PR12+25-006: Measurement of the Two-Photon Exchange in Electron-Neutron and Positron-Neutron Elastic Scattering

A Proposal to PAC53

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On behalf of the nTPE collaboration

Program Advisory Committee Meeting

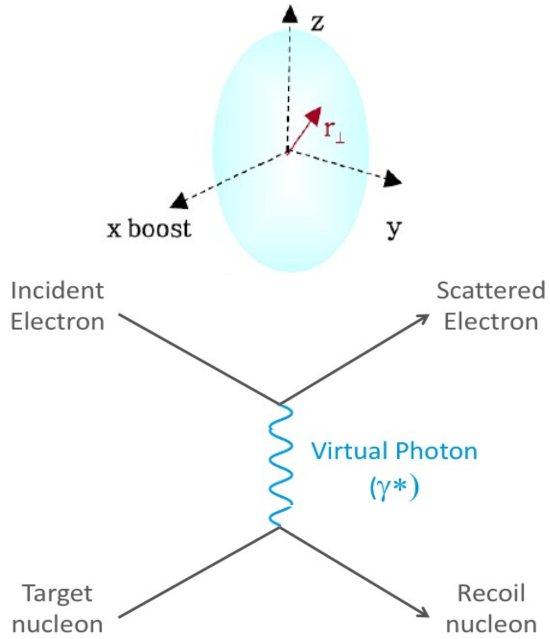
July 22th, 2025

WILLIAM & MARY

CHARTERED 1693

Jefferson Lab

Elastic *e-N* scattering: Rosenbluth



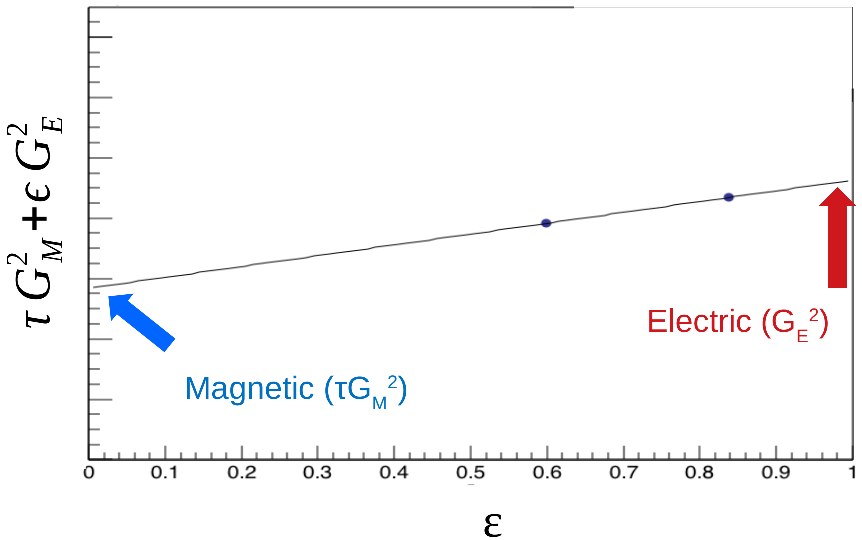
- Space-like Form Factors ≡ charge distribution
- In the One-Photon Exchange (Born) approximation:

$$\left(\frac{d\sigma}{d\Omega}\right)_{eN\to eN} = \frac{\sigma_{Mott}}{\epsilon(1+\tau)}\left[\underbrace{\tau G_M^2(Q^2)}_{\text{Sachs magnetic FF squared}} + \epsilon \underbrace{G_E^2(Q^2)}_{\text{Sachs Electric FF squared}}\right]$$

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

- 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

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

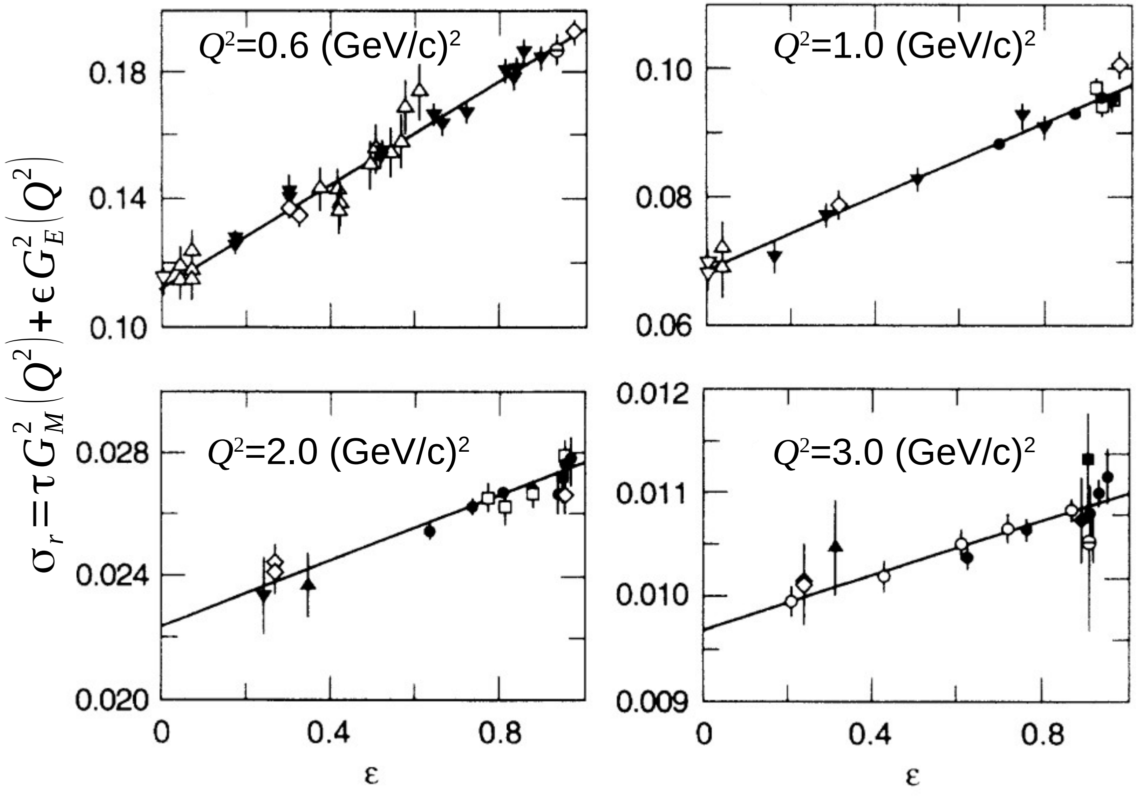


- Two or more measurements, same Q^2, different E and θ (different ε)

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 $Q^2 \leq 3$ (GeV/c)^2**

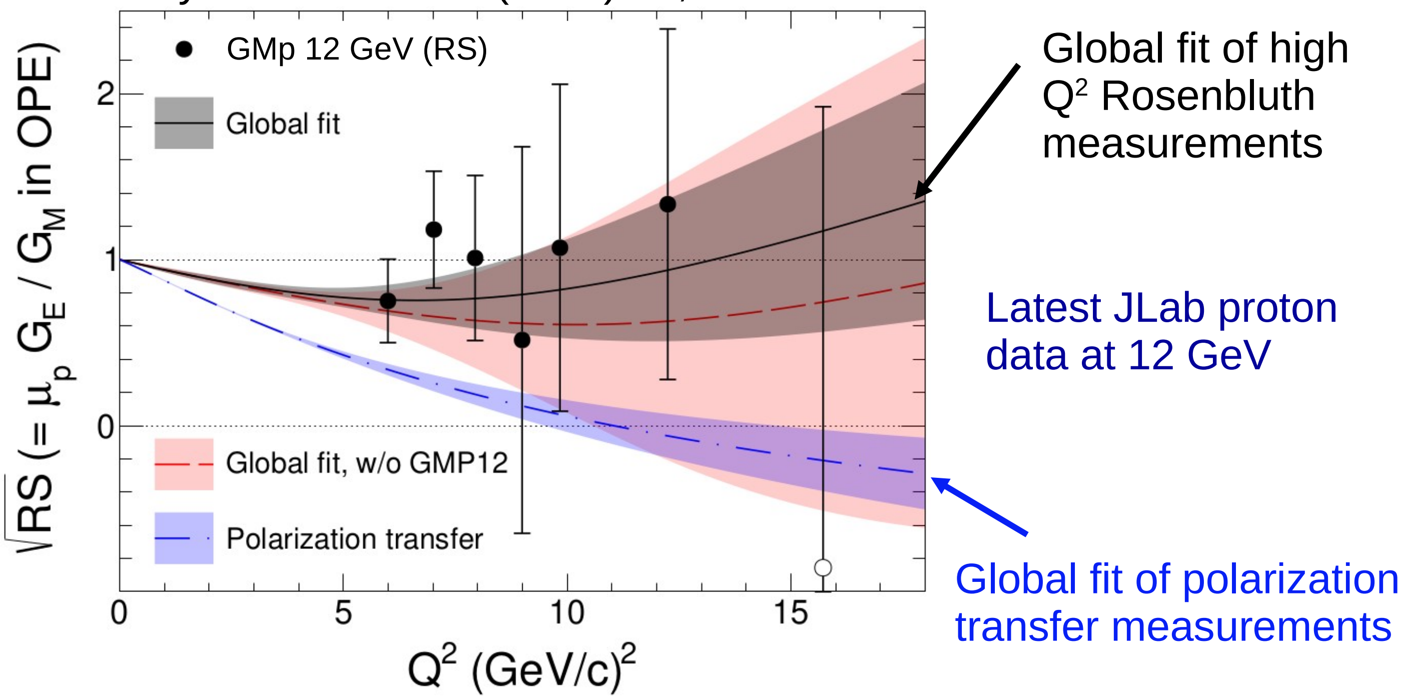
RS: Walker et al. Phys. Rev. D49, 5671 (1994)



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

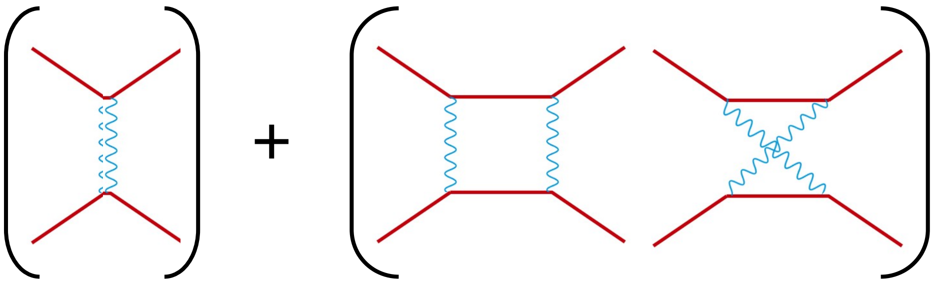


Two-Photon Exchange with Positrons

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

Lepton charge

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

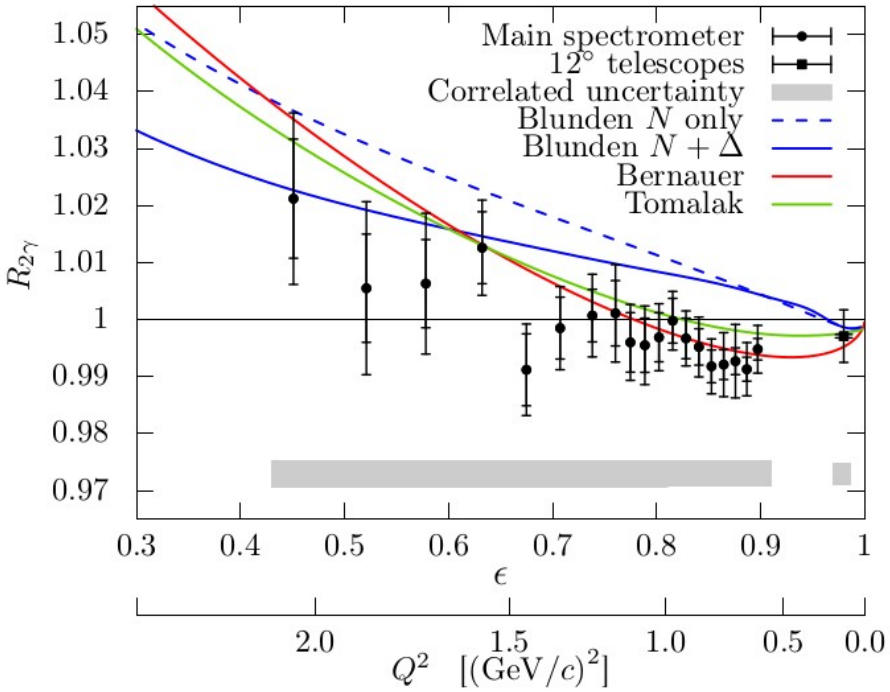


- Interference term depends on the lepton charge to the power 3:
  - TPE expected to be of same magnitude opposite sign in e^+N and e^-N;
  - measurement e^+N / e^-N => (1 + *2 TPE*)

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)

