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Measurement of the Neutron Elastic Electric Form Factor, G_E^n, up to Q^2 = 9.7 GeV^2 at Jefferson Lab

Todd Averett, William & Mary
Williamsburg, VA USA

on behalf of the Jefferson Lab SBS Collaboration
with special thanks to the graduate students and postdocs

Jefferson Lab

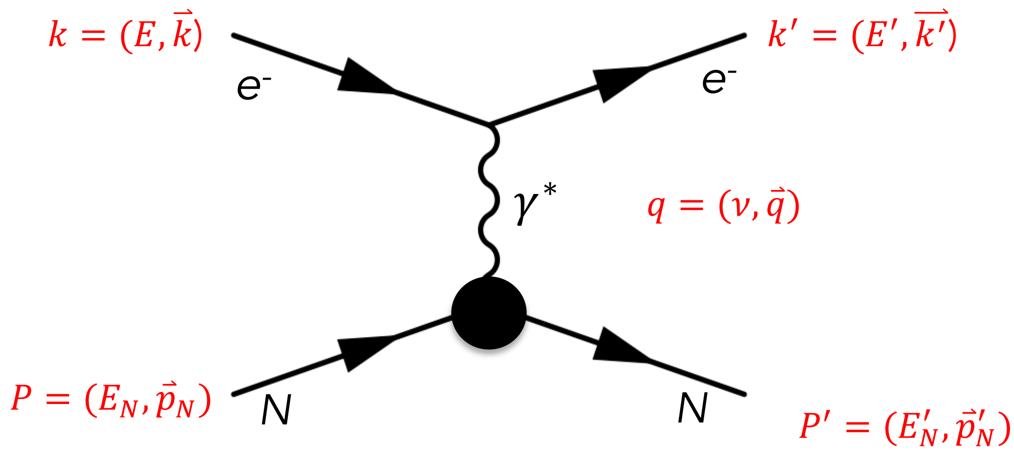
- e-N scattering is a clean scalpel to study basic properties of the nucleon such as charge, magnetization, spin and flavor distributions/dynamics.

- Super BigBite Spectrometer (SBS) program in Hall A at Jefferson Lab
  - Large acceptance spectrometer + high luminosity + high target polarization

- <u>Present SBS focus</u>: Measurement of nucleon elastic form factors at large Q^2

Research Supported by DOE Grant DE-FG02-96ER41003

Kinematics and Elastic Cross Section



Fixed target N(e,e')

Measure $E, E', \theta \rightarrow Q^2, W$

Unpolarized elastic scattering

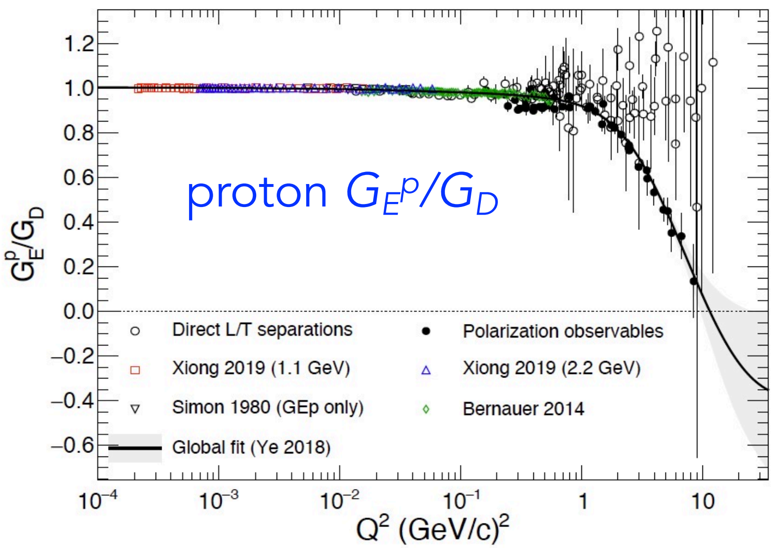
$$\left(\frac{d\sigma}{d\Omega}\right)_{eN} = \frac{\sigma_M}{\epsilon(1+\tau)}\left(\frac{E'}{E}\right)\left[\epsilon G_E^2(Q^2) + \tau G_M^2(Q^2)\right]$$

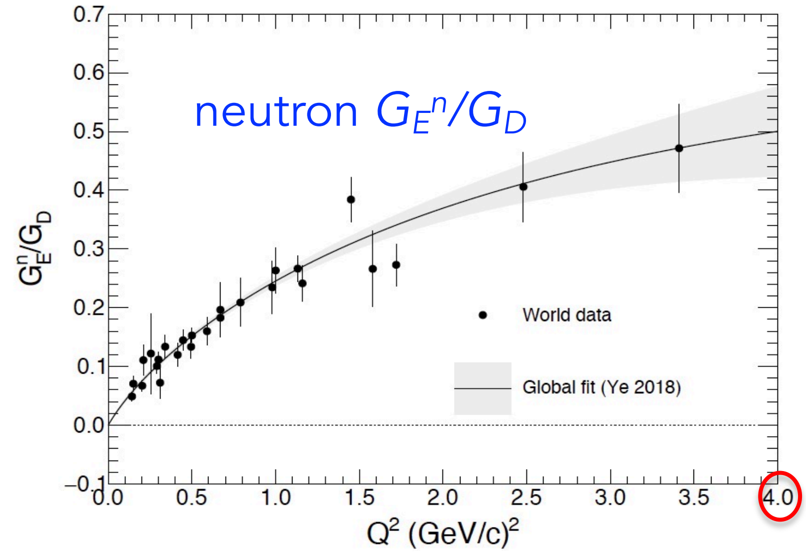
$$\epsilon = \left(1 + 2(1+\tau)\tan^2\left(\frac{\theta}{2}\right)\right)^{-1}, \quad \tau = \frac{Q^2}{4M^2}$$

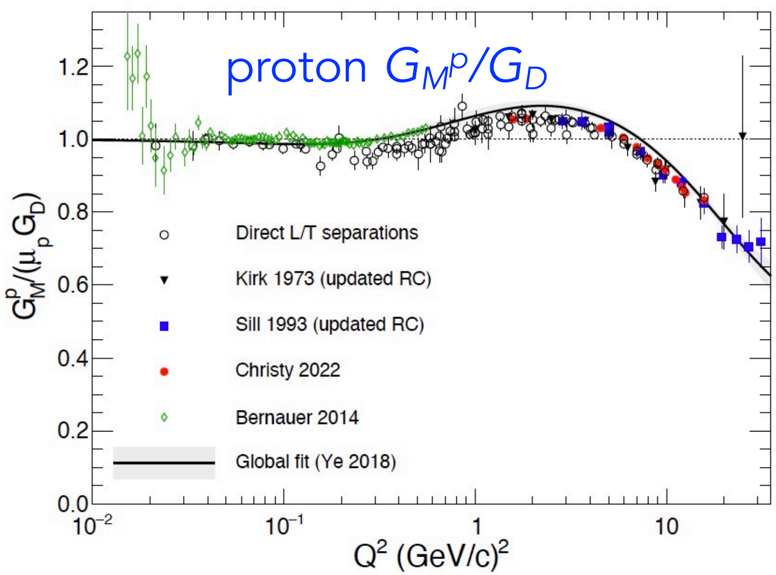
$$G_E(Q^2) = F_1(Q^2) - \tau F_2(Q^2)$$
$$G_M(Q^2) = F_1(Q^2) + F_2(Q^2)$$

