RG-M Analysis Update

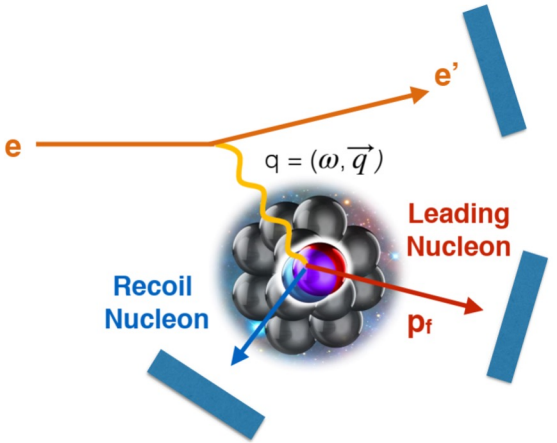
Andrew Denniston (MIT)

Overview

- Run Group M Introduction
- Low Level Analysis
- Physics Analyses
  - Short Range Correlations (SRCs)
  - Electrons for Neutrinos (e4v)

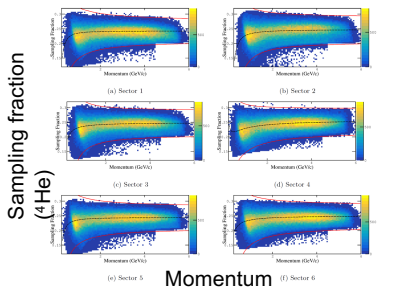
RG-M Experiment at CLAS12

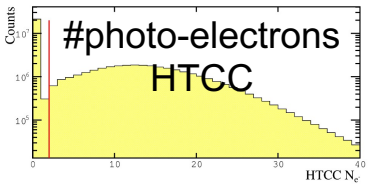
- November 2021 – February 2022
- Fully cooked production runs
- 2, 4, and 6 Gev Beam Energies
- H, D, He, C, 40Ca, 48Ca, Ar, and Sn



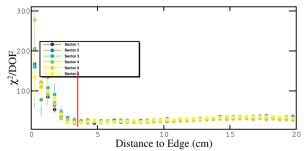
Particle ID for Electrons in 6 GeV data

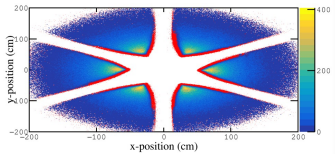
(charge, HTCC photo-electrons, ΔE(PCal), Sampling fraction)



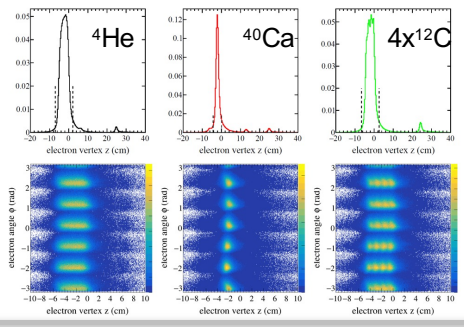


Fiducial Cuts

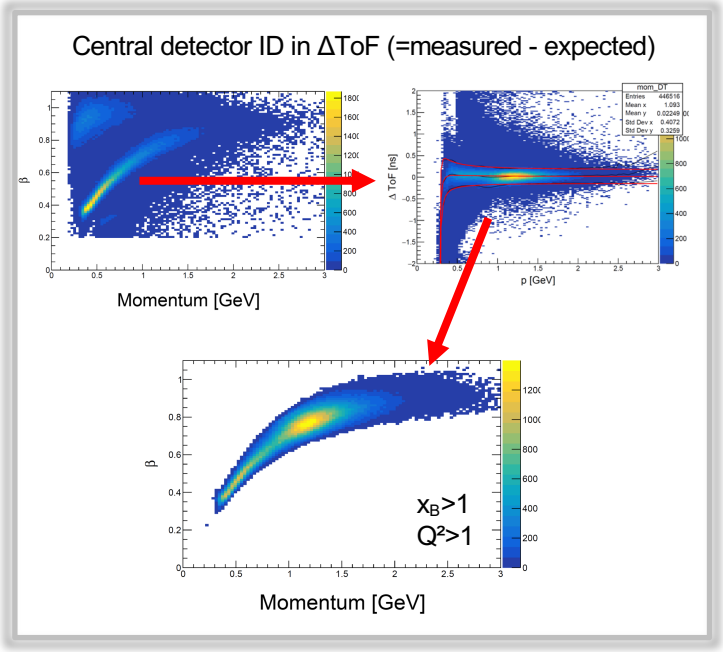


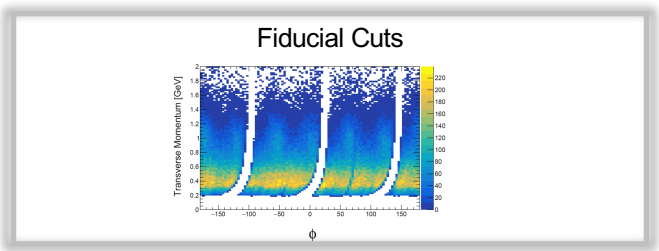


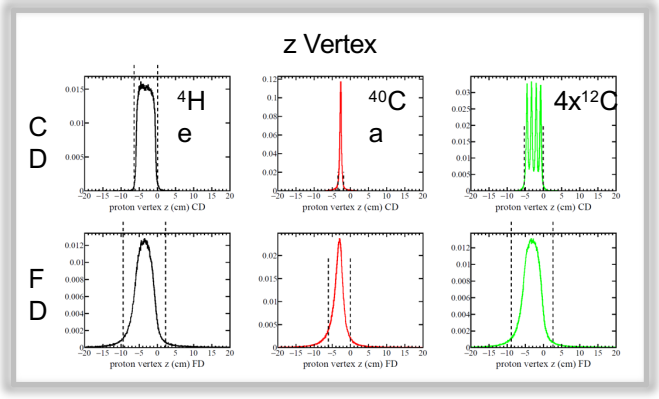
z Vertex



Particle ID for Protons in 6 GeV data







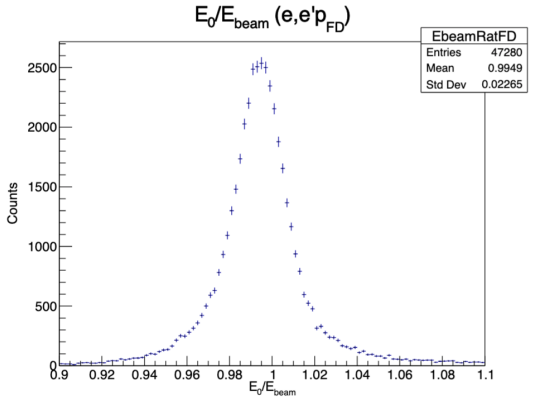
Additional on Detector Level Analysis

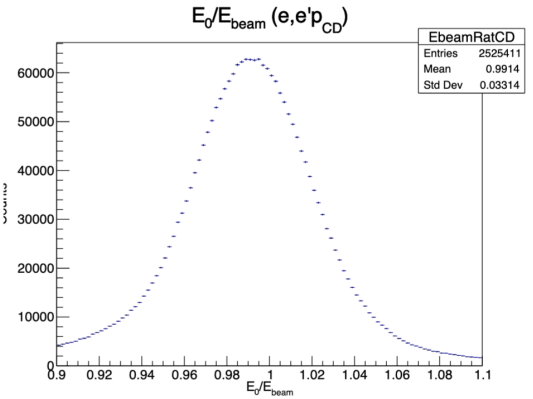
- Energy Loss Corrections
- Angular Corrections
- Momentum Corrections
- Momentum Smearing Simulation
- Vertex Resolution

Use Elastic Scattering Angles to Calculate Beam Energy

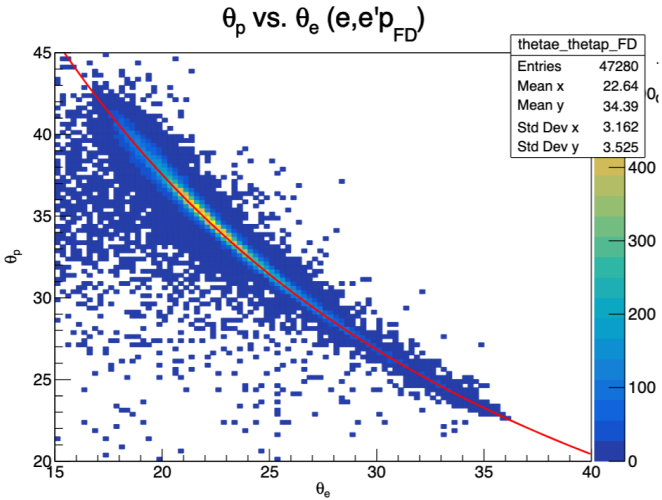
- $0.7\ GeV < W < 1.1 GeV$
- $-3° < \Delta\phi_{ep} < 3°$
- Separate events with a proton in the FD and CD

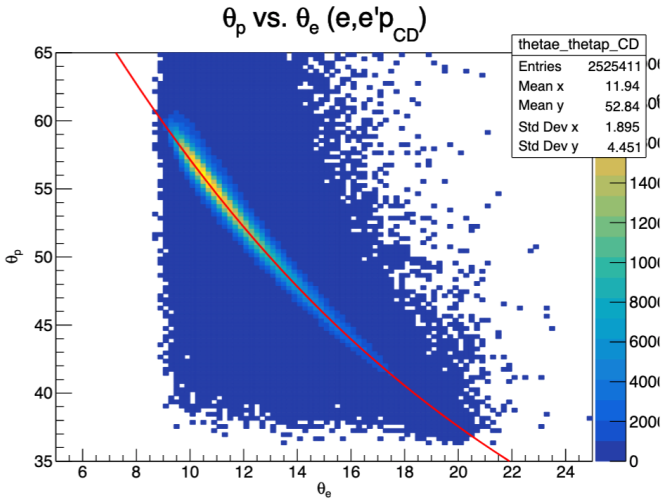
$$E_0 = m_N\left(\cot(\theta_e/2)\cot\left(\theta_p\right) - 1\right)$$





We use Elastic Kinematics to Correct the Electron and Proton at the same time





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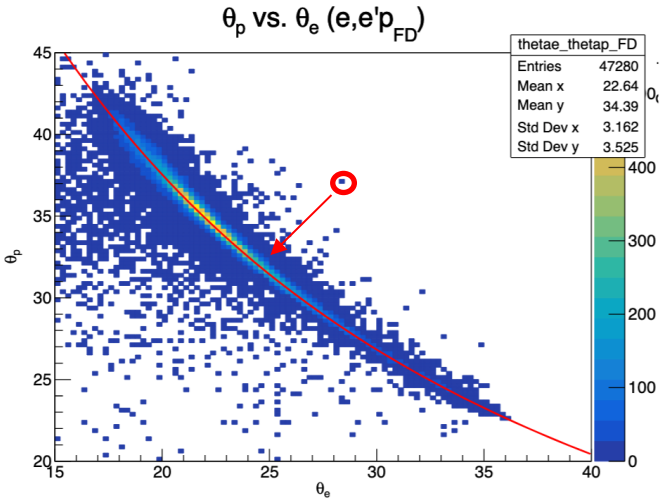

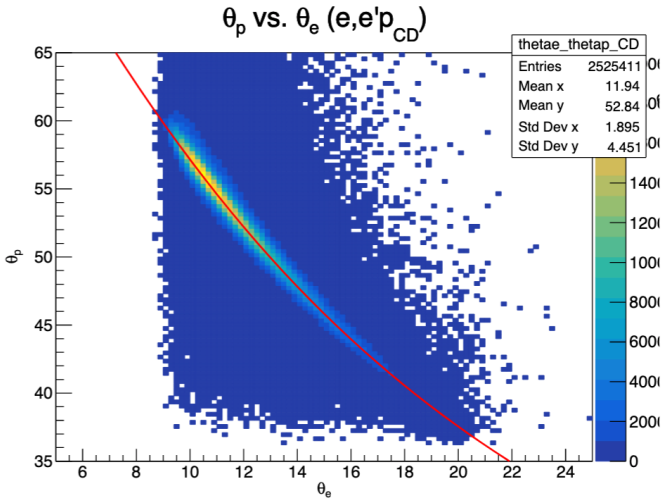

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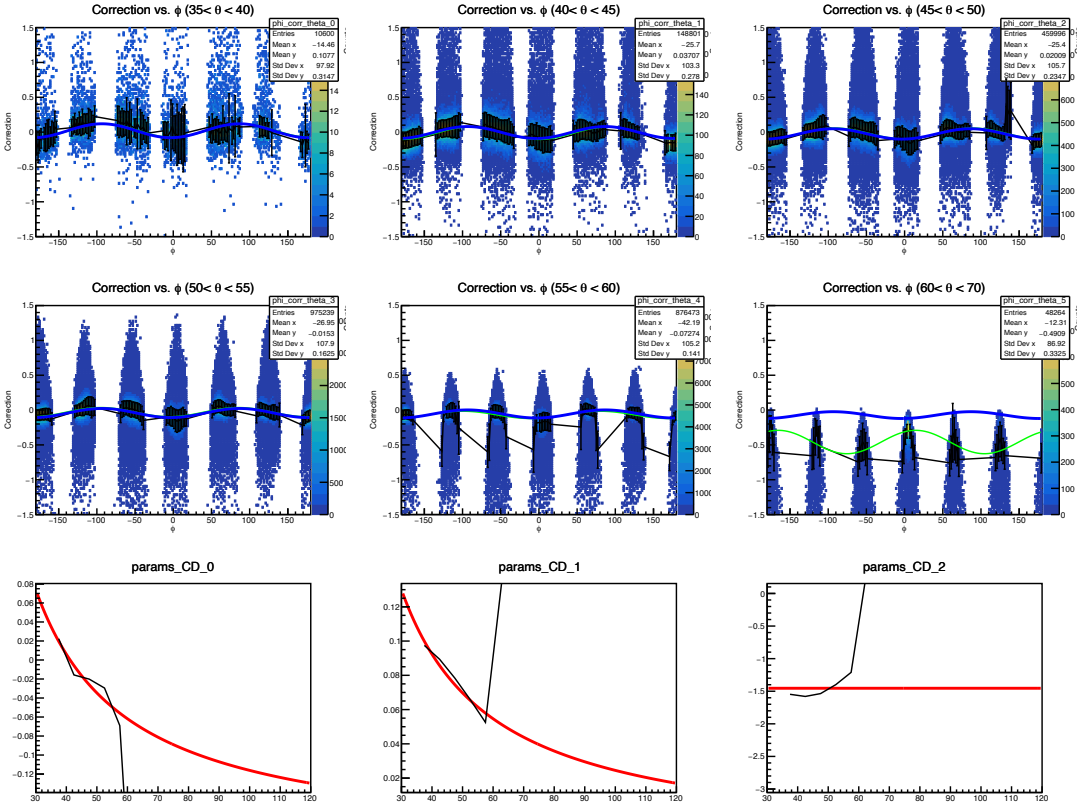
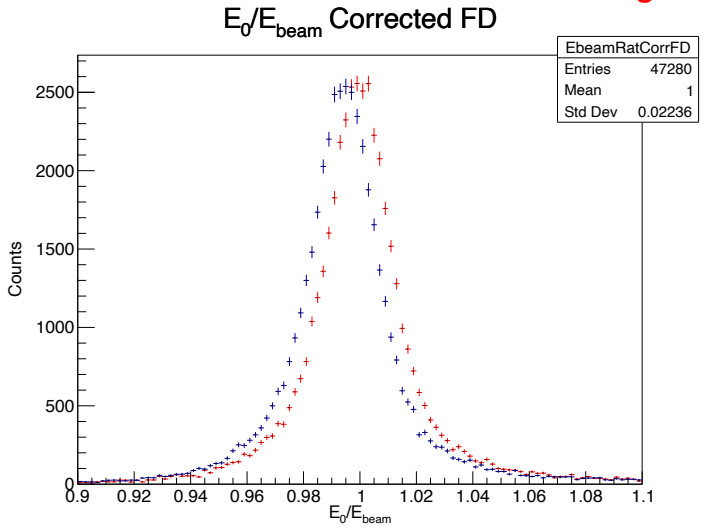
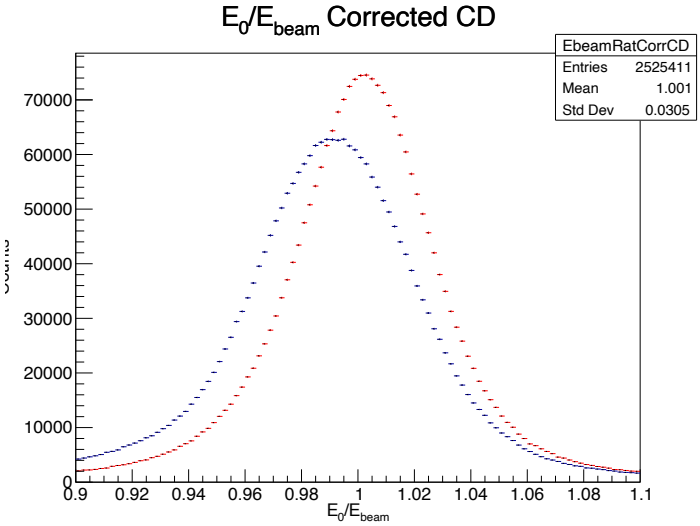
CD Angular Corrections