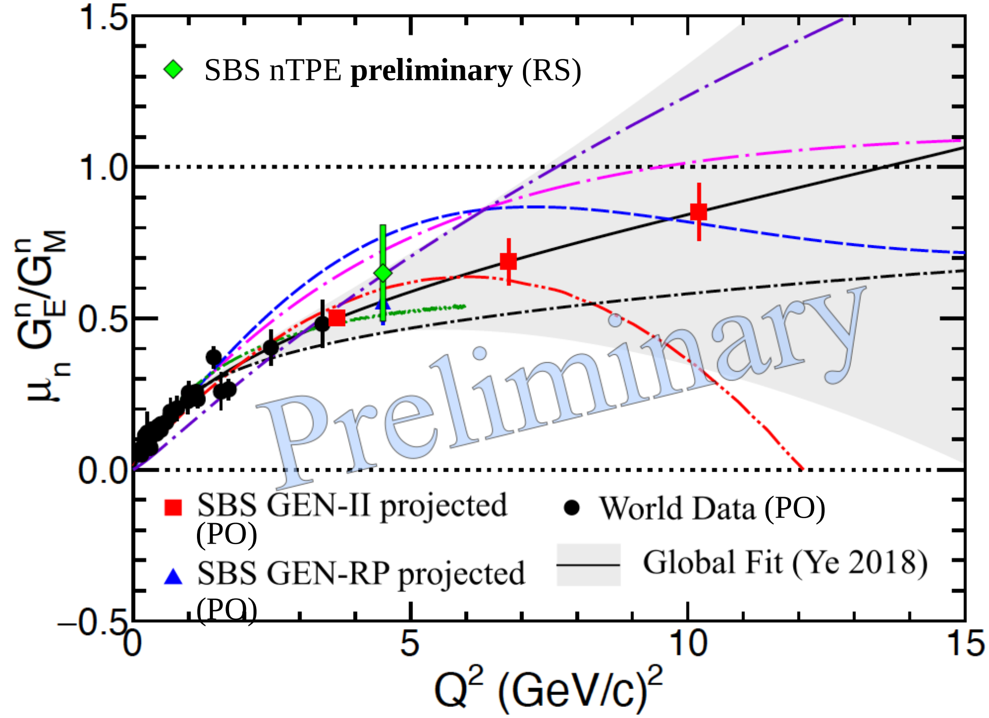


- Inconclusive results on significance of TPE effect at $Q^2 < 2$ GeV^2:
- Note: Rosenbluth/polarization discrepancy not very significant at low Q^2

en Scattering Measurements

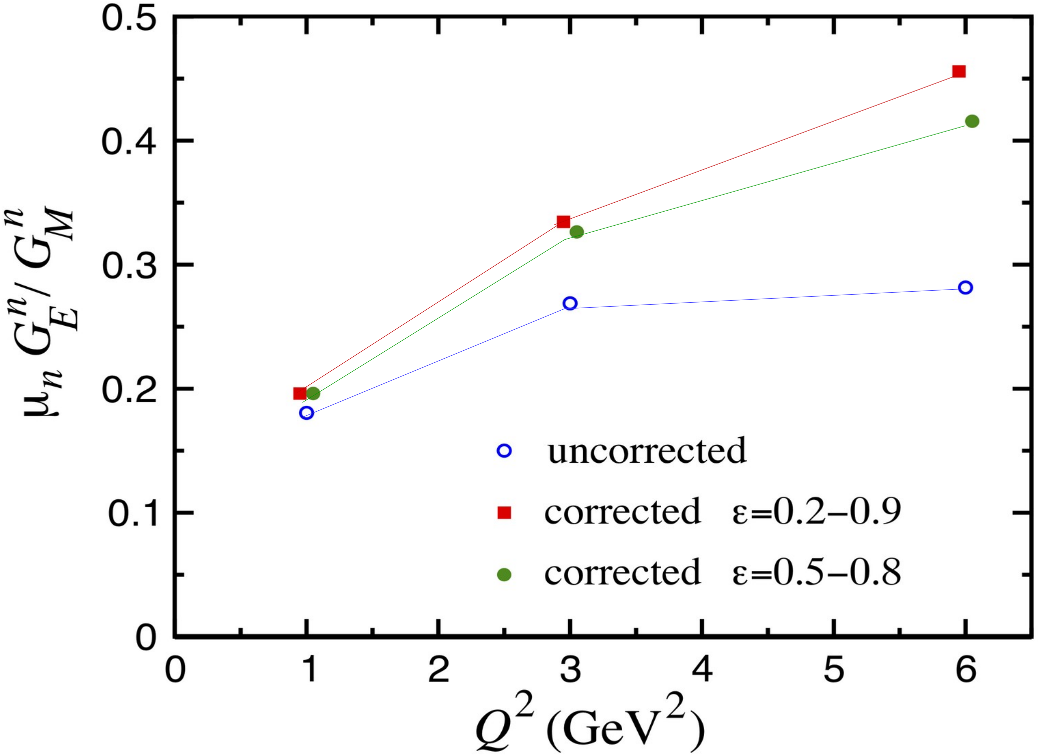
- **Existing measurements of G_E^n not as extensive as G_E^p:**
  - ◘ All *published* data below Q^2 = 3.5 GeV^2 (PO);
  - ◘ Measurements beyond Q^2 = 3.5 GeV^2 from SBS (analysis underway);
  - ◘ No recent (<50 years !) published Rosenbluth measurements on the neutron:
    - ♦ *Preliminary analysis 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)

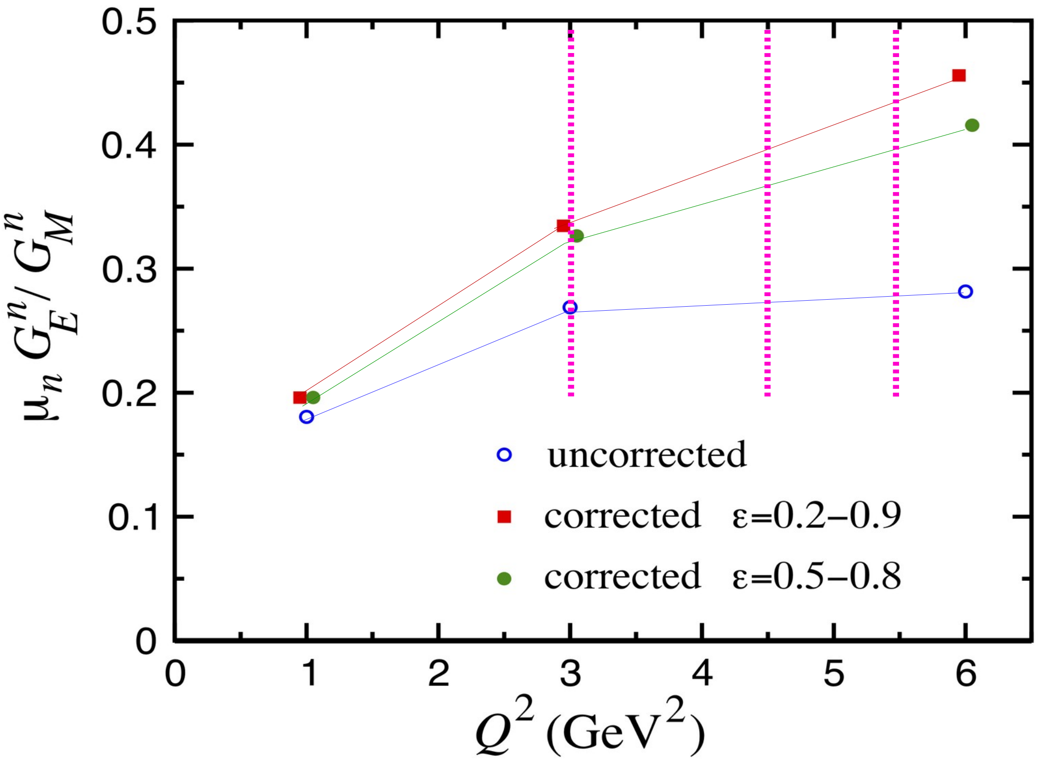
○ $\mu_n G_E^n/G_M^n$ *PO data fit*
from Mergell Meissner Drechsel
Nucl. Phys. A596, 367 (1996)

■ *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**
  - Followup of LOI12+24-008: **neutron TPE at Q^2 = 3 GeV^2, 4.5 GeV^2, 5.5 GeV^2**
  - 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



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

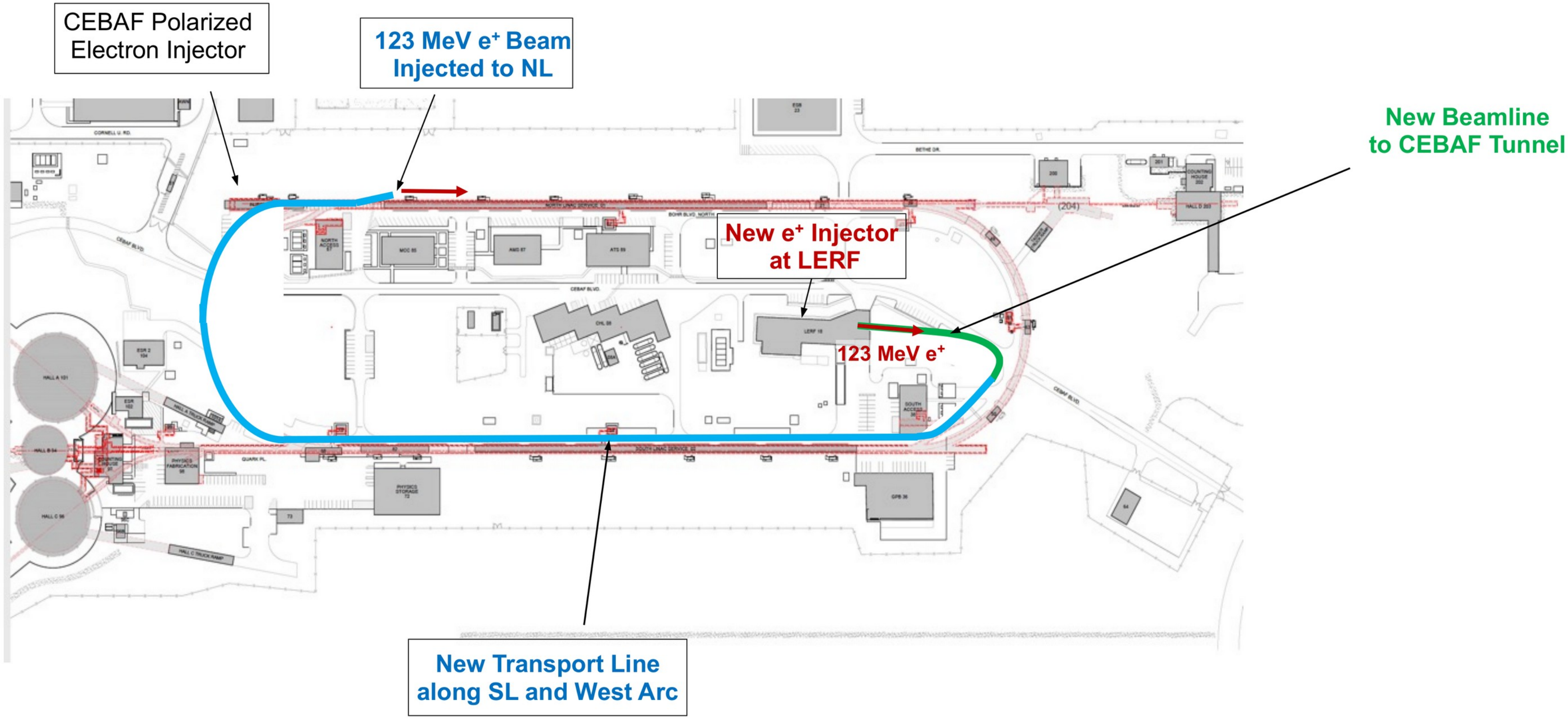
○ $\mu_n G_E^n/G_M^n$ *PO data fit* from Mergell Meissner Drechsel Nucl. Phys. A596, 367 (1996)

■ *Expected RS* measurement of $\mu_n G_E^n/G_M^n$ between ε = 0.2 and 0.9

● *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

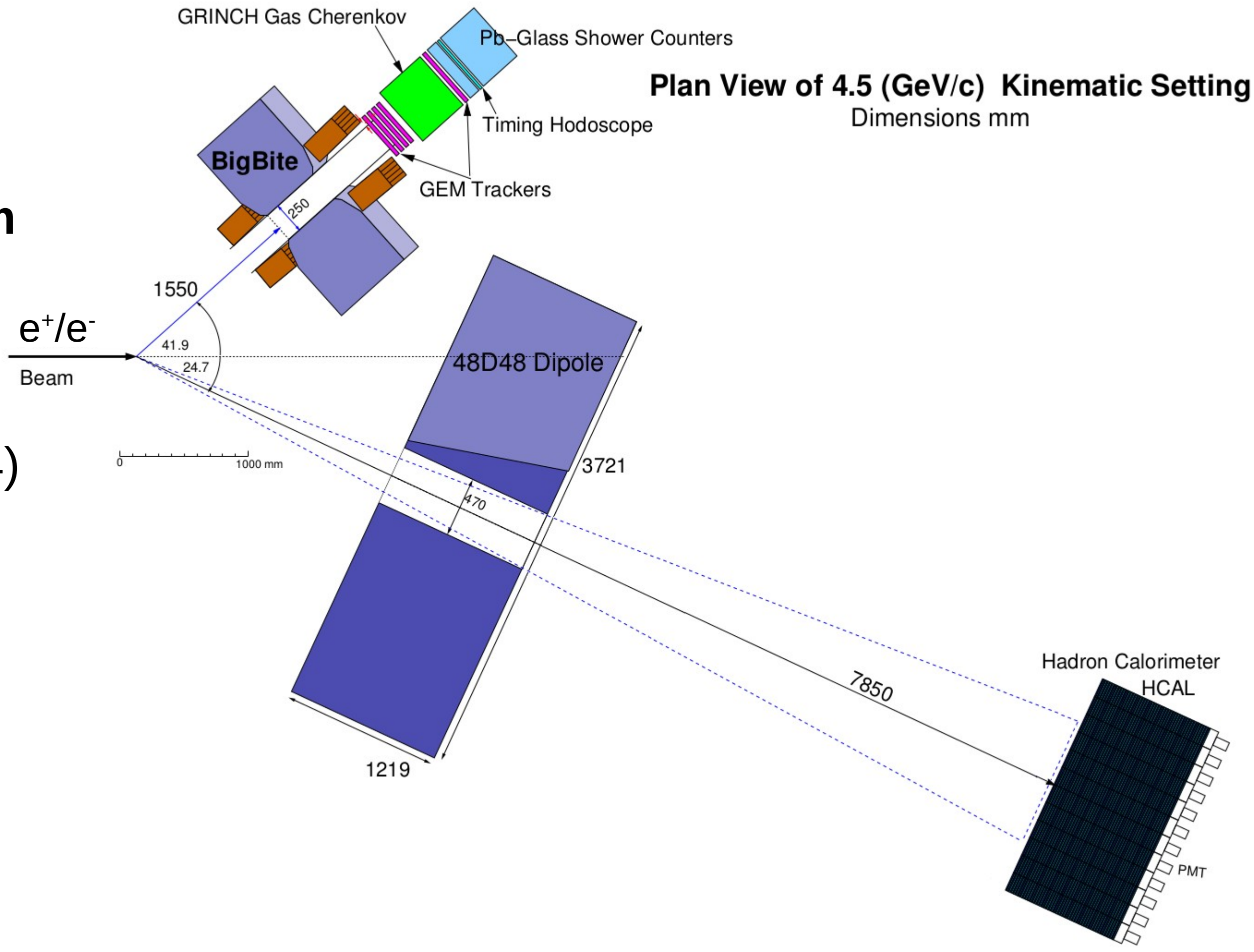
- New injector to produce polarized positrons (and electrons)
- Promised specifications:
  - **1μA e^+ without polarization**;
  - 60nA with polarization;