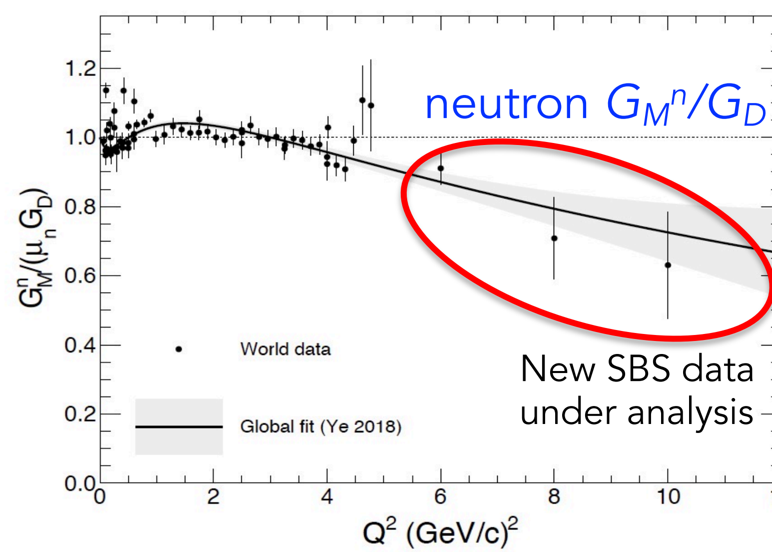
World Form Factor Data versus Dipole FF

- Sachs form factors ~ not too different from dipole FF at lower Q^2 (ex. G_E^n)
- Lots of nucleon dynamics entering at large Q^2









Plots from "50 years of QCD", hep-ph>arXiv:2212.11107

Neutron G_E^n/G_M^n versus Q^2

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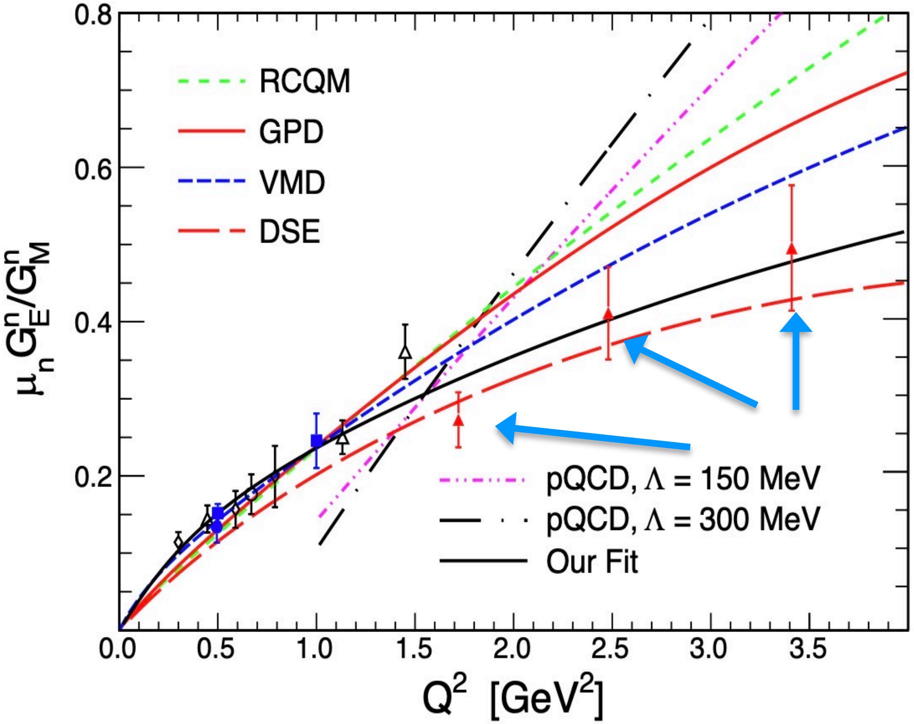
World data



S. Riordan, et al., PRL 105 (2010) 262302

- G_E^n measured to Q^2 ~ 3.5 GeV^2
- All other FFs measured to Q^2 ~ 10 GeV^2
- Large Q^2 → theory not constrained
- Highest Q^2 data was measured by this collaboration in ~2009 using 6 GeV beam on polarized ^{3}He

- Goal of this experiment: Measure $\frac{G_E^n}{G_M^n}$ to Q^2 ~10 GeV^2 using the quasi-elastic reaction $^3\overrightarrow{\mathrm{He}}(\vec{e}, e'\mathrm{n})\mathrm{pp}$ to further our understanding of nucleon structure.

Form Factors and GPDs

- With sufficient precision, proton and neutron FF measurements can be used for flavor decomposition

$$F_i^p = e_u F_i^u + e_d F_i^d$$
$$F_i^n = e_u F_i^d + e_d F_i^u$$

- Notice no s-quarks
→ see K. Paschke's talk

- These can be used to further constrain moments of GPDs

$$\int_{-1}^{1} dx\, H^q(x,\xi,t) = F_1^q(t), \qquad \int_{-1}^{1} dx\, E^q(x,\xi,t) = F_2^q(t)$$

- Related to PDFs

$$\begin{aligned} H^q(x,0,0) &= q(x), & \tilde{H}^q(x,0,0) &= \Delta q(x) & \text{for } x > 0, \\ H^q(x,0,0) &= -\bar{q}(-x), & \tilde{H}^q(x,0,0) &= \Delta \bar{q}(-x) & \text{for } x < 0 \end{aligned}$$

