SBS-G_M^n Experiment

Provakar Datta

(Supervisor: Prof. Andrew Puckett)

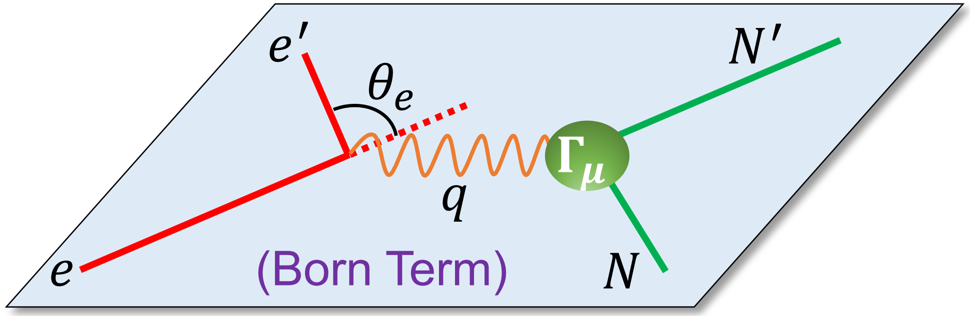
Thesis Topic: SBS-G_M^n Experiment

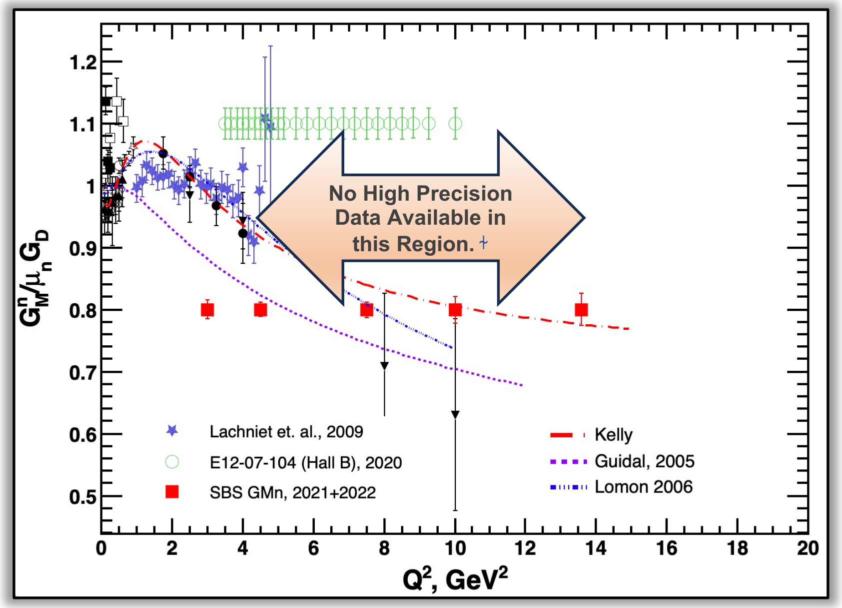
- Ran in Jefferson Lab's Experimental Hall A from Fall 2021 to February 2022.

❖ **Goal:** High precision measurement of G_M^n at Q^2 = 3, 4.5, 7.5, 10 & 13.6 $(GeV/c)^2$.

- Nucleon vertex (elastic e-N scattering):

$$\Gamma_\mu(q) = \gamma_\mu \underbrace{F_1(-q^2)}_{\text{Dirac FF}} + \frac{i\sigma_{\mu\nu}q^\nu}{2M_N}\underbrace{F_2(-q^2)}_{\text{Pauli FF}}$$





- 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:

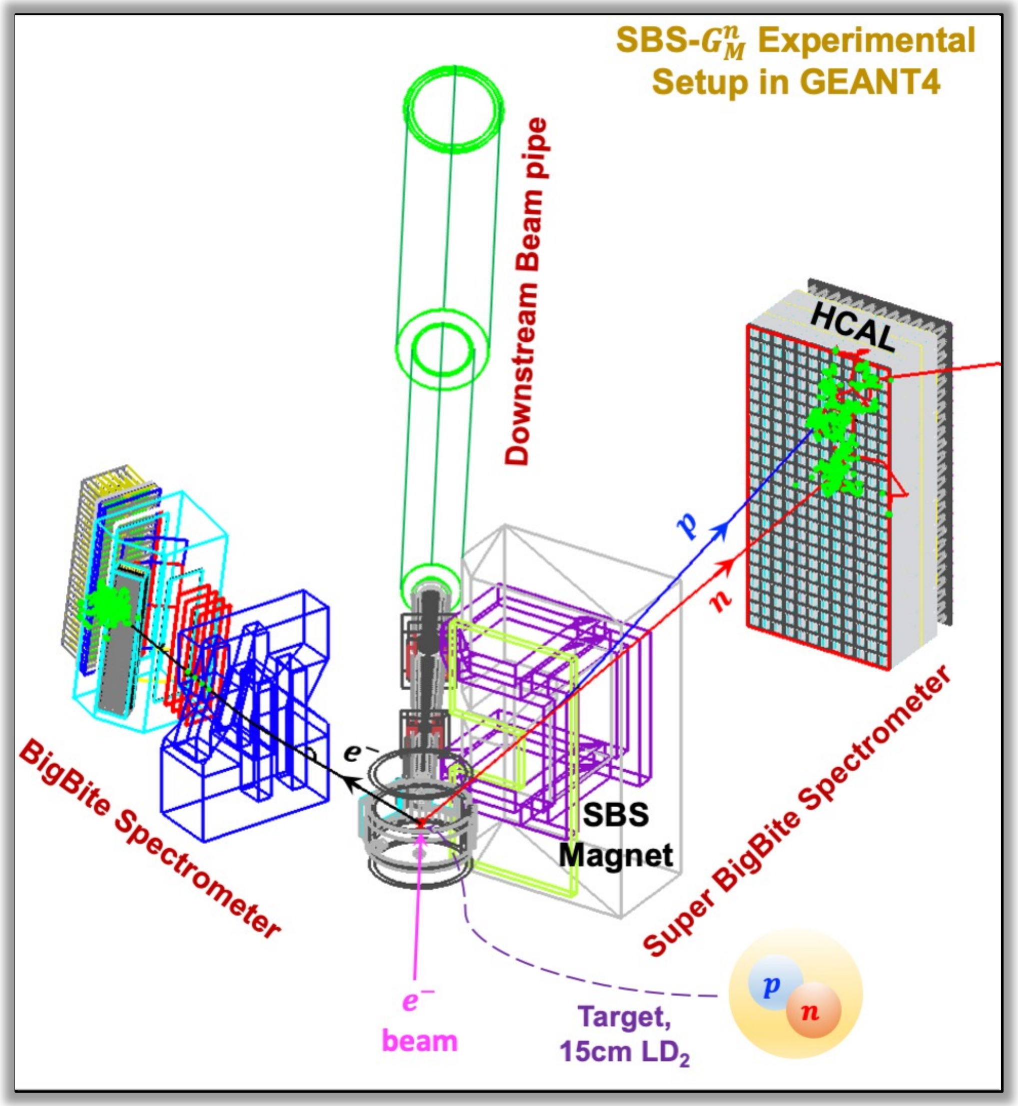
$$\frac{d\sigma}{d\Omega} = \frac{\sigma_{Mott}}{1+\tau}\left(G_E^2(Q^2) + \frac{\tau}{\epsilon}G_M^2(Q^2)\right)$$

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

❖ 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]

