Nucleon structure with tagged DIS

Tyler Kutz
MIT/TAU

Program INT-23-1a:
Intersection of nuclear structure
and high-energy nuclear collisions

Seattle, WA
February 23, 2023

Nucleons in nuclei bound by $\mathcal{O}(1\%)$ of their mass

Nucleus mass ≈1 GeV
(most dynamically generated)

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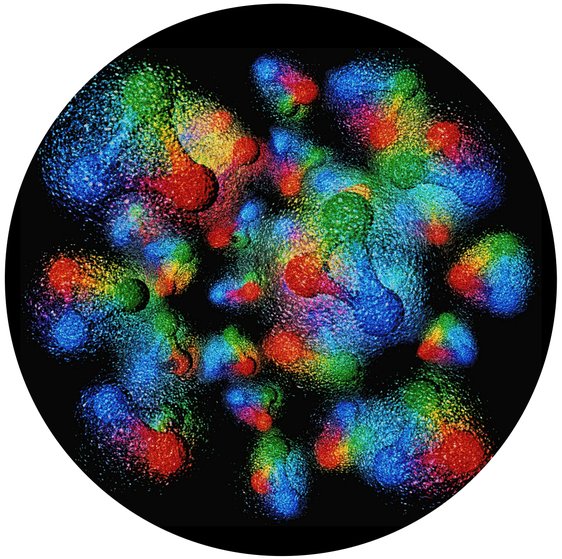
Nuclear binding energy
$\leq$ 10 MeV/nucleon



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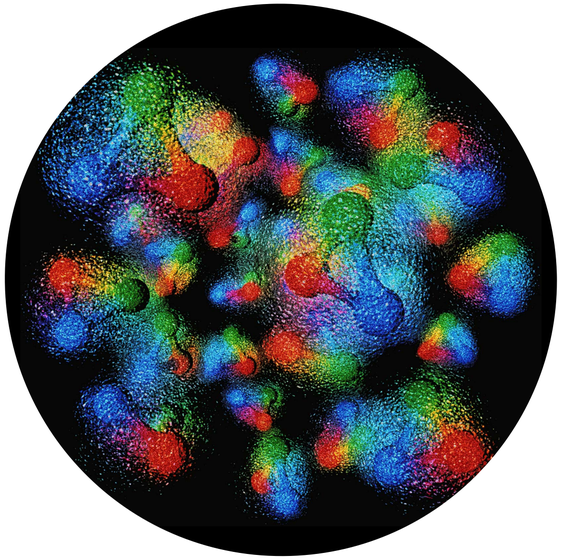

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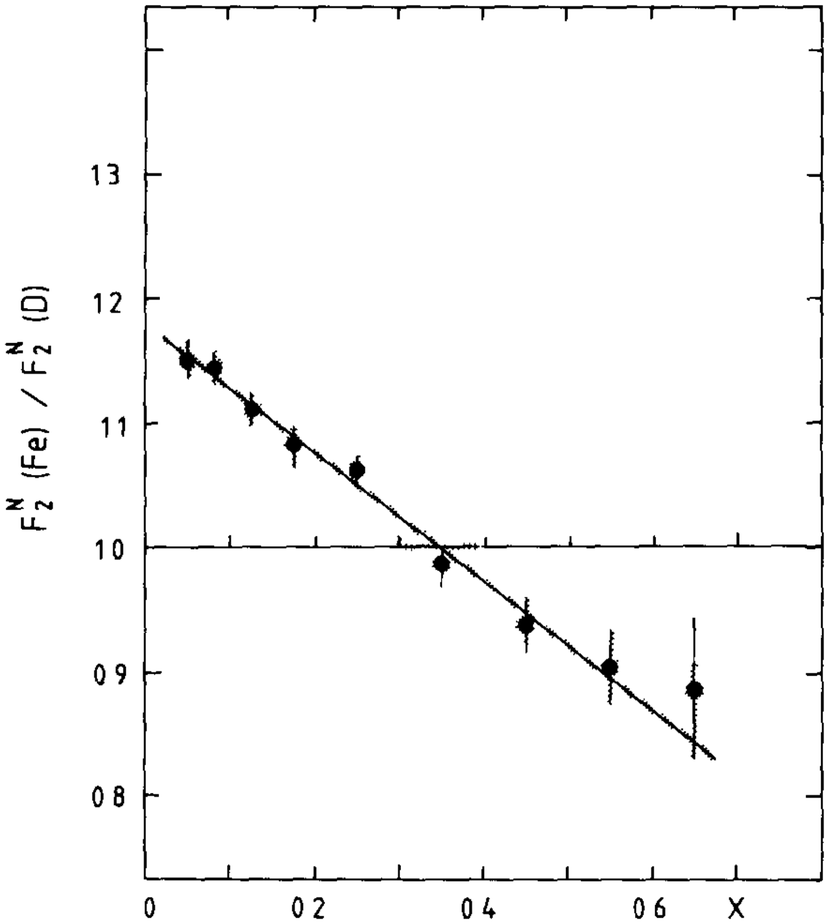
Naive intuition says that MeV-scale binding
shouldn't impact GeV-scale parton dynamics

But it does!

EMC, PLB 123, 275 (1983)



[Personal account by Hugh Montgomery]

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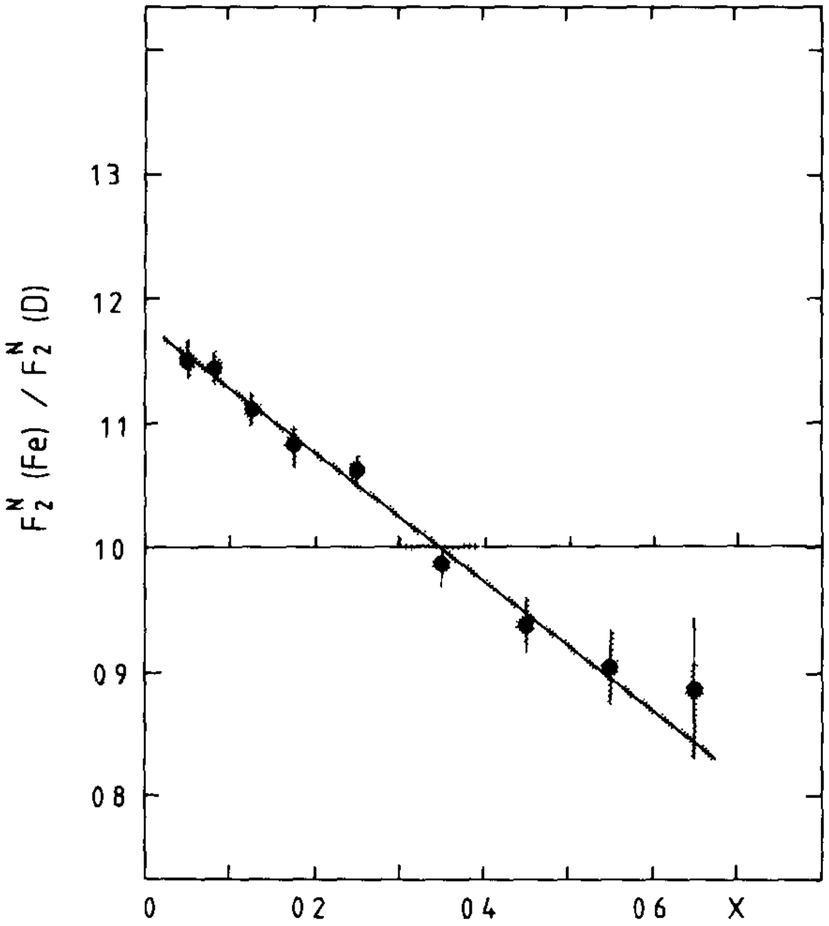
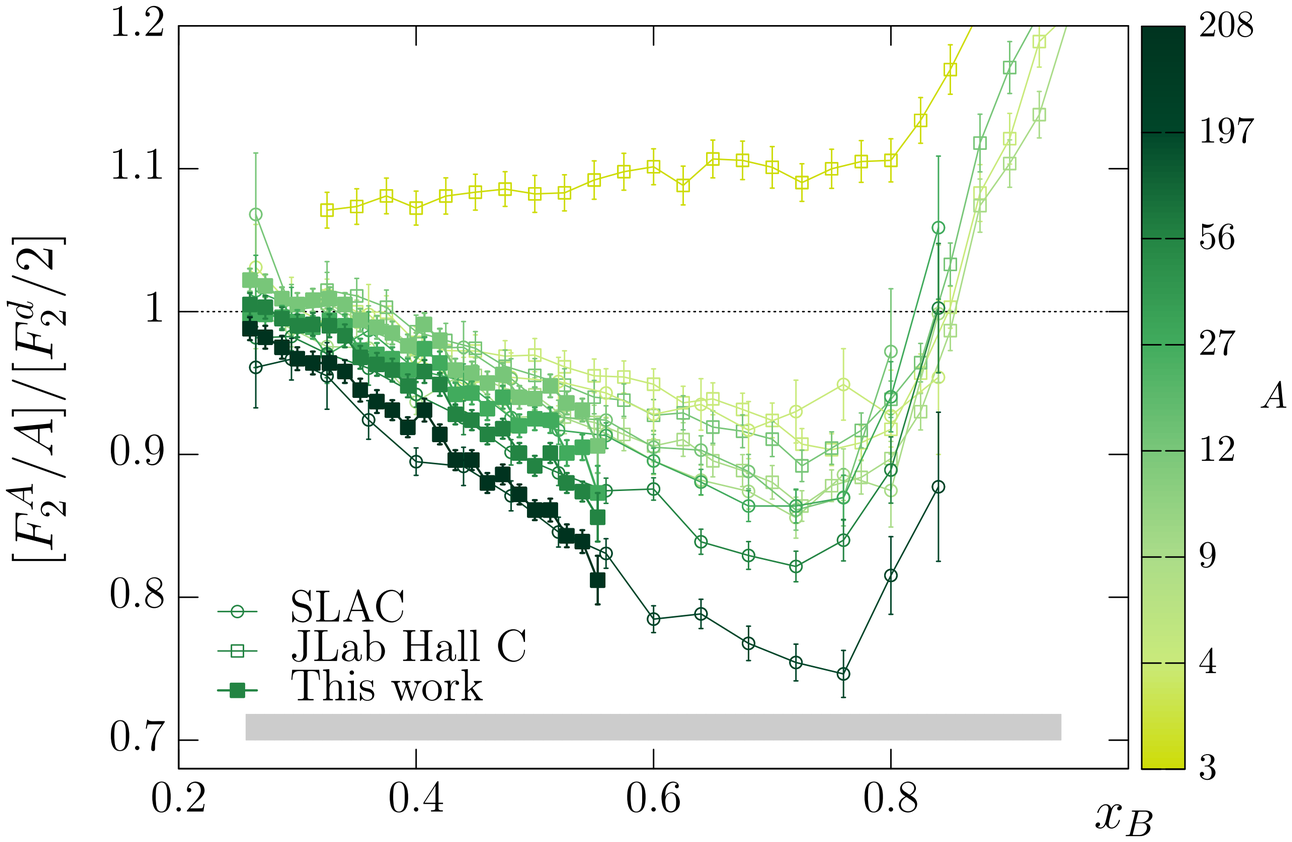


Schmookler *et al.*, Nature (2019)



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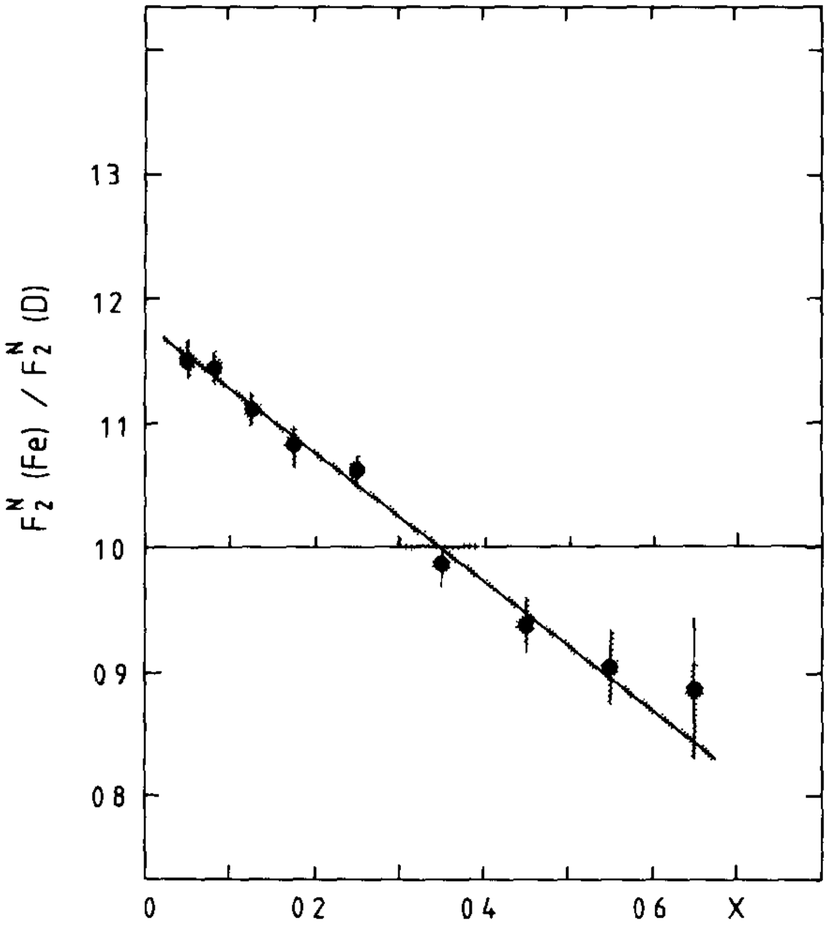

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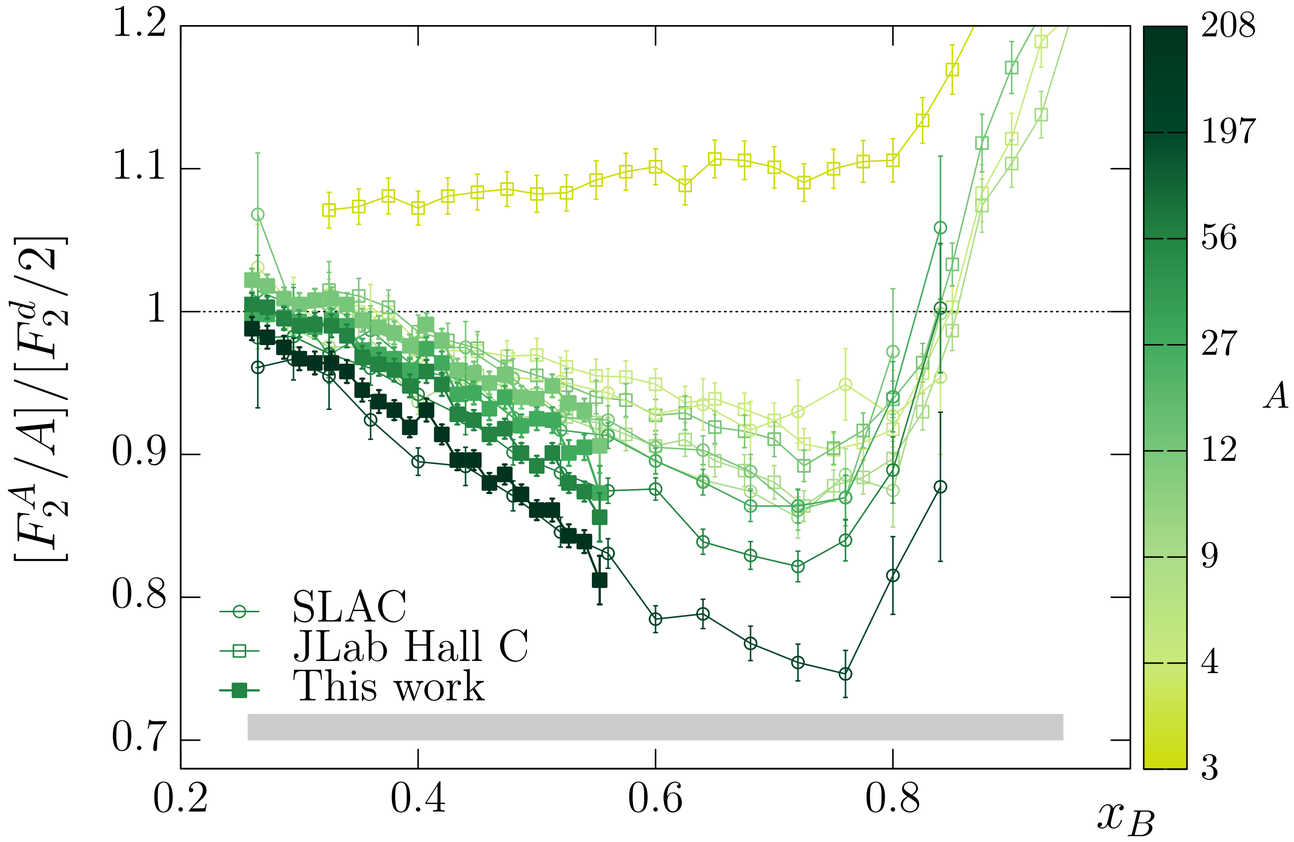

[Personal account by Hugh Montgomery]

$$F_2^A \neq ZF_2^p + (A-Z)F_2^n$$

Not explained by conventional nuclear physics

- Nucleons are moving

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TOTAL NEUTRON CROSS SECTIONS
MAY NOT BE WHAT THEY SEEM TO BE

G. B. WEST
Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, Calif. 94305, *USA*

Received 27 September 1971

rections, etc.) but, here, we would like to focus on a subtlety in what is perhaps the simplest correction, namely, that due to Fermi motion

Not explained by conventional nuclear physics

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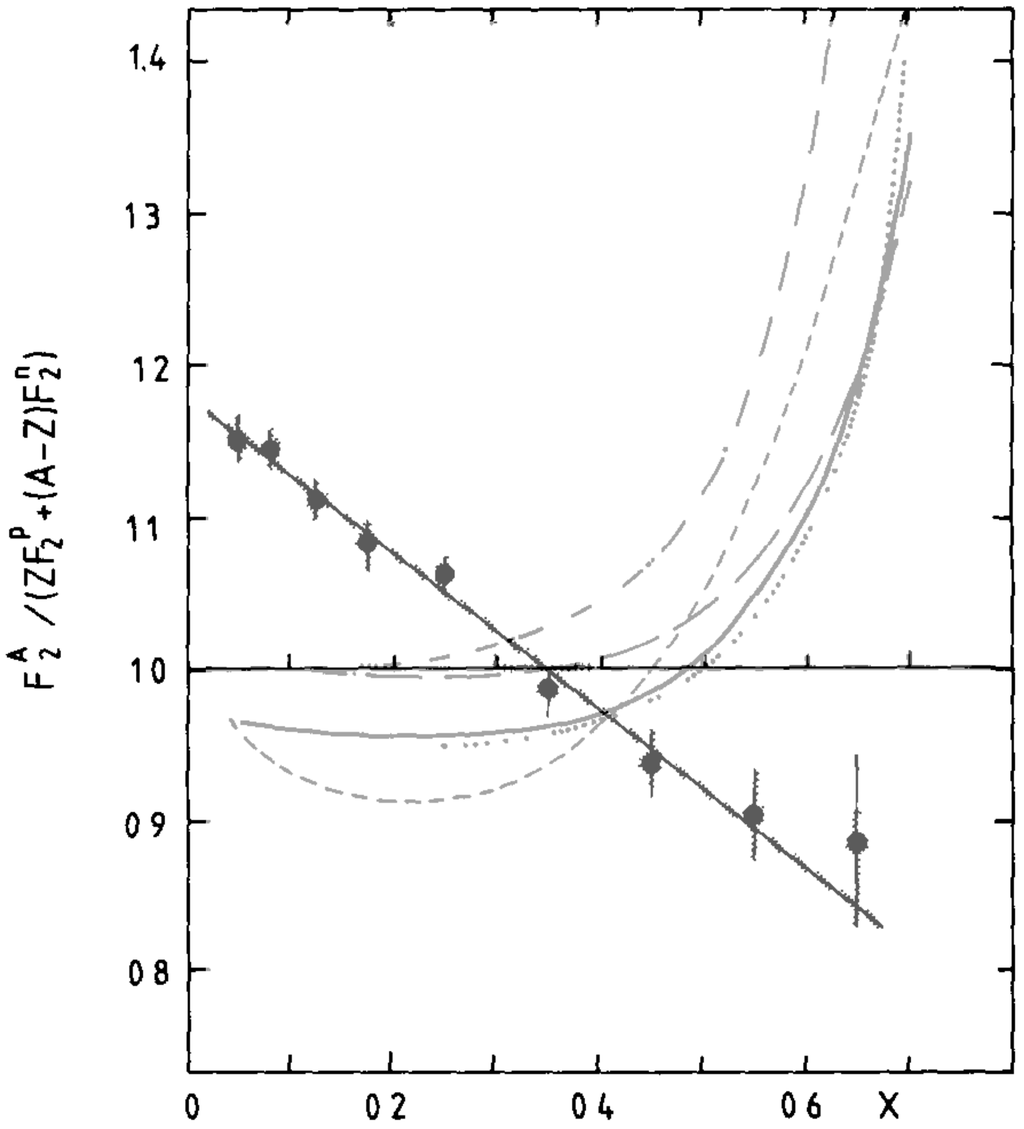

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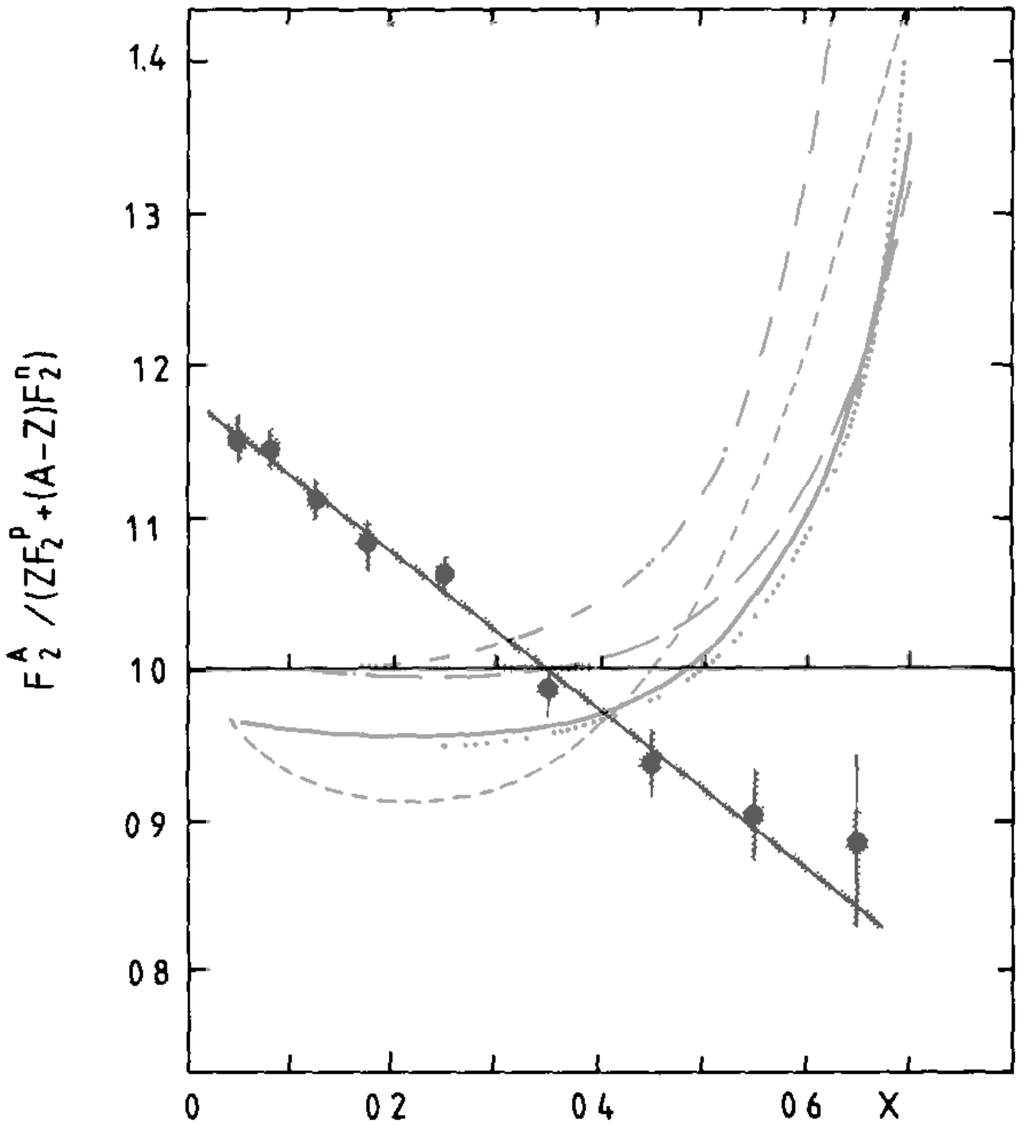

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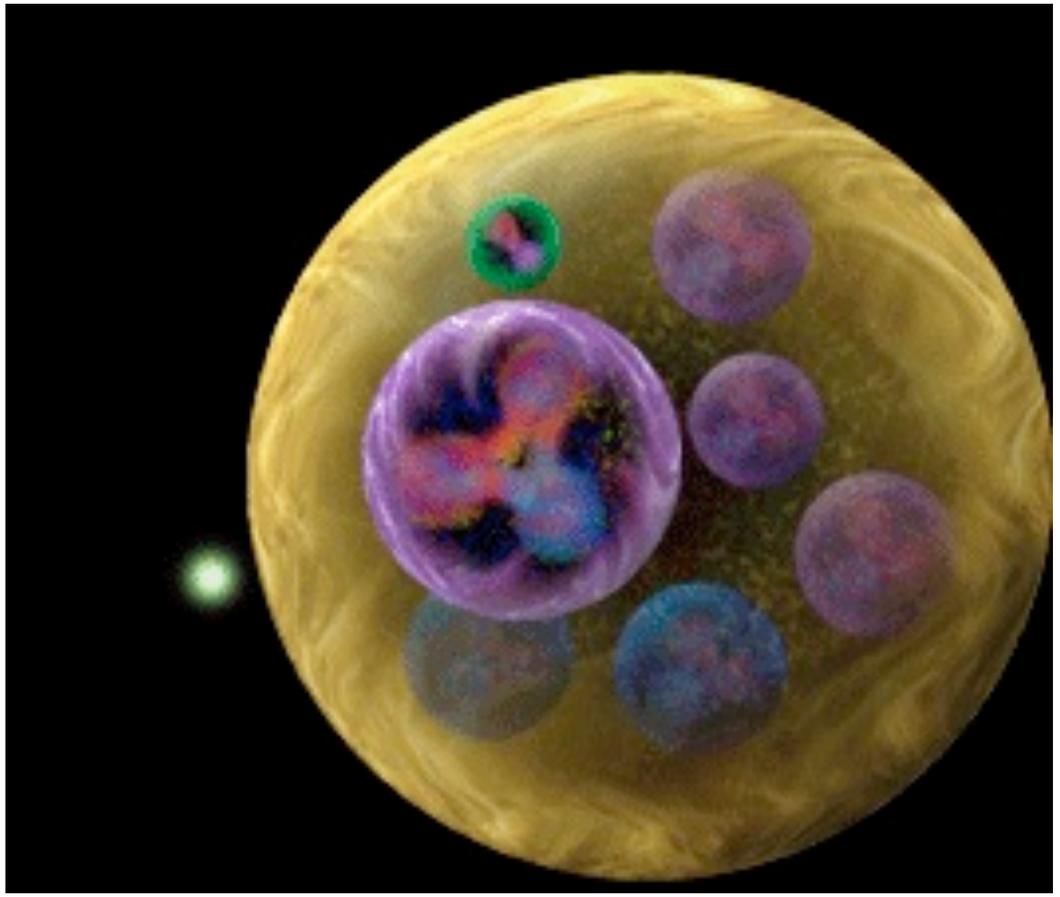

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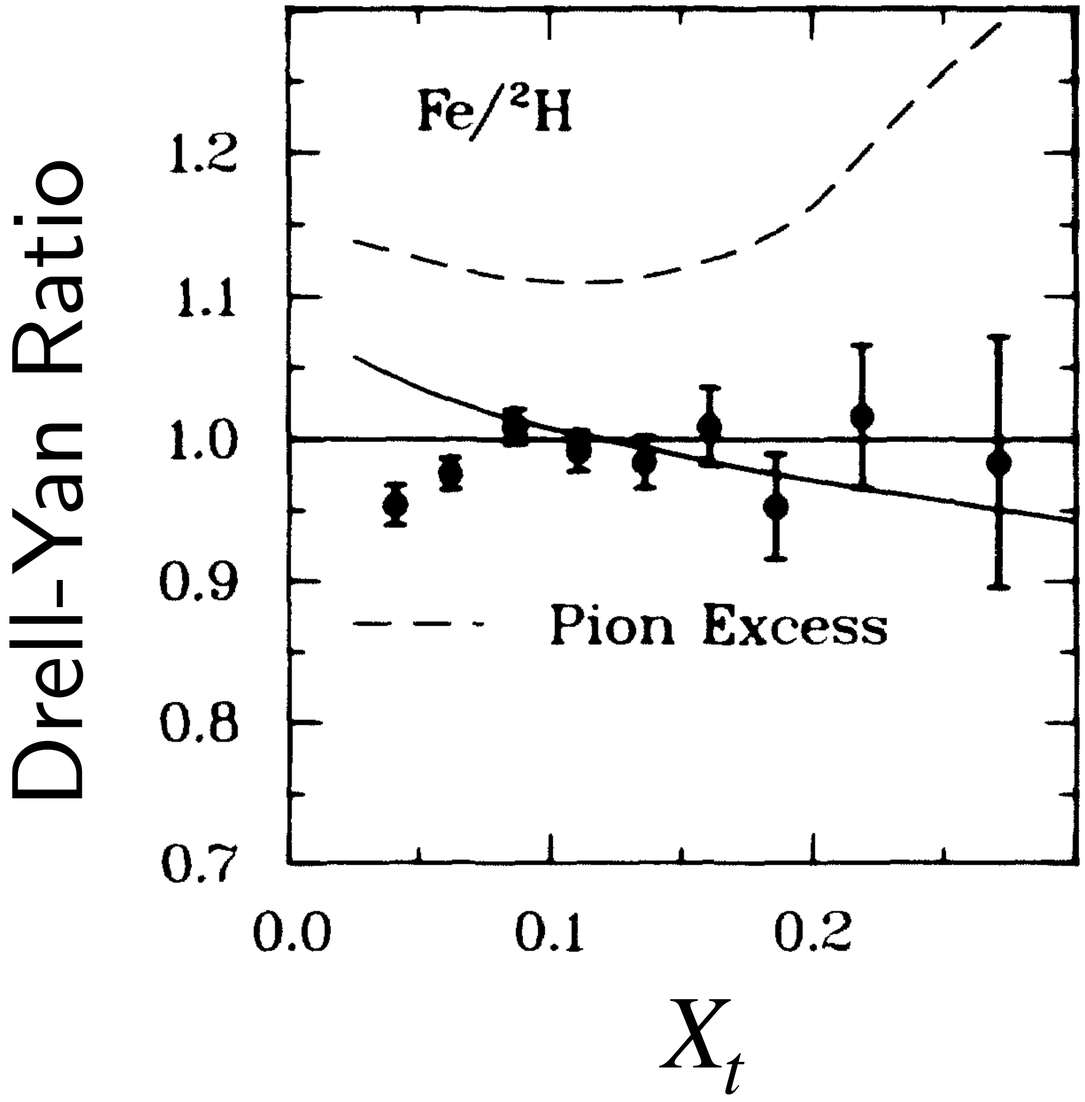

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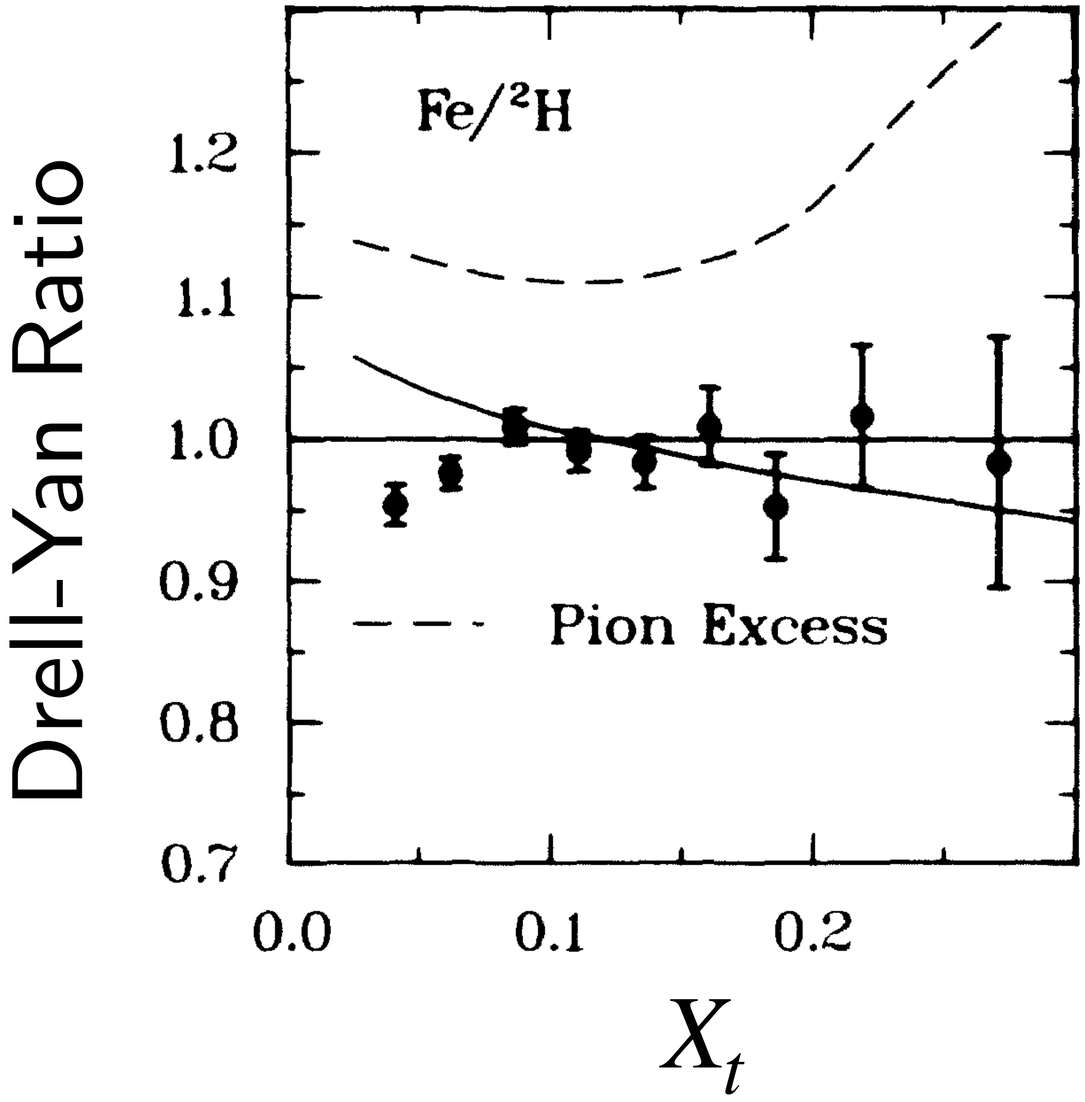

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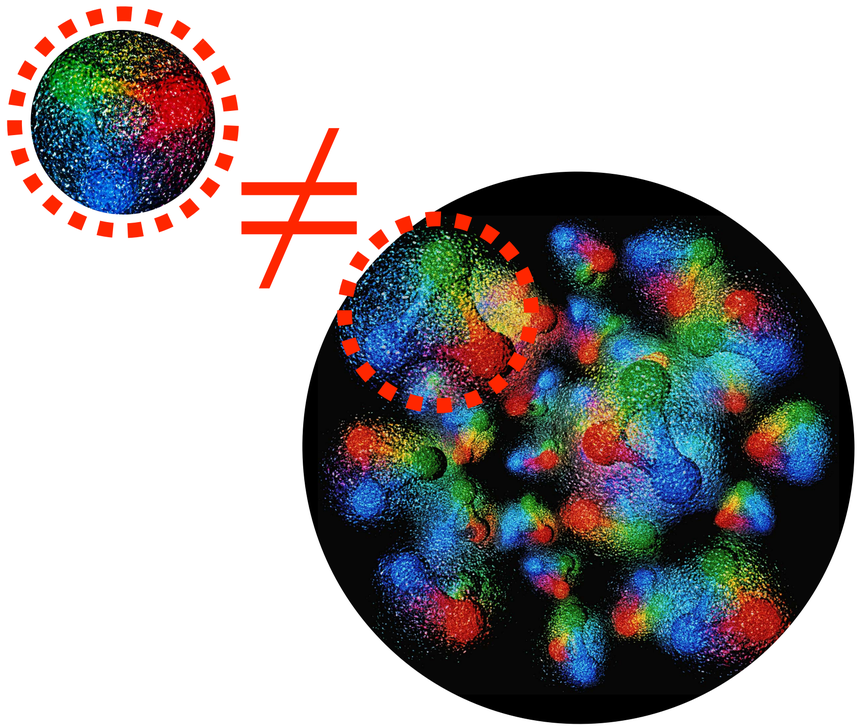
✗ Non-nucleon (e.g. π) DOF

✓ Parton structure of bound nucleons is different



Bound nucleons are modified...so what?

