SBS 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
CHARTERED 1693

Jefferson Lab

Open Questions in Nucleon Structure
Form Factors at High Q^2

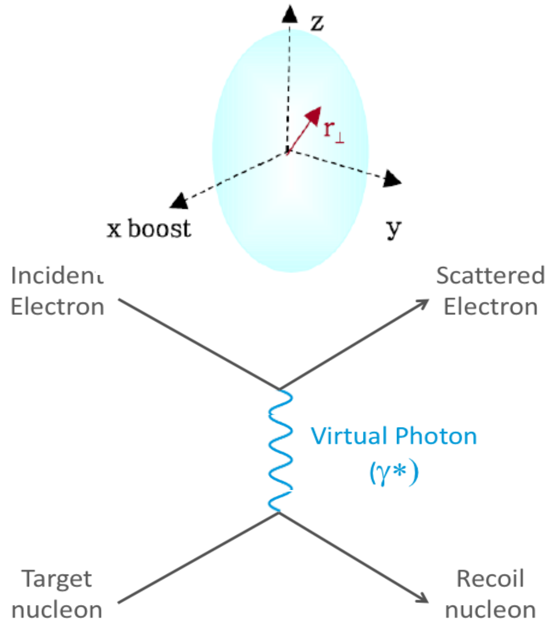
- Space-like Form Factors ≡ charge distribution
- In the One-Photon Exchange (Born) approximation:

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

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

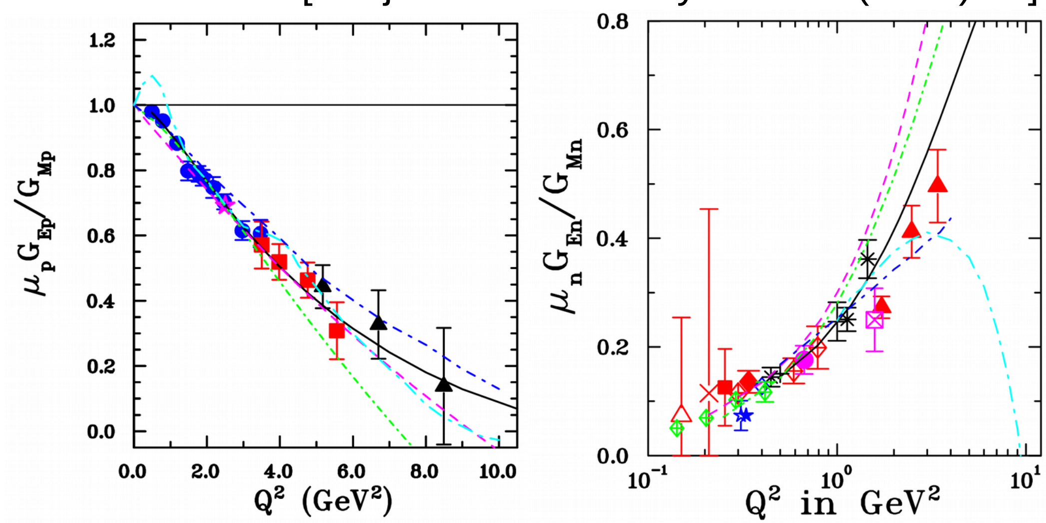
Sachs magnetic FF squared

Sachs Electric FF squared



- FF Descriptions diverge for higher $Q^2 \geq 10$ GeV^2
- Precise data sets up to and beyond Q^2 = 10 GeV^2 => *powerful insight on QCD*

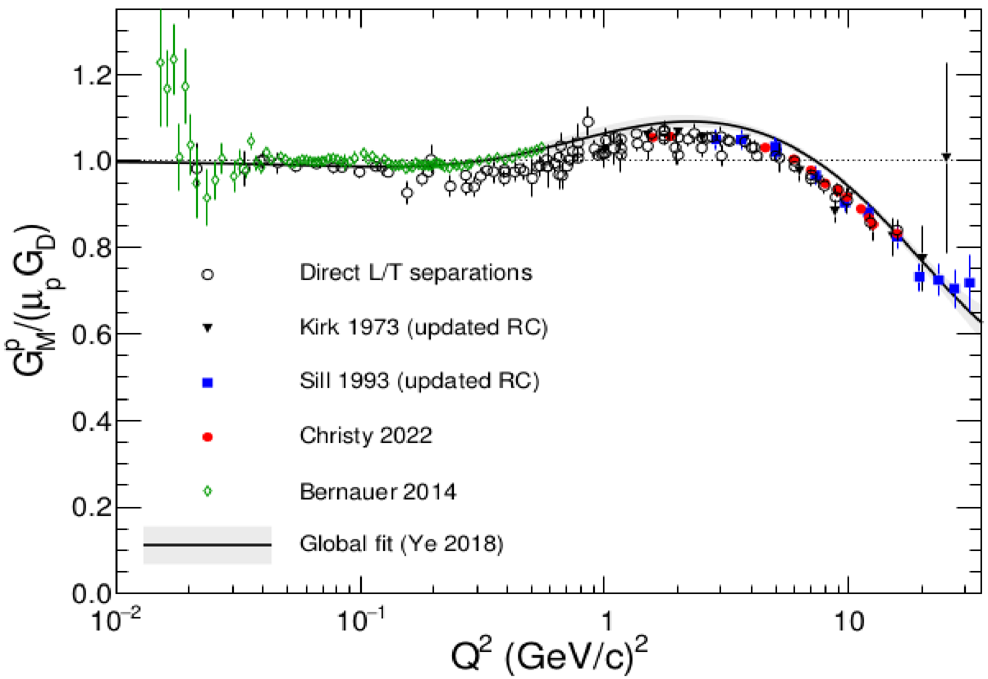
Plots from [Punjabi *et al.* Eur.Phys.J. **A51** (2015) 79]

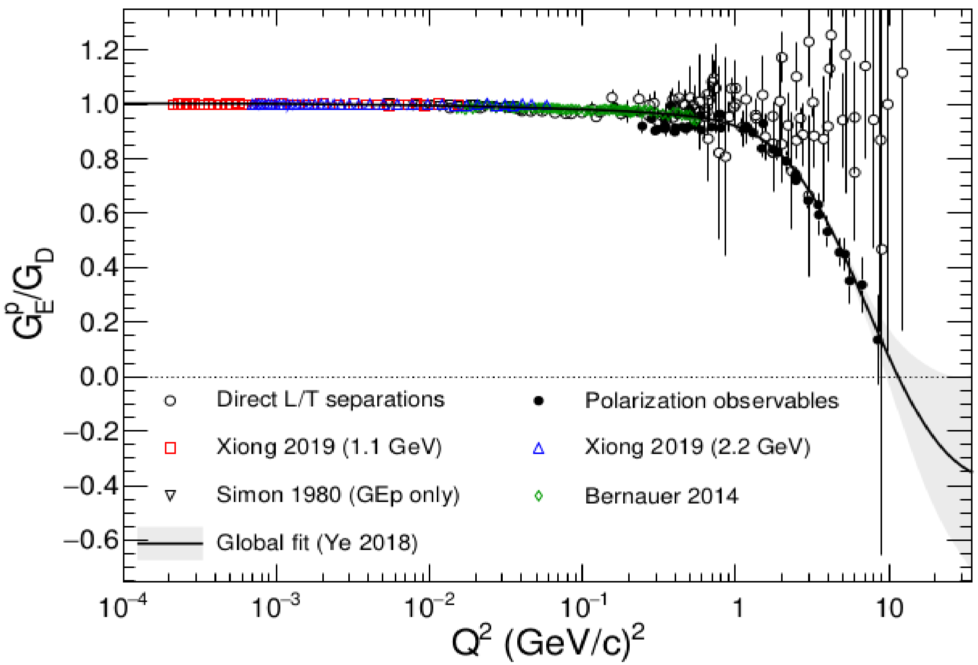


Vector Meson Dominance [arXiv:nucl-th/0609020 (2006)]
Constituent Quark Model [Phys. Rev. **C77**, 015202 (2008)]
Dyson Schwinger Equations (DSE) [Phys. Rev. Lett. **111,** 101803 (2013)]
DSE + quark-diquark [Phys. Rev. **C86**, 015208 (2012)]
Generalized Partons Distributions [Phys. Rev. **D60**, 094017 (1999)]

Form Factors Datasets: Proton

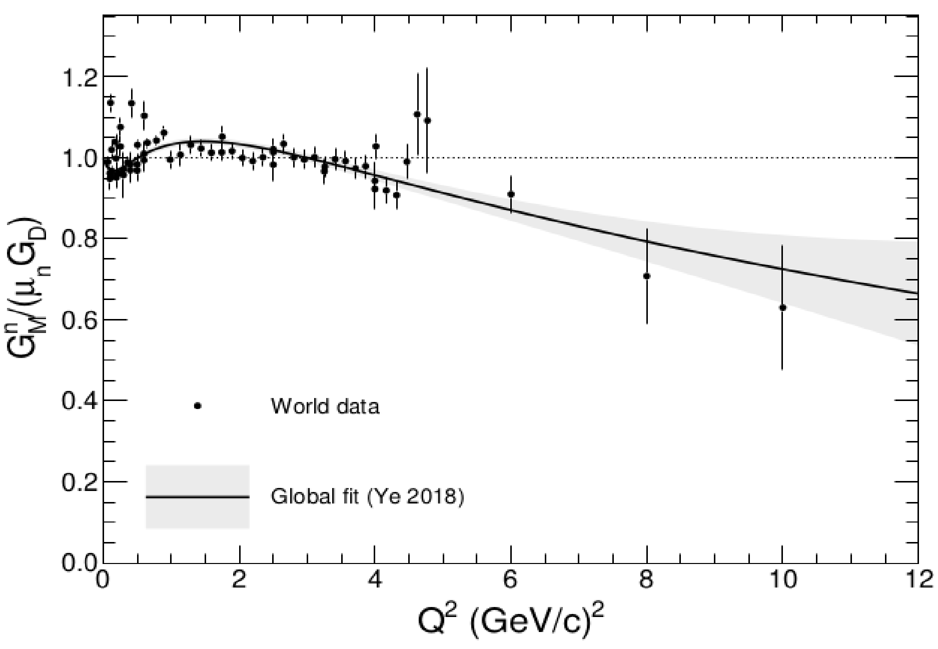
- World Form Factors Datasets [arXiv:2212.11107 [hep-ph]]:
  - Proton: Rosenbluth / polarization measurements discrepancies at large Q^2

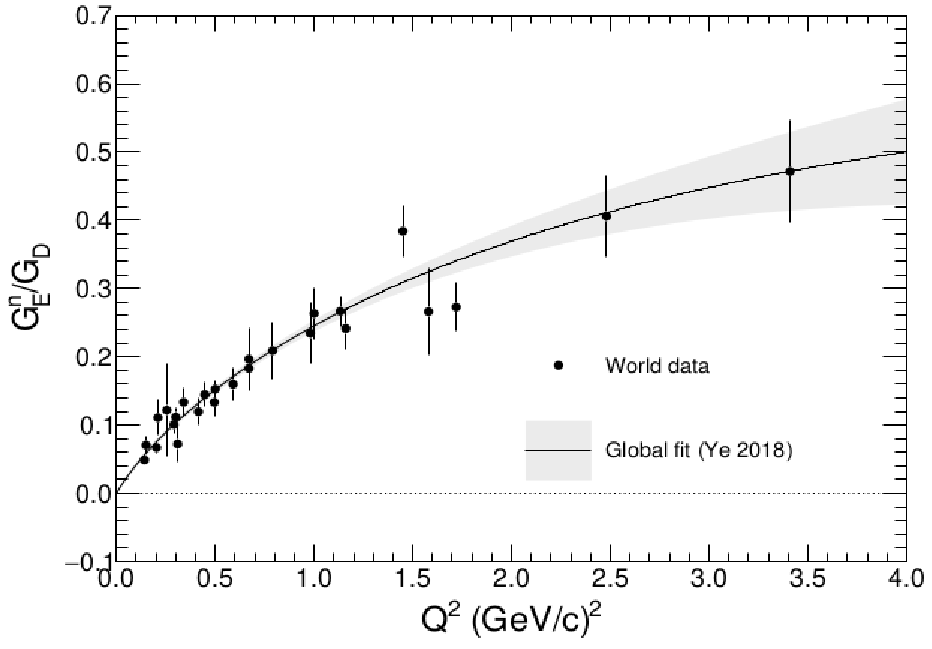




Form Factors Datasets: Neutron

- World Form Factors Datasets [arXiv:2212.11107 [hep-ph]]:
  - Proton: Rosenbluth / polarization measurements discrepancies at large Q^2
  - Neutron: Scarce data beyond Q^2 ~ 3-4 GeV^2