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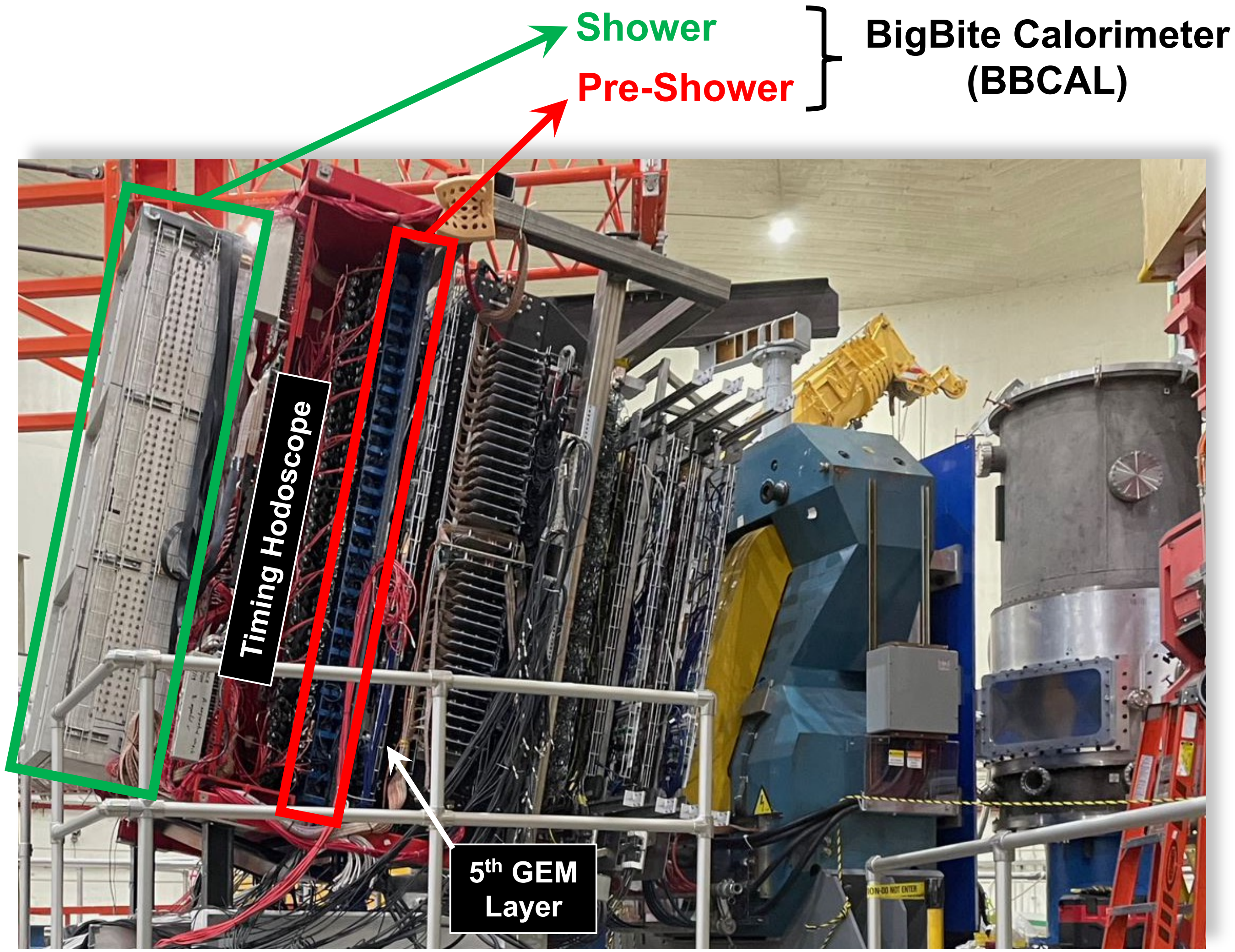
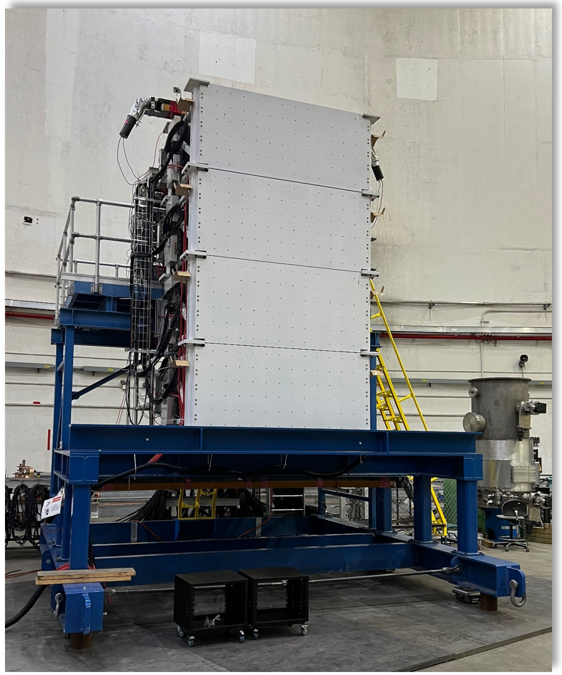
[1] L. Durand, Phys. Rev. 115 1020 (1959).

Hardware Focus: SBS Calorimeters (BBCAL & HCAL)



The BigBite Spectrometer in Hall A (Side View)

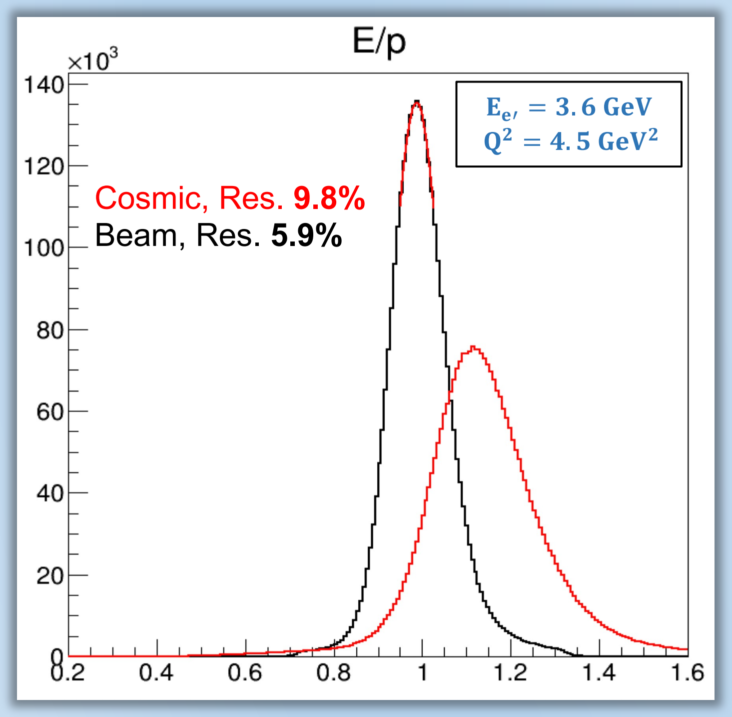
Hadron Calorimeter (HCAL)



- I am a part of the SBS calorimeter group.
- Primarily worked on the testing, commissioning, and calibration of the BigBite calorimeter (BBCAL). Offline fine tuning of the calibration for G_M^n is still ongoing.
- Provided expert support during G_M^n experiment and doing the same during G_E^n-II.

Analysis Status

- We finished 1st pass cooking of the entire $\mathrm{SBS\text{-}G_M^n}$ experiment in January this year. Now, we are almost ready to start 2nd pass cooking.
- Realistic MC event generator including nuclear and radiative effects is now available for $\mathrm{G_M^n/nTPE}$ analysis.
- Sophisticated physics analysis machineries for quasi-elastic event selection, yield extraction, data/MC comparison, nucleon detection efficiency estimation are in place. A huge effort is ongoing to optimize them.



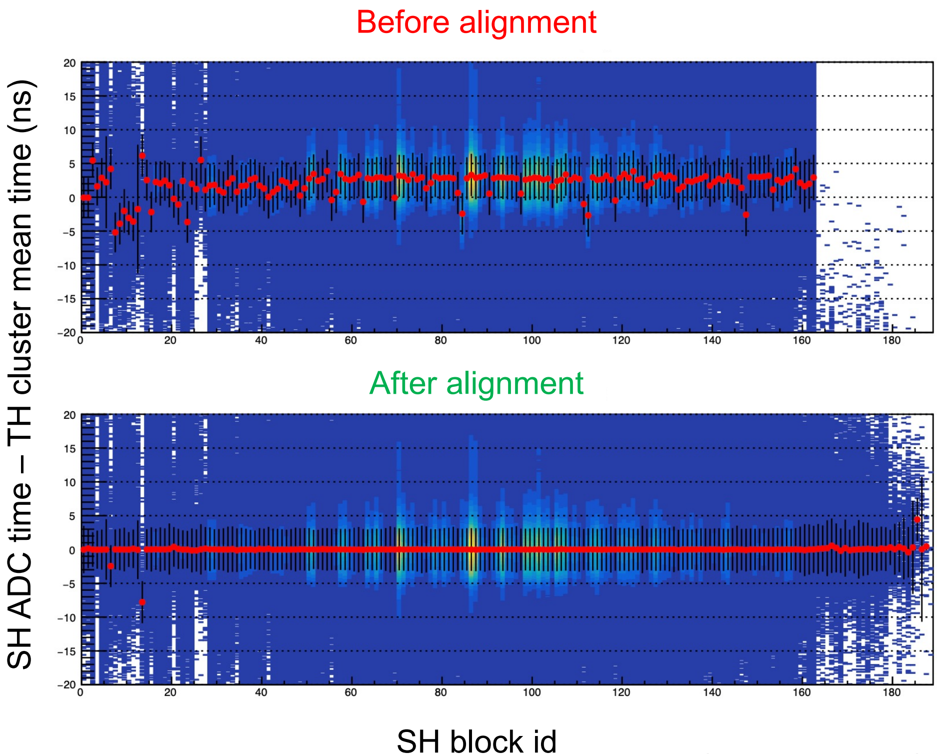
- Highlights of Detector Performance using pass 0/1 data:
  - BigBite Spectrometer:
    - Momentum resolution: $\frac{\sigma_p}{p} \approx 1 - 1.5\%$
    - Angular resolution (in-plane & out-of-plane): **$1 - 2$ mrad**
    - Vertex resolution: **$\sigma_z \leq 1$ cm**
    - BigBite Calorimeter(BBCAL) energy resolution: **5.9% at 3.6 GeV** scattered e^- energy.
  - Super BigBite Spectrometer:
    - Hadron Calorimeter (HCAL):
      - Time Resolution: **$\sigma_t \approx 1.7$ ns**
      - Angular Resolution: **~ 2 mrad**

