Update on nTPE Analysis & Thesis Progress

Ezekiel W. Wertz

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Jefferson Lab
Exploring the Nature of Matter

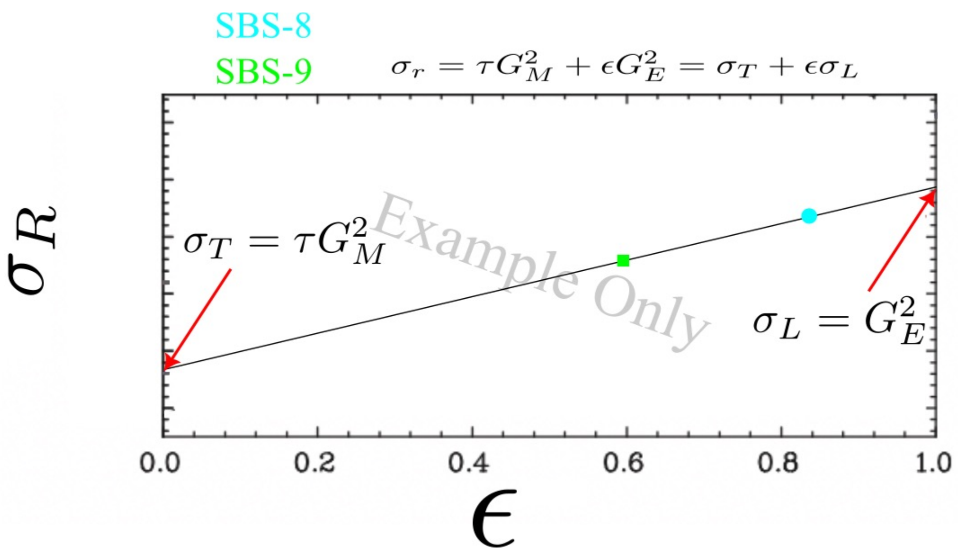
William & Mary
Chartered 1693

NSF

Super BigBite Spectrometer

Neutron Two-Photon Exchange (nTPE) Experiment

Name	Ebeam (GeV)	BigBite angle (deg)	BigBite Distance (m)	SBS angle (deg)	SBS distance (m)	HCAL "angle" (deg)	HCAL distance (m)	Q^2 (GeV^2)	Electron P (GeV)	Nucleon P (GeV)
SBS-8	5.965	26.5	2.00	29.9	2.25	**29.4**	11.0	4.5	3.58	3.2
SBS-9	4.015	49.0	1.55	22.5	2.25	**22.0**	11.0	4.5	1.6	3.2



- SBS nTPE is the first measurement of the Rosenbluth Slope(RS) for the neutron using the ratio method
- Data taken January & February 2022 for total of 19 days at 2 different kinematic (ϵ) values
- Exploiting the linearity of the reduced cross section (σ_r) in ϵ and assuming OPE, neutron FFs can be extracted:
  - $\sigma_L = G_E^2$ is slope
  - $\sigma_T = \tau G_M^2$ is vertical-axis intercept
- Rosenbluth Slope Extraction:

$$\sqrt{\tau \cdot RS} = \sqrt{\frac{\tau|\sigma_L|}{\sigma_T}} = \frac{G_E}{G_M}$$

From Observable to Physics Result

Measured Observable: $R_{observed} = \frac{N_{e,e'n}}{N_{e,e'p}}$, $N_{e,e'n}\,/N_{e,e'p}$ are detector yields for quasi-elastic neutrons/protons

- No free neutron target, so use deuterium. Taking ratios from double-arm experiment cancels many systematic effects (Durand/Ratio Method).

Nuclear & Radiative Corrections: $R_{corrected} = f_{corr} \times R_{observed}$

- Neutron & Proton in Deuteron are not free particles.

Relation to Cross-Sections: $R_{corrected} = \frac{\sigma^n_{Mott} \cdot (1+\tau_p)}{\sigma^p_{Mott} \cdot (1+\tau_n)} \times \frac{\epsilon\sigma^n_L + \sigma^n_T}{\epsilon\sigma^p_L + \sigma^p_T}$

$$R_{corrected,\epsilon_1} = R_{Mott,\epsilon_1} \times \frac{\epsilon_1\sigma^n_L + \sigma^n_T}{\epsilon_1\sigma^p_L + \sigma^p_T} \qquad R_{corrected,\epsilon_2} = R_{Mott,\epsilon_2} \times \frac{\epsilon_2\sigma^n_L + \sigma^n_T}{\epsilon_2\sigma^p_L + \sigma^p_T}$$

From Observable to Physics Result

Physics result, σ_L^n and σ_T^n:

Consider ratio of $R_{corrected}$ for two values of ϵ and define $S_c^{n(p)} = \sigma_L^{n(p)} / \sigma_T^{n(p)}$

$$\mathrm{A} \equiv \frac{R_{corrected,\epsilon_1}}{R_{corrected,\epsilon_2}} = B \times \frac{1+\epsilon_1 S_c^n}{1+\epsilon_2 S_c^n} \approx B \times (1 + \Delta\epsilon \cdot S_c^n)$$

From Data

Proton Global Data

Kinematic Info

Physics Result!

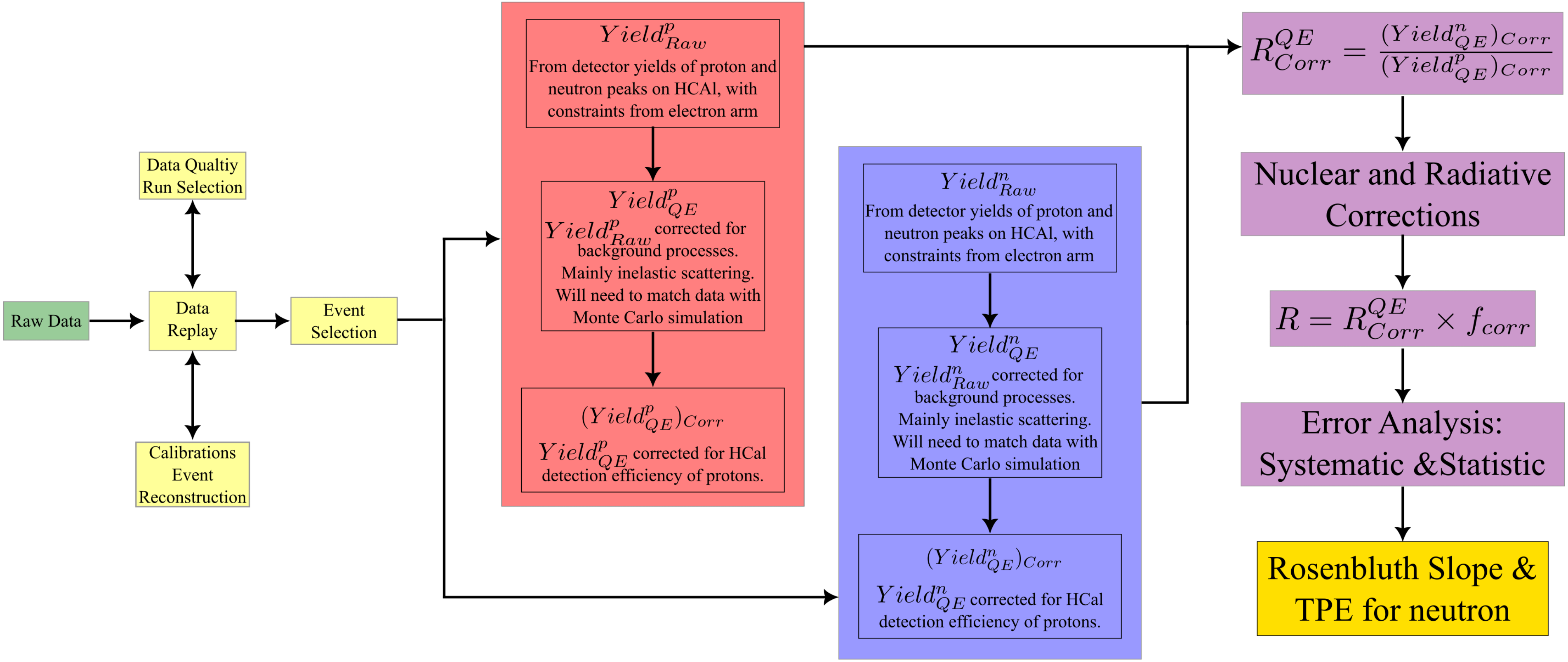
Proton Global Data:
From global analysis of
e-*p* cross-section.
Taken as known.

$$B = \frac{R_{Mott,\epsilon_1}}{R_{Mott,\epsilon_2}} \times \frac{1+\epsilon_2 S_c^p}{1+\epsilon_1 S_c^p} \approx 1 - \Delta\epsilon \cdot S_c^p$$

