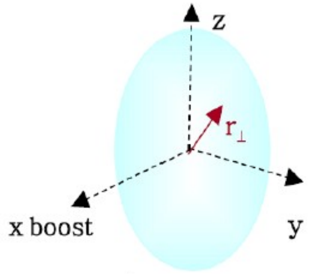
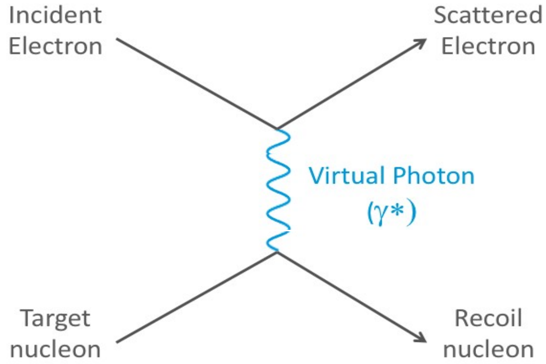
NTPE+: measurement of the neutron two-photon exchange with quasi-elastic positron-neutron and electron-neutron scattering

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

Positron Working Group Workshop 2025
Newport News, VA
March 25th, 2025

Elastic *e-N* scattering: Rosenbluth





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

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

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

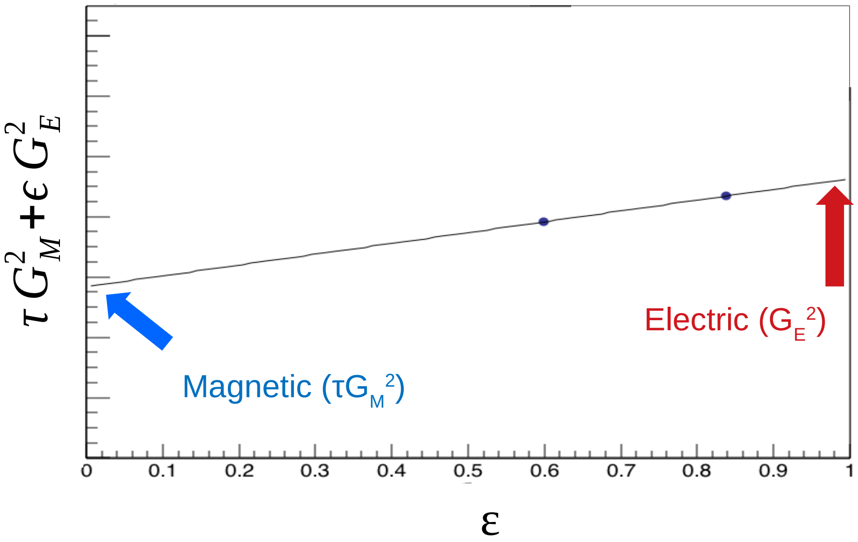
- Rosenbluth technique: separate G_M^2 and G_E^2 based

on the linear dependence in $\epsilon=\left[1+2(1+\tau)\tan^2(\theta/2)\right]^{-1}$ of

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

- Two or more measurements, same Q^2,

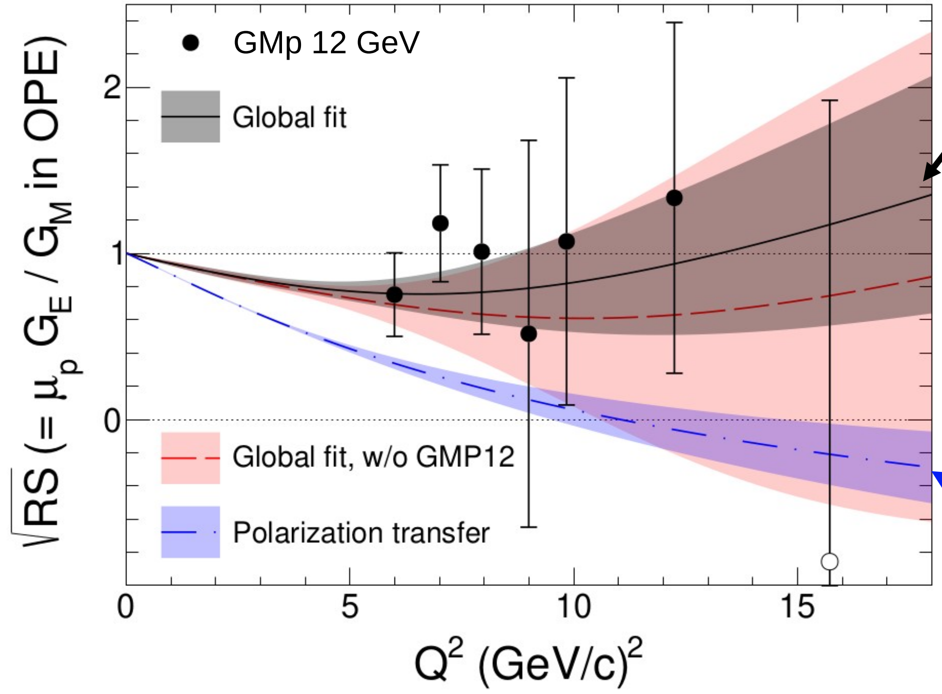
different E and θ (different ε)



Global Fit on Rosenbluth Slope in e^-p Scattering

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

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



Global fit of Rosenbluth measurements

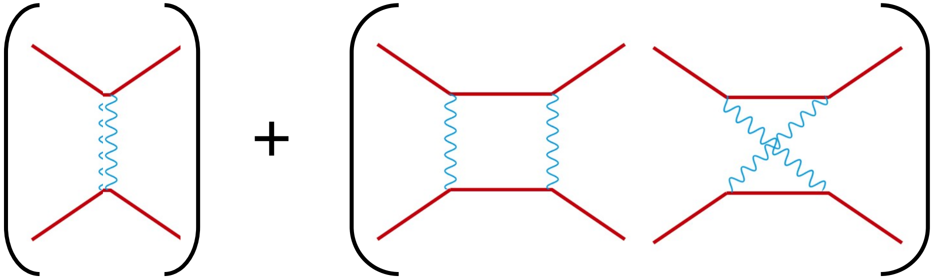
Latest JLab proton data at 12 GeV

Global fit of polarization transfer measurements

Two-Photon Exchange in Elastic Scattering

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

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

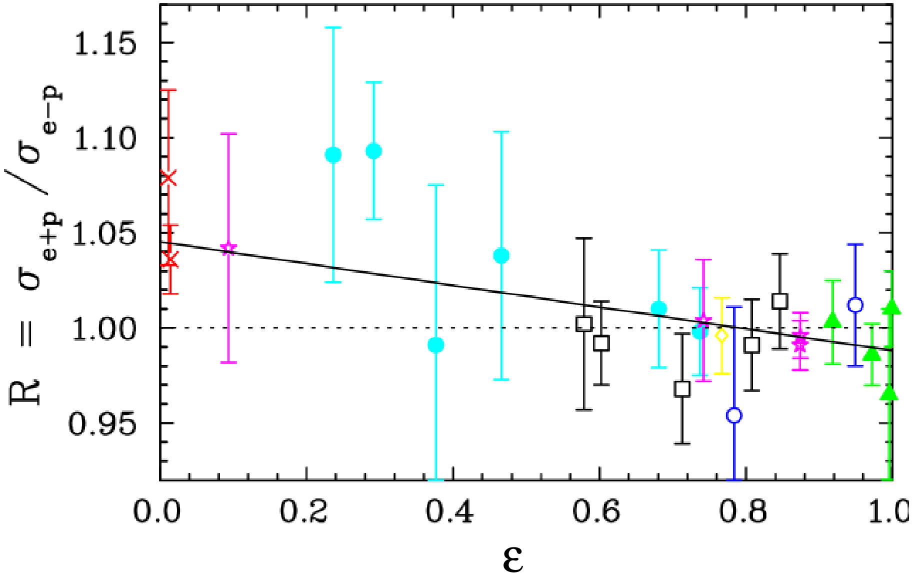


- Interference term depends on the lepton charge to the power 3:
    - TPE expected to be of opposite magnitude between $e^{+}N$ and $e^{-}N$;

