Bound nucleon structure from tagged DIS with a 22 GeV CEBAF

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Opportunities with JLab
Energy and Luminosity Upgrade

ECT*, Trento, Italy

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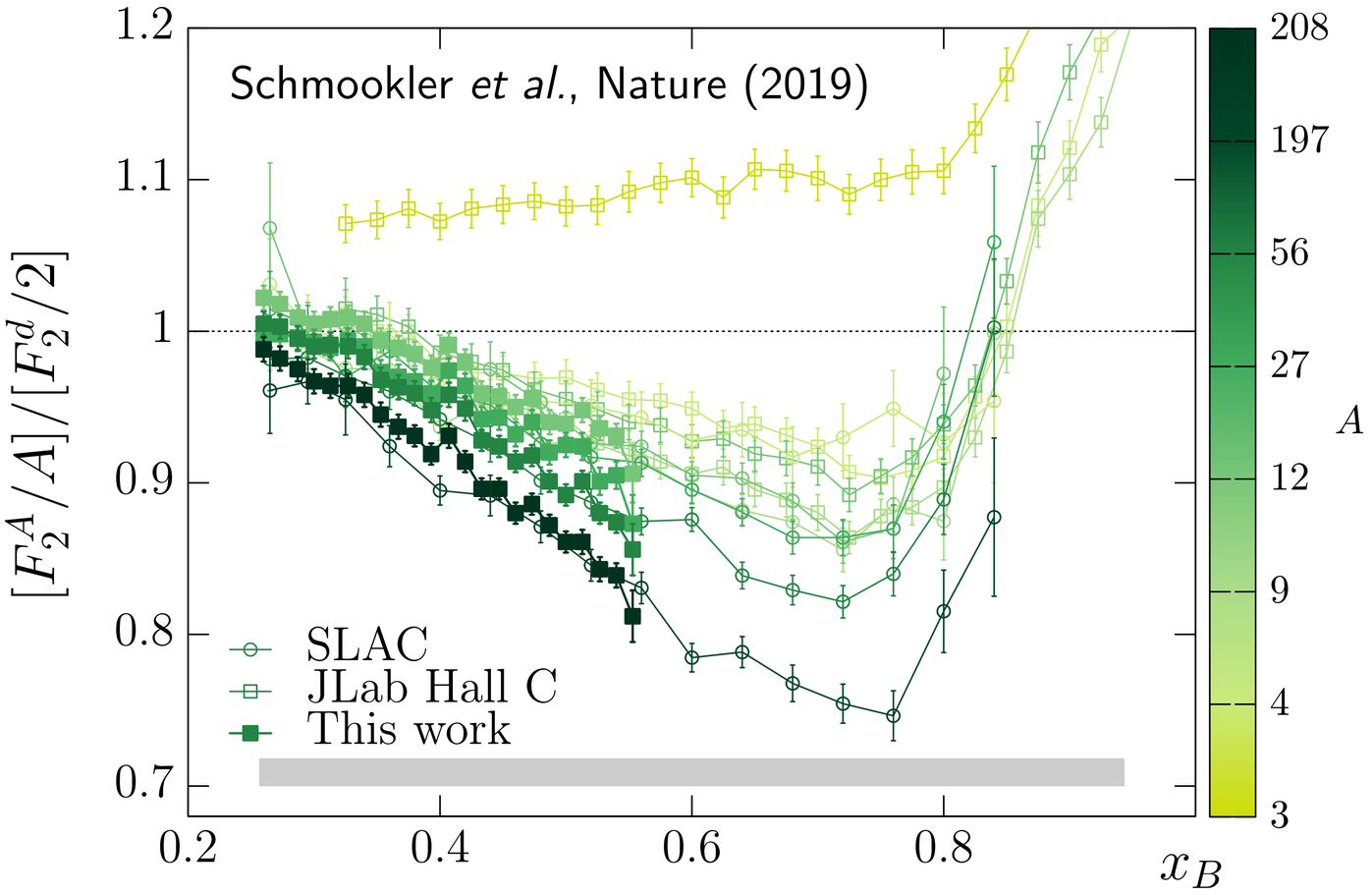
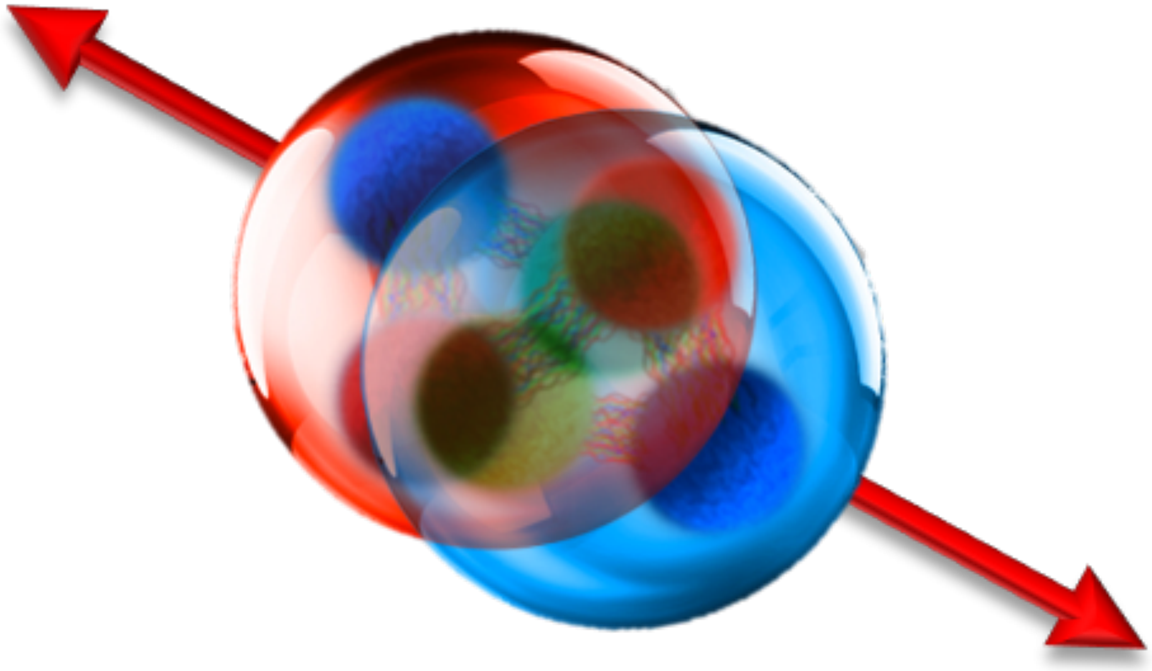
Bound nucleons are not the same as free nucleons (the EMC effect)



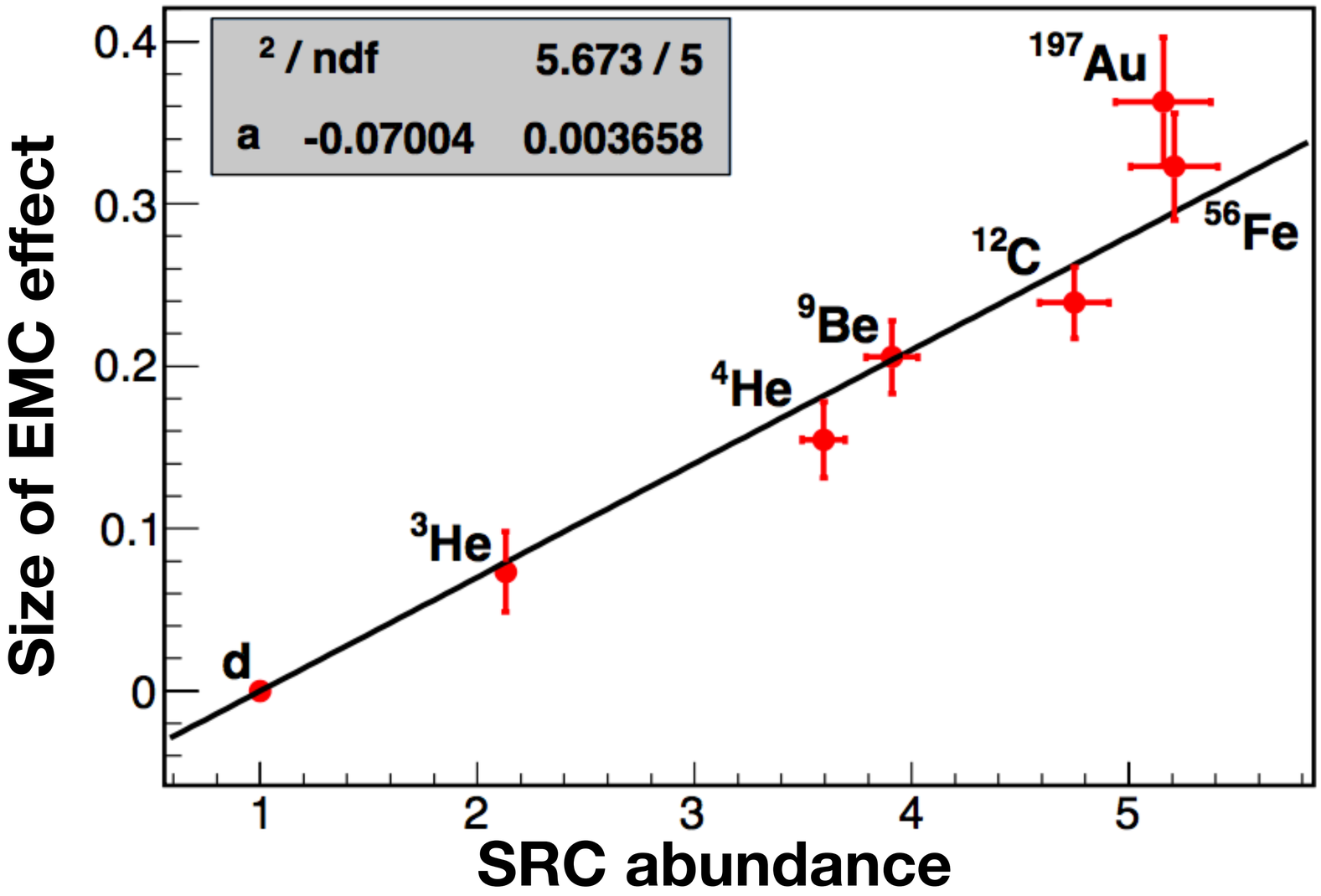
- Extensively studied with *inclusive* DIS
- Systematic effect in all nuclei
- Magnitude grows with A
- *No consensus on the origin of the EMC effect!*

Short-range correlations are at the interface of nucleon and parton degrees of freedom

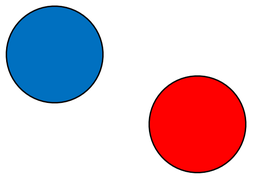
- Pairs of nucleons with very small separation
- High relative and low center-of-mass momentum compared to k_F
- Produce *high-momentum* tail in nuclear wavefunction



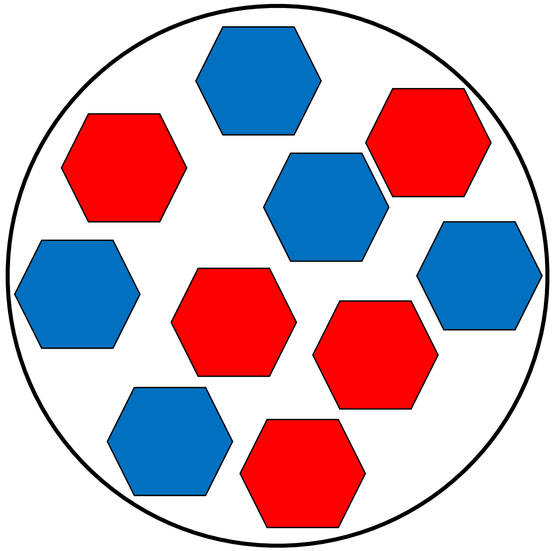
Measurements suggest connection between EMC effect and SRCs



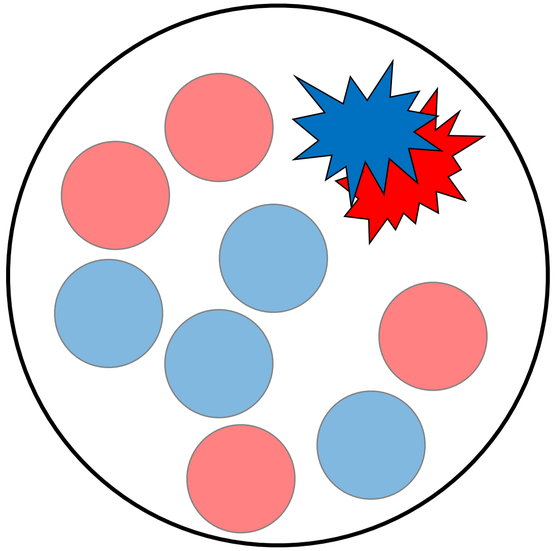
SRC-EMC hypothesis: EMC effect driven by modification of rare SRC nucleon pairs



Free nucleons



Mean-field:
many nucleons
slightly modified



SRC-EMC:
Few (SRC) nucleons
highly modified

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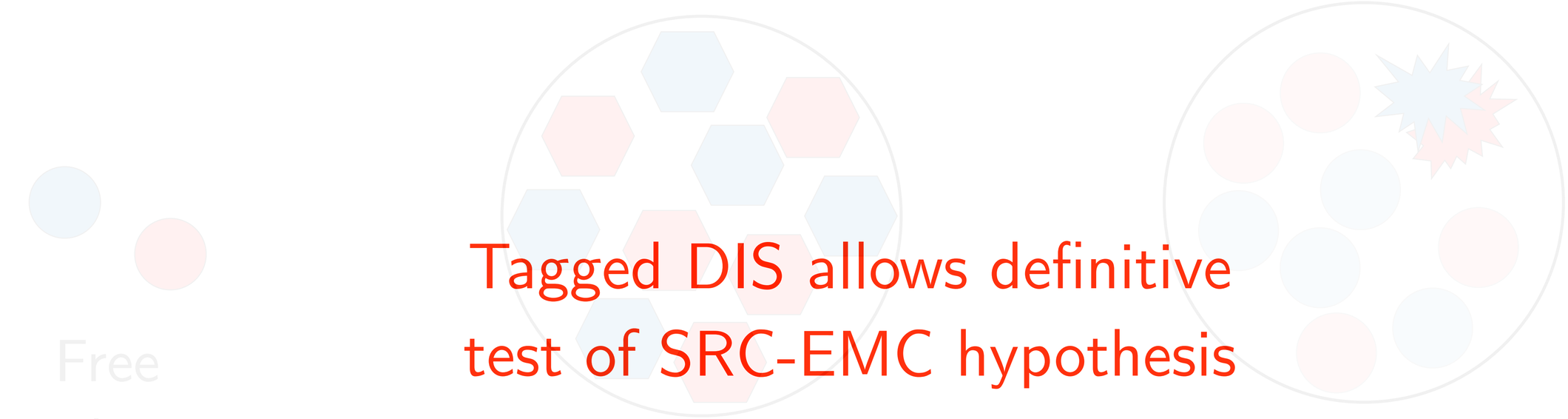