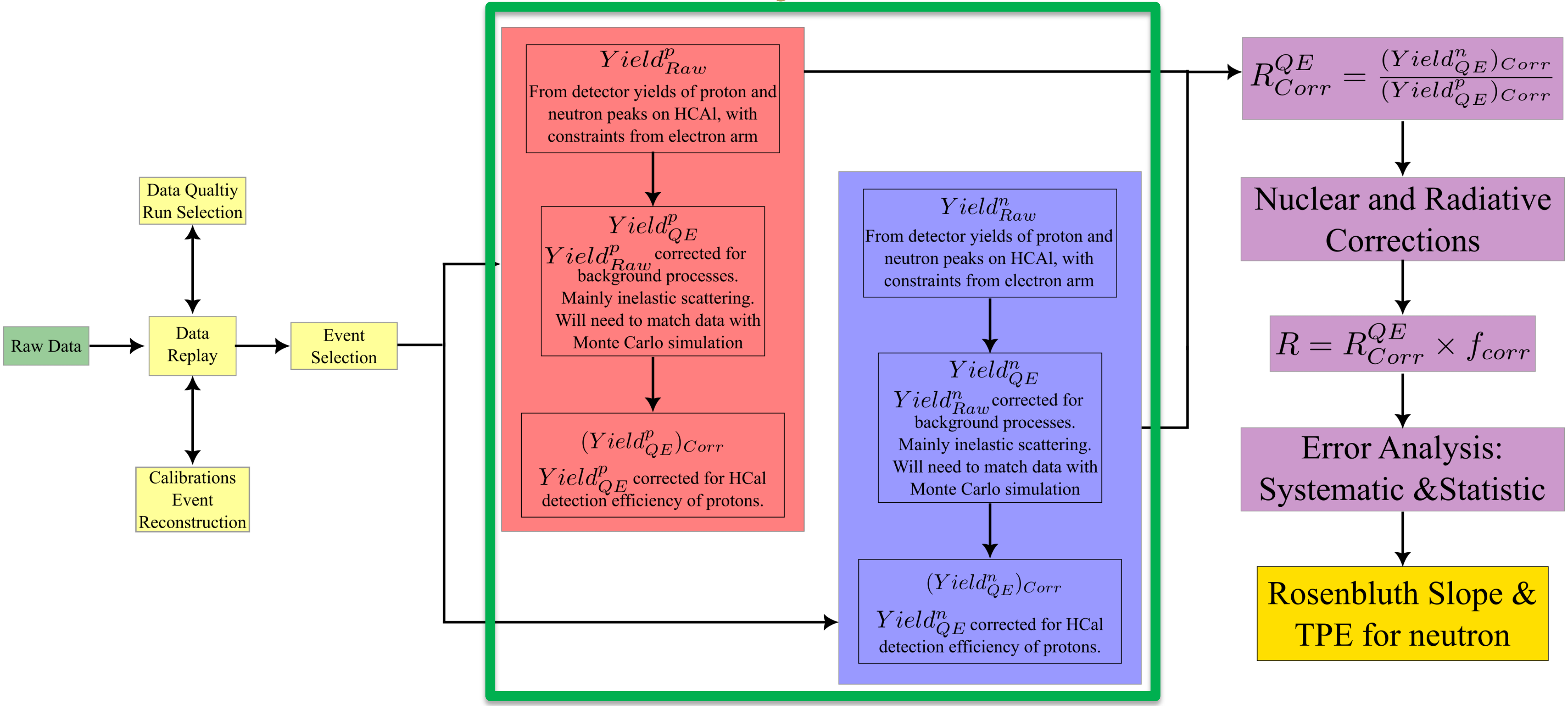
Thesis Scope

- **Primary focus:** physics extraction for the nTPE experiment to determine the Rosenbluth slope for the neutron.
- SBS nTPE is the first measurement of the Rosenbluth Slope for the neutron using the ratio method
- Thesis will also include the following:
  1. GEM Hardware commissioning and installation work for G_M^n/nTPE run period
  2. GEM gain match software calibration for G_M^n/nTPE run period

Data Analysis Overview

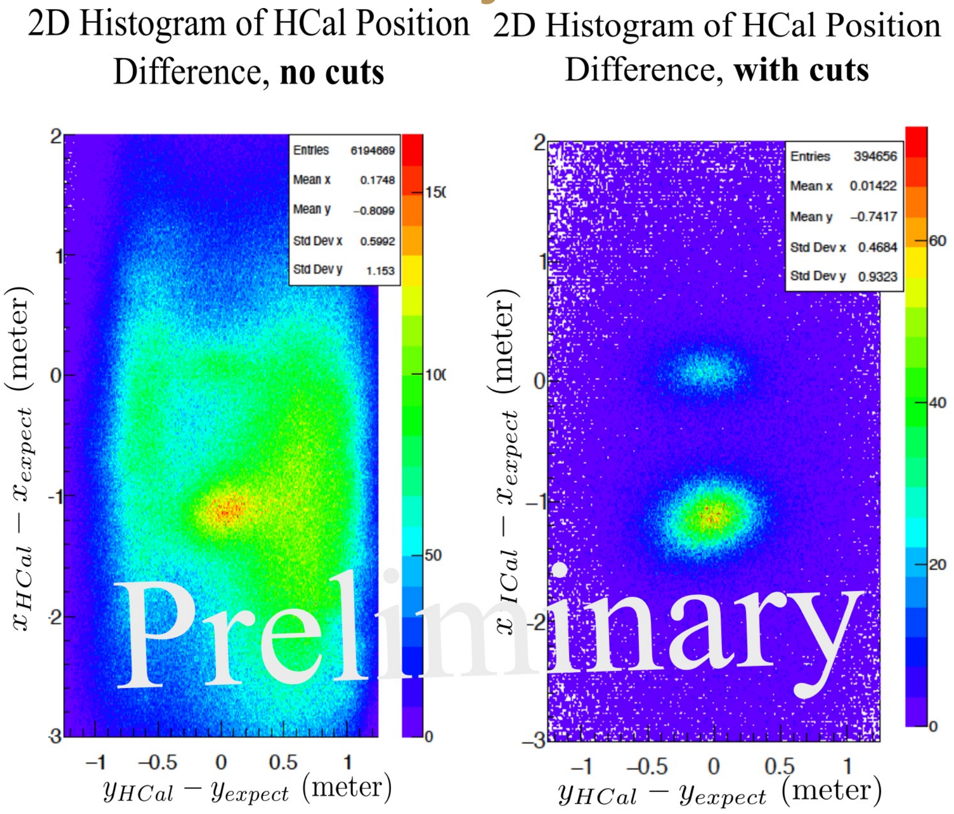


Data Analysis Part 1



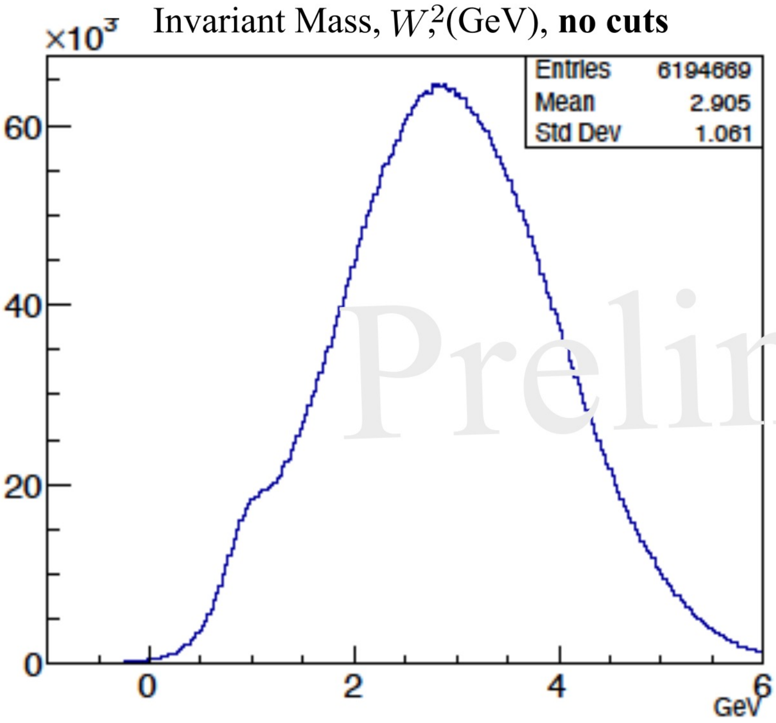
Data Analysis Part 2

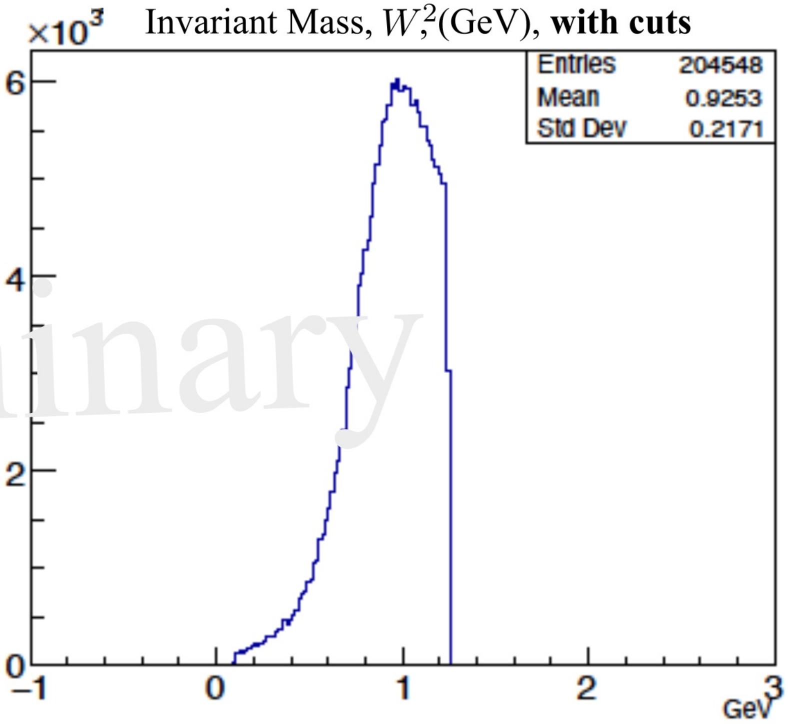
SBS8 & SBS field 100%



Data Analysis Part 3

SBS8 & SBS field 100%

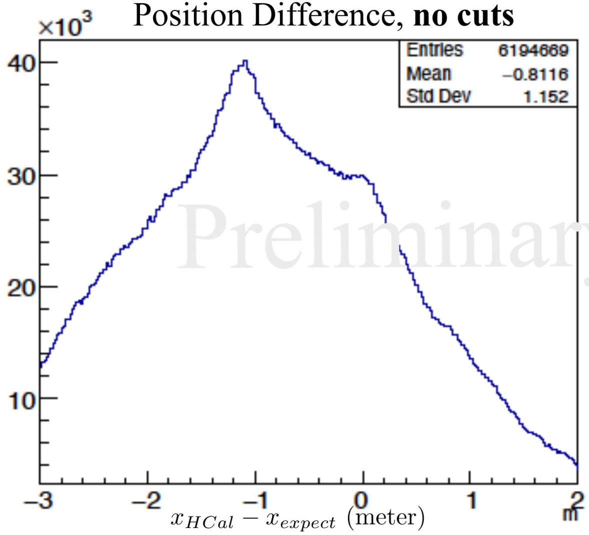




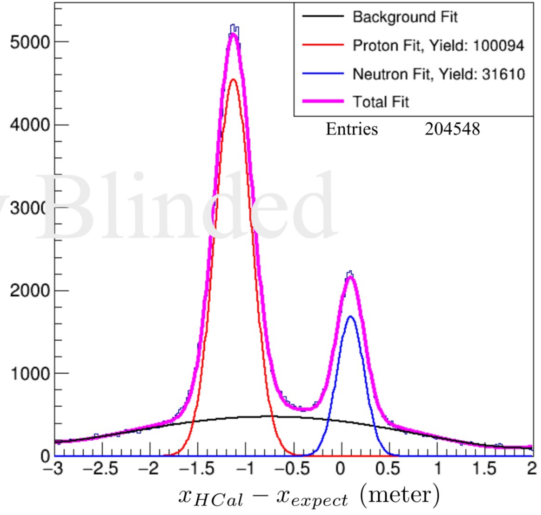
Data Analysis Part 4

SBS8 & SBS field 100%

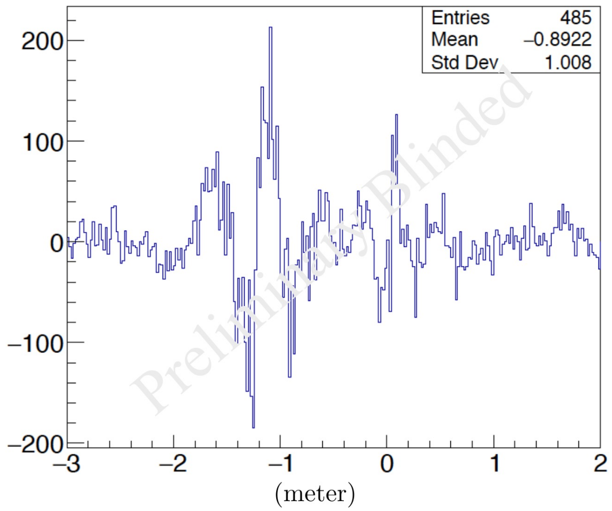
1D Histogram of HCal x-direction Position Difference, **no cuts**



