Preliminary Results of the SBS-GMn Experiment with Super BigBite Spectrometer at Jefferson Lab's Hall A

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(for the SBS collaboration)

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Outline

- Nucleon Form Factors and the Structure of the Nucleon
- SBS Program at Jefferson Lab and SBS-GMn Experiment: Brief Overview
- Physics Analysis Methodology, Challenges, and Preliminary Results
- Summary and outlook

Elastic eN Scattering and Nucleon Form Factors

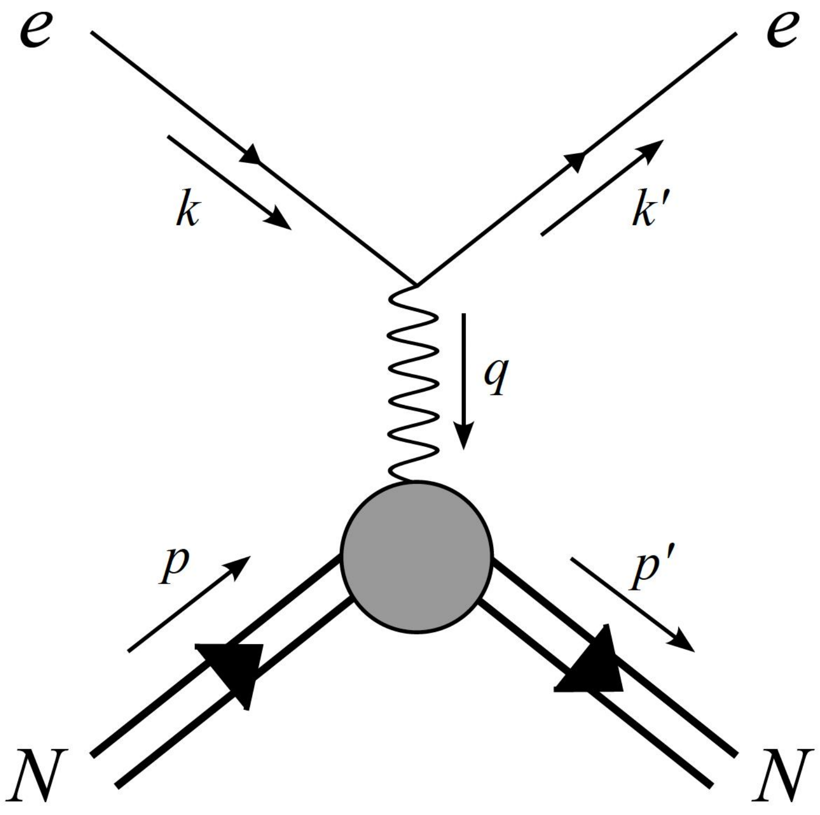


Figure: Elastic eN scattering in OPE Approximation

❖ Differential Cross Section in OPE Approx. (Rosenbluth Formula):

$$\frac{d\sigma}{d\Omega} = \frac{\sigma_{\text{Mott}}\epsilon_N}{1+\tau_N}\left(\epsilon_N {G_E^N}^2(Q^2) + \tau_N {G_M^N}^2(Q^2)\right)$$

- $N \Rightarrow$ Proton (p), Neutron (n)
- $Q^2 = -q^2$
- $\tau_N = Q^2/4M_N^2$
- $\epsilon_N = (1 + 2(1+\tau_N)\tan^2(\theta_e/2))^{-1}$

$G_E^N \Rightarrow$ Electric Form Factor

$G_M^N \Rightarrow$ Magnetic Form Factor

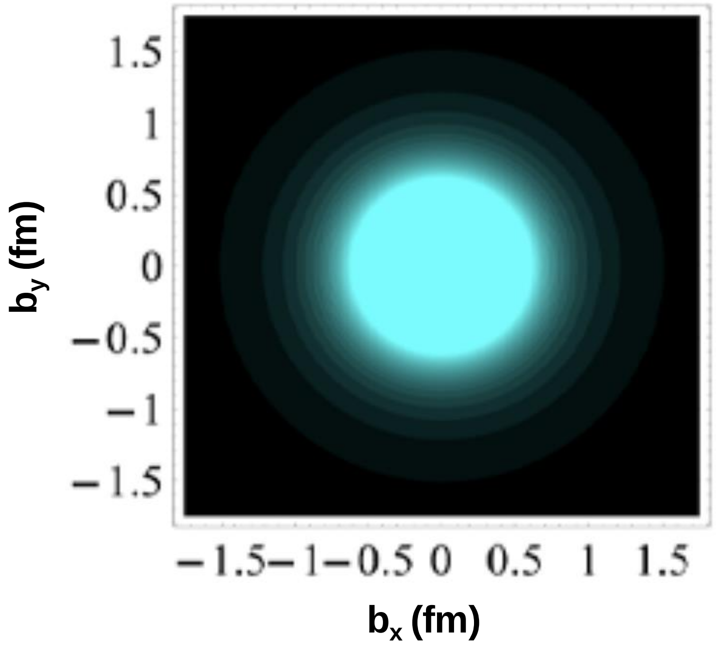
$$\text{At } Q^2 = 0, \begin{cases} G_E^p(0) = 1, & G_M^p(0) = \mu_p \\ G_E^n(0) = 0, & G_M^n(0) = \mu_n \end{cases}$$

Electromagnetic Form Factors & Nucleon Imaging

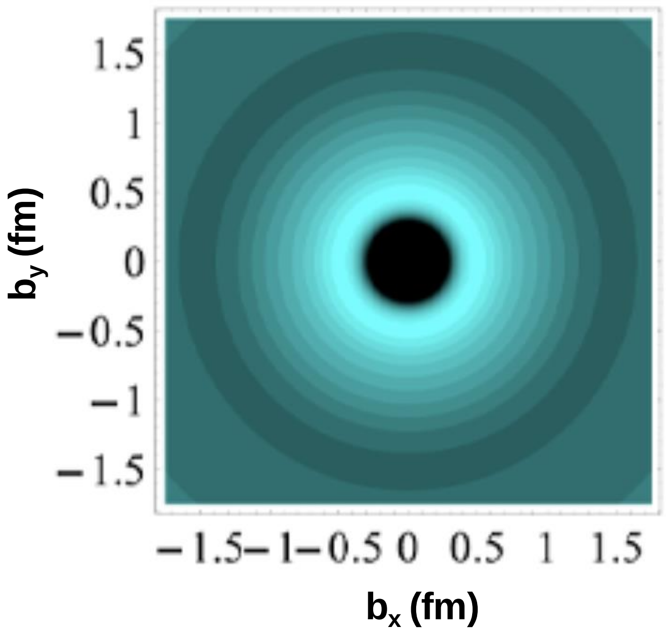
- In non-relativistic limit G_E and G_M are related to the 3D Fourier transforms of the spatial charge and current distributions within the nucleon, respectively. But relativistic corrections are large and model dependent.

- However, in the infinite momentum frame (IMF), a **model-independent** density interpretation can be drawn in terms of transverse distributions by relating the form factors to Generalized Parton Distribution (GPD) moments.

Transverse charge density of Longitudinally Polarized **Proton**



Transverse charge density of Longitudinally Polarized **Neutron**



Ref: Carlson *et al*: Phys. Rev. Lett. 100, 032004 (2008)

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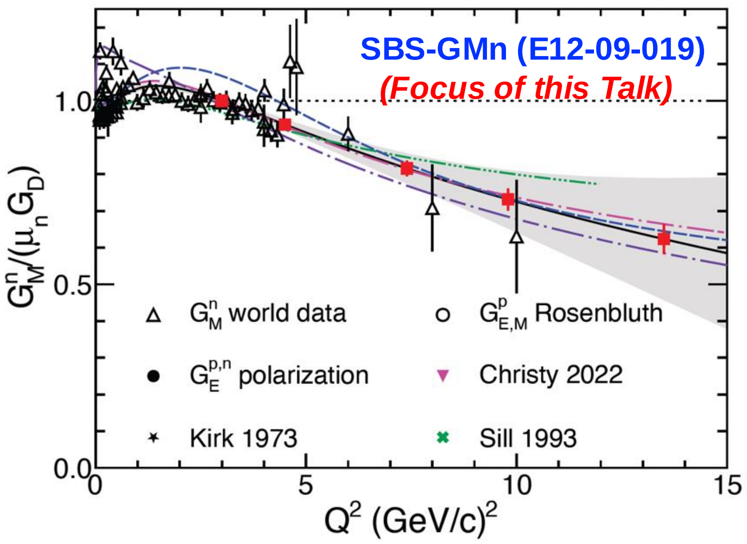
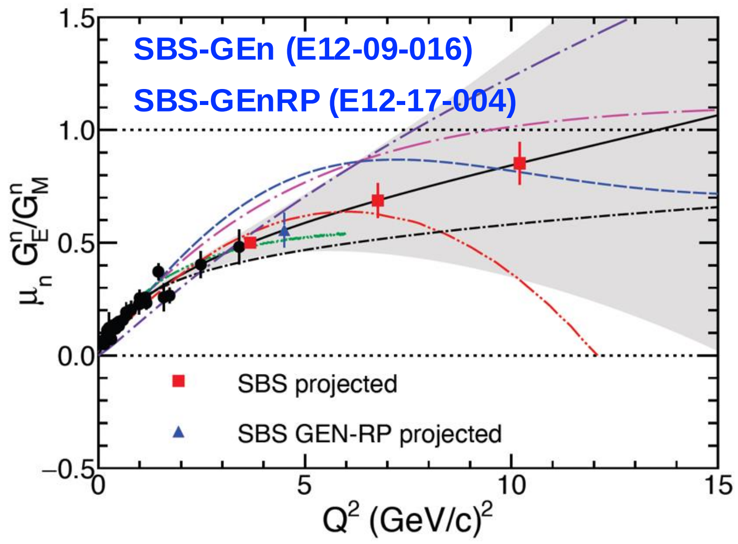
Super BigBite Spectrometer (SBS) Program – 2021- 25

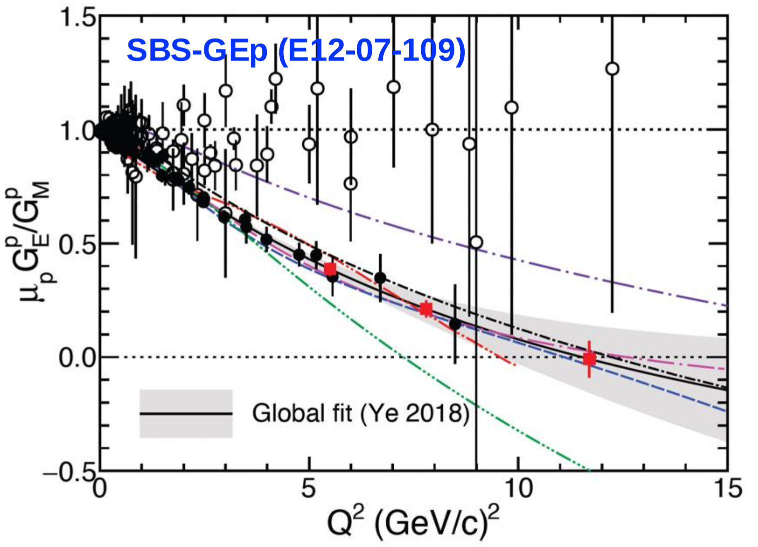
Q^2 increase: 6 → 13.6 (GeV/c)^2



Q^2 increase: 3.4 → 10 (GeV/c)^2



Q^2 increase: 8.5 → 12 (GeV/c)^2



[*] Plots from: F. Gross *et al.*, "50 Years of Quantum Chromodynamics," Dec. 2022. arXiv: 2212.1107

- **Goal:** High-precision measurements of neutron and proton electromagnetic form factors in unprecedented Q^2 regime.
- **Challenges:**
  - Elastic eN scattering cross-section falls like $1/Q^{12}$!!
  - High precision tracking at very high rates.
  - Simultaneous detection of high energy nucleons with high and comparable efficiencies.

The Super BigBite Spectrometer – Design Highlights

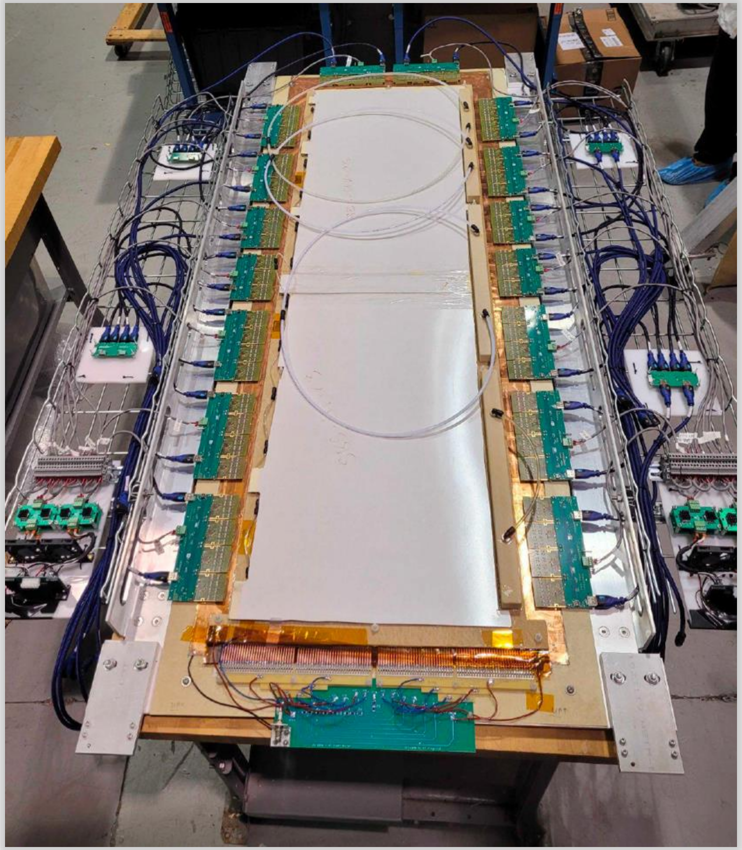
SBS Dipole Magnet

- 1.6 Tm field integral
- 50 msr solid angle acceptance at $15°$ (Achieved with a cut in the yoke for passage of the beam line)
- Separates high energy nucleons by charge

Hadron Calorimeter (HCAL)

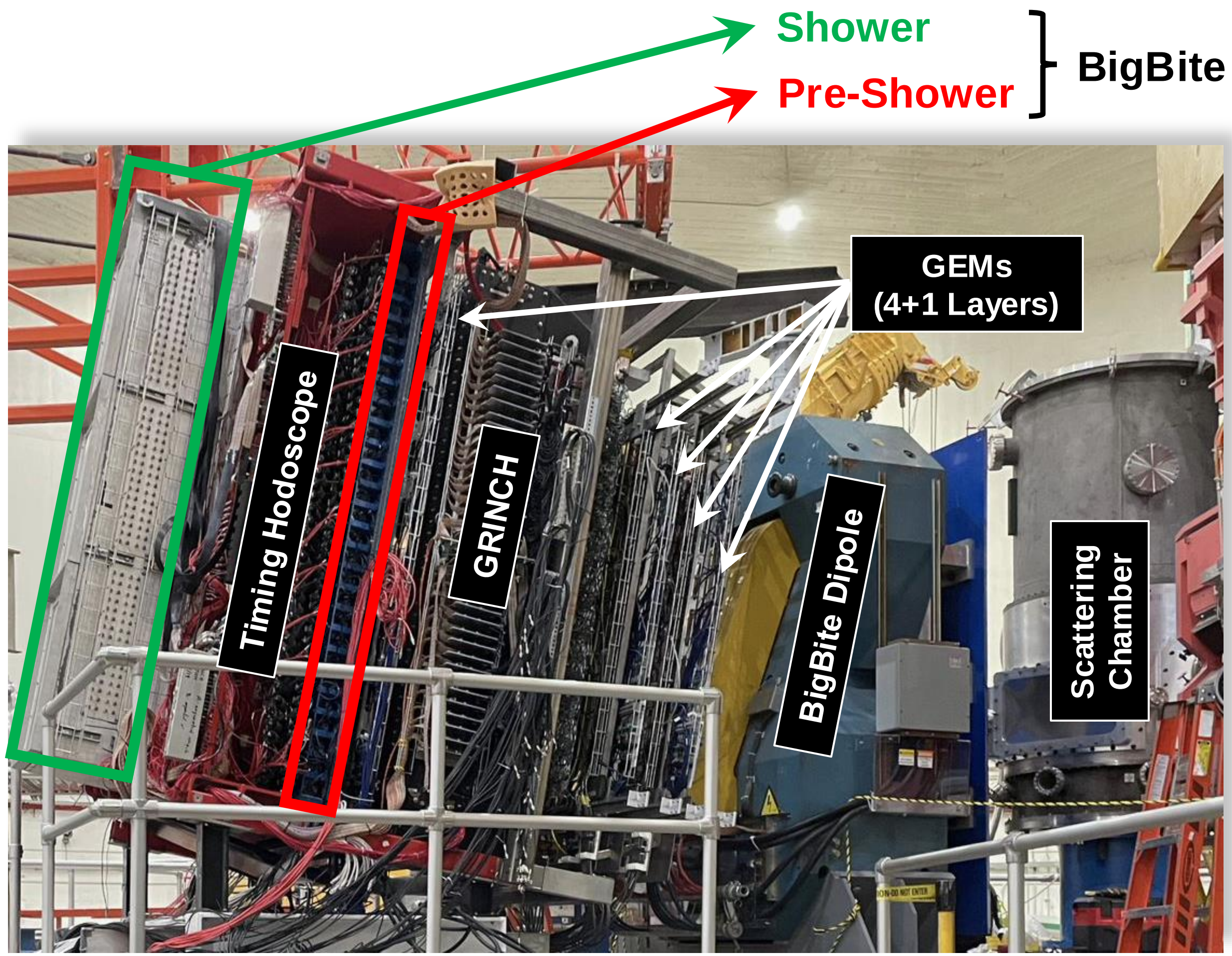
- $2 \times 3.7\ \mathrm{m}^2$ active area
- Detects both the nucleons with high & comparable efficiencies
- $\approx 5\ \mathrm{cm}$ position resolution
- $\approx 1.2\ \mathrm{ns}$ time resolution

Gas Electron Multiplier (GEM) Tracker

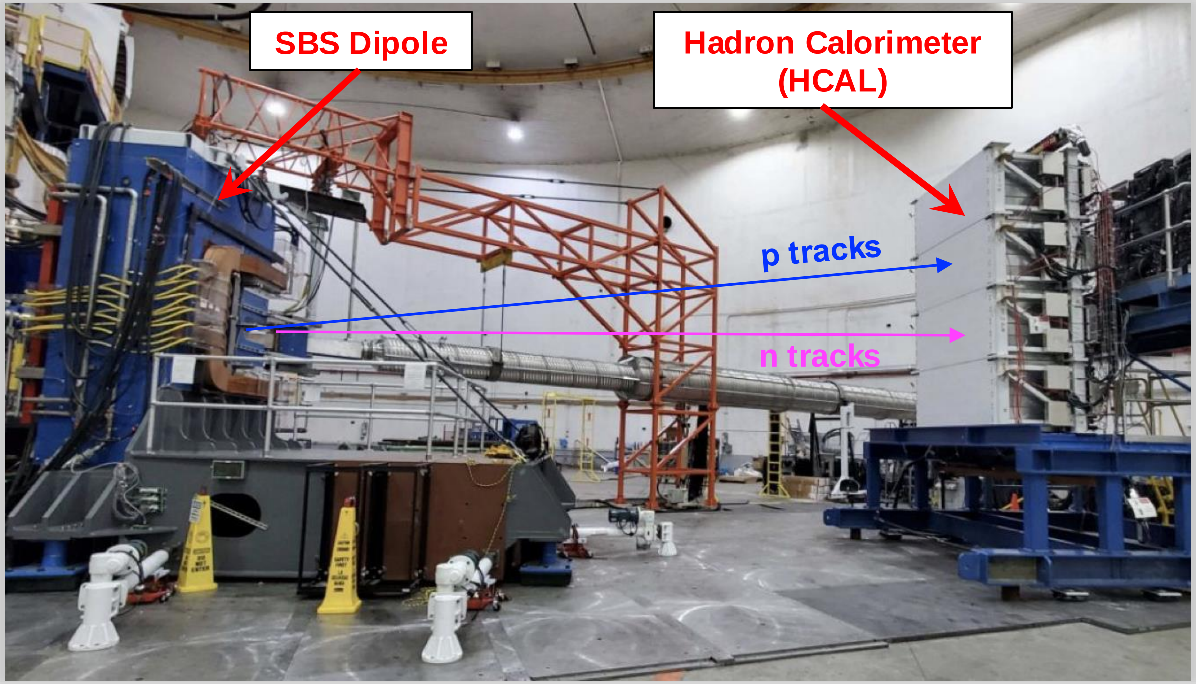


- $50 \times 150\ \mathrm{cm}^2$ active area
- $\approx 70\ \mu\mathrm{m}$ position resolution
- Capable of handling hundreds of kHz rates per cm^2.

