# Understanding the EMC effect with tagged DIS measurements

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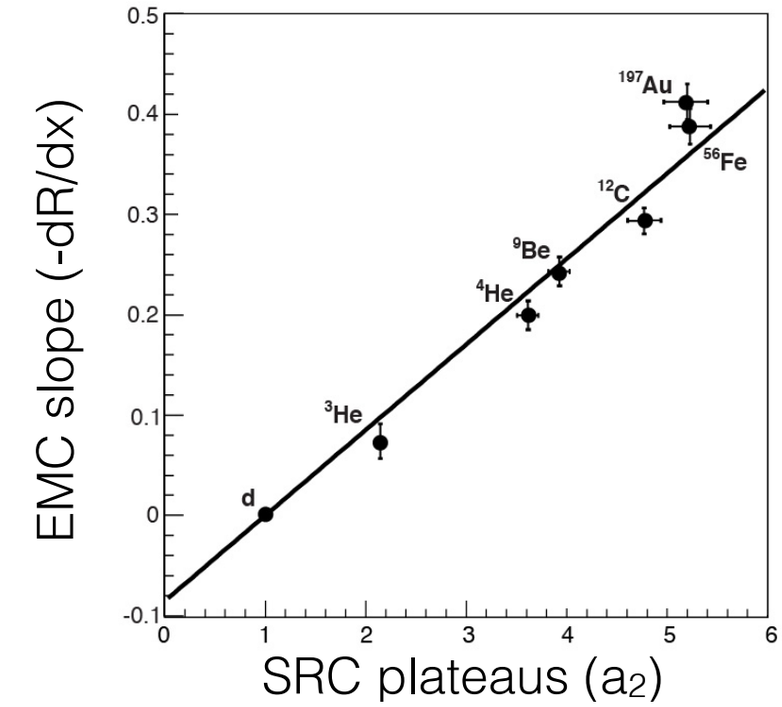
# EMC Effect: Need New Observables

- A lot of inclusive data but still a lot of models („every model is cool“)
- Previous Drell-Yan measurements excluded a set of models
- New observables:
  - PVDIS (see John’s talk)
  - EMC effect on polarized target
  - Tagged DIS measurements —> directly probes EMC-SRC correlation and isospin dependence

# Why Tagged DIS Measurements?

Weinstein et al., PRL 106, 052301 (2011)
Hen et al., Rev. Mod. Phys. 89, 045002 (2017)



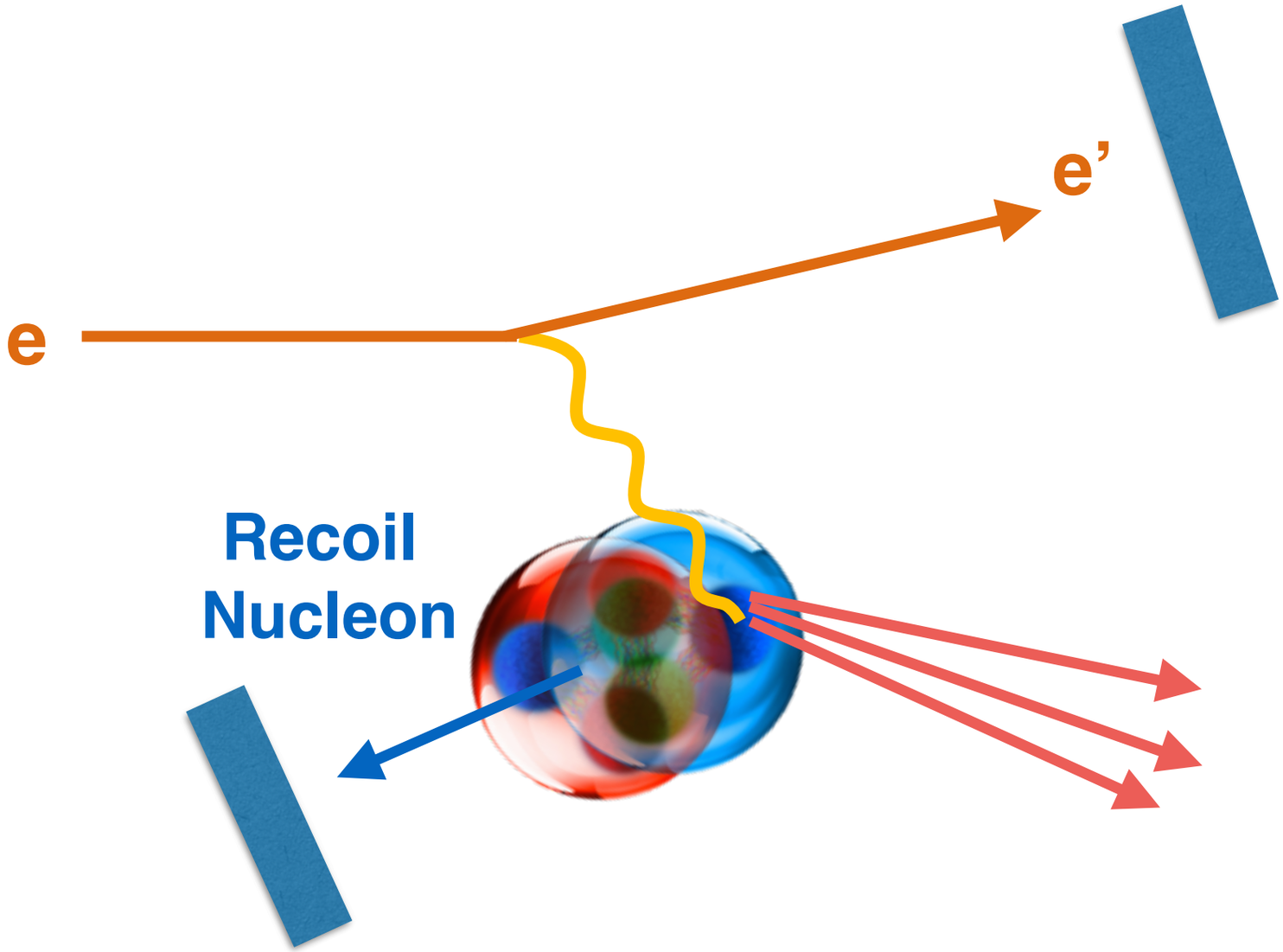

- Assume: EMC effect driven by DIS scattering off SRC nucleon

- „Tag“ SRC nucleon not part of the interaction to select initial state

- Determine nucleon modification for high nucleon momentum

—> New observable, expect strong modification

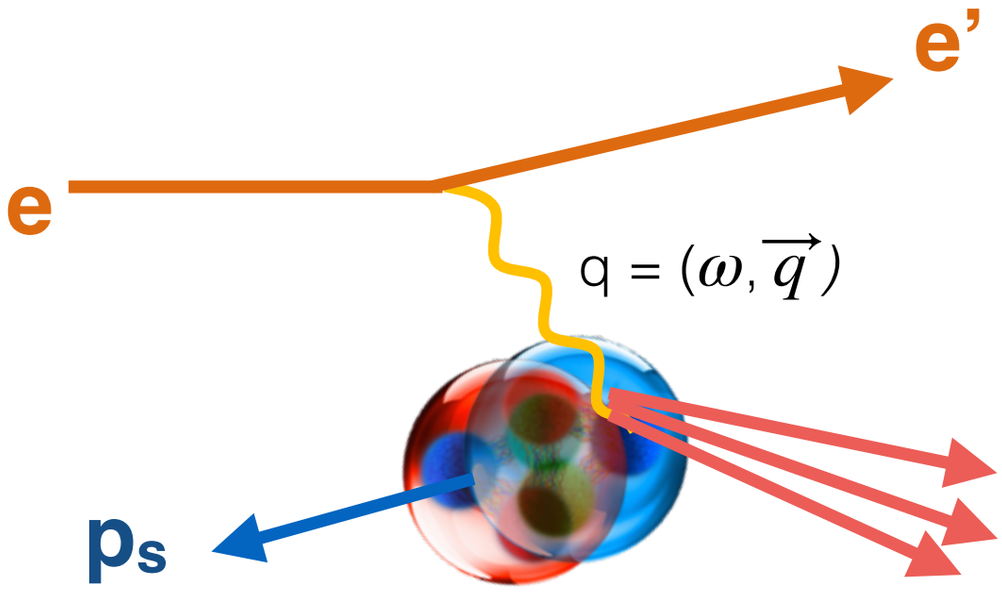
# Simplest Case: Tagged DIS with Deuterium




**Electrons** (DIS)

**Fragments of struck nucleon**

# Tagging Kinematics 101



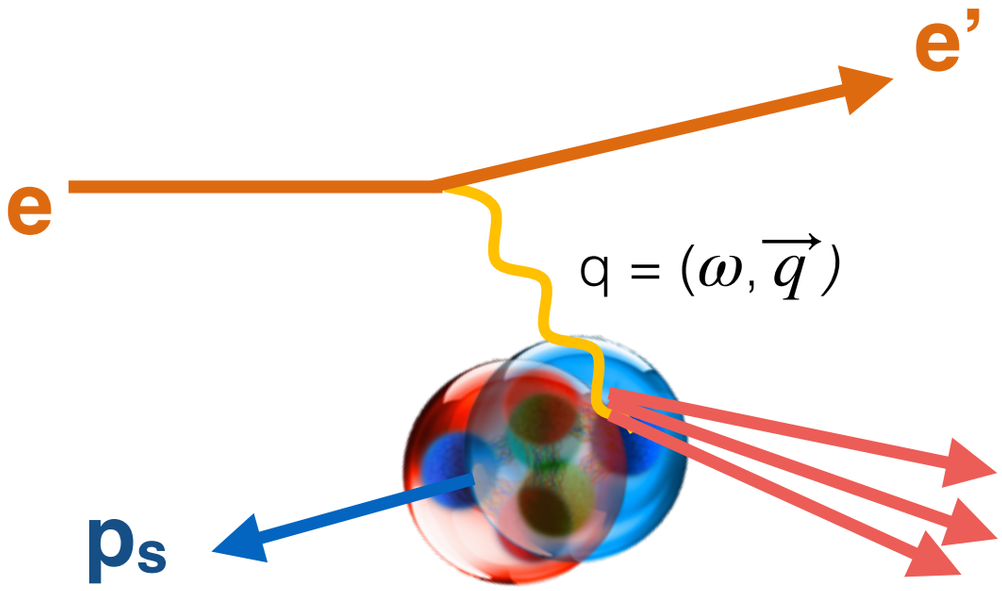

$$Q^2 = -q^2 = |\vec{q}|^2 - \omega^2$$

Standing nucleon $P_0 = (m_n, 0)$

$$(W)^2 = (P_0 + q)^2$$

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

# Tagging Kinematics 101




$$Q^2 = -q^2 = |\vec{q}|^2 - \omega^2$$

Standing nucleon $P_0 = (m_n, 0)$

$$(W)^2 = (P_0 + q)^2$$

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

Moving nucleon $P_\mu = (E, -\vec{p}_s)$

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

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

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

# Measure Tagged Ratio

$$R_{tag} = \frac{\sigma_{tag}^{exp}\left(Q^2, p_T, \alpha_S, x'\right) / \sigma_{tag}^{exp}\left(Q_0^2, p_T, \alpha_S, x' = x_0\right)}{\sigma_{tag}^{theory}\left(Q^2, p_T, \alpha_S, x'\right) / \sigma_{tag}^{theory}\left(Q_0^2, p_T, \alpha_S, x' = x_0\right)}$$

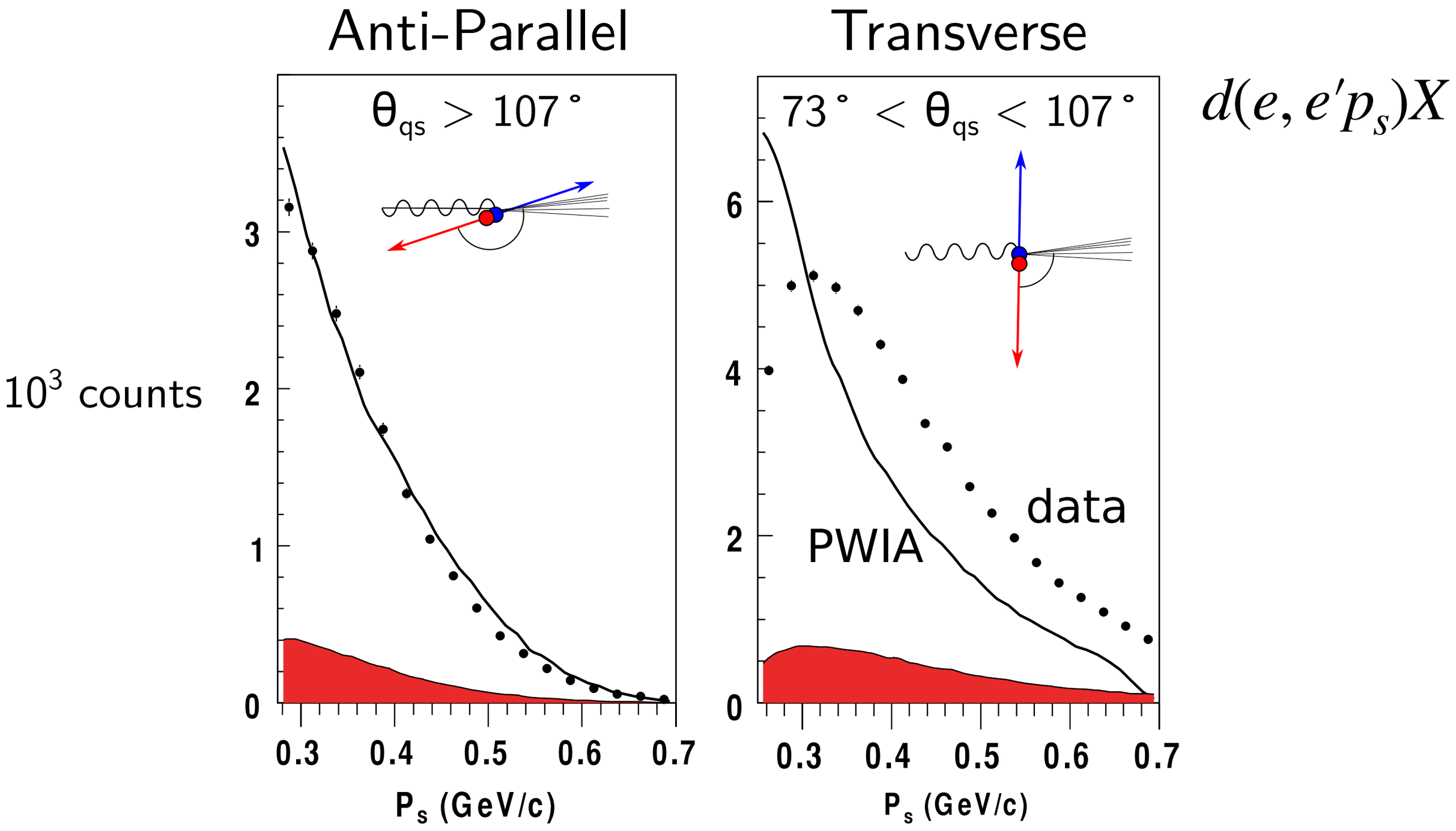
$$\approx \frac{\text{bound nucleon } F_2^*}{\text{free nucleon } F_2}$$

Theory assumptions:

- Plane Wave Impuls Approximation
  - Factorization
  - no spectator rescattering (final state interaction)

# Minimize Final-State-Interaction in Tagged DIS

Klimenko et. al, PRC73, 035212 (2006)



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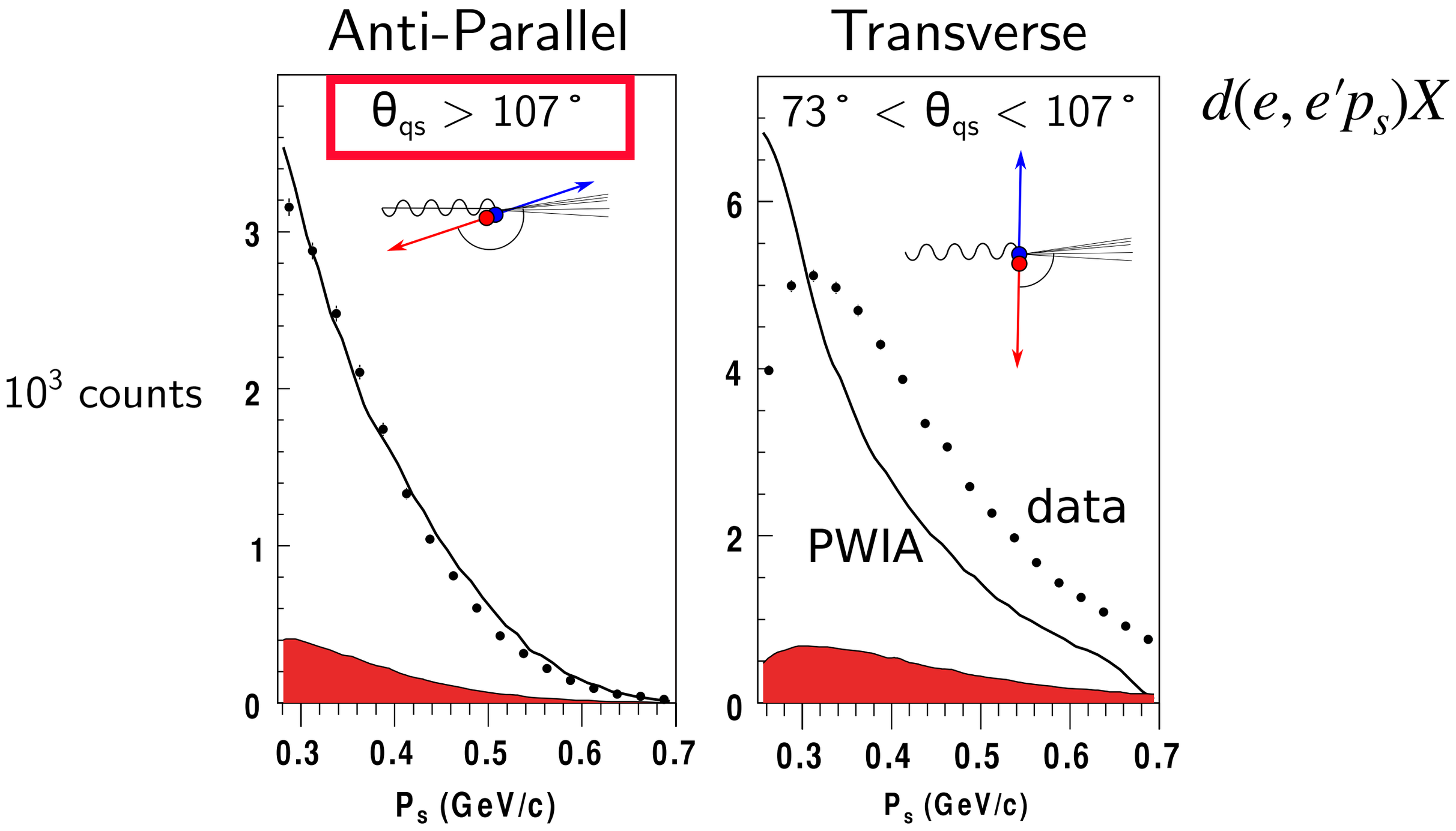
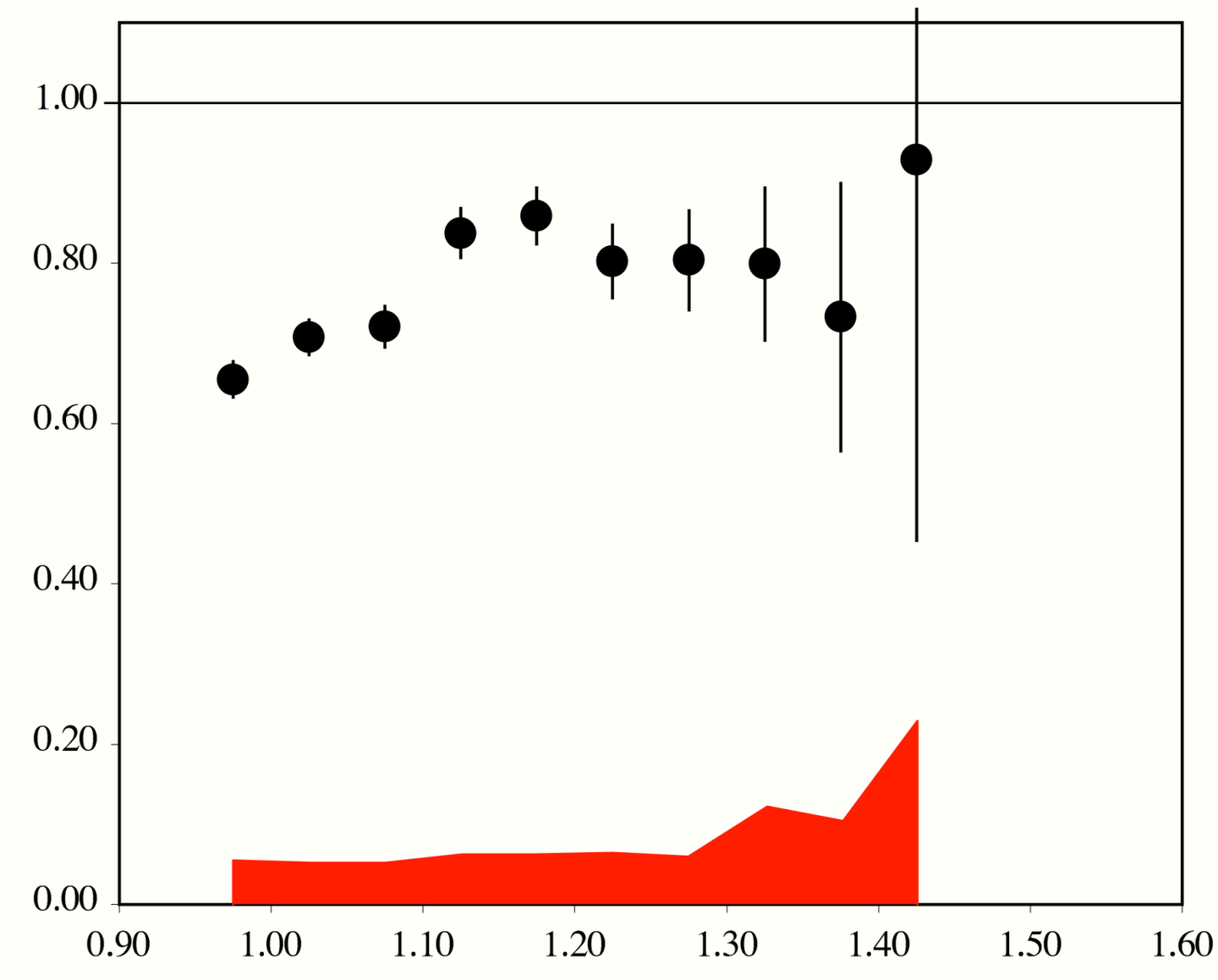


# Previous Results $d(e, e'p_s)X$

$$\frac{\dfrac{F_2^{n*}(x' = 0.55, Q^2 = 2.8)}{F_2^{n*}(x' = 0.25, Q^2 = 1.8)}}{\dfrac{F_2^{n}(x = 0.55, Q^2 = 2.8)}{F_2^{n}(x = 0.25, Q^2 = 1.8)}}$$




Non ideal kinematics

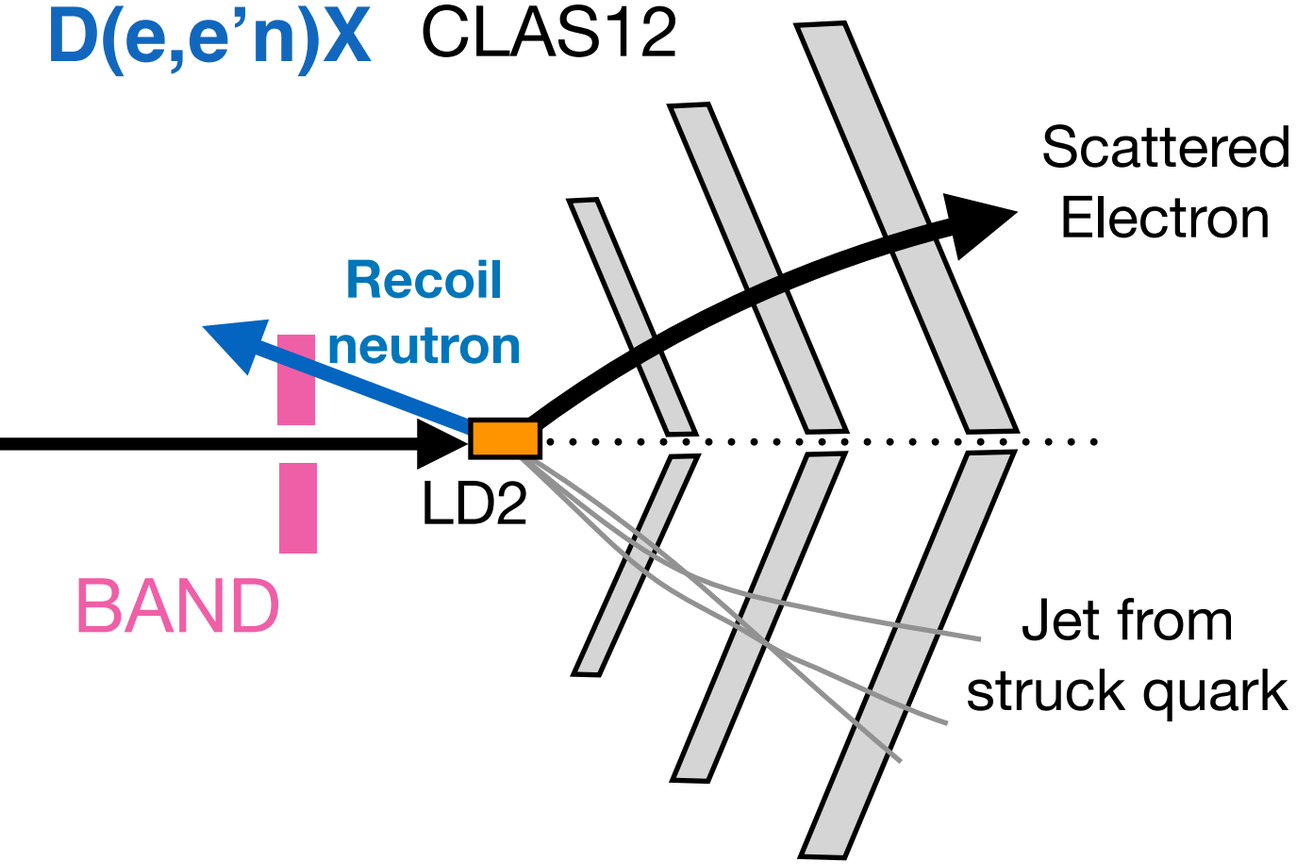
- Not so high in $Q^2$
- Low $\alpha_S$ has $\theta_{nq} \sim 90\,\mathrm{deg}$
- $p_T = [0.25 - 0.35]$ [GeV/c]

A. V. Klimenko *et al.* Phys. Rev. C **73**, 035212 (2006)

# Tagged Experiments at JLab

Hall B:
CLAS 12 + Backward Angle Neutron Detector (BAND)

