Tagged DIS with CLAS12 and BAND

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CLAS collaboration meeting
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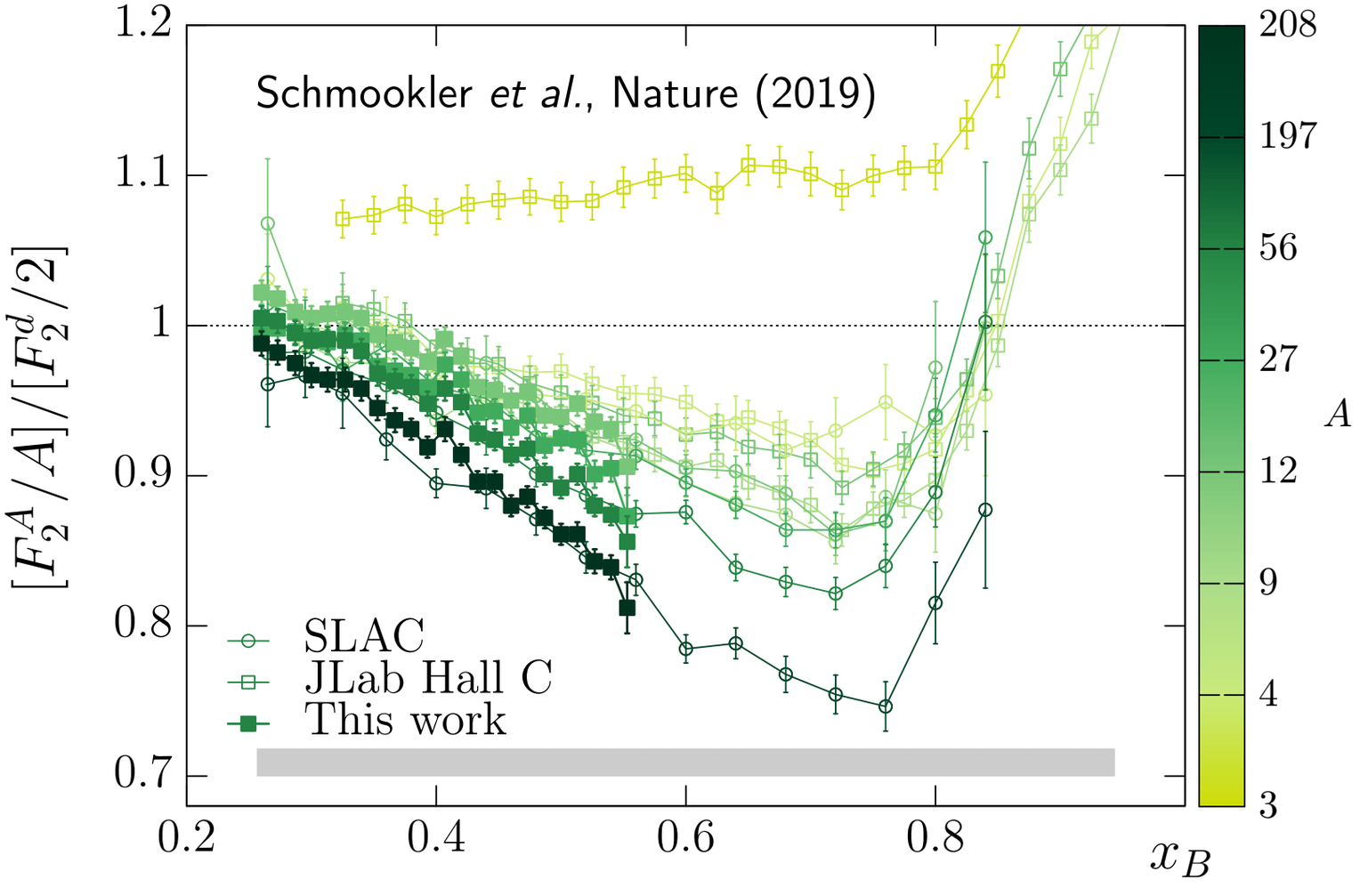
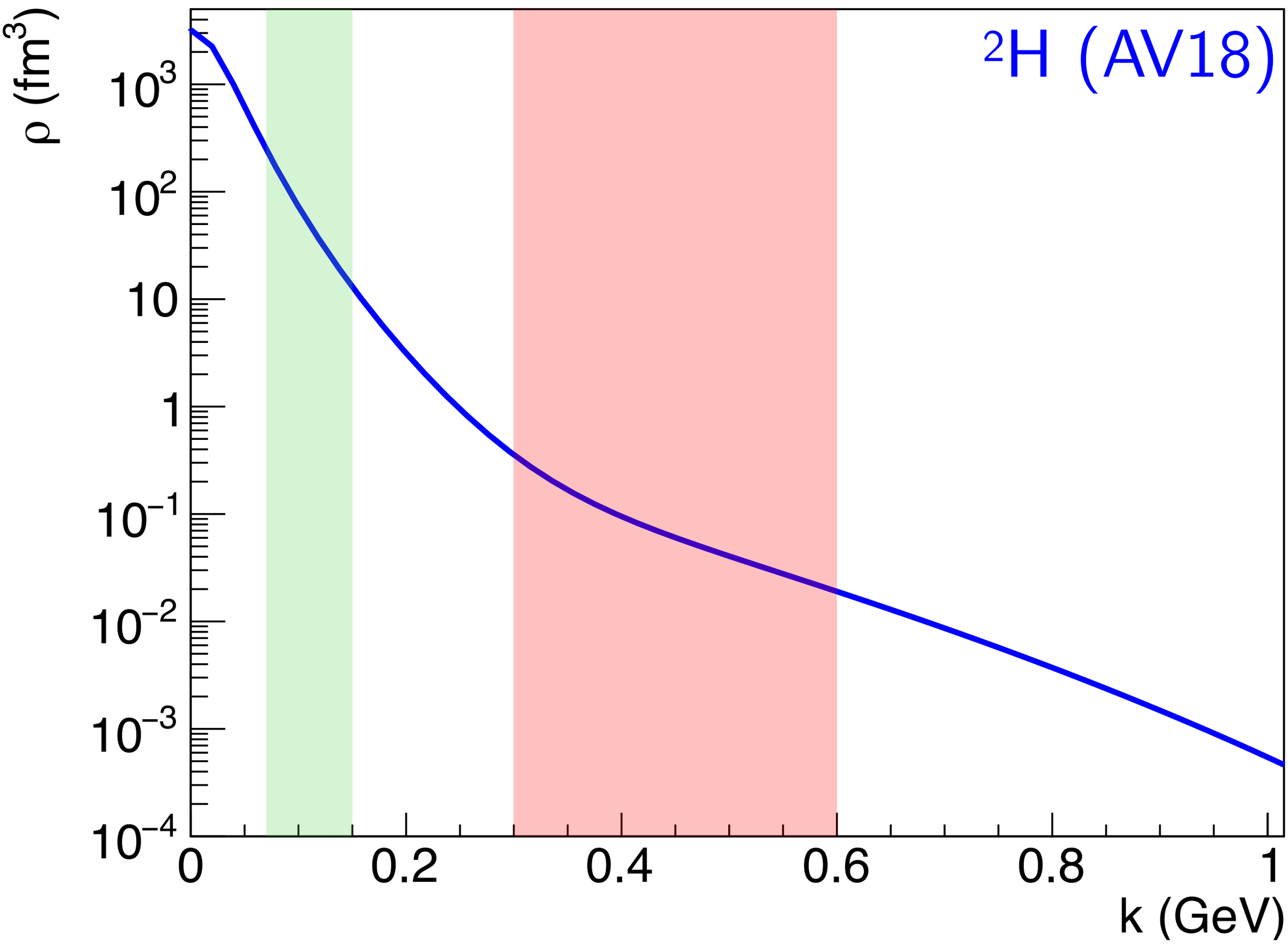
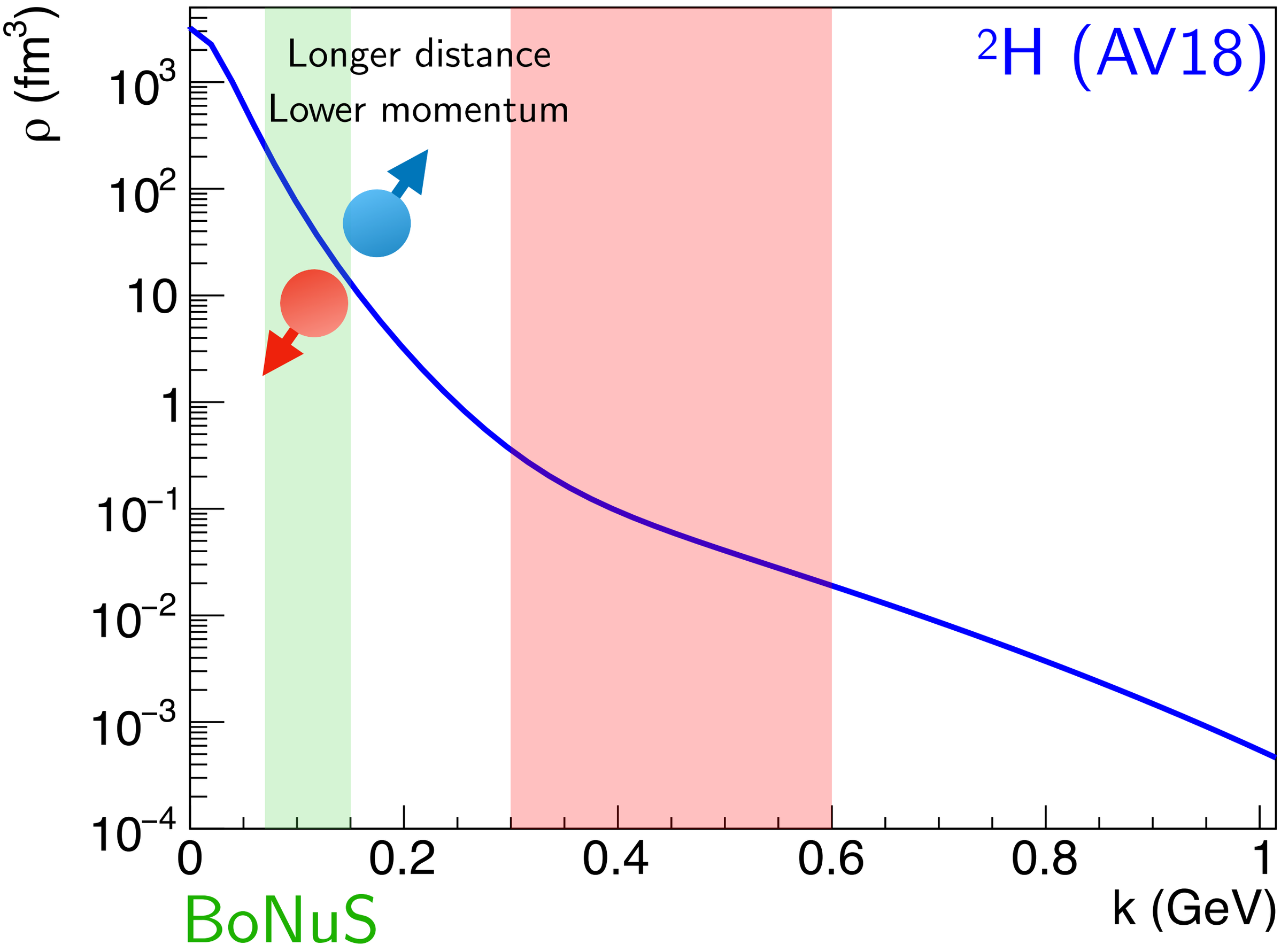
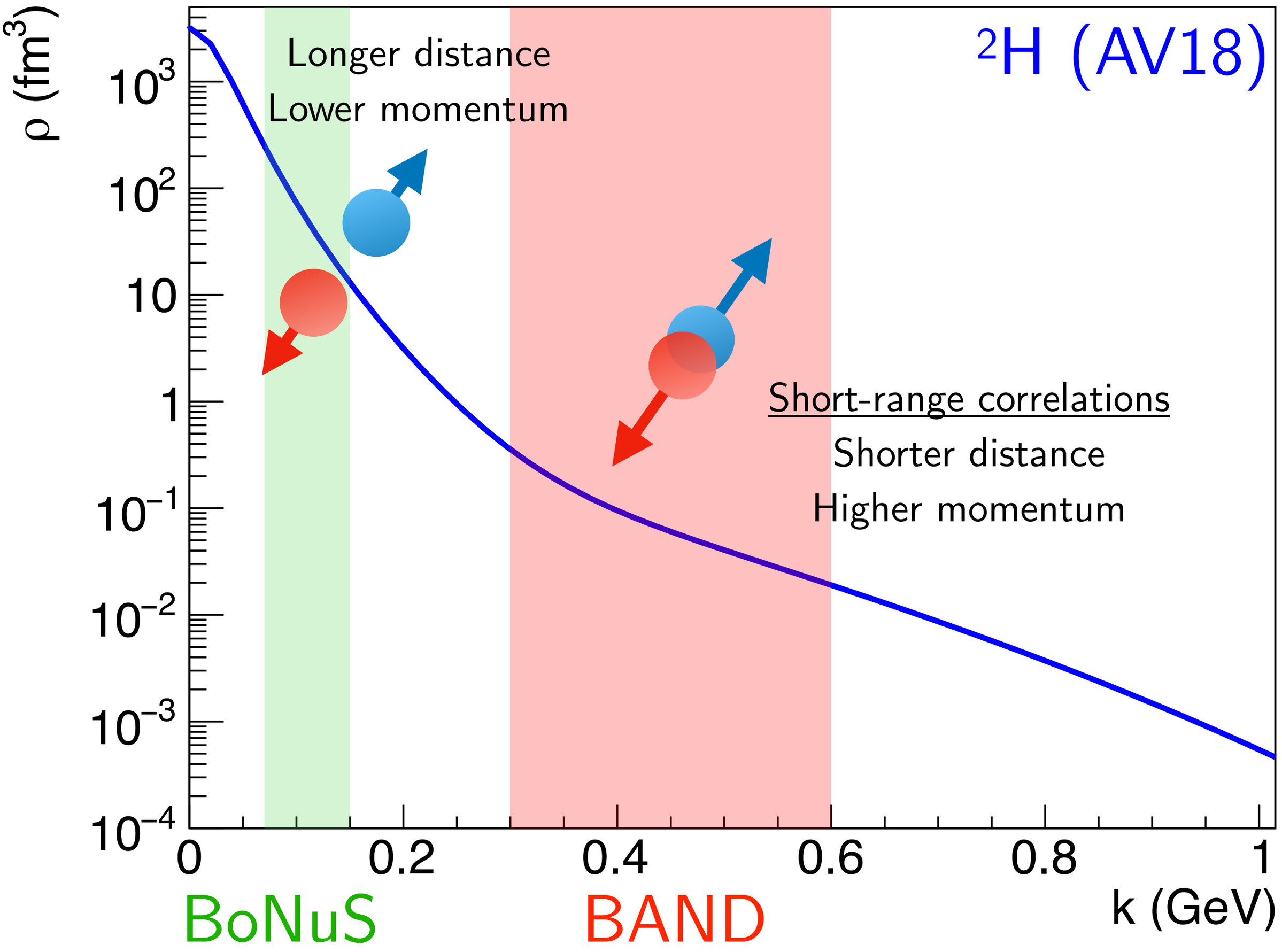
EMC effect: free nucleons ≠ bound nucleons

- Nearly 4 decades, 1000 publications of experiment & theory
- Majority of data from *inclusive measurements*, which integrate parton structure over all nuclear configurations
- Emerging *tagged DIS measurements* are sensitive to initial configuration of the nucleus




^{2}H (AV18)
ρ (fm^3)
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.2
0.4
0.6
0.8
1
k (GeV)

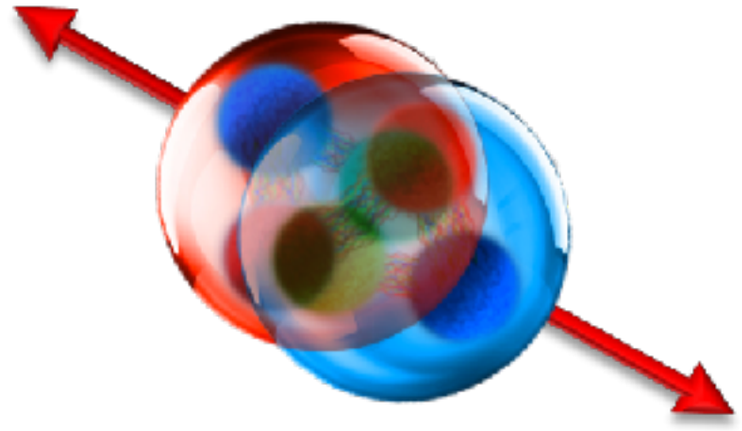

ρ (fm^3)
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Longer distance
Lower momentum
^{2}H (AV18)
0
0.2
0.4
0.6
0.8
1
k (GeV)
BoNuS


ρ (fm^3)
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.2
0.4
0.6
0.8
1
k (GeV)
Longer distance
Lower momentum
Short-range correlations
Shorter distance
Higher momentum
^{2}H (AV18)
BoNuS
BAND

Tagged DIS off deuterium

Deuterium ideal nucleus:

- Know which nucleon was struck (n or p)
- "Simple" two-body system *always correlated*



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- Know which nucleon was struck (n or p)
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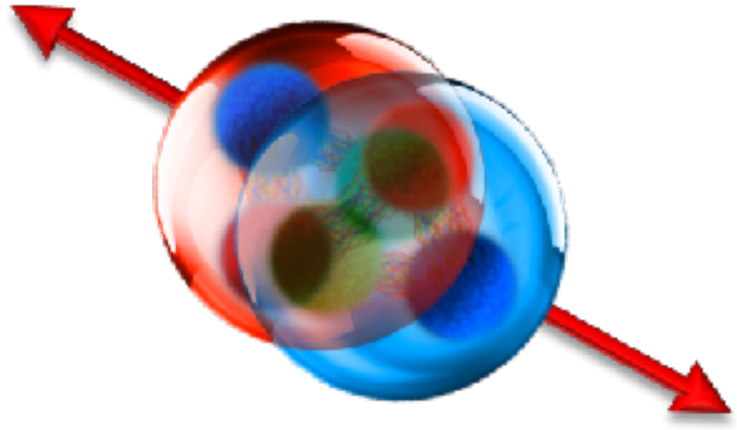
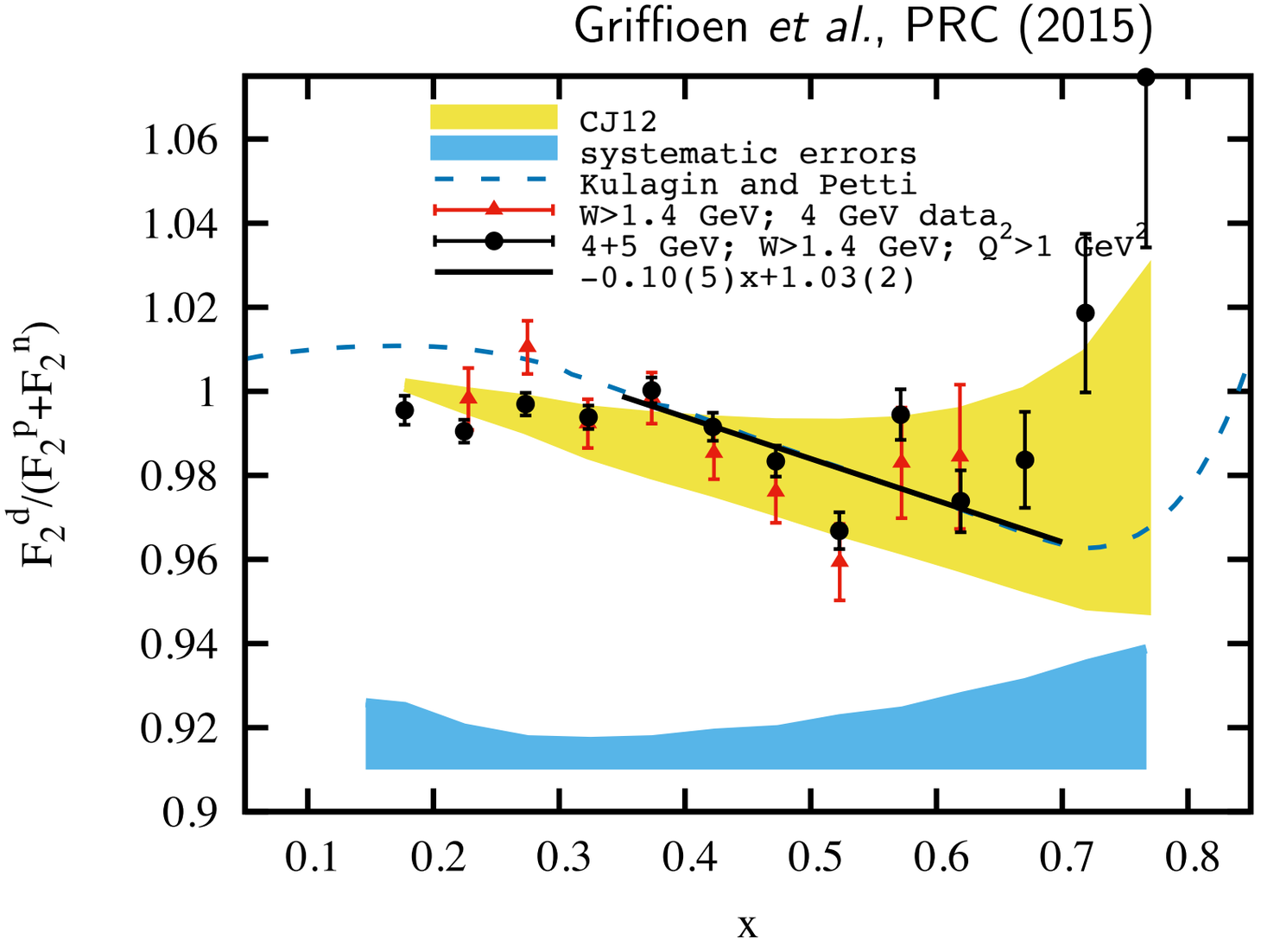
- But EMC effect is *small*



