Probing the Neutron's Current Distribution with Unprecedented Q^2 reach

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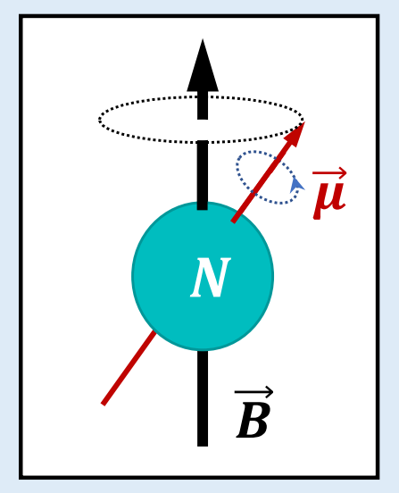
That's How It All Started!



In 1933, **Otto Stern** discovered, $\mu_p = 2.79\ \mu_N$

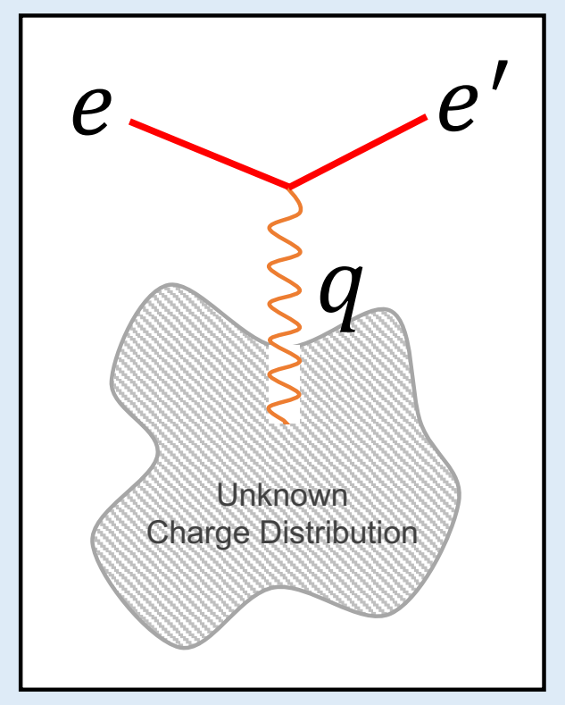
In 1940, **Alvarez et al** measured, $\mu_n = -1.93\ \mu_N$

❖ Nucleons are not point-like particles!!

Awesome! Let's look inside them!

In 1950's, **Robert Hofstadter** started unveiling nucleon's internal structure via his pioneering studies of e^- scattering in atomic nuclei.

Basic Idea:



○ Scatter an e^- off an unknown charge distribution.
○ Measure the angular distribution of scattered e^-.
○ Compare with known e^- scattering cross section from a point charge, in the form

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{point} |F(q)|^2$$

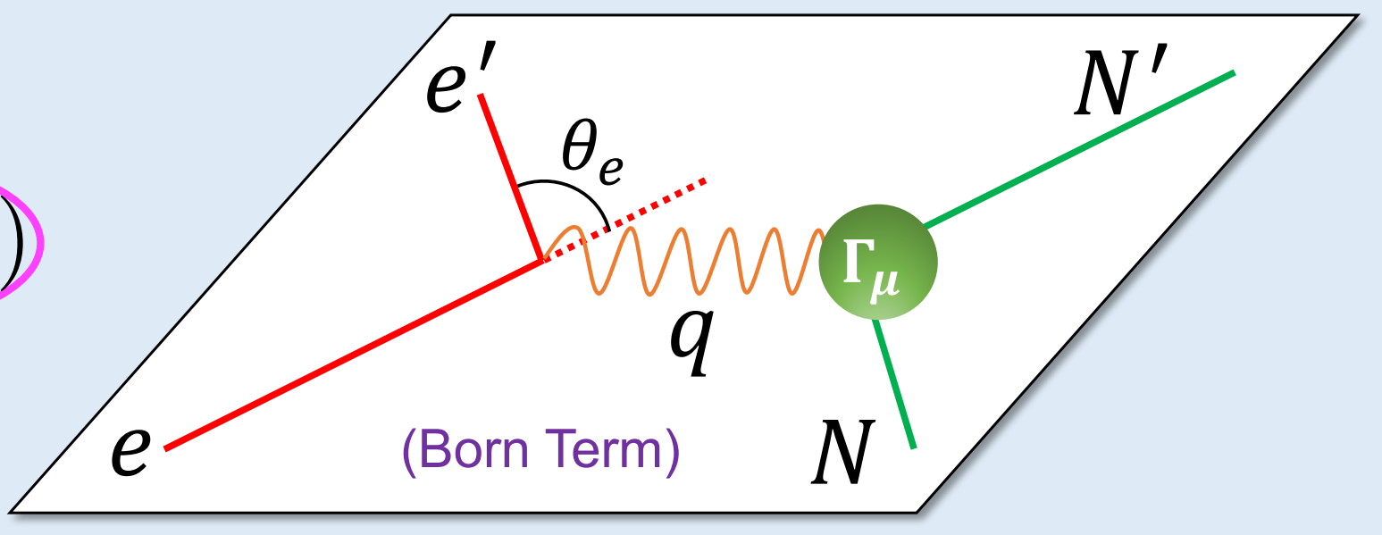
Form Factor (Carries the structure of unknown charge distribution.)

Elastic e-N Scattering & Sachs FFs

Nucleon Vertex:

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

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 Form Factors, respectively.