**D(e,e'n)X** CLAS12

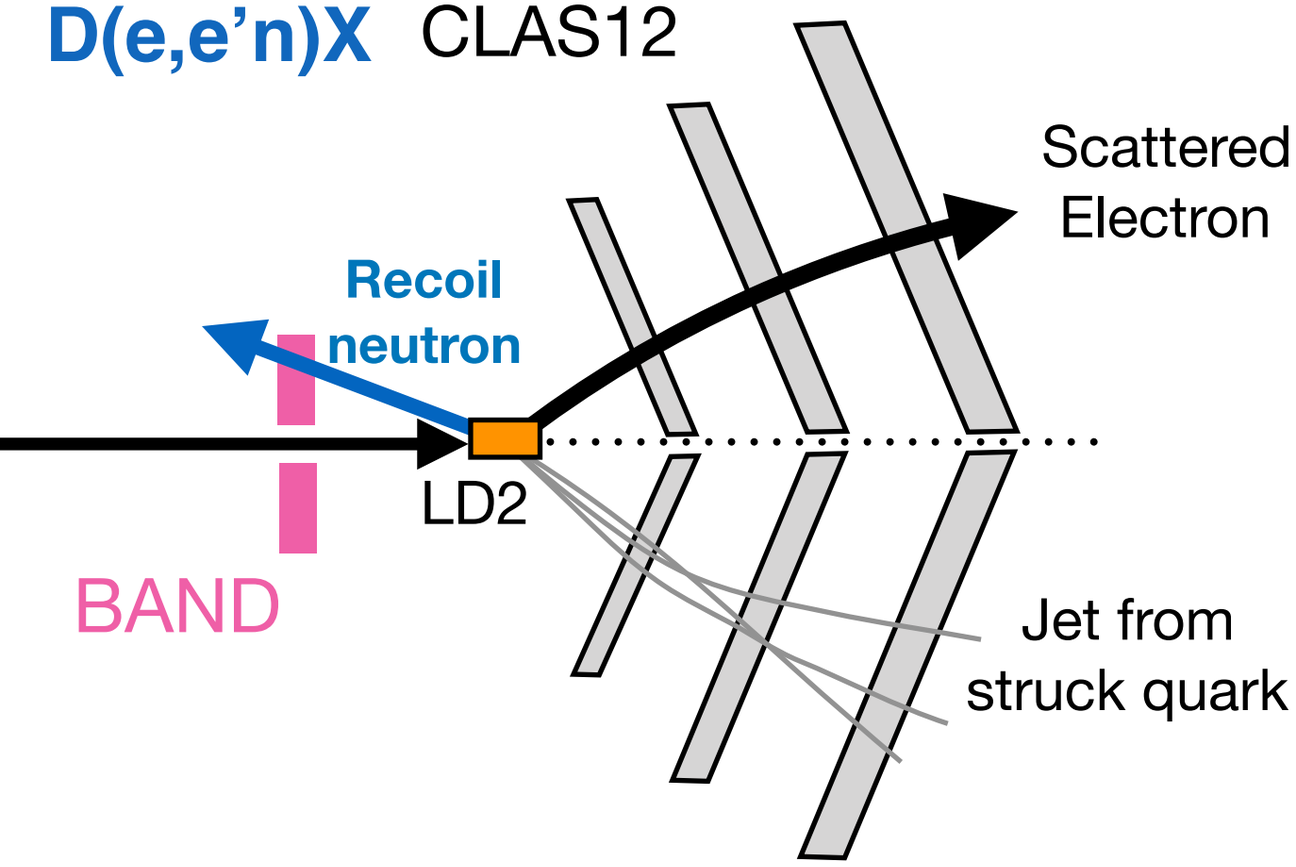



- Run Group B
- Analysis under review

# Tagged Experiments at JLab

## Hall B:
## CLAS 12 + Backward Angle Neutron Detector (BAND)

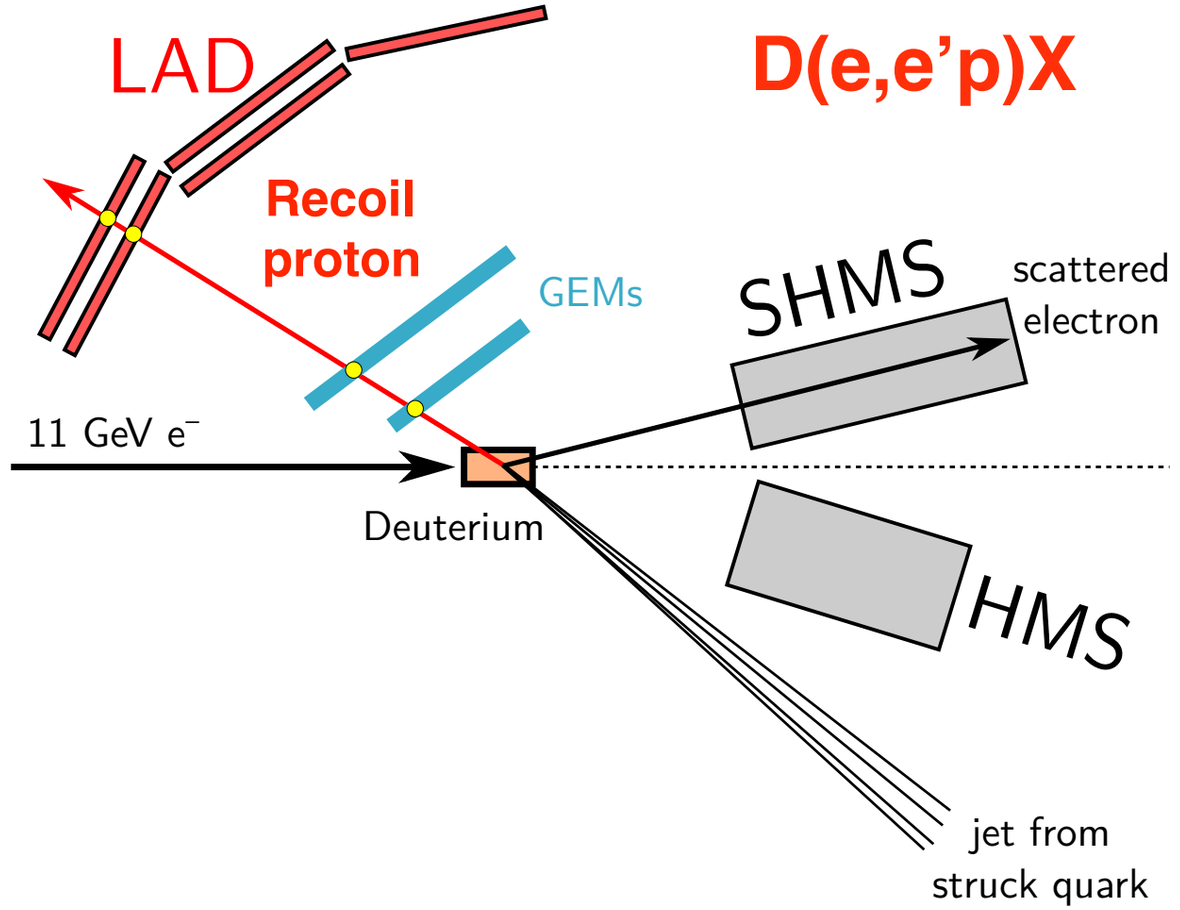
**D(e,e'n)X** CLAS12




- Run Group B
- Analysis under review

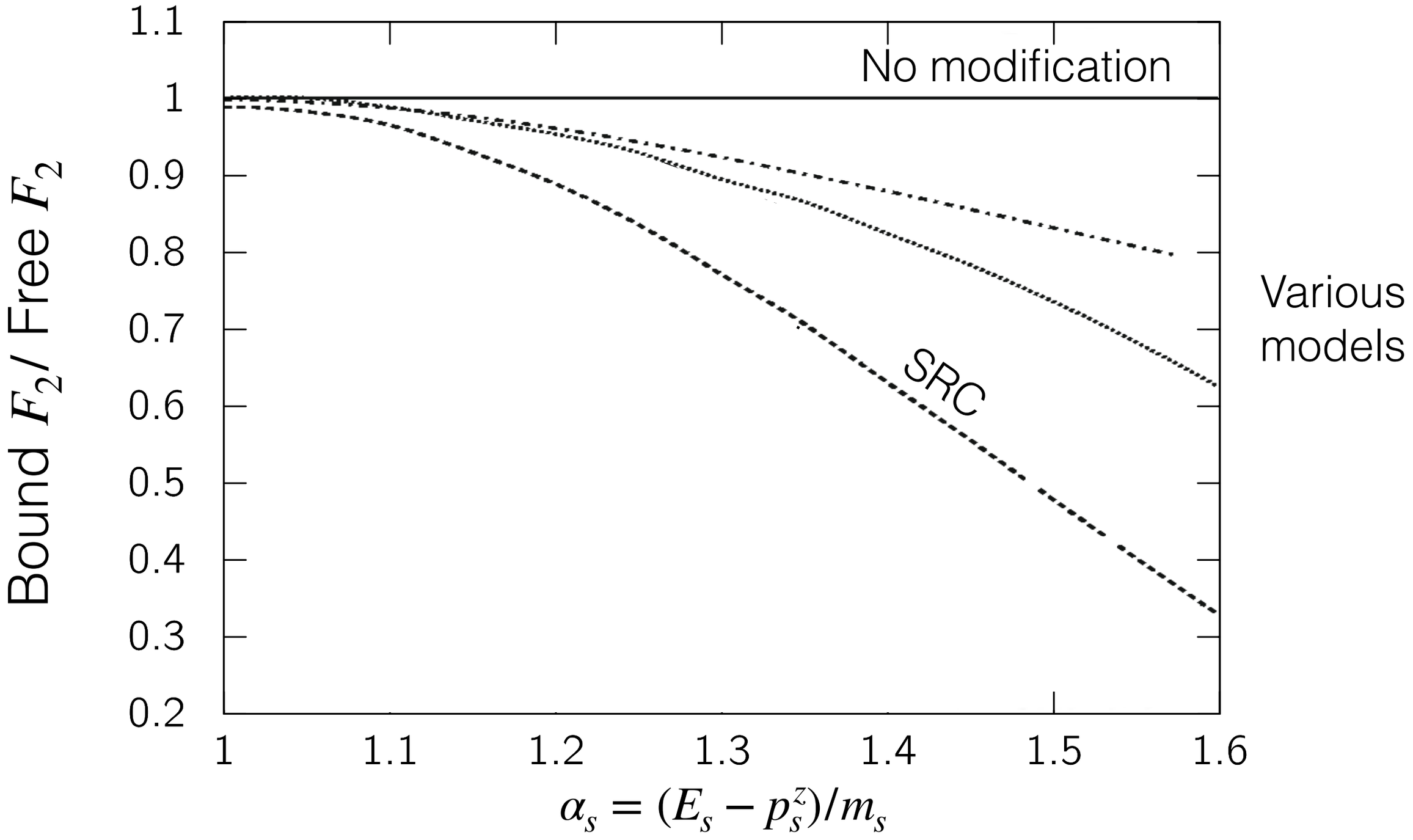
## Hall C:
## SHMS/HMS + Large Angle Detector (LAD)

**D(e,e'p)X**



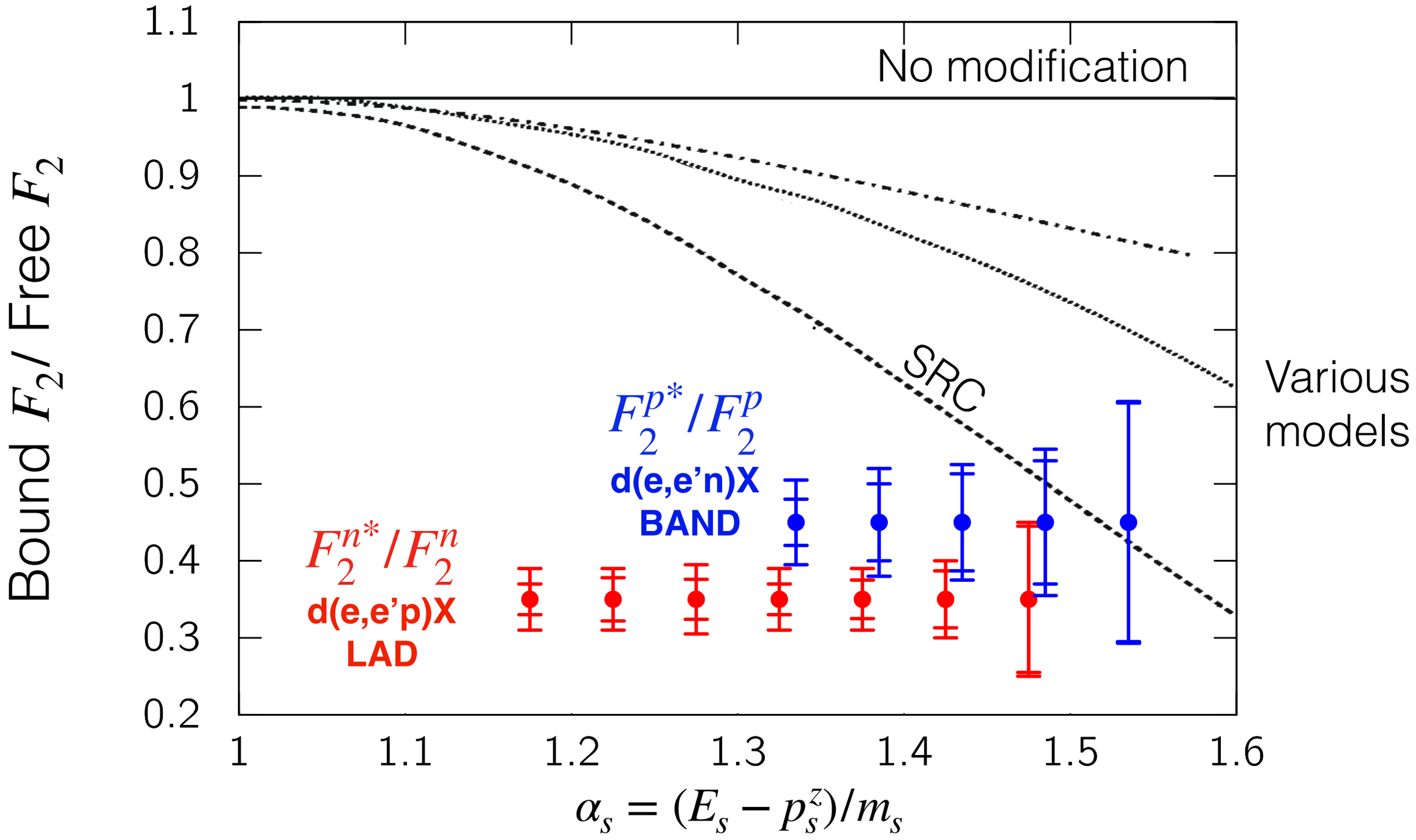

- Experiment ready
- Run in 2024?

# d(e,e'N)X - Expected Results




Melnitchouk, Sargsian, Strikman, Z.Phys. A359, 99 (1997)

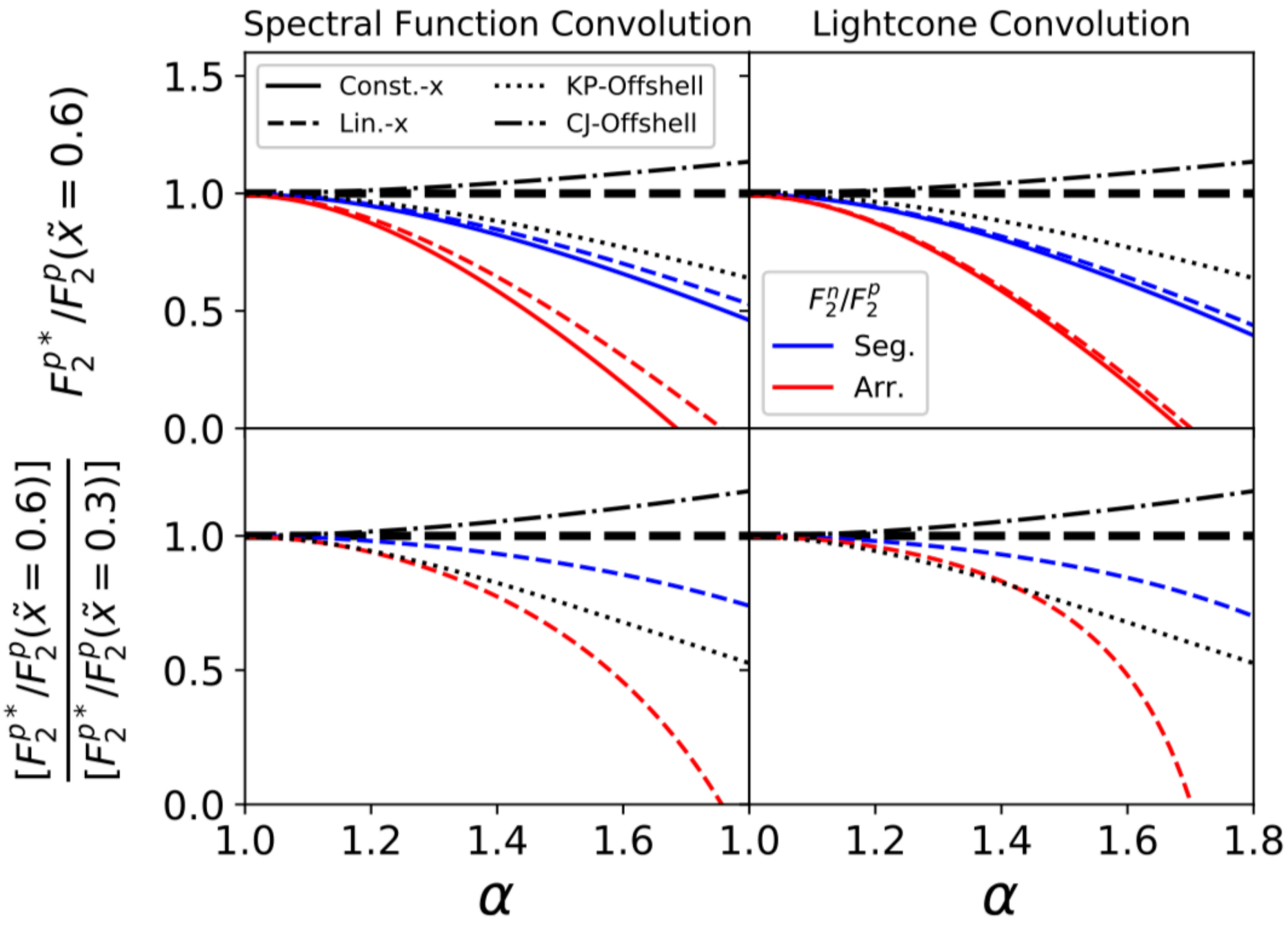
# d(e,e'N)X - Expected Results




Melnitchouk, Sargsian, Strikman, Z.Phys. A359, 99 (1997)

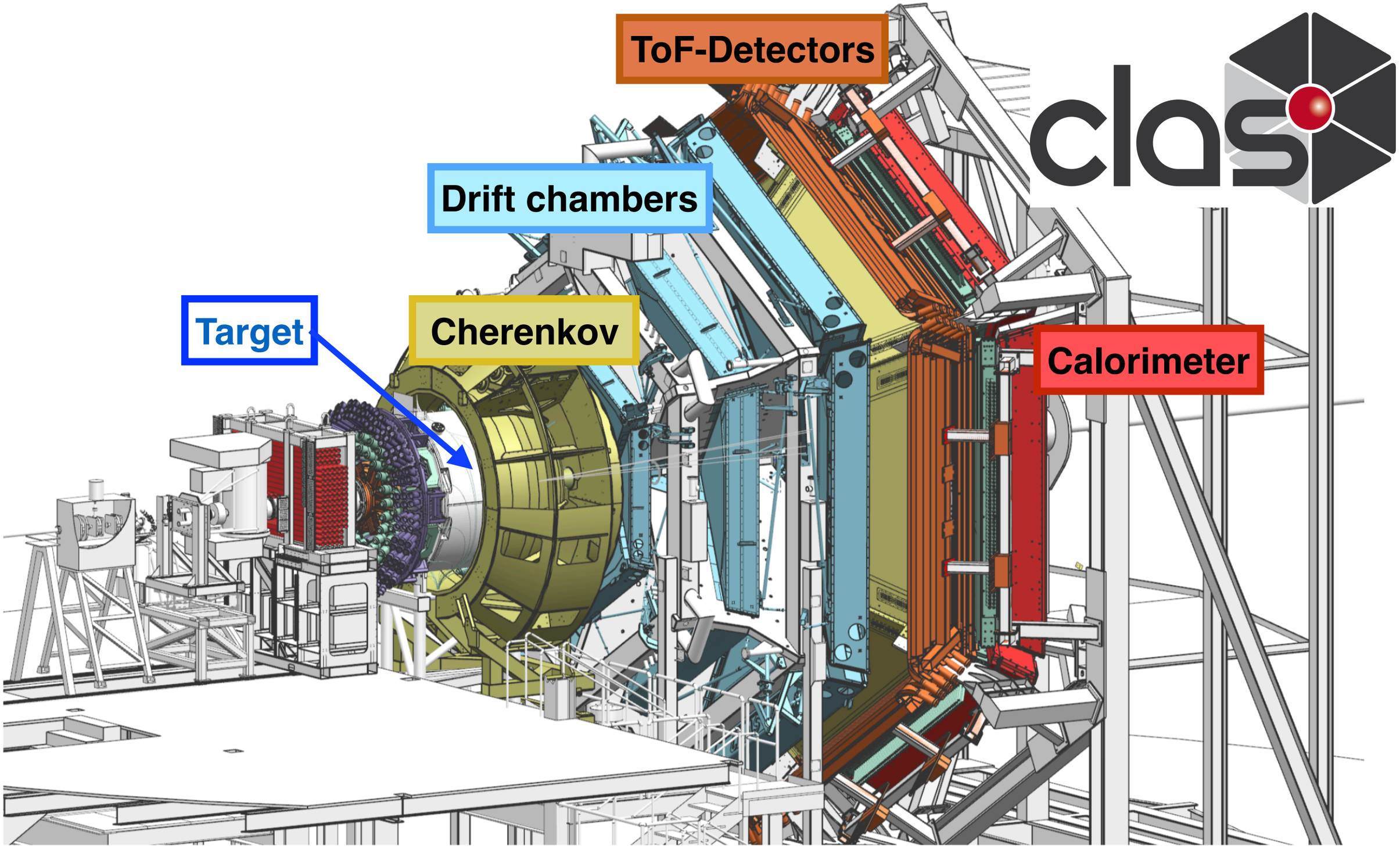
# Tagged Predictions for Different Models

Segarra et al, Phys. Rev. Research 3 (2021)



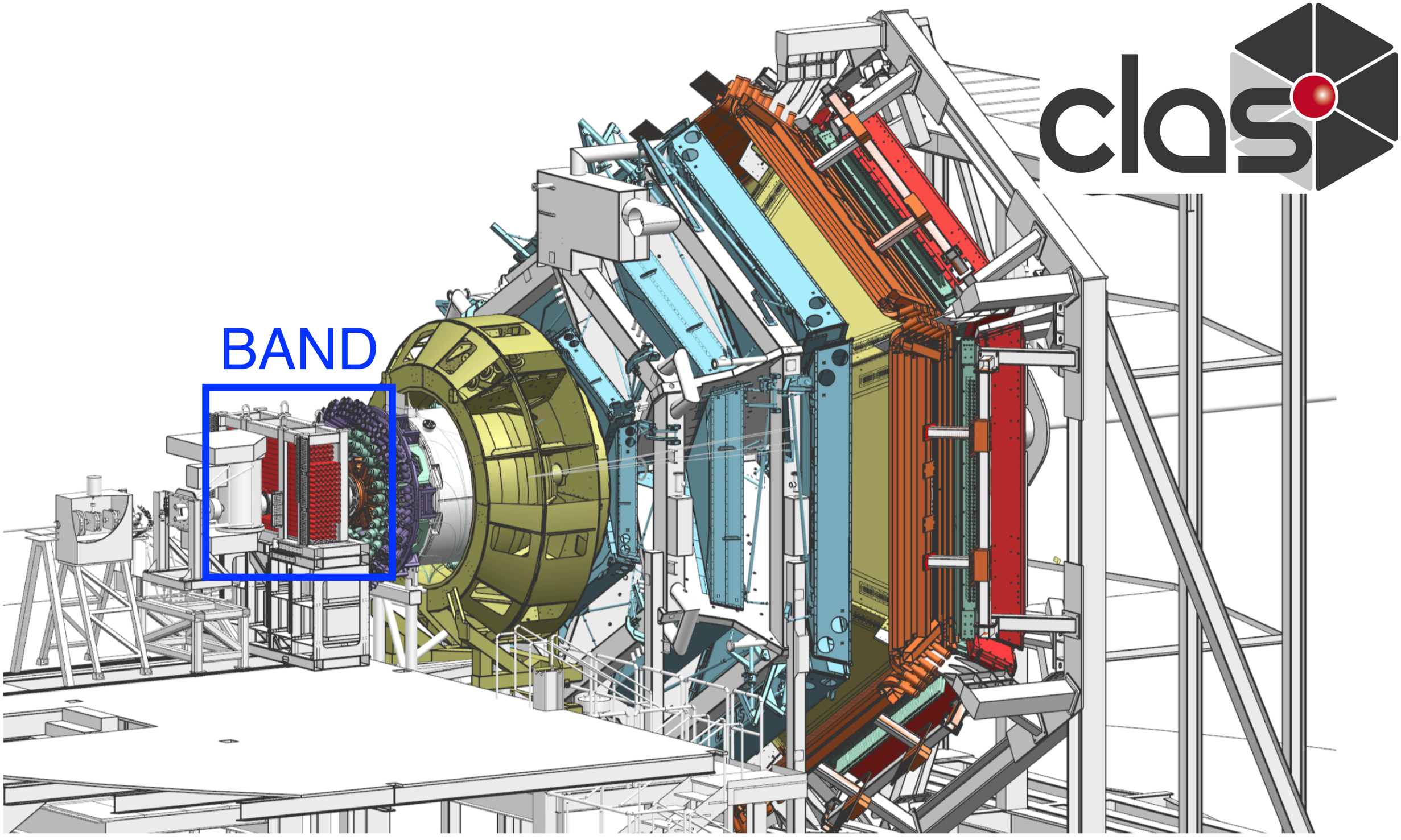

Predictions from convolution model fits to data

# CLAS12 in HallB




V. Burkert et al., NIMA 959 (2020), 163419

# BAND in HallB




E.P. Segarra et al., NIM A978 (2020), 164356

# Overview of BAND

Segarra et al., NIM A978 (2020)

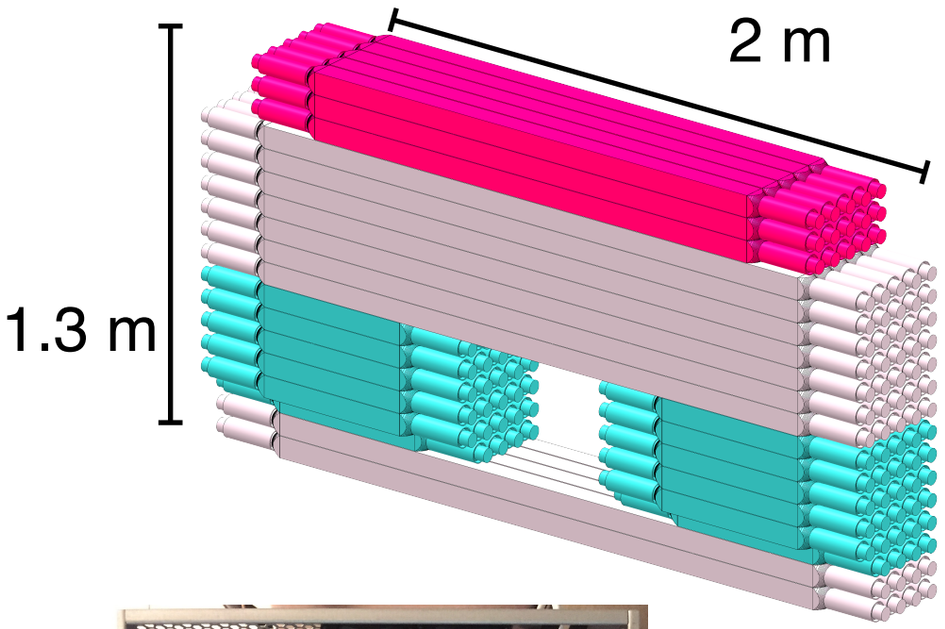
- 140 scintillator bars
  - 5 layers (36cm total thickness)
  - veto layer (1cm thick)
  - time resolution < 250 ps