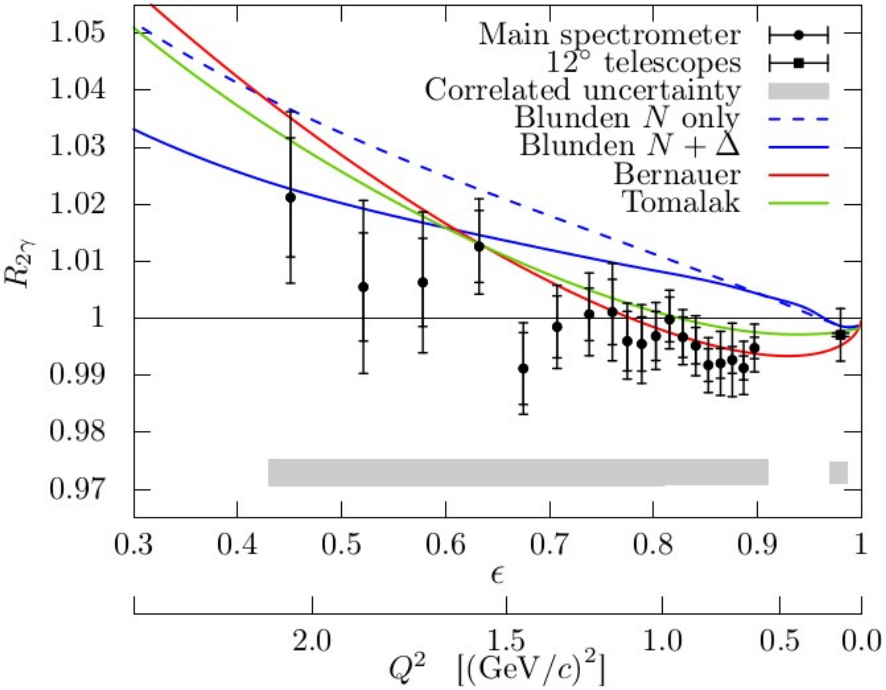
e^+p measurements

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

Phys. Rev. C 69, 032201 (2004).526



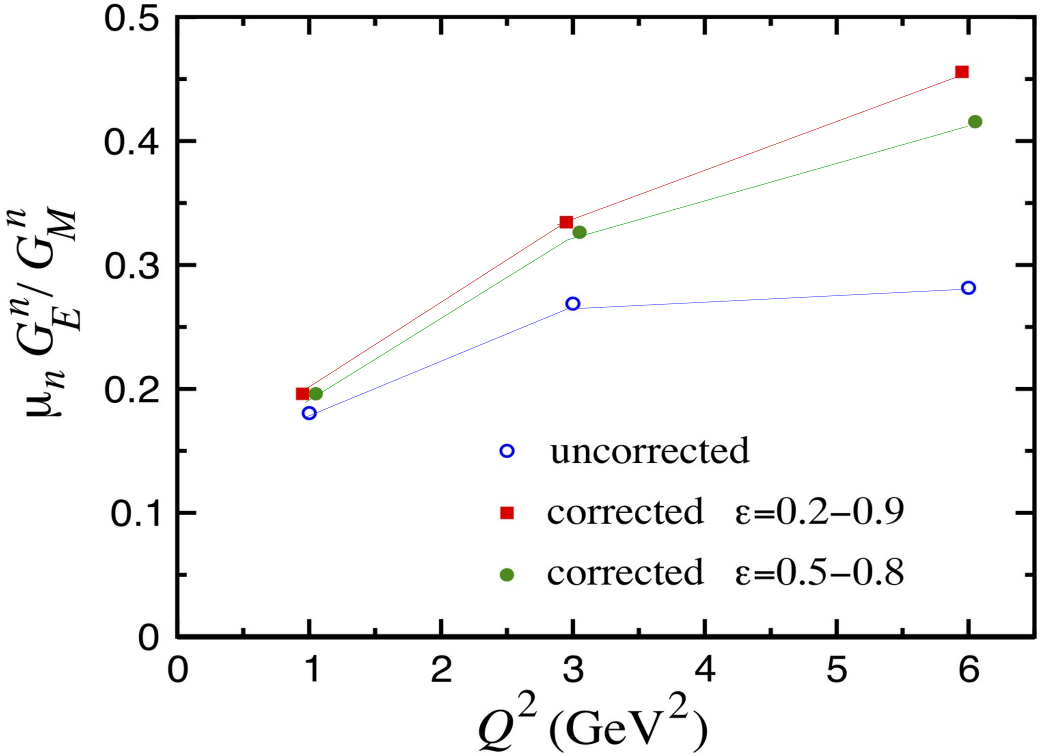
Phys. Rev. Lett. 118, 092501 (2017)



- ***Essentially inconclusive results***

Two-Photon Exchange 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;
  - ◘ ***No TPE measurement on the neutron* => *nTPE*(+) *at Jefferson Lab***



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

○ Uncorrected $\mu_n G_E^n/G_M^n$ from Mergell Meissner Drechsel parameterization in Nucl. Phys. A596, 367 (1996)

■ $\mu_n G_E^n/G_M^n$ +TPE between ε = 0.2 and 0.9

● $\mu_n G_E^n/G_M^n$ +TPE between ε = 0.5 and 0.8

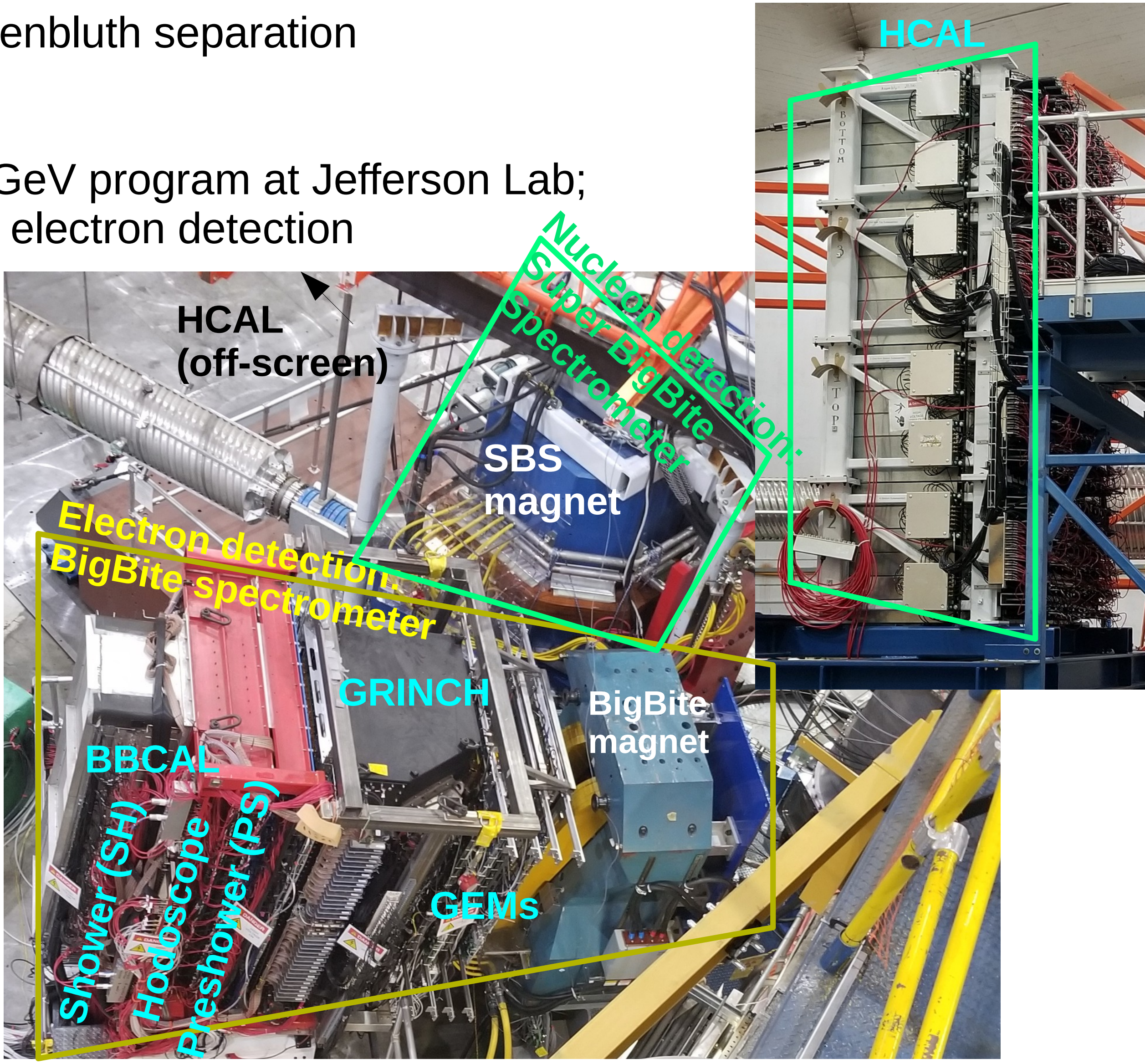
nTPE with Super BigBite Spectrometer

- **nTPE:** (E12-20-010) *en* Rosenbluth separation

- **SBS:**
  - Major part of Hall A 12 GeV program at Jefferson Lab;
  - coupled with Bigbite for electron detection

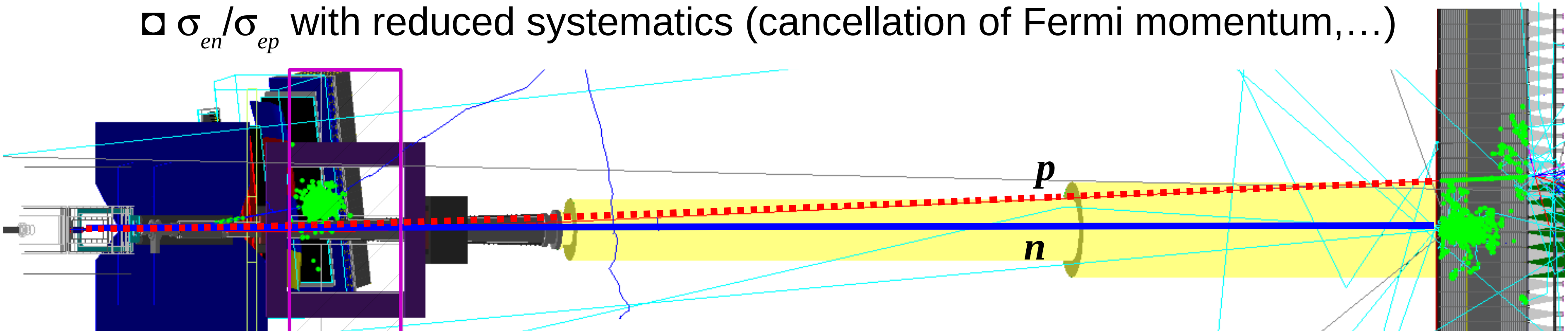
- **SBS form factor program**
  - GMN
  - **nTPE**
  - GEN
  - GEN-RP
  - GEP

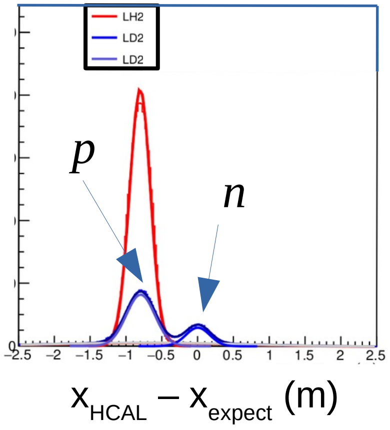
- Other Physics:
  - SIDIS
  - KLL
  - TDIS
  - nDVCS



Neutron Measurement with Durand Technique

- Established by Durand in Phys. Rev. 115, 1020 (1959).
- Used for SBS experiments GMN, nTPE, **nTPE+**:
  - ◘ simultaneous en/ep measurement on D_2
  - ◘ Separation of p and n with SBS magnet
  - ◘ σ_{en}/σ_{ep} with reduced systematics (cancellation of Fermi momentum,…)



