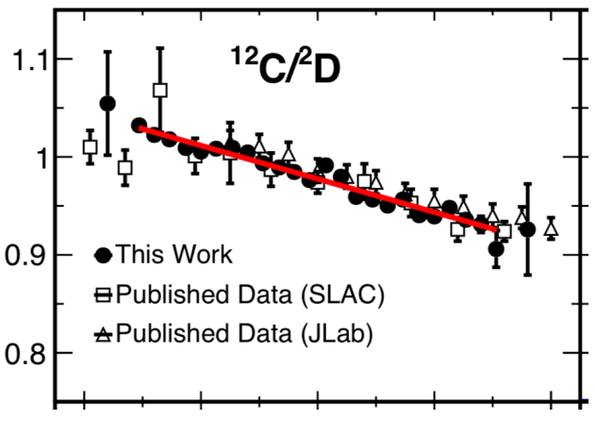
Understanding the EMC effect with tagged DIS measurements

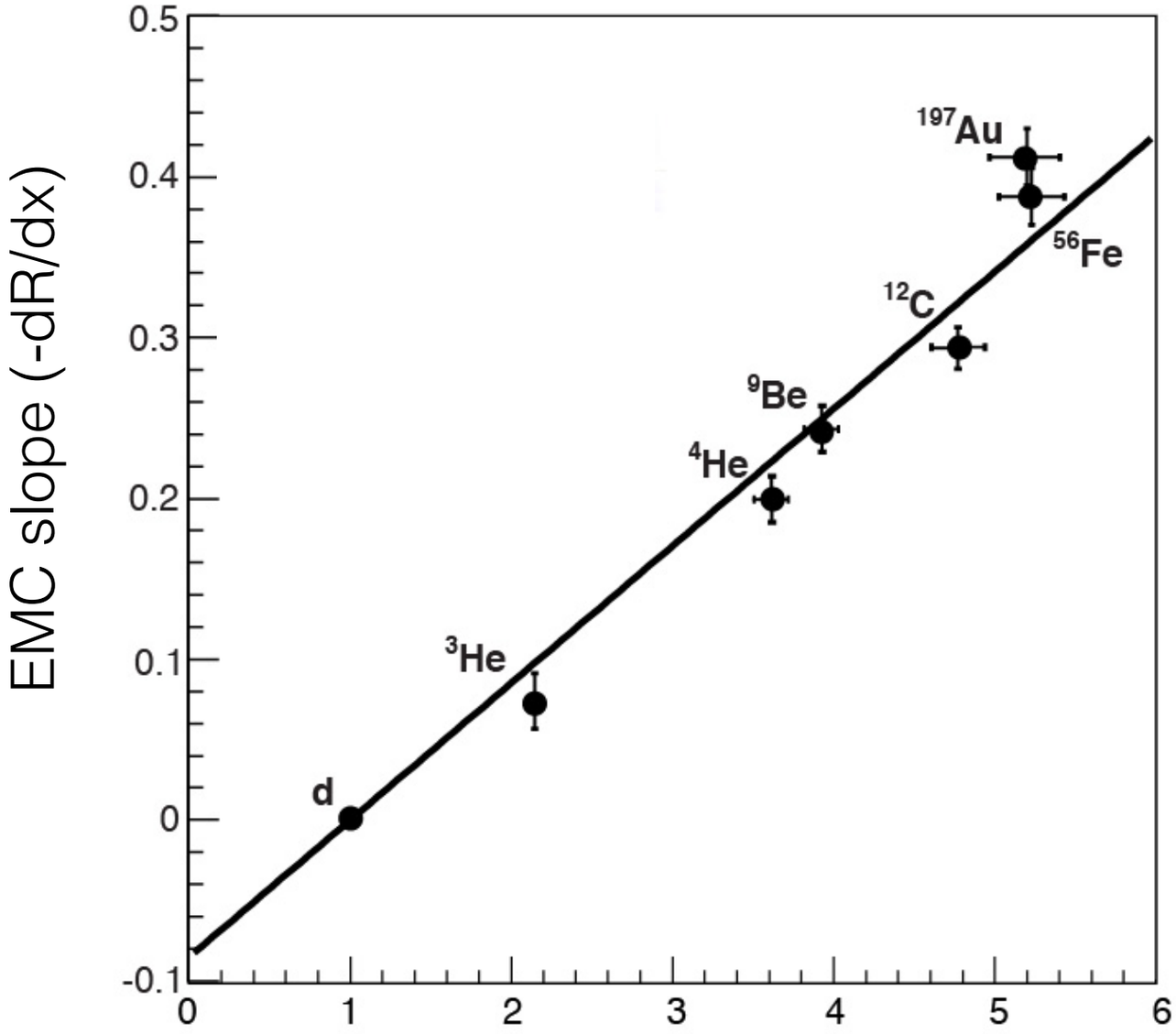
Florian Hauenstein,

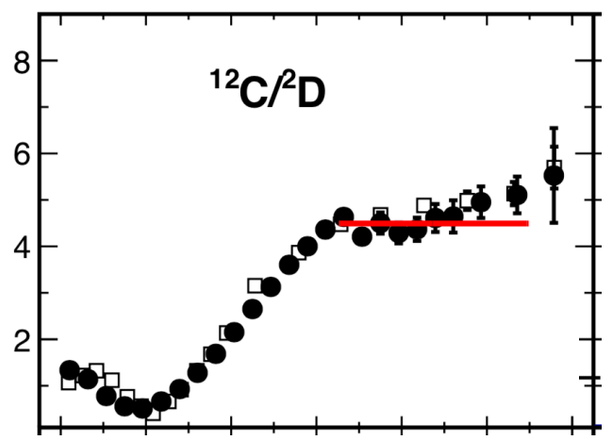
GHP 2023,

04/13/22

EMC and SRC Correlation







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

Probe EMC-SRC Correlation with Tagged DIS Measurements

- EMC-SRC: Large modification for SRC nucleons

- Determine modification with DIS scattering on nucleons with high momentum

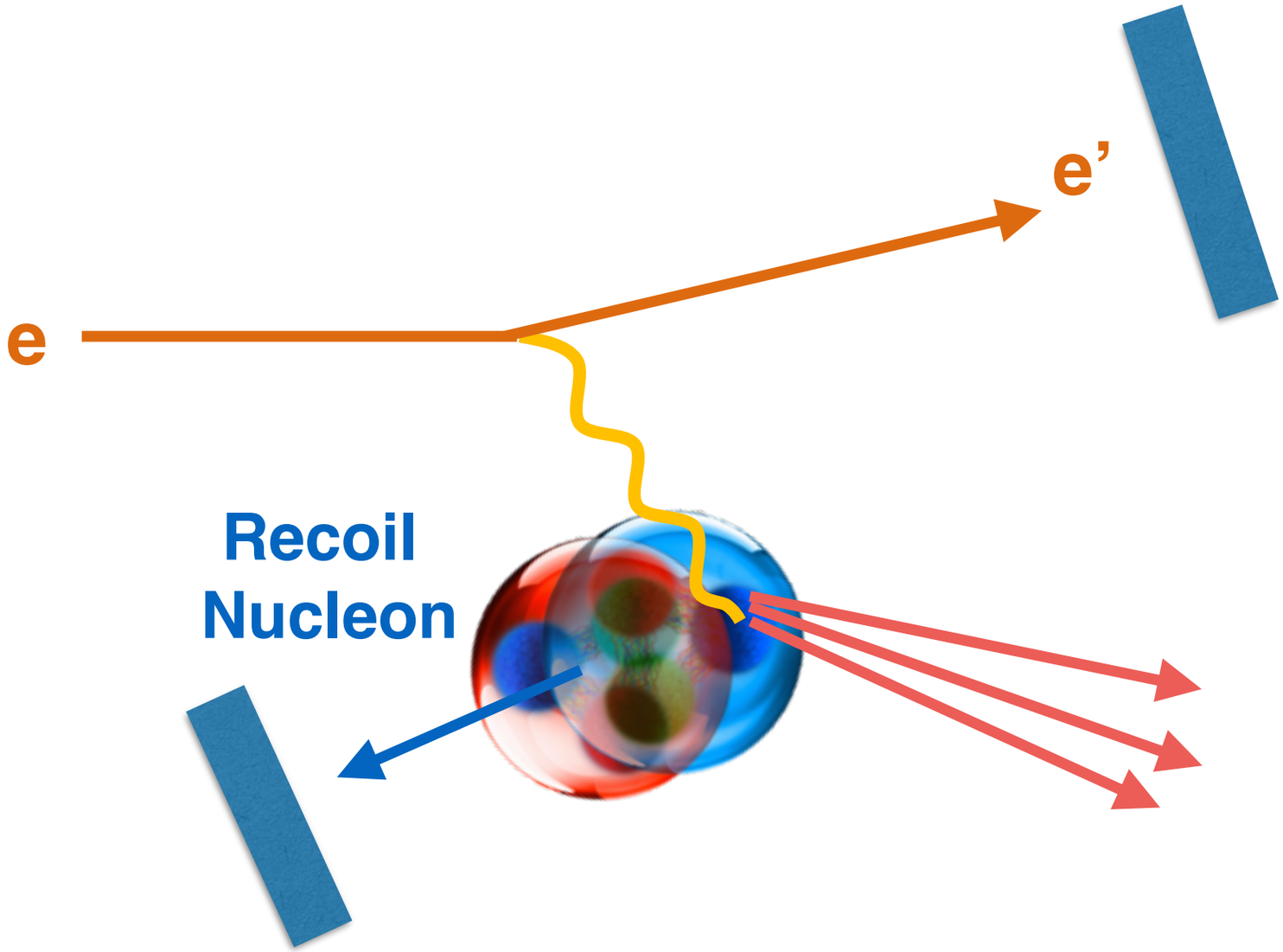
- „Tag“ SRC nucleon not part of the DIS interaction to select initial state

—> New observable

—> Modification dependence on α

  - strong —> SRCs
  - weak —> MF

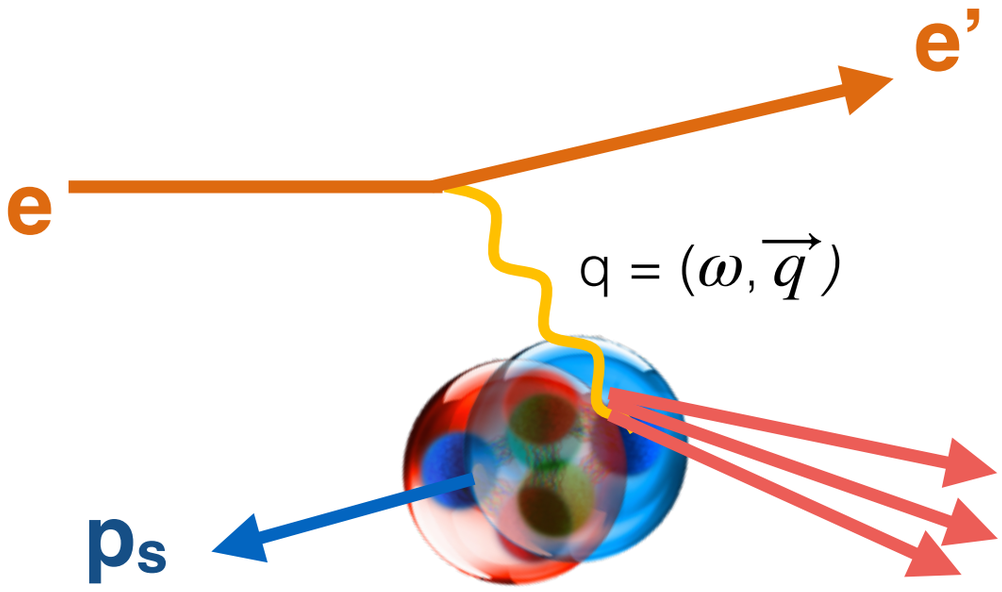
Simplest Case: Tagged DIS with Deuterium



Electrons (DIS)

Fragments of struck nucleon

Tagging Kinematics 101



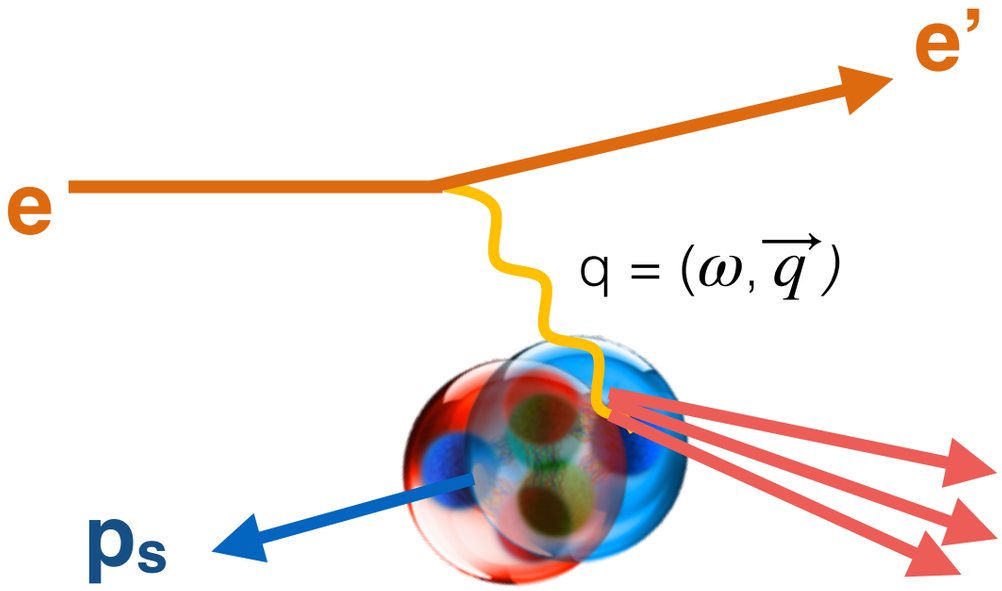
$$Q^2 = -q^2 = |\vec{q}|^2 - \omega^2$$

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

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

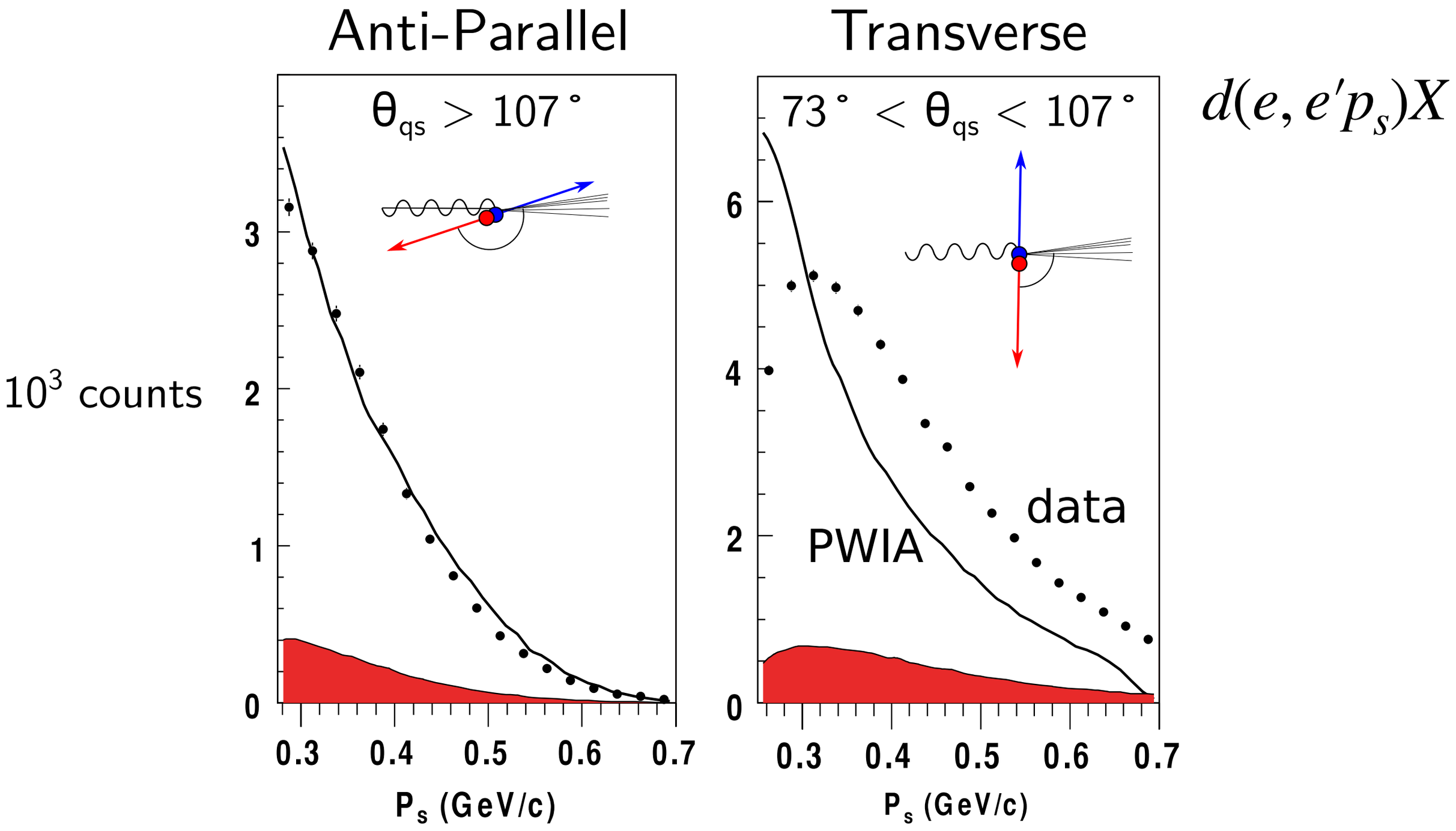
$$\approx \frac{\text{bound nucleon } F_2^*}{\text{free nucleon } F_2}$$

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)



Minimize Final-State-Interaction in Tagged DIS

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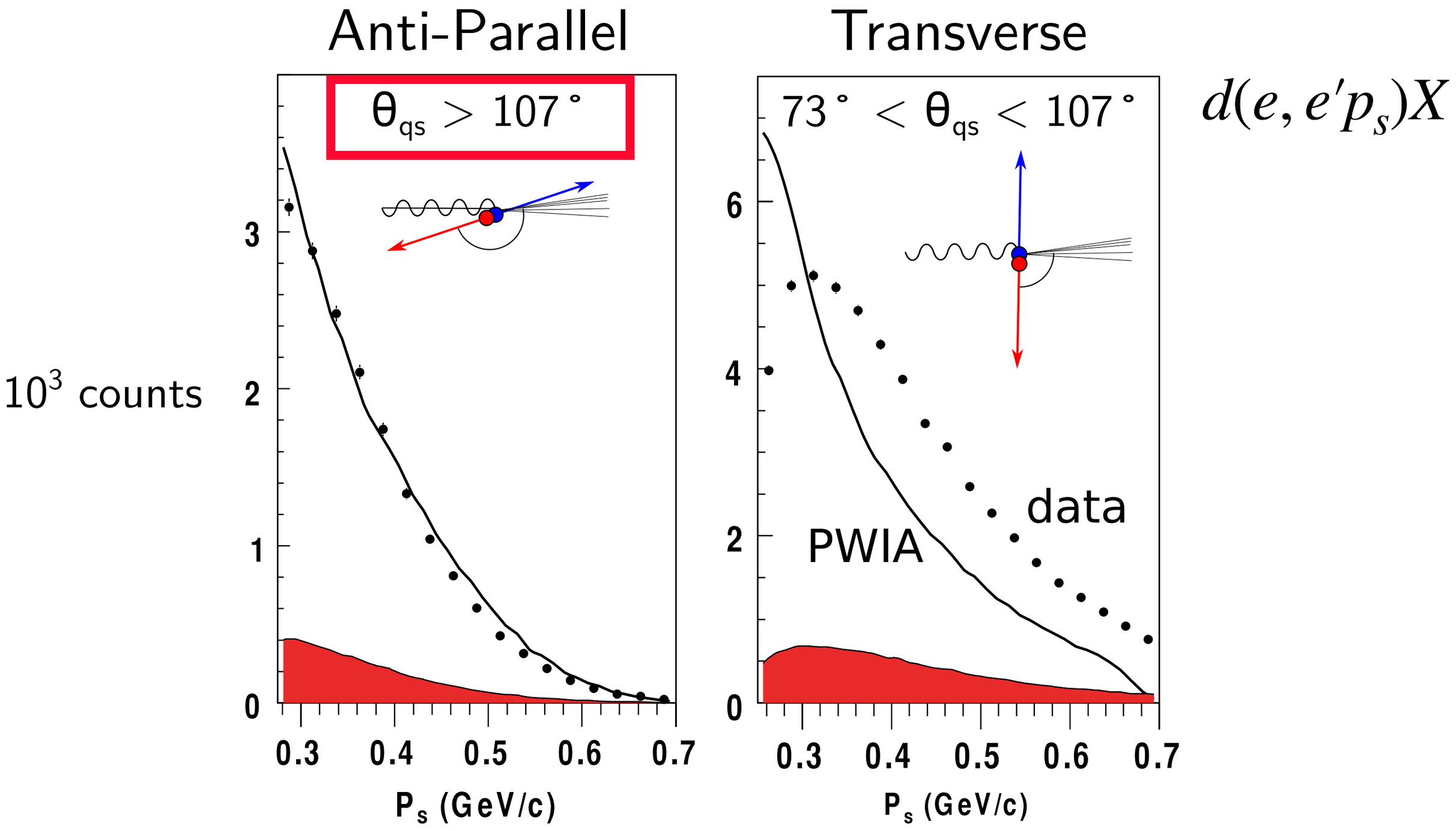
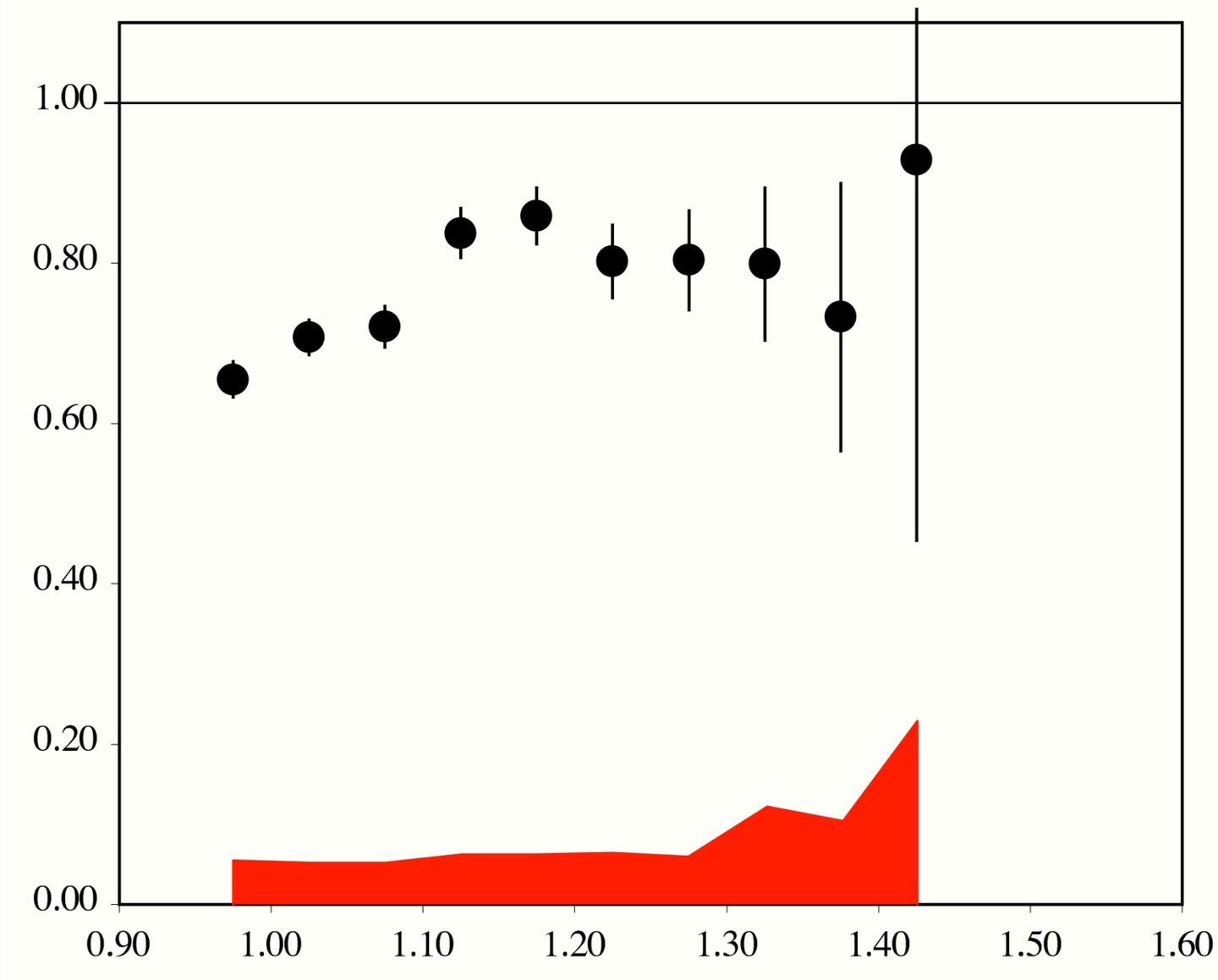


