SBS-G_M^n Analysis Update

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(On behalf of the SBS Collaboration)

Theory & Motivation

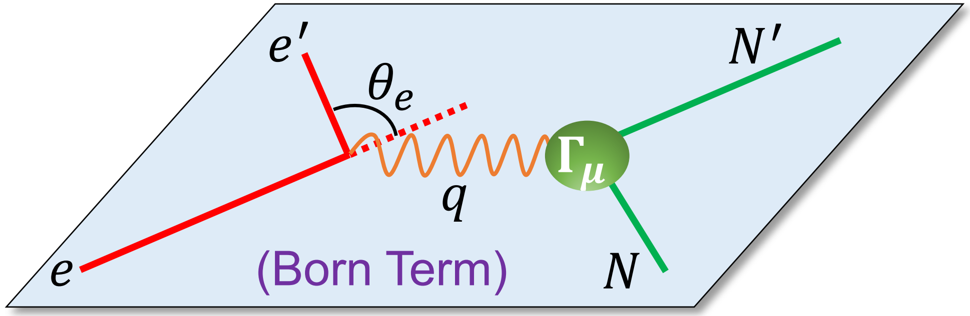
- Ran in Jefferson Lab's Experimental Hall A from Fall 2021 to February 2022.

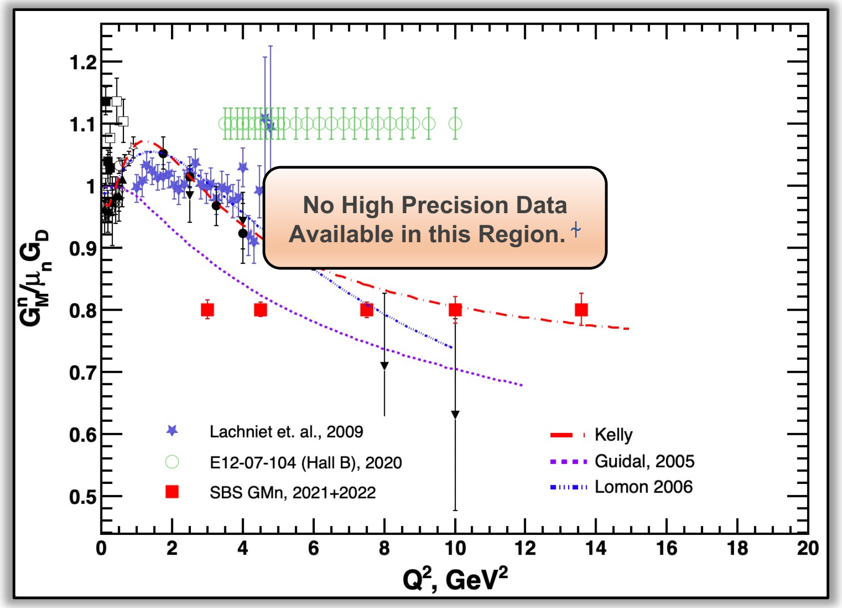
❖ **Goal:** High precision measurement of G_M^n at Q^2 = 3, 4.5, 7.5, 10 & 13.5 $(GeV/c)^2$.

- Nucleon vertex (elastic e-N scattering):

$$\Gamma_\mu(q) = \gamma_\mu F_1(-q^2) + \frac{i\sigma_{\mu\nu}q^\nu}{2M_N} F_2(-q^2)$$

Dirac FF — Pauli FF





- Defining Sachs Form Factors (FFs): $\begin{cases} G_E(Q^2) \equiv F_1(Q^2) - \tau F_2(Q^2) \\ G_M(Q^2) \equiv F_1(Q^2) + F_2(Q^2) \end{cases}$

- G_E, G_M: Sachs Electric and Magnetic FFs, respectively.

- Differential Cross Section:

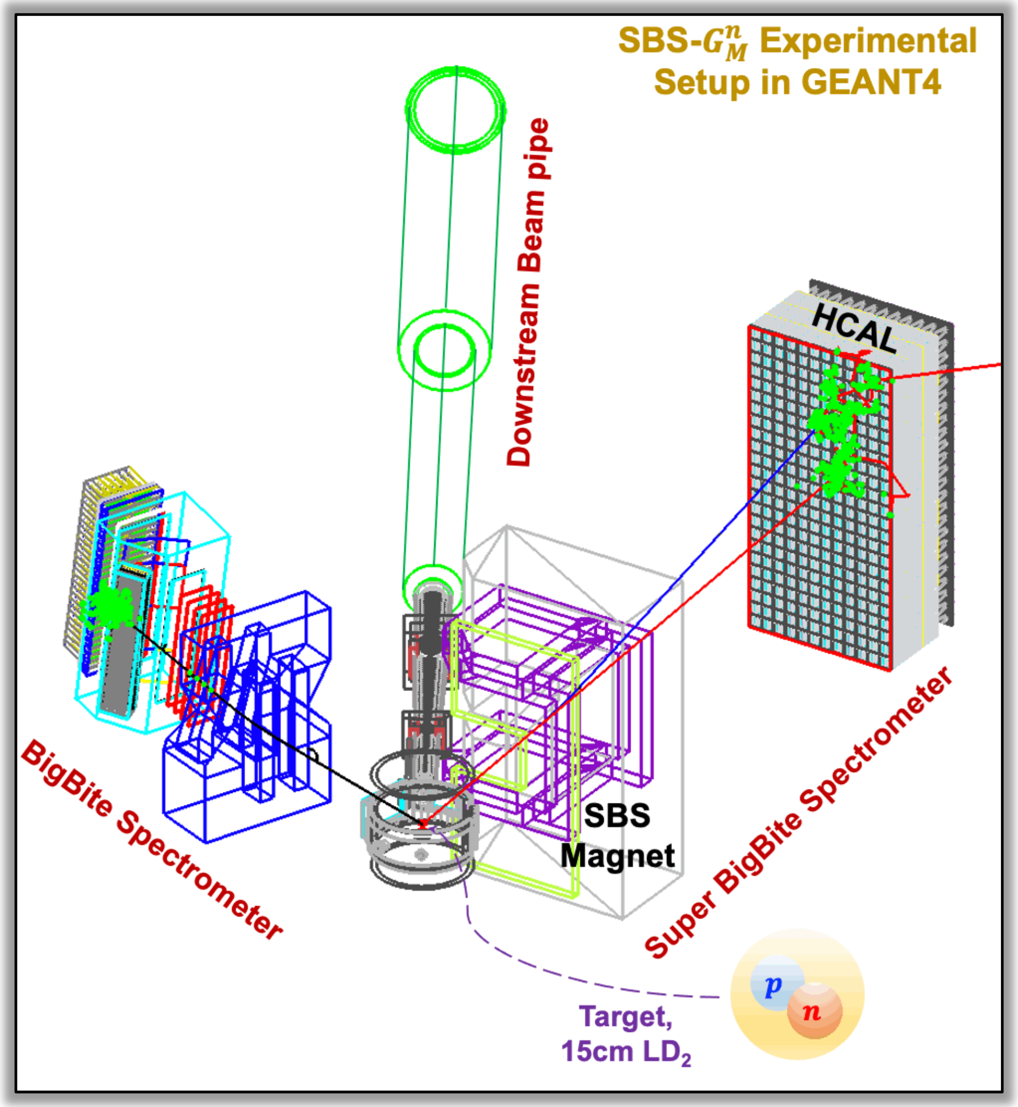
$$\frac{d\sigma}{d\Omega} = \frac{\sigma_{Mott}}{1+\tau}\left(G_E^2(Q^2) + \frac{\tau}{\epsilon}G_M^2(Q^2)\right)$$

- $Q^2 = -q^2$
- $\tau = Q^2/4M_N^2$
- $\epsilon = (1 + 2(1+\tau)tan^2(\theta_e/2))^{-1}$

❖ Q^2 evolution of Sachs FFs reveal nucleon's internal structure.

† CLAS12 measured G_M^n up to $Q^2 = 10\ GeV^2$, results are yet to be published.

Apparatus & Measurement Technique



- Simultaneous detection of elastically scattered electrons and nucleons lets us use "ratio method".[1]
- 3 major steps to get G_M^n:

1. Extracting QE cross section ratio, R'', directly from the experiment:

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

2. Apply nuclear corrections to obtain:

$$R' = \frac{\frac{d\sigma}{d\Omega}\Big|_{n(e,e')}}{\frac{d\sigma}{d\Omega}\Big|_{p(e,e')}} \equiv \frac{\frac{\sigma_{Mott}}{1+\tau}\left({G_E^n}^2 + \frac{\tau}{\epsilon}{G_M^n}^2\right)}{\frac{d\sigma}{d\Omega}\Big|_{p(e,e')}}$$

3. Finally,

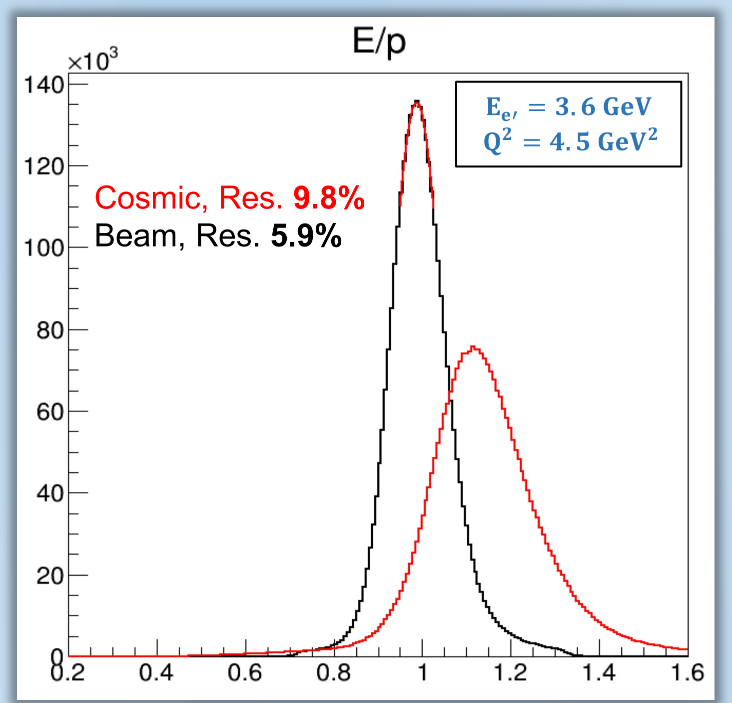
$$G_M^n = -\left[\frac{1}{\tau}\frac{d\sigma}{d\Omega}\Big|_{p(e,e')} R' - \frac{\epsilon}{\tau}{G_E^n}^2\right]^{\frac{1}{2}}$$

❖ "Ratio method" is way less sensitive to systematic errors than other measurement techniques.[1]

