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

A Proposal to PAC53

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College of William & Mary

(On behalf of the nTPE collaboration)

Hall A/C Summer Collaboration Meeting

June 17th, 2025

WILLIAM & MARY

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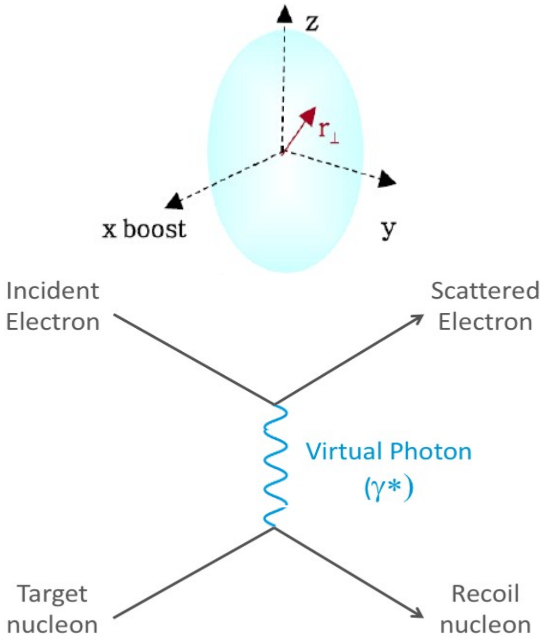
Jefferson Lab

Elastic *e*-*N* scattering: Rosenbluth



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

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

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

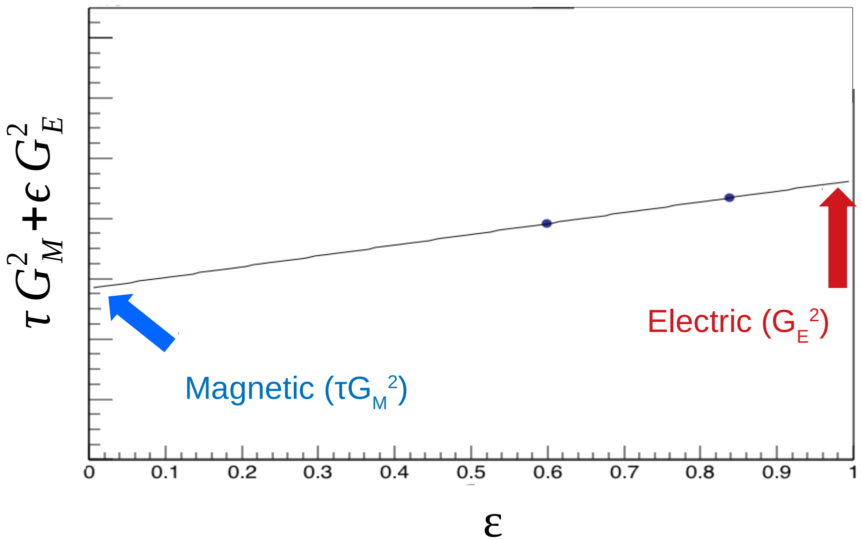
Sachs magnetic FF squared | Sachs Electric FF squared

- 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

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

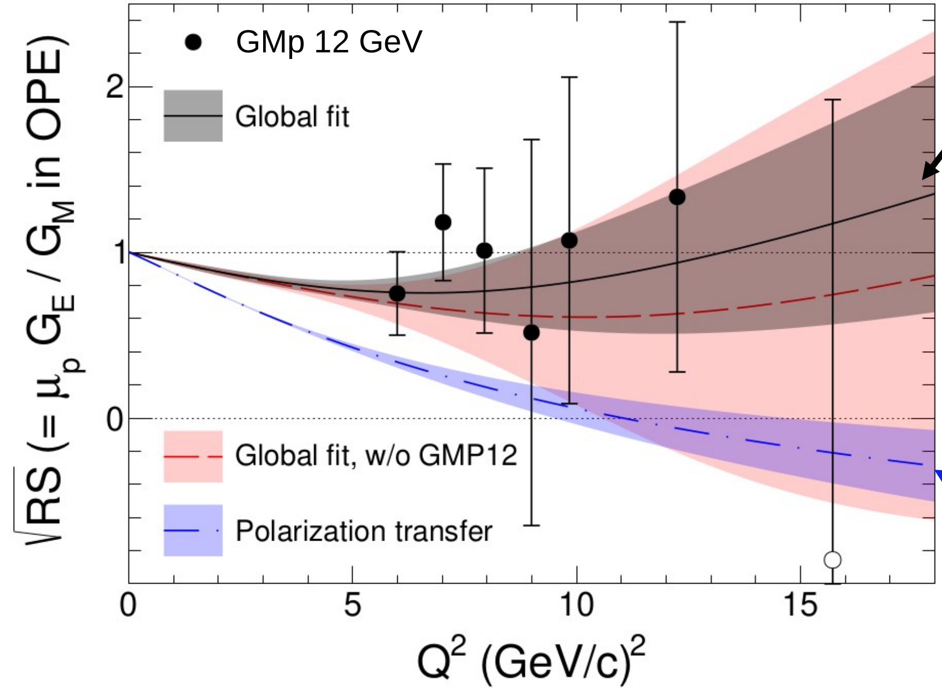
- Two or more measurements, same Q^2, different E and θ (different ε)



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 (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



Global fit of high Q^2 Rosenbluth measurements

Latest JLab proton data at 12 GeV

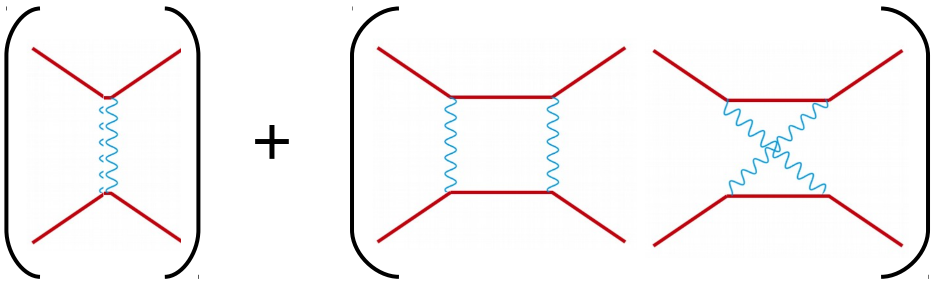
Global fit of polarization transfer measurements

Two-Photon Exchange with Positrons

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

Lepton charge

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

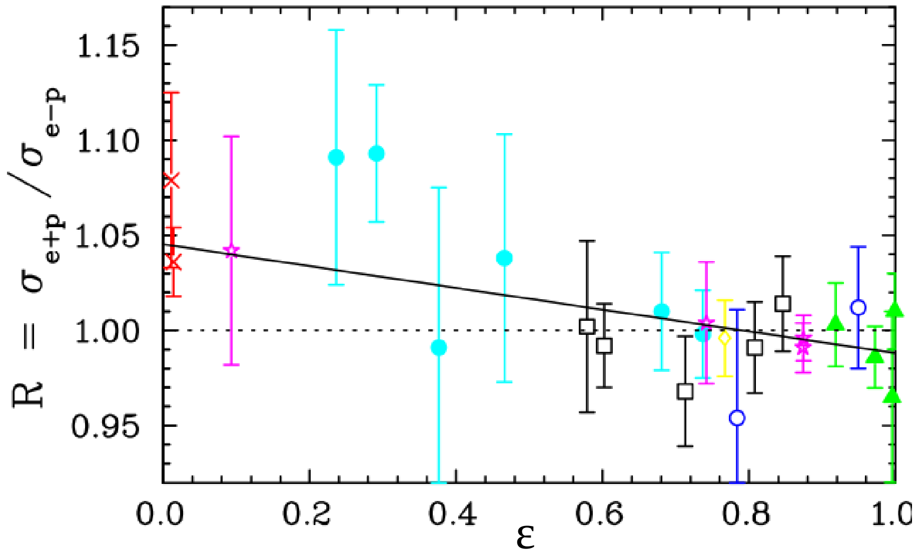


- Interference term depends on the lepton charge to the power 3:
  - TPE expected to be of same magnitude opposite sign in $e^{+}N$ and $e^{-}N$;
  - measurement $e^{+}N$ / $e^{-}N$ => 2 TPE

