Study of the Nucleon Structure Modifications Induced by SRC Nucleon-Nucleon Pairs via DVCS

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CLAS Collaboration Meeting
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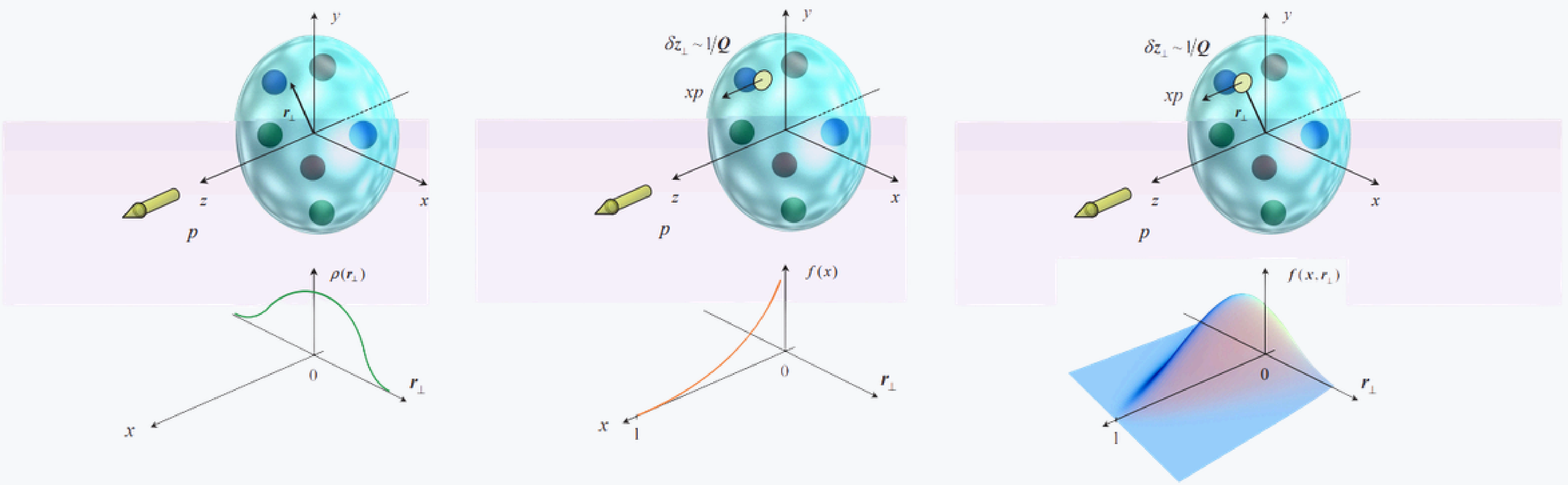
Introduction

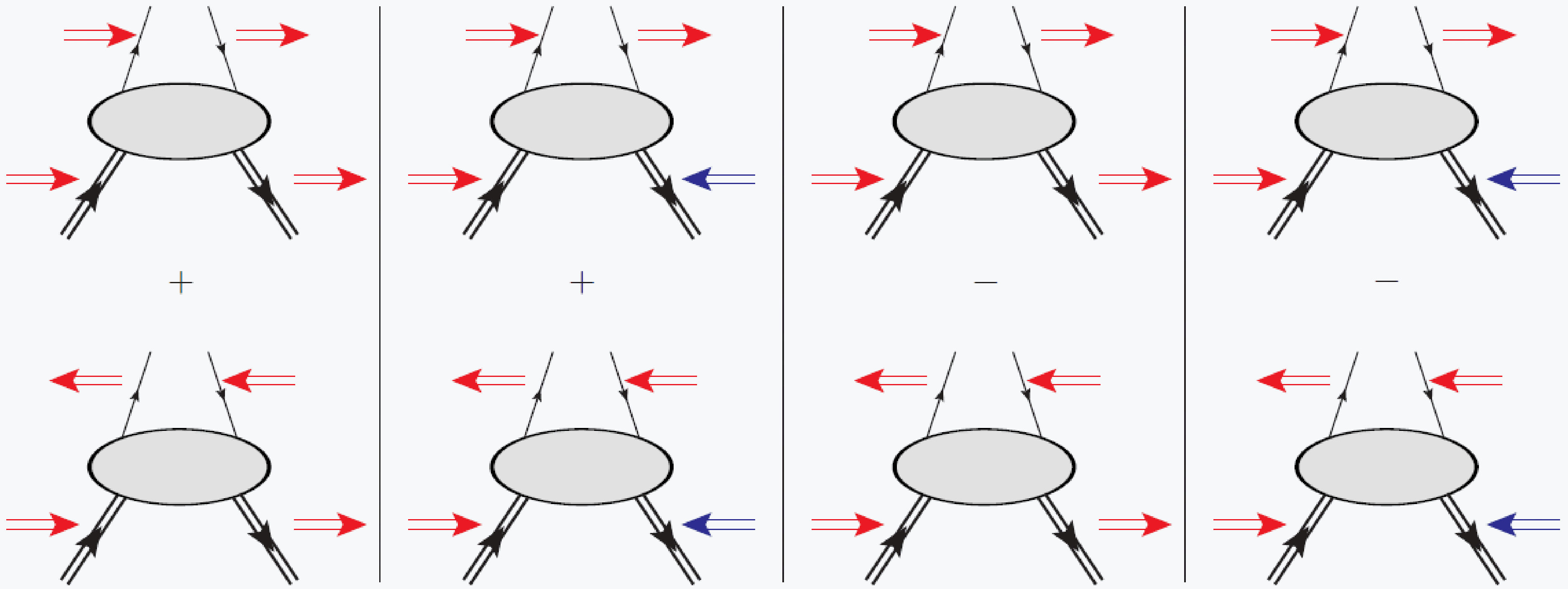
- Understanding the internal structure of nucleons remains a fundamental goal in nuclear and particle physics.
- The nucleon structure is usually studied using electromagnetic probes, such as electrons.



Nucleon structure in low-energy QCD is described through structure functions:

1. **Form Factors (FF):** Transverse spatial distribution of partons.
2. **Parton Distribution Functions (PDFs):** Longitudinal momentum distribution (x).
3. **Generalized Parton Distributions (GPDs):** Correlate transverse position and longitudinal momentum distribution→ 3D tomography of the nucleon, understand the origin of spin, gravitational form factors.

At LO QCD, each of the 4 helicity-conserving GPDs corresponds to a combination of the possible quark-nucleon helicity-spin flips.



H	E	$\tilde{H}$	$\tilde{E}$
Conserve the nucleon's spin	Flip of the nucleon's spin	Conserve the nucleon's spin	Flip of the nucleon's spin

DVCS off Bound Proton in Deuterium and SRC Pairs

$$ed \rightarrow e'p\gamma$$

- GPDs(x, ξ, t) can be accessed through exclusive lepto-production reactions. The **Golden Channel** to access GPDs is the Deeply Virtual Compton Scattering **(DVCS)**

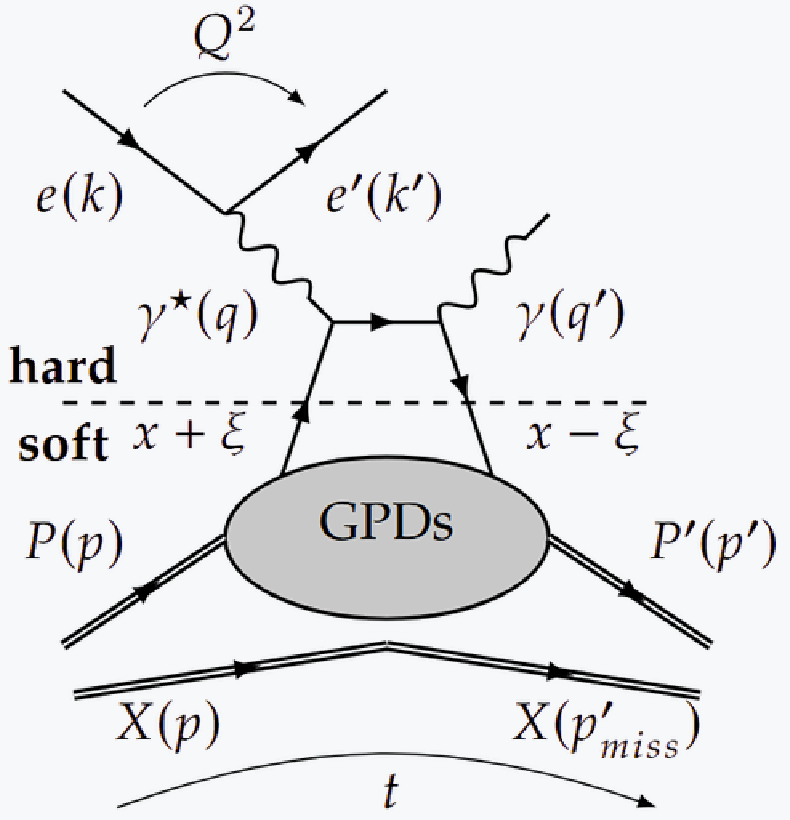
- However, DVCS observables do not directly access these GPDs.

- DVCS gives access to 4 complex GPDs-related quantities: Compton Form Factors (CFF) $\mathcal{H}, \mathcal{E}, \tilde{\mathcal{H}}, \hat{\mathcal{E}}$

- CFF are GPD integrals that appear naturally when integrating over the quark loop of the DVCS diagram. At leading order, DVCS CFFs are

$$\{\mathcal{H}, \mathcal{E}\}(\xi, t) = \int_{-1}^{1} dx \{\mathcal{H}, \mathcal{E}\}(x, \xi, t) \left(\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon} \right)$$

$$\{\tilde{\mathcal{H}}, \tilde{\mathcal{E}}\}(\xi, t) = \int_{-1}^{1} dx \{\tilde{\mathcal{H}}, \tilde{\mathcal{E}}\}(x, \xi, t) \left(\frac{1}{\xi - x - i\epsilon} + \frac{1}{\xi + x - i\epsilon} \right)$$



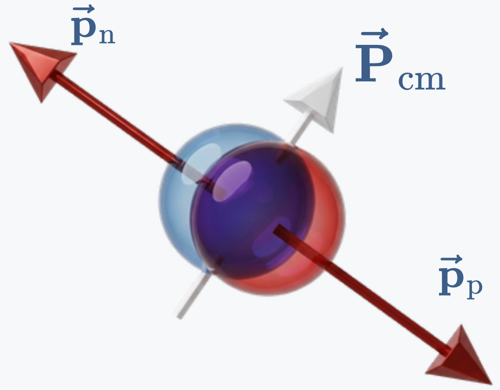
$$Q^2 \equiv -q^2 = -(p_{e'} - p_e)^2$$

$$\xi = \frac{x}{2 - x}$$

$$-t = (p' - p)^2$$

$$x_B = \frac{Q^2}{2q \cdot p} = \frac{Q^2}{2m\nu}$$

The proton may belong to a short-range correlated (SRC) pair with the neutron



- SRC are pairs of nucleons that are close together in the nucleus (wave functions overlap)
- Momentum space: pairs with high relative momentum and low c.m. momentum compared to the Fermi momentum (kF)

Beam Spin Asymmetry

1. **Helicity-spin observables** are an important means of extracting CFFs.
   - Experimentally, one can change the helicity of the incoming electron and use an unpolarized target. In this case, deuterium.
   - It is then possible to measure cross-section asymmetries in this beam helicity-unpolarized target configuration

$$A_{LU}(\phi) = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{1}{\langle|P_l|\rangle}\frac{N^+(\phi) - N^-(\phi)}{N^+(\phi) + N^-(\phi)}$$

   - With the estimated shape

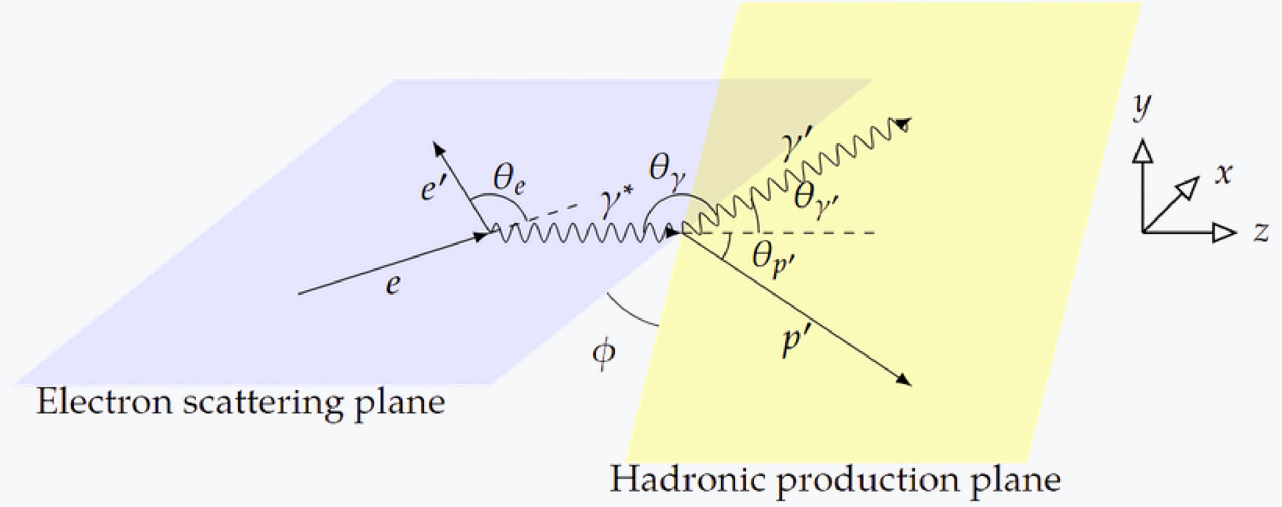
$$f(\phi, \mathrm{a}, \mathrm{b}) = \frac{A\sin(\phi)}{1 + \alpha\cos(\phi)},$$