BBCAL Calibration Highlights

Energy calibration

Configuration	E_{beam} (GeV)	$E_{e'}$ (GeV)	Magnet current (A)		E/p peak position		BBCAL resolution (%)	
			BB	SBS	Before calib.	After calib.	Before calib.	After calib.
SBS-4	3.728	2.11	750	0	0.97	**0.99**	6.4	**6.2**
			750	630	0.97	**0.99**	6.4	**6.3**
			750	1050	0.98	**0.99**	6.6	**6.3**
SBS-7	7.906	2.67	750	1785	0.97	**0.99**	6.4	**6.2**
SBS-11	9.91	2.67	750	0	1.01	**1.00**	8.0	**7.7**
			750	2100	1.02	**0.99**	7.0	**6.2**
SBS-14	5.965	2.00	750	0	0.98	**0.99**	7.5	**7.4**
			750	1470	0.99	**0.99**	6.9	**6.4**
SBS-8	5.965	3.59	750	0	0.96	**0.99**	5.6	**5.7**
			750	1050	0.95	**0.99**	5.6	**5.6**
			750	1470	0.99	**0.99**	6.8	**6.2**
			750	2100	0.96	**0.99**	5.6	**5.6**
SBS-9	4.015	1.63	750	1470	0.99	**0.99**	7.4	**7.0**

ADC time alignment



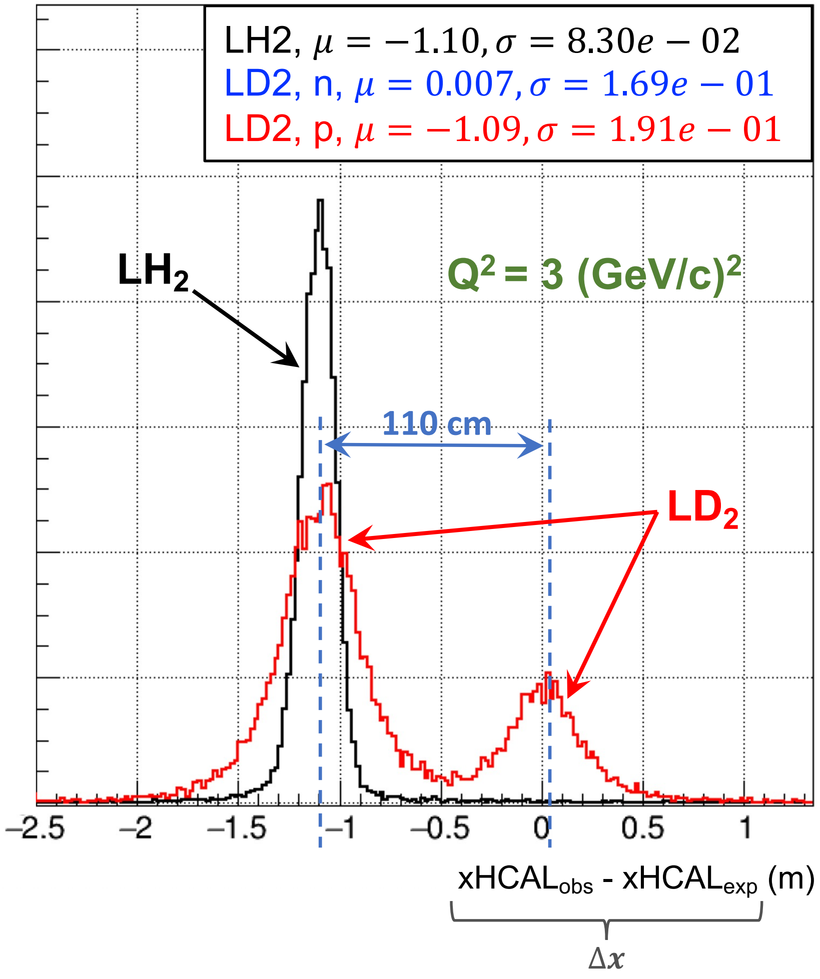
$\text{SBS 11 } [Q^2 = 13.6\ (\text{GeV/c})^2]$

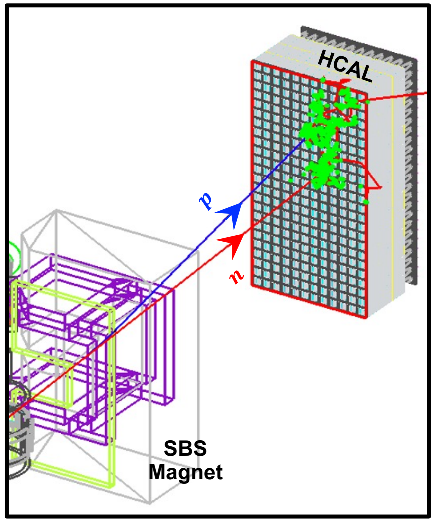
- Fine tuning of BBCAL energy calibration for all 13 different settings is done for pass 2 readiness. **5.6%** energy resolution at **3.6 GeV** elastic e^- energy.
- ADC time alignment is done as well for both SH and PS for all the G_M^n/nTPE configurations. Achieved **1.6 ns** time resolution from BBCAL-HCAL coincidence ADC time for $\mathbf{Q^2 = 3\ (GeV/c)^2}$.

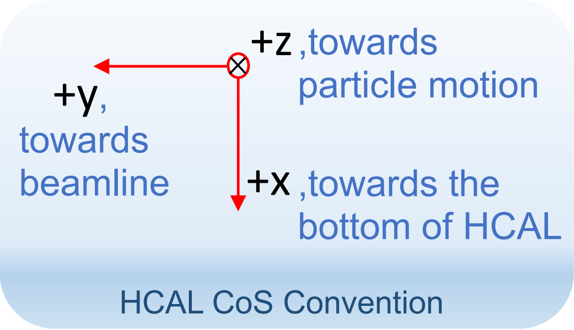
BBCAL is ready for 2nd pass cooking!