Differential Cross Section:

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

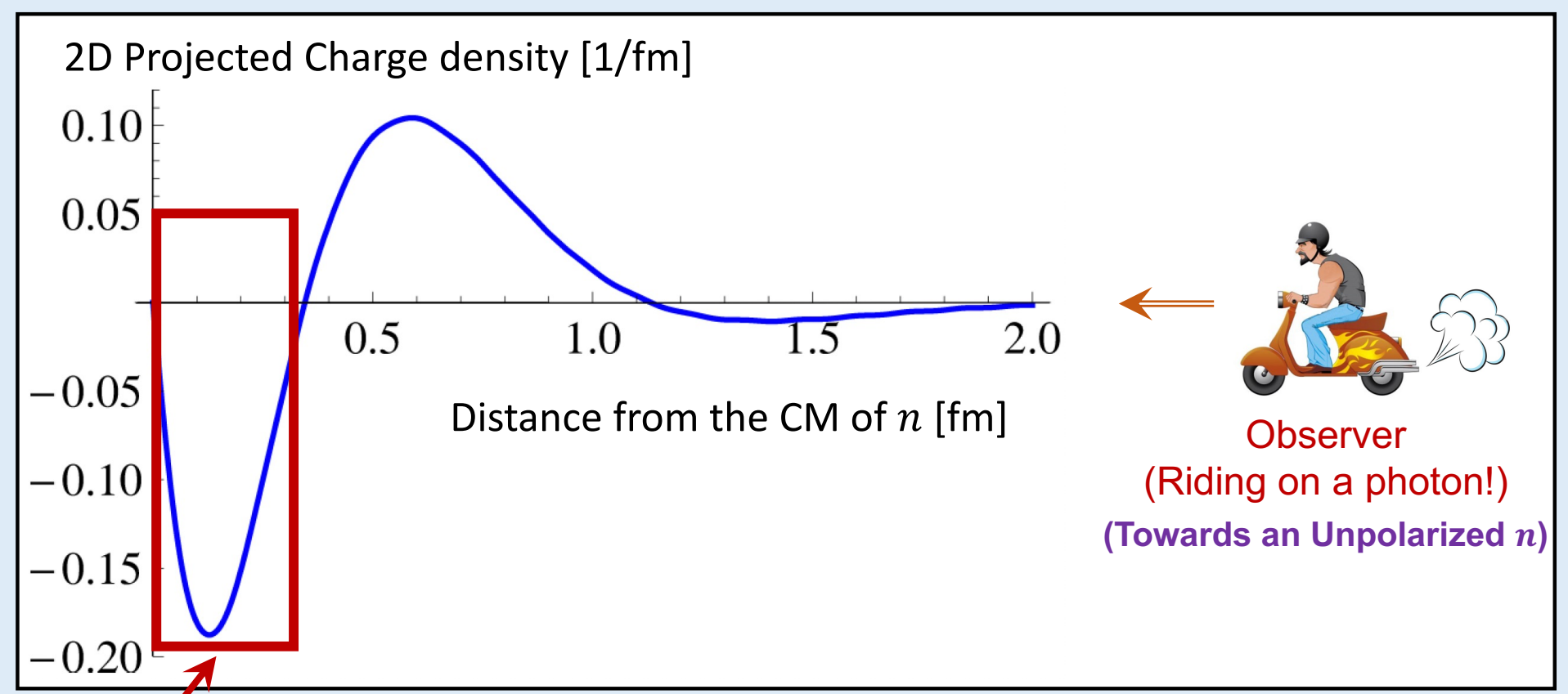
- $Q^2 = -q^2$
- $\tau = Q^2/4M_N^2$
- $\epsilon = (1 + 2(1+\tau)tan^2(\theta_e/2))^{-1}$

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

Visualizing n Charge Distribution

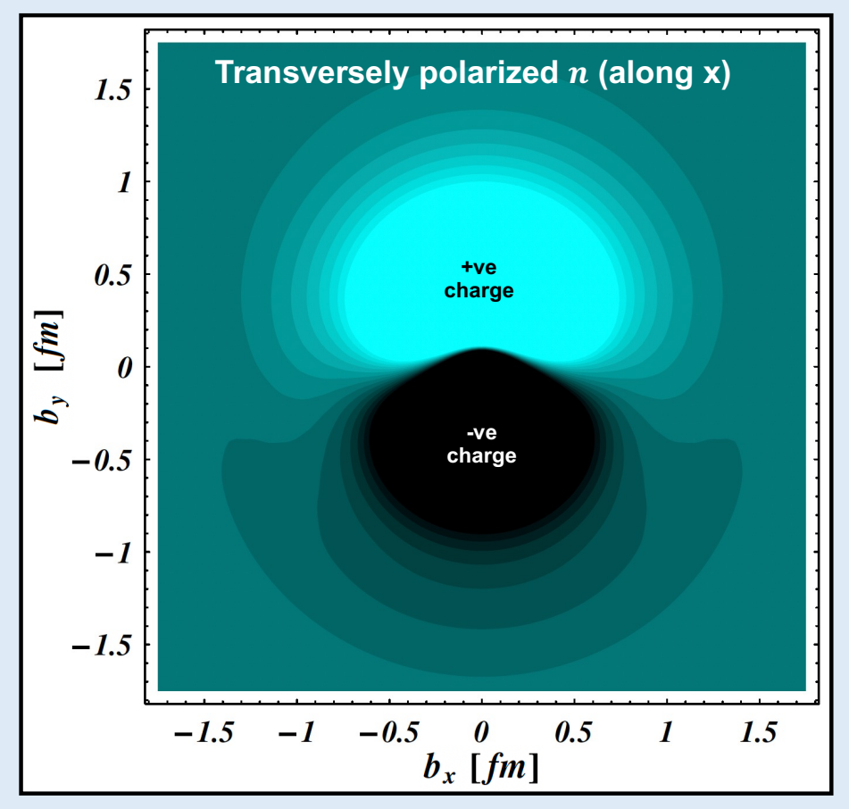
In 2007, **G. A. Miller:**

○ Studied Breit frame charge density, ρ_0^N, of partons in the transverse plane using existing nucleon FF data.