Griffioen *et al.*, PRC (2015)



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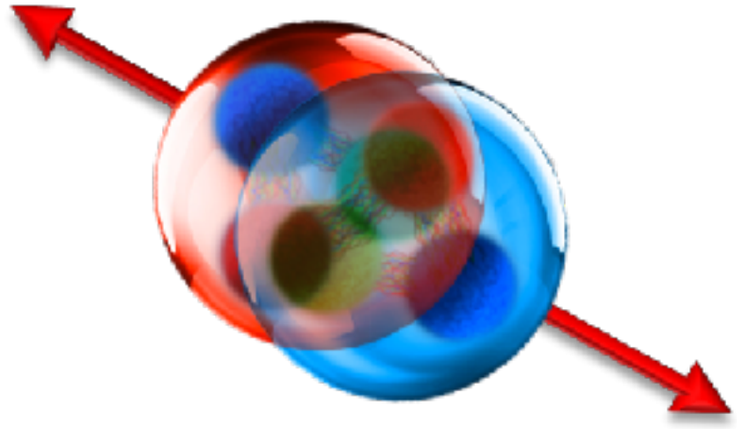
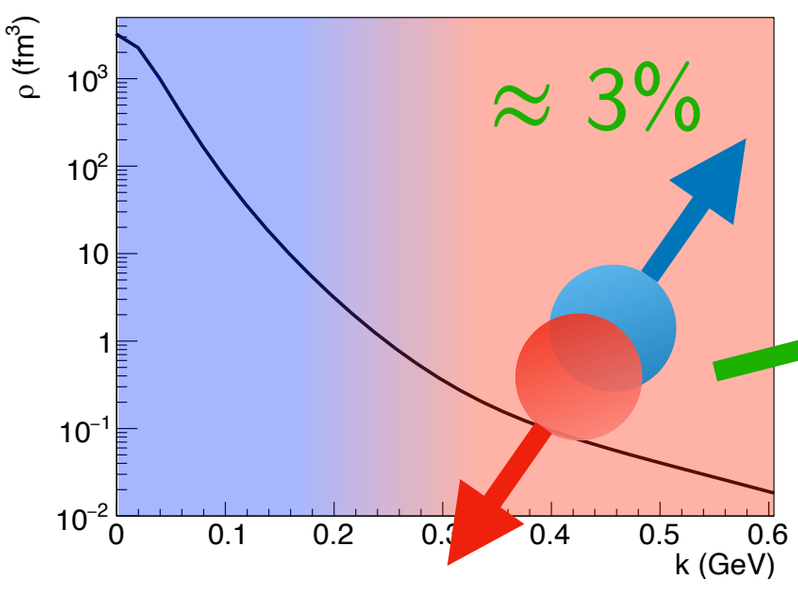
Deuterium ideal nucleus:



- Know which nucleon was struck (n or p)
- "Simple" two-body system *always correlated*
- But EMC effect is *small*
- *SRC hypothesis predicts large modification of (rare) SRC states!*



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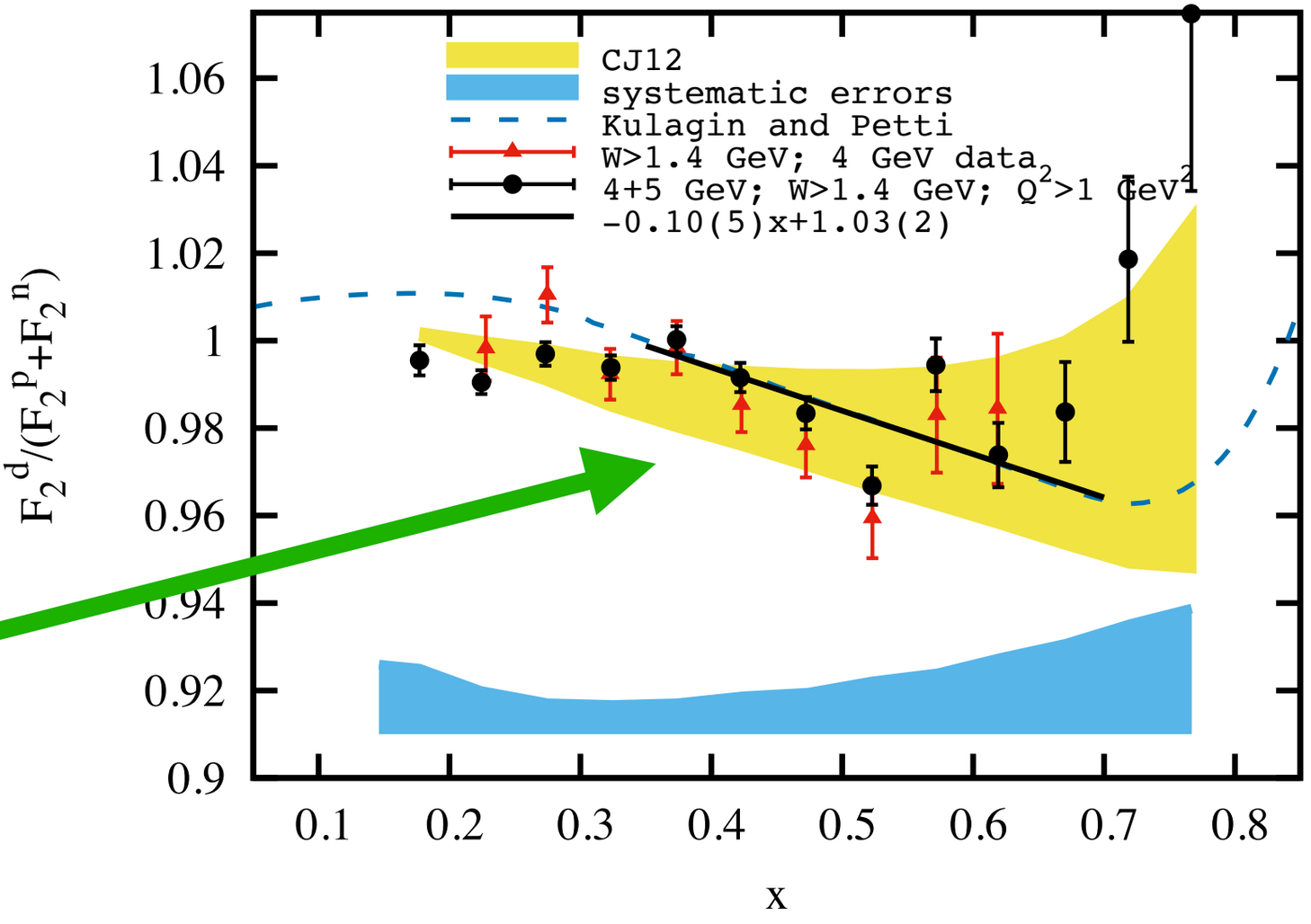
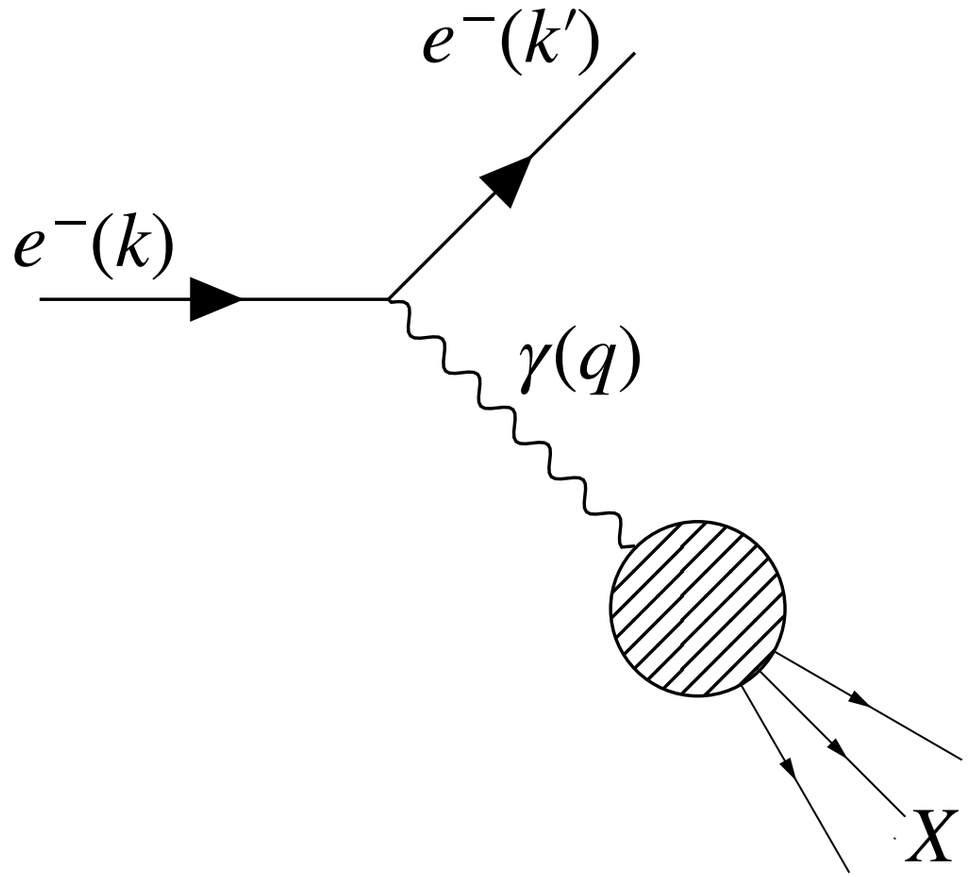
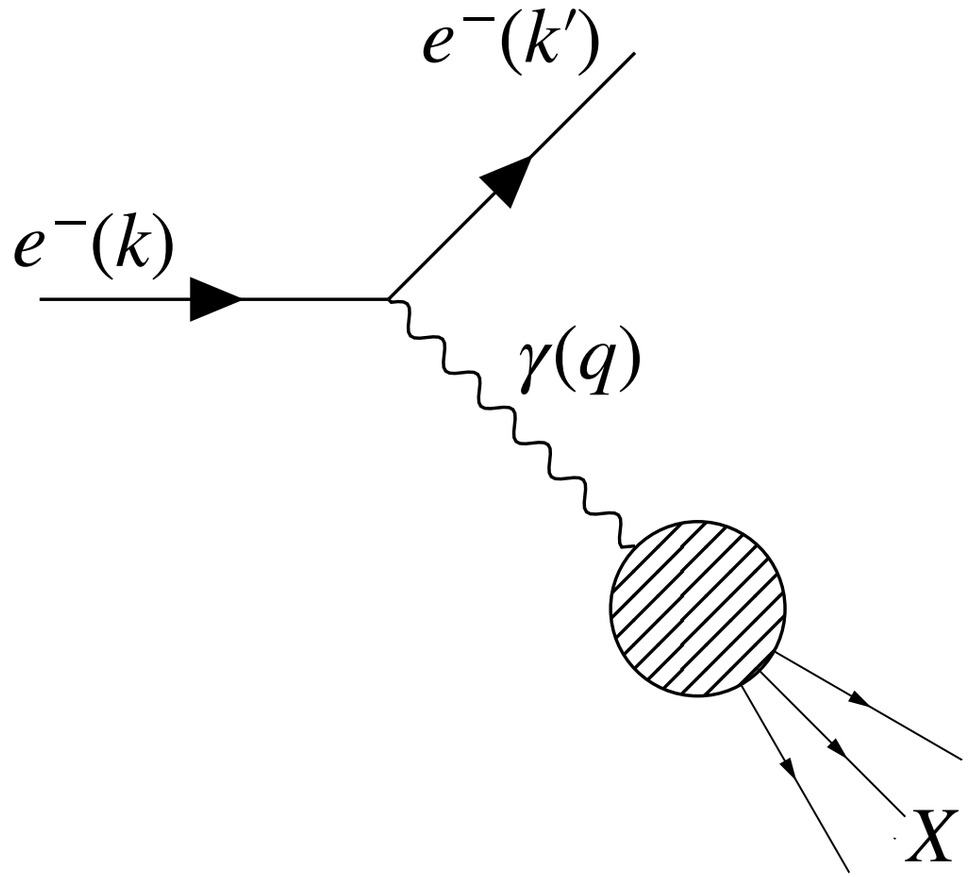


Tagged DIS 101



Tagged DIS 101

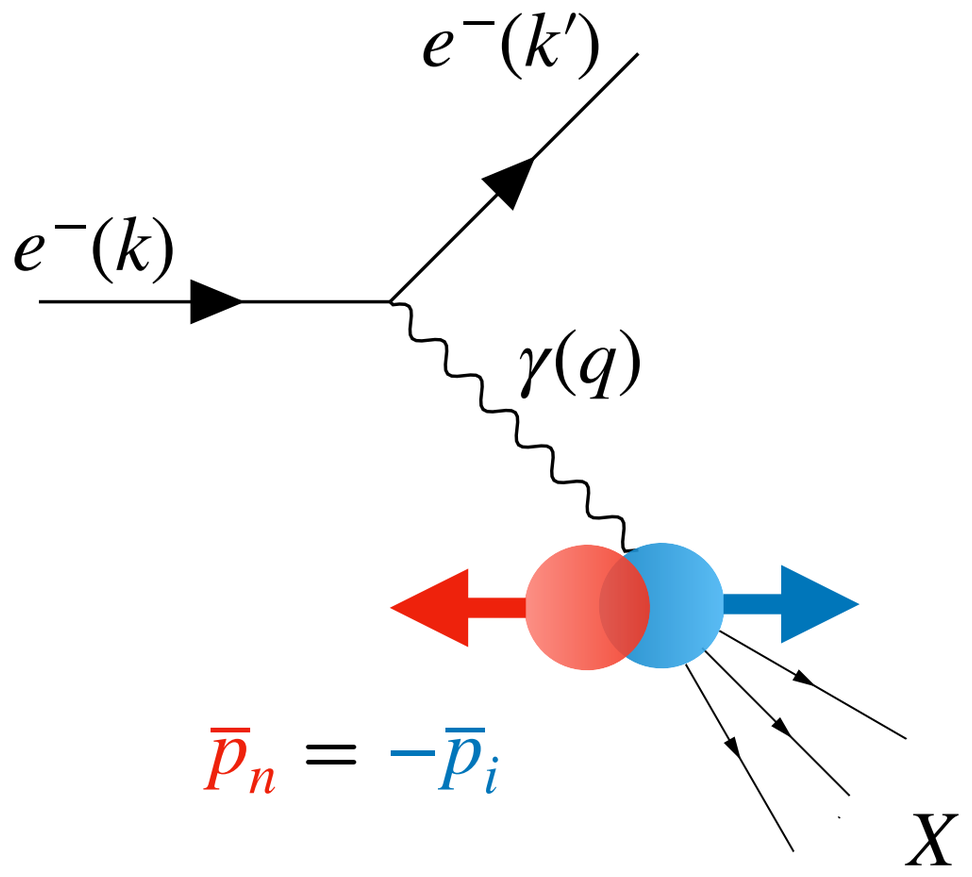


Standing nucleon $P_0 = (\overline{0}, M_i)$

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

$$x_B = \frac{Q^2}{2M\nu}$$

Tagged DIS 101



Standing nucleon $P_0 = (\overline{0}, M_i)$

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

$$x_B = \frac{Q^2}{2M\nu}$$

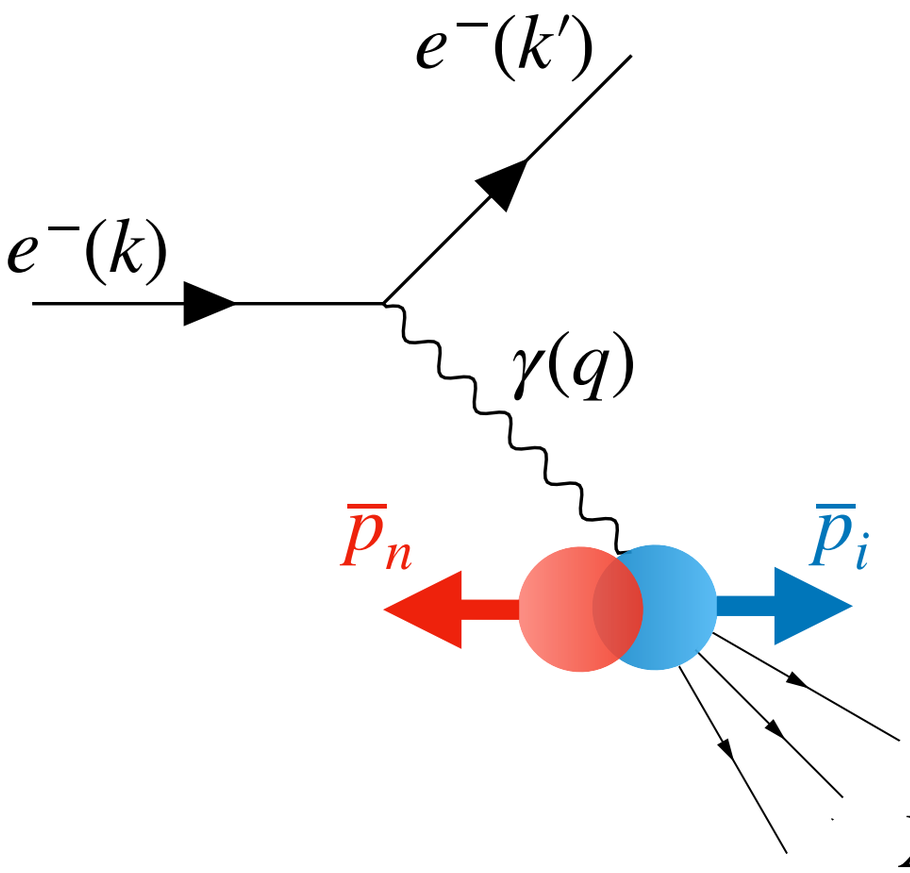
Moving nucleon: $P_i = (\overline{p}_i, E_i)$

$$(W')^2 = (P_i + q)^2$$

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

$$\alpha_S = \frac{E_n - |p_n| \cos\theta_{nq}}{M_n}$$

Bound proton structure with tagged DIS

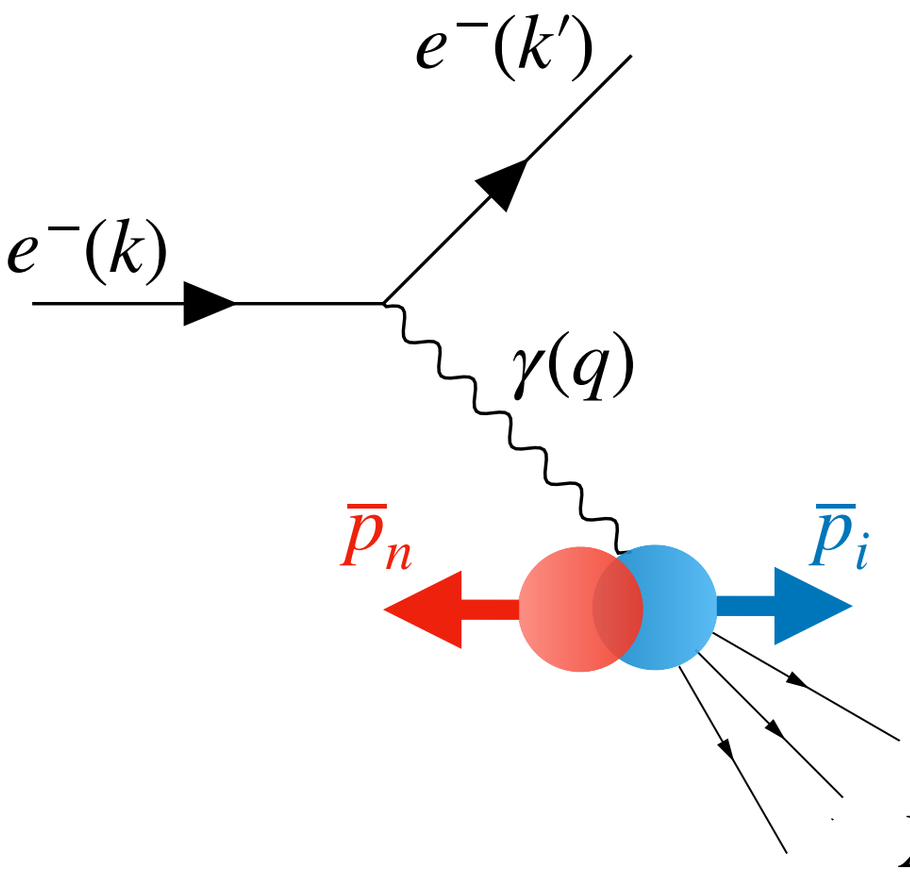


PWIA: assume *factorization* and

no spectator rescattering

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

Bound proton structure with tagged DIS



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

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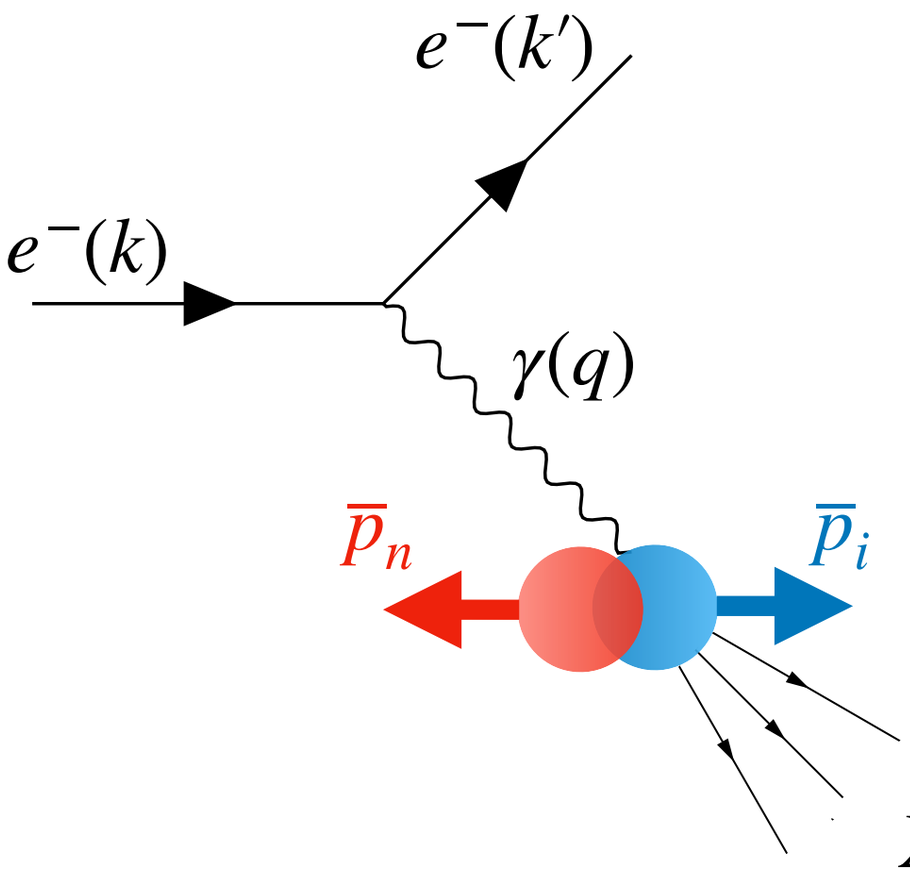