   - Such asymmetries present two main advantages, as they depend linearly on CFFs and are usually easier to extract than cross sections

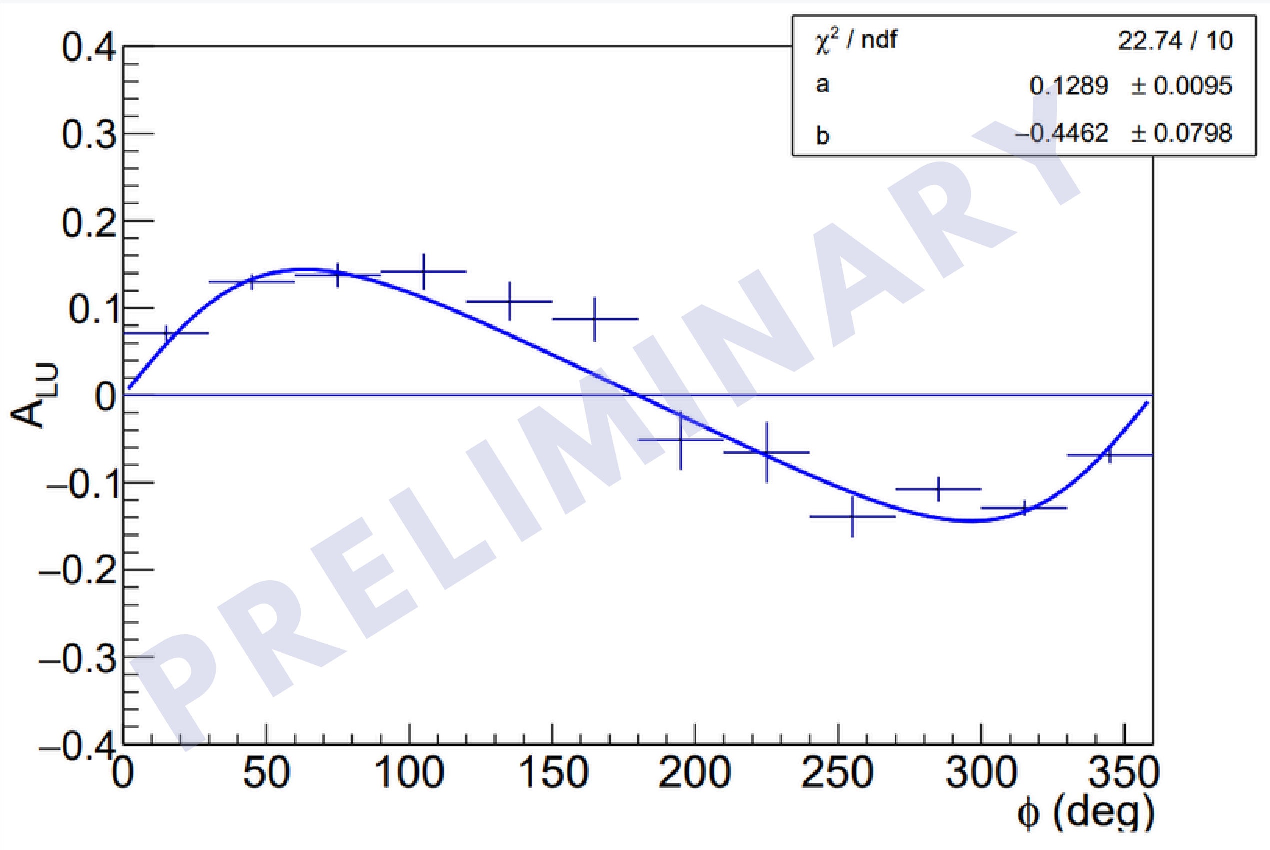
$$A_{LU} \approx \sin(\phi)\mathcal{I}\{F_1\mathcal{H} + \xi(F_1 + F_2)\tilde{\mathcal{H}} - kF_2\mathcal{E} + \ldots\}$$

2. From kinematics, we can reconstruct the neutron momentum (missing momentum)

$$ed \rightarrow e'p\gamma(n)$$



And analyze events with high missing momentum to select SRC candidates and then measure Beam Spin Asymmetries (BSA) in bins of missing momentum.



(b) $0.30 < |\vec{P}_{miss}| < 0.60$ GeV

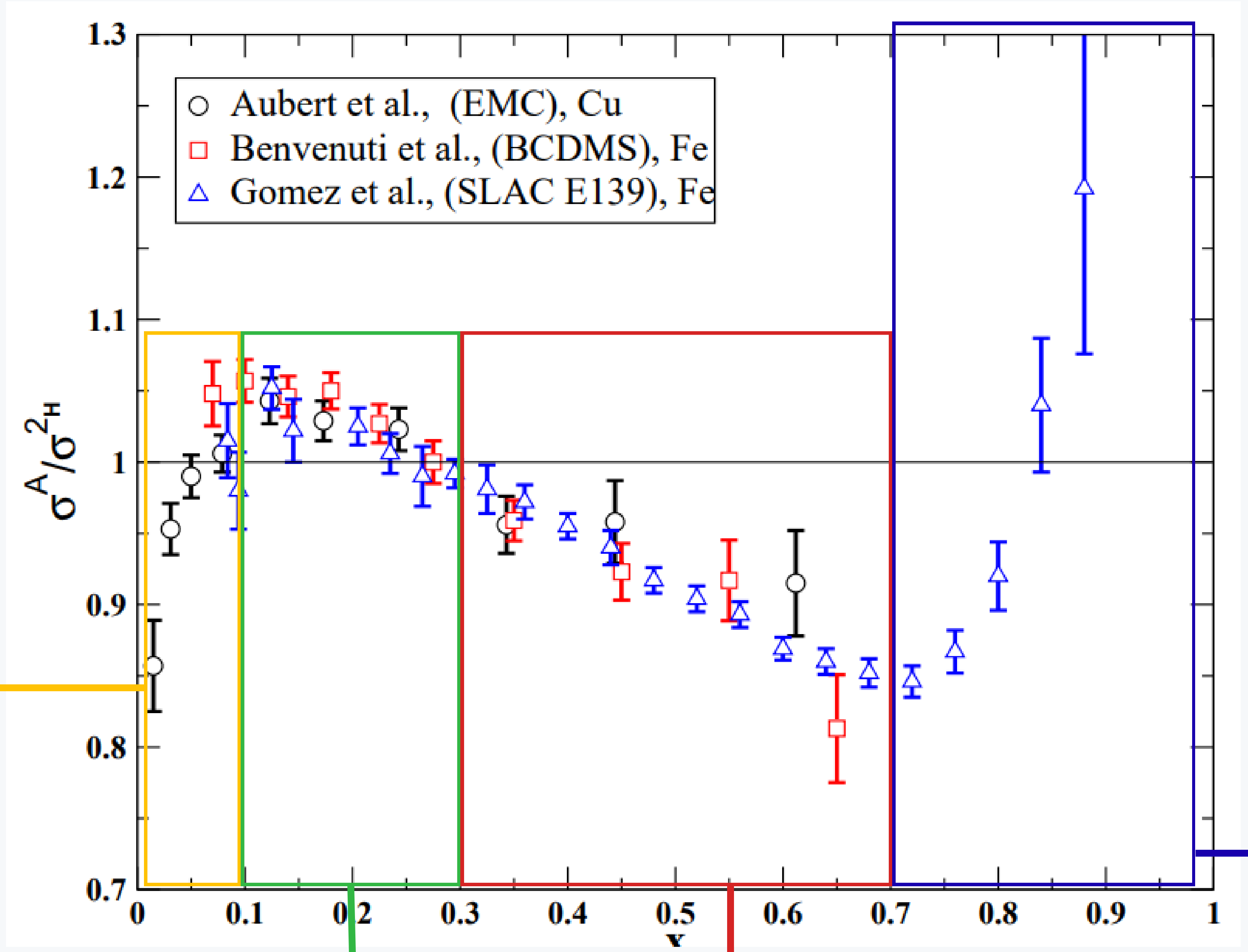
Variation in BSA with missing momentum may indicate a modification in nucleon structure. This could be linked to the EMC effect, which is associated with nucleon-nucleon correlations.

- Nature 566, 354–358 (2019).
- N.-N. Ma, T.-F. Wang, R. Wang, Phys. Rev. C 108, 065203 (2023).
- K.S. Egiyan et al., Phys. Rev. Lett. 96, 082501 (2006).
- W. Xing, X.-G. Wang, A.W. Thomas, Phys. Lett. B 846, 138195 (2023).

EMC Effect - The Discovery

$$F_2^A = ZF_2^p + (A-Z)F_2^n?$$

The binding E of nucleons in the nucleus are << Q² → such a ratio should be 1 except for small corrections for the Fermi motion of nucleons in the nucleus.



Contrary to expectations, **nucleons inside a nucleus behave differently from "free" nucleons.**

Shadowing (x≲0.1) → Coherent multi-nucleon effects

The virtual photon "sees" the nucleus as a collective object

Antishadowing (0.1≲x≲0.3) → mild enhancement above 1

EMC Effect (0.3≲x≲0.7)

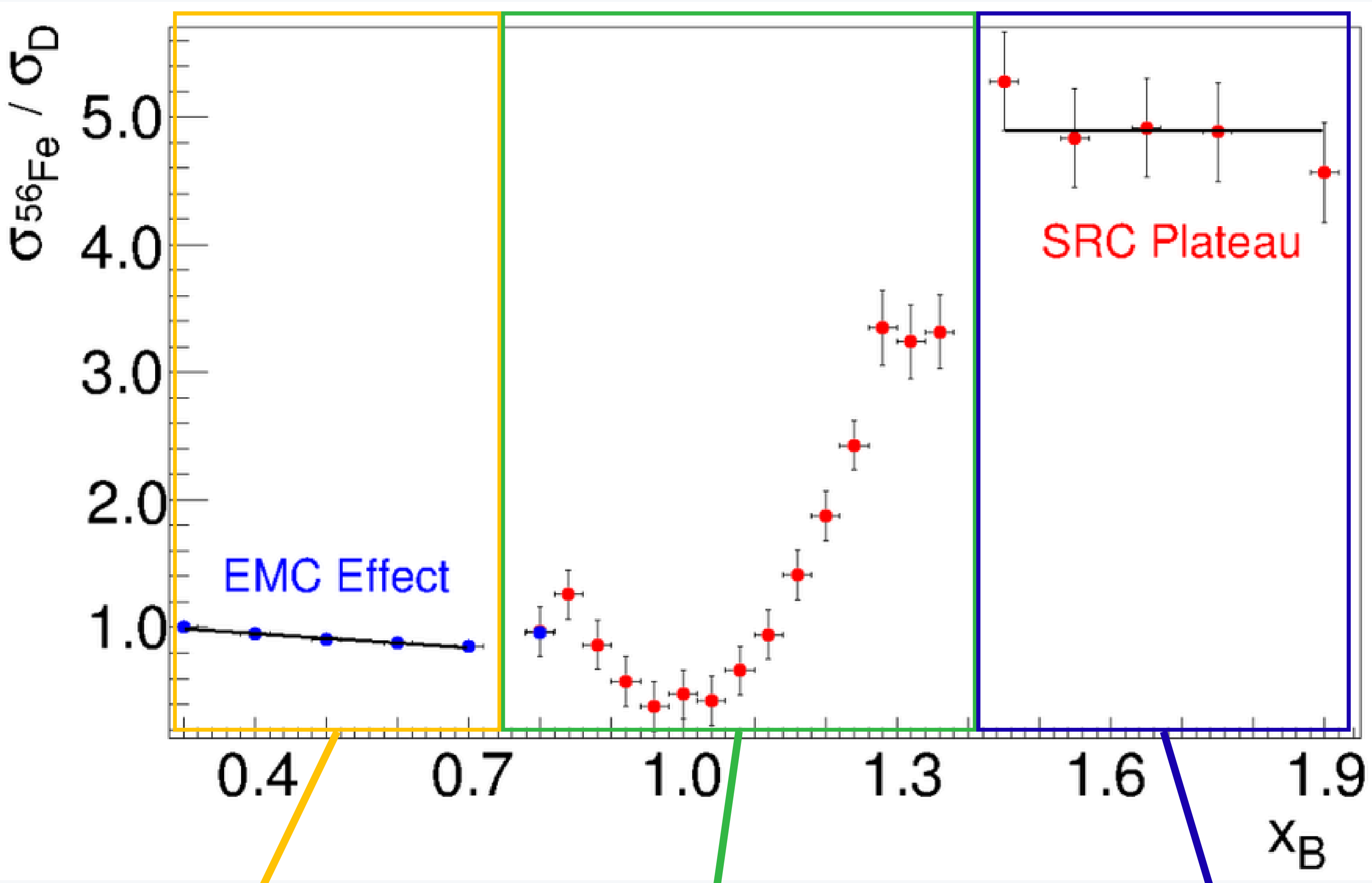
A significant depletion where quarks carry less momentum than expected.