Result of Angular Corrections

Before Angular Correction
After Angular Correction





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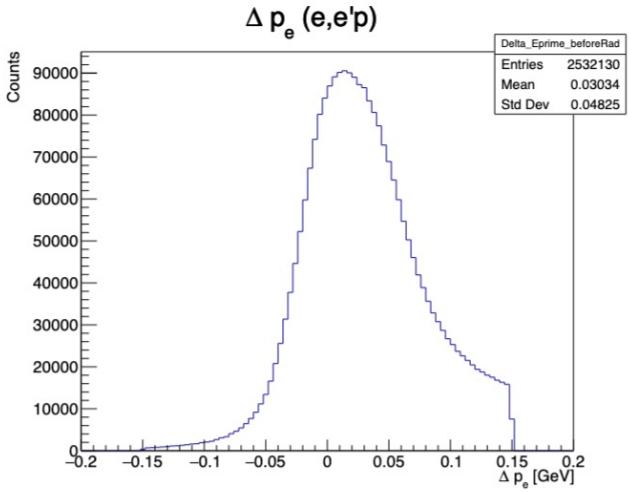
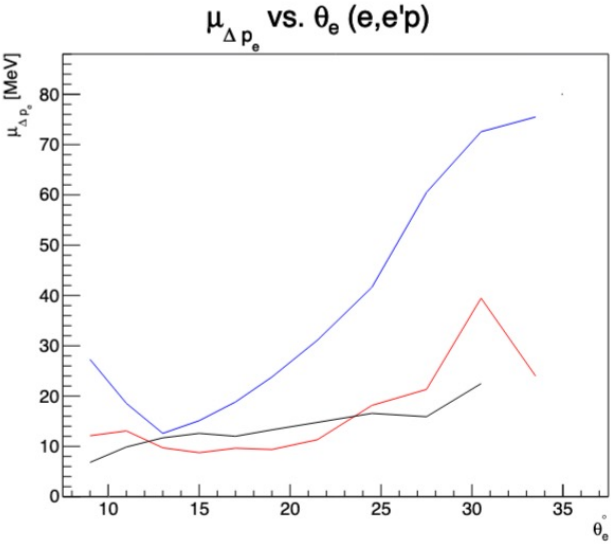
Momentum Correction of Electrons



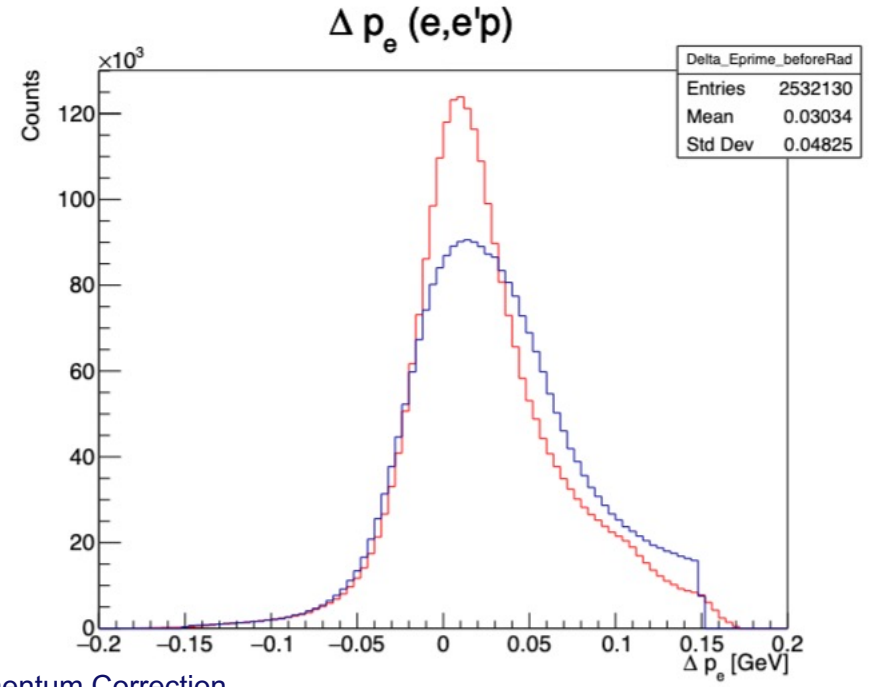


Before Momentum Correction

After Momentum Correction

H(e,e'p) Simulation with Radiation

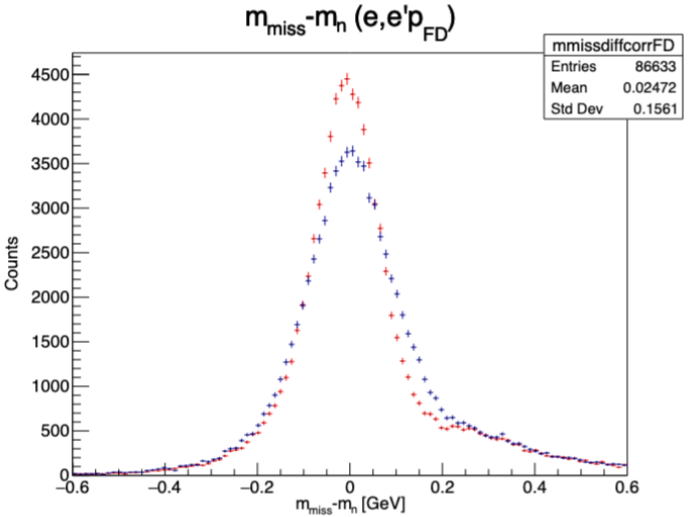
Momentum Corrections Improve Resolution

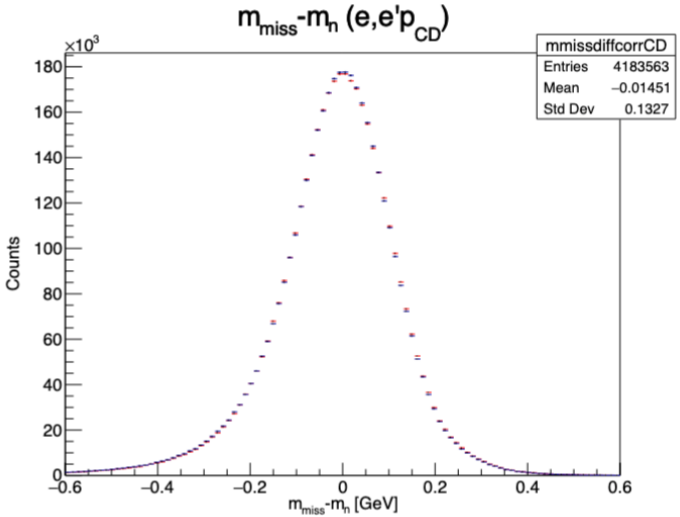


Before Momentum Correction

After Momentum Correction

Applying Corrections to D(e,e’p)n

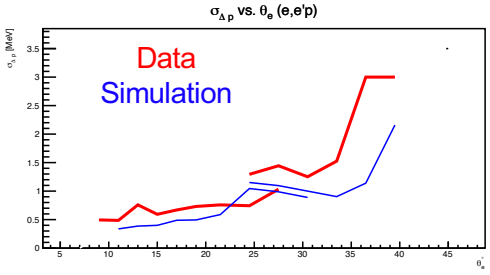


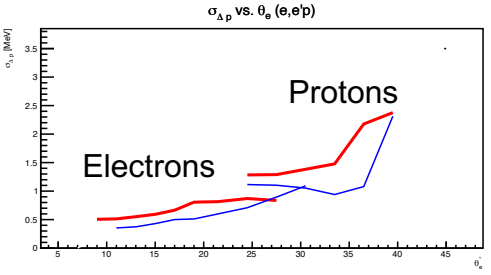


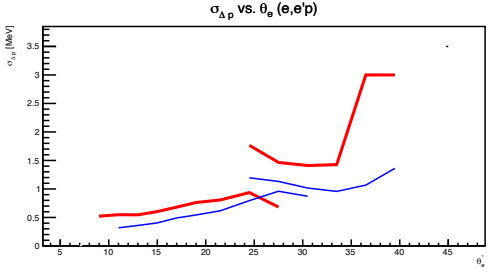
Before Momentum Correction
After Momentum Correction

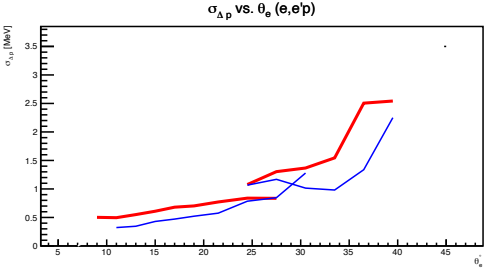
Data vs. Simulation

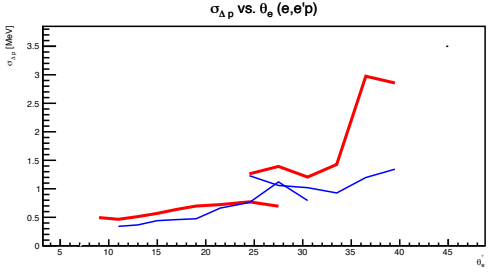
Resolution $\frac{p_{angle} - p}{p_{angle}}$

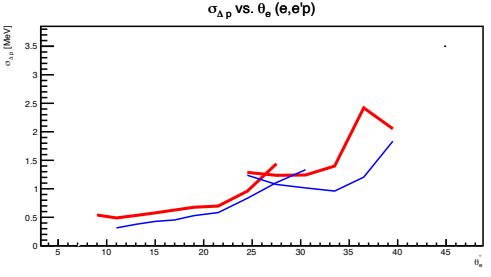






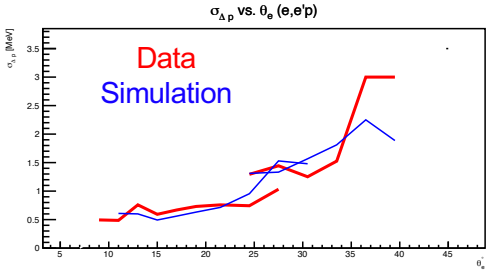


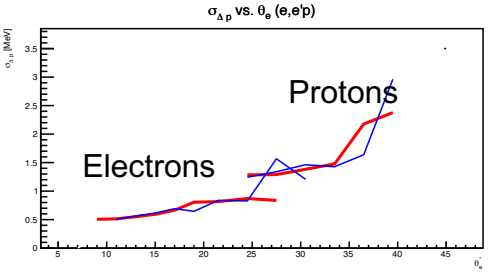


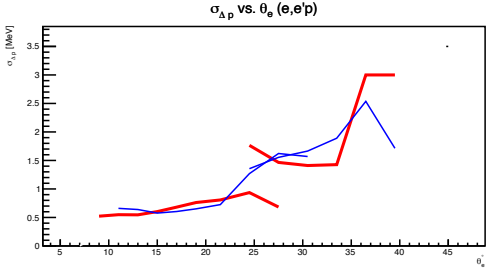


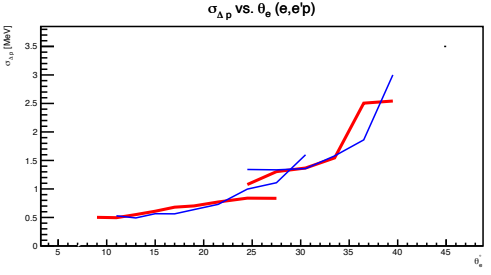
Data vs. Simulation with Smearing

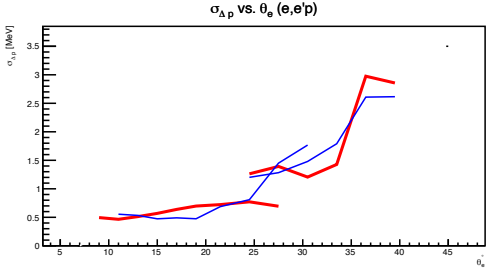
Resolution $\frac{p_{angle} - p}{p_{angle}}$

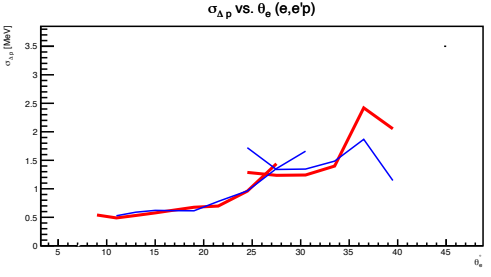












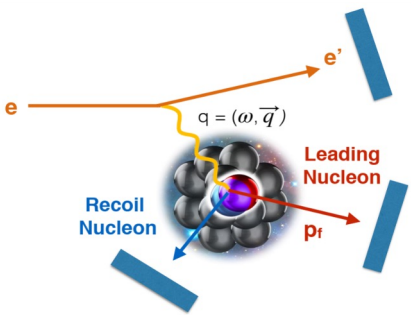
Particle ID for 6 GeV data

RG-M Analysis Note: 6 GeV electron proton selection and Particle ID

Andrew Denniston[1], Justin Estee[1], Julian Kahlbow[1], and Erin Marshall Seroka[2]

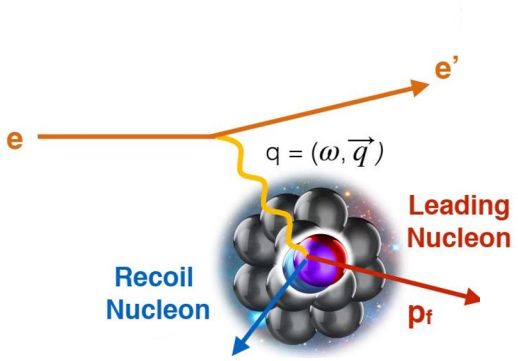
[1]Department of Physics, Massachusetts Institute of Technology
[2]Department of Physics, The George Washington University

