NTPE+: Measurement of the Two-Photon Exchange in Electron-Neutron and Positron-Neutron Elastic Scattering

Eric Fuchey
College of William & Mary
(On behalf of the nTPE collaboration)

SBS Collaboration Meeting
March 3rd, 2026

WILLIAM & MARY
CHARTERED 1693

Jefferson Lab

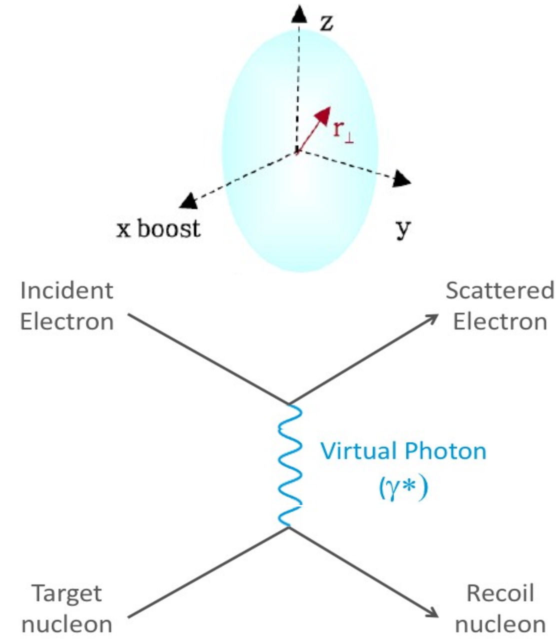
Elastic *e-N* scattering: Rosenbluth

- Space-like Form Factors ≡ charge distribution
- In the One-Photon Exchange (Born) approximation:

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

with $\tau = Q^2/(4M_N)$

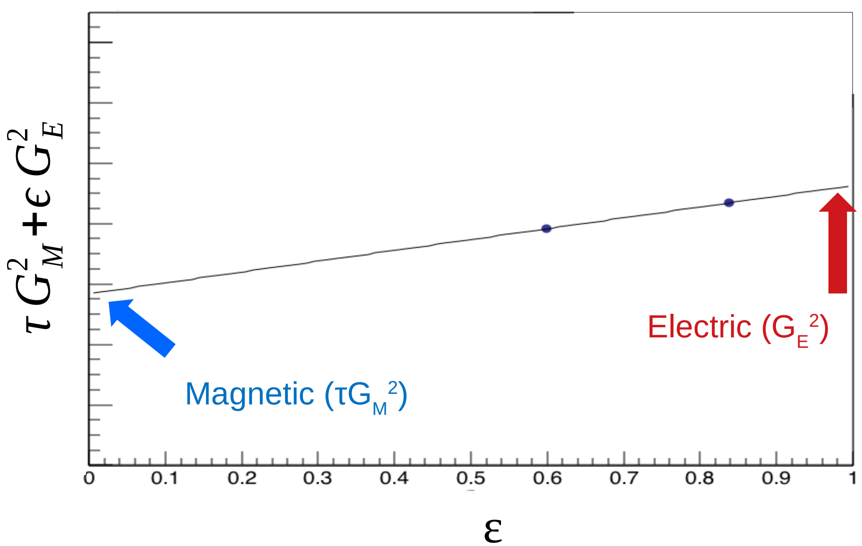
Sachs magnetic FF squared ($\tau G_M^2(Q^2)$); Sachs Electric FF squared ($G_E^2(Q^2)$)



- Rosenbluth technique: separate G_M^2 and G_E^2 based on the linear dependence in $\epsilon = \left[1+2(1+\tau)\tan^2(\theta/2)\right]^{-1}$ of

$$\sigma_r = (d\sigma/d\Omega)\cdot\epsilon(1+\tau)/\sigma_{Mott}$$
$$= \tau G_M^2(Q^2) + \epsilon G_E^2(Q^2)$$
$$= \sigma_T + \epsilon\sigma_L$$

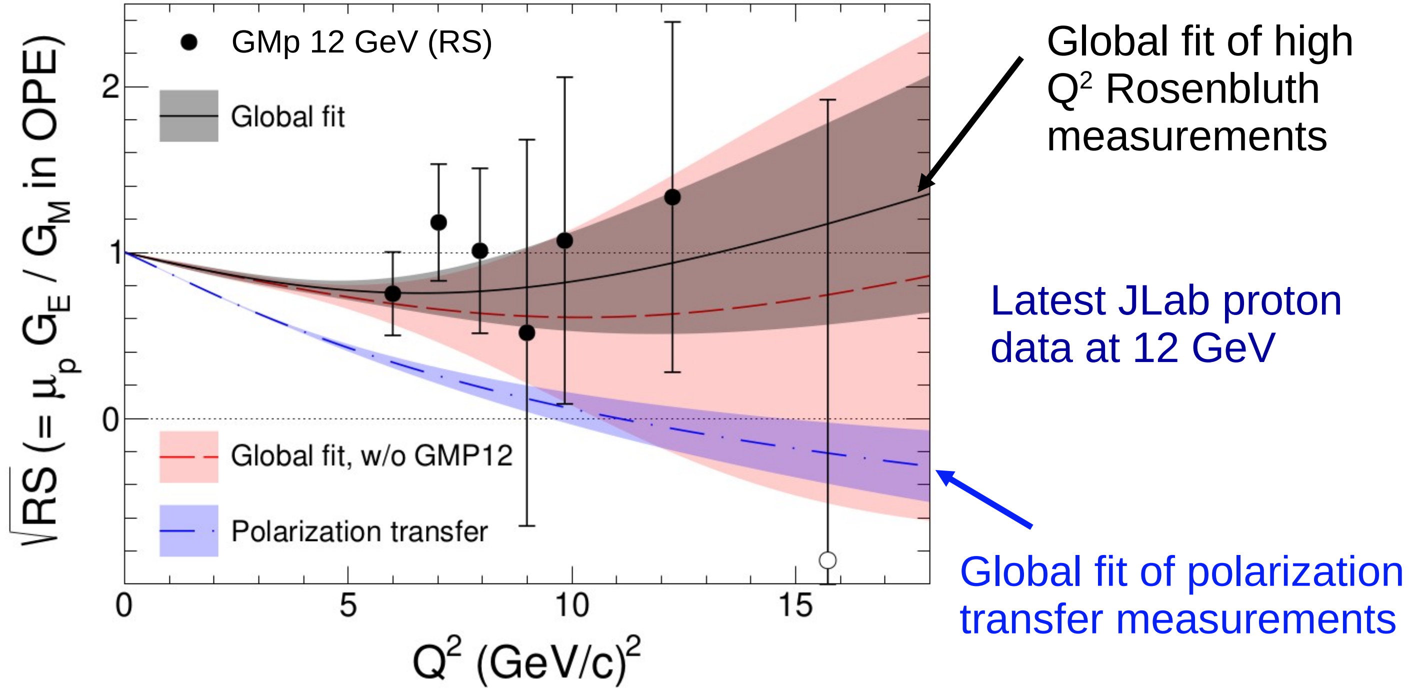
- Two or more measurements, same Q^2, different E and θ (different ε)



Global Fit on Rosenbluth Slope in e^-p Scattering

- Until GEp-I (PO) at Jefferson Lab [Phys. Rev. Lett. 84, 1398 (2000)], OPE accepted to be a sufficient approximation
- ***Large* discrepancy** between Rosenbluth and polarization transfer (for measurements at $Q^2 \geq 2$ GeV^2);
- Missing contribution likely due to Two-Photon Exchange (TPE).

Phys.Rev.Lett. 128 (2022) 10, 102002

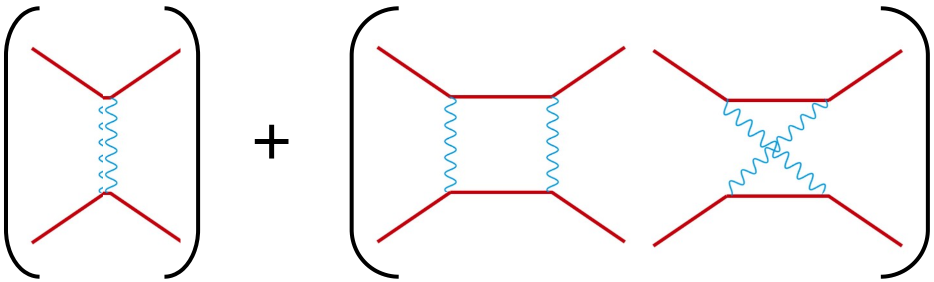


Two-Photon Exchange with Positrons

- TPE in elastic e^+N scattering:
- Hard TPE amplitude interferes with OPE amplitude:

Lepton charge

$$\sigma_{eN} = |M_{1\gamma}|^2 \pm 2\,\Re e[M_{1\gamma} M_{2\gamma}]$$

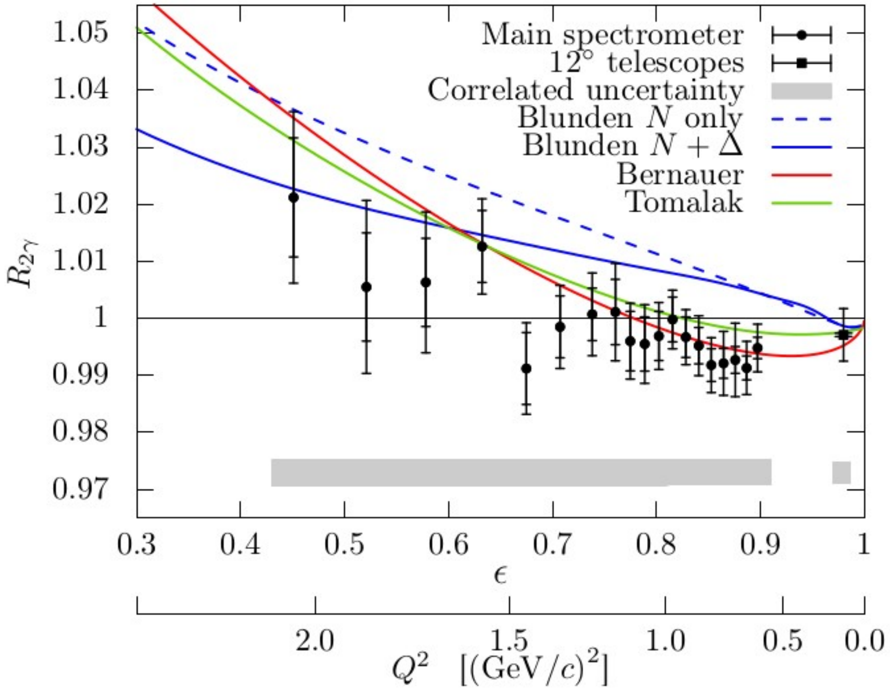


- Interference term depends on the lepton charge to the power 3:
  - TPE expected to be of same magnitude opposite sign in e^+N and e^-N;
  - measurement e^+N / e^-N => (1 + *2 TPE*)

e^+p measurements

- Ratio of cross sections e^+p/e^-p measured in several experiments;
- Latest measurements in Olympus, with Q^2 up to 2 GeV^2:

Phys. Rev. Lett. 118, 092501 (2017)

