RG-M Analysis Update

Andrew Denniston

Overview

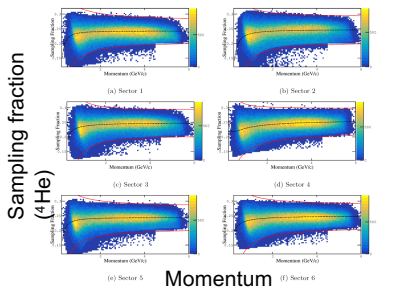
- Run Group M Introduction
- Proton and Electron Cuts
- Neutron Algorithms
- LAr target
- Physics Analyses
  - Short Range Correlations (SRCs)
  - Electrons for Neutrinos (e4v)

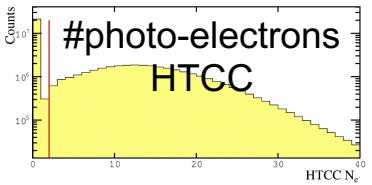
RG-M Experiment at CLAS12

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

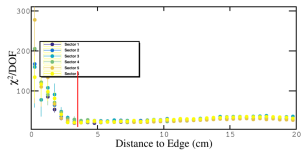
Particle ID for Electrons in 6 GeV data

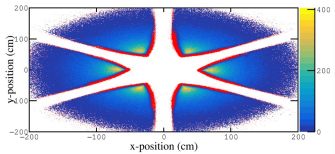
(charge, HTCC photo-electrons, ΔE(PCal), Sampling fraction)



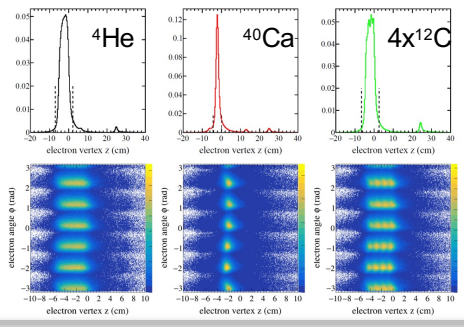


Fiducial Cuts

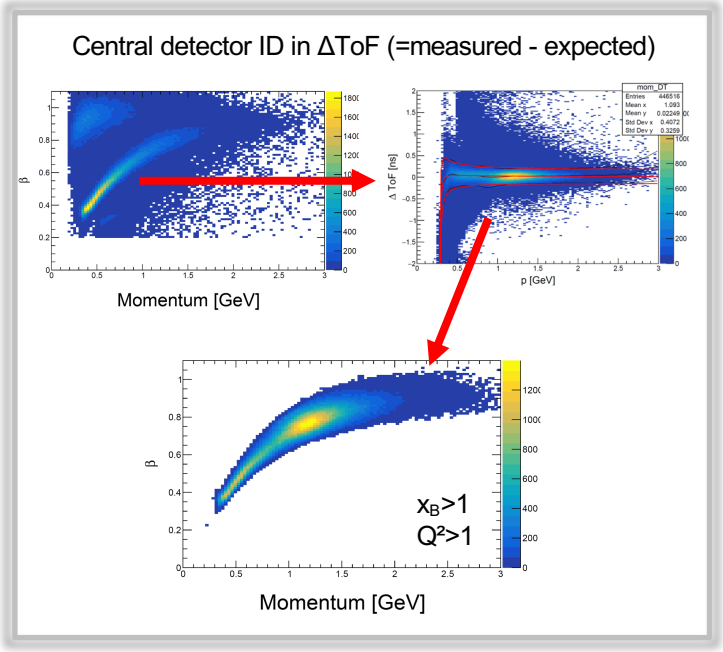


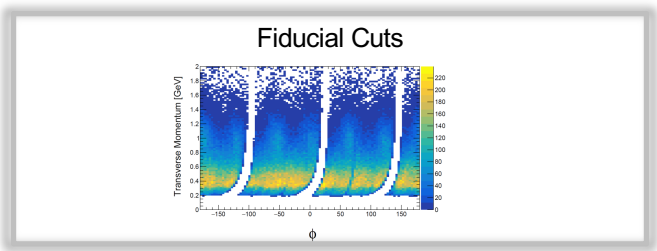


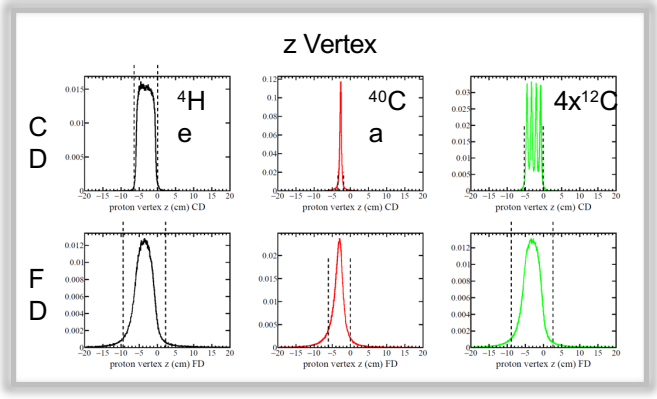
z Vertex



Particle ID for Protons in 6 GeV data



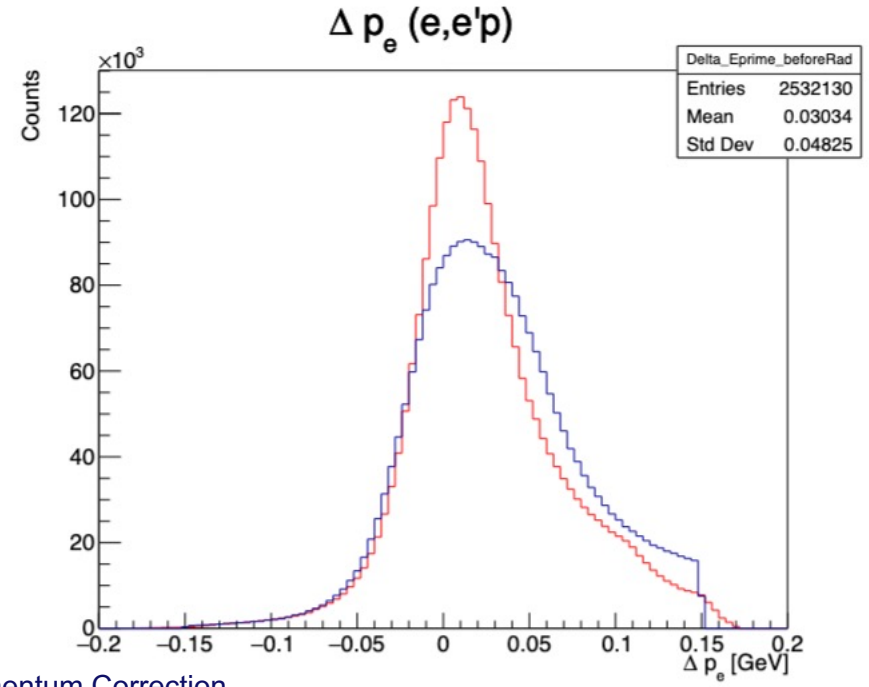




Additional on Detector Level Analysis

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

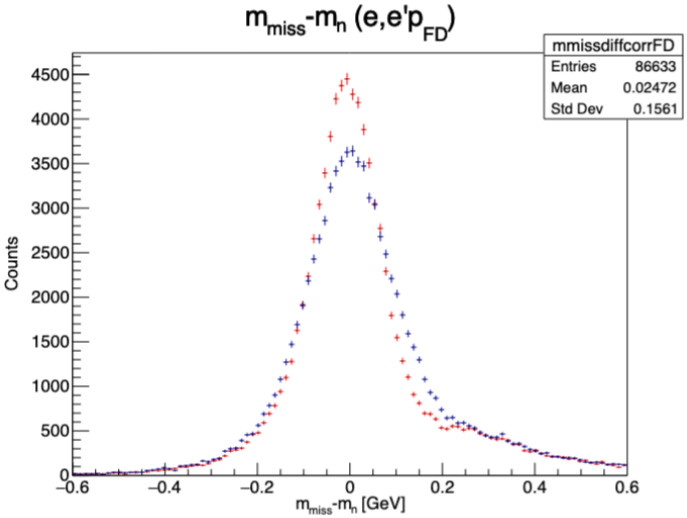
Momentum Corrections Improve Resolution

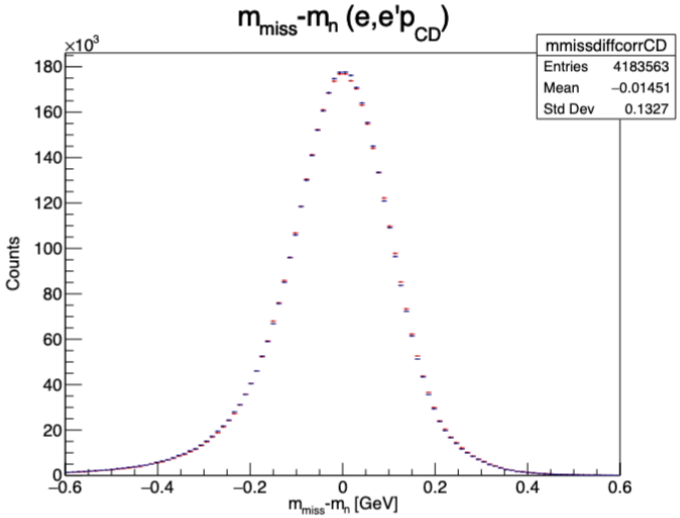


Before Momentum Correction

After Momentum Correction

Applying Corrections to d(e,e’p)n

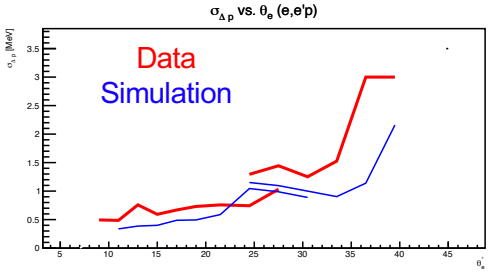


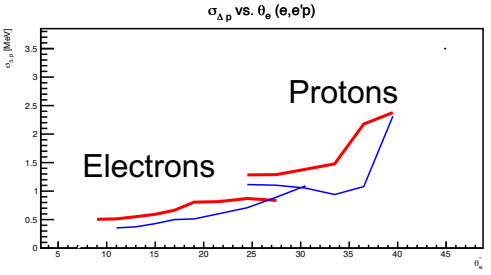


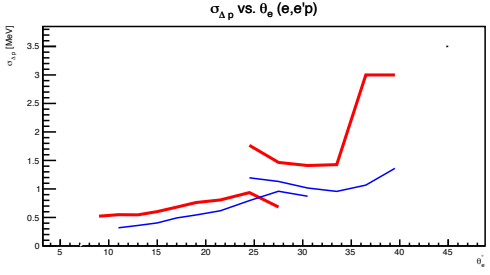
Before Momentum Correction
After Momentum Correction

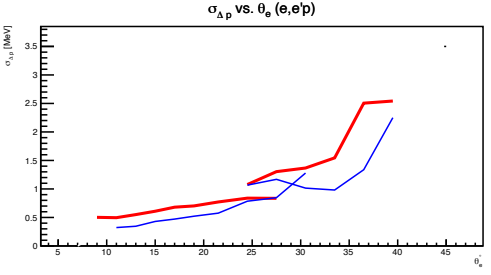
Data vs. Simulation

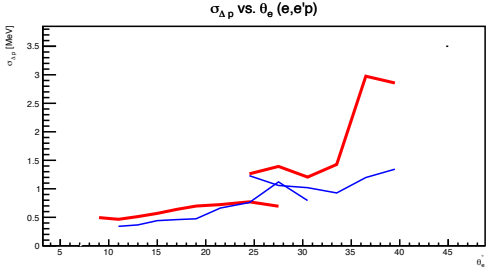
Resolution $\frac{p_{angle} - p}{p_{angle}}$

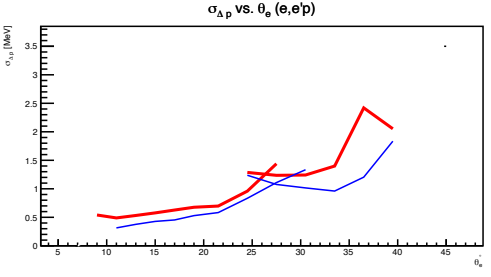






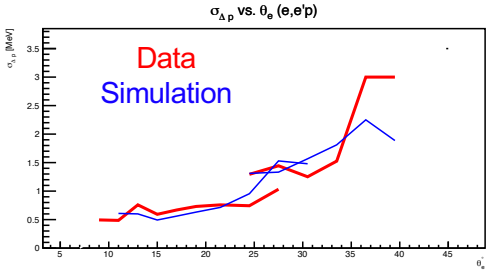


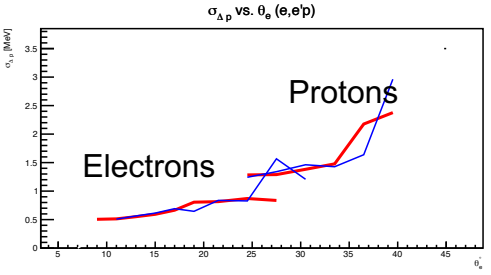


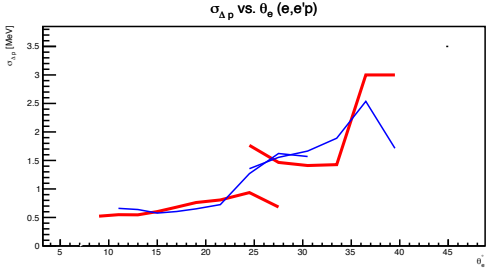


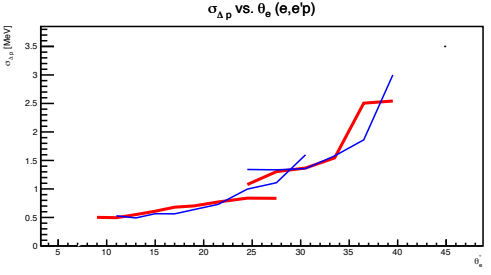
Data vs. Simulation with Smearing

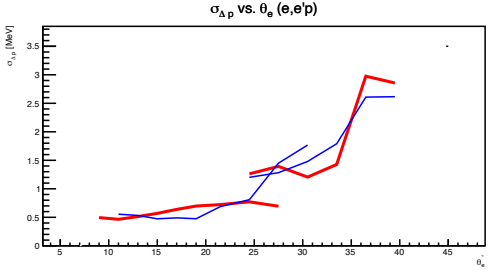
Resolution $\frac{p_{angle} - p}{p_{angle}}$

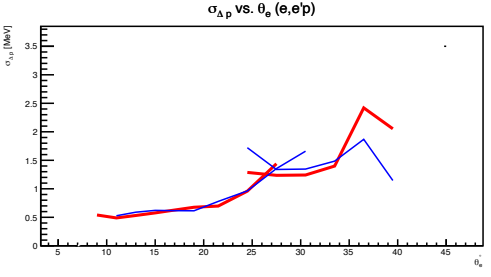












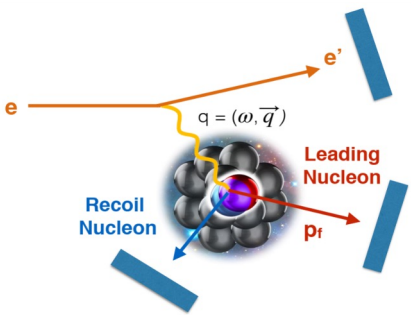
Particle ID for 6 GeV data

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

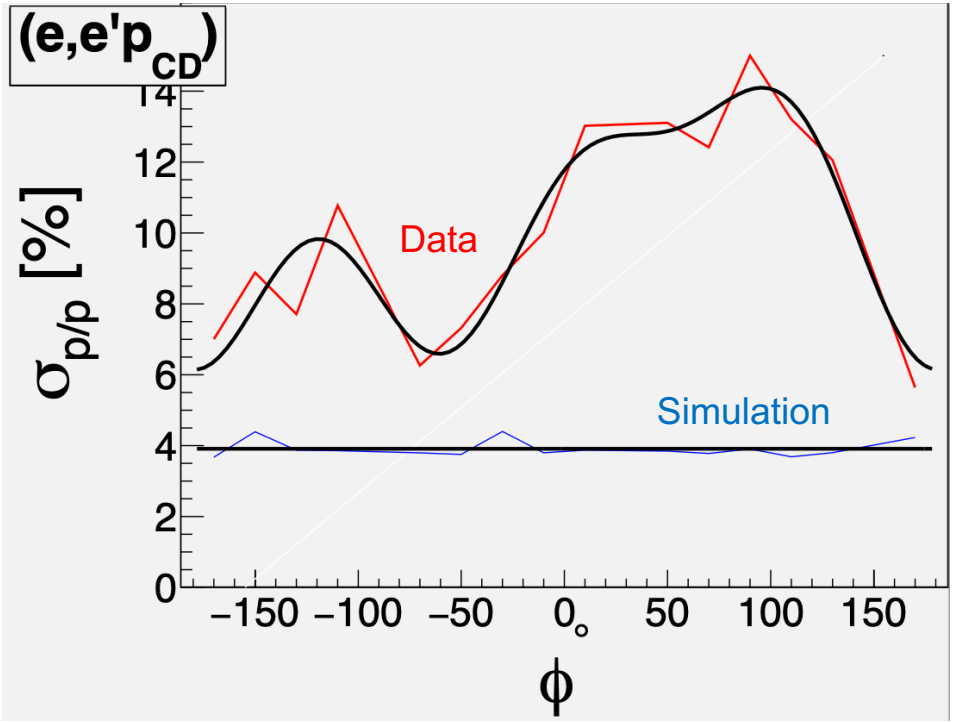
Andrew Denniston[1], Justin Estee[1], Julian Kahlbow[1], and Erin Marshall Seroka[2]