→ Re-submit “General“ Analysis Note Soon



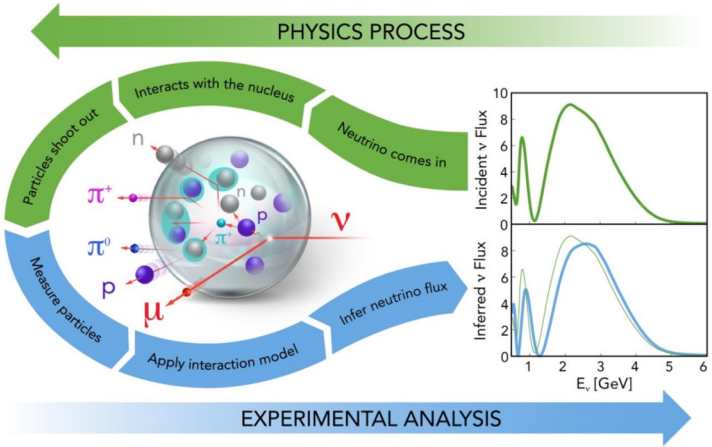
Run Group-M Proposals

Short Range Correlations

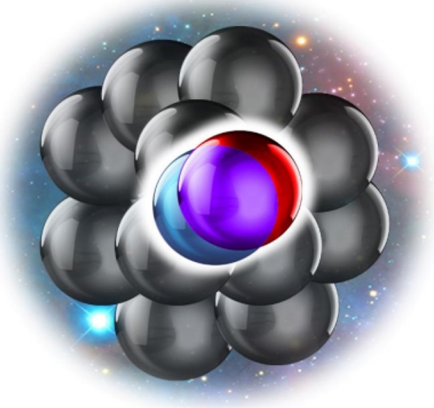


- (e,e') inclusive
- (e,e'N)
- (e,e'NN)

Electrons for Neutrinos (e4ν)



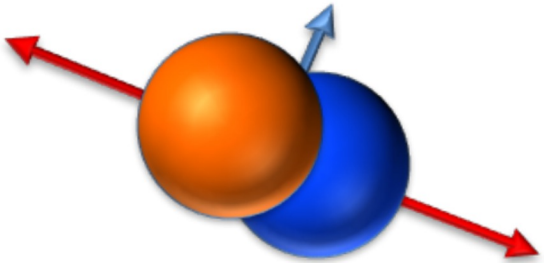
Short range, short lived, highly correlated pairs



r-space

High relative momentum

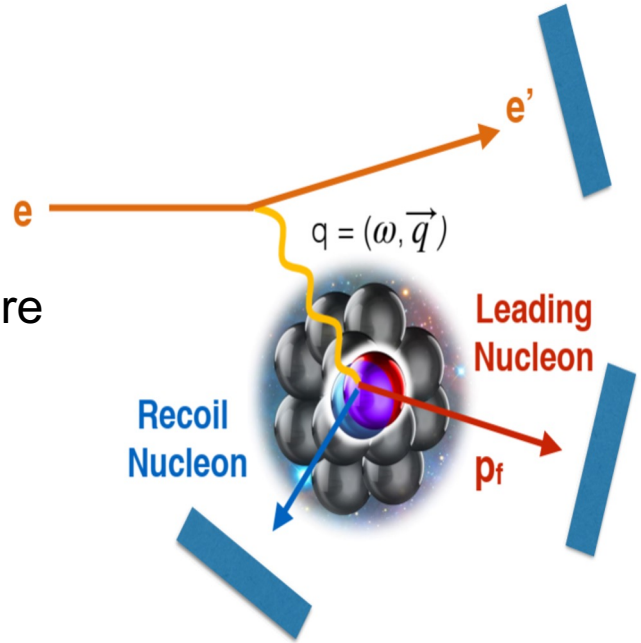
Low center of mass momentum



k-space

SRCs Goals with CLAS

- Compare old CLAS6 results with RGM results (30X the statistics).
- Verify that our observables are probe independent.
- Determine how SRCs are formed.



SRC Cuts

- $x_B > 1.3$
- $Q^2 > 1.5$
- $p_{lead} > 1$ GeV/c
- 0.8 GeV/c² < M_{miss} < Cut(x_B,p_{miss})
- 0.4 GeV/c < p_{miss} < 1.0 GeV/c
- |p|/|q| < 0.96

Derived From the CLAS6 Analysis Cuts:

- Physics Letters B 722 (2013) 63–68
- Science 346, 614 (2014)
- Nature 560, 617–621 (2018)
- Physics Letters B 797 (2019) 134792
- Cohen et al. Phys. Rev. Lett. 121, 092501 2018
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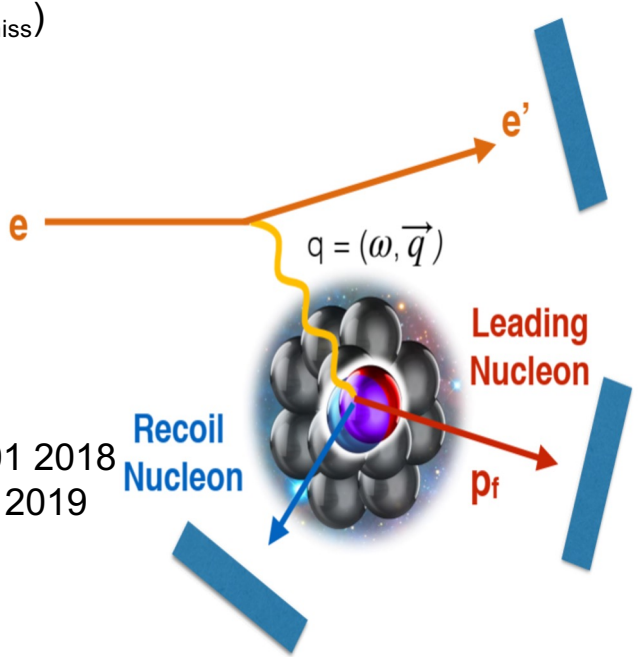
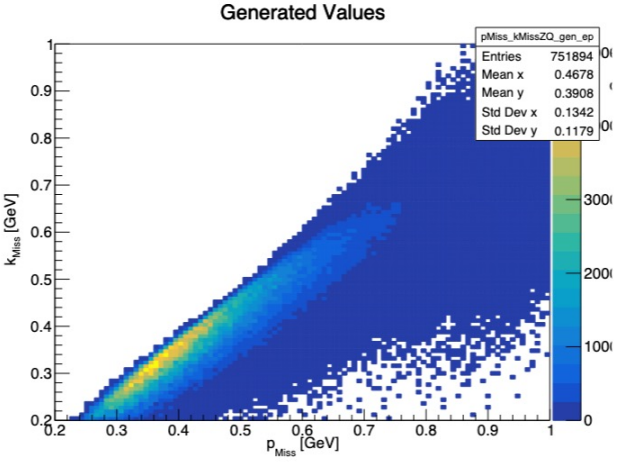
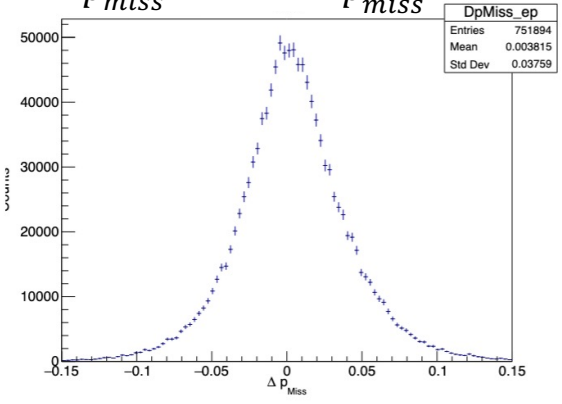


K_{Miss} correlates with p_{Miss} with better resolution

$$k^2_{miss} \equiv m^2_N \left(\frac{p^2_{miss,\perp} + m^2_N}{p^-_{miss}(2m_N - p^-_{miss})} \right) - m^2_N$$



$p^{reconstructed}_{miss} - p^{generated}_{miss}$



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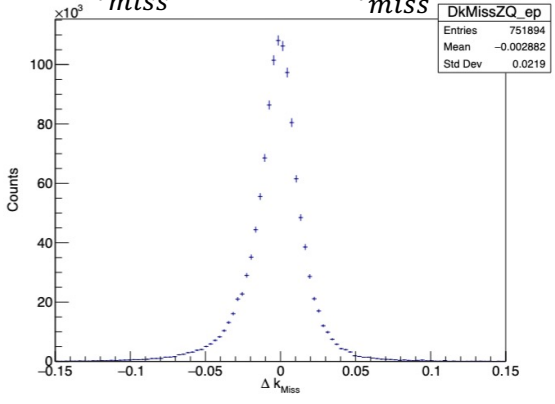
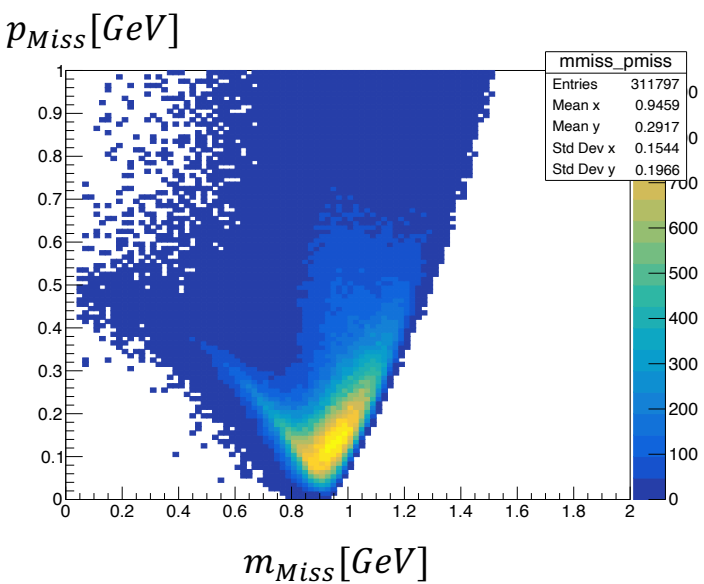
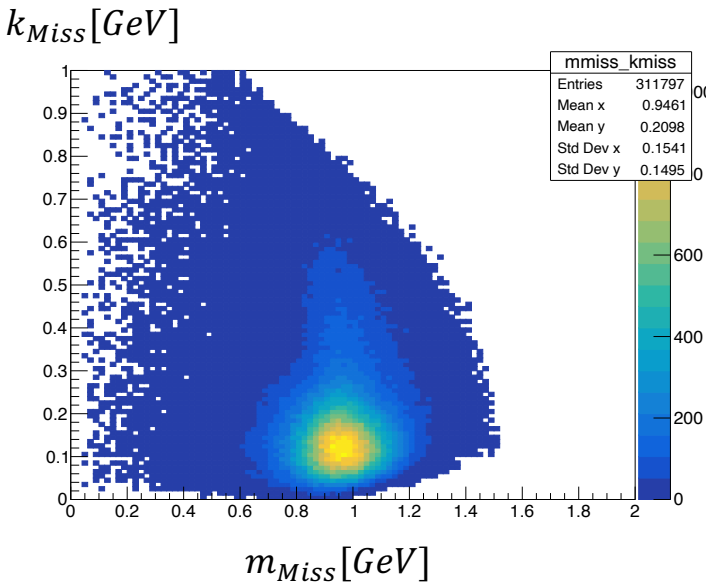


Frankfurt and Strikman, Phys. Rep. (1982)

K_{Miss} can improve our event selection





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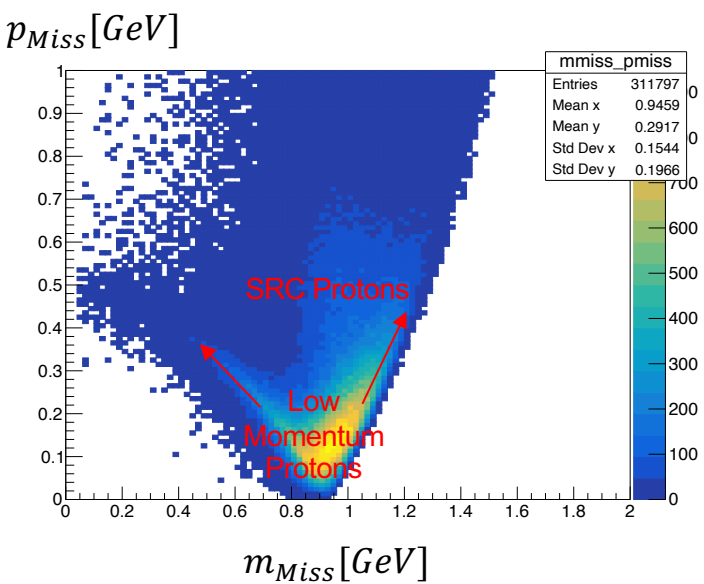

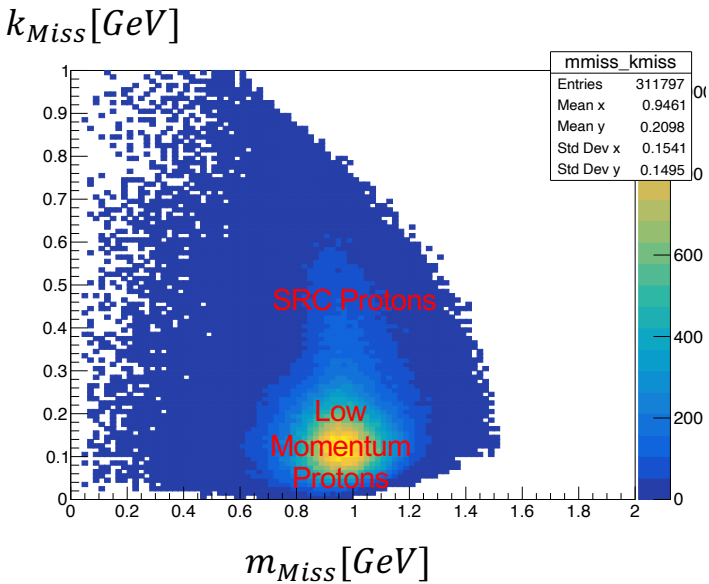

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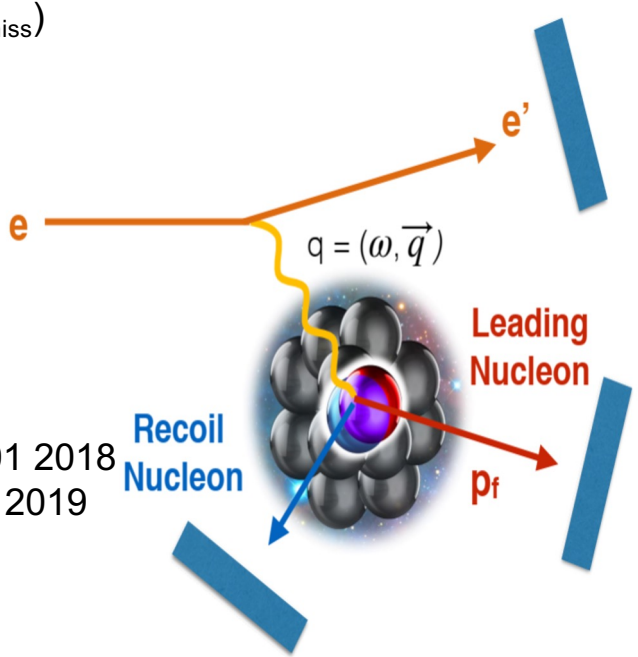
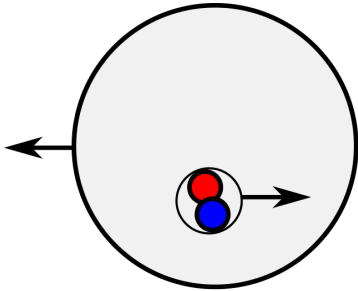
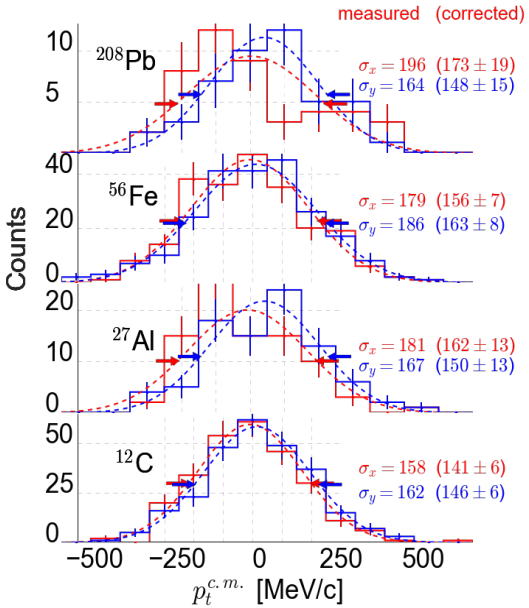