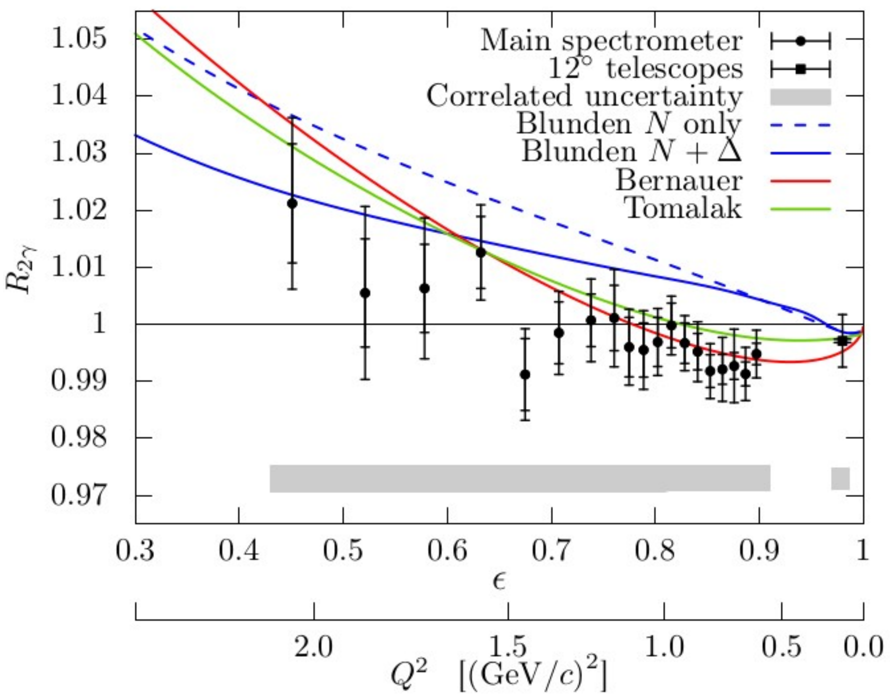
$e^{+}p$ measurements

- 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



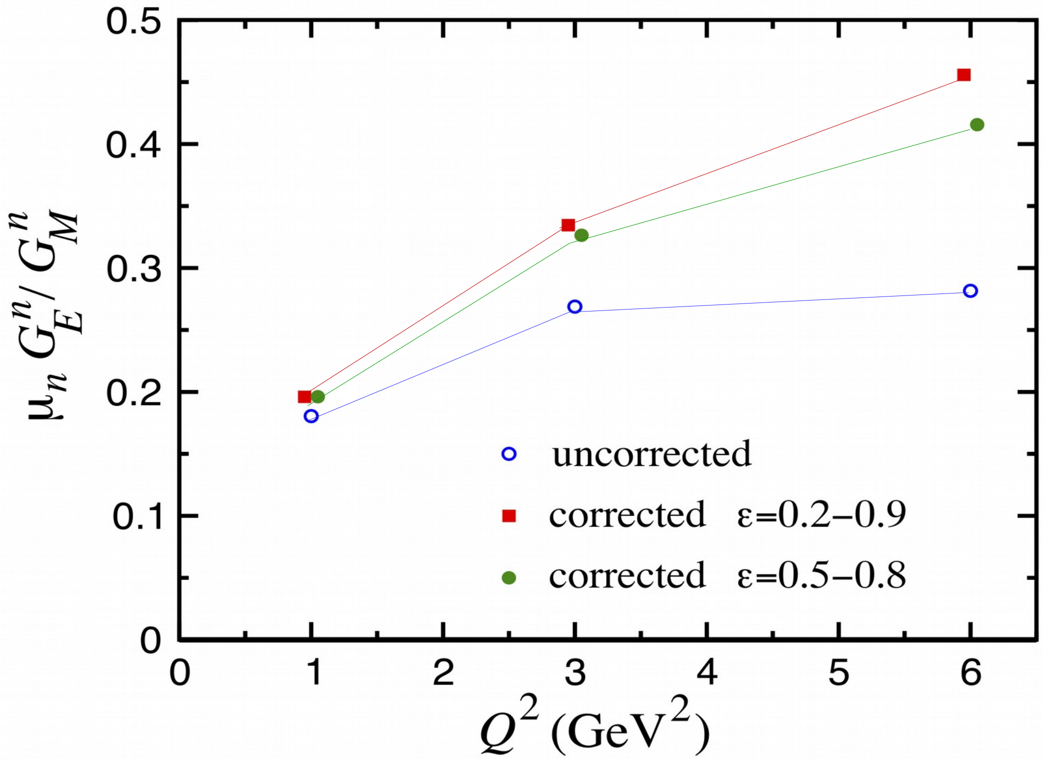
Phys. Rev. Lett. 118, 092501 (2017)



- ***Essentially inconclusive results***
- Note: Rosenbluth/polarization discrepancy insignificant at low Q^2

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 Rosenbluth/TPE measurement on the neutron* => *nTPE+***



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

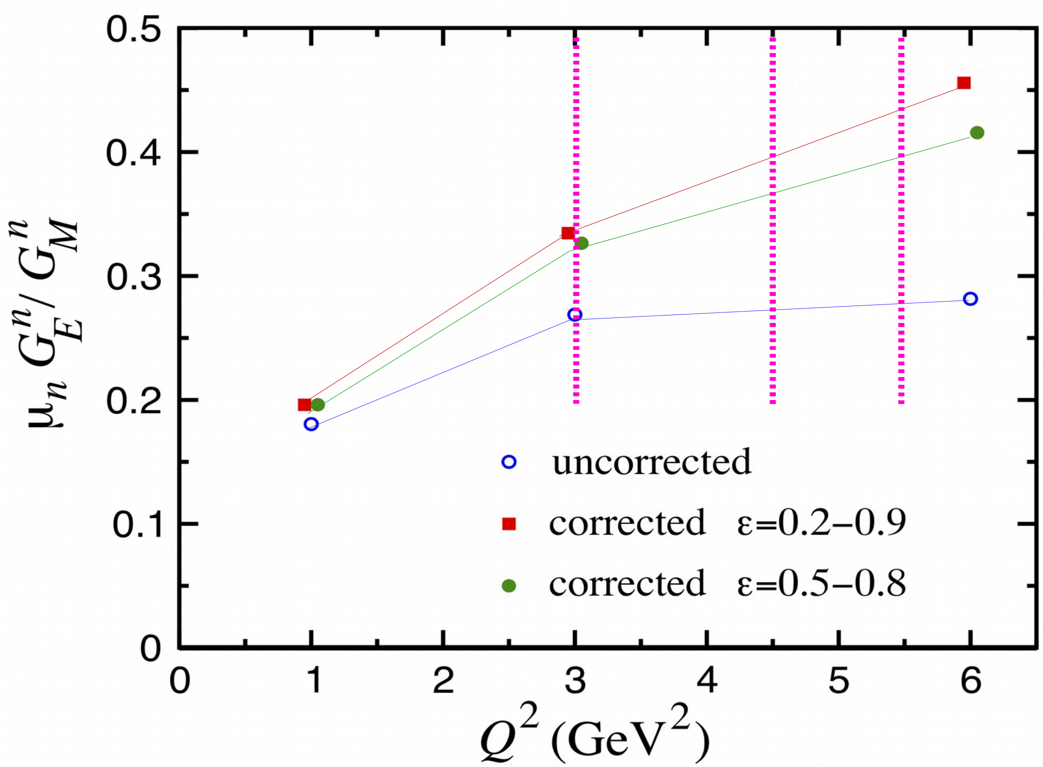
○ $\mu_n G_E^n/G_M^n$ from Mergell Meissner Drechsel parameterization of polarized data in Nucl. Phys. A596, 367 (1996)

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

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

Two-Photon Exchange in *en* Scattering

- NTPE+: E.F. (contact), S. Alsalmi, P. Blunden, P.Datta, E. Wertz
  - measure neutron TPE at Q2 = 3 GeV2, 4.5 GeV2, 5.5 GeV2
  - Direct measurement of nTPE via e+n/e-n ratio
  - Rosenbluth measurements of e-n and e+n cross section
  - => disentangle contribution of TPE in Rosenbluth/polarization discrepancies



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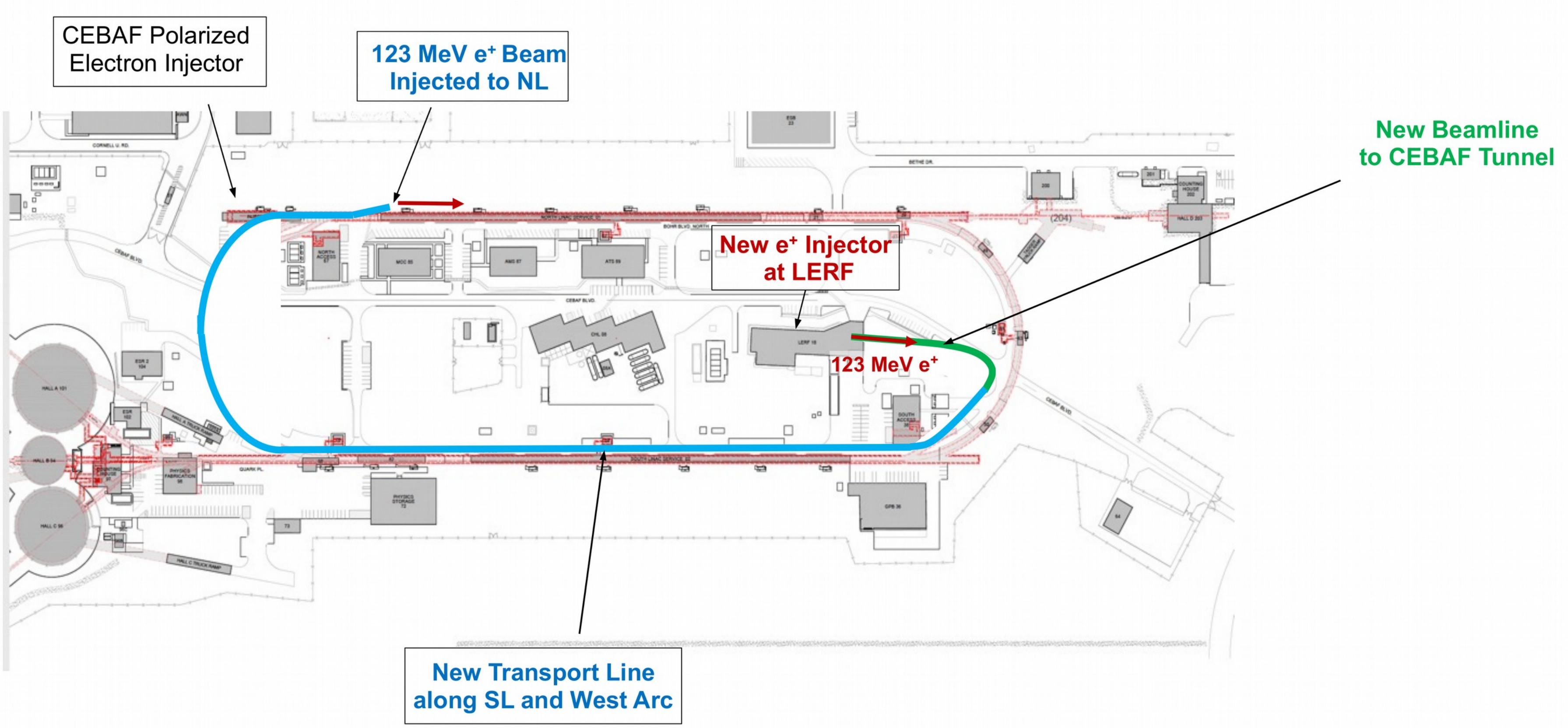
● $\mu_n G_E^n/G_M^n$ +TPE between ε = 0.5 and 0.8