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

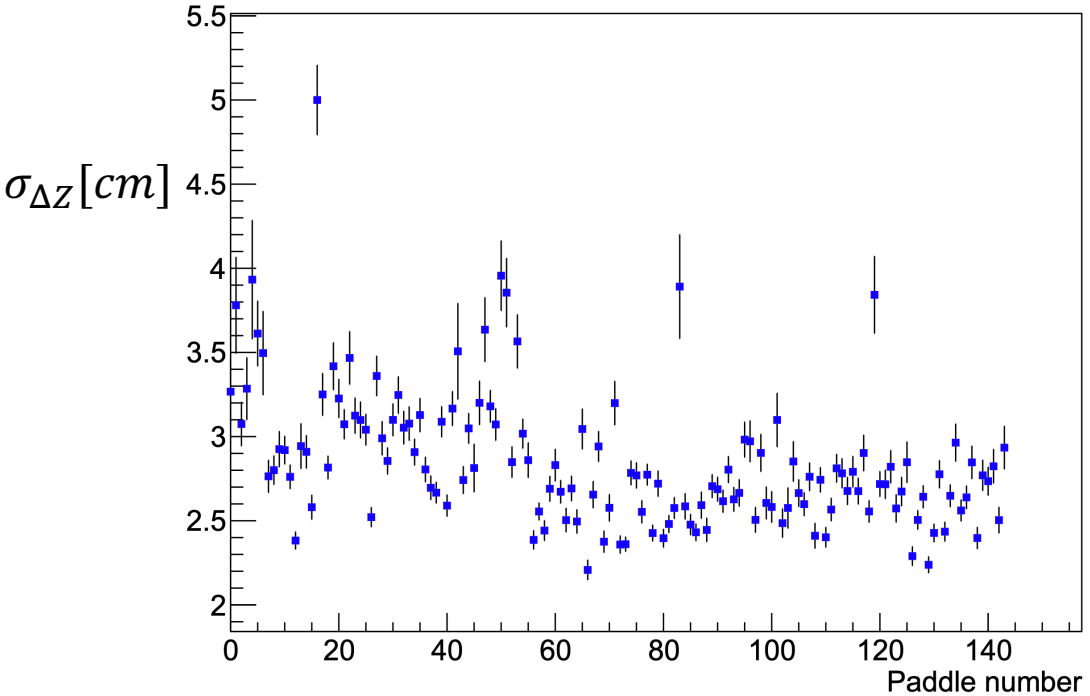
→ Re-submit “General“ Analysis Note Soon



Central Detector Momentum Resolution



Central Detector Hit Resolution



$$\Delta Z = Z_{CND,Hit} - Z_{CVT,Trajectory}$$

Pierre Chatagnon Thesis

Particle ID for 6 GeV data

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

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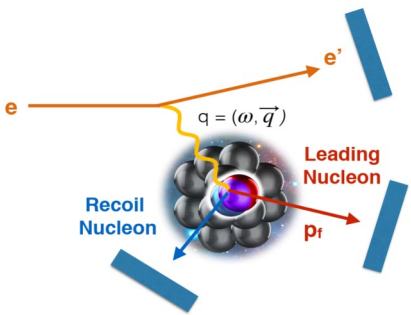

Overview

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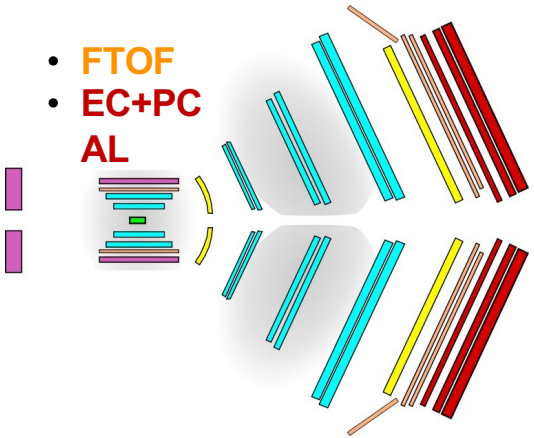
  - Electrons for Neutrinos (e4v)

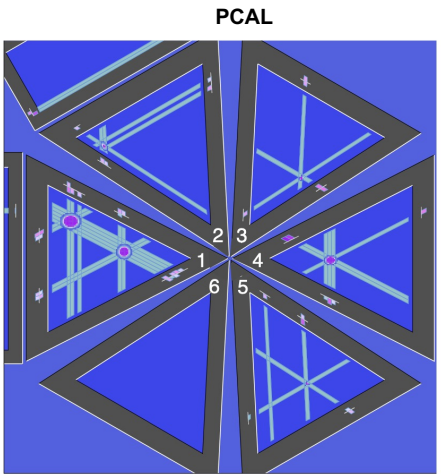
Neutrons

- ECAL Neutrons
- CND Neutrons
- BAND Neutrons

ECAL Neutrons (Ron Wagner)

- Collect all neutral and charged particle related hits in the FTOF, PCAL, ECAL.

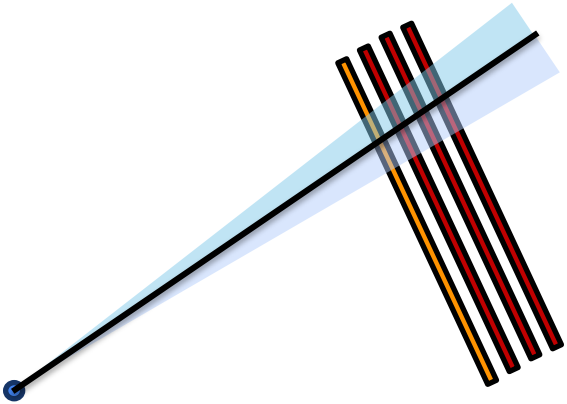


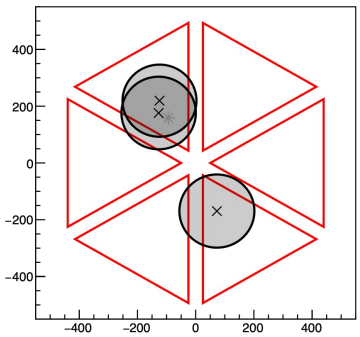


ECAL Neutrons (Ron Wagner)

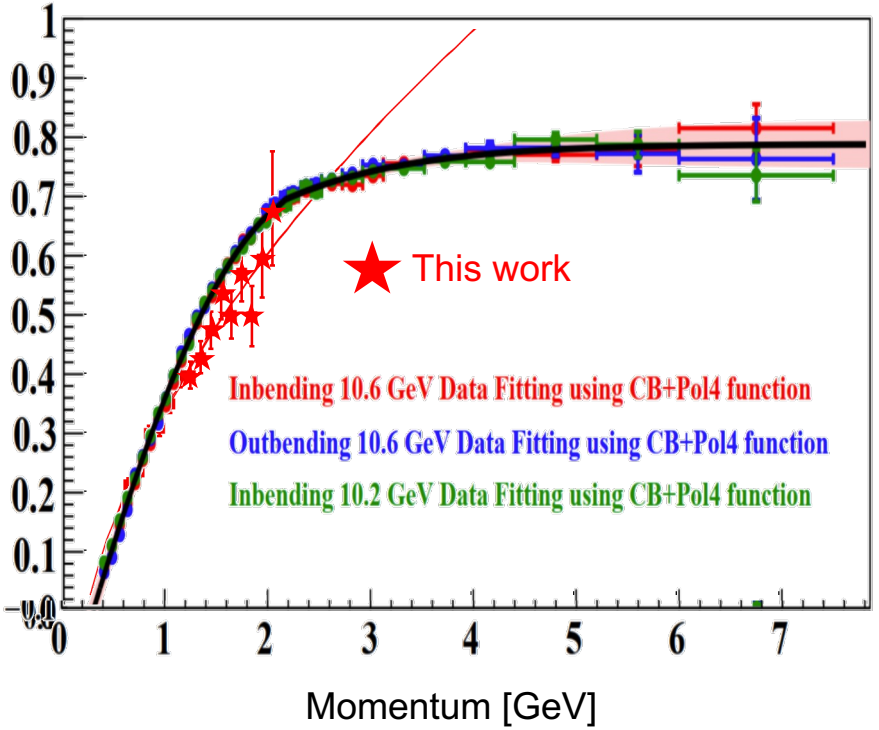
- For each neutral hit in the EC+PCAL check the following:
  - Was there a neutral hit in the FTOF that is related to it?
  - Was there a charge hit in the EC+PCAL layers near it?
  - Was there a neutral hit in the layers behind it?
  - Was there a neutral hit in the same layer?

Related:
- Same sector
- Inside the angular cone
- Close ToF





ECAL Neutrons (Ron Wagner)



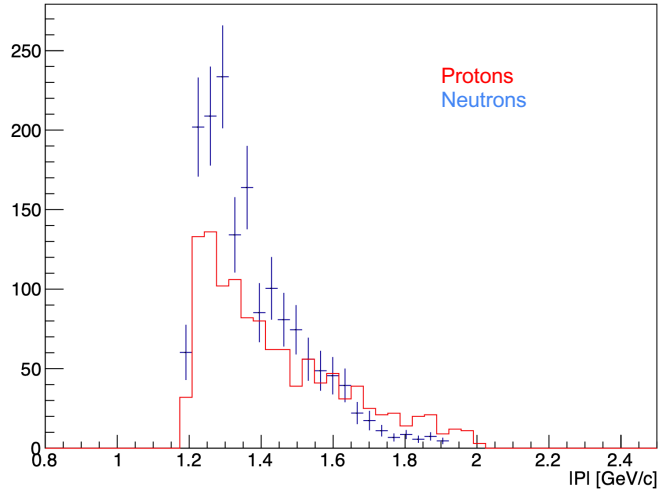
ECAL Neutrons (Ron Wagner)

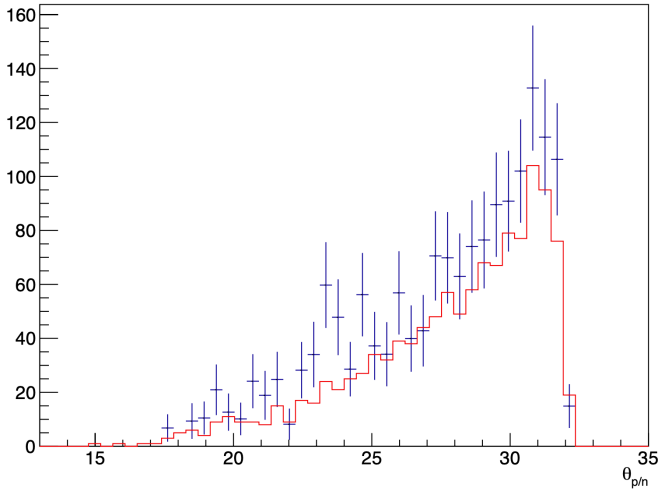
- To validate the above procedure we calculated the (e,e'p)/(e,e'n) ratio.
- This was done after smearing the protons and correct the efficiency.
- We also scale it with σ_n/σ_p, the ratio of the cross section of interacting with neutron or proton.
- We acceptance match the protons and neutrons to only include regions of phase space where both particles have maximum acceptance.

A – a symmetric nuclei

$$\frac{A(e,e'p)}{A(e,e'n)} = \frac{\gamma_n \cdot \#(e,e'p)}{\#(e,e'n)} \cdot \frac{\sigma_n}{\sigma_p}$$

ECAL Neutrons (Ron Wagner)



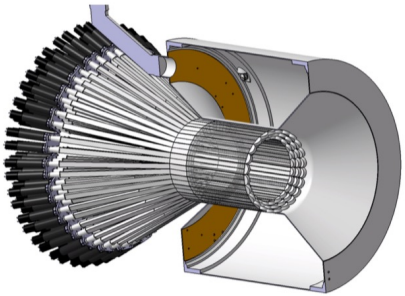


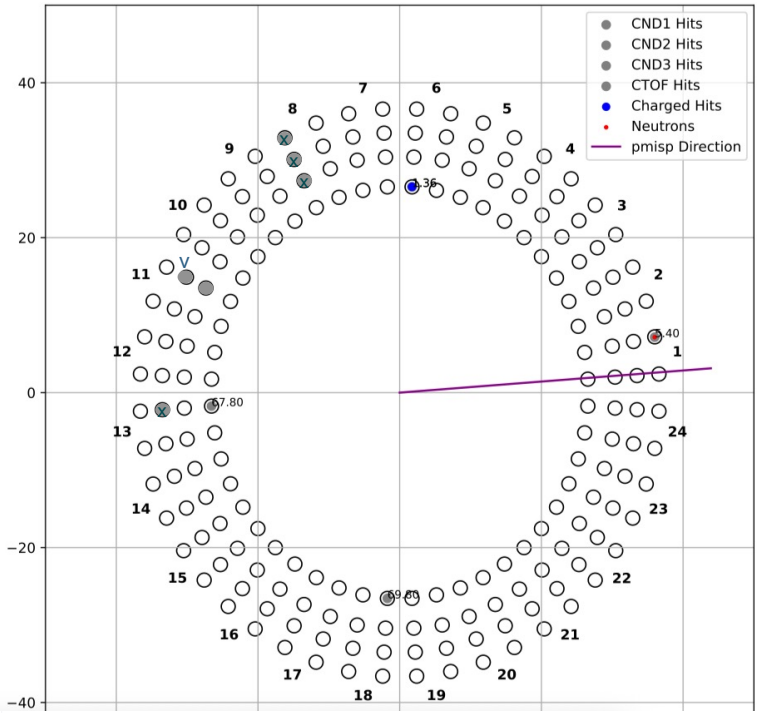
Neutrons

- ECAL Neutrons
- CND Neutrons
- BAND Neutrons

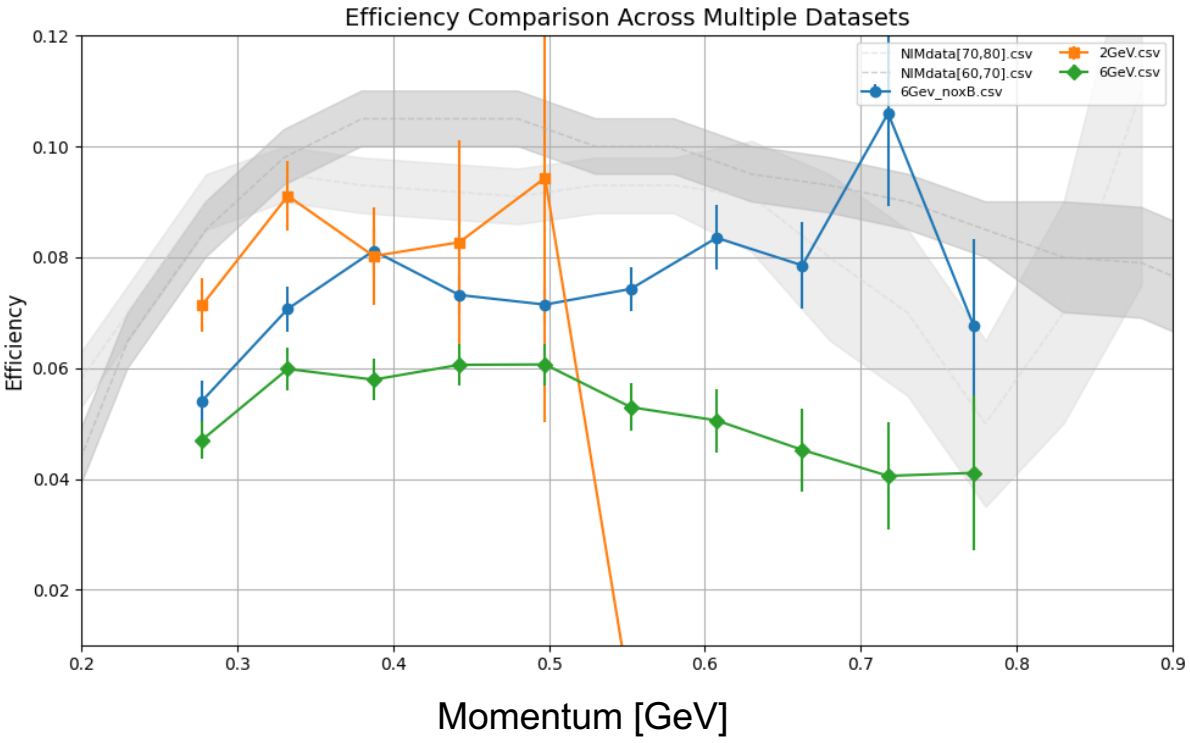
CND Neutrons (Igor Parshkin)

- Remove all hits on the same sector as charged hits
- Remove all simultaneous hits on all 3 layers of CND
- Remove all hits on the same sector as a simultaneous CTOF hit
- Combine all hits and their energies on the same sector into one

