GMn and nTPE measurements with Super Bigbite Spectrometer

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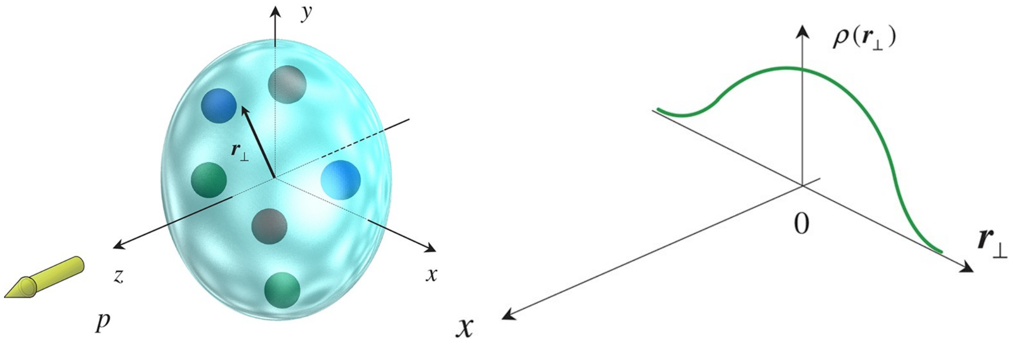
College of William & Mary

Jefferson Lab Users Meeting

Newport News, June 24th, 2026

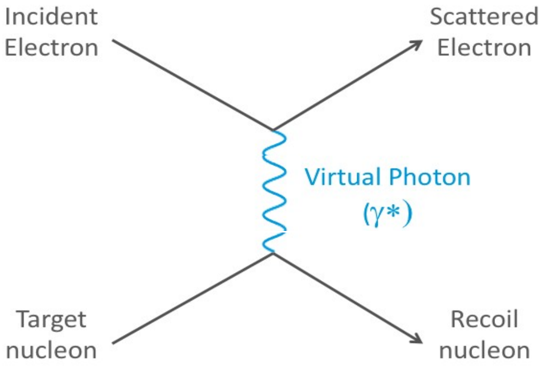
Open Questions in Nucleon Structure
Form Factors at High Q^2

- Space-like Form Factors ≡ charge distribution



- elastic *eN* scattering in the One-Photon Exchange (Born) approximation:

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

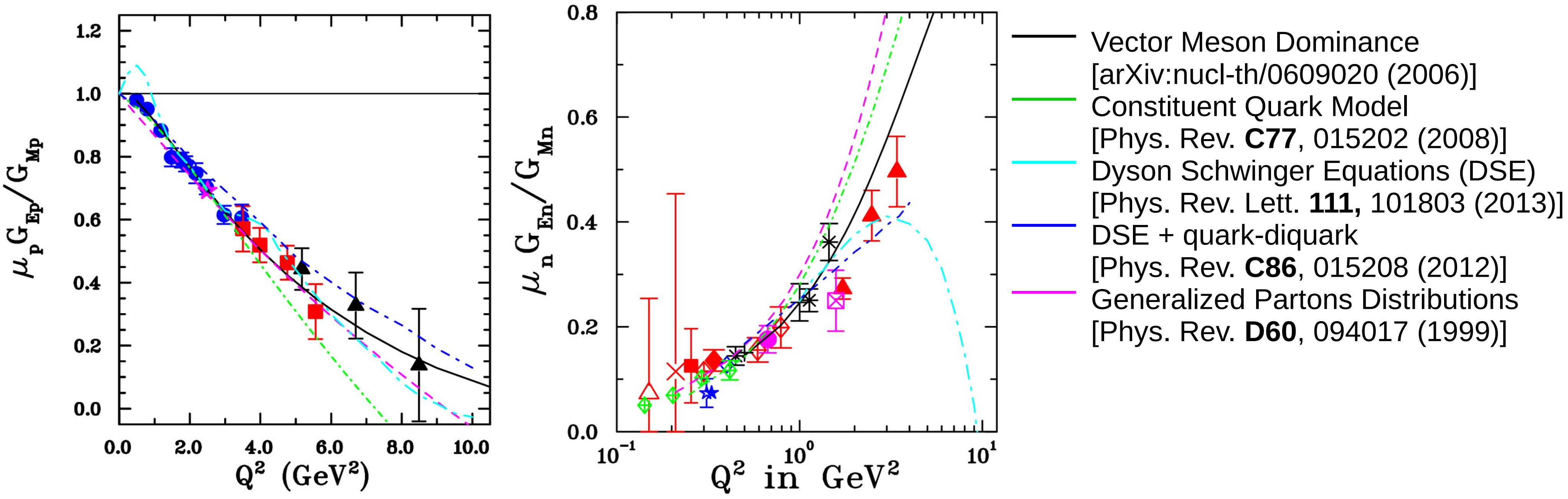


with $\sigma_{Mott}=\hbar c\,\alpha_{EM}\dfrac{1}{4E^2}\left(\dfrac{\cos\theta/2}{\sin\theta/2}\right)^2\dfrac{E'}{E}$ $\quad\tau=Q^2/(4M_N)$ $\quad\epsilon=\left[1+2(1+\tau)\tan^2(\theta/2)\right]^{-1}$

Open Questions in Nucleon Structure
Form Factors at High Q^2

- Space-like Form Factors ≡ charge distribution
- FF Descriptions diverge for higher $Q^2 \geq 10$ GeV^2

Plots from [Punjabi *et al.* Eur.Phys.J. **A51** (2015) 79]

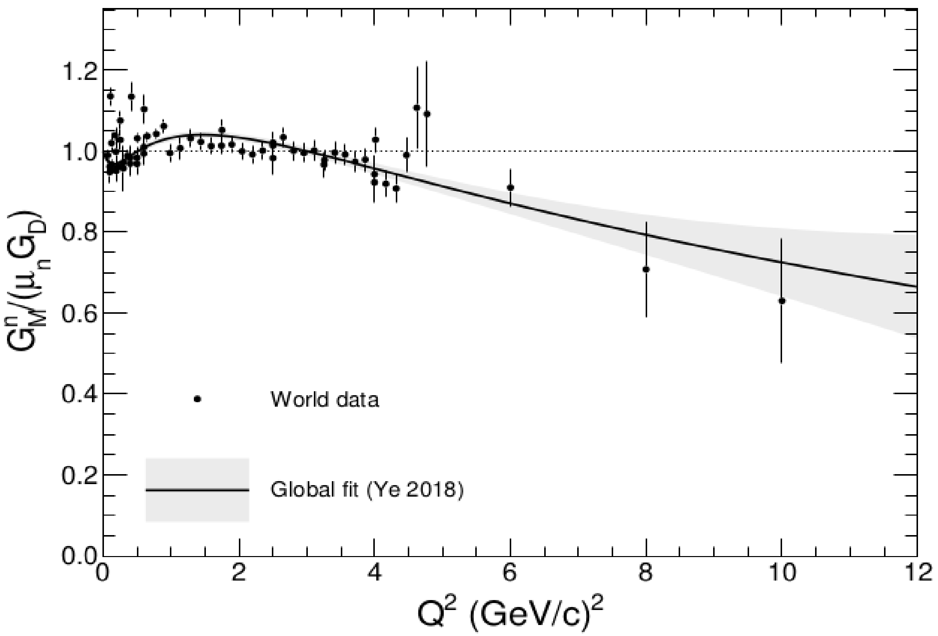


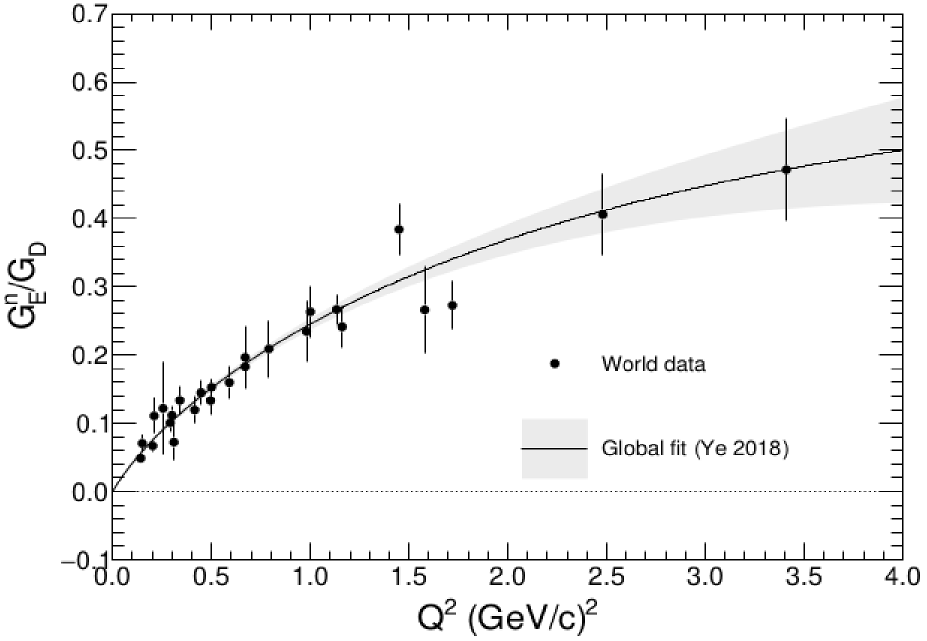
Vector Meson Dominance
[arXiv:nucl-th/0609020 (2006)]
Constituent Quark Model
[Phys. Rev. **C77**, 015202 (2008)]
Dyson Schwinger Equations (DSE)
[Phys. Rev. Lett. **111,** 101803 (2013)]
DSE + quark-diquark
[Phys. Rev. **C86**, 015208 (2012)]
Generalized Partons Distributions
[Phys. Rev. **D60**, 094017 (1999)]

- Precise data sets at $Q^2 \geq 10$ GeV^2 => *powerful insight on QCD*

GMn/nTPE: Neutron Form Factors

- World Form Factors Datasets [arXiv:2212.11107 [hep-ph]]:
  - ◘ Neutron: Scarce data beyond Q^2 ~ 3-4 GeV^2





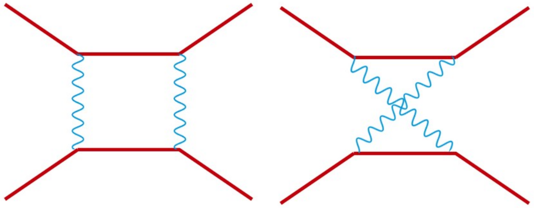
  - ◘ **=> *GMn measurements at high Q^2 with SBS***

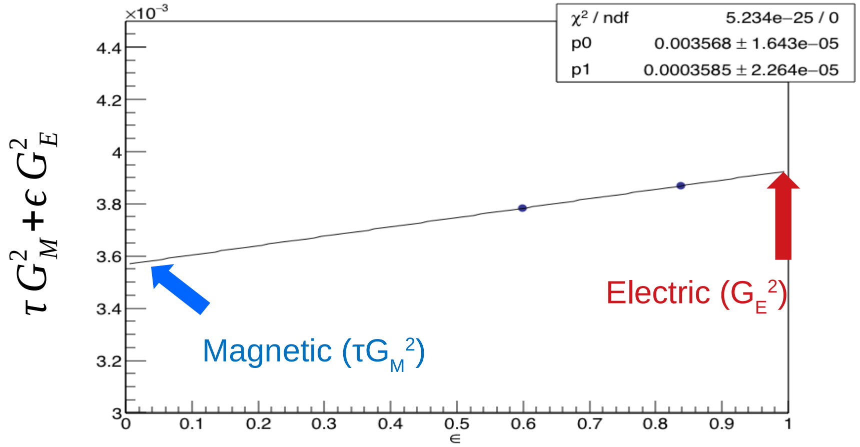
Two-Photon Exchange in *eN* Scattering

- Discrepancy between polarization measurements and direct separation of

$$\underline{\tau G_M^2(Q^2)}+\underline{\epsilon G_E^2(Q^2)} \text{ with } \epsilon=\left[1+2(1+\tau)\tan^2(\theta/2)\right]^{-1}$$

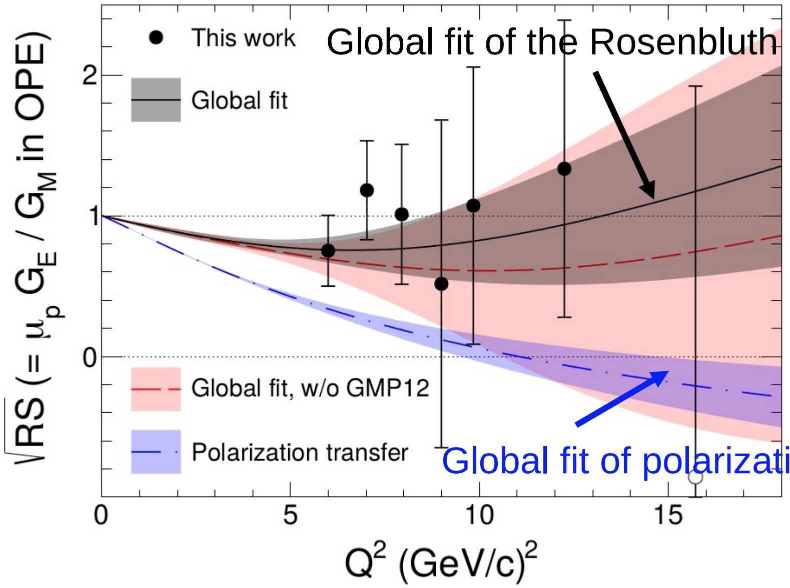
- Discrepancy suspected to be due to ***Two Photon Exchange***





Electric (G_E^2)

Magnetic (τG_M^2)



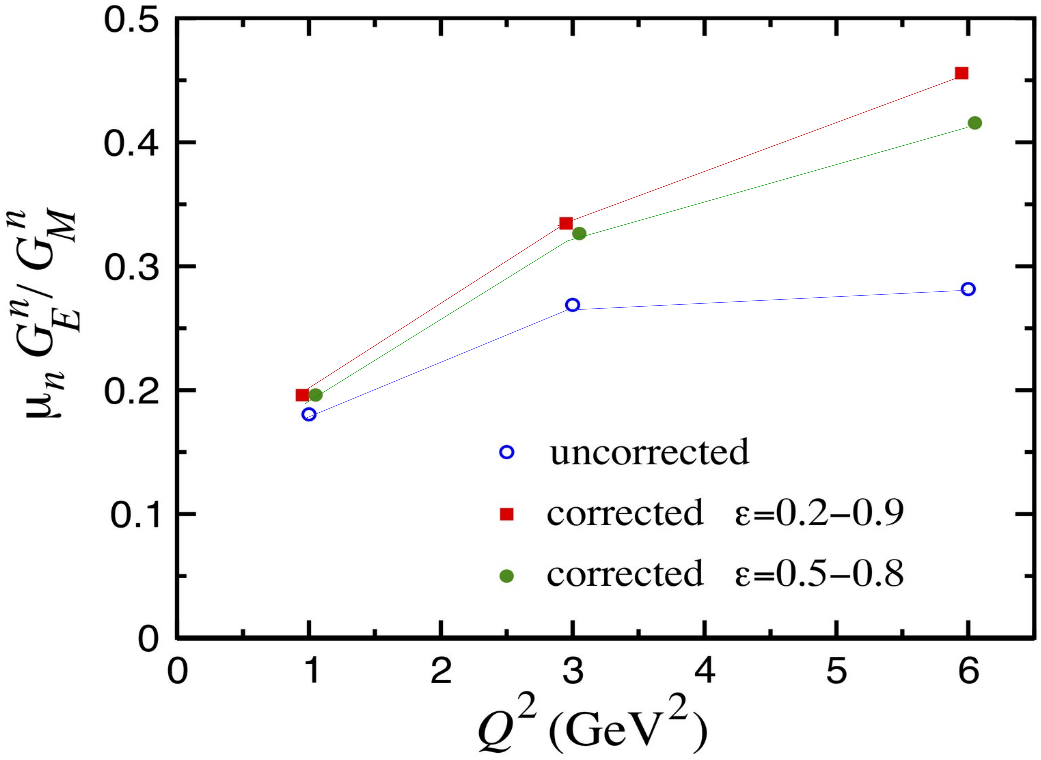
Global fit of the Rosenbluth slope

Global fit of polarization transfer data

E. Christy et al.,
Phys.Rev.Lett.
128 *(2022) 10,*
102002

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 at Q^2 = 4.5 GeV^2 with SBS**