nTPE+ with Jefferson Lab Positron Upgrade

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

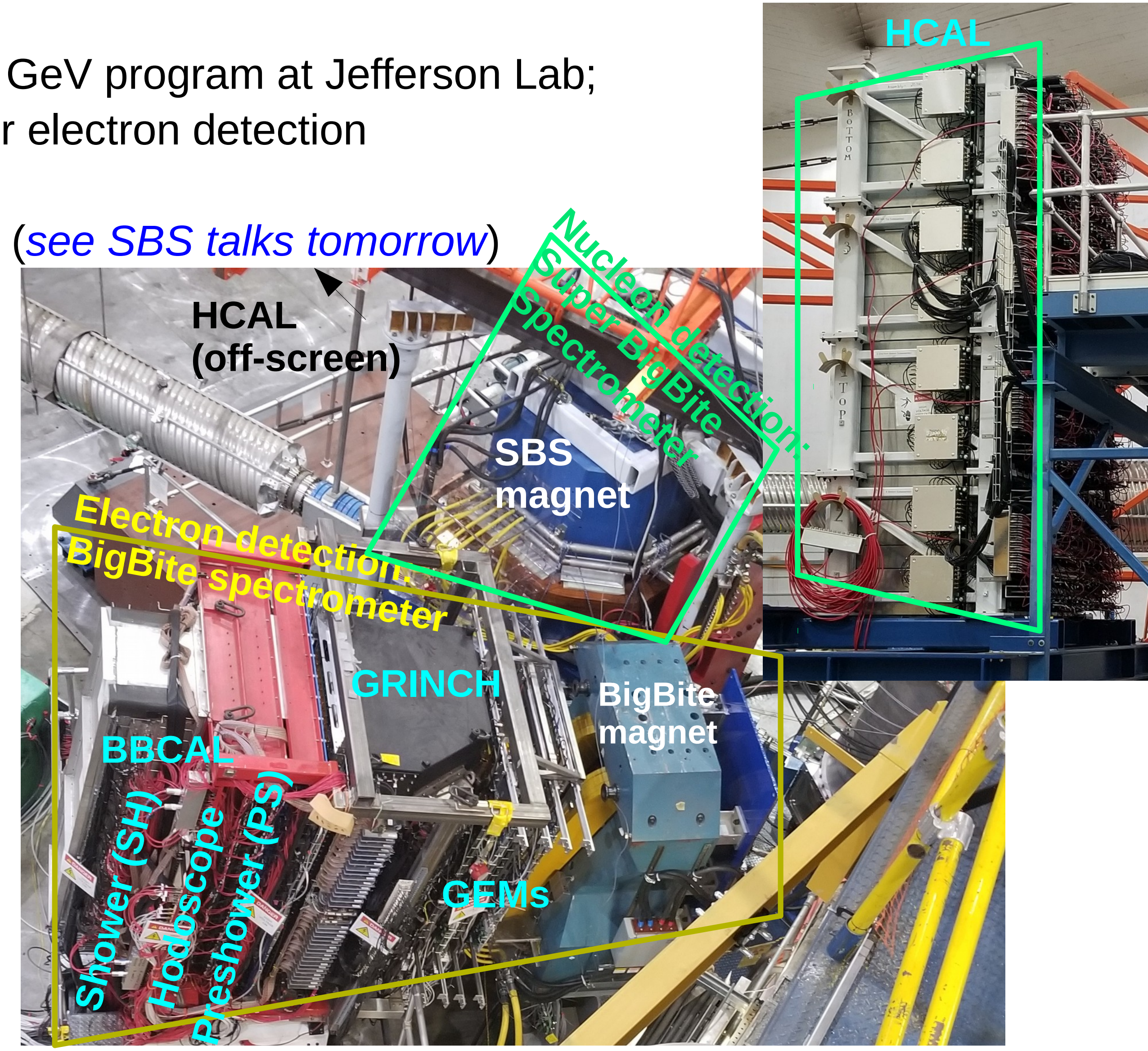


nTPE with Super BigBite Spectrometer

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

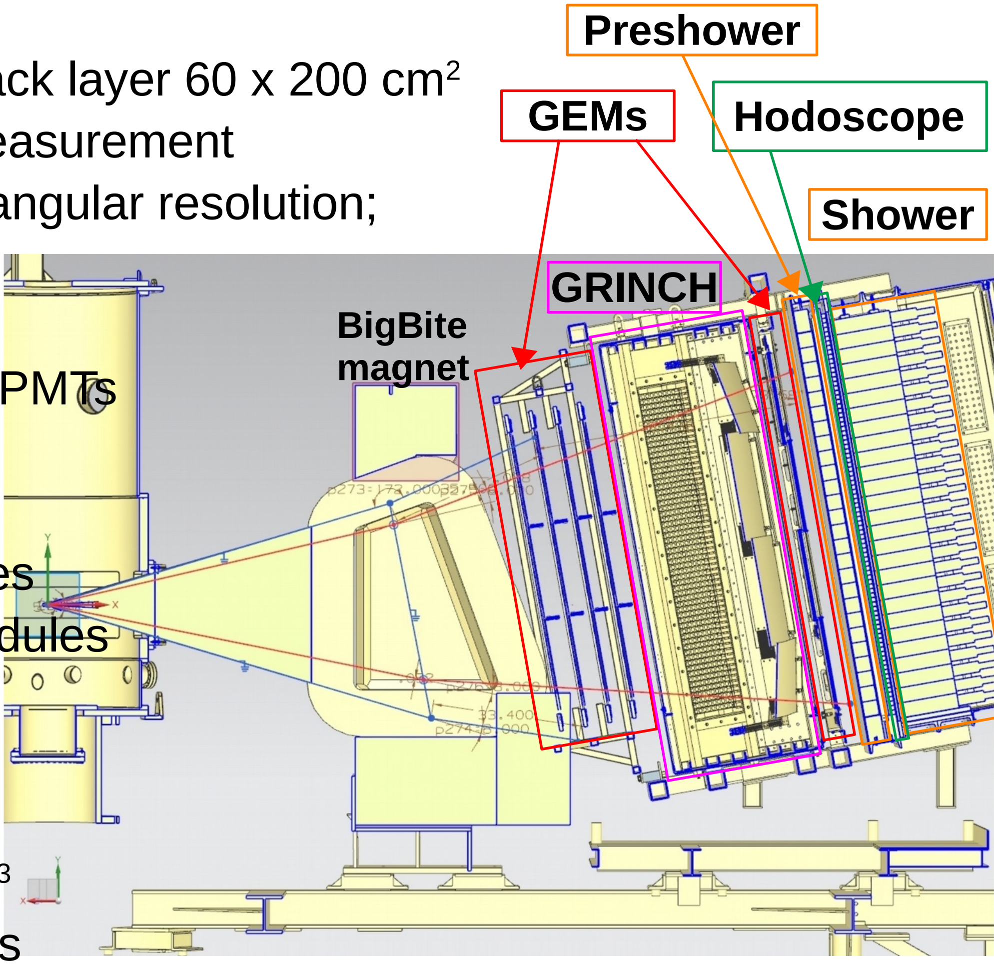
- **SBS form factor program** (*see SBS talks tomorrow*)
  - GMN
  - **nTPE** (E12-20-010):
    - ♦ *en* Rosenbluth separation
  - GEN
  - GEN-RP
  - GEP

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



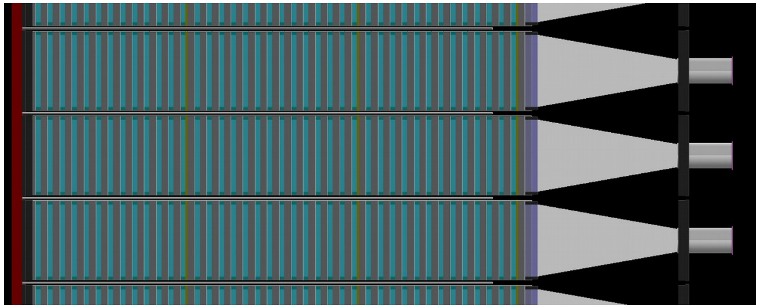
Super BigBite Spectrometer: BigBite

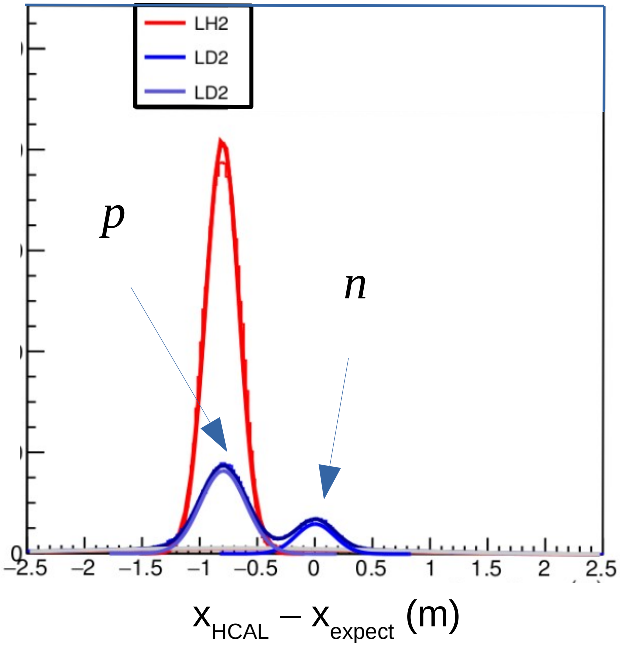
- Detector package tilted 10% behind dipole magnet
- **Function: Electron measurement;**
- Detector package:
  - GEMs:
    - 4 front layers 40 x 150 cm^2, 1 back layer 60 x 200 cm^2
    - momentum trivector + vertex measurement
    - 1% momentum resolution, 1mr angular resolution;
  - GRINCH:
    - C4F8 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