Observer
(Riding on a photon!)
(Towards an Unpolarized n)

$$\rho_0^N(b) = \int_0^\infty \frac{dQ}{2\pi} Q J_0(bQ) \frac{G_E^n(Q^2) + \tau G_M^n(Q^2)}{1+\tau}$$



○ Concluded, ***n* has a negative core!** Contradicted both meson-cloud & gluon-exchange models.

○ Such contradiction makes it of great interest to probe deeper inside n i.e., to measure G_E^n & G_M^n at very high Q^2 values.

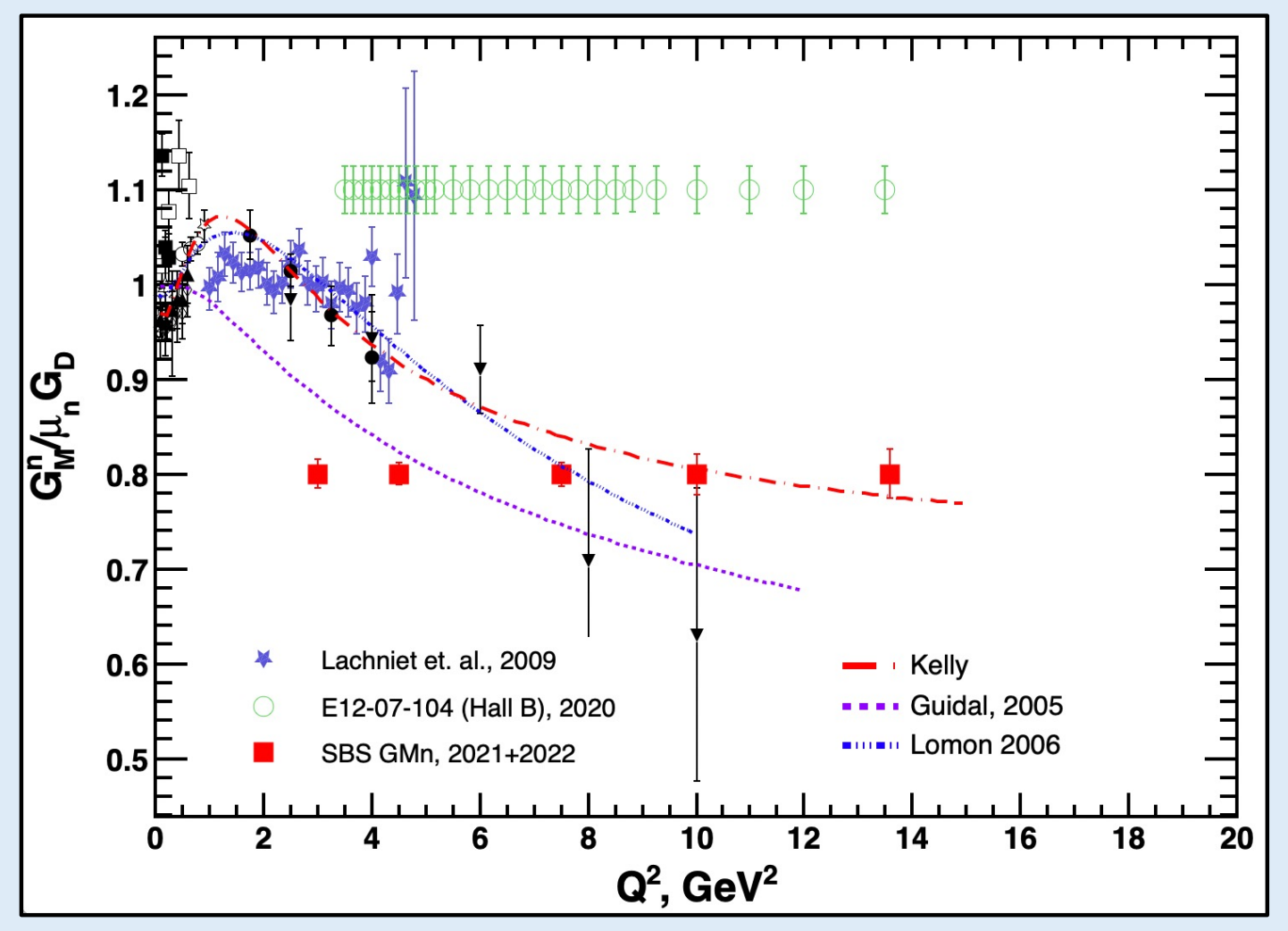
❖ G_E^n & G_M^n experimental data exist only up to $Q^2 = 4(GeV/c)^2$!