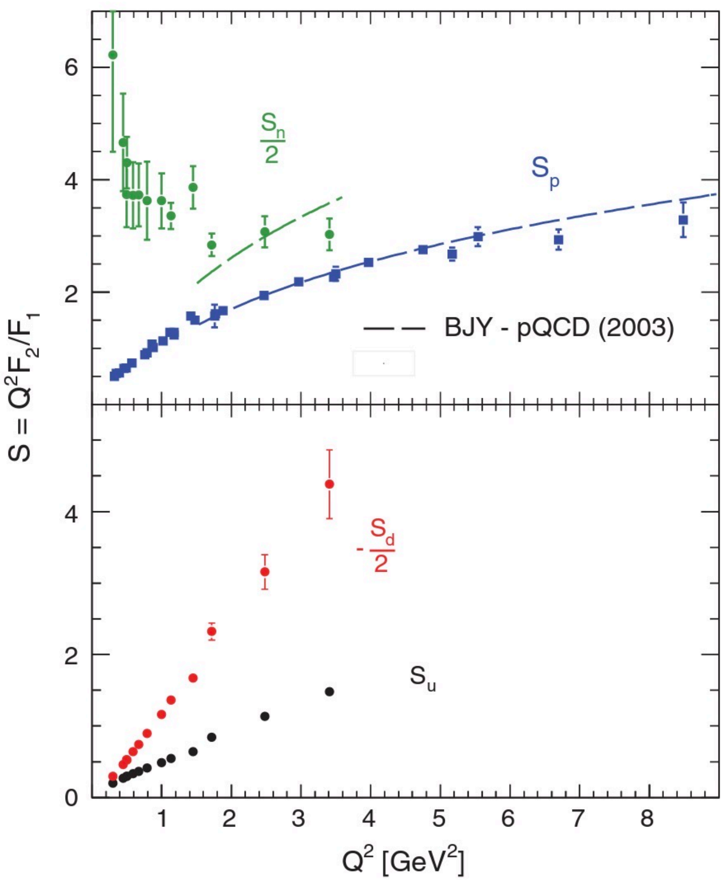
M. Diehl, arXiv:hep-ph/0307382v2

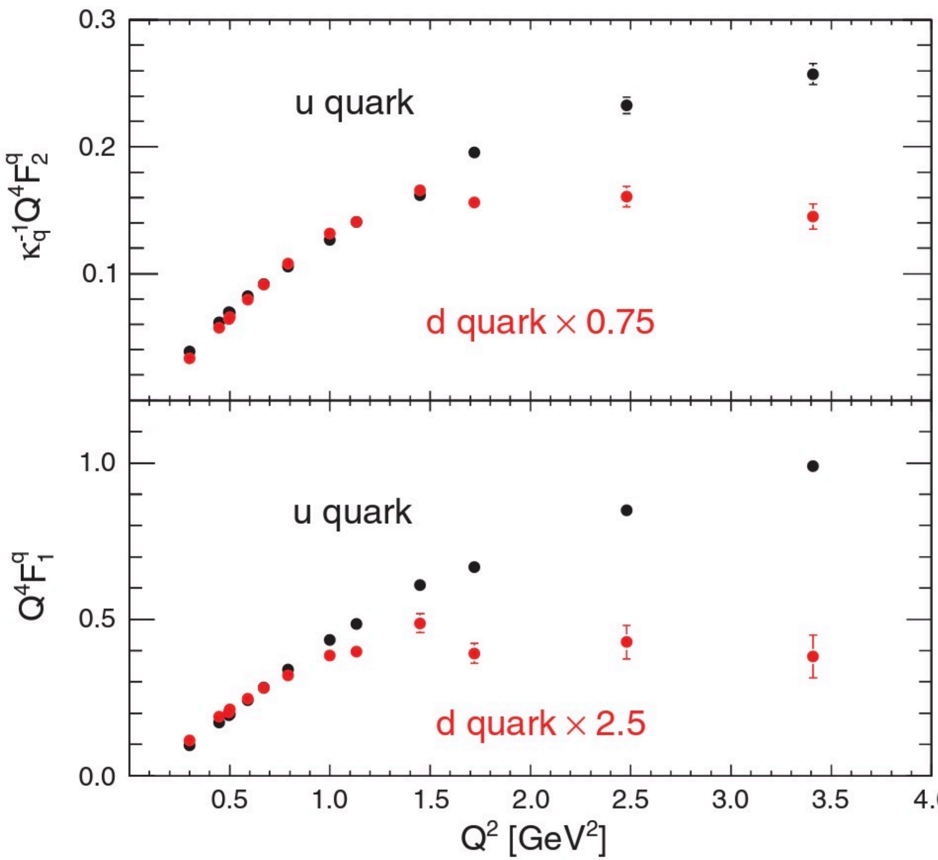
Interesting Behavior from Flavor Decomposition

Decomposition above Q^2 =1 GeV^2 possible with arrival of G_E^n results to Q^2 = 3.4 GeV^2

$$F_1^p = \frac{2}{3}F_1^u - \frac{1}{3}F_1^d \quad , \quad F_1^n = -\frac{1}{3}F_1^u + \frac{2}{3}F_1^d \quad \leftarrow \rightarrow \quad F_1^u = 2F_1^p + F_1^n \quad , \quad F_1^d = 2F_1^n + F_1^p$$

also for F_2





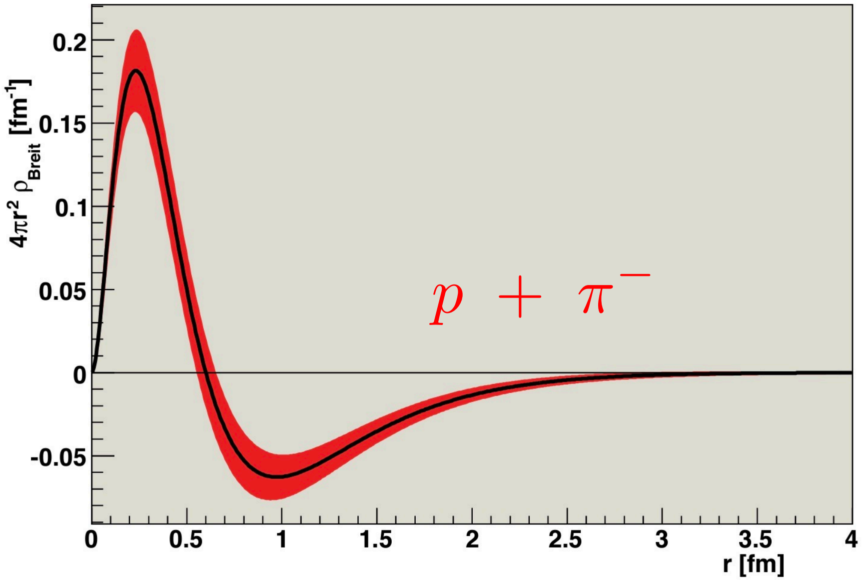
G. D. Cates, C.W. de Jager, S. Riordan, B. Wojtsekhowski, PRL 106, 252003 (2011)

Neutron Charge Distribution

<u>What is the charge distribution within the nucleon? → Frame dependent</u> 😈

- Non-relativistic: Fourier transform of lab frame spatial distributions
- With relativistic corrections: No probabilistic interpretation, $|p_f| \neq |p_i|$
- Breit Frame: $\vec{p_i} = -\vec{p_f}$ → probabilistic interpretation but…model-dependent boost corrections

$4\pi r^2 \rho(r)$ Breit Frame neutron



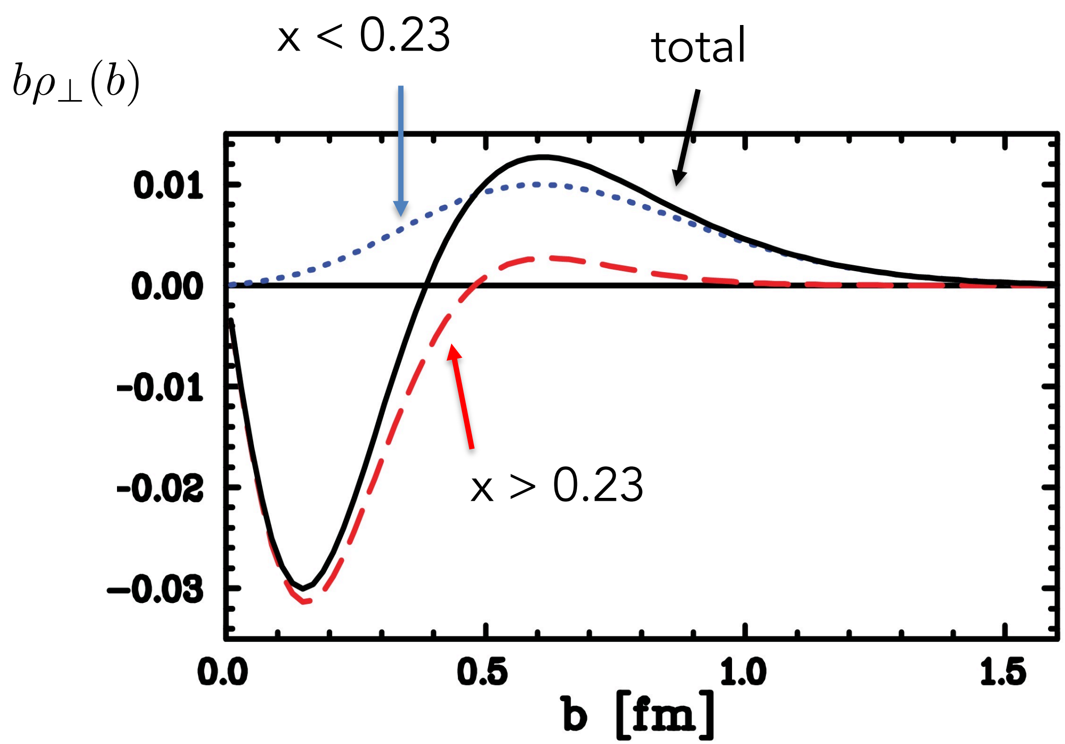
<u>NSAC 2007 Report, "recent achievement"</u>