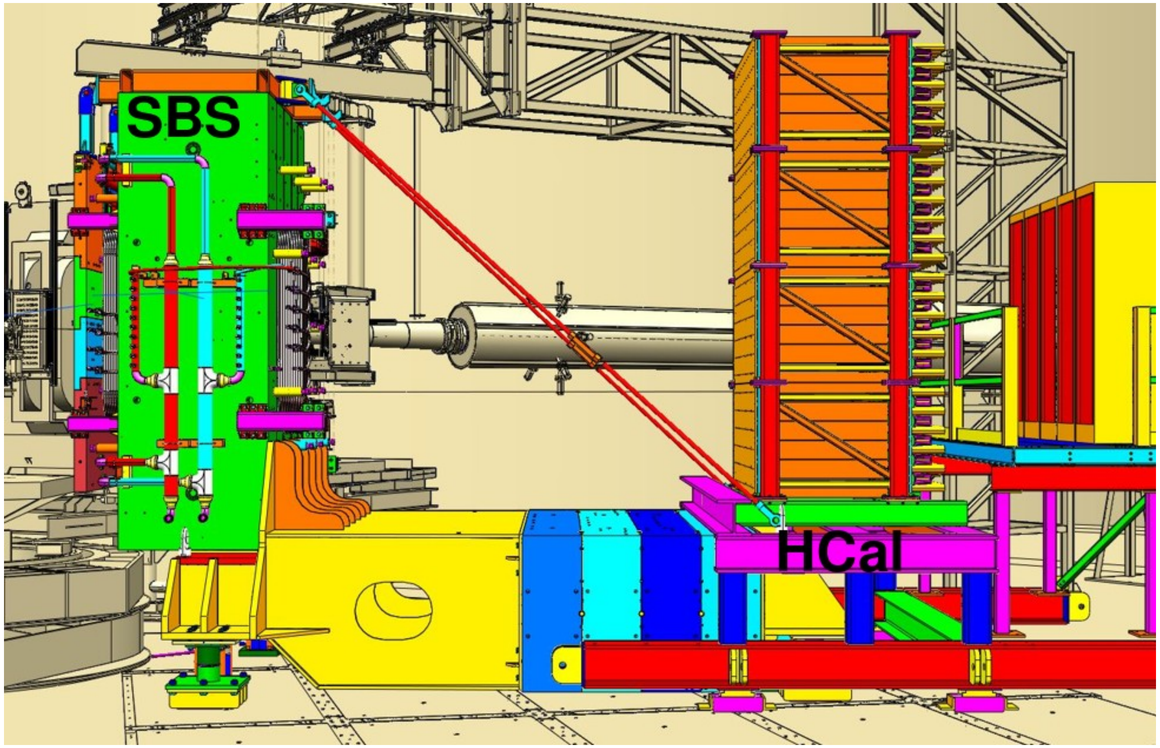
- 12 x 24 iron/scintillator modules 15 x 15 * 90 cm^3
- **Function: Nucleon measurement:**
  - Position resolution ~5.5cm
  - Timing resolution (*ADC only*) ~1.5 ns
  - Energy resolution ~50 %
- **Nucleon identification (see next)**





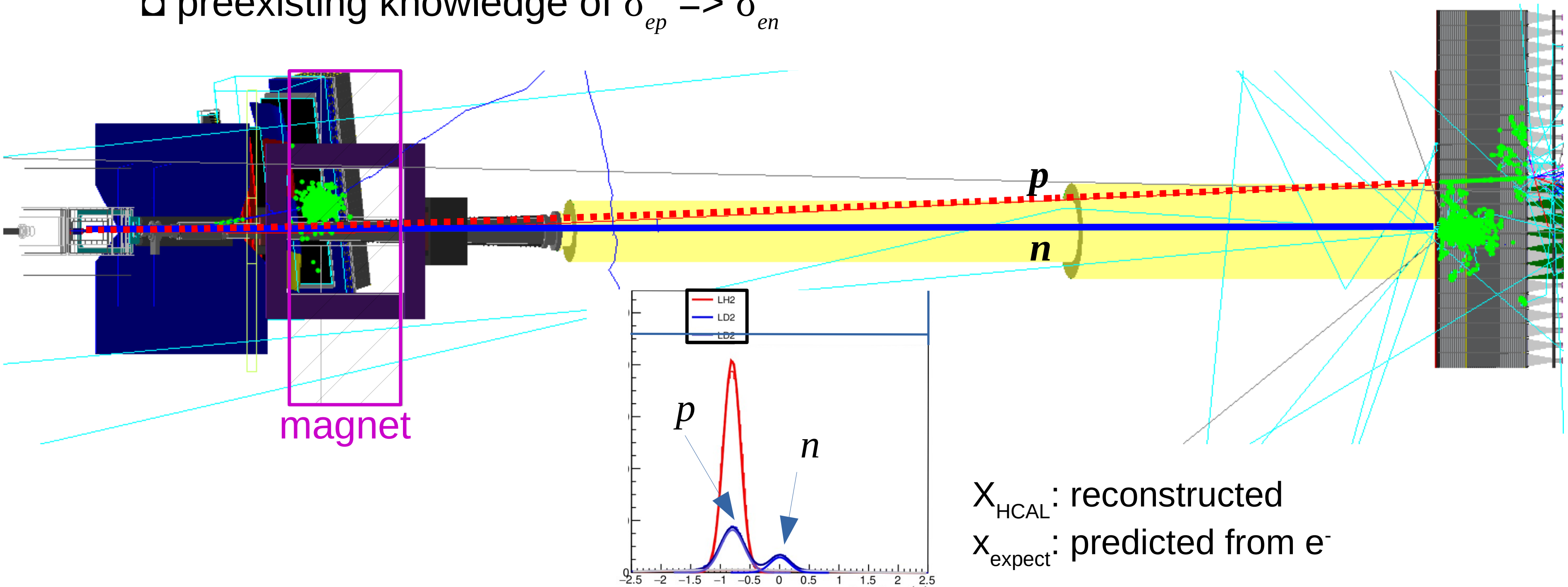
X_{HCAL}: reconstructed

x_{expect}: predicted from e^-



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 magnet
  - σ_{en}/σ_{ep} with reduced systematics (cancellation of Fermi momentum,…)
  - preexisting knowledge of σ_{ep} => σ_{en}

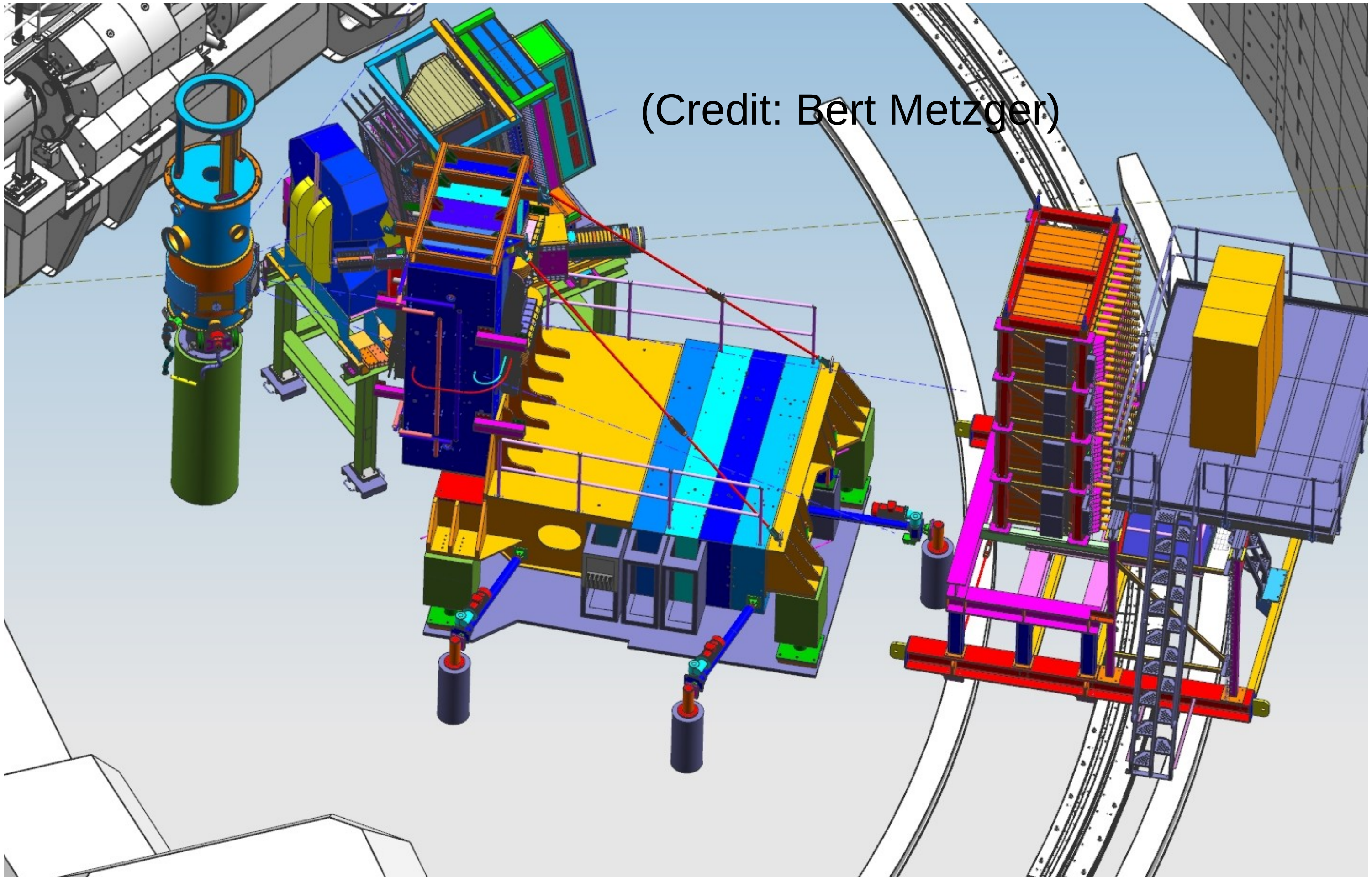


X_{HCAL}: reconstructed
x_{expect}: predicted from e^-

$x_{HCAL} - x_{expect}$ (m)

nTPE+ Kinematics

- 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;