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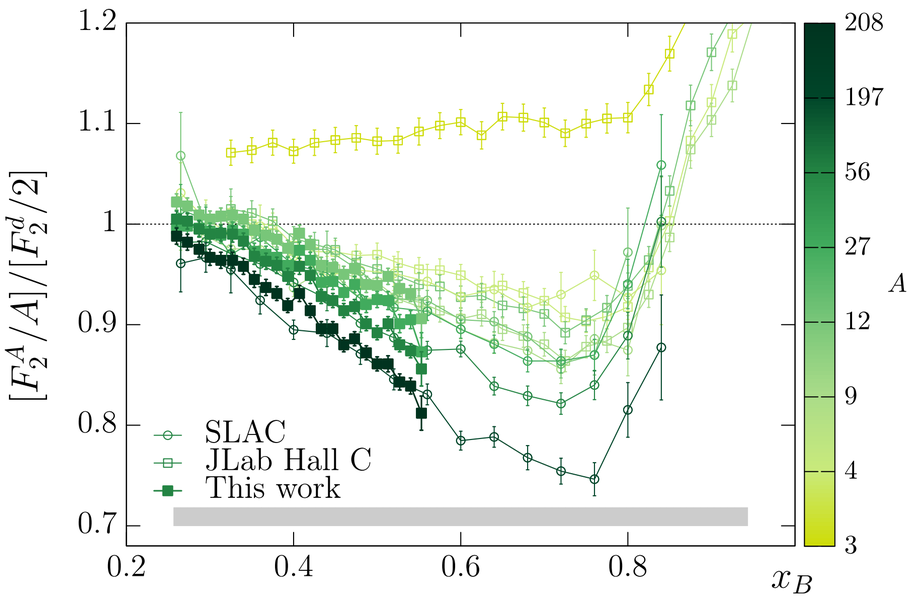
Fundamental:

Need to separate *conventional* from *exotic* nuclear effects to pinpoint origin of EMC effect



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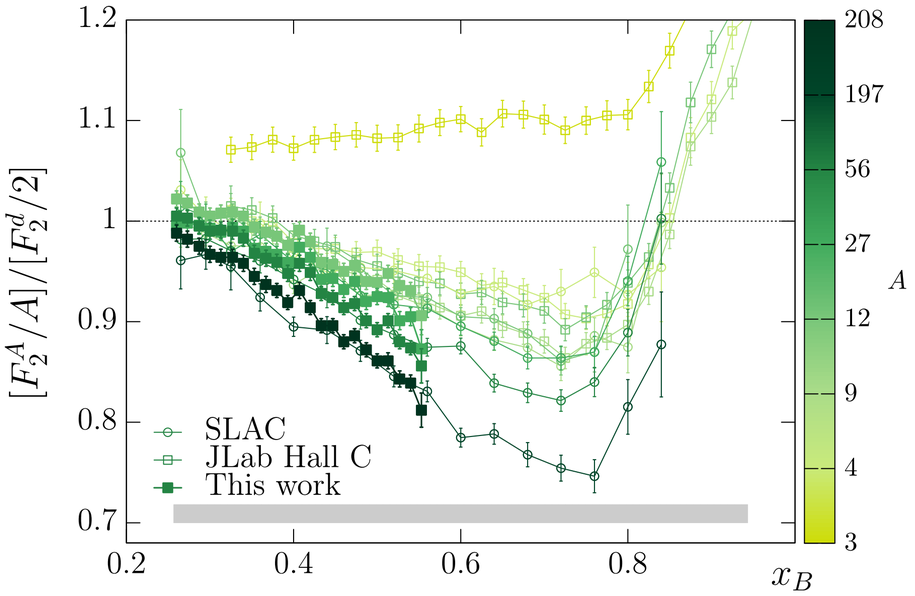
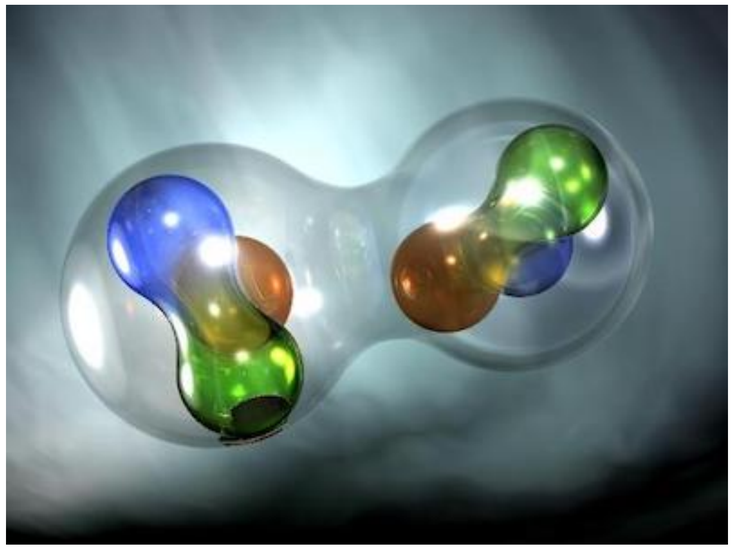
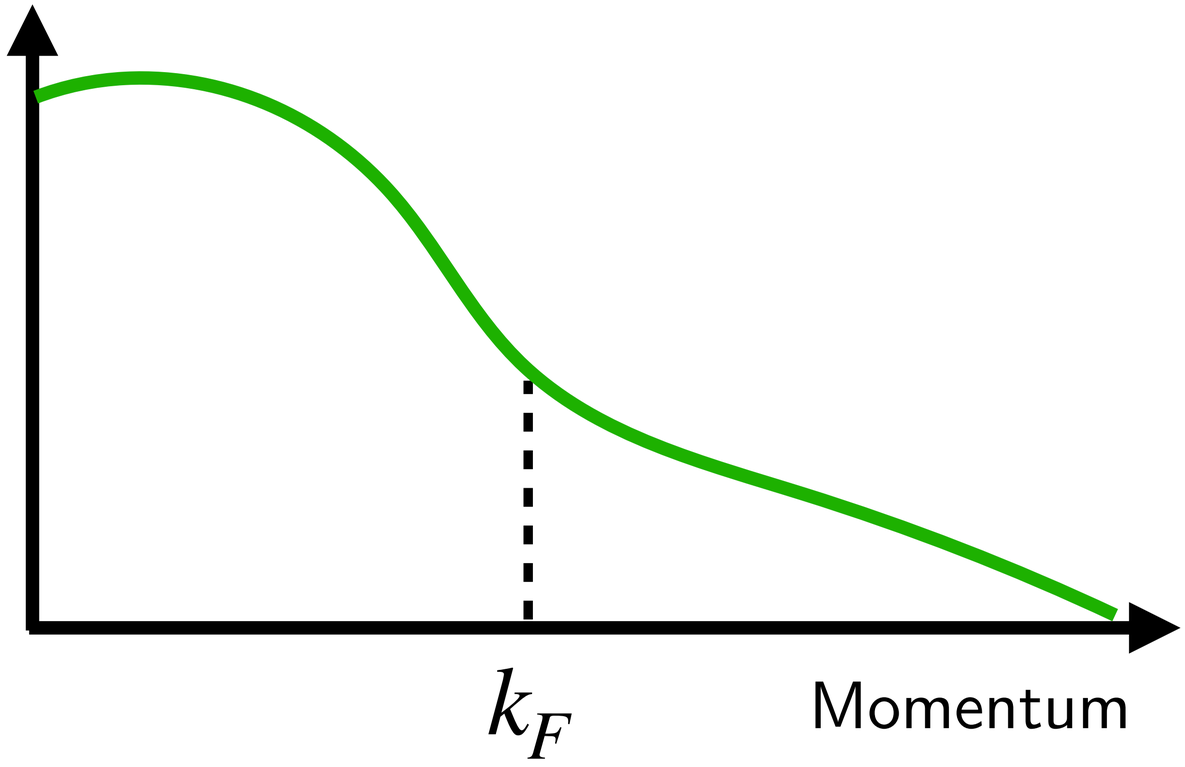


Practical:

Must learn about the structure of *free* neutrons by studying *bound* neutrons.



Many conventional effects encoded in wavefunction



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Mean field nucleons:

- Large separation
- Low momentum
- Interact with

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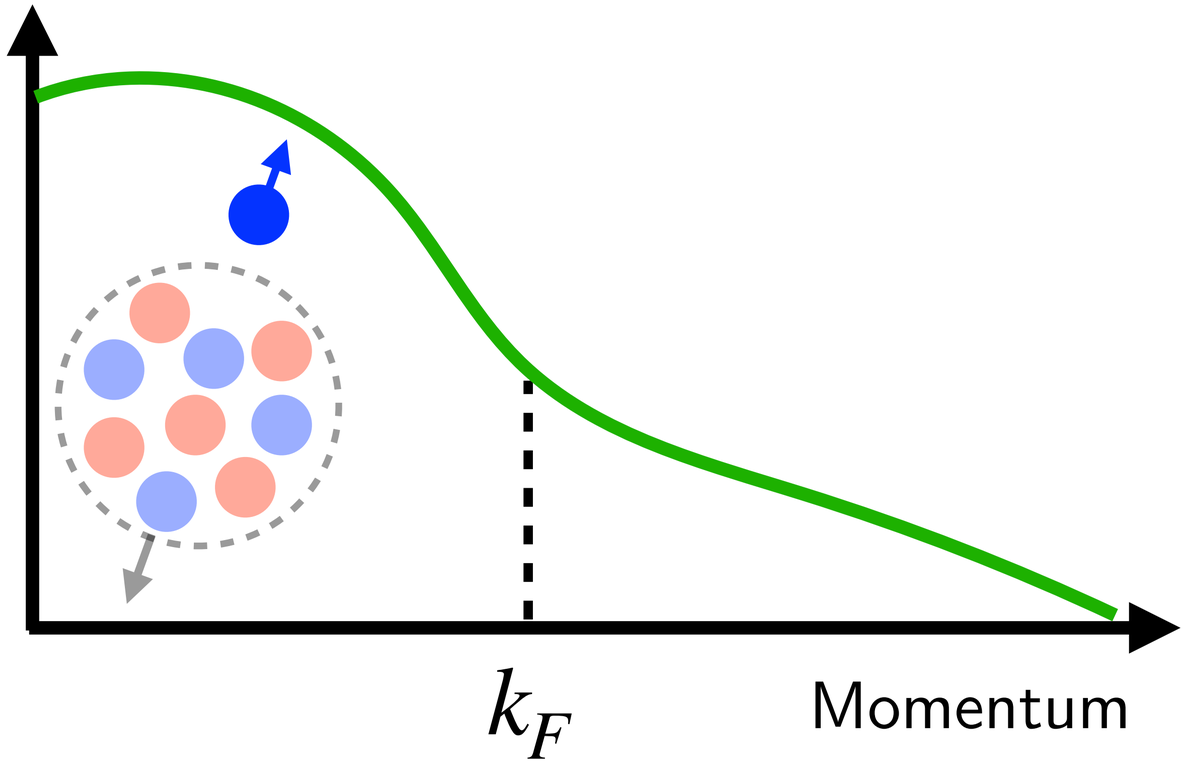

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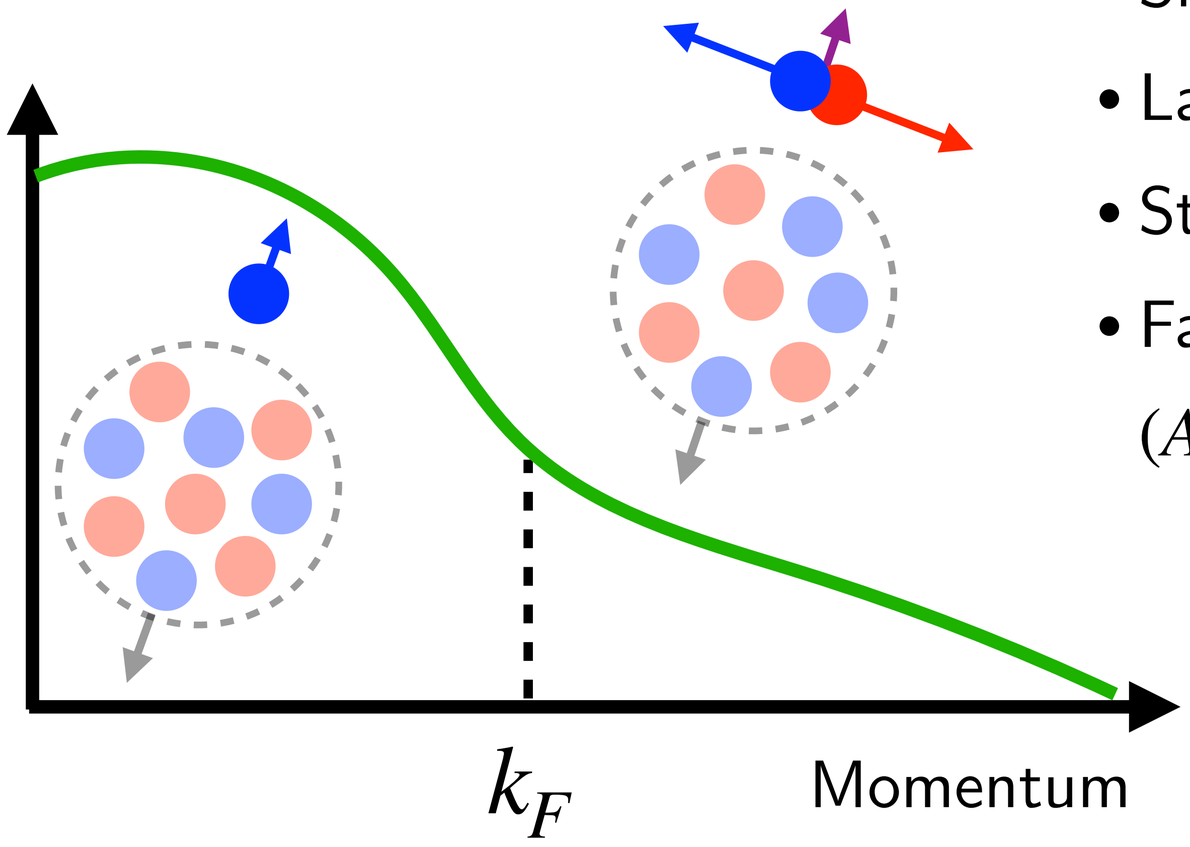
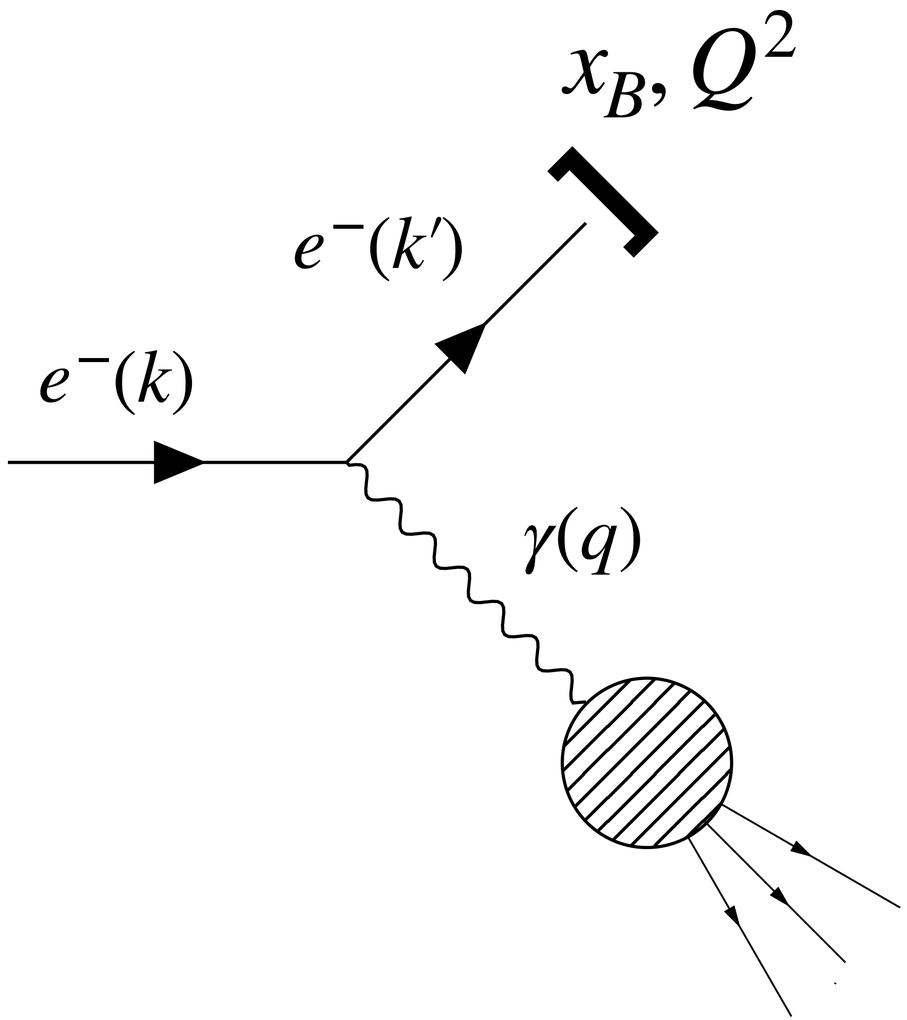


Short-range correlated nucleons

- Small separation
- Large momentum
- Strong pair interaction
- Factorized from $(A-2)$ system

Inclusive DIS gives average structure of nucleus



- Detect scattered electron

$$Q^2 = 2EE'(1 - \cos\theta)$$

$$x_B = Q^2 / 2M\nu$$

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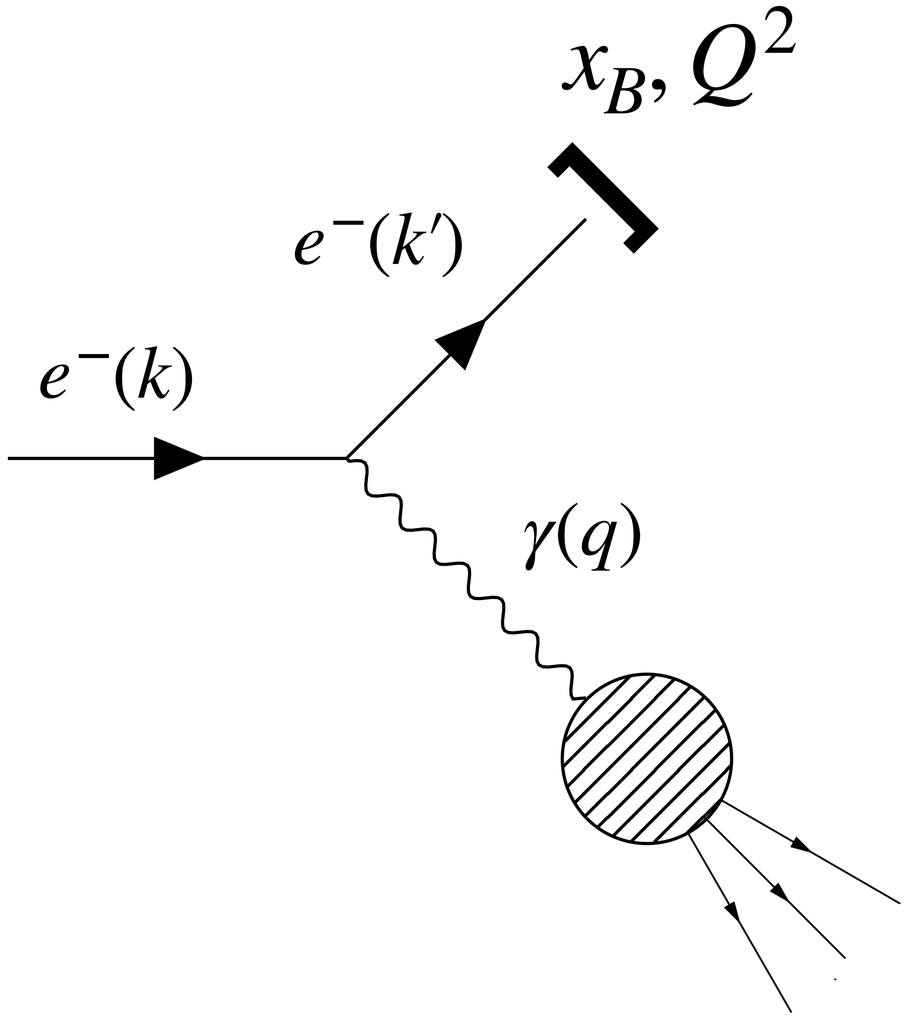

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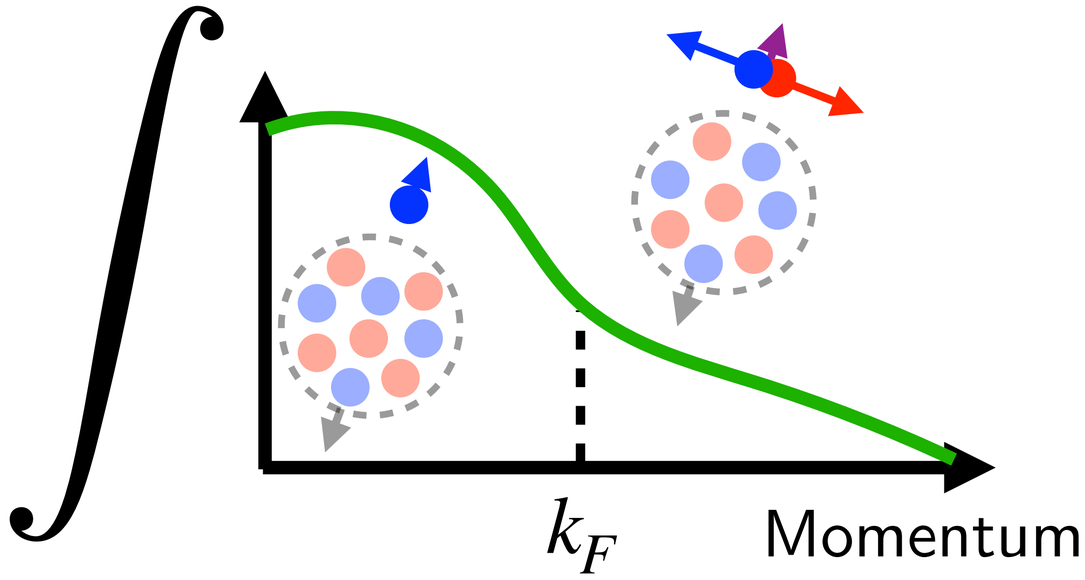

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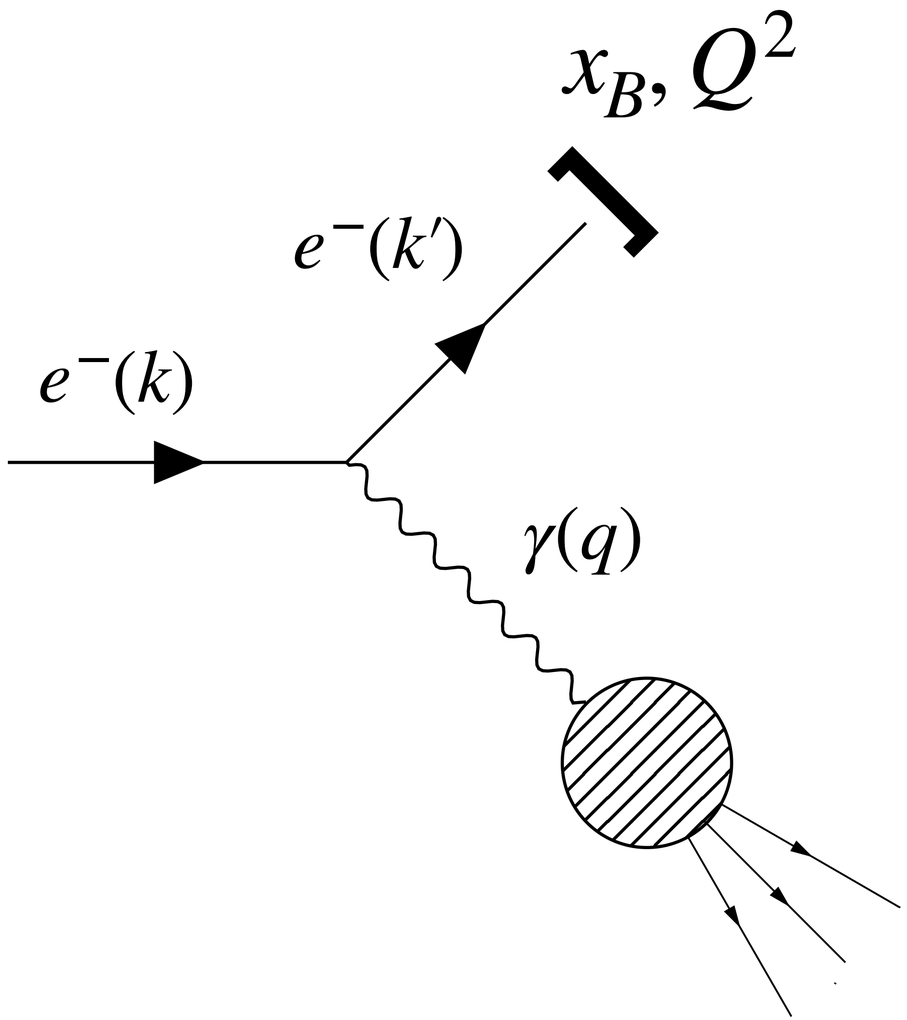

- Detect scattered electron

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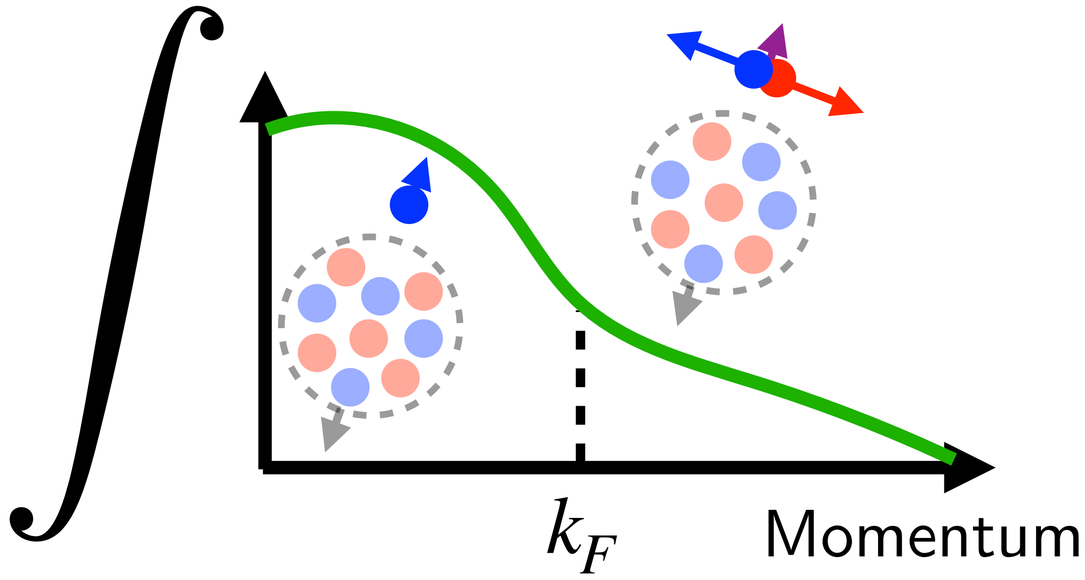
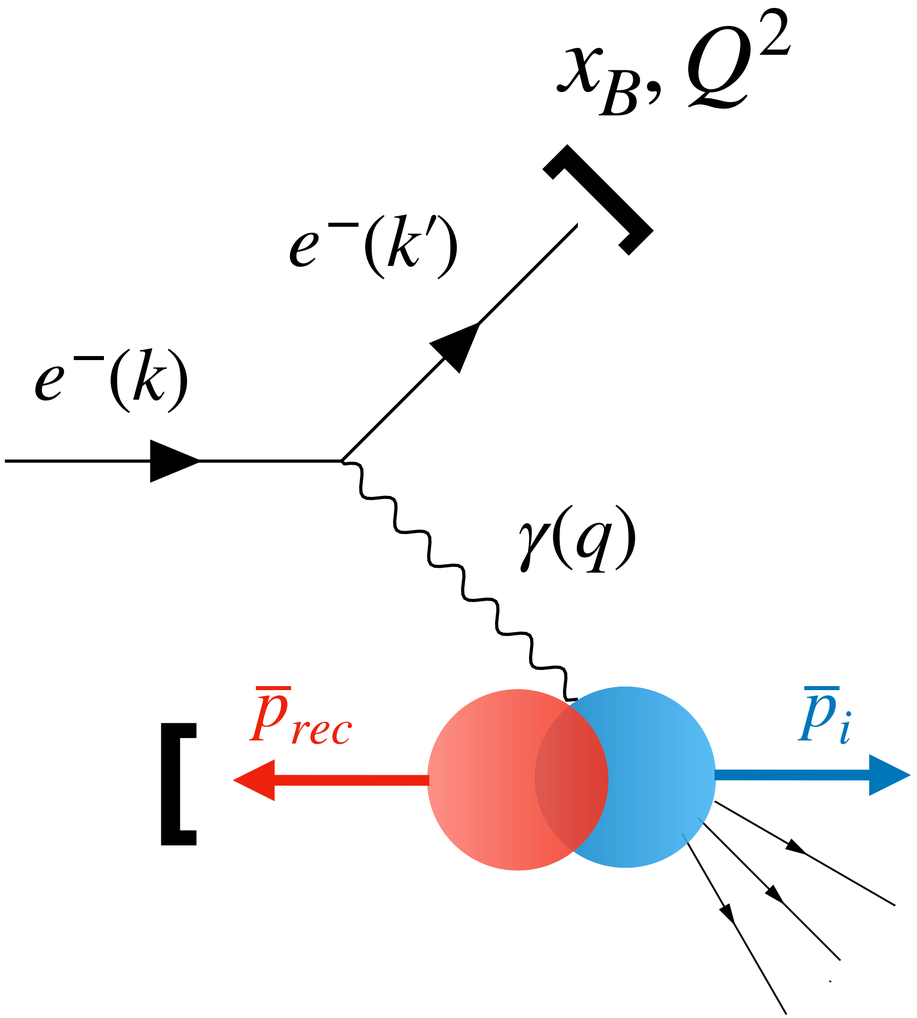
- Integrates over entire nucleus
- Variables smeared by Fermi motion



Tagged DIS can provide the remedy



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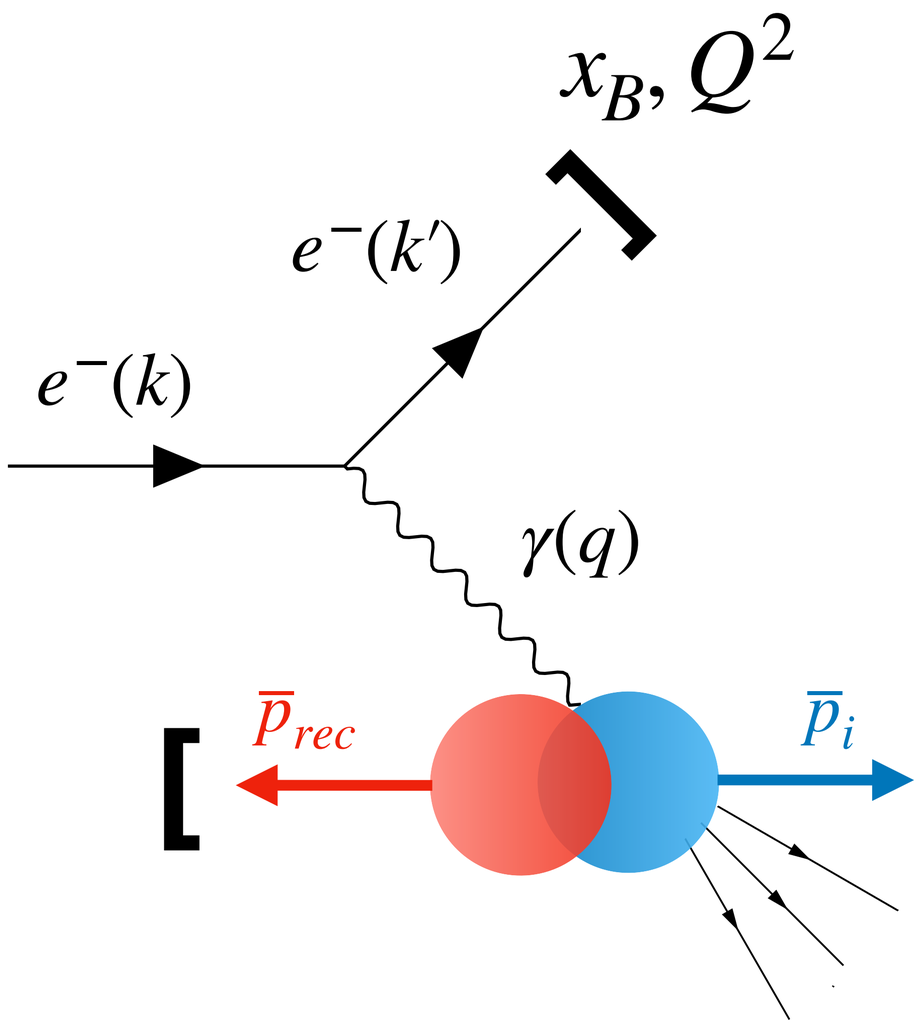