1D Histogram of HCal x-direction Position Difference, **with cuts**



1D Histogram of HCal x-direction Position Difference Residual (data-fit), **with cuts**

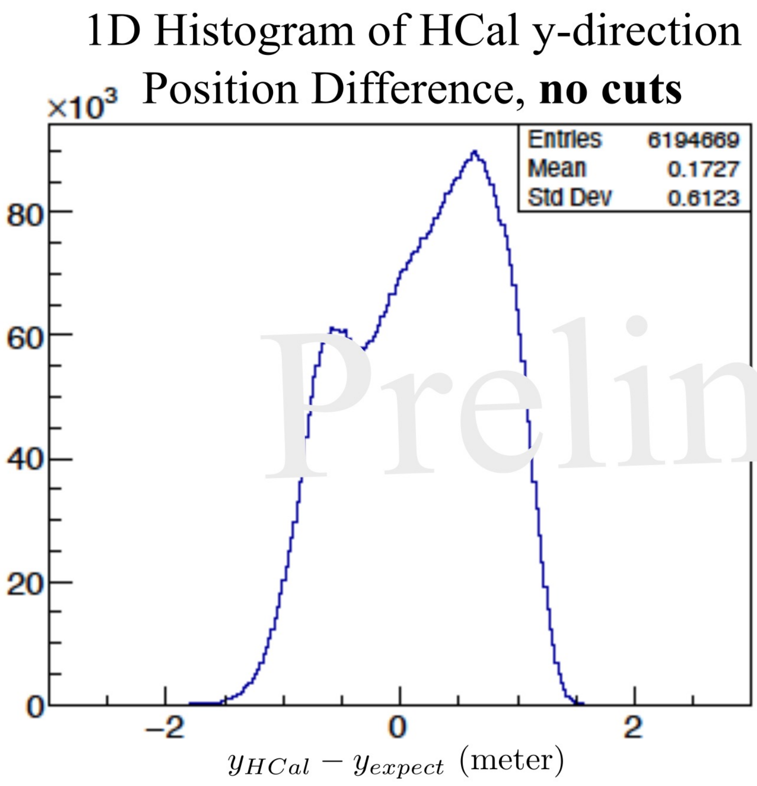


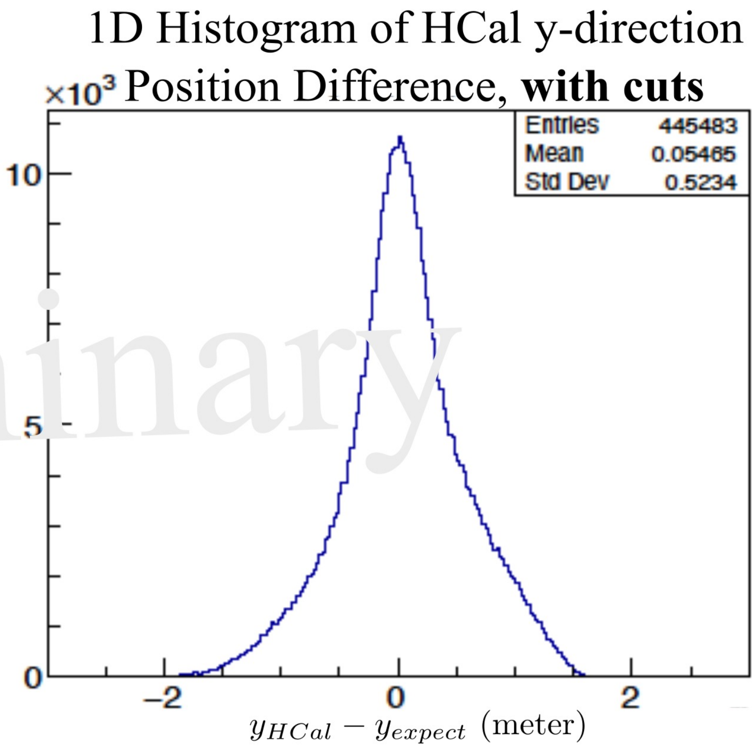
Background fit: 4th order polynomial

Nucleon Fits: Gaussian

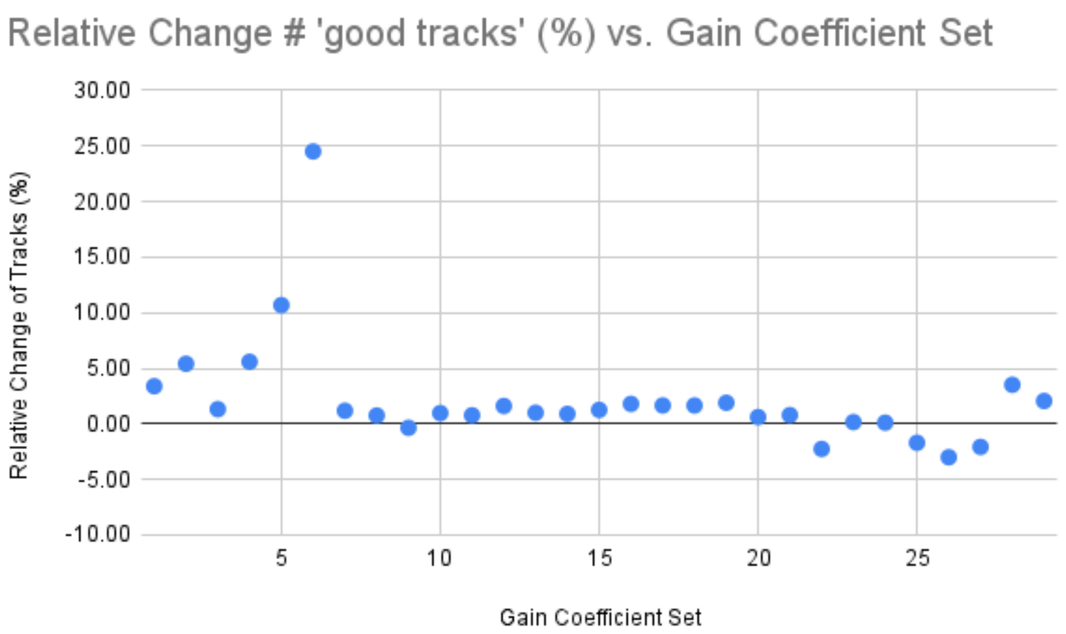
Data Analysis Part 5

SBS8 & SBS field 100%





GEM Gain Match Calibration & Status



Vertical Axis Percentage:

$$\frac{After\ - Before}{Before} * 100$$

- **Purpose**: Compare signal amplitudes from amplifier cards (APV). Correct amplitude variations for each amplifier card by generating gain coefficients.
- First-pass creation of gain coefficients (max 29 sets) & thresholds complete.
- After gain match most sets see slight increase in # good tracks
- Some runs see reduction in # good tracks or track based efficiency, requires investigation.
- Need to compare yields from hydrogen data for subset of gain coefficient sets and add to main software.

Analysis Outlook

In-Progress (me):

- Refine Yield fits by implementing ROOT interpolation function and sideband analysis
- Refine code for HCal Detection Efficiency for proton. Evaluate multiple methods already suggested by HCal expert
- HCal Detection Efficiency for Neutron will be based on Monte Carlo and Proton Efficiency matching
- Implement better method for backgrounds based on W^2 Anti-cut
- Implement better fiducial and acceptance cuts
- Implement Gain Coefficients for pass-2.

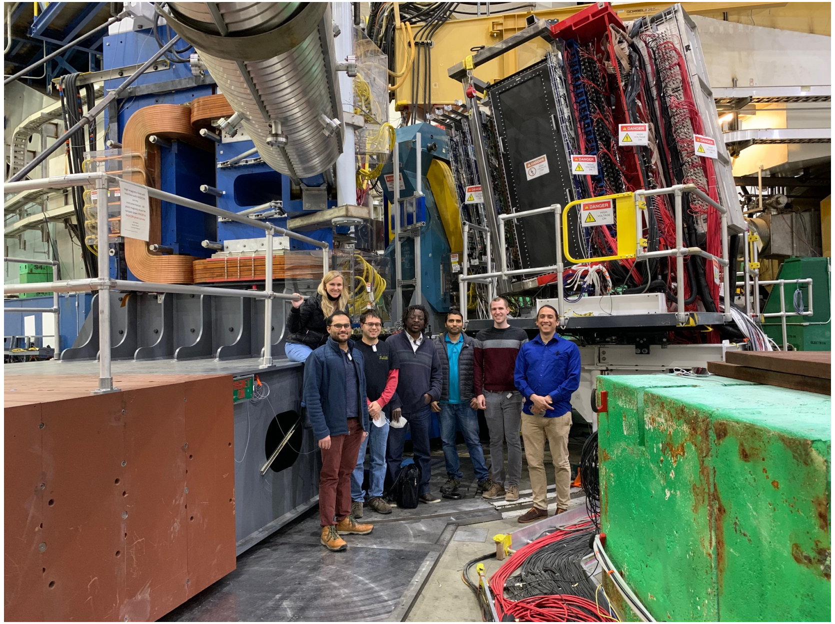
In-Progress (collaboration):

- Dedicated effort to implement nuclear & radiative corrections into simulation from existing framework from Hall C
- Effort for 2^{nd} Mass-Replay & Detector Calibration is underway, tasks necessary for preliminary physics results
- Determine error analysis, mainly systematics

Research Outlook: The Big Plan™

	2023									2024					
Task	April	May	June	July	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	April	May	June
Analysis/ Result															
2nd Pass Replay															
Writing Thesis Parts															
Writing Thesis Only															
Find Job															
Defense															
JLUO Grad Rep			Ends												
GSA Board		Ends													
Other		Comp Works hop	HUGs JLUO				DNP			GRAD 520		GHRS	APS/ Later Conf		