nTPE+ with Super BigBite Spectrometer

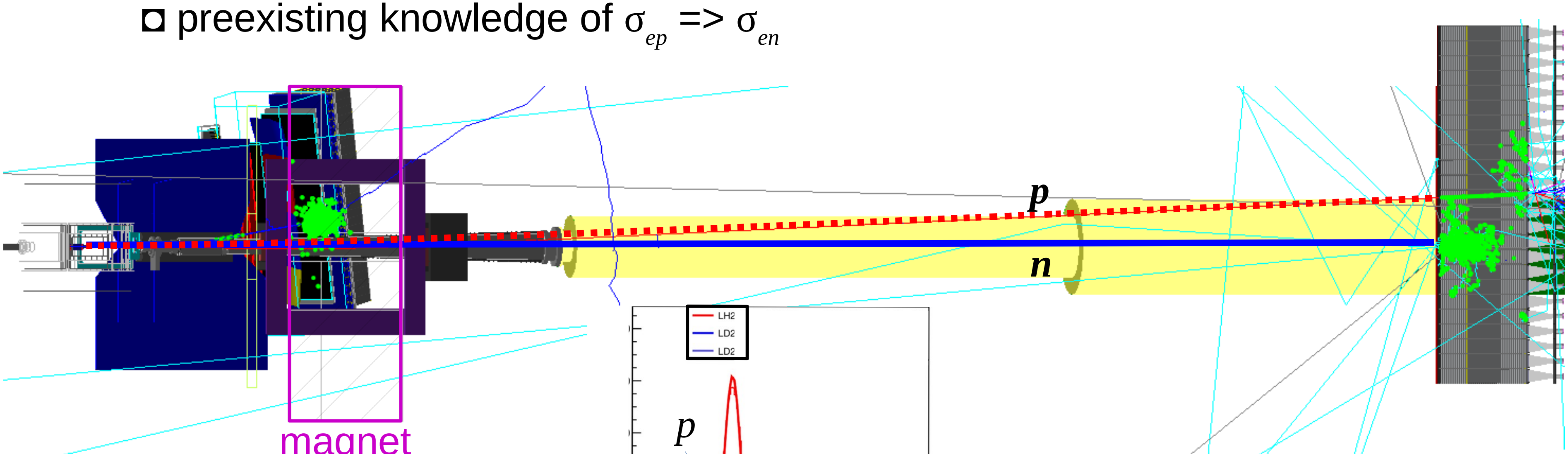
- **SBS:**
  - Major part of Hall A 12 GeV program at Jefferson Lab;
  - SBS coupled with Bigbite spectrometer for electron measurement;
  - SBS uses Hadron Calorimeter (HCal) for nucleon detection / ID;

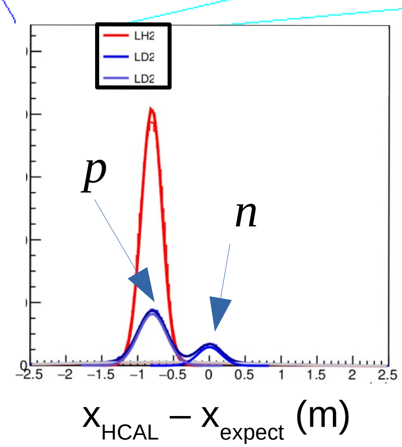
- **SBS form factor program**
  - GMN (E12-09-019)
  - *nTPE* (E12-20-010)
  - GEN (E12-06-016)
  - GEN-RP (E12-17-004)
  - GEP (E12-07-109)



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 $\sigma_{ep} \Rightarrow \sigma_{en}$

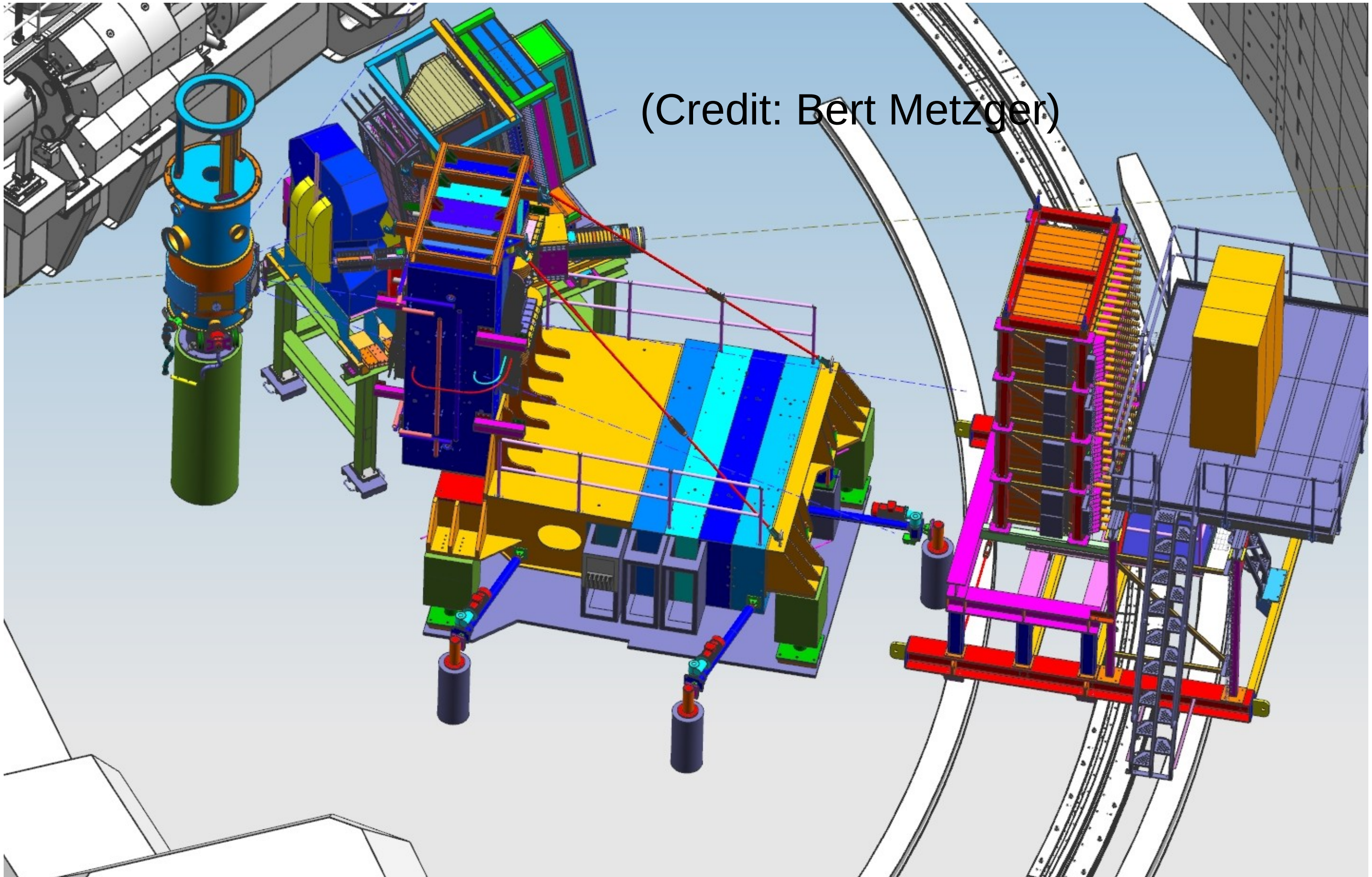




X_{HCAL}: reconstructed
x_{expect}: predicted from e^-

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;



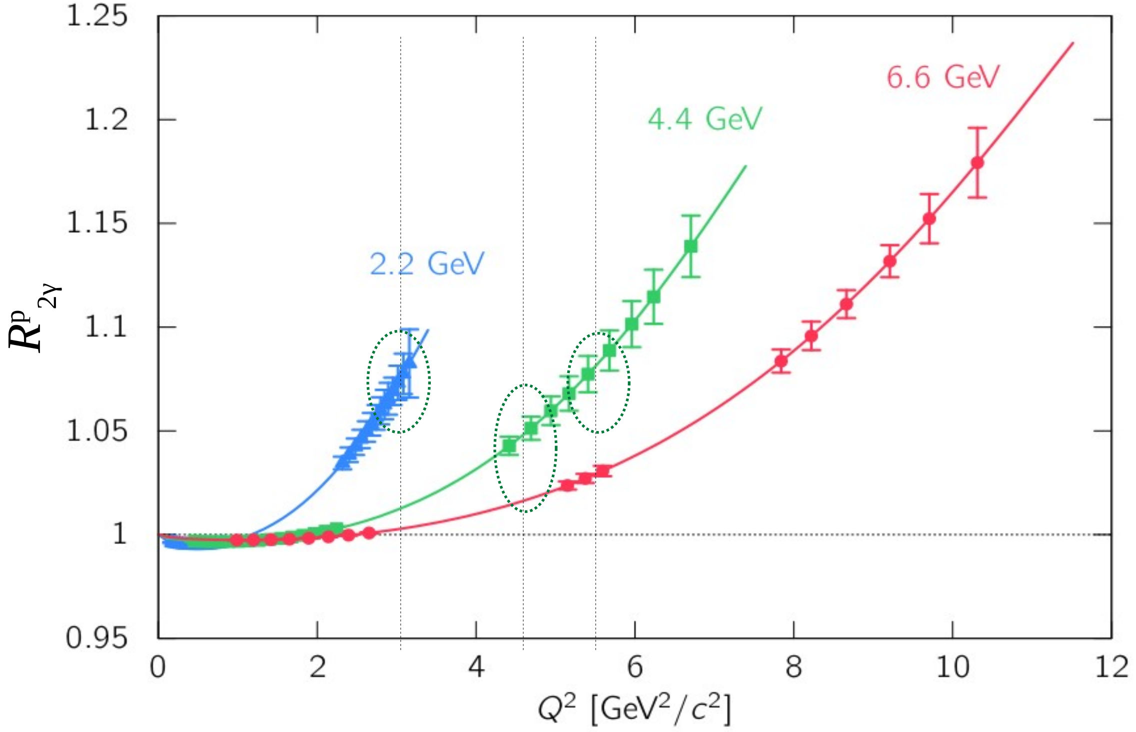
nTPE+ Kinematics

- 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

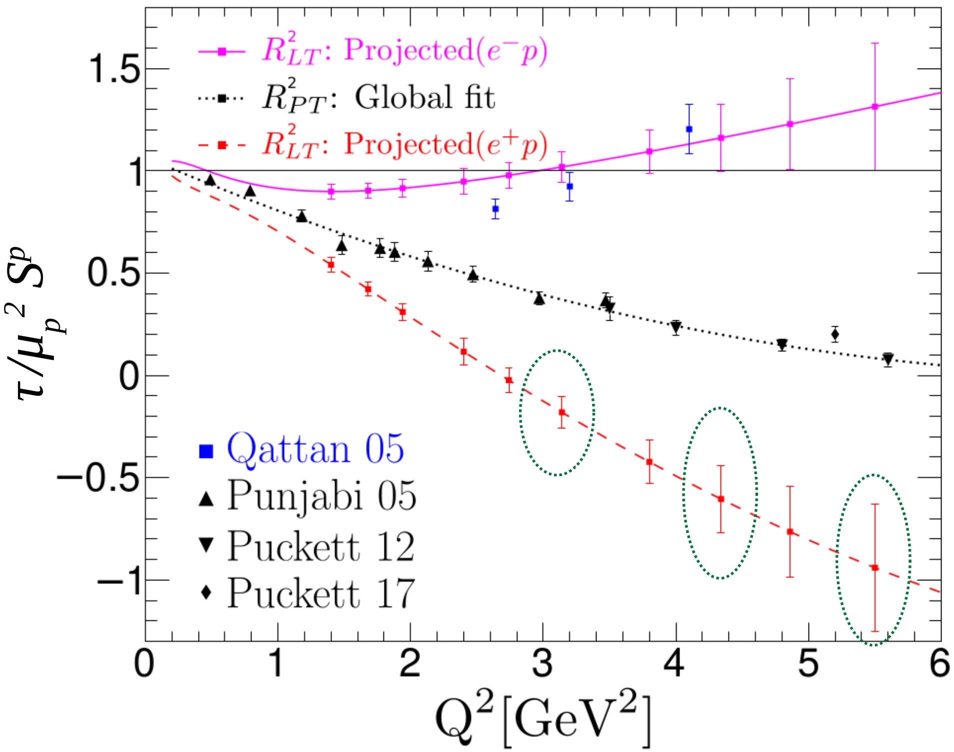
nTPE+ Measurements: e^+n/e^-n ratios $R^n_{2\gamma}$

- $R^n_{2\gamma}$ 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)
  - $\rho_\pm = \dfrac{R^{e^+}_{n/p}}{R^{e^-}_{n/p}} = \dfrac{R^n_{2\gamma}}{R^p_{2\gamma}}$ 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;
  - $$A = \frac{R^{\epsilon_1}_{n/p}}{R^{\epsilon_2}_{n/p}} \simeq \frac{1+\epsilon_2 S^p}{1+\epsilon_1 S^p} \times (1 + S^n \Delta\epsilon)$$
  - 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
    - 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 $((\mathrm{GeV/c})^2)$	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