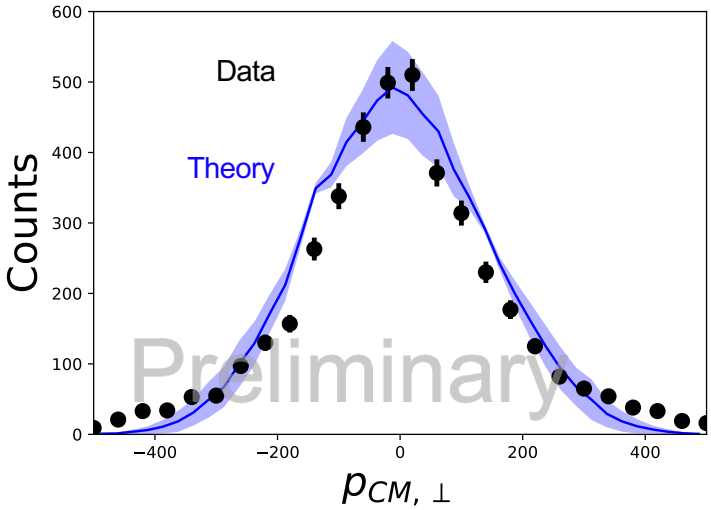
Center of Mass Motion



CLAS6 Data



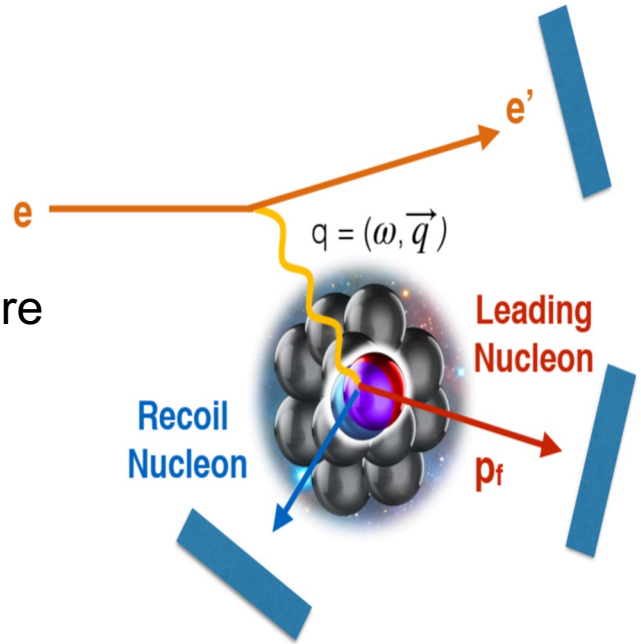
RGM Helium



- Cohen, PRL (2018)

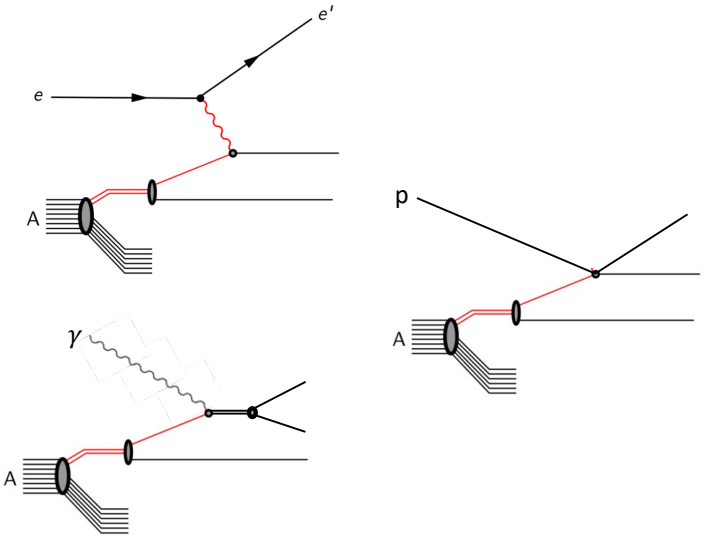
SRCs Goals with CLAS

- Compare old CLAS6 results with RGM results (30X the statistics).
- Verify that our observables are probe independent.
- Determine how SRCs are formed.

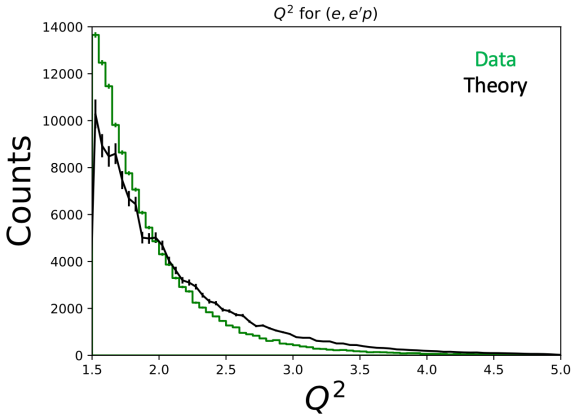


Measuring SRC Probe (In)dependence

Change the Probe

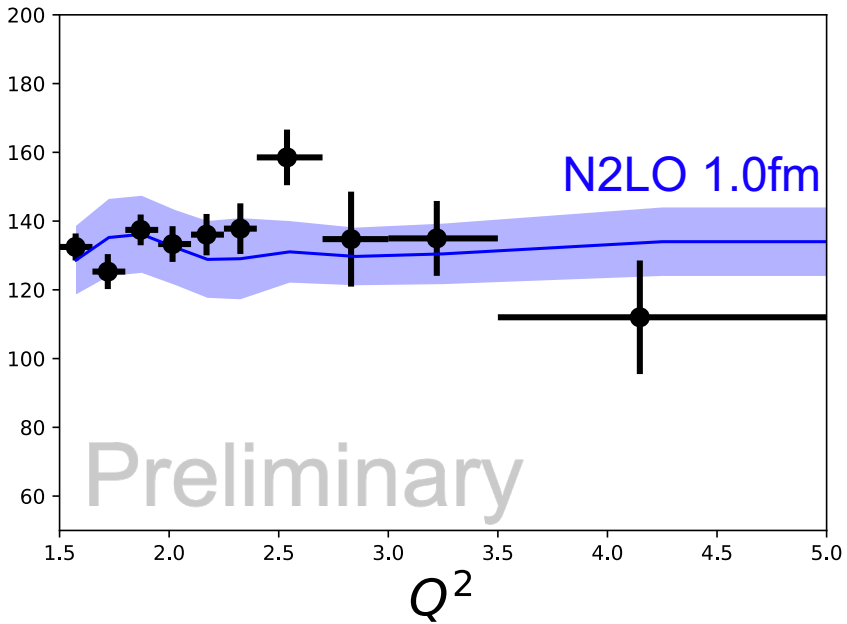


Change the Scale of the Probe



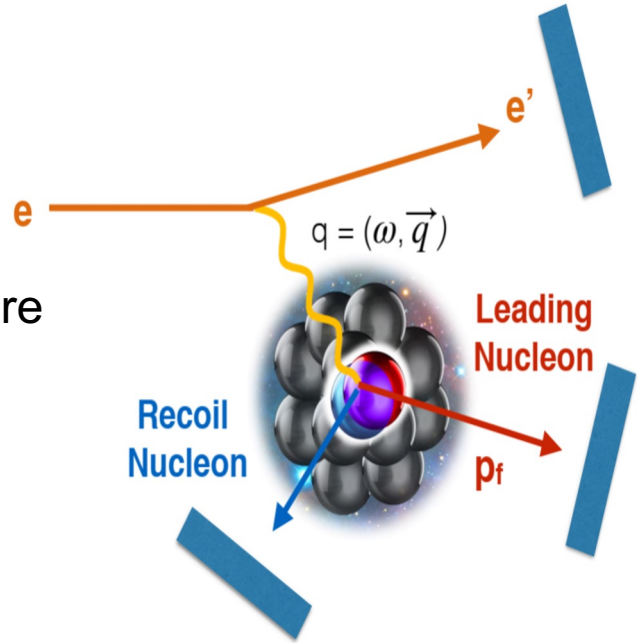
Measuring SRC Probe (In)dependence

σ_{CM} $[MeV]$
Center of Mass
Motion of SRC

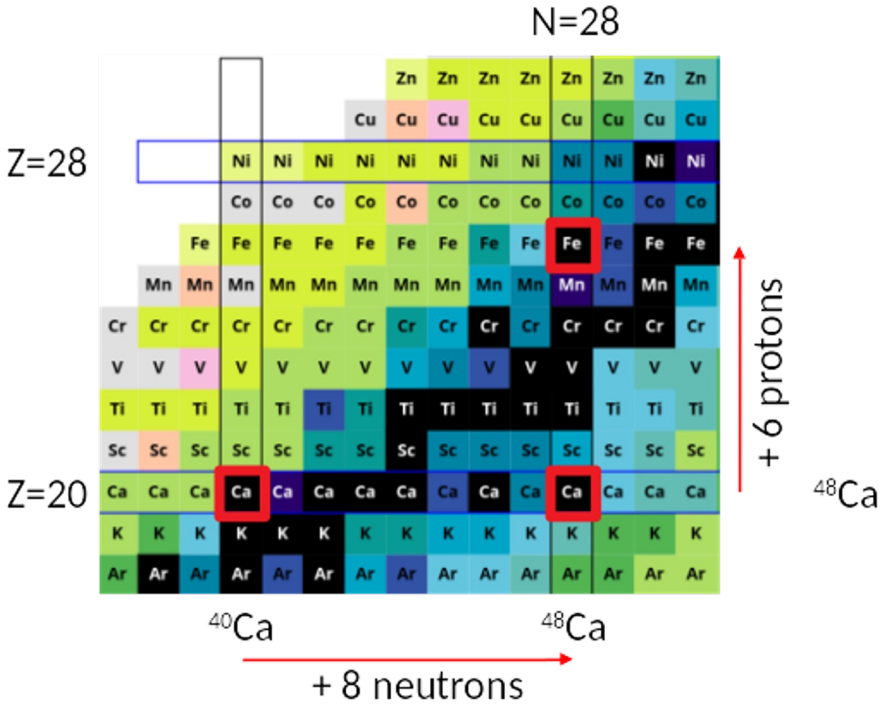


SRCs Goals with CLAS

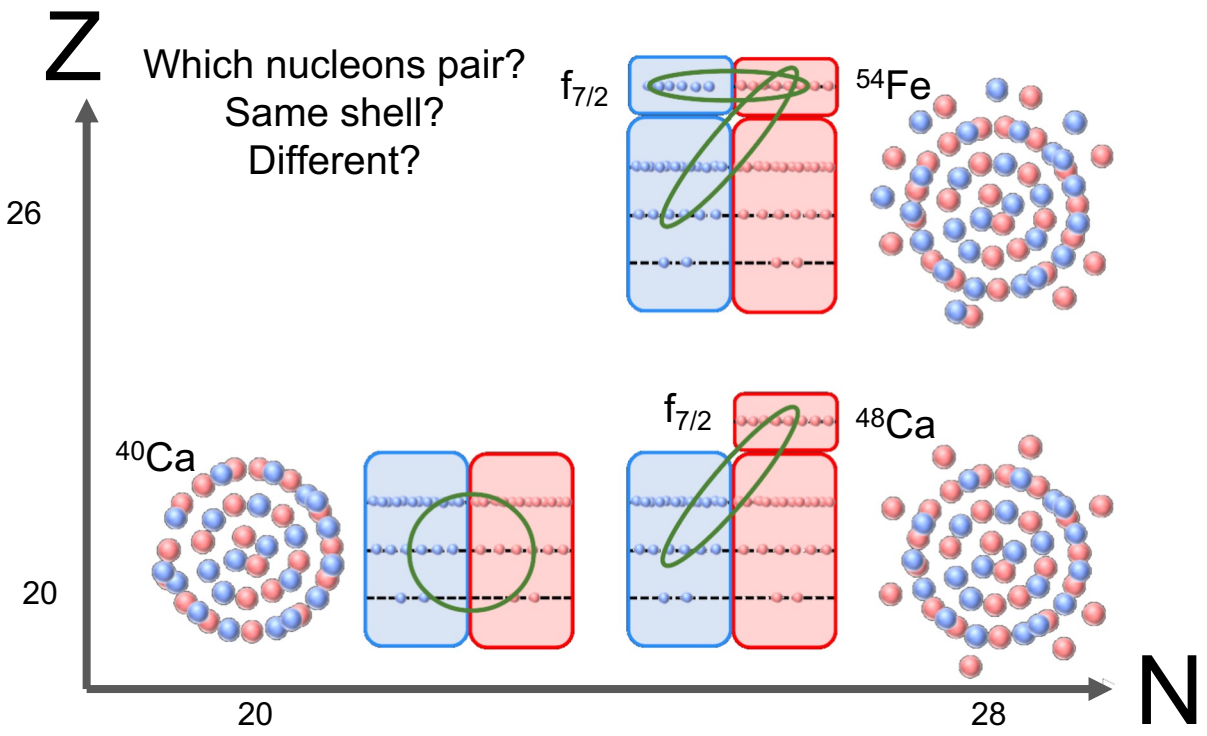
- Compare old CLAS6 results with RGM results (30X the statistics).
- Verify that our observables are probe independent.
- Determine how SRCs are formed.



SRCs in Asymmetric Nuclei



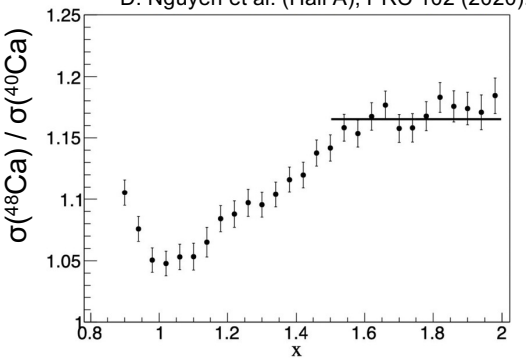
SRCs in Asymmetric Nuclei



SRCs in Asymmetric Nuclei

- (e,e’)
- (e,e’p)
- (e,e’n)
- (e,e’pp)
- (e,e’pn)

D. Nguyen et al. (Hall A), PRC 102 (2020).



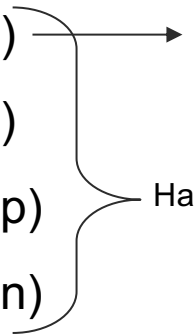
Conclusion: *np* pair dominance

SRCs in Asymmetric Nuclei

- (e,e’)
- (e,e’p) → Hall C experiment 2022, under analysis: ^{40}Ca, ^{48}Ca, ^{54}Fe, ^{197}Au
- (e,e’n)
- (e,e’pp)
- (e,e’pn)

SRCs in Asymmetric Nuclei

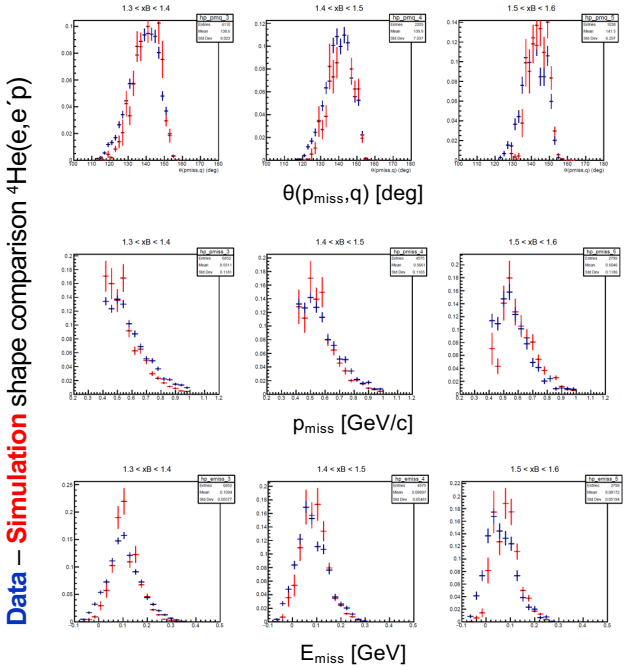
- (e,e’)
- (e,e’p)
- (e,e’n)
- (e,e’pp)
- (e,e’pn)