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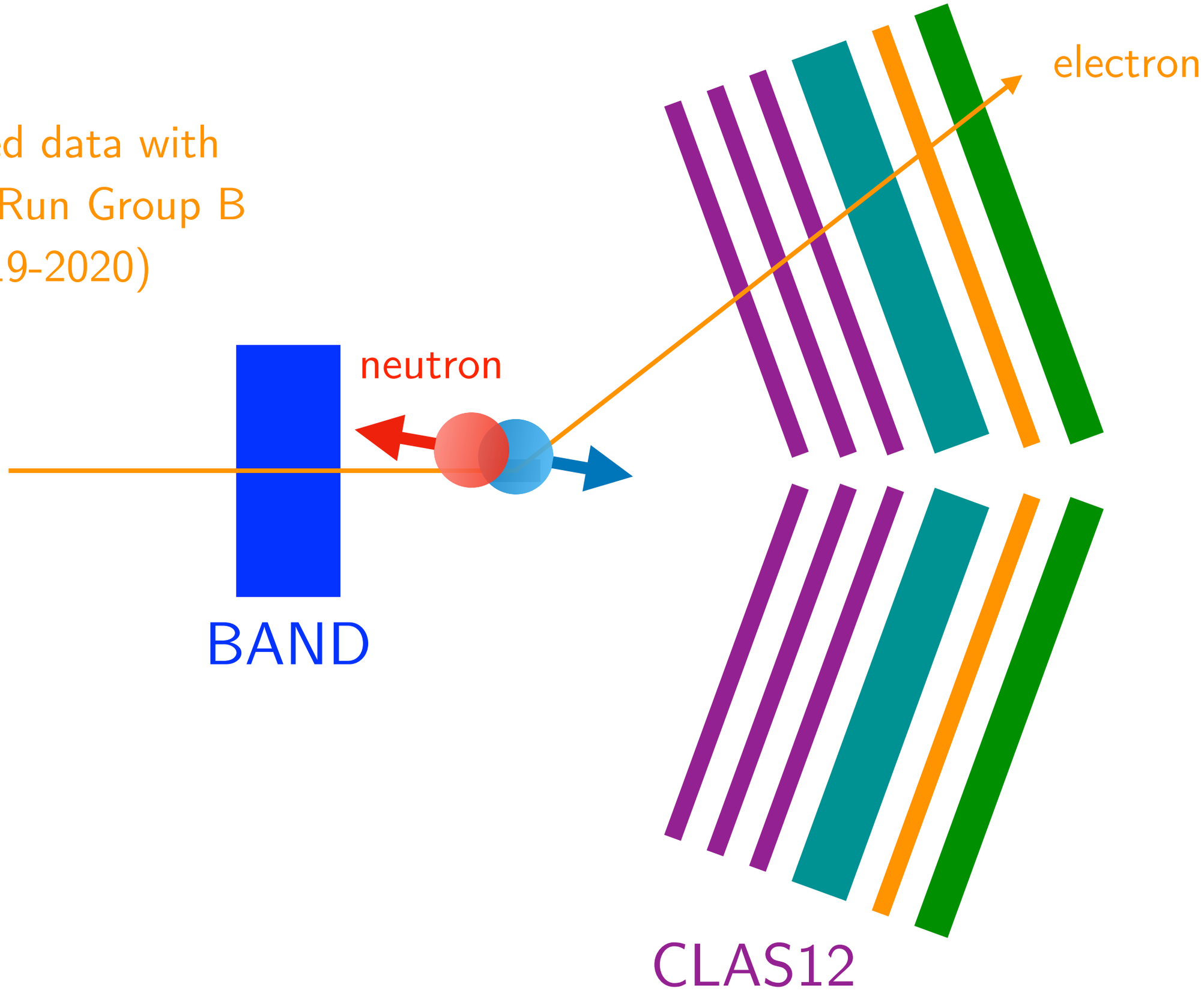
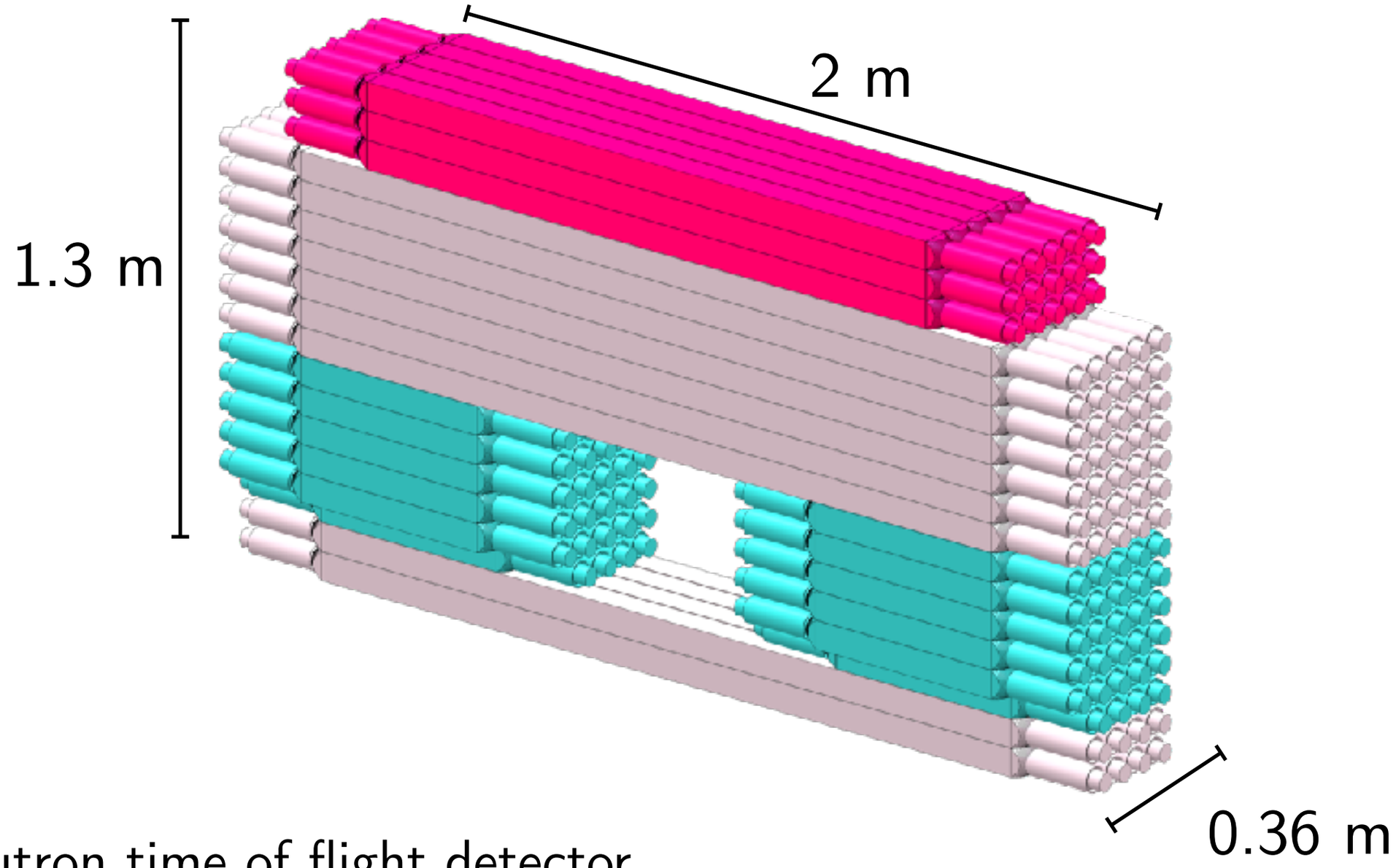
$$\frac{\textit{bound}\ \text{proton}}{\textit{free}\ \text{proton}}$$

Tagged DIS with BAND

Collected data with
CLAS12 Run Group B
(2019-2020)



Backward Angle Neutron Detector (BAND)

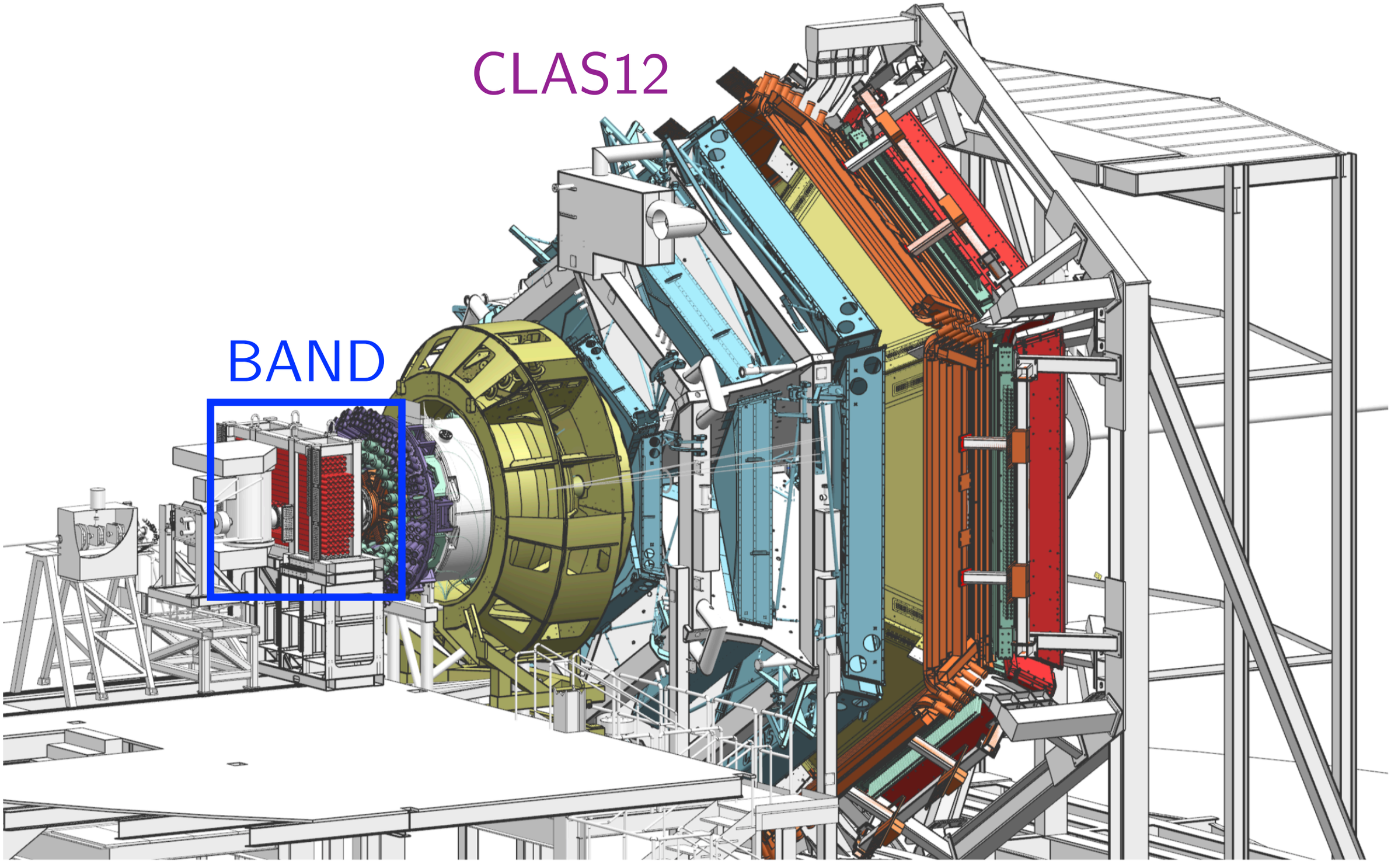


- Neutron time of flight detector
- 116 plastic scintillator bars + veto layer
- ≈3 m upstream of target

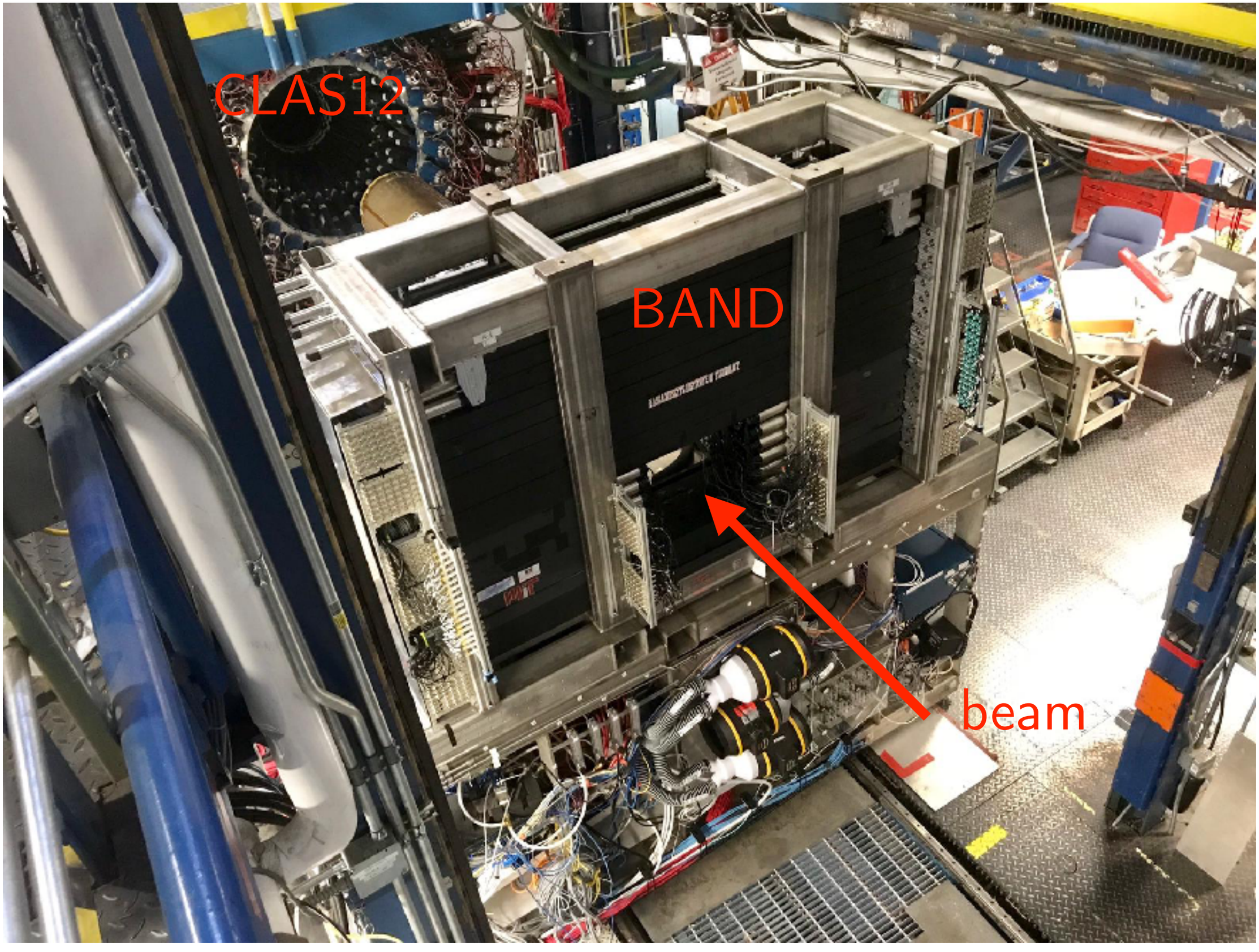
Segarra *et al.*, NIMA (2020)

Denniston *et al.*, NIMA (2020)

Tagged DIS with BAND



BAND in Hall B



Analysis outline

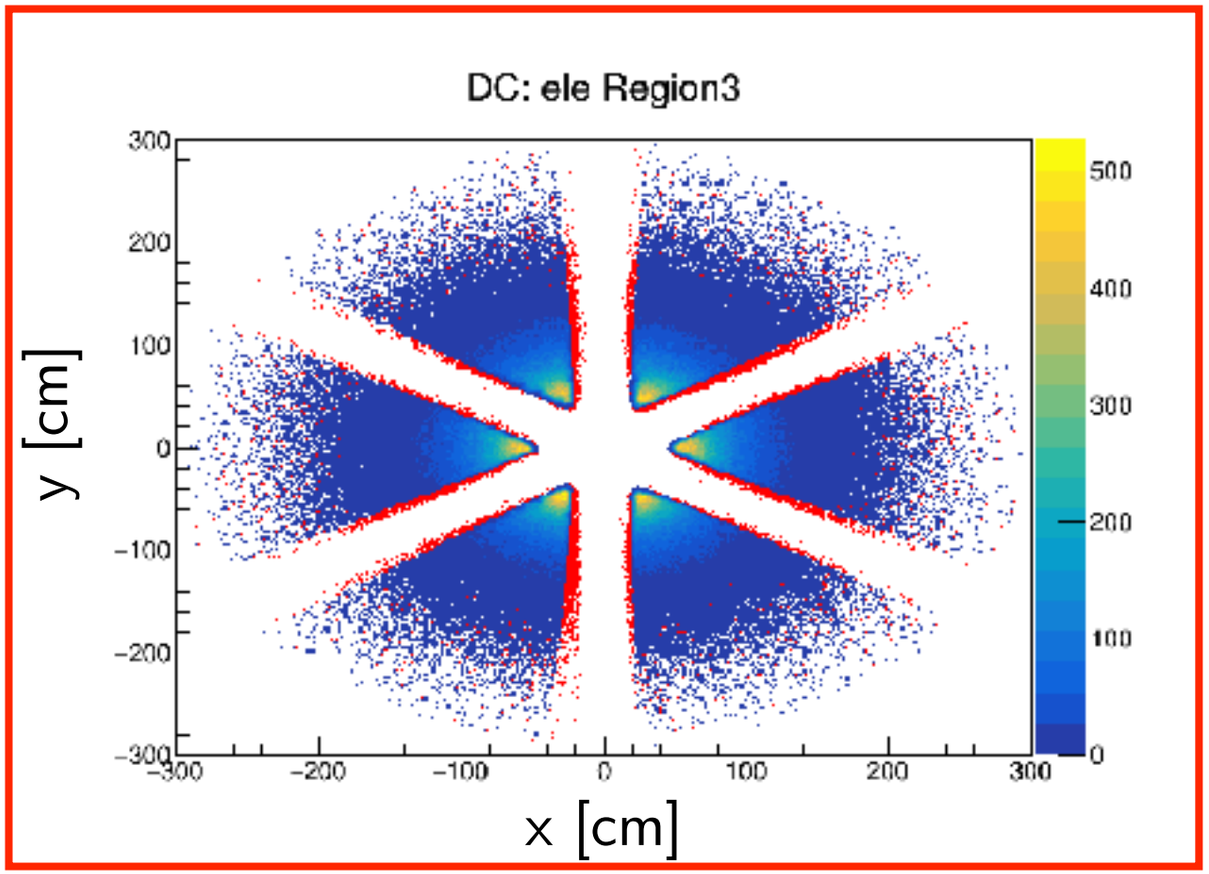
- Event selection

- Inclusive DIS analysis
  → *CLAS12 electron*

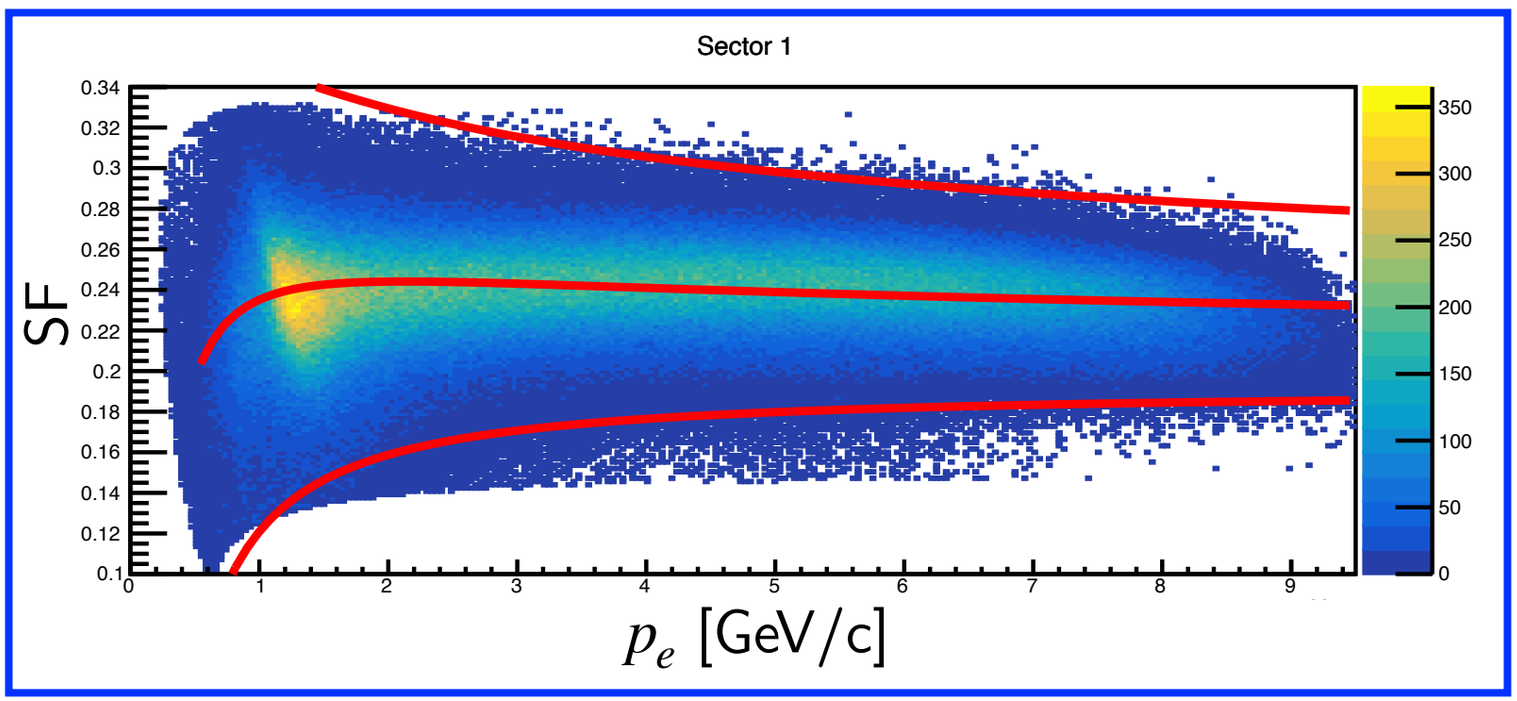
- Quasielastic analysis
  → *CLAS12 electron/proton + BAND neutron*

