Rosenbluth

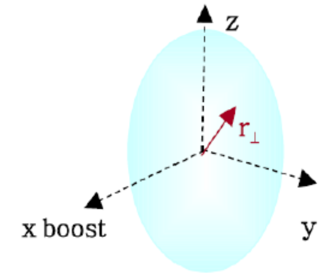
- Space-like Form Factors ≡ charge distribution
- In the One-Photon Exchange (Born) approximation:

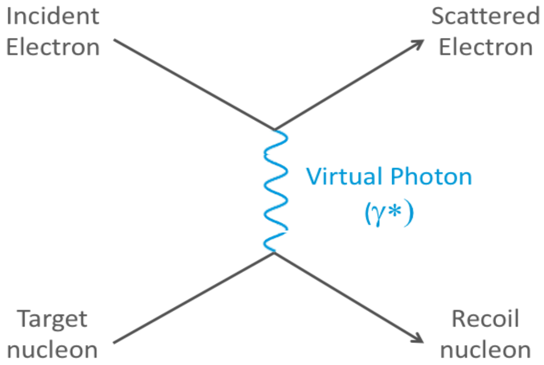
$$\left(\frac{d\sigma}{d\Omega}\right)_{eN\rightarrow eN} = \frac{\sigma_{Mott}}{\epsilon(1+\tau)}\left[\tau G_M^2(Q^2) + \epsilon G_E^2(Q^2)\right]$$

with $\tau = Q^2/(4M_N)$

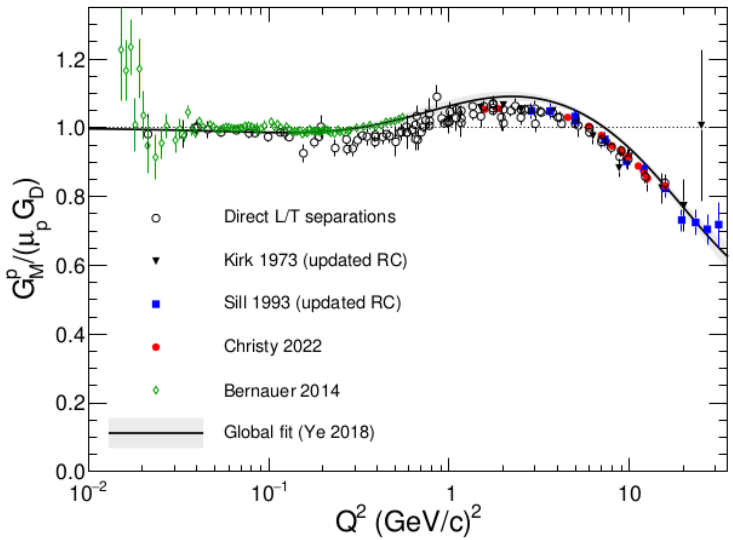
Sachs magnetic FF squared

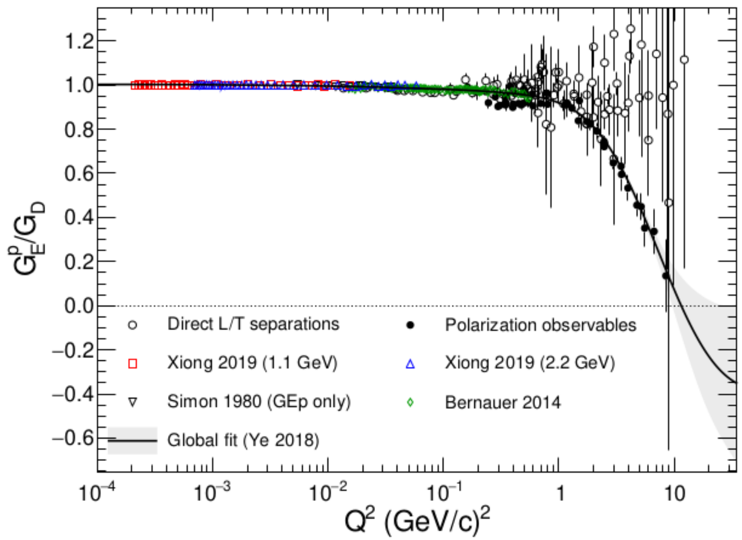
Sachs Electric FF squared



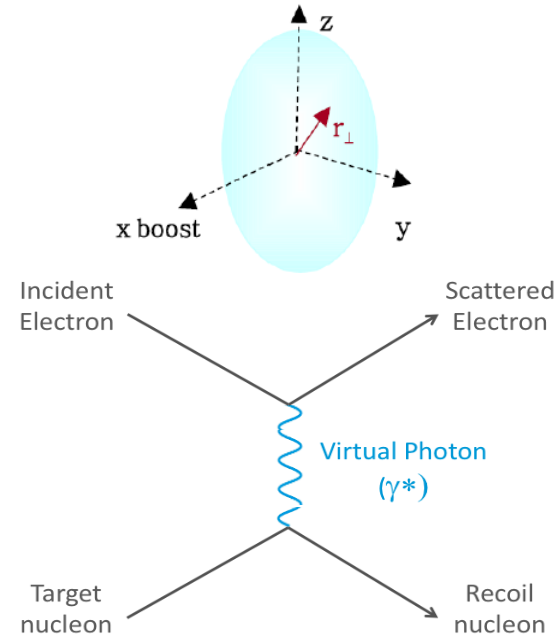


- Proton data:





Elastic *e*-*N* scattering: Rosenbluth



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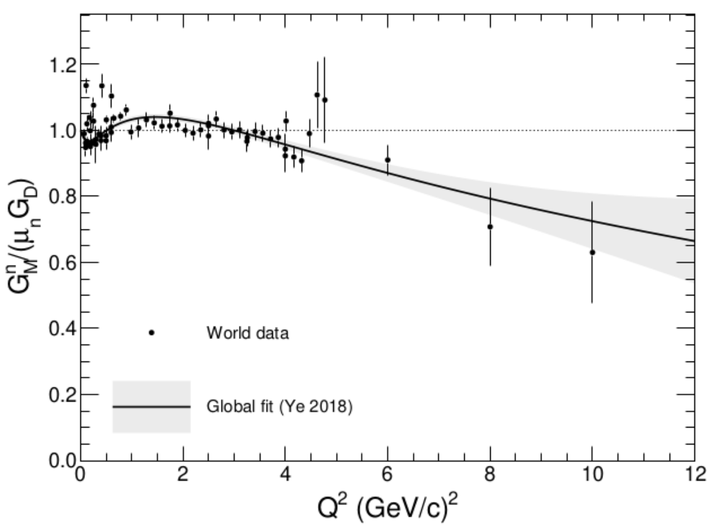
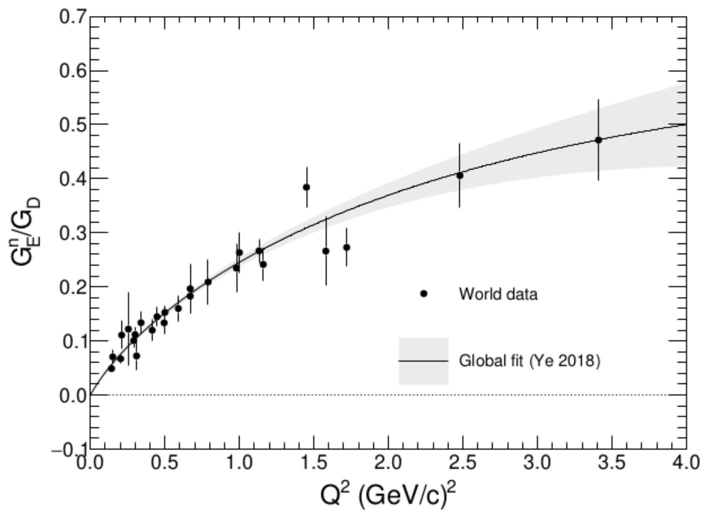
with $\tau = Q^2/(4M_N)$