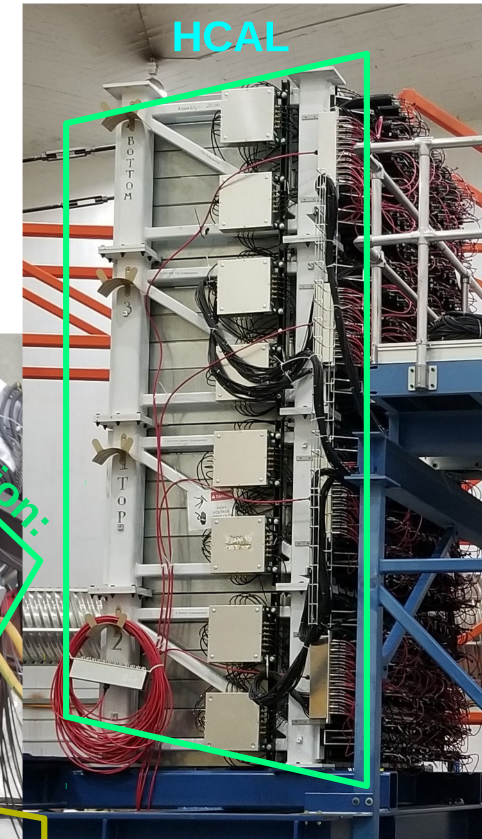


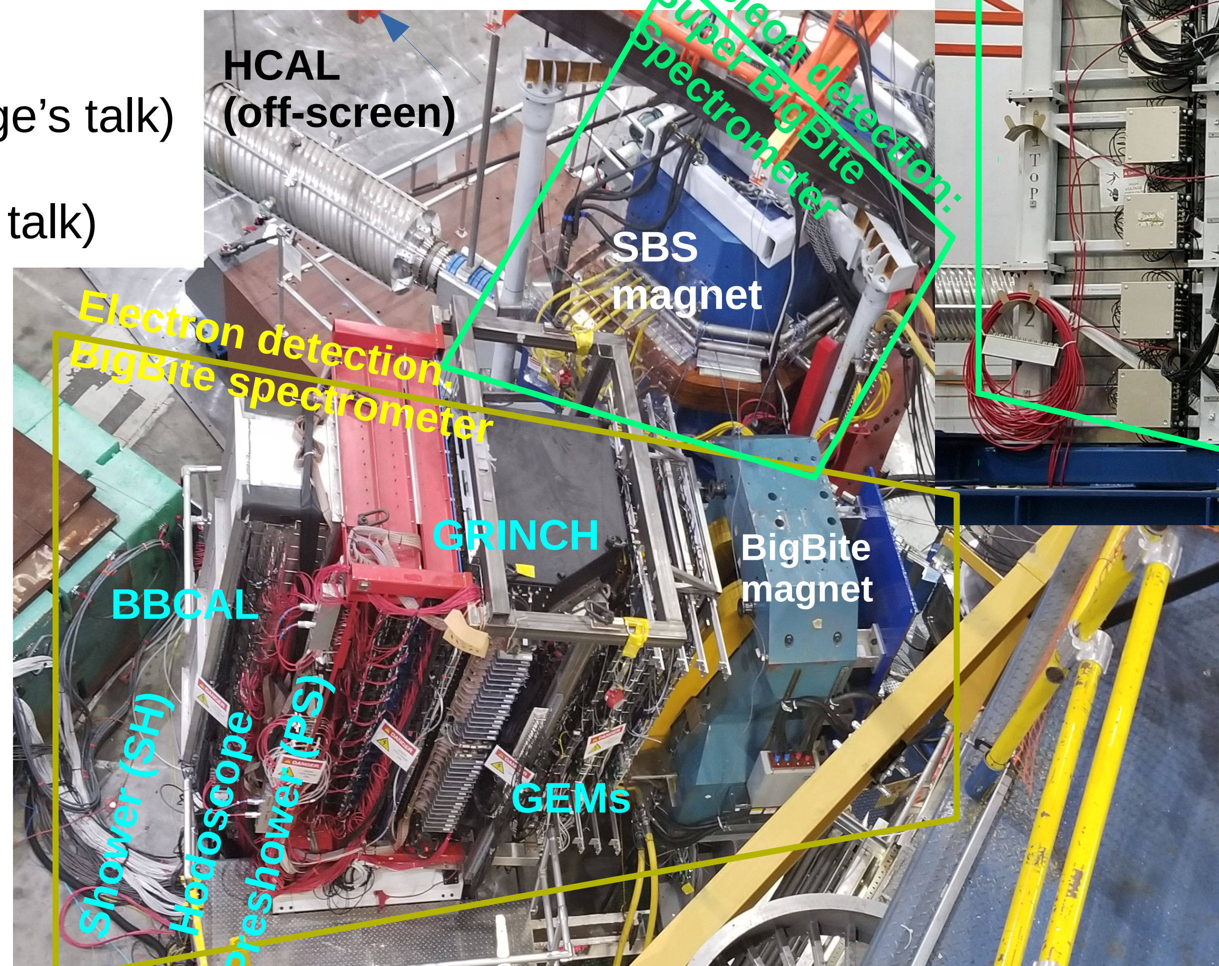
Super BigBite Spectrometer

- **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 (V. Gamage’s talk)
  - GEN-RP
  - GEP (D. Jones’ talk)

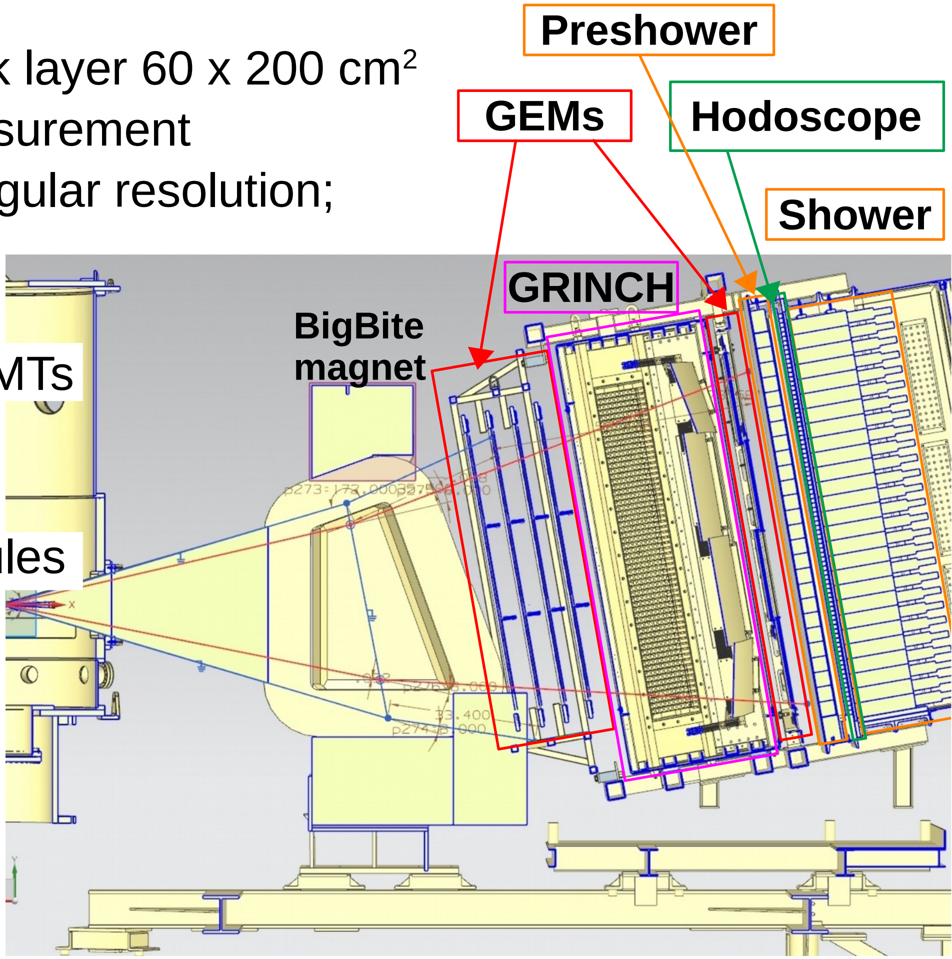
- Other Physics:
  - SIDIS
  - KLL
  - TDIS
  - nDVCS





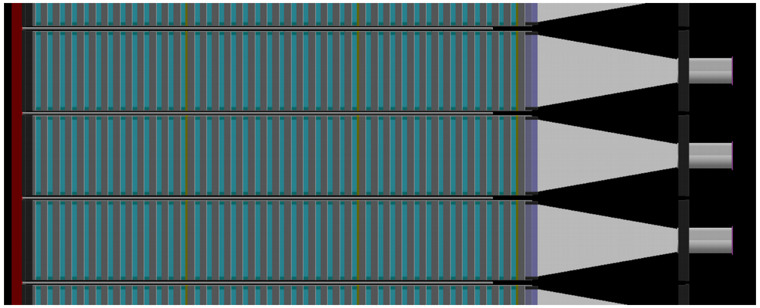
Super BigBite Spectrometer: BigBite

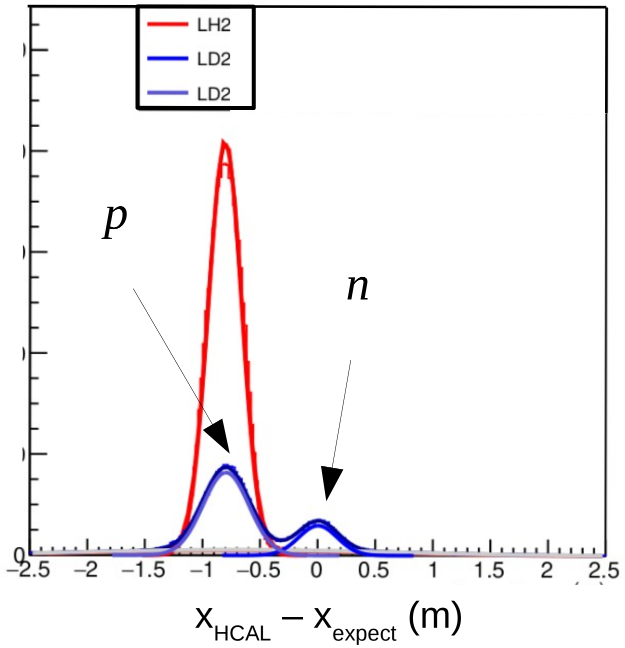
- Detector package tilted 10% behind dipole magnet
- **Function: Electron measurement**
- Detector package:
  - GEMs:
    - 4 front layers 40 x 150 cm^2, 1 back layer 60 x 200 cm^2
    - momentum trivector + vertex measurement
    - 1% momentum resolution, 1mr angular resolution;
  - GRINCH:
    - C4F8 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



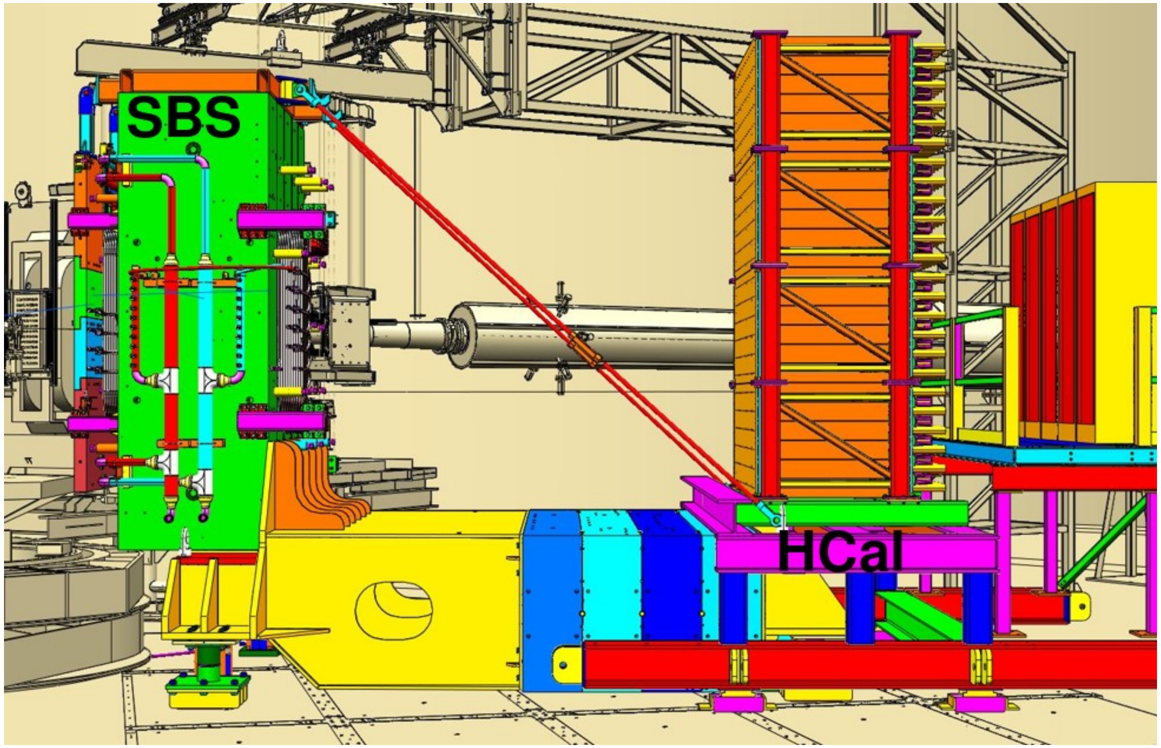
Super BigBite Spectrometer: HCal

- 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 %
- **Nucleon identification**



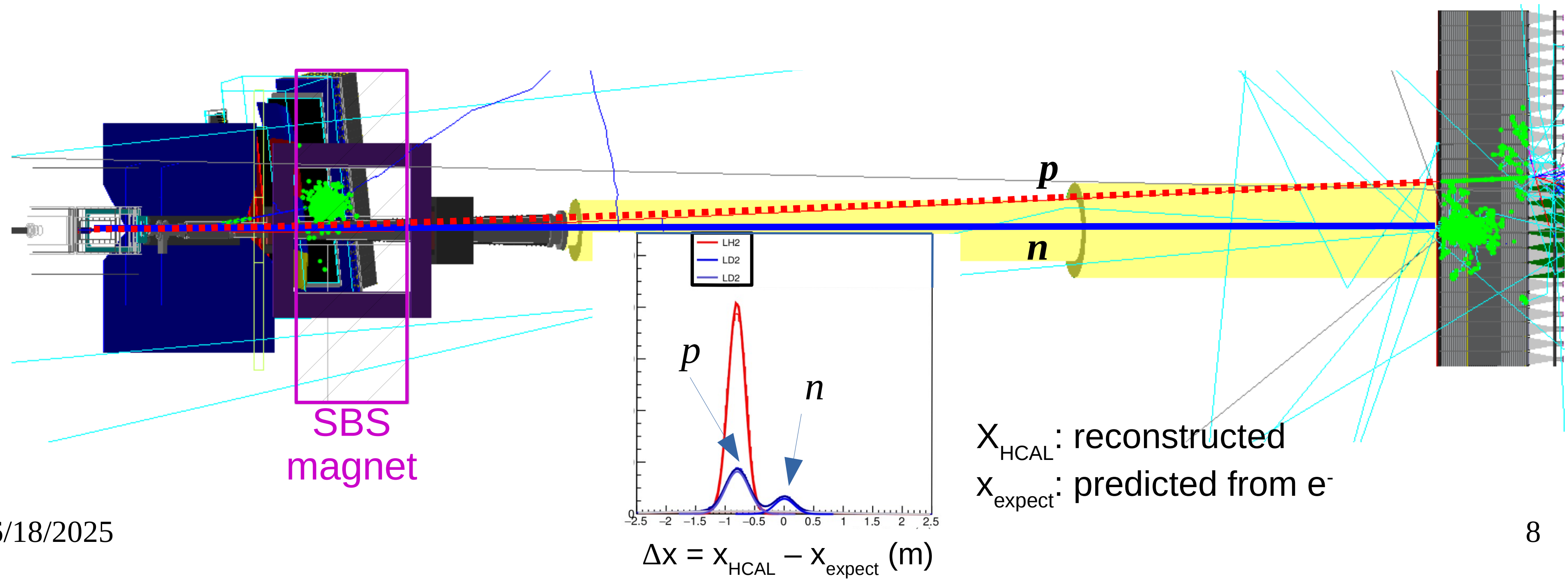


X_{HCAL}: reconstructed
x_{expect}: predicted from e^-



GMn Measurement

- GMn: E12-09-019 (A. Camsonne, B. Quinn, B. Wojteskhowski)
  - Measurement of G_M^n at five Q^2 values: 3, 4.5, 7.5, 10, 13.6 GeV^2
  - Durand technique: simultaneous *en*/*ep* measurement on D_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



GMn Measurement

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

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

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

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

neutron/proton detection efficiency

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

GMn Measurement

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  - $\tau_n (G_M^n)^2 + \epsilon (G_E^n)^2 = R_{n/p} \boxed{\left(\tau_p (G_M^p)^2 + \epsilon (G_E^p)^2\right)}$ From proton data

  - $\boxed{(G_M^n)^2 = \frac{1}{\tau_n}\left(R_{n/p}\left(\tau_p (G_M^p)^2 + \epsilon (G_E^p)^2\right) - \boxed{\epsilon (G_E^n)^2} - \boxed{\delta_{2\gamma}}\right)}$