$Q^2((\mathrm{GeV/c})^2)$	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

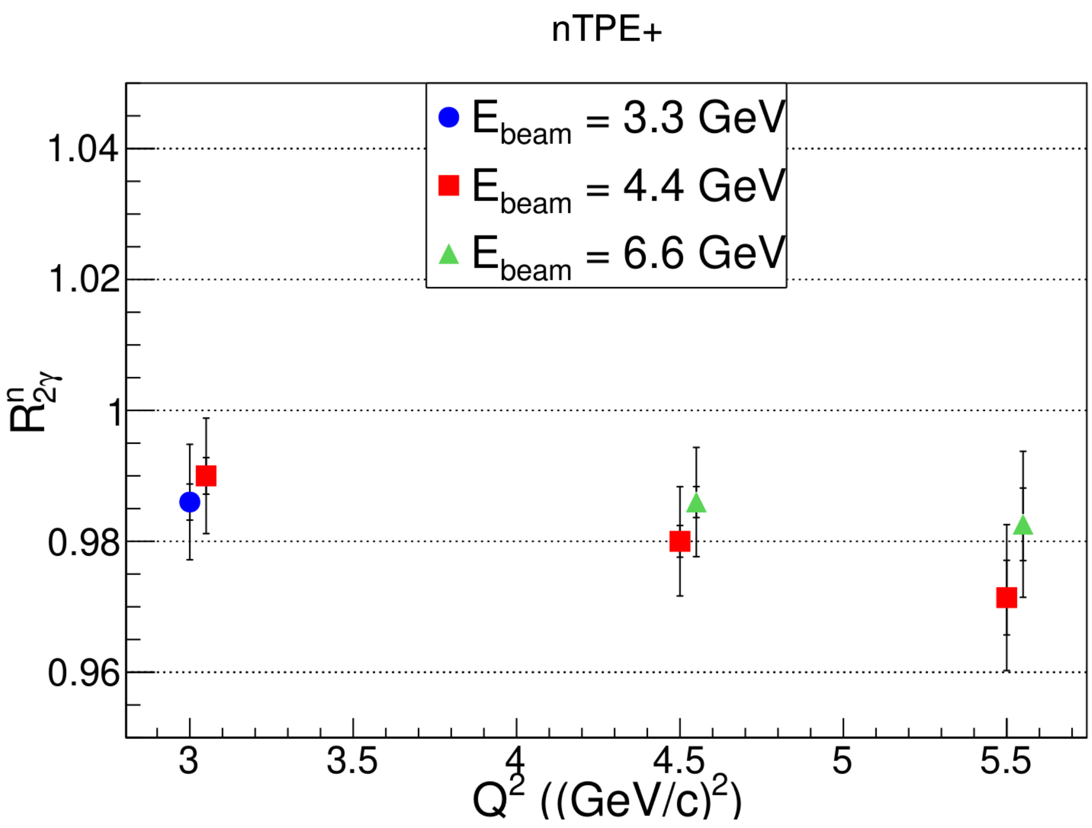
[3] Projected $e^+ p$ S^p: M. Nycz *et al.* PR12+23-012

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 (outer bars);

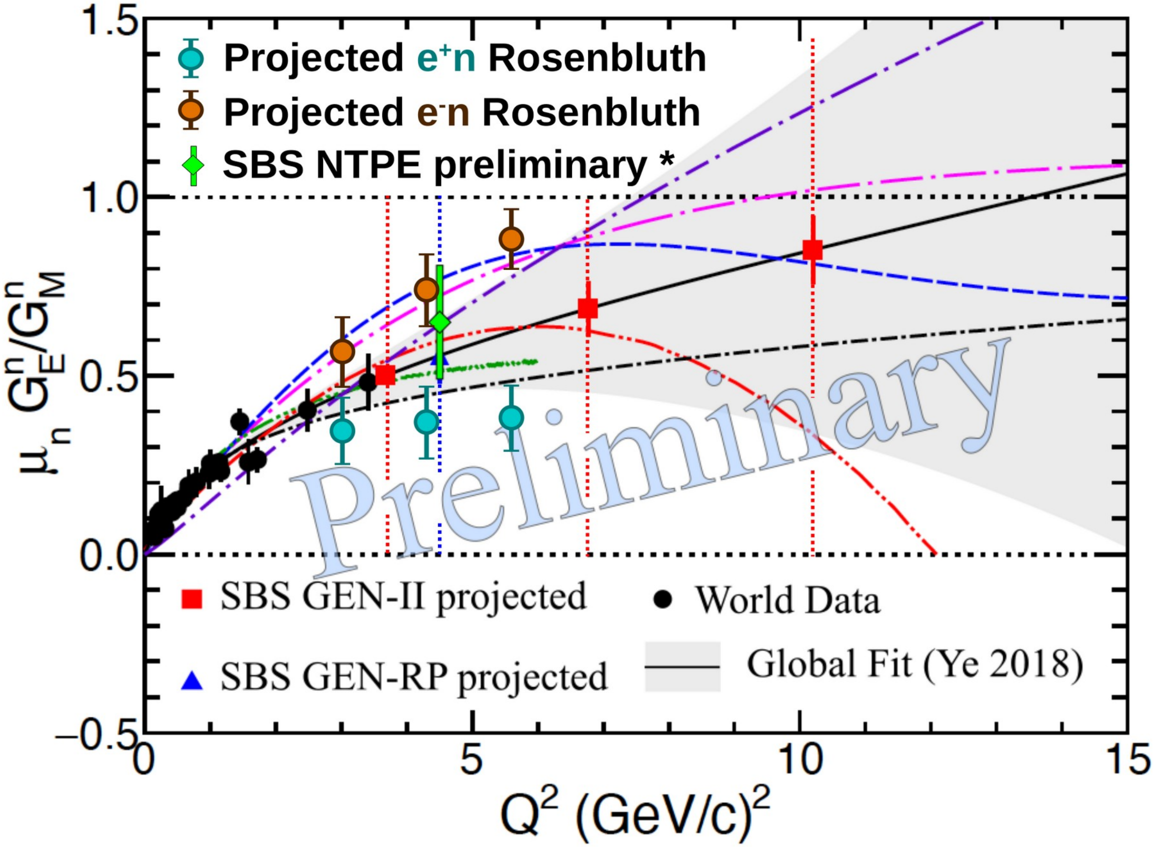


* Note/Erratum: The TPE effect on the neutron should decrease the ratio $R^{n}_{2\gamma}$ as shown here, not increase it as shown on Figure 8 of the original PR12+25-006 document.

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).



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:

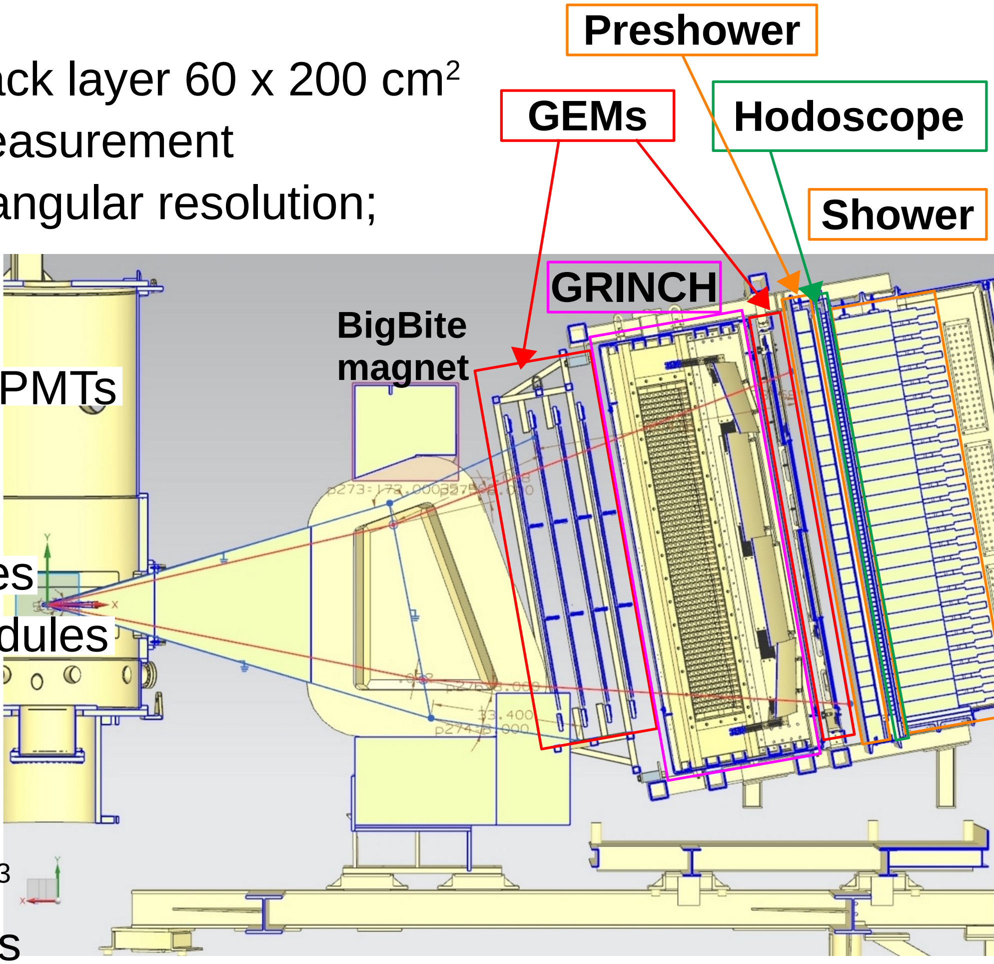
- Both complementary *and* "contradictory" to existing G_E^n measurements**:**
  - complements current SBS Form Factors program;

- Analysis will benefit from the return of experience of the nTPE (E12-20-010):
  - Extraction method worked out;
  - Systematics mostly under control;

Thank you for your attention !

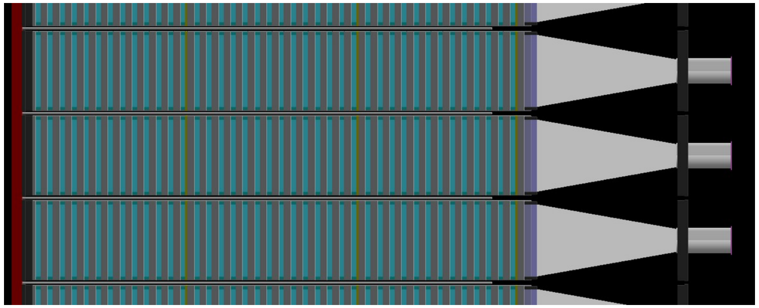
Super BigBite Spectrometer: BigBite

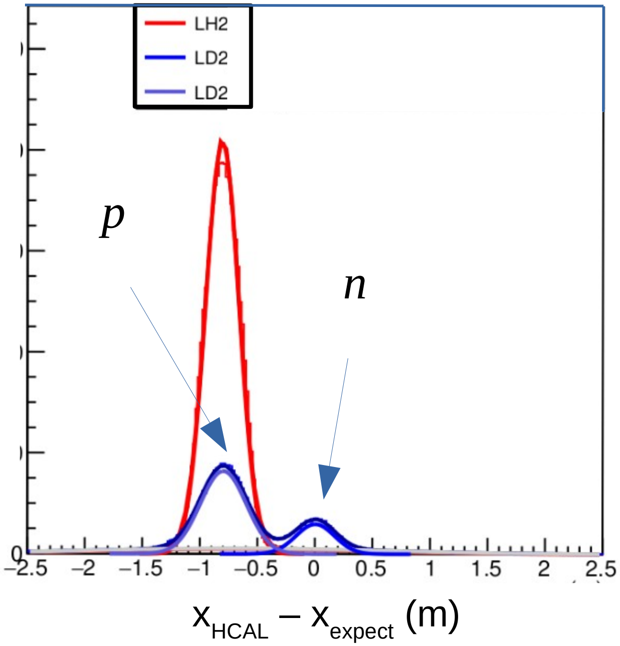
- Detector package tilted 10% behind dipole magnet
- **Function: Electron measurement;**
- Detector package:
  - GEMs:
    - 4 front layers 40 x 150 cm^2, 1 back layer 60 x 200 cm^2
    - momentum trivector + vertex measurement
    - 1% momentum resolution, 1mr angular resolution;
  - GRINCH:
    - C4F8 Cherenkov radiator
    - Cherenkov light readout by 510 PMTs
    - Electron ID ~98% Pion rejection
  - Calorimeter: (shower+preshower)
    - Shower: 7x27 lead glass modules
    - PreShower: 2x26 lead glass modules
    - Trigger
    - Electron ID/Pion rejection
  - Hodoscope:
    - 90 Scintillators 60 x 2.5 x2.5 cm^3
    - scintillators readout on both ends
    - Precision Timing: 500 ps resolution



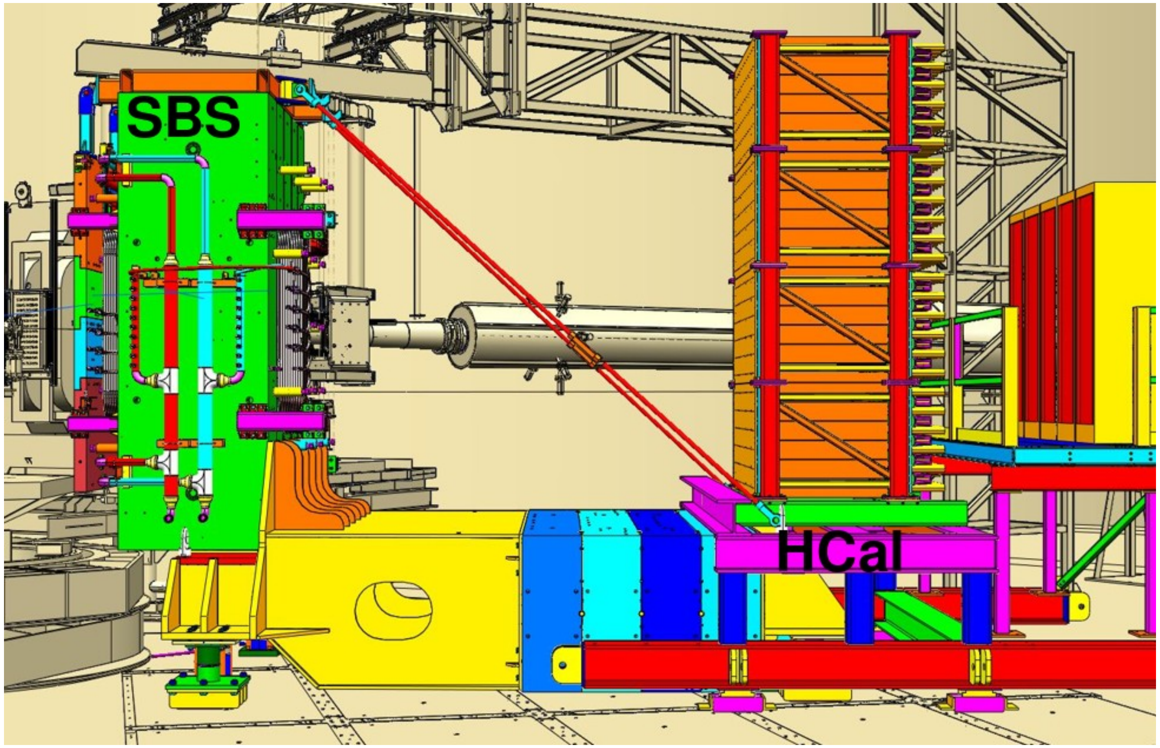
Super BigBite Spectrometer: HCal

- 12 x 24 iron/scintillator modules 15 x 15 * 90 cm^3
- **Function: Nucleon measurement:**
  - Position resolution ~5.5cm
  - Timing resolution (*ADC only*) ~1.5 ns
  - Energy resolution ~50 %
- **Nucleon identification (see next)**