Previous Results $d(e, e'p_s)X$

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



Non ideal kinematics

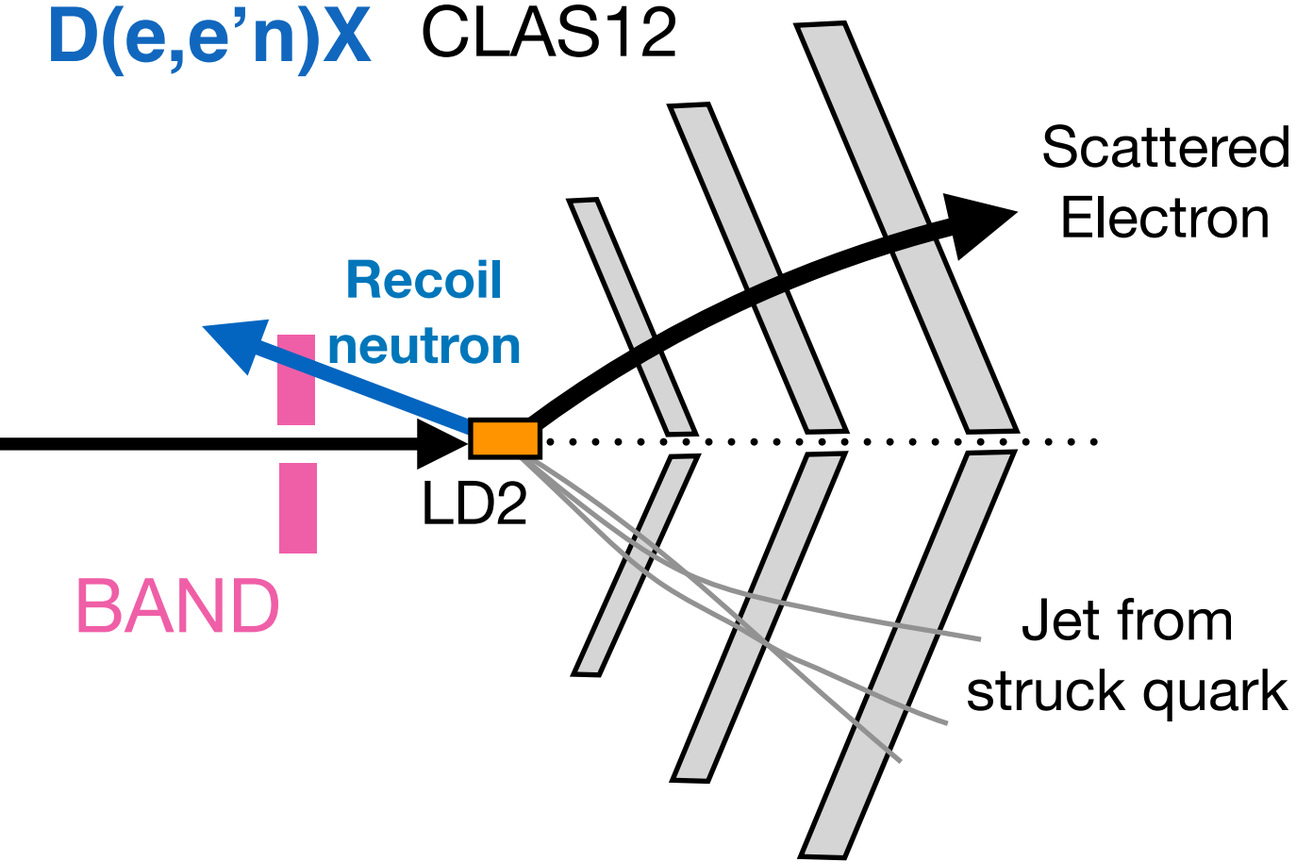
- Not so high in Q^2
- Low α_S has $\theta_{nq} \sim 90\,\mathrm{deg}$
- $p_T = [0.25 - 0.35]$ [GeV/c]

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



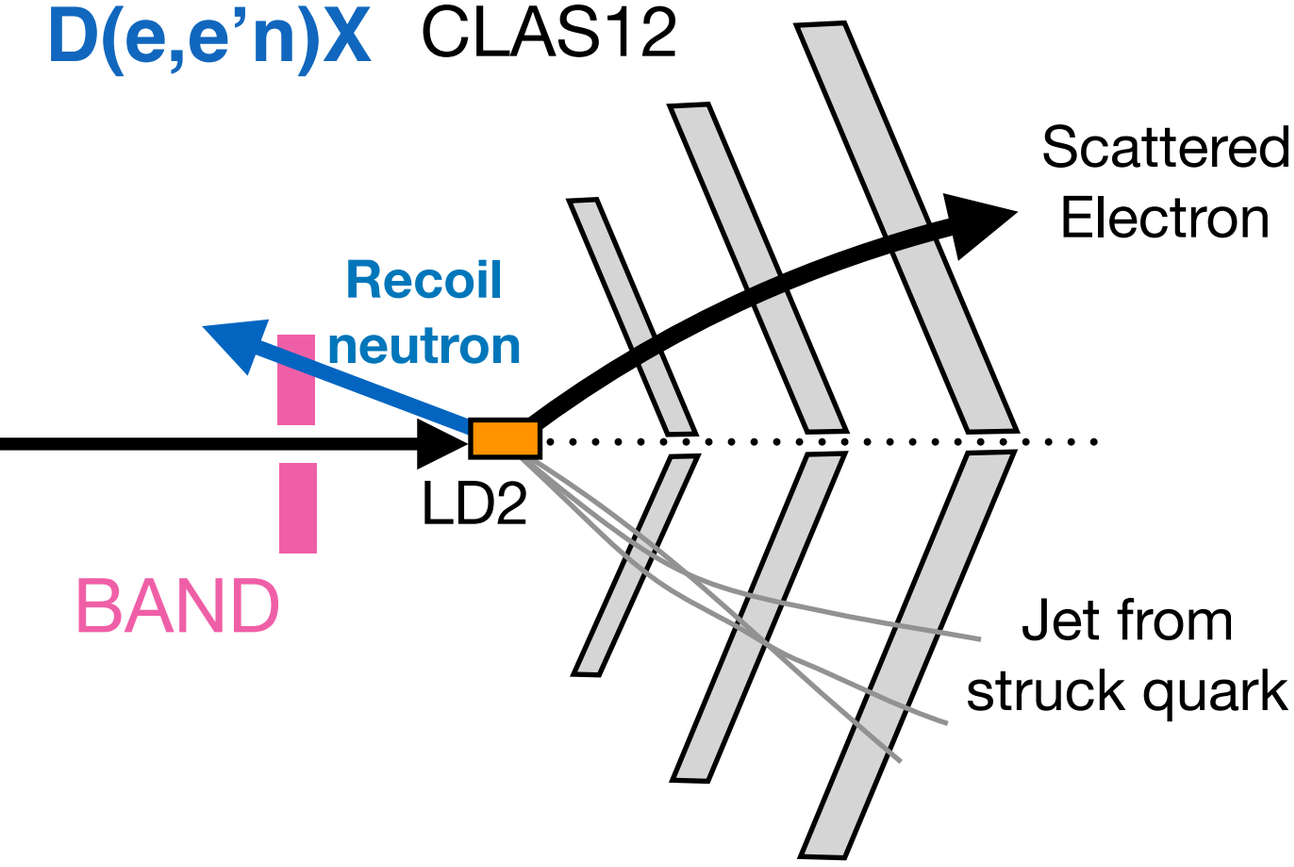
- Run Group B
- Analysis under review

Tagged Experiments at JLab

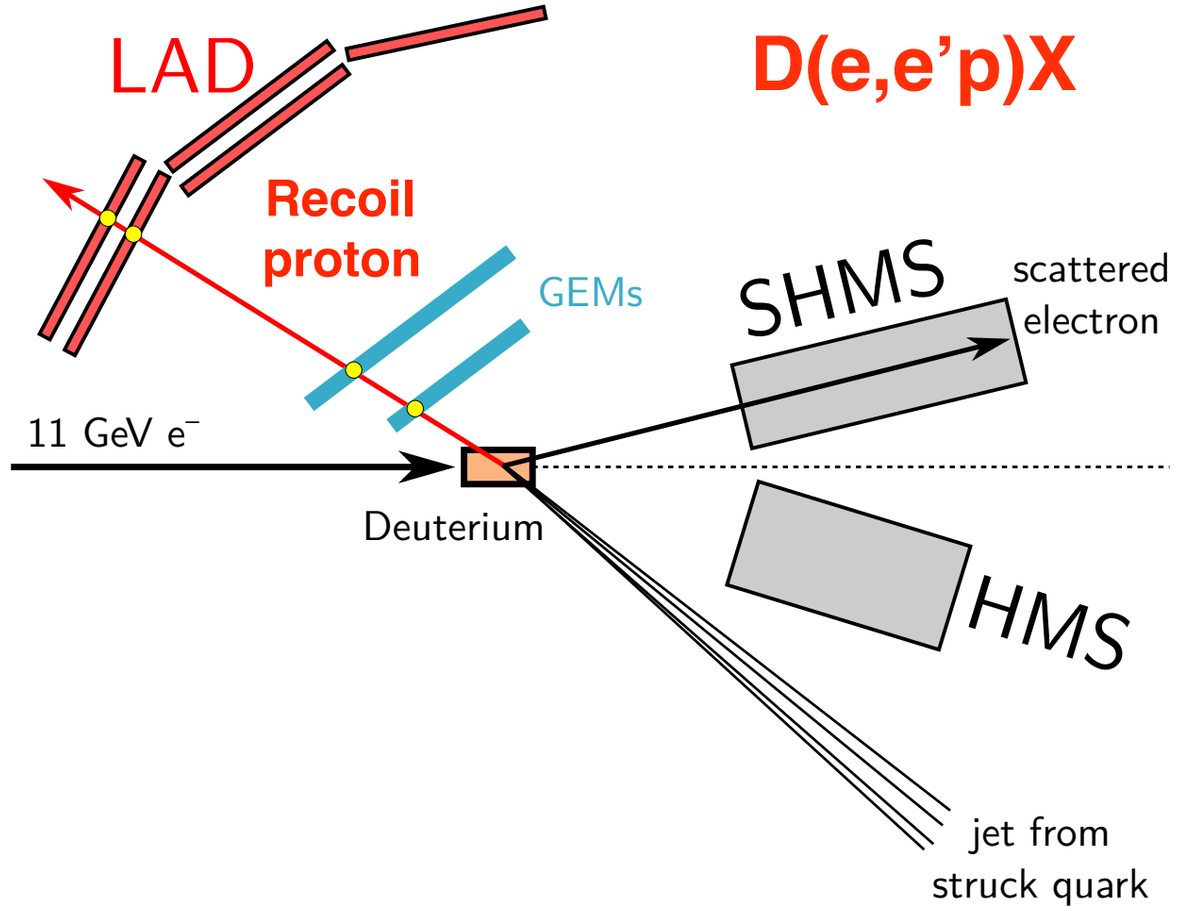
Hall B:
CLAS 12 + Backward Angle Neutron Detector (BAND)

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

D(e,e'n)X CLAS12



D(e,e'p)X



- Run Group B
- Analysis under review

- Experiment ready
- Run in 2024!

Tagged Experiments at JLab

Hall B:
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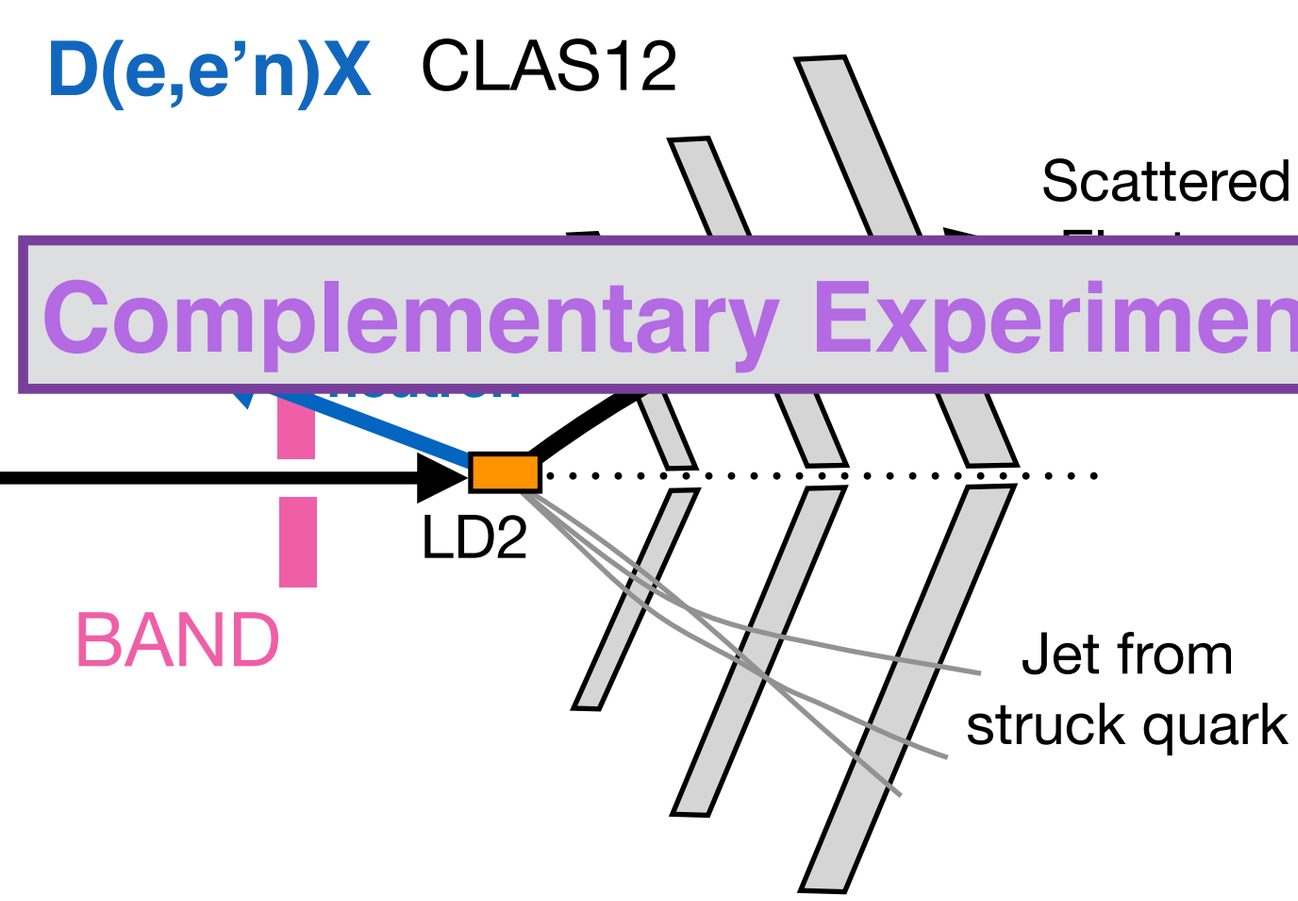
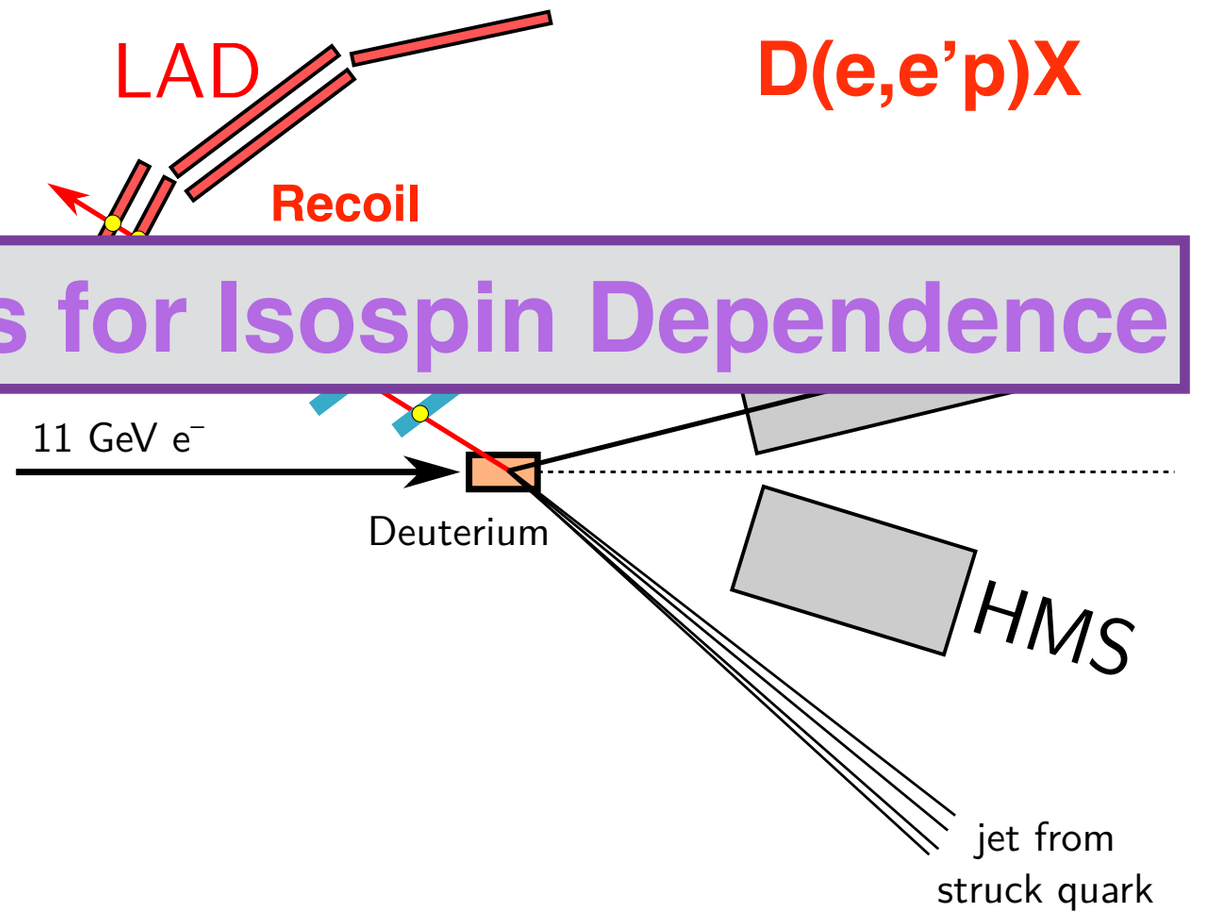


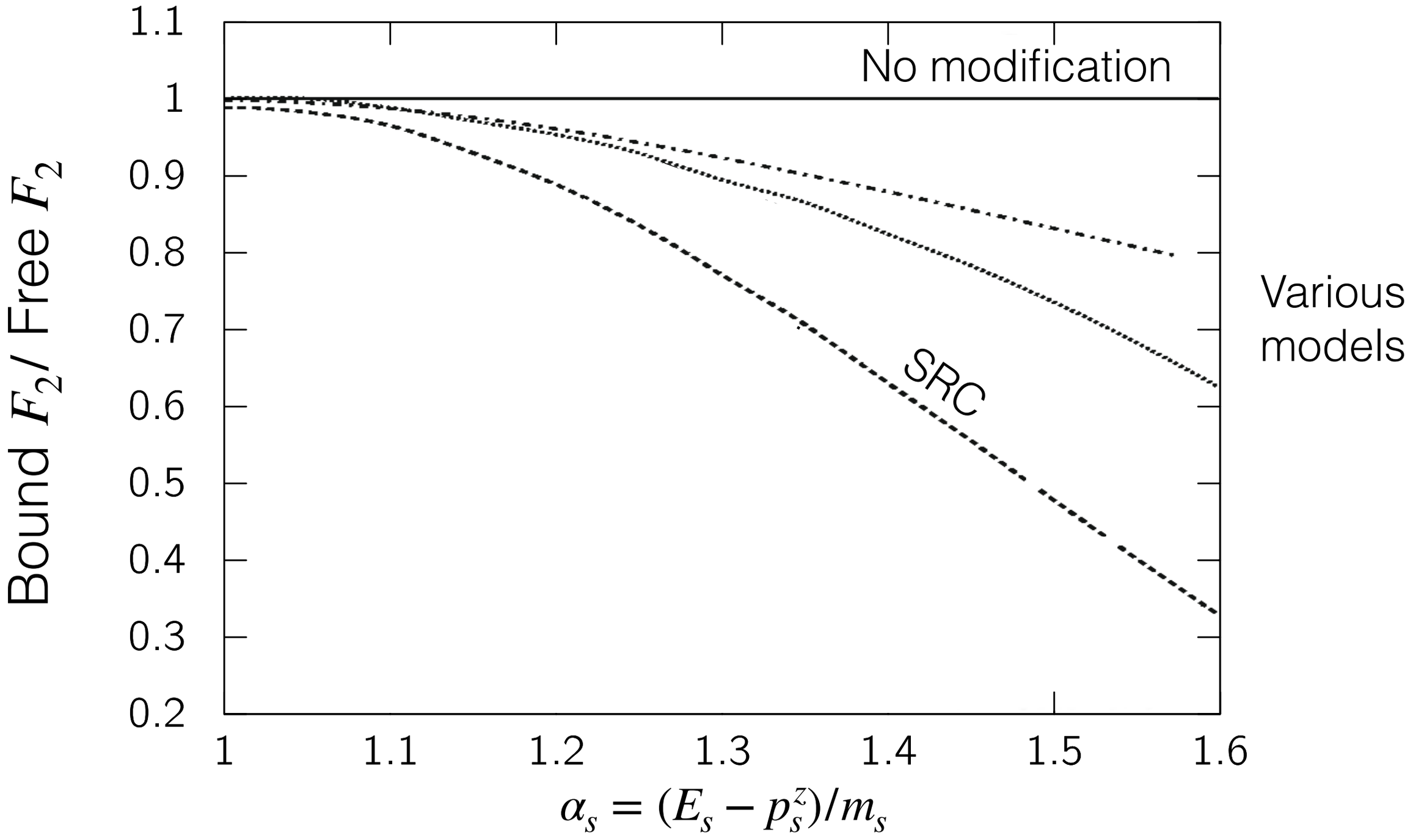


Complementary Experiments for Isospin Dependence

- Run Group B
- Analysis under review

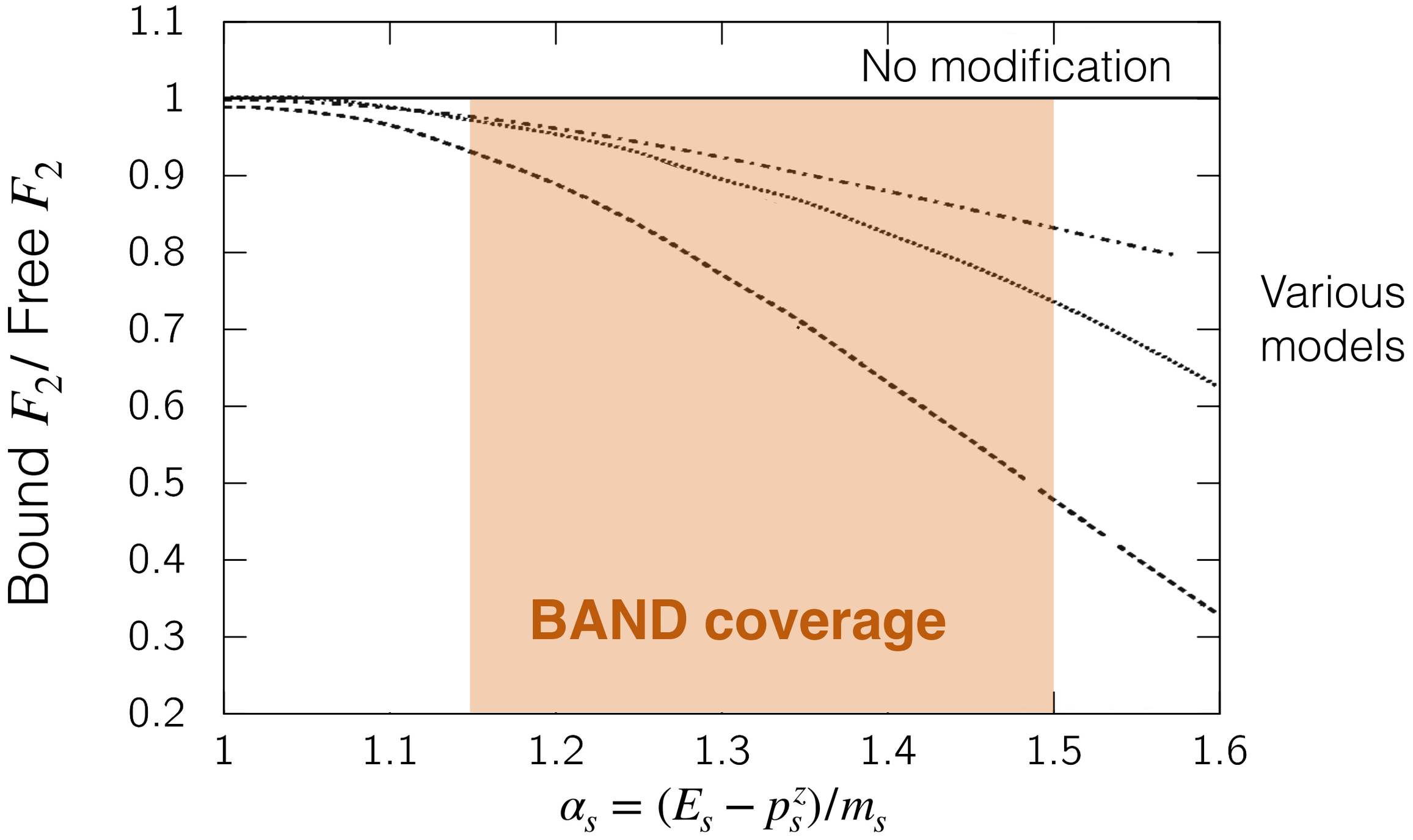
- Experiment ready
- Run in 2024!

