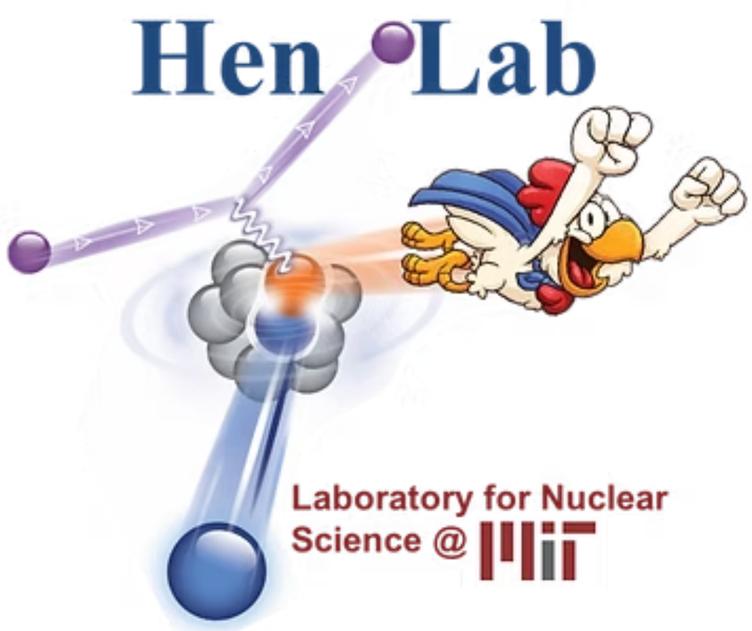
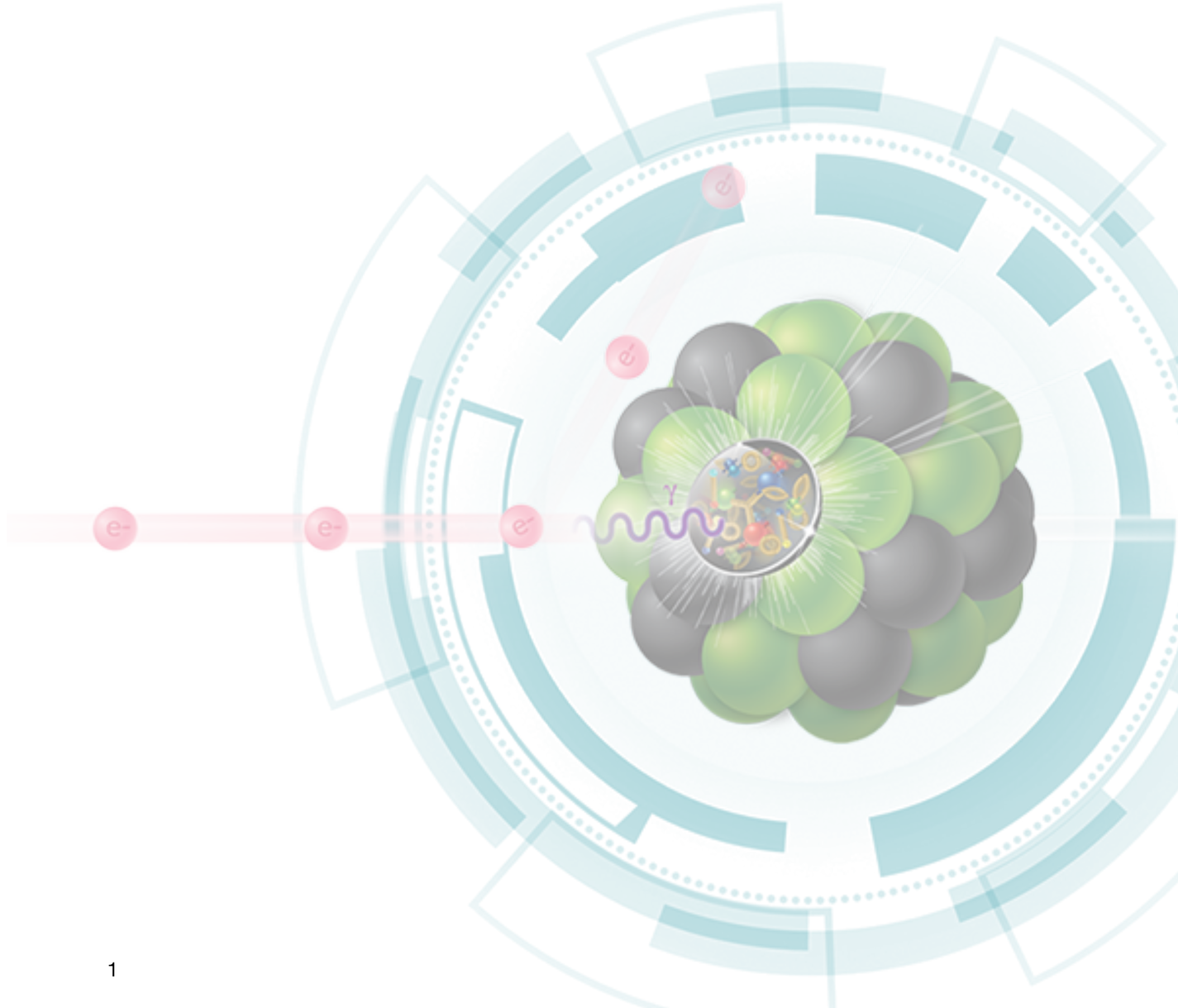
SRCs Across Nuclear Scales

Natalie Wright (MIT)





CIPANP 2025

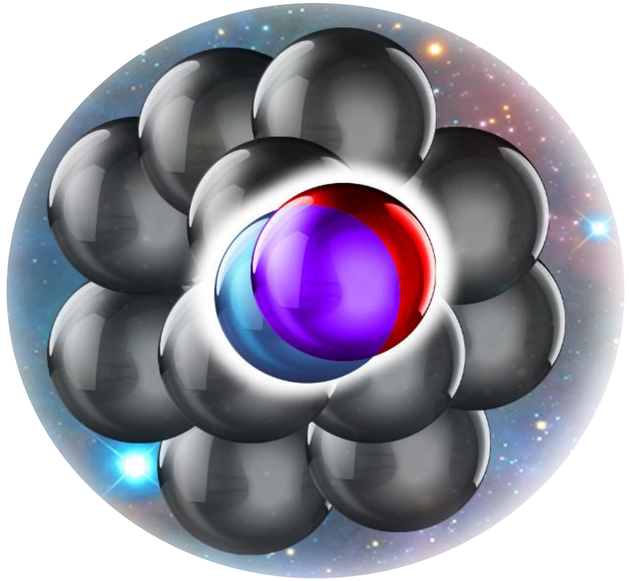
Short Range Correlated Nucleons

Nucleon pairs* with:

Small spatial separation

High relative and low CM momentum compared to k_F

Significant contribution to nuclear momentum distribution $p > k_F$



*(that we've seen! more on this later)

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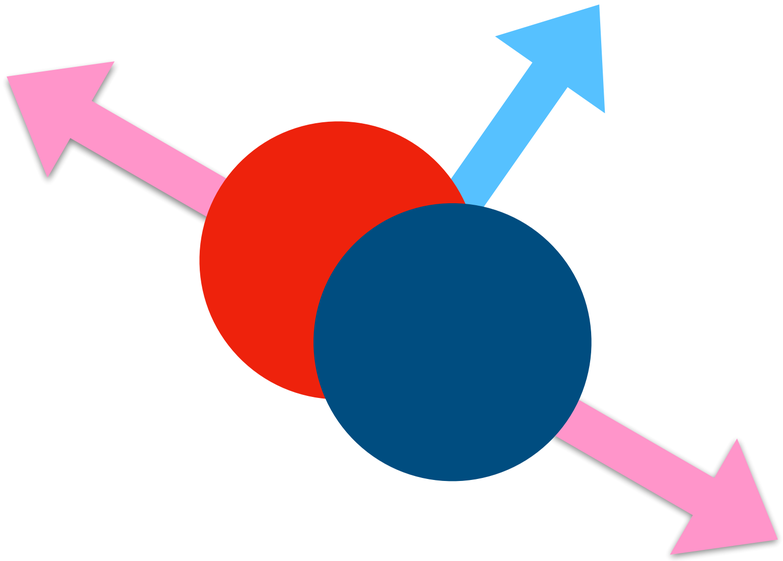

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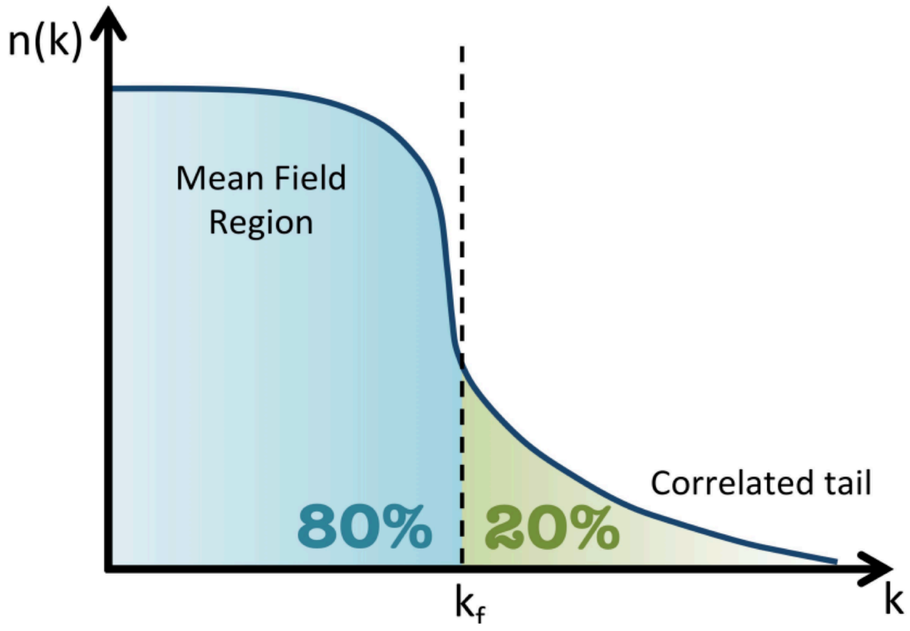
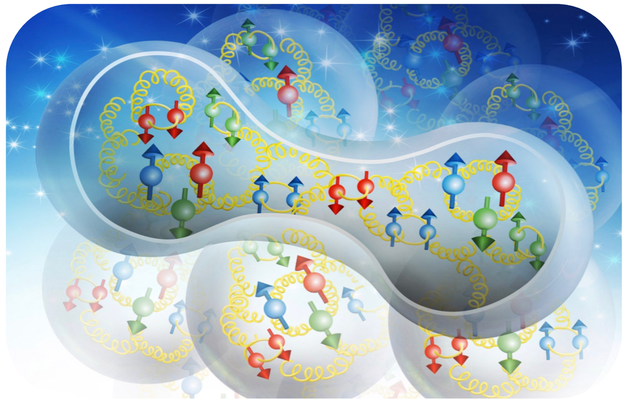
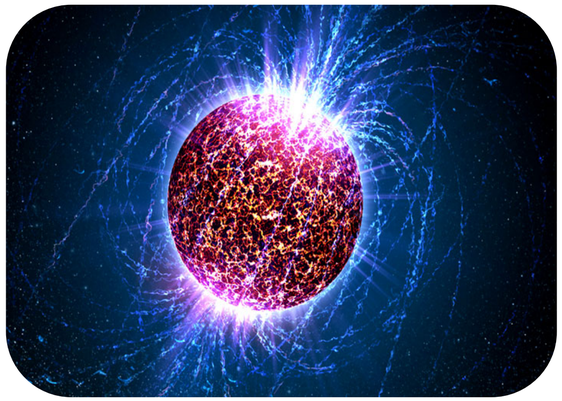


*(that we've seen! more on this later)

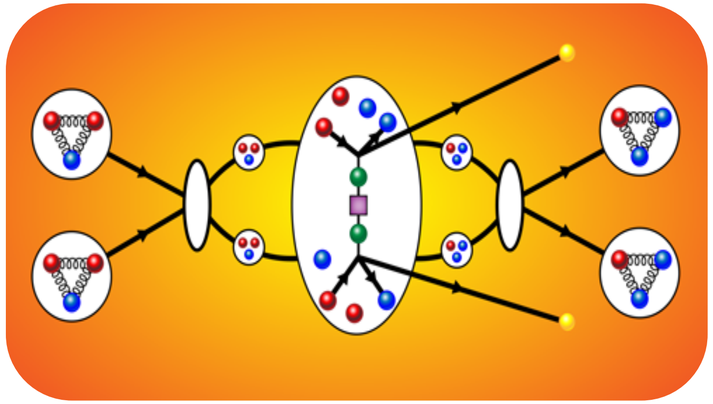
SRCs required to fully describe nuclear systems and processes



NN interactions and QCD in nuclei

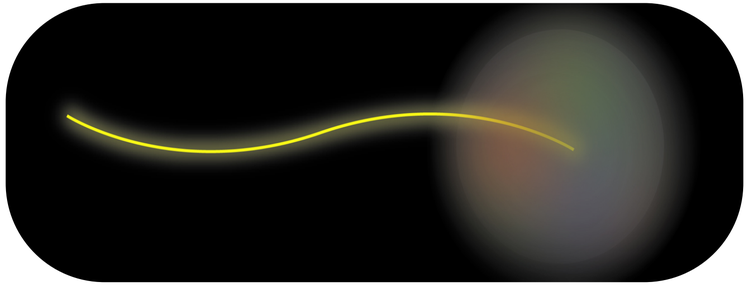


High-density systems

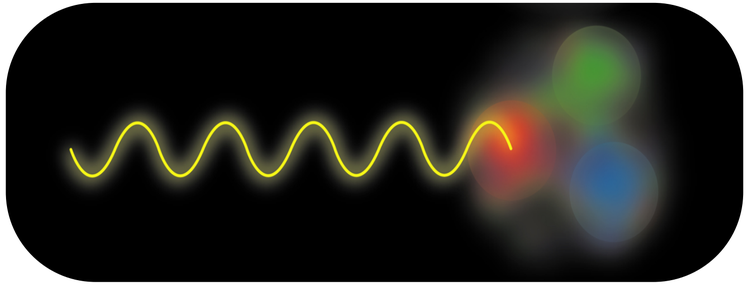


Nuclear processes

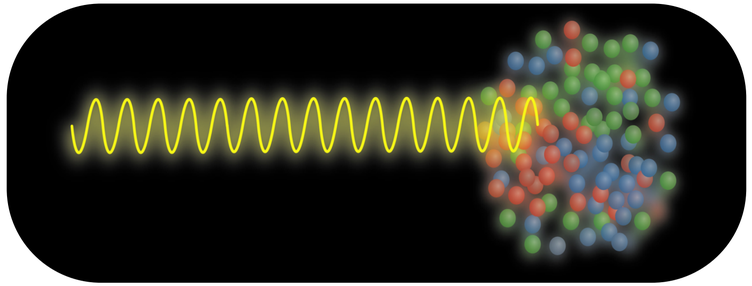
SRCs Relevant Across Scales



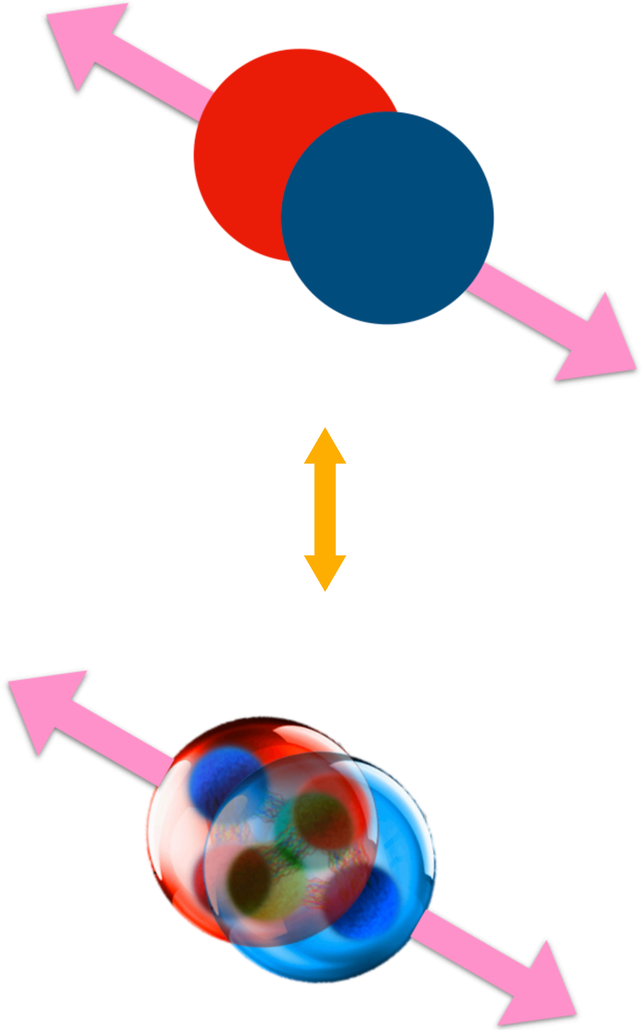
Many-Body Systems



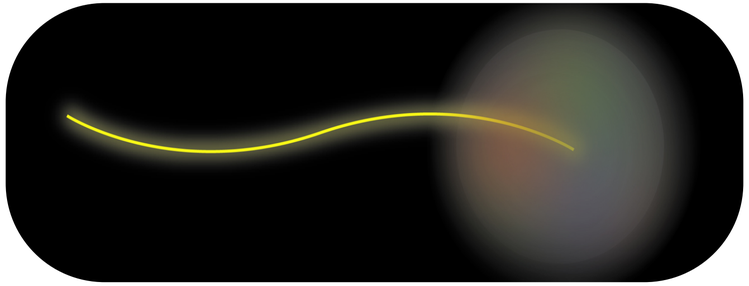
NN Interaction



Nucleon Substructure



SRCs Relevant Across Scales



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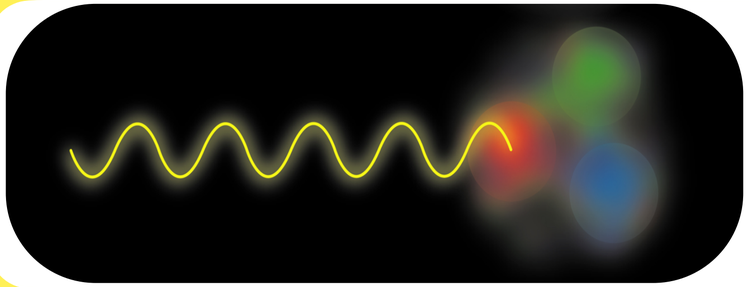
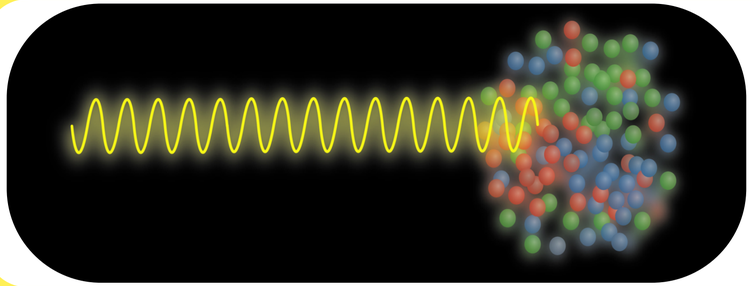


NN Interaction



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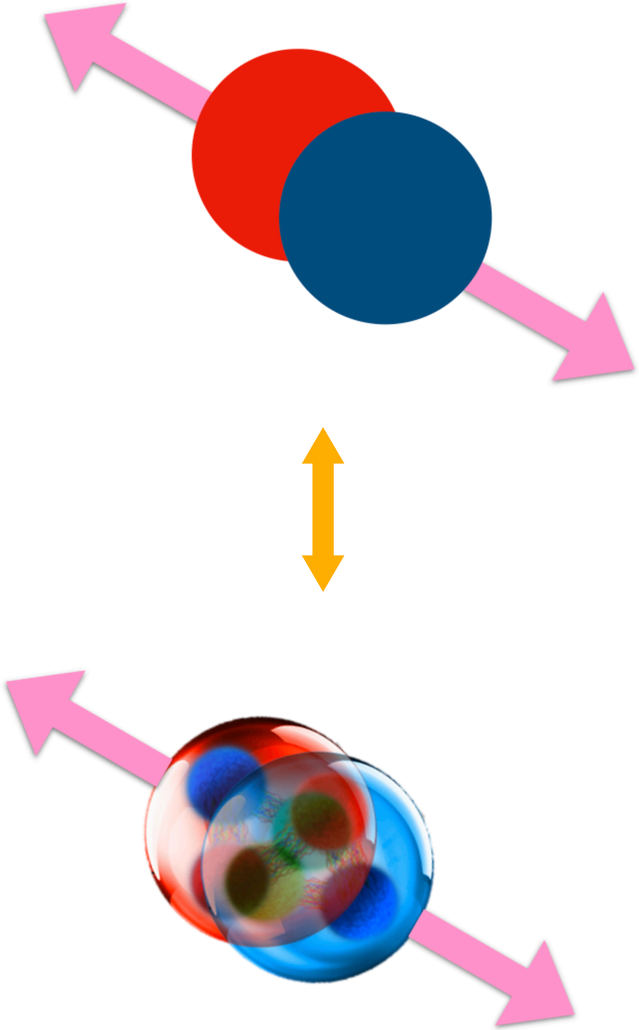
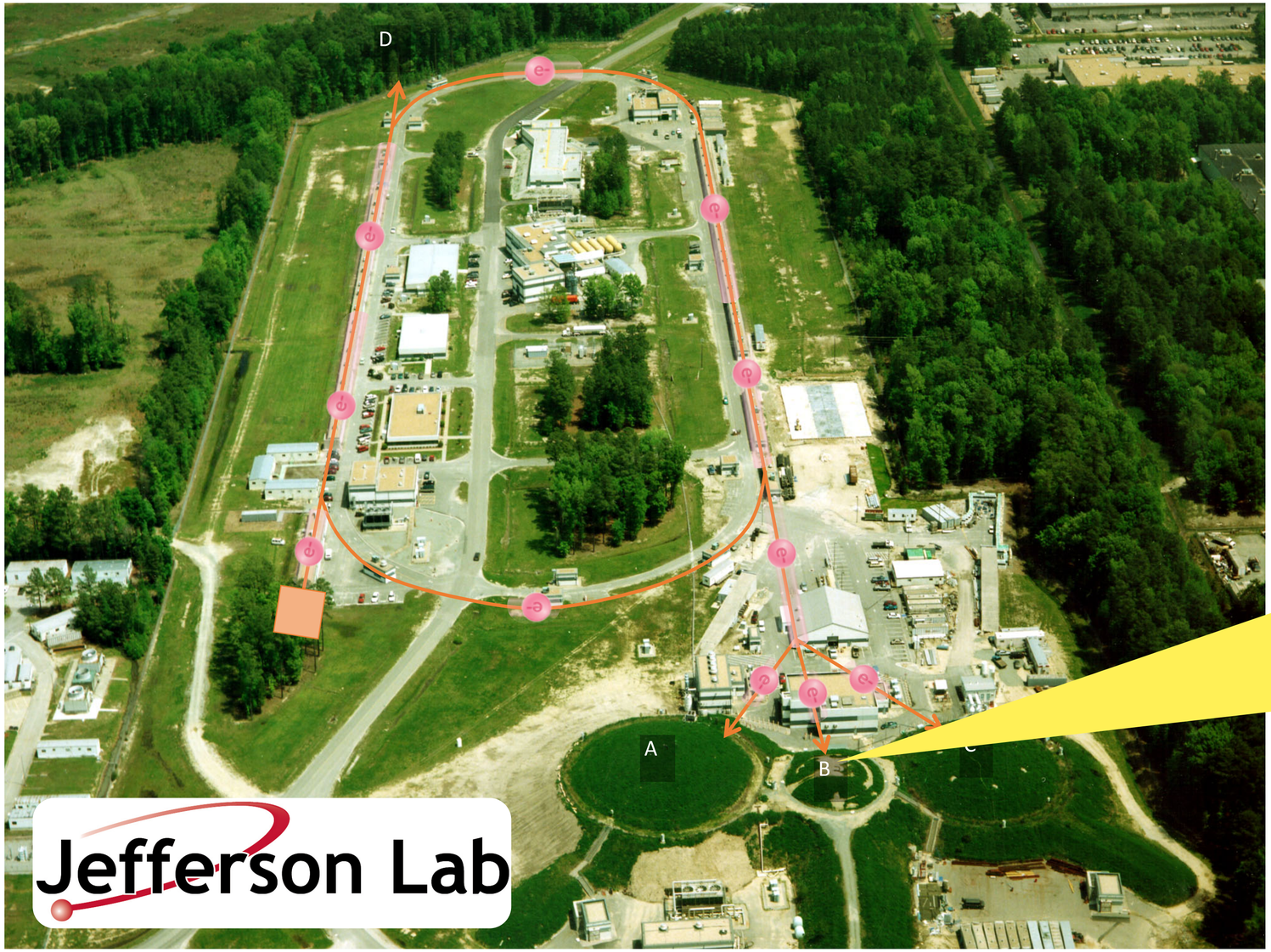
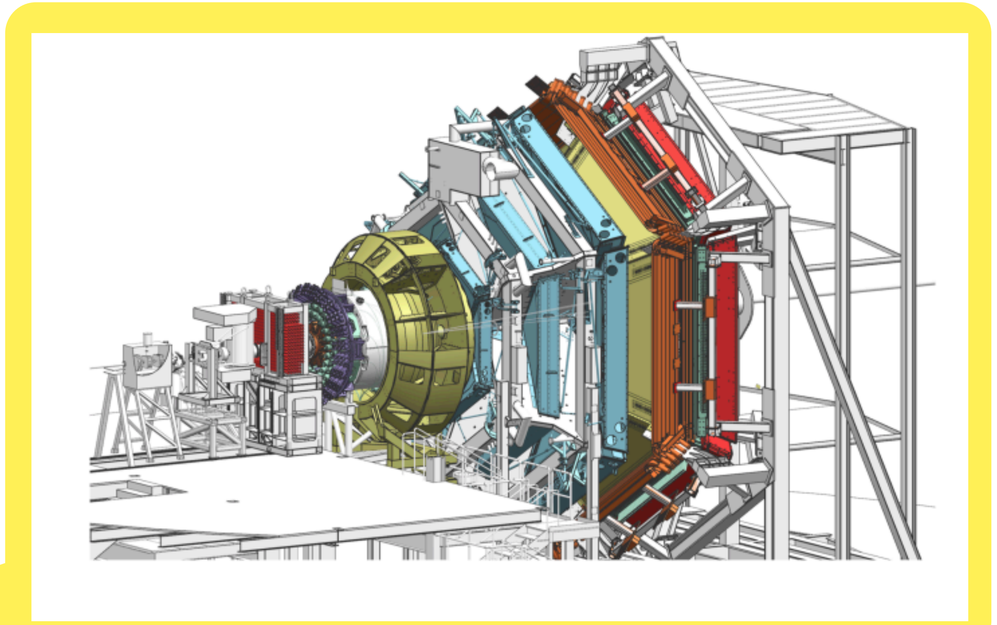


This talk

Today: Electron Scattering at JLab (Hall B)