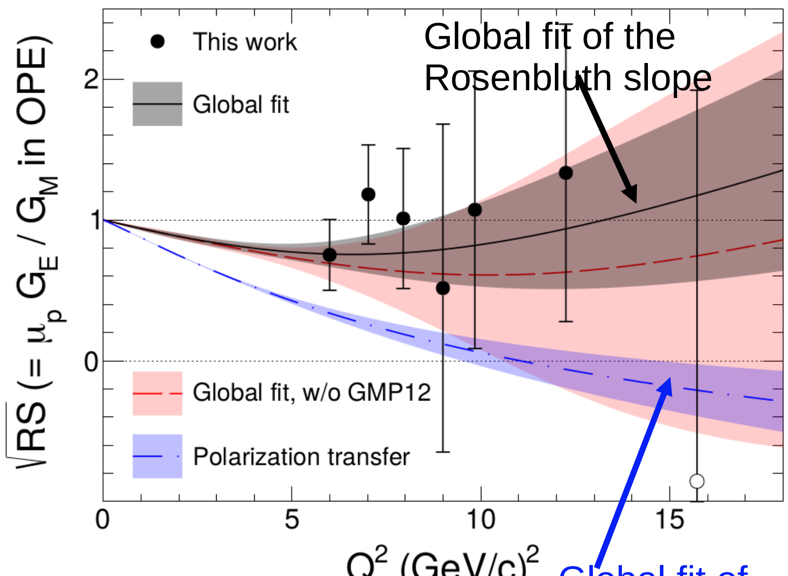
From GEn fits

From calculations

nTPE Measurement

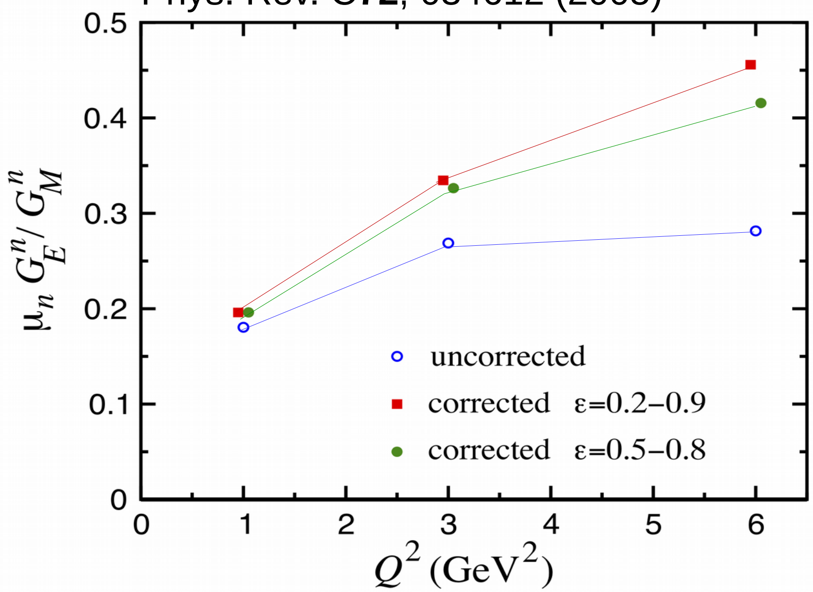
- nTPE: E12-20-010 (E.F., S. Alsalmi, B. Wojteskhowski)
  - **Rosenbluth/TPE measurement on the neutron, Q^2 = 4.5 GeV^2**
  - measurement of σ_{en}/σ_{ep} at two beam energies
  - σ_{en}/σ_{ep} superratio dependent on proton and neutron Rosenbluth slopes
  - knowledge on proton Rosenbluth slope => neutron Rosenbluth slope;
  - NTPE = Rosenbluth slope <=> polarization data discrepancy

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



Global fit of polarization transfer data

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



Uncorrected $\mu_n G_E^n/G_M^n$ (Polarized data)
Mergell, Meissner and Drechsel,
Nucl. Phys. A596, 367 (1996)

$\mu_n G_E^n/G_M^n$ +TPE
ε = 0.2 <=> 0.9

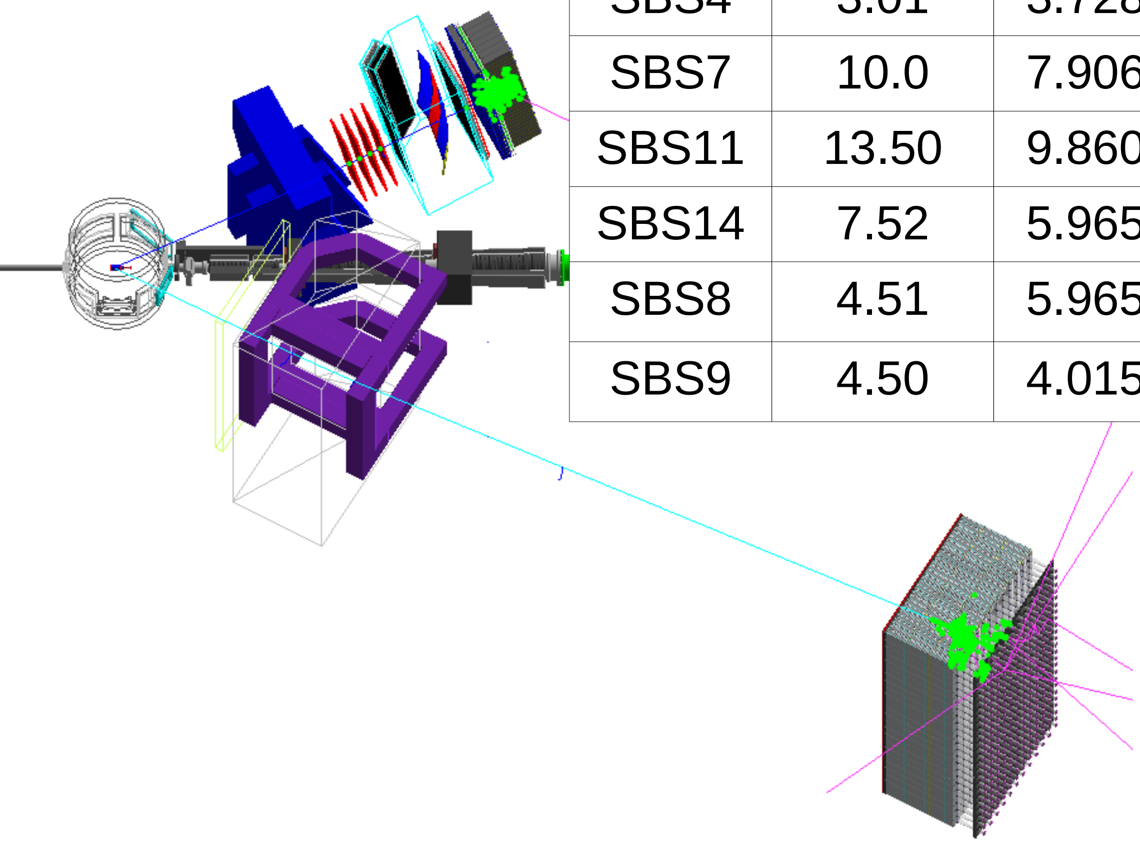
$\mu_n G_E^n/G_M^n$ +TPE
ε = 0.5 <=> 0.8

nTPE Measurement

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

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	NTPE
SBS9	4.50	4.015	1.618	49.0	22.5	0.512	

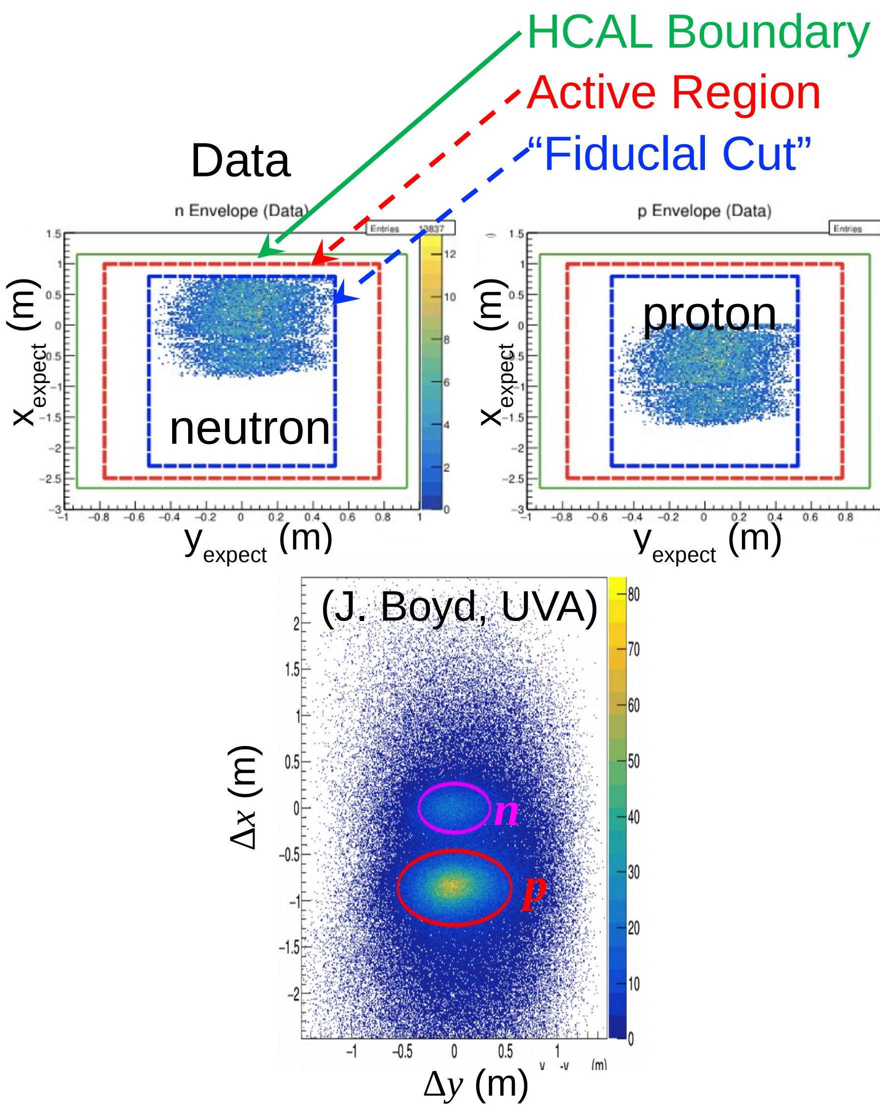


Elastic Selection

- 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*
  (eliminates systematics from neutron/proton acceptance)

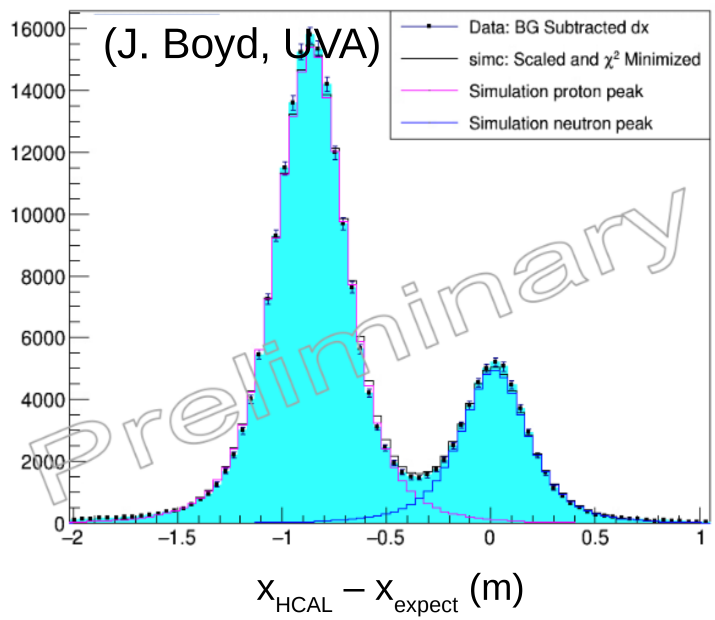
- Exclusivity cut:
  - *W^2 within elastic nucleon peak;*

- 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

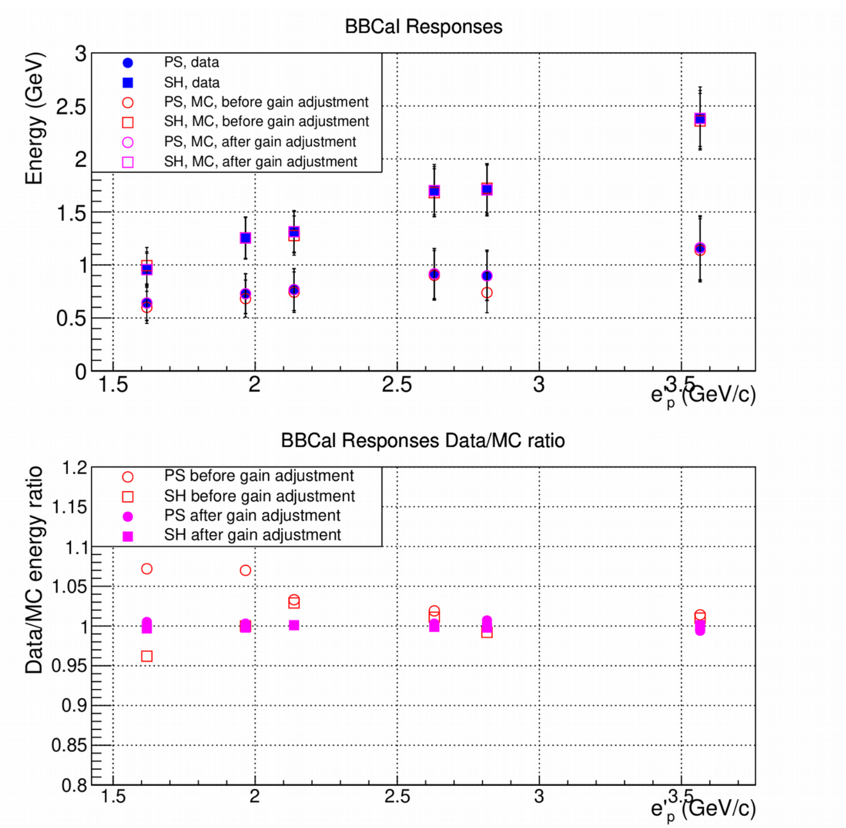
- Monte Carlo quasi elastic *en*/*ep* *including radiative corrections* (SIMC):
  - MC: kinematic "migration" due to radiative corrections, energy losses, etc
  - MC cross section models known, but inexact
  - Comparison with data counts: correction of MC correction models
  - => provides correction term: $R_{n/p} = \frac{\sigma_{en}}{\sigma_{ep}} = \frac{(N_{en \to en})_{meas}}{(N_{ep \to ep})_{meas}} \boxed{f_{corr}}$
  - Example: MC/data yield comparison, SBS8 (high ε):



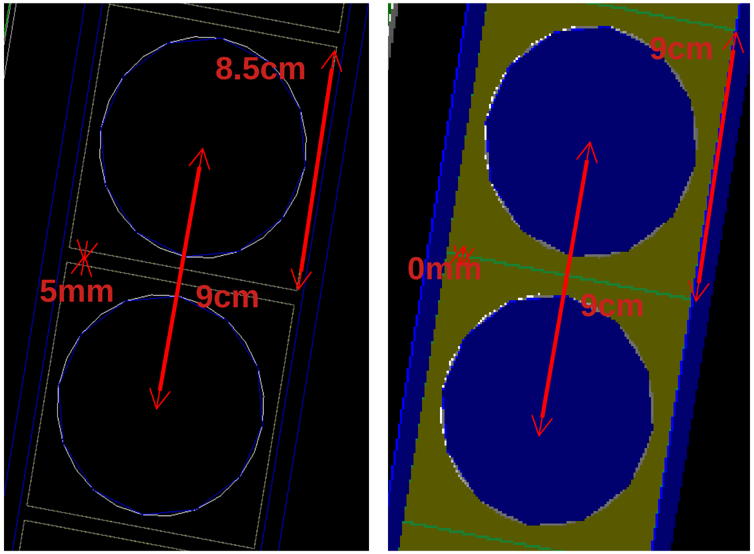
x_{HCAL}: reconstructed
x_{expect}: predicted from e^-