Sachs magnetic FF squared

Sachs Electric FF squared

- Neutron data:
  - Scarce data beyond Q^2 ~ 3-4 GeV^2

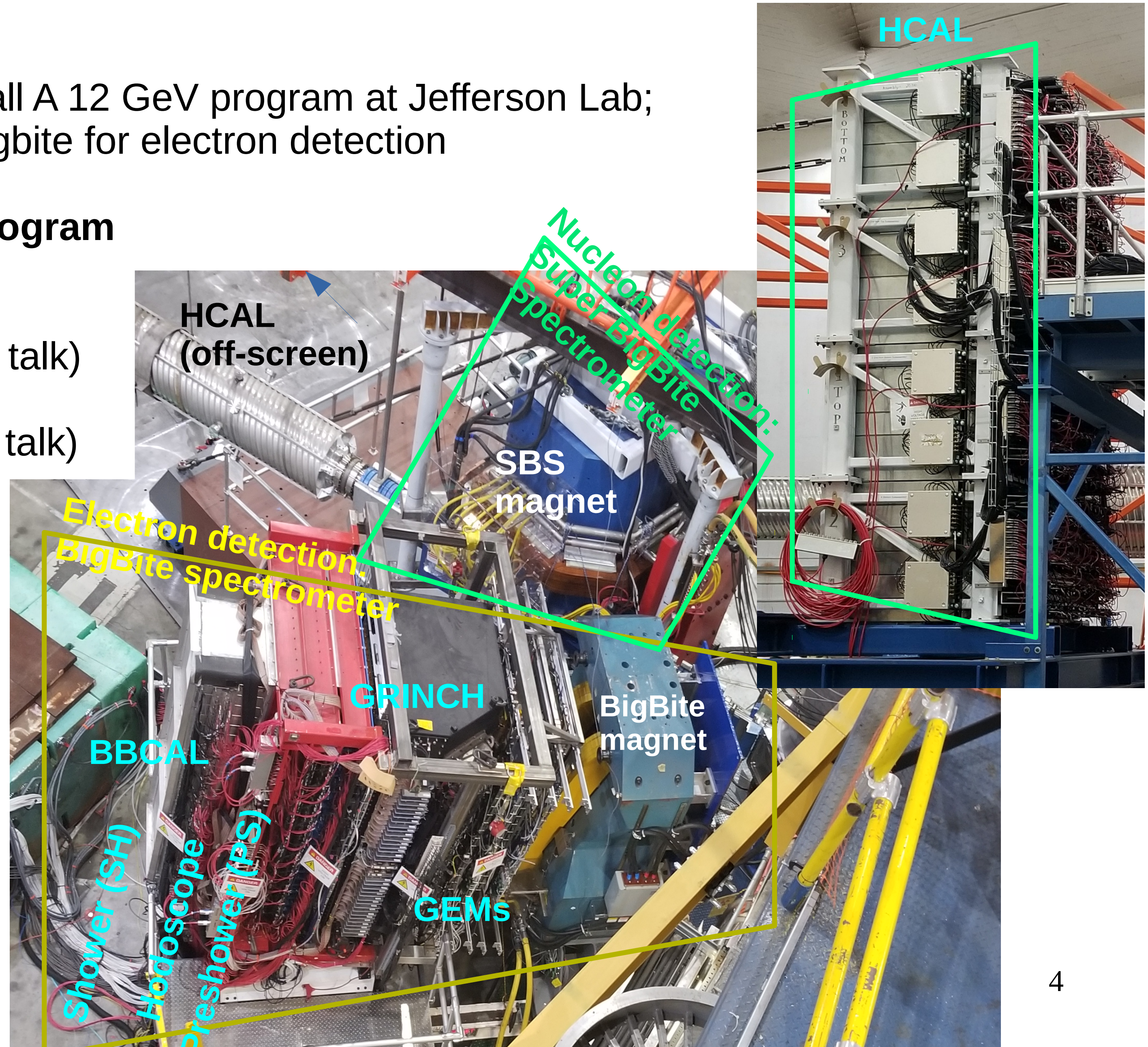




Super BigBite Spectrometer

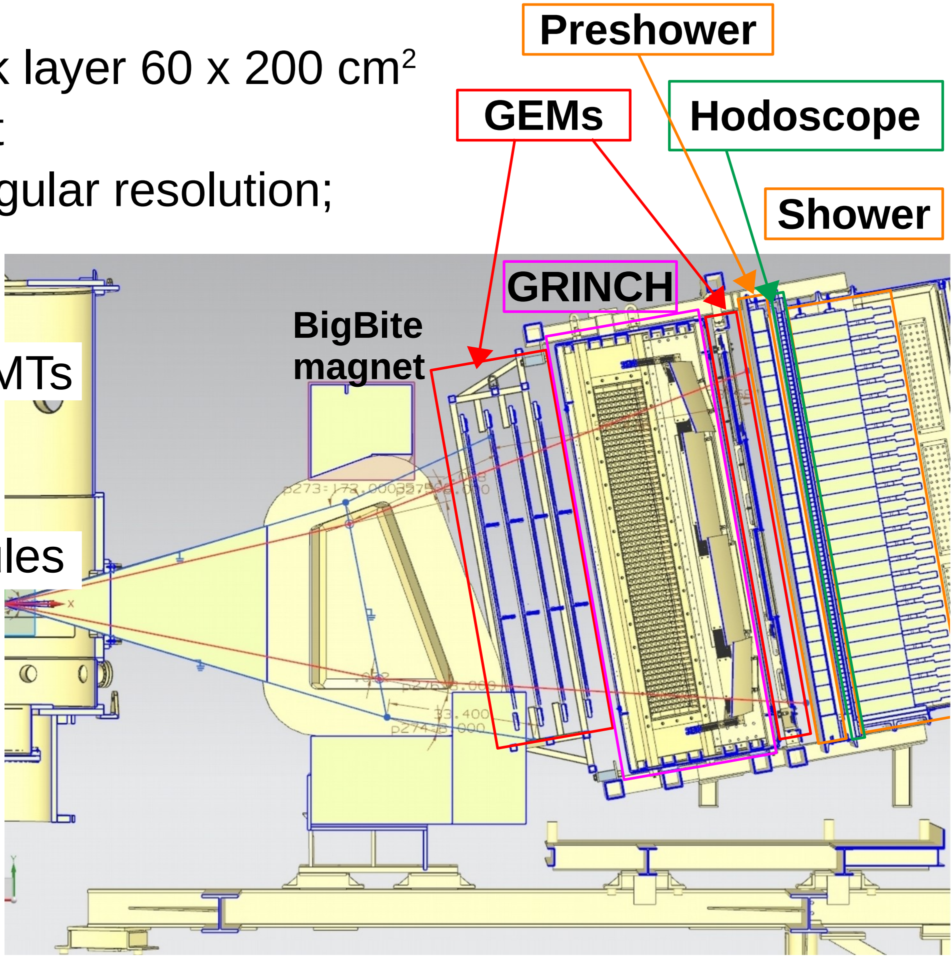
- **SBS:**
  - Major part of Hall A 12 GeV program at Jefferson Lab;
  - coupled with Bigbite for electron detection

- **SBS form factor program**
  - **GMn** (this talk)
  - **nTPE** (this talk)
  - GEN (G. Cates' talk)
  - GEN-RP
  - GEP (D. Jones' talk)



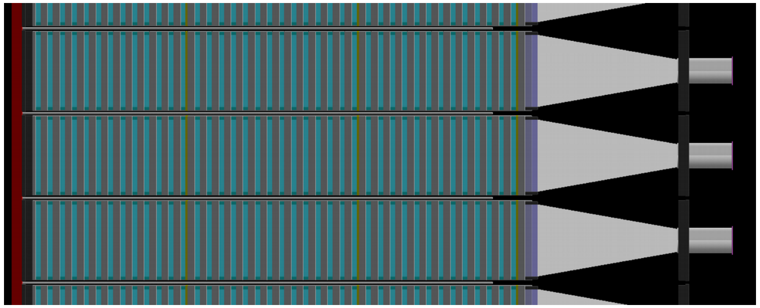
Super BigBite Spectrometer: BigBite

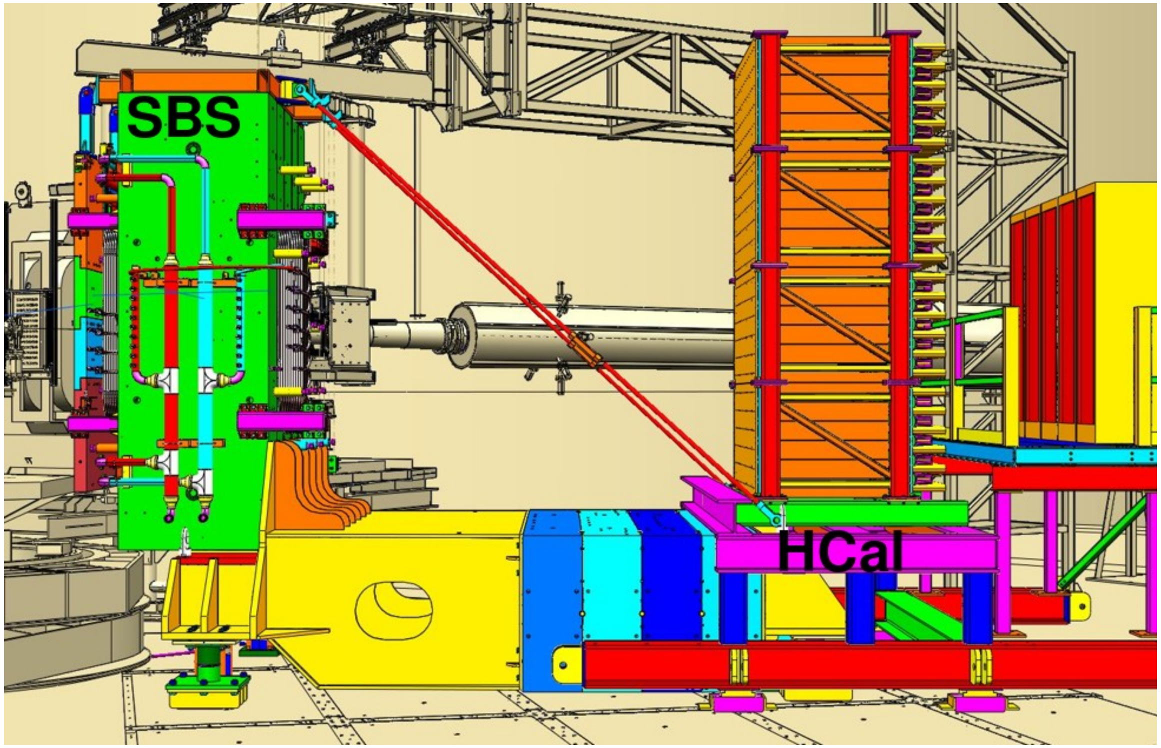
- Detector package tilted 10% behind dipole magnet
- Function: Electron measurement;
- Detector package:
  - GEMs:
    - 4 front layers 40 x 150 cm^2, 1 back layer 60 x 200 cm^2
    - momentum trivector measurement
    - 1% momentum resolution, 1mr angular resolution;
  - GRINCH:
    - C4F8 Cherenkov radiator
    - Cherenkov light readout by 510 PMTs
    - Electron ID ~98% Pion rejection
  - Calorimeter: (shower+preshower)
    - PreShower: 2x26 lead glass modules
    - Shower: 7x27 lead glass modules
    - Trigger
    - Electron ID/Pion rejection
  - Hodoscope:
    - 90 Scintillators 60 x 2.5 x2.5 cm^3
    - scintillators readout on both ends
    - Precision Timing: 500 ps resolution



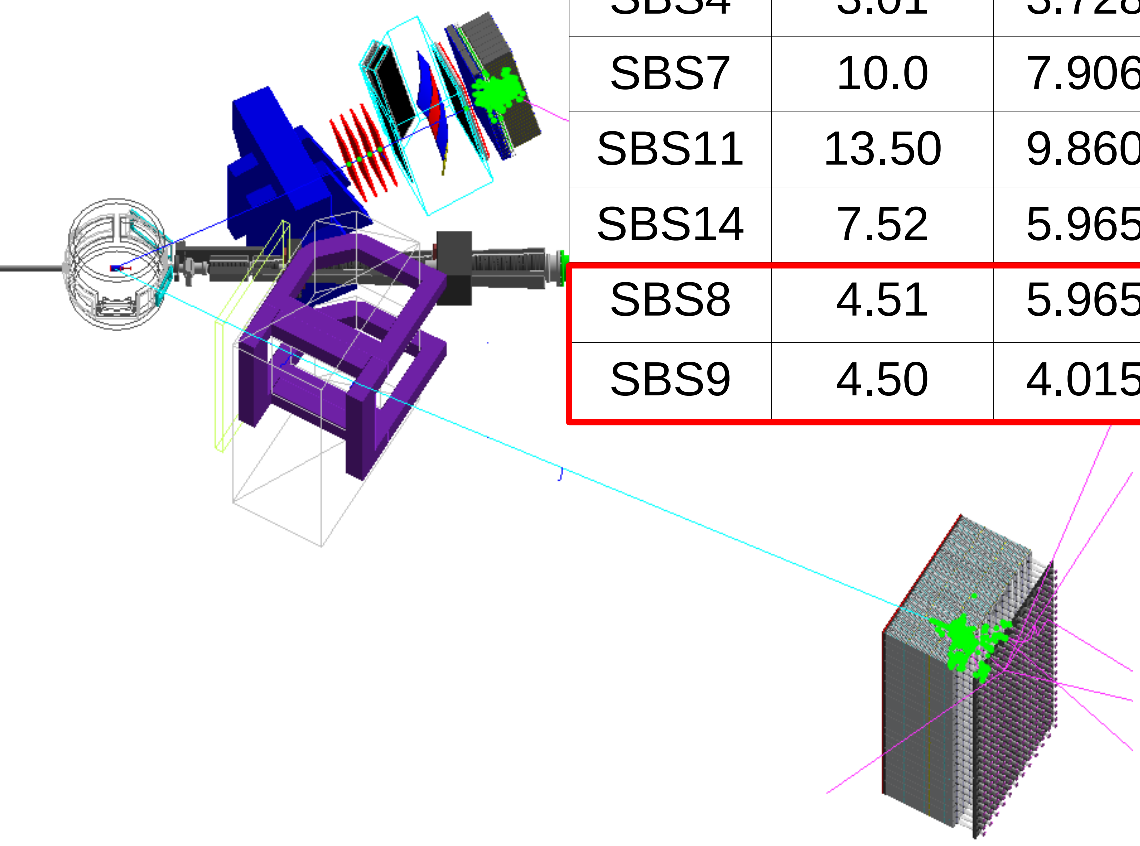
Super BigBite Spectrometer: HCal

- 12 x 24 iron/scintillator modules 15 x 15 * 90 cm^3
- Function: Nucleon measurement:
  - Position resolution ~5.5cm
  - Timing resolution (*ADC only*) ~1.5 ns
  - Energy resolution ~50 %