SBS-G_M^n Experiment (E1209019)

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

Goal:

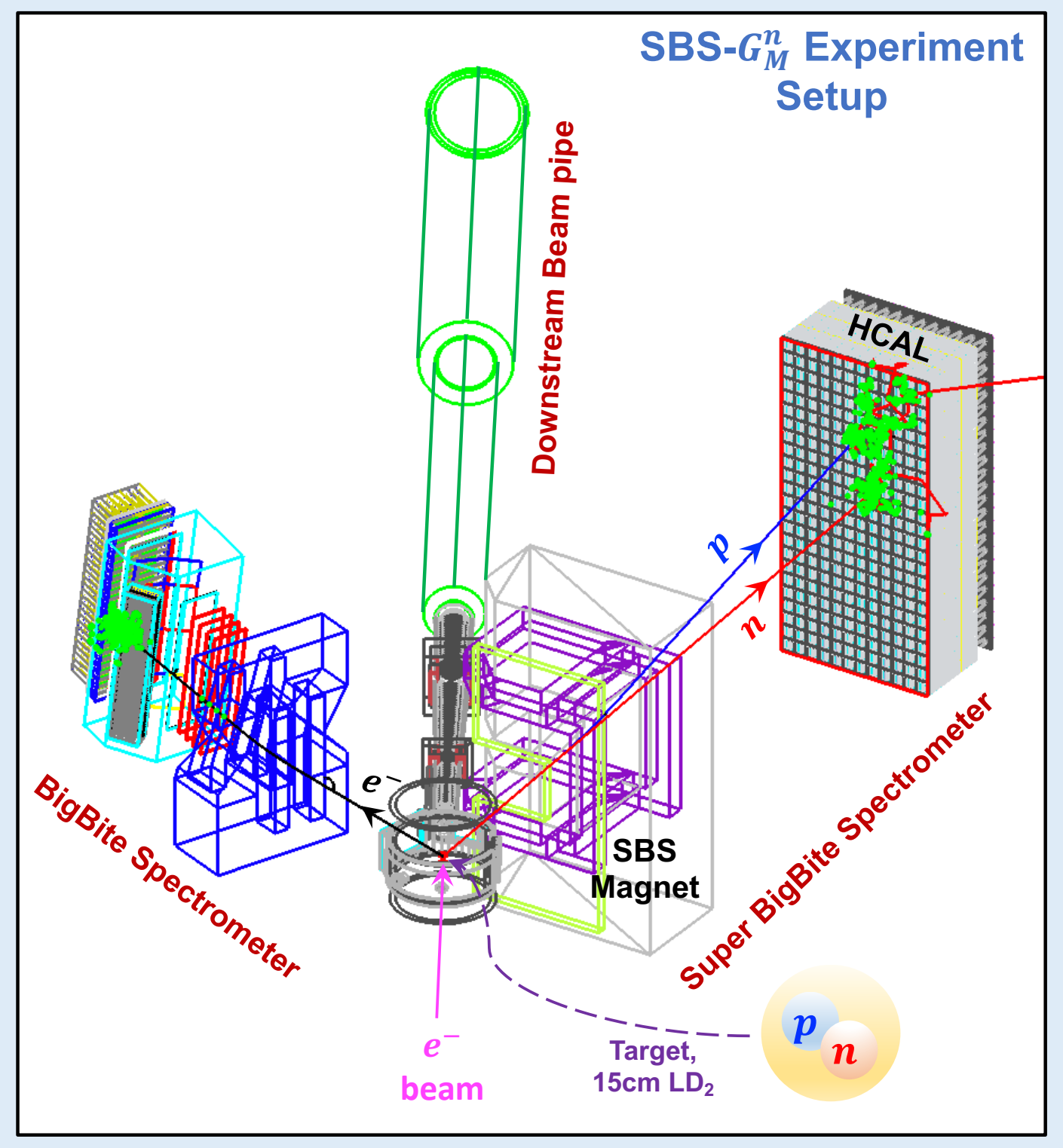
○ High precision measurement of G_M^n at Q^2 = **3, 4.5, 7.5, 10 & 13.6** $(GeV/c)^2$.



Technique:

○ Simultaneous detection of elastically scattered e^-s and nucleons.

○ 3 major steps to get G_M^n:



① Forming QE cross section ratio:

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

② With nuclear correction extract,

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

③ Finally, we obtain:

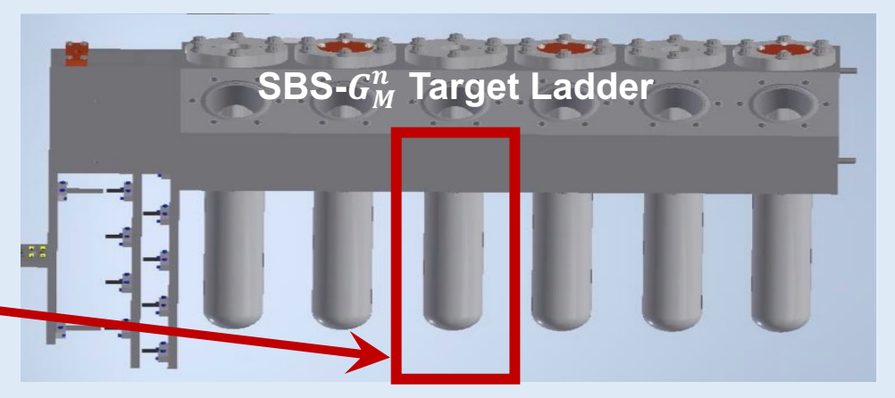
$$G_M^n = -\left[\frac{1}{\tau}\frac{d\sigma}{d\Omega}\bigg|_{p(e,e')} R' - \frac{\epsilon}{\tau}{G_E^n}^2\right]^{\frac{1}{2}}$$

❖ Use of "Ratio Method" greatly reduces systematics.