Monte Carlo Improvements

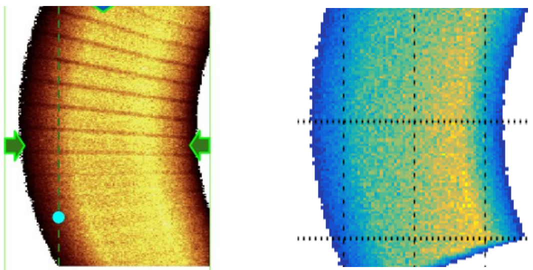
- Multiple Monte Carlo improvements:
  - Small Geant4 geometry fixes:
    - Preshower blocks geometry (featured)
    - Scattering chamber window clearance;
  - Adjustement of digitization gains for HCal, shower, preshower (featured)



Preshower block geometry:
before → after

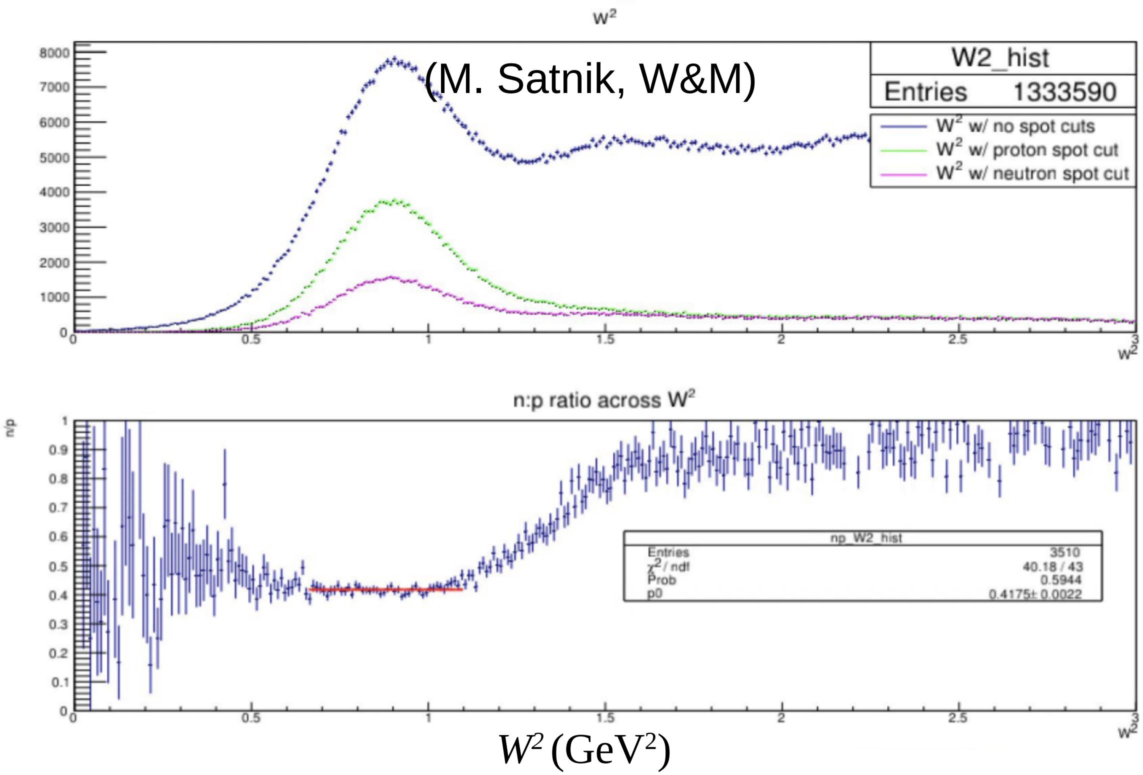


Nucleon expected position from reconstructed electron:
before → after



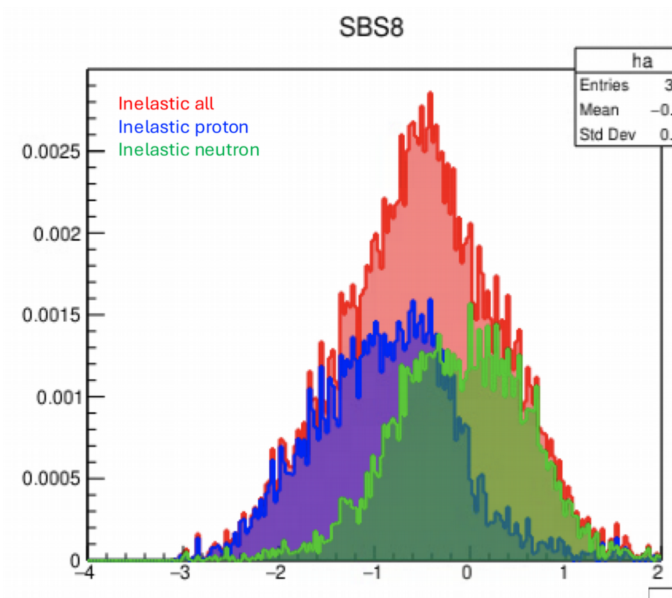
Selection Optimization

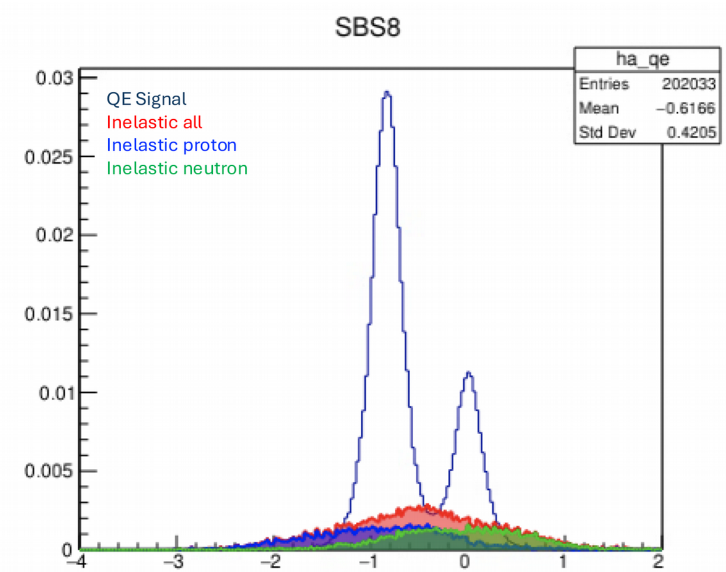
- ***n/p*** **stability over selection cuts:**
  - W^2;
  - E_{PS}, E_{SH}, E_{HCAL};
  - t_{HCAL}-t_{Shower};
  - Δx, Δy, fiducial cuts;

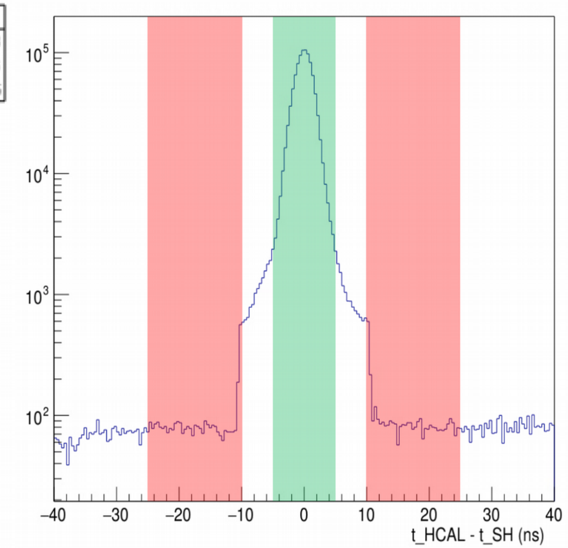


Systematic uncertainties: Inelastic contamination

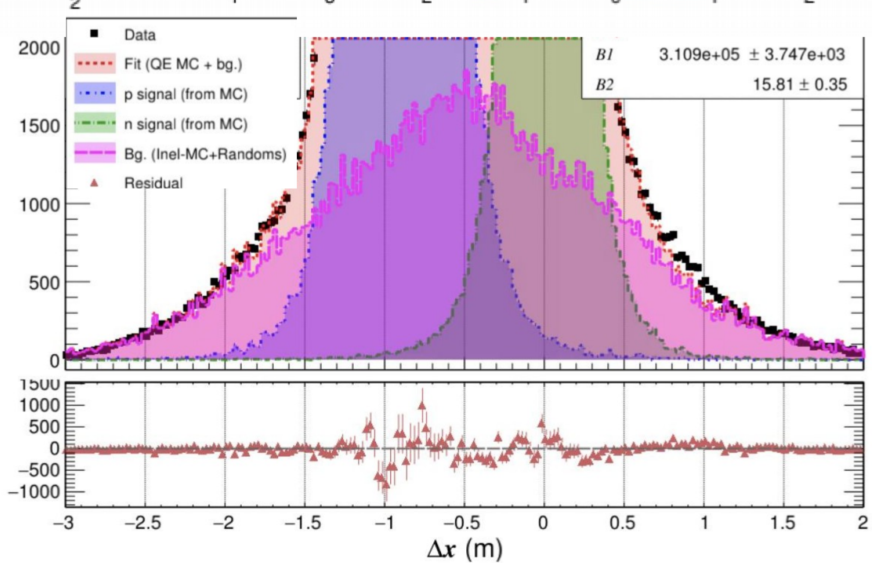
- Latest improvements on estimation of inelastic contamination:
  - Inelastic Monte Carlo combined with out-of-time events





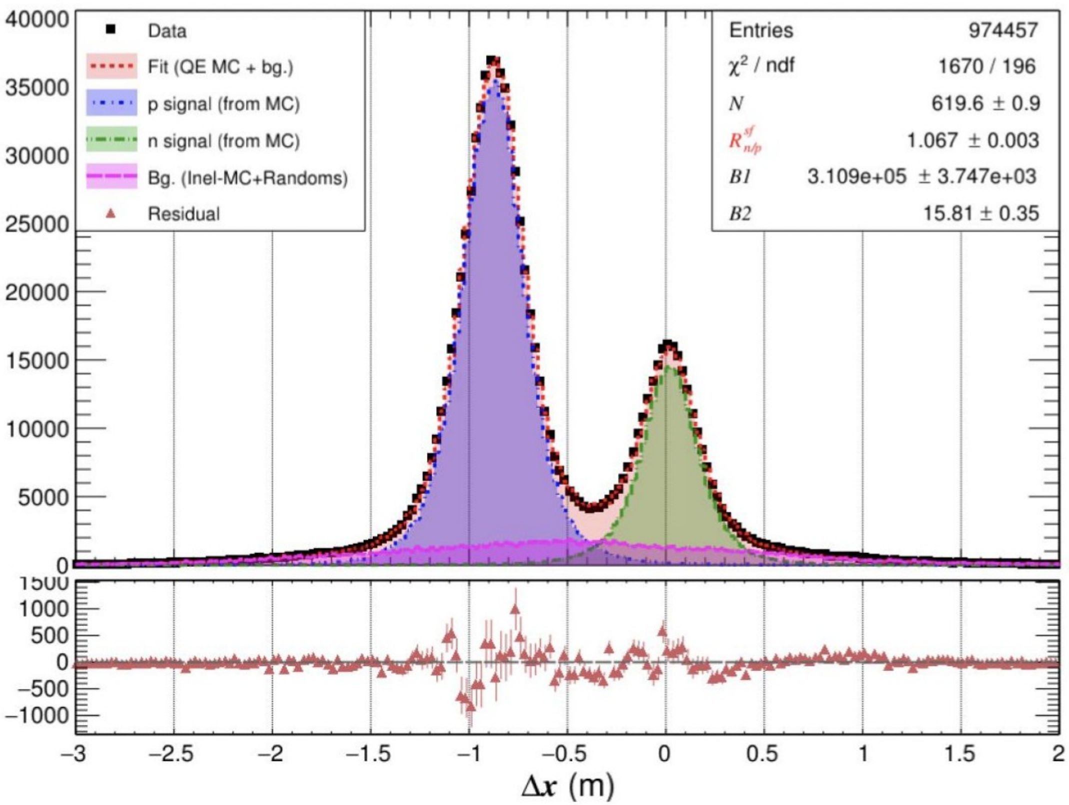


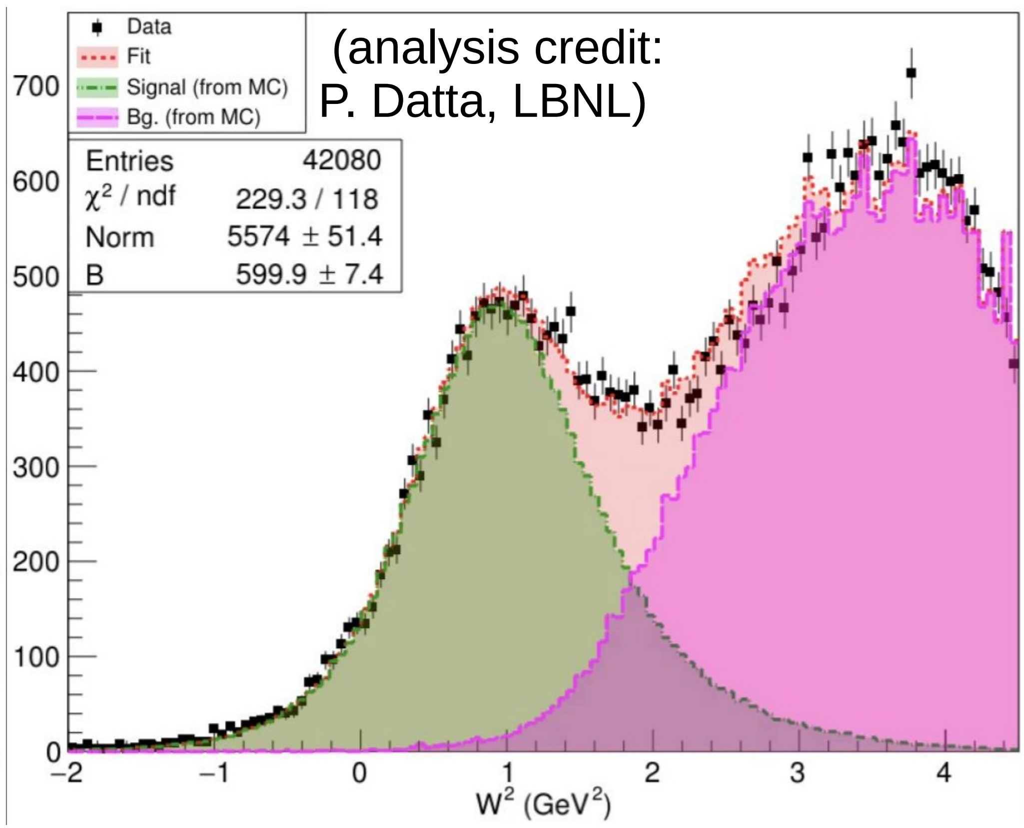
(analysis credit:
P. Datta, LBNL)