GMn/nTPE Kinematic tables

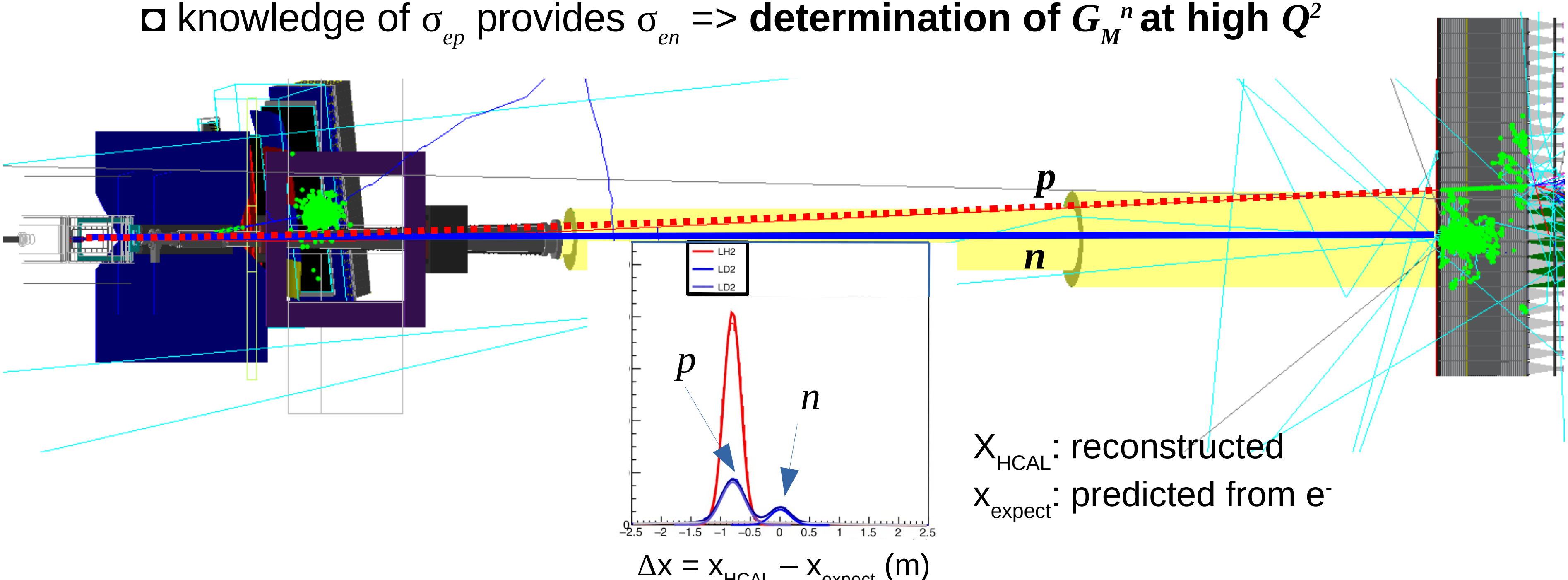


Kin	Q^2 (GeV/c)^2	E (GeV)	E' (GeV)	θ_{BB} (deg)	θ_{SBS} (deg)	ε
SBS4	3.01	3.728	2.129	36.0	31.9	0.721
SBS7	10.0	7.906	2.588	40.9	15.9	0.492
SBS11	13.50	9.860	2.676	41.9	12.8	0.437
SBS14	7.52	5.965	1.965	47.2	17.3	0.456
SBS8	4.51	5.965	3.565	26.5	29.9	0.797
SBS9	4.50	4.015	1.618	49.0	22.5	0.512

NTPE (SBS8, SBS9)

GMn Measurement

- 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,…)
  - knowledge of σ_{ep} provides σ_{en} => **determination of G_M^n at high Q^2**



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

GMn Measurement

- GMn: E12-09-019 (A. Camsonne, B. Quinn, B. Wojteskhowski)
  - $R = \frac{N_{en \to en}}{N_{ep \to ep}}$
  - $R' = \frac{\sigma_{en}}{\sigma_{ep}} = R f_{corr} - N_{inel}$

$$= \frac{\sigma_{Mott}\left(1+\tau_p\right)\left(\sigma_T^n + \epsilon \sigma_L^n\right)}{\sigma_{Mott}\left(1+\tau_n\right)\left(\sigma_T^p + \epsilon \sigma_L^p\right)} = \frac{\left(1+\tau_p\right)\left(\tau_n \left(G_M^n\right)^2 + \epsilon \left(G_E^n\right)^2\right)}{\left(1+\tau_n\right)\left(\tau_p \left(G_M^p\right)^2 + \epsilon \left(G_E^p\right)^2\right)}$$

=1

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

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

neutron/proton detection efficiency

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

GMn Measurement

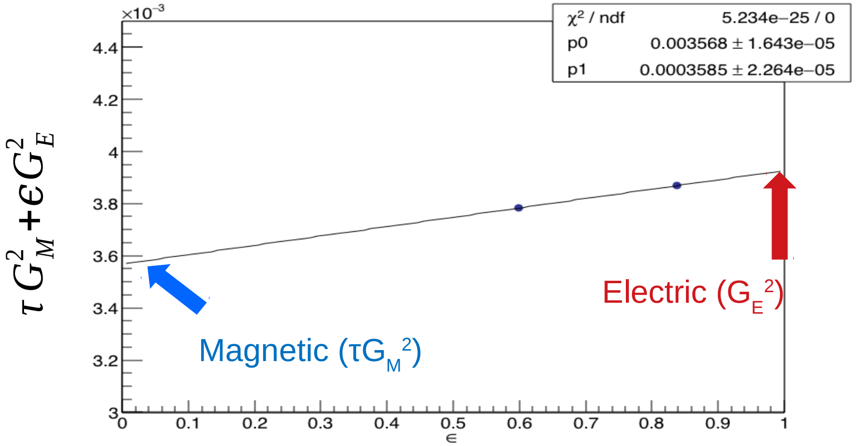
- GMn: E12-09-019 (A. Camsonne, B. Quinn, B. Wojteskhowski)
  - $$R = \frac{N_{en \to en}}{N_{ep \to ep}}$$
  - $$R' = \frac{\sigma_{en}}{\sigma_{ep}} = R\, f_{corr} - N_{inel}$$
    $$= \frac{\sigma_{Mott}\left(1+\tau_p\right)\left(\sigma_T^n + \epsilon\,\sigma_L^n\right)}{\sigma_{Mott}\left(1+\tau_n\right)\left(\sigma_T^p + \epsilon\,\sigma_L^p\right)} = \frac{\left(1+\tau_p\right)\left(\tau_n\left(G_M^n\right)^2 + \epsilon\left(G_E^n\right)^2\right)}{\left(1+\tau_n\right)\left(\tau_p\left(G_M^p\right)^2 + \epsilon\left(G_E^p\right)^2\right)}$$
    =1
  - $$\tau_n\left(G_M^n\right)^2 + \epsilon\left(G_E^n\right)^2 = R'\,\tau_p\left(G_M^p\right)^2 + \epsilon\left(G_E^p\right)^2$$
    From proton data
  - $$\left(G_M^n\right)^2 = \frac{1}{\tau_n}\left(\frac{N_{en,gen,acc}\, f_{scale\ n}}{N_{ep\ gen,acc}\, f_{scale\ p}} \times \frac{1+\tau_n}{1+\tau_p}\left(\tau_p\left(G_M^p\right)^2 + \epsilon\left(G_E^p\right)^2\right) - \epsilon\left(G_E^n\right)^2 - \delta_{2\gamma}\right)$$

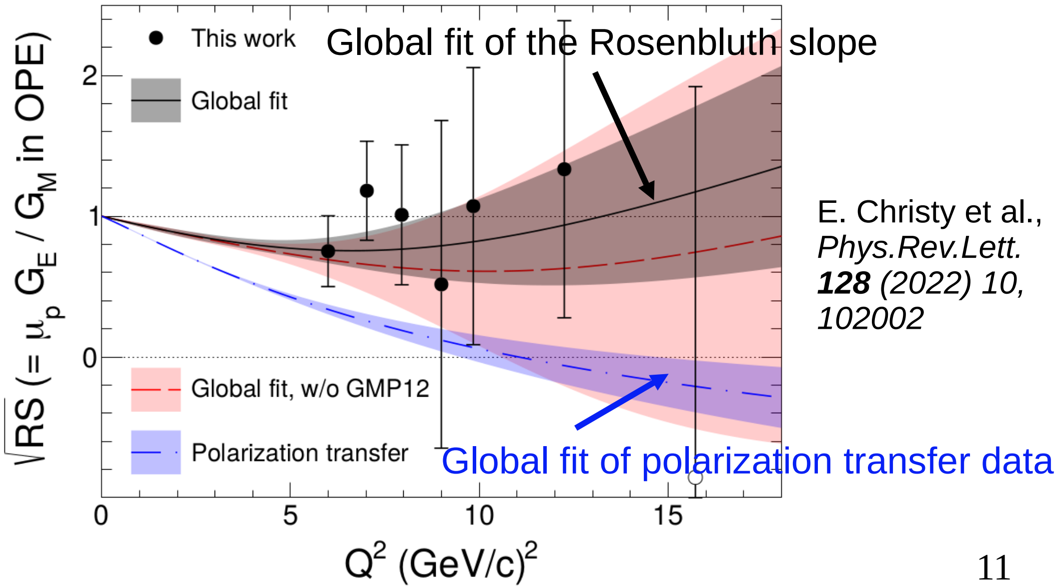
From GEn fits

From calculations

nTPE Measurement

- 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
  - σ_{en}/σ_{ep} superratio dependent on proton and neutron Rosenbluth slopes
  - knowledge on proton Rosenbluth slope => **Neutron Rosenbluth slope;**
  - *NTPE = Discrepancy neutron Rosenbluth slope <=> polarization data*

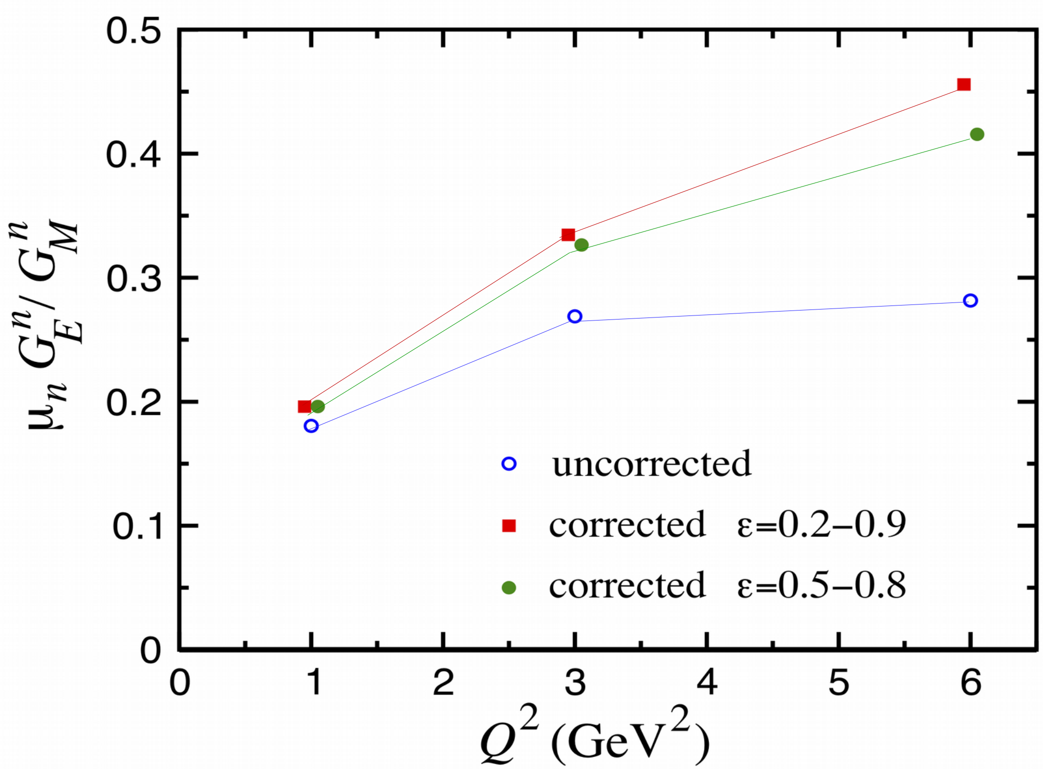




E. Christy et al., *Phys.Rev.Lett.* ***128*** *(2022) 10, 102002*

Two-Photon Exchange in *en* Scattering

- Predictions from Phys. Rev. C**72**, 034612 (2005) on *en* scattering:
  - small TPE contribution at Q^2 around 1 GeV^2;
  - significant at 3 GeV^2 and beyond;
  - ***No TPE measurement on the neutron* => *nTPE*(+) *at Jefferson Lab***



Blunden, Melnitchouk and Tjon, Phys. Rev. C**72**, 034612 (2005)

○ Uncorrected $\mu_n G_E^n/G_M^n$ from Mergell Meissner Drechsel parameterization in Nucl. Phys. A596, 367 (1996)