BigBite and Super BigBite Spectrometers in Hall A



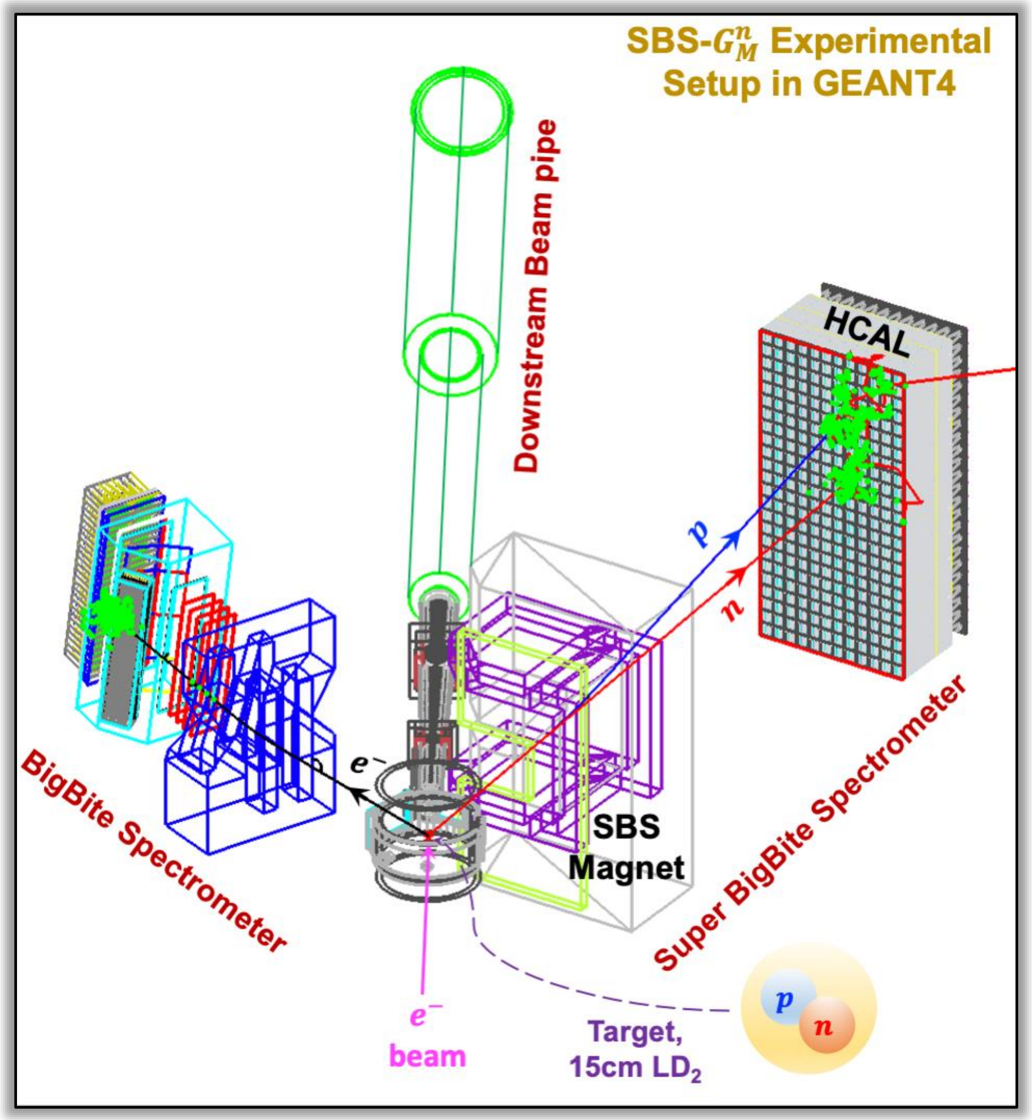
Electron Arm: The BigBite Spectrometer (Side View)



Hadron Arm: The Super BigBite Spectrometer

Outline

SBS-GMn Measurement Technique ("Ratio Method")



- Simultaneous detection of electrons and nucleons lets us use "ratio method"[1], which offers significant cancellation of some systematic errors.

- 3 major steps to get G_M^n:

1. Extracting QE cross section ratio, R^{QE}, directly from the experiment:

$$R^{QE} = \frac{\frac{d\sigma}{d\Omega}\big|_{D(e,e'n)}}{\frac{d\sigma}{d\Omega}\big|_{D(e,e'p)}}$$

2. Apply nuclear and radiative corrections to obtain:

$$R = \frac{\frac{d\sigma}{d\Omega}\big|_{n(e,e')}}{\frac{d\sigma}{d\Omega}\big|_{p(e,e')}} = \frac{\frac{\sigma_{\mathrm{Mott}}\epsilon_n}{1+\tau_n}\left(\epsilon_n {G_E^n}^2 + \tau_n {G_M^n}^2\right)}{\frac{\sigma_{\mathrm{Mott}}\epsilon_p}{1+\tau_p}\sigma_{Red}^p}$$

3. Finally,

$$G_M^n = -\left[\frac{1}{\tau_n}\frac{\epsilon_n(1+\tau_n)}{\epsilon_p(1+\tau_p)}\sigma_{Red}^p R - \frac{\epsilon_n}{\tau_n}{G_E^n}^2\right]^{\frac{1}{2}}$$

[1] L. Durand, Phys. Rev. 115 1020 (1959).

Kinematics of SBS-GMn

Table 1: Kinematics of SBS-GMn. Q^2 is the central Q^2, E_{beam} is the beam energy, θ_{BB} is the BigBite central angle, θ_{SBS} is the Super BigBite central angle, ϵ is the longitudinal polarization of the virtual photon, $E_{e'}$ is the average scattered electron energy, and $E_{p'}$ is the average scattered proton energy.

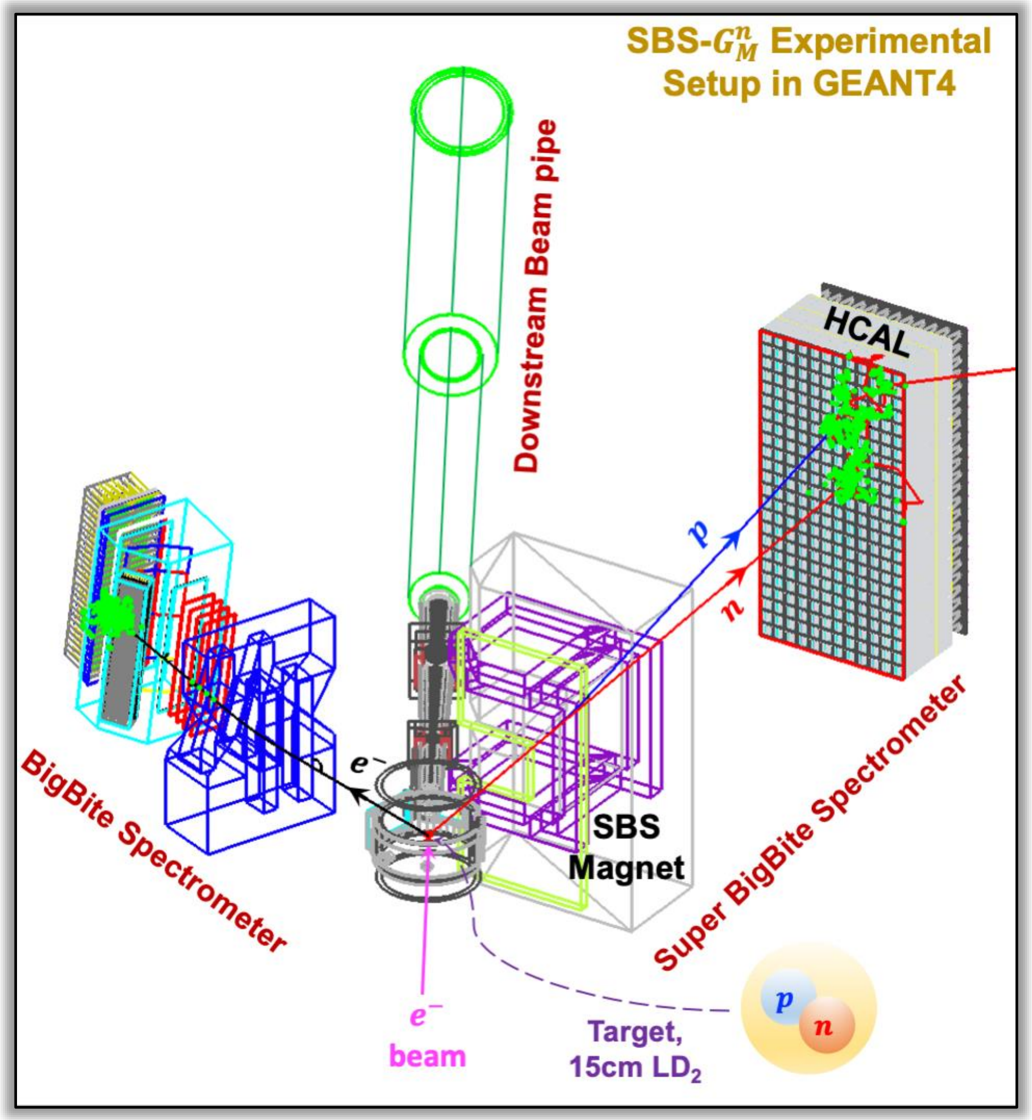
Q^2 $(GeV/c)^2$	ϵ	E_{beam} (GeV)	θ_{BB} (deg)	θ_{SBS} (deg)	$E_{e'}$ (GeV)	$E_{p'}$ (GeV)
3.0	**0.72**	3.73	36.0	31.9	2.12	2.4
4.5	**0.51**	4.03	49.0	22.5	1.63	3.2
4.5	**0.80**	5.98	26.5	29.9	3.58	3.2
7.4	**0.46**	5.97	46.5	17.3	2.00	4.8
9.9	**0.50**	7.91	40.0	16.1	2.66	6.1
13.5	**0.41**	9.86	42.0	13.3	2.67	8.1

- Data was collected at five different Q^2 points for G_M^n extraction.
- The high ϵ data at 4.5 GeV^2 is dedicated to the SBS-nTPE (E12-20-010) experiment, which aims to do first high precision Rosenbluth separation of the neutron form factors to shed some light on the two-photon exchange (TPE) contribution in the elastic en scattering.

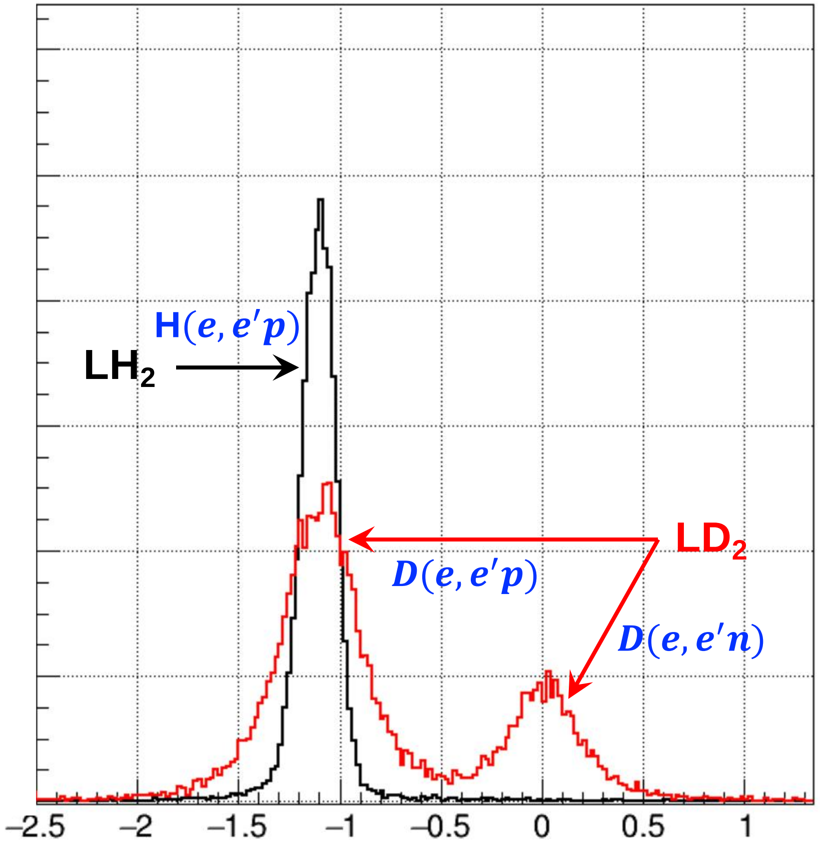
Detector Performance Highlights

- **BigBite Spectrometer:**
  - Momentum resolution $\left(\frac{\sigma_p}{p}\right)$: $\mathbf{1 - 1.5\%}$
  - Angular resolution (in-plane & out-of-plane): $\mathbf{1 - 2}$ **mrad**
  - Vertex resolution: $\mathbf{2 - 6}$ **mm**

- **Super BigBite Spectrometer:**
  - Hadron Calorimeter (HCAL):
    - Time Resolution: $\mathbf{1.2 - 1.3}$ **ns**
    - Position Resolution: $\mathbf{5 - 6}$ **cm**

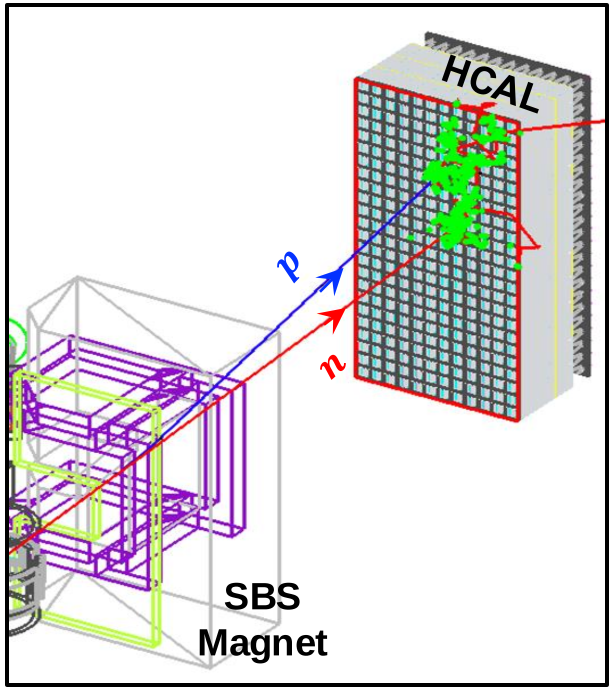


Physics Analysis Methods – Introducing HCAL Δx Variable



$\Delta x = x_{HCAL}^{meas} - x_{HCAL}^{pred}$ (m)

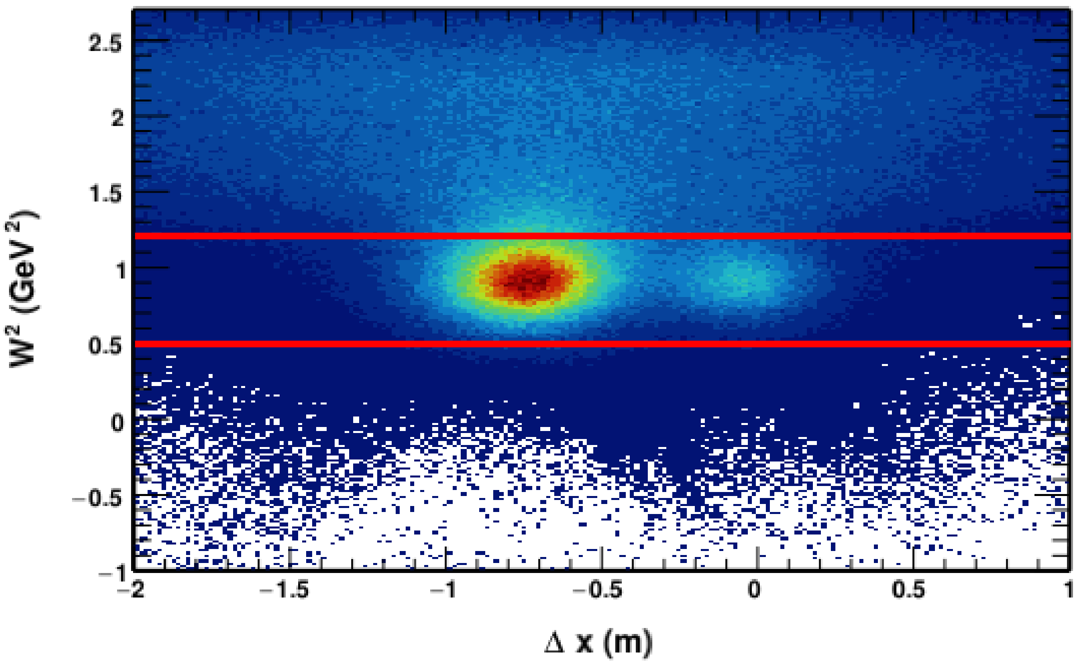
x_{HCAL}^{meas} ⇒ Measured Proton/Neutron Position at HCAL
x_{HCAL}^{pred} ⇒ Predicted **Neutron** Position at HCAL