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



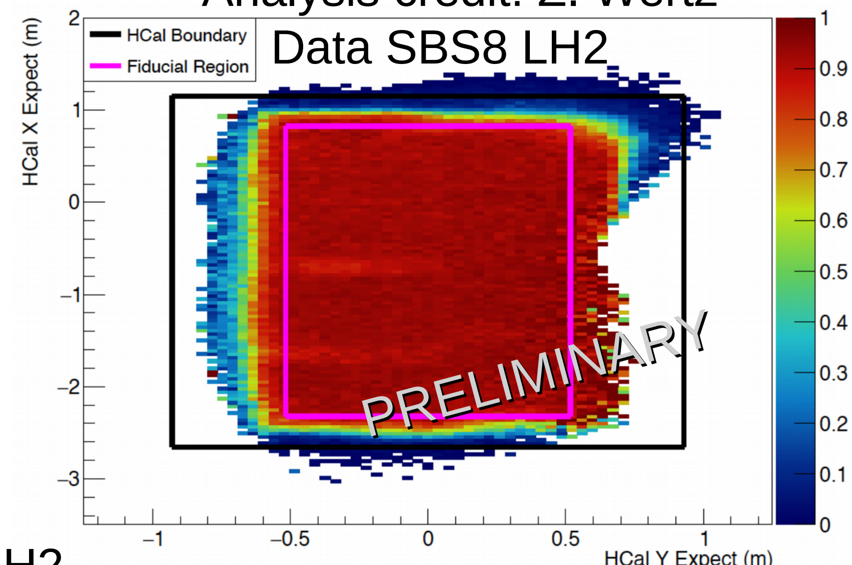


(analysis credit:
P. Datta, LBNL)

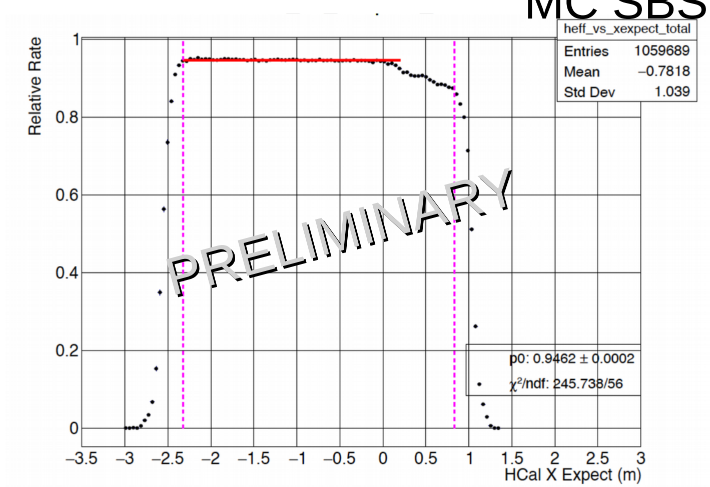
HCAL Non-Uniformity Corrections

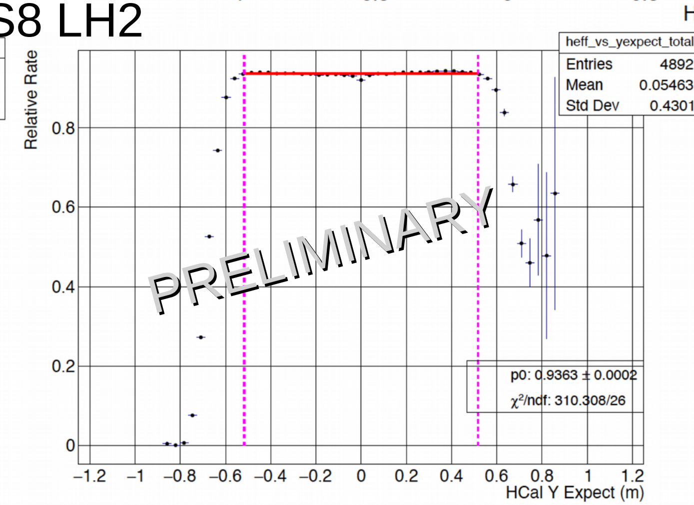
- Method to correct for HCal efficiency non-uniformity:
  - Reweight MC events with HCal non-uniformity map;
  - Map efficiency along x_{expect}, y_{expect};
  - Efficiency analysis for data, MC;
    - MC weight: η_{data}/η_{MC};
    - deployed in analysis;
  - Hurdle:
    - proton and neutron detection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

Analysis credit: Z. Wertz



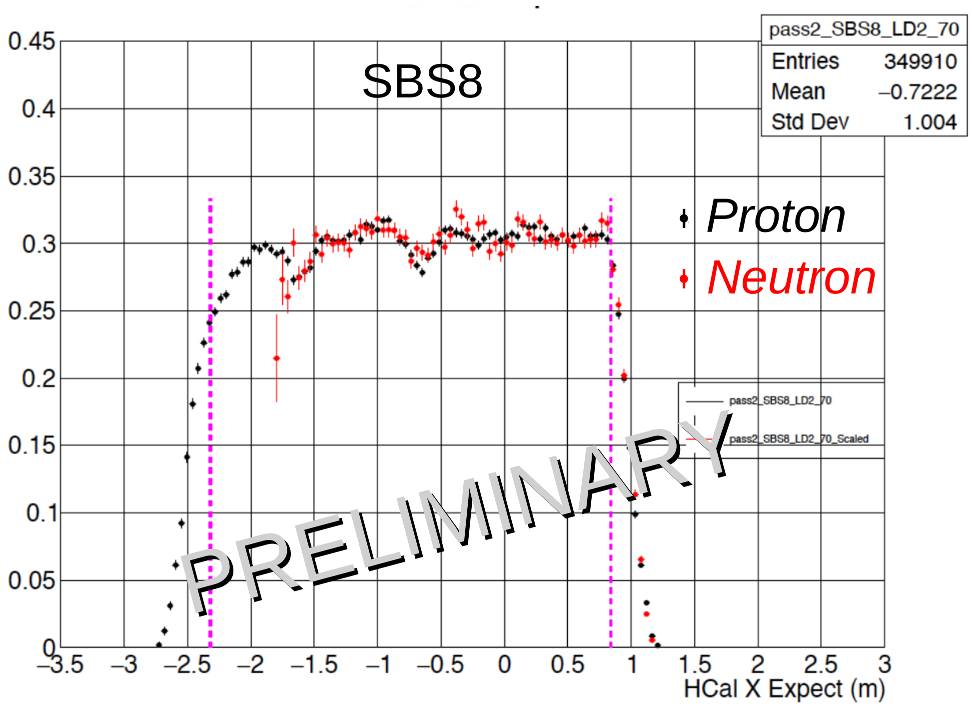
MC SBS8 LH2

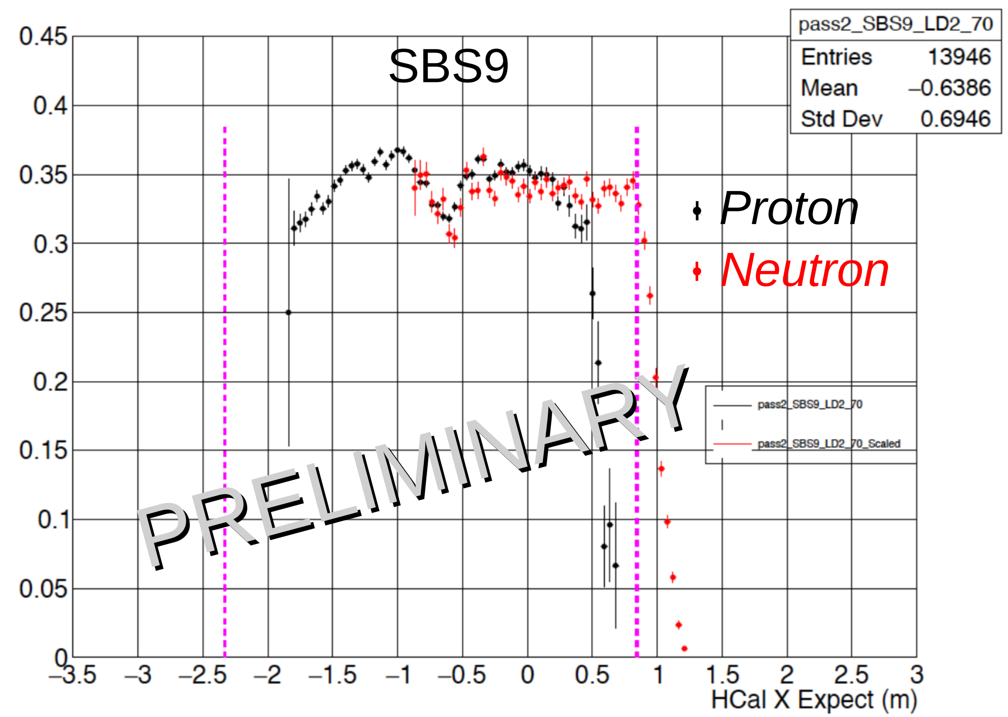




HCAL Non-Uniformity Corrections

- 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 σ_{en}/σ_{ep} by ~0.2 % (SBS8) and ~0.5 % (SBS9);
  - Other sources of systematics:
    - Lack of absolute neutron detection efficiency measurement;
    - Absolute proton detection efficiency uncertainty larger at high Q^2;



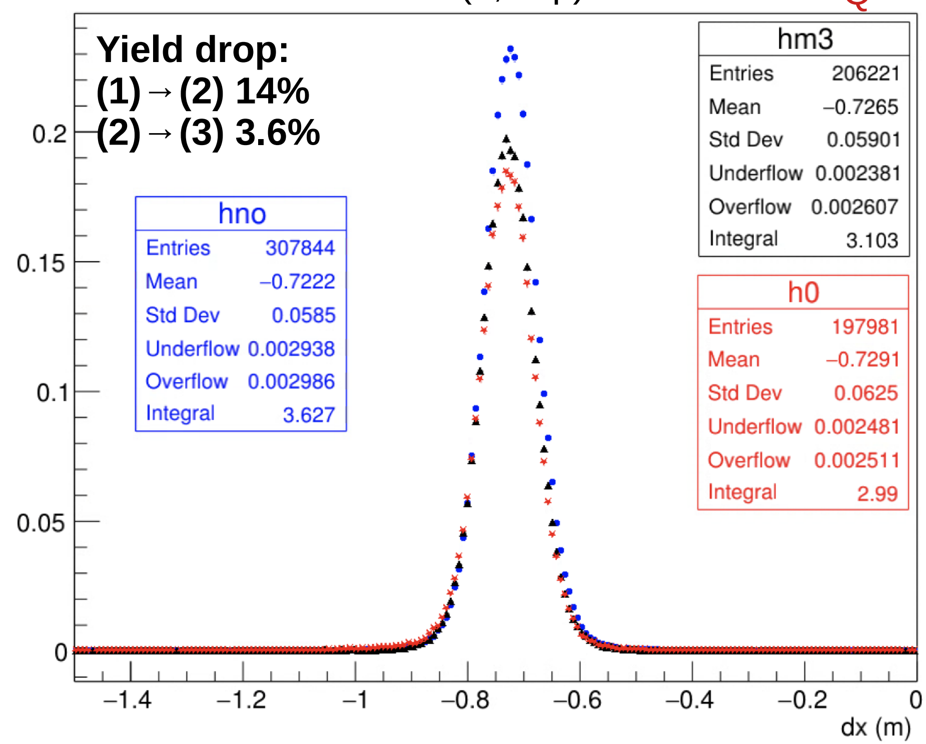


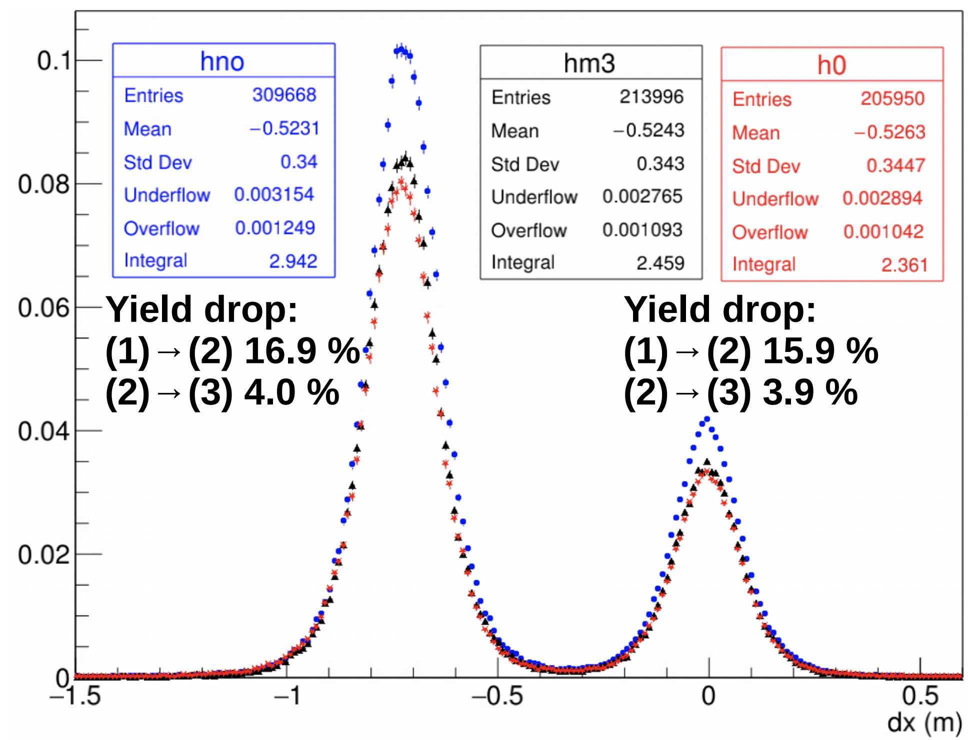
Analysis credit: E. Wertz

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

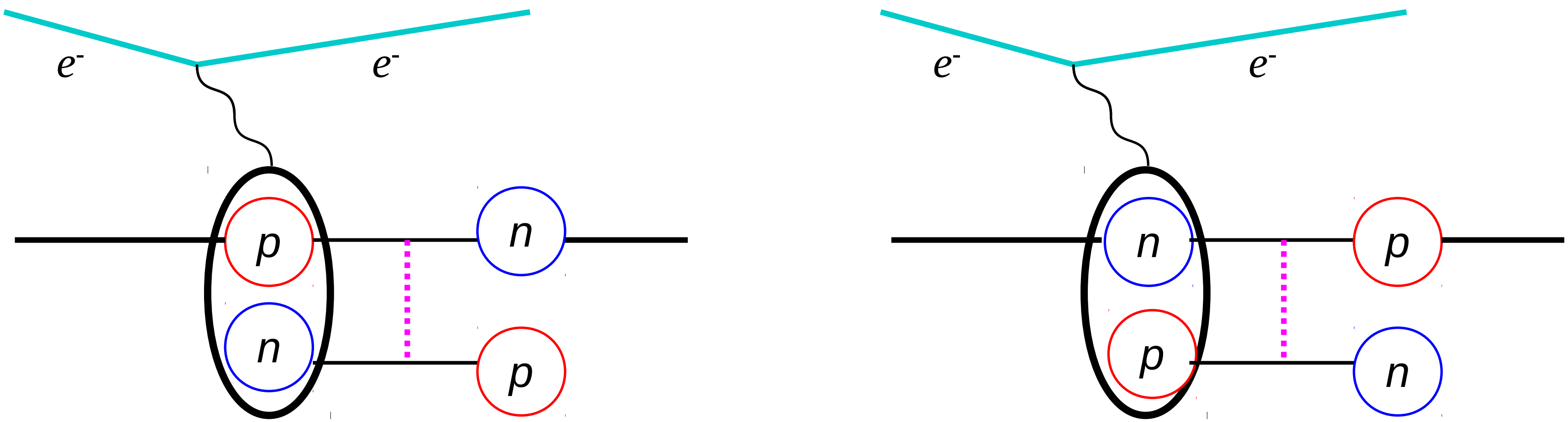
H(e, e' p) $Q^2 = 13.5\ \text{GeV}^2$ D(e, e' p) + D(e, e' n)