- Detect scattered electron *and* spectator nucleon

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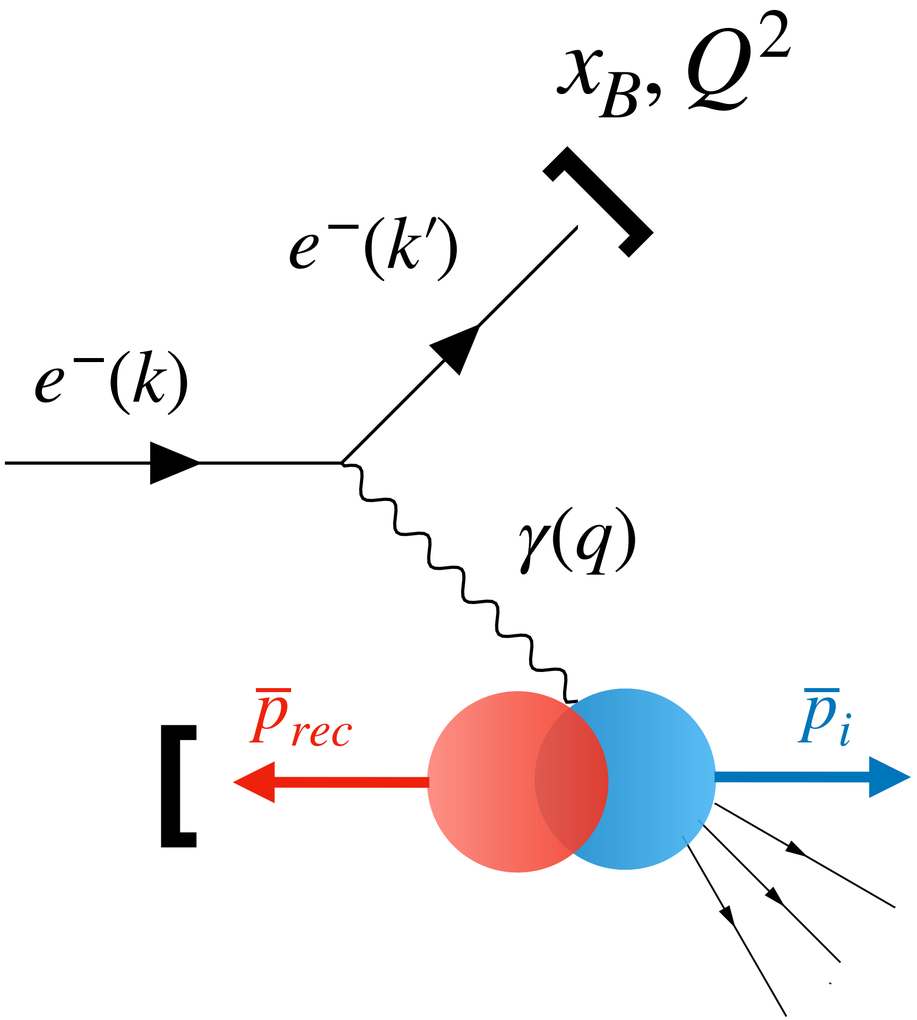
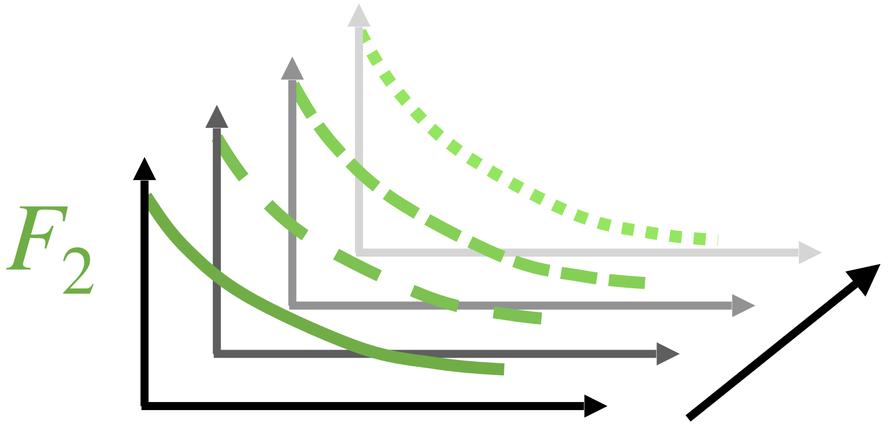


- Detect scattered electron *and* spectator nucleon
- Measure structure as function of nuclear state



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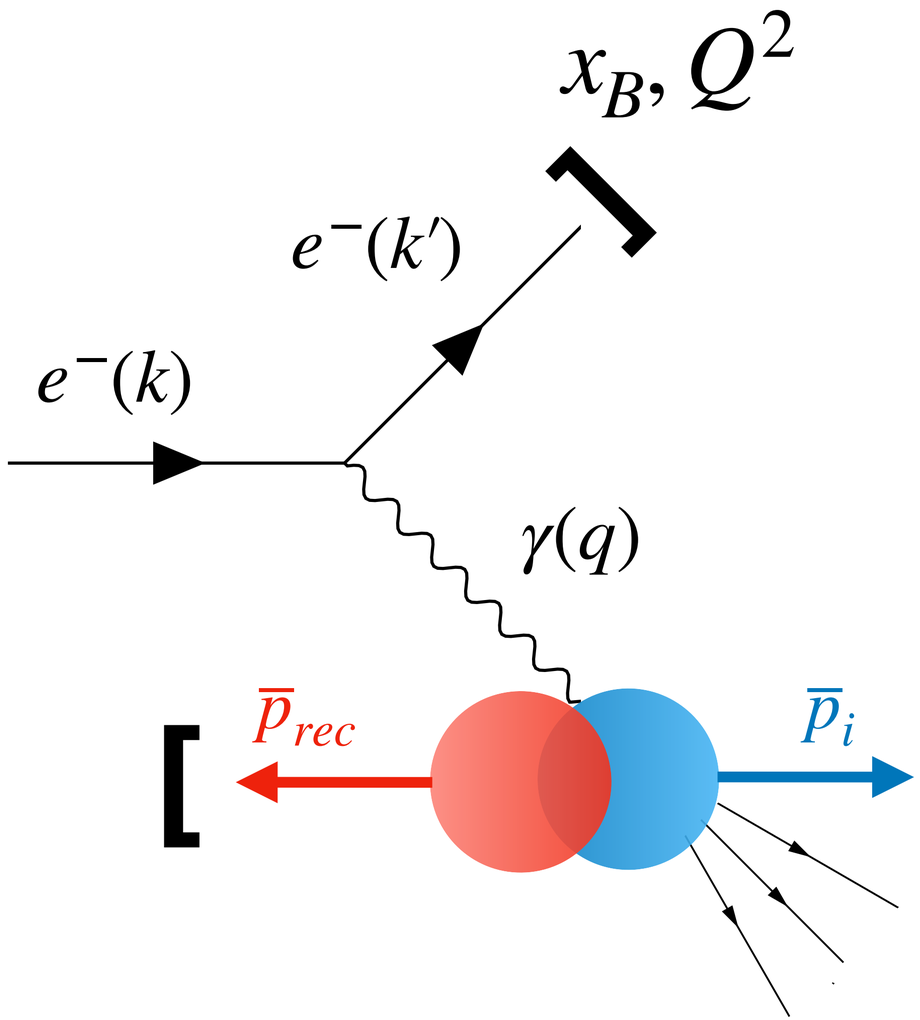

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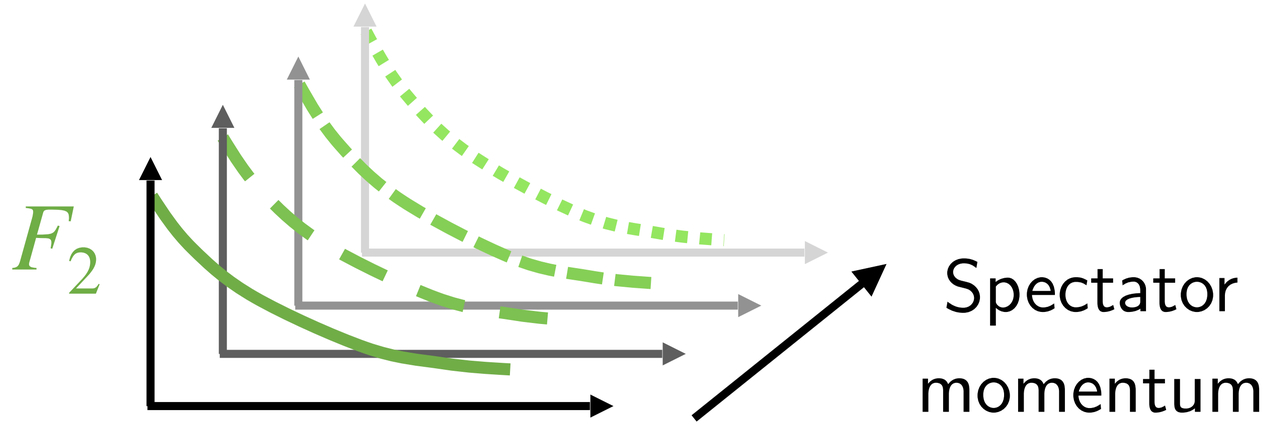

- Account for nucleon motion

$$\alpha_S = \left(E_s - p_s^{\parallel}\right)/M$$

$$W \to W' = (P+q),\ P = (\overline{p}_s, E_s)$$

$$x_B \to x' = Q^2/(2P\cdot q) \approx x_B/(2-\alpha_S)$$

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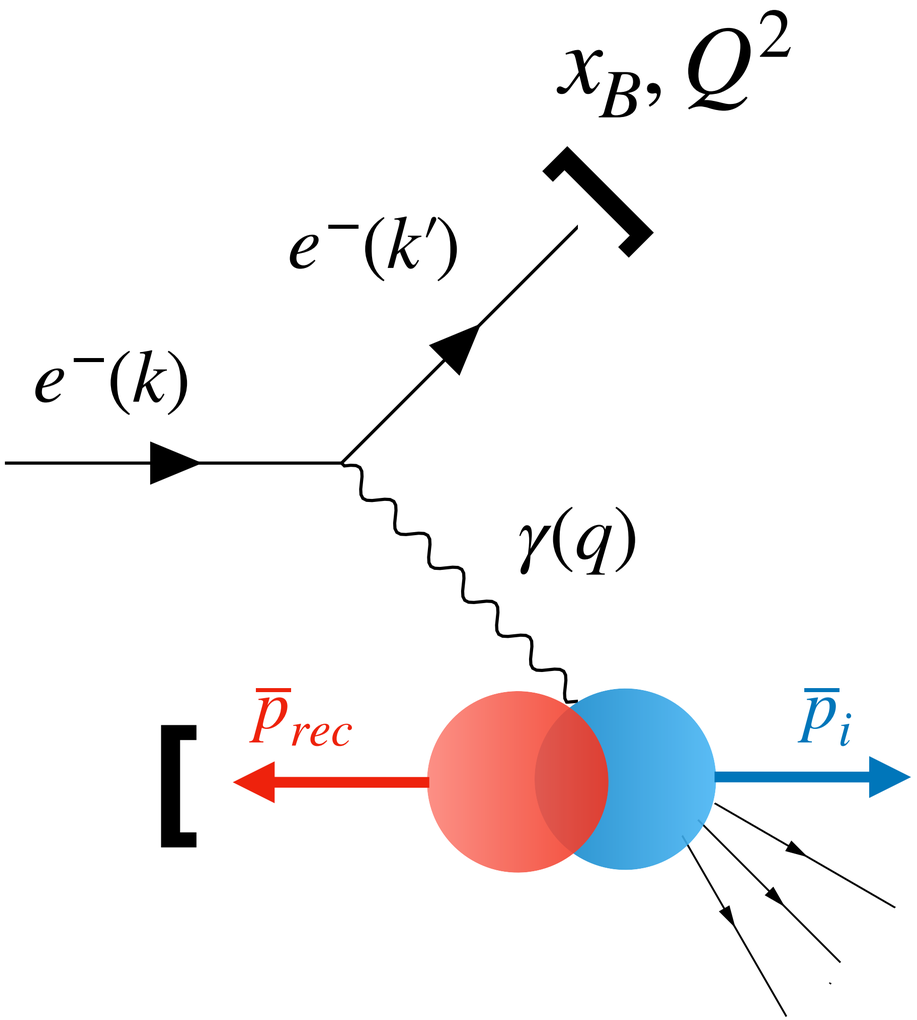

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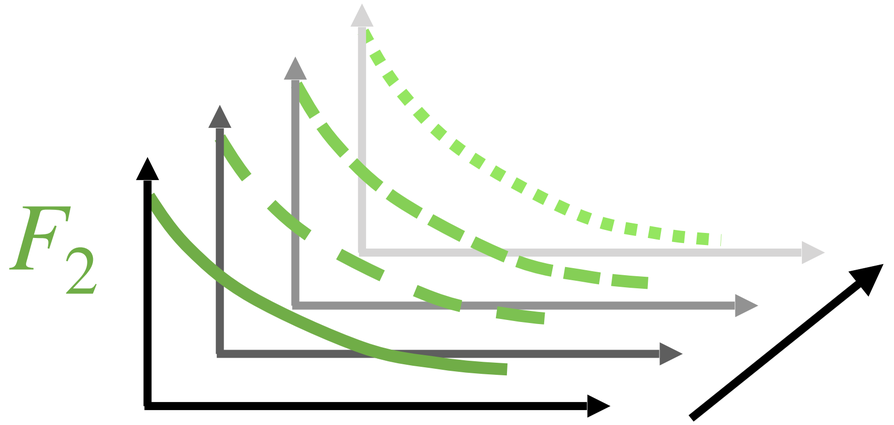

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🚨 *Not* strong coupling! 🚨

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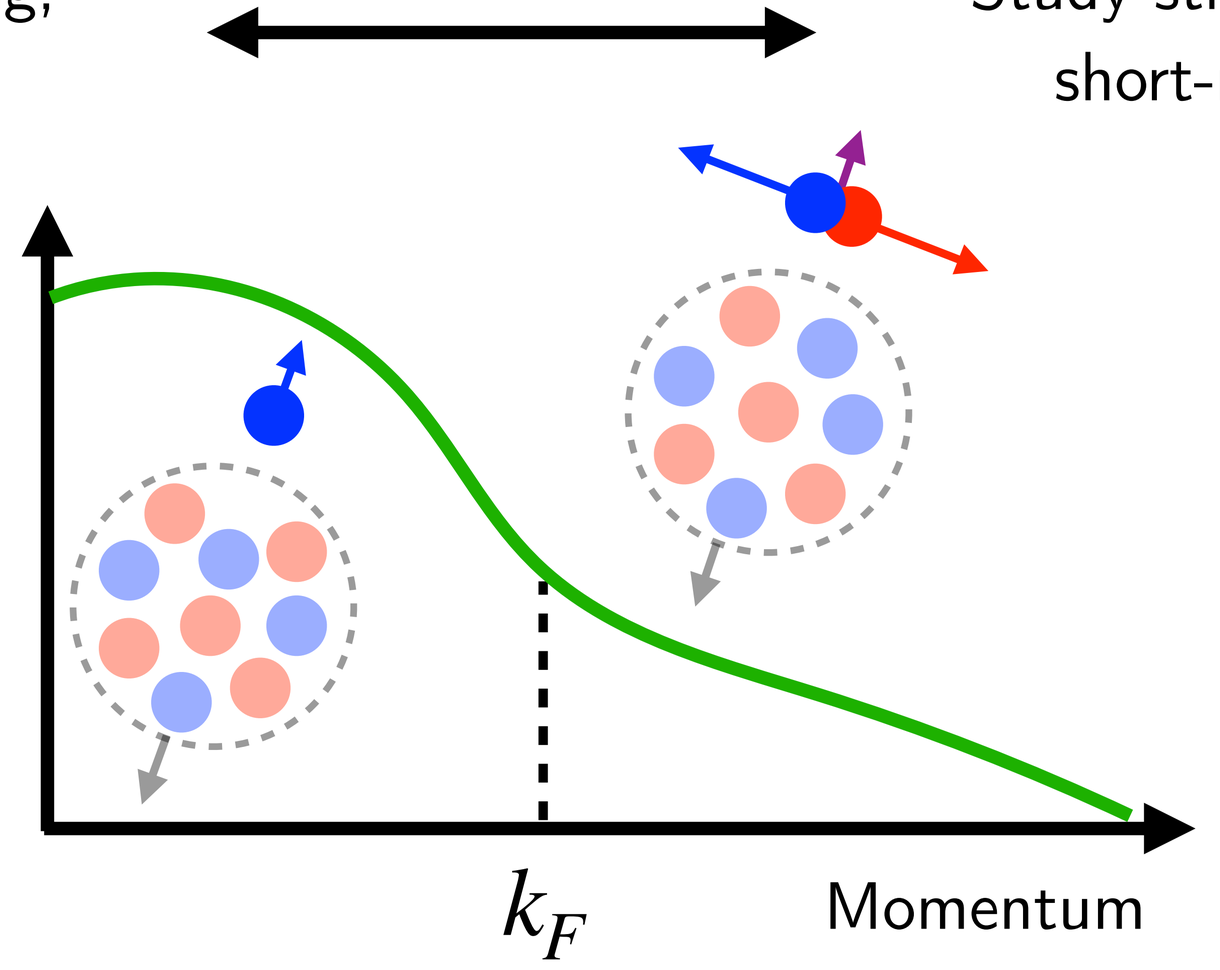
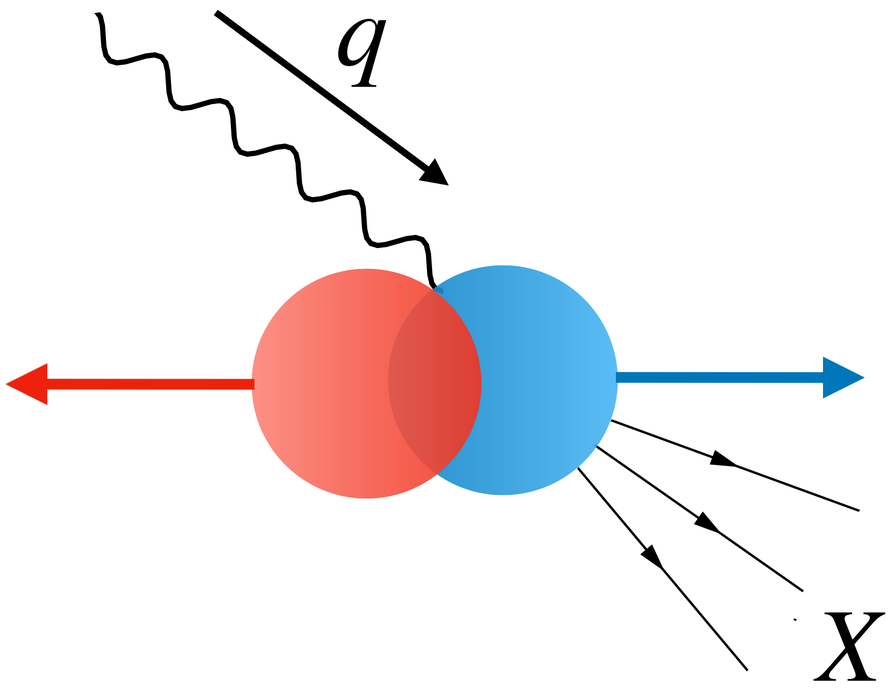
Tagged DIS turns wavefunction into laboratory for nucleons of various off-shellness

Study weakly interacting, quasi-free nucleons

Study strongly interacting, short-range nucleons



Mitigating final state interactions

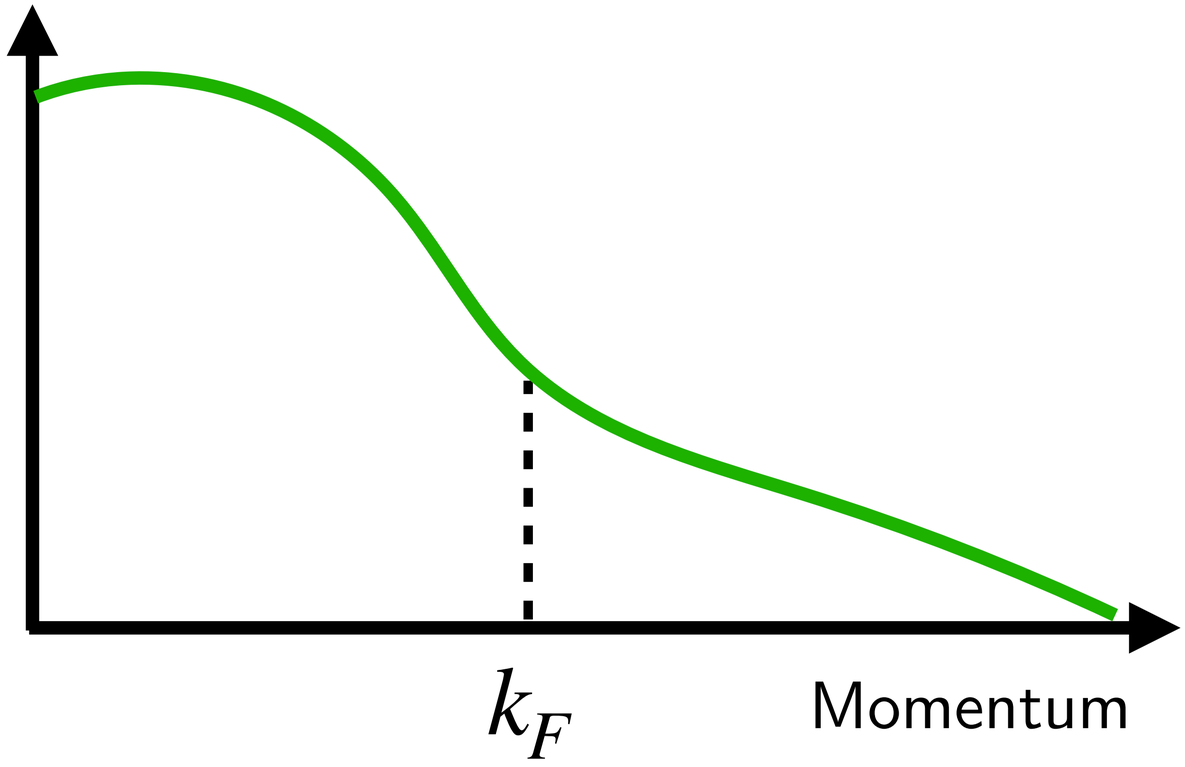


- Final state X goes in direction of q

  → Look at backward-going spectators

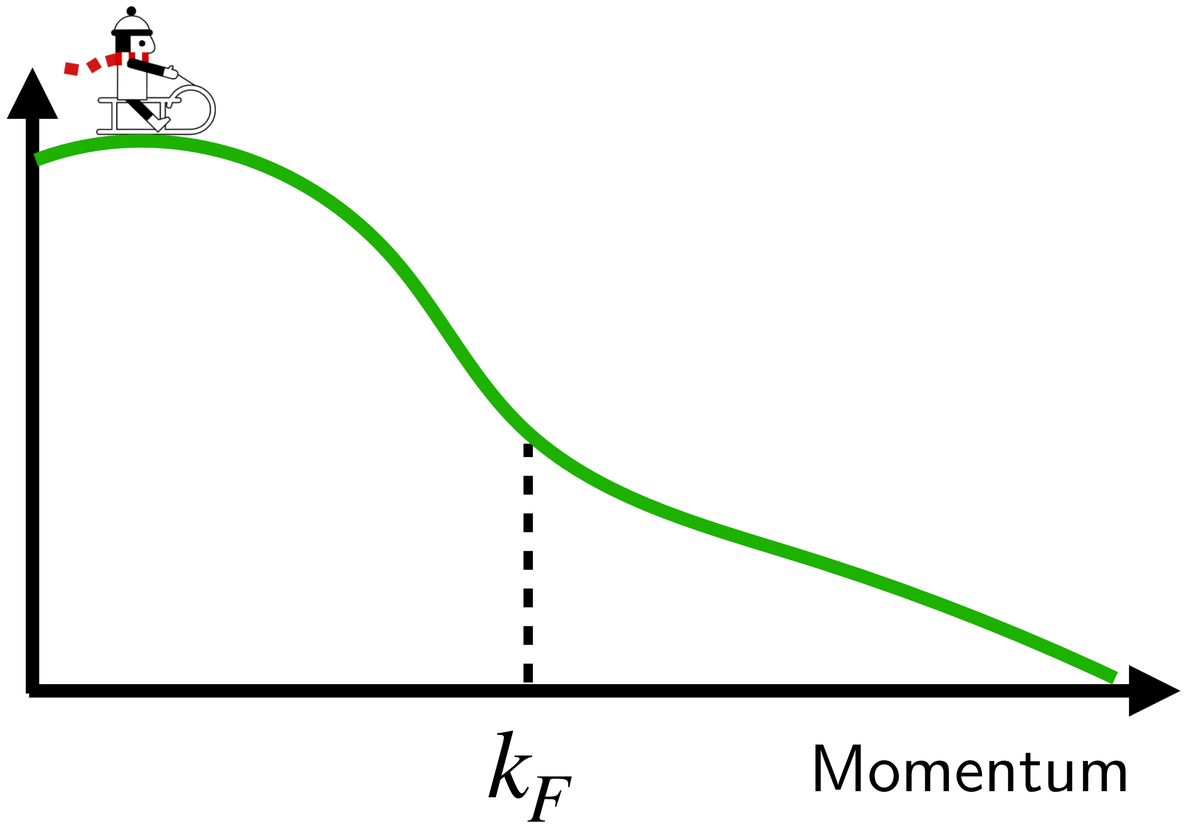
- FSI calculations largely independent of x

  → Form ratios of kinematic points


k_F
Momentum

1. BoNuS

Free nucleon structure function ratio F_2^n / F_2^p



2. EIC

Spin structure of the neutron

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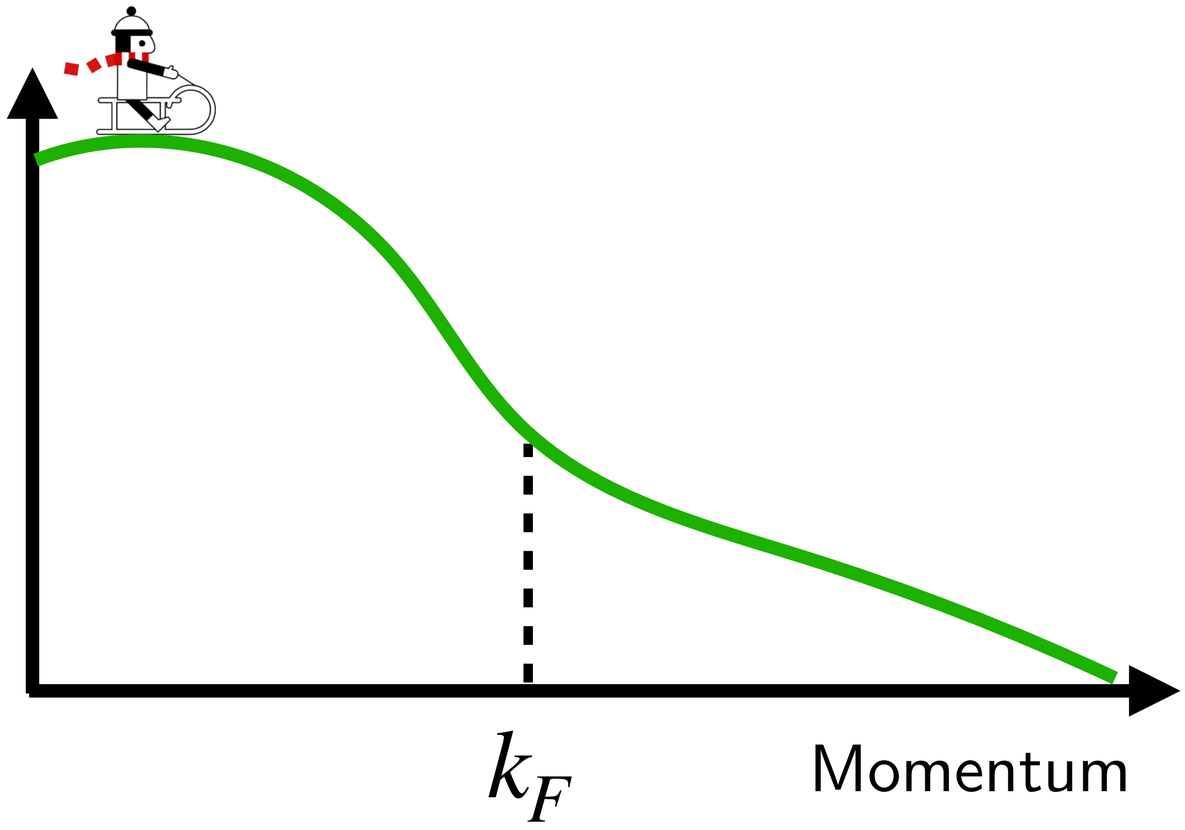

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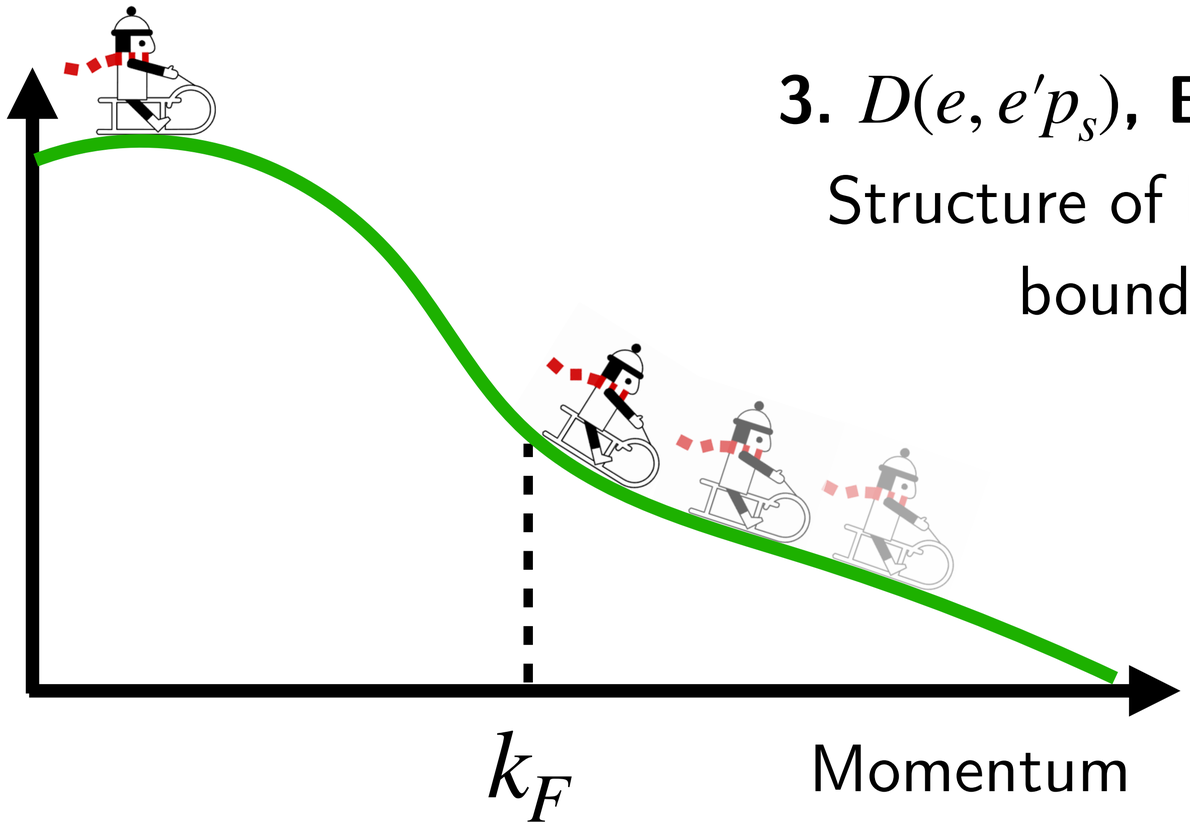

3. $D(e, e'p_s)$, BAND, and LAD

Structure of high-momentum bound nucleons

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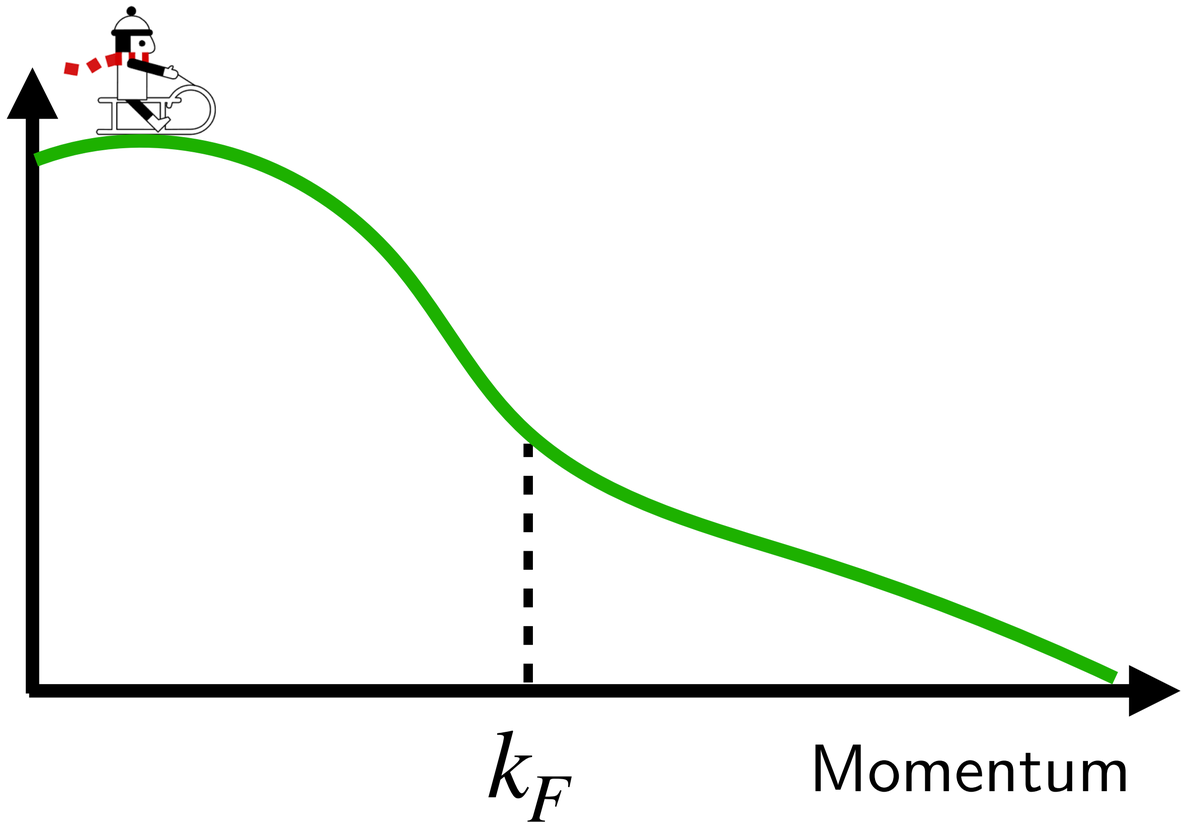
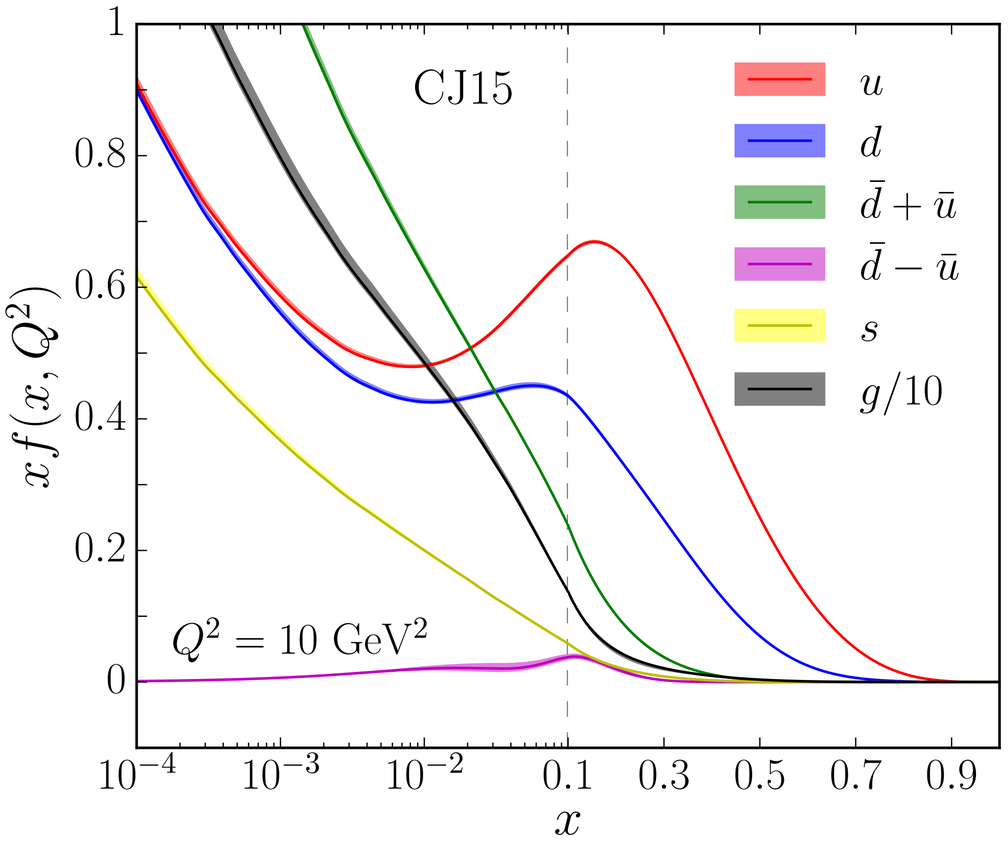


