RG-M Analysis Update

Andrew Denniston

Overview

- Run Group M Introduction
- 1st Analysis Note
- Neutron Algorithms
- LAr target
- Physics Analyses
  - Short Range Correlations (SRCs)
  - Electrons for Neutrinos (e4v)

RG-M Experiment at CLAS12

- November 2021 – February 2022
- 2, 4, and 6 Gev Beam Energies
- H, D, He, C, 40Ca, 48Ca, Ar, and Sn
- Fully cooked pass 1 production runs
- Future cooking after CVT improvements (not in the next 6 months)

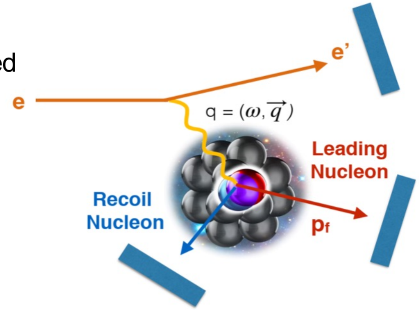
Analysis Note

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]

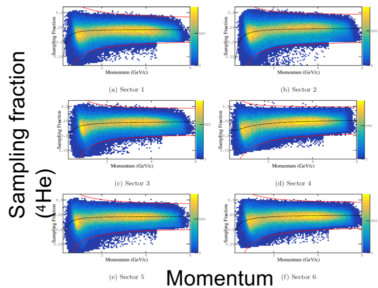
[1]Department of Physics, Massachusetts Institute of Technology
[2]Department of Physics, The George Washington University

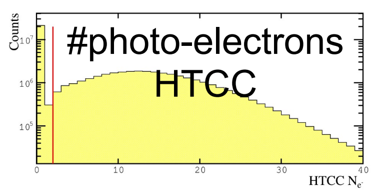
→ “General“ Analysis Note has been resubmitted



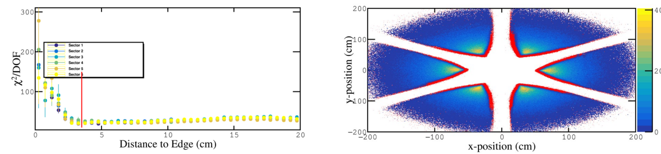
PID, Fiducial, and Vertex Cuts for Electrons in 6 GeV data

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

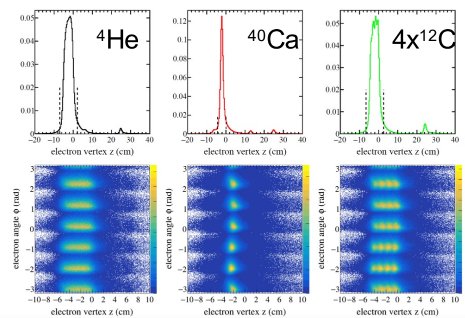




Fiducial Cuts

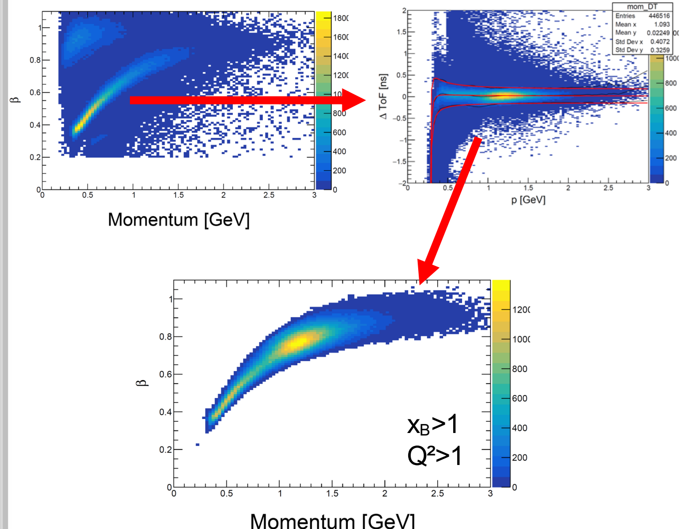


z Vertex

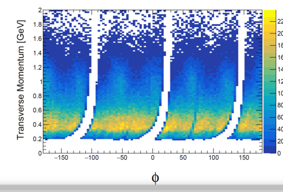


PID, Fiducial, and Vertex Cuts for Protons in 6 GeV data

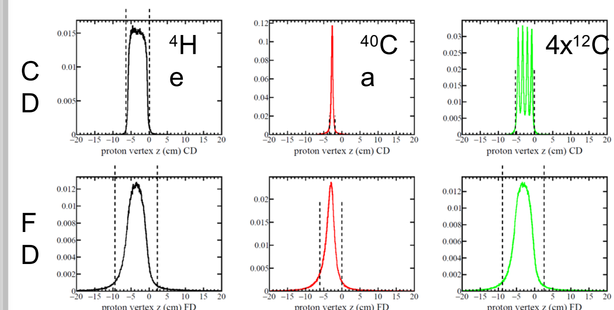
Central detector ID in ΔToF (=measured - expected)



Fiducial Cuts



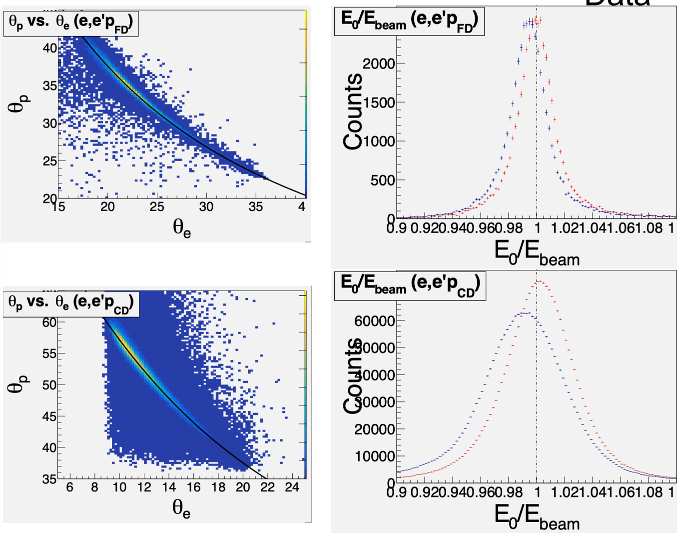
z Vertex



Momentum and Angular Corrections

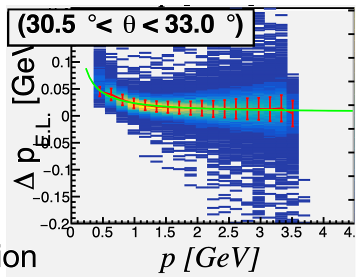
Angular Corrections

Data



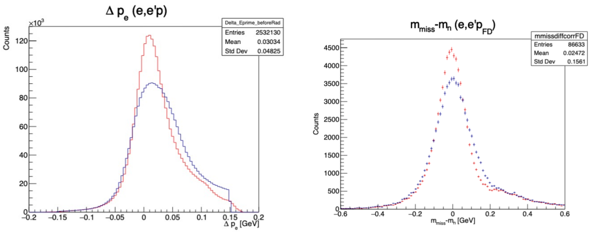
Before Momentum Correction
After Momentum Correction

Energy Loss Correction



Simulation

Momentum Corrections



Before Momentum Correction
After Momentum Correction

Data

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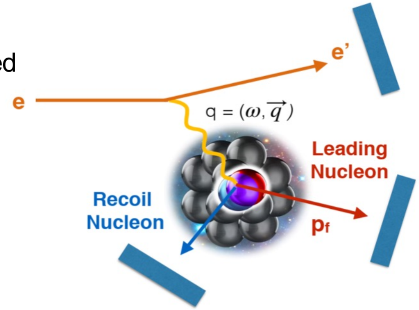
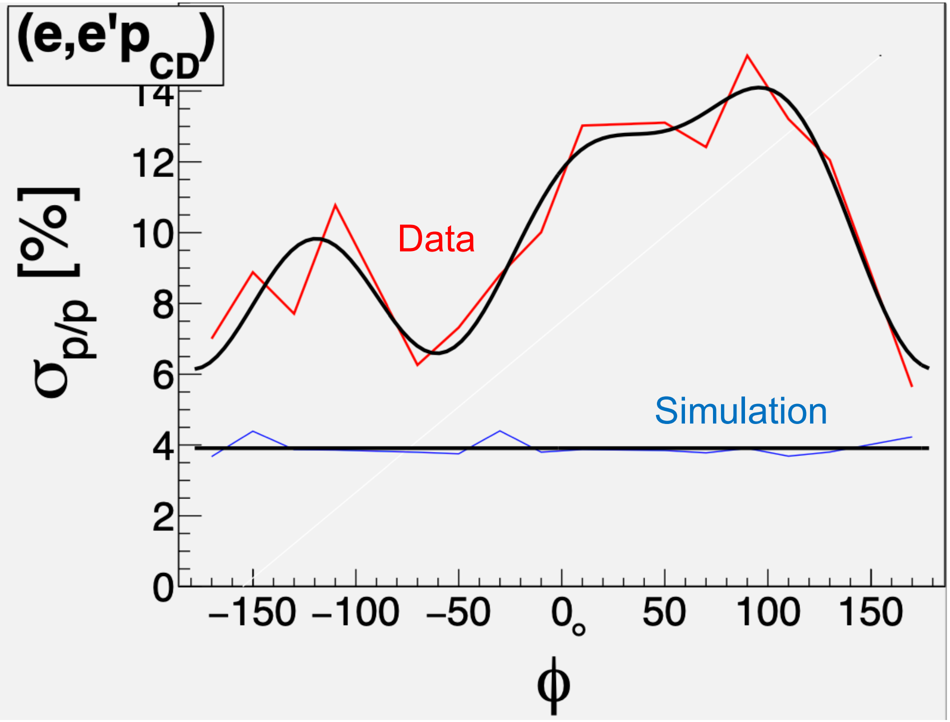