Apparatus

Target:

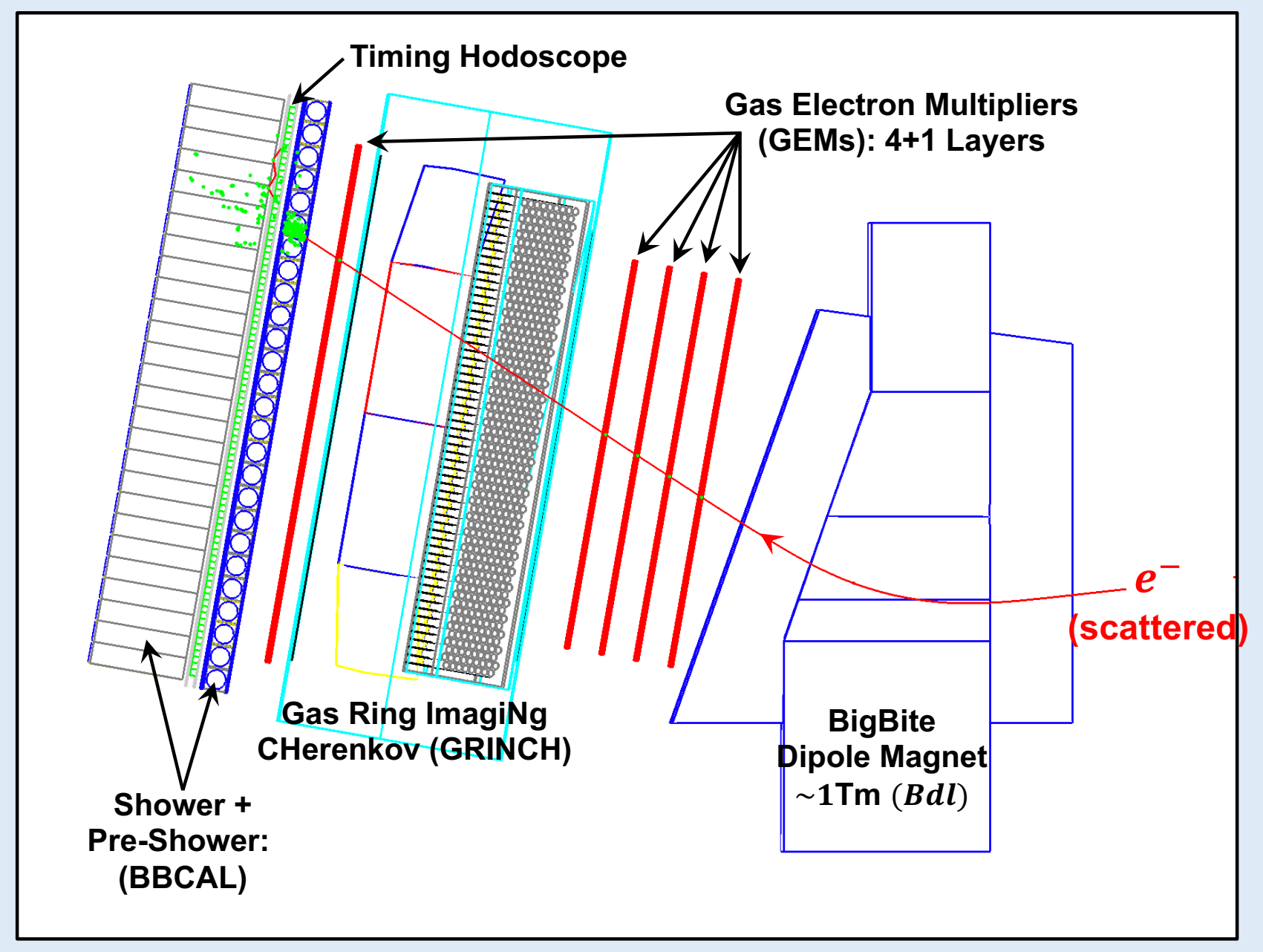
○ Production: **15 *cm* LD$_2$**

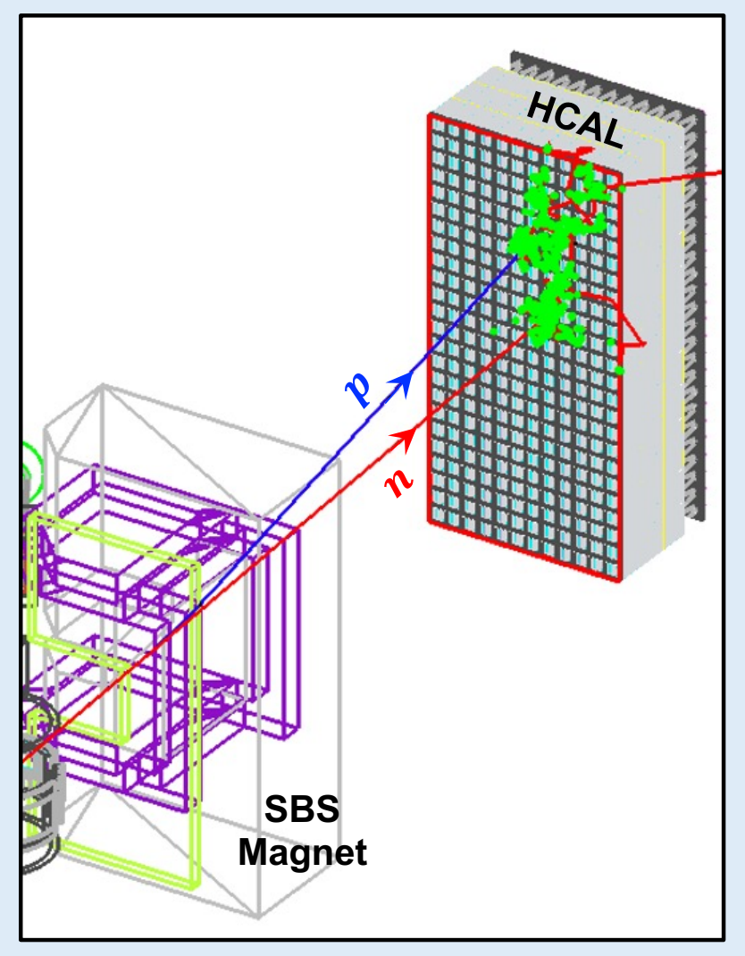


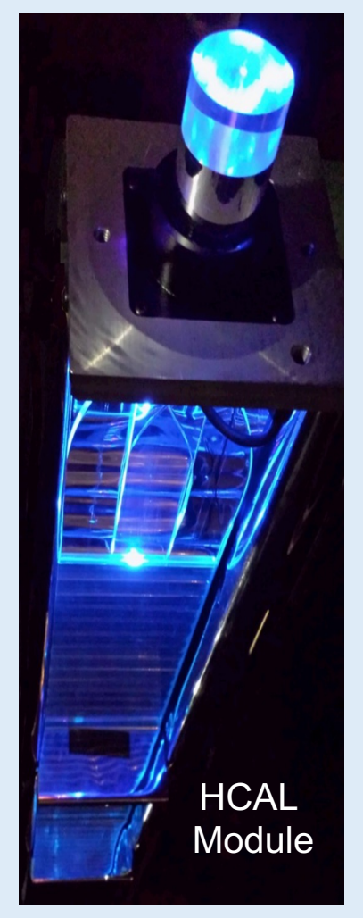
BigBite Spectrometer:

○ Detects scattered e^-s and fully characterizes their kinematics.

- BigBite dipole bends HE e^- tracks.
- 5 GEM layers measure:
  - track position with μm precision &
  - track angle with **1-2 *mrad*** res.
- BBCAL:
  - measures e^- energy &
  - triggers DAQ.