■ $\mu_n G_E^n/G_M^n$ +TPE between ε = 0.2 and 0.9

● $\mu_n G_E^n/G_M^n$ +TPE between ε = 0.5 and 0.8

nTPE Measurement

- nTPE: E12-20-010 (E.F., S. Alsalmi, B. Wojteskhowski)
  - $R=\frac{N_{en\rightarrow en}}{N_{ep\rightarrow ep}}$
  - $R'=\frac{\sigma_{en}}{\sigma_{ep}}=R f_{corr}-N_{inel}=\ldots$
  - $R'_{\epsilon_{1/2}}=\frac{\sigma_T^n\left(1+\epsilon_{1/2}S^n\right)}{\sigma_T^p\left(1+\epsilon_{1/2}\boxed{S^p}\right)}$ → From proton data
  - $A=\frac{R'_{\epsilon_1}}{R'_{\epsilon_2}}\simeq B\left(S^p\right)\times\left(1+S^n\Delta\epsilon\right)$
    - $B=\frac{1+\epsilon_2 S^p}{1+\epsilon_1 S^p}$
  - $\boxed{S^n=\frac{A-B}{B\Delta\epsilon}}$
  - $nTPE=S^n-\boxed{\left(G_E^n\right)^2/\tau\left(G_M^n\right)^2}$ → GEN fits *or GEN-RP measurement at* **Q^2 = 4.5 GeV^2** (when available)

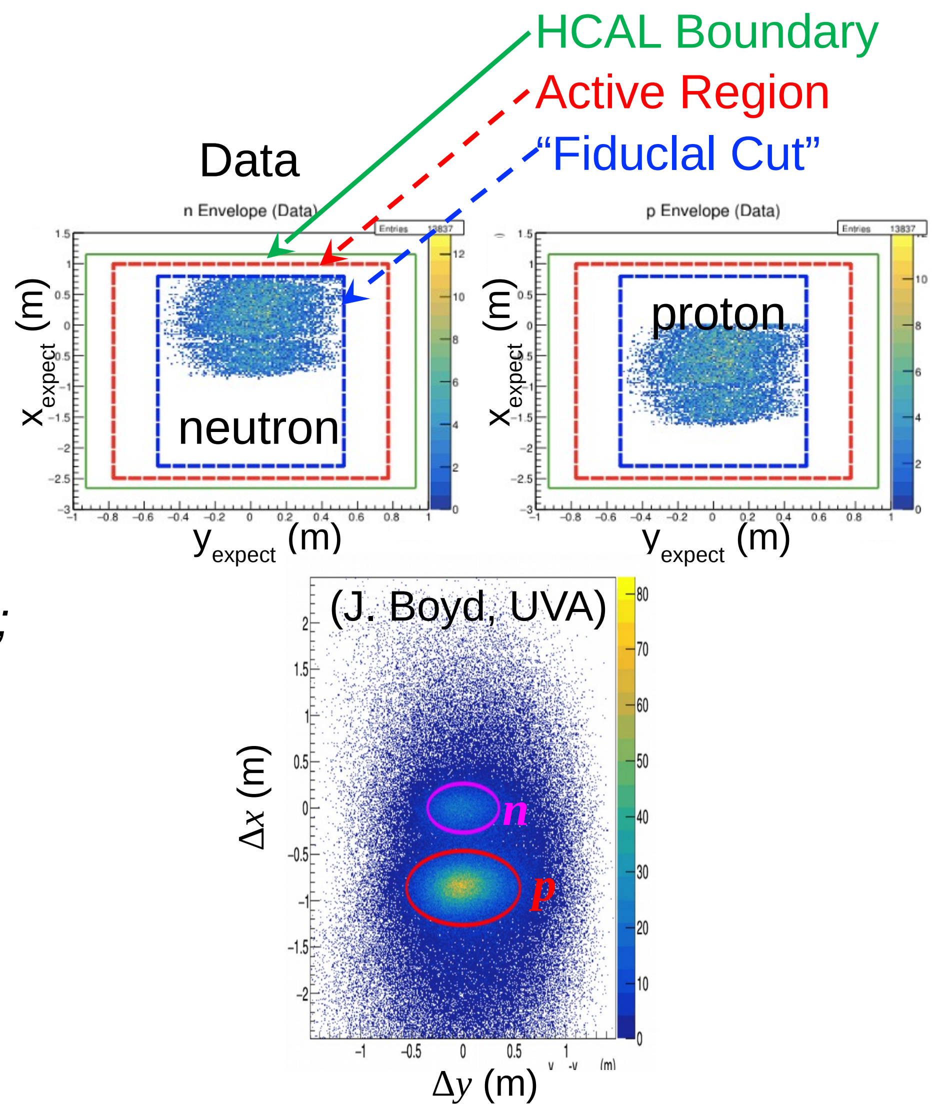
Elastic Selection

- 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;*

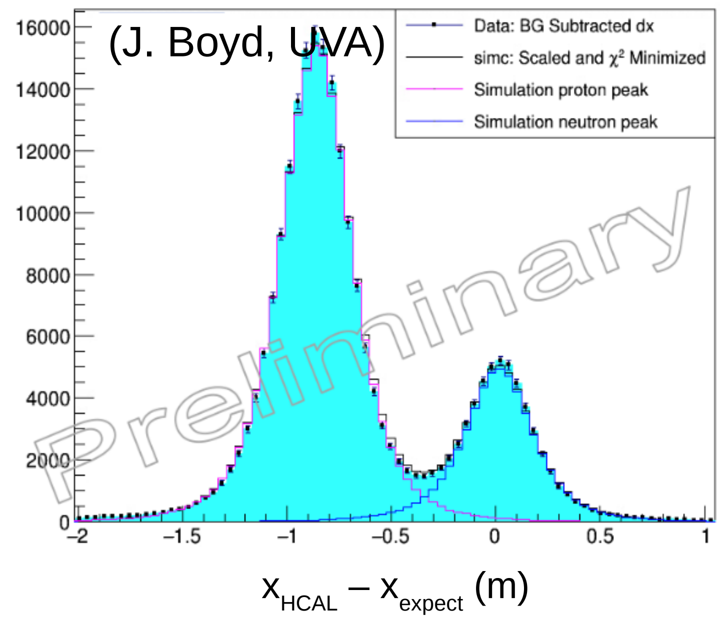
- Nucleon selection:
  - $E_{HCAL} > 0.1$

  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

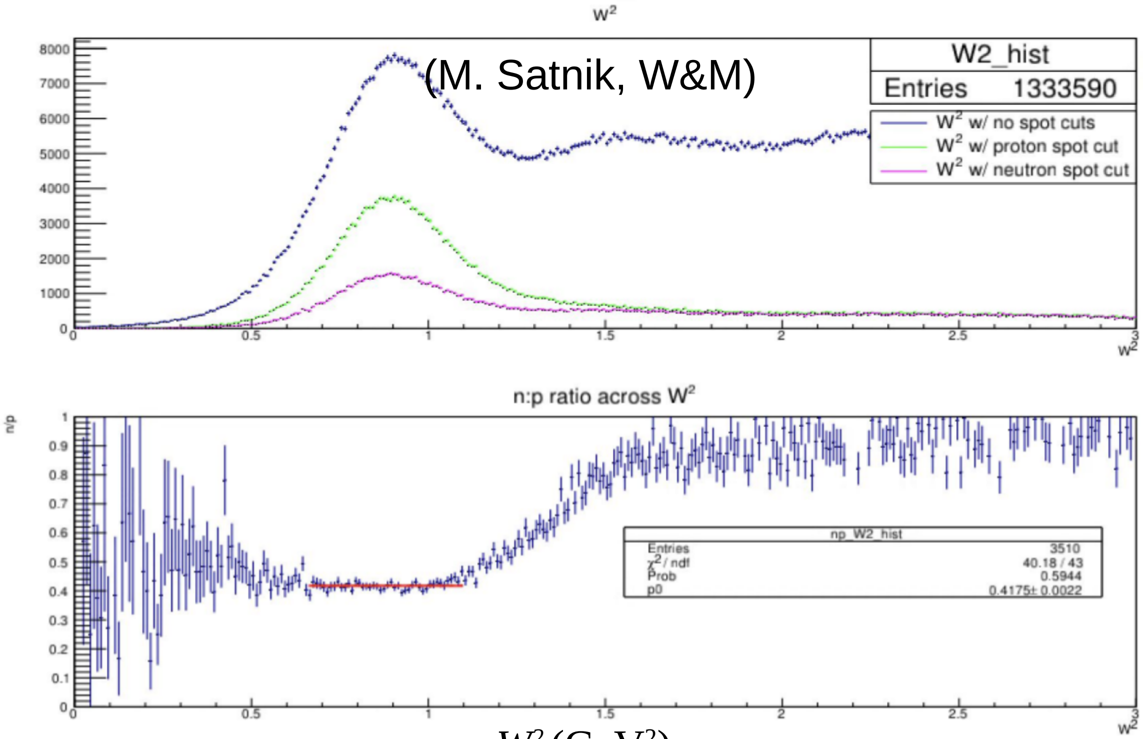
- Comparison between data and MC *including radiative corrections* (SIMC):
  - provides correction term: $$R' = \frac{\sigma_{en}}{\sigma_{ep}} = \frac{(N_{en \to en})_{meas}}{(N_{ep \to ep})_{meas}} f_{corr}$$
  - MC/data yield comparison, SBS8 (high ε):



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

Selection Optimization

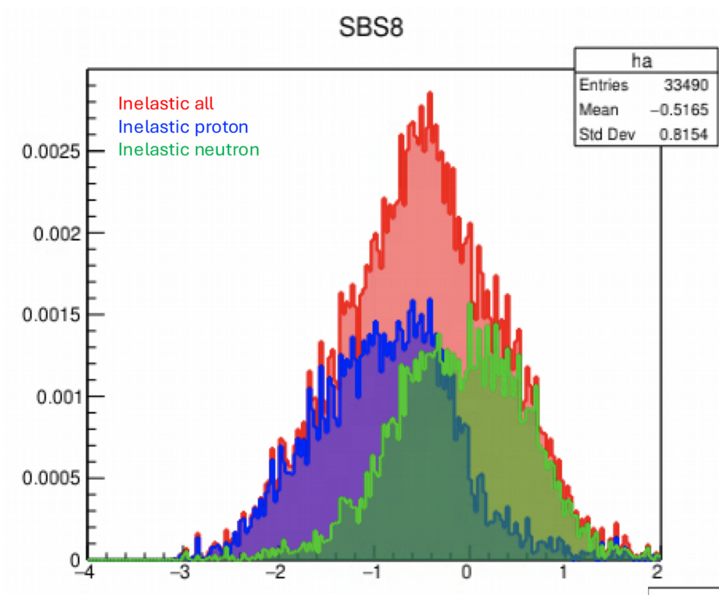
- ***n/p* stability over selection cuts:**
  - W^2;
  - E_{PS}, E_{SH}, E_{HCAL};
  - t_{HCAL}-t_{Shower};
  - Δx, Δy, fiducial cuts;

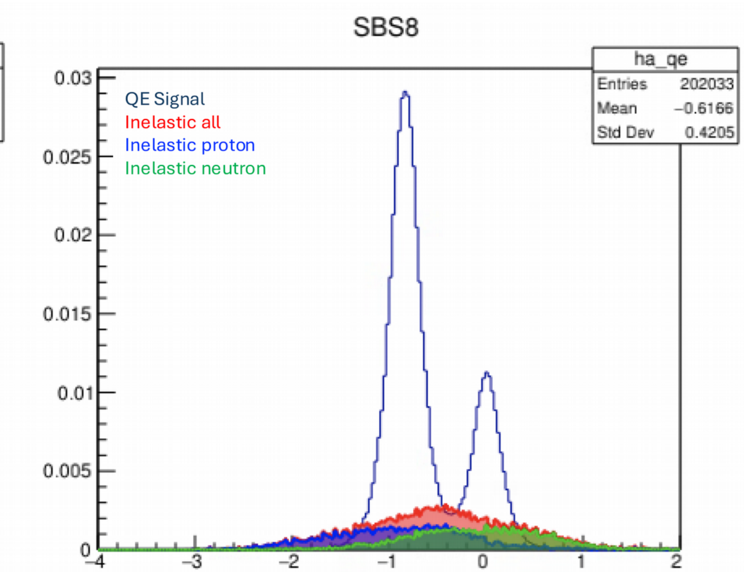


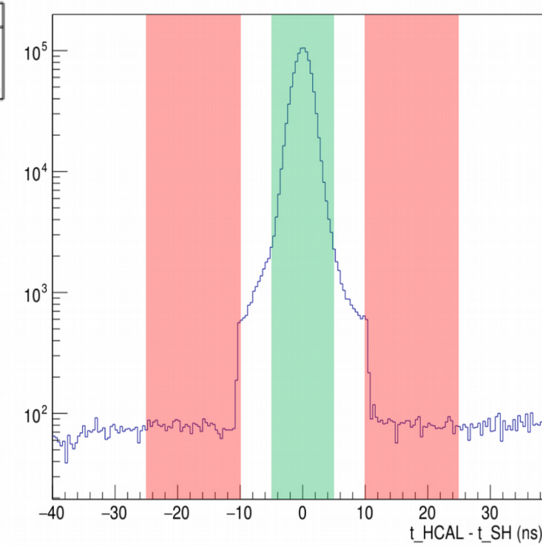
W^2 (GeV^2)

