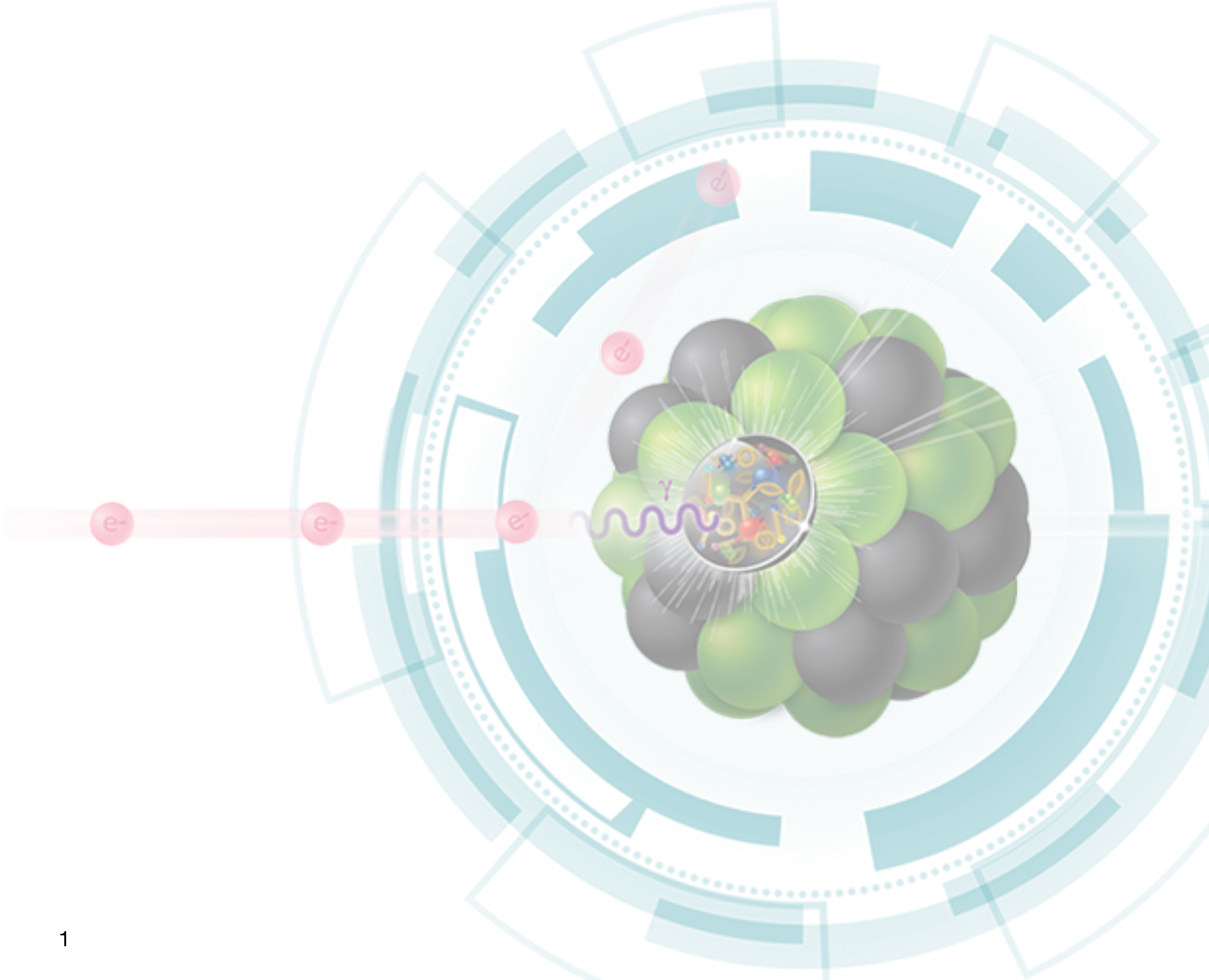
ML-Enhanced Neutron Detection for SRC Measurements

Natalie Wright (MIT)



EINN 2025

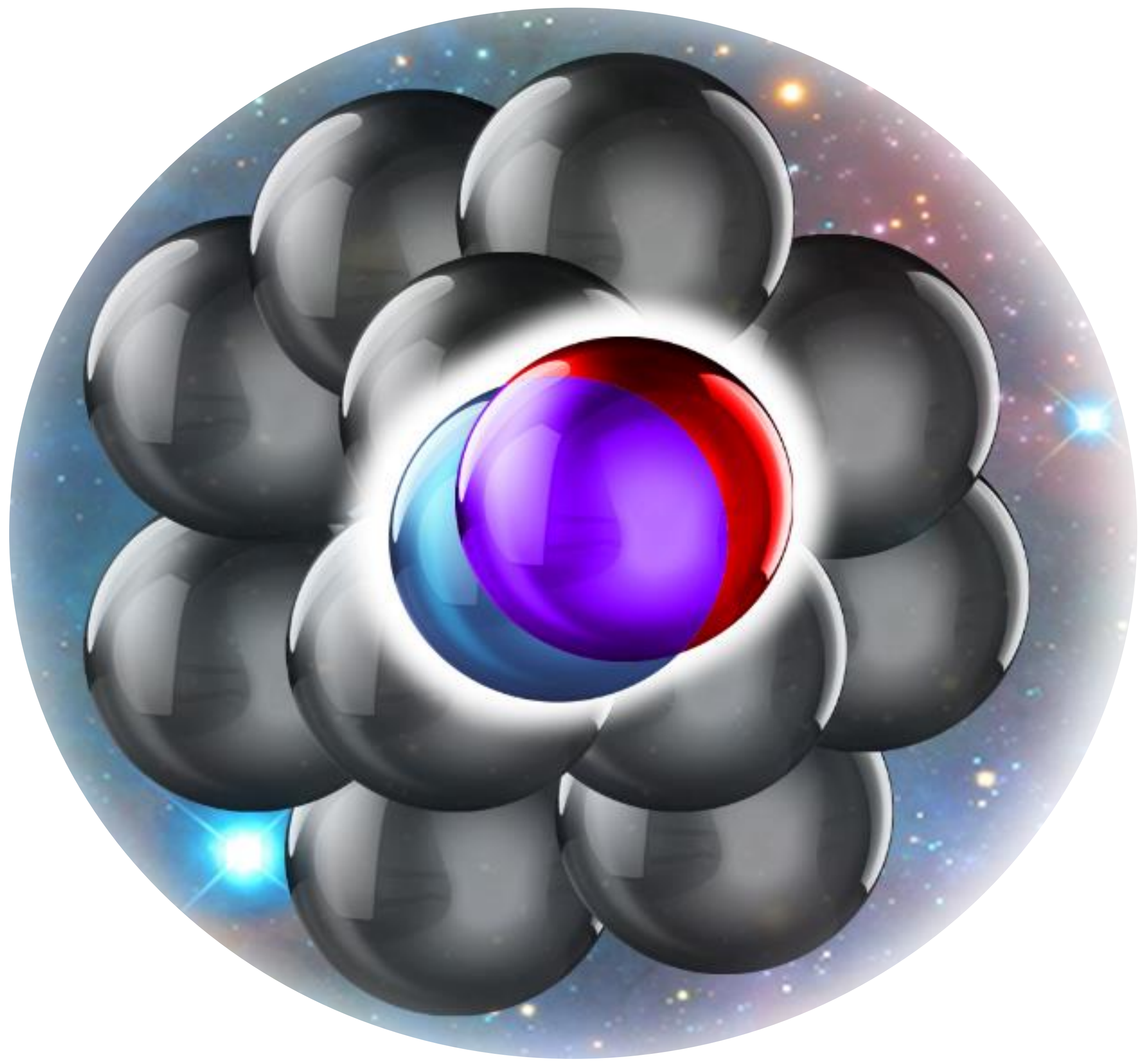
Short Range Correlated Nucleons

Nucleon pairs* with:

Small spatial separation

High relative and low CM momentum compared to k_F

Significant contribution to nuclear momentum distribution $p > k_F$



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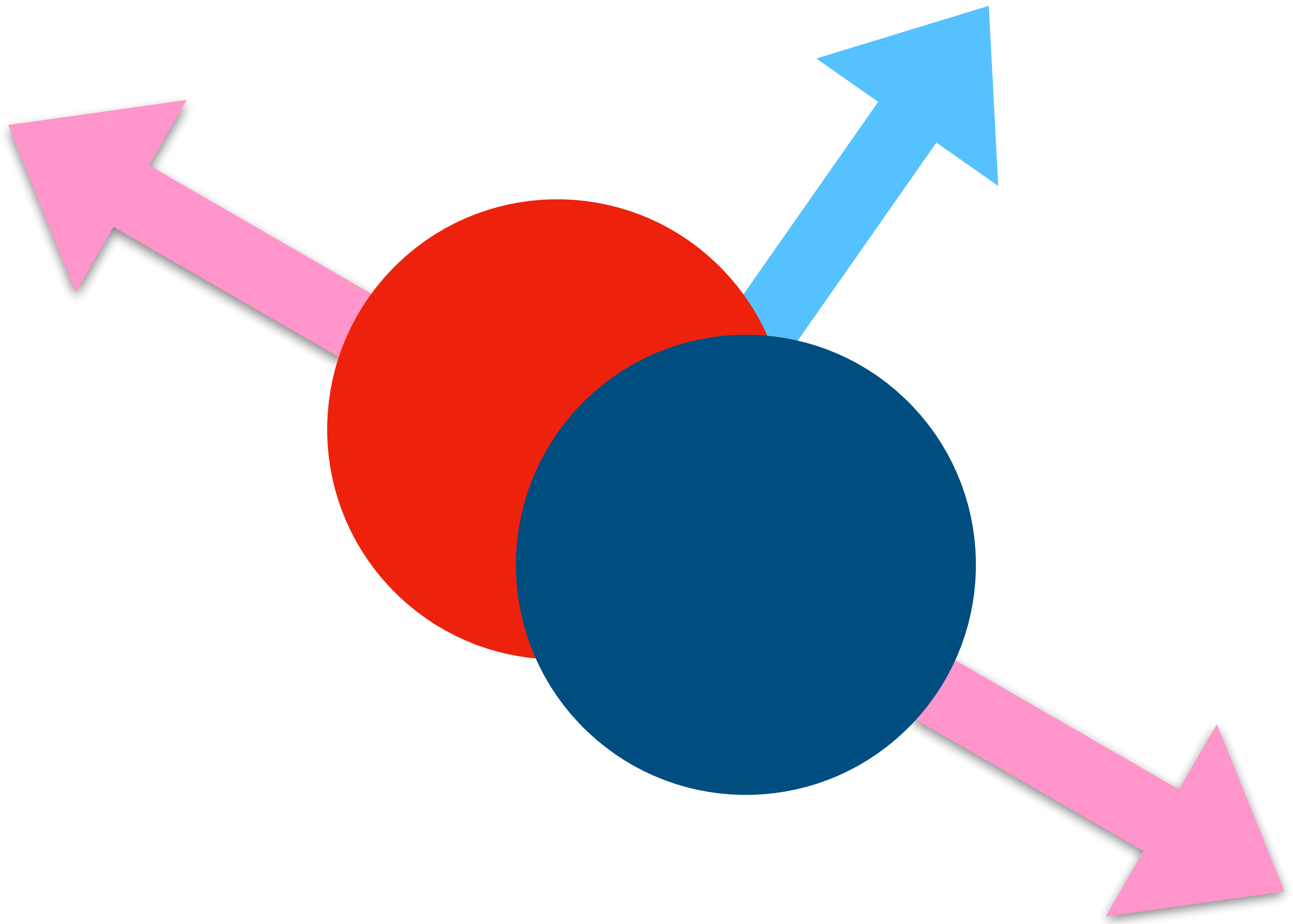

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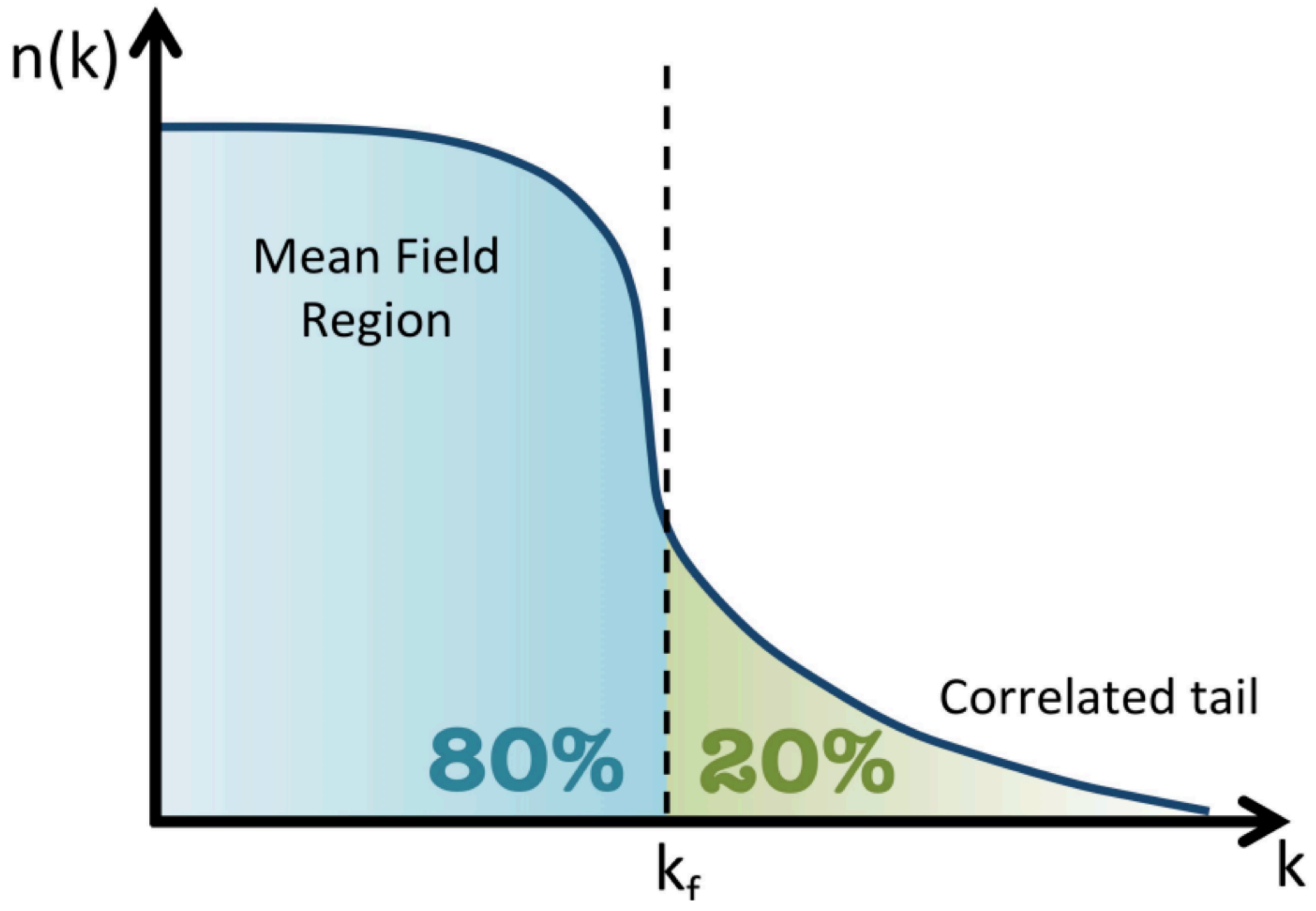
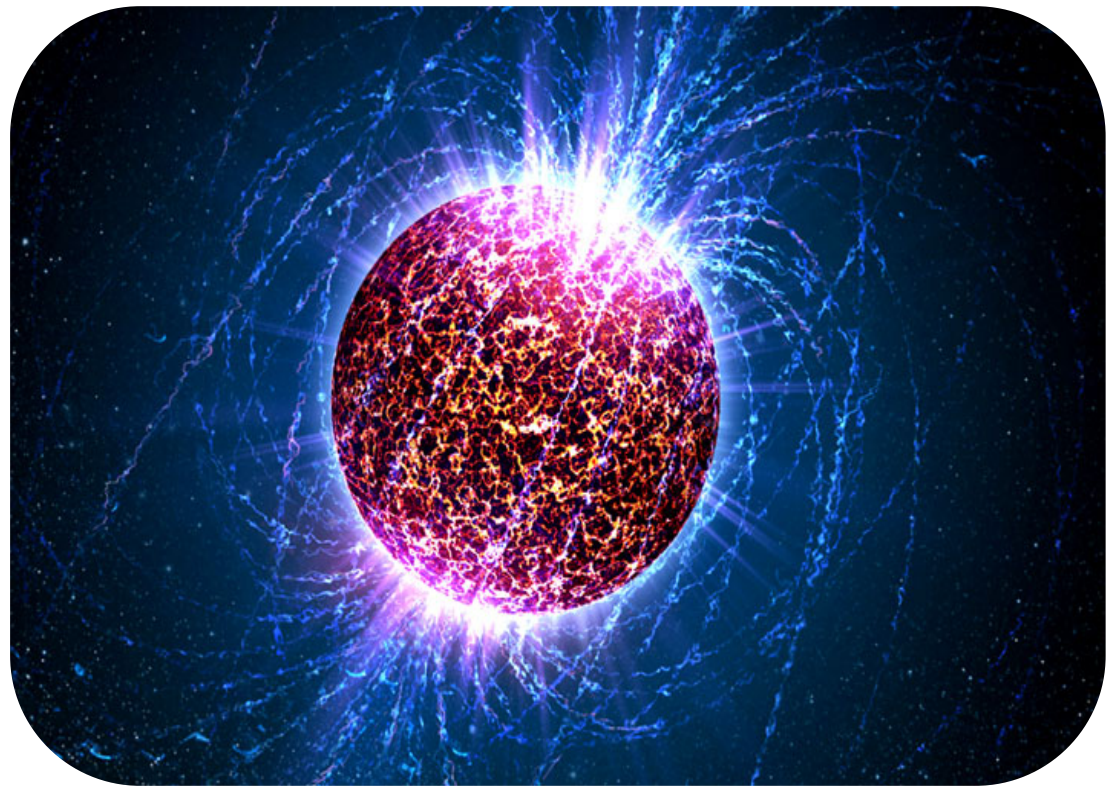
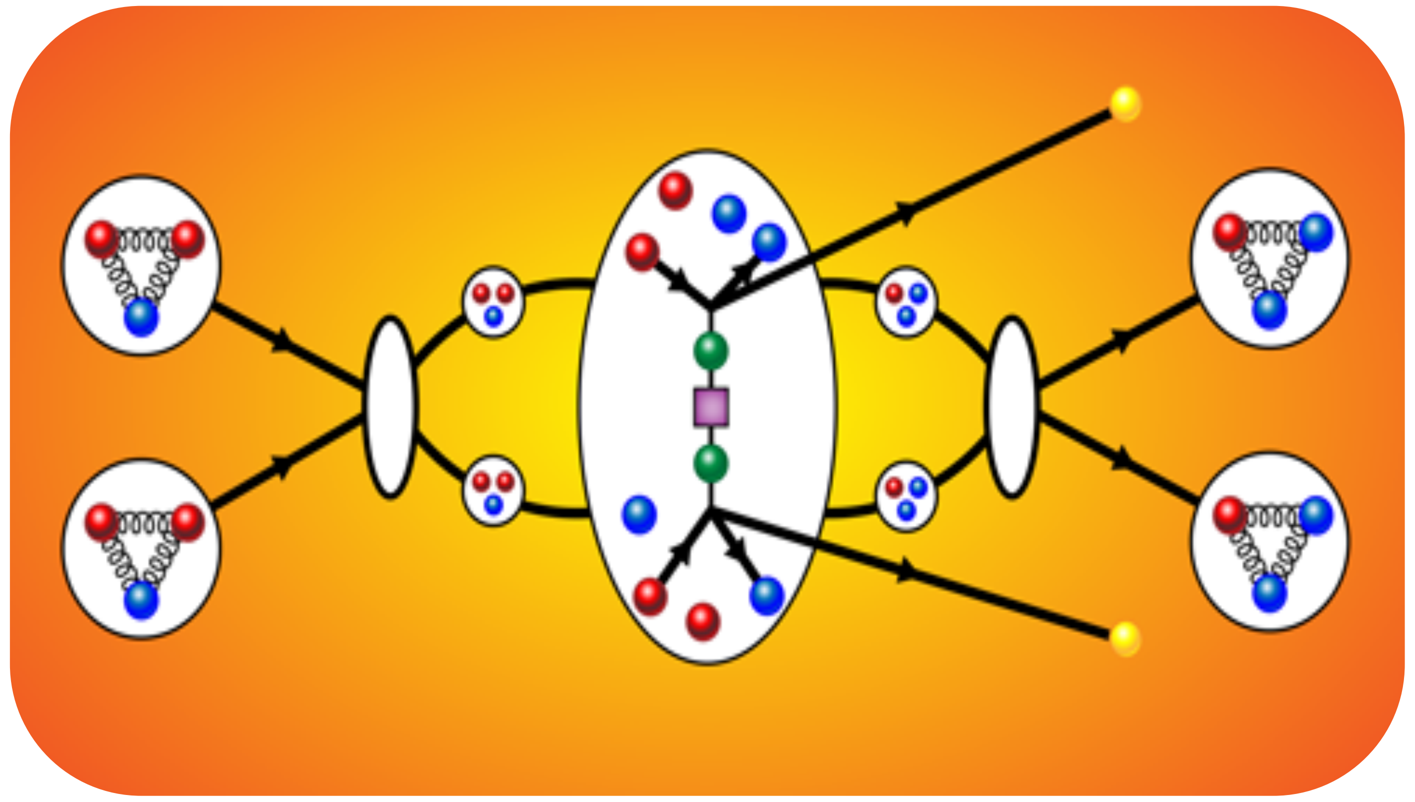


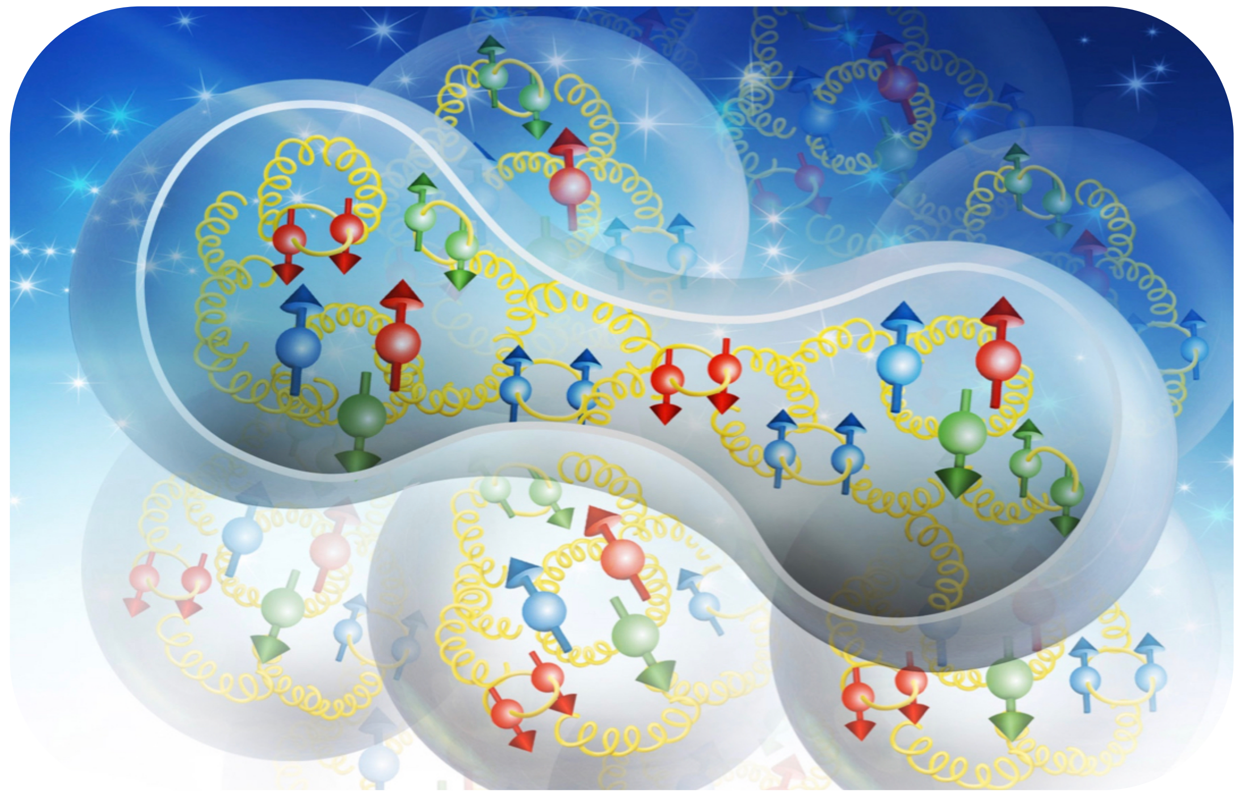
SRCs required to fully describe nuclear systems and processes