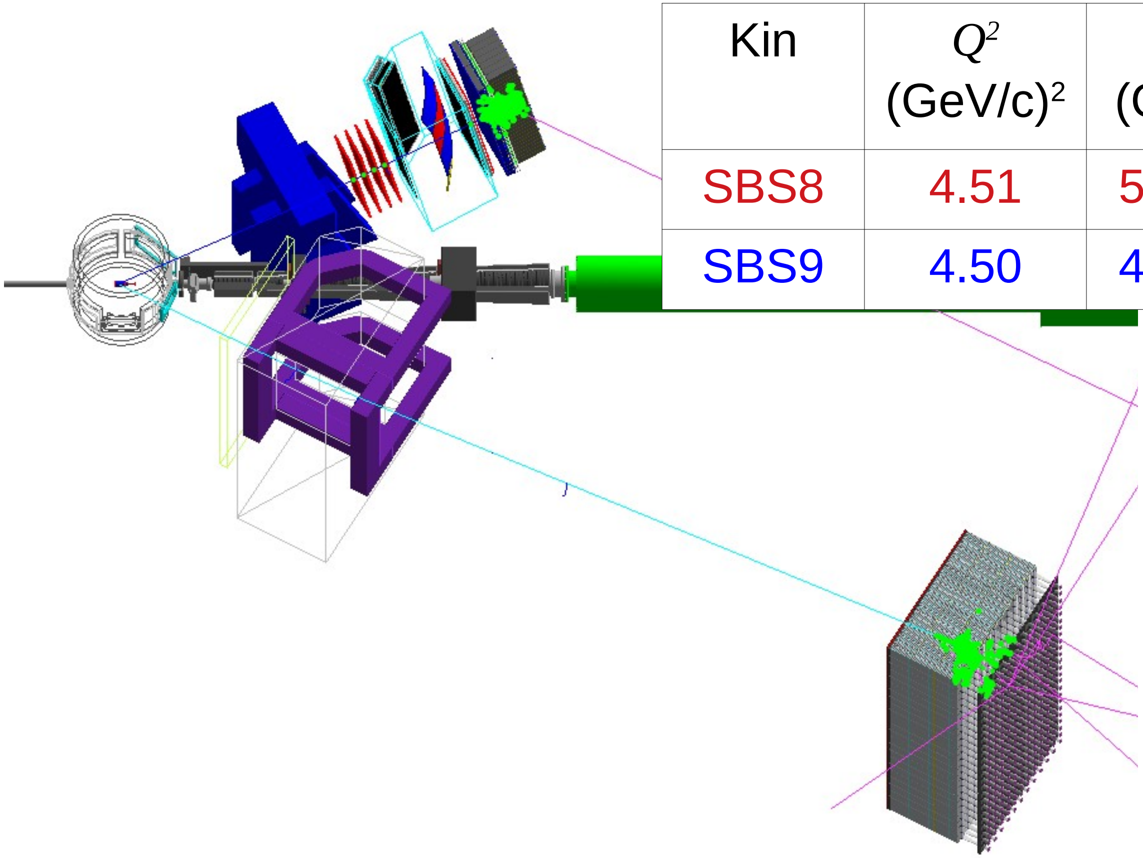


X_{HCAL}: reconstructed

x_{expect}: predicted from e^-

Rosenbluth Slope in Electron-Neutron: nTPE

- **E12-20-010:** E. F., S. Alsalmi, B. Wojteskhowski
  - ◘ *en*/*ep* measurement at **two beam energies**
  - ◘ **Rosenbluth separation of σ_{en}/σ_{ep} at Q^2 = 4.5 GeV^2**



Kin	Q^2 (GeV/c)^2	E (GeV)	E' (GeV)	θ_{BB} (deg)	θ_{SBS} (deg)	ε
SBS8	4.51	5.965	3.565	26.5	29.9	0.797
SBS9	4.50	4.015	1.618	49.0	22.5	0.512

Extraction of nTPE

- **E12-20-010:** E. F., S. Alsalmi, B. Wojteskhowski
  - ◘ **Rosenbluth separation of σ_{en}/σ_{ep} at Q^2 = 4.5 GeV^2**
  - ◘ Neutron Rosenbluth slope extracted from proton data

$$R=\frac{N_{en\to en}}{N_{ep\to ep}} \qquad R'=\frac{\sigma_{en}}{\sigma_{ep}}=R\,f_{corr}$$

$$f_{corr}=\boxed{\frac{\eta_{en}(t)}{\eta_{ep}(t)}}\times\boxed{\eta_{RC}(v,Q2,\ldots)}\times\ldots$$

Radiative corrections (radiative corrections at vertex, energy loss, ...)

neutron/proton detection efficiency

$$R'_{\epsilon_{1/2}}=R_{Mott,\,\epsilon_{1/2}}\frac{\sigma_T^n(1+\epsilon_{1/2}S^n)}{\sigma_T^p(1+\epsilon_{1/2}\boxed{S^p})}$$

proton data

$$A=\frac{R'_{\epsilon_1}}{R'_{\epsilon_2}}\simeq B(S^p)\times(1+S^n\Delta\,\epsilon)$$

$$B=\frac{R_{Mott,\,\epsilon_1}}{R_{Mott,\,\epsilon_2}}\frac{1+\epsilon_2 S^p}{1+\epsilon_1 S^p}$$

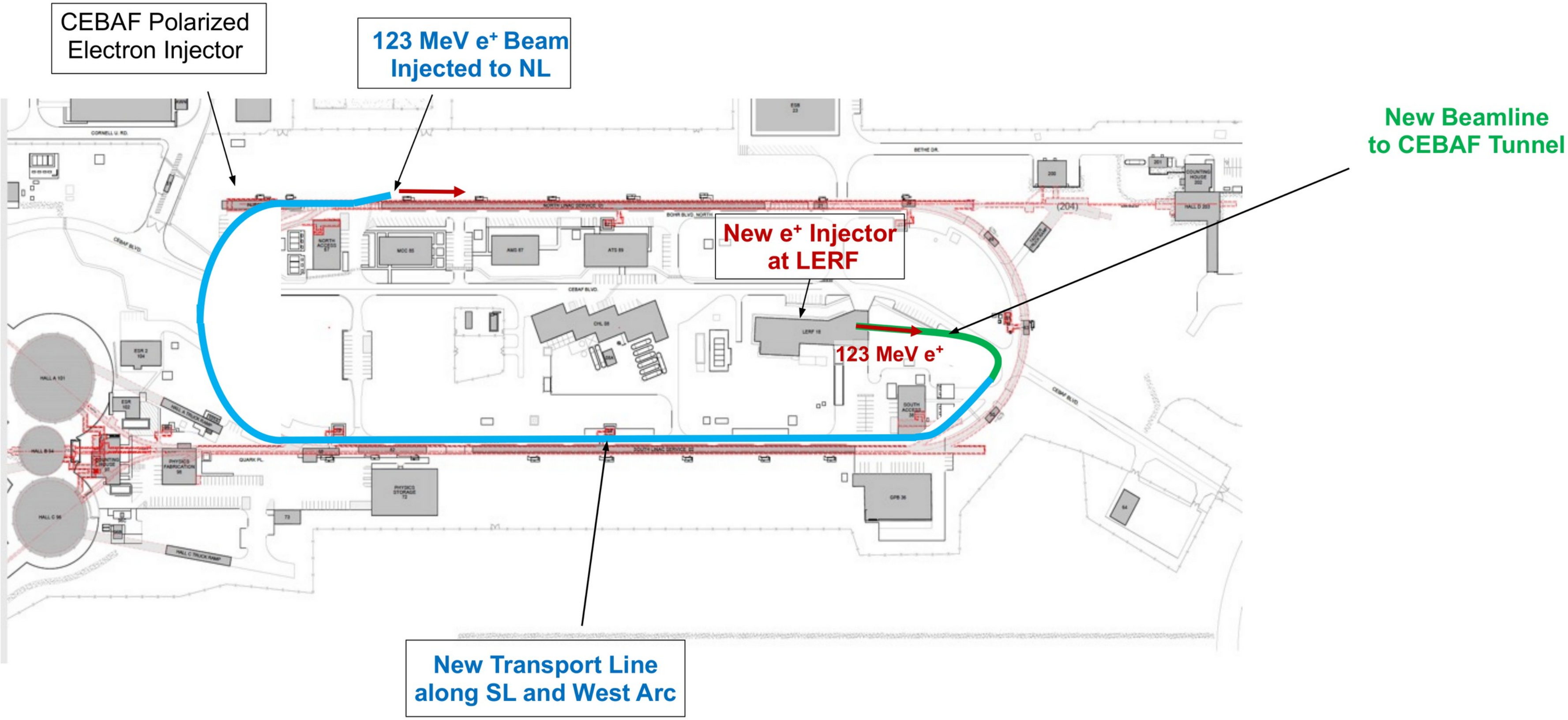
$$\Delta\,\epsilon=\epsilon_1-\epsilon_2$$

$$\boxed{S^n=\frac{A-B}{B\,\Delta\,\epsilon} \qquad nTPE=S^n-\boxed{(G_E^n)^2/\tau(G_M^n)^2}}$$

GEN fits and *GEN-RP measurement at* **Q^2 = 4.5 GeV^2**

nTPE+ with Jefferson Lab Positron Upgrade

- Upgrade of the injector to produce polarized positrons (and electrons)
- Promised specifications:
    - **1μA without polarization**;
    - 60nA with polarization;