Fermi Motion (x≳0.7) → Rise driven by nucleon momentum smearing and binding.

A sharp rise as the motion of nucleons within the nucleus takes over.

- J. Gomez et al., Phys. Rev. D 49, 4348 (1994).
- J. J. Aubert et al., Nucl. Phys. B 293, 740 (1987).
- A. C. Benvenuti et al., Phys. Lett. B 189, 483 (1987)

EMC Effect and SRC Nucleon-Nucleon Pairs

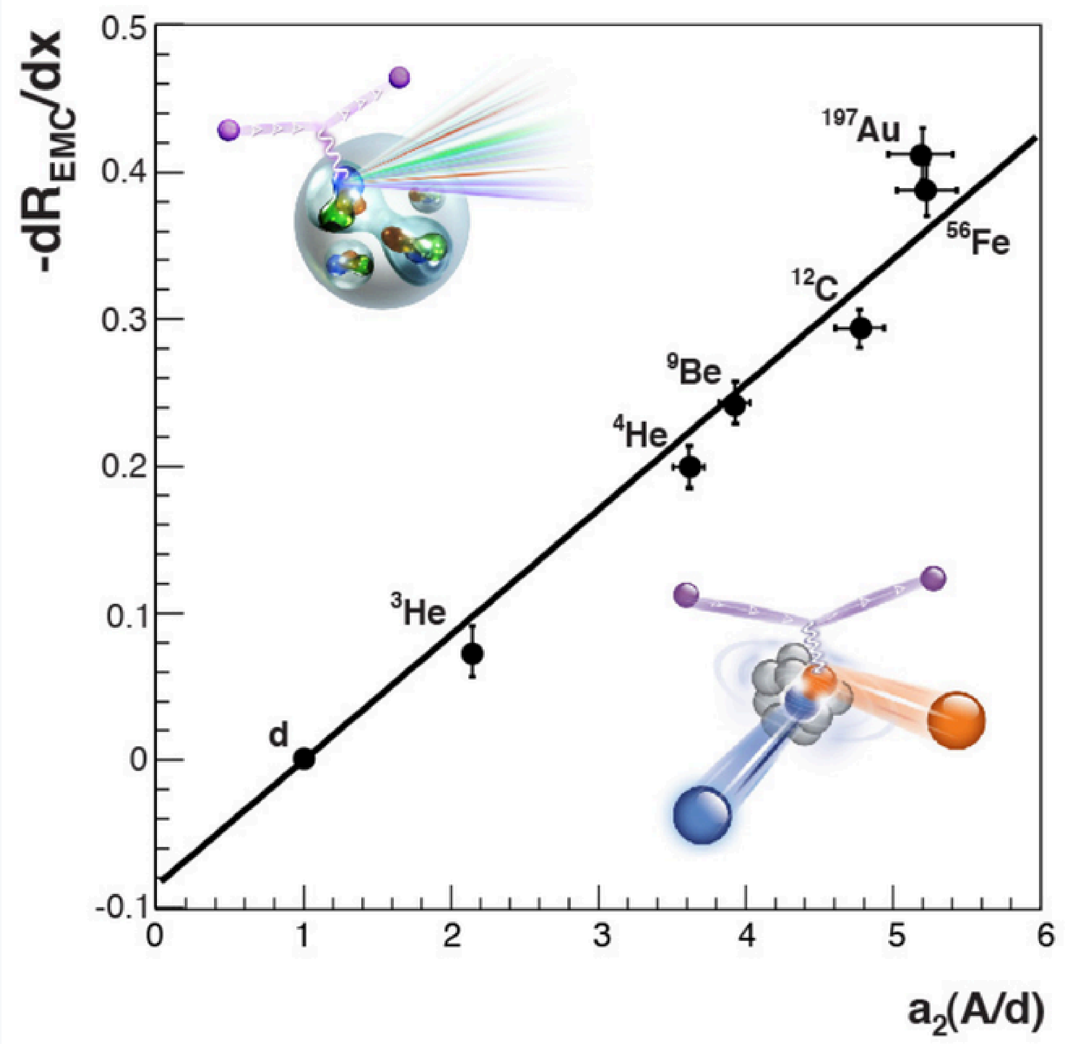


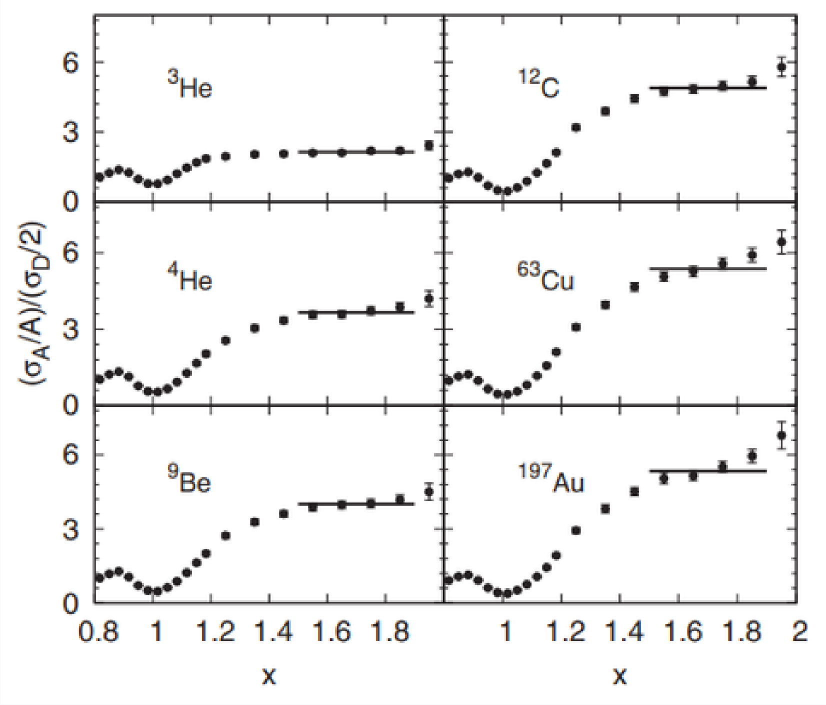
the EMC effect slope (Q^2 independent)

Dip at x = 1 fills in as Q^2 increases

Plateaus due to nucleon-nucleon SRC (Q^2 independent)

- Recent research[2, 3] links the EMC effect to SRC—pairs of nucleons.
- There is a striking **linear relationship between** the "slope" of the **EMC** effect and the number of **SRC pairs in a nucleus**.
- The modification of partons might only happen when nucleons are extremely close together, rather than being a "medium" effect felt by all nucleons equally.





1. D. Higinbotham, G. A. Miller, O. Hen, K. Rith, "The EMC effect still puzzles after 30 years" (CERN Courier 53N4, 2013) arXiv:1305.7143
2. Weinstein, L. B., et al. "Short range correlations and the EMC effect." Physical Review Letters 106.5 (2011): 052301.
3. Fomin, N., et al. "New measurements of high-momentum nucleons and short-range structures in nuclei." Physical review letters 108.9 (2012): 092502.

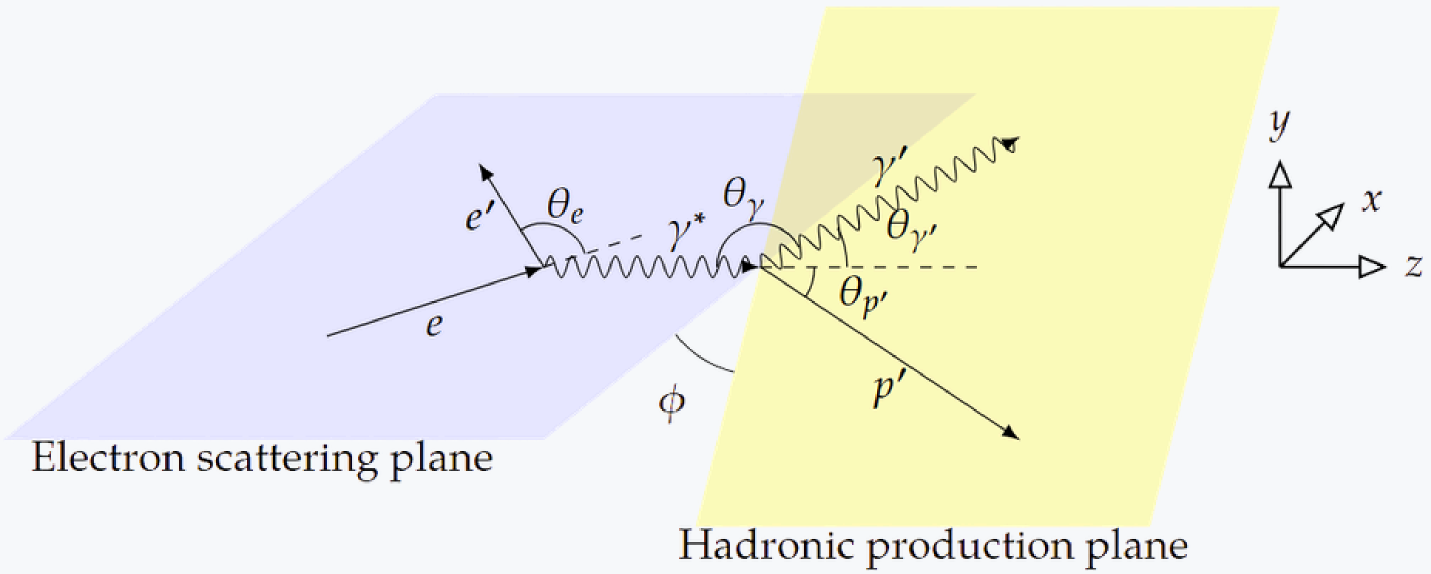
Data Selection

CLAS12 RGB dataset:

- CLAS12 collected data in three run periods:
  - Spring 2019 (inbending): $E_e = 10.6$ and 10.2 GeV
  - Fall 2019 (outbending): $E_e = 10.4$ GeV
  - Spring 2020 (inbending): $E_e = 10.4$ GeV

Beam & target configuration

- Polarized electron beam on an unpolarized fixed deuteron target



Kinematic Variables:

- W ⩾ 2 GeV
- $Q^2 \geqslant 1$ GeV^2
- γ′ ⩾ 2 GeV
- e′ ⩾ 1 GeV
- p′ ⩾ 0.2 GeV

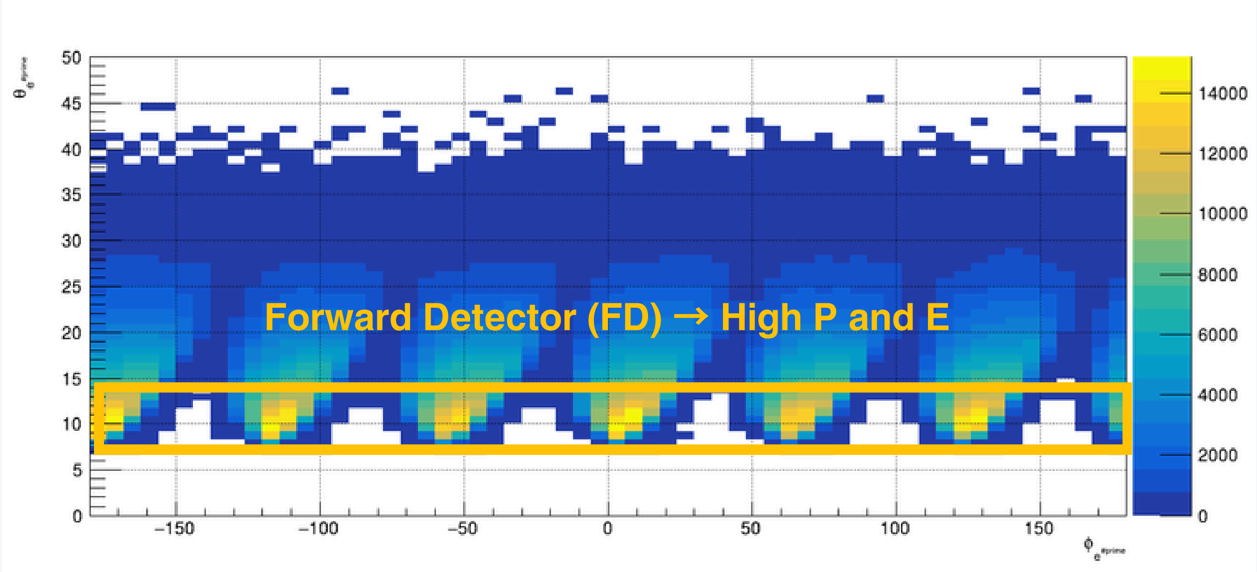
Exclusivity cuts:

- Missing Momentum
  - $P_{\text{miss}}(eD \to e'p'\gamma'(n)) = (E + p_{\text{deutron}} - e' - \gamma' - p')^2$
  - $P_{\text{miss}}(\text{Nuc})(ep \to e'p'\gamma') = (e + p - e' - \gamma' - p')^2$
- Missing Mass Squared
  - $MM_n^2(eD \to e'p'\gamma'(n)) = (e + p_{\text{deutron}} - e' - \gamma' - p')^2 \leq 3\sigma,$
  - $MM_X^2(ep \to e'p'\gamma') = (e + p - e' - \gamma' - p')^2 \leq 3\sigma,$
  - $MM_p^2(ep \to e'\gamma'(p')) = (e + p - e' - \gamma')^2 \leq 3\sigma,$
  - $MM_\gamma^2(ep \to e'p'(\gamma')) = (e + p - e' - p')^2 \leq 3\sigma$
- $|\Delta\phi| = |\measuredangle(\mathbf{n}_{\text{leptonic}}, \mathbf{n}_{\text{vhadro}}) - \measuredangle(\mathbf{n}_{\text{leptonic}}, \mathbf{n}_{\text{hadro}})| \leq 1.5^\circ$
  - $\mathbf{n}_{\text{leptonic}} = \mathbf{e} \times \mathbf{e}',\ \mathbf{n}_{\text{vhadro}} = \mathbf{p}' \times \gamma^*,\ \mathbf{n}_{\text{hadro}} = \mathbf{p}' \times \gamma'.$
- $|\Delta t| = |(p' - p)^2 - (e - e' - \gamma')^2| \leq 3\sigma,\ \theta_{\gamma x} = \arccos \frac{(e + p - e' - p') \cdot (\gamma')}{|(e + p - e' - p')||\gamma'|} < 3\sigma$
- Suppression of Bremsstrahlung radiation
  - $\theta_{\gamma e'} = \arccos\left(\frac{\gamma' \cdot \mathbf{e}'}{|\gamma'||\mathbf{e}'|}\right) > 6^\circ$

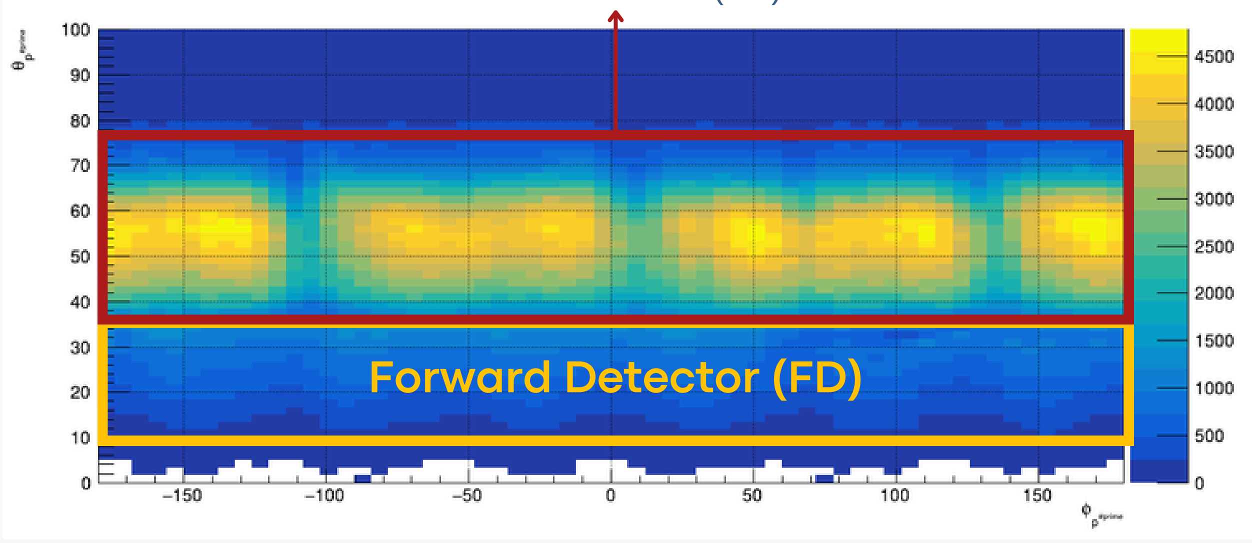
Data Selection - Exploration After Cuts - Work Ongoing

Exploration of momentum, θ, and ϕ of: Scattered electron, Recoil proton, and Produced photon.

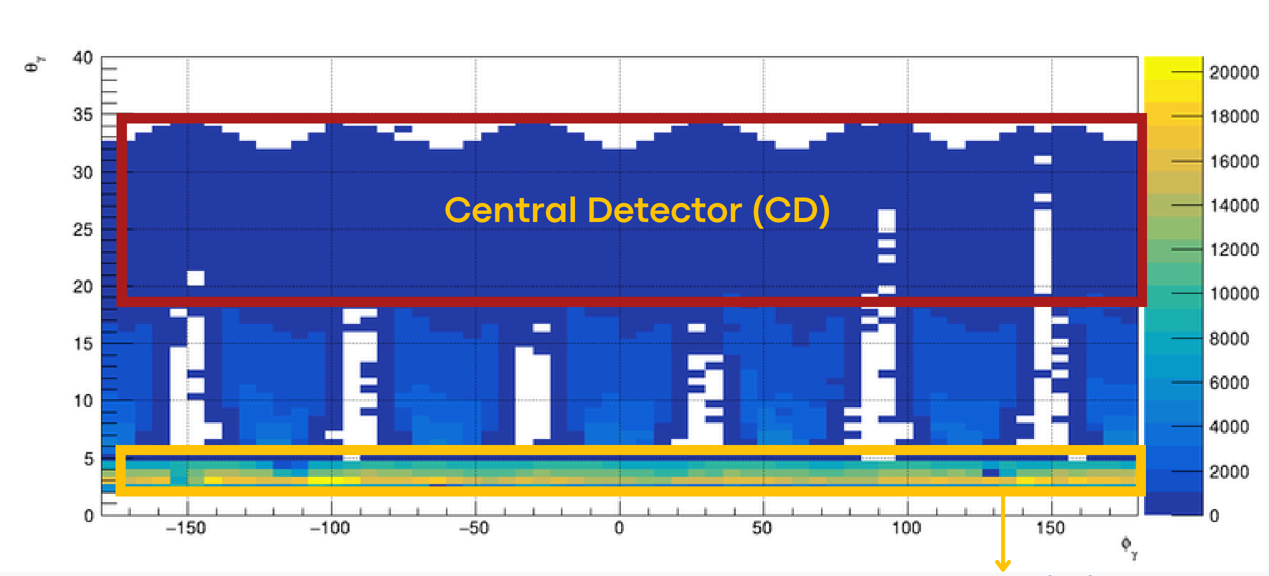
$\theta_{e'}$ vs. $\phi_{e'}$



$\theta_{p'}$ vs. $\phi_{p'}$

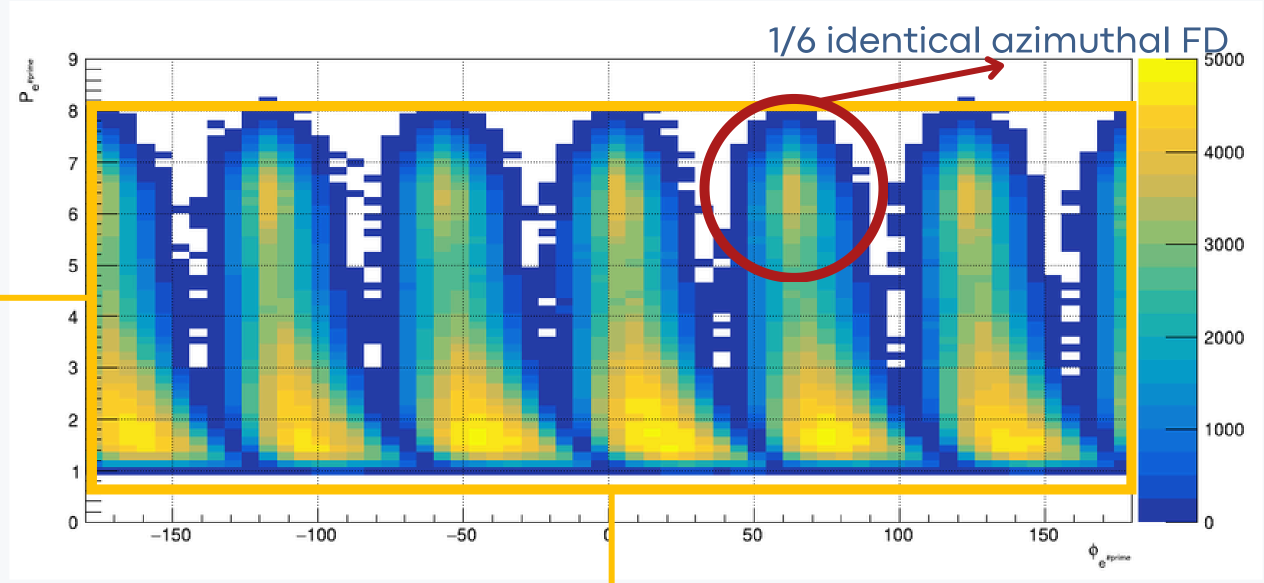


θ_{γ} vs. ϕ_{γ}



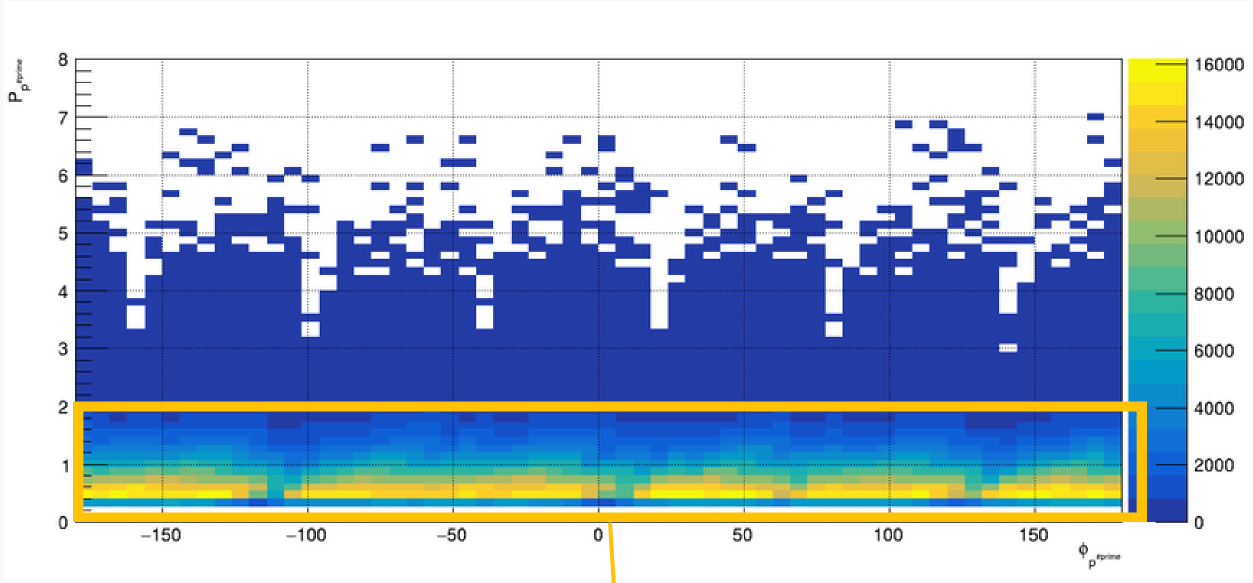
Forward Tagger (FT) → Bremsstrahlung

$P_{e'}$ vs. $\phi_{e'}$



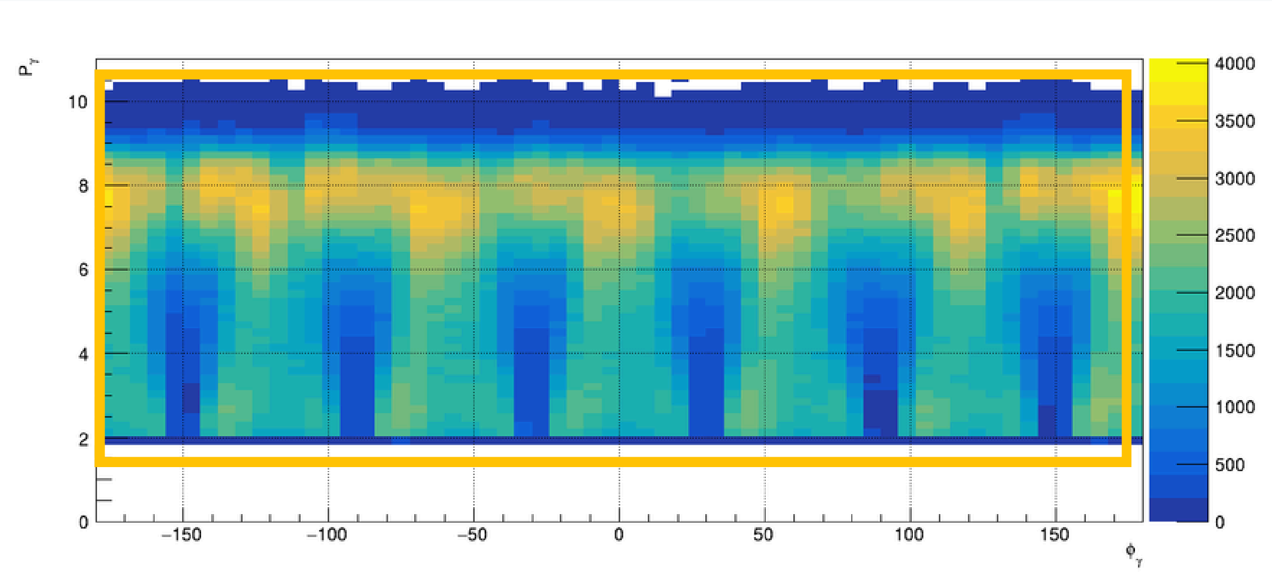
Consistent with expectations for forward-going electrons resulting from high-Q^2 interactions such as DVCS.