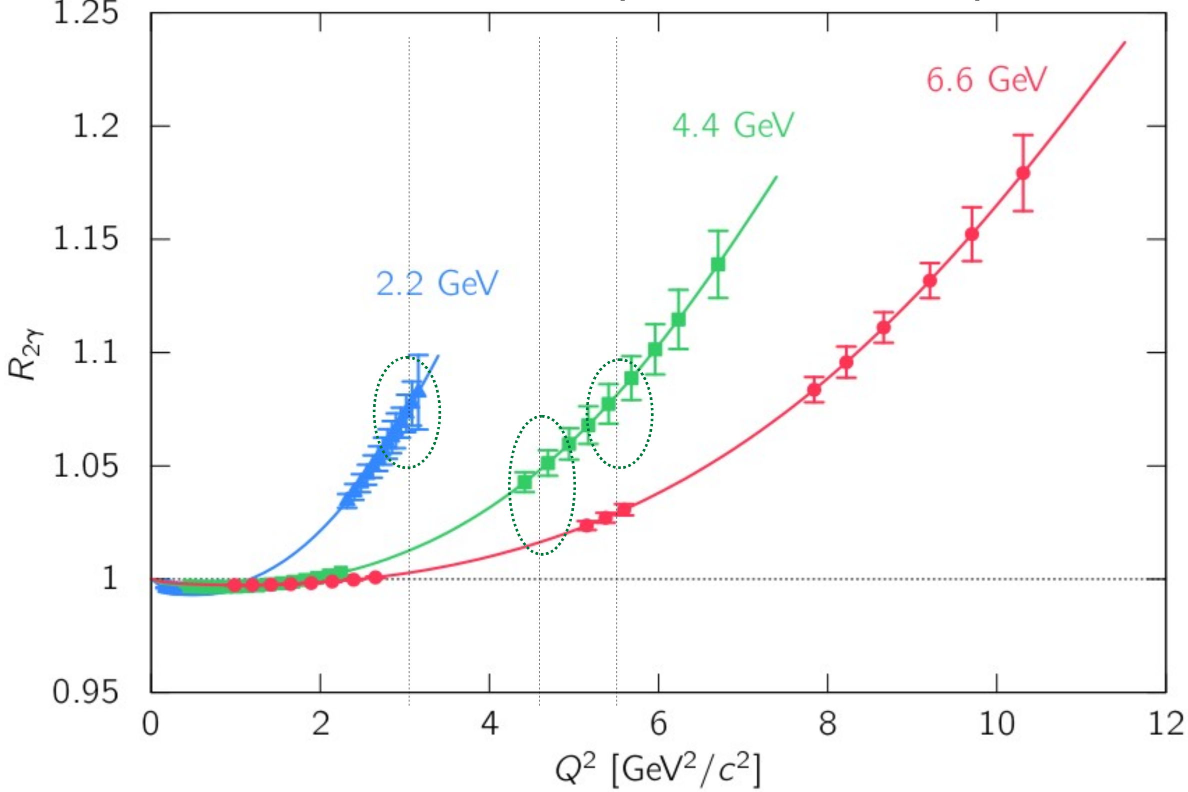
nTPE+ Kinematics

- 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;
  - Three settings at 2 pass, two settings at 3 pass, one setting at 1.5 pass.

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+ Measurements: *e+/e-* ratios $R_{2\gamma}$

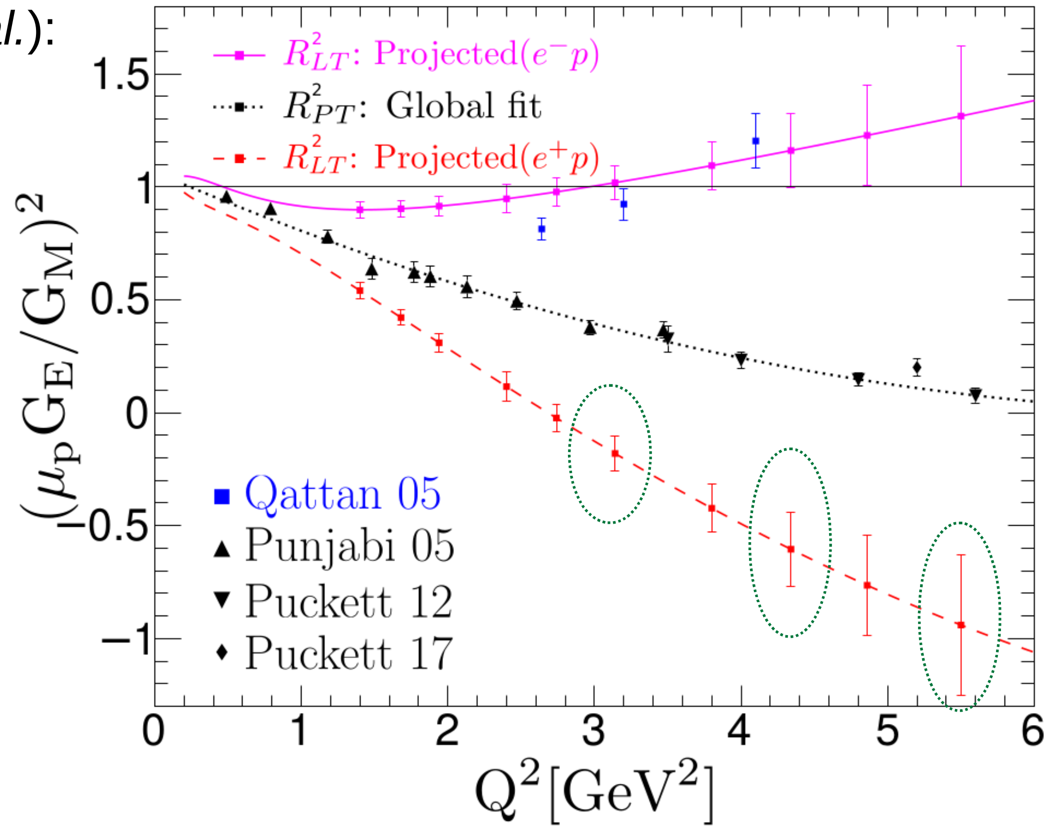
- $R^n_{2\gamma}$ measurement with Durand technique:
  - Measure $R_{n/p} = \sigma_{en}/\sigma_{ep}$ consecutively for positrons and electrons;
  - $\rho_{\pm} = \left(\frac{\sigma_{e^+n}}{\sigma_{e^+p}}\right) / \left(\frac{\sigma_{e^-n}}{\sigma_{e^-p}}\right) = R^n_{2\gamma} / R^p_{2\gamma}$ for **Q^2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



nTPE+ Measurements: Rosenbluth slopes S^n

- Rosenbluth measurement with Durand technique:
  - Measure $R_{n/p} = \sigma_{en}/\sigma_{ep}$ for both ε points;
  - $A = \frac{R_{n/p}^{\epsilon_1}}{R_{n/p}^{\epsilon_2}} \simeq \frac{1+\epsilon_2 S^p}{1+\epsilon_1 S^p} \times \left(1 + S^n \Delta \epsilon\right)$
  - Rosenbluth e^+p *up to Q^2 = 5.5 GeV^2* sourced from PR12+23-012

(M. Nycz *et al.*):



nTPE+ Systematics: GMn/nTPE Analysis

- Sources of systematics for $R_{n/p}$:
  - See GMn/nTPE analysis talk tomorrow for more details;

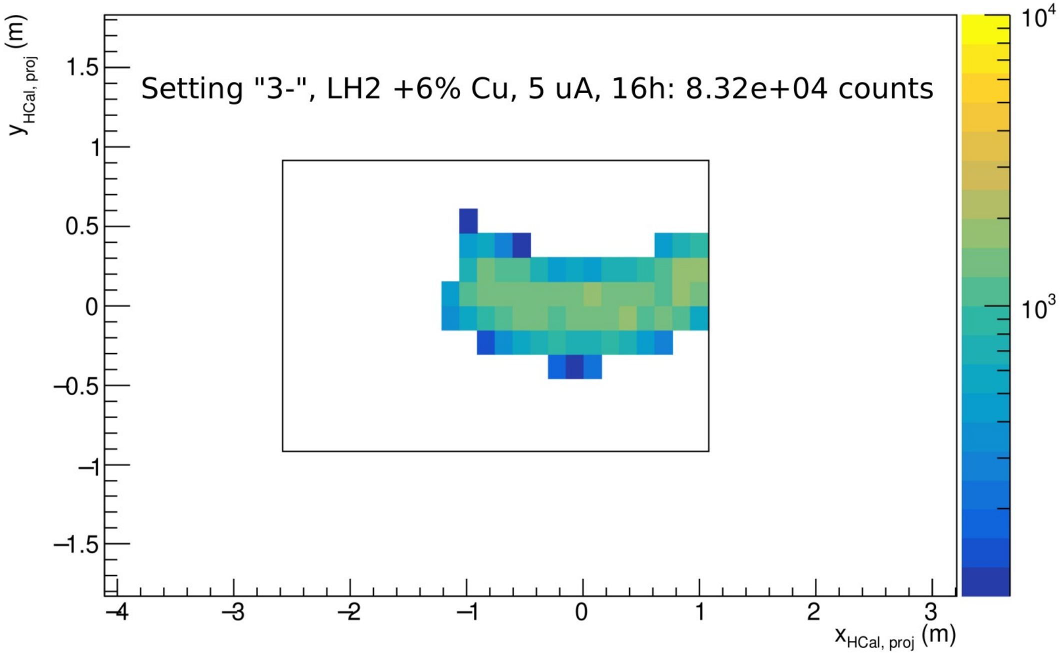
- Preliminary estimation of systematics for GMn analysis:
  (credit: P. Datta, LBNL, formerly UConn)
  - (*) => Divided by a factor 3 to account for possible improvements
  - Introduced factors of covariance for correlations between settings

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	+0.80	0.0
Inelastic contamination	0.33	0.75	0.84	+0.5	0.0
Nucleon detection efficiency*	0.7	0.7	0.7	+0.95	+0.5
Nucleon charge exchange in FSI	0.04	0.01	0.02	+0.95	0.0
Selection stability	0.16	0.15	0.40	+1.00	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	-	-

