

Bound Proton Structure from Neutron-Tagged DIS

Florian Hauenstein for the BAND
analysis team
4th SRC/EMC Workshop
02/03/23



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

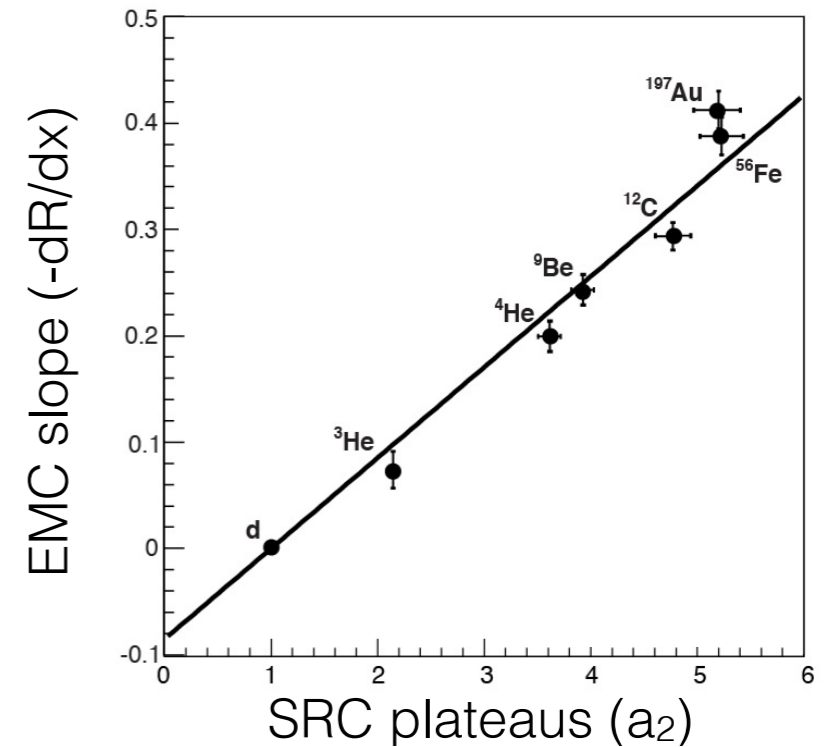


- „Tag“ SRC nucleon not part of the interaction to select initial state

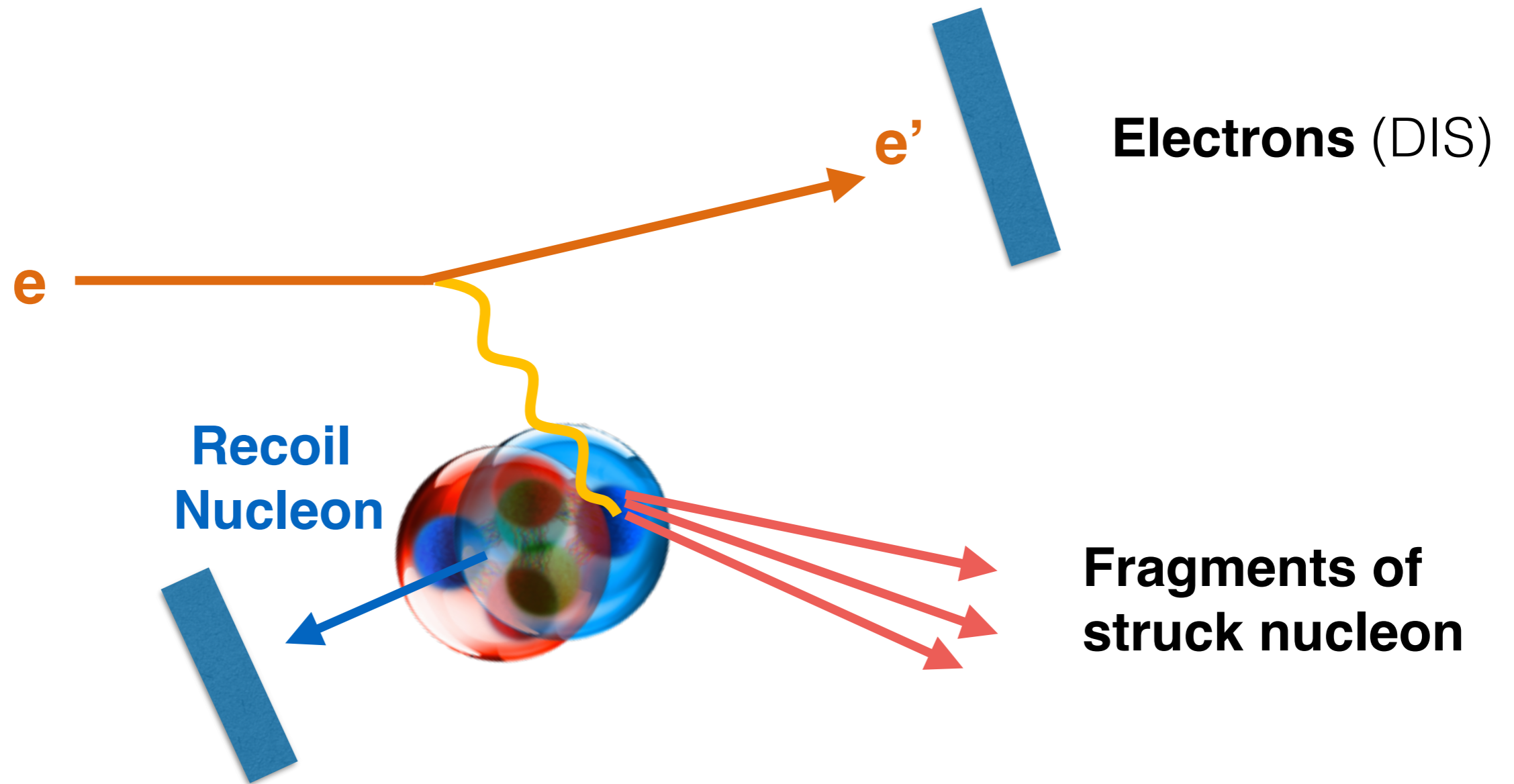


- Determine nucleon modification for high nucleon momentum

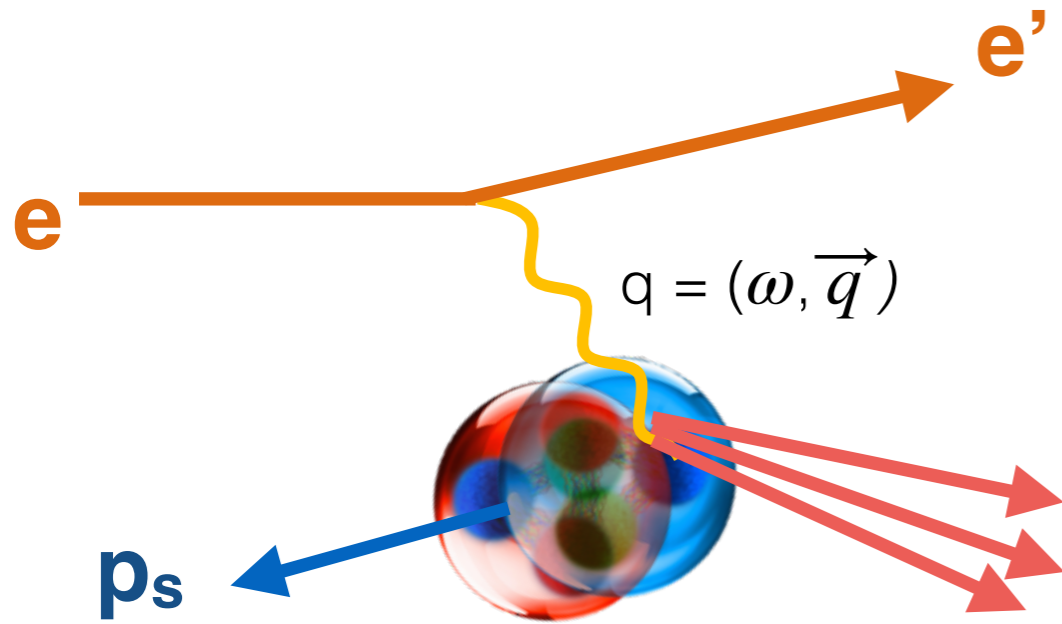
—> New observable, expect strong modification



Simplest Case: Tagged DIS with Deuterium



Tagging Kinematics 101



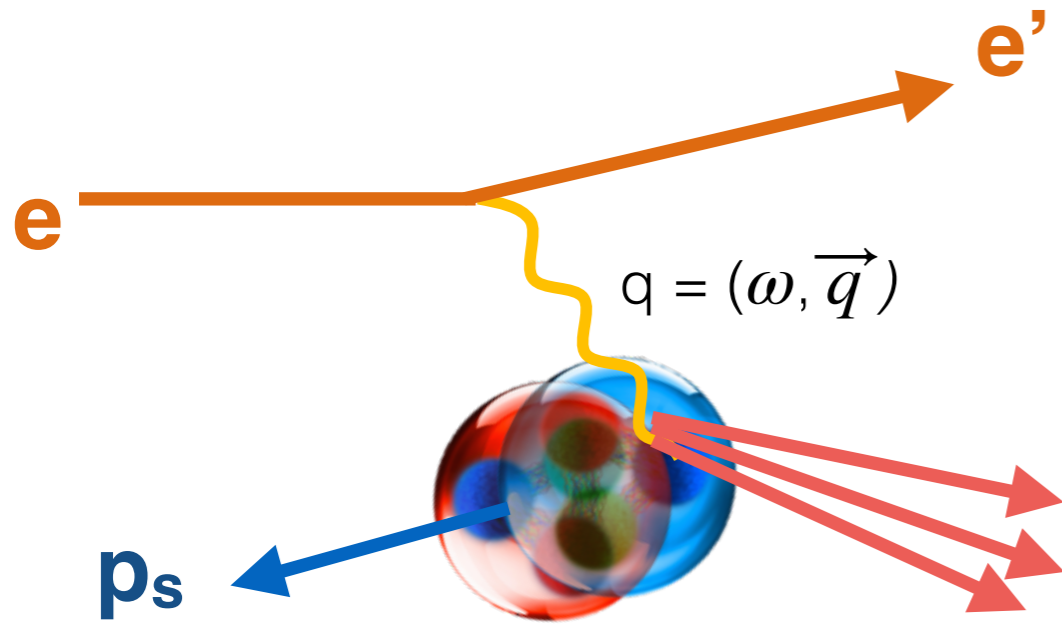
$$Q^2 = -q^2 = |\vec{q}|^2 - \omega^2$$

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

$$R_{tag} = \frac{\sigma_{tag}^{exp} (Q^2, p_T, \alpha_S, x') / \sigma_{tag}^{exp} (Q_0^2, p_T, \alpha_S, x' = x_0)}{\sigma_{tag}^{theory} (Q^2, p_T, \alpha_S, x') / \sigma_{tag}^{theory} (Q_0^2, p_T, \alpha_S, x' = x_0)}$$
$$\approx \frac{\text{bound nucleon } F_2^*}{\text{free nucleon } F_2}$$

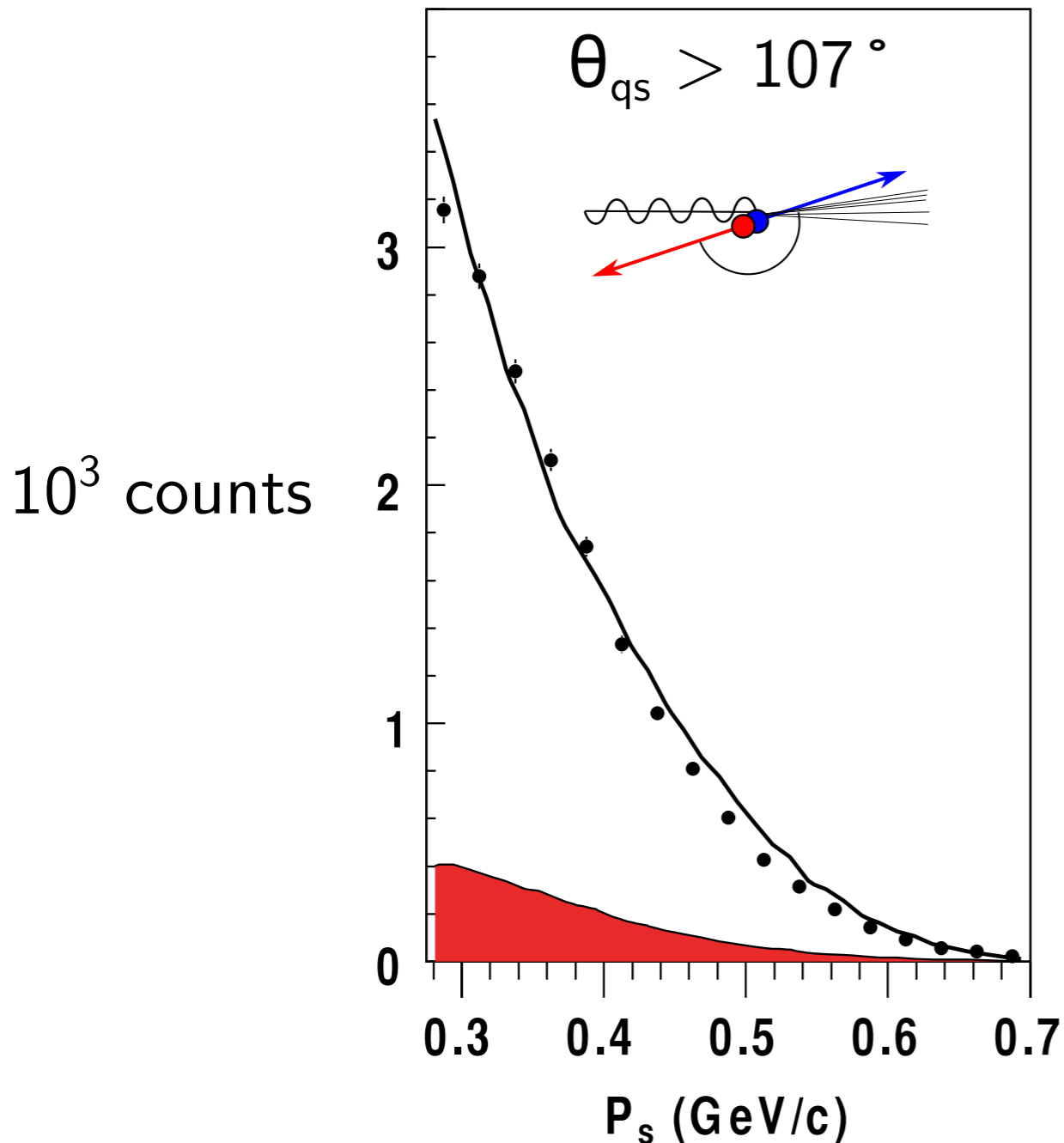
Theory assumptions:

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

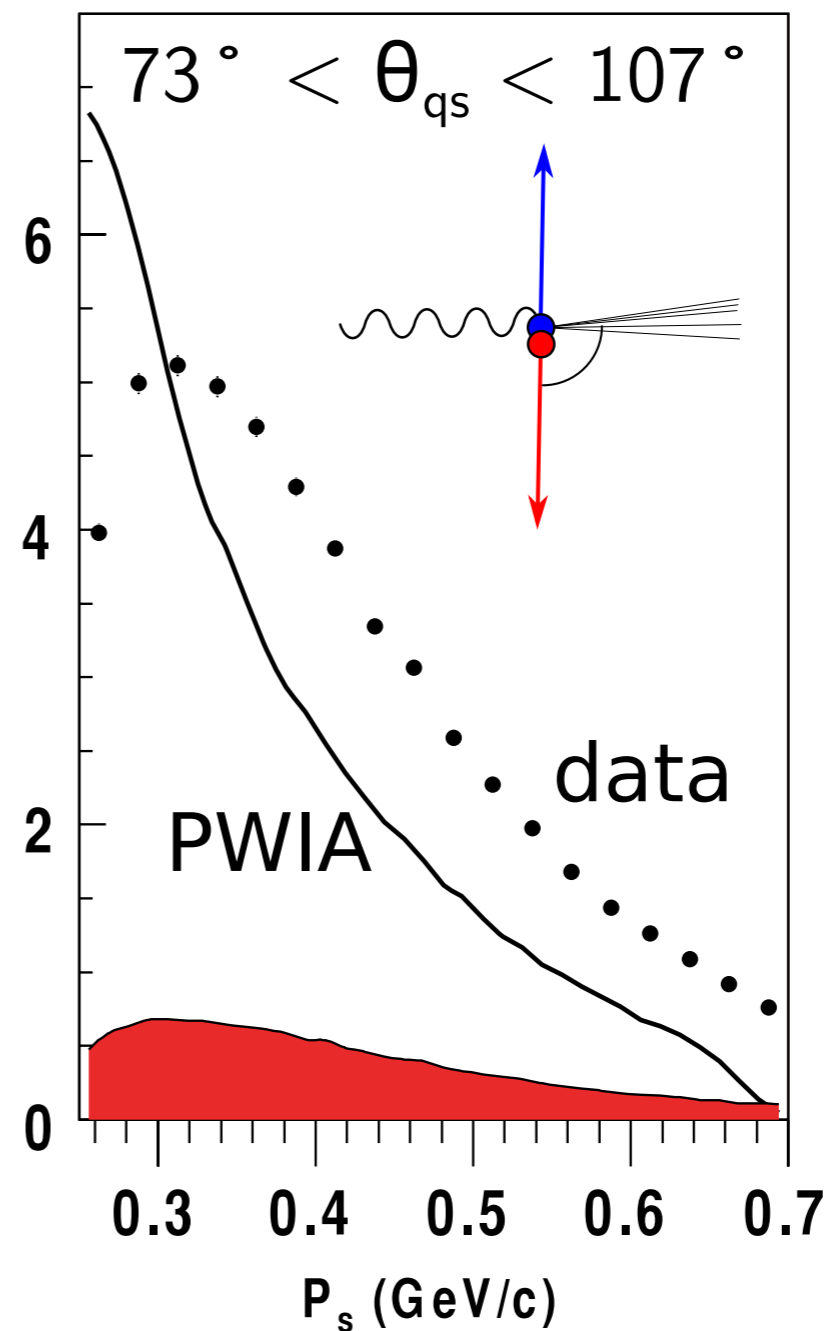
Minimize Final-State-Interaction in Tagged DIS

Klimenko et. al, PRC73, 035212 (2006)

Anti-Parallel



Transverse

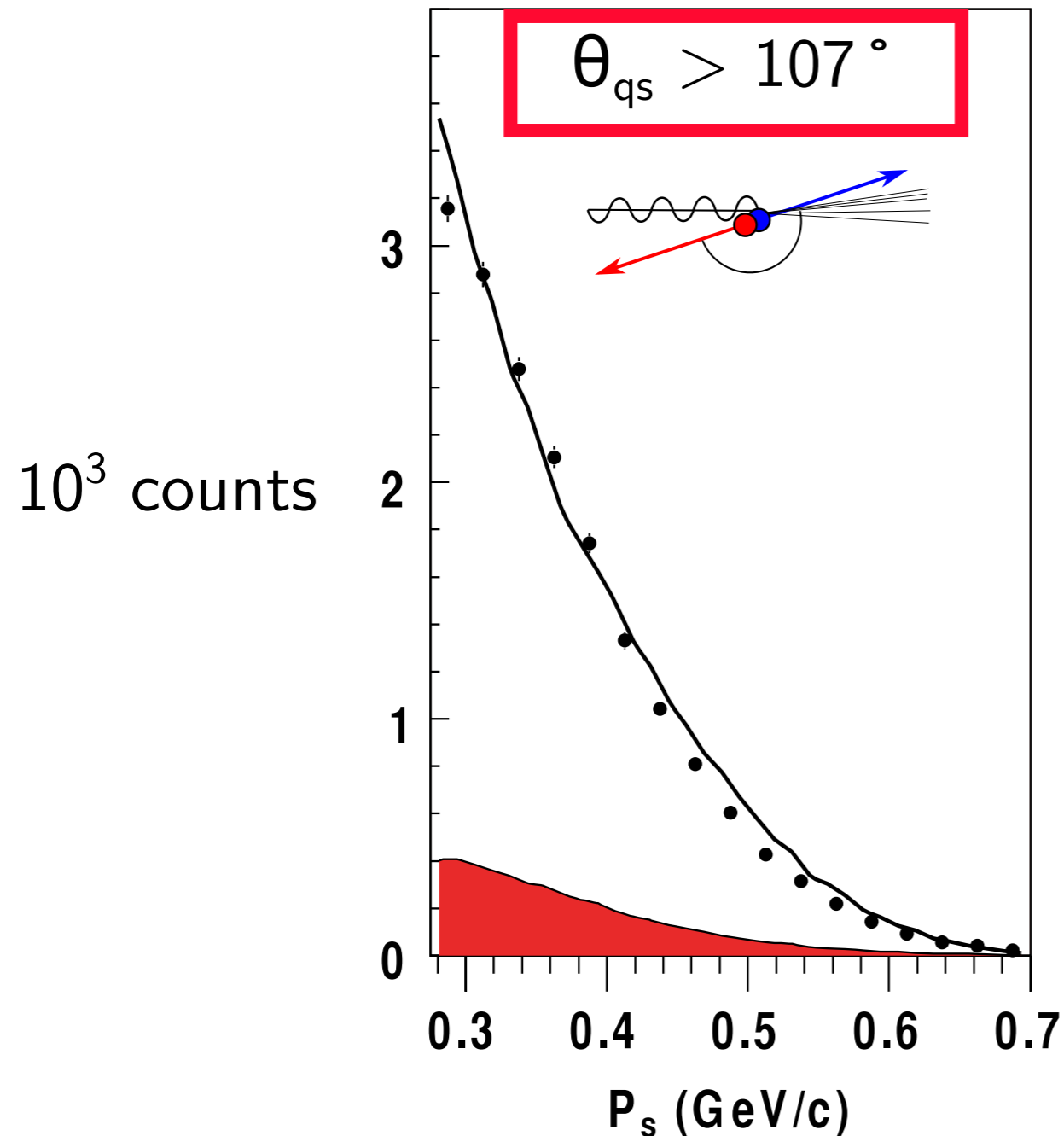


$d(e, e'p_s)X$

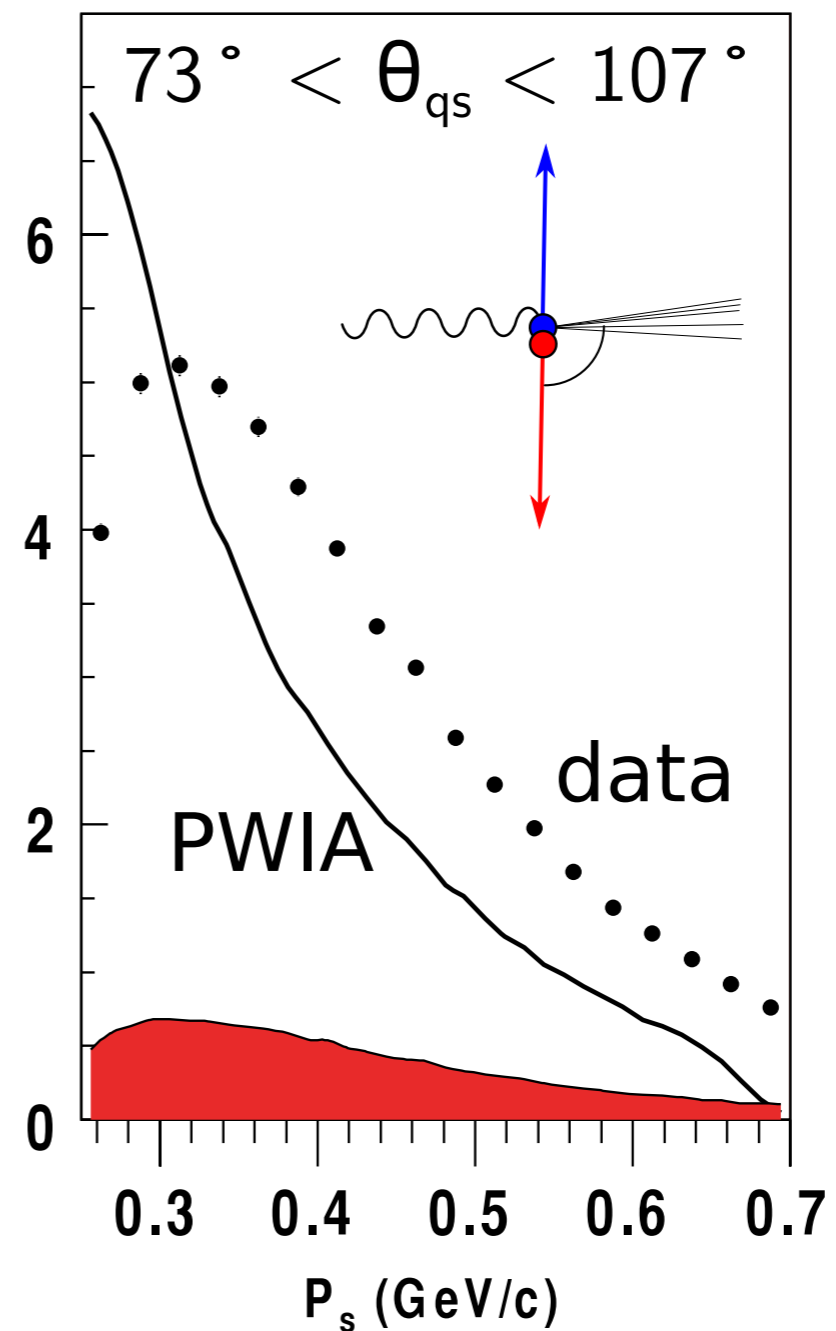
Minimize Final-State-Interaction in Tagged DIS