Systematic uncertainties: FSI

- Final state interactions calculated by M. Sargsian:
  - ◘ calculations of final state charge exchange $ep \rightarrow en$ and $en \rightarrow ep$ on deuterium



  - ◘ Since D is symmetric, $ep \rightarrow en \equiv en \rightarrow ep$:
    - ♦ ratio $R_{n/p}$ basically not affected
    - ♦ uncertainty on ratio $R_{n/p}$ extremely small

Preliminary systematic uncertainties

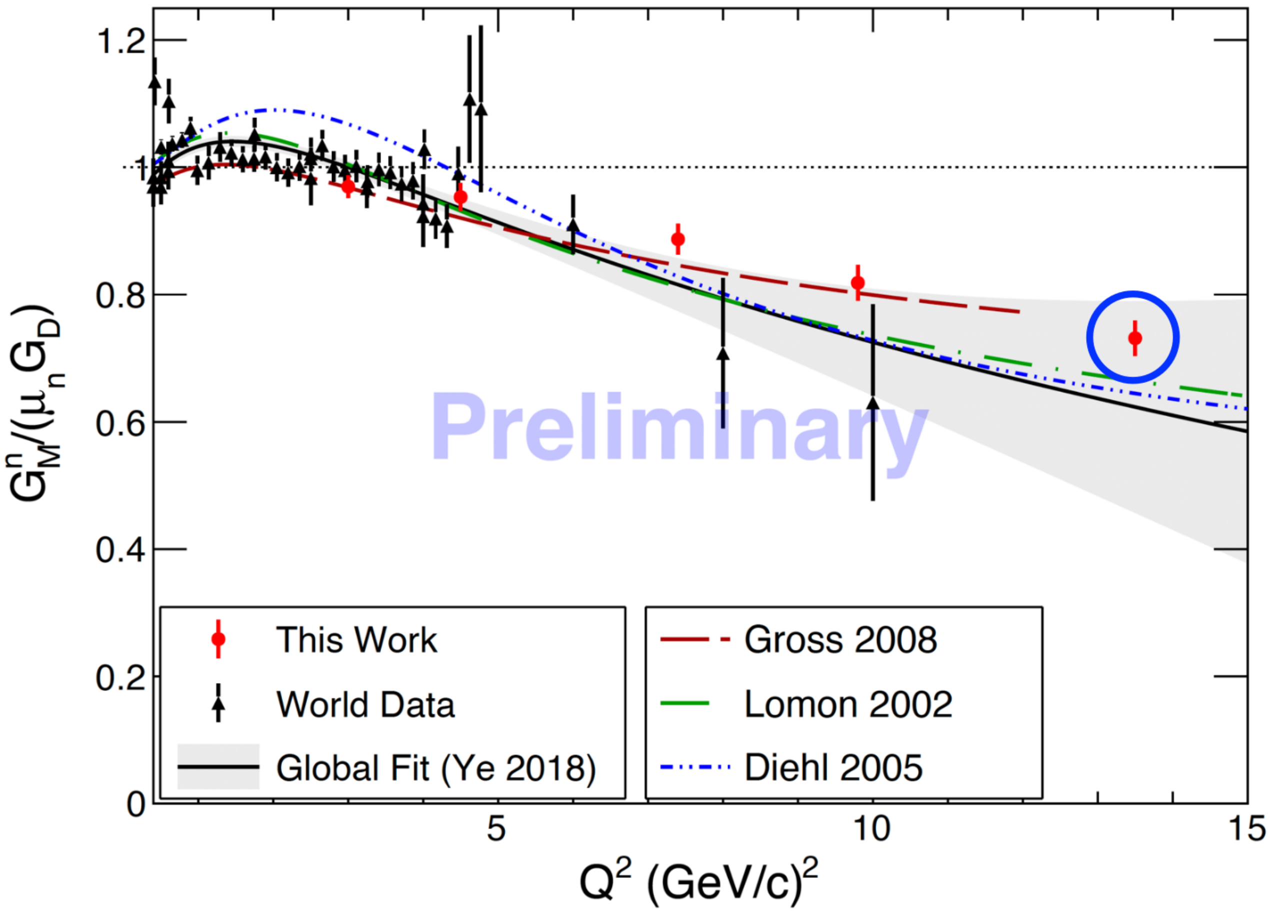
- Systematics analysis credit: P. Datta (LBNL);
  - Improvement can be achieved for radiative corrections and nucleon detection efficiency

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

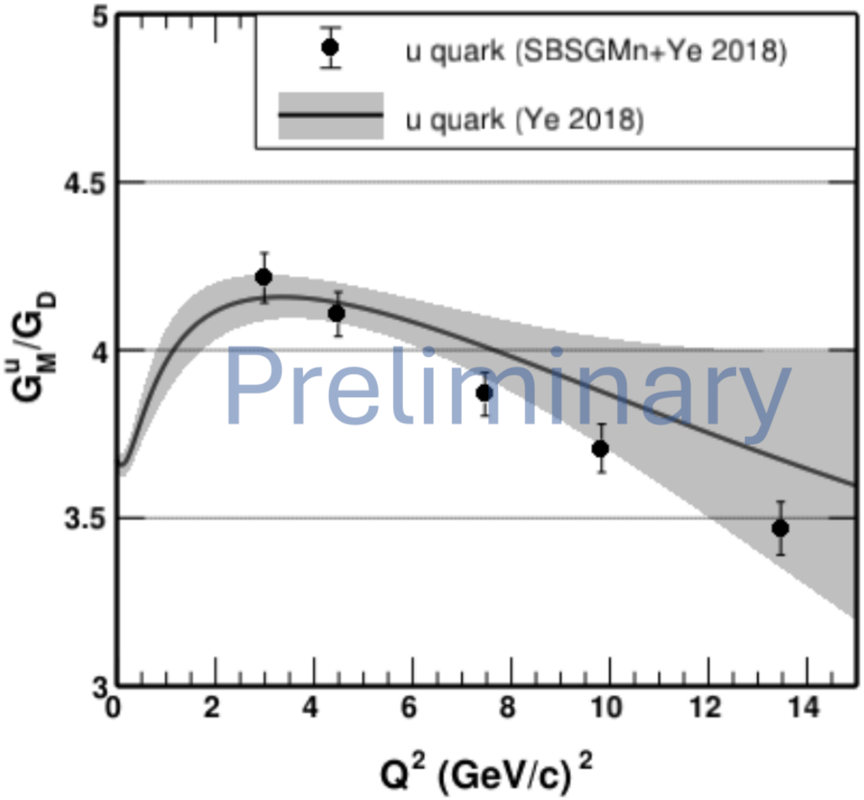
GMN Preliminary Results

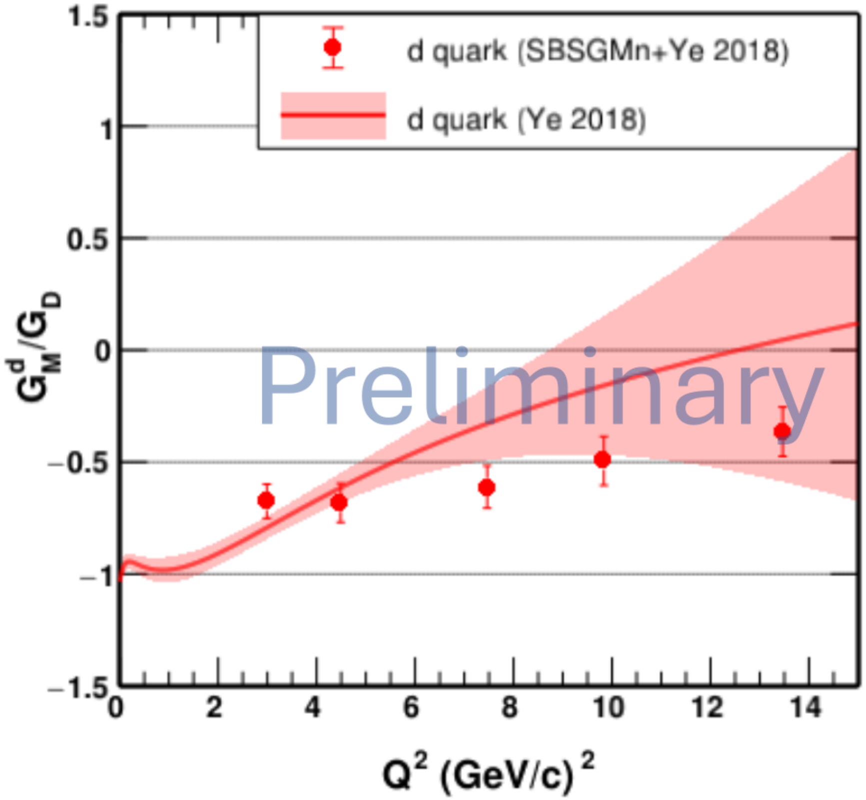
- Shown at the *APS 2025 SBS mini-symposium* by P. Datta (LBNL)



Flavor separation

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

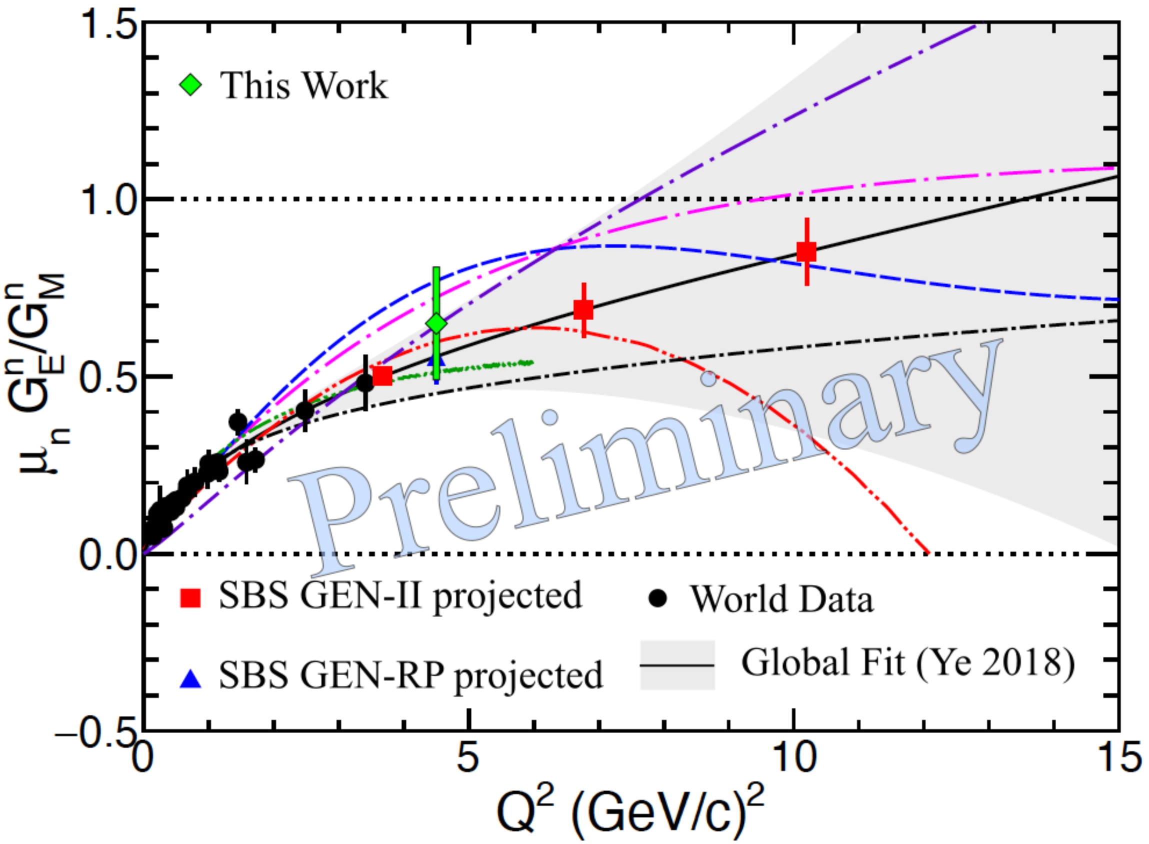




NTPE Preliminary Results

- 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;
  - HCal systematics uncertainties:
    - Non-uniformity estimated to 0.5% at most;
    - Remaining uncertainties from lack of absolute neutron detection efficiency;
  - Preliminary estimation of radiative corrections;
  - Uncertainty from Final State Interactions extremely small;
- 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;
- Not all the work that has been put in these results can be presented!
- Massive credit to all students and everyone involved!