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 $\gamma p \rightarrow \pi^{+} n$ at “kinematic end-point”:
  - 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;
  - Coverage of ~1/4 of HCal surface sufficient to determine neutron efficiency



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

- Sources of systematics for $R_{n/p}$:
  - See GMn/nTPE analysis talk tomorrow;
- 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
$\Delta R^p_{2\gamma}/R^p_{2\gamma}$ [13]	0.78	0.42	0.79
$\Delta R^n_{2\gamma}/R^n_{2\gamma}$ (syst)	0.93	0.89	1.28

S^n

$\mathrm{Q}^2((\mathrm{GeV/c})^2)$	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 [3, 14]	0.1056	-0.0267	0.0616	-0.0608	0.0478	-0.0773
ΔS^p [3, 14]	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

[3] Phys.Rev.Lett. 128 (2022) 10, 102002
[13] A. Schmidt *et al.* PR12+23-008
[14] M. Nycz *et al.* PR12+23-012

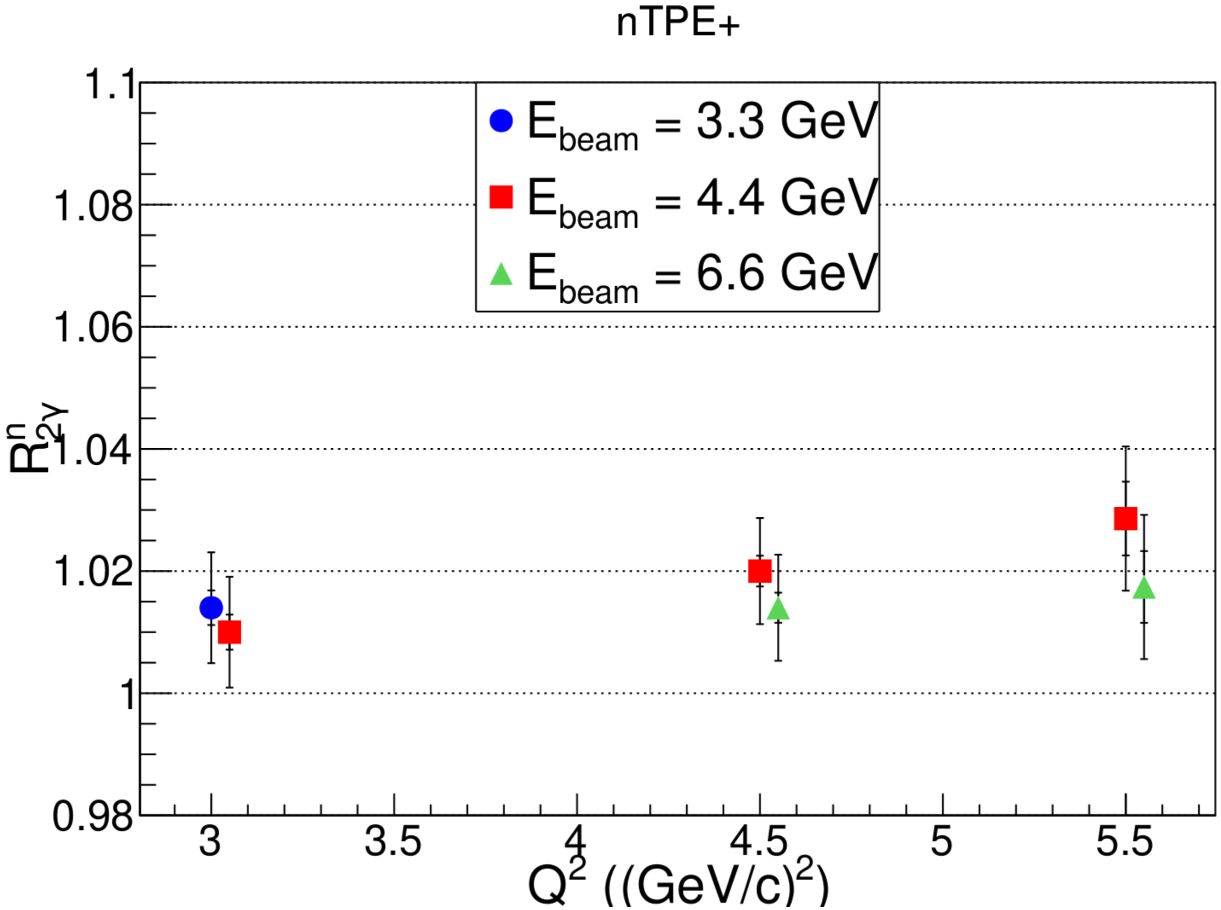
NTPE+ Time Request

- All 6 kinematics with e+/e- LD2/LH2:
  - requires 952 PAC hours (almost 40 days) beam on target:
  - 224 additional PAC hours necessary for setting changes:
    - ♦ 144 hours for 6 e+/e- changes;
    - ♦ 80 hours for 5 magnet angle changes (and pass changes);

Kin	e^+ or e^-	E_{Beam} (pass) (GeV)	I_{Beam} μA	Q^2 $(\text{GeV/c})^2$	θ_{BB} / θ_{SBS} (degrees)	target	PAC Time (hours)
Optics	e^-	3.3 (1.5)	10.0	3.0	42.8/29.5	C-foil	16
1-	e^-	3.3 (1.5)	1.0	3.0	42.8/29.5	LD2/LH2	24/12
Reconfiguration to positrons							$24^\dagger$
1+	e^+	3.3 (3*)	1.0	3.0	42.8/29.5	LD2/LH2	24/12
Pass change + BB/SBS magnet configuration change							16
2+	e^+	4.4 (2)	1.0	3.0	28.5/34.7	LD2/LH2	16/16
Reconfiguration to electrons							$24^\dagger$
2-	e^-	4.4 (2)	1.0	3.0	28.5/34.7	LD2/LH2	16/16
BB/SBS magnet configuration change							16
3-	e^-	4.4 (2)	1.0	4.5	41.9/24.7	LD2/LH2	96/16
NDE	e^-	4.4 (2)	1.0	4.5	41.9/24.7	LH2+6% Cu Rad	16
Reconfiguration to positrons							$24^\dagger$
3+	e^+	4.4 (2)	1.0	4.5	41.9/24.7	LD2/LH2	96/32
BB/SBS magnet configuration change							16
5+	e^+	4.4 (2)	1.0	5.5	54.9/18.7	LD2/LD2	120/40
Reconfiguration to electrons							$24^\dagger$
5-	e^-	4.4 (2)	1.0	5.5	54.9/18.7	LD2/LH2	120/40
Pass change + BB/SBS magnet configuration change							16
4-	e^-	6.6 (3)	1.0	4.5	23.3/31.2	LD2/LH2	48/16
Reconfiguration to positrons							$24^\dagger$
4+	e^+	6.6 (3)	1.0	4.5	23.3/31.2	LD2/LH2	48/16
BB/SBS magnet configuration change							16
6+	e^+	6.6 (3)	1.0	5.5	27.6/26.9	LD2/LH2	36/12
Reconfiguration to electrons							$24^\dagger$
6-	e^-	6.6 (3)	1.0	5.5	27.6/26.9	LD2/LH2	36/12
Total beam							**952**
Total time request							**1176**

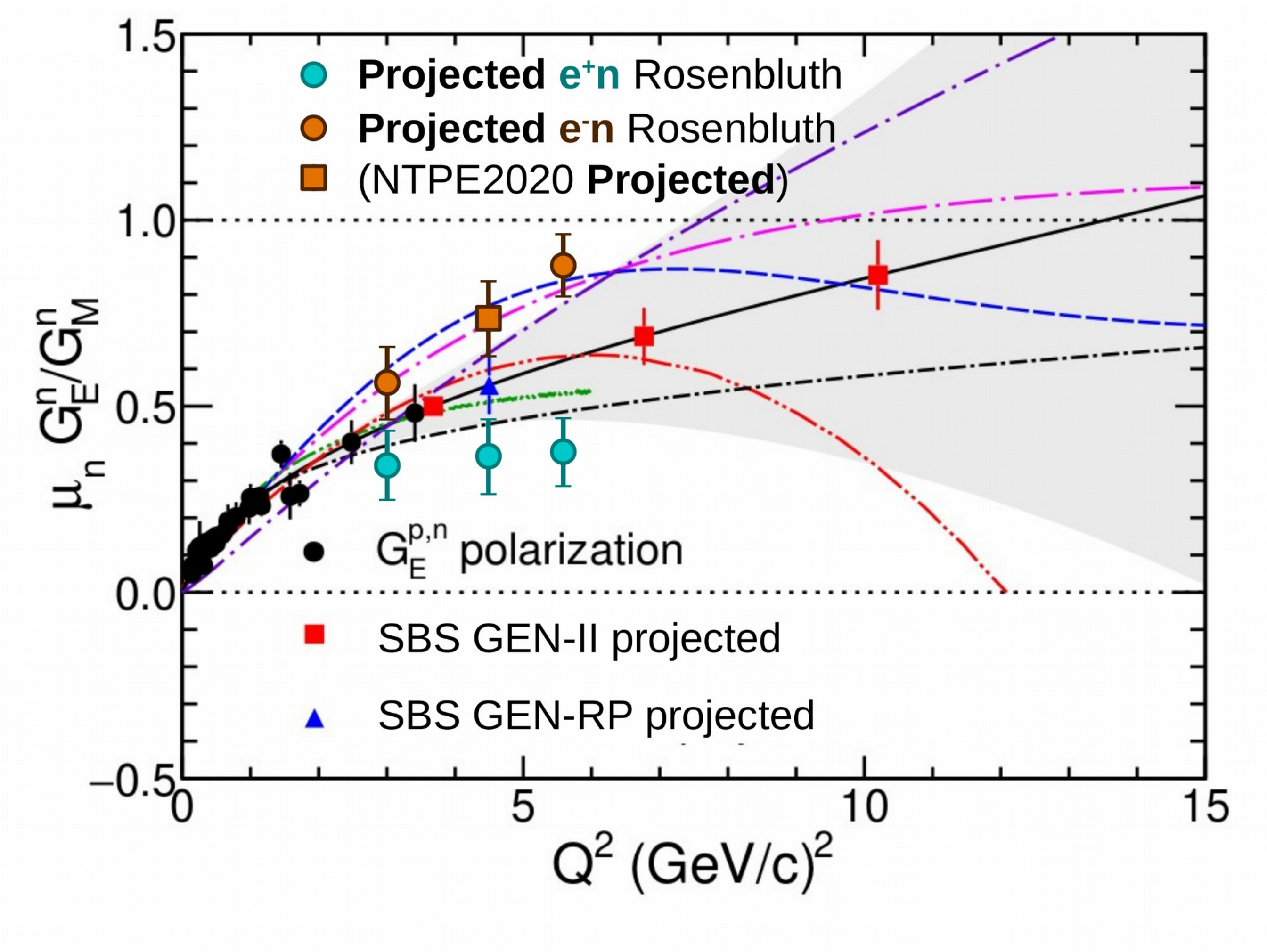
NTPE+ Projections

- $R^{n}_{2\gamma}$ for all 6 settings:
  - statistical uncertainty (inner bars);
  - statistical + systematics (outer bars);