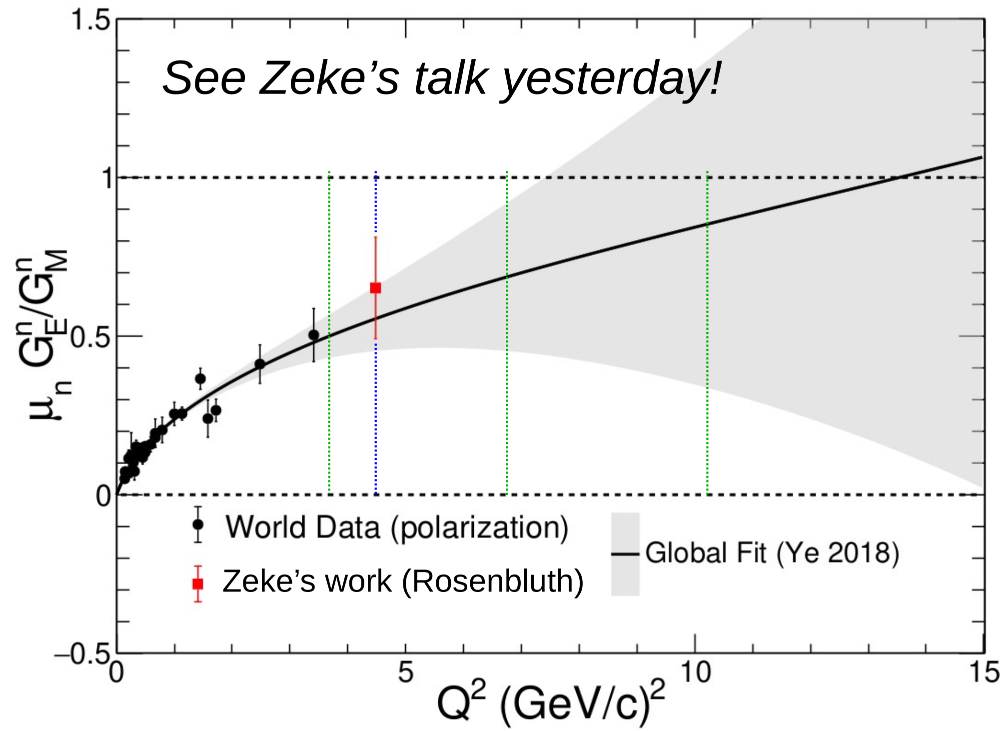


- Inconclusive results on significance of TPE effect at $Q^2 < 2$ GeV^2:
- Note: Rosenbluth/polarization discrepancy not very significant at low Q^2

en Scattering Measurements

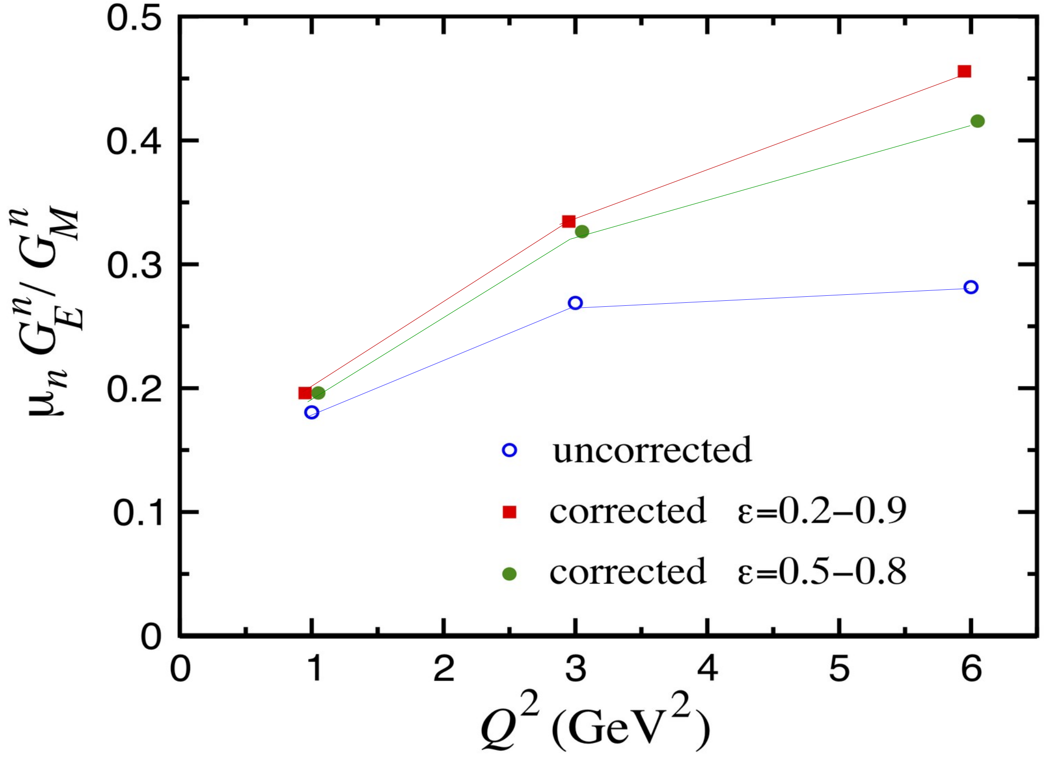
- **Existing measurements of G_E^n not as extensive as G_E^p:**
  - All *published* data below Q^2 = 3.5 GeV^2 (PO);
  - Measurements beyond Q^2 = 3.5 GeV^2 from SBS (GEn, GEn-RP);
  - No recent (<50 years!) published Rosenbluth measurements on the neutron:
    - ♦ *Preliminary analysis of SBS nTPE* (E12-20-010) at Q^2 = 4.5 GeV^2 by E. Wertz

[*"A Measurement of the Neutron Electromagnetic Form Factor Ratio from a Rosenbluth Technique with Simultaneous Detection of Neutrons and Protons"*, Ph.D Thesis, William & Mary (July 2025)]



Two-Photon Exchange in *en* Scattering

- Lack of "contradictory" measurements to evidence TPE in *en* scattering
- Predictions from Phys. Rev. C**72**, 034612 (2005) on *en* scattering:
    - small TPE contribution at Q^2 around 1 GeV^2;
    - significant at 3 GeV^2 and beyond;



Blunden, Melnitchouk and Tjon,
Phys. Rev. C**72**, 034612 (2005)

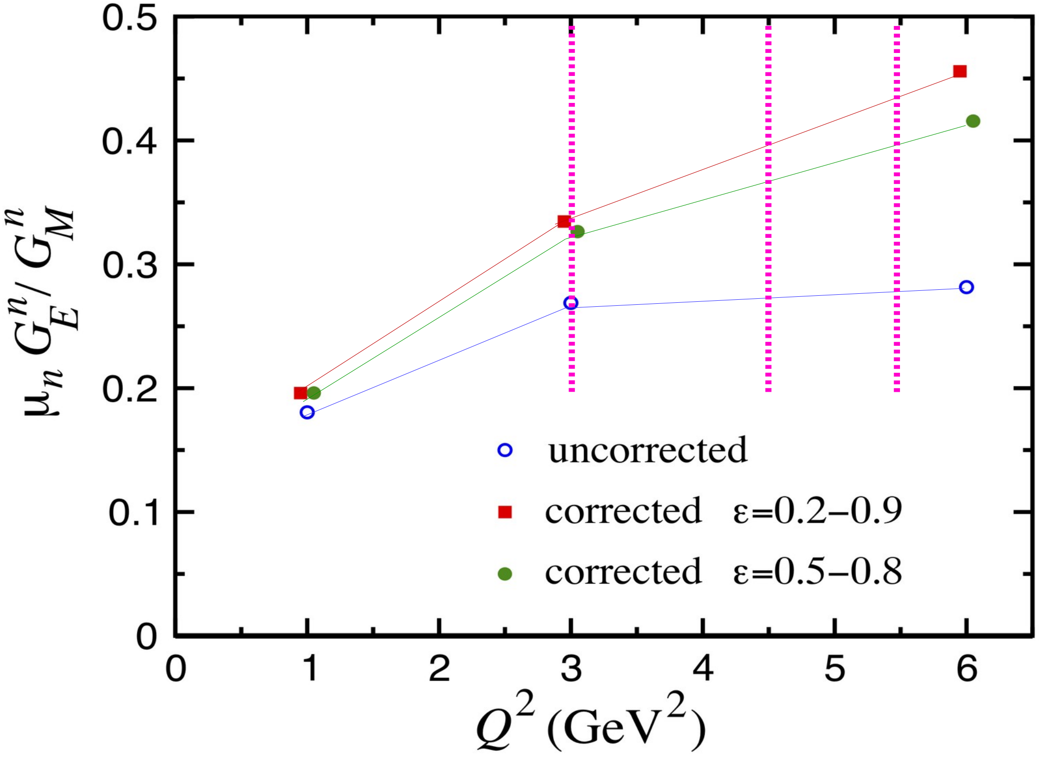
○ $\mu_n G_E^n/G_M^n$ *PO data fit*
from Mergell Meissner Drechsel
Nucl. Phys. A596, 367 (1996)

■ *Expected RS* measurement of
$\mu_n G_E^n/G_M^n$ + nTPE for ε = 0.2 <-> 0.9

● *Expected RS* measurement of
$\mu_n G_E^n/G_M^n$ + nTPE for ε = 0.5 <-> 0.8

Two-Photon Exchange in *en* Scattering

- **PR12+25-006 (nTPE+): E.F. (contact), S. Alsalmi, P. Blunden, P.Datta, E. Wertz**
  - Followup of LOI12+24-008: **neutron TPE at Q^2 = 3 GeV², 4.5 GeV², 5.5 GeV²**
  - Rosenbluth measurements of e^-n and e^+n cross section
  - Direct measurement of nTPE via e^+n/e^-n ratio → *Suggested by LOI 2024 review*
  - => disentangle contribution of TPE in Rosenbluth/polarization discrepancies



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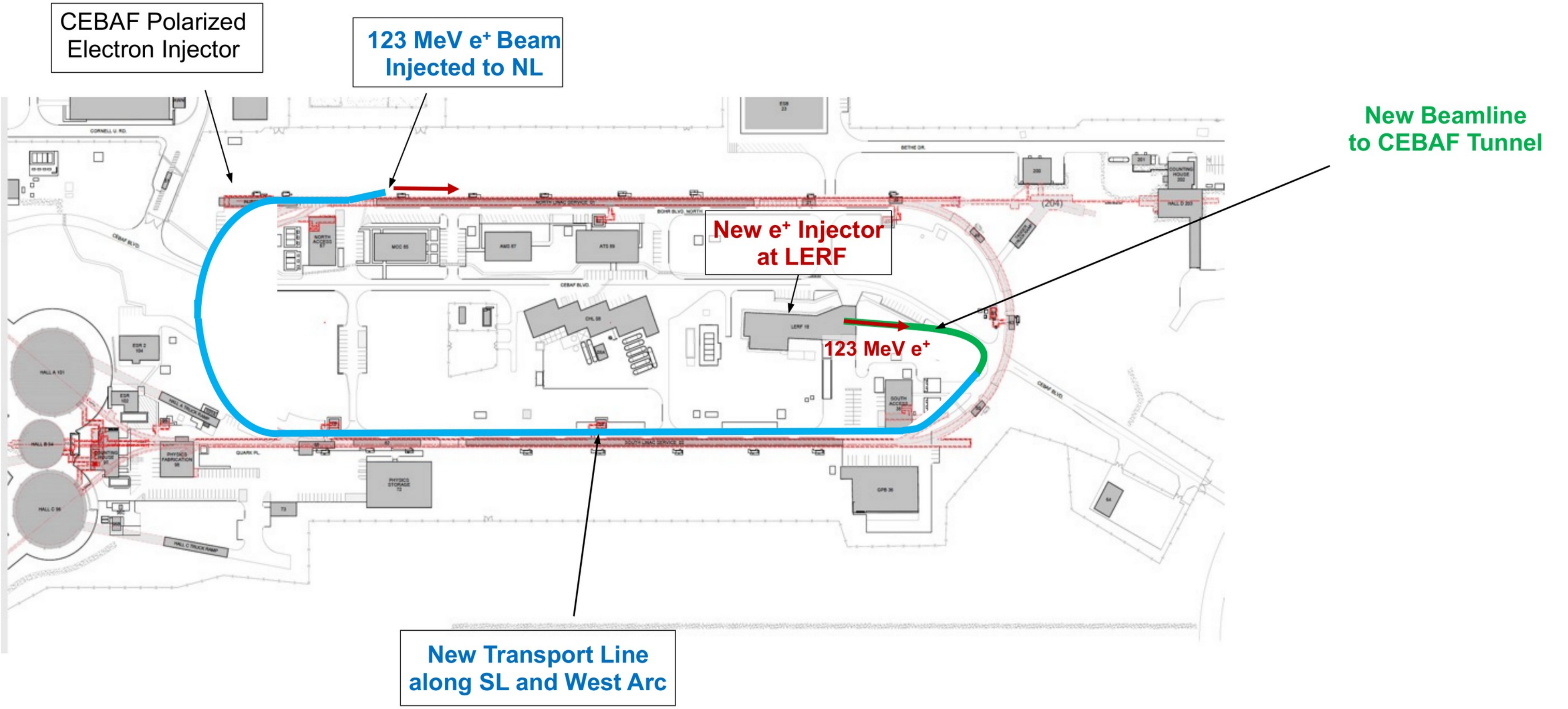
● *Expected RS* measurement of $\mu_n G_E^n/G_M^n$ between ε = 0.5 and 0.8