Central Detector Momentum Resolution



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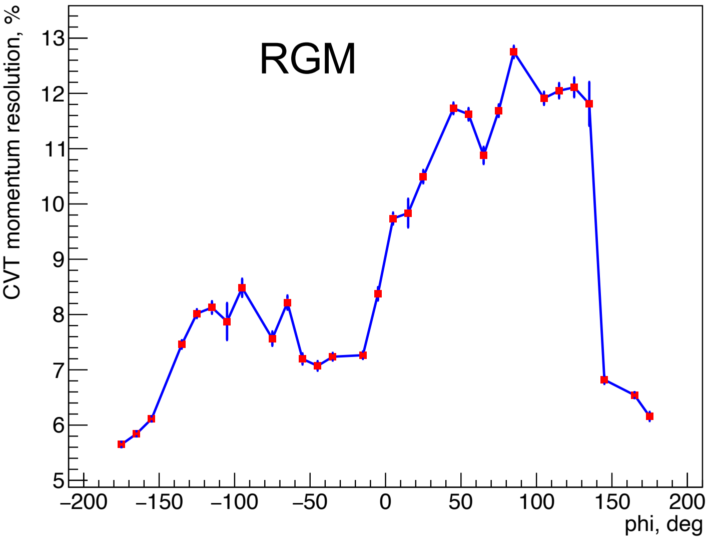
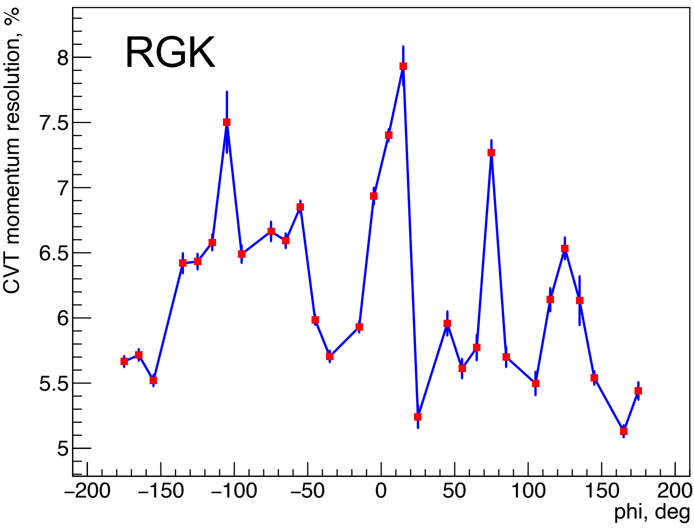
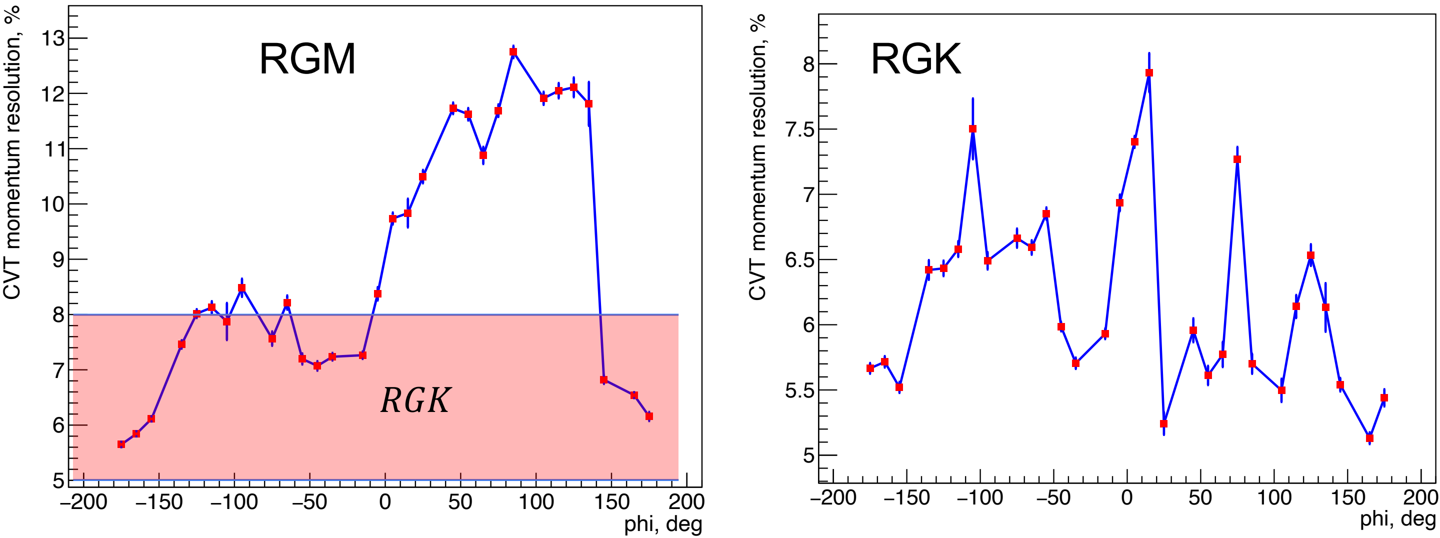


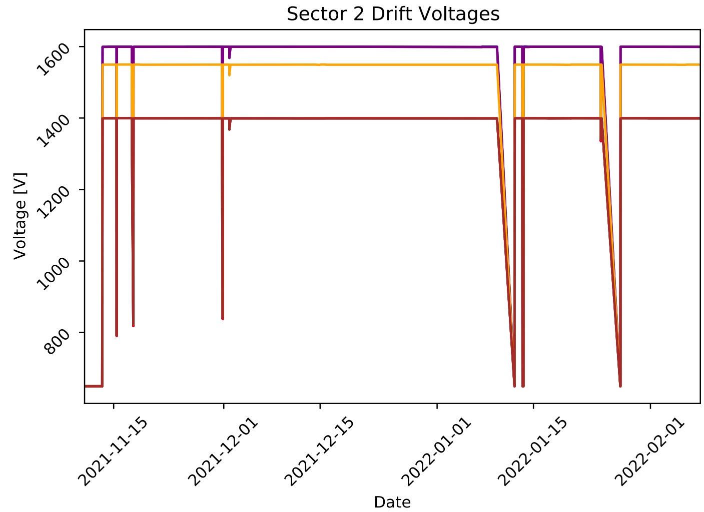


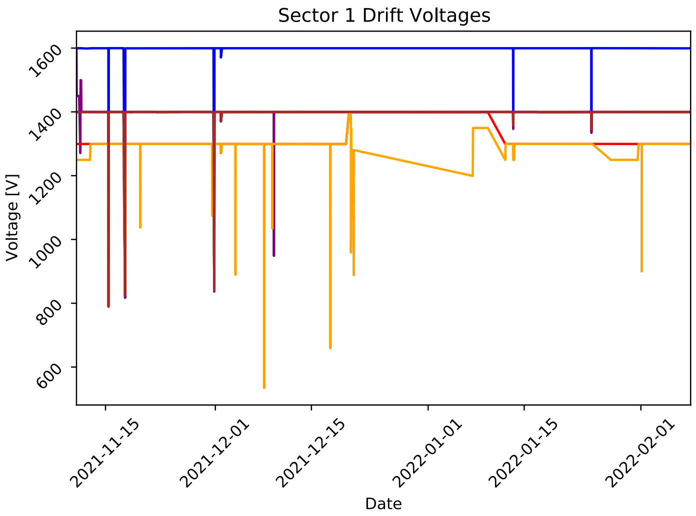
Central Detector Momentum Resolution

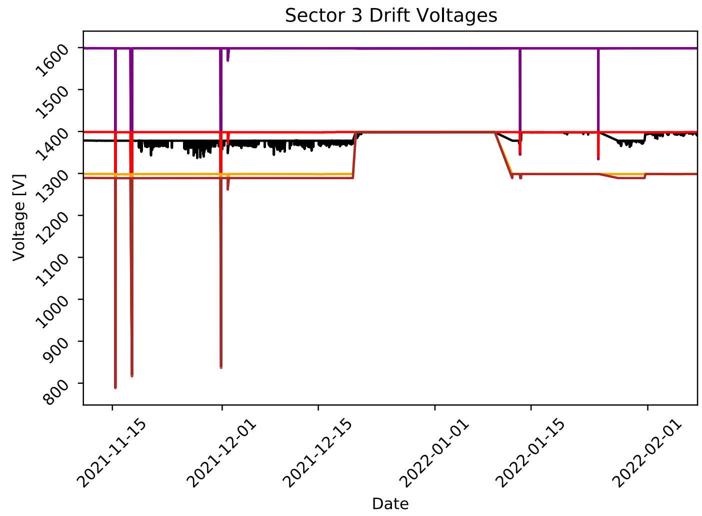


Strip Chart Archive

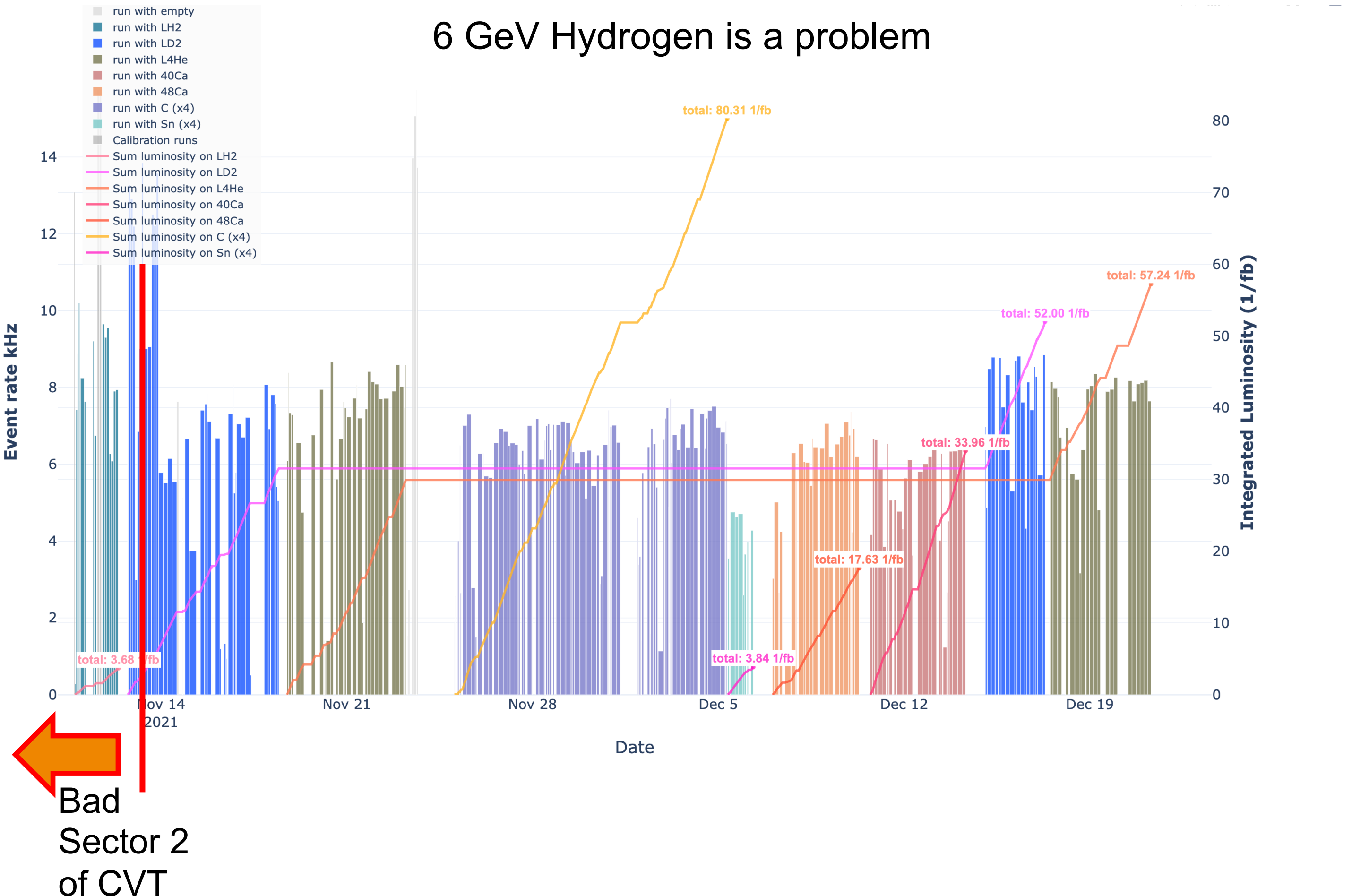
- Look over the RGM run in 15-minute intervals.
- Cut out events with livetime<90%.
- Cut out events where 1/3 of the detector is "off"
- Look at Drift Voltage of BMT Sectors and Layers







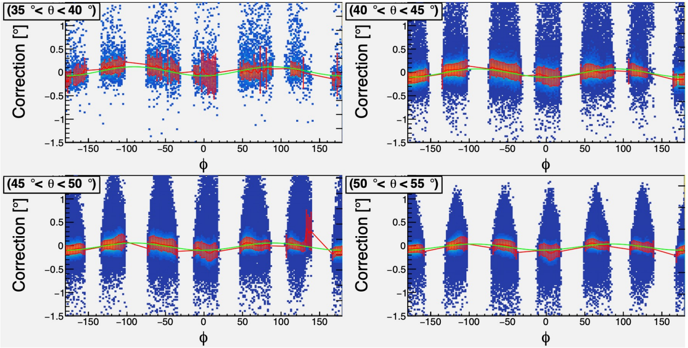
All nuclear targets are good!

