nTPE Analysis Progress

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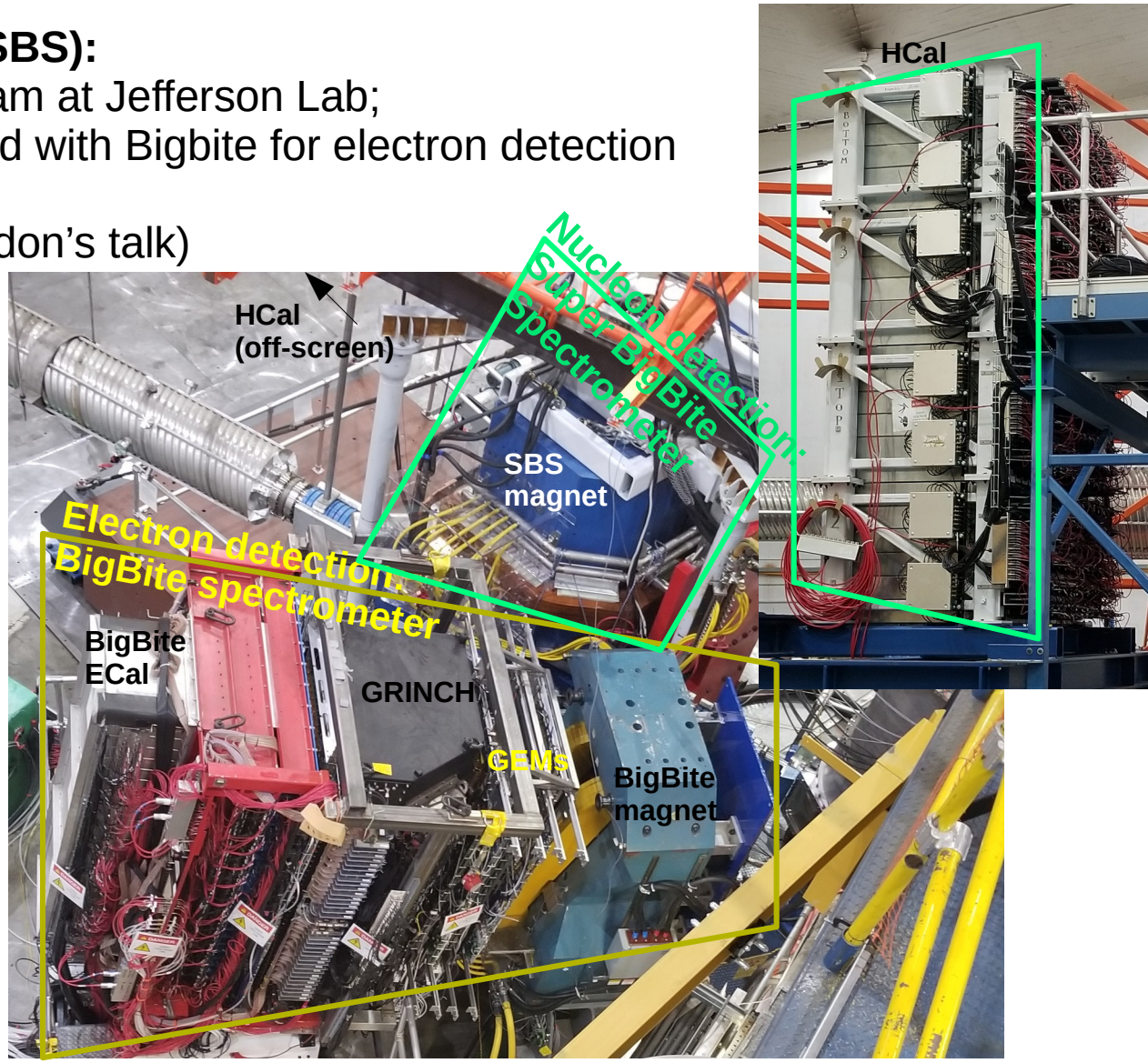
(On behalf of the nTPE collaboration)

Winter Hall A Collaboration Meeting
January 17th, 2024

NTPE experiment with Super BigBite Spectrometer

*** Super BigBite Spectrometer (SBS):**
Major part of Hall A 12 GeV program at Jefferson Lab;
Neutron experiments: SBS coupled with Bigbite for electron detection

*** SBS form factor program** (Gordon's talk)
- GEP (Jimmy's talk);
- GMN (Provakar's talk);
- GEN (Sean's talk);
- **nTPE:**
  - → Motivation;
  - → Analysis status;
  - → Next steps;



Elastic e-N scattering: Rosenbluth

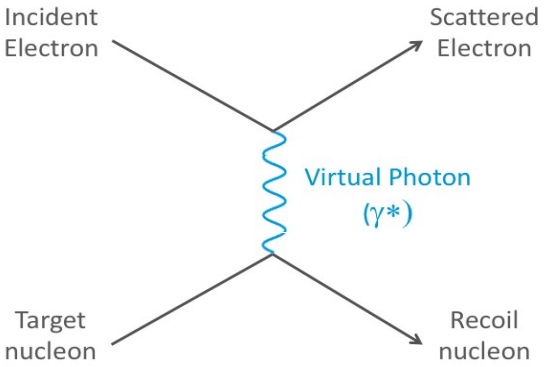
* In the One-Photon Exchange (Born) approximation:

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

Sachs magnetic FF squared

Sachs Electric FF squared

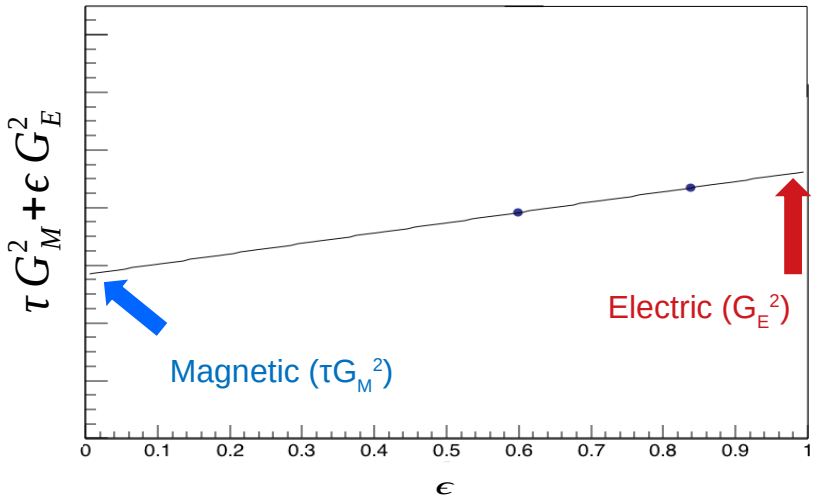
with $\tau = Q^2/(4M_N)$



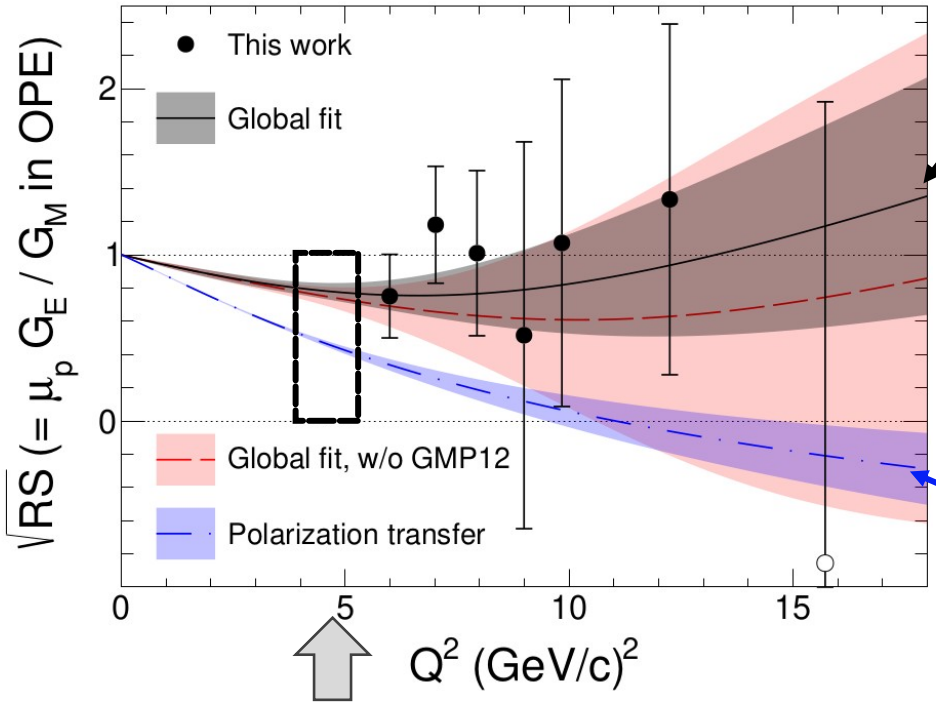
* Rosenbluth technique: separate G_M^2 and G_E^2 based on the linear dependence in $\epsilon = \left[1+2(1+\tau)\tan^2(\theta/2)\right]^{-1}$ of