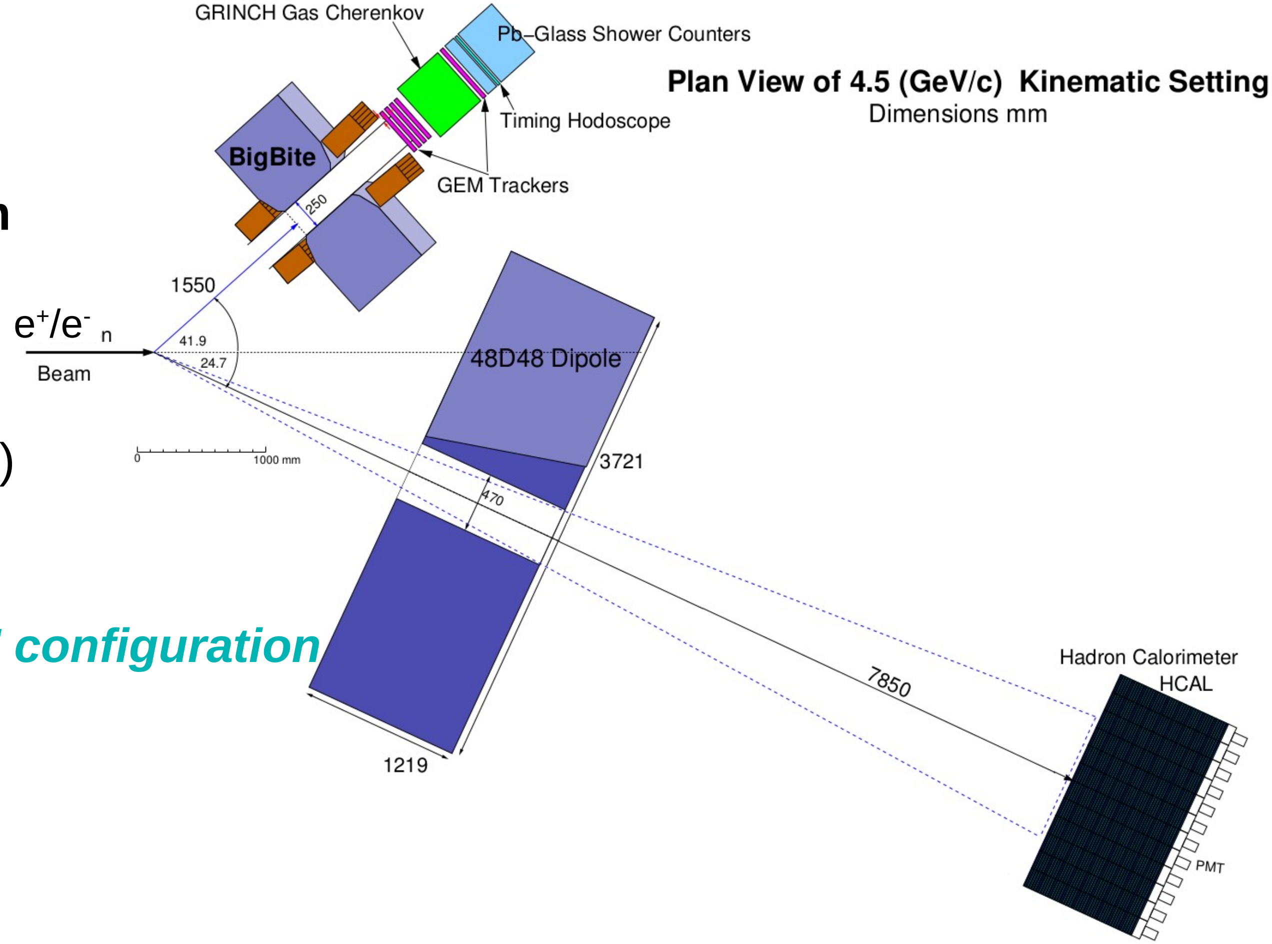
nTPE+ with Jefferson Lab Positron Upgrade

- New injector to produce polarized positrons (and electrons)
- Promised specifications:
  - **1μA e^+ without polarization**;
  - 60nA with polarization;



nTPE+ with Super BigBite Spectrometer

- **SBS:**
  - Major part of Hall A 12 GeV program at Jefferson Lab;
  - SBS coupled with Bigbite spectrometer for electron measurement;
  - SBS uses Hadron Calorimeter (HCal) for nucleon detection / ID;

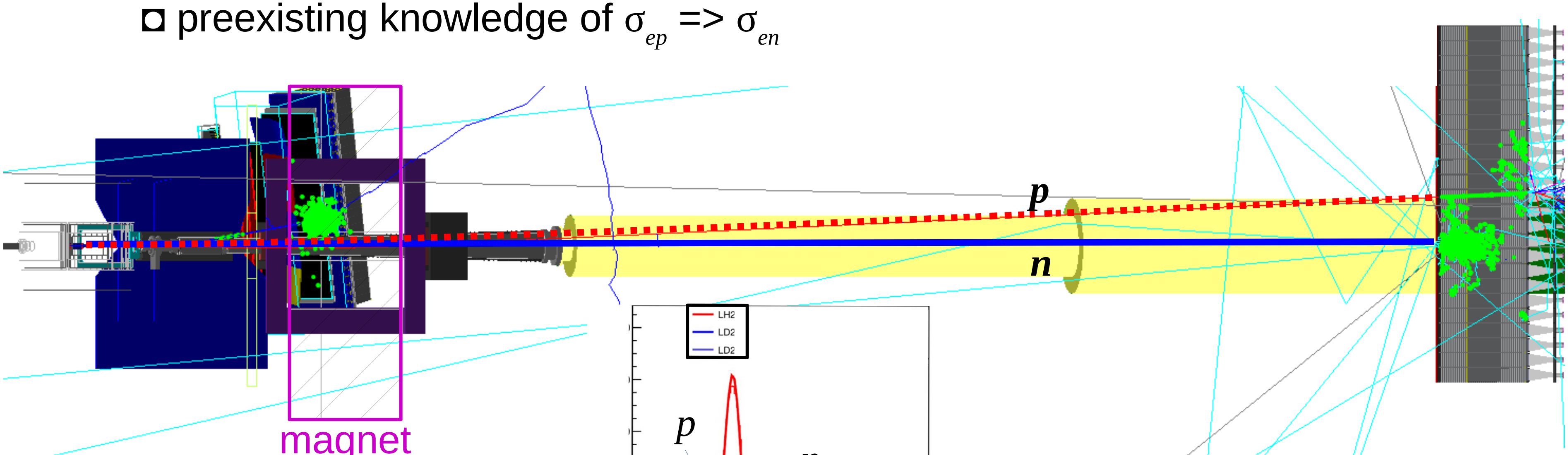


- **SBS form factor program**
  - GMN (E12-09-019)
  - *nTPE* (E12-20-010)
  - GEN (E12-06-016)
  - GEN-RP (E12-17-004)
  - GEP (E12-07-109)

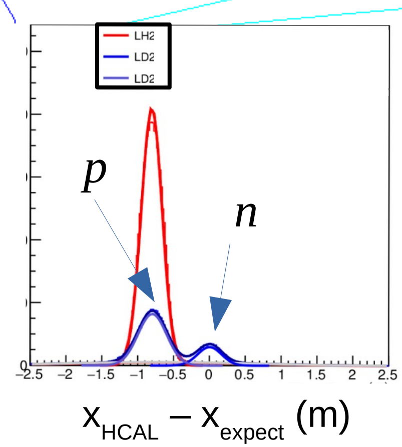
- ***This proposal uses GMN configuration***

Neutron Measurement with Durand Technique

- Established by Durand in Phys. Rev. 115, 1020 (1959).
- Used for SBS experiments GMN (E12-09-019), nTPE (E12-20-010), **nTPE+**:
  - simultaneous *en*/*ep* quasielastic measurement on D_2
  - Separation of *p* and *n* with magnet
  - $R_{n/p} = \sigma_{en}/\sigma_{ep}$ with reduced systematics (Cancellation of Fermi momentum)
  - preexisting knowledge of σ_{ep} => σ_{en}



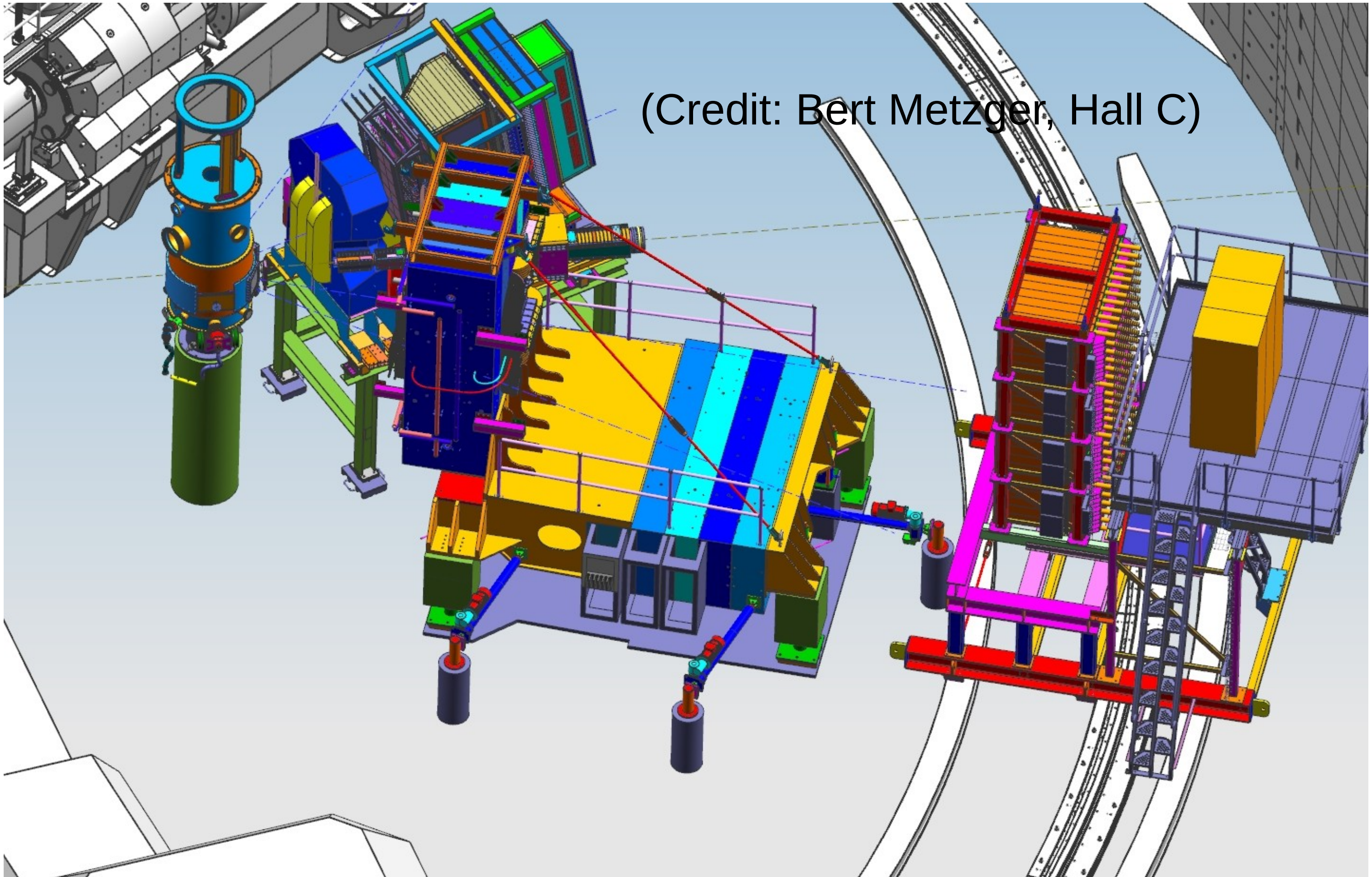
See Provakar and Zeke talks yesterday!