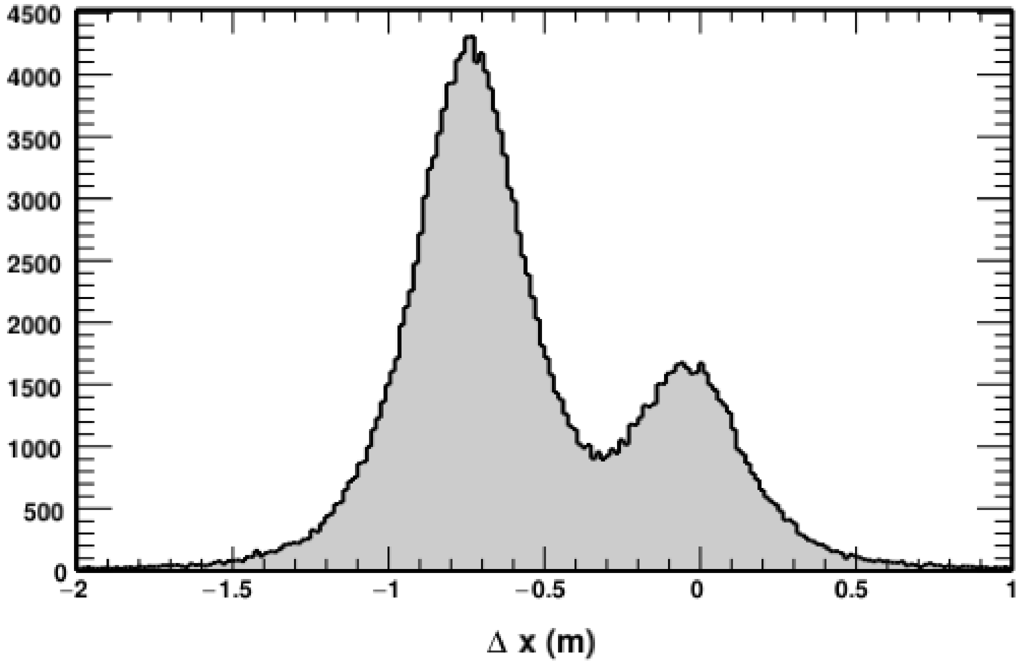


- From the Δx plot we can extract $D(e, e'n)$ & $D(e, e'p)$ counts to form ratio of interest:

$$R^{QE} = \frac{\frac{d\sigma}{d\Omega}\Big|_{D(e,e'n)}}{\frac{d\sigma}{d\Omega}\Big|_{D(e,e'p)}}$$

Quasi-Elastic (QE) Event Selection: $\mathbf{Q^2 = 3\ (GeV/c)^2}$



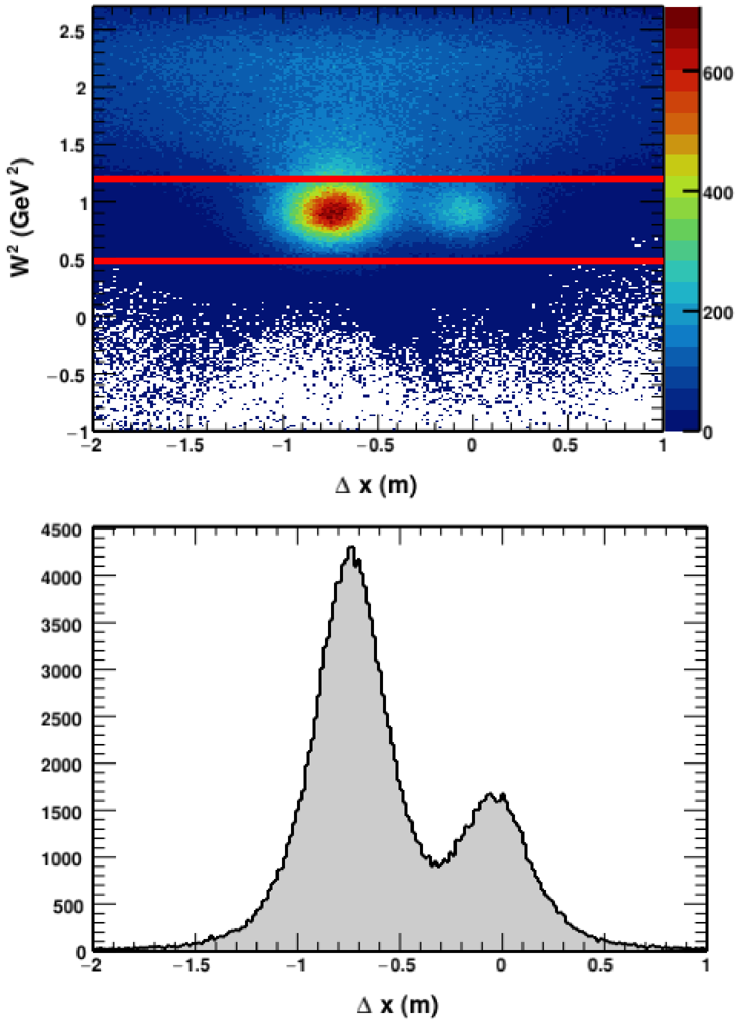


❖ Squared invariant mass of the virtual photon–struck nucleon system:

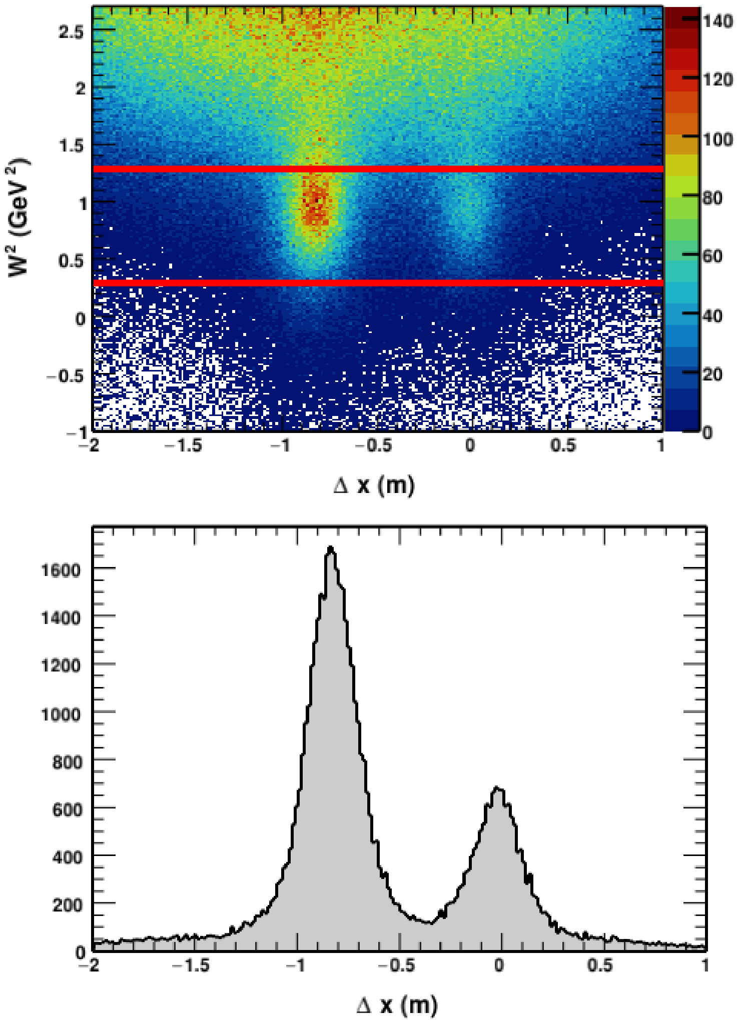
$$\begin{aligned} W^2 &= (P_N^i + q)^2 \\ &= M_N^2 \quad \text{(Elastic Scattering)} \end{aligned}$$

Quasi-Elastic (QE) Event Selection Across Q^2 Points

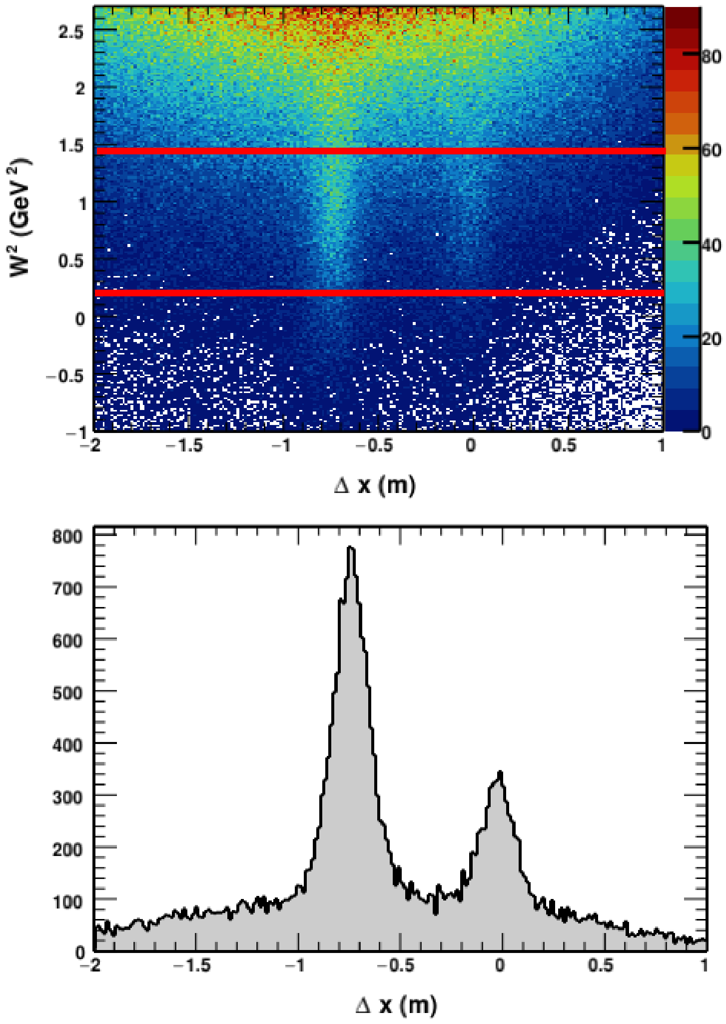
$Q^2 = 3\ (\mathrm{GeV}/c)^2$



$Q^2 = 7.4\ (\mathrm{GeV}/c)^2$

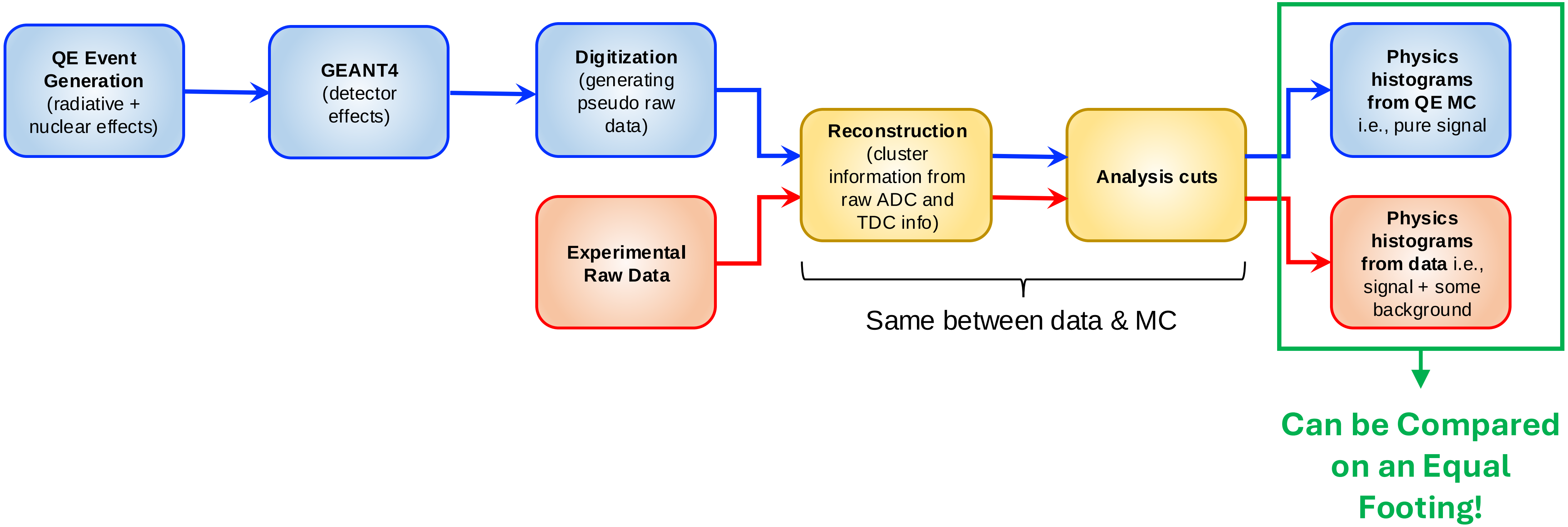


$Q^2 = 13.5\ (\mathrm{GeV}/c)^2$

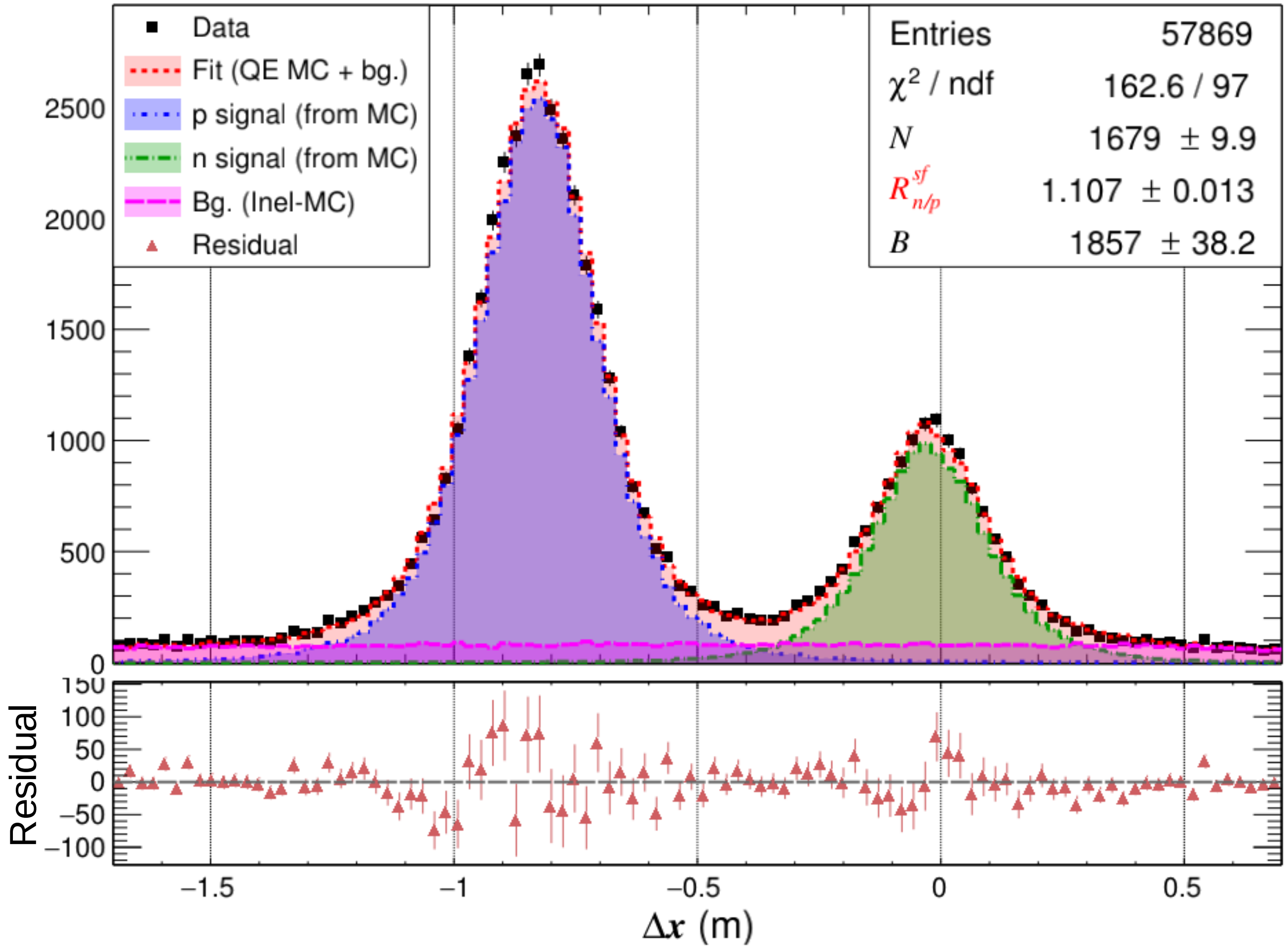


Signal Shapes from Monte Carlo (MC) Simulation

❖ Steps to generate realistic signal shapes from MC:



Data/MC Fit to Δx Distribution: $Q^2 = 7.4\ (\mathrm{GeV/c})^2$



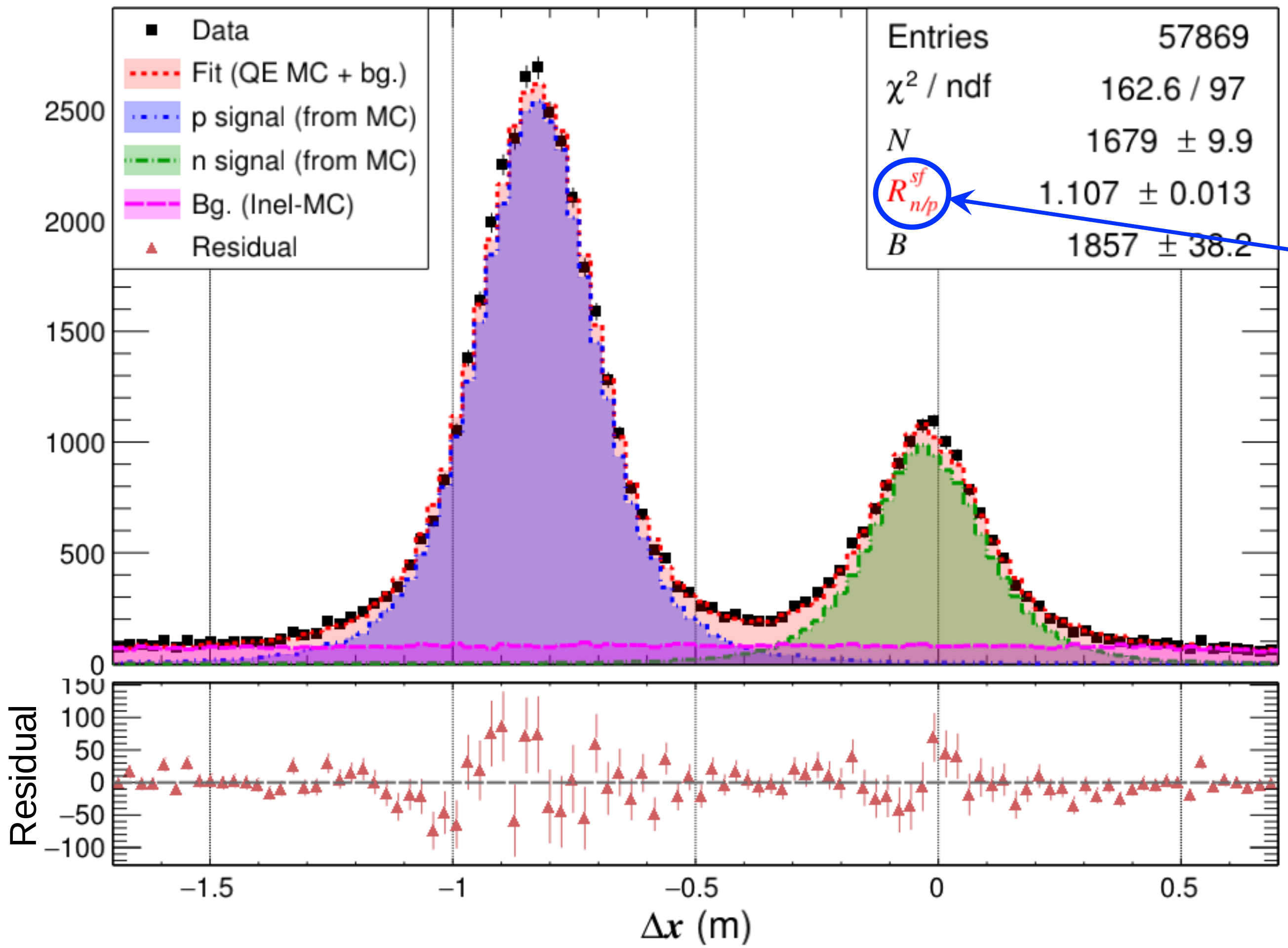
- ❖ Fit equation:

$$\mathrm{Data} = N * (\mathrm{p}_{\mathrm{signal}}^{\mathrm{MC}} + R_{n/p}^{sf} * \mathrm{n}_{\mathrm{signal}}^{\mathrm{MC}}) + B * \mathrm{Inel}_{\mathrm{bg}}^{\mathrm{MC}}$$

- ❖ Fit parameters:
  1. N – Overall proton (p) normalization.
  2. $R_{n/p}^{sf}$ – Relative neutron (n) to proton normalization.
  3. B – Overall background normalization.