→ *The charge distribution of the neutron was mapped precisely and with high resolution. The measurements confirmed that the neutron has a positively charged core and a negatively charged pion cloud.*

Neutron Charge Distribution in IMF (2008)

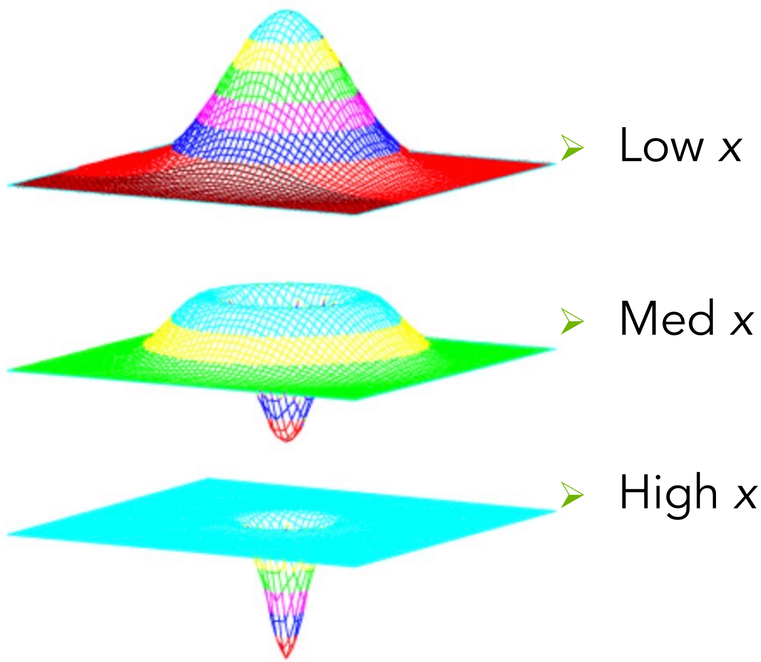
- IMF: Model-independent interpretation
- No recoil correction needed

Transverse charge density vs. *b*
found to have negative core…hmmmm…



Miller, Arrington PRC 78, 032201 (R) (2008)

Transverse charge distribution

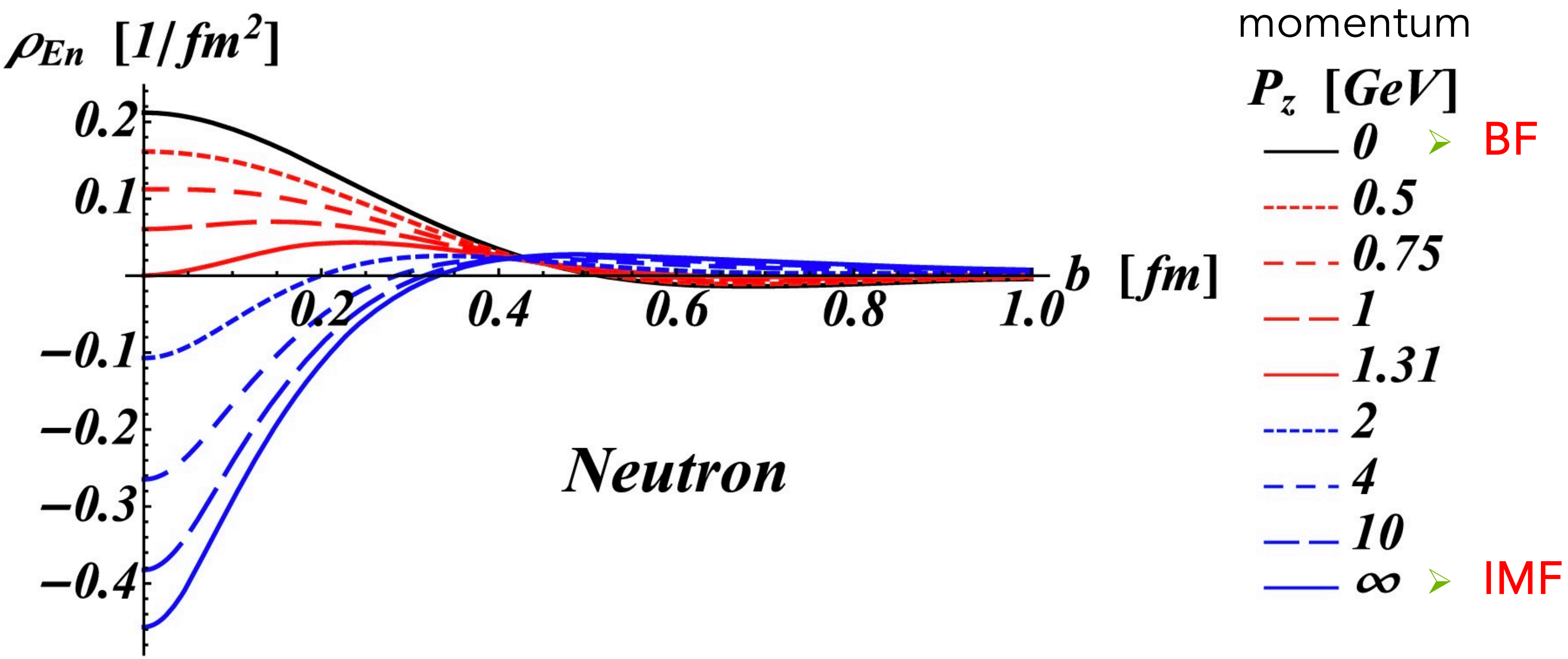


John Arrington, ANL

Phase Space Interpretation (2020)

Appearance (disappearance) of negative neutron core in IMF (BF) is due to contribution from magnetization as nucleon momentum increases. Interpreted as the frame-dependence of the direction of the nucleon polarization.