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



nTPE+ Updated for 2025

Feedback for LOI-E12+24-008

- Reviewers recommends:
  - measuring ratios of cross sections $\left(\frac{\sigma_{e^+n}}{\sigma_{e^+p}}\right) / \left(\frac{\sigma_{e^-n}}{\sigma_{e^-p}}\right)$ at each ε point;
    - would provide $\delta^n_{TPE}(\varepsilon_2) - \delta^n_{TPE}(\varepsilon_1)$ and $\delta^p_{TPE}(\varepsilon_2) - \delta^p_{TPE}(\varepsilon_1)$
    - hydrogen data (e^+, e^-) needed to check systematics
    - *same nucleon footprint on* σ_{e+n}, $\sigma_{e\text{-}n}$ may reduce HCal systematics

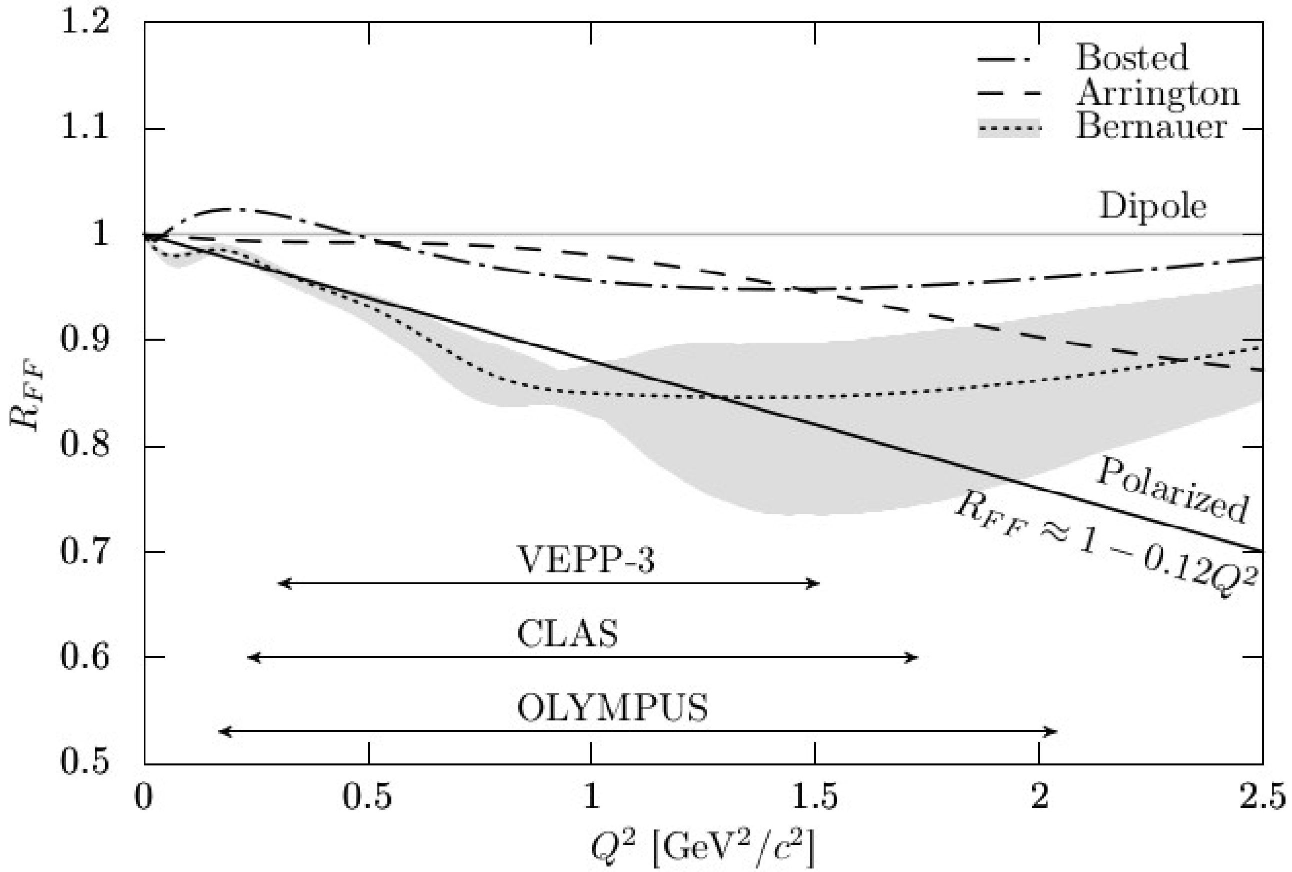
- Reviewers concerned with:
  - difference of current between e^+ (1μA) and e^- (10μA) running;
    - Not so relevent for Rosenbluth measurements;
    - *becomes more important in* $\sigma_{e+n}/\sigma_{e\text{-}n}$

- Reviewers suggest another point at higher Q^2

Global Fit on Rosenbluth Slope in e^-p Scattering

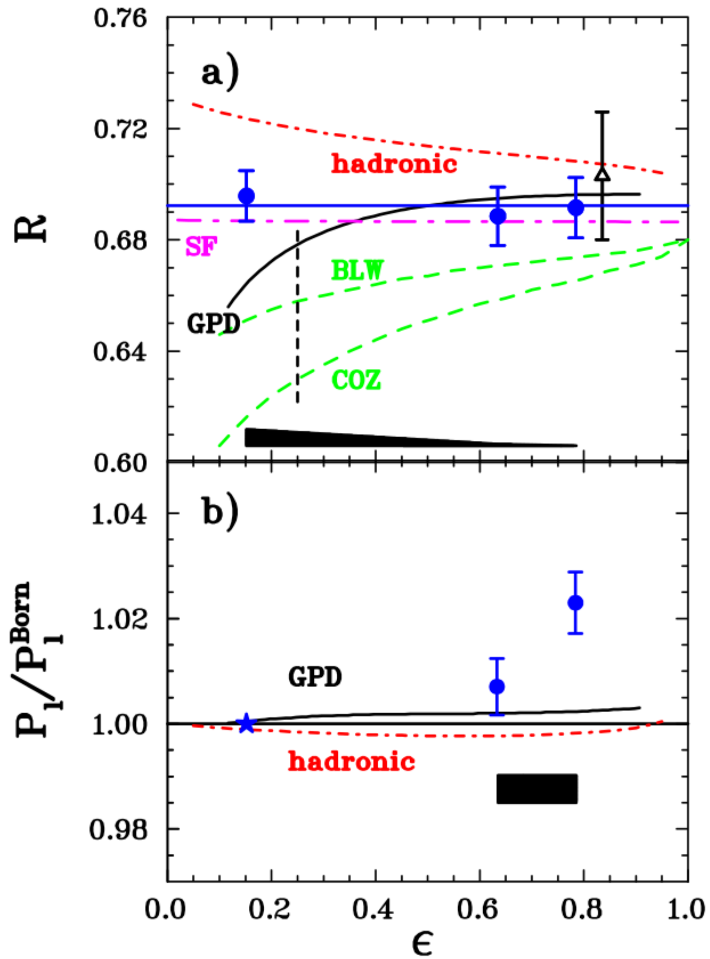
- Rosenbluth/polarization discrepancy not very significant at low Q^2

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



$e^{-}p$ Scattering: G_E^p-2γ results

- Results from [Phys.Rev.Lett. 106 (2011) 132501] :
  - Rosenbluth separation combined with polarization transfer



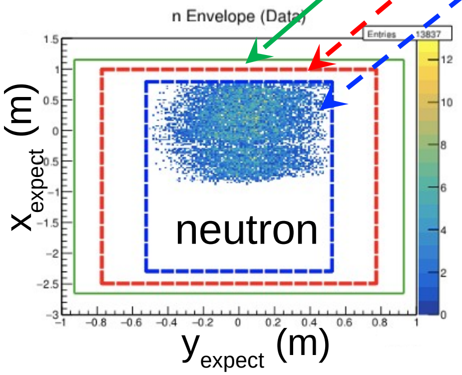
nTPE+ Systematics: GMn/nTPE Analysis

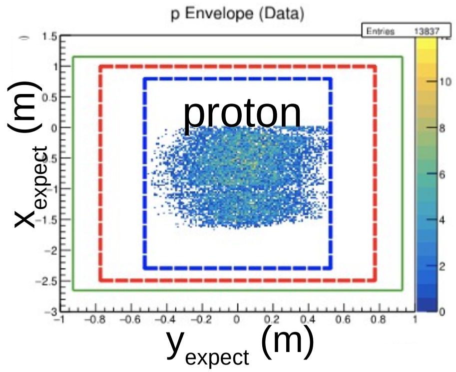
- Analysis: extraction of n/p ratios:

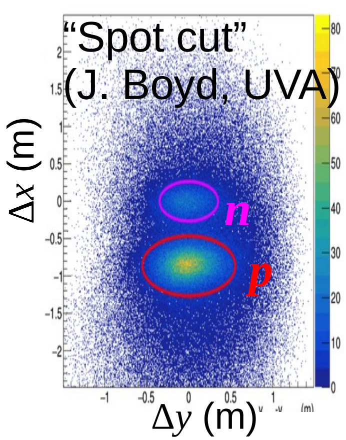
Elastic selection

HCAL Boundary
Active Region
"Fiduclal Cut"

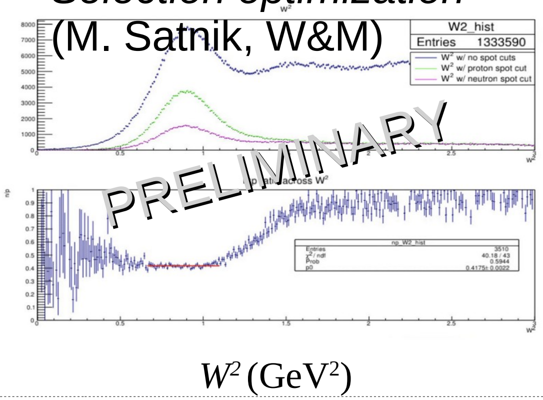
Fiducial cut
(P. Datta, UConn/LBNL)



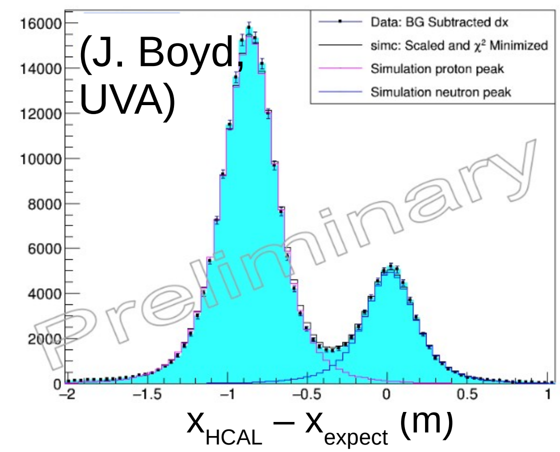




Selection optimization
(M. Satnik, W&M)



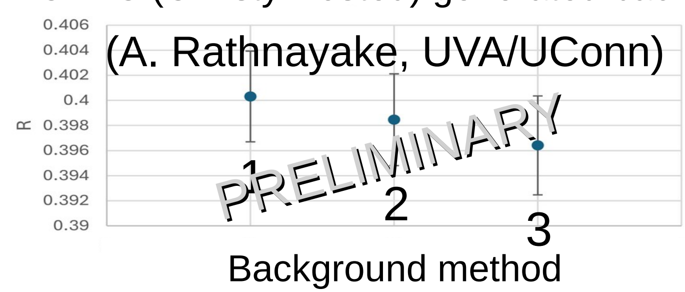
$N_n/N_p \rightarrow \sigma_n/\sigma_p$ correction with MC



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

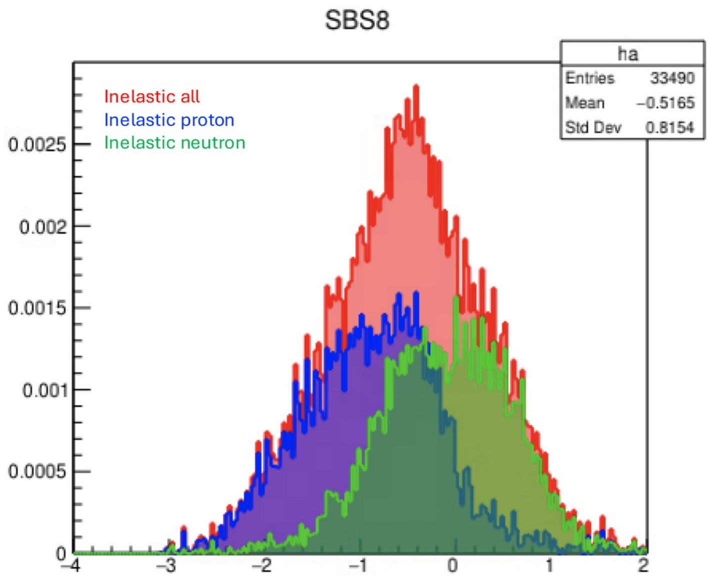
Inelastic background subtraction

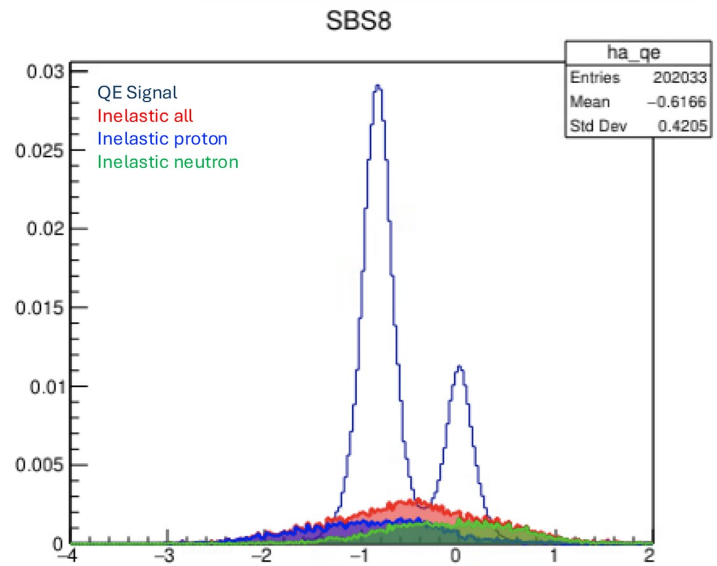
- 1: Combined fit $en+ep$ +background of data Δx
- 2: Data background (HCal "antiselection");
- 3: MC (Christy-Bosted) generated background