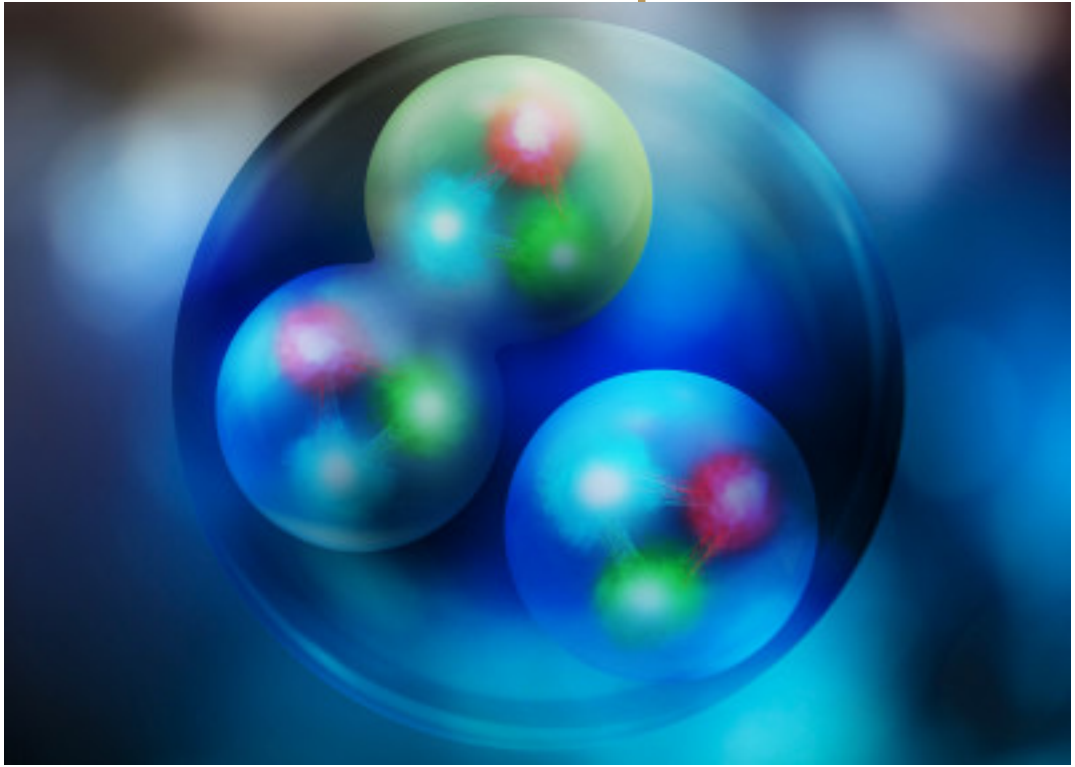
Thank You!
Questions?



References:

1. Benmokhtar, F., et al. "Precision Measurement of the Neutron Magnetic Form Factor up to Q 2= 18.0 (GeV/c) 2 by the Ratio Method." (2008). Proposal# E12-09-19.
2. Cates, G., et al. "Measurement of the neutron electromagnetic form factor ratio Gn E/Gn M at high Q2." (2009). Proposal# E12-09-16.
3. Perdrisat, C. F., et al. "Large Acceptance Proton Form Factor Ratio Measurements at 13 and 15 (GeV/c) 2 Using Recoil Polarization Method." (2007). Proposal# E12-07-109.
4. Afansev, A., et al. "Two-Photon exchange in elastic electron-proton scattering" *Prog. Part Nucl. Phy.* 95, 245 (2017)
5. Alsalmi, S., et al. "Measurement of the Two-Photon Exchange Contribution to the Electron-Neutron Elastic Scattering Cross Section." (2020).Proposal# E12-20-010

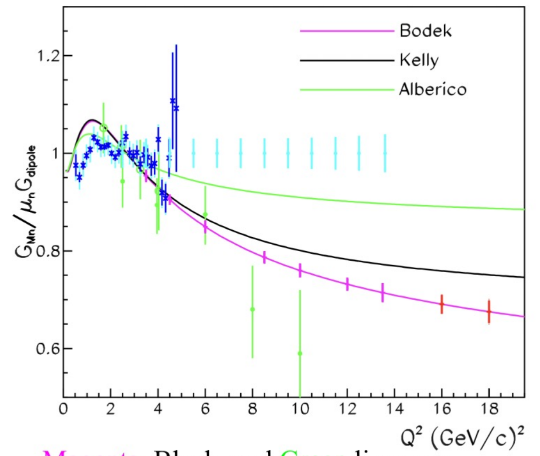
Backup



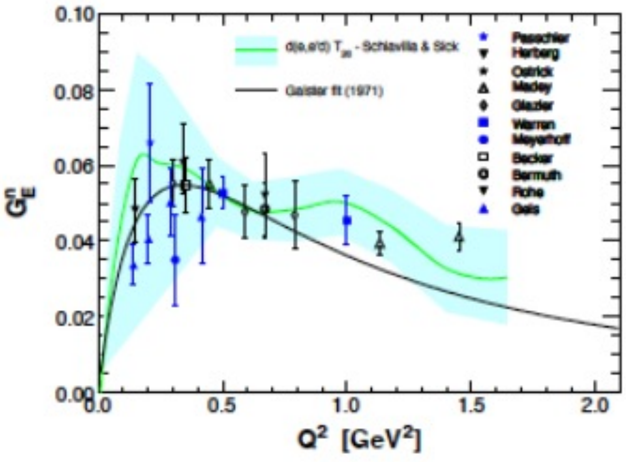
Nucleon Form Factors (FF)

- Electromagnetic FFs are some of the most basic observables of the nucleon
- Encodes internal electric charge and magnetic distributions of the nucleon
- Electromagnetic FFs are the Fourier transform of the charge/magnetic distributions
- Nucleons are the building blocks of ordinary matter in the Universe!

Neutron Magnetic FF

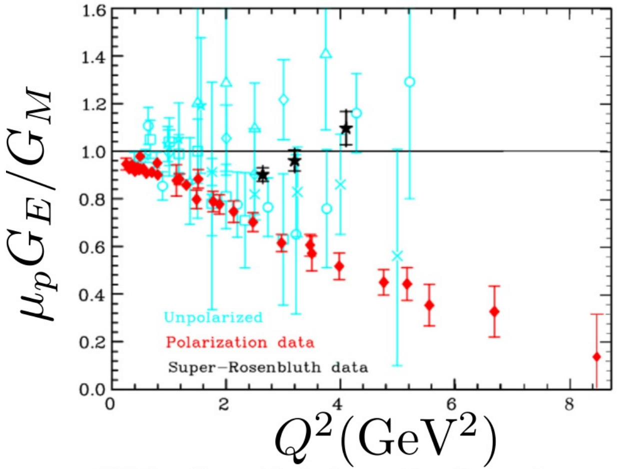


Magenta, Black, and Green lines are theoretical models.
Blue and Green points are from previous experiments.
Cyan and Magenta points expected data points from experiment.



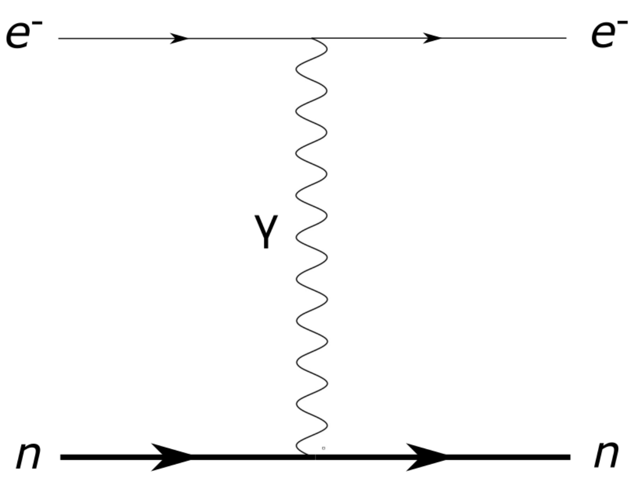
Experimental World Data

Proton Electric & Magnetic FF Ratio

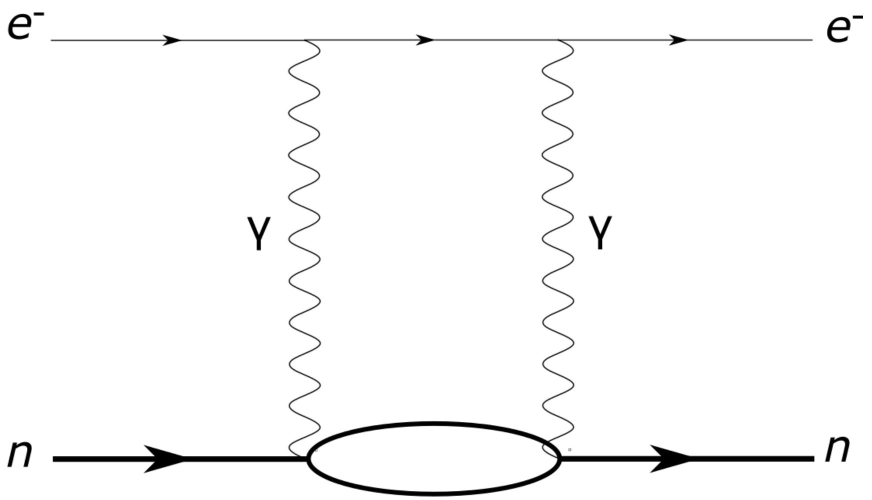


Cyan = Rosenbluth Separation Extraction
Red = Polarization Transfer Measurements
Black = Super Rosenbluth

Elastic Electron-Nucleon Scattering



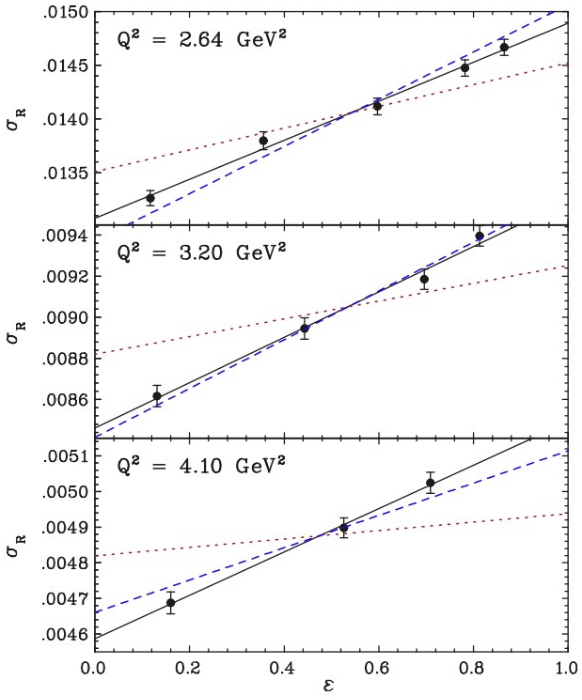
One Photon Exchange (OPE):
Can calculate with Quantum Electrodynamics (QED)



Two Photon Exchange (TPE):
Hard to calculate with QED & Strong Interaction!