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

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



Global fit on Rosenbluth slope in *ep* scattering



Global fit of the Rosenbluth slope

E. Christy et al., "Two-photon exchange in electron-proton elastic scattering at large four-momentum transfer", (2020), including last Jlab proton data at 12 GeV

Global fit of polarization transfer data

* Rosenbluth slope Q^2 = 4.5 (GeV/c)^2: $S^p = \sigma_L^p / \sigma_T^p \simeq 0.087 \pm 0.01$
* ***large* discrepancy** between Rosenbluth and polarization transfer;
* Missing contribution likely due to two-photon exchange (TPE)

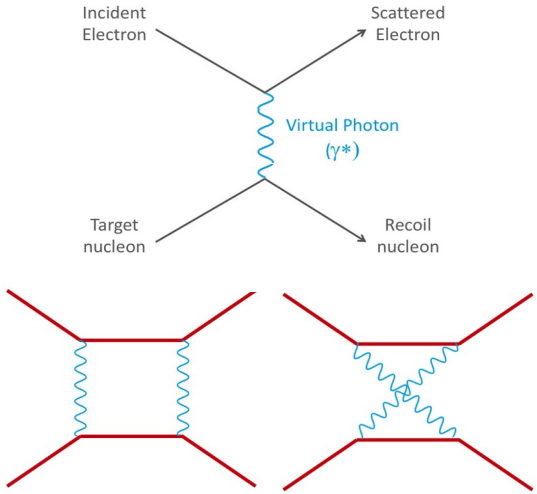
Two-photon exchange in e-N scattering

* Until GEp-I at Jefferson Lab, Phys. Rev. Lett. 84, 1398 (2000), OPE accepted to be a sufficient approximation

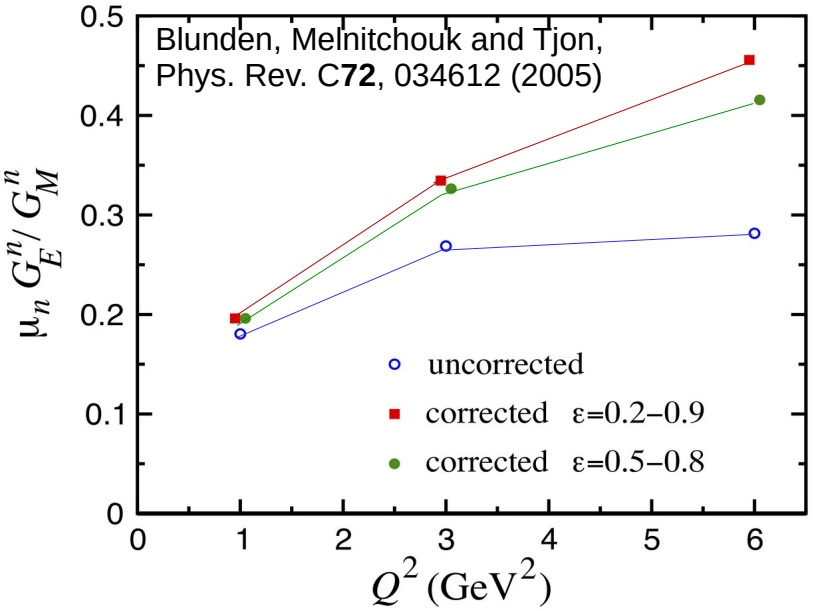
* Investigation of two-photon exchange mandatory;

* Many experiments were dedicated to measure two-photon exchange (TPE), including Rosenbluth and $e^{\pm}$-p scattering

**** Never measured for the neutron.***



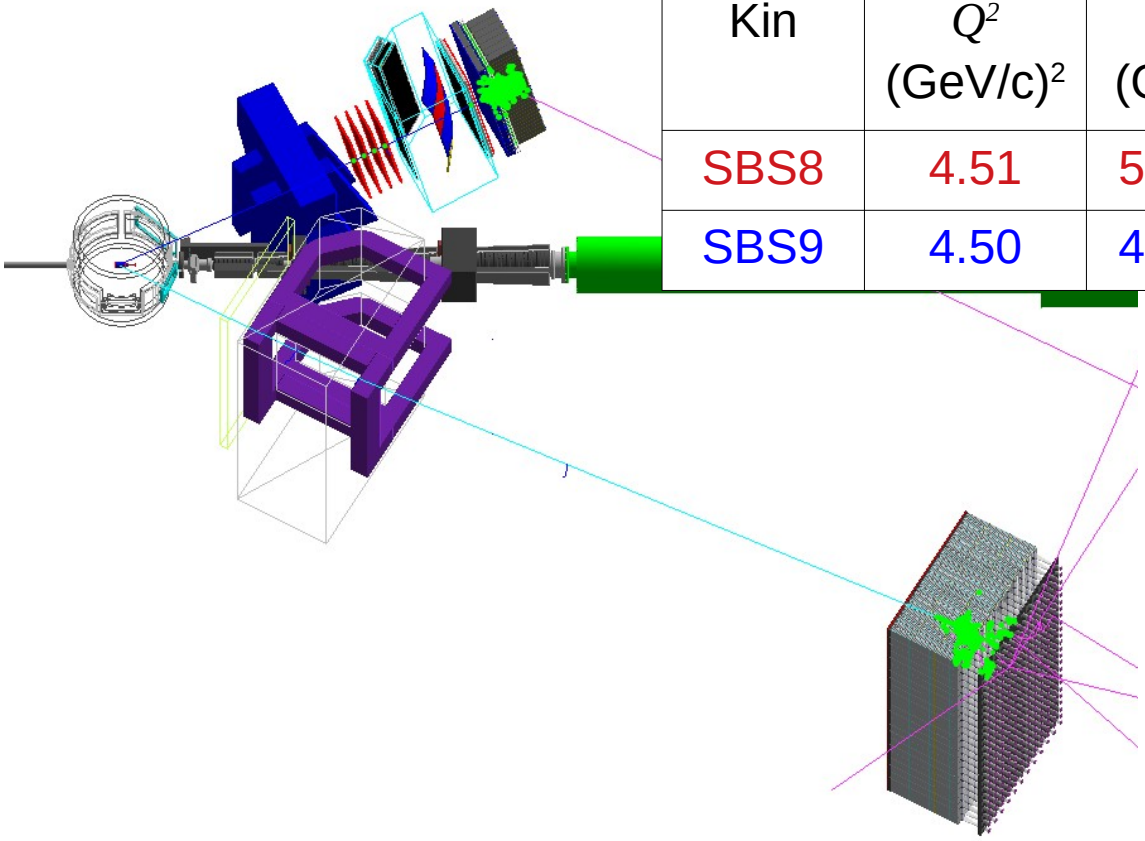
Prediction of the impact of the TPE correction on G_E^n/G_M^n



- 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

Rosenbluth slope on neutron: nTPE

E12-20-010: E. F., S. Alsalmi, B. Wojteskhowski
σ_{en}/σ_{ep} at two beam energies at Q^2 = 4.5 GeV²
Rosenbluth separation of σ_{en}/σ_{ep}
=> data taken in Winter 2022