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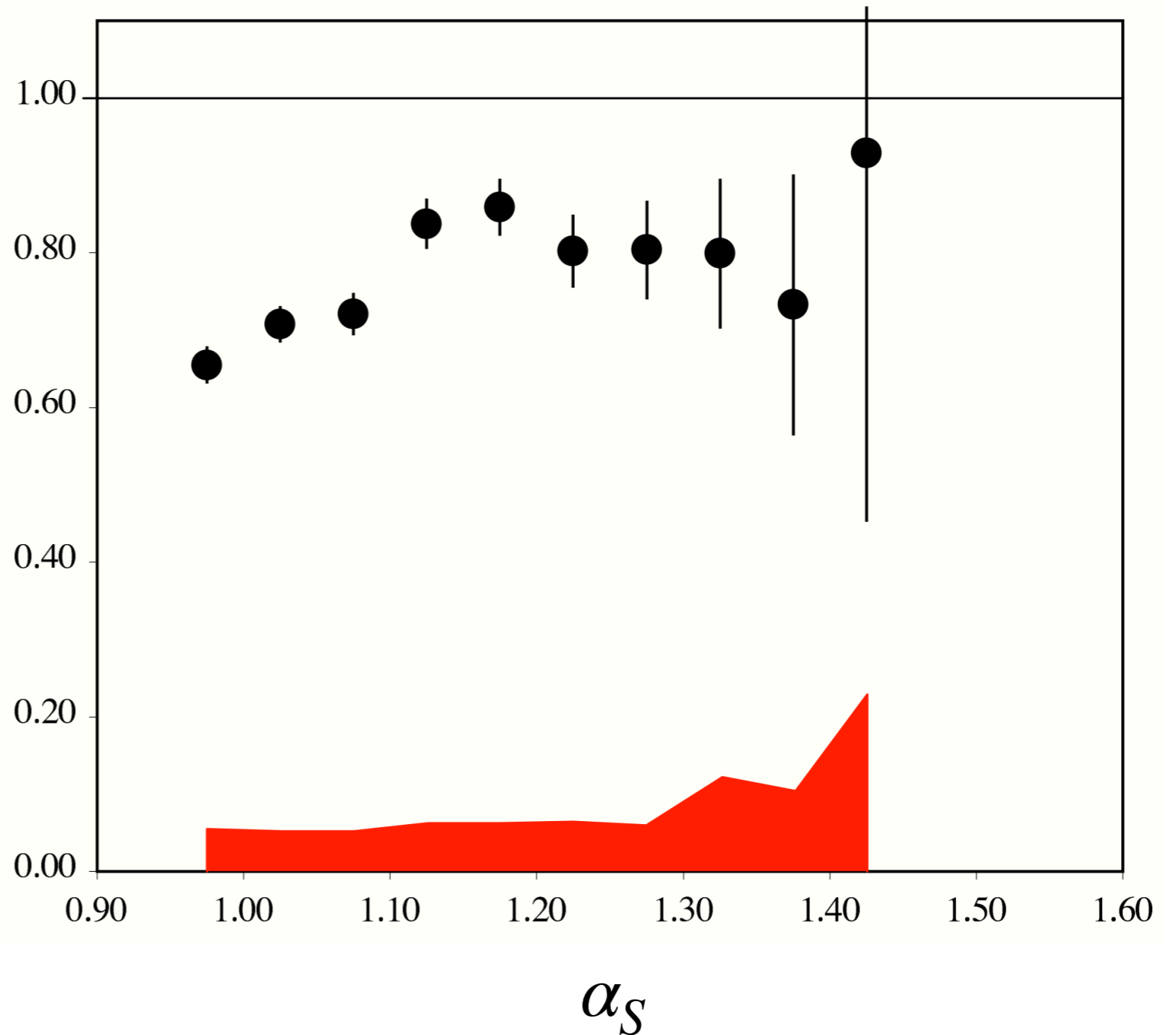


$d(e, e'p_s)X$

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

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

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



Non ideal kinematics

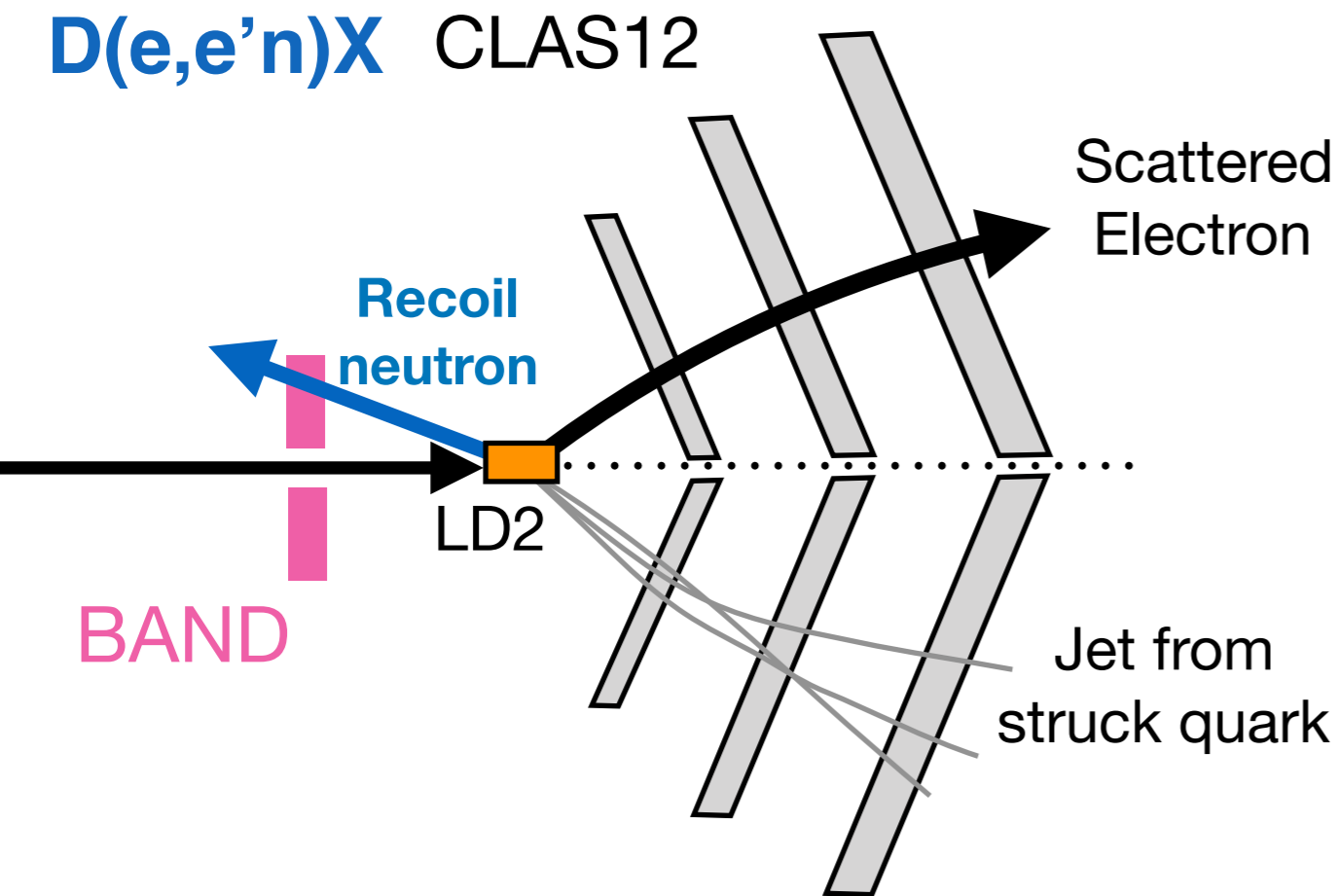
- Not so high in Q^2
- Low α_S has $\theta_{nq} \sim 90$ deg
- $p_T = [0.25 - 0.35]$ [GeV/c]

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

Tagged Experiments at JLab

Hall B:

CLAS 12 + Backward Angle
Neutron Detector (BAND)

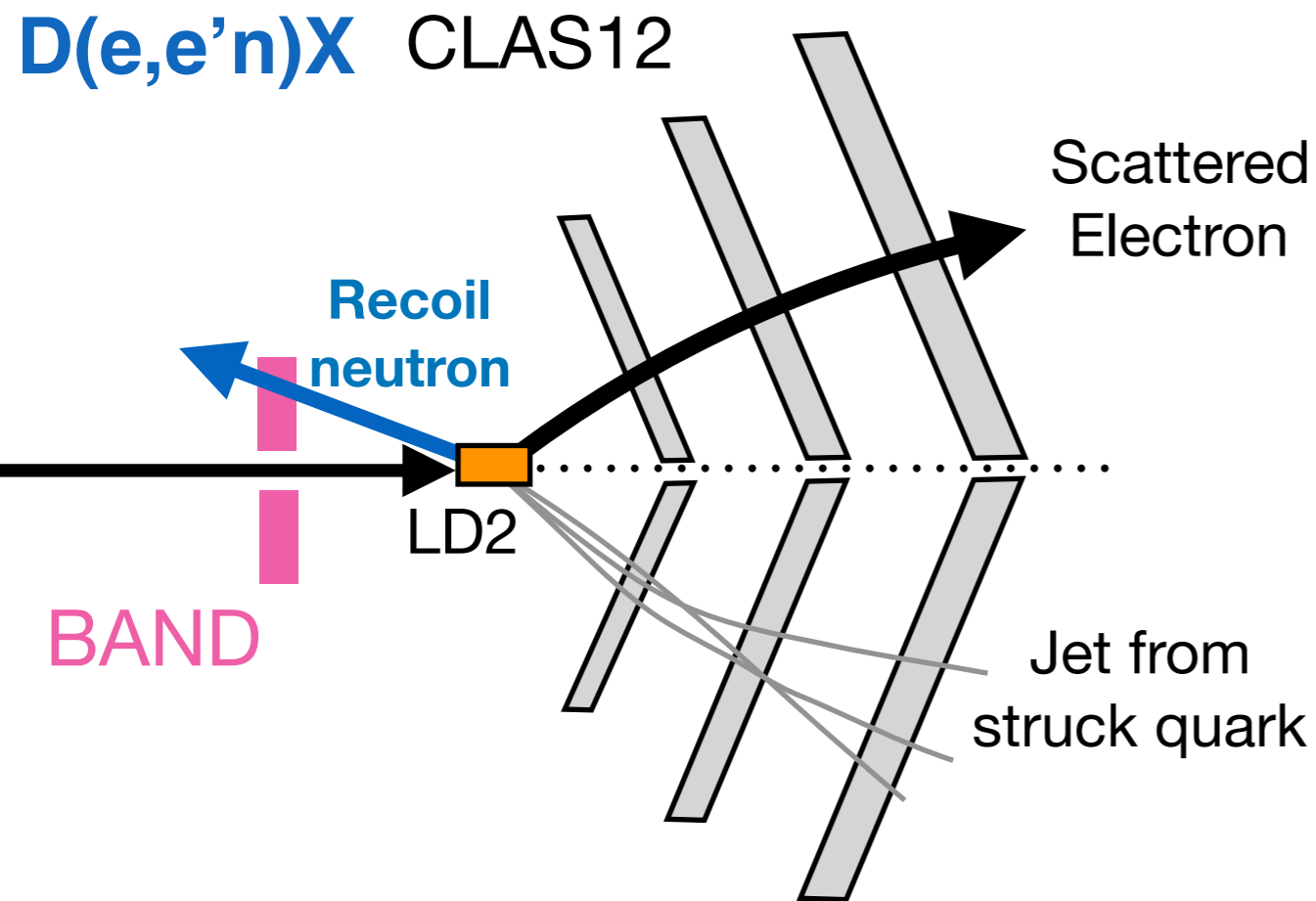


- Run Group B
- Analysis under review

Tagged Experiments at JLab

Hall B:

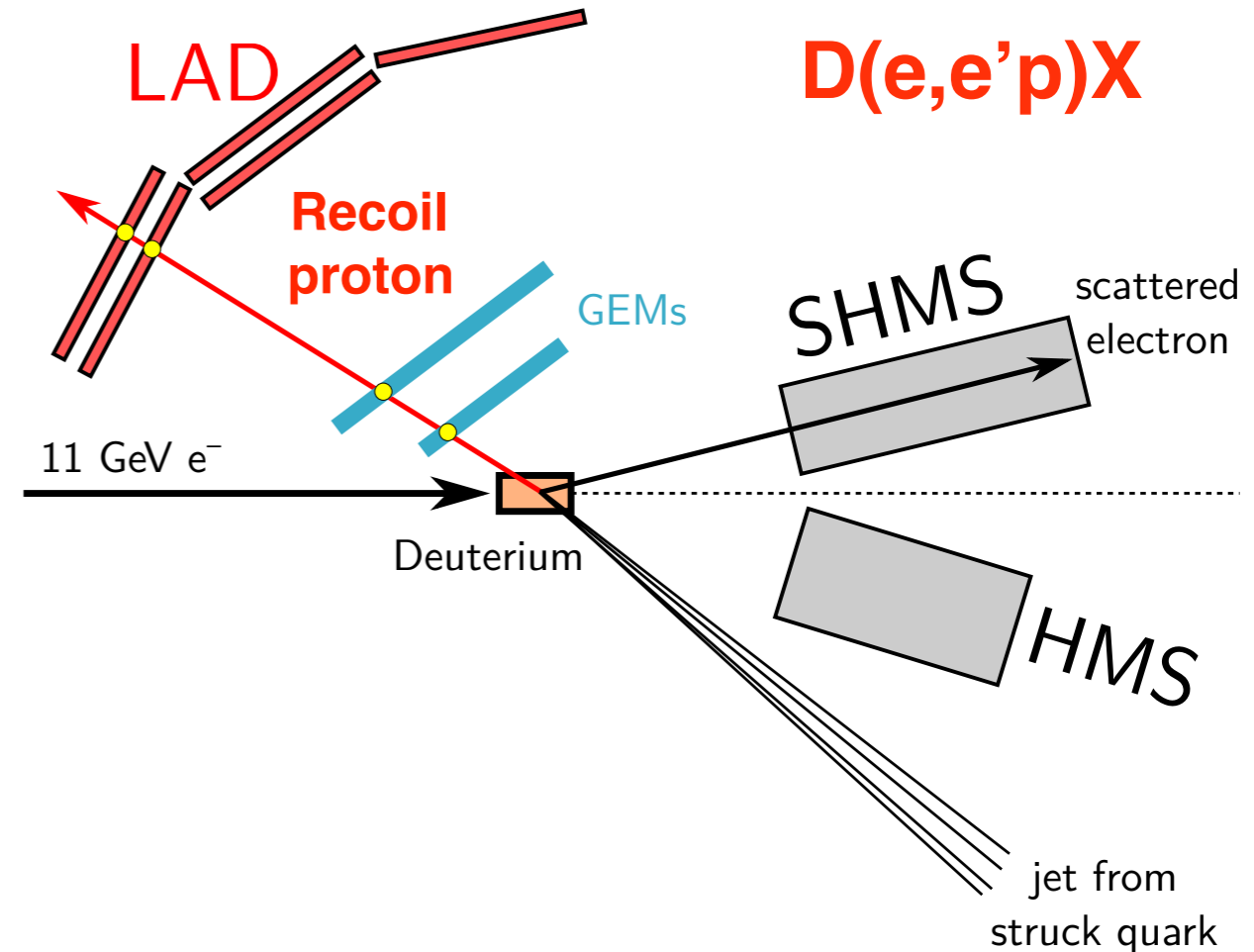
CLAS 12 + Backward Angle Neutron Detector (BAND)



- Run Group B
- Analysis under review

Hall C:

SHMS/HMS + Large Angle Detector (LAD)



- Experiment ready
- Run in 2024

Tagged Experiments at JLab

Hall B:

CLAS 12 + Backward Angle Neutron Detector (BAND)

Hall C:

SHMS/HMS + Large Angle Detector (LAD)

$D(e,e'n)X$

CLAS12

Scattered

LAD

Recoil

$D(e,e'p)X$

Complementary Experiments for Isospin Dependence

LD2

BAND

Jet from struck quark

11 GeV e^-

Deuterium

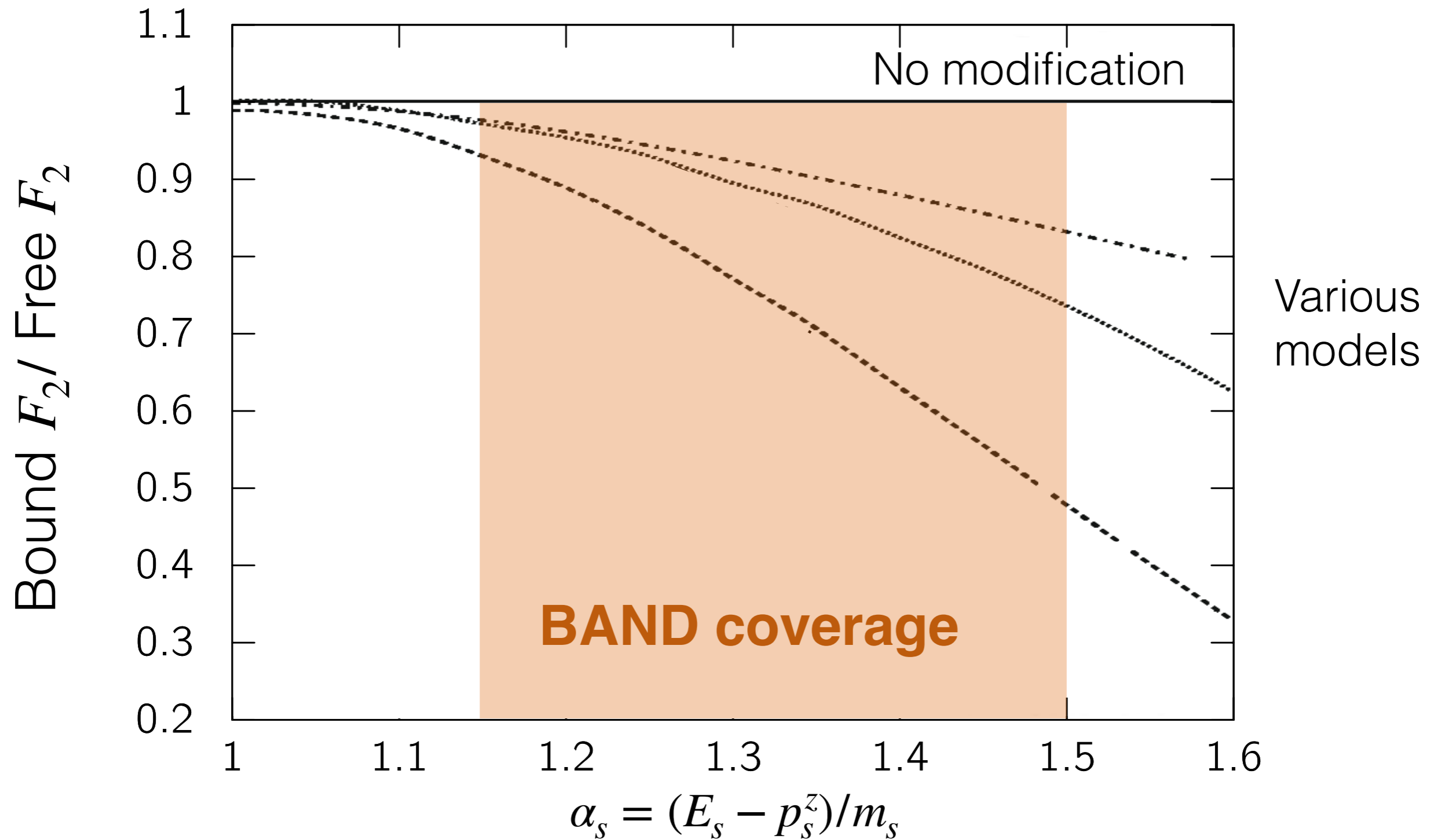
HMS

jet from struck quark

- Run Group B
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- Experiment ready
- Run in 2024

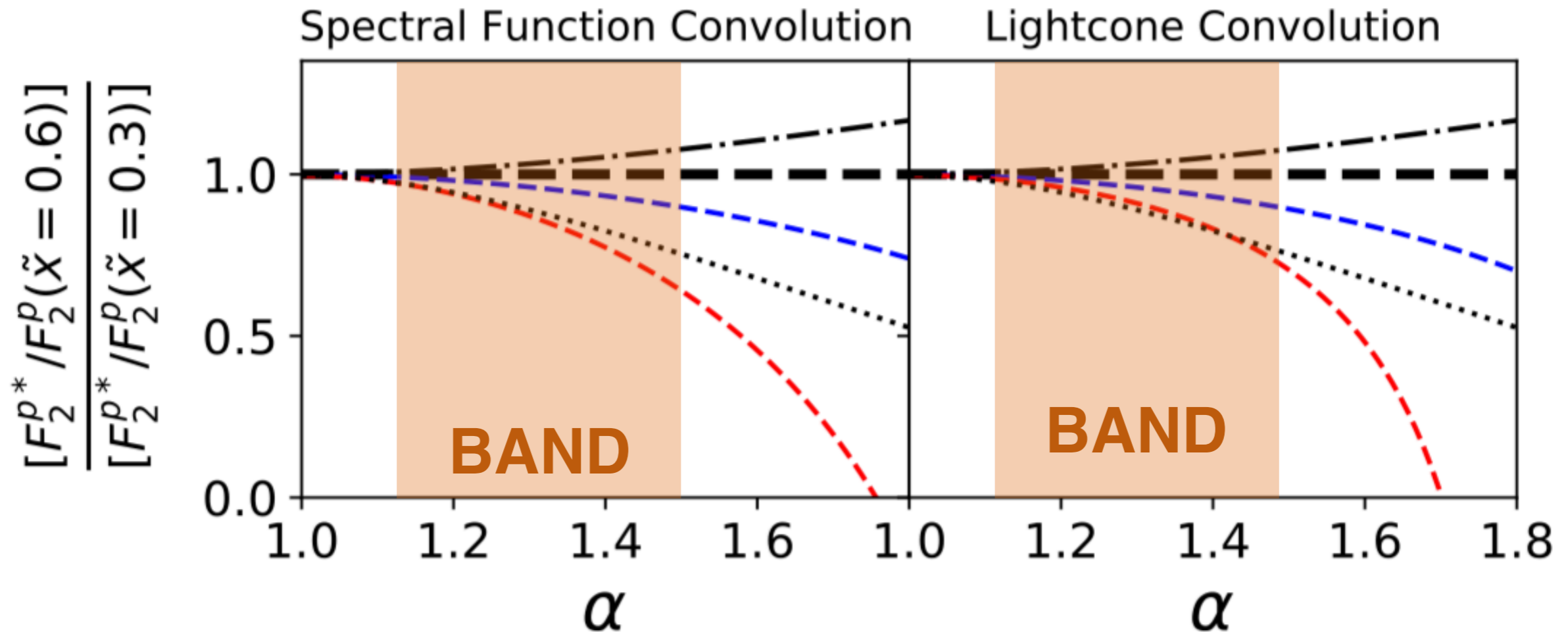
d(e,e'N)X - Expected Results



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

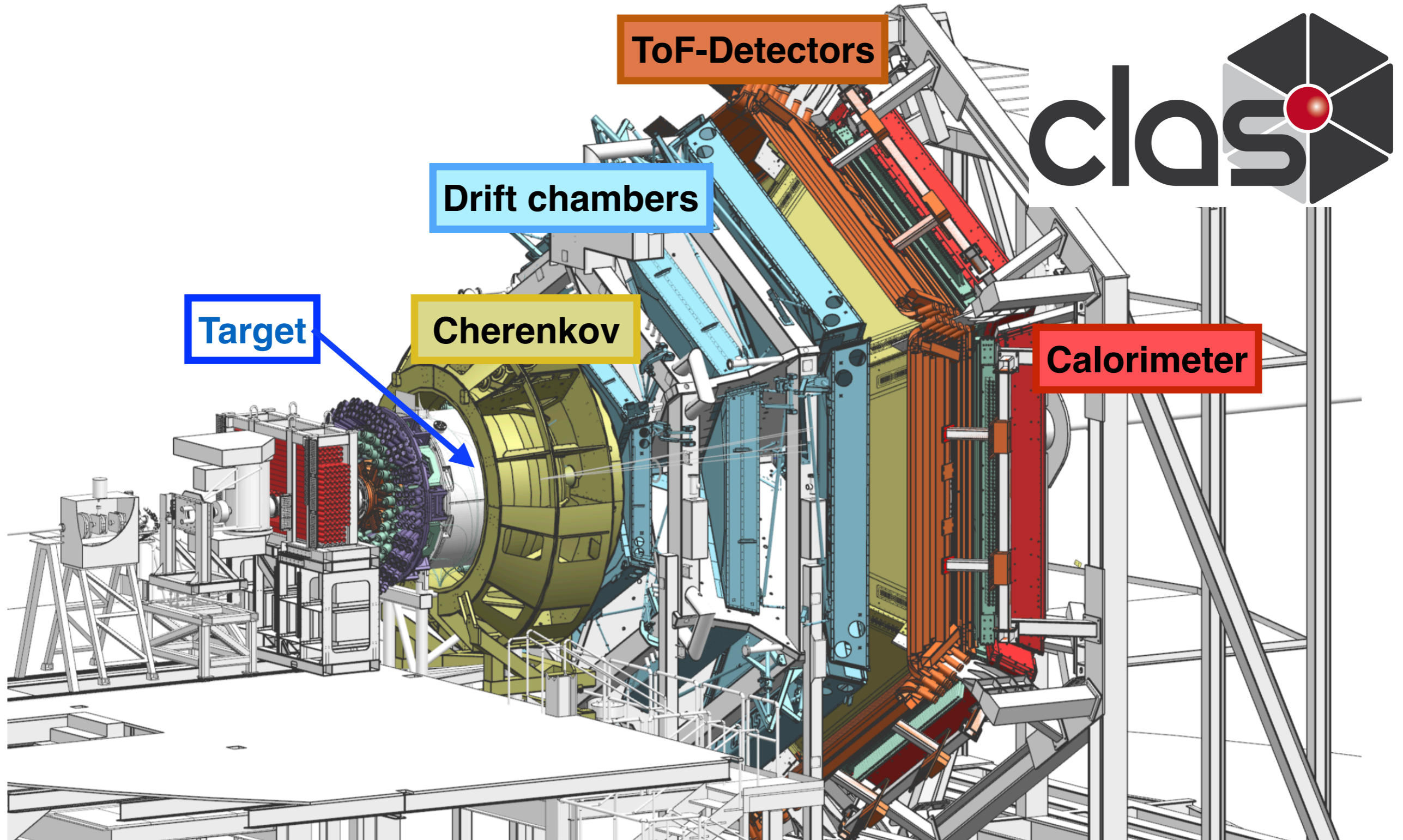
Tagged Predictions for Different Models

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



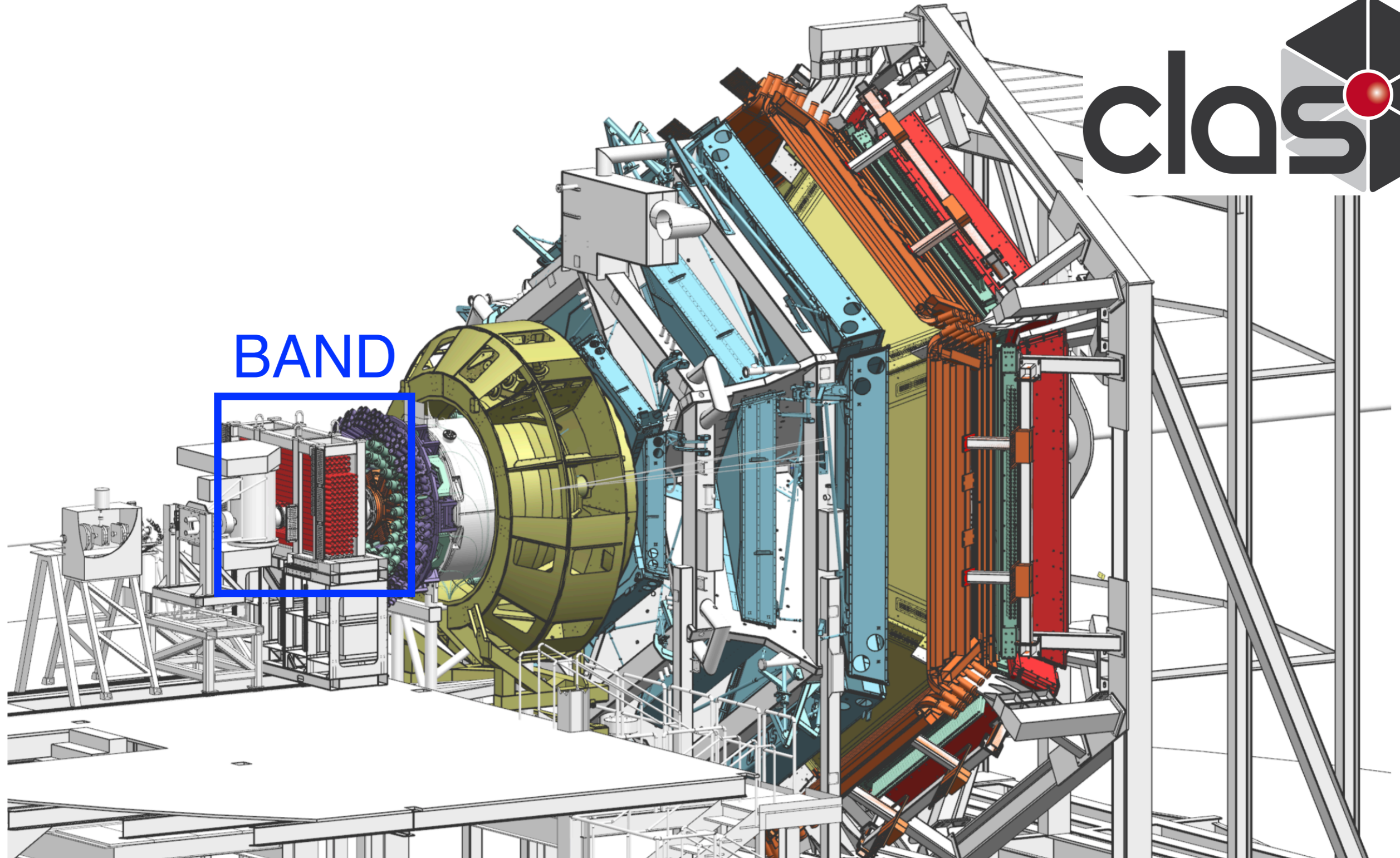
Predictions from convolution model fits to data up to $A=3$