Physics Analysis Highlights: Quasi-Elastic (QE) Event Selection

❖ Introducing HCAL Δx plot:







+z ,towards particle motion

+y, towards beamline

+x ,towards the bottom of HCAL

HCAL CoS Convention

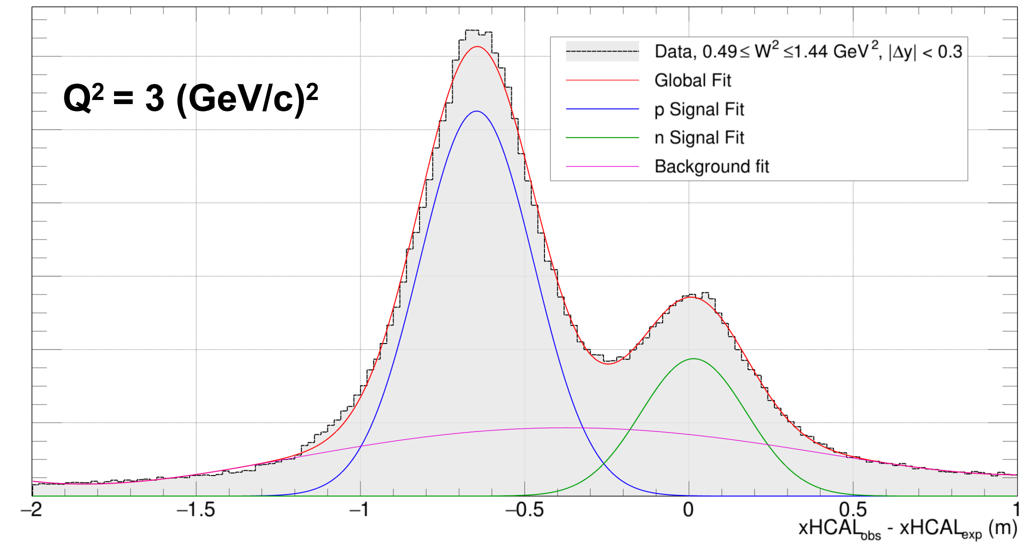
- Primary Cuts:
  1. Presence of a track
  2. $|(\text{vertex})_z| < 0.08$ m
  3. PS cluster energy > 0.2 GeV
  4. Cut on reconstructed track momentum (kinematics dependent)

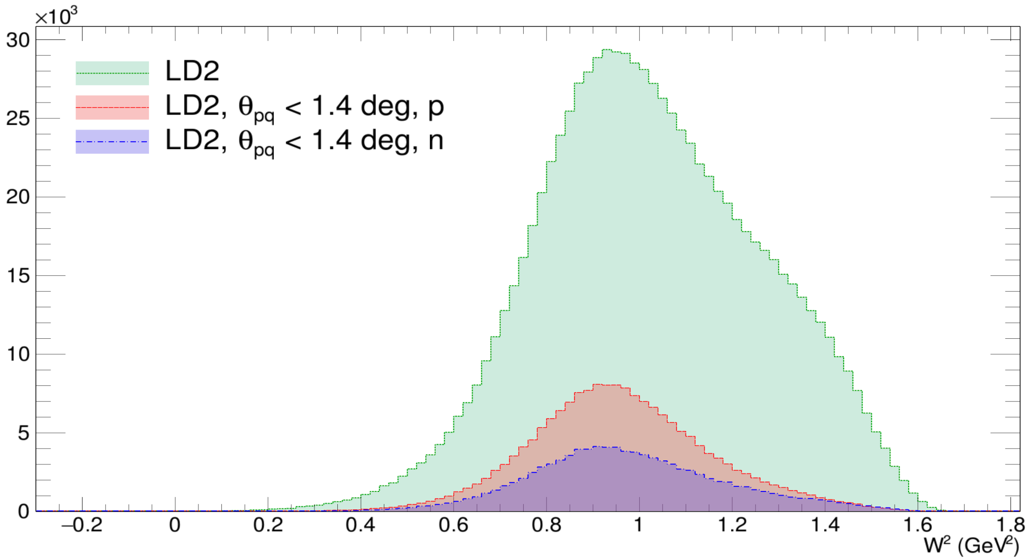
- QE Event Selection Cuts: (Q^2 dep.)
  1. Cut on W^2
  2. Cut on Δy
  3. Cut on θ_{pq} (angle between reconstructed nucleon momentum ($\vec{p}$) and the momentum transfer vector ($\vec{q}$))
  4. Fiducial/Acceptance Cuts

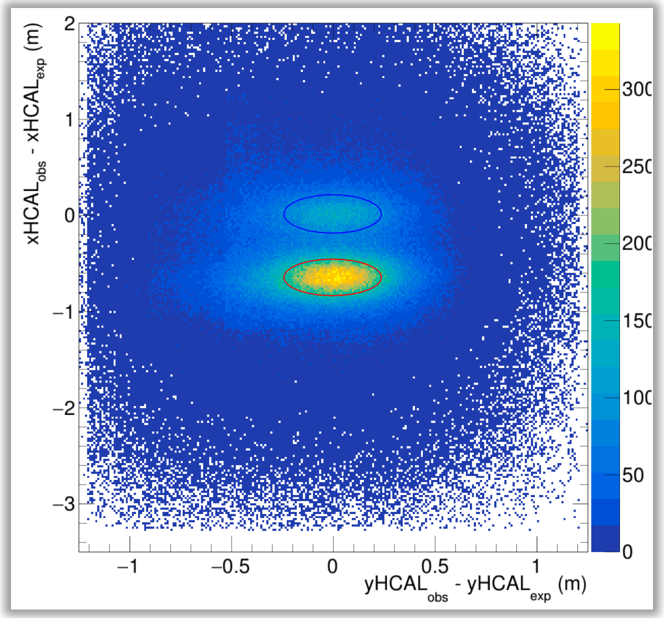
❖ Fitting Δx plot we can extract $d(ee'n)p$ & $d(ee'p)n$ yields and then form the ratio:

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

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





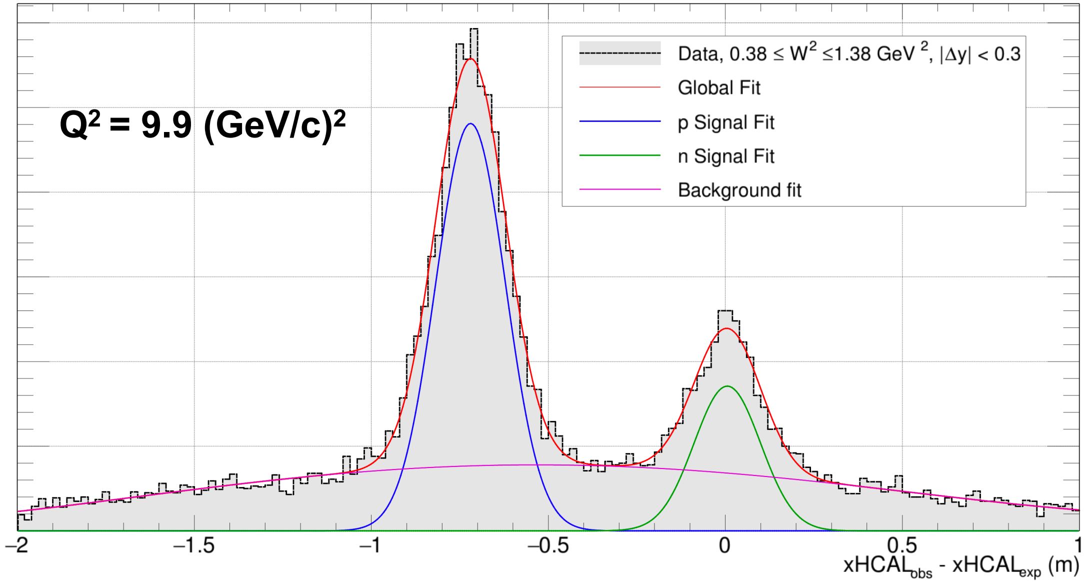


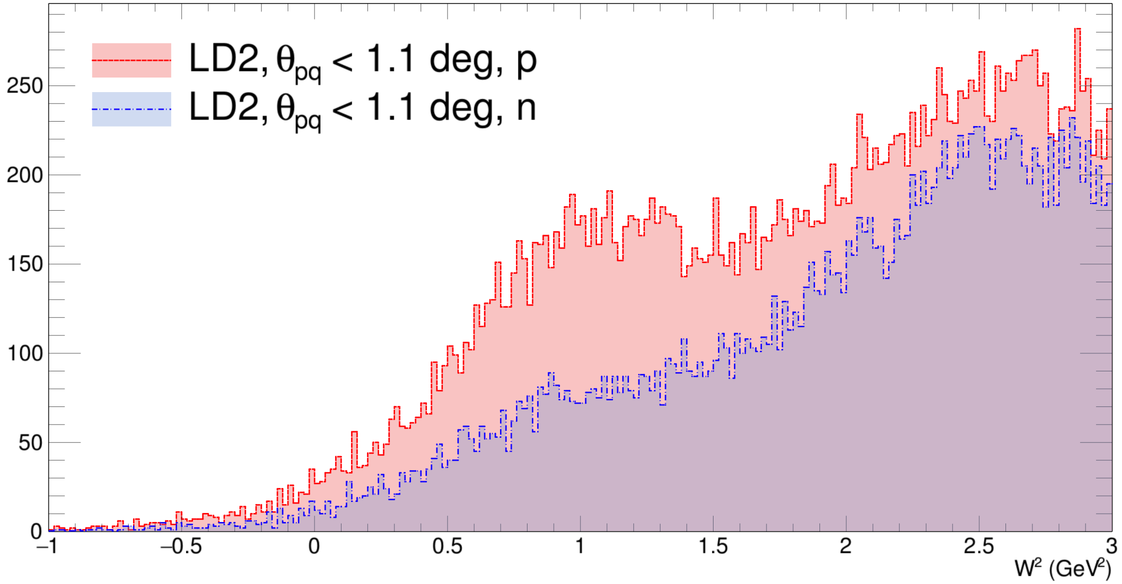
Figures: HCAL Δx (Top Left), HCAL Δx vs Δy (Top Right), W^2 (Bottom Left)