Free structure function ratio F_2^n/F_2^p

- Limit as $x_B \to 1$ sensitive to spin-flavor symmetry breaking mechanism
- Provides critical constraints on PDFs



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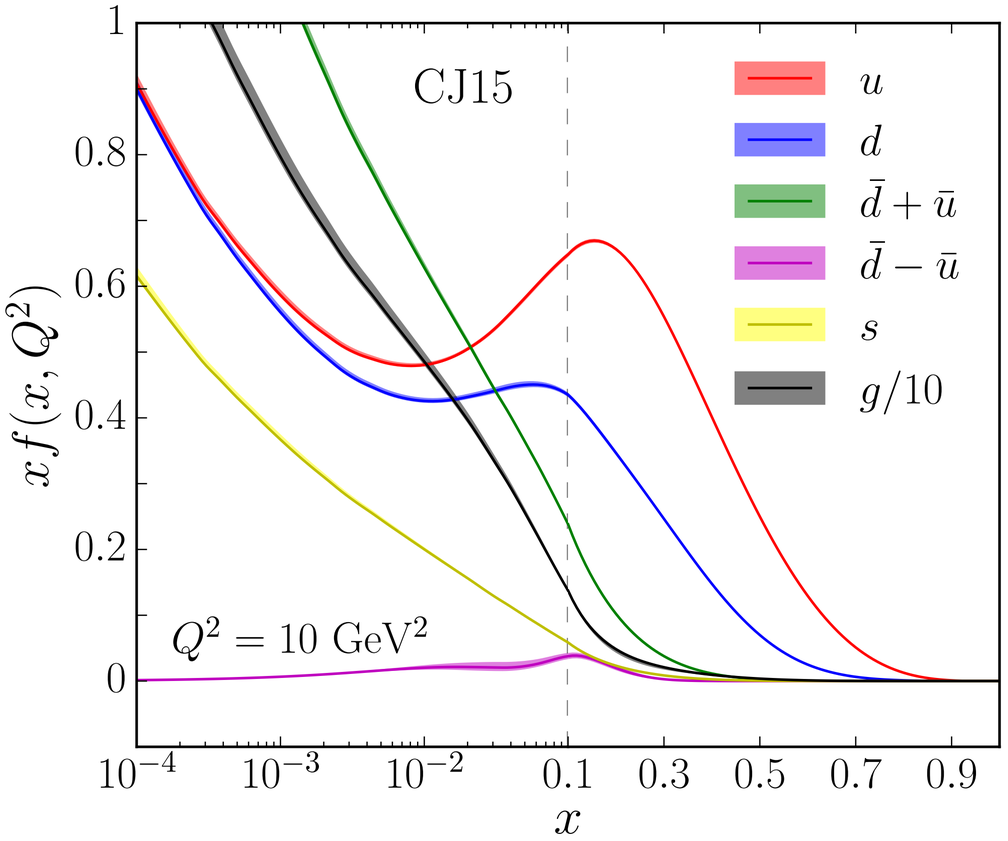
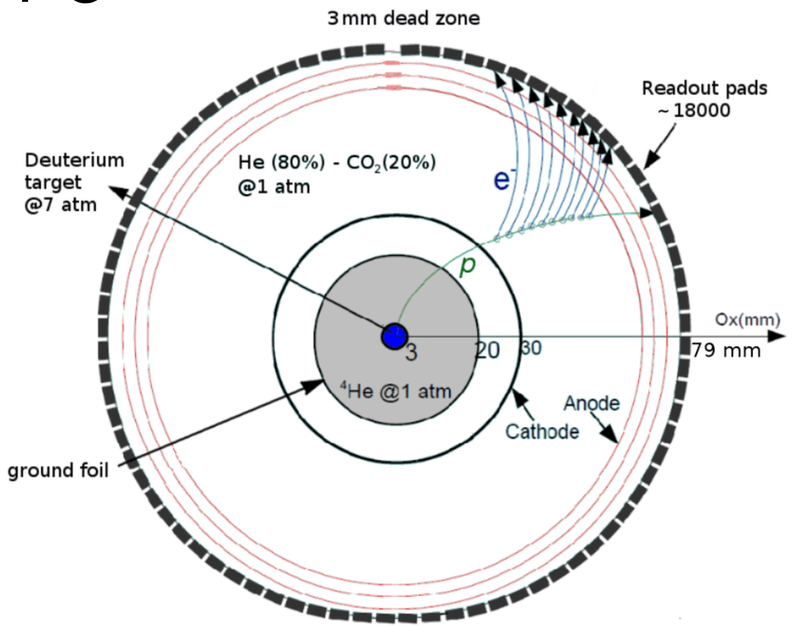


- Methods:
  - Extract from nuclear structure functions with nuclear corrections
  - Use tagged DIS to extract structure of barely-off-shell neutrons in deuterium

BoNuS (barely off-sell nucleon structure)

- JLab (6 GeV) Hall B
- 2.1, 4.2, and 5.3 GeV electrons on thin 2H gas
- Detect scattered electron in CLAS
- Detect recoiling spectator proton in RTPC



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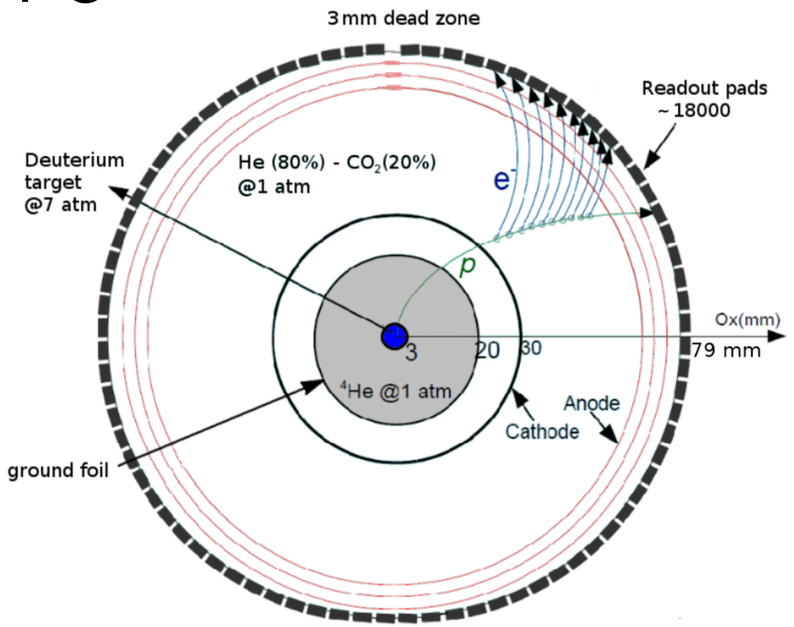
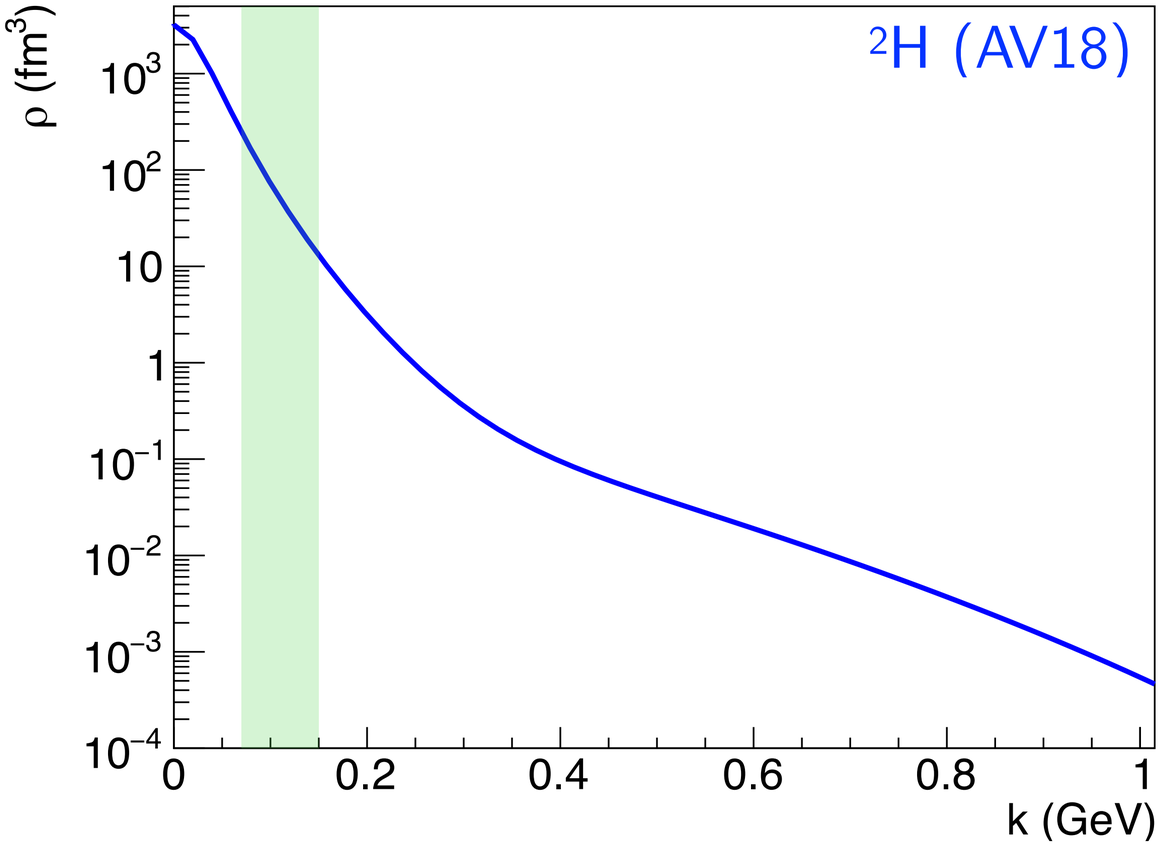
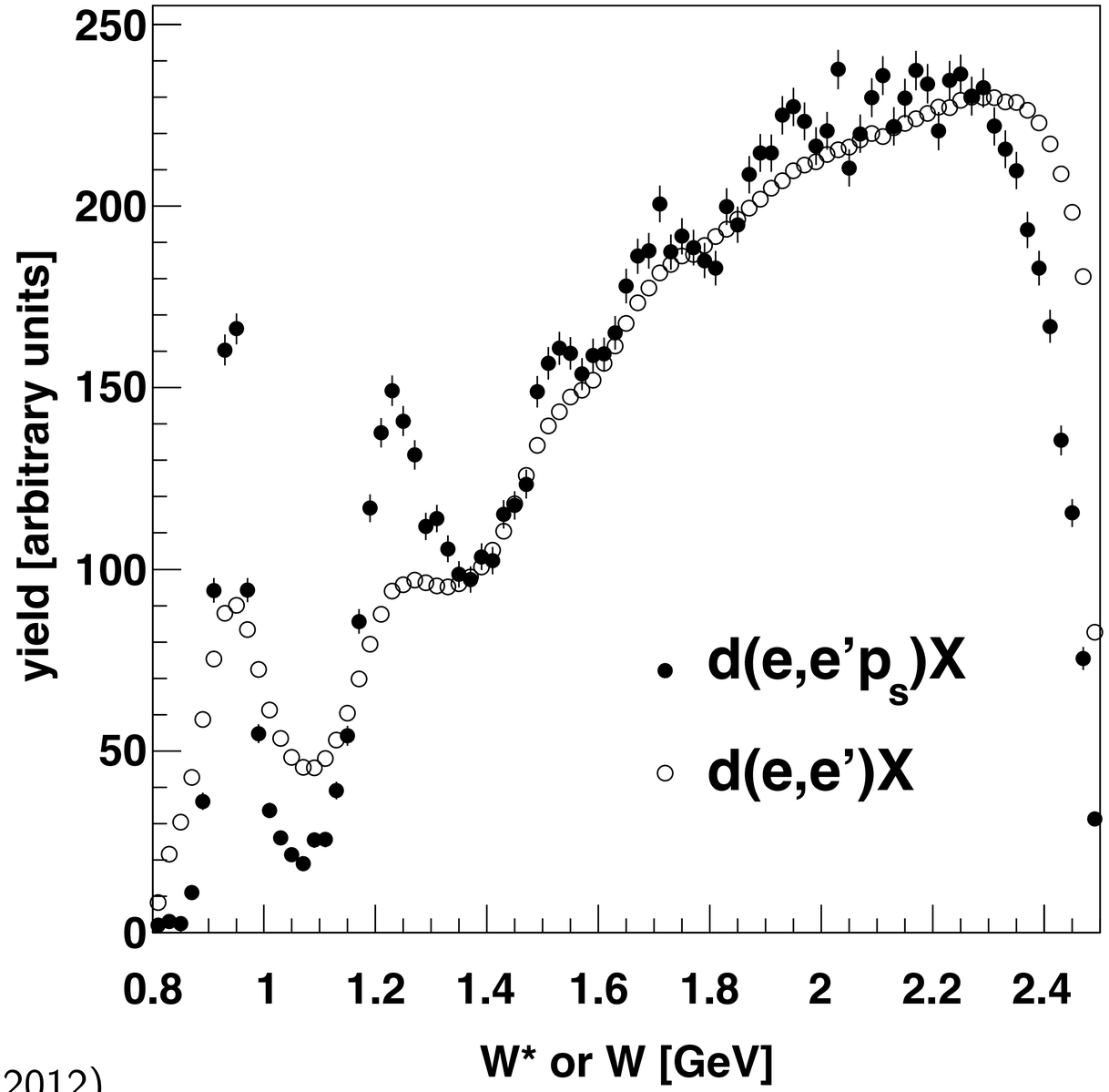


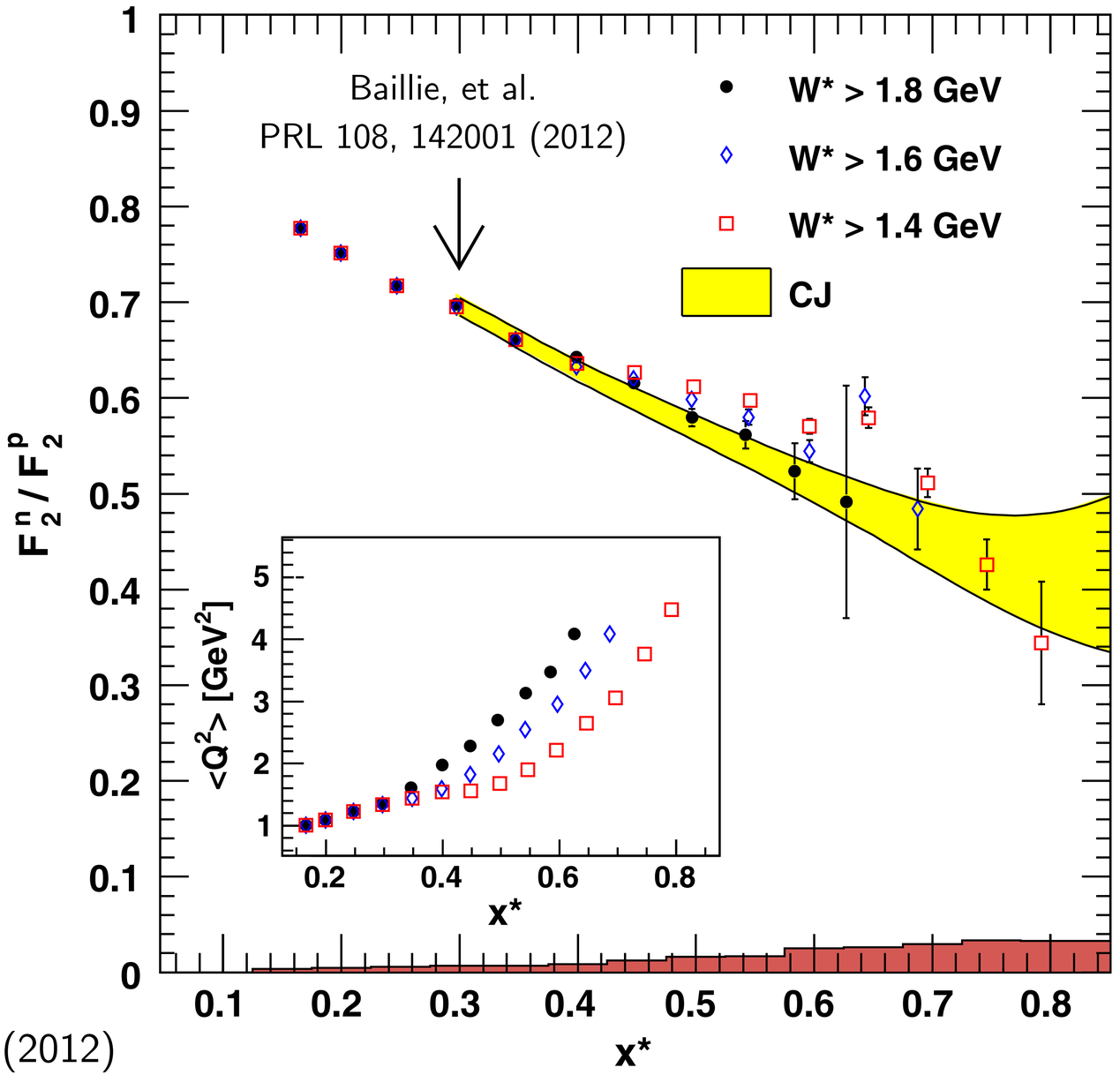


BoNuS invariant mass with/without tagging



Baillie, et al. PRL 108, 142001 (2012)

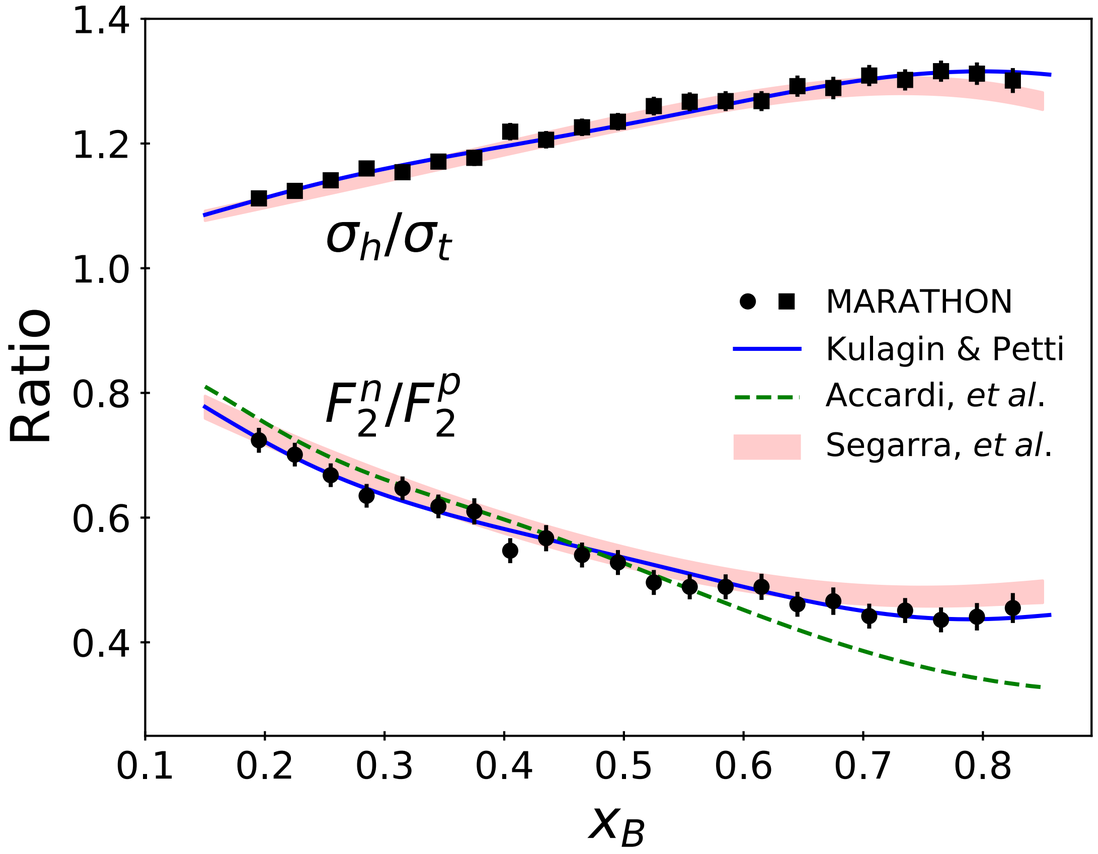
BoNuS results

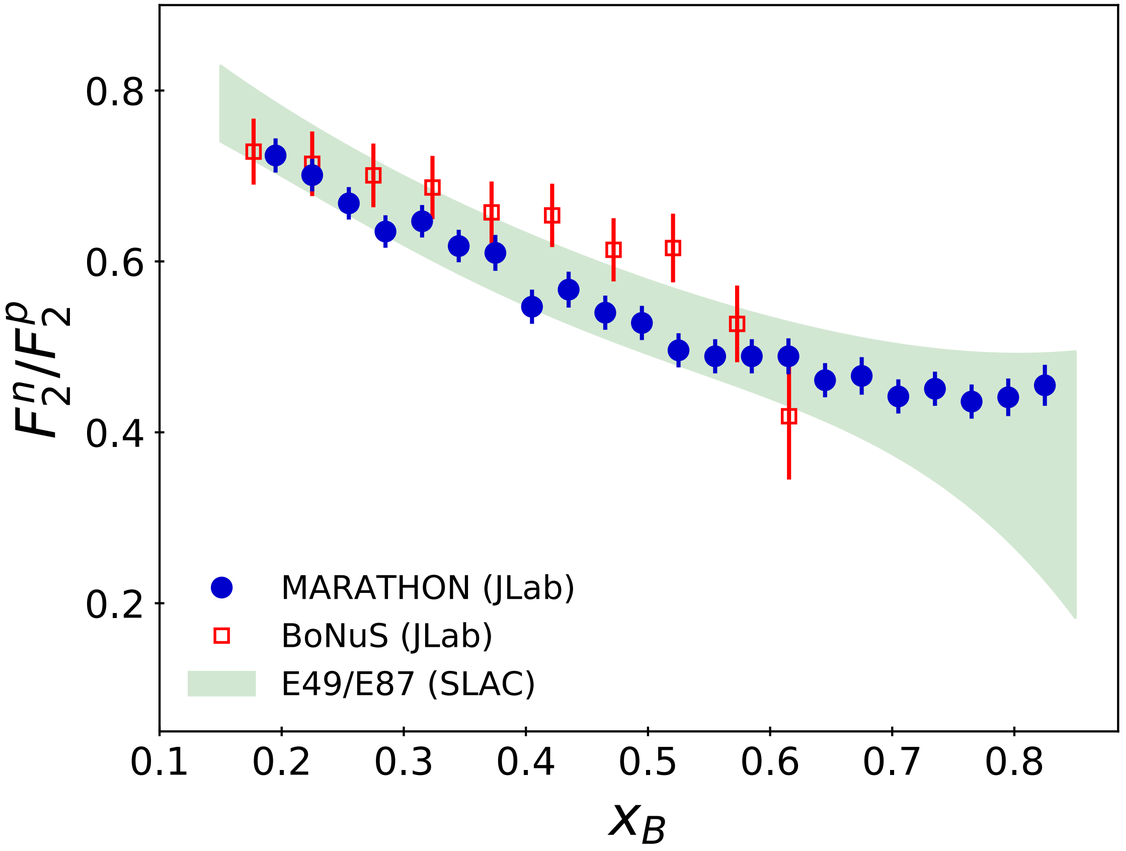


Baillie, et al. PRL 108, 142001 (2012)

Compared to latest nuclear correction extraction

Adapted from Abrams, et al. PRL 128, 132003 (2022)

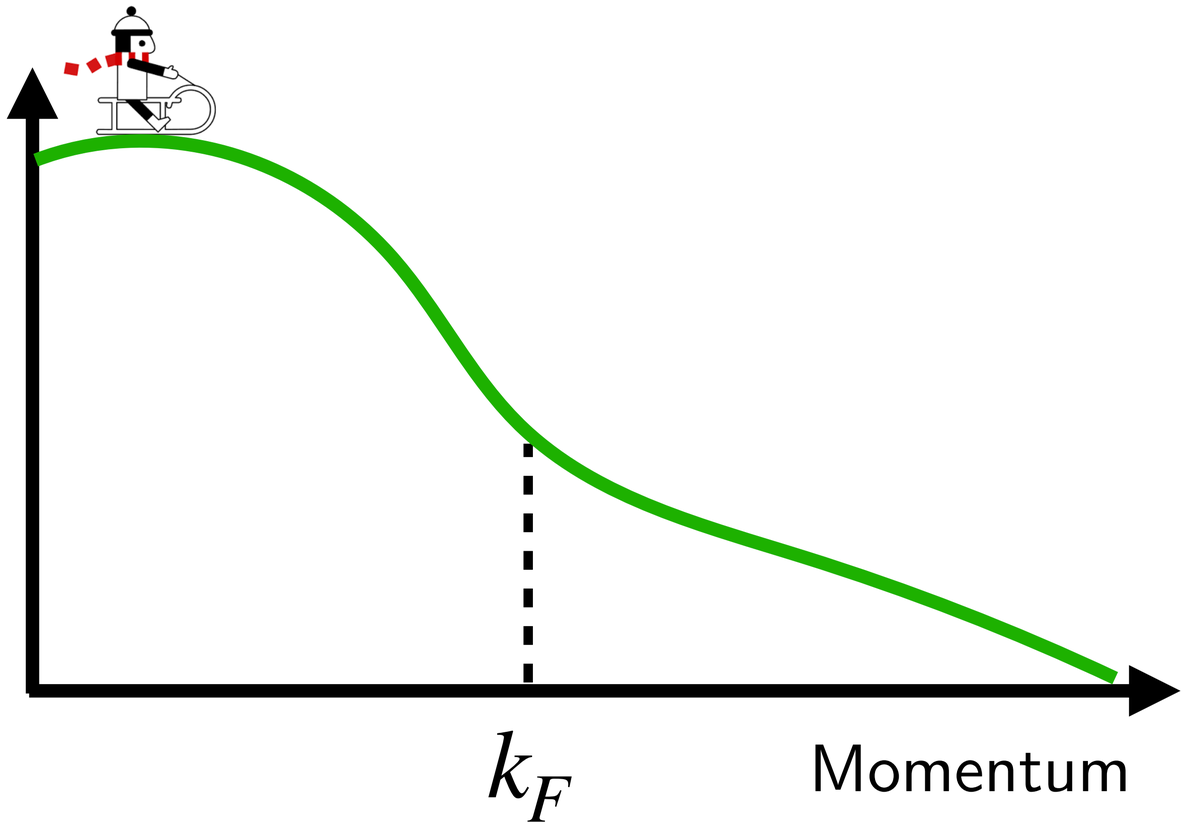




- MARATHON extraction from ^{3}He/^{3}H ratio
- Only need to account for relative nuclear corrections in A = 3 nuclei

2. EIC

Spin structure of the neutron



Nucleon spin structure

Polarized PDFs

$$A_{\parallel} = \frac{\sigma^{\leftrightarrows} - \sigma^{\rightrightarrows}}{\sigma^{\leftrightarrows} + \sigma^{\rightrightarrows}} \quad \text{and} \quad A_{\perp} = \frac{\sigma^{\rightarrow\uparrow} - \sigma^{\rightarrow\downarrow}}{\sigma^{\rightarrow\uparrow} + \sigma^{\rightarrow\downarrow}} \qquad \rightarrow A_1(x) \approx g_1(x) \Big/ F_1(x)$$

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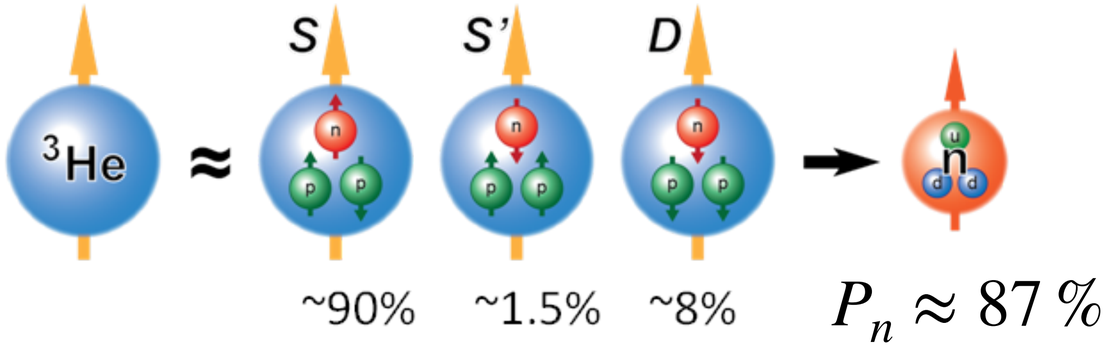
Neutron carries most of the spin in polarized ^{3}He



$P_n \approx 87\,\%$

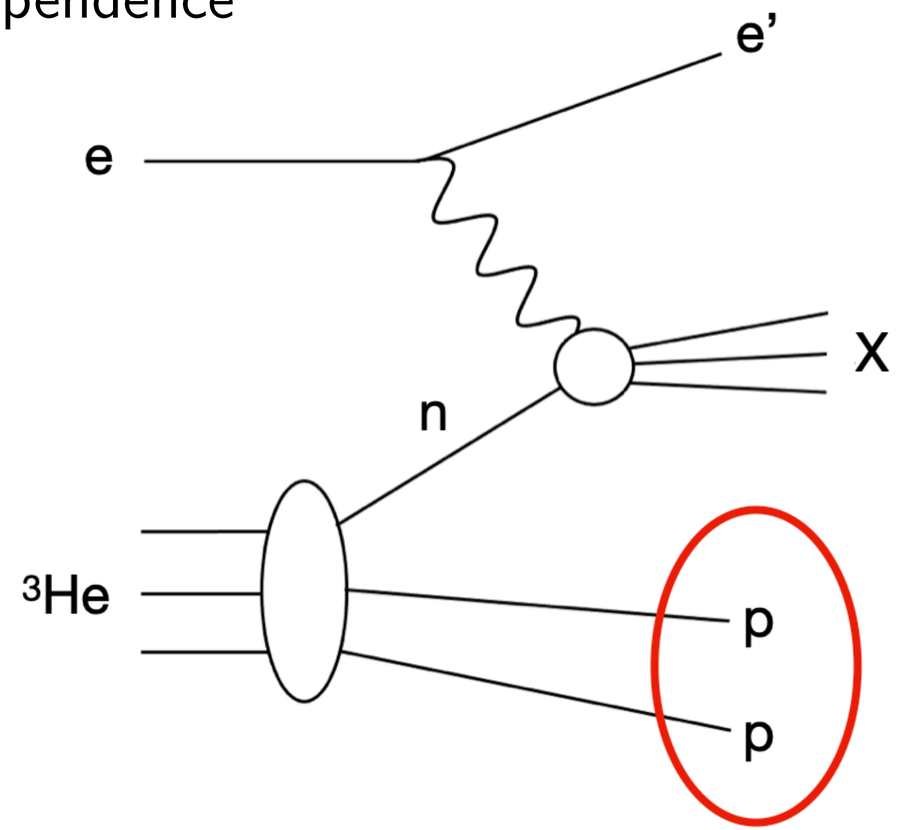
Can extract A_1^n from inclusive $A_1^{^3He}$

$$A_1^n \approx \frac{1}{P_n} \frac{F_2^{3\mathrm{He}}}{F_2^n} \left(A_1^{3\mathrm{He}} - 2P_p \frac{F_2^p}{F_2^{3\mathrm{He}}} A_1^p\right)$$

Nuclear corrections introduce large uncertainties!