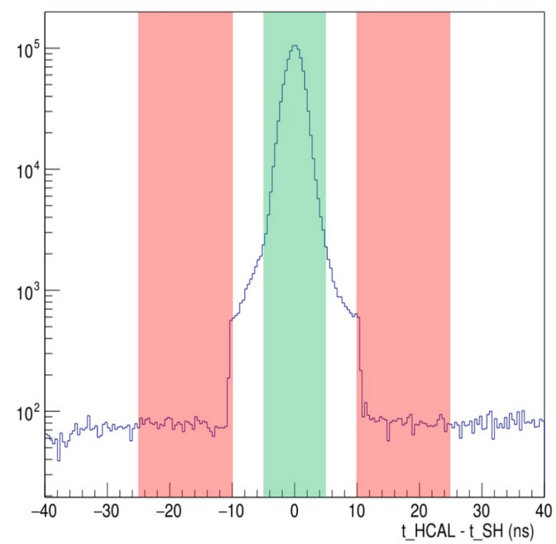


Systematic uncertainties: Inelastic contamination

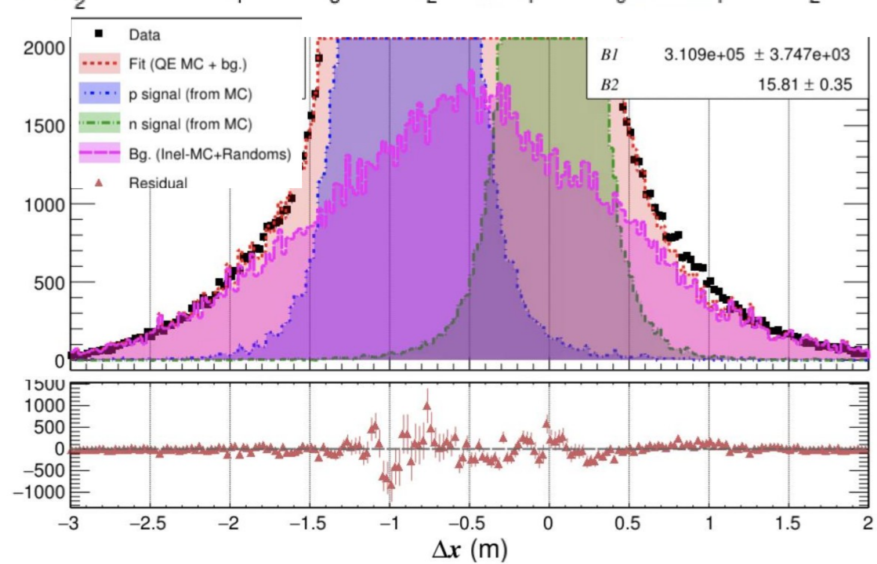
- Latest improvements on estimation of inelastic contamination:
  - Inelastic Monte Carlo combined with out-of-time events





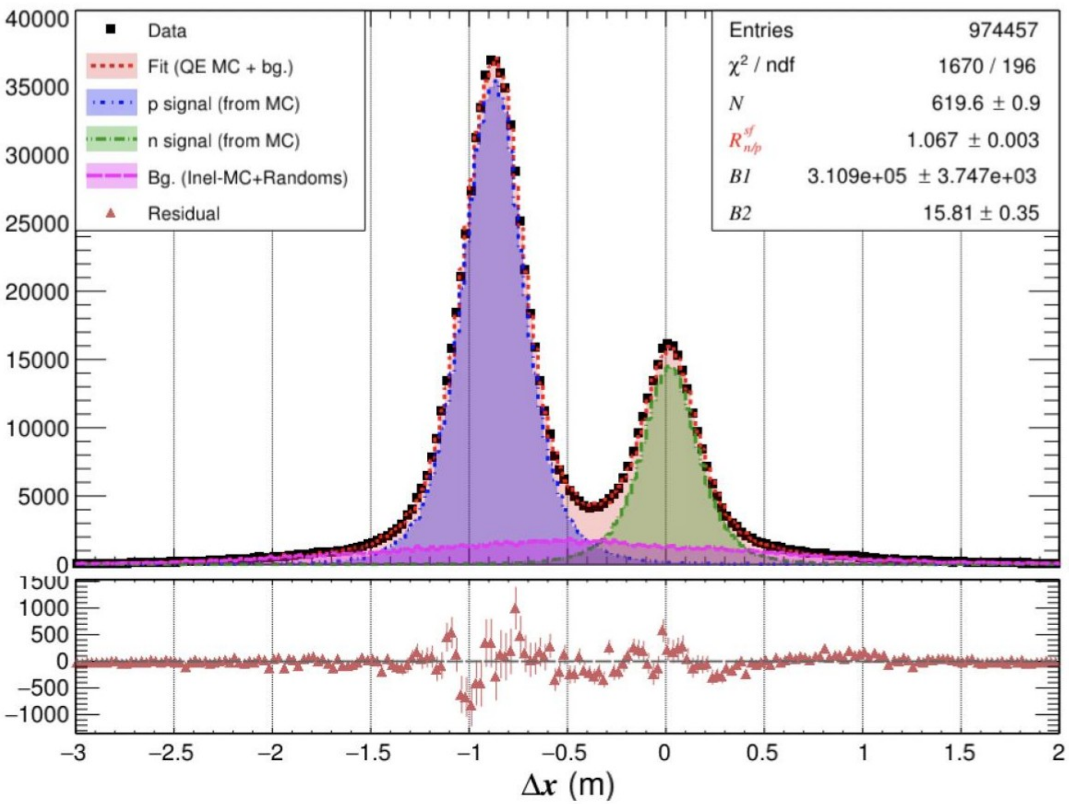


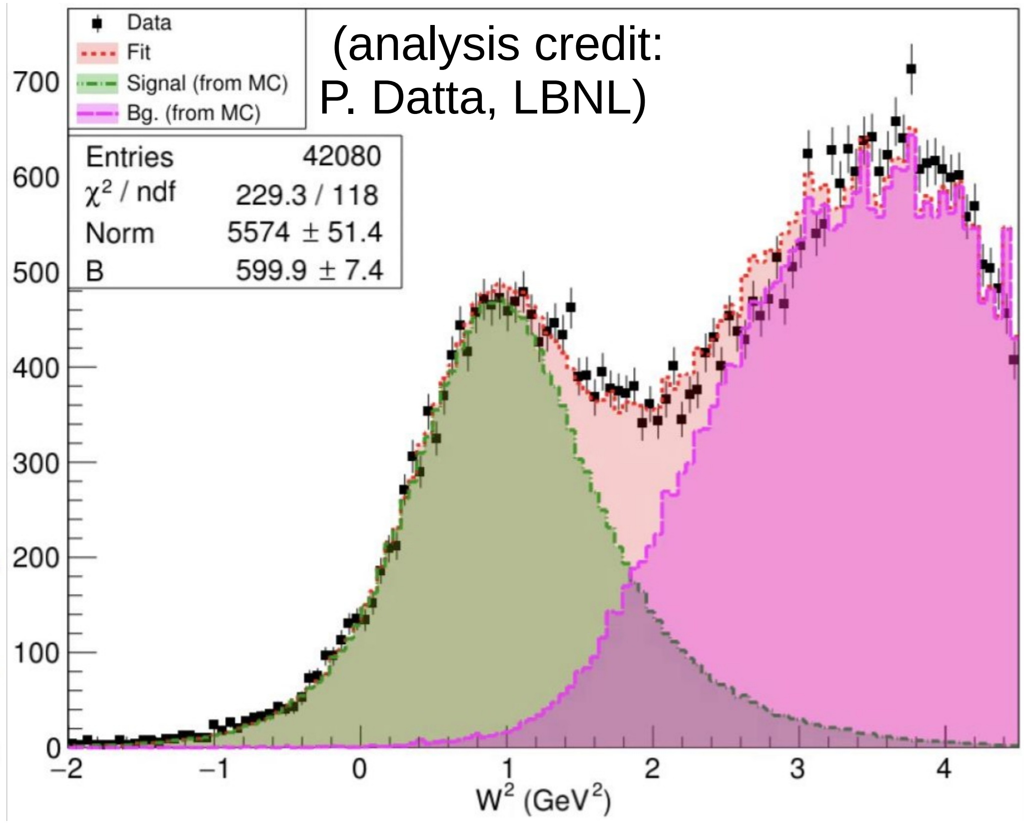
(analysis credit:
P. Datta, LBNL)



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



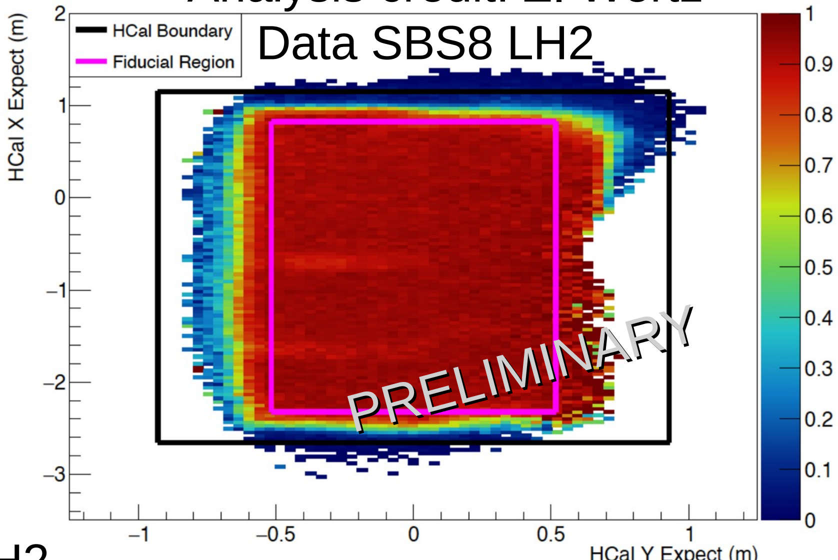


(analysis credit: P. Datta, LBNL)

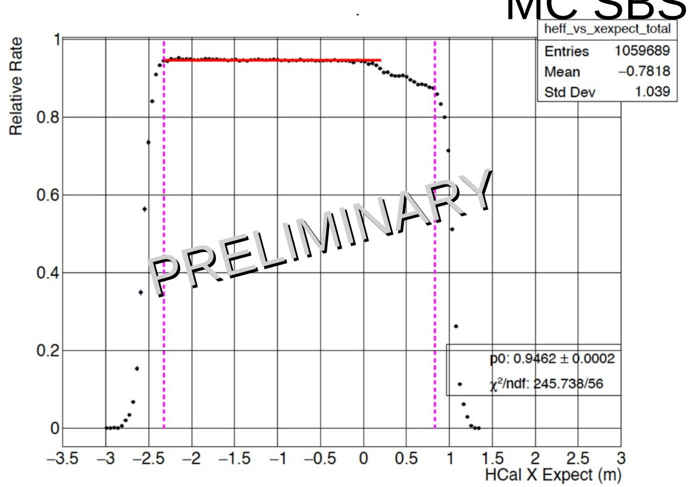
HCAL Non-Uniformity Corrections

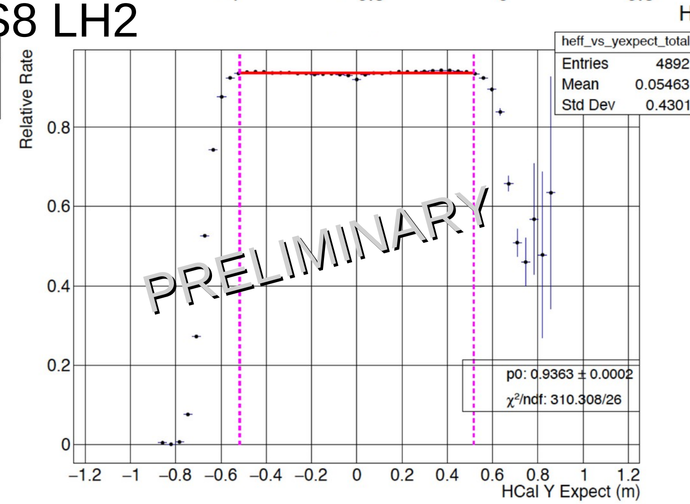
- Method to correct for HCal efficiency non-uniformity:
  - Reweight MC events with HCal non-uniformity map;
  - Map efficiency along x_{expect}, y_{expect};
  - Efficiency analysis for data, MC;
    - ♦ MC weight: η_{data}/η_{MC};
    - ♦ deployed in analysis;
  - Hurdle:
    - ♦ proton and neutron detection efficiency not equal a priori;