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



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

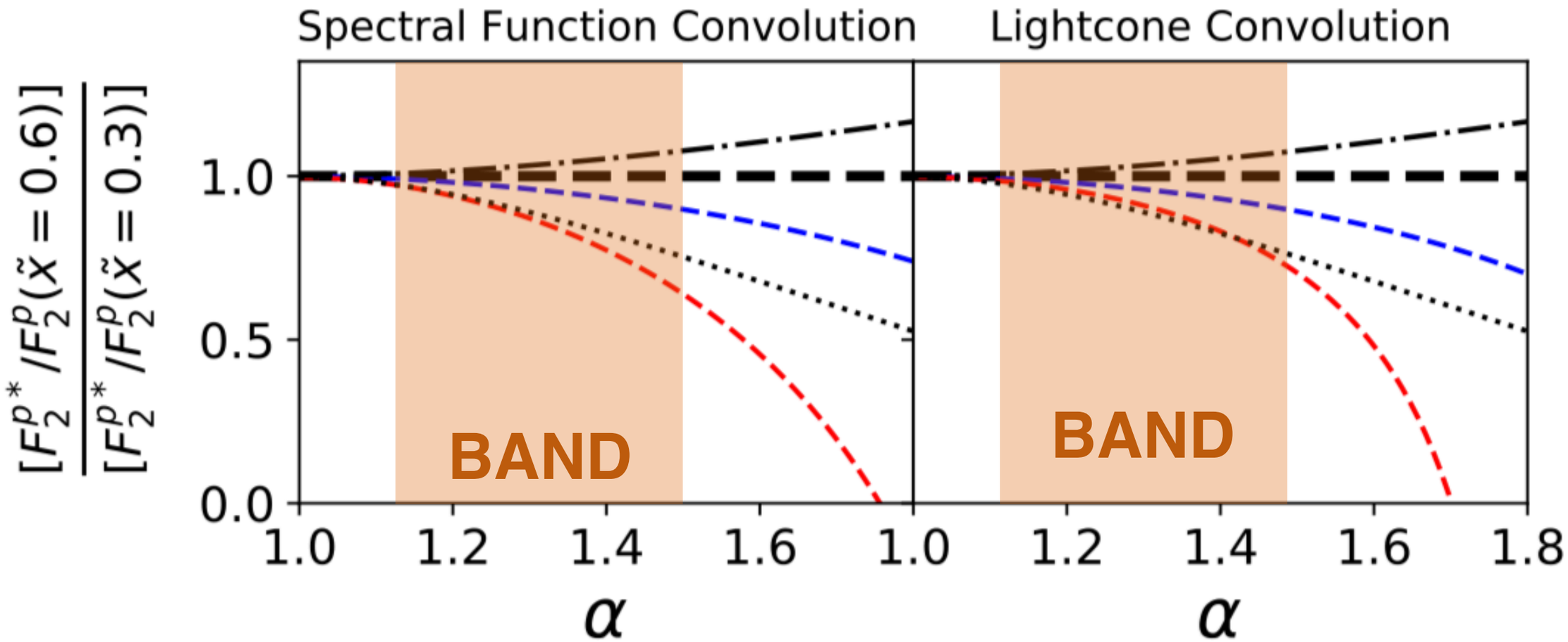
d(e,e'N)X - Expected Results



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

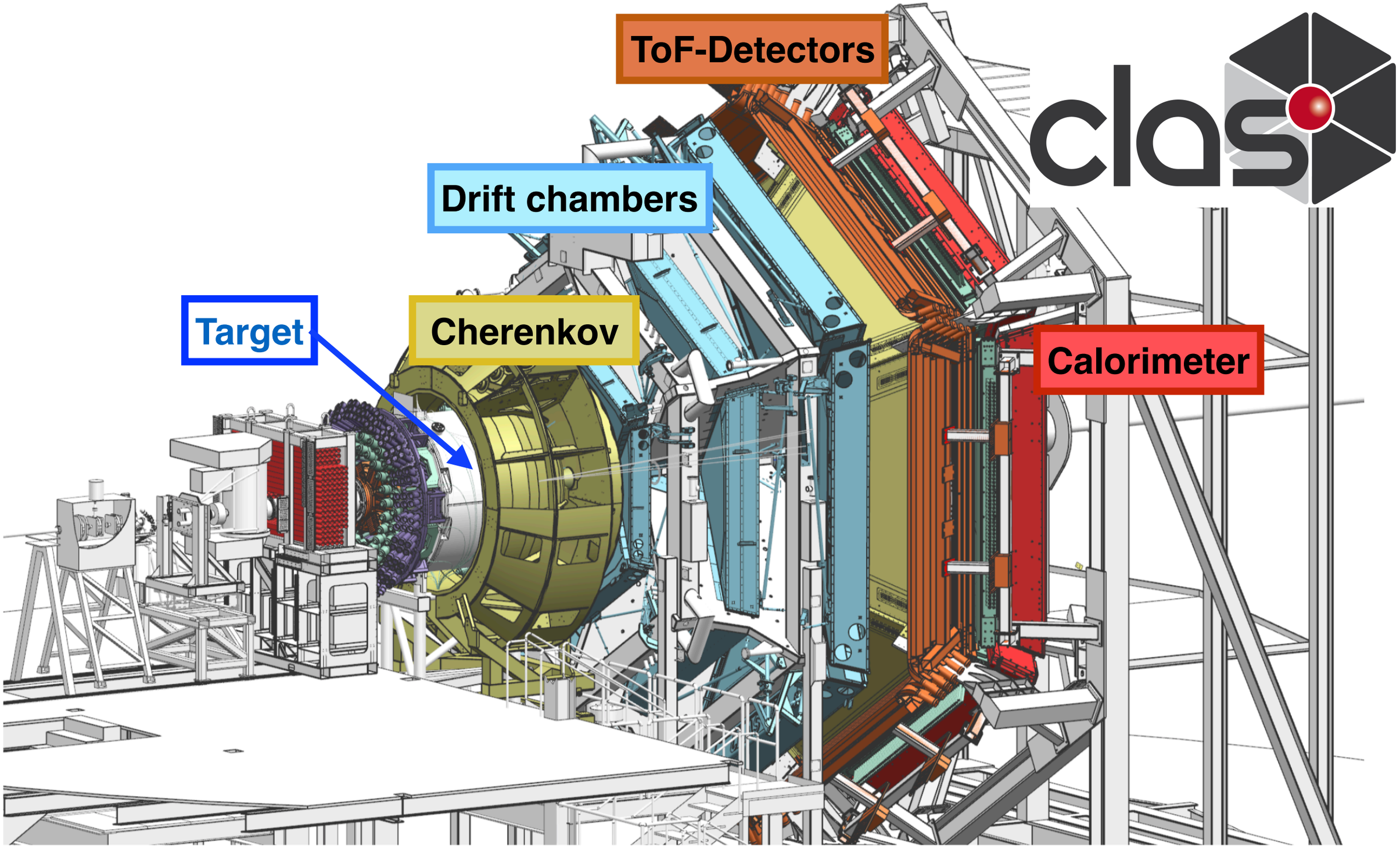
Tagged Predictions for Different Models

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



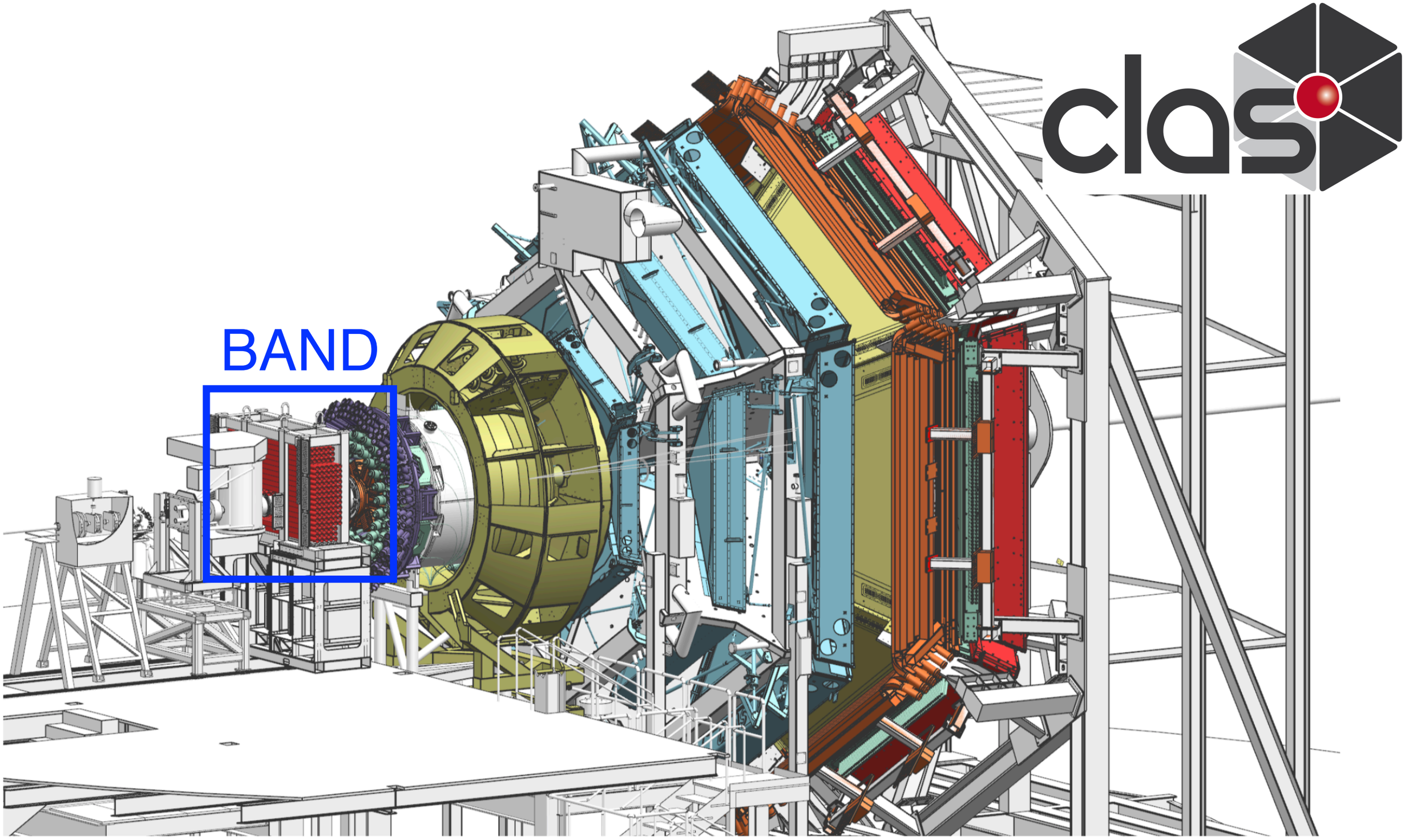
Predictions from convolution model fits to data up to A=3

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)

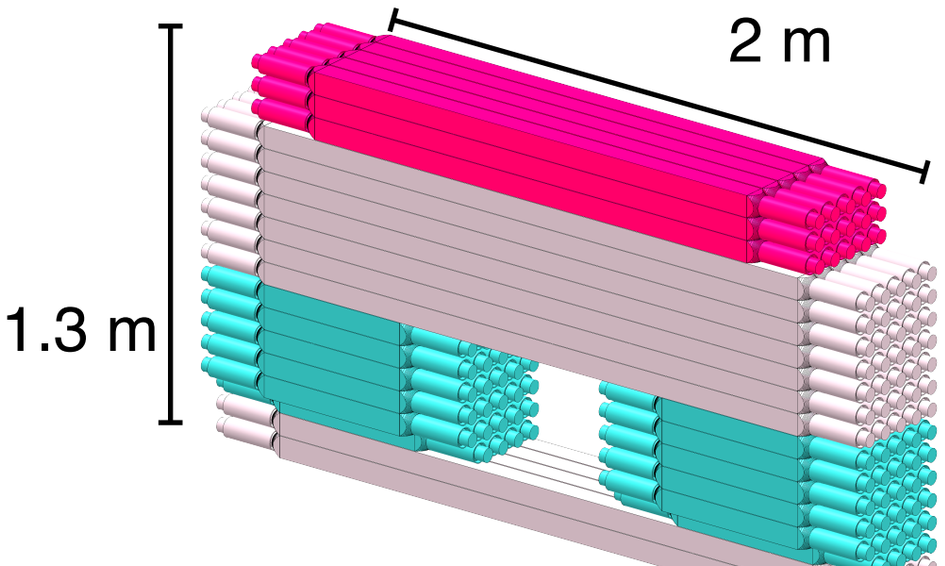
- 140 scintillator bars
  - 5 layers (36cm total thickness)
  - veto layer (1cm thick)
  - time resolution < 250 ps

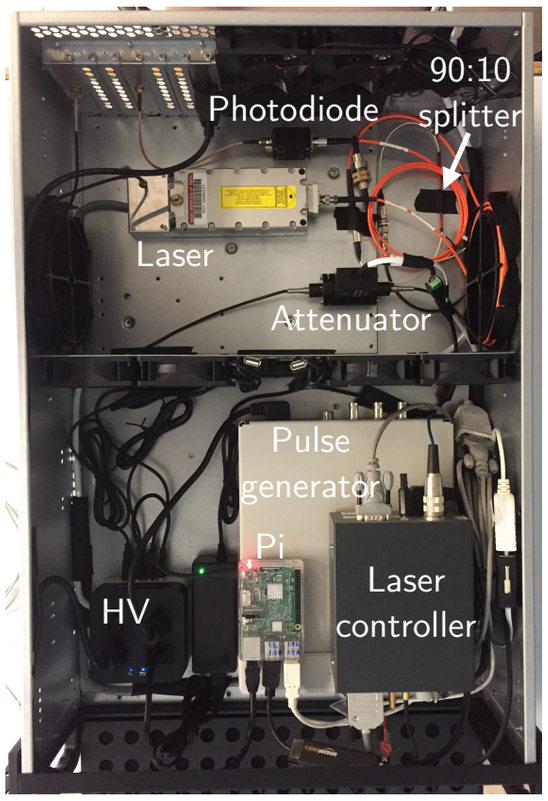
- 3 meters upstream of target

- coverage in θ ~ 155-176°

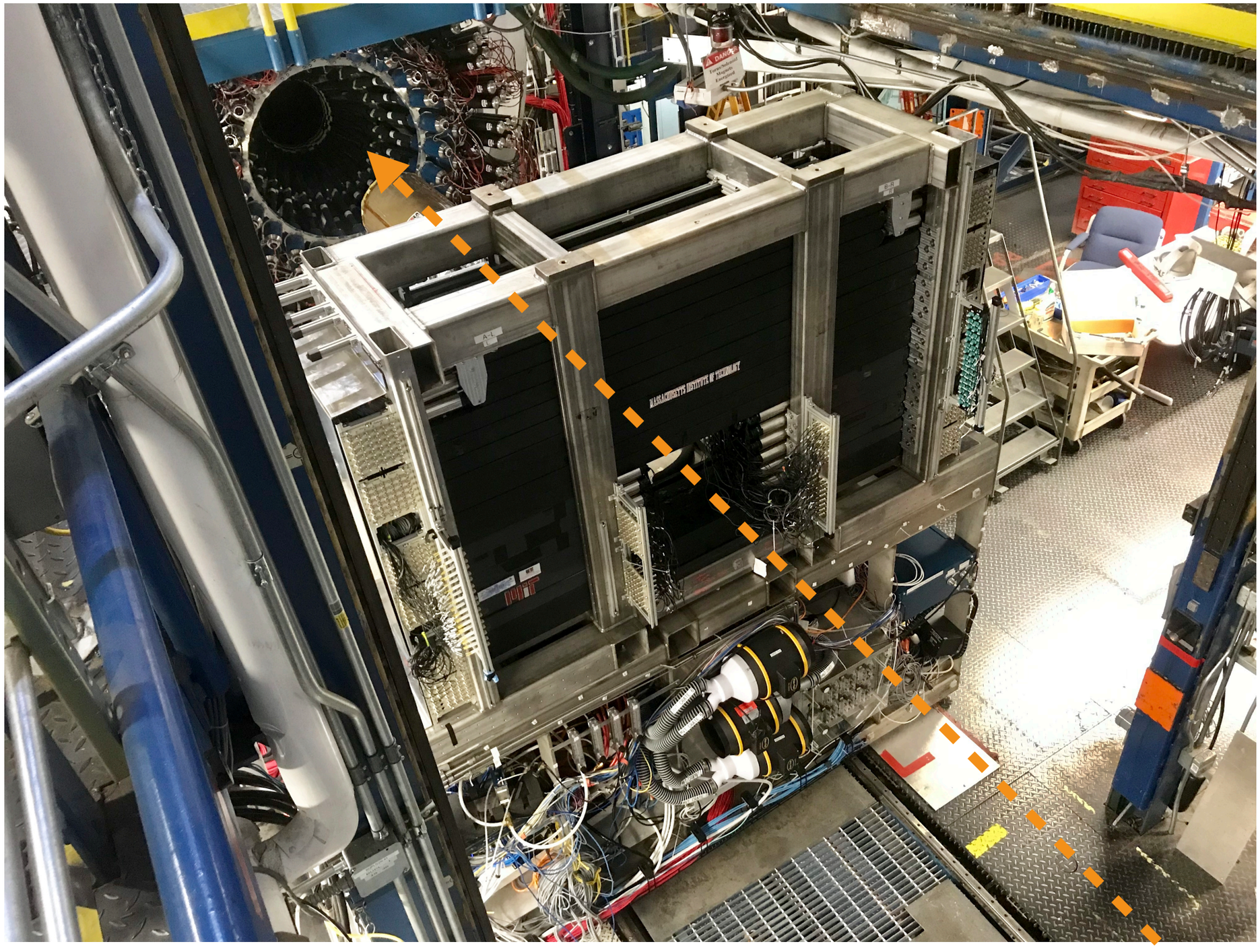
- Lead wall (downstream)

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



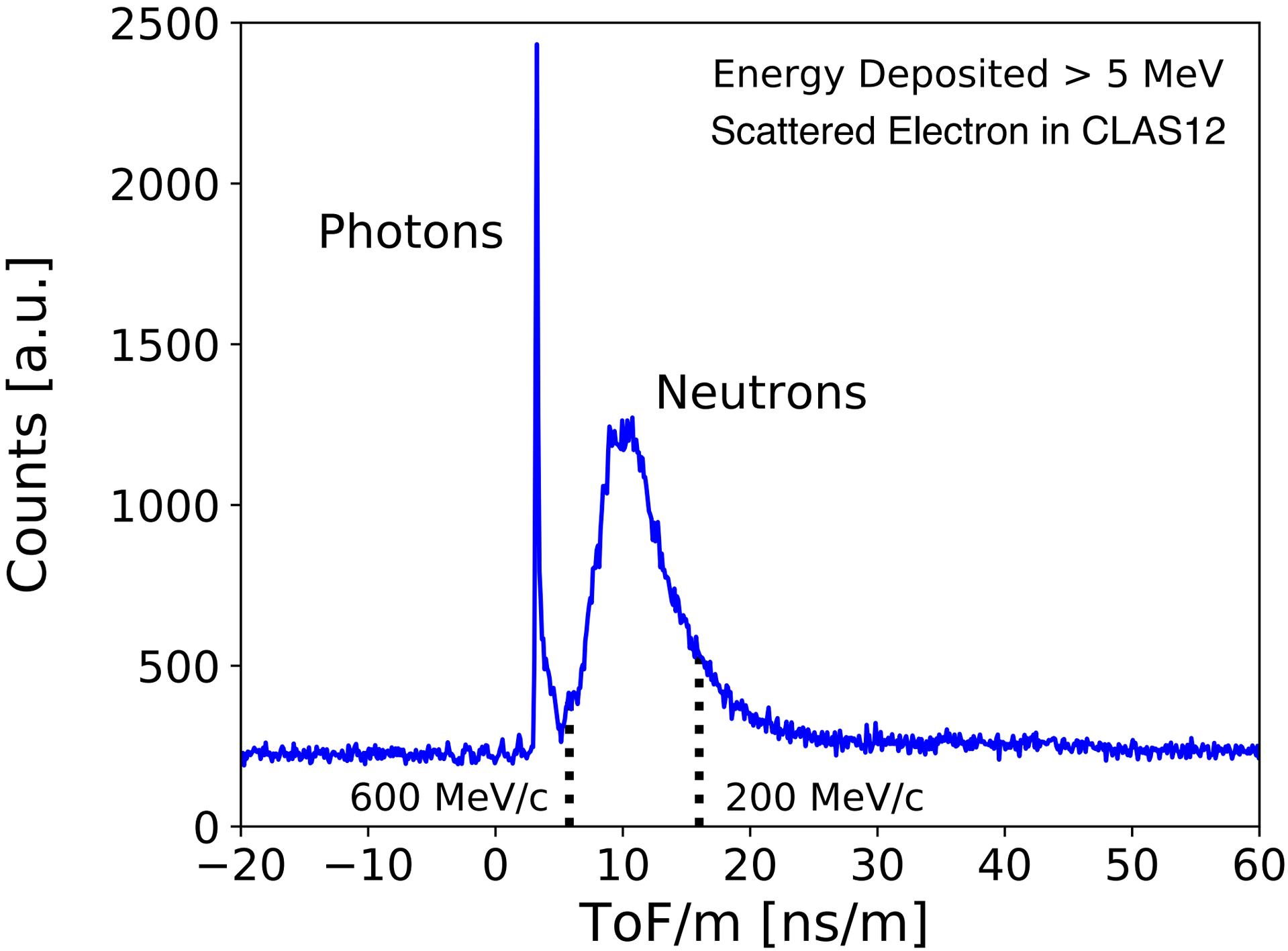


BAND in HallB



Clear Signal of Neutrons in BAND

Segarra et al., NIM A978 (2020)



Data and Analysis Overview

- CLAS12: Run Group B data
  - beam energies: 10.2, 10.4, 10.6 and 4.2 GeV
  - liquid deuterium target

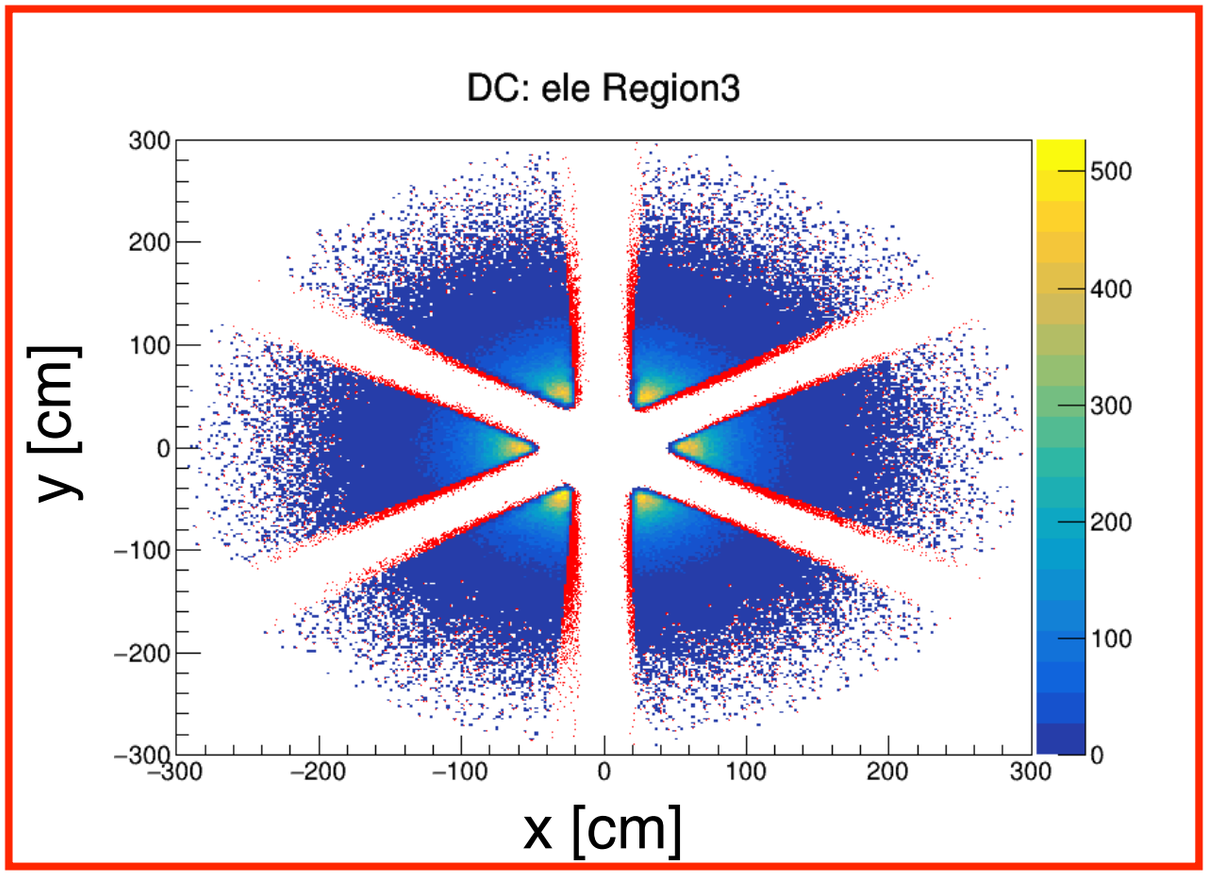
- Event selection
  - Electrons in CLAS12
  - Neutrons in BAND
  - Background subtraction

- Inclusive DIS d(e,e’) analysis

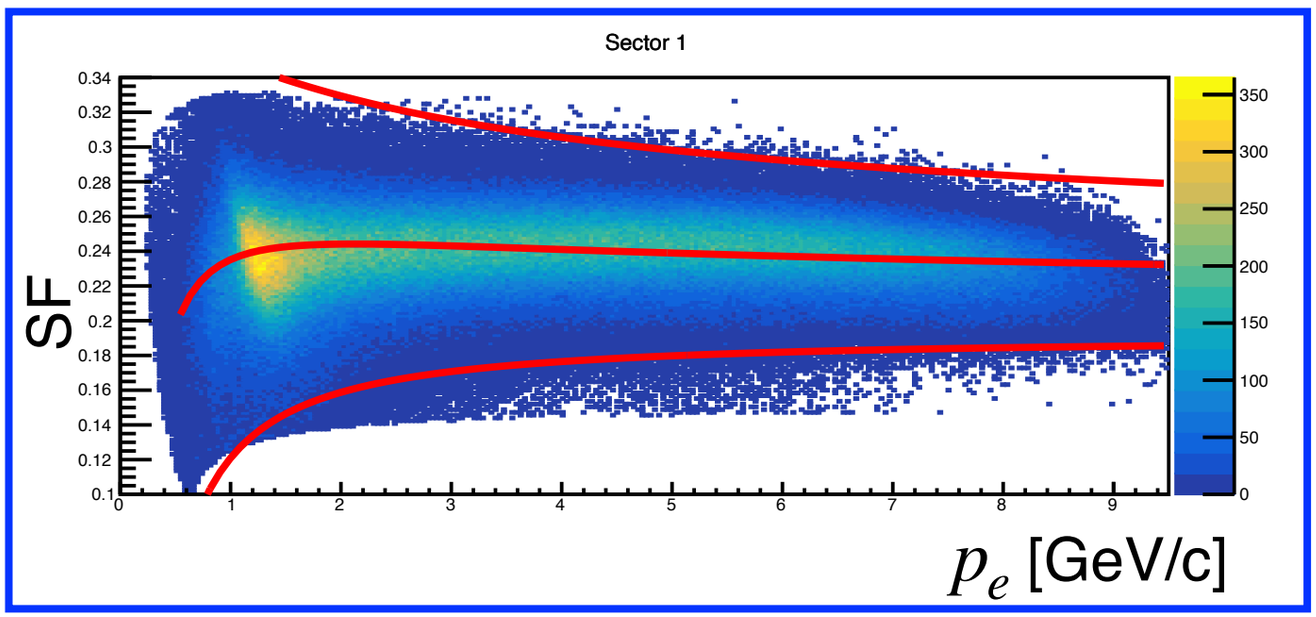
- Quasi-elastic d(e,e’pn) and d(e,e’p)n analysis