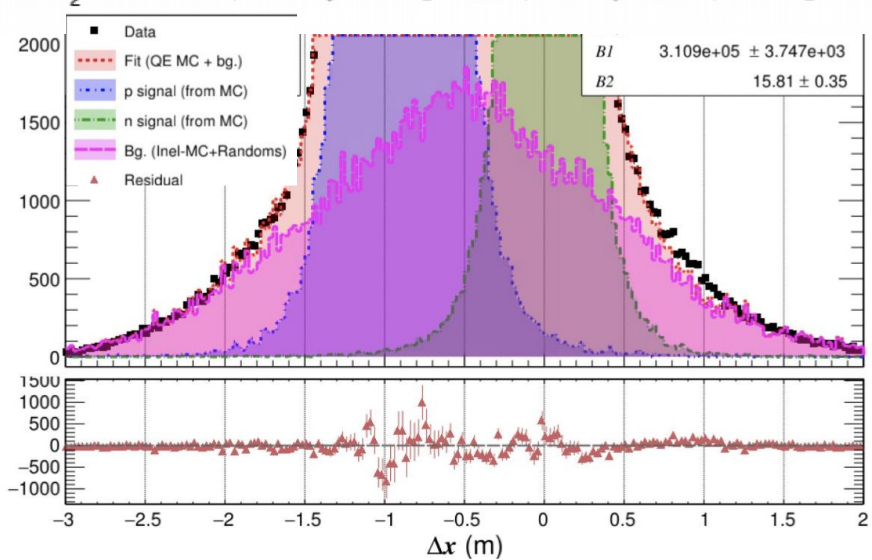
Systematic uncertainties: Inelastic contamination

- Latest improvements on estimation of inelastic contamination:
  - Inelastic Monte Carlo combined with out-of-time events





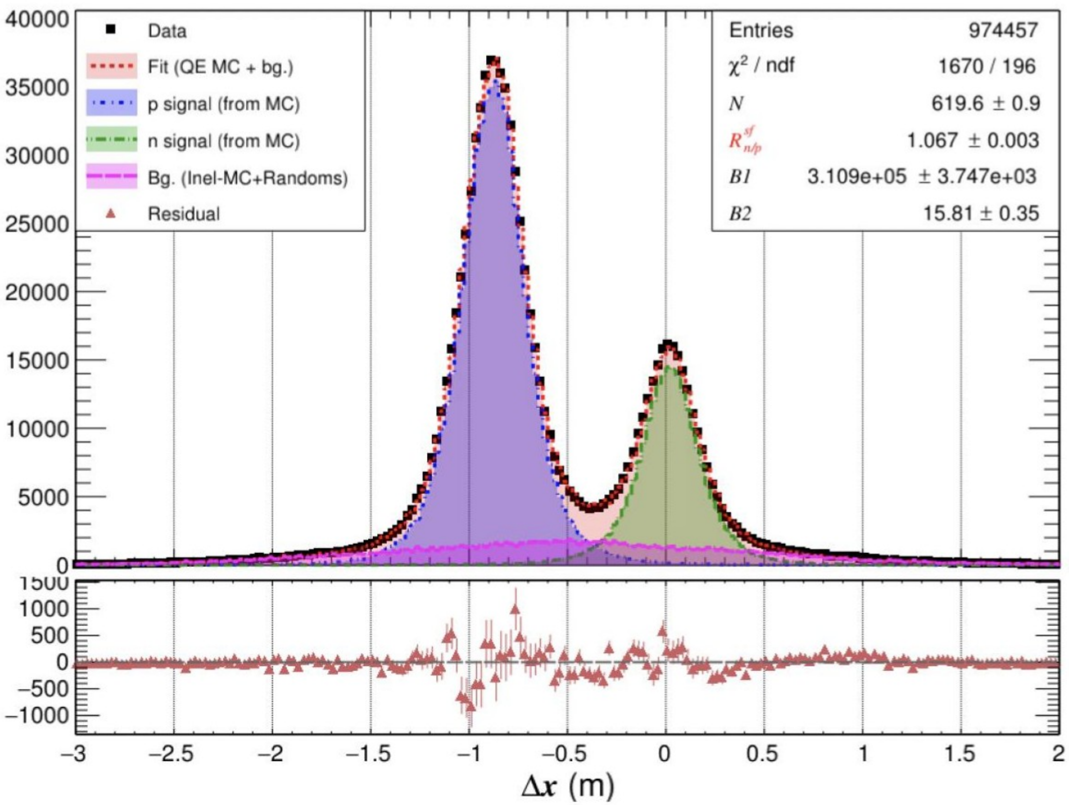


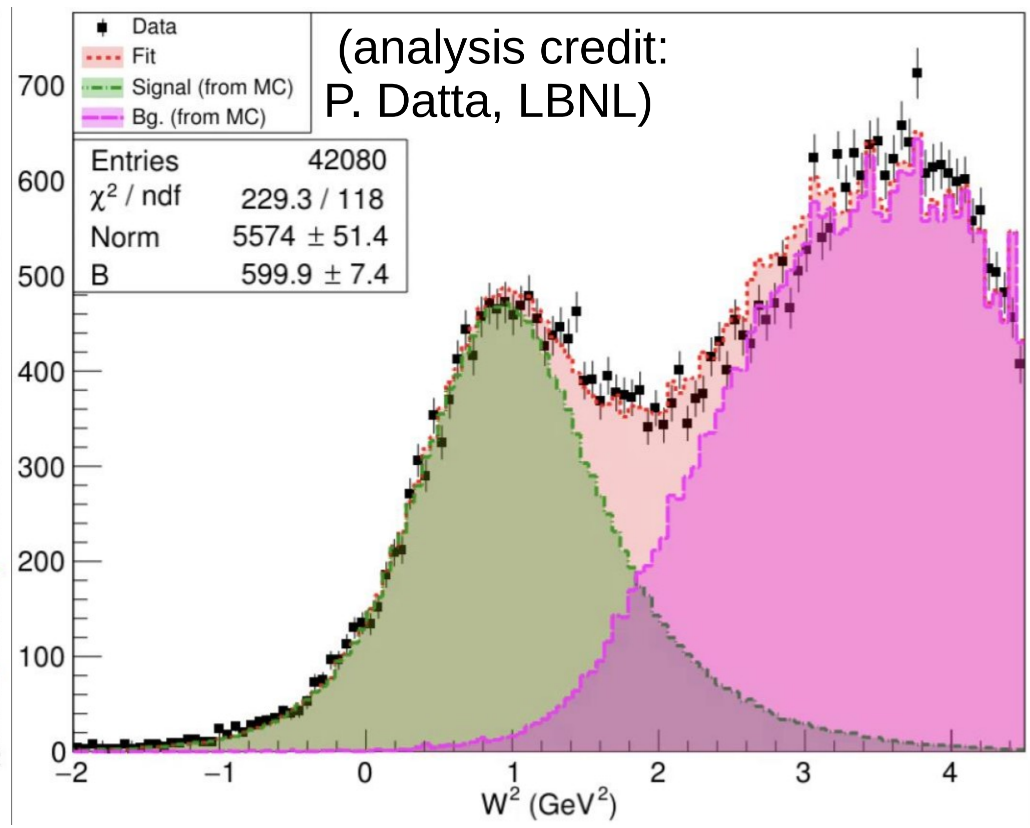


(analysis credit:
P. Datta, LBNL)

Systematic uncertainties: Inelastic contamination

- Latest improvements on estimation of inelastic contamination:
  - Inelastic Monte Carlo combined with out-of-time events
  - neutron/proton cross section ratio obtained with newest function compared with:
    - 2^{nd} and 4^{th} order polynomials, gaussian to fit inelastic background;
    - Δy side-band selection

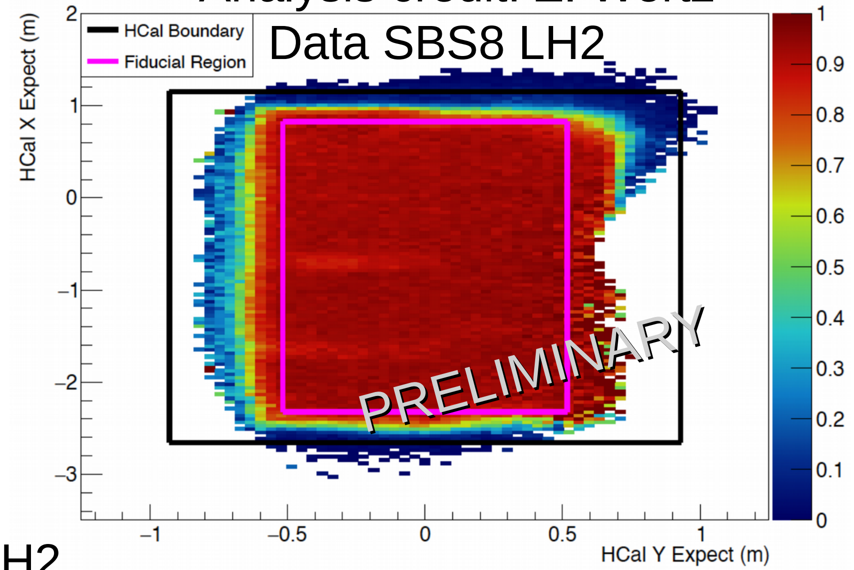




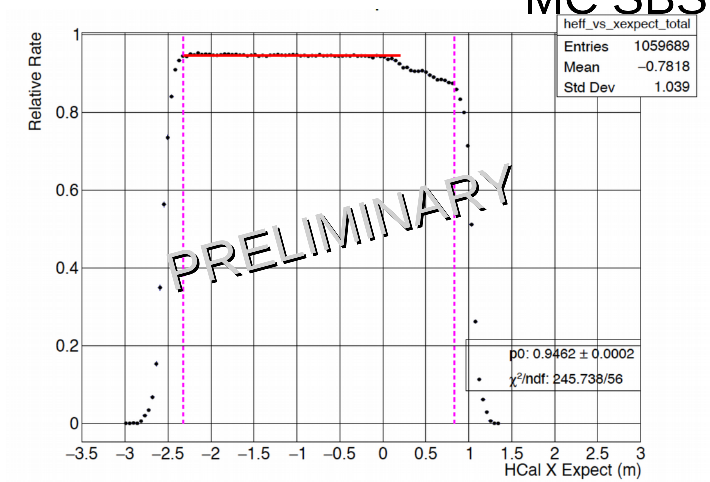
HCAL Non-Uniformity Corrections

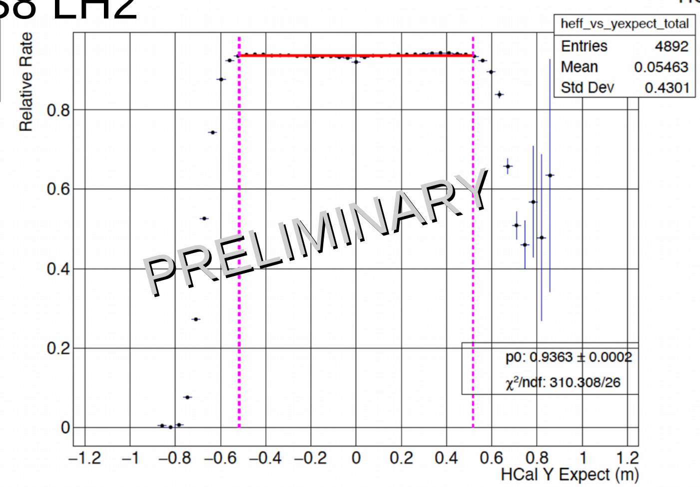
- Method to correct for HCal efficiency non-uniformity:
  - Reweight MC events with HCal non-uniformity map;
  - Map efficiency along x_{expect}, y_{expect};
  - Efficiency analysis for data, MC;
    - MC weight: h_{data}/h_{MC};
    - deployed in analysis;
  - Hurdle:
    - proton and neutron detection efficiency not equal a priori;

