RG-M Analysis Update

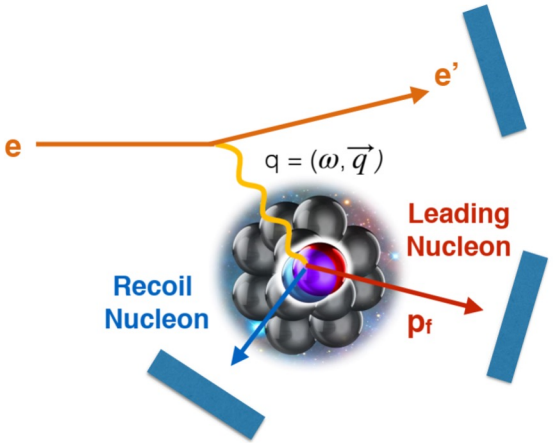
Andrew Denniston (MIT)

Overview

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

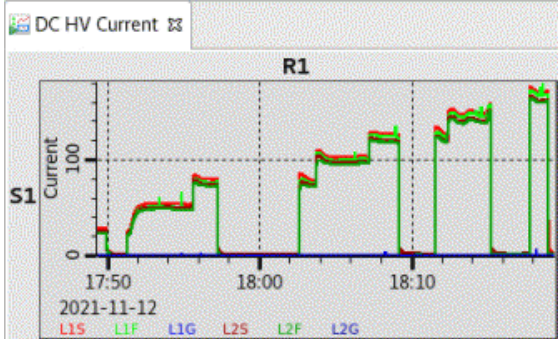
RG-M Experiment at CLAS12

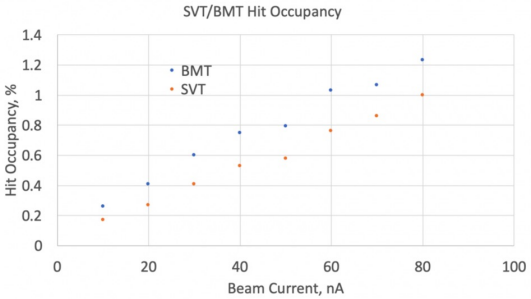
- November 2021 – February 2022
- Fully cooked production runs
- 2, 4, and 6 Gev Beam Energies
- H, D, He, C, 40Ca, 48Ca, Ar, and Sn

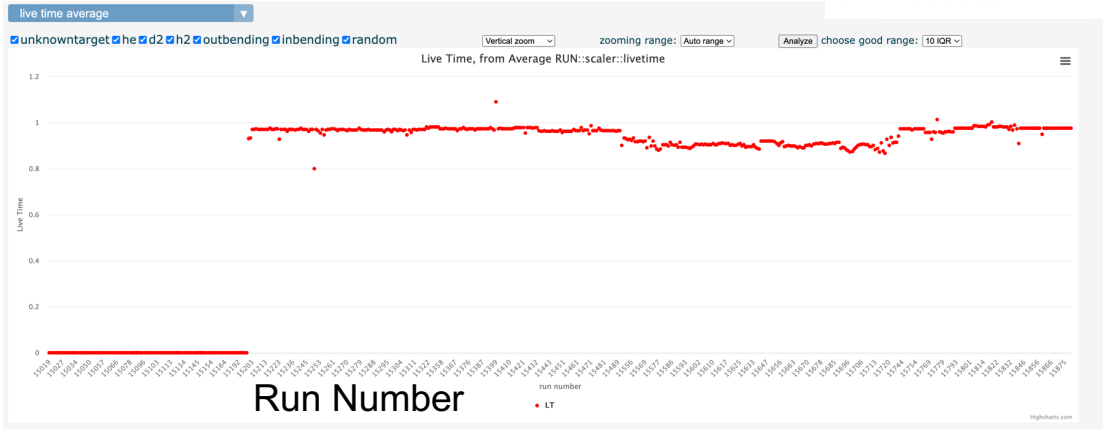


RGM Tasks

- Cook luminosity scans and empty target runs.
- Recover collected charge for H, D, and He targets.

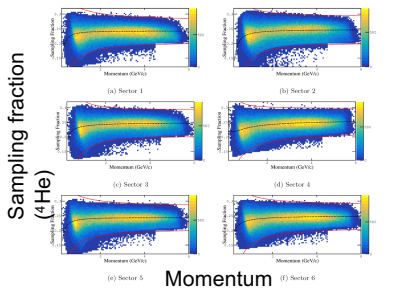


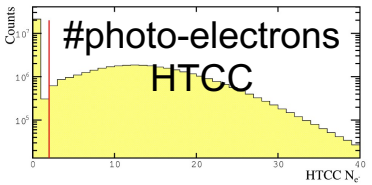




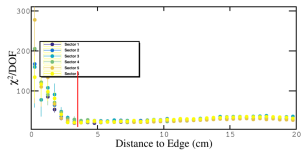
Particle ID for Electrons in 6 GeV data

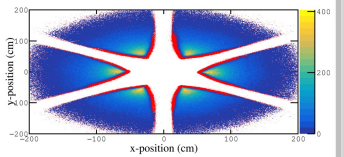
(charge, HTCC photo-electrons, ΔE(PCal), Sampling fraction)



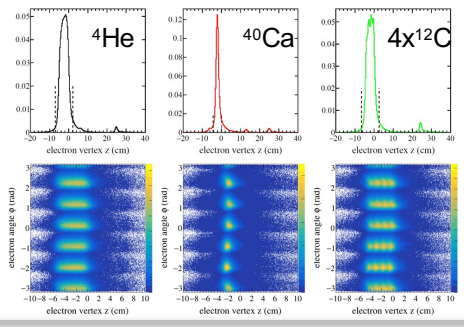


Fiducial Cuts

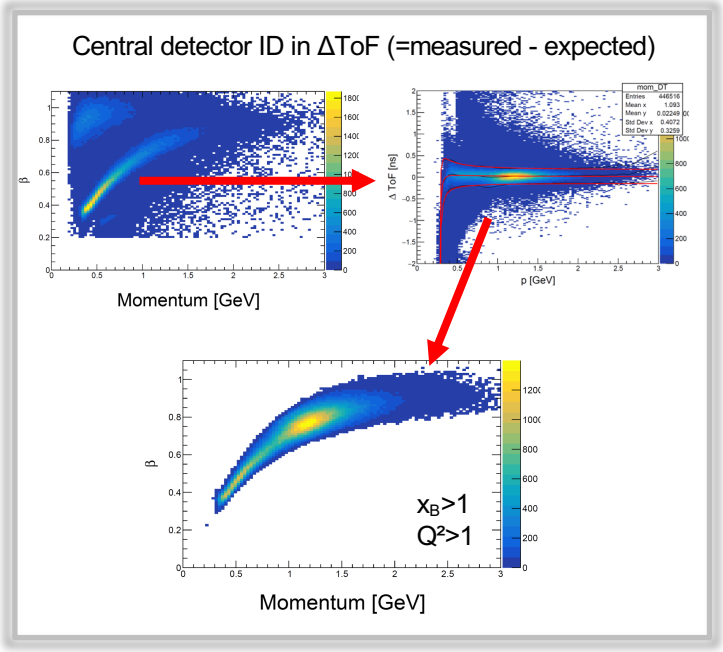


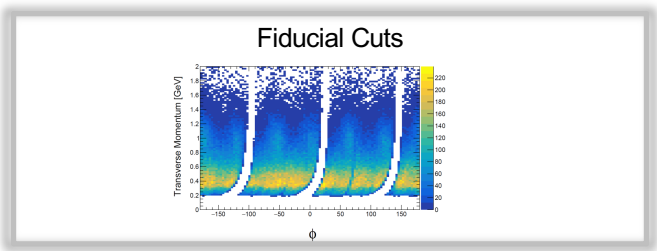


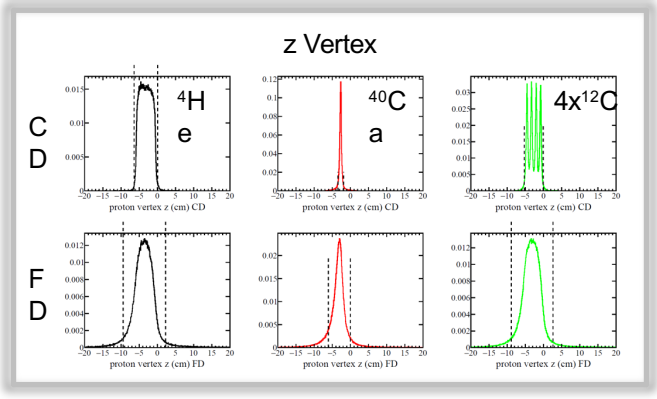
z Vertex



Particle ID for Protons in 6 GeV data







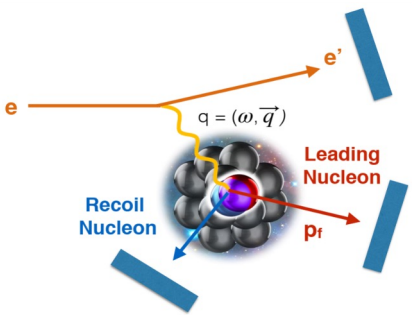
Particle ID for 6 GeV data

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]

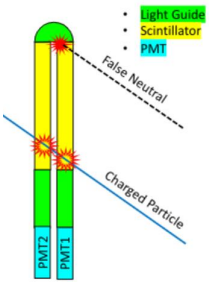
[1]Department of Physics, Massachusetts Institute of Technology
[2]Department of Physics, The George Washington University