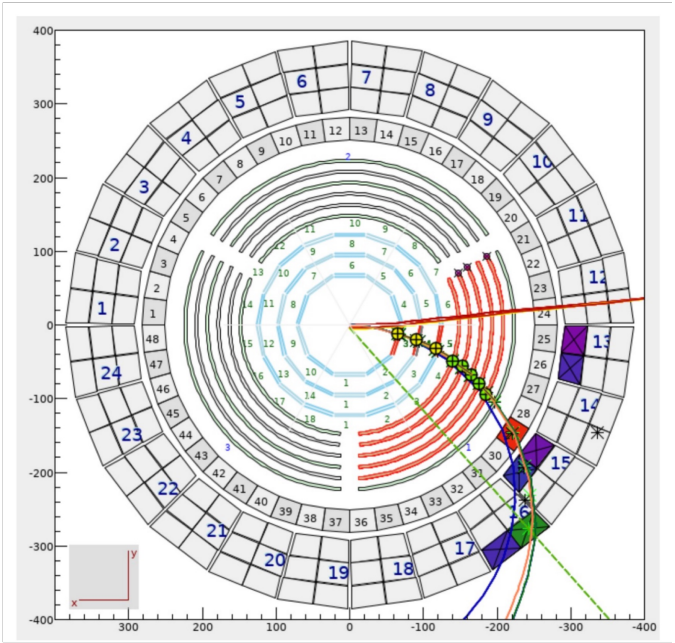




CND Neutrons (Igor Parshkin)



CND Neutrons



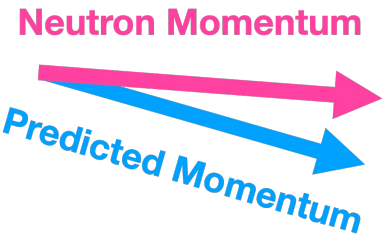
CND Neutrons (Natalie Wright & Shakuntala Mitra)

Exclusive topologies from 2 GeV deuterium data

Signal: Correctly ID'd neutrons $d(e, e'pn)$

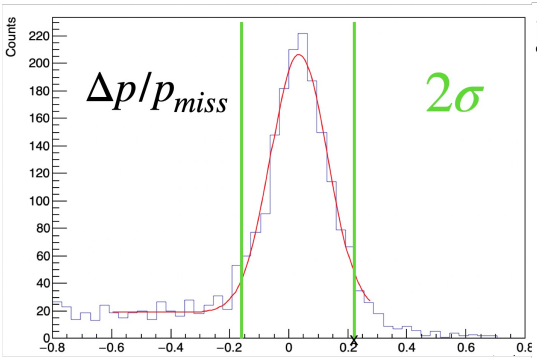
Background: Protons ID'd as neutrons $d(e, e'p\pi^- n)$

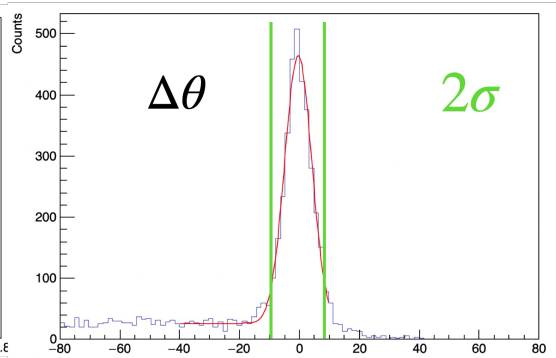
Protons ID'd as protons $d(e, e'p\pi^- p)$



QE Selection:

$M_{miss} < 1.02$



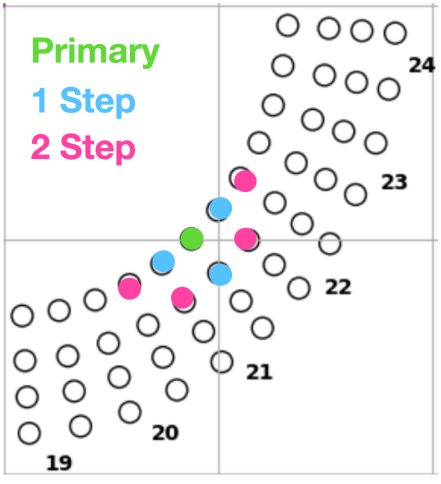


CND Neutrons (Natalie Wright & Shakuntala Mitra)

If multiple hits attributed to particle:

Define primary hit in CND based on highest Edep

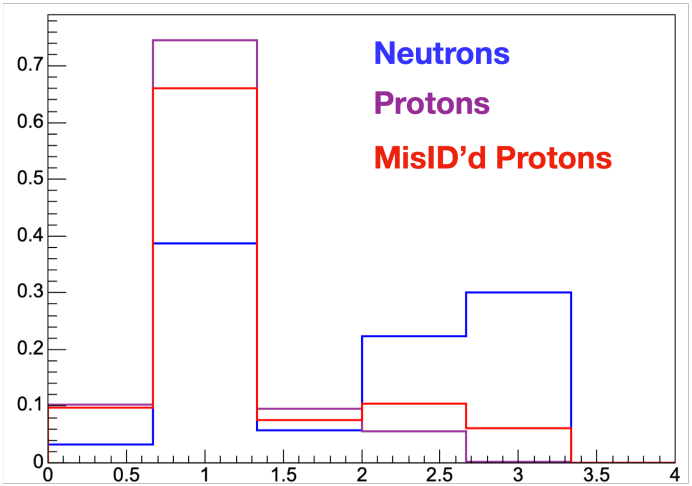
Calculate features (nearby energy, hits, etc) relative to number of ‘steps’ away



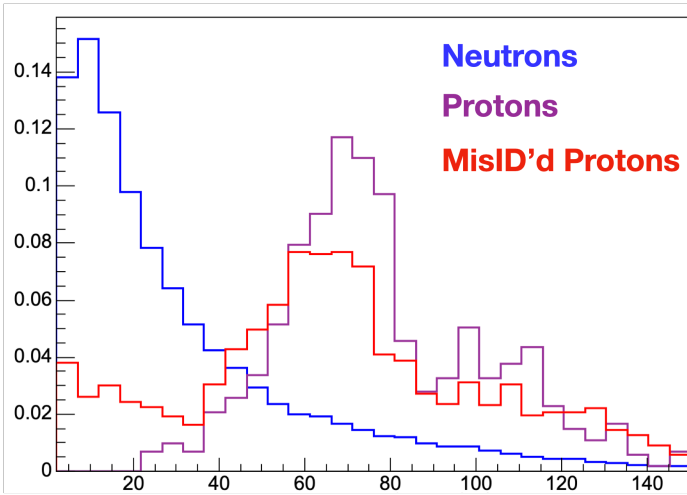
x

CND Neutrons (Natalie Wright & Shakuntala Mitra)

2 Most Important Features



CND Hit Layer / Number of CND hits



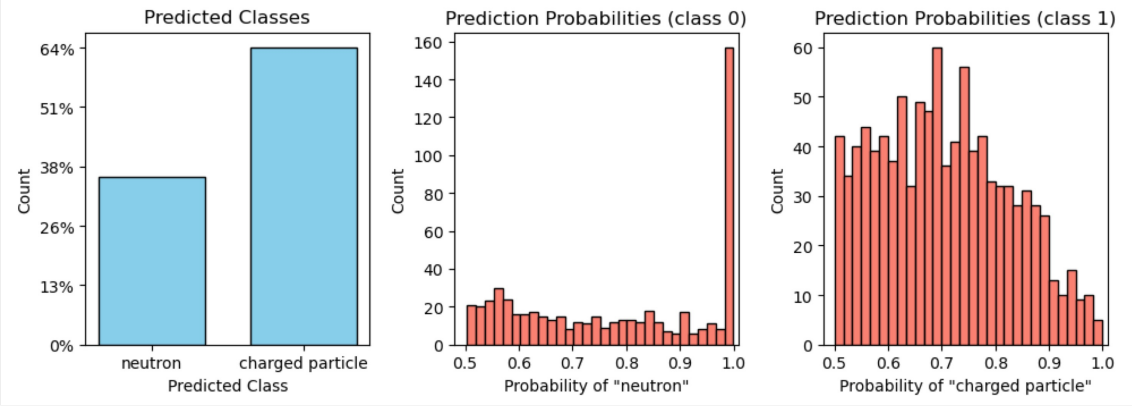
Total CND+CTOF Edep in < 3 Steps

x

Initial results show ~ 65% veto rate

From a subset of $d(e, e'p\pi^{-}n)$ selection

Originally, 100% misclassified as neutrons → now 65% classified as charged particles



x

Next Steps

Optimize ANN parameters

Create larger training samples

Determine if/which manual cuts are complementary

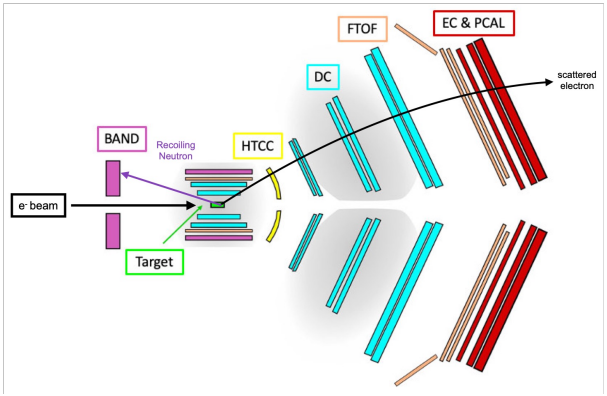
Validate on known ep/epN measurements

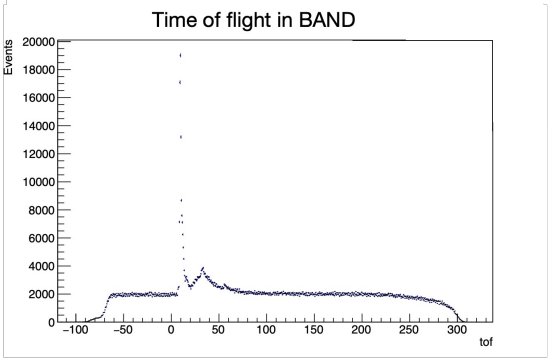
Neutrons

- ECAL Neutrons
- CND Neutrons
- BAND Neutrons

BAND Neutrons (Sara Ratliff)

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





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Motivation

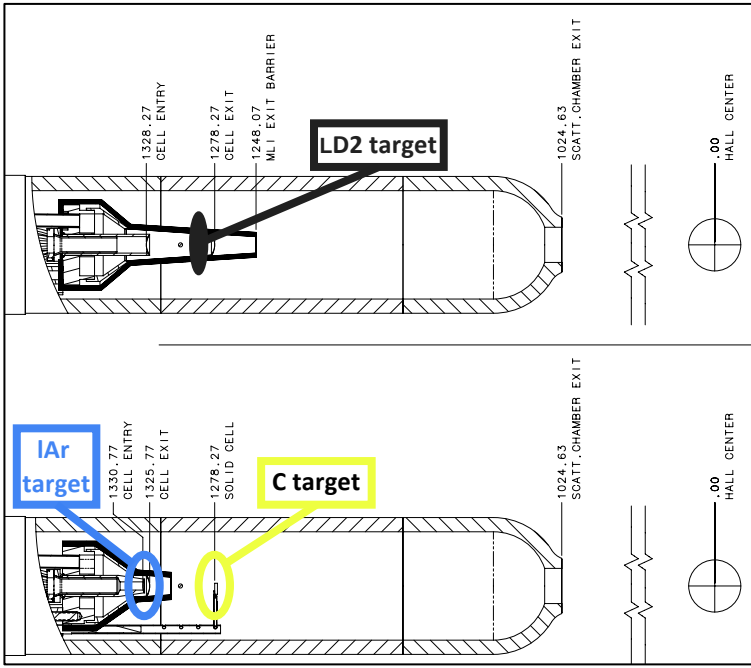
Goal: implement the combined **short-cryocell** and **1-foil** target in GEMC with updated experimental conditions

A new lAr target variation:

- Includes the 1-foil C and Sn
- The short-cryocell implementation is similar to that of the **LD2 target**

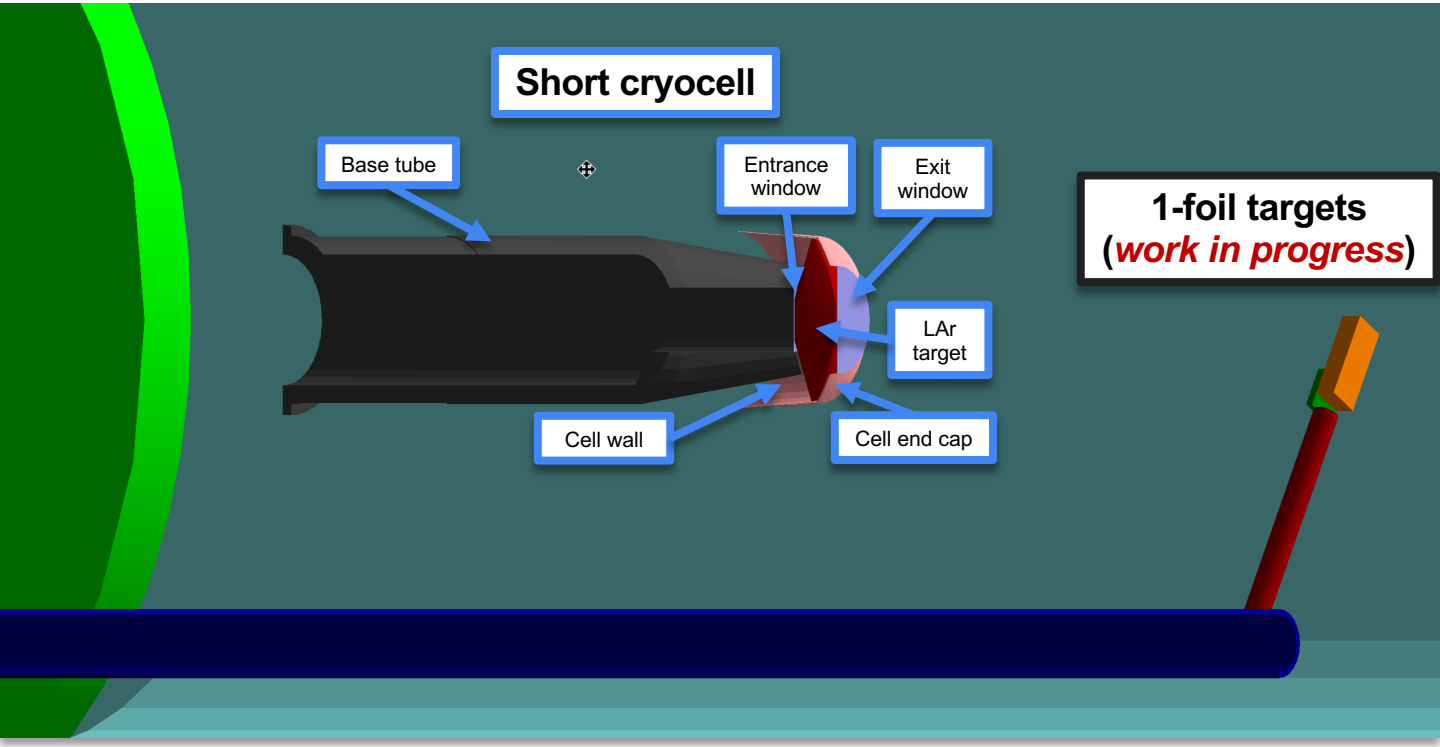
Updated 1-foil C target variations:

- The empty cryocell is present
- Small, 4-mm-wide, foils for 2 GeV runs
- Larger, 6-mm-wide, foils for 4 GeV runs
- Correction for the C foil position along the beamline (***work in progress***)



Source: technical drawing No. BM2101-02-00-0000

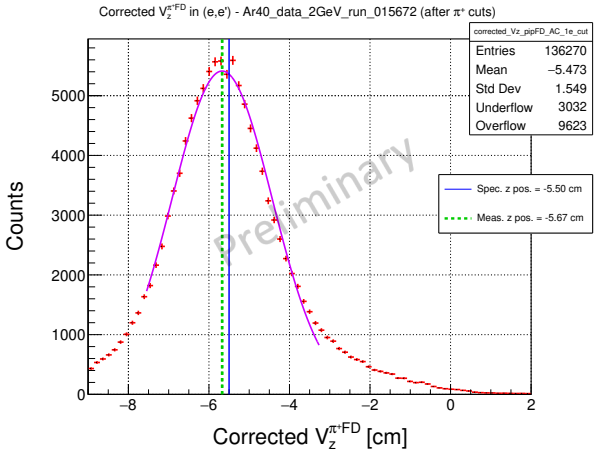
The new RG-M targets



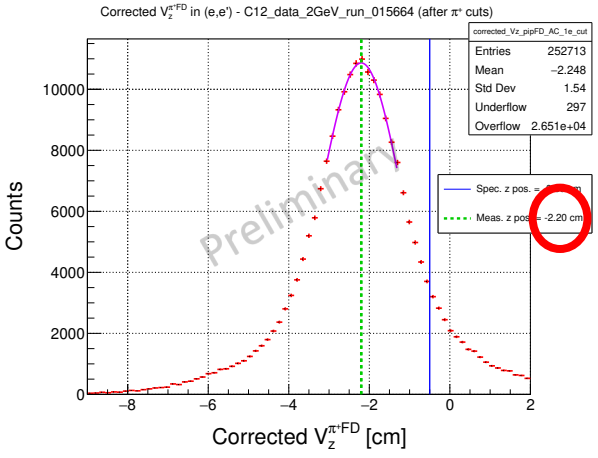
Alon Sportes

Corrected $V_z^{\pi^{\pm FD}}$ plots

Ar40_data_2GeV_run_015672



C12_data_2GeV_run_015664



$\pi^{\pm}$ cuts = electron PID cuts + $\pi^{\pm}$ PID cuts + dV_z cuts

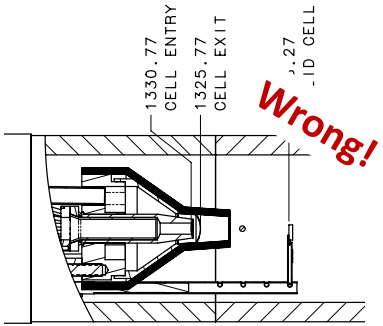
Notation: $\pi^{\pm FD}$ = FD $\pi^{\pm}$