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

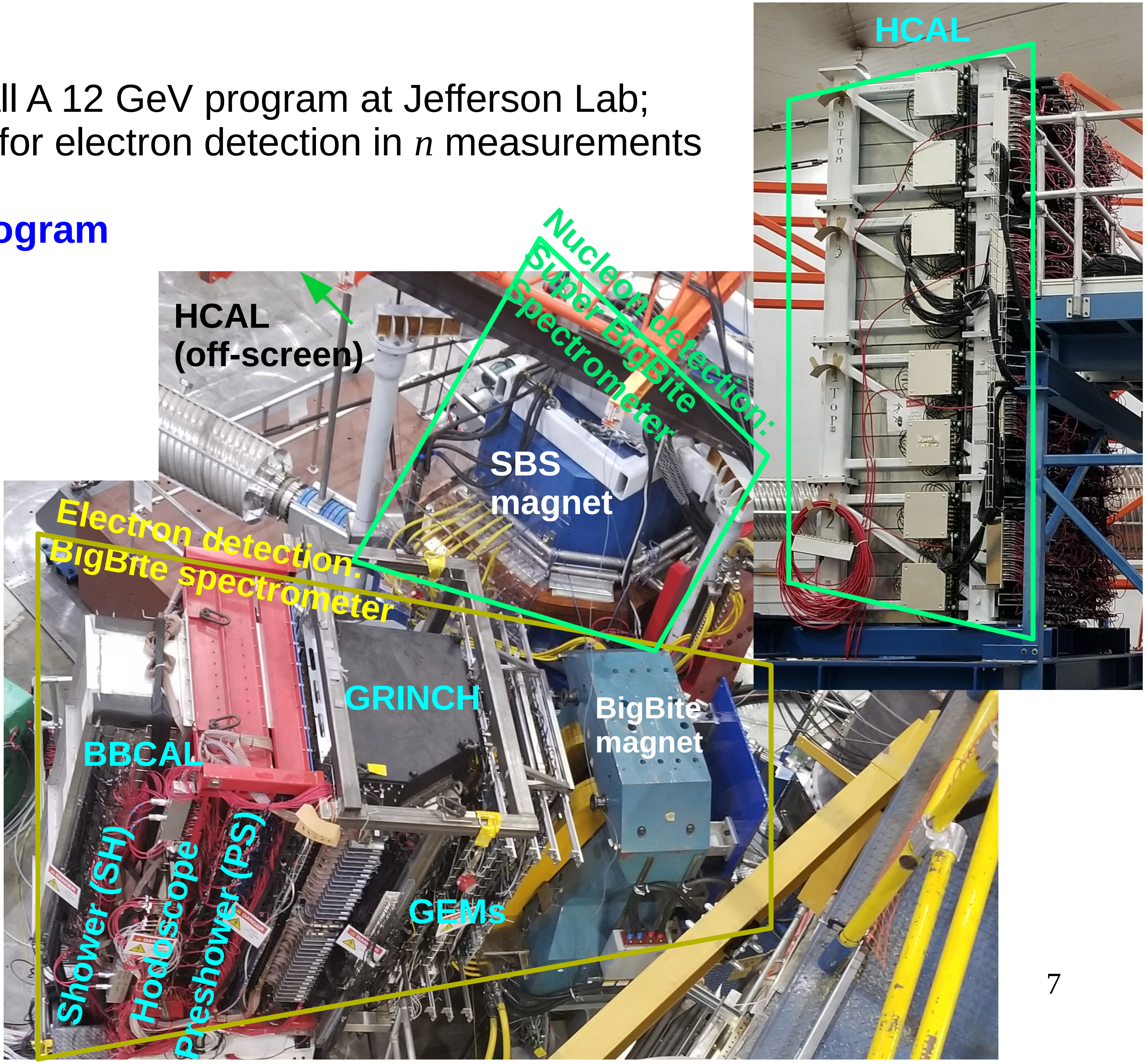
● $\mu_n G_E^n/G_M^n$ +TPE between ε = 0.5 and 0.8

Super BigBite Spectrometer

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

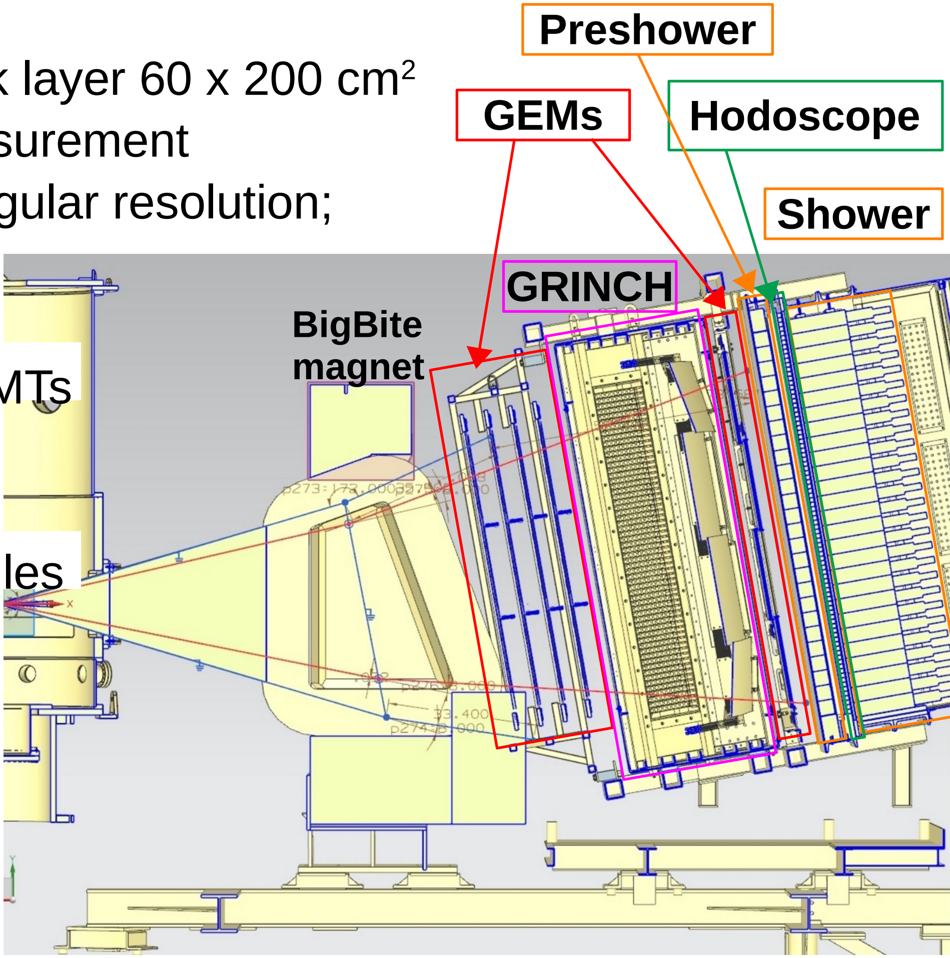
- **SBS form factor program**
    - ◘ **GMn**
    - ◘ **nTPE**
    - ◘ GEN
    - ◘ GEN-RP
    - ◘ GEP

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

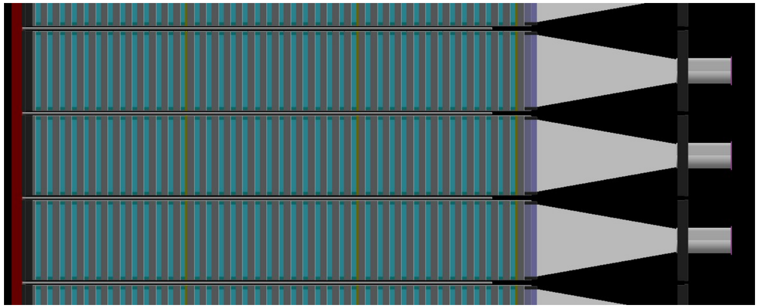


Super BigBite Spectrometer: BigBite

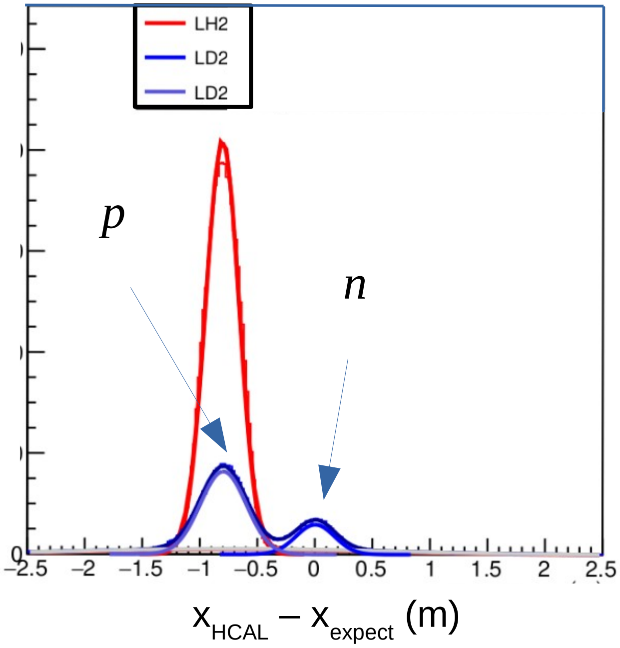
- Detector package tilted 10% behind dipole magnet
- **Function: Electron measurement**
- Detector package:
  - GEMs:
    - 4 front layers 40 x 150 cm^2, 1 back layer 60 x 200 cm^2
    - momentum trivector + vertex measurement
    - 1% momentum resolution, 1mr angular resolution;
  - GRINCH:
    - C4F8 Cherenkov radiator
    - Cherenkov light readout by 510 PMTs
    - Electron ID ~98% Pion rejection
  - Calorimeter: (shower+preshower)
    - PreShower: 2x26 lead glass modules
    - Shower: 7x27 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

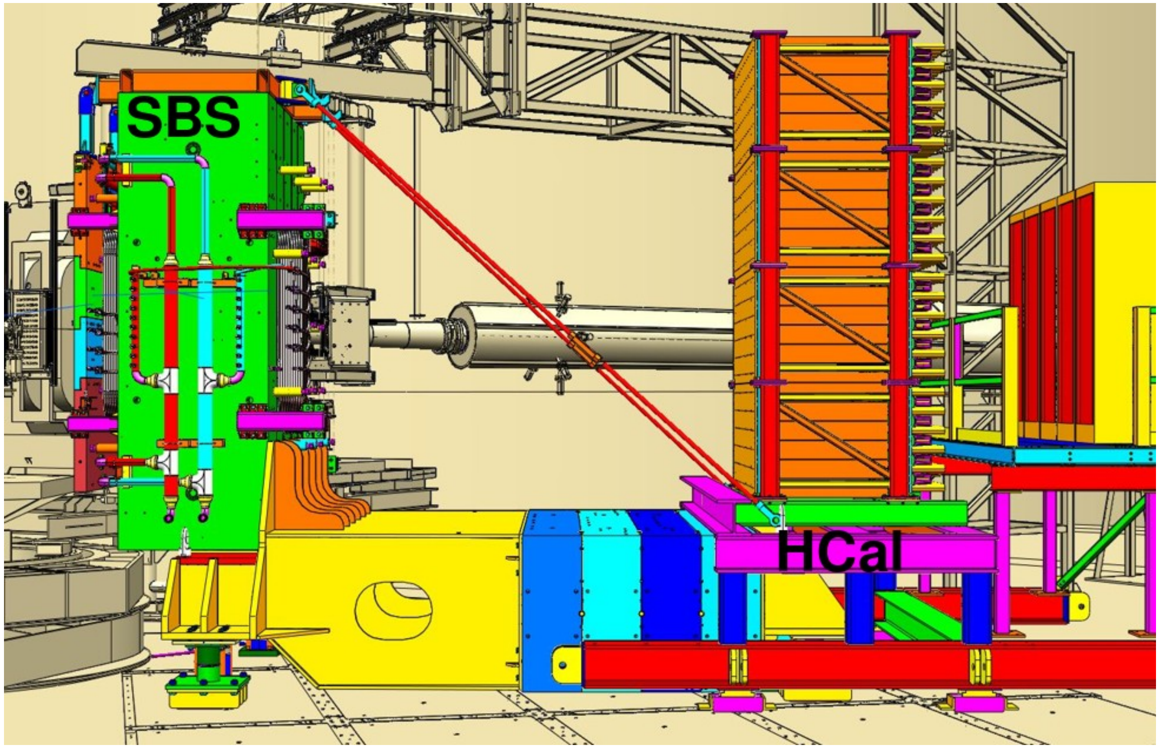


- 12 x 24 iron/scintillator modules 15 x 15 * 90 cm^3
- **Function: Nucleon measurement**
  - ◘ Position resolution ~5.5cm
  - ◘ Timing resolution (*ADC only*) ~1.5 ns
  - ◘ Energy resolution ~50 %
- **Nucleon identification**



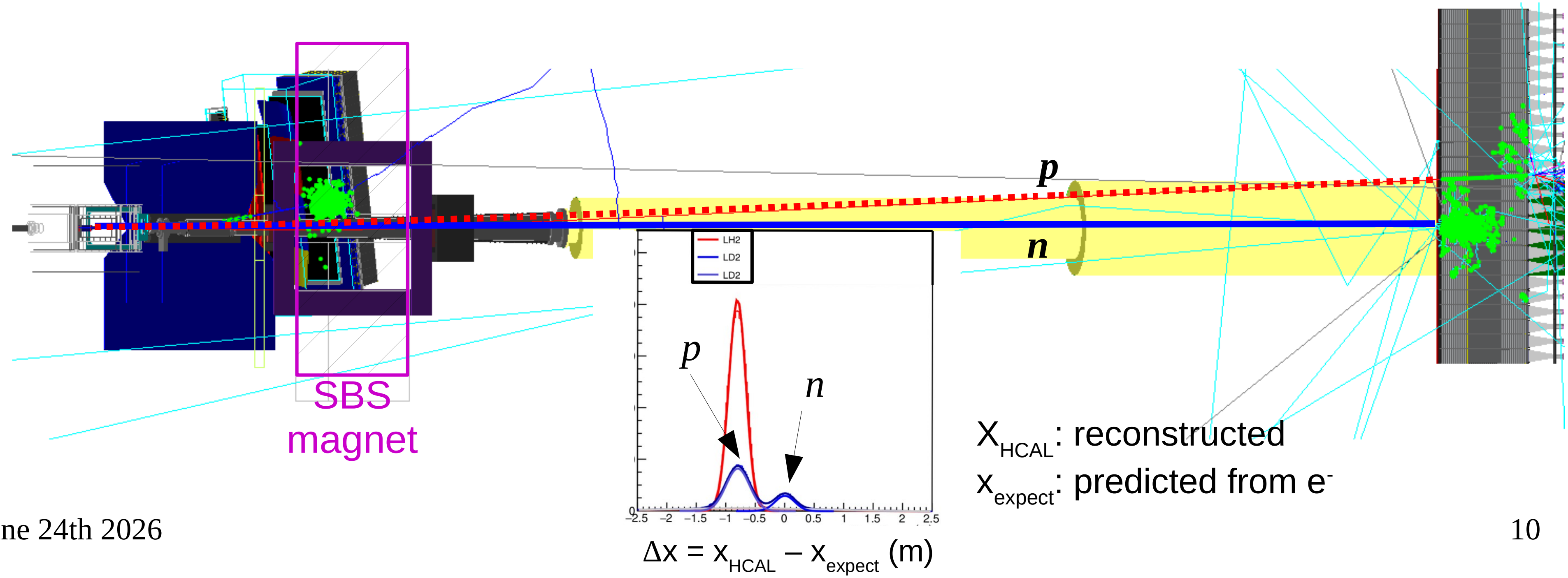
X_{HCAL}: reconstructed

x_{expect}: predicted from e^-



GMn Measurement

- GMn: E12-09-019 (A. Camsonne, B. Quinn, B. Wojteskhowski)
  - Durand technique: simultaneous en/ep measurement on D_2
  - Separation of p and n with SBS
  - σ_{en}/σ_{ep} with reduced systematics (cancellation of Fermi momentum,…)
  - knowledge of σ_{ep} provides σ_{en} => determination of G_M^n
  - **5 Q^2 values: 3, 4.5, 7.5, 10, 13.6 GeV^2**