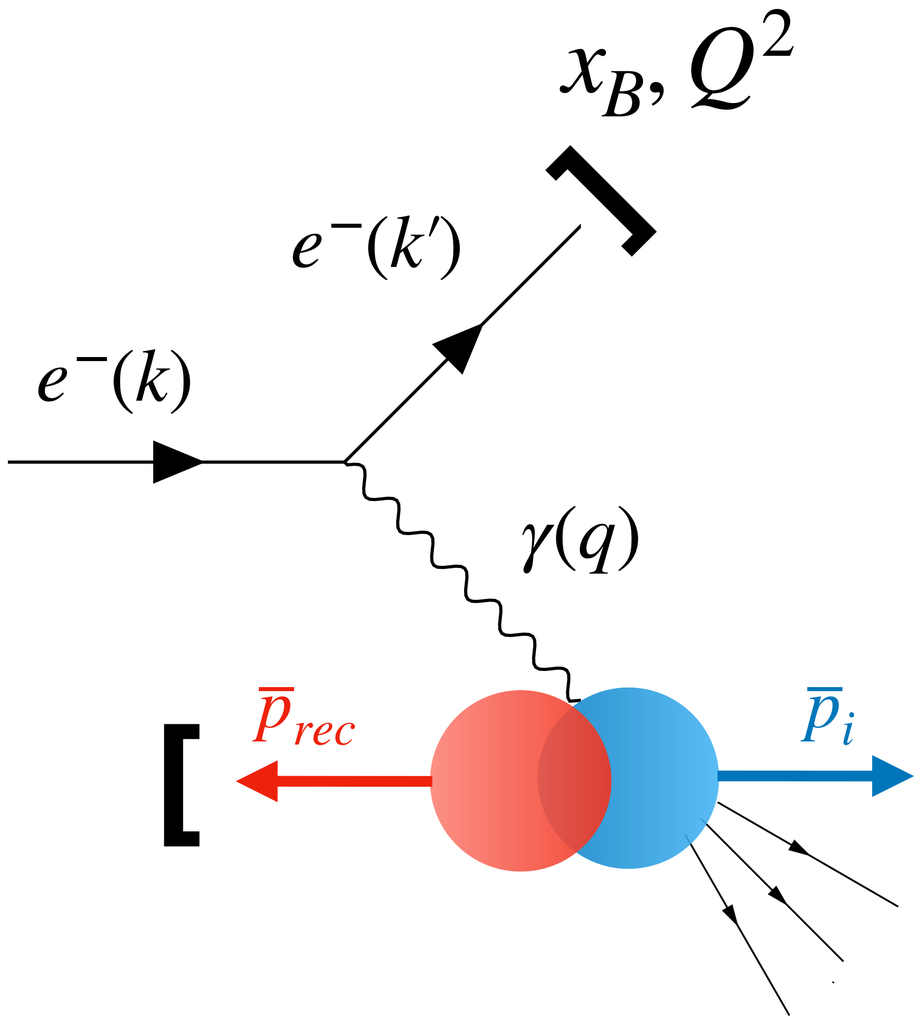
Free nucleons

Mean-field: many nucleons slightly modified

SRC-EMC: Few (SRC) nucleons highly modified

Tagged DIS allows definitive test of SRC-EMC hypothesis

Why tagged DIS?



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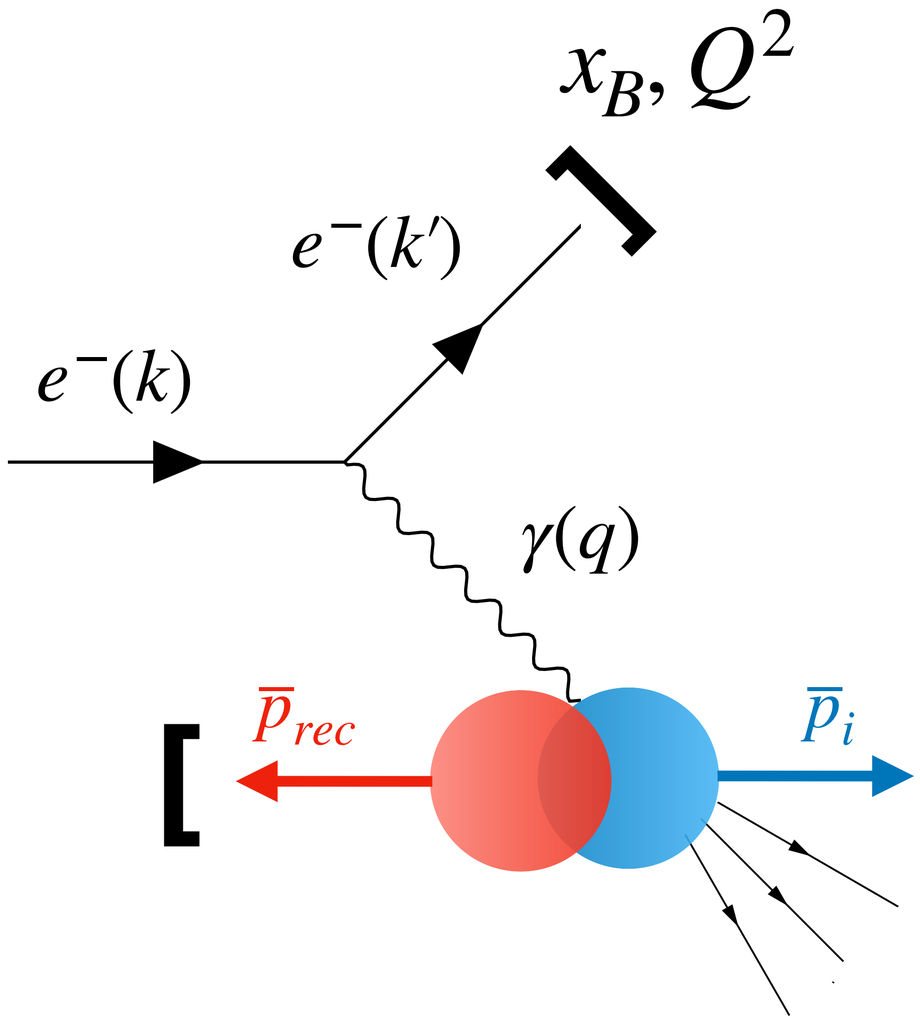

- Parton structure from electron
- Nuclear state from spectator nucleon
- Account for initial momentum of nucleon
  - $x_B \to x'$
  - $W \to W'$
  - $\alpha_S \sim p_i$

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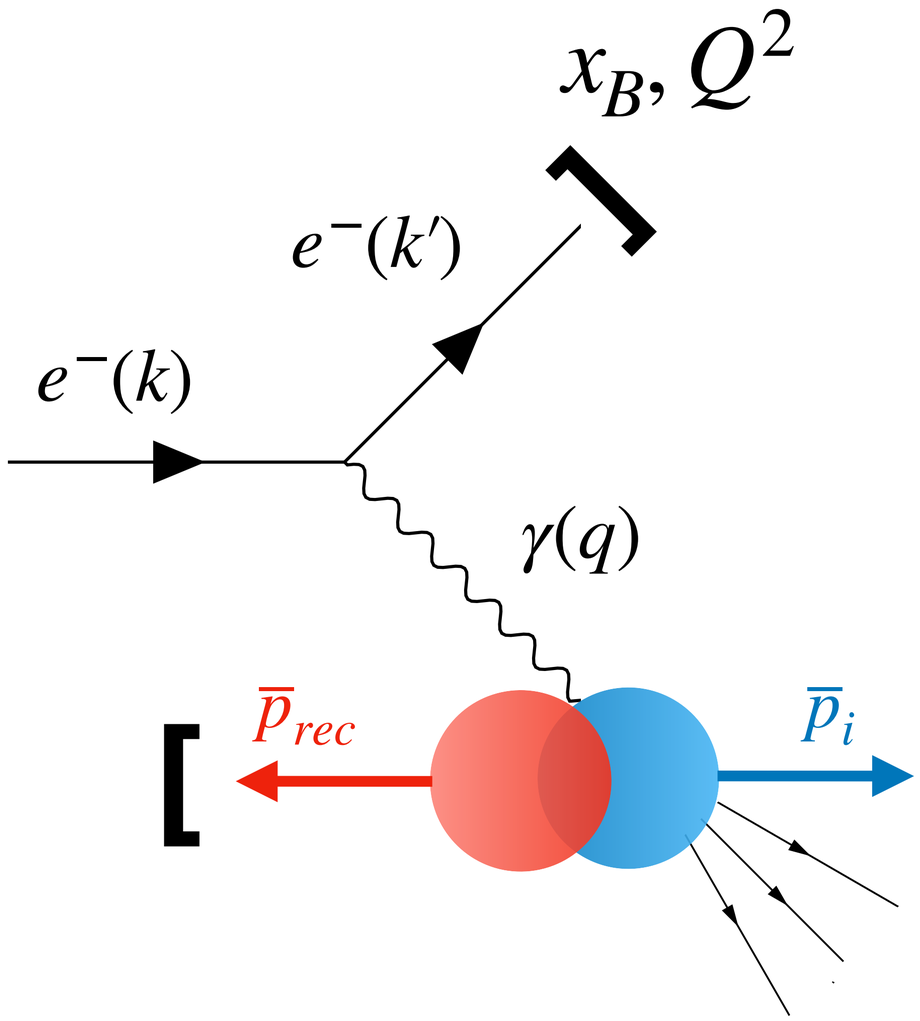


- Parton structure from electron
- Nuclear state from spectator nucleon
- Account for initial momentum of nucleon
  - $x_B \to x'$
  - $W \to W'$
  - $\alpha_S \sim p_i$
- Minimize FSI by detecting backward spectators and forming ratios

Tagged DIS efforts at Jefferson Lab

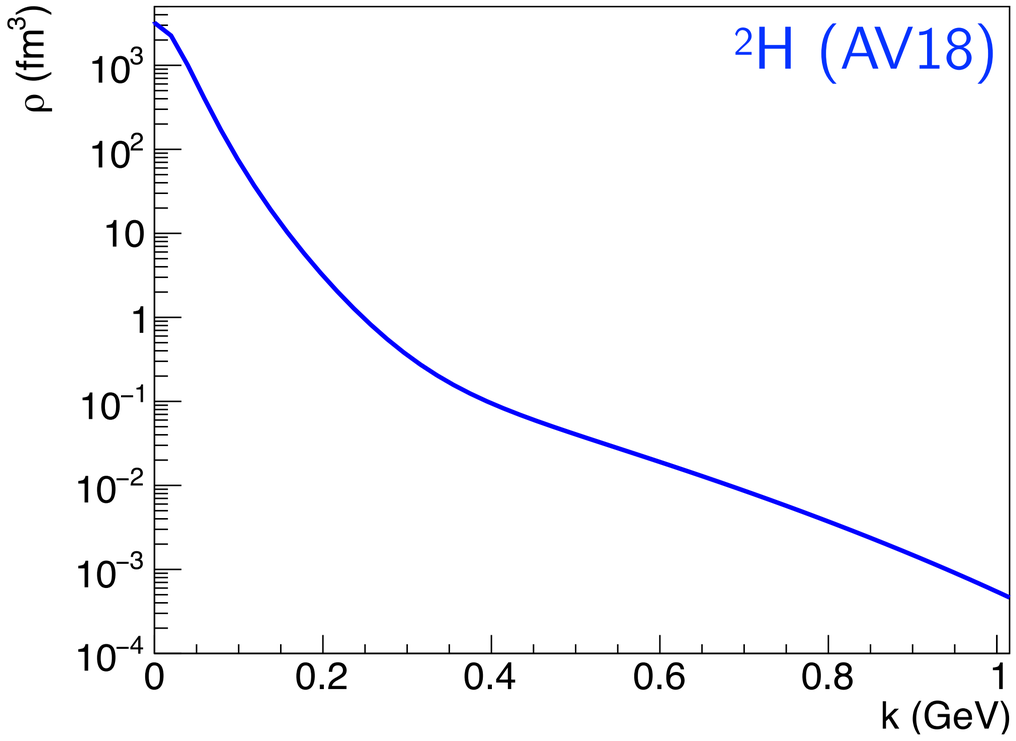
Past/current

- BoNuS (Proton-tagged DIS from deuterium)
- BAND (Neutron-tagged DIS from deuterium)

Future:

- ALERT (^{3}H/^{3}He tagged DIS from ^{4}He)
- LAD (Proton-tagged DIS from deuterium)

Tagged DIS can probe selected regions of the nuclear wave function



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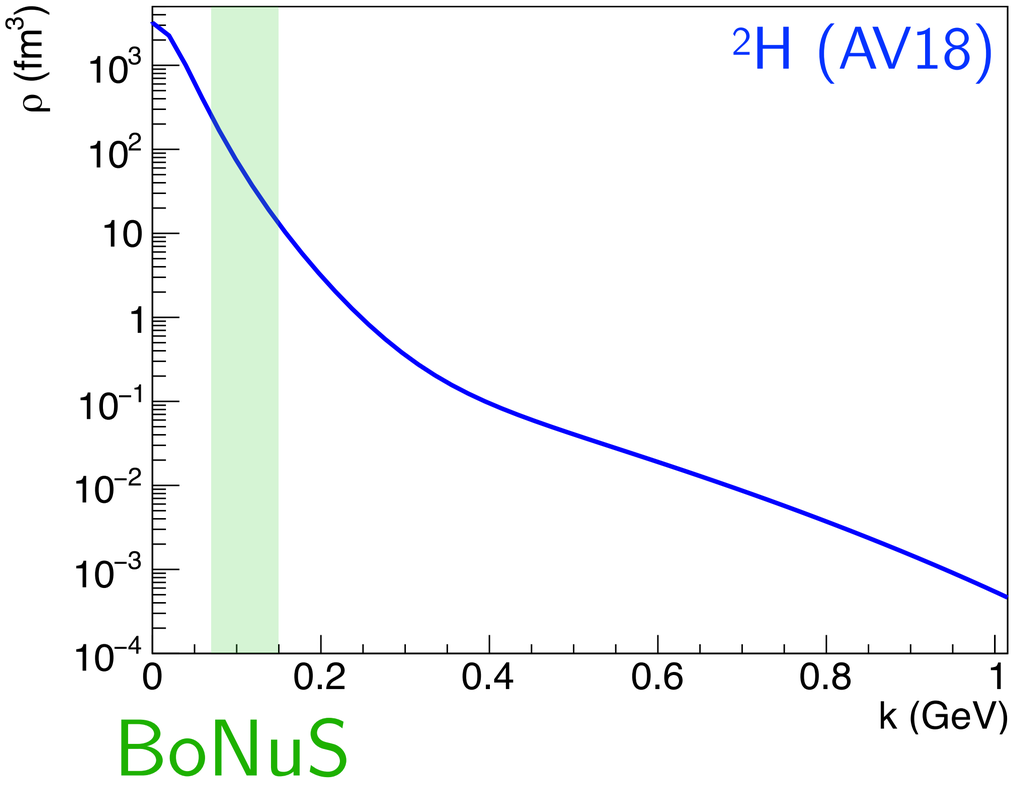
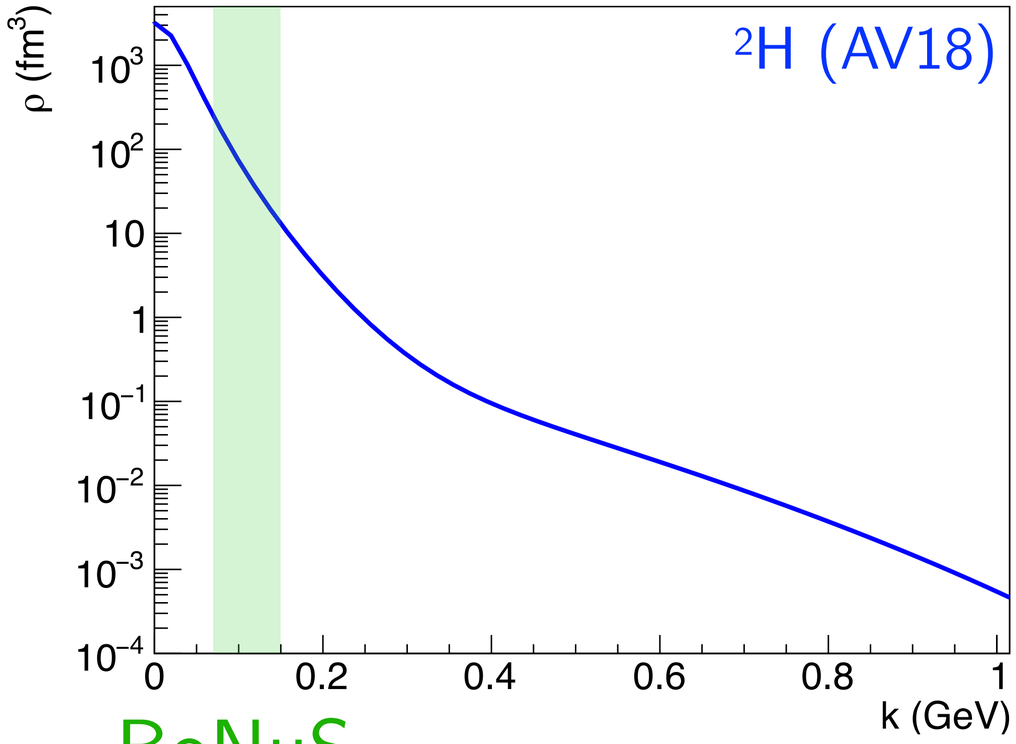