- Tagged DIS analysis

Analysis: Electron Selection

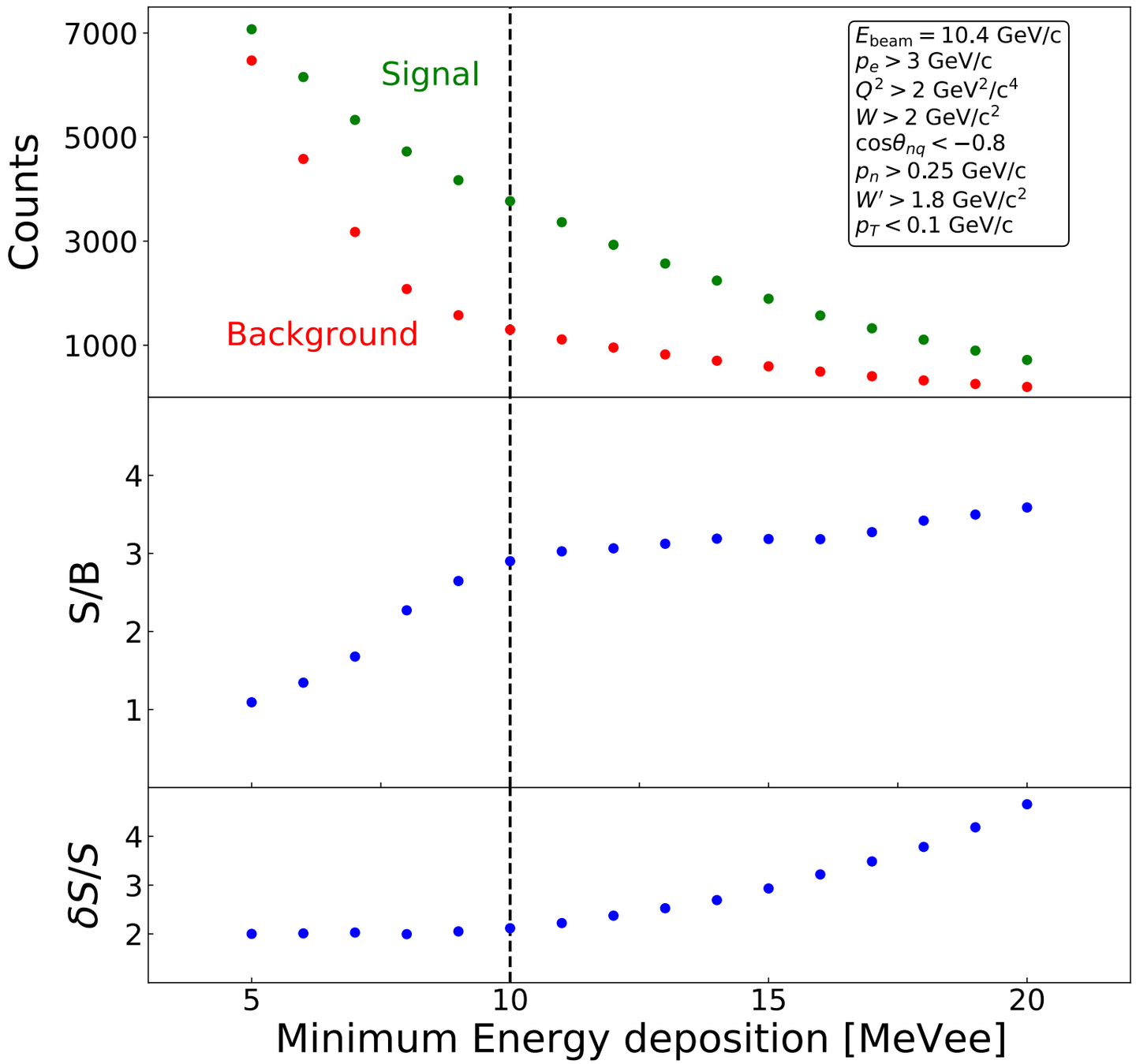


- Charge/PID requirement
- Driftchamber fiducial cuts
- Calorimeter fiducial cuts
- Calorimeter sampling fraction cuts



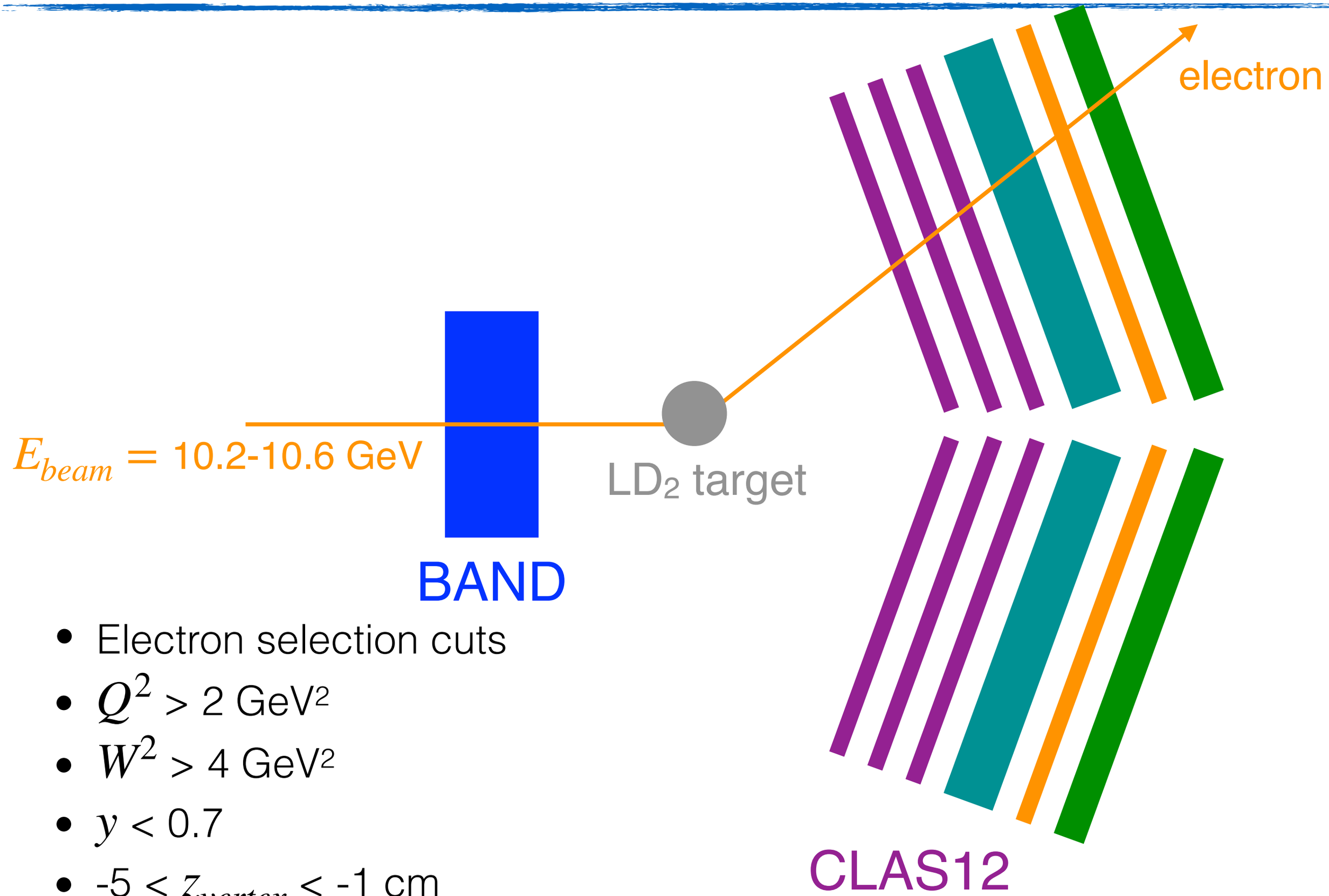
Neutron Selection: E_{dep} and Fiducials

- E_{dep} > 10 MeVee



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

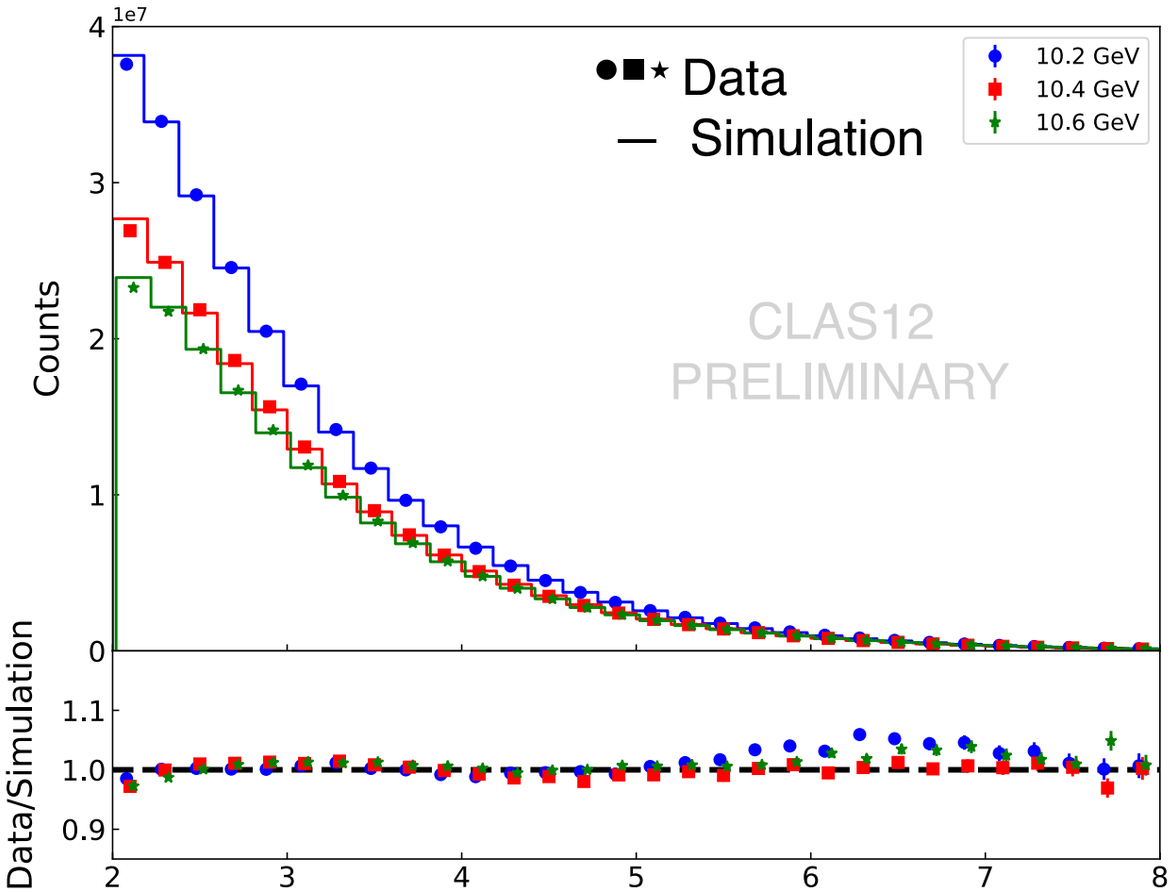
Inclusive DIS *d(e,e')X*



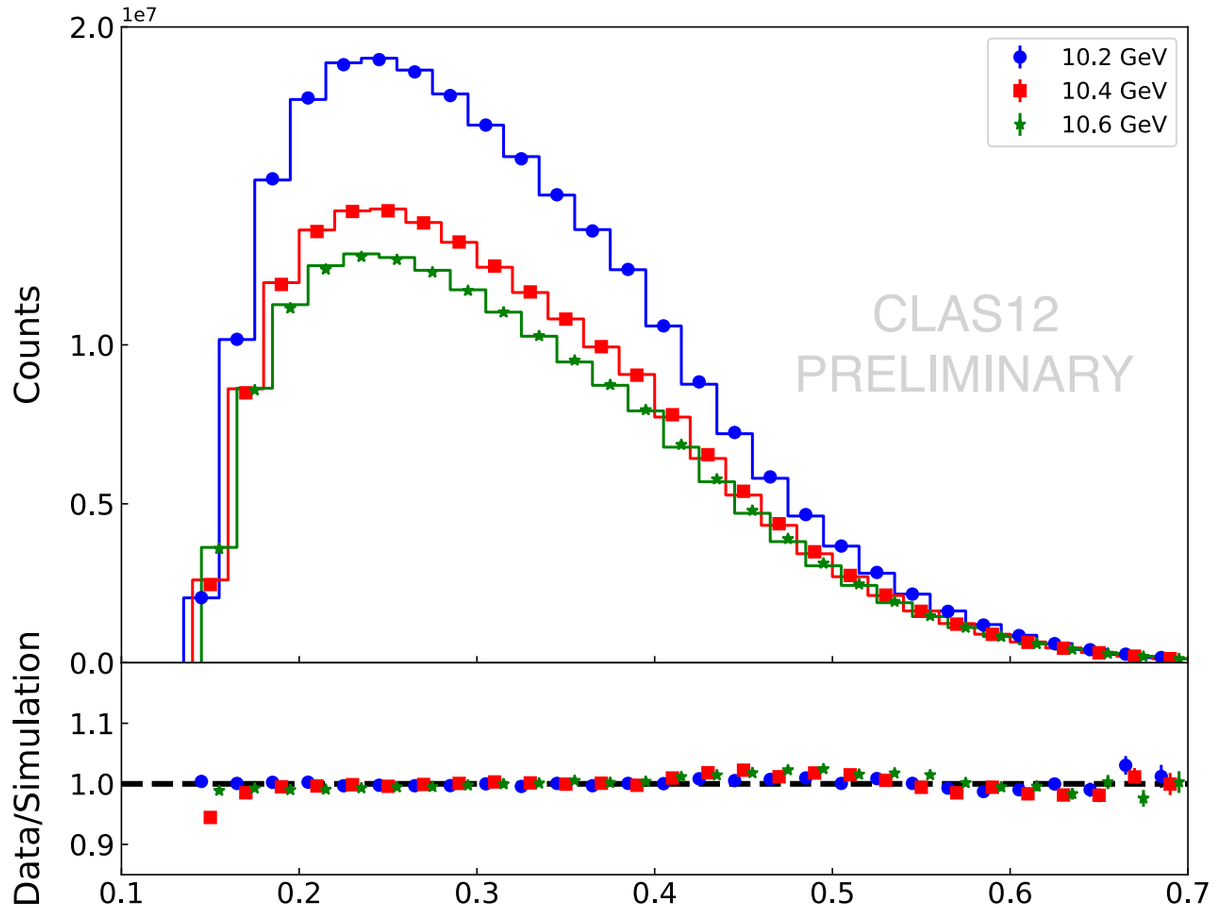
- Electron selection cuts
- Q^2 > 2 GeV²
- W^2 > 4 GeV²
- y < 0.7
- -5 < z_{vertex} < -1 cm

Inclusive Data - MC comparisons

Integral normalized



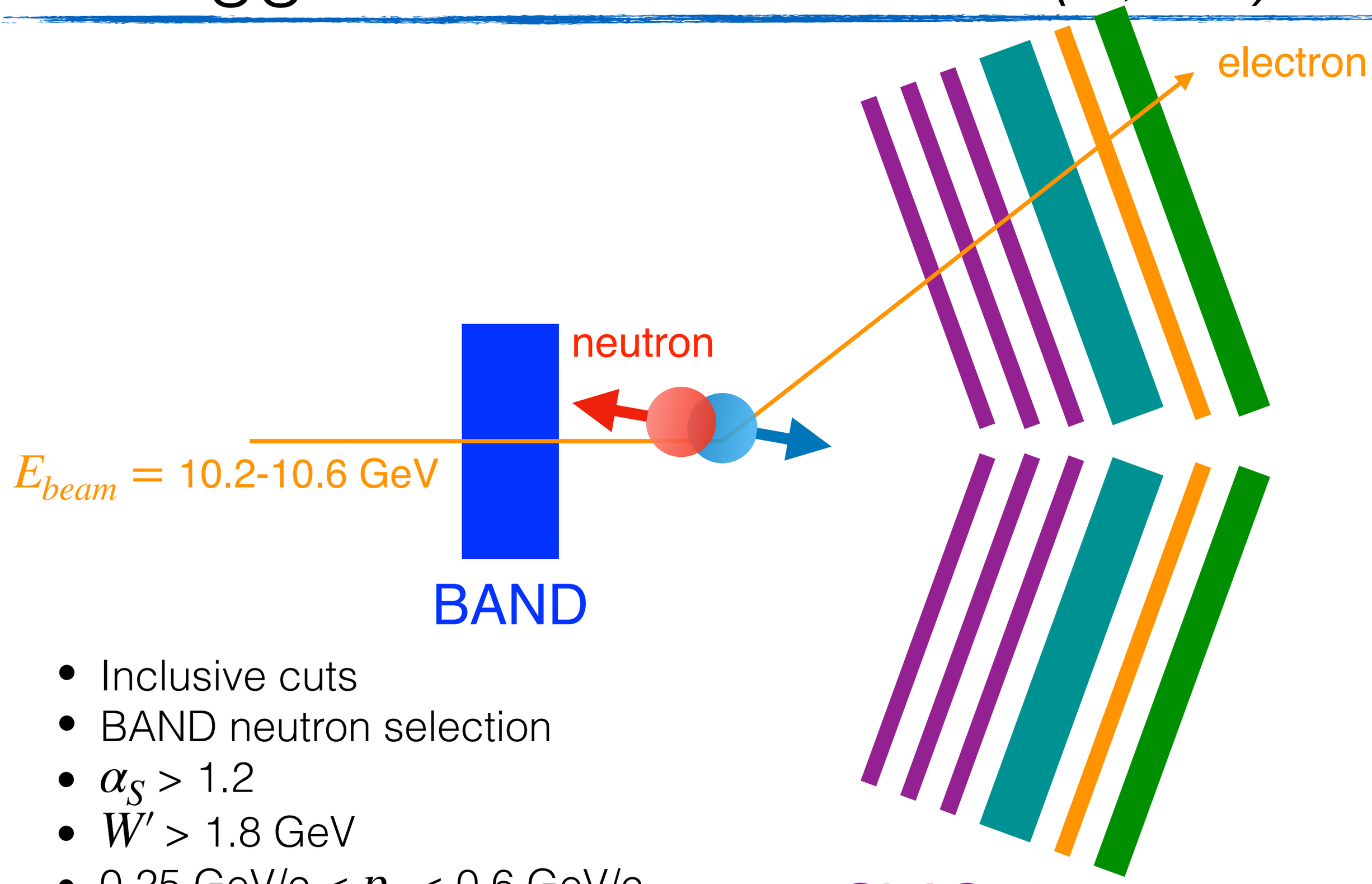
Q^2 (GeV²)



x_B

- Inclusive data well described by simulation

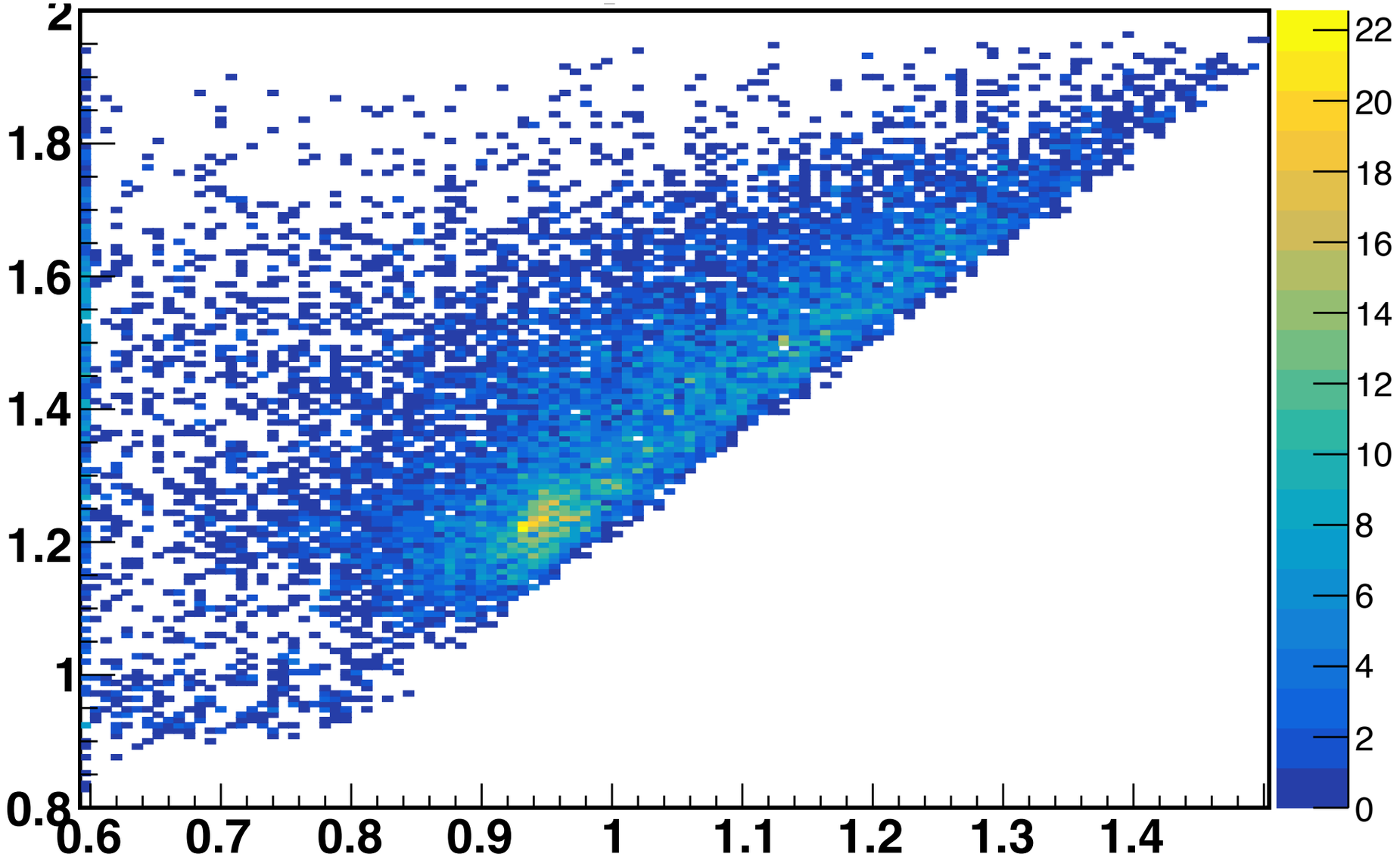
Tagged DIS with BAND *d(e,e'n)X*



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

W and W' in d(e,e'n)

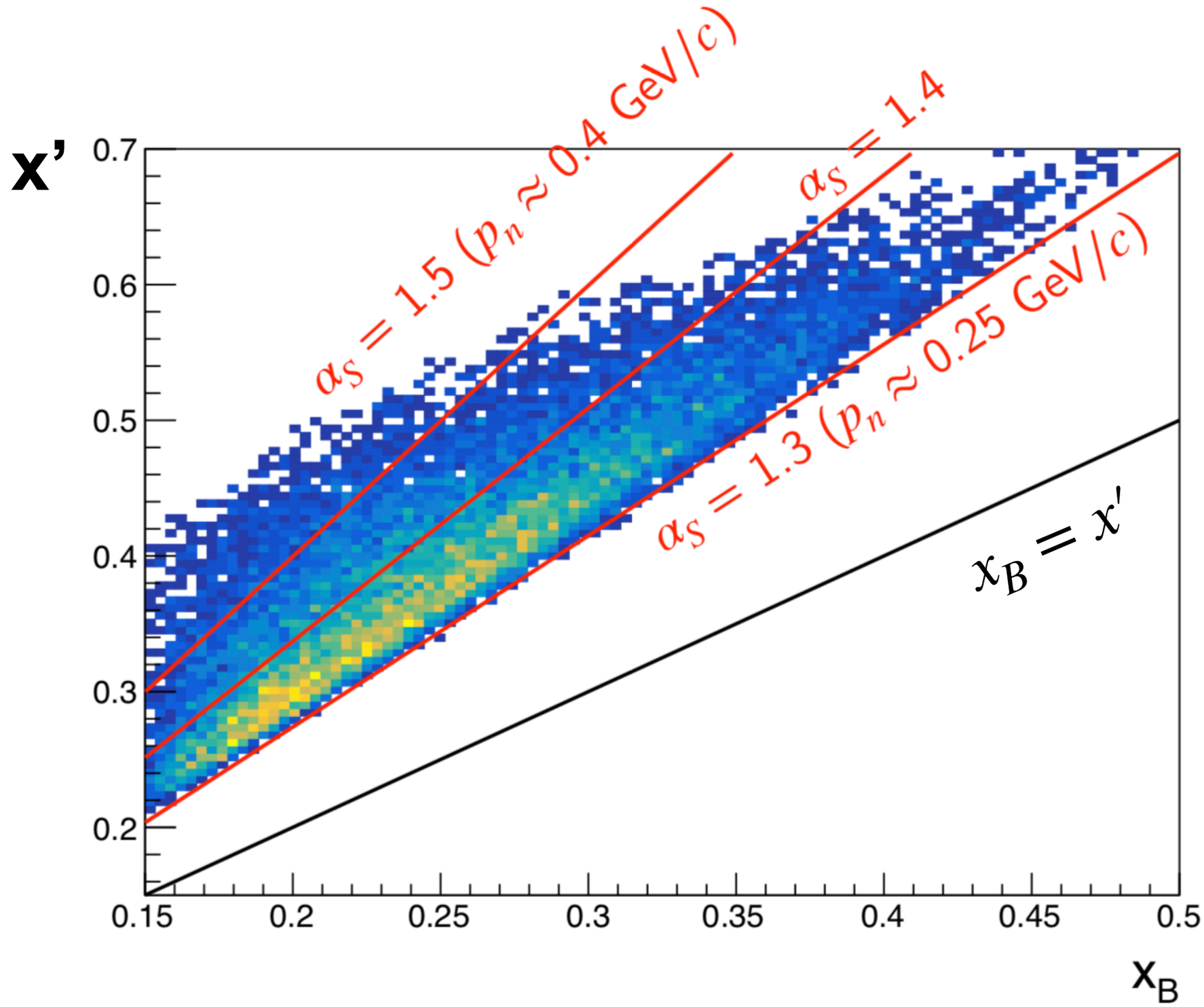
p_n > 350 MeV/c



courtesy Natalie Wright

- Background subtracted data with 2 GeV beam energy
- Visible QE peak in W'