- Tagged DIS analysis

CLAS12 electron selection



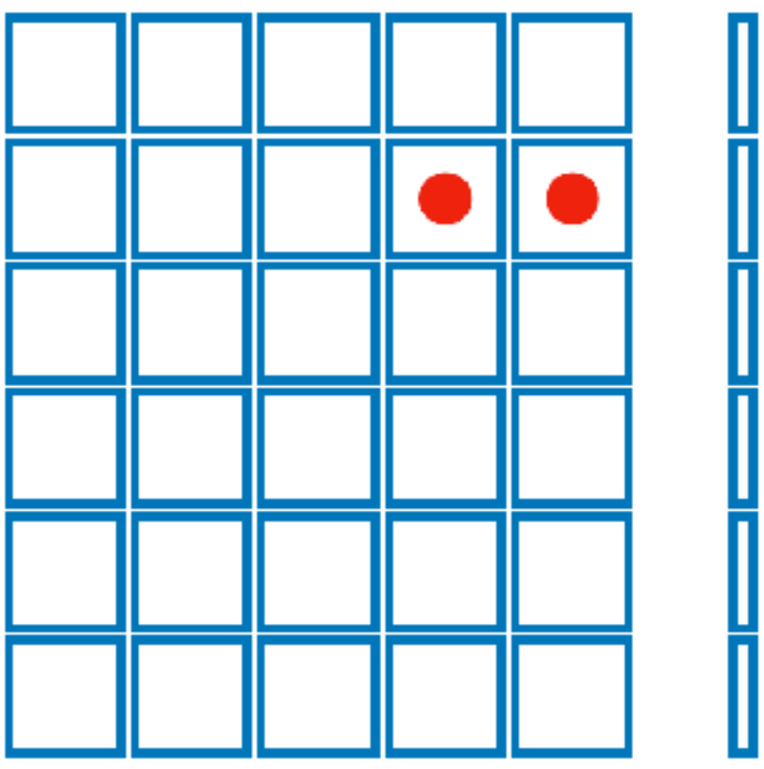
- Charge/PID requirement
- DC fiducial cuts
- ECAL/PCAL fiducial cuts
- Sampling fraction vs. E_{PCAL} ($\pm 5\sigma$)
- Sampling fraction vs. p_e ($\pm 5\sigma$)
- $0.17 < E/p_e < 0.3$ GeV
  ($0.2 < E/p_e$ for $p_e > 4.5$ GeV)



Electron survival rates consistent with RGA & GEMC

Neutron selection: Identifying good hits

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



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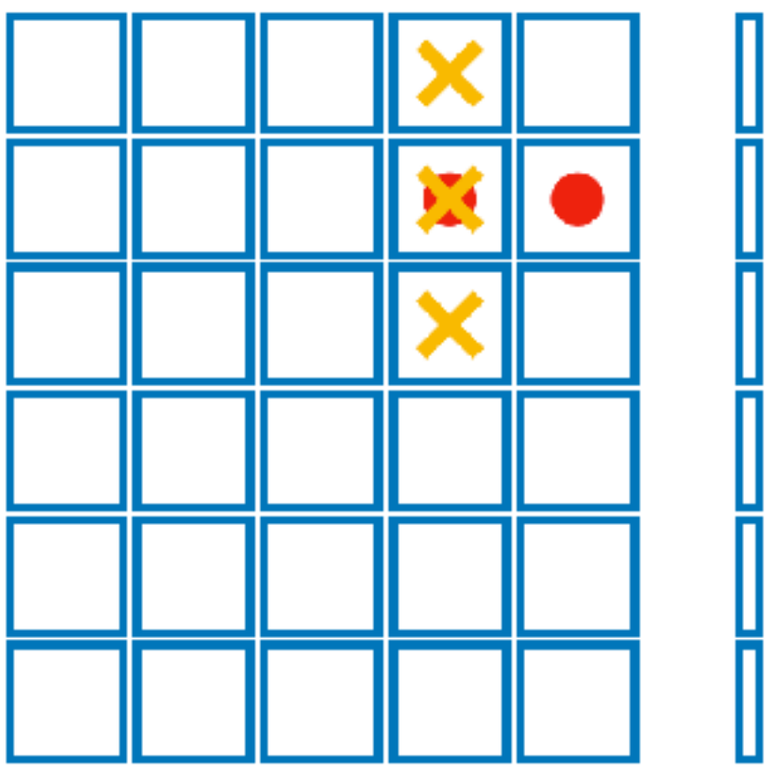

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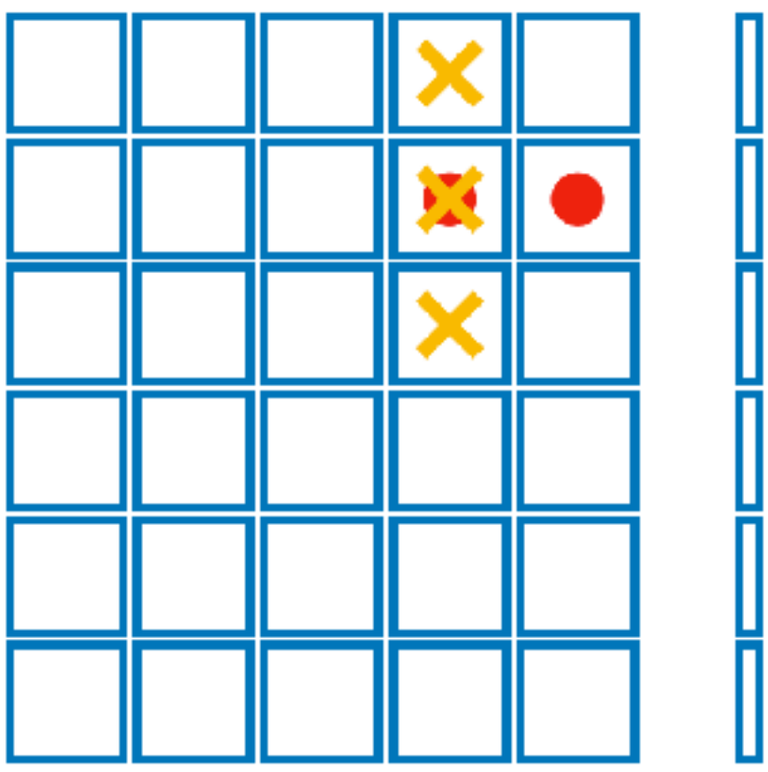
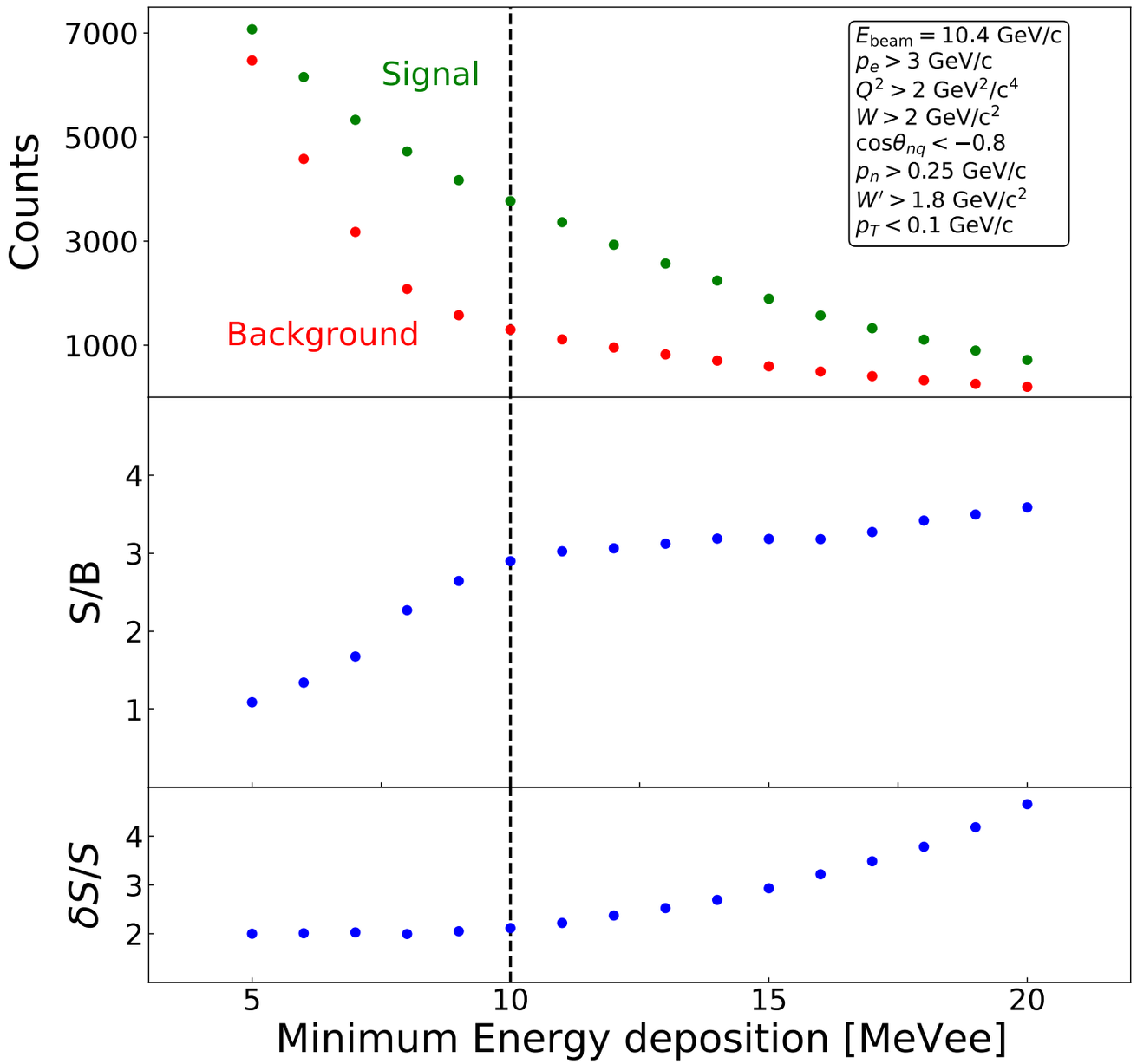


- If single hit (most of the time) ✔
- If 2 hits:
  - Close together (from same interaction)? ✔
  - Far apart? ✘
- If $>$ 2 hits ✘

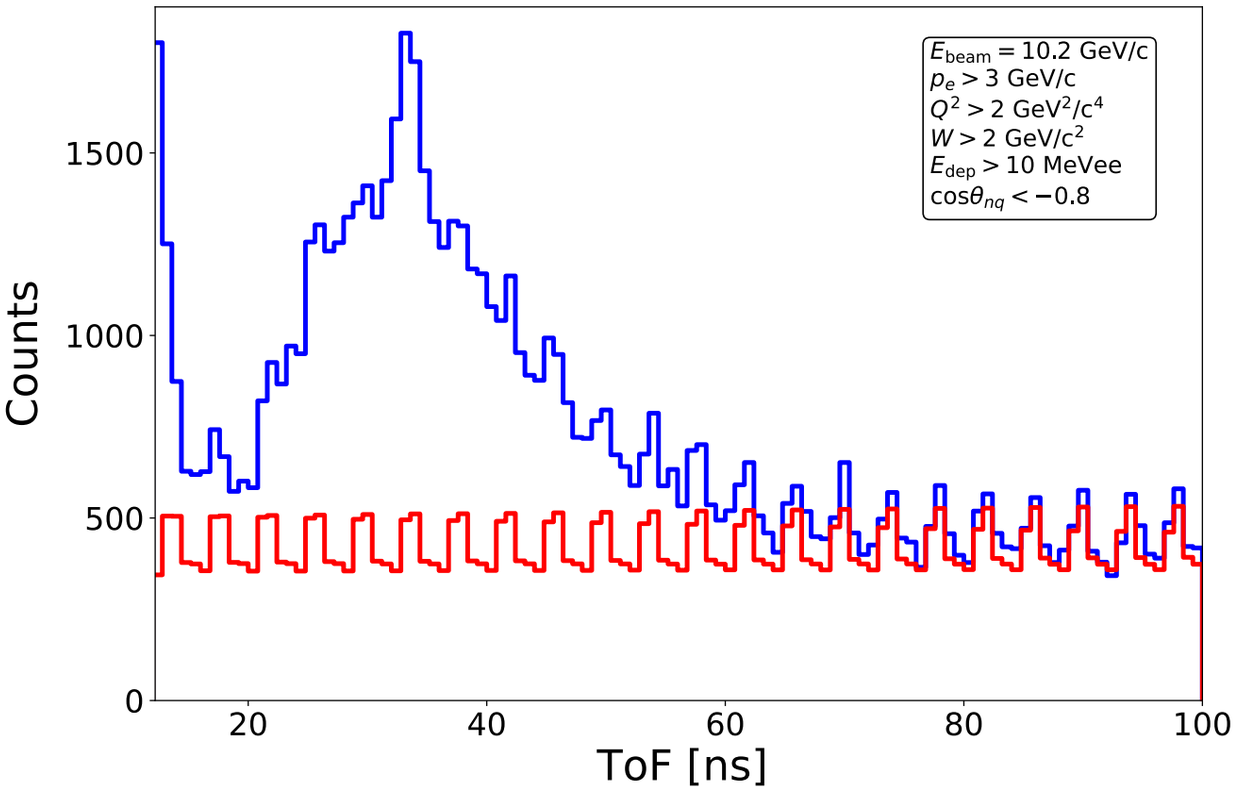
Neutron selection: E_{dep} and fiducial cuts

- $E_{dep} > 10$ MeVee



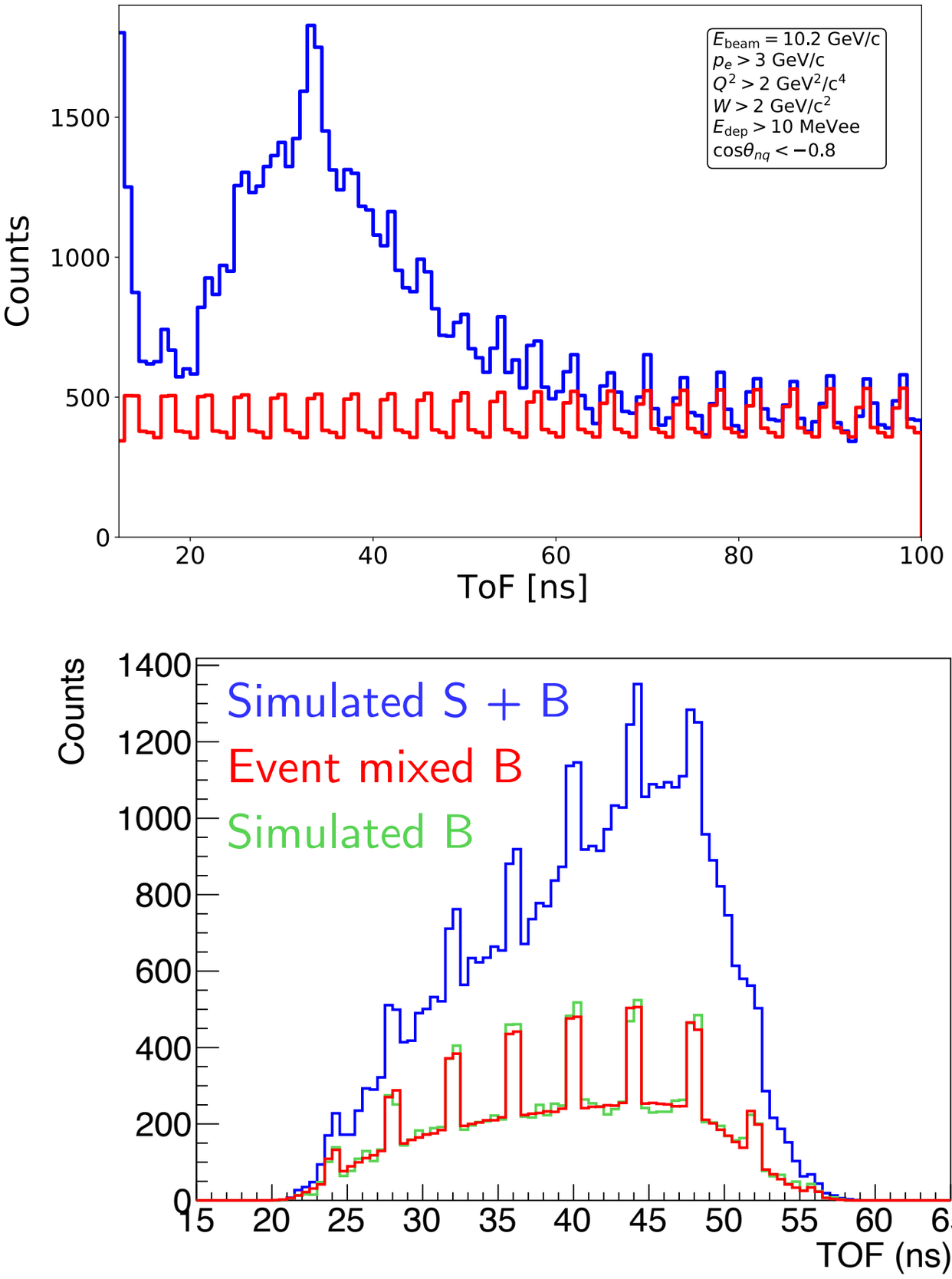
- Fiducial cut 10 cm from BAND edges (reflection)
- $\theta_n < 168.5°$ (beam pipe)

Random coincidence background subtraction

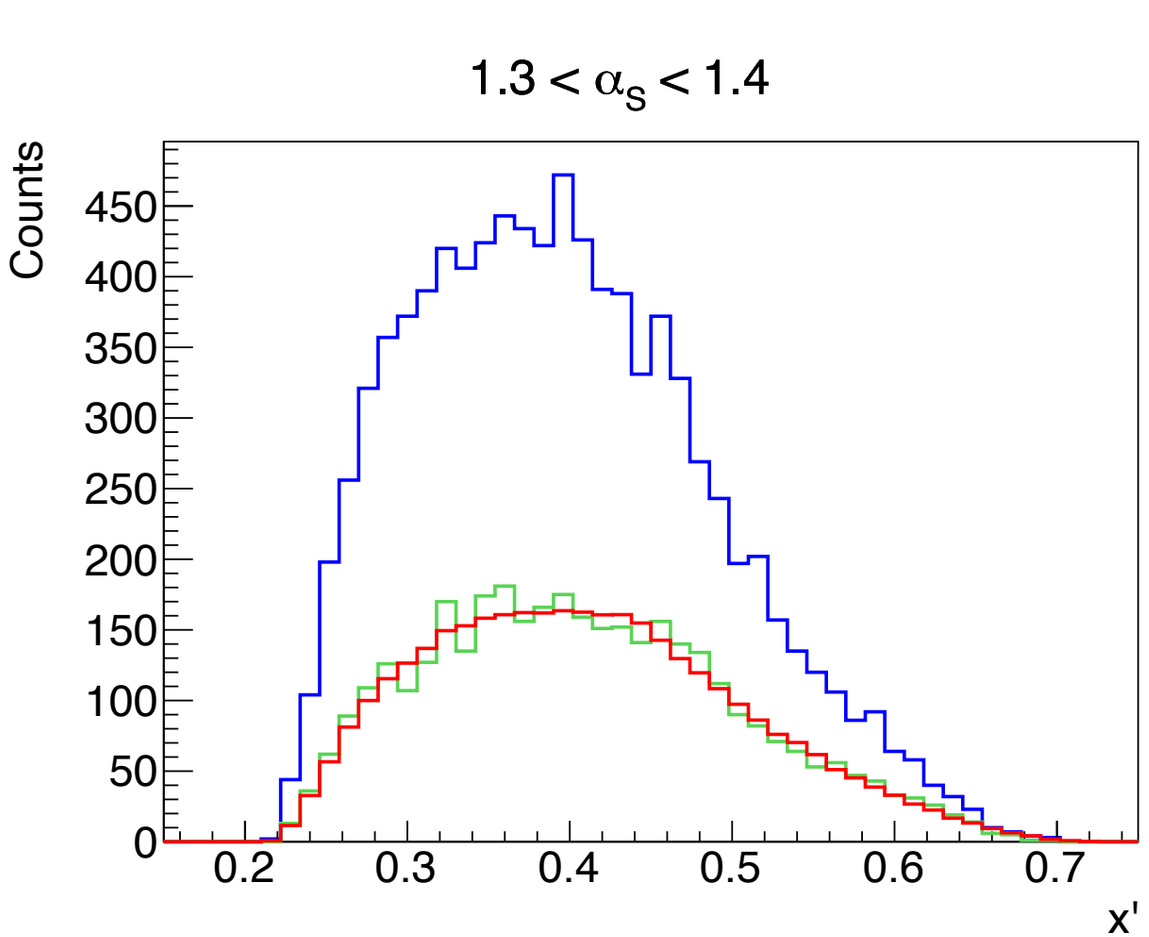


- Event mixing for background subtraction
- Account for beam structure

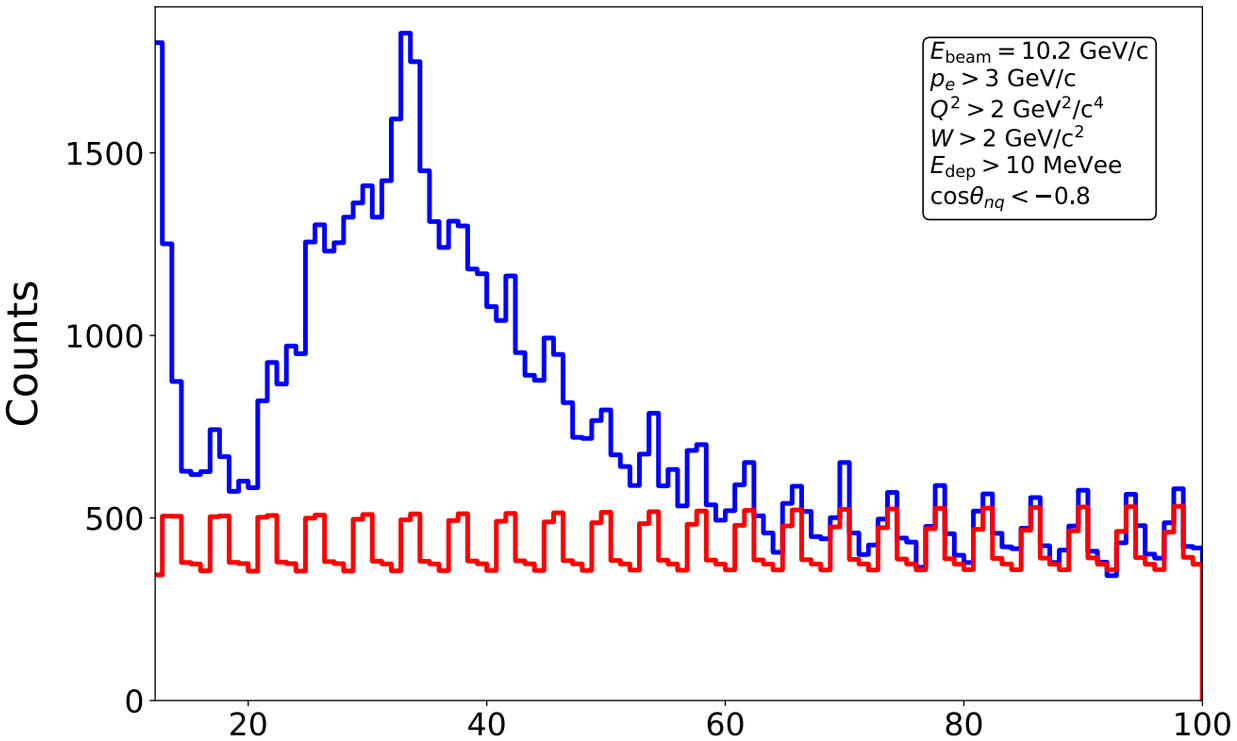
Random coincidence background subtraction