Super BigBite Spectrometer:

○ Detects scattered nucleons.

- SBS dipole separates scattered hadrons by charge.
- HCAL, a sampling calorimeter:
  - spatial resolution: **3-4 *cm*** at 8 GeV
  - temporal resolution: **0.5-1 *ns***

❖ BigBite TH (**0.1 *ns*** res.) and HCAL time can be combined to get ToF.

Preliminary Analysis

Raw Data Volume:

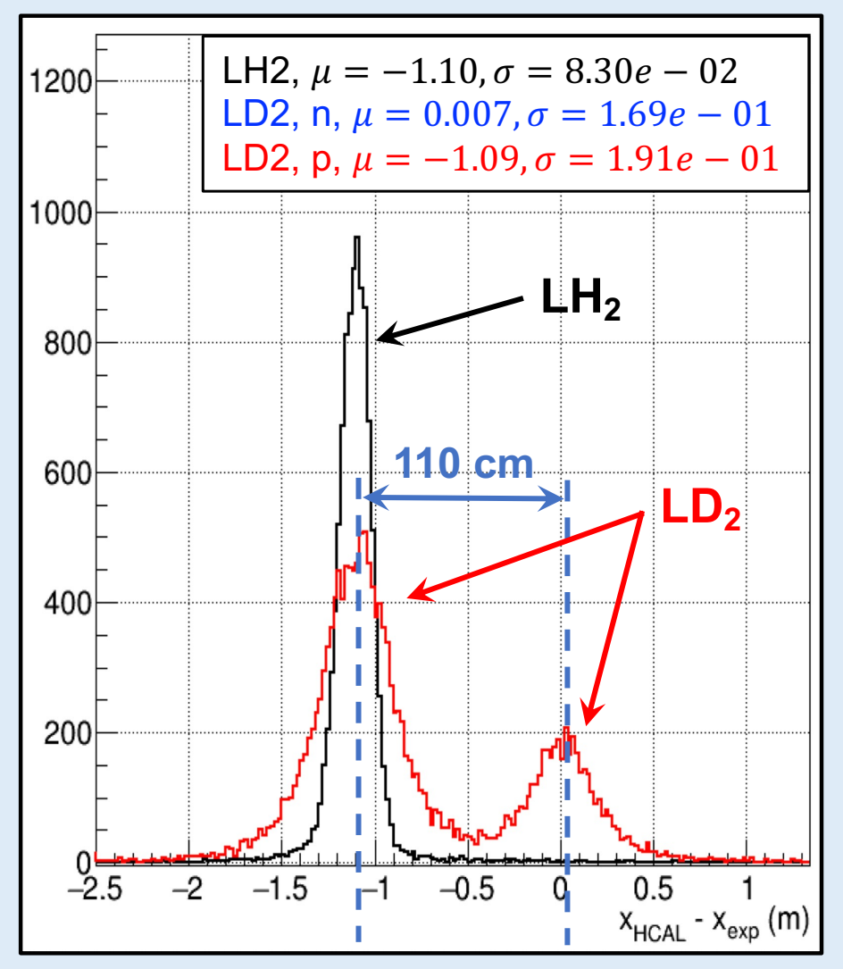
○ **43,000+** detector channels & very high luminosity led to **2 *PB*** raw data.