- Tool to probe internal structure of the nucleon
- From measuring the cross-section and comparing OPE, can extract TPE effects

Rosenbluth Separation for Nucleon FFs



= reduced cross-section linear fit

= polarization transfer prediction

= slope expected from $\mu_p G_E/G_M$

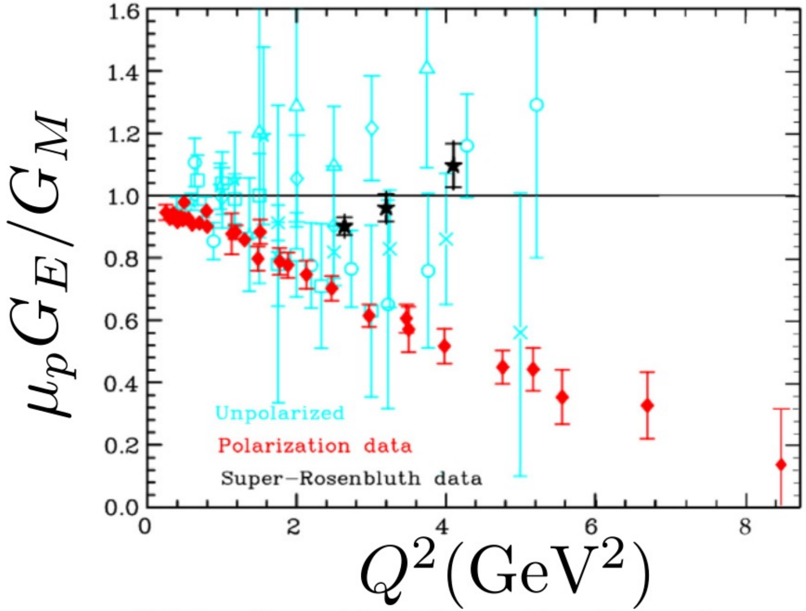
$$\frac{d\sigma}{d\Omega} = \left(\frac{\alpha}{4MQ^2}\frac{E'}{E}\right)^2 |M_\gamma|^2 = \frac{\sigma_{Mott}}{\epsilon(1+\tau)}\left(\epsilon G_E^2(Q^2) + \tau G_M^2(Q^2)\right)$$

$$= \frac{\sigma_{Mott}}{\epsilon(1+\tau)}\sigma_R = \frac{\sigma_{Mott}}{\epsilon(1+\tau)}(\epsilon\sigma_L + \sigma_T)$$

- $\frac{d\sigma}{d\Omega}$ is the differential Born cross-section for electron-nucleon scattering, with invariant amplitude M_γ.
- α is the fine structure constant.
- σ_{Mott} is the scattering for a point-like particle.
- ϵ is the longitudinal polarization of the virtual photon.
- $\tau \equiv Q^2/4M^2$. *E* and E' are initial and final state energies.
- G_E and G_M are the Sachs Form Factors.
- Method used extensively for proton.
- nTPE experiment is first time this method used for neutron.

Proton Form Factor Discrepancy

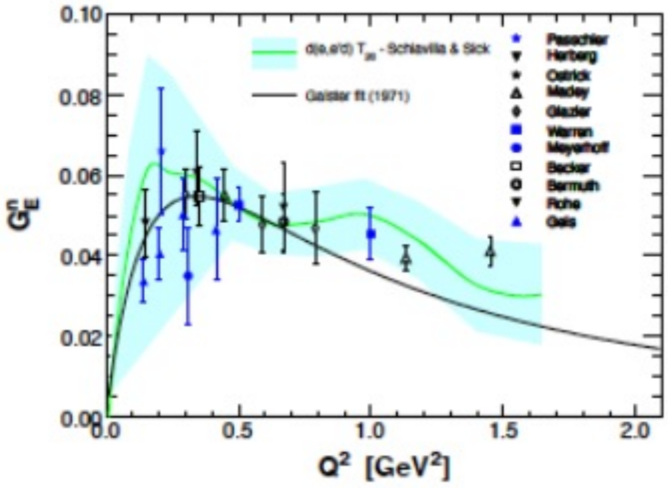
Proton Electric &
Magnetic FF Ratio



Cyan = Rosenbluth Separation Extraction
Red = Polarization Transfer Measurements
Black = Super Rosenbluth

- Two primary measurement methods:
  1. Rosenbluth Separation (Cross-Section data)
  2. Polarization Transfer
- G_E / G_M from Rosenbluth consistent with 1.0
- G_E / G_M from Polarization Transfer disagrees by 3-4 sigma
- Rosenbluth, identical spatial dependences.
- Polarization Transfer, proton's charge distribution is more spatially spread out than magnetization distribution.
- Rosenbluth sensitive to TPE, while Polarization Transfer is insensitive.
- TPE could explain discrepancy
- Understanding TPE effects gives more complete characterization of Nucleon FFs

Neutron Electric Form Factor



Experimental World Data

Polarization Transfer

nTPE experiment (Rosenbluth)

Name	Ebeam (GeV)	BigBite angle (deg)	BigBite Distance (m)	SBS angle (deg)	SBS distance (m)	HCAL "angle" (deg)	HCAL distance (m)	Q^2 (GeV^2)	Electron P (GeV)	Nucleon P (GeV)
SBS-8	5.965	26.5	2.00	29.9	2.25	29.4	11.0	4.5	3.58	3.2
SBS-9	4.015	49.0	1.55	22.5	2.25	22.0	11.0	4.5	1.6	3.2

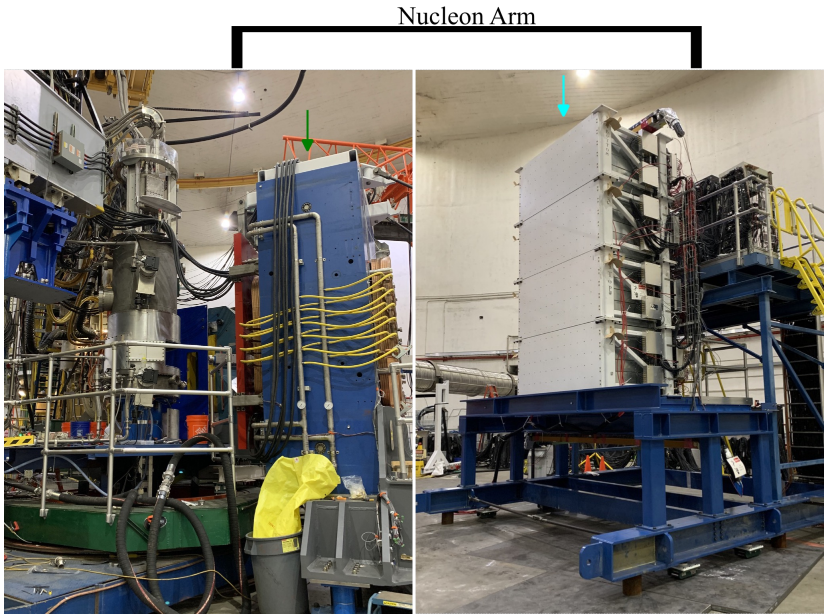
SBS G_E^n

Q^2 (GeV^2)	E_i (GeV)	θ_e (deg)	p_e (GeV/c)	θ_n (deg)	p_n (GeV/c)
5.02	4.400	48.0	1.73	21.6	3.49
6.77	6.600	34.0	3.00	22.2	4.44
10.18	8.800	34.0	3.38	17.5	6.29

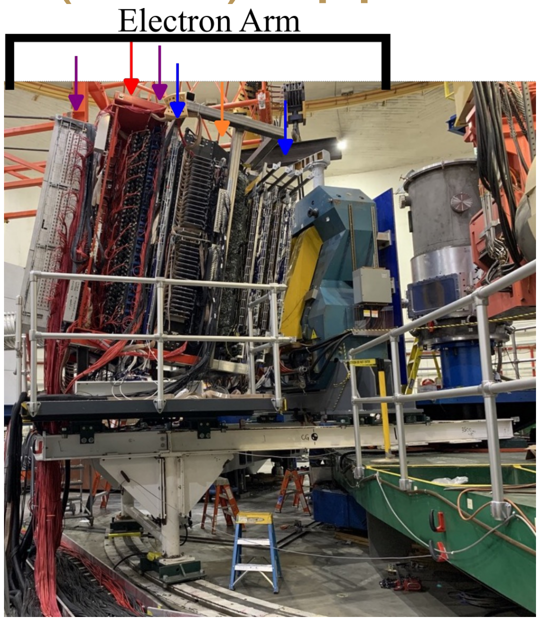
SBS G_E^n-RP

Setting	Q^2 (GeV/c)^2	E_e (GeV)	$p_{e'}$ (GeV)	θ_e (deg.)	θ_n (deg.)
1	4.5	4.4	2.01	41.9	24.7
2	6.0	6.6	3.40	30.0	25.0
3	9.3	8.8	3.81	30.7	19.4

Super BigBite Spectrometer (SBS) Apparatus



Super BigBite Spectrometer includes Super BigBite Magnet & Hadron Calorimeter (HCal)



Deuteron Target & BigBite Spectrometer includes Gas Electron Multipliers (GEMs), GRINCH, Calorimeters, Timing Hodoscope

Hardware installation, commissioning, & expert shifts for GEM tracking detectors

Research Outlook: Last Year Plan

- G_M^n & nTPE data analysis & GEM analysis. **In-progress**
- GEM Expert support for G_E^n install & run. **Yes, expert shifts, RC**
- Technical Note for SBS GEMs. **In-Progress**
- Read nucleon FF & nTPE literature. **Yes, Continuing**
- Collect/Write material for theory related sections of thesis. **Need to do**
- Give talk at GHRS. **Yes**
- Do HUGs, **Accepted for June 2023**
- Attending talk, colloquia, seminars about nucleon FFs. **Yes, Continuing**
- Give talk at APS or DNP. **Yes**
  Focus: Preliminary Result, **No**
- Preliminary Result in 1 Year. **Not Yet**
- Poster at JLUO Annual Meeting **Planning for June 2023, I'm an organizer**
- Continue on understanding of big picture nucleon FF and nTPE physics

Gas Electron Multiplier (GEM)

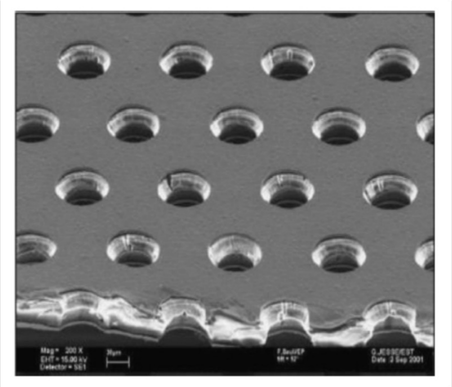


Diagram of a typical GEM electrode

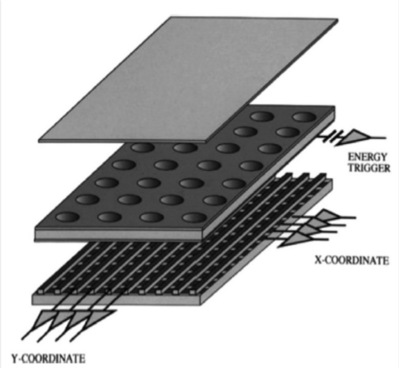
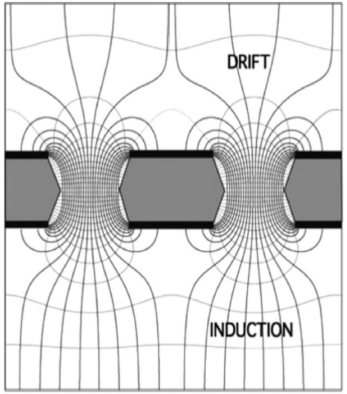


Diagram of a single GEM detector with Cartesian readout



Electric Field in the region of the holes of a GEM electrode

- Type of gaseous ionization detector, reliant on electron avalanche and a subclass of detectors known as Micro-Pattern Gas Detectors (MPGDs).
- Used as tracking detectors, preamplification, drift chambers, time projection chambers, radio imaging.
- Single GEM detector gains typically are 10^3 or 10^4 .
- Triple GEM detector effective gains typically are 10^4 or 10^5 .