X_{HCAL}: reconstructed
x_{expect}: predicted from e^-

nTPE+ Kinematics

- PR12+25-006 (NTPE+) will be proposed in **Hall C**:
  - SBS, BigBite and target installed downstream of pivot;
  - SBS, BigBite locations for our kinematics don't interfere with HMS/SHMS at their largest angles;



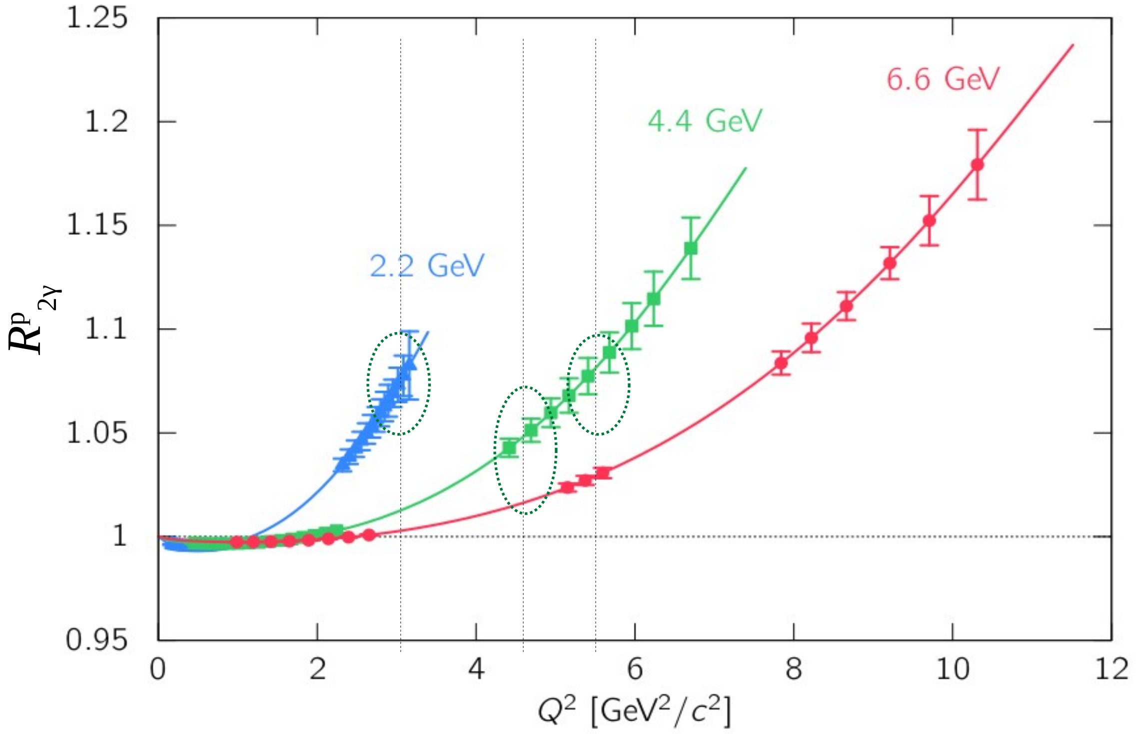
nTPE+ Kinematics

- PR12+25-006 (NTPE+) will be proposed in **Hall C**:
  - SBS, BigBite and target installed downstream of pivot;
  - SBS, BigBite locations for our kinematics don't interfere with HMS/SHMS at their largest angles;
- Six kinematic settings:
  - each will run e^+, e^-, LD_2, LH_2;
    - ♦ **TAC recommendation**: 30cm targets instead of 15cm;
  - Three settings at 2 pass, two settings at 3 pass, *one setting at 1.5 pass*.

Kinematic	e^+/e^- - I_{beam} (μA)	Q^2 $(\mathrm{GeV/c})^2$	E (GeV)	E′ (GeV)	θ_{BB} degrees	p' (GeV/c)	θ_{SBS} degrees	ϵ
1+/-	$e^{+/-}$ (1.0)	4.5	4.4	2.00	41.9	3.20	24.7	0.600
2+/-	$e^{+/-}$ (1.0)	4.5	6.6	4.20	23.3	3.20	31.2	0.838
3+/-	$e^{+/-}$ (1.0)	3.0	3.3	1.71	42.8	2.35	29.5	0.638
4+/-	$e^{+/-}$ (1.0)	3.0	4.4	2.81	28.5	2.35	34.7	0.808
5+/-	$e^{+/-}$ (1.0)	5.5	4.4	1.47	54.9	3.75	18.7	0.420
6+/-	$e^{+/-}$ (1.0)	5.5	6.6	3.67	27.6	3.76	26.9	0.764

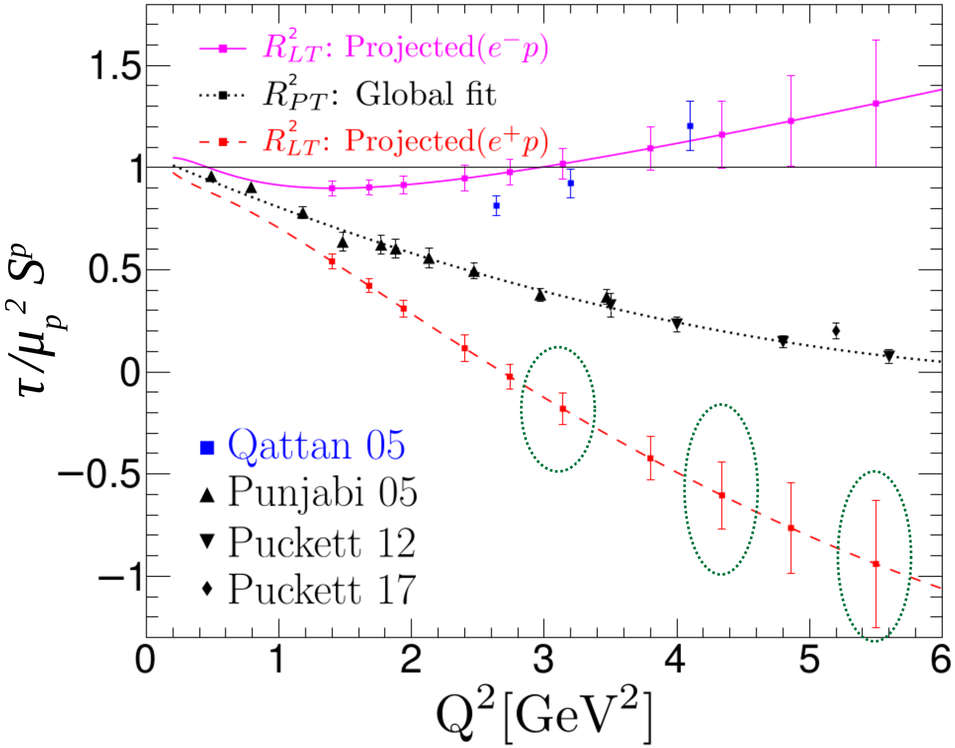
nTPE+ Measurements: e^+n/e^-n ratios $R^n_{2\gamma}$

- $R^n_{2\gamma}$ measurement with Durand technique:
  - Measure $R_{n/p} = \sigma_{en}/\sigma_{ep}$ consecutively for positrons and electrons ;
  - e^- data at same beam intensity as e^+ data (1μA)
  - $\rho_\pm = \frac{R^{e^+}_{n/p}}{R^{e^-}_{n/p}} = \frac{R^n_{2\gamma}}{R^p_{2\gamma}}$ for **Q^2 = 3 GeV², 4.5 GeV², 5.5 GeV²**
  - $R^p_{2\gamma}$ sourced from CLAS12 $R_{2\gamma}$ experiment PR12+23-008 (A. Schmidt *et al.*)



nTPE+ Measurements: e^+n/e^-n Rosenbluth slopes S^n

- Rosenbluth measurement with Durand technique:
  - Measure $R_{n/p} = \sigma_{en}/\sigma_{ep}$ for both ε points;
  - $A = \frac{R_{n/p}^{\epsilon_1}}{R_{n/p}^{\epsilon_2}} \simeq \frac{1+\epsilon_2 S^p}{1+\epsilon_1 S^p} \times (1+S^n \Delta\epsilon)$
  - Rosenbluth e^-p from latest S^p fit [Phys.Rev.Lett. 128 (2022) 10, 102002];
  - Rosenbluth e^+p from Hall C Super Rosenbluth PR12+23-012 (M. Nycz *et al.*);



nTPE+ Systematics: GMn/nTPE Analysis

- Sources of systematics for $R_{n/p}$ (*in %*):
  - **Preliminary systematics for GMn (E12-09-019) analysis by P. Datta**
    - (*) Divided by a factor 3 to account for possible improvements (best case – not divided by 3 for worst case)
    - e.g. Neutron detection efficiency measurement explicitely requested to improve uncertainty on nucleon detection efficiency
  - Introduced factors of covariance (in %) for correlations between settings

Q^2 ((GeV/c)^2)	3.0	4.5	5.5	$\delta_{cov,\ e+/e-}$	$\delta_{cov,\ \epsilon_1/\epsilon_2}$
Radiative corrections*	0.77	1.11	1.26	+80.0	0.0
Inelastic contamination	0.33	0.75	0.84	+50.0	0.0
Nucleon detection efficiency*	0.7	0.7	0.7	+95.0	+50.0
Nucleon charge exchange in FSI	0.04	0.01	0.02	+95.0	0.0
Selection stability	0.16	0.15	0.40	+100.0	0.0
$\Delta R_{n/p}$	1.10	1.52	1.72	-	-
$\Delta\rho_\pm/\rho_\pm$	0.44	0.74	0.83	-	-
$\Delta A/A$	1.40	2.03	2.32	-	-

nTPE+ Systematics: Uncertainties for $R_{2\gamma}$, S^n

- Systematics specific to $R_{2\gamma}{}^n$ and S^n:

$R_{2\gamma}{}^n$

Q^2 ((GeV/c)^2)	3.0	4.5	5.5
$\Delta\rho_\pm/\rho_\pm$ (stat)	0.28	0.25	0.58
$\Delta\rho_\pm/\rho_\pm$ (syst)	0.44	0.74	0.83
$\Delta R^p_{2\gamma}/R^p_{2\gamma}$ [1]	0.78	0.42	0.79
$\Delta R^n_{2\gamma}/R^n_{2\gamma}$ (syst)	0.93	0.89	1.28