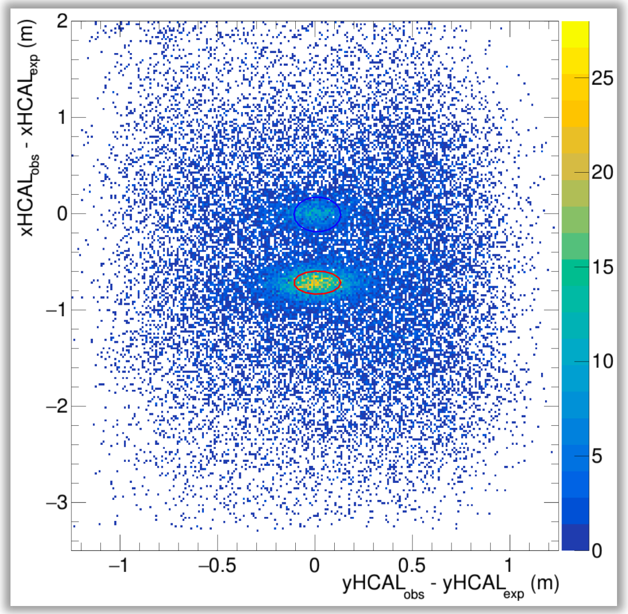
- All primary cuts listed on page 5.
- Fiducial Cuts
- $0.49 \leq W^2 \leq 1.44$ GeV^2 (Δx & Δx vs Δy plots)
- $|\Delta y| < 0.3$ m (Δx & Δx vs Δy plots)
- $\theta_{pq} < 1.4^0$ with p hypothesis (W^2 plot)
- $\theta_{pq} < 1.4^0$ with n hypothesis (W^2 plot)

- 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: $Q^2 = 9.9$ (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
- $0.38 \le W^2 \le 1.38$ 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.

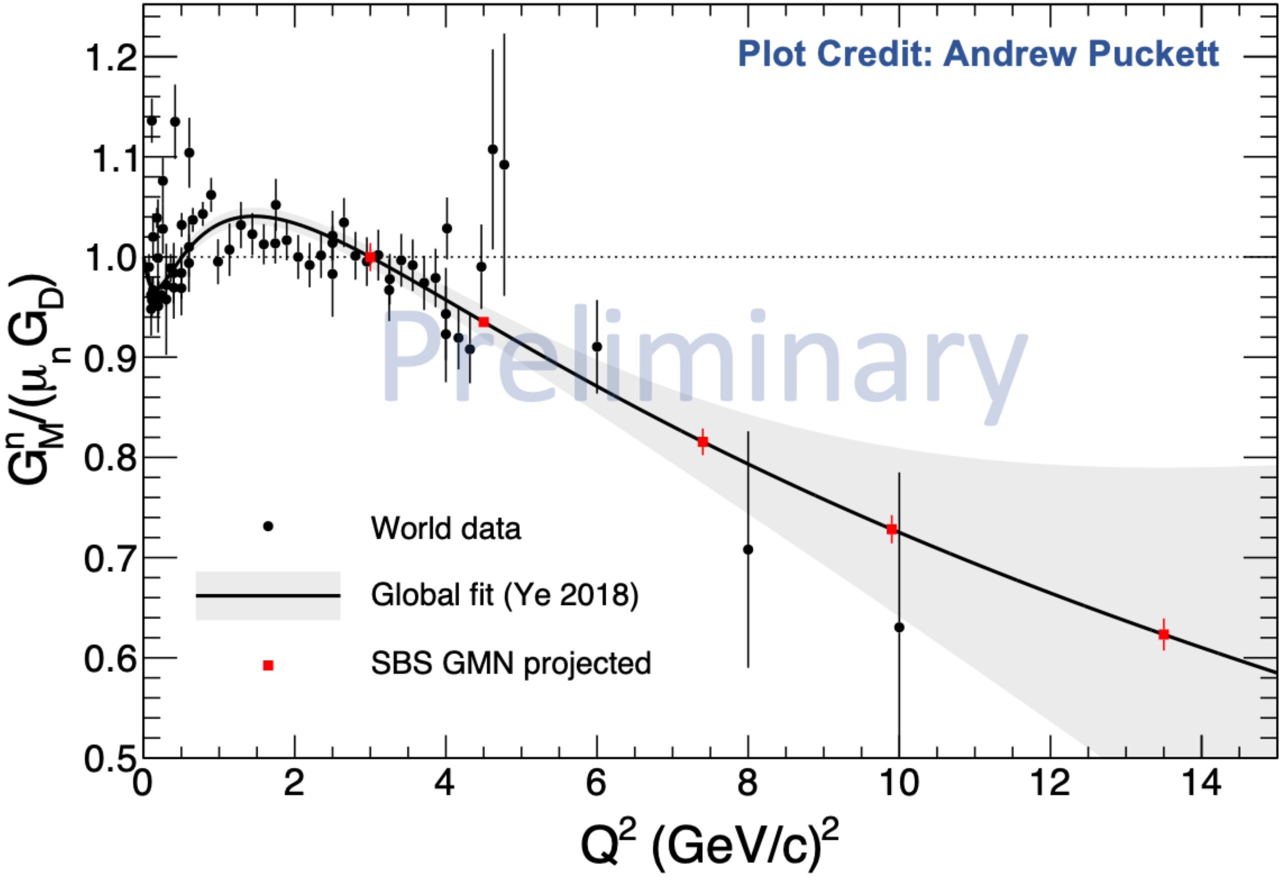
Raw Yields & Preliminary Uncertainty Projections

Table I: Estimated Raw QE Yields from SBS-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%

- 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

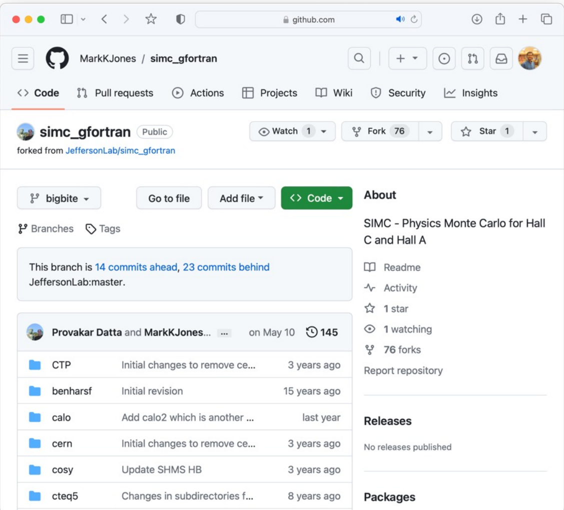


Realistic MC Event Generator for $\mathrm{G_M^n}$/nTPE Analysis

- Realistic deuteron model.
- Radiative corrections for $(ee'p)$ reaction at energies suitable for $\mathrm{G_M^n}$/nTPE. [2]
- MC event generation machinery for $H(ee'p)$ and $D(ee'p)$ processes.

SIMC (simc_gfortran)

Standard Hall C MC framework for coincidence experiments



forked from JeffersonLab/simc_gfortran

SIMC - Physics Monte Carlo for Hall C and Hall A

This branch is 14 commits ahead, 23 commits behind JeffersonLab:master.