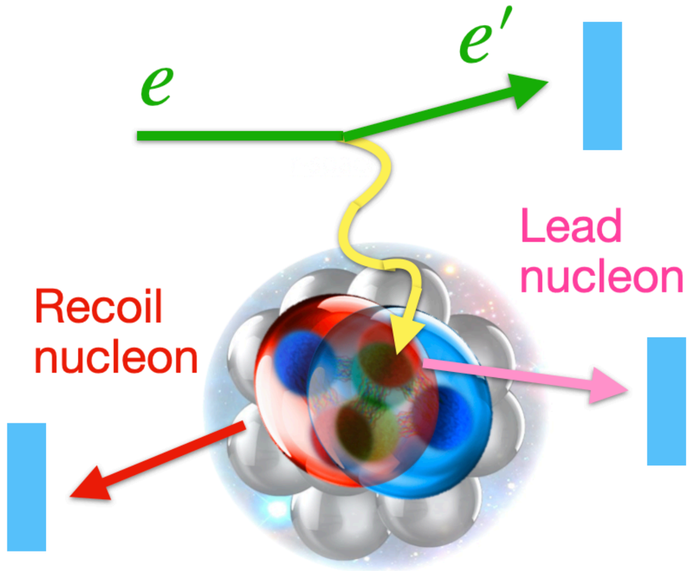




Today: Two Main Regimes

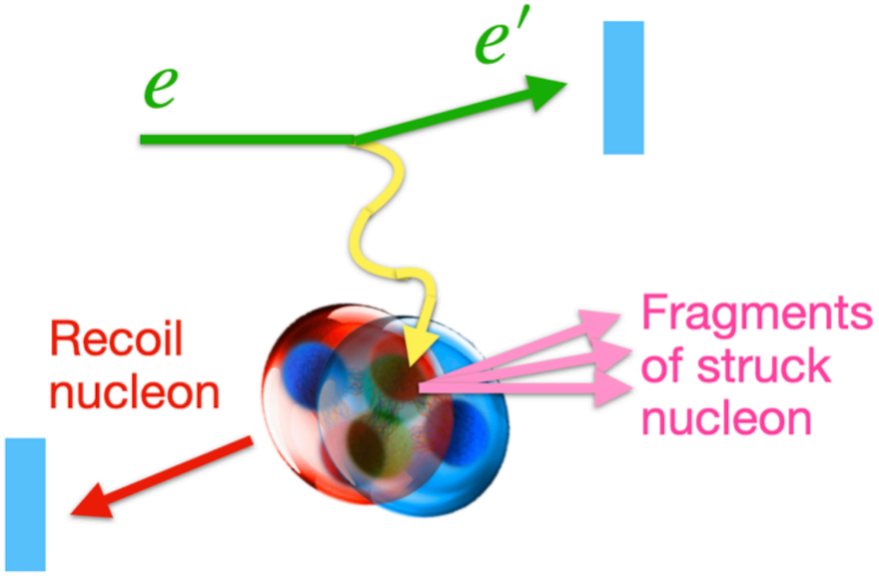
Exclusive Quasielastic Scattering

- Recent RGM results
- Development of neutron detection algorithm

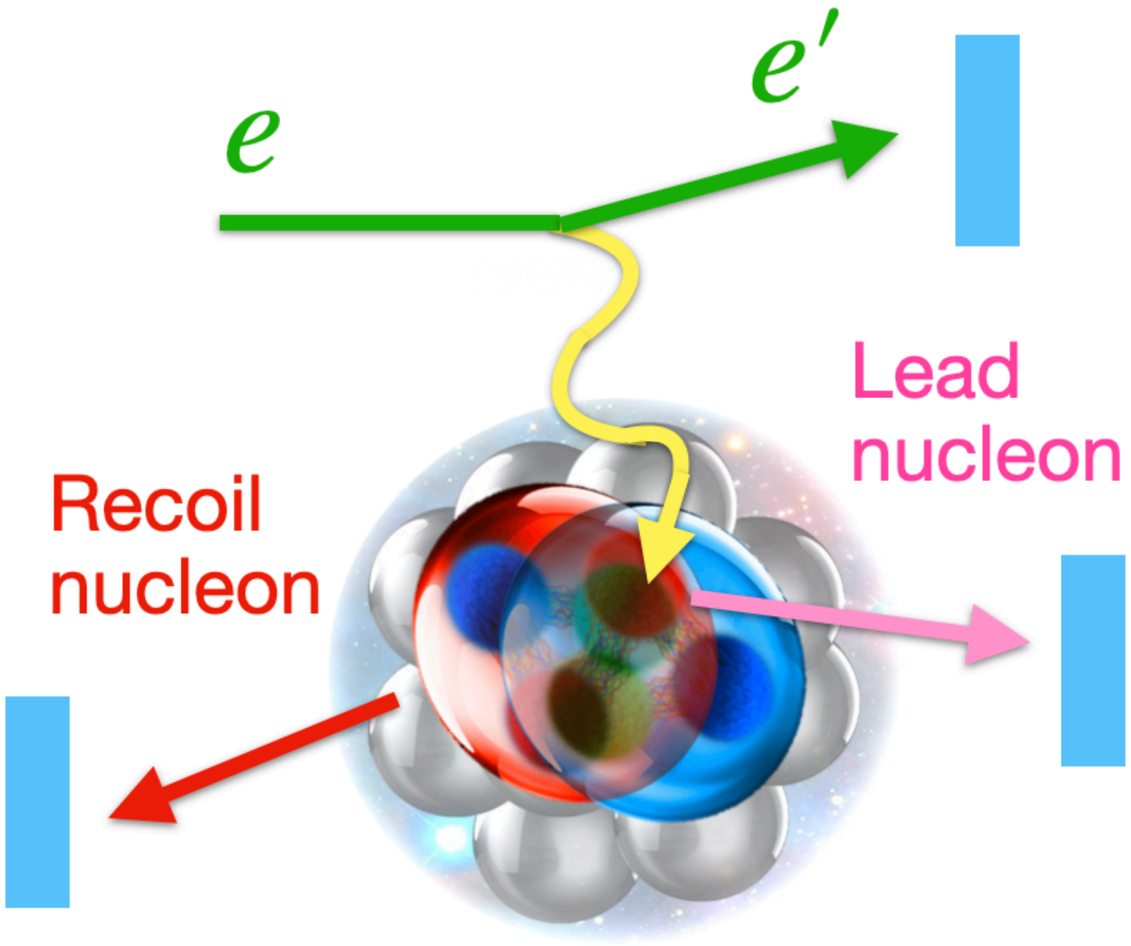


Tagged Deep Inelastic Scattering

- TDIS with BAND
- Comparison to inclusive datasets

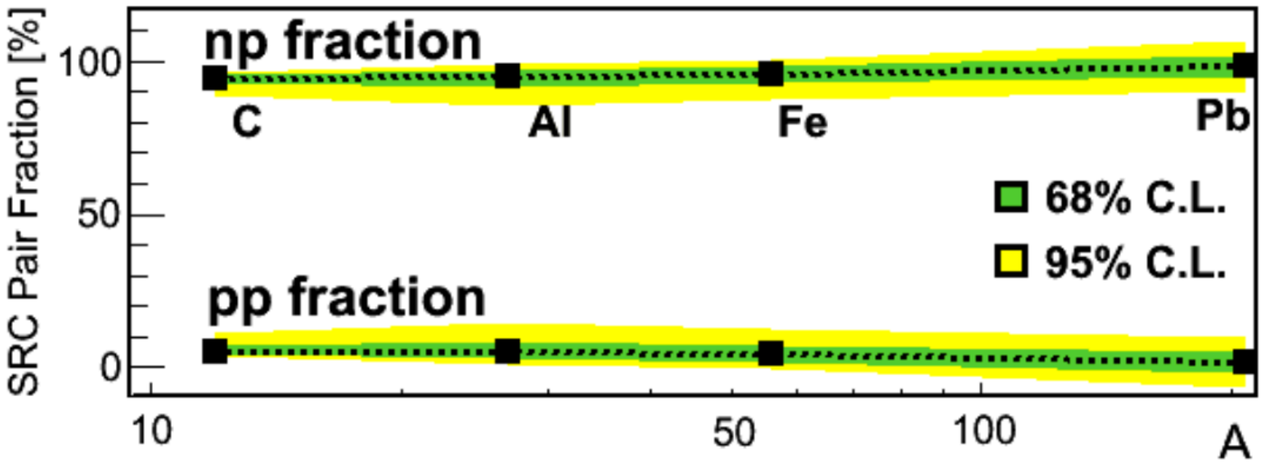


NN Interaction via Quasielastic Scattering

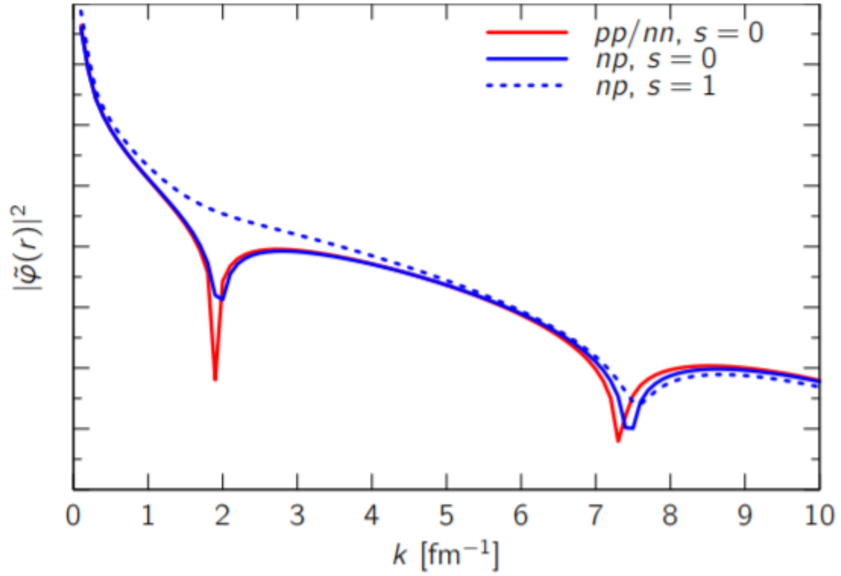


A(e,e'pp) / A(e,e'p) sensitive to isospin structure

NP pair dominance → SRCs predominately in S = 1 state



O. Hen et al., Science 364 (2014) 614



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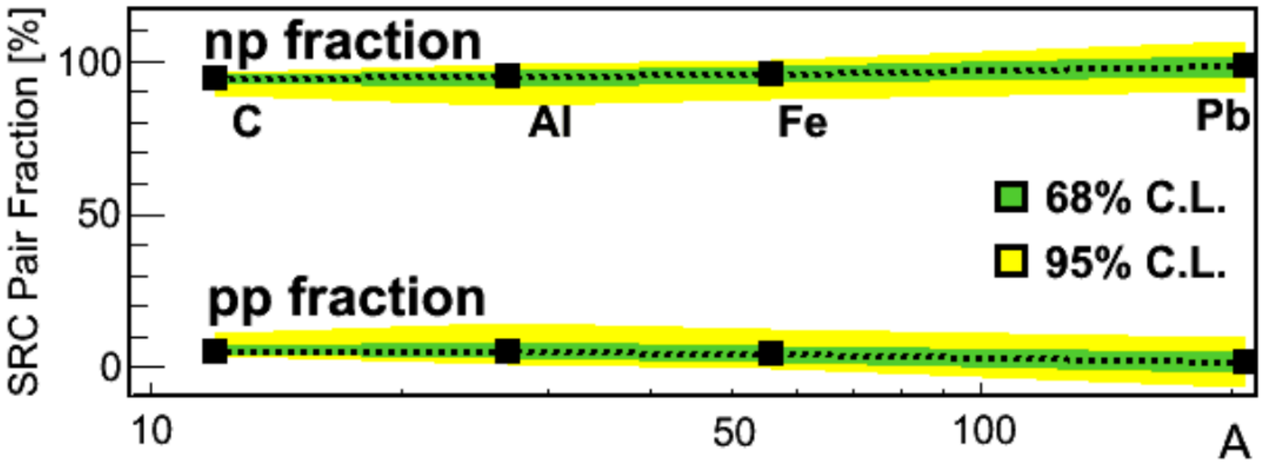
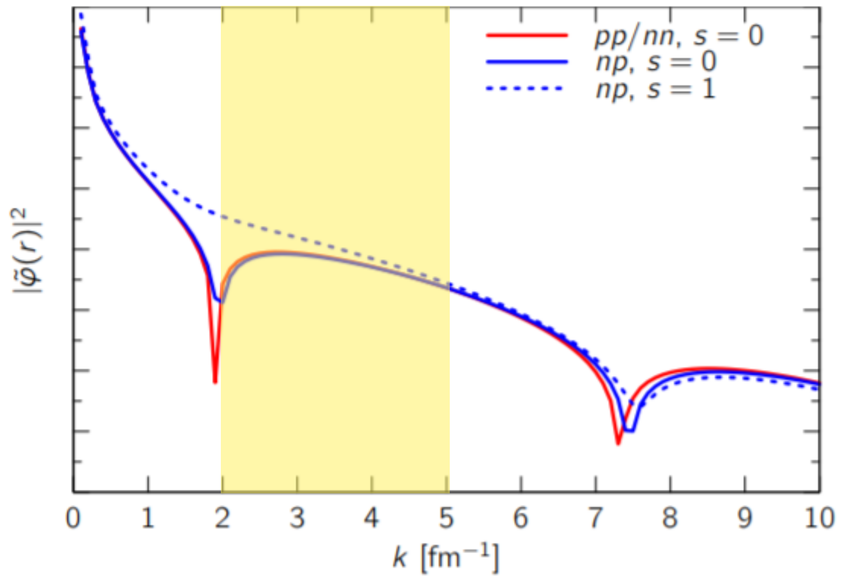
NP pair dominance → SRCs predominately in S = 1 state

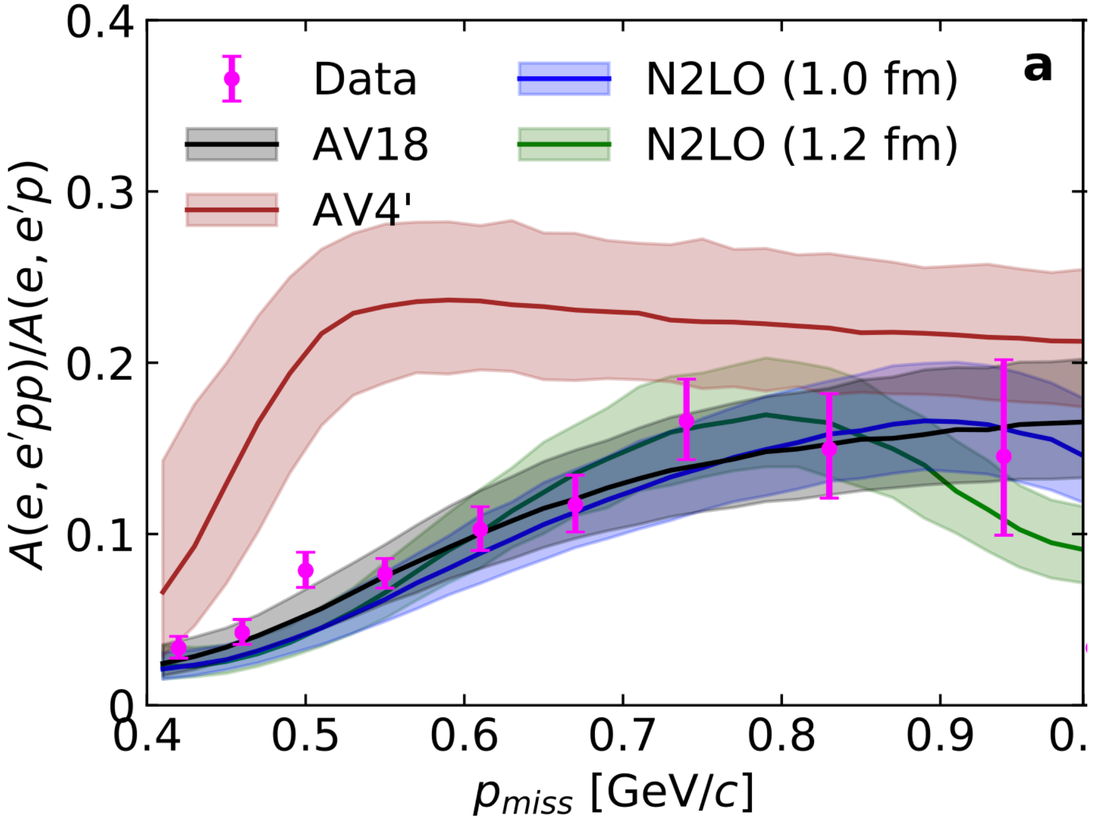
Can use exclusive measurements to map the tensor to scalar transition



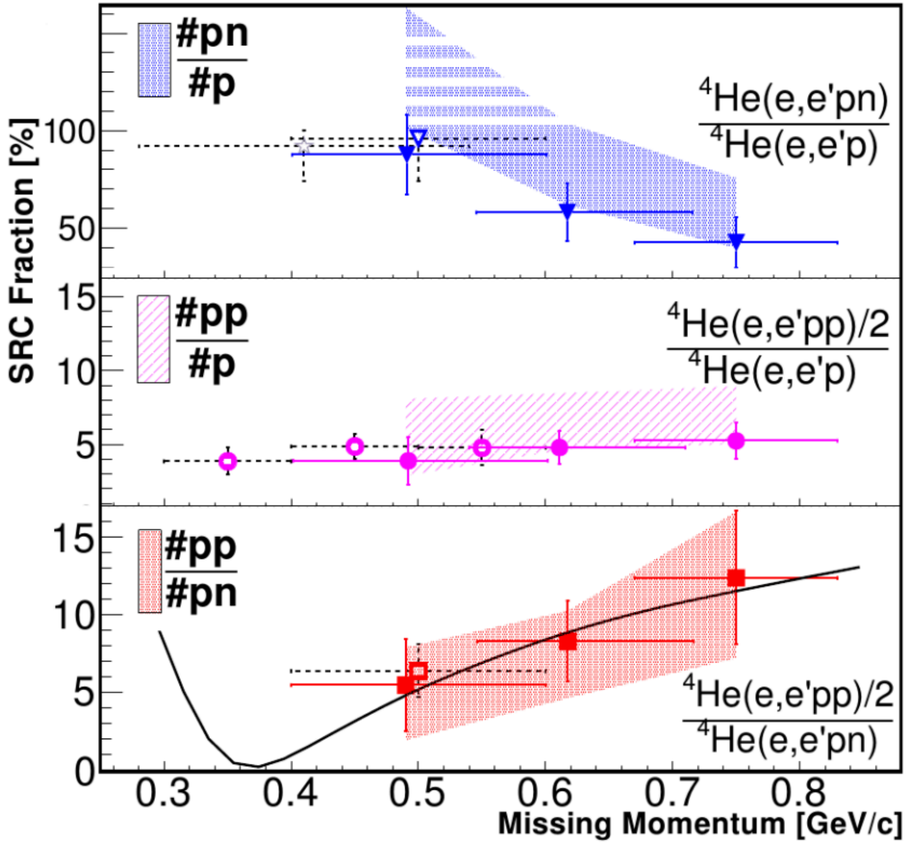
O. Hen et al., Science 364 (2014) 614



…which varies with interaction strength



Schmidt, Nature (2020)

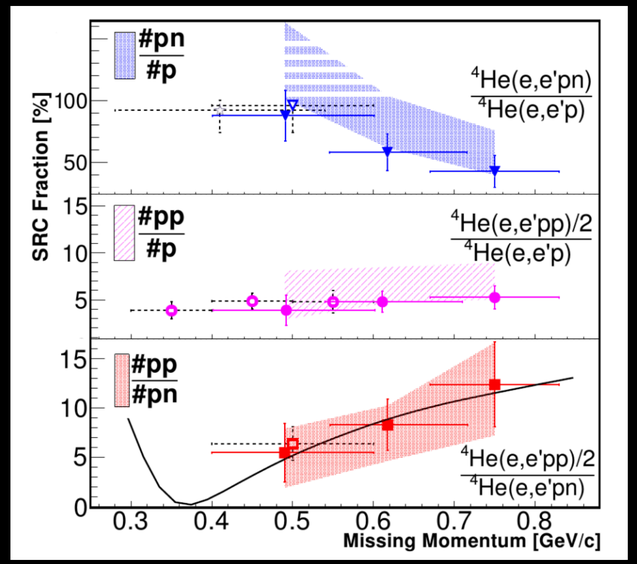


I. Korover et al, PRL 113 (2014) 022501

…which varies with interaction strength

What I'd like to address:

1. High statistics for model comparison



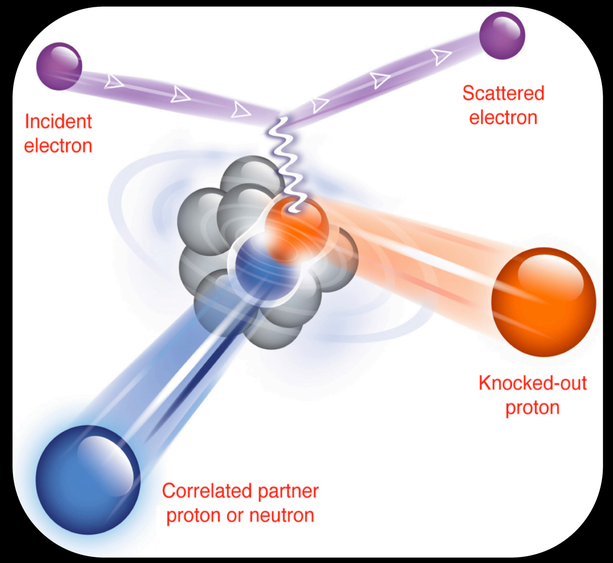
I. Korover et al, PRL 113 (2014) 022501

…which varies with interaction strength

What I'd like to address:

1. High statistics for model comparison

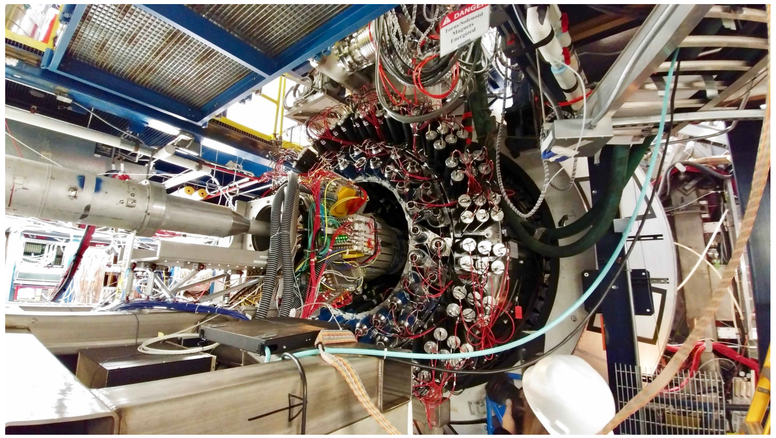
2. Interpretability of results
   (scale dependence)



RGM for Exclusive SRC Studies

Ran Nov 2021-Feb 2022

2, 4, 6 GeV beam energies



Targets:

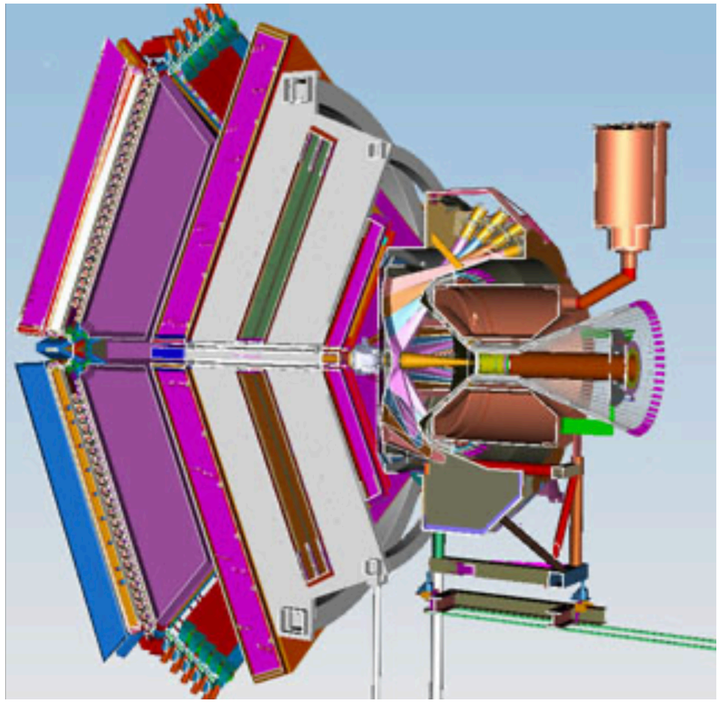
LH2, LD2

^{40}Ar, ^{40}Ca, ^{48}Ca, ^{120}Sn

^{4}He, ^{12}C

Scale, A-dependence, asymmetries

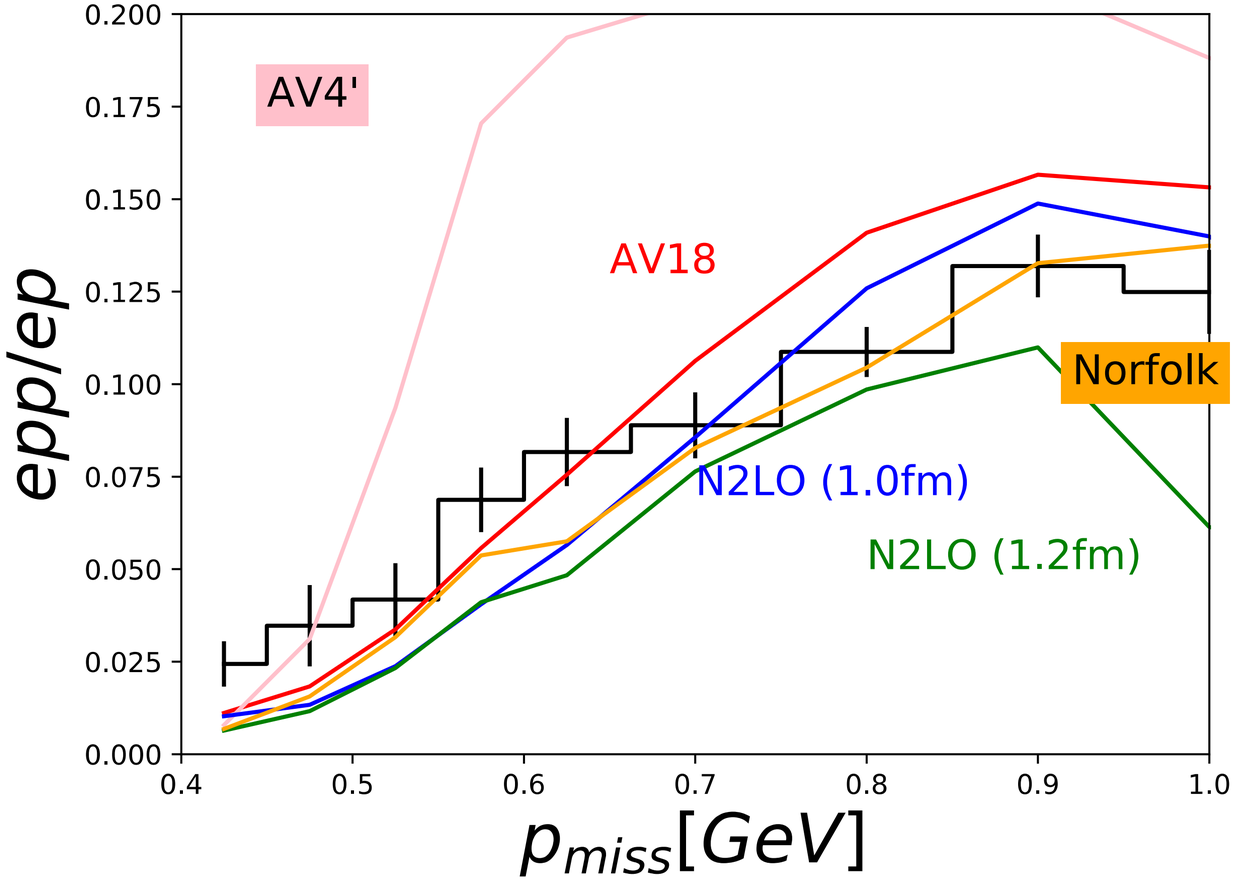
3N SRC search



RGM for Exclusive SRC Studies

Andrew Denniston

Reproduce 2N results with high precision



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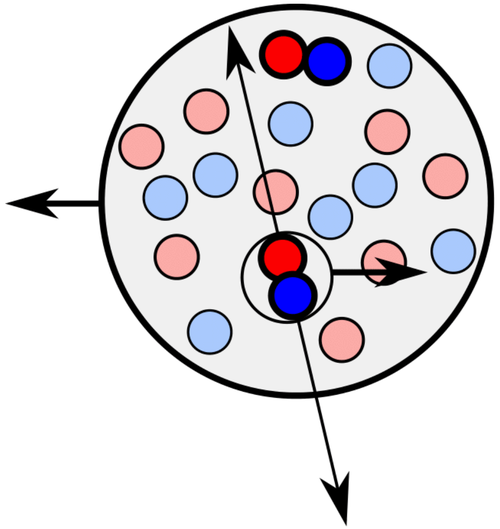
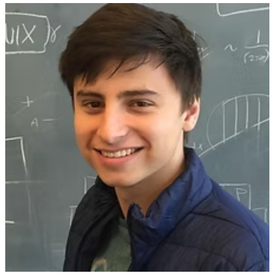
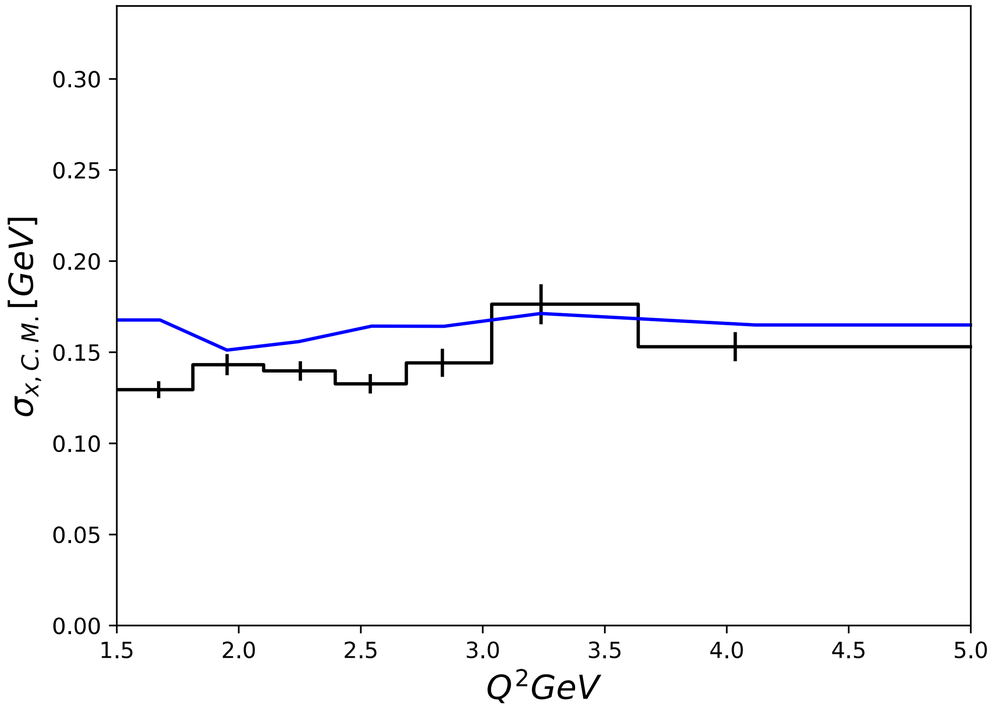