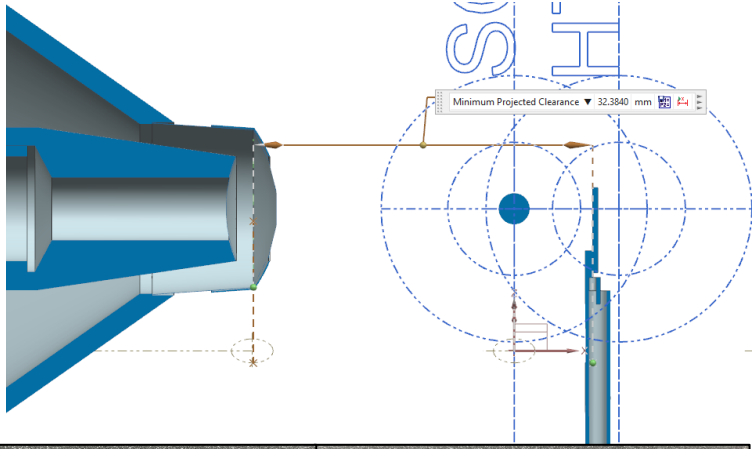
New target measurements

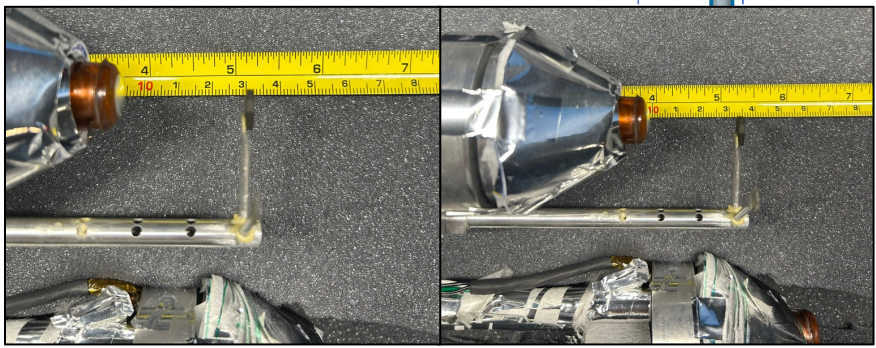
- **In the previous update:** we have seen that the C is approximately 3.5 cm from the lAr target

- This result seems to be consistent with recent measurements of both CAD models and the cryocell

⇒ **The technical drawing is wrong!**







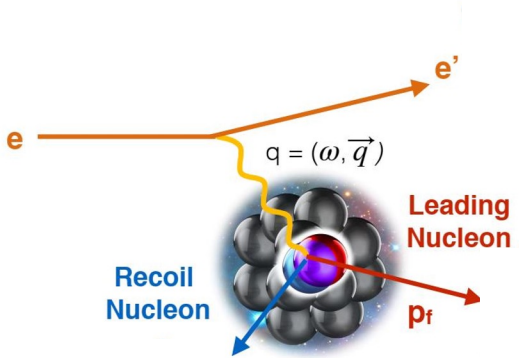
Source: Bob Miller

Overview

- Run Group M Introduction
- Proton and Electron Cuts
- Neutron Algorithms
- LAr target
- Physics Analyses
  - Short Range Correlations (SRCs)
  - Electrons for Neutrinos (e4v)

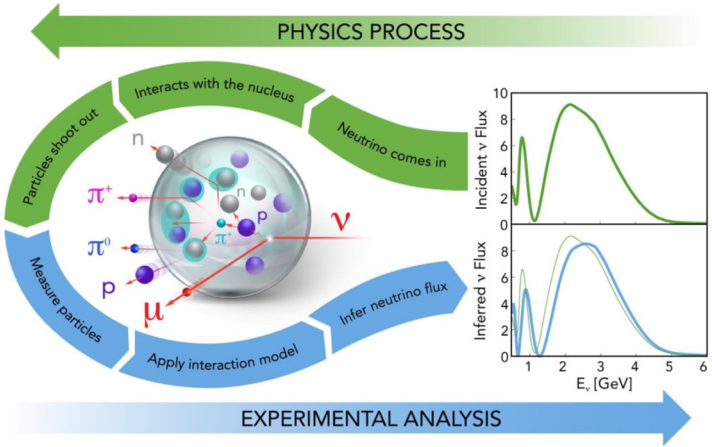
Run Group-M Proposals

Short Range Correlations

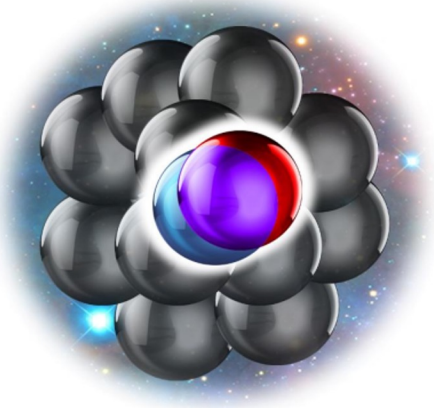


- (e,e') inclusive
- (e,e'N)
- (e,e'NN)

Electrons for Neutrinos (e4ν)

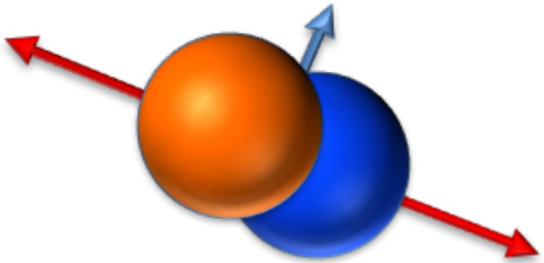


Short range, short lived,
highly correlated pairs



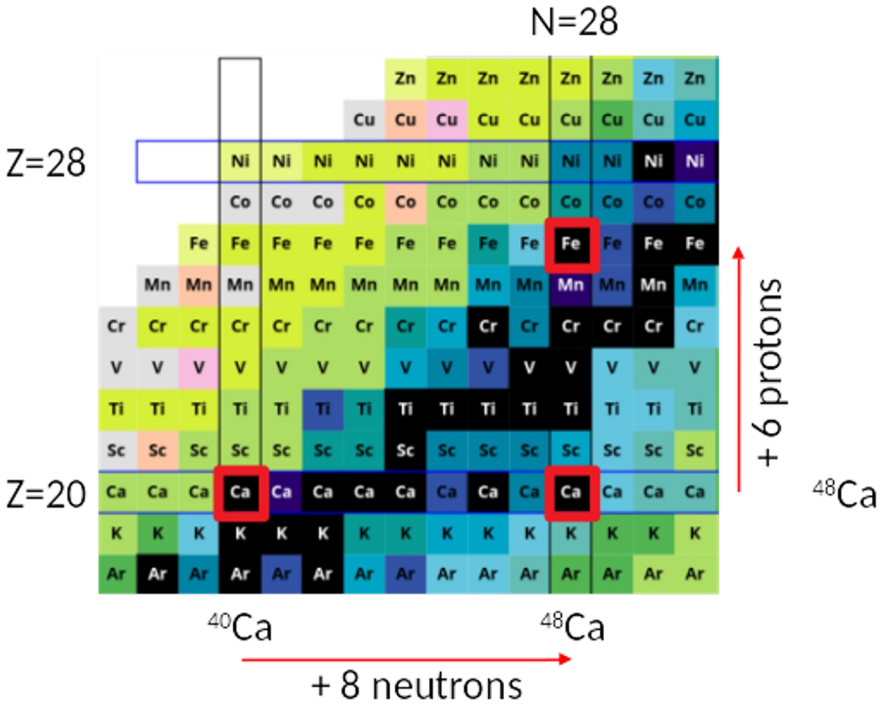
r-space

High relative momentum
Low center of mass momentum

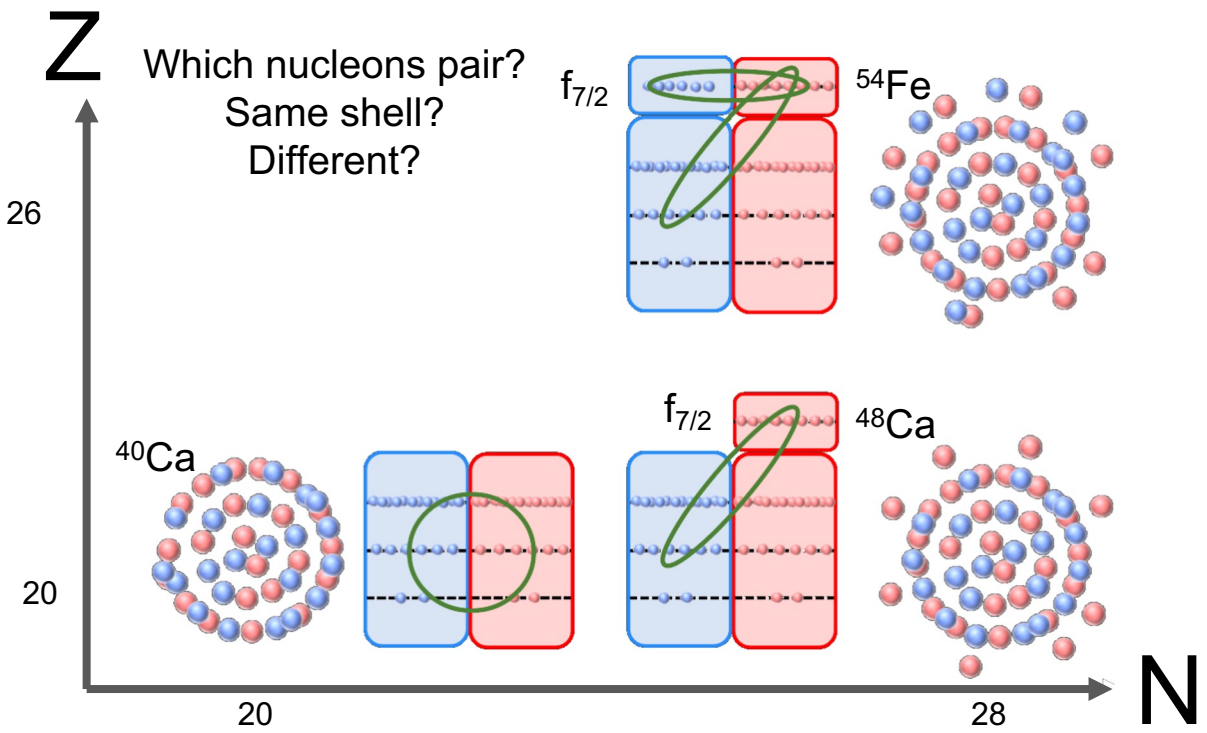


k-space

SRCs in Asymmetric Nuclei



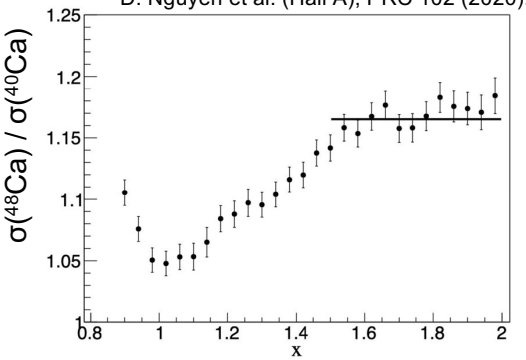
SRCs in Asymmetric Nuclei



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

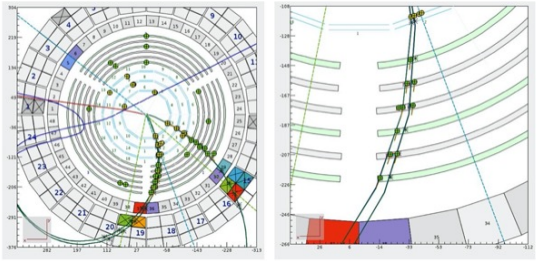
- (e,e’)
- (e,e’p)
- (e,e’n)
- (e,e’pp)
- (e,e’pn)

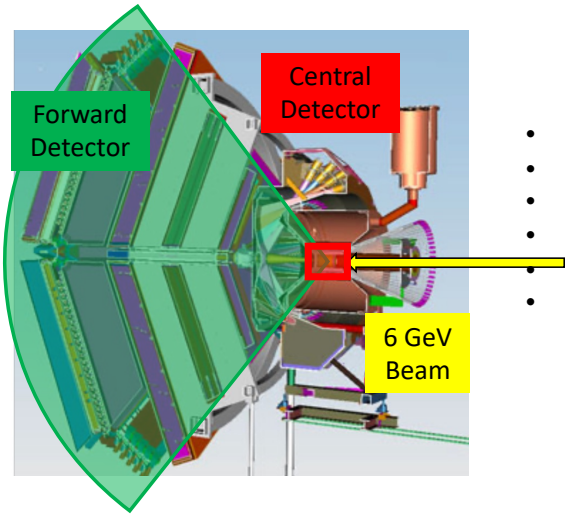
Hall C experiment 2022, under analysis: ^{40}Ca, ^{48}Ca, ^{54}Fe, ^{197}Au

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

SRC Event Selection

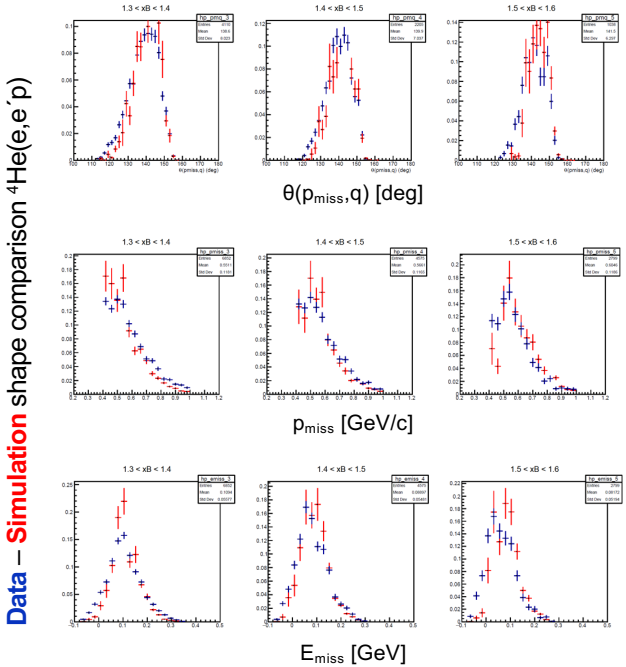
1. $1.2 < x_B < 2$
2. $1.5\ GeV^2 < Q^2$
3. $1.0\ GeV < p_{Lead}$
4. $0.3\ GeV < k_{Miss} < 1.0\ GeV$
5. $0.65\ GeV < m_{Miss} < 1.1\ GeV$
6. $\theta_{Lead} < 37°$





- 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
- Duer et al. Phys. Rev. Lett. 122, 172502 2019

SRCs in Asymmetric Nuclei



Good Agreement with SRC Simulation

SRCs in Asymmetric Nuclei

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

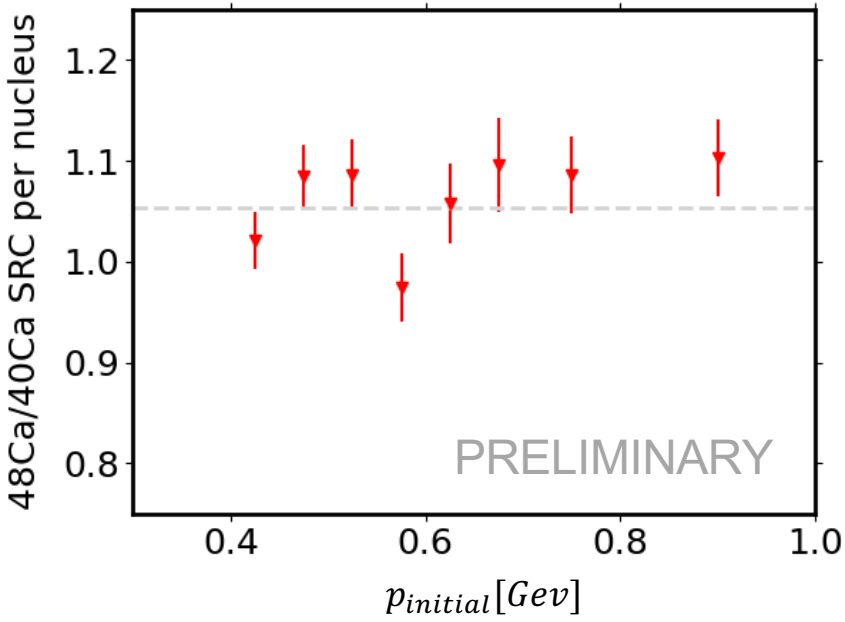
$$Ratio = \frac{yield_A/(N \cdot \rho_A)/T_A \cdot A \cdot \cancel{\epsilon}}{yield_{40Ca}/(N \cdot \rho_{40Ca})/T_{40Ca} \cdot A_{40Ca} \cdot \cancel{\epsilon}}$$