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

Analysis Status

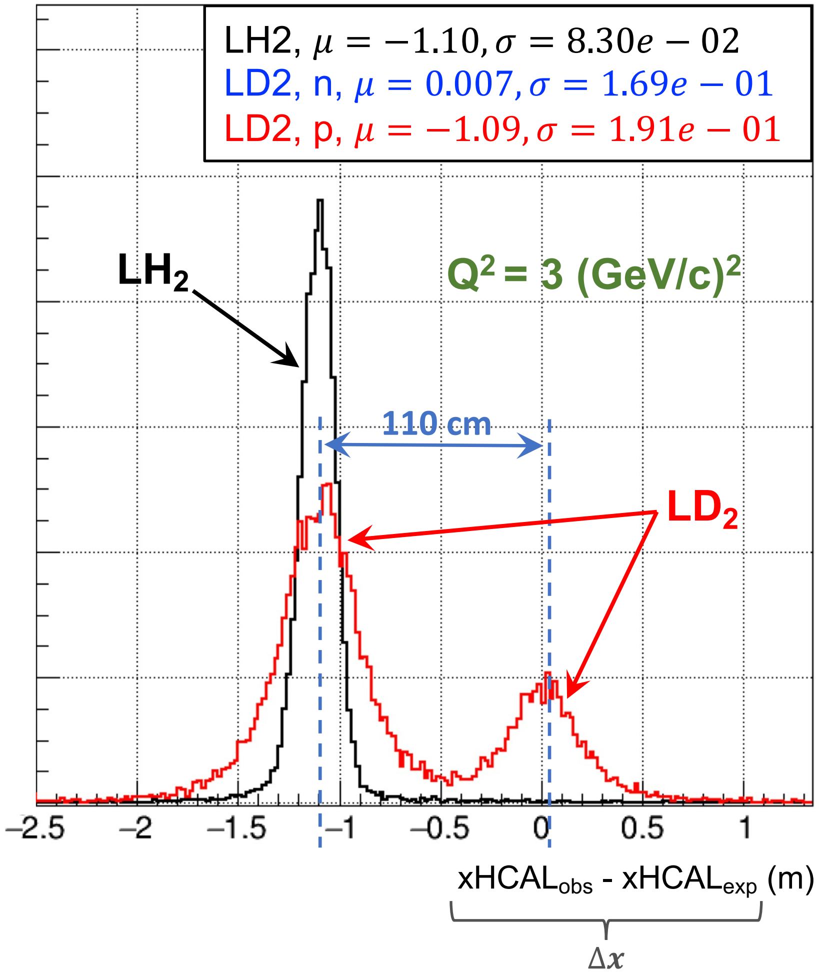
- We have recently finished 1st pass cooking of the entire $\mathrm{SBS\text{-}G_M^n}$ dataset. We wanted it to happen faster but both BigBite & Super BigBite spectrometers are new, which has made calibration significantly harder for us. In addition to that, an enormous raw data volume (≈ 2 PB!) was also not helping.
- Currently we are working on developing the analysis machinery to do quasi-elastic event selection. We are also fine-tuning various detector calibrations to get ready for 2nd pass cooking.
- In parallel, a huge effort is ongoing to create a MC event generator with realistic nuclear and radiative effects.

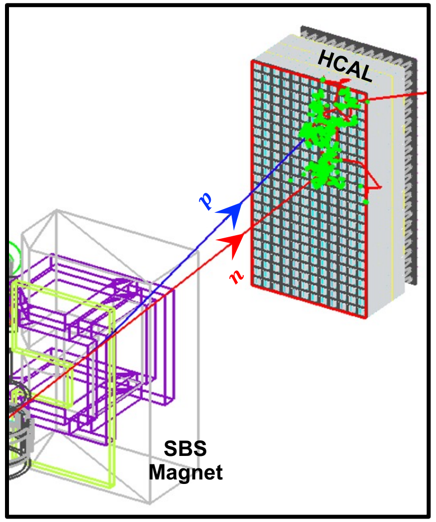


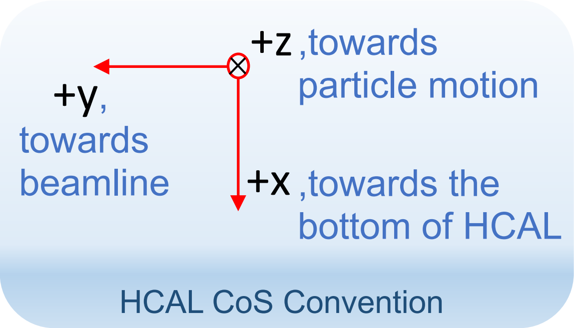
- Highlights of Detector Performance with Preliminary Calibrations:
  - BigBite Spectrometer:
    - Momentum resolution: $\frac{\sigma_p}{p} \approx 1 - 1.5\%$
    - Angular resolution (in-plane & out-of-plane): $1 - 2$ **mrad**
    - Vertex resolution: $\sigma_z \leq 1$ **cm**
    - BigBite Calorimeter(BBCAL) energy resolution: 5.9% **at** 3.6 **GeV** scattered e^- energy.
  - Super BigBite Spectrometer:
    - Hadron Calorimeter (HCAL):
      - Time Resolution: $\sigma_t \approx 0.5 - 1$ **ns**
      - Angular Resolution: $\sim$**2 mrad**

Quasi-Elastic (QE) Event Selection

❖ Introducing HCAL Δx plot:







- Primary Cuts:
  1. Presence of a track
  2. $|(\text{vertex})_z| < 0.08$ m
  3. PS cluster energy > 0.2 GeV
  4. Cut on reconstructed track momentum (kinematics dependent)

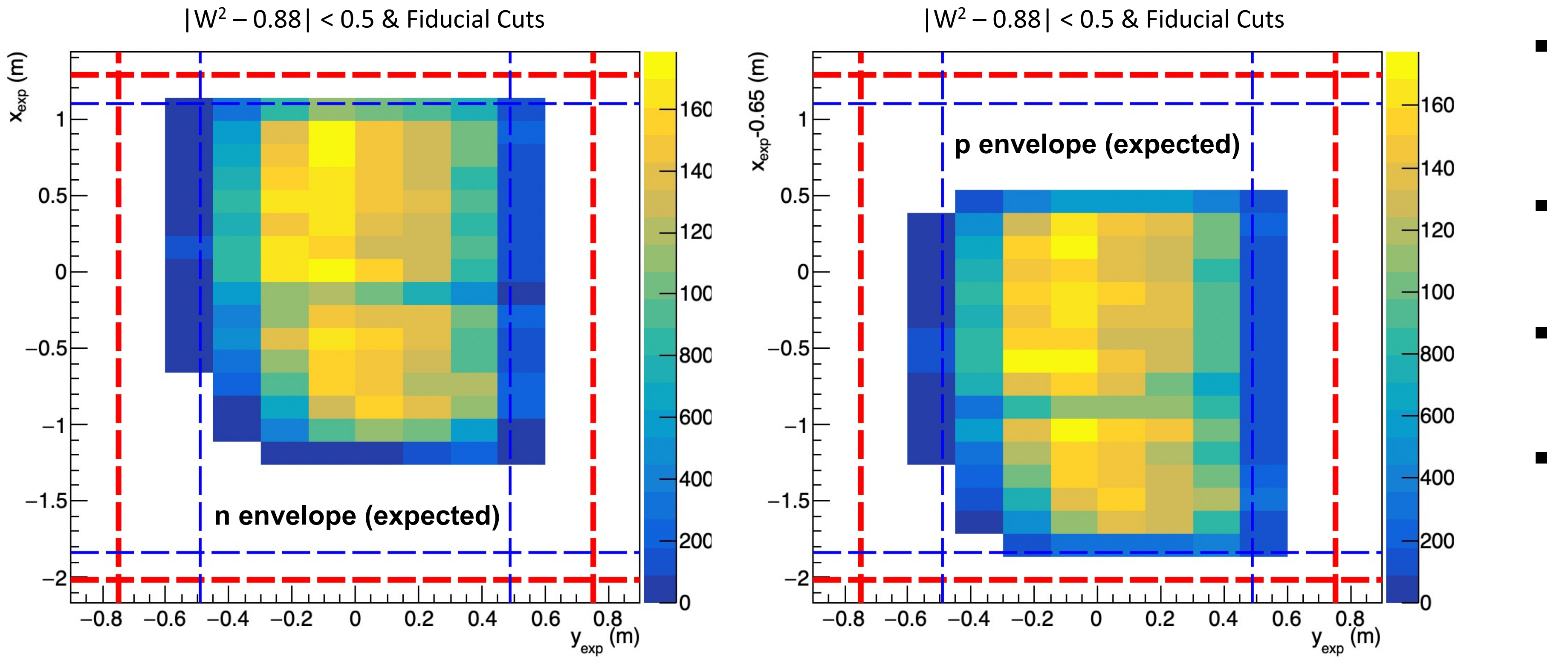
- QE Event Selection Cuts: (Q^2 dep.)
  1. Cut on W^2
  2. Cut on Δy
  3. Cut on θ_{pq} (angle between reconstructed nucleon momentum ($\vec{p}$) and the momentum transfer vector ($\vec{q}$))
  4. Fiducial/Acceptance Cuts

❖ Fitting Δx plot we can extract $d(ee'n)$ & $d(ee'p)$ yields and then form the ratio:

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

Implementation of Fiducial Cut on $\vec{q}$

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



--- Top of HCAL ---

- The idea is to accept a $n\ (p)$ event only if a $p\ (n)$ event with equivalent kinematics would also be guaranteed to hit the active area of HCAL.
- The fiducial cut is only based on the scattered-electron angle and momentum measured by BigBite.
- As "active area" (red dashed lines) we consider entire HCAL excluding the outermost rows and columns.
- We also use an additional "safety margin" (blue dashed lines) based on the widths of the Δx & Δy distributions for p & n to encounter the effects of Fermi motion to some extent.

QE Event Selection contd.

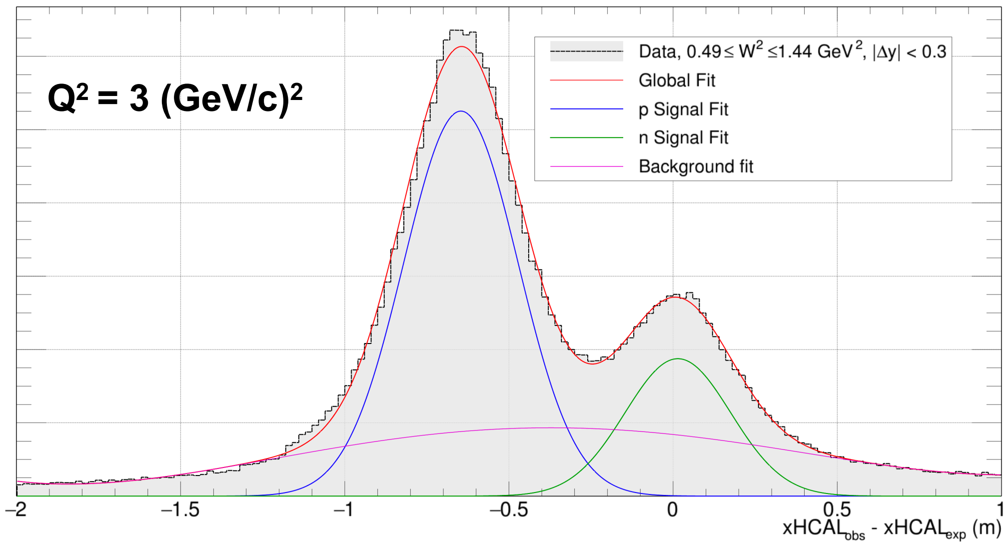
Table I: Kinematics of SBS-G_M^n

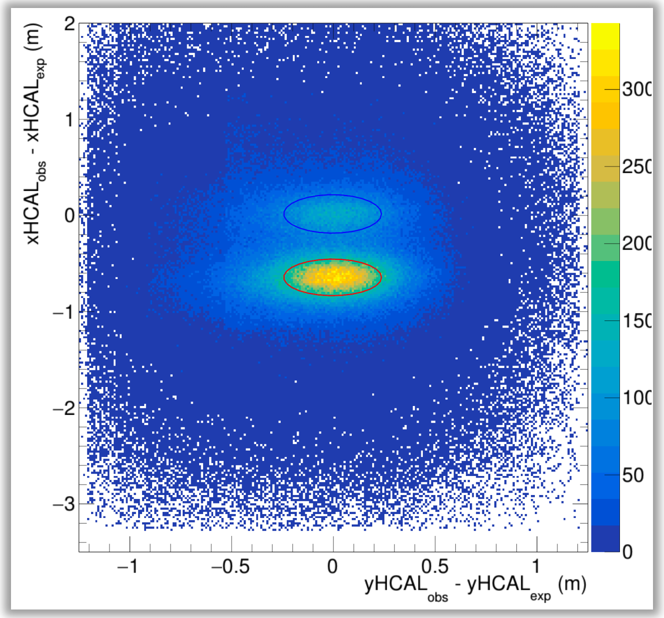
SBS Config.	Q^2 $(GeV/c)^2$	E_{beam} (GeV)	θ_{BB} (deg)	d_{BB} (m)	θ_{SBS} (deg)	d_{SBS} (m)	d_{HCAL} (m)
SBS-4	3.0	3.73	36.0	1.79	31.9	2.25	11.0
SBS-9	4.5	5.97	49.0	1.55	22.5	2.25	11.0
SBS-14	7.4	5.97	46.5	1.85	17.3	2.25	14.0
SBS-7	9.9	7.91	40.0	1.85	16.1	2.25	14.0
SBS-11	13.5	9.86	42.0	1.55	13.3	2.25	14.5