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

SBS neutron form factor program: nTPE

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σ_{en}/σ_{ep} at two beam energies at Q^2 = 4.5 GeV²
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$$R = \frac{N_{en \to en}}{N_{ep \to ep}} \qquad R' = \frac{\sigma_{en}}{\sigma_{ep}} = R\, f_{corr}$$

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

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

neutron/proton detection efficiency

$$R'_{\epsilon_{1/2}} = R_{Mott,\epsilon_{1/2}} \frac{\sigma_T^n (1 + \epsilon_{1/2} S^n)}{\sigma_T^p (1 + \epsilon_{1/2} S^p)} \qquad A = \frac{R'_{\epsilon_1}}{R'_{\epsilon_2}} \simeq B(S^p) \times (1 + \Delta\epsilon) \qquad B = \frac{R_{Mott,\epsilon_1}}{R_{Mott,\epsilon_2}} \frac{1 + \epsilon_2 S^p}{1 + \epsilon_1 S^p}$$

proton data

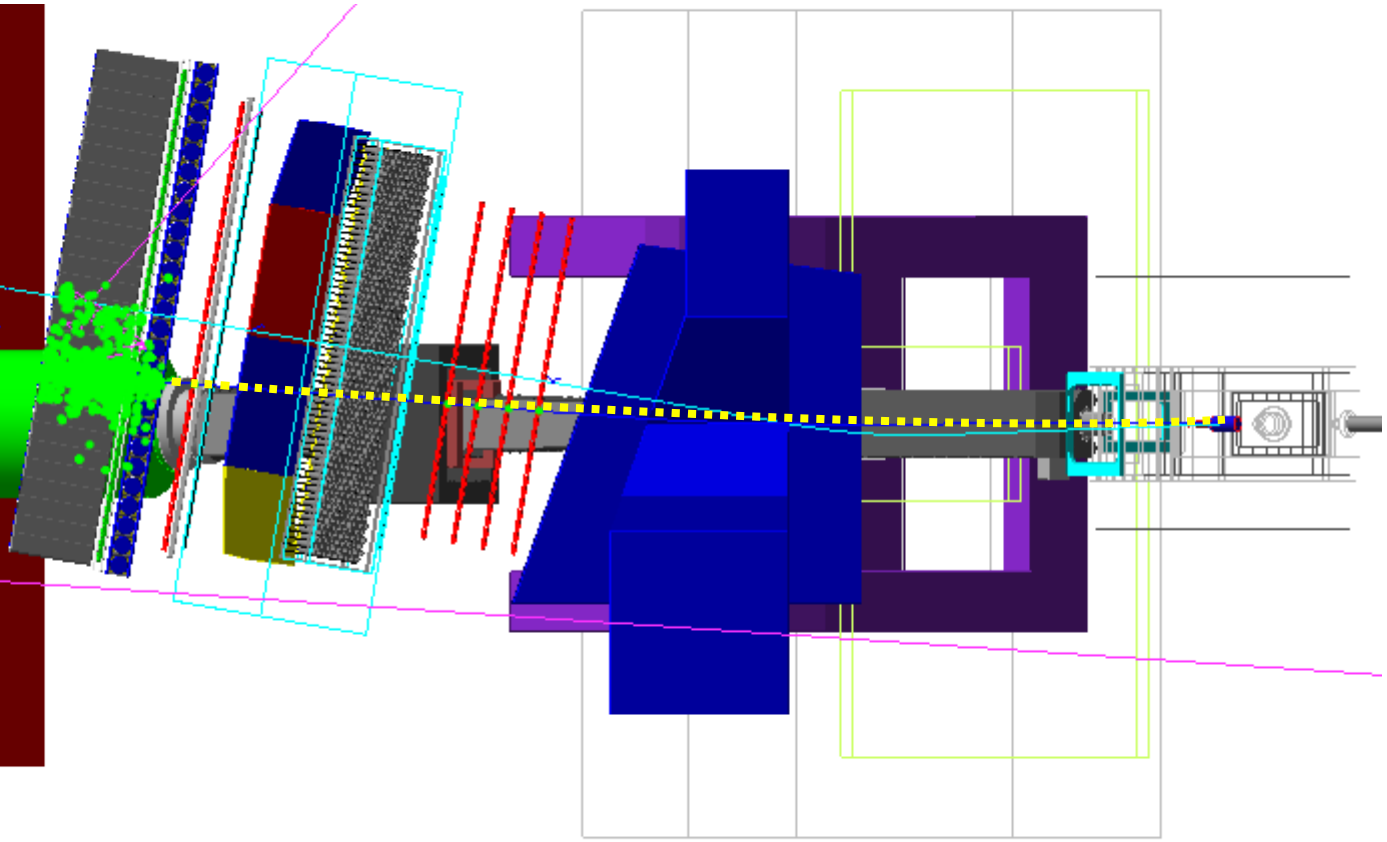
$$\Delta\epsilon = \epsilon_1 - \epsilon_2$$

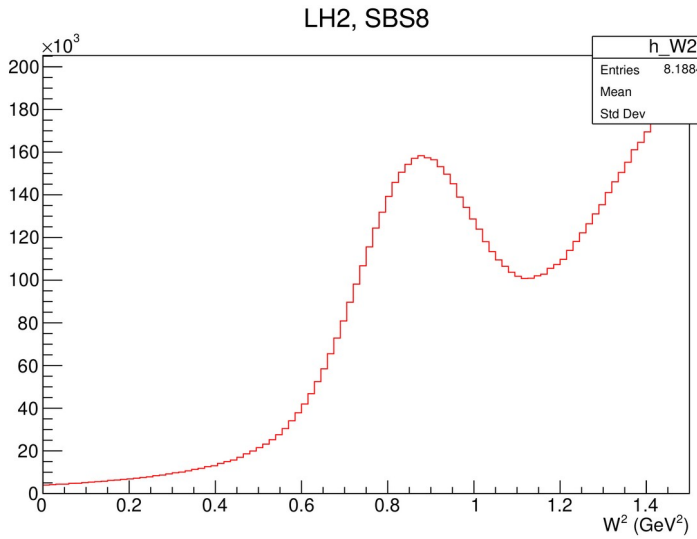
$$S^n = \frac{A - B}{B\,\Delta\epsilon} \qquad nTPE = S^n - (G_E^n)^2 / \tau (G_M^n)^2$$

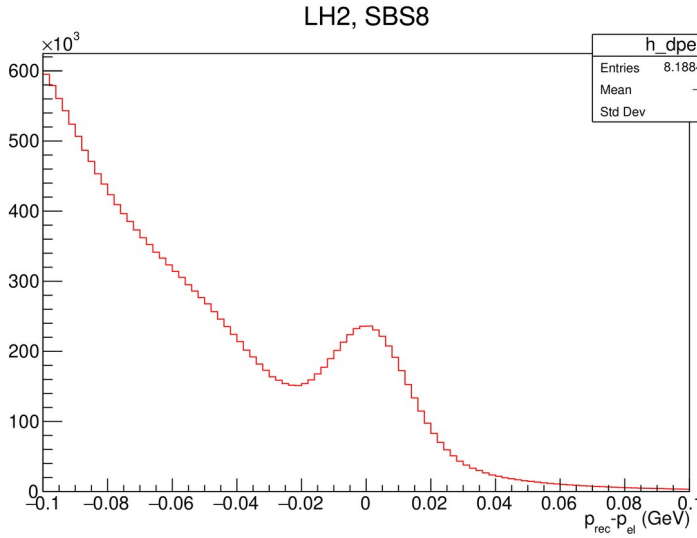
GEN fits and *upcoming GENRP measurement at* **Q^2 = 4.5 GeV²**

nTPE analysis: *e* selection

SBS8 (ε = 0.8) elastic selection:

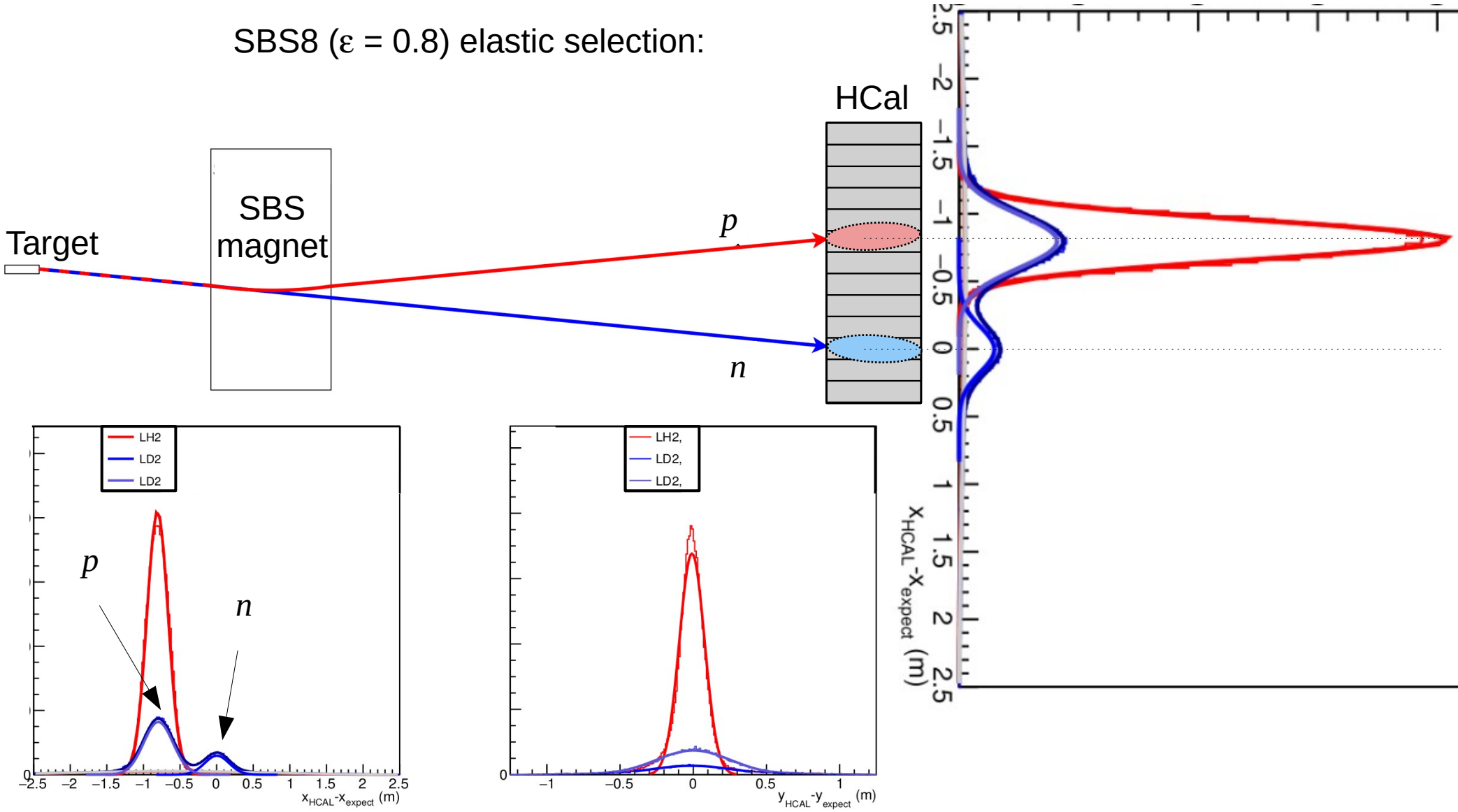






nTPE analysis: *p/n* separation

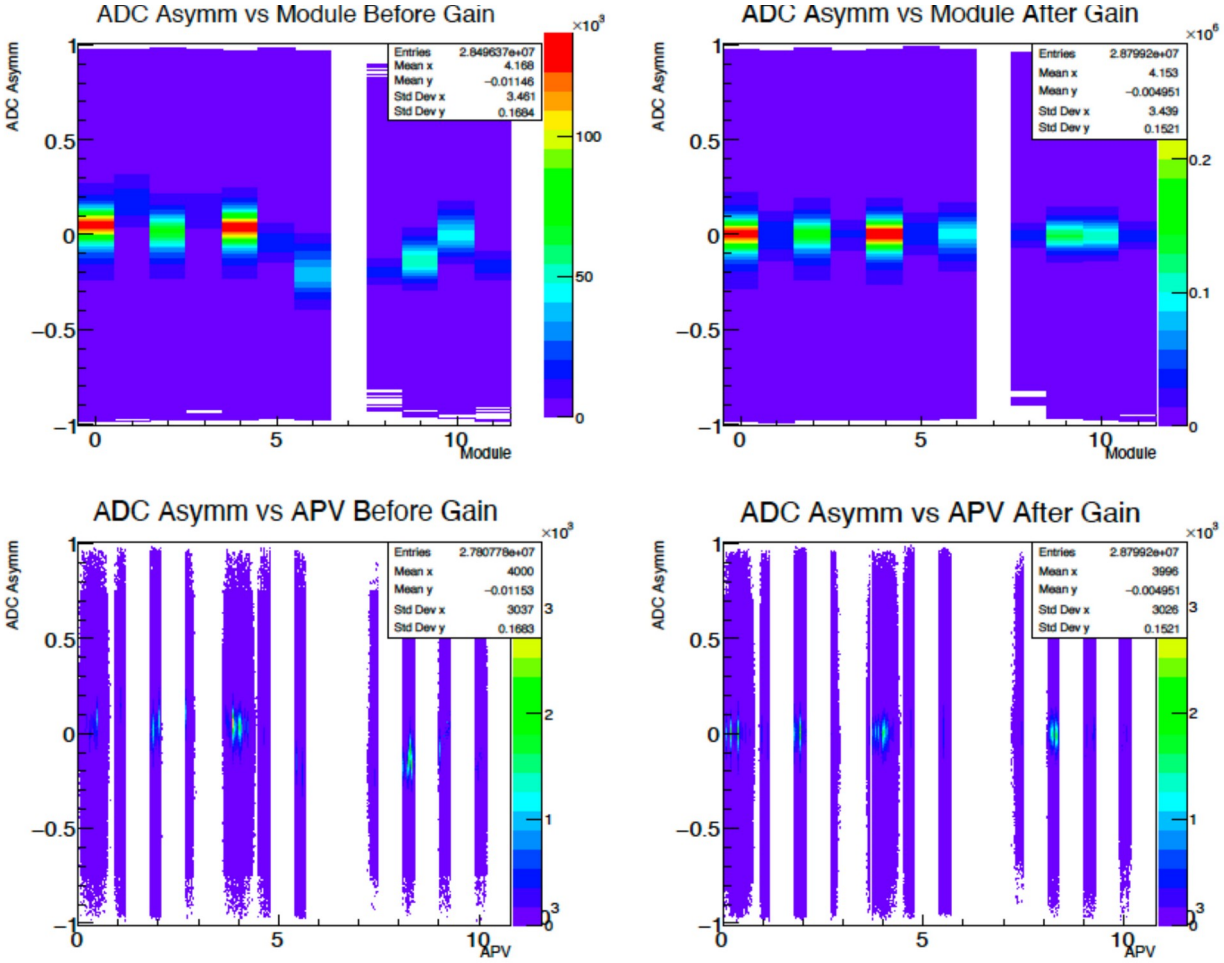
SBS8 (ε = 0.8) elastic selection:



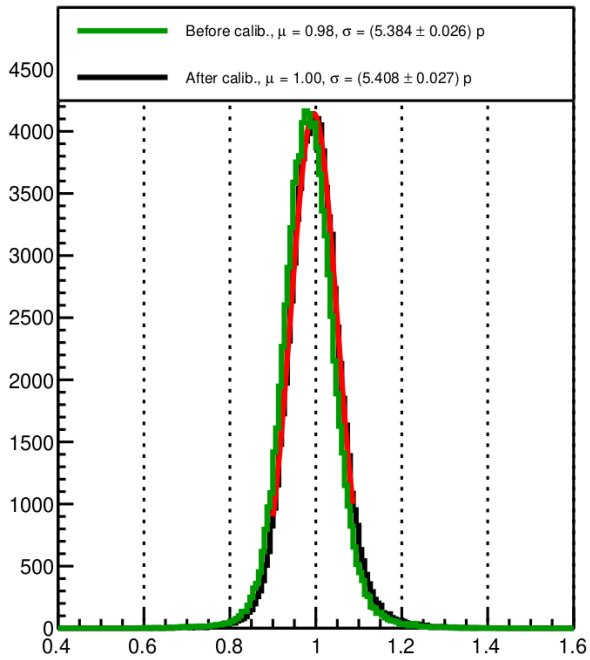
nTPE Analysis Status: Calibrations

Calibrations ready for data processing pass 2:

SBS4 (Q^2 = 3.5 GeV^2) GEM gain match
(plot credit: Zeke Wertz)



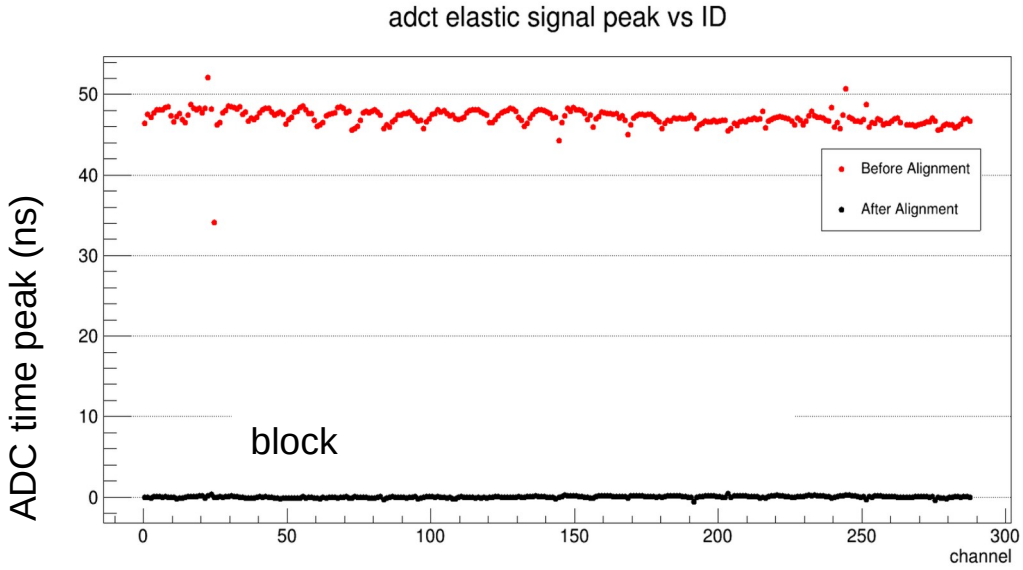
Bigbite Calorimeter
(plot credit: Provakar Datta)



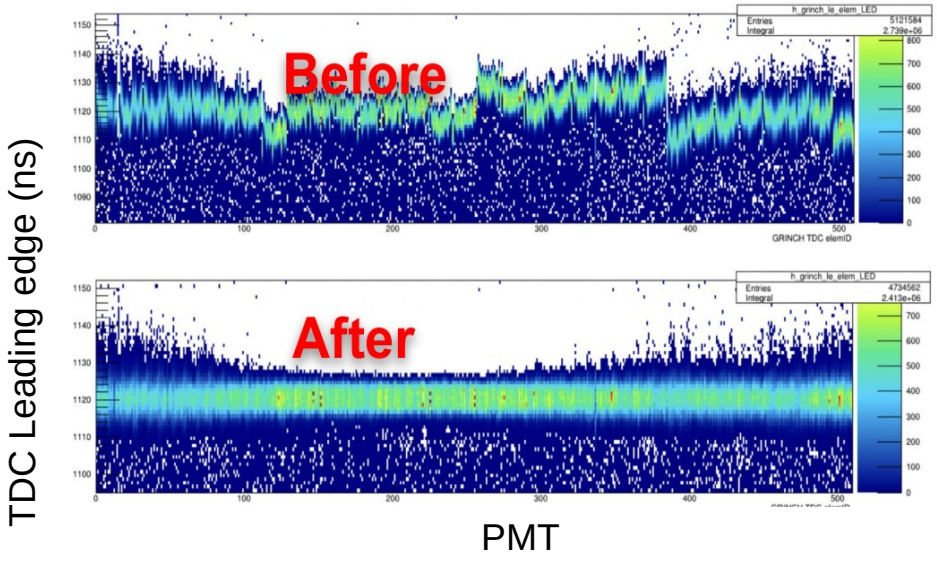
nTPE Analysis Status: Calibrations (cont'd)

Calibration mostly ready for data processing pass 2:

HCal (plot credit: Sebastian Seeds)