→ per nucleus yield ratio

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

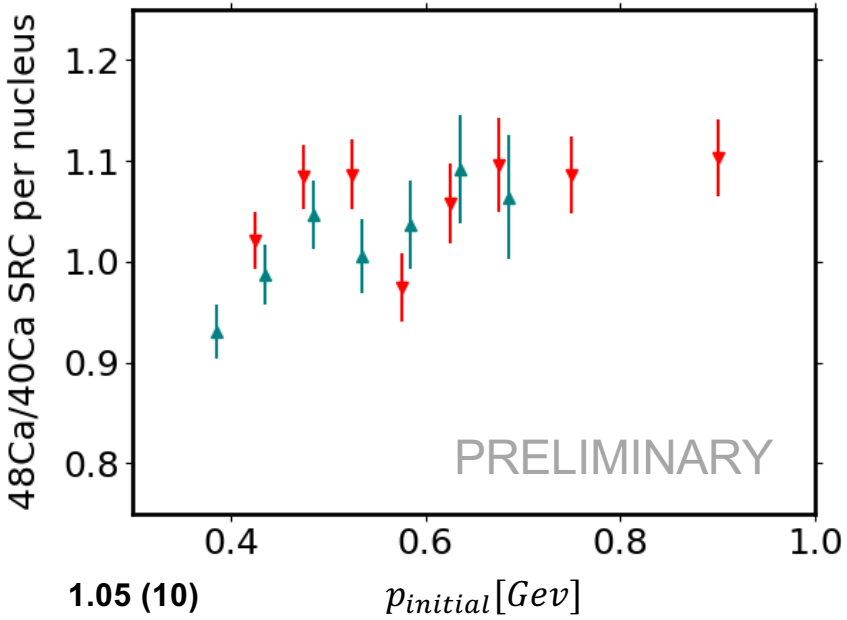
T : transparency
ϵ: detector efficiency

SRCs in Asymmetric Nuclei



≠ ~1.2

SRCs in Asymmetric Nuclei

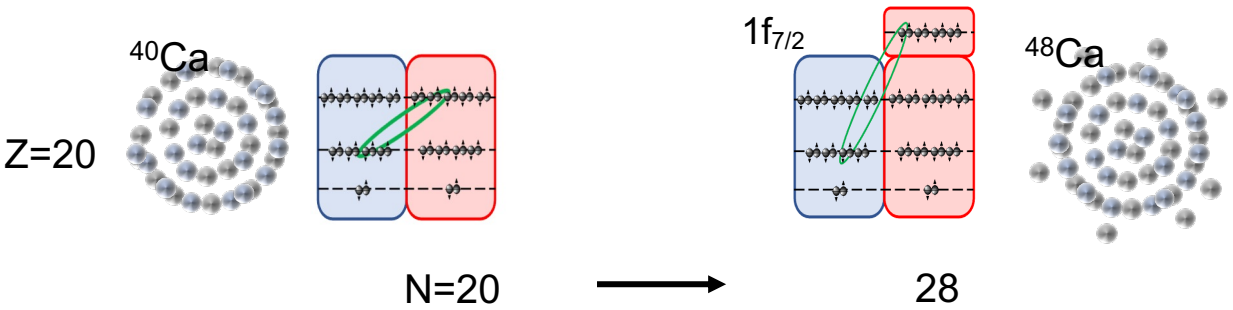


RG-M (Hall B) **1.05 (10)**

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

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

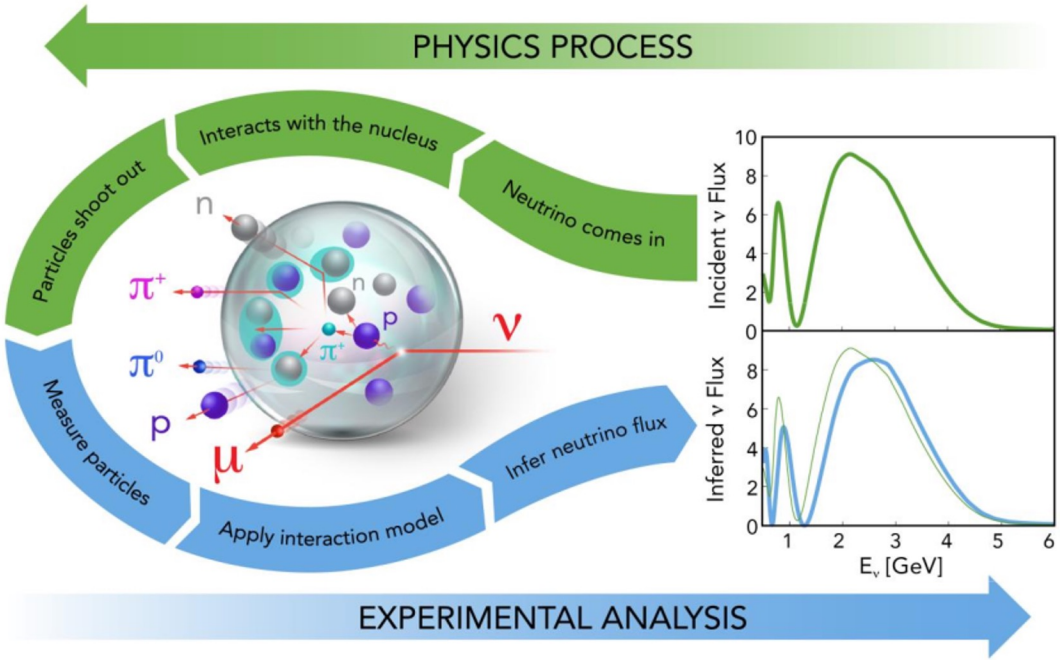
SRCs in Asymmetric Nuclei



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

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

Electrons for Neutrinos



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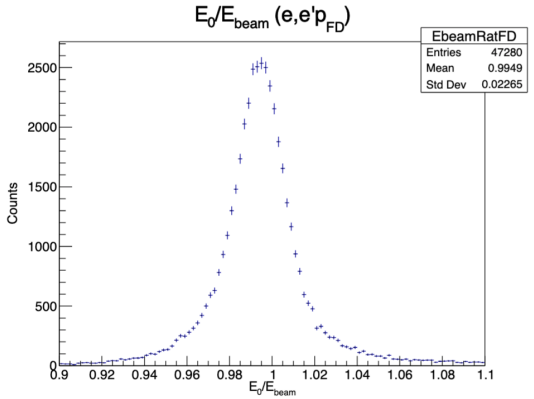
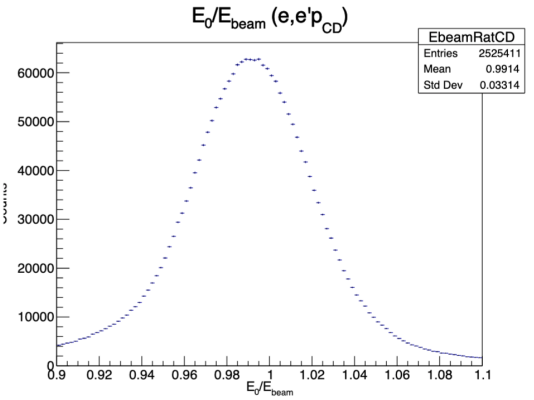
Backup

Use Elastic Scattering Angles to Calculate Beam Energy

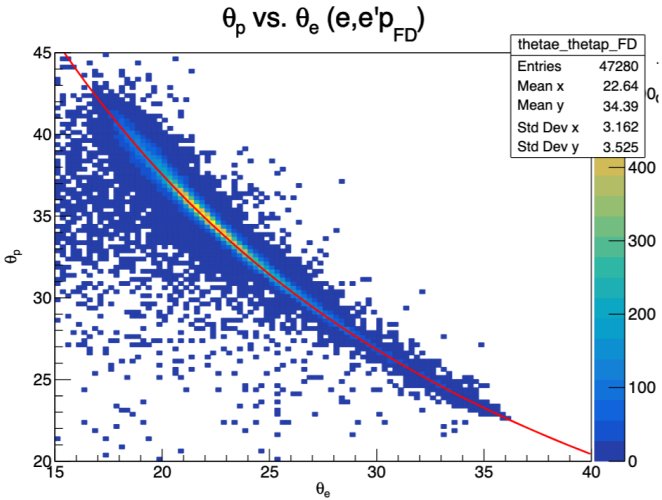
- $0.7\ GeV < W < 1.1 GeV$
- $-3° < \Delta\phi_{ep} < 3°$
- Separate events with a proton in the FD and CD

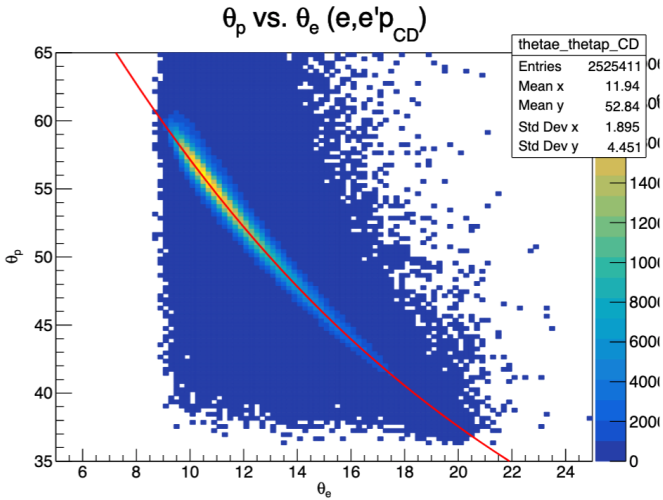
$$E_0 = m_N\left(\cot(\theta_e/2)\cot\left(\theta_p\right) - 1\right)$$





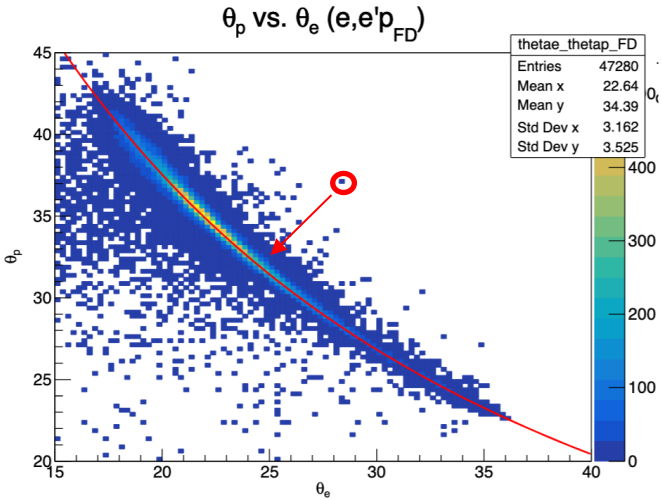
We use Elastic Kinematics to Correct the Electron and Proton at the same time

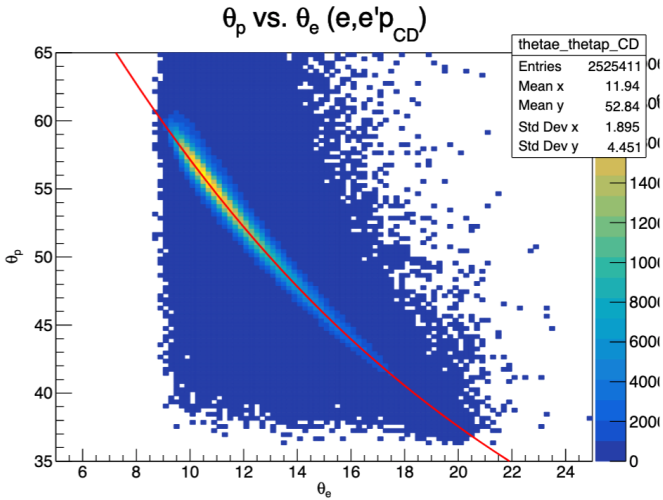




$$E_0 = m_N\left(\cot(\theta_e/2)\cot\left(\theta_p\right) - 1\right)$$

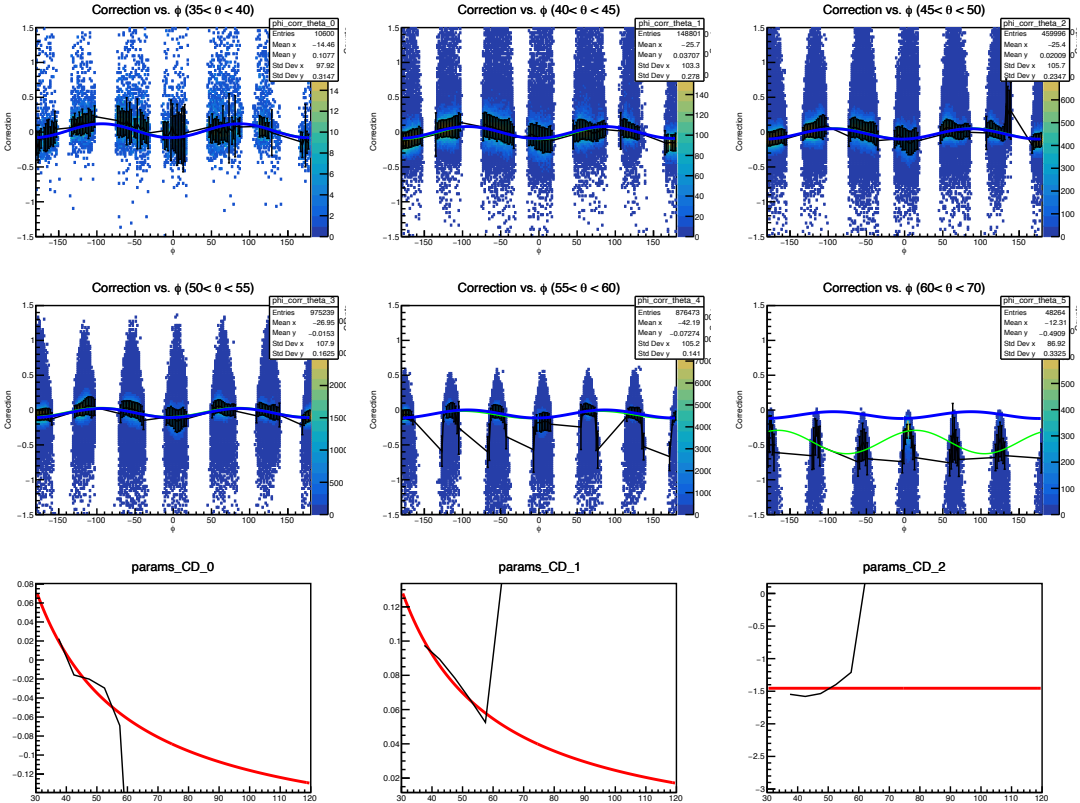
We use Elastic Kinematics to Correct the Electron and Proton at the same time



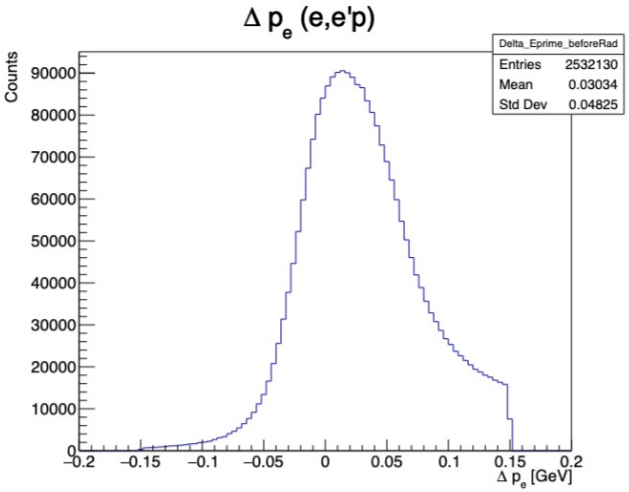


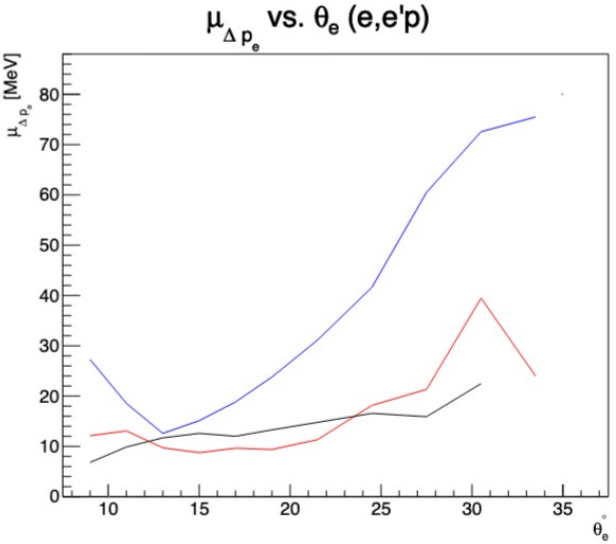
$$E_0 = m_N\left(\cot(\theta_e/2)\cot\left(\theta_p\right) - 1\right)$$