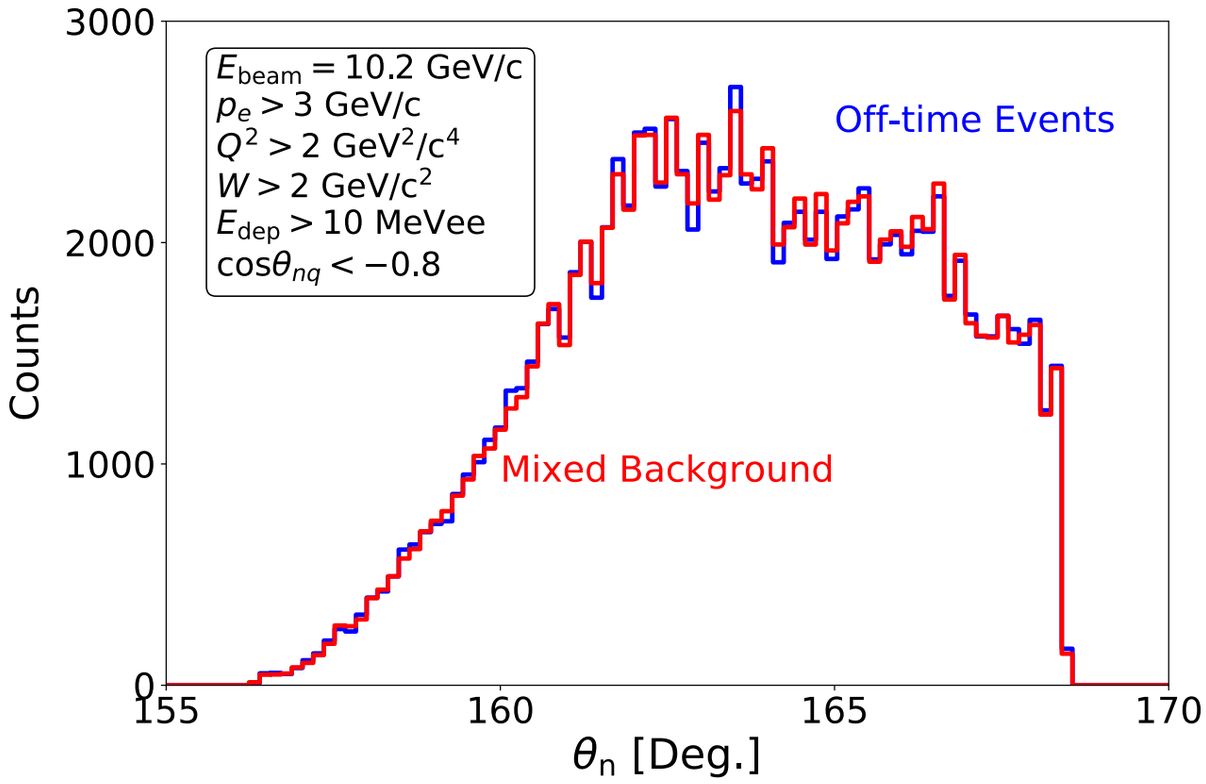
- Event mixing for background subtraction
- Account for beam structure
- Simulation closure test

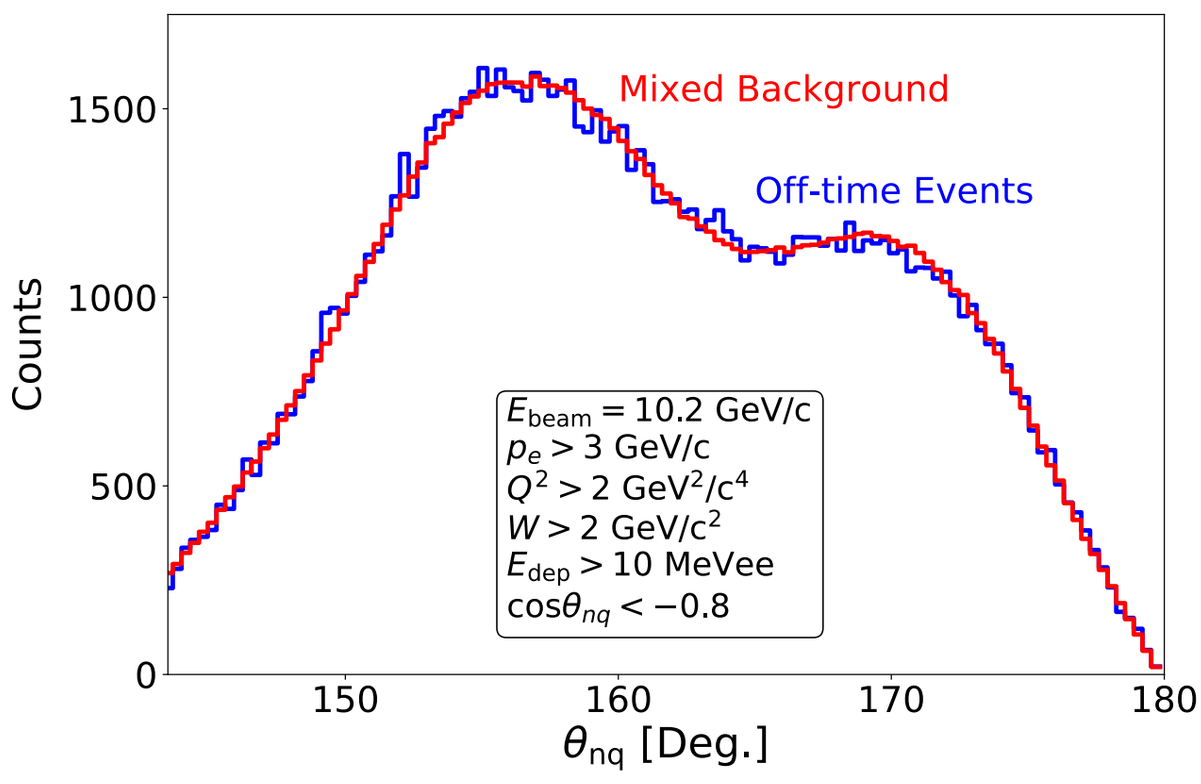


Random coincidence background subtraction



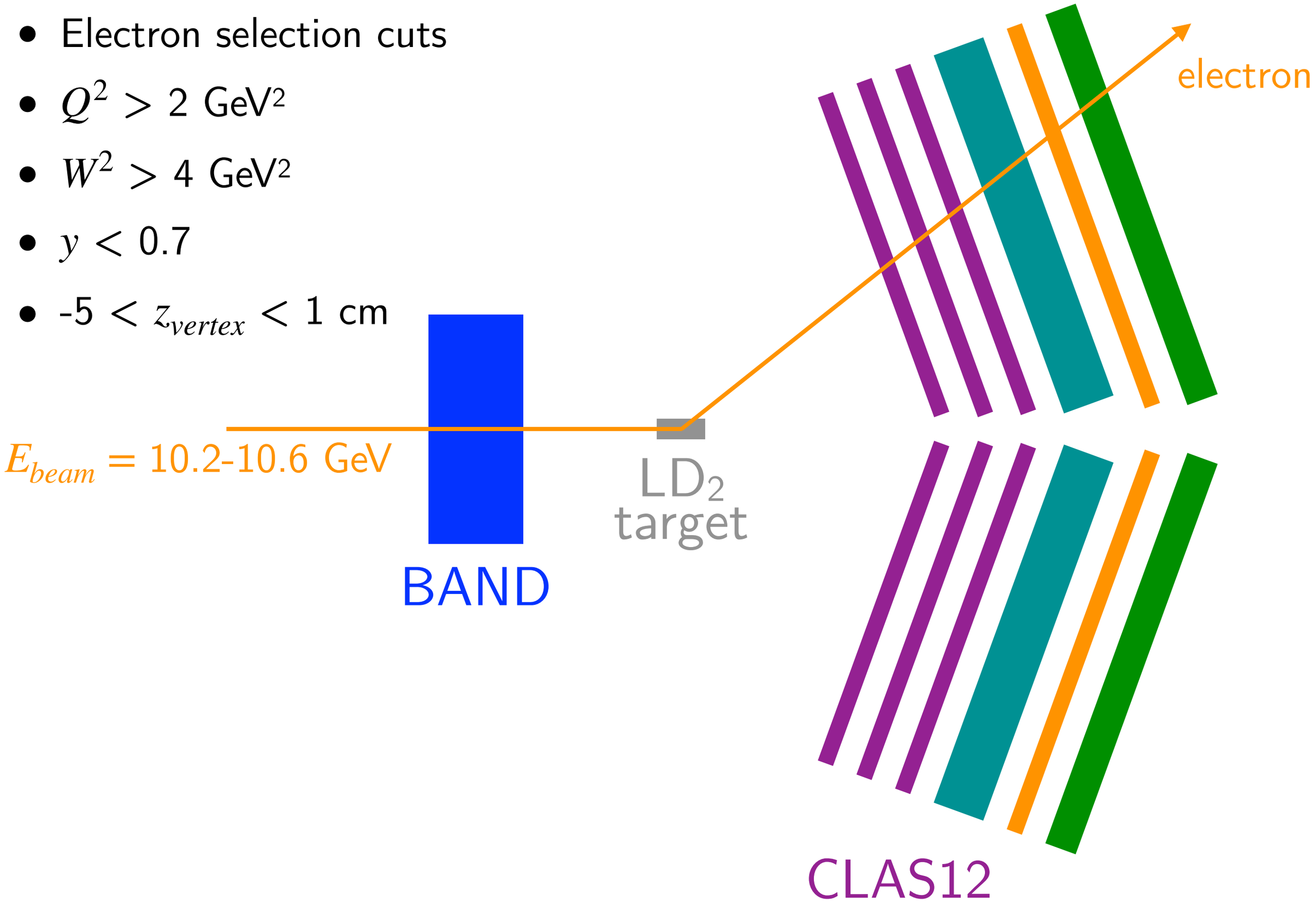
- Event mixing for background subtraction
- Account for beam structure
- Simulation closure test
- Offtime/event mixed consistency