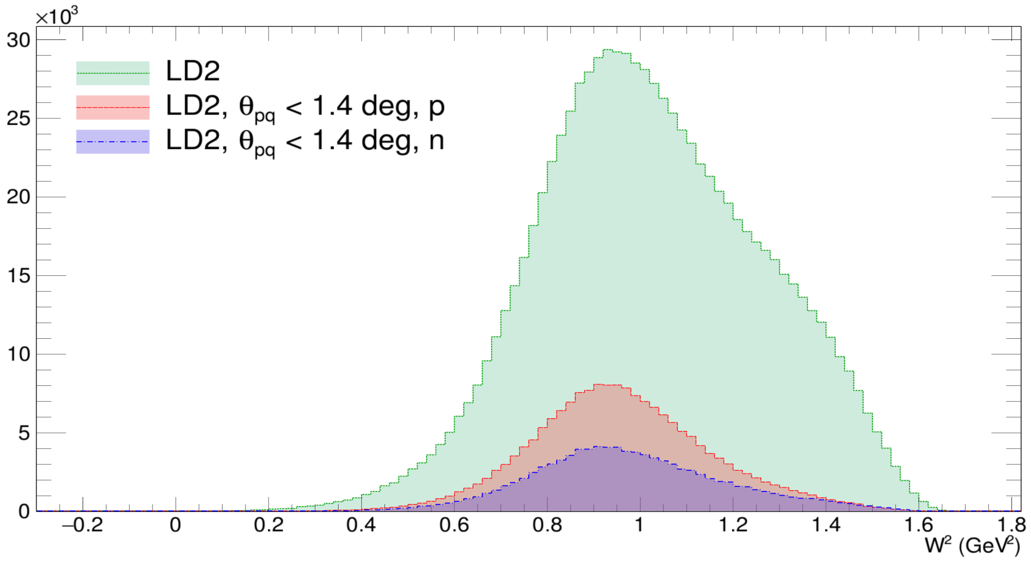
- Apart from G_M^n extraction, SBS-9 data will also be used for Rosenbluth separation to shed some light on the TPE contribution in the elastic e-n scattering. Sebastian Seeds will talk about this data set in his presentation, which is scheduled to take place right after mine.

- In the following few slides I will be showing representative **preliminary** quasi-elastic event selection plots from all the SBS-G_M^n configurations excluding SBS-9 to avoid duplication.

QE Event Selection: $Q^2 = 3\ (GeV/c)^2$ [SBS-4]





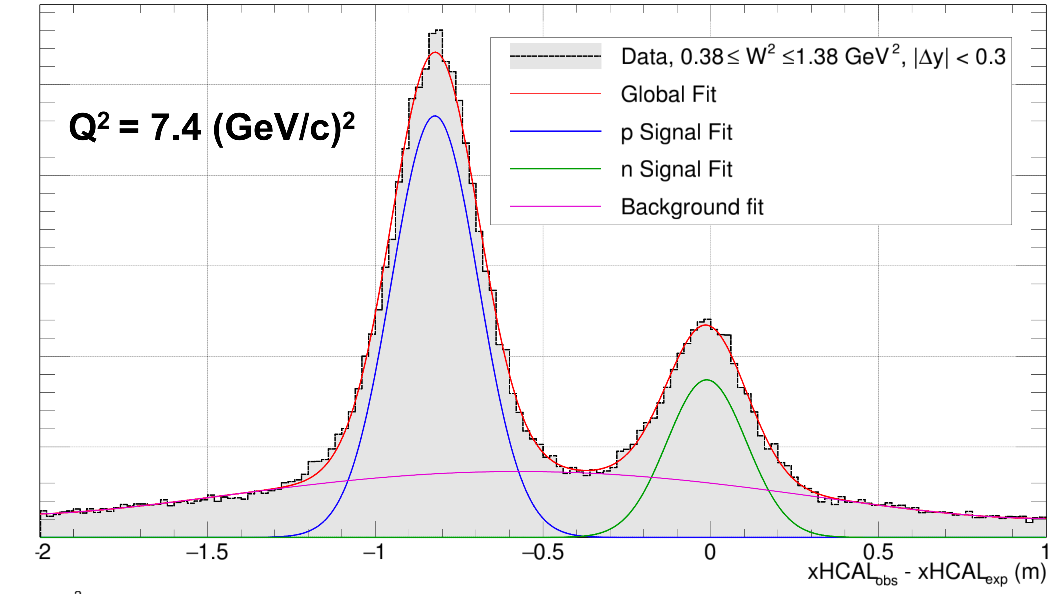


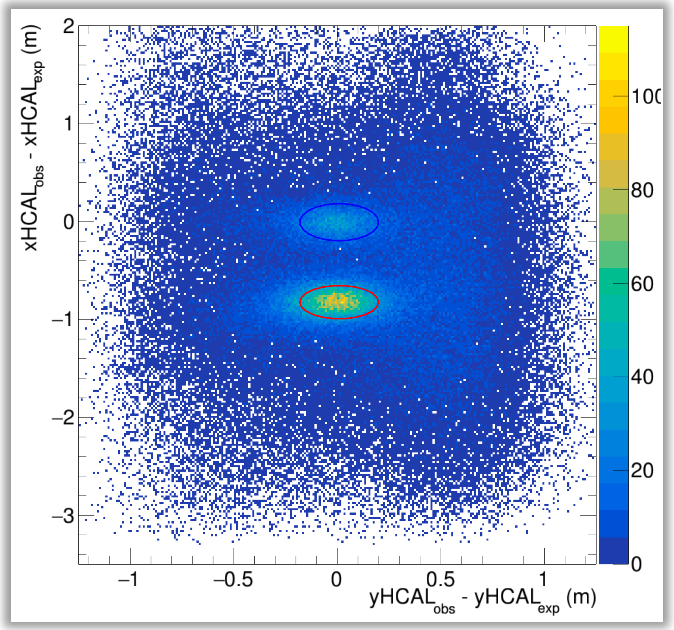
Figures: HCAL Δx (Top Left), HCAL Δx vs Δy (Top Right), W^2 (Bottom Left)

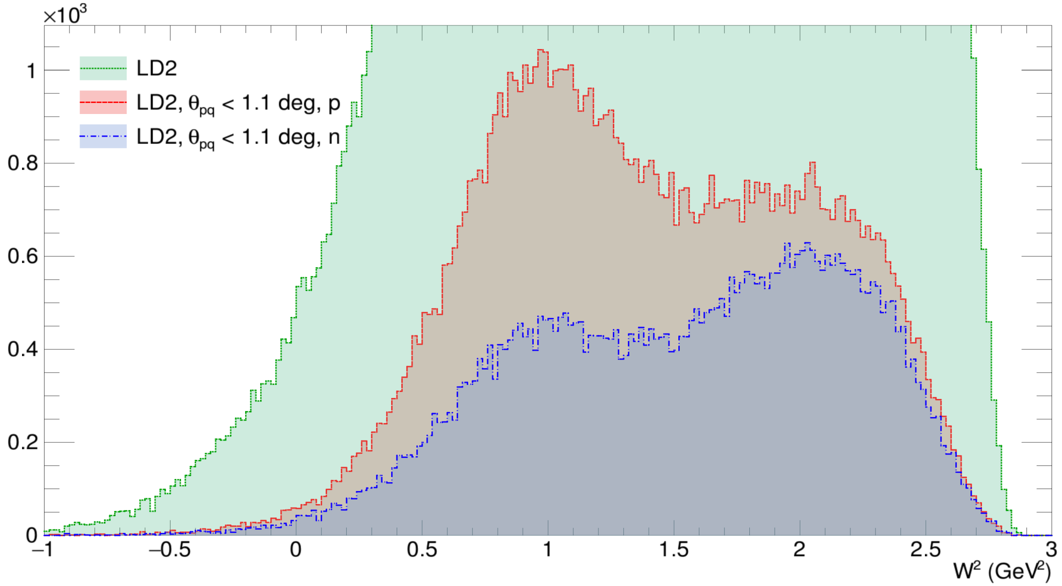
- All primary cuts listed on page 5.
- Fiducial Cuts
- $0.49 \leq W^2 \leq 1.44$ GeV^2 (Δx & Δx vs Δy plots)
- $|\Delta y| < 0.3$ m (Δx & Δx vs Δy plots)
- $\theta_{pq} < 1.4^0$ with p hypothesis (W^2 plot)
- $\theta_{pq} < 1.4^0$ with n hypothesis (W^2 plot)

- We fit the Δx distribution to sum of two Gaussian signals (p & n) along with a 4th degree polynomial background to extract raw $d(e,e'(p,n))$ yields.