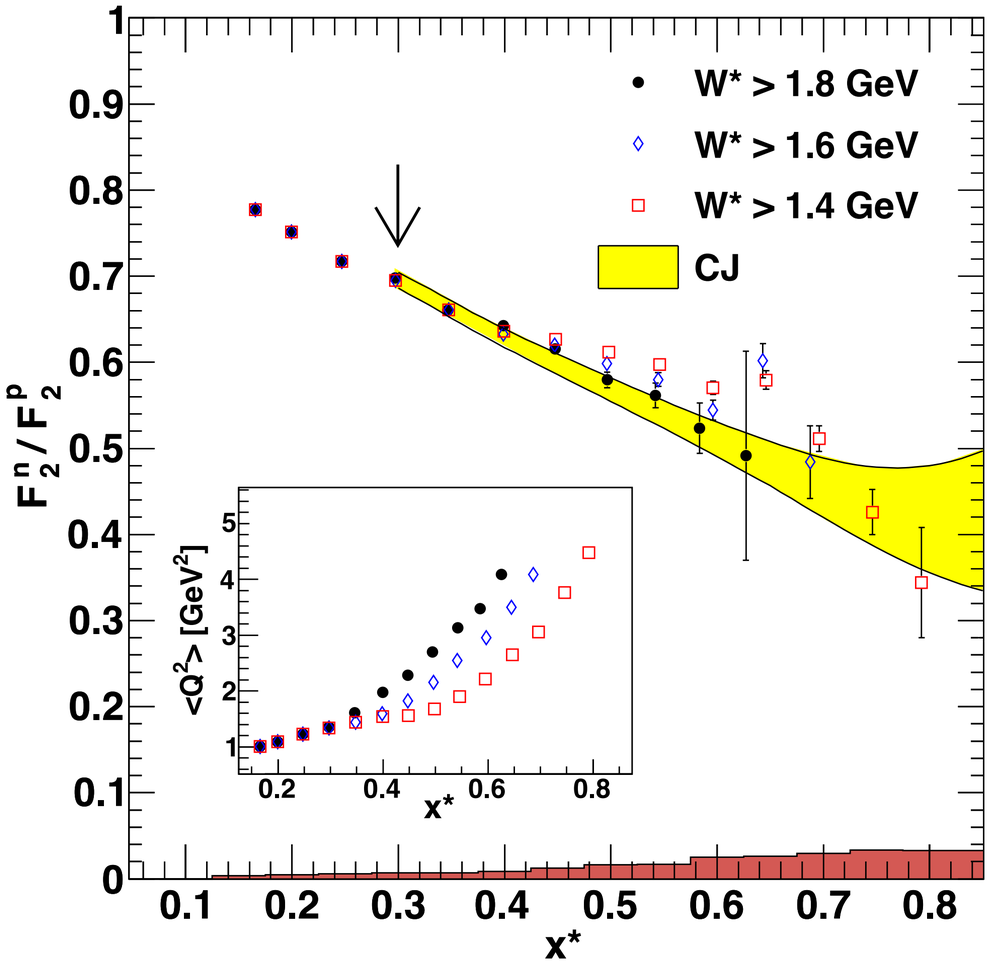
What is the free neutron structure?

Tagged DIS can probe selected regions of the nuclear wave function



BoNuS

PRL 108, 142001



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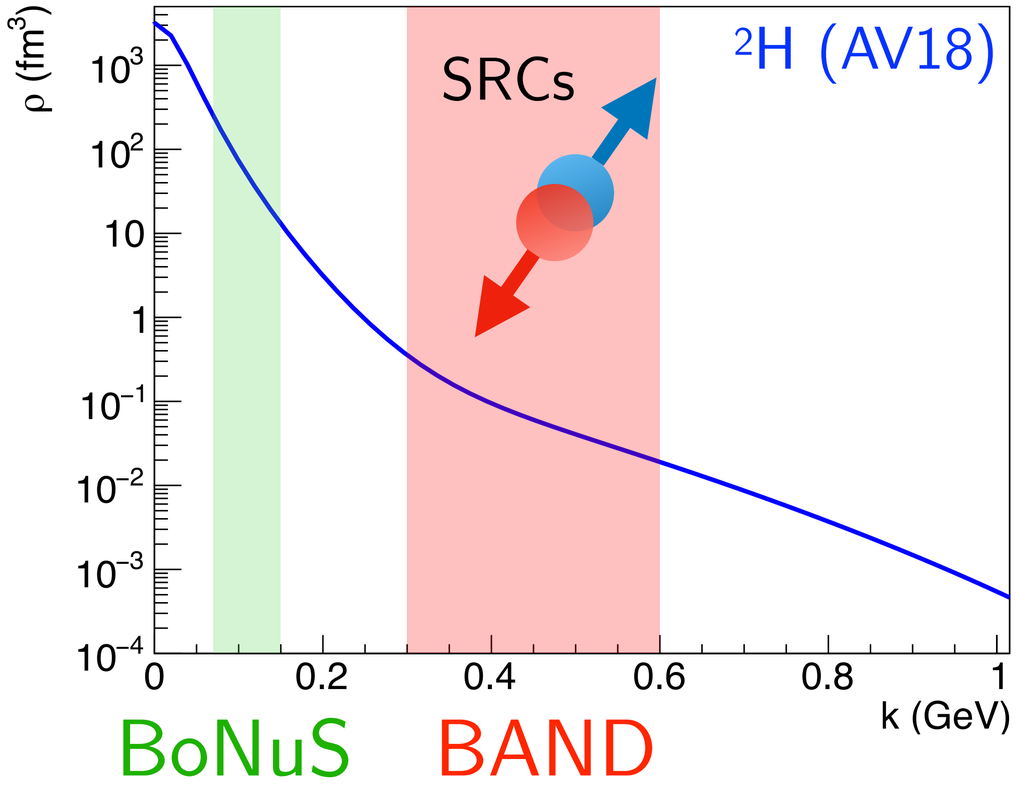

Is the EMC effect driven by SRCs?

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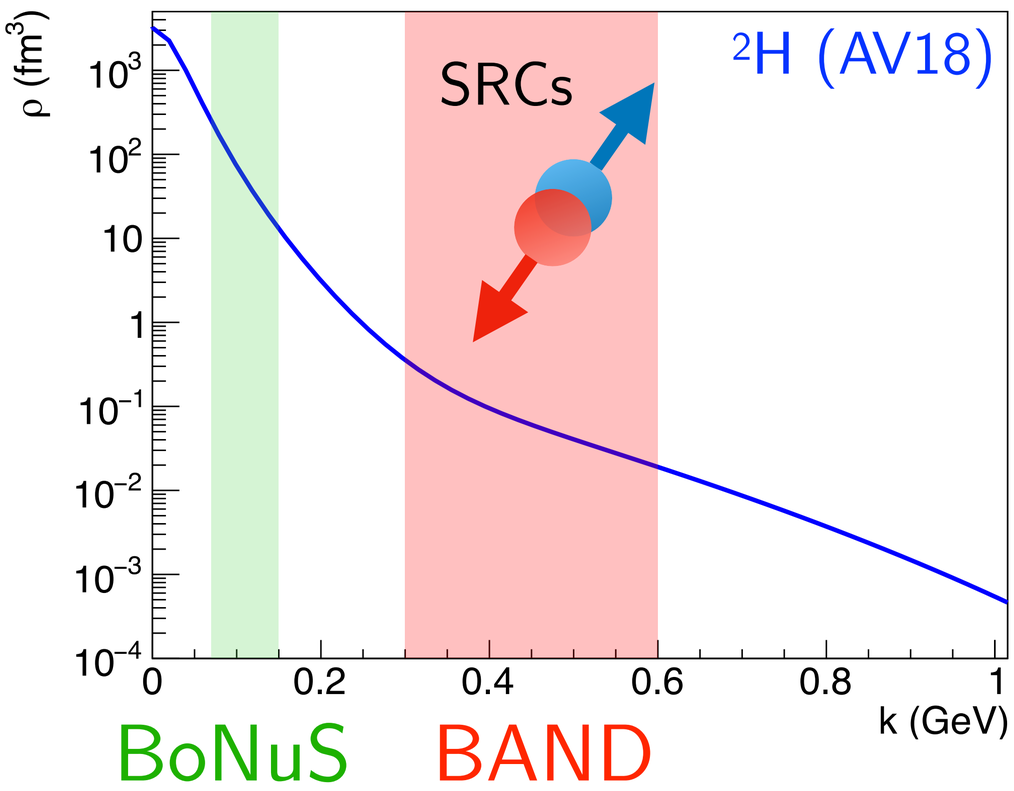
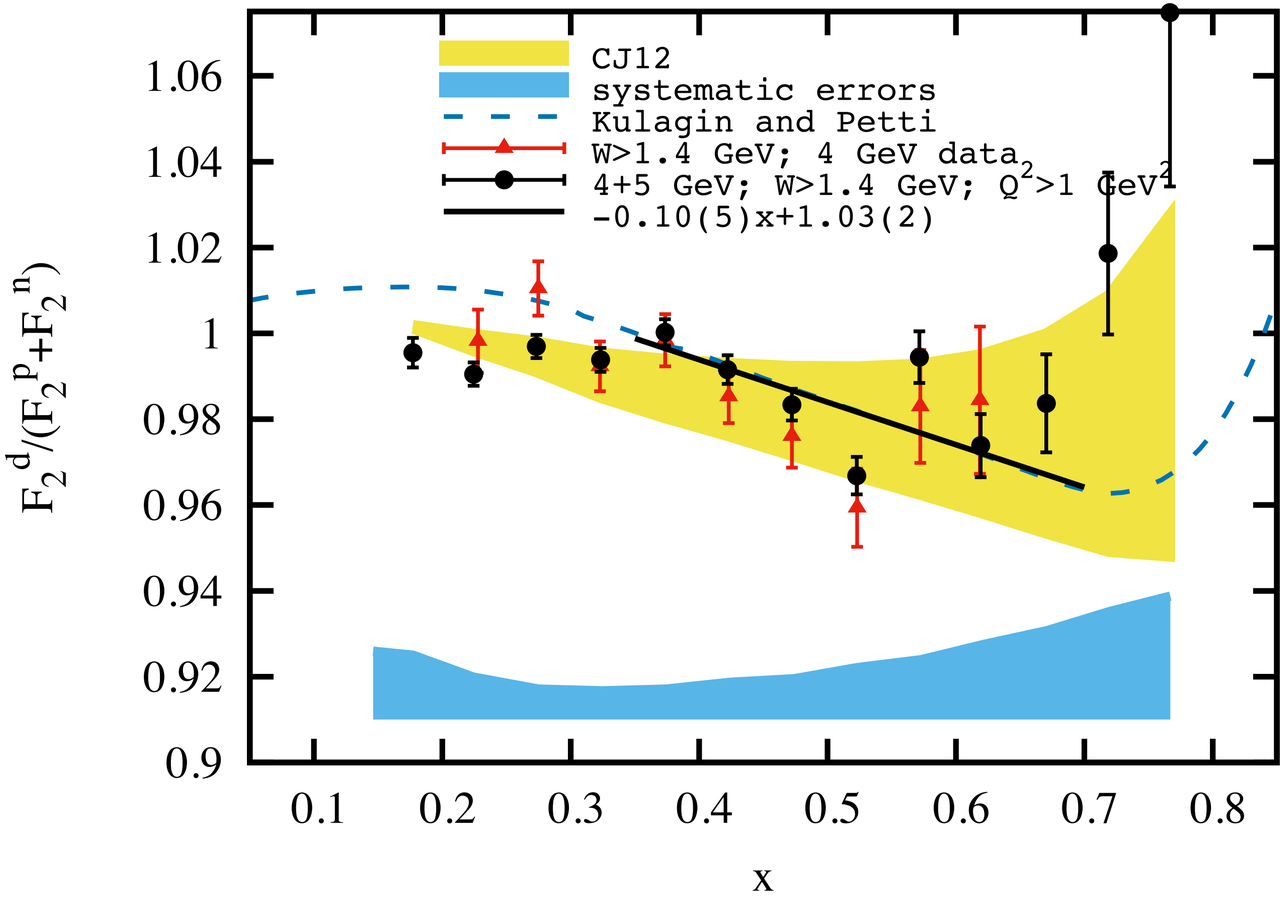


Griffioen *et al.*, PRC (2015)



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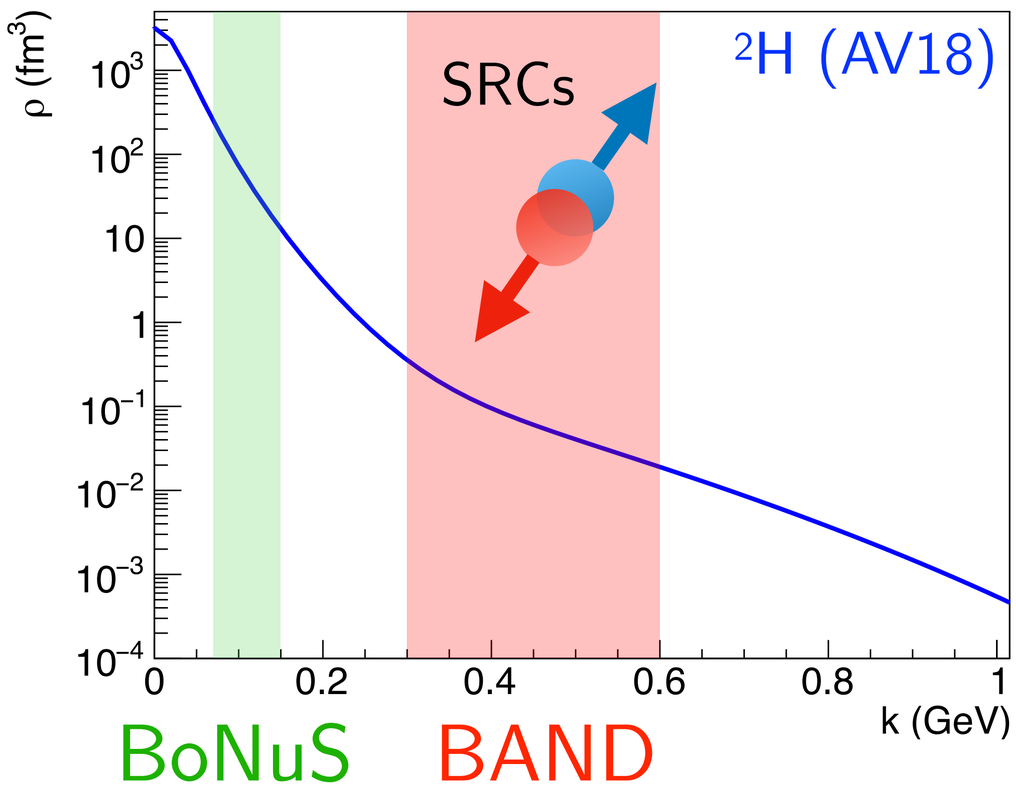