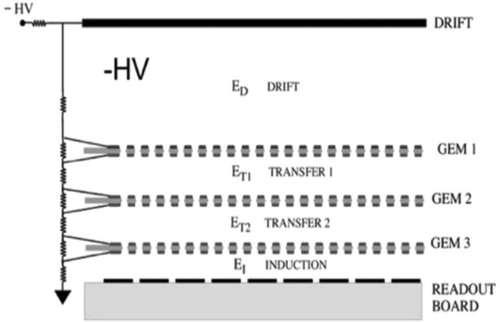
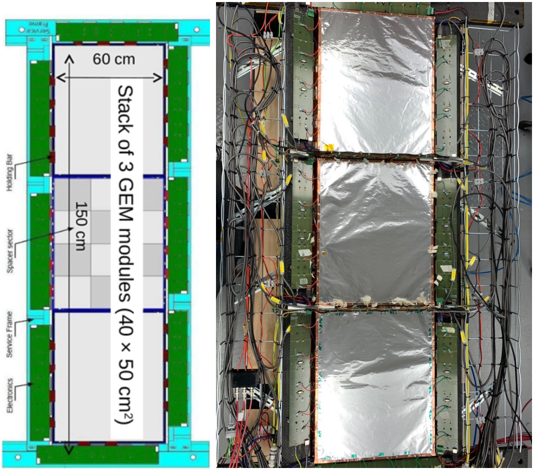
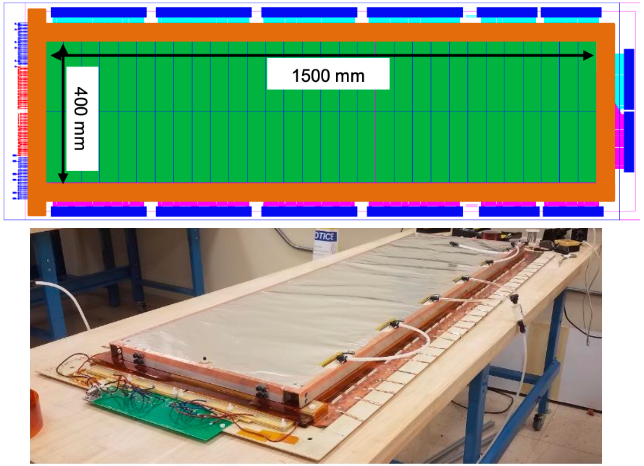


Diagram of a triple GEM detector

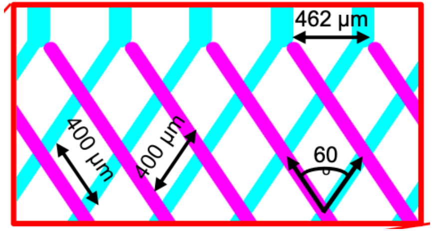
GEM Detectors for SBS Program



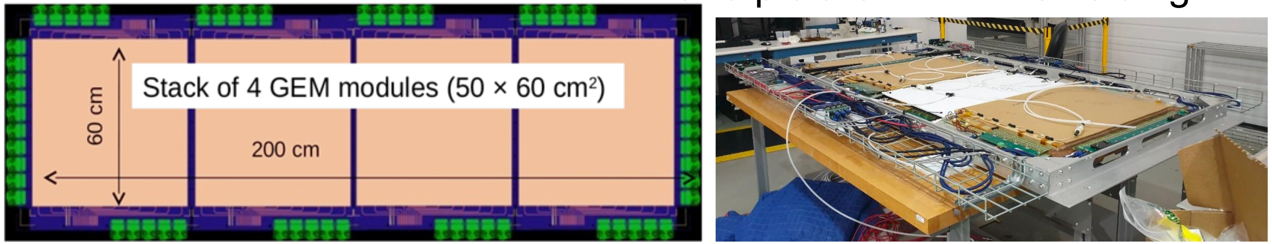
INFN XY-GEM Layer schematic and picture with RF shielding



UVA UV-GEM Layer schematic and picture with RF shielding



- 4 INFN GEM layers prepared for SBS program
- 4 UVA UV-GEM layers prepared for SBS program
- 11 UVA XY-GEM layers prepared for SBS program
- 2 INFN GEM layers operated during G_M^n
- 2 UVA UV-GEM layers operated during G_M^n
- 2 more UVA UV-GEM layers moved to BigBite during G_M^n



UVA XY-GEM Layer schematic and picture without RF shielding

From Observable to Physics Result

Measured Observable: $R_{observed} = \frac{N_{e,e'n}}{N_{e,e'p}}$, $N_{e,e'n}\,/N_{e,e'p}$ are detector yields for quasi-elastic neutrons/protons

- No free neutron target, so use deuterium. Taking ratios from double-arm experiment cancels many systematic effects (Durand/Ratio Method).

Nuclear & Radiative Corrections: $R_{corrected} = f_{corr} \times R_{observed}$

- Neutron & Proton in Deuteron are not free particles.

Relation to Cross-Sections: $R_{corrected} = \frac{\sigma^n_{Mott} \cdot (1+\tau_p)}{\sigma^p_{Mott} \cdot (1+\tau_n)} \times \frac{\epsilon\sigma^n_L + \sigma^n_T}{\epsilon\sigma^p_L + \sigma^p_T}$

$$R_{corrected,\epsilon_1} = R_{Mott,\epsilon_1} \times \frac{\epsilon_1\sigma^n_L + \sigma^n_T}{\epsilon_1\sigma^p_L + \sigma^p_T} \qquad R_{corrected,\epsilon_2} = R_{Mott,\epsilon_2} \times \frac{\epsilon_2\sigma^n_L + \sigma^n_T}{\epsilon_2\sigma^p_L + \sigma^p_T}$$

From Observable to Physics Result

Physics result, σ_L^n and σ_T^n:

Consider ratio of $R_{corrected}$ for two values of ϵ and define $S_c^{n(p)} = \sigma_L^{n(p)}/\sigma_T^{n(p)}$

$$A \equiv \frac{R_{corrected,\epsilon_1}}{R_{corrected,\epsilon_2}} = \frac{R_{Mott,\epsilon_1} \times \dfrac{\epsilon_1\sigma_L^n + \sigma_T^n}{\epsilon_1\sigma_L^p + \sigma_T^p}}{R_{Mott,\epsilon_2} \times \dfrac{\epsilon_2\sigma_L^n + \sigma_T^n}{\epsilon_2\sigma_L^p + \sigma_T^p}} = \frac{R_{Mott,\epsilon_1}}{R_{Mott,\epsilon_2}} \cdot \frac{\epsilon_2\sigma_L^p + \sigma_T^p}{\epsilon_1\sigma_L^p + \sigma_T^p} \cdot \frac{\epsilon_1\sigma_L^n + \sigma_T^n}{\epsilon_2\sigma_L^n + \sigma_T^n}$$

$$= \frac{R_{Mott,\epsilon_1}}{R_{Mott,\epsilon_2}} \frac{\epsilon_2 S_c^p + 1}{\epsilon_1 S_c^p + 1} \cdot \frac{\epsilon_1 S_c^n + 1}{\epsilon_2 S_c^n + 1} = B \cdot \frac{\epsilon_1 S_c^n + 1}{\epsilon_2 S_c^n + 1}$$

$$B = \frac{R_{Mott,\epsilon_1}}{R_{Mott,\epsilon_2}} \times \frac{1 + \epsilon_2 S_c^p}{1 + \epsilon_1 S_c^p}$$

From Observable to Physics Result

Physics result, σ_L^n and σ_T^n:

Consider ratio of $R_{corrected}$ for two values of ϵ and define $S_c^{n(p)} = \sigma_L^{n(p)}/\sigma_T^{n(p)}$

$$A = B \cdot \frac{\epsilon_1 S_c^n + 1}{\epsilon_2 S_c^n + 1} = B \cdot \frac{\epsilon_1 S_c^n + 1}{\epsilon_2 S_c^n + 1} \cdot \frac{1 - \epsilon_2 S_c^n}{1 - \epsilon_2 S_c^n} = B \cdot \frac{1 + \epsilon_1 S_c^n - \epsilon_2 S_c^n - \epsilon_1 \epsilon_2 (S_c^n)^2}{1 + \epsilon_2 S_c^n - \epsilon_2 S_c^n - (\epsilon_2 S_c^n)^2}$$

$$= B \cdot \frac{1 + (\epsilon_1 - \epsilon_2) S_c^n - \epsilon_1 \epsilon_2 (S_c^n)^2}{1 - (\epsilon_2 S_c^n)^2} = B \cdot \frac{1 + \Delta\epsilon \cdot S_c^n - \epsilon_1 \epsilon_2 (S_c^n)^2}{1 - (\epsilon_2 S_c^n)^2}$$

From Proposal: Equal values of Q^2 for two kinematics, the τ and σ_T for two kinematics cancel. For actual small range of ϵ and small value of the slope. Does this get rid of the higher order ϵ terms and justify the approximation? Similar derivation and argument for *B*,

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

From Observable to Physics Result

Physics result, σ_L^n and σ_T^n:

Consider ratio of $R_{corrected}$ for two values of ϵ and define $S_c^{n(p)} = \sigma_L^{n(p)}/\sigma_T^{n(p)}$

$$A \equiv \frac{R_{corrected,\epsilon_1}}{R_{corrected,\epsilon_2}} = B \times \frac{1+\epsilon_1 S_c^n}{1+\epsilon_2 S_c^n} \approx B \times (1 + \Delta\epsilon \cdot S_c^n)$$

From Data

Proton Global Data

Kinematic Info

Physics Result!