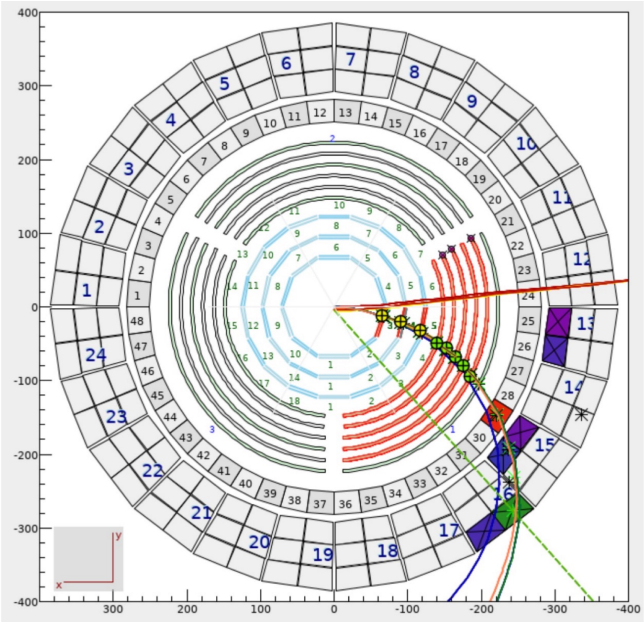


Our 6 GeV Hydrogen Data is Used for

- NOT important for physics results (SRC/e4v)
- Angular Corrections
- Momentum Corrections and Resolution

SVT dominates the θ resolution





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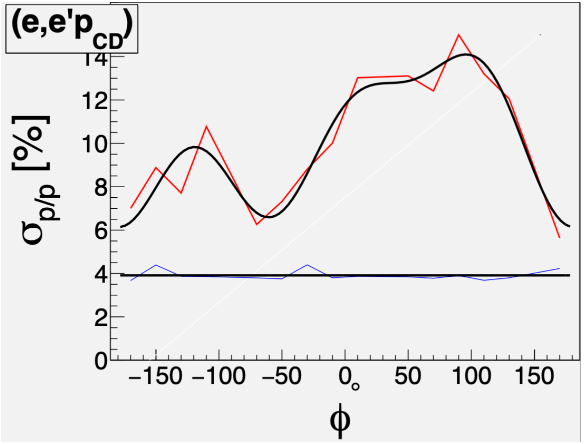

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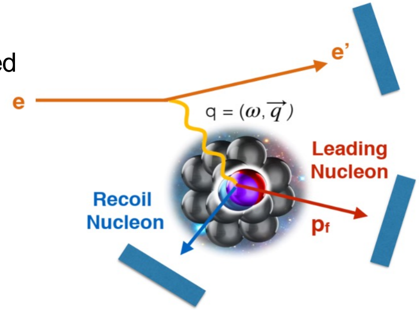

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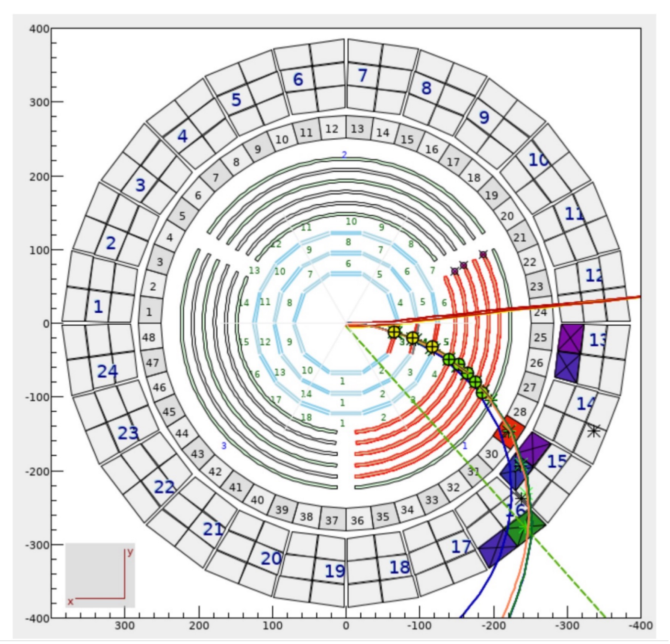
Neutrons

- ECAL Neutrons
- CND Neutrons
- BAND Neutrons

CND Neutrons



Ingredients for Veto Algorithm:

1. Training and test samples

How to isolate examples of neutrons vs untracked charged particles?

2. Feature Engineering

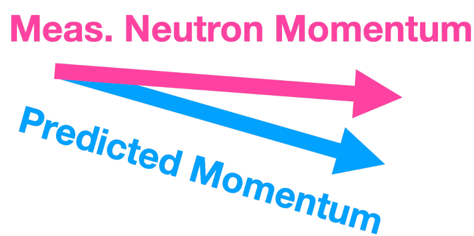
What information should we give to the algorithm?

3. Model structure

What hyperparameters and network size serve our problem best?

Natalie Wright

Data-driven train/test samples



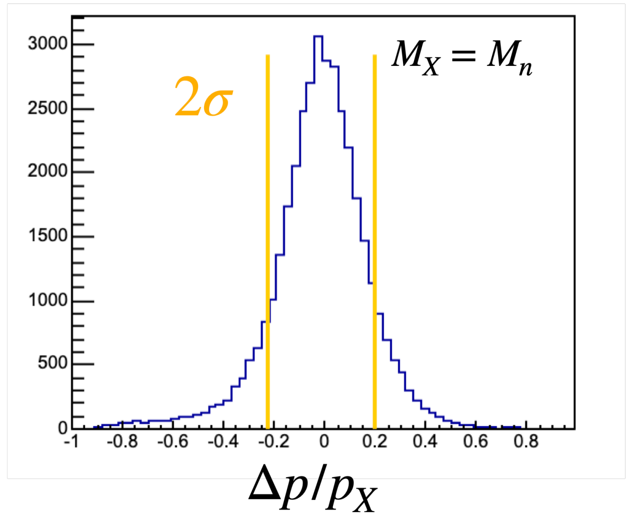
Nucleons selected from exclusive topologies

Ex: $D + e \rightarrow e' + p + X$

$$\overrightarrow{p}_X = \overrightarrow{q} - \overrightarrow{p}_p$$

$$E_X = M_D + \omega - E_p$$

1. Require $M_X = M_n$
2. Select neutrons with $\overrightarrow{p}_X = \overrightarrow{p}_n$



x

Data-driven train/test samples

Samples span a range of beam energies and interaction processes:

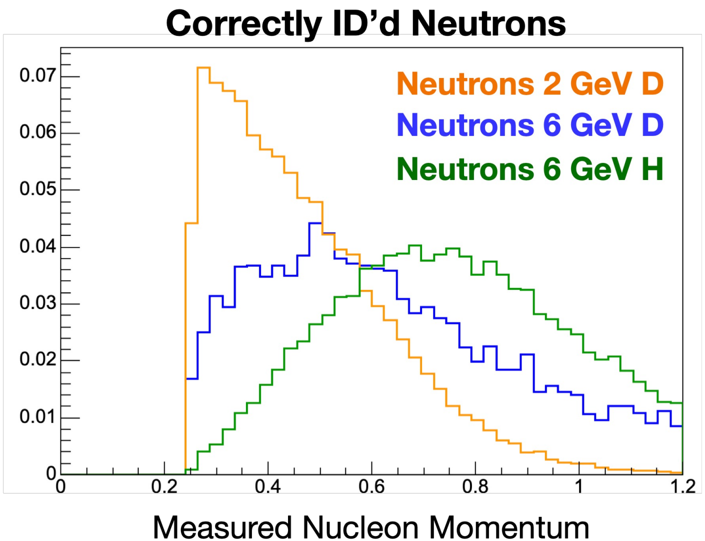
Signal: Correctly ID'd neutrons

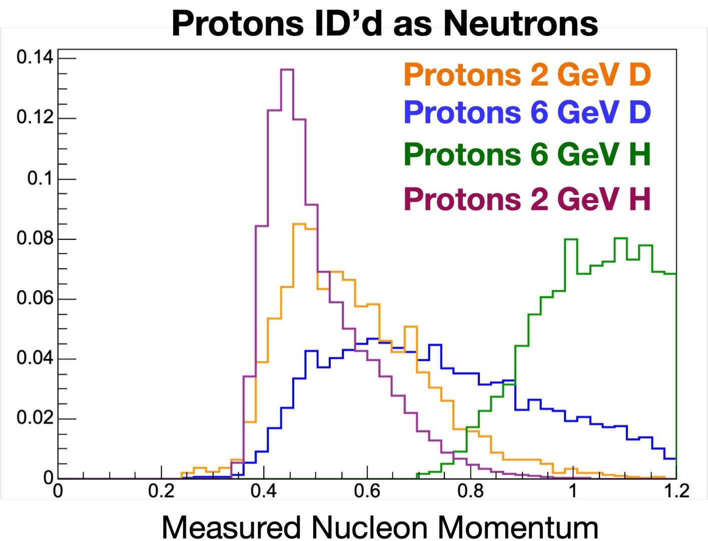
$D(e, e'pn)$	2 GeV
$D(e, e'pn)$	6 GeV
$H(e, e'\pi^+n)$	6 GeV

Background: Protons ID'd as neutrons

$D(e, e'p\pi^-n)$	2 GeV
$D(e, e'p\pi^-n)$	6 GeV
$H(e, e'n)$	2 GeV
$H(e, e'n)$	6 GeV

Each sample has different kinematics





LD2 6 GeV:

Similar p, n kinematics

Momenta most similar to SRC recoil

→ Use for training, validate with other reactions

Natalie Wright

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General variables to construct features:

Primary hit energies E_{CND}, E_{CTOF}

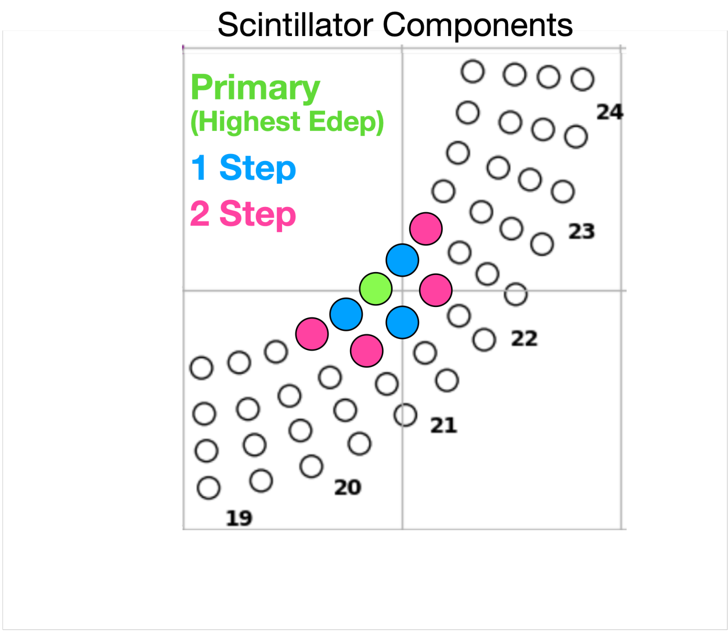
Within N steps:

$\sum$ Hit energy

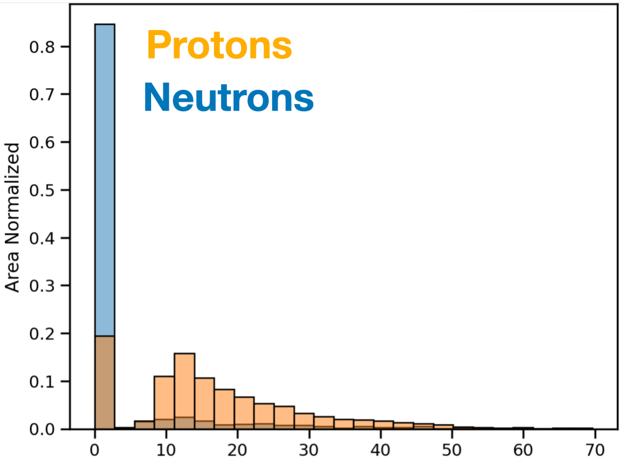
Hit multiplicity

$< | \vec{r} - \vec{r}_{prim.} | >$

$<$ Hit energy / layer $>$



CTOF Veto is ~80% Successful



Total CTOF Edep in 3 Steps

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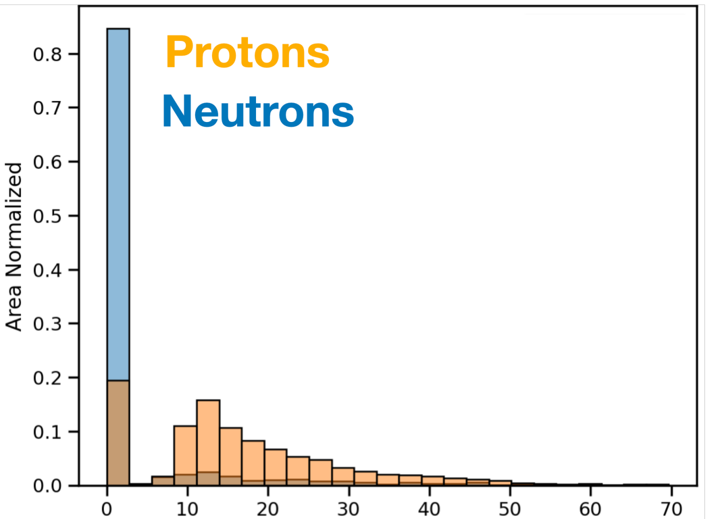
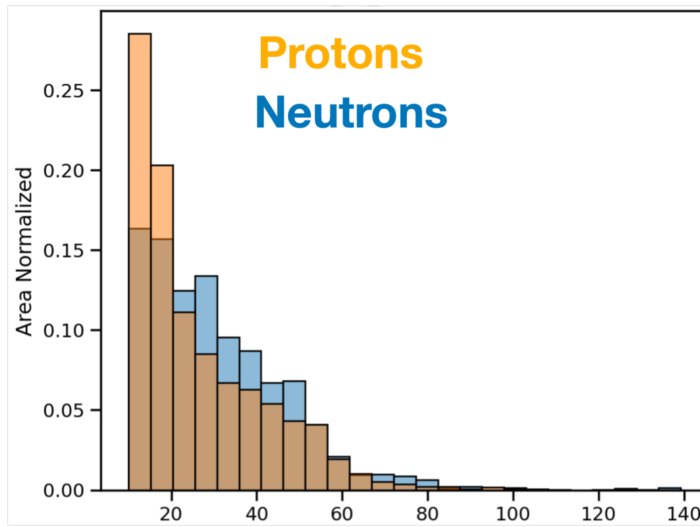
But additional features help with edge cases!



Total CTOF Edep in 3 Steps



Primary CND Hit Energy

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Model Performance on Exclusive Samples

Exclusive Channel	Neutron Recall
6 GeV $D(e, e'pn)*$	0.872
2 GeV $D(e, e'pn)$	0.826
6 GeV $H(e, e'\pi^+n)$	0.926

Exclusive Channel	Proton Recall
6 GeV $D(e, e'p\pi^-n)*$	0.897
2 GeV $D(e, e'p\pi^-n)$	0.923
6 GeV $H(e, e'n)$	0.895
2 GeV $H(e, e'n)$	0.926

**held out from training sample*

Validation with New Helium-4 Data

SRC Analysis:

$x_B > 1.2$

$Q^2 > 1.5$ GeV^2/c^2

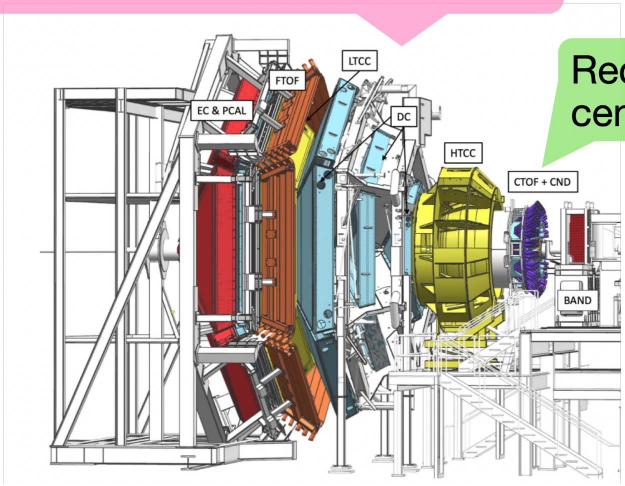
$p_{Lead} > 1.$ GeV/c

$.65 < m_{Miss} < 1.1$

$.3 < k_{Miss} < 1.$

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

Lead proton in forward detector



Recoil neutron in central detector

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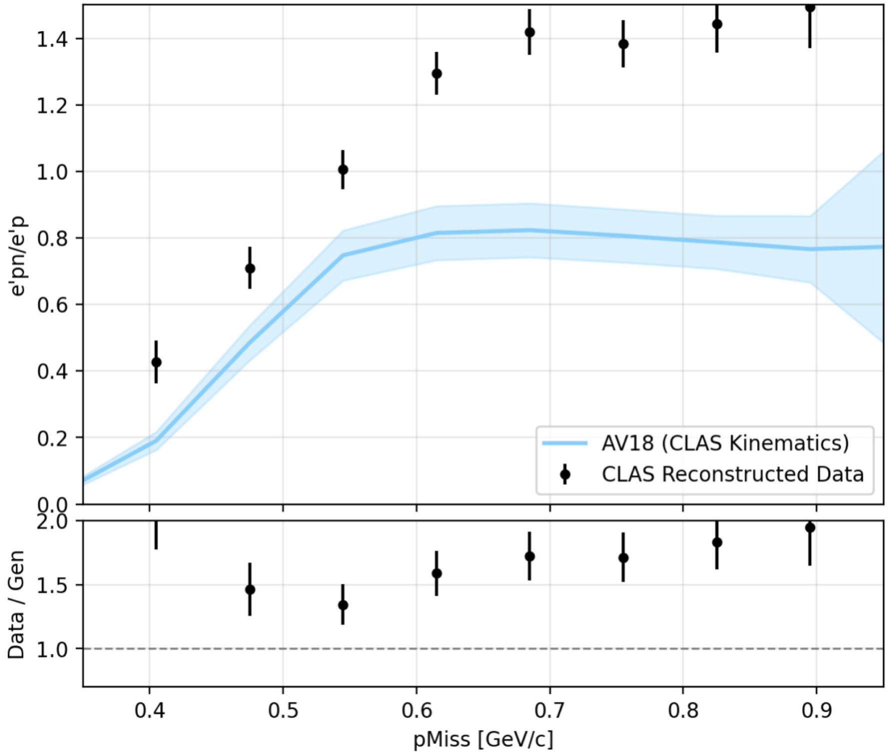
Out of the box PID overpredicts neutrons



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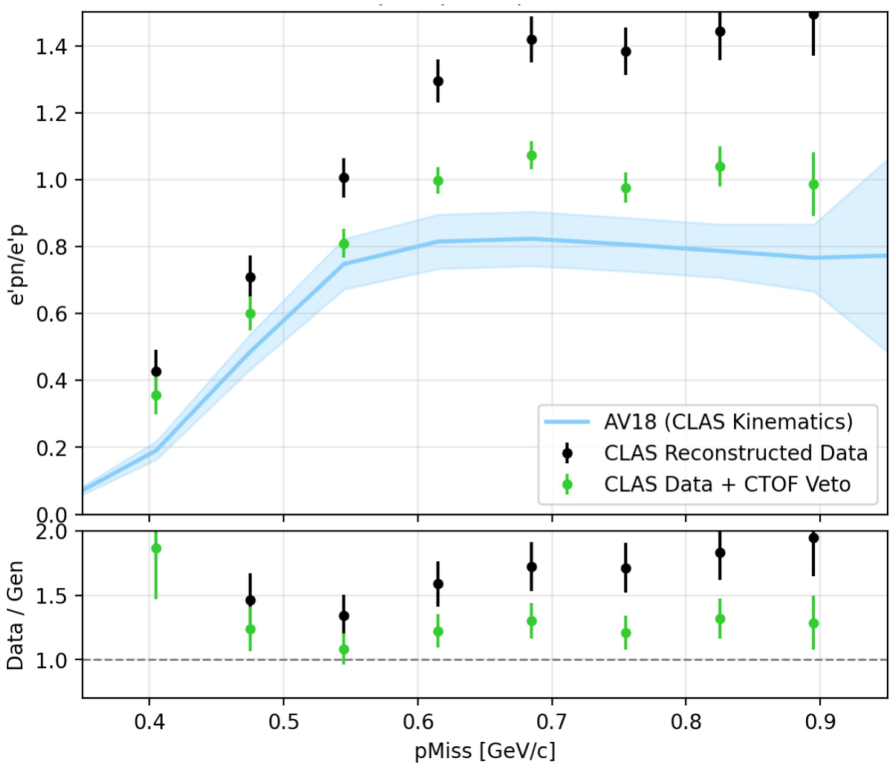
Using CTOF veto helps



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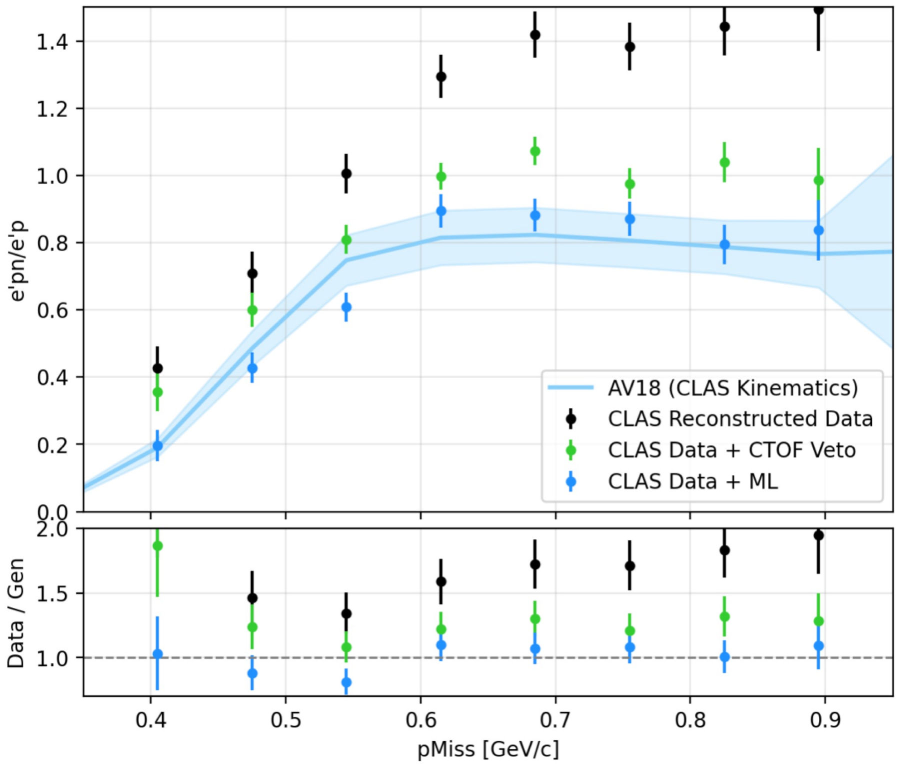
ML agrees with theory/previous measurements