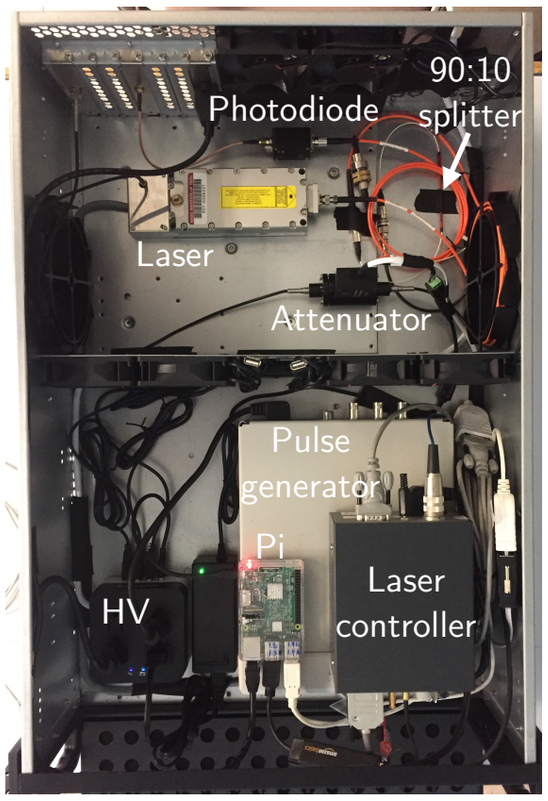
- 3 meters upstream of target

- coverage in θ ~ 155-176°

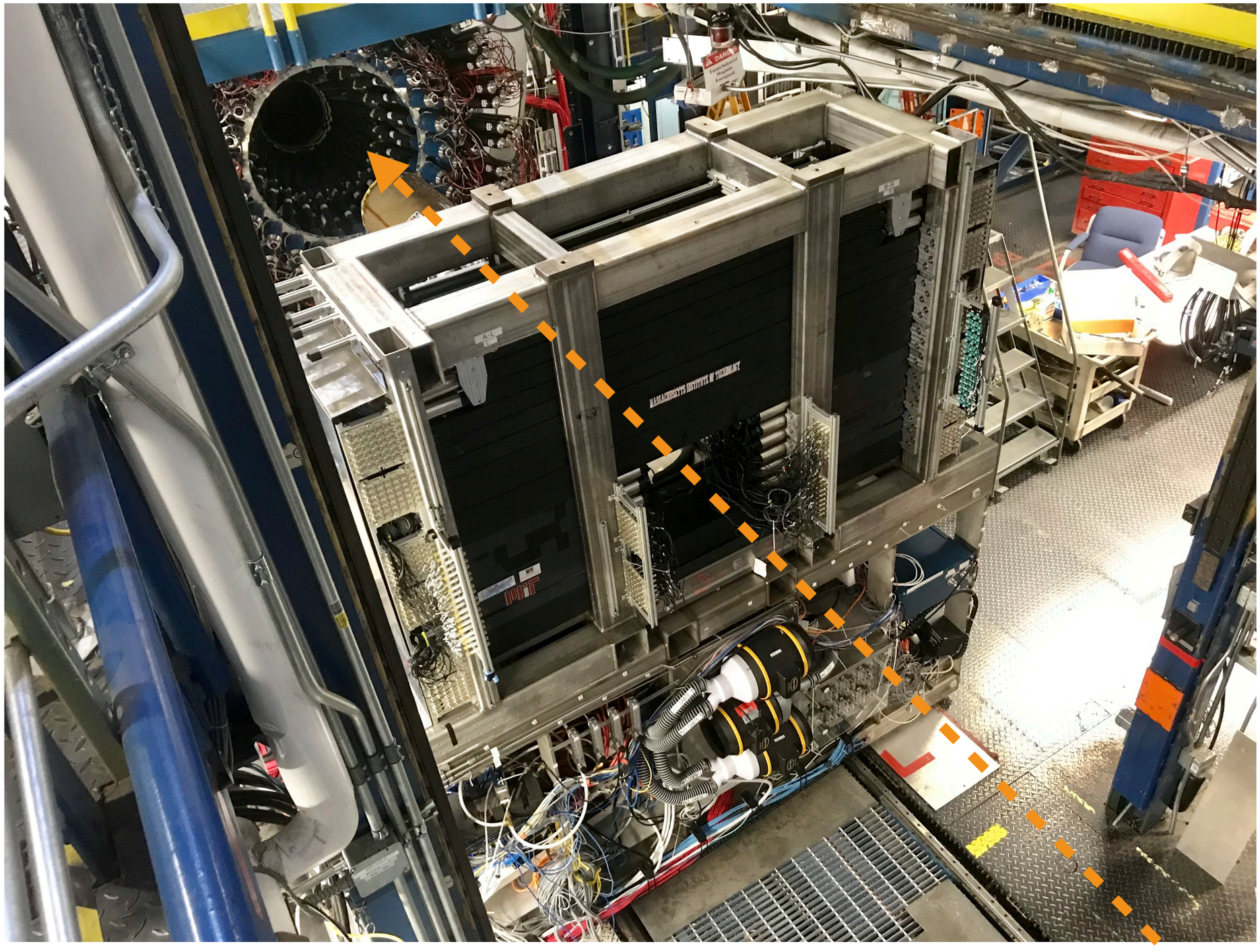
- Lead wall (downstream)

- Laser system for calibrations
  [Denniston et al., NIM A973 (2020)]

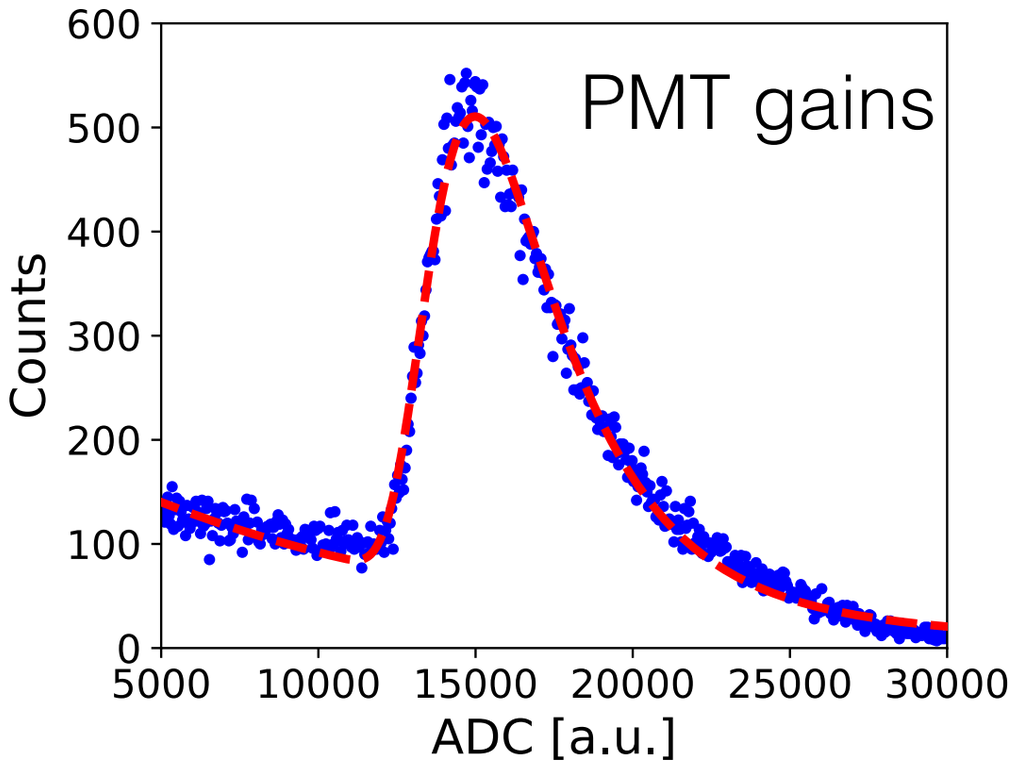


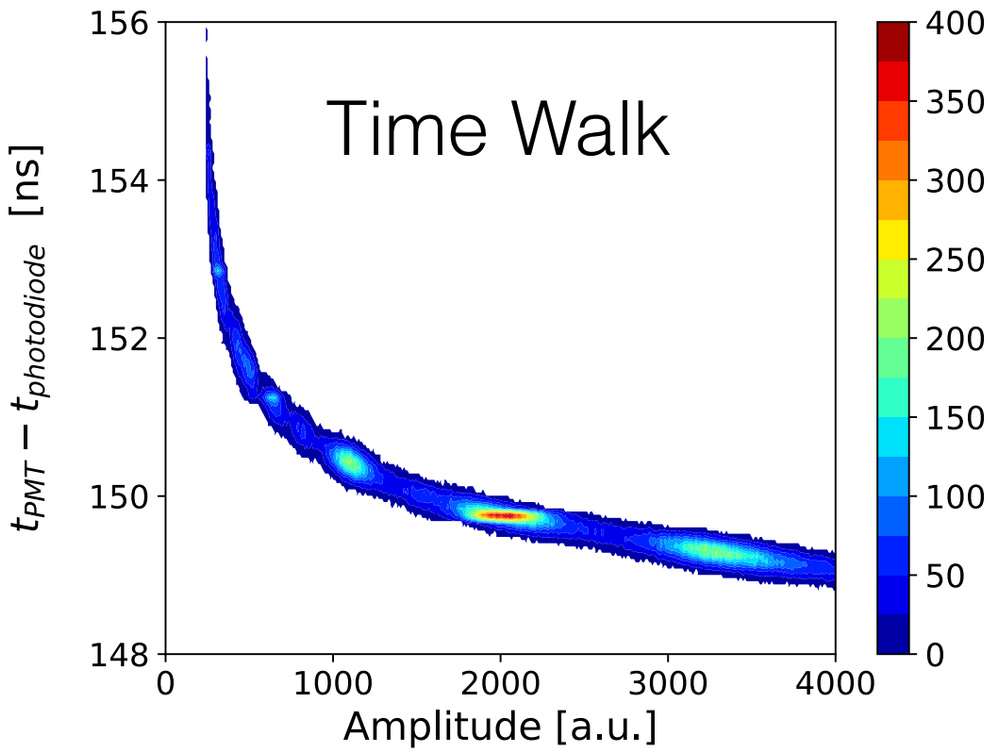



# BAND in HallB

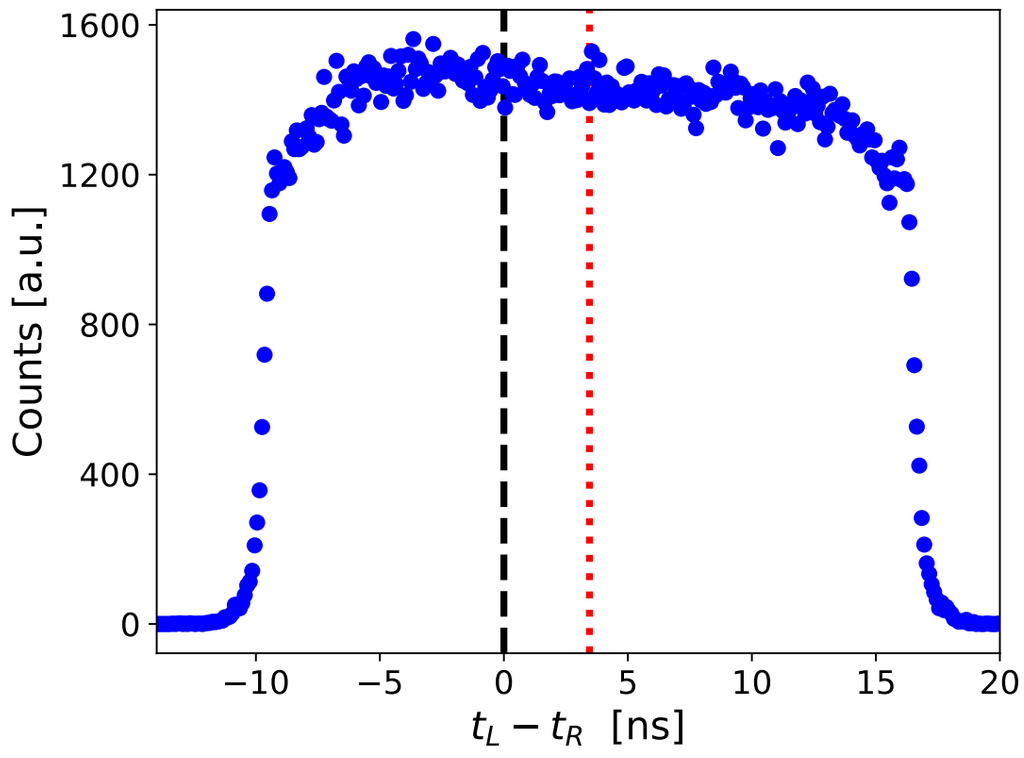


# BAND Calibrations



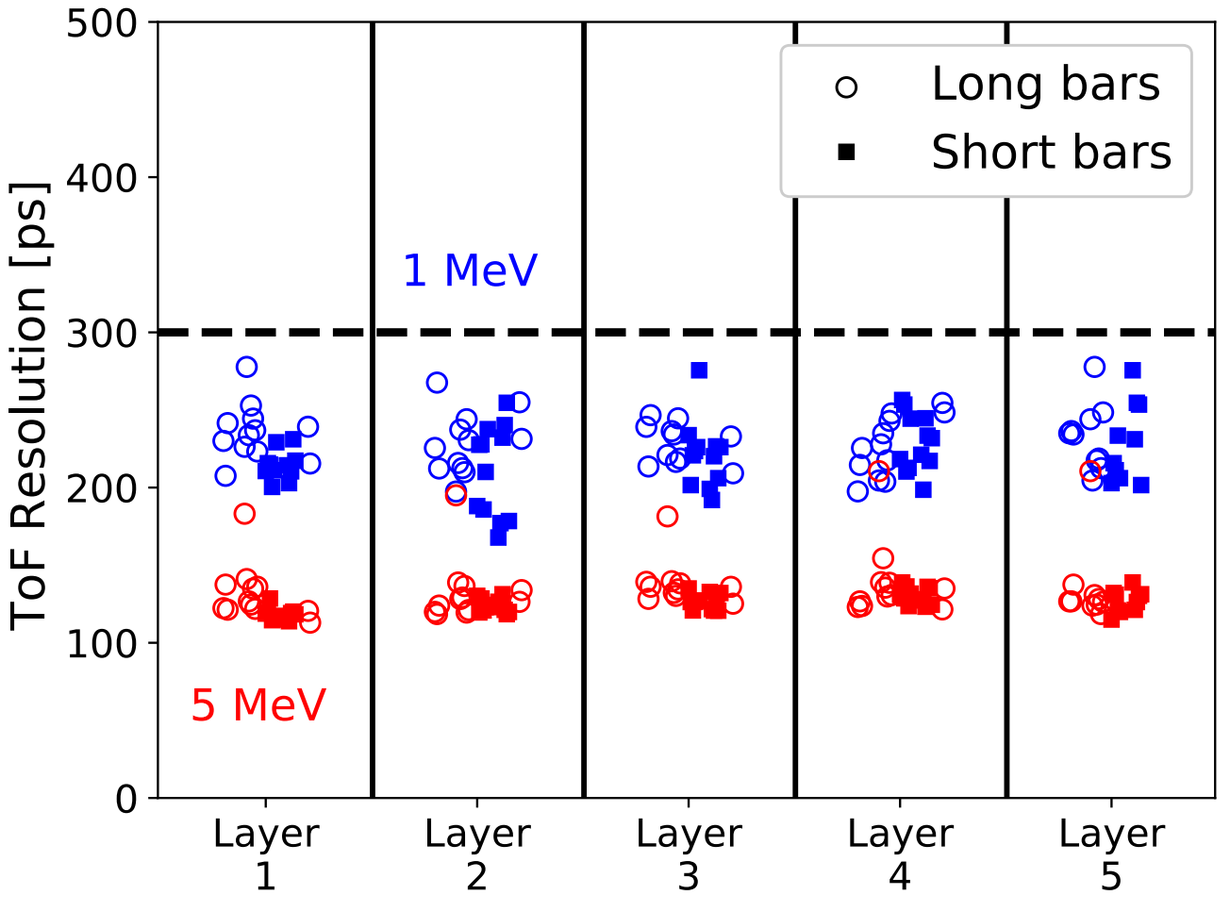

## Timing Offsets



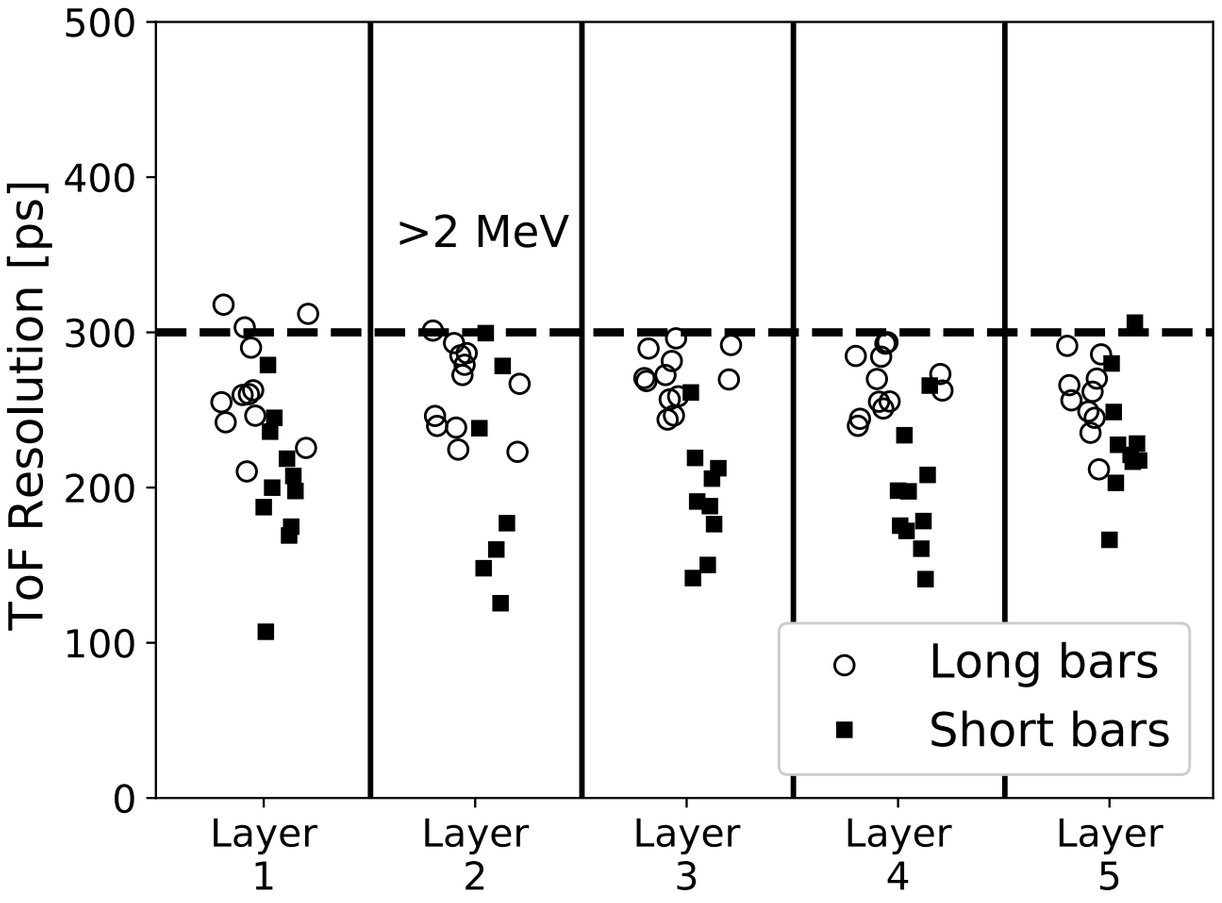
# Time Resolutions of BAND Bars

Segarra et al., NIM A978 (2020)

## Laser

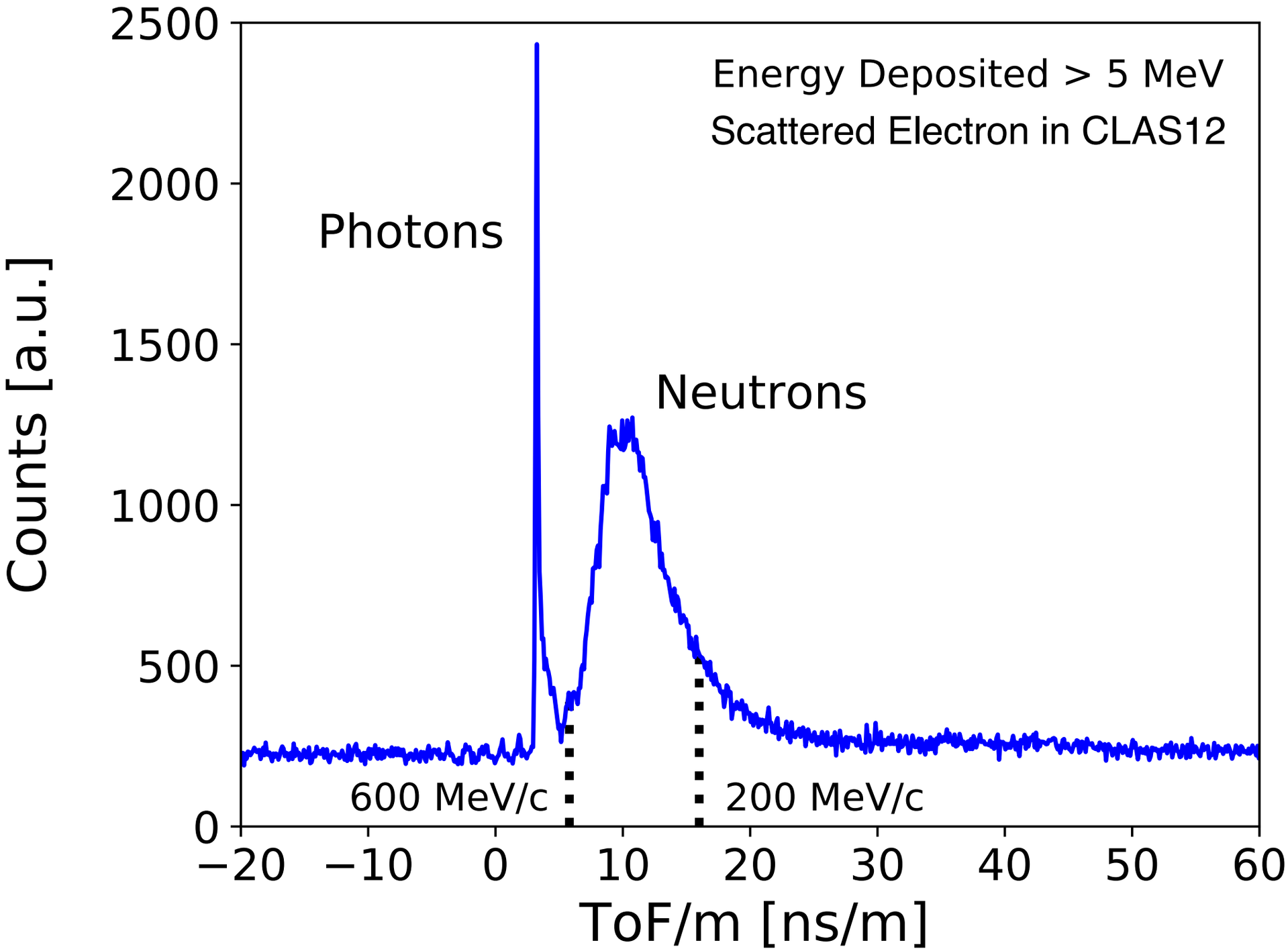



## Photons



# Clear Signal of Neutrons in BAND

Segarra et al., NIM A978 (2020)



# Data and Analysis Overview

- Run group B data
  - beam energies: 10.2, 10.4, 10.6 and 4.2 GeV
  - liquid deuterium target

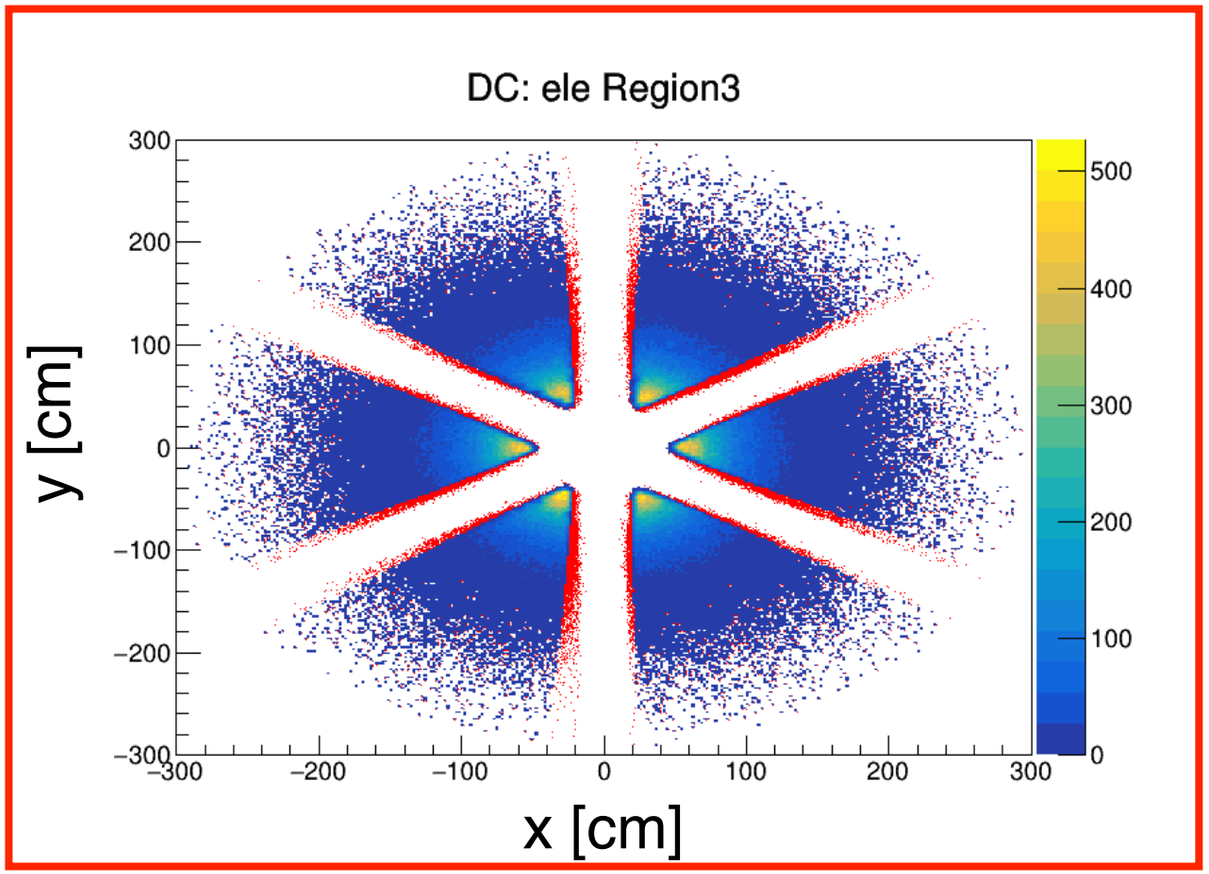
- Event selection
  - Electrons in CLAS12
  - Neutrons in BAND
  - Background subtraction