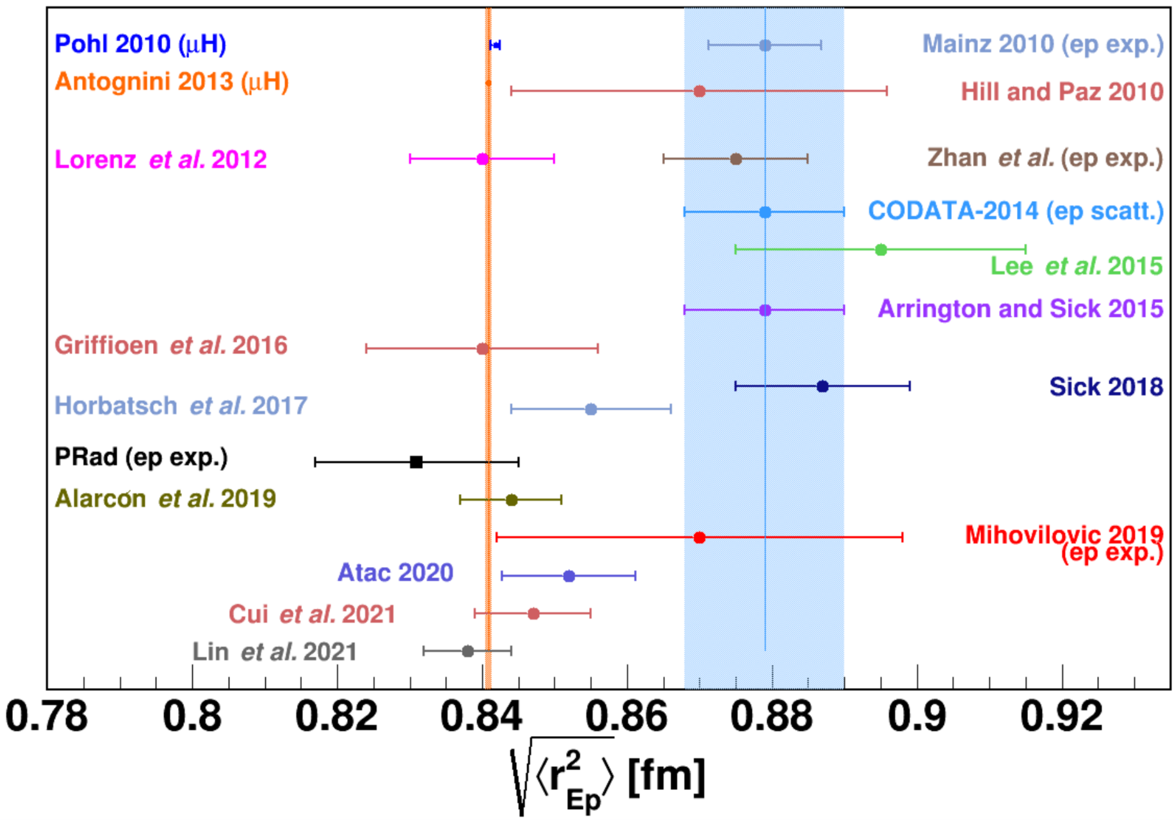
Back up

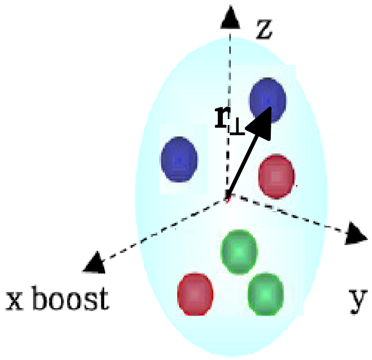
Open Questions in Nucleon Structure
Form Factors

Form factors ≡ **charge spatial distribution inside the nucleon**

- Measured by *elastic electron nucleon scattering;*
- linked to proton size [R. Hofstadter, R.W. McAllister, Phys. Rev. 98, 217 (1955)]
- Proton radius puzzle [R. Pohl, A. Antognini, F. Nez, *et al.* Nature 466]
  (*not* the focus of this talk!)
- Tackled by FF measurements at ***low*** **Q²**: MUSE @ PSI, PRad @ Jefferson Lab, ...;

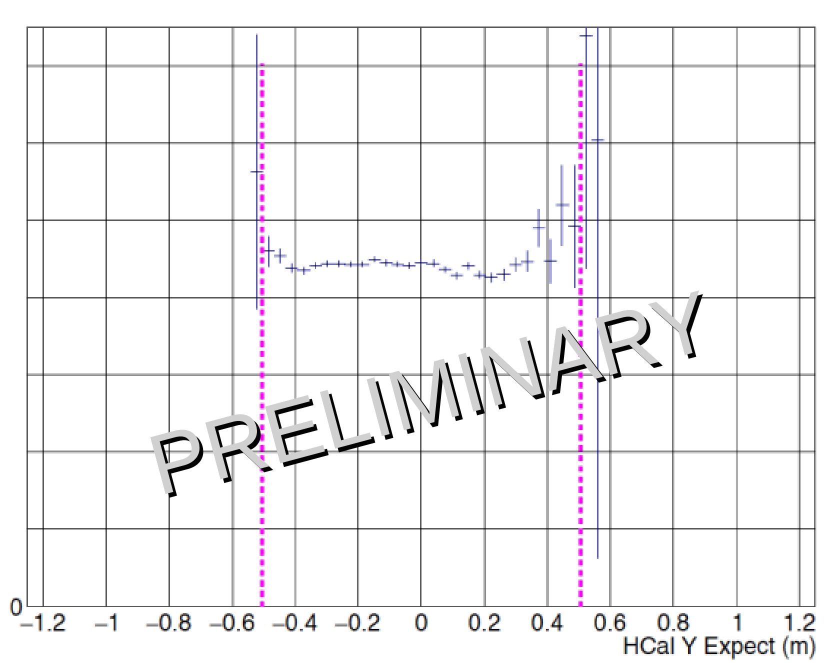
[H. Gao, M. Vanderhaeghen Rev. Mod. Phys. 94, 015002]





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

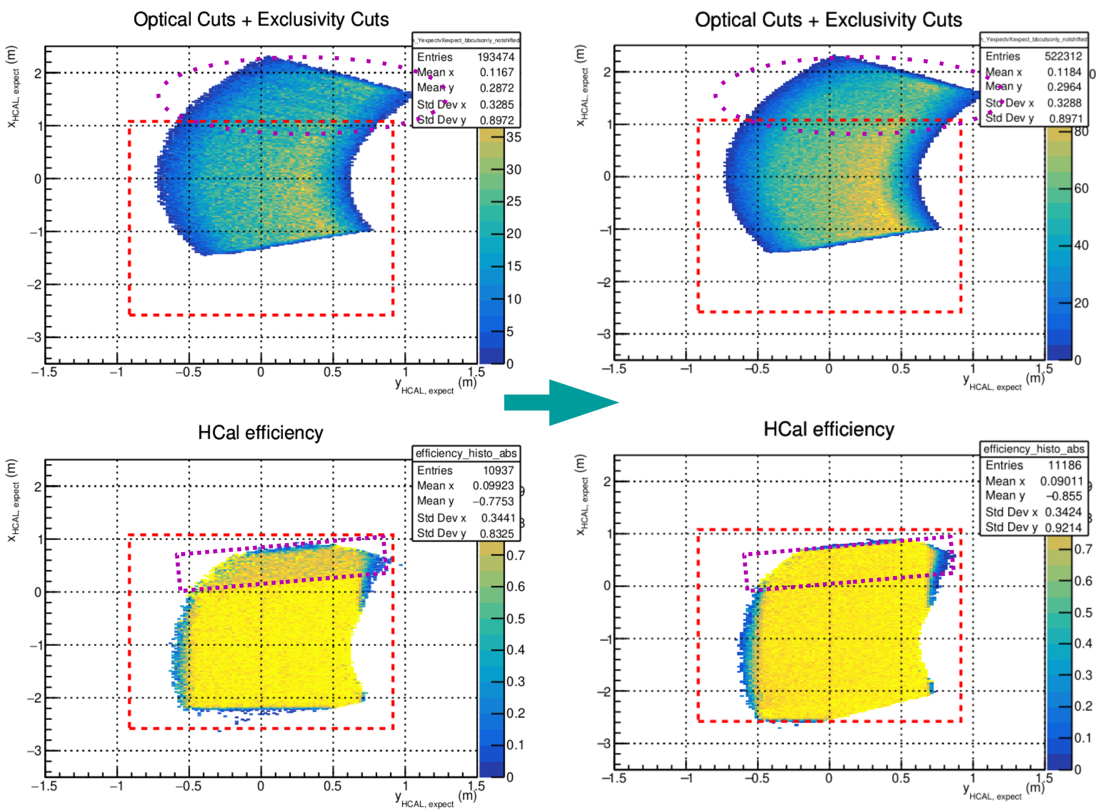
Monte-Carlo Fixes: G4SBS Geometry

- 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;

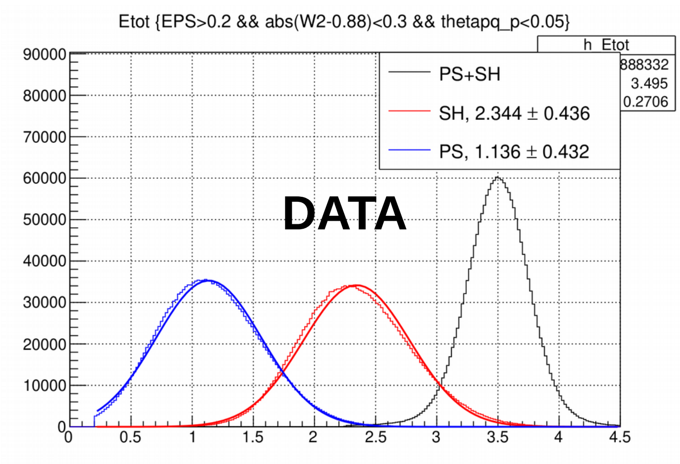


Before fixes

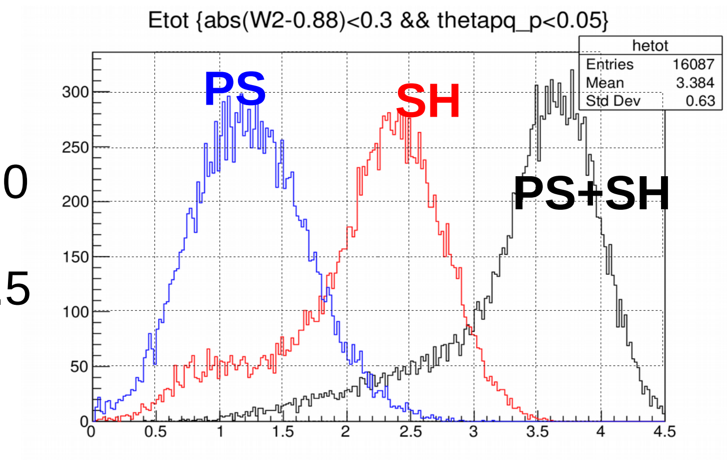
After fixes

Monte-Carlo Fixes: Digitization

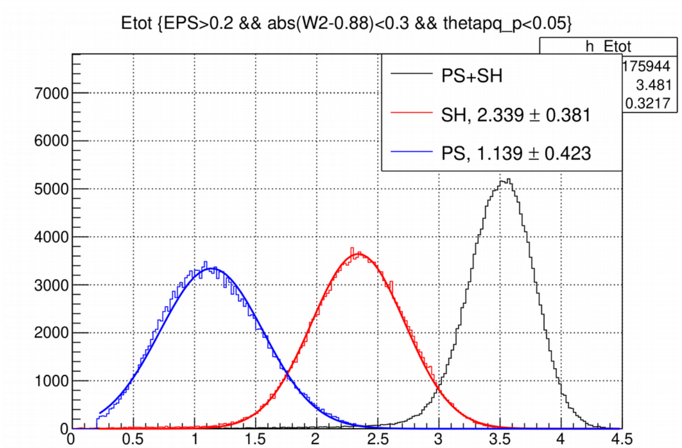
- Digitization parameters for BBCal readjusted to fit the data better (e.g. SBS8)
- *HCal gain adjustments underway*



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

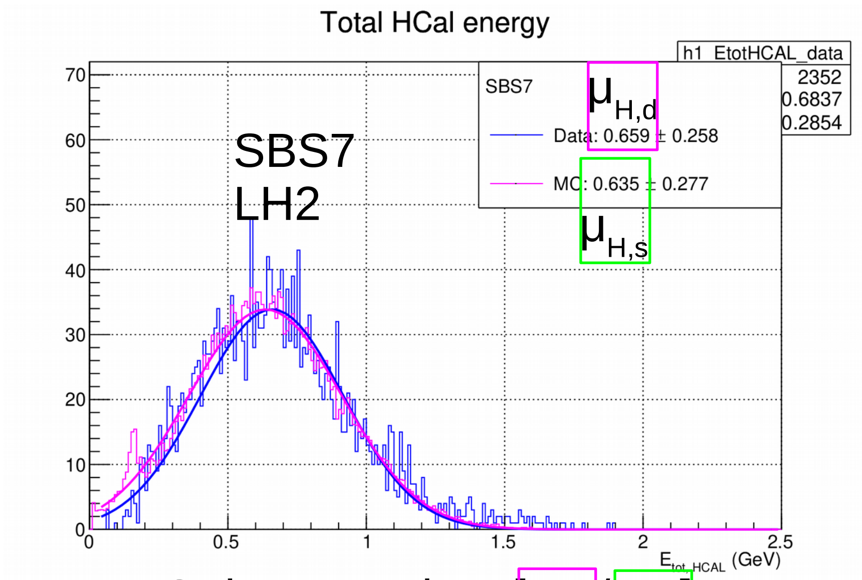


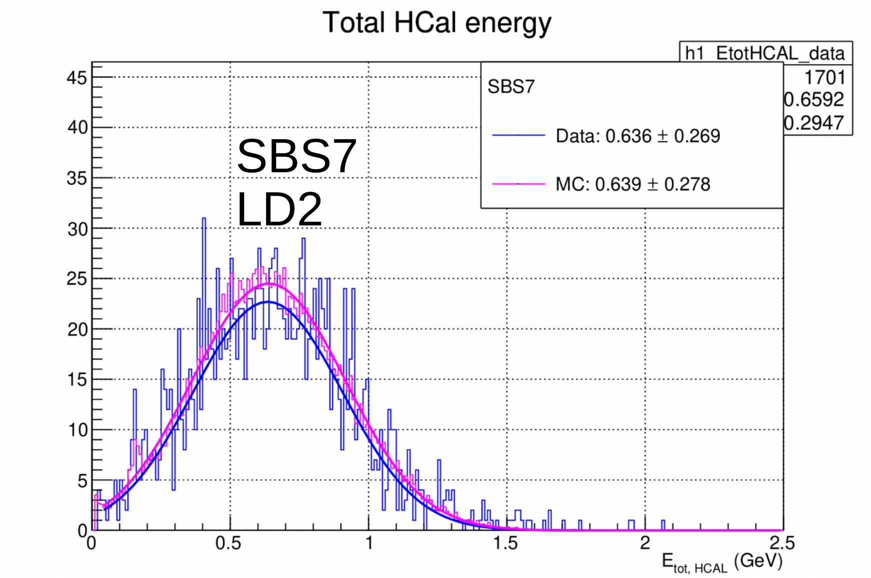
PS gain: 1.84e6
PS pedestal noise 3.0
SH gain: 8.03e5
SH pedestal noise 3.0



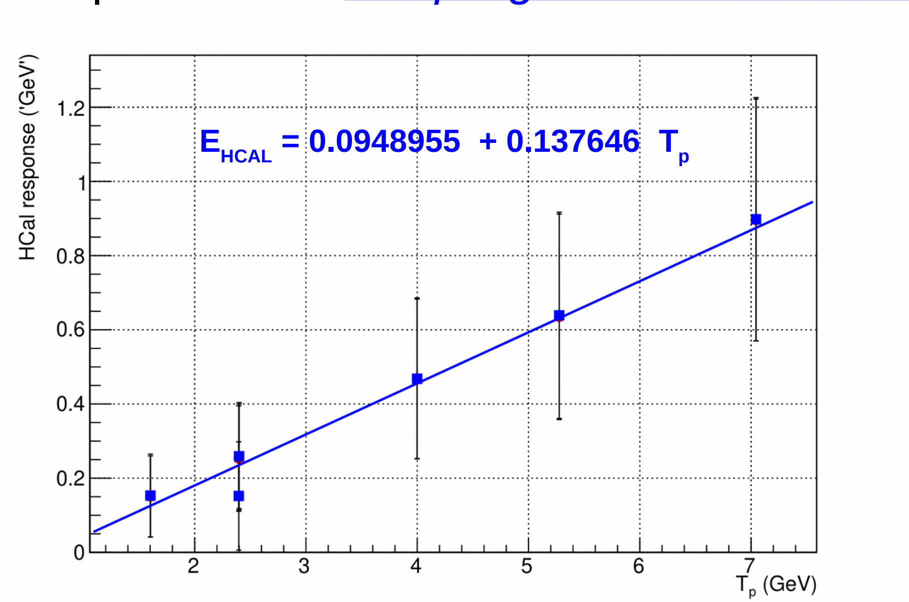
Digitization gain adjustments: BBPS, BBSH

- Link to tables for all GMN kinematics: [Share point], [spreadsheet on wiki]