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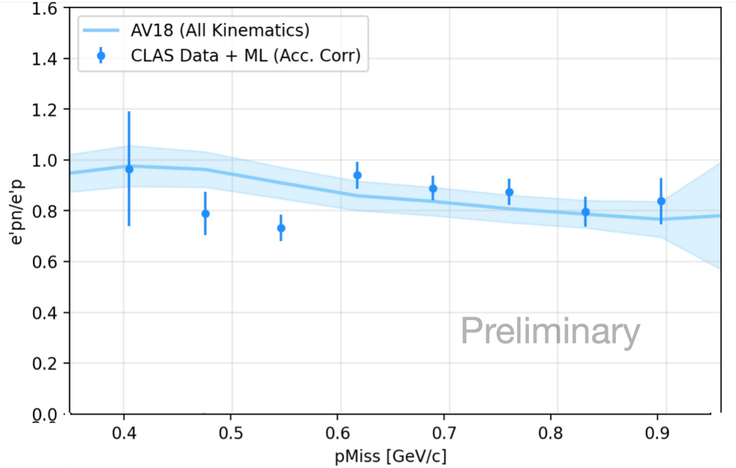
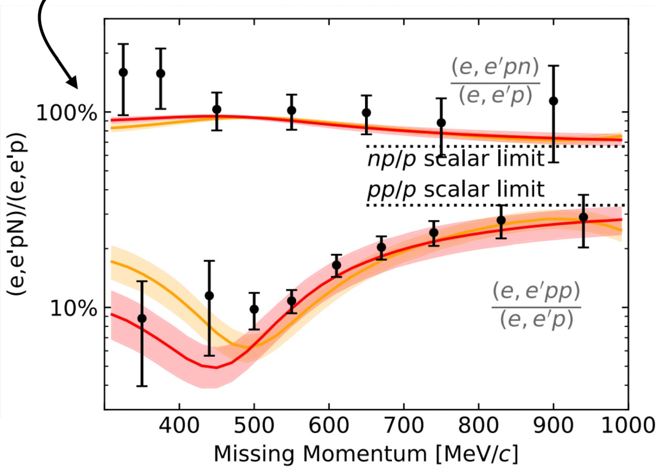


Note log scale



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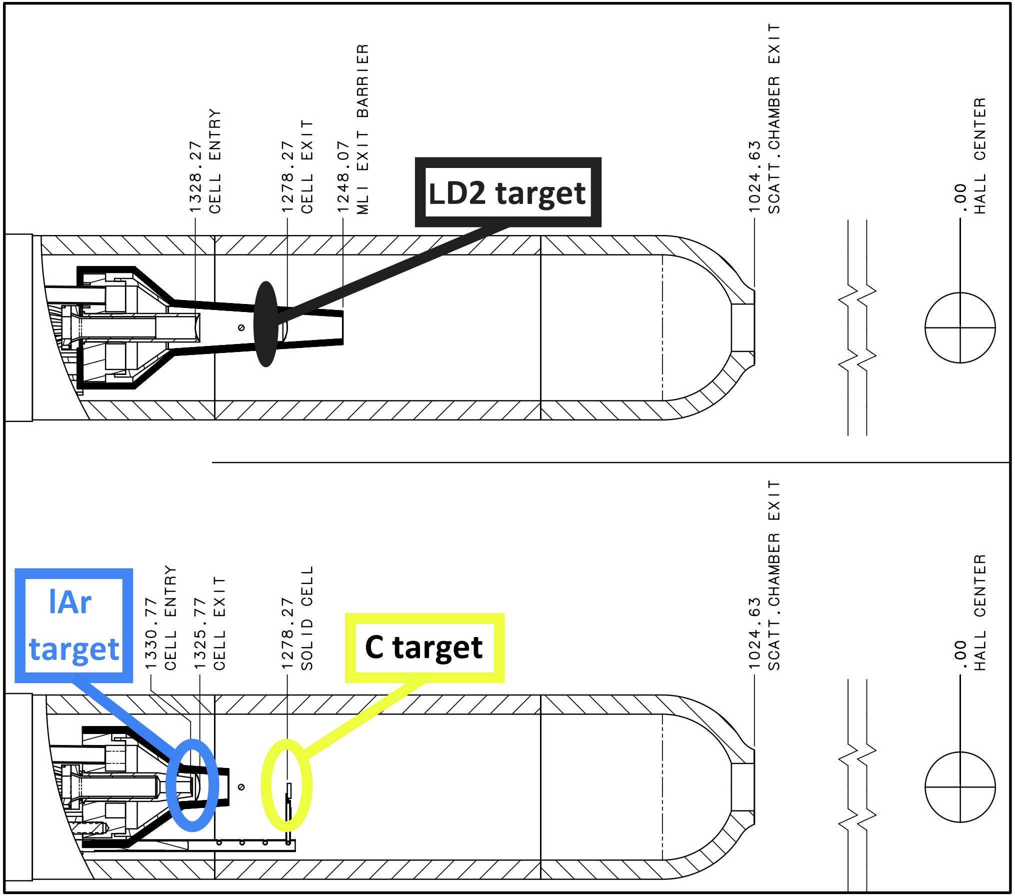
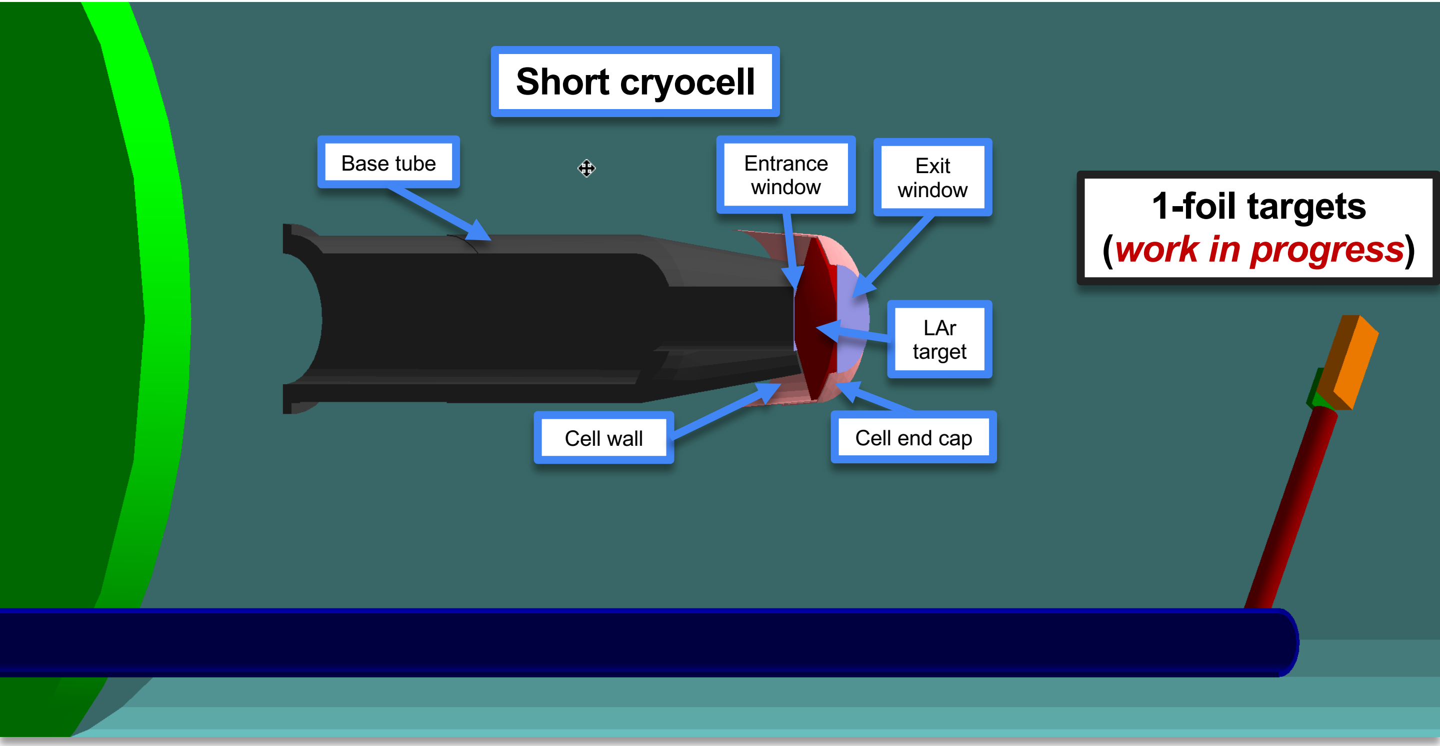
Alon Sportes



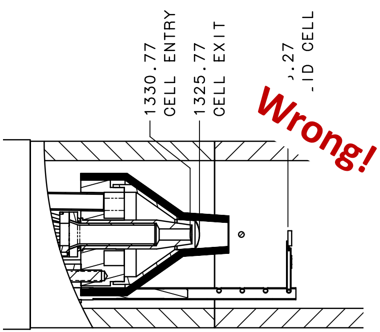
Source: technical drawing No. BM2101-02-00-0000

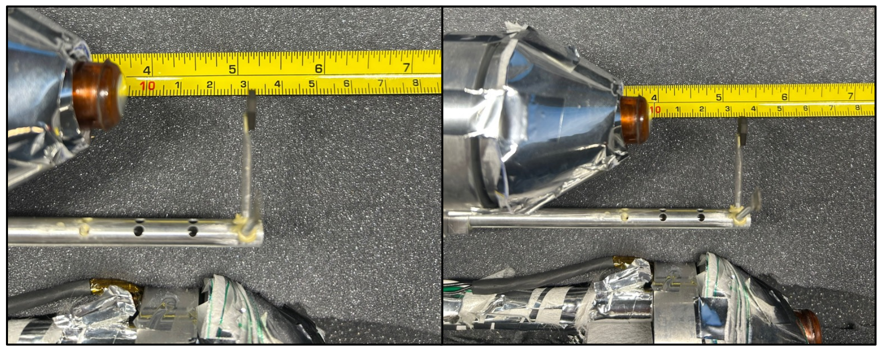
The new RG-M targets



Alon Sportes

New target measurements





Source: Bob Miller

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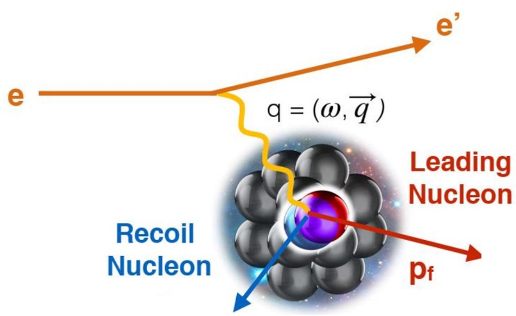
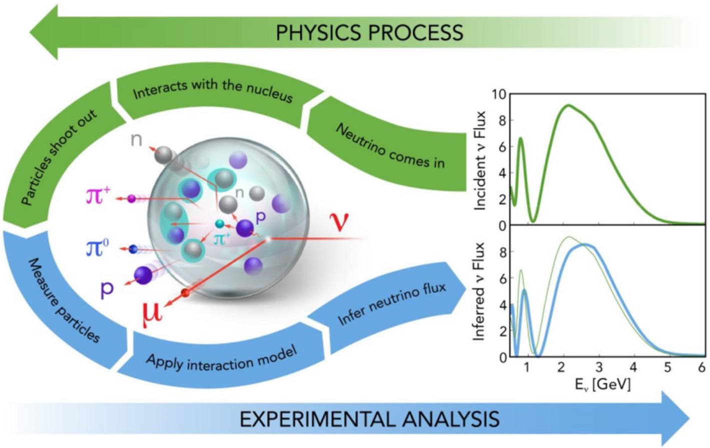
Run Group-M Proposals

Short Range Correlations

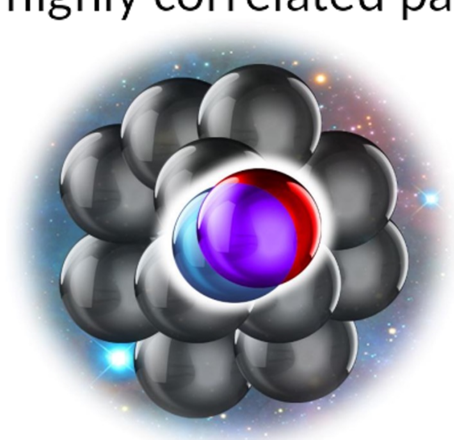


Electrons for Neutrinos (e4ν)