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

Theoretical PWIA Model

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

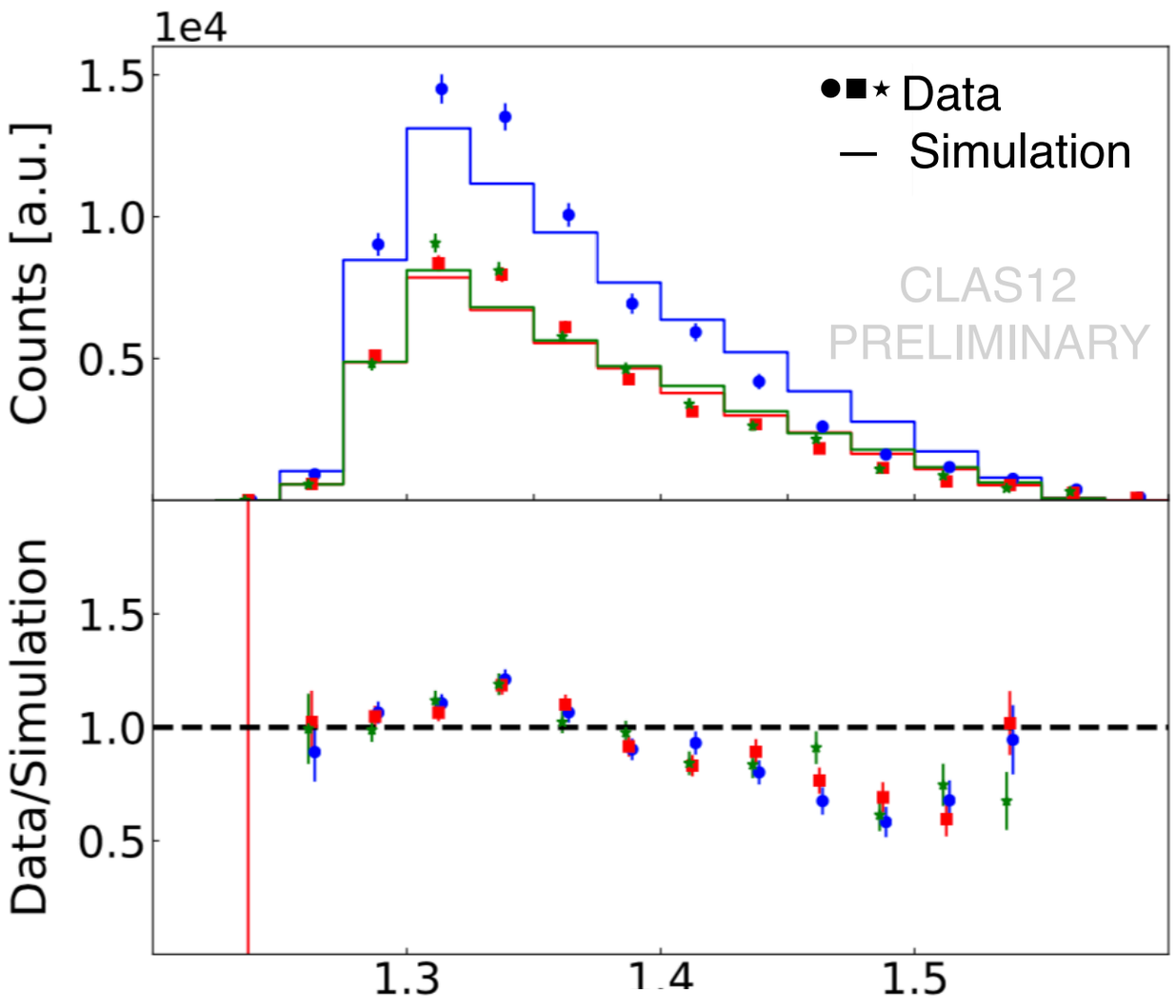
$$d\sigma[eD \rightarrow e' n_s X] = K \frac{2S(\alpha_s, p_{sT})}{2-\alpha_s} \times F_2$$

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

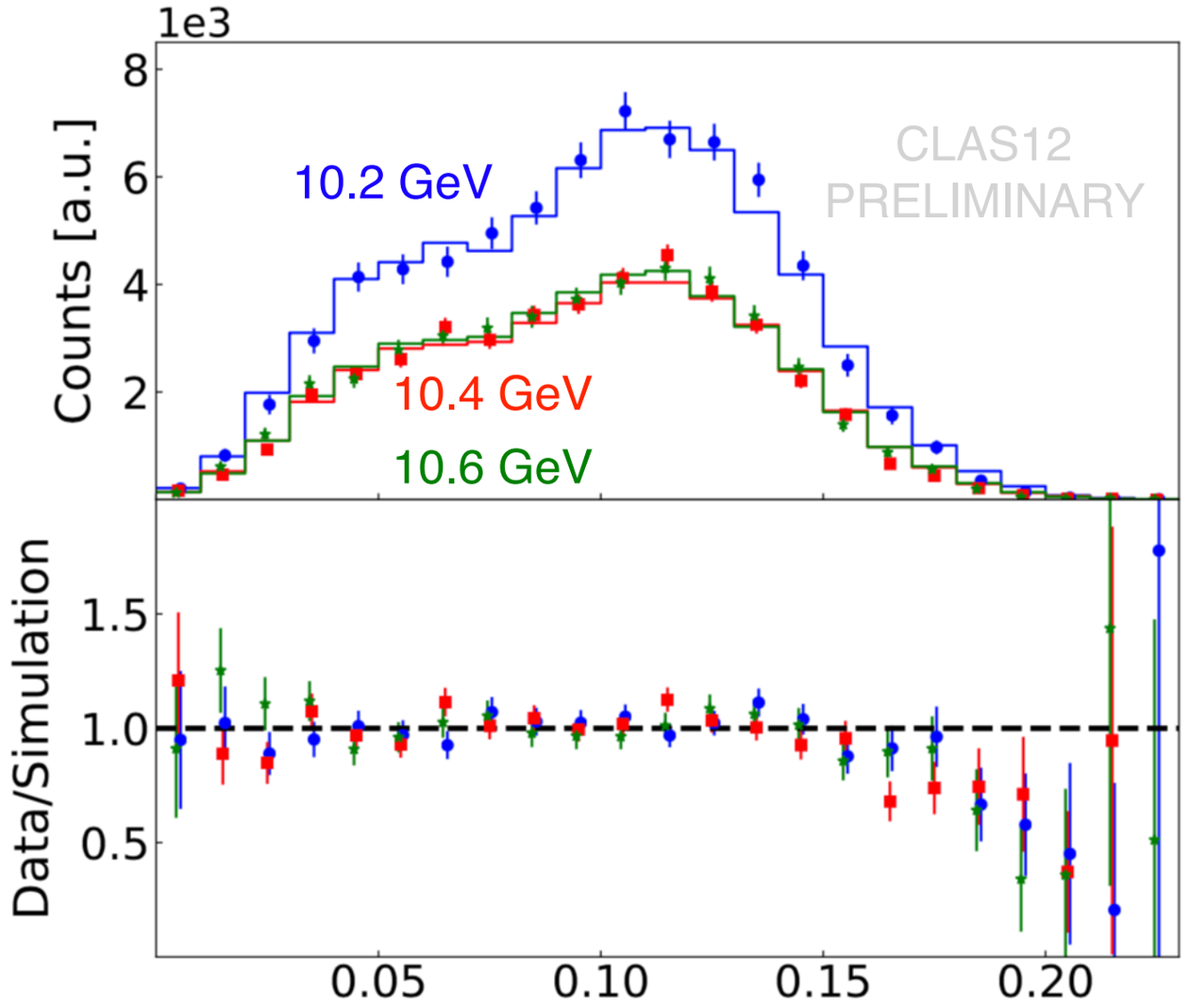
- Simulate generated events with radiation in CLAS12-GEANT4 (GEMC)

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

Integral normalized



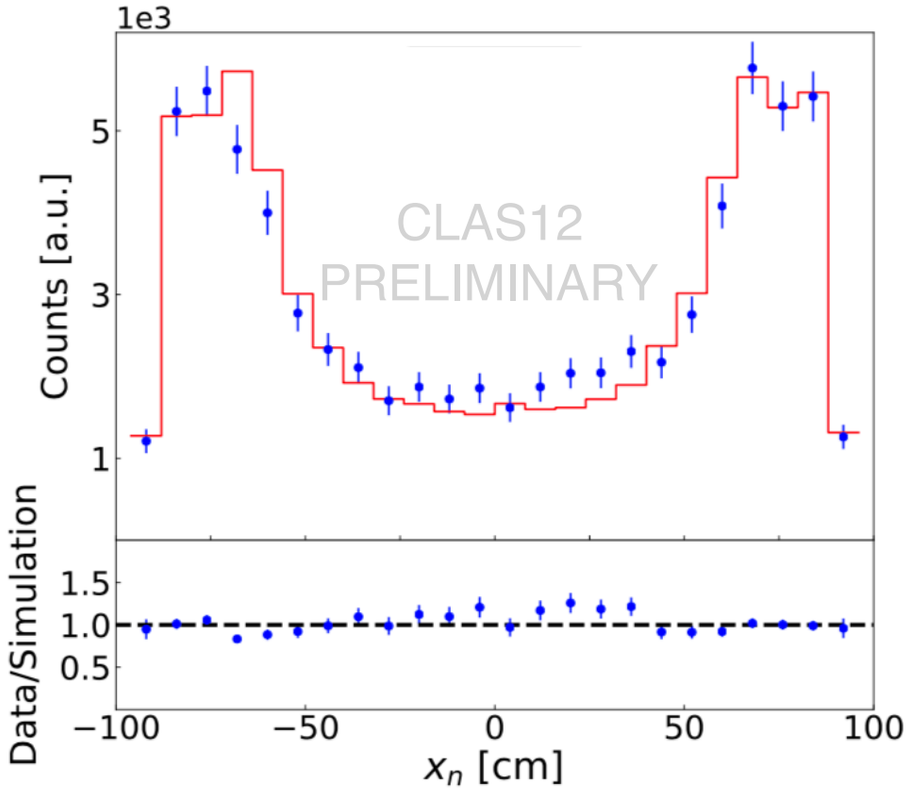
α_S

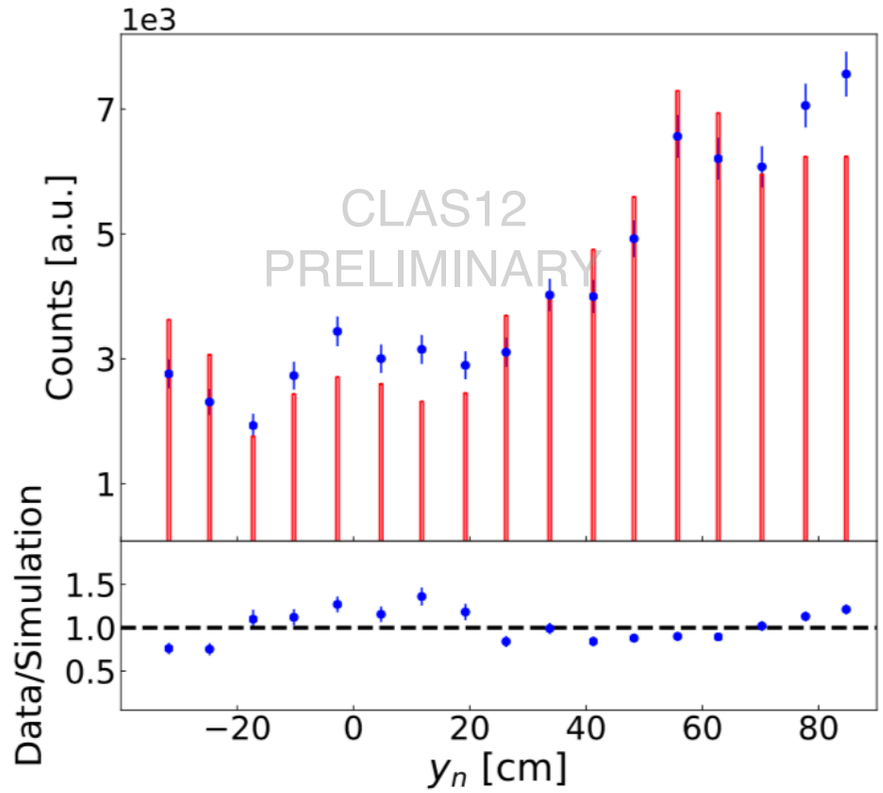


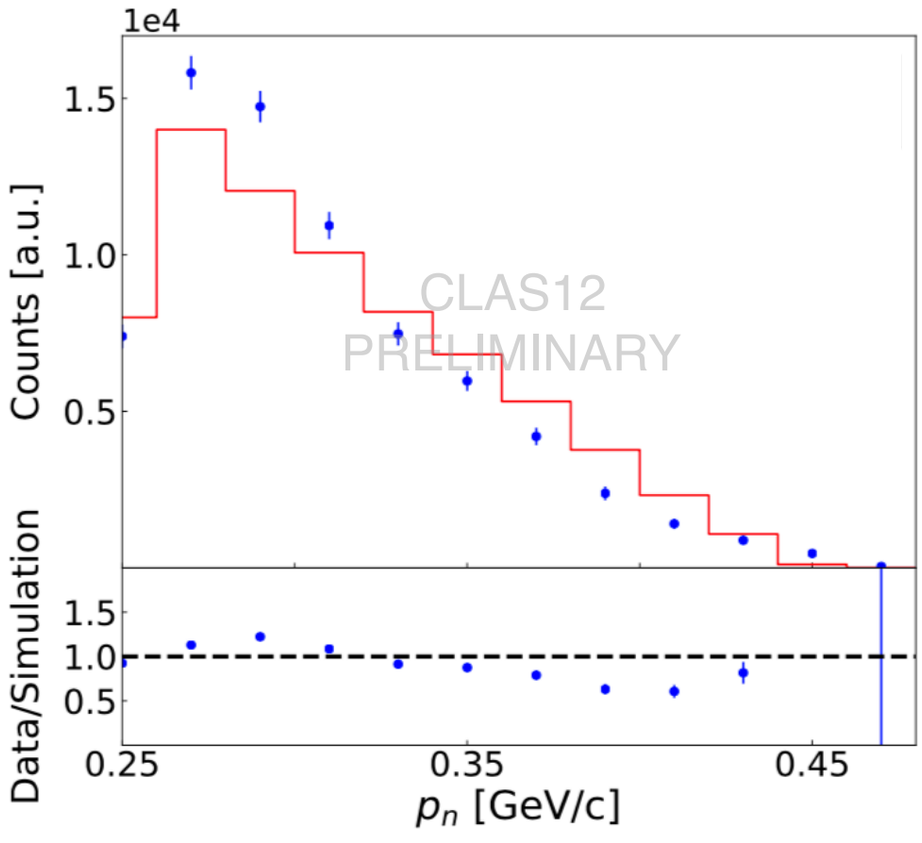
p_T (GeV/c)

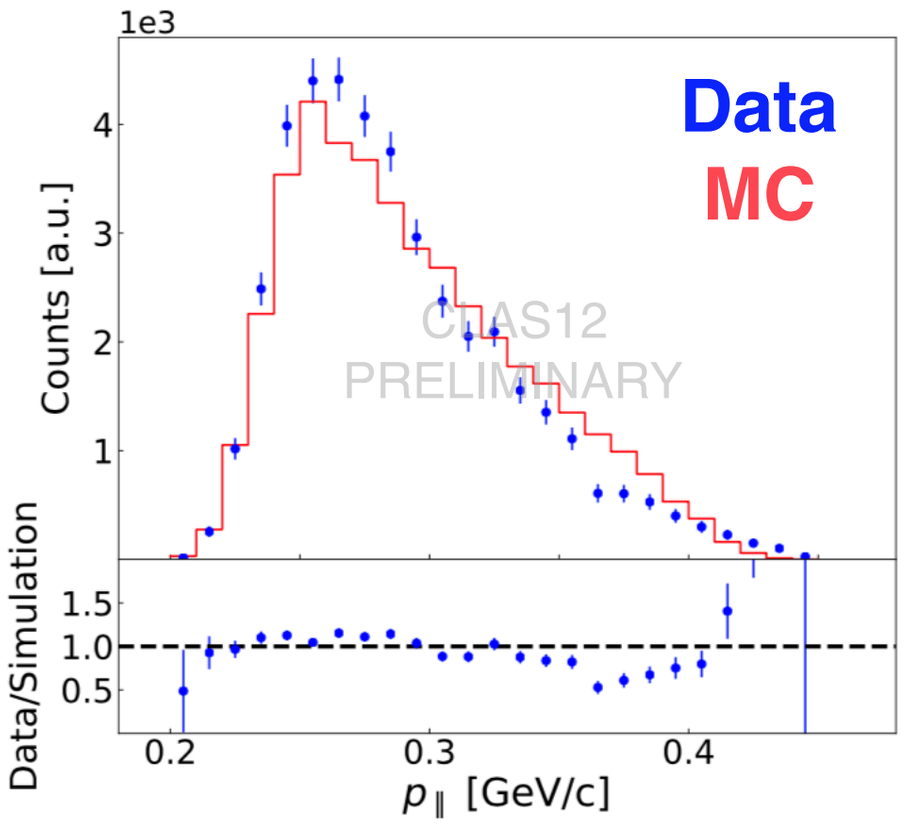
(transv. mom with respect to q)

More Tagged Comparisons (10.2 GeV)









Tagged Yield Ratio

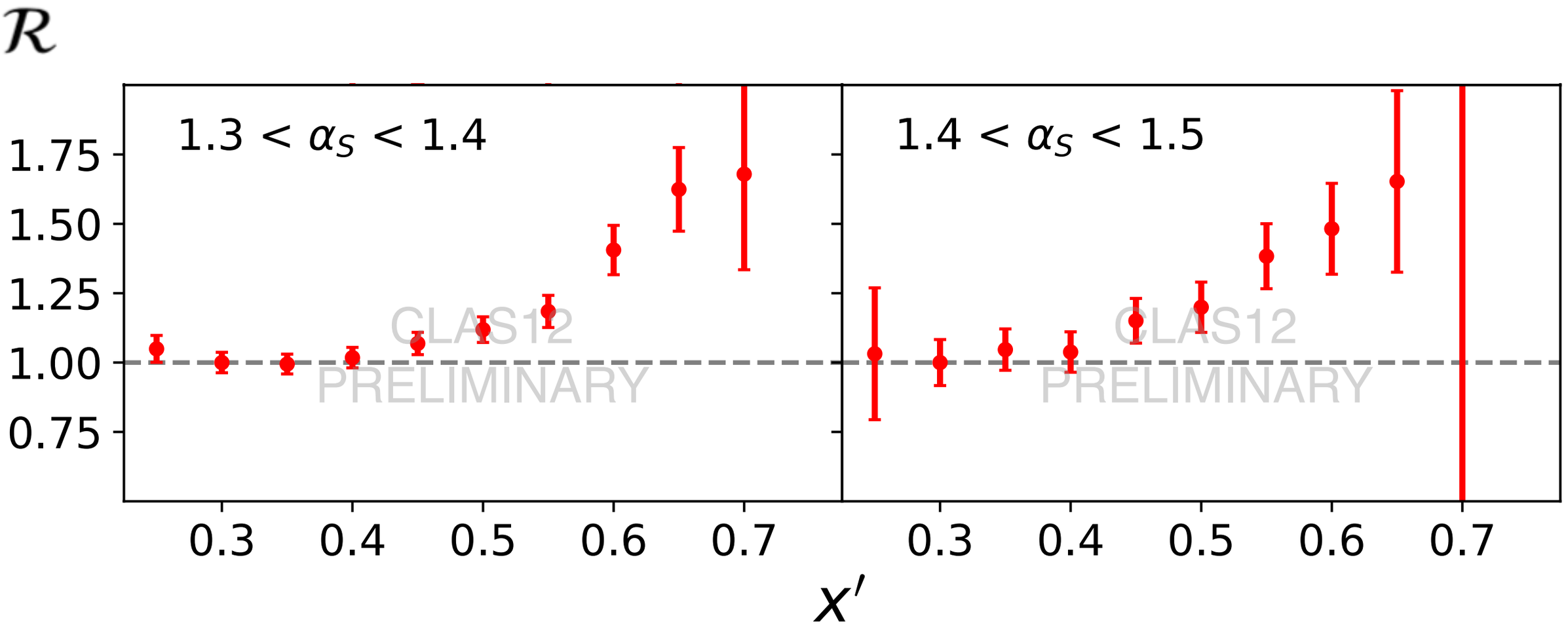
$$R_{tag} = \frac{\sigma_{tag}^{exp}\left(Q^2, p_T, \alpha_S, x'\right) \Big/ \sigma_{tag}^{exp}\left(Q_0^2, p_T, \alpha_S, x' = x_0\right)}{\sigma_{tag}^{theory}\left(Q^2, p_T, \alpha_S, x'\right) \Big/ \sigma_{tag}^{theory}\left(Q_0^2, p_T, \alpha_S, x' = x_0\right)}$$

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

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

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

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
- Extend to lower α_S
- Other studies:
  - Impact of finite Q^2 effects
  - Different event generators
  - Cut sensitivity

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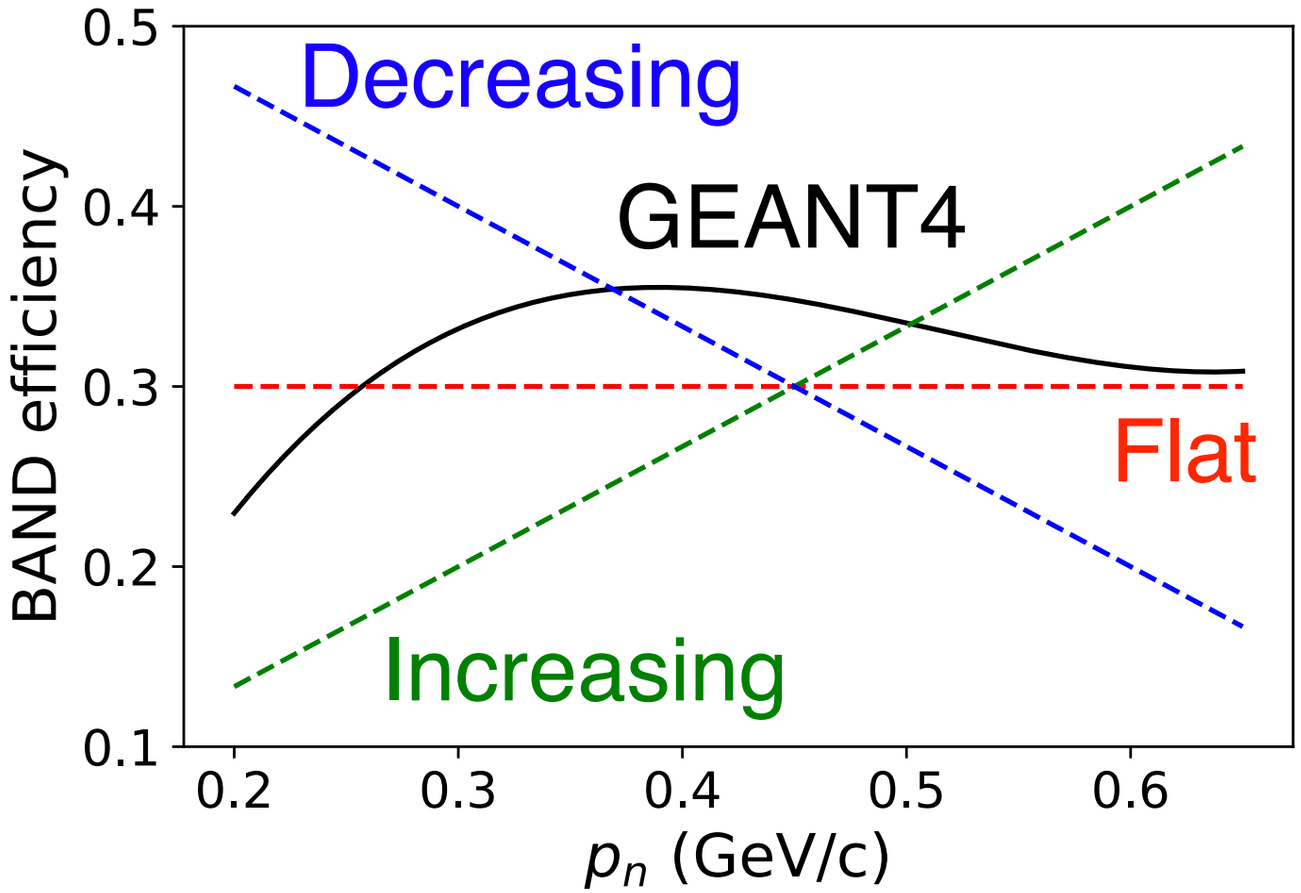
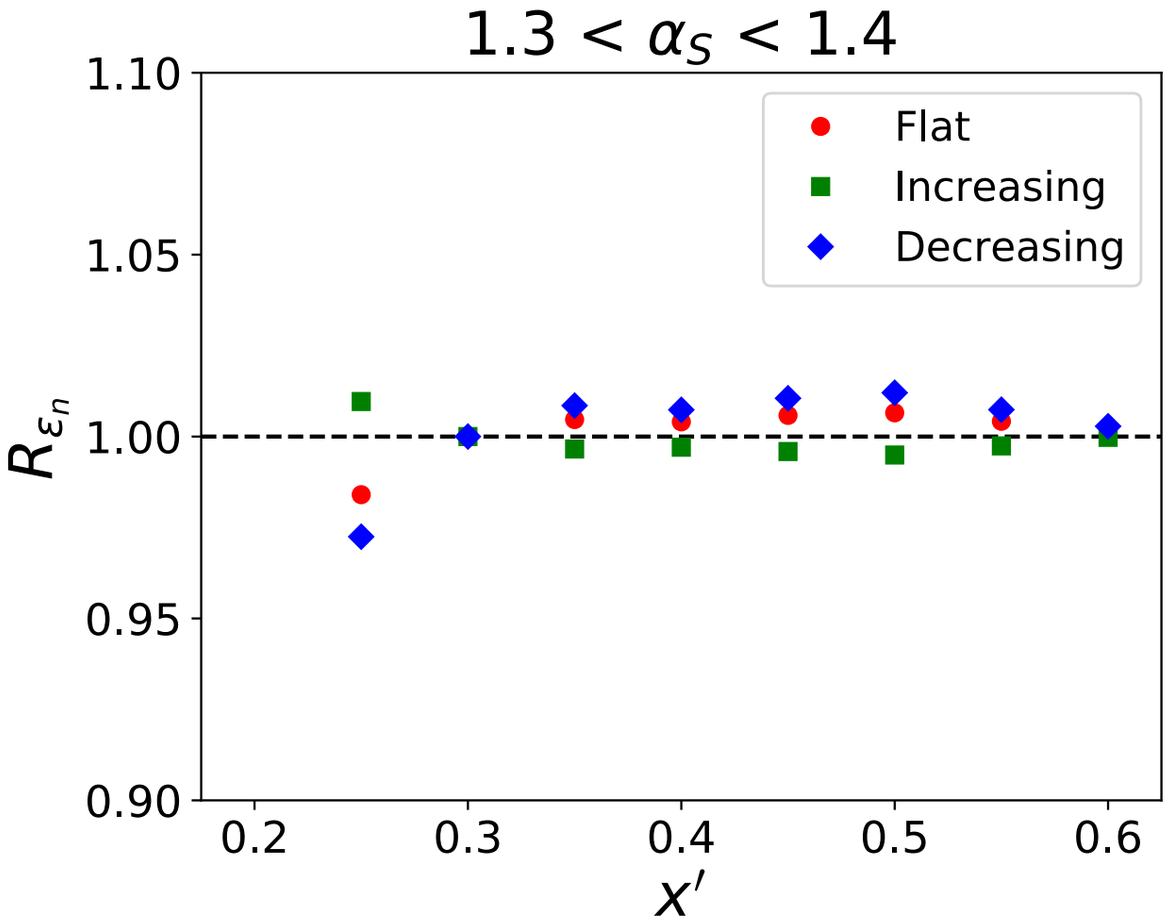
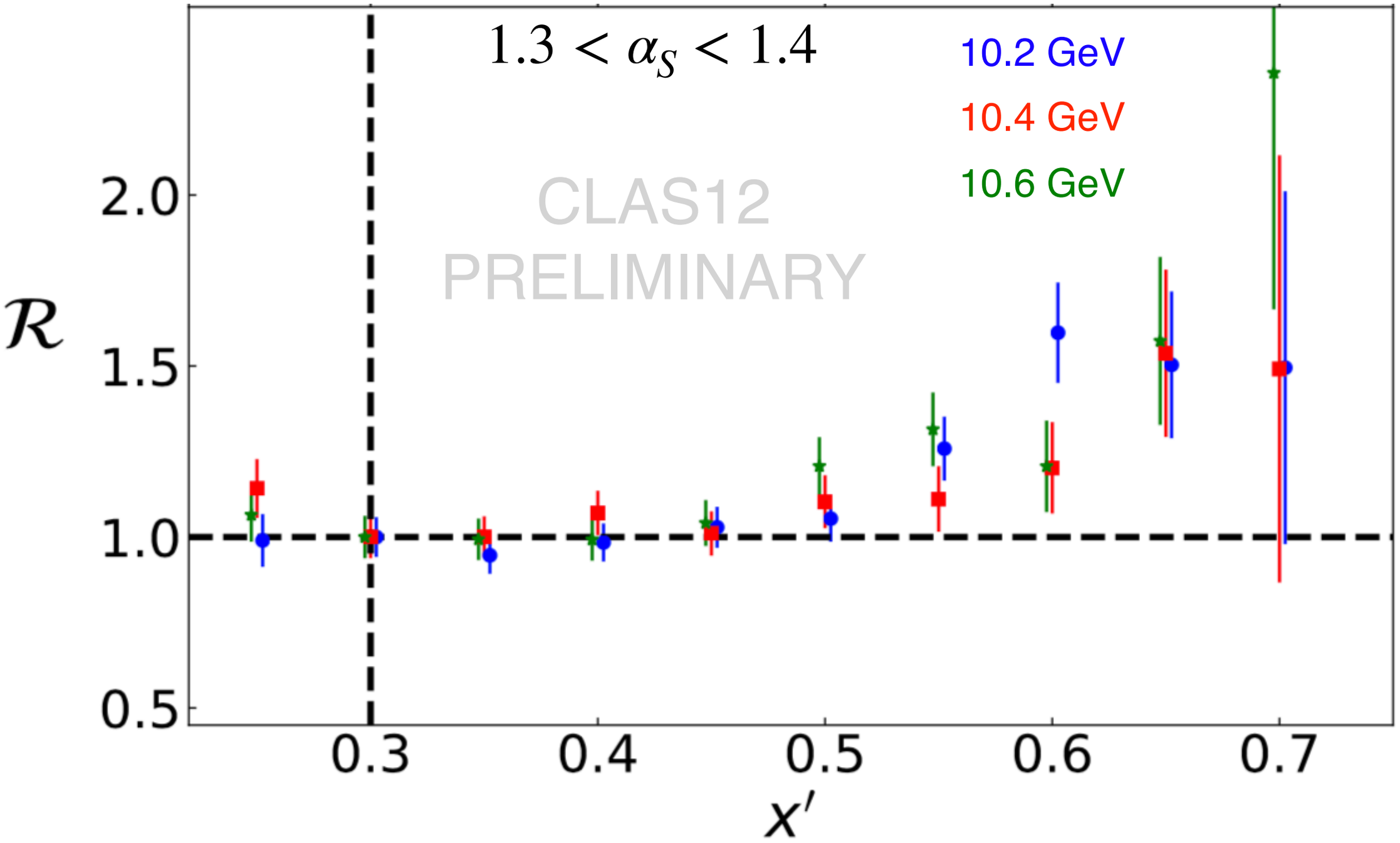
Systematics: BAND Efficiency