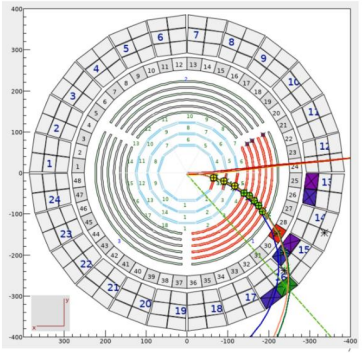
→ Submitted “General“ Analysis Note

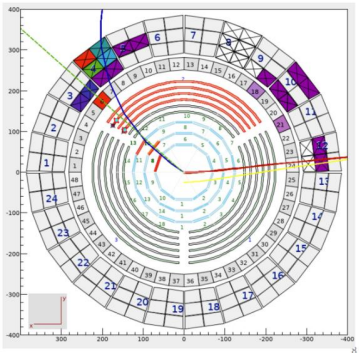


Particle ID for Neutrons in 6 GeV data

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

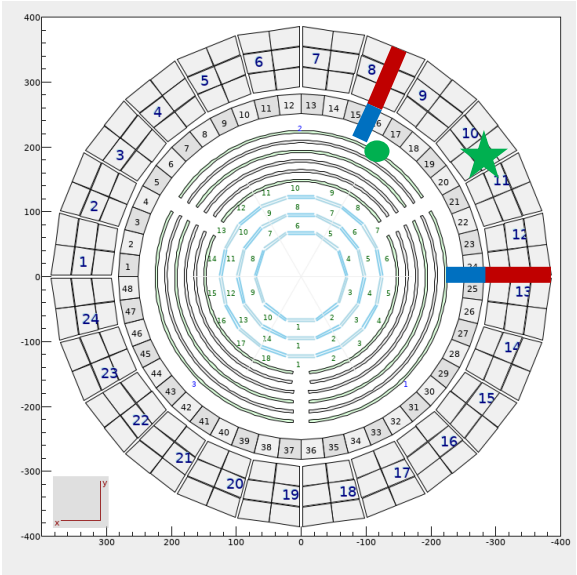






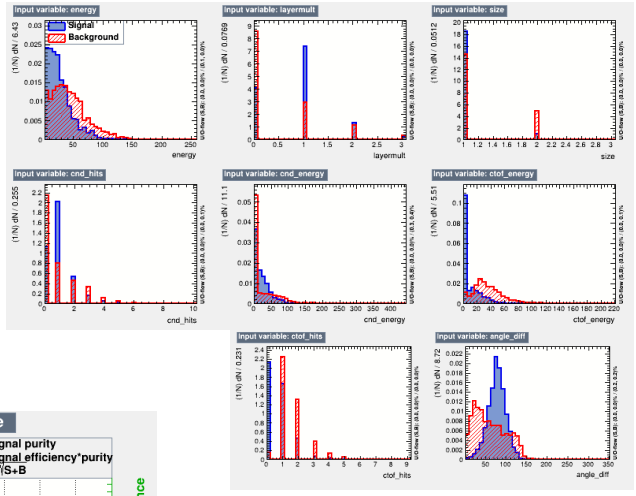
Particle ID for Neutrons in 6 GeV data

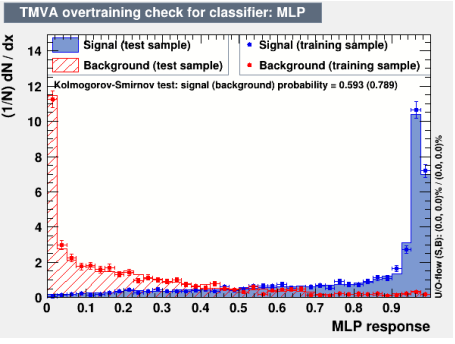
- Number of CND hits within 30 degrees of neutron
- CND energy deposition within 30 degrees of neutron
- Number of CTOF hits within 30 degrees of neutron
- CTOF energy deposition within 30 degrees of neutron
- Number of hits in CND cluster
- Neutron energy
- CND layer multiplicity (0 if CTOF only)
-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

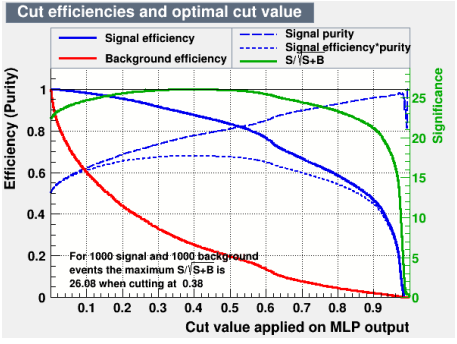


Particle ID for Neutrons in 6 GeV data

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

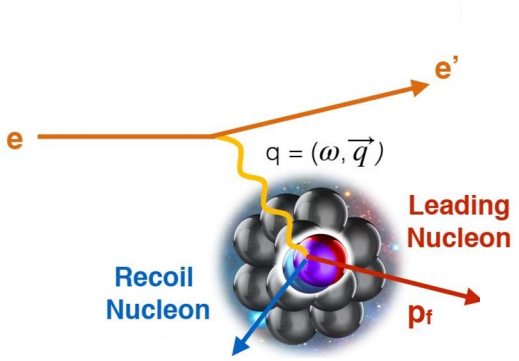






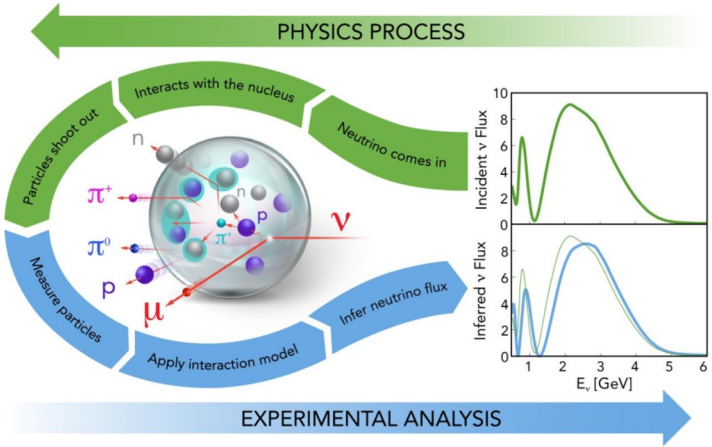
Run Group-M Proposals

Short Range Correlations

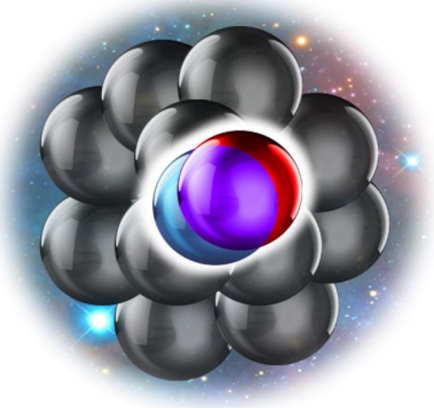


- (e,e') inclusive
- (e,e'N)
- (e,e'NN)

Electrons for Neutrinos (e4ν)



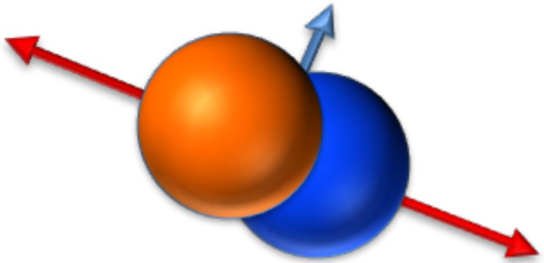
Short range, short lived, highly correlated pairs



r-space

High relative momentum

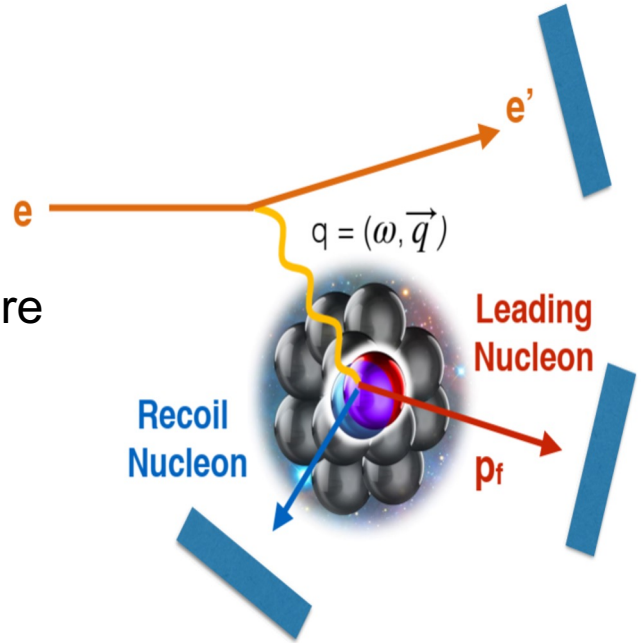
Low center of mass momentum



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.

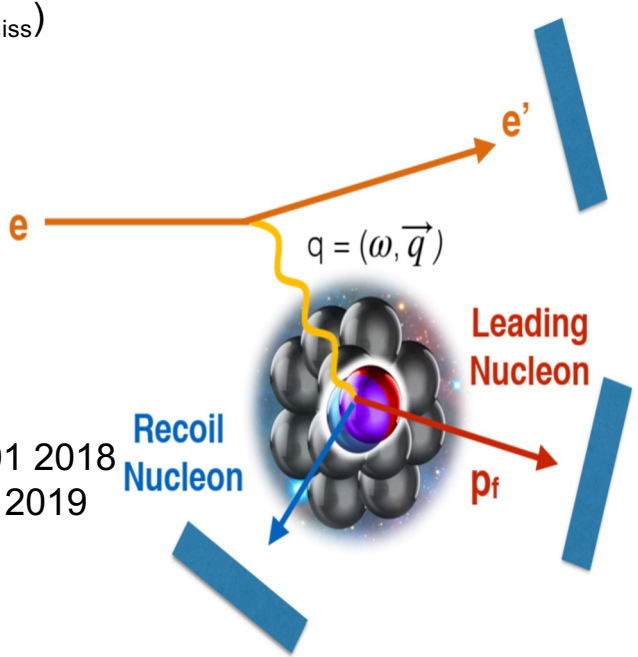


SRC Cuts

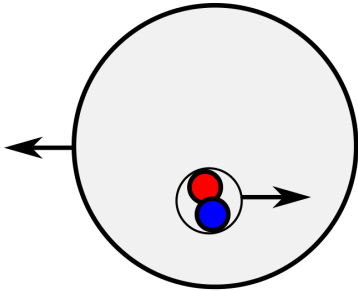
- $x_B > 1.3$
- $Q^2 > 1.5$
- $p_{lead} > 1$ GeV/c
- 0.8 GeV/c² < M_{miss} < Cut(x_B,p_{miss})
- 0.4 GeV/c < p_{miss} < 1.0 GeV/c
- |p|/|q| < 0.96

Derived From the CLAS6 Analysis Cuts:

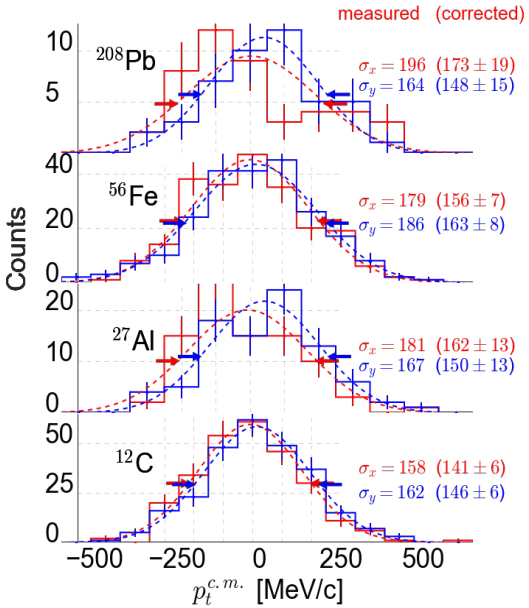
- Physics Letters B 722 (2013) 63–68
- Science 346, 614 (2014)
- Nature 560, 617–621 (2018)
- Physics Letters B 797 (2019) 134792
- Cohen et al. Phys. Rev. Lett. 121, 092501 2018
- Duer et al. Phys. Rev. Lett. 122, 172502 2019