S^n

Q^2((GeV/c)^2)	3.0 (e^-)	3.0 (e^+)	4.5 (e^-)	4.5 (e^+)	5.5 (e^-)	5.5 (e^+)
$\Delta A/A$ (stat, %)	0.32	0.32	0.40	0.40	0.58	0.58
$\Delta A/A$ (syst, %)	1.40	1.40	2.03	2.03	2.32	2.32
S^p [2, 3]	0.1056	-0.0267	0.0616	-0.0608	0.0478	-0.0773
ΔS^p [2, 3]	0.0160	0.0114	0.0165	0.0164	0.0170	0.0254
ΔS^n	0.100	0.096	0.103	0.103	0.087	0.094

- References:

[1] Projected $R^p_{2\gamma}$: A. Schmidt *et al.* PR12+23-008

[2] e^-p S^p fit: Phys.Rev.Lett. 128 (2022) 10, 102002

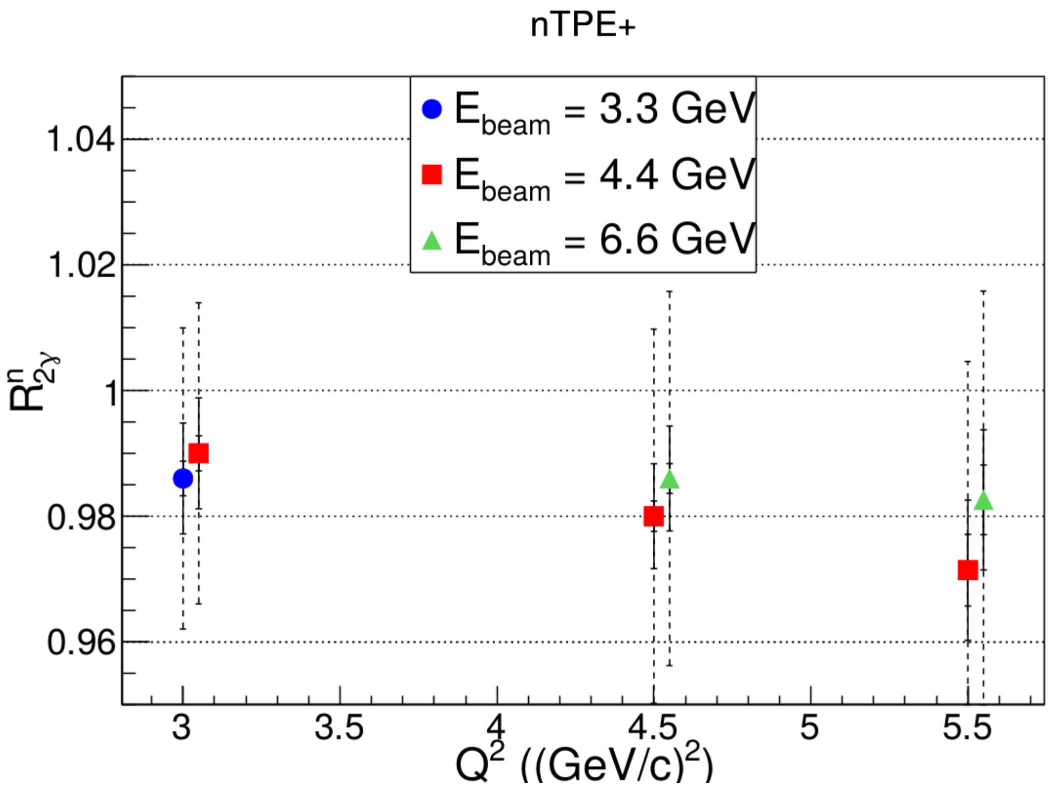
[3] Projected e^+p S^p: M. Nycz *et al.* PR12+23-012

nTPE+ Time Request

- **Updated run plan following TAC remarks and recommendations**:
- 6 kinematics with e+/e- LD2/LH2 30 cm (instead of 15 cm): **38.5 PAC days total**
  - ◘ ***536 PAC hours beam on target*** (down from 952) ;
    - ♦ 88 PAC hours on setting 1 (Q^2 = 3.0 GeV^2, E = 3.3 GeV);
    - ♦ 48 PAC hours on setting 2 (Q^2 = 3.0 GeV^2, E = 4.4 GeV);
    - ♦ 128 PAC hours on setting 3 (Q^2 = 4.5 GeV^2, E = 4.4 GeV);
    - ♦ 64 PAC hours on setting 4 (Q^2 = 4.5 GeV^2, E = 6.6 GeV);
    - ♦ 160 PAC hours on setting 5 (Q^2 = 5.5 GeV^2, E = 4.4 GeV);
    - ♦ 48 PAC hours on setting 6 (Q^2 = 5.5 GeV^2, E = 6.6 GeV);
  - ◘ *380 PAC hours* (up from 224...) for setting changes *(40 % of total)*:
    - ♦ two **e^+/e^- changes**, assuming 84 PAC hours (**one calendar week**) each;
    - ♦ one **pass change** to 3.3 GeV (1.5 pass) taking 84 PAC hours (**one calendar week**) plus two pass changes overlapped with magnet changes;
    - ♦ nine magnet angle changes taking 16 PAC hours (32 real hours) each; (one completely overlapped with long pass change);

nTPE+ Projections

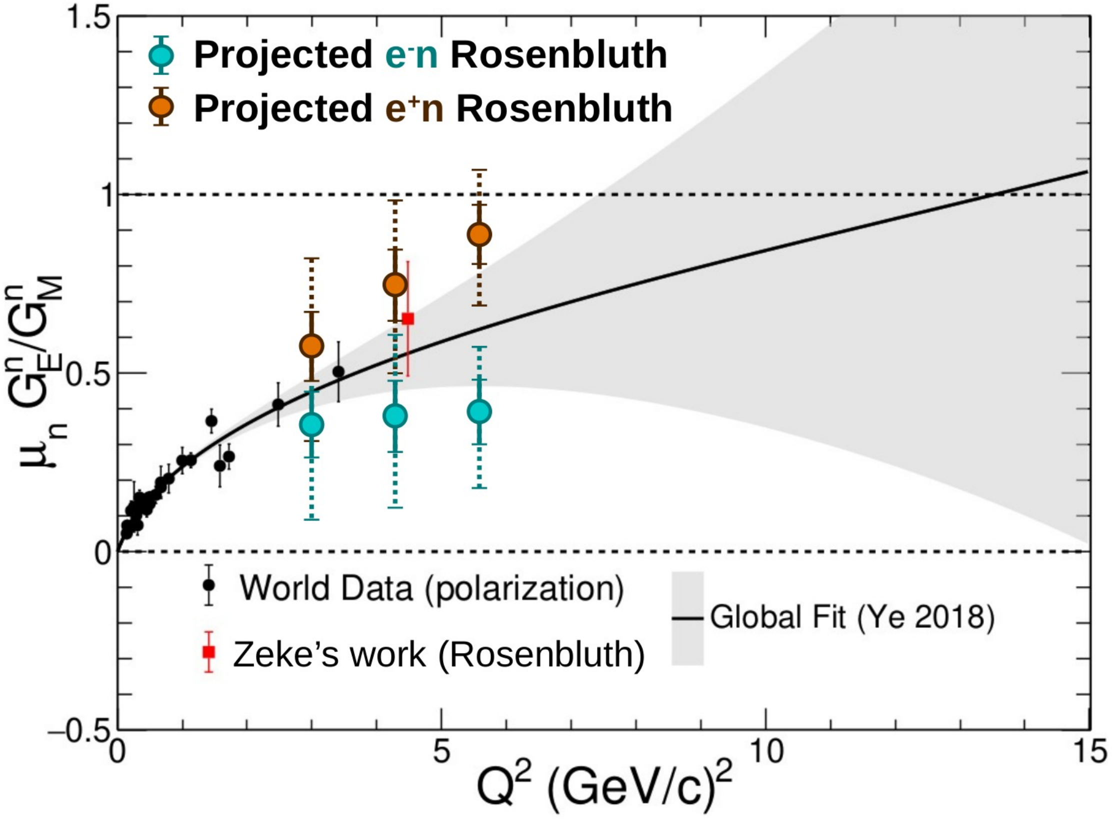
- **Predictions from P. Blunden:** $R^n_{2\gamma}$ for all settings
  - statistical uncertainty (inner bars);
  - statistical + systematics, best case (outer solid bars);
  - statistical + systematics, worst case (outer dashed bars);



nTPE+ Projections

- **Predictions from P. Blunden:** $e^{+}n$ and $e^{-}n$ Rosenbluth slopes for all settings
  - Superimposed on nTPE (E12-20-010) *preliminary analysis* by E. Wertz
  - $\mu_n\, G_E^n/G_M^n$ calculated from projected Rosenbluth slopes;
  - Other G_E^n measurements and projections are polarization data;

* *"A Measurement of the Neutron Electromagnetic Form Factor Ratio from a Rosenbluth Technique with Simultaneous Detection of Neutrons and Protons"*, Ph.D Thesis, William & Mary (July 2025).



nTPE+ Feedback from PAC

PR12+25-006

Scientific Rating: N/A

Recommendation: Conditionally approved (C2) in Hall C

Title: Measurement of the Two-Photon Exchange Contribution in Electron-Neutron and Positron-Neutron Elastic Scattering

Spokespersons: S. Alsalmi, P. Blunden, P. Datta, E. Fuchey (contact), E. Wertz

Motivation: This experiment proposes to measure the two-photon exchange (TPE) contribution in elastic e^+-neutron and e^--neutron scattering. Such measurements are interesting because a significant two-photon exchange current would lead to a measurable difference in the respective Rosenbluth slopes between the positron and electron scattering results. The measurement program is focused on the neutron where there has not been as extensive a measurement campaign as for the proton and targets a Q^2 region where larger two-photon exchange contributions are expected.

Measurement and Feasibilty, Issues, on next slide

Summary: This experiment would provide new explorations of two photon exchange spanning a range of Q^2 from 3.0-5.5 GeV^2 in elastic e^+ and e^- neutron scattering. The PAC conditionally approves this proposal (C2) pending the resolution of the above issues at a future PAC and preparation of a revised run time request after a final decision is made on the target length.

nTPE+ Feedback from PAC

Measurement and Feasibility: The experiment plans to use the same experimental setup as the GMn/TPE experiments in Hall A, but with equipment that the laboratory plans to move to Hall C. Their simulation/analysis efforts are benefitting from experience gained from E12-20-010. Their plans are to measure G^n_E/G^n_M, S^n, and $R^n_{2\gamma}$, the later providing the first such measurements for the neutron. The data will be taken at 6 kinematic settings which includes 3 momentum transfers (Q^2=3.0, 4.5, 5.5 GeV^2) and 3 beam energies (E_{beam}=3.3, 4.4, 6.6 GeV). Since their LOI, the proponents have added H_2 data-taking to aid in reducing systematics (following a PAC52 recommendation) as well as a higher Q^2 point, both of which have further strengthened their measurement program. The requested 38.5 PAC days (30 cm target) as presented in their presentation to PAC53, includes both physics running and time for configuration changes. Assumptions have been made about how long beam changes will take. When a better understanding of the change times are available, it may be necessary to reexamine the requested PAC days.