- ❖ Agreement of fit looks good in the entire range of interest.

GMn Extraction from Data/MC Fit : $Q^2 = 7.4\ (\mathrm{GeV/c})^2$



- Assumption:
  - Simulation accurately represents nuclear, radiative, and detector effects that are known to be present in data.
- Interpretation:
  - The fit parameter $R^{sf}_{n/p}$, i.e. the relative n/p normalization, is a measure of the discrepancy in the neutron to proton Born cross section ratio between simulation and data.
- GMn extraction:

$$R = \frac{\frac{d\sigma}{d\Omega}\big|_{n(e,e')}}{\frac{d\sigma}{d\Omega}\big|_{p(e,e')}} = R^{sf}_{n/p} * R_{MC}$$

$$\Rightarrow G_M^n = -\left[\frac{1}{\tau_n}\frac{\epsilon_n(1+\tau_n)}{\epsilon_p(1+\tau_p)}\sigma^p_{Red}R - \frac{\epsilon_n}{\tau_n}{G_E^n}^2\right]^{\frac{1}{2}}$$

Total Systematic Error Budget (Preliminary)

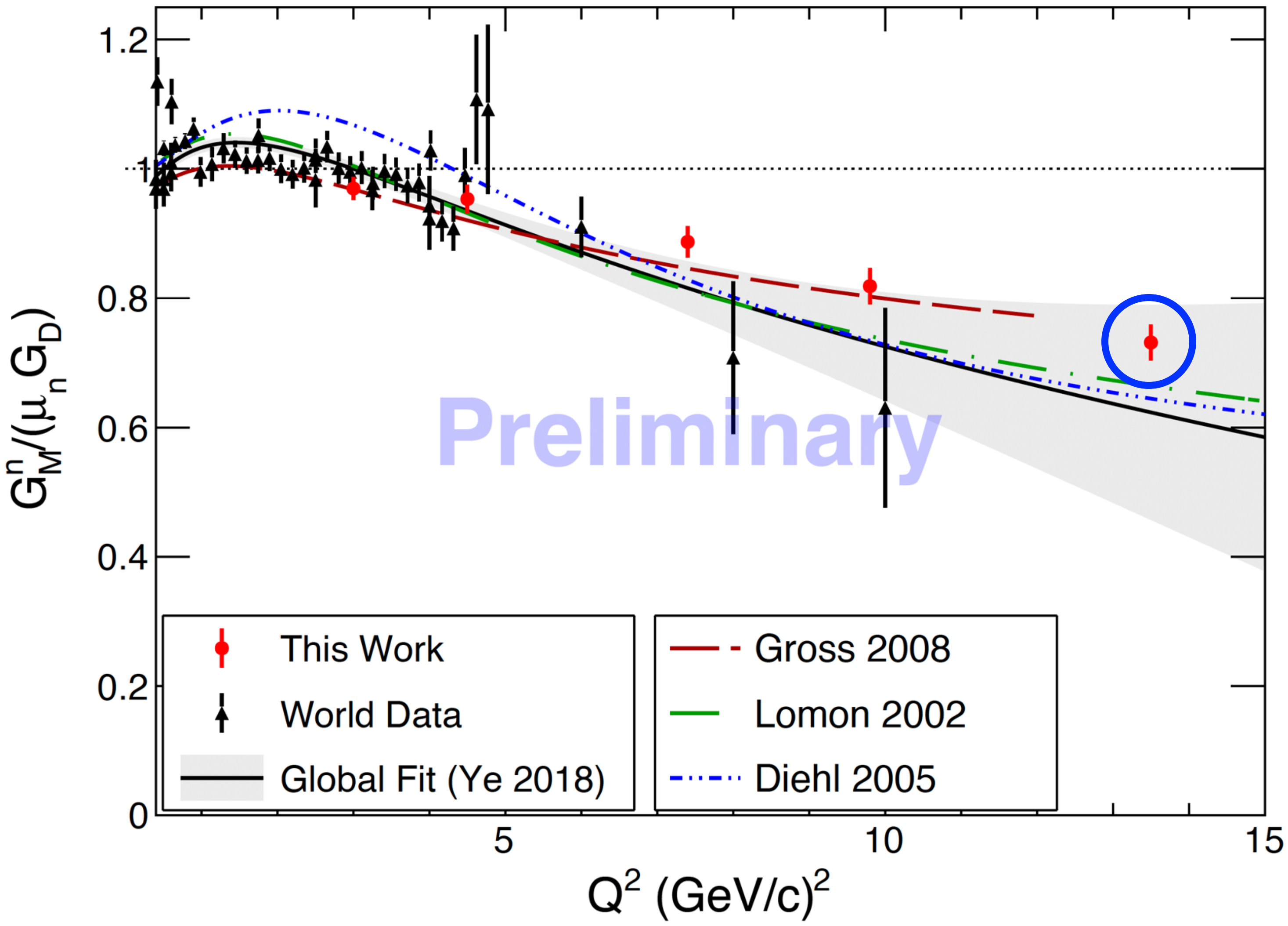
Table 2: Estimated contributions (in percent) to systematic error on R and $\frac{G_M^n}{\mu_n G_D}$.

	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_{Red}^p	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

Preliminary

Preliminary

Preliminary Results

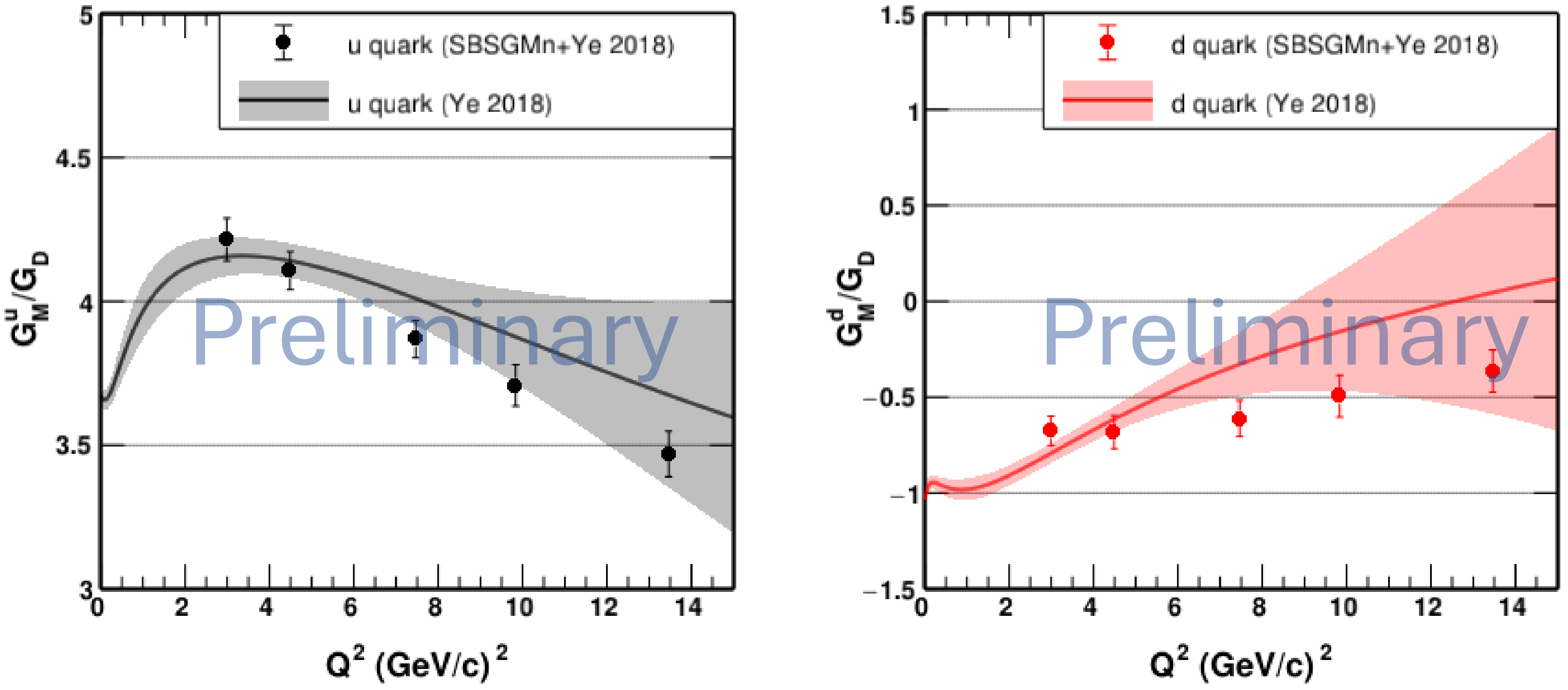


❖ Statistical and Systematic errors have been added in quadrature.

Impact on the Quark Form Factors (Preliminary)

- Flavor Decomposition of Magnetic Form Factors:

$$G_M^u = 2G_M^p + G_M^n$$
$$G_M^d = 2G_M^n + G_M^p$$



- The bands represent flavor decomposition from Ye 2018 fit.
- The points are obtained by replacing G_M^n values from the fit with the ones from this work.

Summary and Outlook

- High-precision measurements of the nucleon form factors in a wide range of Q^2 reveals their electromagnetic structure. The SBS program at JLab's Hall A will extend these measurements up to and beyond $10\ (\mathrm{GeV/c})^2$.

- SBS-GMn, the first SBS experiment, finished data collection in Feb 2022, to extend the range of high-precision G_M^n measurement from $Q^2 = 4$ to $13.5\ (\mathrm{GeV/c})^2$.

- The extracted preliminary results is in line with our precision goal and will vastly advance the current understanding of the neutron's internal structure.

- Significant efforts are ongoing to publish these beautiful results as soon as possible. Stay tuned!

Acknowledgements

- Thanks to SBS-GMn and -nTPE Graduate Students–Vanessa Brio (Catania U.), John Boyd (UVA), Provakar Datta (UConn), Nathaniel Lashley-Colthirst (Hampton U.), Ralph Marinaro (University of Glasgow), Anuruddha Rathnayake (UVA) , Maria Satnik (W&M), Sebastian Seeds (UConn), Ezekiel Wertz (W&M)
- Thanks to SBS-GMn Spokespeople–Bogdan Wojtsekhowski (JLab), Brian Quinn (CMU), Alexandre Camsonne (JLab)
- Thanks to the Jefferson Lab Hall A collaboration and of course the SBS collaboration and anyone else who has contributed to the success of SBS-GMn.
- Thanks to US Department of Energy Office of Science, Office of Nuclear Physics, for supporting this work.

SBS Collaboration Meeting (July 2023, JLab)

Thank You for Your Attention!

Questions? Comments?

Backup Slides

Quark Flavor Decomposition of Nucleon Form Factors

- Assumption of charge symmetry enables us to perform a quark flavor decomposition of the nucleon form factors, $F_1^{p(n)}$ and $F_2^{p(n)}$, in the form:

$$F^u_{1(2)} = 2F^p_{1(2)} + F^n_{1(2)}$$
$$F^d_{1(2)} = 2F^n_{1(2)} + F^p_{1(2)}$$

Ref: Cates *et al*: Phys. Rev. Lett. 106, 252003 (2011)

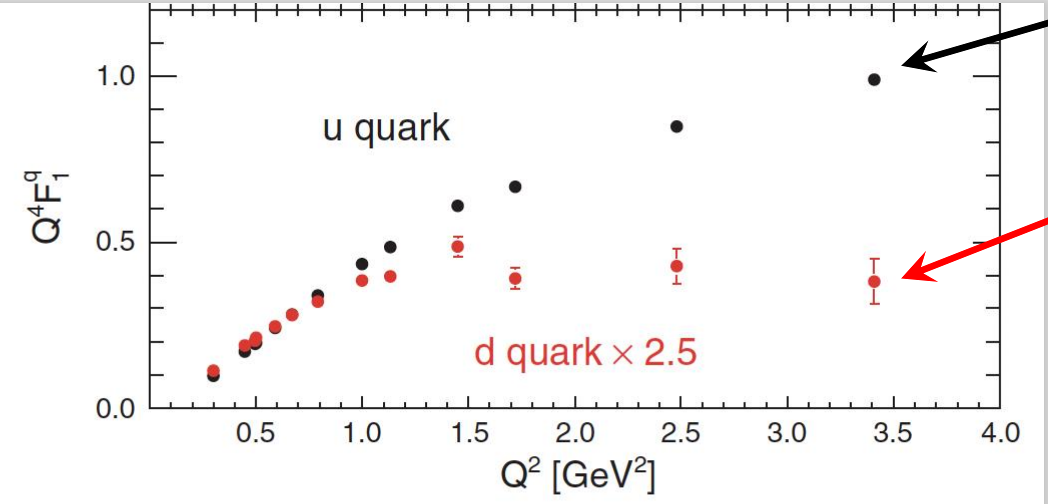
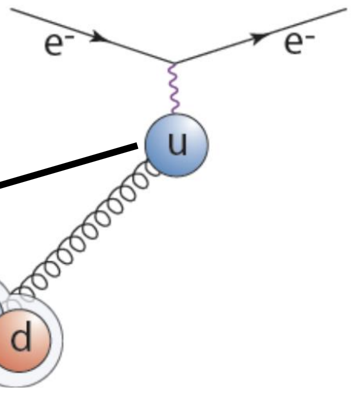


FIG. 3 (color). The Q^2 dependence for the u and d contributions to the proton form factors (multiplied by Q^4). The data points are explained in the text.

Scaling goes like $1/Q^2$. Indicates 1 gluon exchange i.e., scattering from the lone "outside" u quark.



Scaling goes like $1/Q^4$. Indicates 2 gluons exchange i.e., probing inside the diquark.

- u and d quark FFs show dramatically different Q^2 dependence!
- Naïve scaling argument proposed by Gerry Miller invokes diquark degrees of freedom.

Far-Reaching Significance of Form Factor Measurements

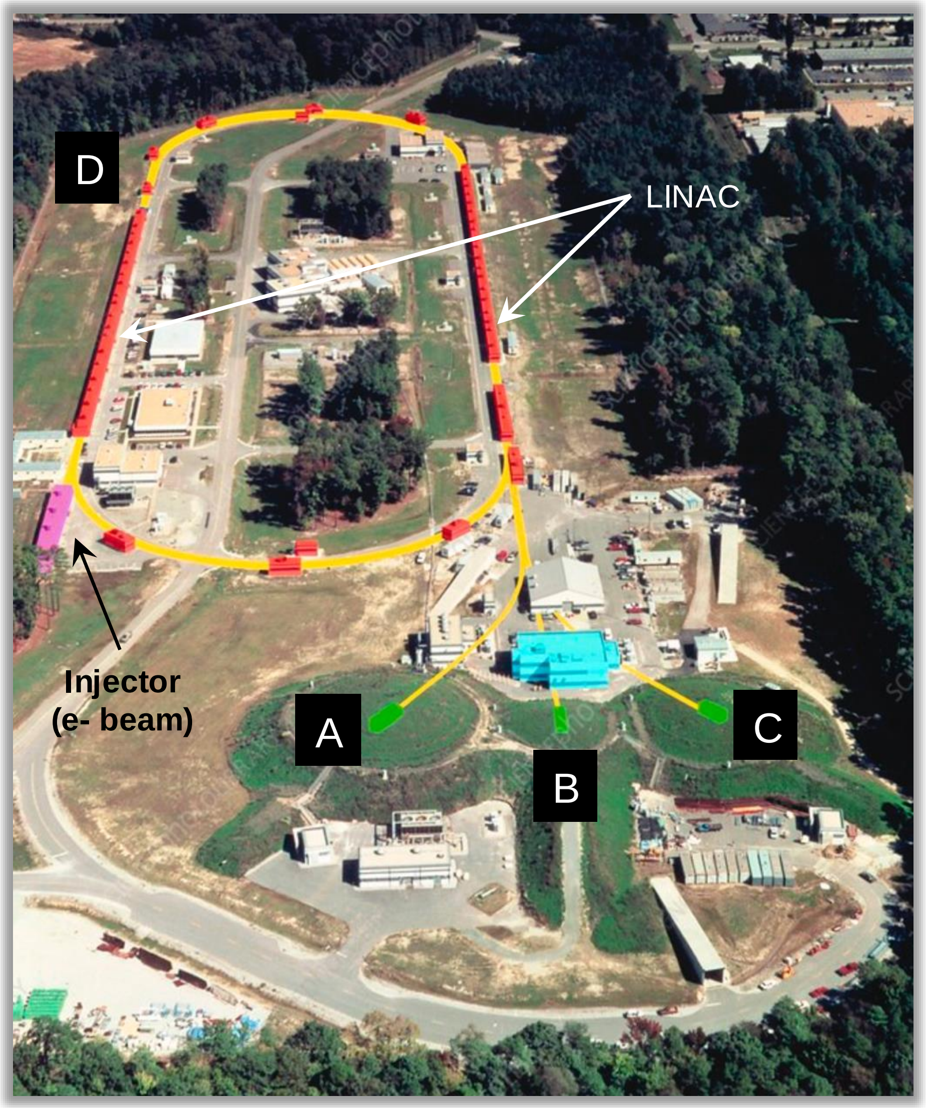
- By assuming charge symmetry, flavor decomposition of the nucleon form factors is possible. The u and d quark form factors show dramatically different Q^2 dependence. A possible explanation invokes diquark degrees of freedom within the nucleons.

$$F^u_{1(2)} = 2F^p_{1(2)} + F^n_{1(2)} \qquad F^d_{1(2)} = 2F^n_{1(2)} + F^p_{1(2)}$$

- Nucleon form factors constraint GPDs through sum rules and enable their extraction from hard exclusive processes.

$$F^q_1(t) = \int_0^1 \mathrm{d}x H^q_v(x,t) \qquad F^q_2(t) = \int_0^1 \mathrm{d}x E^q_v(x,t)$$

The CEBAF at Jefferson Lab (JLab)



CEBAF at Jefferson Lab (JLab) [Aerial View]

- Jefferson Lab (JLab) is a DoE owned national accelerator facility located in Newport News, VA.
- The Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab is a racetrack-shaped electron accelerator located 25 feet underground.
- It can deliver up to 12 GeV continuous wave (CW) electron beam with unparalleled intensity and precision.
- JLab has 4 experimental Halls – A, B, C, & D. SBS-GMn ran in Hall A.