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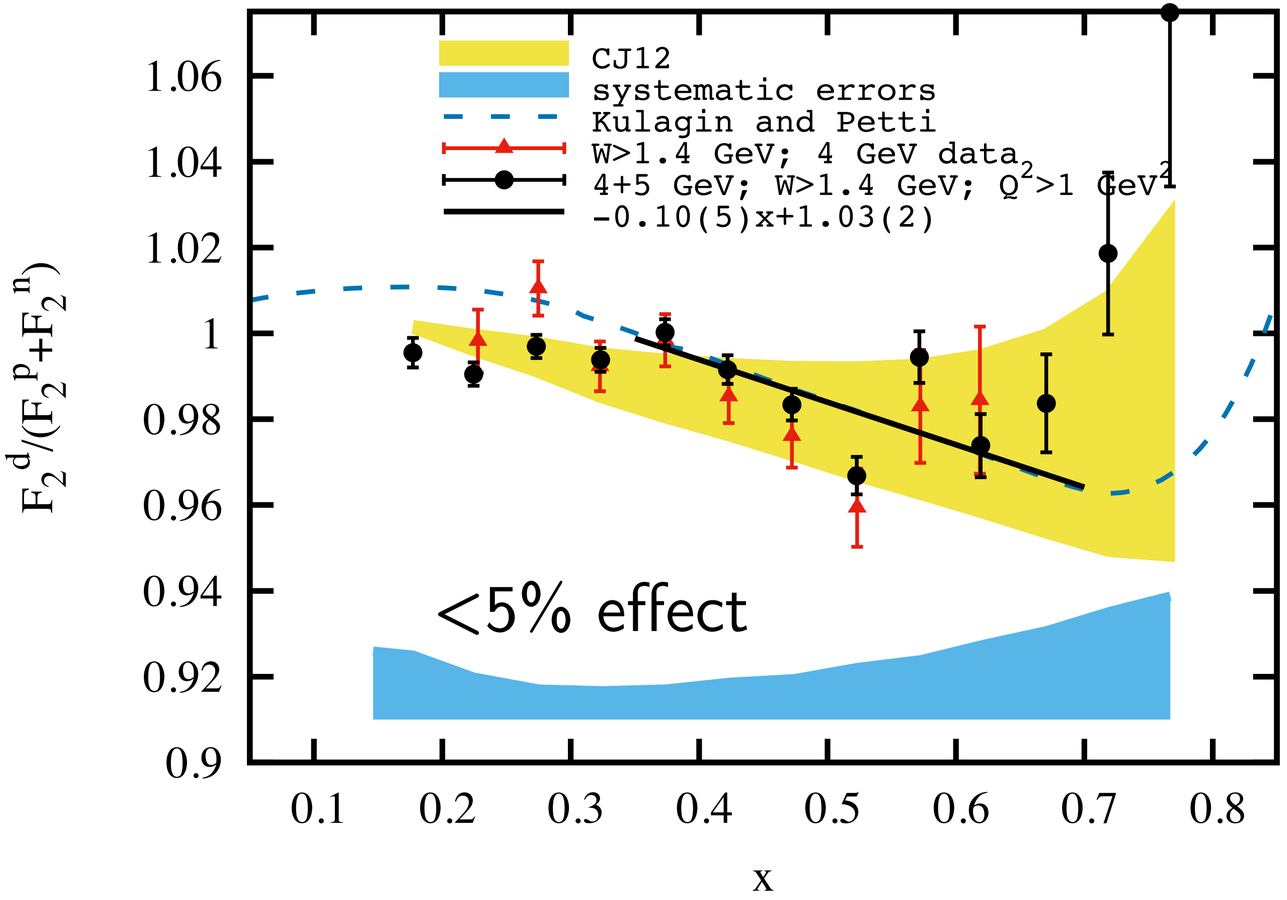

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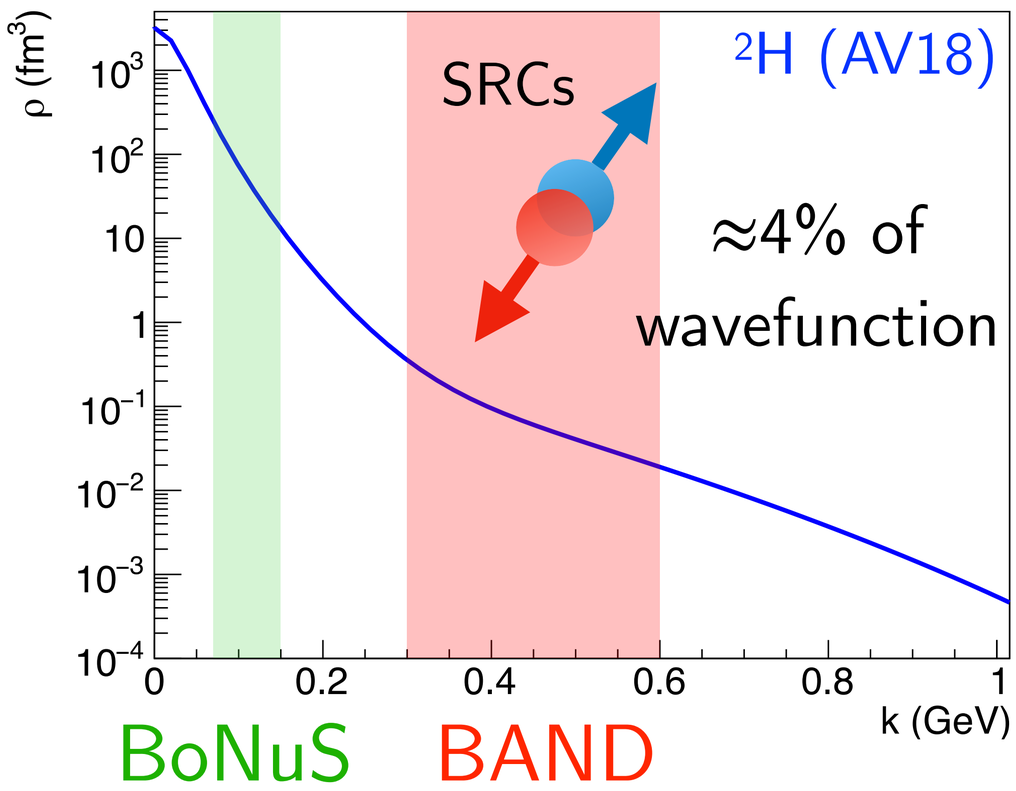

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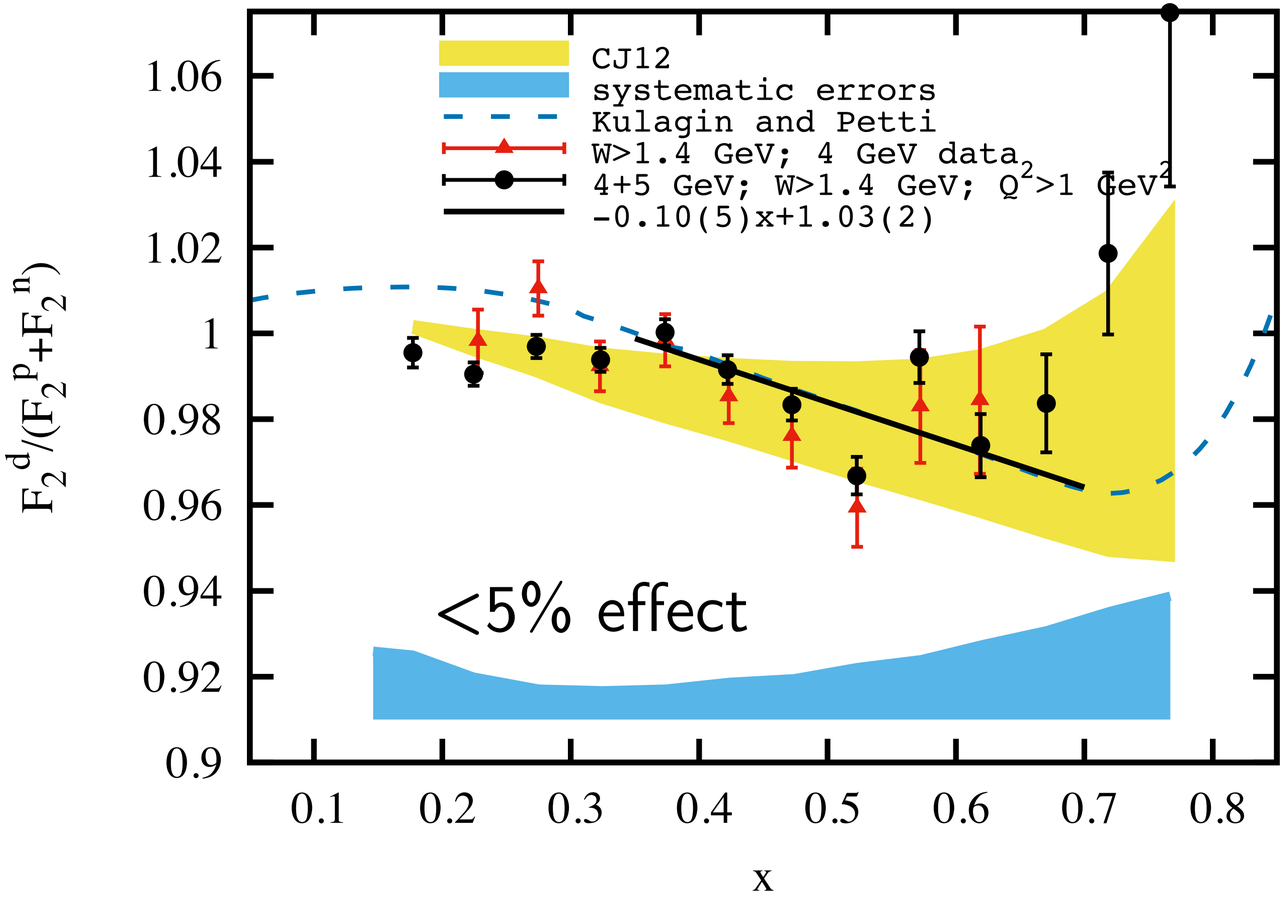

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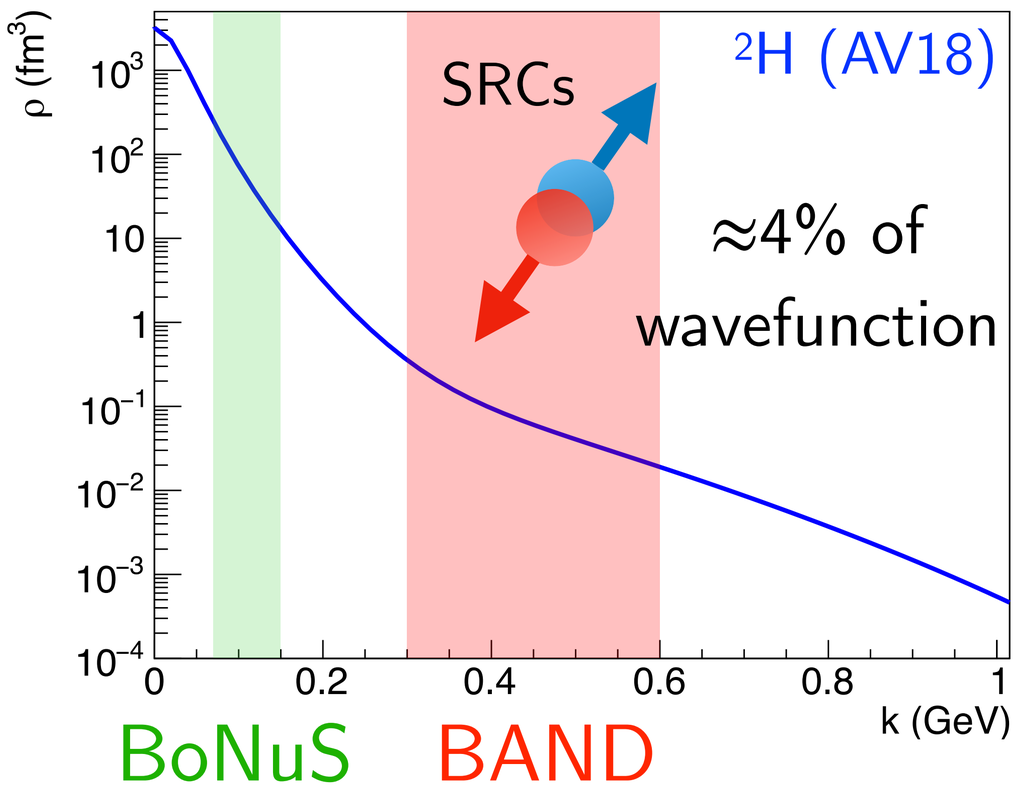