Analysis credit: Z. Wertz



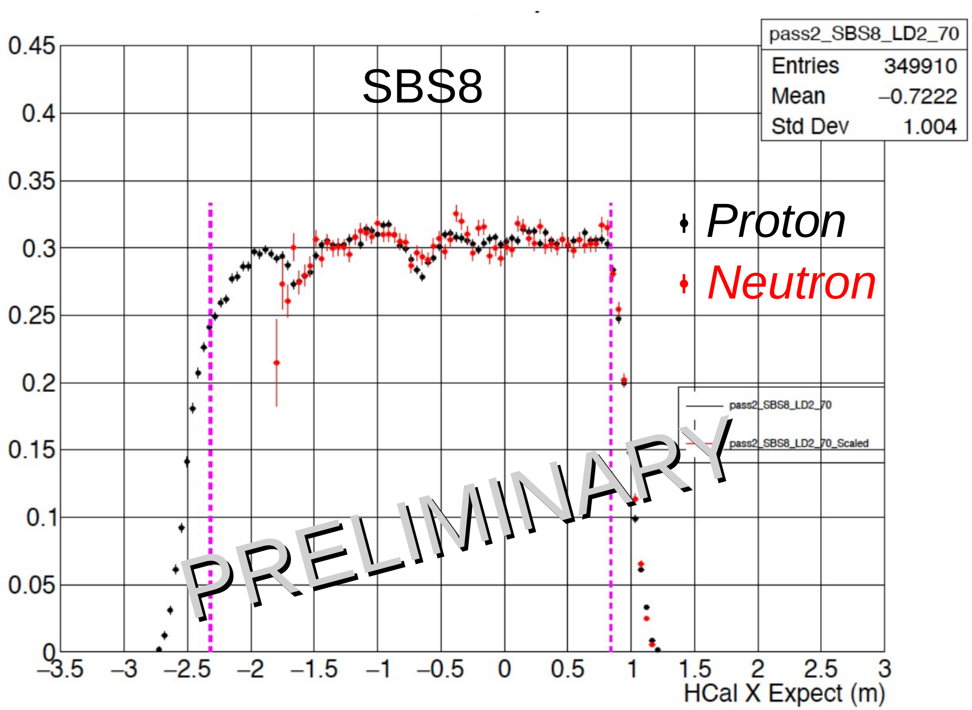
MC SBS8 LH2

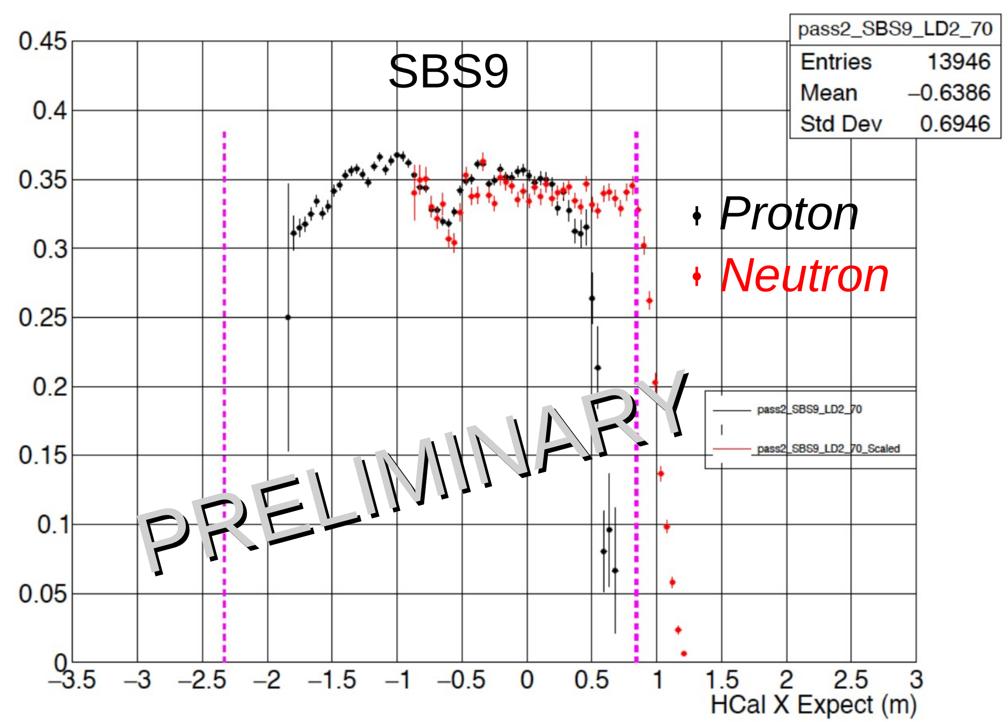




HCAL Non-Uniformity Corrections

- 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);
  - Other sources of systematics:
    - Lack of absolute neutron detection efficiency measurement;
    - Absolute proton detection efficiency uncertainty larger at high Q^2;



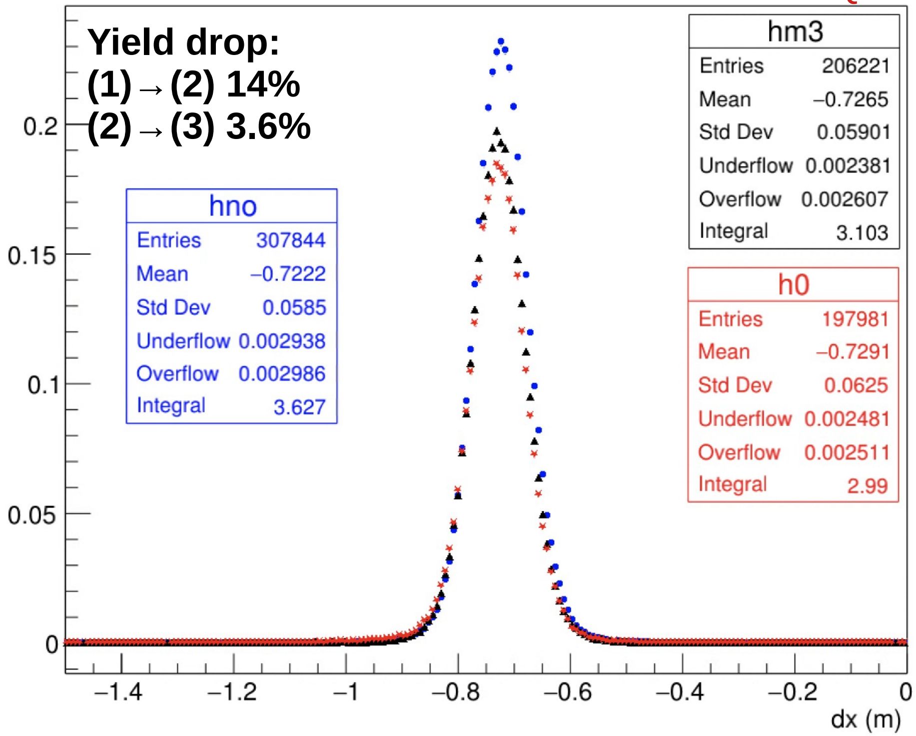


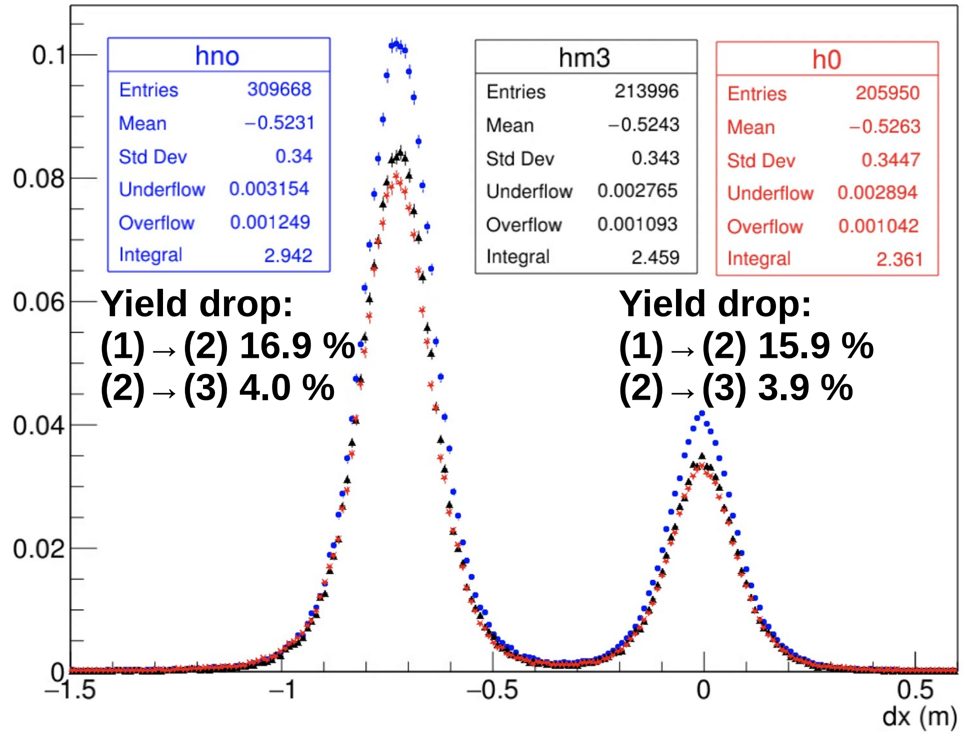
Analysis credit: E. Wertz

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

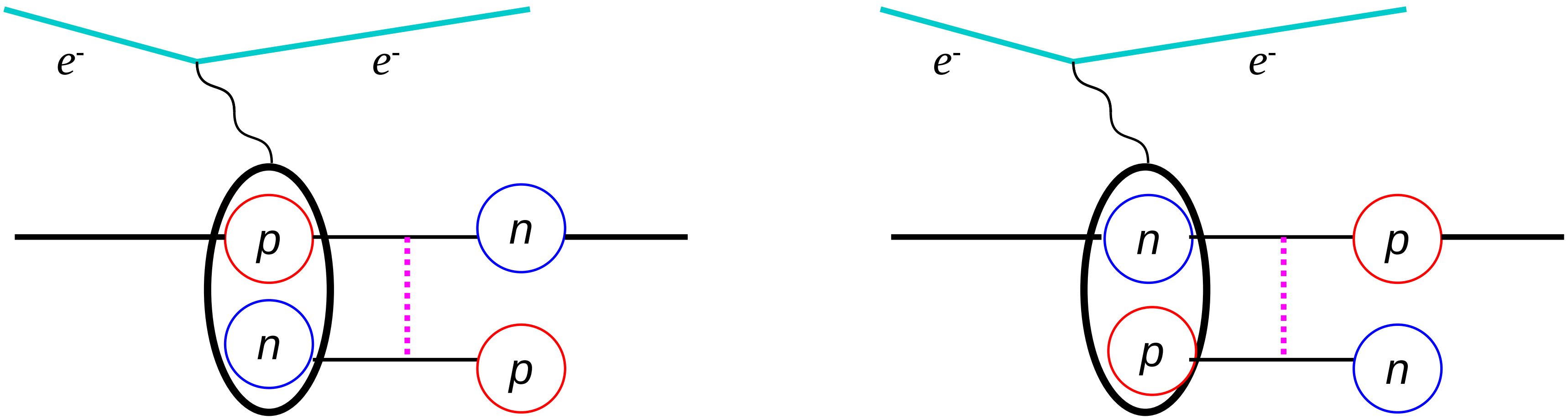
H(e, e’ p) Q^2 = 13.5 GeV^2 D(e, e’ p) + D(e, e’ n)





Systematic uncertainties: FSI

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

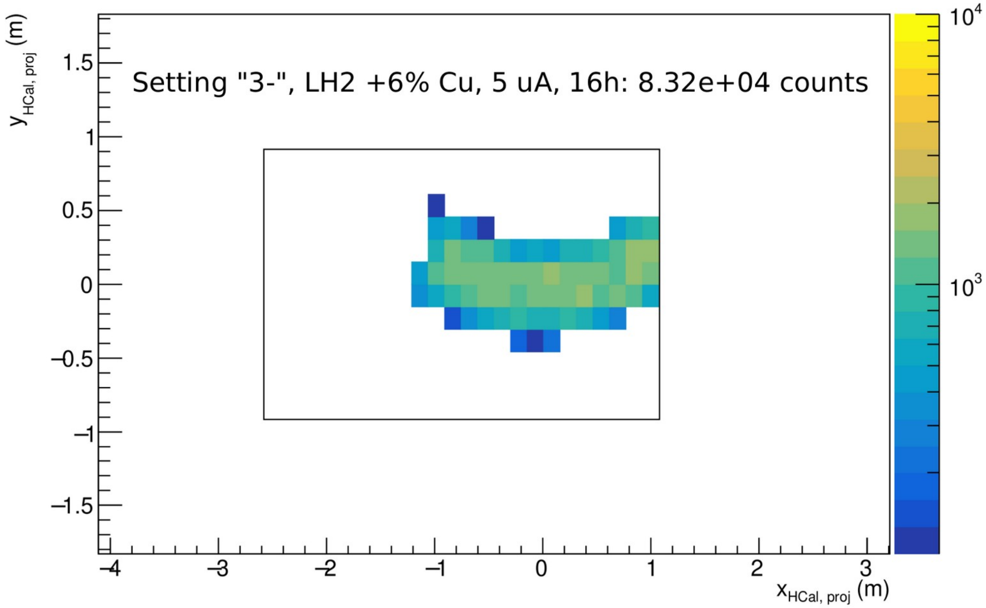


  - Since D is symmetric, $ep \rightarrow en \equiv en \rightarrow ep$:
    - ratio $R_{n/p}$ basically not affected
    - uncertainty on ratio $R_{n/p}$ extremely small

nTPE+ Systematics: Neutron Detection Efficiency

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

- *Explicit* beam request to measure $\gamma p \rightarrow \pi^+ n$ at Setting 3 (Q^2=4.5 GeV^2, E=4.4 GeV):
  - π^+ measured by BigBite, n measured by HCal;
  - Strict kinematic selection to ensure $\gamma p \rightarrow \pi^+ n$ exclusivity;
  - LH_2 target with 6 % X_0 copper upstream to enhance photon production;
  - Electron beam to increase luminosity;
  - HCal uniformity observed in GMn/nTPE data except for localized areas
  - => Coverage of ~1/4 of HCal surface sufficient



Preliminary systematic uncertainties

- Systematics analysis credit: P. Datta (LBNL);
  - Improvement can be achieved for radiative corrections and nucleon detection efficiency

Table 2: Estimated contributions (in percent) to systematic error on R and $\frac{G_M^n}{\mu_n G_D}$.