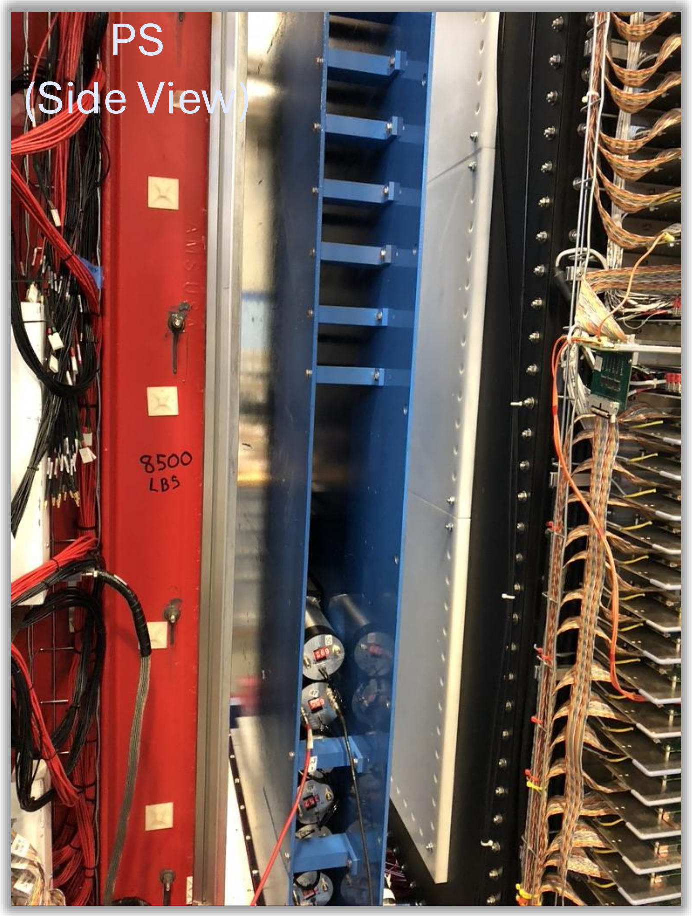
BigBite Calorimeter (BBCAL): Pre-Shower

+y, away from beamline

+z, towards particle motion

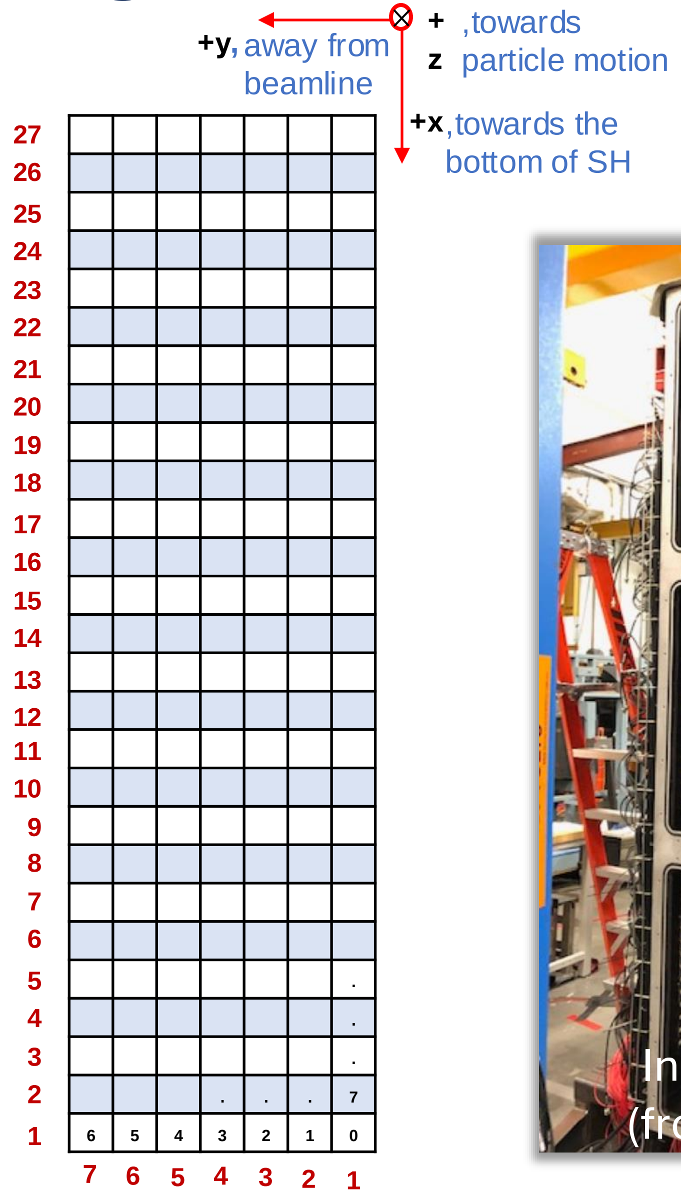
+x, towards the bottom of PS

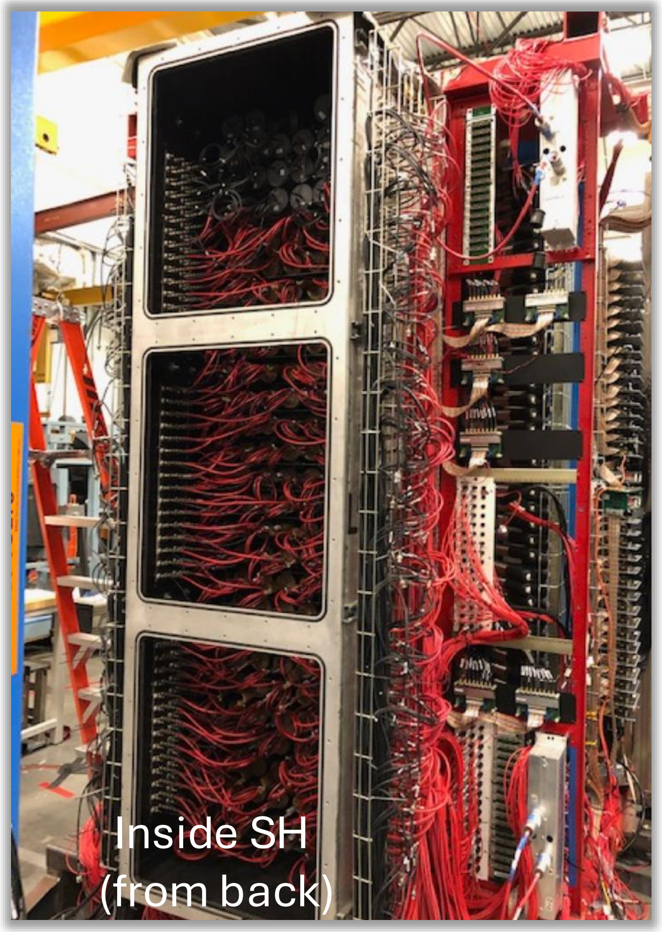
	2	1
26	51	50
25	49	48
24	47	46
23	45	44
22	43	42
21	41	40
20	39	38
19	37	36
18	35	34
17	33	32
16	31	30
15	29	28
14	27	26
13	25	24
12	23	22
11	21	20
10	19	18
9	17	16
8	15	14
7	13	12
6	11	10
5	9	8
4	7	6
3	5	4
2	3	2
1	1	0



- PS is made of 52 rad-hard lead-glass blocks.
- Signals generated in each block are readout by a PMT.
- Block dimension: 9 x 9 x 29.5 cm^3
- Blocks are stacked in 26 rows of 2 columns facing each other.
- mu-metal shielding around each block.

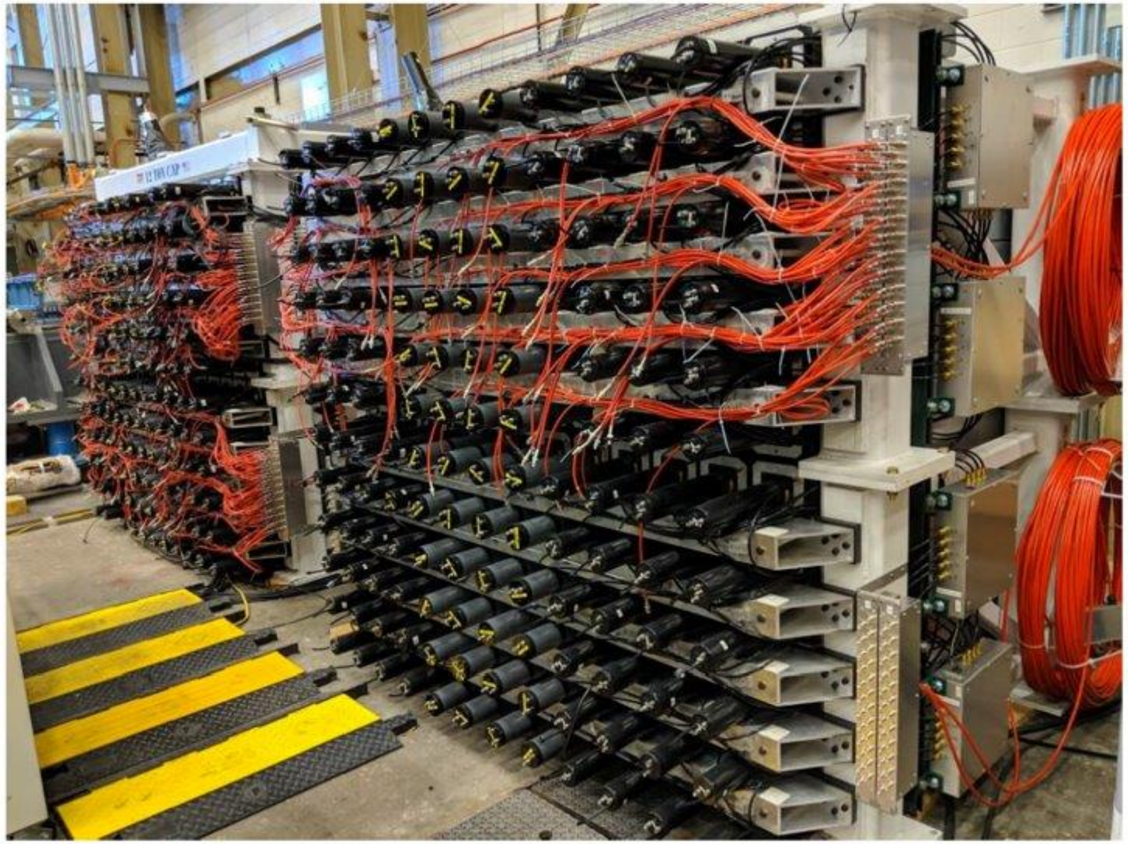
BigBite Calorimeter (BBCAL): Shower

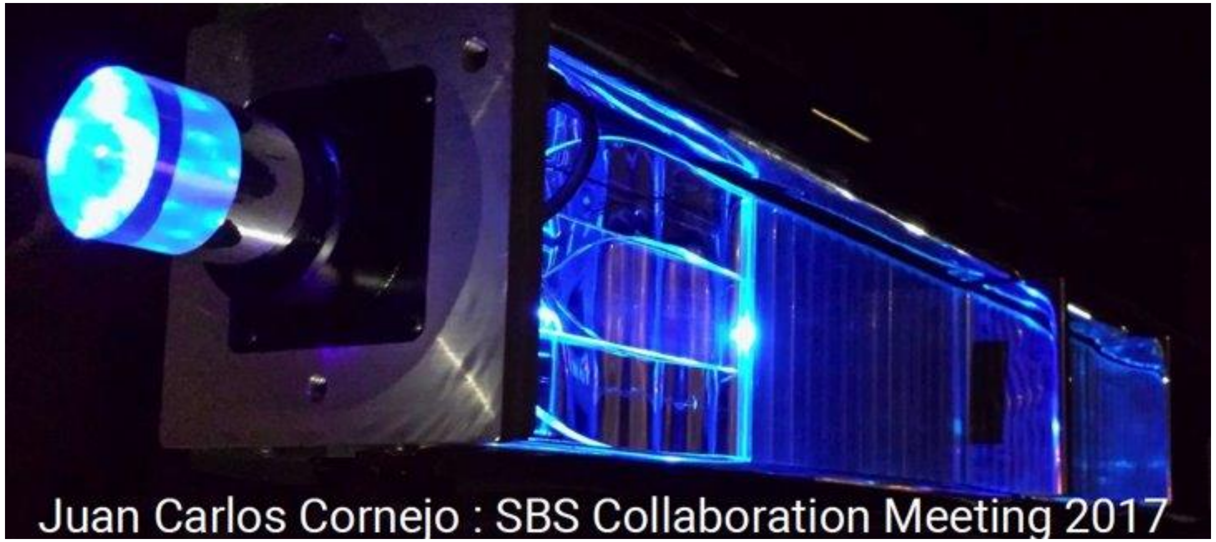




- BB Shower is made of 189 lead-glass blocks.
- Signals generated in each block are readout by a PMT.
- Block dimension: 8.5 x 8.5 x 34 cm^3
- Blocks are stacked in 27 rows of 7 columns facing the spectrometer axis.
- mu-metal shielding outside & between rows.

Hadron Calorimeter (HCAL)





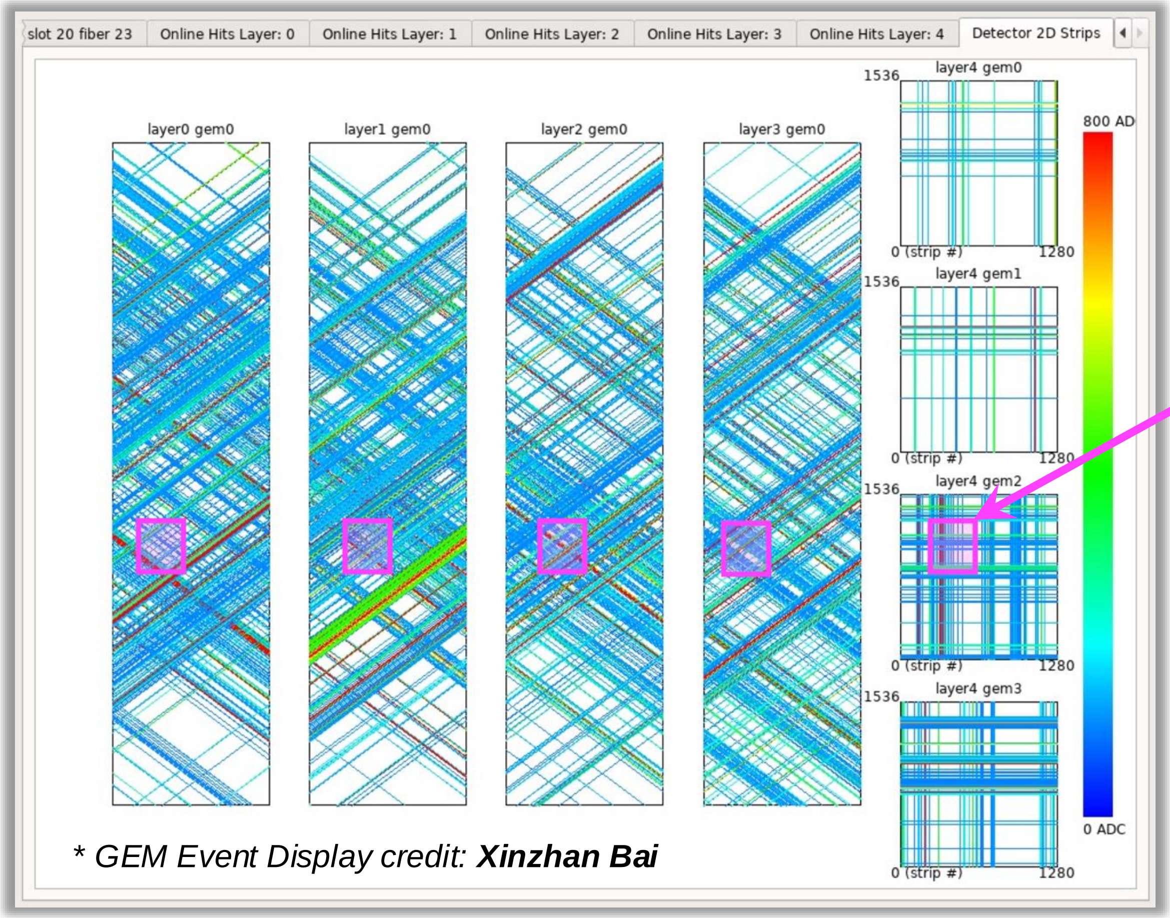
Kinematics of SBS-GMn (Detailed)

Table I: Kinematics of SBS-GMn. Q^2 is the central Q^2, E_{beam} is the beam energy, $\theta_{BB}(d_{BB})$ is the BigBite central angle (target-magnet distance), $\theta_{SBS}(d_{SBS})$ is the Super BigBite central angle (target-magnet distance), $\theta_{HCAL}(d_{HCAL})$ is the HCAL central angle (target-HCAL distance), ϵ is the longitudinal polarization of the virtual photon, $E_{e'}$ is the average scattered electron energy, and $E_{p'}$ is the average scattered proton energy.

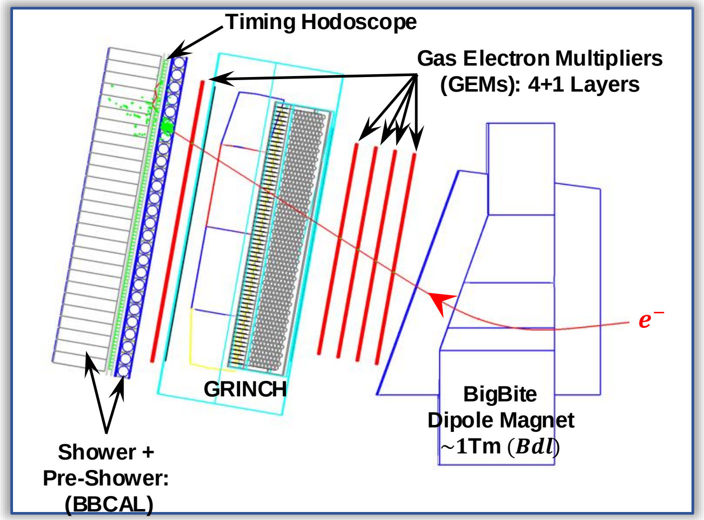
SBS config.	Q^2 $(GeV/c)^2$	ϵ	E_{beam} (GeV)	θ_{BB} (deg)	d_{BB} (m)	θ_{SBS} (deg)	d_{SBS} (m)	θ_{HCAL} (deg)	d_{HCAL} (m)	$E_{e'}$ (GeV)	$E_{p'}$ (GeV)
4	3.0	0.72	3.73	36.0	1.79	31.9	2.25	31.9	11.0	2.12	2.4
9	4.5	0.51	4.03	49.0	1.55	22.5	2.25	22.0	11.0	1.63	3.2
8	4.5	0.80	5.98	26.5	1.97	29.9	2.25	29.4	11.0	3.58	3.2
14	7.4	0.46	5.97	46.5	1.85	17.3	2.25	17.3	14.0	2.00	4.8
7	9.9	0.50	7.91	40.0	1.85	16.1	2.25	16.0	14.0	2.66	6.1
11	13.6	0.41	9.86	42.0	1.55	13.3	2.25	13.3	14.5	2.67	8.1

Reconstruction Challenges – Looking for Needle in a Haystack!

GEM Layers on a Single Event Display ($Q^2 = 4.5 (GeV/c)^2$)



BBCAL constraint



❖ **Remedy:** Define a smaller track search region based on the position of highest energy BBCAL cluster.

❖ BBCAL constraint reduces the track search region to **2-3%** of the entire GEM active area enabling reconstruction. But it required maintaining excellent gain-matching and calibration of BBCAL during run!

❖ **Challenge:** Due to very high luminosity number of 2D hit combinatorics can get astronomically high making reconstruction impossible!