❖ This is **5 times** more data than all prior Hall A experiments combined!!

Data Analysis Status:

✓ Preliminary calibration and quality assurance checks complete.
✓ Started the cooking of entire 2 PB data set for the first time!

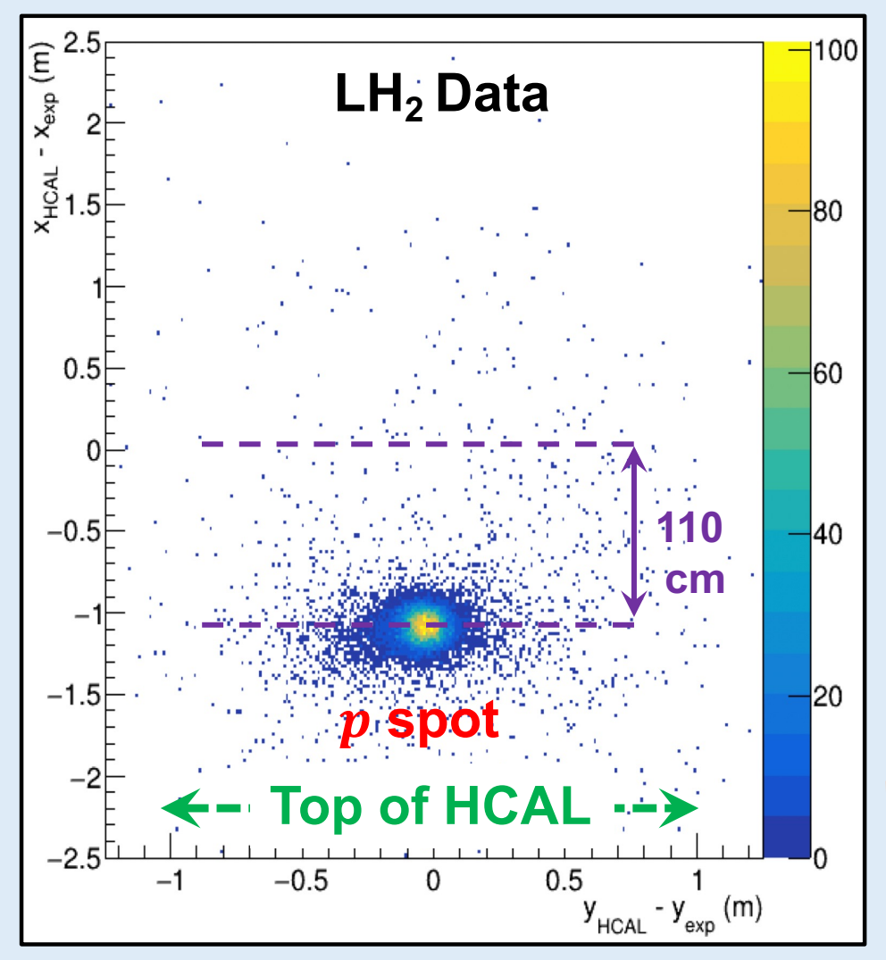
First Look at Production Data [Q^2 = 3 $(GeV/c)^2$]:



① For both LH$_2$ & LD$_2$ runs we project a "straight-line" hadron track from interaction vertex to the face of HCAL using elastically scattered e^- kinematics measured by BigBite.

② Then plot the difference between observed (x_{HCAL}) & calculated (x_{exp}) hadron positions on HCAL.