Neutron spin structure from double spectator tagging

- Detect *both* spectator protons
- Require low-momentum for quasi-free neutrons
- Extract spin structure with reduced model dependence



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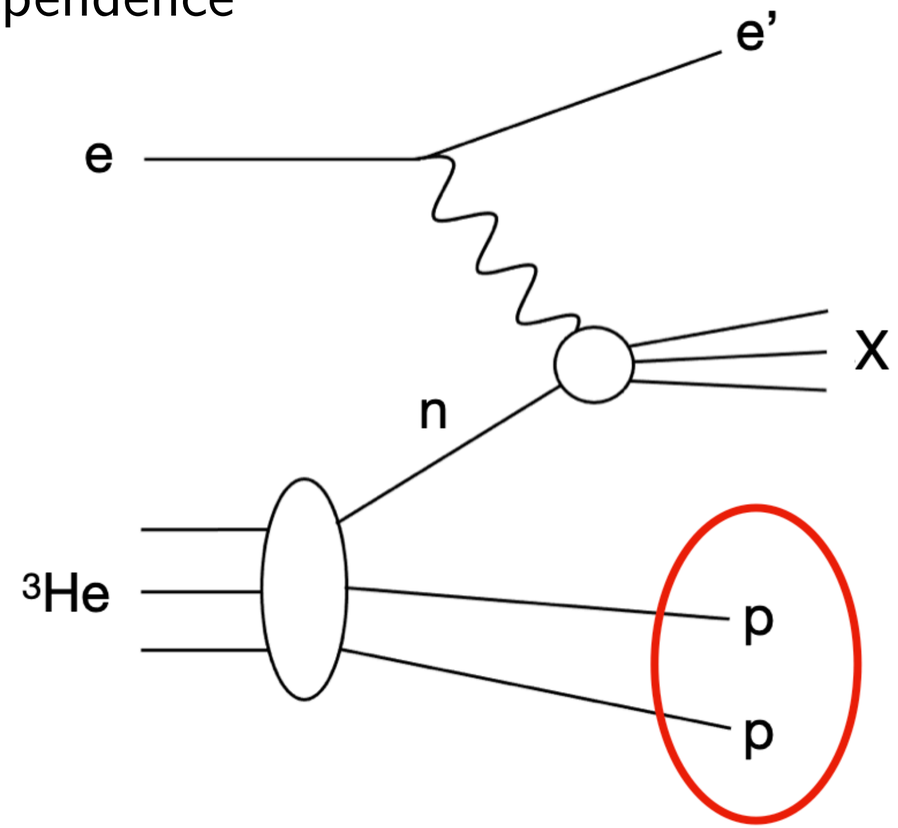

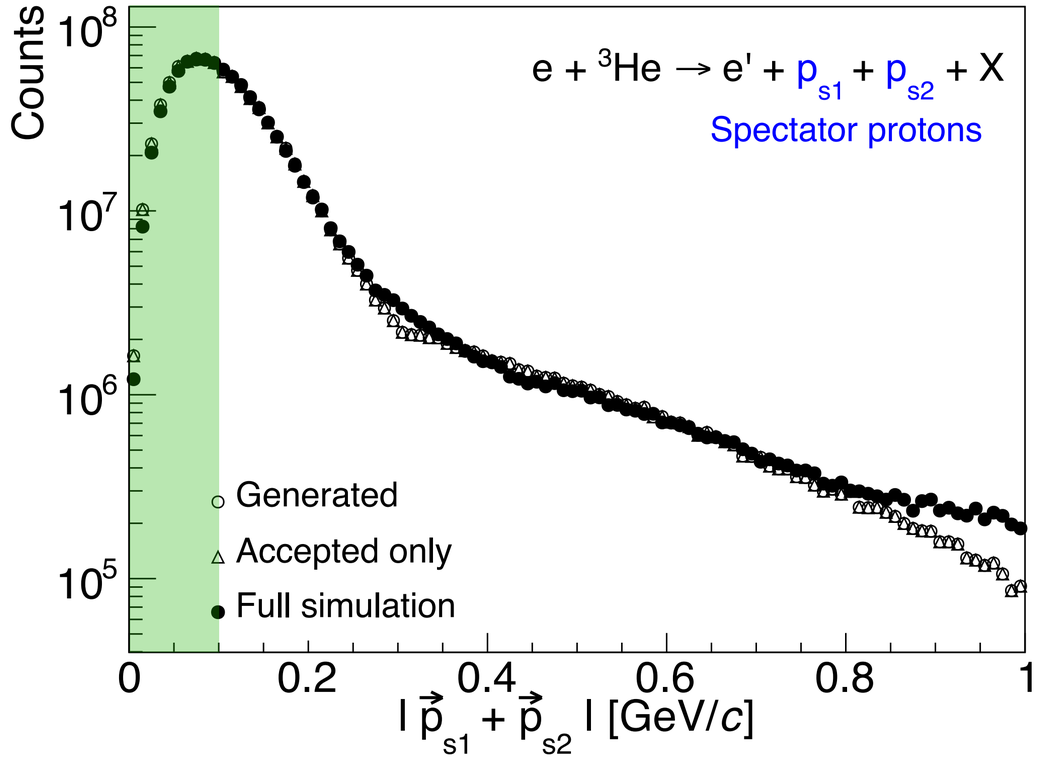

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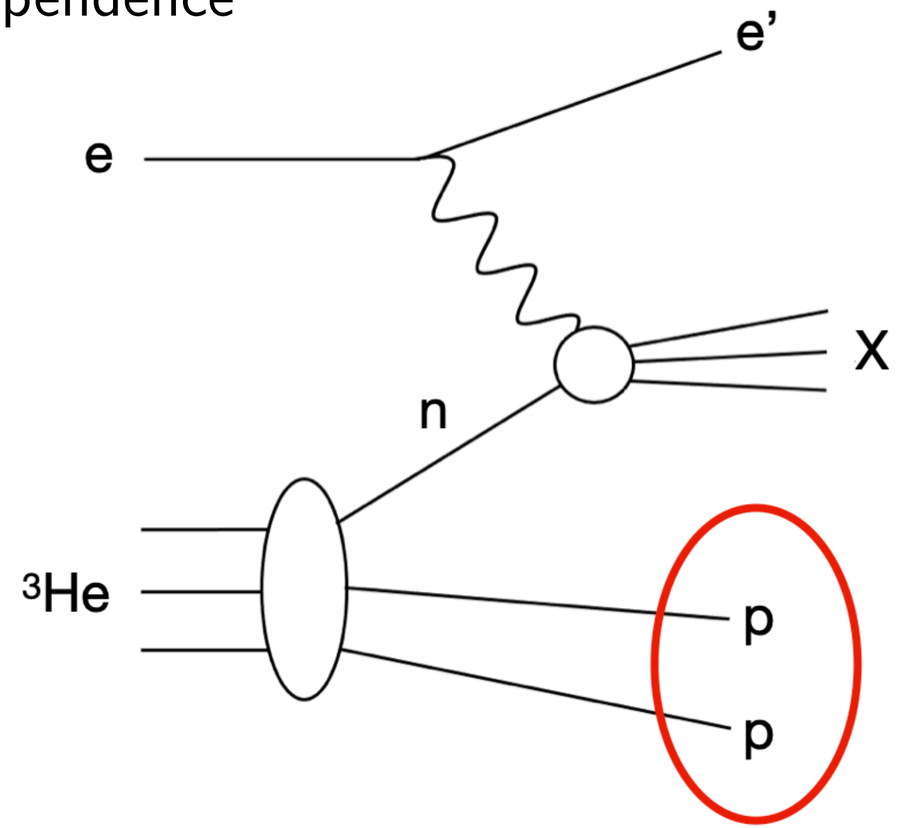
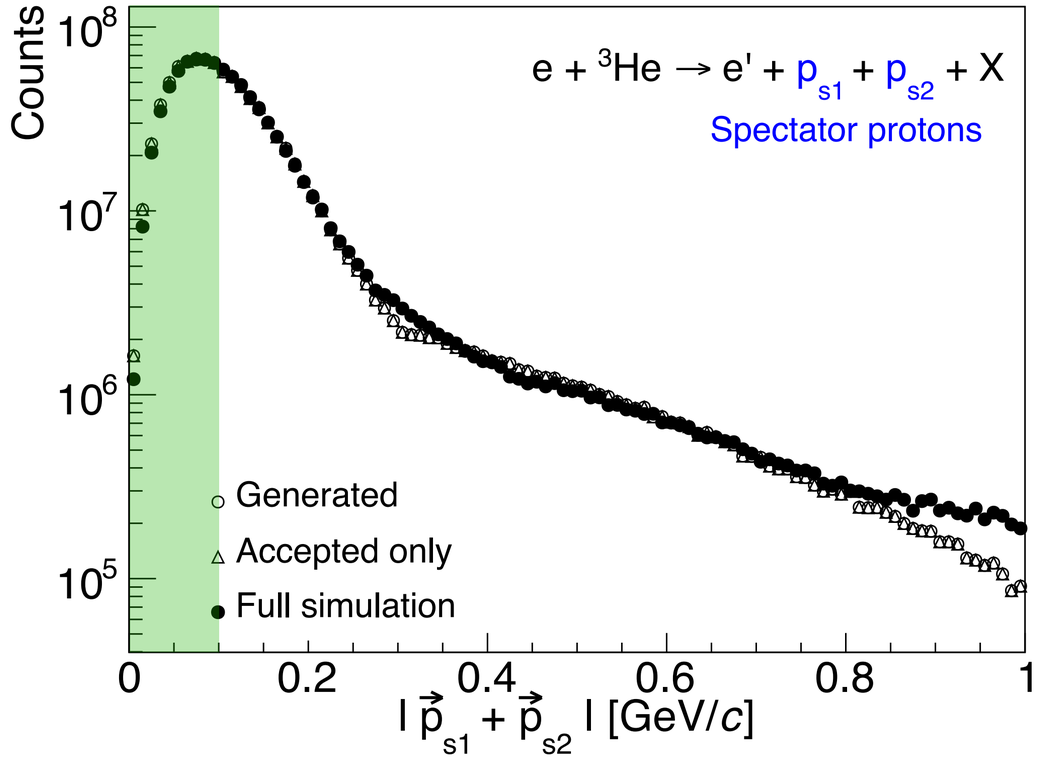
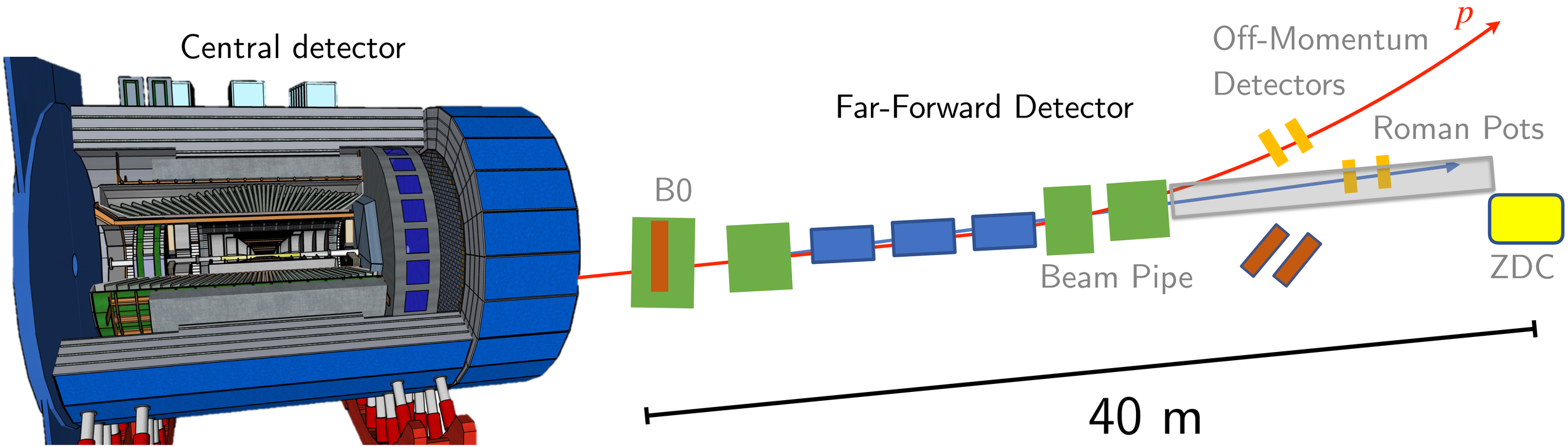




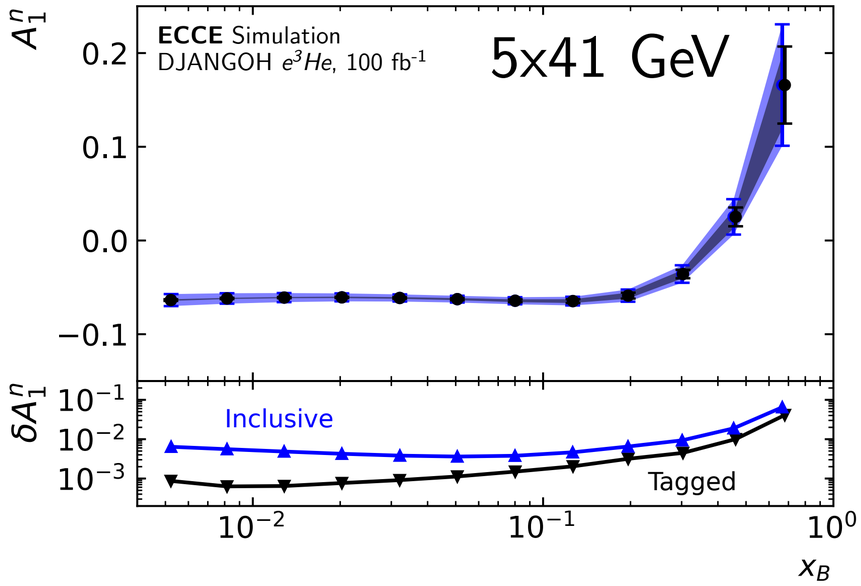
Not feasible at fixed target facility!

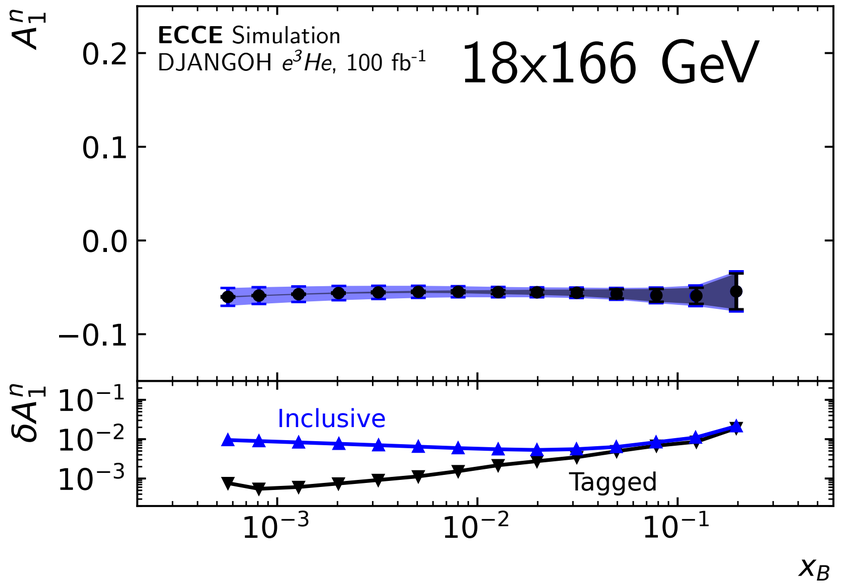
Double spectator tagging at the EIC

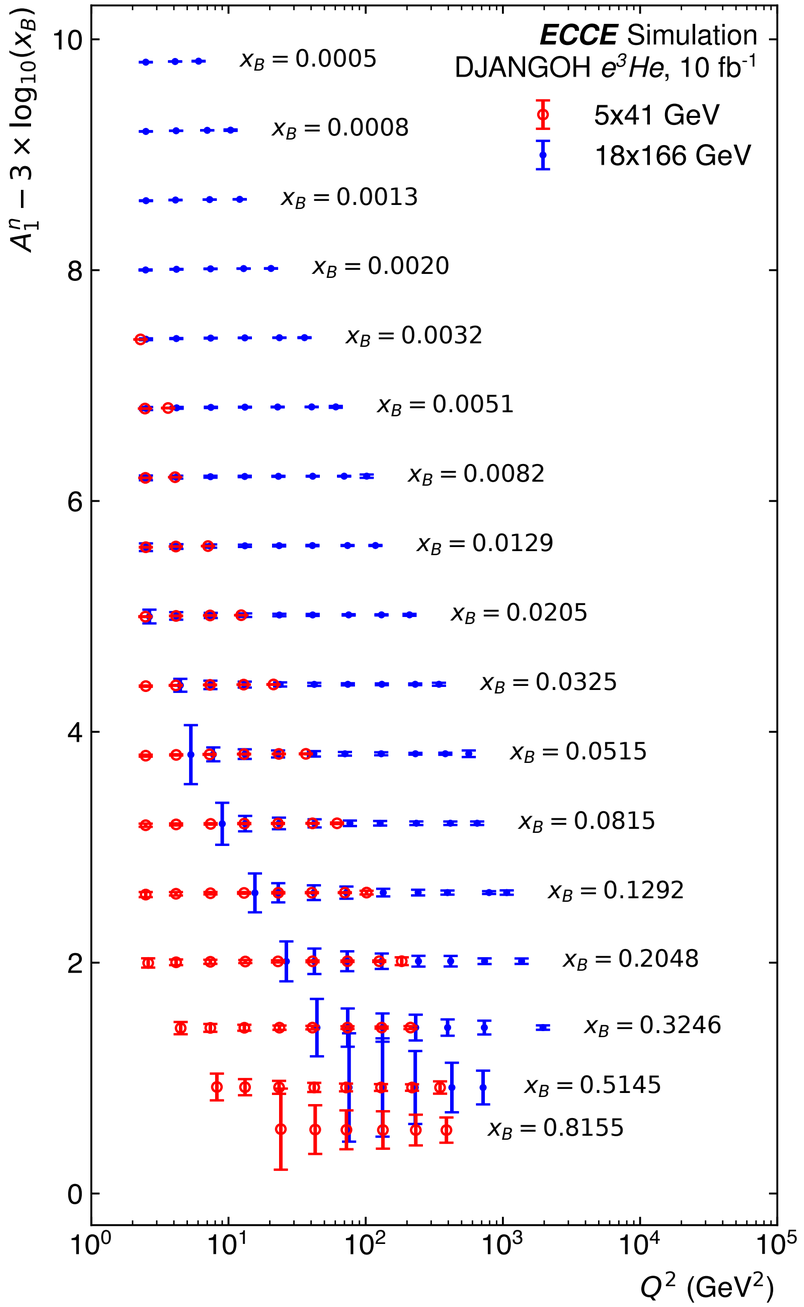


- Low-momentum protons in ion rest frame highly boosted in lab frame
- Electron to central detector
- Protons to far-forward detector

Projected results



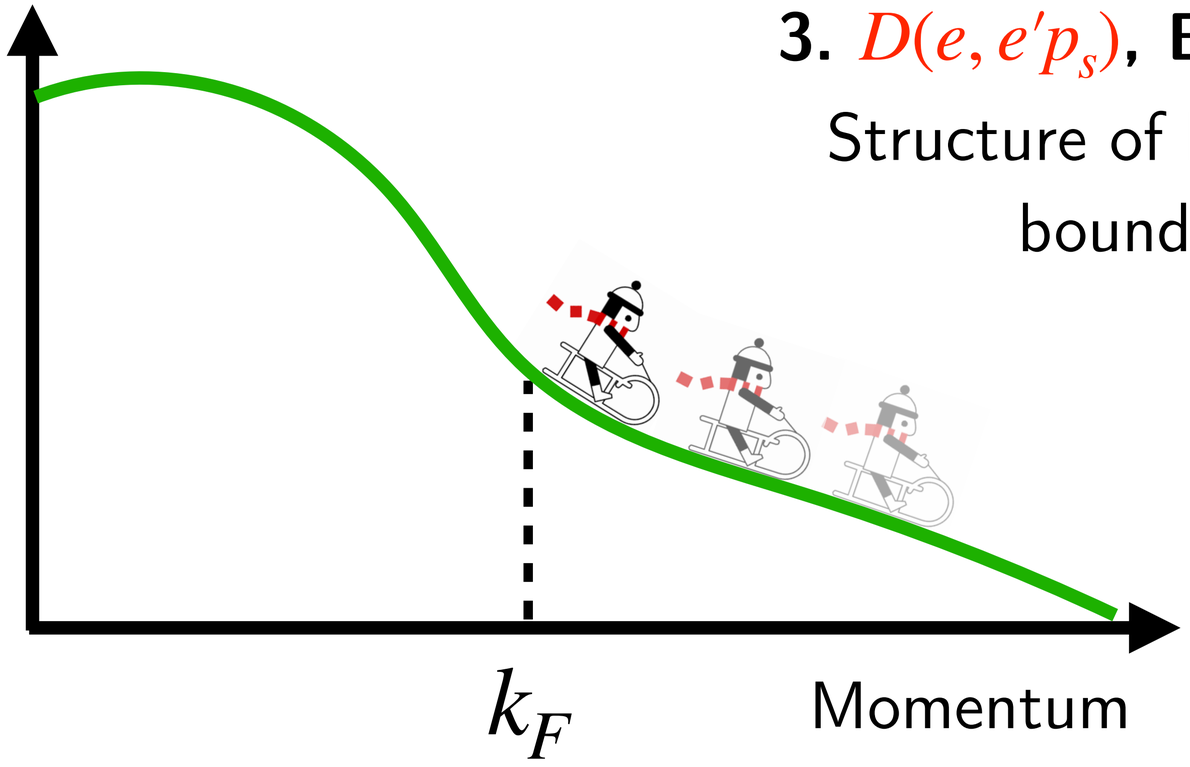




Friščić, et al. PLB 823, 136726 (2021), updated for ECCE proposal

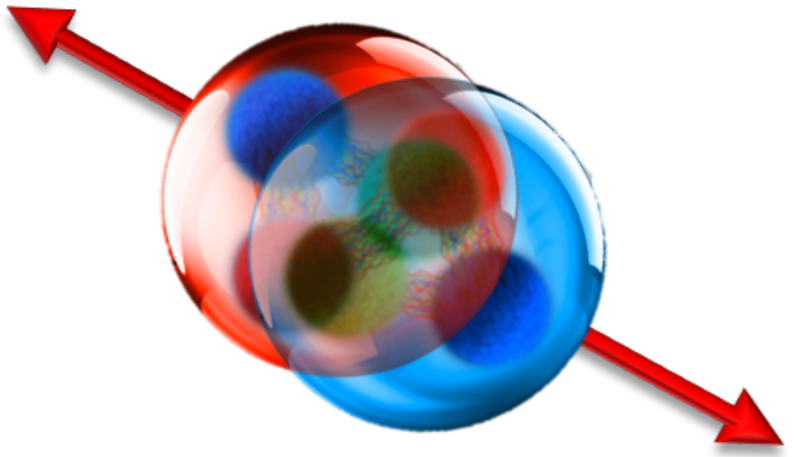
3. $D(e, e'p_s)$, BAND, and LAD

Structure of high-momentum bound nucleons

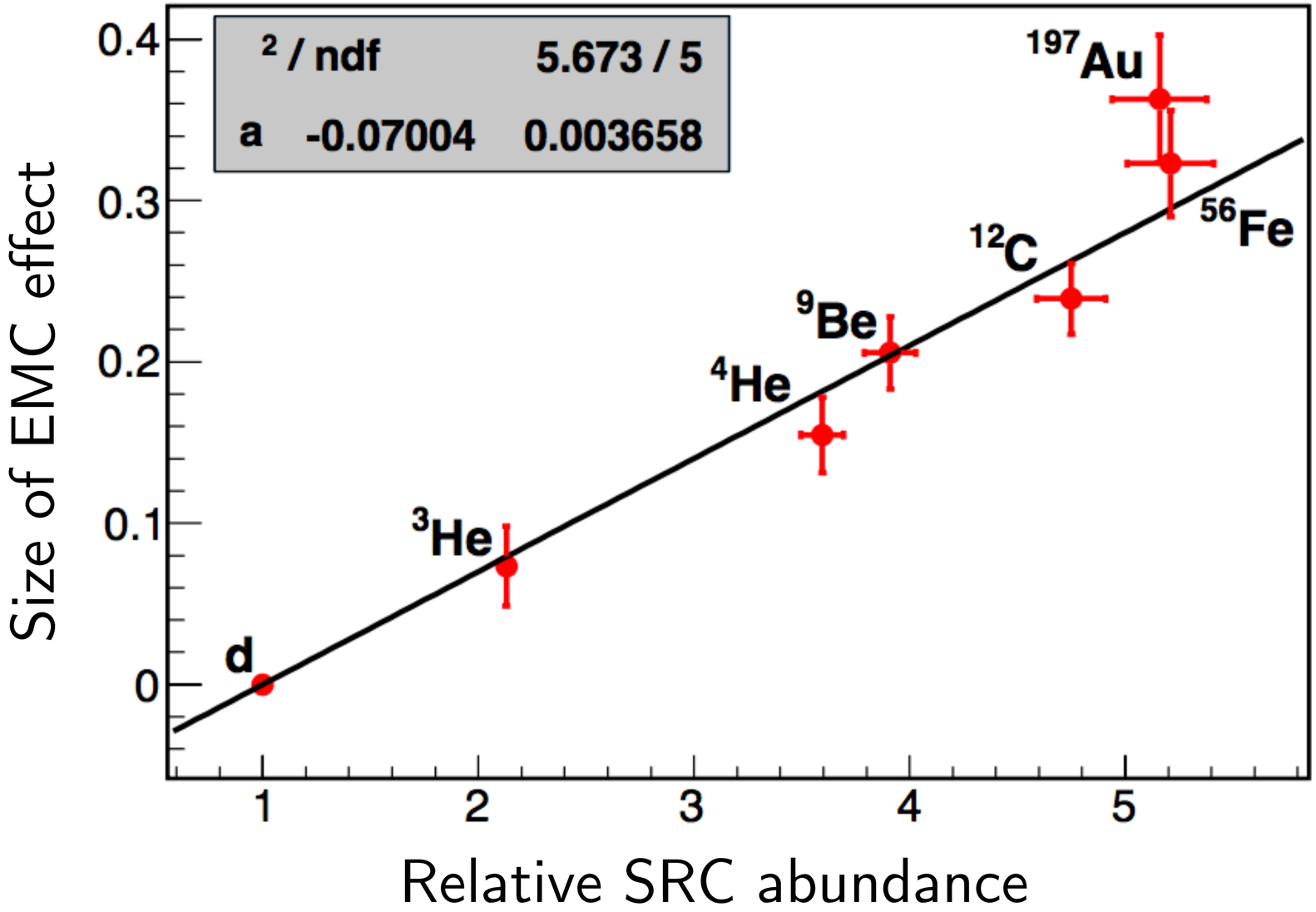


Short-range correlations

- Fluctuation of nucleon pairs into short-range, strongly interacting state
- Predominantly np pairs with universal deuteron-like scaling
- Produces high-momentum ($>k_F$) tail
- Scale separated from the rest of the nucleus



SRC abundance and EMC magnitude are correlated



EMC effect can be described by universal modification of SRC pairs

$$F_2^A = \left(Z - n_{SRC}\right) F_2^p + \left(N - n_{SRC}\right) F_2^n + n_{SRC} \left(F_2^{n*} + F_2^{p*} \right)$$

Schmookler *et al.*, Nature (2019)

EMC effect can be described by universal modification of SRC pairs

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Schmookler *et al.*, Nature (2019)

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Schmookler *et al.*, Nature (2019)

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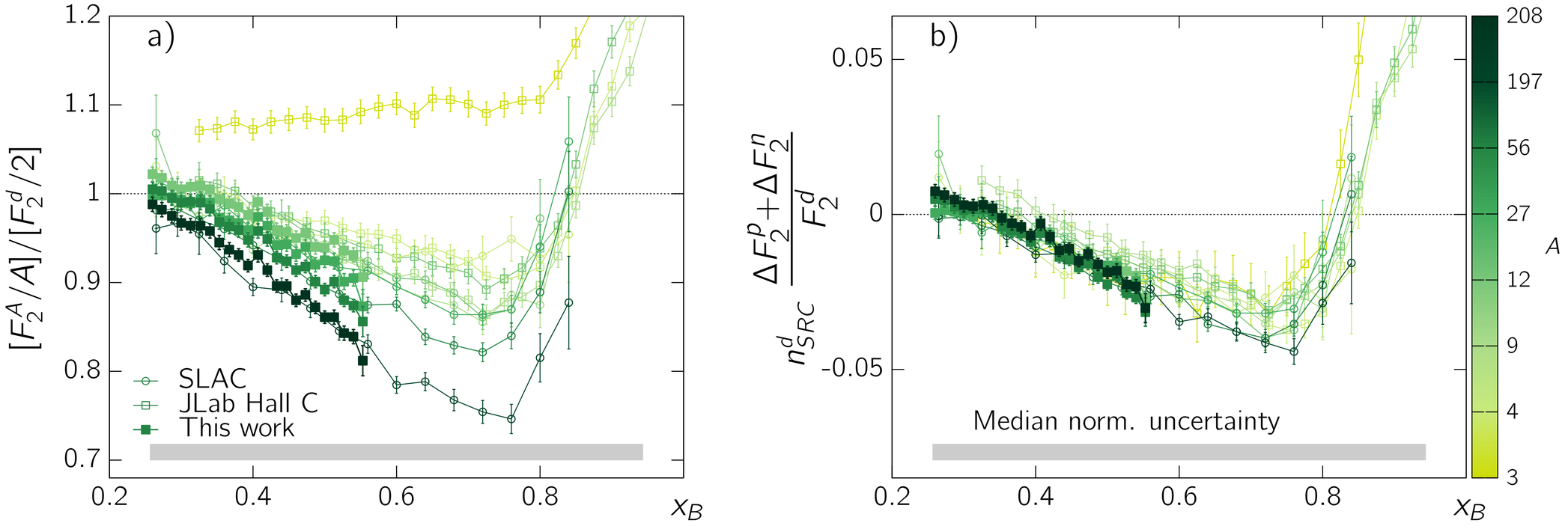
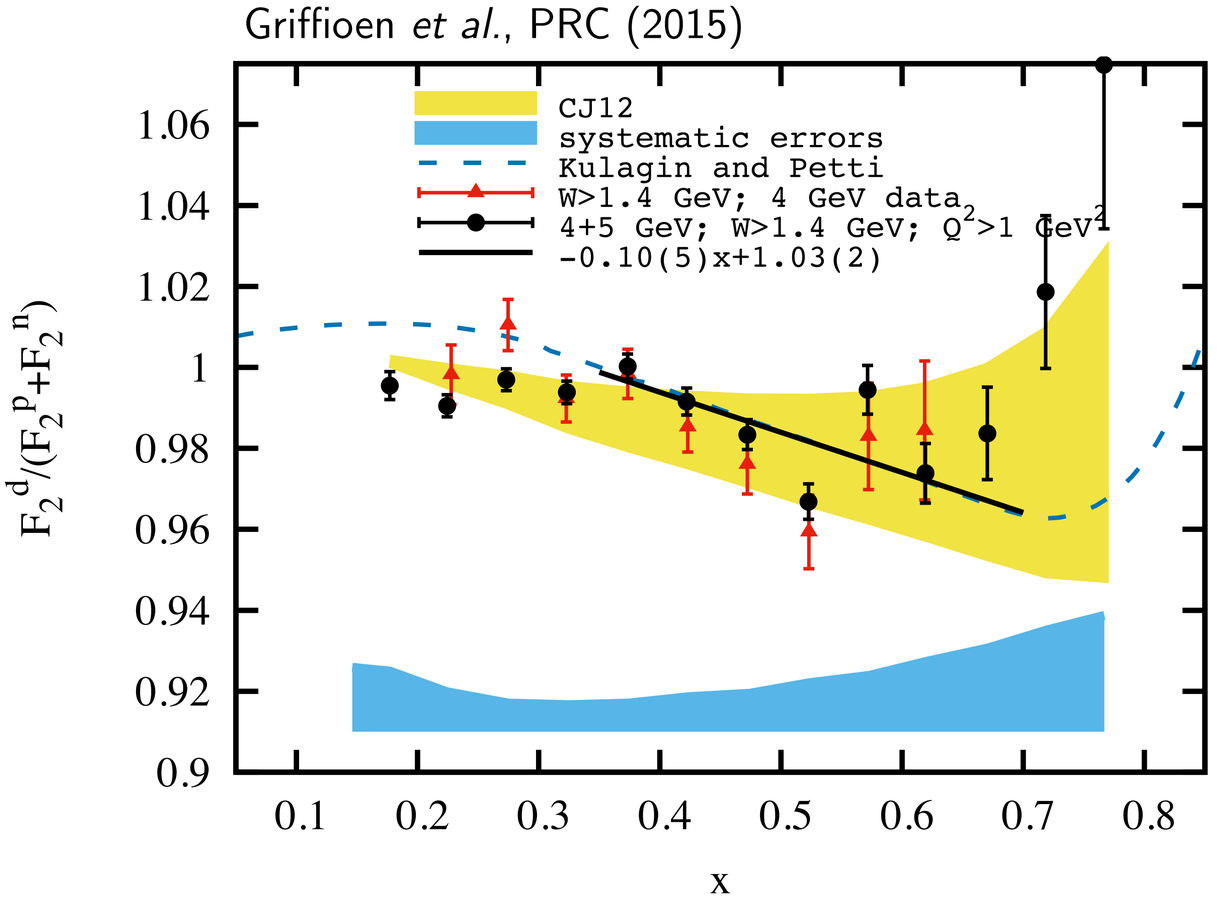
extract



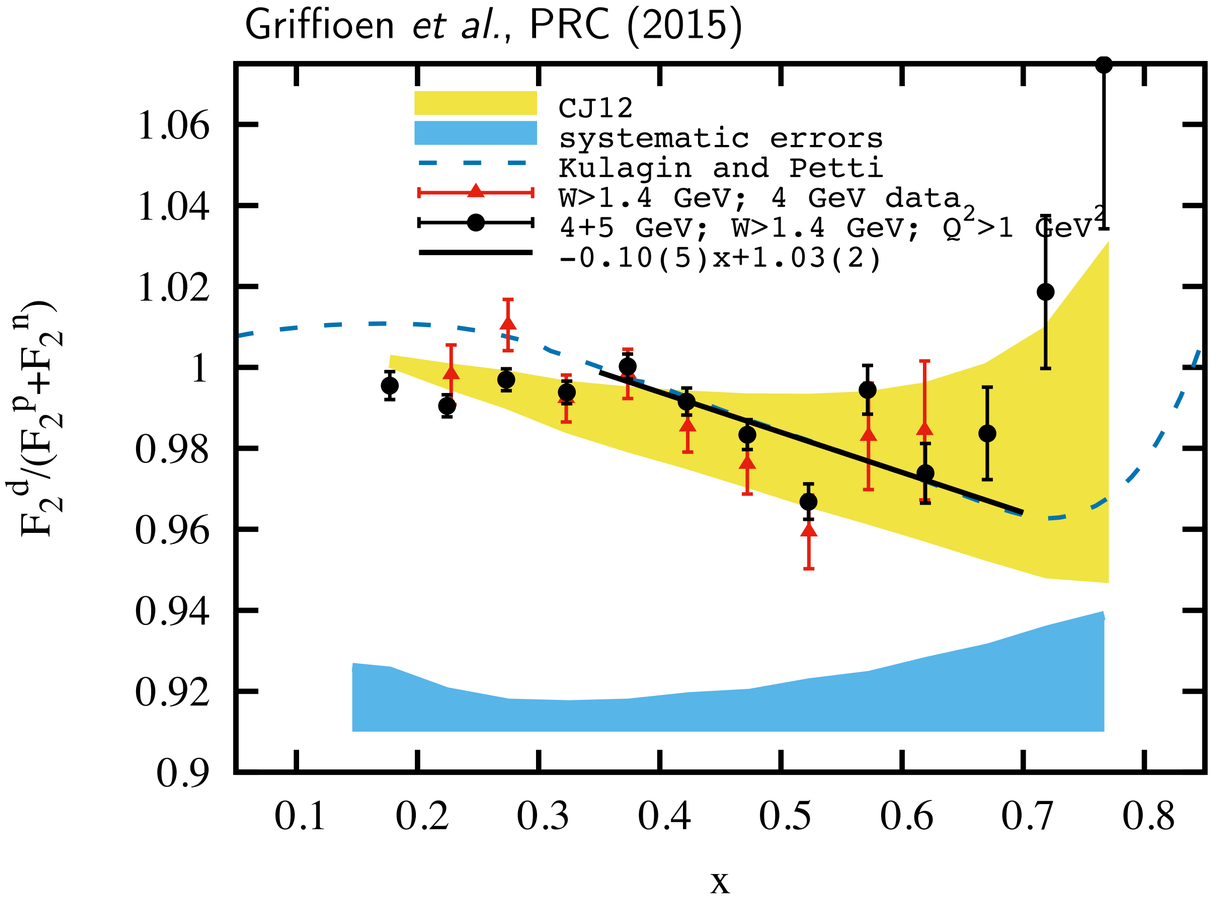
Schmookler *et al.*, Nature (2019)