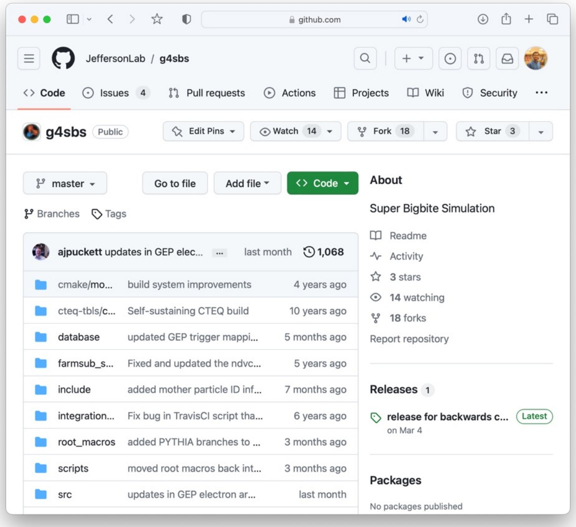
Provakar Datta and MarkKJones... on May 10 145

CTP	Initial changes to remove ce...	3 years ago
benharsf	Initial revision	15 years ago
calo	Add calo2 which is another ...	last year
cern	Initial changes to remove ce...	3 years ago
cosy	Update SHMS HB	3 years ago
cteq5	Changes in subdirectories f...	8 years ago

No releases published

G4SBS

Standard MC framework for SBS experiments



Super Bigbite Simulation

ajpuckett updates in GEP elec... last month 1,068

cmake/mo...	build system improvements	4 years ago
cteq-tbls/c...	Self-sustaining CTEQ build	10 years ago
database	updated GEP trigger mappi...	5 months ago
farmsub_s...	Fixed and updated the ndvc...	5 years ago
include	added mother particle ID inf...	7 months ago
integration...	Fix bug in TravisCI script tha...	6 years ago
root_macros	added PYTHIA branches to ...	3 months ago
scripts	moved root macros back int...	3 months ago
src	updates in GEP electron ar...	last month

release for backwards c... on Mar 4

No packages published

- Realistic detector geometry built using GENAT4 for SBS spectrometers.

- ✓ Build box detectors in SIMC to mimic the acceptance of SBS spectrometers. (Mark Jones)
- ✓ Write an interface for G4SBS which enables is to interpret SIMC generated events. (Eric Fuchey)
- ✓ Upgrade SIMC to generate $D(ee'n)$ events. Generation of both $D(ee'p)$ and $D(ee'n)$ events are required for our analysis.
- ✓ Finally, upgrade and optimize the existing digitization and reconstruction machinery for realistic data/MC comparisons.

We now have realistic MC event generator available for $\mathrm{G_M^n}$/nTPE analysis!

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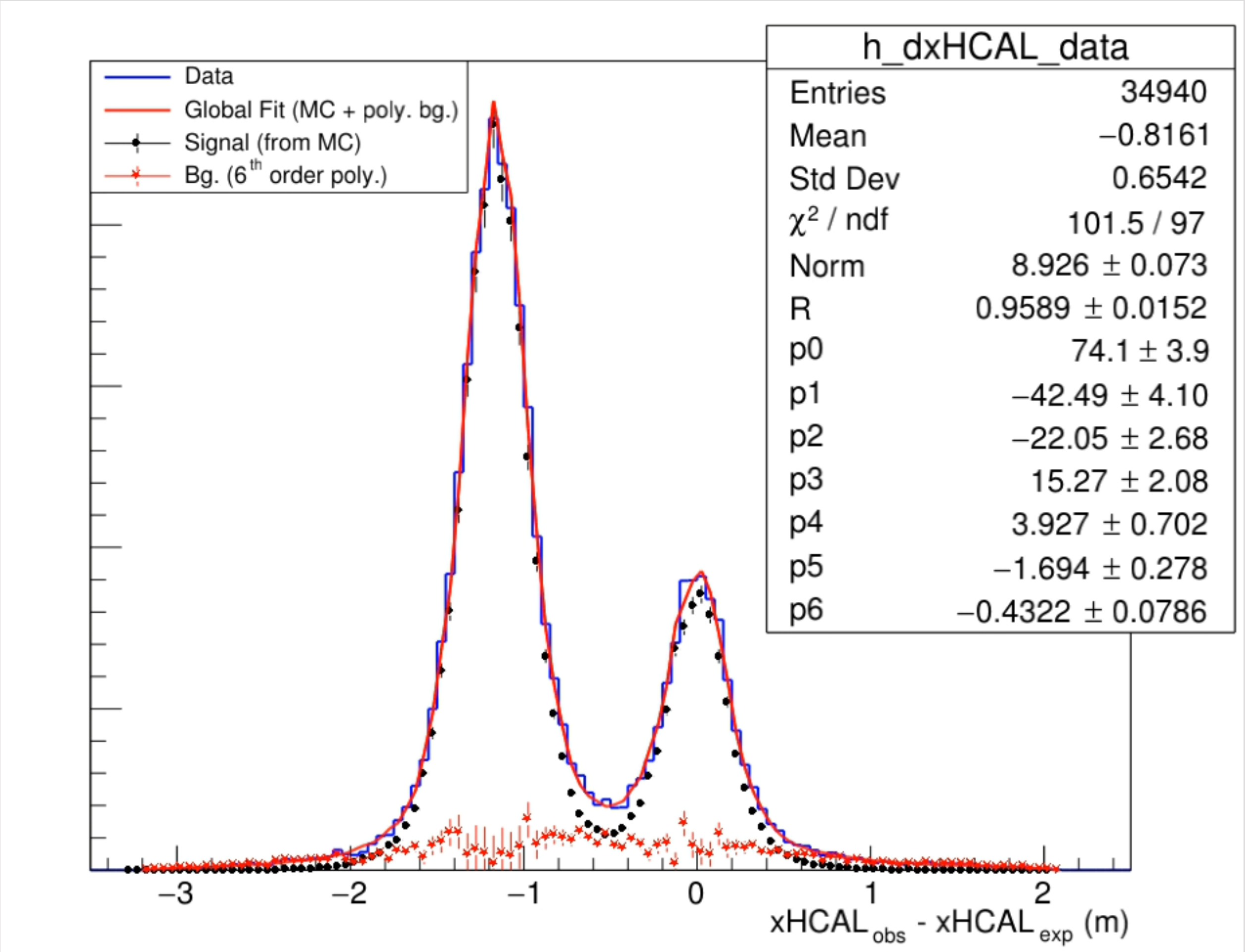
[2] R. Ent et al, Phys. Rev. C 64, 054610 (2001).

Preliminary Data vs MC for Δx Dist.: $Q^2 = 3\ (\mathrm{GeV}/c)^2$ [SBS-4]

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



- Steps to generate realistic MC events:

SIMC → G4SBS → LIBSBSDIG → SBS-offline + SBS-replay

SIMC	G4SBS	LIBSBSDIG	SBS-offline + SBS-replay
Generate QE events on LD2 with radiative correction and nuclear effects.	Propagate SIMC generated events through SBS spectrometers.	Digitize output simulation ROOT files from G4SBS to generate pseudo raw data.	Reconstruct the pseudo raw data using the same machinery used for real data.

- All the same cuts have been used for data and simulation analysis.

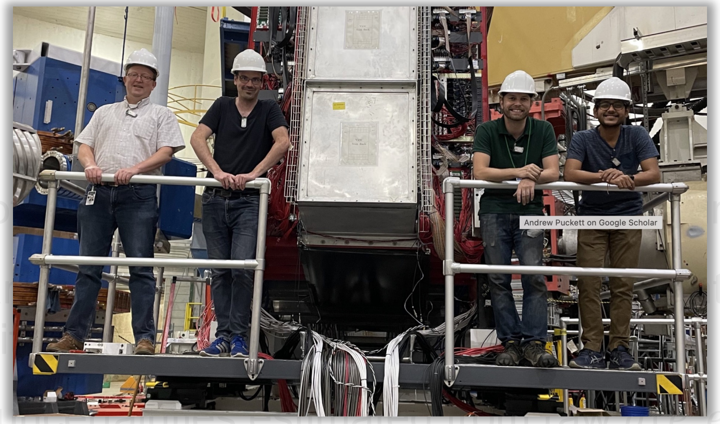
❖ Agreement of fit looks very promising with preliminary analysis. Further optimization and systematic studies are ongoing.