$P_{p'}$ vs. $\phi_{p'}$



the proton absorbs minimal momentum transfer and recoils slowly, as expected when it is the struck nucleon.

P_{γ} vs. ϕ_{γ}



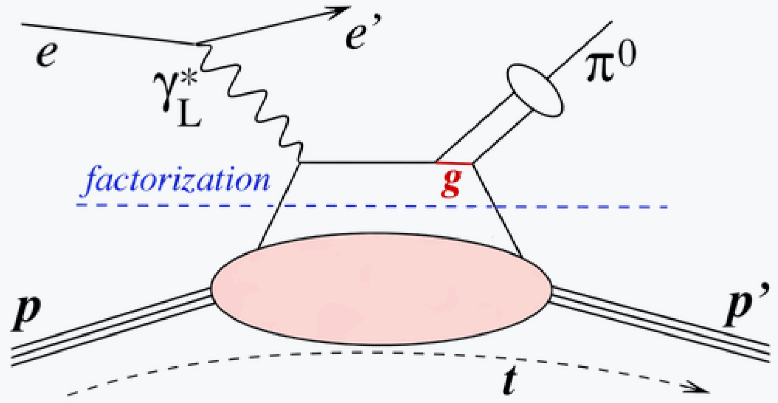
Kinematic Variables:

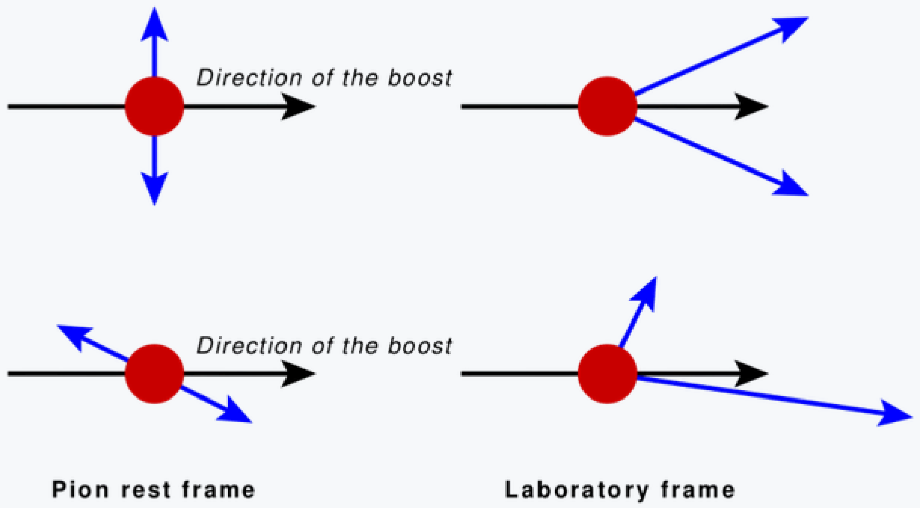
- γ′ ≥ 2 GeV
- e′ ≥ 1 GeV
- p′ ≥ 0.2 GeV

Data Selection - Work Ongoing

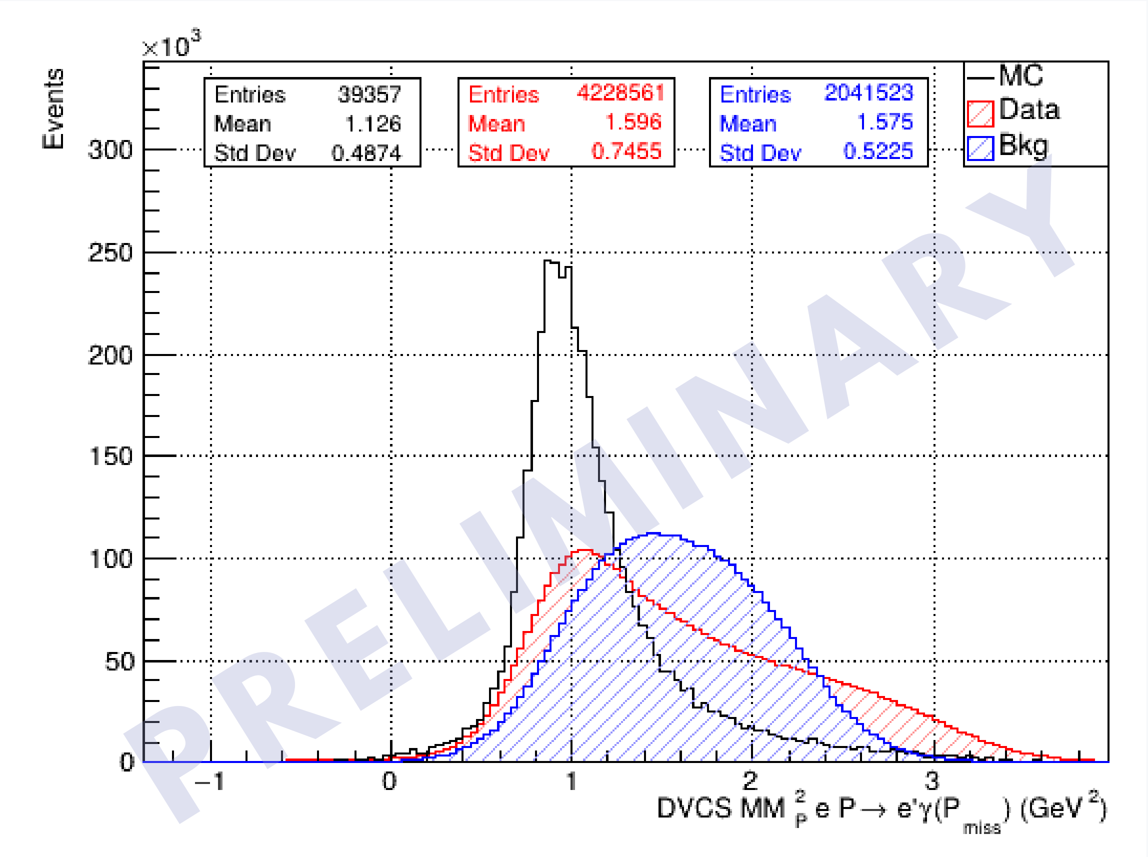
The main contamination channel is

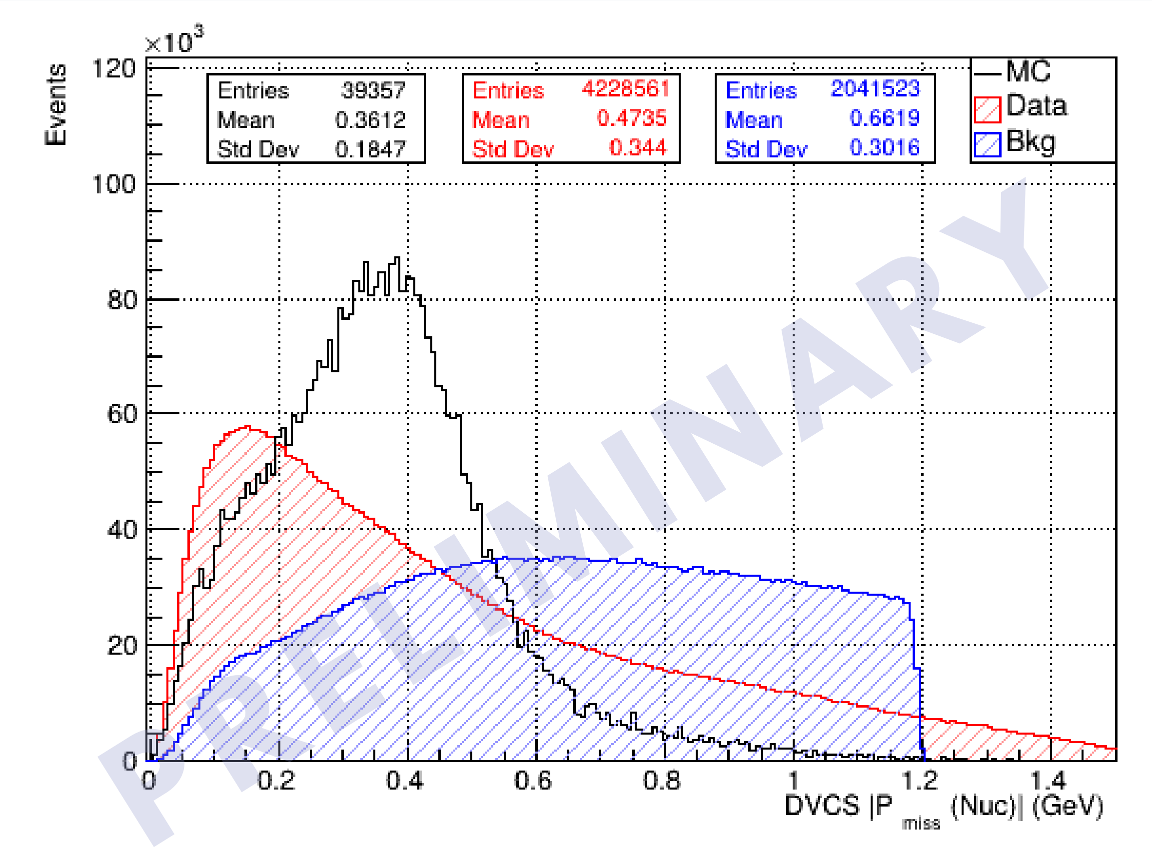
$$ep \rightarrow ep\pi^0 \rightarrow e'p'\gamma(\gamma)$$



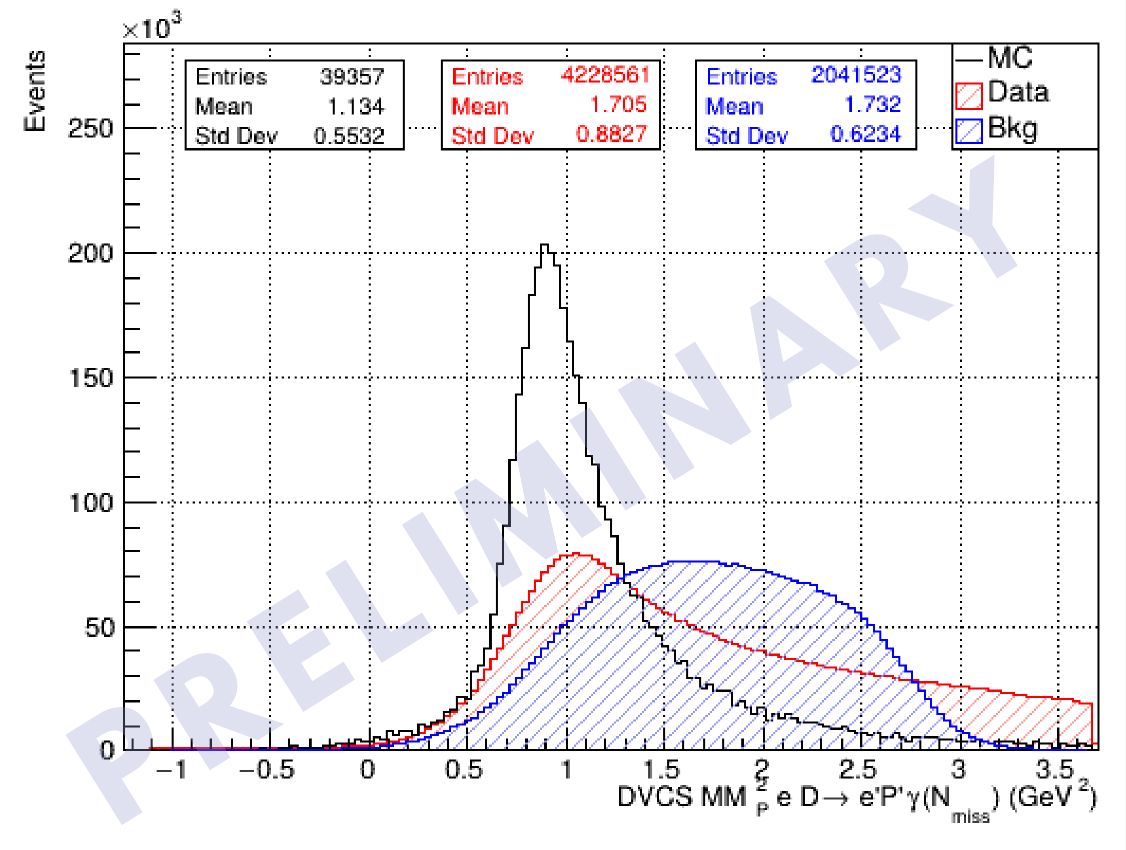


Missing proton mass distribution and missing momentum of proton $MM_{\mathrm{p}}^2 ep \rightarrow e'\gamma(p_{\mathrm{miss}})(\mathrm{GeV}^2)$





Missing neutron mass distribution $MM_{\mathrm{n}}^2 ep \rightarrow e'p'\gamma(n_{\mathrm{miss}})(\mathrm{GeV}^2)$