NTPE+ Projections

- Estimations of e^+n and e^-n Rosenbluth slopes
  - Superimposed on Fig. 10.1.9 of [arXiv:2212.11107 [hep-ph]](https://arxiv.org/abs/2212.11107).
  - $\mu_n\, G_E^n/G_M^n$ calculated from projected Rosenbluth slopes;
  - Other G_E^n measurements and projections are polarization data;



Summary

- NTPE+: unprecedented measurements on Two-Photon Exchange on Neutron:
  - Direct measurement of nTPE via e+n/e-n ratio
  - Rosenbluth measurements of e-n and e+n cross section
  - Disentangle contribution of TPE in Rosenbluth/polarization discrepancies
  - complements current SBS Form Factors program;

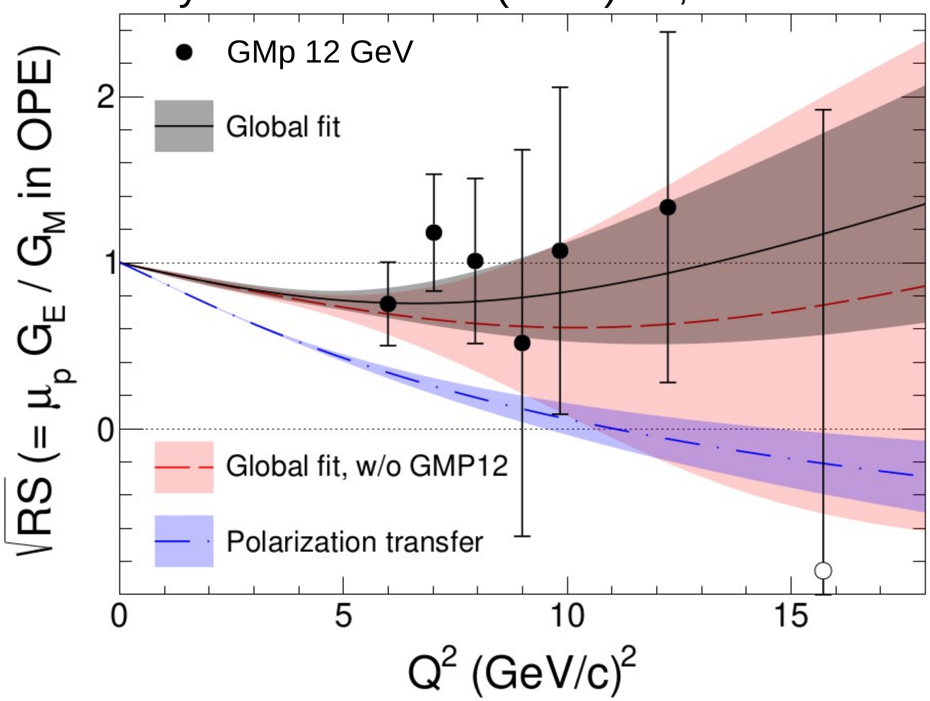
- NTPE+ will benefit from the return of experience of the NTPE analysis
  - Extraction method worked out;
  - Systematics mostly under control:
    - HCal detection efficiency systematics significantly improved with a dedicated measurement;

Thank you for your attention !

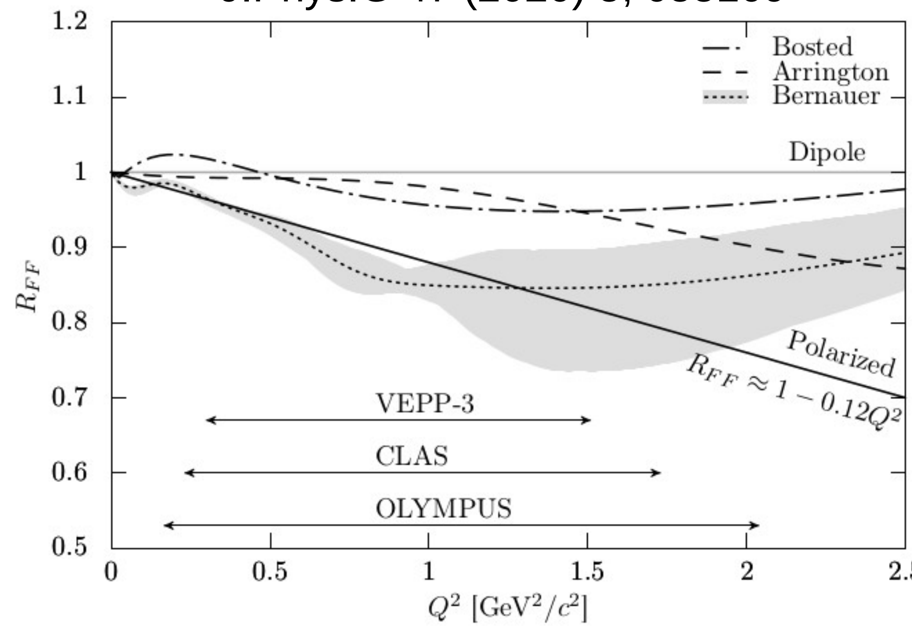
Global Fit on Rosenbluth Slope in e^-p Scattering

- 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 (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