Physics Analysis Methods – Introducing HCAL Δx and Δy

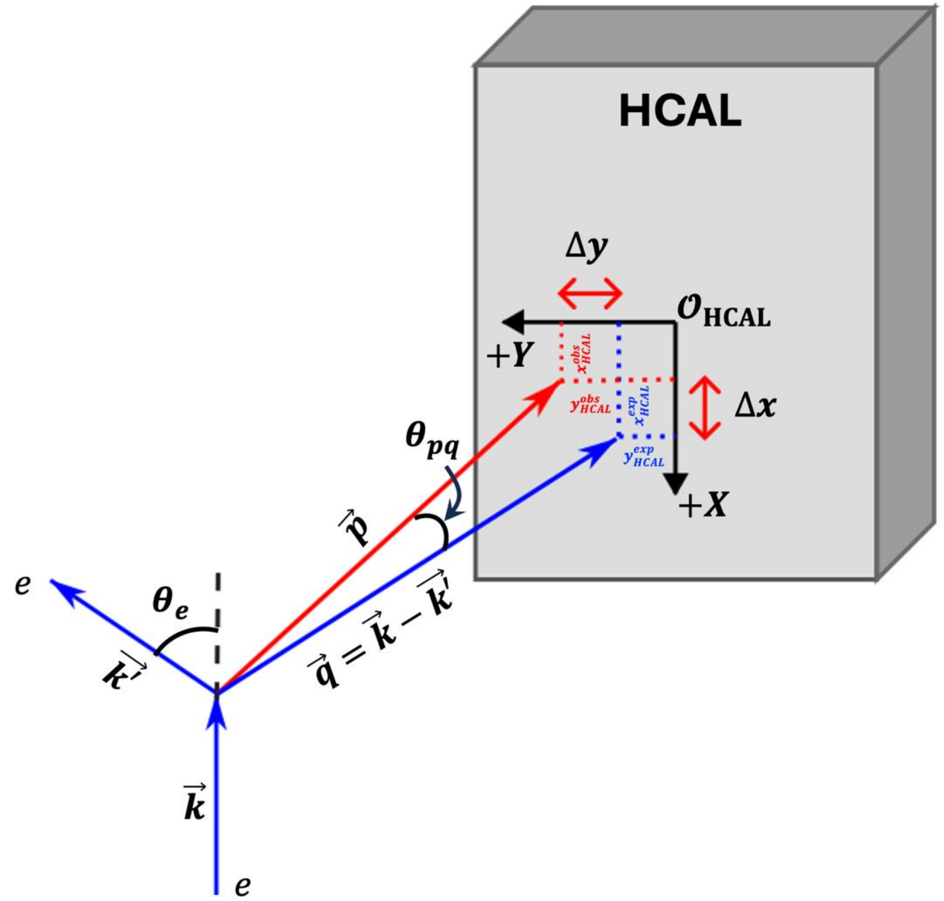


Figure I: A conceptual and exaggerated diagram introducing HCAL Δx and Δy variables. **NOTE:** The presence of the SBS magnet has been **ignored** here.

$\hat{x}$ = Vertical/Dispersive direction

$\hat{y}$ = Transverse direction

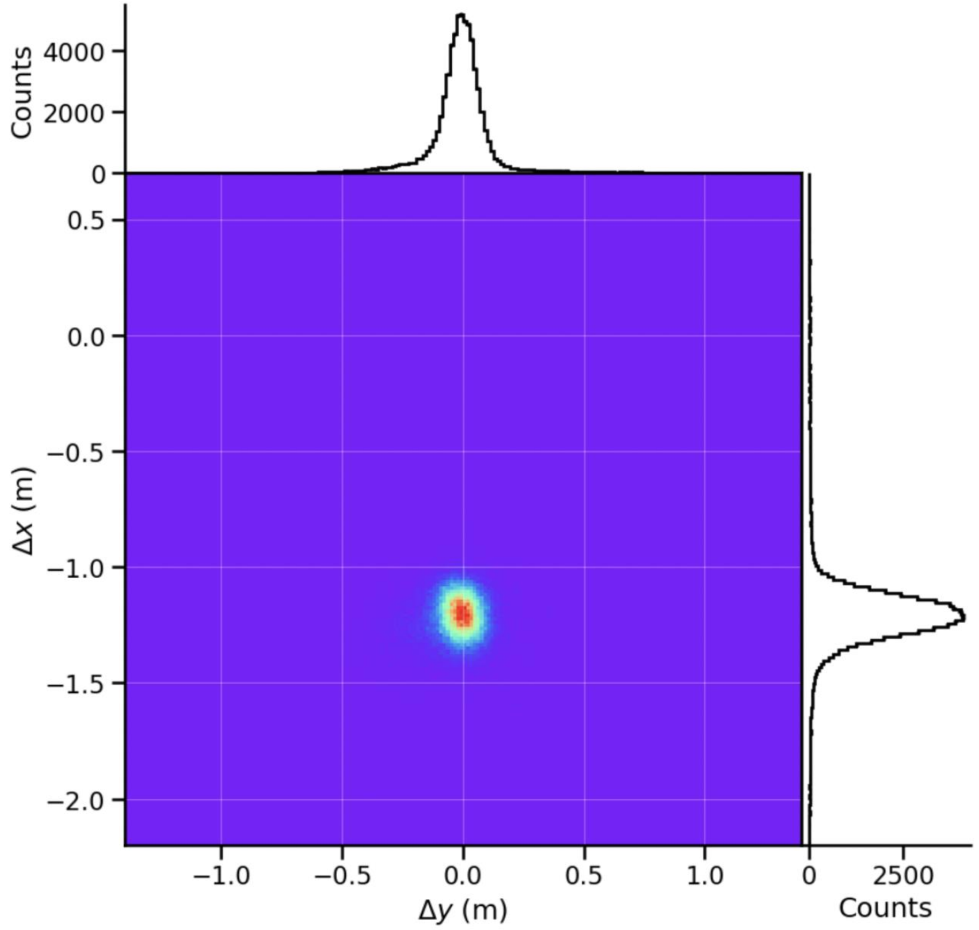
- **Definition of Δx:** The difference between the observed (x_{HCAL}^{obs}) and expected (x_{HCAL}^{exp}) nucleon position on HCAL in the vertical (dispersive) direction.

- **Definition of Δy:** The difference between the observed (y_{HCAL}^{obs}) and expected (y_{HCAL}^{exp}) nucleon position on HCAL in the horizontal (non-dispersive) direction.

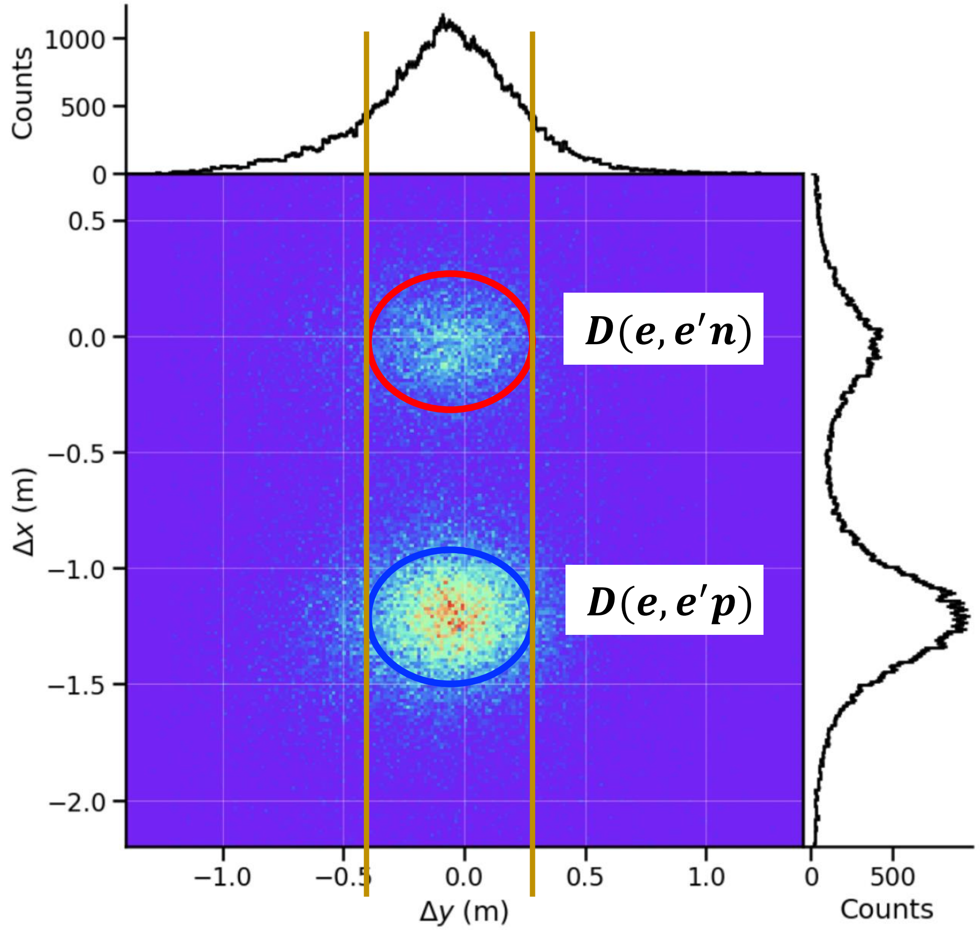
HCAL Δx and Δy Correlation

Q^2 = 3 $(GeV/c)^2$, SBS 50% Field

Elastic Spot (LH_2 Data)



Quasi-Elastic Spots (LD_2 Data)



Analysis Cuts

- **Good *e* Track Selection Cuts:**
  1. Track Quality
     1. No. of GEM layers with hits > 3
     2. $|(\text{vertex})_z| < 0.08$ m
     3. E/p
     4. BB optics validity
  2. PID Cuts
     1. Pre-Shower energy > 0.2 GeV
     2. GRINCH cluster size > 2

- **Good HCAL Event Selection:**
  1. HCAL energy
  2. HCAL active area
  3. Shower-HCAL ADC coincidence time

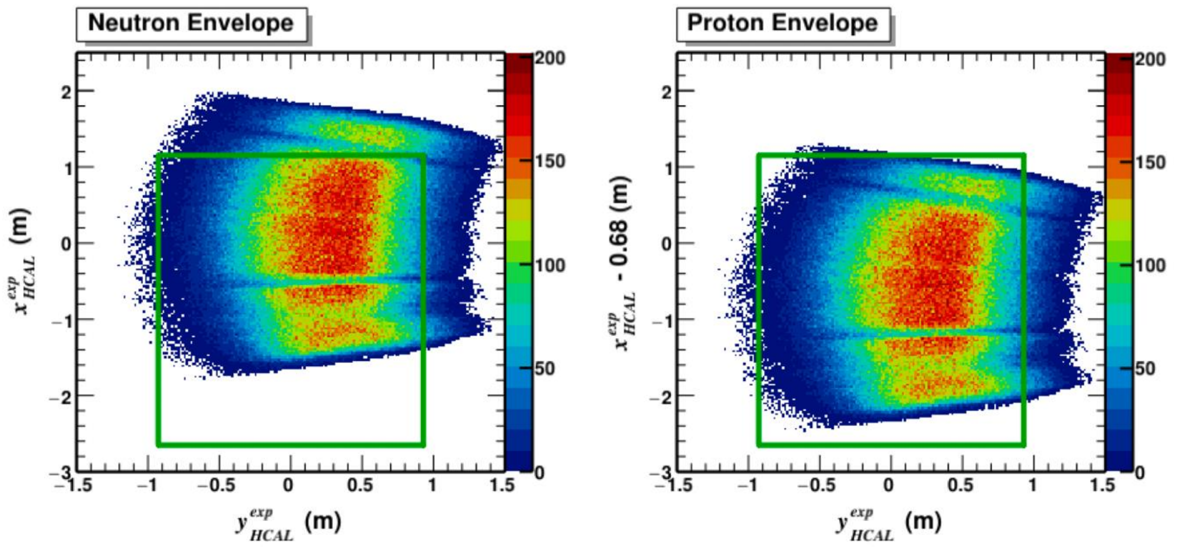
- **Quasi-Elastic Event Selection Cuts:**
  1. W^2 cut
  2. Δx-Δy correlation / θ_{pq} cut
  3. Δy cut

- **Fiducial Cut**
  - to match acceptance for proton and neutron

Effect of Fiducial Cut

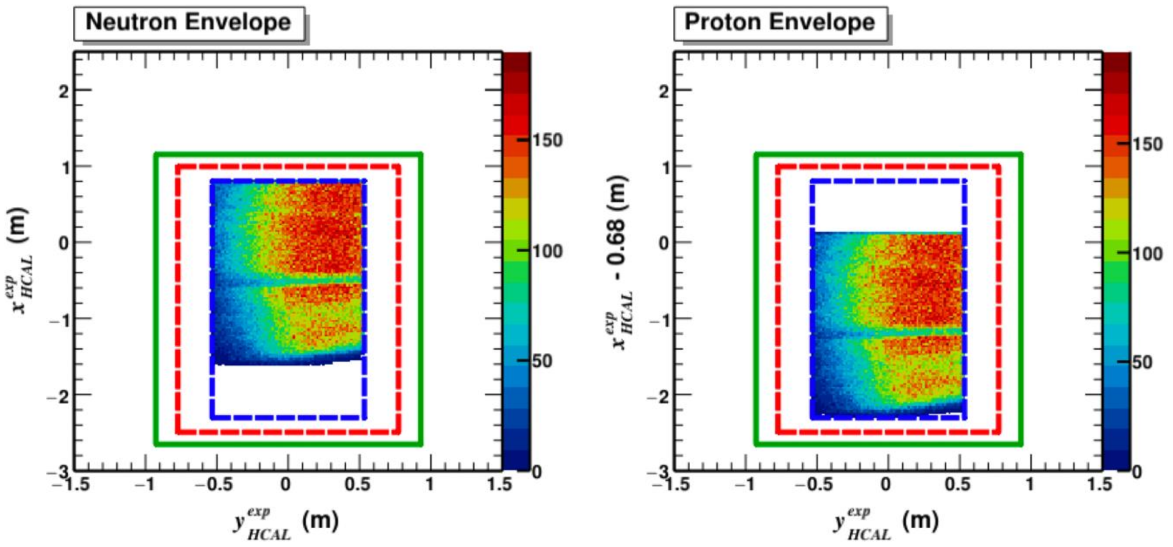
Q^2 = 3 (GeV/c)^2

No Fiducial Cut



--- Top of HCAL ---

With Fiducial Cut



--- Top of HCAL ---

HCAL Physical Boundary

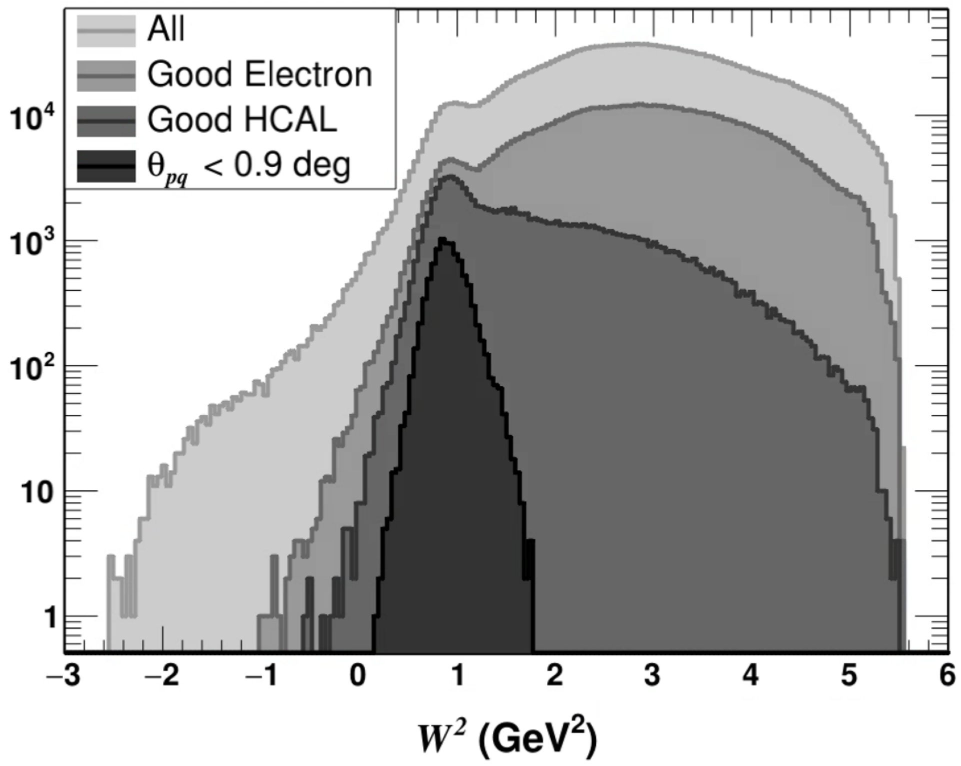
HCAL Active Area

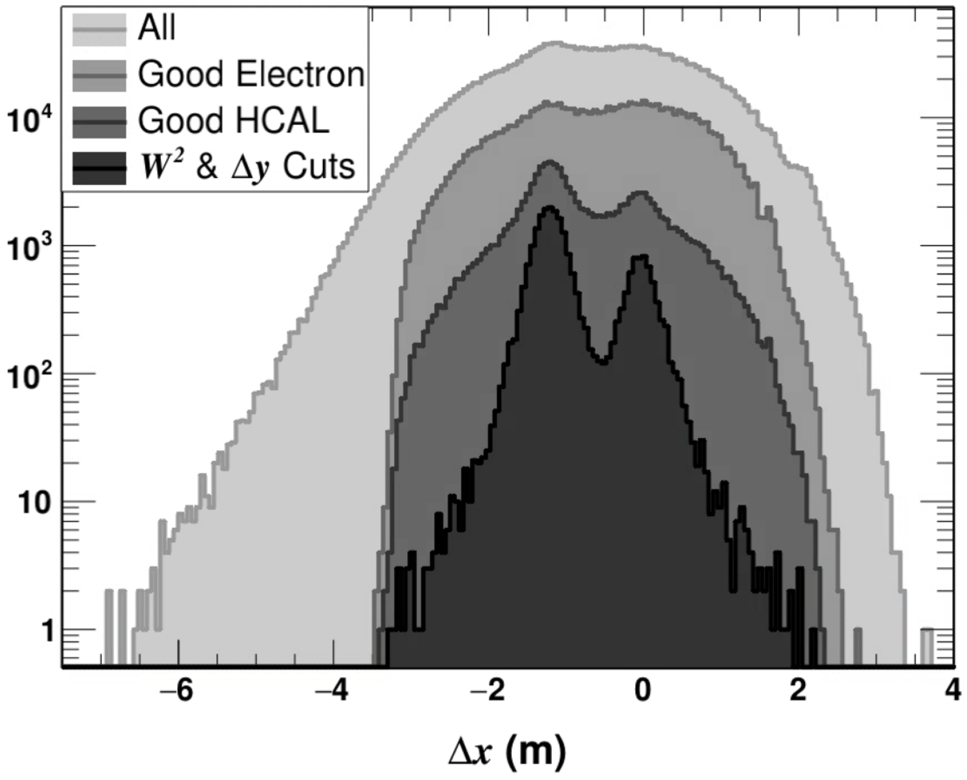
HCAL Safety Margin

- Fiducial cut effectively matches the acceptances for D(e,e'n) and D(e,e'p) events, essential to reduce systematic error in the ratio.