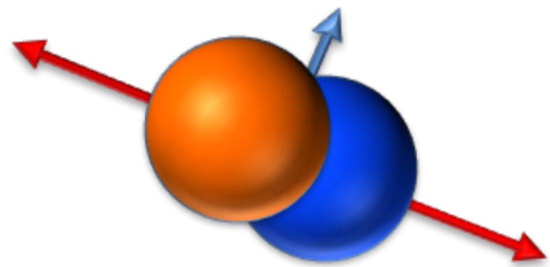
- (e,e') inclusive
- (e,e'N)
- (e,e'NN)

Short range, short lived,
highly correlated pairs



r-space

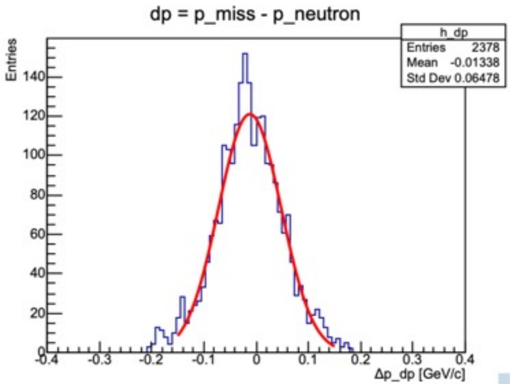
High relative momentum
Lower center of mass momentum



k-space

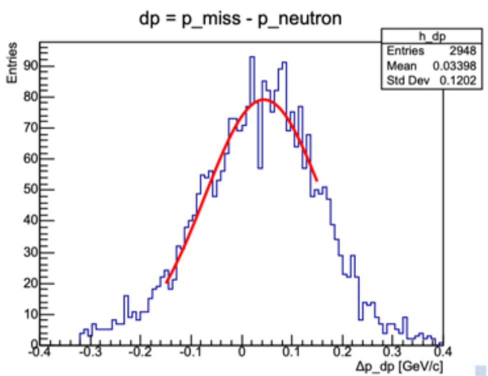
Igor Parshkin

He4 and D2 6GeV data



Deuterium
Center of
Mass Motion
of SRC

dp: sigma = 0.07669 ± 0.00185



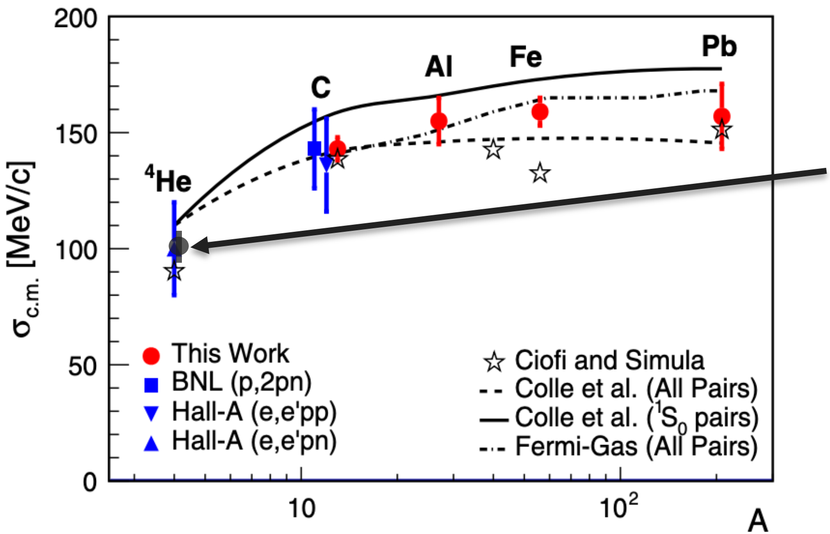
Helium
Center of
Mass Motion
of SRC

dp: sigma = 0.11722 ± 0.00536

$$\sigma_{Total} = \sqrt{\sigma_{res}^2 + \sigma_{CM}^2}$$

Igor Parshkin

CM motion - Results



- σ_CM(dpx) = **0.094**± **0.05** 0.0GeV/c
- σ_CM(dpy) = **0.110** ± **0.06** GeV/c
- σ_CM(dpz) = **0.097** ± **0.06** GeV/c
- σ_CM(dp) = **0.1012** ± **0.06** GeV/c

* Systematic uncertainty has not yet been calculated

Phys. Rev. Lett. **121**, 092501 (2018). arXiv: 1805.01981

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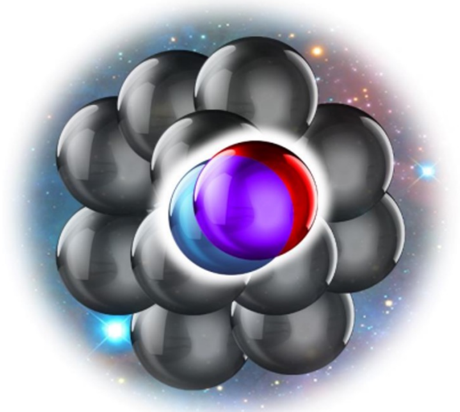
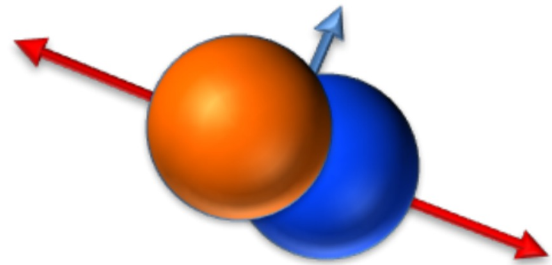
highly correlated pairs