QE Event Selection: $Q^2 = 7.4\ (GeV/c)^2$ [SBS-14]





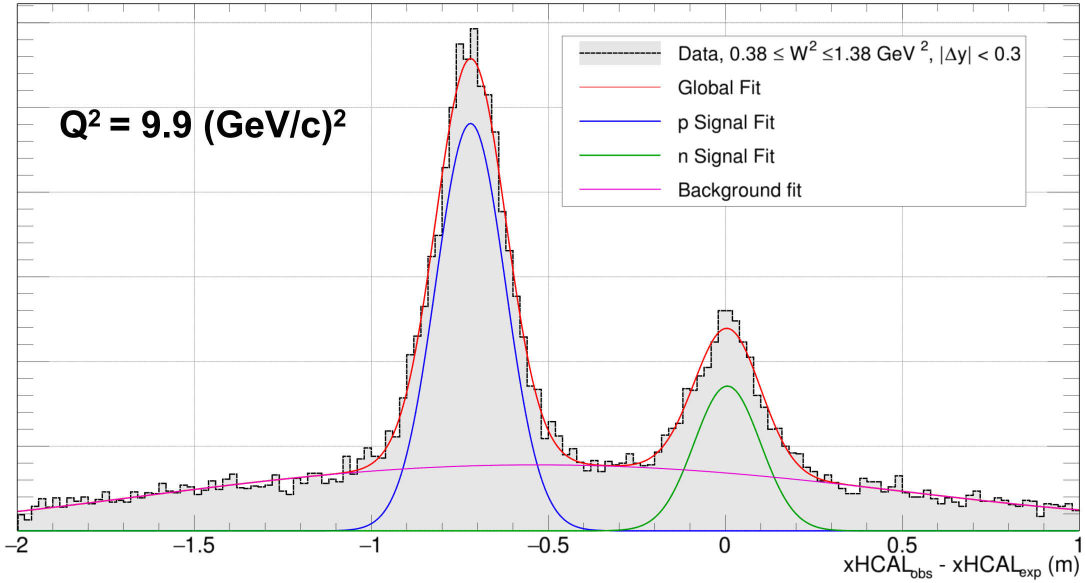


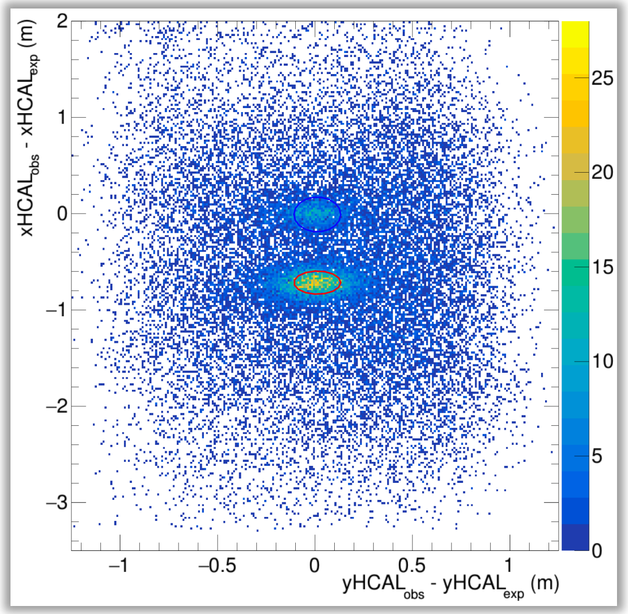
Figures: HCAL Δx (Top Left), HCAL Δx vs Δy (Top Right), W^2 (Bottom Left)

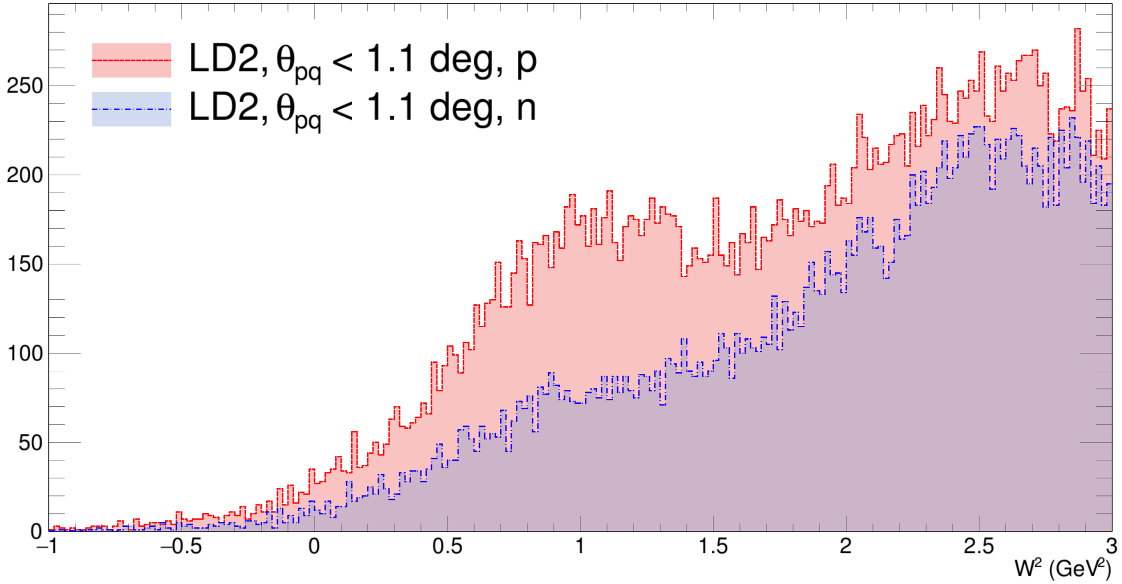
- All primary cuts listed on page 5.
- Fiducial Cuts
- $0.38 \leq W^2 \leq 1.38$ GeV^2 (Δx & Δx vs Δy plots)
- $|\Delta y| < 0.3$ m (Δx & Δx vs Δy plots)
- $\theta_{pq} < 1.1^0$ with p hypothesis (W^2 plot)
- $\theta_{pq} < 1.1^0$ with n hypothesis (W^2 plot)

- We fit the Δx distribution to sum of two Gaussian signals (p & n) along with a 4th degree polynomial background to extract raw $d(e, e'(p, n))$ yields.

QE Event Selection: $Q^2 = 9.9\ (GeV/c)^2$ [SBS-7]





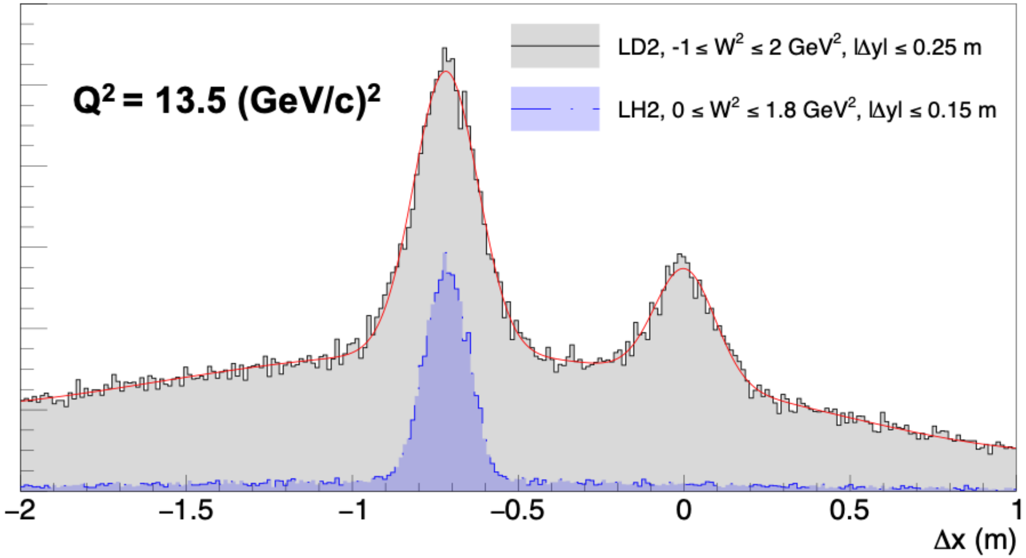


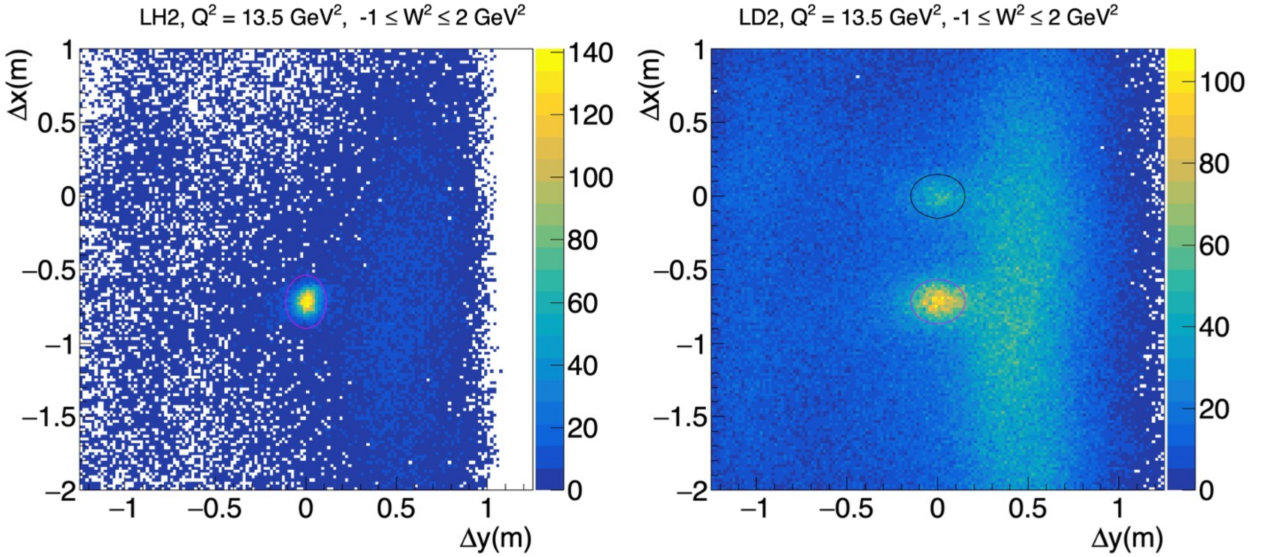
Figures: HCAL Δx (Top Left), HCAL Δx vs Δy (Top Right), W^2 (Bottom Left)

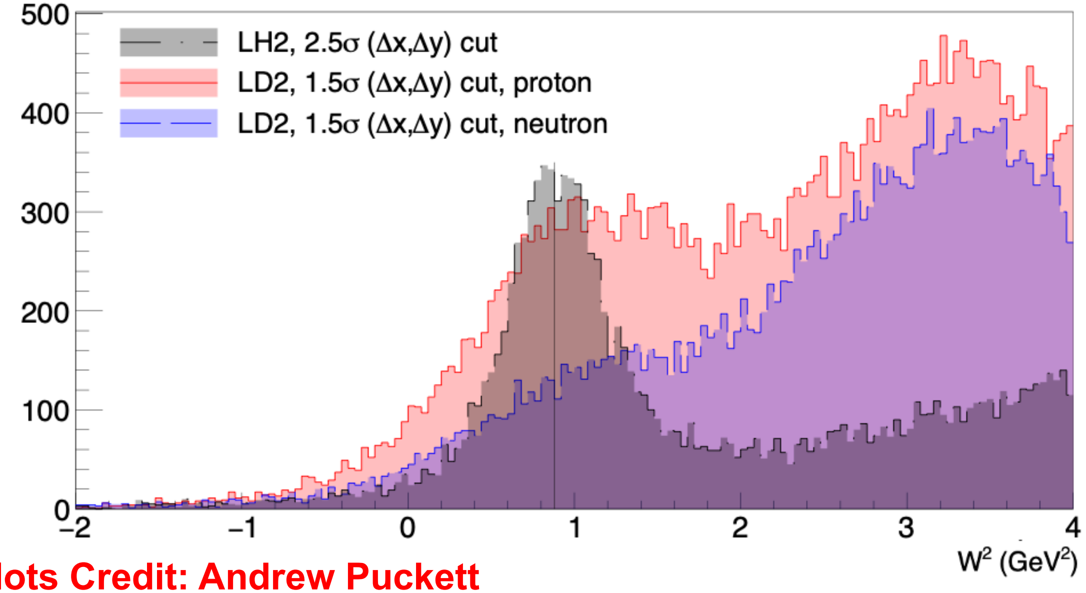
- All primary cuts listed on page 5.
- Fiducial Cuts
- $0.38 \leq W^2 \leq 1.38$ GeV^2 (Δx & Δx vs Δy plots)
- $|\Delta y| < 0.3$ m (Δx & Δx vs Δy plots)
- $\theta_{pq} < 1.1^0$ with p hypothesis (W^2 plot)
- $\theta_{pq} < 1.1^0$ with n hypothesis (W^2 plot)

- We fit the Δx distribution to sum of two Gaussian signals (p & n) along with a 4th degree polynomial background to extract raw $d(e, e'(p, n))$ yields.