Analysis credit: Z. Wertz



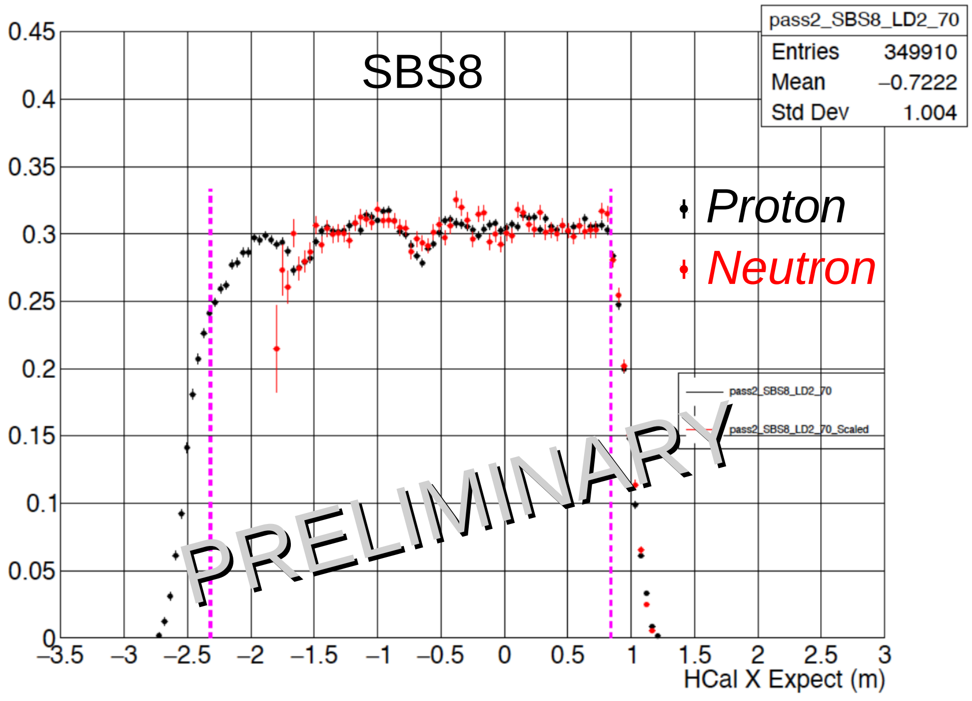
MC SBS8 LH2

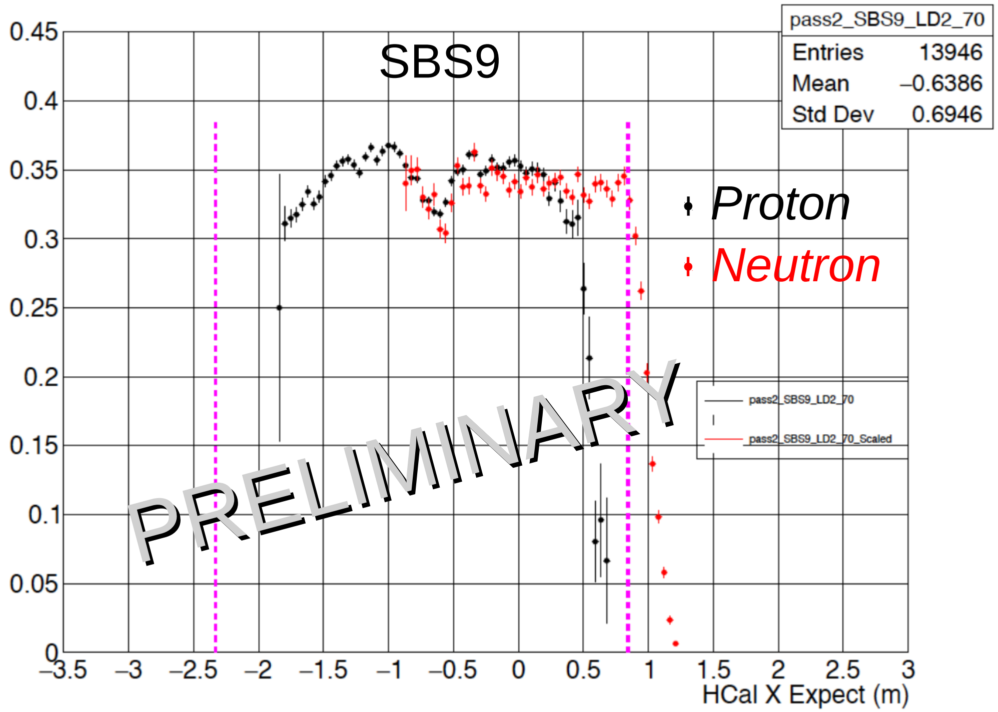




HCAL Non-Uniformity Corrections

- Reweight MC events with HCal non-uniformity map:
  - Analysis of all combined SBS8 LH2 settings for map efficiency:
  - *Neutron* efficiency drop comparable to *proton;*
  - Correction modifies s_{en}/s_{ep} by ~0.2 % (SBS8) and ~0.5 % (SBS9);
  - TODO:
    - understand neutron response for systematic uncertainty estimation;



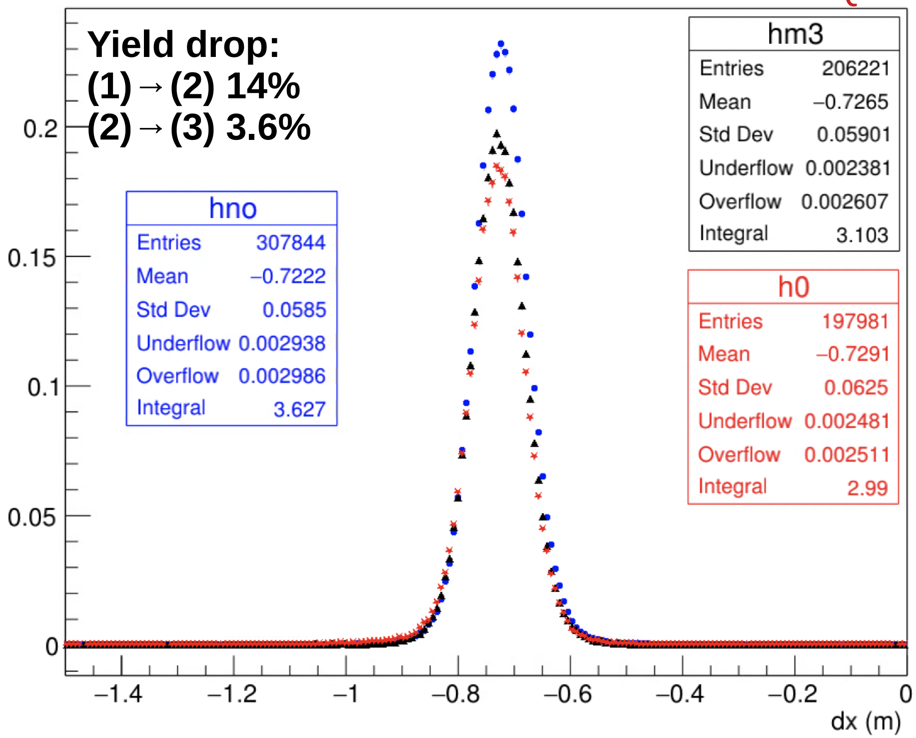


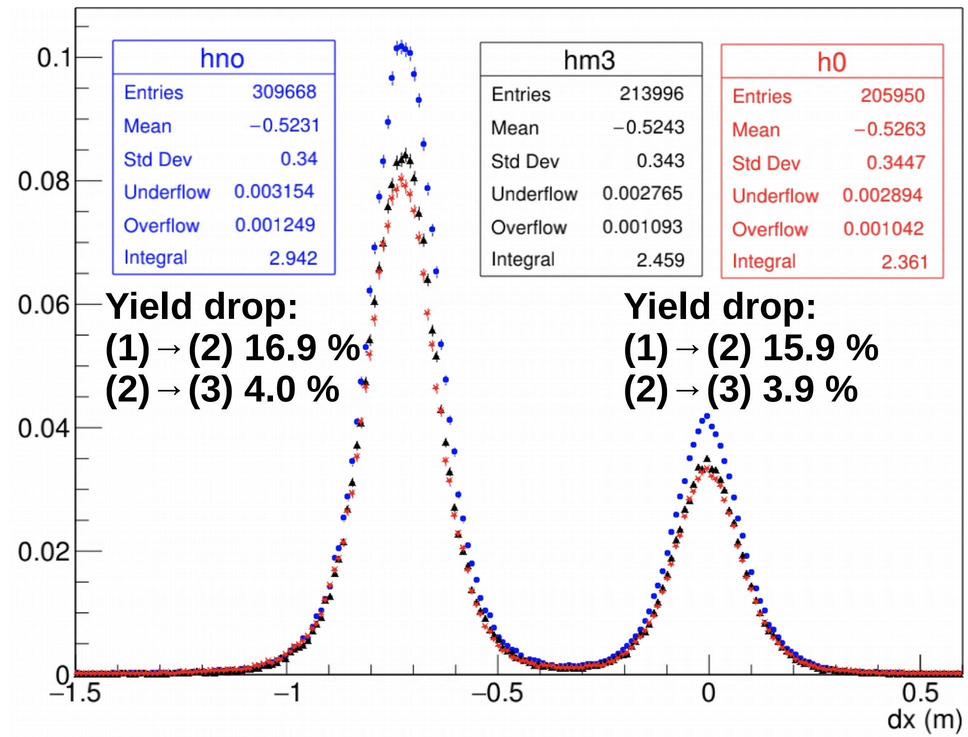
Analysis credit: E. Wertz

Systematic uncertainties: Radiative corrections

- Radiative corrections (analysis credit: P. Datta, LBNL):
  - SIMC events with the following configurations for radiative effects:
    - (1) - No radiative corrections i.e. none of the tails are radiated
    - (2) - One tail = 0 => All (e, e', and p) tails are radiated
    - (3) - One tail = -3 => All but p tails are radiated
  - SIMC events processed through g4sbs → libsbsdig → SBS-offline;
  - Properly weighted Dx distribution for all types of events with the same selection
  - Extract individual yields and then quantify the correction

H(e, e' p) $Q^2 = 13.5\ GeV^2$ D(e, e' p) + D(e, e' n)