CEBAF Polarized Electron Injector

123 MeV e^+ Beam Injected to NL

New Beamline to CEBAF Tunnel

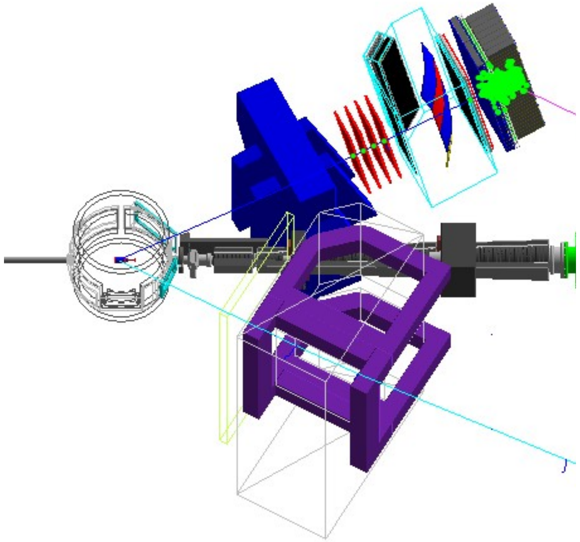
New e^+ Injector at LERF

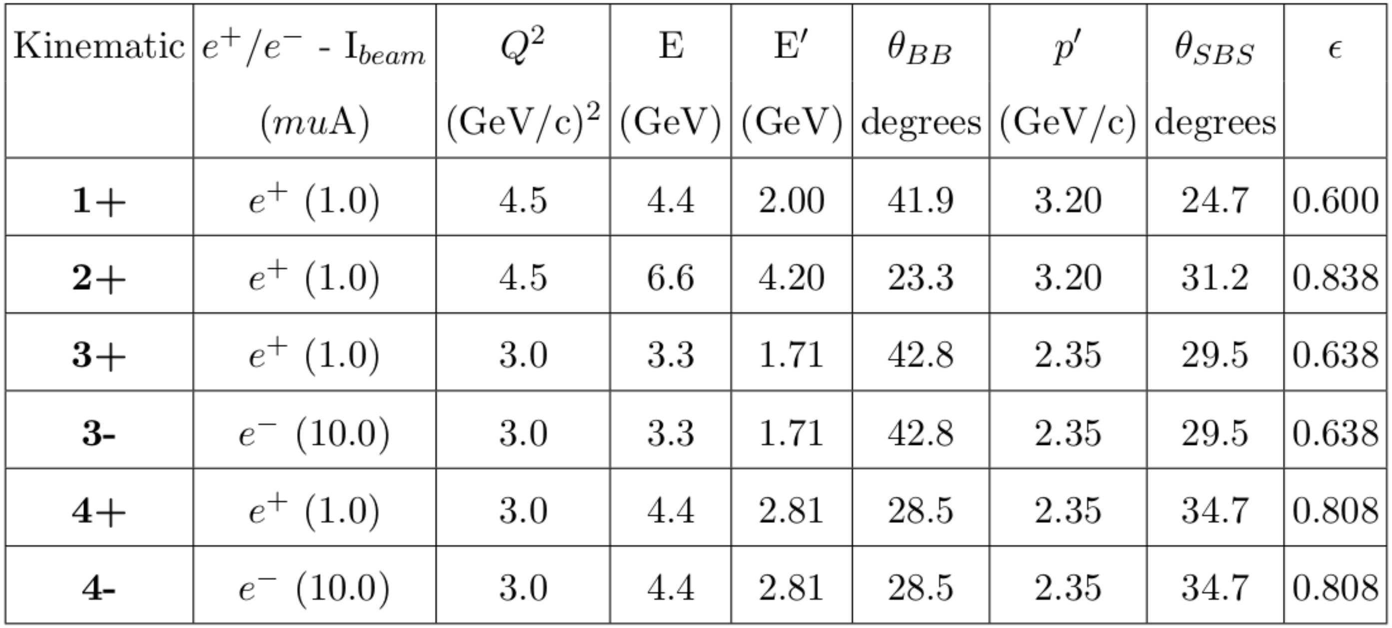
123 MeV e^+

New Transport Line along SL and West Arc

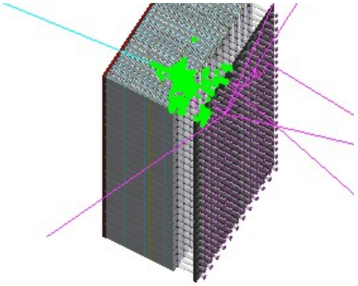
nTPE+ LOI 2024

- E12+24-008: E. F.:
  - **uses Jefferson Lab positron upgrade!**
  - Same technique as nTPE
  - $\boldsymbol{\sigma_{e+n}/\sigma_{e+p}}$, $\sigma_{e-n}/\sigma_{e-p}$ at *two* beam energies at **Q^2 = 3 GeV^2, Q^2 = 4.5 GeV^2**





Kinematic	e^+/e^- - I_{beam} (muA)	Q^2 (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
3-	e^- (10.0)	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
4-	e^- (10.0)	3.0	4.4	2.81	28.5	2.35	34.7	0.808



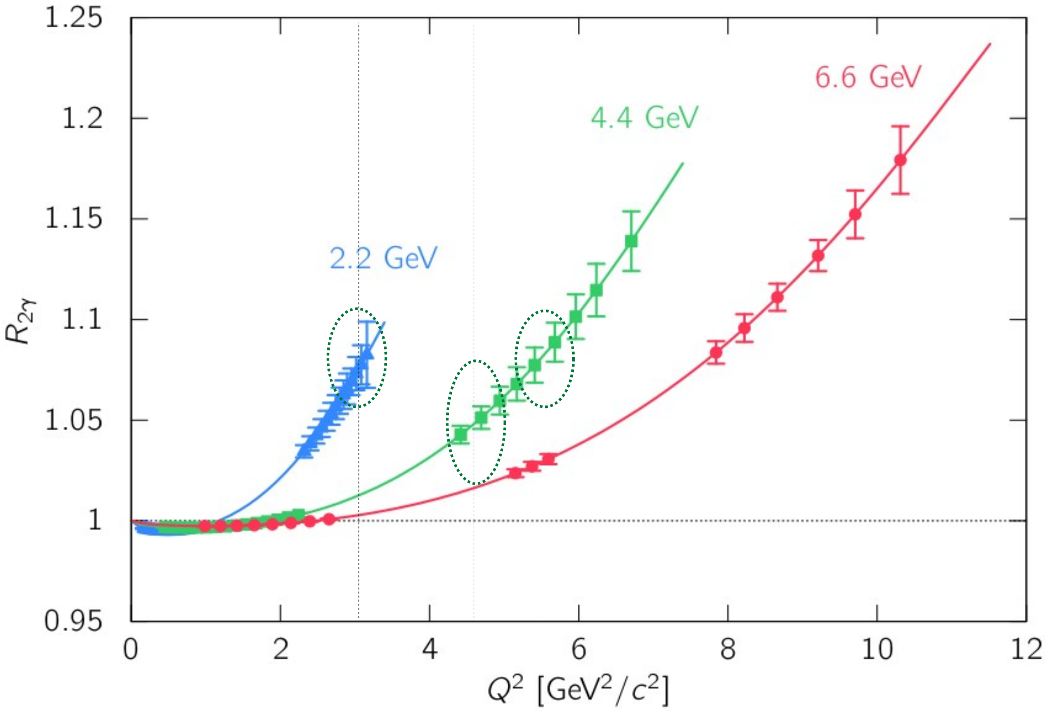
nTPE+ Updated for 2025

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

nTPE+ Updated for 2025

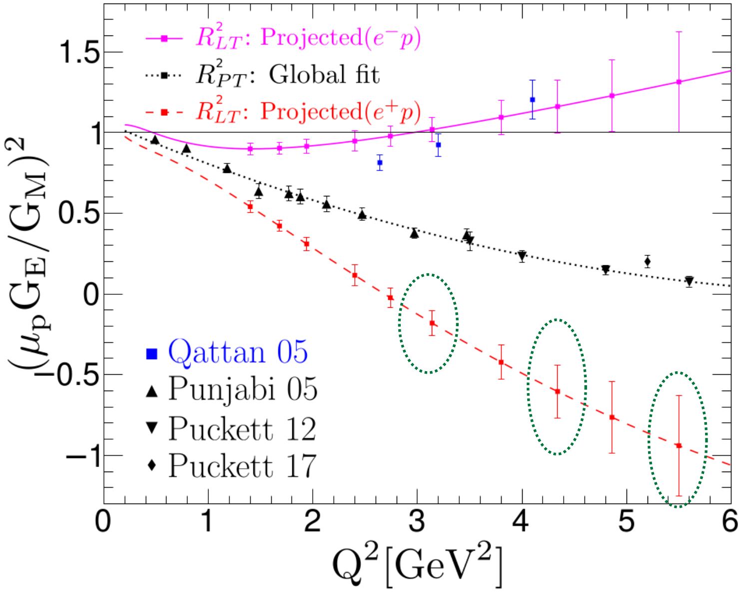
- Integrating feedback from reviewers:
  - ◘ Same Durand technique as nTPE;
  - ◘ $\left(\frac{\sigma_{e^{+}n}}{\sigma_{e^{+}p}}\right)/\left(\frac{\sigma_{e^{-}n}}{\sigma_{e^{-}p}}\right)=R^{n}_{2\gamma}/R^{p}_{2\gamma}$ for **Q^2 = 3 GeV^2, Q^2 = 4.5 GeV^2, Q^2 = 5.5 GeV^2**
  - ◘ e^- data at same beam intensity as e^+ data (1μA)
  - ◘ $R^{p}_{2\gamma}$ can be sourced from PR12+23-008 (Axel Schmidt *et al.*)
  - ◘ $R^{p}_{2\gamma}$ can also be measured by us with LH_2