QE Event Selection: $Q^2 = 13.5\ (GeV/c)^2$ [SBS-11]







Figures: HCAL Δx (Top Left), HCAL Δx vs Δy (Top Right), W^2 (Bottom Left)

- At 13.5 GeV^2 kinematic broadening of W^2 is significant. Hence, we have used a wider W^2 cut: $-1 \leq W^2 \leq 2\ GeV^2$
- Same as other Q^2 points, we fit the Δx distribution to sum of two Gaussian signals (p & n) along with a 4th degree polynomial background to extract raw $d(e,e'(p,n))$ yields.

Plots Credit: Andrew Puckett

Raw Yields & Preliminary Uncertainty Projections

Table I: Estimated Raw QE Yields from $SBS\text{-}G_M^n$ dataset

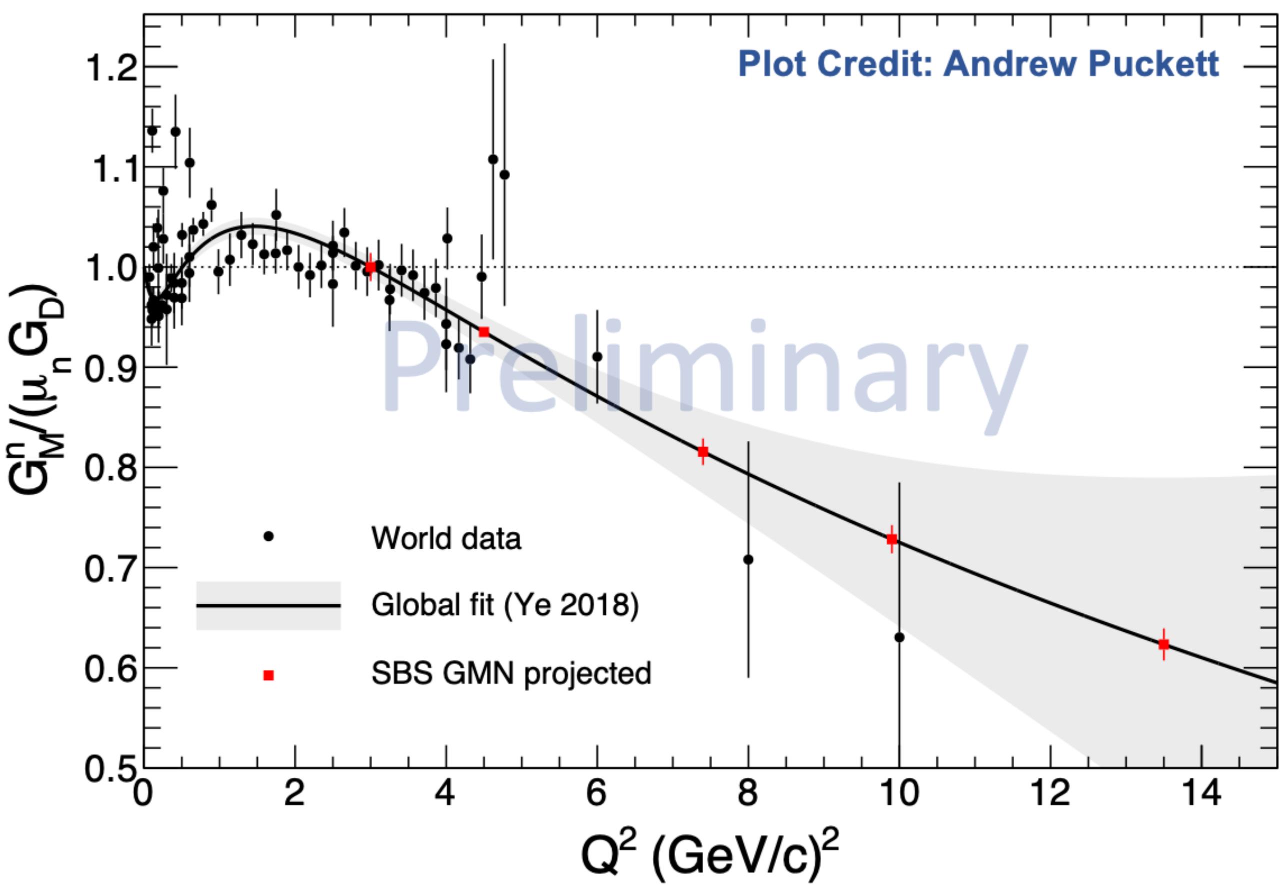
Q^2 $(GeV/c)^2$	E_{beam} (GeV)	Raw QE Yields	Projected $\Delta_{stat}(G_M^n/G_M^p)$	Projected $\Delta_{syst}(G_M^n/G_M^p)$
3.0	3.73	471,000	0.12%	1.4%
4.5	5.97	1,092,000	0.07%	0.6%
7.4	5.97	76,700	0.30%	1.6%
9.9	7.91	13,100	0.70%	1.8%
13.5	9.86	19,200	0.60%	2.5%

Preliminary

- Relative statistical uncertainties in G_M^n/G_M^p is estimated from the raw yields we got using the analysis shown in the previous slides.
- Projected systematic uncertainties have been taken from experiment proposal.

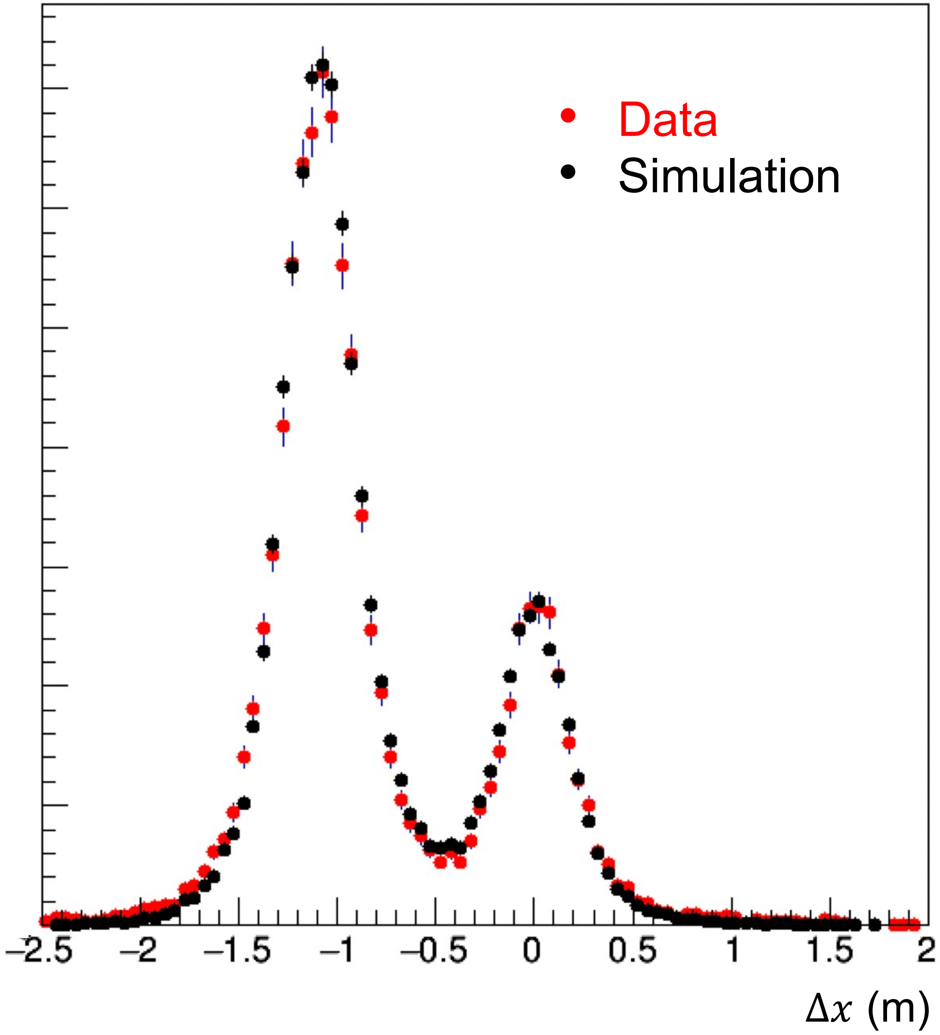
❖ Things we haven't considered:

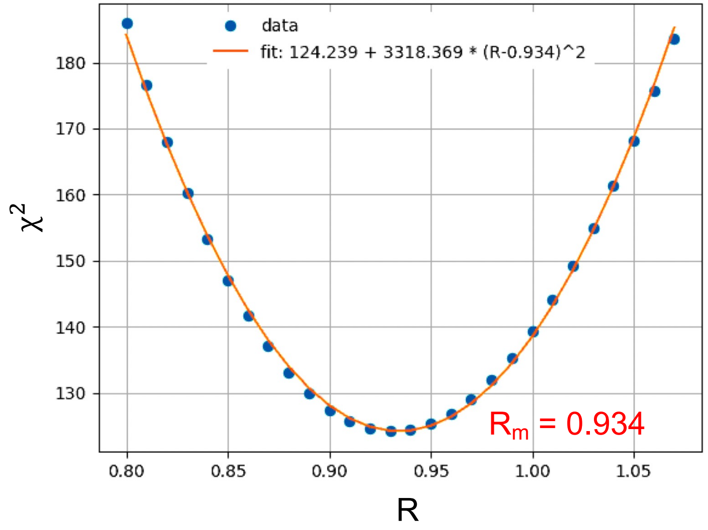
- HCAL p/n detection efficiency corrections
- Radiative corrections
- Nuclear corrections
- Nucleon misidentification probabilities and many more



Data vs Simulation: $Q^2 = 3\ (\text{GeV}/c)^2$ [SBS-4]