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



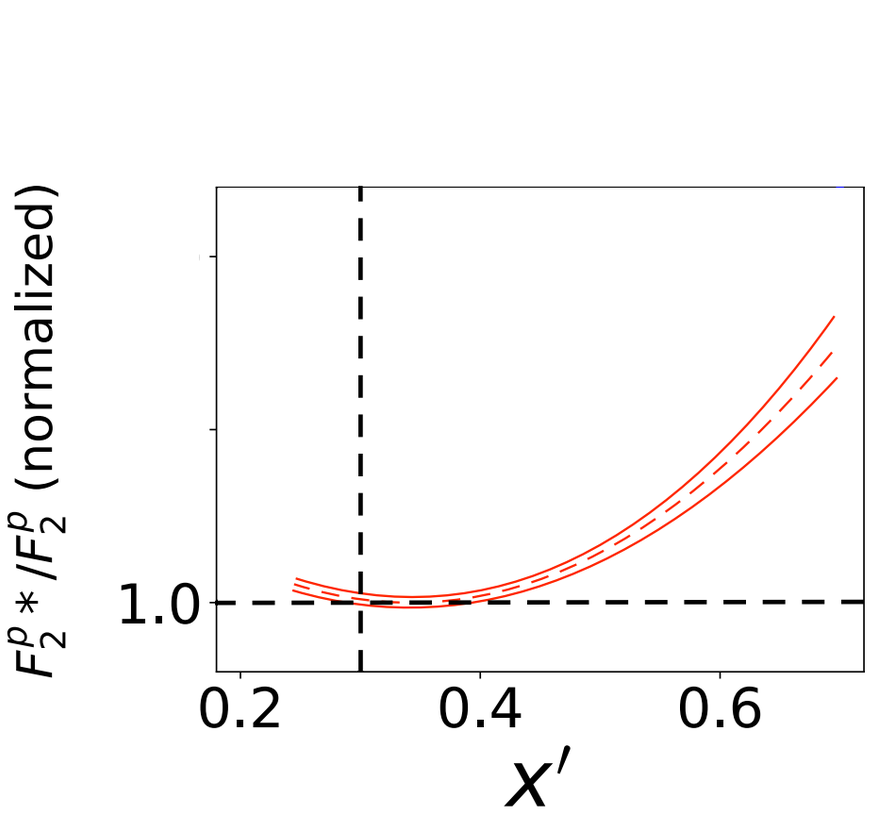


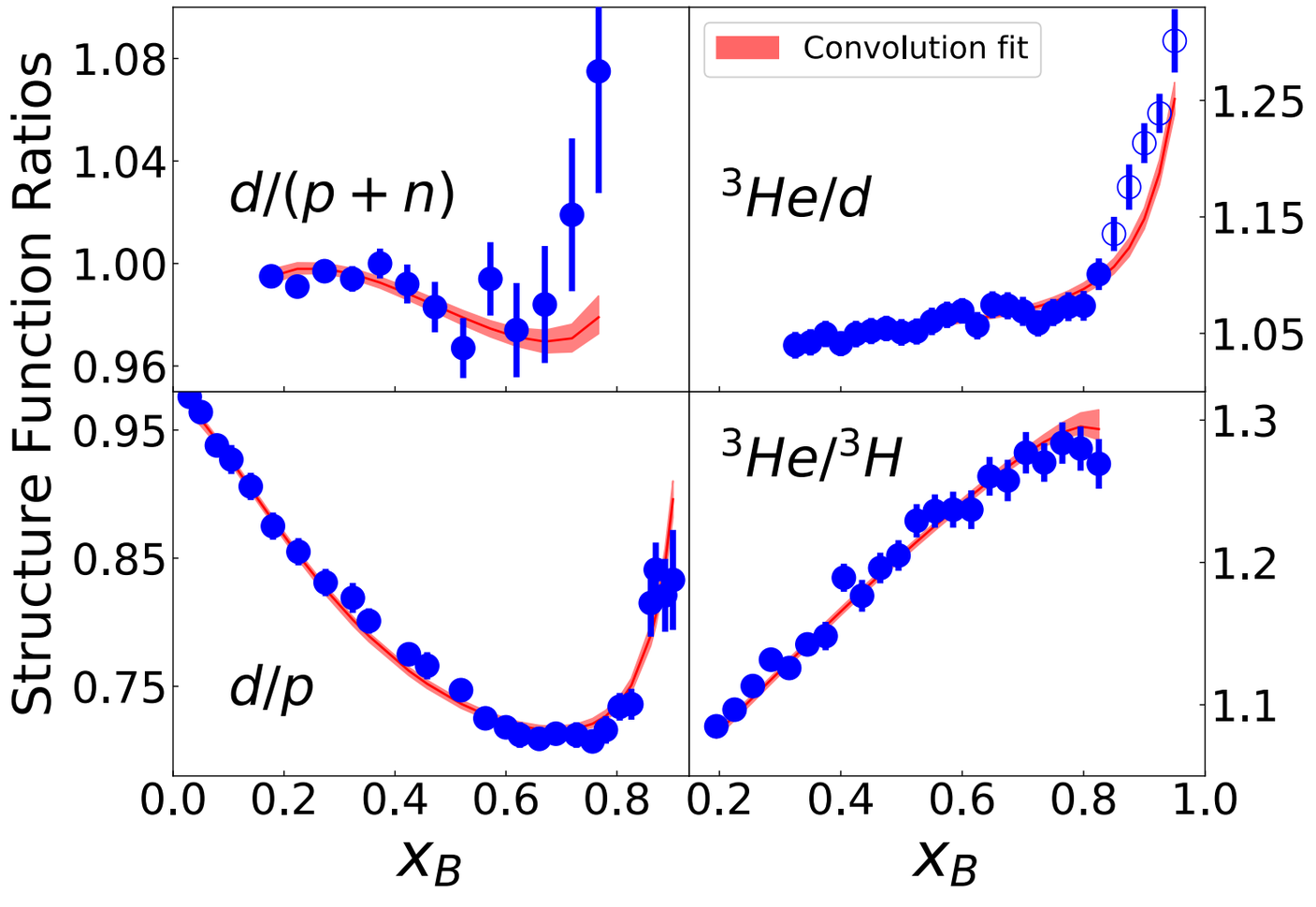
Systematics: Stability with Beam Energy



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



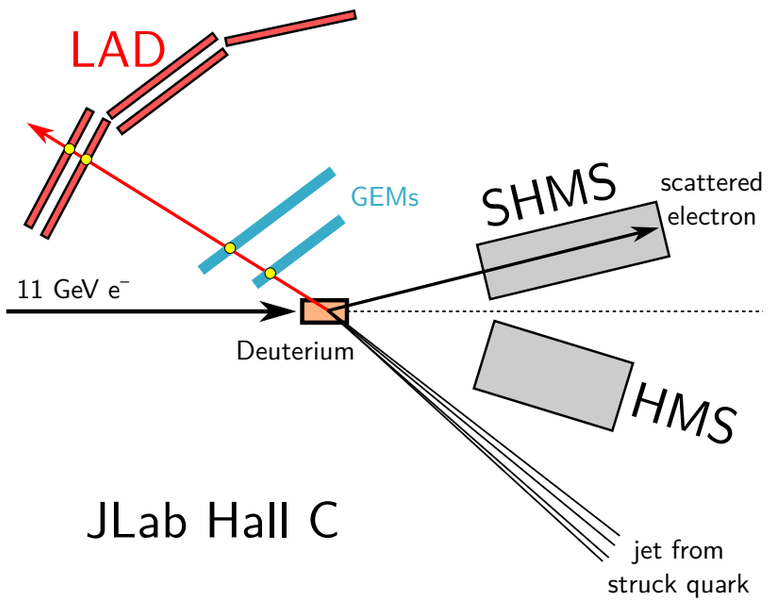


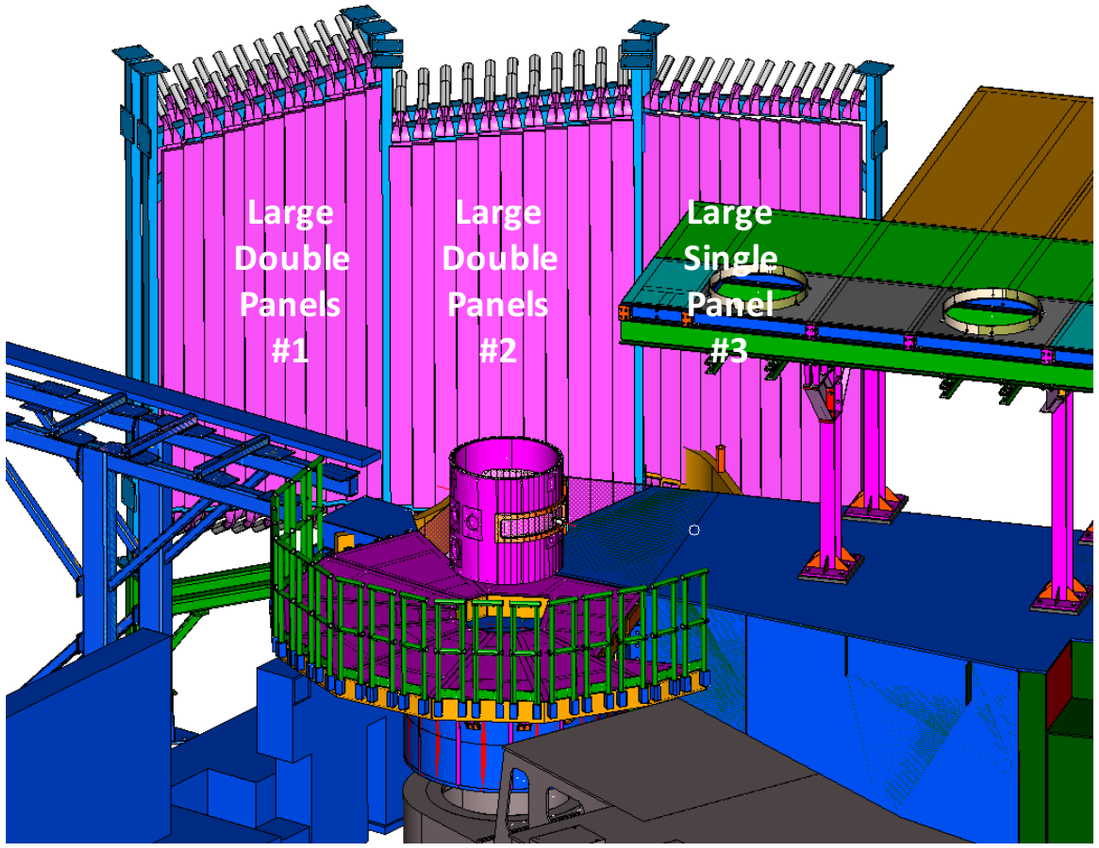
Summary

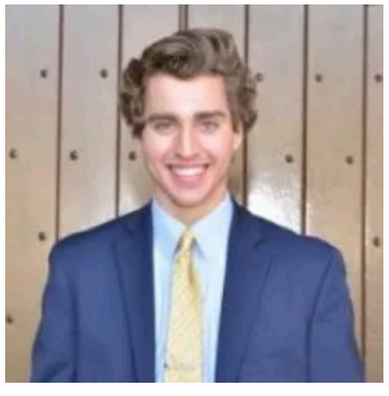
- Tagged DIS measurements to understand nucleon modification for high momentum nucleons
- First measurement of neutron-tagged DIS with CLAS12 + BAND
- Preliminary ratios show large modification of deeply bound proton structure
- CLAS12 analysis review is underway

Outlook

- Publication of BAND results within a year
- LAD experiment in HallC in 2024 (complemental to BAND)
- ALERT experiment in HallB in 2024 (tagging on recoil nuclei from ^{4}He(e,e'))







Efrain Segarra
(Student)

Tyler Kutz
(Postdoc)

Caleb Fogler
(Student)

Andrew Denniston
(Student)

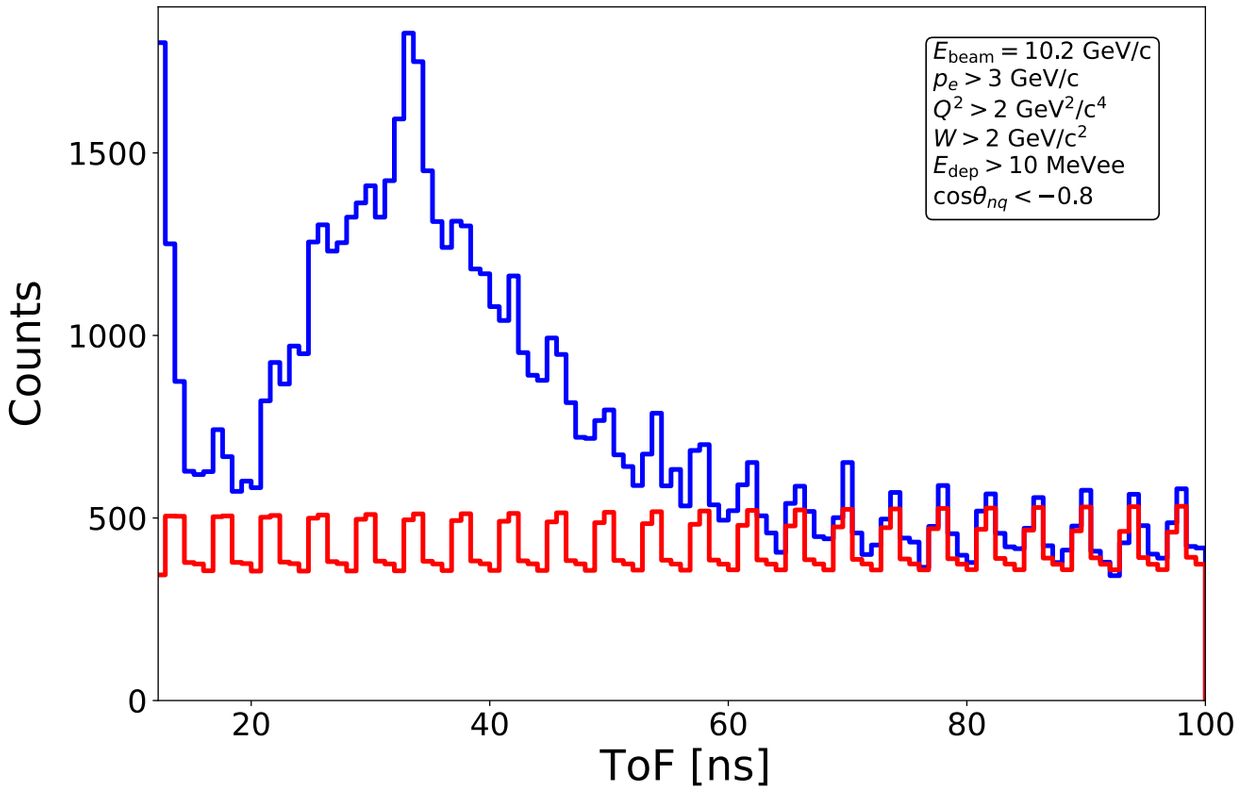
Justin Estee
(Postdoc)

Dien Nguyen
(Isgur postdoc)

Thank you

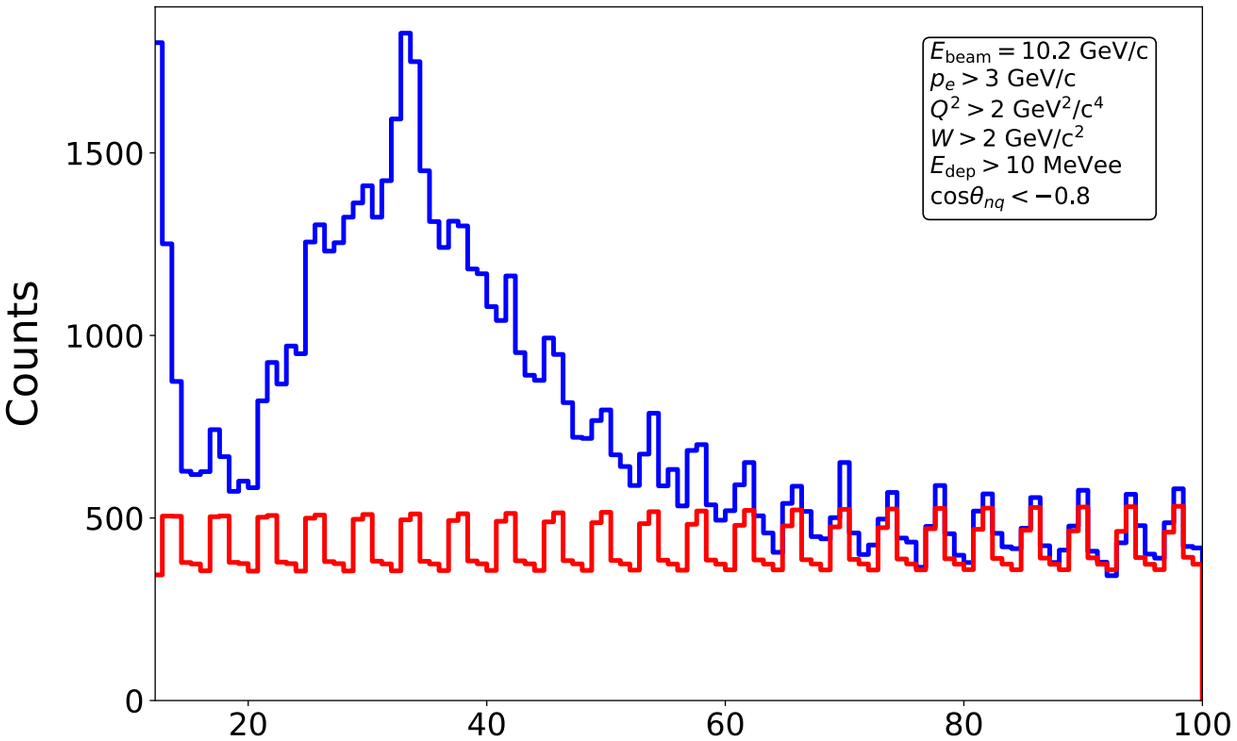
Backup slides

Random Coincidence Background Subtraction

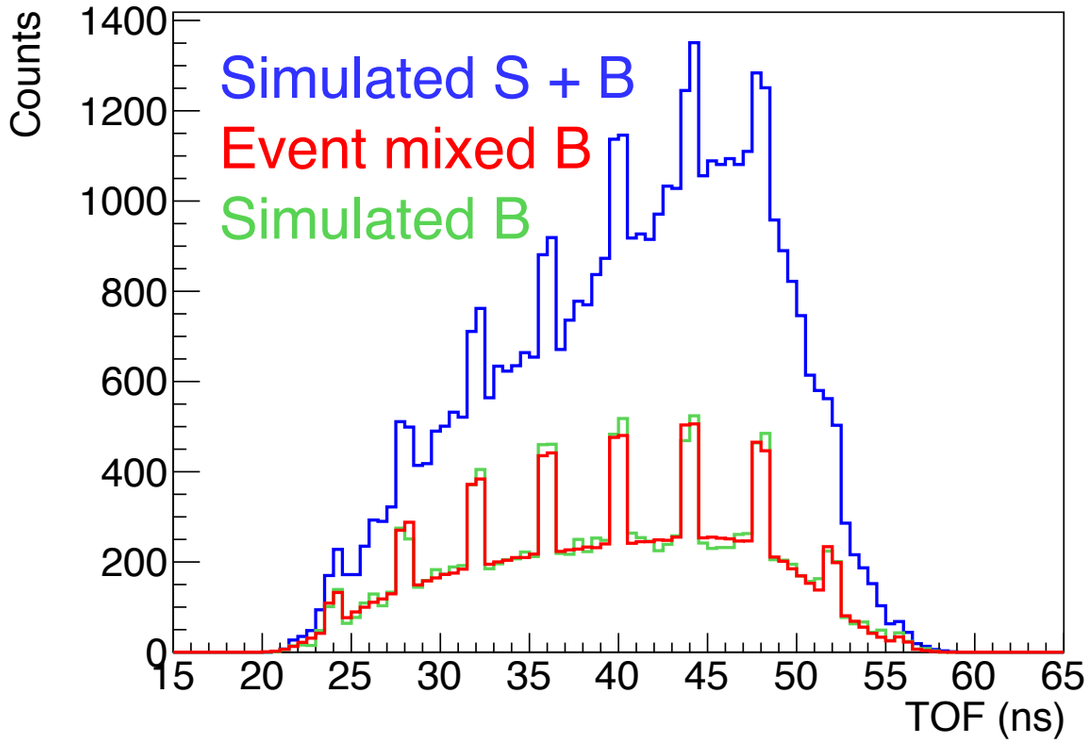


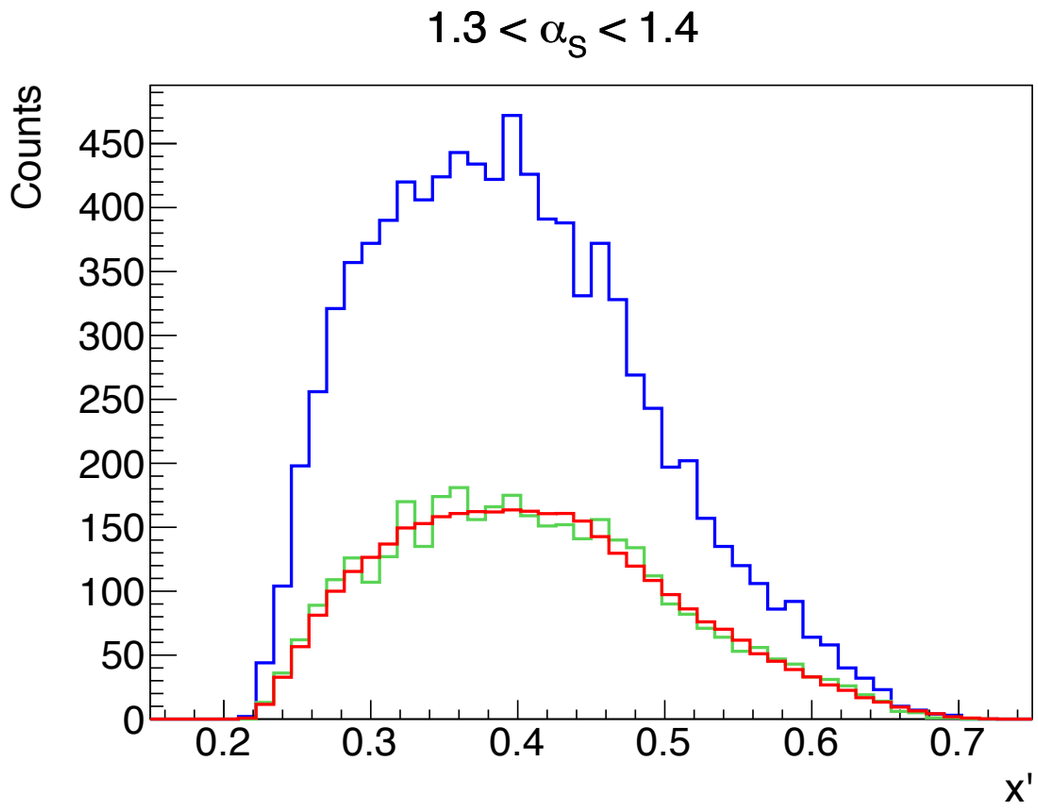
- Event mixing for background subtraction
- Account for beam structure