nTPE+ Updated for 2025

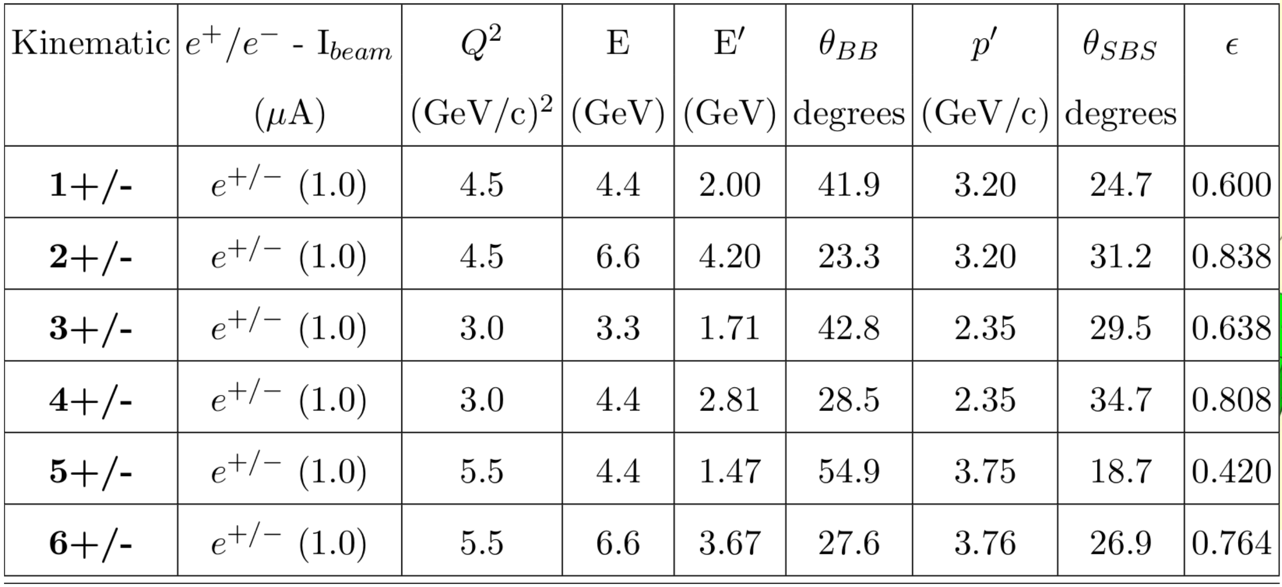
- Integrating feedback from reviewers:
  - Same Durand technique as nTPE;
  - $\left(\frac{\sigma_{e^{+}n}}{\sigma_{e^{+}p}}\right) / \left(\frac{\sigma_{e^{-}n}}{\sigma_{e^{-}p}}\right) = R^{n}_{2\gamma} / R^{p}_{2\gamma}$ for **Q^2 = 3 GeV^2, Q^2 = 4.5 GeV^2, Q^2 = 5.5 GeV^2**
  - e^- data at same beam intensity as e^+ data
  - *In addition*, Rosenbluth measurement can be maintained
    - ♦ e^-n Rosenbluth measurement relies on existing e^-p data;
    - ♦ No *existing* dataset for Rosenbluth e^+p
    - ♦ PR12+23-012 (Michael Nycz *et al.*):

      Rosenbluth e^+p up to Q^2 = 5.5 GeV^2

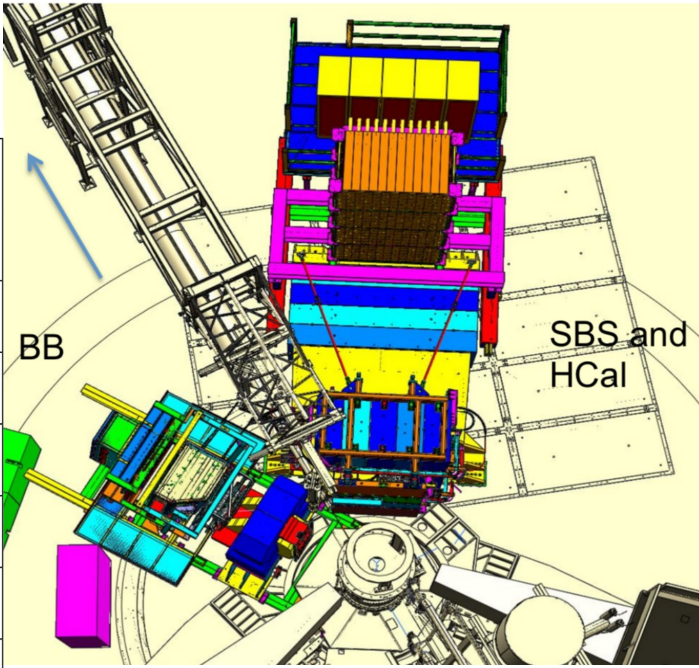


nTPE+ Kinematics

- Six kinematic settings:
  - each will run e^+, e^-, LD_2, LH_2;
  - Five settings with 2200 MeV/pass, one with 1100 MeV/pass;
- nTPE+ will be proposed in **Hall C**:
  - Spectrometer placements for our kinematics (Bert Metzger)
    - won’t interfere with HMS/SHMS:
    - Will have updated CAD drawings



Kinematic	e^+/e^- - I_{beam} (μA)	Q^2 (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

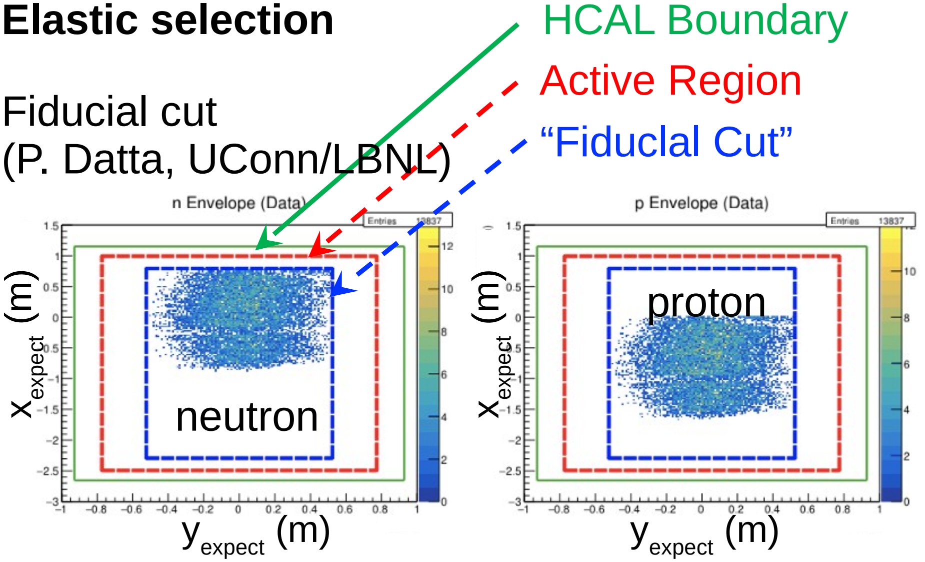


nTPE+ Systematics: GMn/nTPE Analysis

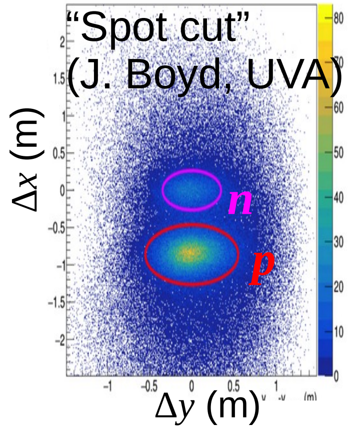
- Analysis: extraction of n/p ratios:

Elastic selection

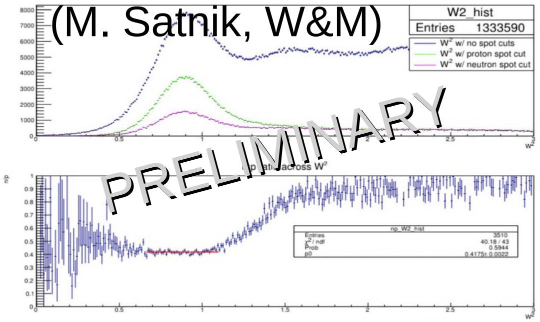
Fiducial cut
(P. Datta, UConn/LBNL)



“Spot cut”
(J. Boyd, UVA)

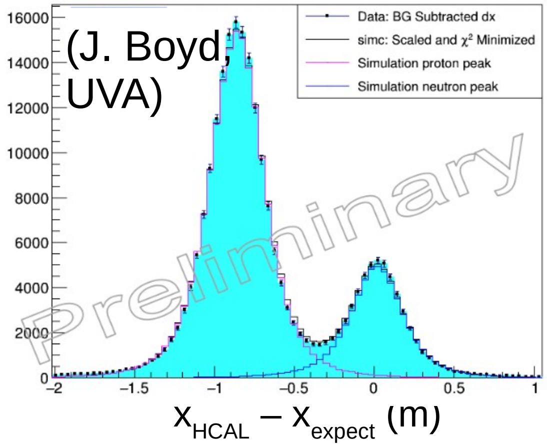


Selection optimization
(M. Satnik, W&M)



W^2 (GeV^2)

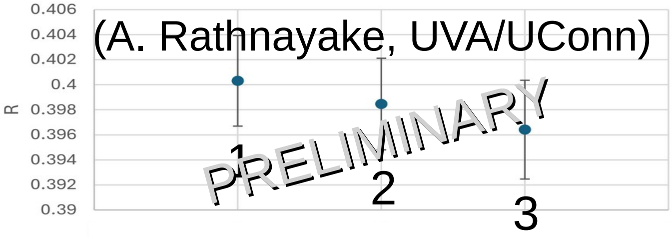
N_n/N_p → σ_n/σ_p correction with MC



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

Inelastic background subtraction

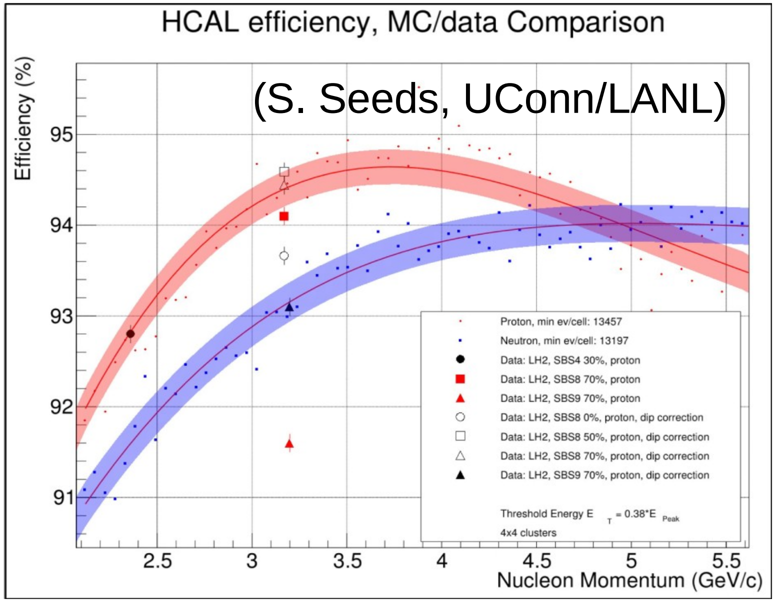
- ◘ 1: Combined fit $en+ep$ +background of data Δx
- ◘ 2: Data background (HCal “antiselection”);
- ◘ 3: MC (Christy-Bosted) generated background