CLAS12 in Hall B



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)

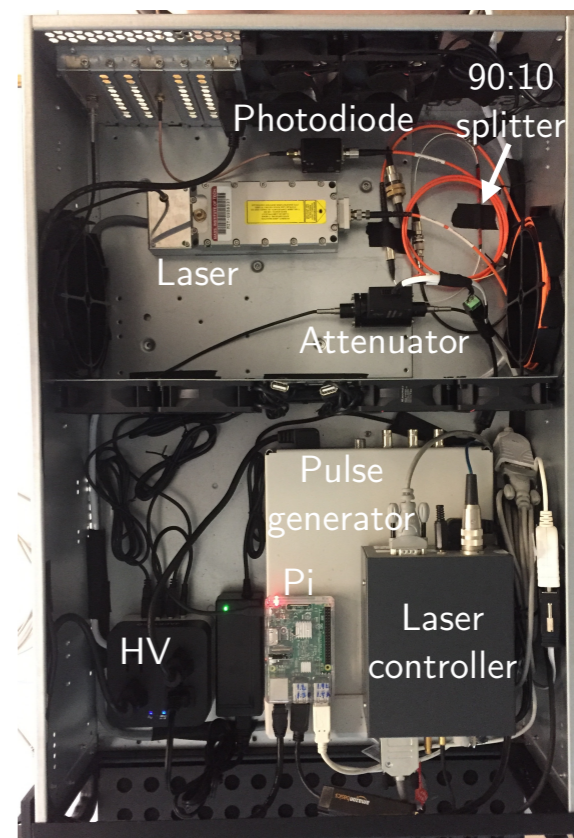
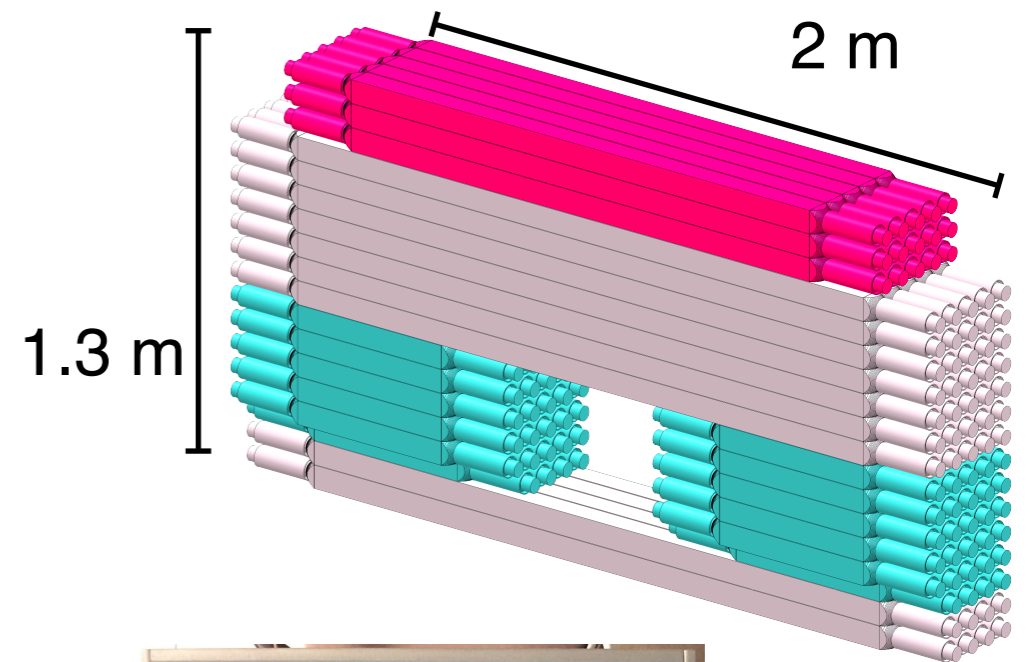
- 140 scintillator bars
- 5 layers (36cm total thickness)
- veto layer (1cm thick)
- time resolution < 250 ps

- 3 meters upstream of target

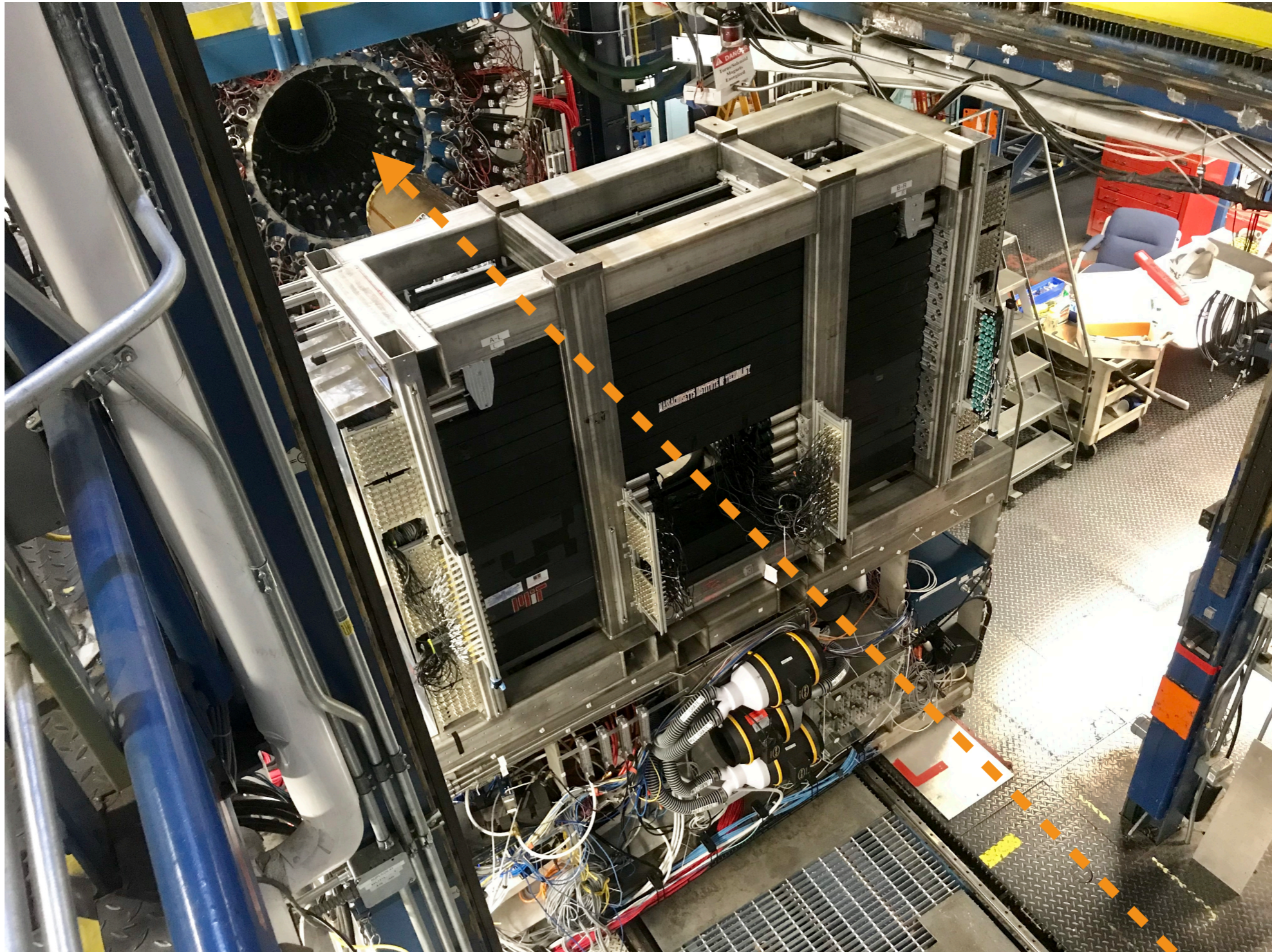
- coverage in $\theta \sim 155-176^\circ$

- Lead wall (downstream)

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

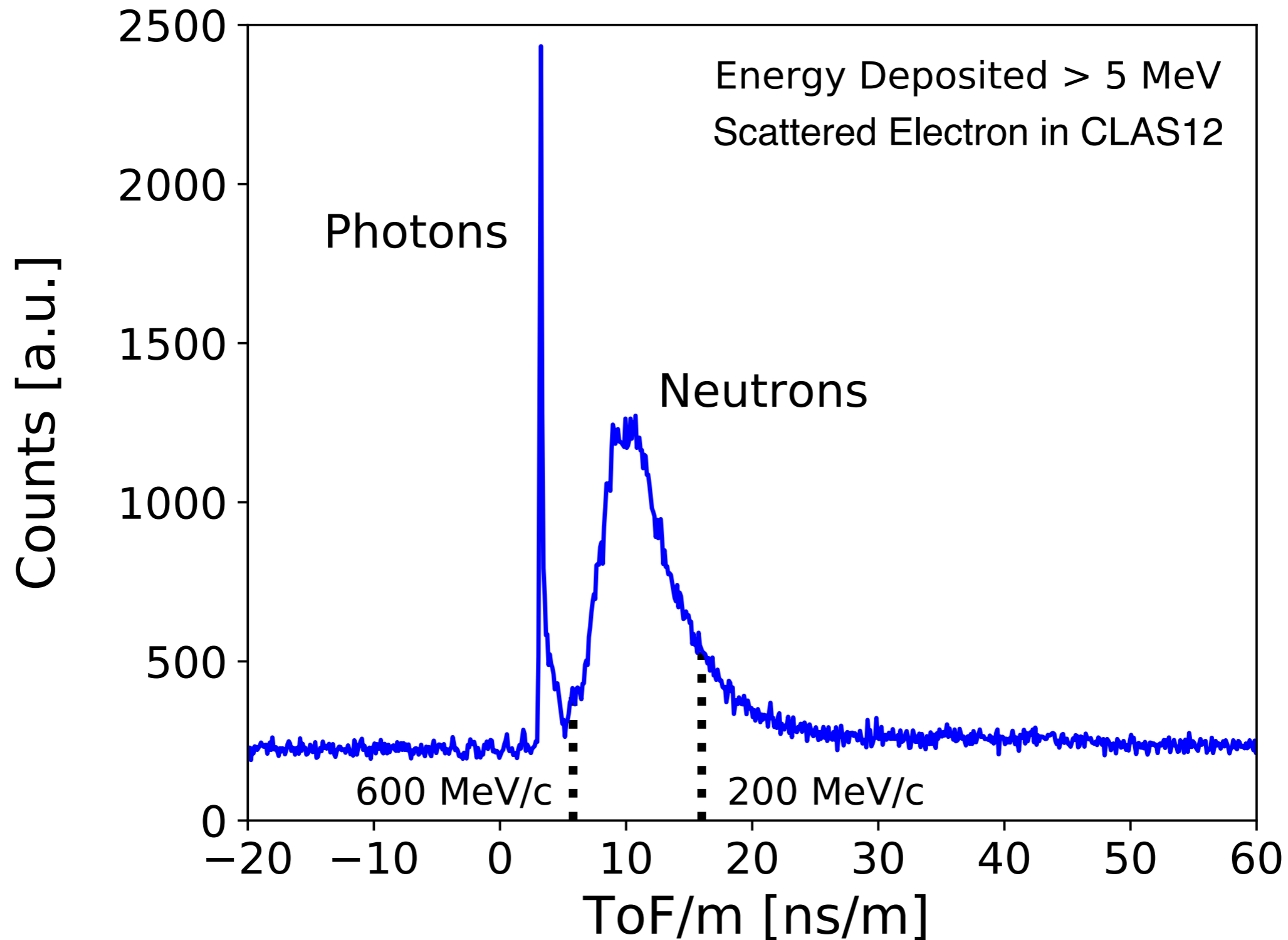


BAND in HallB



Clear Signal of Neutrons in BAND

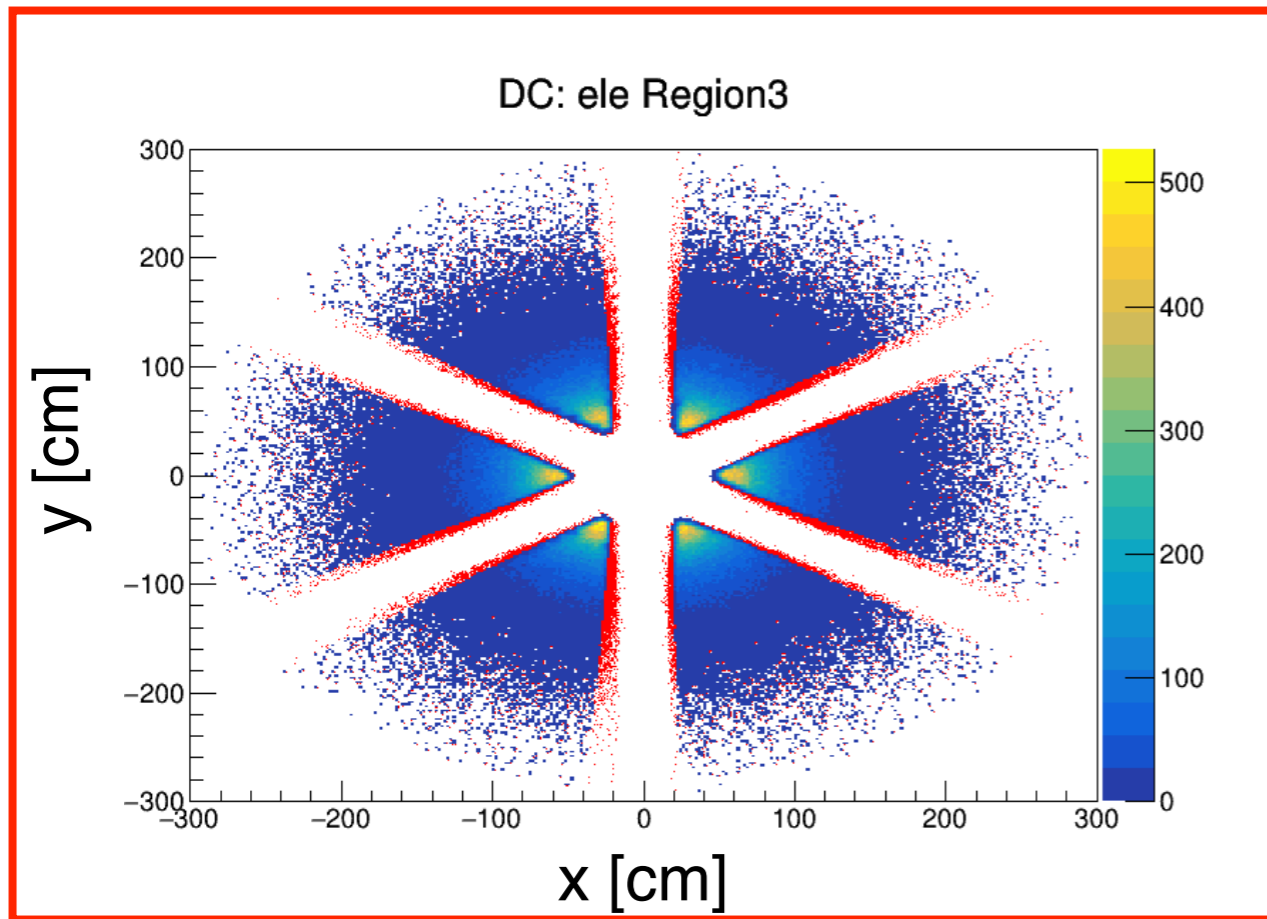
Segarra et al., NIM A978 (2020)



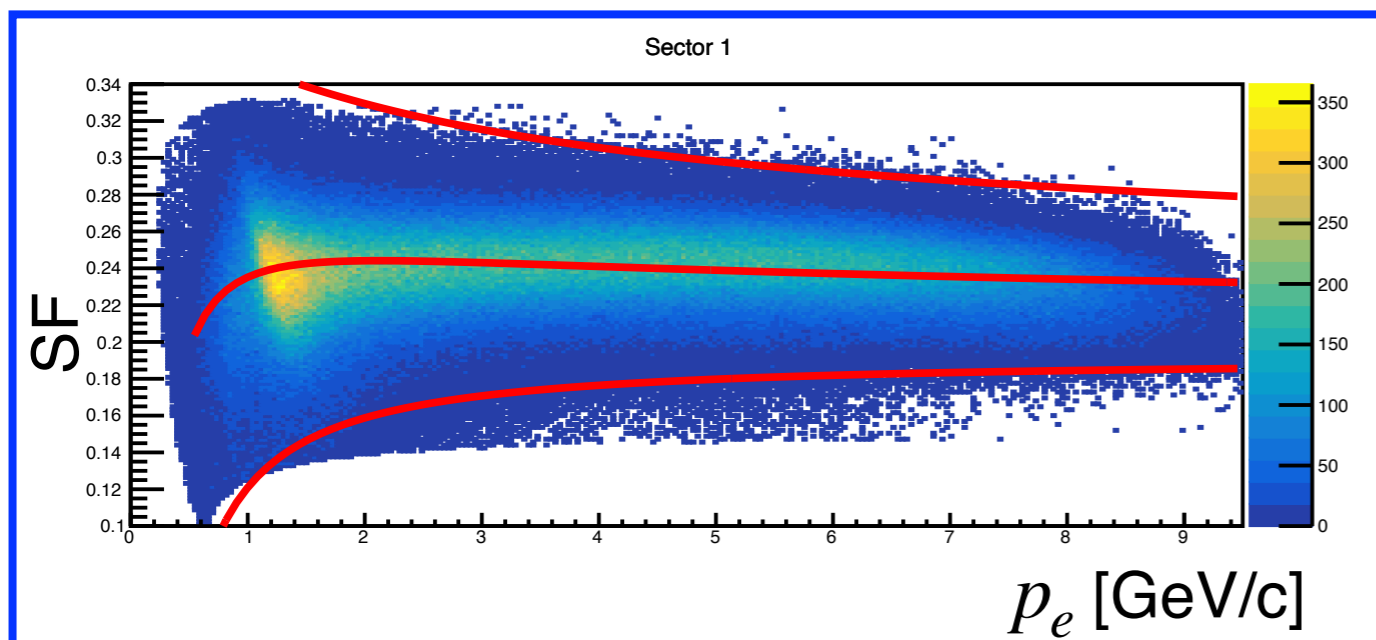
Data and Analysis Overview

- 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

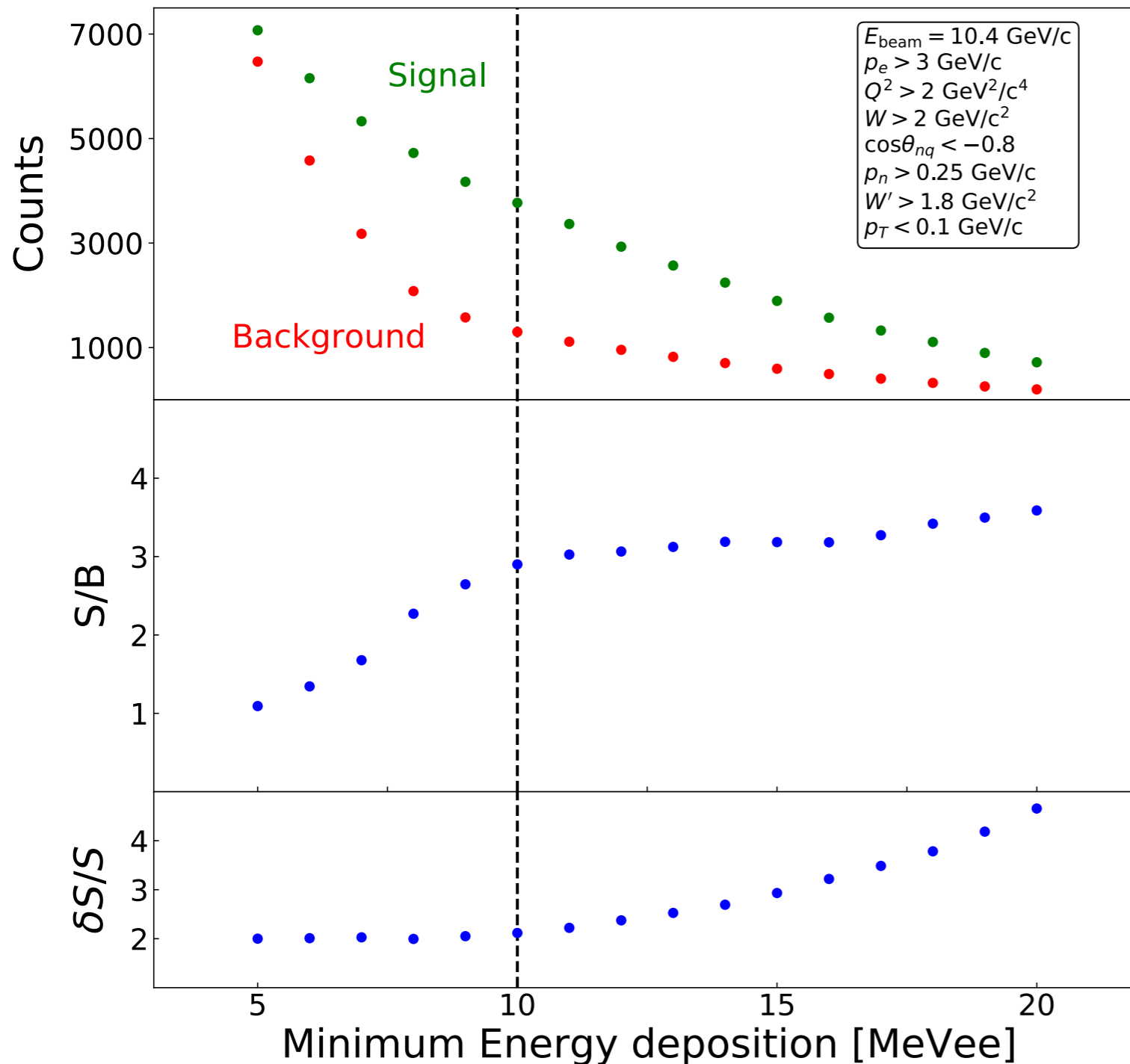


- Charge/PID requirement
- Driftchamber fiducial cuts
- Calorimeter fiducial cuts
- Calorimeter sampling fraction cuts



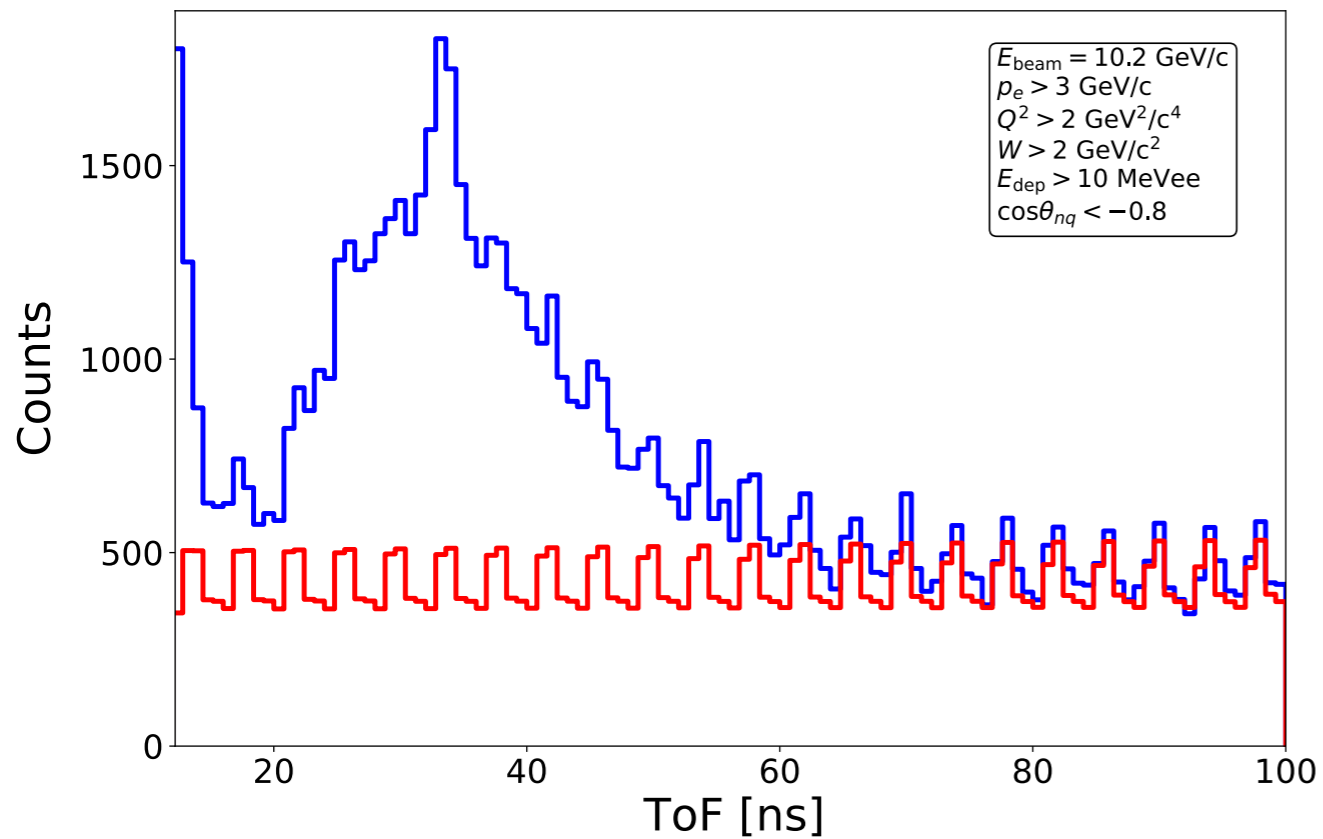
Neutron Selection: E_{dep} and Fiducials