Preliminary systematic uncertainties

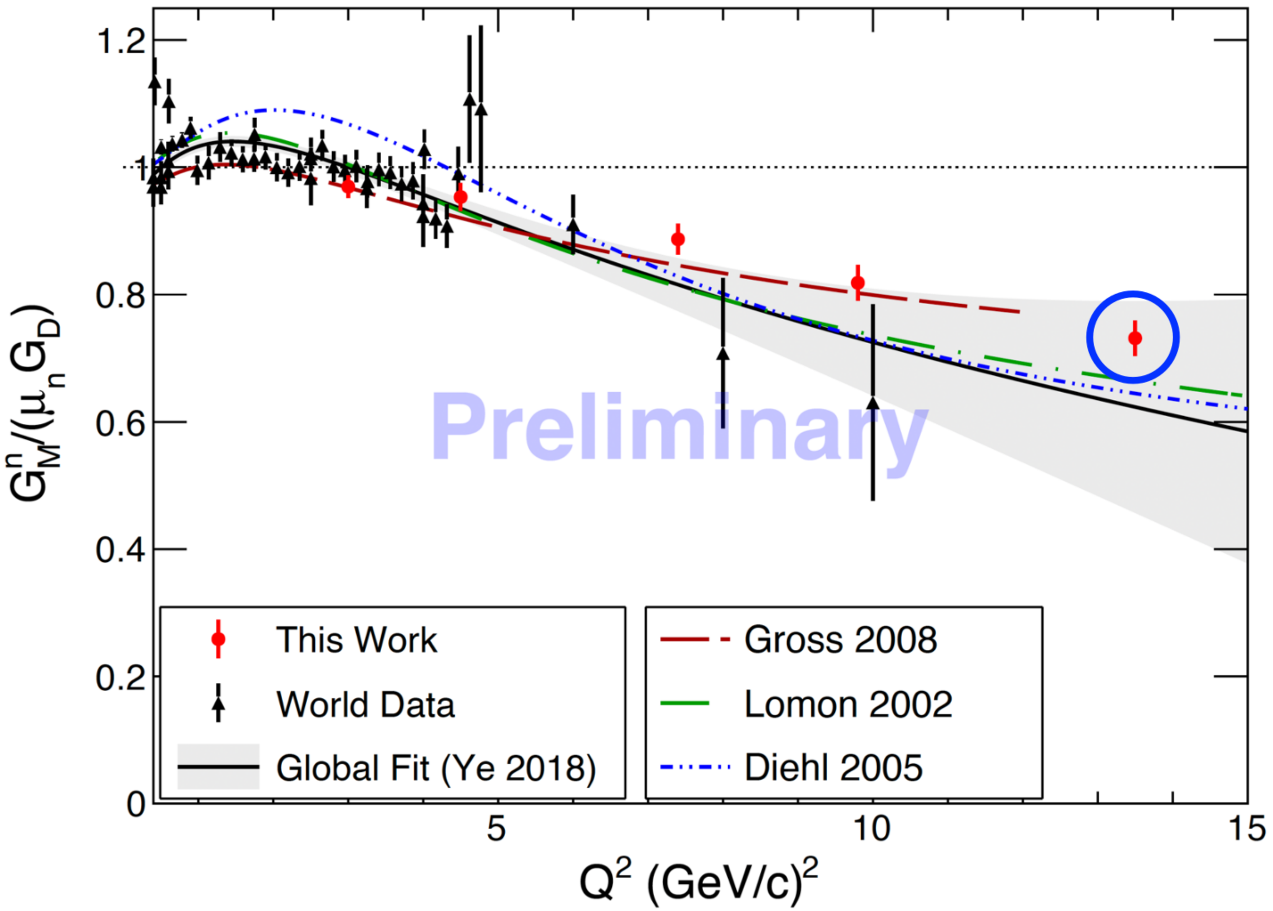
- Systematics analysis credit: P. Datta (LBNL);
  - Improvement can be achieved for radiative corrections and nucleon detection efficiency

Table 2: Estimated contributions (in percent) to systematic error on R and $\frac{G_M^n}{\mu_n G_D}$.

	Error Sources	Q^2 (ϵ)				
		3 (0.72)	4.5 (0.51)	7.4 (0.46)	9.9 (0.50)	13.5 (0.41)
$\Delta(R)_{sys}$	Inelastic Cont.	0.33	0.75	0.84	0.75	2.67
	Nucleon Det. Effi.	2.00	2.01	2.01	2.02	2.02
	Radiative Corr.	2.31	3.32	3.77	3.87	5.47
	Cut Stability	0.16	0.15	0.40	0.67	0.60
	FSI	0.04	0.01	0.02	0.02	0.03
	Total	3.08	3.95	4.37	4.48	6.44
$\Delta(\frac{G_M^n}{\mu_n G_D})_{sys}$	Inelastic Cont.	0.17	0.38	0.42	0.37	1.34
	Nucleon Det. Effi.	1.00	1.00	1.01	1.01	1.01
	Radiative Corr.	1.16	1.66	1.88	1.94	2.73
	Cut Stability	0.03	0.07	0.20	0.33	0.30
	FSI	0.02	0.00	0.01	0.01	0.01
	σ^p_{Red}	0.82	0.92	1.35	1.52	1.33
	G_E^n	0.55	0.65	0.62	0.66	0.55
	Total	1.83	2.27	2.64	2.79	3.53

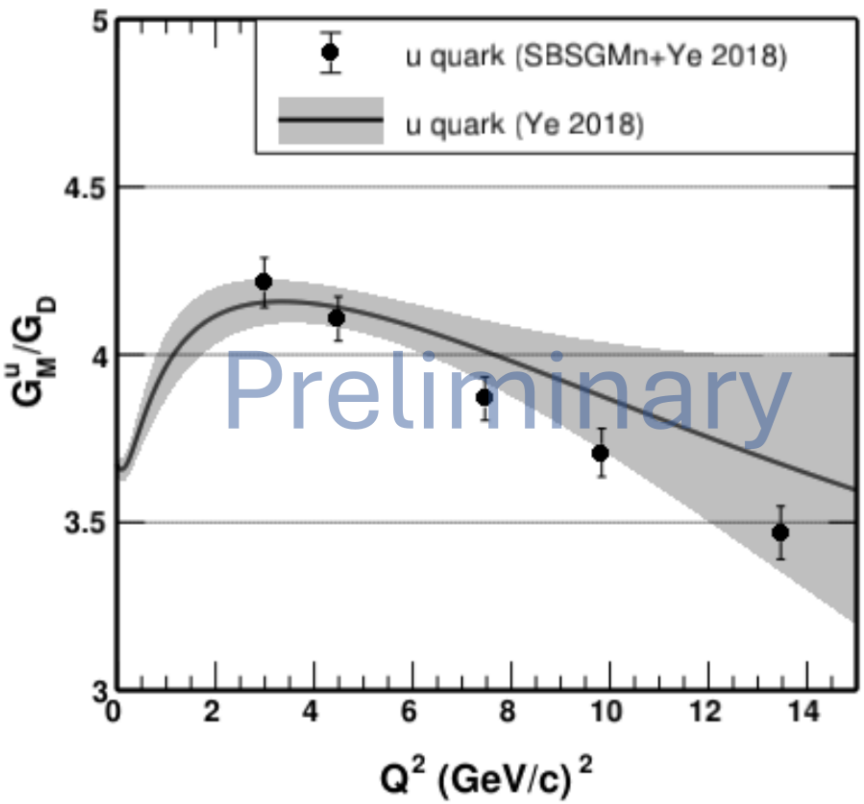
GMN Preliminary Results

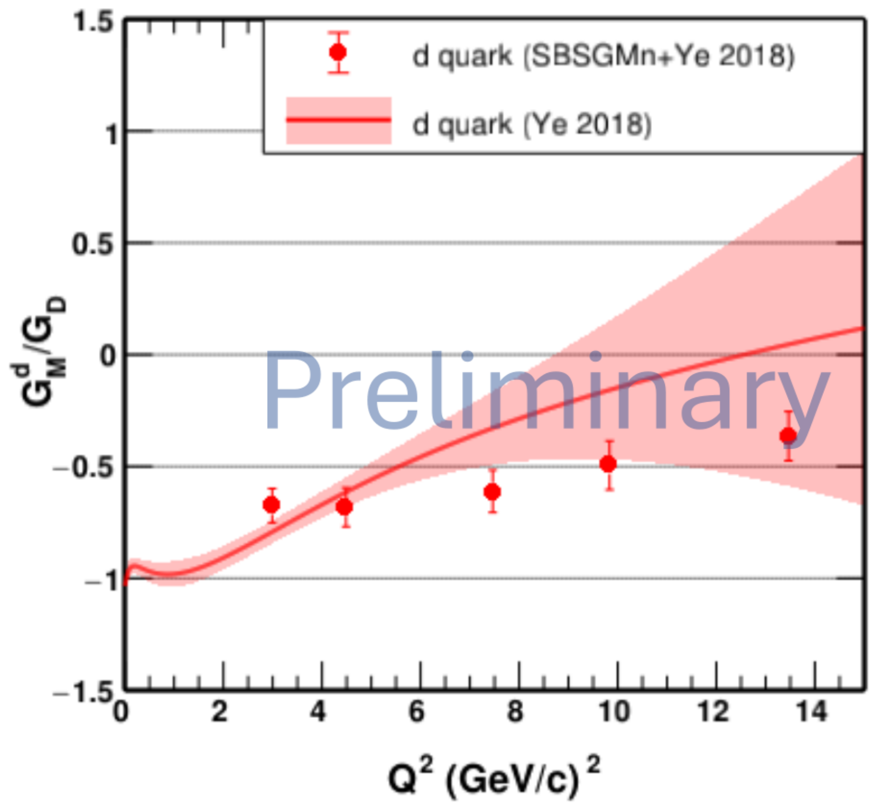
- Shown at the *APS 2025 SBS mini-symposium* by P. Datta (LBNL)



Flavor separation

- Shown at the *APS 2025 SBS mini-symposium* by P. Datta (LBNL)

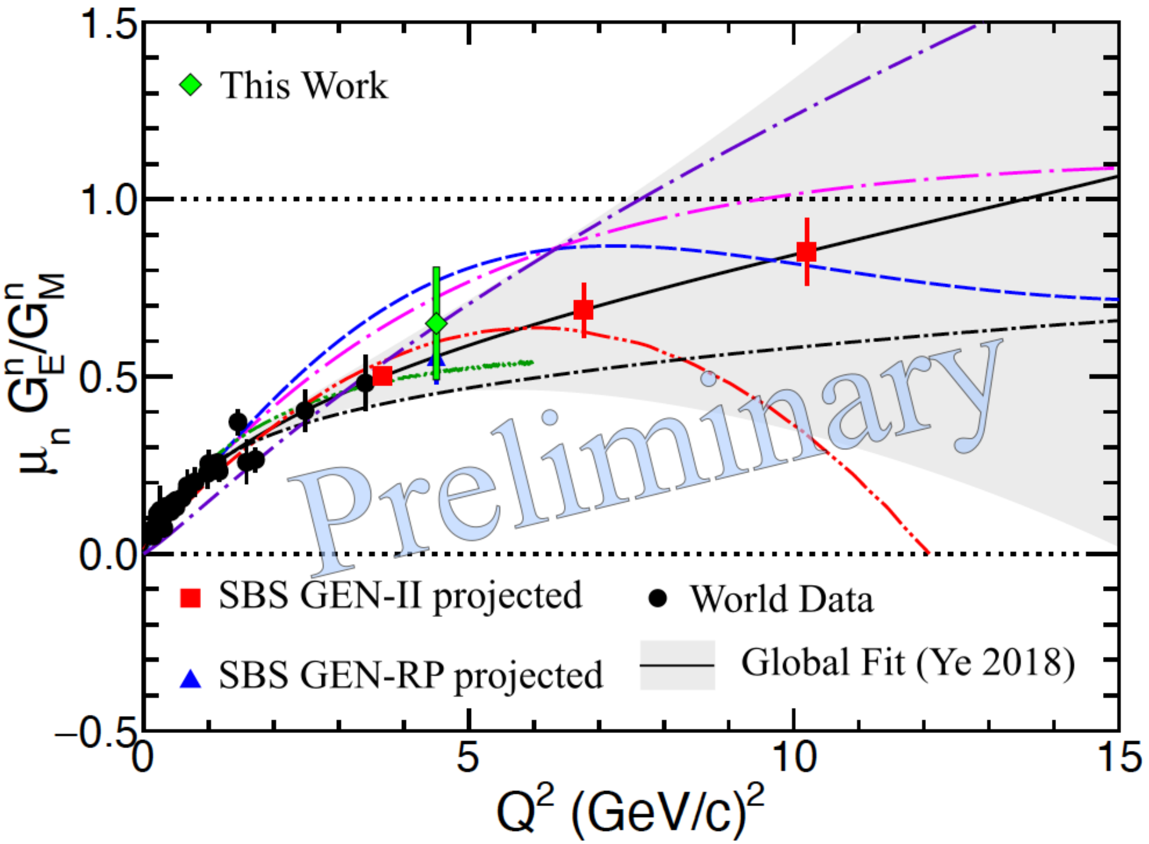




NTPE Preliminary Results

- First estimation of the neutron Rosenbluth slope (analysis credit E. Wertz):
  - $\mu_n\, G_E^n/G_M^n$ calculated from Rosenbluth slope *without accounting for TPE*;
  - Other G_E^n measurements and projections are polarization data;
  - *Measured Rosenbluth slope hints for the existence of TPE*
  - Plan: refine systematic uncertainties.