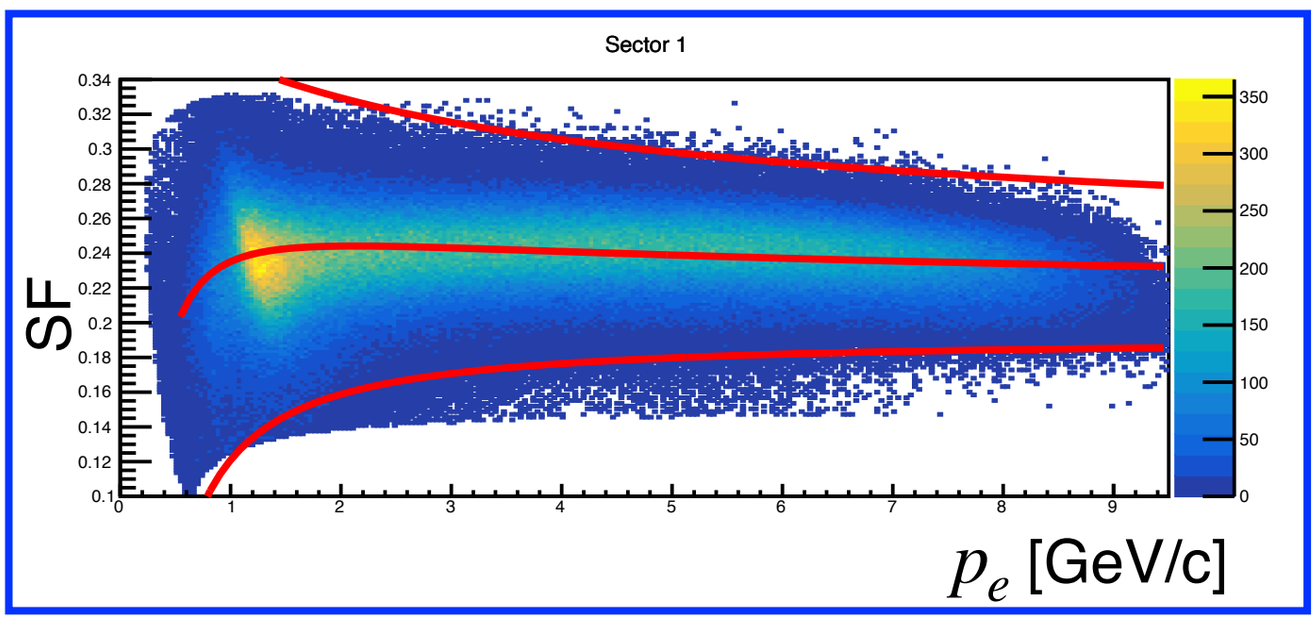
- Inclusive d(e,e’) analysis

- Quasi-elastic d(e,e’pn) and d(e,e’p)n analysis

- Tagged DIS analysis

# Analysis: Electron Selection

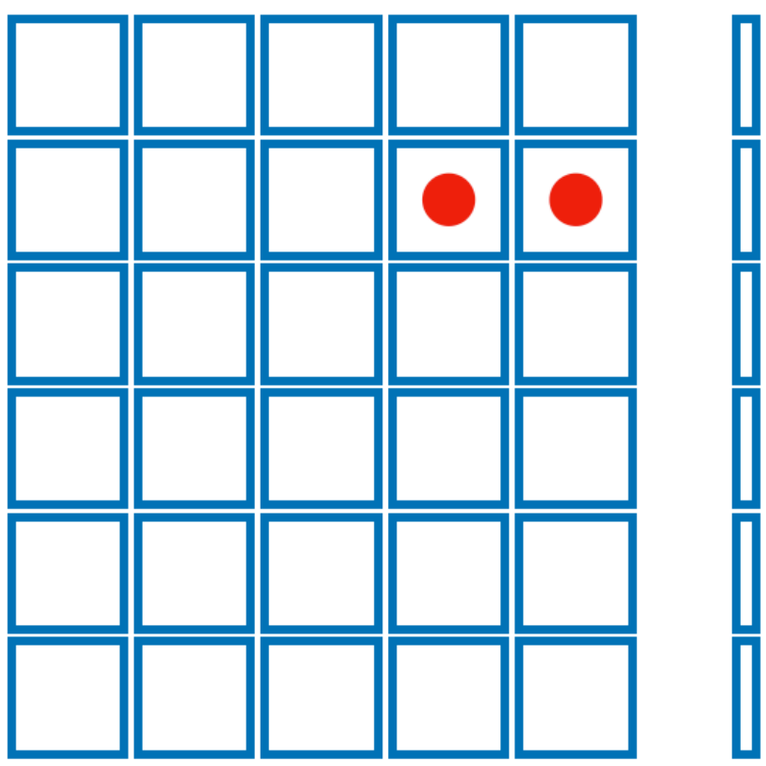



- Charge/PID requirement
- Driftchamber fiducial cuts
- Calorimeter fiducial cuts
- Calorimeter sampling fraction cuts

# Neutron Selection: Identifying Good Hits

- Hit must have $E_{dep}$ > 2 MeVee to be considered
- Veto algorithm:



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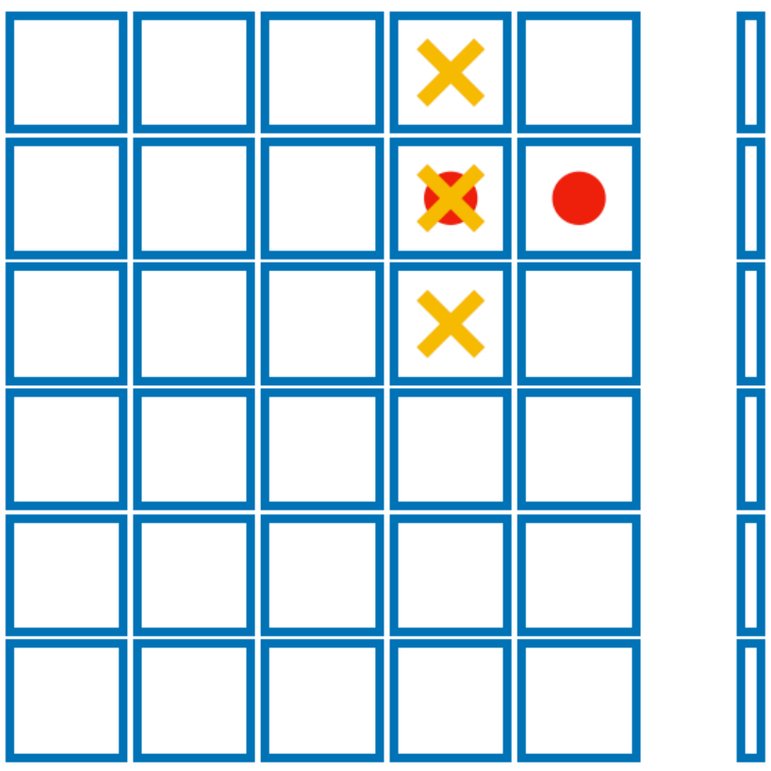

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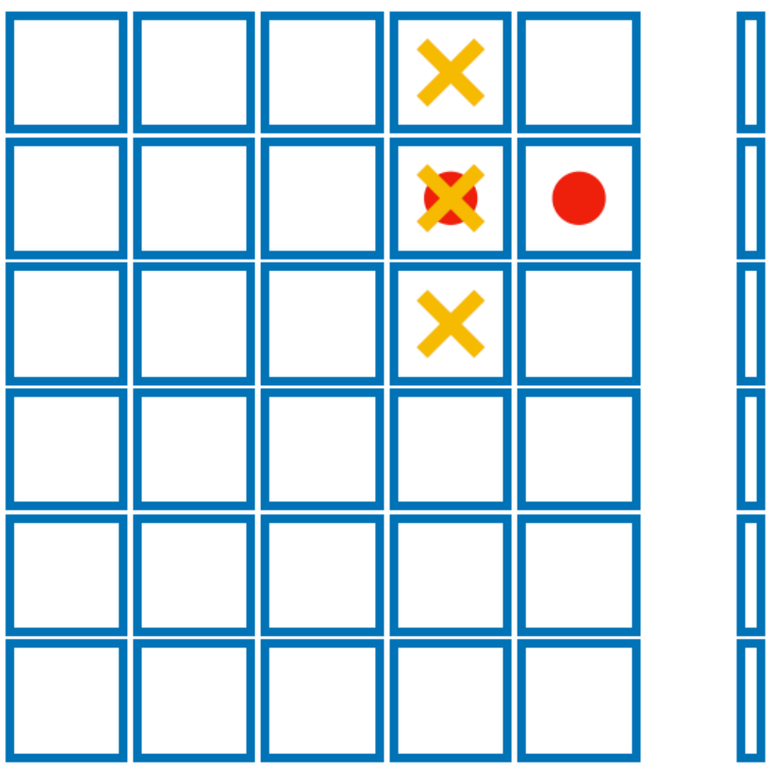
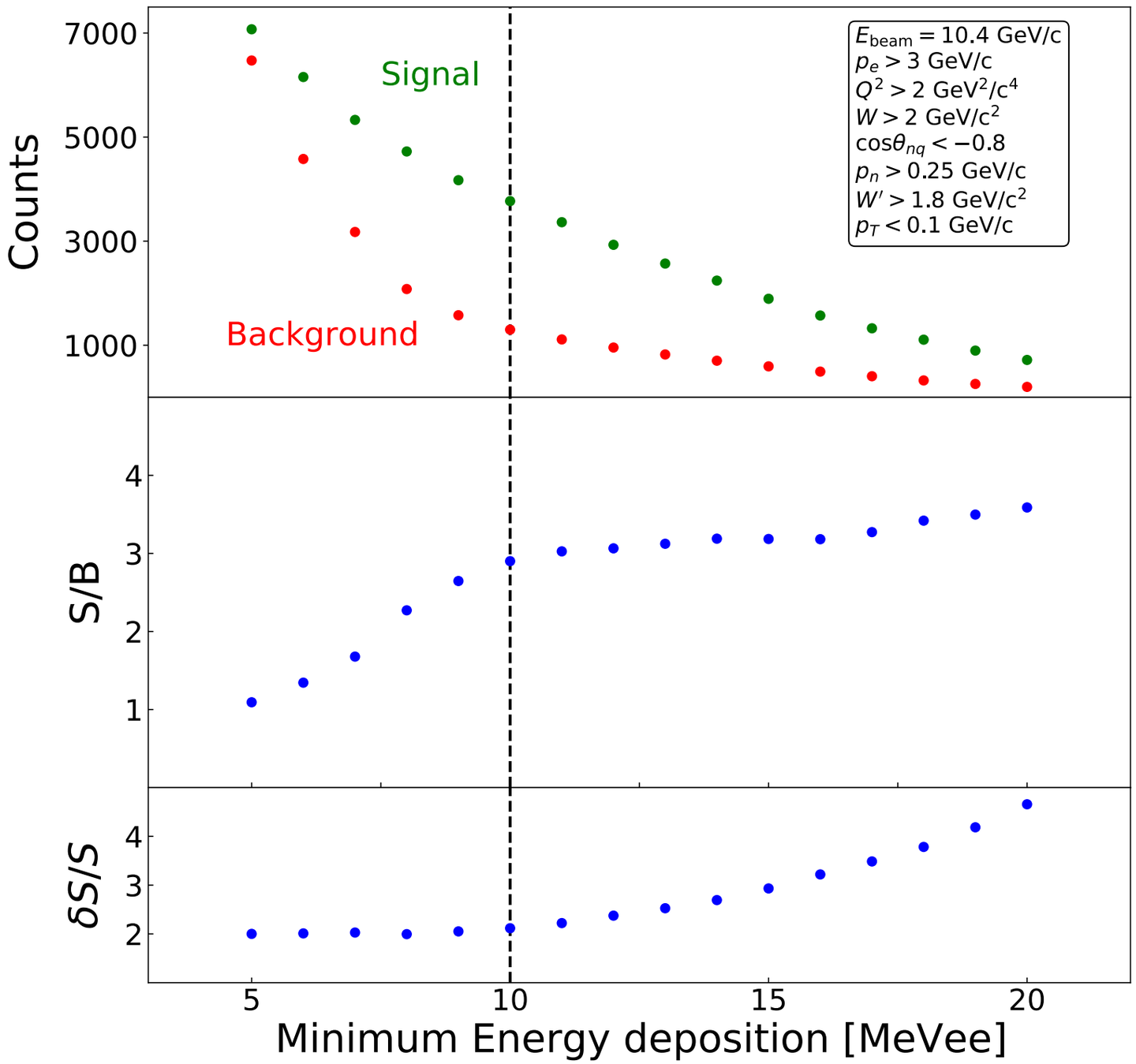


- If single hit (most of the time) ✔
- If 2 hits:
  - Close together (from same interaction)? ✔
  - Far apart? ✘
- If > 2 hits ✘

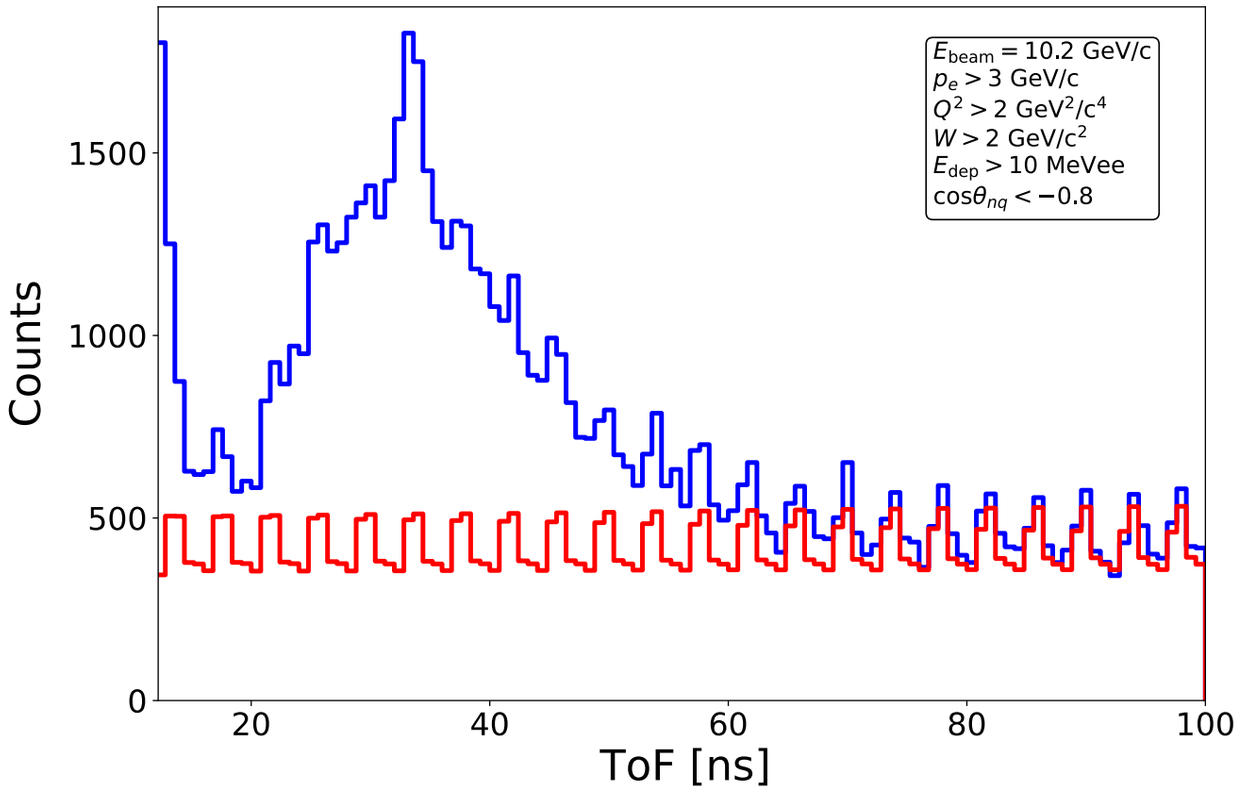
# Neutron Selection: $E_{dep}$ and Fiducials

- $E_{dep}$ > 10 MeVee



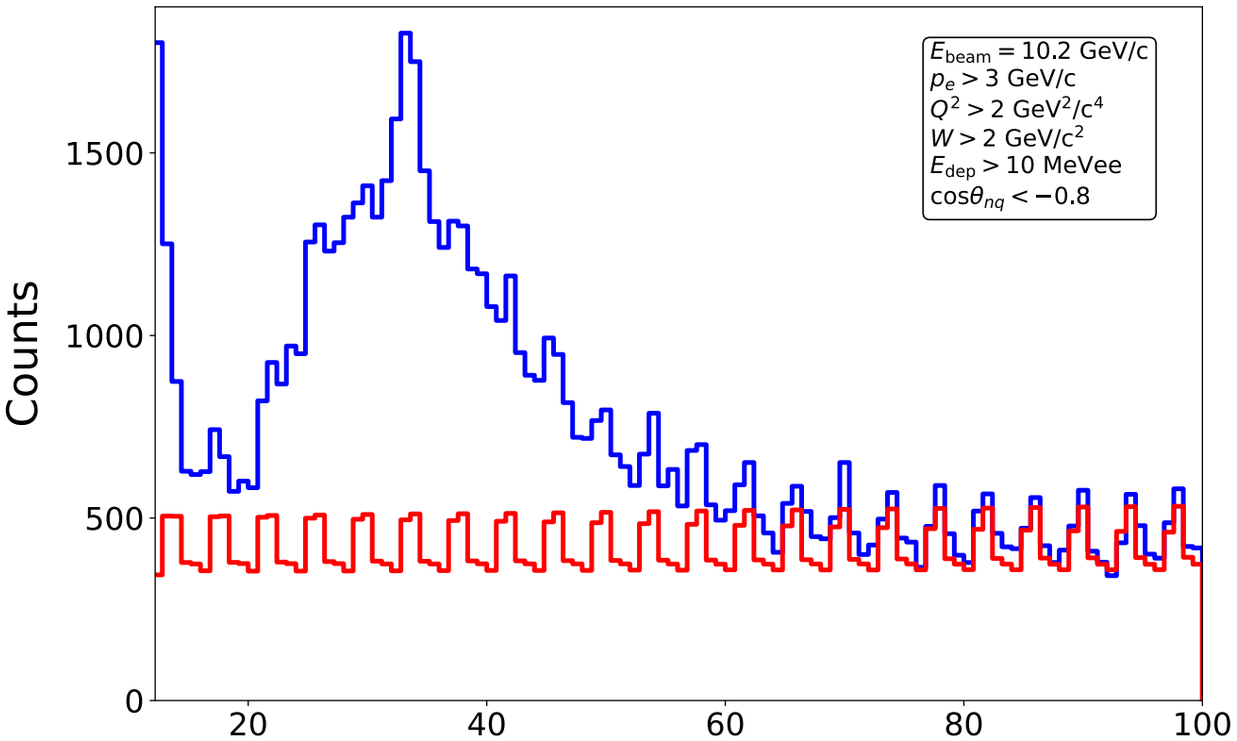

- Fiducial cut 10 cm from BAND edges (reflection)
- $\theta_n$ < 168.5° (beam pipe)

# Random Coincidence Background Subtraction

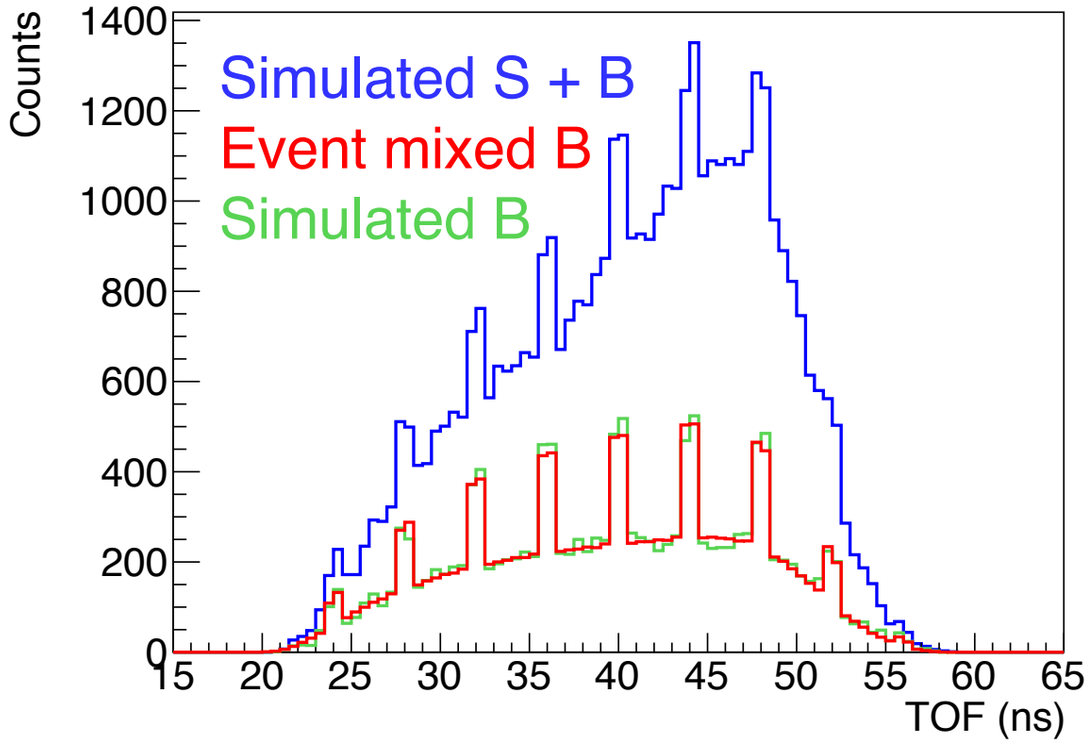


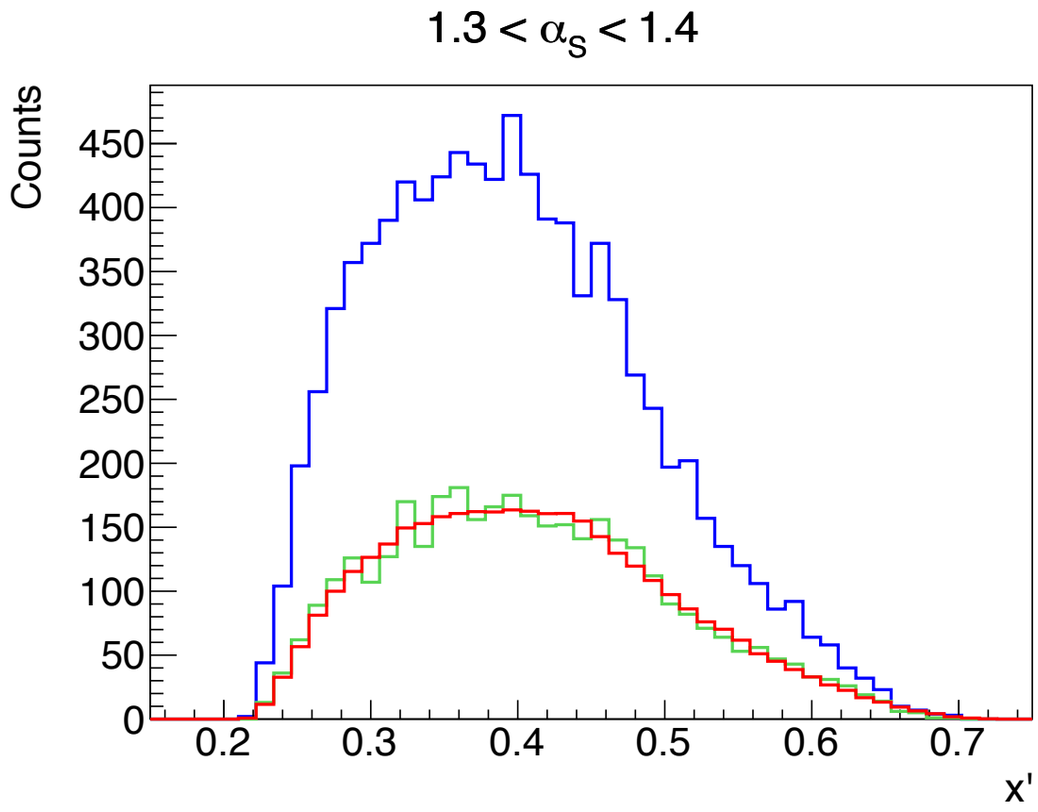

- Event mixing for background subtraction
- Account for beam structure

# Random Coincidence Background Subtraction




- Event mixing for background subtraction
- Account for beam structure
- Simulation closure test