- $E_{dep} > 10$ MeVee

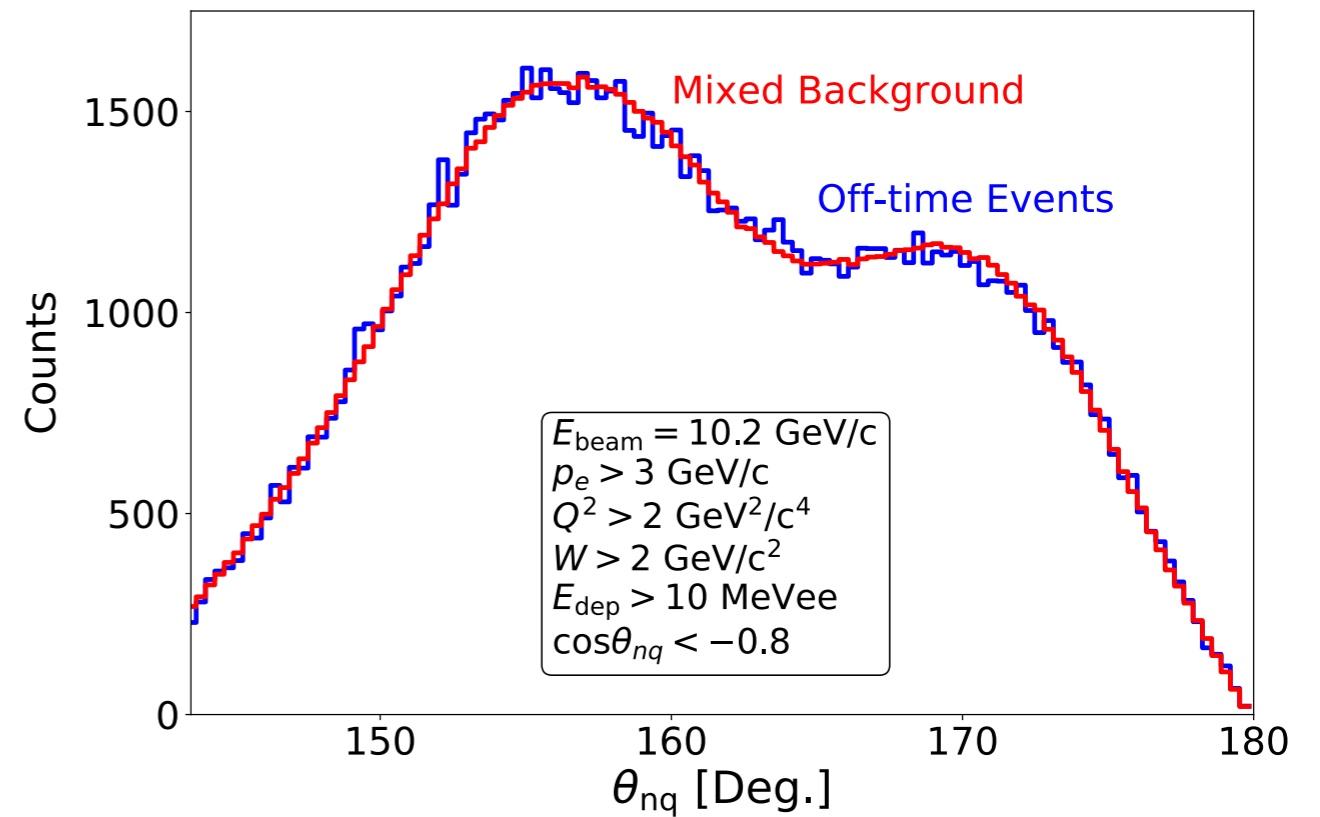
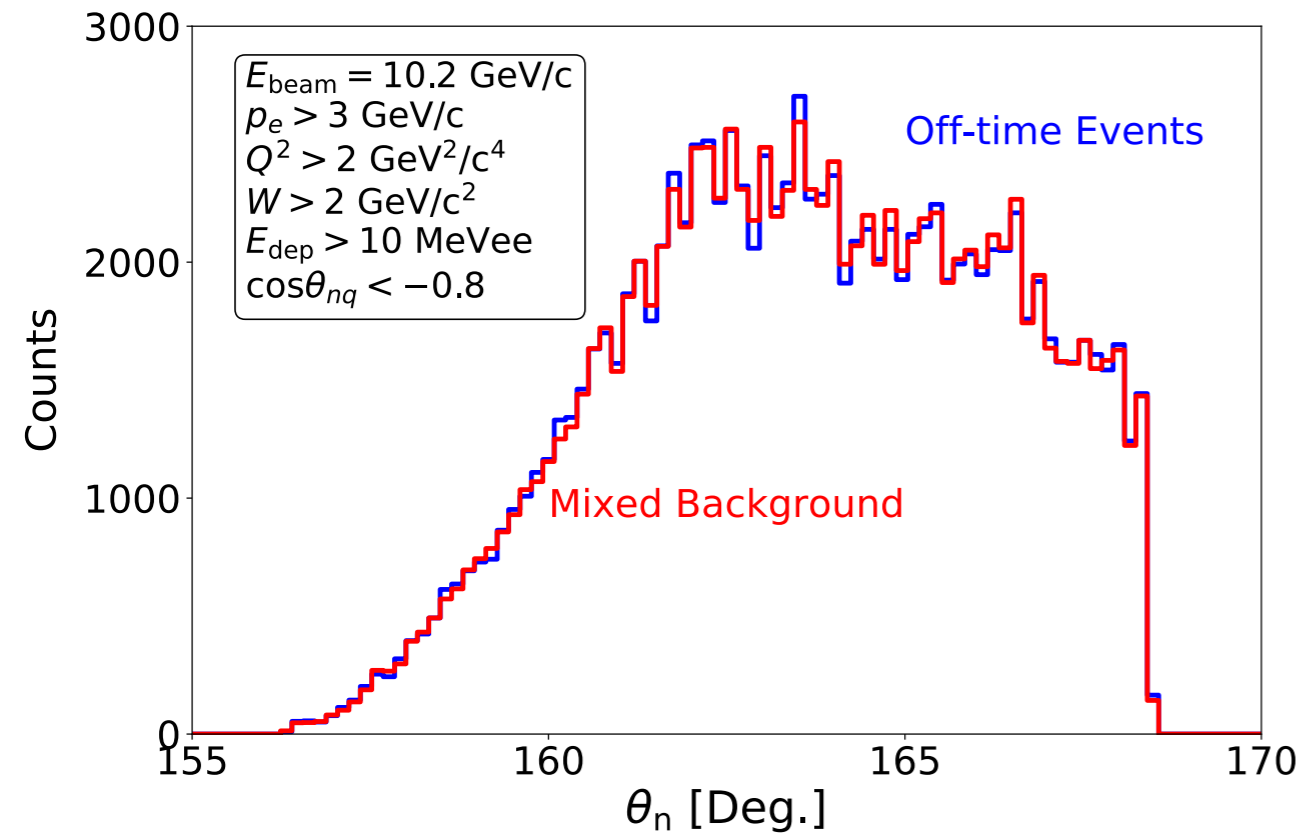


- Fiducial cut 10 cm from BAND edges (reflection)
- $\theta_n < 168.5^\circ$ (beam pipe)

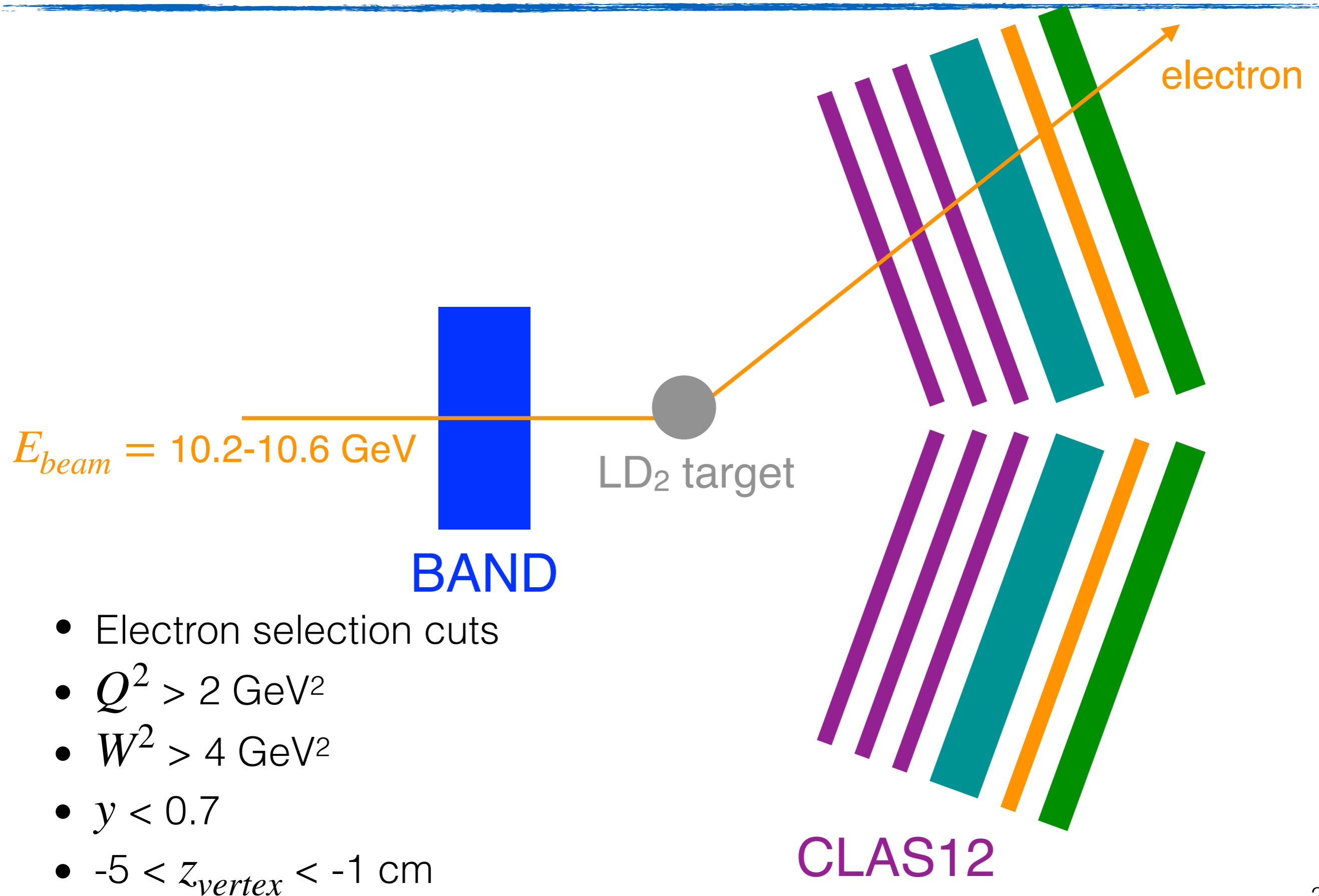
Random Coincidence Background Subtraction



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

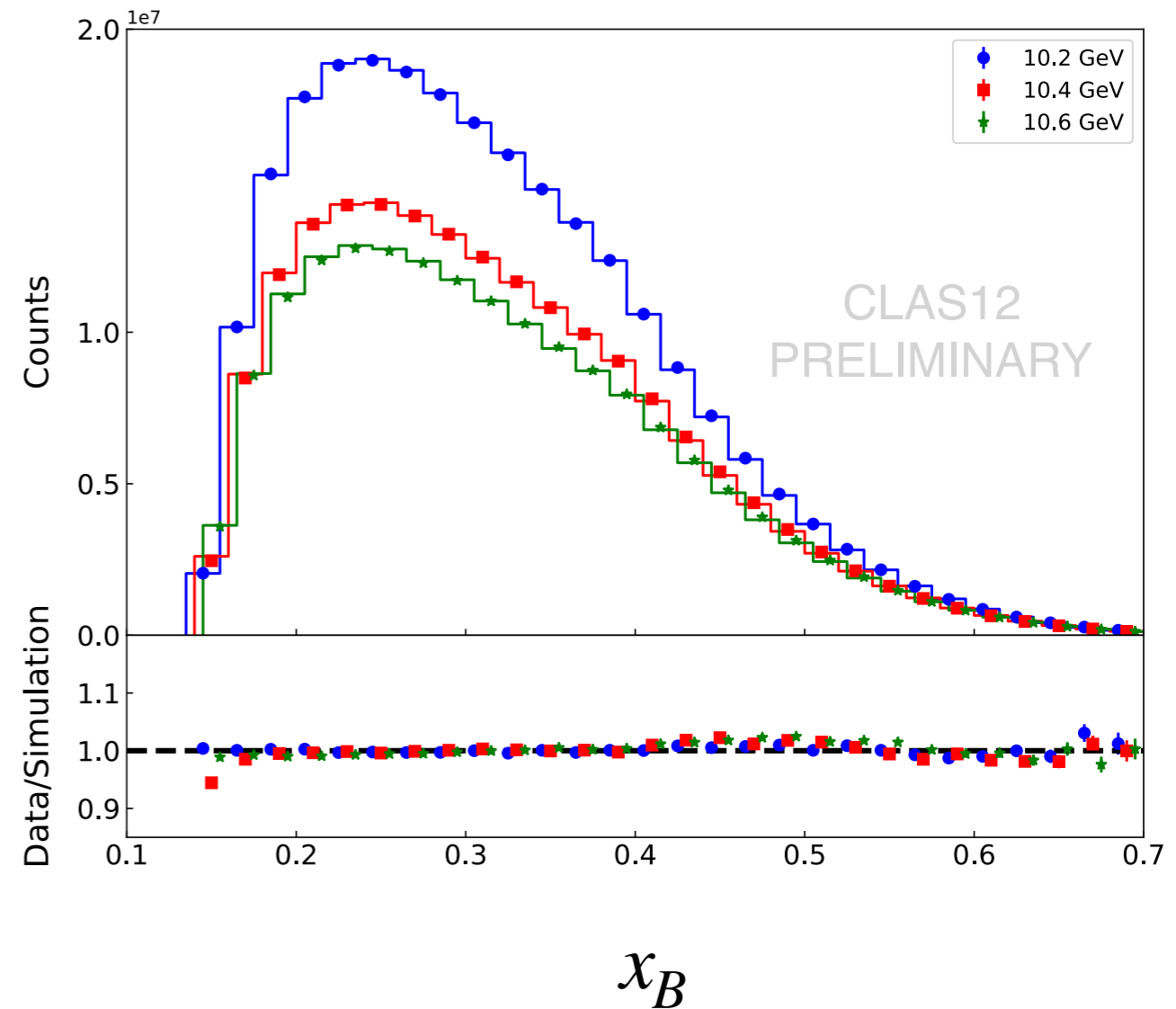
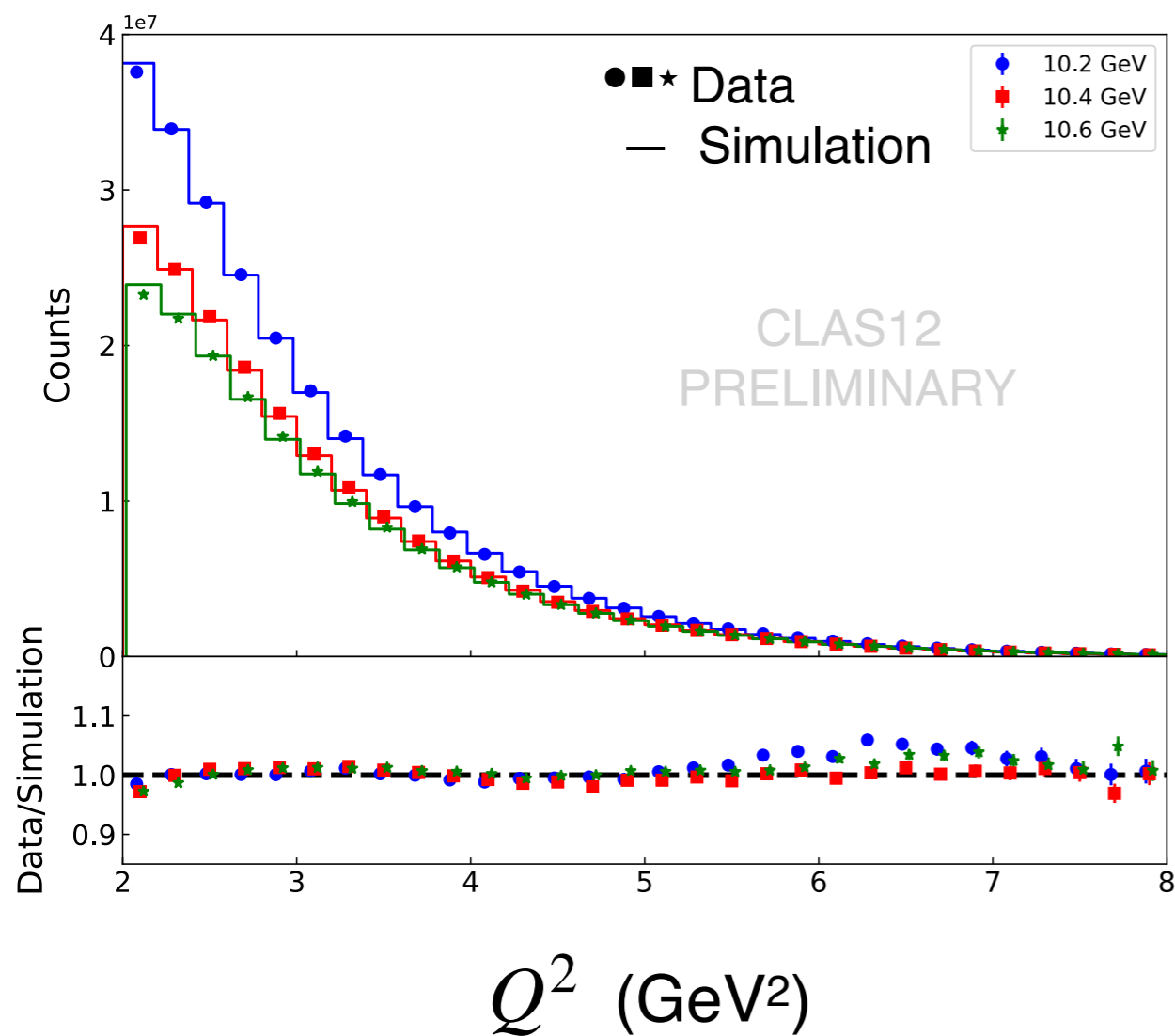


Inclusive $d(e, e')X$



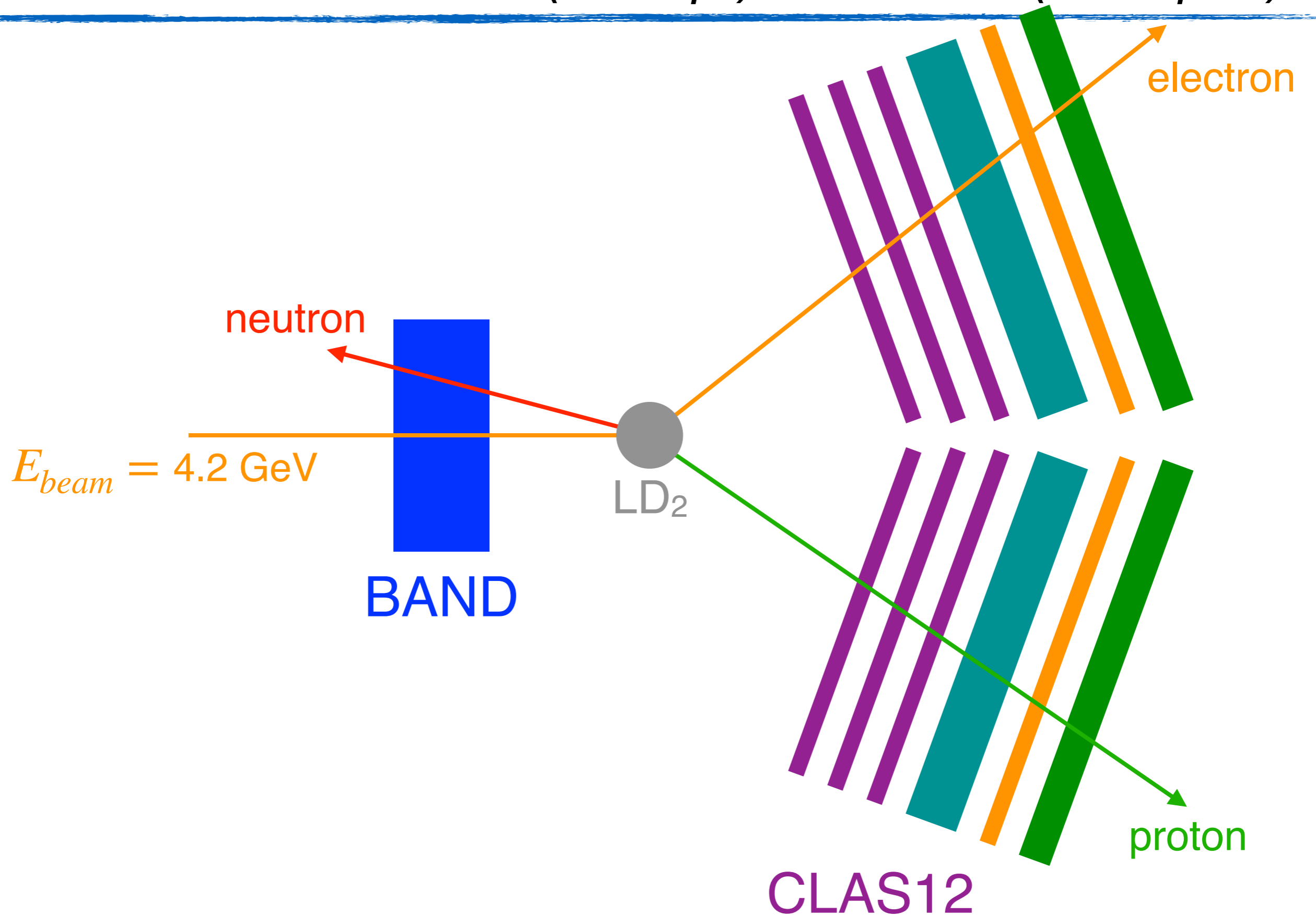
Inclusive Data - MC comparisons

Integral normalized



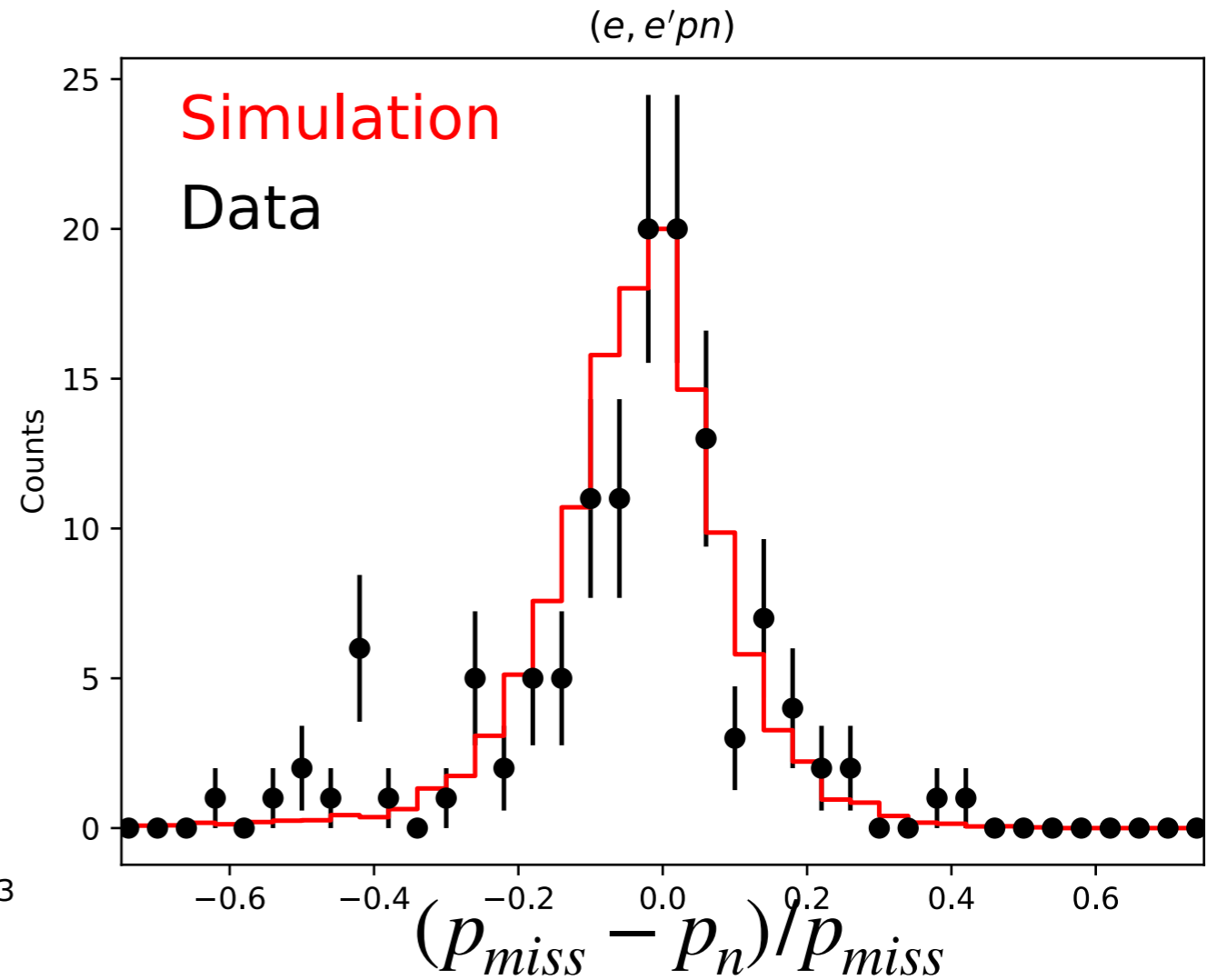
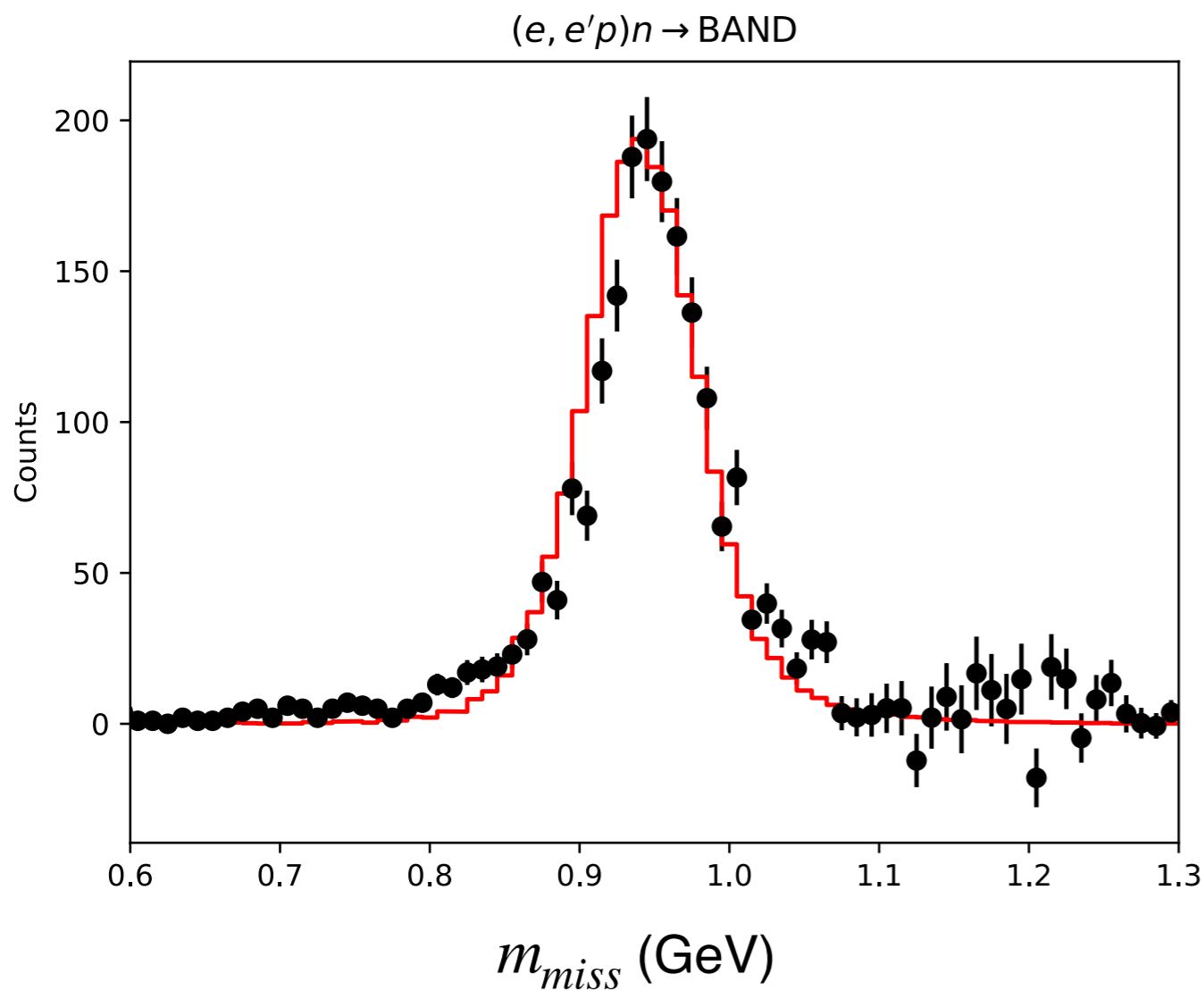
- Inclusive data well described by simulation