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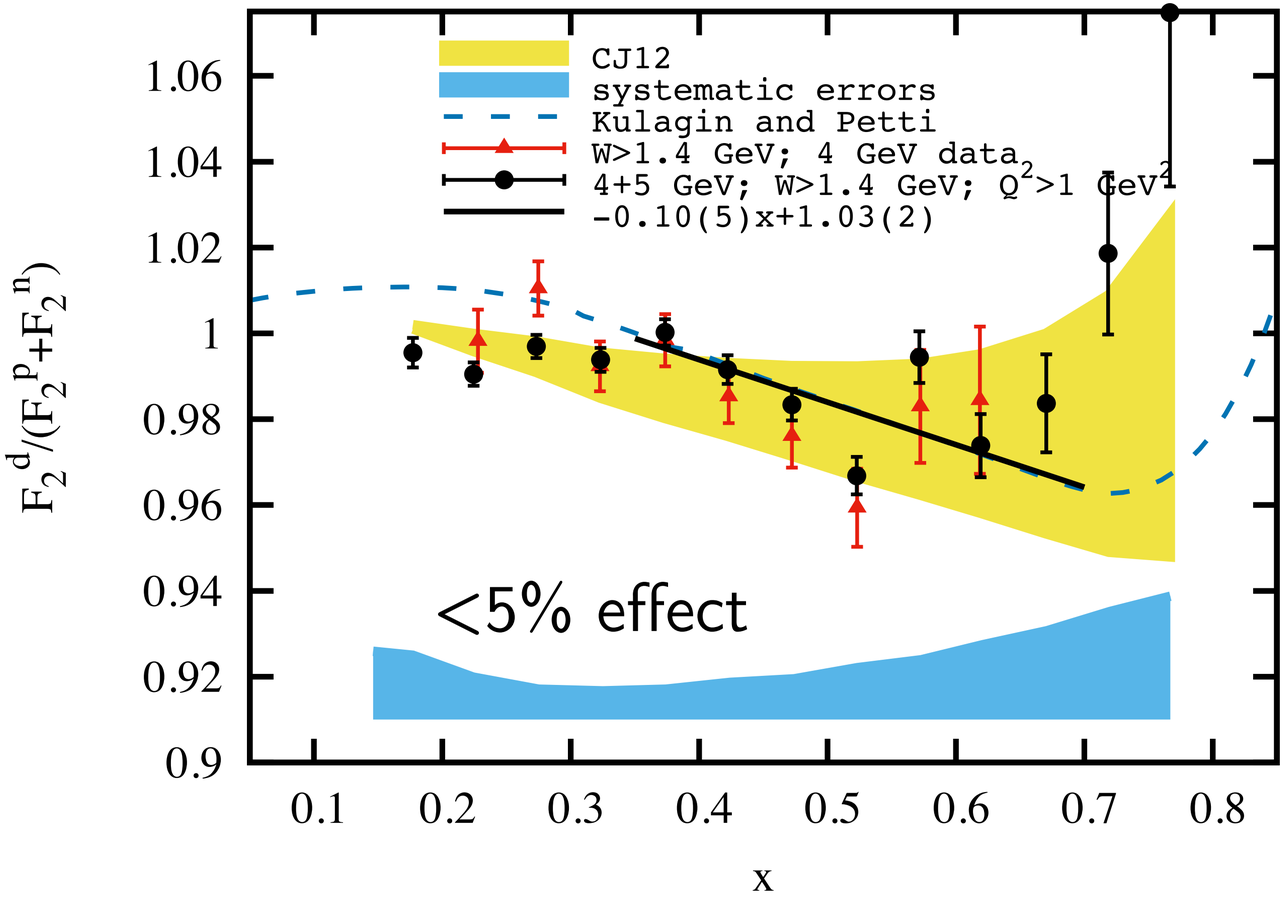
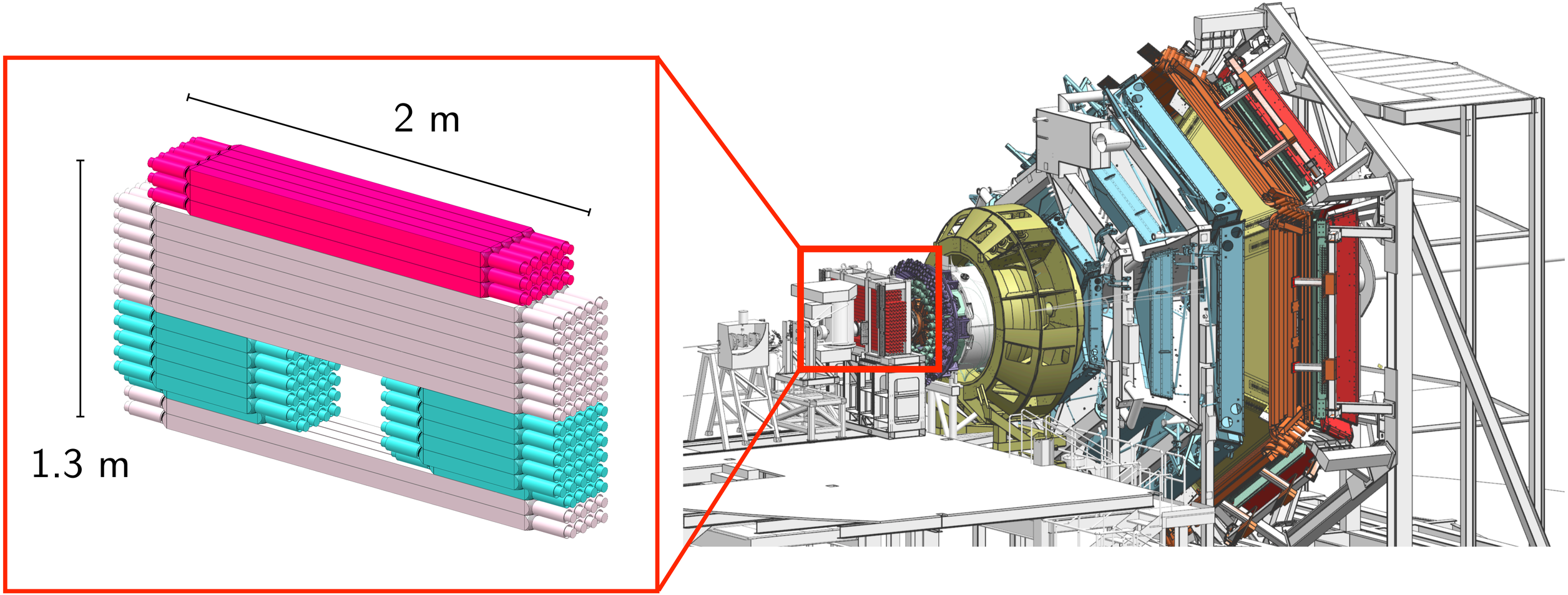


SRC-EMC hypothesis predicts large modification of (rare) SRC states!

Enter the BAND (Backward Angle Neutron Detector)



- 116 plastic scintillator bars + veto layer
- ≈3 m upstream of target

Segarra et al., NIMA 978, 164356 (2020)
Denniston et al., NIMA 973 164177 (2020)

PWIA theory calculation for tagged DIS

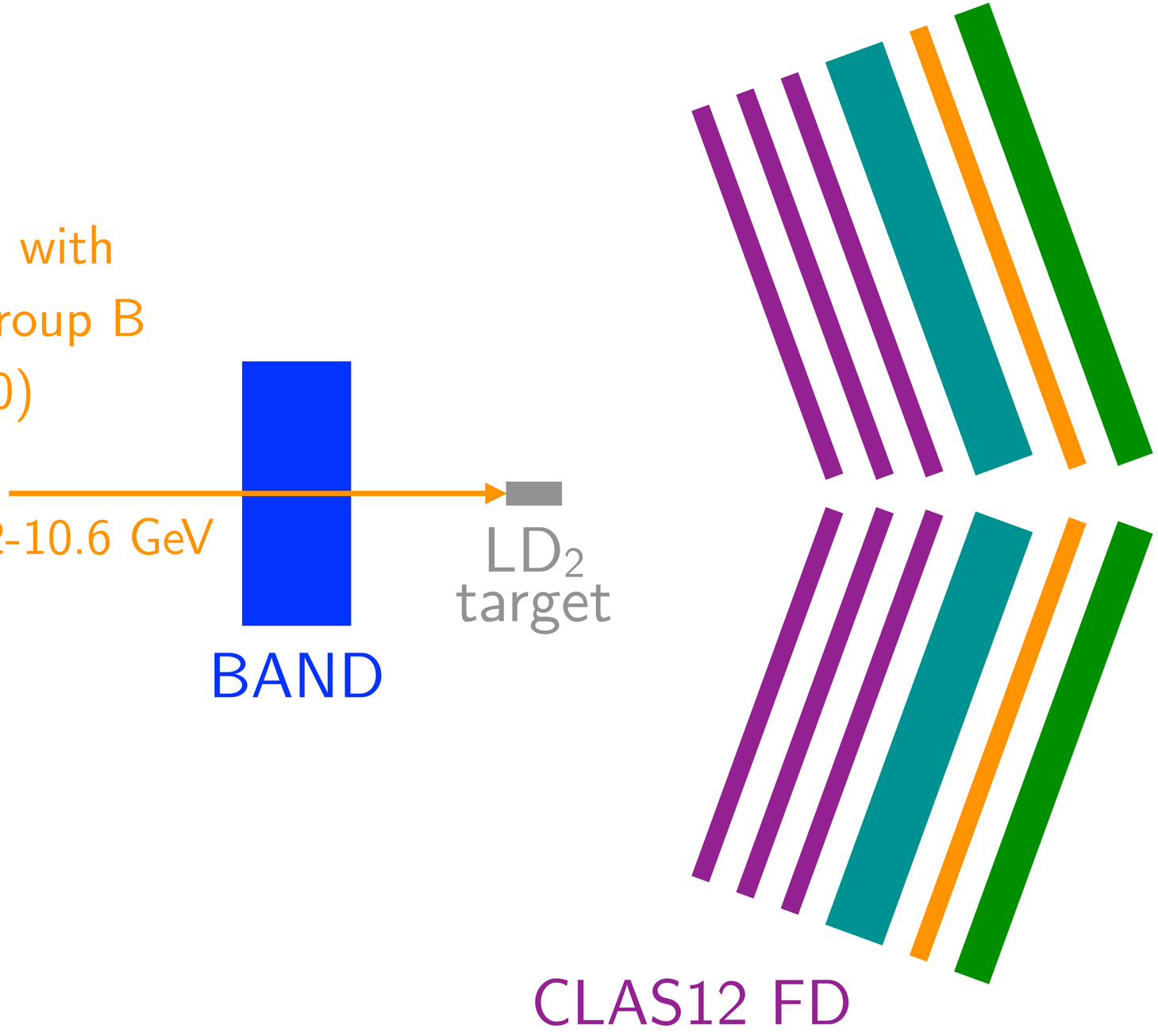
- Cross section model from Strikman & Weiss PRC 97, 035209 (2018):

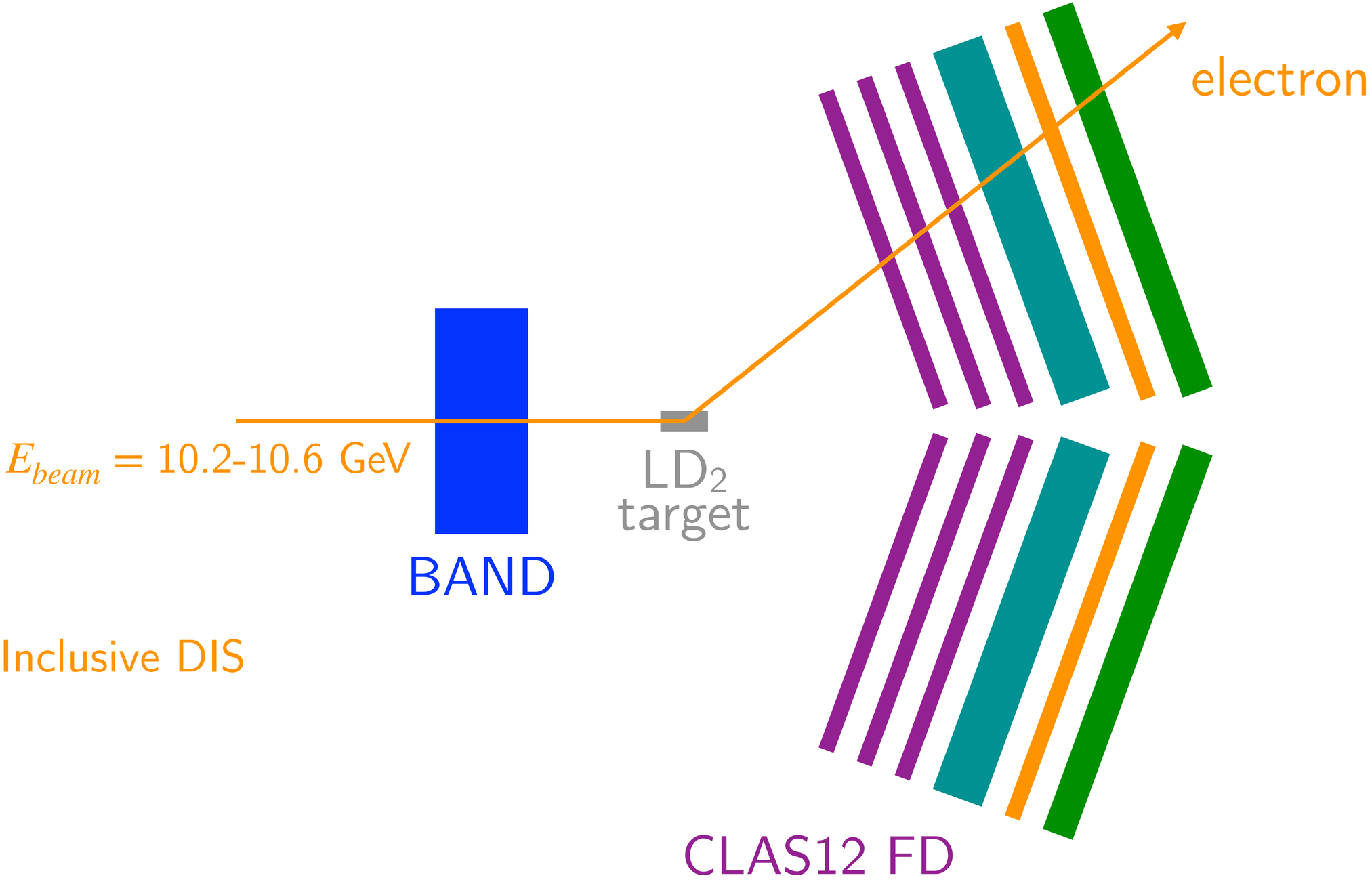
$$d\sigma[eD \to e' n_s X] = K \frac{2S(\alpha_s, p_{sT})}{2 - \alpha_s} \times F_2$$

- Kinematic factors
- Deuterium spectral function (momentum distribution of bound protons)
- Free proton structure functions (no EMC modification!)
- Simulate generated events (with QED radiation) in GEANT4

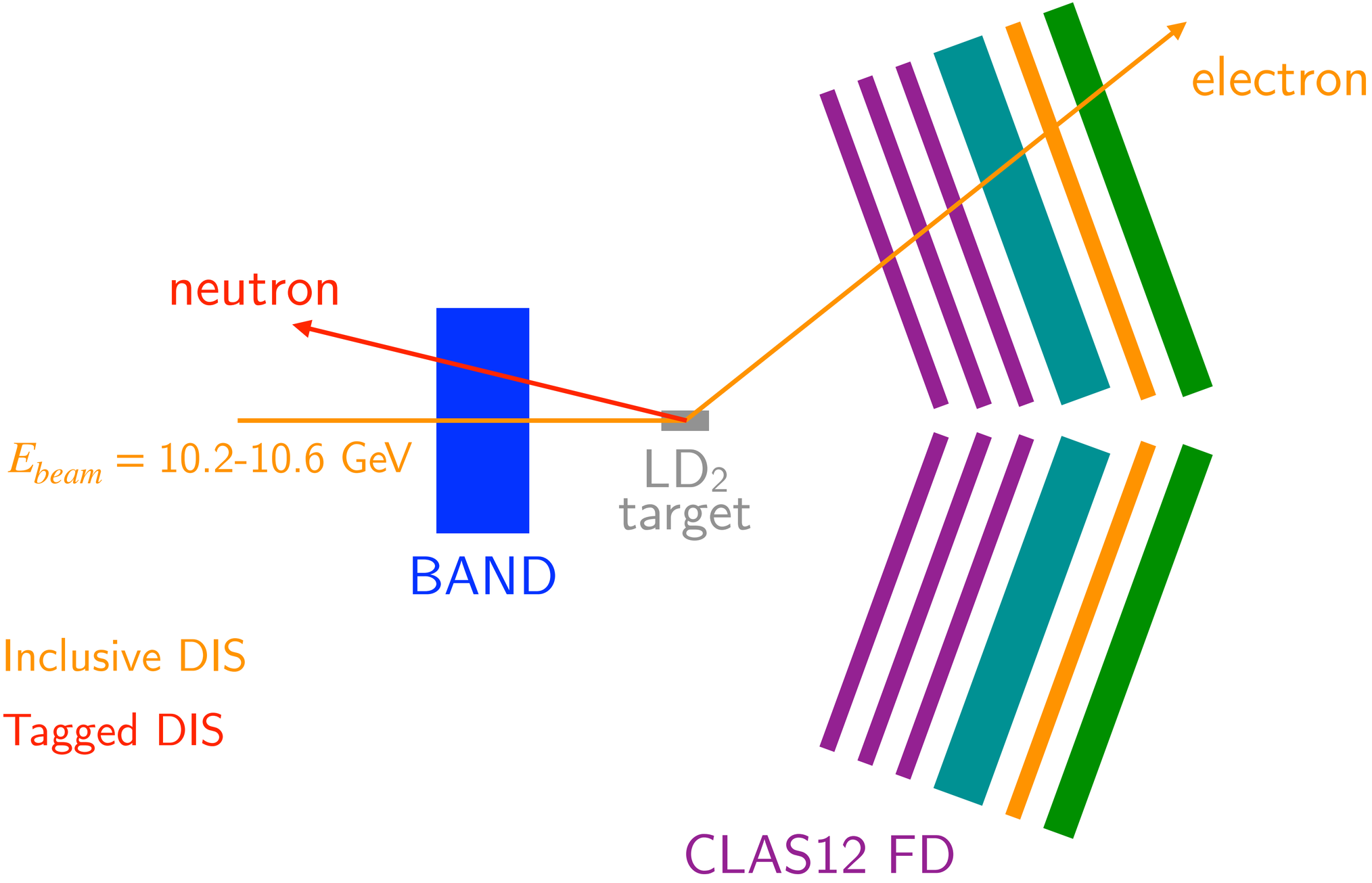
Collected data with
CLAS12 Run Group B
(2019-2020)