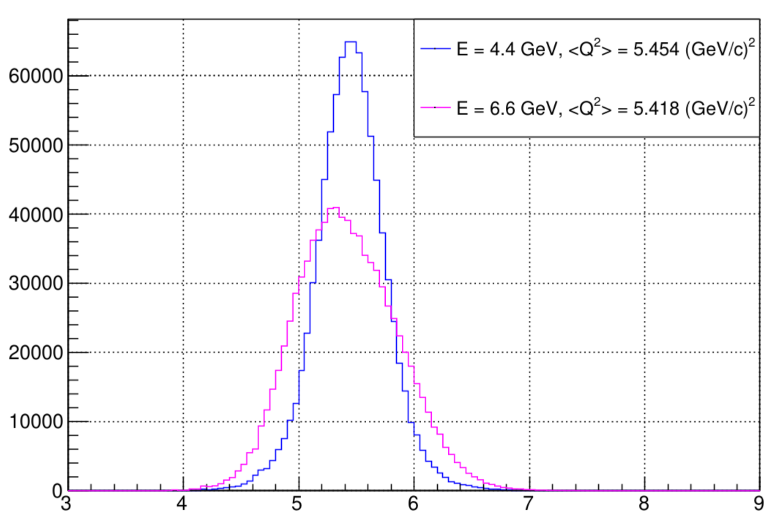
Issues: In their measurement projections, the proponents assume that a factor of three improvement in radiative correction uncertainties will be realized, which if not achieved, would significantly change the precision of the results. The PAC would like to see further justification that this error reduction is a reasonable assumption. Following a suggestion from the TAC, the possibility of running with a longer 30 cm target was also presented. The PAC would like to see a more detailed analysis of how systematic uncertainties are impacted for the 30 cm target.

nTPE+ Feedback from PAC

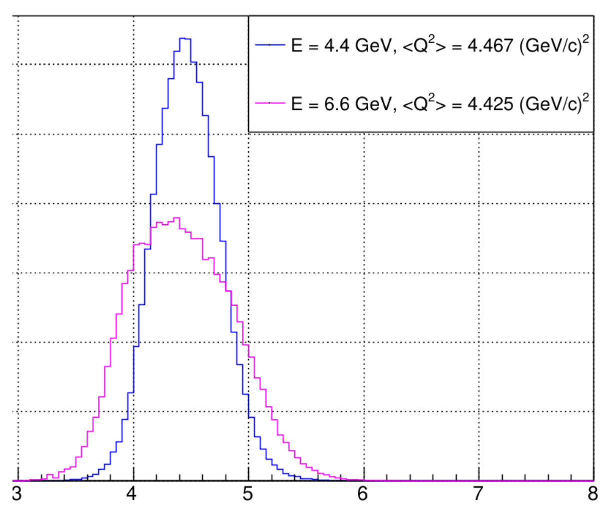
- Radiative corrections:
  - radiative corrections (SIMC baked-in) for GMn overly conservative;
  - effort required to update RC-induced uncertainty with different RC models :
    - *ESEPP* (not successful yet, would need guidance)
    - Other models

- Systematic effect from longer target:
  - Mostly due to slightly difference in average Q^2 from different acceptance
  - Induces slightly different p cross section value to account in superratio
  - To be integrated in the analysis for this proposal

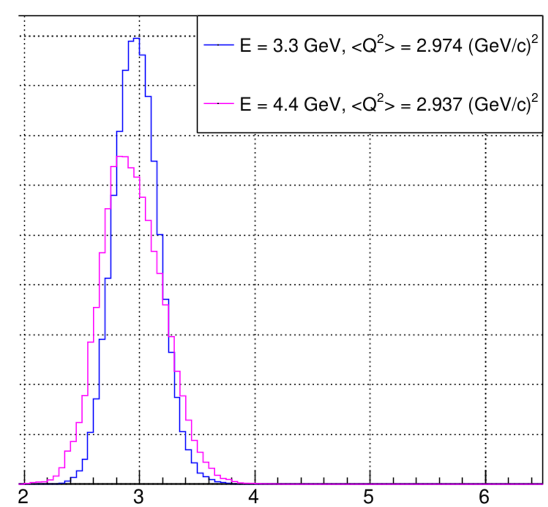
Q^2 = 5.5 $(GeV/c)^2$



Q^2 = 4.5 $(GeV/c)^2$



Q^2 = 3.0 $(GeV/c)^2$



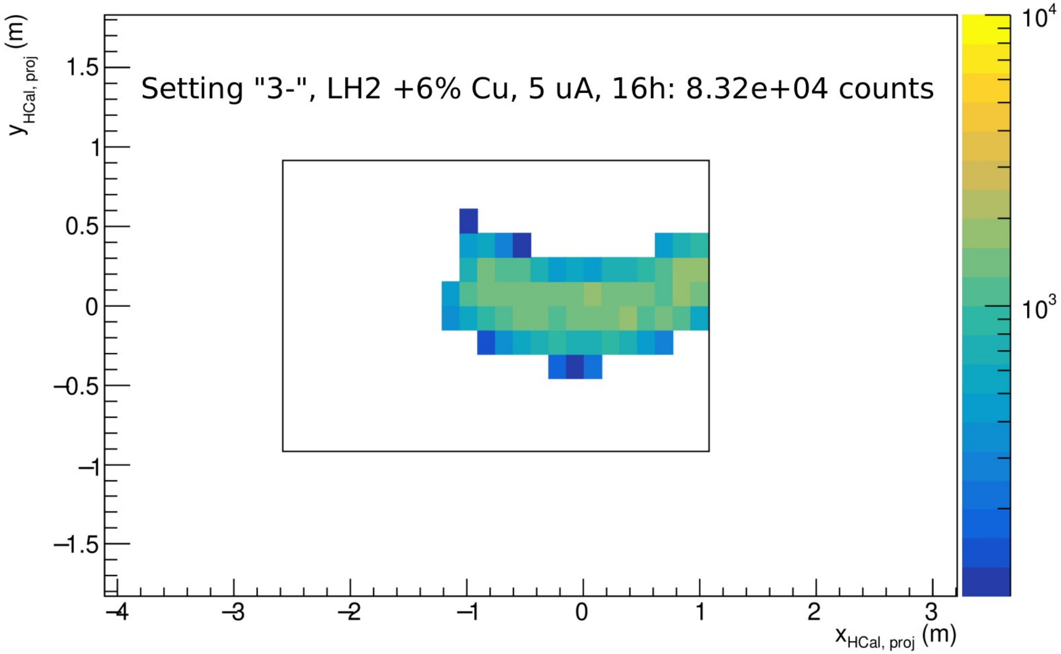
Summary

- PR12+25-006 (nTPE+):
  - unprecedented measurements on Two-Photon Exchange on Neutron:
  - Direct measurements of TPE in neutron with $R^n_{2\gamma}$
  - Rosenbluth measurements for e^+n and e^-n:
- Both complementary *and* "contradictory" to existing G_E^n measurements**:**
  - complements current SBS Form Factors program;
- Analysis will benefit from the return of experience of the nTPE (E12-20-010):
  - Extraction method worked out;
  - Systematics mostly under control;
- Conditionally approved C2 by PAC53:
  - Acknowledged interest for the proposal ;
  - Two questions to address

Neutron Detection Efficiency Measurement

- Neutron and protons detection efficiencies similar, but not identical;
  - Determine absolute detection efficiency for both protons and neutrons;

- *Explicit* beam request to measure $\gamma p \to \pi^+ n$ at “kinematic end-point”:
  - π^+ measured by BigBite, n measured by HCal;
  - Strict kinematic selection to ensure $\gamma p \to \pi^+ n$ exclusivity;
  - LH_2 target with 6 % X_0 copper upstream to enhance photon production ;
  - Electron beam to increase luminosity;
  - Coverage of ~1/4 of HCal surface sufficient to determine neutron efficiency



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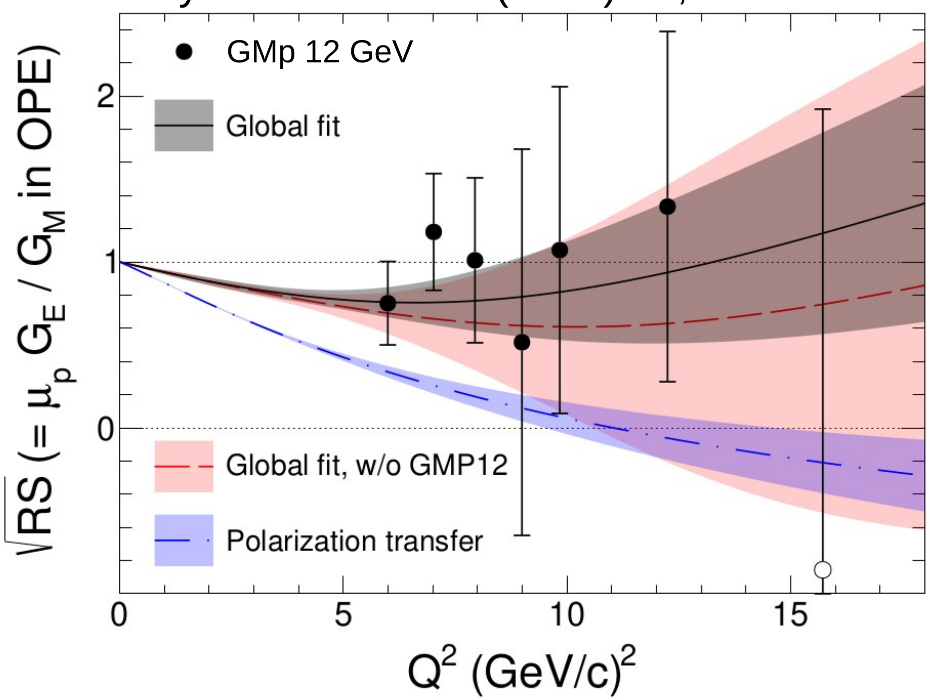
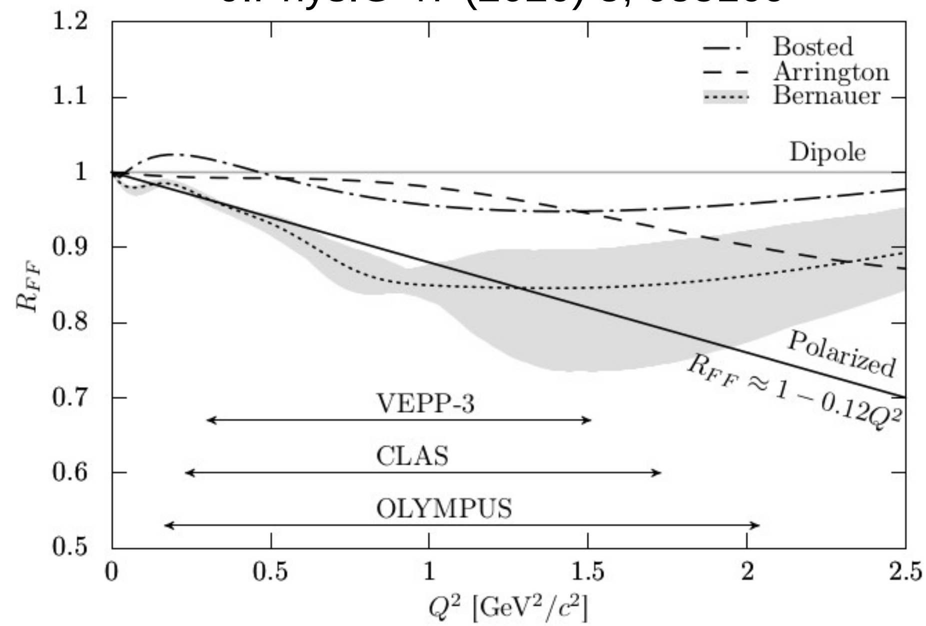
Phys.Rev.Lett. 128 (2022) 10, 102002