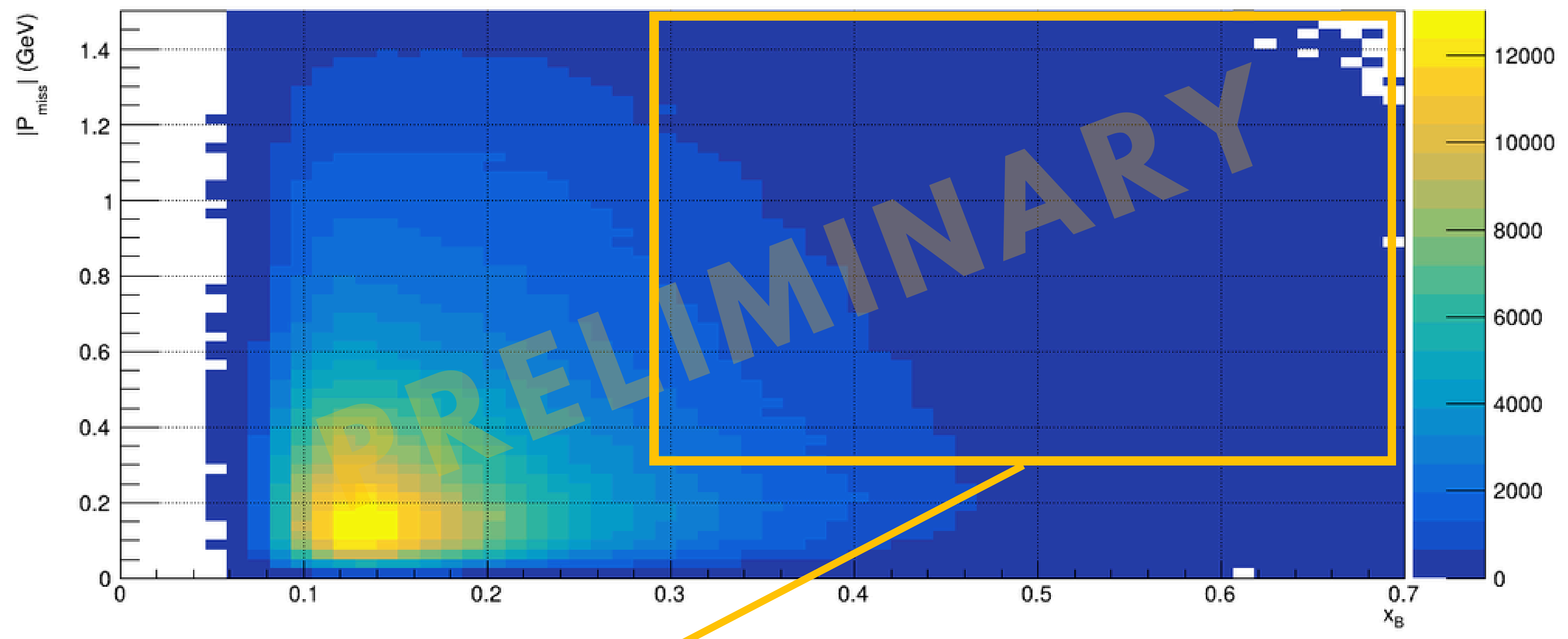


- There is background contamination that cannot be removed only using exclusivity cuts

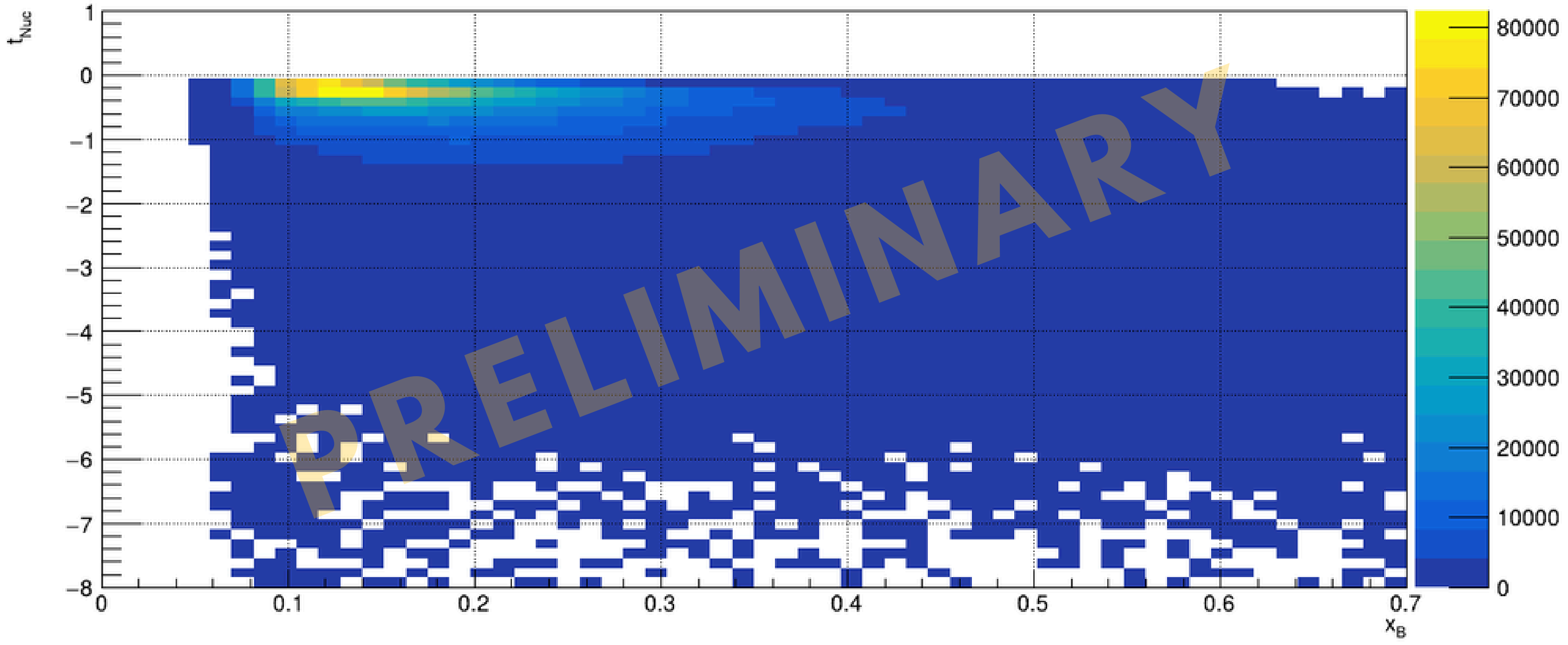
Data Selection - Exploration After Cuts - Work Ongoing

Exploration of the kinematic variables process:

$|P_{\text{miss}}|(\text{GeV})$ vs $x_B(eD \to e'p'\gamma(n_{\text{miss}}))$

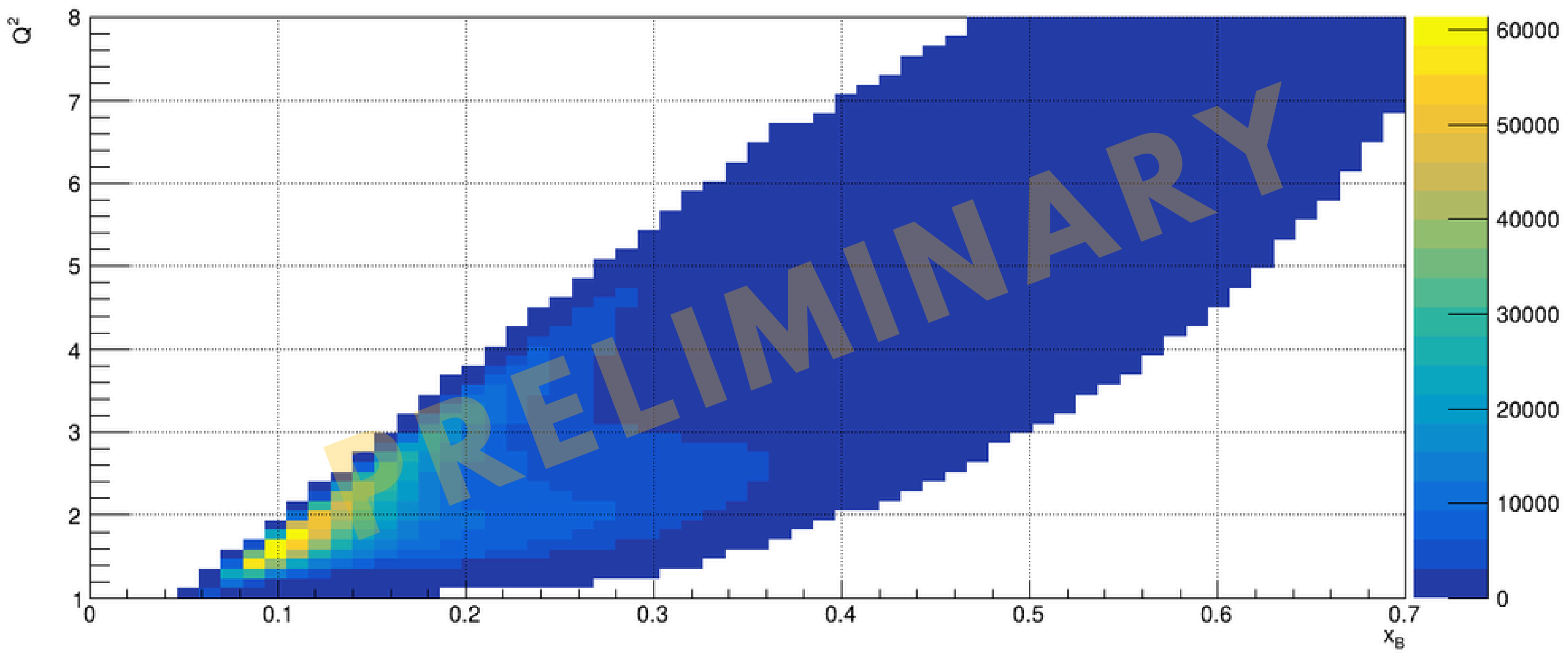


$t_{\text{nuc}}(\text{GeV}^2)$ vs. $x_B(t_{\text{nuc}} = MM_n^2 p \to p')$



EMC region + SRC region

Q^2 vs $x_B(ep \to e'p'\gamma)$



Data Selection - BDT - Work Ongoing

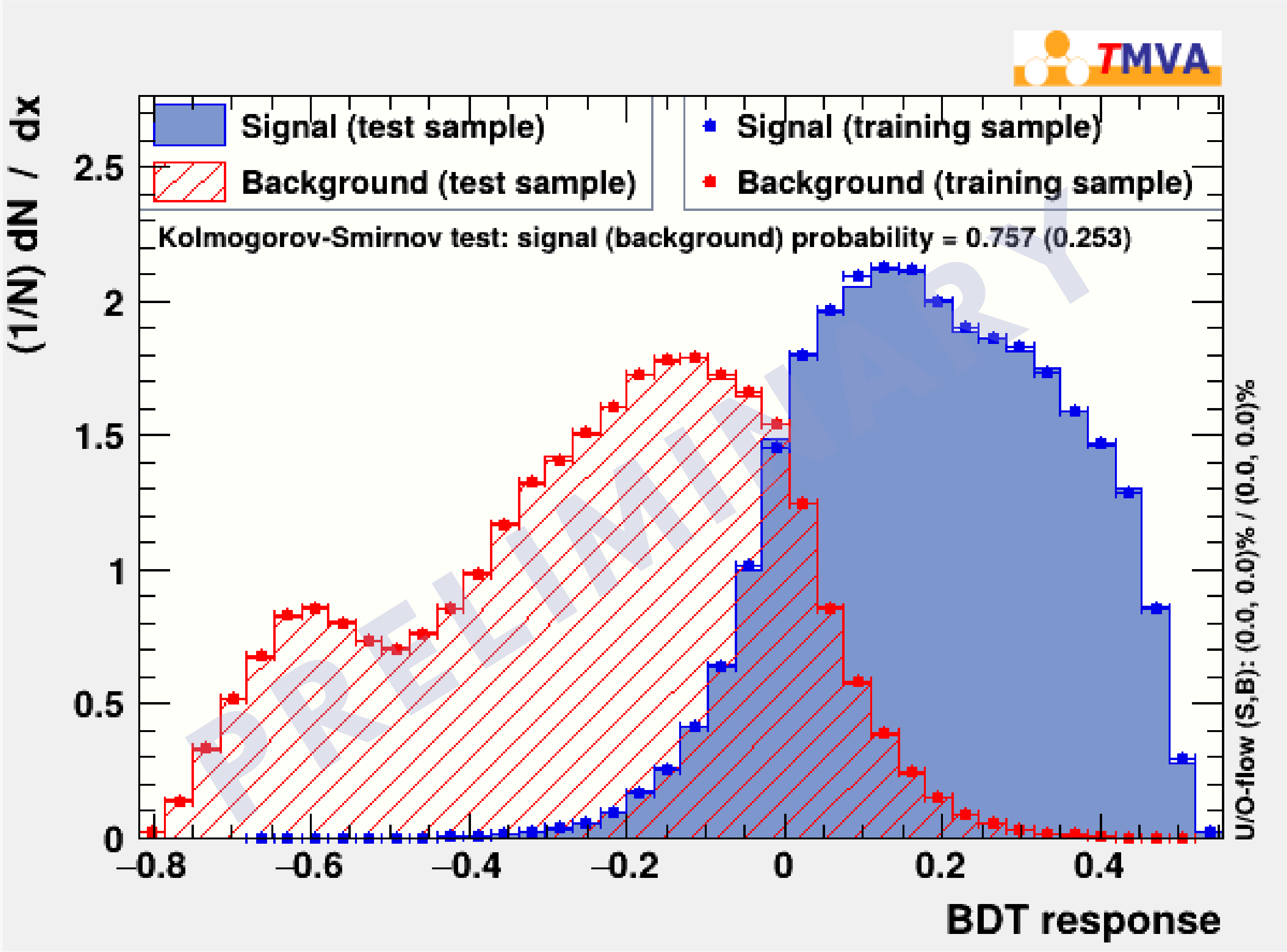
Instead of applying simple cuts on the exclusivity variables, we use a Boosted Decision Tree (BDT) to improve the event selection

The variables listed are used to train the BDT because they provide good separation between Deeply Virtual Compton Scattering (DVCS) and neutral pion production.