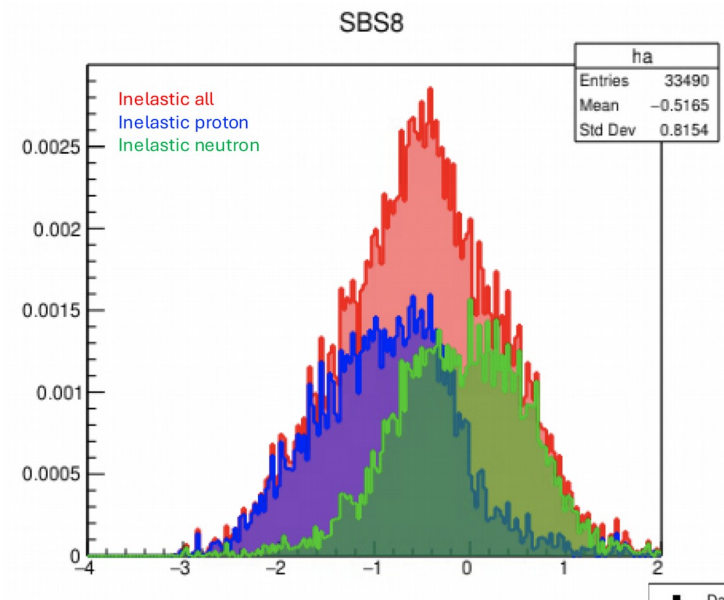


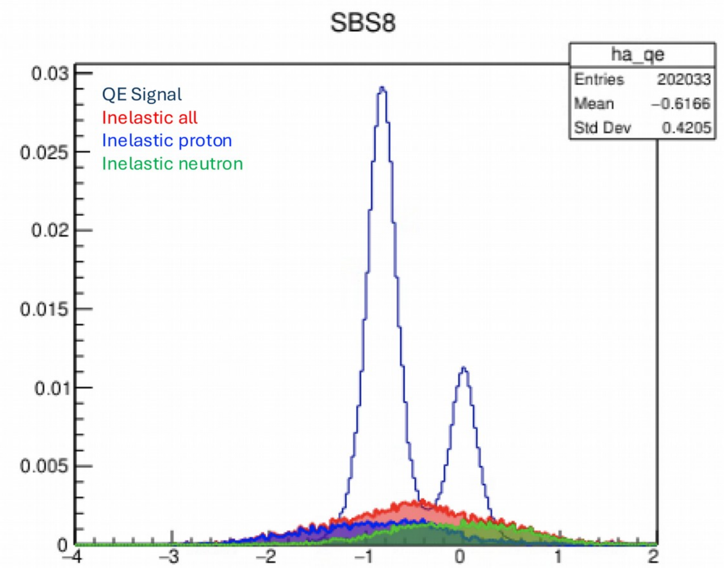
J.Phys.G 47 (2020) 5, 055109

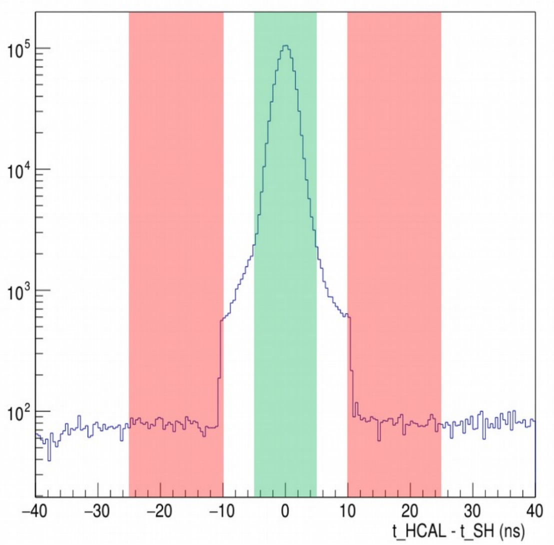


Systematic uncertainties: Inelastic contamination

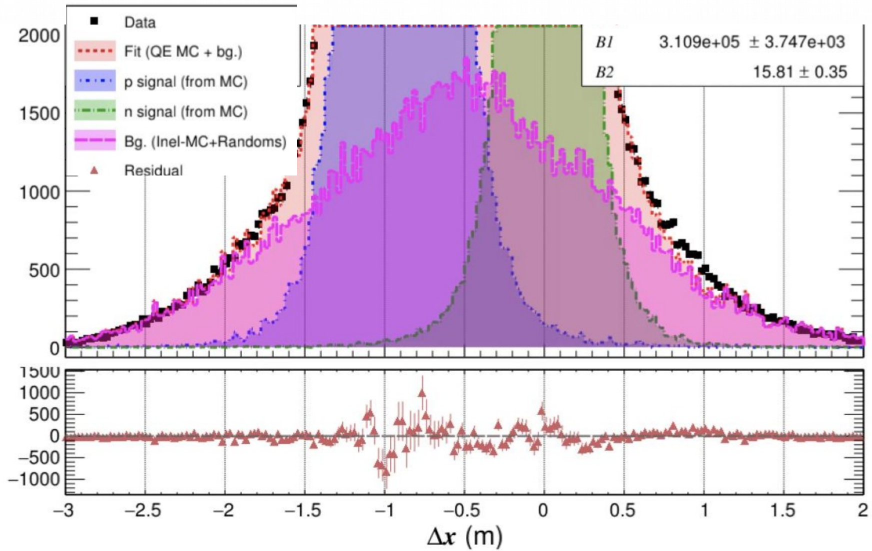
- Latest improvements on estimation of inelastic contamination:
  - Inelastic Monte Carlo combined with out-of-time events





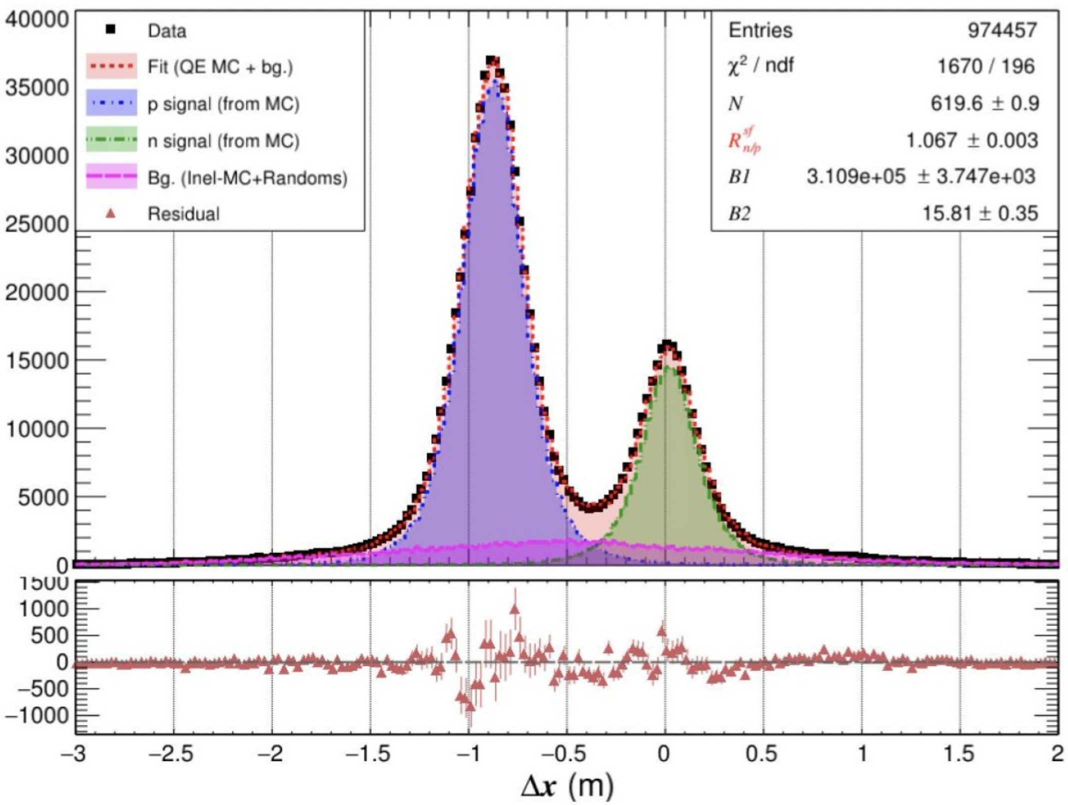


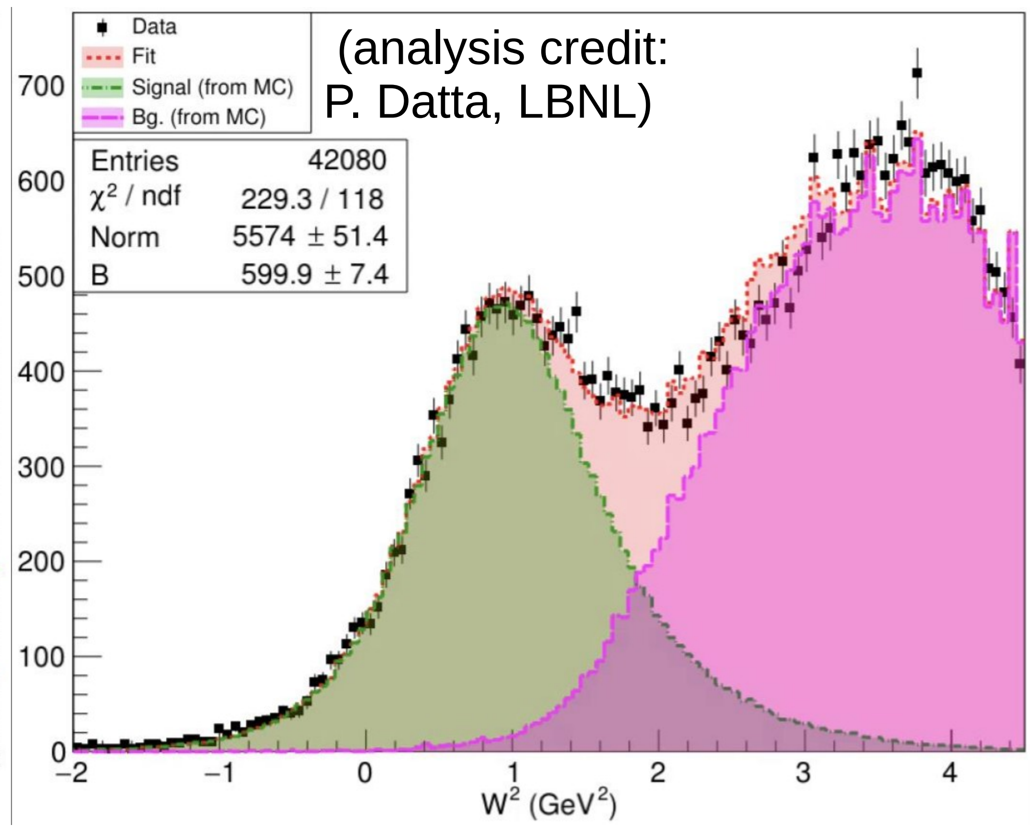
(analysis credit:
P. Datta, LBNL)



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:
    - ♦ 2nd and 4th order polynomials, gaussian to fit inelastic background;
    - ♦ Δy side-band selection

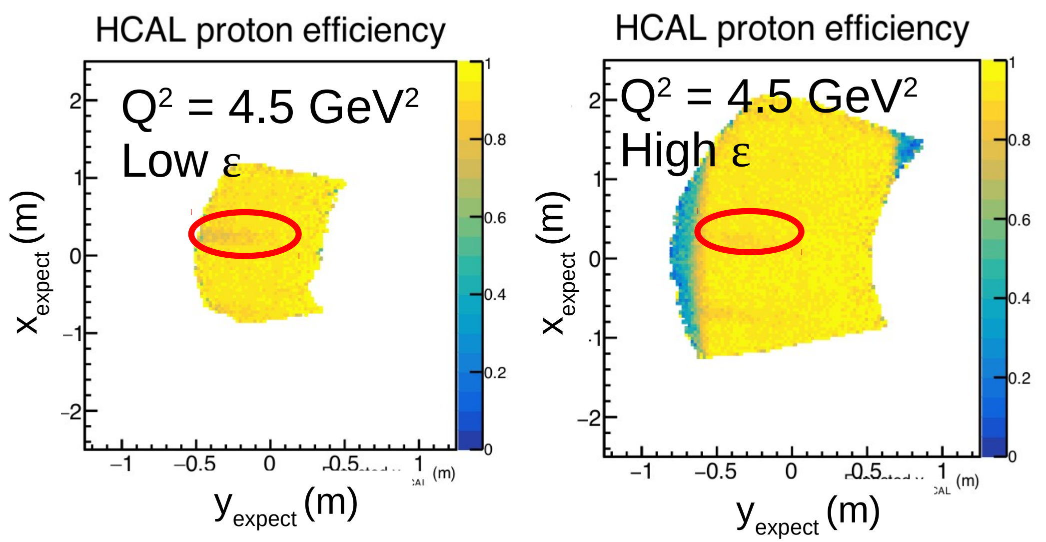




(analysis credit:
P. Datta, LBNL)

nTPE+ Systematics: HCAL Detection Efficiency

- HCal detection efficiency major source of systematic **especially for nTPE(+)**:
  - ◘ Neutron and protons detection efficiencies 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;
    - ♦ *n/p* cross section ratio biased for both, more biased for low ε;
  - ◘ For e^+/e^- measurements, nucleon projection footprint is identical



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

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 Dx distribution for all types of events with the same selection
  - Extract individual yields and then quantify the correction

H(e, e' p) $Q^2 = 13.5\ \mathrm{GeV}^2$ D(e, e' p) + D(e, e' n)