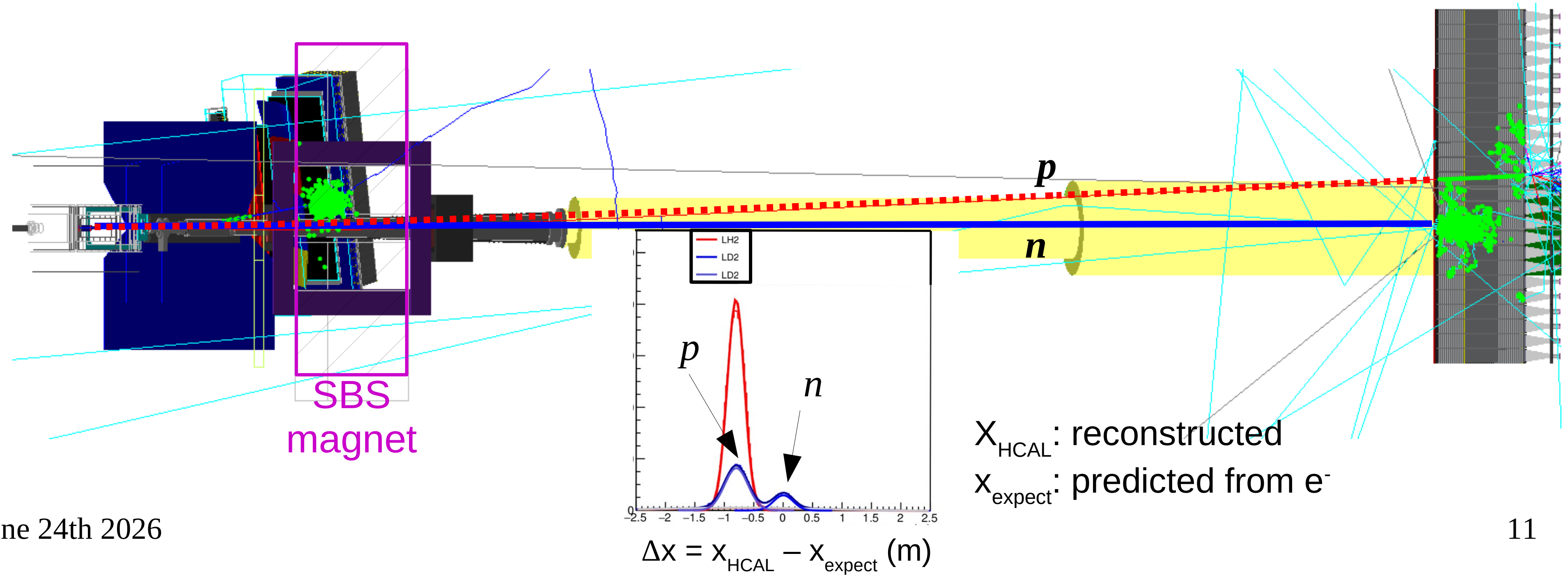


X_{HCAL}: reconstructed

x_{expect}: predicted from e^-

nTPE Measurement

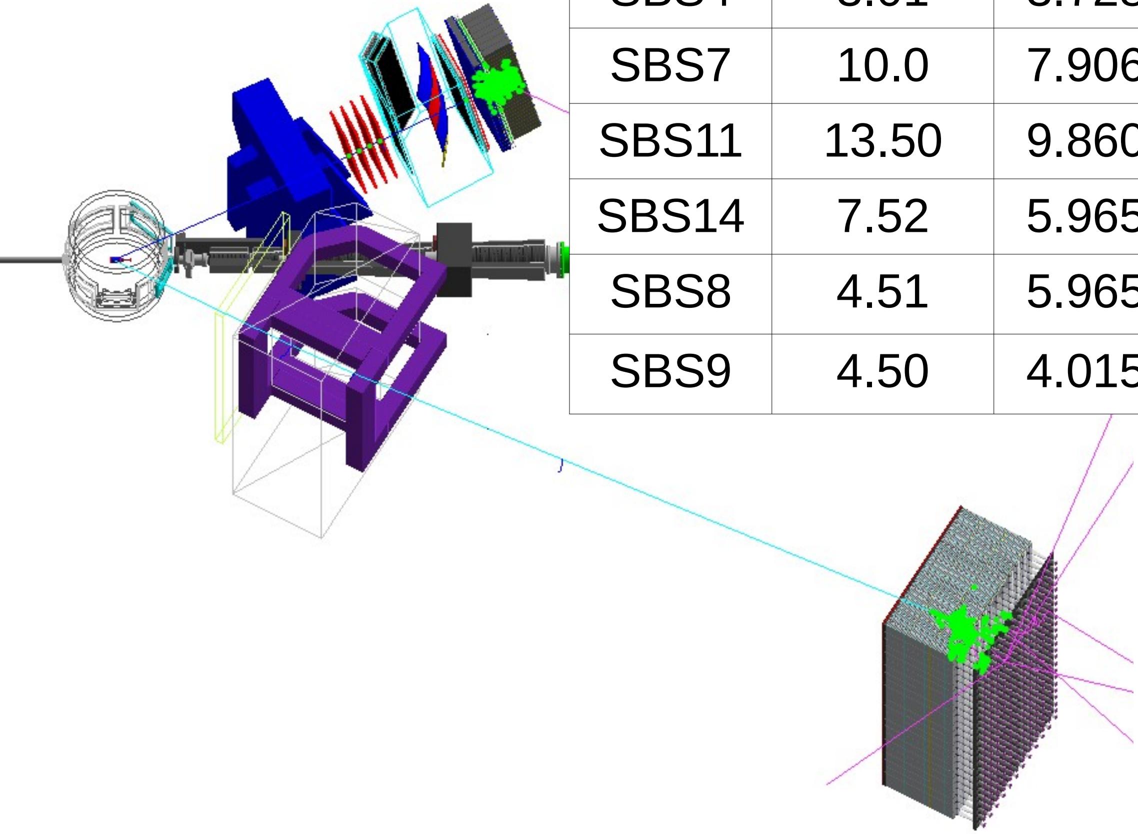
- **nTPE: E12-20-010 (E.F., S. Alsalmi, B. Wojteskhowski) :**
  - ◘ measurement of σ_{en}/σ_{ep} at two beam energies, $Q^2 = 4.5$ GeV^2
  - ◘ σ_{en}/σ_{ep} superratio dependent on proton and neutron Rosenbluth slopes
  - ◘ knowledge on proton Rosenbluth slope => neutron Rosenbluth slope;
  - ◘ NTPE = Discrepancy neutron Rosenbluth slope <=> polarization data



X_{HCAL}: reconstructed

x_{expect}: predicted from e^-

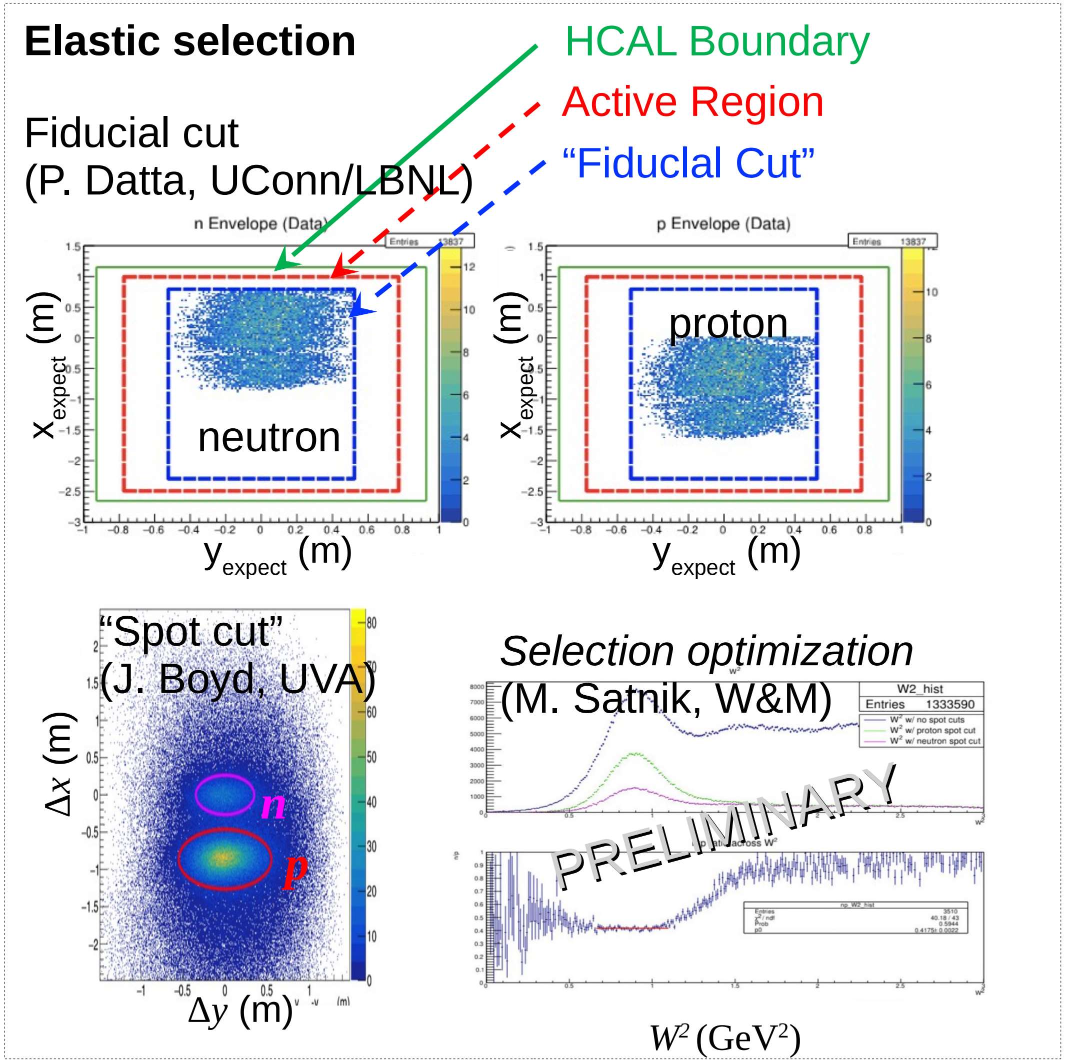
GMn/nTPE Kinematic tables



Kin	Q^2 (GeV/c)^2	E (GeV)	E' (GeV)	θ_{BB} (deg)	θ_{SBS} (deg)	ε	
SBS4	3.01	3.728	2.129	36.0	31.9	0.721	
SBS7	10.0	7.906	2.588	40.9	15.9	0.492	
SBS11	13.50	9.860	2.676	41.9	12.8	0.437	
SBS14	7.52	5.965	1.965	47.2	17.3	0.456	
SBS8	4.51	5.965	3.565	26.5	29.9	0.797	NTPE
SBS9	4.50	4.015	1.618	49.0	22.5	0.512	

GMN/NTPE Analysis

- Common steps to GMN/nTPE: quasielastic *en*, *ep* selection:
  - tracks:
    - ntracks ;
    - track nhits;
    - track vertex;
    - $|x_{fp}\text{-}0.9{*}th_{fp}|$
    - $|y_{fp}\text{-}0.9{*}ph_{fp}|$
  - calorimeters:
    - E_{PS};
    - $E_{PS}+E_{SH}$;
    - $(E_{PS}+E_{SH})/p_{track}$;
    - E_{HCal};
    - $|\delta t_{HCal\text{-}SH}|$;
  - exclusivity:
    - x_{expect} ;
    - y_{expect};
    - W^2;
    - θ_{pq}^{p}
    - θ_{pq}^{n}



Elastic selection

Fiducial cut
(P. Datta, UConn/LBNL)

HCAL Boundary

Active Region

“Fiduclal Cut”

“Spot cut”
(J. Boyd, UVA)

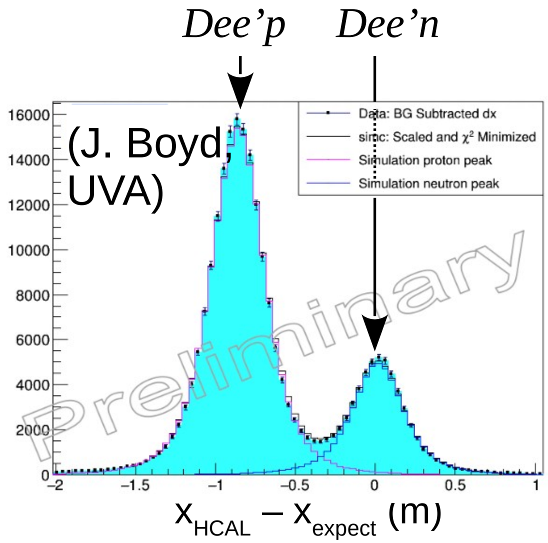
Selection optimization
(M. Satnik, W&M)

PRELIMINARY

GMN/NTPE Analysis

- Common steps to GMN/nTPE: extraction of σ_{en}/σ_{ep} with Monte Carlo

N_n/N_p → σ_n/σ_p correction:
Monte Carlo *Dee'p*, *Dee'n* samples *including radiative corrections* (SIMC) adjusted to data*;



(J. Boyd, UVA)

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

$$\frac{\sigma_{en}}{\sigma_{ep}} = \frac{(N_{en\rightarrow en})_{MC,corr}}{(N_{ep\rightarrow ep})_{MC,corr}}$$

*accounting for inelastic background in data – see next

$$R = \frac{N_{en\rightarrow en}}{N_{ep\rightarrow ep}}$$

$$R_{n/p} = \frac{\sigma_{en}}{\sigma_{ep}} = R f_{corr} - N_{inel}$$

$$= \underset{=1}{\boxed{\frac{\sigma_{Mott}}{\sigma_{Mott}}}}\frac{(1+\tau_p)(\sigma_T^n+\epsilon\,\sigma_L^n)}{(1+\tau_n)(\sigma_T^p+\epsilon\,\sigma_L^p)} = \frac{(1+\tau_p)\left(\tau_n(G_M^n)^2+\epsilon(G_E^n)^2\right)}{(1+\tau_n)\left(\tau_p(G_M^p)^2+\epsilon(G_E^p)^2\right)}$$