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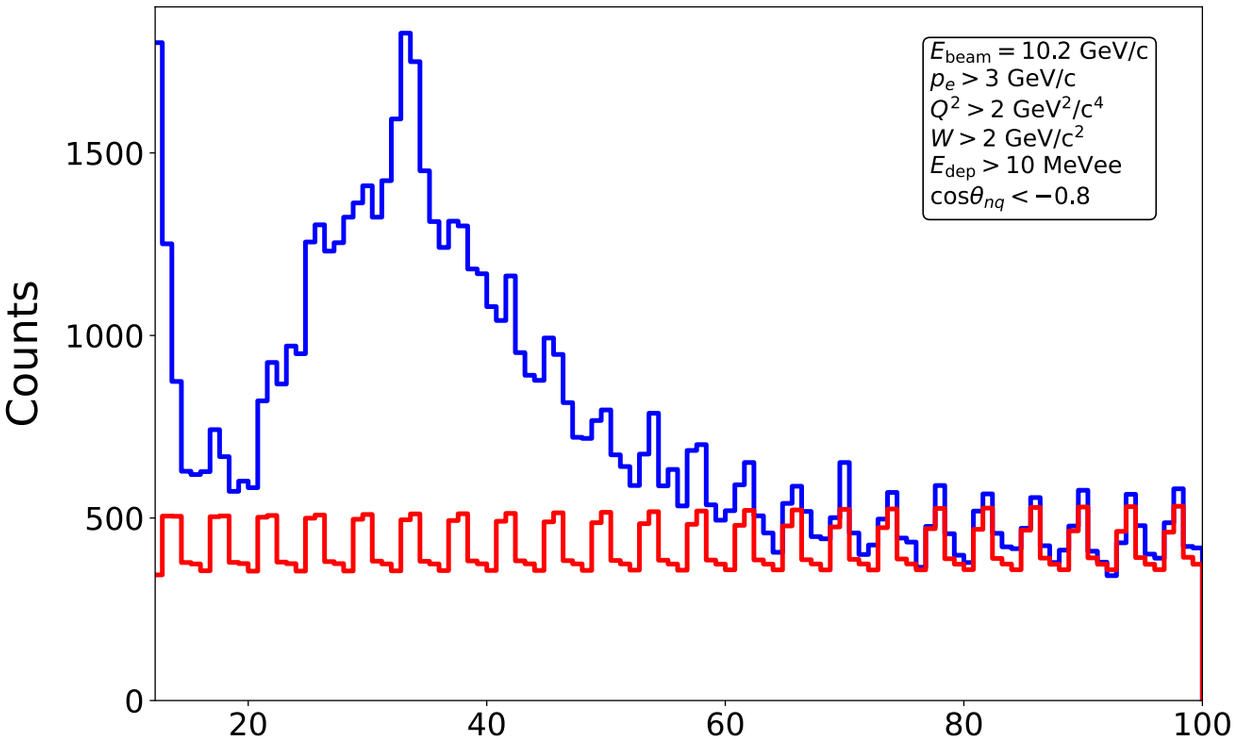
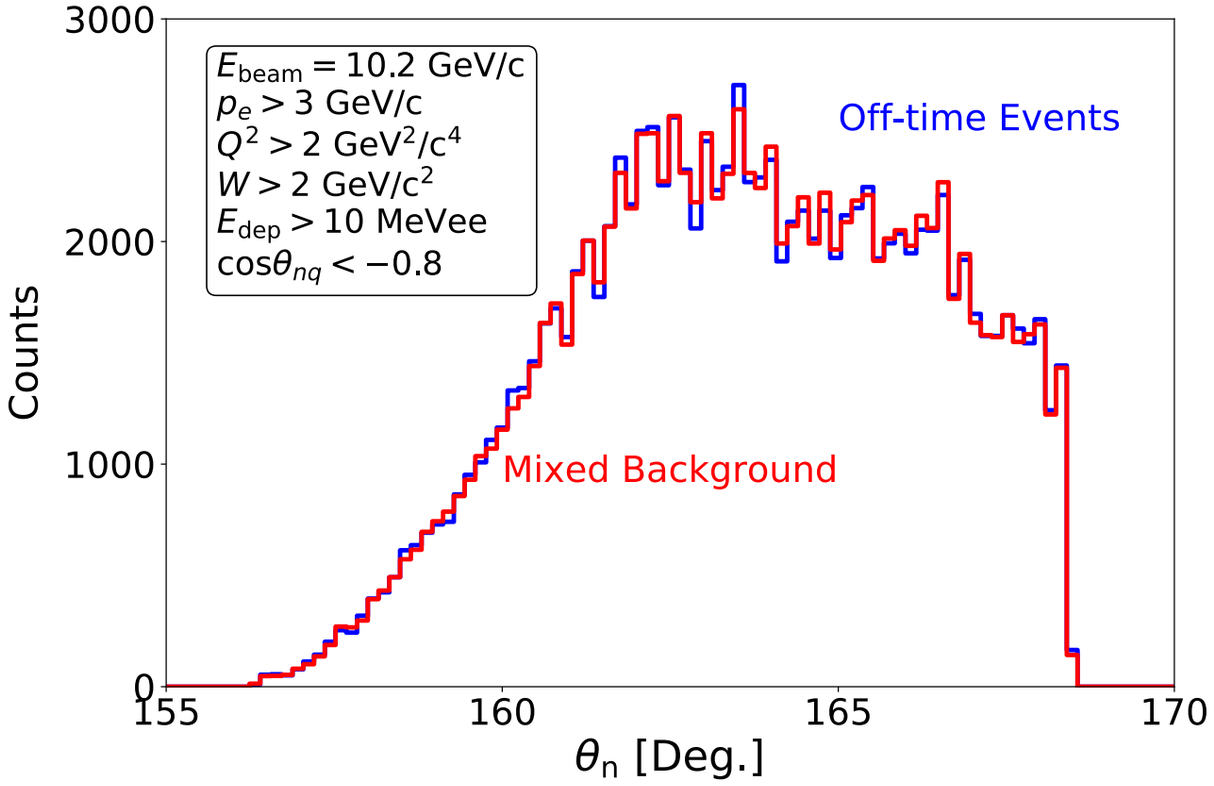
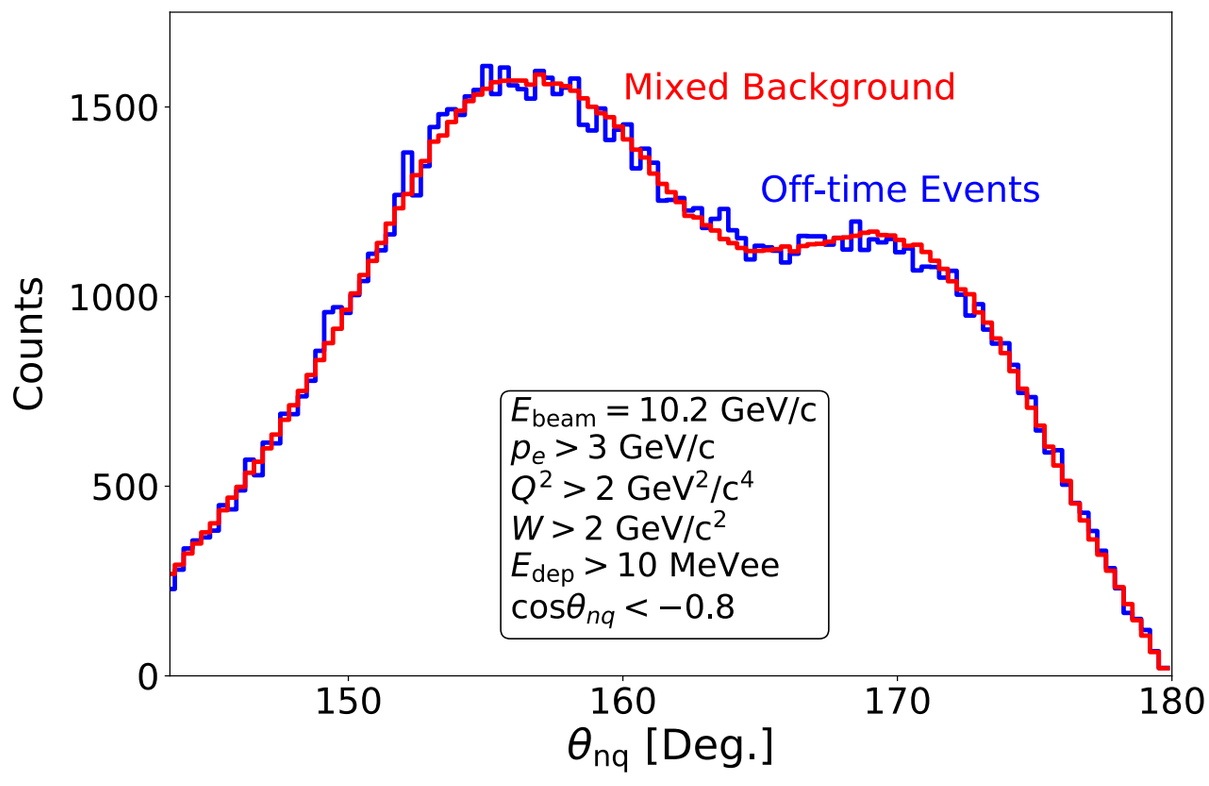
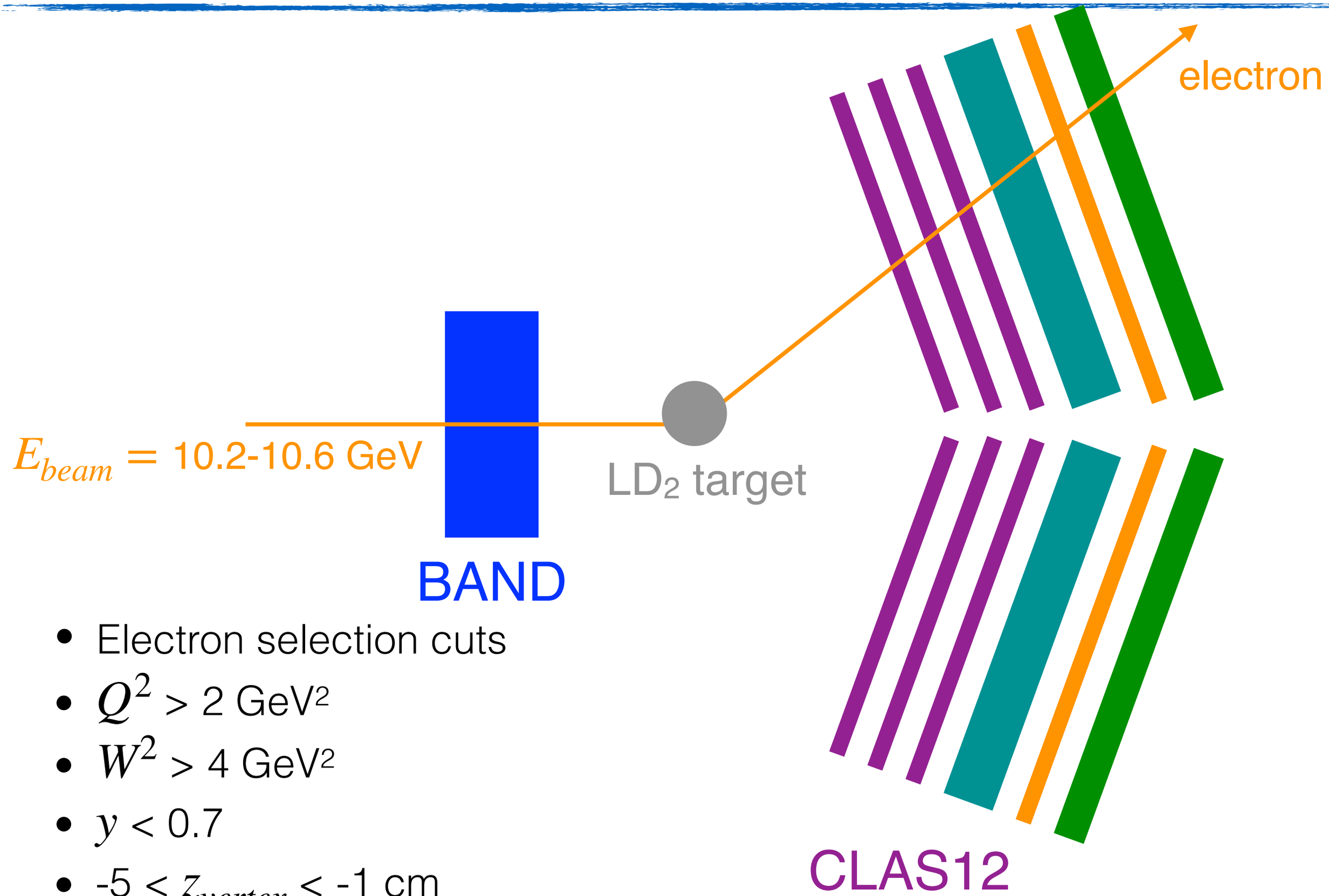



- Event mixing for background subtraction
- Account for beam structure
- Simulation closure test
- Offtime/event mixed consistency



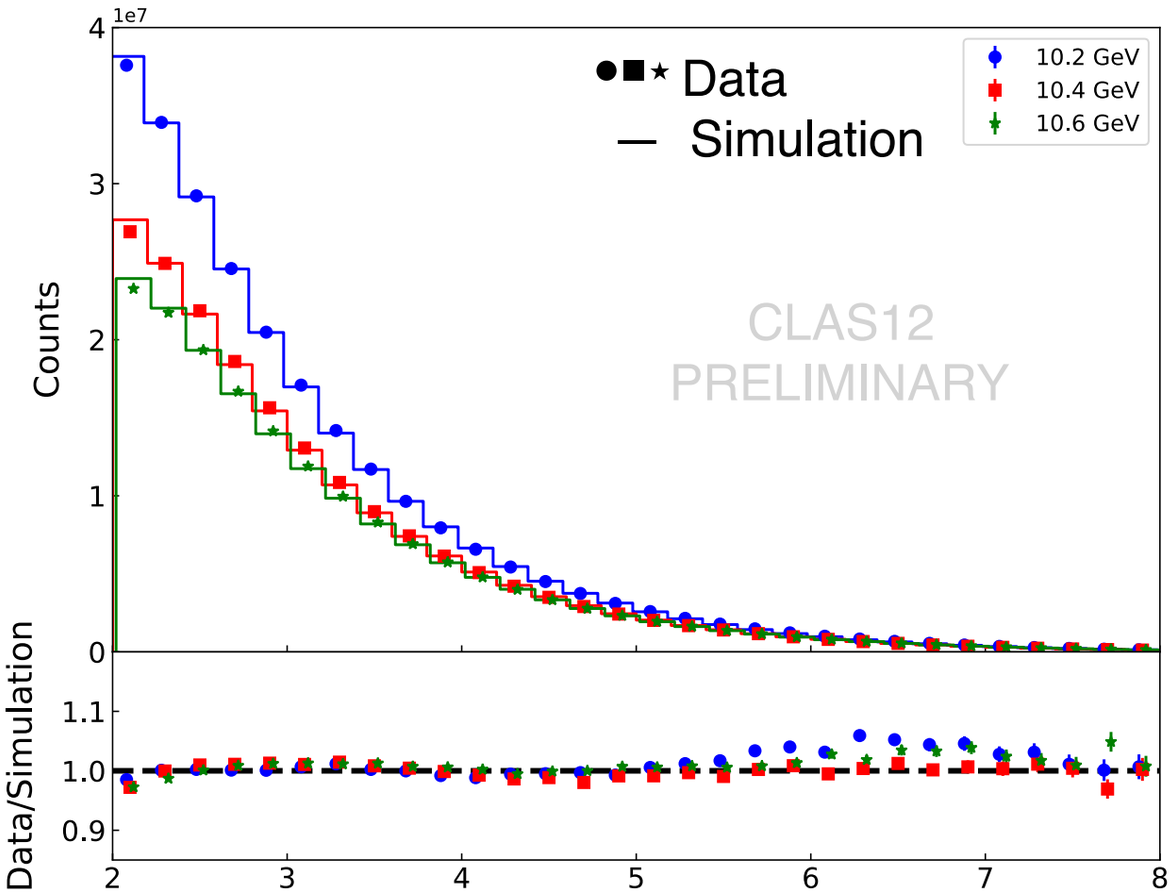
# Inclusive *d(e,e')X*



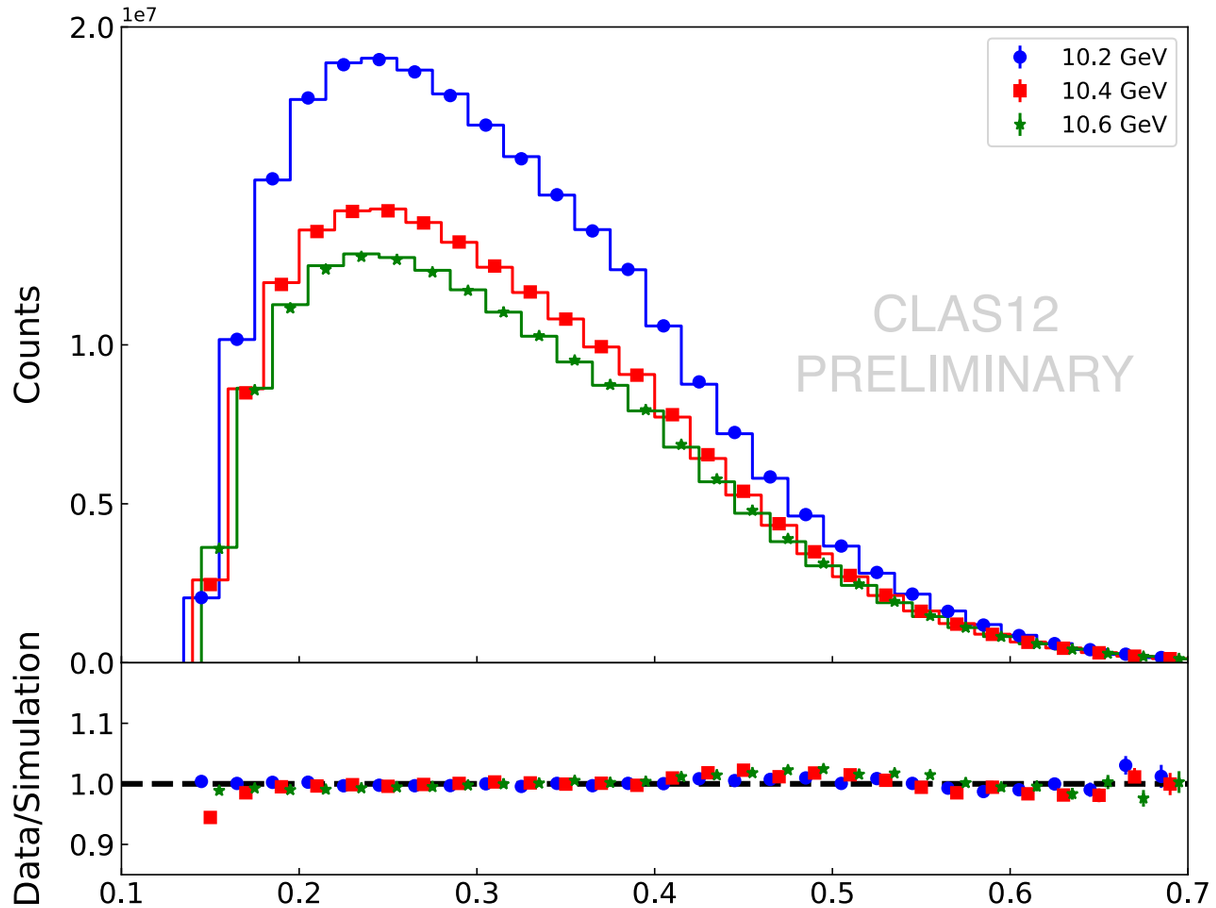

- Electron selection cuts
- $Q^2$ > 2 GeV²
- $W^2$ > 4 GeV²
- $y$ < 0.7
- -5 < $z_{vertex}$ < -1 cm

# Inclusive Data - MC comparisons

## Integral normalized



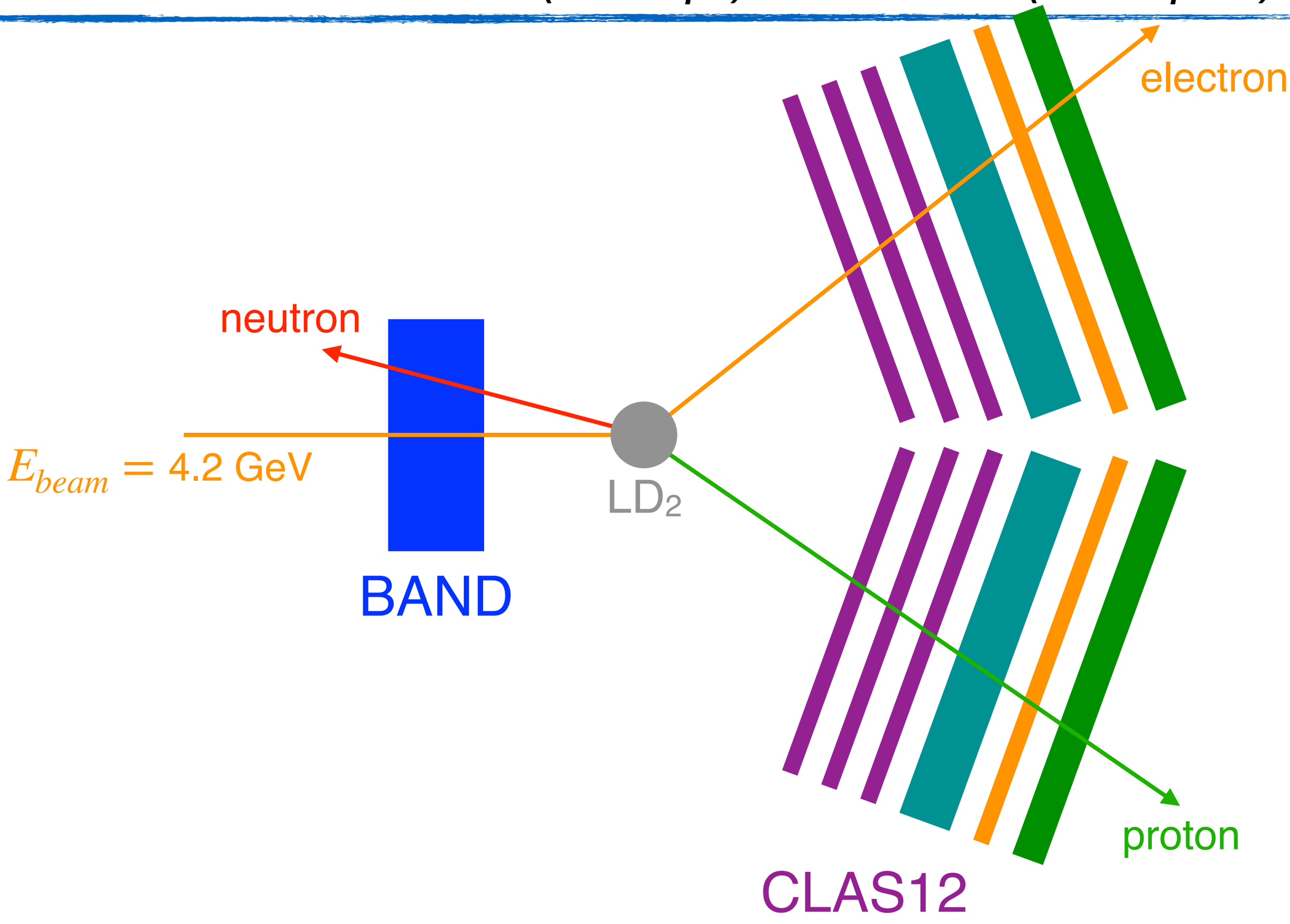

$Q^2$ (GeV²)




$x_B$

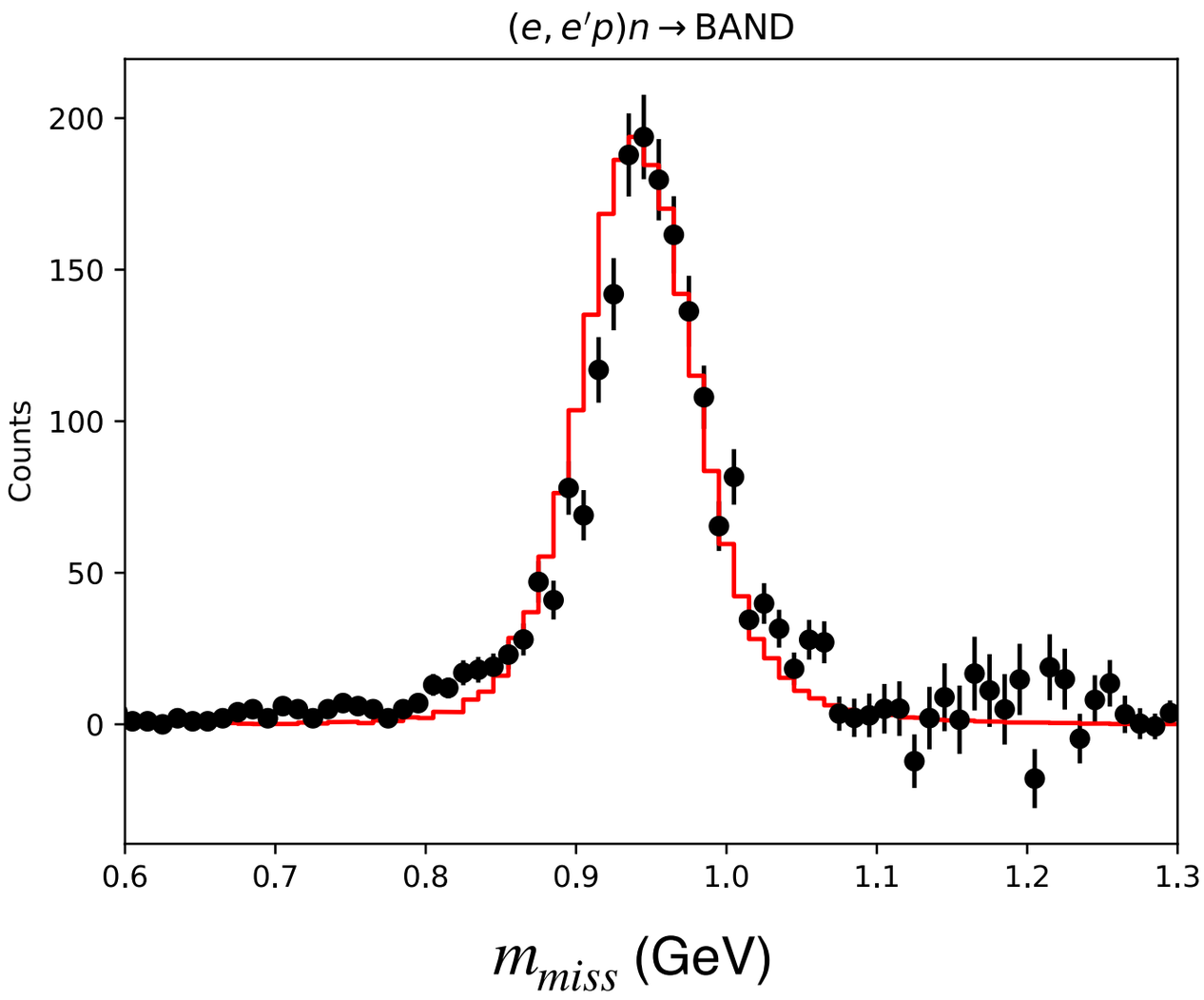
- Inclusive data well described by simulation

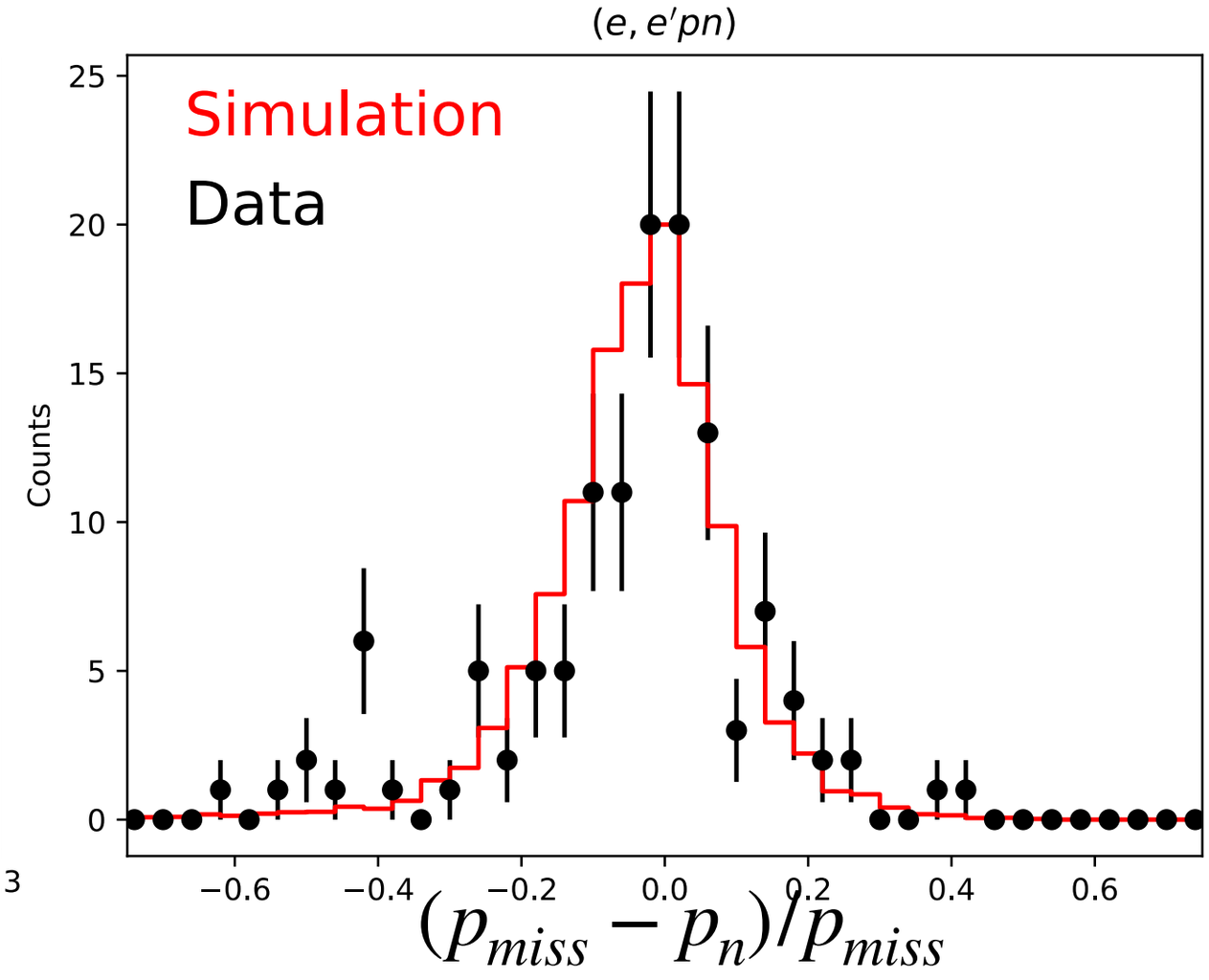
# Quasi-elastic *d(e,e'p)n* and *d(e,e'pn)*