Random Coincidence Background Subtraction

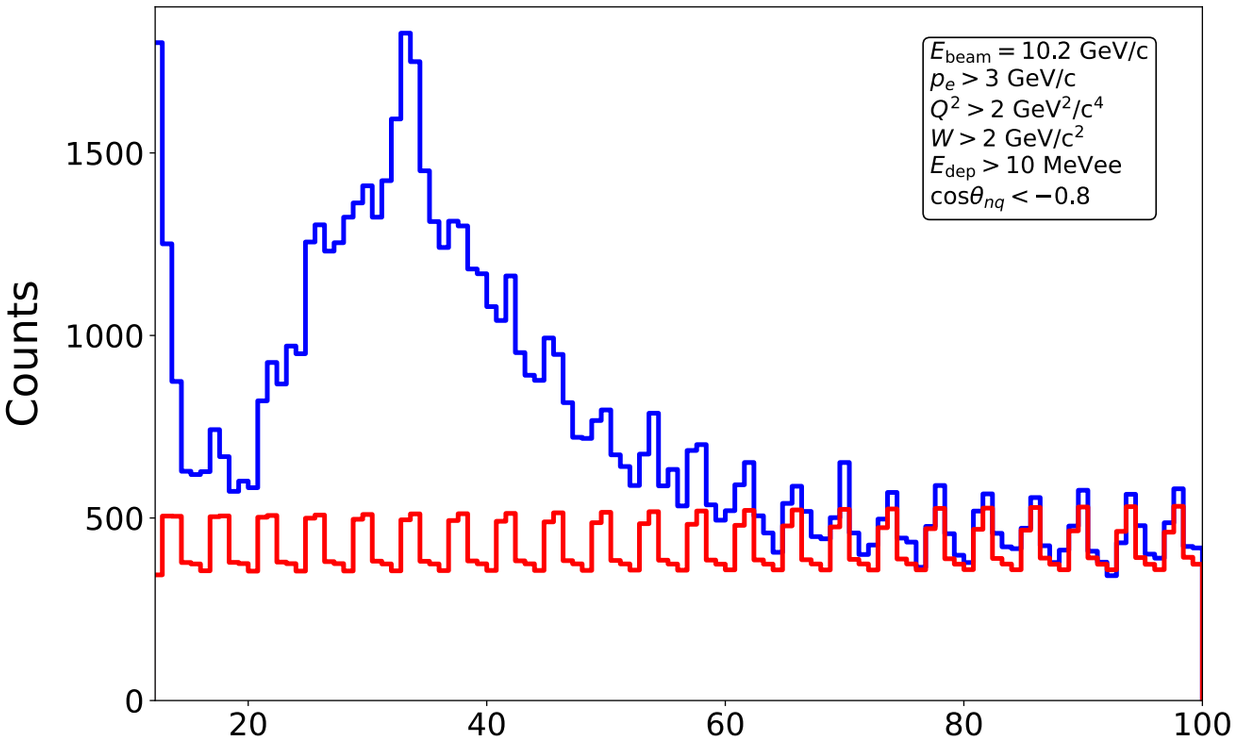


- Event mixing for background subtraction
- Account for beam structure
- Simulation closure test

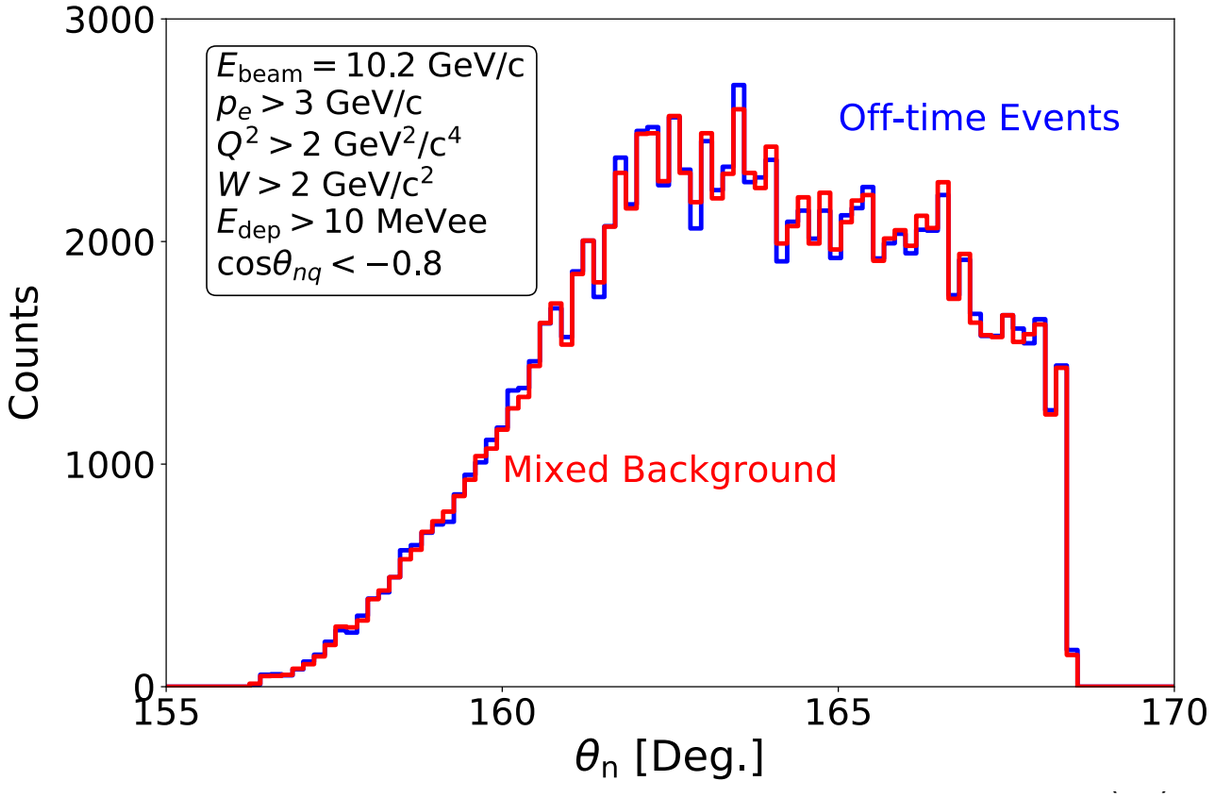


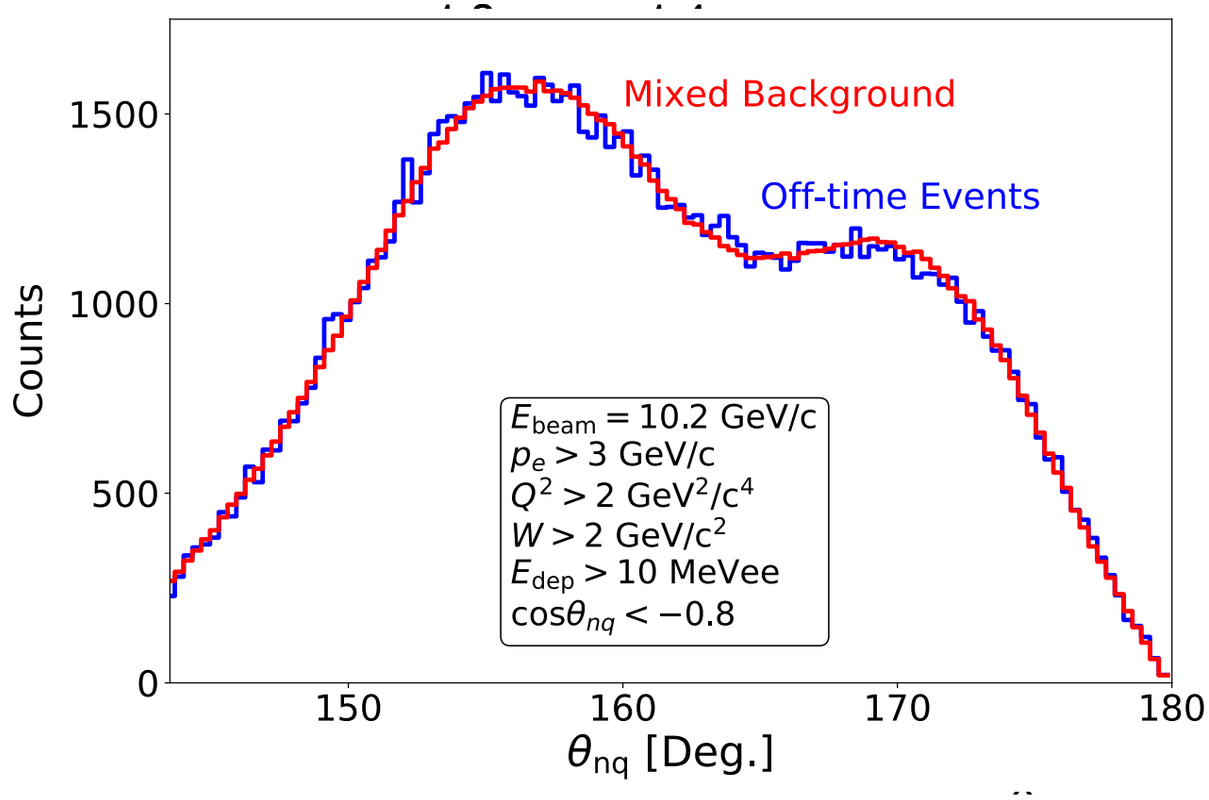


Random Coincidence Background Subtraction

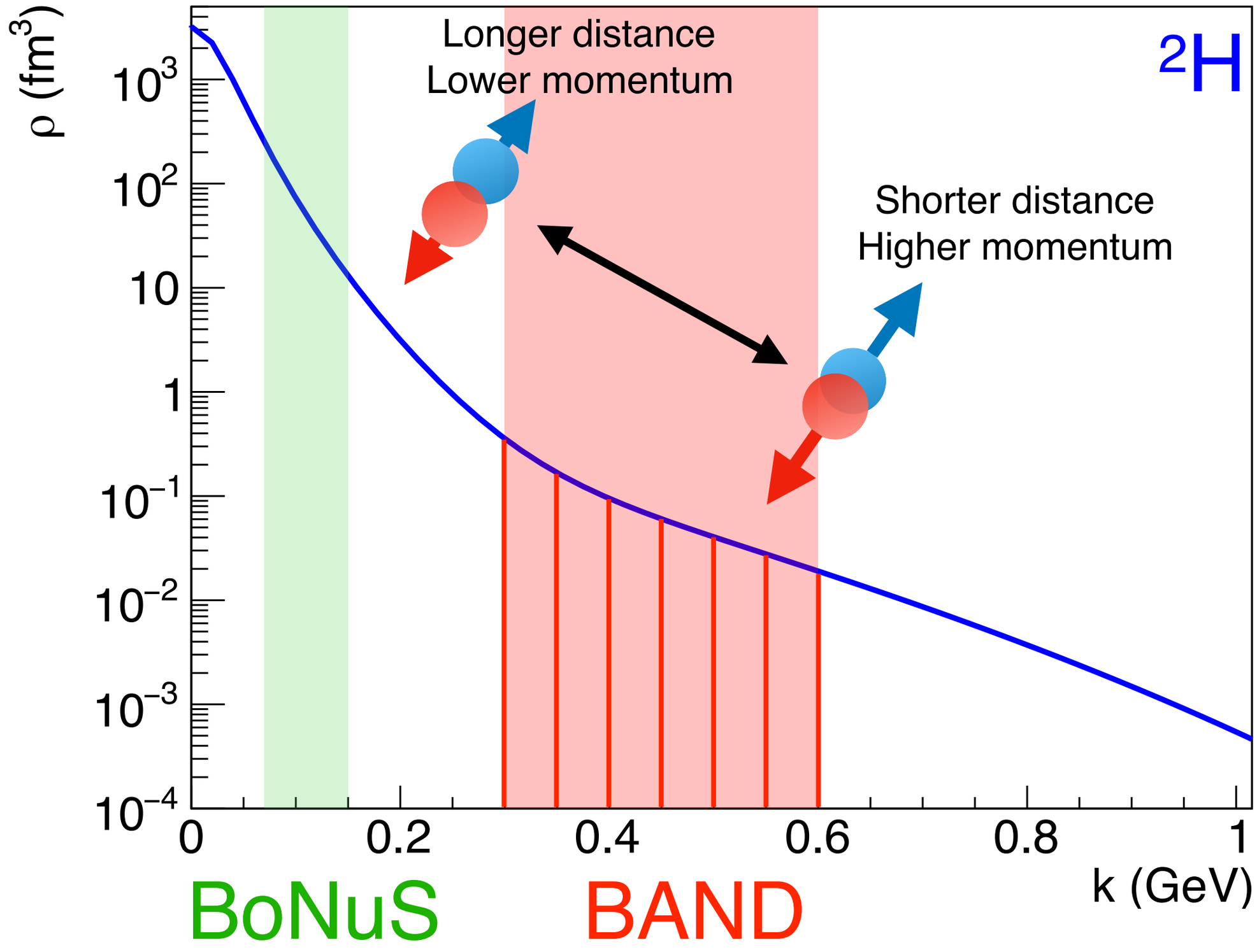


- Event mixing for background subtraction
- Account for beam structure
- Simulation closure test
- Offtime/event mixed consistency

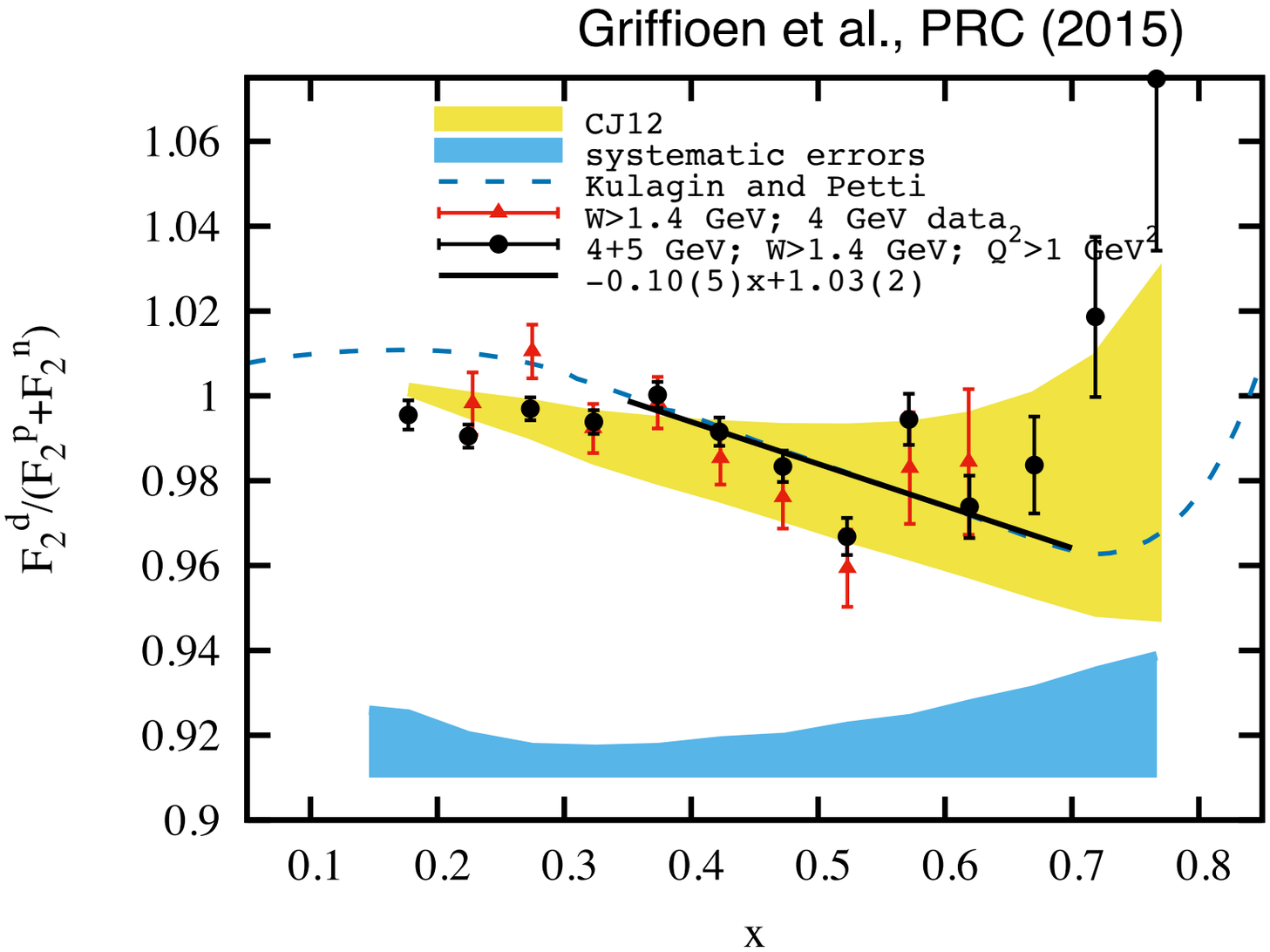




Momentum Coverage

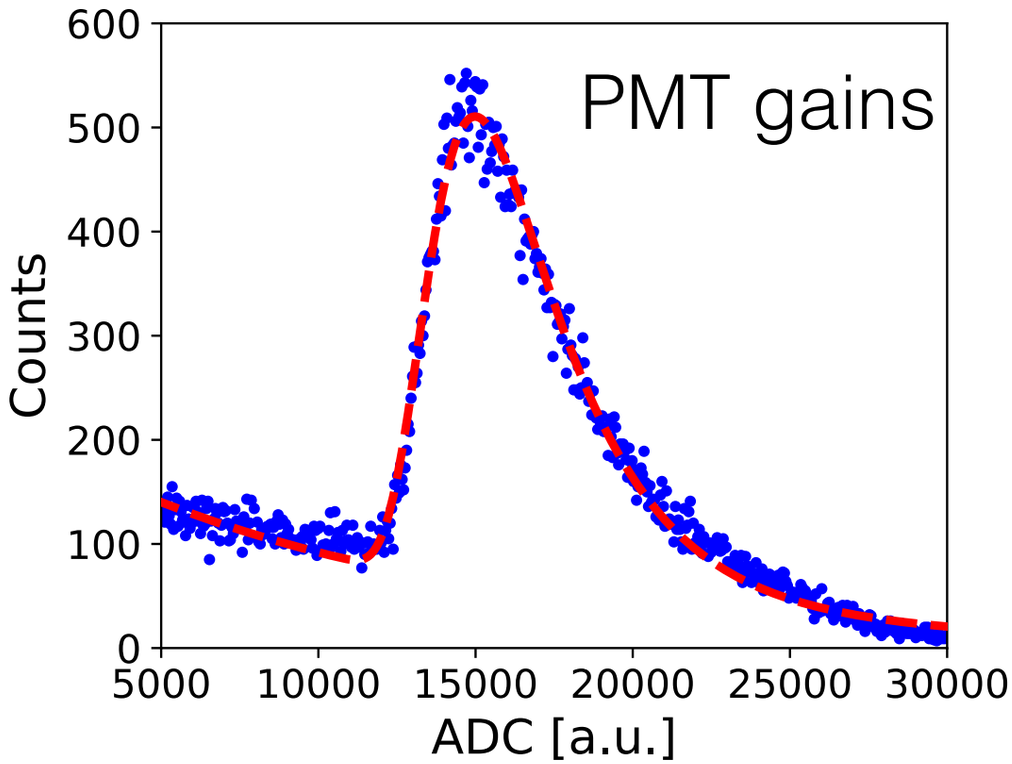


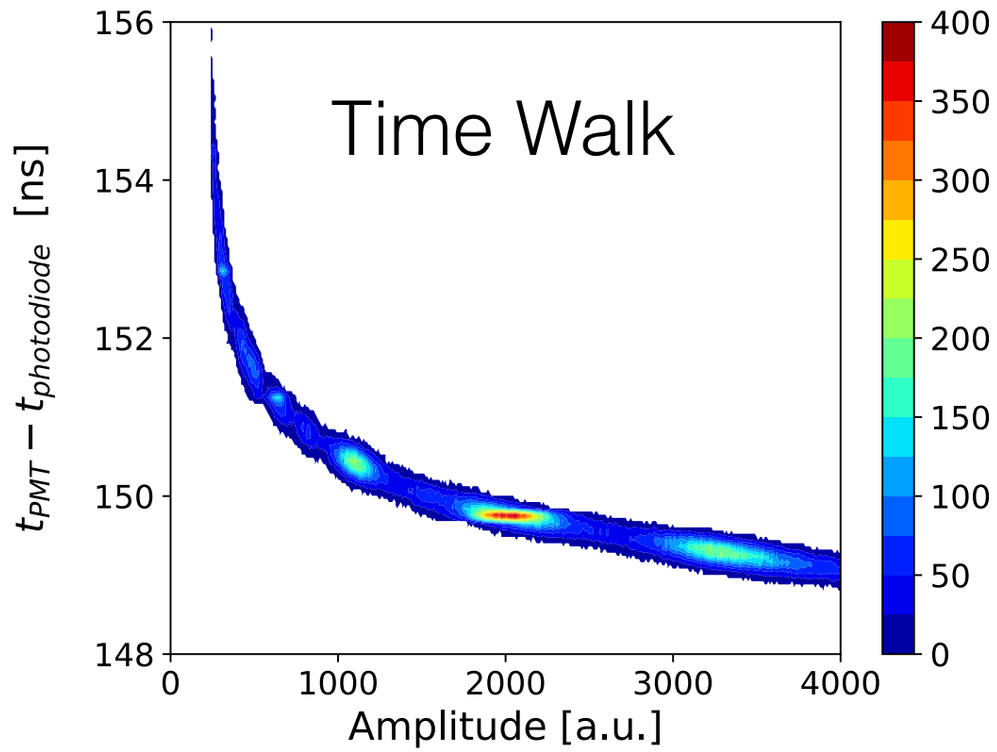
EMC Effect in Deuterium



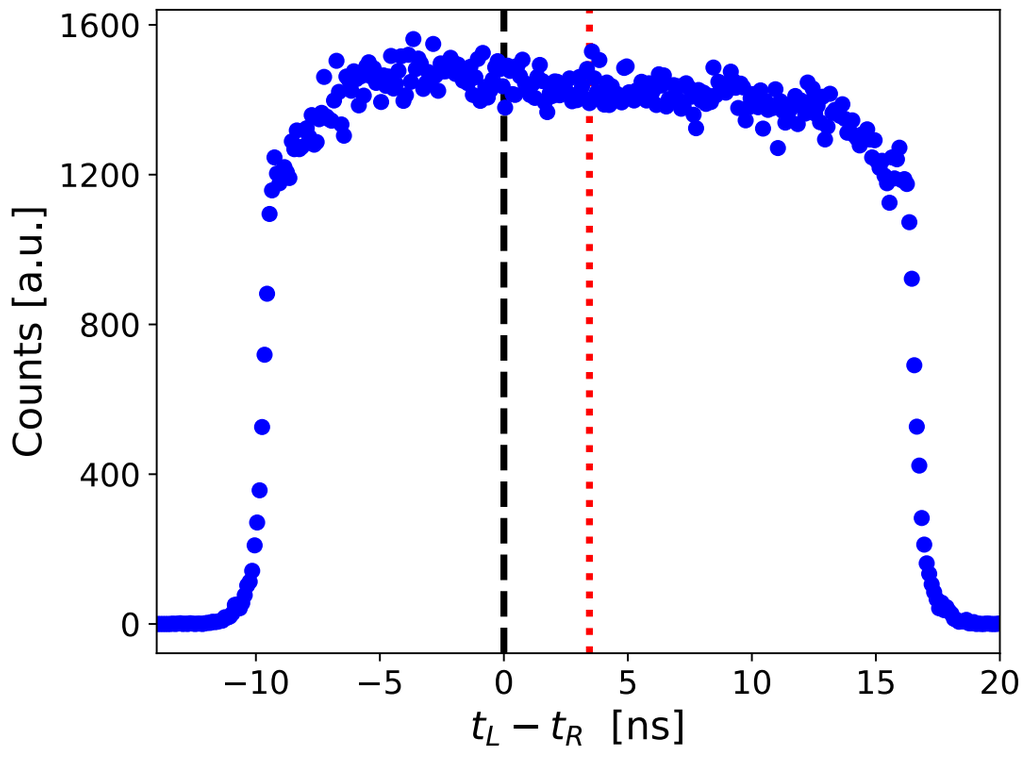
- EMC is small BUT
- SRC hypothesis predicts large modification of (rare) SRC states!