[E. Wertz, *A Measurement of the Neutron Electromagnetic Form Factor Ratio from a Rosenbluth Technique with Simultaneous Detection of Neutrons and Protons*, Ph.D Thesis, William & Mary (July 2025).]



Summary

- **GMN preliminary results presented at APS 2025**

- **NTPE preliminary results presented here for the first time!**

- Monte Carlo:
  - Digitization gain adjusments done for all SBS kinematics;
  - Monte Carlo pass 2 generated with a few important fixes;

- Systematics:
  - Update on inelastic subtraction;
  - Preliminary estimation of radiative corrections;
  - HCal systematics uncertainties:
    - understand neutron detection;
    - evaluate uncertainty correlations between SBS8 and SBS9;

- Next steps:
  - third pass of calibration for optimization of HCal timing;
  - preparation of publication for PRL;

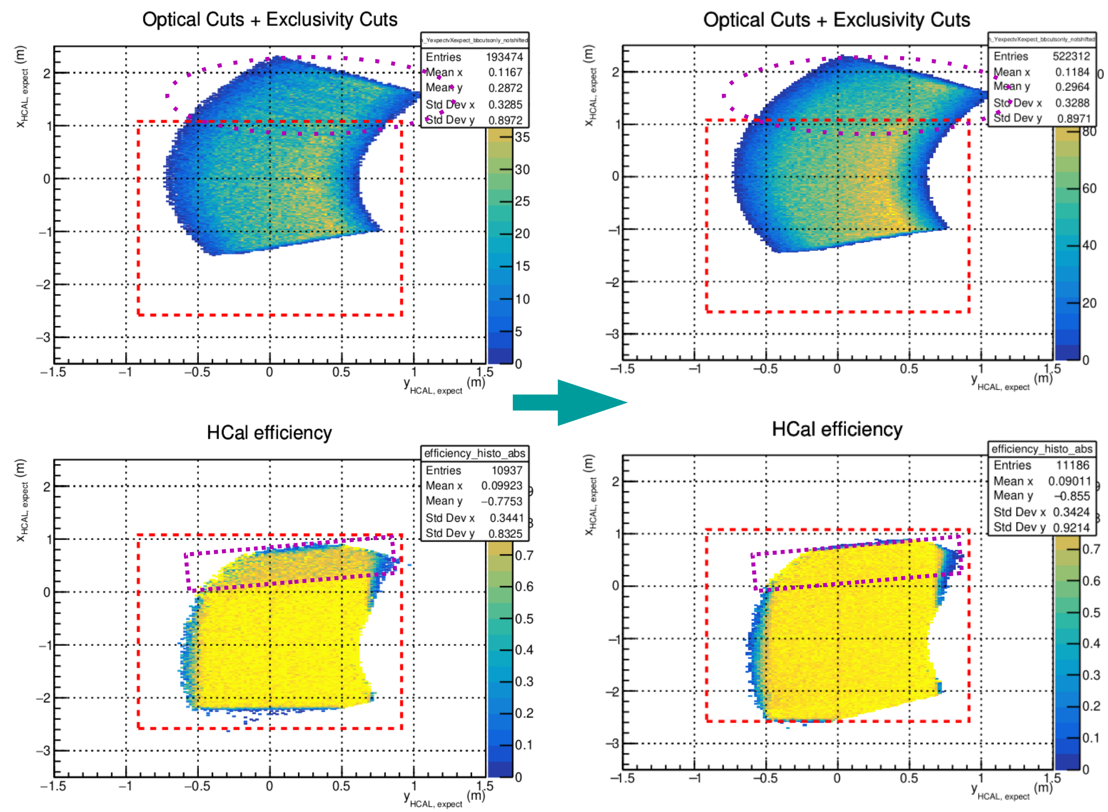
Students status

- John, Sebastian, Nathaniel, Anu, Provakar, Maria already graduated
- Zeke to graduate soon!
- Anu, Provakar, Nathaniel continue analysis as post-docs;

Back up

Monte-Carlo Fixes: G4SBS Geometry

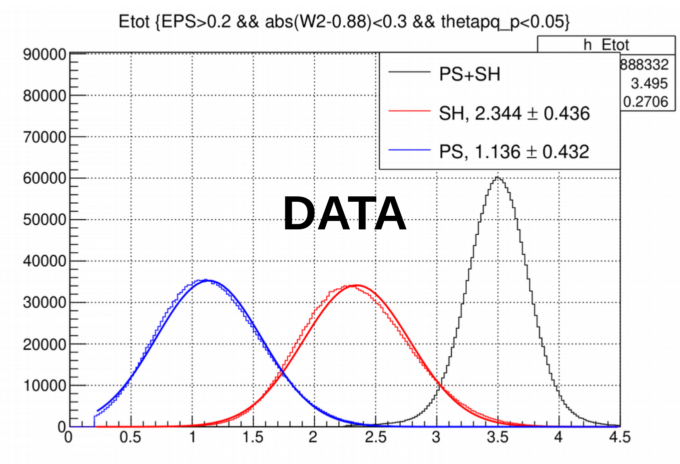
- G4SBS geometry bugs fixes:
  - ◘ Dimensions of PS block (8.5 mm) not matched with block center-to-center distance (9mm) => “ribs” in X_{expect} Vs Y_{expect}
  - ◘ PS block material density out-of-date
  - ◘ Scattering chamber right beam window vertical aperture too small => HCAL MC efficiency degraded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



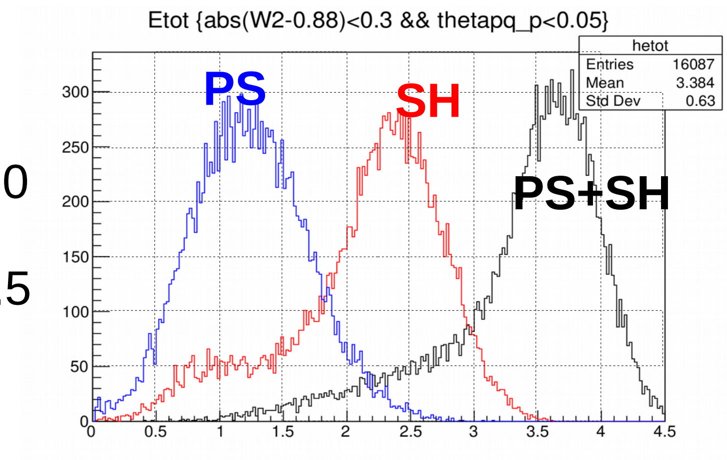
Before fixes   After fixes

Monte-Carlo Fixes: Digitization

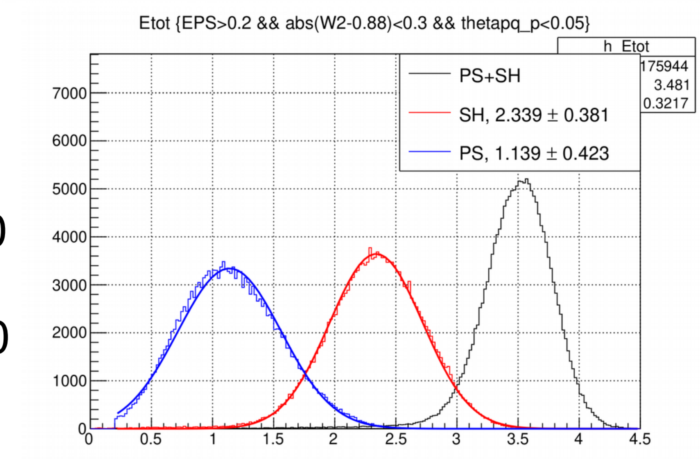
- Digitization parameters for BBCal readjusted to fit the data better (e.g. SBS8)
- *HCal gain adjustments underway*



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



Reminder: GMN/NTPE

- GMN:

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

=1

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

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

From proton data

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

Reminder: GMN/NTPE

- **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

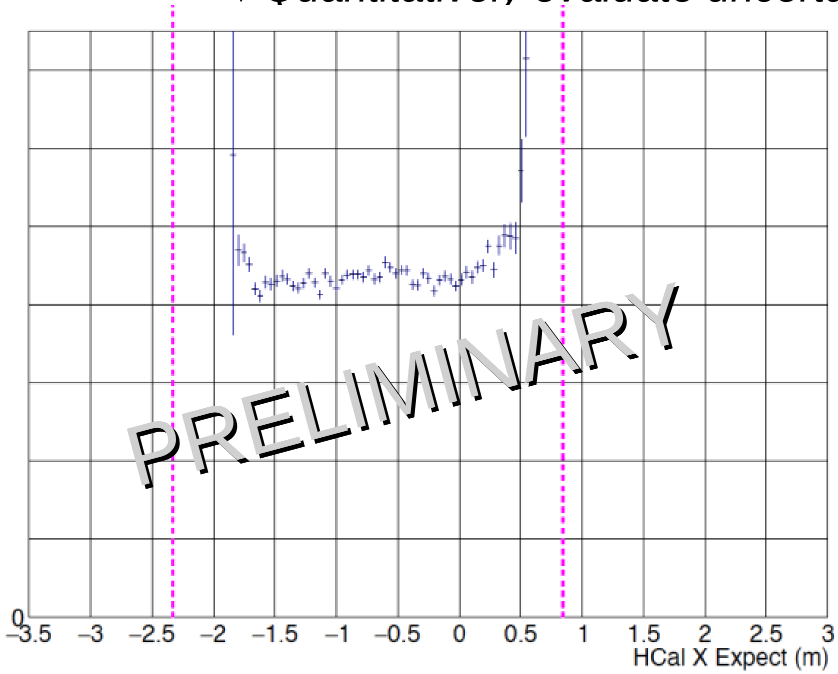
$$\Delta\epsilon = \epsilon_2 S^p ¿/(1+\epsilon_2 S^p)¿$$

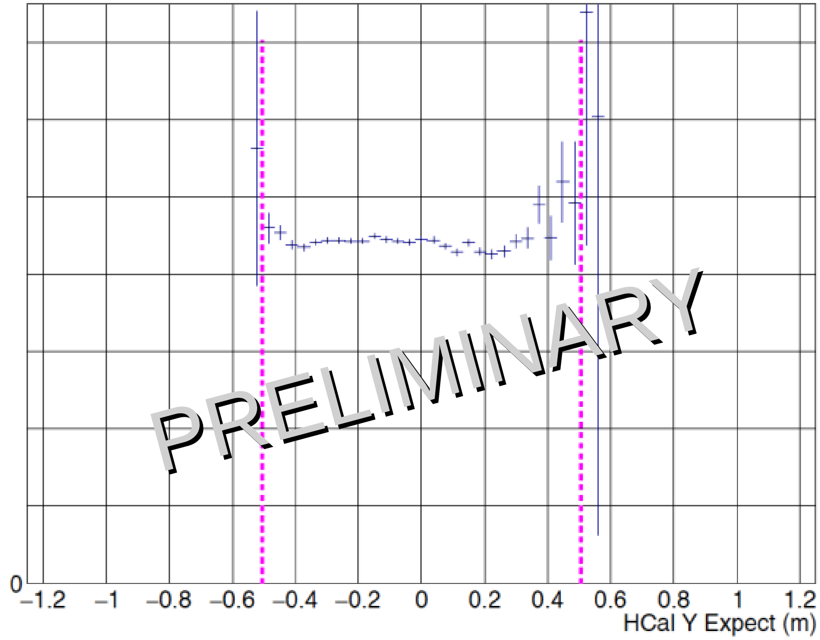
$$S^n = \frac{A-B}{B\,\Delta\epsilon} \qquad nTPE = S^n - (G_E^n)^2/\tau(G_M^n)^2$$

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

HCAL Non-Uniformity Corrections

- Reweight MC events with HCal non-uniformity map:
  - Analysis of all combined SBS8 LH2 settings for map efficiency:
  - SBS8/SBS9 Stable ratio over HCal position;
  - Correction modifies s_{en}/s_{ep} by ~0.2 % (SBS8) and ~0.5 % (SBS9);
  - TODO:
    - understand neutron response for systematic uncertainty estimation;
    - *Quantitatively evaluate uncertainty correlation between SBS8 and SBS9*





Analysis credit: E. Wertz