Hall C experiment 2022, under analysis: ^{40}Ca, ^{48}Ca, ^{54}Fe, ^{197}Au

Hall B RG-M experiment 2021/22, under analysis: ^{40}Ca, ^{48}Ca, ^{120}Sn, …

SRCs in Asymmetric Nuclei



Good Agreement with SRC Simulation

SRC selection:

- $x_B > 1.3$
- $Q^2 > 1.5$
- $p_{lead} > 1$ GeV/c
- 0.8 GeV/c² < M_{miss} < Cut(x_B,p_{miss})
- 0.4 GeV/c < p_{miss} < 1.0 GeV/c
- $|p|/|q| < 0.96$

SRCs in Asymmetric Nuclei

Advantages:
- informs on impact of nuclear structure
- many systematic effects cancel (ϵ)

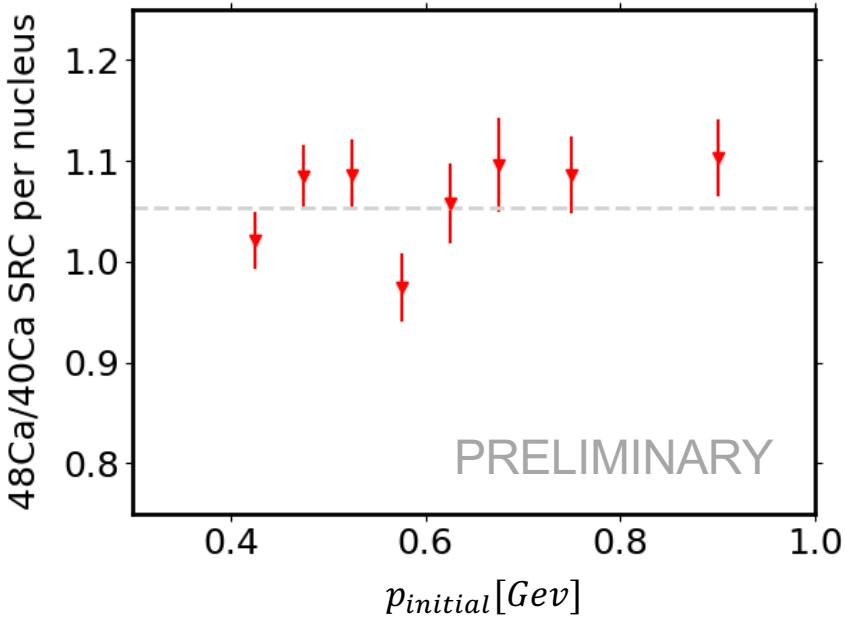
$$Ratio = \frac{yield_A/(N \cdot \rho_A)/T_A \cdot A \cdot \cancel{\epsilon}}{yield_{40Ca}/(N \cdot \rho_{40Ca})/T_{40Ca} \cdot A_{40Ca} \cdot \cancel{\epsilon}}$$

→ per nucleus yield ratio

N : norm (~ beam charge)
ϱ : area density
→ luminosity normalization

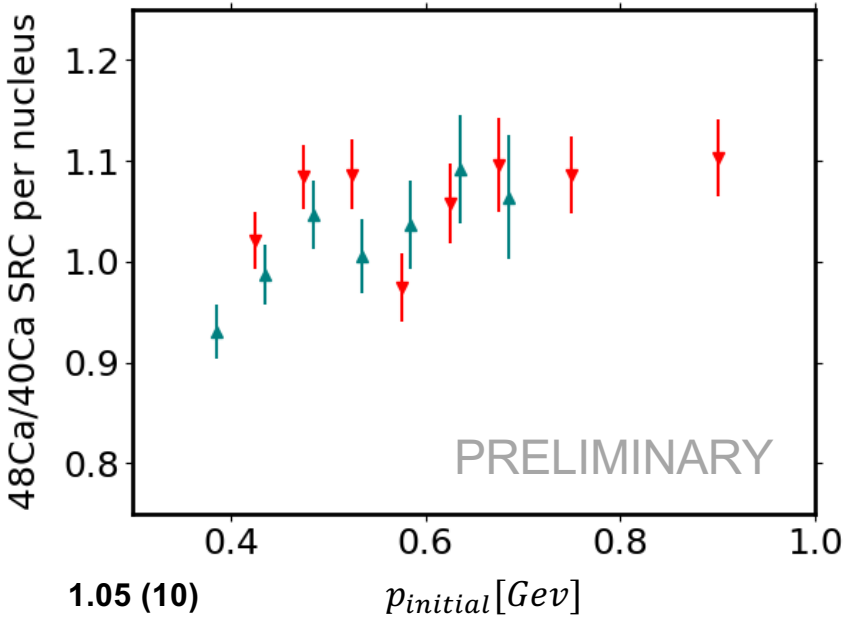
T : transparency
ϵ: detector efficiency

SRCs in Asymmetric Nuclei



≠ ~1.2

SRCs in Asymmetric Nuclei

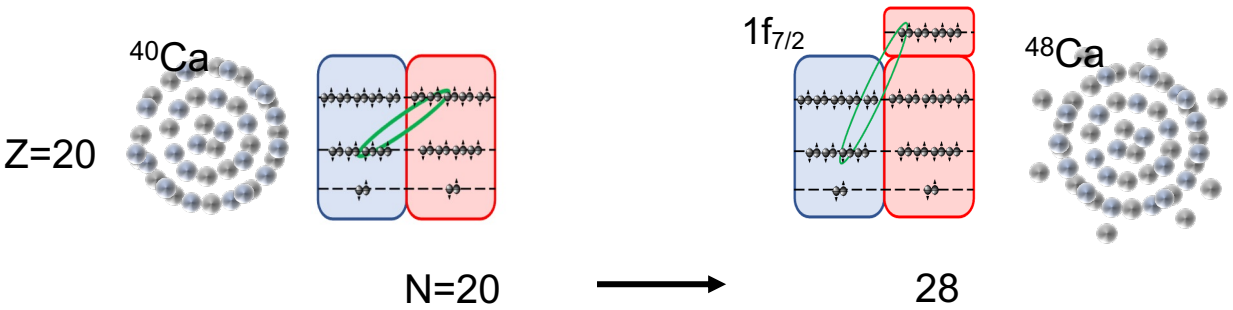


RG-M (Hall B) **1.05 (10)**

CaFe (Hall C) **1.02 (1)**

[Carlos Yero (ODU), Dien Nguyen (JLAB) et al.]

SRCs in Asymmetric Nuclei

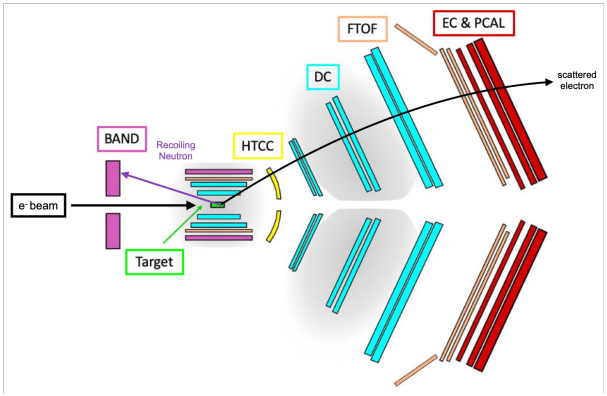


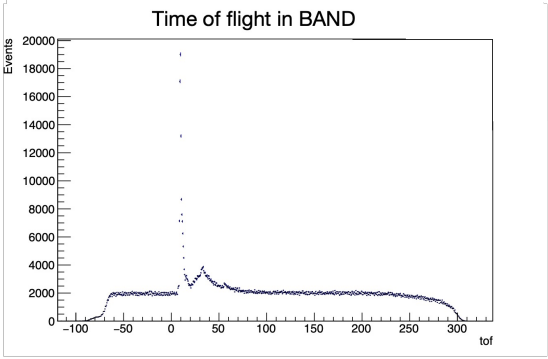
48Ca/40Ca(e,e'p) = 1.05

Reduction in short-range pairing across shells! Long-range nuclear structure to impact SRC

Recoil-Tagged DIS in He-4

- 6 GeV He-4 data from RGM
- Neutrons in BAND
- Detect recoiling neutron to determine correlation status between struck and detected nucleons



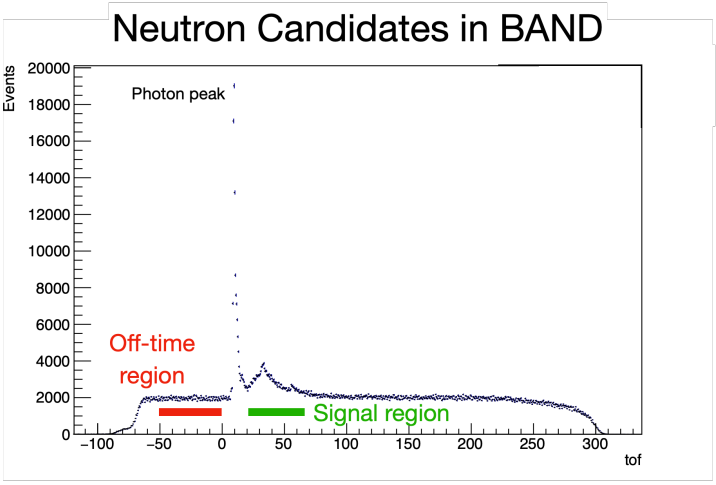


Recoil-Tagged DIS in He-4

Random-Coincidence Background Subtraction

"Event-mixed background":

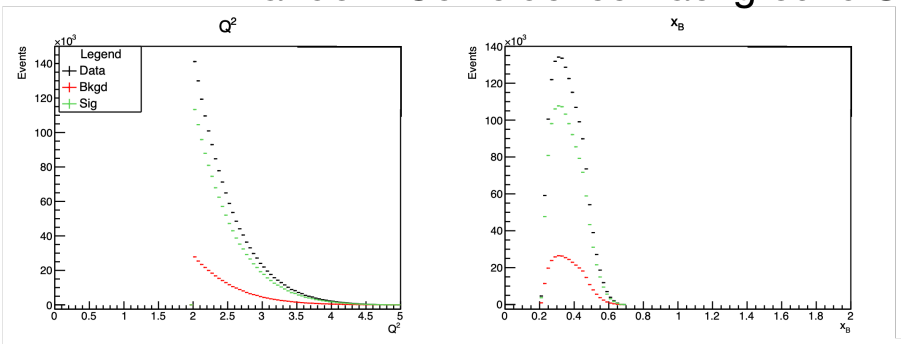
Using off-time neutrons shifted into the signal region to create artificial random-coincidence background