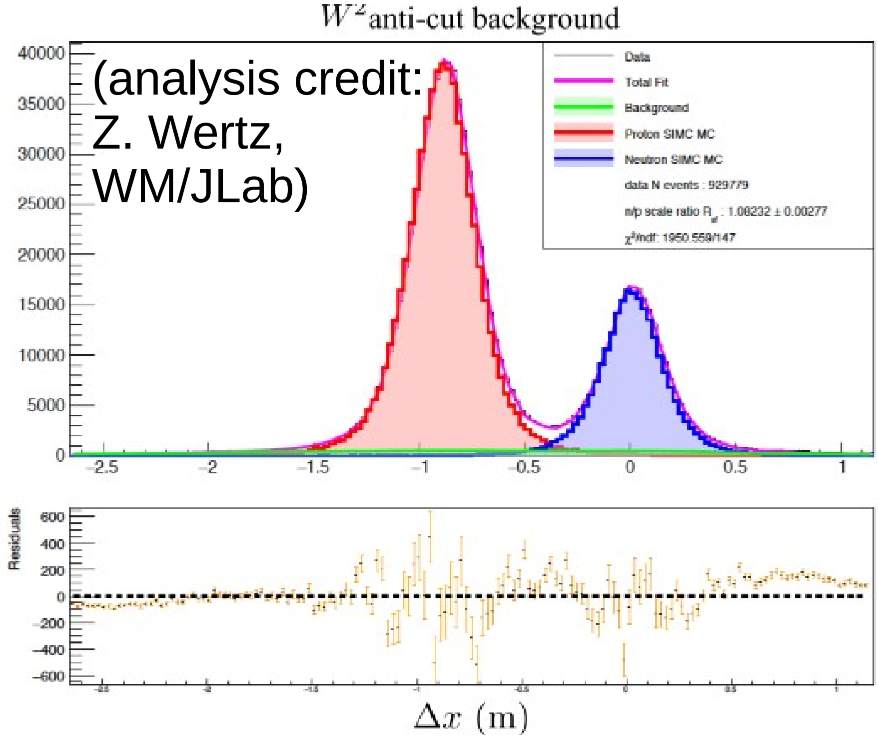
$$f_{corr} = \boxed{\frac{\eta_{en}(t)}{\eta_{ep}(t)}} \times \boxed{\eta_{RC}(v, Q2, \ldots)} \times \ldots$$

Radiative corrections

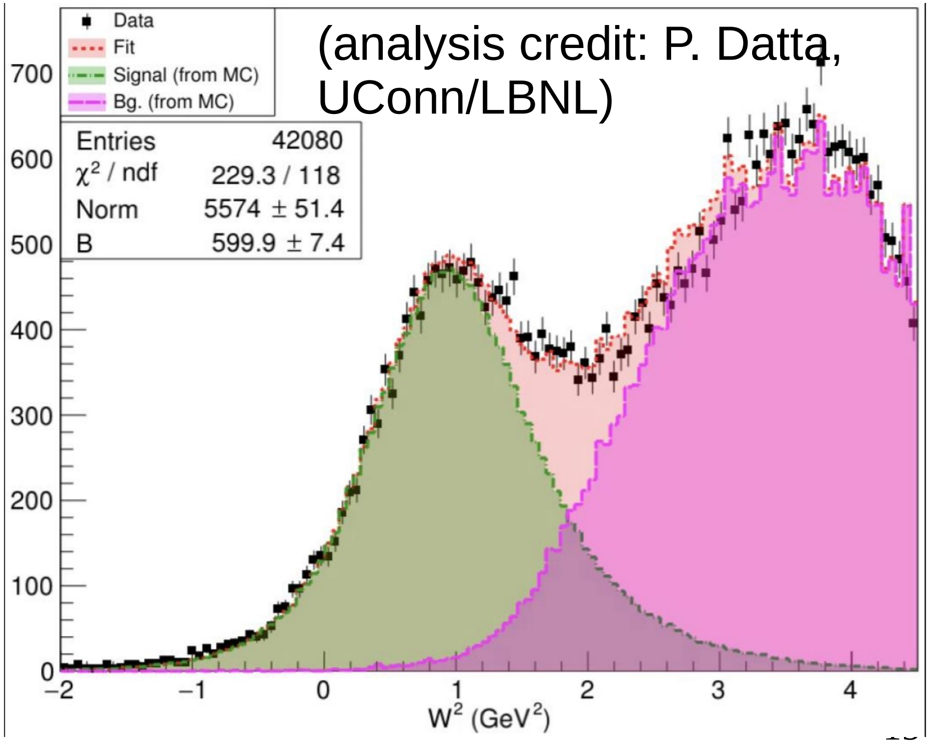
neutron/proton detection efficiency

Systematic uncertainties: Inelastic contamination

- Estimation of inelastic contamination:
  - 2^{nd} and 3^{rd} order polynomials, gaussian fit to inelastic background;
  - selection of events outside elastic W^2 peak or Δx, Δy peaks;
  - selection of out-of-time events
  - **inelastic Monte Carlo (Christy-Bosted) with out-of-time events**
- extraction of σ_{en}/σ_{ep} with all inelastic estimation methods:
  - Systematic uncertainty: discrepancy between all σ_{en}/σ_{ep} extractions
  - <1% for each setting



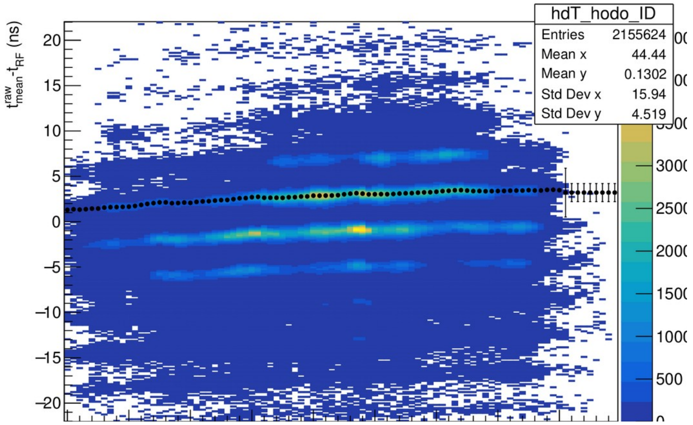
(analysis credit: Z. Wertz, WM/JLab)



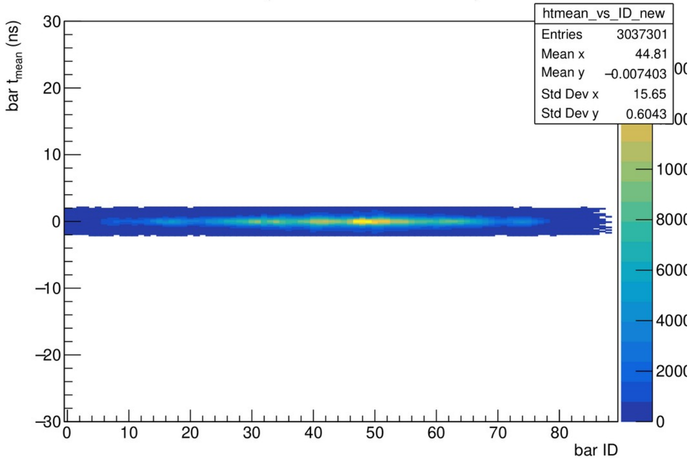
(analysis credit: P. Datta, UConn/LBNL)

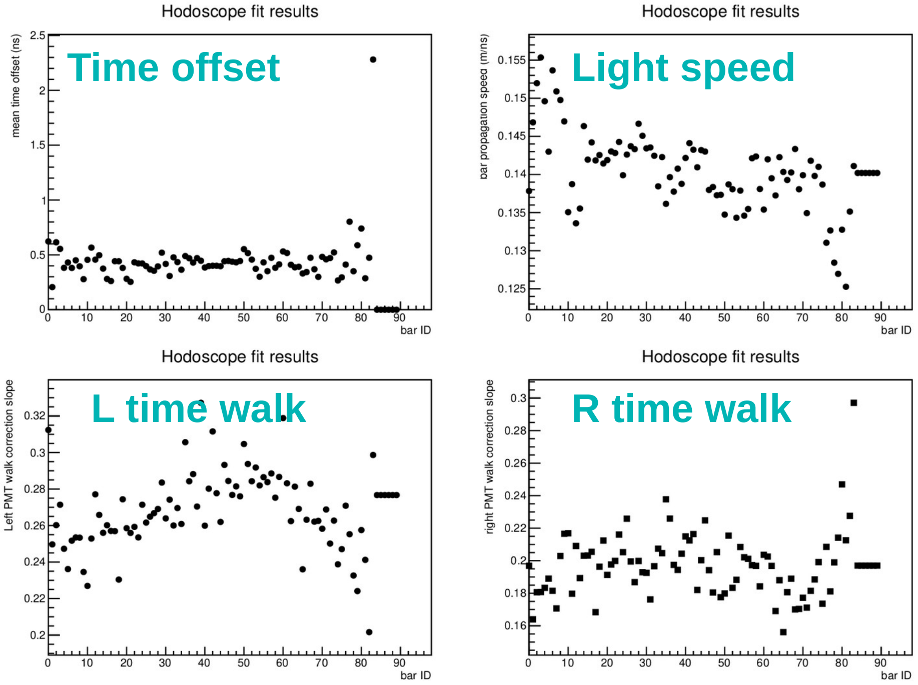
GMN/NTPE Analysis updates: Pass-3 upgrade

- Previous passes: Energy + Optics calibrations
- Pass 3: **BB Hodoscope timing calibration** (Analysis credit A. Puckett)
  - ◘ Hodoscope timing recorded with a trigger phase
  - ◘ Correction for trigger phase, then timing alignment;
  - ◘ extraction of time offset, light speed, time walk corrections
  - ◘ Timing alignment of all other detectors to hodoscope



NEW (with RF corrections)

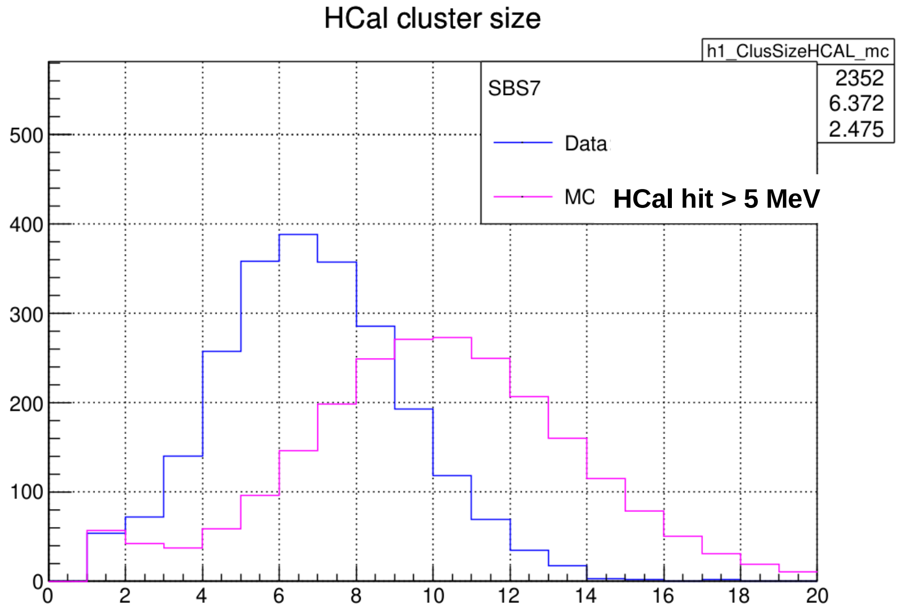


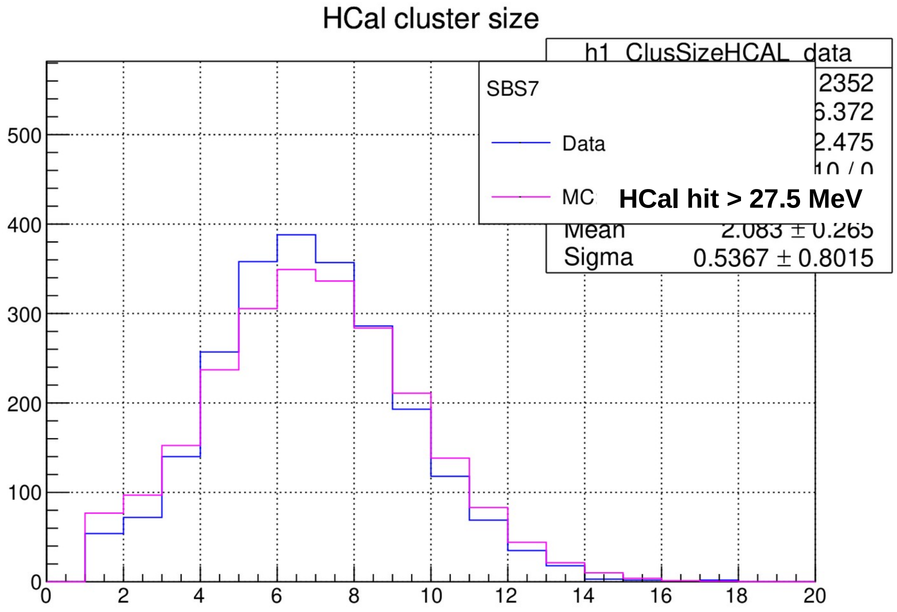


Remaining analysis roadblock for GMN

GMN analysis with pass-3: last roadblock

- **Issue:** lingering apparent discrepancies between Monte Carlo and Data:
  - Hcal cluster size significantly different (in apparence) to data
  - MIP signal visible in HCal energy spectrum for MC, not from data
  - induces avoidable systematics
  - **Solved:**
    - ♦ hidden HCal hit threshold in data due to pulse finding threshold;
    - ♦ matching threshold in MC provides similar cluster size;
  - in the process of producing new simulations.


HCal cluster size


HCal cluster size

GMN Systematic uncertainties

- Systematics analysis credit: P. Datta (LBNL);
  - Improvements possible for radiative corrections and nucleon detection efficiency