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



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

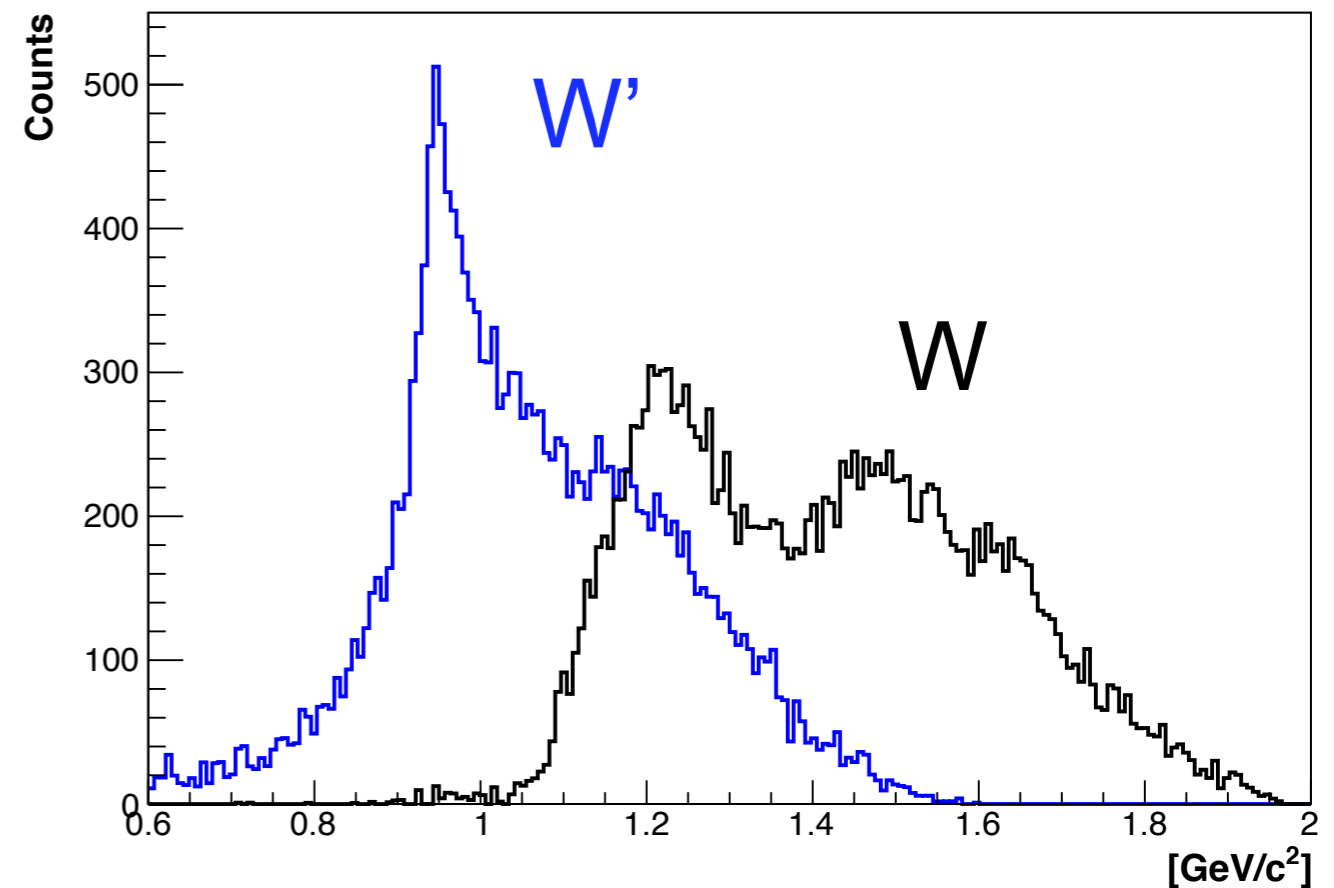
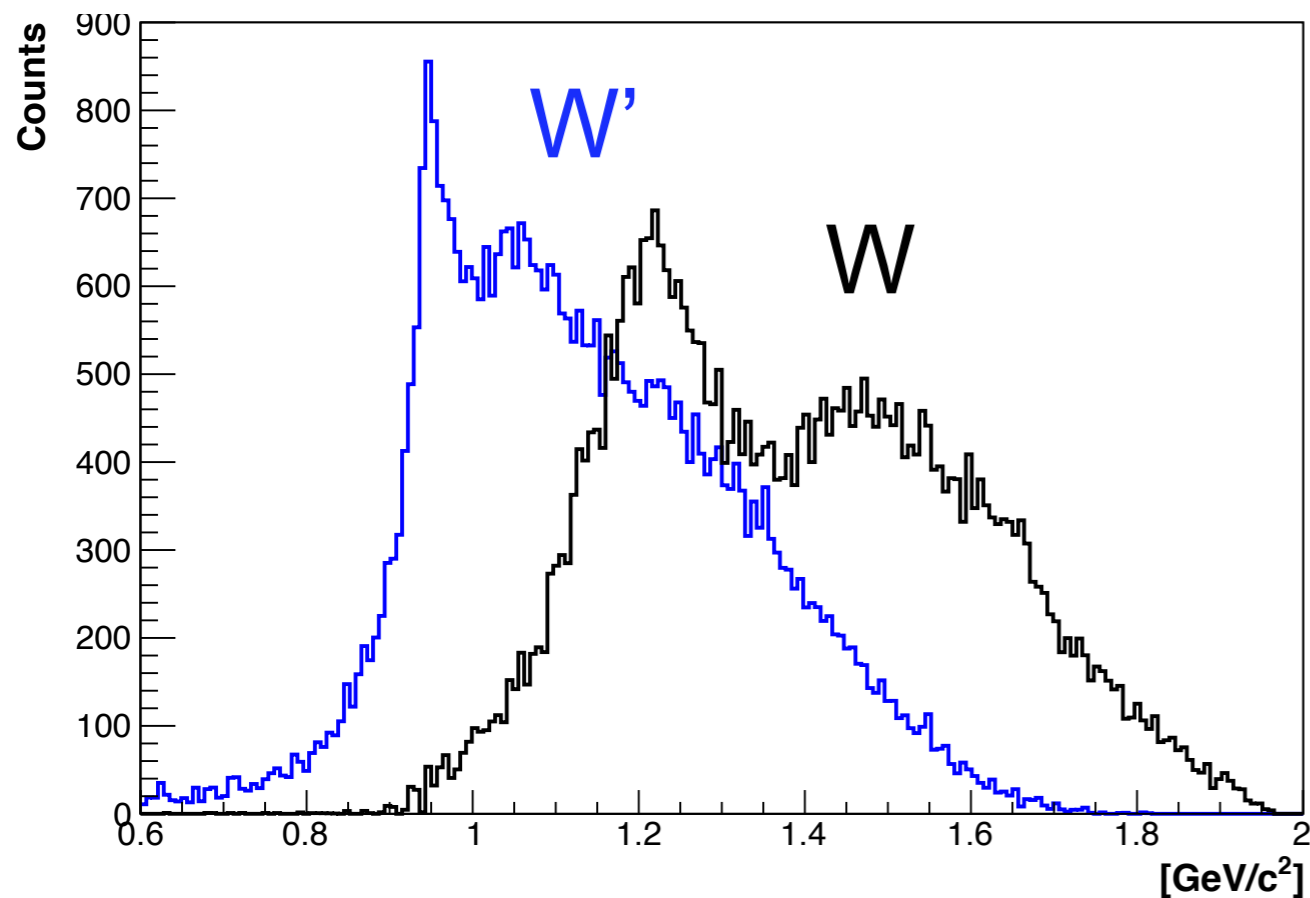
Integral-normalized



- Excellent agreement in resolution of data and simulation

W and W' in d(e,e'n) at 2 GeV

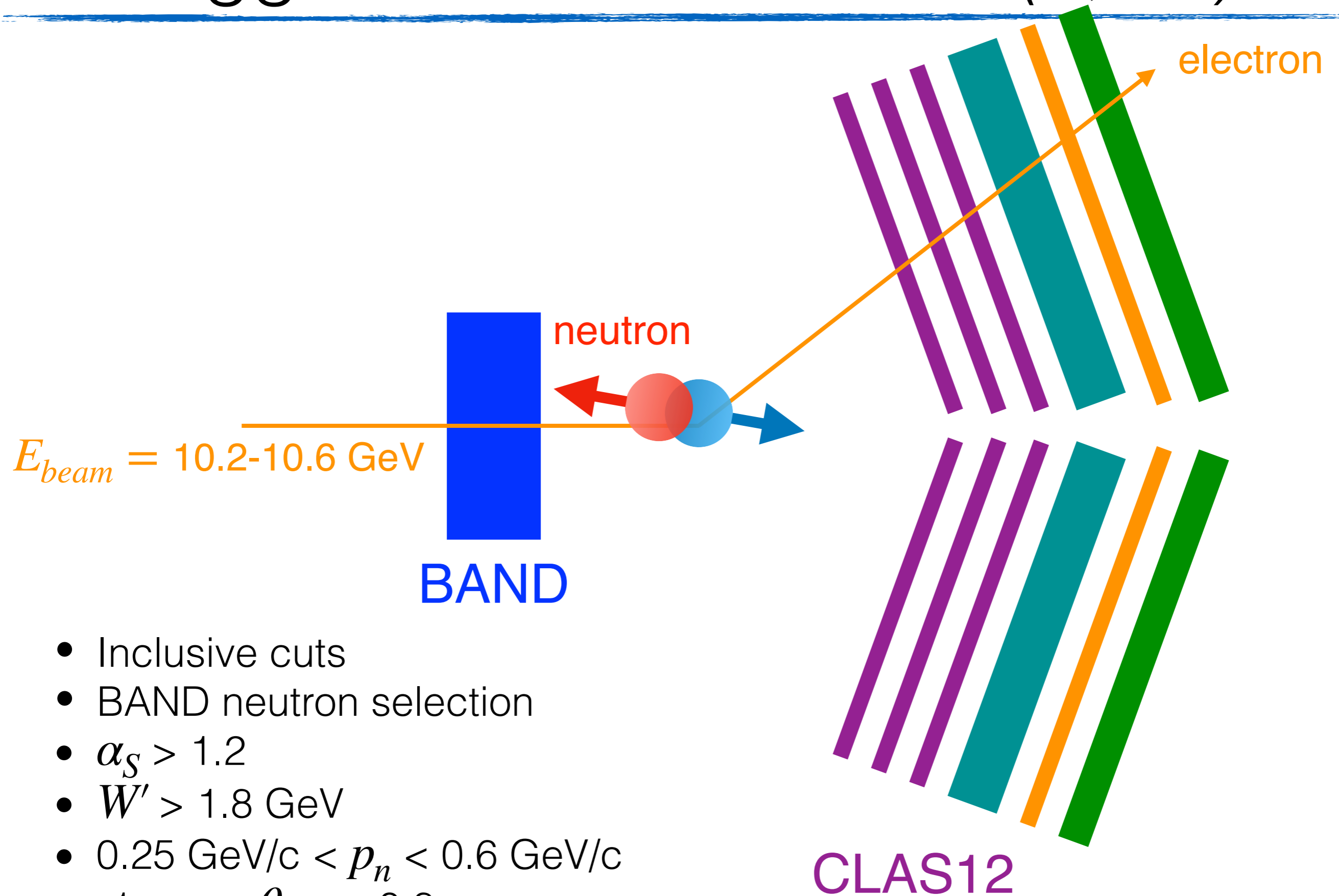
$p_n > 300 \text{ MeV}/c$



plots from Natalie Wright

- Background subtracted data from RGM
- Visible QE peak in W'


Tagged DIS with BAND $d(e, e'n)n$



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

Tagged Yield Ratio

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



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

- Cancellation of systematics in ratio
- Choose to normalize to $x'_0 = 0.3$
- Sensitive to ratio of **bound** to **free** proton structure

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

Theoretical PWIA Model

- Cross section model - [Strikman & Weiss PRC 97, 035209 \(2018\)](#):

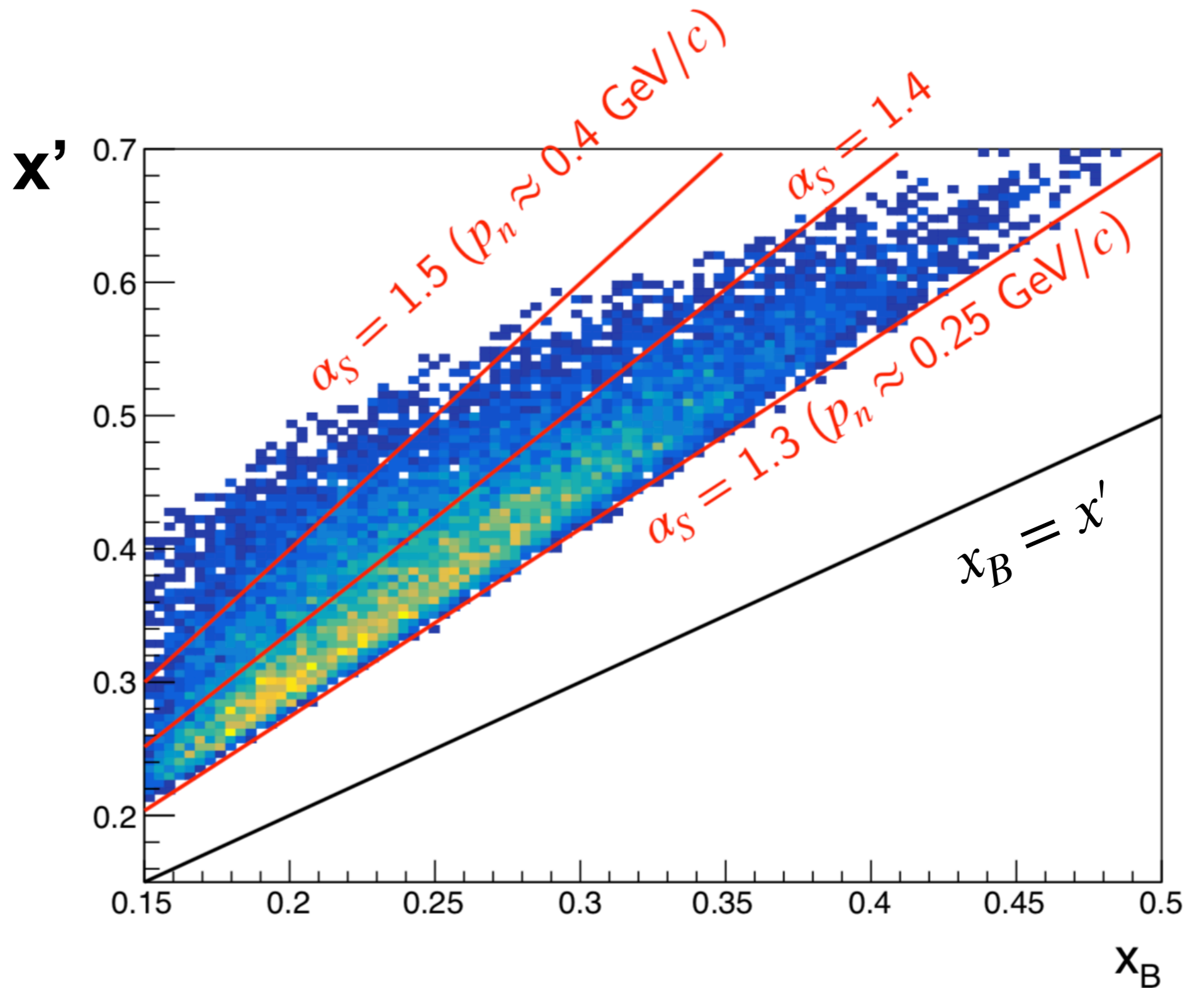
$$d\sigma[eD \rightarrow e'n_s X] = K \frac{2S(\alpha_s, p_{sT})}{2 - \alpha_s} \times F_2$$

- 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

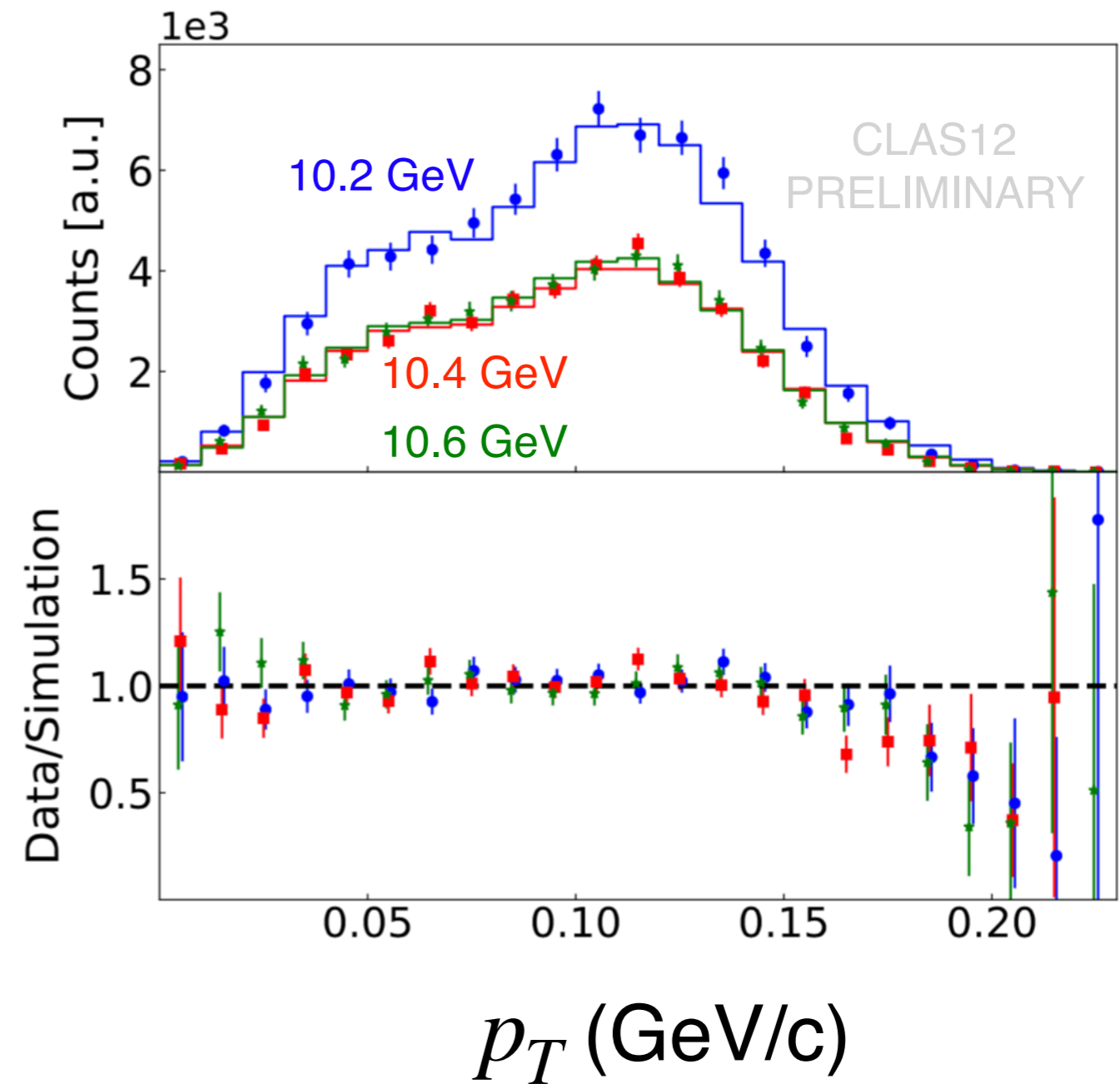
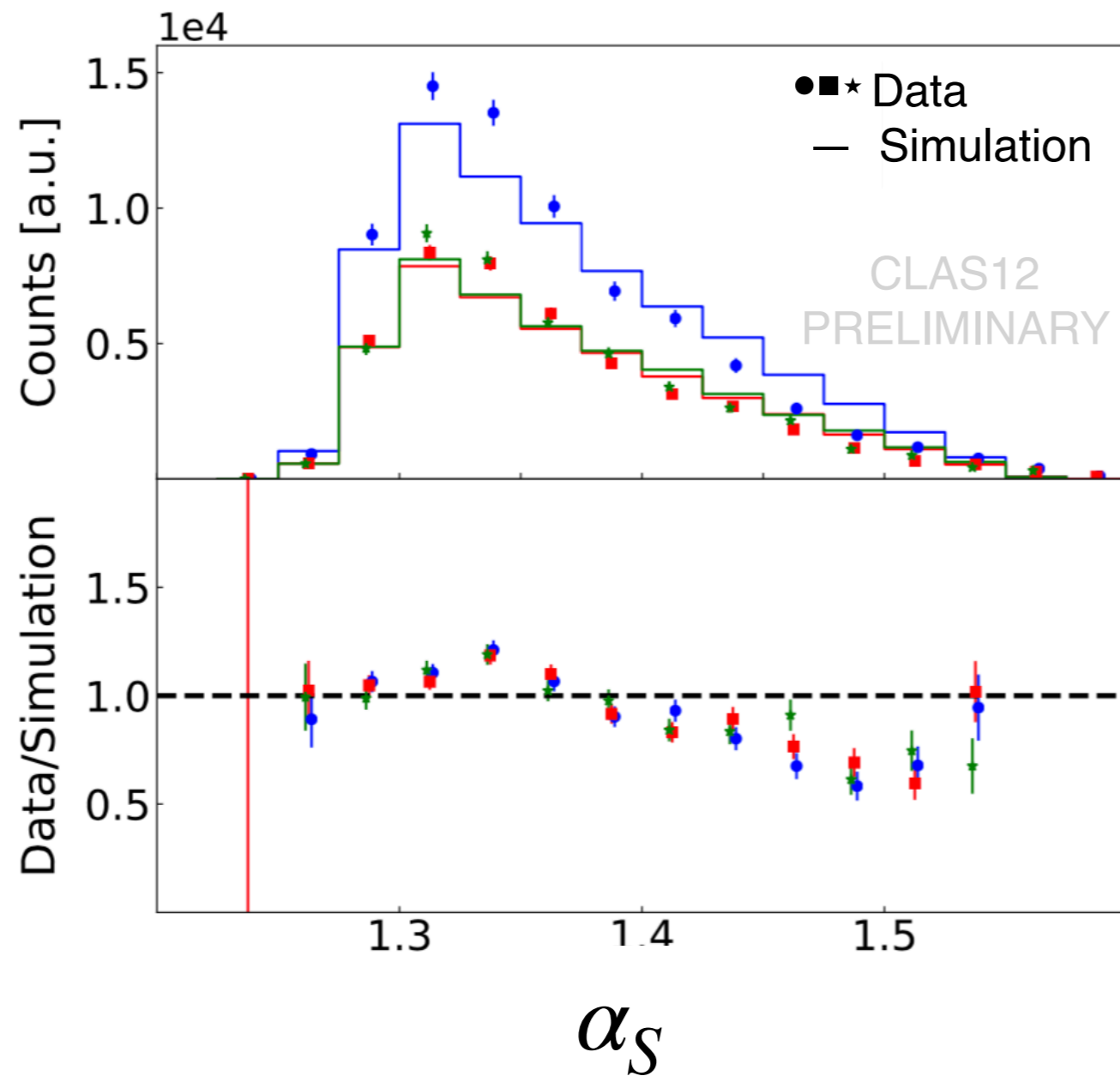
- $Q^2 > 2 \text{ GeV}^2$
- $W^2 > 4 \text{ GeV}^2$
- $y < 0.7$