CD Angular Corrections



Momentum Correction of Electrons





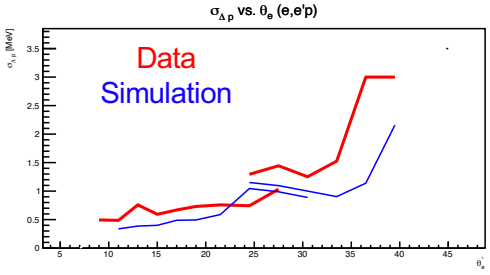
Before Momentum Correction

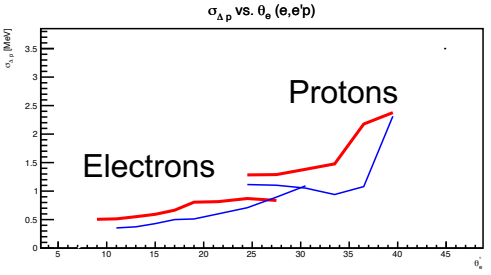
After Momentum Correction

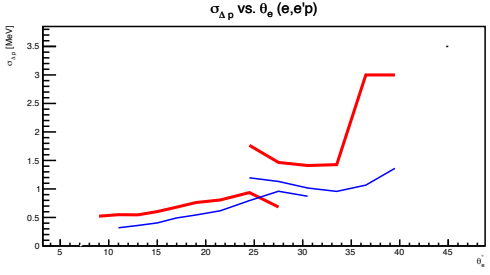
H(e,e'p) Simulation with Radiation

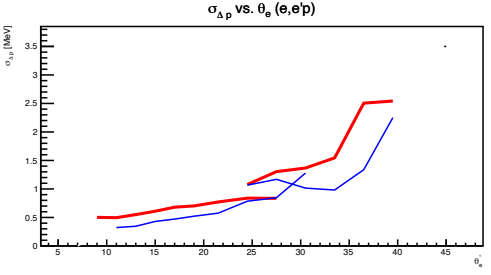
Data vs. Simulation

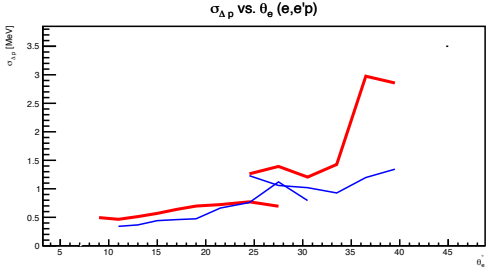
Resolution $\frac{p_{angle} - p}{p_{angle}}$

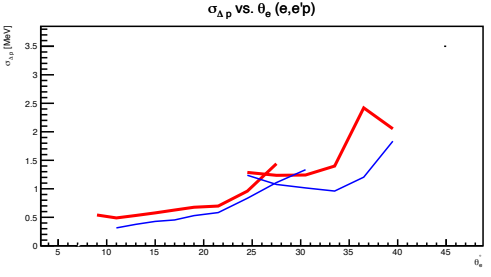






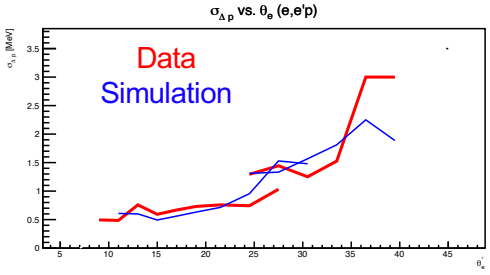


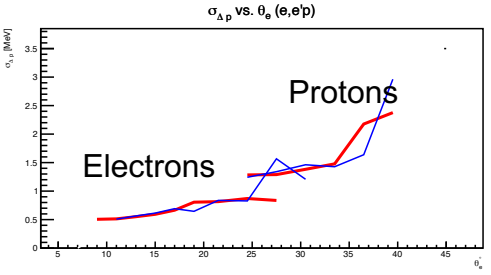


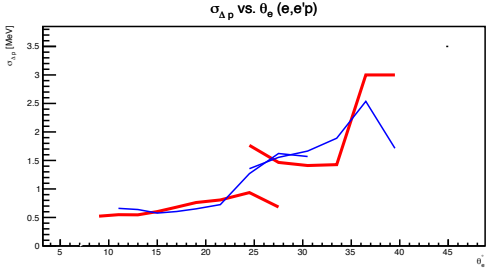


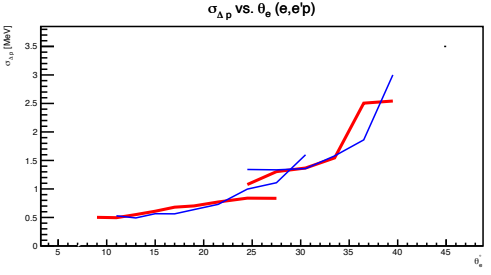
Data vs. Simulation with Smearing

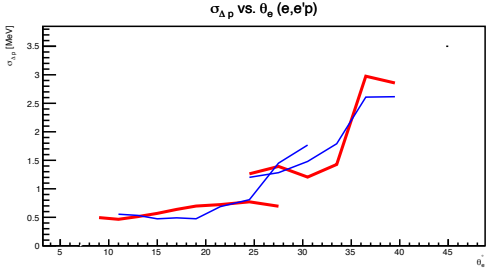
Resolution $\frac{p_{angle} - p}{p_{angle}}$

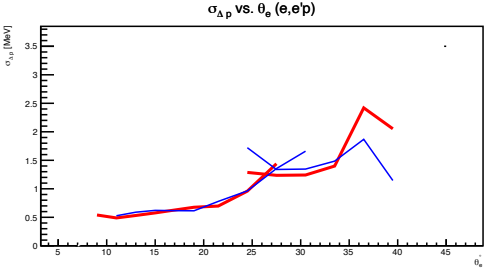




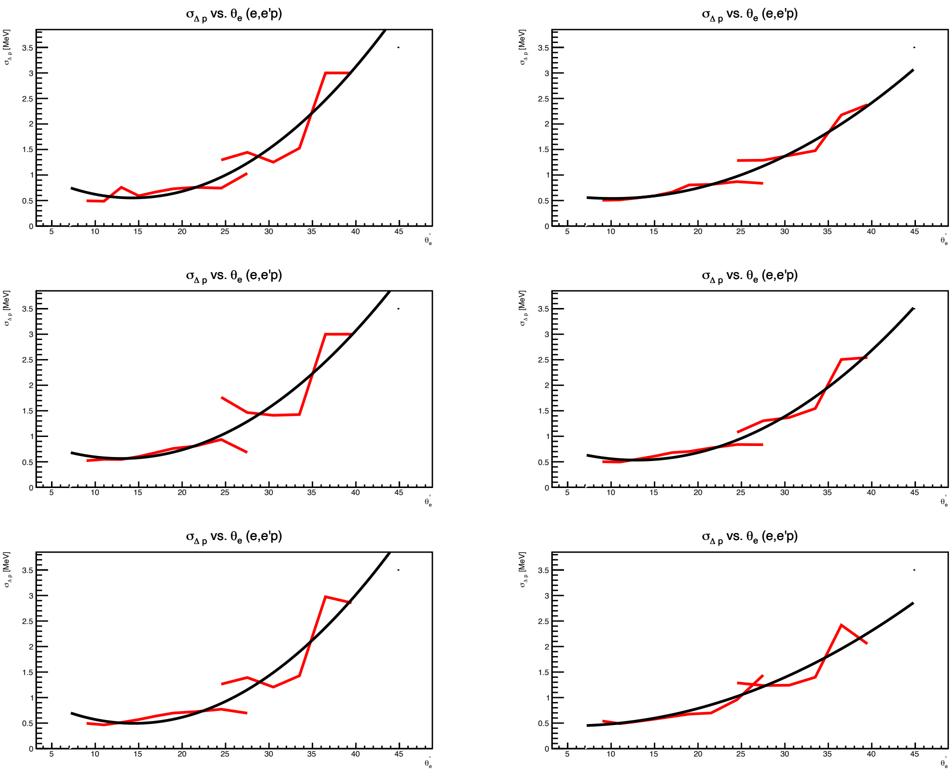


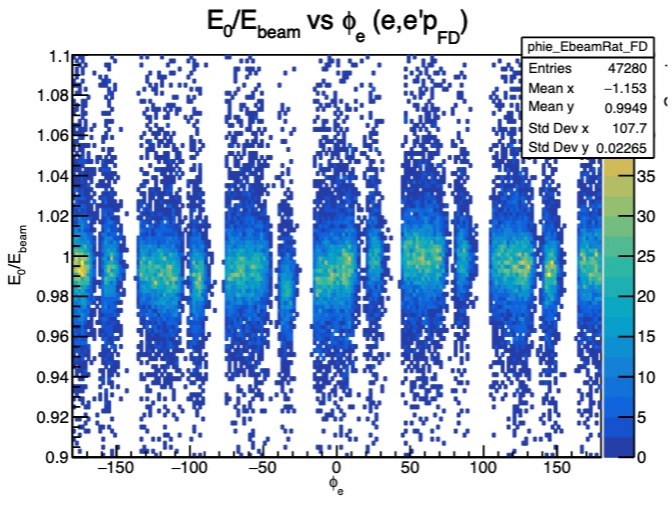


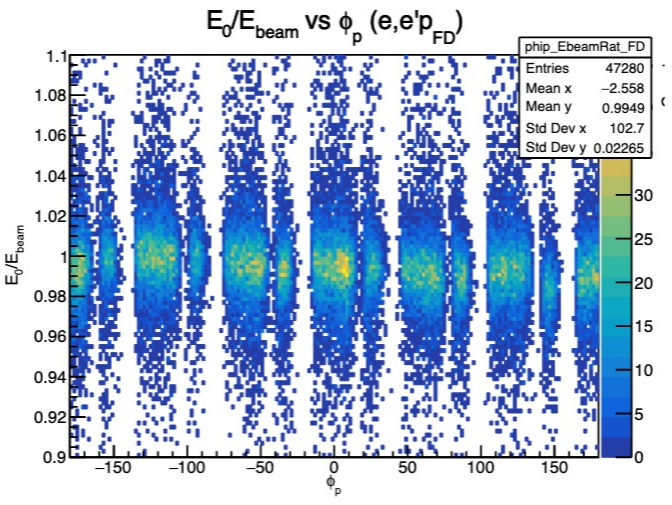


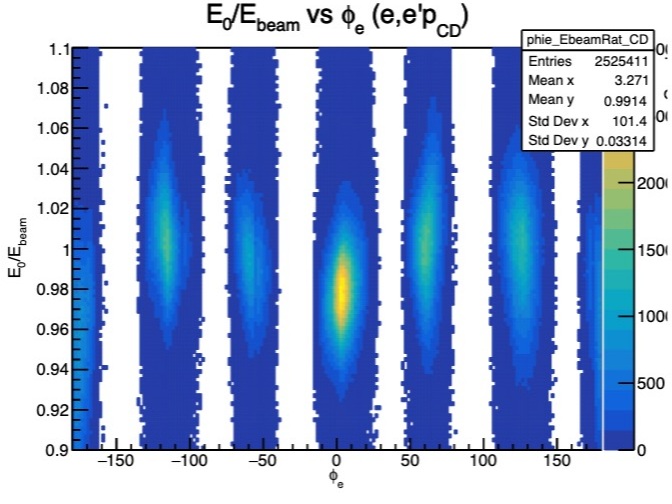


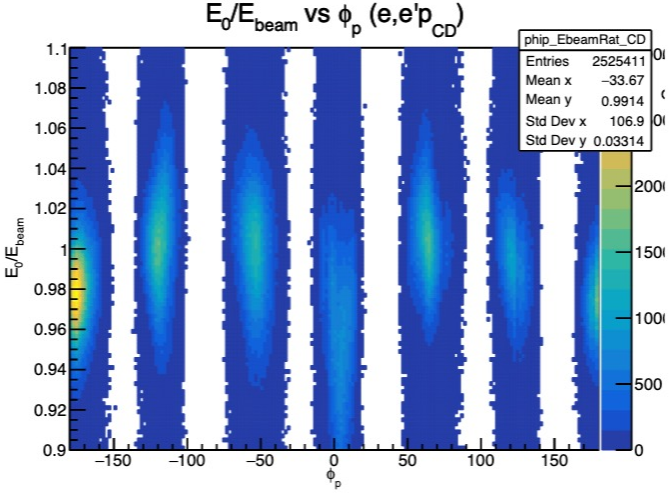
Fit both as a function of Theta to get resolution

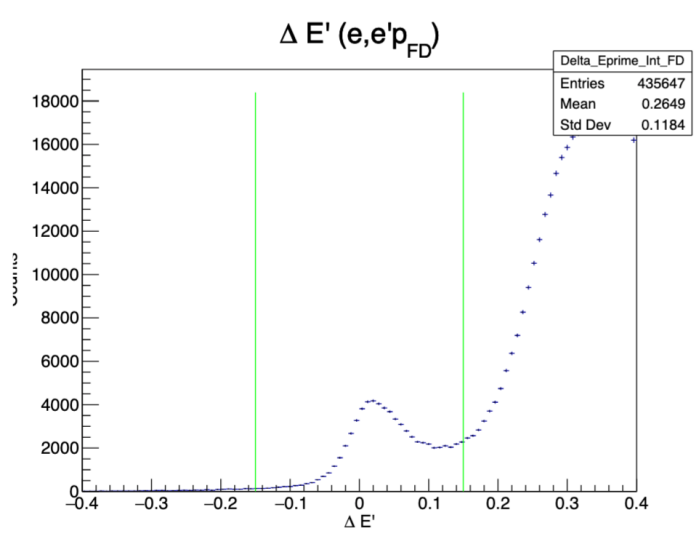


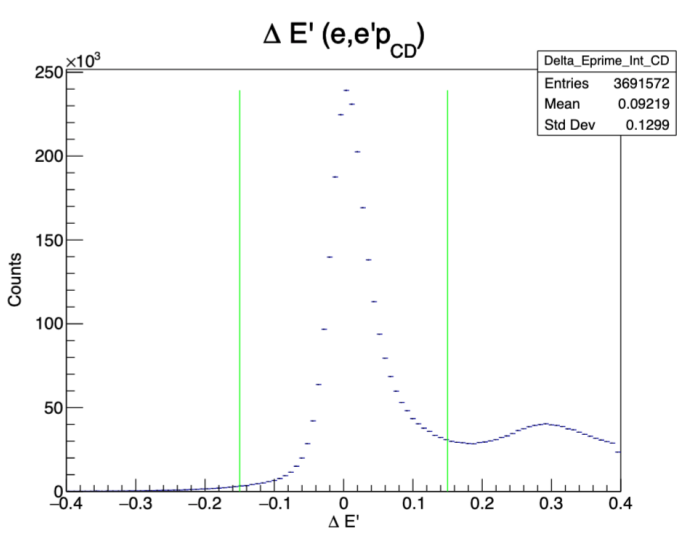

E_0/E_{beam} vs ϕ_e $(e,e'p_{FD})$
phie_EbeamRat_FD
Entries 47280
Mean x −1.153
Mean y 0.9949
Std Dev x 107.7
Std Dev y 0.02265
E_0/E_{beam}
ϕ_e

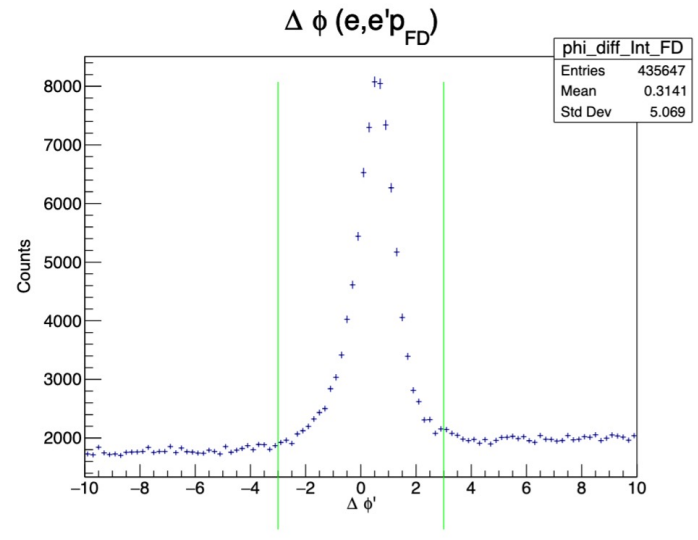

E_0/E_{beam} vs ϕ_p $(e,e'p_{FD})$
phip_EbeamRat_FD
Entries 47280
Mean x −2.558
Mean y 0.9949
Std Dev x 102.7
Std Dev y 0.02265
E_0/E_{beam}
ϕ_p