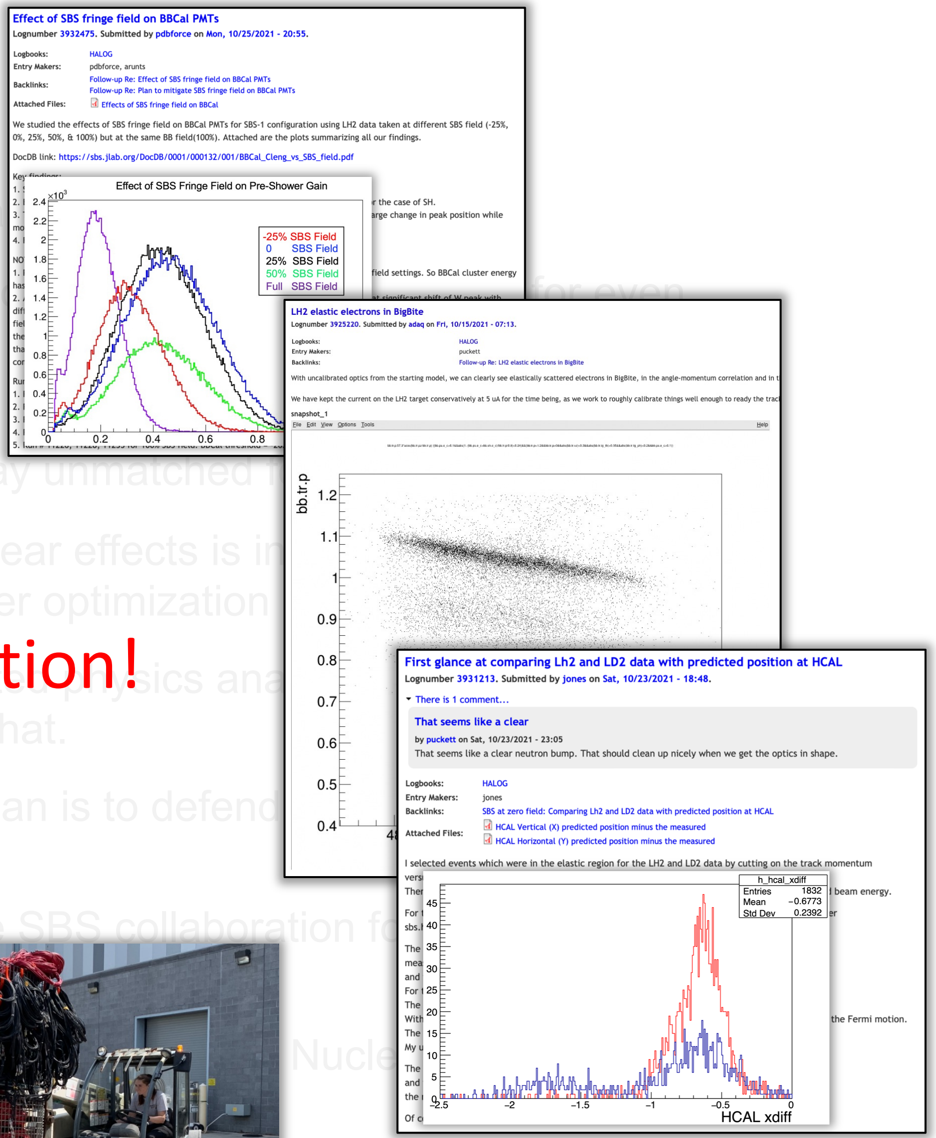
Summary and Acknowledgements

- The 1st pass cooking of entire $\mathrm{SBS\text{-}G_M^n}$ dataset was finished in January this year!
- 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.
- 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.
- Realistic MC event generator including radiative correction and nuclear effects is in place. Data/MC comparison looks very encouraging with preliminary analysis. Further optimization is ongoing.
- We are aiming to finish 2nd pass cooking within a month. Sophisticated physics analysis machinery is already in place, so will try to get preliminary results out soon after that.
- In parallel with analysis work, I have started writing my thesis. My plan is to defend by the end of this year.

❖ I would like to thank the entire Hall A collaboration and of course the SBS collaboration for letting me be a part of this program and write my thesis on the $\mathrm{SBS\text{-}G_M^n}$ experiment.

❖ I would also like to thank the US Department of Energy Office of Science, Office of Nuclear Physics, for supporting this work (Award ID DE-SC0021200).





Effect of SBS fringe field on BBCal PMTs

Lognumber 3932475. Submitted by pdbforce on Mon, 10/25/2021 - 20:55.

Logbooks: HALOG
Entry Makers: pdbforce, arunts
Backlinks: Follow-up Re: Effect of SBS fringe field on BBCal PMTs
Follow-up Re: Plan to mitigate SBS fringe field on BBCal PMTs
Attached Files: Effects of SBS fringe field on BBCal

We studied the effects of SBS fringe field on BBCal PMTs for SBS-1 configuration using LH2 data taken at different SBS field (-25%, 0%, 25%, 50%, & 100%) but at the same BB field(100%). Attached are the plots summarizing all our findings.

DocDB link: https://sbs.jlab.org/DocDB/0001/000132/001/BBCal_Cleng_vs_SBS_field.pdf

LH2 elastic electrons in BigBite

Lognumber 3925220. Submitted by adaq on Fri, 10/15/2021 - 07:13.

Logbooks: HALOG
Entry Makers: puckett
Backlinks: Follow-up Re: LH2 elastic electrons in BigBite

With uncalibrated optics from the starting model, we can clearly see elastically scattered electrons in BigBite, in the angle-momentum correlation and in t

We have kept the current on the LH2 target conservatively at 5 uA for the time being, as we work to roughly calibrate things well enough to ready the trac

snapshot_1

First glance at comparing Lh2 and LD2 data with predicted position at HCAL

Lognumber 3931213. Submitted by jones on Sat, 10/23/2021 - 18:48.

There is 1 comment...

That seems like a clear

by puckett on Sat, 10/23/2021 - 23:05
That seems like a clear neutron bump. That should clean up nicely when we get the optics in shape.

Logbooks: HALOG
Entry Makers: jones
Backlinks: SBS at zero field: Comparing Lh2 and LD2 data with predicted position at HCAL
Attached Files: HCAL Vertical (X) predicted position minus the measured
HCAL Horizontal (Y) predicted position minus the measured

I selected events which were in the elastic region for the LH2 and LD2 data by cutting on the track momentum

Thank You for Your Attention!

Questions? Comments?

The 1st pass cooking o
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for even the highest Q2 point wi
Preliminary projected uncertainties estimated from raw $d(e,e'(p,n))$
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I would like to thank the entire Hall A collaboration and of course the SBS collaboration fo
part of this program
BS-G
I would also like to th
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supporting this work

Backup Slides

Kinematic of SBS-G_M^n

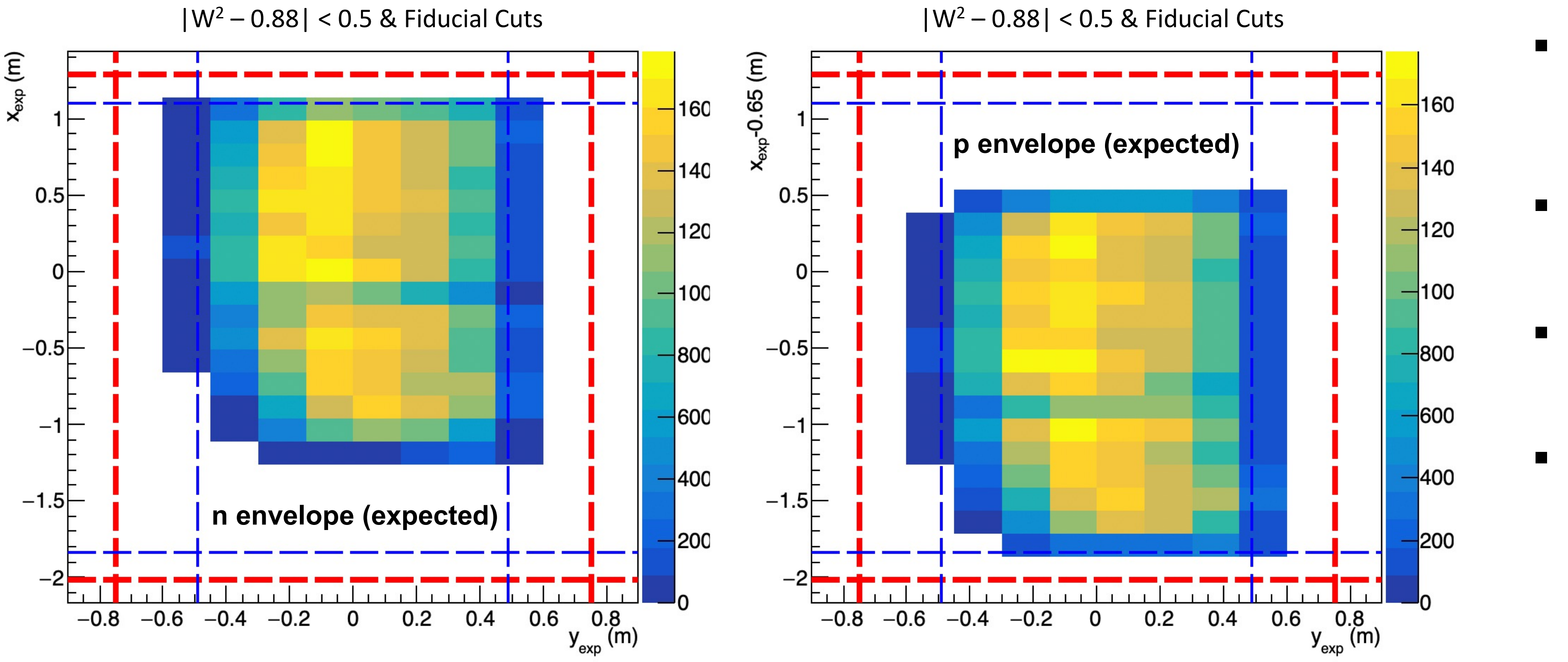
Table I: Kinematics of SBS-G_M^n

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.