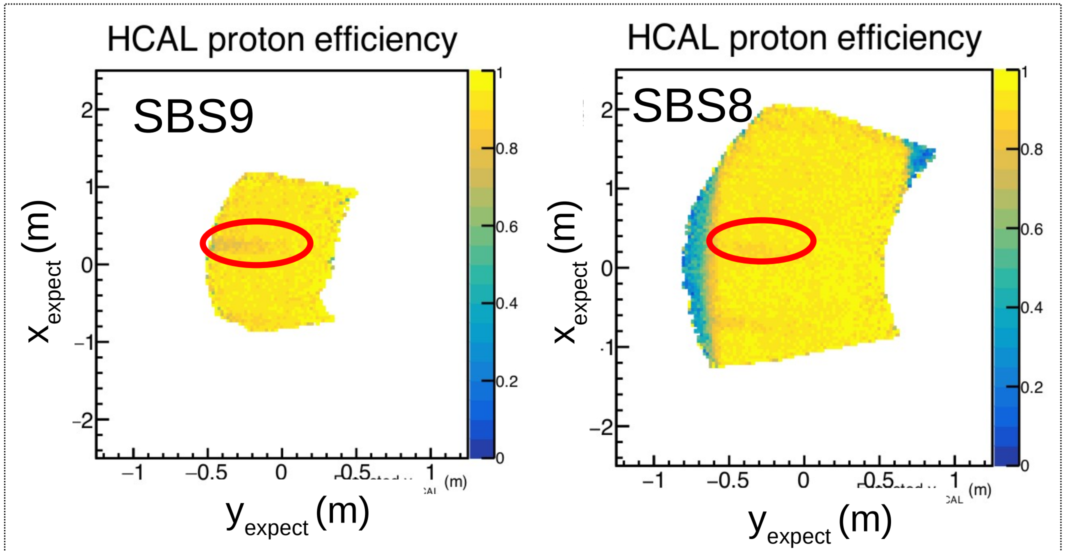
Background method

nTPE+ Systematics: HCAL Detection Efficiency

- HCal detection efficiency major source of systematic **especially for nTPE(+)**:
  - ◘ n and p detection efficiency expected to be similar, but not identical;
  - ◘ HCal efficiency from LH2 data shows non-uniformity of HCAL efficiency:
  - ◘ Larger nucleon projection footprint on HCal for higher ε kinematic:
    - ♦ non-uniformity has more impact on low ε kinematic (*less impact on* $R^{n}_{2\gamma}$);
    - ♦ n/p cross section ratio biased for both, more biased for low ε;



(S. Seeds, UConn/LANL)

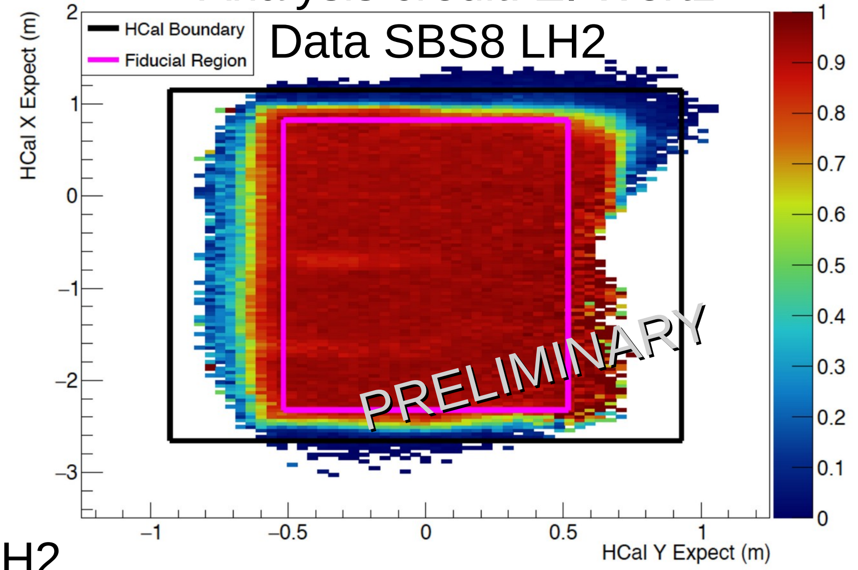


(A. Puckett, UConn, EF, W&M)

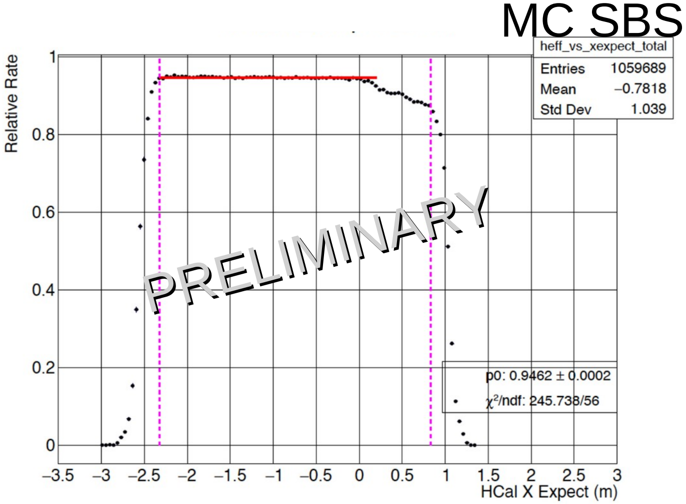
HCAL Non-Uniformity Corrections

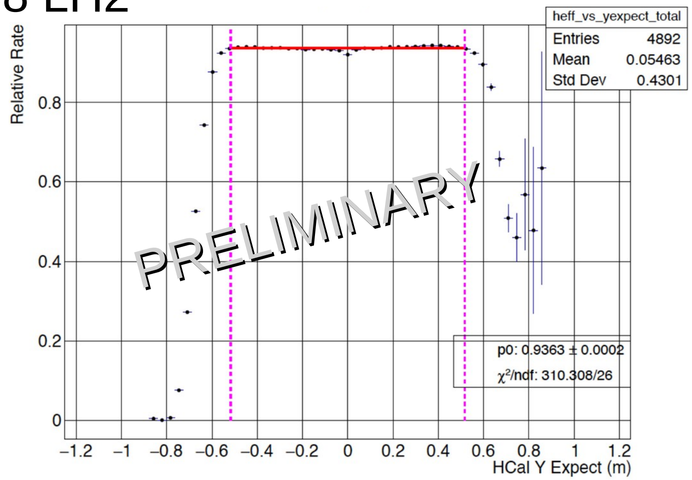
- Method to work around HCal efficiency non-uniformity:
  - ◘ Reweight MC events with HCal non-uniformity map;
  - ◘ Map efficiency along x_{expect}, y_{expect};
  - ◘ Efficiency analysis for data, MC;
    - ♦ MC weight: η_{data}/η_{MC};
    - ♦ deployed in analysis;
  - ◘ Similar efficiency drop for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

Analysis credit: Z. Wertz


Data SBS8 LH2

MC SBS8 LH2



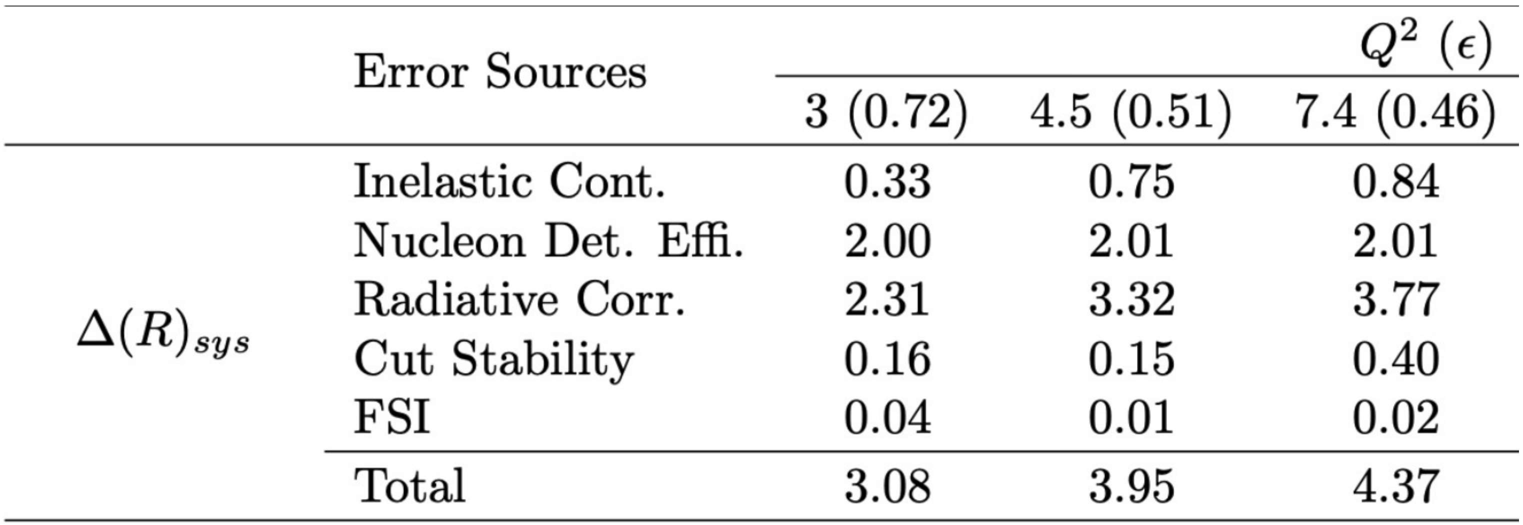


nTPE+ Systematics: GMn/nTPE Analysis

- Analysis: extraction of n/p ratios:

- Sources of systematics:
  - Radiative corrections
  - Nucleon detection efficiency;
  - Inelastic contamination;
  - selection;
  - Final State Interactions;

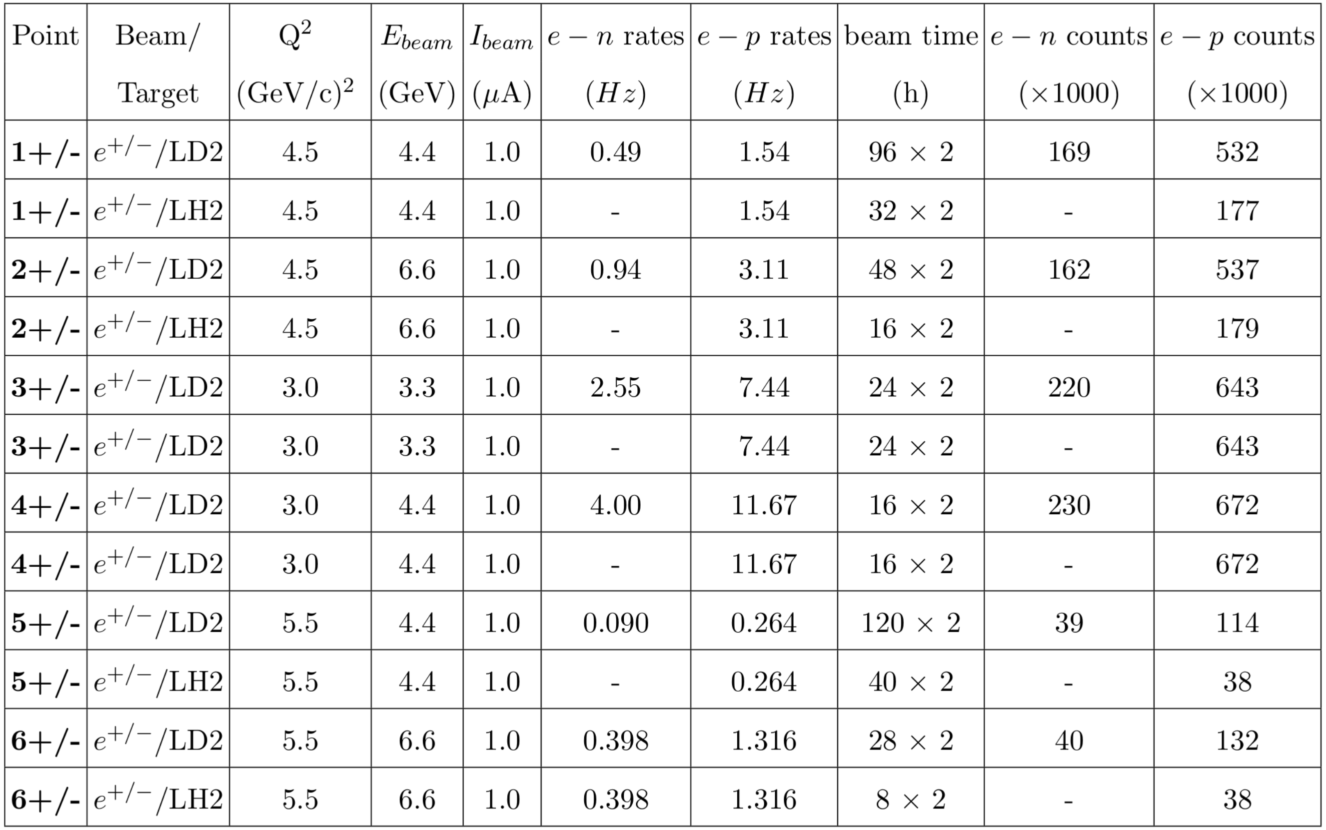
- Table/Analysis credit: Provakar Datta, UConn, LBNL



	Error Sources			Q^2 (ϵ)
		3 (0.72)	4.5 (0.51)	7.4 (0.46)
$\Delta(R)_{sys}$	Inelastic Cont.	0.33	0.75	0.84
	Nucleon Det. Effi.	2.00	2.01	2.01
	Radiative Corr.	2.31	3.32	3.77
	Cut Stability	0.16	0.15	0.40
	FSI	0.04	0.01	0.02
	Total	3.08	3.95	4.37

NTPE+ Time Request

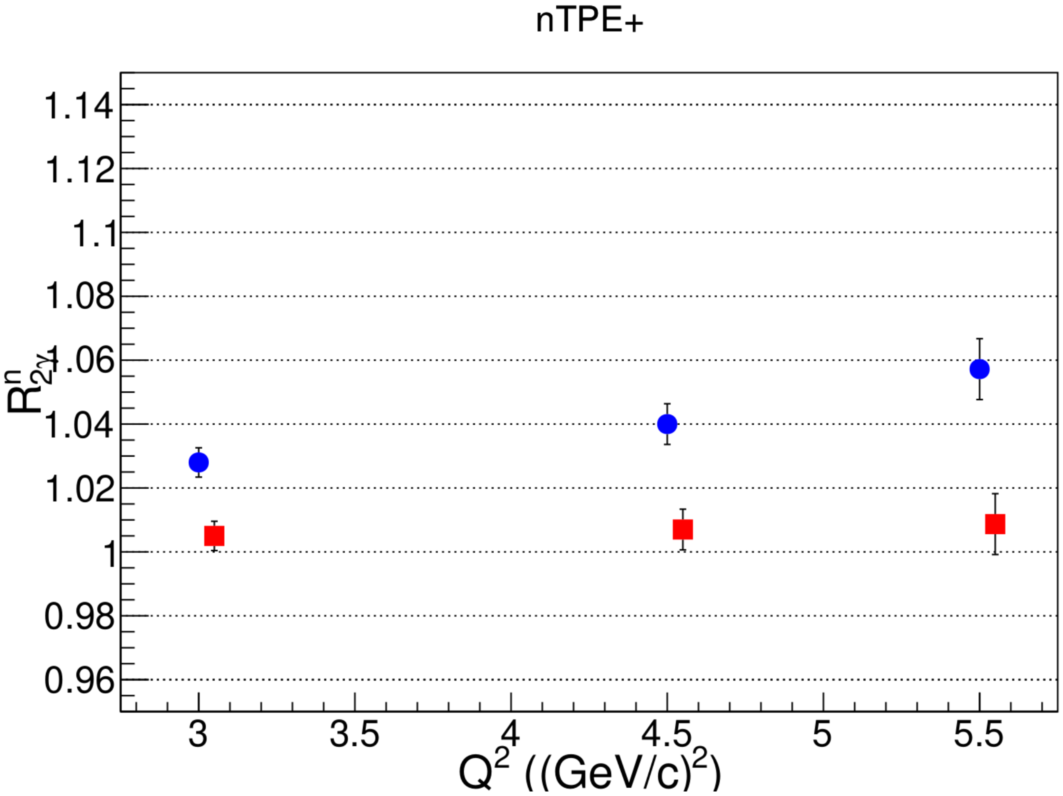
- All 6 kinematics with e+/e- LD2/LH2:
    - requires 936 hours (almost 40 days) beam on target:
    - 5 additional calendar days necessary for setting changes;
    - also need to add e+/e- changes (one shift ?);

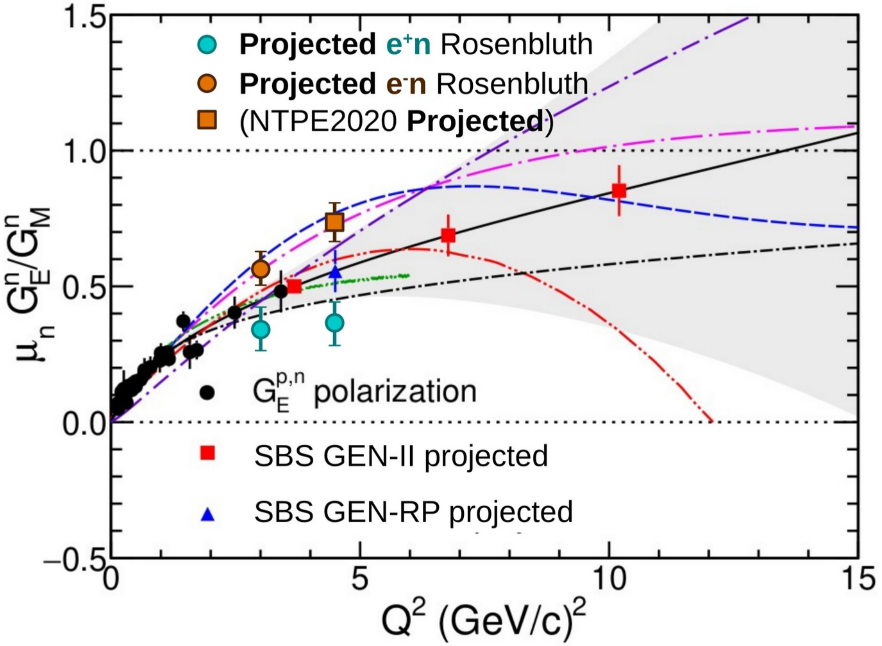


Point	Beam/ Target	Q^2 $(GeV/c)^2$	E_{beam} (GeV)	I_{beam} (μA)	$e-n$ rates (Hz)	$e-p$ rates (Hz)	beam time (h)	$e-n$ counts ($\times$1000)	$e-p$ counts ($\times$1000)
1+/-	$e^{+/-}$/LD2	4.5	4.4	1.0	0.49	1.54	96 × 2	169	532
1+/-	$e^{+/-}$/LH2	4.5	4.4	1.0	-	1.54	32 × 2	-	177
2+/-	$e^{+/-}$/LD2	4.5	6.6	1.0	0.94	3.11	48 × 2	162	537
2+/-	$e^{+/-}$/LH2	4.5	6.6	1.0	-	3.11	16 × 2	-	179
3+/-	$e^{+/-}$/LD2	3.0	3.3	1.0	2.55	7.44	24 × 2	220	643
3+/-	$e^{+/-}$/LD2	3.0	3.3	1.0	-	7.44	24 × 2	-	643
4+/-	$e^{+/-}$/LD2	3.0	4.4	1.0	4.00	11.67	16 × 2	230	672
4+/-	$e^{+/-}$/LD2	3.0	4.4	1.0	-	11.67	16 × 2	-	672
5+/-	$e^{+/-}$/LD2	5.5	4.4	1.0	0.090	0.264	120 × 2	39	114
5+/-	$e^{+/-}$/LH2	5.5	4.4	1.0	-	0.264	40 × 2	-	38
6+/-	$e^{+/-}$/LD2	5.5	6.6	1.0	0.398	1.316	28 × 2	40	132
6+/-	$e^{+/-}$/LH2	5.5	6.6	1.0	0.398	1.316	8 × 2	-	38