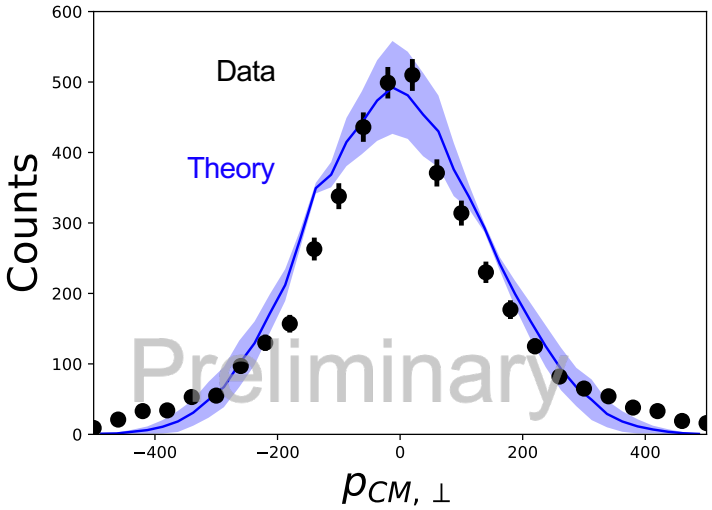
Center of Mass Motion



CLAS6 Data

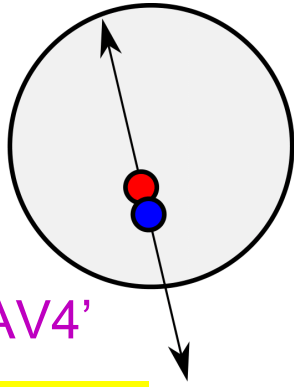


RGM Helium

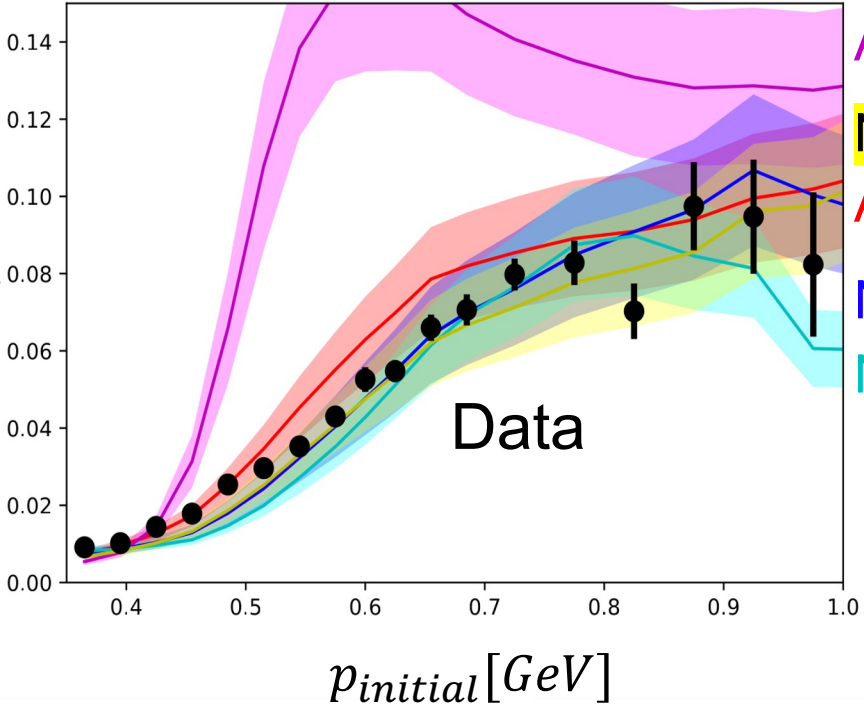


- Cohen, PRL (2018)

Precision NN interaction



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



AV4'

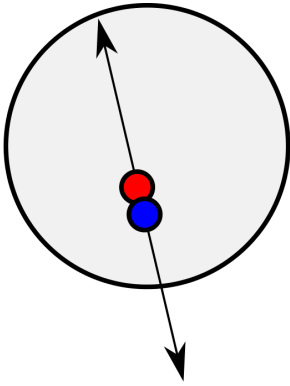
Norfolk

AV18

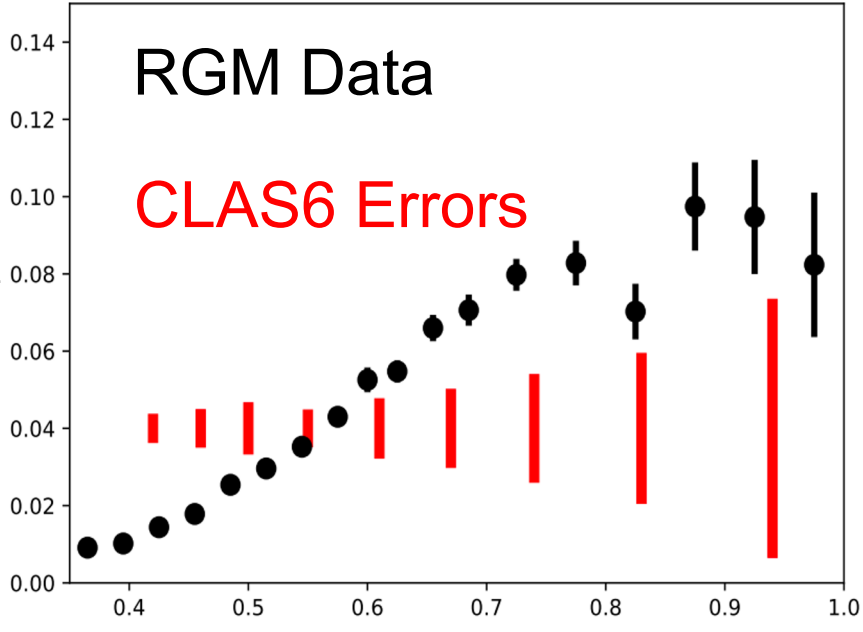
N2LO 1.0fm

N2LO 1.2fm

Precision NN interaction



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



$p_{initial}[GeV]$

SRCs Goals with CLAS

- Compare old CLAS6 results with RGM results (30X the statistics).
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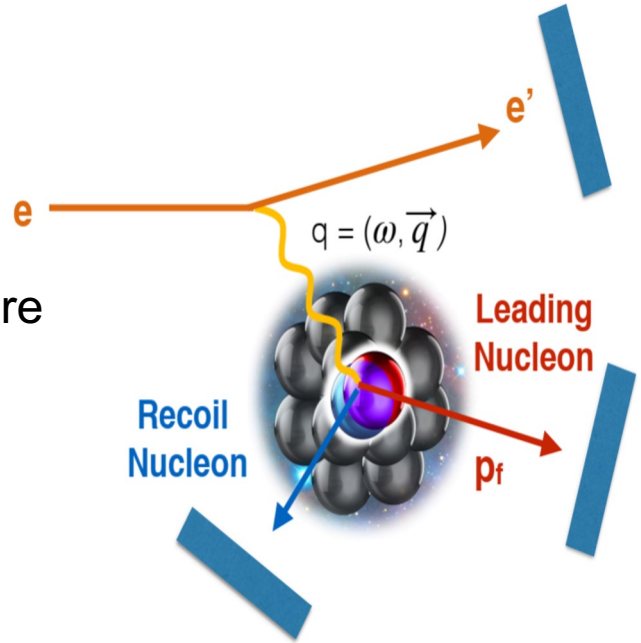
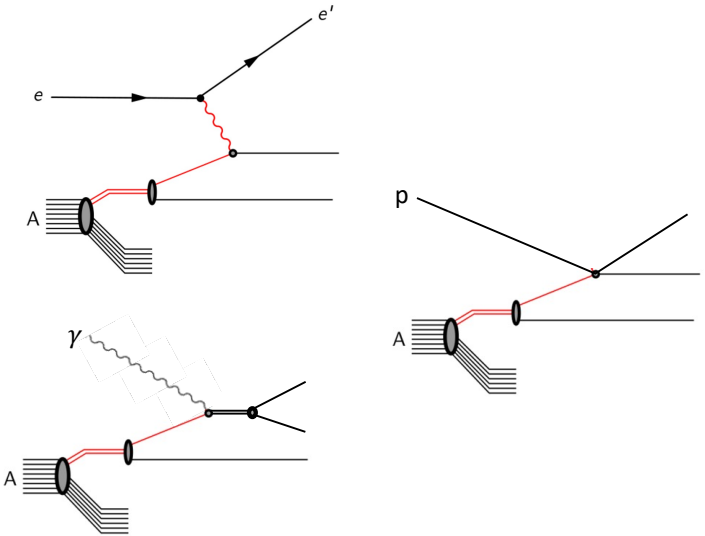
- Determine how SRCs are formed.