$Q^2 = 3\ \text{GeV}^2$, $0.49 \leq W^2 \leq 1.44\ \text{GeV}^2$, Fiducial Cuts





$$\chi^2 = \sum_{i=0}^{Tot.Bins} \frac{(data_i - simu_i)^2}{(\Delta data_i)^2}$$

$$\Delta data_i = \sqrt{data_i}/N_{data}$$

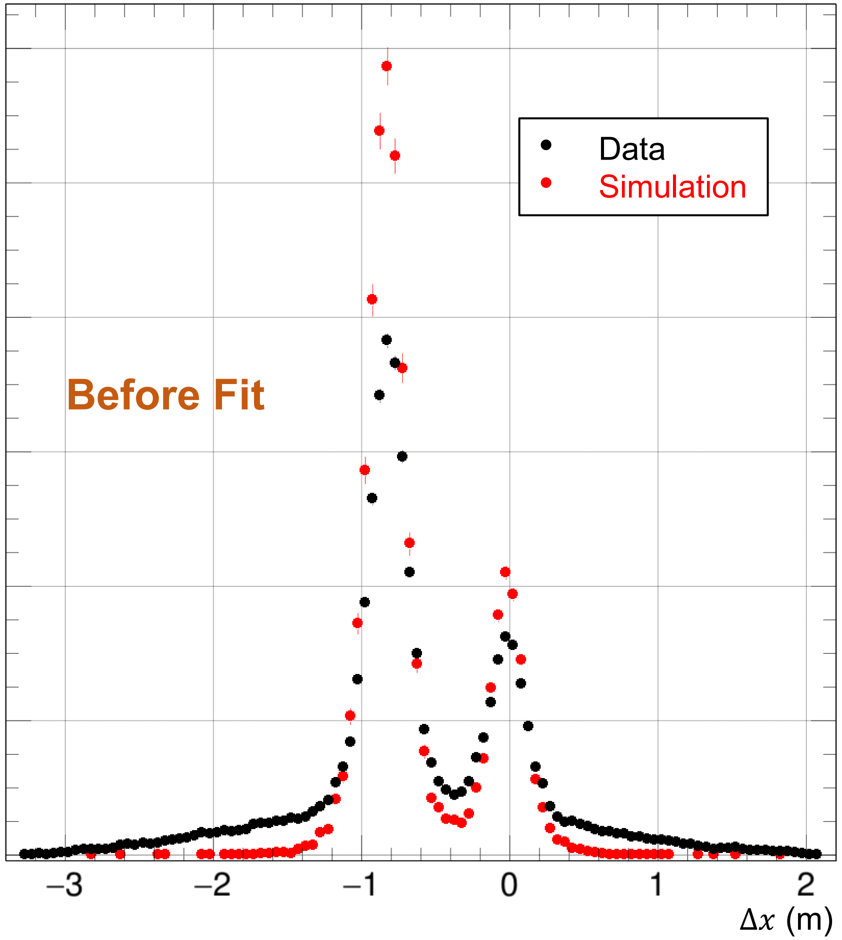
$$simu_i = \mathcal{N}_i * (p\_histo_i + R * n\_histo_i)$$

Fit Parameter

- We used GEANT4 framework to generate quasi-elastic events on LD2 target which we then digitized and reconstructed using the same replay machinery we use to cook real data.
- All the same cuts have been used for data and simulation analysis.
- Radiative corrections are yet to be implemented in MC event generator.

❖ Agreement of fit looks very promising even at this early stage of analysis.

Data vs Simulation: $Q^2 = 7.4\ (GeV/c)^2$ [SBS-14]

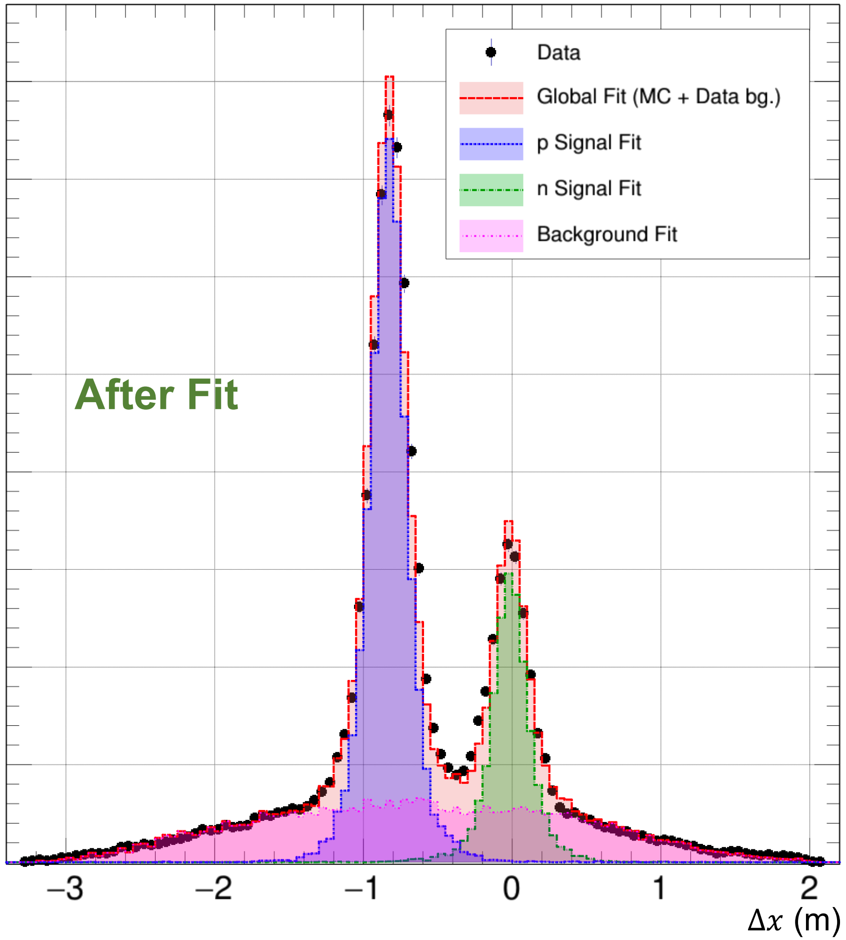


$Q^2 = 7.4\ GeV^2$

$0.5 \leq W^2 \leq 1.3\ GeV^2$

$|\Delta y| < 0.3$ m

Fiducial Cuts



- Unlike 3 GeV^2, at 7.4 GeV^2 we have significant inelastic contamination. Hence, we had to add a second parameter (*B*) to fit an appropriate background distribution. We got the background distribution from data using $\Delta y > 0.6$ m cut.

$$simu_i = \mathcal{N}_i * (p\_histo_i + R * n\_histo_i + B * bg\_histo_i)$$

❖ Resulting fit looks encouraging in this case as well.

Summary

- $\mathrm{SBS\text{-}G_M^n}$ experiment was completed successfully in February 2022. Thanks to the tireless work of Hall A technicians, Graduate students, Post Docs, JLab Staff Scientists, and Professors.
- Calibration of entirely new spectrometers and enormous raw data volume ($\approx$ 2 PB!) have made preliminary data processing very challenging for us.
- Despite all these challenges we have recently finished the 1st pass cooking of entire $\mathrm{SBS\text{-}G_M^n}$ dataset!
- A huge effort of data analysis is ongoing. Quasi-elastic event selection seems reasonably clean for even the highest Q^2 point with very basic cuts. Agreement with simulation looks encouraging as well.
- Preliminary projected uncertainties estimated from raw $d(e,e'(p,n))$ counts show promising results. Precision of the highest Q^2 data point (13.5 GeV^2) is expected to stay unmatched for years to come.
- Our goal is to get preliminary results out by the end of this summer.

❖ **Acknowledgement:** This work is supported by the US Department of Energy Office of Science, Office of Nuclear Physics, Award ID DE-SC0021200.

Anuruddha Rathnayake
(GEMs)

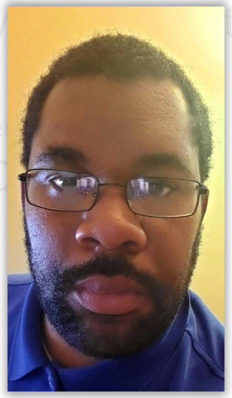
Ralph Marinaro
(BigBite Hodoscope)

Provakar Datta
(BigBite Calorimeter)

Thank You for Your Attention!

Questions? Comments?

Maria Satnik
(GRINCH)

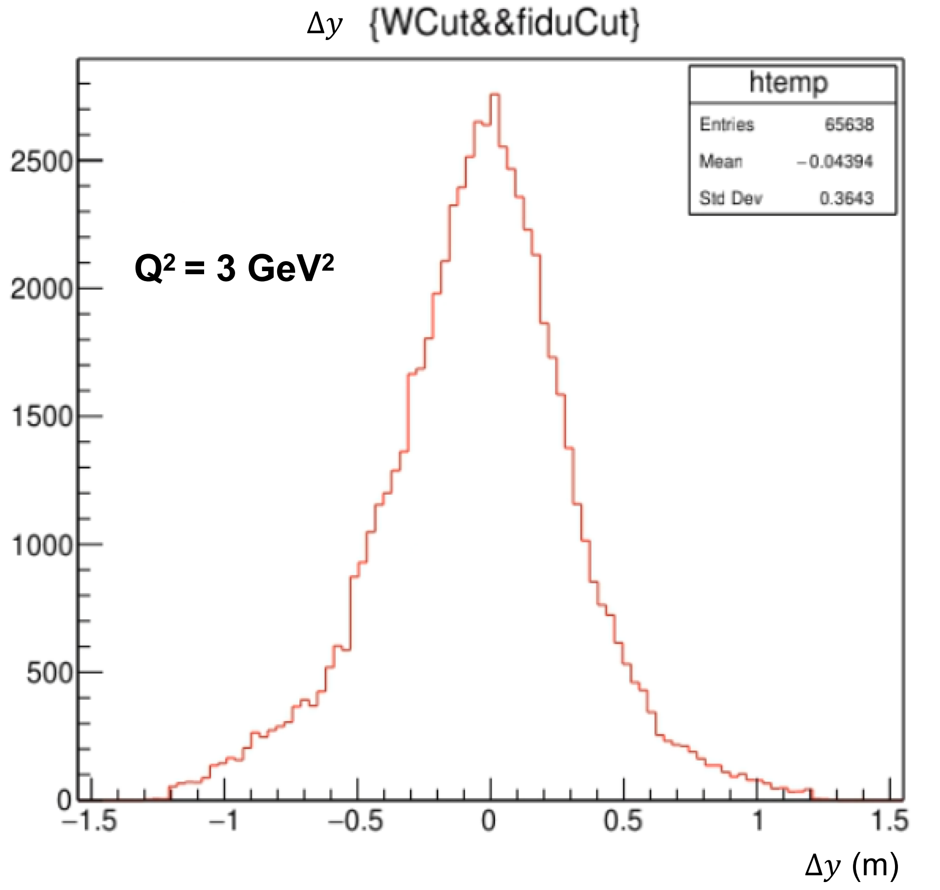


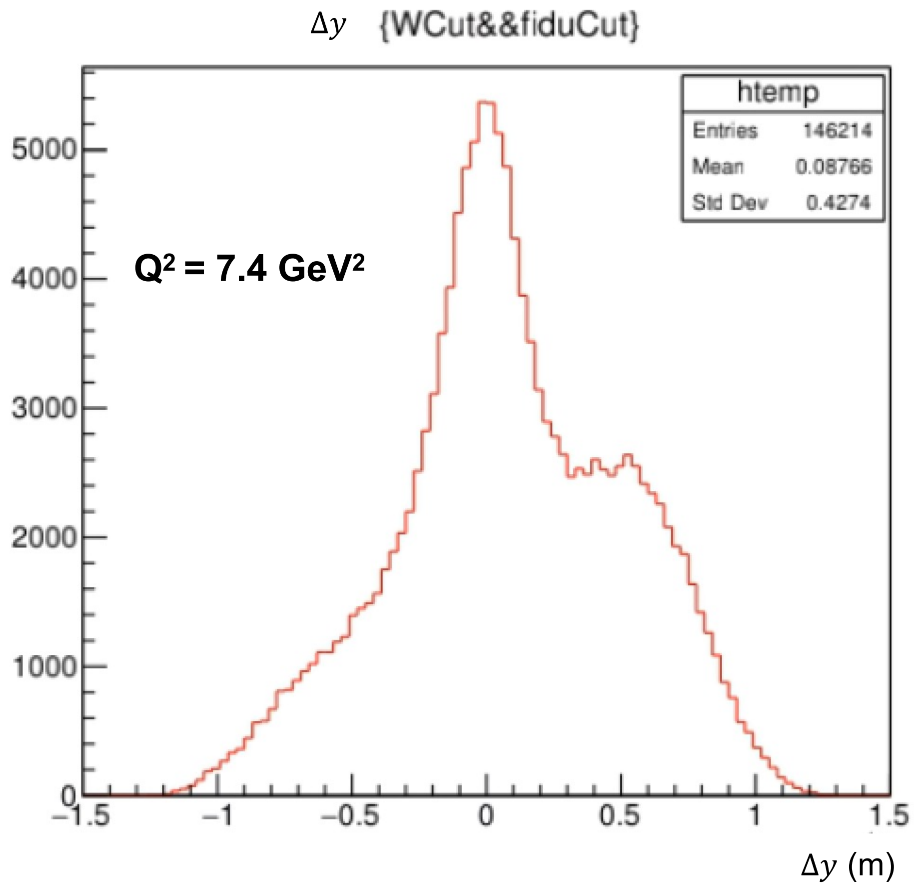
Nathaniel Lashley
(Beamline)