P_z = average longitudinal momentum



C. Lorce, PRL 125, 232002 (2020)

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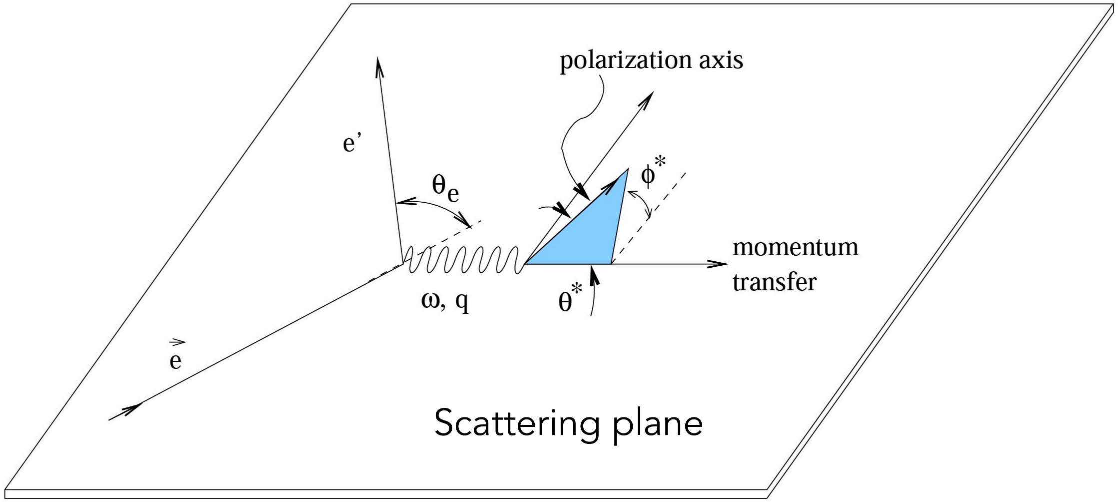
- Measure asymmetry for scattering longitudinally polarized electrons from polarized ^{3}He

$$^3\overrightarrow{\mathrm{He}}(\vec{e}, e'\mathrm{n})\mathrm{pp}$$

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



$$\Sigma = \frac{d\sigma}{d\Omega}\bigg|_{\mathrm{Mott}} \frac{E_f}{E_i} \left(\frac{G_E^2 + \tau G_M^2}{1+\tau} + 2\tau G_M^2 \tan^2(\theta/2) \right)$$

Minimize

$$\Delta = -2 \frac{d\sigma}{d\Omega}\bigg|_{\mathrm{Mott}} \frac{E_f}{E_i} \sqrt{\frac{\tau}{1+\tau}} \tan(\theta/2) \left[\sqrt{\tau(1+(1+\tau)\tan^2(\theta/2))} \cos\theta^* G_M^2 + \sin\theta^* \cos\phi^* G_M G_E \right]$$

Formalism con't

- Orient target polarization perpendicular to $\vec{q}$, $(\theta^* = \pi/2)$
- Detect in reaction plane with $\phi^* = 0$

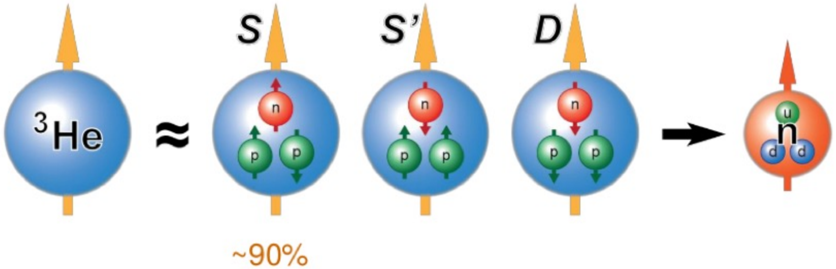
$$A_\perp = -\frac{G_E^n}{G_M^n} \frac{2\sqrt{\tau(\tau+1)}\tan(\theta/2)}{(G_E^n/G_M^n)^2 + (\tau + 2\tau(1+\tau)\tan^2(\theta/2))}$$

Use: $(G_E^n/G_M^n)^2 << (\tau + (2\tau(1+\tau)\tan^2(\theta/2))$

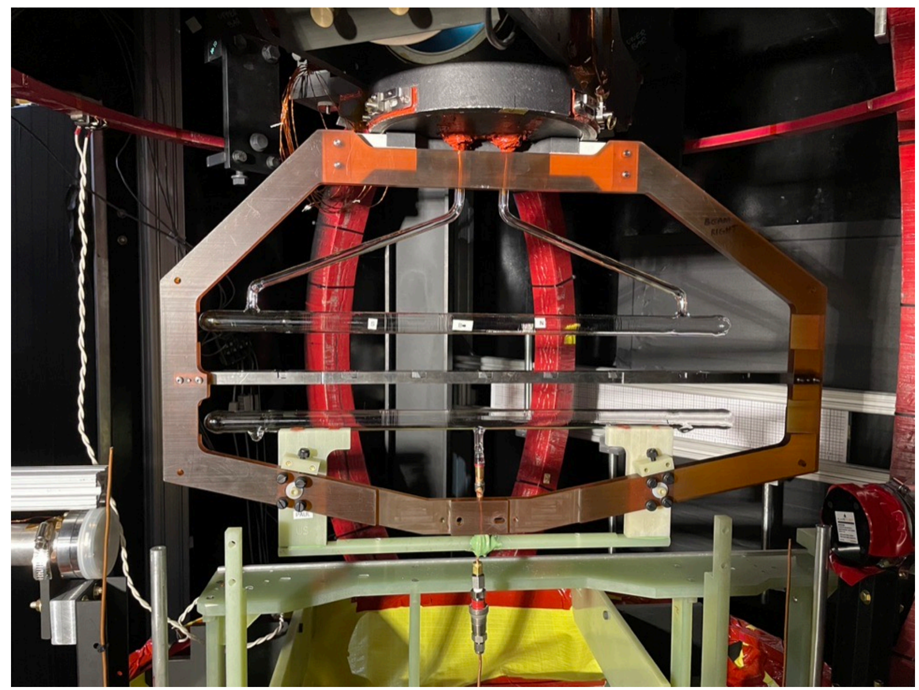
$$\Rightarrow \quad A_\perp \simeq -\frac{G_E^n}{G_M^n}\left[\frac{2\sqrt{\tau(\tau+1}\tan(\theta/2)}{\tau + 2\tau(1+\tau)\tan^2(\theta/2)}\right] \propto \frac{G_E^n}{G_M^n}$$

$A_{meas} = P_b P_t D_{N_2} A_\perp$ + other corrections

SEOP Polarized ^{3}He Target



- Glass convection cell
- Pressure ~ 10 atm
- 45 uA rastered beam
- Length = 60 cm
- P_max ~ 50% in beam

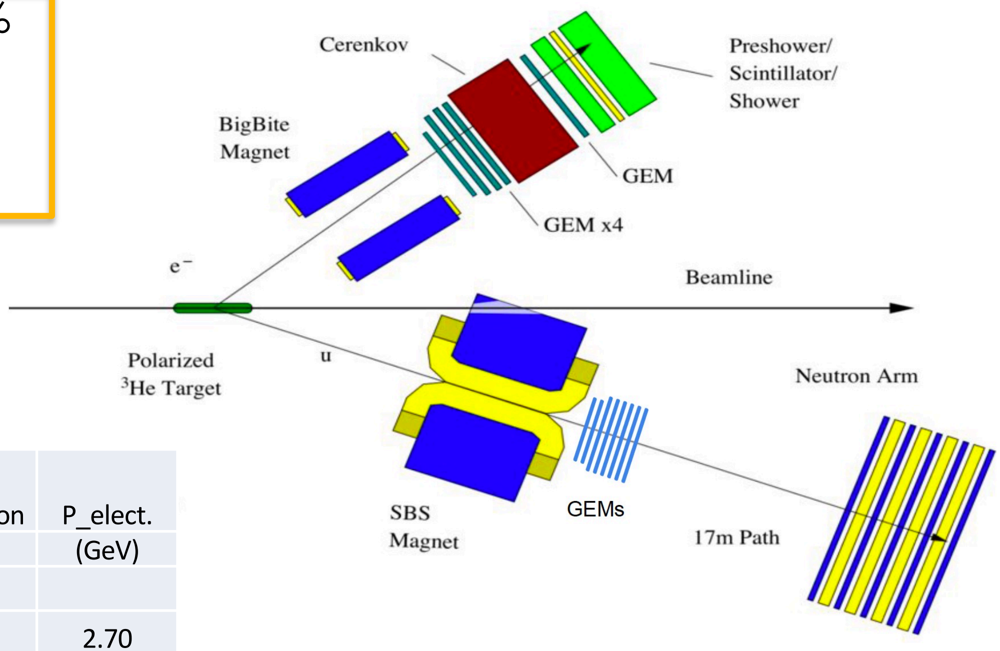


- See talk by Arun Tadepalli, Weds. 11:00

Experimental Setup for G_E^n

- Small cross sections require spectrometers with large angular and momentum acceptance
- SBS = Super BigBite Spectrometer system: electron spectrometer (BigBite) and hadron calorimeter (HCAL)