- Δt
- $\Delta\phi$
- Missing mass squared $MM_n^2(eD \to e'p'\gamma(n)) = (k + p_{\text{deutron}} - k' - q - p')^2$.
- Missing mass squared $MM_p^2(ep \to e'\gamma(p')) = (k + p - k' - q)^2$.
- Momentum magnitude of the outgoing particles:
  - Recoil proton.
  - Scattered electron.
  - Real photon.
- Angle

$$\theta_{\gamma x} = \arccos \frac{(e + p - e' - p') \cdot (\gamma')}{|(e + p - e' - p')||\gamma'|}$$

After the BDT classification, the remaining background is removed using well-established methods.



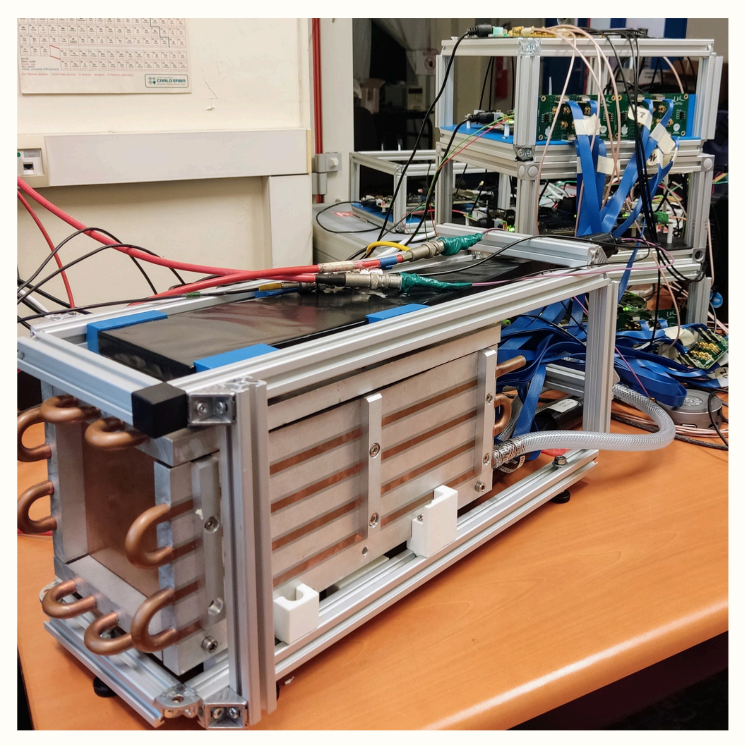
- Signal (DVCS): clusters at positive response values.
- Background (π^0): peaks at negative values.
- Overlap near 0: ambiguous events due to kinematic similarity.
- Training vs. test: good agreement (KS probs: 0.76 signal, 0.25 background) → no overtraining.
- Result: input variables capture correlations well → strong signal–background separation.

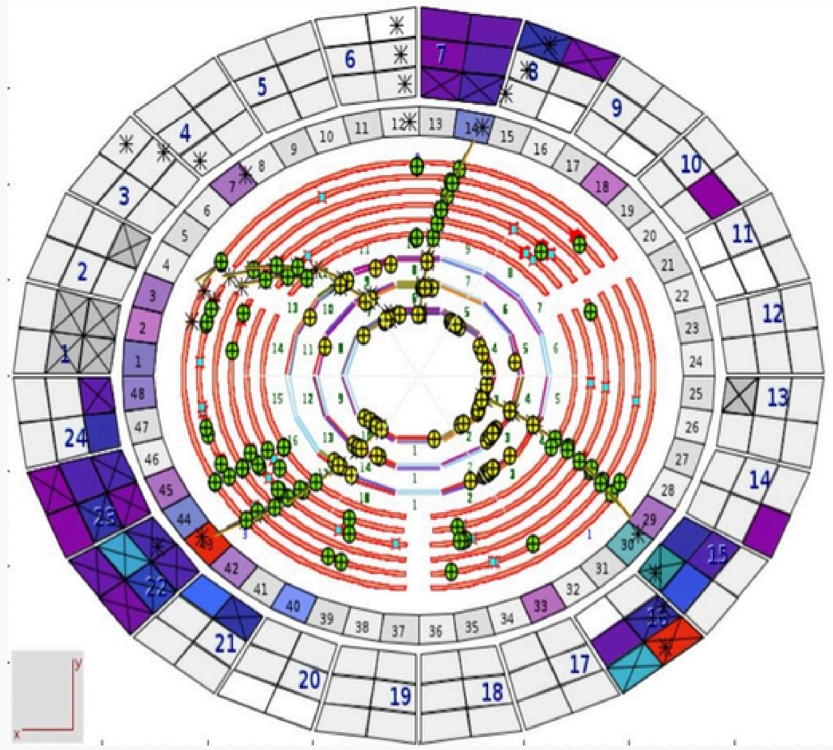
Prospective

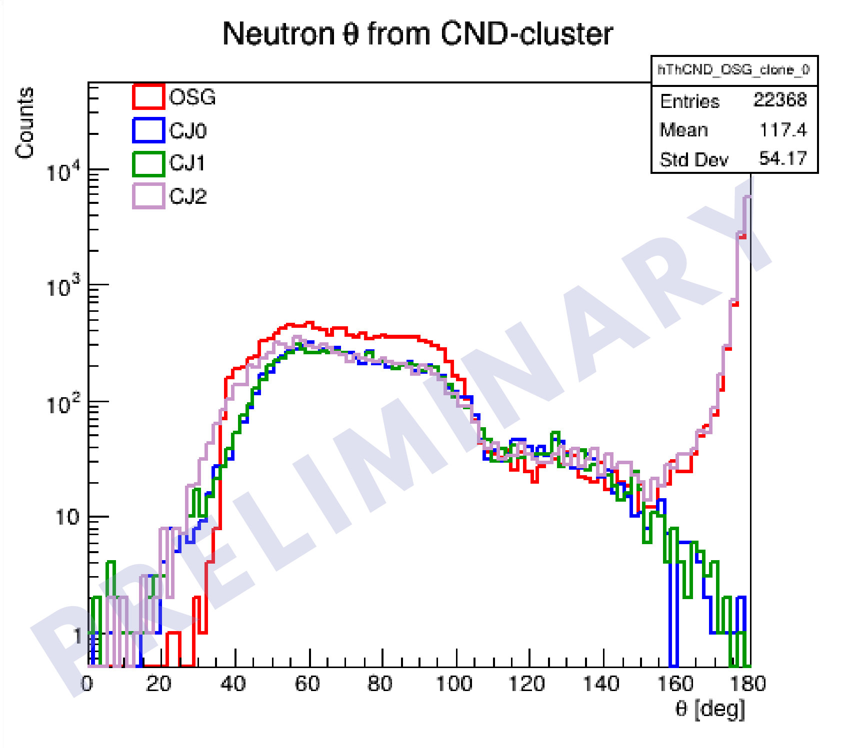
- With RGB deuterium data, we are studying DVCS off-bound protons to investigate how nucleon structure may be modified inside SRC proton–neutron pairs.
- The analysis code is already developed, and current efforts focus on background subtraction, with future extensions to heavier nuclei using ALERT data.

- **Service work:** I collaborate in optimising the Central Neutron Detector reconstruction for Pass 3 cooking

- Half of my PhD thesis is dedicated to studying and characterizing the readout chain based on HGCROC of a 25-crystal EEEMCal prototype for ePIC.

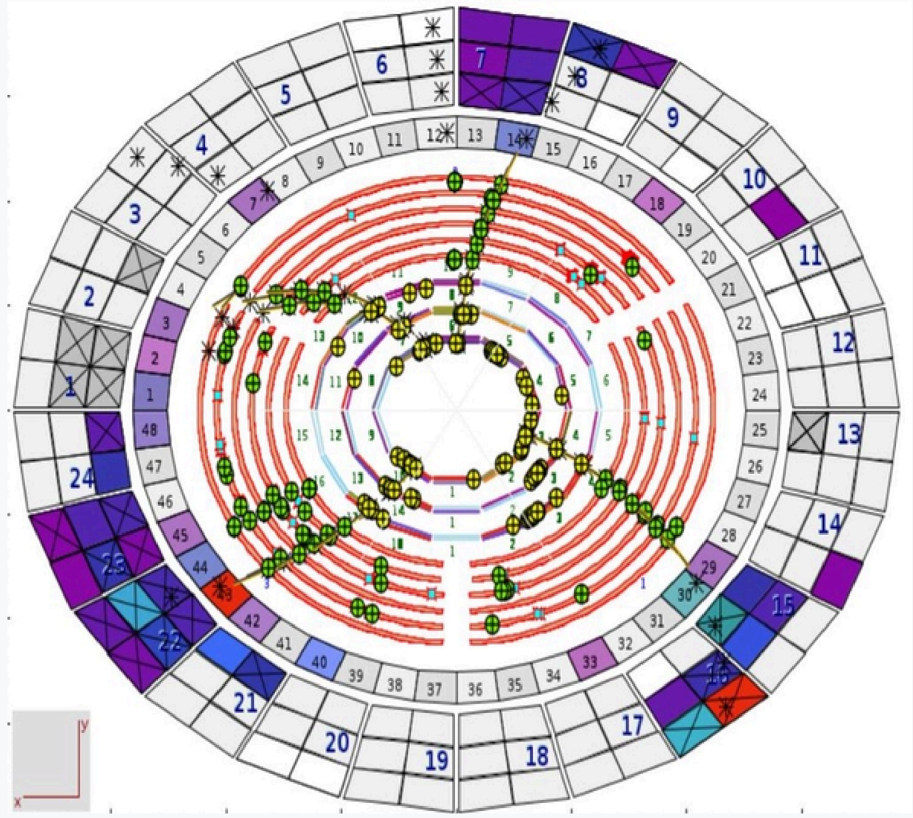






Thank you

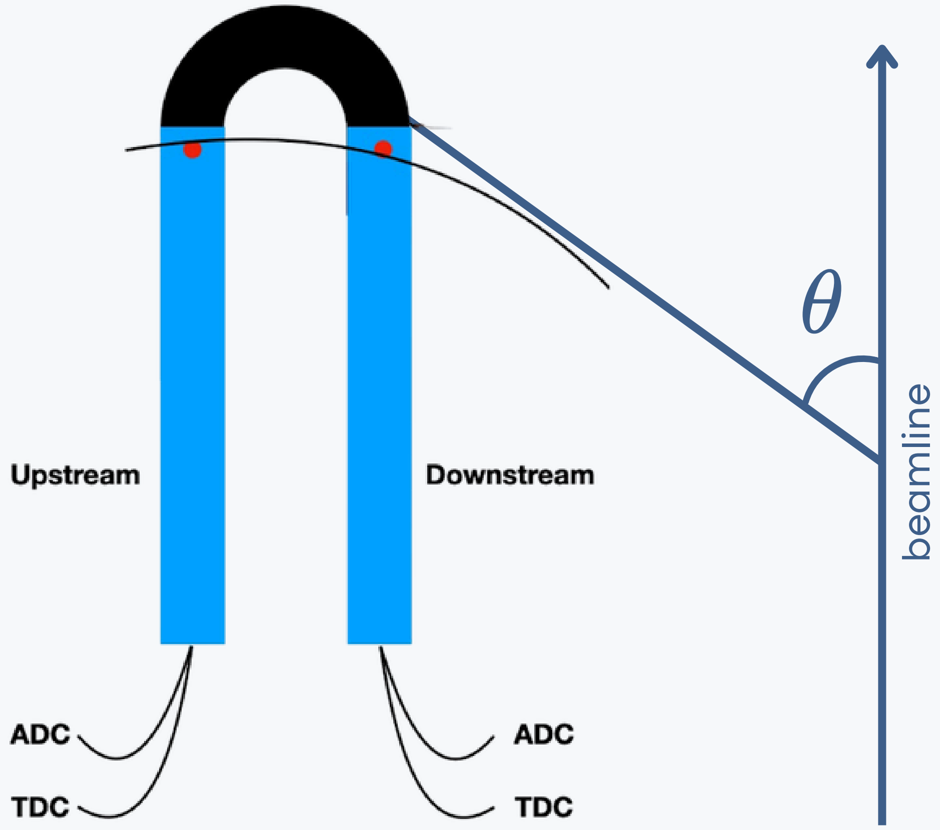
Service Task - CLAS12 Central Neutron Detector (CND)



- The Central Neutral Detector (CND) is the outermost sub-detector of the CLAS12 Central Detector
- 3 Radial layers of 48 plastic scintillator counters
- It is a single-sided readout detector
- Two adjacent paddles are optically coupled by a light guide at their upstream ends

Service task:

- Look over the CND reconstruction algorithm and verify whether, in reconstruction mode, after modifying the time-matching between left and right paddles for clusters, it rejects unphysical events without losing statistics and removes events mislocated in large θ



$$Z_{av} \in [-\frac{2}{L} - \Delta Z, +\frac{2}{L} + \Delta Z]$$

- z_av = reconstructed local hit position along the paddle
- L = paddle length
- ΔZ=Zres (position tolerance)

Purpose:

- Ensures the reconstructed hit lies within the physical paddle length

$$T_{\text{hit}} \approx \frac{t_{\text{up}} + t_{\text{down}} - t_{\text{prop}}}{2}$$

$$T_{\text{hit}} \in [\text{Min time}, \text{Max time}]$$

- T_hit = reconstructed hit time from L/R signals
- Window defined per layer

Purpose:

- Removes out-of-time hits
- Ensures physically consistent event timing

Timing χ^2 for HalfHit Matching (CND HitFinder)

Modification:

- Compute χ^2 for every candidate (d,n) half-hit pair
- Store in the hit object
- Keep the candidate with the smallest χ^2 (best timing consistency), thus resolving ambiguities by ranking.

$$\chi^2_{\text{match}} = \left(\frac{T_{\text{down}} - T^{\text{expected}}_{\text{down}}}{T_{\text{resolution}}} \right)$$

OSG: Original.