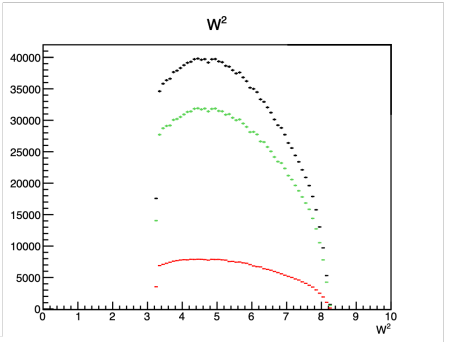


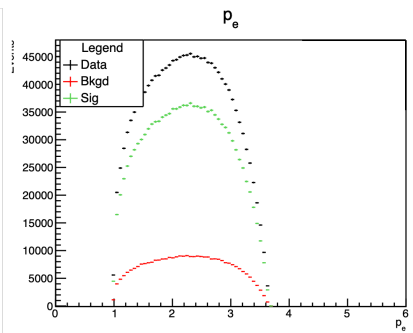
Sara Ratliff

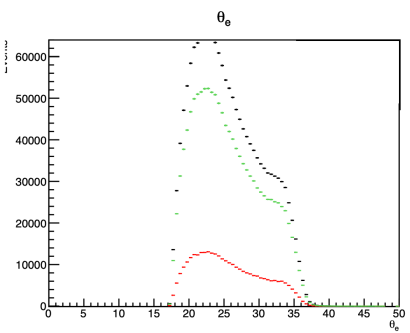
Recoil-Tagged DIS in He-4

Random-Coincidence Background Subtraction





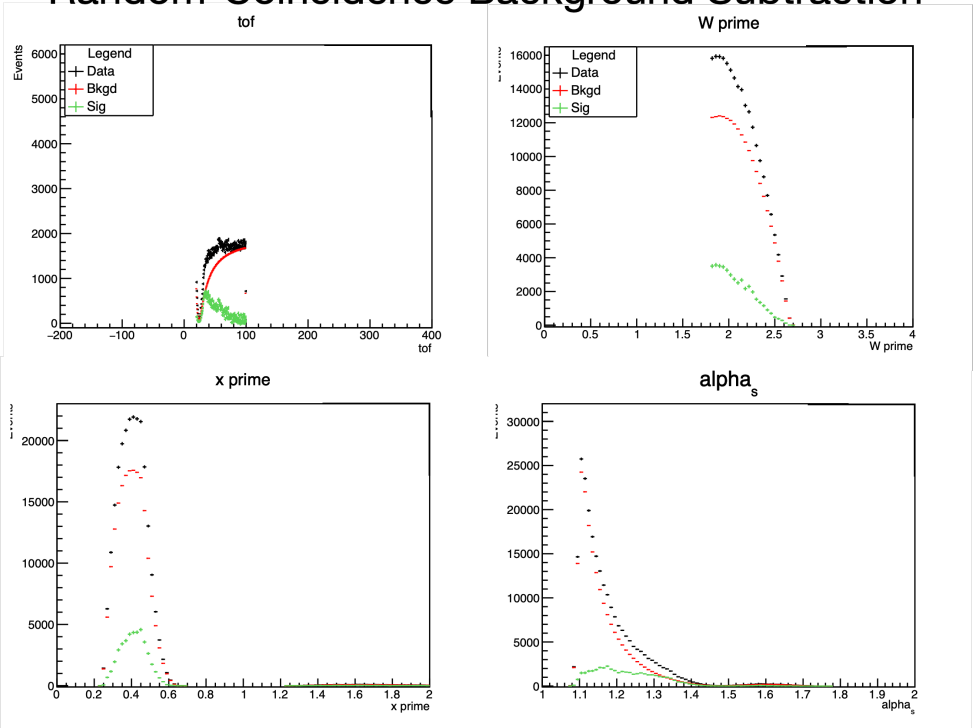




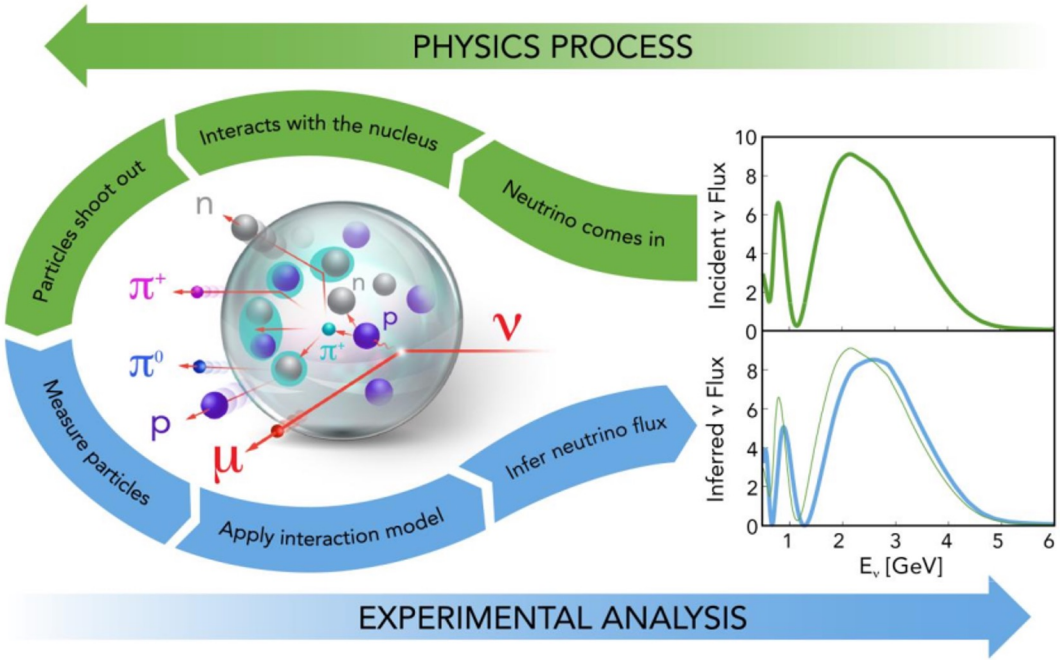
Sara Ratliff

Recoil-Tagged DIS in He-4

Random-Coincidence Background Subtraction



Electrons for Neutrinos



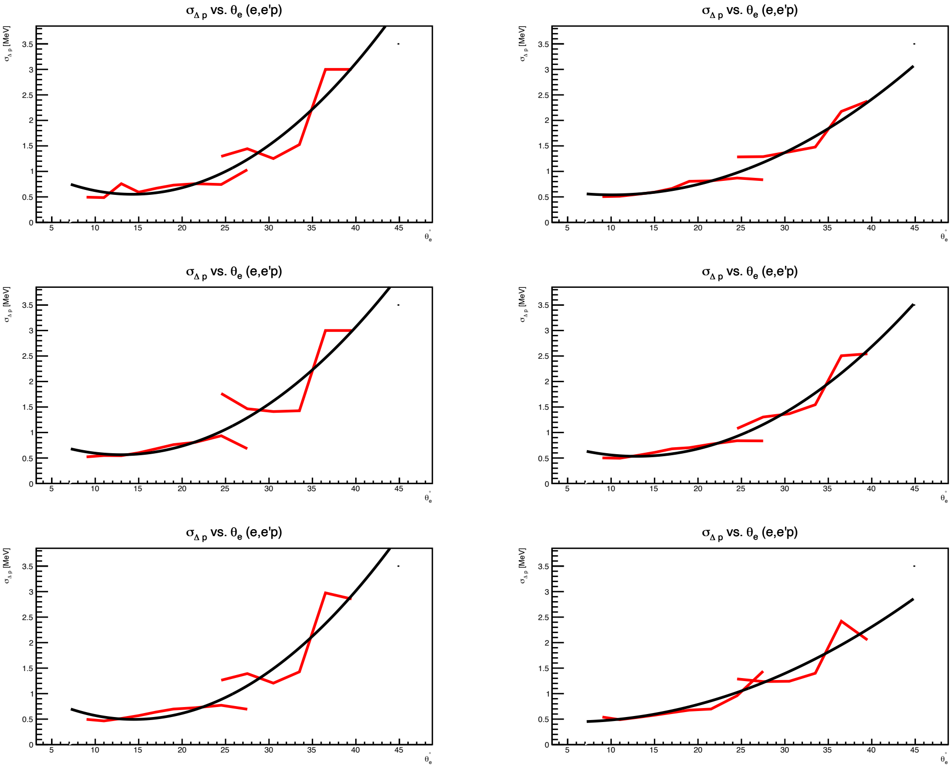
Looking Forward

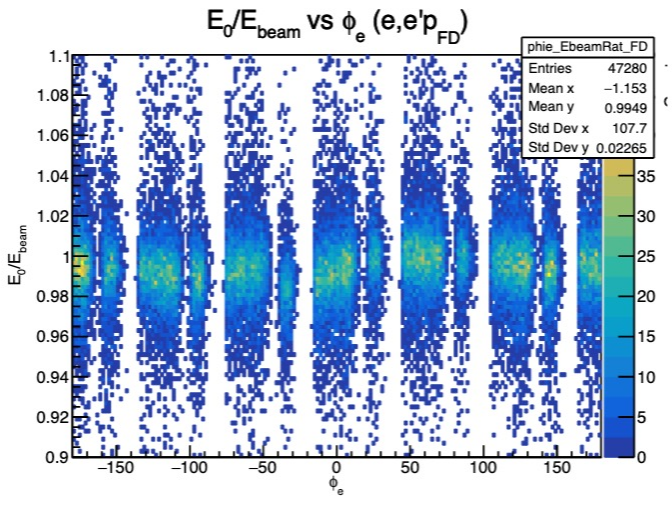
- Low Level Analysis
  - CVT acceptance needs to be understood.
  - CND neutrons are mature but still not complete.
- Other Physics Analyses
  - Measure SRC Neutrons.

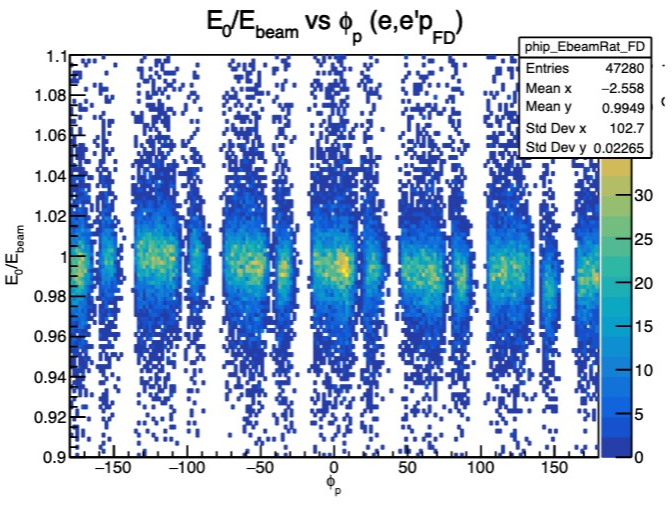
Conclusion

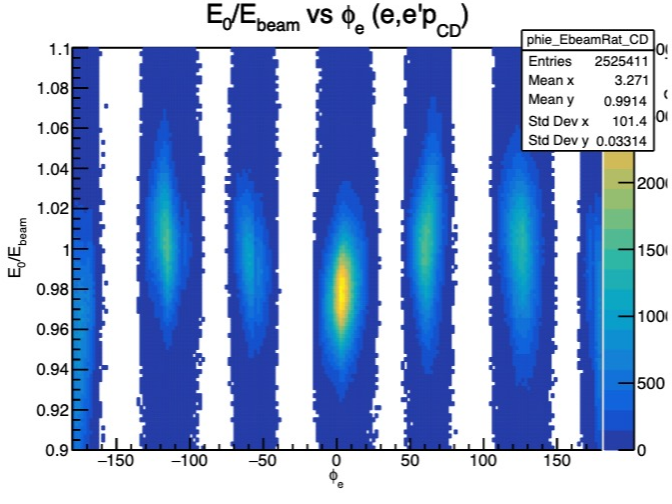
- Low Level Analysis
  - Electron PID, Fiducial, and Vertex Cuts
  - Proton PID, Fiducial, and Vertex Cuts
  - Angular and Momentum Corrections
  - Simulation Smearing to Match Resolution
- SRC Analysis
  - Q2 dependence of SRCs
  - SRCs in Asymmetric Nuclei
  - Recoil Neutrons in BAND Detector
- e4v Analysis

Fit both as a function of Theta to get resolution




E_0/E_{beam} vs ϕ_e $(e,e'p_{FD})$
phie_EbeamRat_FD
Entries 47280
Mean x −1.153
Mean y 0.9949
Std Dev x 107.7
Std Dev y 0.02265
E_0/E_{beam}
ϕ_e


E_0/E_{beam} vs ϕ_p $(e,e'p_{FD})$
phip_EbeamRat_FD
Entries 47280
Mean x −2.558
Mean y 0.9949
Std Dev x 102.7
Std Dev y 0.02265
E_0/E_{beam}
ϕ_p


E_0/E_{beam} vs ϕ_e $(e,e'p_{CD})$
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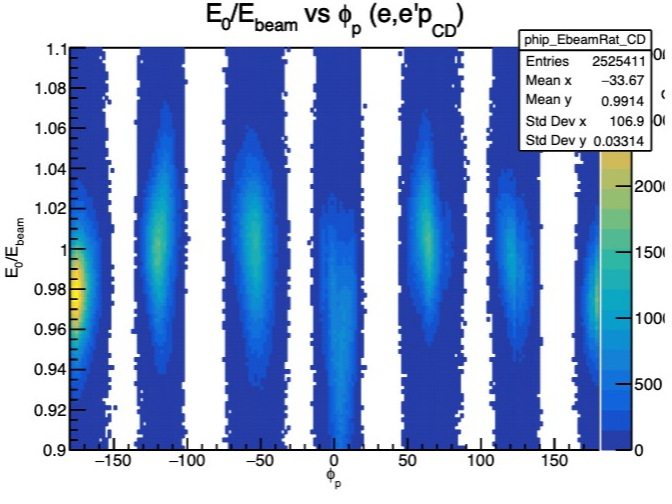
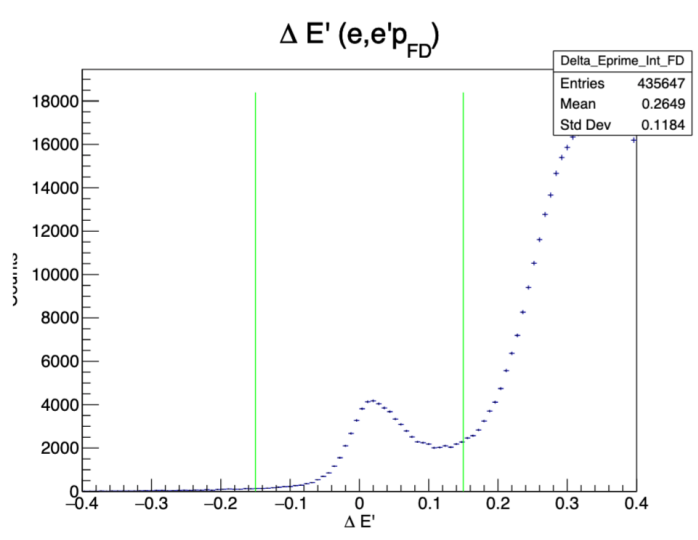
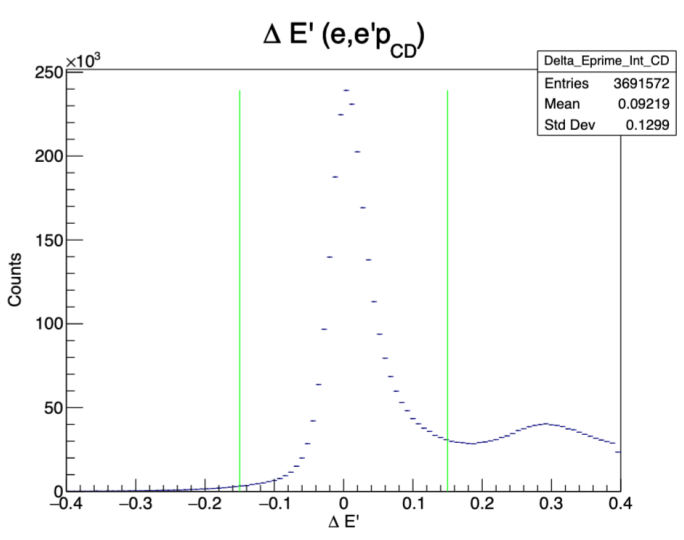
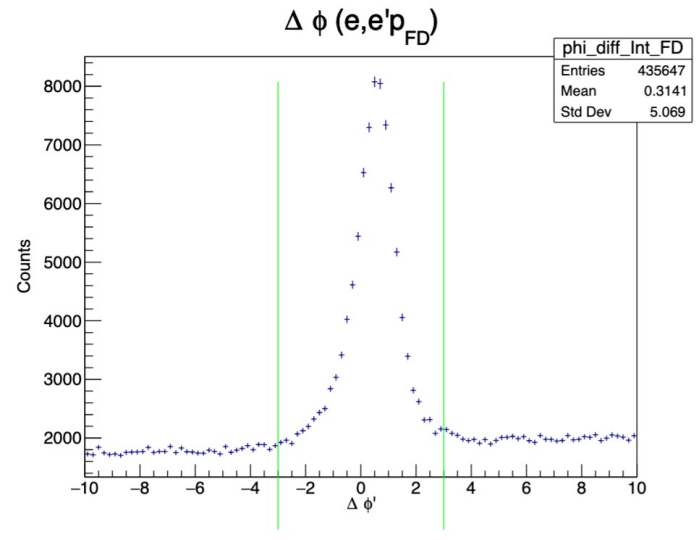
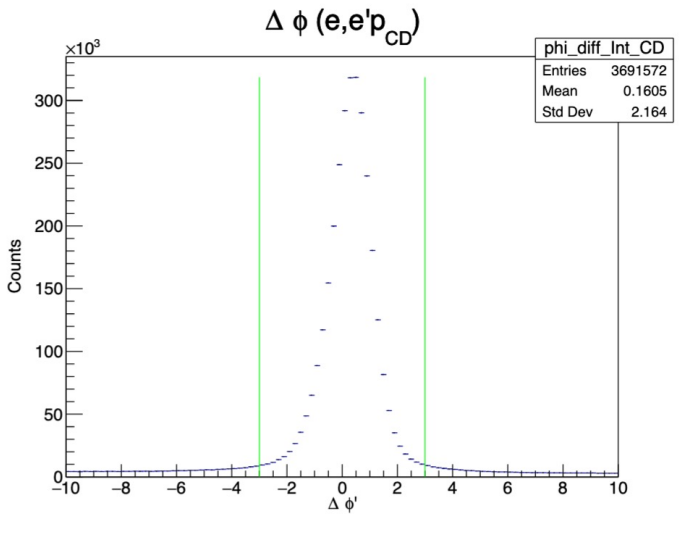
Mean x 3.271
Mean y 0.9914
Std Dev x 101.4
Std Dev y 0.03314
E_0/E_{beam}
ϕ_e


E_0/E_{beam} vs ϕ_p $(e,e'p_{CD})$
phip_EbeamRat_CD
Entries 2525411
Mean x −33.67
Mean y 0.9914
Std Dev x 106.9
Std Dev y 0.03314
E_0/E_{beam}
ϕ_p

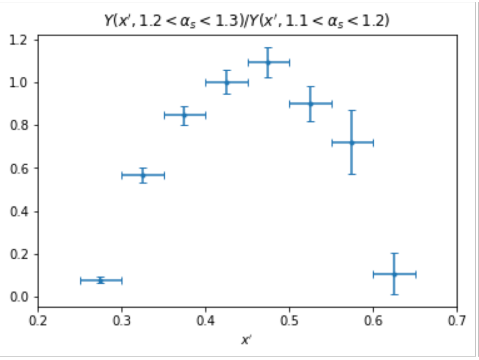

Δ E' (e,e'p_FD)
Delta_Eprime_Int_FD
Entries 435647
Mean 0.2649
Std Dev 0.1184
Counts
Δ E'

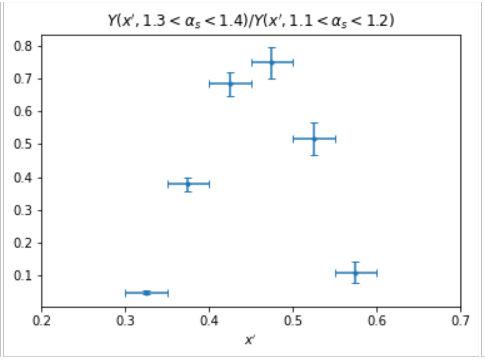

Δ E' (e,e'p_CD)
×10^3
Delta_Eprime_Int_CD
Entries 3691572
Mean 0.09219
Std Dev 0.1299
Counts
Δ E'