High-density systems

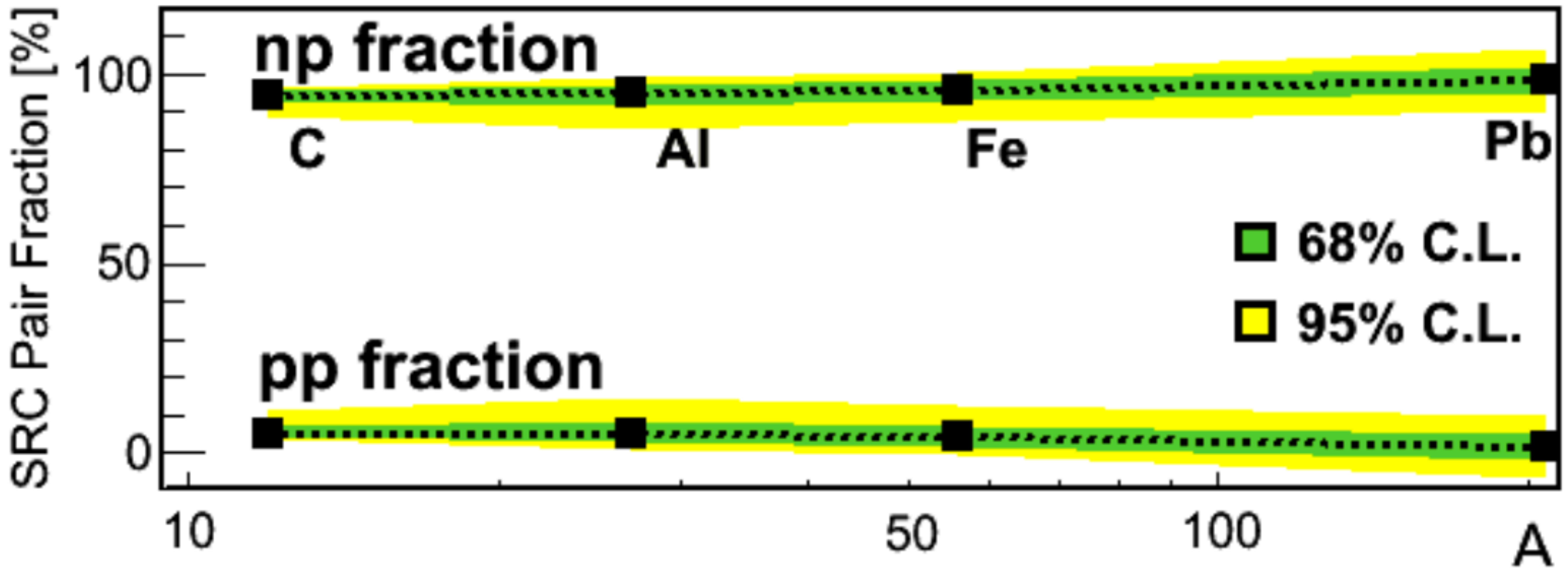


Nuclear processes

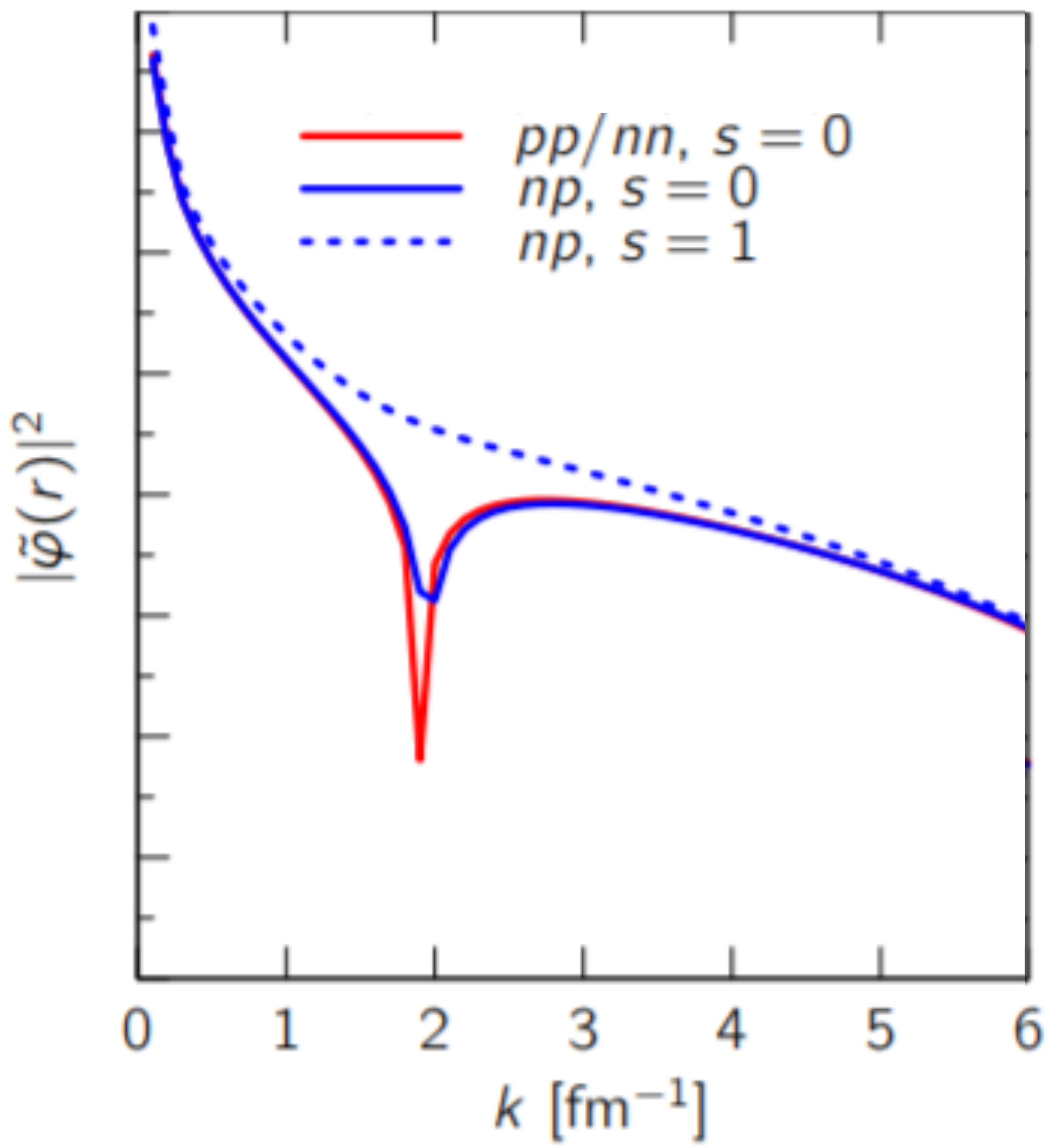


NN interactions and QCD in nuclei

SRC isospin properties sensitive to NN interaction

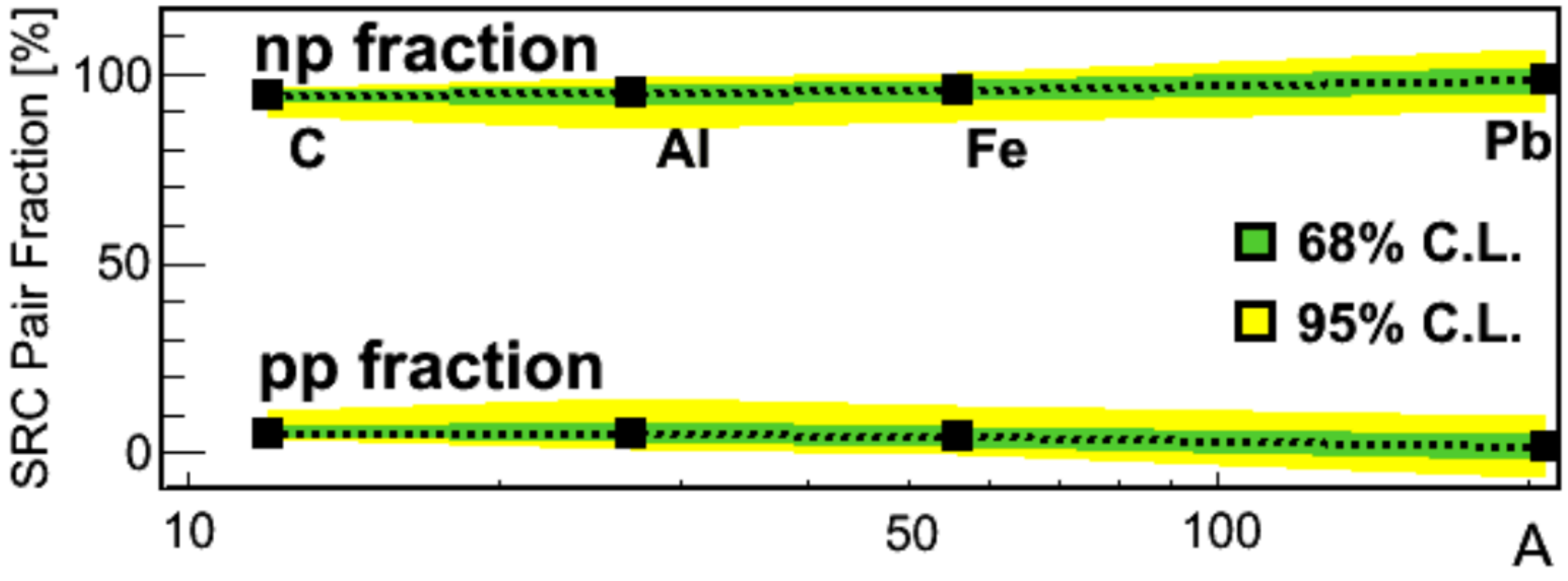


O. Hen et al., Science 364 (2014) 614



np pair dominance → SRCs predominately in S = 1 state

SRC isospin properties sensitive to NN interaction



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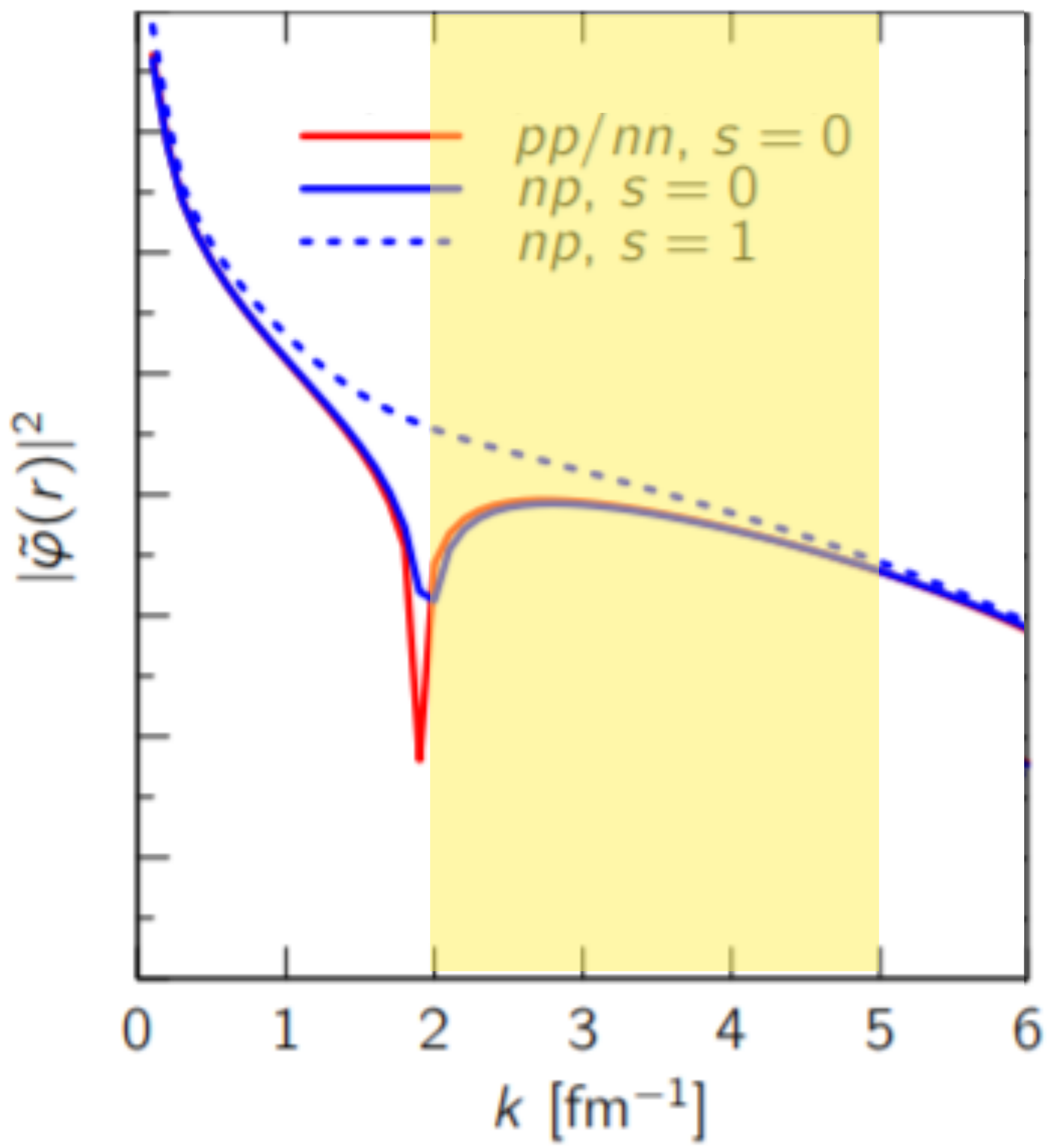
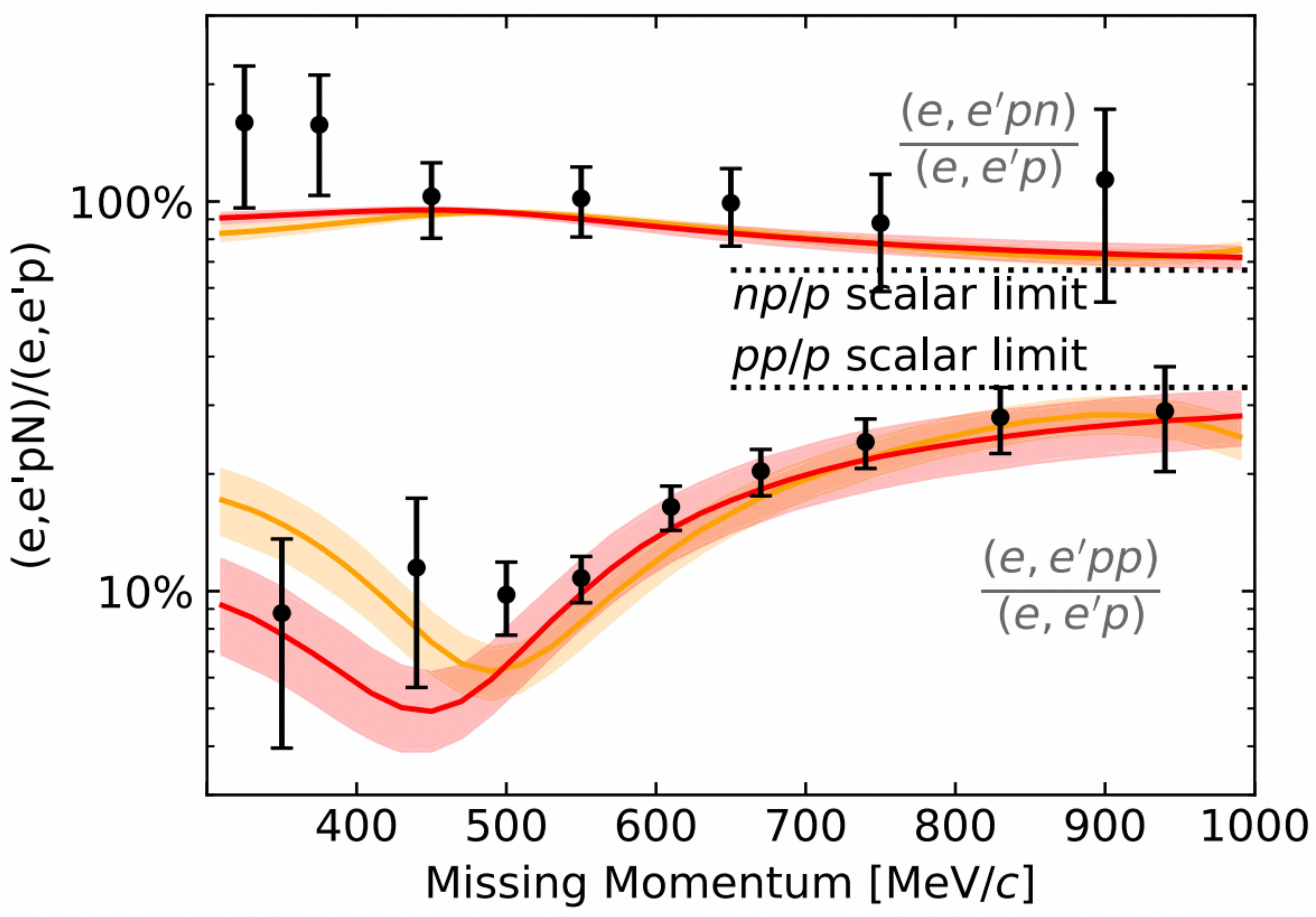
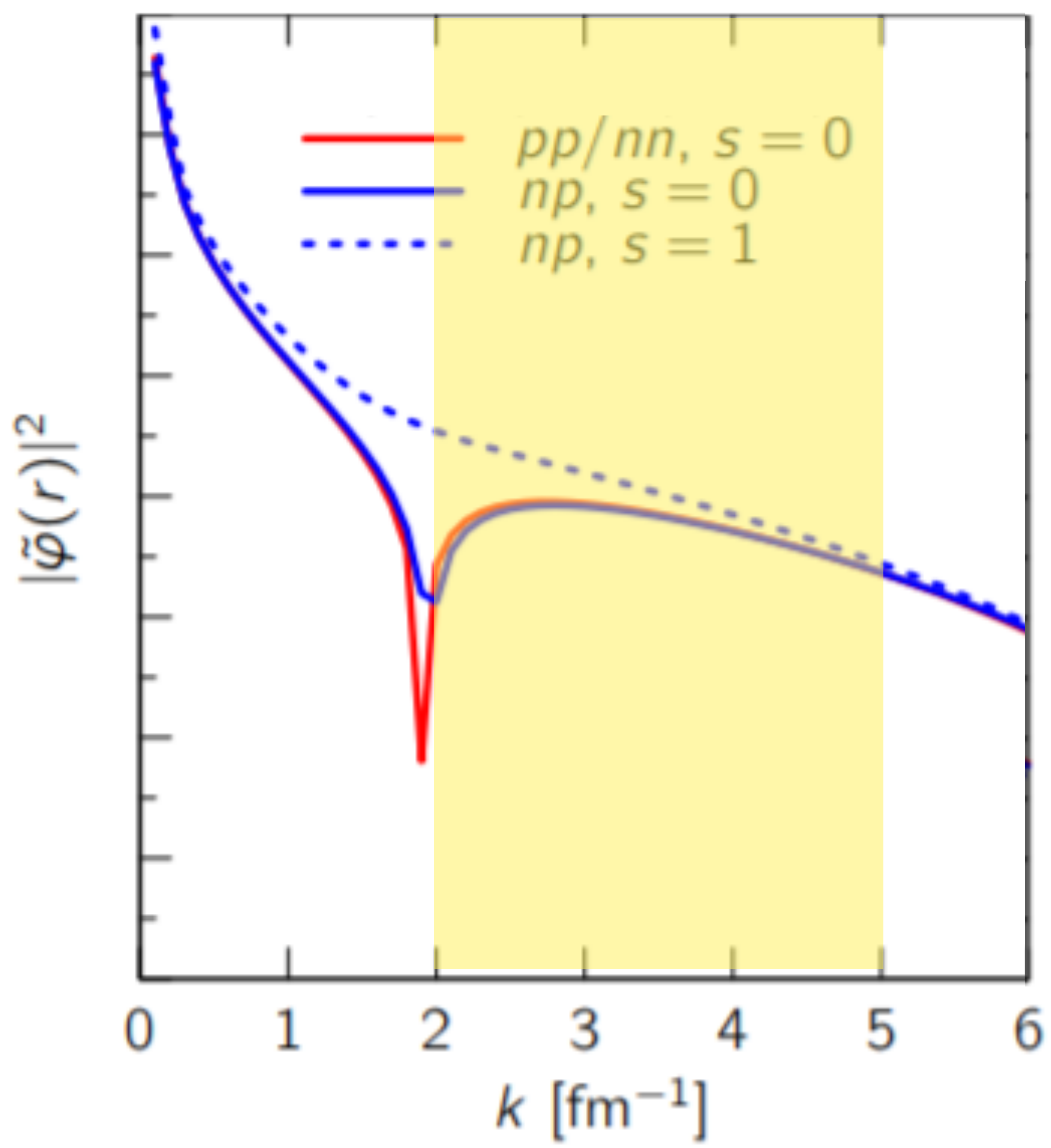


np pair dominance → SRCs predominately in S = 1 state

Can use exclusive measurements to map the tensor to scalar transition

SRC isospin properties sensitive to NN interaction



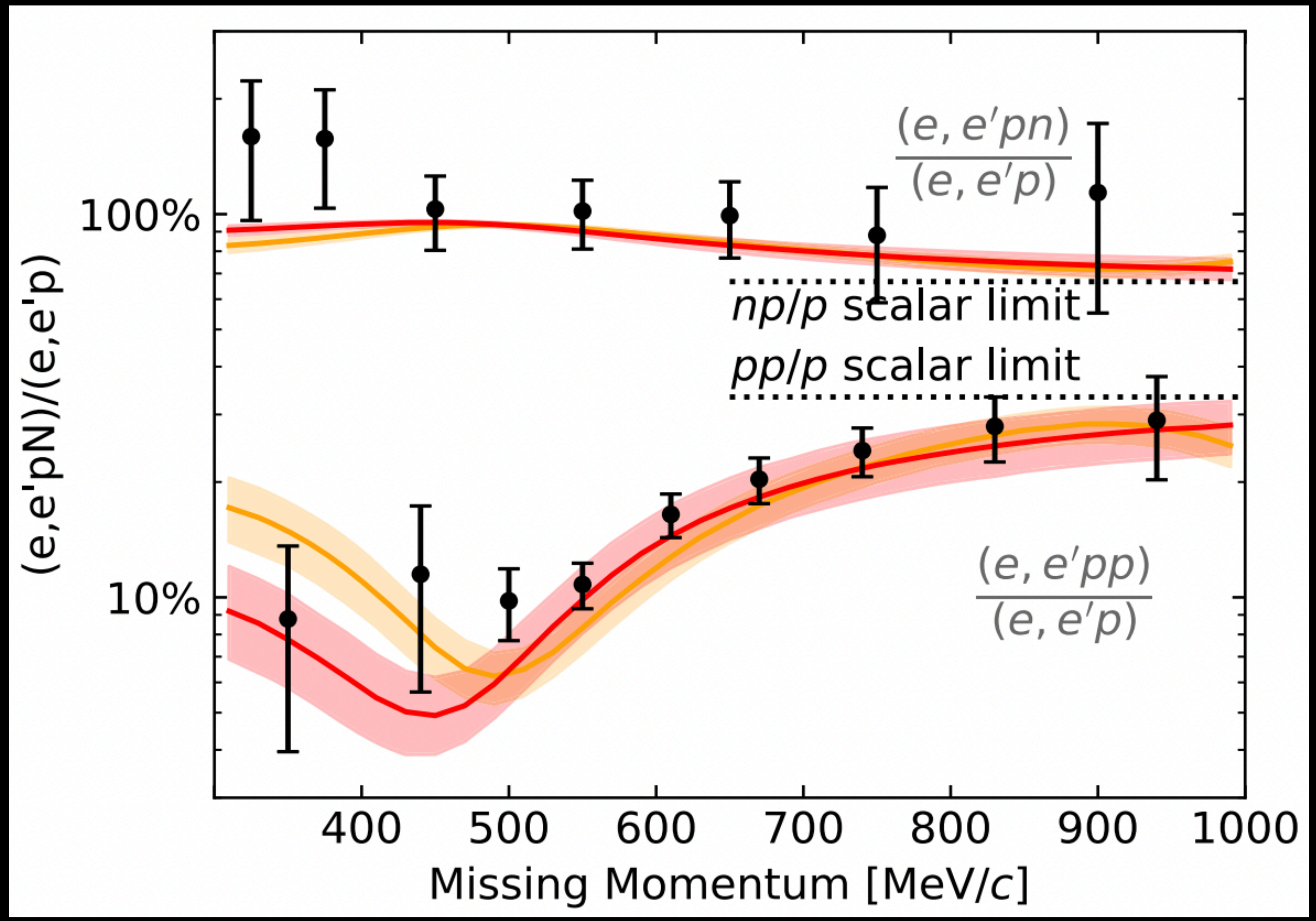


I. Korover *et al.* (CLAS Collaboration), Physics Letters B **820** (2021) 136523.

SRC isospin structure sensitive to NN interaction

What I'd like to address:

1. High 2N statistics for model comparison



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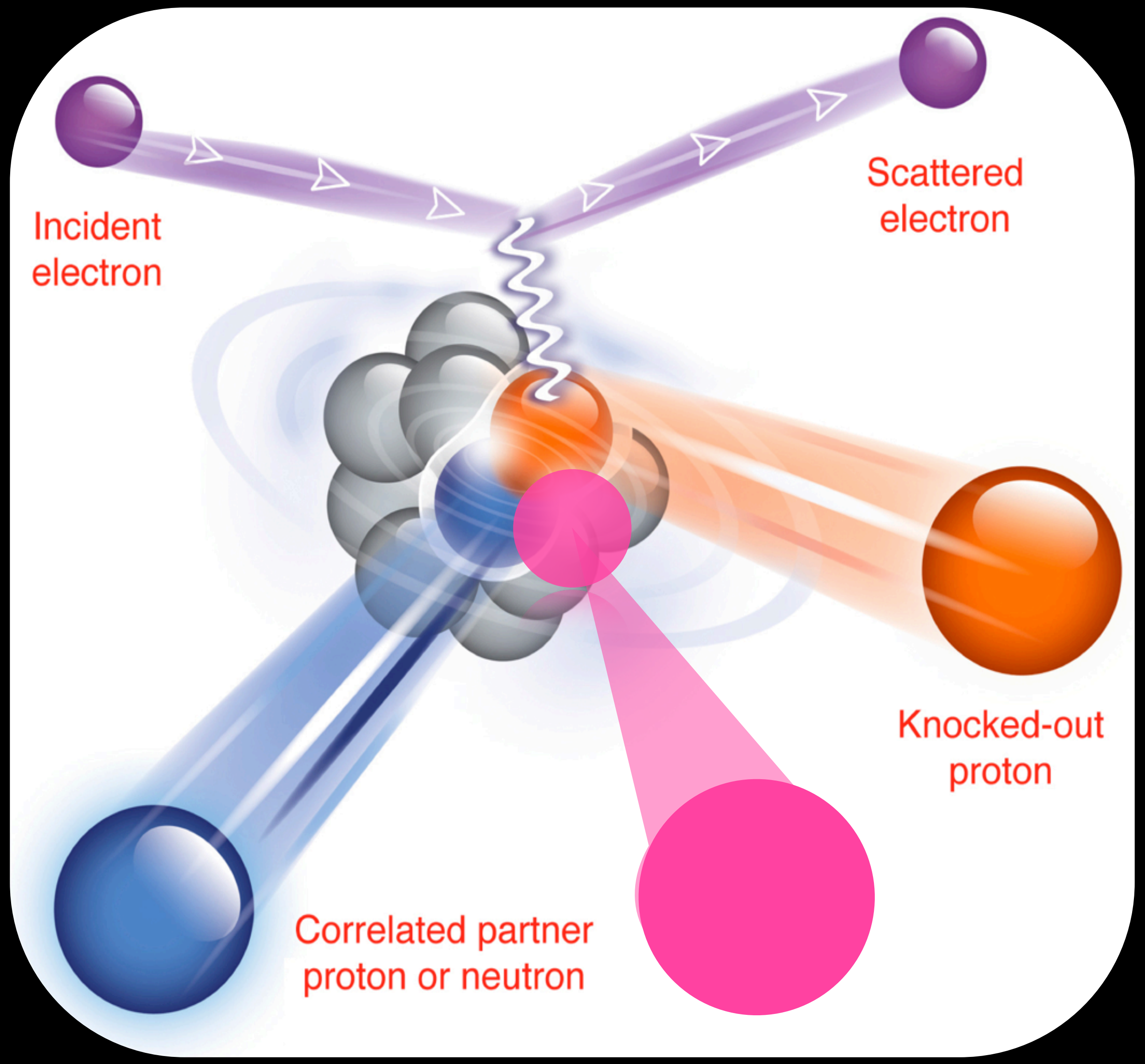
SRC isospin structure sensitive to NN interaction

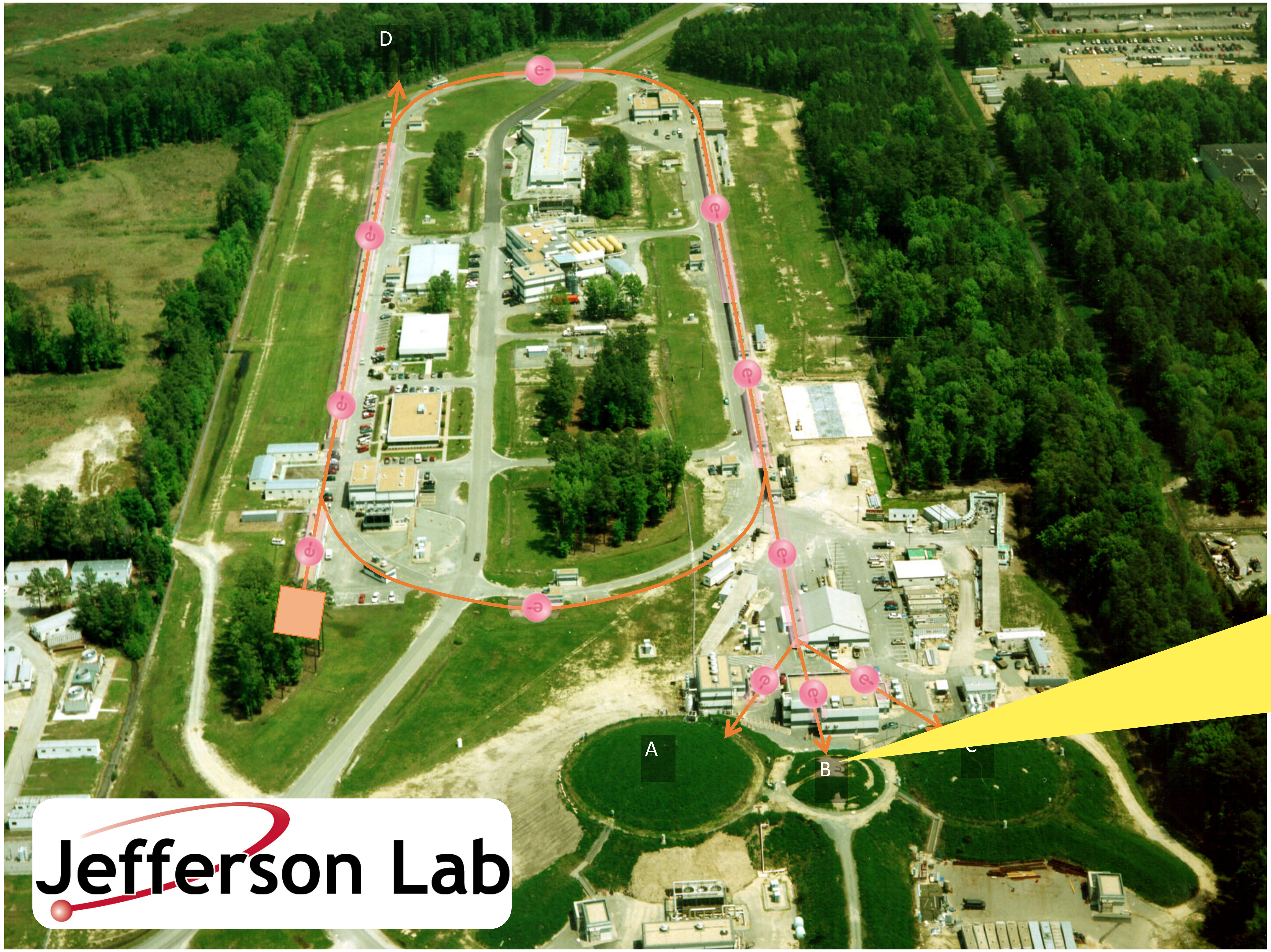
What I'd like to address:

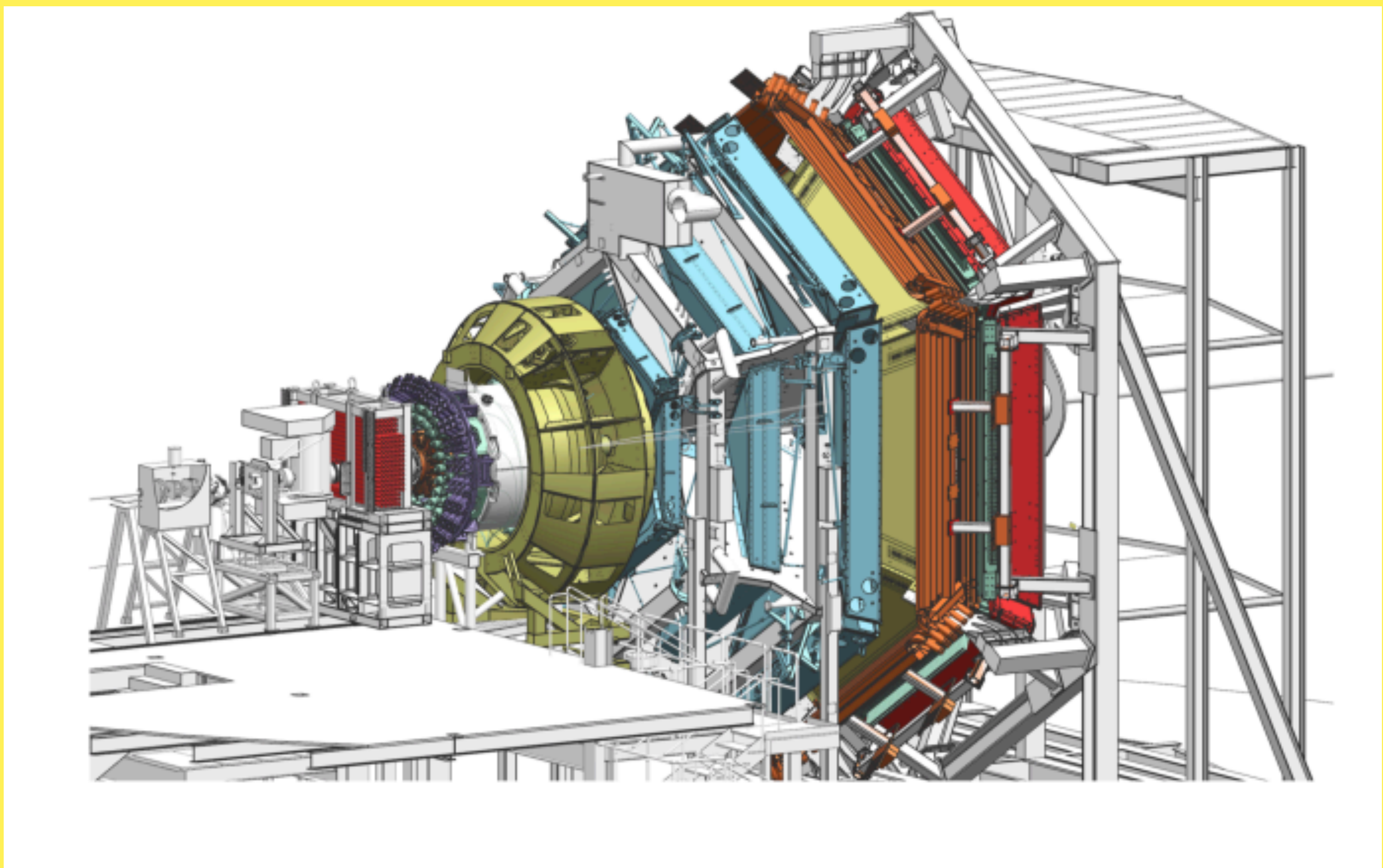
1. High 2N statistics for model comparison

2. PID and statistics for 3N measurement



Today: Electron Scattering at JLab (Hall B)