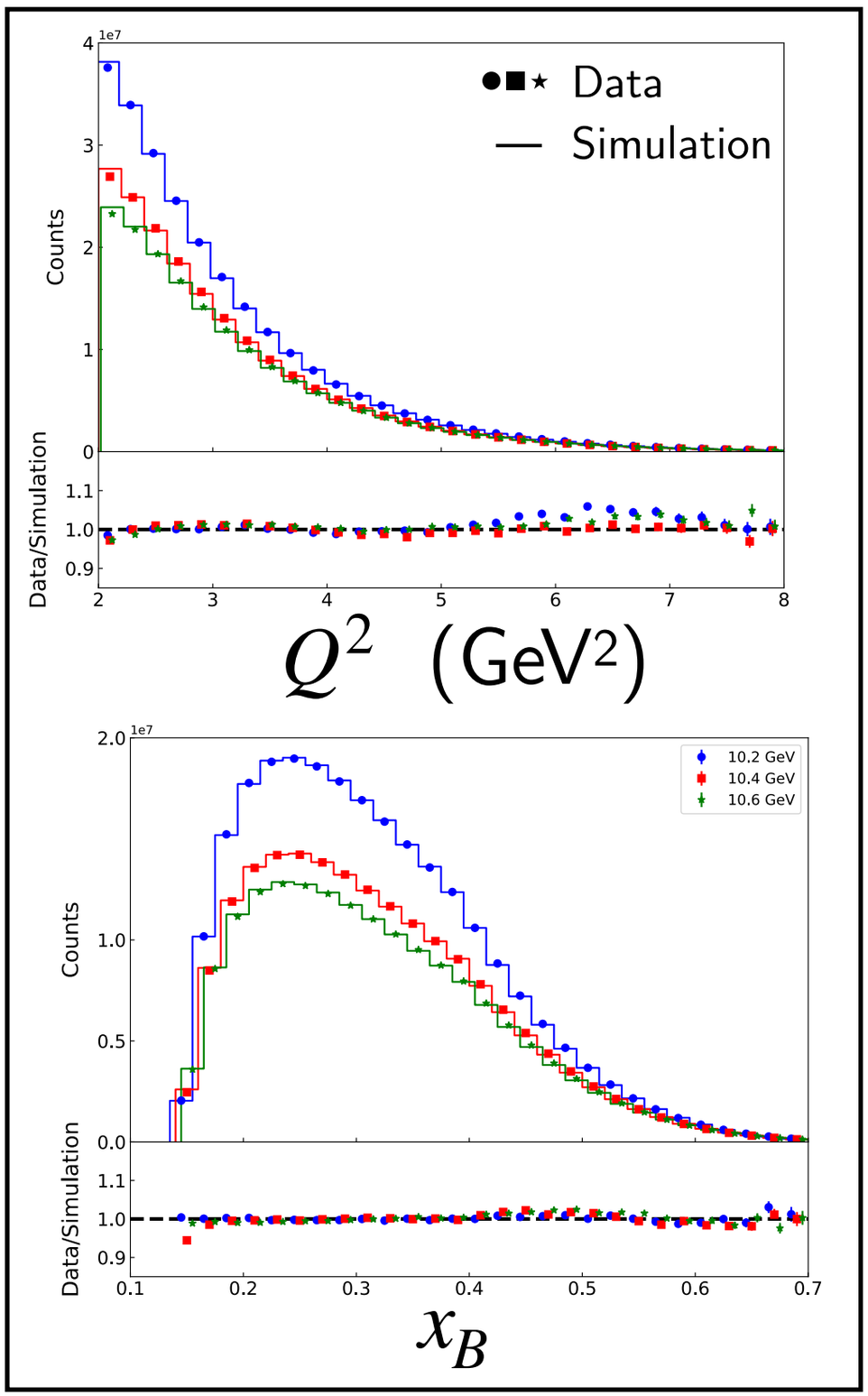
CLAS12: Inclusive DIS

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

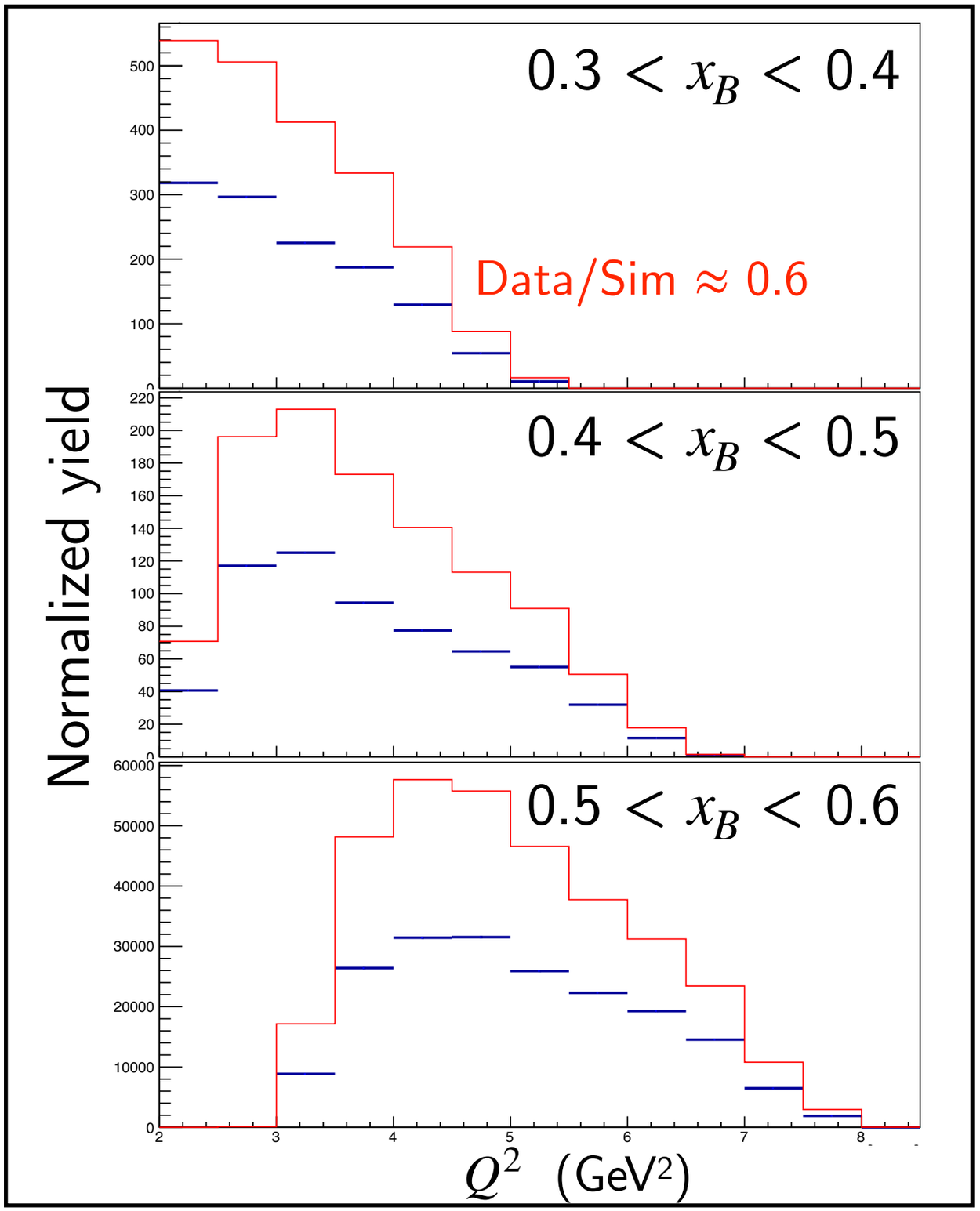


Inclusive DIS $D(e,e')X$

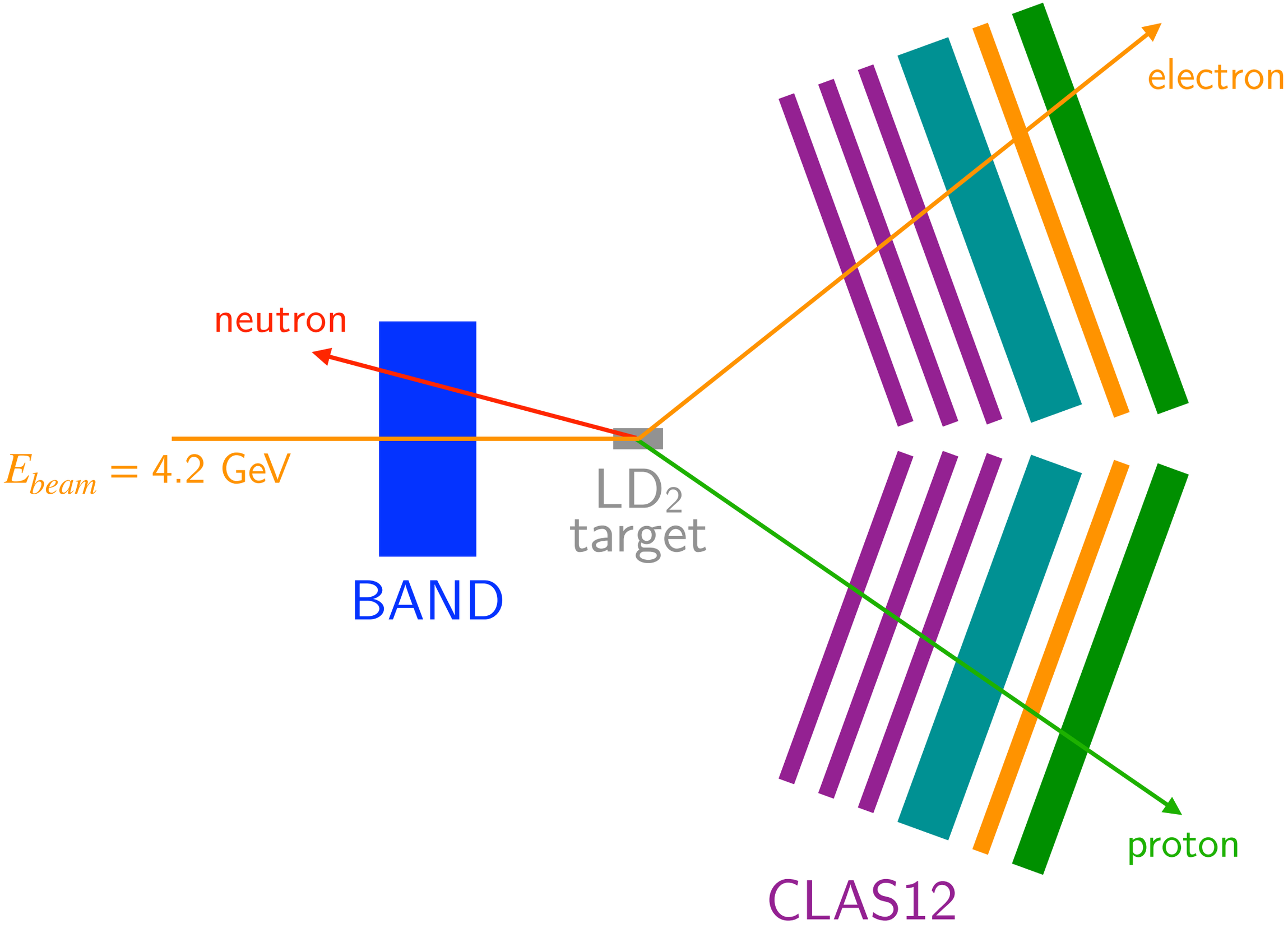
Integral normalized



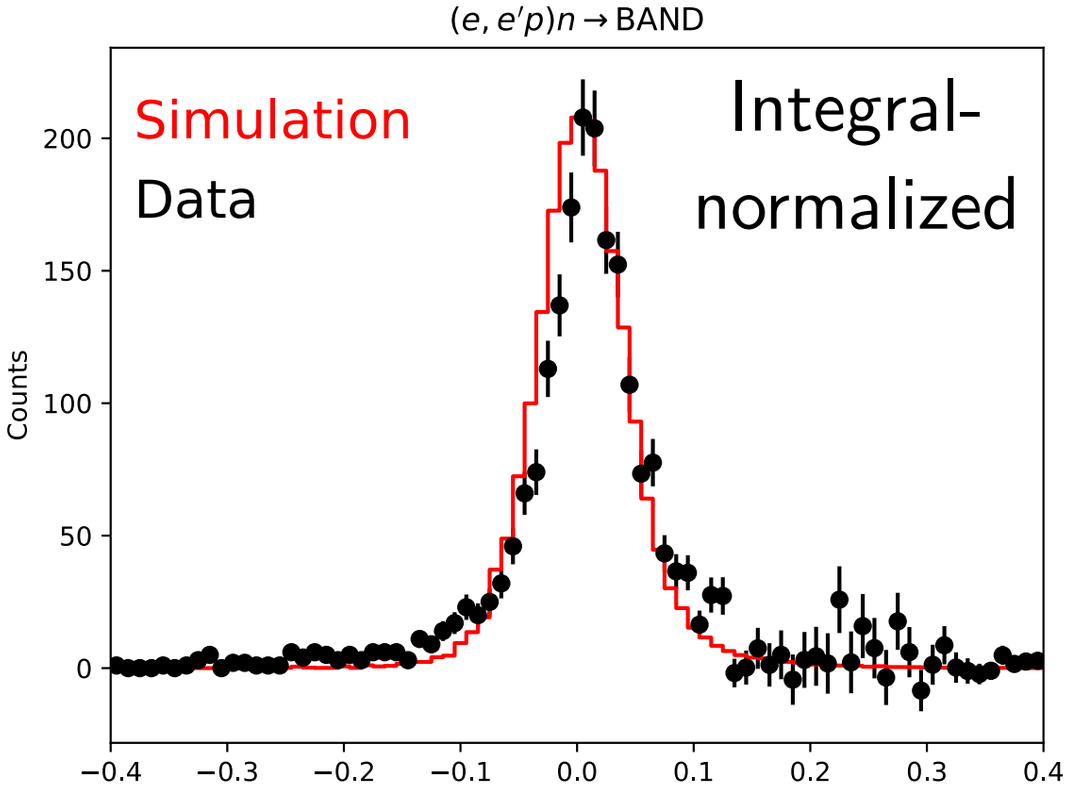
Luminosity normalized

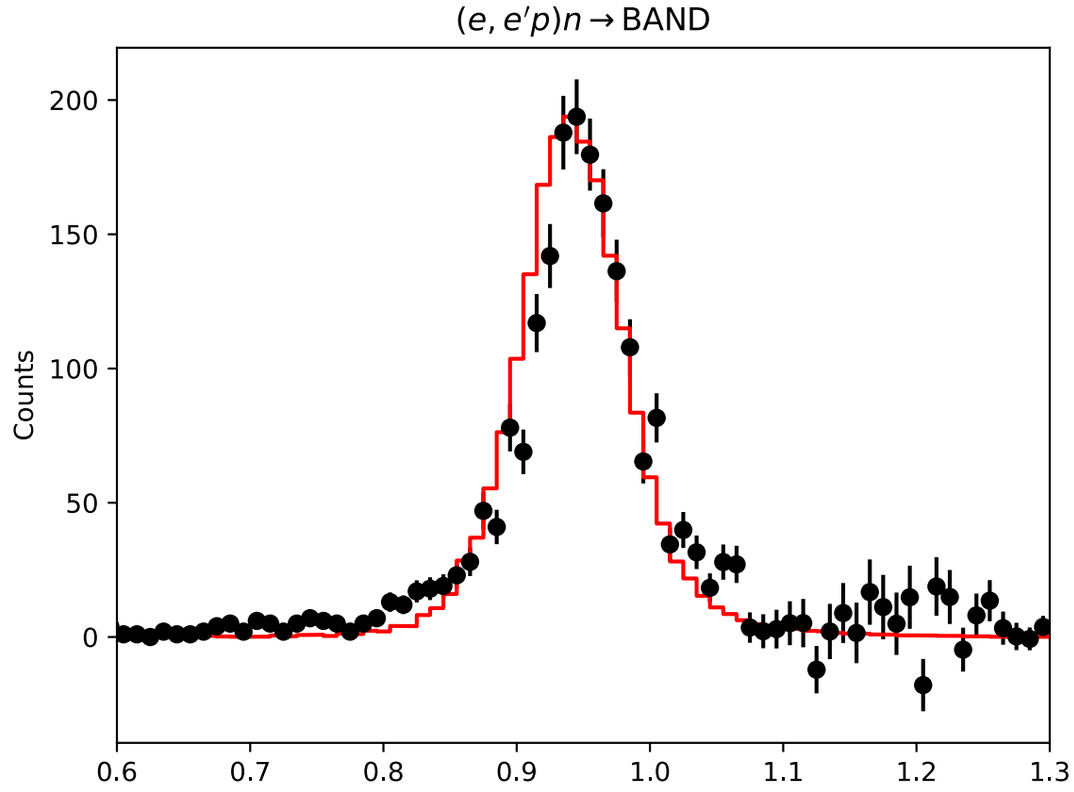


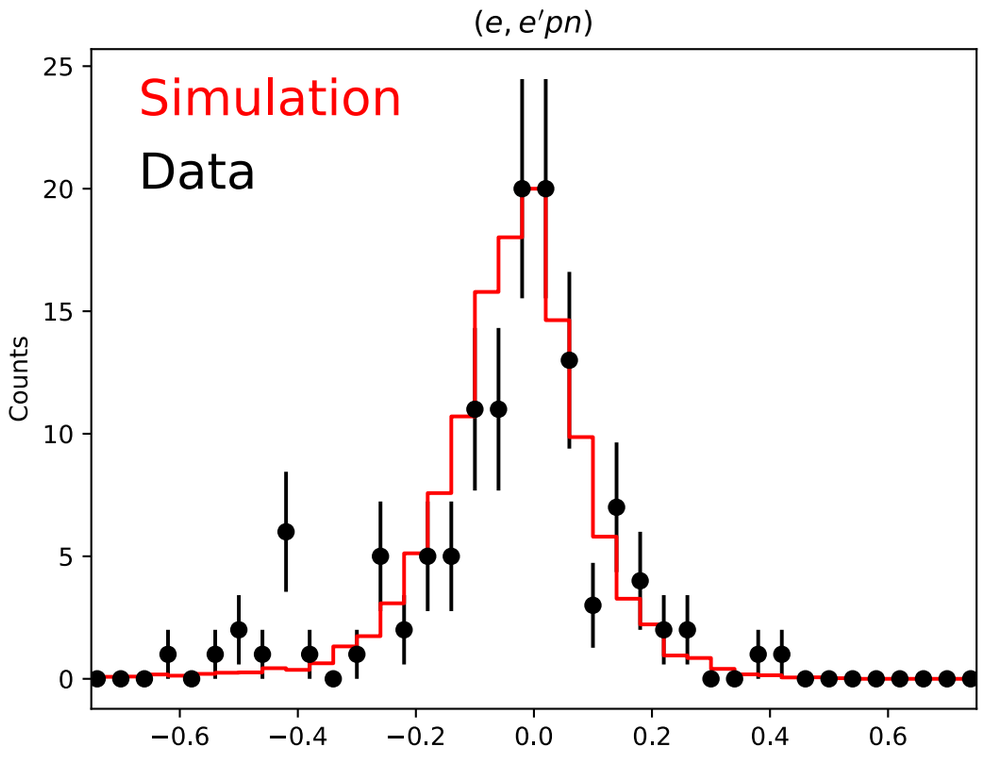
CLAS12 + BAND: quasielastic $D(e, e'p)n$



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

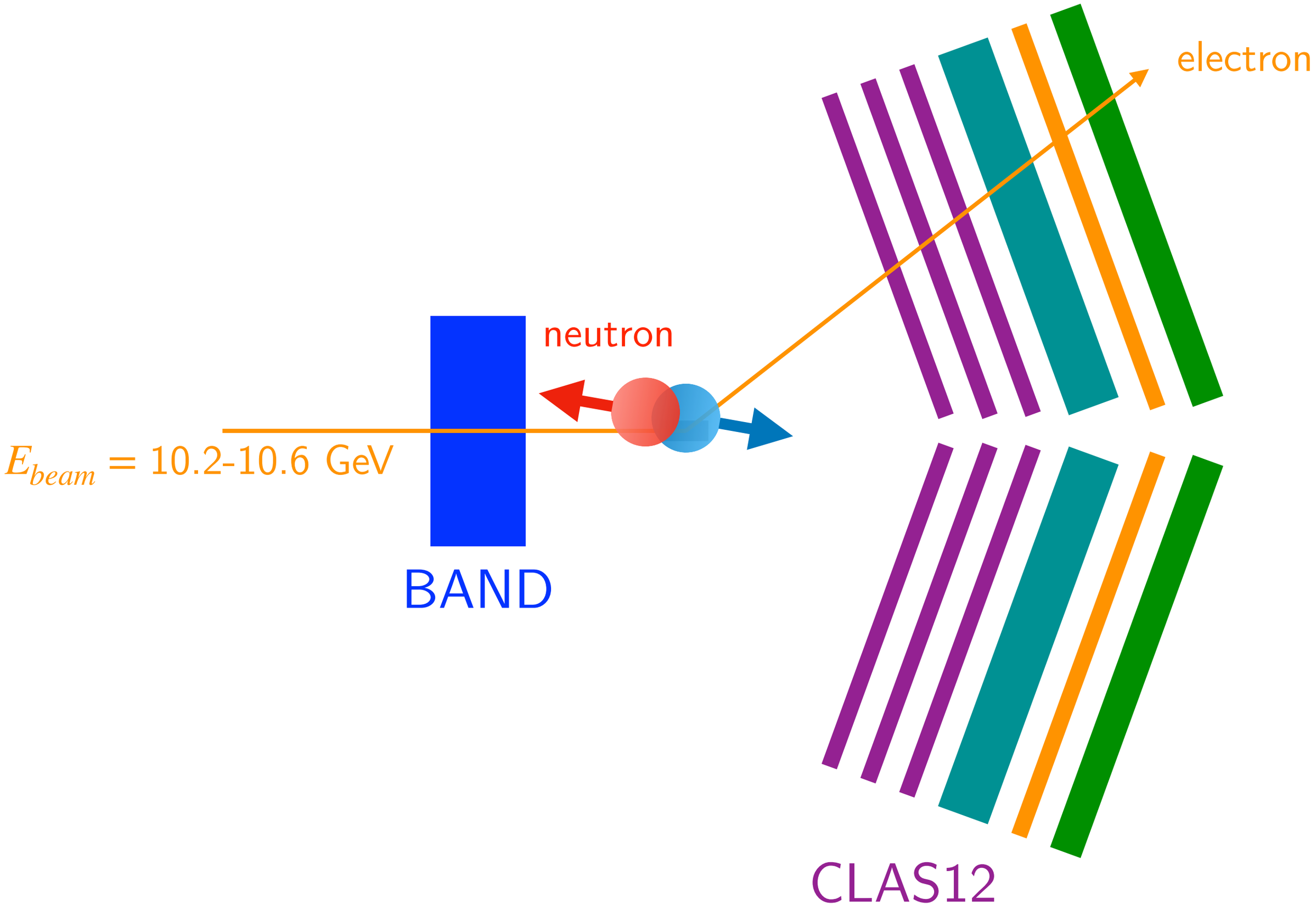






- Good agreement in shape of data and simulation
- Luminosity-normalized data/simulation ratio ≈ 2-3

Tagged DIS with BAND



Tagged $D(e, e'n)X$

$Q^2 > 2$ GeV^2

$W^2 > 4$ GeV^2

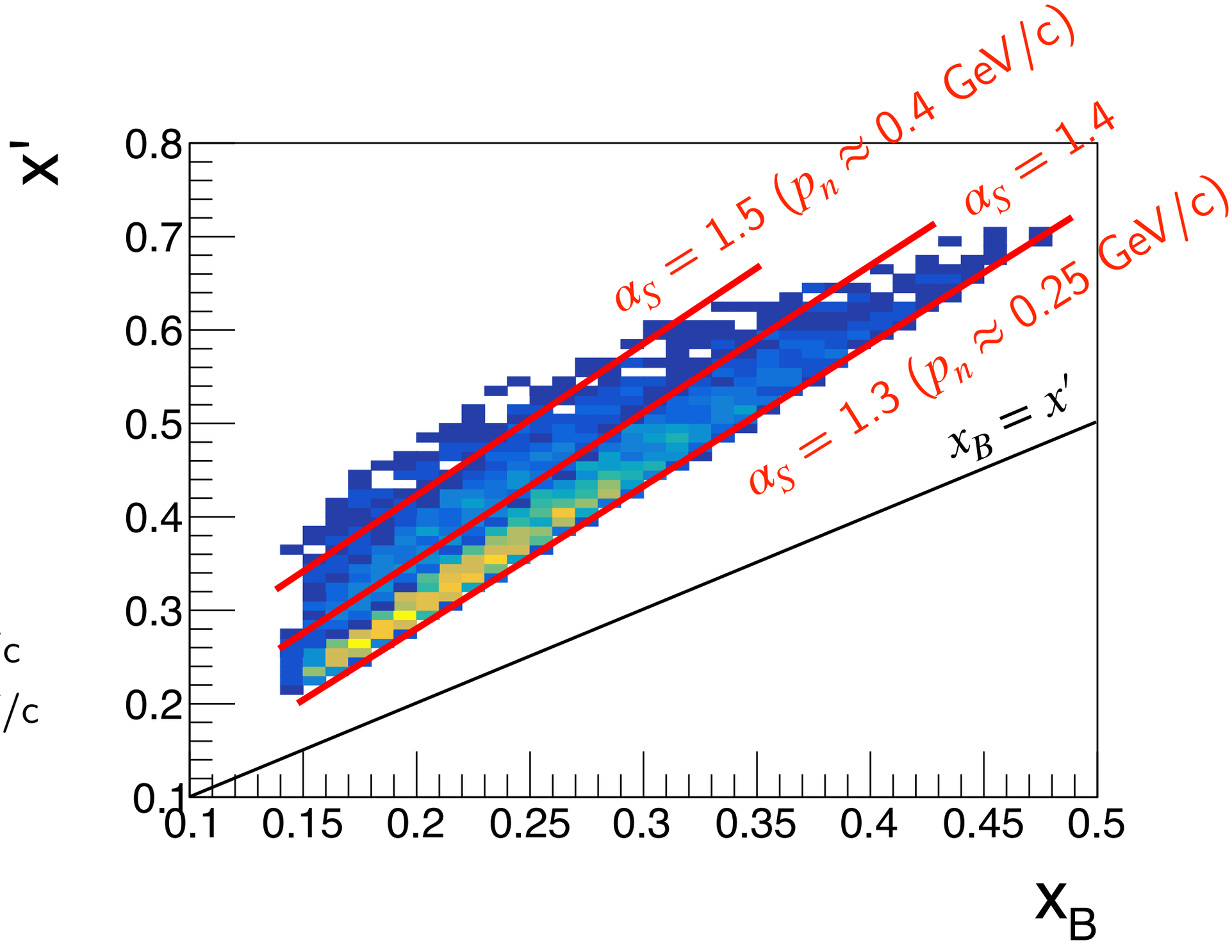
$y < 0.7$

cos $\theta_{nq} < -0.8$

$W' > 1.8$ GeV

$p_T < 0.1$ GeV/c

$p_n > 0.25$ GeV/c



Theoretical PWIA calculation

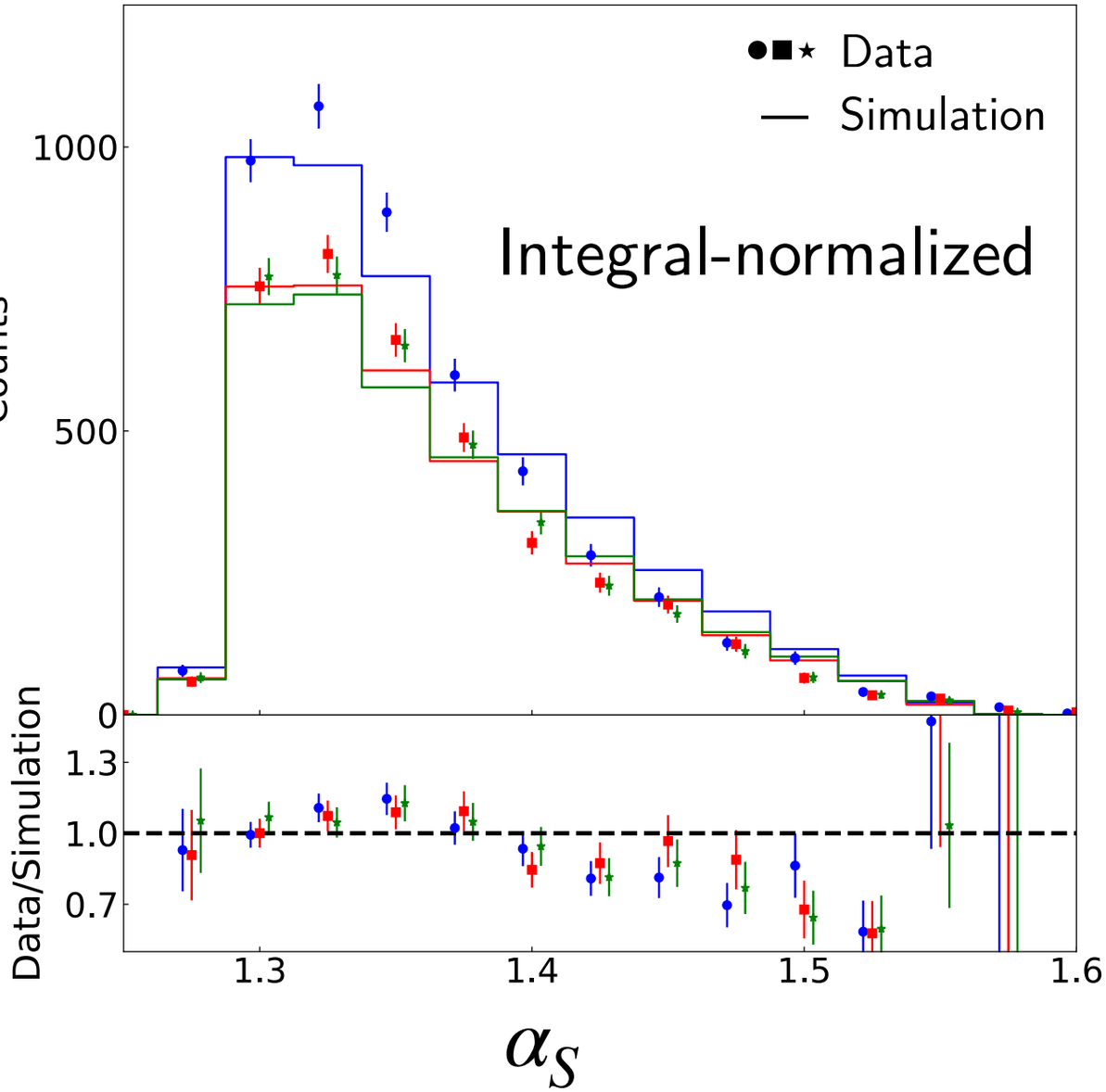
- Cross section model from Strikman & Weiss PRC 97, 035209 (2018):