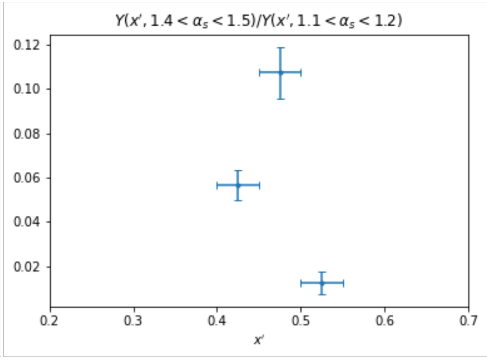

Δ ϕ (e,e'p_FD)
phi_diff_Int_FD
Entries 435647
Mean 0.3141
Std Dev 5.069
Counts
Δ ϕ'


Δ ϕ (e,e'p_CD)
×10^3
phi_diff_Int_CD
Entries 3691572
Mean 0.1605
Std Dev 2.164
Counts
Δ ϕ'

x' dependence



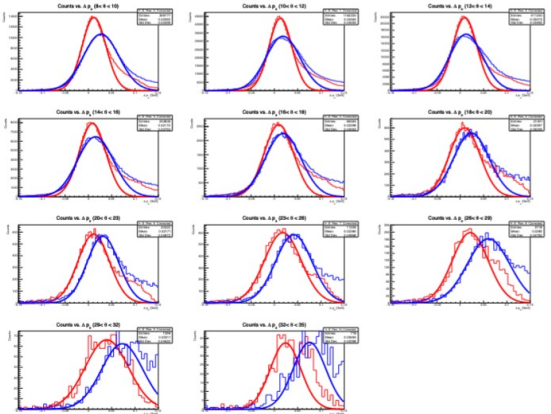


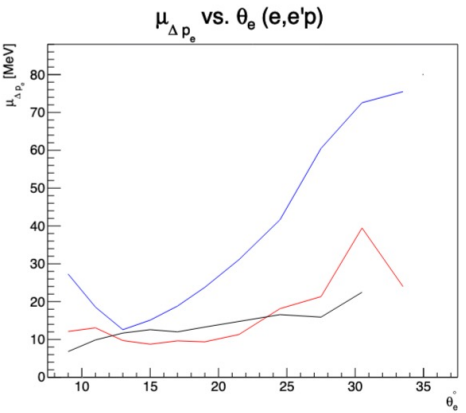


- Looking at x' dependence, for α_s bins
- Ratio against reference bin $1.1 < \alpha_s < 1.2$
- Building simulation for comparison

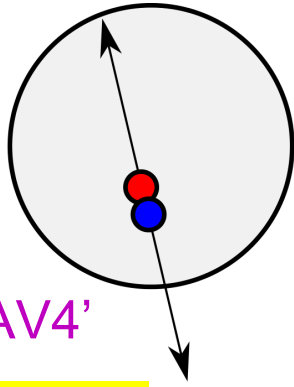
X

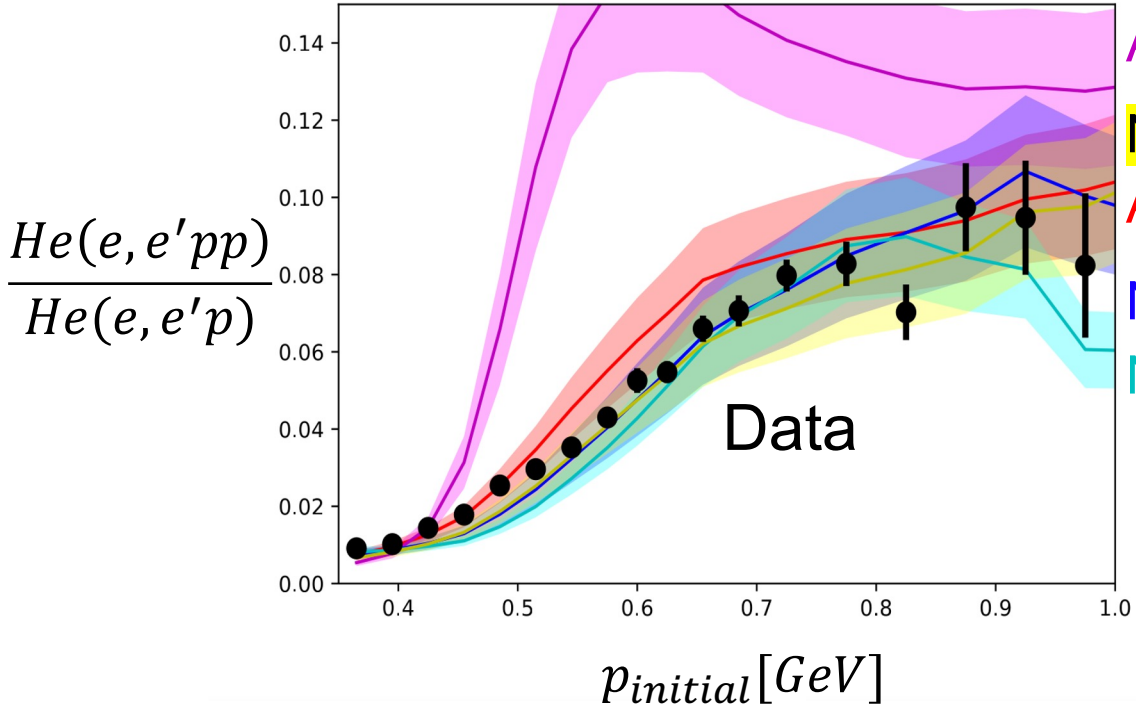
Momentum Correction of FD Electrons



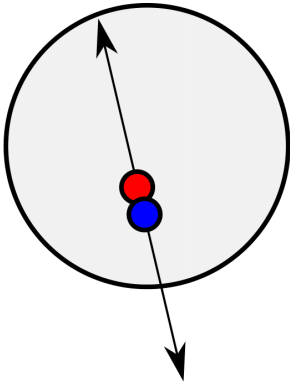


Precision NN interaction

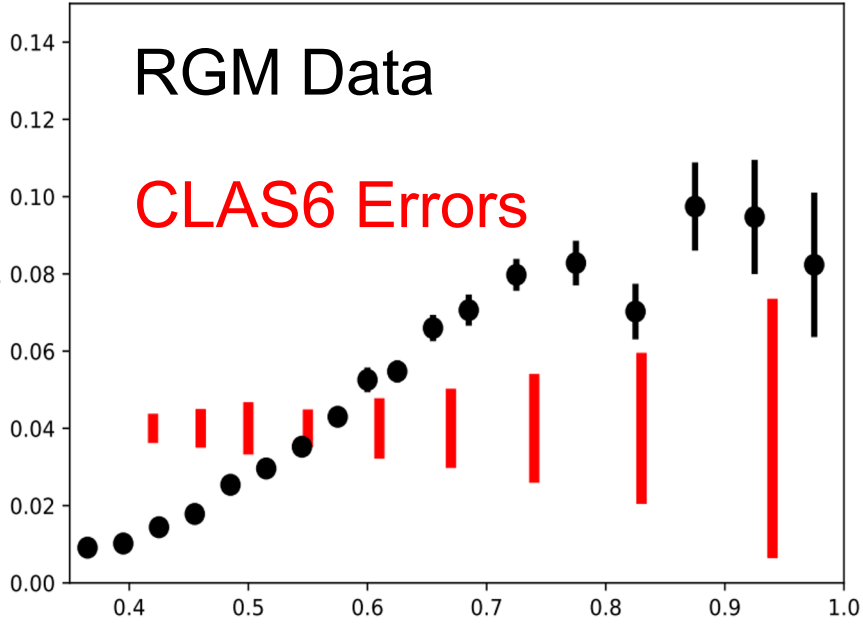




Precision NN interaction

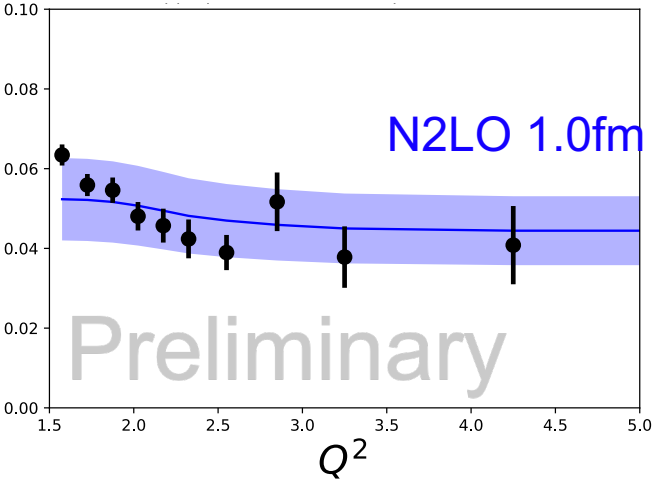


$$\frac{He(e,e'pp)}{He(e,e'p)}$$



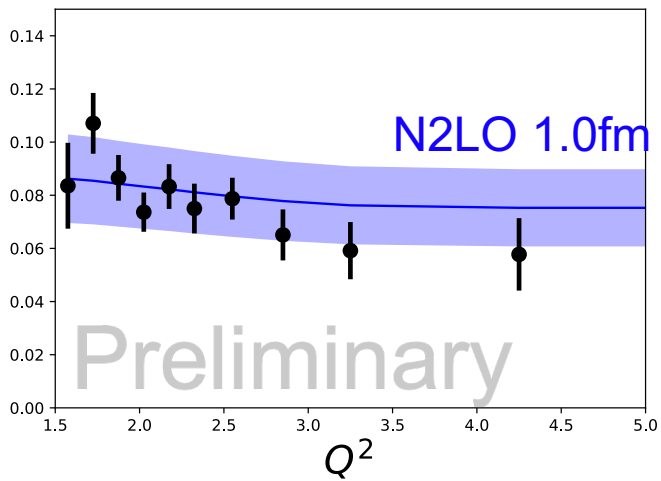
Measuring SRC Probe (In)dependence

$$\frac{He(e,e'pp)}{He(e,e'p)}$$



$0.55GeV < p_{miss} < 0.7GeV$

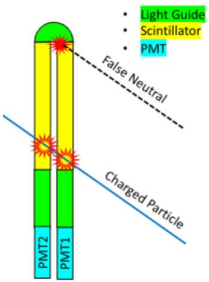
$$\frac{He(e,e'pp)}{He(e,e'p)}$$

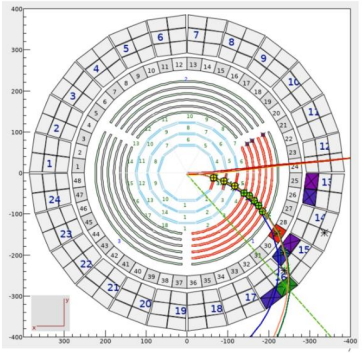


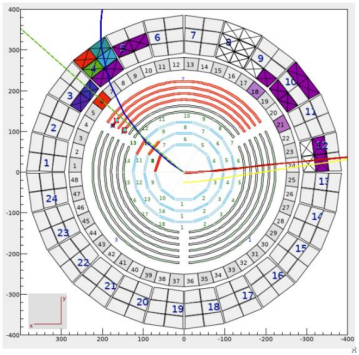
$0.7GeV < p_{miss} < 0.85GeV$

Particle ID for Neutrons in 6 GeV data

- Developed a general neutron veto for CND with Machine Learning.
- Define “features” to train model on training sample
- Evaluate performance using testing sample

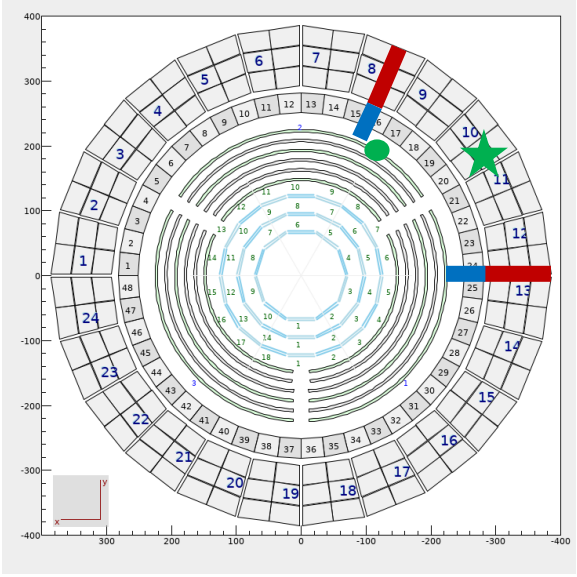






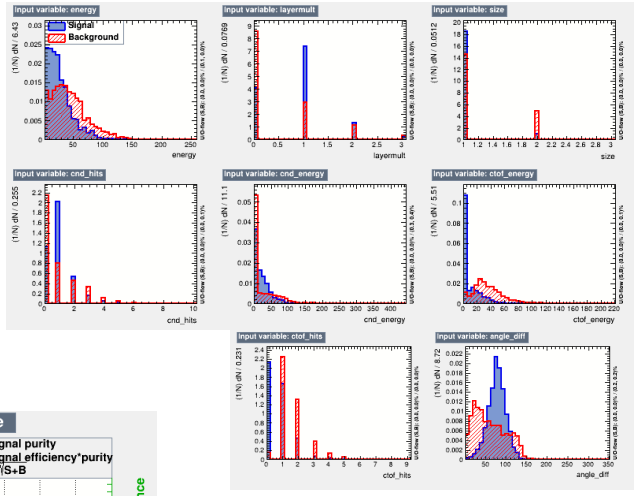
Particle ID for Neutrons in 6 GeV data

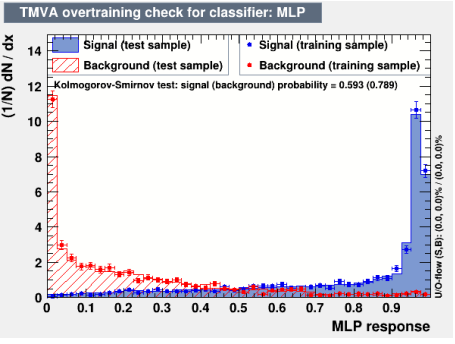
- Number of CND hits within 30 degrees of neutron
- CND energy deposition within 30 degrees of neutron
- Number of CTOF hits within 30 degrees of neutron
- CTOF energy deposition within 30 degrees of neutron
- Number of hits in CND cluster
- Neutron energy
- CND layer multiplicity (0 if CTOF only)
- Angular separation between hit in CVT layer 12 and neutron hit (180° if no track)

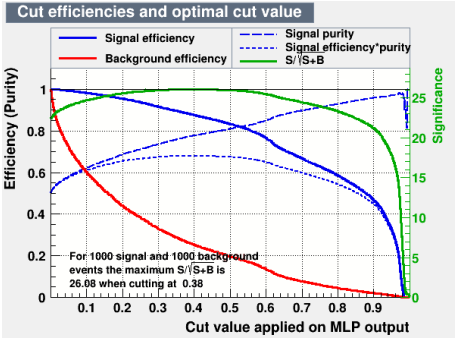


Particle ID for Neutrons in 6 GeV data

- $d(e, e'pn)$ (signal)
- $d(e, e'p\pi^-p)$ in which CLAS12 reconstruction misidentifies protons as neutrons (background)