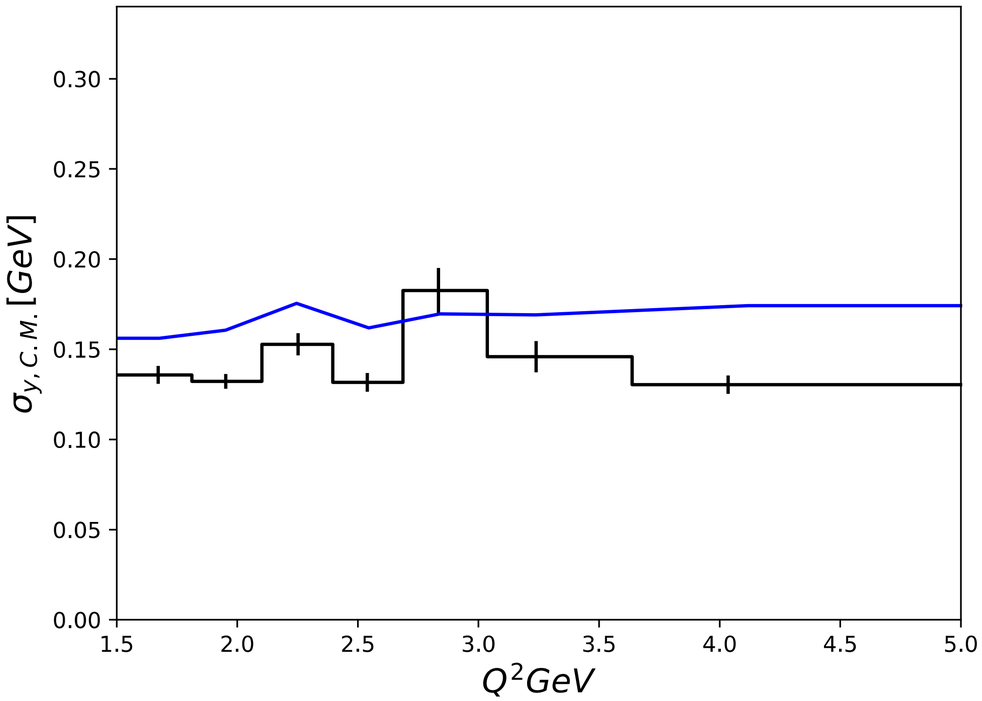


Andrew Denniston

Reproduce 2N results with high precision

Test SRC scale independence





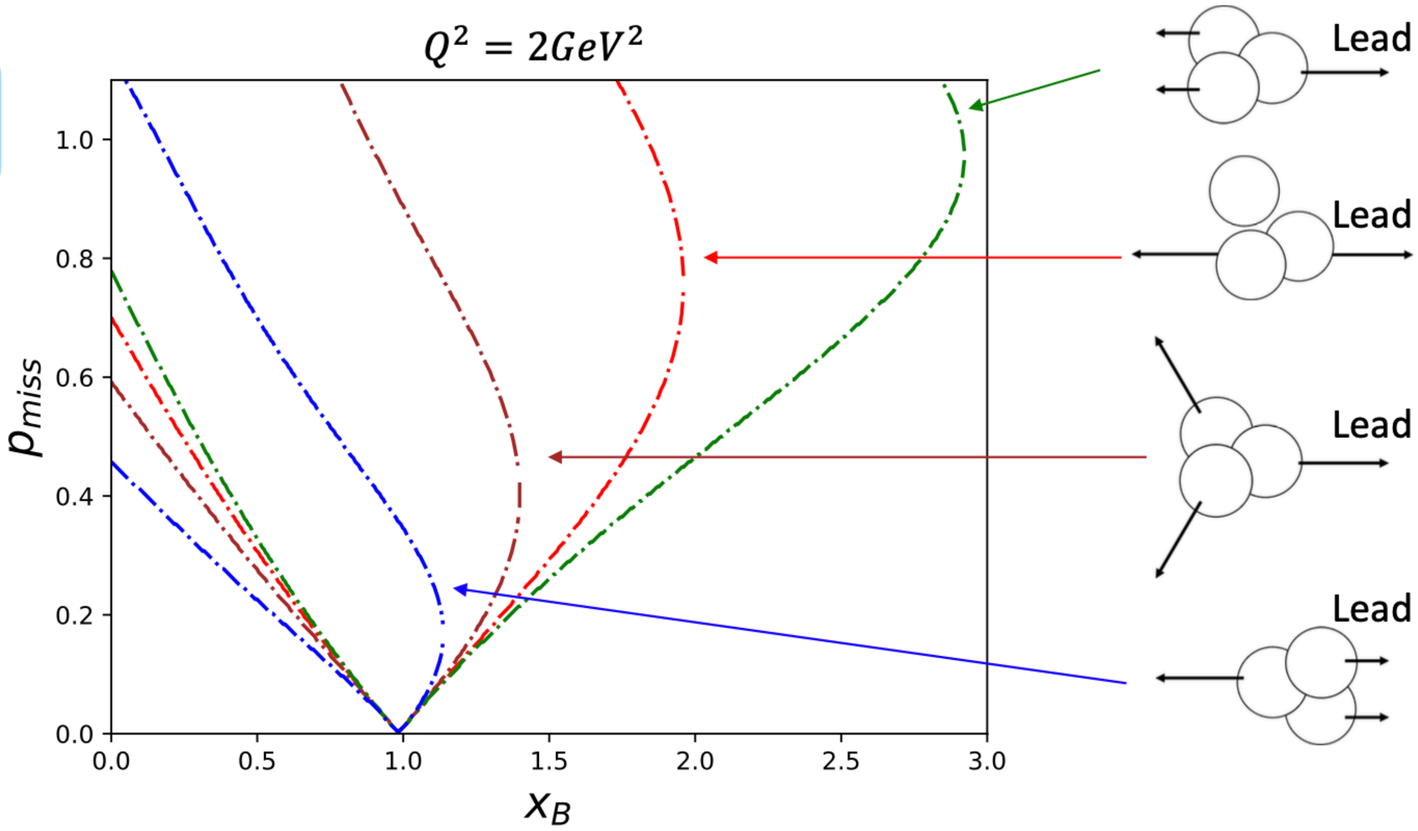
RGM for Exclusive SRC Studies

Andrew Denniston

Reproduce 2N results with high precision

Test SRC scale independence

Model 3N SRC phase space



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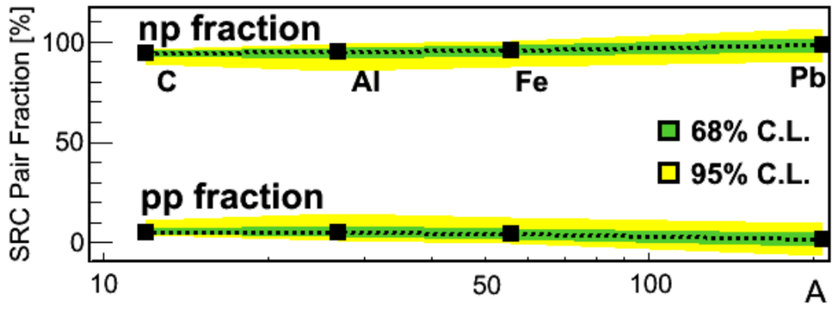


O. Hen et al., Science 364 (2014) 614

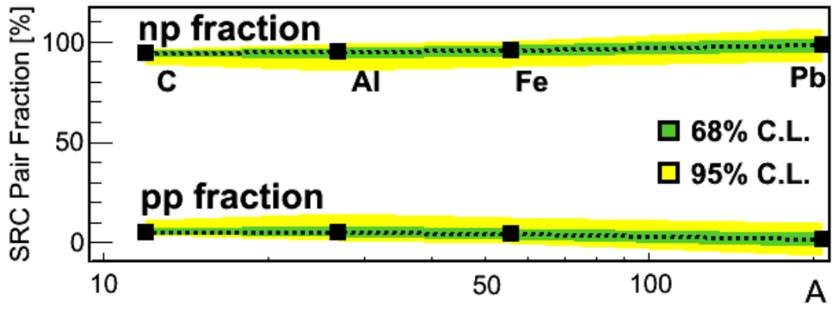
SRCs are mostly pn pairs…these are all proton measurements?

RGM for Exclusive SRC Studies

Reproduce 2N results with high precision

Test SRC scale independence

Model 3N SRC phase space



O. Hen et al., Science 364 (2014) 614

SRCs are mostly pn pairs…these are all proton measurements?

CD neutrons are tricky, but we need them to move forward!

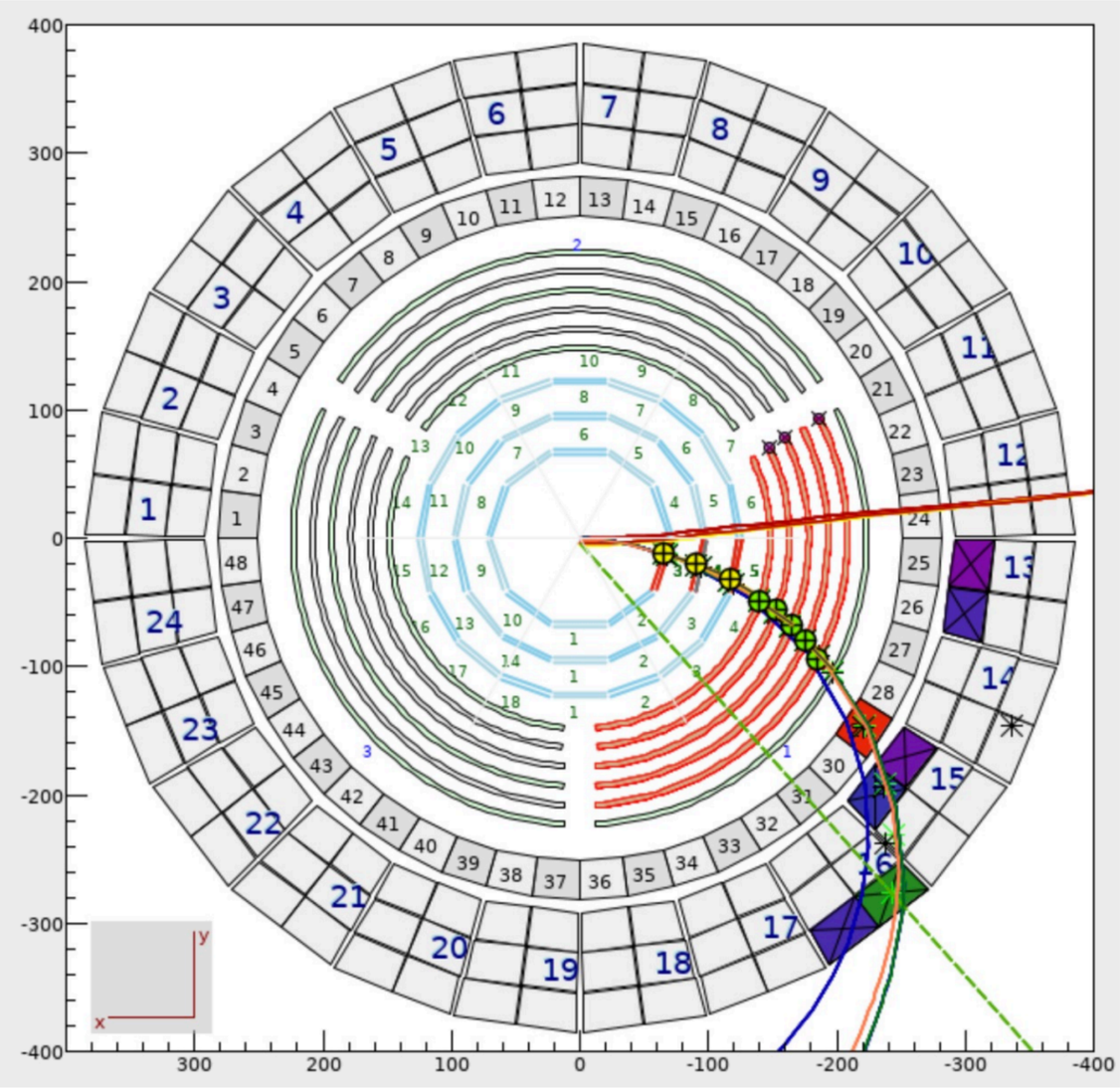
For neutrons, must reject charged particles

How CD particles are ID'd:

Hit in Central Vertex Tracker?

Yes → Charged PID via trajectory

No → Neutral PID via ToF



For neutrons, must reject charged particles

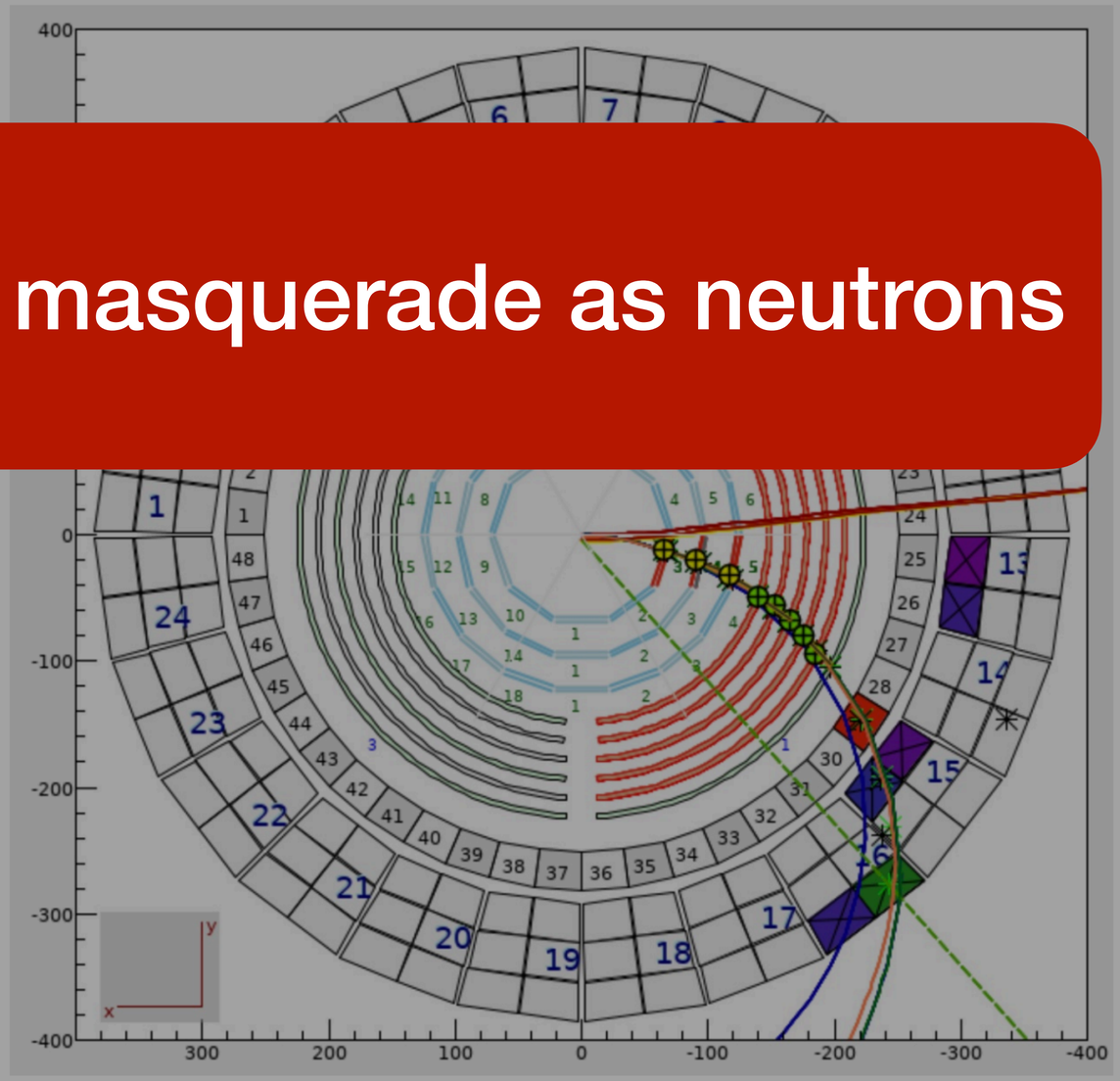
CVT inefficiency $\Longrightarrow$ Protons masquerade as neutrons

Yes

Charged PID via trajectory

No

Neutral PID via Tof



For neutrons, must reject charged particles

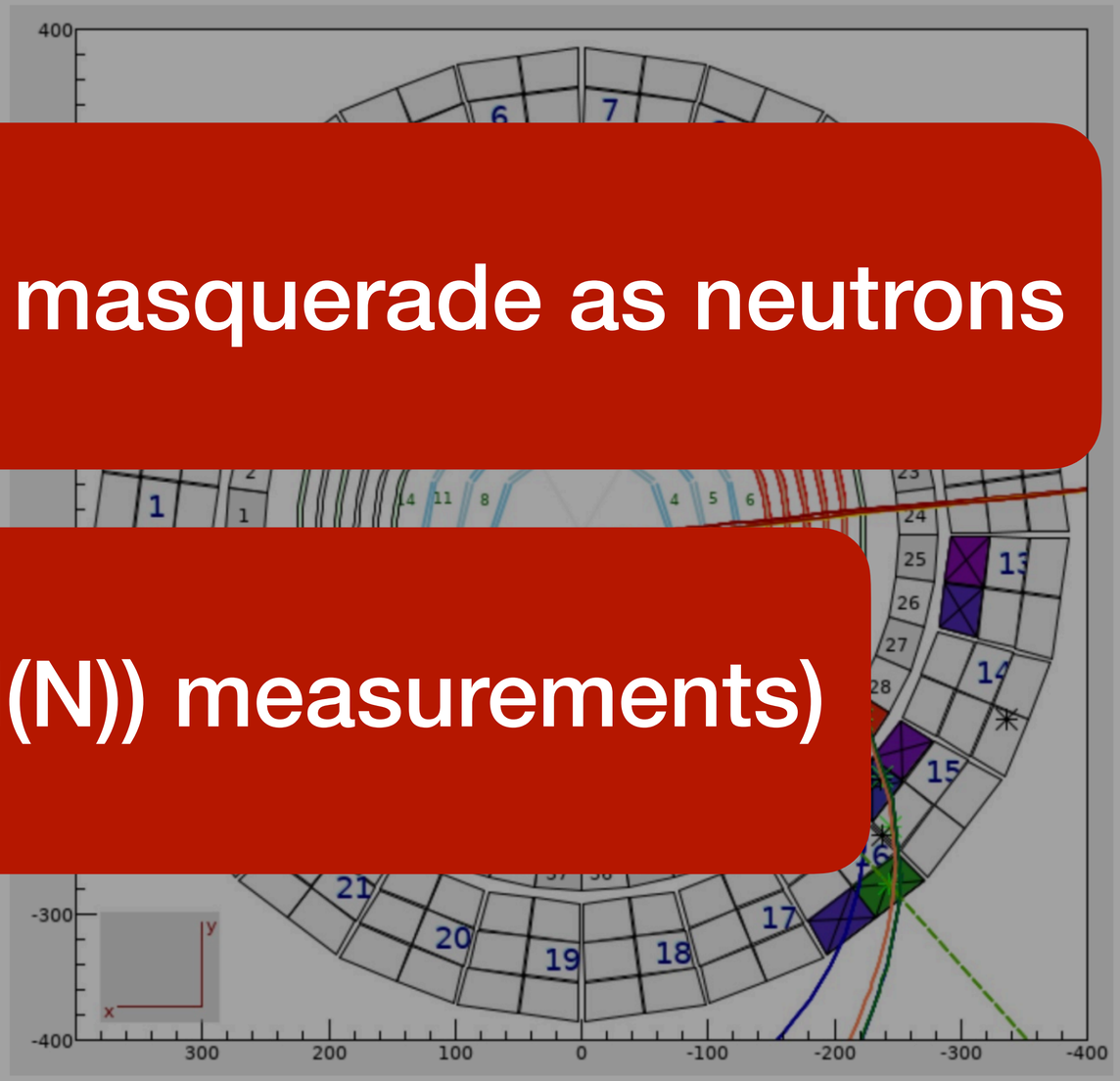
CVT inefficiency $\Longrightarrow$ Protons masquerade as neutrons

Yes

No

Cha
via

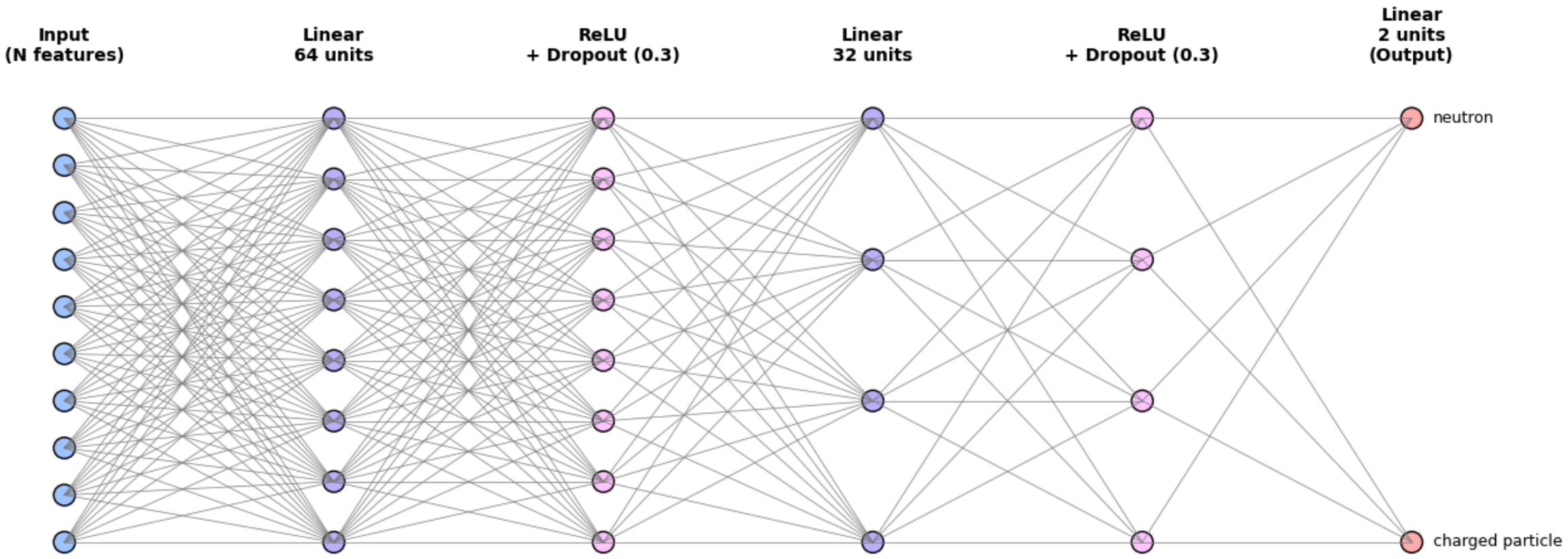
(This is <u>BAD</u> for A(e,e'pN(N)) measurements)



ML algorithm to veto charged particles

Shakuntala Mitra

Multilayer ANN classifier architecture:



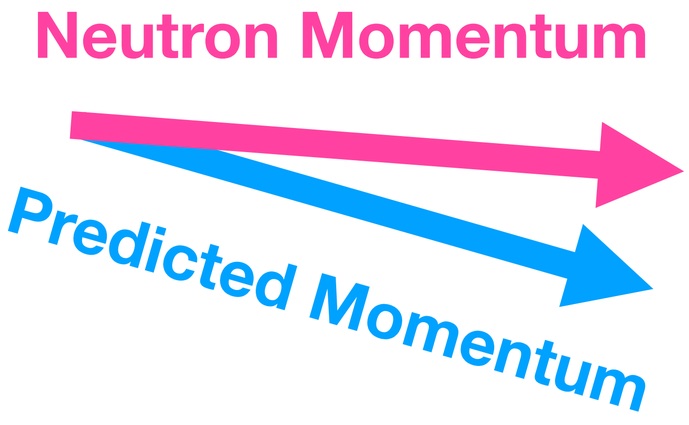
Data-driven training samples

Exclusive topologies from 2 GeV deuterium data

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

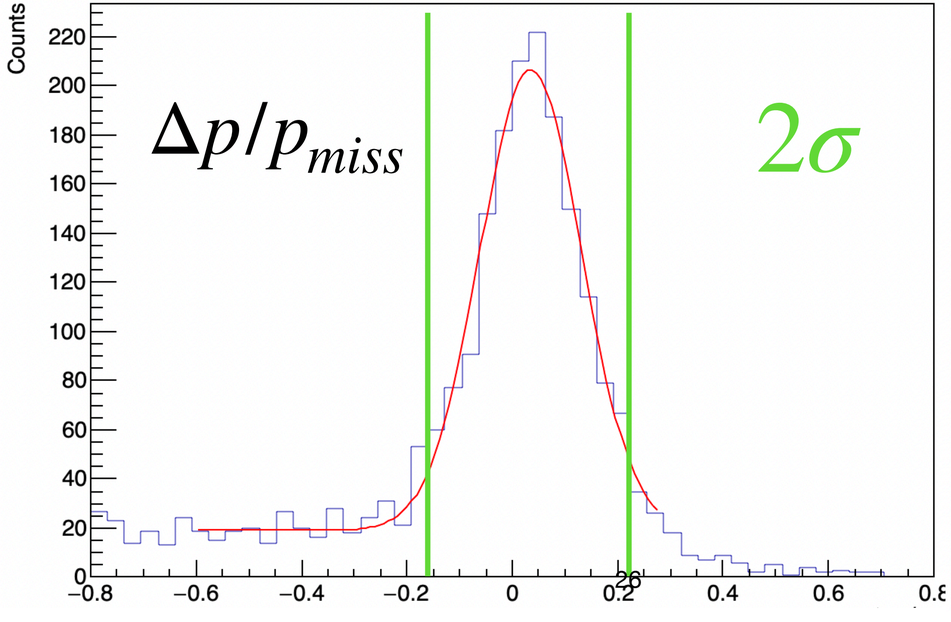
Background: Protons ID'd as neutrons $d(e, e'p\pi^- n)$

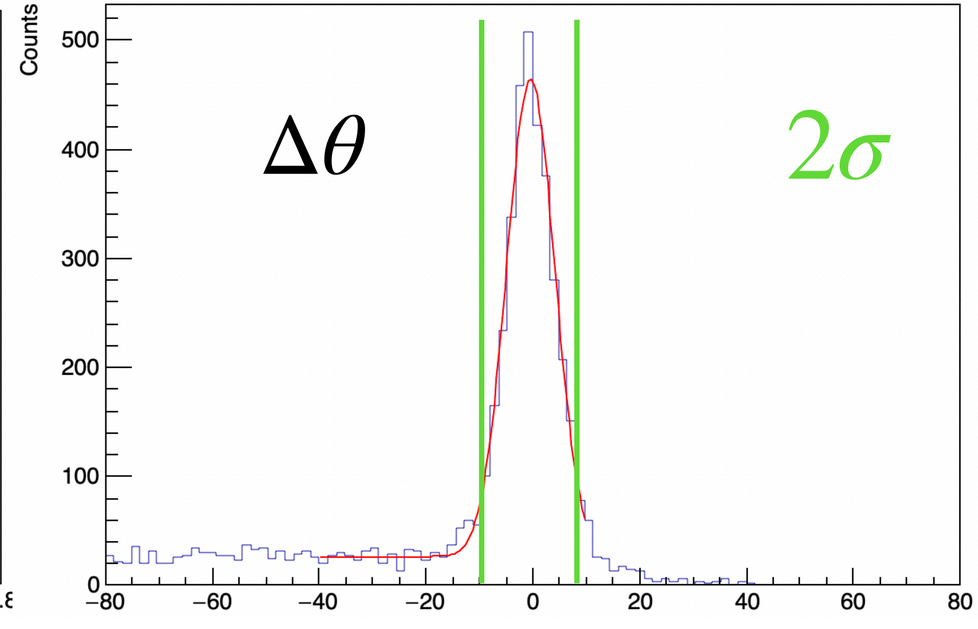
Protons ID'd as protons $d(e, e'p\pi^- p)$



QE Selection:

$M_{miss} < 1.02$





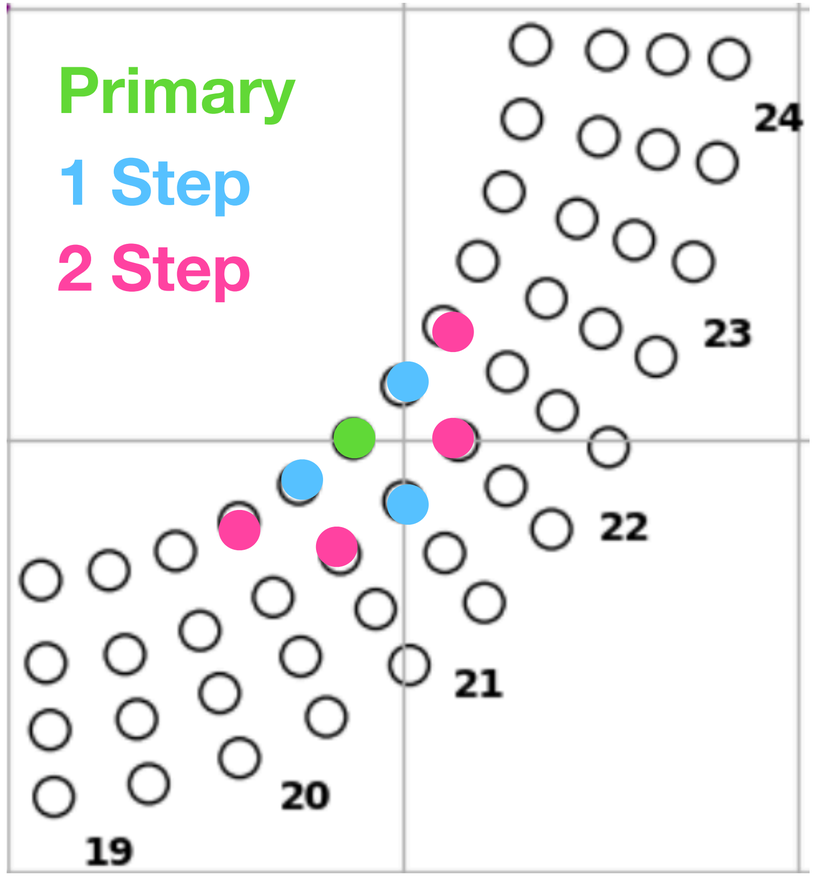
Features relative to detector segments

If multiple hits attributed to particle:

Define primary hit in CND based on highest Edep

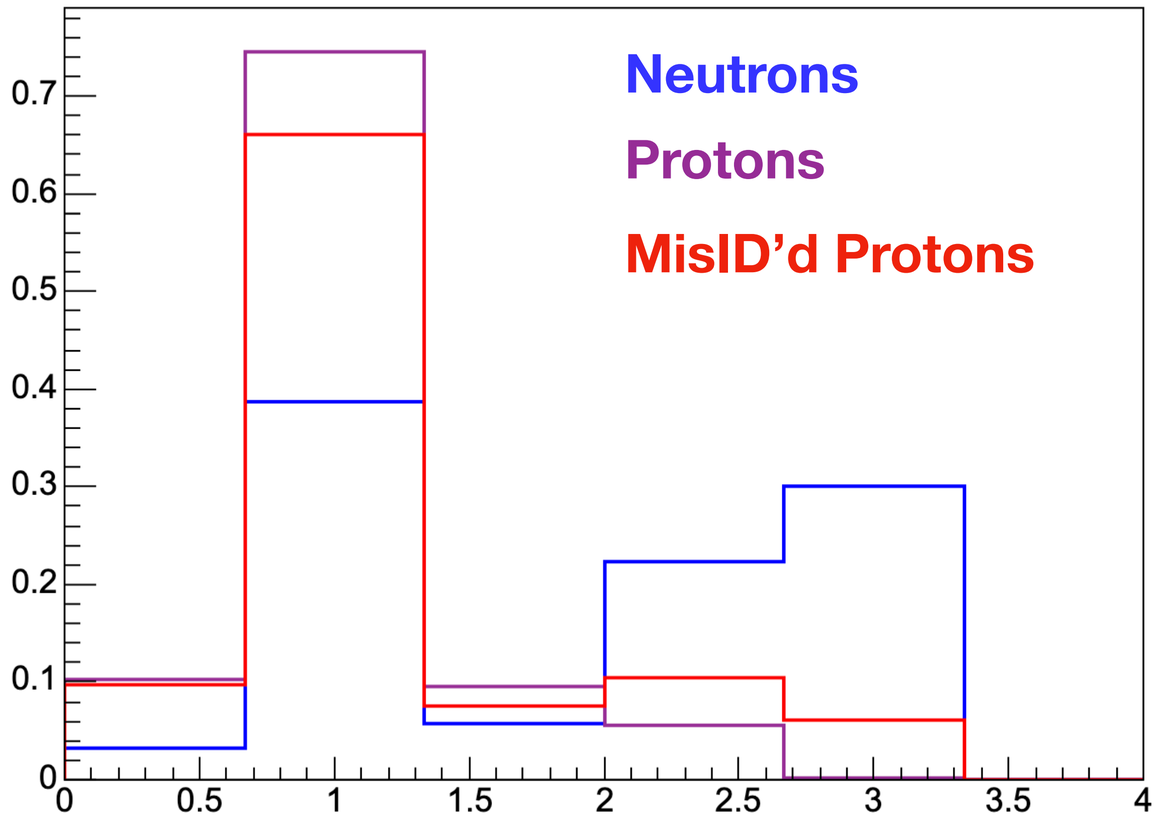
Calculate features (nearby energy, hits, etc) relative to number of ‘steps’ away

Minimize reliance on particle reconstruction software

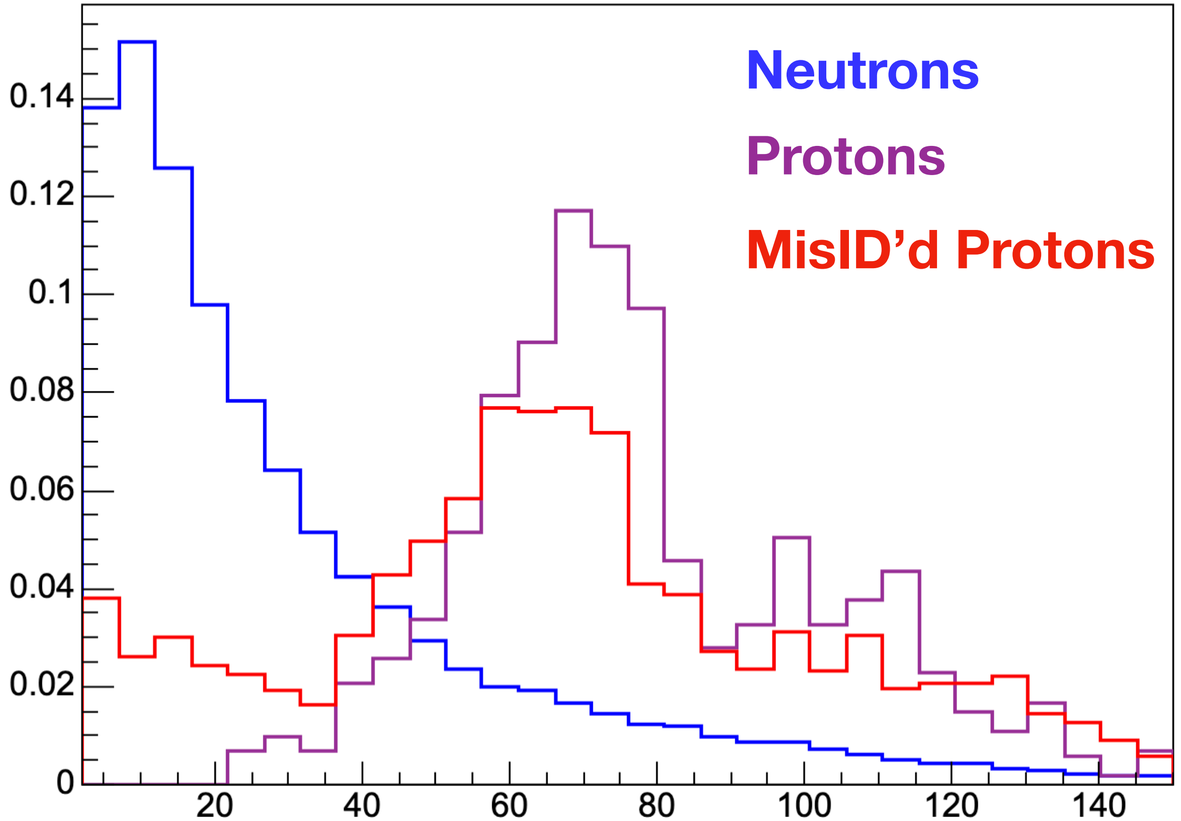


Top features

Feature importances determined via Random Forest

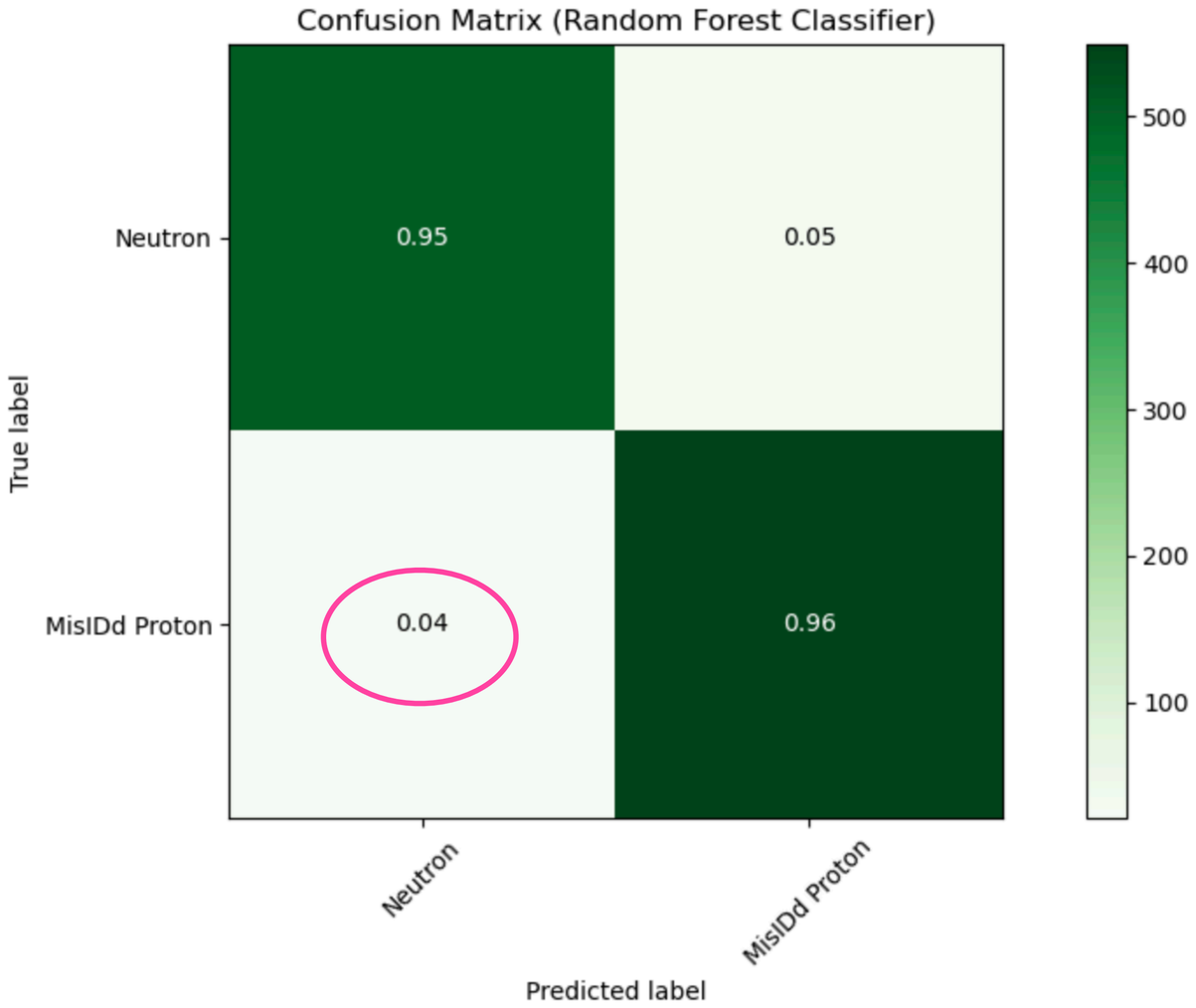


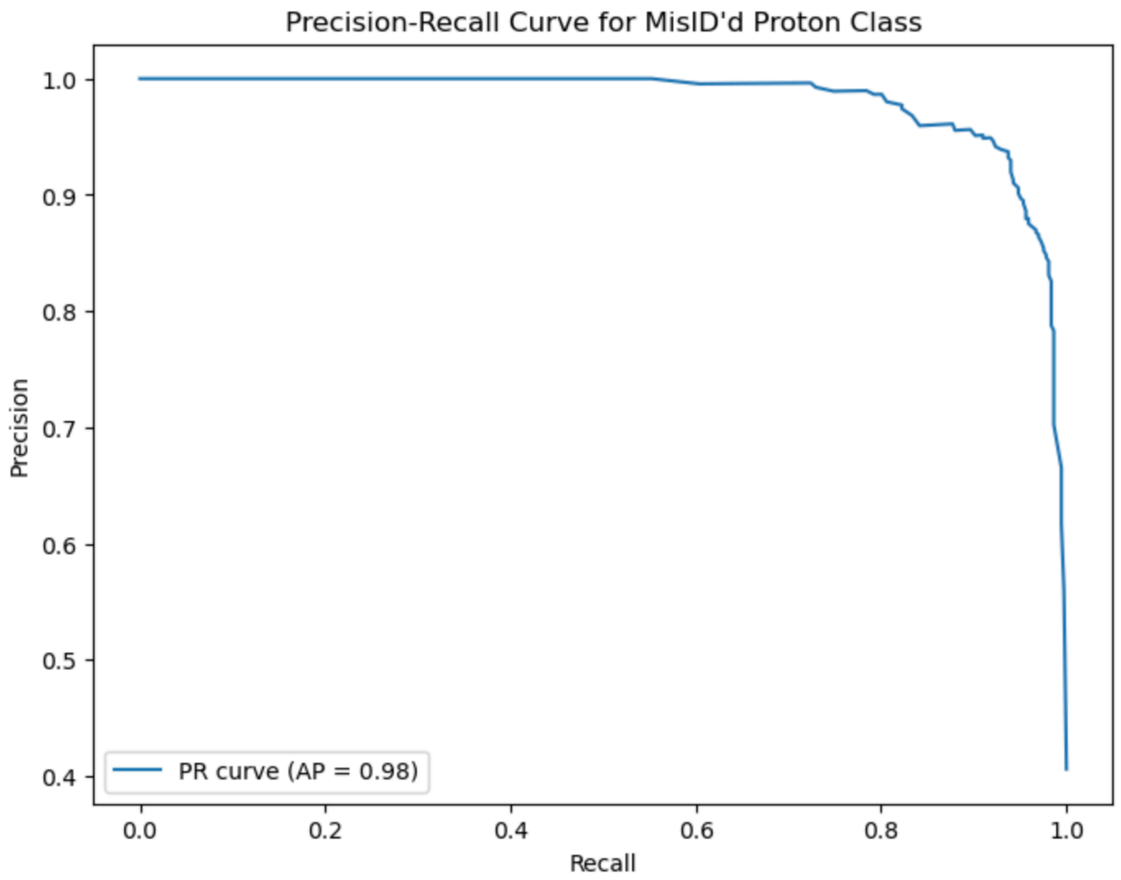
CND Hit Layer / Number of CND hits



Total CND+CTOF Edep in < 3 Steps

Initial results show good separation





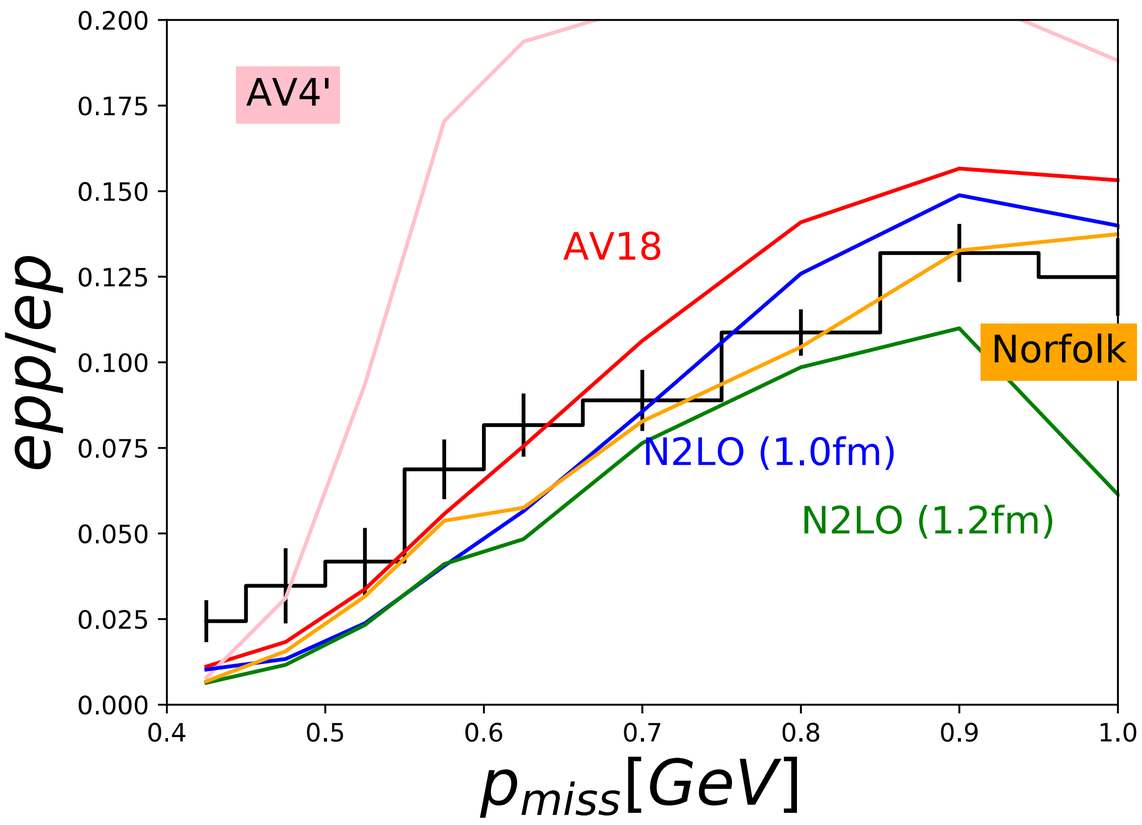
… and ANN results are $\mathcal{O}$(days) away!

Quasielastic Mini Summary:

Recent RGM 2p analyses:

Expand on existing 2N SRC results for model comparison

Demonstrate SRC scale universality



Quasielastic Mini Summary:

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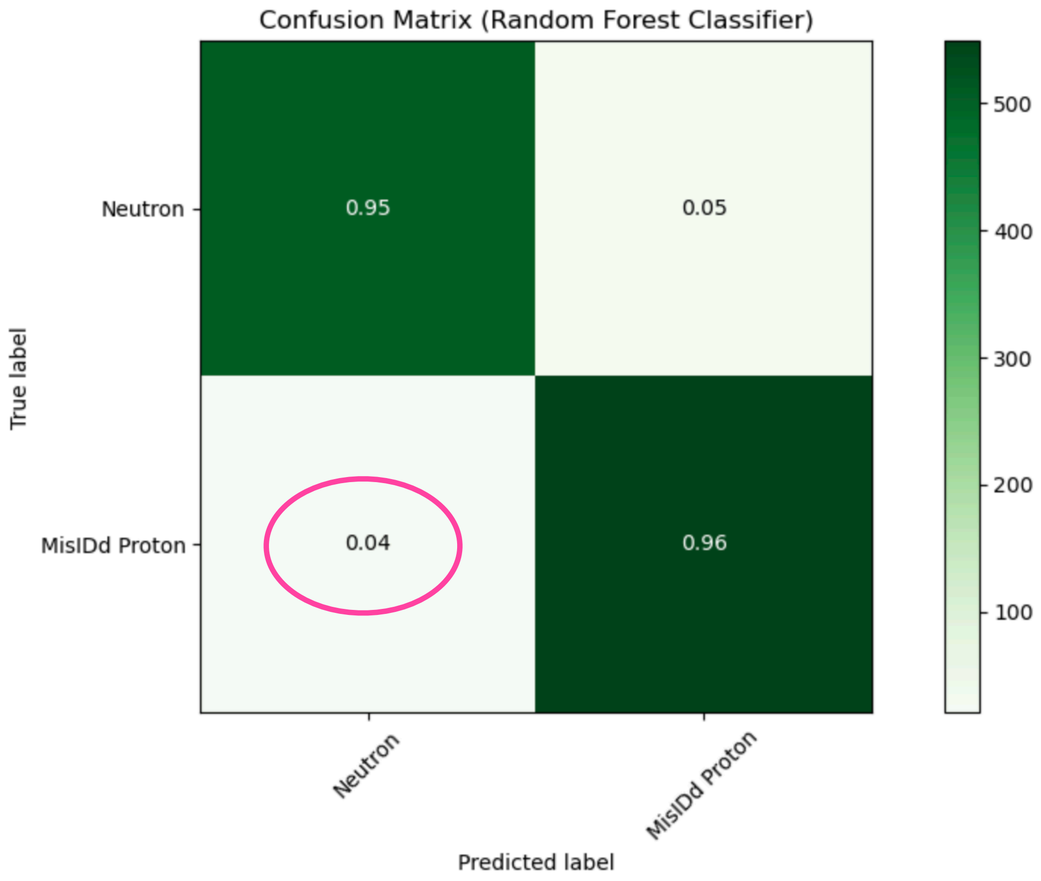
Demonstrate SRC scale universality

Need neutrons to go further!

ML algorithm to address CVT inefficiency



Quasielastic Mini Summary:

Recent RGM 2p analyses:

Expand on existing 2N SRC results for model comparison

Demonstrate SRC scale universality

Need neutrons to go further!

ML algorithm to address CVT inefficiency

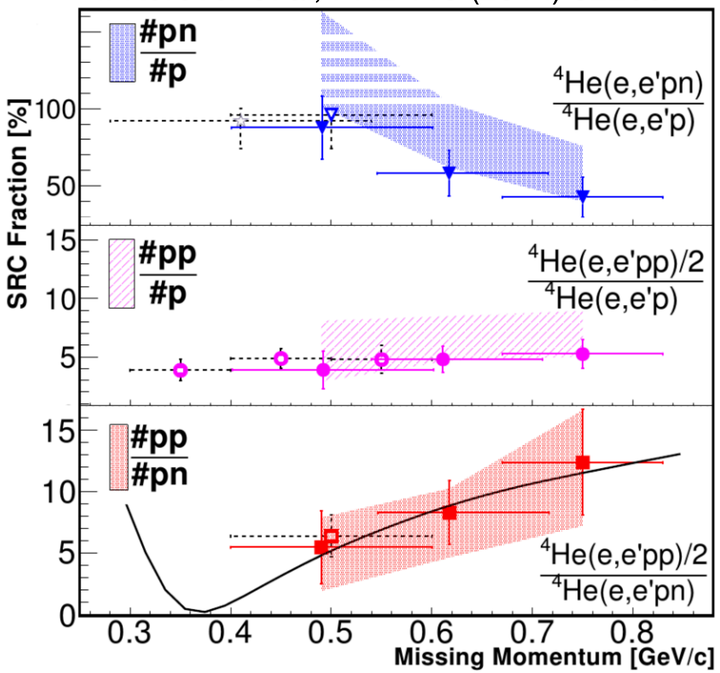
Next Steps:

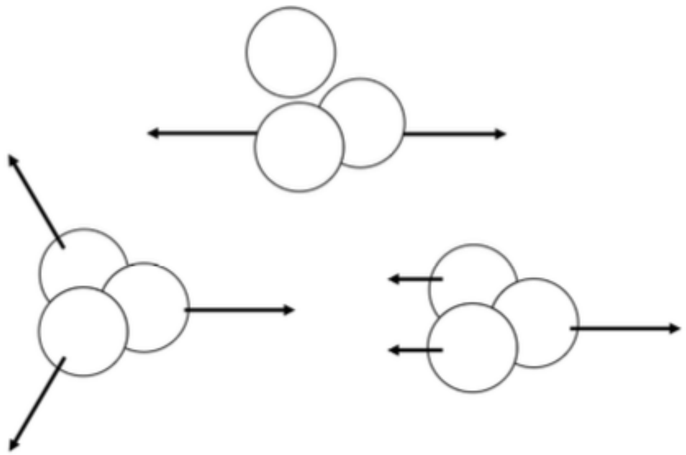
Validate ANN performance (add charged π)