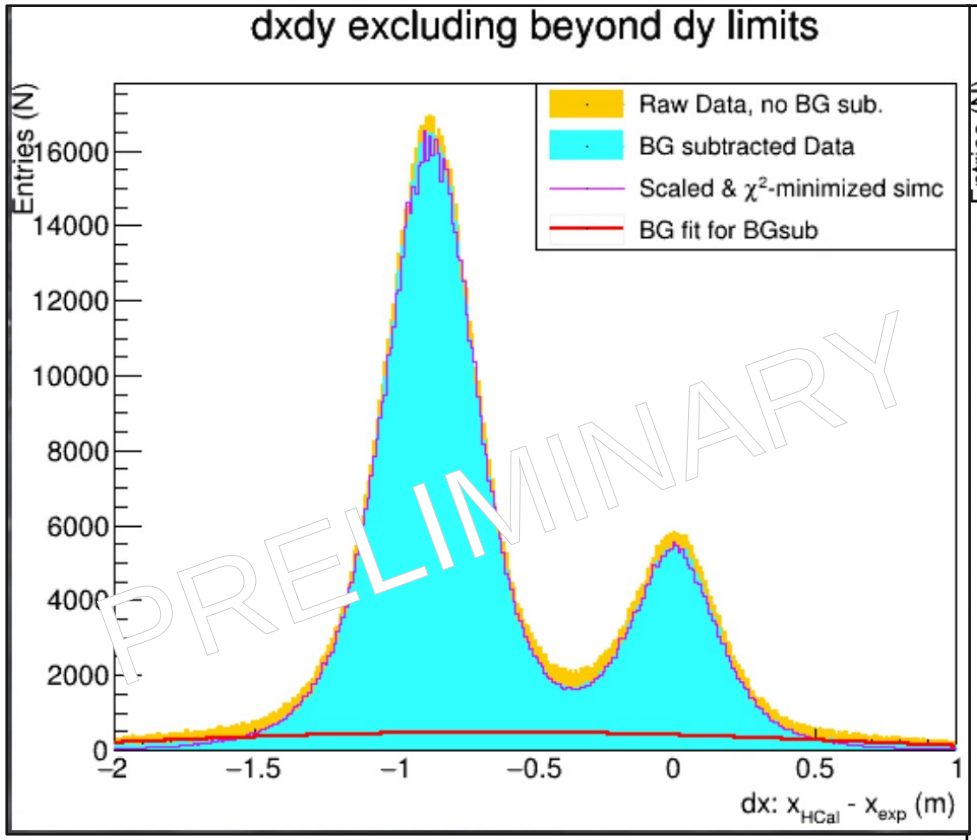


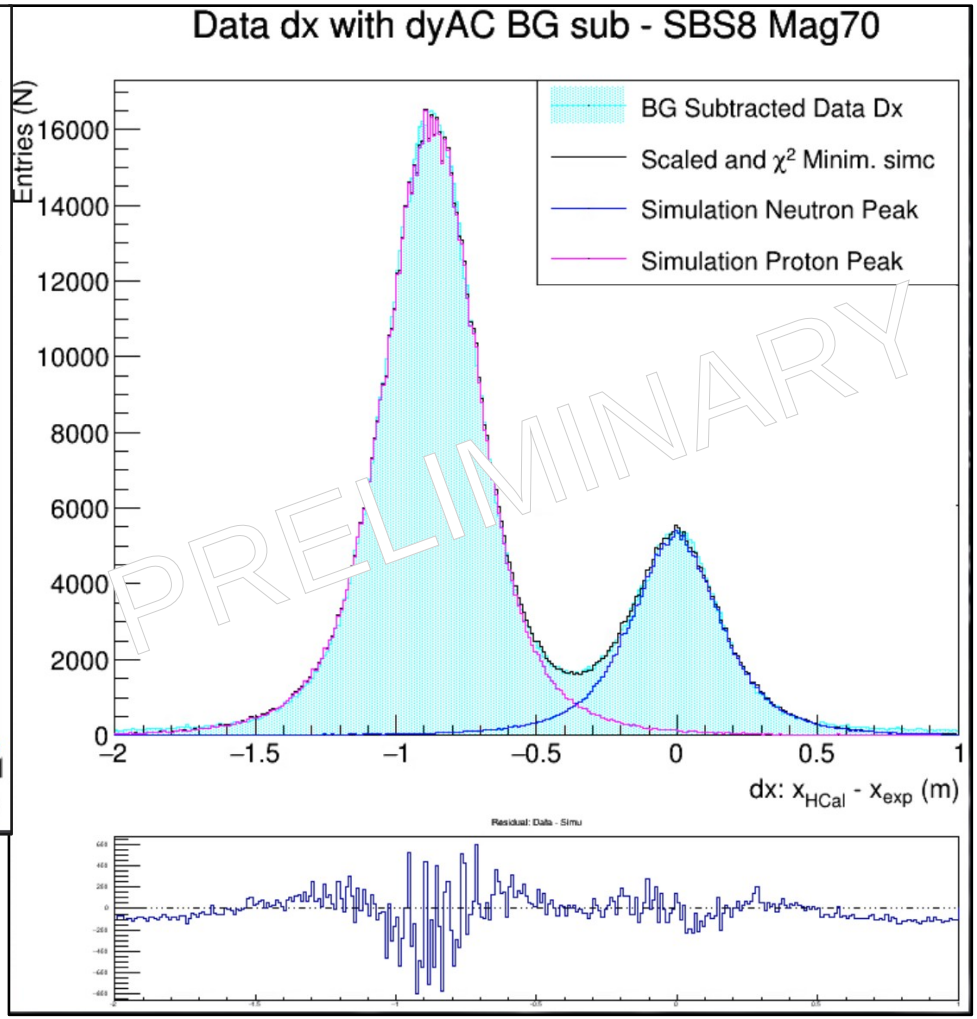
GRINCH (plot credit: Maria Satnik)



nTPE Analysis Status: Correction of en, ep yields with MC

* SBS8: SIMC generated events (with radiative effects) compared with data yields;
* Background subtracted by background fit





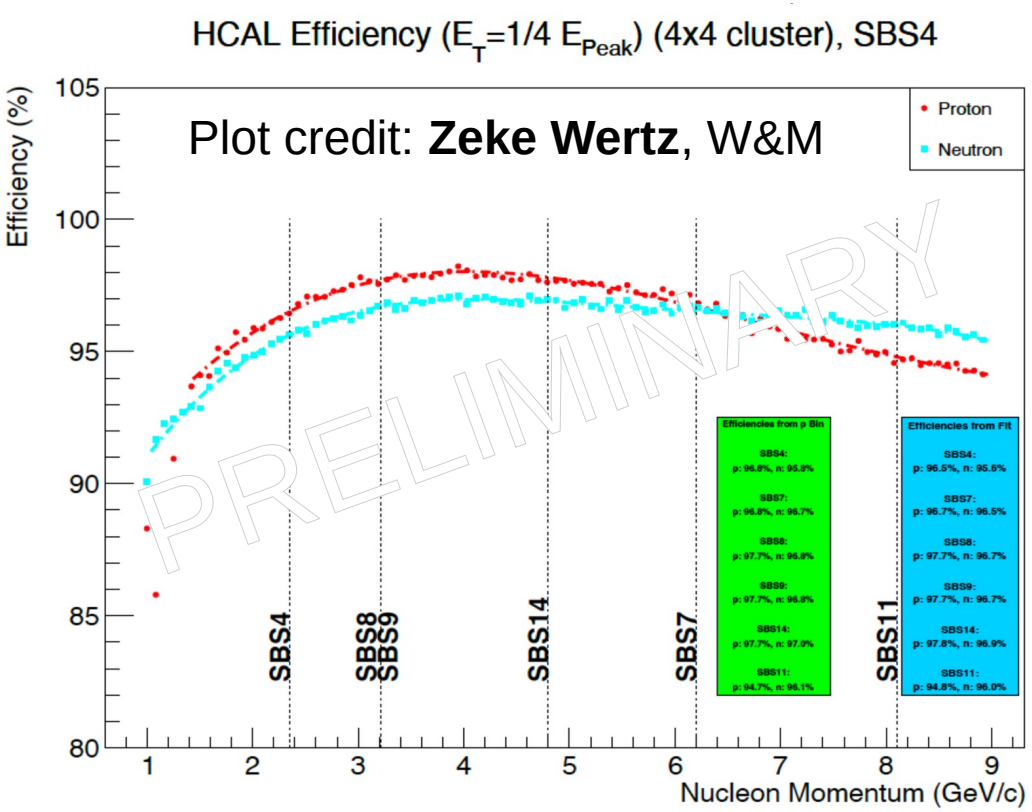
Plots credit: **John Boyd**, UVA

nTPE analysis next steps: Systematics

Sources of systematics:

- **HCal efficiency** as a function of position, time
  * Dedicated elastic hydrogen data to cover all HCal acceptance for SBS8, SBS9
    => *to be analyzed in detail*

- **Inelastic contamination**:
  * need estimation by simulation of inelastic;



Summary

* Analysis of nTPE (and GMn) is getting close to converge;

* Analysis tools are ready and deliver results;

* Calibration mostly converged for pass 2 data processing:
=> reprocess all nTPE (GMn) data analysis and update *en*, *ep* yields,...;

* Emphasis must now be set on systematic errors estimation!

* Coordination of the GMN and NTPE analysis efforts (weekly meetings);

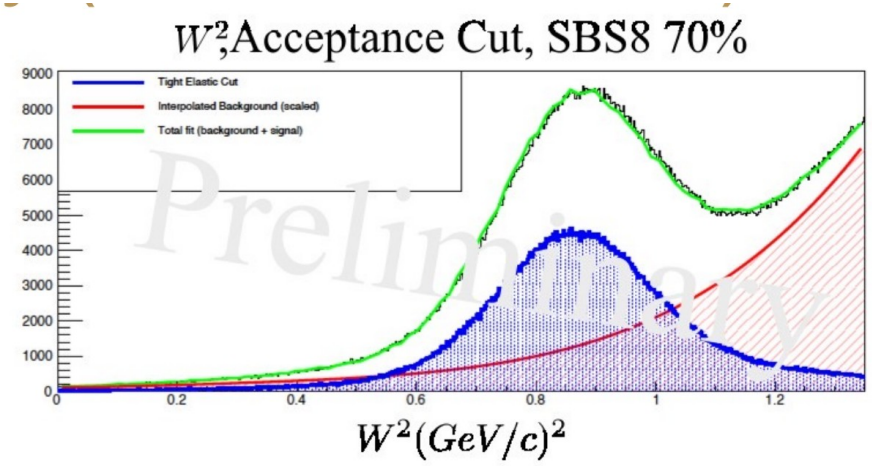
*** Thanks to all graduate students and the SBS collaborators for their dedicated effort towards the GMN/nTPE analysis!**