NTPE+ **Projections**

- $R^n_{2\gamma}$ for all 6 settings
- Estimations of e^+n/e^-n Rosenbluth slopes from LOI E12+24-008 to be updated;





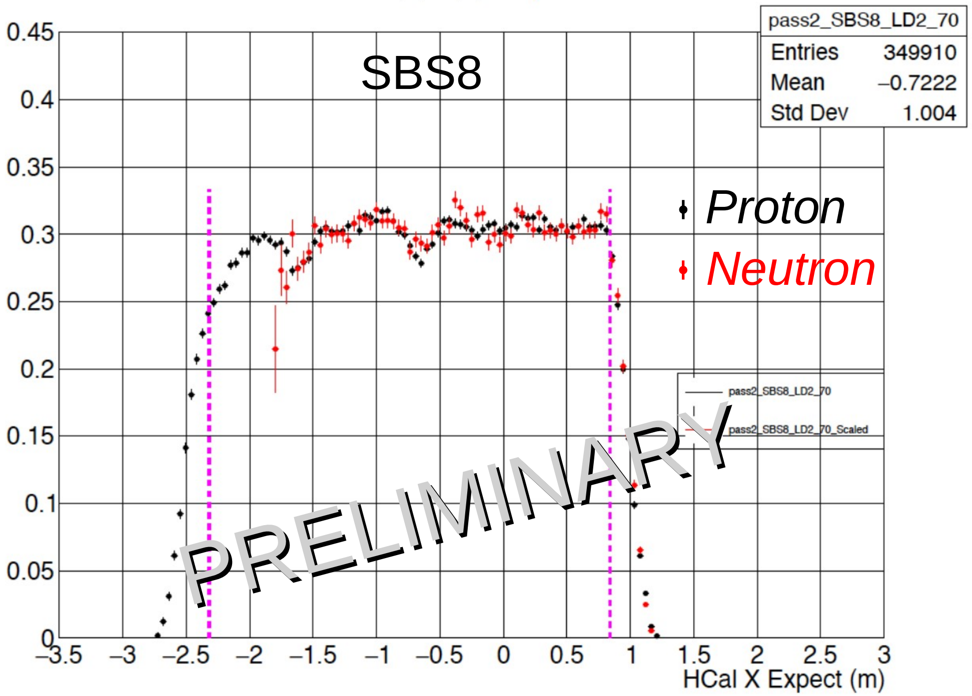
Summary

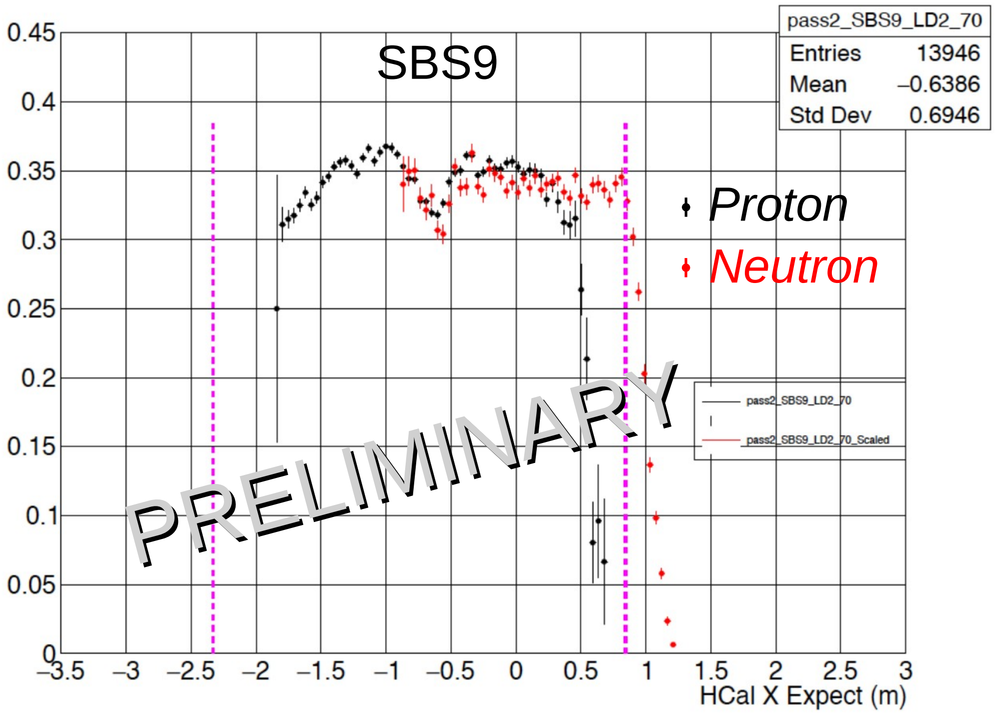
- Rosenbluth measurement of e^+n **NTPE+** will provide valuable insight on TPE in combination with the following measurements:
  - ◘ e^-n Rosenbluth measurement NTPE;
  - ◘ e^-n with polarization transfer measurement (GEN, GENRP);
- NTPE+ will benefit from the return of experience of the NTPE analysis
  - ◘ Extraction method worked out;
  - ◘ Systematics, mostly under control;
- TO-DO:
  - ◘ Update estimations of e^+n/e^-n Rosenbluth slopes
  - ◘ Update proposal document;
  - ◘ Draft a preliminary run plan to add to the document

Thank you for your attention !

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;

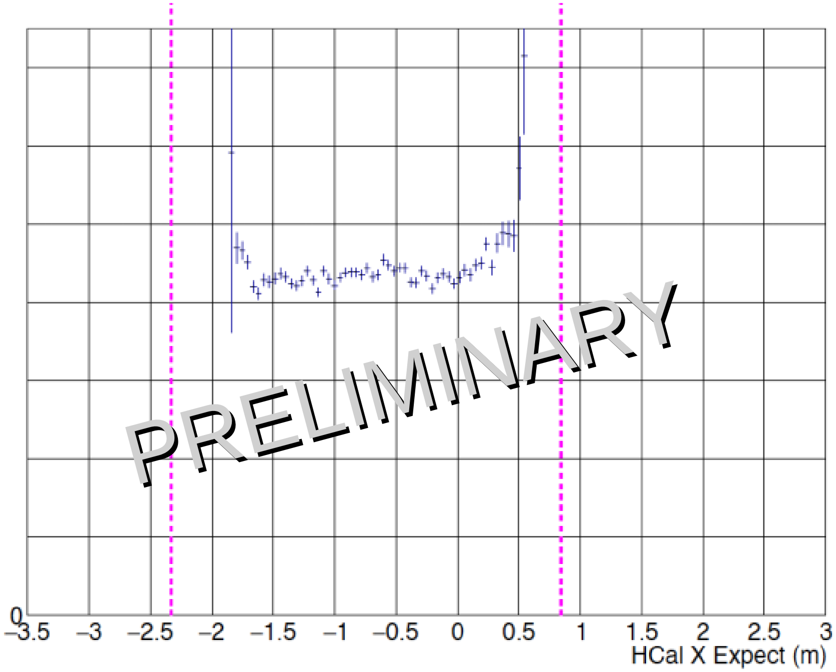


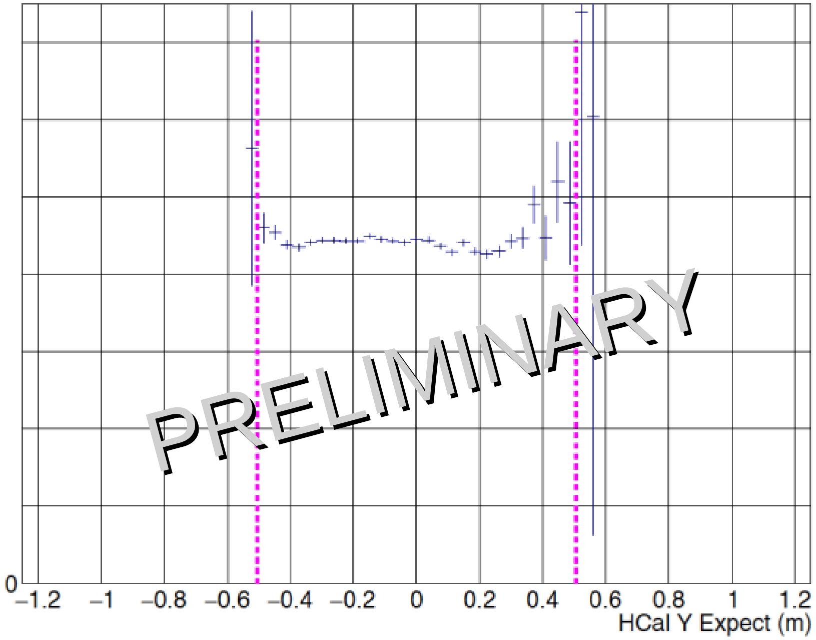


Analysis credit: Z. Wertz

HCAL Non-Uniformity Corrections

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





Analysis credit: Z. Wertz