Precision studies of pn SRCs

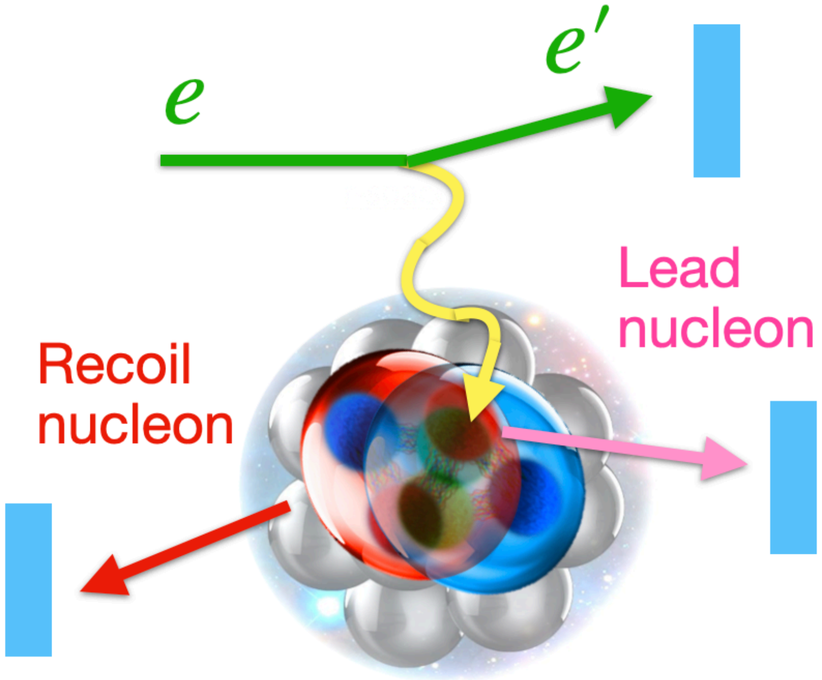
3N SRCs 👀

I. Korover et al, PRL 113 (2014) 022501



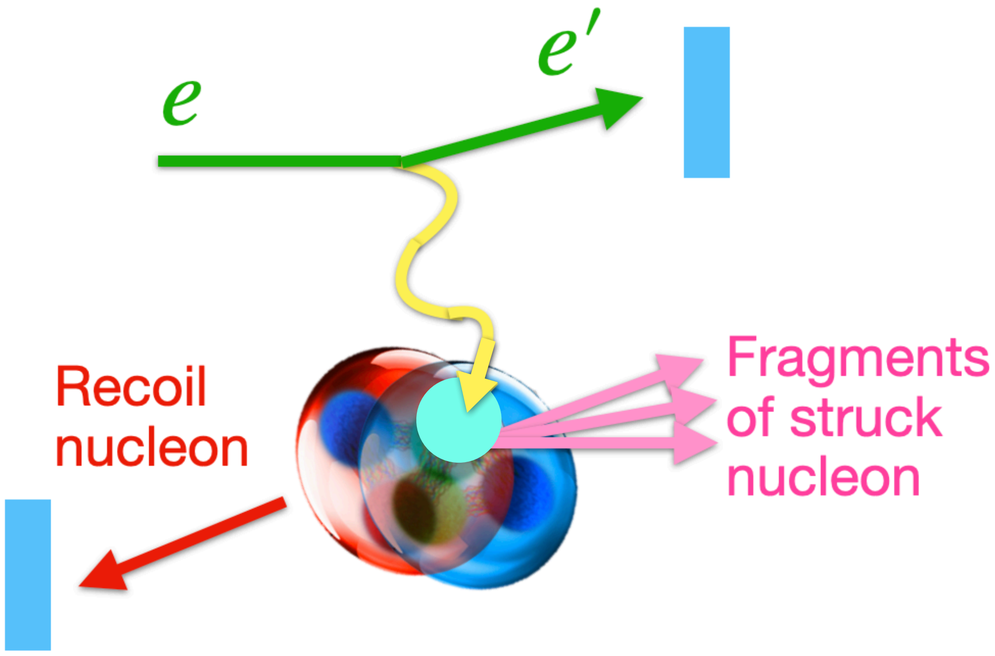


Quasielastic



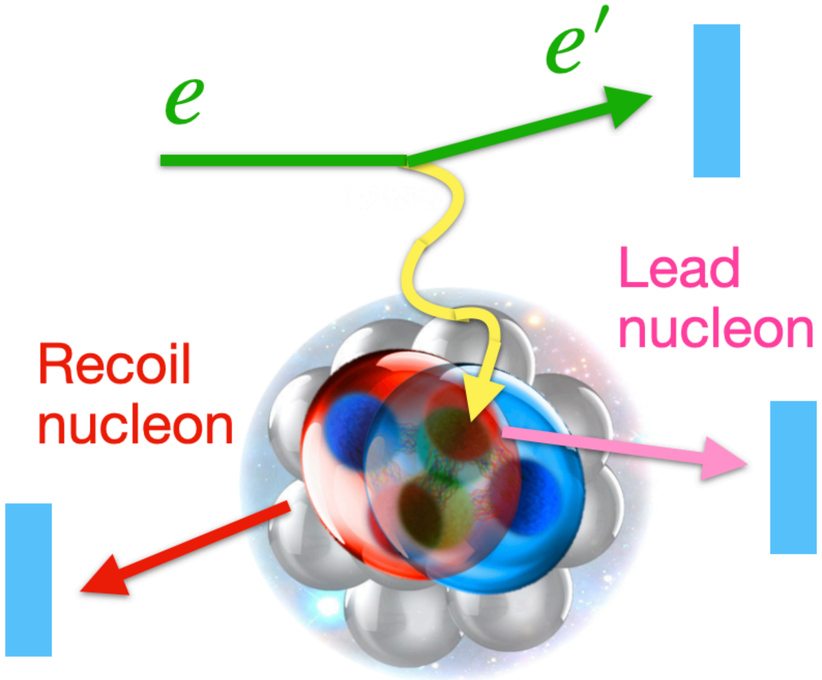
Exclusive Measurements

Deep Inelastic



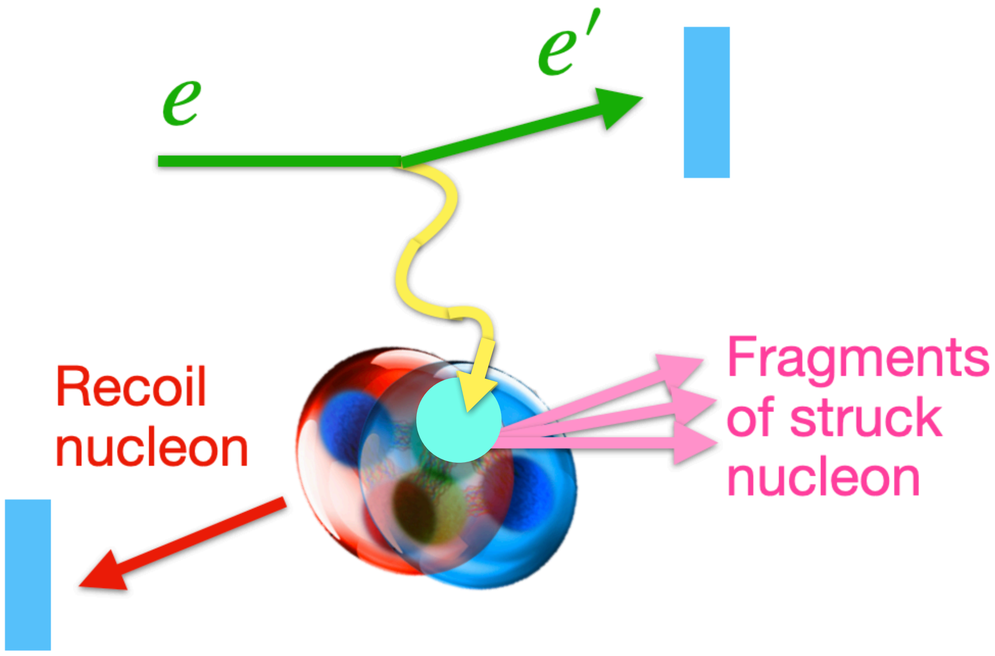
Tagged DIS Measurements

Quasielastic



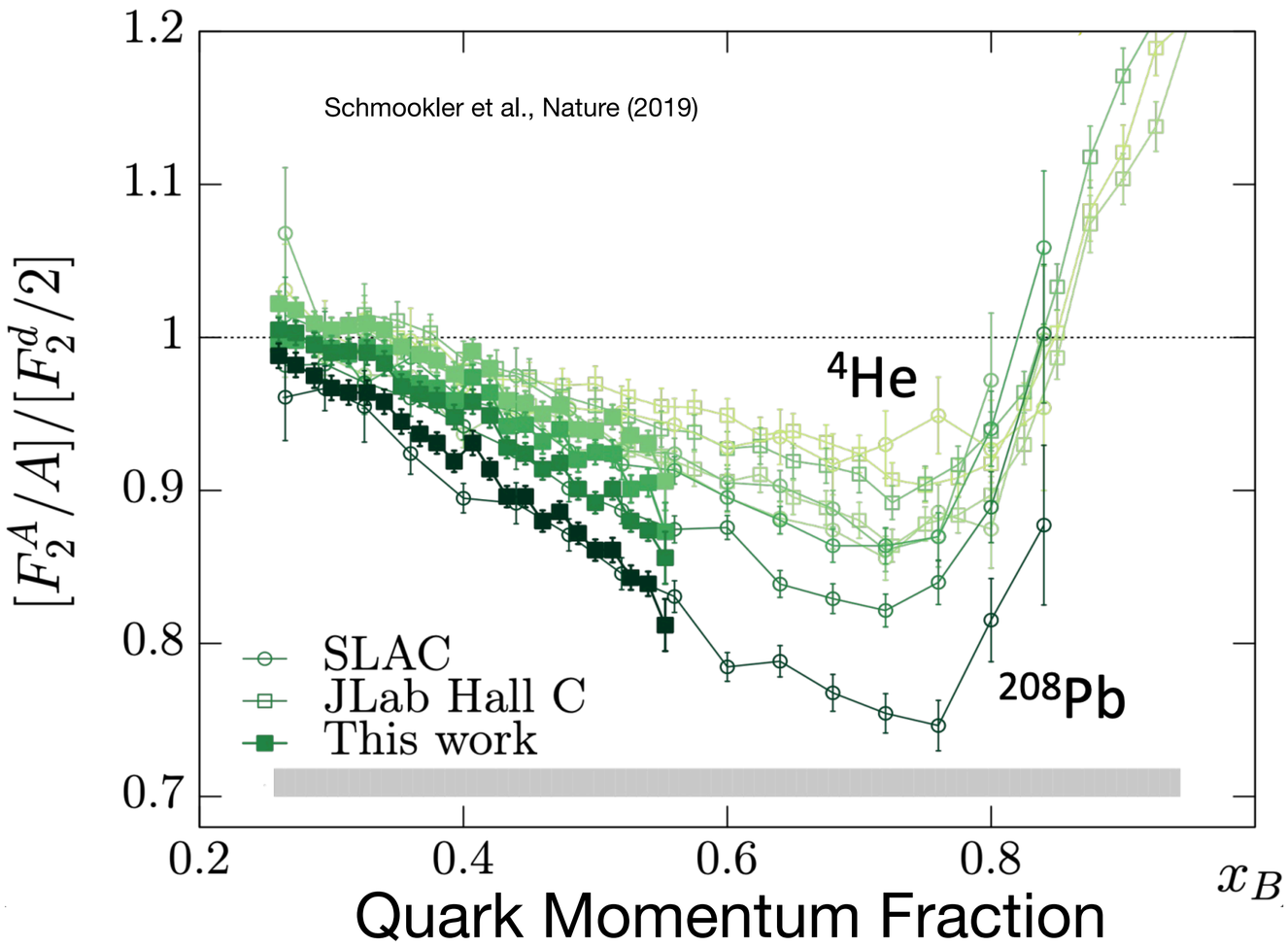
Exclusive Measurements

Deep Inelastic



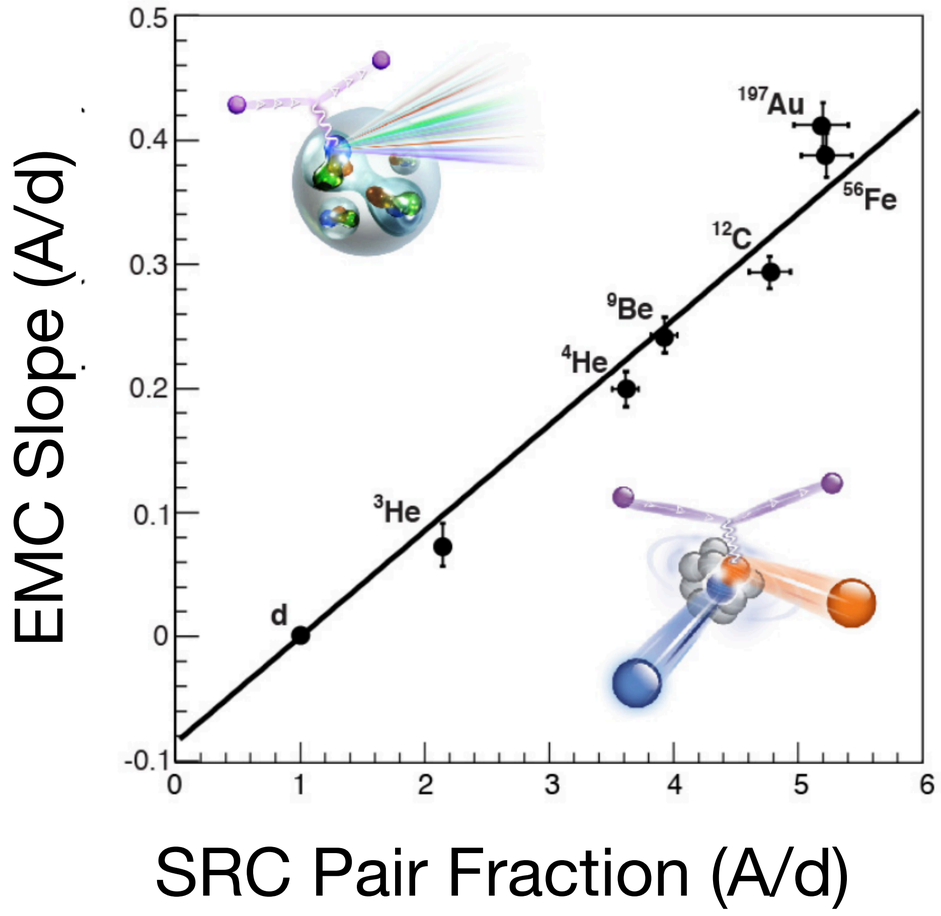
Tagged DIS Measurements

Quark momentum suppressed in bound nucleons (EMC Effect)

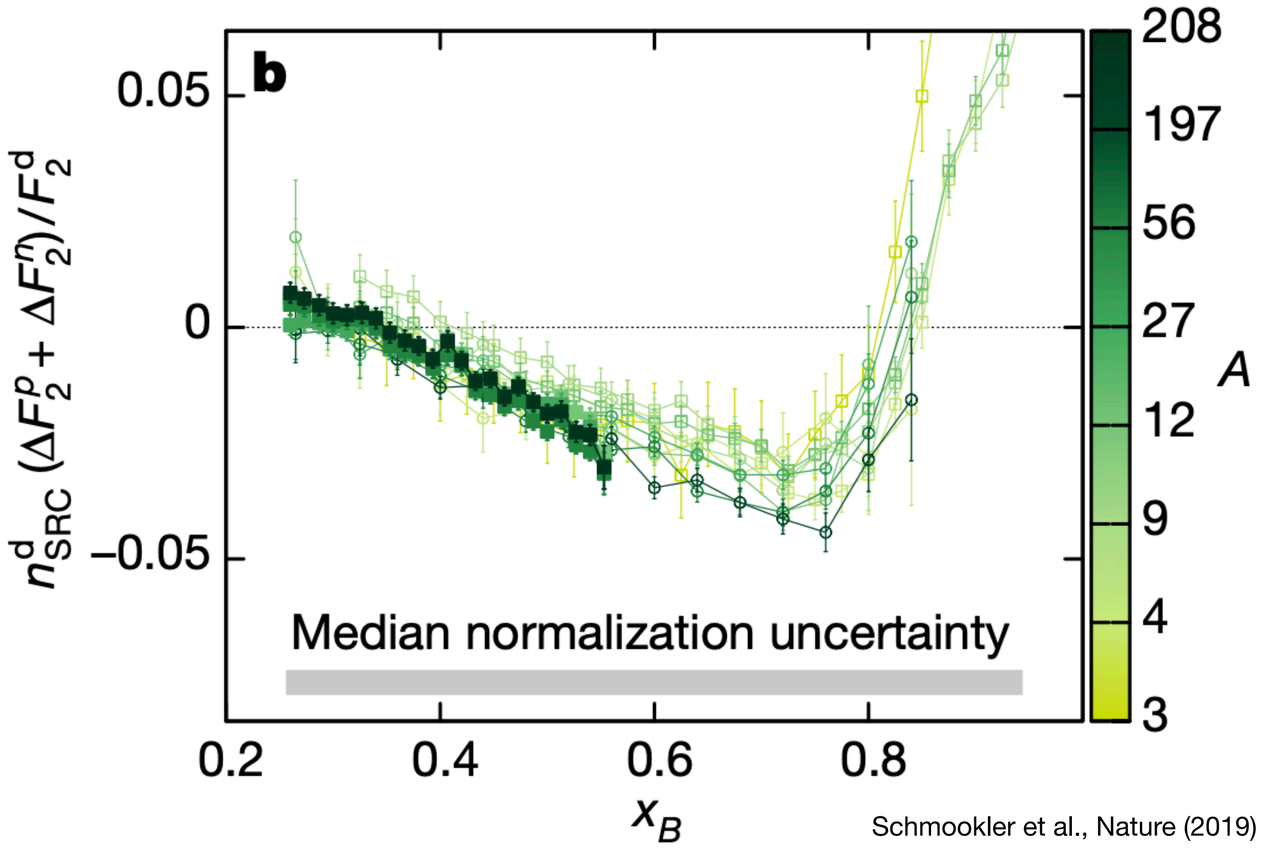


Inclusive DIS shows EMC-SRC correlation

Weinstein et al., PRL 106, 052301 (2011),

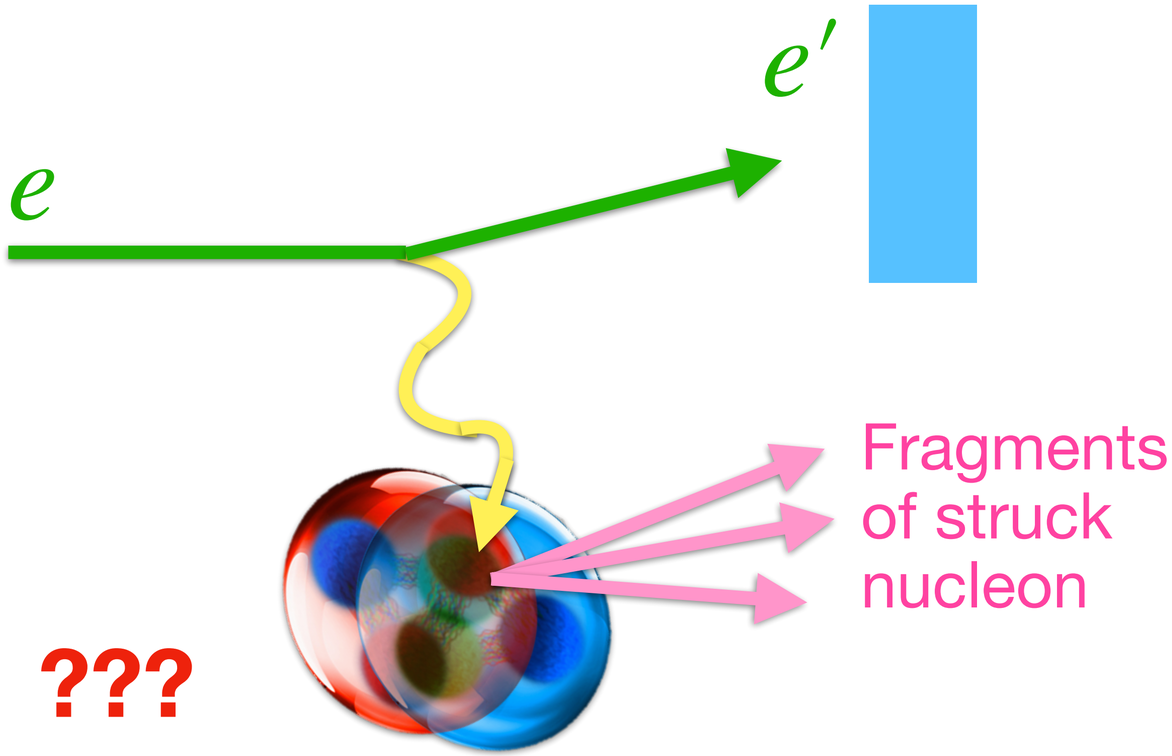


$$F_2^A = ZF_2^p + NF_2^n + n_{SRC}^A(\Delta F_2^p + \Delta F_2^n)$$



Schmookler et al., Nature (2019)

But lacks info on nuclear state



Standing nucleon target:

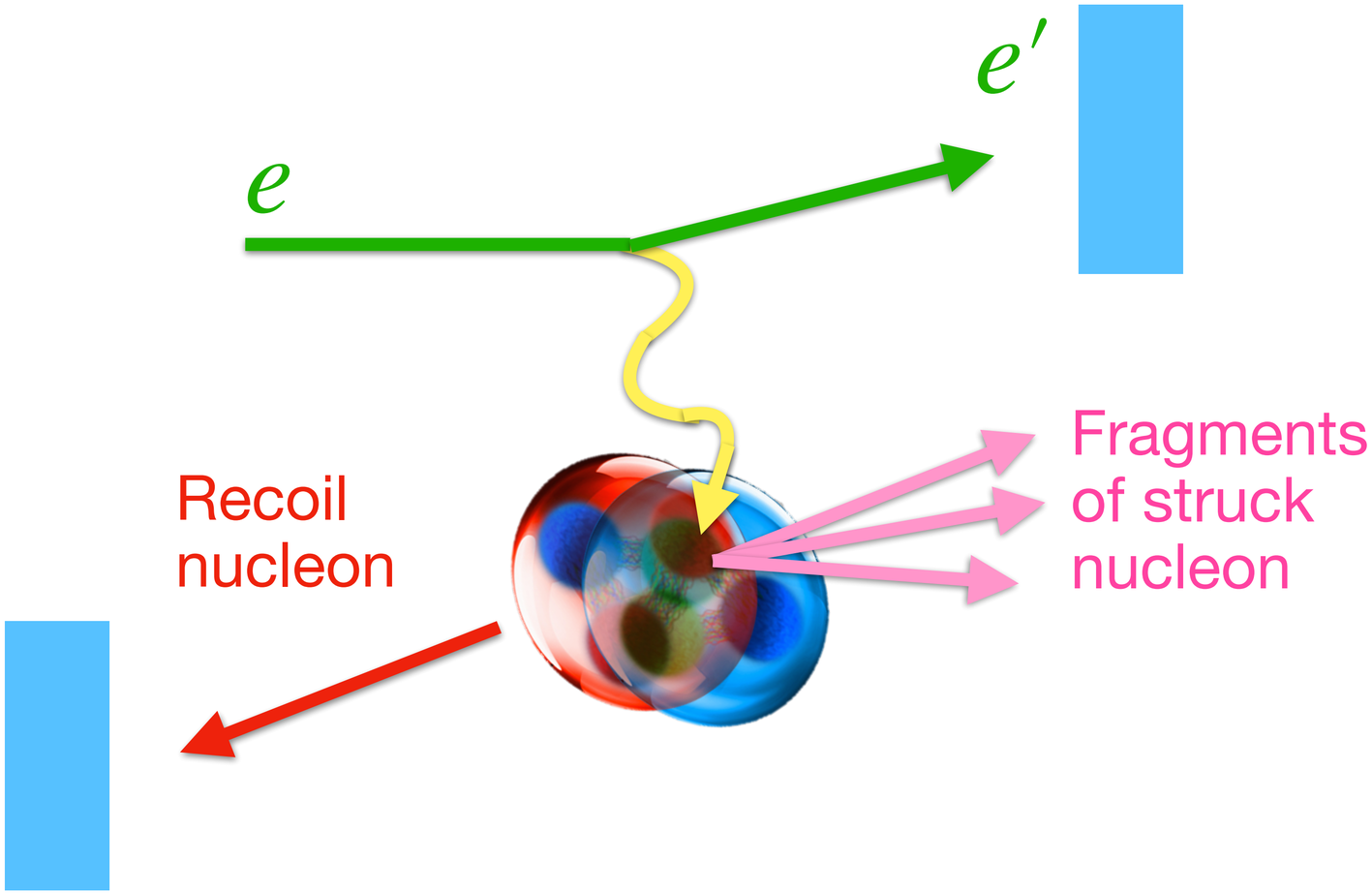
$$p_0 = (m_n \ , \ 0)$$

$$W^2 = (p_0 + q)^2$$

$$x_B = \frac{Q^2}{2m_n\omega}$$

Measure Parton Information

Add initial nuclear state via tagging!



Moving nucleon target:

$$p_\mu = (E, \ -p_s \ )$$

$$(W')^2 = (p_\mu + q)^2$$

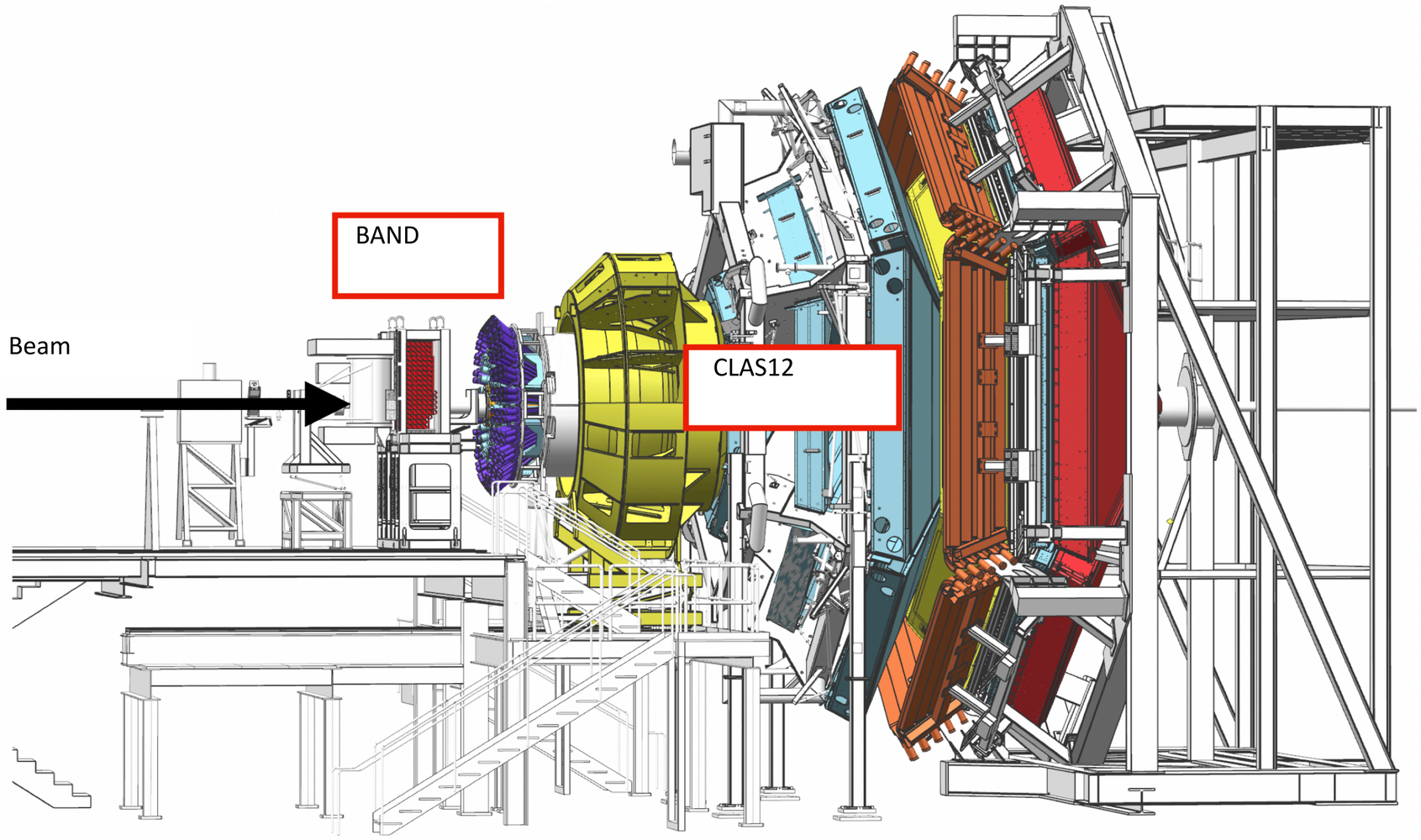
$$x' = \frac{Q^2}{(W')^2 - m_n^2 + Q^2}$$

$$\alpha_S = \frac{E_s - p_s \cos\theta_{sq}}{m_n}$$

Measure Parton + **Nucleon** Information

Tagged DIS with BAND

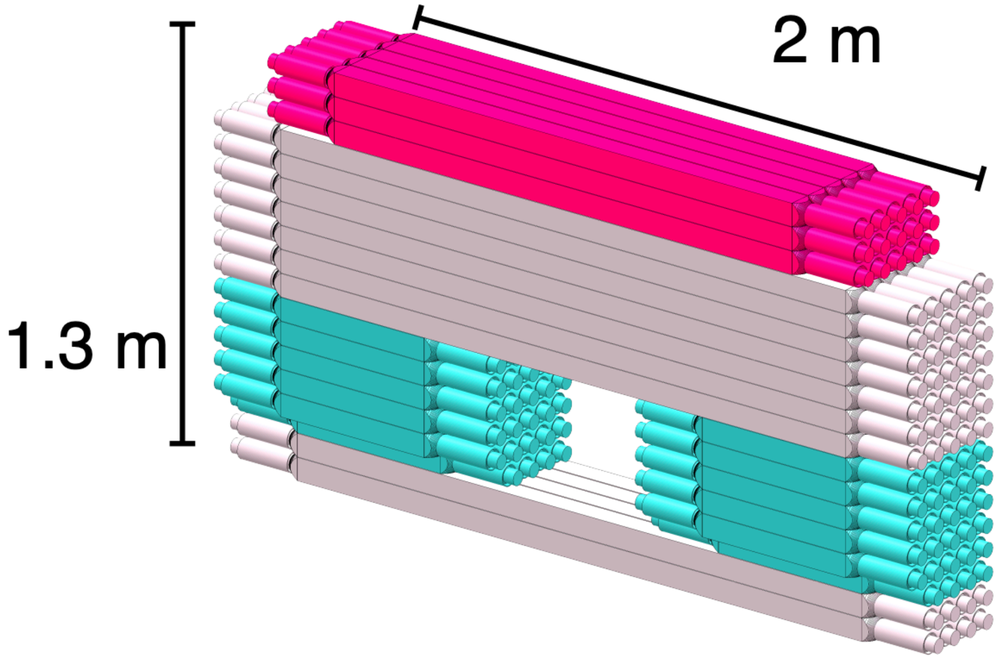
CLAS12 + Backward Angle Neutron Detector (BAND)



Backward Angle Neutron Detector

The detector:

- 140 scintillator bars
- 5 layers (+ 1cm thick veto)
- 3 meters upstream of target
- Lead wall downstream



Segarra et al., NIM A978 (2020)

Backward Angle Neutron Detector

The detector:

140 scintillator bars

5 layers (+ 1cm thick veto)

3 meters upstream of target

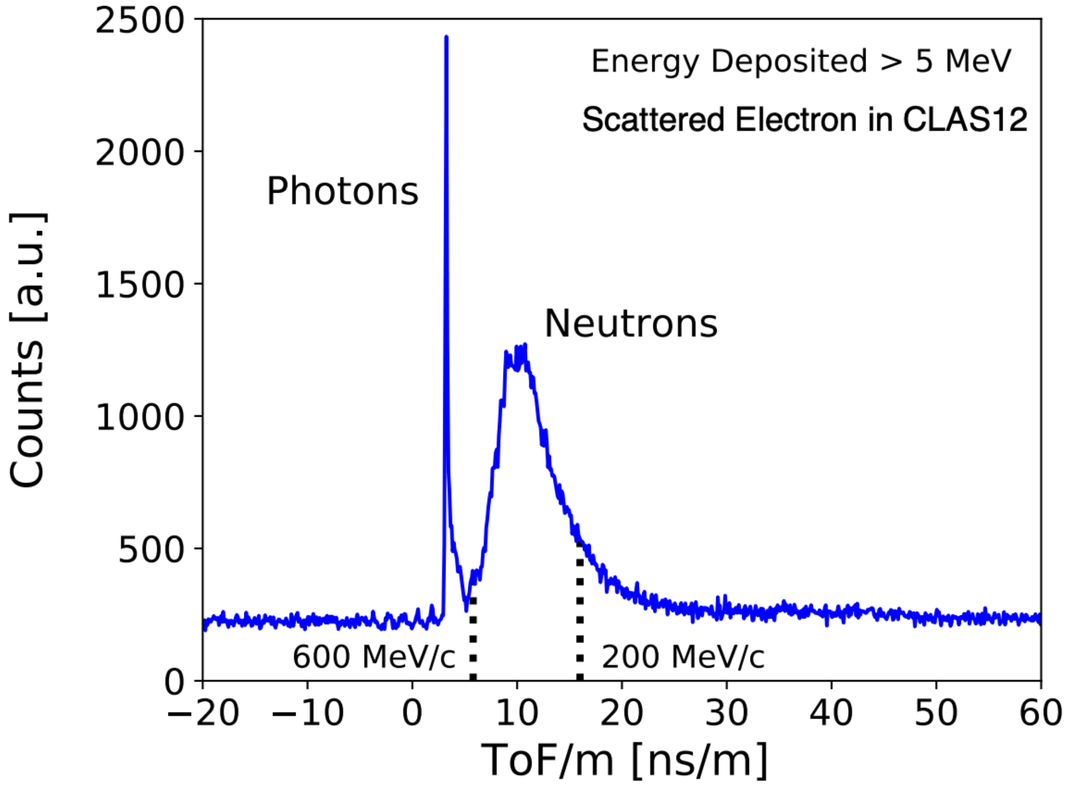
Lead wall downstream

The neutrons:

Time resolution < 250 ps

$\theta \sim$ 155-175°

$p \sim 200 - 600$ MeV/c



Segarra et al., NIM A978 (2020)

Tagged DIS with BAND

RGB: $d(e, e'n)$ at 10.2-10.6 GeV

Event mixing to subtract random coincidence background

Electron:

$Q^2 > 2$ GeV^2

$W > 2$ GeV^2

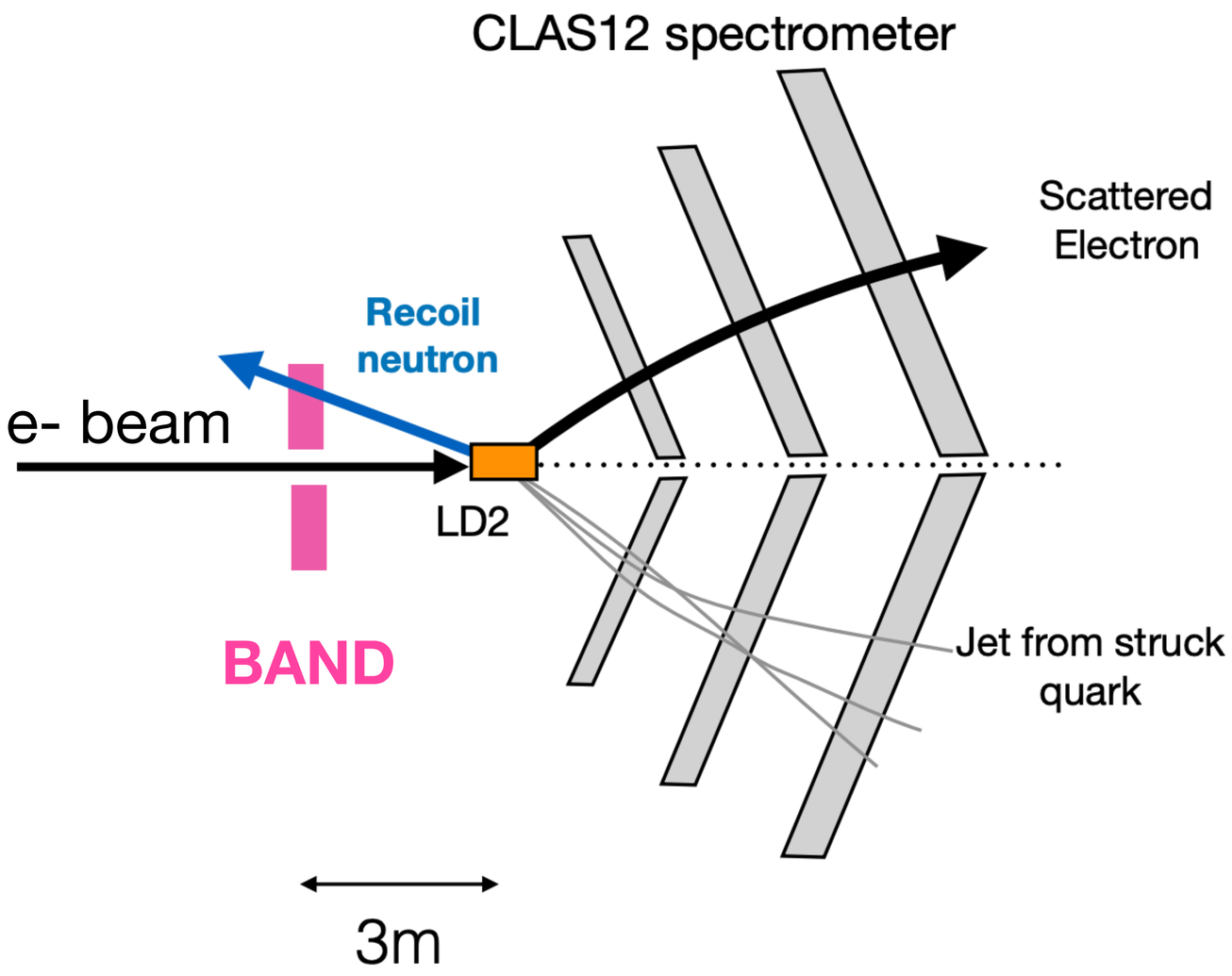
$p_e > 3$ GeV/c

Neutron:

$W'^2 > 1.8$ GeV^2

$.1 < p_n < .6$ GeV/c

$E_{dep} > 5$ MeVee



Constructing an observable

PWIA Tagged DIS Cross Section:

$$\frac{d\sigma_{tag}}{dx dQ^2 d\alpha dp_\perp} = K(x, Q^2) \cdot S(\alpha, p_\perp) \cdot F_2^{p*}(x, Q^2, \alpha, p_\perp)$$

Kinetic term

Spectral function

Tagged structure function

Constructing an observable

PWIA Tagged DIS Cross Section:

$$\frac{d\sigma_{tag}}{dx dQ^2 d\alpha dp_\perp} = K(x, Q^2) \cdot S(\alpha, p_\perp) \cdot F_2^{p*}(x, Q^2, \alpha, p_\perp)$$

Kinetic term

Spectral function

Tagged structure function

We want sensitivity to $\frac{F_2^{p*}}{F_2^p}$

Tagged double ratio

We want sensitivity to $\frac{F_2^{p*}}{F_2^p}$

$$\mathscr{R} = \frac{\sigma_{tag}^{meas.}(x', Q^2, \alpha, p_\perp)}{\sigma_{tag}^{meas.}(.3, Q^2, \alpha, p_\perp)} \Bigg/ \frac{\sigma_{tag}^{theory}(x', Q^2, \alpha, p_\perp)}{\sigma_{tag}^{theory}(.3, Q^2, \alpha, p_\perp)} = \frac{Y_{tag}^{meas.}(x')}{Y^{meas.}(.3)} \Bigg/ \frac{Y_{tag}^{theory}(x')}{Y_{tag}^{theory}(.3)}$$

where theory cross section is proportional to free proton structure function

Tagged double ratio

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$$\mathscr{R} = \frac{\sigma_{tag}^{meas.}(x', Q^2, \alpha, p_\perp)}{\sigma_{tag}^{meas.}(.3, Q^2, \alpha, p_\perp)} \Bigg/ \frac{\sigma_{tag}^{theory}(x', Q^2, \alpha, p_\perp)}{\sigma_{tag}^{theory}(.3, Q^2, \alpha, p_\perp)} = \frac{Y_{tag}^{meas.}(x')}{Y^{meas.}(.3)} \Bigg/ \frac{Y_{tag}^{theory}(x')}{Y_{tag}^{theory}(.3)}$$

Theory prediction generated with radiation in CLAS12-GEANT4 (GEMC)

→ Systematics cancel in the data/sim ratio

Tagged double ratio

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Theory prediction generated with radiation in CLAS12-GEANT4 (GEMC)

→ Systematics cancel in the data/sim ratio

Normalization of each sample at x' = .3

→ Nuclear effects cancel in each α bin

Tagged double ratio

We want sensitivity to $\frac{F_2^{p*}}{F_2^p}$

$$\mathscr{R} = \frac{\sigma_{tag}^{meas.}(x', Q^2, \alpha, p_\perp)}{\sigma_{tag}^{meas.}(.3, Q^2, \alpha, p_\perp)} \Big/ \frac{\sigma_{tag}^{theory}(x', Q^2, \alpha, p_\perp)}{\sigma_{tag}^{theory}(.3, Q^2, \alpha, p_\perp)} = \frac{Y_{tag}^{meas.}(x')}{Y^{meas.}(.3)} \Big/ \frac{Y_{tag}^{theory}(x')}{Y_{tag}^{theory}(.3)}$$

$$\mathscr{R} \approx \frac{F_2^{p*}(x') \,/\, F_2^p(x')}{F_2^{p*}(.3) \,/\, F_2^p(.3)}$$

Measured **bound** proton structure function

Simulated **free** proton structure function

Tagged double ratio

$$\mathscr{R} = \frac{\sigma_{tag}^{meas.}(x', Q^2, \alpha,}{\sigma_{tag}^{meas.}(.3, Q^2, \alpha,} \quad \frac{x')}{3)} \Big/ \frac{Y_{tag}^{theory}(x')}{Y_{tag}^{theory}(.3)}$$

This is sensitive to $\dfrac{F_2^{p*}}{F_2^{p}}$!

$$\mathscr{R} \approx \frac{F_2^{p*}(x') \,/\, F_2^{p}(x')}{F_2^{p*}(.3) \,/\, F_2^{p}(.3)}$$

Measured **bound** proton structure function

Simulated **free** proton structure function

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$$\mathscr{R} = \frac{\sigma_{tag}^{meas.}(x', Q^2, \alpha,}{\sigma_{tag}^{meas.}(.3, Q^2, \alpha,} \quad \frac{Y_{tag}^{theory}(x')}{Y_{tag}^{theory}(.3)}$$

This is sensitive to $\dfrac{F_2^{p*}}{F_2^p}$!

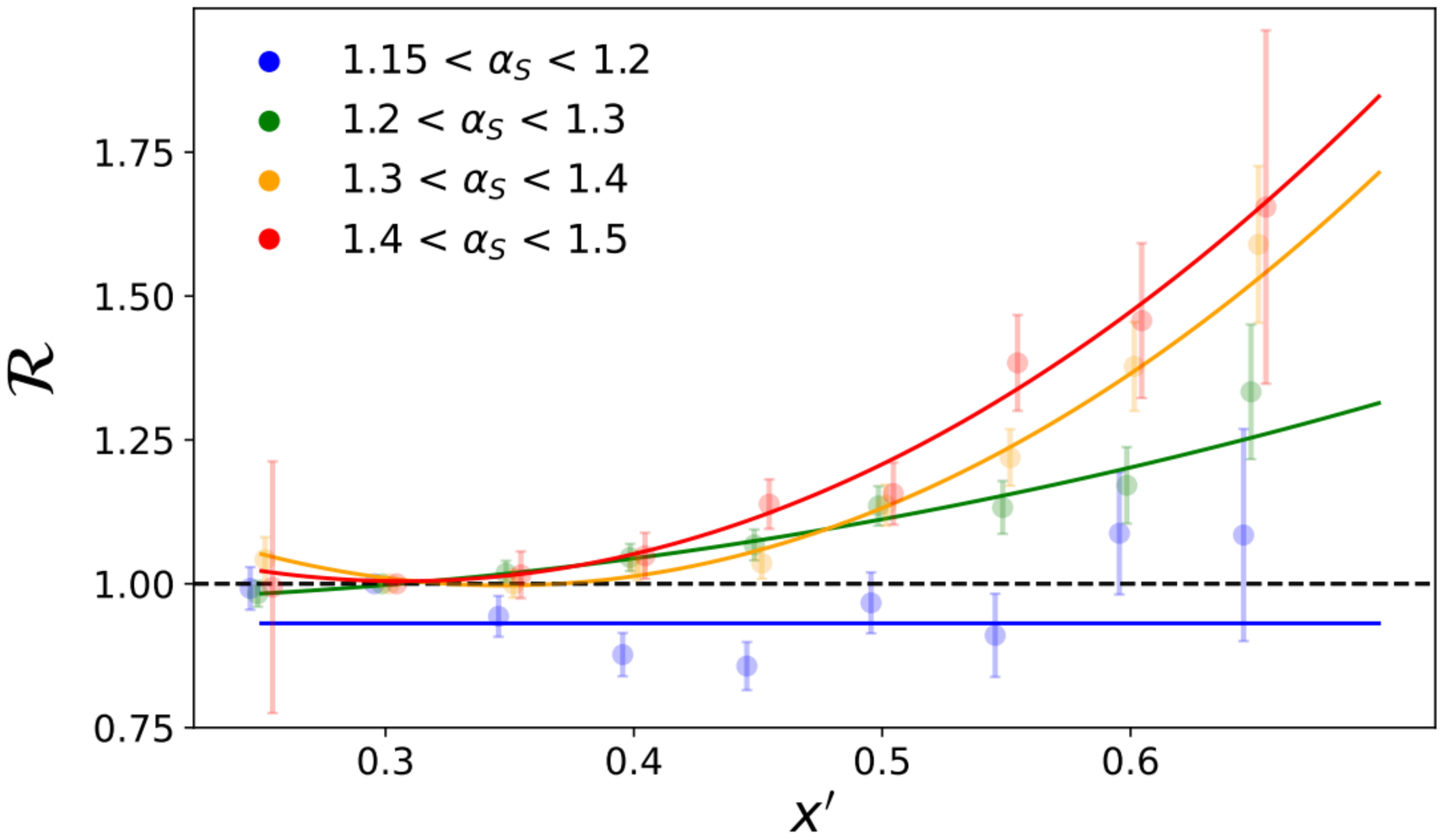
$\mathscr{R}$?

Now, what happens with increasing virtuality?

nction

tion

Strong modification with virtuality!



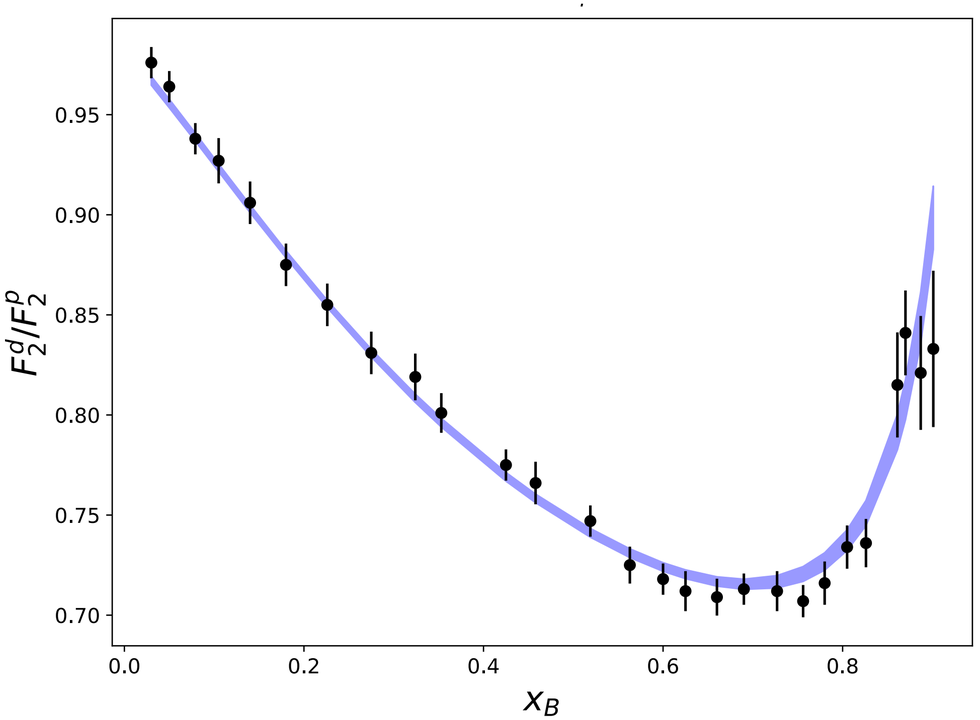
Measurement compatible with inclusive data

Convolution formalism:

$$F_2^A(x) = \frac{1}{A}\int_x^A \frac{d\alpha}{\alpha}\int_{-\infty}^0 d\nu\; F_2^p(\tilde{x})\left[Z\frac{F_2^{p*}(\tilde{x})}{F_2^p(\tilde{x})}\rho_p^A(\alpha,\nu) + N\frac{F_2^{n*}(\tilde{x})}{F_2^p(\tilde{x})}\rho_n^A(\alpha,\nu)\right]$$

$$F_2^p(x) = \frac{4}{9}u(x) + \frac{1}{9}d(x)$$

$$F_2^{*p}(x) = \frac{4}{9}u(x)\left(1+\nu f_u^{off}(x)\right) + \frac{1}{9}d(x)\left(1+\nu f_d^{off}(x)\right)$$



Jason Phelan

$\nu =$ Virtuality

$f^{off}(x) =$ Flavor-dept off-shell modification function

Measurement compatible with inclusive data

Data used for fitting:

"Inclusive"

F_2^d/F_2^p (Global re-analysis, Arrington et al., J. Phys. G 36, 025005 (2009))

$F_2^{^3He}/F_2^d$ (Hall C, Seely et al., Phys. Rev. Lett. 103, 202301 (2009))

$F_2^d/(F_2^p + F_2^n)$ (BoNuS, Tkachenko et al., Phys. Rev. C 89, 045206 (2014))

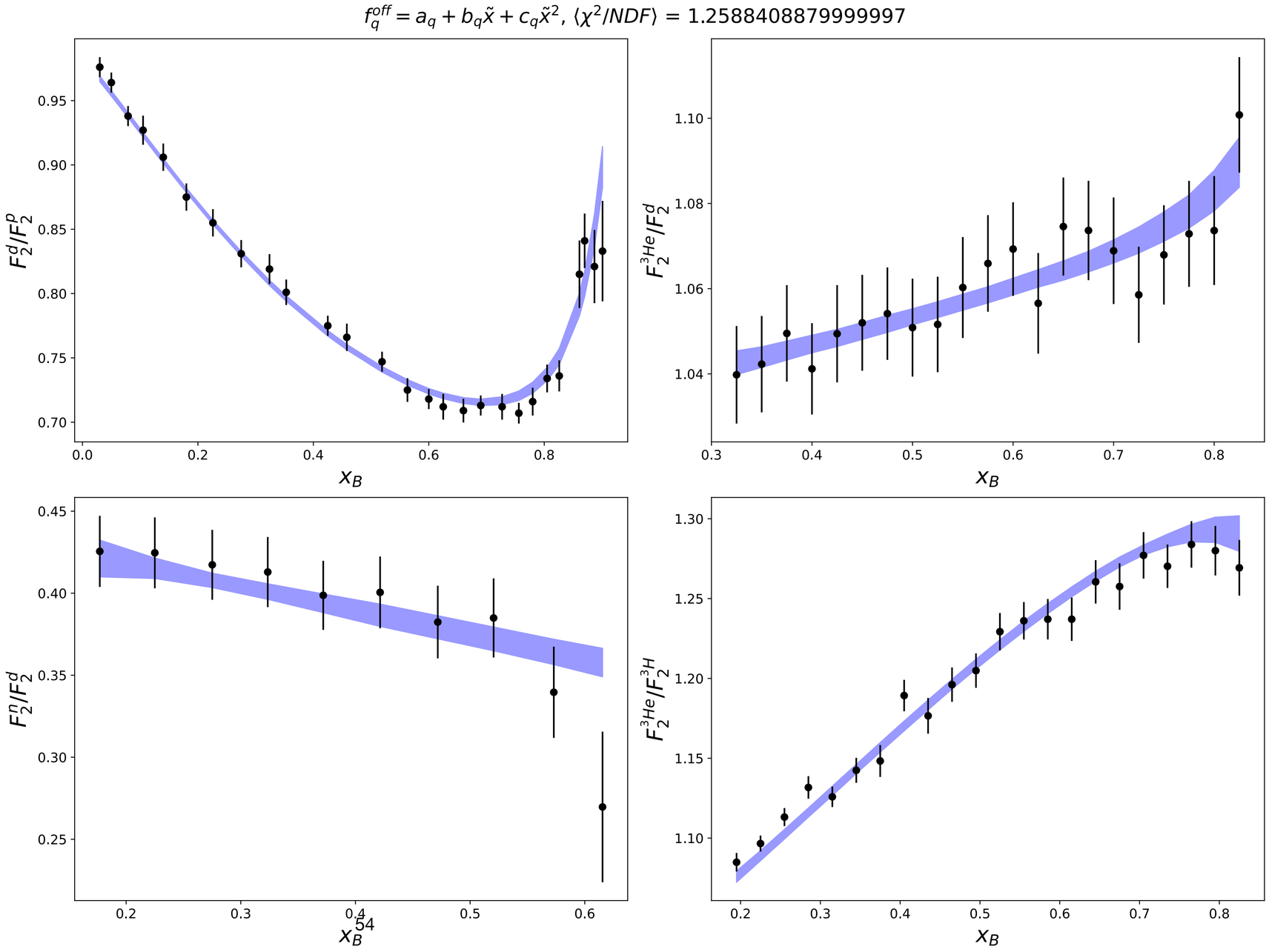
$F_2^{^3He}/F_2^{^3H}$ (Marathon, D. Abrams et al., Phys. Rev. Lett. 128, 132003 (2022))

+Tagged: $F_2^{p,tagged}/F_2^p$ (BAND)

Jason Phelan

Measurement compatible with inclusive data

Inclusive simultaneous fit results:



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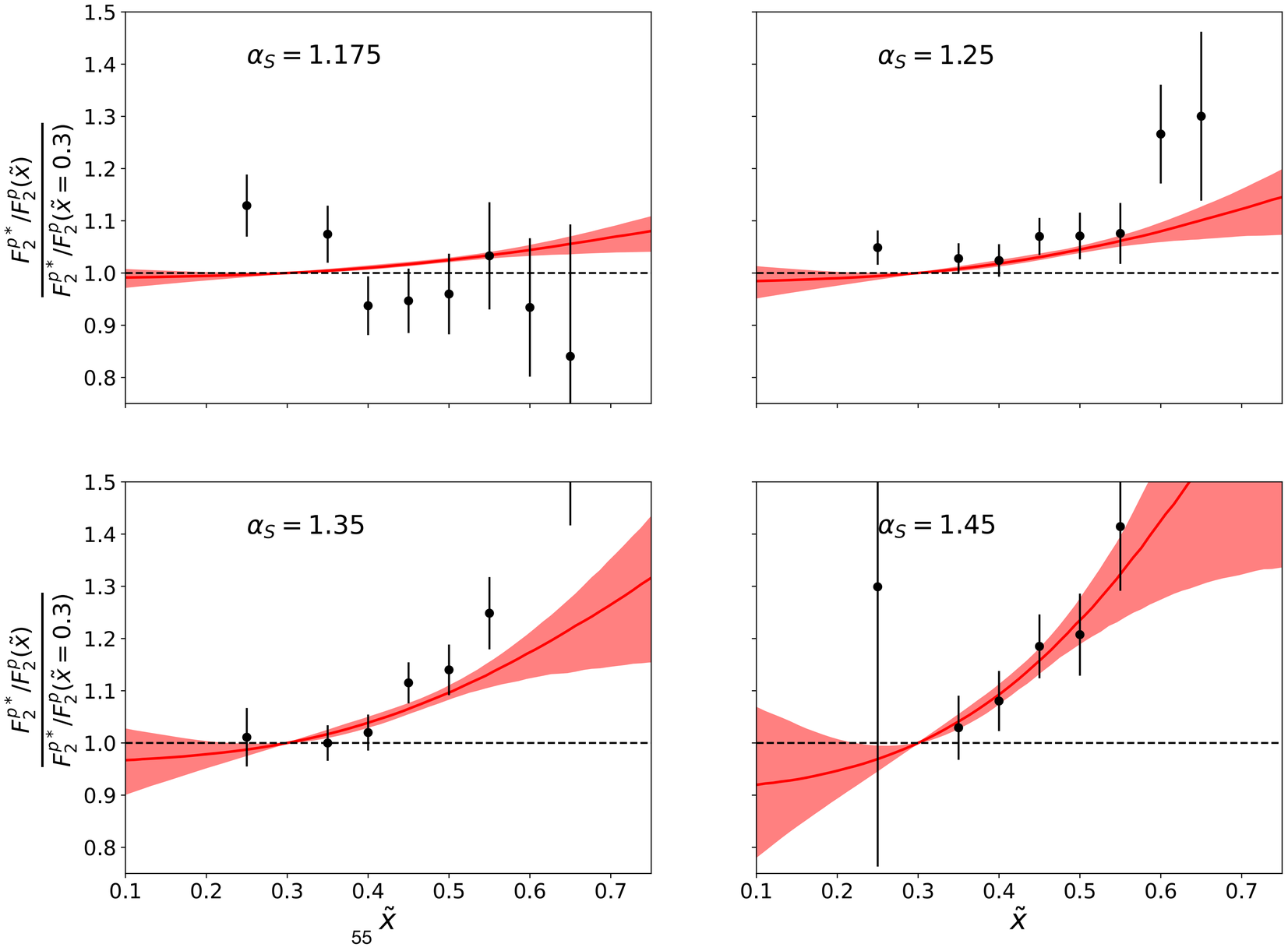
Measurement compatible with inclusive data

BAND tagged simulataneous fit results:



Jason Phelan

Summary and Outlook

QE Measurements with RGM

-Successful A(e,e'pp) studies

-Need neutrons to go further

→ ML to separate neutrons/ charged particles looks promising

-Next: Validate ML with 2N analyses, then exclusive 3N searches!

Tagged DIS with BAND

-Bound nucleon modification is virtuality-dependent!

-Results compatible with global fits to inclusive data + BoNuS

-Analysis note in review

-Tagged SIDIS in the works!

Summary and Outlook

QE Measurements with RGM

-Succ

-Need

→ M

charg

-Next: Validate ML with 2N analyses, then exclusive 3N searches!

Tagged DIS with BAND

on is

global

NuS

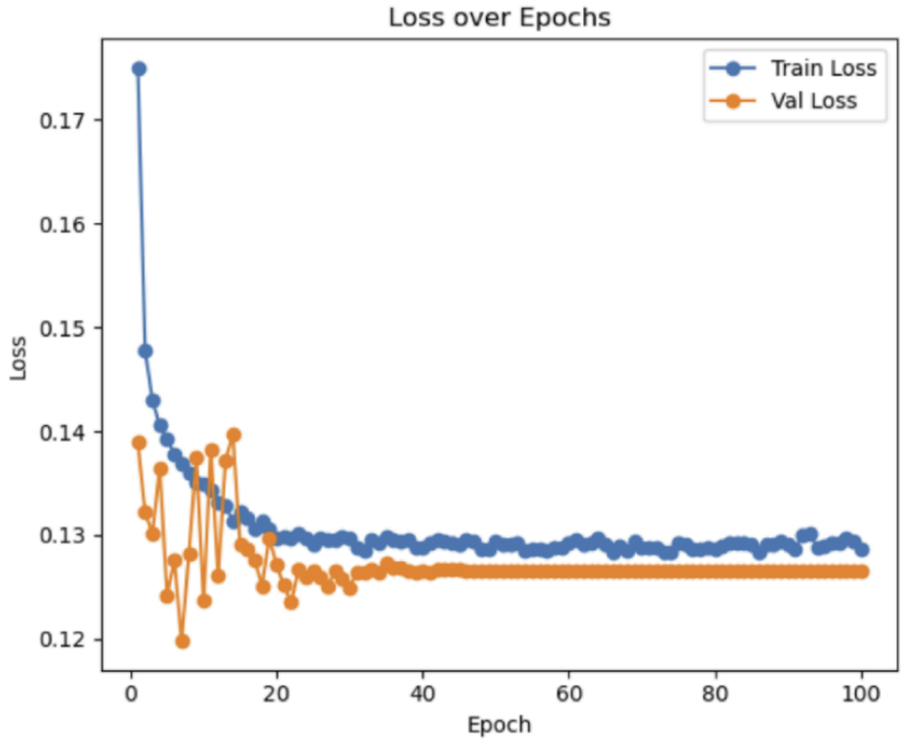
-Analysis note in review

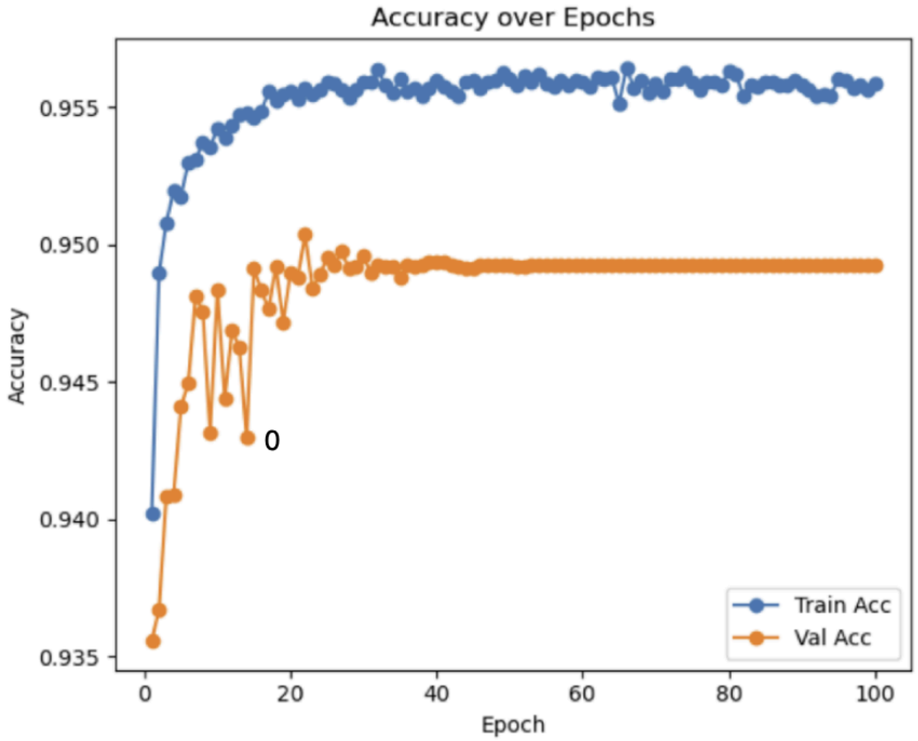
-Tagged SIDIS in the works!