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

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



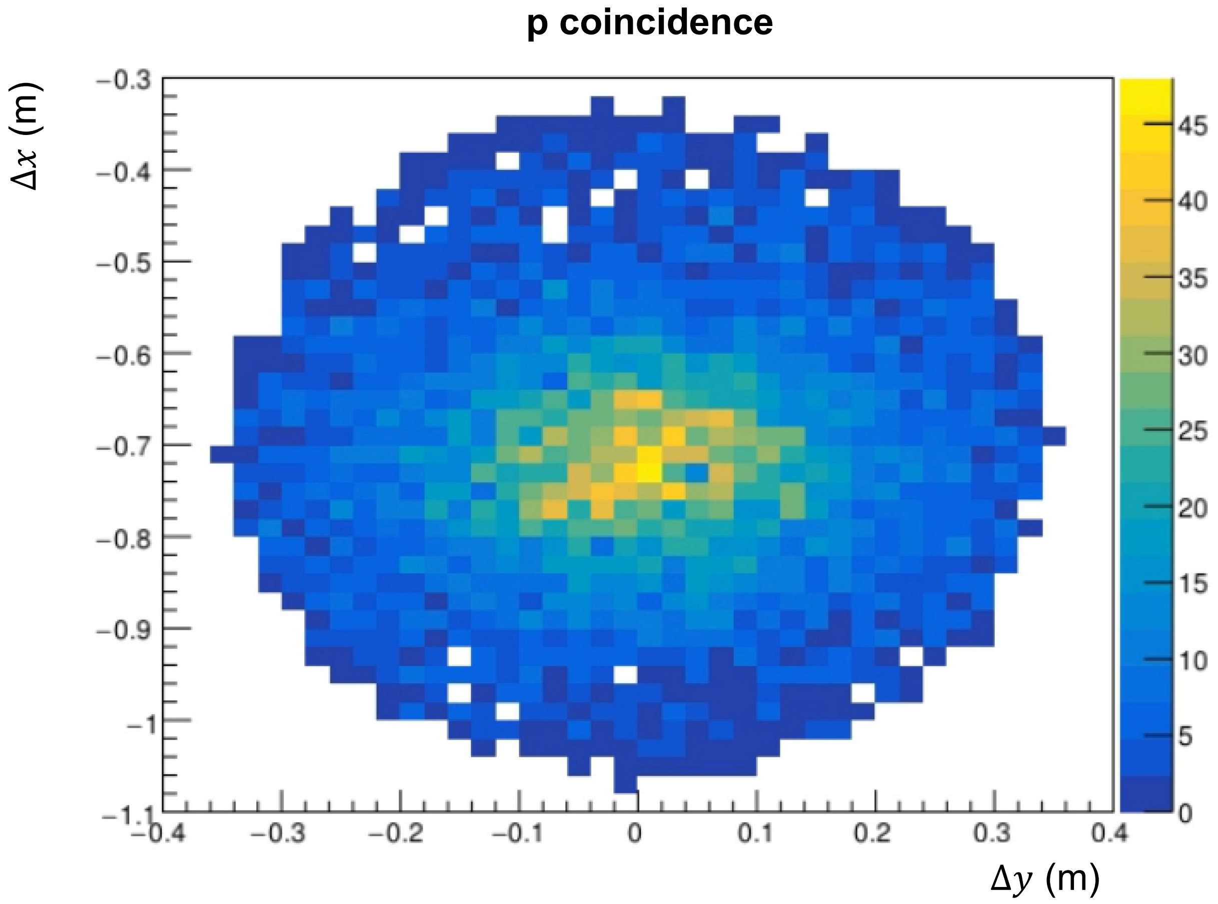
$|W^2 - 0.88| < 0.5$ & Fiducial Cuts

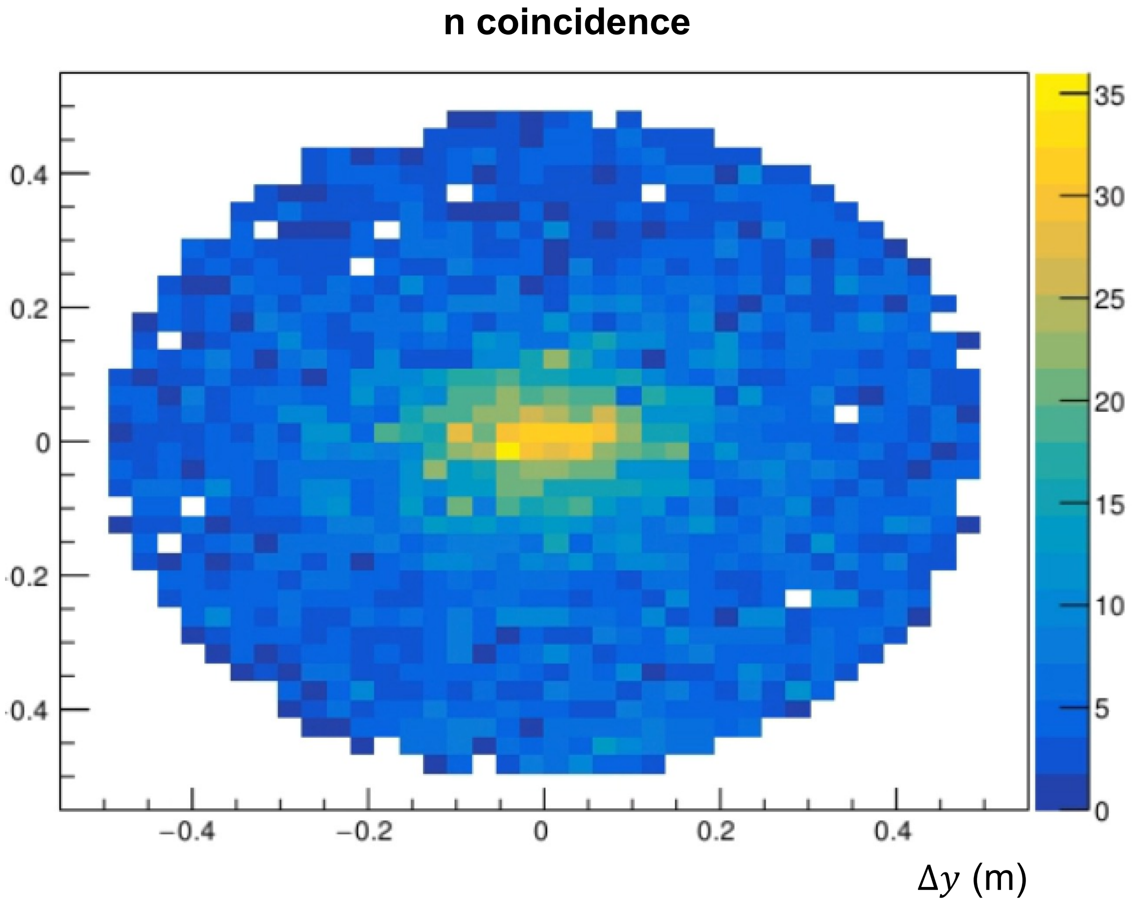
$|W^2 - 0.88| < 0.5$ & Fiducial Cuts

--- 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.

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


p coincidence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