Effects of Analysis Cuts

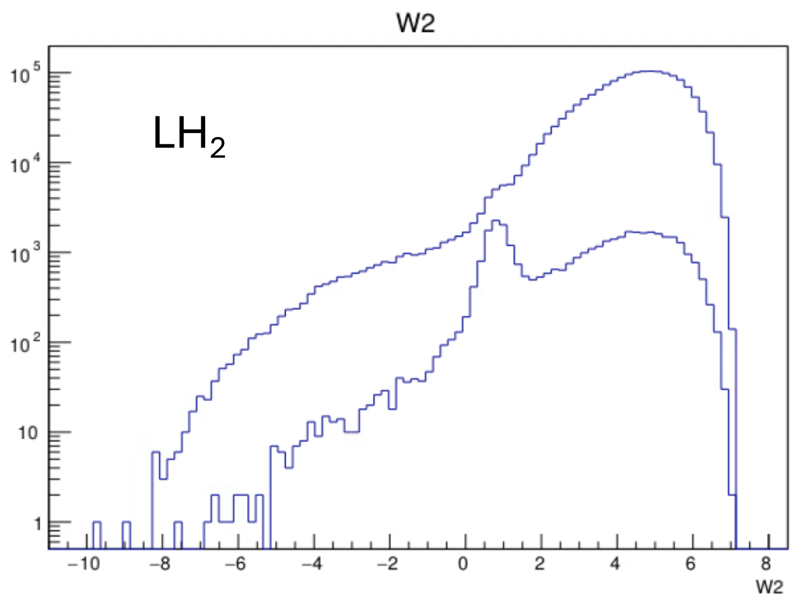
Q^2 = 3 $(GeV/c)^2$

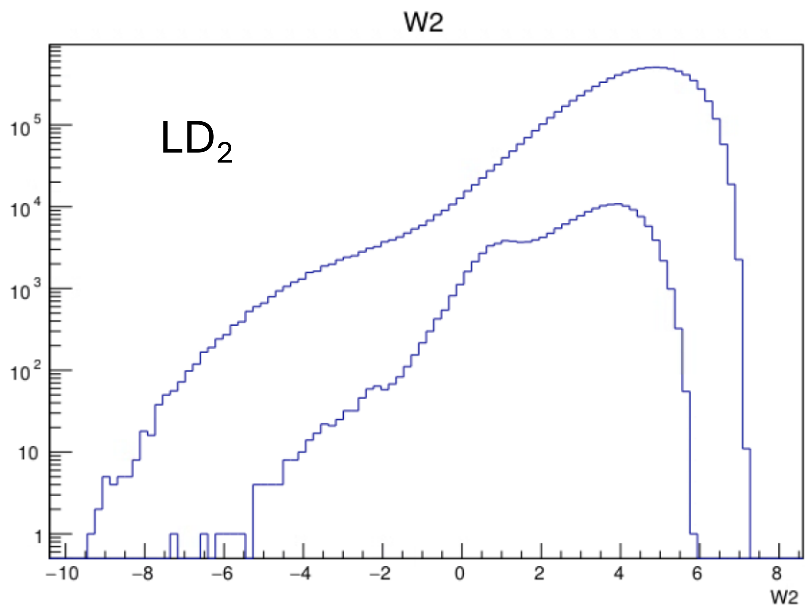




Inclusive W^2

Q^2 = 13.6 (GeV/c)^2

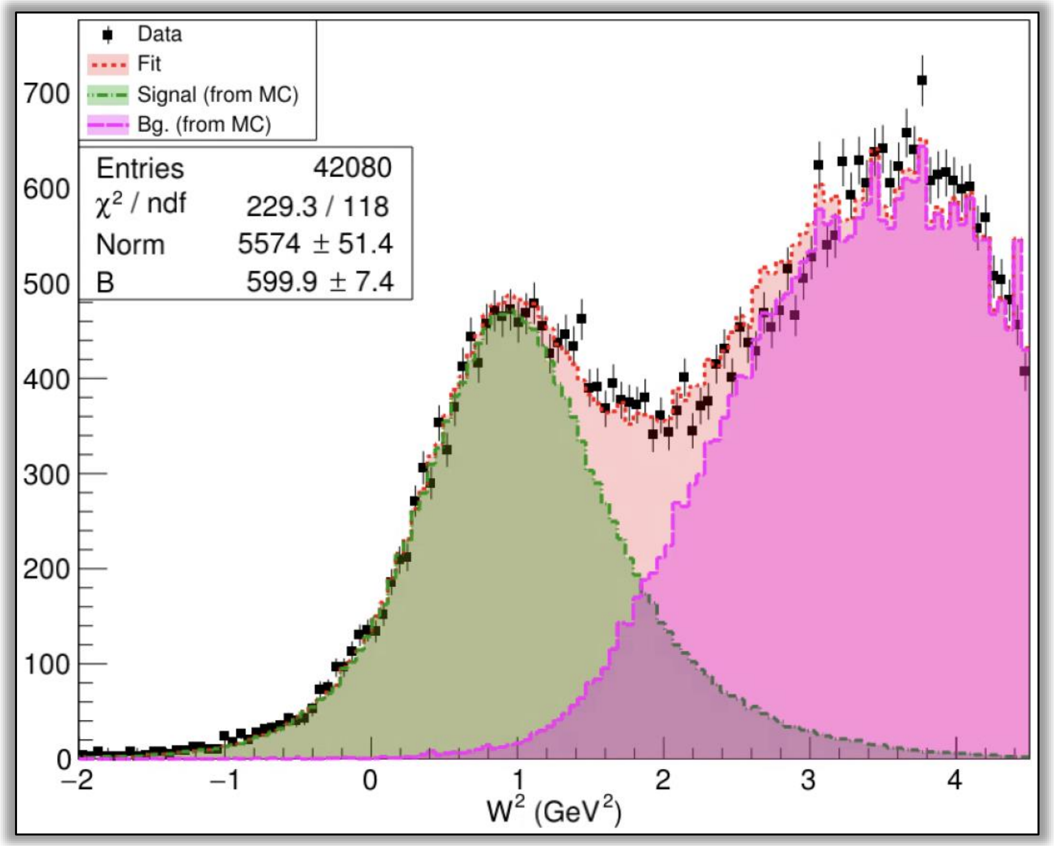




- Inclusive W^2 distribution with and without $\theta_{pq} < 0.6$ deg cut.

Qualitative Data/MC Comparison of W^2 Distribution

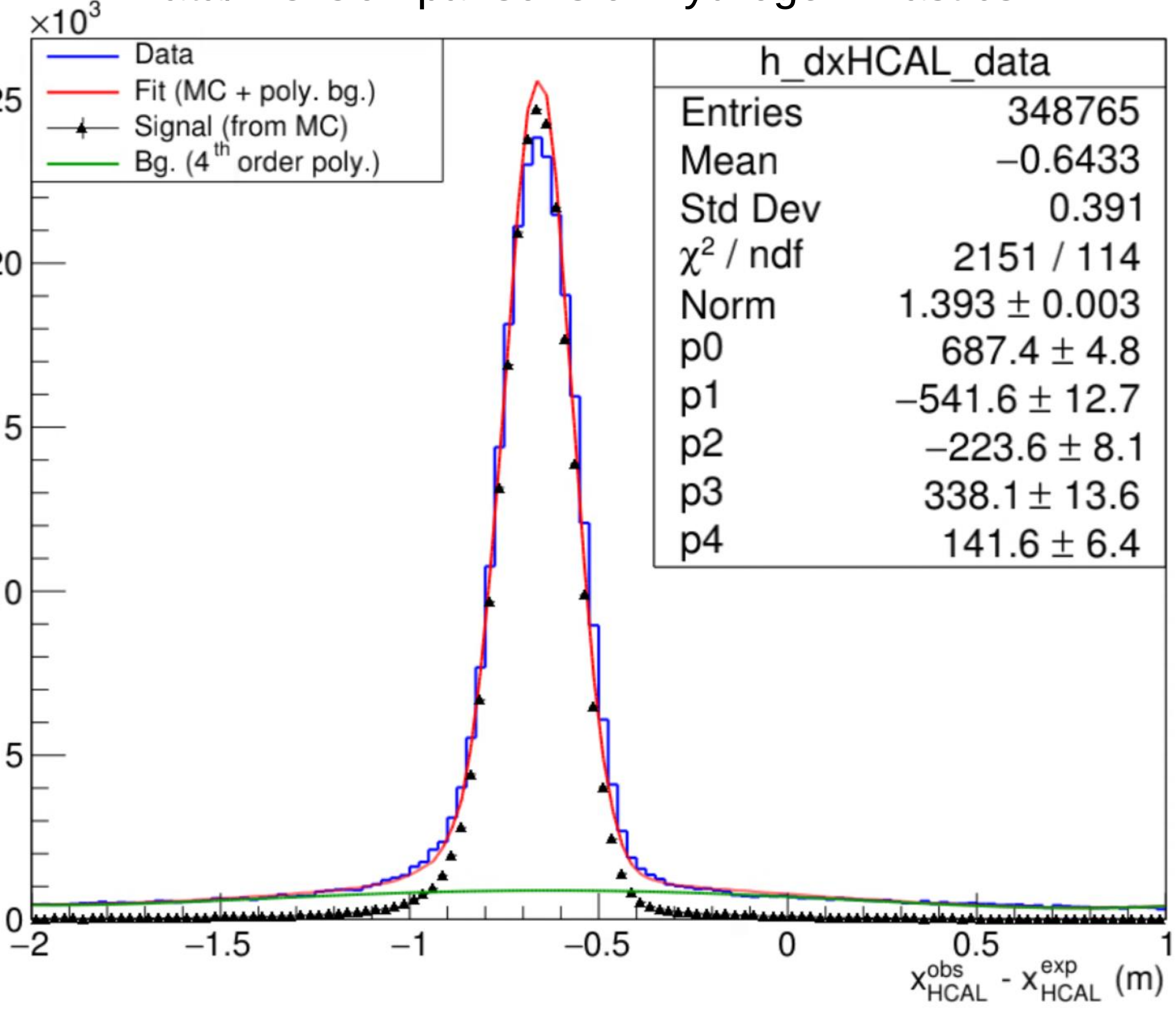
Q^2 = 13.6 (GeV/c)^2



- Qualitative data/MC comparison looks encouraging even for the most challenging kinematics.

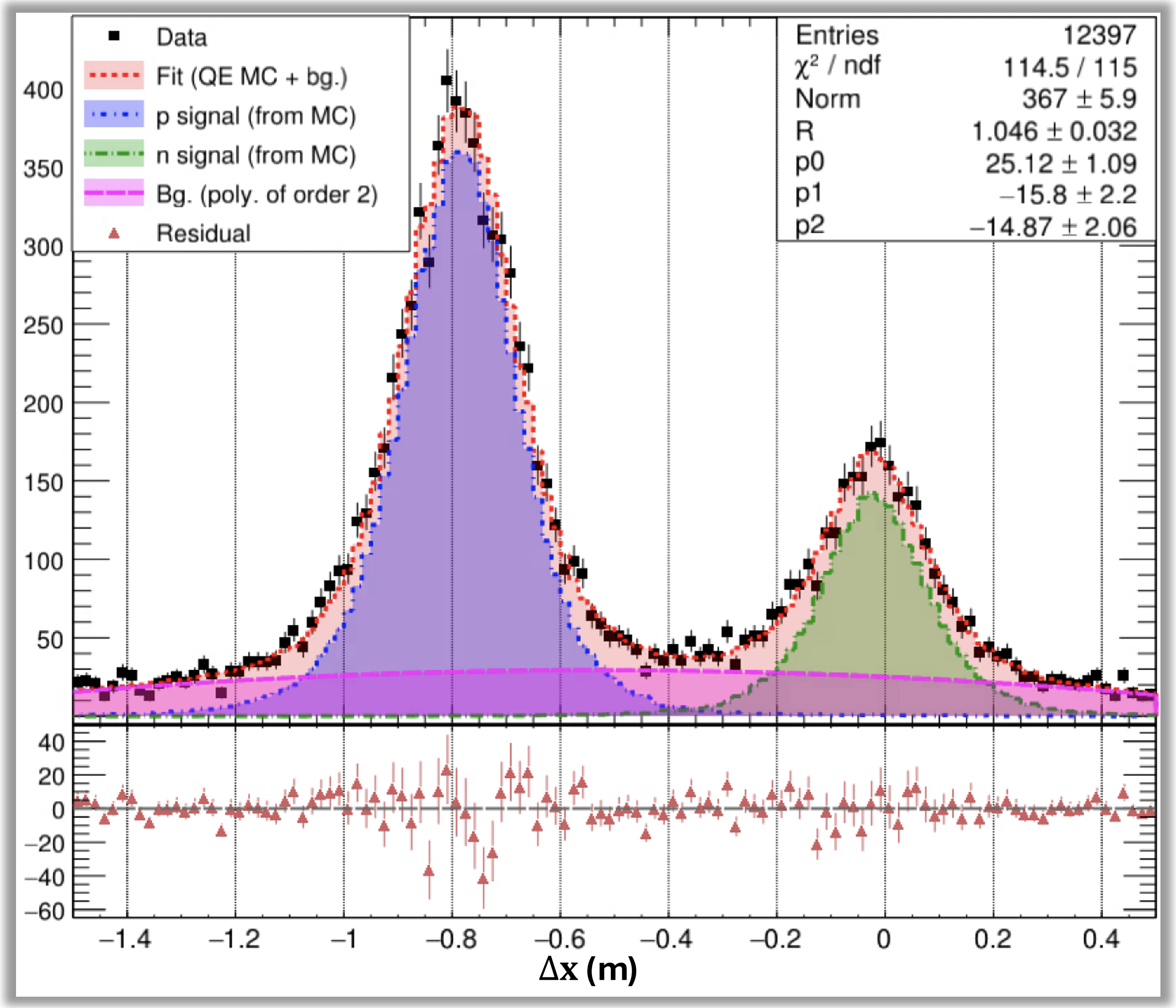
Qualitative Data/MC Comparison for $H(e, e'p)$ Events