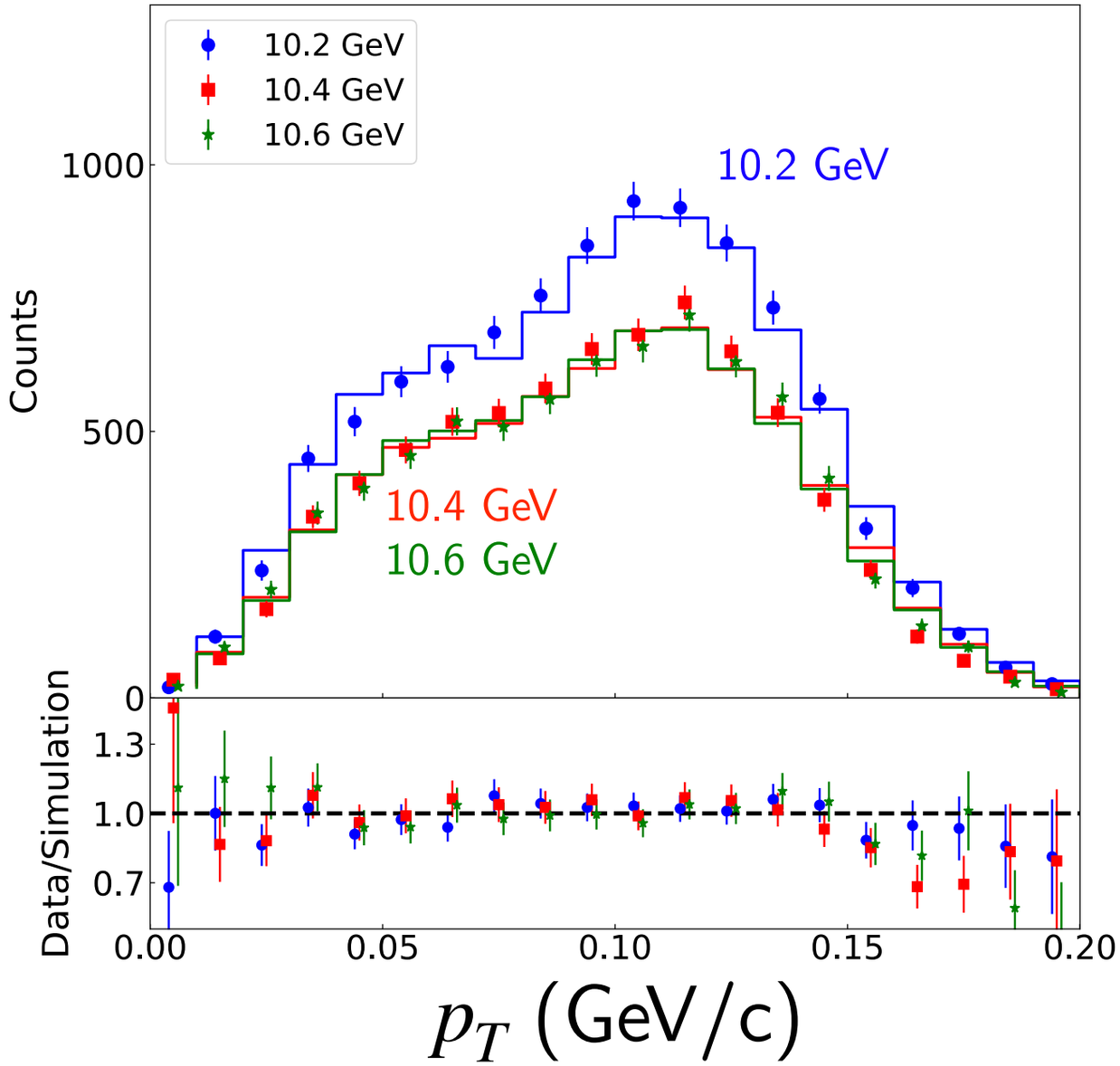
$$d\sigma[eD \to e' n_s X] = K \frac{2S(\alpha_s, p_{sT})}{2 - \alpha_s} \times F_2$$

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

Simulate generated events (with QED radiation) in GEANT4

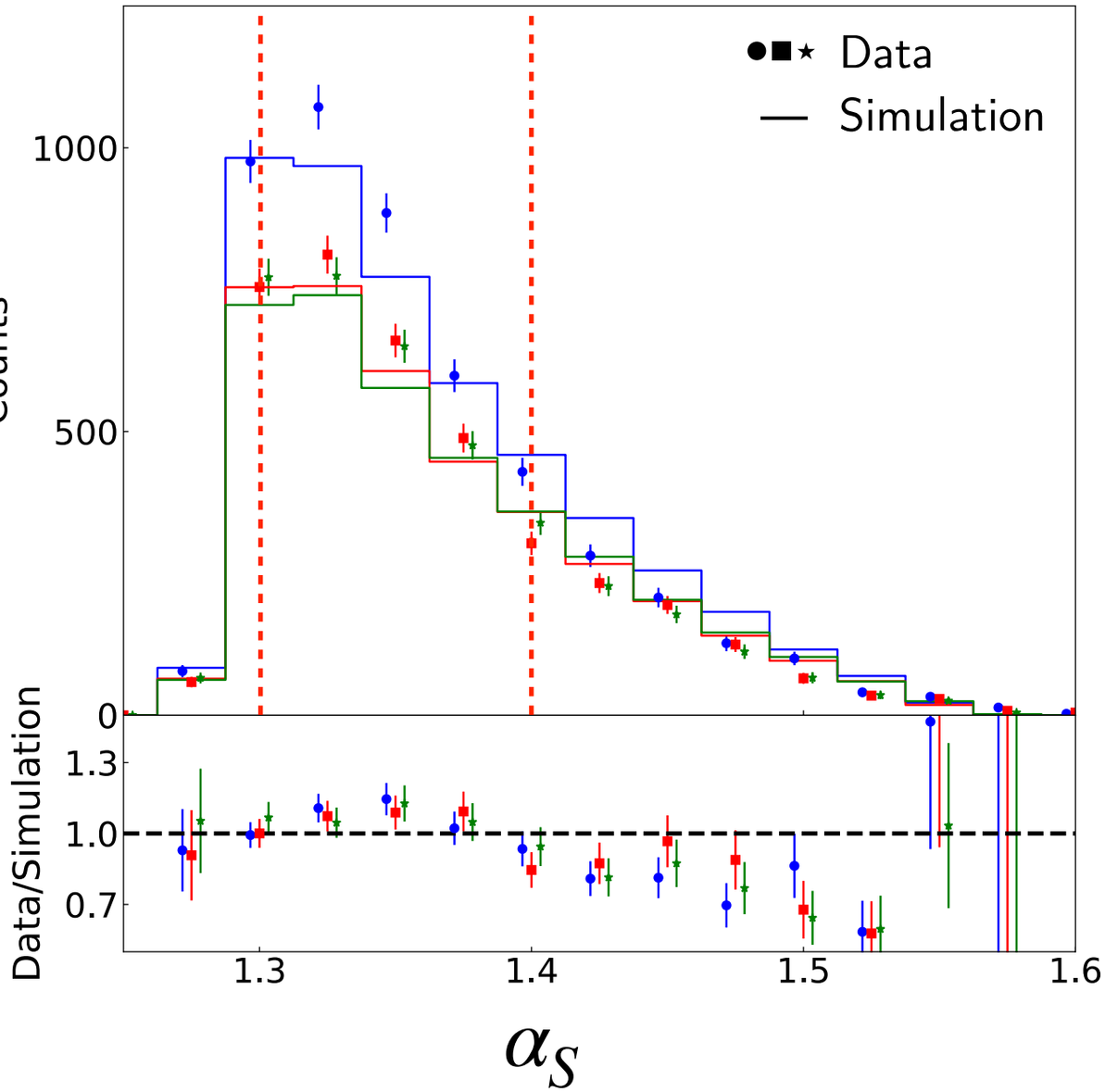
Tagged $D(e, e'n)X$



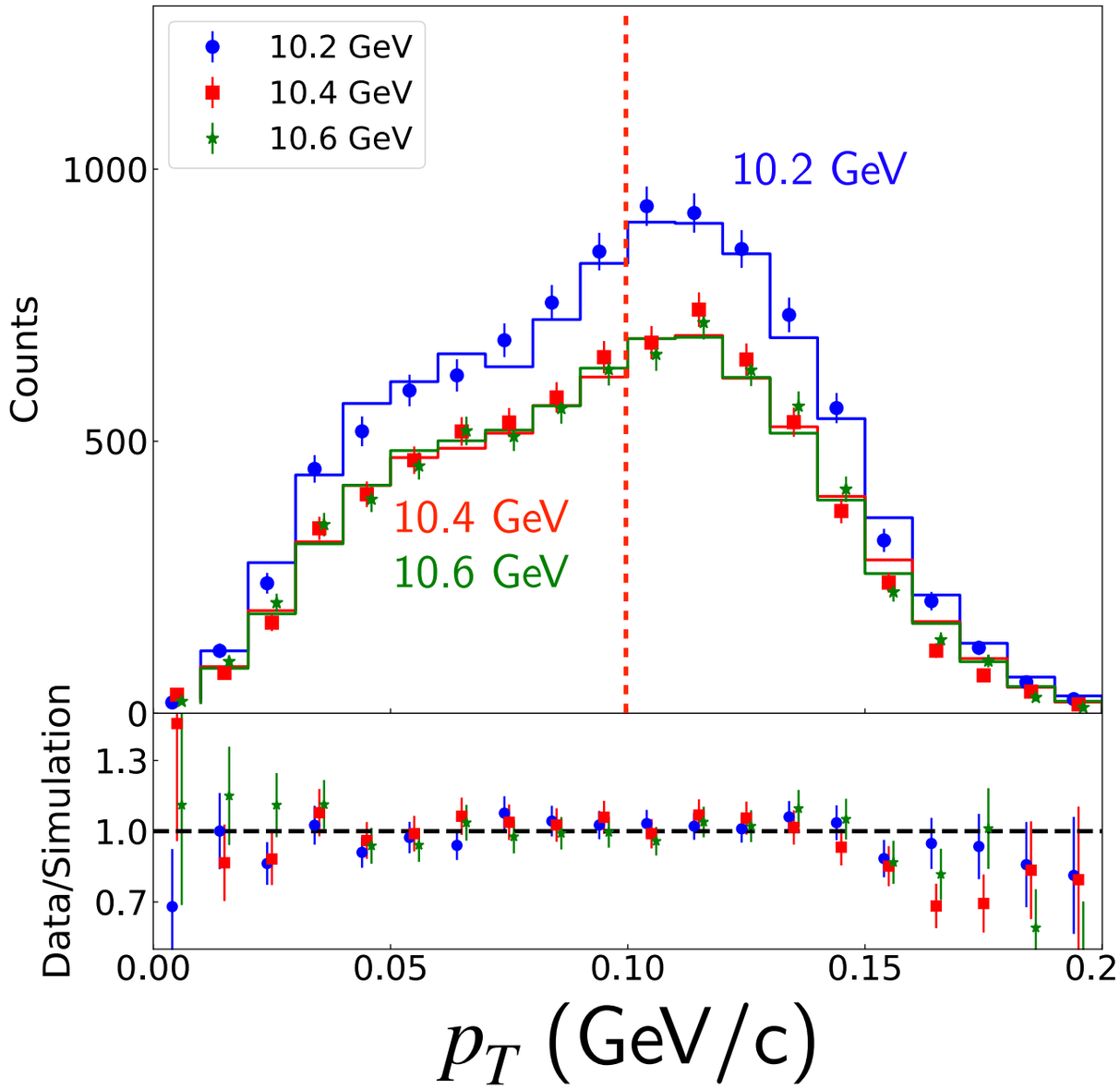


Tagged $D(e, e'n)X$

$1.3 < \alpha_S < 1.4$



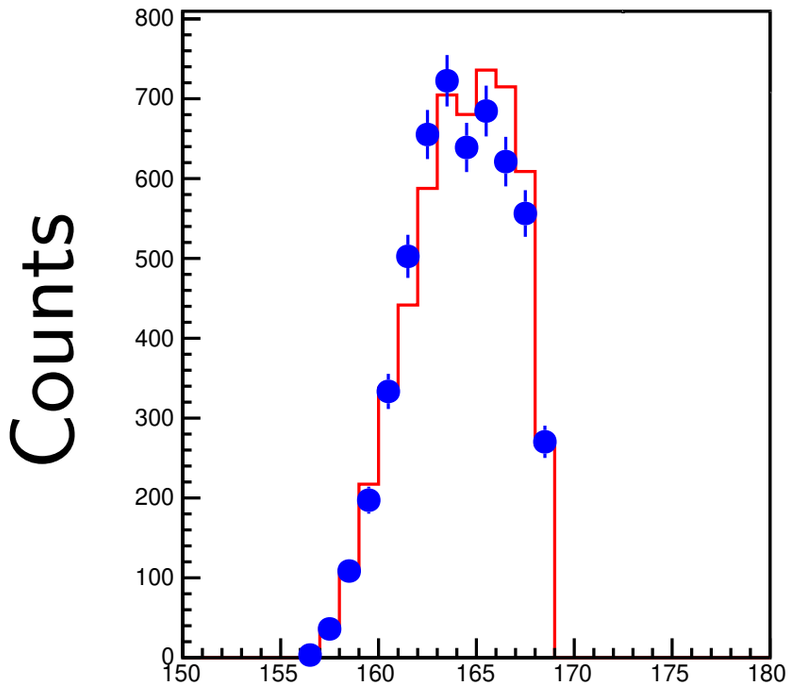
$p_T < 0.1$ GeV

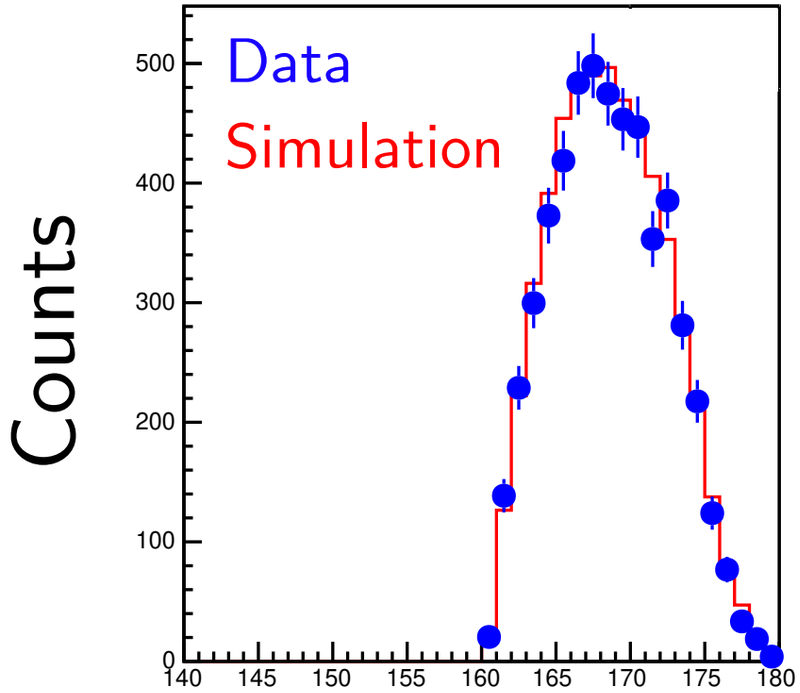


Show results from:

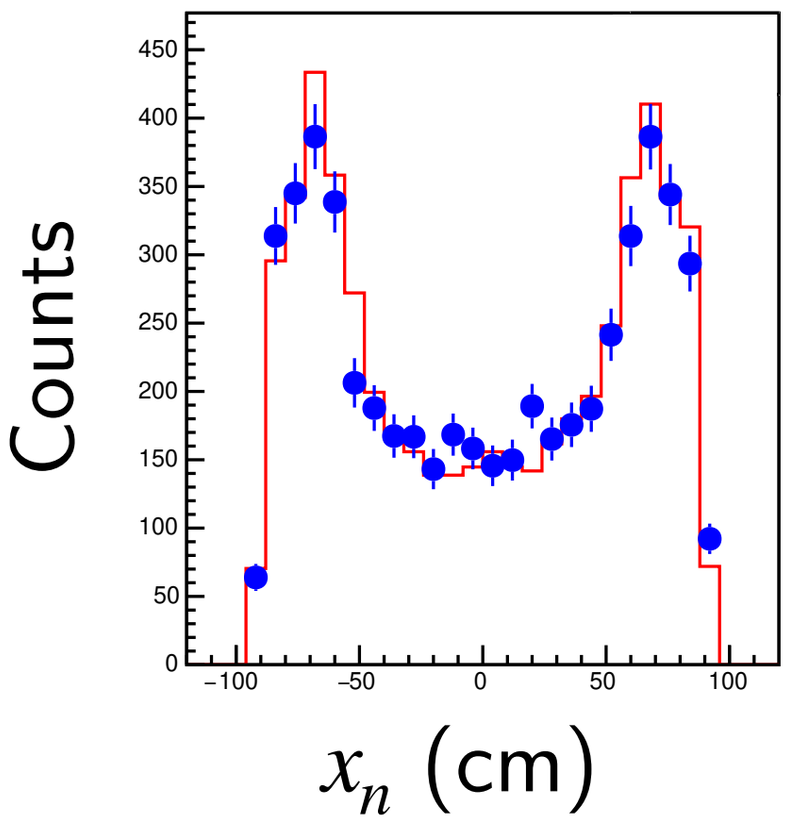
- High-statistics region of α_S
- Low p_T (theoretical convenience)