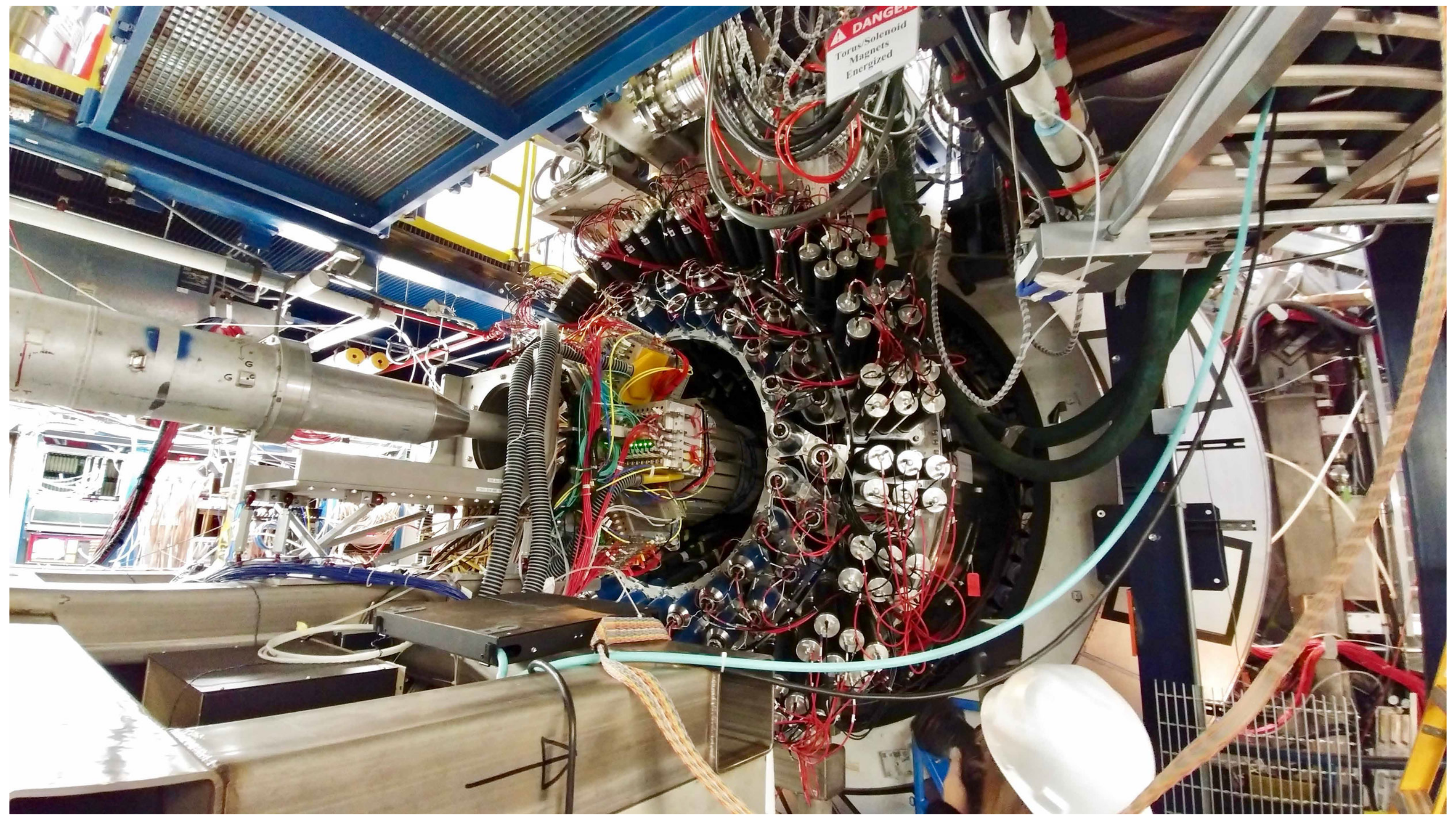
RGM for Exclusive SRC Studies

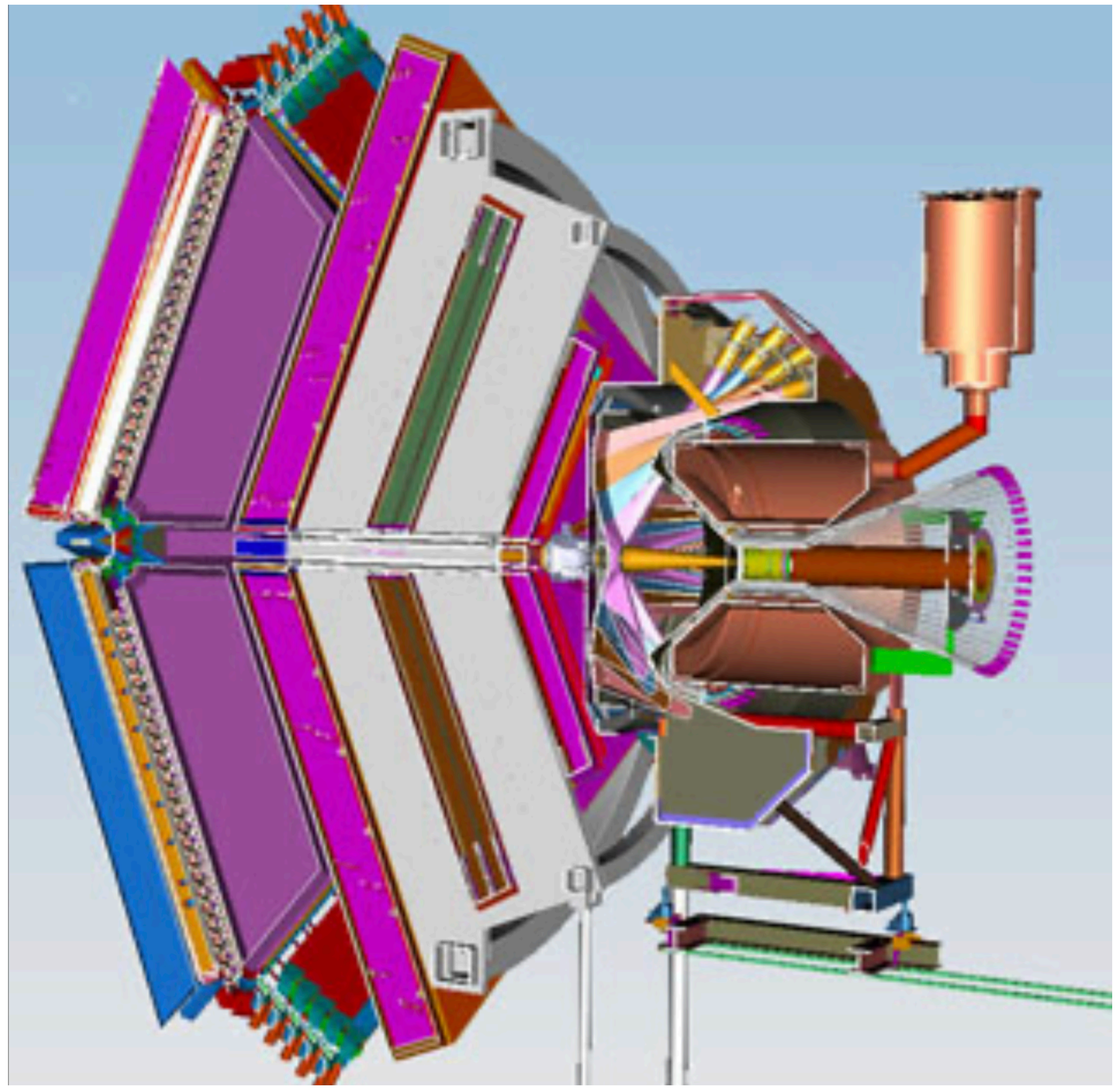
Ran Nov 2021-Feb 2022

2, 4, 6 GeV beam energies

Targets: H, D, ^{4}He, ^{12}C

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





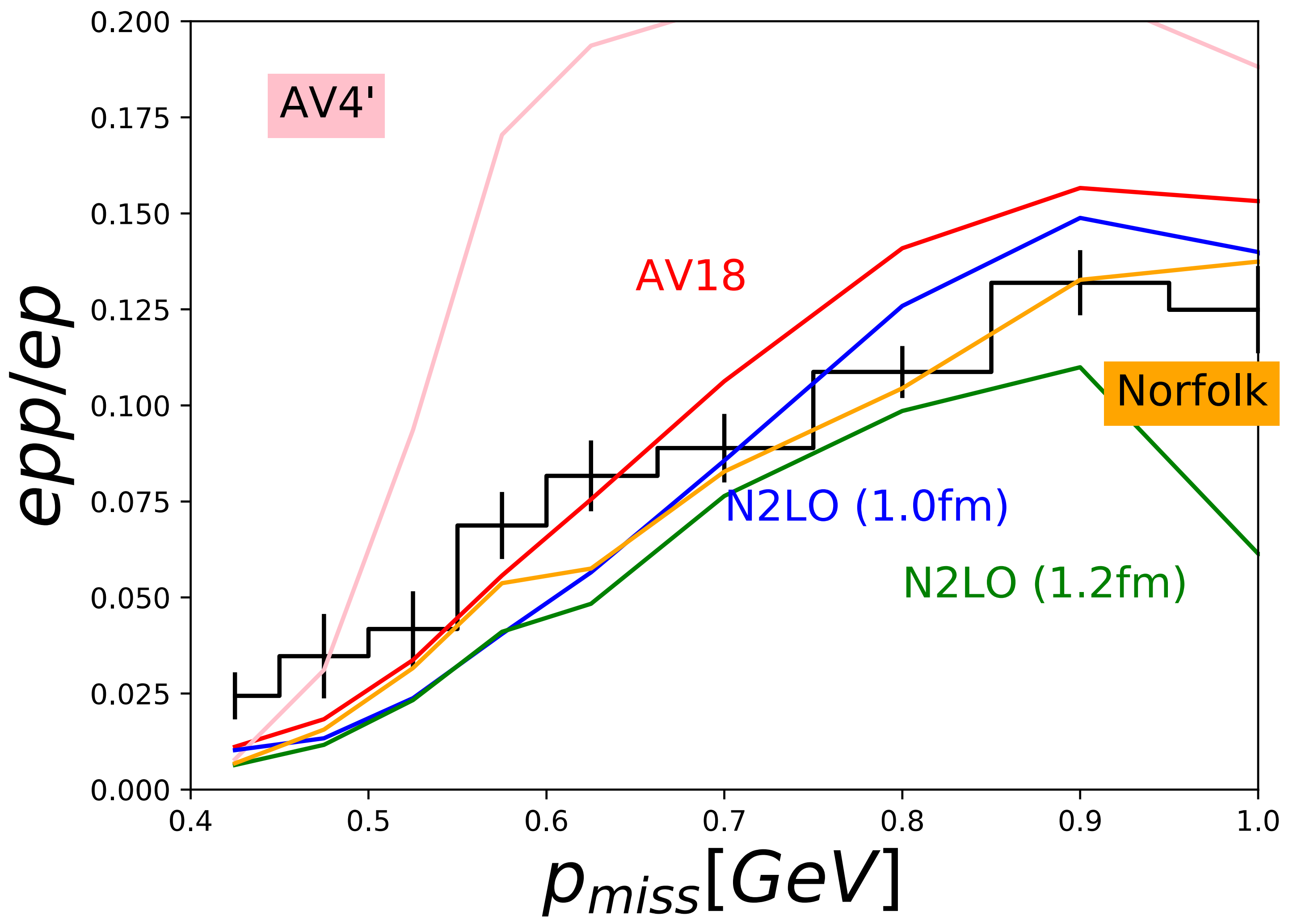
<u>*Precision 2N-SRC (from 100s to 1000s events):*</u>

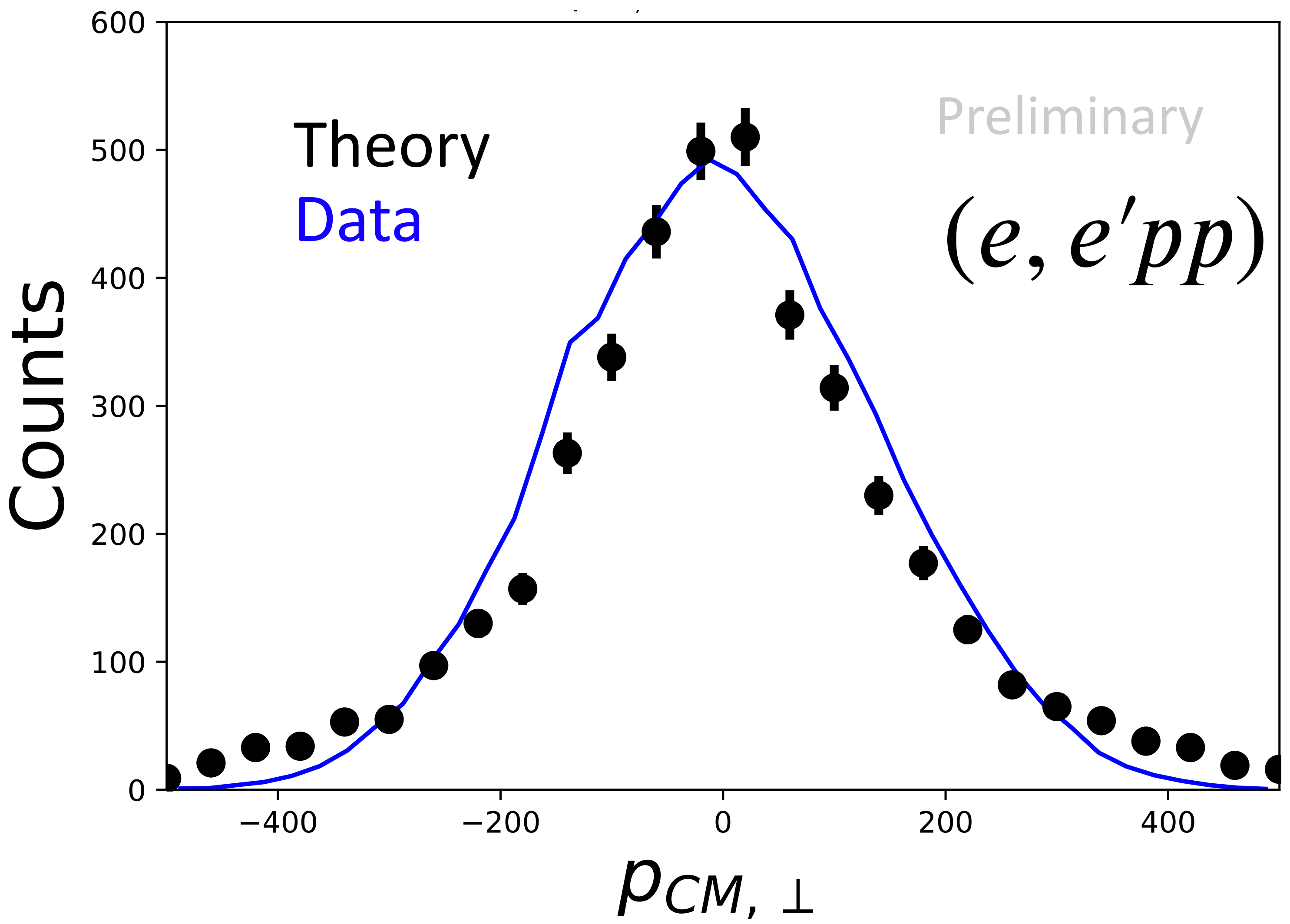
- *Scale (Q2) independence*
- *SRC dominance and universality*
- *Asymmetries and A-dependence*

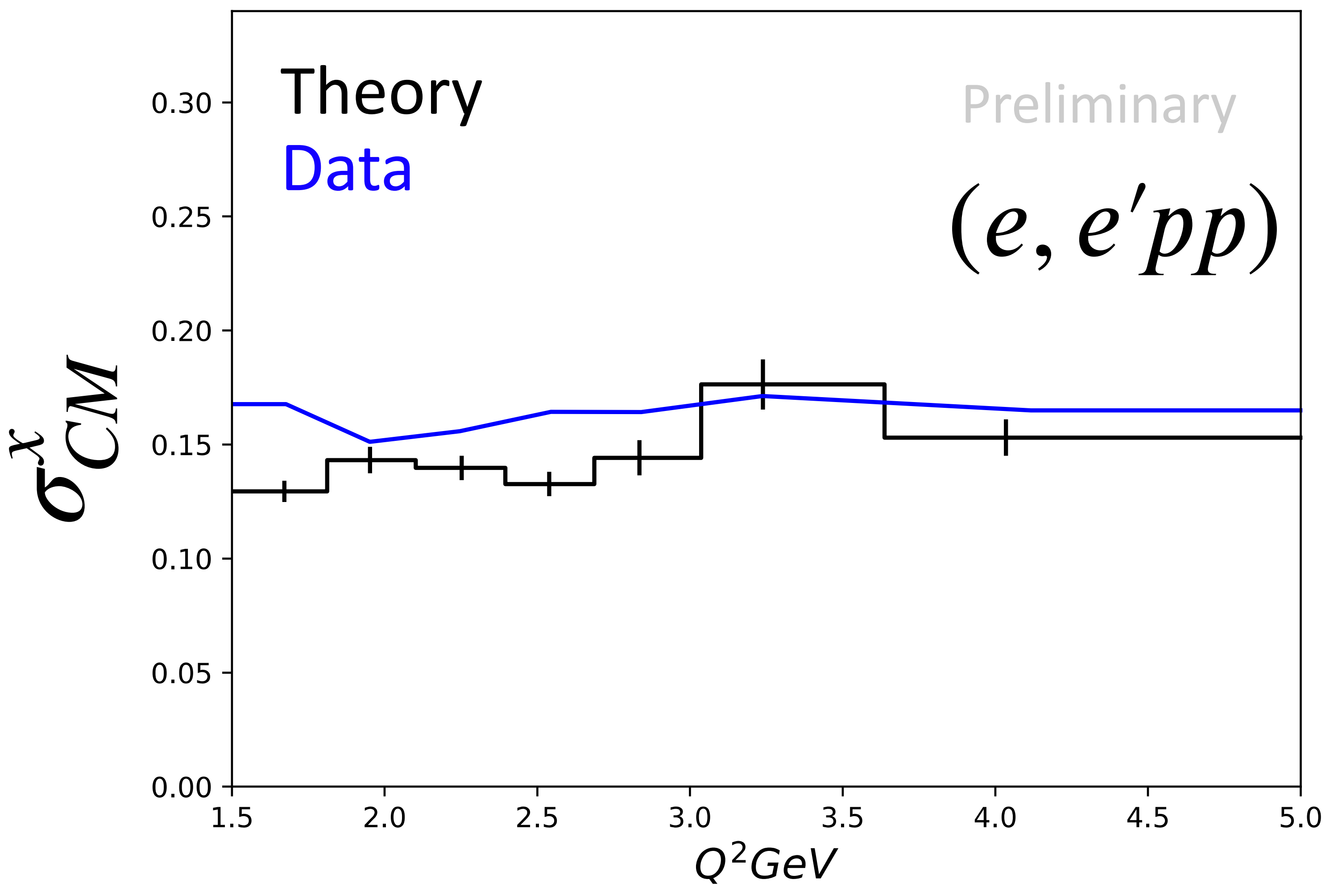
<u>*3N-SRC search in (e,e'ppn) and (e,e'ppp) channels*</u>