- Longitudinal beam polarization > 80%
- Polarized ^{3}He target
- BigBite: Ω = 70-90 msr for $\theta \geq 30°$
- SuperBigBite: Ω = 72 msr for $\theta \geq 15°$



Energy (GeV)	Q^2 (GeV^2)	BB angle (deg)	HCAL angle (deg)	P_nucleon (GeV)	P_elect. (GeV)
4.20	2.9	29.5	34.7	2.36	2.70
6.30	6.6	35.9	21.6	4.45	2.79
8.40	9.7	35.0	17.5	6.15	3.22

SBS Floor Layout – Hall A Jefferson Lab

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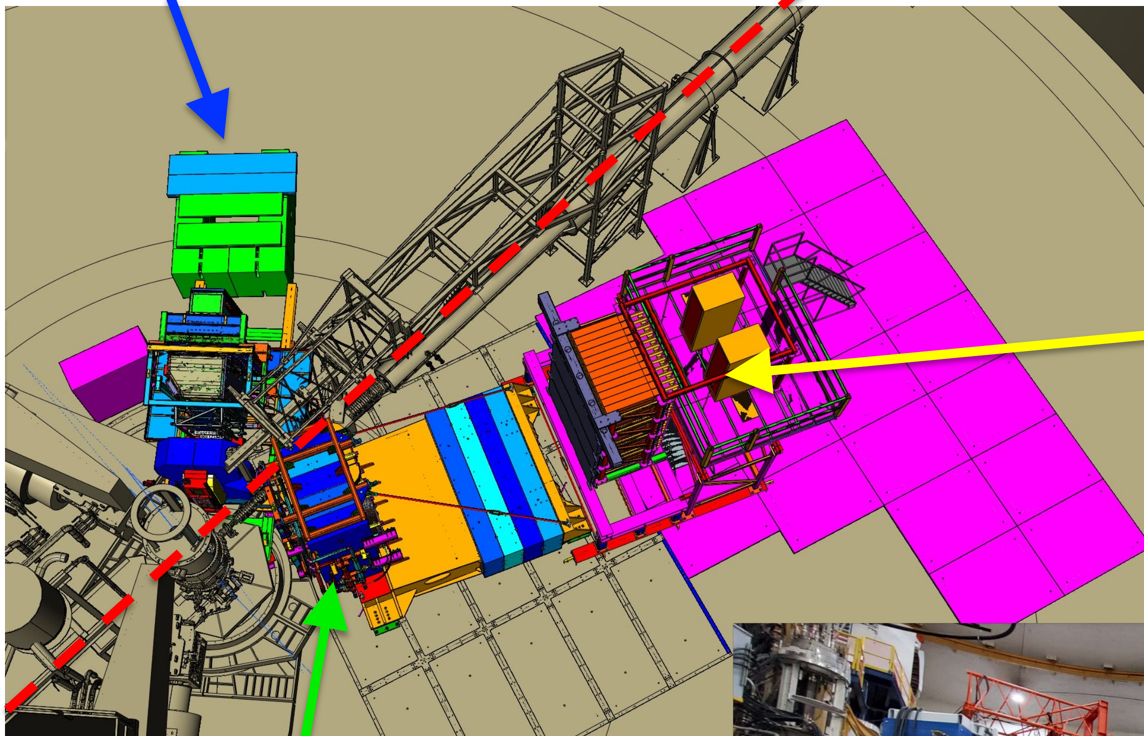
BigBite Spectrometer