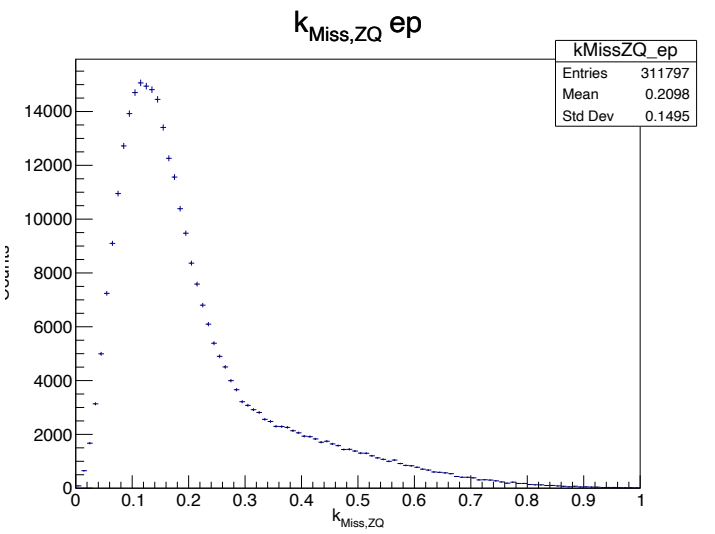


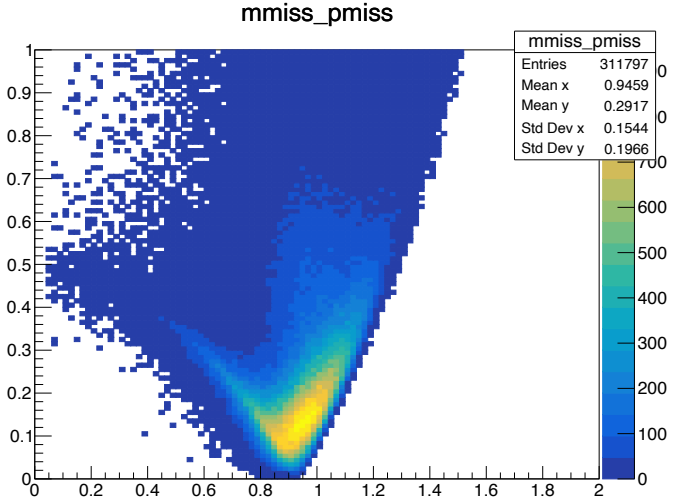


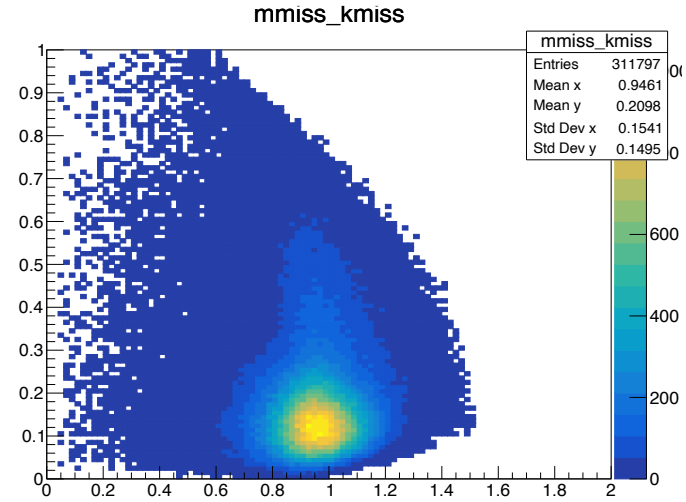


Kmiss in CD Data

$$k^2_{miss} \equiv m^2_N \left(\frac{p^2_{miss,\perp} + m^2_N}{p^-_{miss}(2m_N - p^-_{miss})} \right) - m^2_N$$

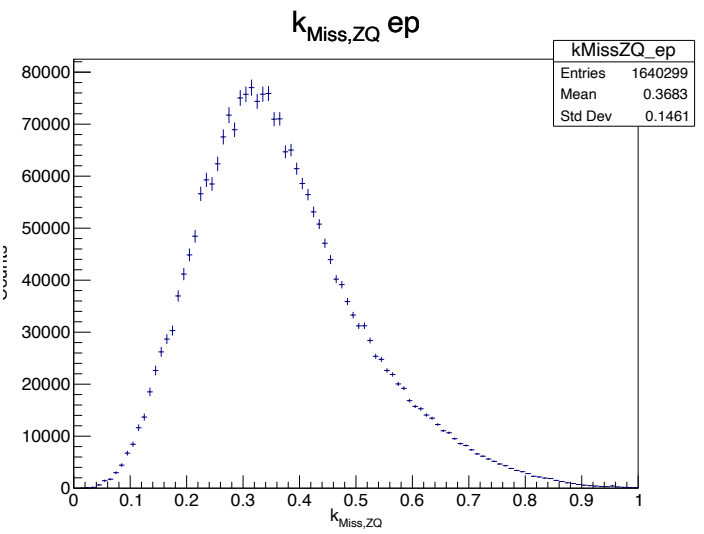


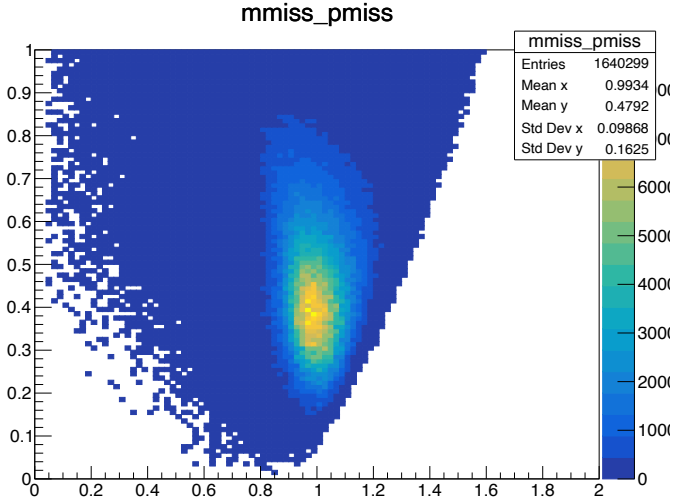


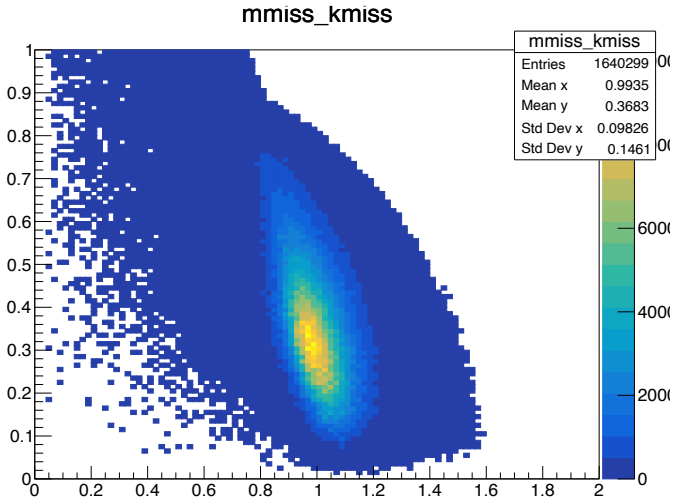


Kmiss in CD Sim

$$k^2_{miss} \equiv m^2_N \left(\frac{p^2_{miss,\perp} + m^2_N}{p^-_{miss}(2m_N - p^-_{miss})} \right) - m^2_N$$

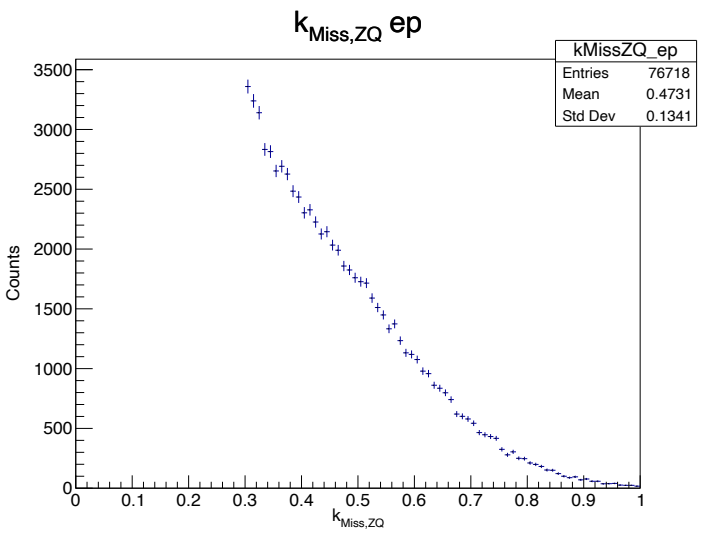


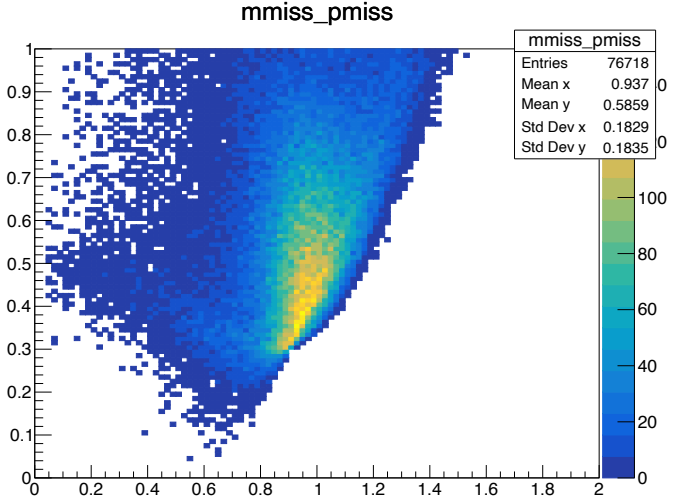


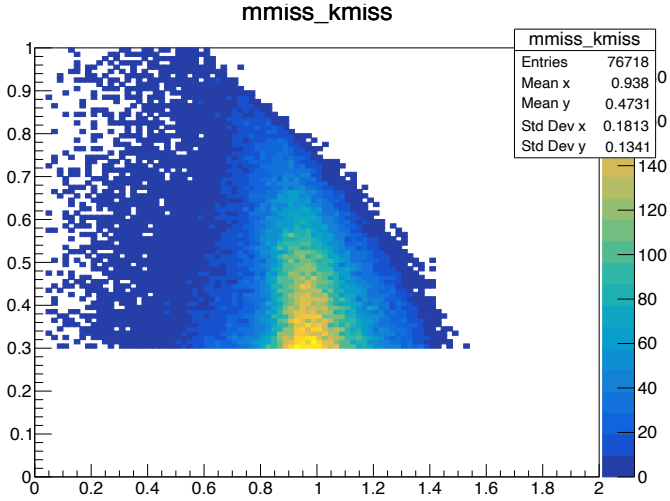


Kmiss Cut in CD Data

$$k^2_{miss} \equiv m^2_N \left(\frac{p^2_{miss,\perp} + m^2_N}{p^-_{miss}(2m_N - p^-_{miss})} \right) - m^2_N$$

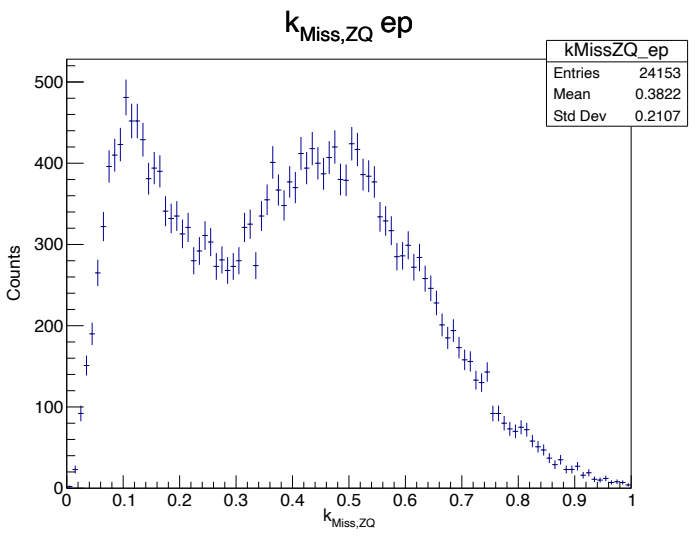


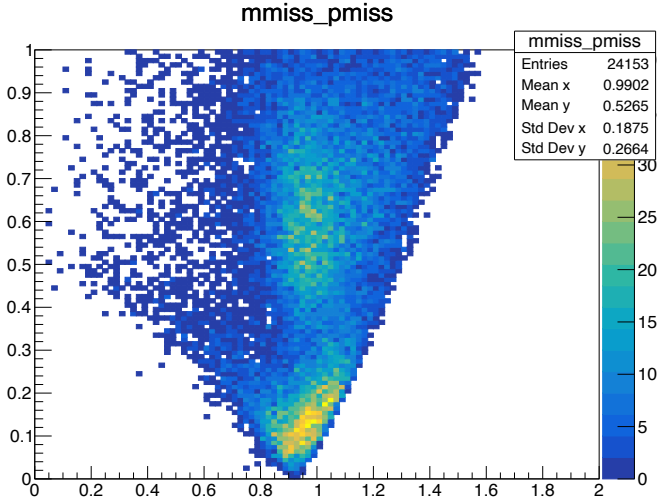


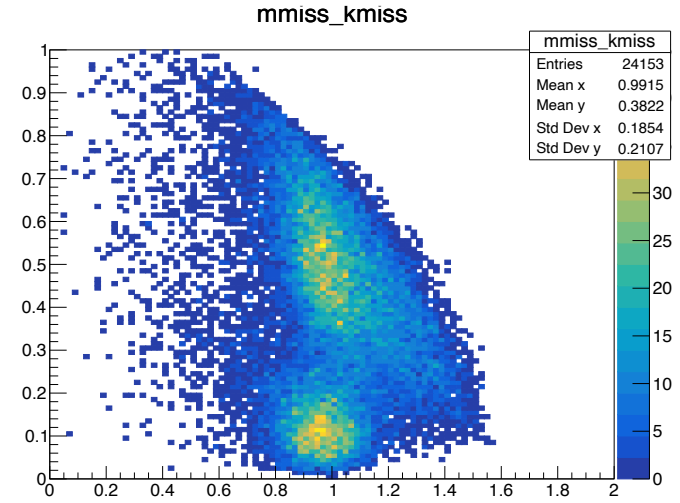


Kmiss in FD Data

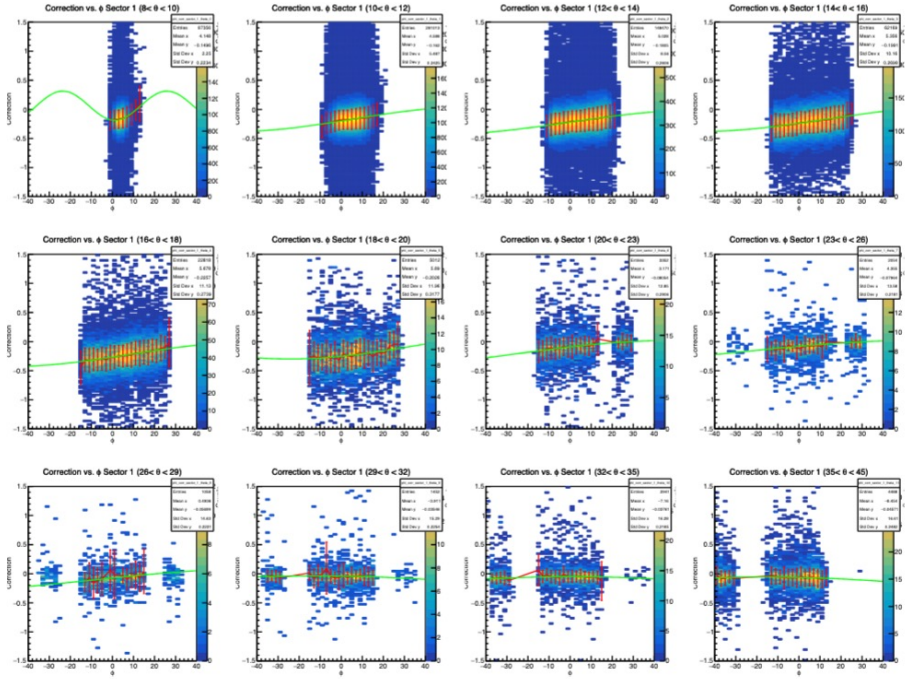
$$k^2_{miss} \equiv m^2_N \left(\frac{p^2_{miss,\perp} + m^2_N}{p^-_{miss}(2m_N - p^-_{miss})} \right) - m^2_N$$







Angular Correction



Momentum Correction