Tagged DIS can definitively test SRC-EMC hypothesis



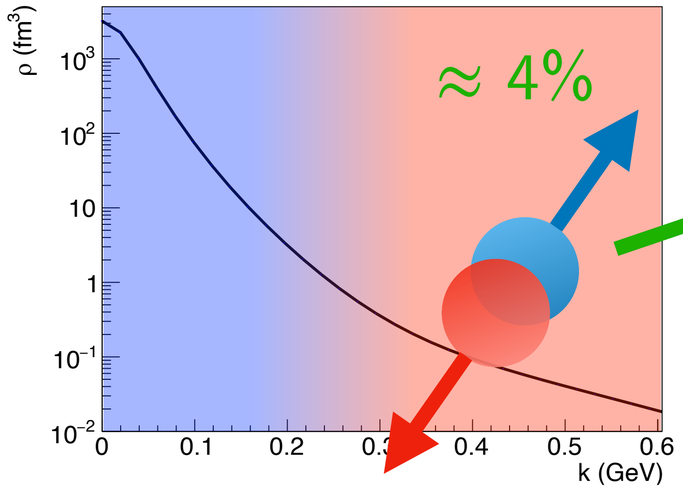
Tagged DIS can definitively test SRC-EMC hypothesis

- EMC effect in deuterium is small

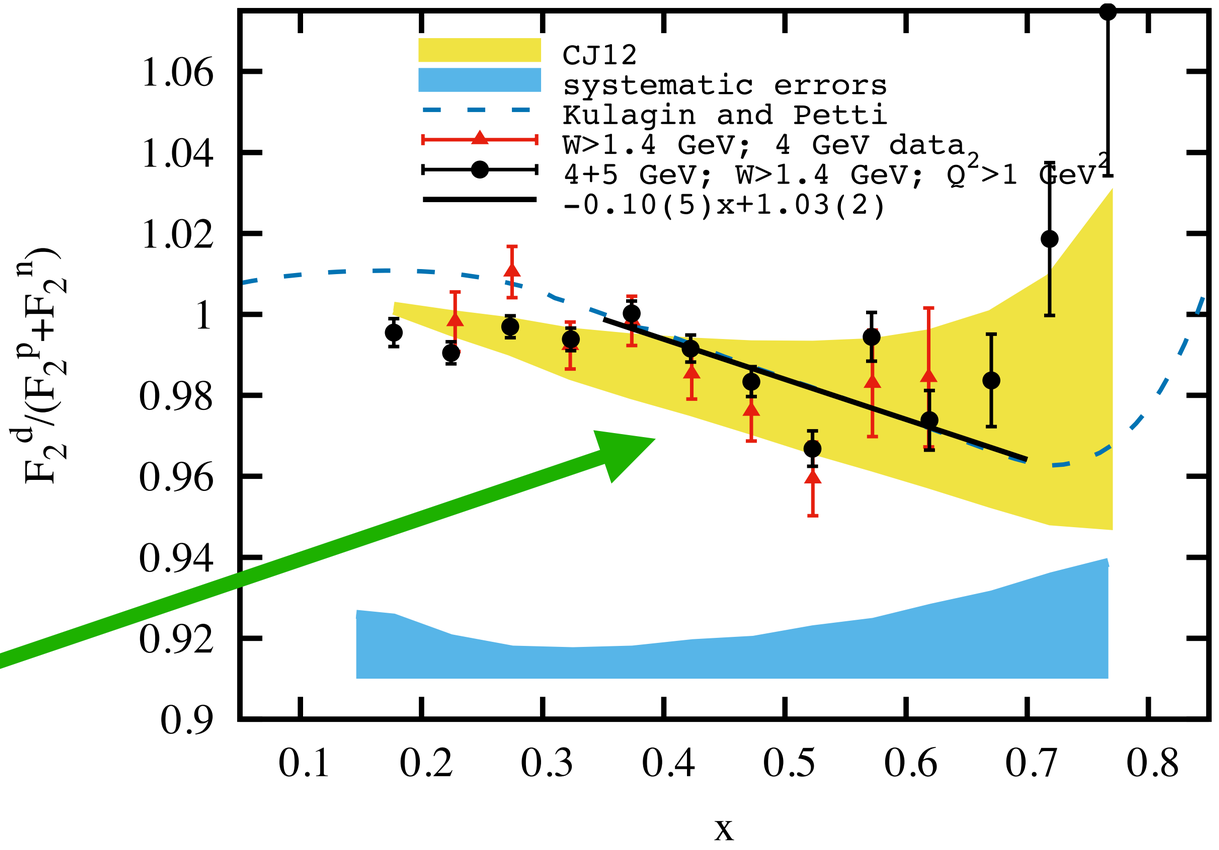


Tagged DIS can definitively test SRC-EMC hypothesis

- EMC effect in deuterium is small
- But SRC states are rare!
- Expect large effect in these states

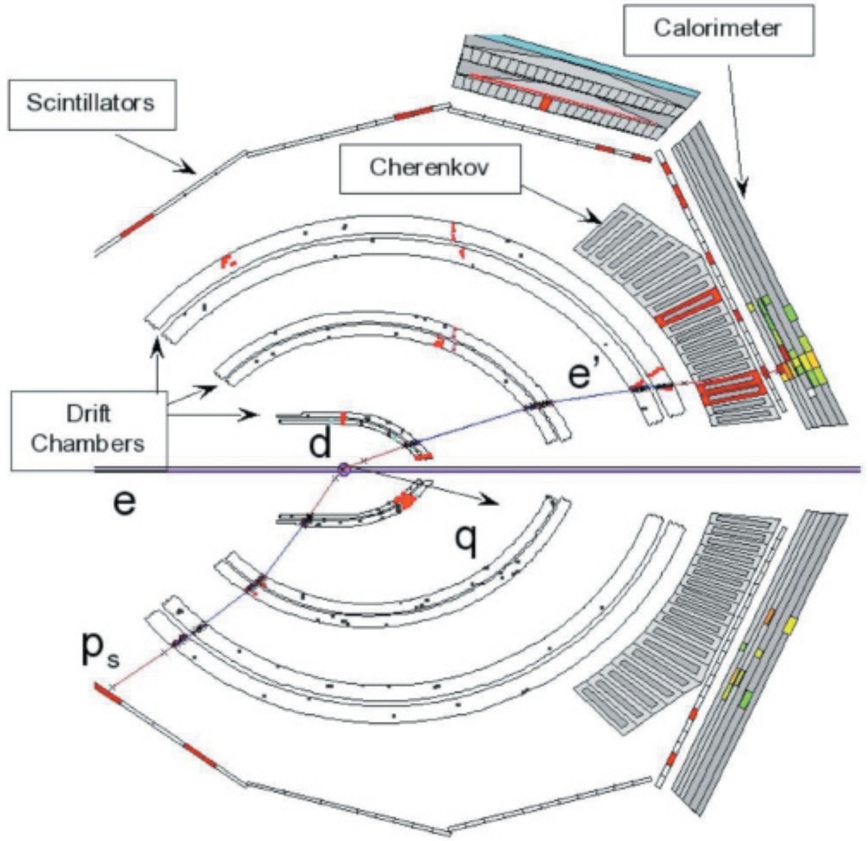


Griffioen *et al.*, PRC (2015)



$D(e, e'p_s)$

- Pioneering tagged DIS experiment
- 5.75 GeV electrons on 5cm LD2
- Detect scattered electron and backward proton in CLAS detector



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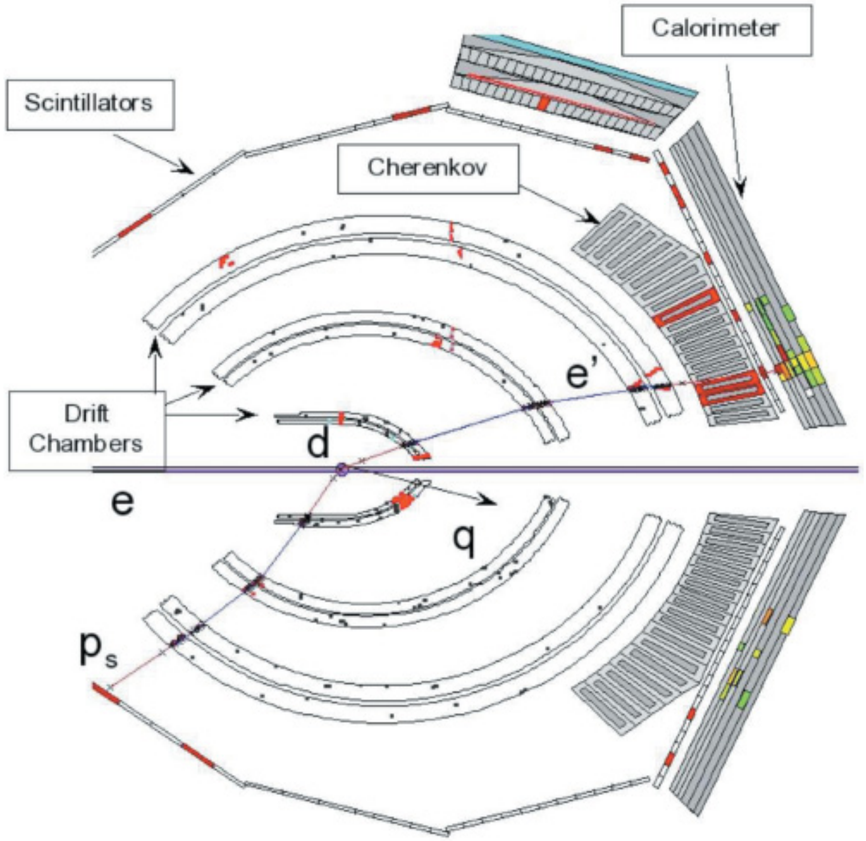
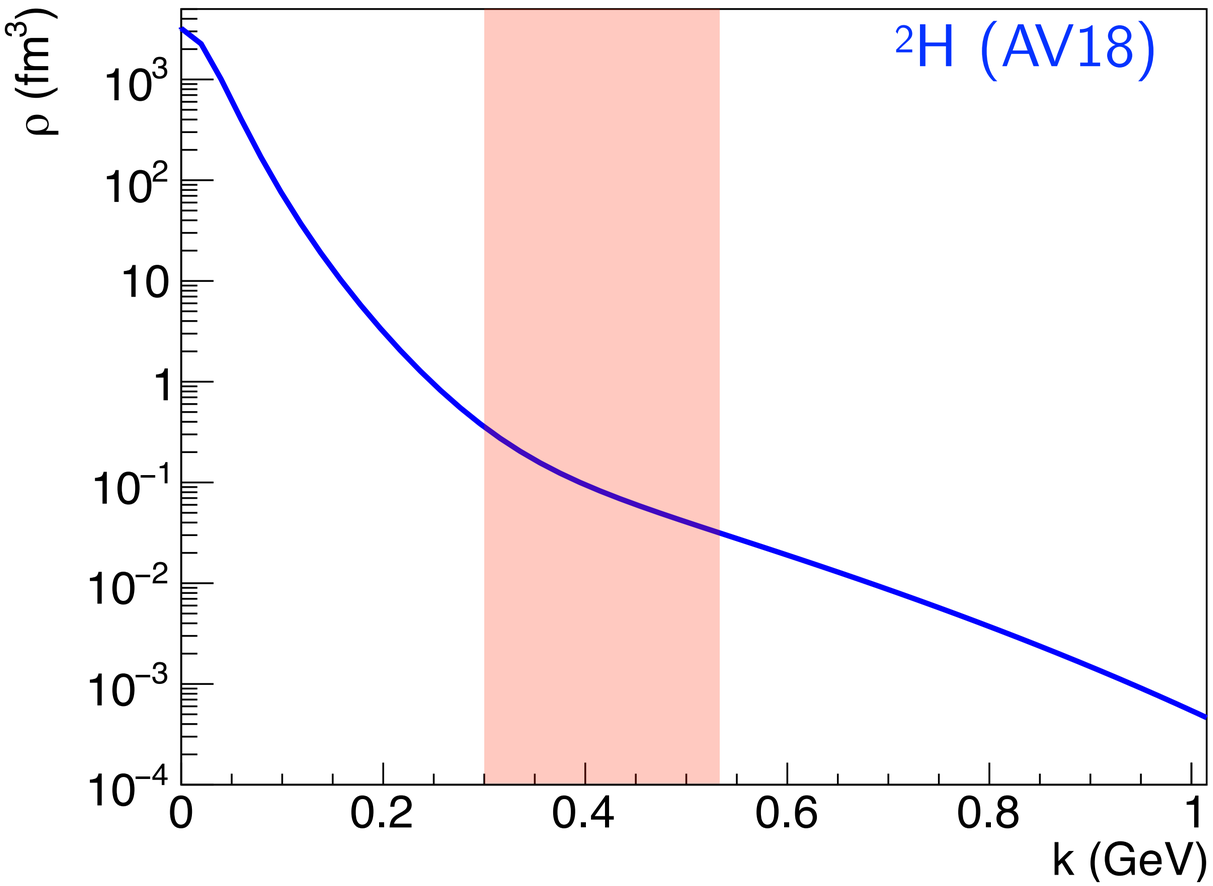
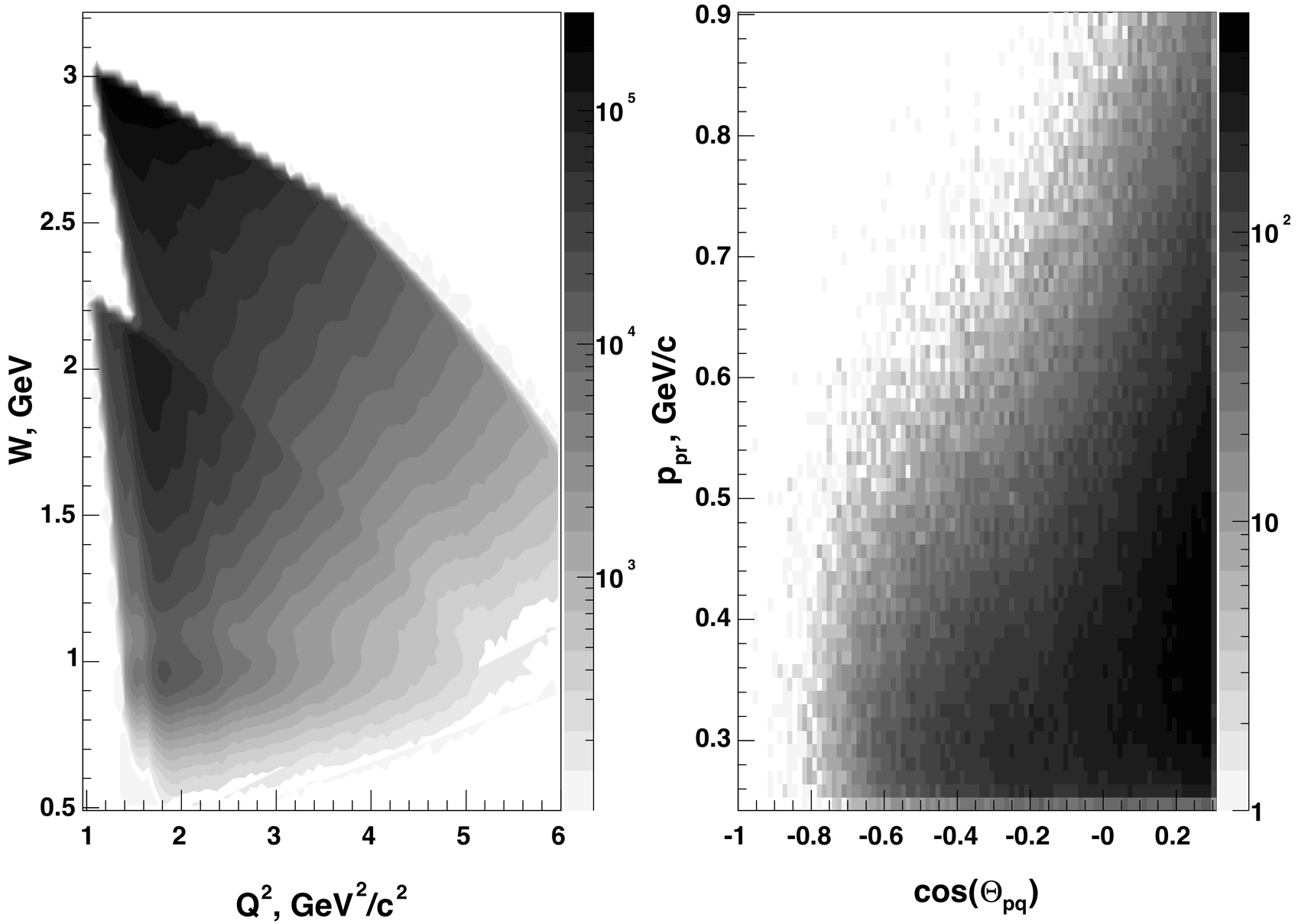




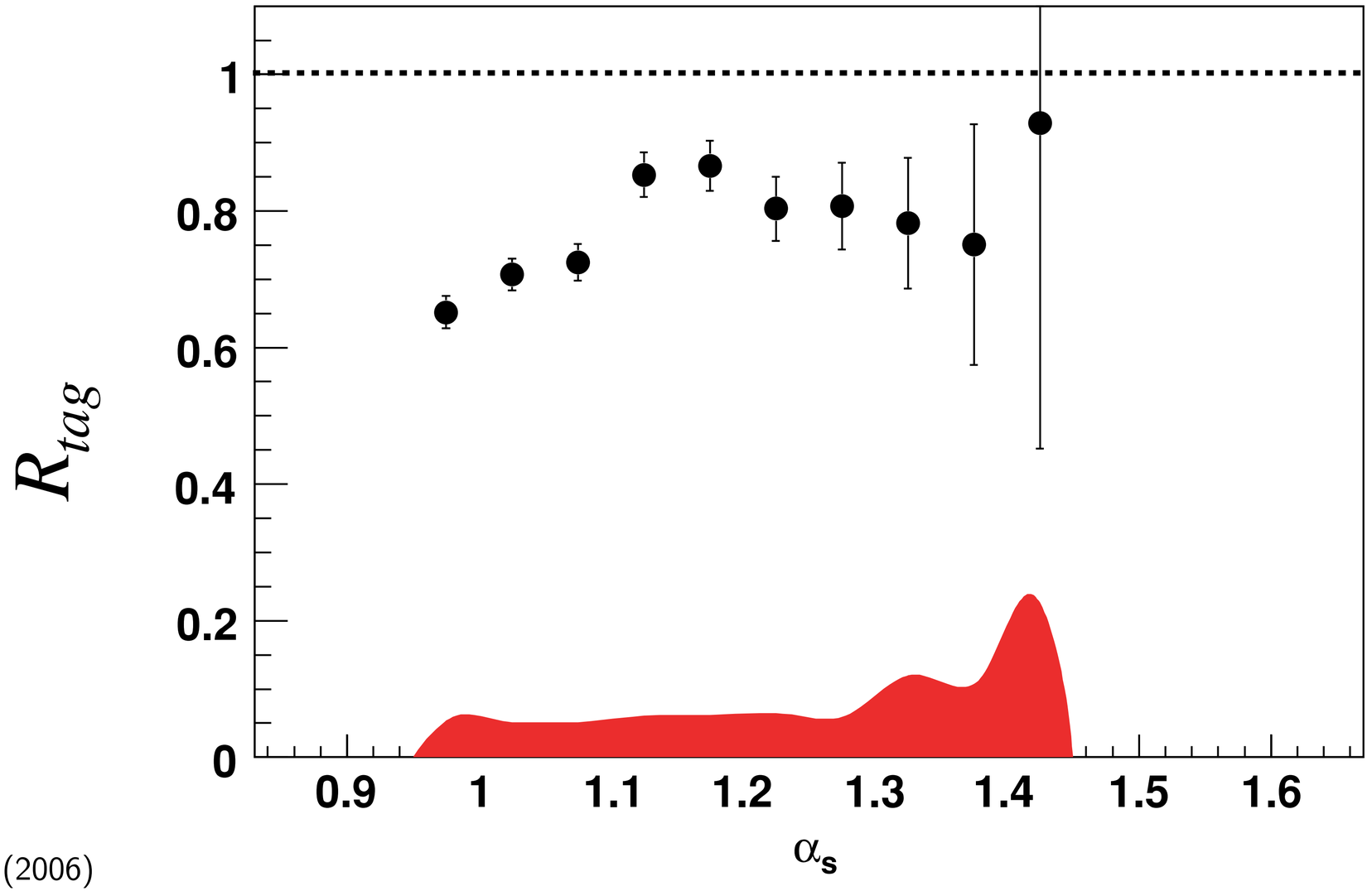
$D(e, e'p_s)$ kinematic coverage was limited



Klimenko, et al. PRC 73, 035212 (2006)

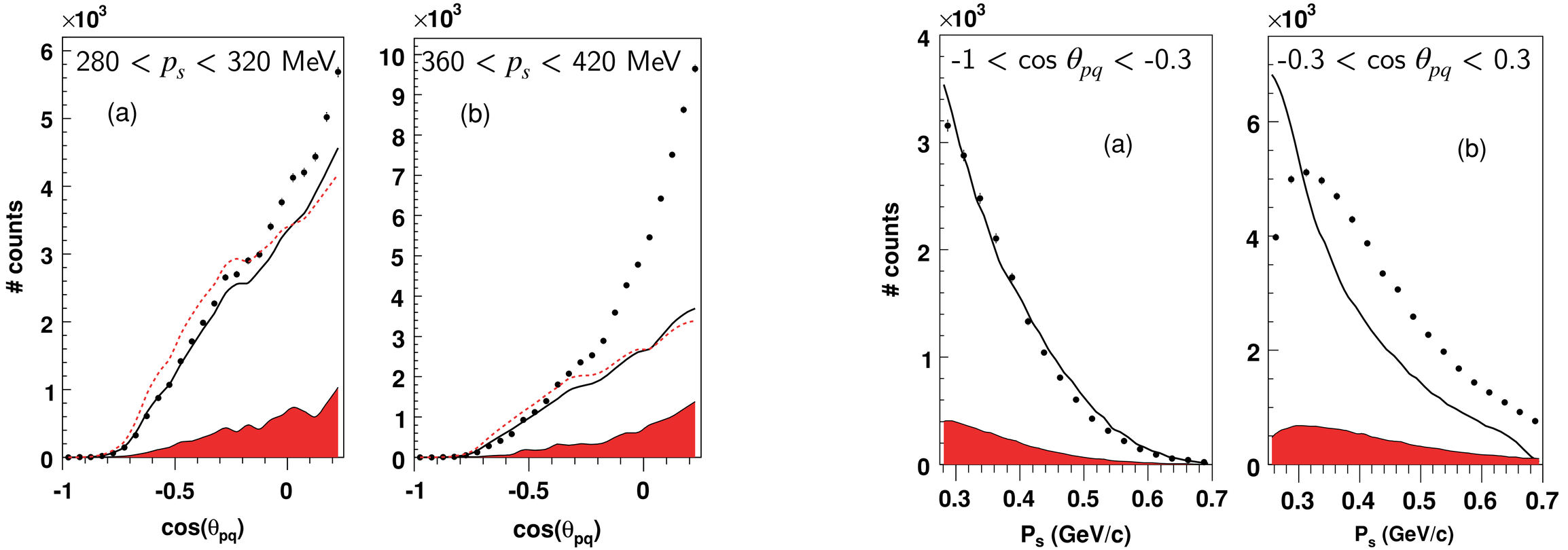
$D(e, e'p_s)$ results

$$R_{tag} = \frac{F_2^n * (x = 0.55) \Big/ F_2^n * (x = 0.25)}{F_2^n(x = 0.55) \Big/ F_2^n(x = 0.25)}$$



Klimenko, et al. PRC 73, 035212 (2006)

$D(e, e'p_s)$ seemed to validate FSI predictions

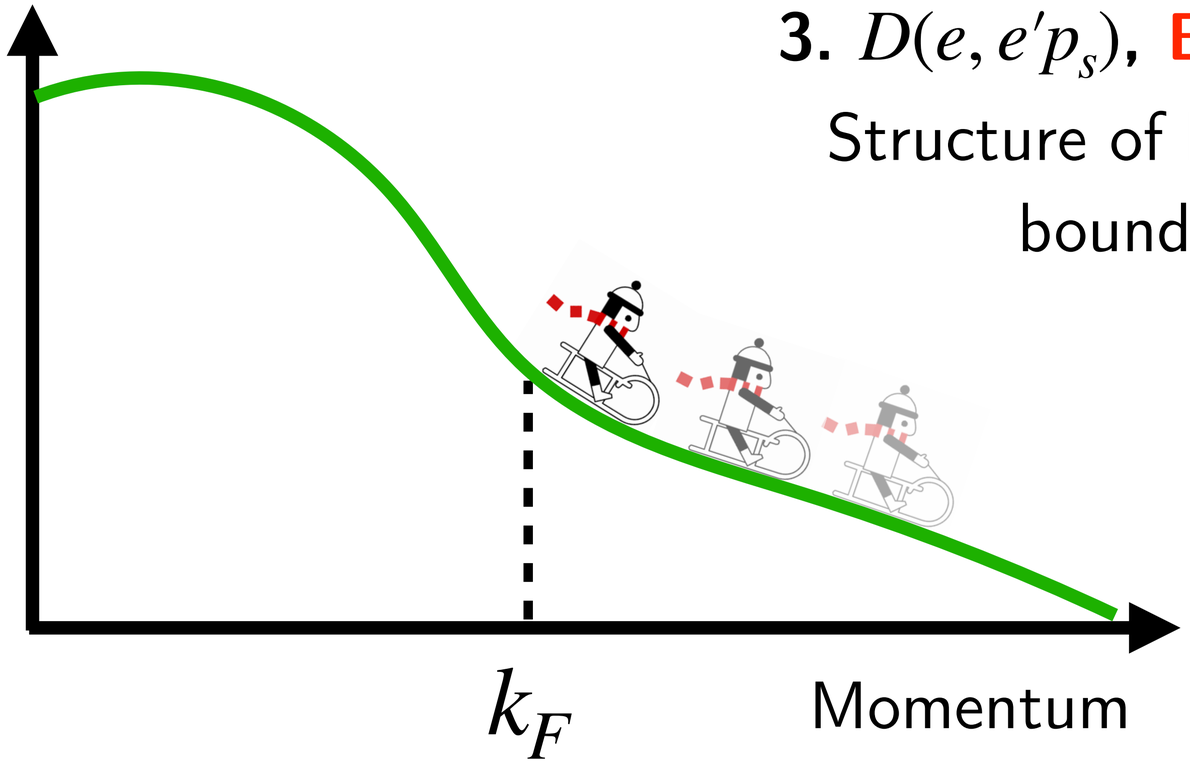


- Good agreement between data and PWIA at backward angles
- Enhancement in data (due to FSI?) at perpendicular angles

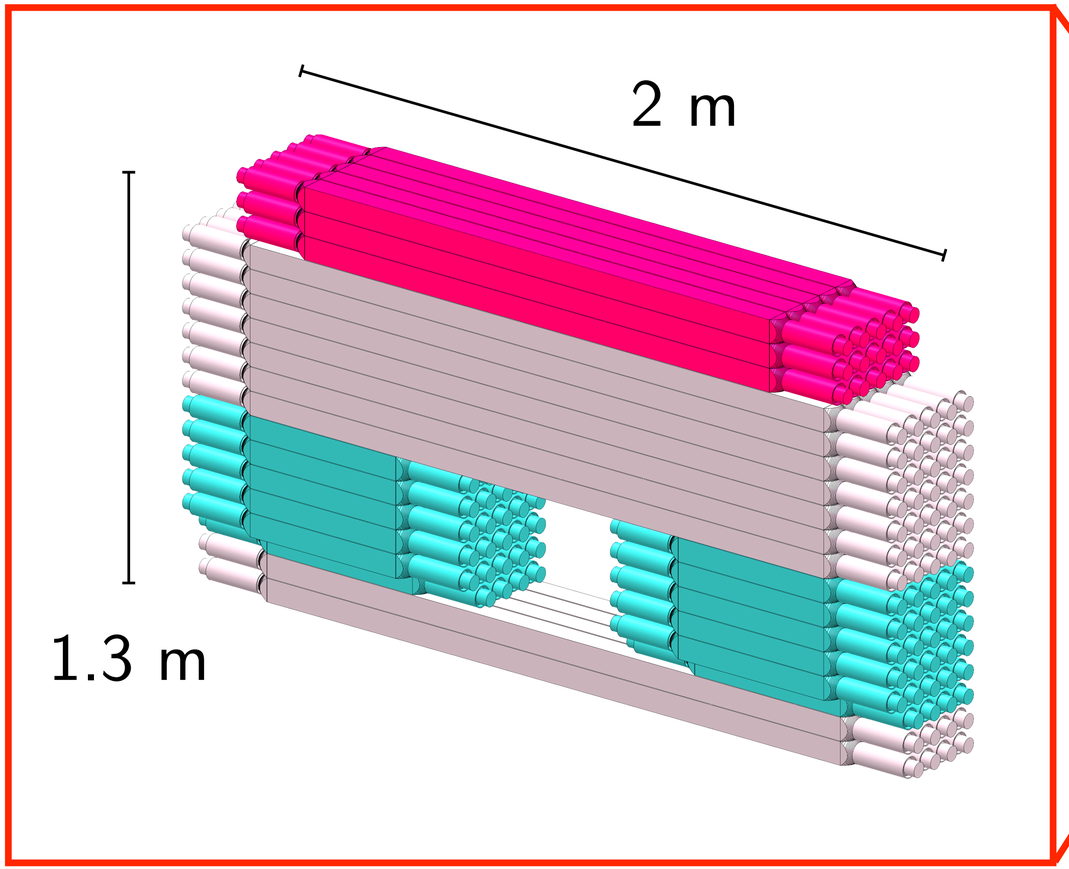
Klimenko, et al. PRC 73, 035212 (2006)

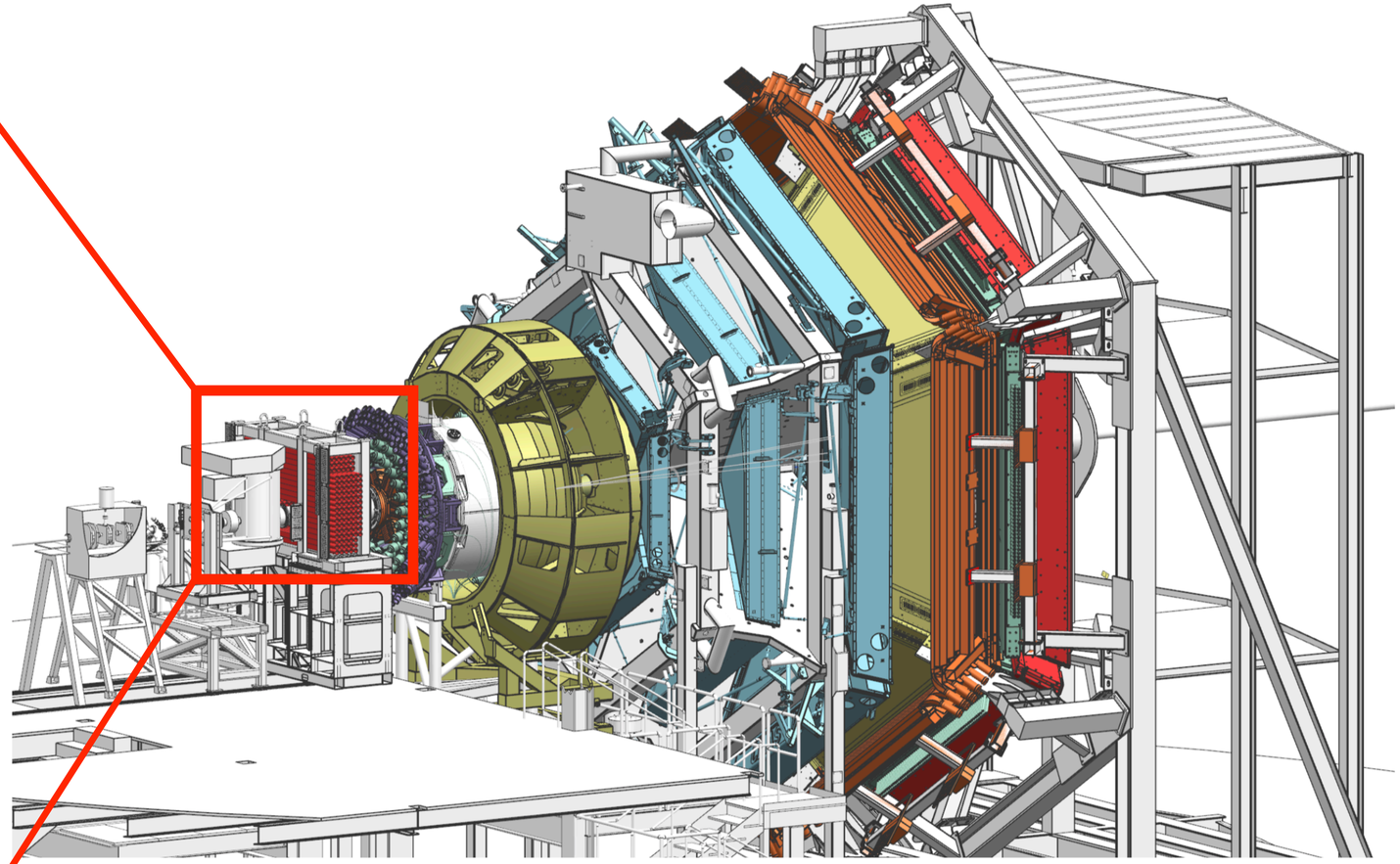
3. $D(e, e'p_s)$, BAND, and LAD

Structure of high-momentum bound nucleons



BAND (Backward Angle Neutron Detector)