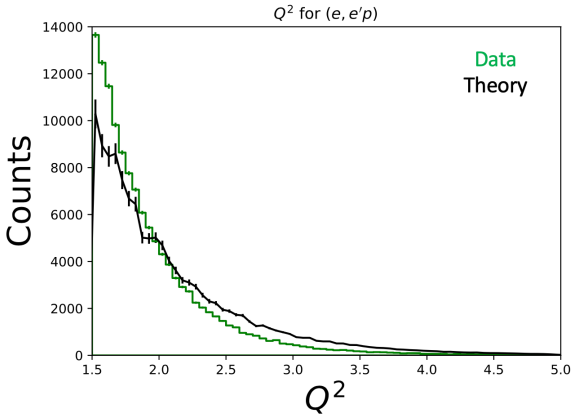


Measuring SRC Probe (In)dependence

Change the Probe

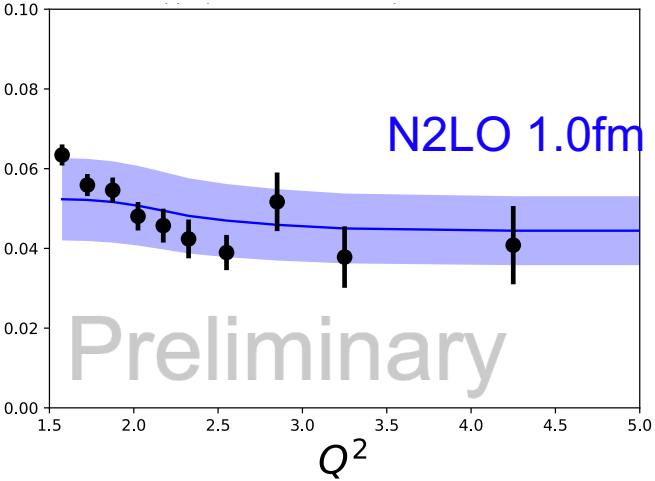


Change the Scale of the Probe



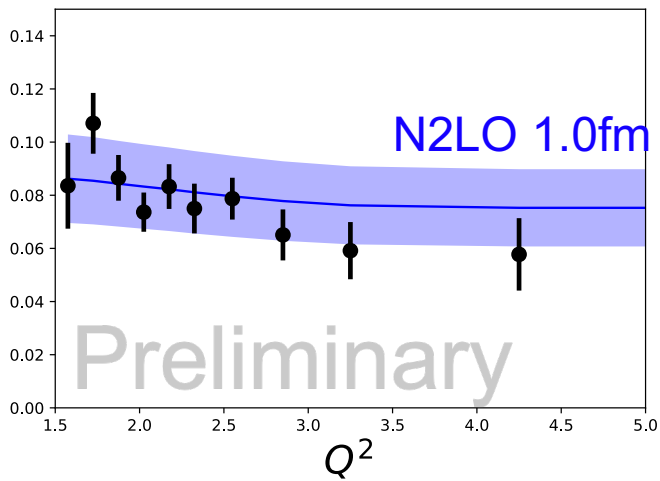
Measuring SRC Probe (In)dependence

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



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

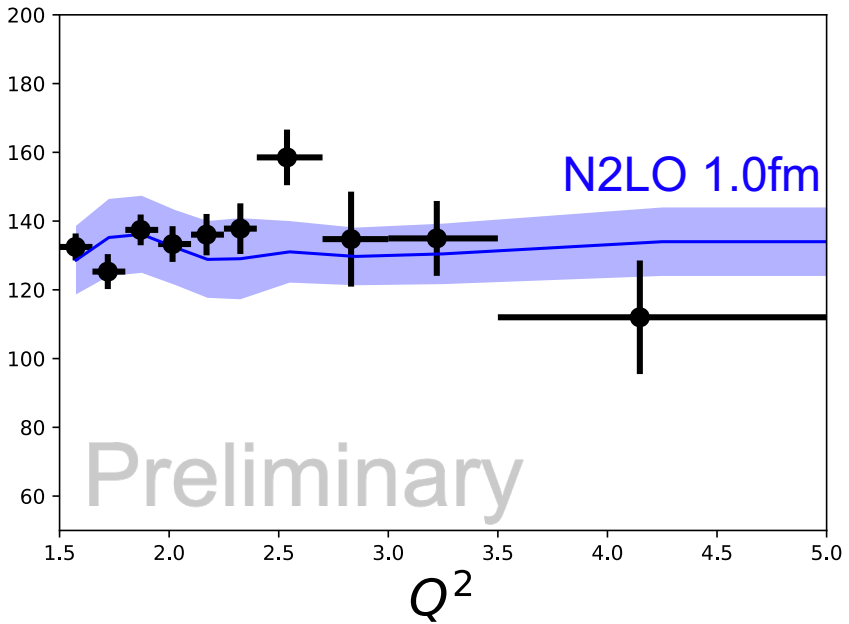
$$\frac{He(e,e'pp)}{He(e,e'p)}$$



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

Measuring SRC Probe (In)dependence

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



SRCs Goals with CLAS

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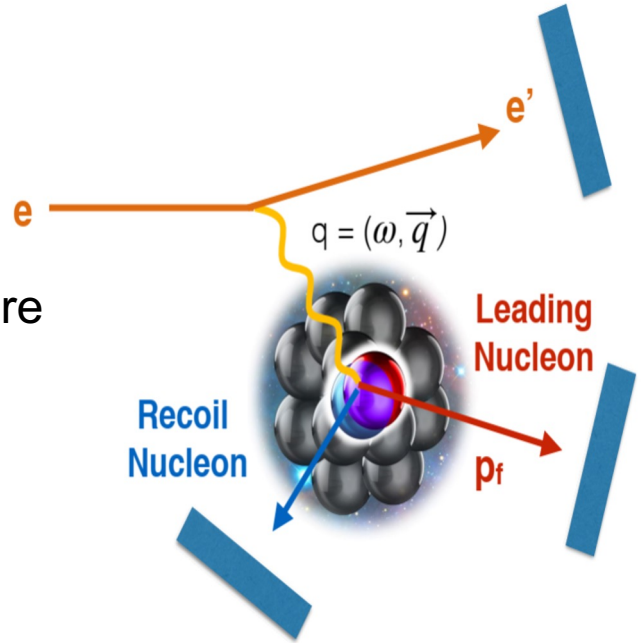
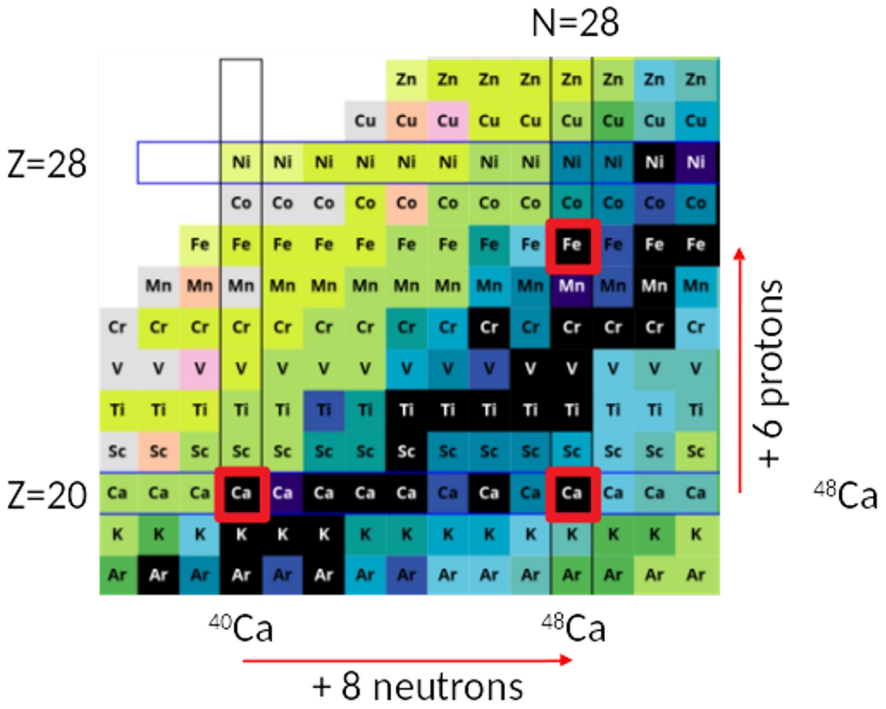
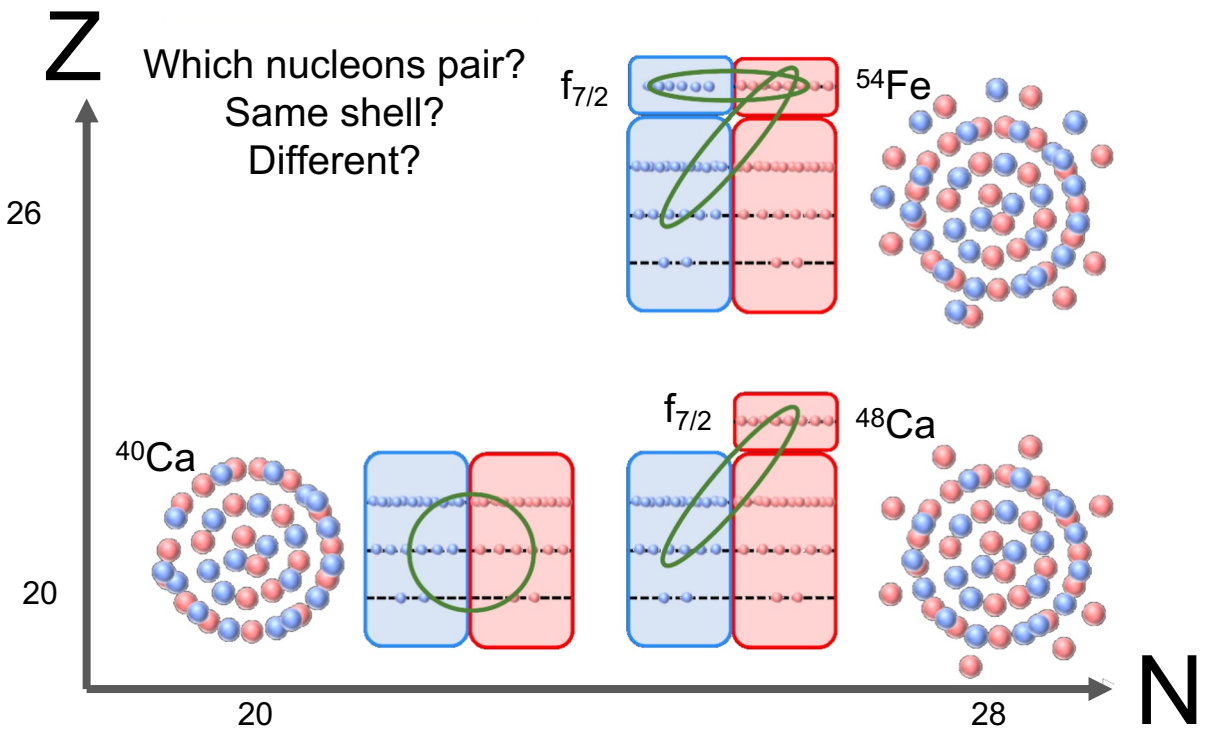


SRCs in Asymmetric Nuclei



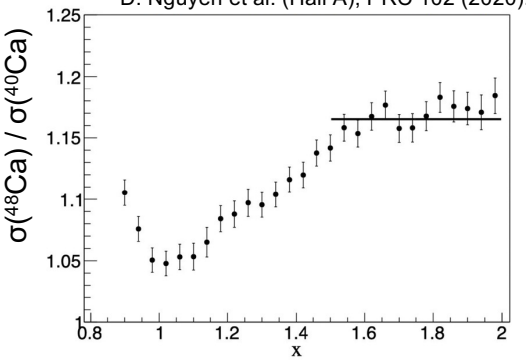
SRCs in Asymmetric Nuclei



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).