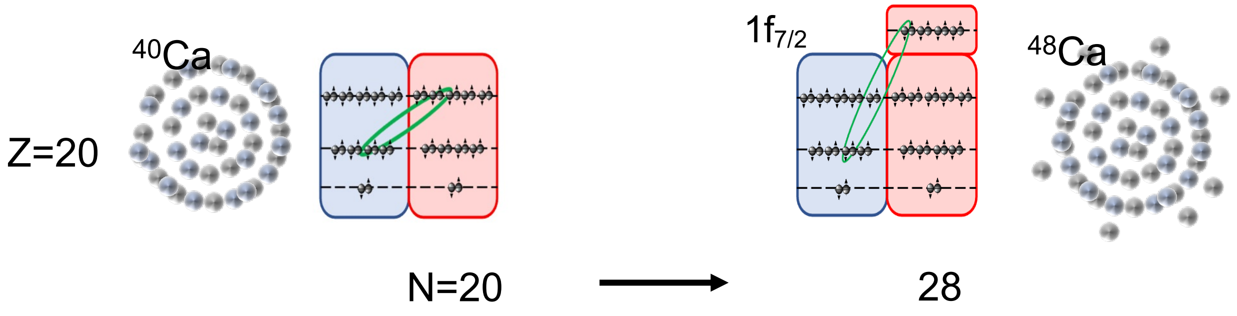
r-space

High relative momentum
Low center of mass momentum



k-space

SRCs in Asymmetric Nuclei

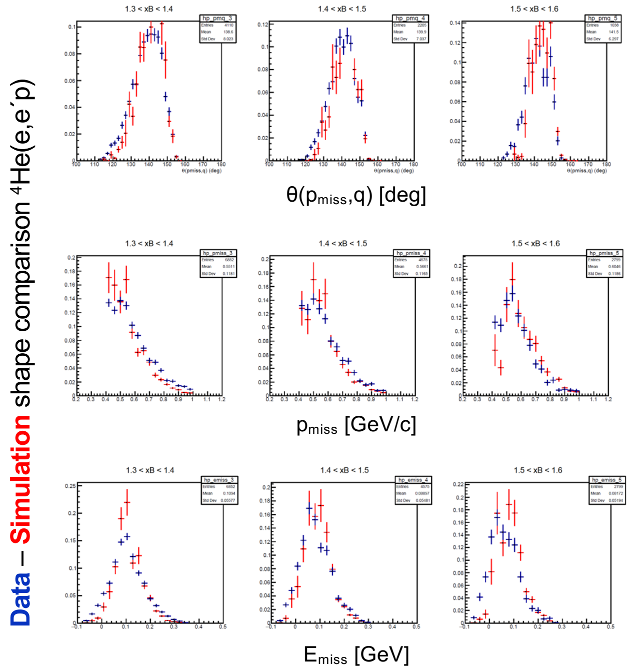


SRC Event Selection

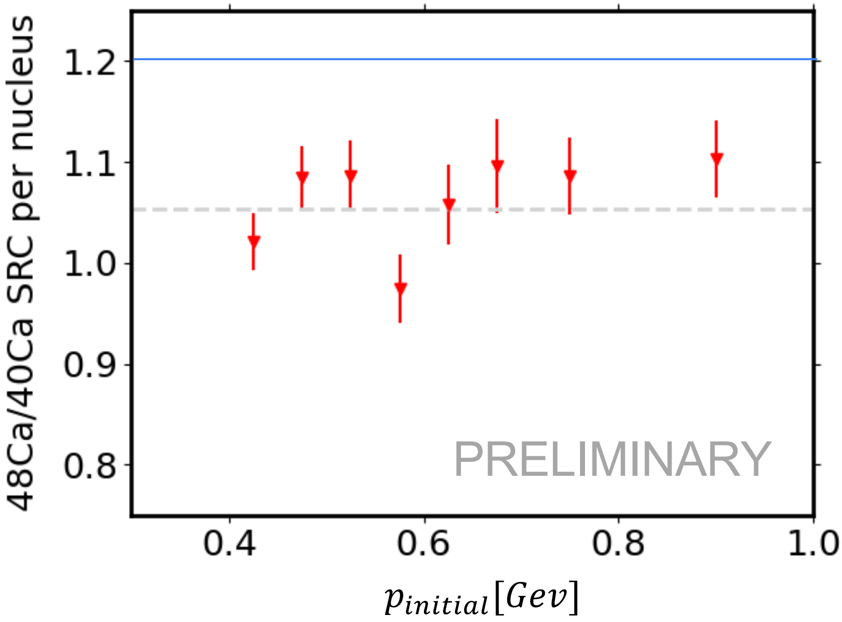
Good Agreement with SRC Simulation

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

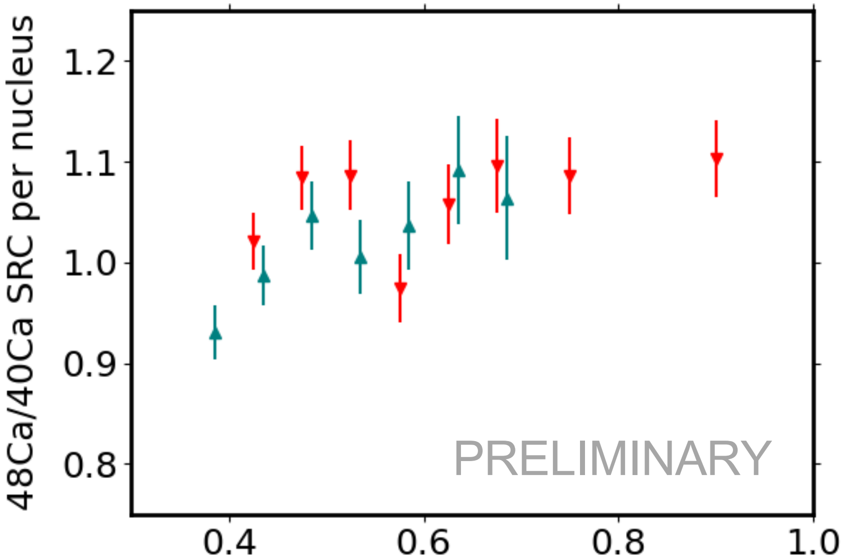


SRCs in Asymmetric Nuclei



≠ ~1.2

SRCs in Asymmetric Nuclei

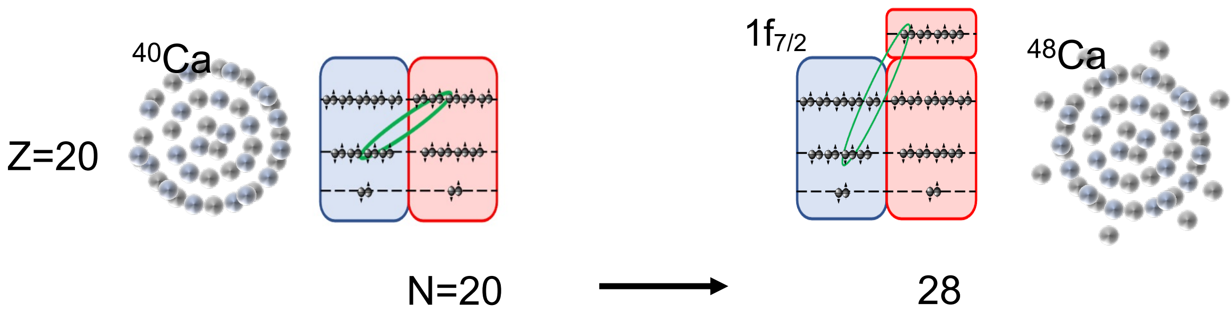


RG-M (Hall B) **1.05 (10)**

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

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

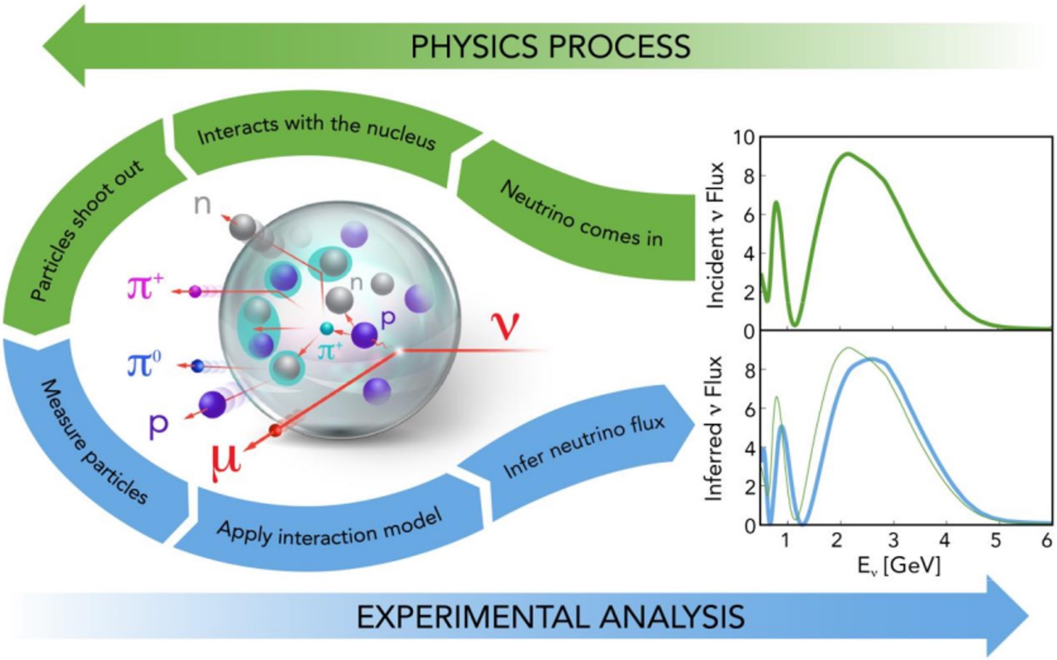
SRCs in Asymmetric Nuclei



48Ca/40Ca(e,e‘p) = 1.05

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

Electrons for Neutrinos



Overview

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

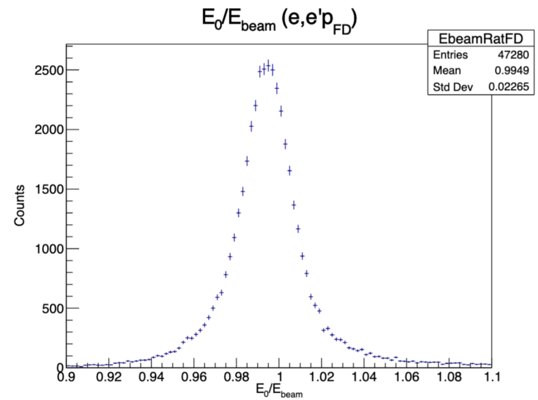
End

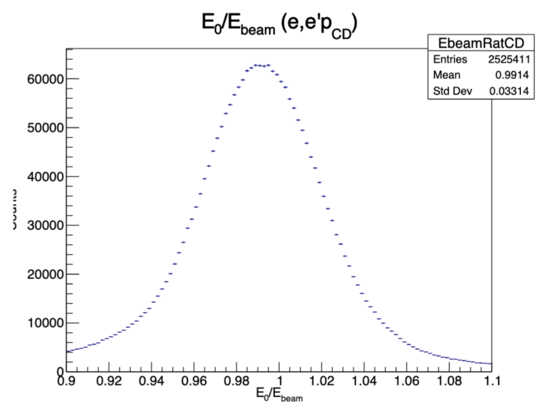
Backup

Use Elastic Scattering Angles to Calculate Beam Energy

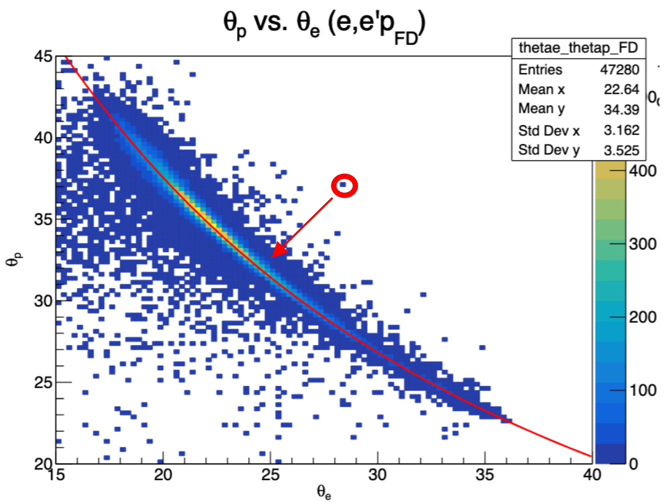
- $0.7\ GeV < W < 1.1 GeV$
- $-3° < \Delta\phi_{ep} < 3°$
- Separate events with a proton in the FD and CD

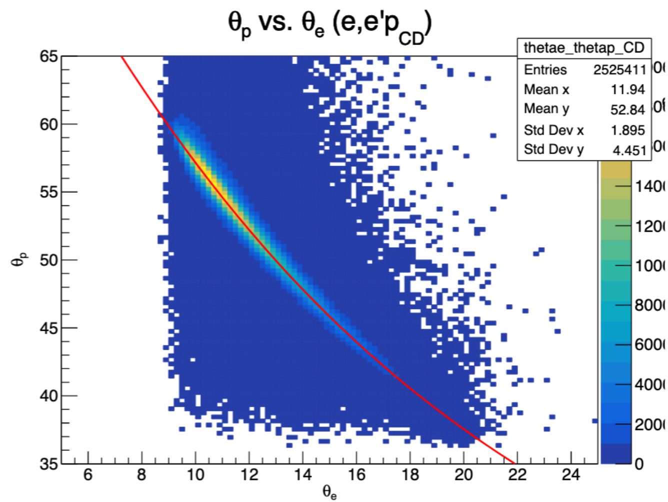
$$E_0 = m_N\left(\cot(\theta_e/2)\cot(\theta_p) - 1\right)$$





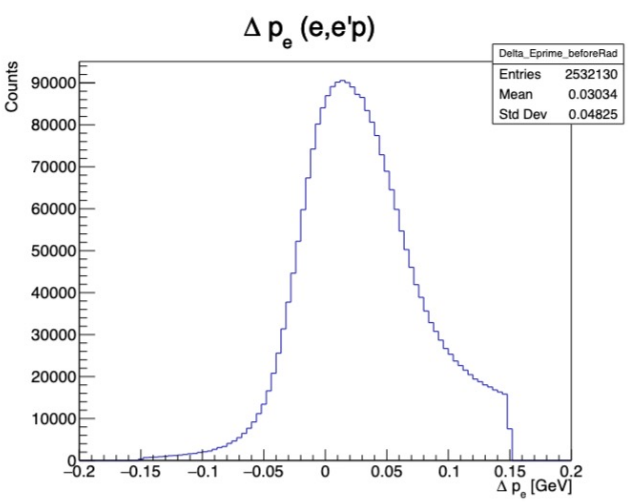
We use Elastic Kinematics to Correct the Electron and Proton at the same time

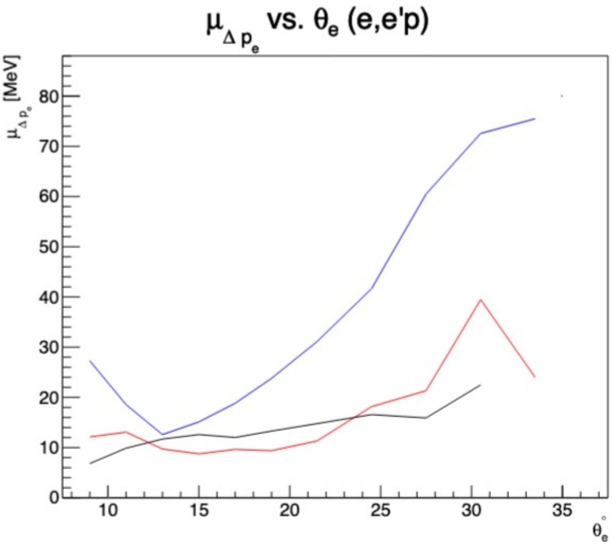




$$E_0 = m_N\left(\cot(\theta_e/2)\cot(\theta_p) - 1\right)$$

Momentum Correction of Electrons





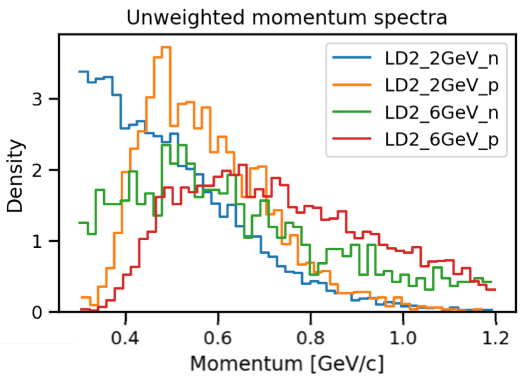
Before Momentum Correction
After Momentum Correction
H(e,e’p) Simulation with Radiation

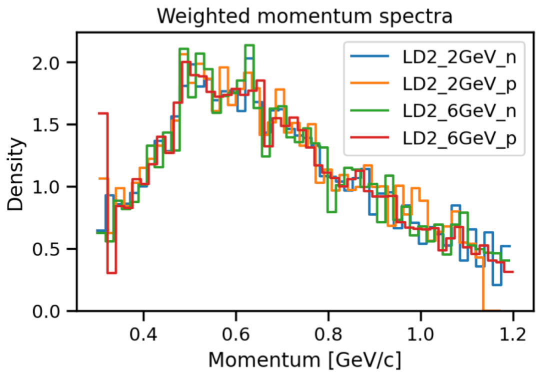
Feature Engineering Concerns:

1. Exclusive reactions constrain kinematics

→ Consider Deuterium data only for feature design

→ Reweight Deuterium data for equal momentum distributions

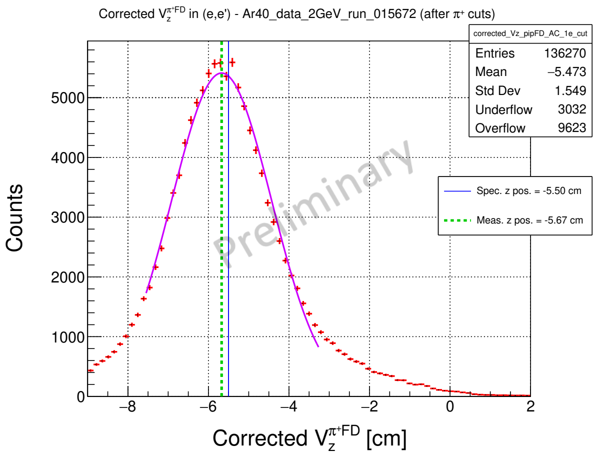




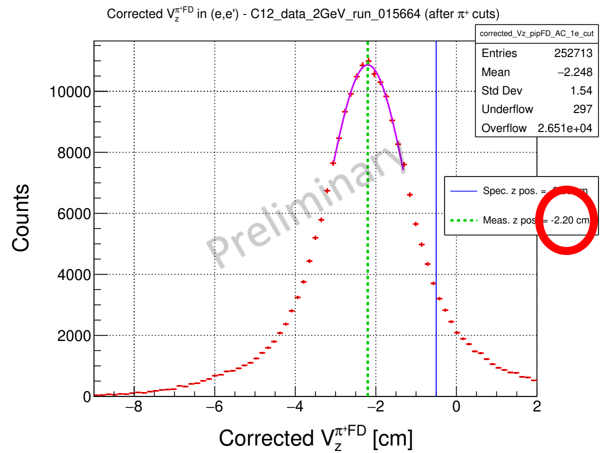
Alon Sportes

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

Ar40_data_2GeV_run_015672



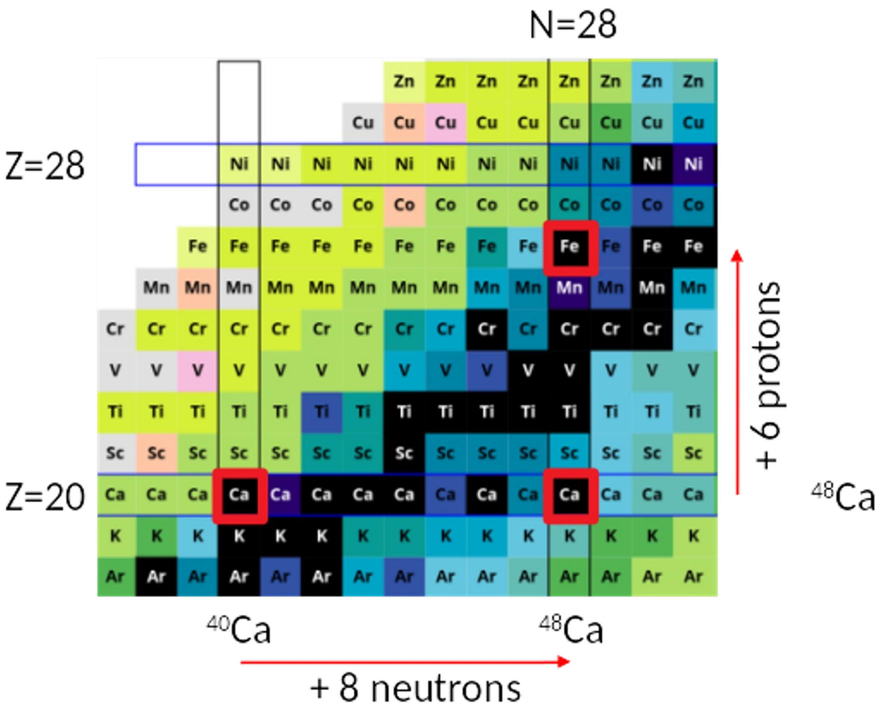
C12_data_2GeV_run_015664



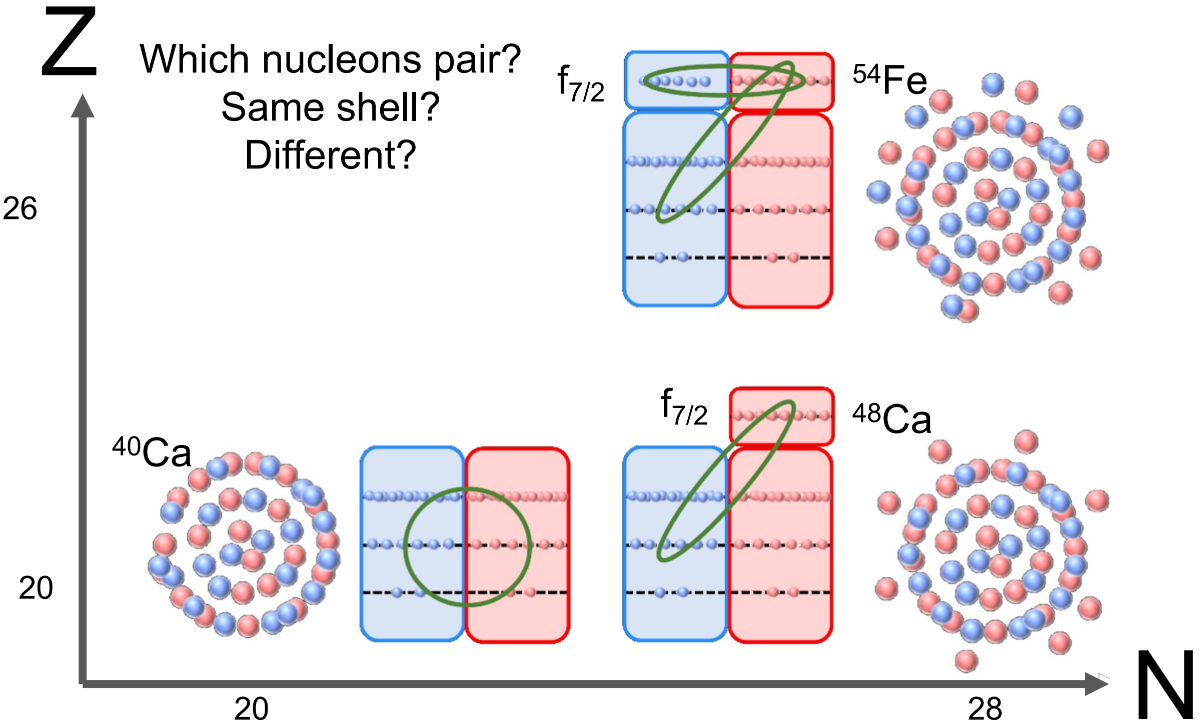
$\pi^{\pm}$ cuts = electron PID cuts + $\pi^{\pm}$ PID cuts + dV_z cuts

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

SRCs in Asymmetric Nuclei



SRCs in Asymmetric Nuclei



SRCs in Asymmetric Nuclei

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

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

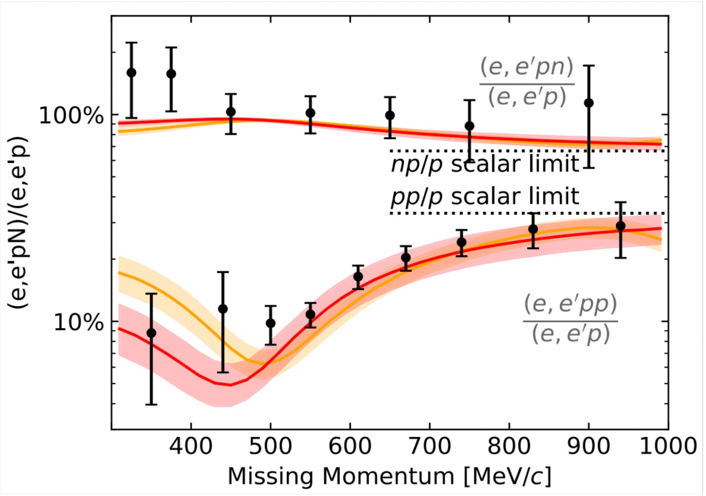
→ per nucleus yield ratio

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

T : transparency
ϵ: detector efficiency

Validation with New Helium-4 Data

Momentum dependence of $e'pn/e'p$ previously measured

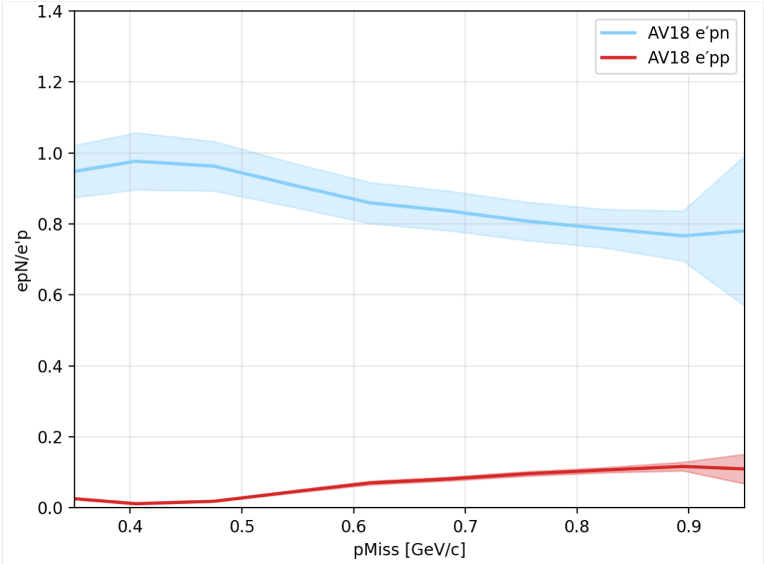


I. Korover *et al.* (CLAS Collaboration), Physics Letters B **820** (2021) 136523.

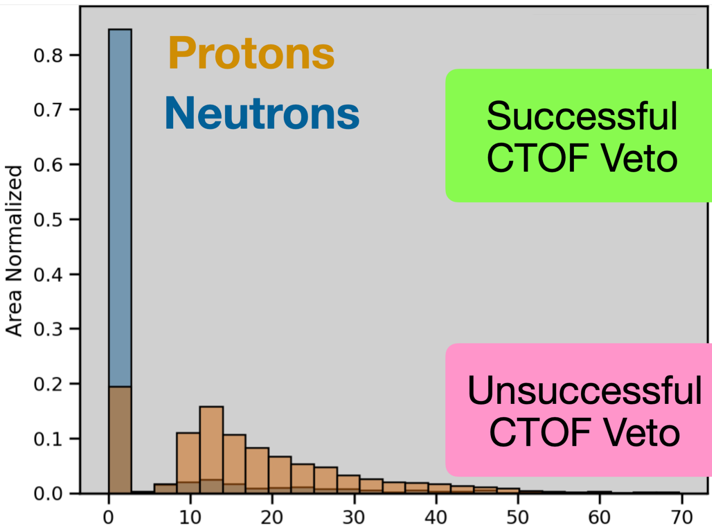
Validation with New Helium-4 Data

Momentum dependence of $e'pn/e'p$ previously measured

Model using AV18 interaction + nuclear transparency, single charge exchange



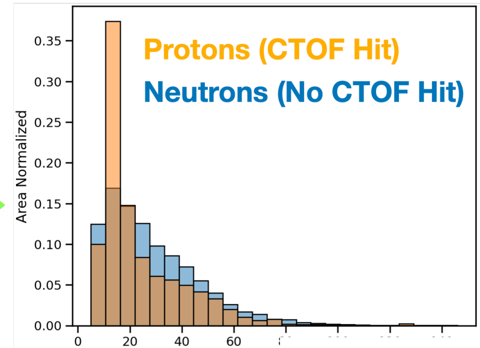
But additional features help with edge cases!

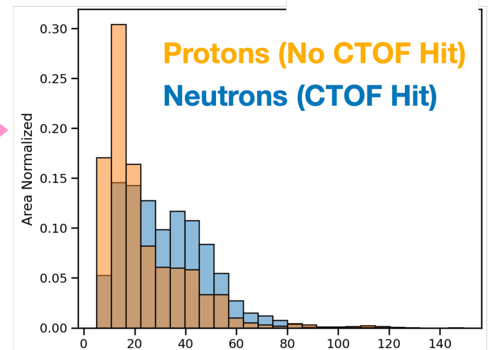


Total CTOF Edep in 3 Steps

Successful CTOF Veto

Unsuccessful CTOF Veto





Primary CND Hit Energy