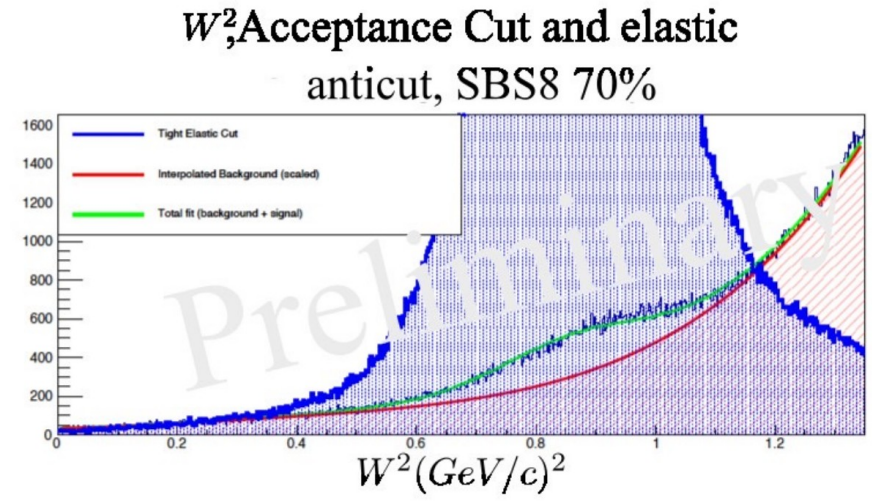
Thank you for your attention !

nTPE analysis next steps: Systematics

Sources of systematics:
- **HCal efficiency** as a function of position, time

Plots credit: **Zeke Wertz**, W&M

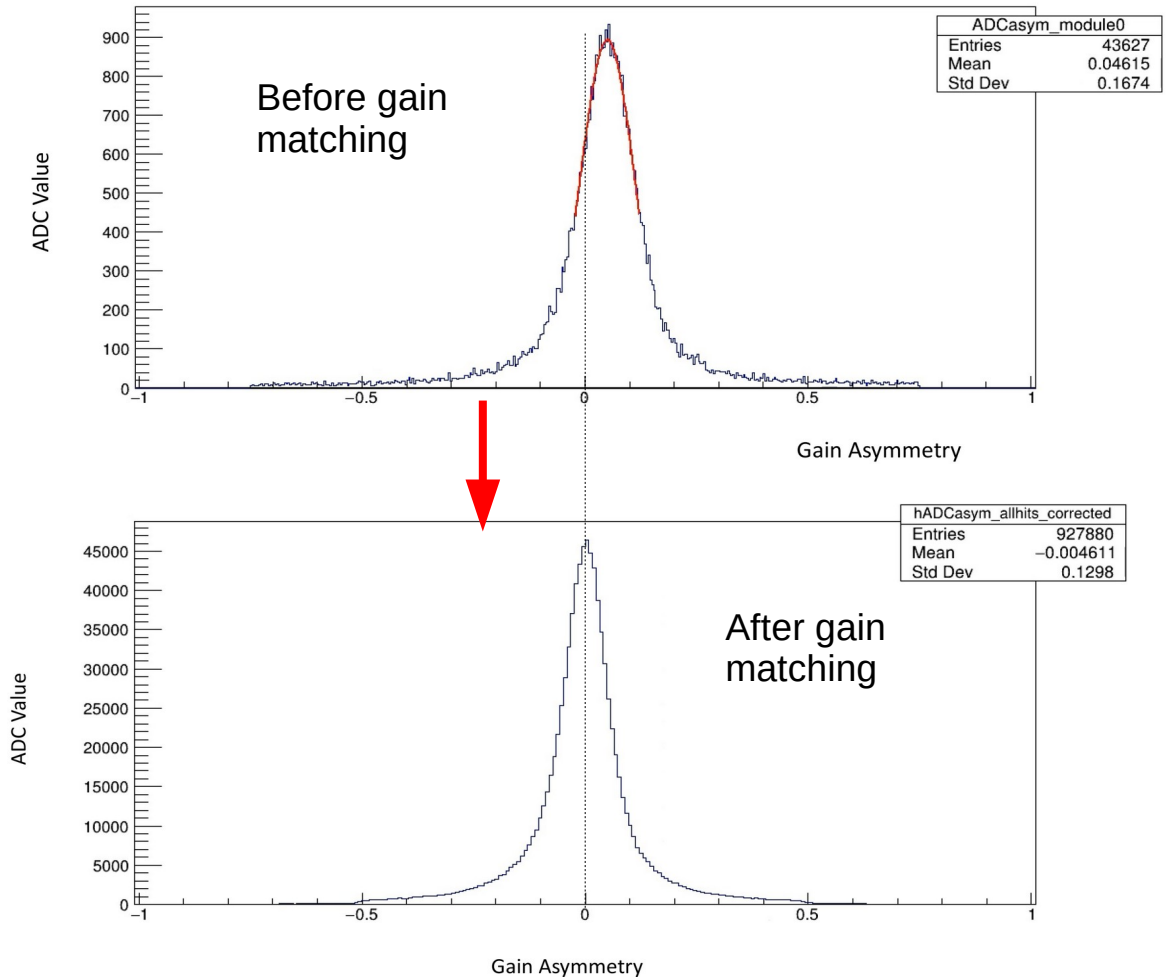




GMN/nTPE analysis
Calibrations/detector analysis

Ongoing efforts: **GEM analysis:**
* gain match (Z. Wertz - W&M)
* deconvolution (A. Rathnayake - UVA) ,
* cross-talk corrections (J. Boyd - UVA));

GEM gain match
(Plots credit: Z. Wertz - W&M)

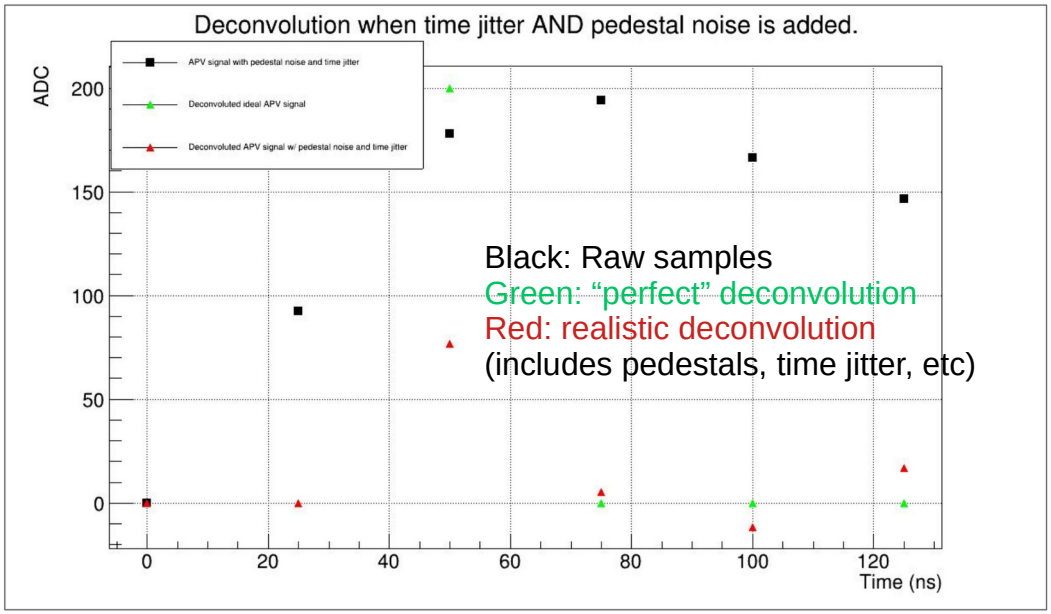


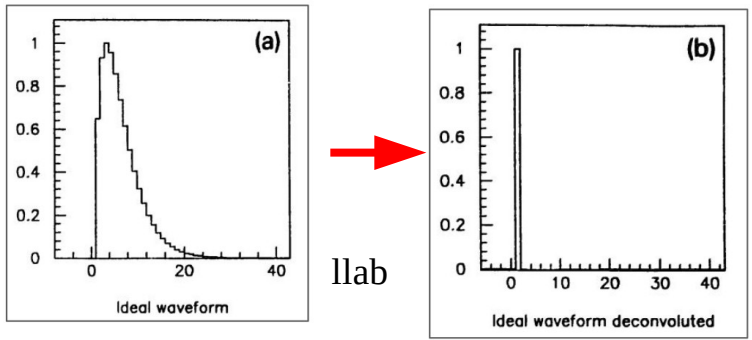
GMN/nTPE analysis
Calibrations/detector analysis