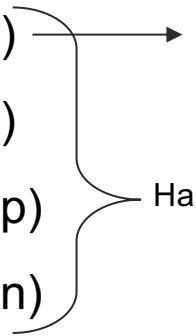
Conclusion: *np* pair dominance

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

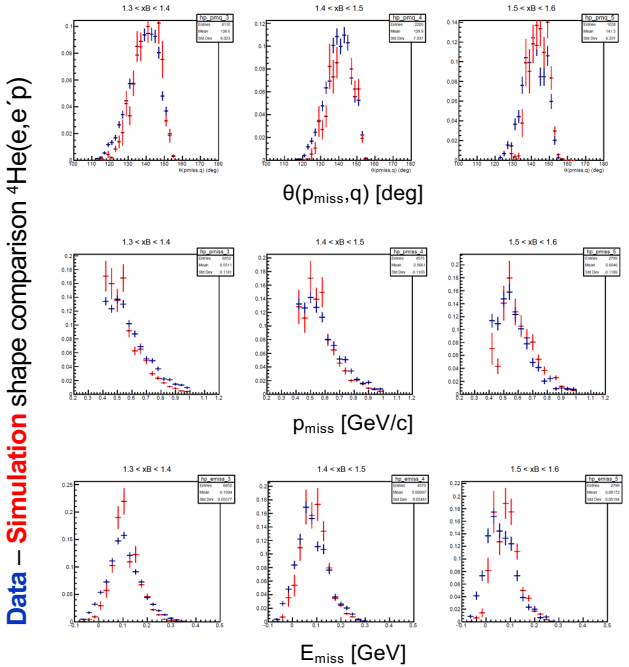
- (e,e’)
- (e,e’p)
- (e,e’n)
- (e,e’pp)
- (e,e’pn)



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)

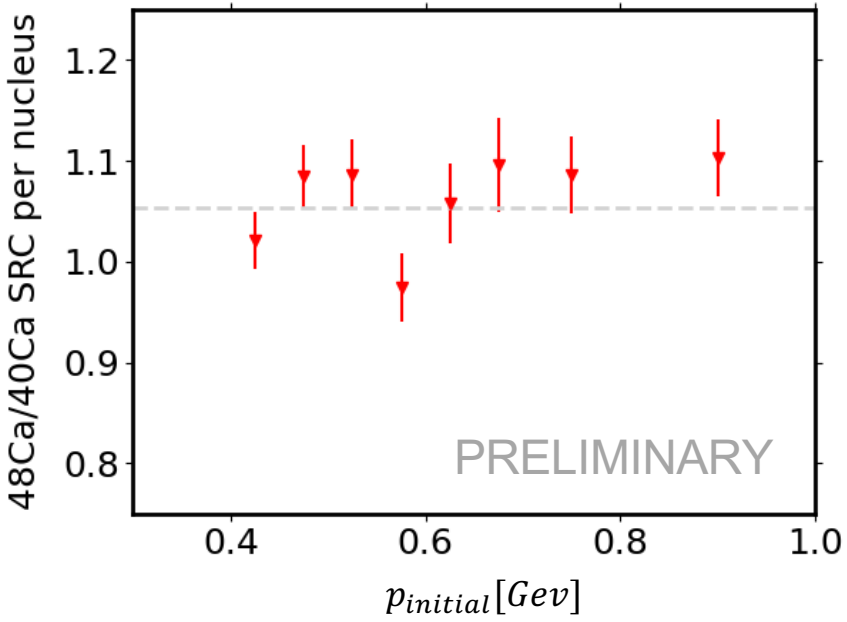
$$Ratio = \frac{yield_A/(N \cdot \rho_A)/T_A \cdot A \cdot \cancel{\epsilon}}{yield_{40Ca}/(N \cdot \rho_{40Ca})/T_{40Ca} \cdot A_{40Ca} \cdot \cancel{\epsilon}}$$

→ per nucleus yield ratio

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

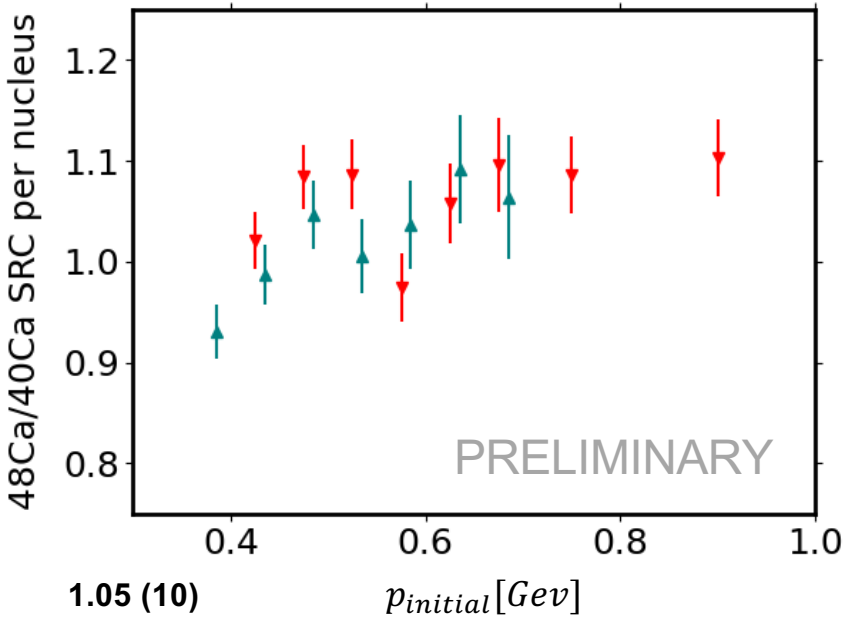
T : transparency
ϵ: detector efficiency

SRCs in Asymmetric Nuclei



≠ ~1.2

SRCs in Asymmetric Nuclei

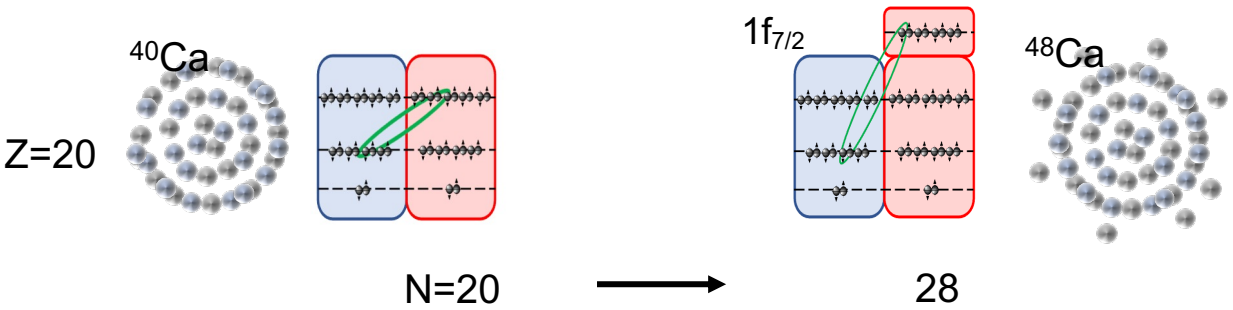


RG-M (Hall B) **1.05 (10)**

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

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

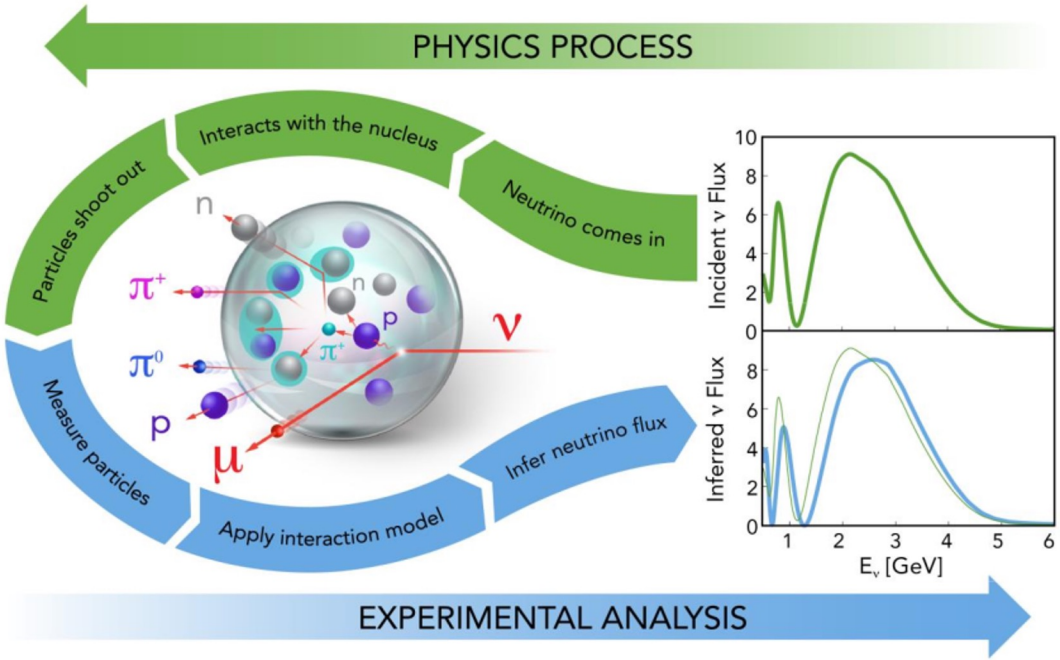
SRCs in Asymmetric Nuclei

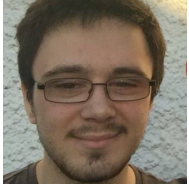


48Ca/40Ca(e,e'p) = 1.05

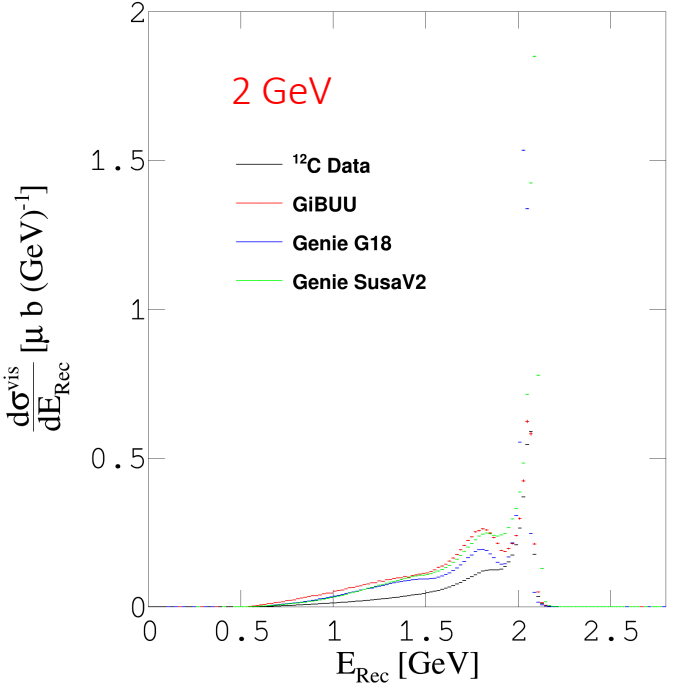
Reduction in short-range pairing across shells! Long-range nuclear structure to impact SRC