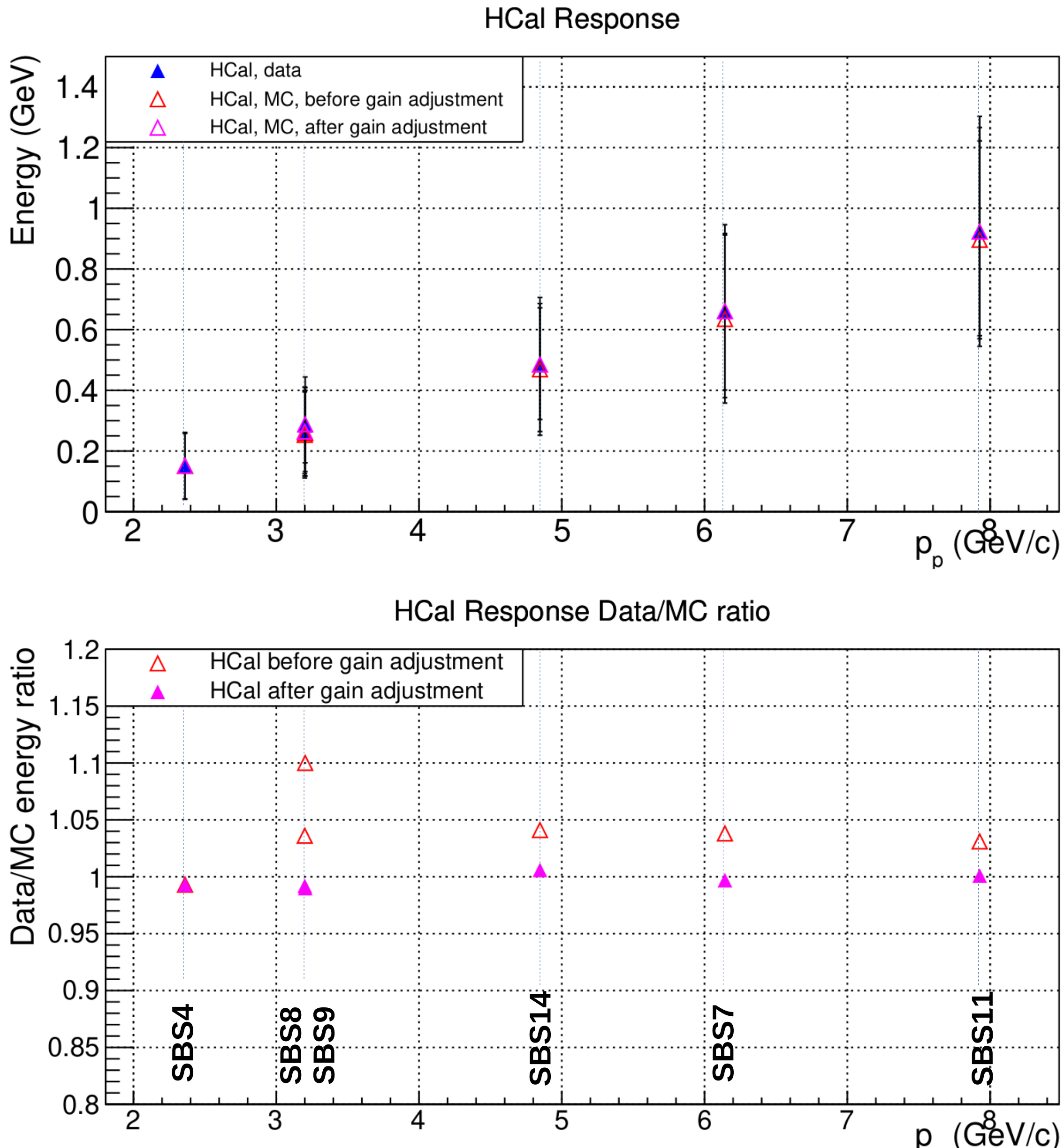




- Gain correction: $[\mu_{H,d}/\mu_{H,s}]$
- Response compatible with *sampling fractions evaluated by Sebastian*



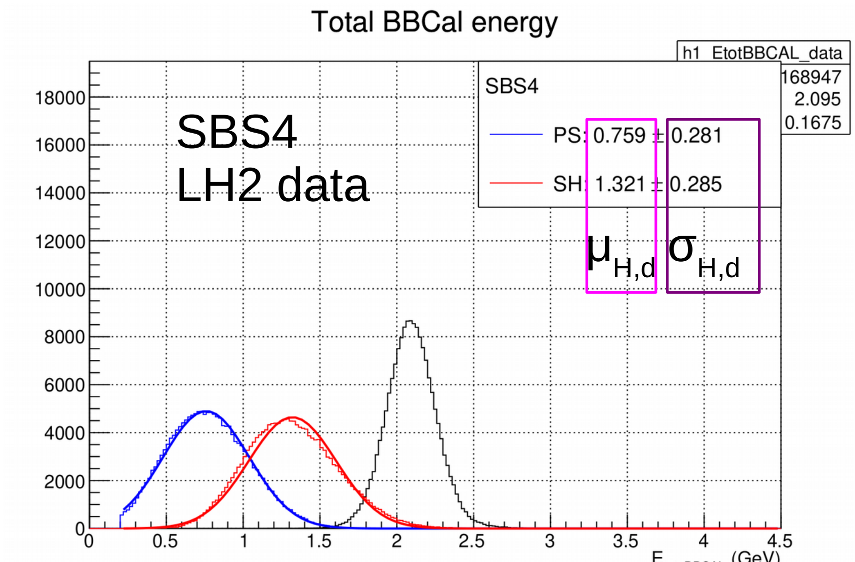
Digitization gain adjustments: HCal

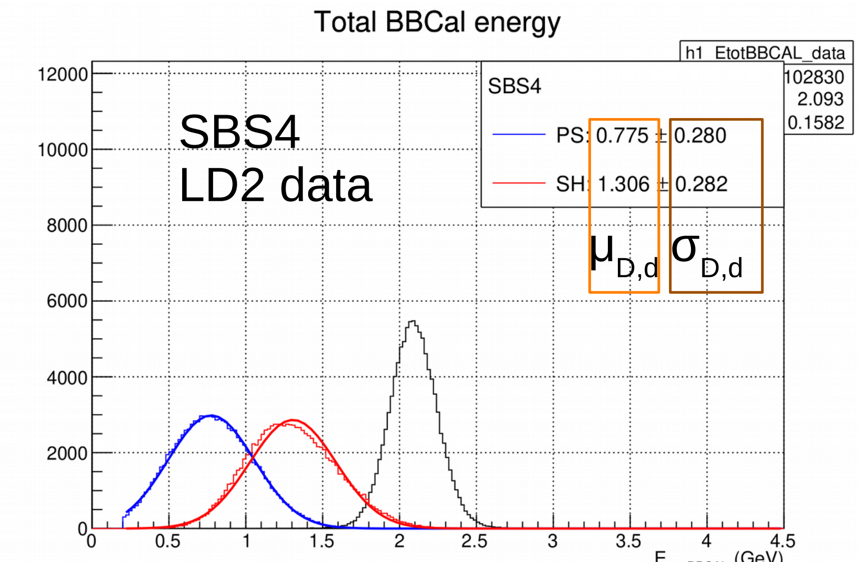


New gains	
Kin	HCal
4	9.93e5
7	1.04e6
11	1.03e6
14	1.04e6
8	1.04e6
9	1.10e6

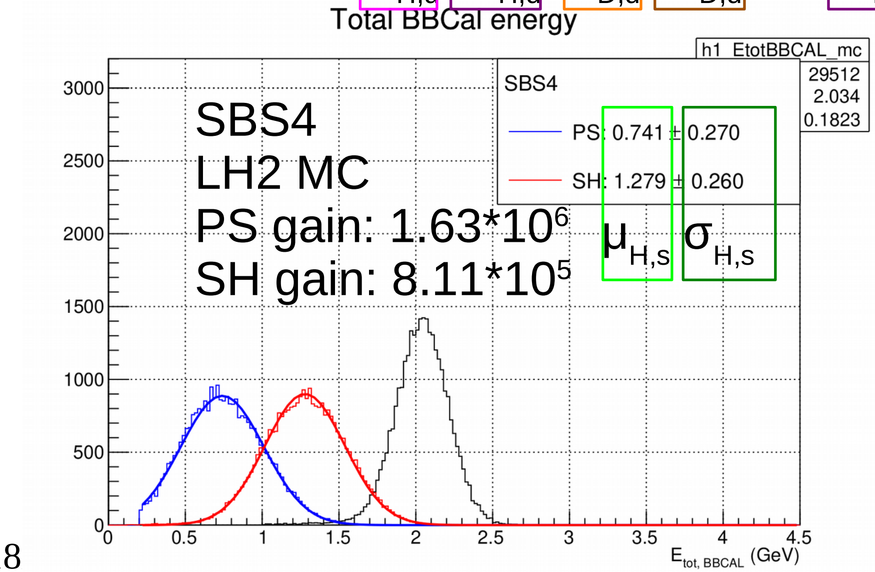
Digitization gain adjustments: BBPS, BBSH

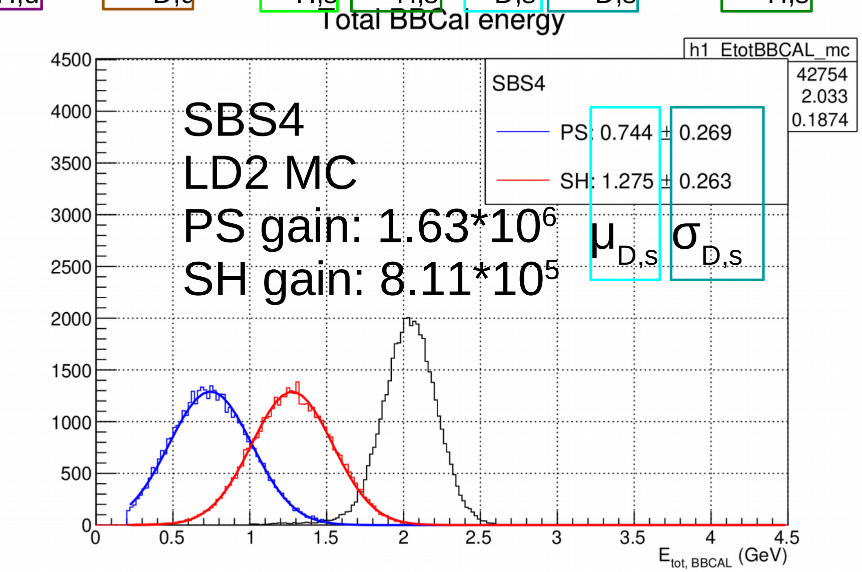
- Link to tables for all GMN kinematics: [Share point], [spreadsheet on wiki]





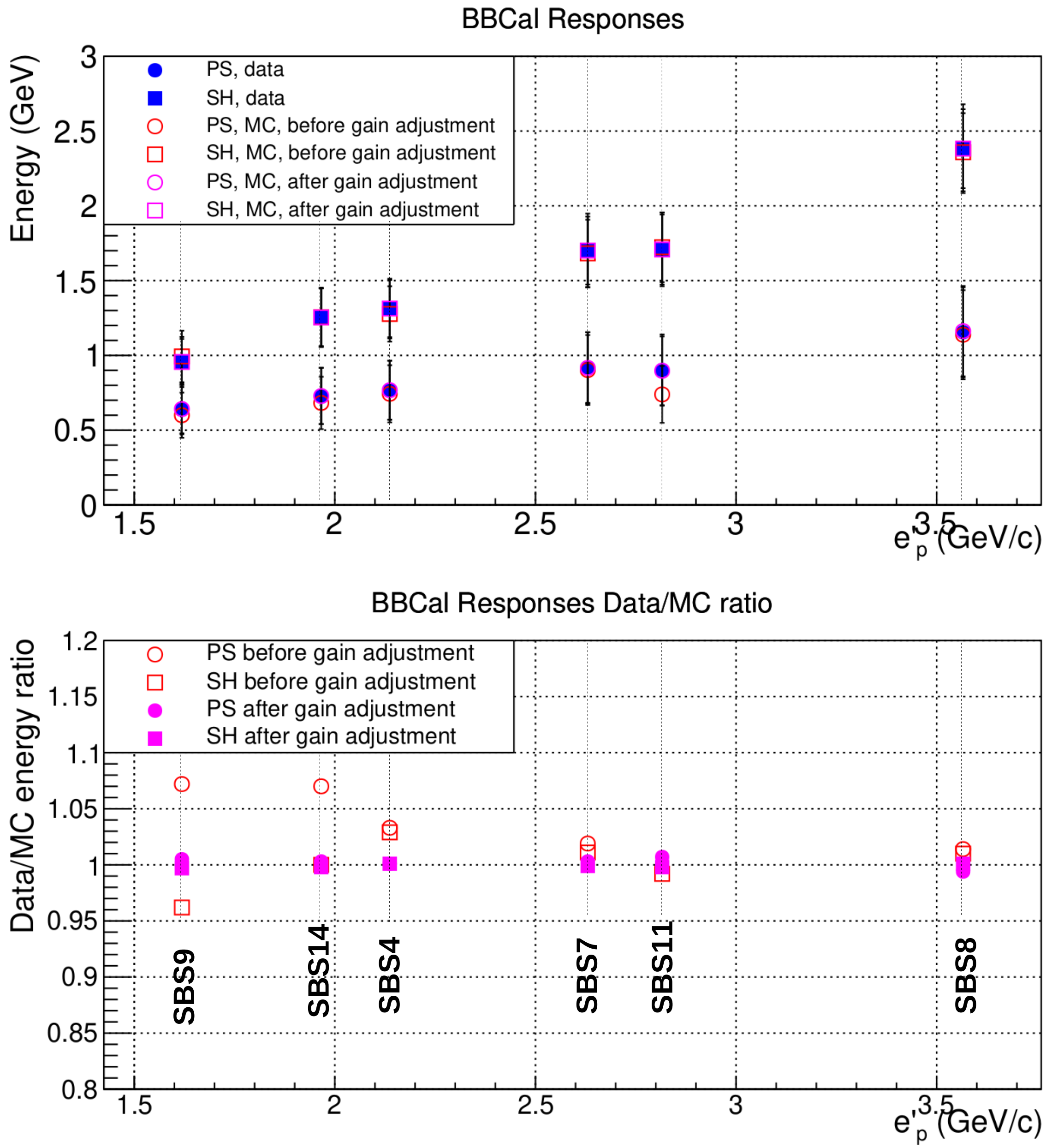
- Gain correction: $[(\mu_{H,d}/\sigma^2_{H,d}+\mu_{D,d}/\sigma^2_{D,d})/(1/\sigma^2_{H,d}+1/\sigma^2_{D,d})]/[(\mu_{H,s}/\sigma^2_{H,s}+\mu_{D,s}/\sigma^2_{D,s})/(1/\sigma^2_{H,s}+1/\sigma^2_{D,s})]$





μ: response peak; **σ**: response width; **_H**: LH2; **_D**: LD2; **_d**: **d**ata; **_s**: **s**imulation

Digitization gain adjustments: BBPS, BBSH



New gains		
Kin	PS	SH
4	1.68e5	8.34e5
7	1.78e5	8.29e5
11	1.72e5	8.32e5
14	1.65e5	8.69e5
8	1.87e5	8.11e5
9	1.63e5	8.66e5