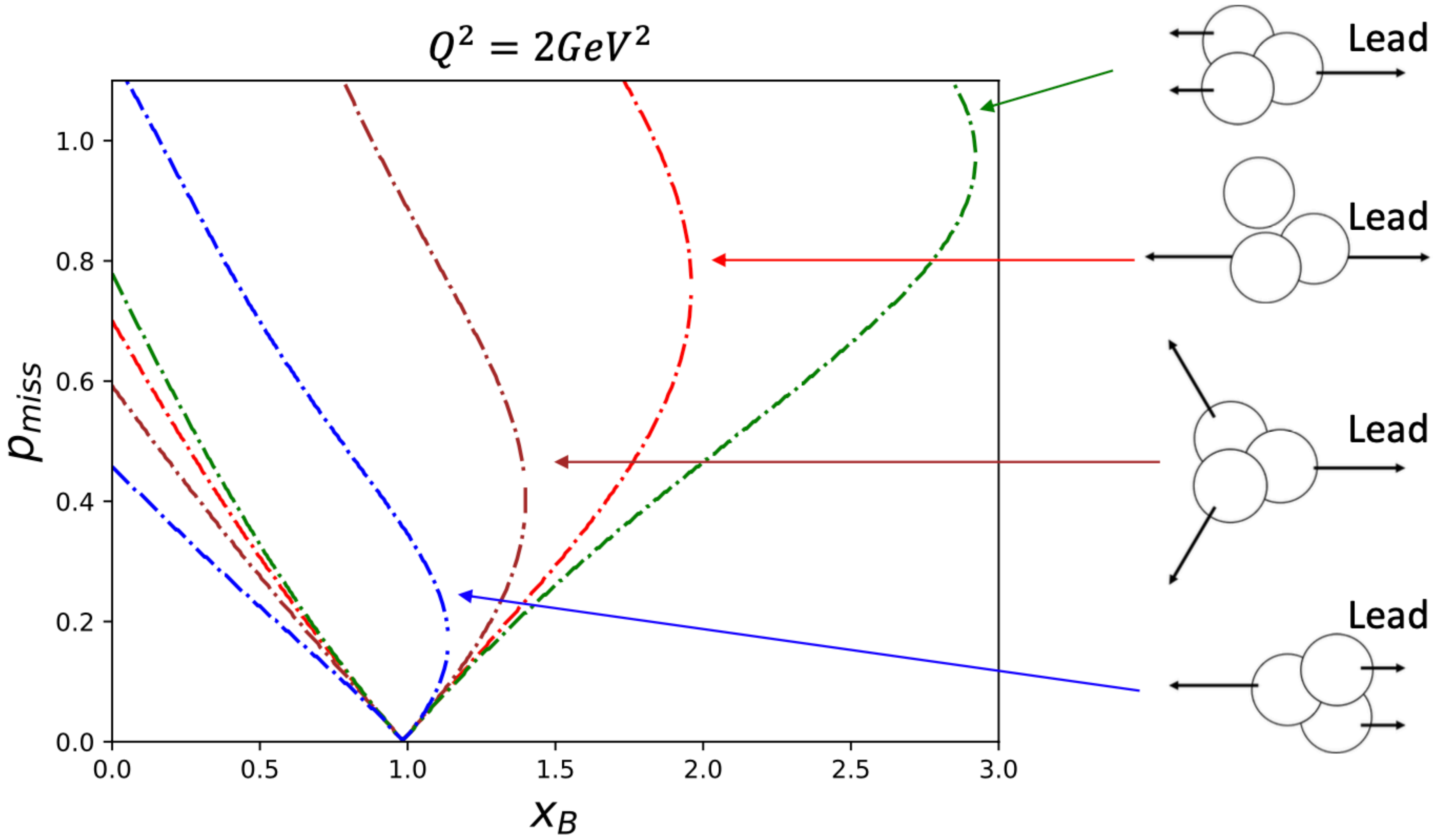
RGM $e'pp$ + Pheno. Studies Underway

Andrew Denniston

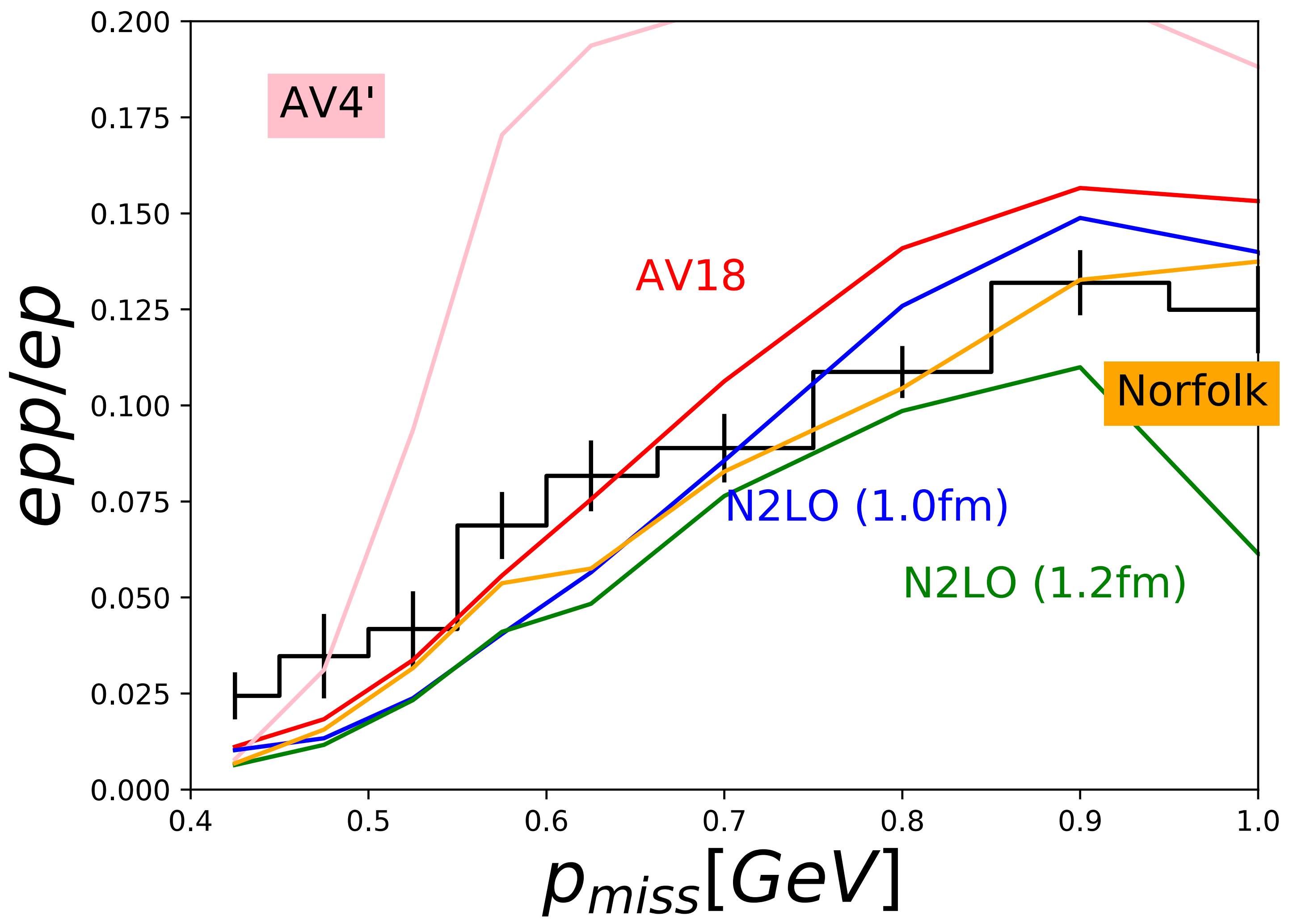


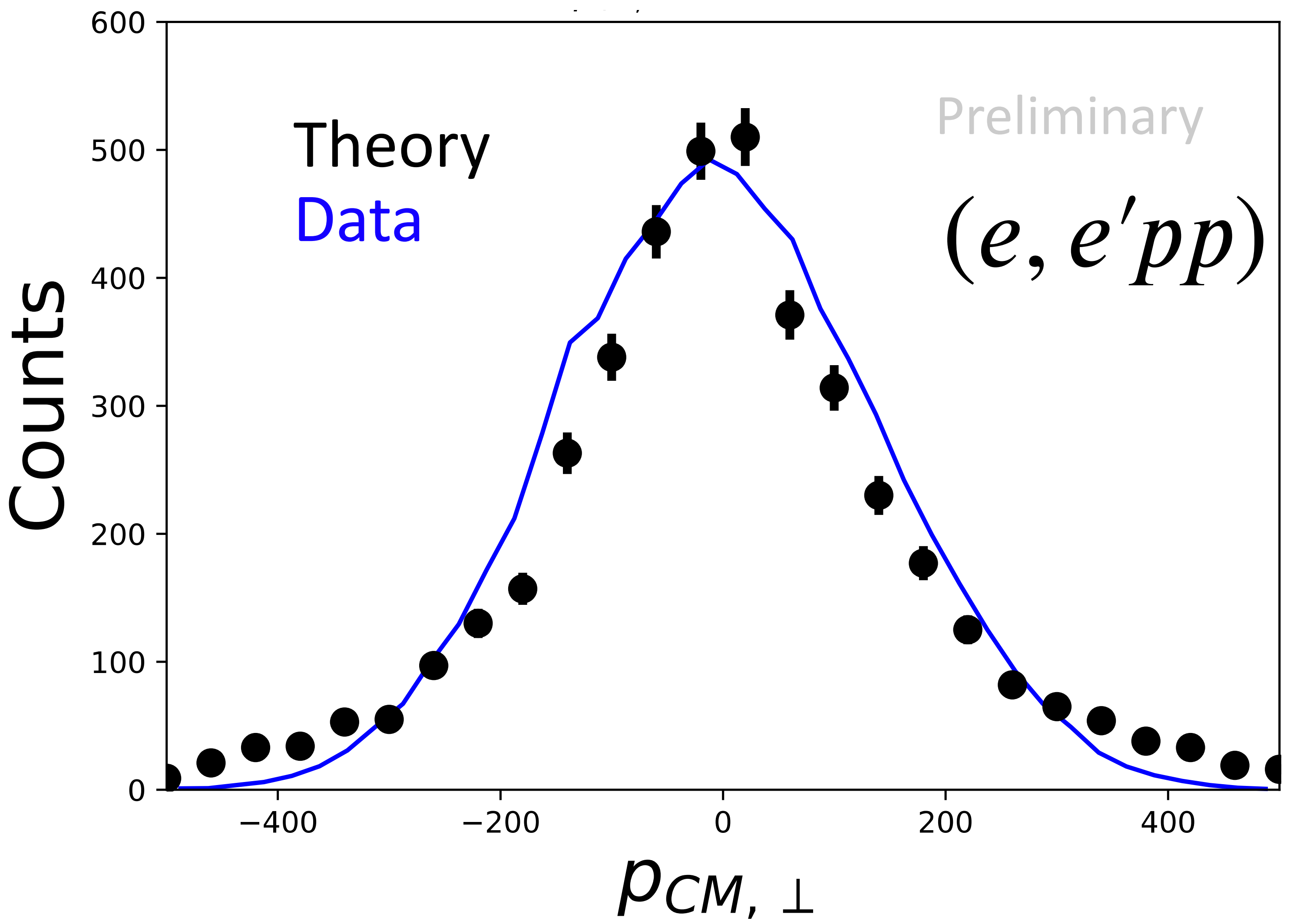


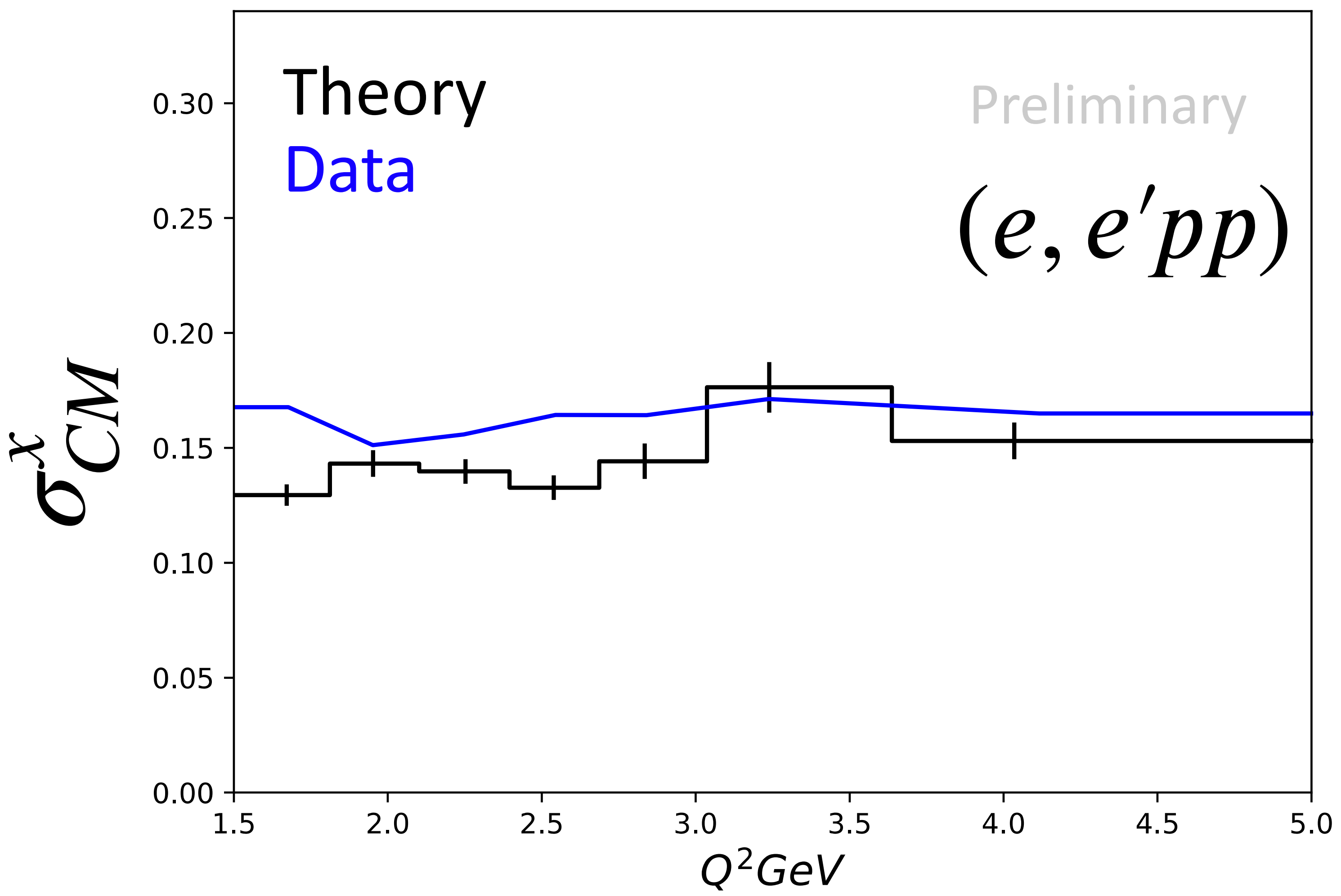




RGM $e'pp$ + Pheno. Studies Underway







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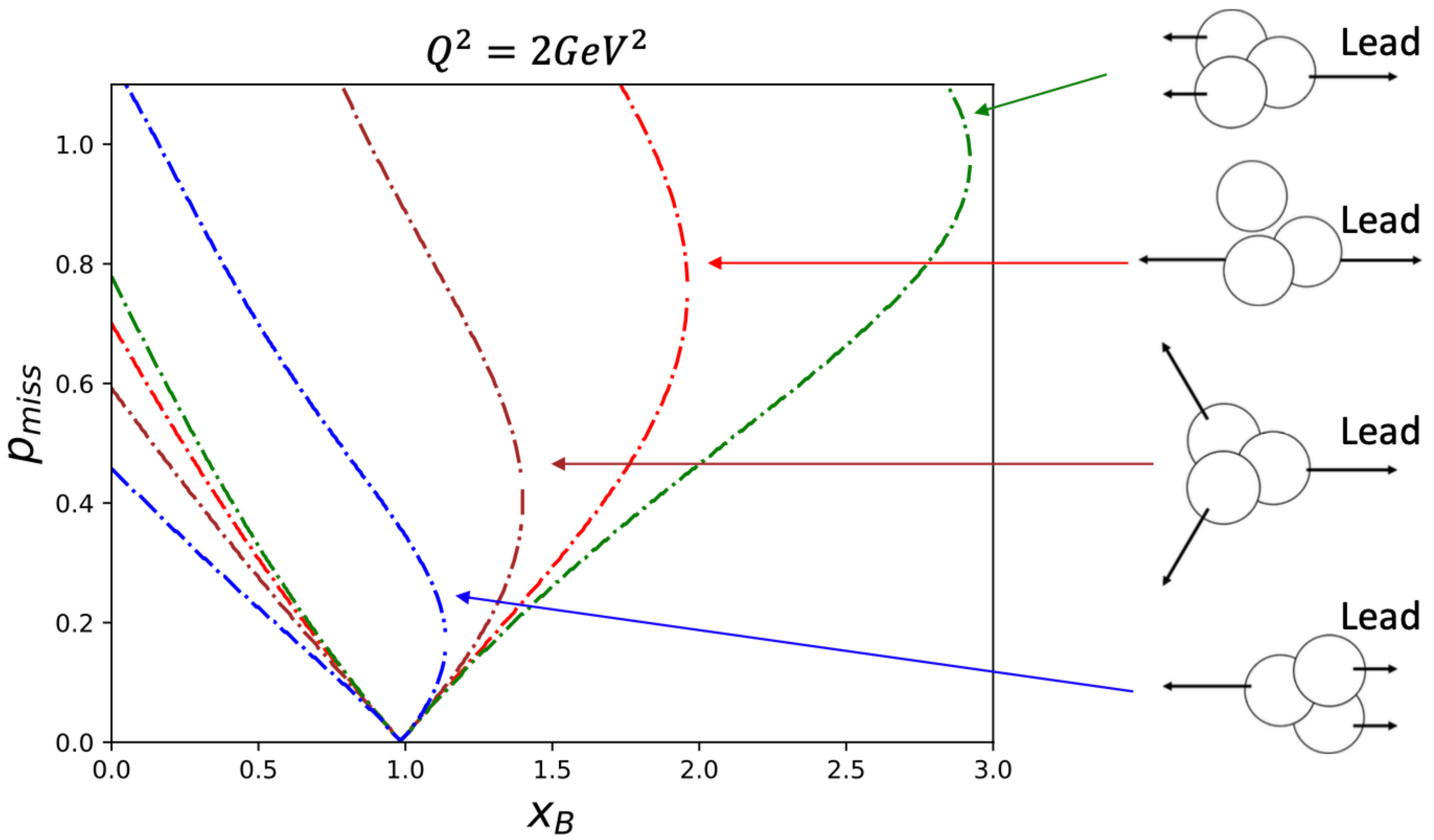
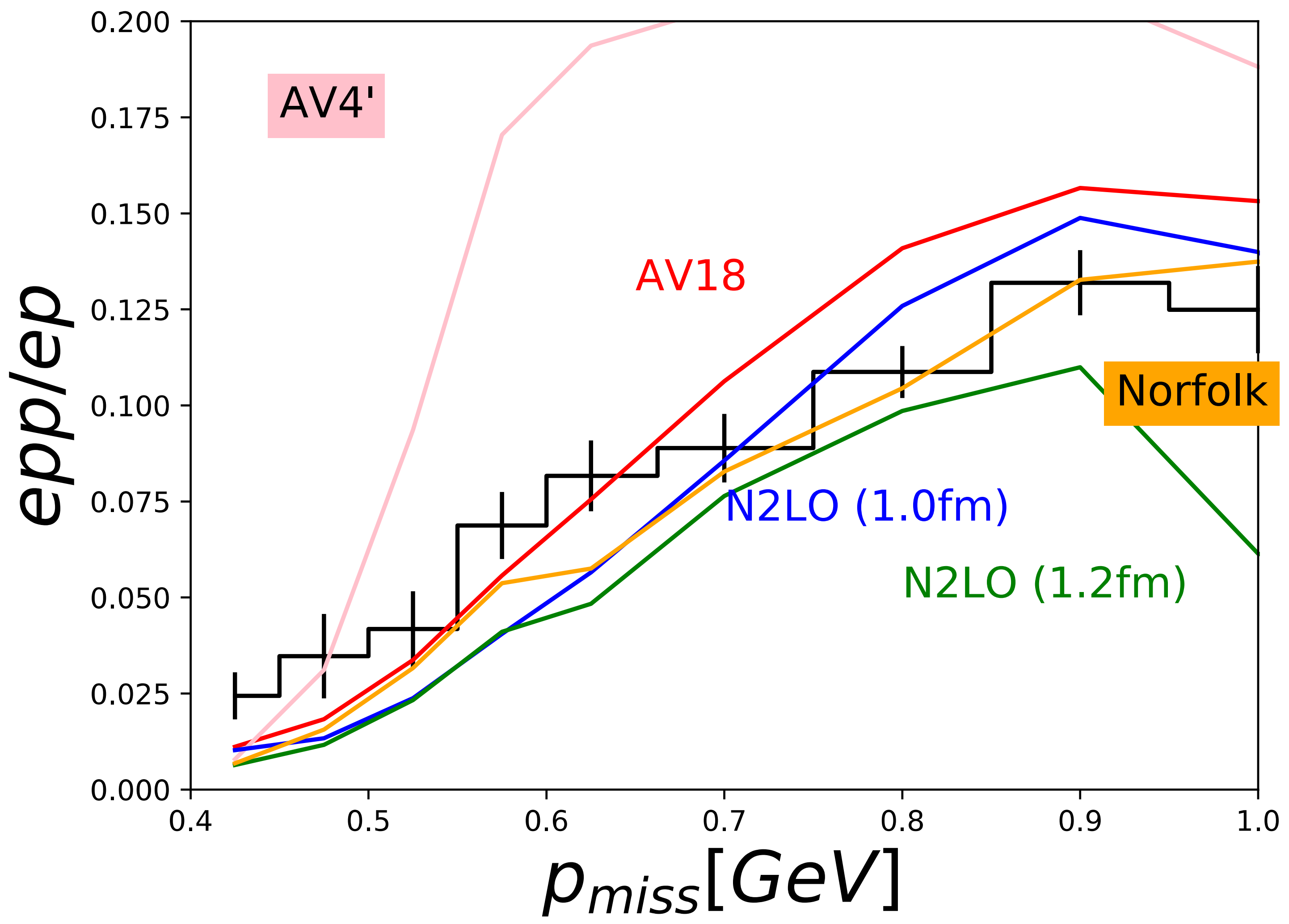
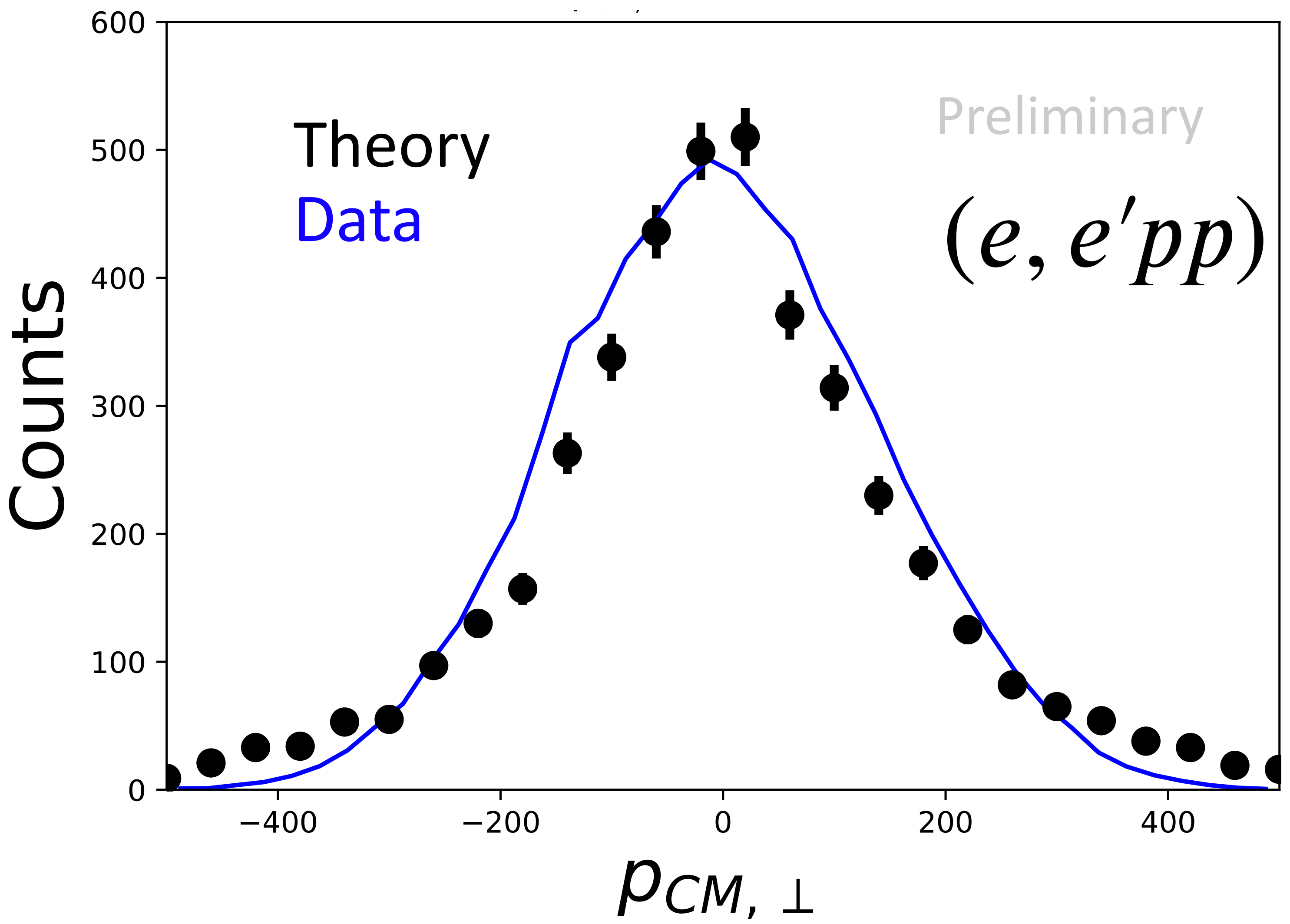
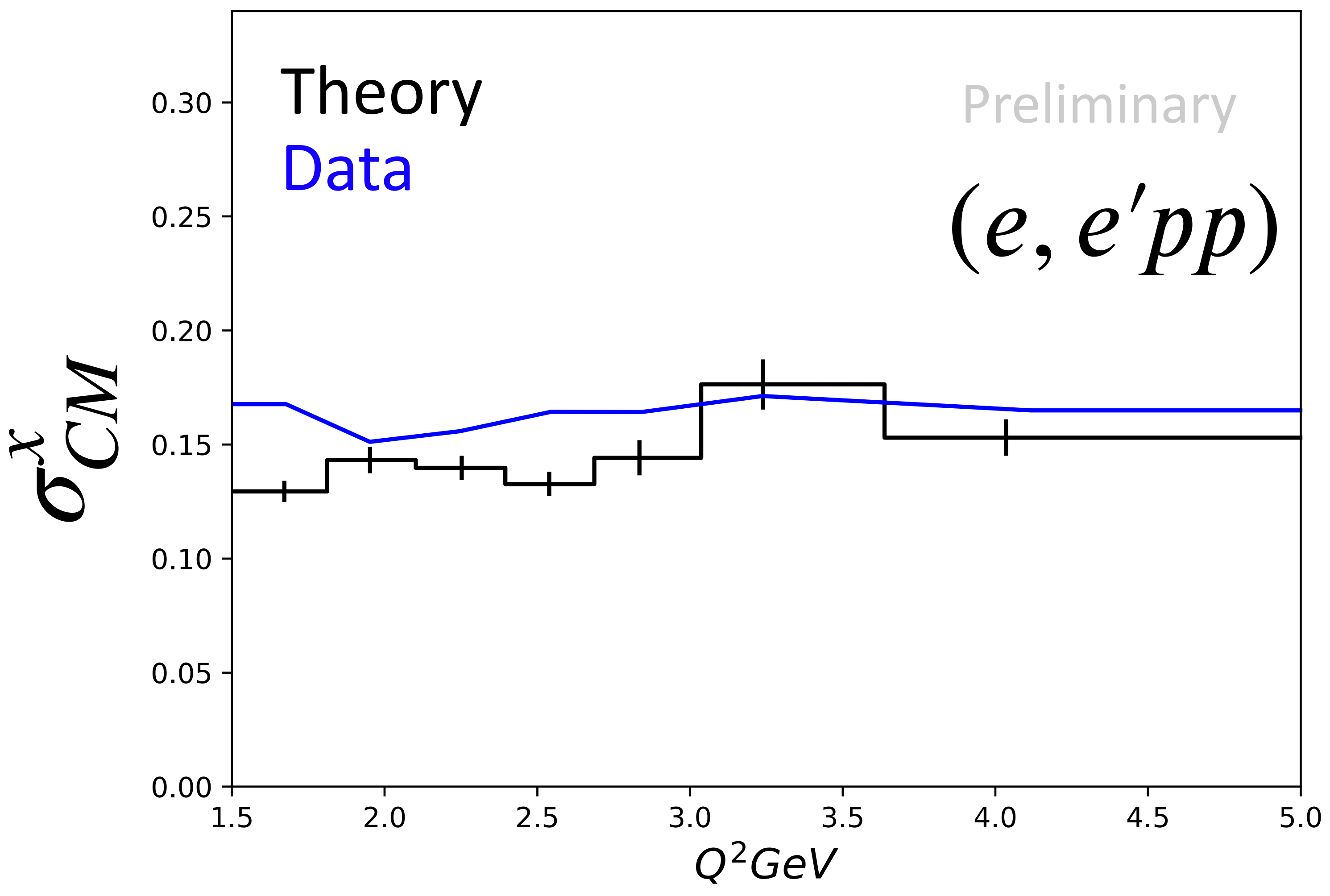


SRCs ~80% pn pairs… these are all proton measurements?

RGM $e'pp$ + Pheno. Studies Underway







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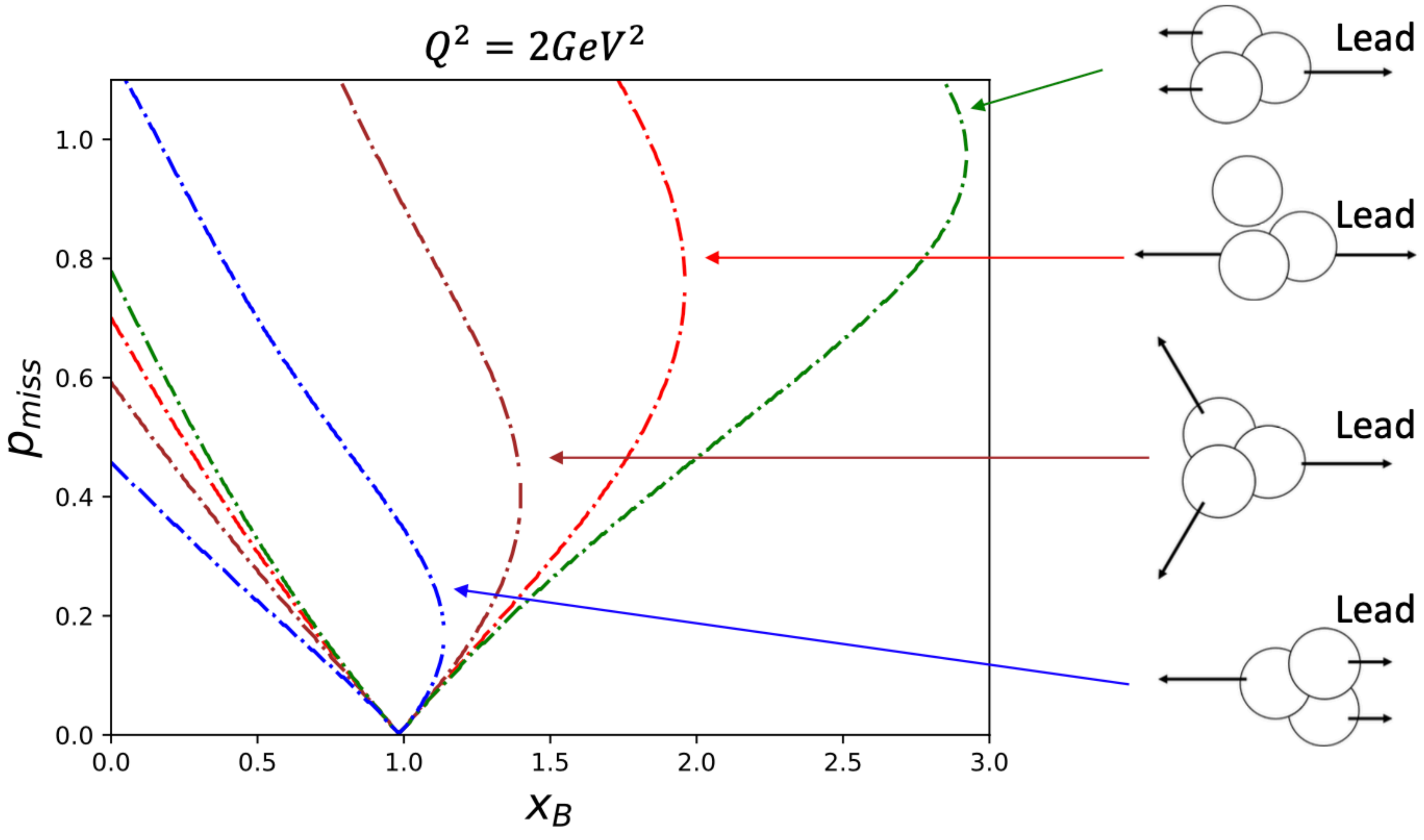


SRCs ~80% pn pairs… these are all proton measurements?

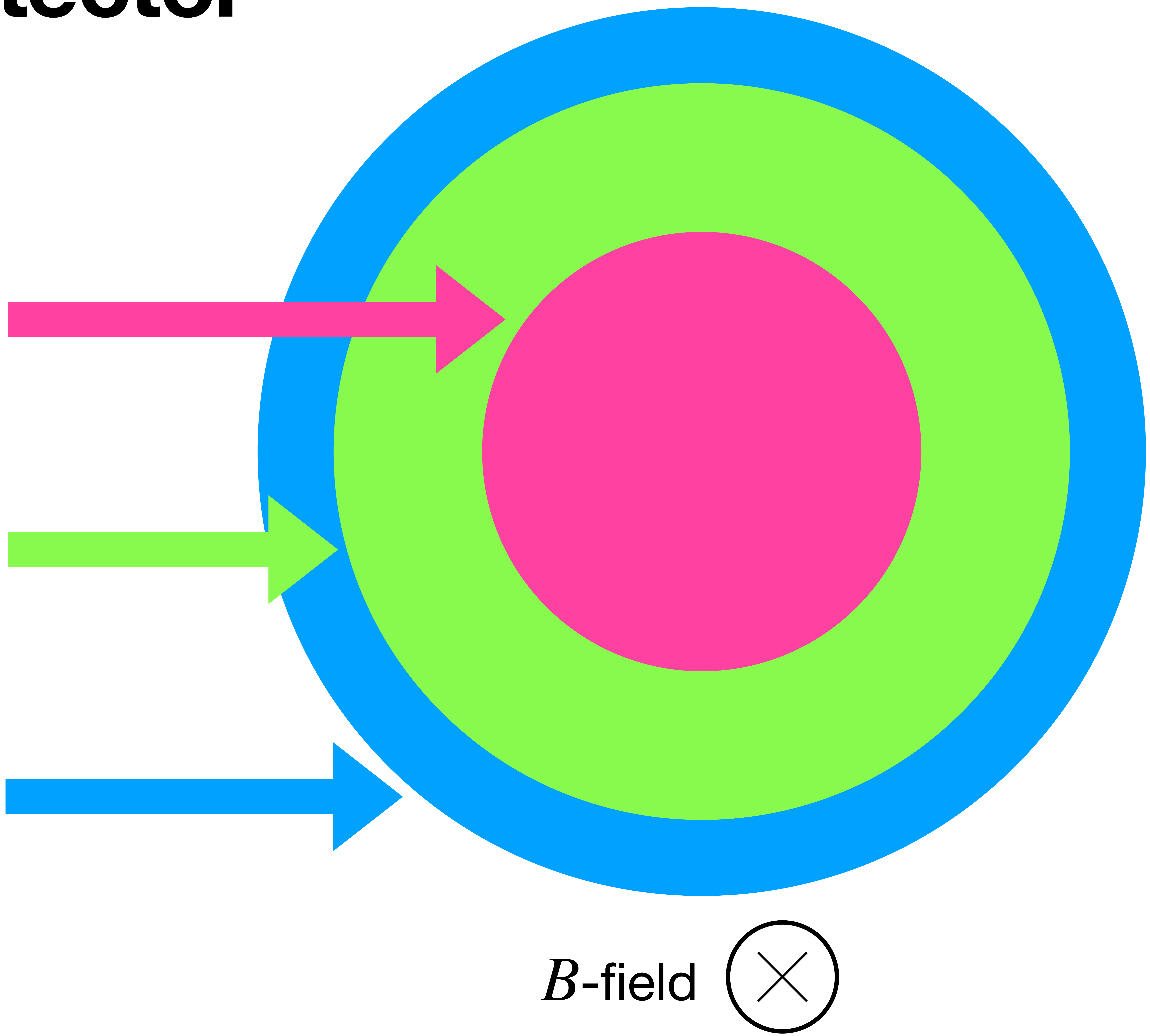
CD neutrons are tricky, but we need them to move forward!

CLAS12 Central Detector

Central Vertex Tracker (CVT)

Central Neutron Detector (CND)

Central Time of Flight Detector (CTOF)



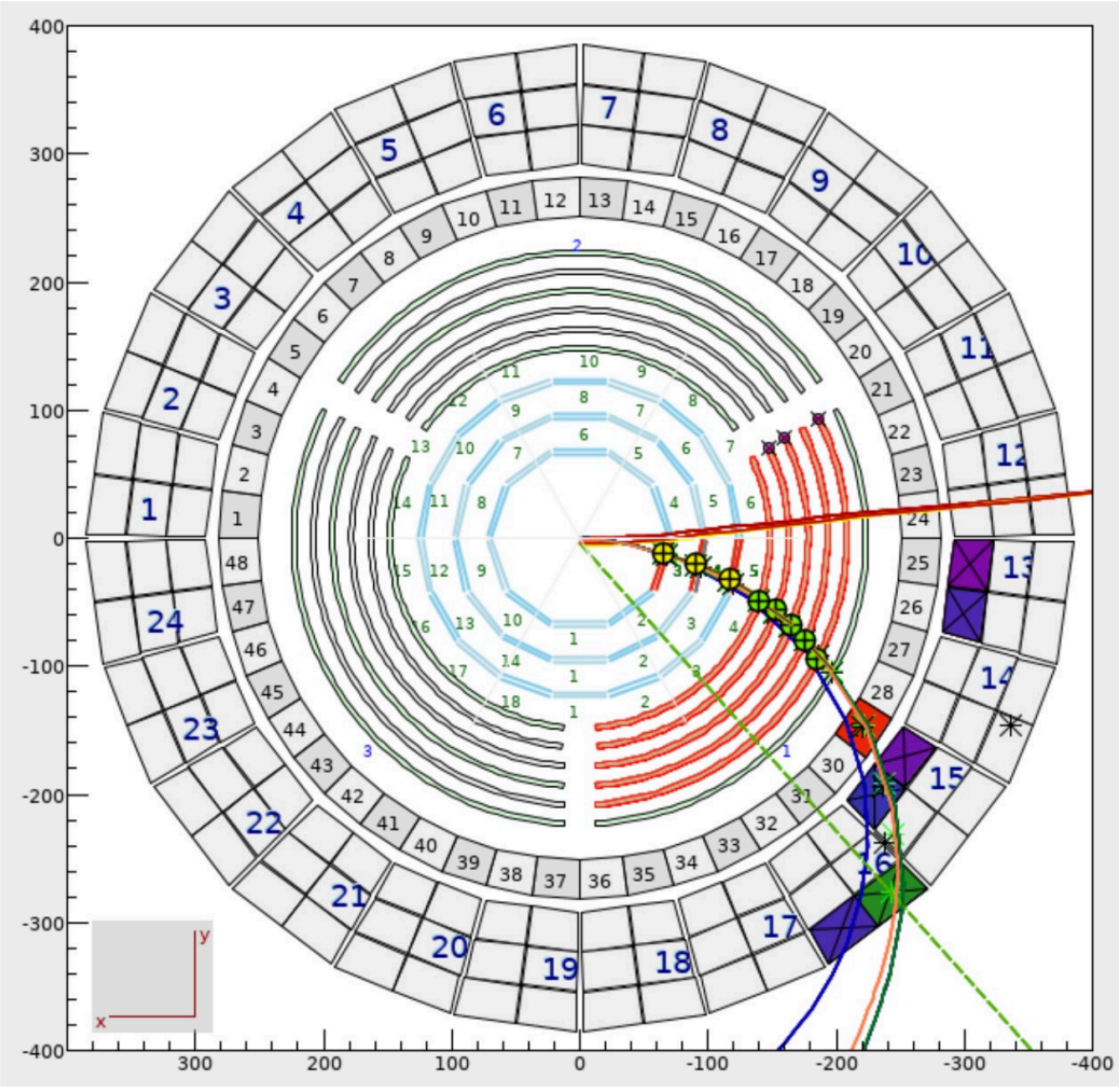
For neutrons, must reject charged particles

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

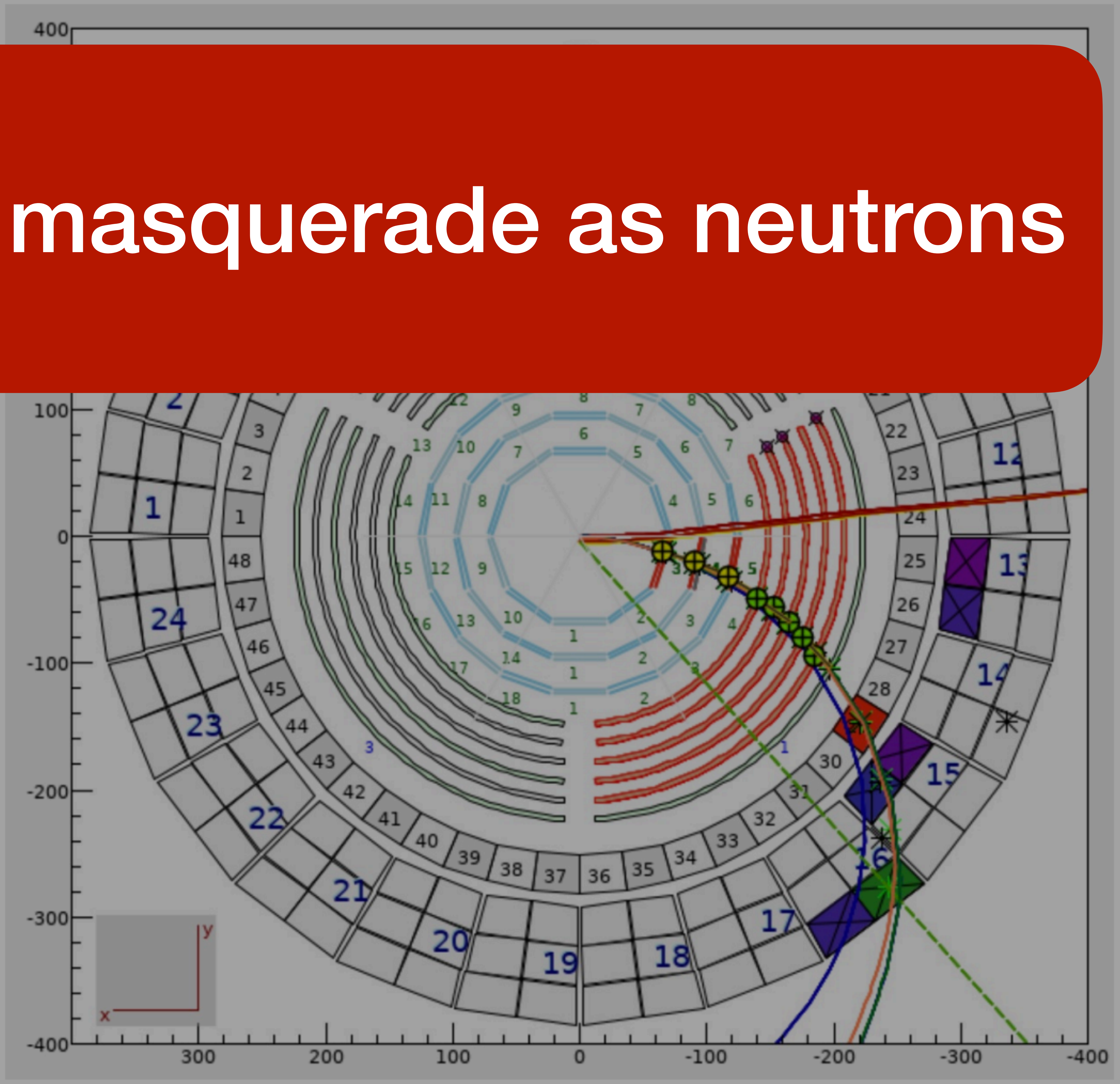
CVT inefficiency $\implies$ Protons masquerade as neutrons

Yes

No

Charged PID via trajectory

Neutral PID via Tof



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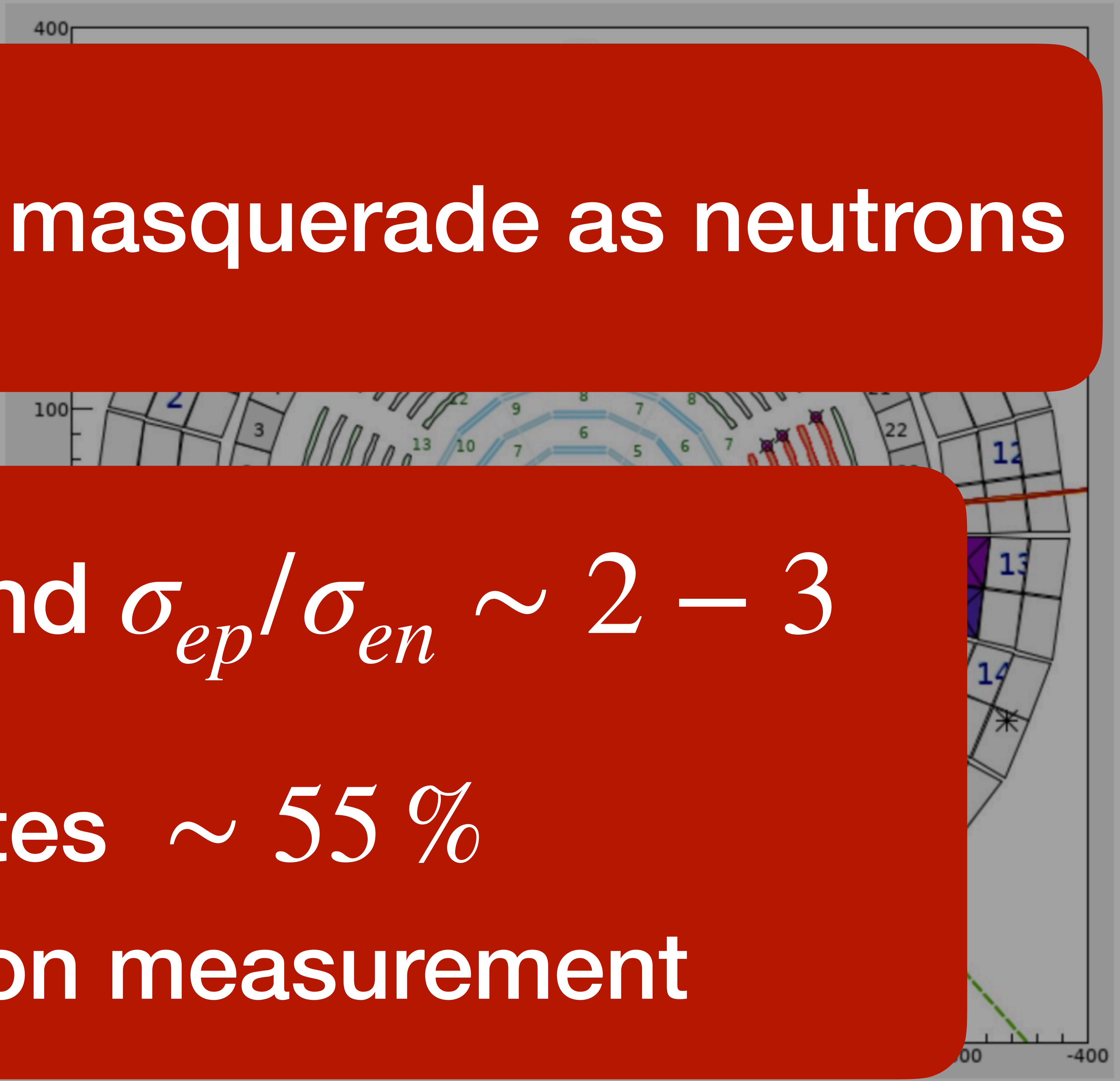

CVT inefficiency $\implies$ Protons masquerade as neutrons

Challenge: $\epsilon_n \sim 10\,\%$ and $\sigma_{ep}/\sigma_{en} \sim 2-3$

$\rightarrow$ Even $\epsilon_p = 95\,\%$ creates $\sim 55\,\%$ background for neutron measurement

ML algorithm for charged particle veto

Multilayer Perceptron Architecture:

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?