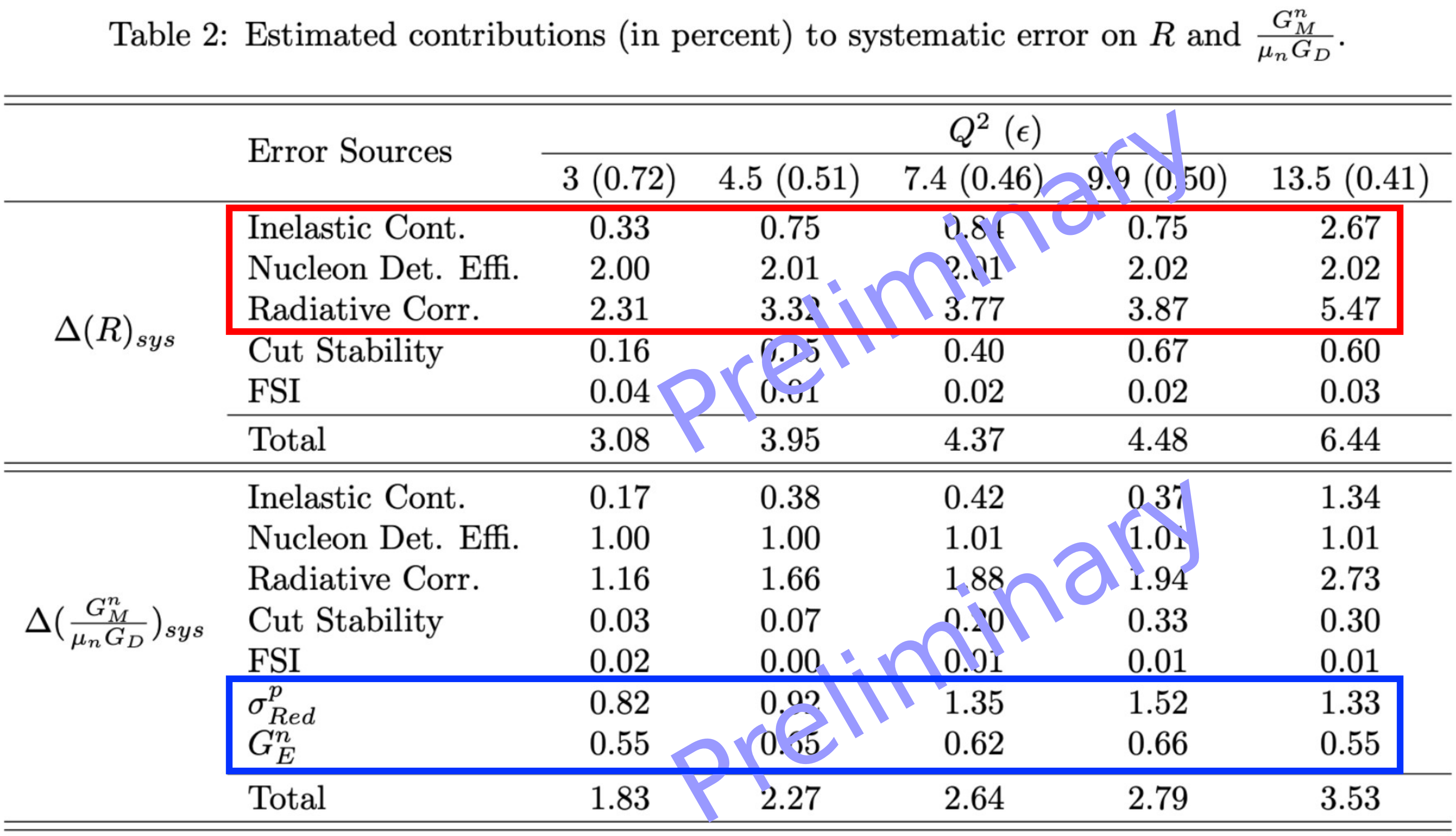
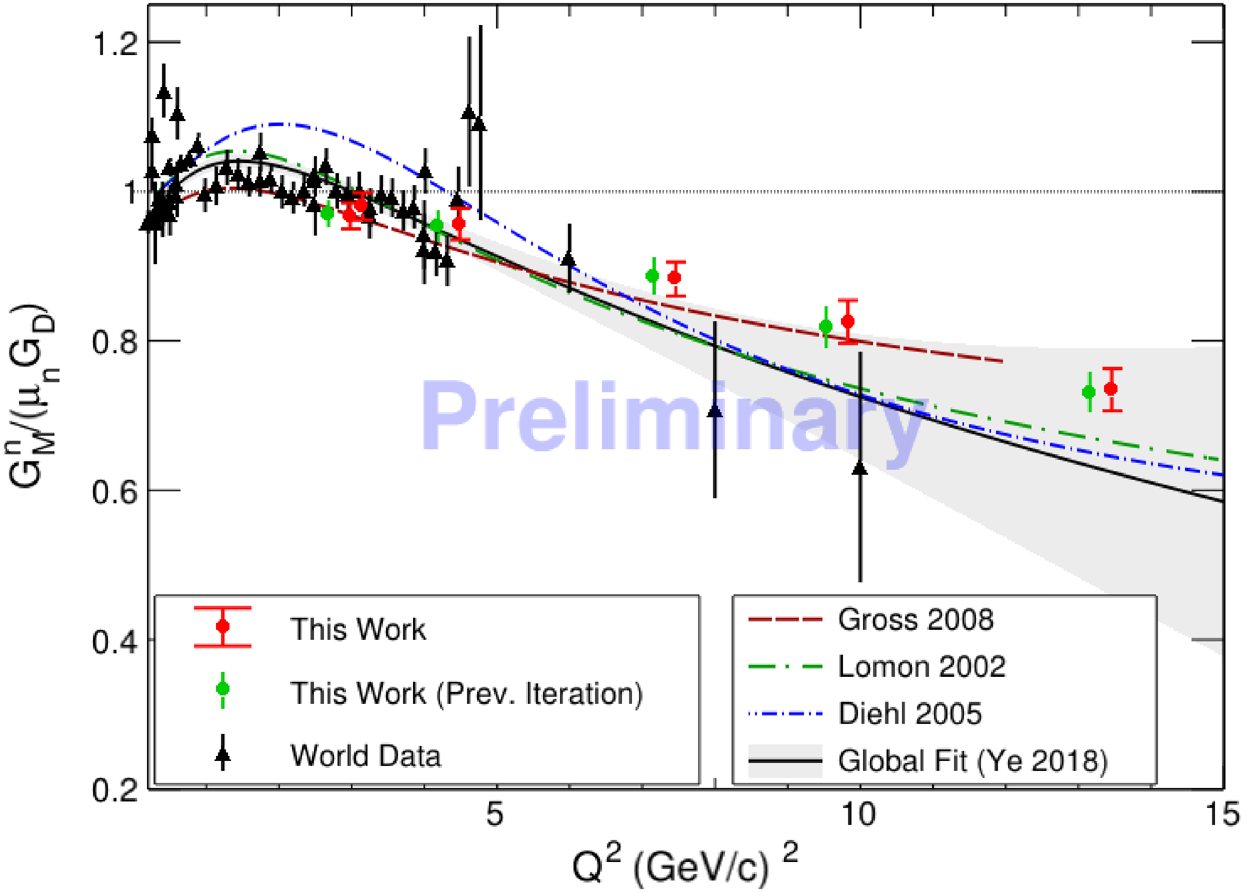


Table 2: Estimated contributions (in percent) to systematic error on R and $\frac{G_M^n}{\mu_n G_D}$.

	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_{Red}^p	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

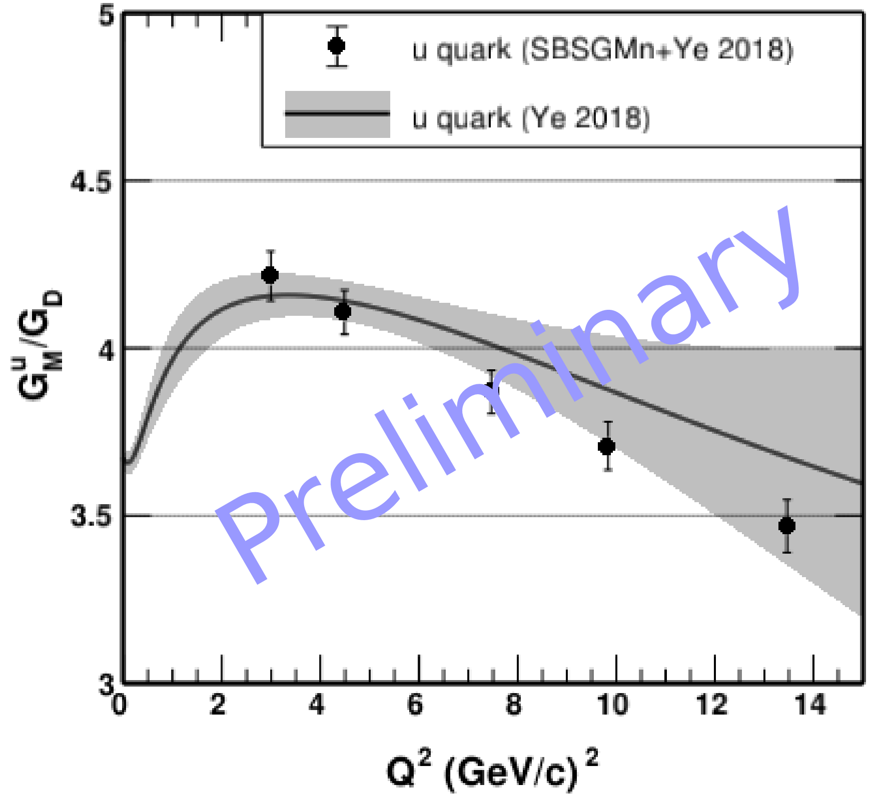
GMN measurements

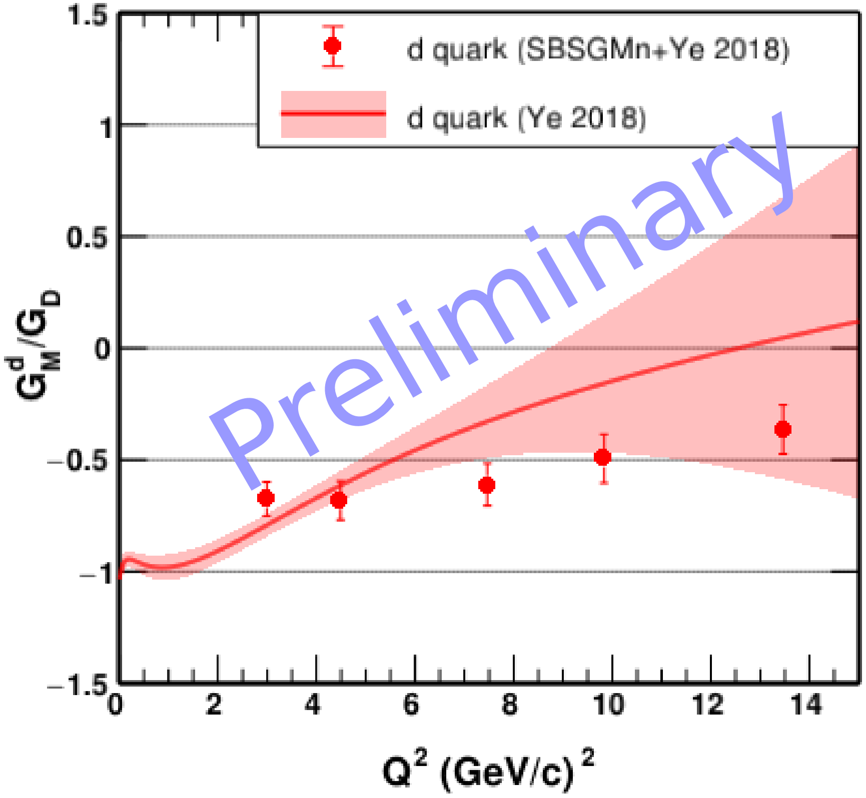
- Shown at the *APS Global Summit 2026* by P. Datta (LBNL)
  - ◘ green: pass-2 (includes energy calibration)
  - ◘ red: pass-3 (includes energy+timing calibration)
- **Getting ready for publication**



Flavor separation

- Shown at the *APS Global Summit 2026* by P. Datta (LBNL)
- **Getting ready for publication**

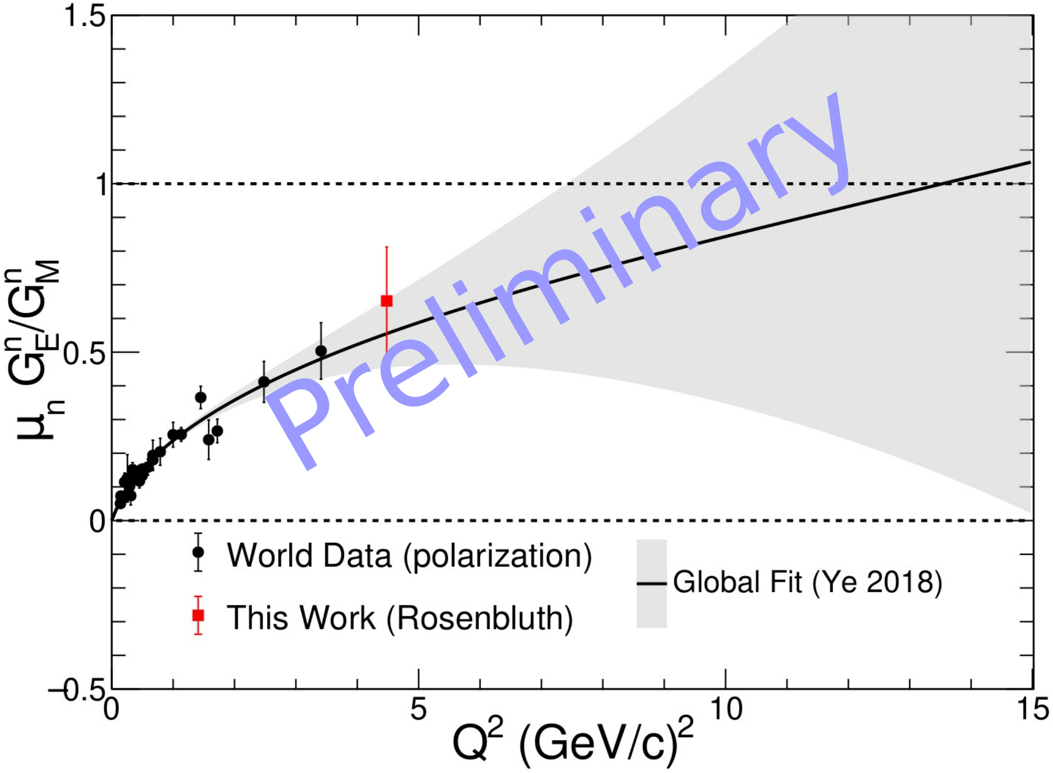




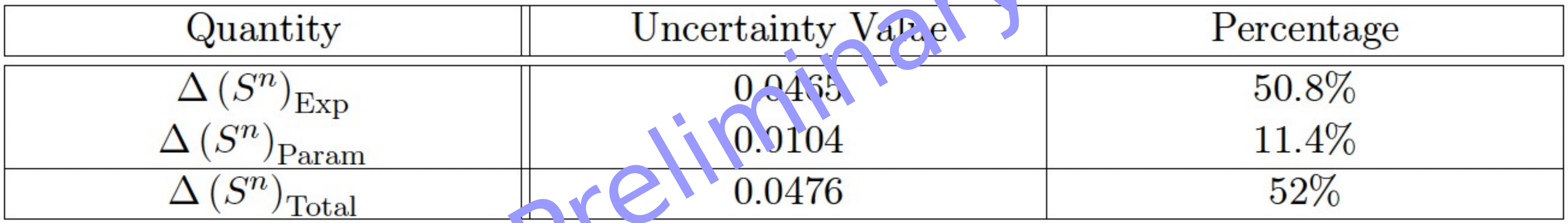
NTPE Preliminary Results

- First estimation of the neutron Rosenbluth slope (credit E. Wertz, WM/JLab):
  - ◘ $\mu_n\, G_E^n/G_M^n$ calculated from Rosenbluth slope *without correcting for TPE*;
  - ◘ Other G_E^n measurements are polarization data;
  - ◘ Plan: refine systematic uncertainties.