# Quasielastic d(e,e'p)n and d(e,e'pn)

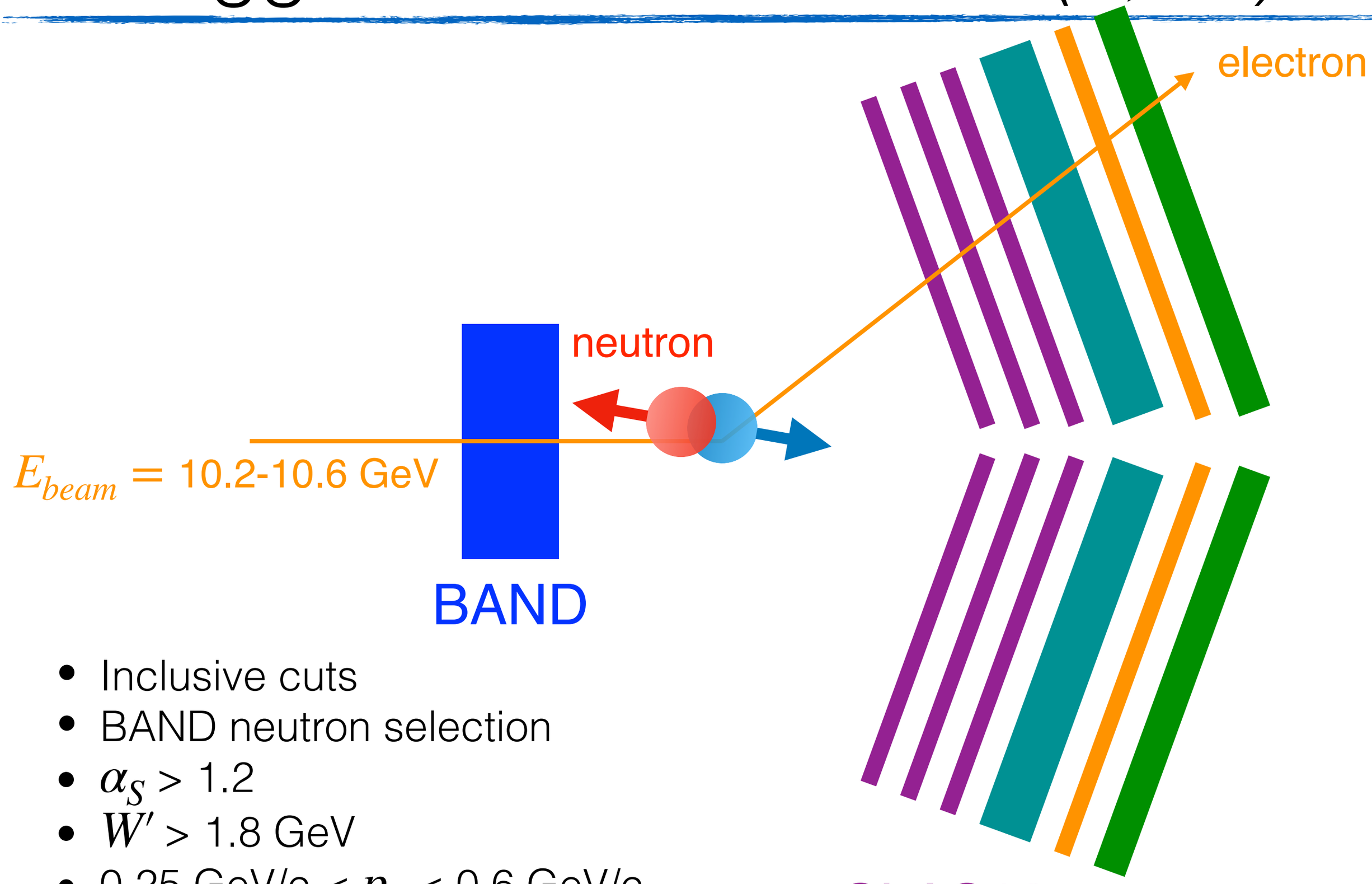
Integral-normalized




- Excellent agreement in resolution of data and simulation

# Tagged DIS with BAND *d(e,e'n)n*




- Inclusive cuts
- BAND neutron selection
- $\alpha_S$ > 1.2
- $W'$ > 1.8 GeV
- 0.25 GeV/c < $p_n$ < 0.6 GeV/c
- -1 < $\cos\theta_{nq}$ < -0.8

# Tagged Yield Ratio

$$R_{tag} = \frac{\sigma_{tag}^{exp}\left(Q^2, p_T, \alpha_S, x'\right) \Big/ \sigma_{tag}^{exp}\left(Q_0^2, p_T, \alpha_S, x' = x_0\right)}{\sigma_{tag}^{theory}\left(Q^2, p_T, \alpha_S, x'\right) \Big/ \sigma_{tag}^{theory}\left(Q_0^2, p_T, \alpha_S, x' = x_0\right)}$$

$$\rightarrow \quad R_{tag} = \frac{Y_{exp}\left(x'\right) \Big/ Y_{exp}\left(x' = x_0\right)}{Y_{sim}\left(x'\right) \Big/ Y_{sim}\left(x' = x_0\right)} = \frac{\sigma_{tag}^{exp}\left(x'\right) \Big/ \sigma_{tag}^{exp}\left(x' = x_0\right)}{\sigma_{tag}^{theory}\left(x'\right) \Big/ \sigma_{tag}^{theory}\left(x' = x_0\right)}$$

- Cancellation of systematics in ratio
- Choose to normalize to $x_0' = 0.3$
- Sensitive to ratio of bound to free proton structure

$$R \approx \frac{F_2^*\left(Q^2, p_T, \alpha_S, x'\right) \Big/ F_2\left(Q^2, p_T, \alpha_S, x'\right)}{F_2^*\left(Q^2, p_T, \alpha_S, x' = x_0\right) \Big/ F_2\left(Q^2, p_T, \alpha_S, x' = x_0\right)}$$

# Theoretical PWIA Model

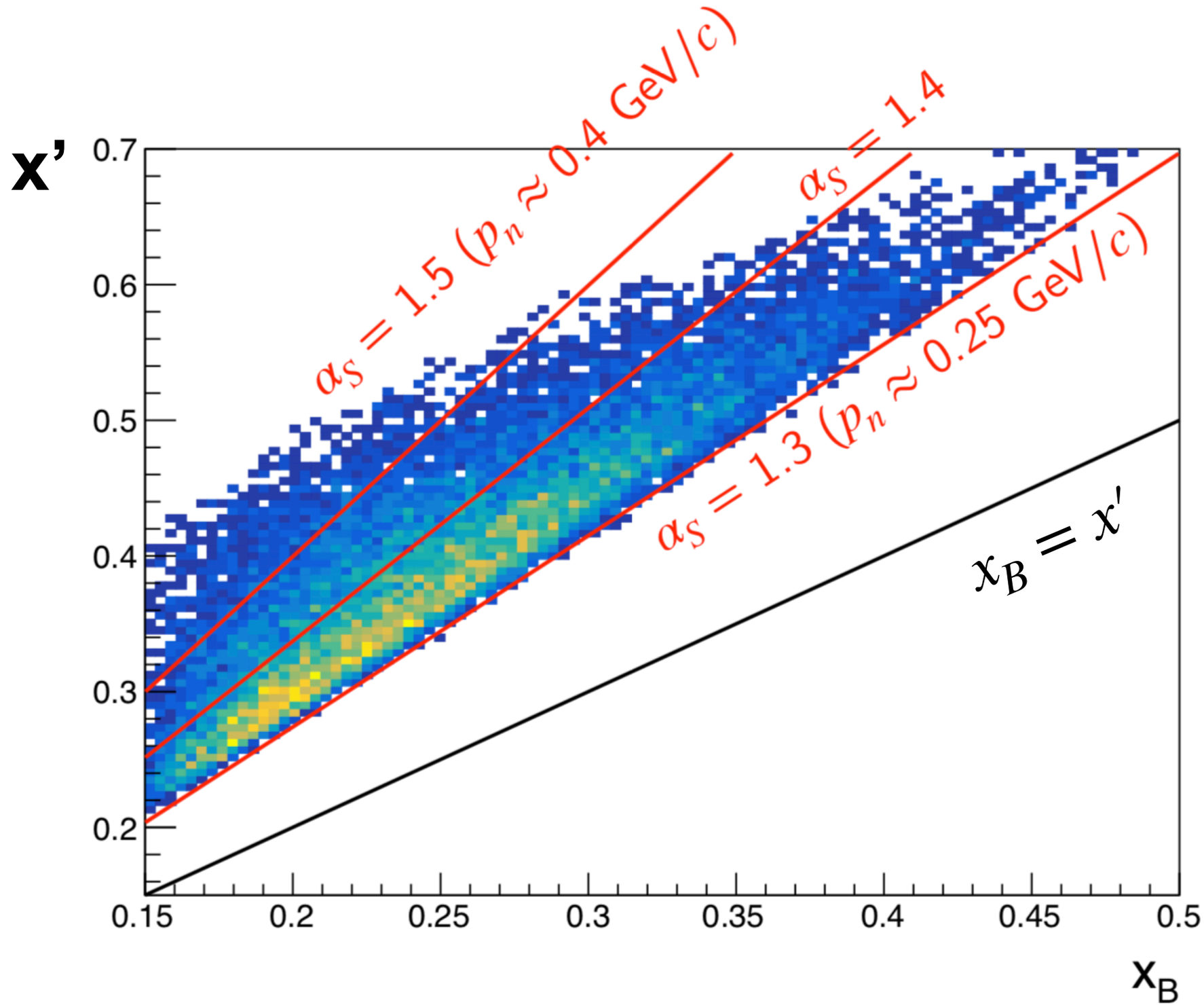
- Cross section model - Strikman & Weiss PRC 97, 035209 (2018):

$$d\sigma[eD \to e' n_s X] = K \frac{2S(\alpha_s, p_{sT})}{2-\alpha_s} \times F_2$$

- Kinematic factors
- Deuterium spectral function (momentum distribution of bound protons)
- Free proton structure function
- Includes finite $Q^2$ effects

- Simulate generated events with radiation in CLAS12-GEANT4 (GEMC)

# Tagged *d(e,e'n)X* Kinematics

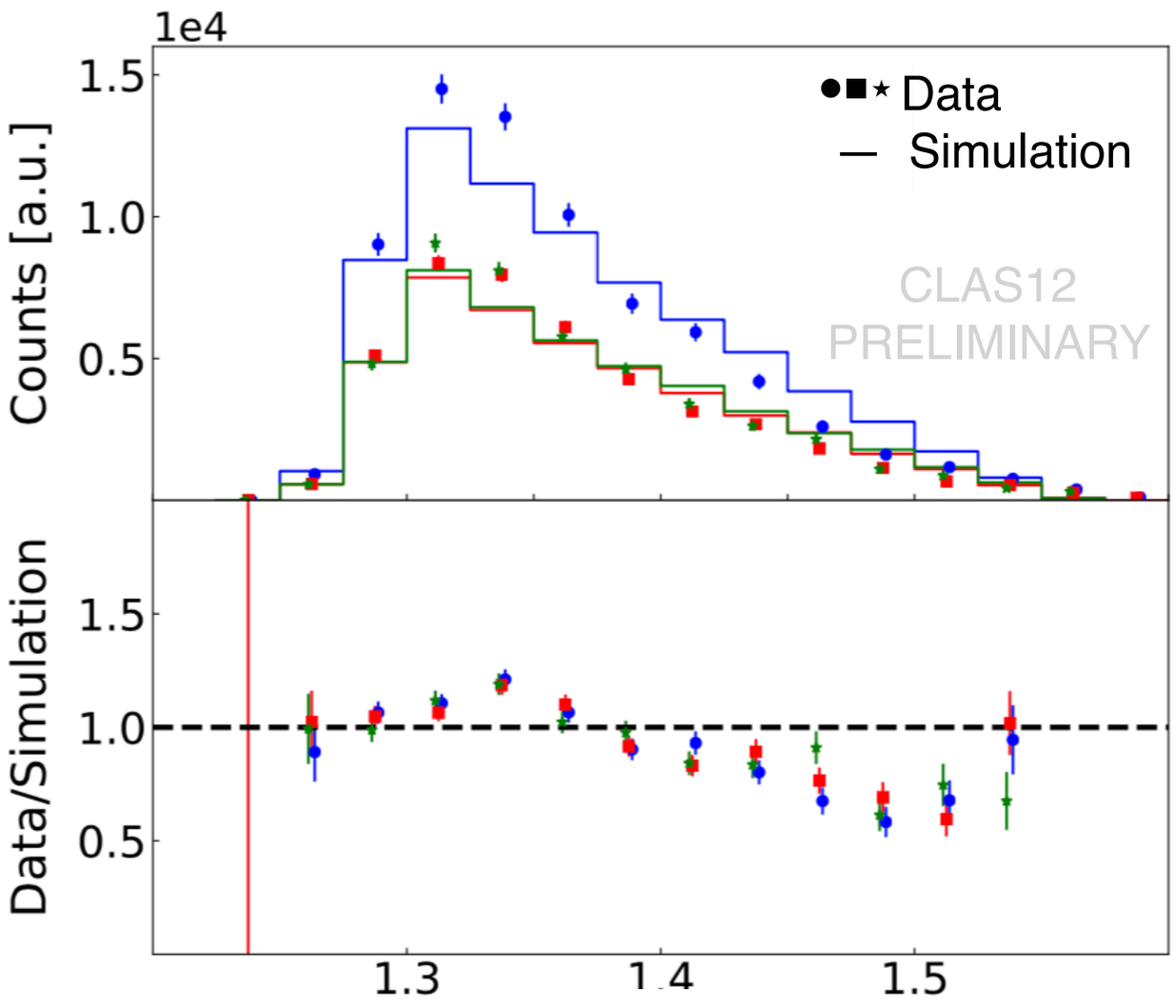



- $Q^2 > 2$ GeV$^2$
- $W^2 > 4$ GeV$^2$
- $y < 0.7$

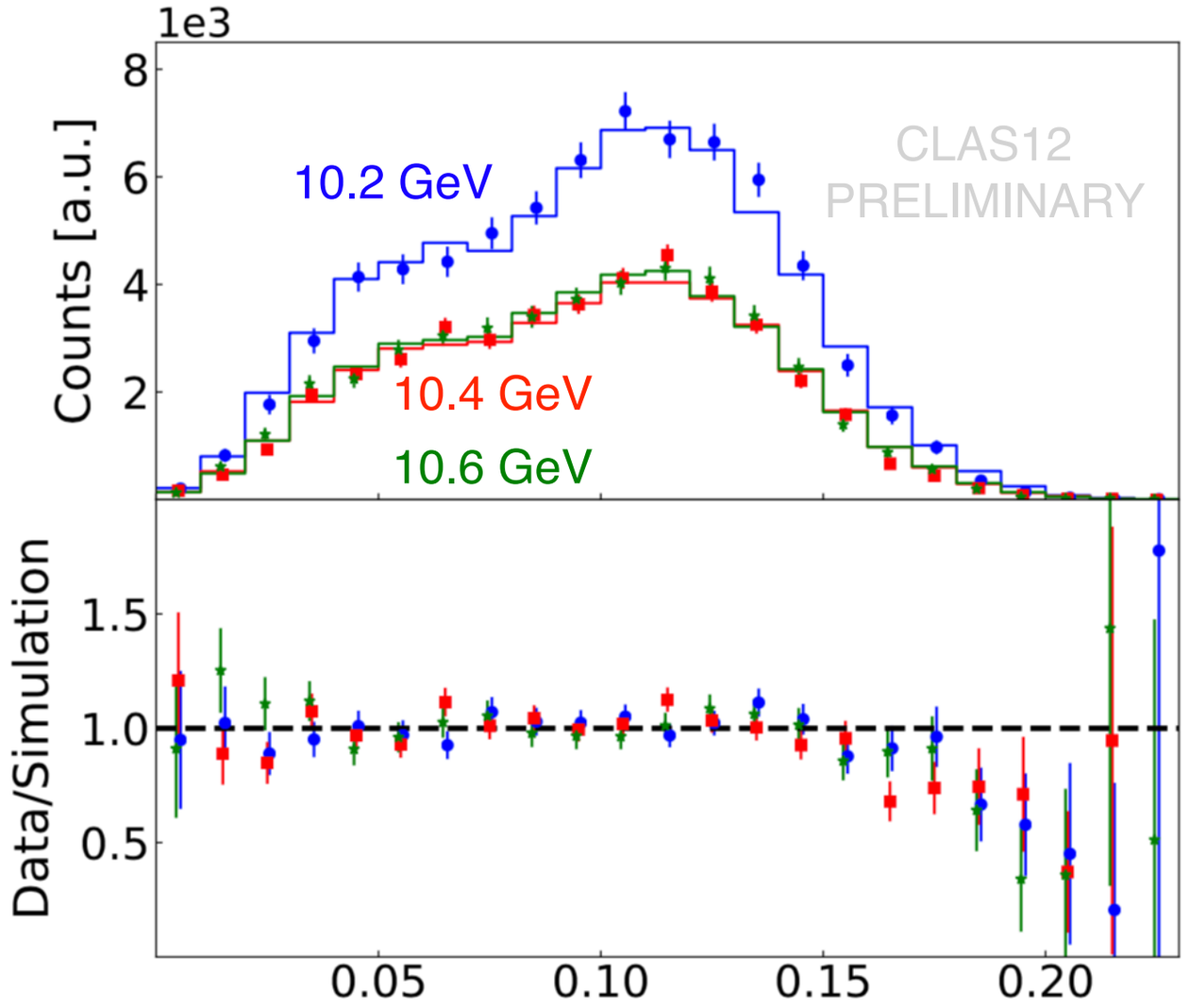
- cos $\theta_{nq}$ < -0.8
- $W' >$ 1.8 GeV
- $p_T$ < 0.1 GeV/c
- $p_n$ > 0.25 GeV/c

# d(e,e'n)X: Data/MC comparisons

Integral normalized



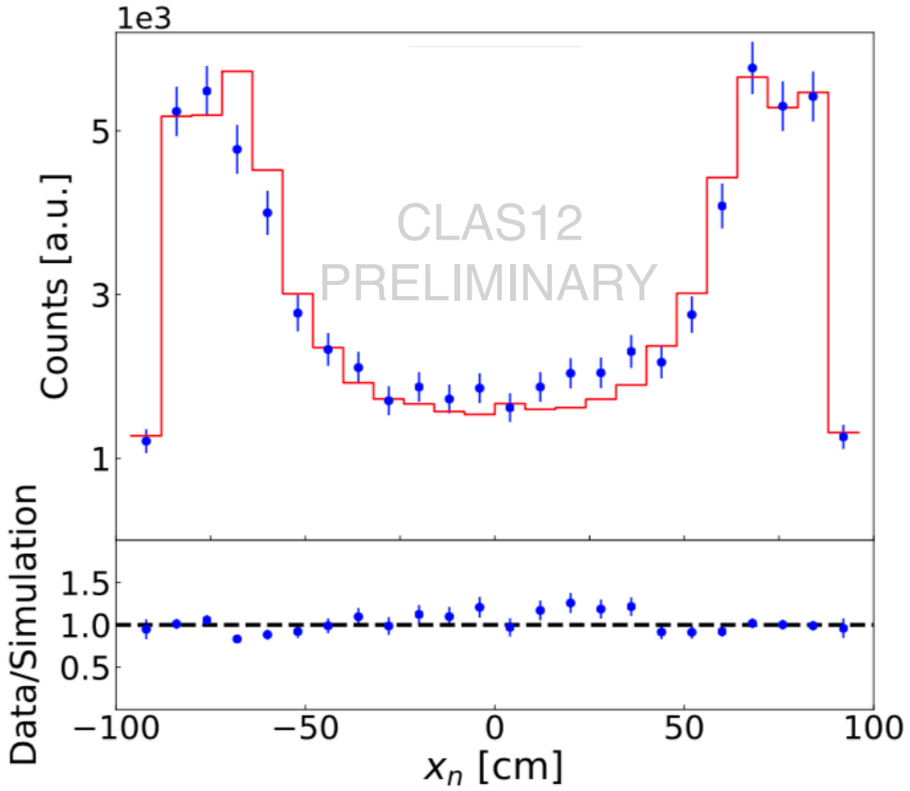

$\alpha_S$

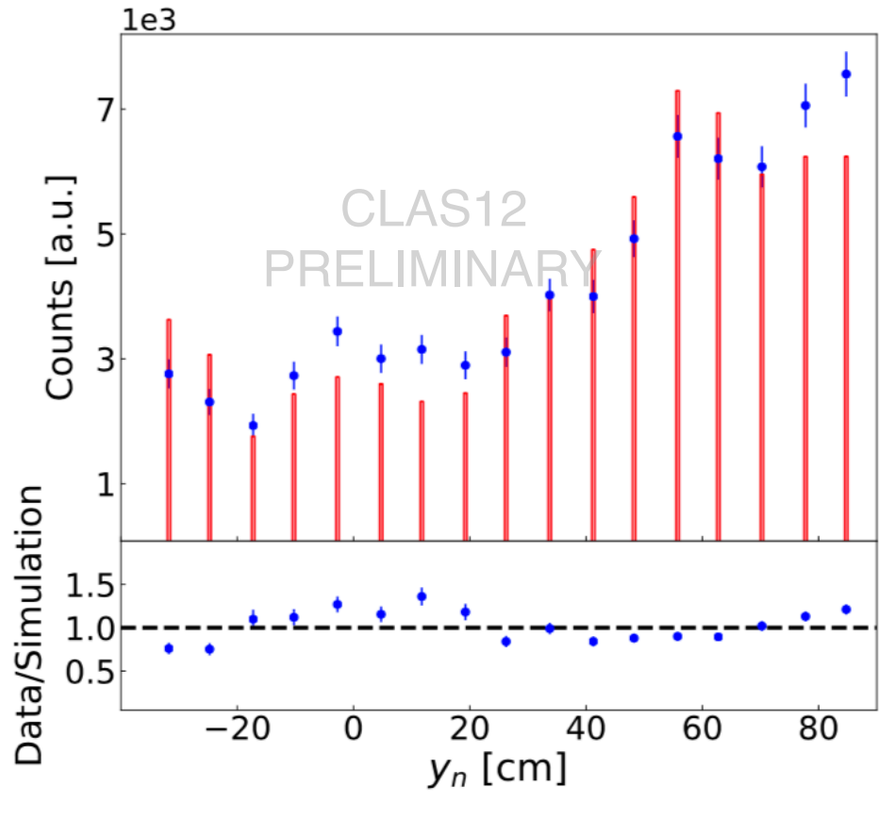


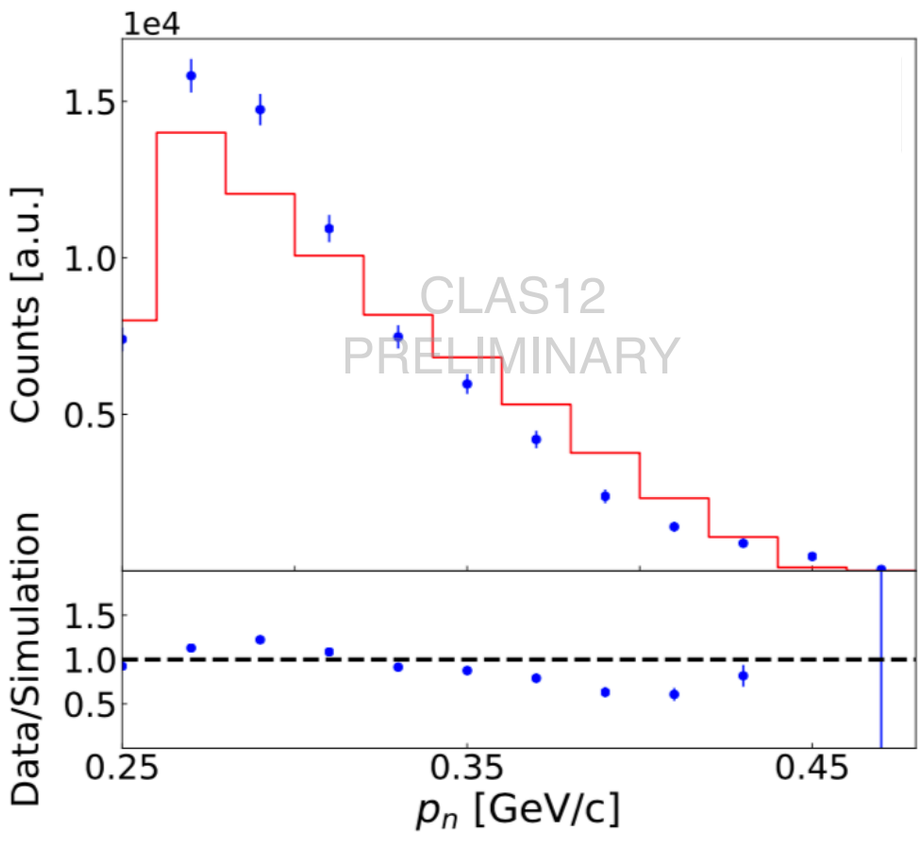

$p_T$ (GeV/c)

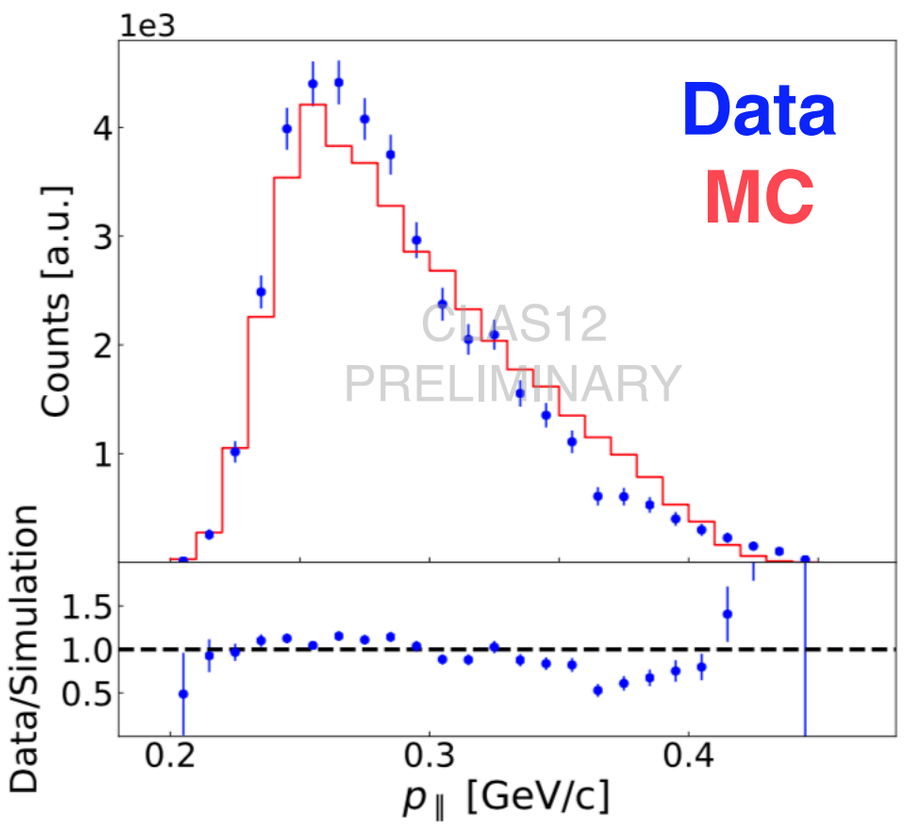
(transv. mom with respect to q)