Data/MC Comparisons of Hydrogen Elastics

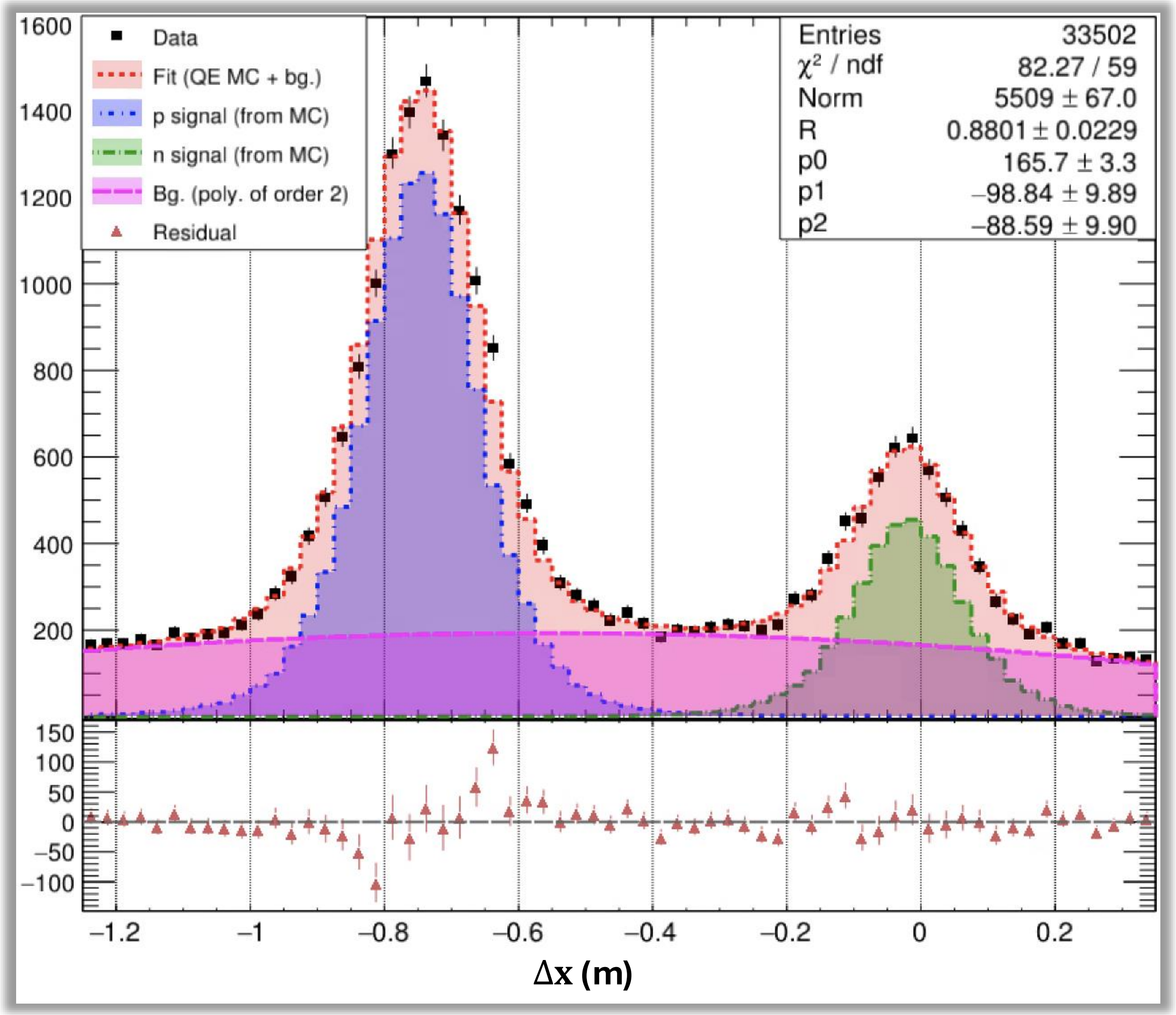


Data/MC Fit to Δx Distribution for Higher Q^2 Points

Q^2 = 9.9 GeV^2, $0.2 \leq W^2 \leq 1.32$ GeV^2, Fiducial Cuts

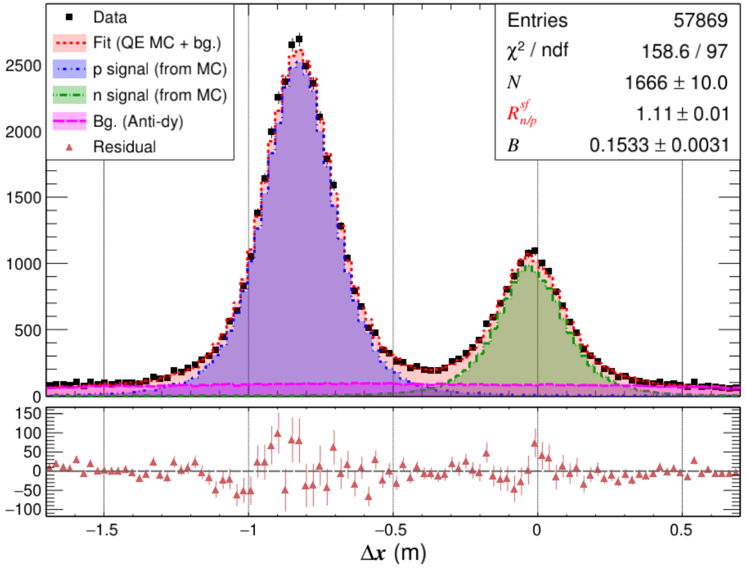


Q^2 = 13.6 GeV^2, $0.16 \leq W^2 \leq 1.44$ GeV^2, Fiducial Cuts

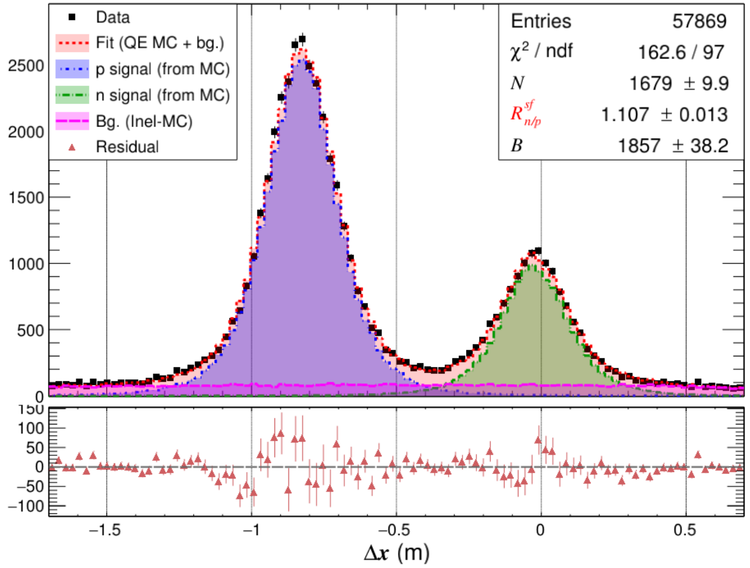


Inelastic Contamination

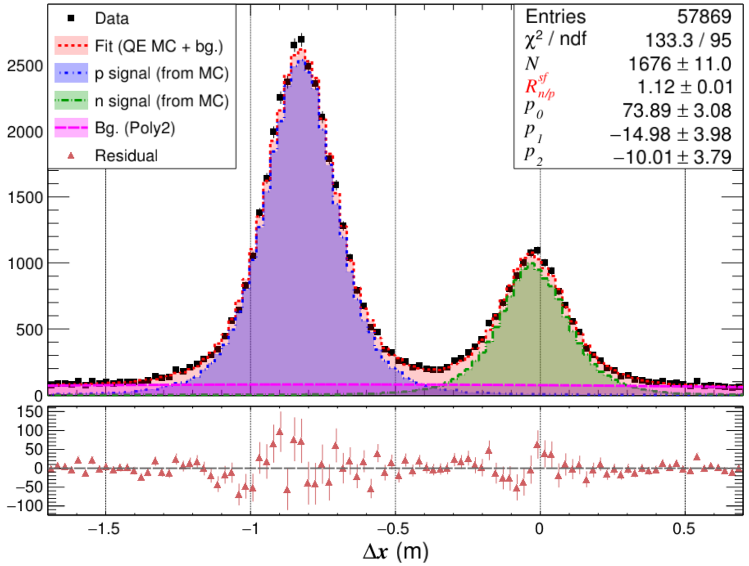
Q^2 = 7.4 (GeV/c)^2



Bg. shape from data



Bg. Shape from Inelastic MC



2nd order polynomial

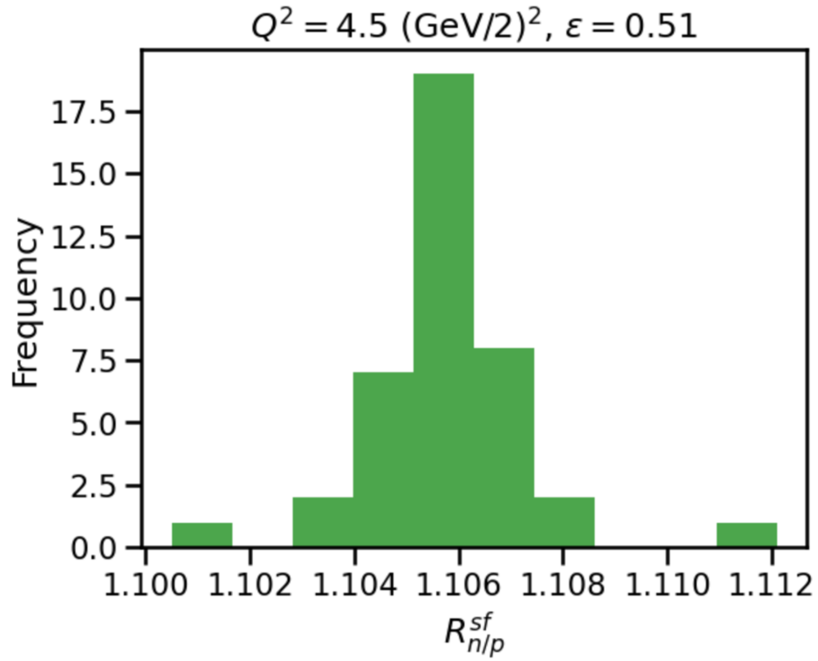
- Perform data/MC fit to Δx distribution using multiple background models.
- Compute standard deviation of $R^{sf}_{n/p}$ values extracted from these fits.
- Quote the result as the systematic uncertainty due to inelastic contamination.

Cut Stability

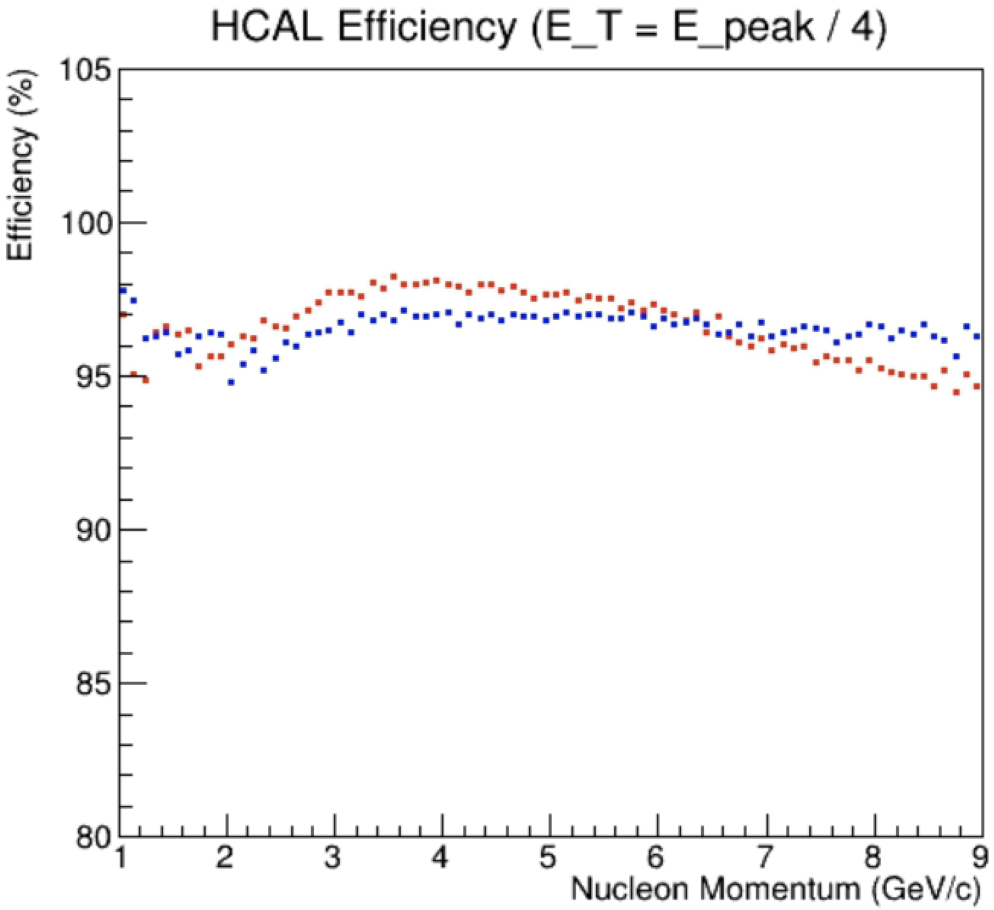
- The choice of optimal cut region has some associated uncertainty.

- We vary each cut range by +10% and -10% while keeping the other cuts constant at their optimized values. Then, for each variation extract $R^{sf}_{n/p}$.

- One standard deviation of the resulting $R^{sf}_{n/p}$ distribution is quoted as the associated systematic uncertainty.



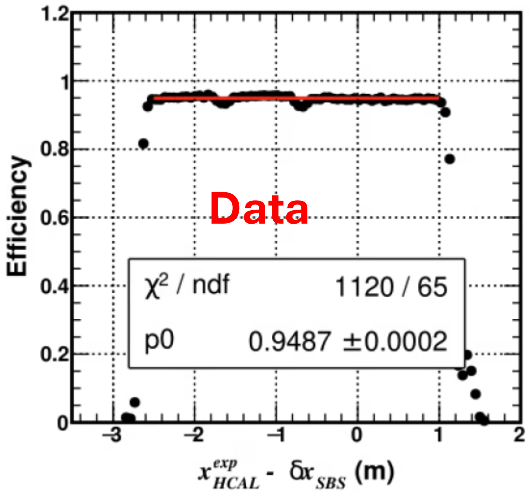
“True” HCAL NDE for MC

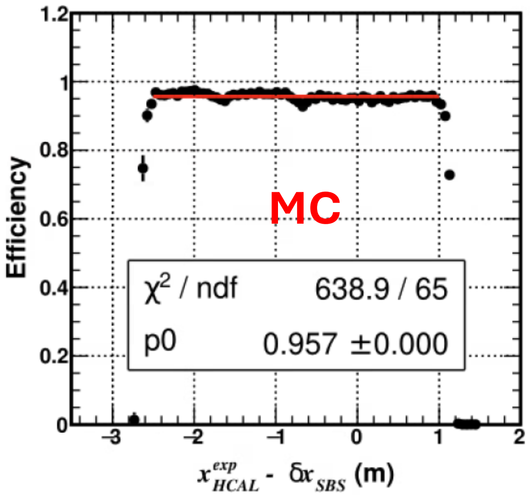


- One of the biggest sources of systematic errors for SBS-GMn/nTPE analysis.
- Very high detection efficiencies, almost independent of nucleon momentum, are expected from simulation.
- MC also show comparable detection efficiencies for proton and neutron, as expected from the design of HCAL.

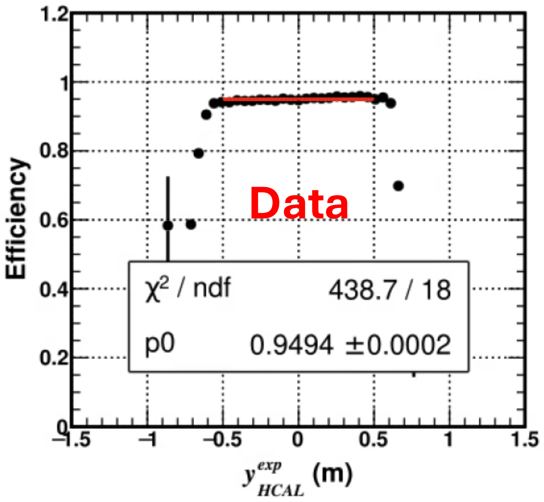
HCAL pDE – Data/MC Comparison

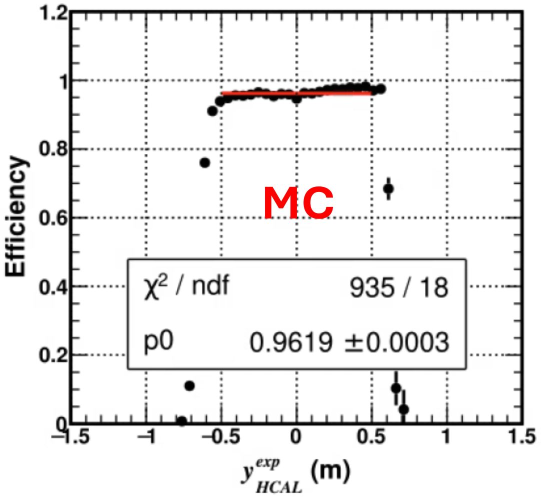
Dispersive





Non-Dispersive





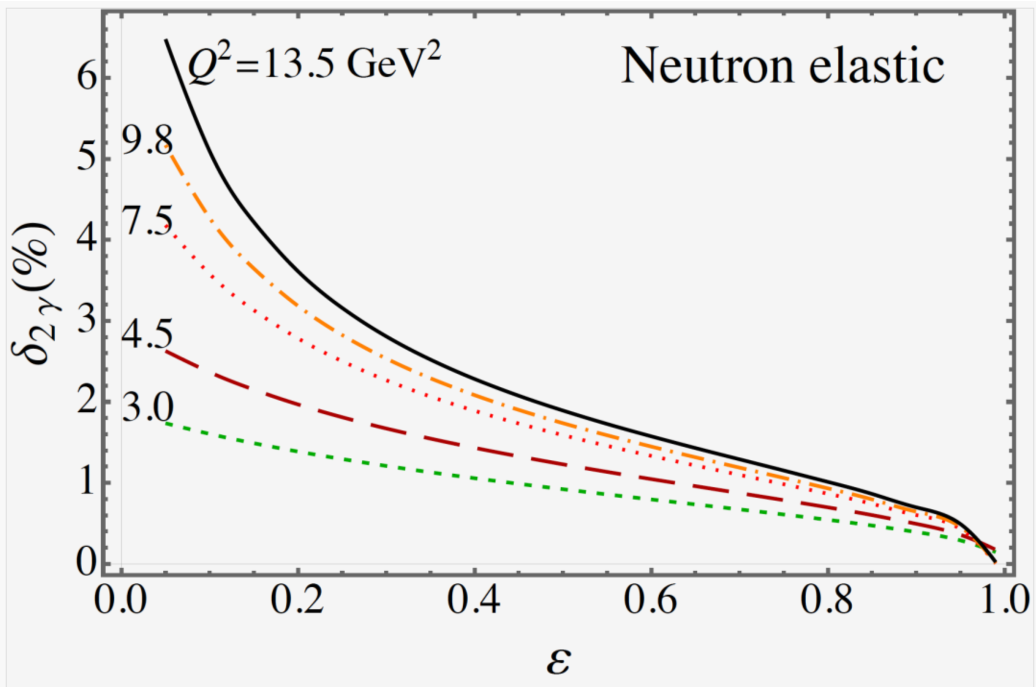
Predicted TPE Contribution

Credit: Andrei Afanasev

E_e GeV	$\theta_{e'}$ deg	Q^2 GeV^2	$(1+\delta)_p$	$(1+\delta)_n$	$(1+\delta)_p/(1+\delta)_n$
3.73	36.0	2.99	1.01809	1.00107	1.01696
4.03	49.0	4.5	1.01746	0.999145	1.01833
5.97	46.5	7.46	1.0202	0.998075	1.02217
7.91	40.0	9.83	1.02168	0.998083	1.02364
9.86	42.0	13.5	1.02242	0.998544	1.02391

Table 1: Table of relevant kinematics in *ep*- and *en*- scattering. The last three columns represent the two-photon corrections for a proton neutron target. The last column is the ratio of the corrections off protons vs neutrons.

Credit: Blunden

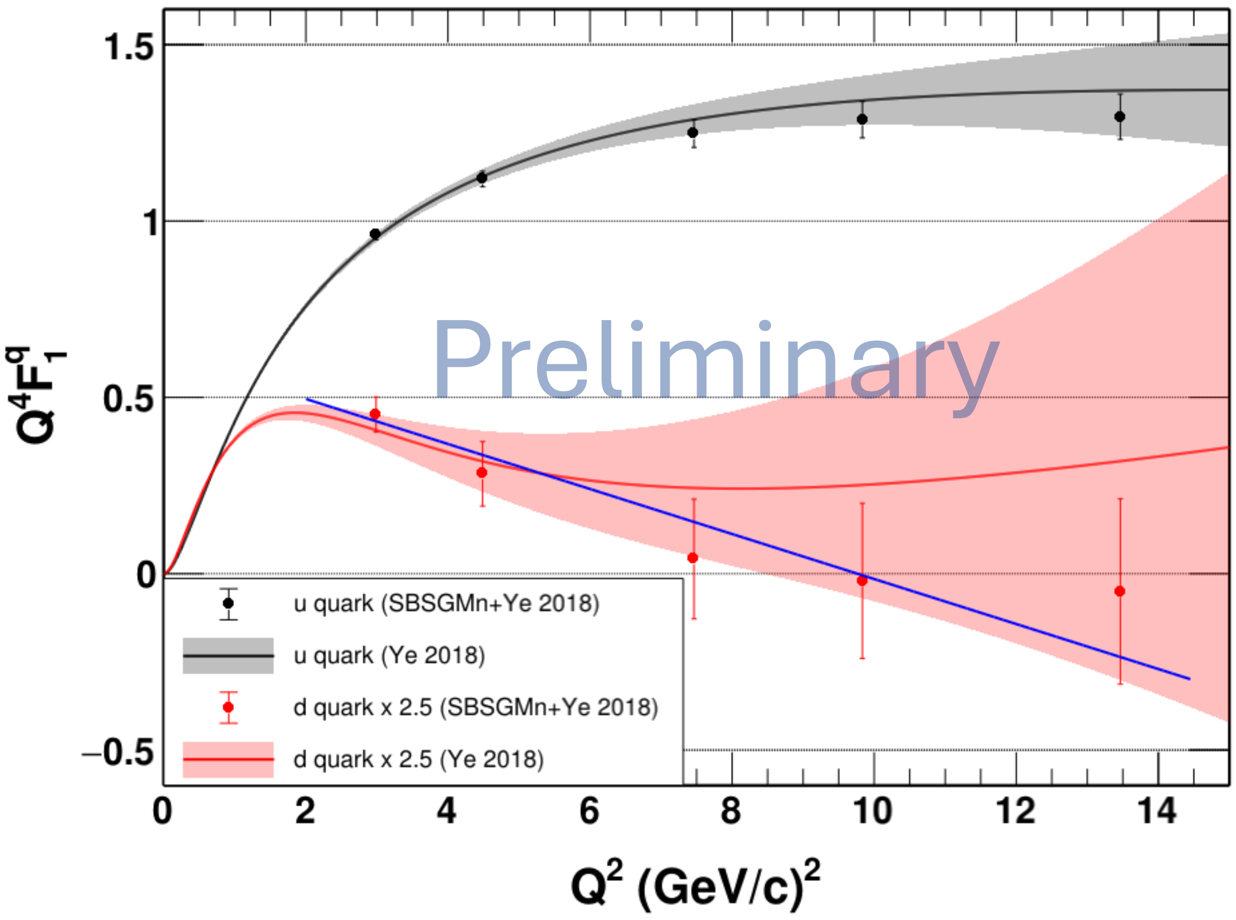


Impact on the Quark Form Factors (Preliminary)

- Fit Equation:

$$y = p_0(1 + p_1 x)$$

```
*********************************************
Minimizer is Minuit2 / Migrad
Chi2                      =      1.37647
NDf                       =            3
Edm                       =  1.08377e-06
NCalls                    =           67
p0                        =     0.623053    +/-    0.0861665
p1                        =    -0.102421    +/-    0.0188333
```



- Possible zero-crossing of F_1^d at $\mathbf{Q^2 = 9.8 \pm 1.8\ (GeV/c)^2}$ (obtained from a linear fit to data).

Impact on the Quark Form Factors (Preliminary) contd.

$$
\begin{aligned}
F_1^d &= 2F_1^n + F_1^p \\
&= 2\frac{\tau_n G_M^n + G_E^n}{1+\tau_n} + \frac{\tau_p G_M^p + G_E^p}{1+\tau_p} \\
&= \frac{2\tau_n}{1+\tau_n} G_M^n + \frac{2}{1+\tau_n} G_E^n + \frac{\tau_p}{1+\tau_p} G_M^p + \frac{1}{1+\tau_p} G_E^p \\
&= G_D \left[\frac{2\tau_n}{1+\tau_n}\frac{G_M^n}{G_D} + \frac{2}{1+\tau_n}\frac{G_E^n}{G_D} + \frac{\tau_p}{1+\tau_p}\frac{G_M^p}{G_D} + \frac{1}{1+\tau_p}\frac{G_E^p}{G_D} \right] \\
&\approx G_D \left[1.6\frac{G_M^n}{G_D} + 0.4\frac{G_E^n}{G_D} + 0.8\frac{G_M^p}{G_D} + 0.2\frac{G_E^p}{G_D} \right] \\
&\approx G_D \left[(-2.239 \pm 0.085) + (0.249 \pm 0.203) + (1.947 \pm 0.023) + (-0.015 \pm 0.033) \right]
\end{aligned}
$$

For $Q^2 = 13.5\ \mathrm{GeV}^2$