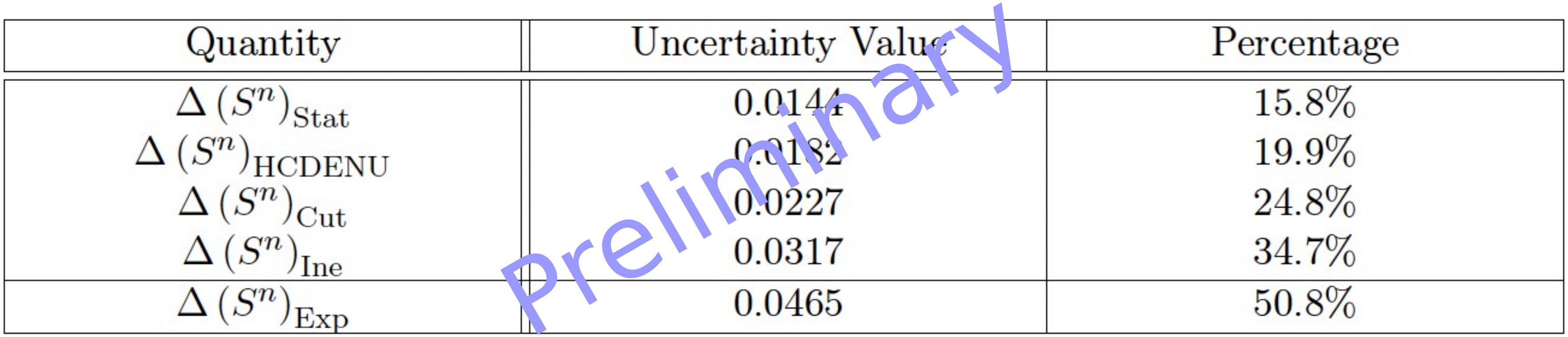
[E. Wertz, *A Measurement of the Neutron Electromagnetic Form Factor Ratio from a Rosenbluth Technique with Simultaneous Detection of Neutrons and Protons*, Ph.D Thesis, William & Mary (July 2025).]



nTPE Statistics + Systematic Uncertainties



Quantity	Uncertainty Value	Percentage
$\Delta\left(S^n\right)_{\text{Exp}}$	0.0465	50.8%
$\Delta\left(S^n\right)_{\text{Param}}$	0.0104	11.4%
$\Delta\left(S^n\right)_{\text{Total}}$	0.0476	52%



Quantity	Uncertainty Value	Percentage
$\Delta\left(S^n\right)_{\text{Stat}}$	0.0144	15.8%
$\Delta\left(S^n\right)_{\text{HCDENU}}$	0.0182	19.9%
$\Delta\left(S^n\right)_{\text{Cut}}$	0.0227	24.8%
$\Delta\left(S^n\right)_{\text{Ine}}$	0.0317	34.7%
$\Delta\left(S^n\right)_{\text{Exp}}$	0.0465	50.8%

Analysis credit E. Wertz (Jefferson Lab)

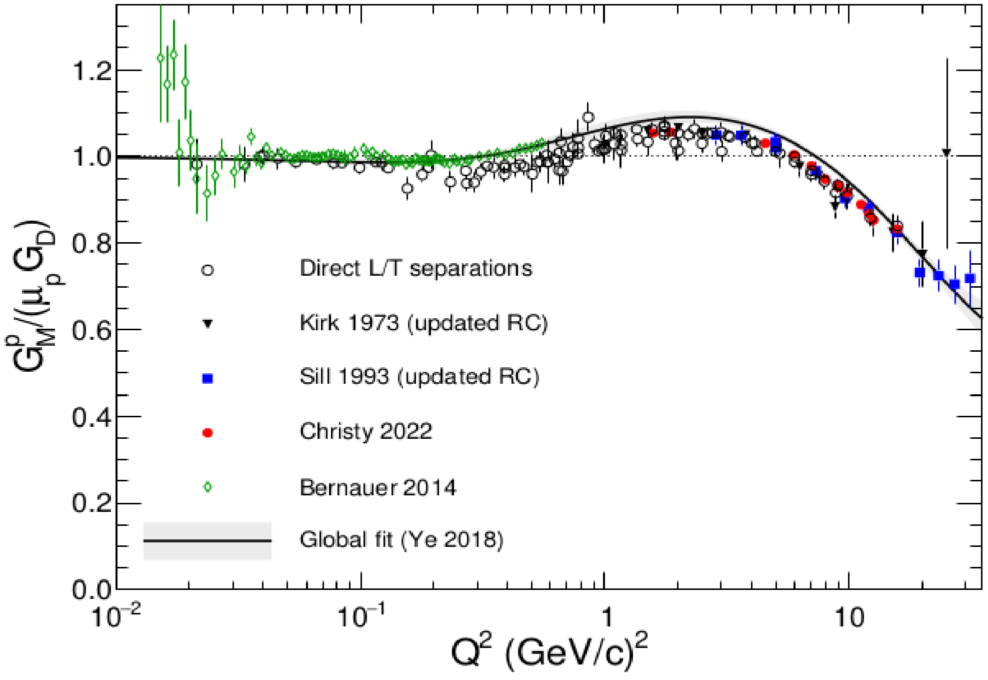
Summary

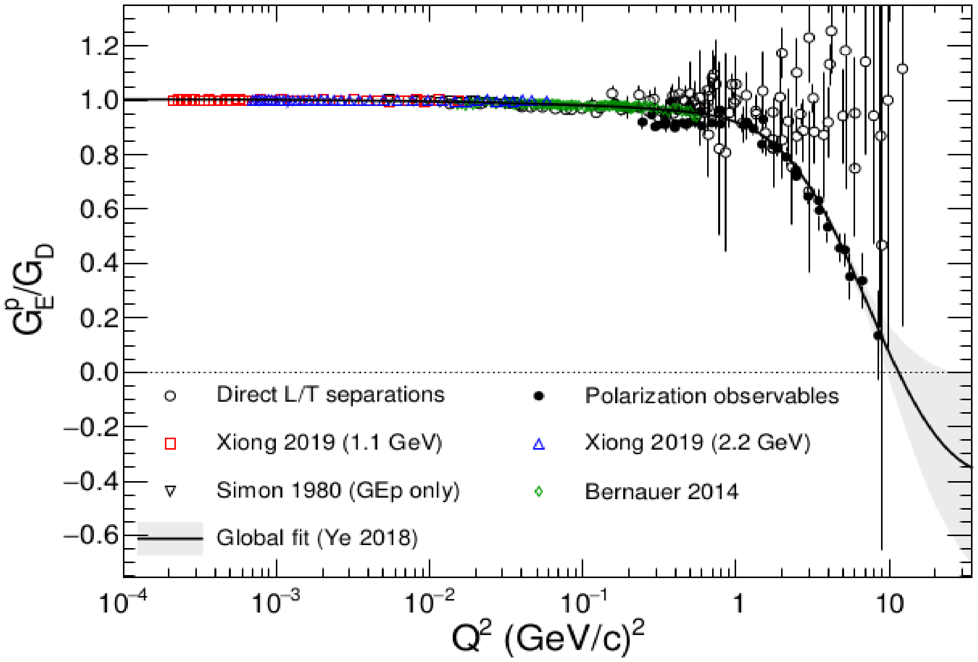
- **GMN results close to final**
  - Last hurdle on the analysis/MC being overcome
  - Publication submission within 2-3 months
- **NTPE preliminary results**
  - Need reevaluation of systematics before final results
  - Publication submission within 6-12 months

Back up

Form Factors Datasets: Proton

- World Form Factors Datasets [arXiv:2212.11107 [hep-ph]]:
  - ◘ Proton: measurements methods discrepancies at large Q^2 (see later)





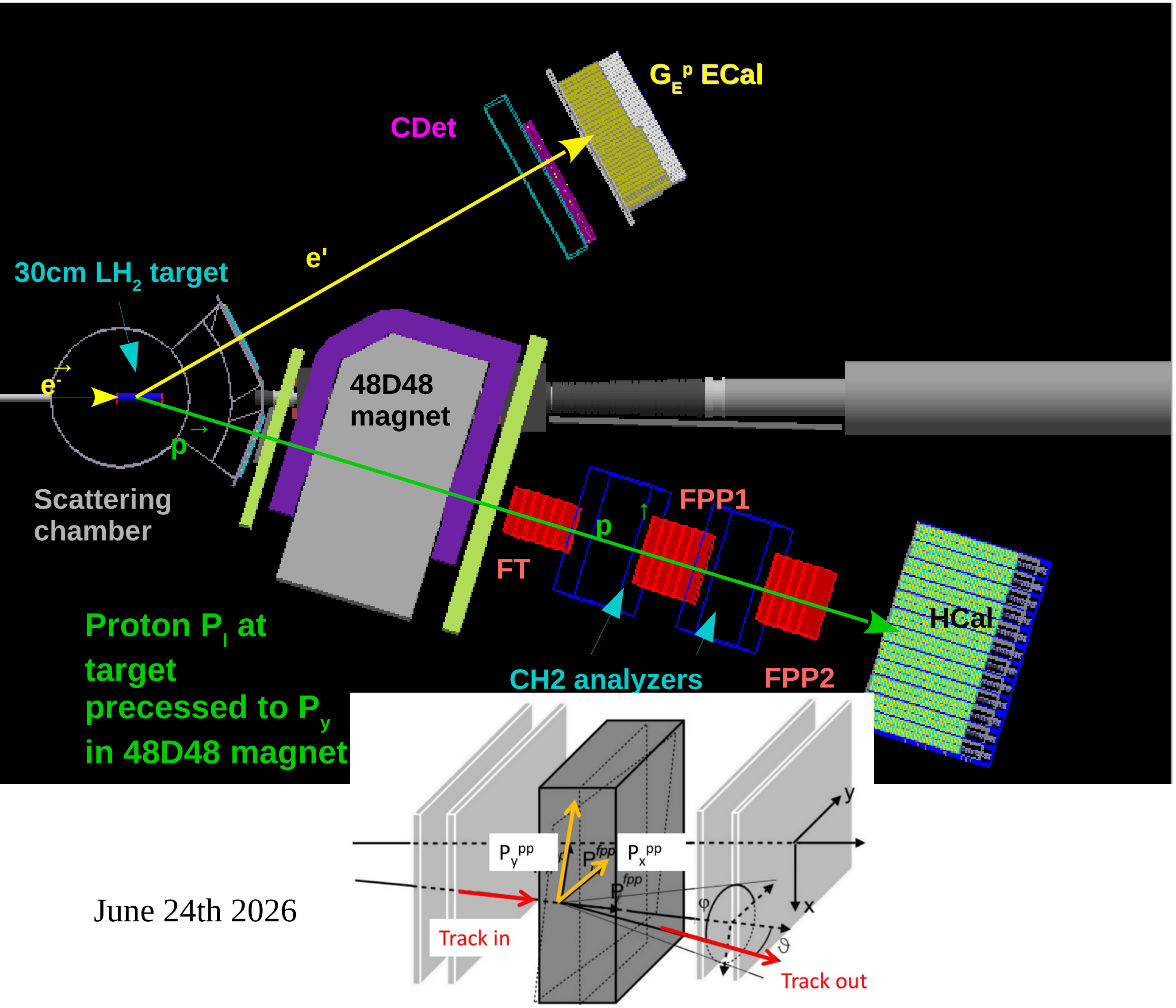
SBS experimental program:
Proton electric Form Factor (G_E^p)

E12-07-109: *L. Pentchev,* E. Cisbani, C. Perdrisat, V. Punjabi, B. Wojtsekhowski

Elastic ep scattering up to 12 GeV² for G_E^p/G_M^p with recoil proton polarization (α P_t/P_l)

Less sensitivity to 2γ exchange than Rosenbluth (σ_T/σ_L) separation (more later)

$$\frac{G_E}{G_M} = -\frac{P_t}{P_l}\frac{E+E'}{2M}\tan\left(\frac{\theta}{2}\right)\left[1+o_{2\gamma}\right]$$



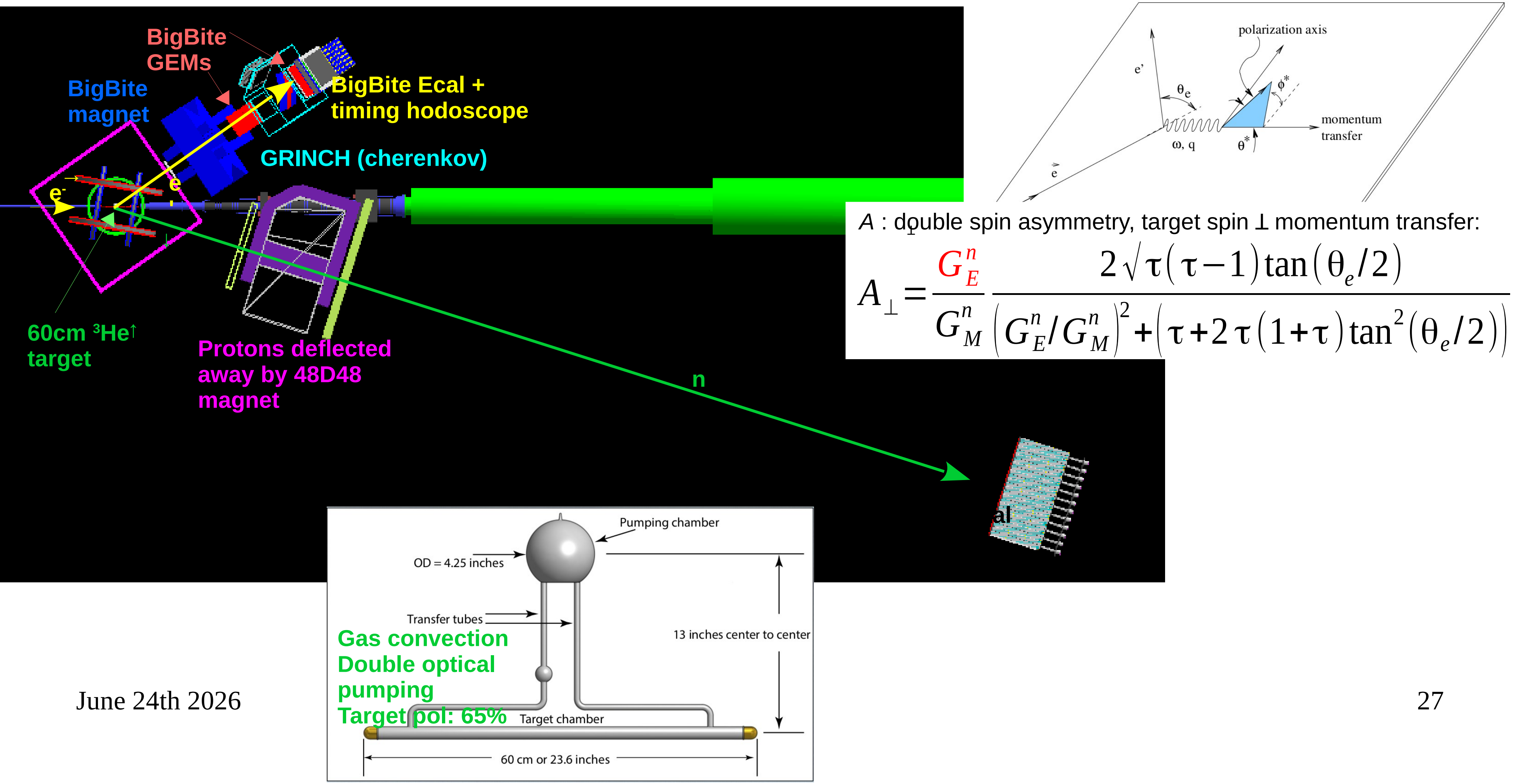
SBS experimental program:
Neutron electric Form Factor (G_E^n)

E12-09-016: *B. Wojteskhowski*, G. Cates, S. Riordan

Measurement of ratio G_E^n/G_M^n with double polarization (L_{beam}, T_{target})

+ GEn measurement with recoil polarization:

E12-17-004: *J. Annand*, V. Bellini, M. Kohl, N. Pisnukov, B. Sawatsky, B. Wojsteskhoski



A : double spin asymmetry, target spin ⊥ momentum transfer:

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

Gas convection
Double optical pumping
Target pol: 65%

GMn Measurement

- GMn: E12-09-019 (A. Camsonne, B. Quinn, B. Wojteskhowski)
  - $$R=\frac{N_{en\to en}}{N_{ep\to ep}}$$
  - $$R_{n/p}=\frac{\sigma_{en}}{\sigma_{ep}}=R f_{corr}-N_{inel}$$

$$=\underbrace{\boxed{\frac{\sigma_{Mott}}{\sigma_{Mott}}}}_{=1}\frac{(1+\tau_p)(\sigma_T^n+\epsilon\,\sigma_L^n)}{(1+\tau_n)(\sigma_T^p+\epsilon\,\sigma_L^p)}=\frac{(1+\tau_p)\left(\tau_n(G_M^n)^2+\epsilon(G_E^n)^2\right)}{(1+\tau_n)\left(\tau_p(G_M^p)^2+\epsilon(G_E^p)^2\right)}$$

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

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

neutron/proton detection efficiency

- ♦ $$\sigma_{Mott}=\hbar c\,\alpha_{EM}\frac{1}{4E^2}\left(\frac{\cos\theta/2}{\sin\theta/2}\right)^2\frac{E'}{E}$$
- ♦ $$\tau_N=\frac{Q^2}{4M_N^2}$$
- ♦ $$\epsilon=\left[1+2(1+\tau)\tan^2(\theta/2)\right]^{-1}$$