# More Tagged Comparisons (10.2 GeV)

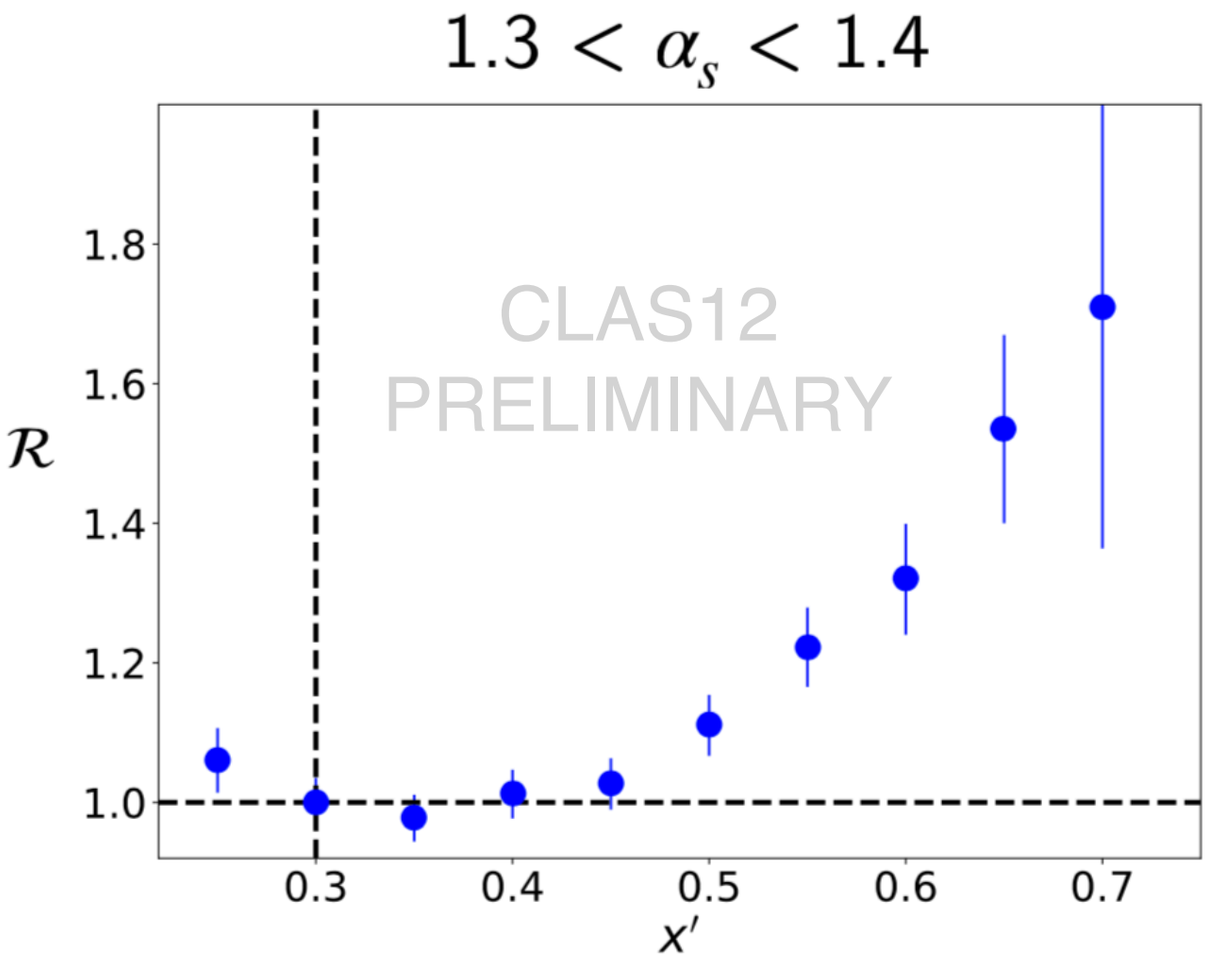


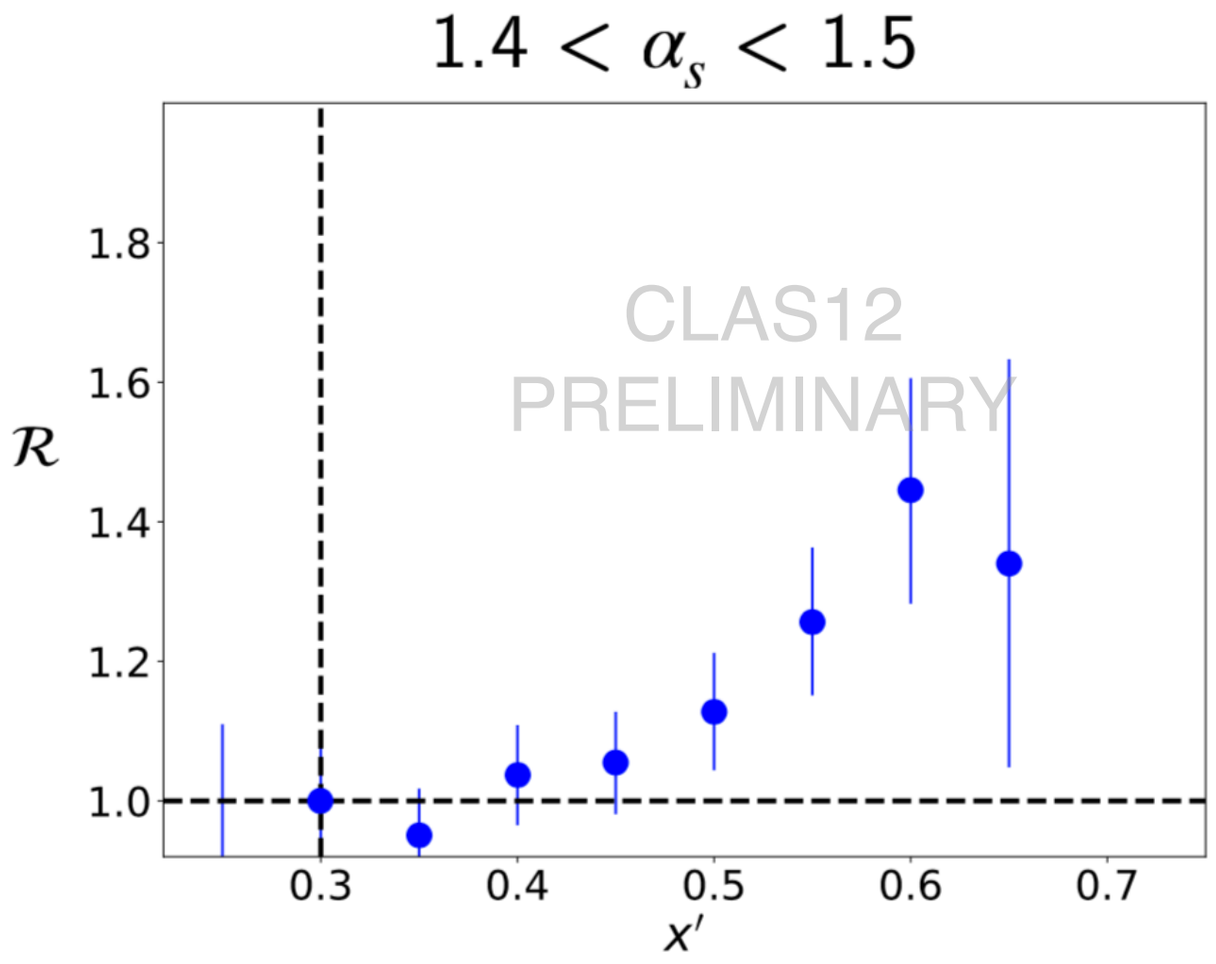



# Tagged Double Ratio



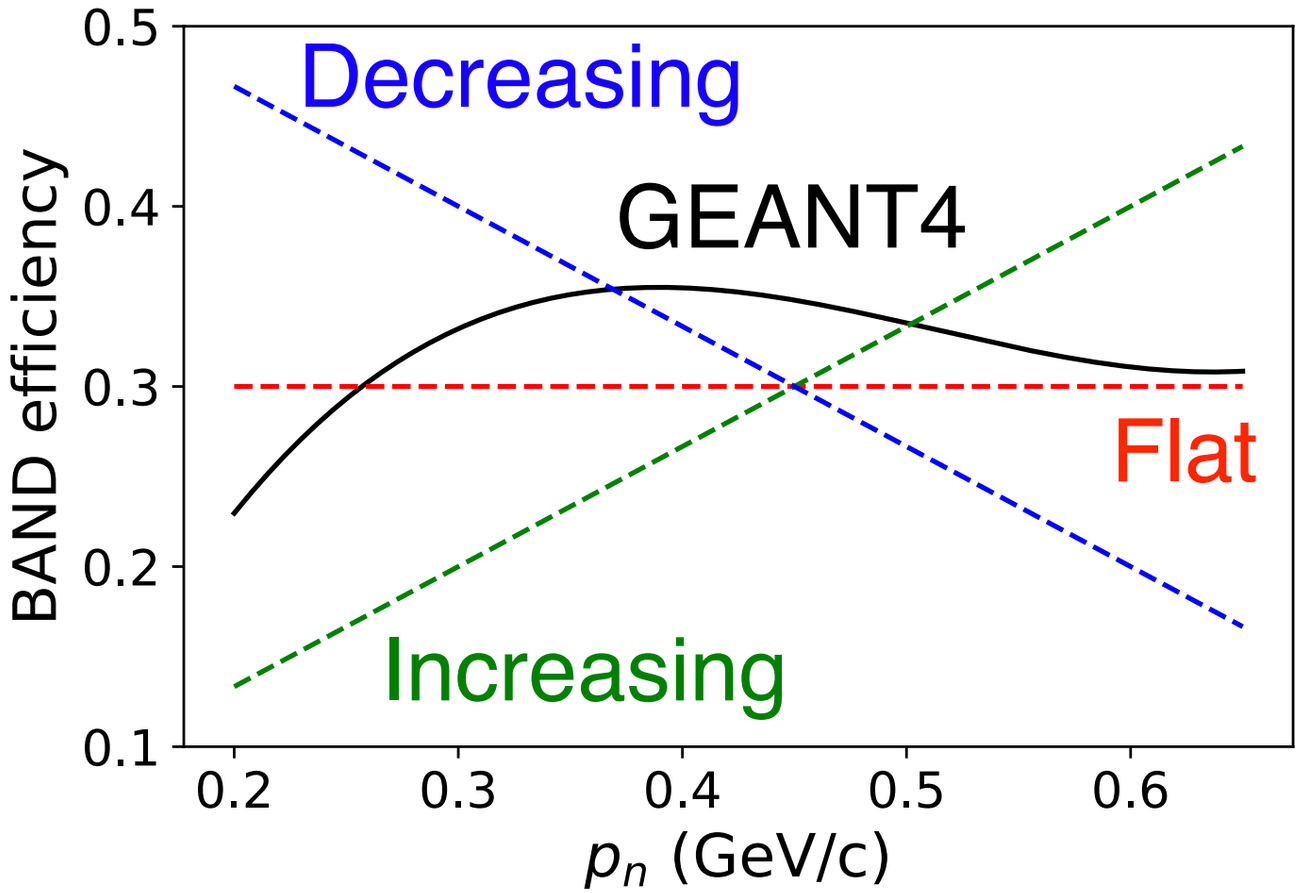

$$R \approx \frac{F_2^*\left(Q^2, p_T, \alpha_S, x'\right) / F_2\left(Q^2, p_T, \alpha_S, x'\right)}{F_2^*\left(Q^2, p_T, \alpha_S, x' = x_0\right) / F_2\left(Q^2, p_T, \alpha_S, x' = x_0\right)}$$

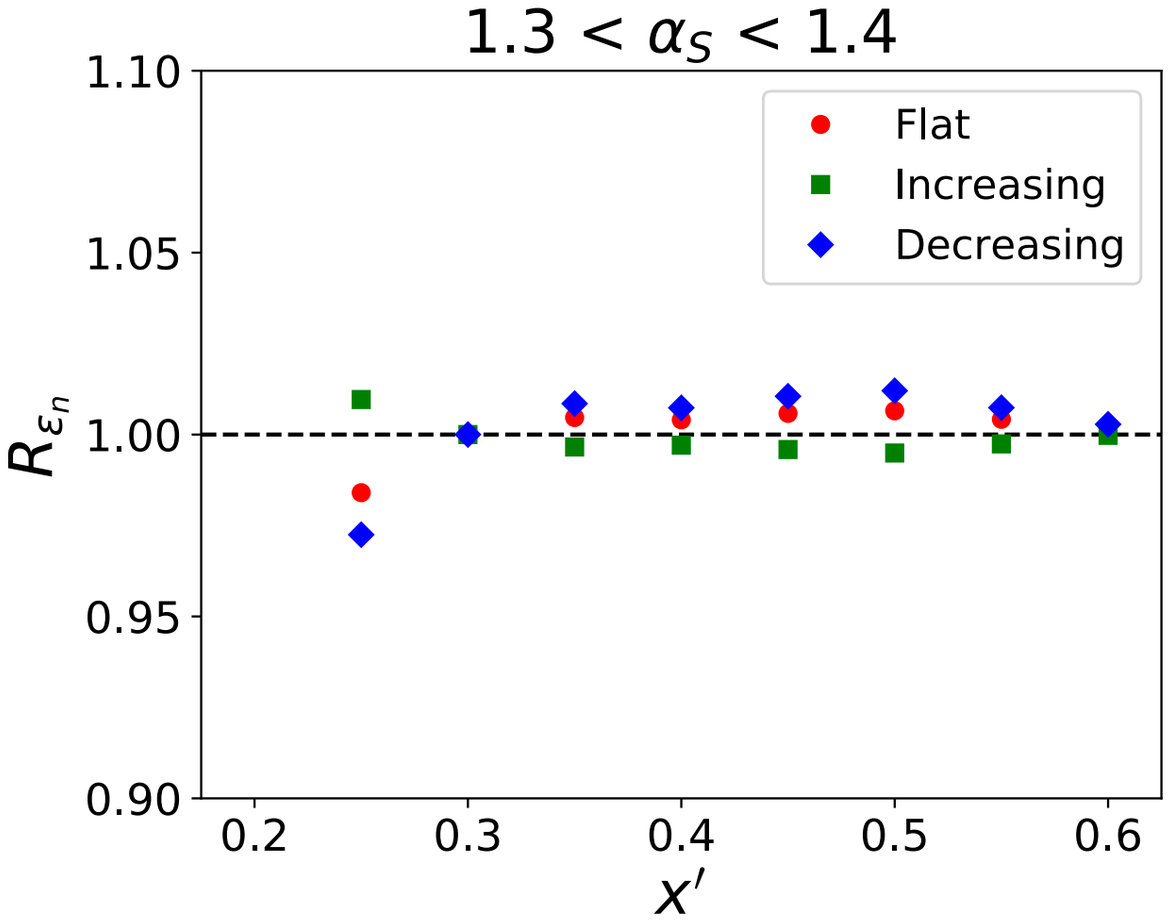
# Systematics

- Impact of BAND neutron detection efficiency
- Measurement stability with different beam energies
- Other studies:
  - Impact of finite $Q^2$ effects
  - Different event generators
  - Cut sensitivity

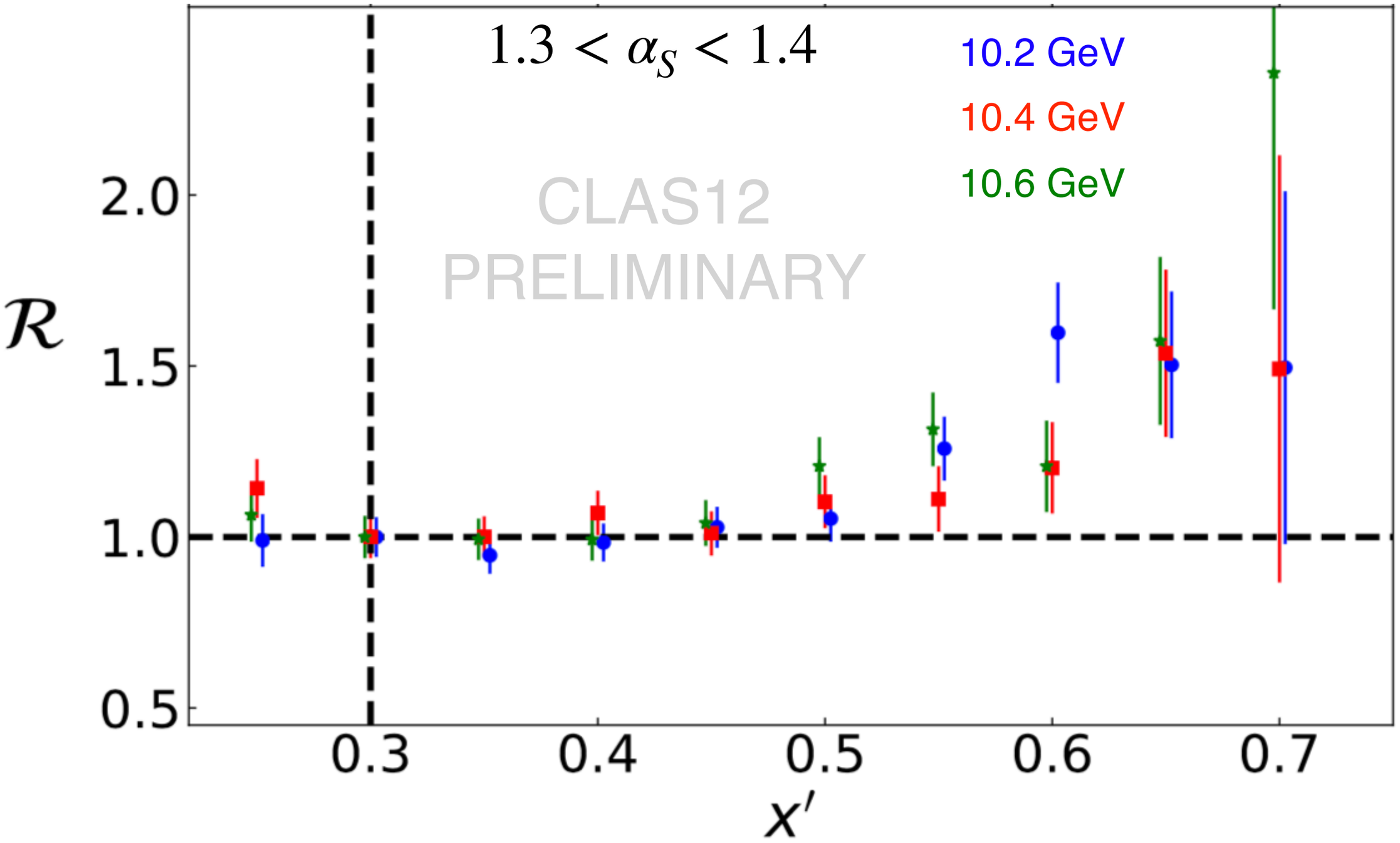
# Systematics: BAND Efficiency

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



# Systematics: Stability with Beam Energy



# Impact on EMC studies with light nuclei

- Convolution model - Segarra et al, Phys. Rev. Research 3 (2021)
- Allow isospin-dependent *n*, *p* modification
- Fit light nuclear structure functions with tagged double ratio as constraint

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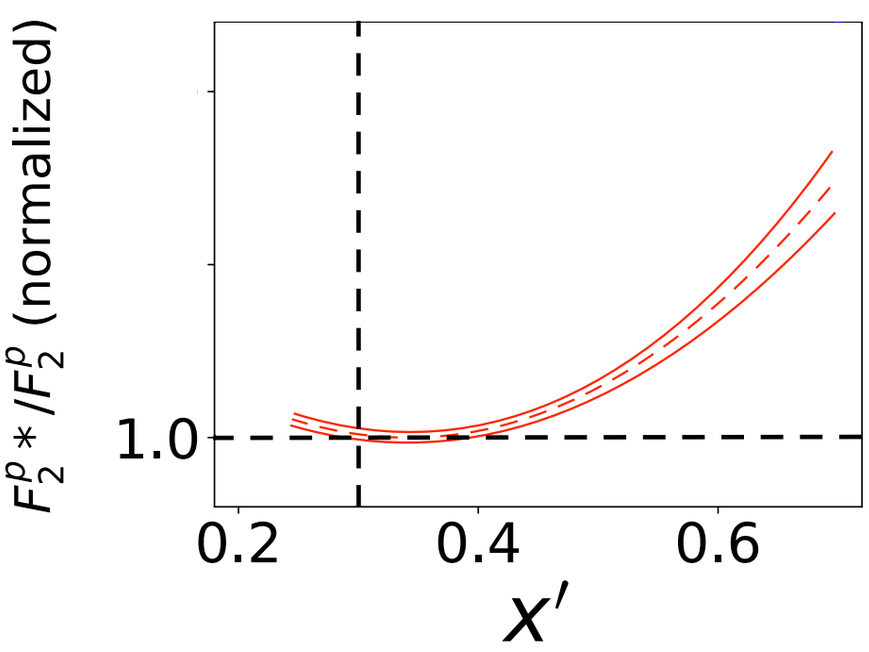

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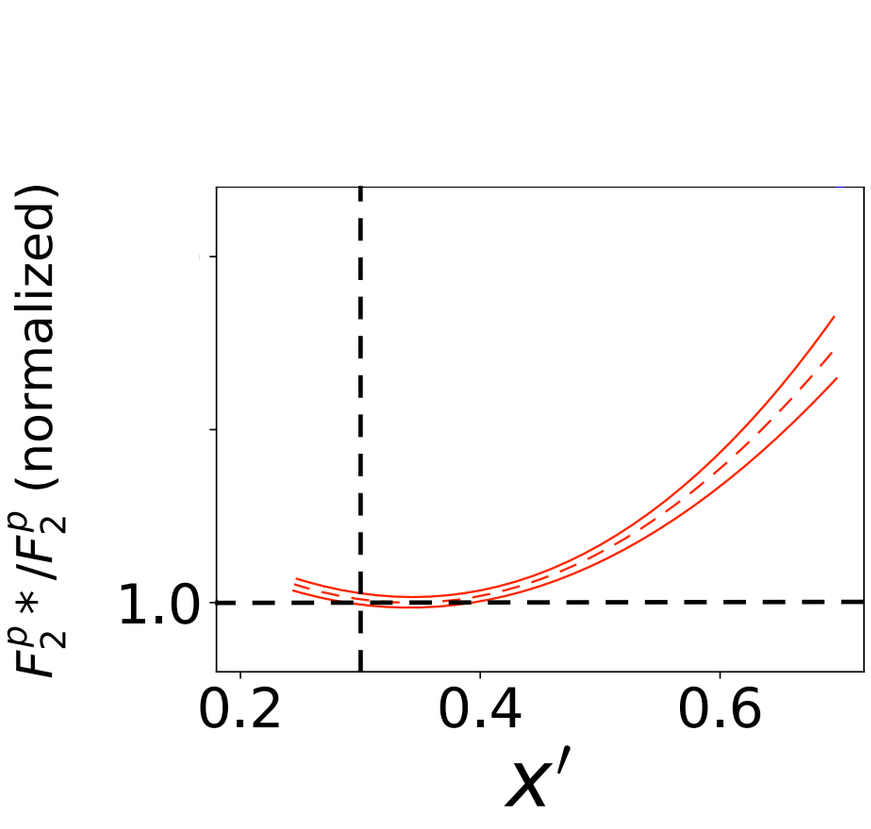
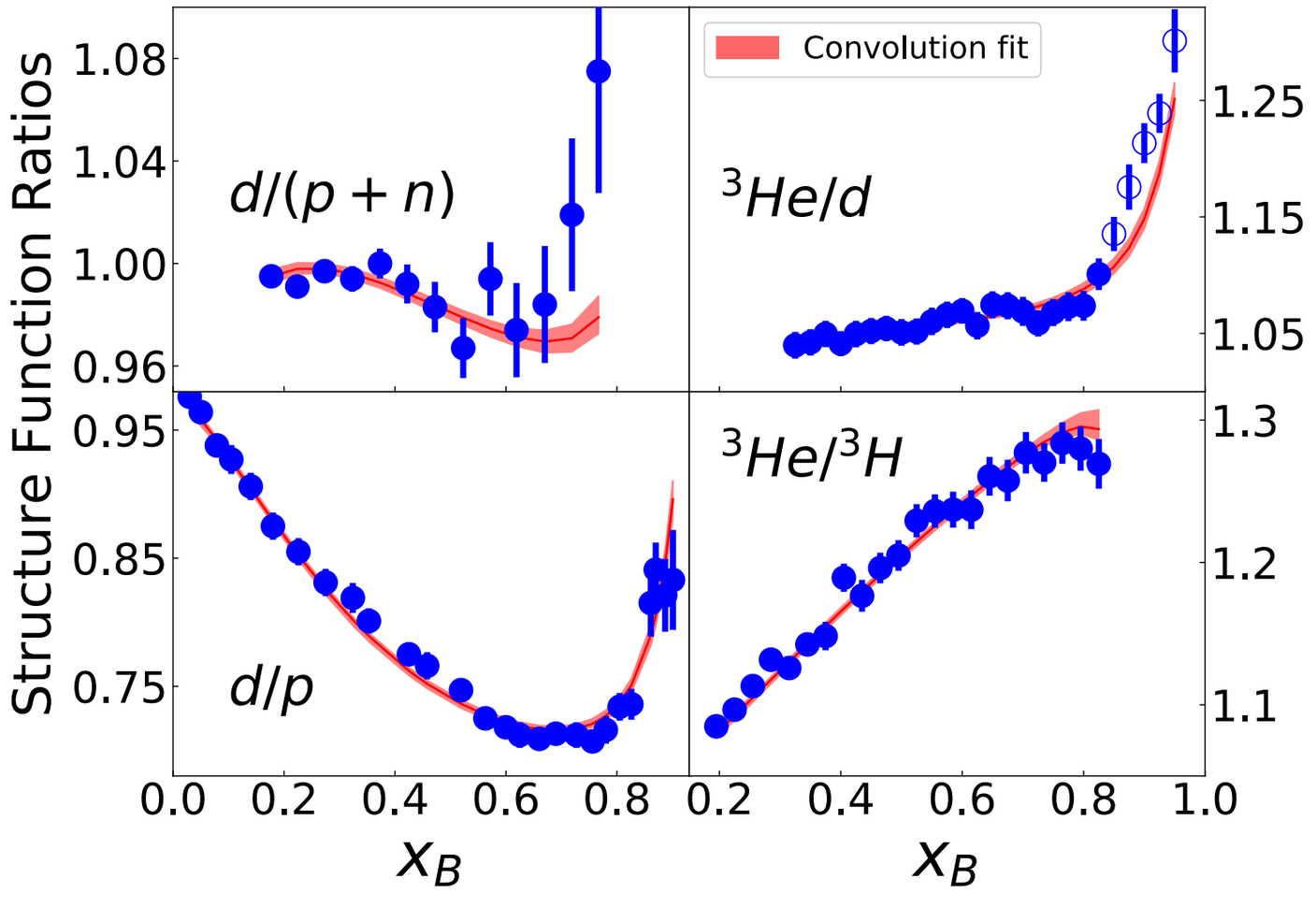


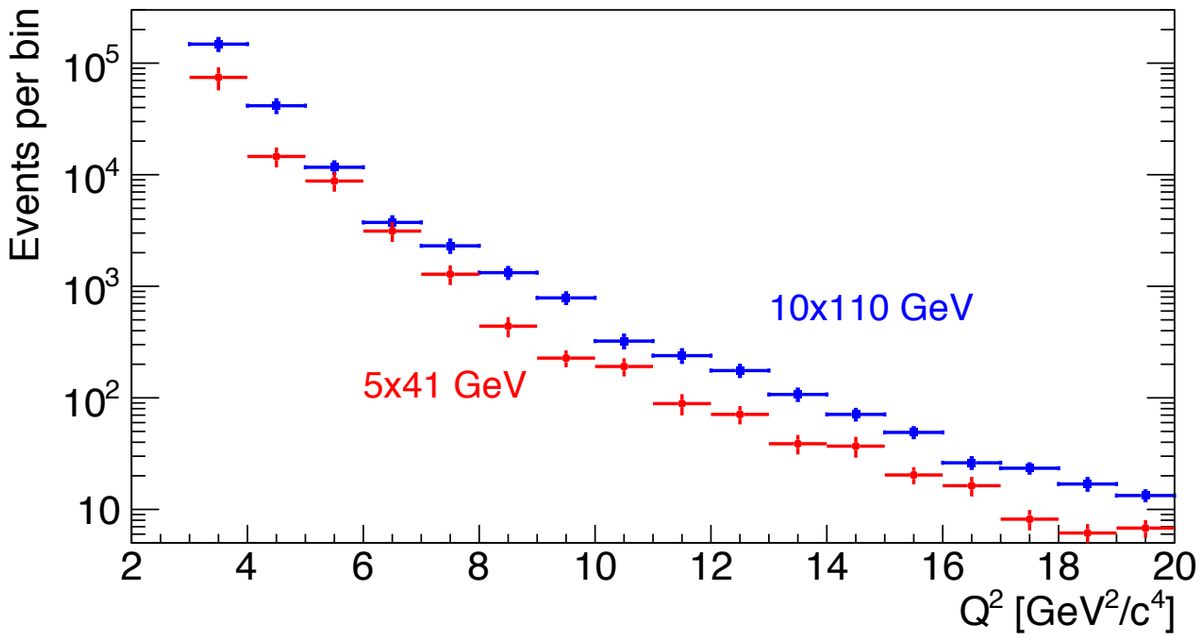
# Summary

- Tagged DIS measurements to understand nucleon modification for high momentum nucleons
- First measurement of neutron-tagged DIS with CLAS12 + BAND
- Preliminary ratios show large modification of deeply bound proton structure
- CLAS12 analysis review is underway