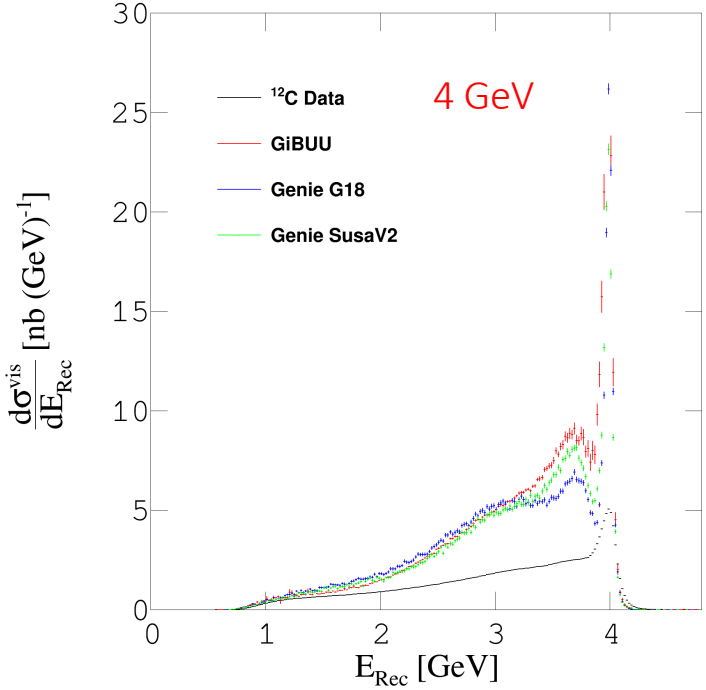
Electrons for Neutrinos



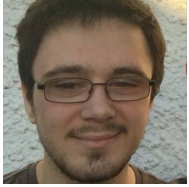


Electrons for Neutrinos



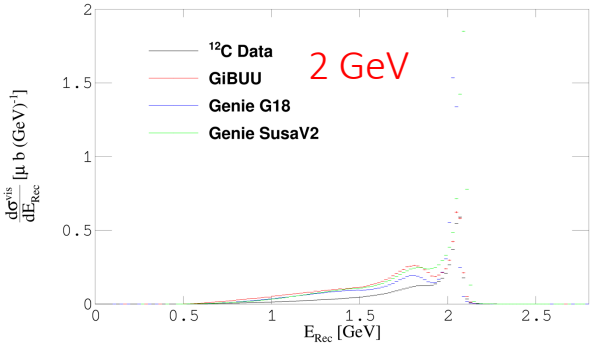


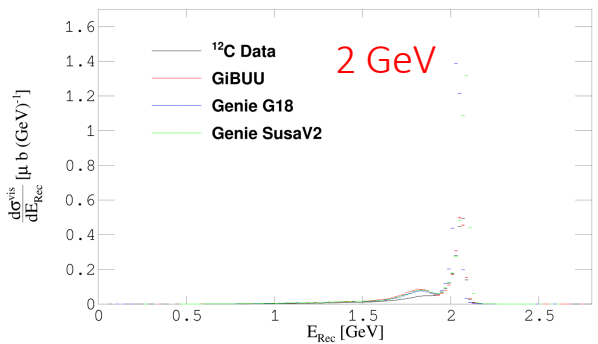
$$E_{Rec} = E_{e'} + \sum E_{nucleons} + \sum E_{mesons}$$

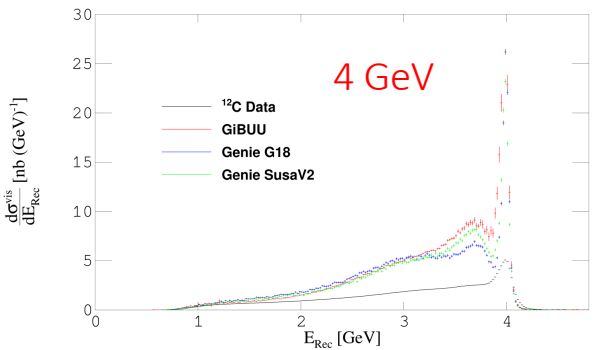


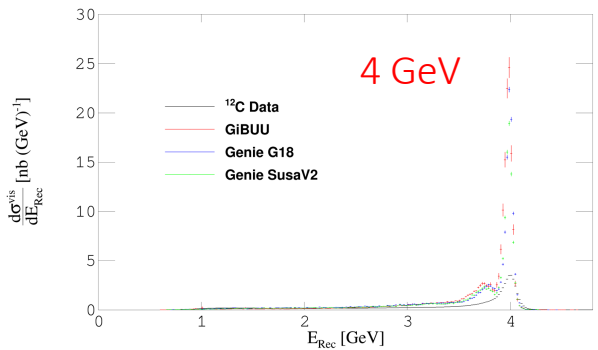
Electrons for Neutrinos

No cut on $p_{\perp}^{miss}$ → Cut on $p_{\perp}^{miss} < 0.2$ GeV/c



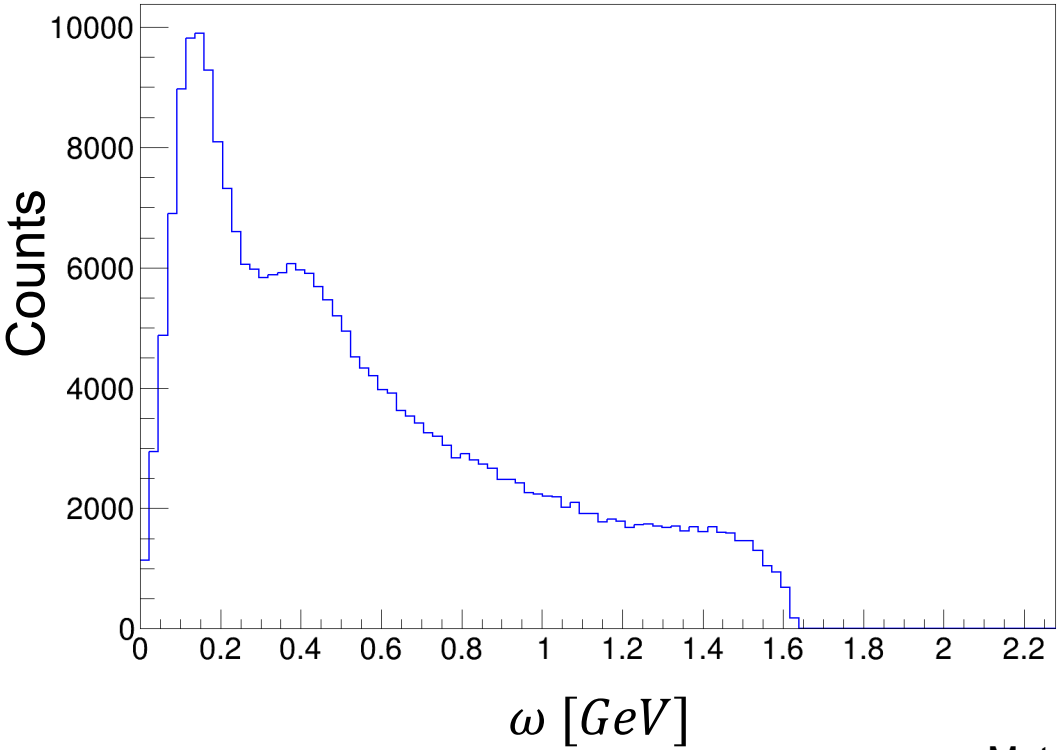






$$E_{Rec} = E_{e'} + \sum T_{nucleons} + \sum E_{mesons}$$

Electrons for Neutrinos (Argon inclusive)

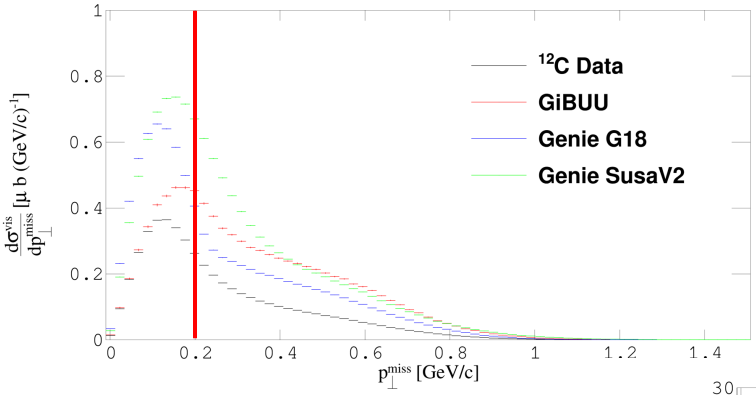


Looking Forward

- Low Level Analysis
  - Energy loss corrections to protons in the FD and CD.
  - CVT acceptance and resolution need to be understood.
  - CND neutrons are mature but still not complete.
- Other Physics Analyses
  - Measure SRC Neutrons.
  - 3 nucleons SRCs.

Conclusion

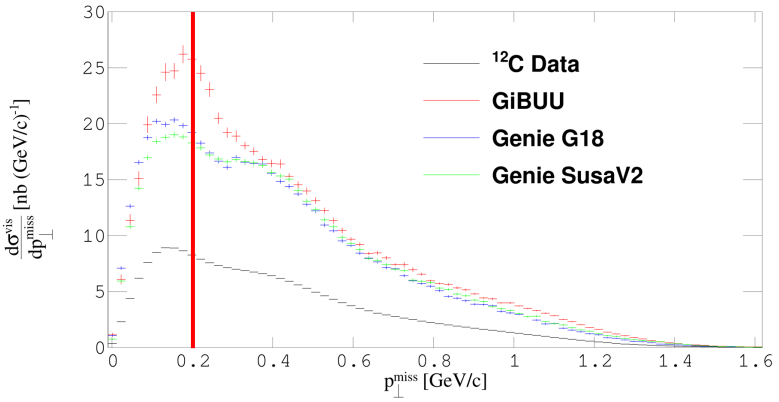
- Low Level Analysis
  - Electron PID, Fiducial, and Vertex Cuts
  - Proton PID, Fiducial, and Vertex Cuts
  - Neutron Machine Learning Algorithm
- SRC Analysis
  - Q2 dependence of SRCs
  - SRCs in Asymmetric Nuclei
- e4v Analysis



2 GeV

Cut on $p_\perp^{miss} < 0.2$ GeV/c

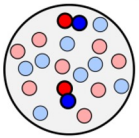
4 GeV



- Low missing transverse momentum -> Direct processes
- Neutrino folk do not know initial beam hence beam independent variables used

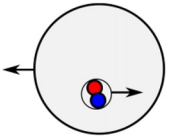
next generation questions…

Pair Abundance



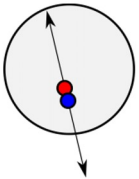
Where are pairs formed?
Which nucleons pair?
Do 3N SRC exist?