ANALYSIS: next steps:

* Refined analysis for all detectors (ongoing):
 - GEM analysis (gain match, deconvolution, cross-talk corrections);

Deconvolution: (useful for background rejection)
(Plot credit: A. Rathnayake - UVA)



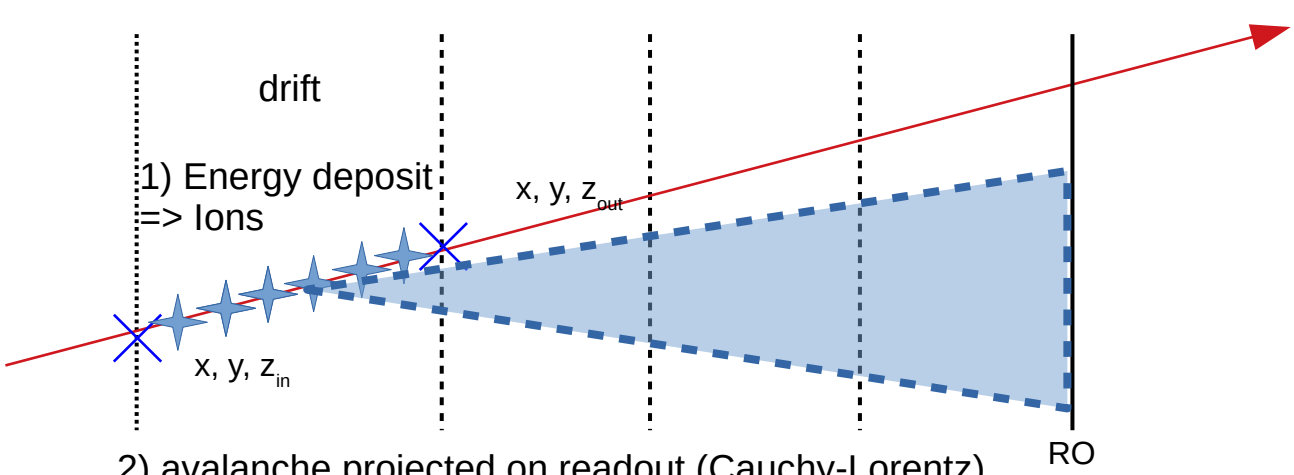


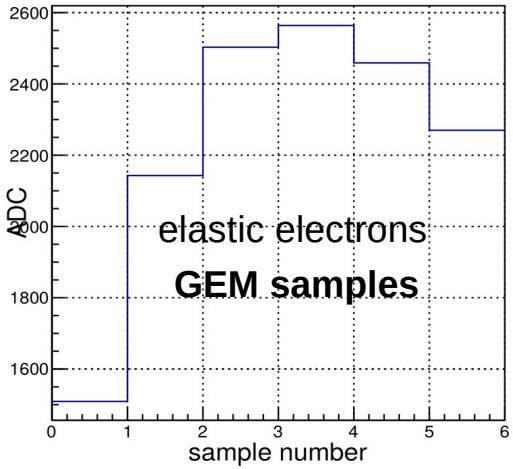
nTPE Analysis: SBS software packages

Simulation/interface with analysis

Libsbsdig: simulates (F)ADC and TDC values (including pedestals) in *all* SBS detectors from energy deposits and number of photoelectrons obtained in G4SBS:

- can superimpose beam-induced background;
- interfaced to SBS analysis package via a specific SimDecoder;





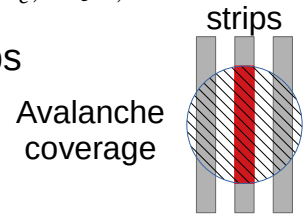
2) avalanche projected on readout (Cauchy-Lorentz)

$$f(x-x_c, y-y_c) = A/(1+(x-x_c)^2/\gamma^2+(y-y_c)^2/\gamma^2)$$

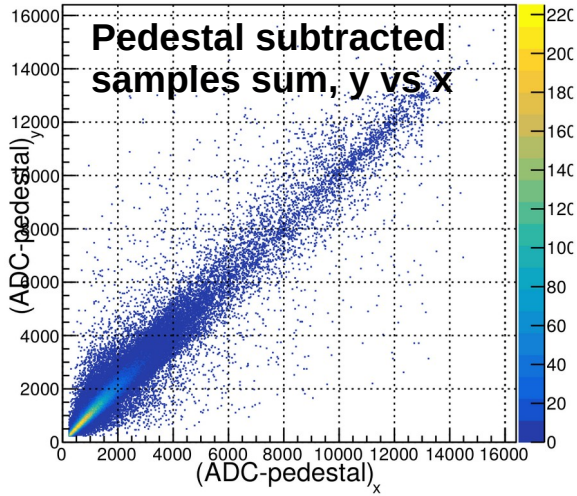
3) avalanche integrated on overlapping strips

$f(t) = C\,(t-t_0)/\tau^2\,\exp(-(t-t_0)/\tau)$ (τ = 56ns)

integrated on APV time samples



4) pedestal added (σ = 20 ADC) on each of the samples;
ADC capped to ADC_{max} = 4096 for saturation



nTPE Analysis: SBS software packages

Analysis

SBS-offline: based on Root-based package “Podd” analyzer for Hall A:

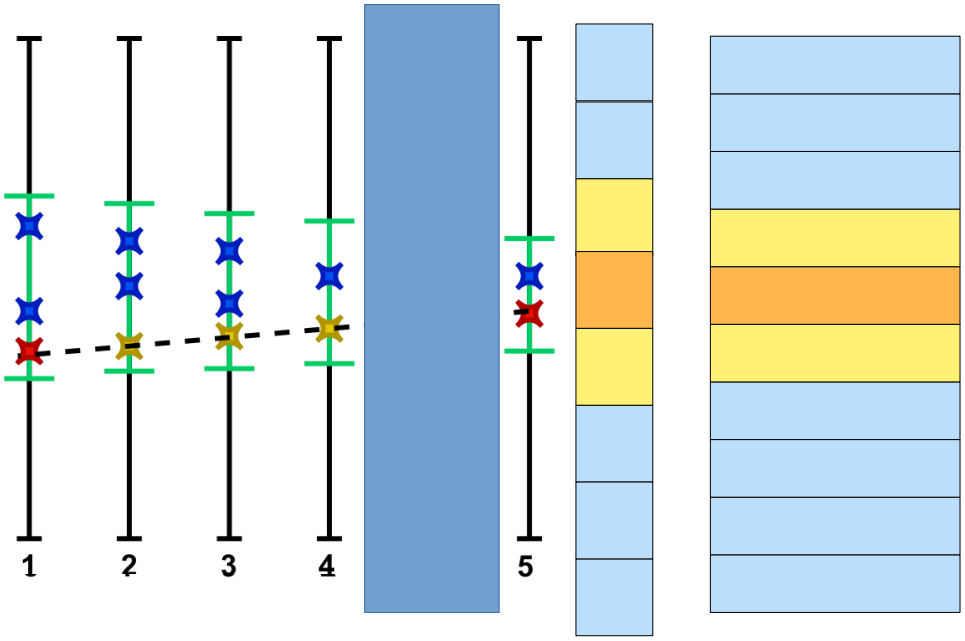
- Clustering, tracking, reconstruction algorithms specific to SBS detectors
- Can use constraints from e.g. calorimeters to restrain tracking region;

Calorimeter clustering:

Search of element with largest energy. Agglomeration of elements around it, with timing requirements

Track-finding algorithm:

Search tracks between combinations of hits in the search region of first and last planes (e.g. red hits here); reject tracks with less than 4 hits



Event display credit: X. Bai - UVA