E_{beam} = 10.2-10.6 GeV



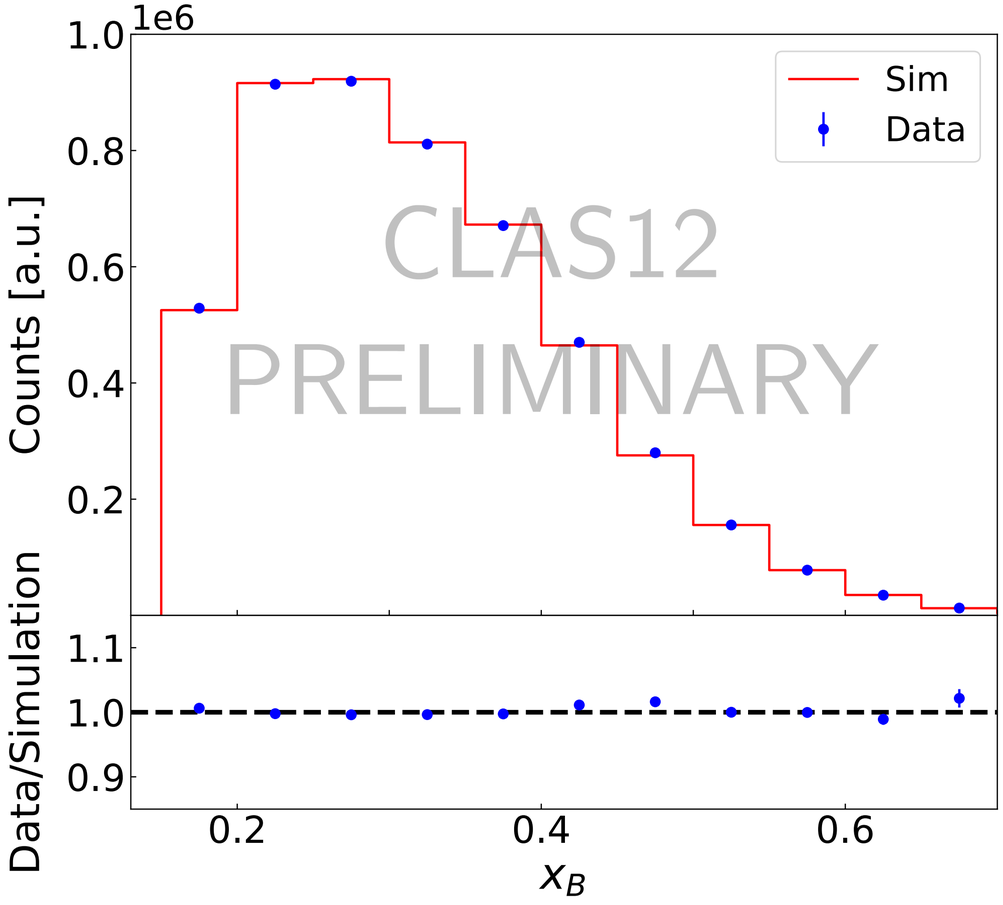


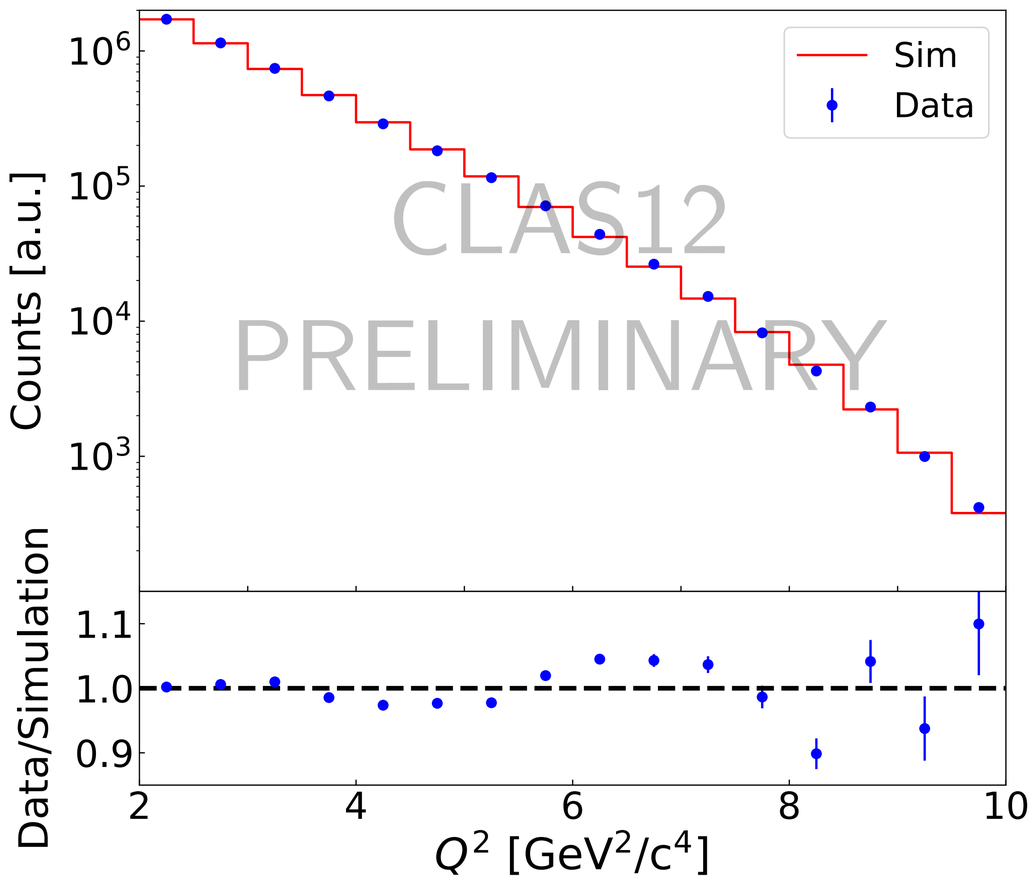
- Inclusive DIS



- Inclusive DIS
- Tagged DIS

Inclusive DIS results



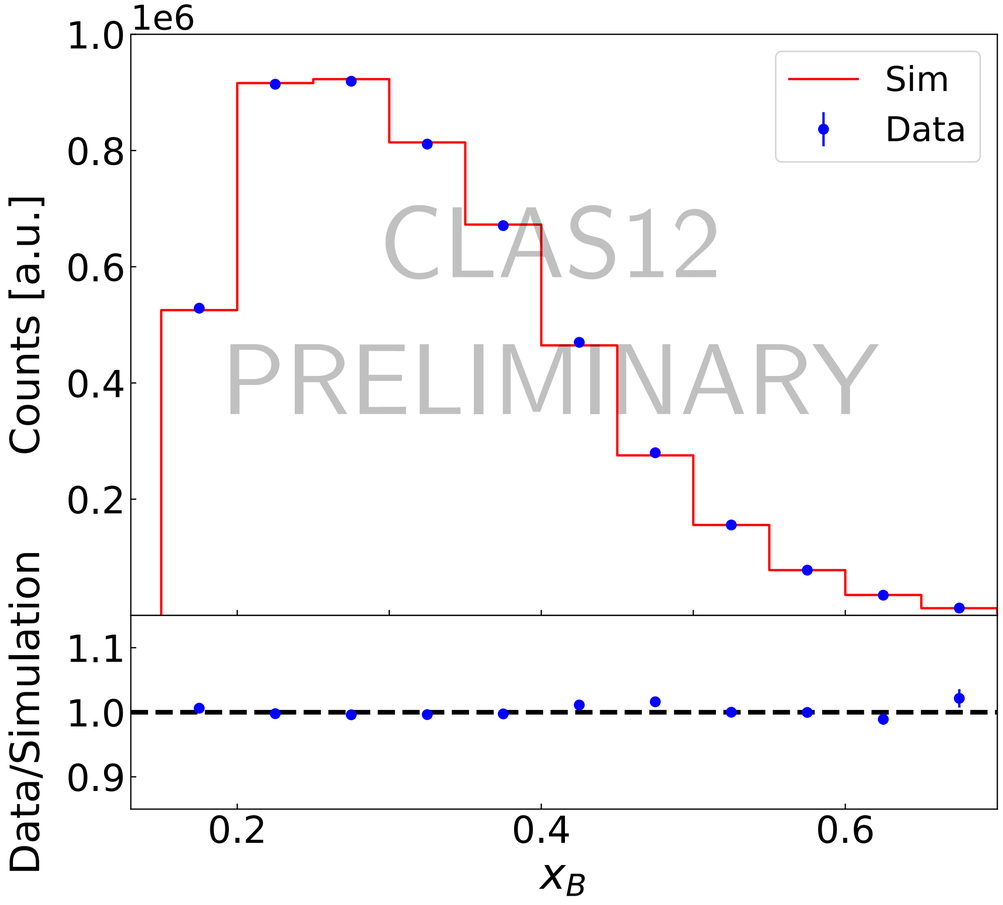


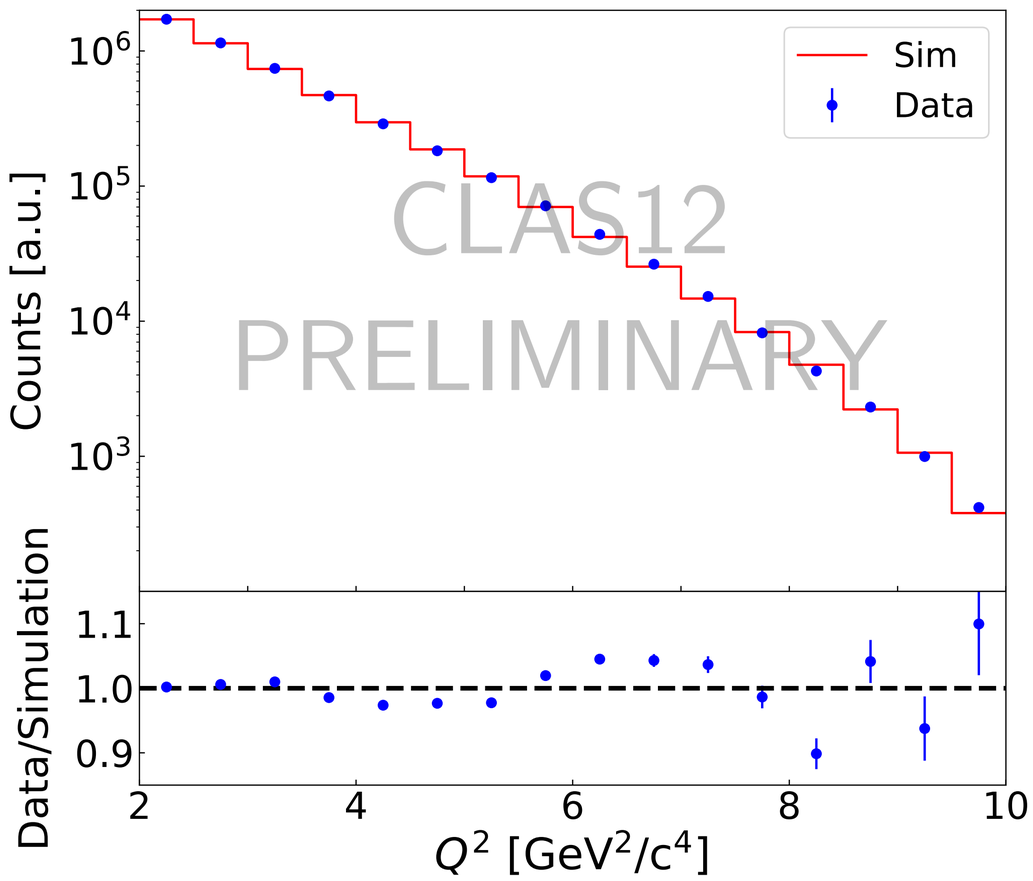
$Q^2 > 2$ GeV^2.

$W^2 > 4$ GeV^2.

$y < 0.7$

Inclusive DIS results





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$W^2 > 4$ GeV^2.

$y < 0.7$

✓ Validates simulation of electron in CLAS12

Yield ratio method for tagged DIS

$$\sigma_{exp}^{Born} = \frac{Y_{exp}}{Y_{sim}} \sigma_{theory}^{Born} \quad \rightarrow \quad \frac{\sigma_{exp}^{Born}}{\sigma_{theory}^{Born}} = \frac{Y_{exp}}{Y_{sim}}$$

$$\mathcal{R} = \frac{Y_{exp}(x')/Y_{exp}(x' = x'_0)}{Y_{sim}(x')/Y_{sim}(x' = x'_0)} = \frac{\sigma_{exp}(x')/\sigma_{exp}(x' = x'_0)}{\sigma_{theory}(x')/\sigma_{theory}(x' = x'_0)}$$

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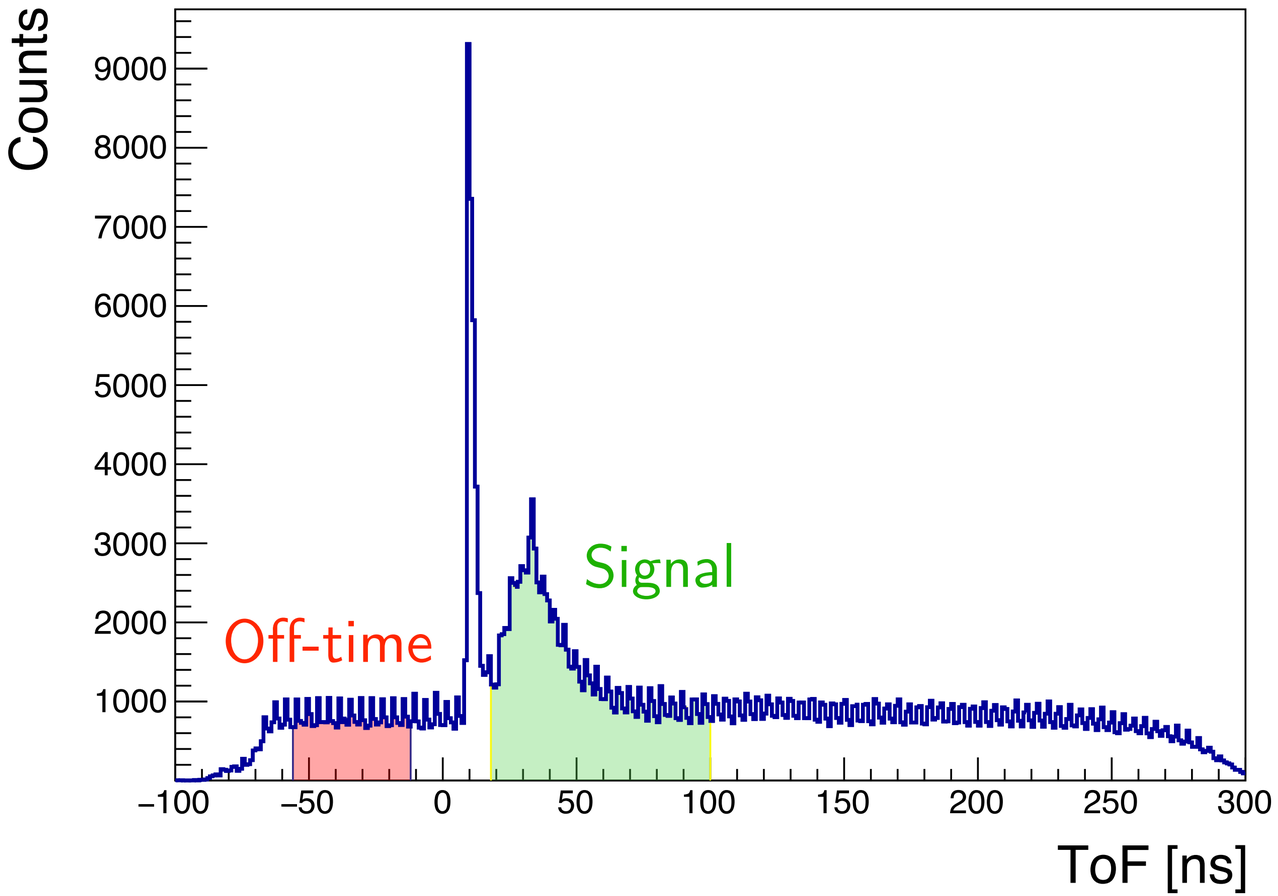
- Ratio gives cancellation of systematics
- Choose to normalize to $x'_0 = 0.3$
- Sensitive to ratio of bound to free proton structure