GMn Measurement

- GMn: E12-09-019 (A. Camsonne, B. Quinn, B. Wojteskhowski)
  - $R=\frac{N_{en\to en}}{N_{ep\to ep}}$
  - $R_{n/p}=\frac{\sigma_{en}}{\sigma_{ep}}=Rf_{corr}-N_{inel}$

    $$=\frac{\boxed{\sigma_{Mott}}(1+\tau_p)(\sigma_T^n+\epsilon\sigma_L^n)}{\underbrace{\boxed{\sigma_{Mott}}}_{=1}(1+\tau_n)(\sigma_T^p+\epsilon\sigma_L^p)}=\frac{(1+\tau_p)\left(\tau_n(G_M^n)^2+\epsilon(G_E^n)^2\right)}{(1+\tau_n)\left(\tau_p(G_M^p)^2+\epsilon(G_E^p)^2\right)}$$
  - $\tau_n(G_M^n)^2+\epsilon(G_E^n)^2=R_{n/p}\boxed{\left(\tau_p(G_M^p)^2+\epsilon(G_E^p)^2\right)}$

    From proton data
  - $$\boxed{(G_M^n)^2=\frac{1}{\tau_n}\left(R_{n/p}\left(\tau_p(G_M^p)^2+\epsilon(G_E^p)^2\right)-\boxed{\epsilon(G_E^n)^2}-\boxed{\delta_{2\gamma}}\right.}$$

    From GEn fits

    From calculations

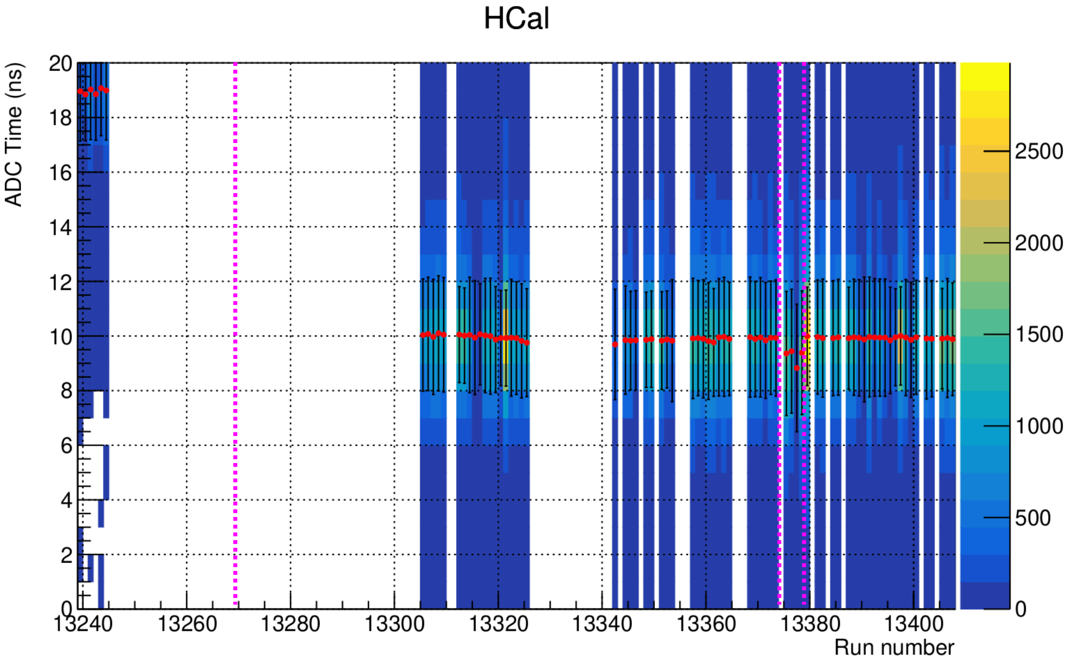
nTPE Measurement

- nTPE: E12-20-010 (E.F., S. Alsalmi, B. Wojteskhowski)
  - $R=\frac{N_{en\rightarrow en}}{N_{ep\rightarrow ep}}$
  - $R_{n/p}=\frac{\sigma_{en}}{\sigma_{ep}}=Rf_{corr}-N_{inel}=\ldots$
  - $R_{n/p}^{\epsilon_{1/2}}=\frac{\sigma_T^n\left(1+\epsilon_{1/2}S^n\right)}{\sigma_T^p\left(1+\epsilon_{1/2}\boxed{S^p}\right)} \rightarrow$ From proton data
  - $A=\frac{R_{n/p}^{\epsilon_1}}{R_{n/p}^{\epsilon_2}}\simeq B\left(S^p\right)\times\left(1+S^n\Delta\epsilon\right)$
    - ♦ $B=\frac{1+\epsilon_2 S^p}{1+\epsilon_1 S^p}$
  - $\boxed{S^n=\frac{A-B}{B\Delta\epsilon}}$
  - $nTPE=S^n-\boxed{\left(G_E^n\right)^2/\tau\left(G_M^n\right)^2} \rightarrow$ GEN fits *or GEN-RP measurement at* **Q² = 4.5 GeV²** (when available)

GMN/NTPE replay status

GMN/NTPE pass-3 replay processed

- Requirements for pass3:
  - ◘ BB Hodoscope time calibration
  - ◘ HCal, BB preshower, BB shower time calibrations w.r.t. BB hodoscope
  - ◘ Done for different periods accounting for SBS field setting, overall trigger latency
  - ◘ SBS14 HCal timing displayed vs run number for pass 2



3 periods:

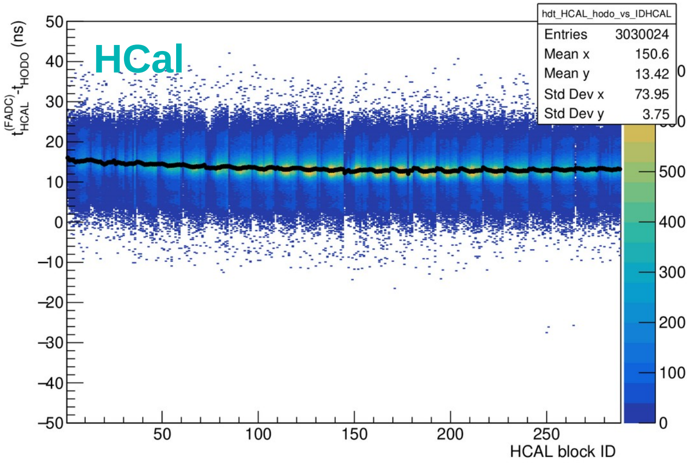
- ◘ 13239-13244
- ◘ 13305-13373 + 13379-13407
- ◘ 13375-13378

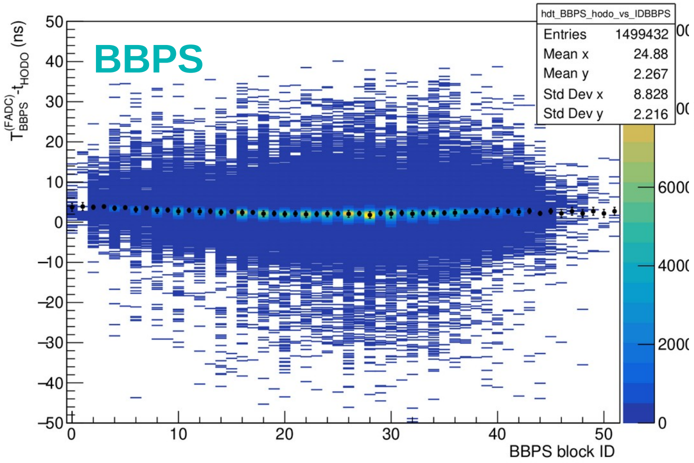
Timing calibrations for Pass-3

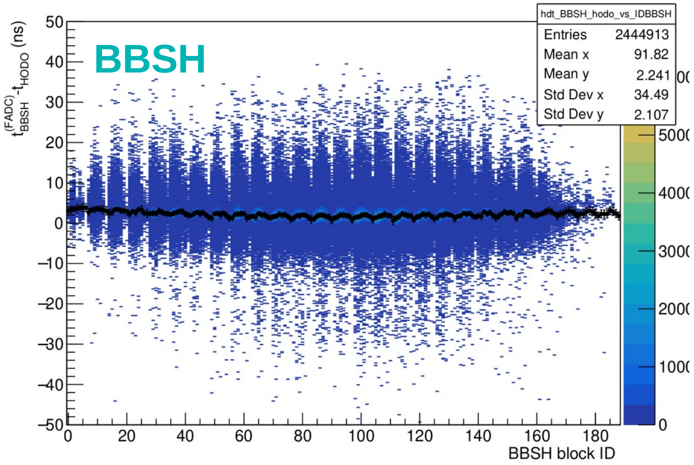
HCal, BB Preshower, BB Shower timing calibration (SBS14 displayed)

- Extracting HCal/BBPS/BBSH - BBHodo time offsets with standard sets of cuts (including elastic selection depending on kinematics)

- Analysis credit: Andrew (SBS8, 9), Anu (SBS4), Provakar (SBS11), Eric (SBS7, 14)



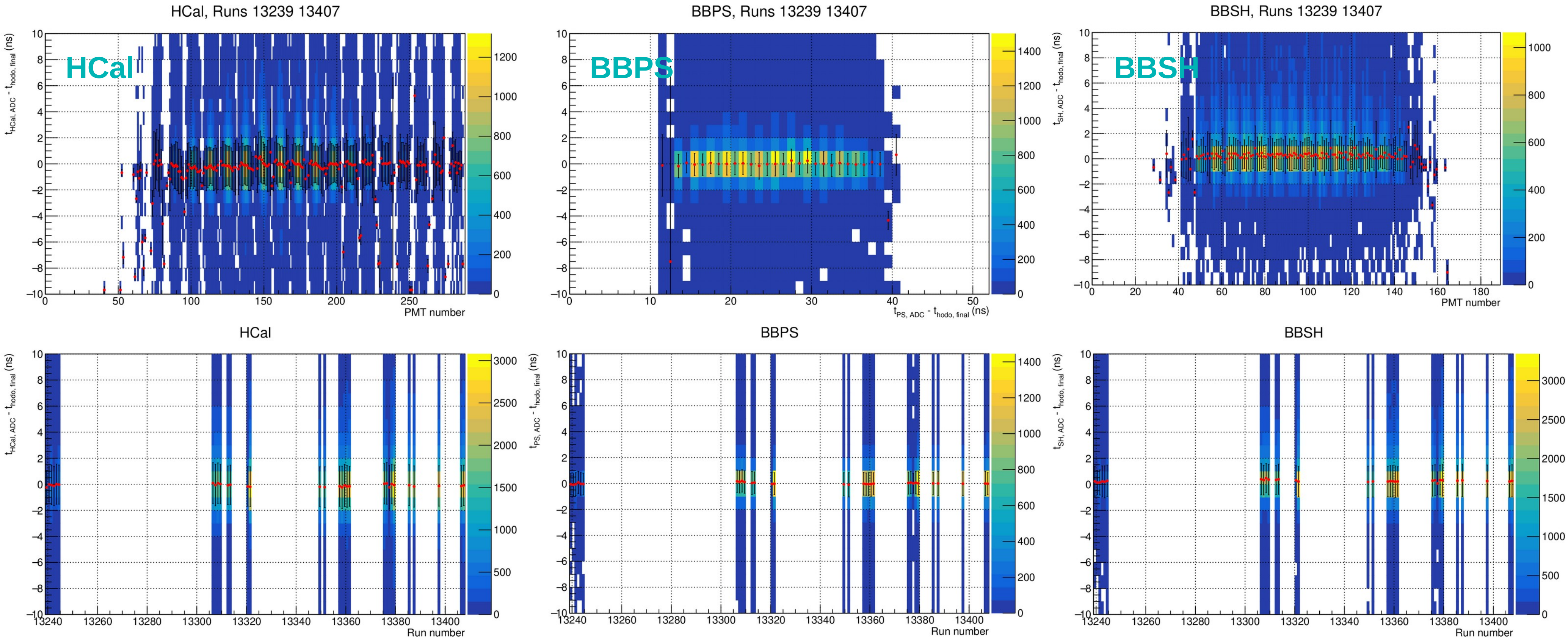




Timing calibrations for Pass-3

HCal, BB Preshower, BB Shower timing calibration (SBS14 displayed)

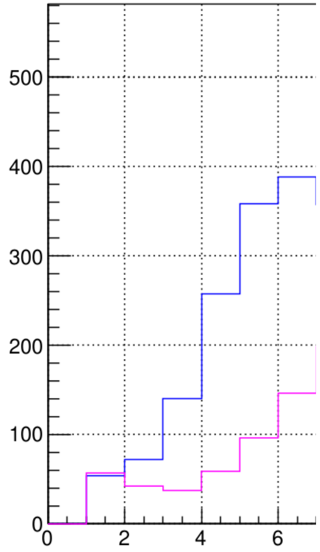
- Quality Analysis: HCal/BBPS/BBSH – BBHodo time offsets vs PMT, Run number
  - Credit: Andrew (SBS8, 9), Anu (SBS4), Provakar (SBS11), Eric (SBS7, 14)

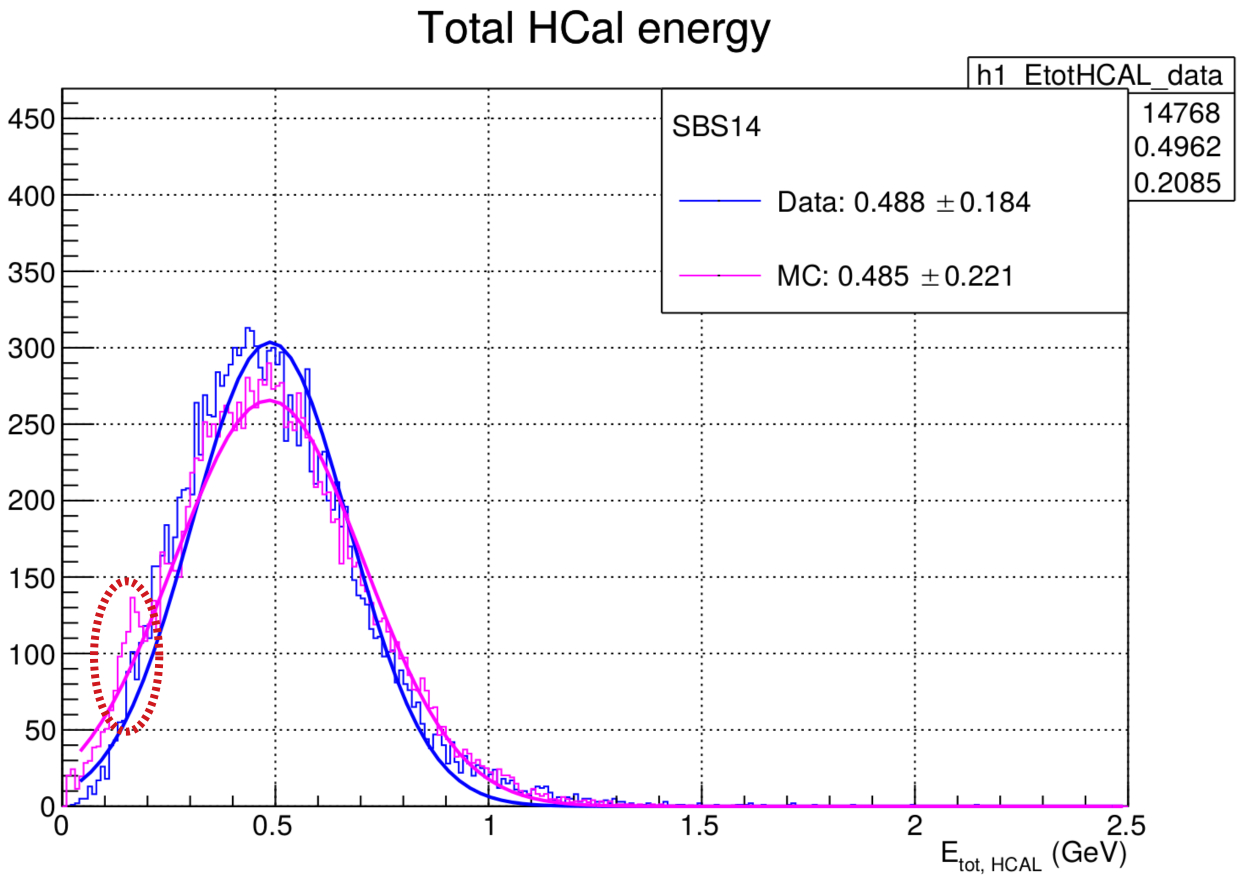


Remaining analysis roadblock for GMN

GMN analysis with pass-3: last roadblock

- **Issue:** lingering apparent discrepancies between Monte Carlo and Data:
  - Hcal cluster size significantly different (in apparence) to data
  - MIP signal visible in HCal energy spectrum for MC, not from data
  - induces avoidable systematics