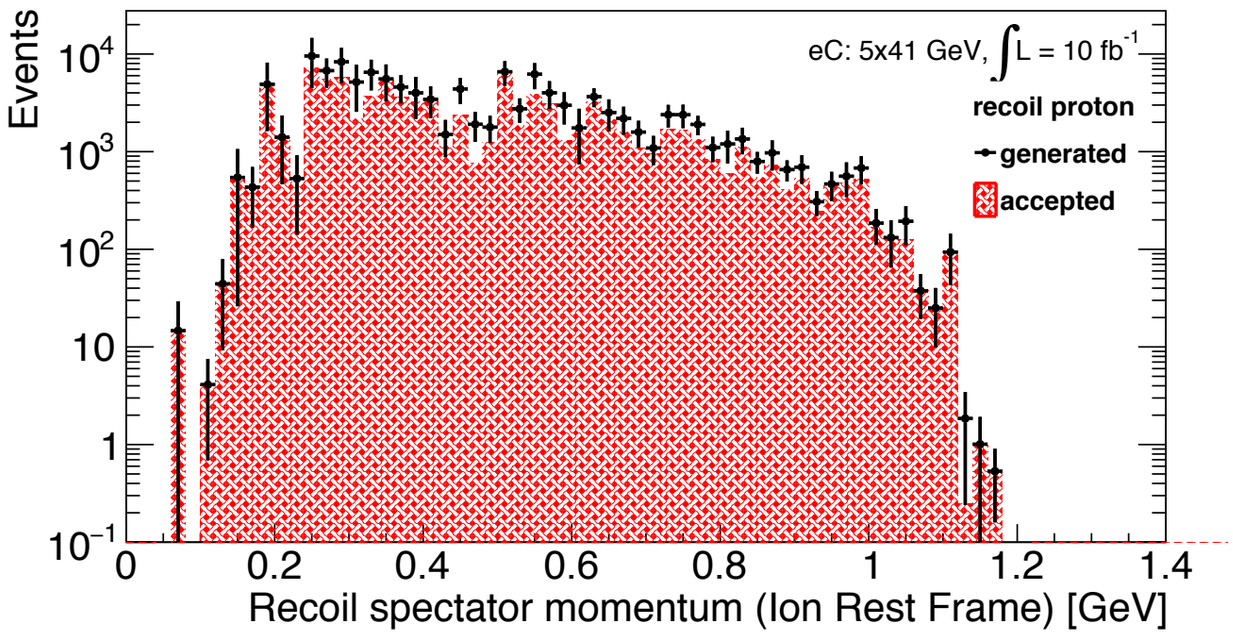
# Outlook

- Publication next year
- LAD experiment in HallC (complemental to BAND)
- ALERT experiment in HallB (tagging on recoil nuclei from $^4$He(e,e'))
- Tagged SRC measurements at EIC (DIS and QE kinematics)

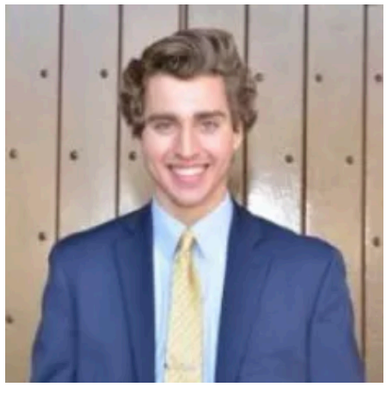
F. Hauenstein et al., PRC 105, 034001 (2022)




High $Q^2$ coverage




Large recoil acceptances



Efrain Segarra
(Student)

Tyler Kutz
(Postdoc)

Caleb Fogler
(Student)

Noah Swan
(Student)

Andrew Denniston
(Student)

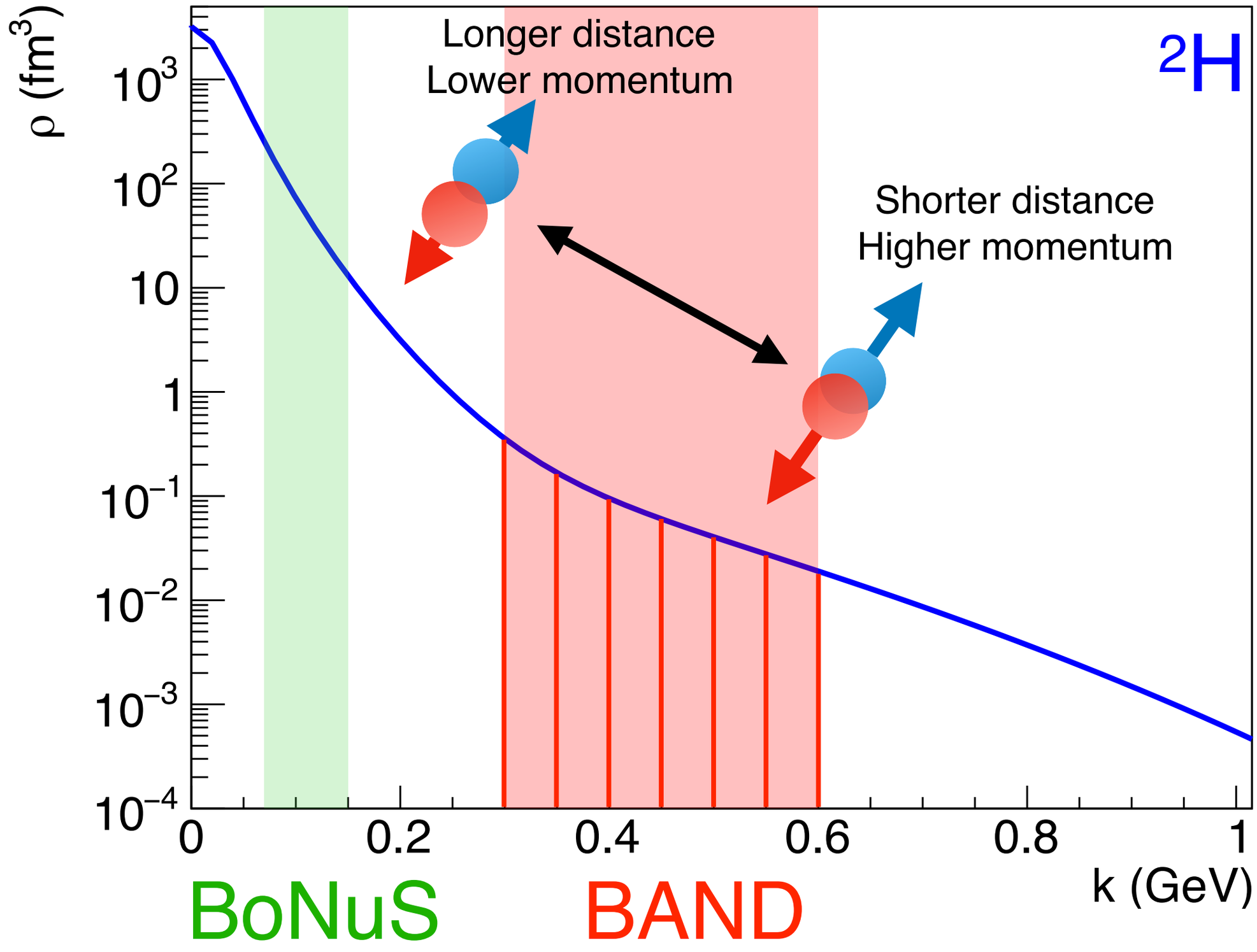
Justin Estee
(Postdoc)

Dien Nguyen
(Isgur postdoc)

# Thank you

# Backup slides

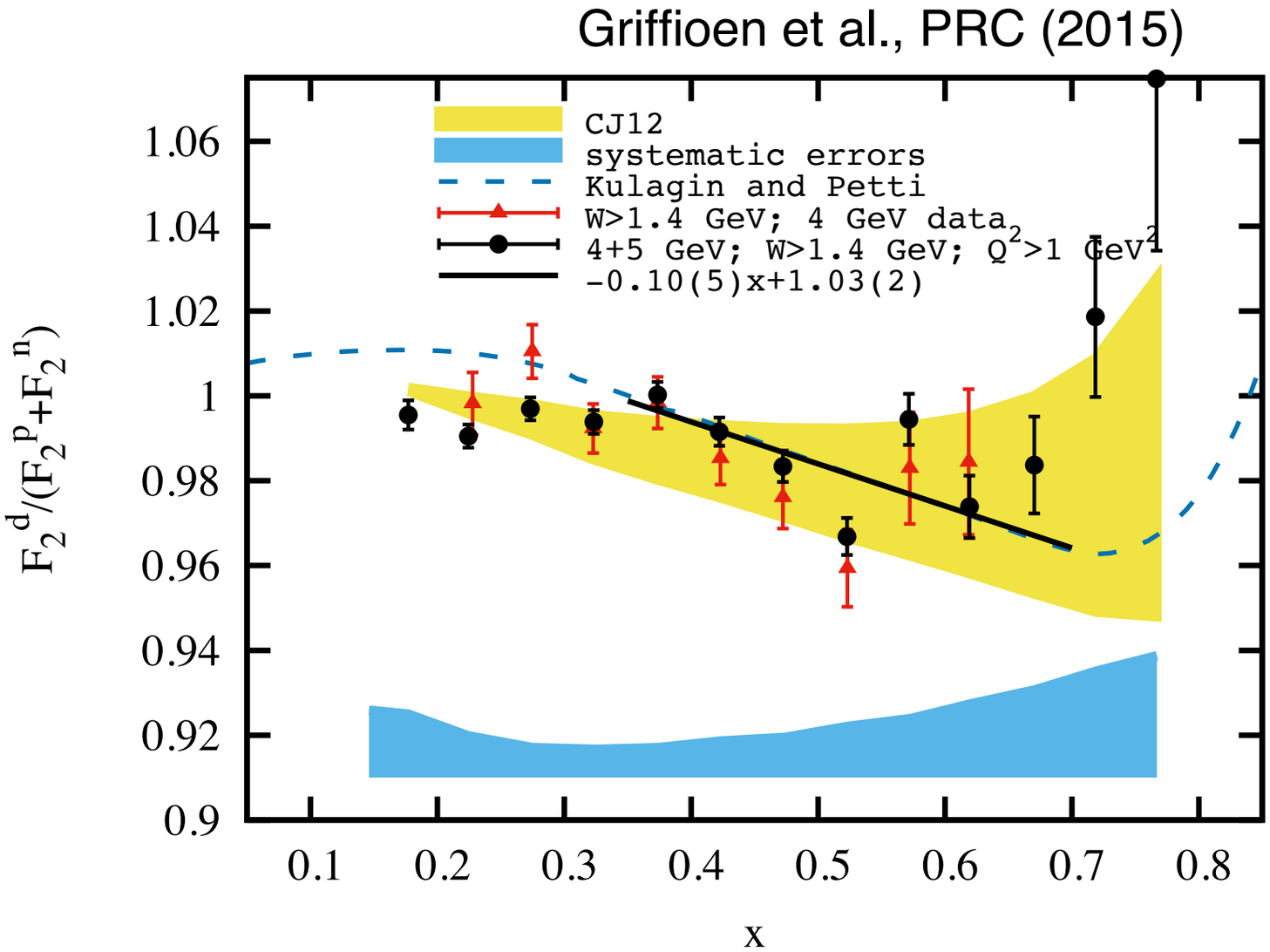
# Momentum Coverage



# EMC Effect in Deuterium

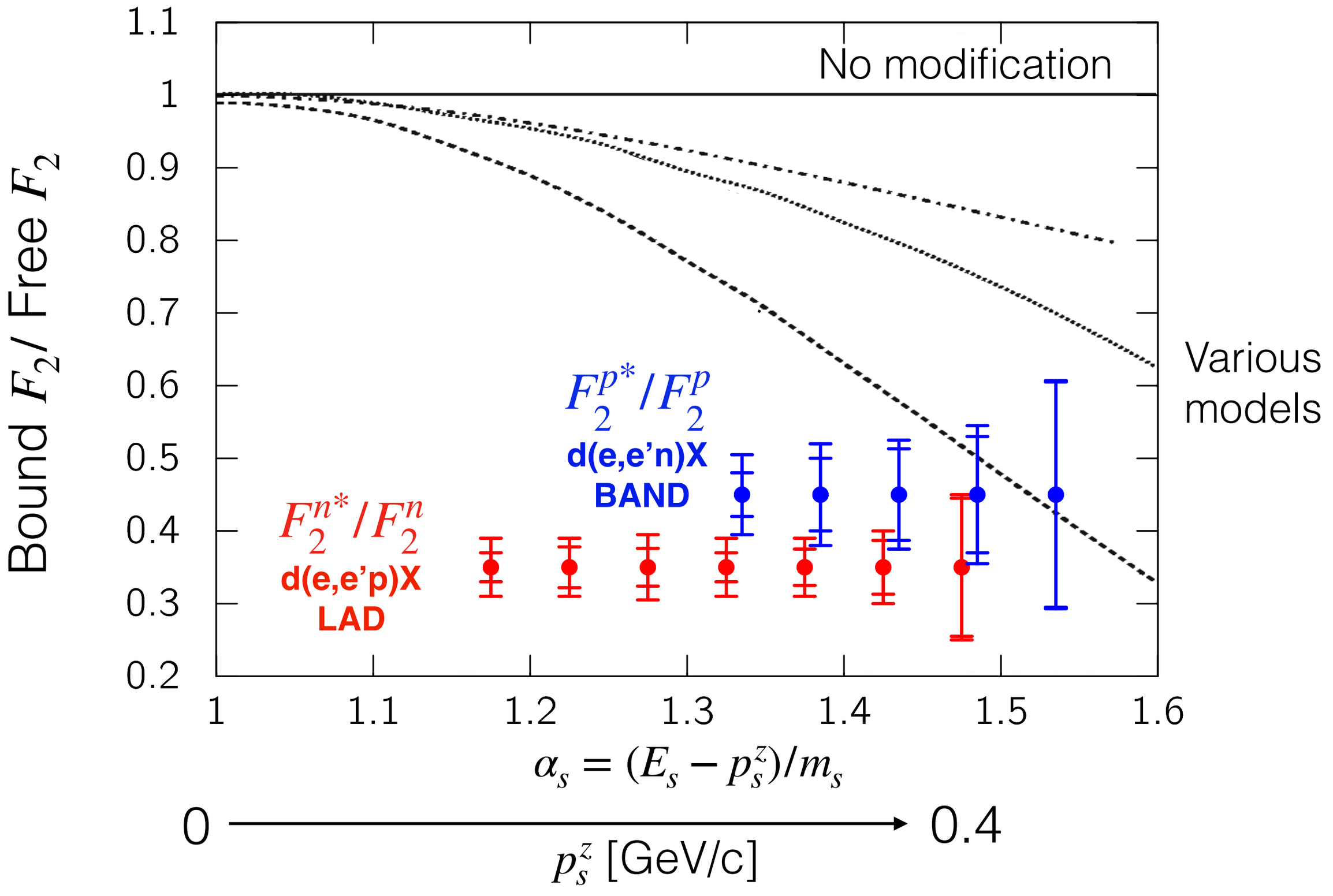
- EMC is small BUT
- SRC hypothesis predicts large modification of (rare) SRC states!

# EMC Effect in Deuterium

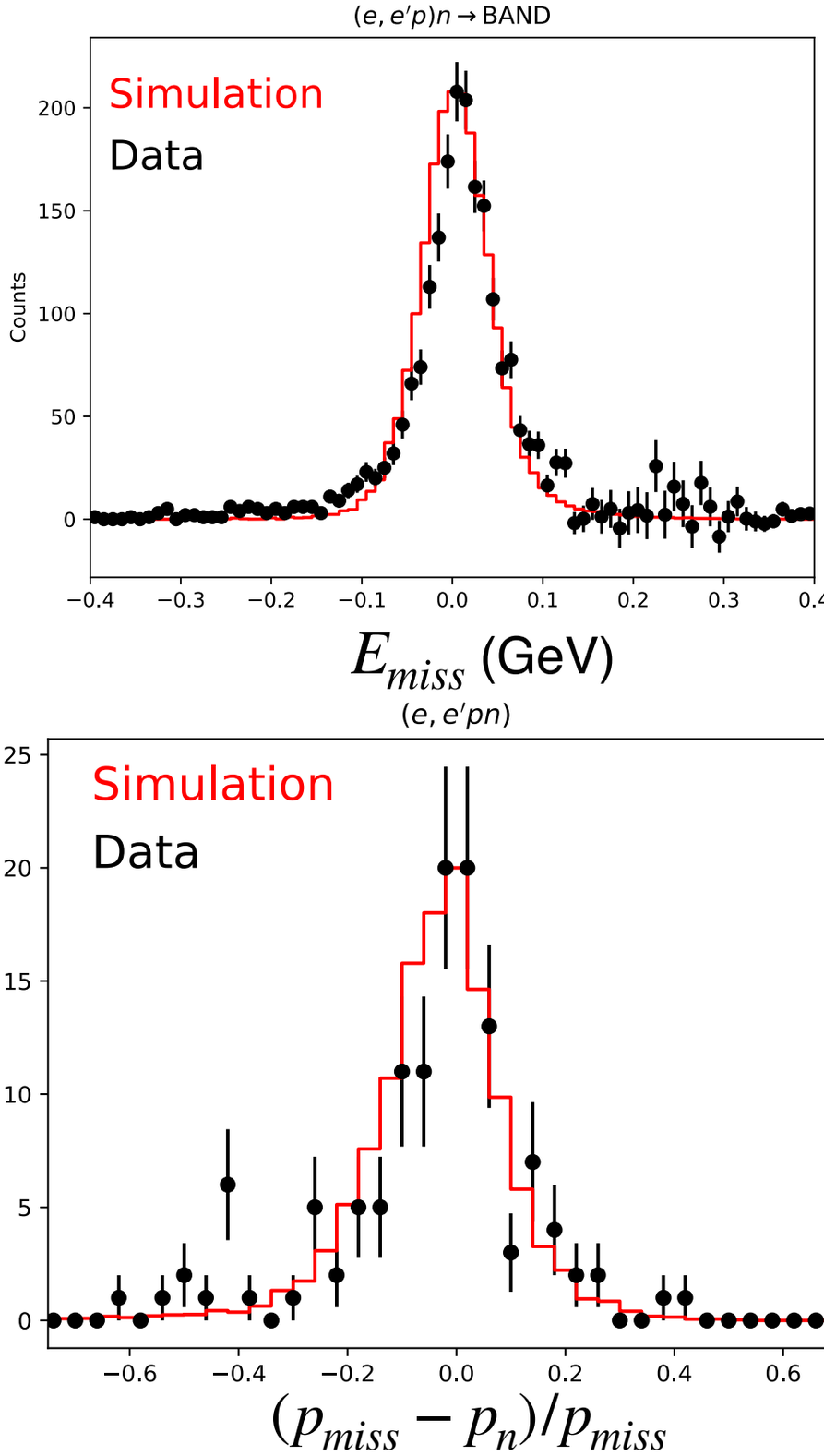



- EMC is small BUT
- SRC hypothesis predicts large modification of (rare) SRC states!

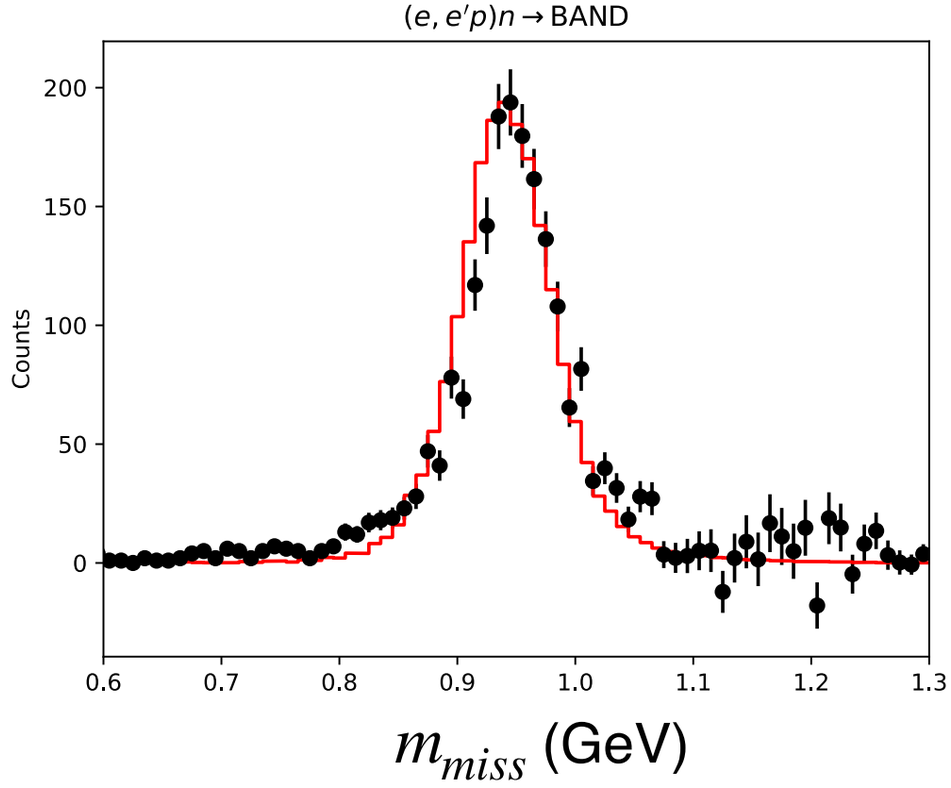
# DIS Recoil Tagging d(e,e'N)X - Expected Results



# Quasielastic d(e,e'p)n and d(e,e'pn)

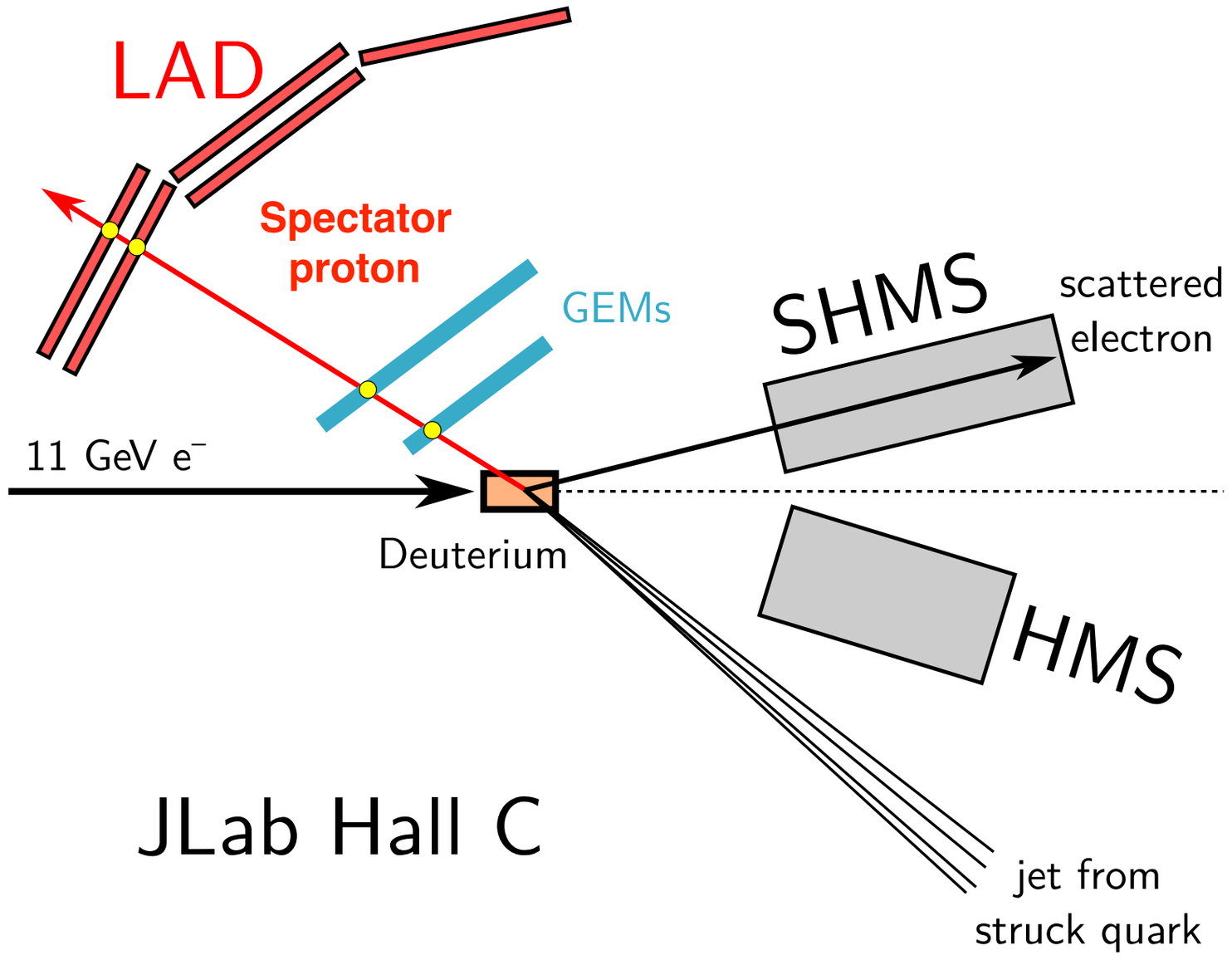



Integral-normalized

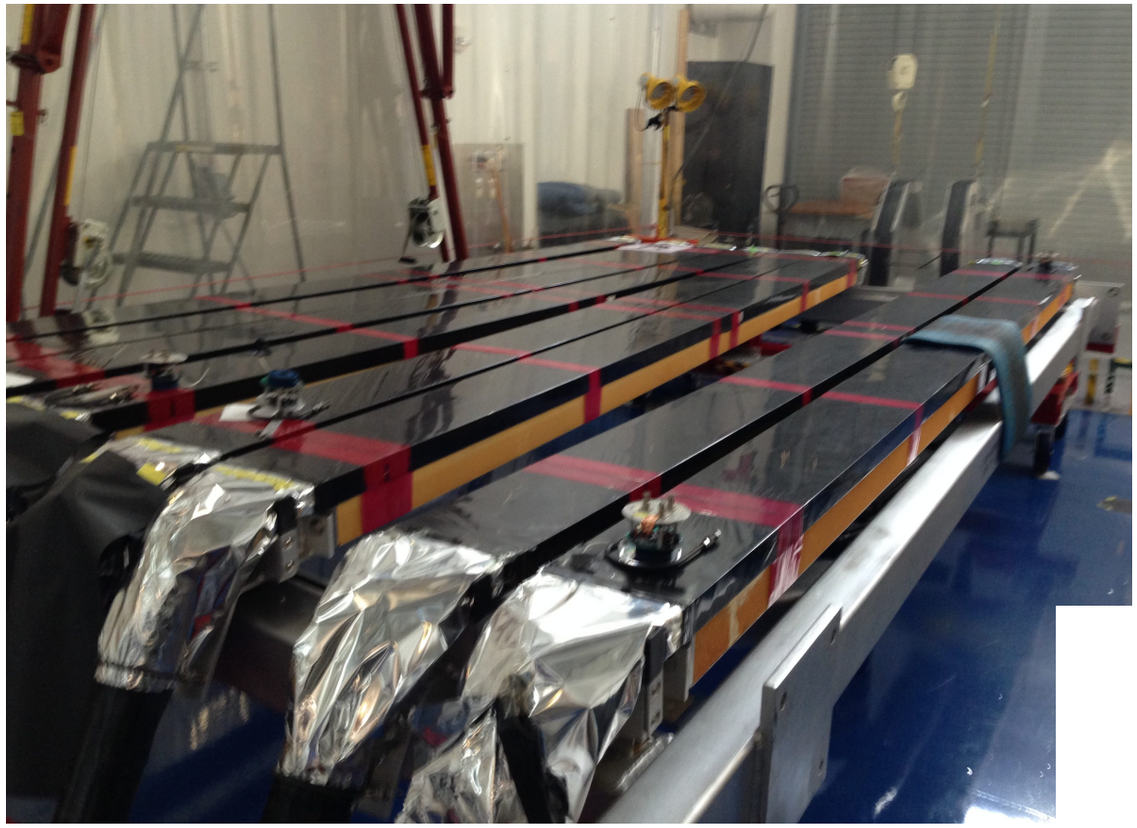



- Excellent agreement in resolution of data and simulation
- Luminosity-normalized data/simulation ratio ≈ 2-3

# LAD in Hall-C


LAD
Spectator
proton
GEMs
SHMS
scattered
electron
11 GeV e⁻
Deuterium
HMS
JLab Hall C
jet from
struck quark

# LAD - Refurbished CLAS6 Scintillators



- 4m long, 5 panels, 55 bars
- 6m away from the target
- coverage 90 - 157 degree
- ~200ps time resolution