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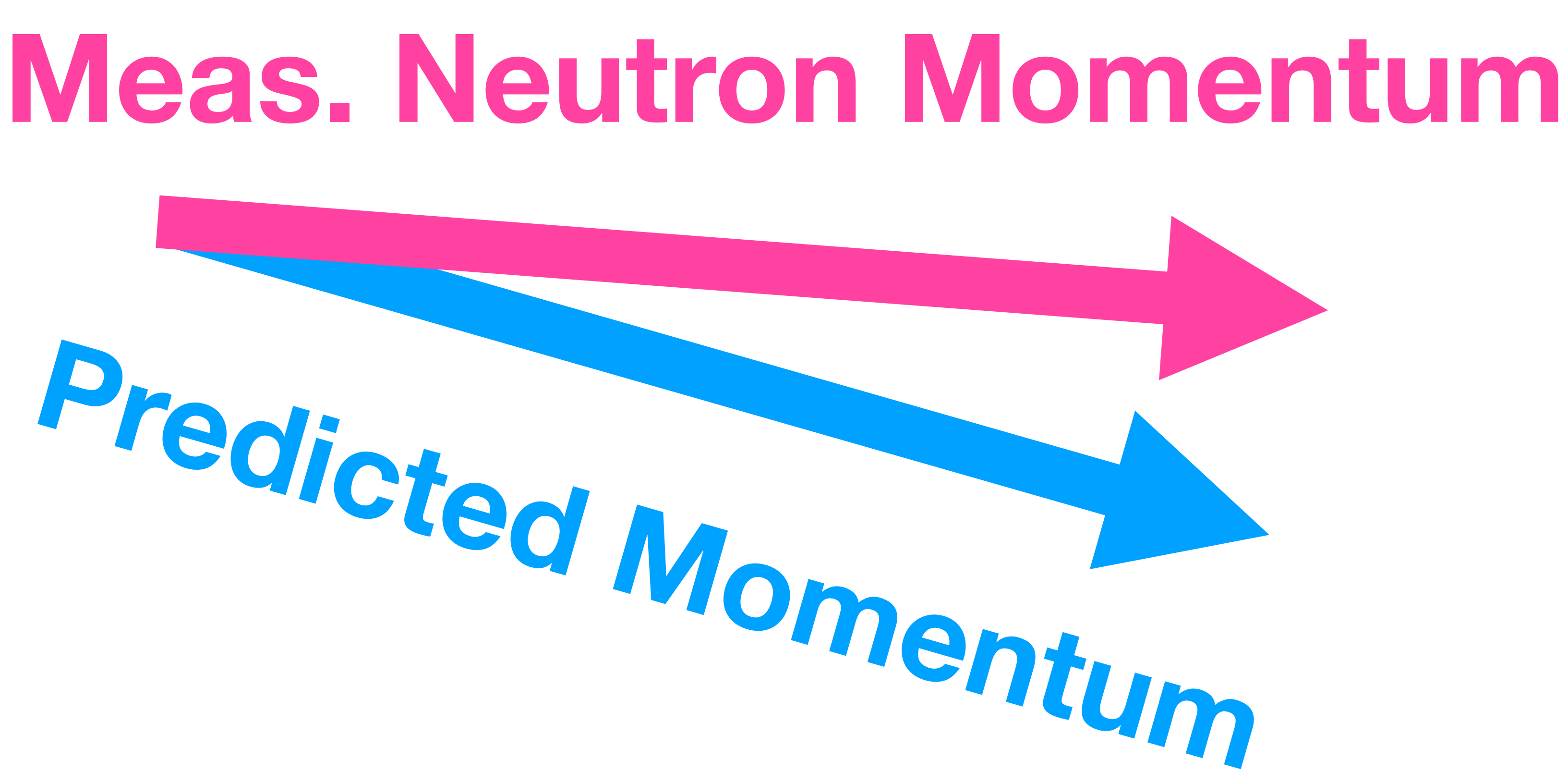
Data-driven train/test samples



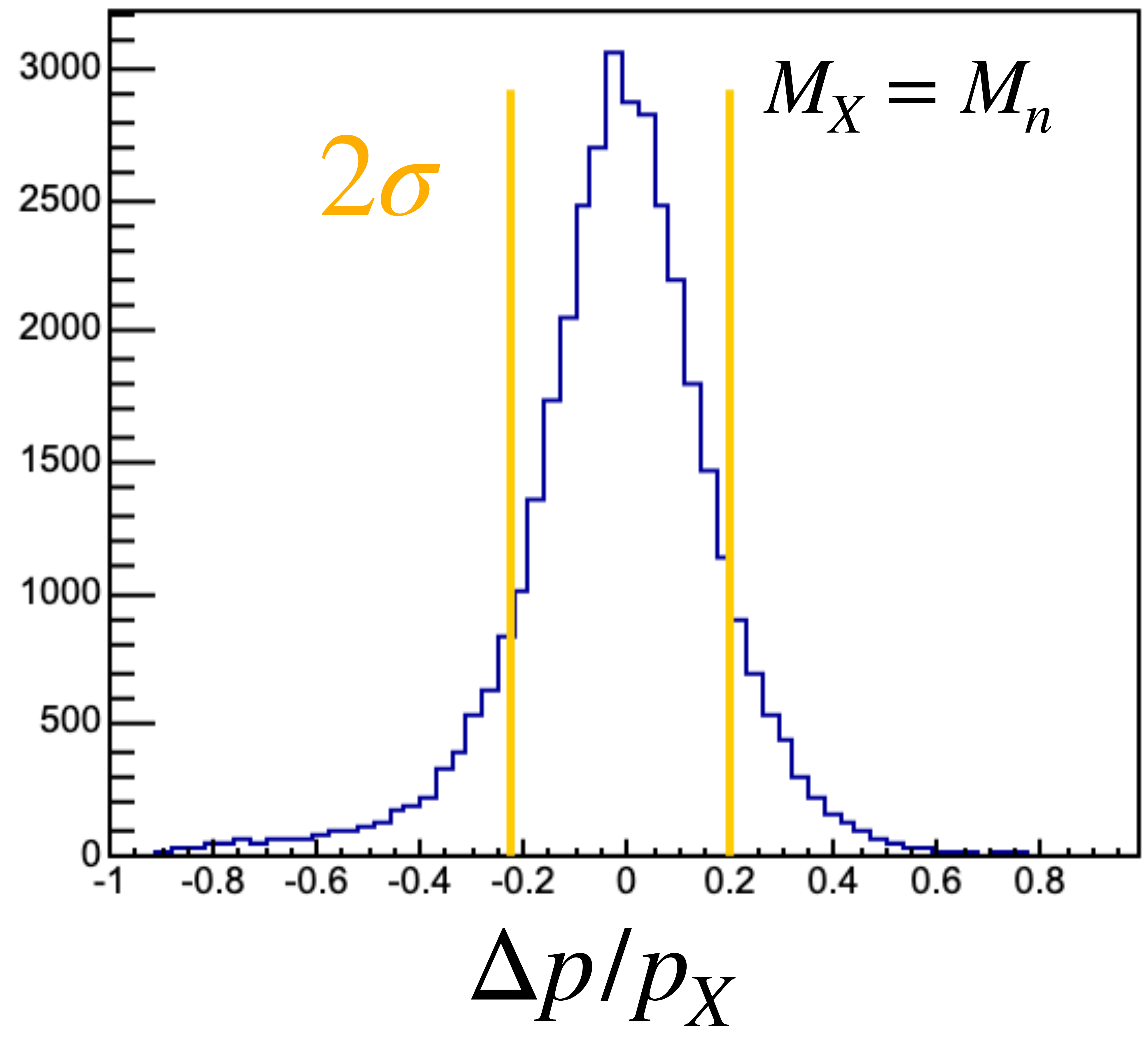
Nucleons selected from exclusive topologies

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

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

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

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



<u>Data-driven</u> train/test samples

Samples span a range of beam energies and interaction processes:

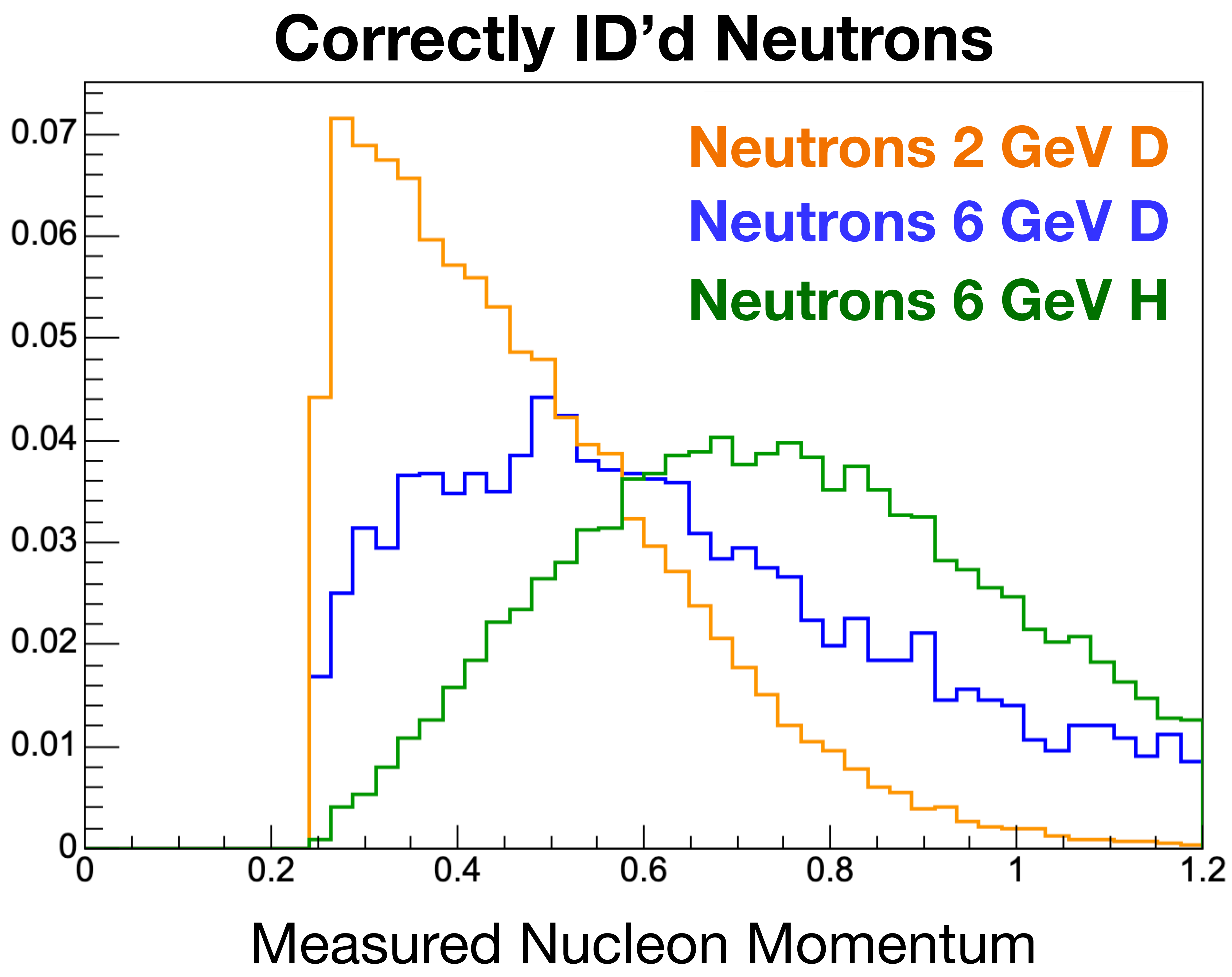
Signal: Correctly ID'd neutrons

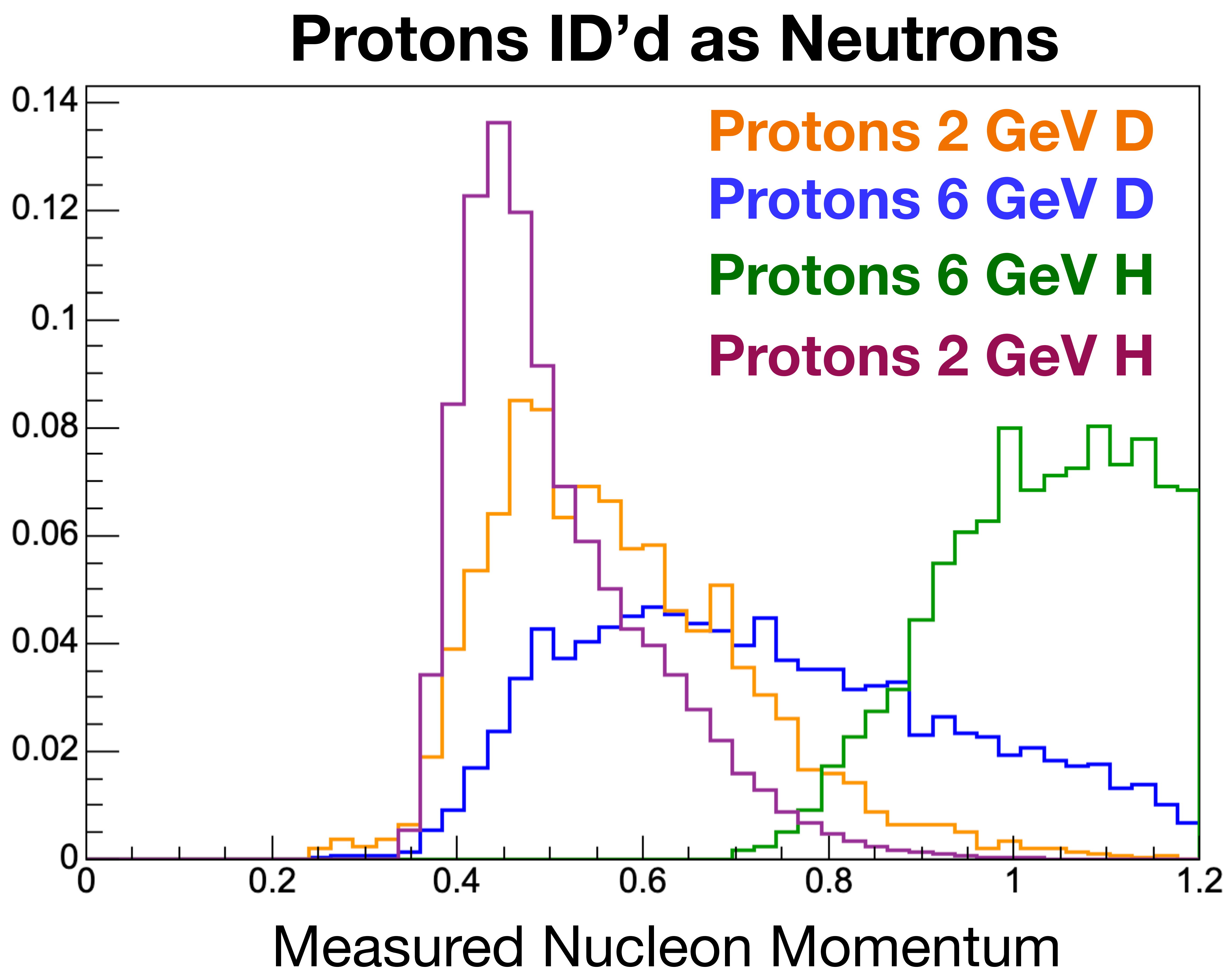
$D(e, e'pn)$	2 GeV
$D(e, e'pn)$	6 GeV
$H(e, e'\pi^+n)$	6 GeV

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





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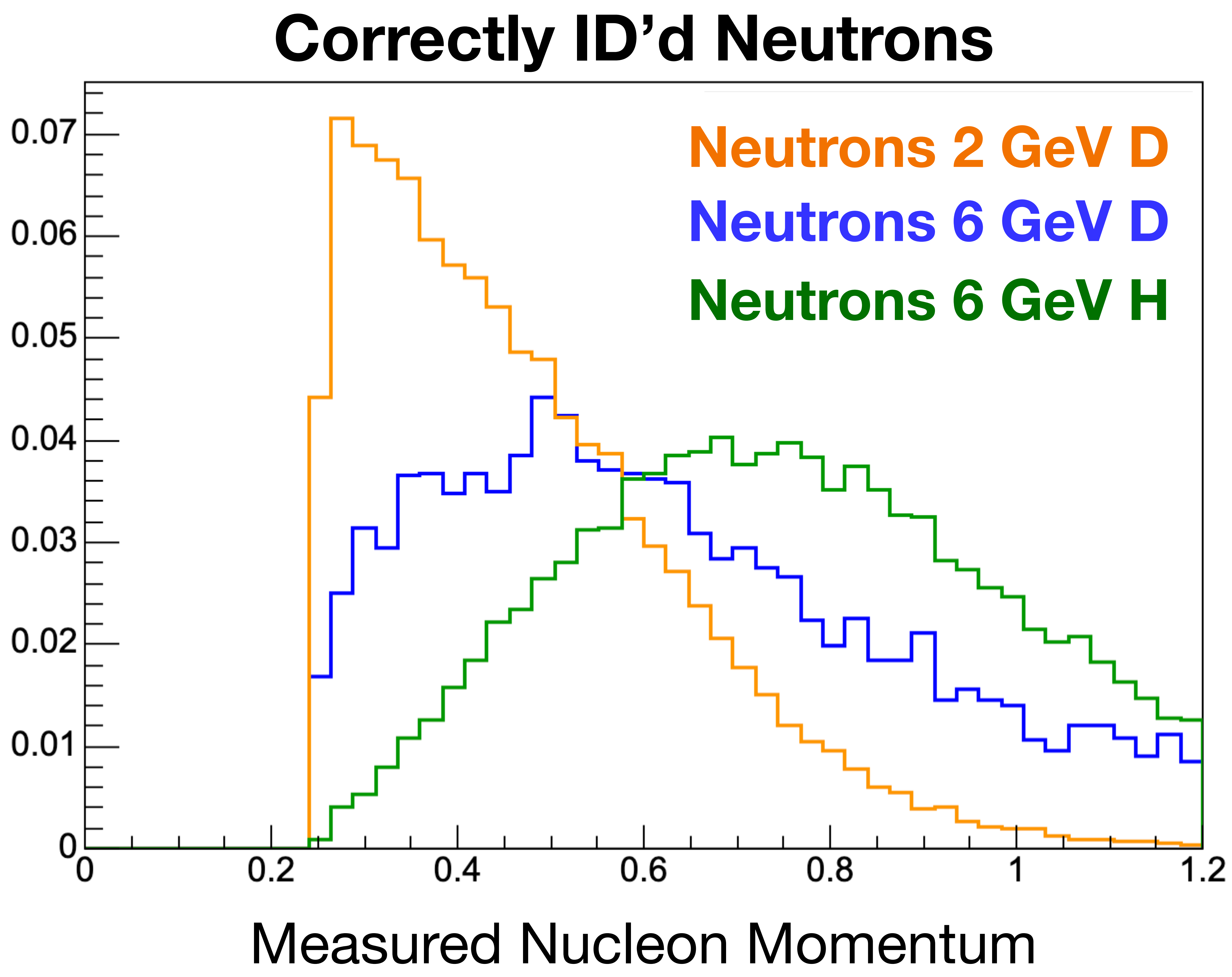

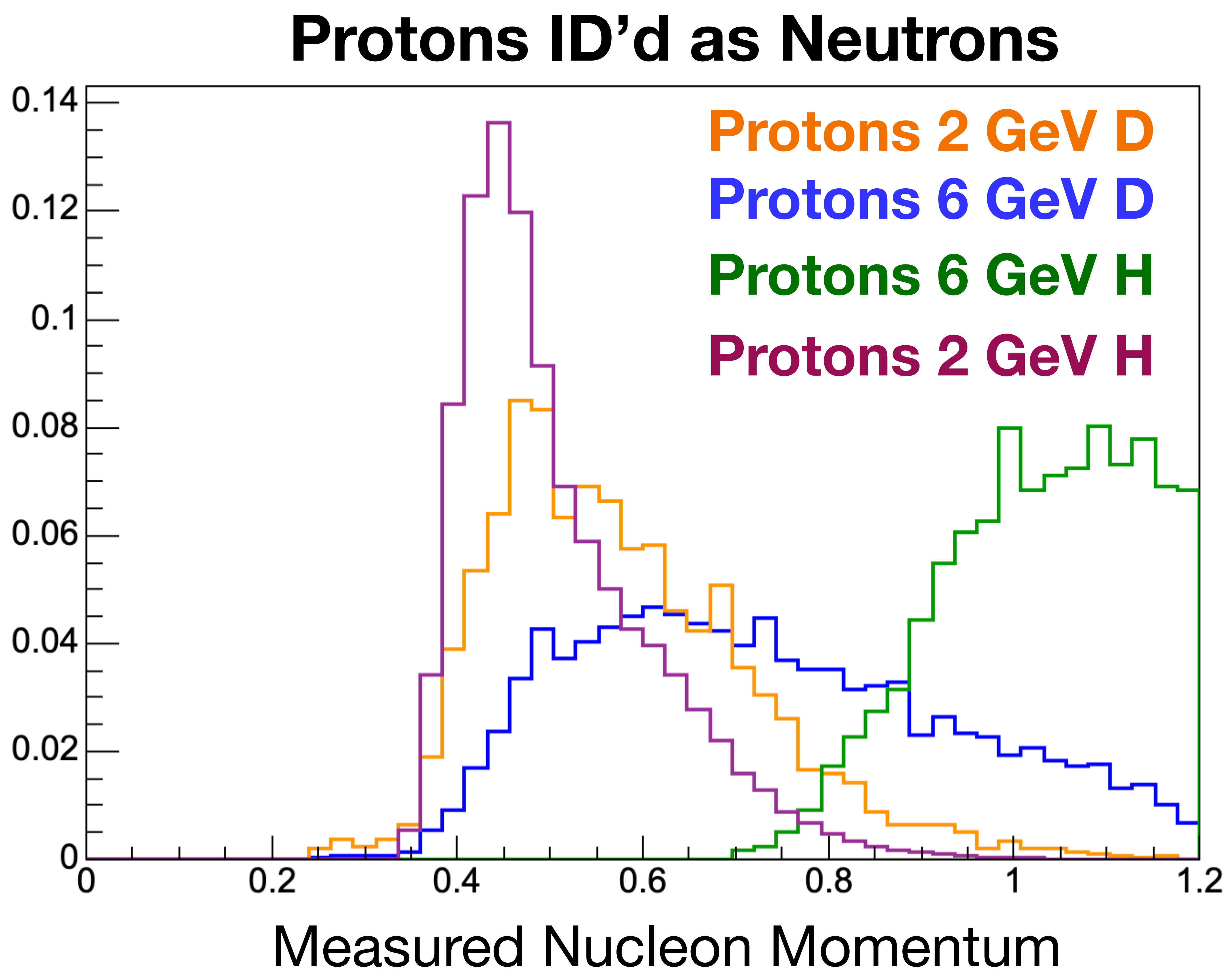

LD2 6 GeV:

Similar p, n kinematics

Momenta most similar to SRC recoil

→ Use for training, validate with other reactions

Ingredients for Veto Algorithm:

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2. **Feature Engineering**

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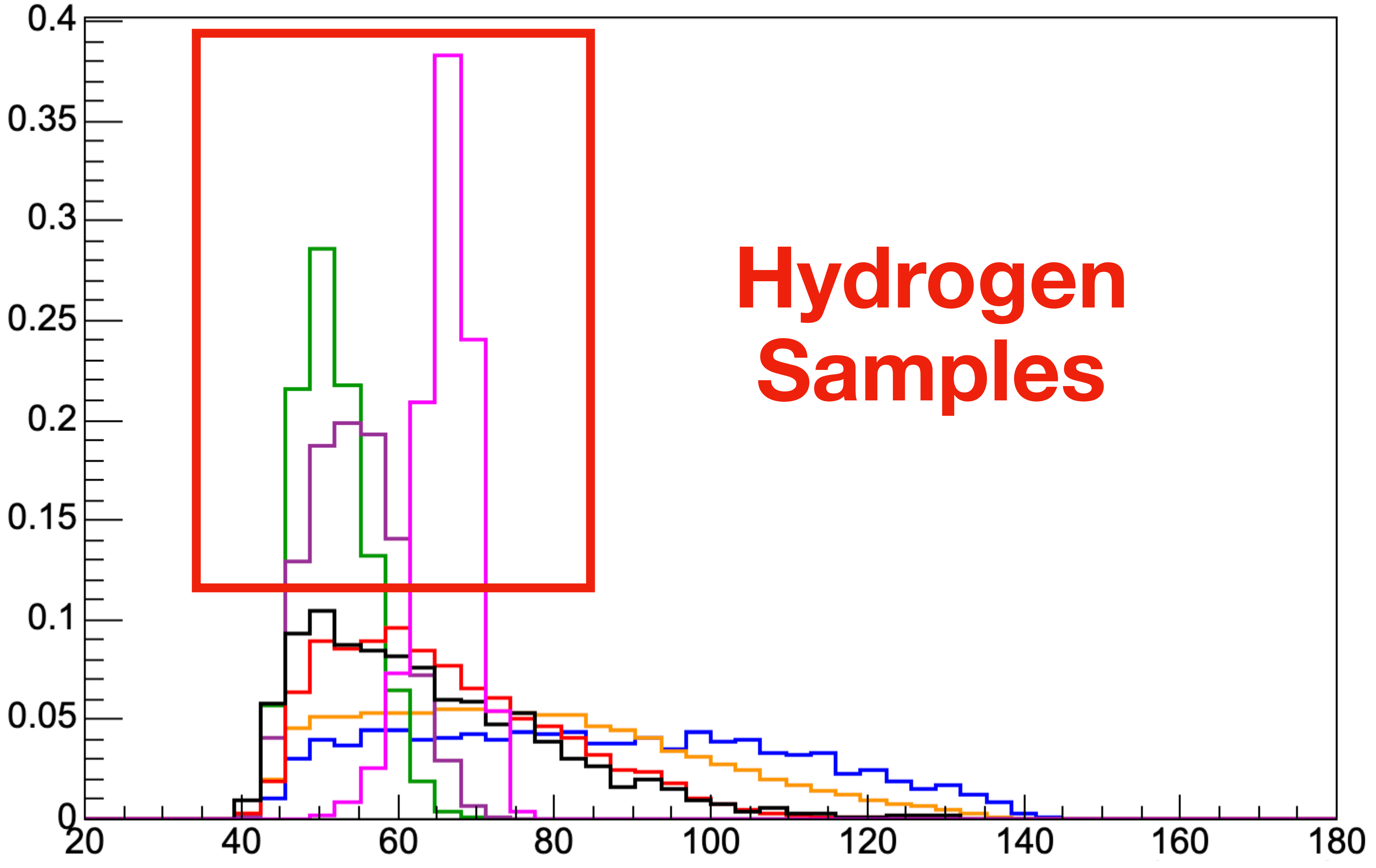
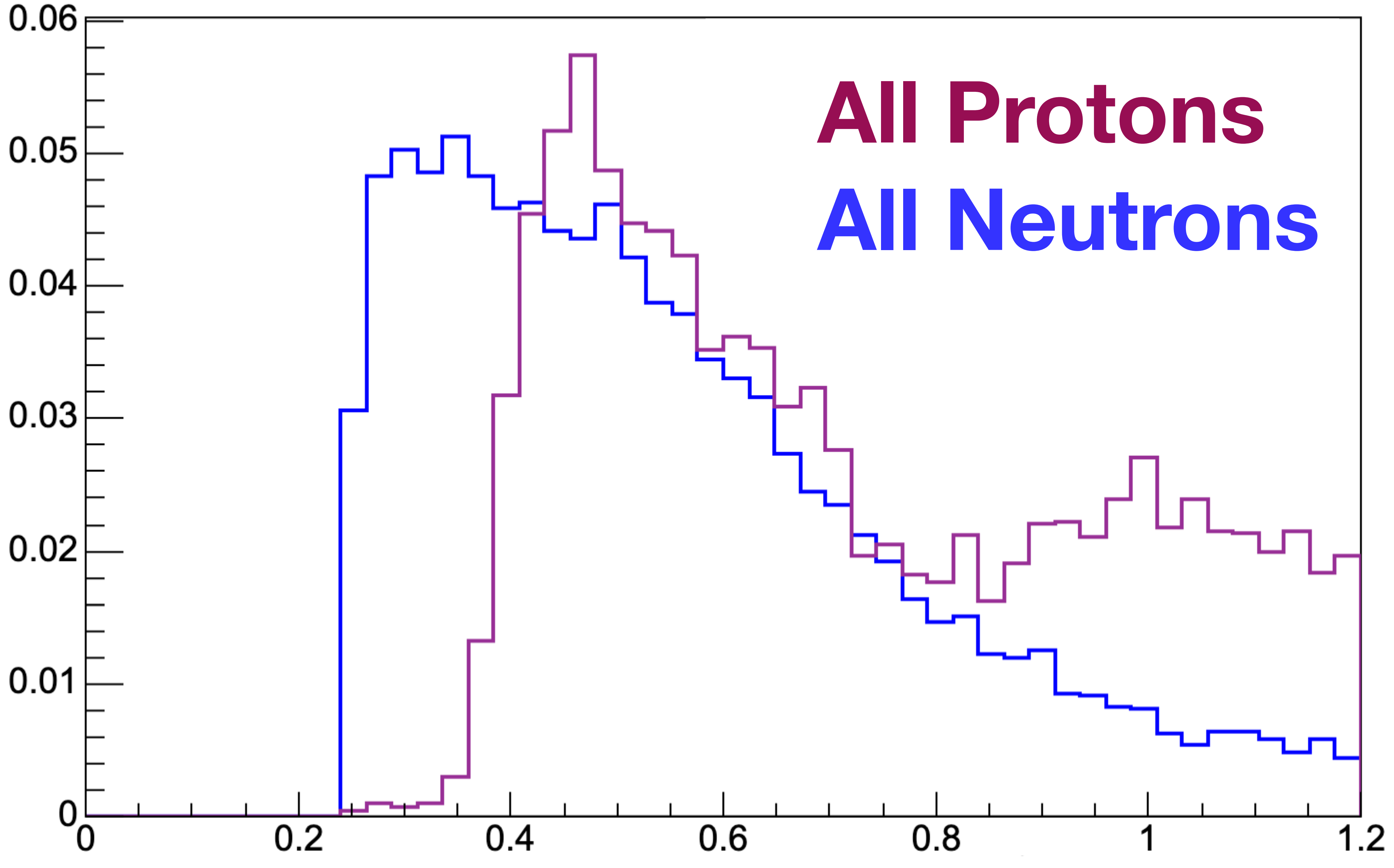
Feature Engineering Concerns:

1. Exclusive reactions constrain kinematics



Measured Nucleon θ

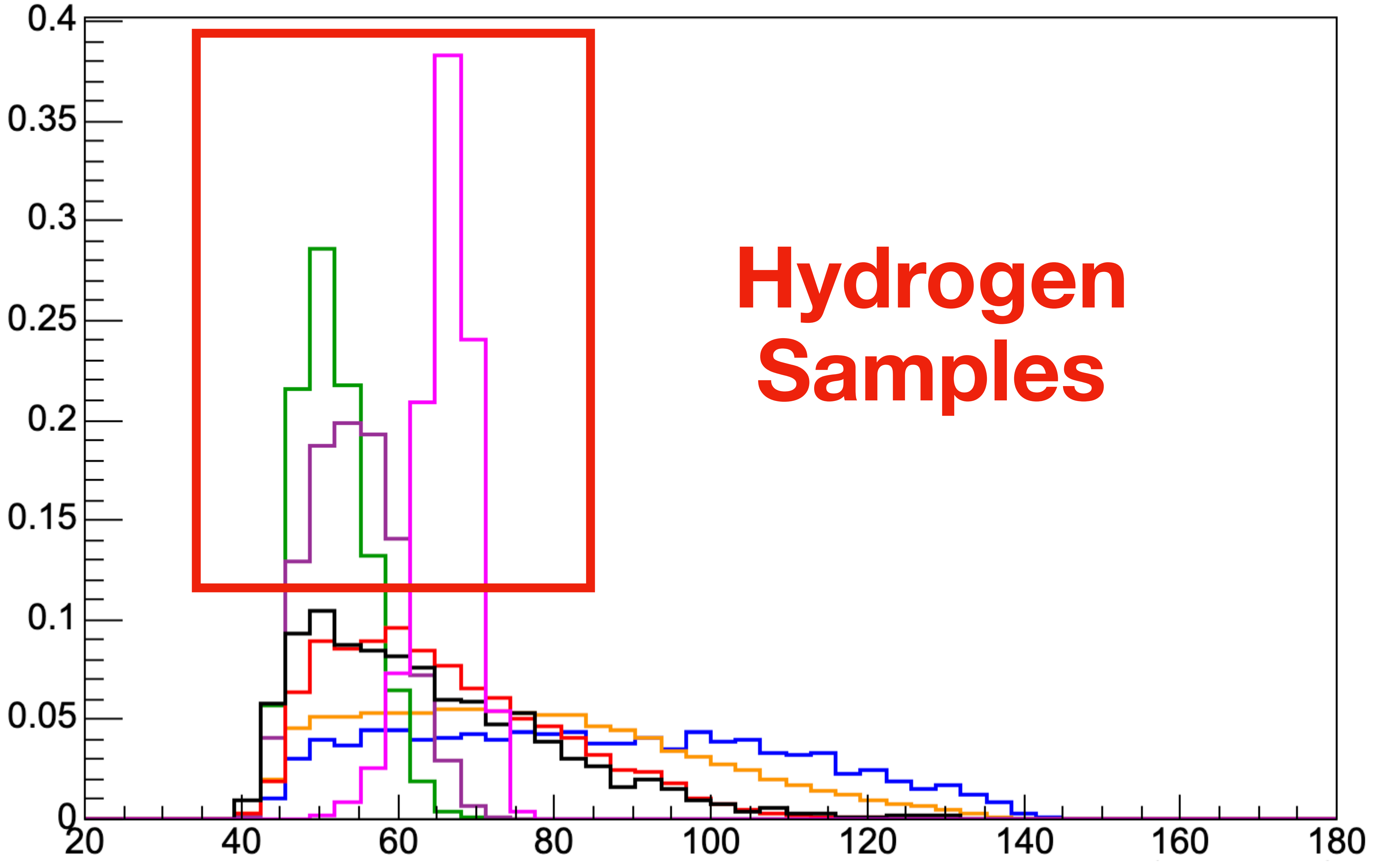


Measured Nucleon Momentum

Feature Engineering Concerns:

1. Exclusive reactions constrain kinematics

→ Consider Deuterium data only for feature design



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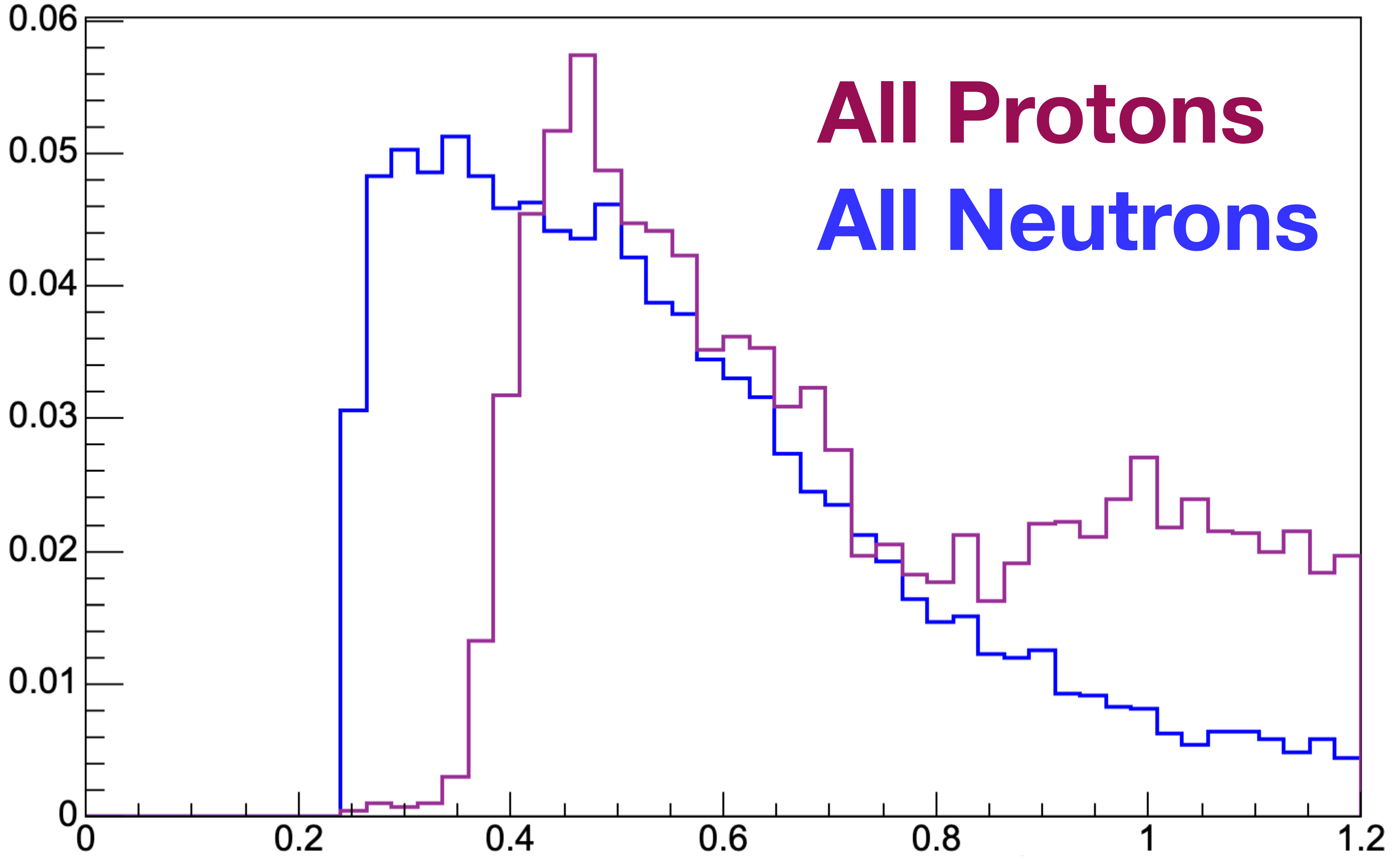


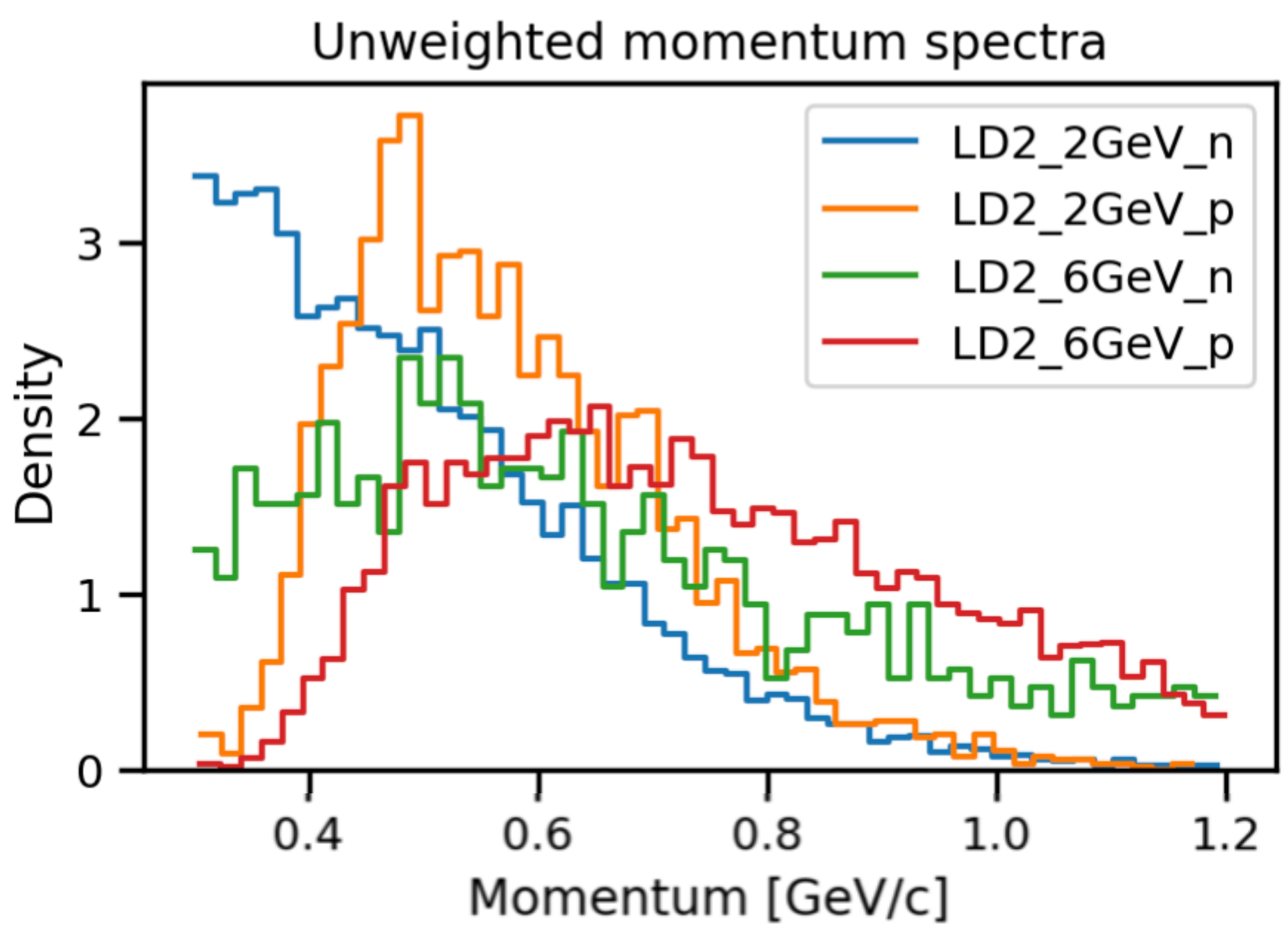
Measured Nucleon Momentum

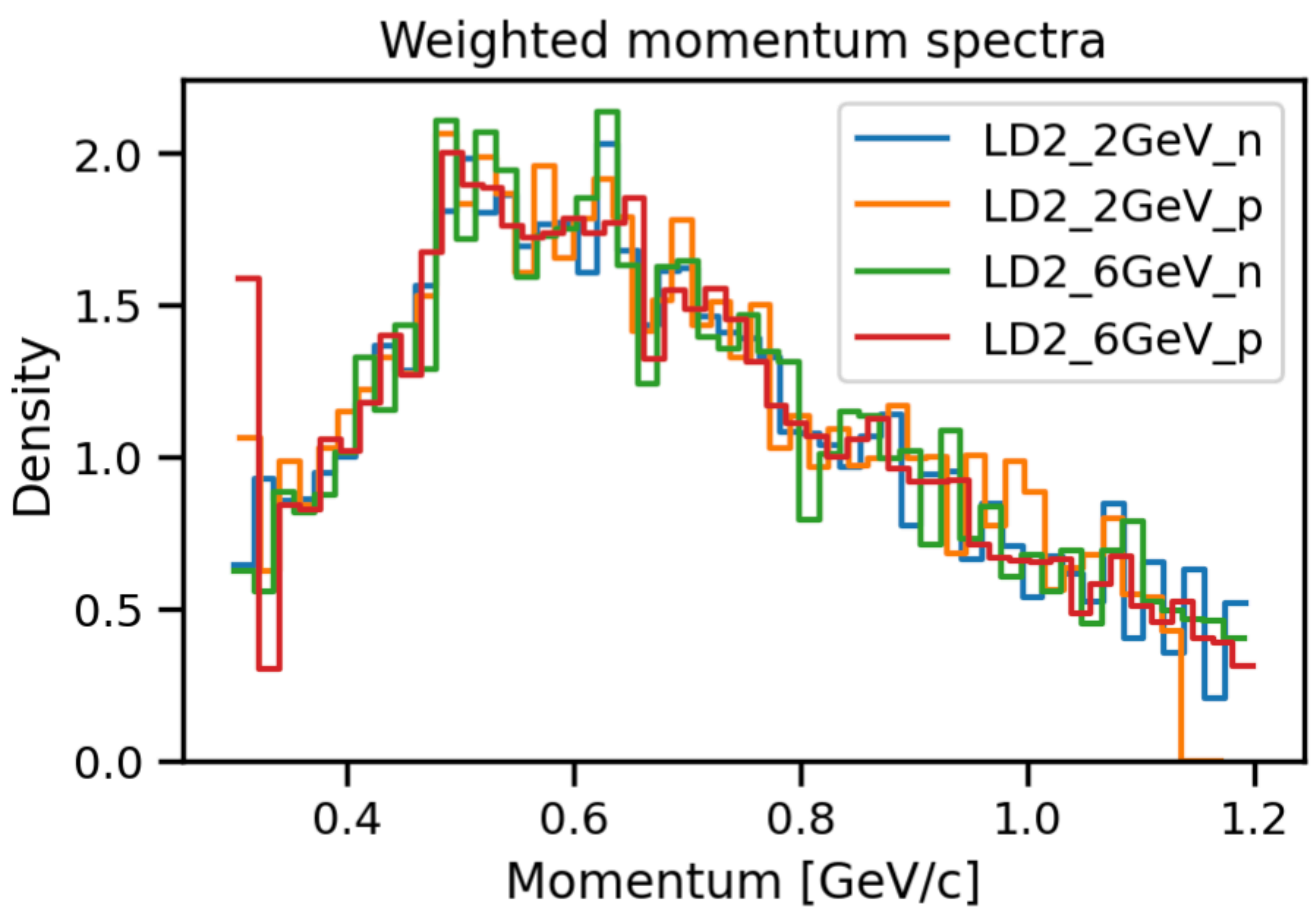
Feature Engineering Concerns:

1. Exclusive reactions constrain kinematics

→ Consider Deuterium data only for feature design

→ Reweight Deuterium data for equal momentum distributions





General variables to construct features:

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

Within N steps:

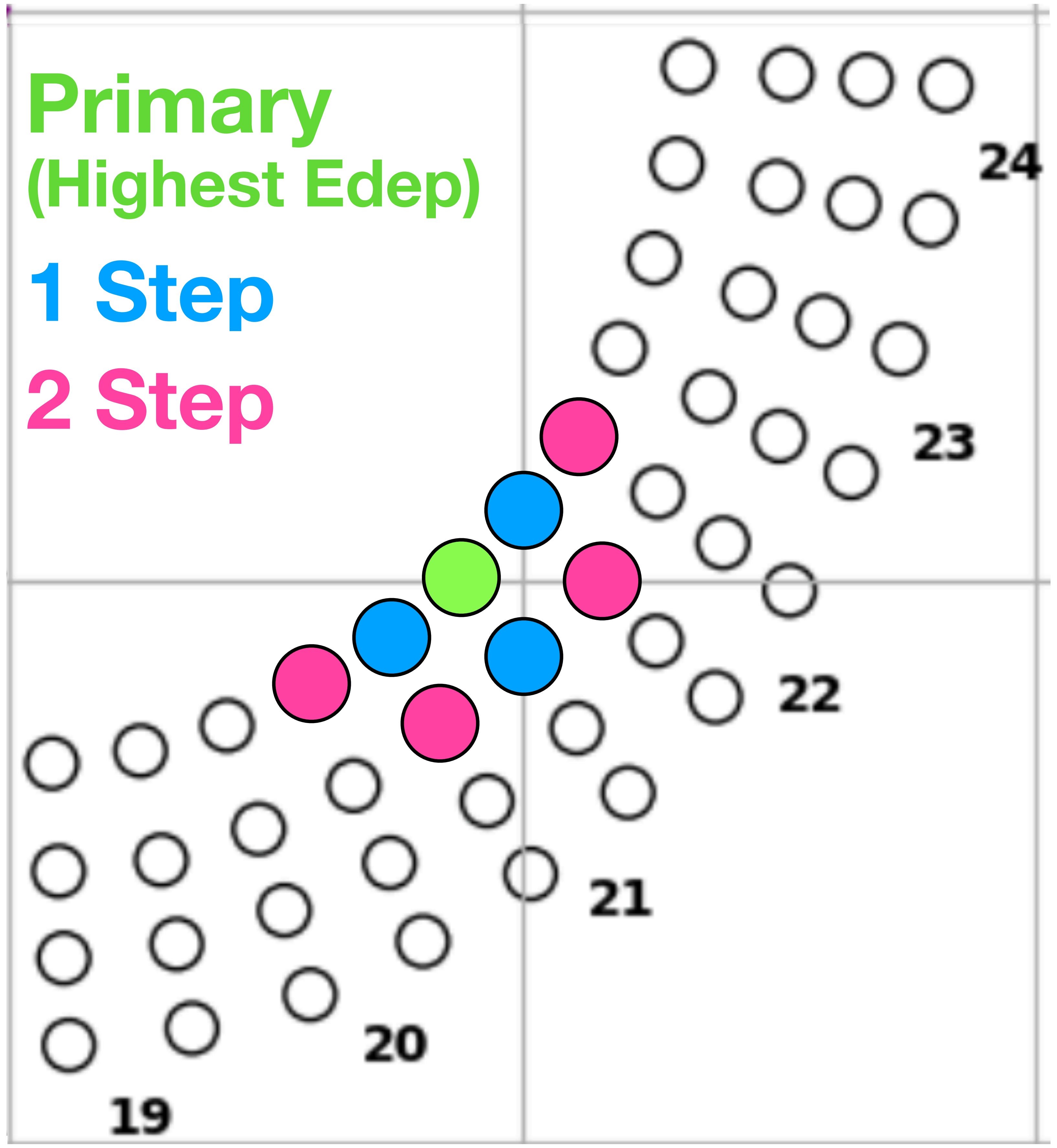
$\sum$ Hit energy

$\sum$ Hit multiplicity

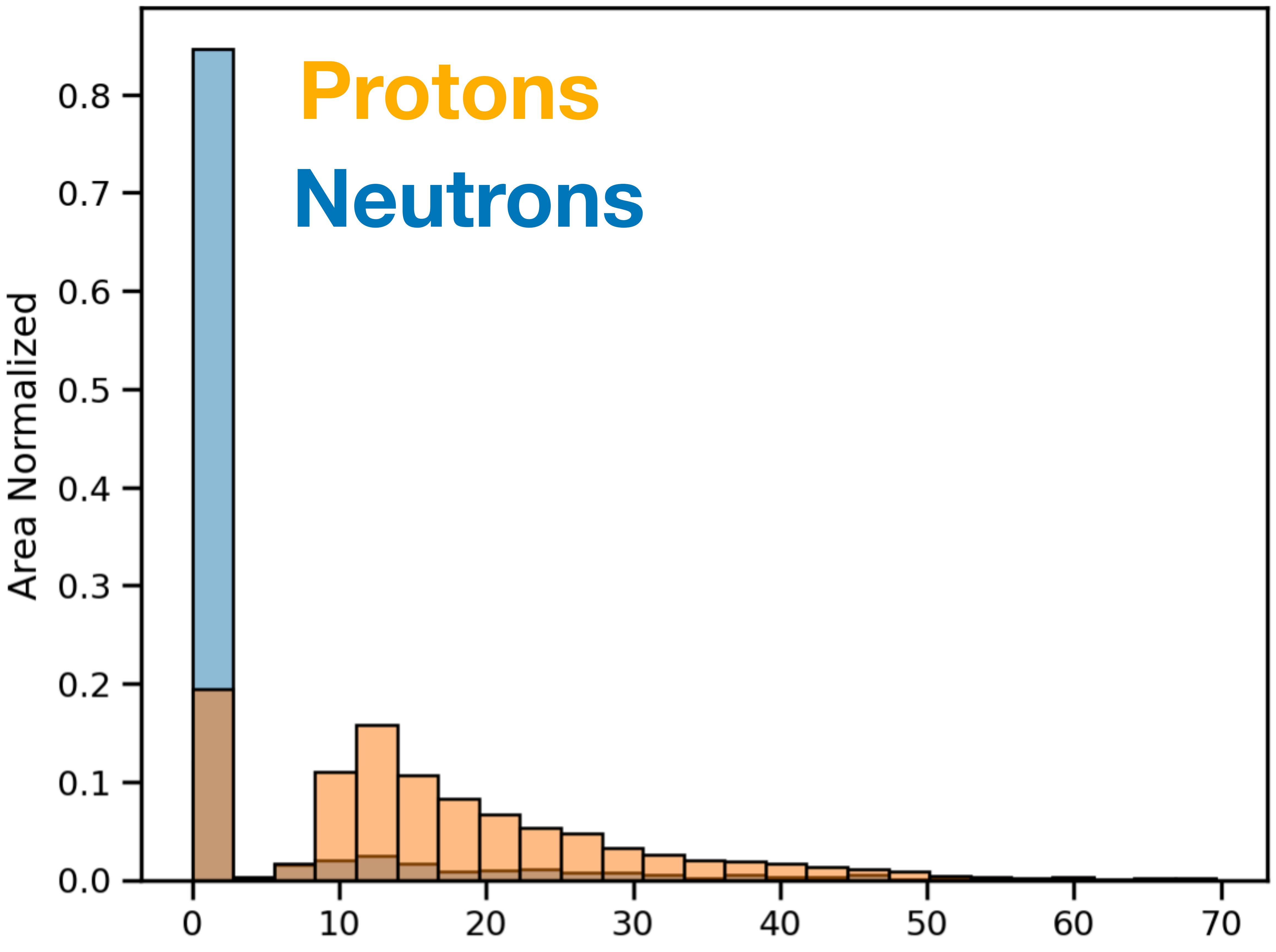
$< |\vec{r} - \vec{r}_{prim.}| >$

$\sum$ Hit energy / layer

Scintillator Components

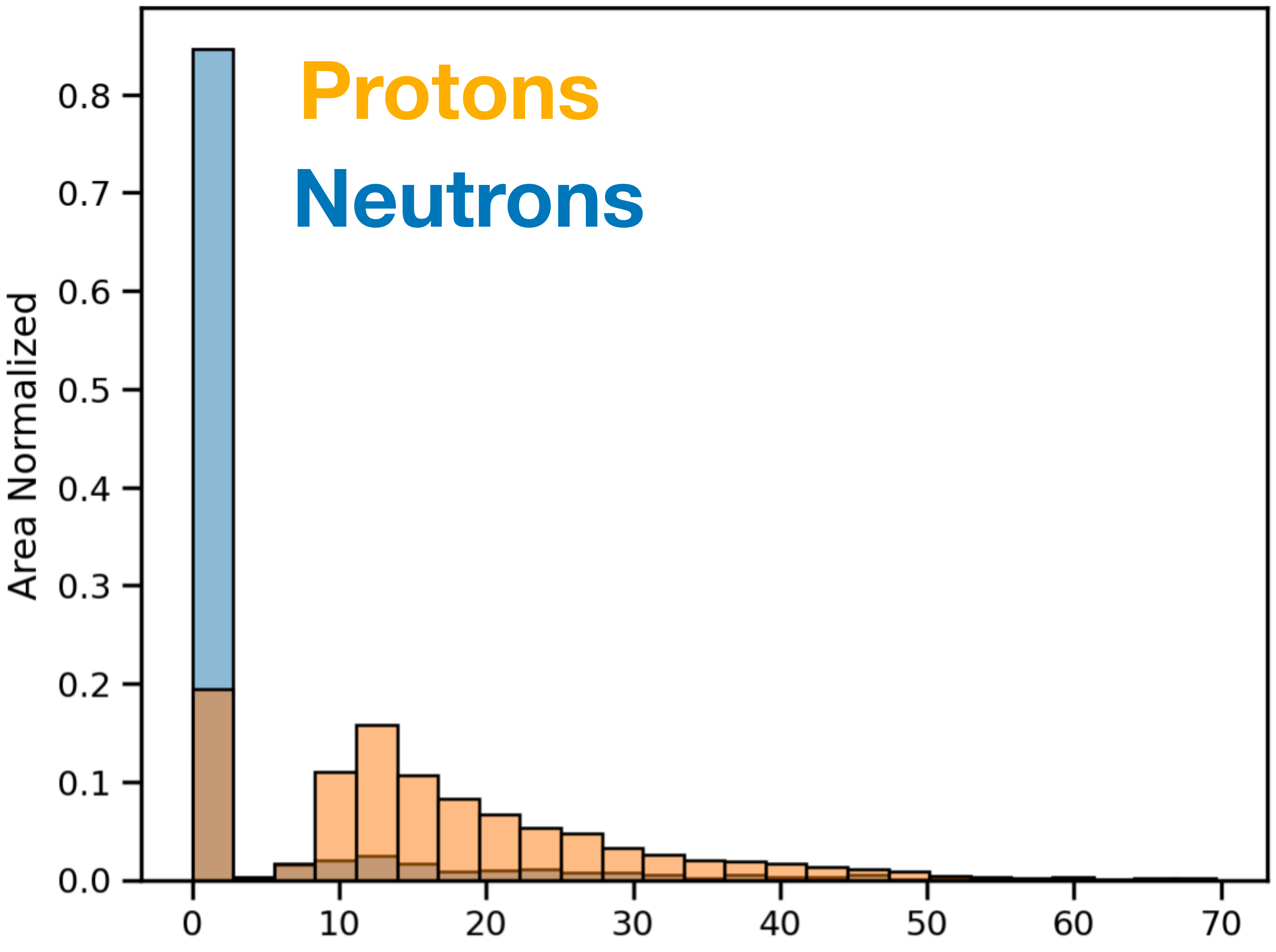


Top Feature Examples



Total CTOF Edep in 3 Steps

Top Feature Examples



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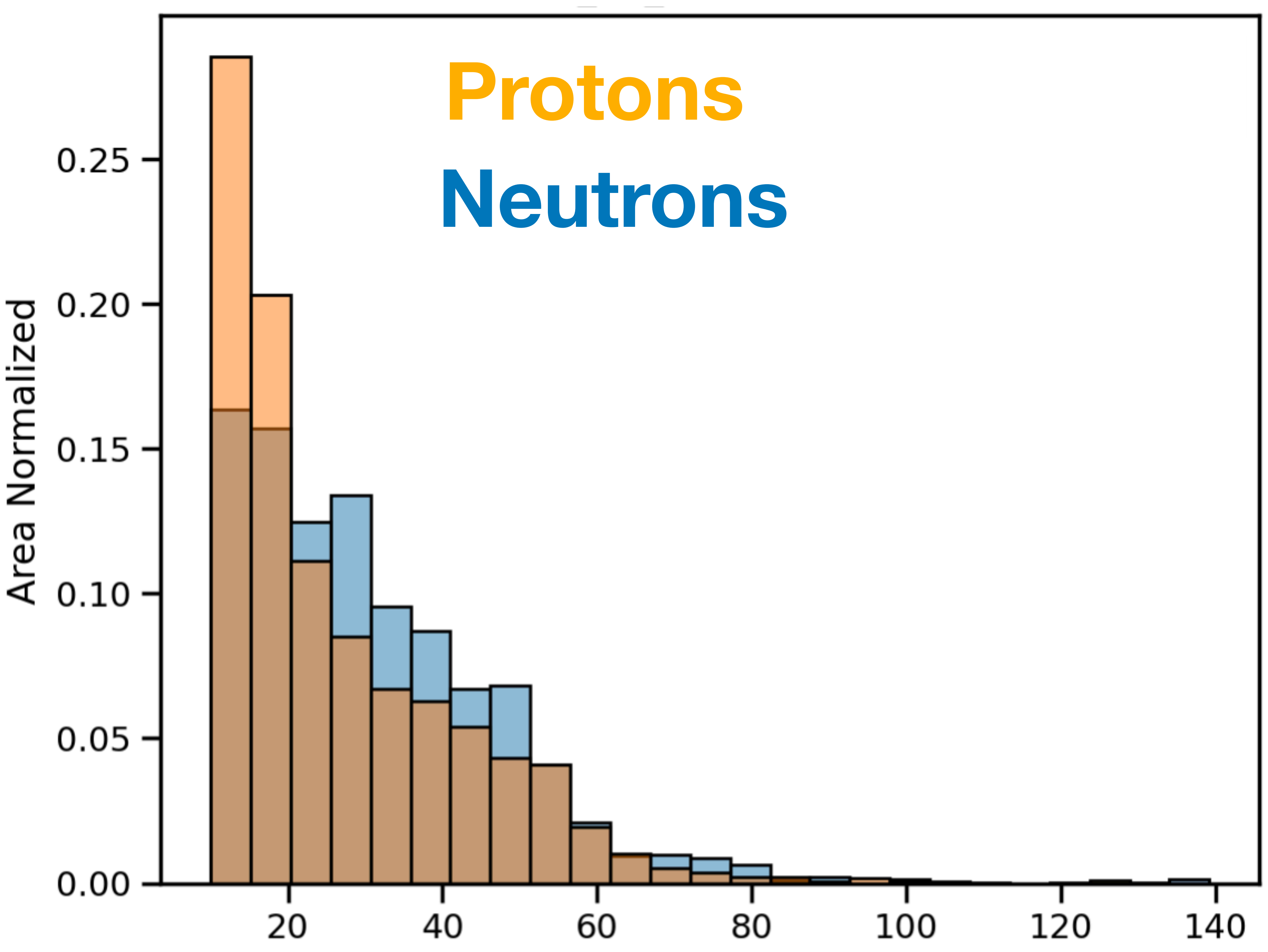
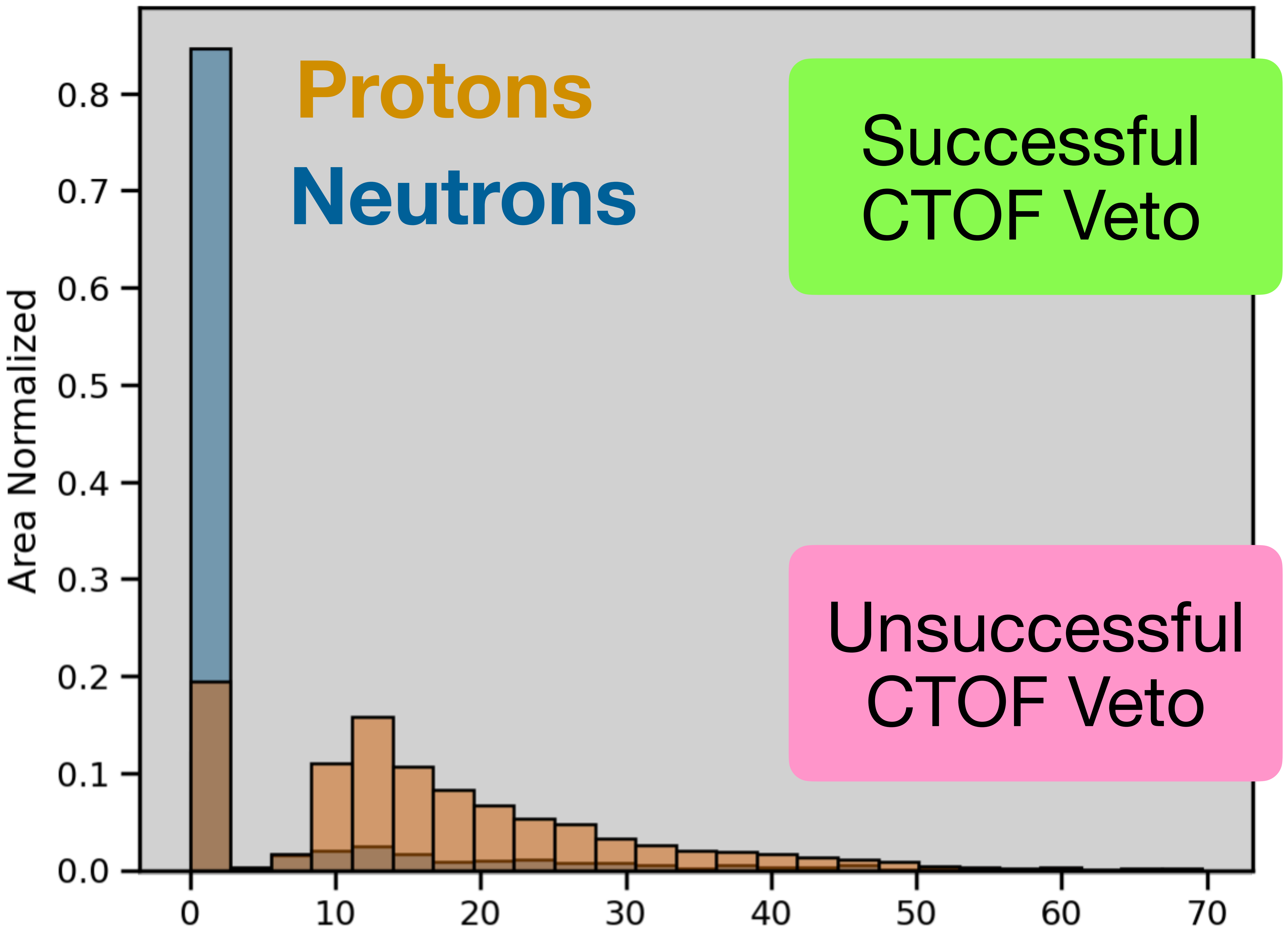