BAND Calibrations





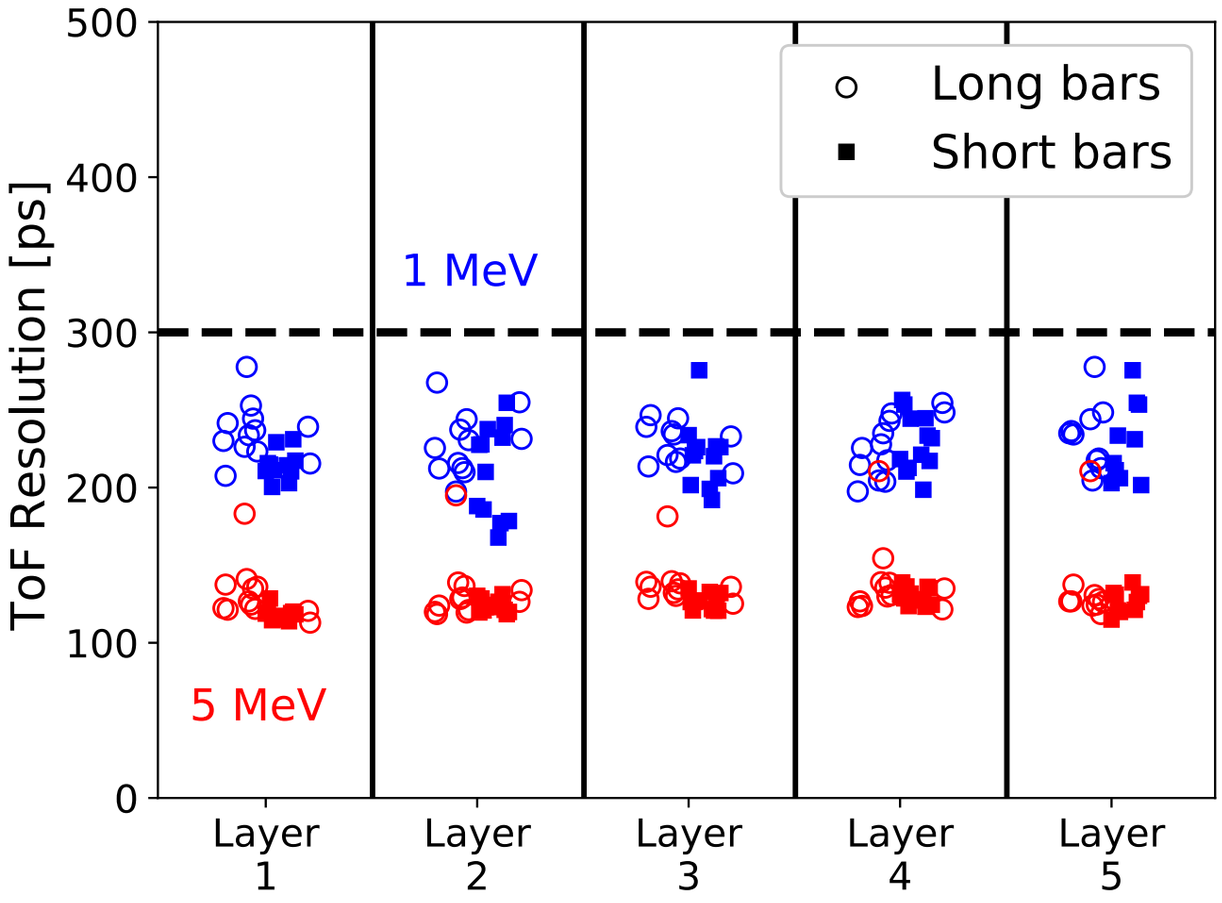
Timing Offsets



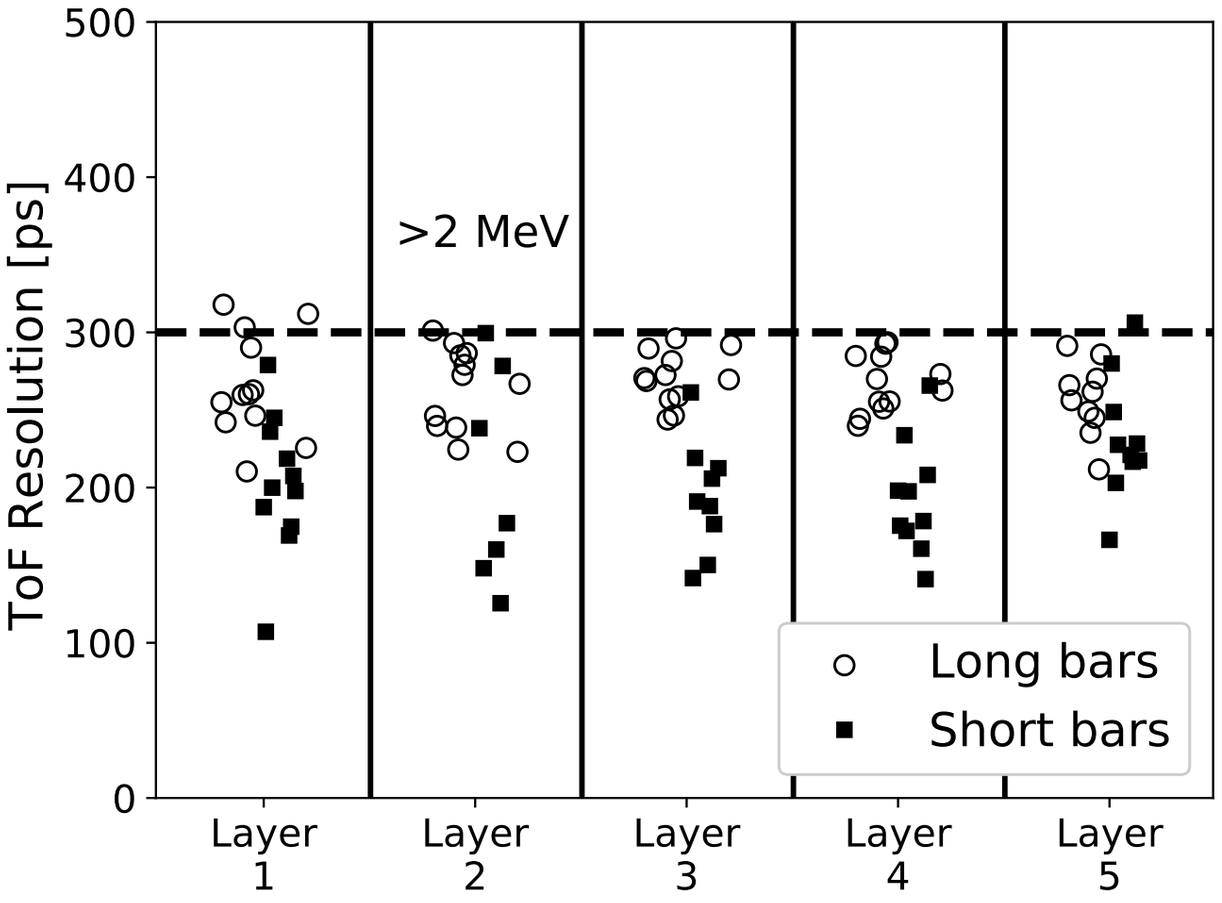
Time Resolutions of BAND Bars

Segarra et al., NIM A978 (2020)

Laser

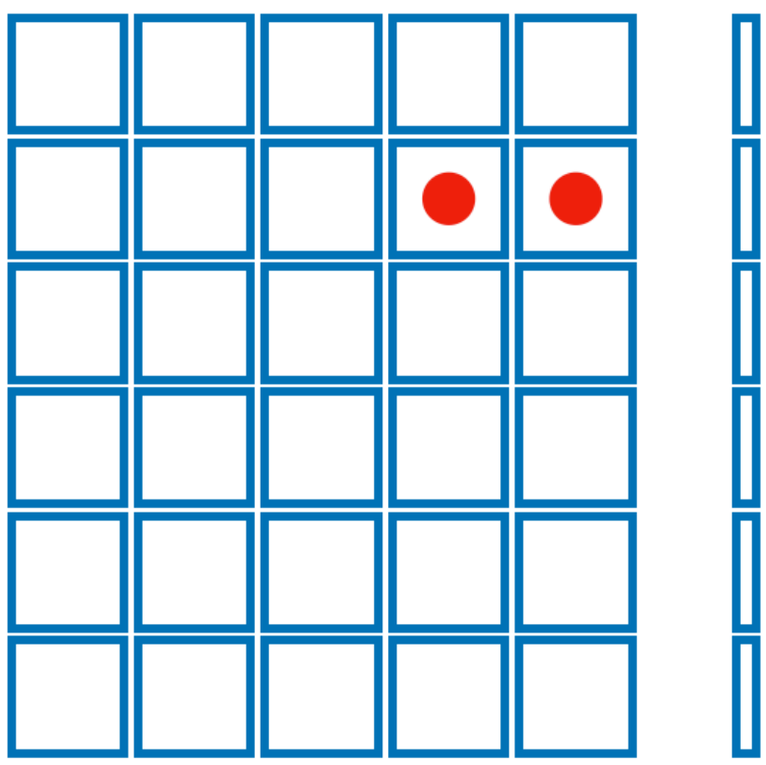


Photons



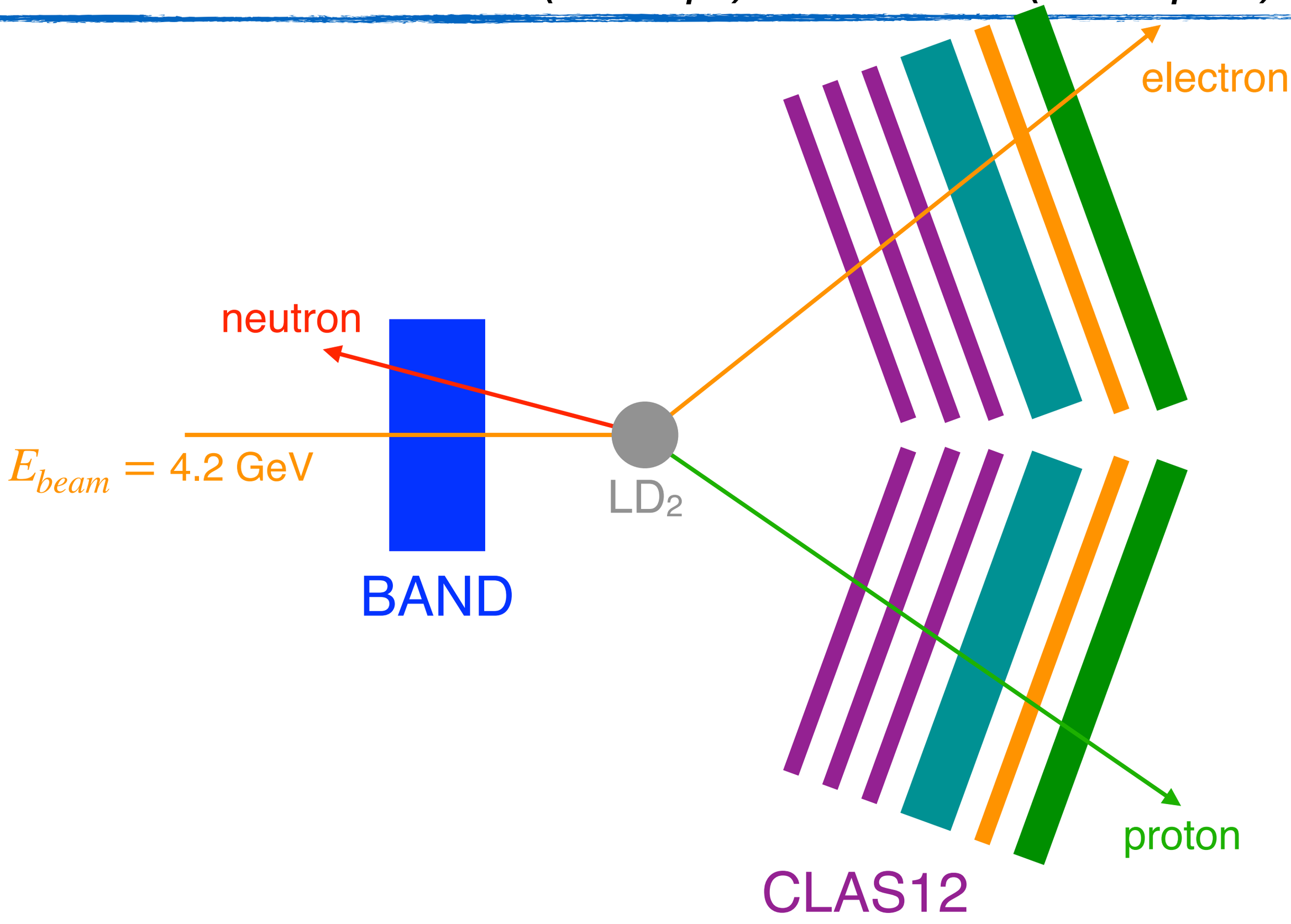
Neutron Selection: Identifying Good Hits

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



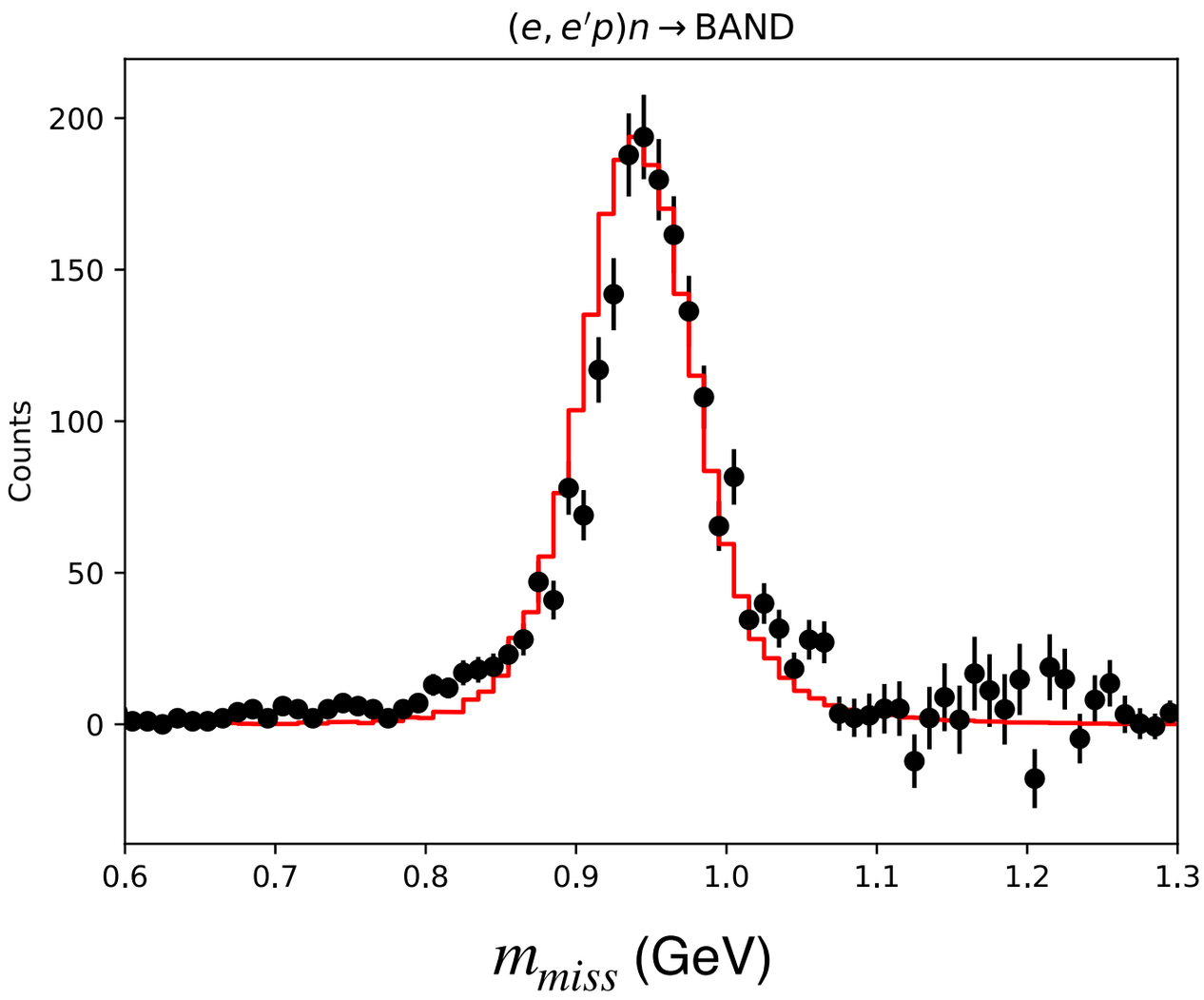
- If single hit (most of the time) ✔
- If 2 hits:
  - Close together (from same interaction)? ✔
  - Far apart? ✘
- If > 2 hits ✘

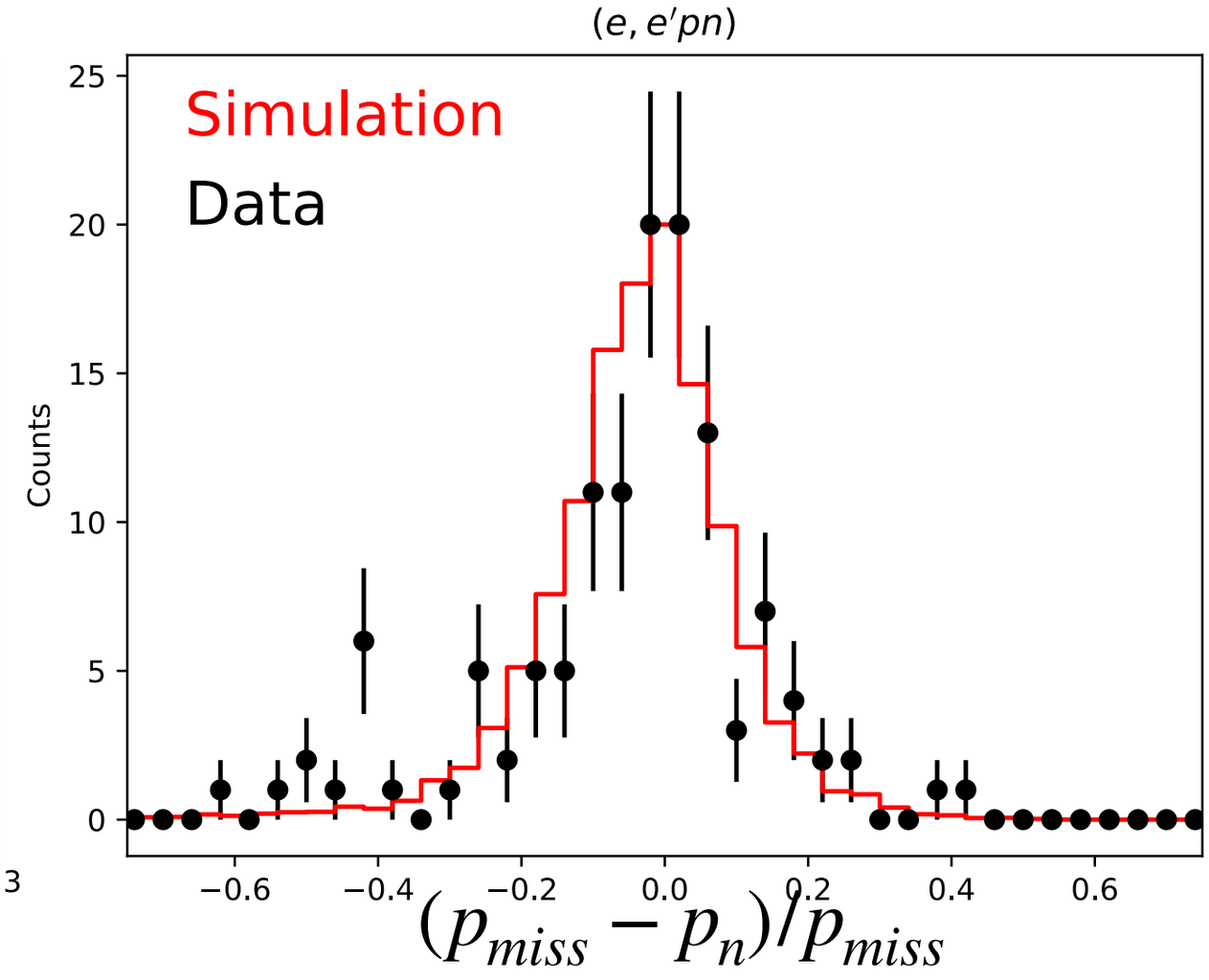
Quasi-elastic *d(e,e'p)n* and *d(e,e'pn)*



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

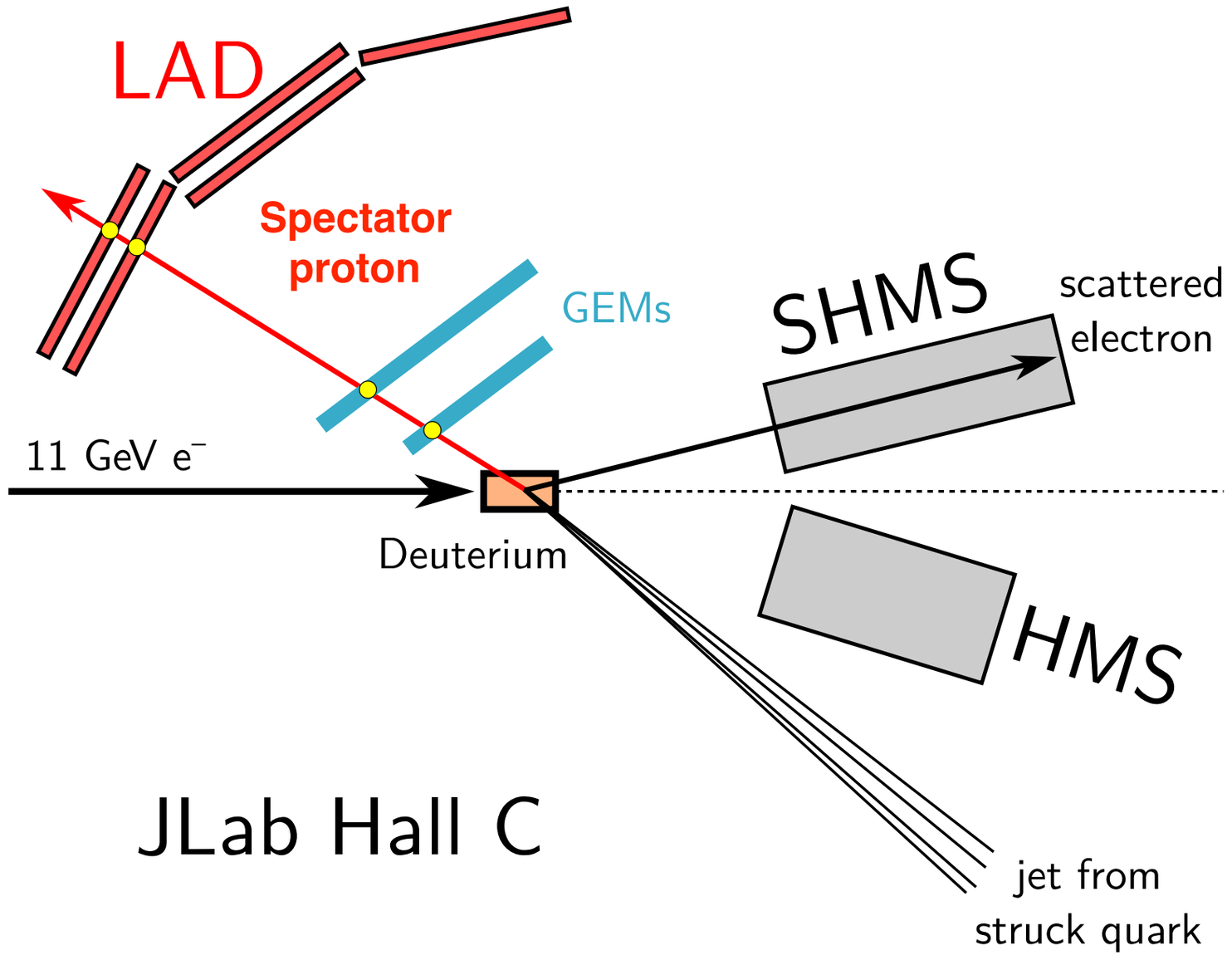
Integral-normalized



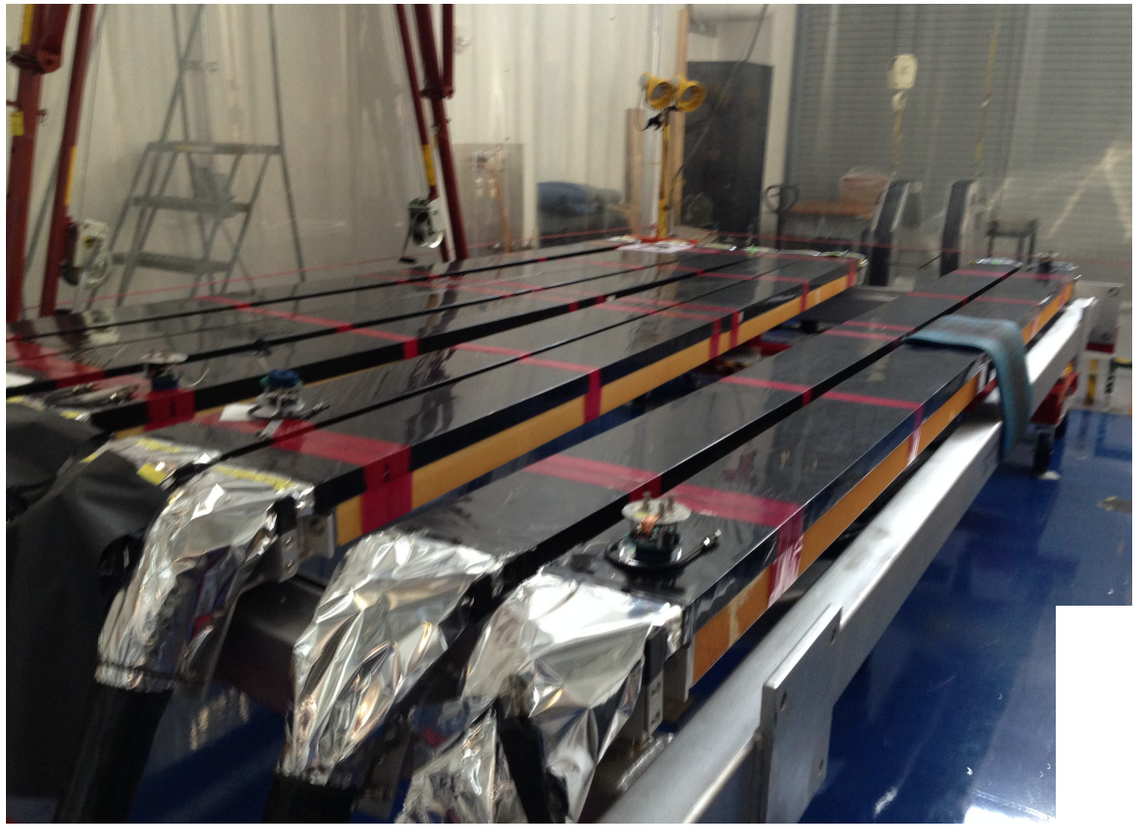


- Excellent agreement in resolution of data and simulation

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