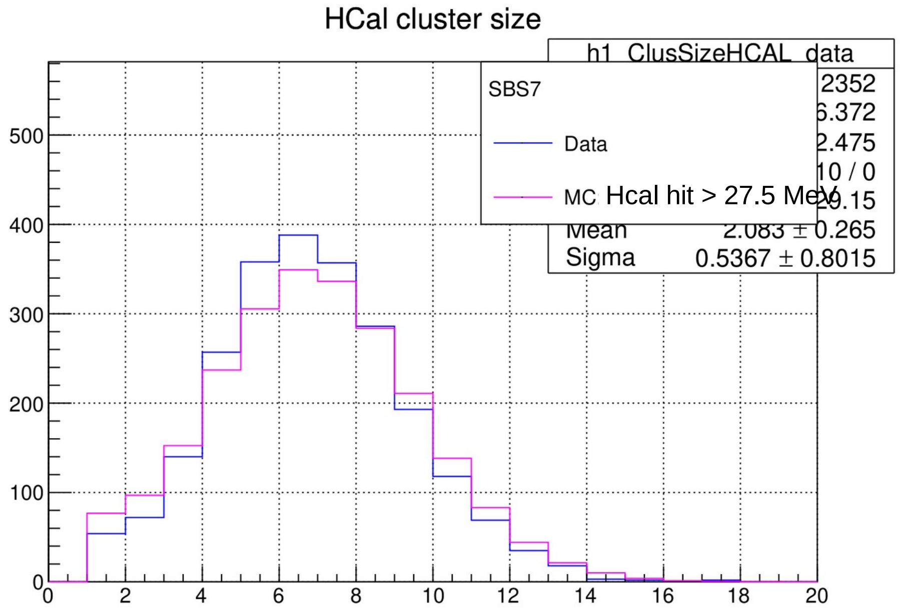


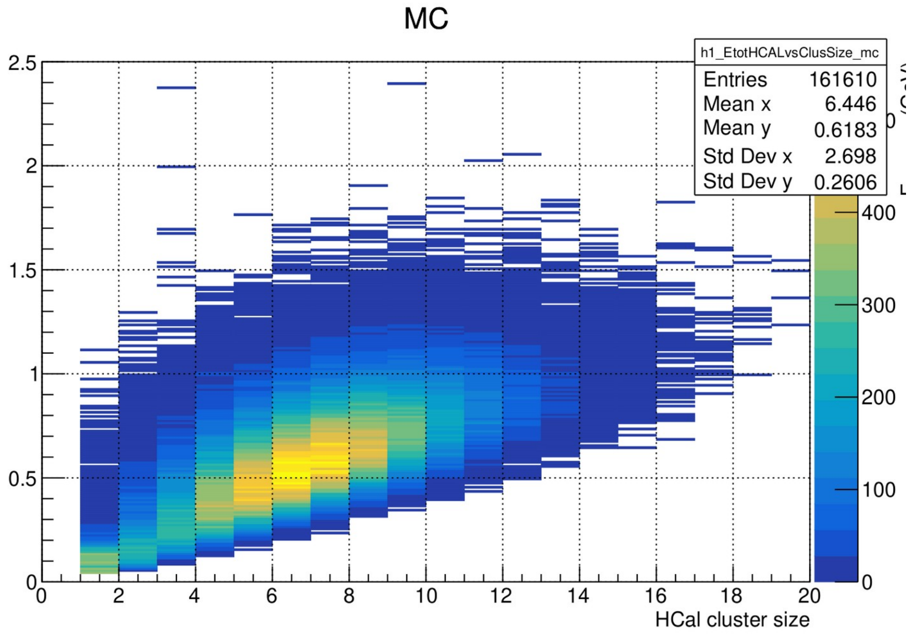


Remaining analysis roadblock for GMN

GMN analysis with pass-3: last roadblock

- **Issue:** lingering apparent discrepancies between Monte Carlo and Data:
    - Hcal cluster size significantly different (in apparence) to data
    - MIP signal visible in HCal energy spectrum for MC, not from data
    - induces avoidable systematics
    - **Solved:**
        - hidden Hcal hit threshold in data due to pulse finding;
        - matching threshold in MC provides similar cluster size;
    - in the process of producing new simulations.

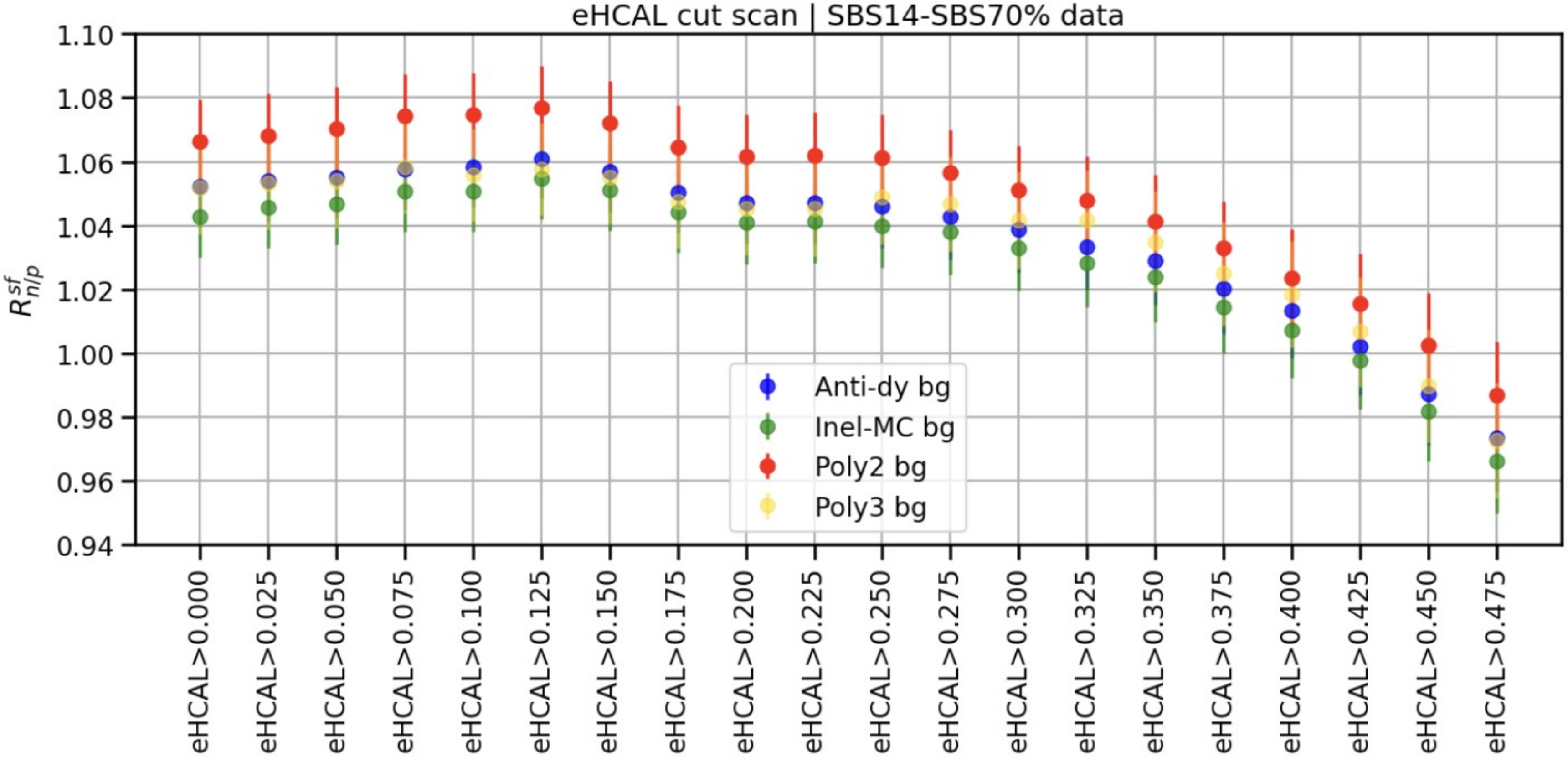




Remaining analysis roadblock for GMN

GMN analysis with pass-3: last roadblock

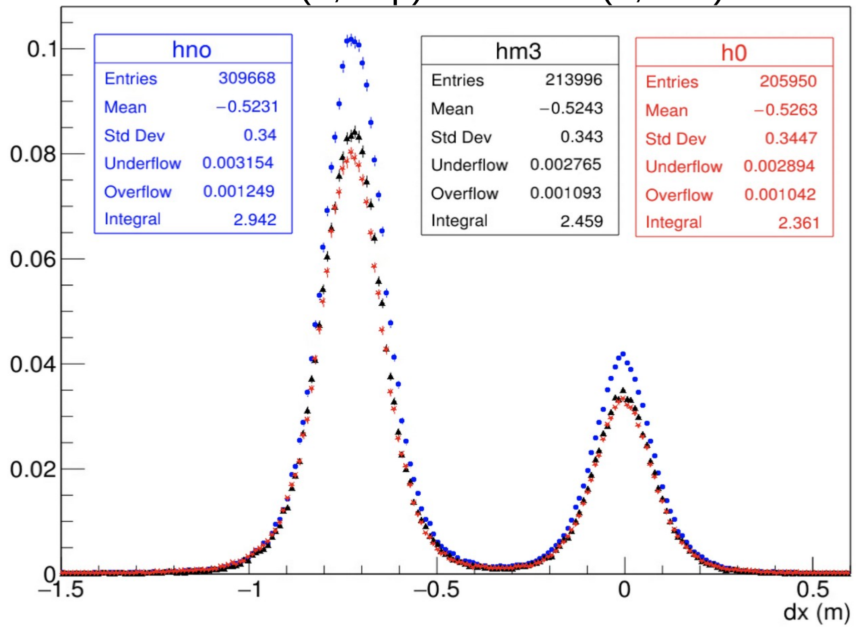
- **Issue:** lingering discrepancy between Monte Carlo and Data:
  - MIP signal visible in HCal energy spectrum for MC, not from data
  - induces unwanted systematics



Systematic uncertainties: Radiative corrections

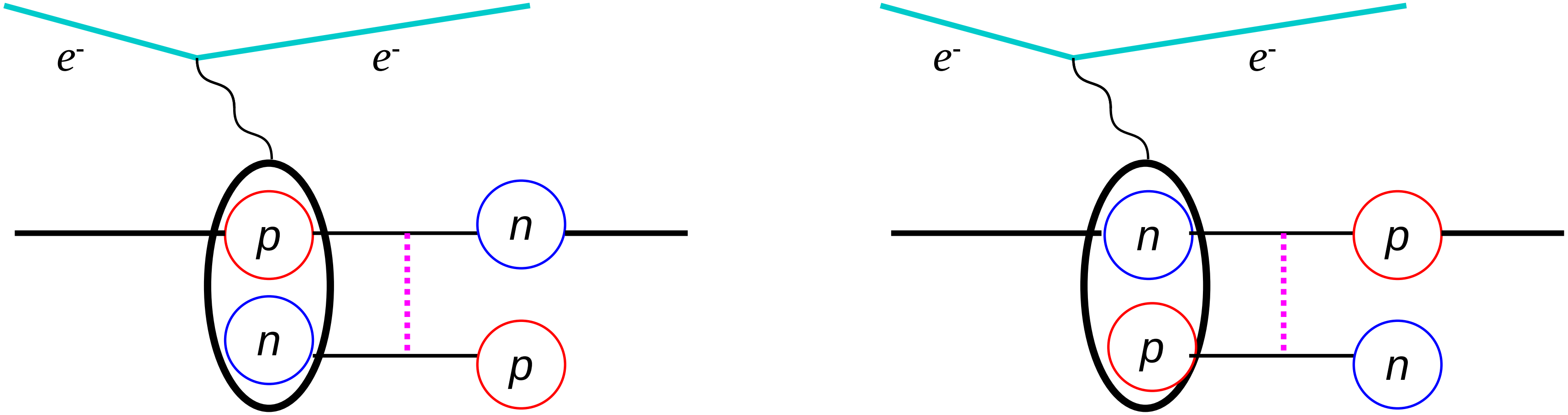
- Radiative corrections (analysis credit: P. Datta, UConn/LBNL):
  - *Dee’p*, *Dee’n*, SIMC samples with the following for radiative effects:
    - (1) - No radiative corrections
    - (2) - *e*, *e’*, and *p* tails radiated
    - (3) - only *e*, *e’* tails radiated
  - Properly weighted Δx distribution for all samples with the same selection
  - Extract $R^{n/p}$ and quantify the correction:
    - $R^{n/p}(2)$ used as reference
    - $|R^{n/p}(3)- R^{n/p}(2)|$ provides systematic error;
  - ~3% error: Need to be improved for nTPE

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

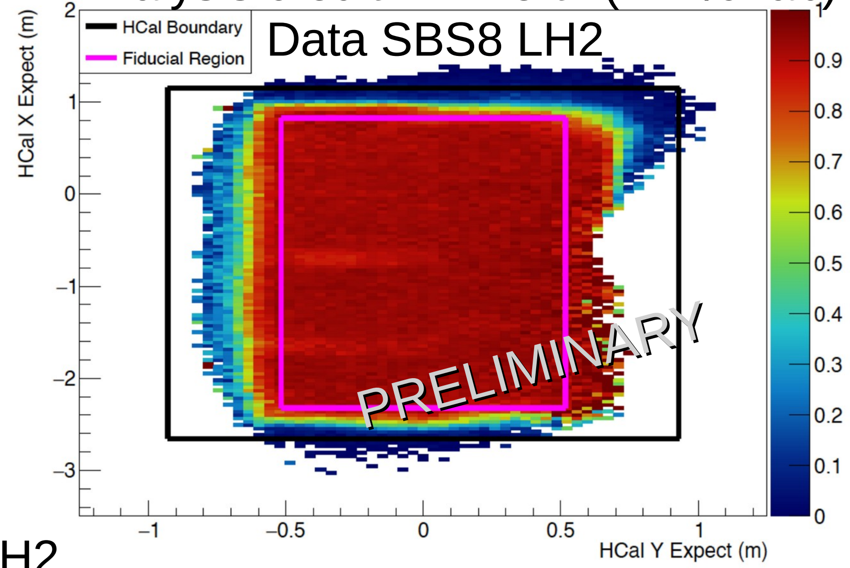


  - ◘ Since D is symmetric, $ep \rightarrow en \equiv en \rightarrow ep$:
    - ♦ ratio $R_{n/p}$ basically not affected
    - ♦ uncertainty on ratio $R_{n/p}$ extremely small

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;
  - Neutron/proton efficiency drop similar
  - 0.5% uncertainty from this effect, total 2% with other effects

Analysis credit: Z. Wertz (WM/JLab)


Data SBS8 LH2

MC SBS8 LH2