SBS-G_M^n Thesis Students

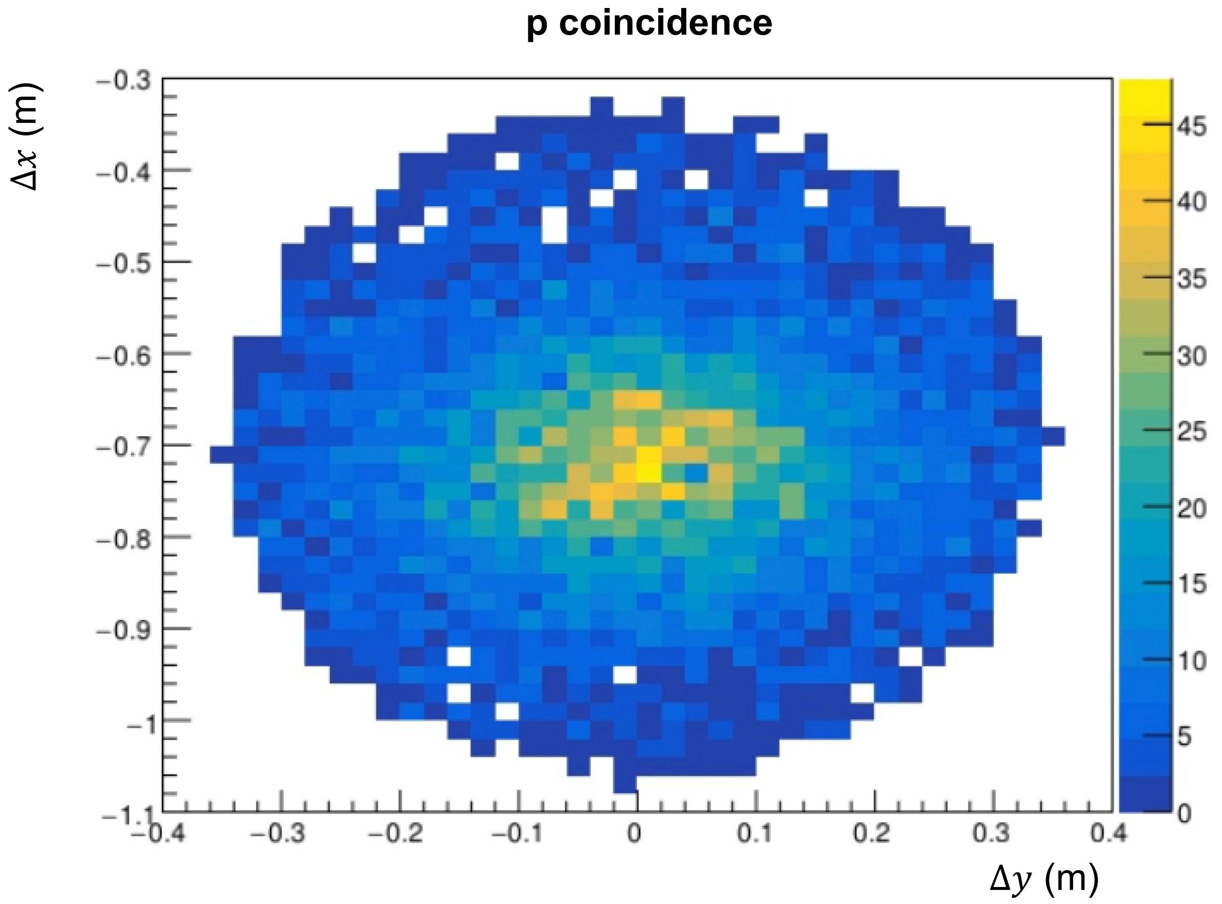
Backup Slides

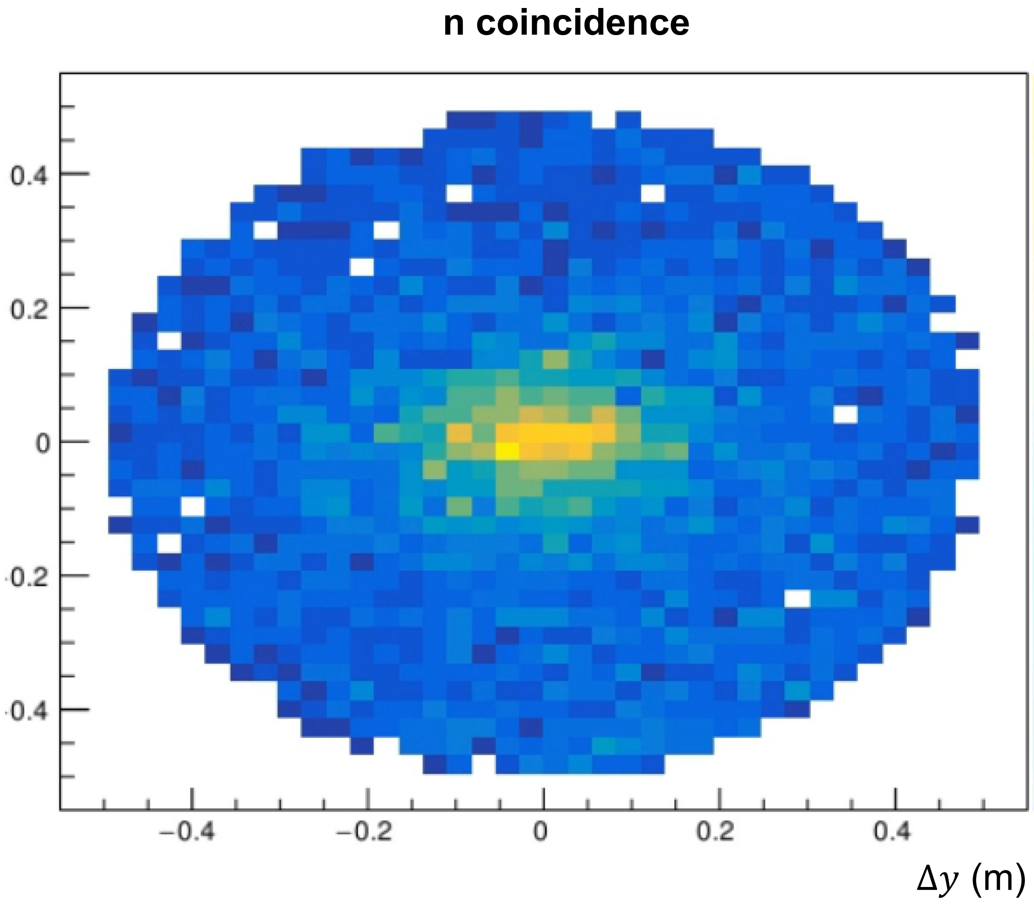
HCAL Δy Distributions



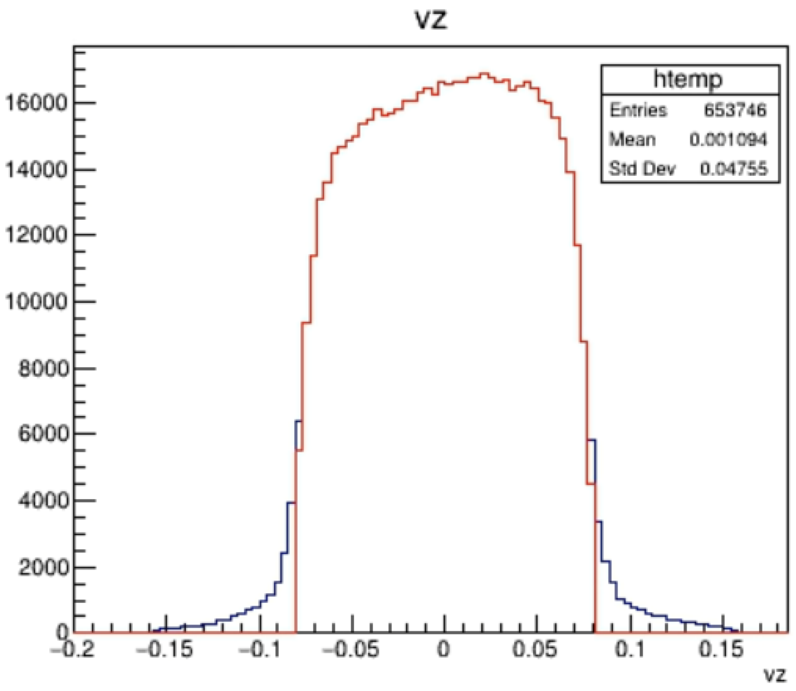


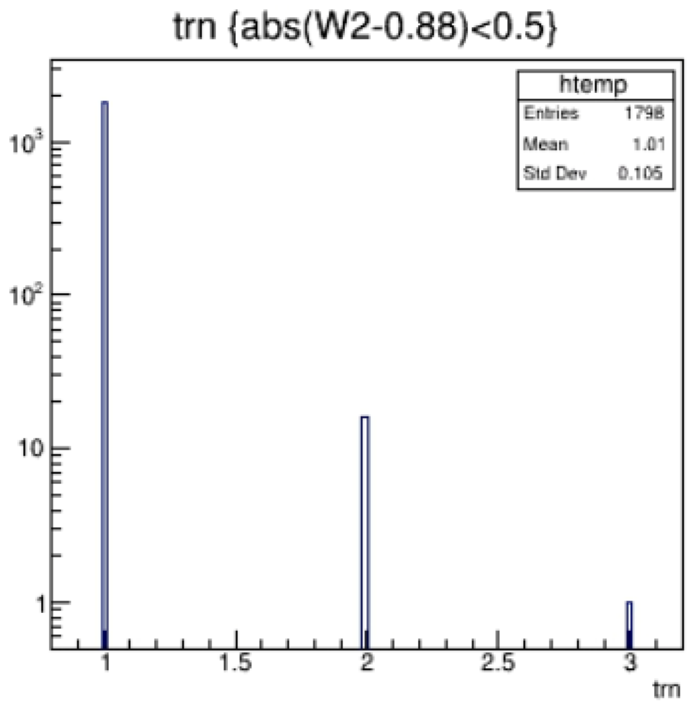
Visualizing θ_{pq} Cuts: $Q^2 = 9.9$ $(GeV/c)^2$ [SBS-7]