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

BAND background subtraction



- Event-mix off-time neutrons with inclusive electrons
- Account for 4 ns beam bunch structure

Tagged DIS

$E_{dep} > 10$ MeVee

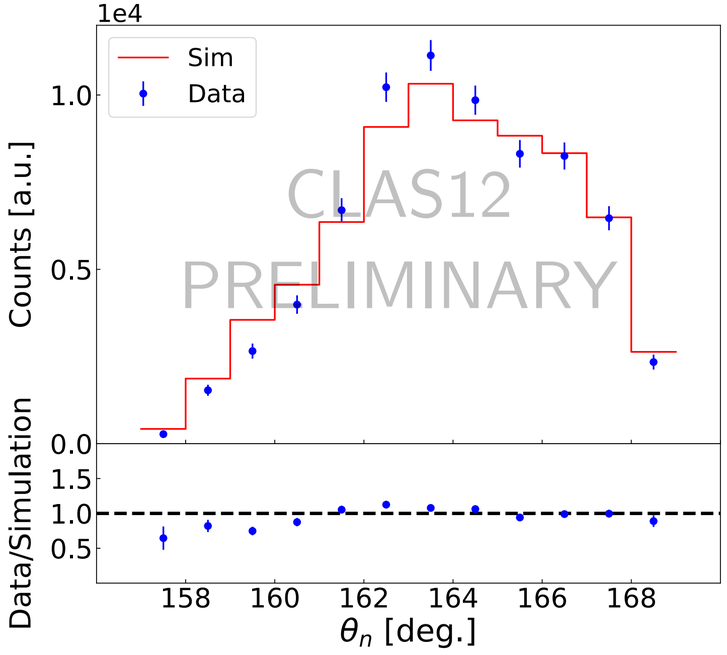
$p_n > 0.25$ GeV

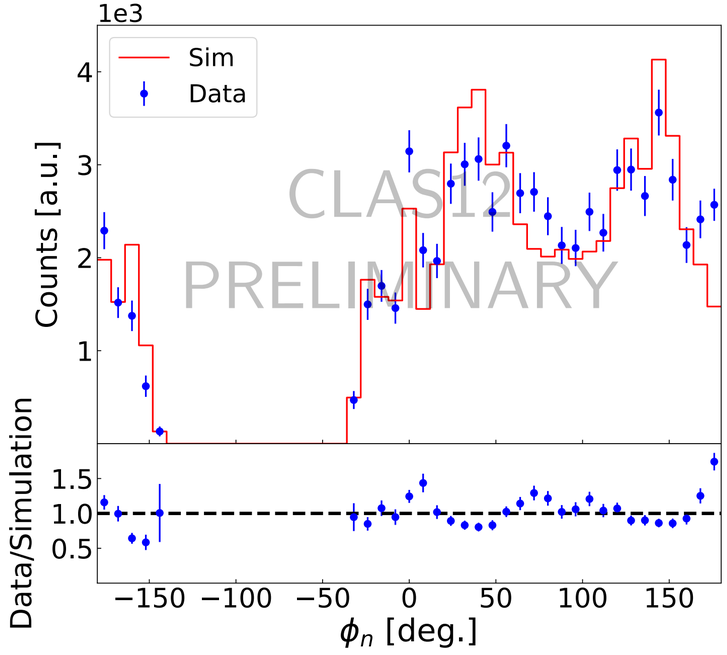
$\theta_n < 168.5°$

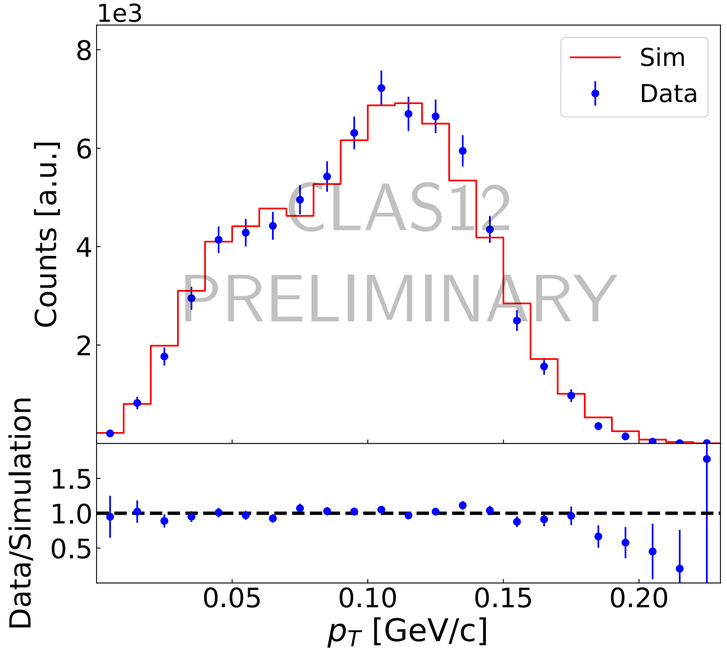
$W' > 1.8$ GeV

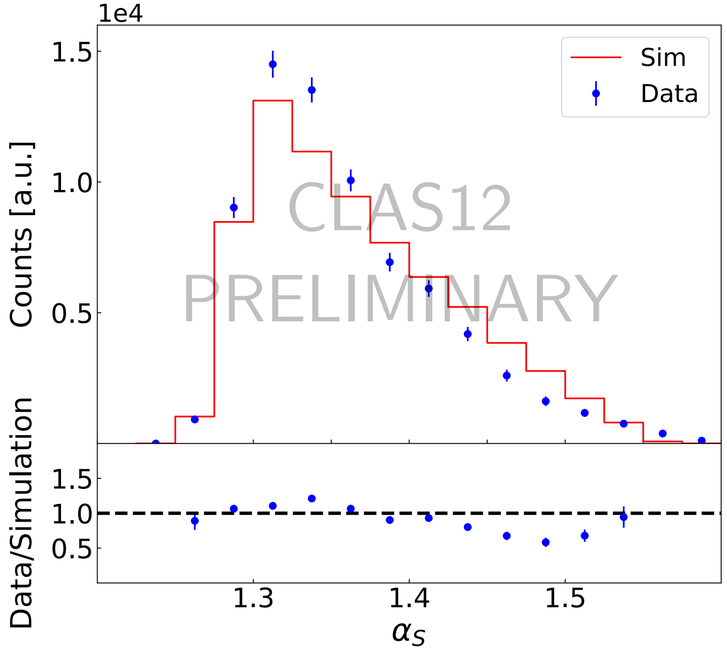
$\alpha_s > 1.2$

$\cos\theta_{nq} < -0.8$

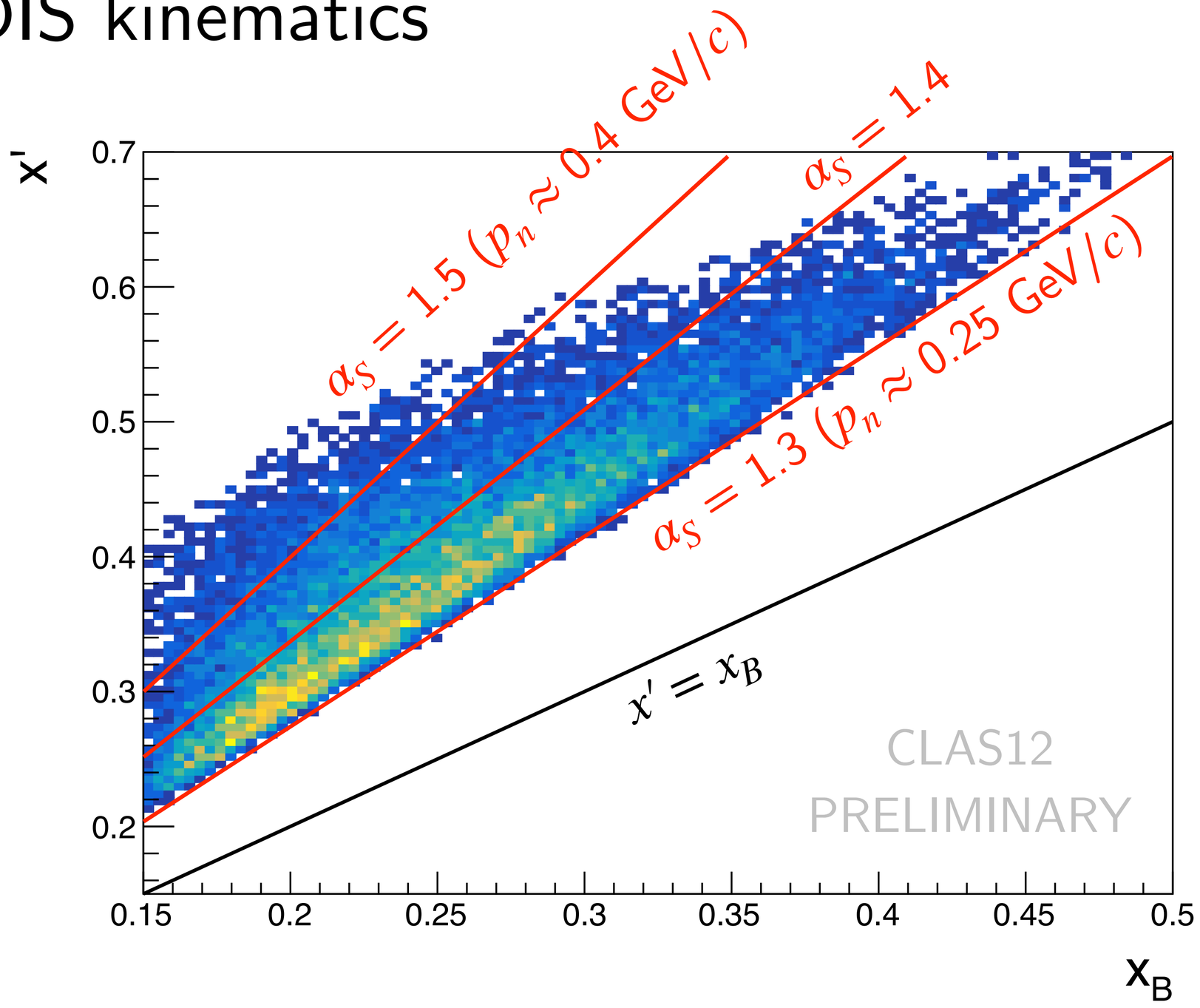




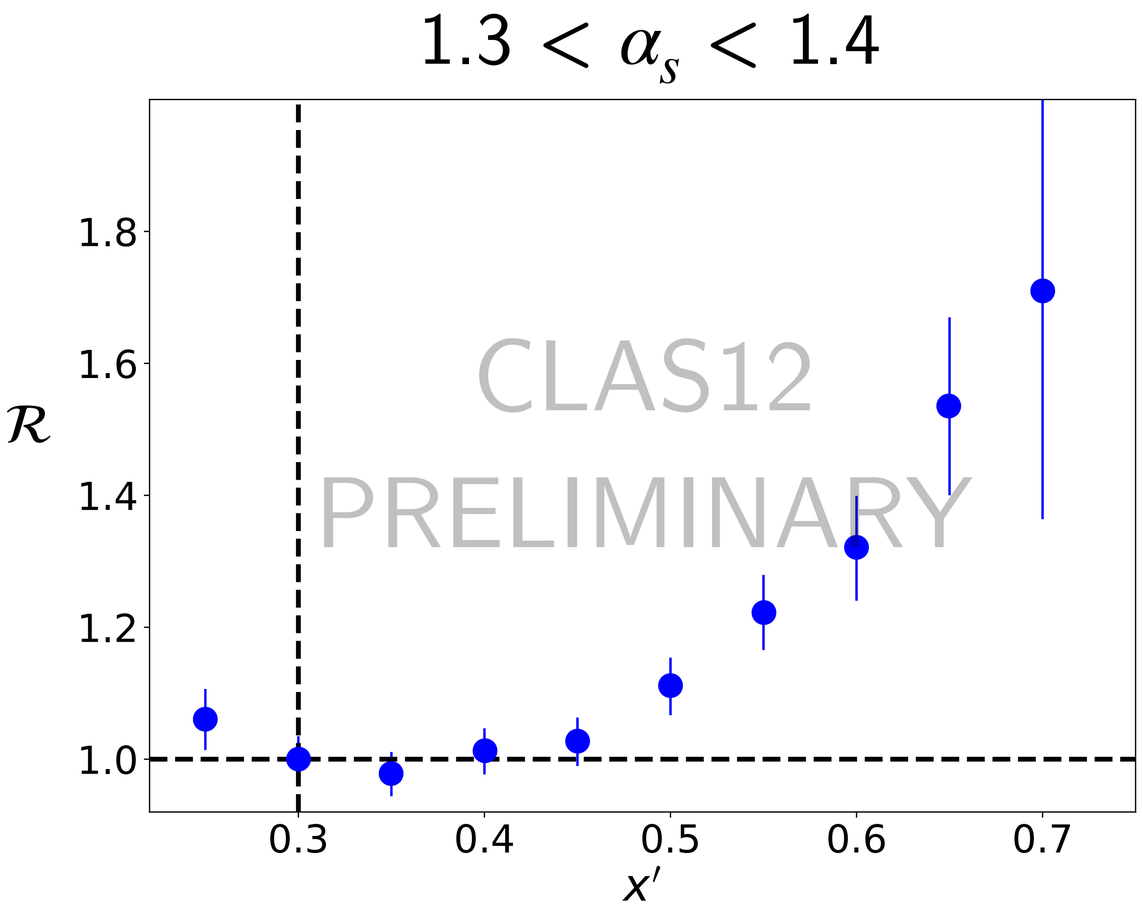


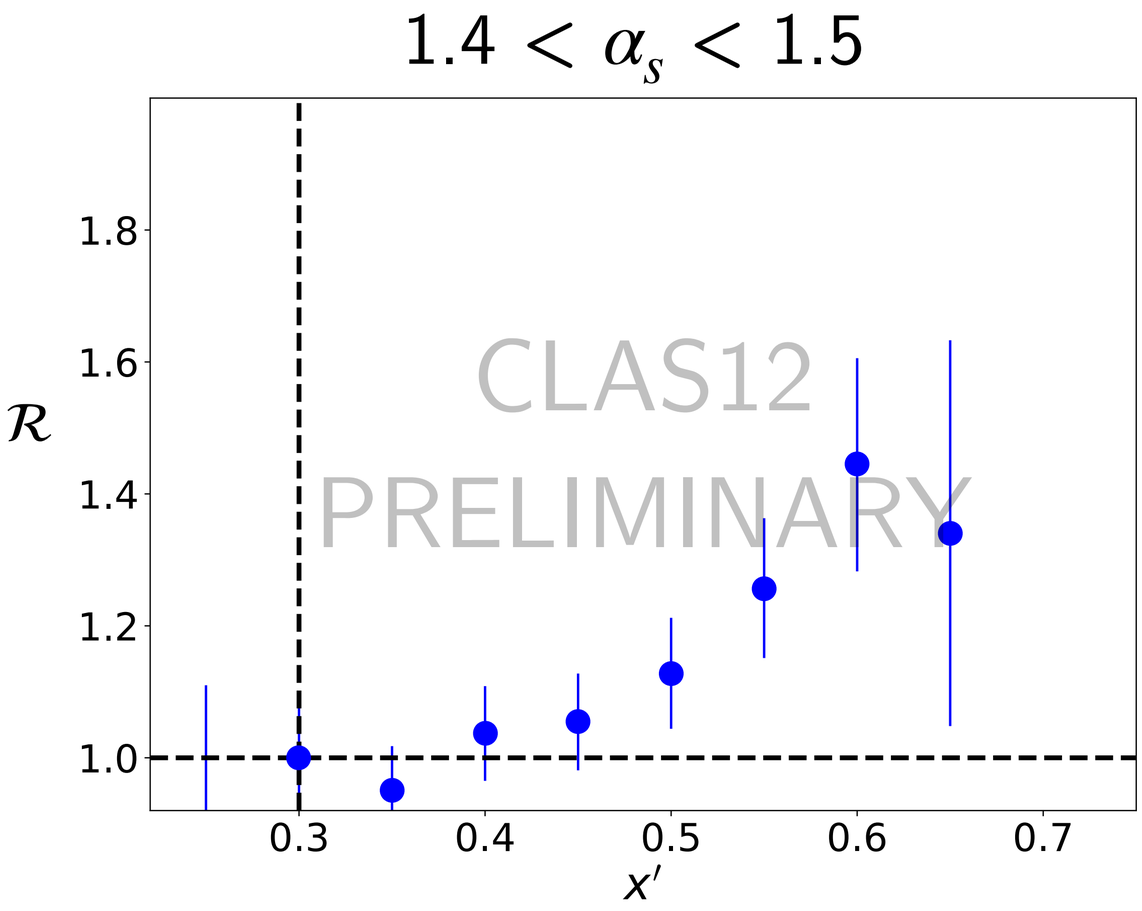


Tagged DIS kinematics



Tagged DIS double ratio



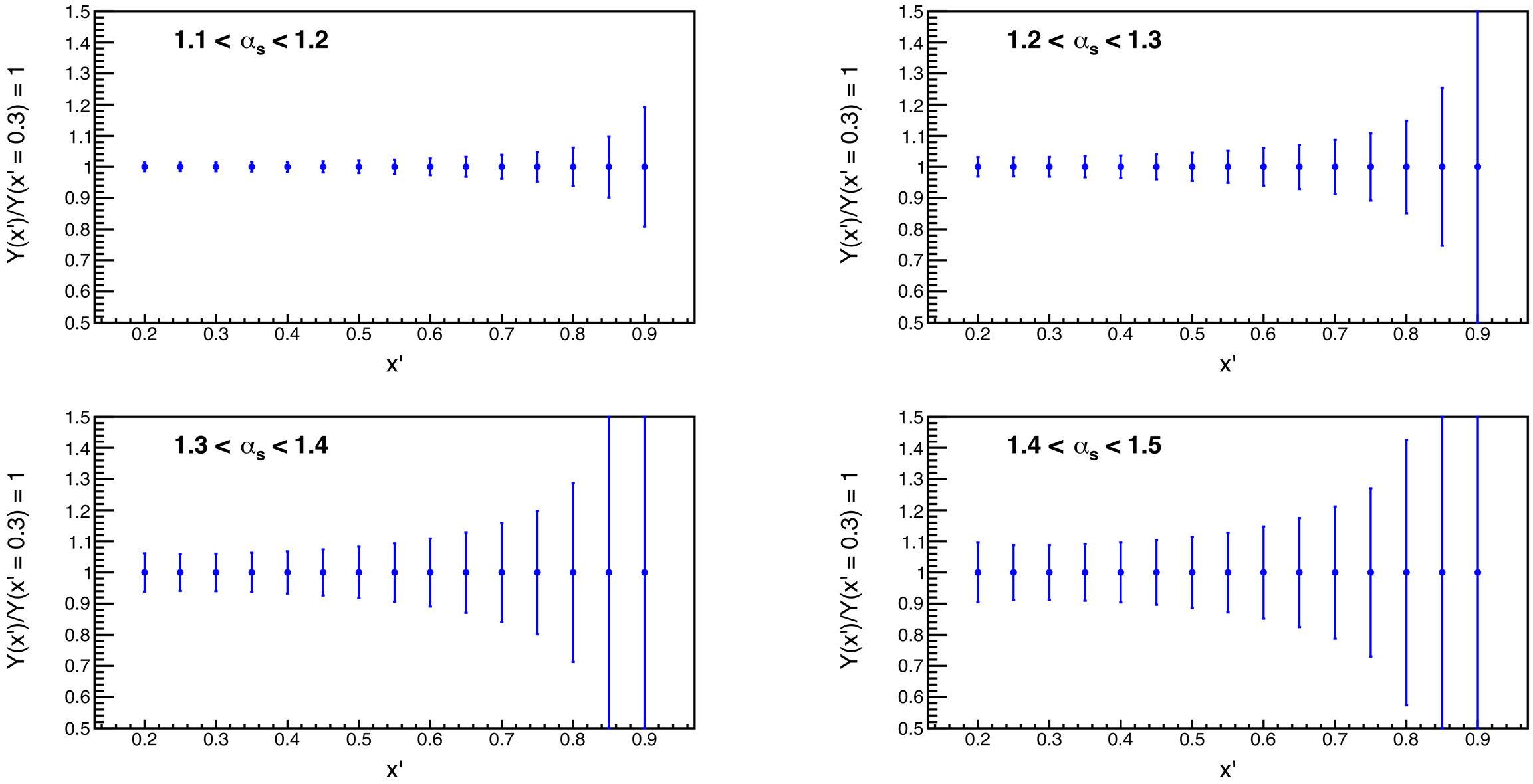


$$\mathcal{R} \propto \frac{F_2^*\left(Q^2, p_T, \alpha_S, x'\right) / F_2\left(Q^2, p_T, \alpha_S, x'\right)}{F_2^*\left(Q^2, p_T, \alpha_S, x' = x_0\right) / F_2\left(Q^2, p_T, \alpha_S, x' = x_0\right)}$$

What could be done with a 22 GeV electron beam?

- Approach:
  - Assume detectors the same, only beam energy changes
  - Use same luminosity (180 fb^{-1}) as RGB data used for present analysis
  - Estimate rates with fast Monte Carlo
    (CLAS12 electron acceptance, BAND neutron acceptance/efficiency)