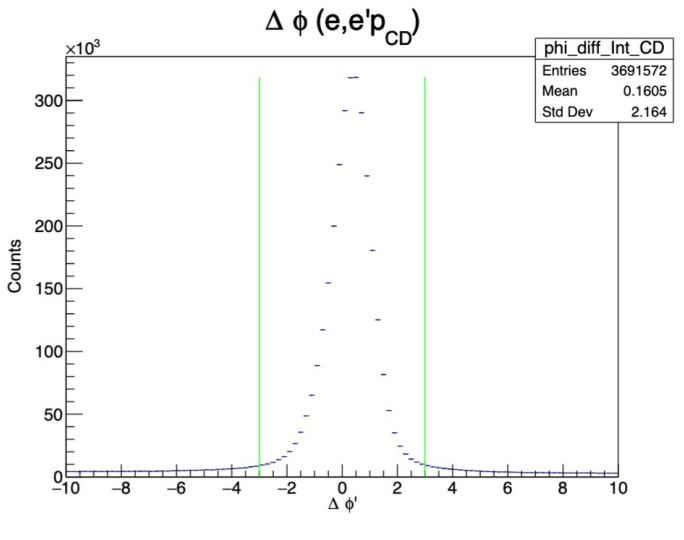

E_0/E_{beam} vs ϕ_e $(e,e'p_{CD})$
phie_EbeamRat_CD
Entries 2525411
Mean x 3.271
Mean y 0.9914
Std Dev x 101.4
Std Dev y 0.03314
E_0/E_{beam}
ϕ_e


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'

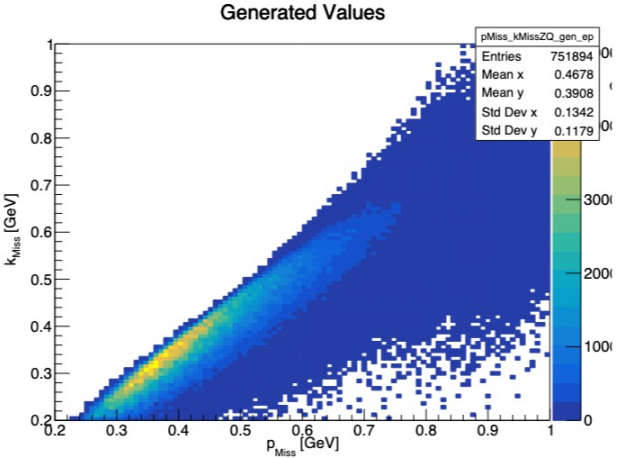

Δ E' (e,e'p_CD)
×10^3
Delta_Eprime_Int_CD
Entries 3691572
Mean 0.09219
Std Dev 0.1299
Counts
Δ E'


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

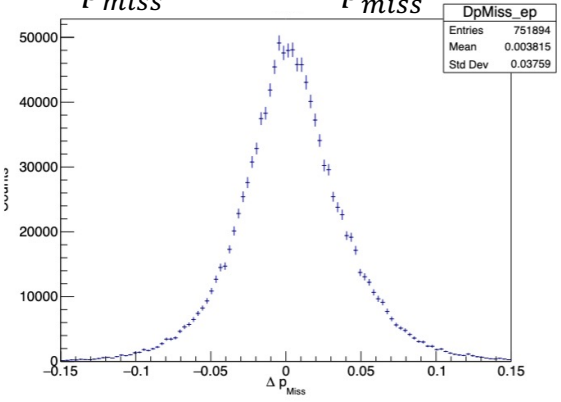

Δ ϕ (e,e'p_CD)
×10^3
phi_diff_Int_CD
Entries 3691572
Mean 0.1605
Std Dev 2.164
Counts
Δ ϕ'

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

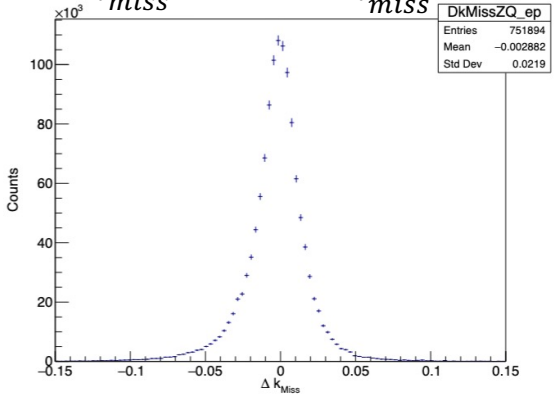
$$k^2_{miss} \equiv m^2_N \left(\frac{p^2_{miss,\perp} + m^2_N}{p^-_{miss}(2m_N - p^-_{miss})} \right) - m^2_N$$



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

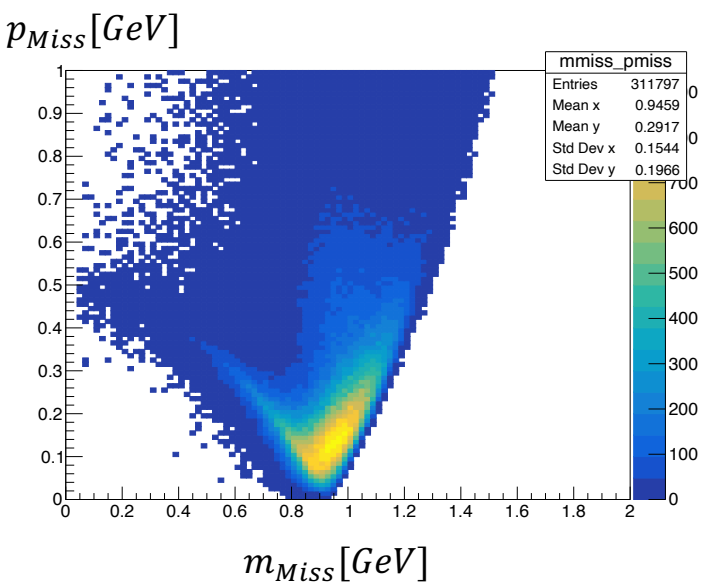


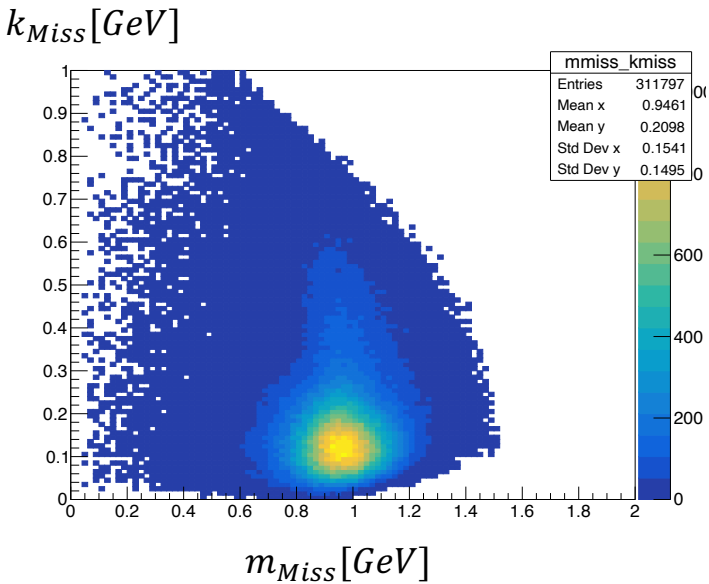
$k^{reconstructed}_{miss} - k^{generated}_{miss}$



Frankfurt and Strikman, Phys. Rep. (1982)

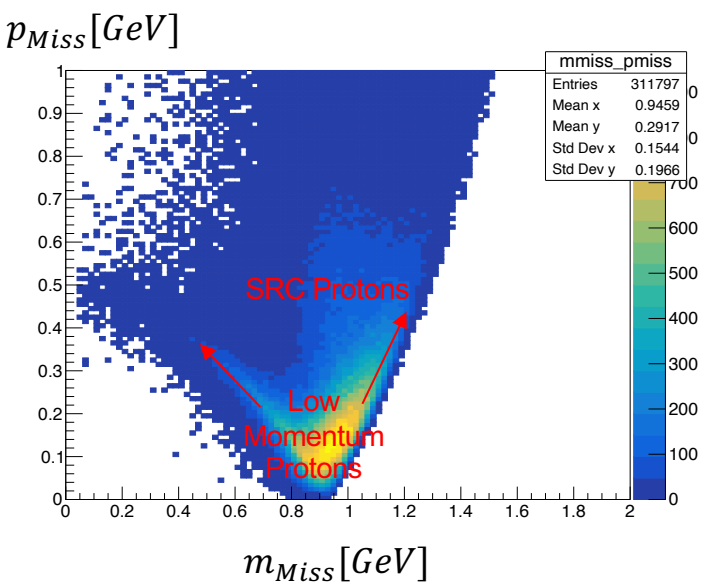
K_{Miss} can improve our event selection

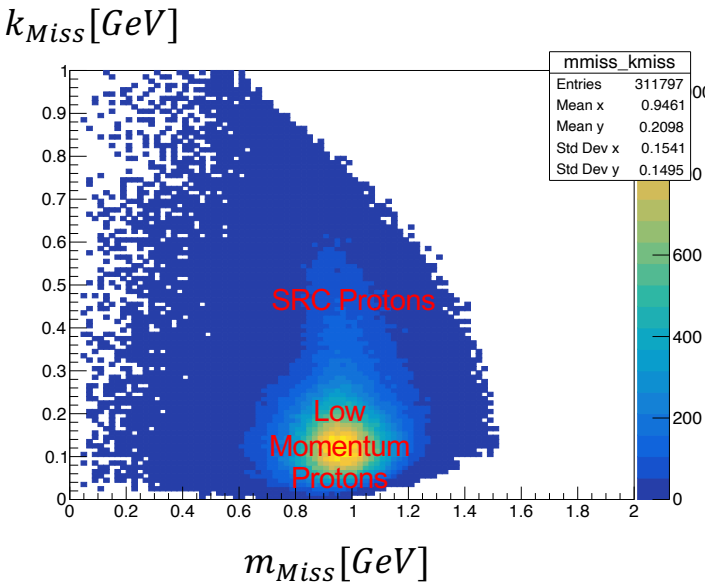




Frankfurt and Strikman, Phys. Rep. (1982)

K_{Miss} can improve our event selection

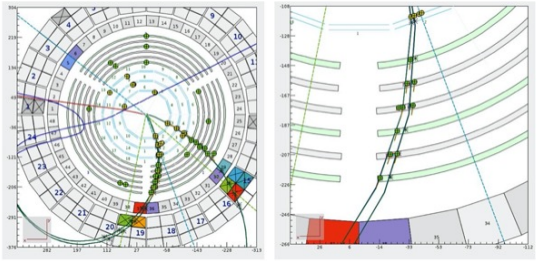


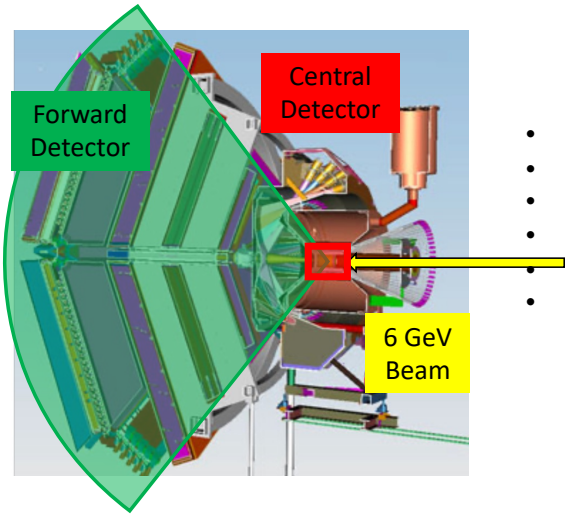


Frankfurt and Strikman, Phys. Rep. (1982)

SRC Event Selection

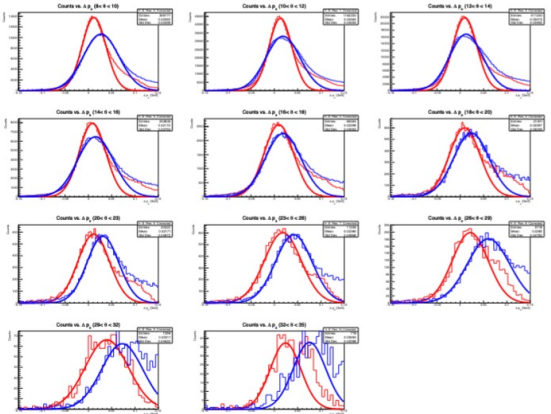
1. $1.2 < x_B < 2$
2. $1.5\ GeV^2 < Q^2$
3. $1.0\ GeV < p_{Lead}$
4. $0.3\ GeV < k_{Miss} < 1.0\ GeV$
5. $0.65\ GeV < m_{Miss} < 1.1\ GeV$
6. $\theta_{Lead} < 37°$

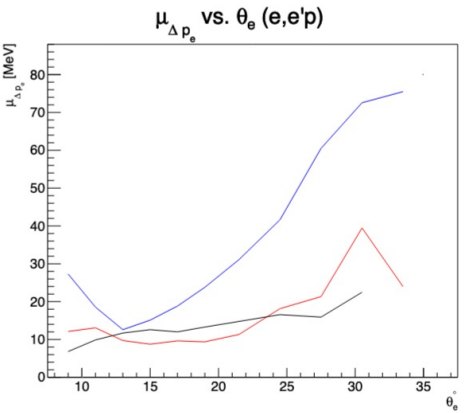




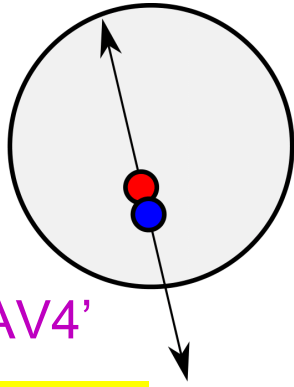
- Physics Letters B 722 (2013) 63–68
- Science 346, 614 (2014)
- Nature 560, 617–621 (2018)
- Physics Letters B 797 (2019) 134792
- Cohen et al. Phys. Rev. Lett. 121, 092501 2018
- Duer et al. Phys. Rev. Lett. 122, 172502 2019