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



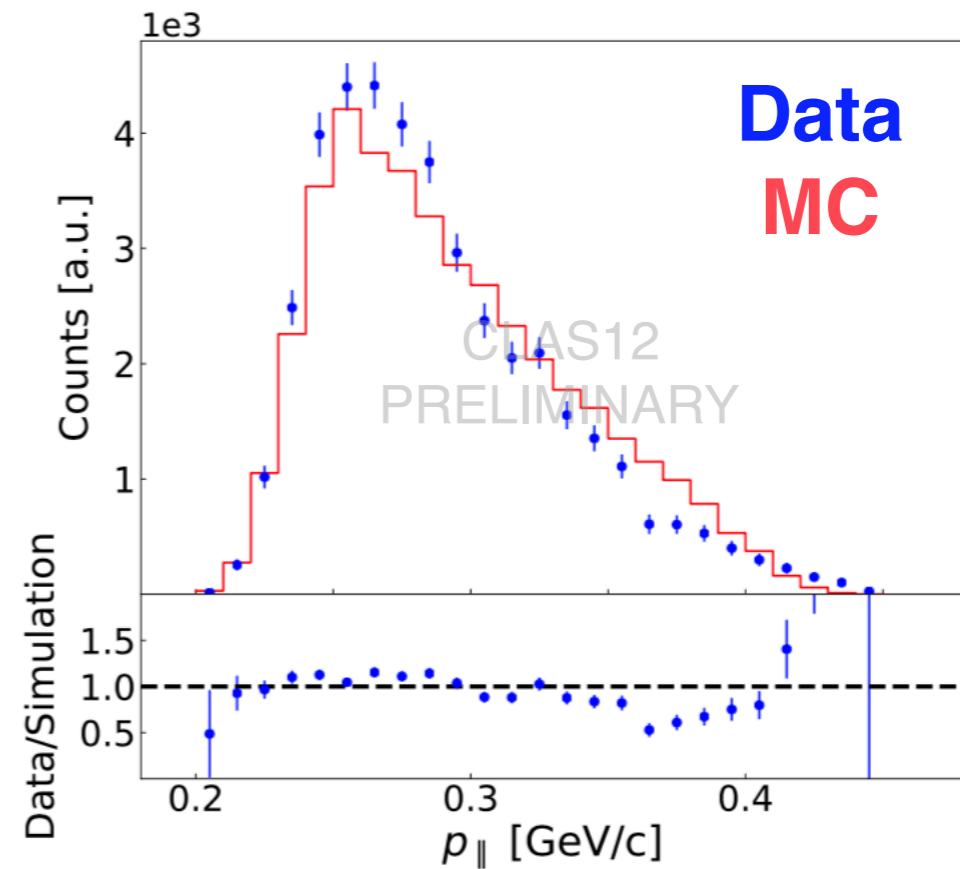
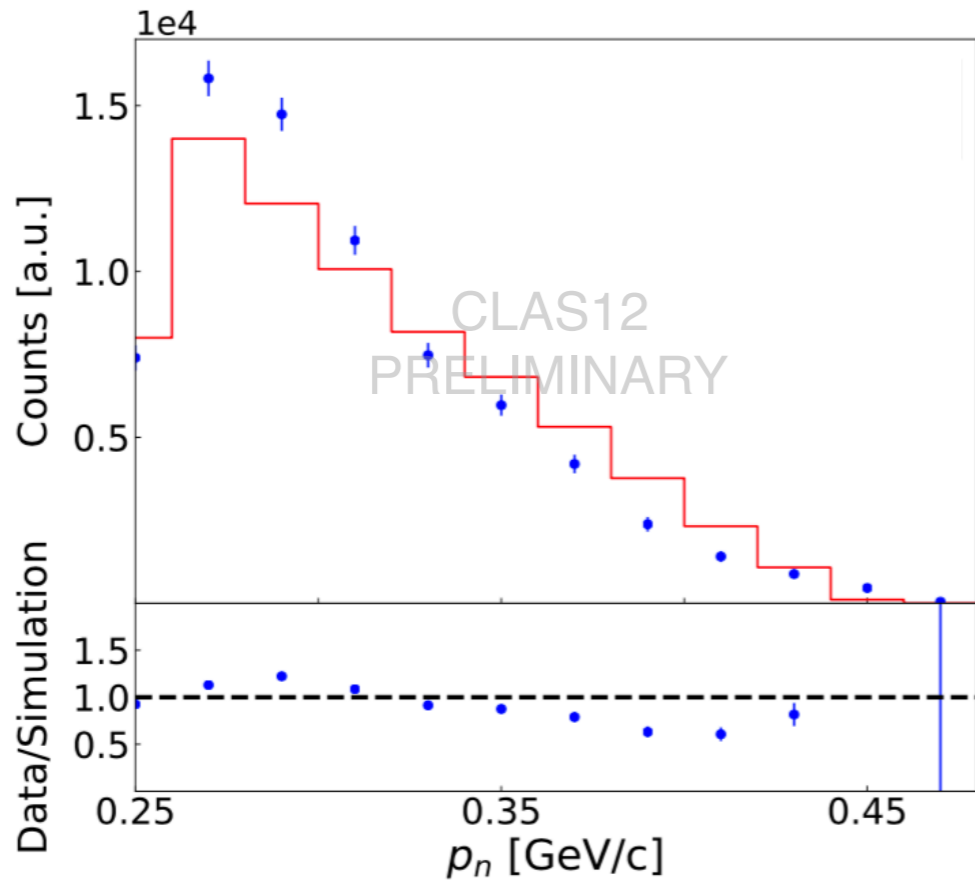
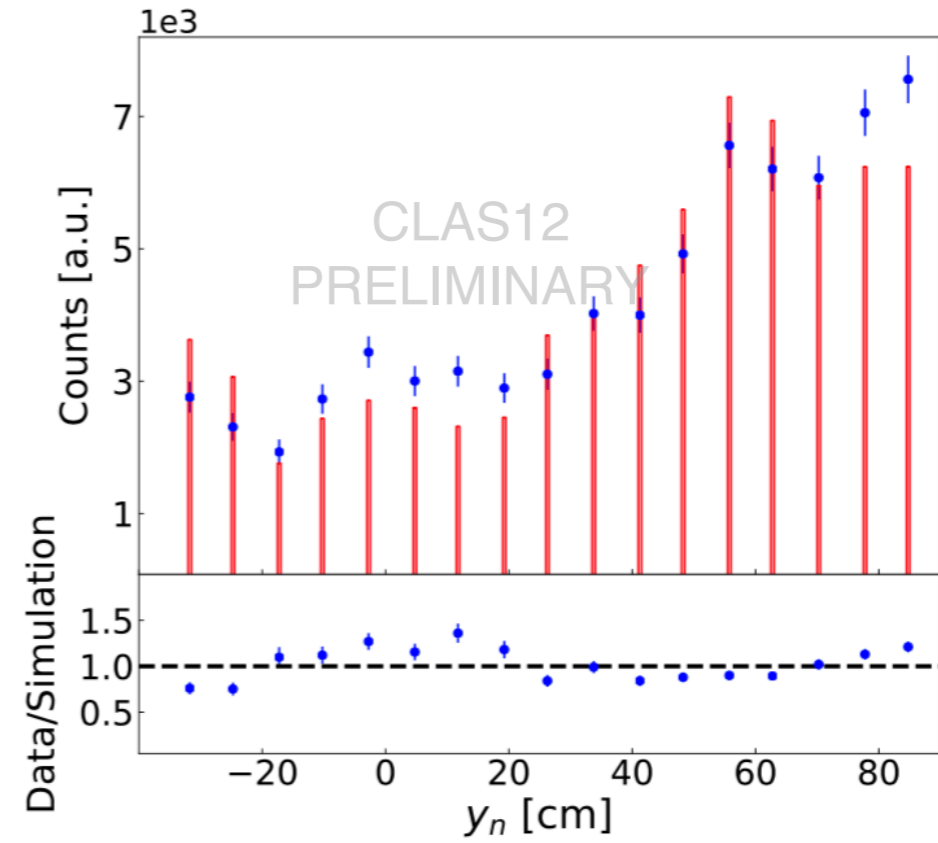
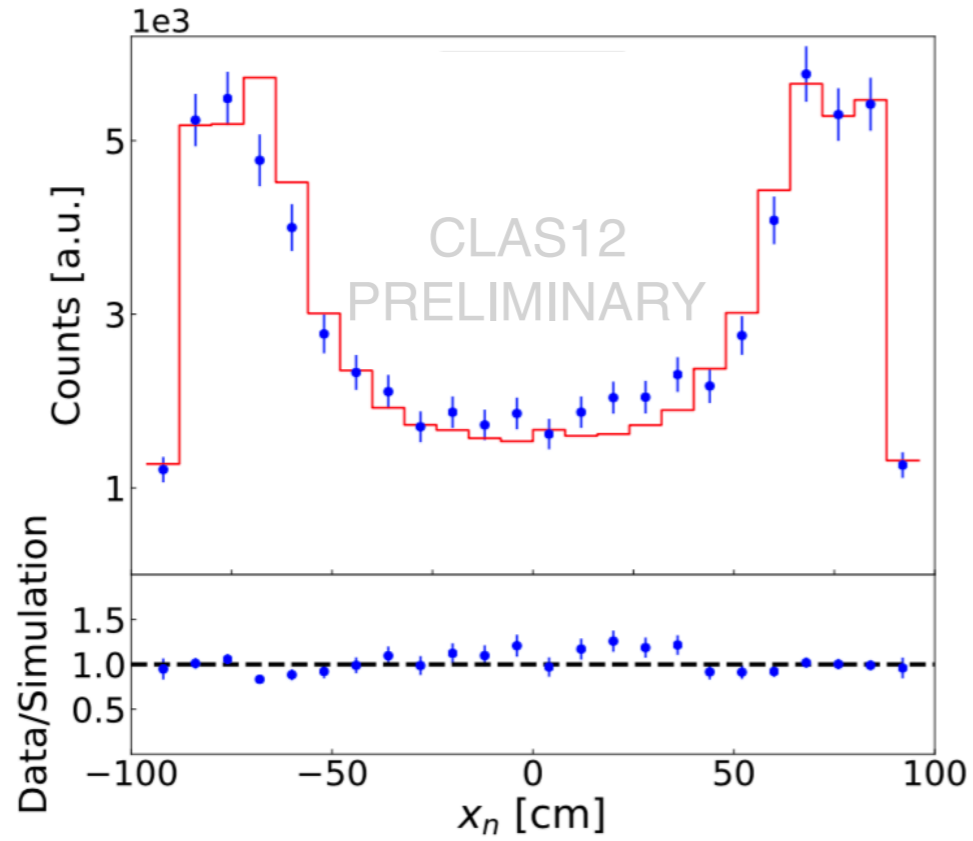
$d(e, e'n)X$: Data/MC comparisons

Integral normalized

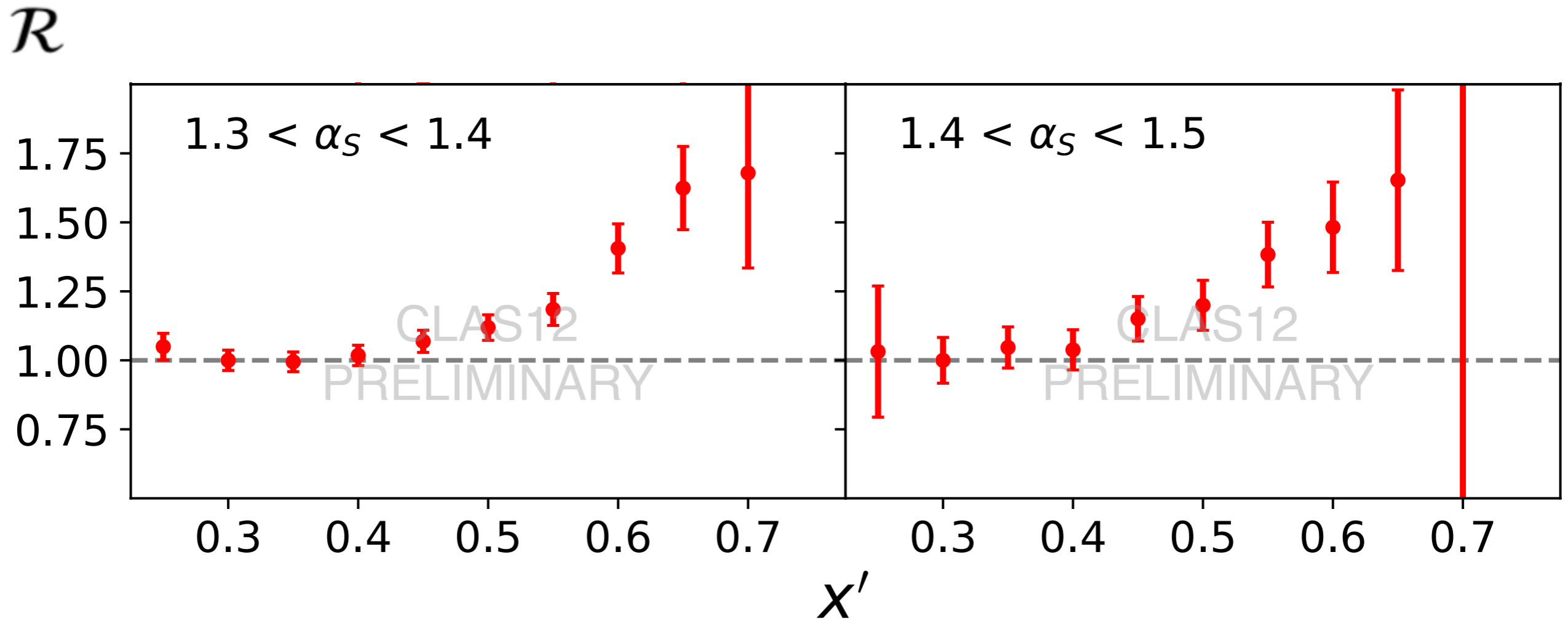


(transv. mom with respect to q)

More Tagged Comparisons (10.2 GeV)



Tagged Double Ratio



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

Systematics

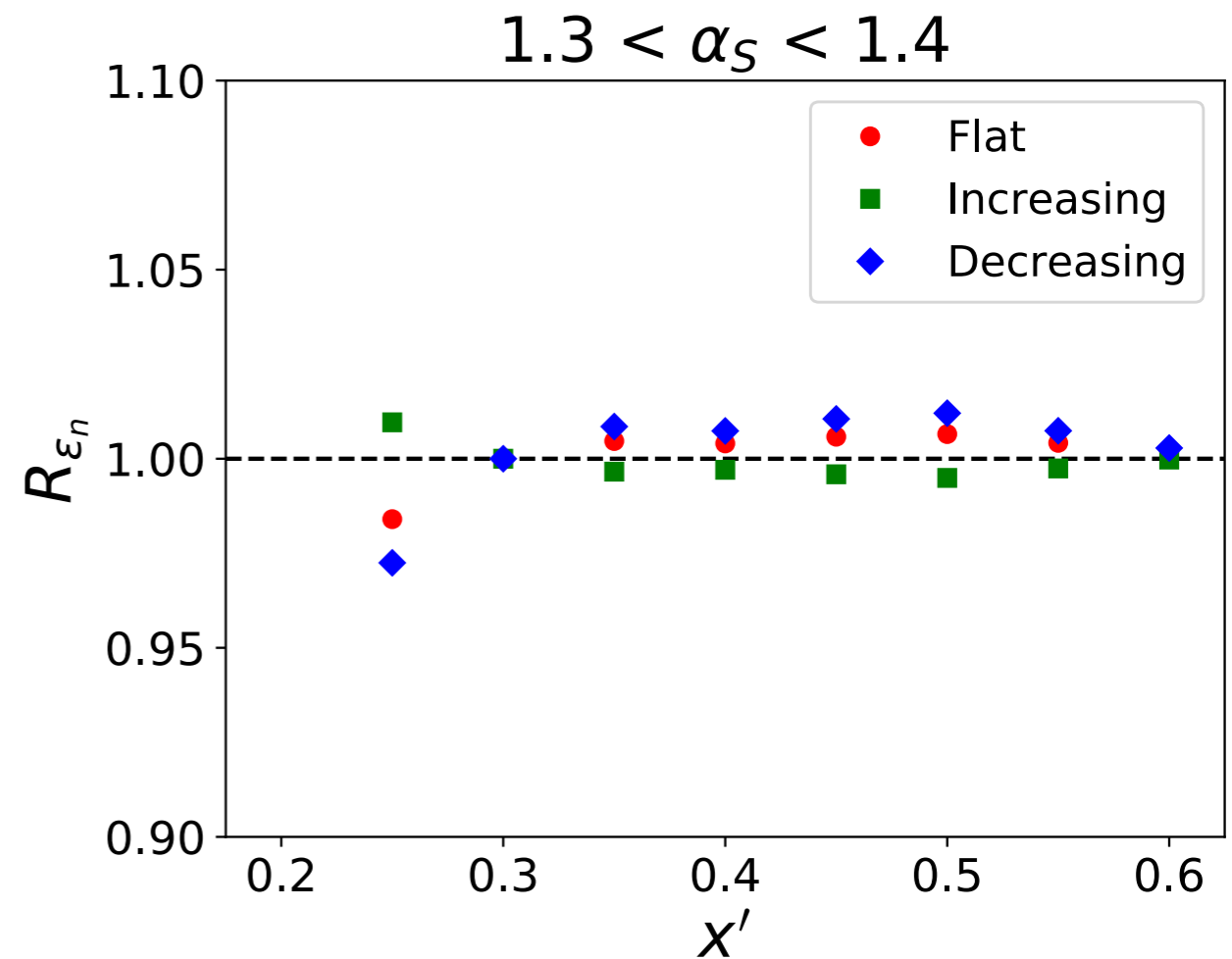
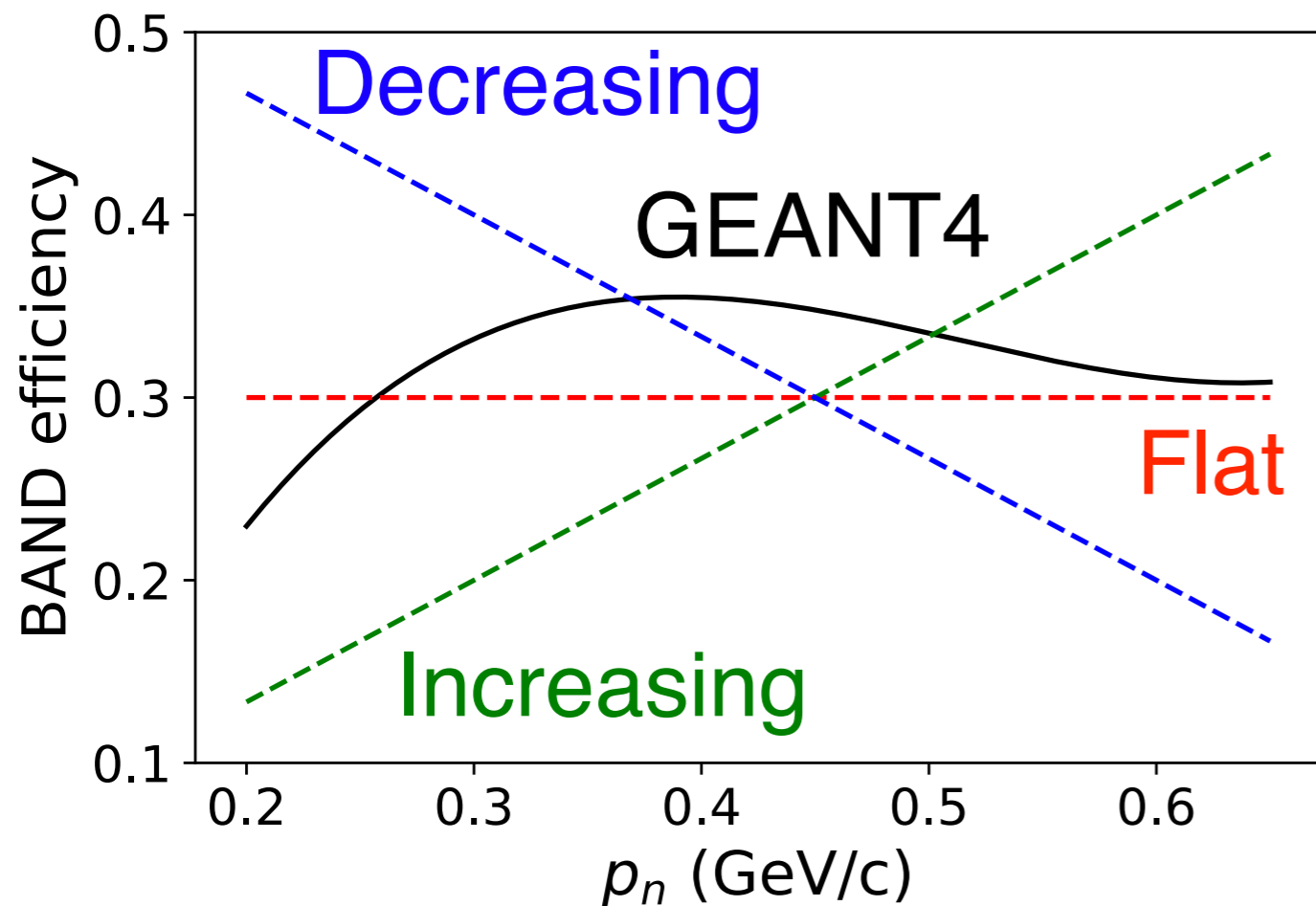
- Impact of BAND neutron detection efficiency
- Measurement stability with different beam energies
- Extend to lower α_S
- Other studies:
 - Impact of finite Q^2 effects
 - Different event generators
 - Cut sensitivity

Systematics

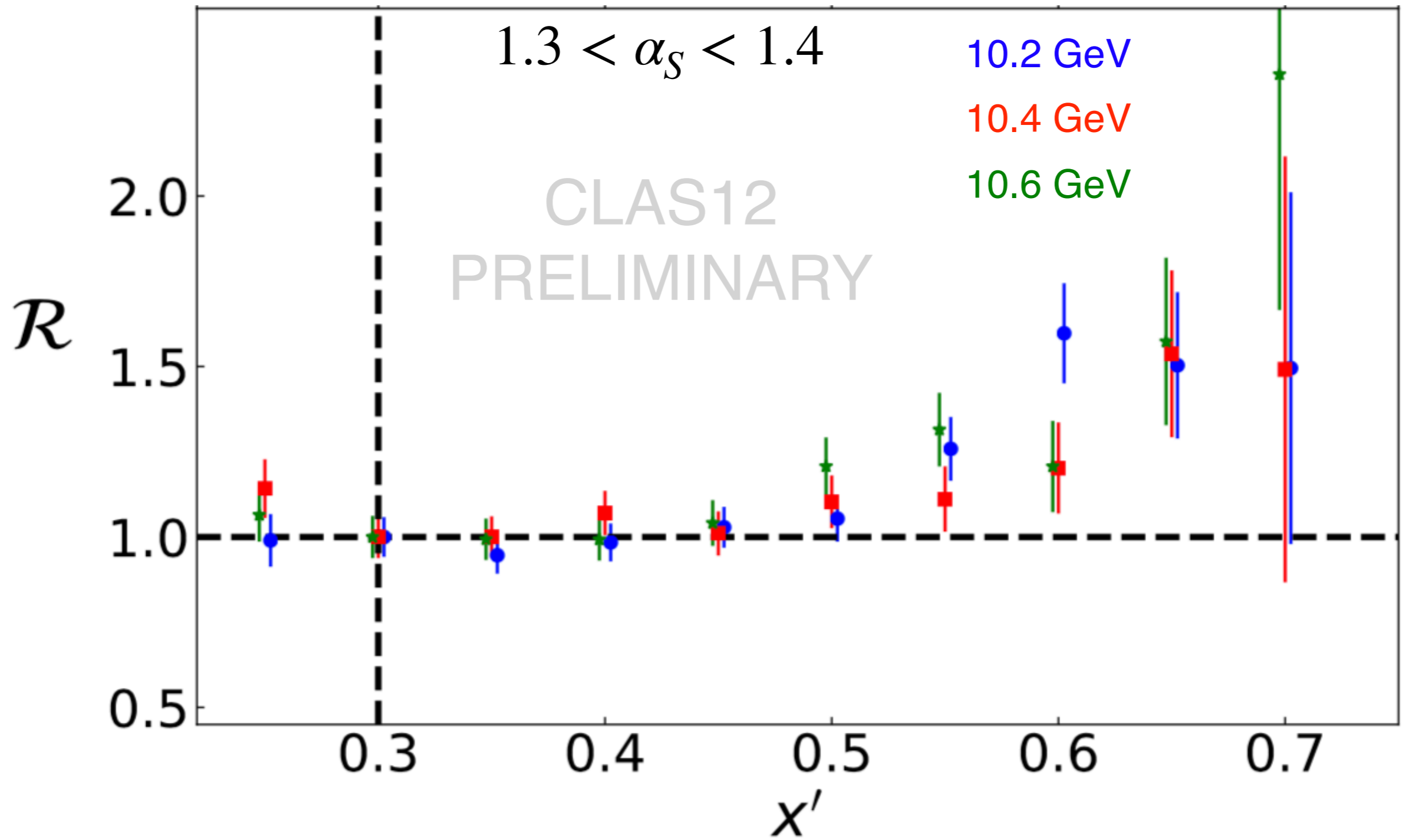
- Impact of BAND neutron detection efficiency
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- Other studies:
 - Impact of finite Q^2 effects
 - Different event generators
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Systematics: BAND Efficiency

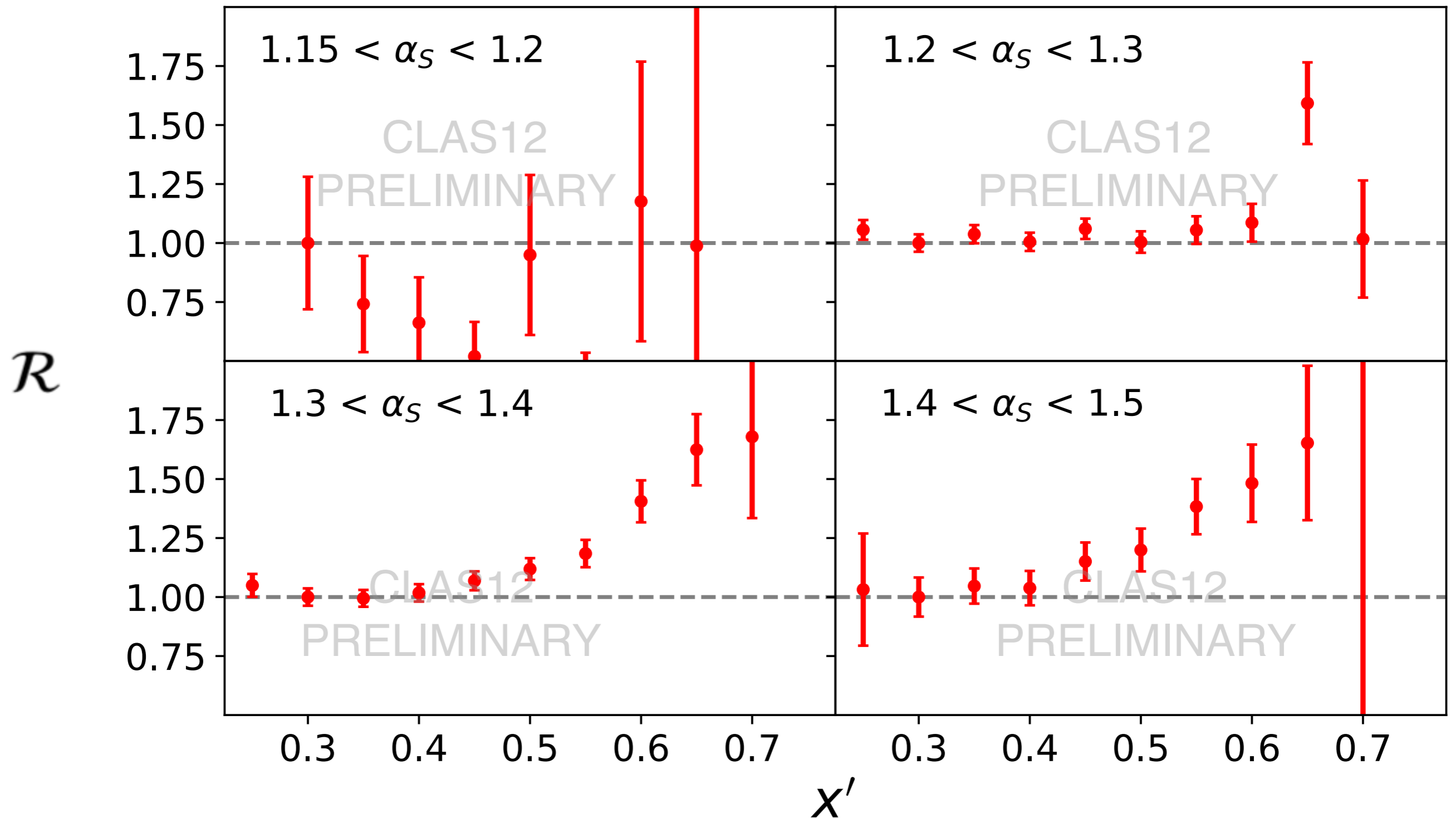
$$R_{\epsilon_n} = \frac{N_{standard}(x') / N_{standard}(x' = x_0)}{N_{reweight}(x') / N_{reweight}(x' = x_0)}$$