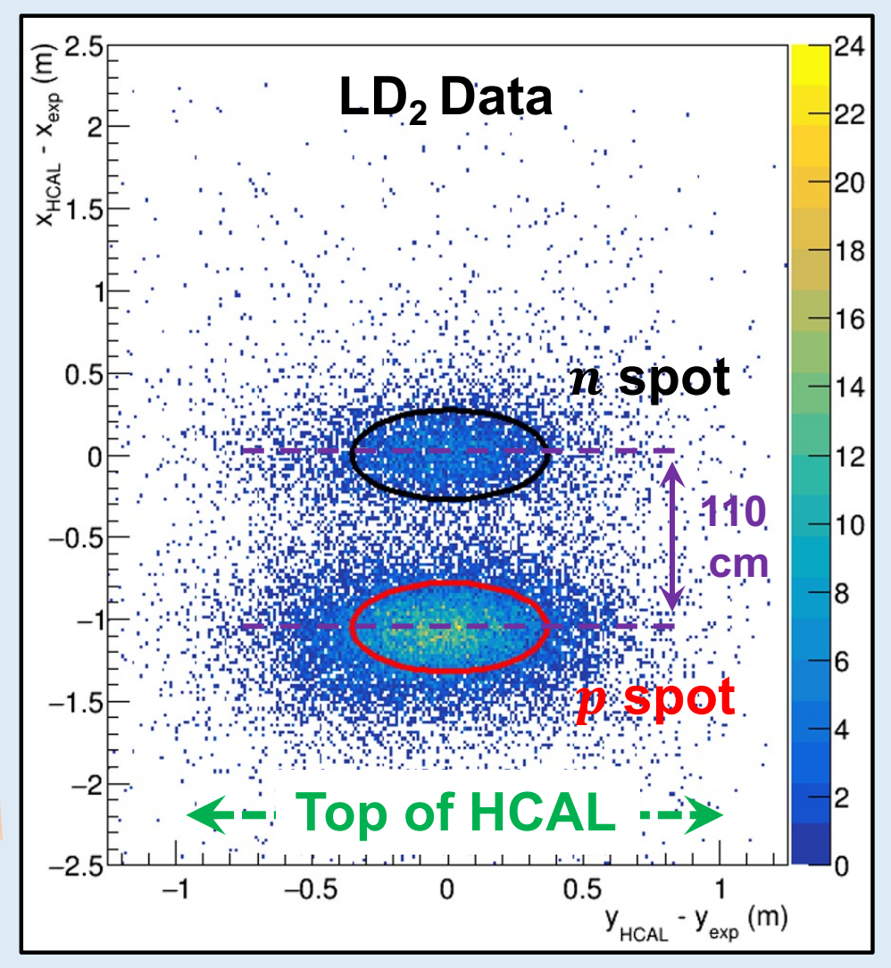
- LH$_2$ data shows one sharp peak away from origin towards the top of HCAL. The shift depends on SBS field strength.
- For LD$_2$ data with same SBS field, we see two broader peaks – one at the origin & the other coincides with the LH$_2$ one.



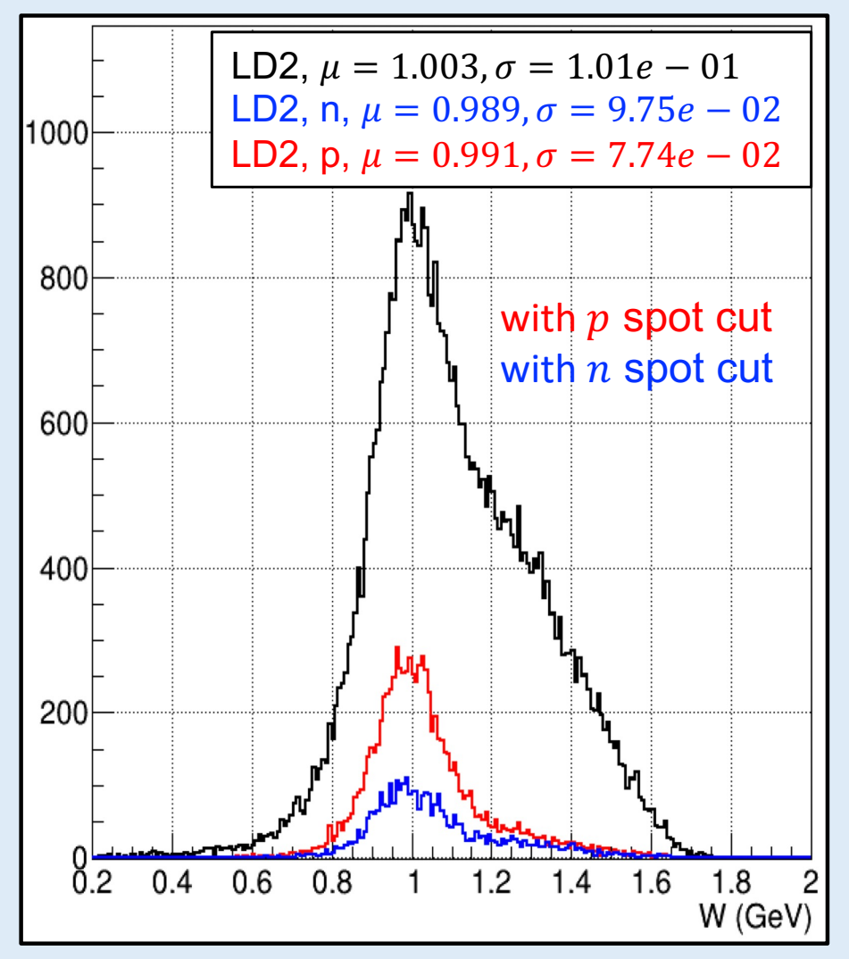
These all makes sense since SBS dipole up-bends p tracks leaving neutrons untouched.

❖ So, the peak at origin for LD2 run is due to neutrons and the shifted one is due to protons.

❖ Ensures the detections of both $d(e,e'n)$ & $d(e,e'p)$ events.



Vertical vs. horizontal HCAL position difference plots show clear n & p spots.



○ Proton and neutron spot cuts on HCAL cleans up the invariant mass (W) distribution significantly.

❖ This is encouraging to see at such an early stage of analysis.

Next Steps of Analysis:

○ Fine tune and finalize calibrations once the mass replay is finished.
○ Extract raw yields for $d(e,e'n)$ and $d(e,e'p)$.
○ Model background and perform nuclear corrections using MC.
○ Estimate systematics and finally extract G_M^n.

Conclusion

○ SBS-G_M^n experiment **was completed successfully** in February 2022.
○ Initial calibrations **complete.** Preliminary results **look promising**.
○ High precision measurement of G_M^n at unexplored Q^2 regime will **guide GPD formalism**, **benchmark LQCD**, and provide **more insight into neutron quark flavor decomposition**.

Acknowledgement

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