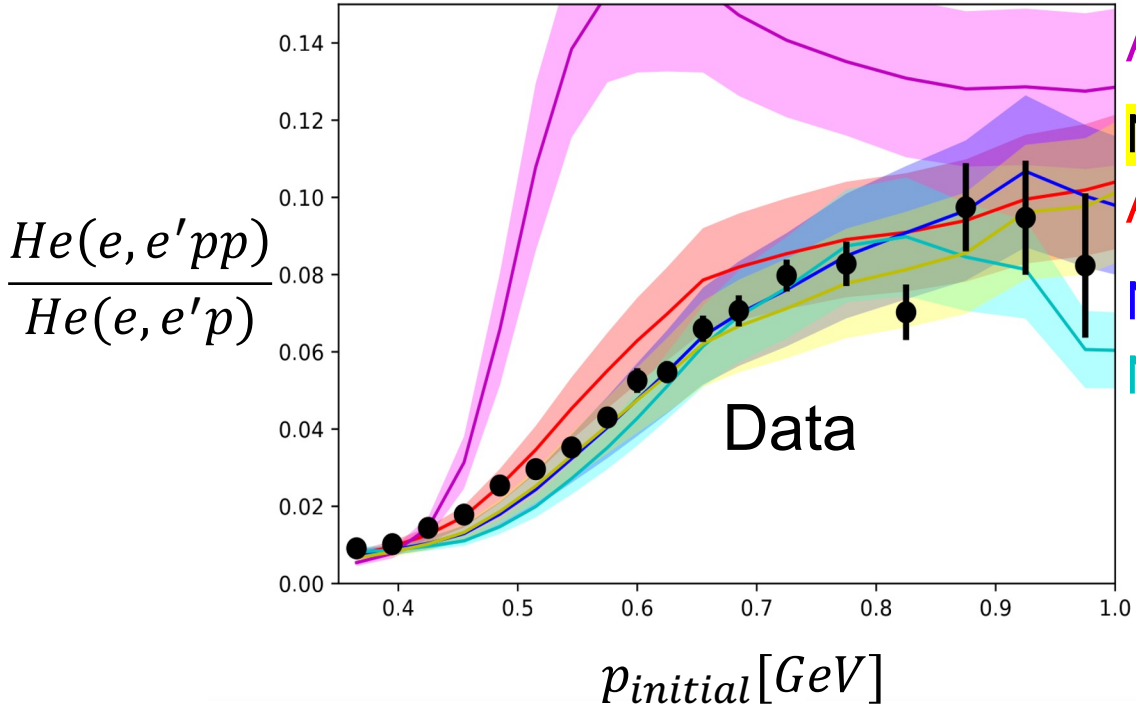
Momentum Correction of FD Electrons



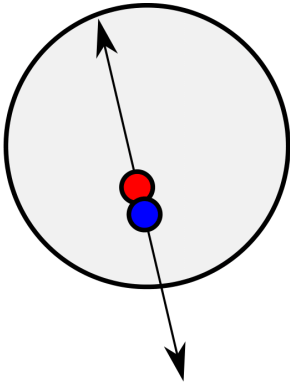


Precision NN interaction

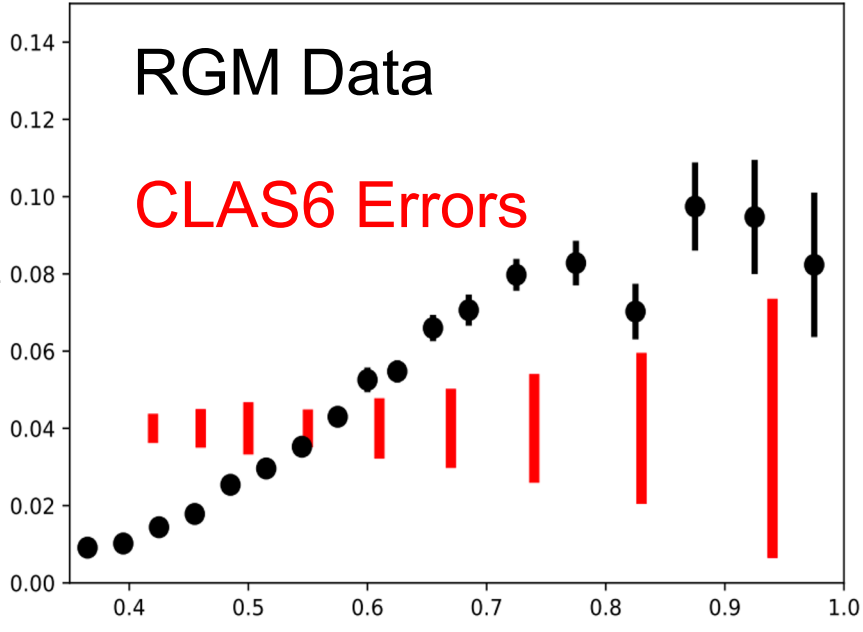




Precision NN interaction



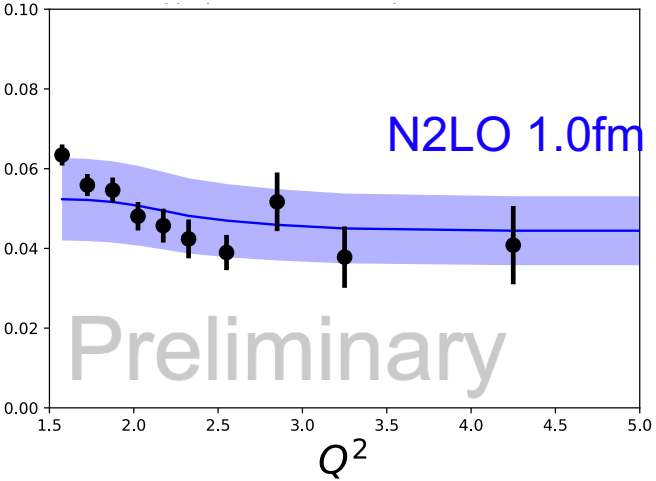
$$\frac{He(e,e'pp)}{He(e,e'p)}$$



$p_{initial}[GeV]$

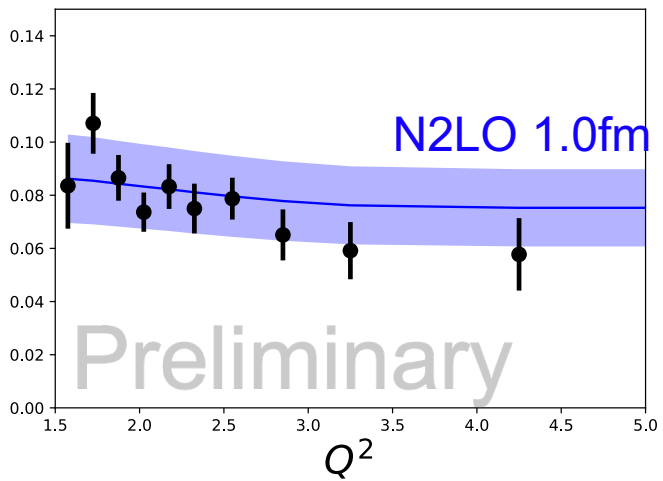
Measuring SRC Probe (In)dependence

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



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

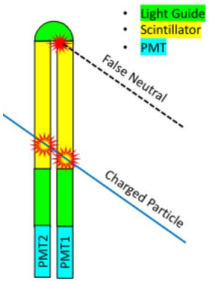
$$\frac{He(e,e'pp)}{He(e,e'p)}$$

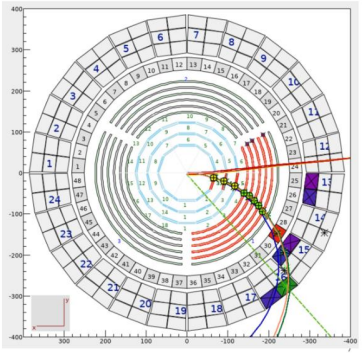


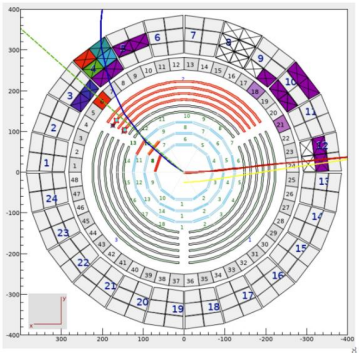
$0.7GeV < p_{miss} < 0.85GeV$

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

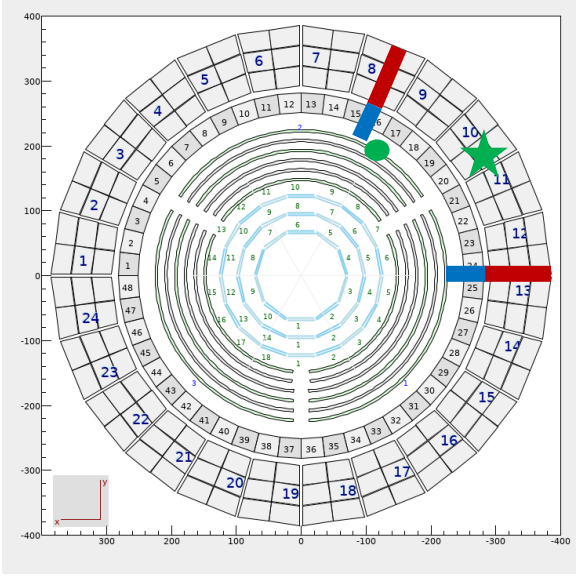






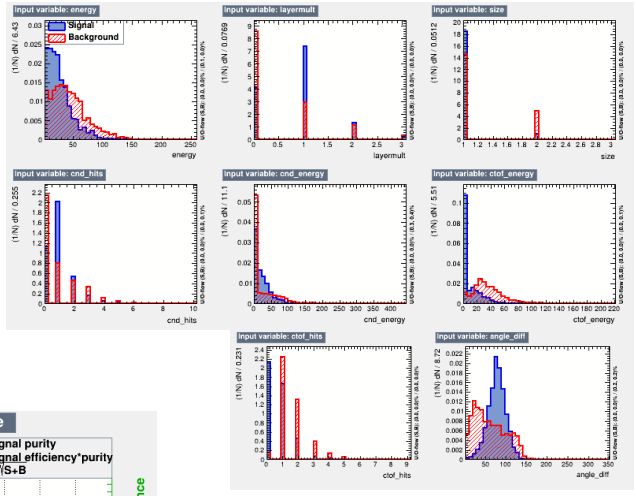
Particle ID for Neutrons in 6 GeV data

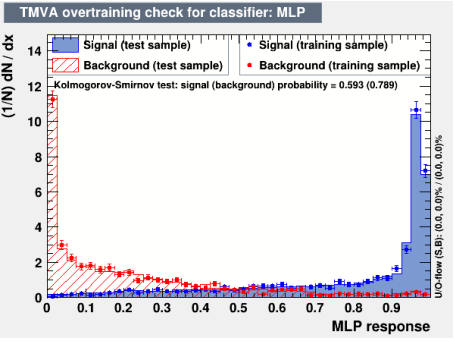
- Number of CND hits within 30 degrees of neutron
- CND energy deposition within 30 degrees of neutron
- Number of CTOF hits within 30 degrees of neutron
- CTOF energy deposition within 30 degrees of neutron
- Number of hits in CND cluster
- Neutron energy
- CND layer multiplicity (0 if CTOF only)
-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

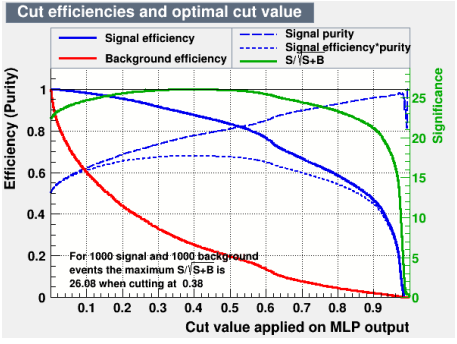


Particle ID for Neutrons in 6 GeV data

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



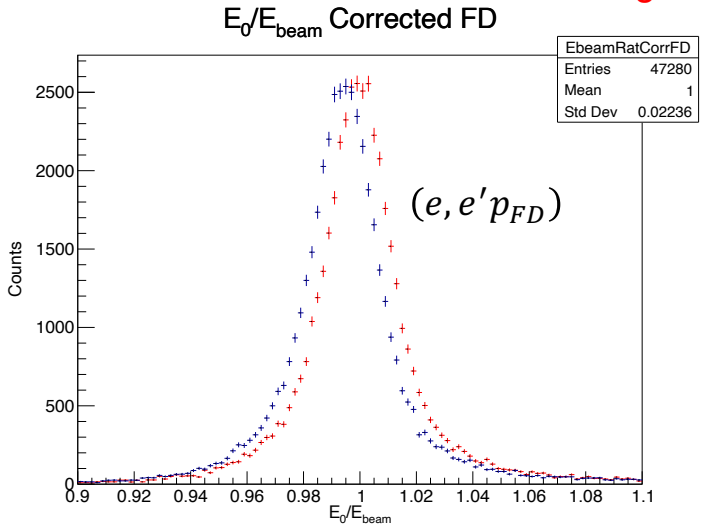


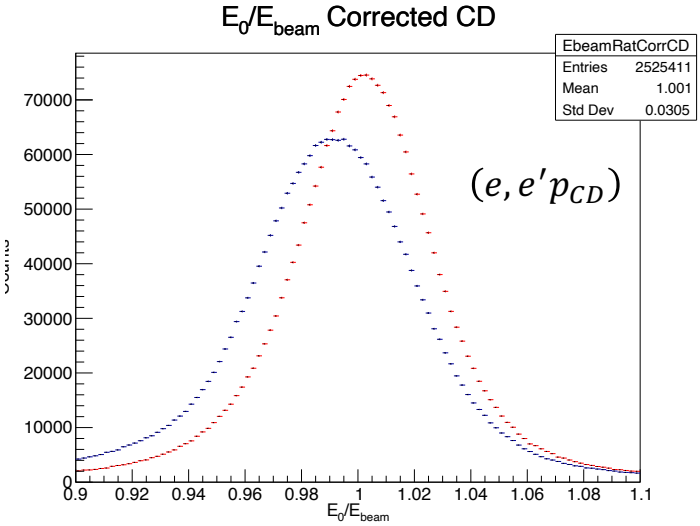


Result of Angular Corrections

Before Angular Correction

After Angular Correction





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

ECAL Neutrons (Ron Wagner)

- The eff. Was calculated from the **D(e,e'pn)** interaction.
- The eff. Value was defined as:

$$eff = \frac{\#(e, e'pn)}{\#(e, e'p)n}$$

- The efficiency was calculated vs the missing momentum of the D(e,e'p)n reaction.

ECAL Neutrons (Ron Wagner)

Reduce the amount of leading protons

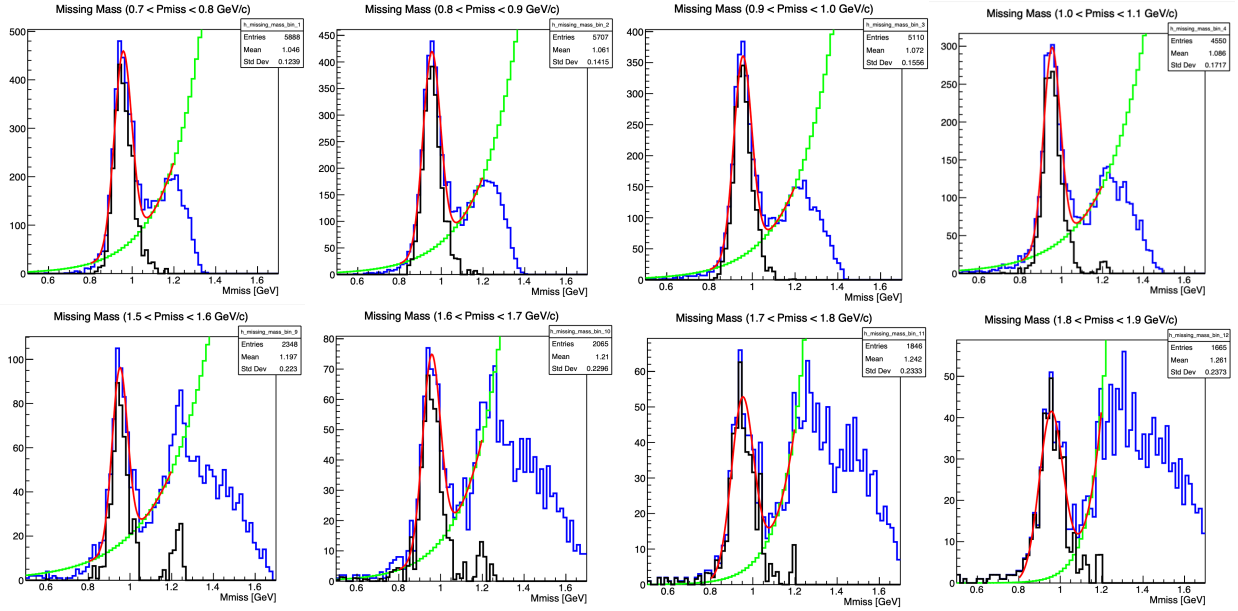
Same angular region

Fully Exclusive interaction cut

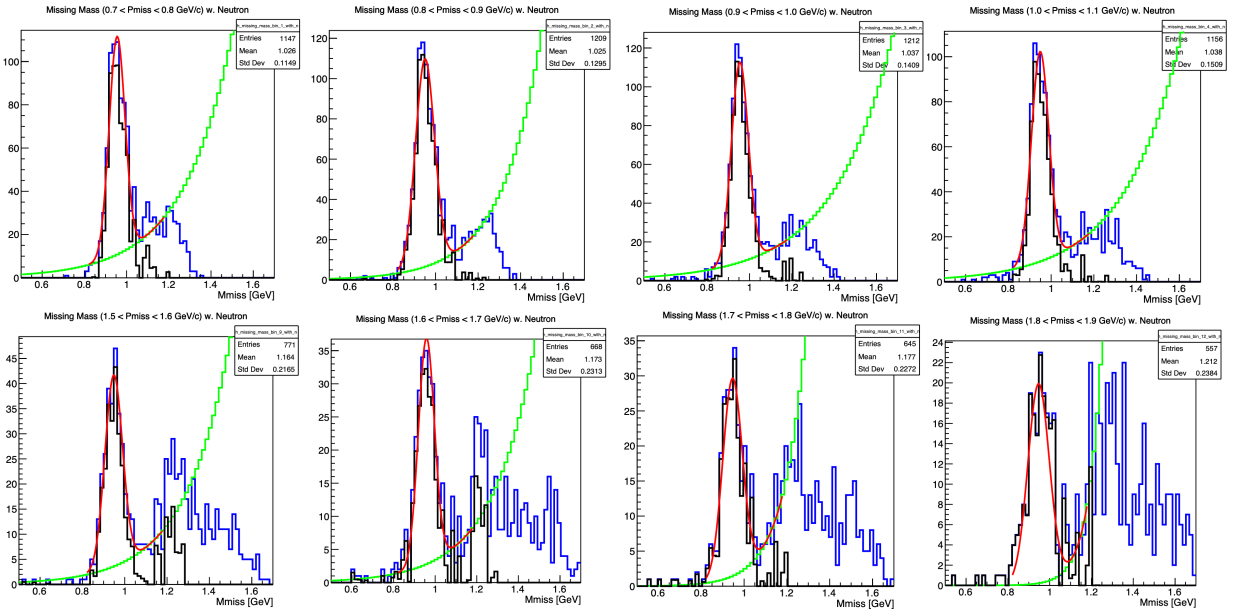
Neutron photon separation

Cut	Value
p/q	$p/q < 0.8$
θ_{pq}	$\theta_{pq} > 20$
$\lvert\vec{p}\rvert$	$\lvert\vec{p}\rvert < 1\ GeV/c$
θ_{Pmiss}	$8 < \theta_{Pmiss} < 32$
ϕ_{Pmiss}	$-20 < \phi_{Pmiss} < 20$ For each sector
$Mmiss$	$0.85 < Mmiss < 1.05$
$\frac{tof}{path}$	$\frac{tof}{path} > 3.6\ ns/m$

ECAL Neutrons (Ron Wagner)



ECAL Neutrons (Ron Wagner)



CND Neutrons (Igor Parshkin)

CUTS

- e'p cuts:
  - xB>1.2 && Q2>1
  - Missing Momentum [0.25, 0.8]
  - Missing Mass 2 sigma cut
  - Theta of Missing Momentum [60,120] deg
  - Electron vertex cut
  - Electron-proton vertex 3 sigma cut
  - Leading proton cuts:
    - (Proton momentum)/q [0.62,0.95]
    - Opening angle (proton and q) [0,25]
  - Phi between proton and missing momentum > 45 deg

- e'pn cuts:
  - Deposited Energy > 5 MeV
  - Neutron theta [60,120] deg
  - Neutron time per meter [4.2,14]
  - Neutron-missing momentum 3 sigma cut
  - Cosine of opening angle between neutron and missing momentum >0.897