Primary CND Hit Energy

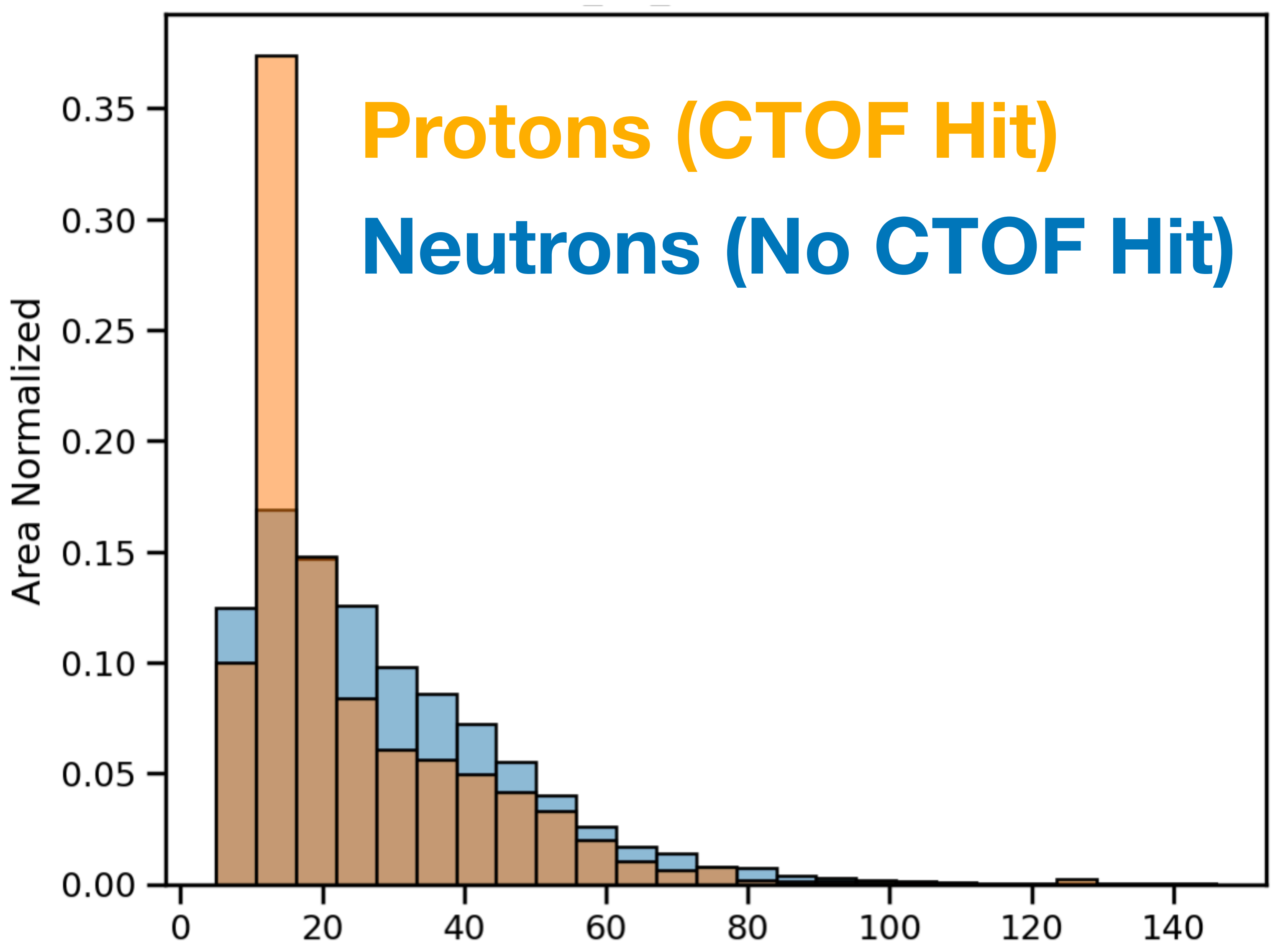
Top Feature Examples

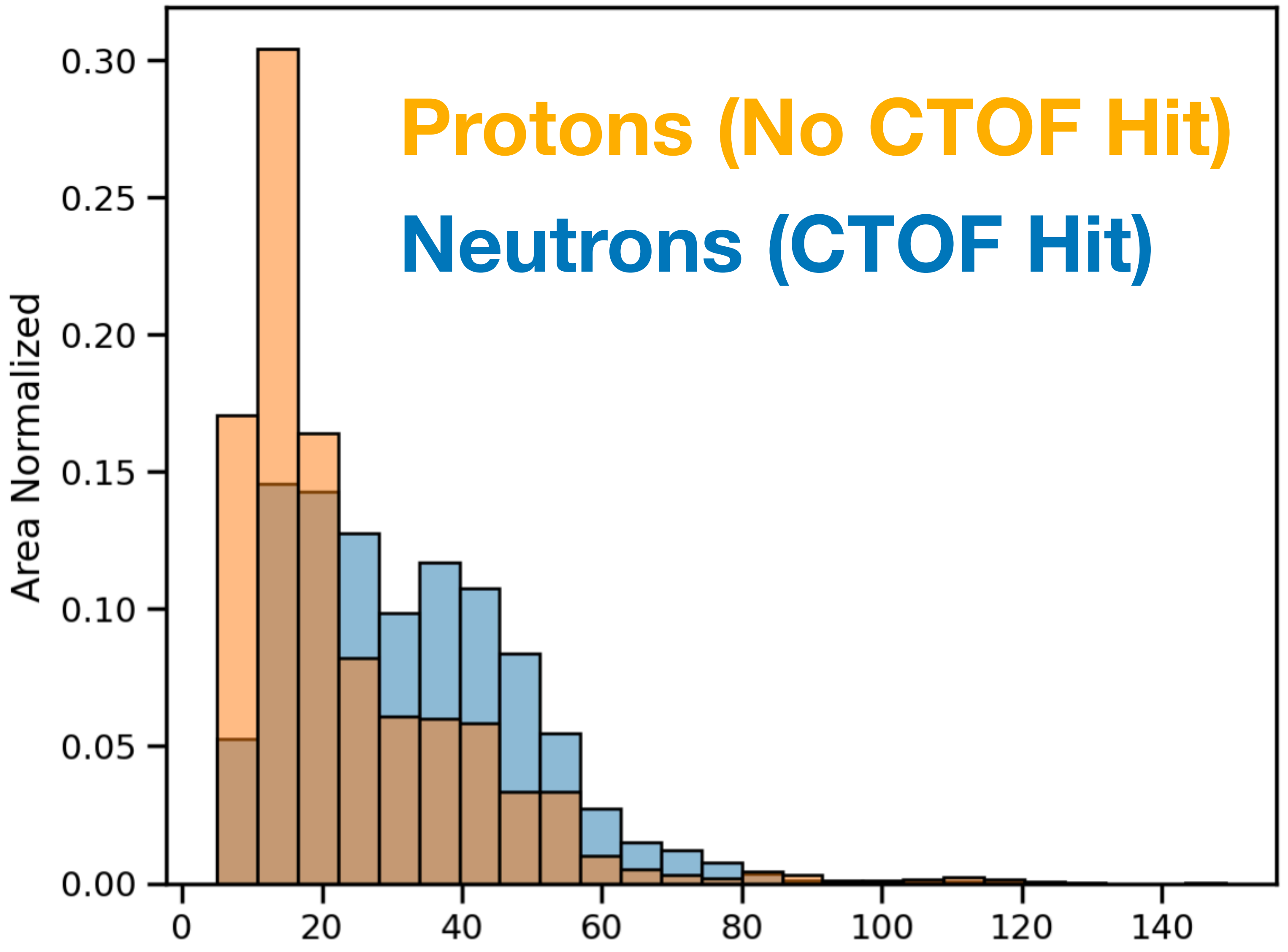


Total CTOF Edep in 3 Steps

Successful CTOF Veto

Unsuccessful CTOF Veto





Primary CND Hit Energy

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Building the MLP

Hyperparameters tuned using 5-fold cross-validation:

1. Sweep parameter space

2. For each parameter value:

   - Train with 5 folds

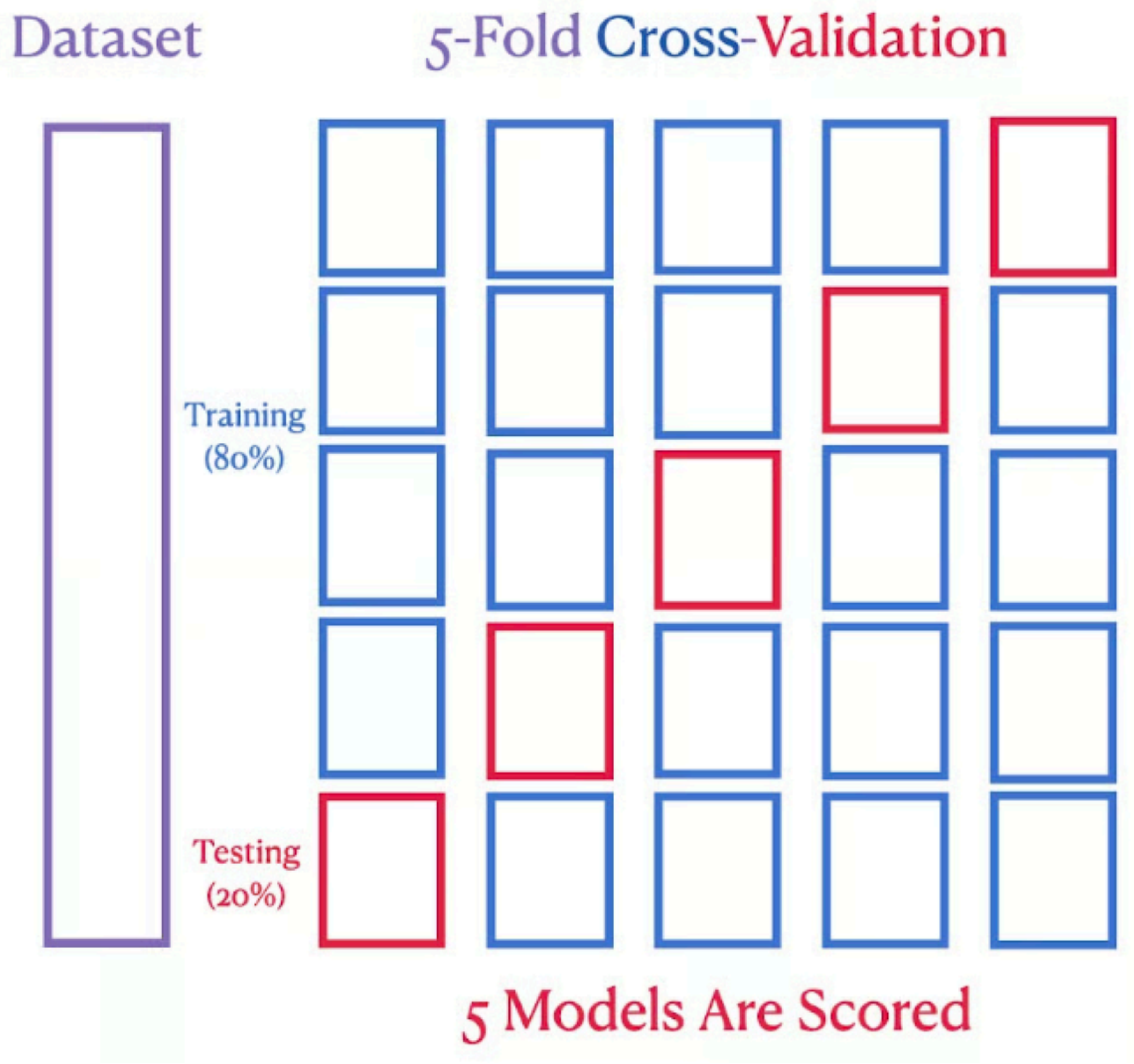
   - Log average model performance

→ Less dependence on choice of validation sample

Optimize for:

- Training Loss Plateau

- Validation Set Generalizability



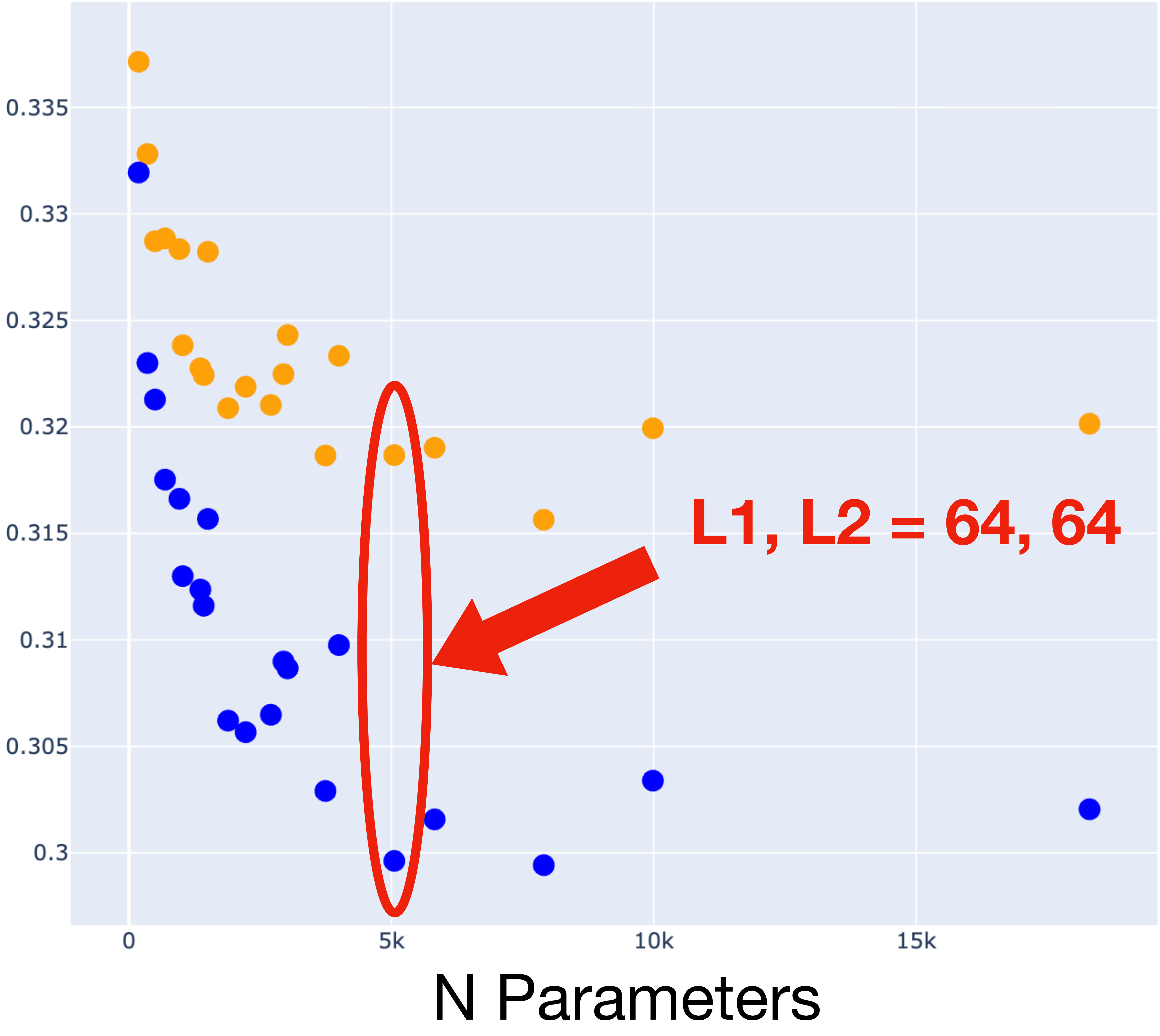
Building the MLP

As a start, 2 hidden layers with sweep over 8-256 neurons (Size L1 >= Size L2)

Optimize for:

Training loss plateau

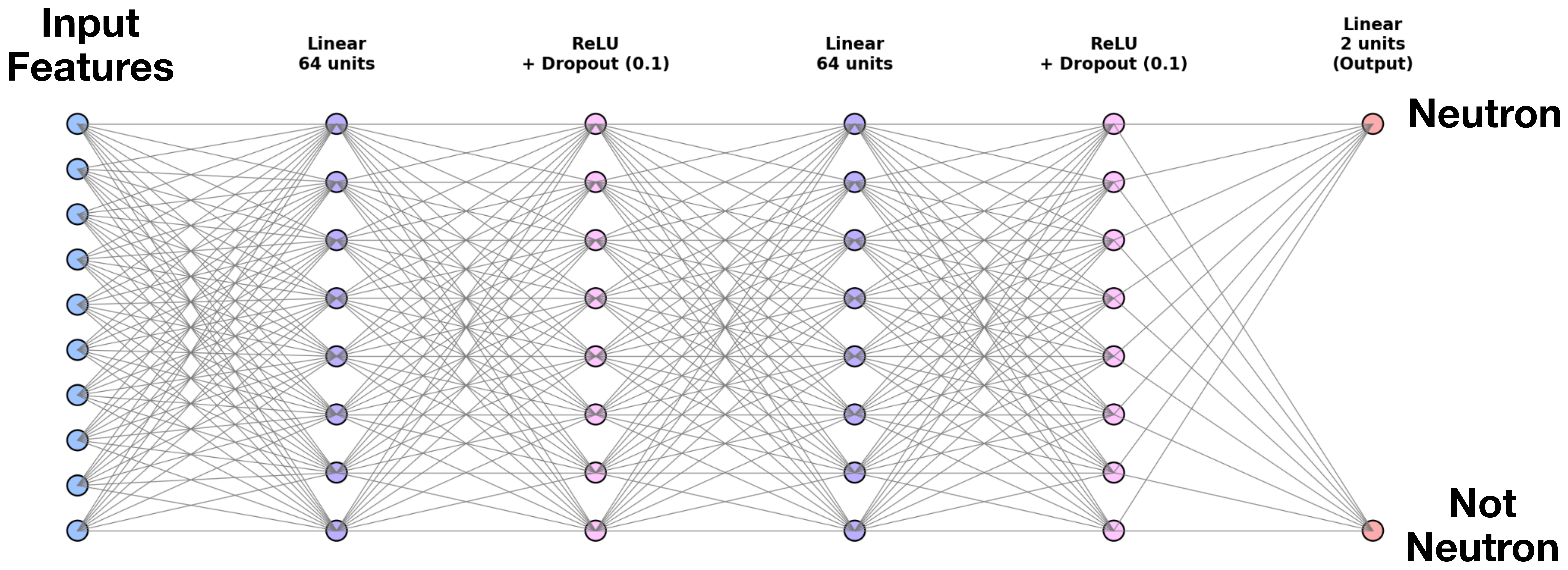
Validation set generalizability



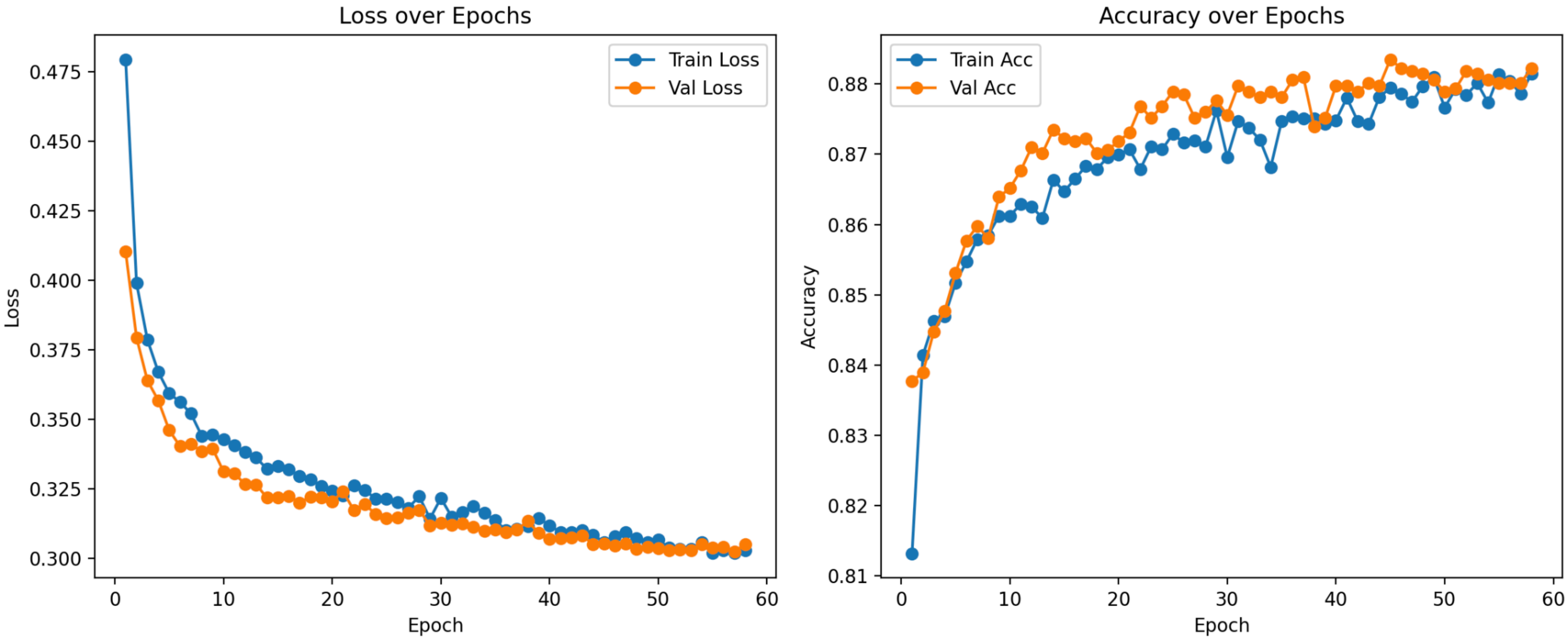
Building the MLP

After repeating the same procedure, land on the following params and structure:

Learning rate: 1e-3 Batch size: 16 Weight decay: 5e-5



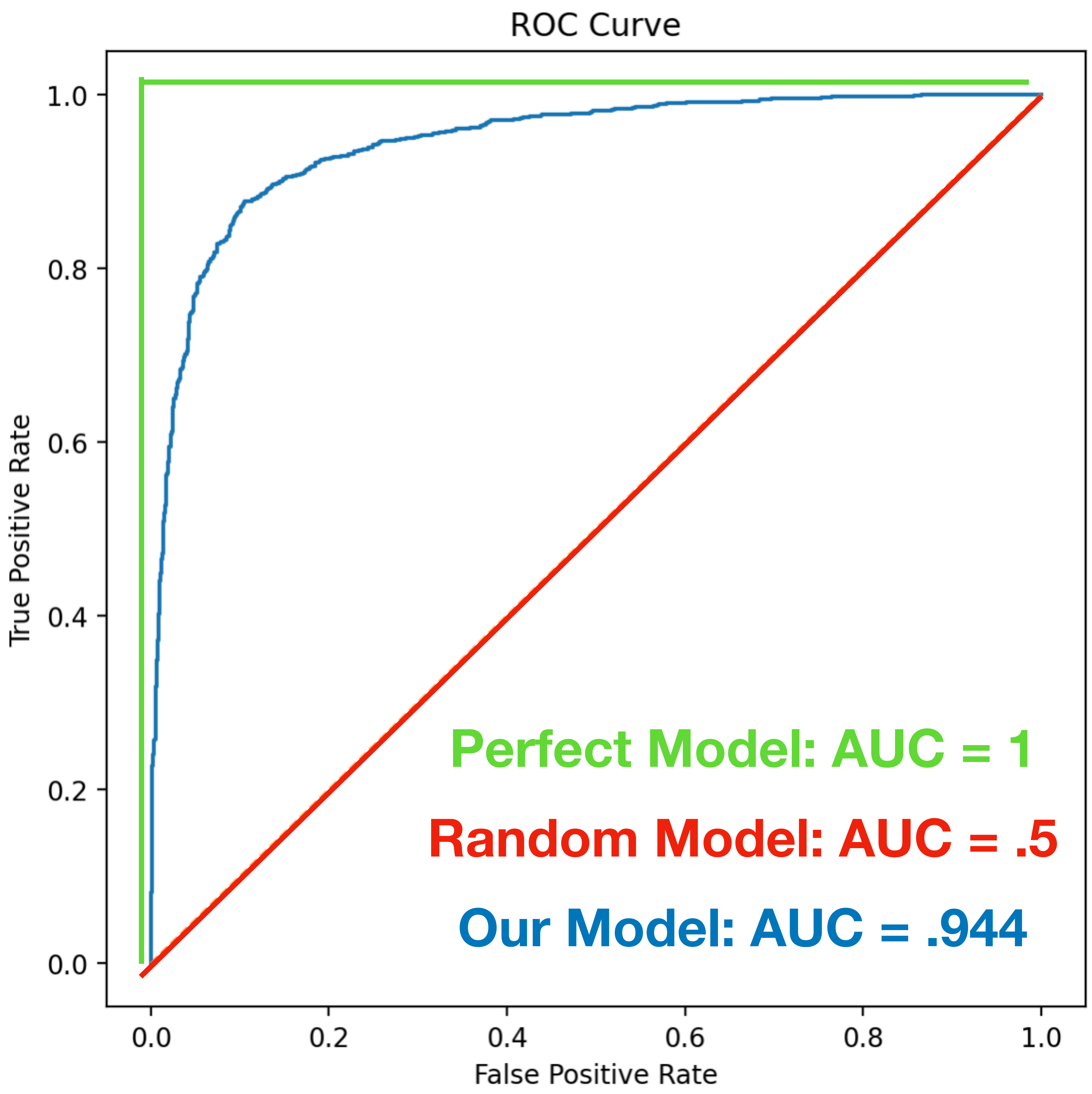
Final training with tuned hyperparameters:



Model Performance on Validation Set

From LD2 6 GeV validation set:

Proton Recall	Neutron Recall	Area Under Curve
0.897	0.872	0.944



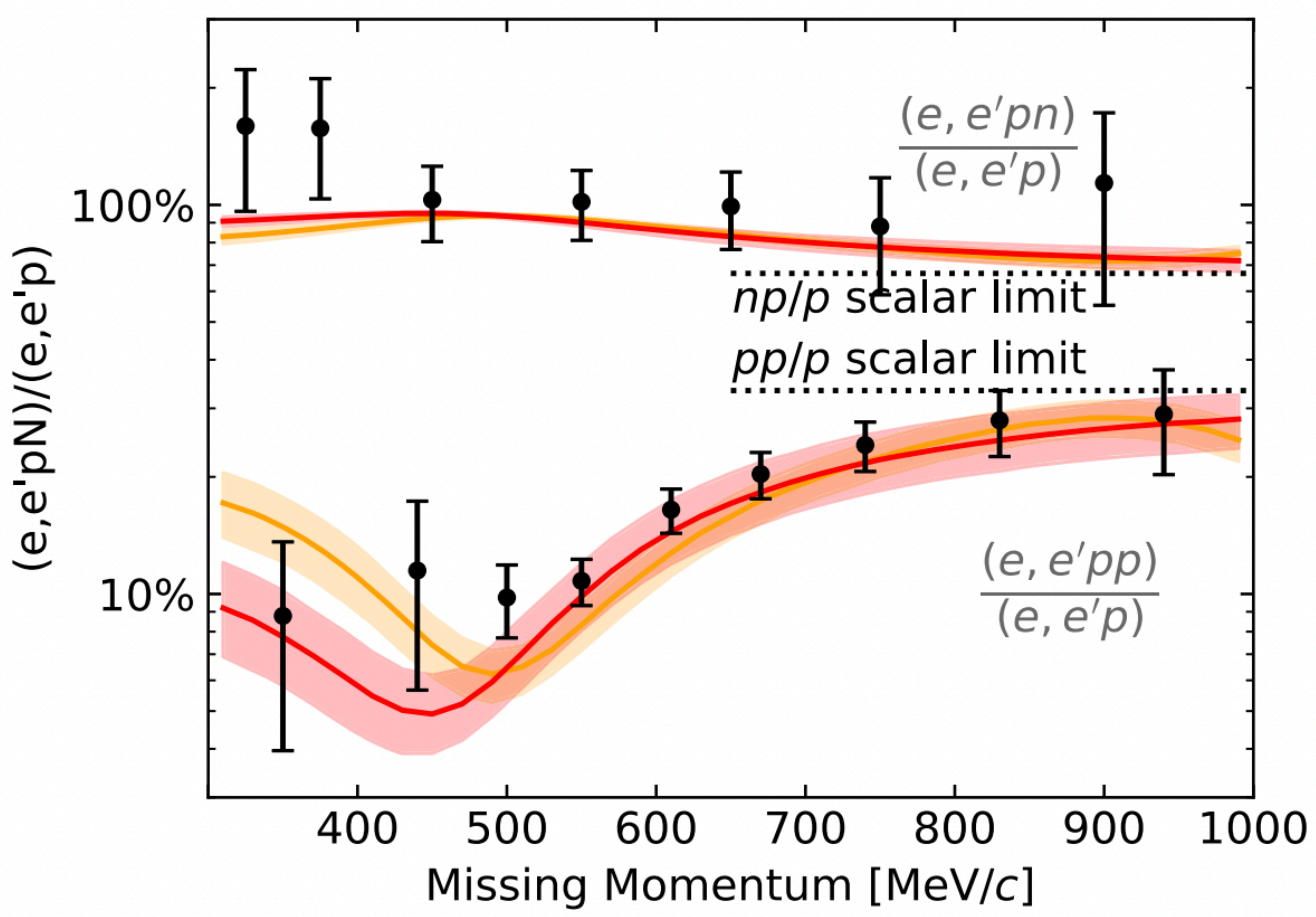
Model Performance on Exclusive Samples

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

Validation with New Helium-4 Data

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

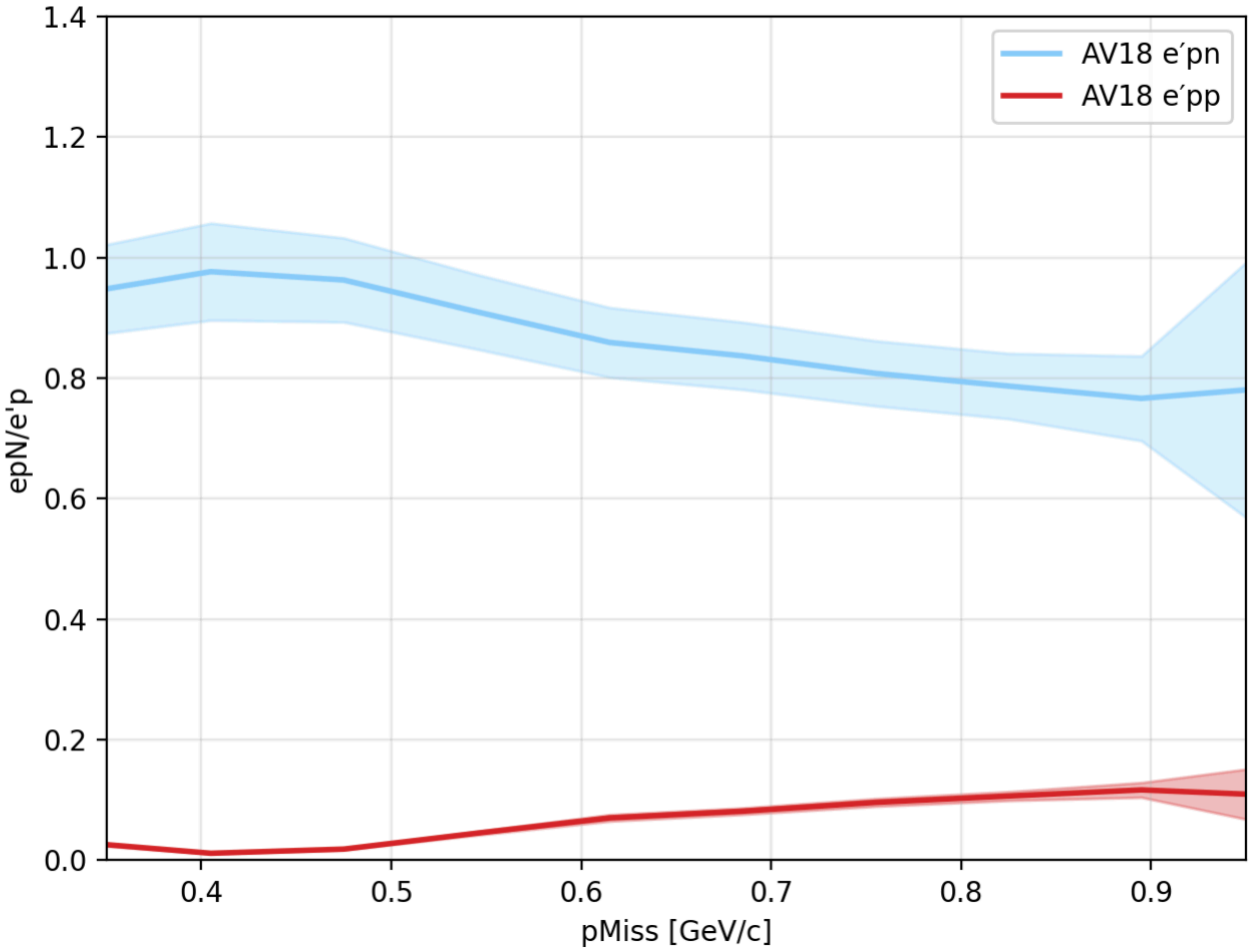


I. Korover *et al.* (CLAS Collaboration), Physics Letters B **820** (2021) 136523.

Validation with New Helium-4 Data

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

Model using AV18 interaction + nuclear transparency, single charge exchange



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

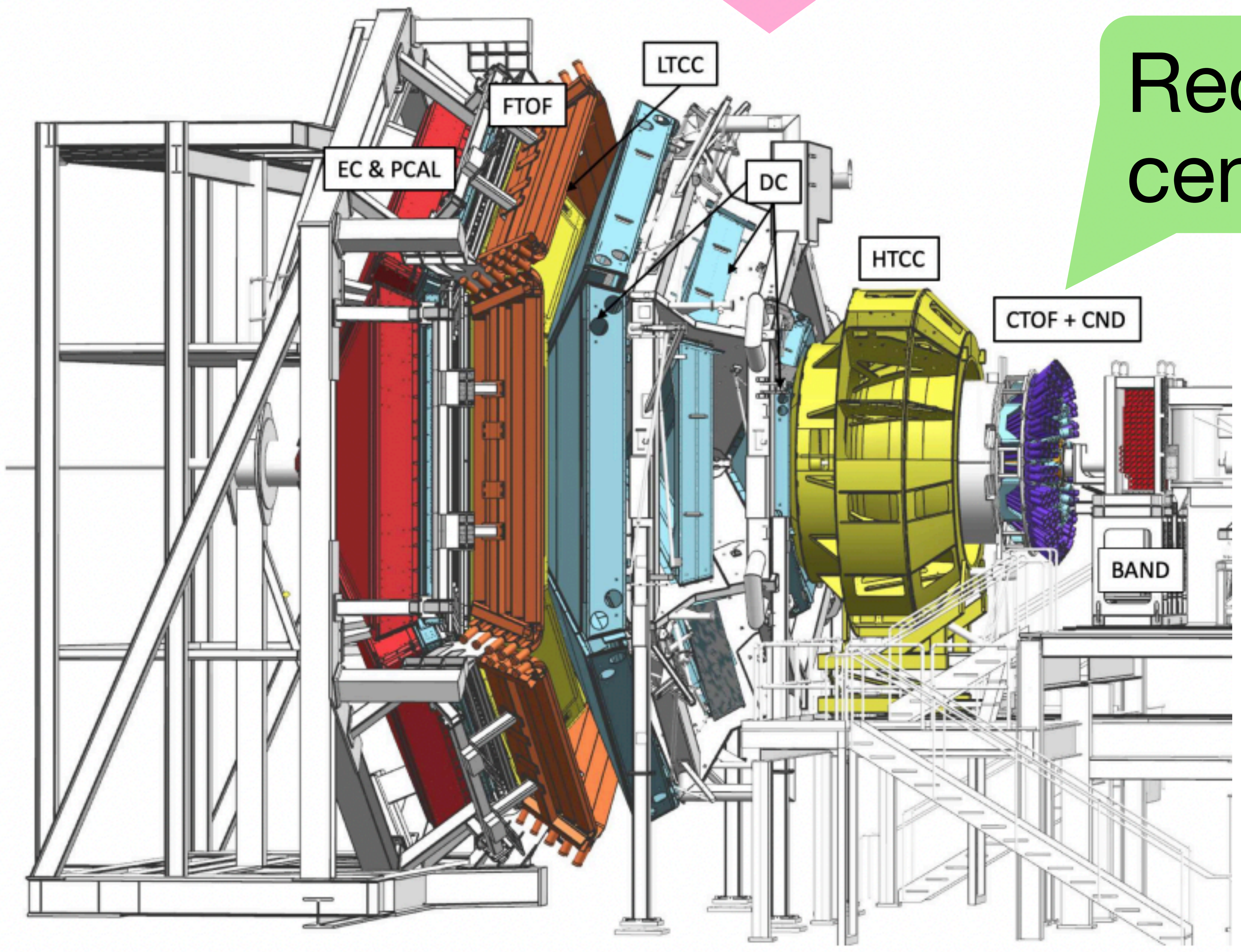
$.65 < m_{Miss} < 1.1$

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

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

Lead proton in forward detector

Recoil neutron in central detector



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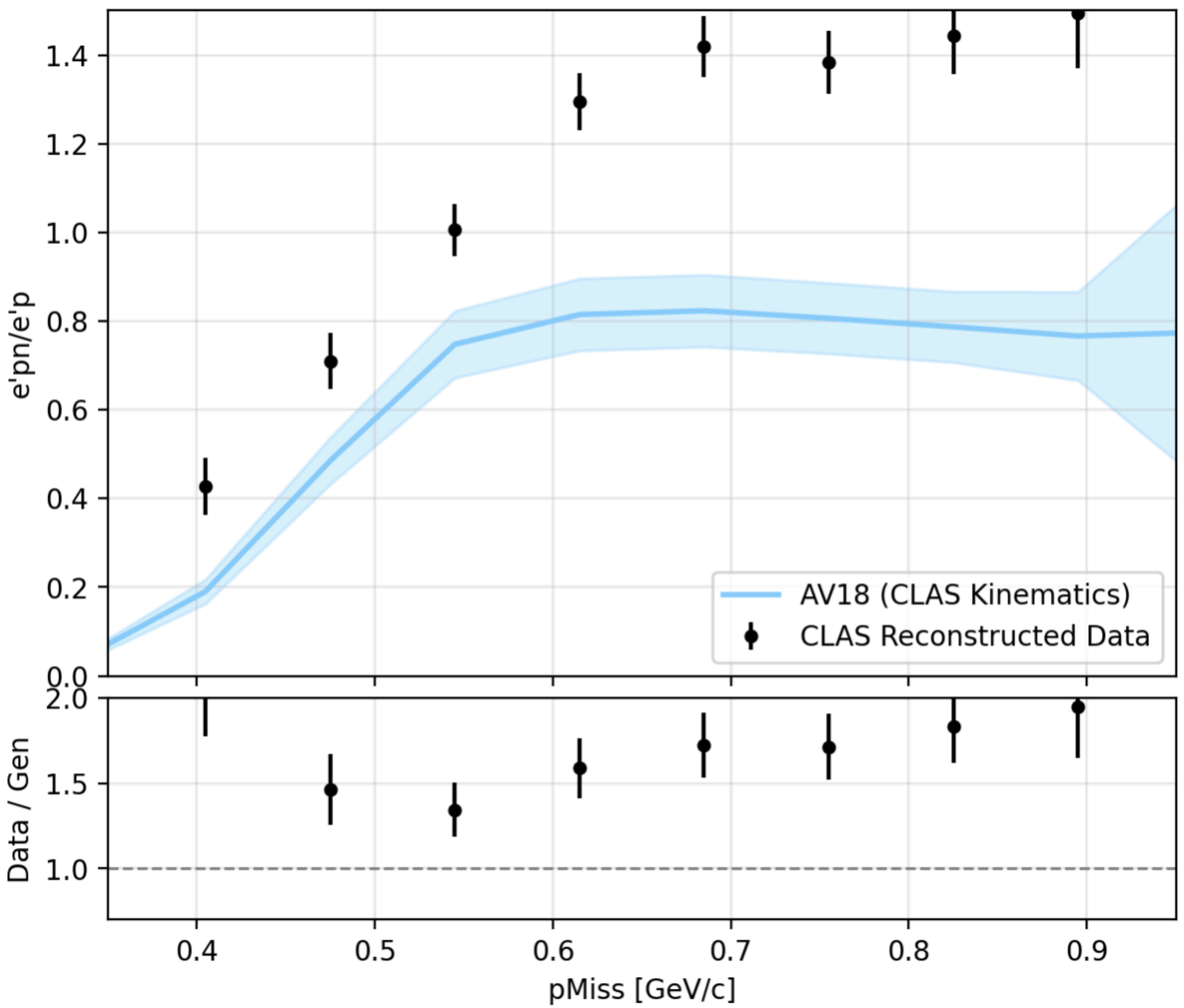

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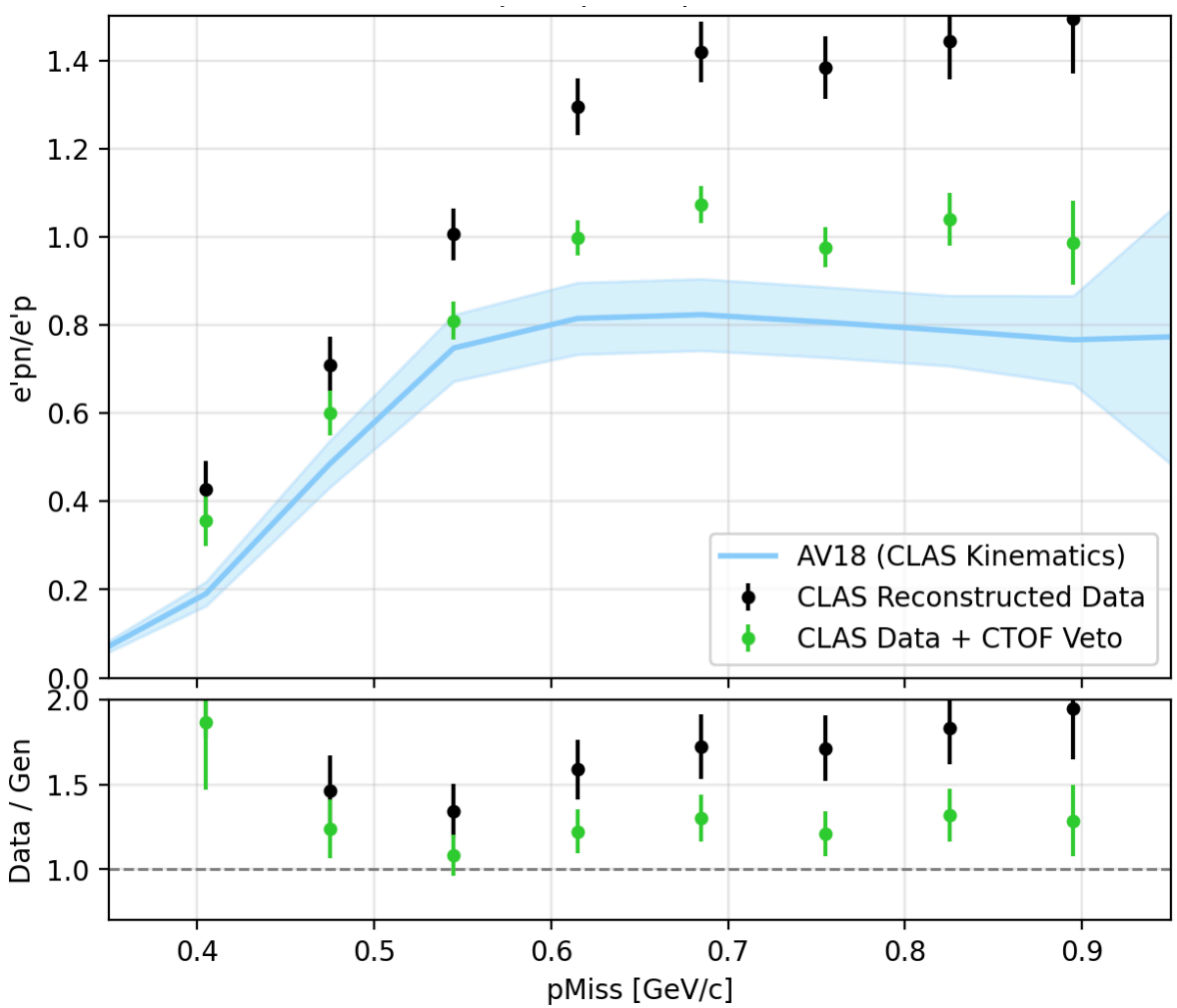

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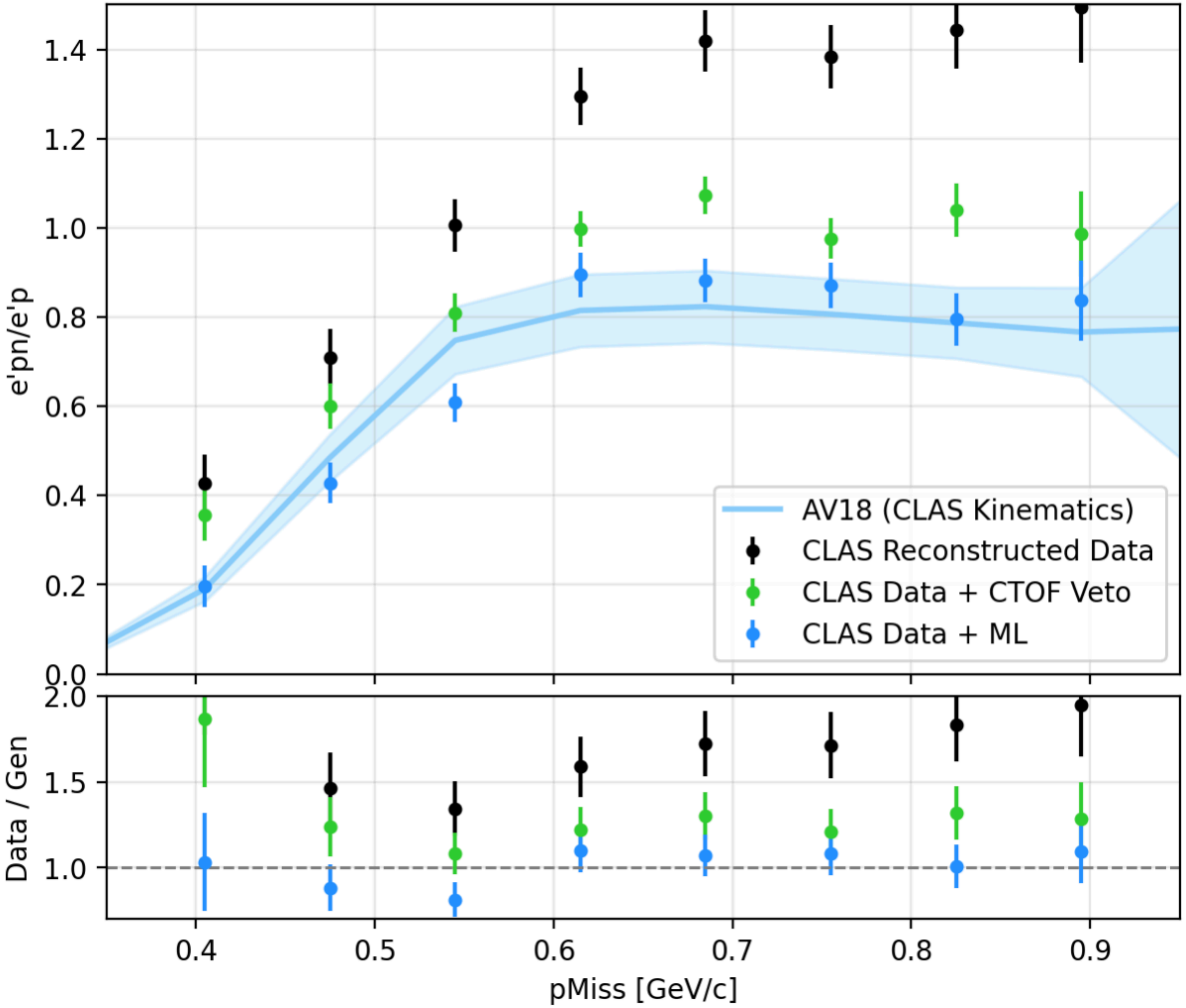

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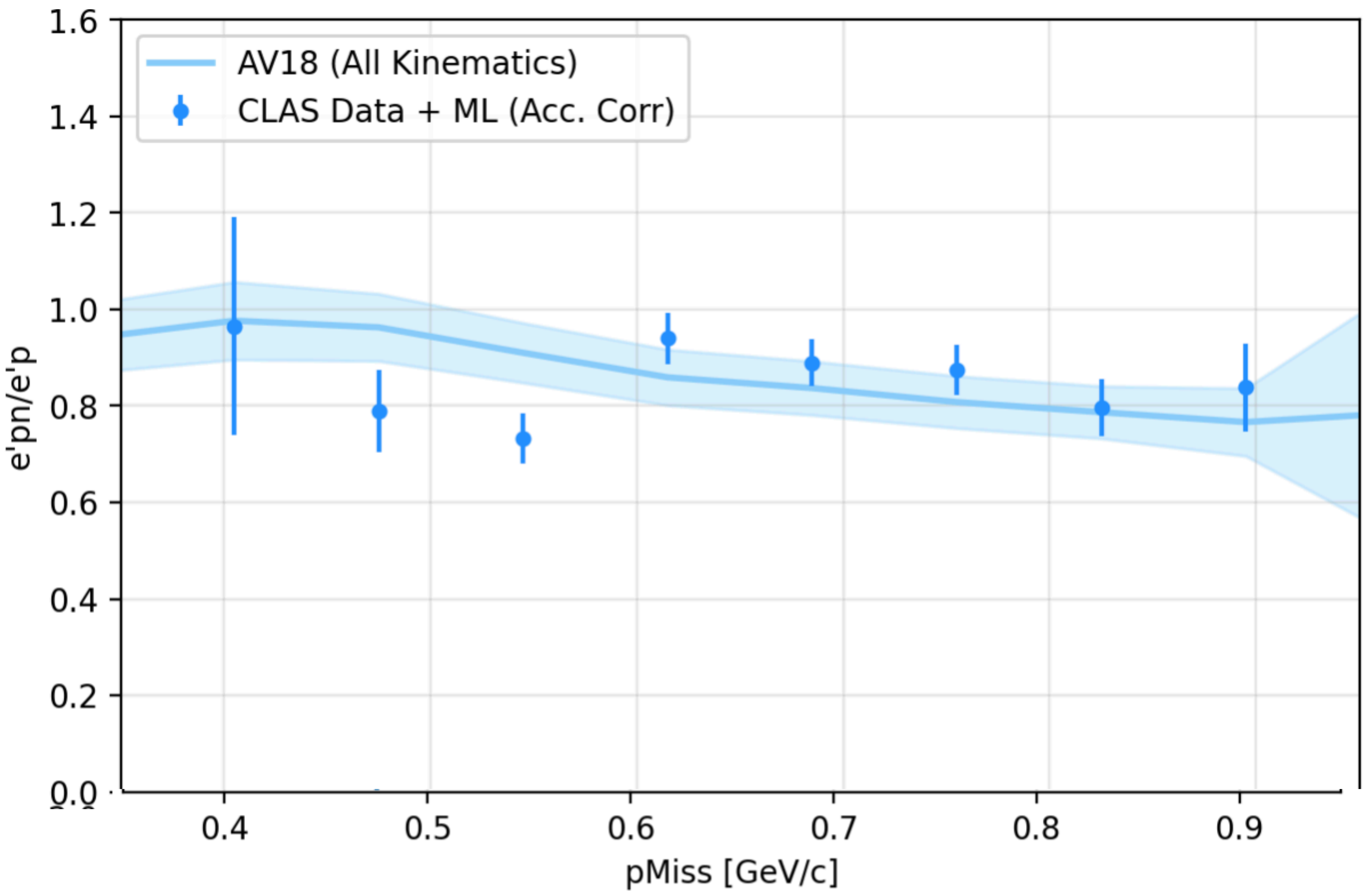
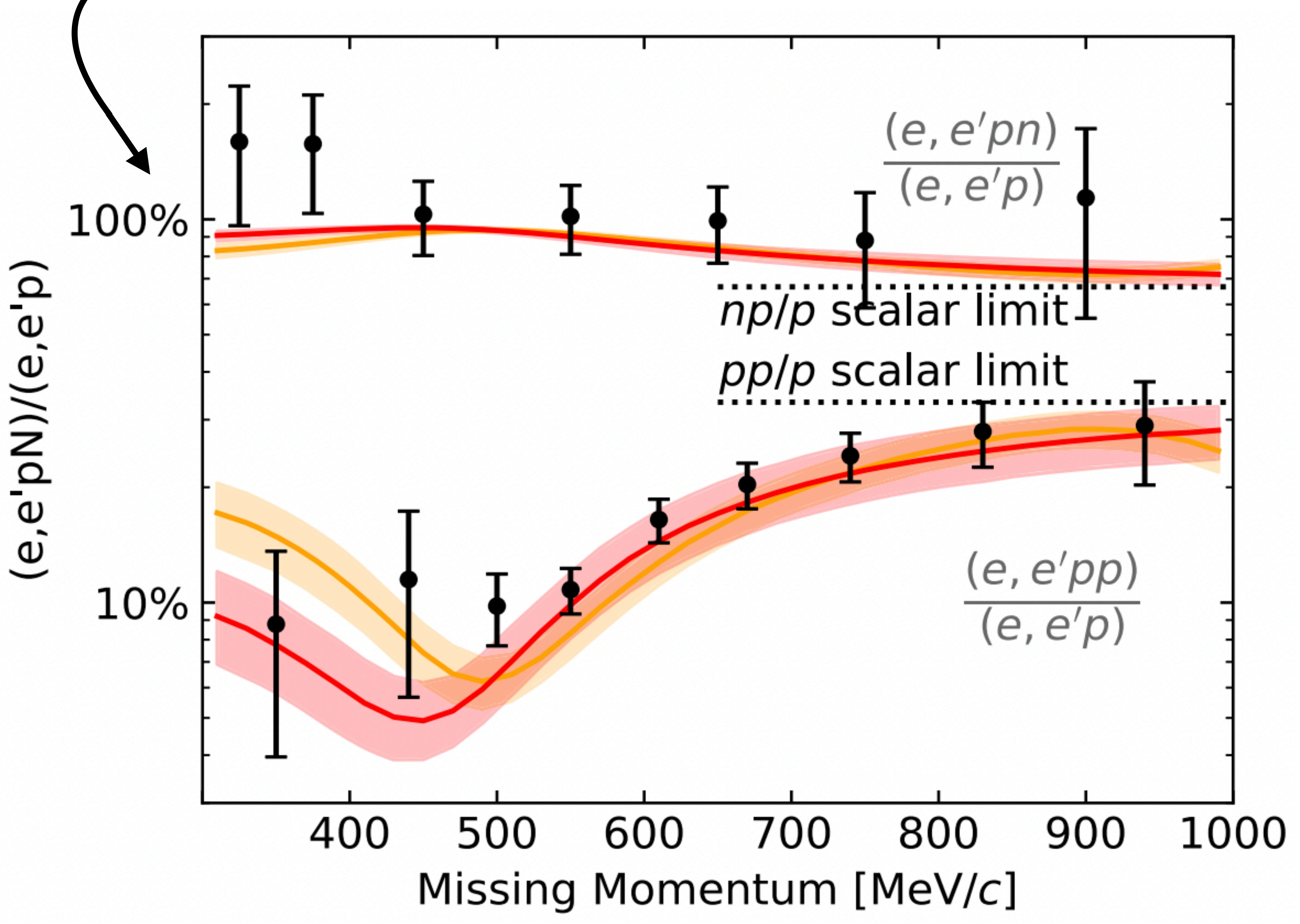


Note log scale



Summary + What's Next

ML Algorithm:

Successfully separates protons and neutrons

Accuracy can be improved with prediction confidences

SRC Pair Ratio Analysis:

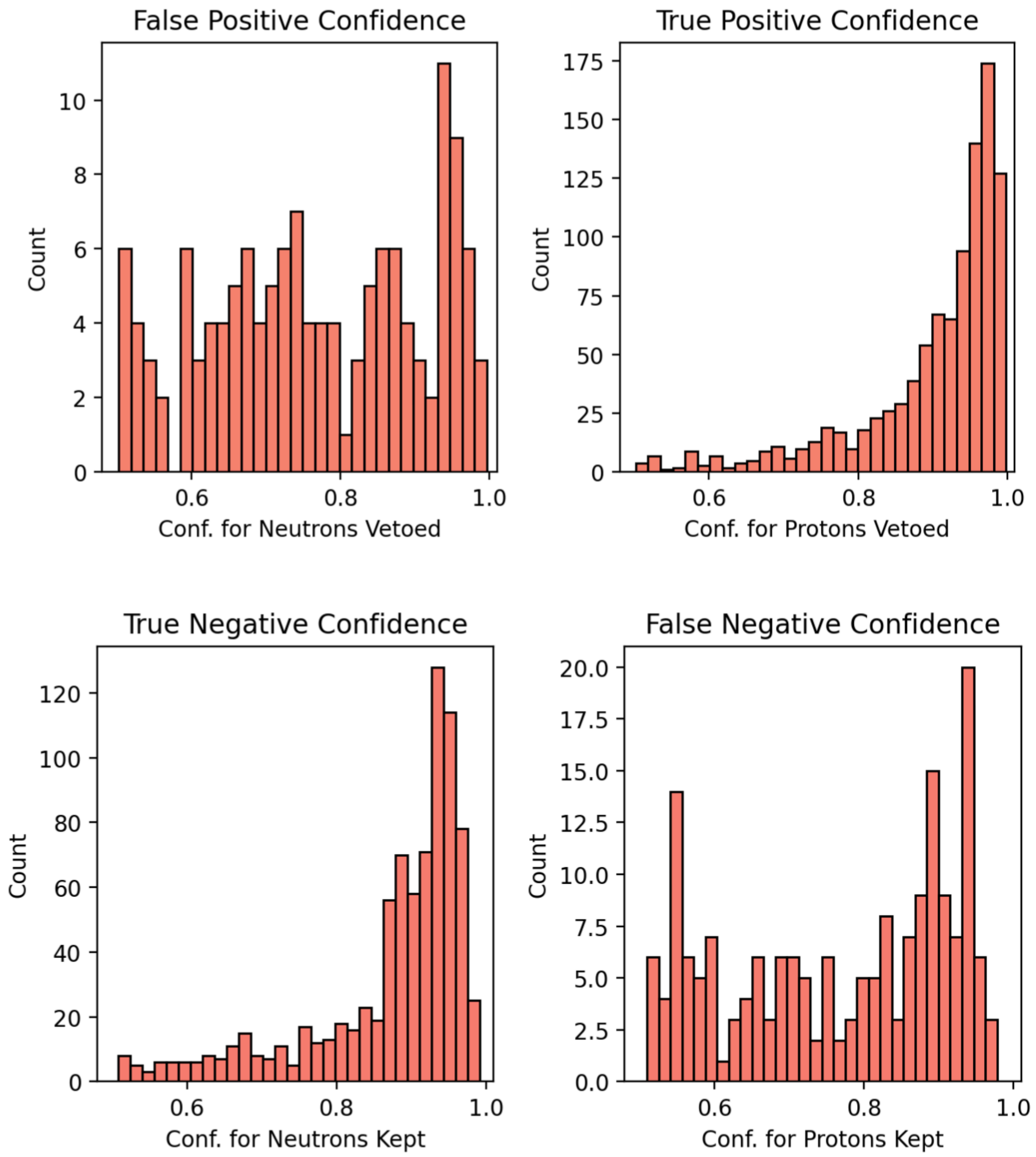
ML veto validated in 4He $e'pn/e'p$

More rigorous acceptance correction/GEANT

Extend to higher A

Beyond:

Use for 3N search!



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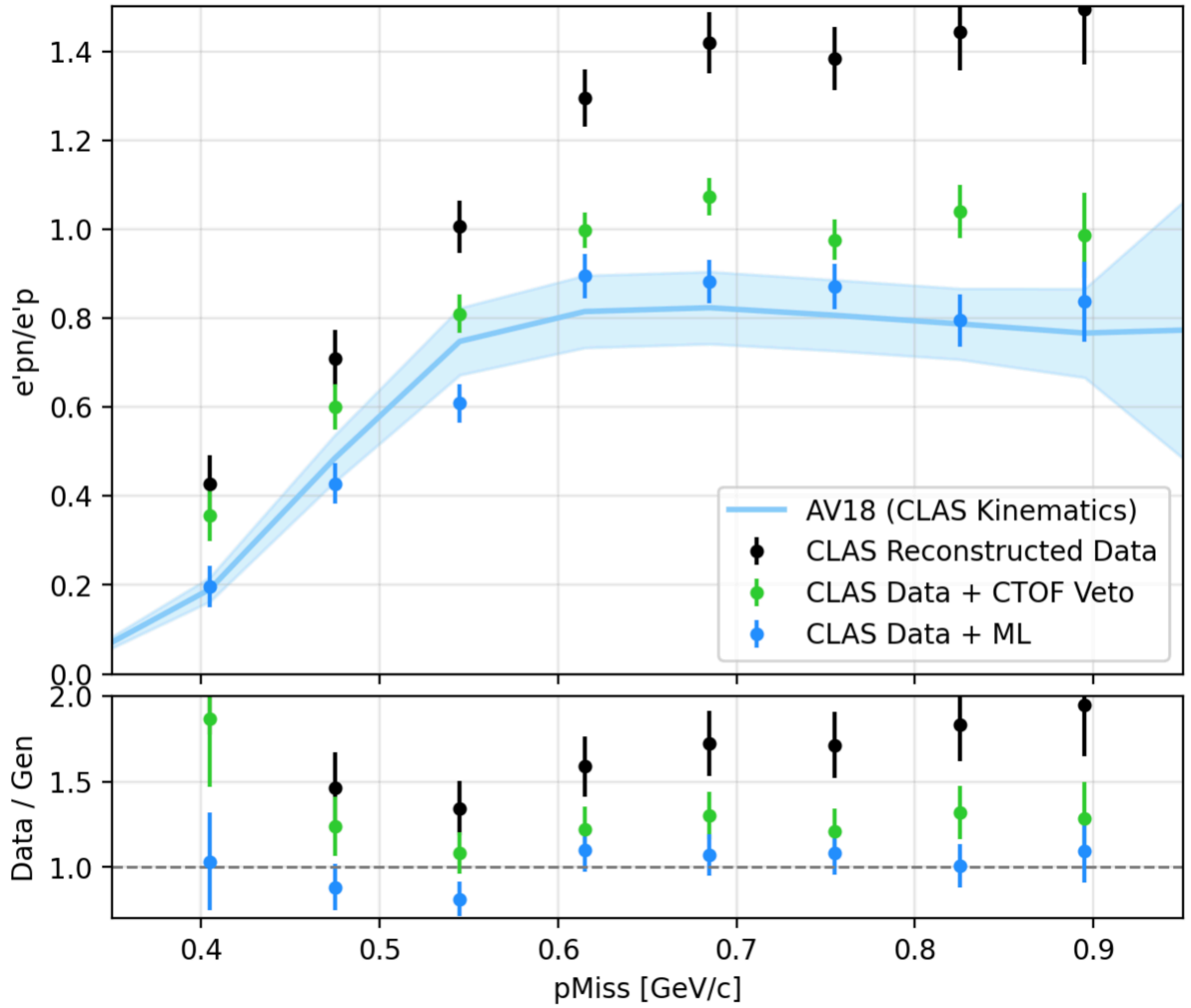

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