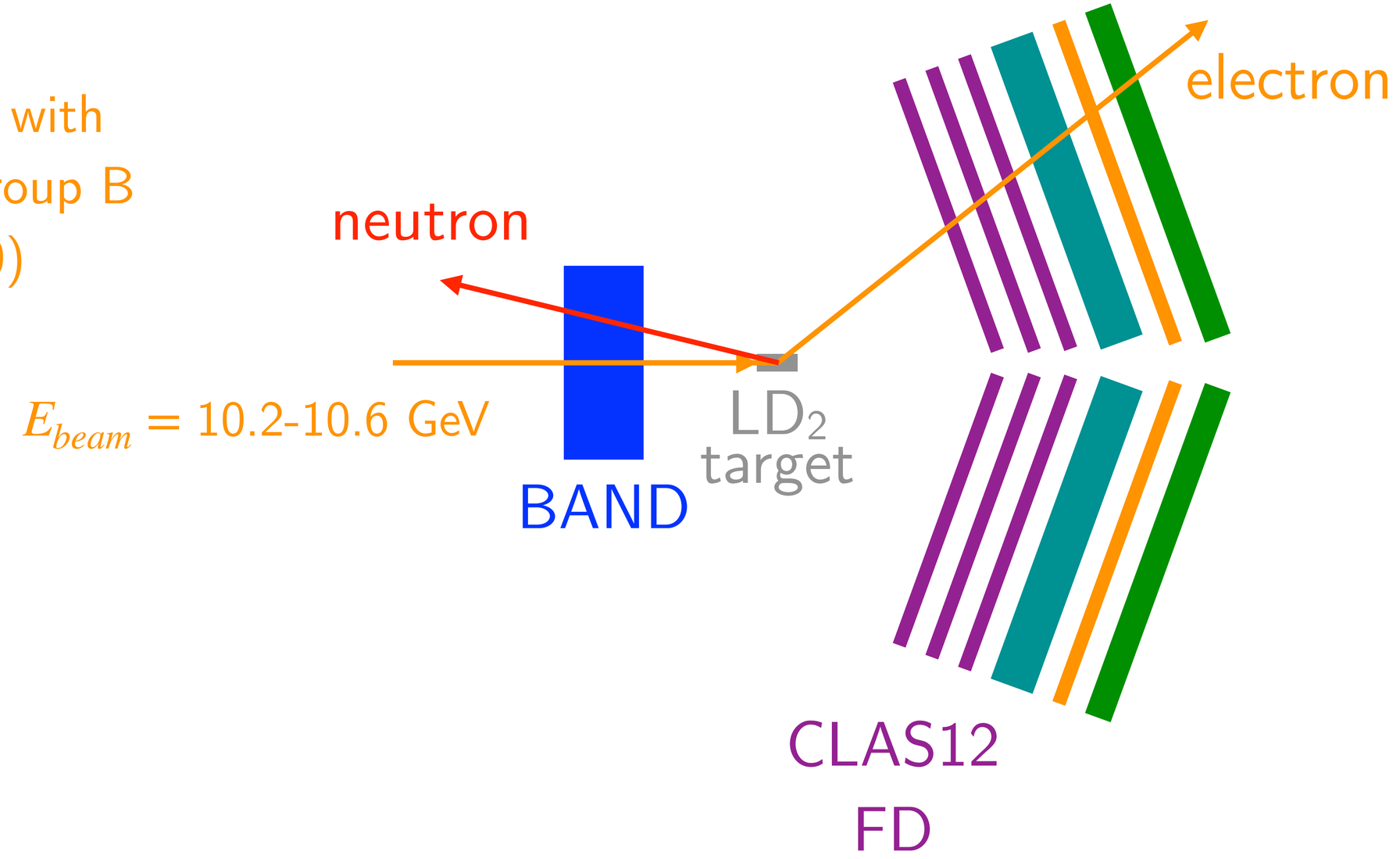




- 116 plastic scintillator bars + veto layer
- ≈3 m upstream of target

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

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



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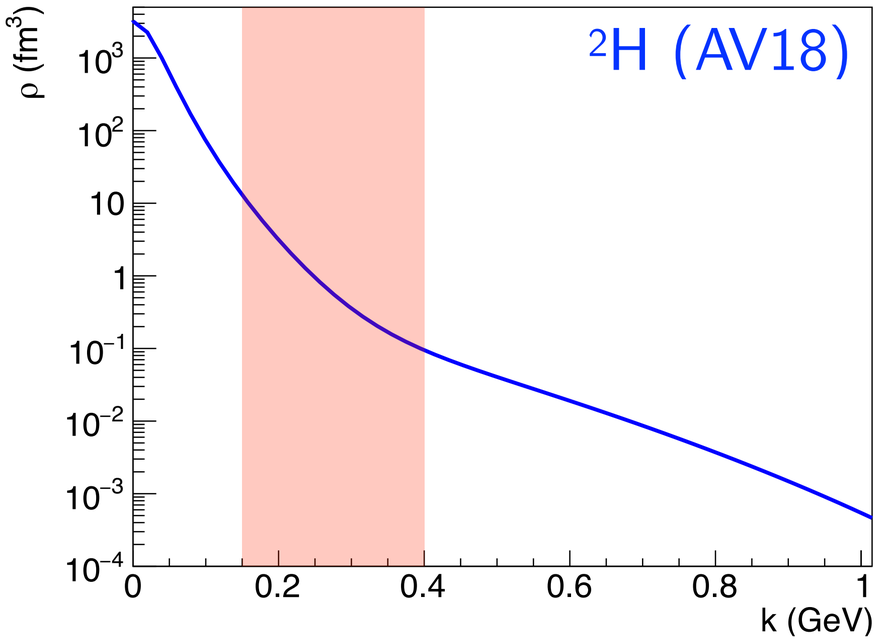
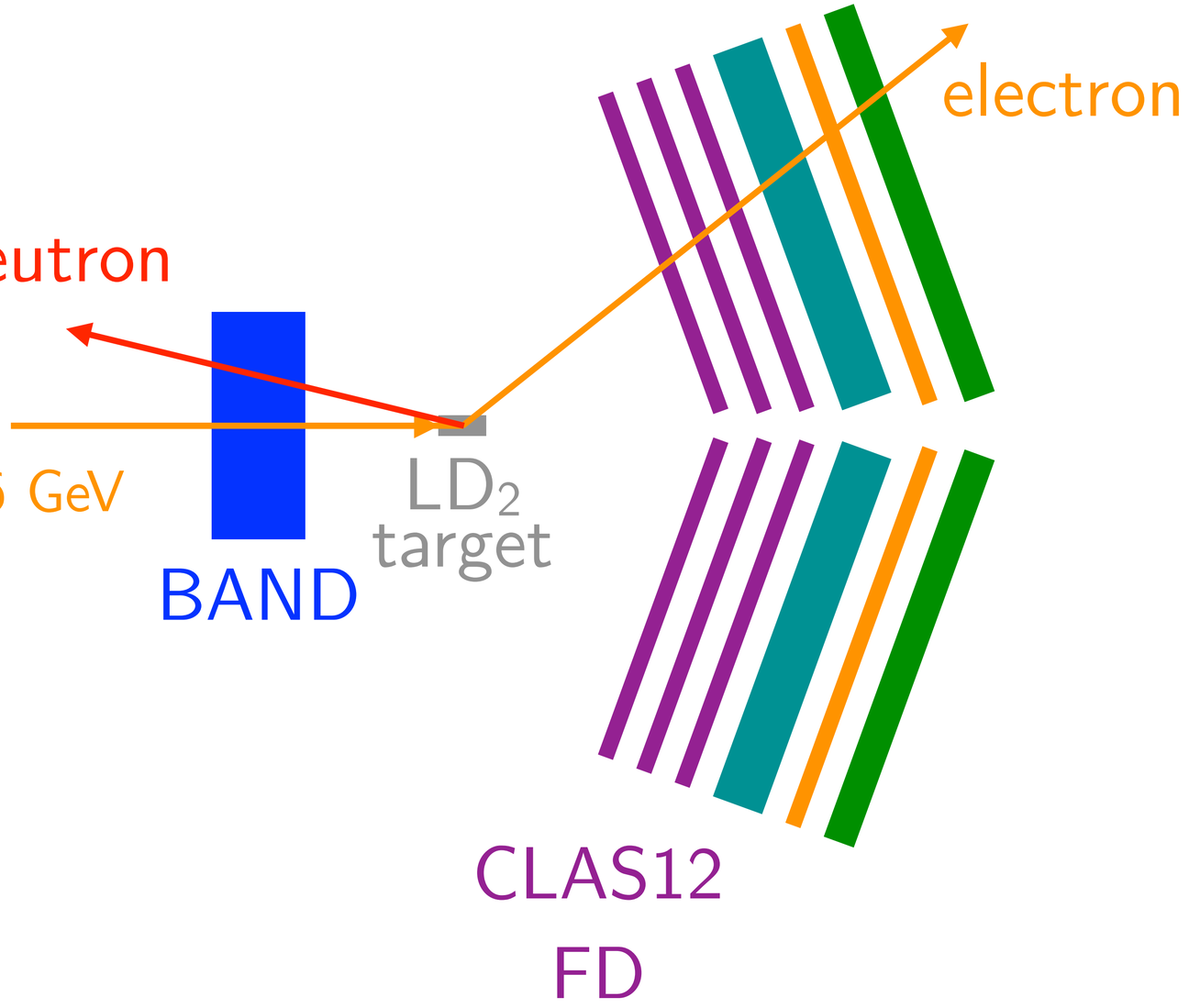
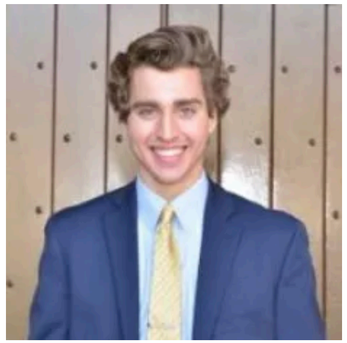




BAND analysis team



Efrain Segarra

Florian Hauenstein

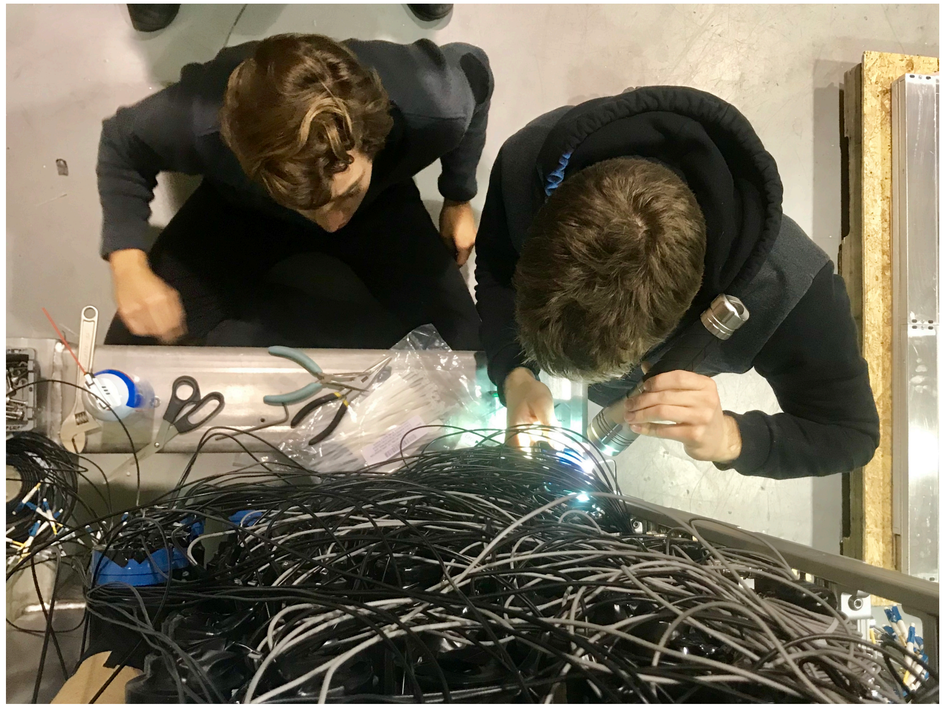
Jackson Pybus

Andrew Denniston

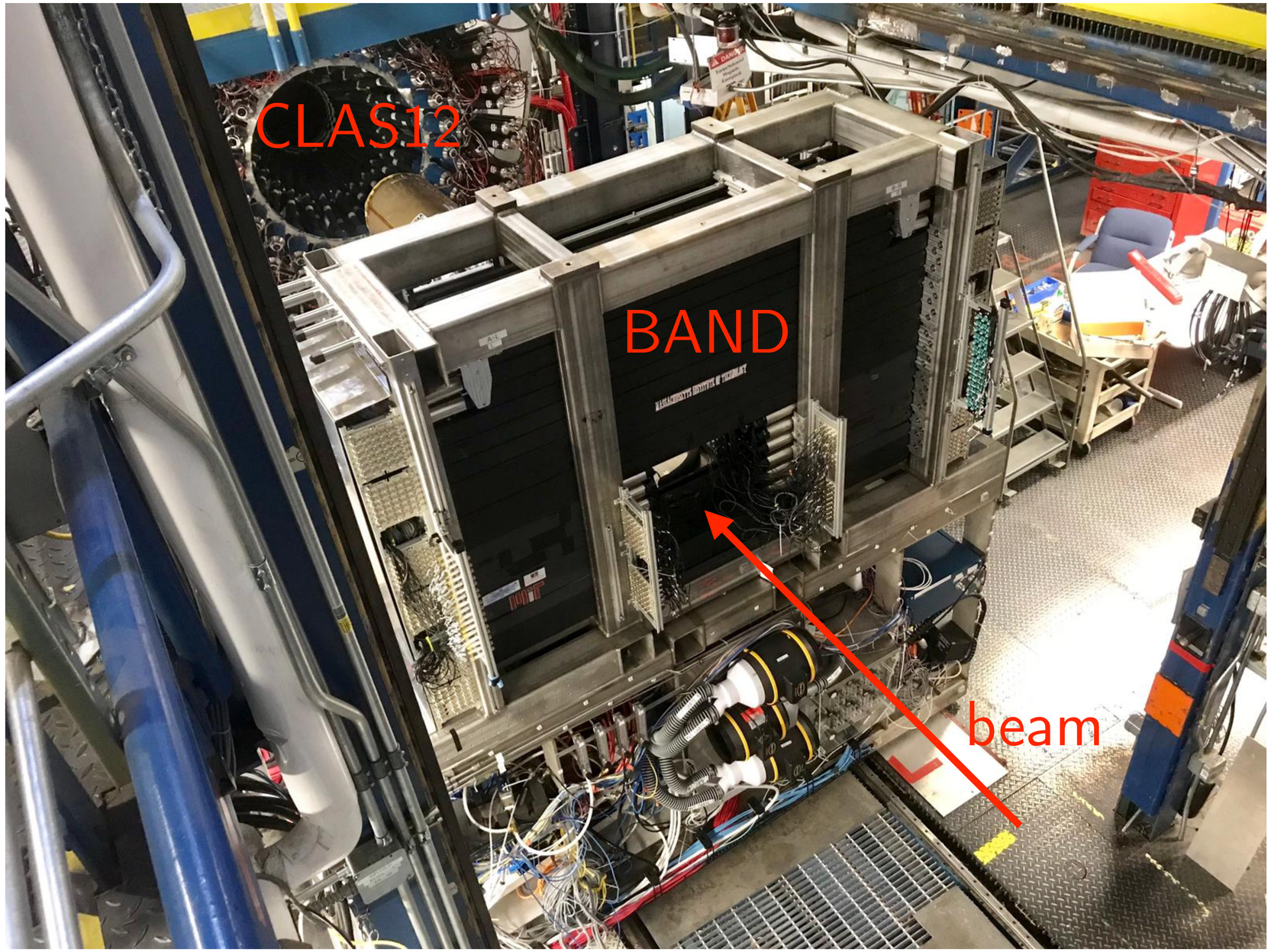
Justin Estee

Dien Nguyen

BAND construction



BAND in Hall B



PWIA theory calculation for tagged DIS

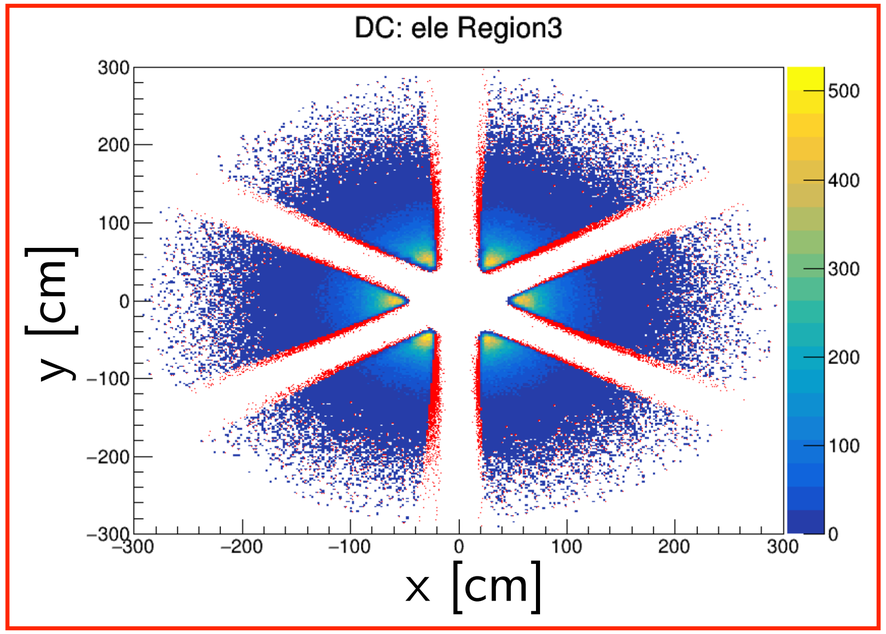
- Non-asymptotic cross section model by Strikman & Weiss

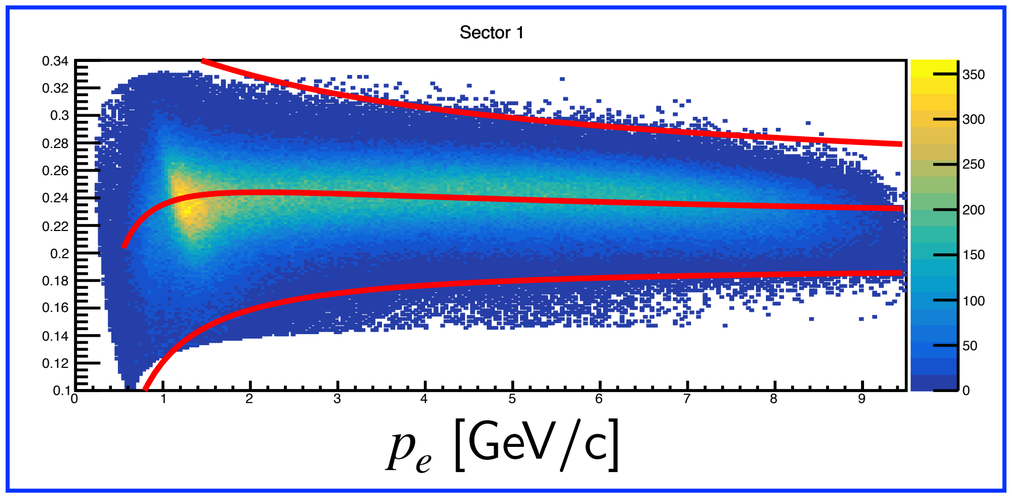
  PRC 97, 035209 (2018):

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

- 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

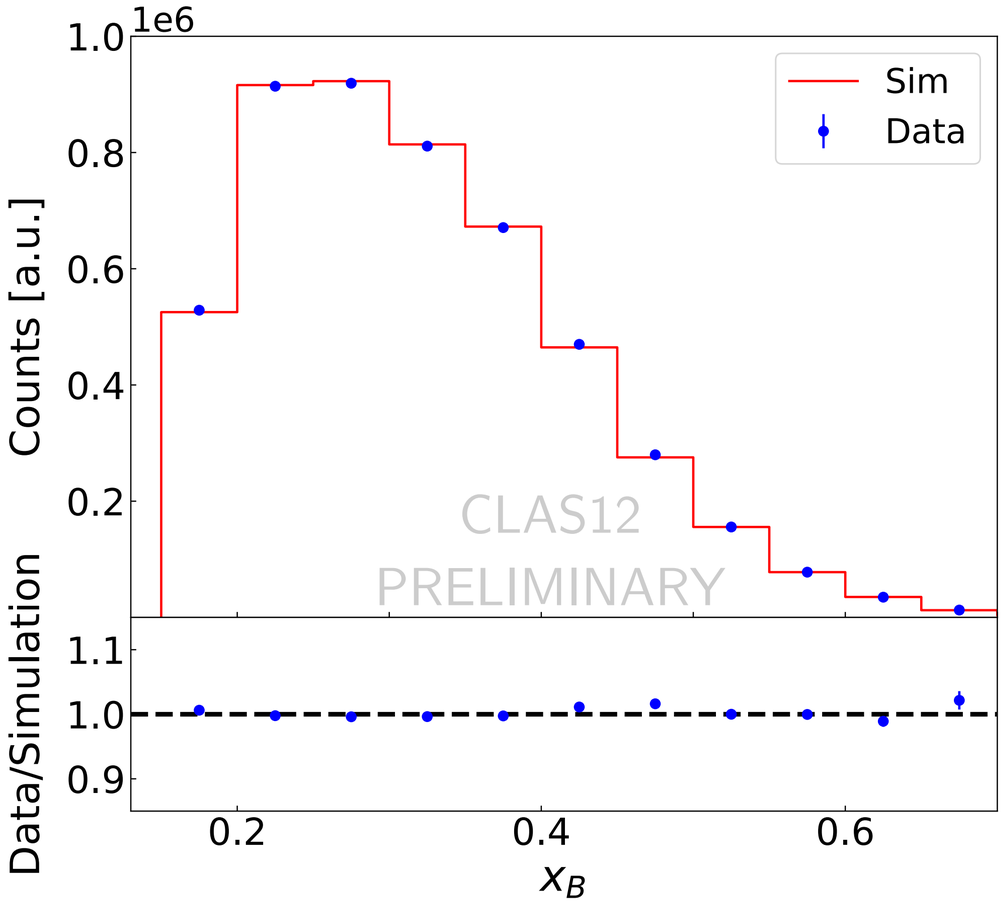
CLAS12 electron selection

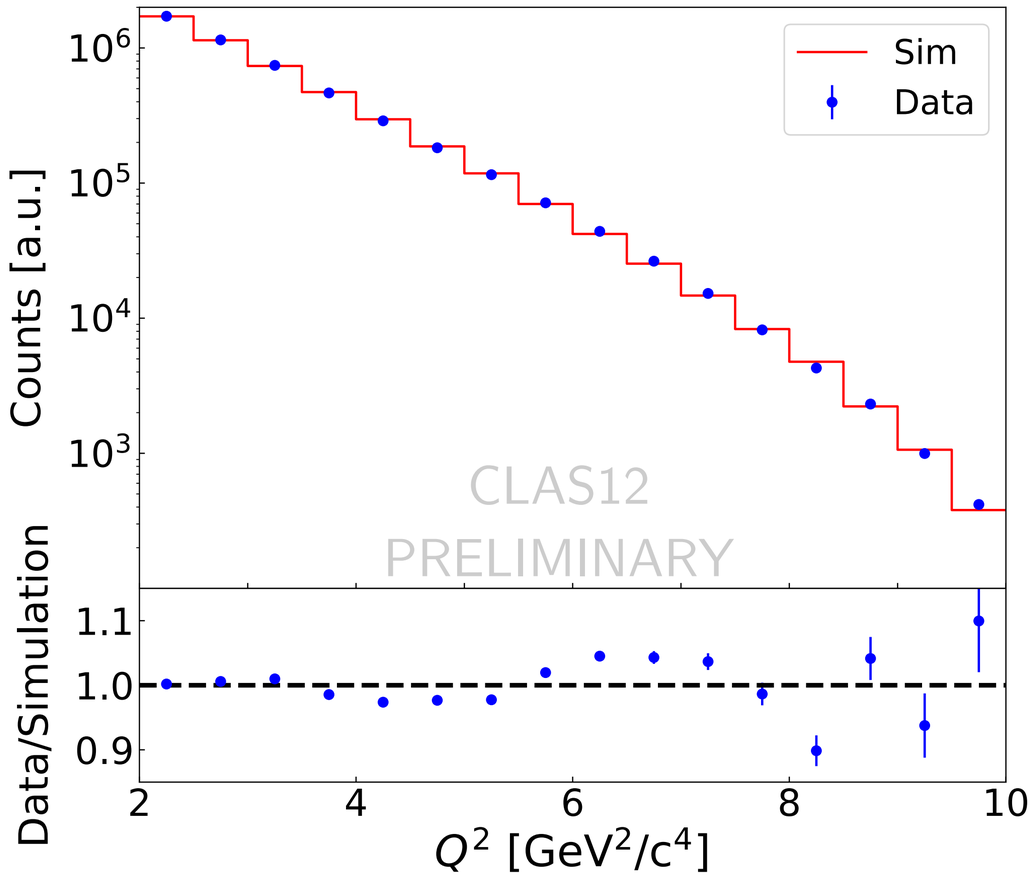




- DC fiducial cuts
- ECAL/PCAL fiducial cuts
- Sampling fraction vs. E_{PCAL} ($\pm 5\sigma$)
- Sampling fraction vs. p_e ($\pm 5\sigma$)
- $0.17 < E/p_e < 0.3$ GeV
  ($0.2 < E/p_e$ for $p_e > 4.5$ GeV)

Inclusive DIS results



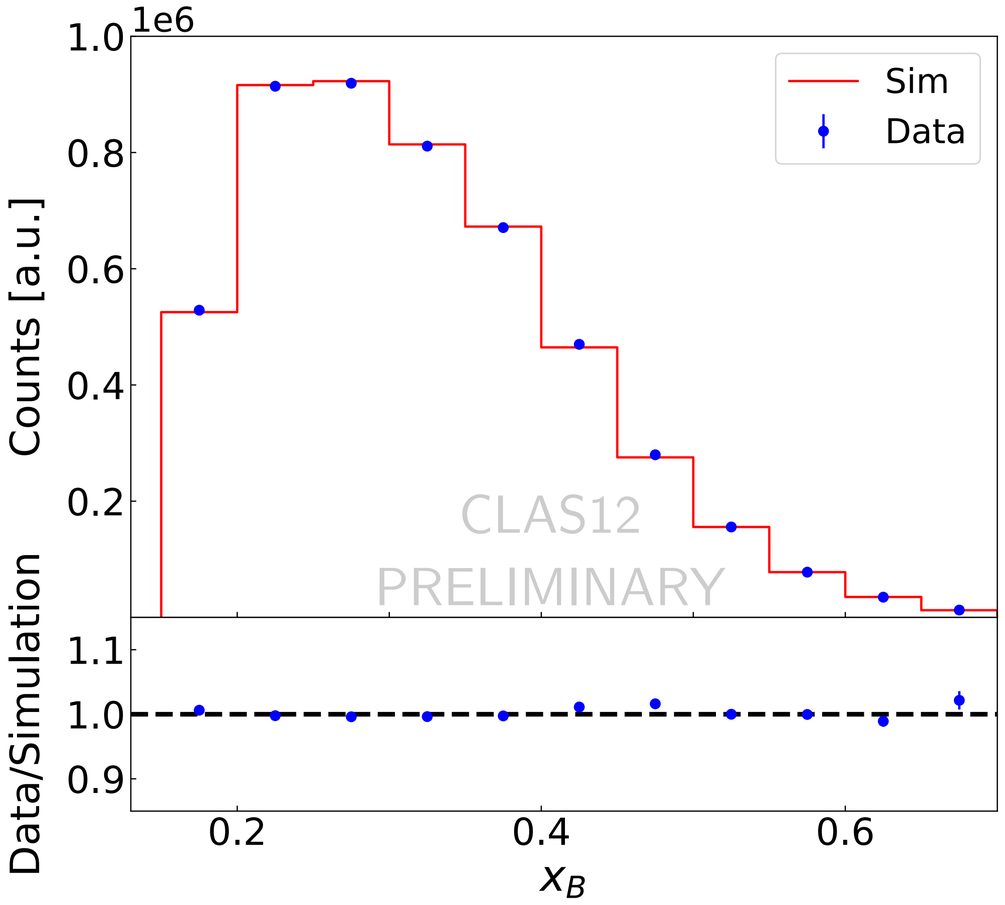


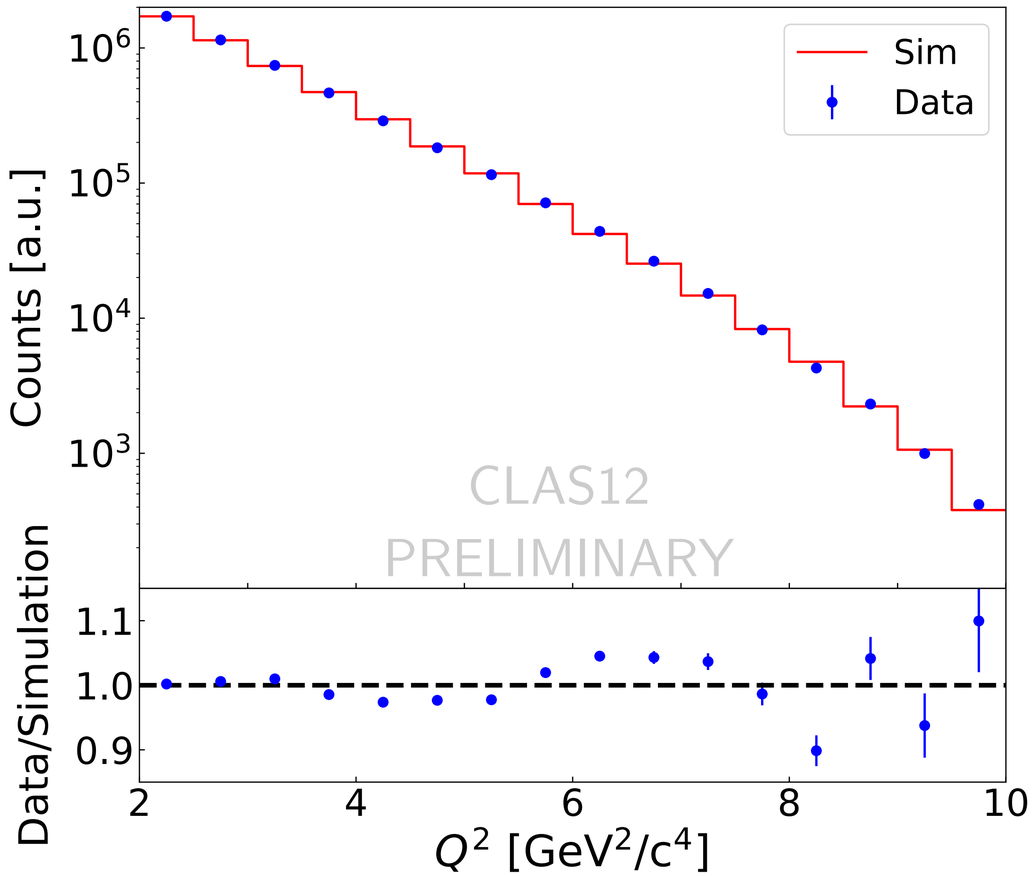
$Q^2 > 2$ GeV^2.

$W^2 > 4$ GeV^2.