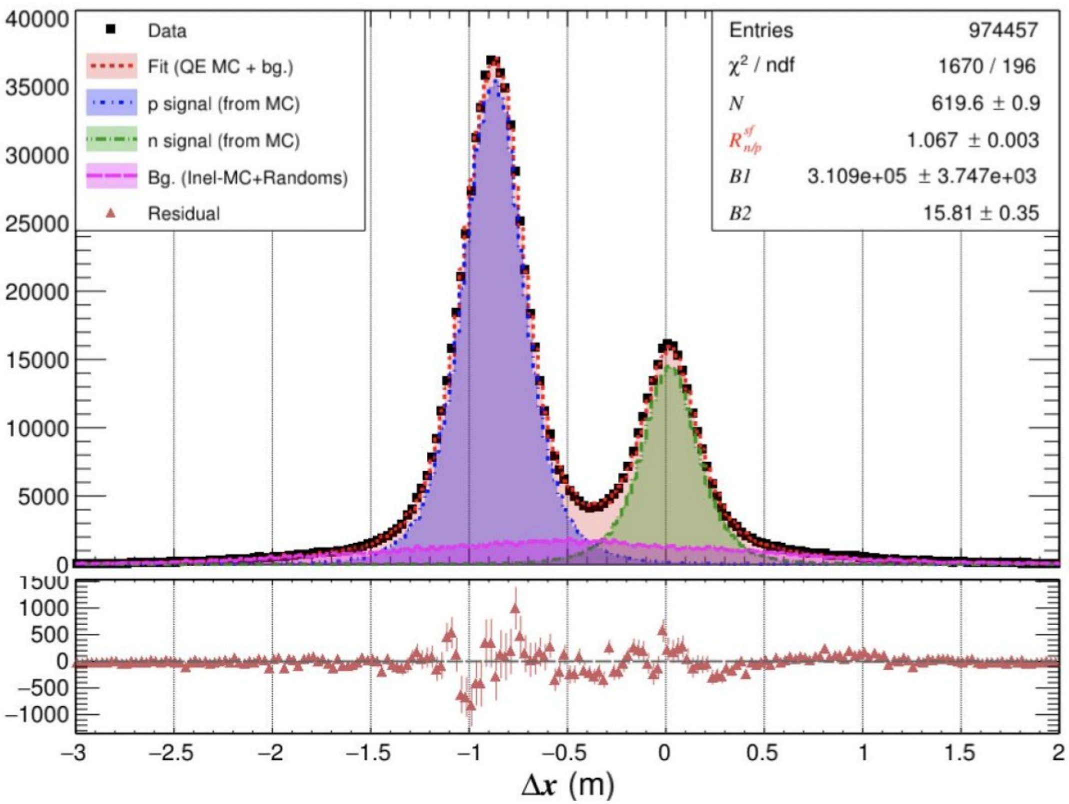


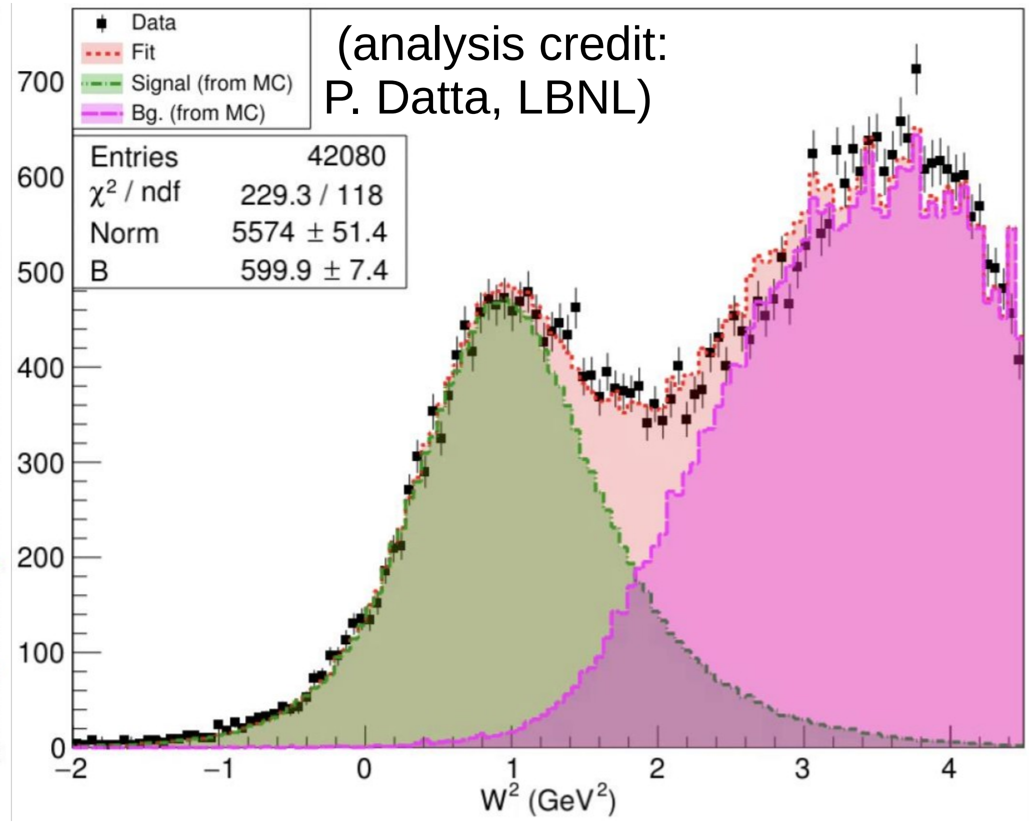
J.Phys.G 47 (2020) 5, 055109



Systematic uncertainties: Inelastic contamination

- Latest improvements on estimation of inelastic contamination:
  - Inelastic Monte Carlo combined with out-of-time events
  - neutron/proton cross section ratio obtained with newest function compared with:
    - 2^{nd} and 4^{th} order polynomials, gaussian to fit inelastic background;
    - Δy side-band selection



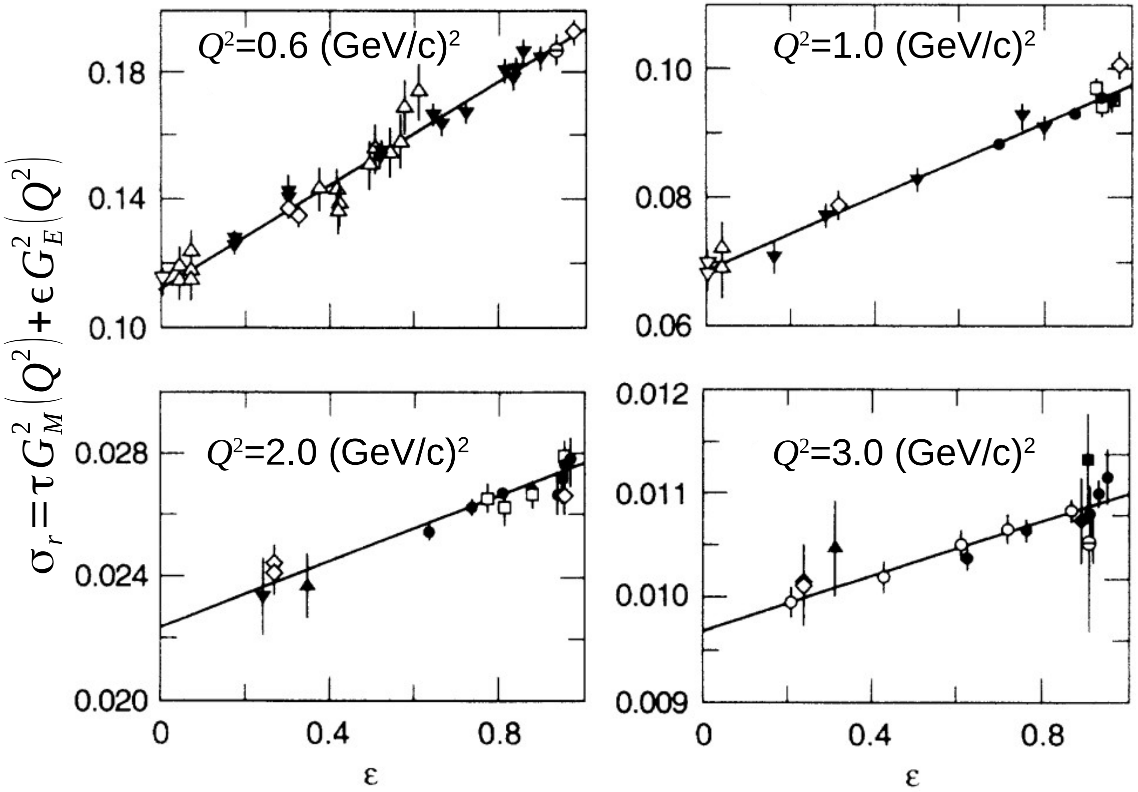


(analysis credit:
P. Datta, LBNL)

Rosenbluth Measurements in e^-p Scattering

- Rosenbluth technique extensively used on the proton to extract G_E^p
- **Linearity in ε well tested up to $Q^2 \le 3$ (GeV/c)^2**

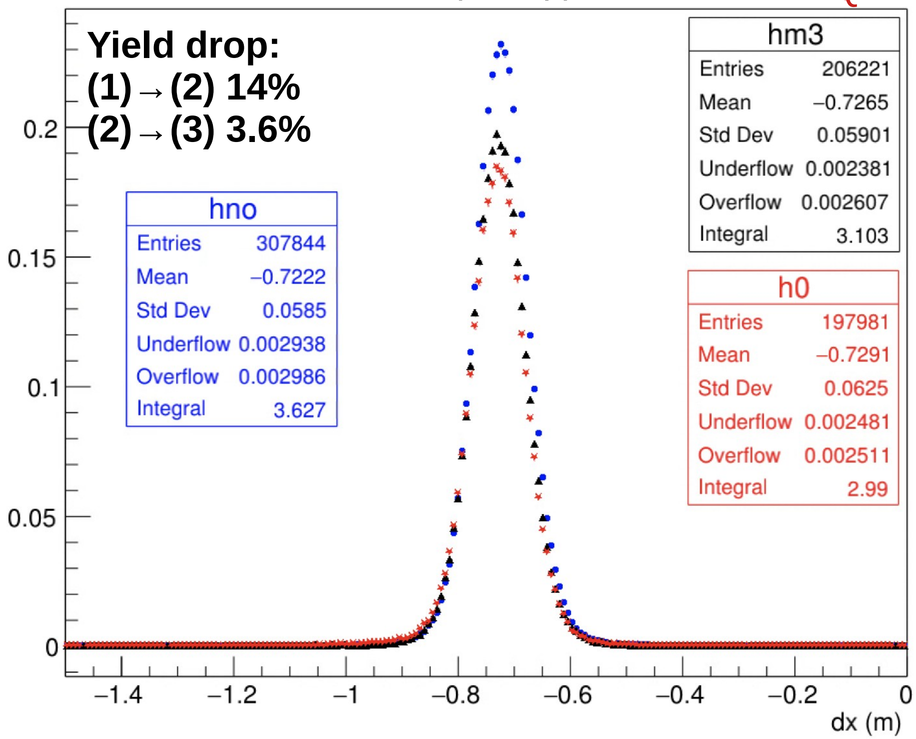
RS: Walker et al. Phys. Rev. D49, 5671 (1994)