Center of
Mass Motion



Precision COM measurements

Pair Interaction

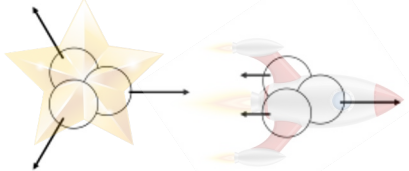


Precision NN interaction at short distances

Scale (Q2) independence of SRC observables

Pathway to 3N SRC Discovery

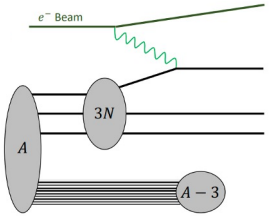
Characterize 3N SRC kinematics…



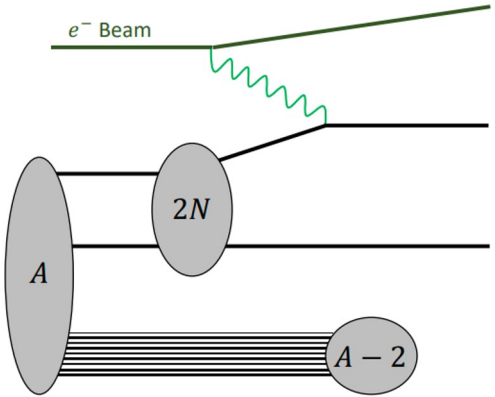
Variables to suppress FSI…

Q2, Xb, p/q ???
New ones

3N SRC cross-section…

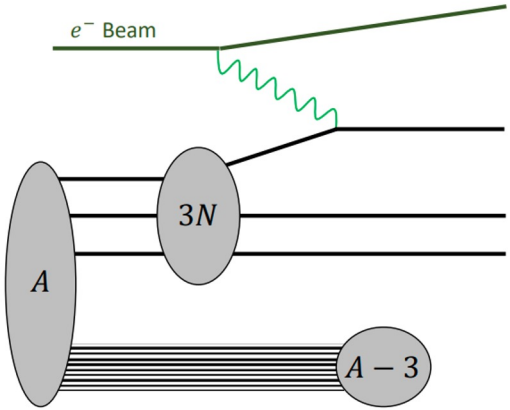


2 Nucleon SRC



$$\frac{d^8\sigma}{d^8X^\mu} = \mathcal{J}\sigma_{eN} * |\phi_\alpha(p_{rel})|^2 * n(p_{cm})$$

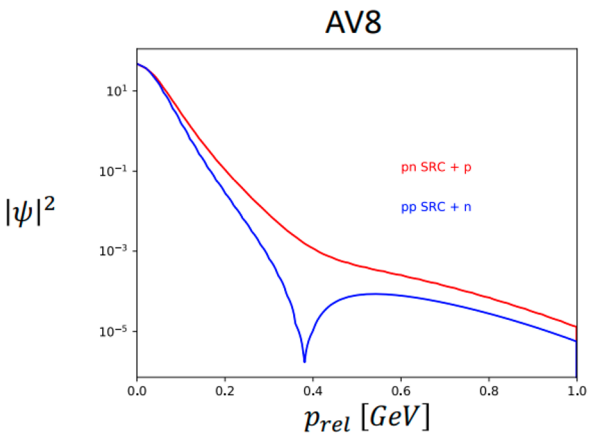
3 Nucleon SRC



$$\frac{d^{11}\sigma}{d^{11}X^\mu} = \mathcal{J}\sigma_{eN} * |\phi_\alpha(\vec{p}_1, \vec{p}_2, \vec{p}_3)|^2 * n(p_{cm})$$

Describing 3-NN interaction

2N-SRC (6 parameters)
3 - center of mass
2 - Euler angles
1 - NN interaction variable (p_{rel})



3N-SRC (9 parameters)
3 - center of mass
3 - Euler angles
3 - NN interaction variables

?

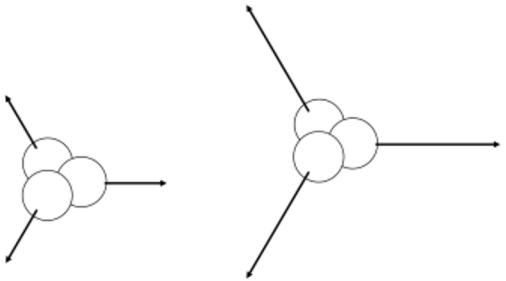
^{3}He wavefunction (ppn)
No 3-body interactions

3NN interaction variables

3 particles -> 9 variables

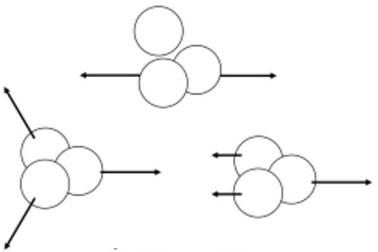
3 - center of mass
3 - euler angles
3 - NN interaction parameters

Size parameter



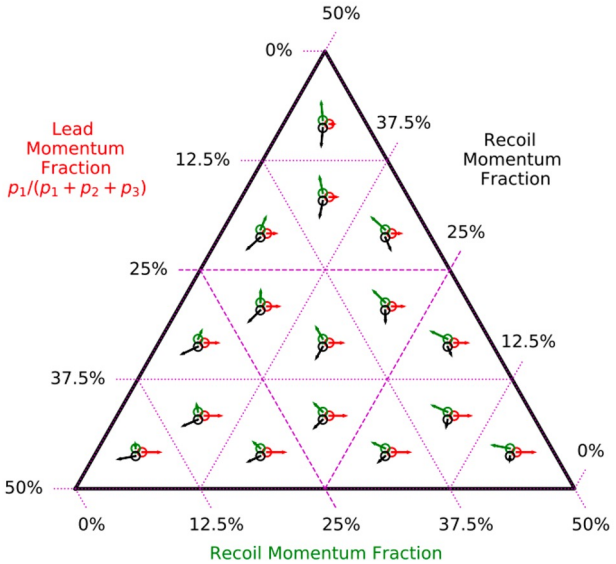
$$p_{tot} = p_1 + p_2 + p_3$$

Shape parameter

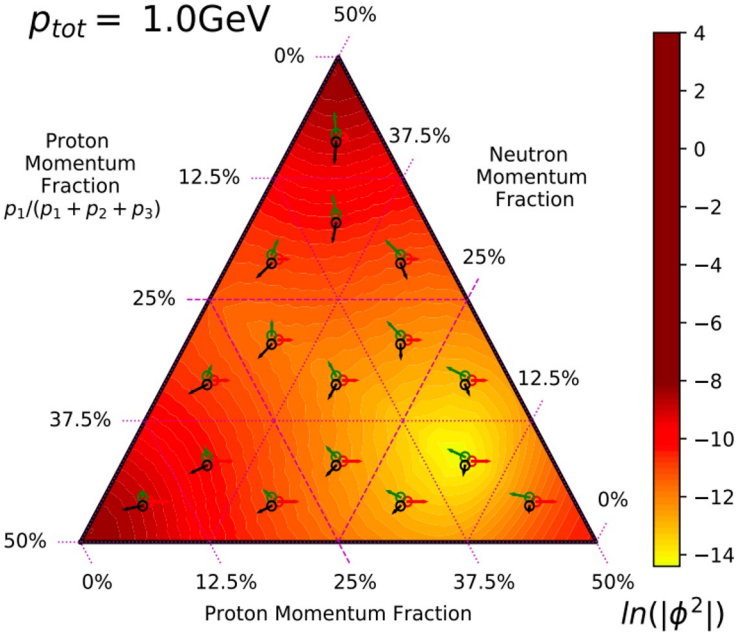


$$\frac{p_1}{p_{tot}}, \frac{p_2}{p_{tot}}$$

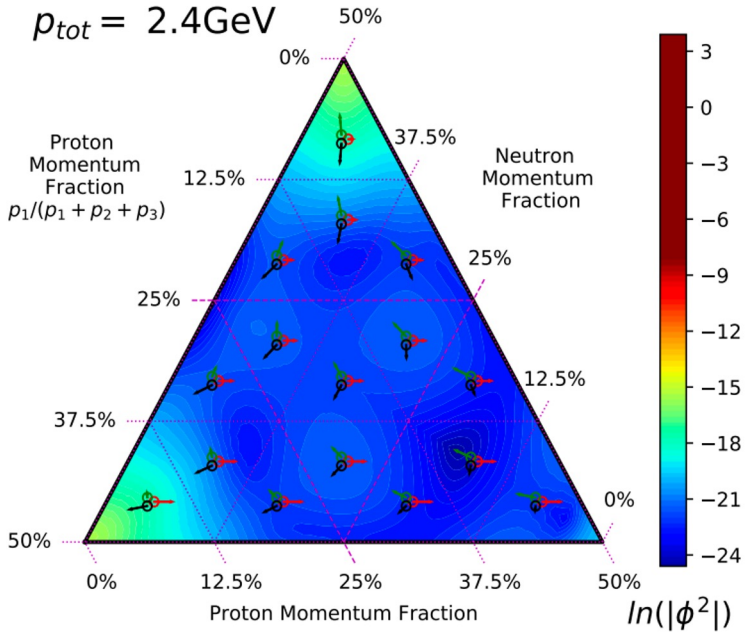
3N SRC modified-Dalitz plot (Denniston plot)