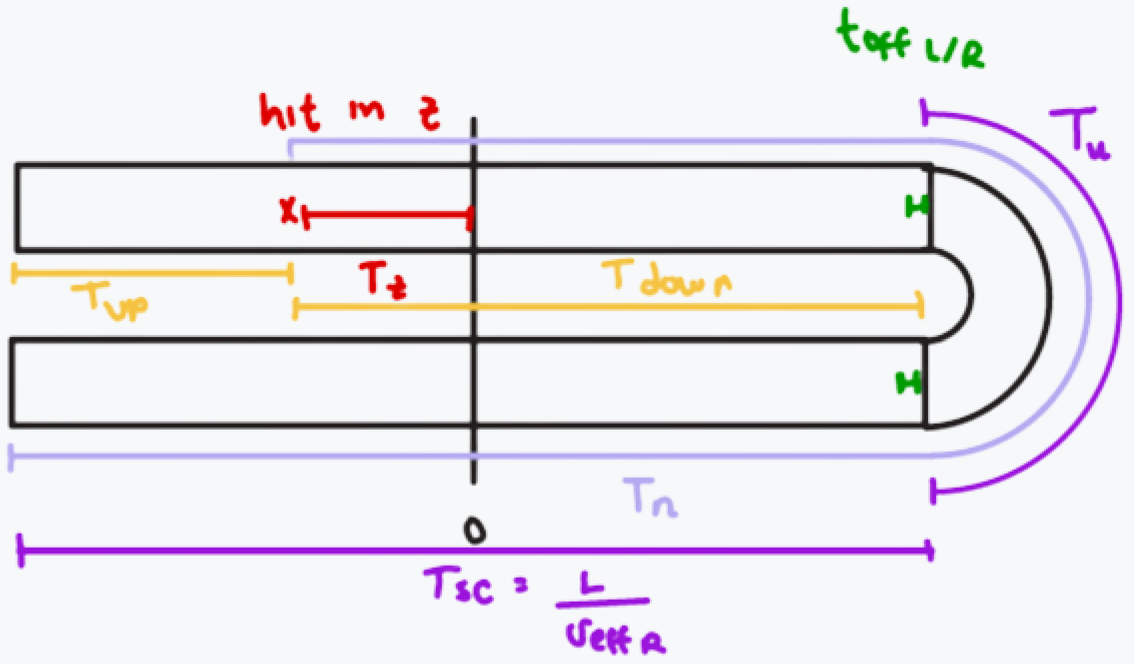
CJO: Cuts

CJ1: Cuts + modification

CJ2: No cuts + modification

Left - Direct

Right- Neighbor

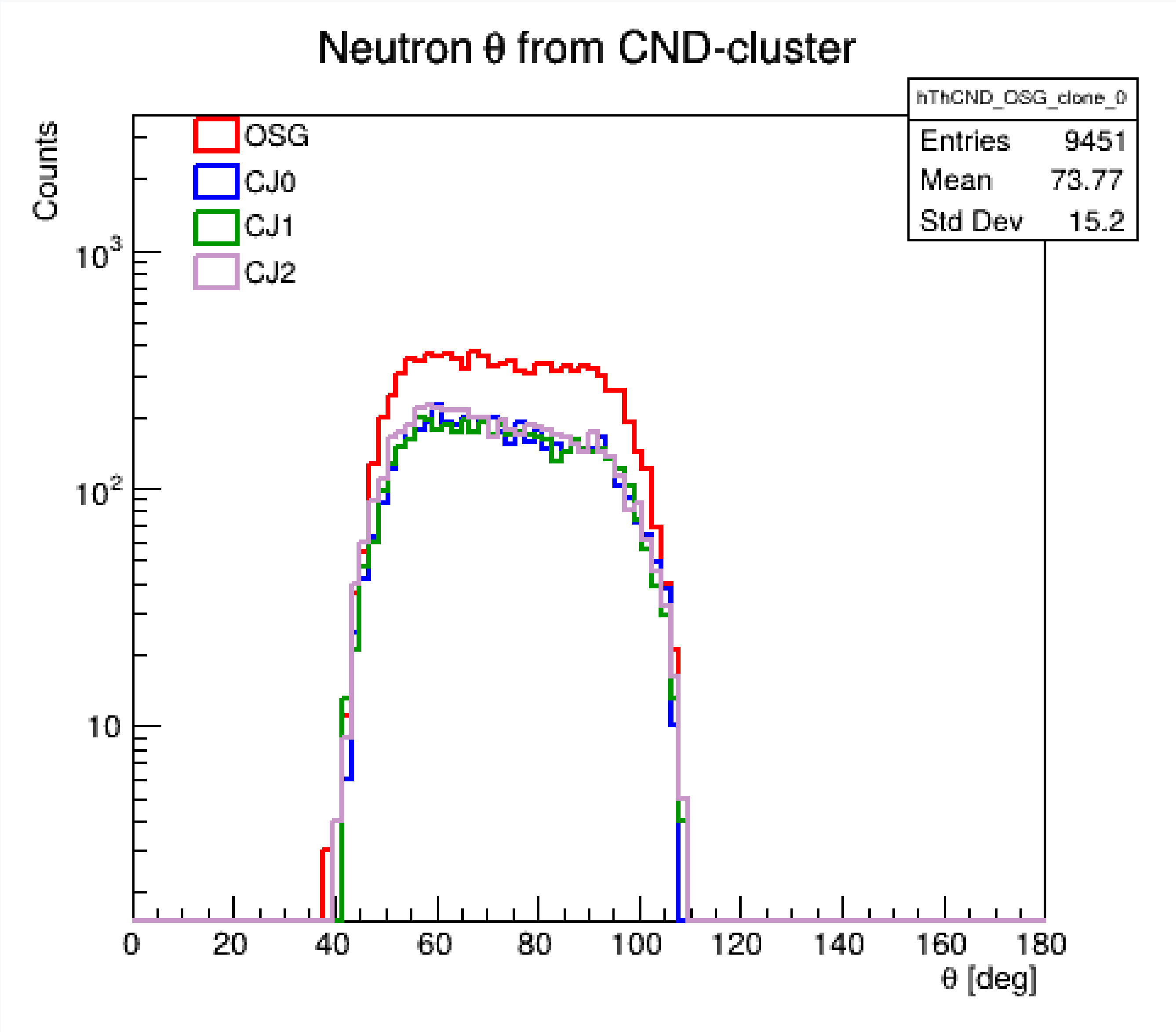


$$T_{\text{up}} = T_{\text{prop}}(d)$$

$$T_{\text{down}} = T_{\text{prop}}(n) - \frac{L}{v_{\text{eff,n}}} - \text{U-turn}_{\text{loss}}$$

$$T^{\text{expected}}_{\text{down}} = \frac{L}{v_{\text{eff,n}}} + \text{U-turn}_{\text{loss}} + \frac{L}{v_{\text{eff,n}}} - T_{\text{up}}$$

$$\Delta T = T_{\text{down(measured)}} - T^{\text{expected}}_{\text{down}}$$



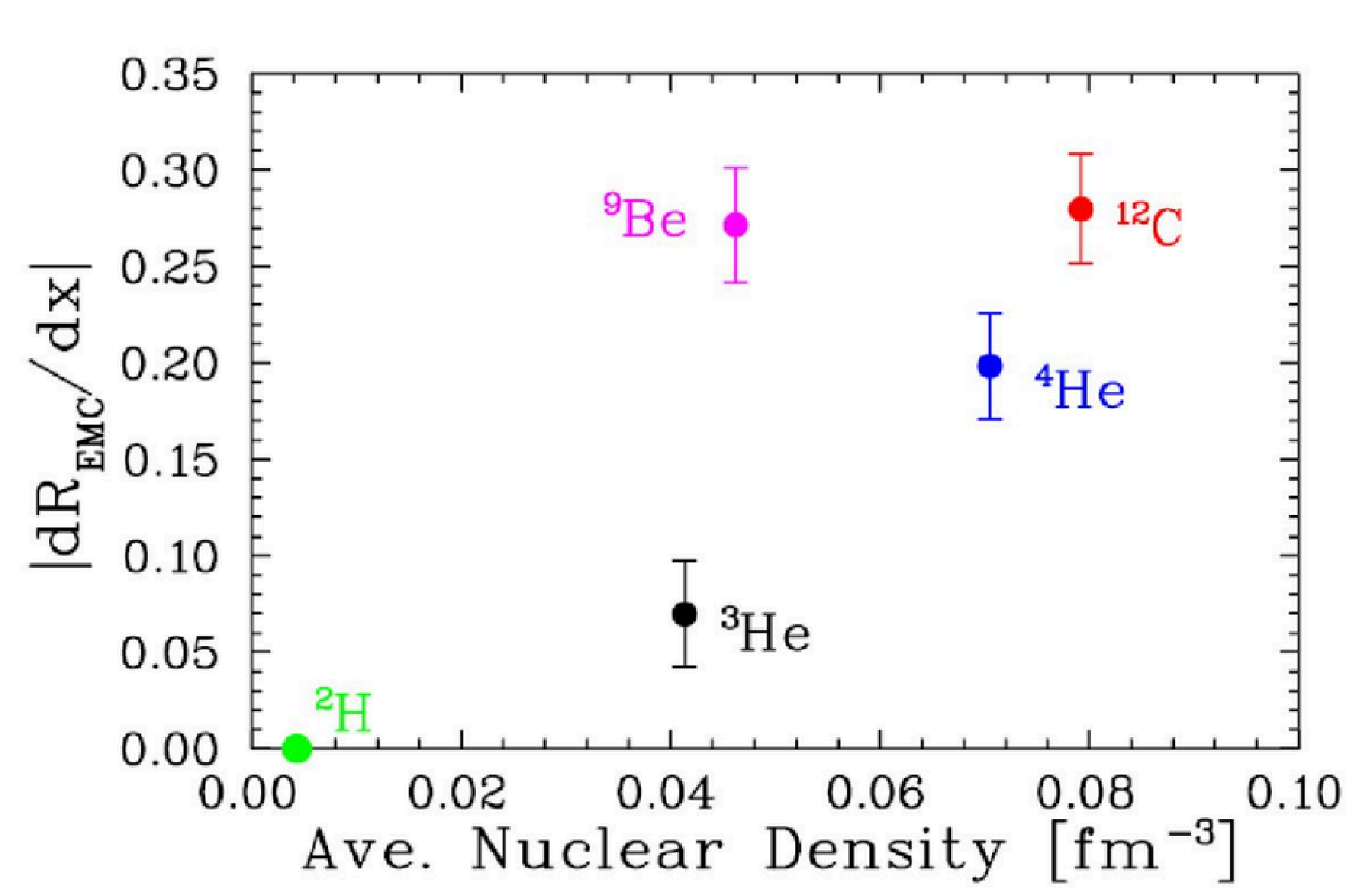
- We are losing statistics.
- We should find why

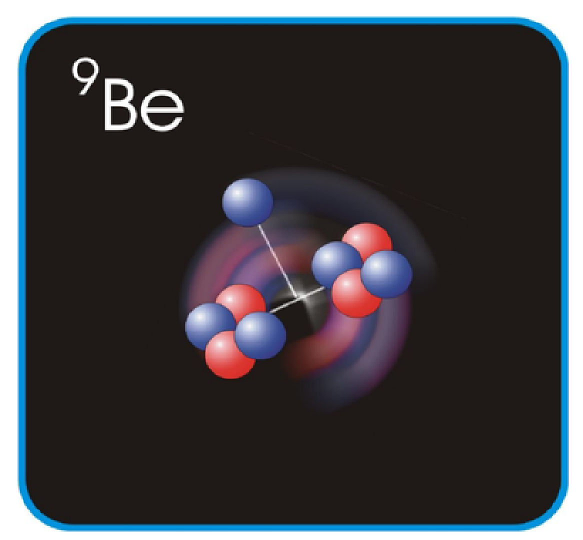
EMC Effect and Nucleus Density

The effect was thought to scale with the average density of the nucleus (getting stronger as A increases).

The New Evidence (JLab) showed that even though Beryllium-9 has low average density, it has a high local density (clusters of nucleons), and its EMC effect was surprisingly large.

$_9$Be seemed to act like two alpha particles with a single nearly free neutron, rather than like a collection of nucleons whose properties were all modified.





- J. Seely et al., "New measurements of the EMC effect in very light nuclei", Physical Review Letters 103, 202301 (2009).