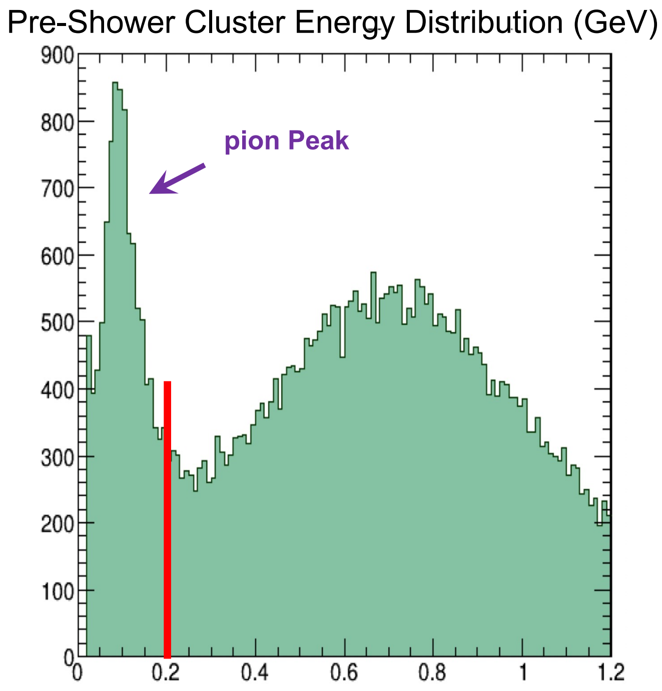




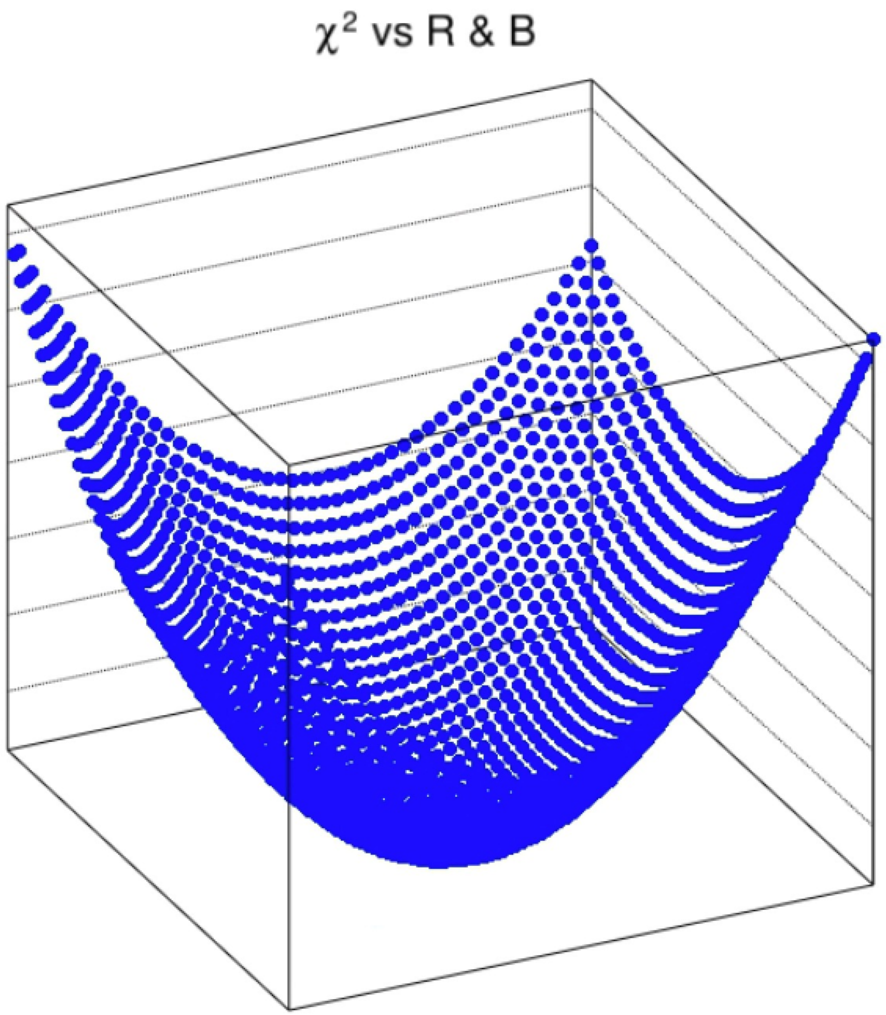
Primary Cuts

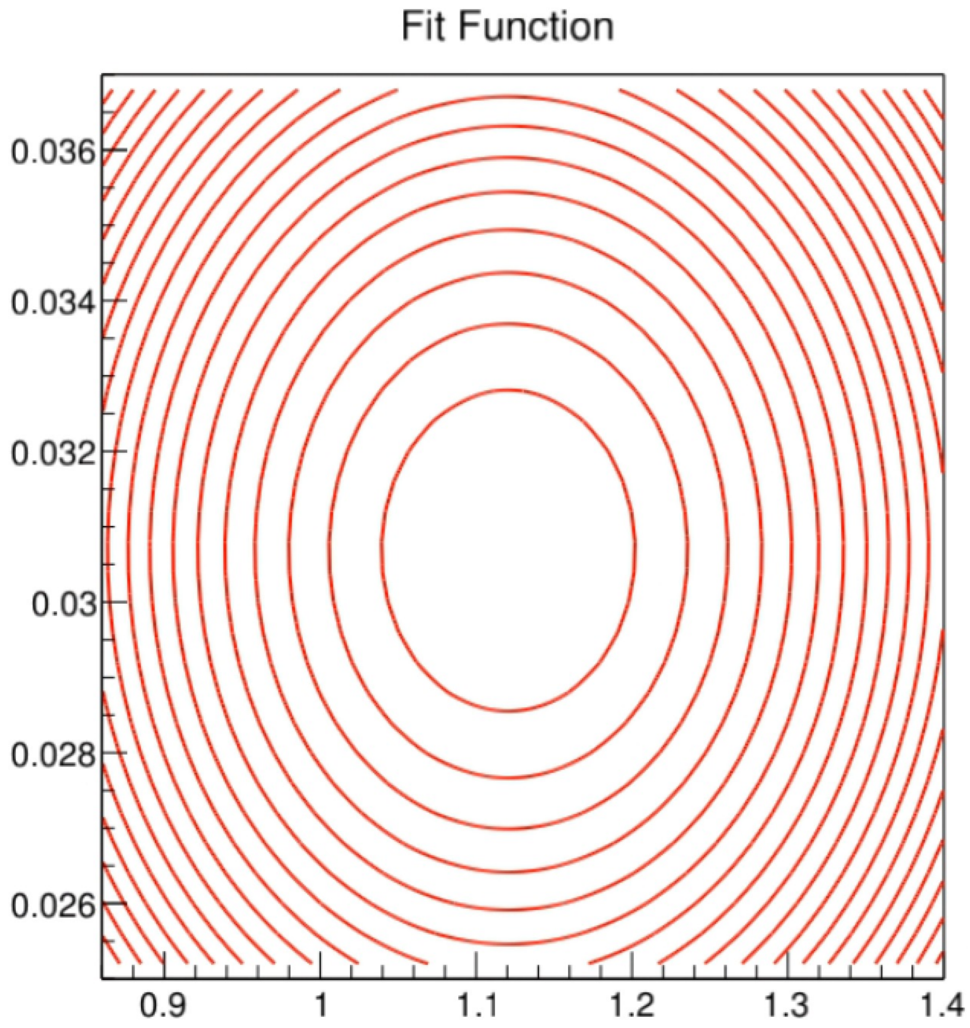




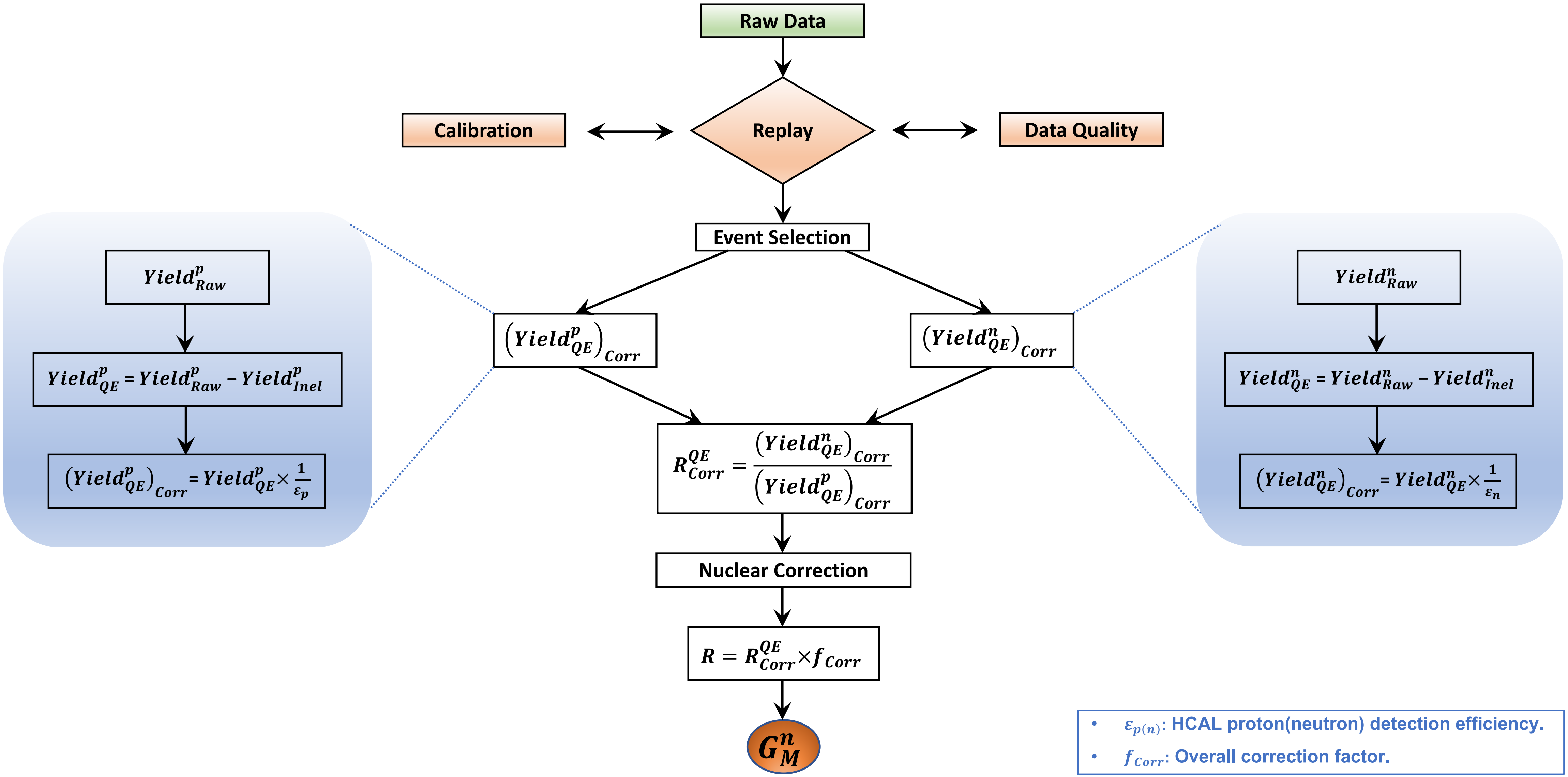


χ^2 Minimization with Two Fit Parameters (R & B)





Analysis Flowchart



- $\varepsilon_{p(n)}$: HCAL proton(neutron) detection efficiency.
- f_{Corr}: Overall correction factor.