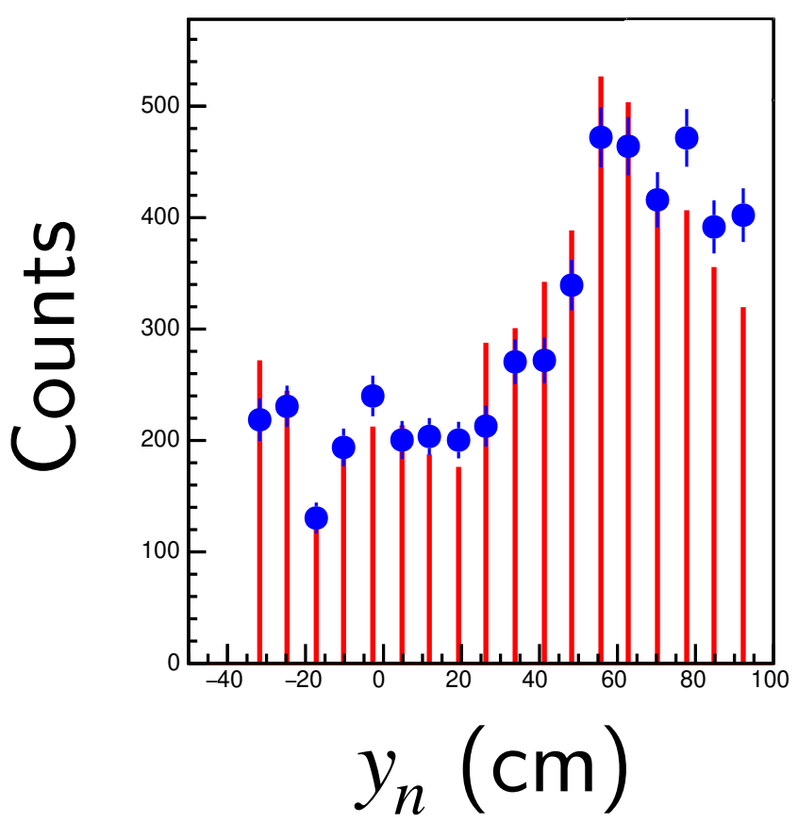
Tagged $D(e, e'n)X$



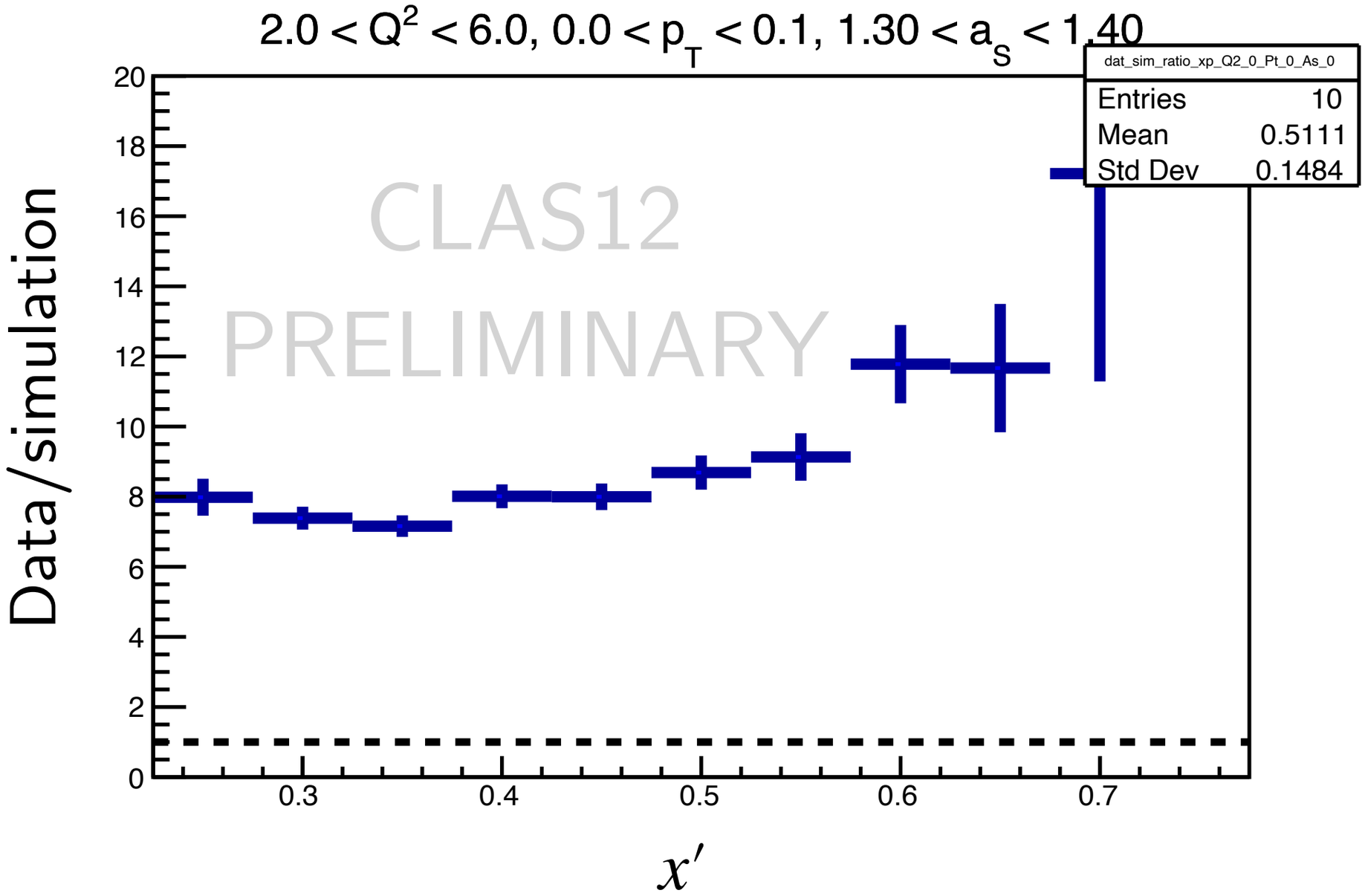


θ_{nq} Integral-normalized θ_n



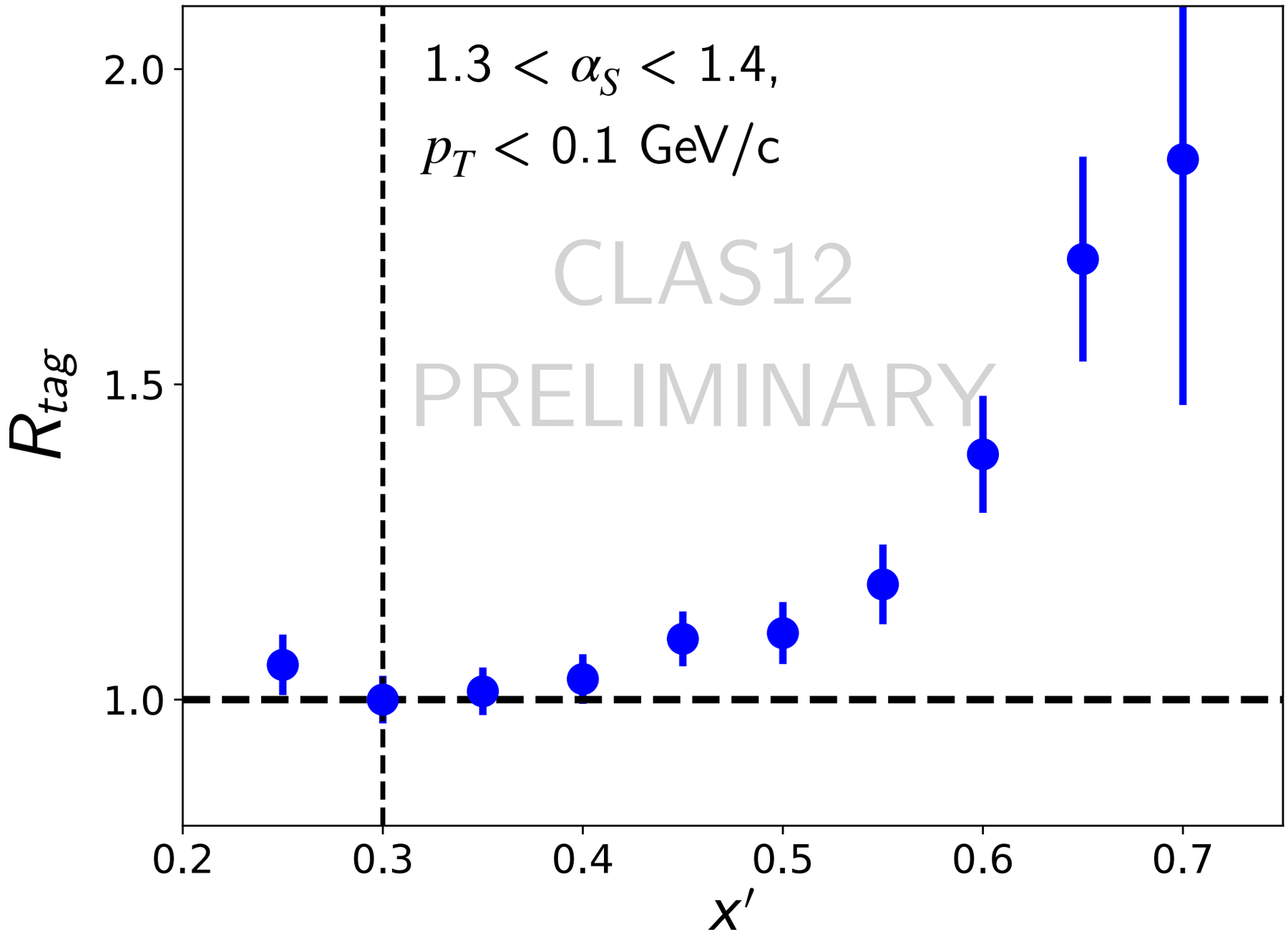


Tagged $D(e, e'n)X$



- Luminosity-normalized data/simulation ratio ≈ 10

$$R_{tag} = \frac{\sigma_{tag}^{exp}(x') \Big/ \sigma_{tag}^{exp}(x' = 0.3)}{\sigma_{tag}^{PWIA}(x') \Big/ \sigma_{tag}^{PWIA}(x' = 0.3)}$$



Checking systematics

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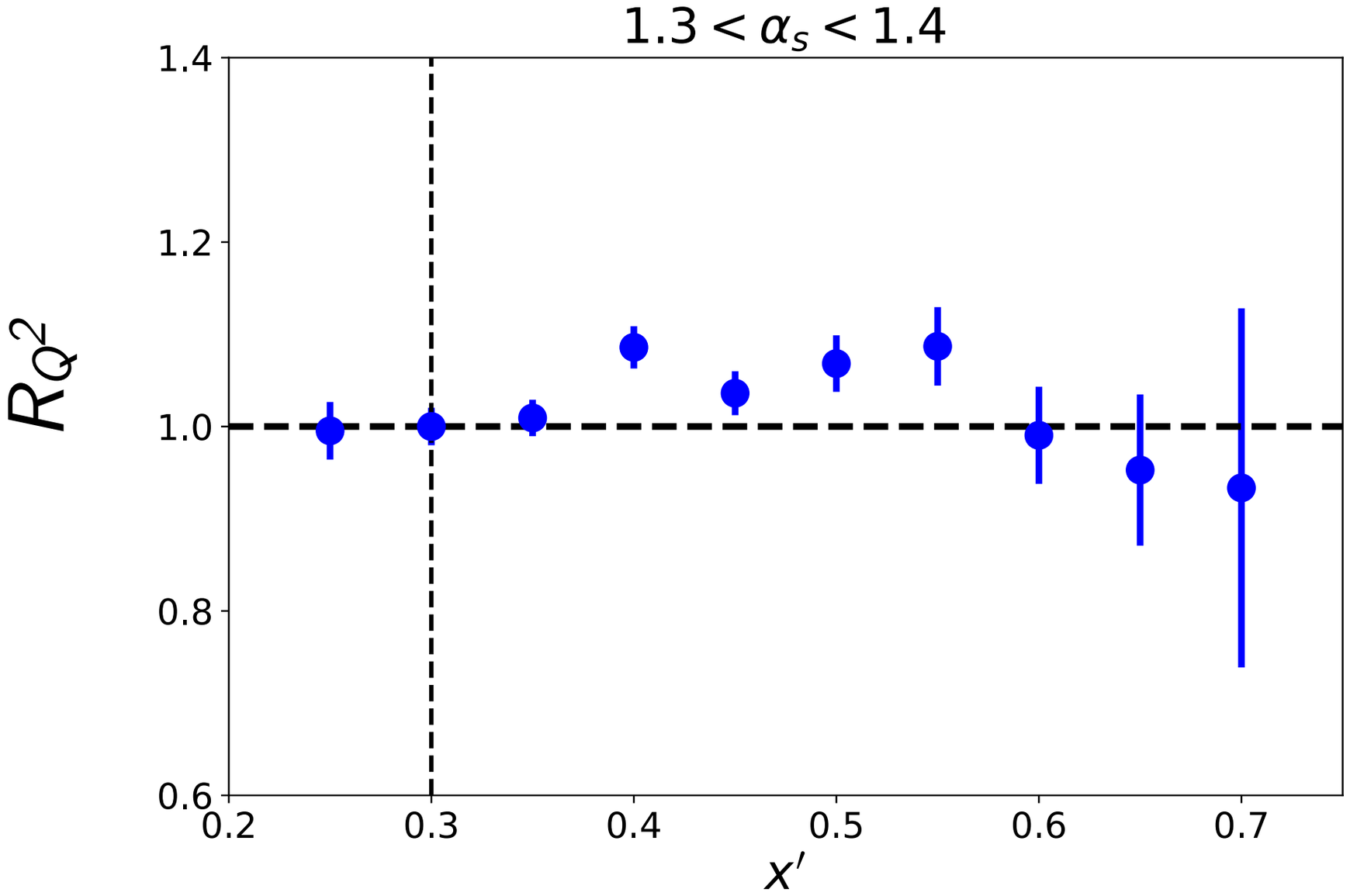
- Novel measurements = *experimental* and *theoretical* challenges!
- Some systematics we have considered:

Checking systematics

- Novel measurements = *experimental* and *theoretical* challenges!
- Some systematics we have considered:
  - Impact of finite Q^2 effects
  - Impact of BAND neutron detection efficiency
  - Measurement stability with run period (different beam energy)

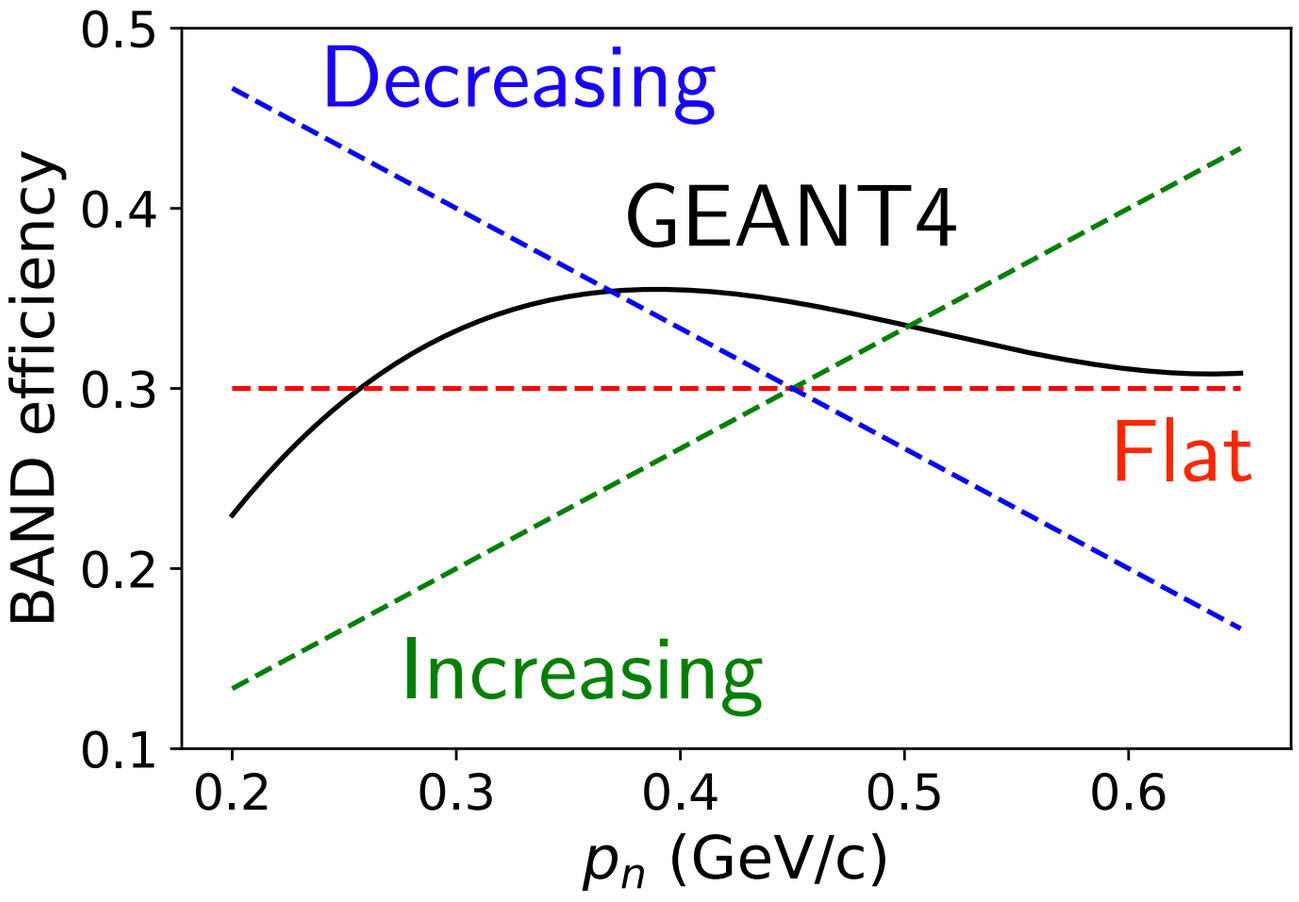
Finite Q^2 vs. asymptotic ($Q^2 \to \infty$) model

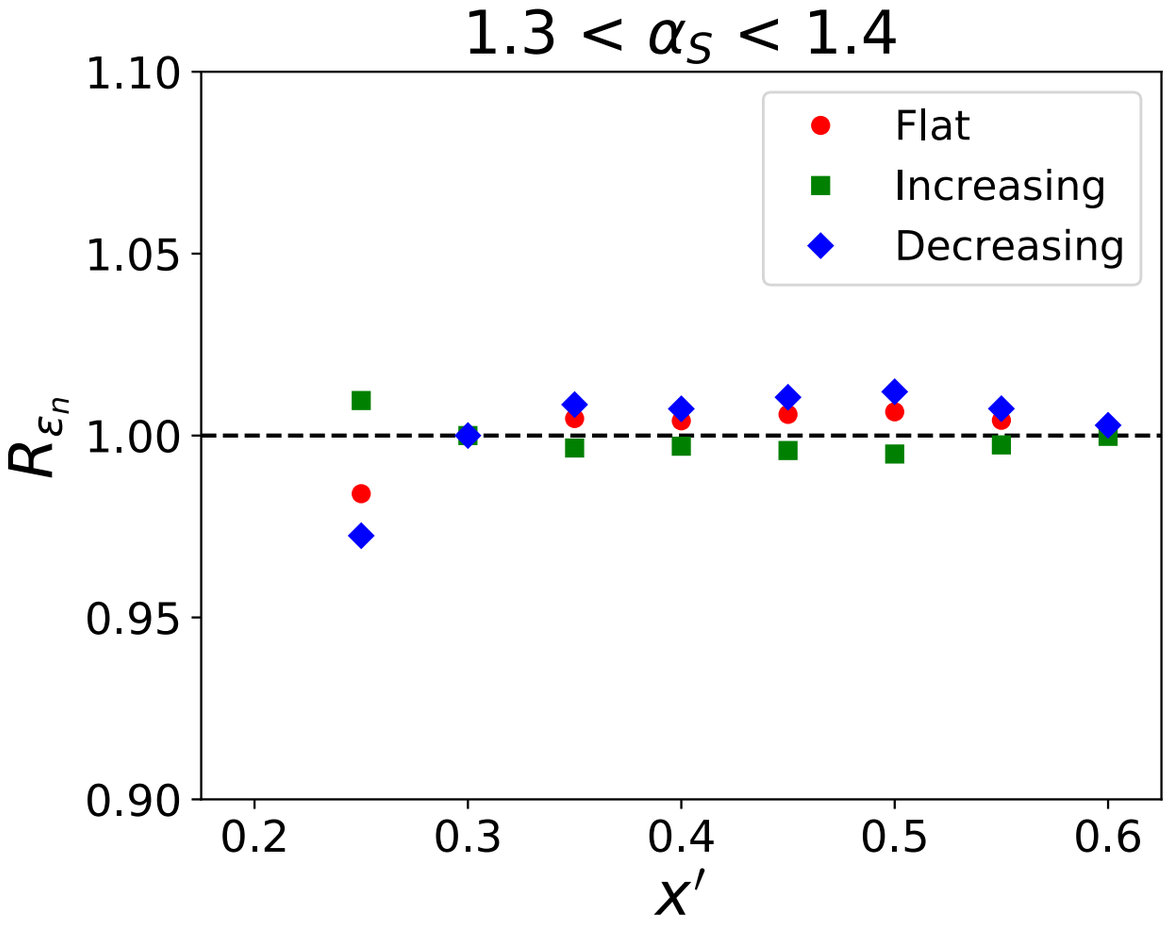
$$R_{Q^2} = \frac{N_{finite}(x') \Big/ N_{finite}\left(x' = x_0\right)}{N_{asymp}(x') \Big/ N_{asymp}\left(x' = x_0\right)}$$



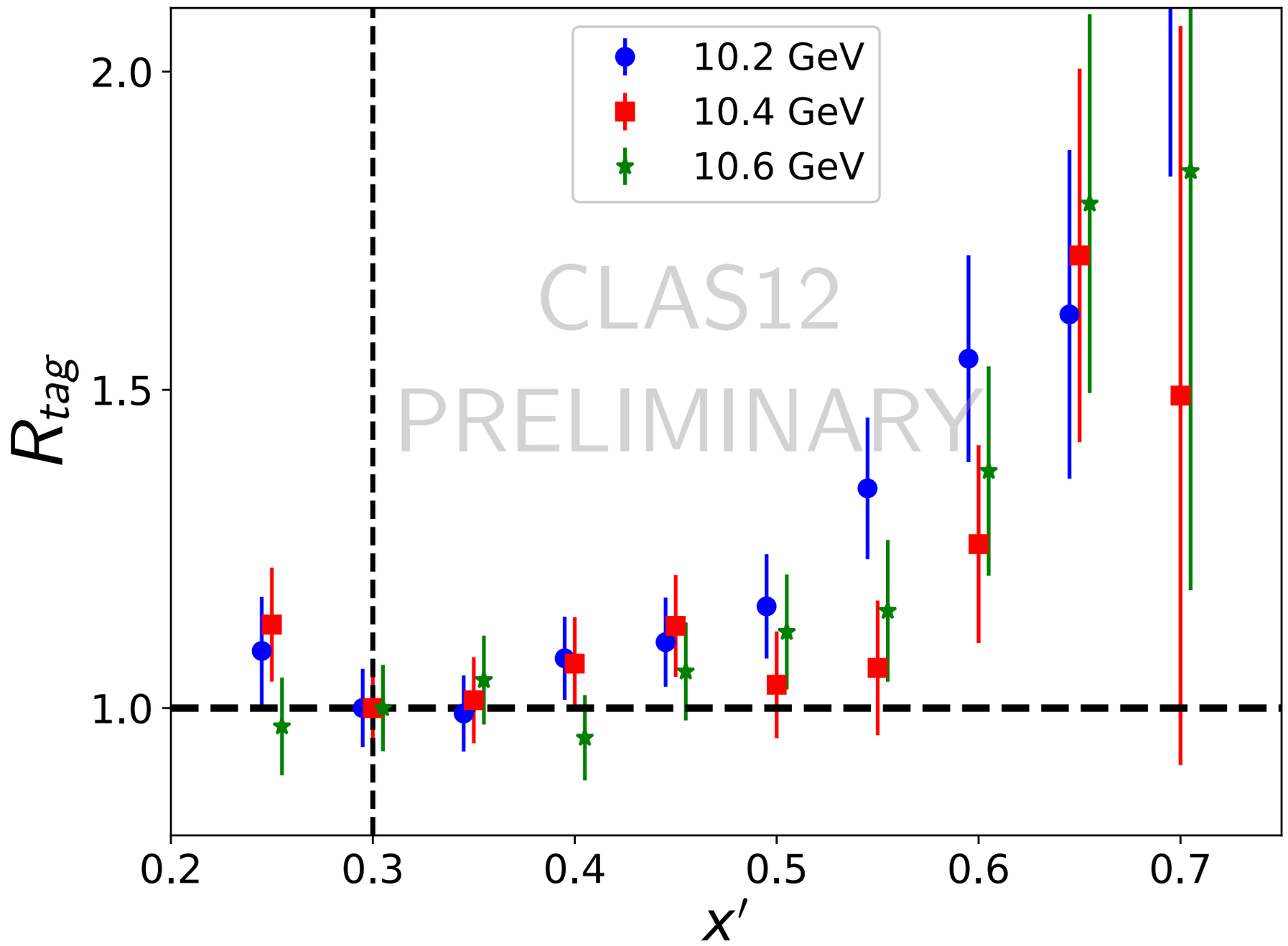
BAND neutron efficiency

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





Stability with run period



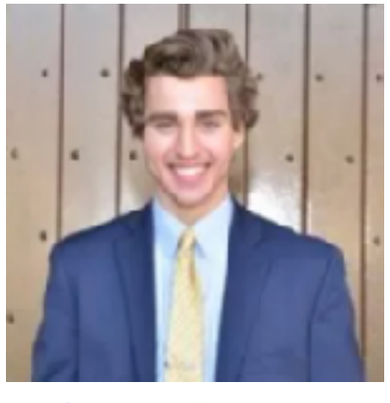
Generator validation

Generator validation

- Have validated numerical/sampling methods used to generate events from cross section model
- Have found good agreement between BAND PWIA generator and independent PWIA generator (from W. Cosyn)
- Have found good agreement in inclusive (e, e') events between BAND PWIA generator and standard F_2^d DIS generator
- Investigating issue with absolute normalization

Summary

- First measurement of neutron-tagged DIS with CLAS12 + BAND
- Inclusive and quasielastic analysis complete and shows well-validated detector simulation
- Tagged analysis shows indications of non-negligible effect
- Analysis note for CLAS review in-progress



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Thank you!