Systematics: Stability with Beam Energy



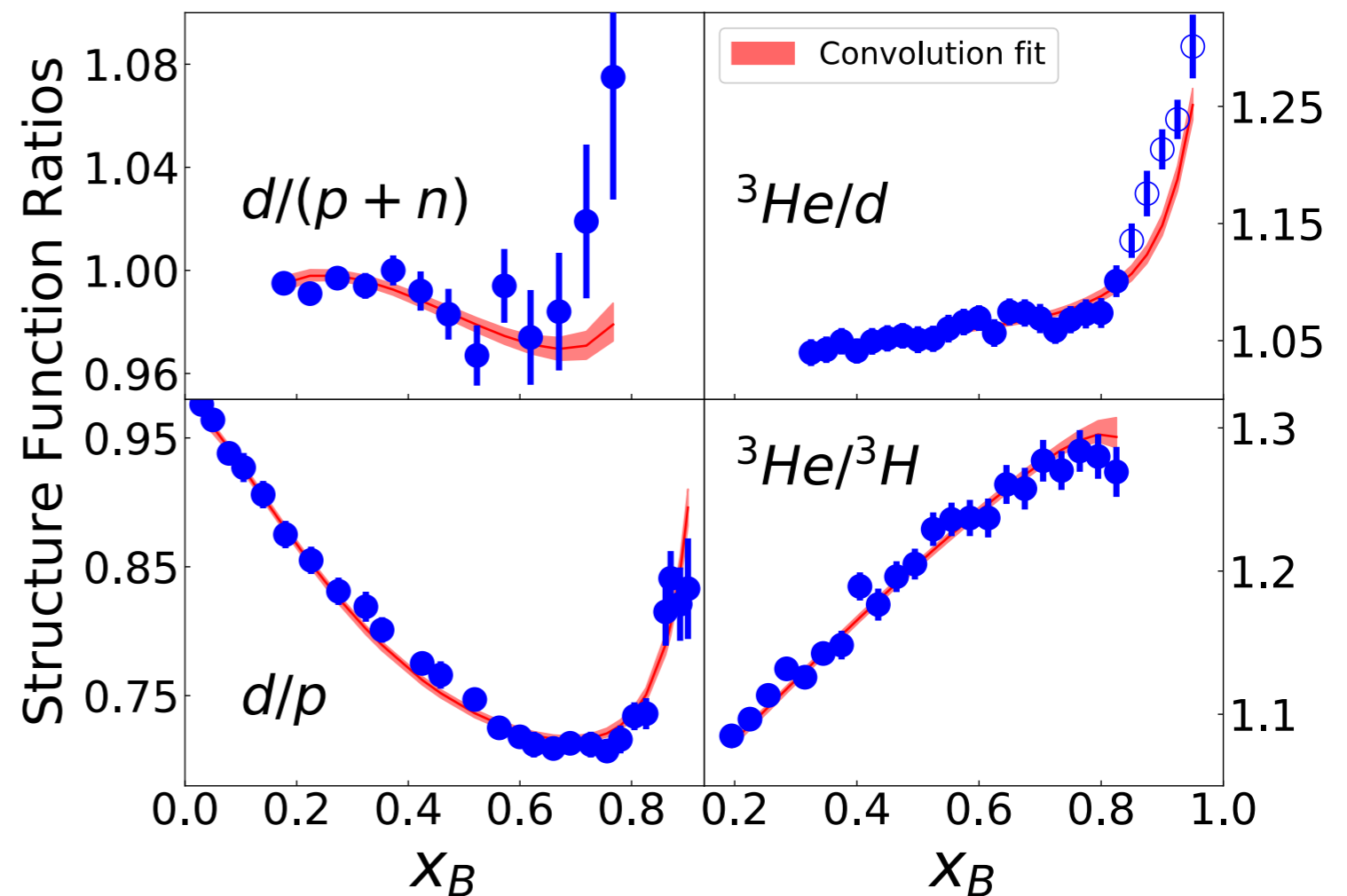
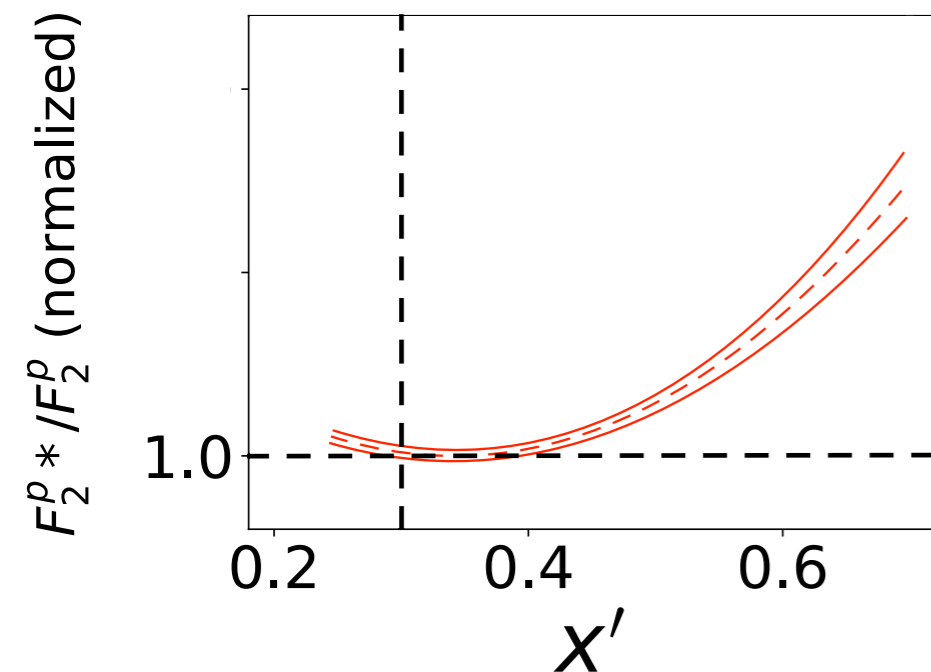
Systematics: Extend to lower alpha



- No modification for lower alpha as expected

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

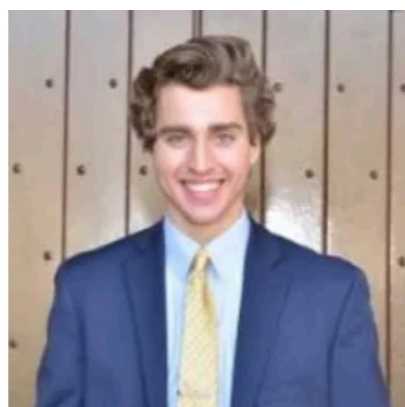


Summary

- 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 to be submitted this year
- LAD experiment in HallC (complemental to BAND)
- ALERT experiment in HallB (tagging on recoil nuclei from $^4\text{He}(e,e')$)



Efrain Segarra
(Student)



Tyler Kutz
(Postdoc)



Caleb Fogler
(Student)



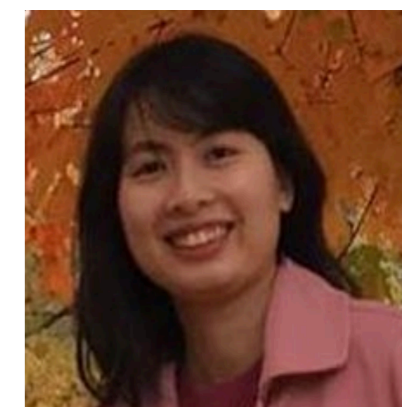
Noah Swan
(Student)



Andrew Denniston
(Student)



Justin Estee
(Postdoc)

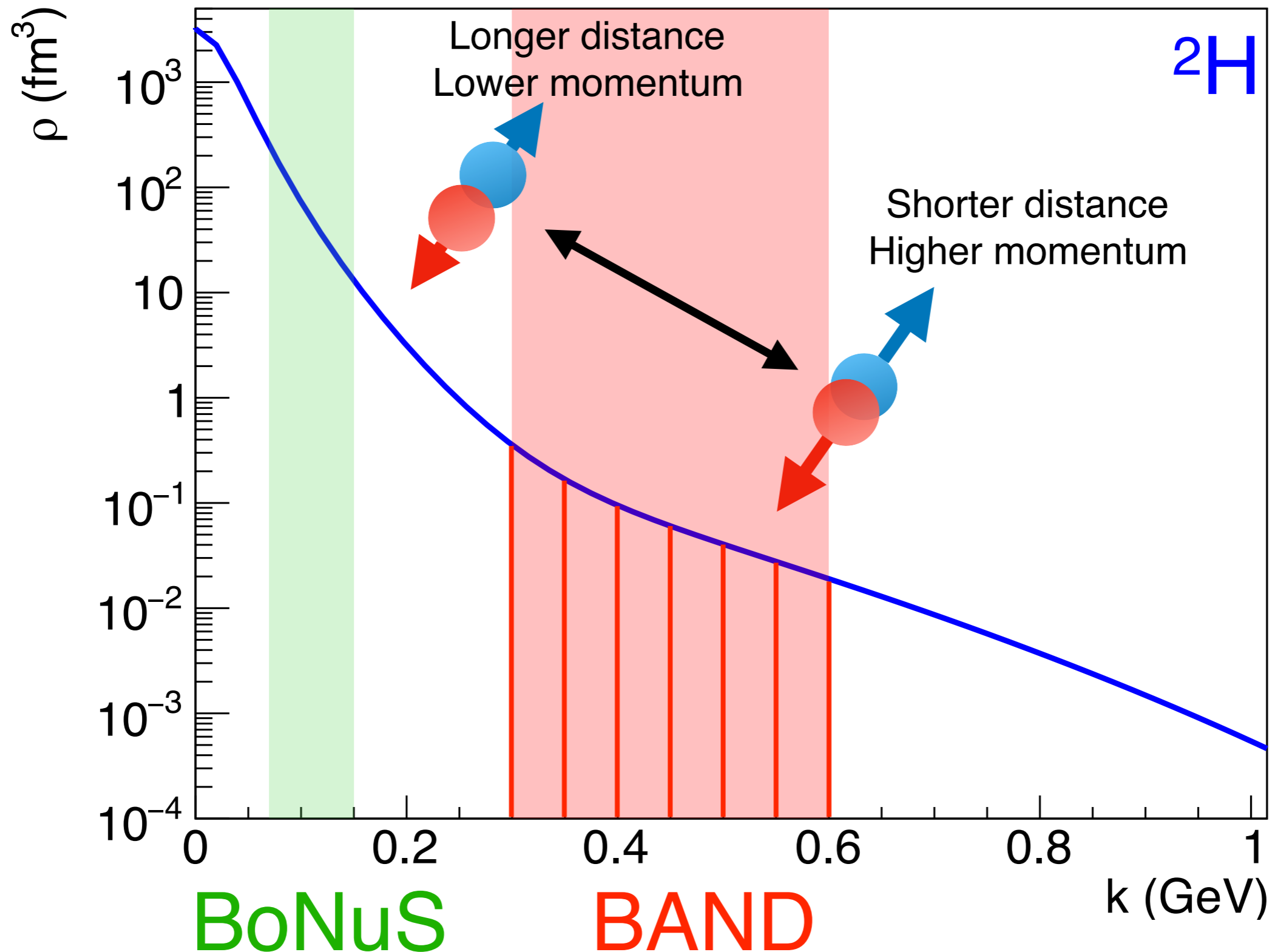


Dien Nguyen
(Isgur postdoc)

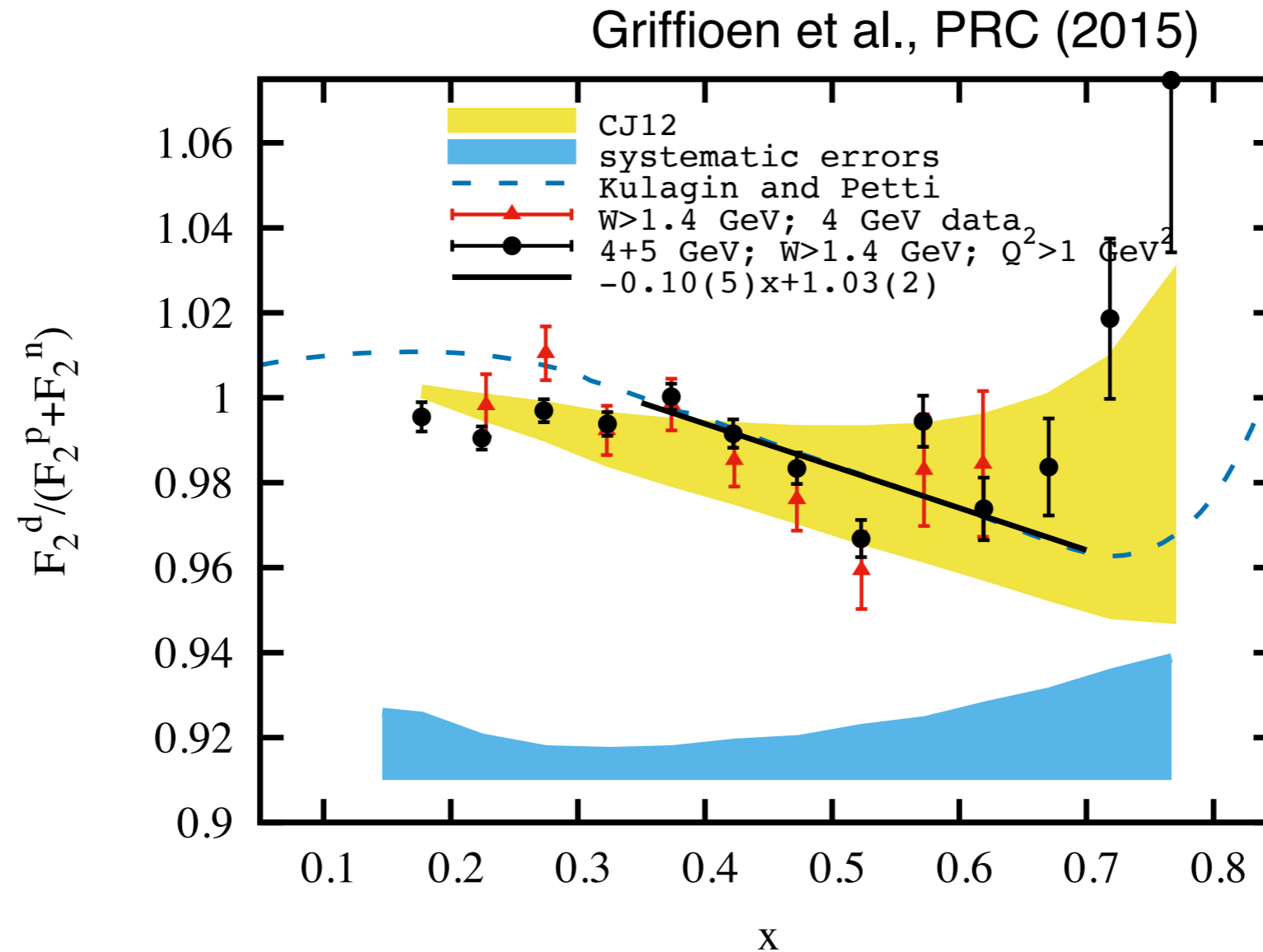
Thank you

Backup slides

Momentum Coverage

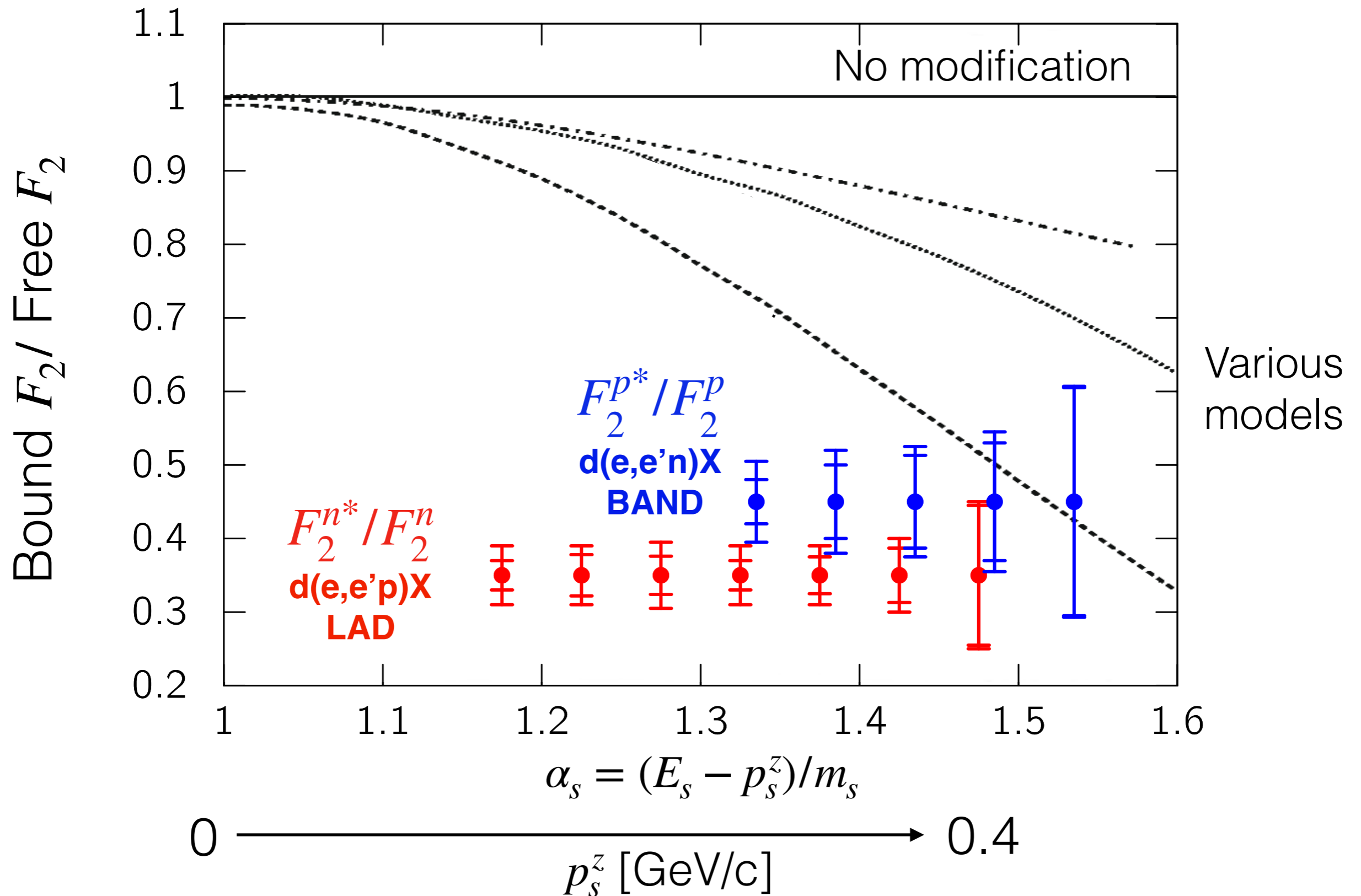


EMC Effect in Deuterium

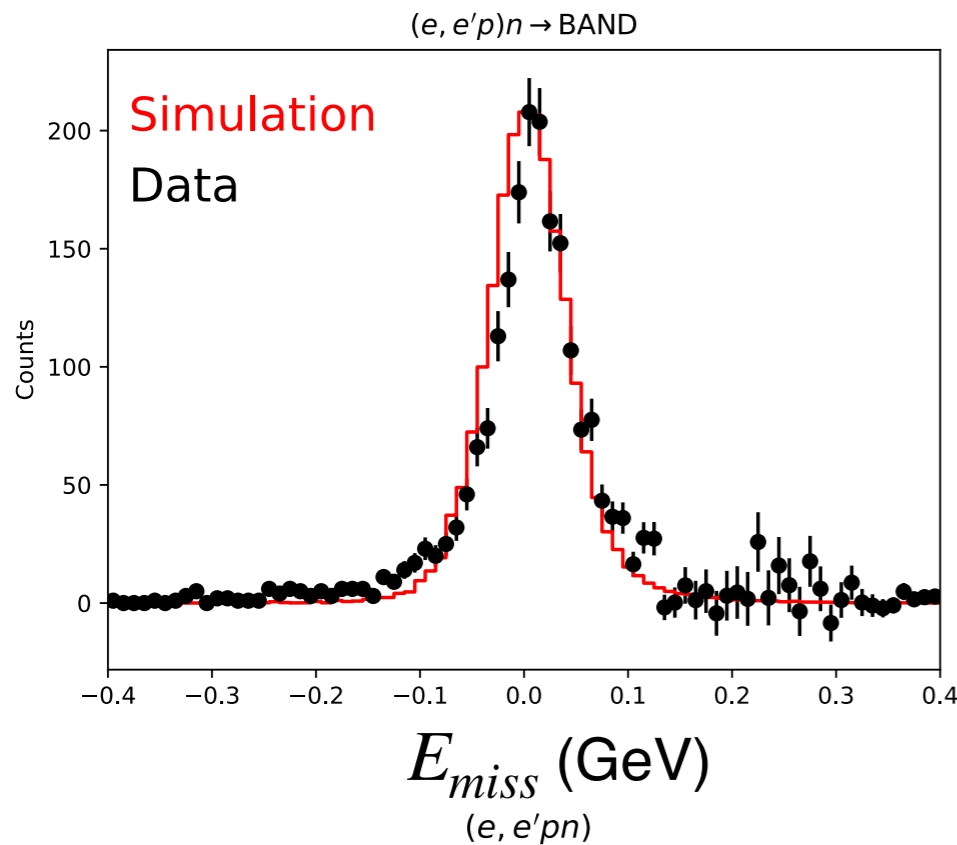


- EMC is small BUT
- SRC hypothesis predicts large modification of (rare) SRC states!