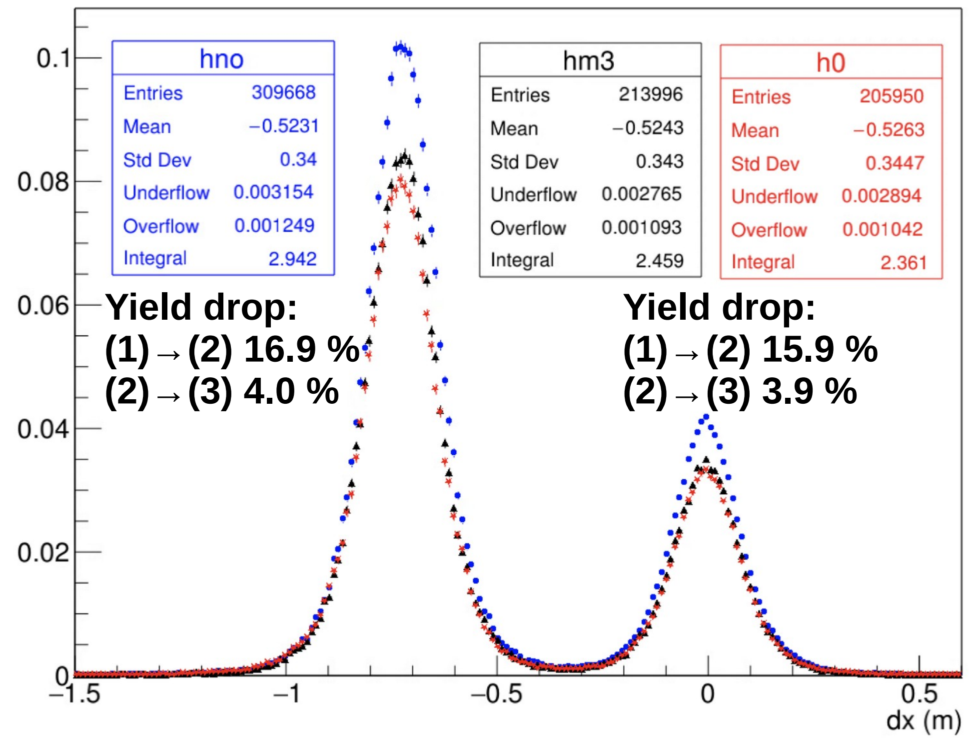


Systematic uncertainties: Radiative corrections

- Radiative corrections (analysis credit: P. Datta, LBNL):
  - SIMC events with the following configurations for radiative effects:
    - (1) - No radiative corrections i.e. none of the tails are radiated
    - (2) - One tail = 0 => All (e, e’, and p) tails are radiated
    - (3) - One tail = -3 => All but p tails are radiated
  - SIMC events processed through g4sbs → libsbsdig → SBS-offline;
  - Properly weighted Δx distribution for all types of events with the same selection
  - Extract individual yields and then quantify the correction

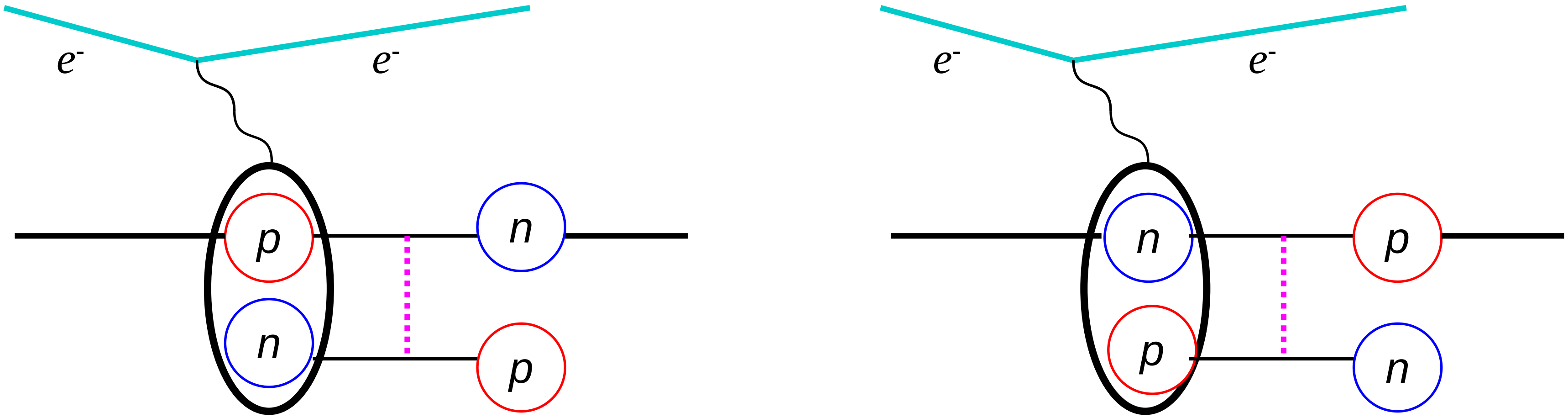
H(e, e’ p) $Q^2 = 13.5\ GeV^2$ D(e, e’ p) + D(e, e’ n)





Systematic uncertainties: FSI

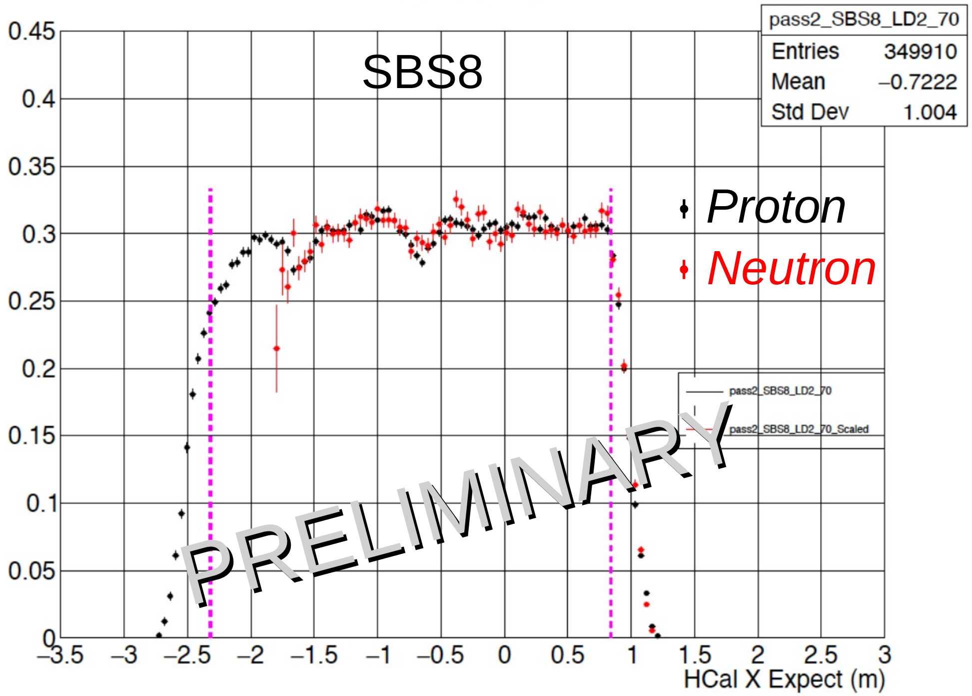
- Final state interactions calculated by M. Sargsian:
  - calculations of final state charge exchange $ep \to en$ and $en \to ep$ on deuterium

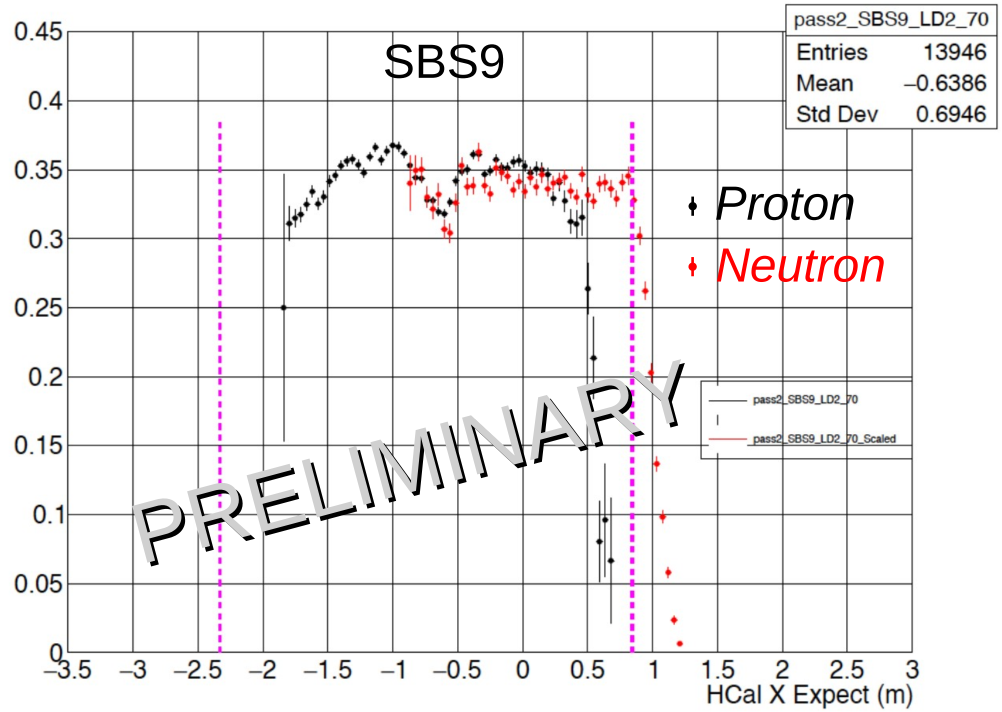


  - Since D is symmetric, $ep \to en \equiv en \to ep$:
    - ratio $R_{n/p}$ basically not affected
    - uncertainty on ratio $R_{n/p}$ extremely small

HCAL Non-Uniformity Corrections

- Reweight MC events with HCal non-uniformity map:
  - Analysis of all combined SBS8 LH2 settings for map efficiency:
  - *Neutron* efficiency drop comparable to *proton;*
  - Correction modifies σ_{en}/σ_{ep} by ~0.2 % (SBS8) and ~0.5 % (SBS9);
  - TODO: refine systematic error estimation;



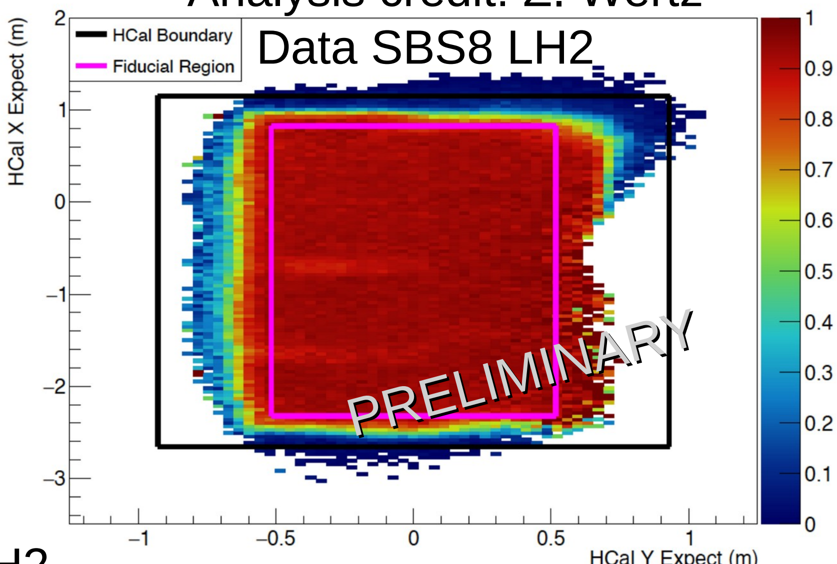


Analysis credit: Z. Wertz

HCAL Non-Uniformity Corrections

- Method to work around HCal efficiency non-uniformity:
  - Reweight MC events with HCal non-uniformity map;
  - Map efficiency along x_{expect}, y_{expect};
  - Efficiency analysis for data, MC;
    - MC weight: η_{data}/η_{MC};
    - deployed in analysis;
  - Similar efficiency drop for *p*, *n*:
    - Correction works for both;

Analysis credit: Z. Wertz



MC SBS8 LH2