	Error Sources	Q^2 (ϵ)				
		3 (0.72)	4.5 (0.51)	7.4 (0.46)	9.9 (0.50)	13.5 (0.41)
$\Delta(R)_{sys}$	Inelastic Cont.	0.33	0.75	0.84	0.75	2.67
	Nucleon Det. Effi.	2.00	2.01	2.01	2.02	2.02
	Radiative Corr.	2.31	3.32	3.77	3.87	5.47
	Cut Stability	0.16	0.15	0.40	0.67	0.60
	FSI	0.04	0.01	0.02	0.02	0.03
	Total	3.08	3.95	4.37	4.48	6.44
$\Delta(\frac{G_M^n}{\mu_n G_D})_{sys}$	Inelastic Cont.	0.17	0.38	0.42	0.37	1.34
	Nucleon Det. Effi.	1.00	1.00	1.01	1.01	1.01
	Radiative Corr.	1.16	1.66	1.88	1.94	2.73
	Cut Stability	0.03	0.07	0.20	0.33	0.30
	FSI	0.02	0.00	0.01	0.01	0.01
	σ^p_{Red}	0.82	0.92	1.35	1.52	1.33
	G_E^n	0.55	0.65	0.62	0.66	0.55
	Total	1.83	2.27	2.64	2.79	3.53

Trigger rates with 30cm LD_2 target

- Triggers rates for all settings:
  - 1 μA, 30 cm LD_2
  - Accounts for the discrepancy evaluated between simulations and data for nTPE (E12-20-010);

Kin point	threshold (GeV)	Trigger rates (Hz)
1	1.1	444
2	1.8	2092
3	1.3	423
4	2.8	817
5	0.9	553
6	2.4	353

Addressing reviewers questions

Question 1: The TAC report commented that your proposal assumes that beam polarity can be switched in 24 hours, but that this changeover time is more likely to be over a week. If this is in fact the case, how might this alter your run plans?

In the event where beam polarity does indeed take one week i.e. 168 hours, this is our plan:
- reduce the number of beam polarity changes from 6 total to 2 total (168 real hours each);
- increase the number of magnet configurations changes (32 real hours each) from 5 total to 9 total;
- increase the number of reqular pass changes (2 pass → 3 pass or vice-versa) from 1 to 2 - those being merged with the magnet configurations changes;
- maintain a single non-regular pass change from 2 pass/4.4 GeV to 1.5 pass 3.3 GeV (such pass change taking 168 real hours, as per our understanding from the TAC report).

The total real time spent on these kinematic changes will be 760 hours. The table of and order of setting changes is shown on table below. It is to be noted that the kinematic point at a beam energy of 3.3 GeV is extra expensive in terms of down time for configuration changes. If we decide to sacrifice the Rosenbluth measurement at Q2 = 3.0 $(\mathrm{GeV}/c)^2$ and only measure $R^n_{2\gamma}$ for $Q^2 = 3.0\ (\mathrm{GeV}/c)^2$, $E_{beam} = 4.4$ GeV kinematic, we could save 336 real hours of kinematic changes in these conditions. We will discuss the relevance of sacrificing the low energy $Q^2 = 3.0\ (\mathrm{GeV}/c)^2$ kinematic in the answer to question 4.

Addressing reviewers questions

Setting or setting change	*Real* time
► Setting 2- (e^- 2 pass)	48 hours
◊ Magnets angle change:	32 hours
► Setting 3-: (e^- 2 pass)	128 hours
◊ Magnets angle change:	32 hours
► Setting 5-: (e^- 2 pass)	160 hours
◊ Magnets angle change + pass change (2 → 3 pass)	32 hours
► Setting 4-: (e^- 3 pass)	64 hours
◊ Magnets angle change:	32 hours
► Setting 6-: (e^- 3 pass)	48 hours
◊ **Beam polarity change e^- → e^+**	**168 hours**
► Setting 6+: (e^+ 3 pass)	48 hours
◊ Magnets angle change:	32 hours
► Setting 4+: (e^+ 3 pass)	64 hours
◊ Magnets angle change + pass change (3 → 2 pass)	32 hours
► Setting 5+: (e^+ 2 pass)	160 hours
◊ Magnets angle change:	32 hours
► Setting 3+: (e^+ 2 pass)	128 hours
◊ Magnets angle change:	32 hours
► Setting 2+ (e^+ 2 pass)	48 hours
◊ **Pass change (3 → 1.5 pass) + Magnets angle change**	**168 hours**
► Setting 1+: (e^+ 1.5 pass)	88 hours
◊ **Beam polarity change e^+ → e^-**	**168 hours**
► Setting 1-: (e^- 1.5 pass) 88 hours	
Total beam time	1072 hours
Total setting change time	760 hours
Total time (hours)	1832 hours

Addressing reviewers questions

Question 2: Is the collaboration considering the feasibility of using LD2 and LH2 target cells significantly longer than 15 cm to help partially compensate for the low positron beam currents expected in the JLAB positron beam era?

We have included in our run plan longer targets of 30 cm. We have run simulations showing that in these conditions, both the trigger rates and the background levels in the detectors remain manageable and have already been encountered and handled during the running of the recorded SBS experiments.

Addressing reviewers questions

Question 3: You mention on page 15, line 245 of your proposal that for the positron measurements, you may rely on the positron-proton Rosenbluth slope measured from the Super-Rosenbluth experiment proposed in Hall C at PAC51. What do you do if this experiment has not run or cannot produce the result?

One way to mitigate a potential lack of results from the Super-Rosenbluth measurements is to use our own e+p data on liquid hydrogen that we plan to use for offline calibrations to perform a Rosenbluth separation of e^+p at our measured Q^2. According to Table V in the original PR12+25-006 document, we expect for any setting at least 8×10^4 elastic ep events, which would lead to a statistical accuracy on the ratio of cross sections of 0.5% in the worst case scenario. In addition, we could also conduct the analysis on e−p and compare it to the existing Rosenbluth separation results on e^-p to validate our analysis. This would certainly lead to a more complex and longer analysis than if we can rely on a preexisting result, but we have options to obtain results regardless. Please note that the same argument would apply in the event the CLAS12 $R^p_{2\gamma}$ measurement cannot run or produce results.

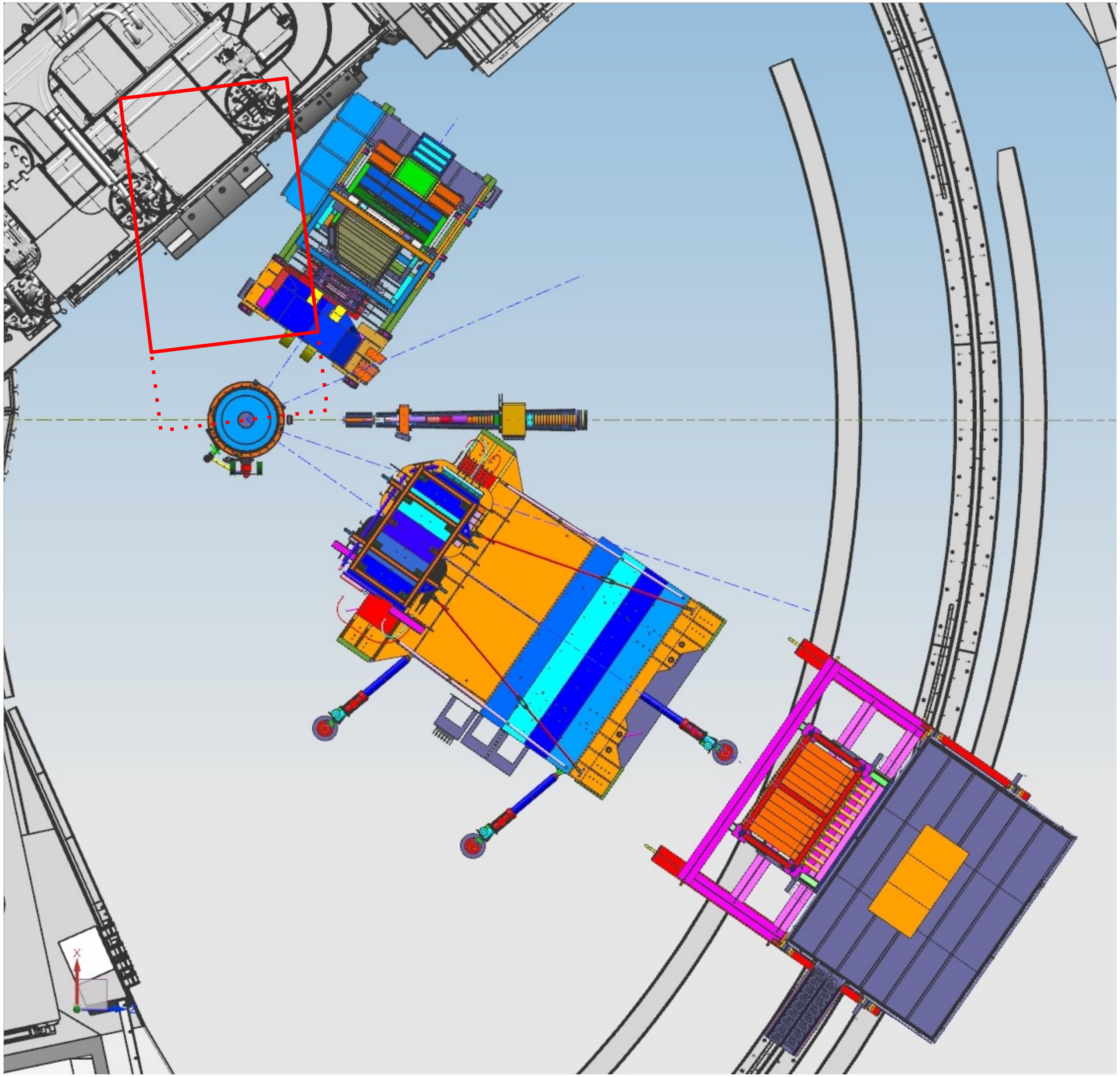
Addressing reviewers questions

Question 4: Could you please also clarify what you mean by 1.5 pass on page 16, line 261? Is this a non-standard configuration? How crucial is it?

”1.5 pass” is a non-standard configuration of the accelerator to deliver a beam energy between 2.2 GeV (1 pass) and 4.4 GeV (2 pass). This configuration will take more time to transition. Our current understanding from the TAC report is that this transition to 1.5 pass is taking one week, as pointed out in the answer to question 1. The low energy Q^2 = 3.0 $(GeV/c)^2$/3.3 GeV kinematic setting may not be the most crucial kinematic, as we expect the neutron two-photon-exchange effect to be the lowest there. Ideally, we would still want to maintain this kinematic, but we acknowledge that in the worst case scenario where a beam polarity change does take much longer than 24 to 48 hours, this kinematic may be too prohibitive in terms of down time for a relatively limited impact. We want to point out that during the development of this proposal we explored replacing this setting with a setting at Q^2 = 3.0 $(GeV/c)^2$/2.2 GeV, but it has been found out to be unfeasible as it requires a backwards BigBite angle (97 deg) that cannot be mechanically accommodated in the existing Hall C setting.

Q2 = 3 GeV2, E=2.2 GeV???

θ_{BB} = 97 deg:
Will not fit with HMS



nTPE+ Time Request (No Q2 = 3 GeV2, E=3.3 GeV measurement)

- **Updated run plan following TAC remarks and recommendations**:
- **If we drop the low energy $Q^2 = 3.0$ GeV^2 setting:**
- 5 kinematics with e+/e- LD2/LH2 30 cm (instead of 15 cm): **27.5 PAC days total**
  - ◘ 448 PAC hours (about 22 days) beam on target:
    - ♦ 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);
  - ◘ 212 additional PAC hours (424 real hours) for setting changes:
    - ♦ One **e^+ /e^- change**, assuming 84 PAC hours (**one calendar week**);
    - ♦ eight magnet angle changes taking 16 PAC hours (32 real hours) each;
    - ♦ two pass changes overlapped with magnet changes;

TAC comments

Technical Comments:
This proposal aims to measure the TPE contribution in elastic positron-neutron and electron-neutron scatterings. It will take data with positron and electron beams at the same beam intensity using the same apparatus, minimizing associated systematic uncertainties.

This experiment uses the experimental setup and analysis techniques as the GMn/nTPE experiments in Hall A. The existing simulation and analysis framework will be used. While it uses the existing instruments, the experiment is proposed to be run in Hall C and therefore requires significant engineering and installation efforts.

The proposal assumes that the beam polarity can be switched in 24 hours. This changeover time is rather likely to be over a week.

Kinematics and run plan:
The proposed experiment has six kinematics settings for positron/electron beams. Each configuration change involves moving spectrometers and hadron calorimeter to different angles which will need to be surveyed. It also involves reconfiguration of positron/electron beam and assumes each reconfiguration will take 24h. The experiment requires 3.3 GeV, implying a setup at 1600 MeV/pass with 90 MeV injection energy. This will reduce positron transmission and take about a week.

TAC comments

Systematic uncertainties:
This experiment uses the ratio method and will measure the ratio of neutron and proton yields simultaneously with electron and positron beams. This largely cancel out many systematic errors.

The proposal includes 10 PAC days with a LH2 target for calibrations and systematic studies. It will also run with LH2 + 6% Cu radiator to measure the neutron detection efficiency of the hadron calorimeter. The proton and neutron detection efficiencies are expected to differ slightly, therefore it is important to measure them through a dedicated auxiliary measurement. The proposal estimated 16h of data taking for this.

Target:
Given the limitation on e+ beam current to only O(1) muA, the collaboration should consider the feasibility of using LD2 and LH 2 target cells significantly longer than 15cm. This would partially compensate for the low e + beam currents expected in the JLab e+ beam era.

It requires installation of an existing, standard target system with major modifications.
The target will need to be moved downstream by a significant amount.

The major installation of the BB and SBS in Hall C has issues for the target but it isn't obvious now how much this would affect the target installation. An entirely new support system would need to be installed with piping/electrical and mechanical/structural supports.

Theory comments

Following up on a previous Letter-of-Intent (LOI12+24-008), this proposal aims to measure the ratio of positron-neutron to electron-neutron cross sections in quasi-elastic scattering from the deuteron at three values of the four-momentum transfer squared, Q 2 = 3.0, 4.5, and 5.5 (GeV/c) 2 . In particular, the positron-neutron to electron-neutron cross section ratio provides direct access to the two-photon exchange (TPE) contribution, which can be compared with that obtained from Rosenbluth slope extractions and polarization transfer measurements. The proposed measurement will complete and extend the measurement of TPE in electron-neutron scattering approved by PAC48, and the analysis will benefit from the experience gained with the ongoing analysis of JLab experiment E12-20-010.
As is well known, the neutron form factors are difficult to determine experimentally because of the absence of free neutron targets, so that in practice deuterium is typically used as an effective neutron target. An advantage of the ratio method is the cancellation of many of the systematic uncertainties, and a number of experiments have previously applied this to determine the magnetic form factor of the neutron. Overall, the proposal is well-motivated and carefully developed, and will benefit from the strong theory support (e.g., with P. Blunden one of the spokespersons) already established by the proponents, with a clear path towards the analysis and interpretation of the data.

Does Fermi Momentum Really Cancel?

Comparisons between Deuteron wave functions and Hall C data