Proton Global Data:
From global analysis of
e-*p* cross-section.
Taken as known.

$$B = \frac{R_{Mott,\epsilon_1}}{R_{Mott,\epsilon_2}} \times \frac{1+\epsilon_2 S_c^p}{1+\epsilon_1 S_c^p} \approx 1 - \Delta\epsilon \cdot S_c^p$$

Double Polarization Method for Neutron Electric FF

From a polarized electron beam on a polarized neutron target the elastic electron-neutron scattering cross section can be written as the sum of 2 parts:

- Σ is the unpolarized elastic cross section
- Δ is the polarized elastic cross section
- *h* is helicity ($\pm$1)

$$\sigma = \Sigma + h\Delta$$

Neutron Spin Asymmetry:

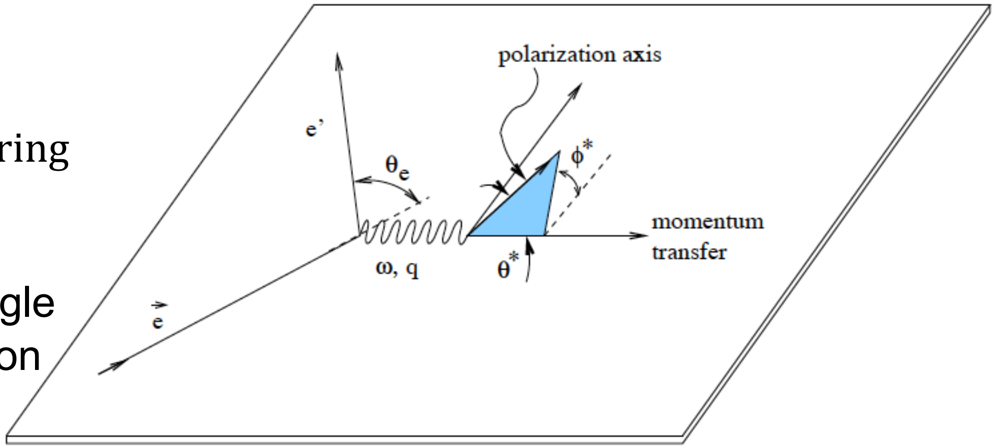
$$A_N = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{\Delta}{\Sigma}$$

$\tau \equiv Q^2/4M^2$

θ is electron scattering angle

θ^* is polar angle,

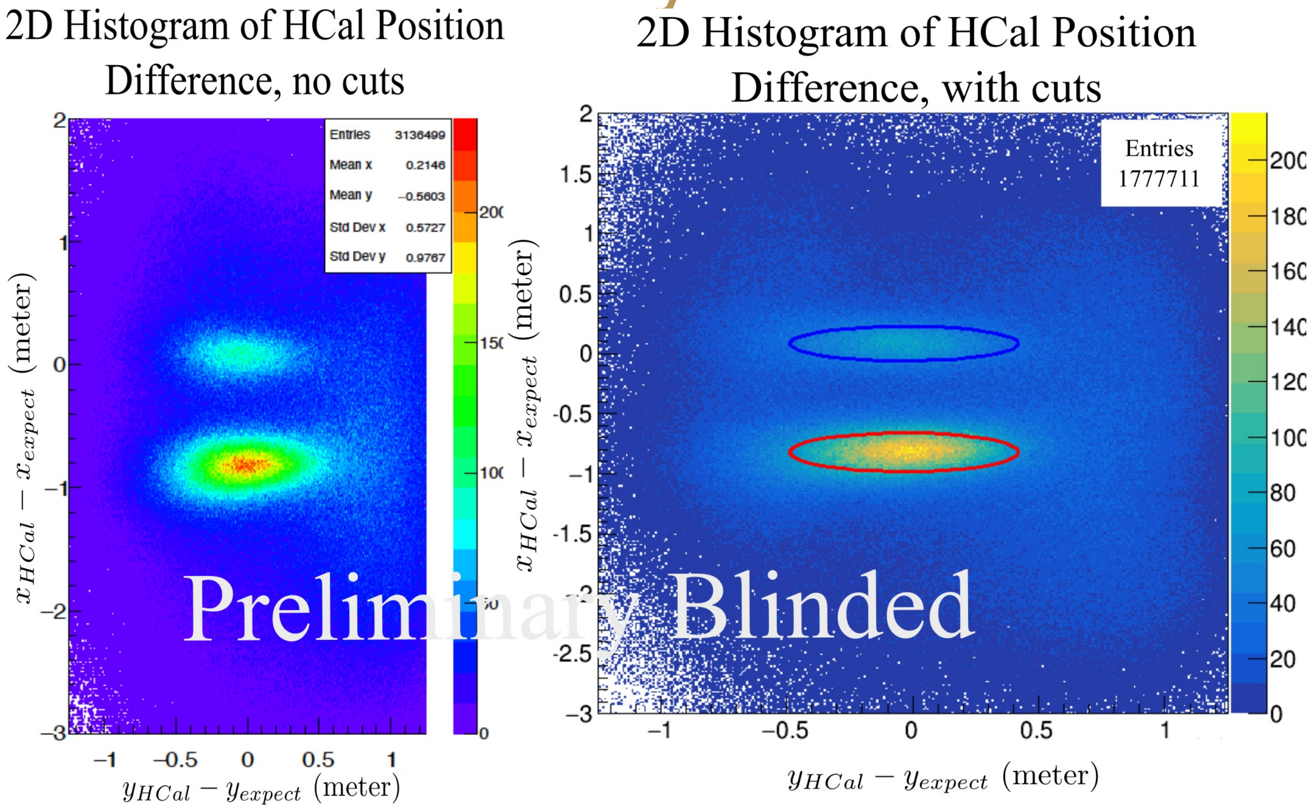
ϕ^* is azimuthal angle of target polarization in lab frame



$$A_N = -\frac{2\sqrt{\tau(\tau+1)}\tan(\theta/2)\frac{G_E^n}{G_M^n}\sin\theta^*\cos\phi^*}{\left(\frac{G_E^n}{G_M^n}\right)^2 + \tau + 2\tau(\tau+1)\tan^2(\theta/2)} - \frac{2\tau\sqrt{1+\tau+(1+\tau)^2\tan^2(\theta/2)}\tan(\theta/2)\cos\theta^*}{\left(\frac{G_E^n}{G_M^n}\right)^2 + \tau + 2\tau(\tau+1)\tan^2(\theta/2)}$$