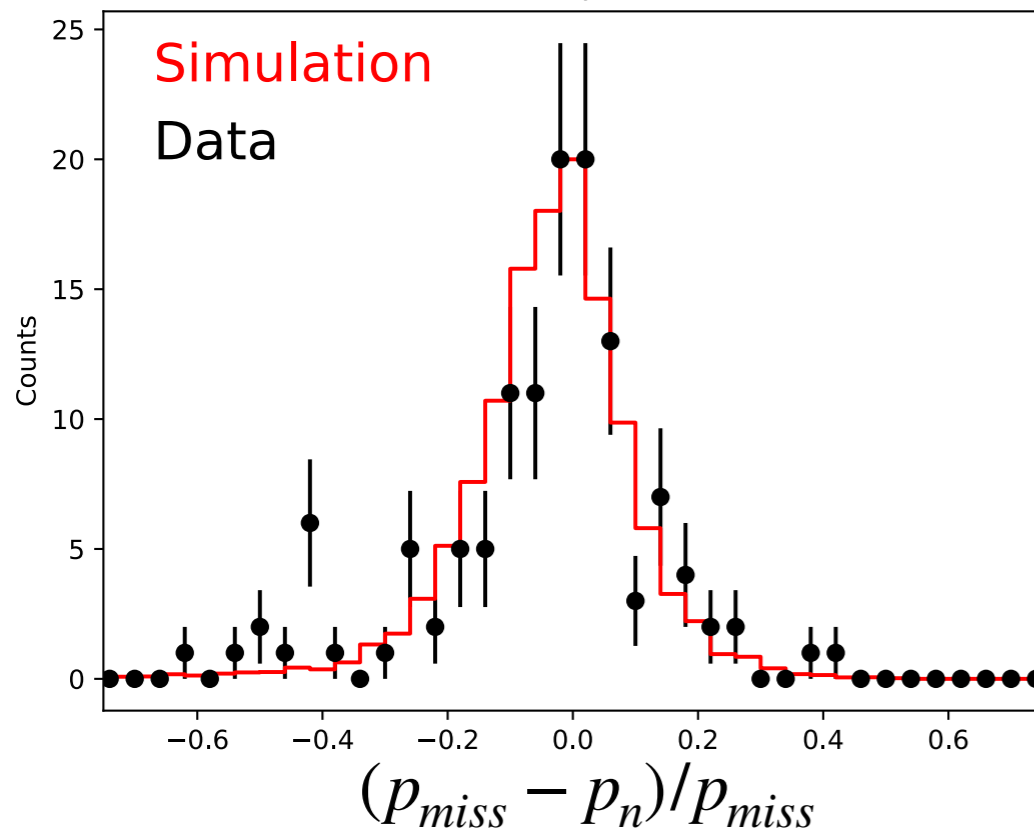
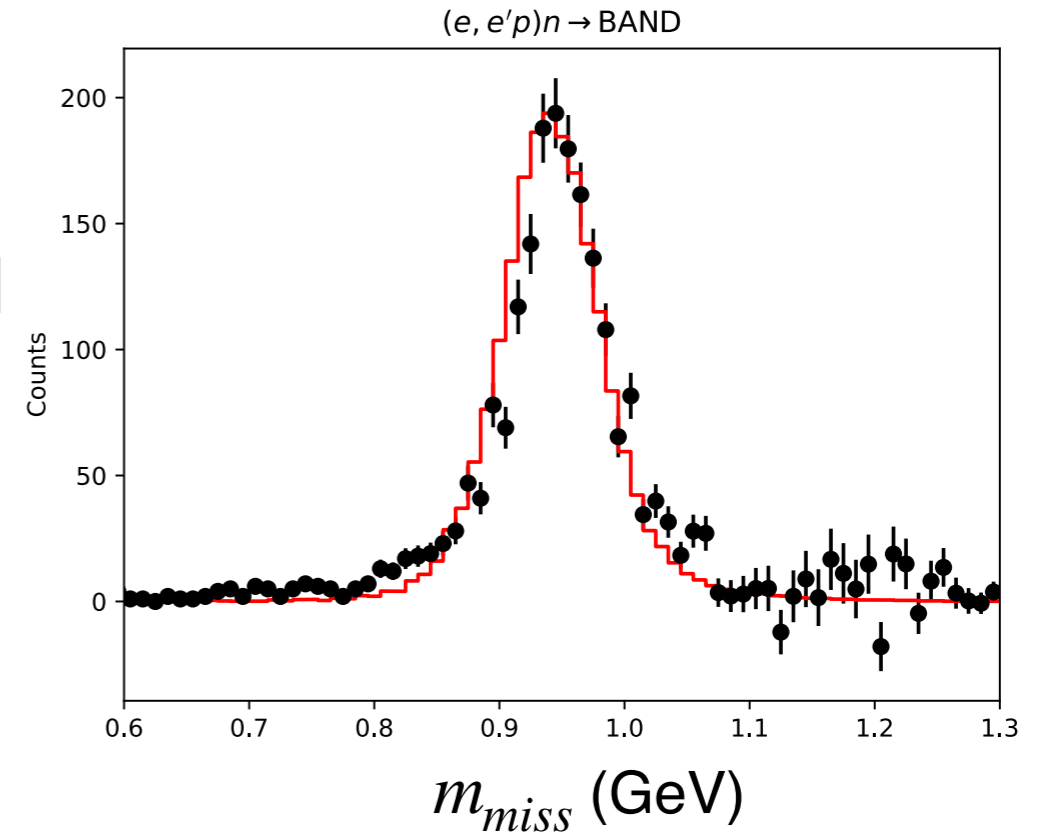
DIS Recoil Tagging $d(e, e'N)X$ - Expected Results



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

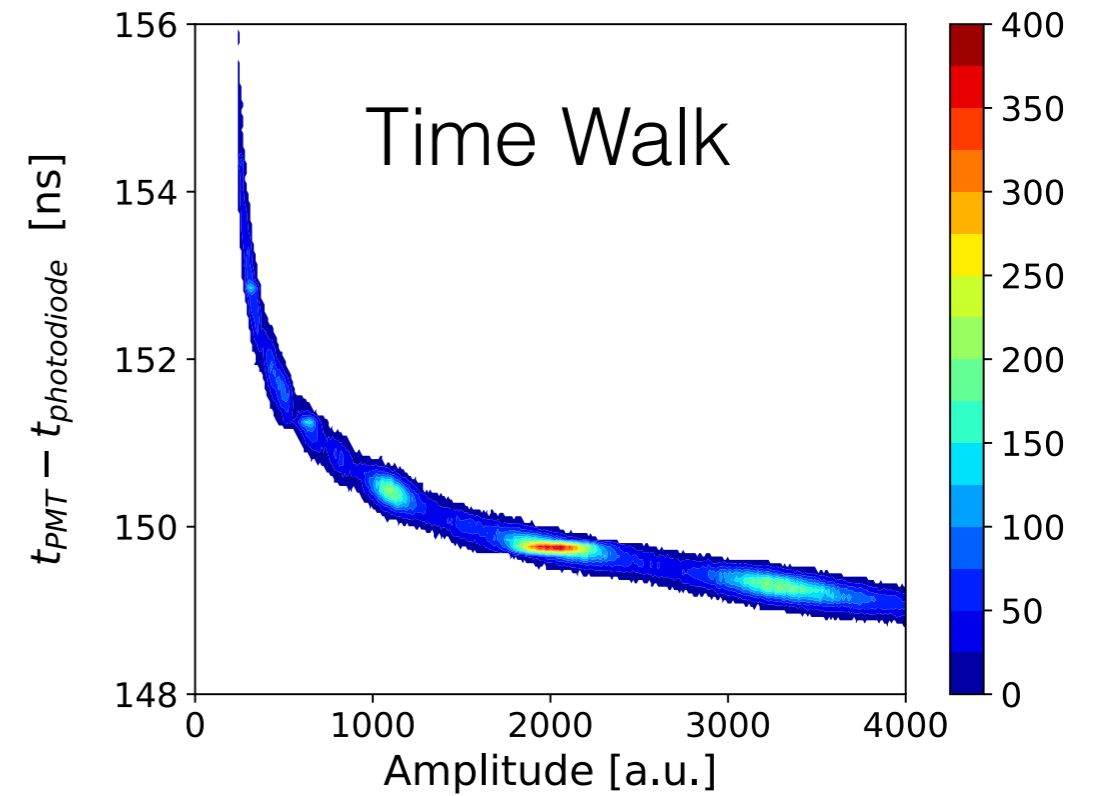
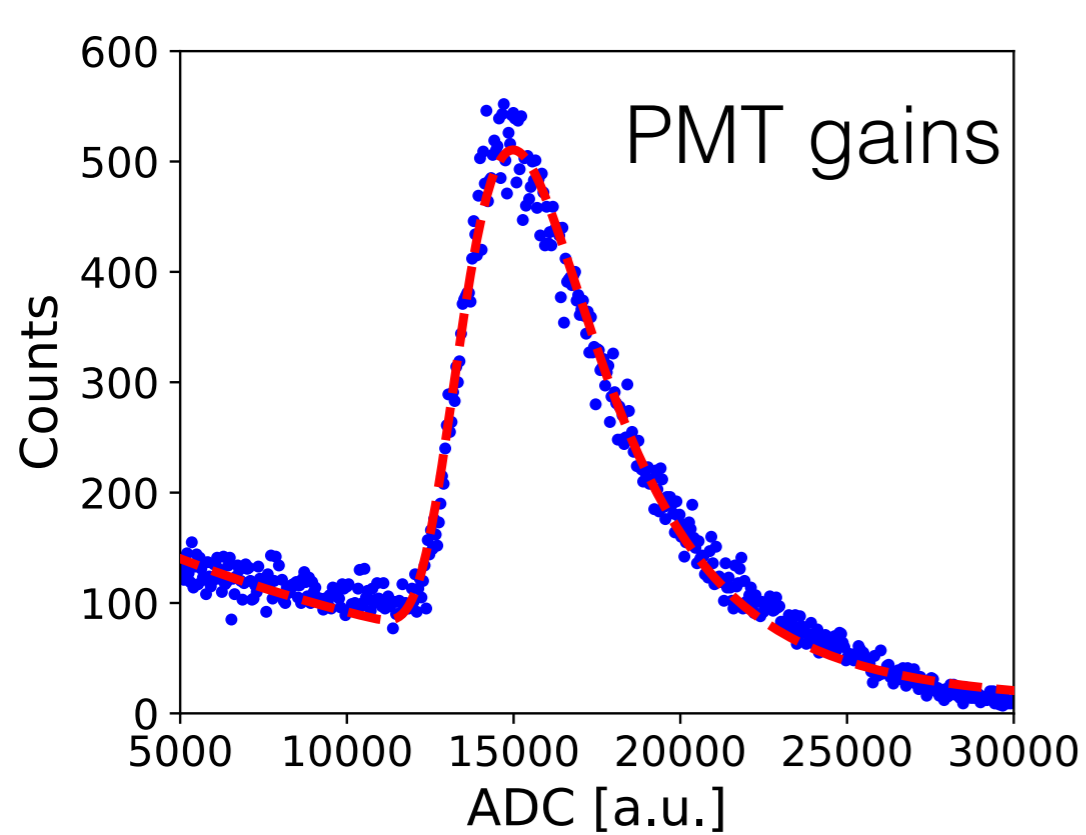


Integral-normalized

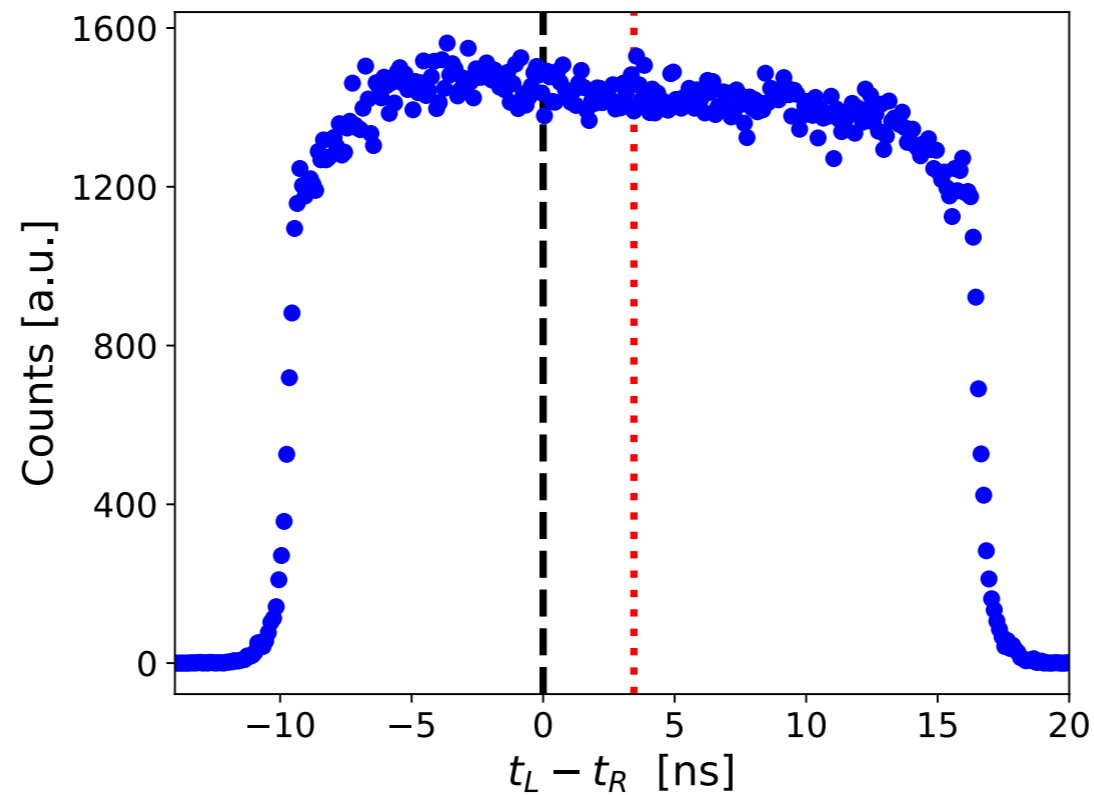


- Excellent agreement in resolution of data and simulation
- Luminosity-normalized data/simulation ratio $\approx 2-3$

BAND Calibrations



Timing Offsets

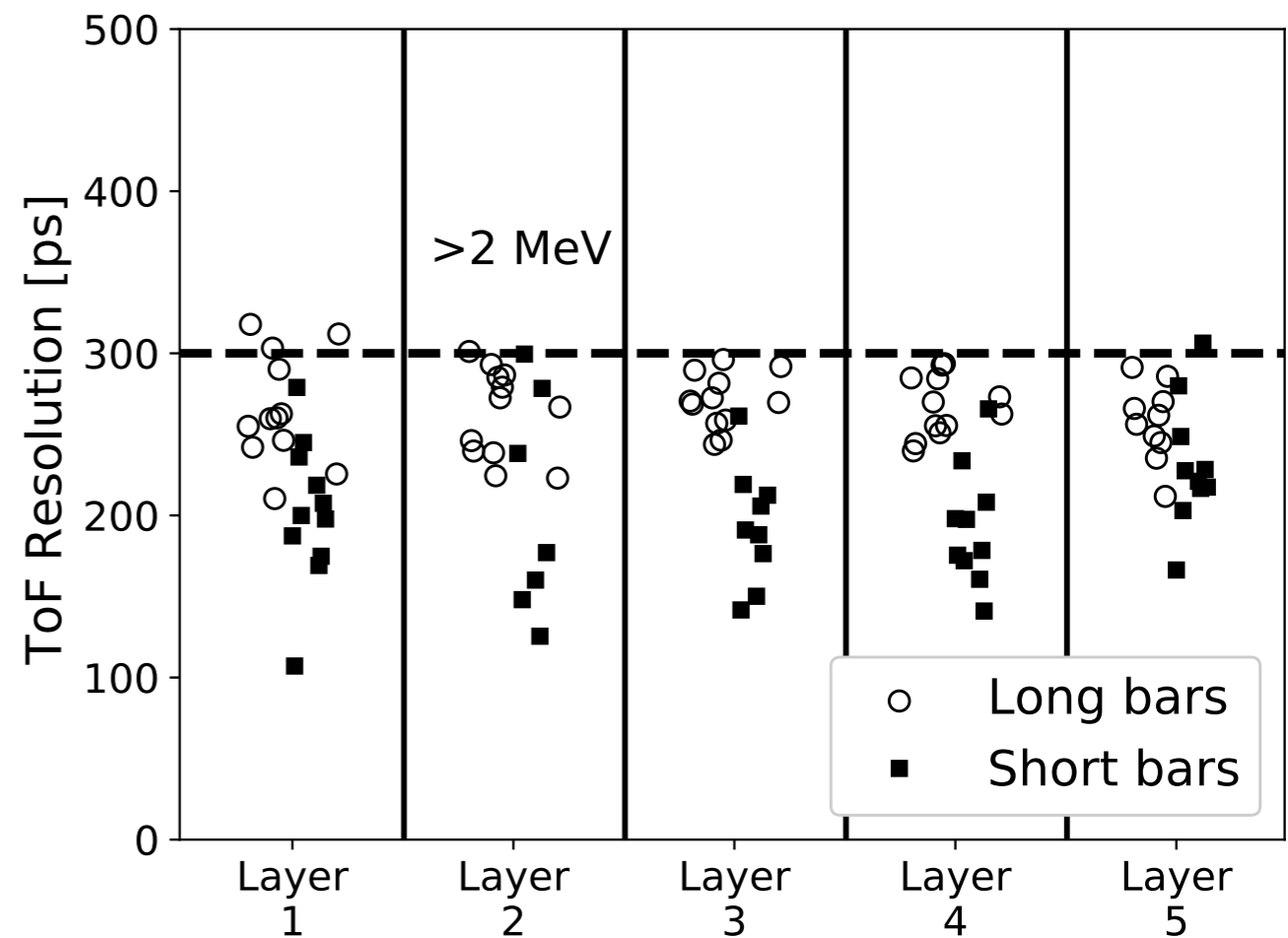
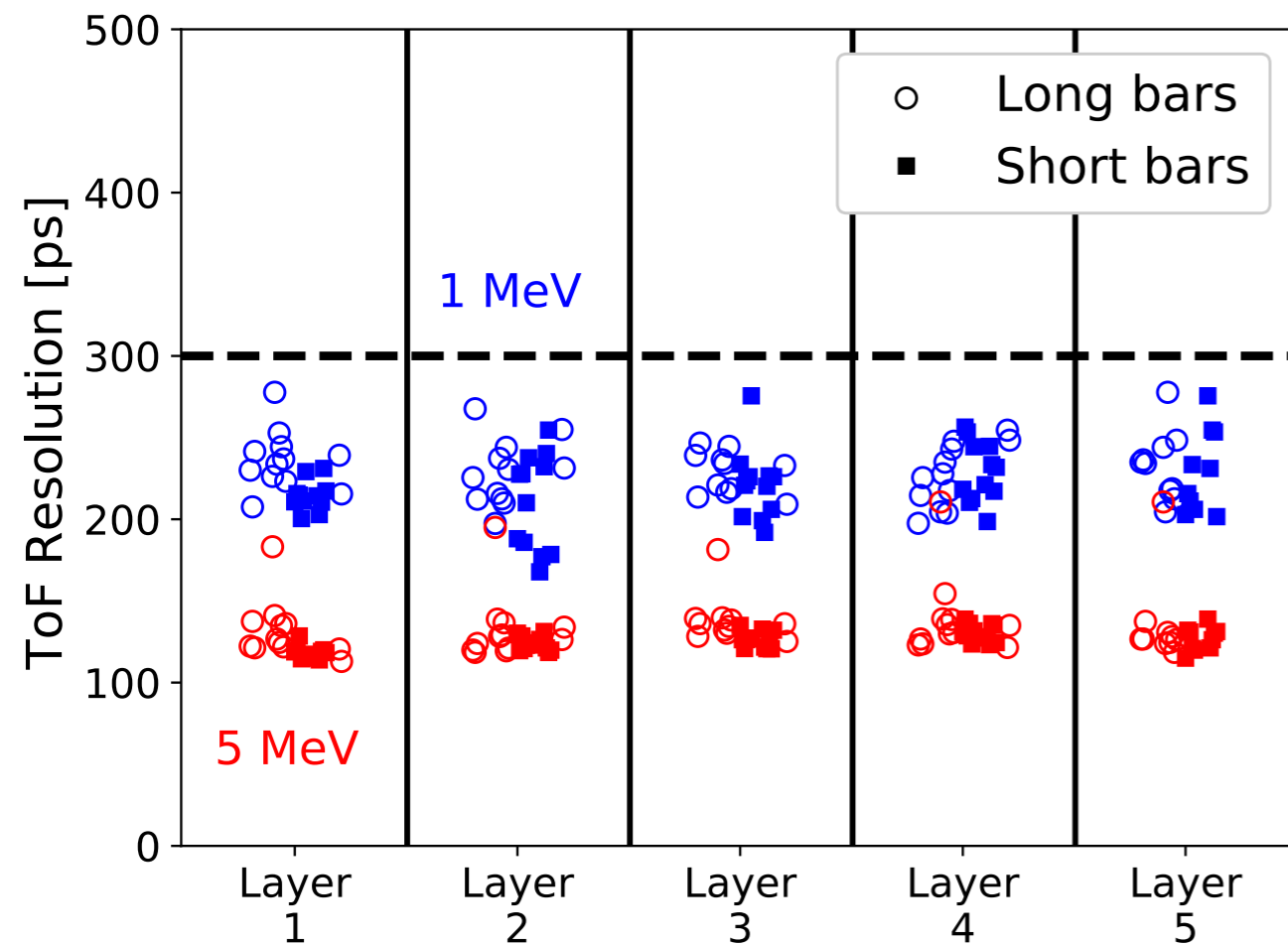


Time Resolutions of BAND Bars

Segarra et al., NIM A978 (2020)

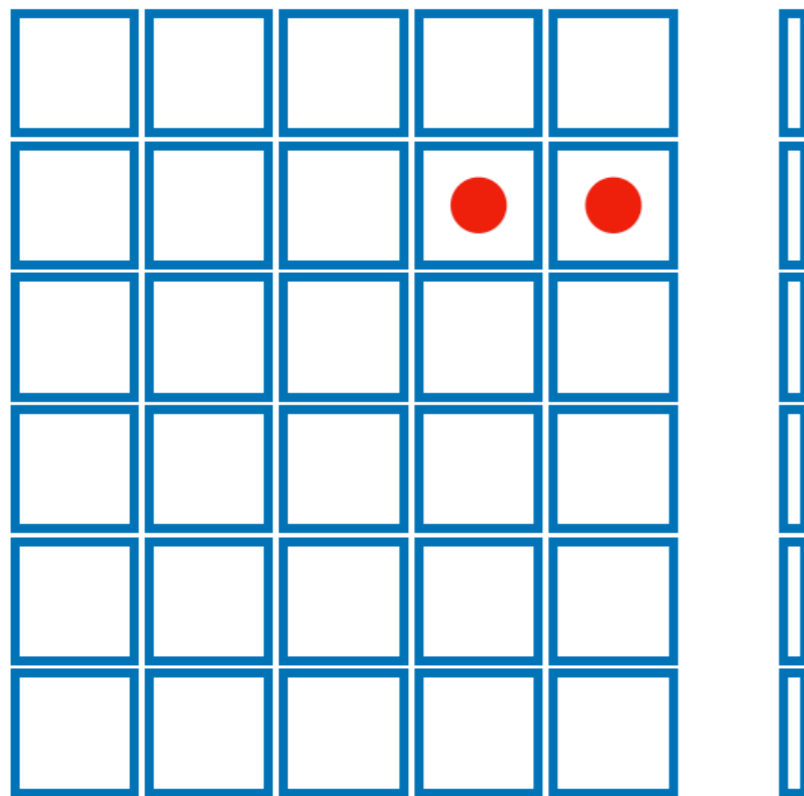
Laser

Photons



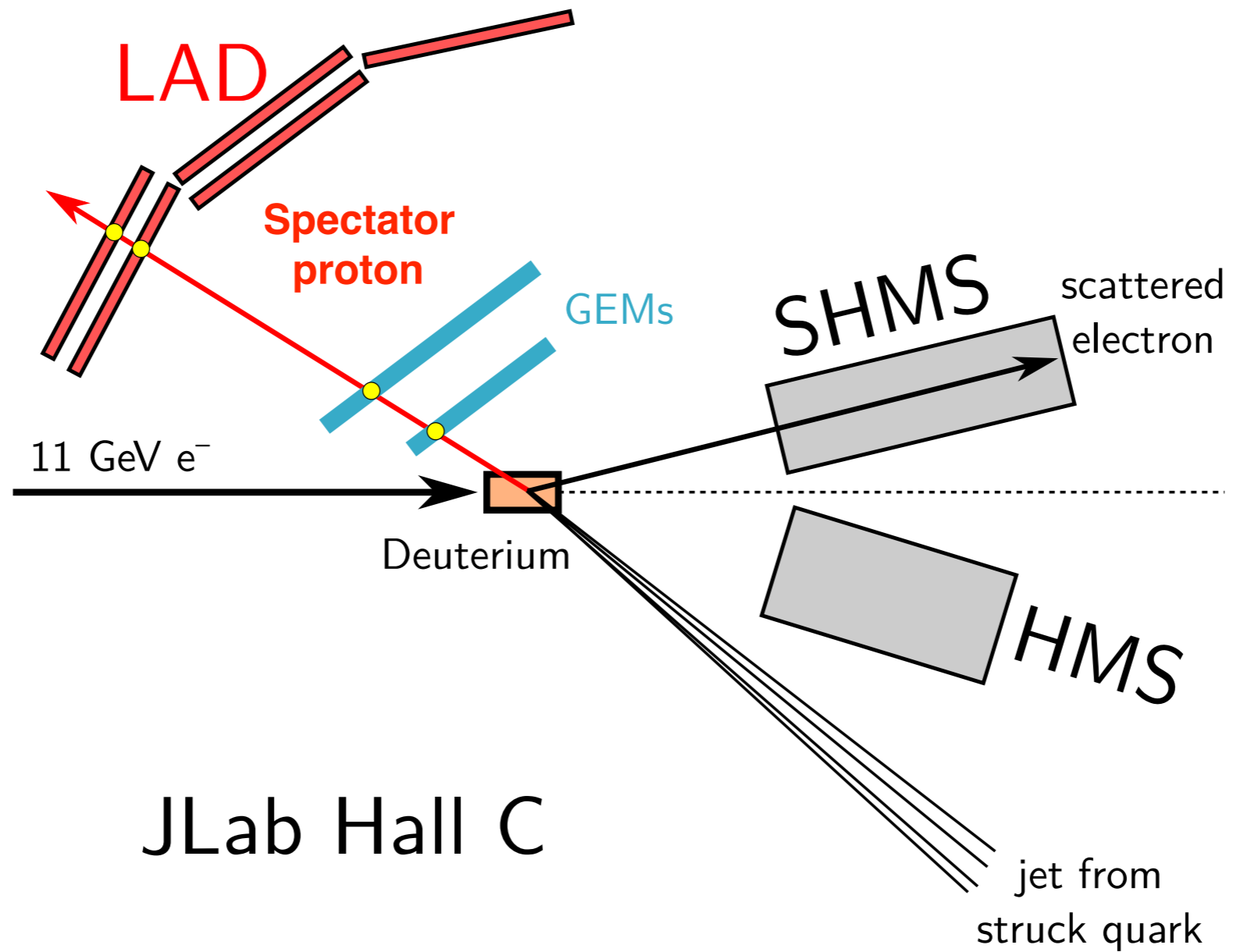
Neutron Selection: Identifying Good Hits

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

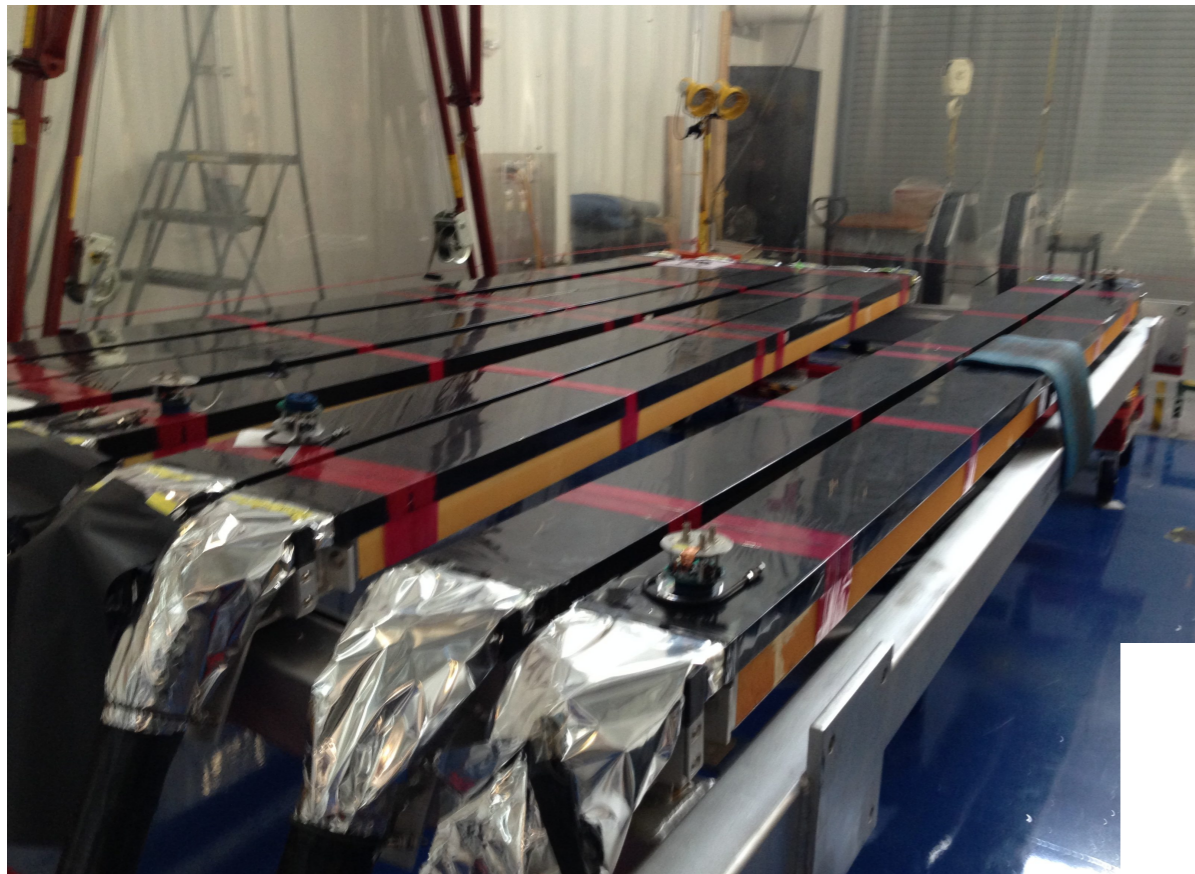


- If single hit (most of the time) ✓
- If 2 hits:
 - Close together (from same interaction)? ✓
 - Far apart? ✗
- If > 2 hits ✗

LAD in Hall-C



LAD - Refurbished CLAS6 Scintillators



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