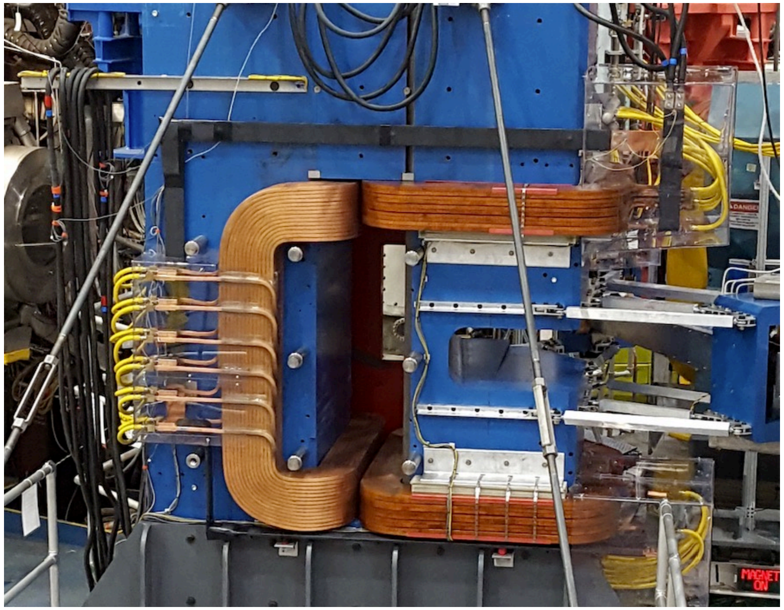


HCAL

e^- beam

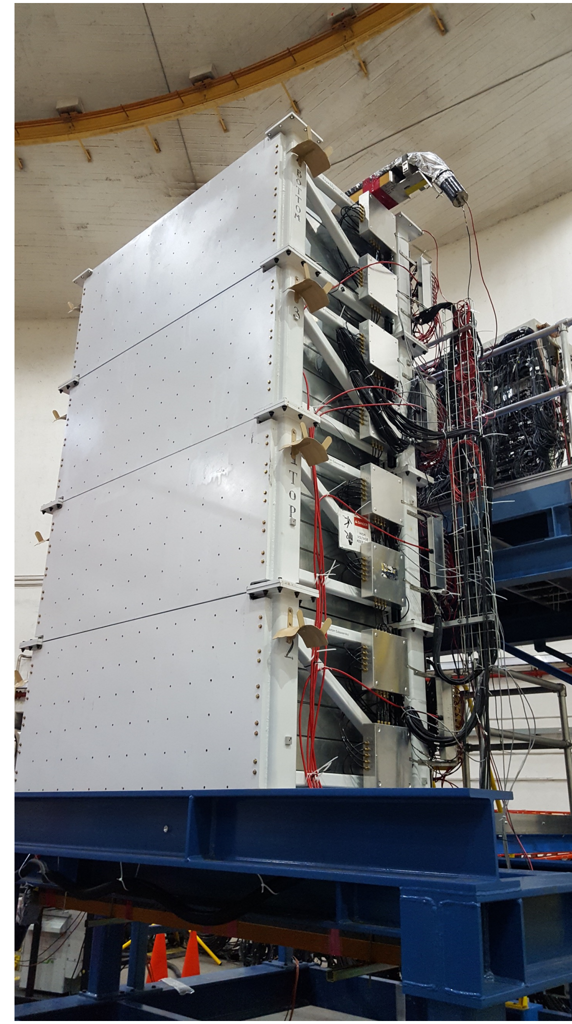
SBS magnet

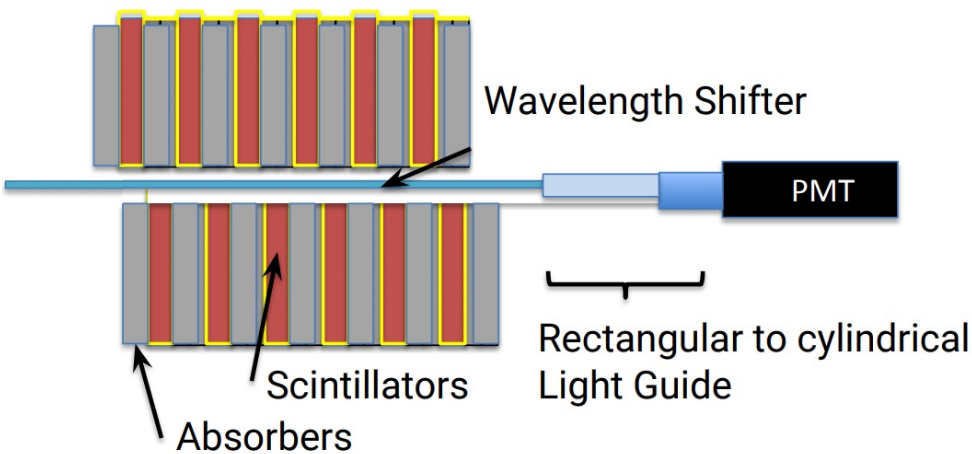
Hadron calorimeter



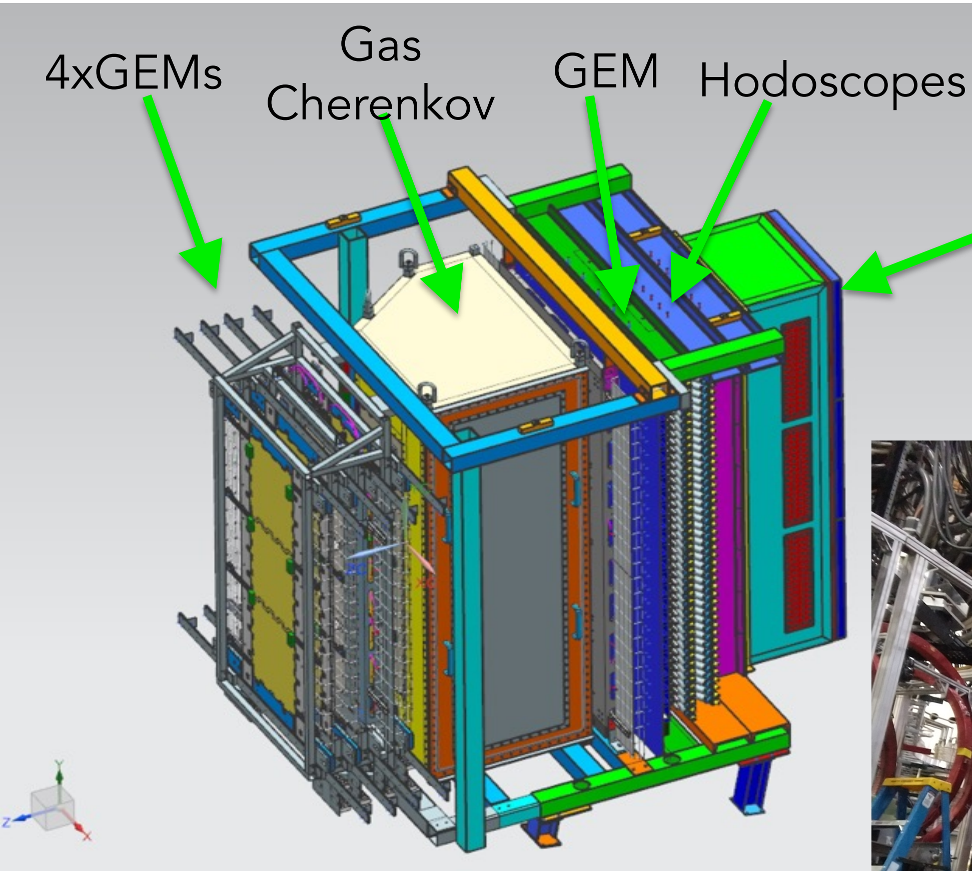
SBS vertical bend magnet for p/n separation

Hadron Calorimeter





BigBite Electron Spectrometer



Glimpses of Analysis

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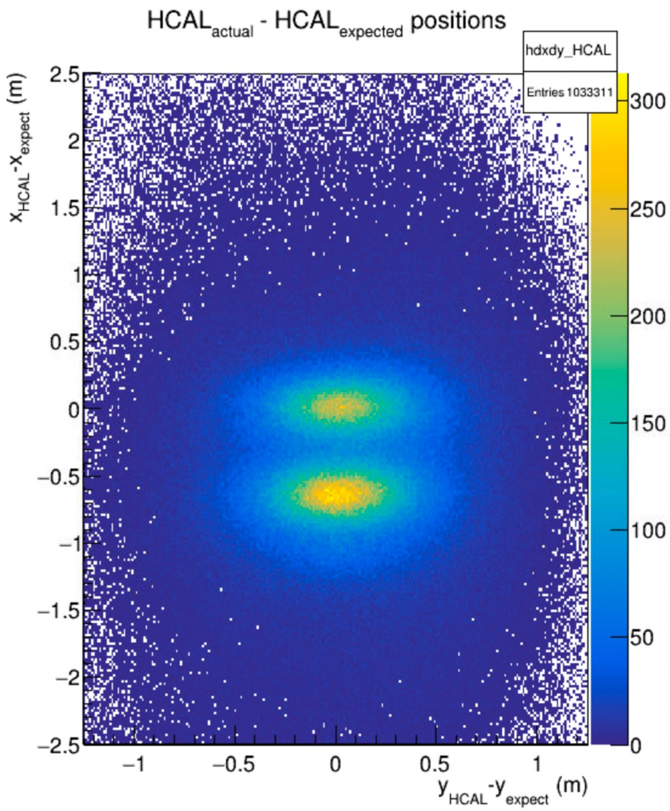
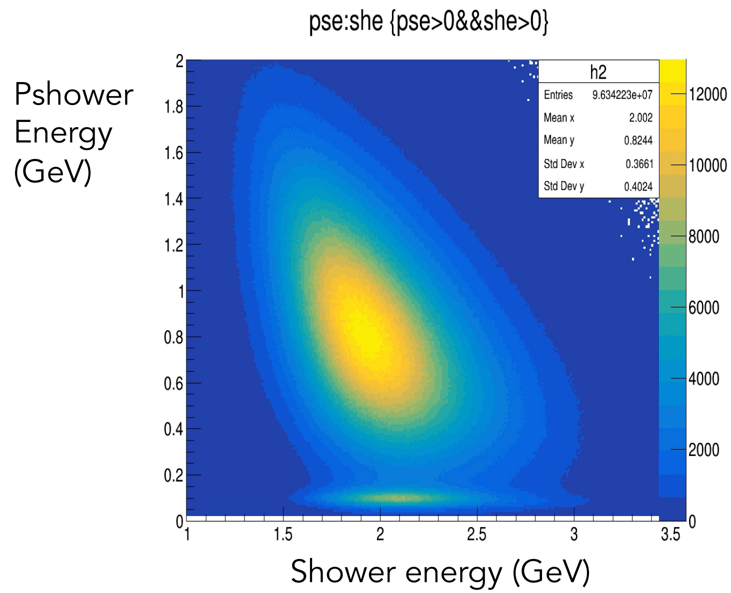
HCAL hits, *x* vs. *y*