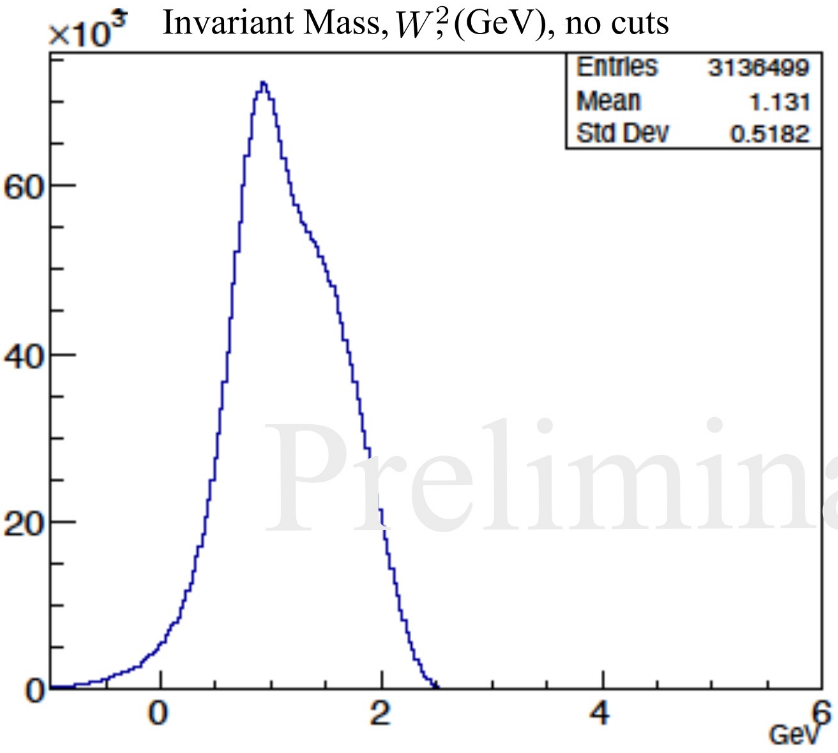
Data Analysis Part 2

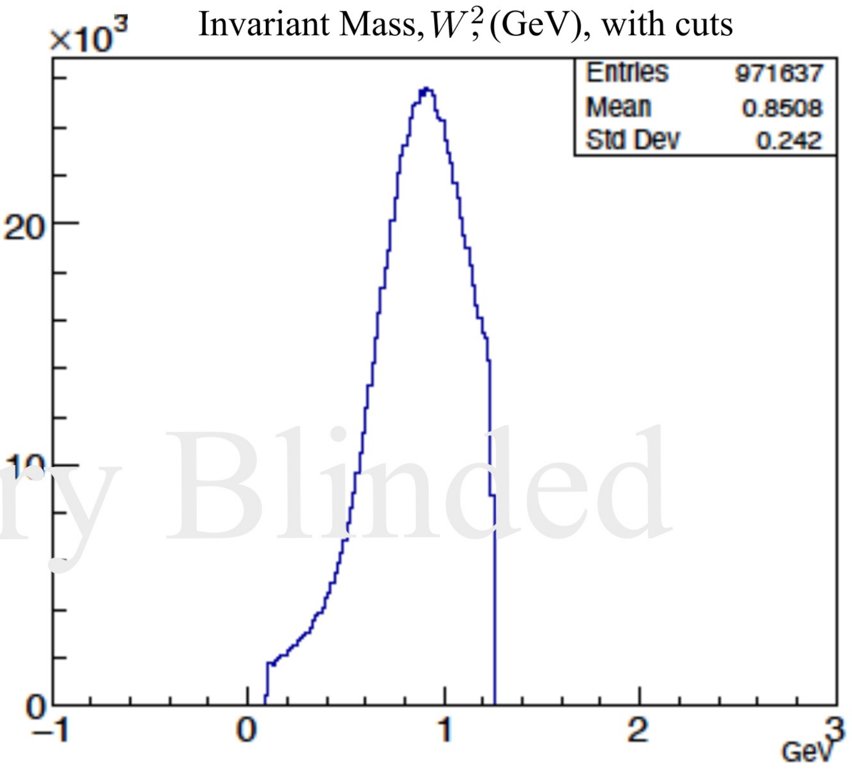
SBS9 & SBS field 70%



Data Analysis Part 3

SBS9 & SBS field 70%

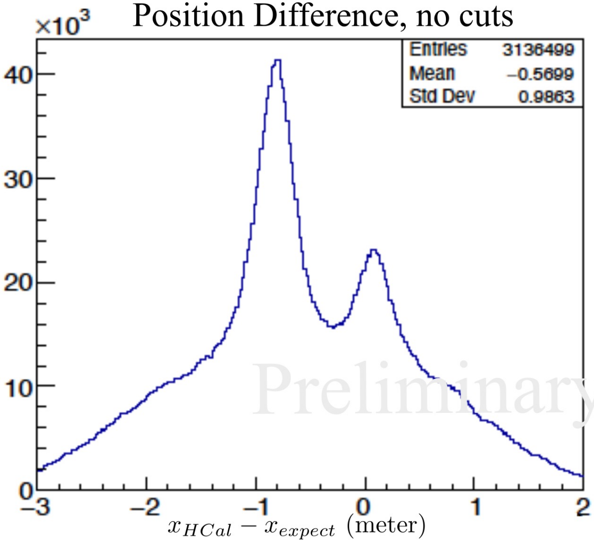




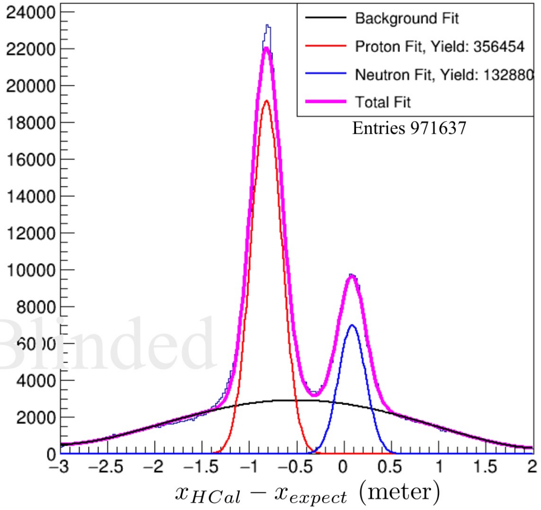
Data Analysis Part 4

SBS9 & SBS field 70%

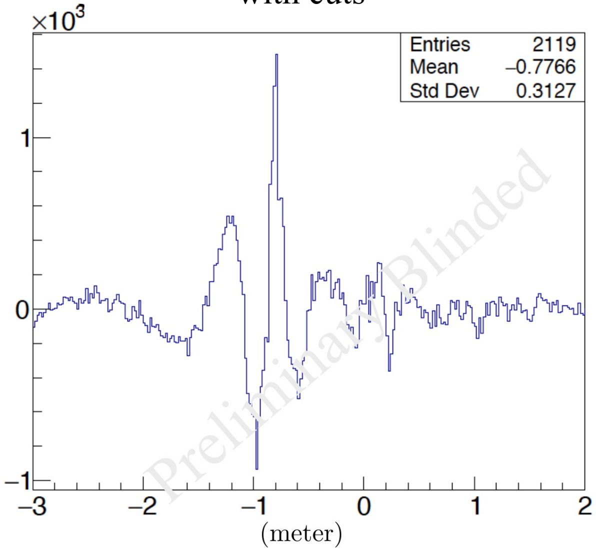
1D Histogram of HCal x-direction Position Difference, no cuts



1D Histogram of HCal x-direction Position Difference, with cuts

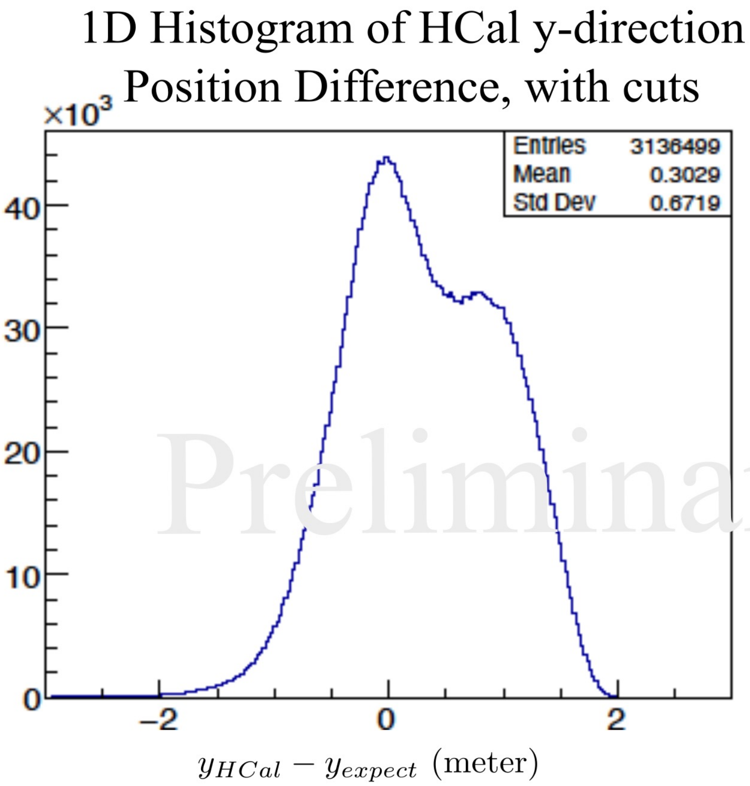


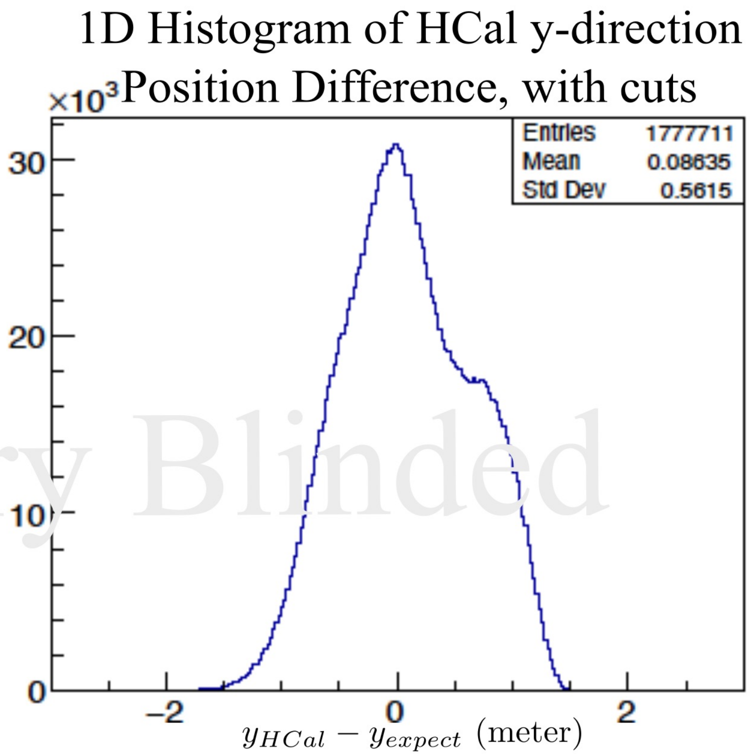
1D Histogram of HCal x-direction Position Difference Residual (data-fit), with cuts



Data Analysis Part 5

SBS9 & SBS field 70%





SBS nTPE Extraction

Big Picture: While TPE has been studied for the proton, there is essentially no TPE data for the neutron. No free neutron target.

$R_{n/p}$ is the ratio of quasi-elastic yields in scattering from a deuteron target. $N_{e,e'n}$ and $N_{e,e'p}$ are the quasi-elastic detector yields for neutrons and protons

$$R_{n/p} \equiv R_{observed} = \frac{N_{e,e'n}}{N_{e,e'p}}$$

To extract the observed ratio from nucleons a correction must occur to account for hadron efficiencies, radiative corrections, final state effects, and re-scattering

$$R_{corrected} = f_{corr} \times R_{observed}$$

In OPE $R_{corrected}$ can be written

$$R_{corrected} = \frac{\sigma_{Mott}^{n} \cdot (1+\tau_p)}{\sigma_{Mott}^{p} \cdot (1+\tau_n)} \times \frac{\epsilon\sigma_L^n + \sigma_T^n}{\epsilon\sigma_L^p + \sigma_T^p}$$

Where $\sigma_{Mott}^{n(p)}$ is the Mott cross-section, $\tau_{n(p)} \equiv -q_{n(p)}^2/4M_{n(p)}^2$, ϵ is the longitudinal polarization of the virtual photon, $\sigma_L^{n(p)}$ and $\sigma_T^{n(p)}$ are the cross sections for longitudinally and transversally polarized virtual photons which are dependent on $G_E^{n(p)}$ and $G_M^{n(p)}$.

SBS nTPE Extraction

$$R_{Mott} = \frac{\sigma^n_{Mott} \cdot (1+\tau_p)}{\sigma^p_{Mott} \cdot (1+\tau_n)}$$

Consider $R_{corrected}$ for two values of ϵ and define $S_c^{n(p)} = \sigma_L^{n(p)}/\sigma_T^{n(p)}$

$$R_{corrected,\epsilon_1} = R_{Mott,\epsilon_1} \times \frac{\epsilon_1\sigma_L^n + \sigma_T^n}{\epsilon_1\sigma_L^p + \sigma_T^p} \qquad R_{corrected,\epsilon_2} = R_{Mott,\epsilon_2} \times \frac{\epsilon_2\sigma_L^n + \sigma_T^n}{\epsilon_2\sigma_L^p + \sigma_T^p}$$

Two unknowns are σ_L^n and σ_T^n. At Q^2 = 4.5 (GeV/c)^2 the value of S_c^p is known.

$$\mathrm{A} = \frac{R_{corrected,\epsilon_1}}{R_{corrected,\epsilon_2}} = B \times \frac{1+\epsilon_1 S_c^n}{1+\epsilon_2 S_c^n} \approx B \times (1 + \Delta\epsilon \cdot S_c^n)$$

$$B = \frac{R_{Mott,\epsilon_1}}{R_{Mott,\epsilon_2}} \times \frac{1+\epsilon_2 S_c^p}{1+\epsilon_1 S_c^p} \approx 1 - \Delta\epsilon \cdot S_c^p$$

SBS nTPE Extraction

- Big Picture: While TPE has been studied for the proton, there is essentially no TPE data for the neutron
- No free neutron targets

Start: $R_{n/p}$ is the ratio of quasi-elastic yields in scattering from a deuteron target. $N_{e,e'n}$ and $N_{e,e'p}$ are the quasi-elastic detector yields for neutrons and protons.

$$R_{n/p} \equiv R_{observed} = \frac{N_{e,e'n}}{N_{e,e'p}}$$

Apply corrections for hadron efficiencies, radiative corrections, final state effects, and re-scattering. Call this ratio $R_{corrected}$, its proportional to $\sigma_L^{n(p)}$ and $\sigma_T^{n(p)}$.

Now fix $Q^2 = 4.5$ (GeV/c)^2 and consider two different kinematic points ($\epsilon_1$and ϵ_2).

Take a corrected ratio for each kinematic point, call them $R_{corrected,\epsilon_1}$and $R_{corrected,\epsilon_2}$.

Consider the ratio of the two corrected ratios and define $S_c^{n(p)} = \sigma_L^{n(p)}/\sigma_T^{n(p)}$

$$\mathrm{A} = \frac{R_{corrected,\epsilon_1}}{R_{corrected,\epsilon_2}} = B \times \frac{1+\epsilon_1 S_c^n}{1+\epsilon_2 S_c^n} \approx B \times (1 + \Delta\epsilon \cdot S_c^n)$$

B only contains known proton information.
End: Two unknowns are σ_L^n and σ_T^n, which can be extracted.