Projected statistical reach in data ratio at 22 GeV

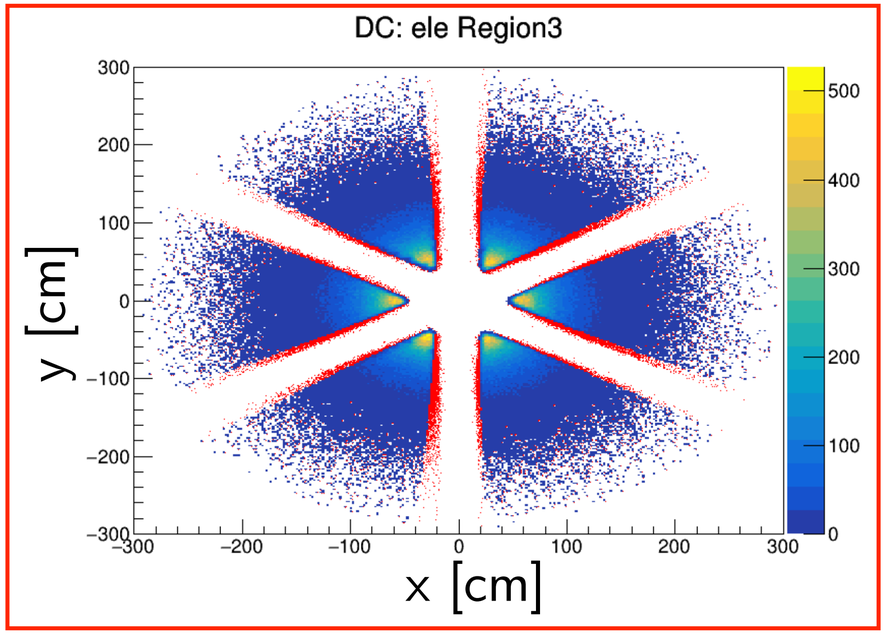


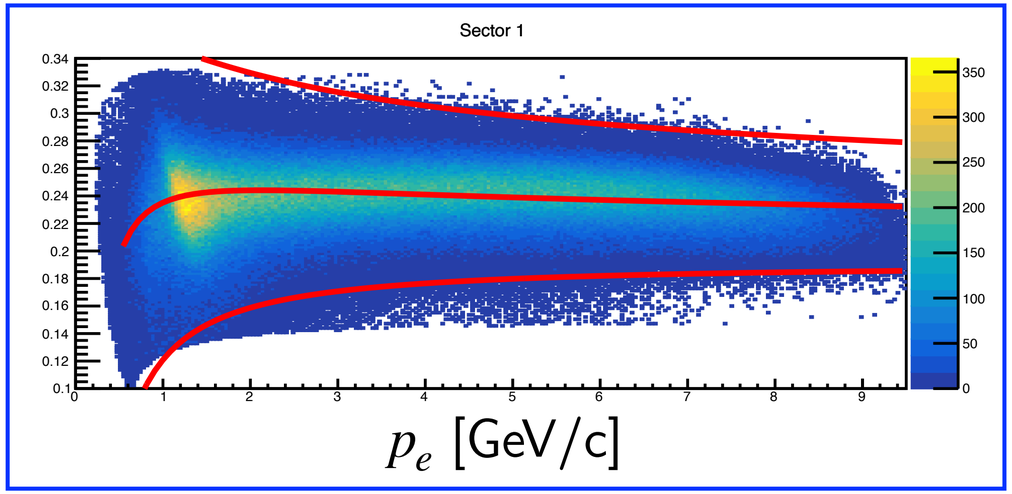
Summary

- Tagged DIS allows measurements of parton structure sensitive to nuclear configuration
- BoNuS used proton-tagged DIS from deuterium to extract free neutron structure
  - Existing BoNuS data from 6 GeV; BoNuS12 collected data in 2020
- BAND/CLAS12 carried out first measurement of neutron-tagged DIS from deuterium
  - Preliminary results (under CLAS12 analysis review) indicates large modification of deeply bound protons
- Upgraded 22 GeV electron beam would allow tagged-DIS measurements at 20-30% higher x_B than existing measurements

Backup

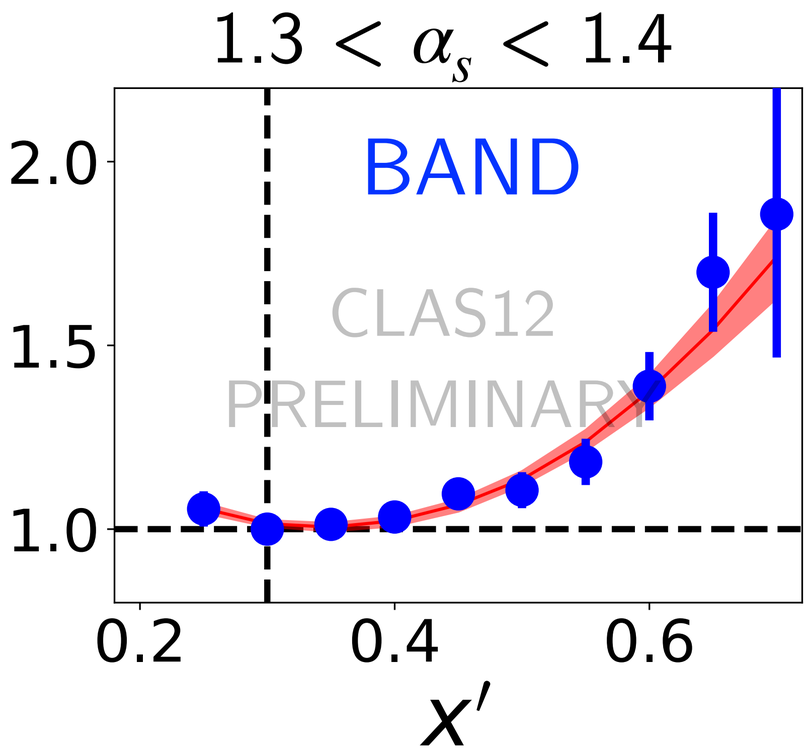
CLAS12 electron selection

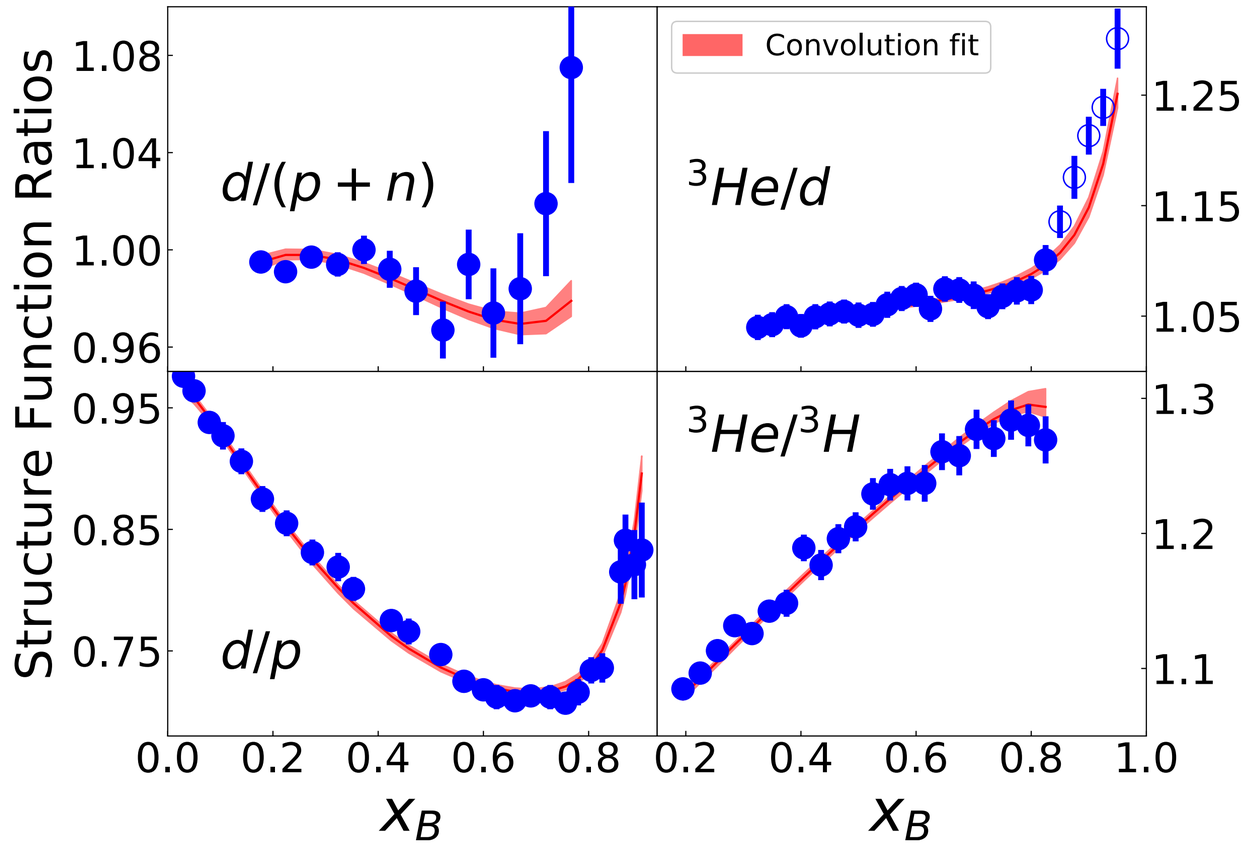




- DC fiducial cuts
- ECAL/PCAL fiducial cuts
- Sampling fraction vs. E_{PCAL} ($\pm 5\sigma$)
- Sampling fraction vs. p_e ($\pm 5\sigma$)
- $0.17 < E/p_e < 0.3$ GeV
  ($0.2 < E/p_e$ for $p_e > 4.5$ GeV)

Result is consistent with existing (inclusive) measurements of light nuclei...





Simultaneous fit of F_2^{p*}/F_2^p from BAND and F_2^A/F_2^B from various light nuclei

...and gives a prediction for bound *neutron* structure!