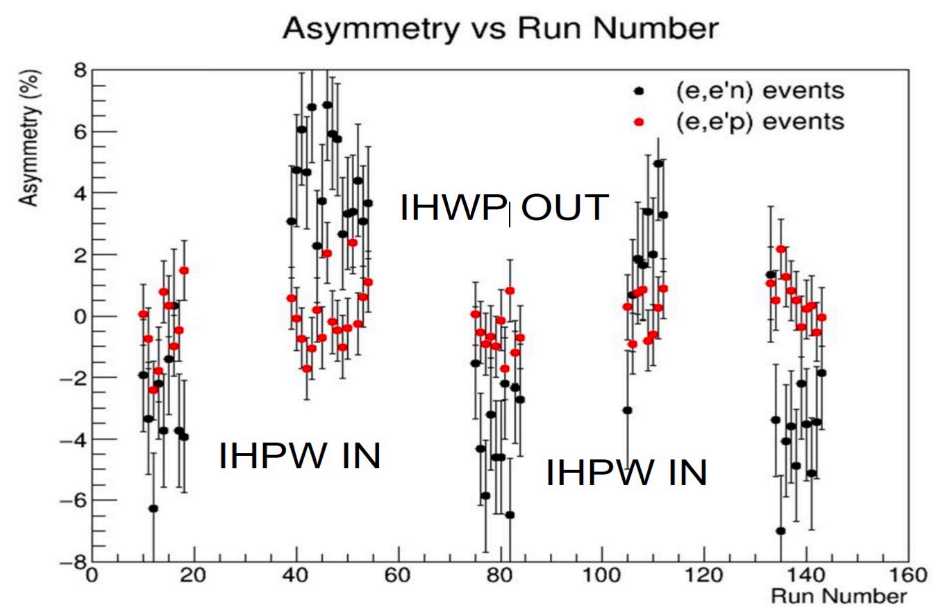
HCAL efficiency ~ 95%

S. Jeffas, P. Datta, A. Puckett



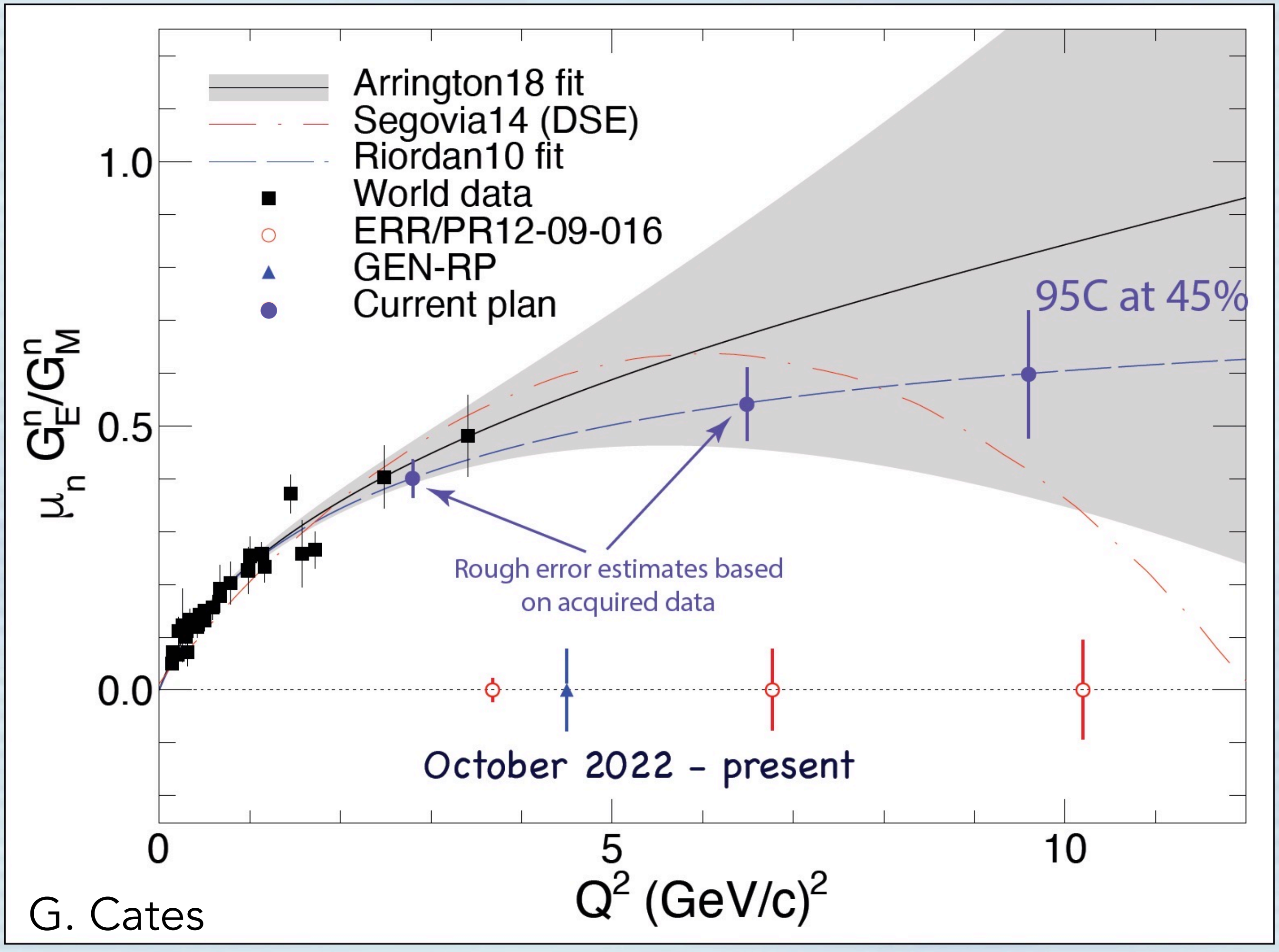
EM calorimeter

- PID, trigger



Where are we? CURRENT STATUS

- First run complete Q^2 = 2.9, 6.6 + some 9.7 GeV²
- Second run in progress at Q^2 = 9.7 GeV²



Summary

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- G_E^n has been measured at Q^2 = 2.9 and 6.6 GeV^2 with precision ~ 15-20%
- We've collected >60% of data at Q^2 = 9.7 GeV^2 – ongoing, expect precision ~ 20%
- Highest performing SEOP target ever used
- Two additional polarized FF measurements will be made in the next 2 years using recoil polarimetry:
  - G_E^n at Q^2 = 4.5 GeV^2
  - G_E^p up to Q^2 ~ 12 GeV^2 (next talk by D. Jones)
- Also note the SBS program has measured G_M^n *to* Q^2 ~ 10 GeV^2
- Beyond FFs, SBS will measure SIDIS, TDIS, PV e-p, …….