Thank you!

BACKUP

Model Training and Validation





- Loss function used is cross-entropy loss
- Validation loss stabilizes after ~20 epochs
- Trends do not indicate overfitting or underfitting

- Validation accuracy plateaus around 95%

ANN Classifier Details

Input Features: 9 engineered variables

Architecture:

- Fully connected feedforward neural network
- Hidden layers: 64 → 32 neurons, each with ReLU activations
- Dropout regularization (p=0.3) after each hidden layer to reduce overfitting
- Output layer: 2 neurons (one for “neutron,” one for “charged-particle”) + softmax activation → outputs

Loss function: Categorical Cross-Entropy Loss

Learning Rate: 1 x 10^-3

Batch Size: 64

ANN Classifier : Preliminary Results

Neutrons:

- Precision of ~99% indicates few to no false positives (almost no charged particles labeled as neutrons)
- Recall of ~95% indicates about 4.95% of true neutrons were misclassified as charged particles

Protons:

- Precision of ~75.11% says of all events predicted as “proton,” 75.11% were truly charged particles
- Recall shows that about 24.89% of predictions labeled as “proton” were actually neutrons (false positives) → some confusion in model

	precision	recall	f1-score	support
Neutron	0.9913	0.9505	0.9705	11155.0
Proton	0.7511	0.9471	0.8378	1759.0
accuracy	0.9501	0.9501	0.9501	0.9501
macro avg	0.8712	0.9488	0.9042	12914.0
weighted avg	0.9586	0.9501	0.9524	12914.0

ANN Classifier

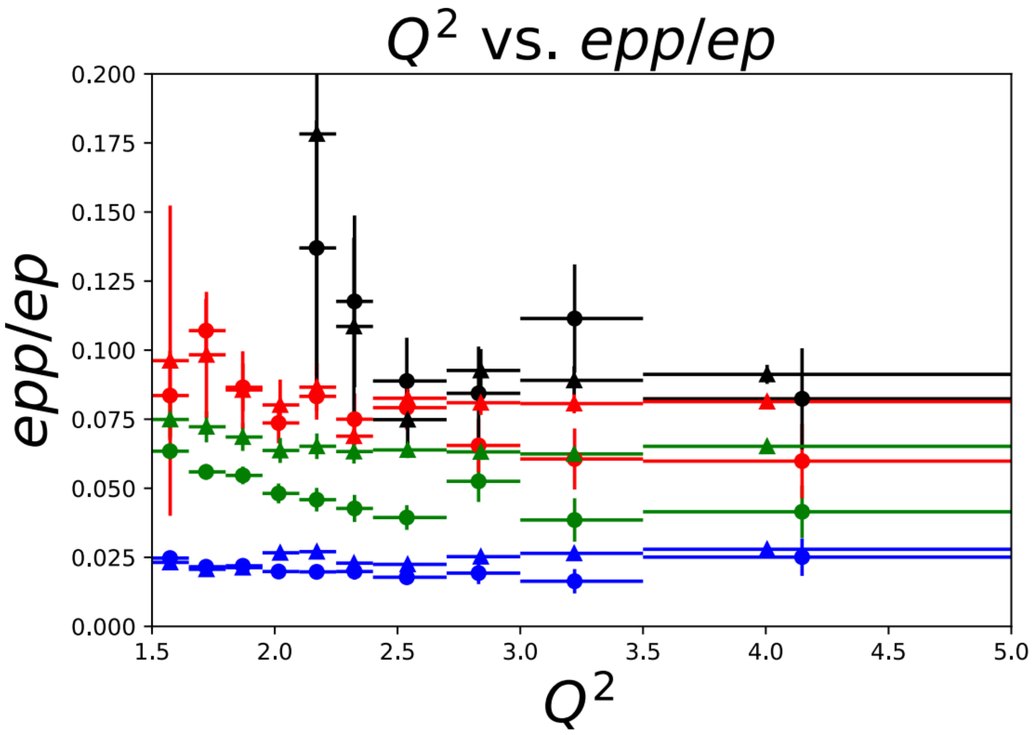
Key Design Rationale:

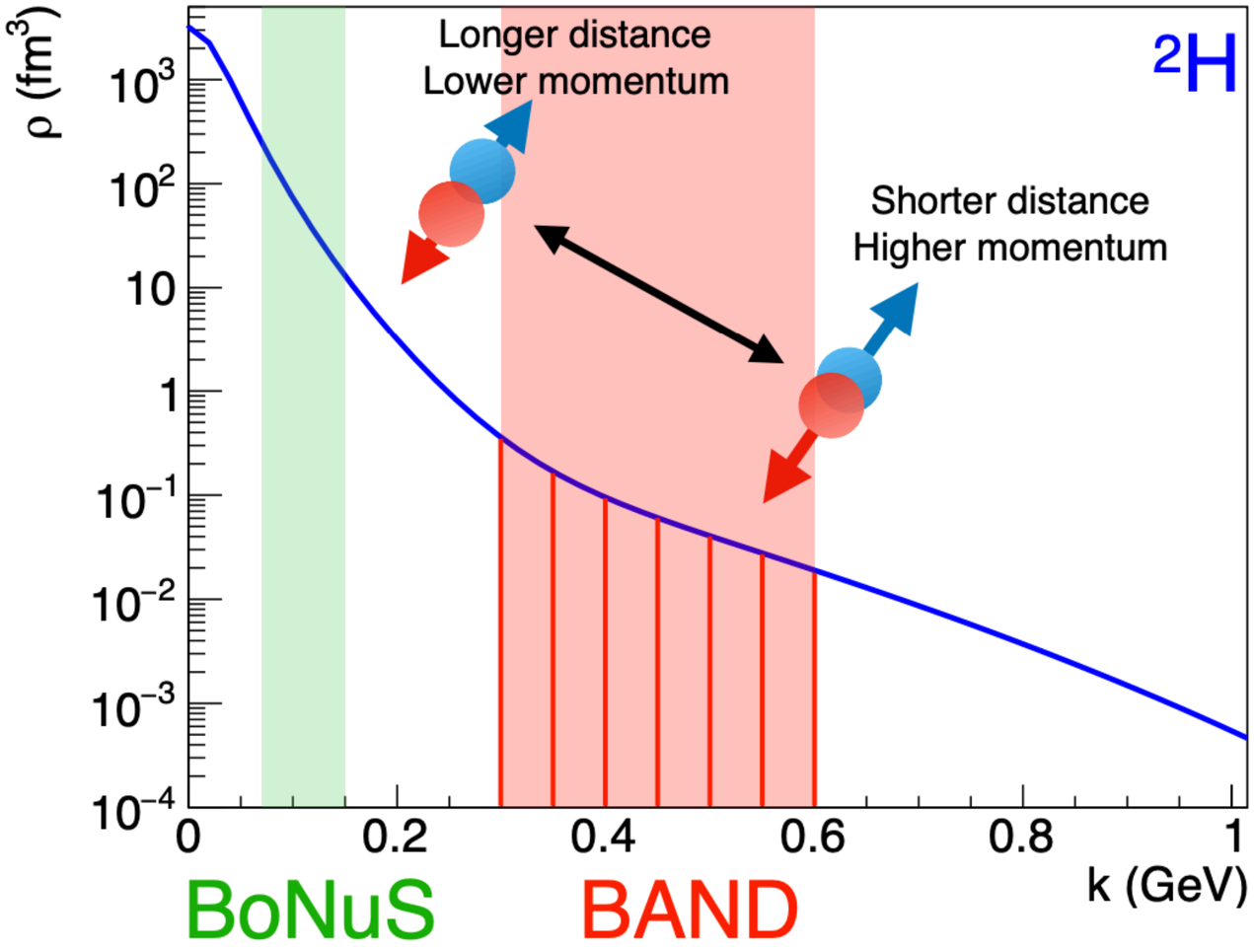
- Moderate depth (2 hidden layers) captures nonlinear correlations without overfitting
- ReLU + dropout regularization balance expressivity and generalization power
- Adam Optimizer with lr = 1e-3 yields stable, fast convergence compared to vanilla Stochastic Gradient Descent

Key Performance Takeaways:

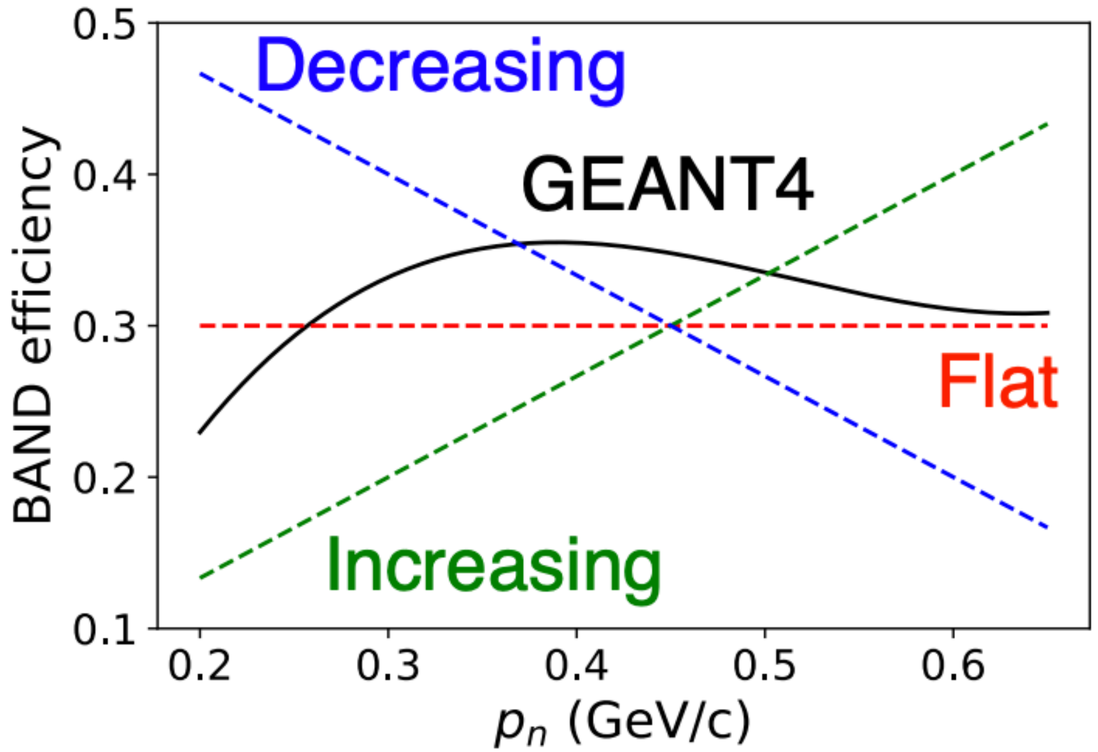
- The model is very good at avoiding false neutrons (neutron precision ≈ 0.99), so few charged particles slip through as neutrons.
- Almost all true protons are found (proton recall ≈ 0.95), meaning very few protons get misclassified as neutrons.
- However, the model erroneously flags some neutrons as protons (proton precision ≈ 0.75), which suggests it's "safer" to call something a proton when uncertain—likely due to overlapping feature distributions.
- Overall, the high F1-score on neutrons (0.97) and decent F1-score on protons (0.84) result in a strong overall accuracy (~95%).

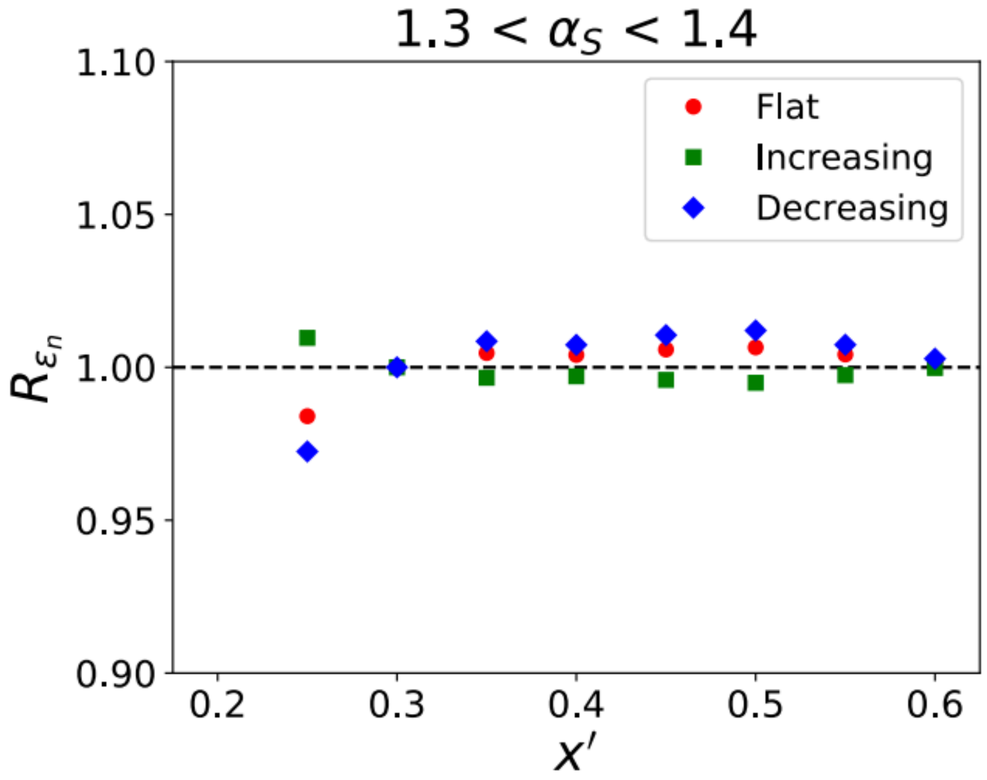
Bins of pmiss

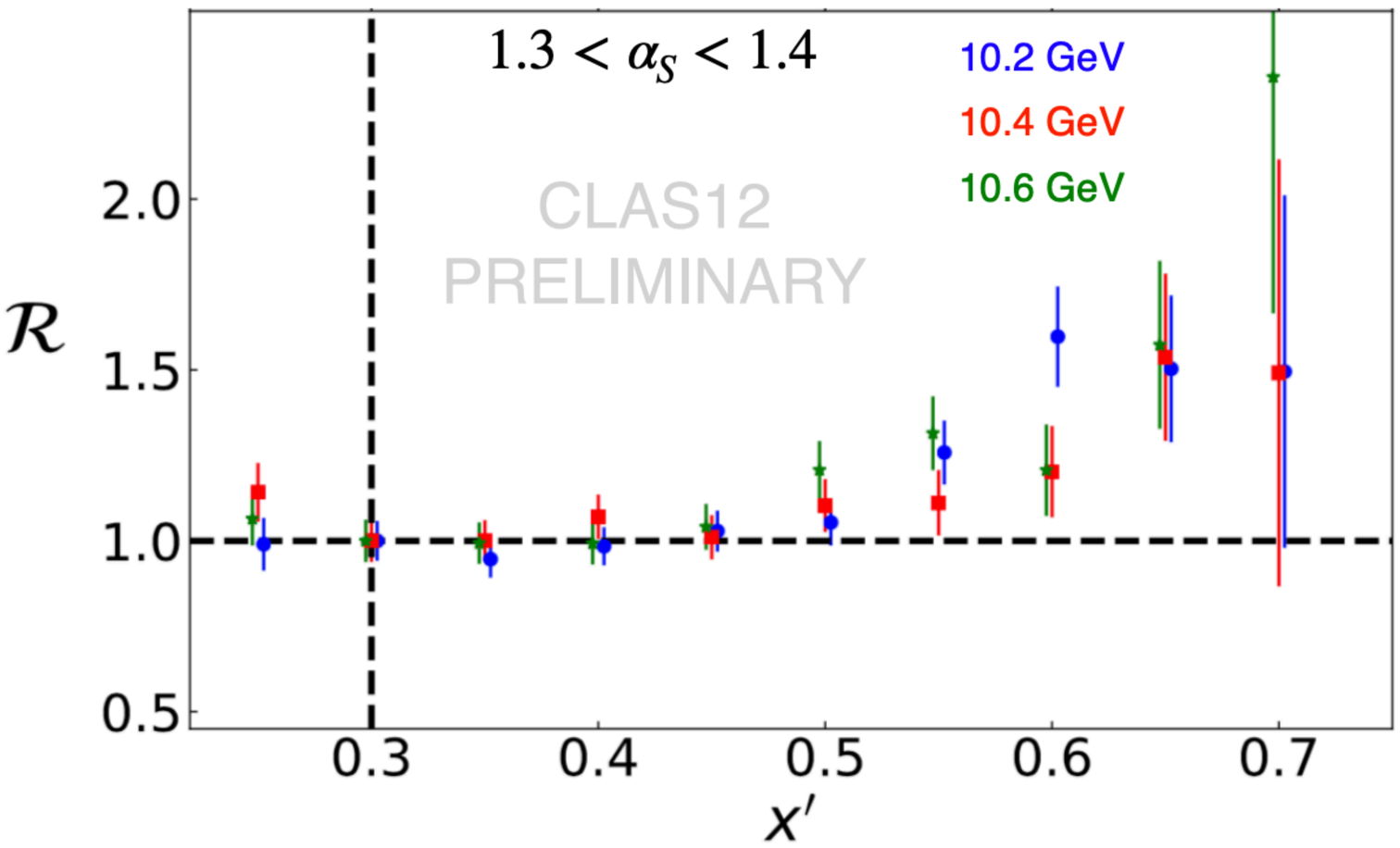



ρ (fm^3)
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.2
0.4
0.6
0.8
1
k (GeV)
Longer distance
Lower momentum
Shorter distance
Higher momentum
^{2}H
BoNuS
BAND

$$R_{\epsilon_n} = \frac{N_{standard}(x')/N_{standard}(x' = x_0)}{N_{reweight}(x')/N_{reweight}(x' = x_0)}$$






$1.3 < \alpha_S < 1.4$
10.2 GeV
10.4 GeV
10.6 GeV
CLAS12
PRELIMINARY
$\mathcal{R}$
2.0
1.5
1.0
0.5
0.3
0.4
0.5
0.6
0.7
x'

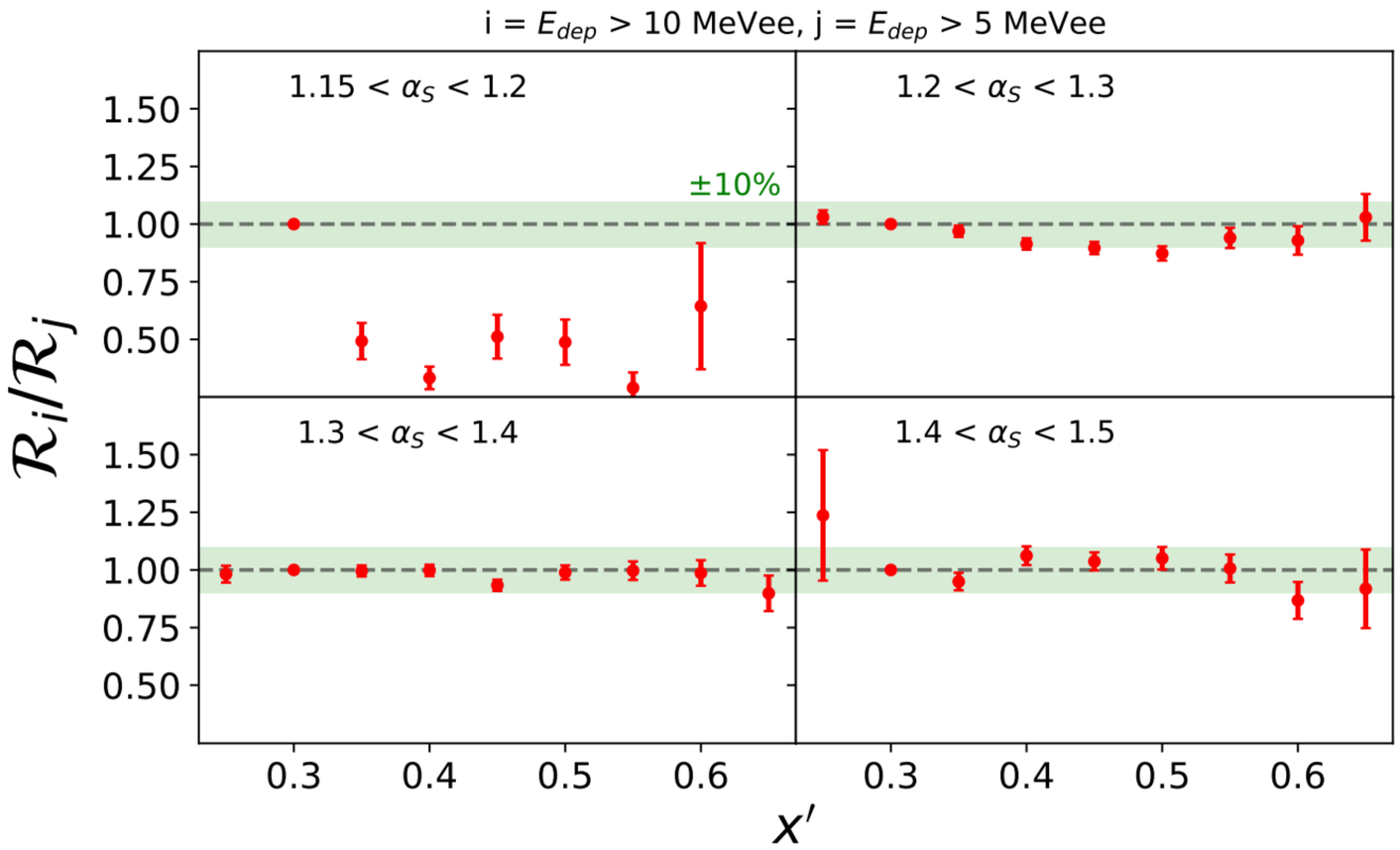


Figure 63: Ratio of the double-ratio for two different E_{dep} cuts. The shaded green band indicates ±10% variation.

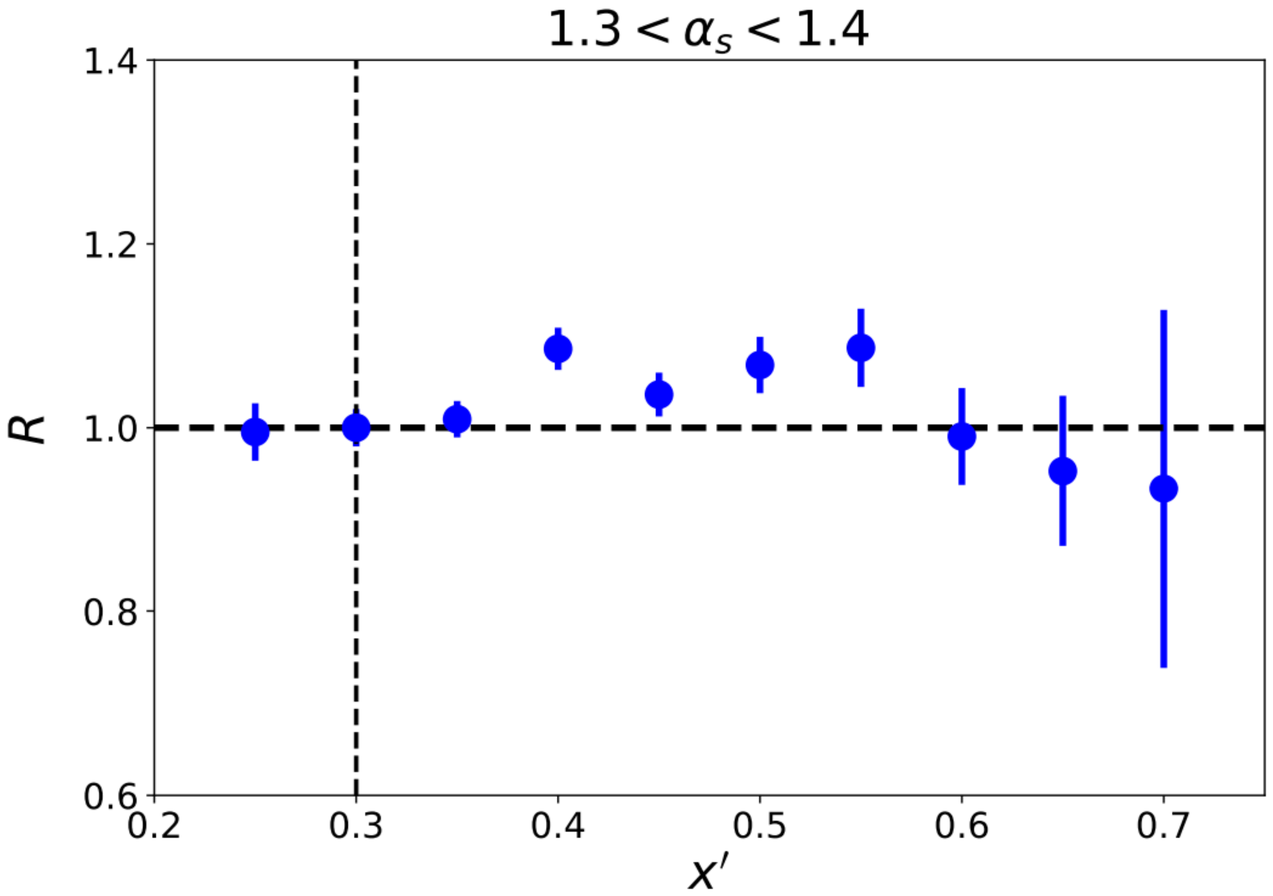
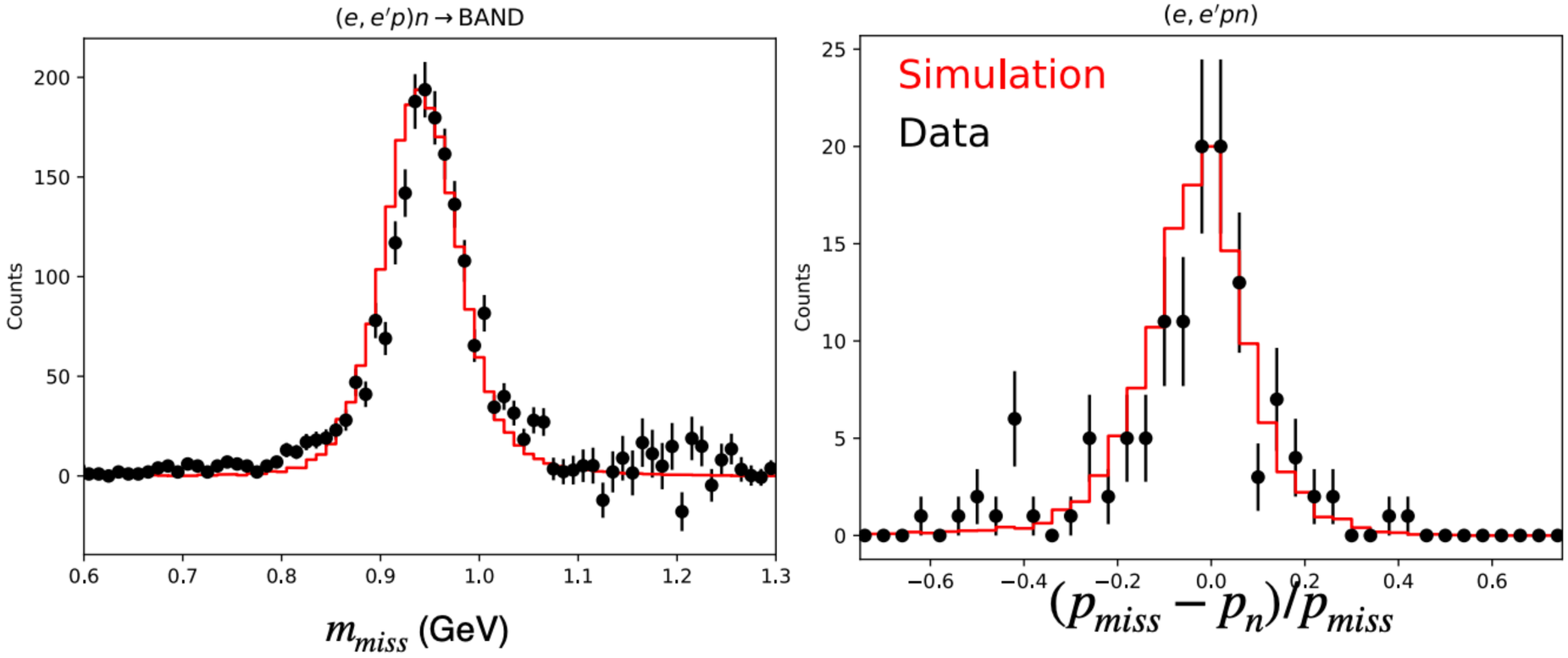


Figure 64: Double ratio comparing simulation double ratio of the finite Q^2 PWIA generator to the asymptotic $Q^2 \to \infty$ PWIA generator.