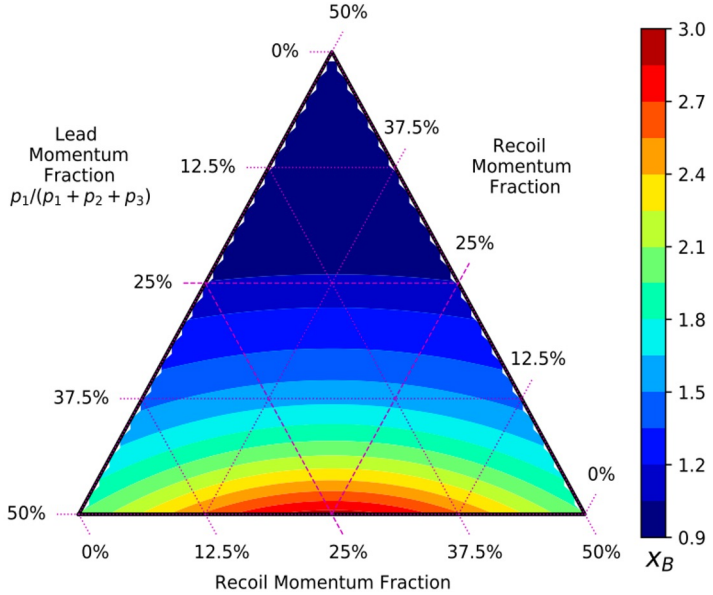
3-NN wavefunction slice



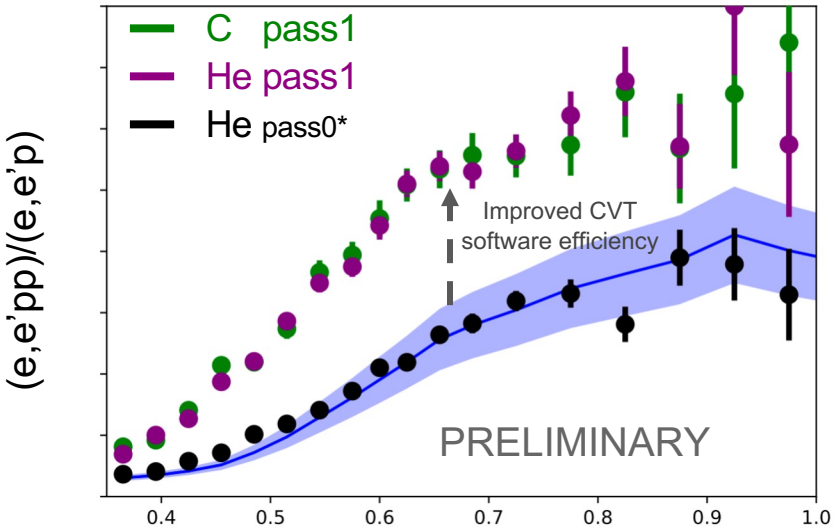
3-NN wavefunction slice



Acceptance


50%
0%
37.5%
12.5%
25%
25%
12.5%
37.5%
0%
50%
0%
12.5%
25%
37.5%
50%
Lead Momentum Fraction $p_1/(p_1+p_2+p_3)$
Recoil Momentum Fraction
Recoil Momentum Fraction
3.0
2.7
2.4
2.1
1.8
1.5
1.2
0.9
x_B

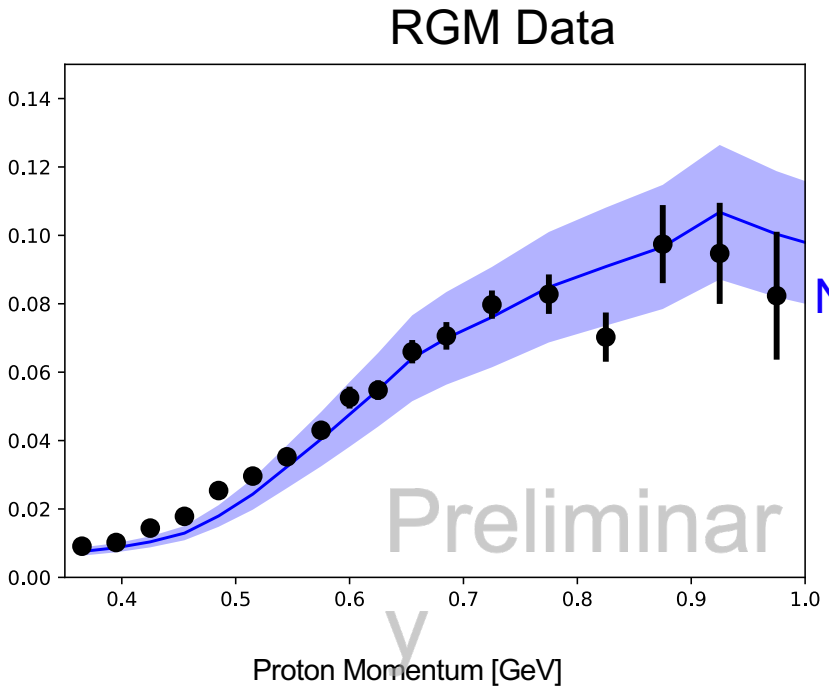
Pass-1 Data preview



*old software notably old CVT tracking.
~90% protons in Central Detector

Scale Dependence of SRC Measurements

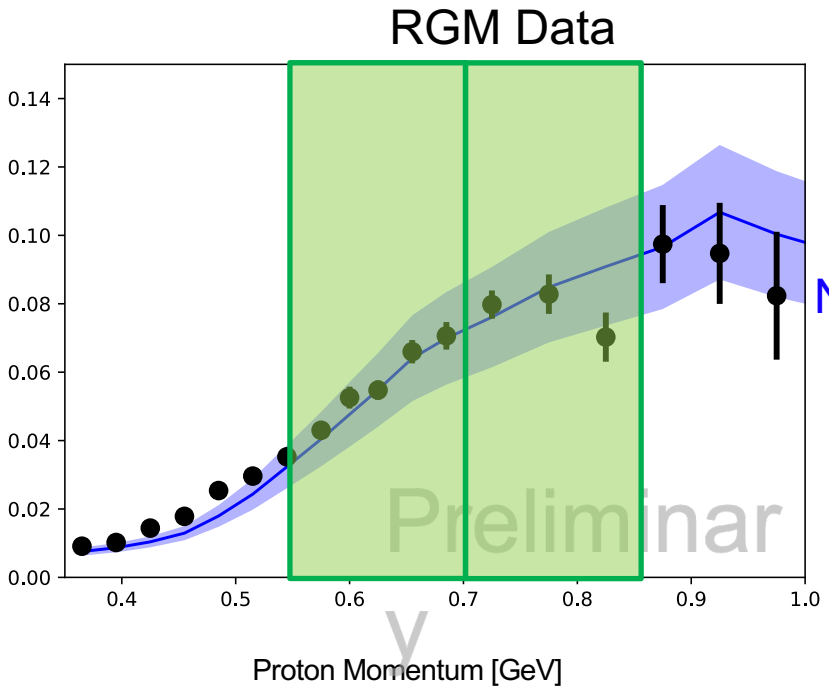
$$\frac{He(e,e'pp)}{He(e,e'p)}$$



N2LO 1.0fm

Scale Dependence of SRC Measurements

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

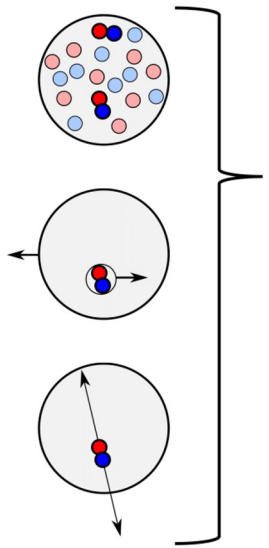


N2LO 1.0fm

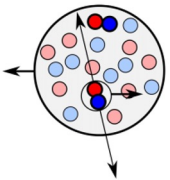
Pair Abundance

Center of Mass Motion

Pair Interaction



SRC Component of the Wave-Function



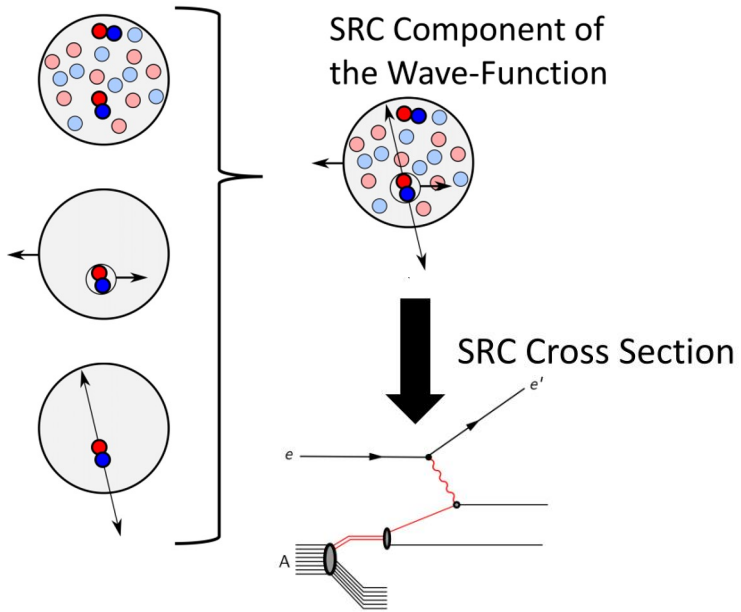
$$\sigma = \sigma_{eN}(q) \cdot C_A^{NN} \cdot |\phi(p_{rel})|^2 \cdot n(p_{CM})$$

NN sum over (np,pp,nn)

Pair Abundance

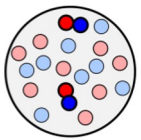
Center of Mass Motion

Pair Interaction

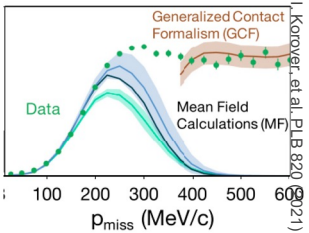


What we know…

Pair Abundance

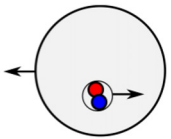


SRC dominate for p > 350 MeV/c

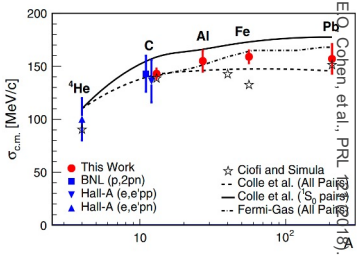


I. Korover, et al. PLB 820 (2021)

Center of Mass Motion

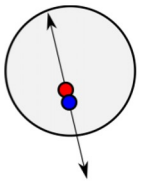


Measured P_{CM} motion

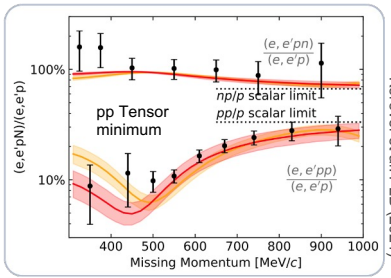


E. O. Cohen, et al., PRL 121 (2018).

Pair Interaction



tensor to scalar transition
neutron-proton pairs dominate



Korover et al. PLB (2021)