QE (3.1 GeV) d(e,e'p)n and d(e,e'pn)

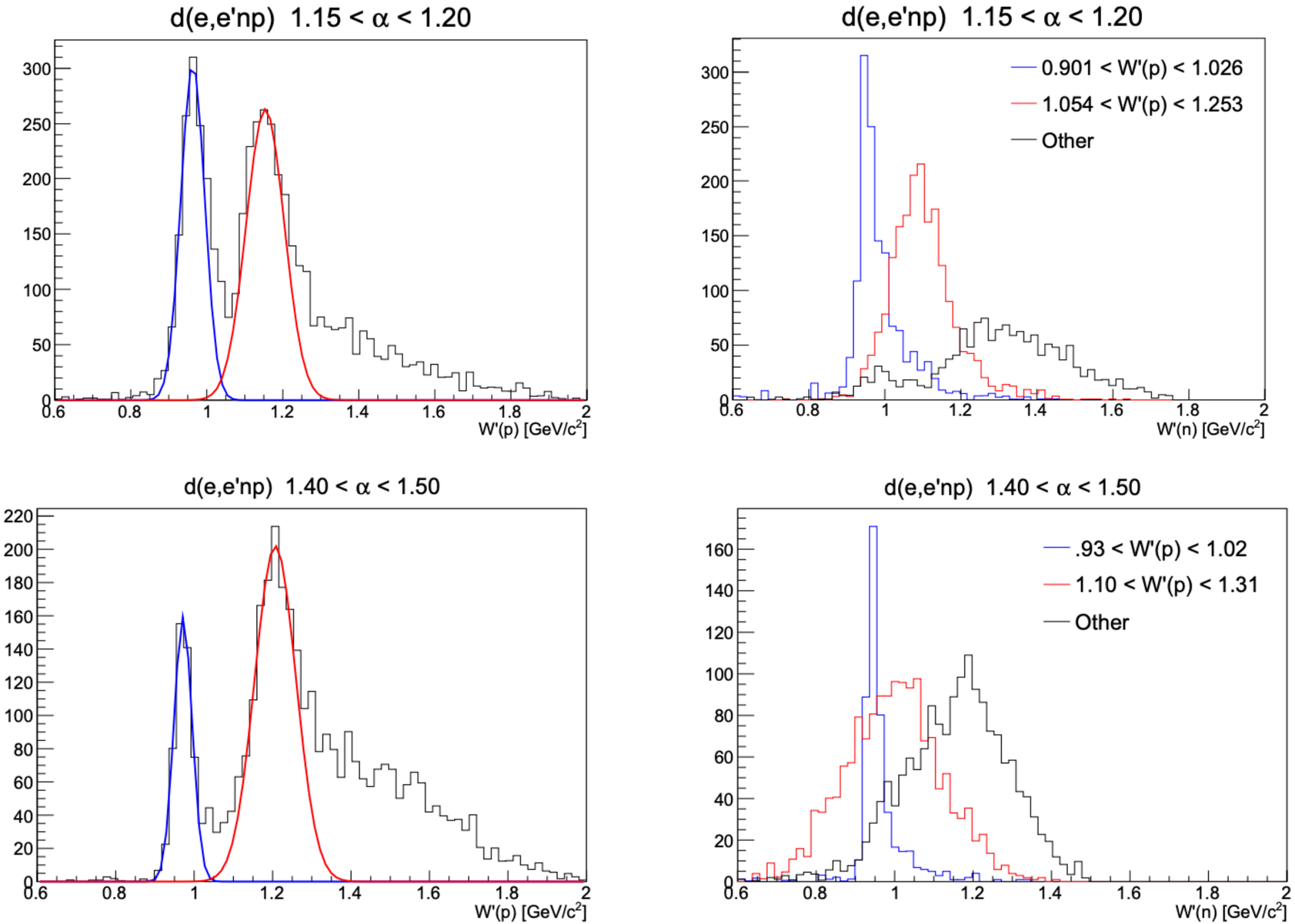


QE (2 GeV) d(e,e'pn)

From RGM LD2

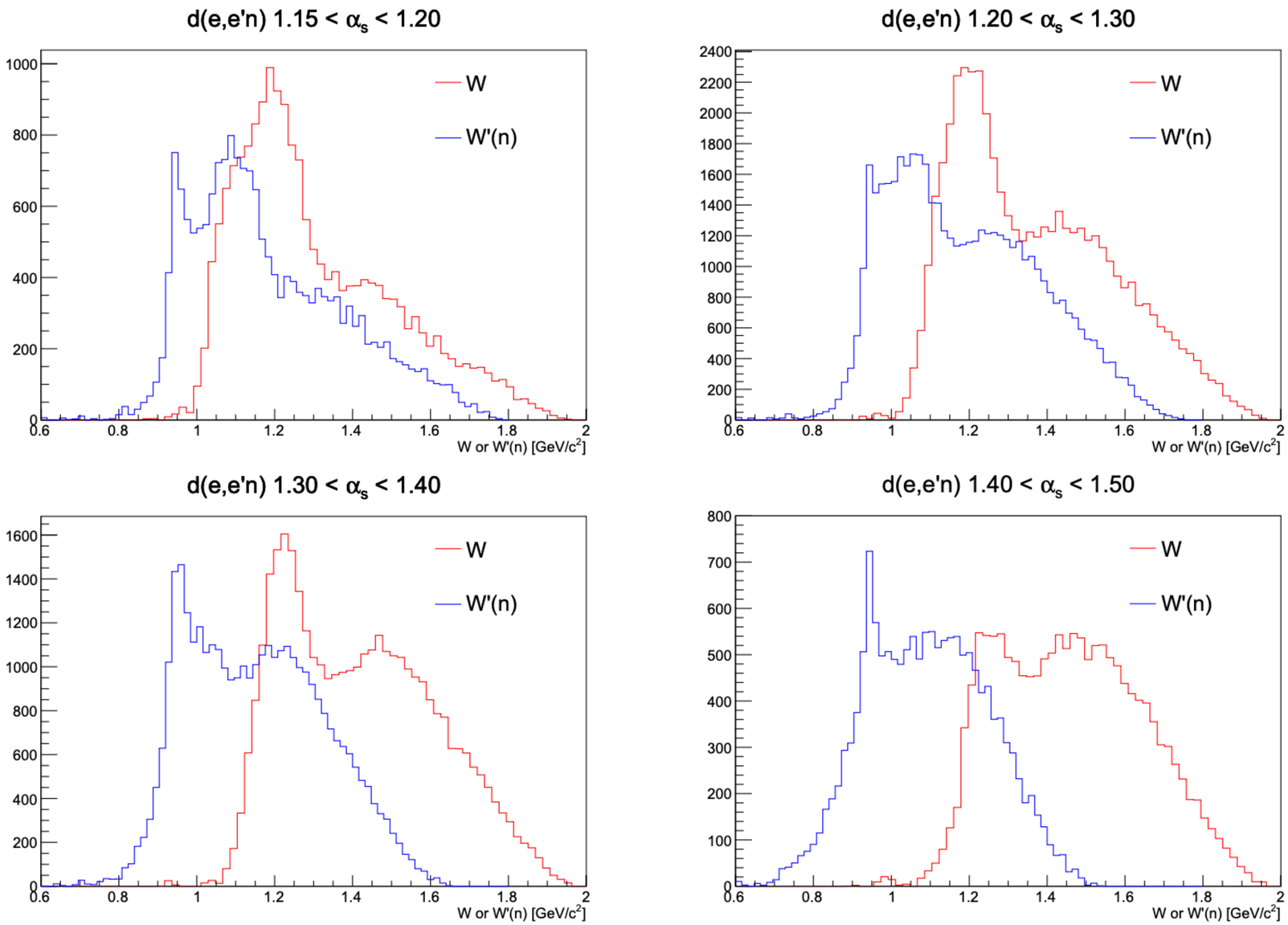
$$M(d+q-p)$$

$$M(d+q-n)$$

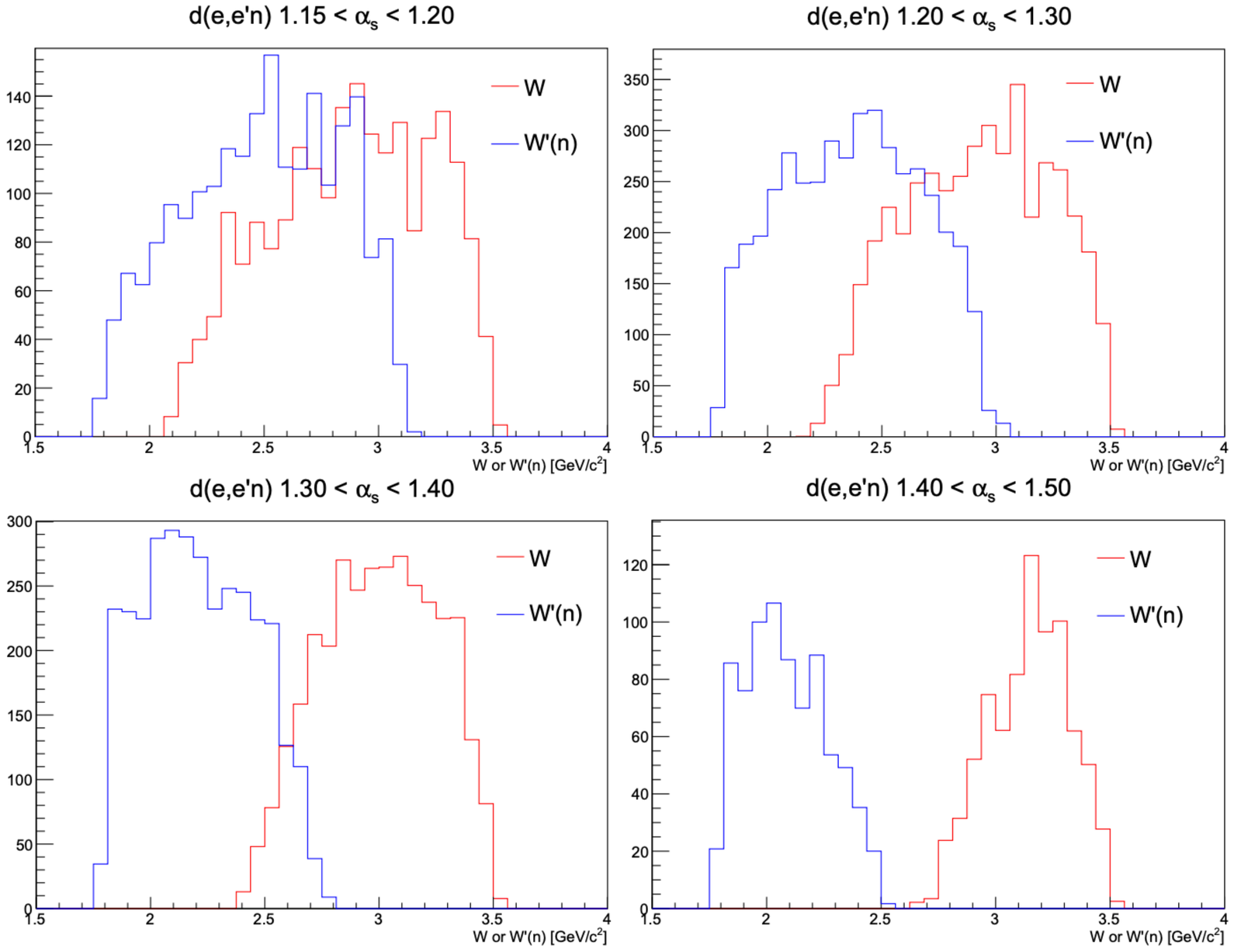


QE (2 GeV) d(e,e'pn)

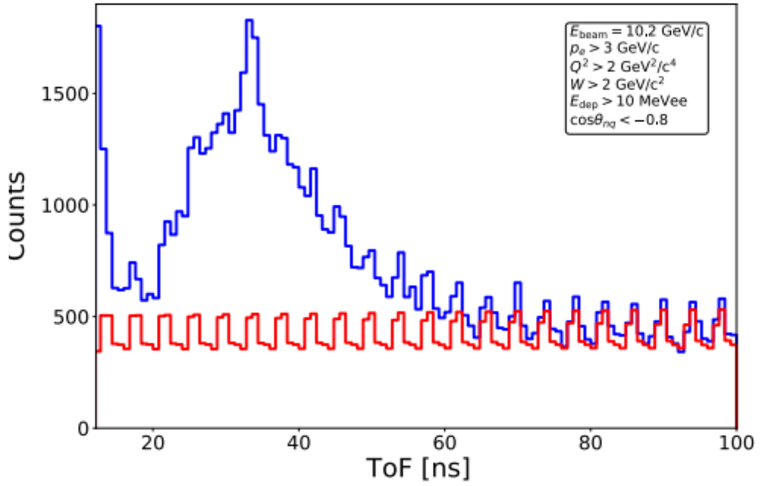
From RGM LD2



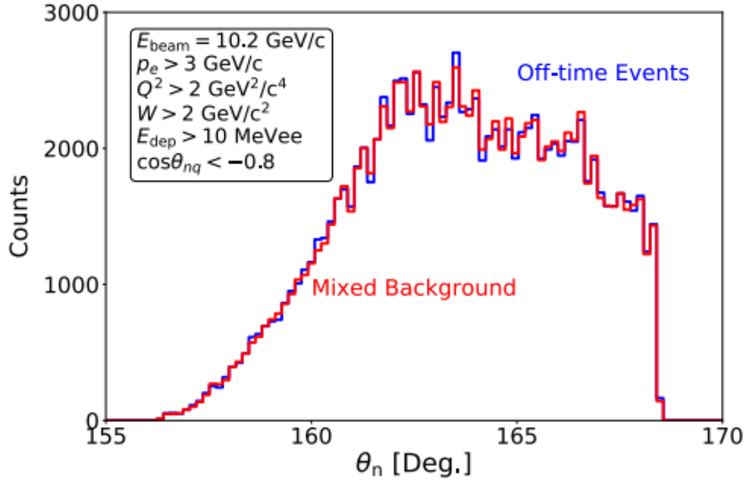
From BAND DIS LD2

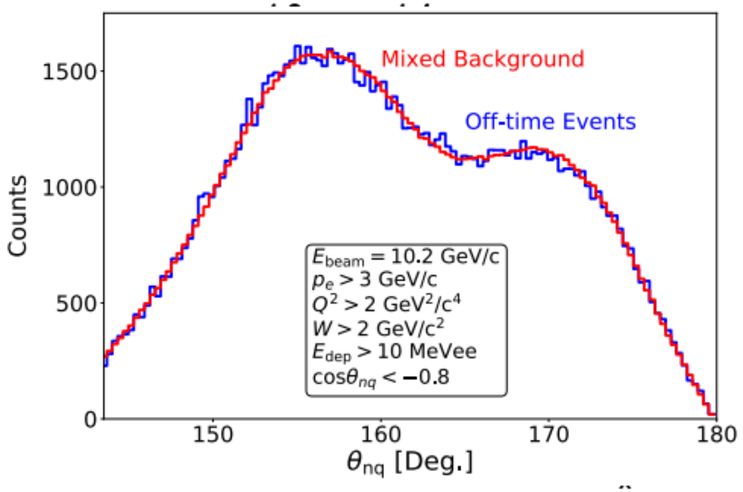


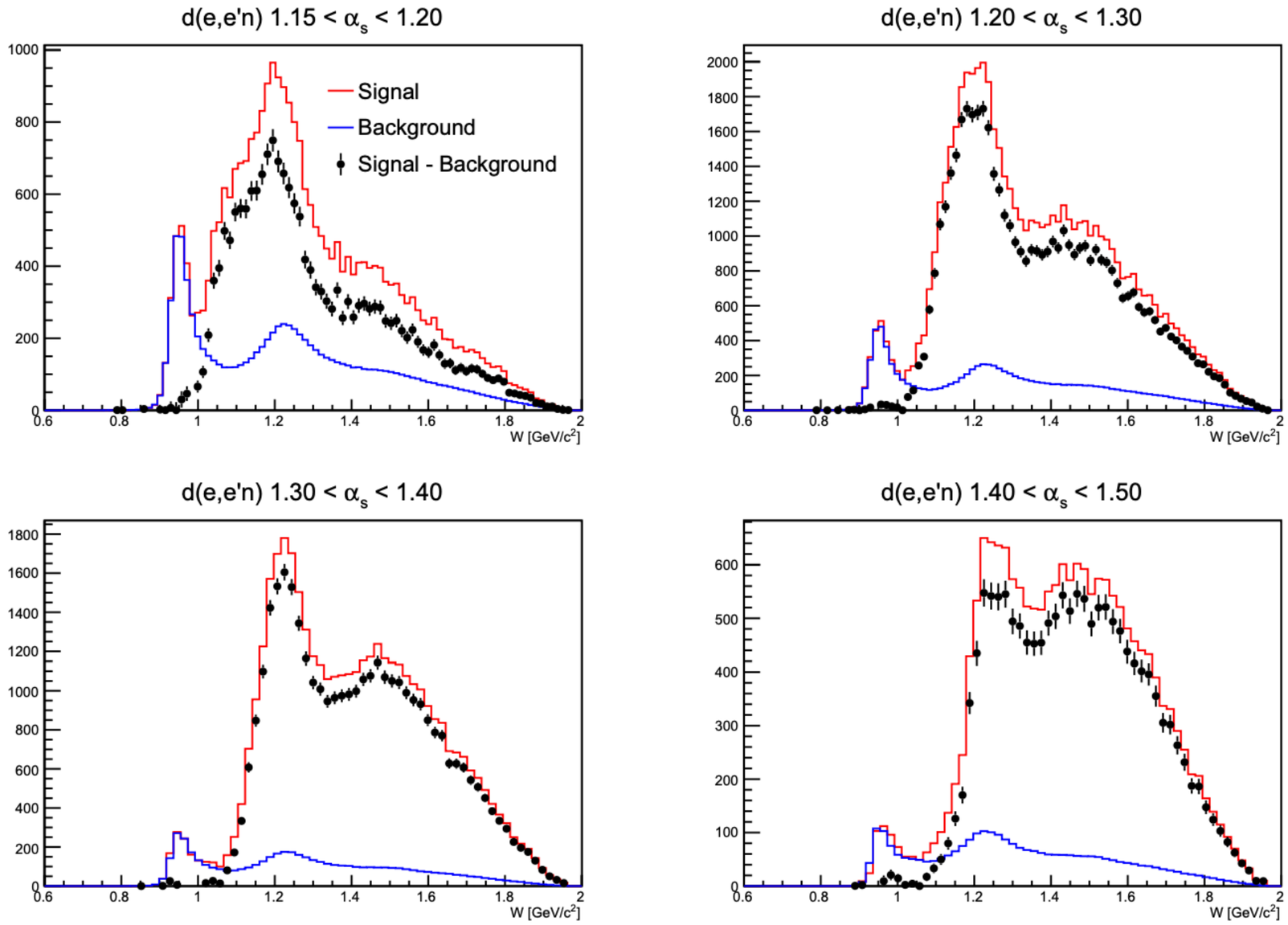
Random Coincidence Background Subtraction



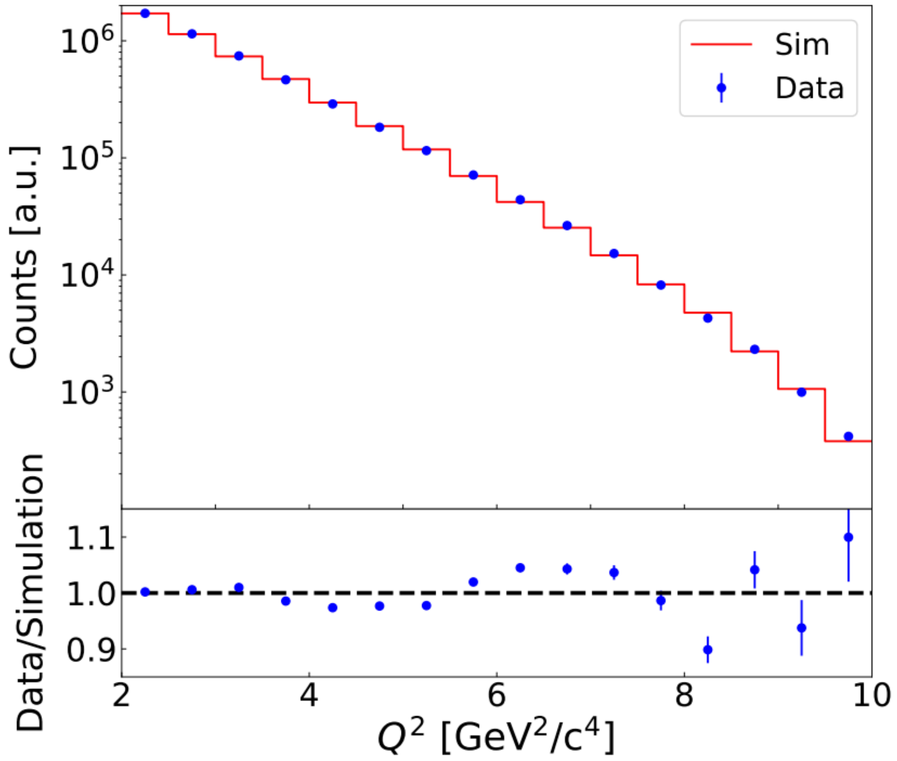
- Event mixing for background subtraction
- Account for beam structure
- Simulation closure test
- Offtime/event mixed consistency

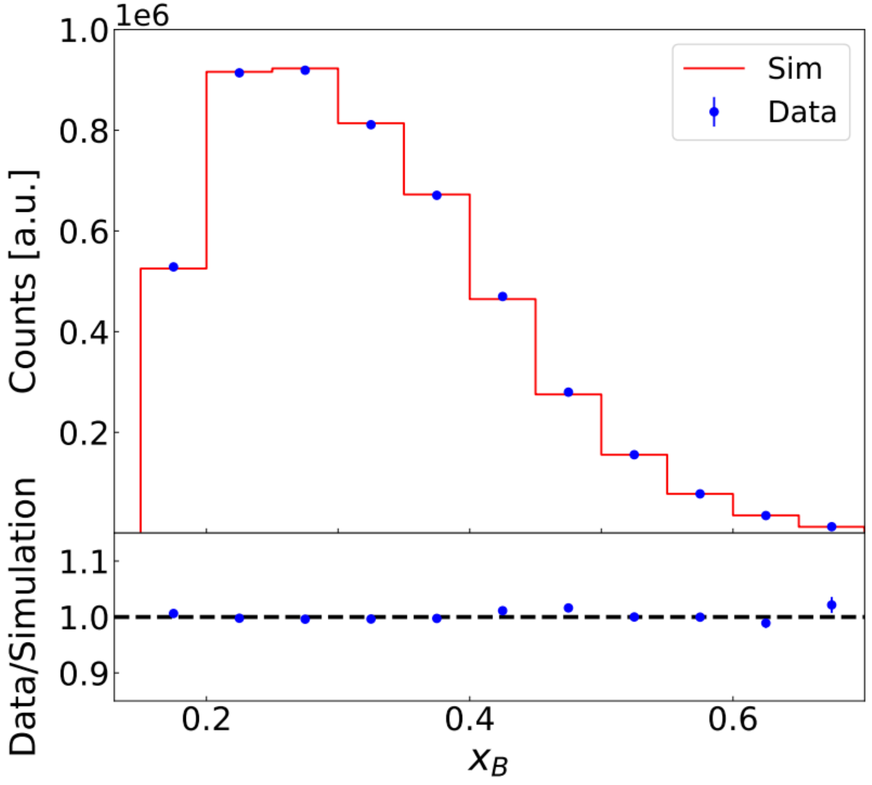





d(e,e'n) 1.15 < α_s < 1.20
Signal
Background
Signal - Background
W [GeV/c^2]
d(e,e'n) 1.20 < α_s < 1.30
W [GeV/c^2]
d(e,e'n) 1.30 < α_s < 1.40
W [GeV/c^2]
d(e,e'n) 1.40 < α_s < 1.50
W [GeV/c^2]

Inclusive Analysis





Tagged Analysis

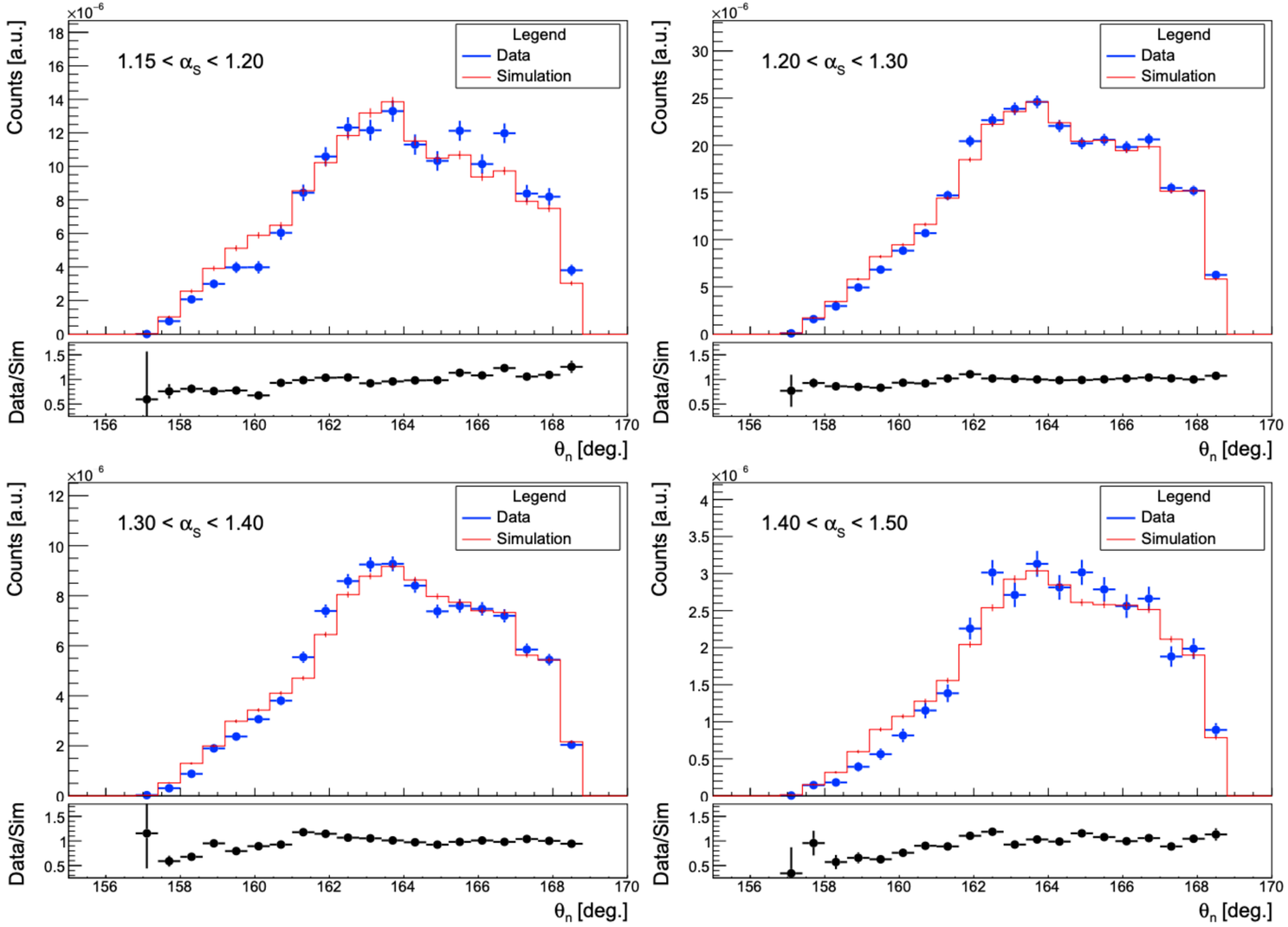


Figure 86: Comparison of θ_n between data and GEMC in bins of α_S.

- Data driven approach
- Modification of F_2 by np-SRC pairs (neglect nn and pp pairs)

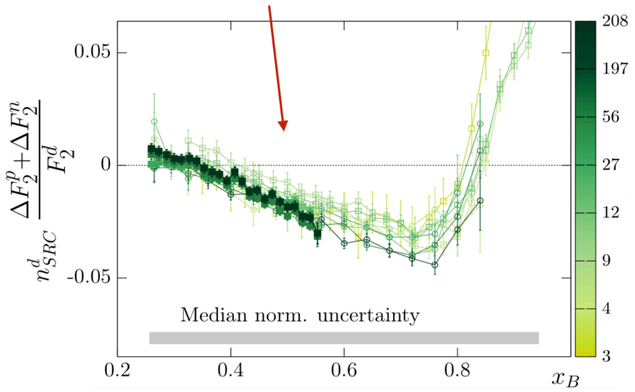
$$F_2^A = ZF_2^p + NF_2^n + n_{SRC}^A(\Delta F_2^p + \Delta F_2^n)$$

Bound = ``Quasi-free“ + Modified SRC

F_2^n not well constrained but solve by

- $F_2^d = F_2^p + F_2^n + n_{SRC}^d(\Delta F_2^p + \Delta F_2^n)$
- $a_2 = \frac{2}{N} n_{SRC}^A / n_{SRC}^d$

$$n_{SRC}^d \frac{\Delta F_2^p + \Delta F_2^n}{F_2^d} = \frac{\frac{F_2^A}{F_2^d} - (Z-N)\frac{F_2^p}{F_2^d} - N}{\frac{A}{2}a_2 - N}$$

Universal function

Nucleus Dependent