$y < 0.7$

Inclusive DIS results





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✓ Validates simulation of electron in CLAS12

Yield ratio method and tagged double ratio

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

Yield ratio method and tagged double ratio

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

$$= \frac{\sigma_{exp}(x')/\sigma_{exp}(x' = x'_0)}{\sigma_{theory}(x')/\sigma_{theory}(x' = x'_0)}$$

- Form double ratio for bins in α_S

Yield ratio method and tagged double ratio

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$$= \frac{\sigma_{exp}(x')/\sigma_{exp}(x' = x'_0)}{\sigma_{theory}(x')/\sigma_{theory}(x' = x'_0)}$$

- Form double ratio for bins in α_S
- Ratio gives cancellation of systematics

Yield ratio method and tagged double ratio

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$$= \frac{\sigma_{exp}(x')/\sigma_{exp}(x' = x'_0)}{\sigma_{theory}(x')/\sigma_{theory}(x' = x'_0)}$$

- Form double ratio for bins in α_S
- Ratio gives cancellation of systematics
- Choose to normalize to $x'_0 = 0.3$

Yield ratio method and tagged double ratio

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

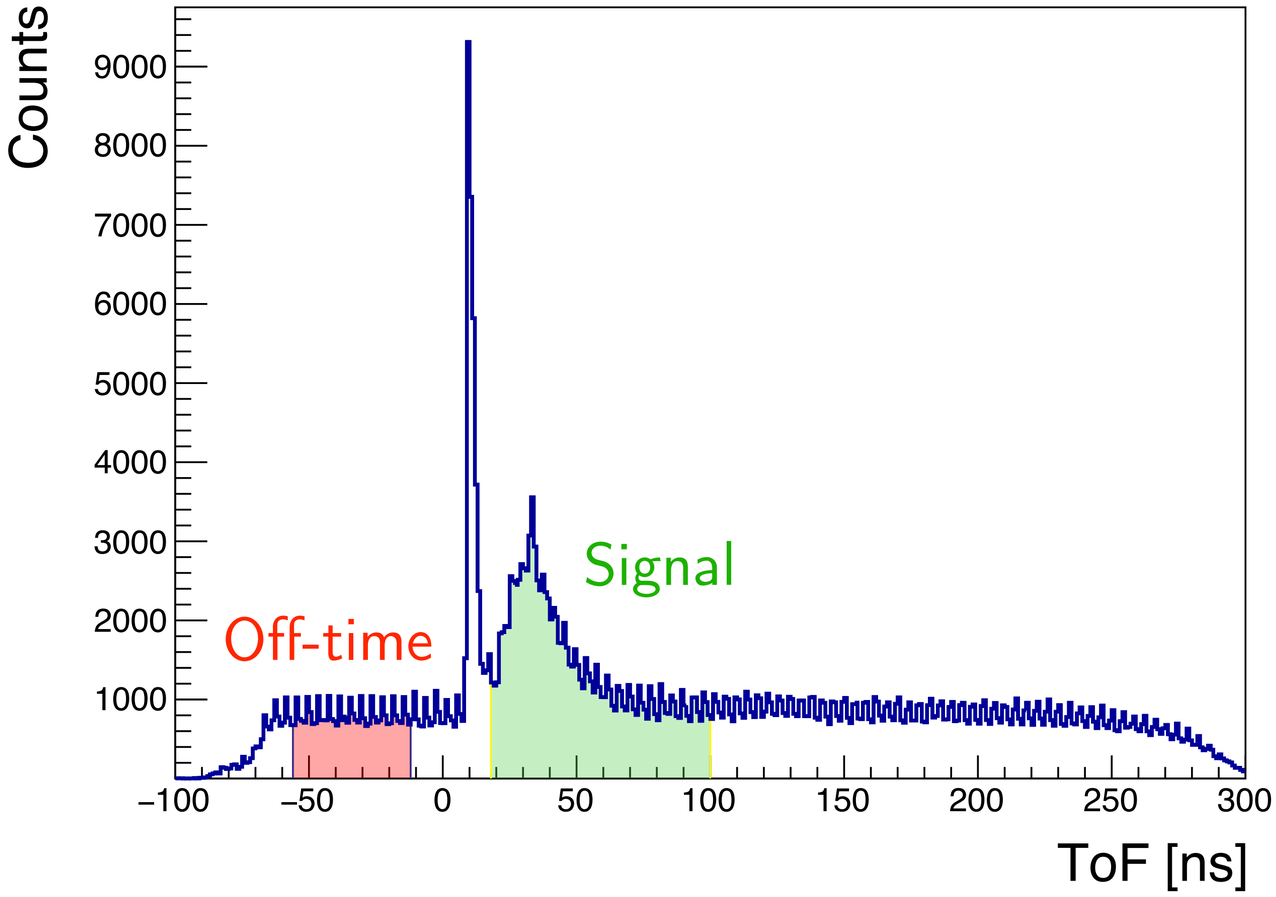
$$\mathcal{R} = \frac{Y_{exp}(x')/Y_{exp}(x' = x'_0)}{Y_{sim}(x')/Y_{sim}(x' = x'_0)}$$

$$= \frac{\sigma_{exp}(x')/\sigma_{exp}(x' = x'_0)}{\sigma_{theory}(x')/\sigma_{theory}(x' = x'_0)}$$

- Form double ratio for bins in α_S
- 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

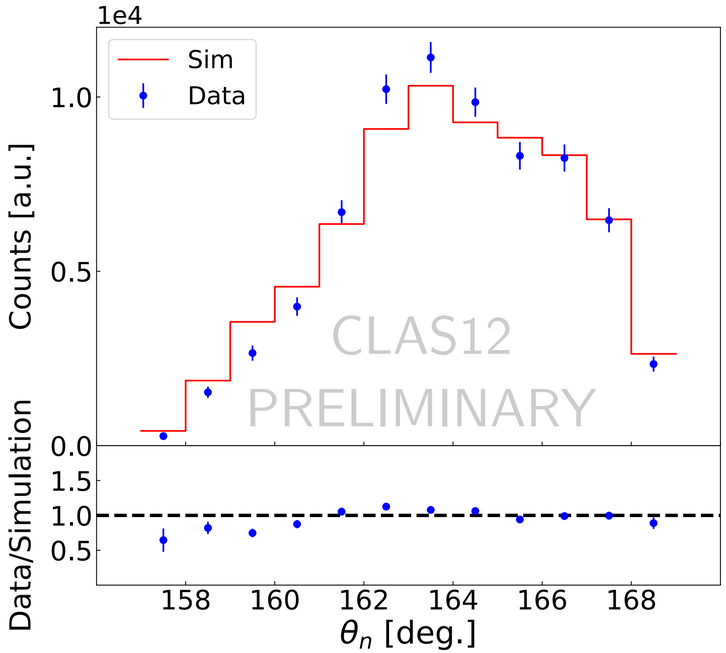
$p_n > 0.25$ GeV

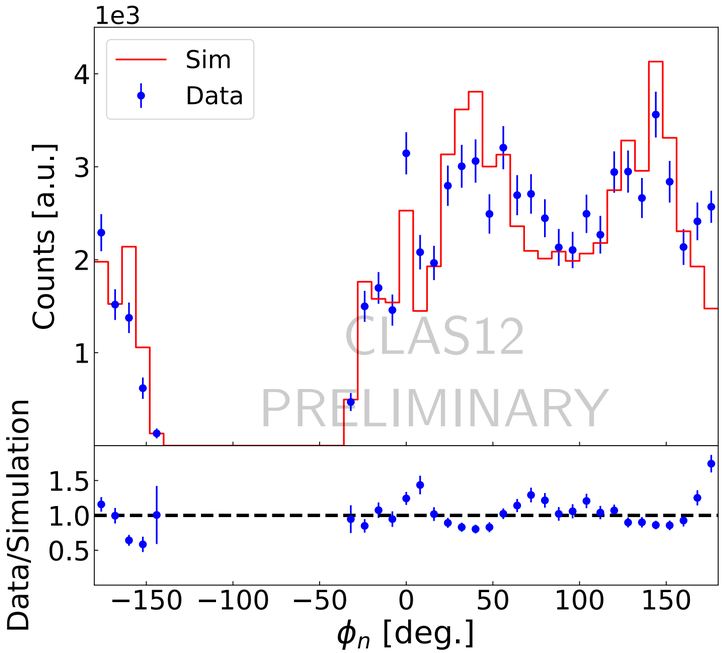
$\theta_n < 168.5°$

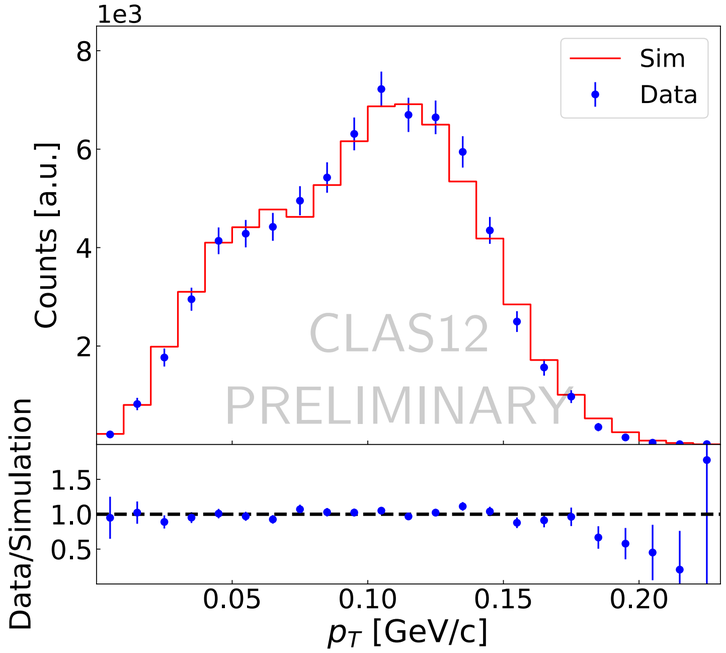
$W' > 1.8$ GeV

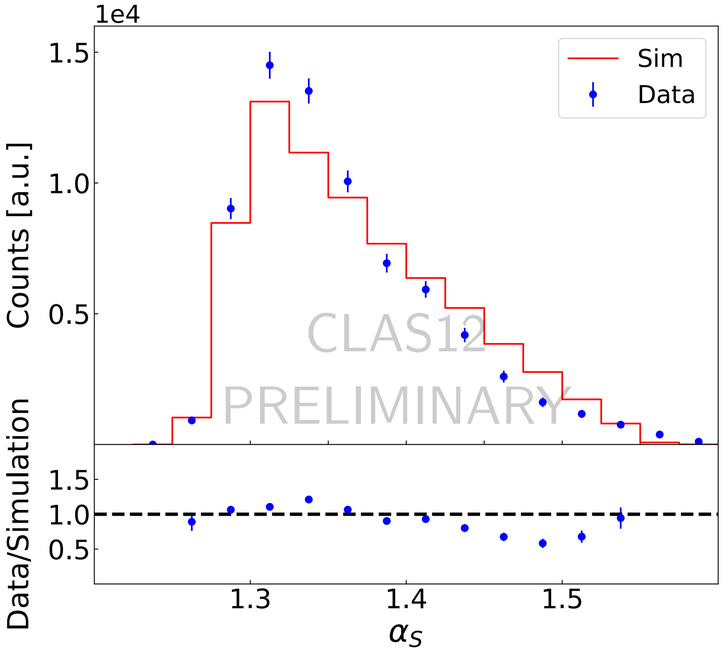
$\alpha_s > 1.2$

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

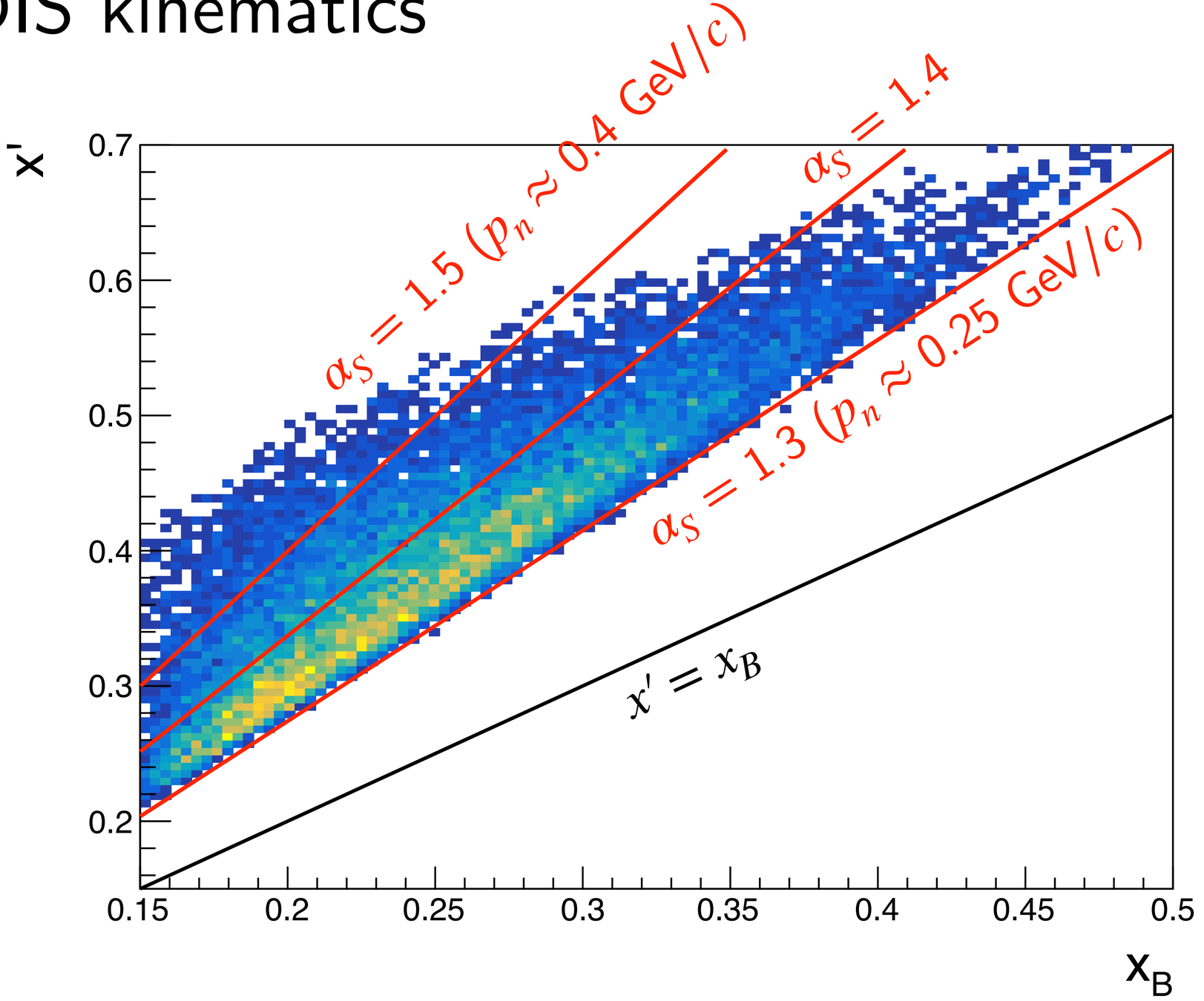




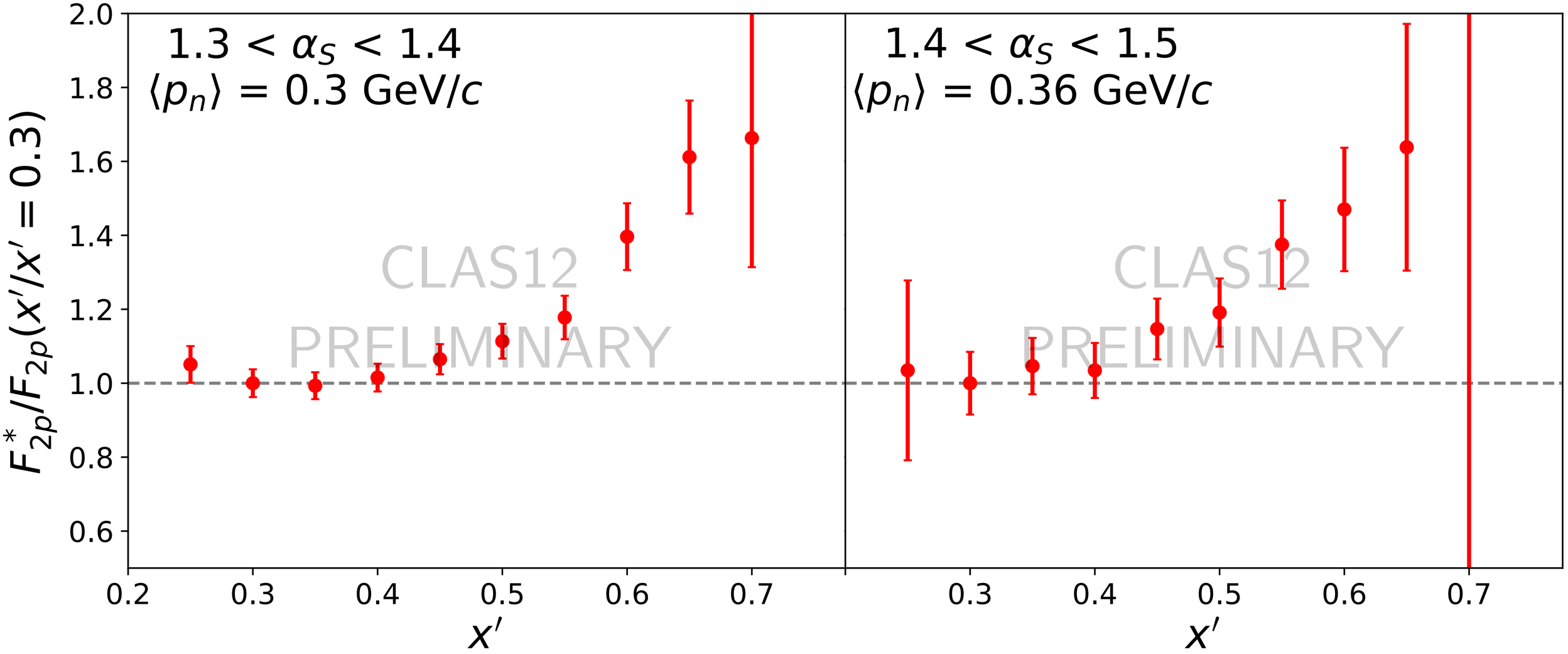




Tagged DIS kinematics

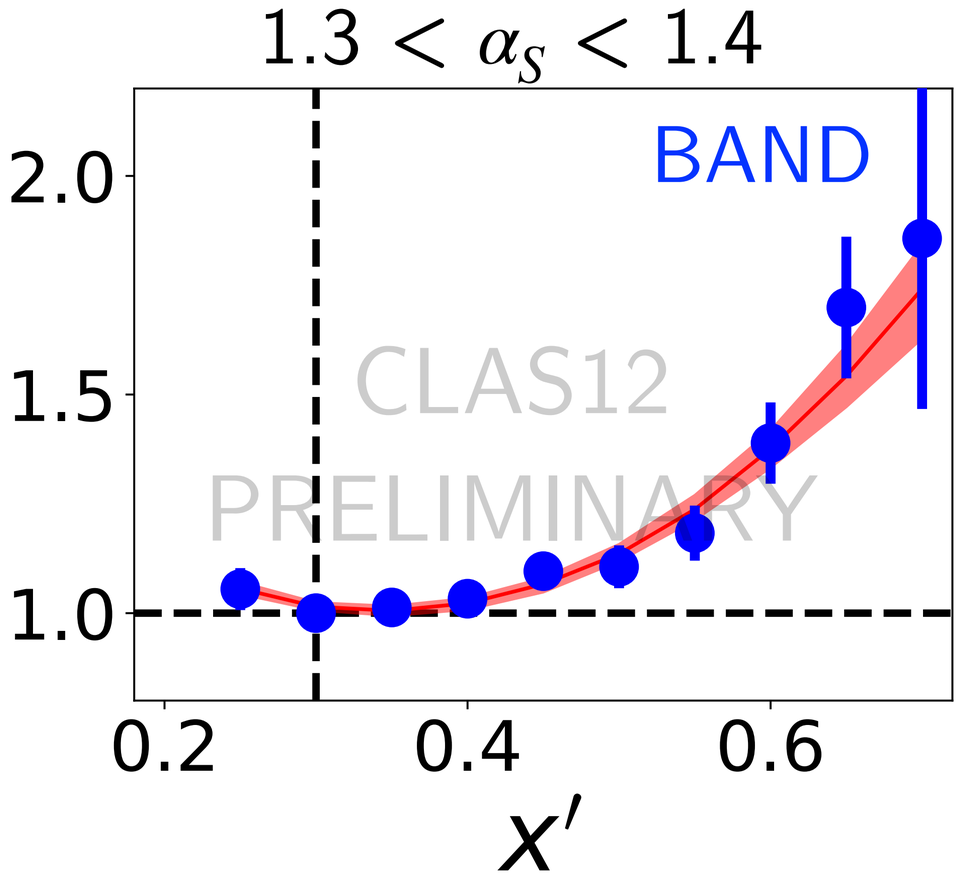


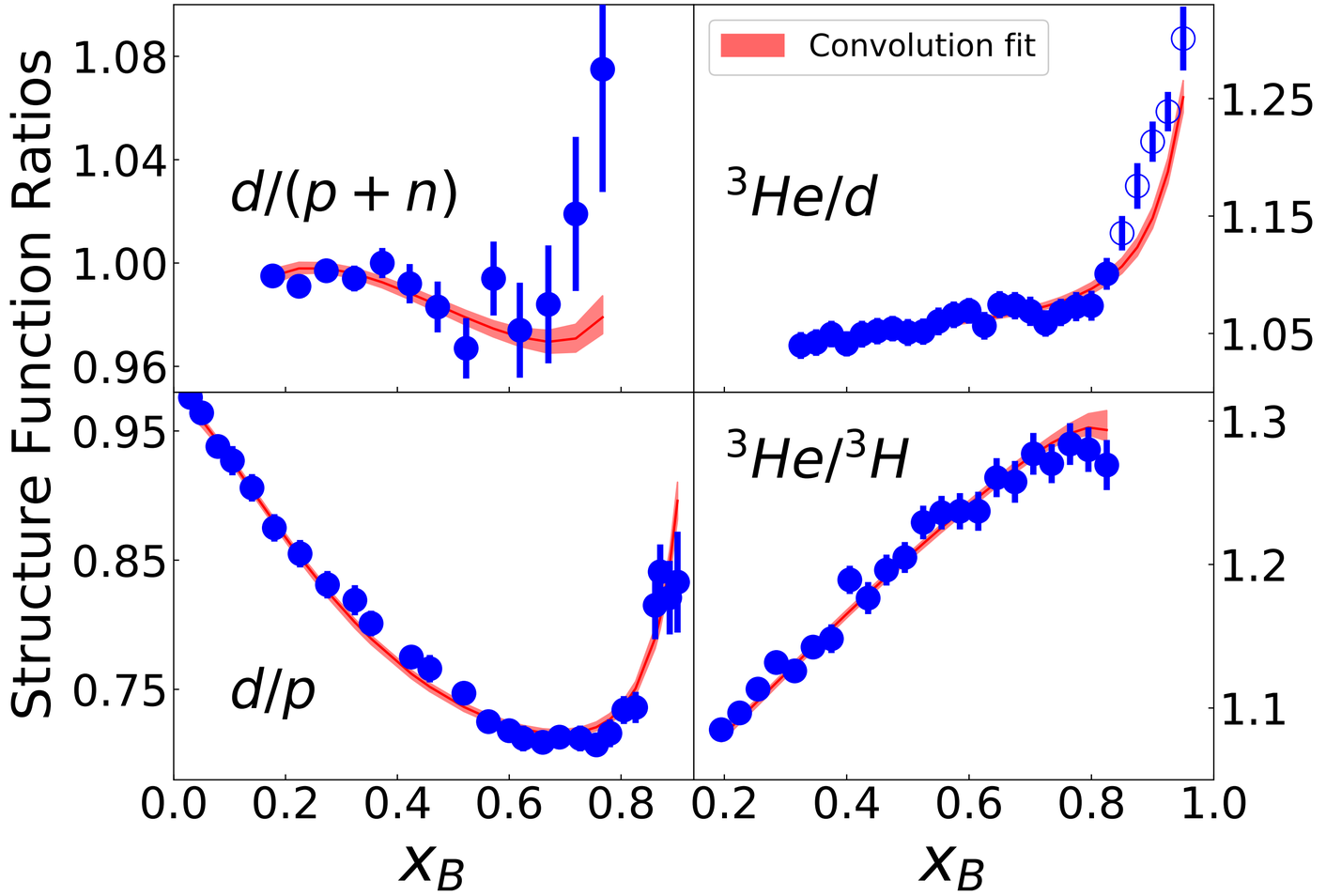
Tagged DIS double ratio



Large, x'-dependent effect in high-α_S protons

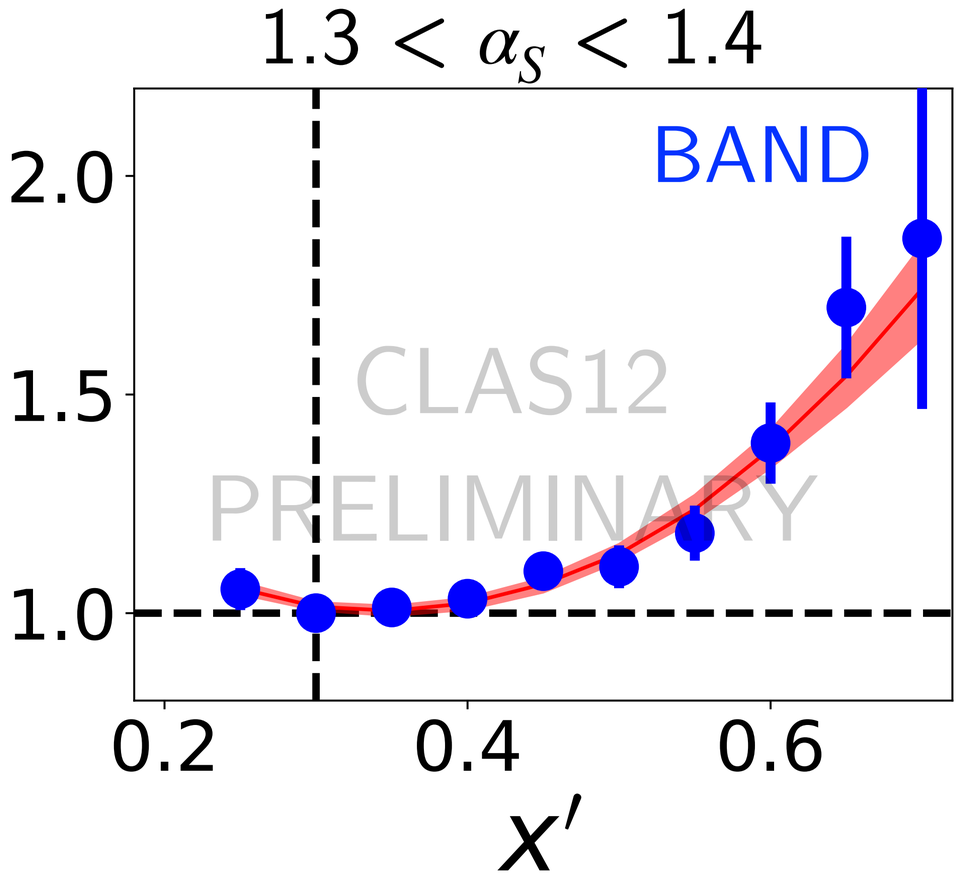
Result consistent with inclusive measurements of light nuclei...

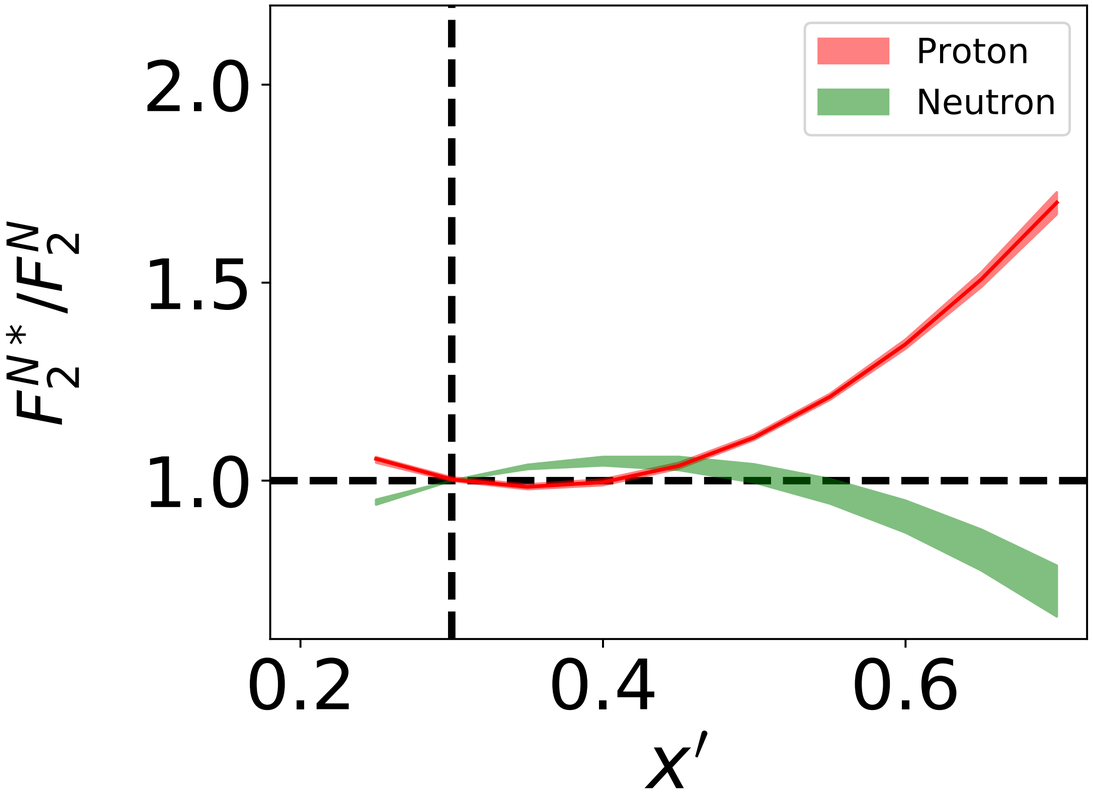




$$F_2^A(x_B) = \frac{1}{A}\int_{x_B}^{A}\frac{d\alpha}{\alpha}\int_{-\infty}^{0} dv\; F_2^p(x')\left[Z\rho_p(\alpha,v) + N\rho_n(\alpha,v)\frac{F_2^n(x')}{F_2^p(x')}\right] \times \left(1 + v\, f^{os}(x')\right)$$

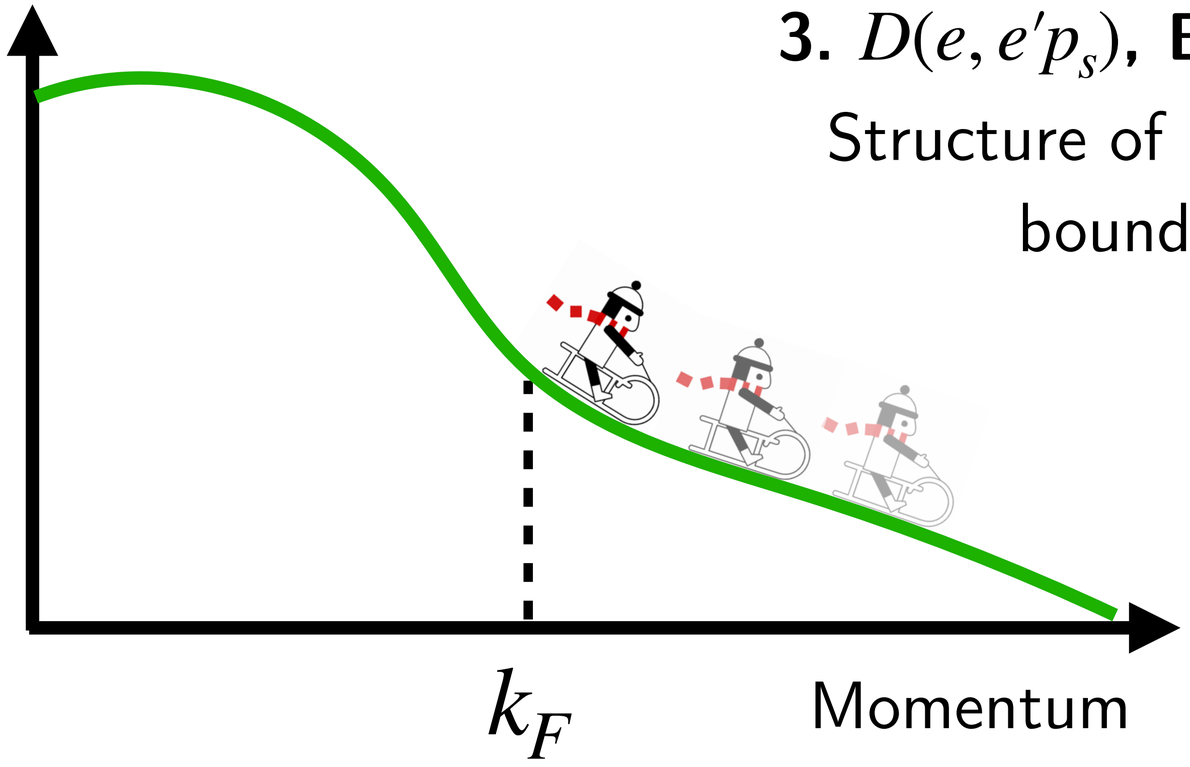
...and gives a prediction for bound *neutron* structure!



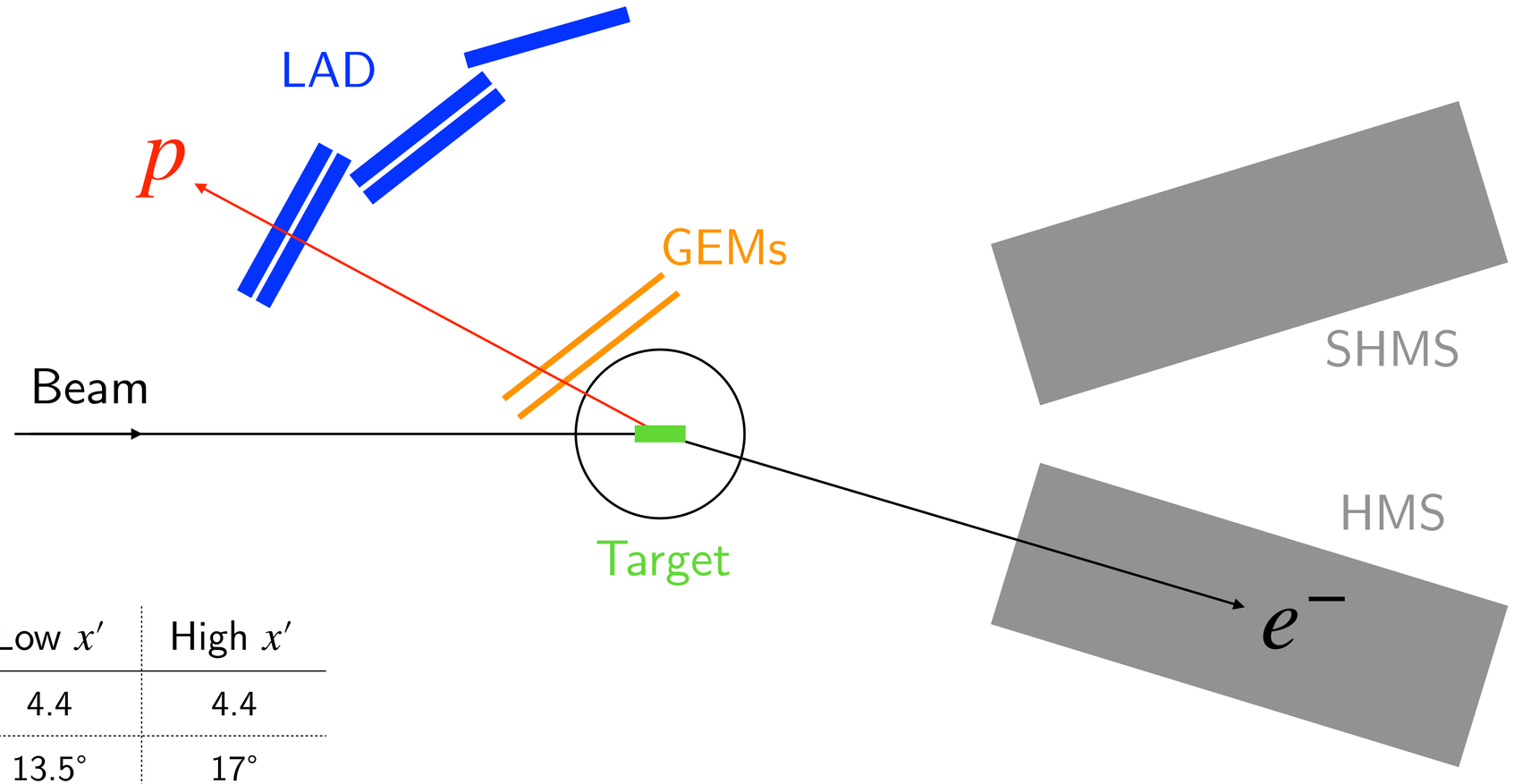


3. $D(e, e'p_s)$, BAND, and LAD

Structure of high-momentum bound nucleons



Large Angle Detector (LAD) in Hall C

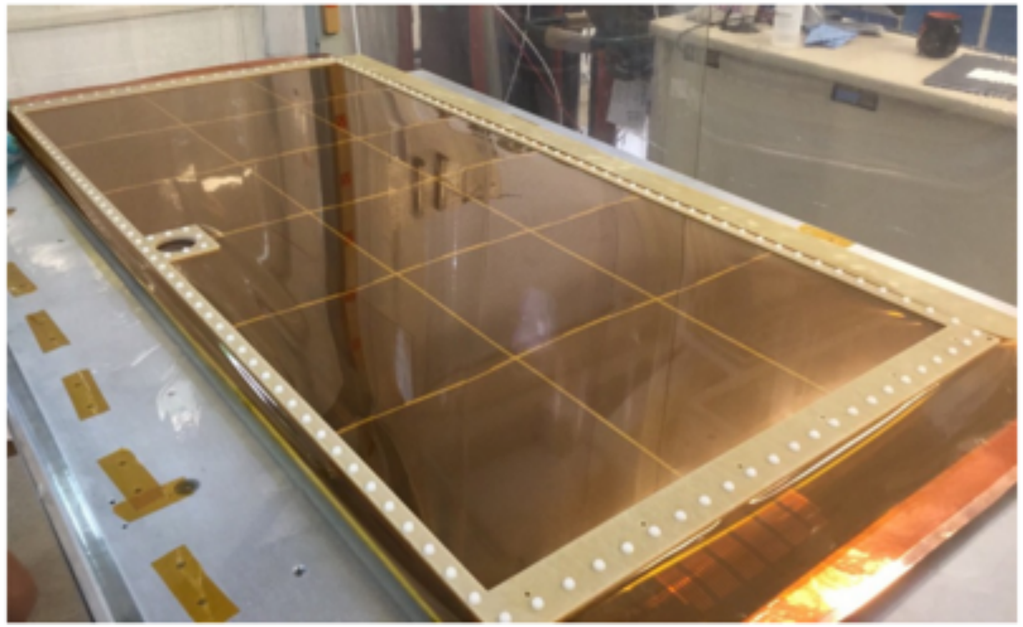


	Low x'	High x'
E' (GeV)	4.4	4.4
θ_e	13.5°	17°
Q^2 (GeV^2)	2.7	4.2
x_B	0.22	0.34

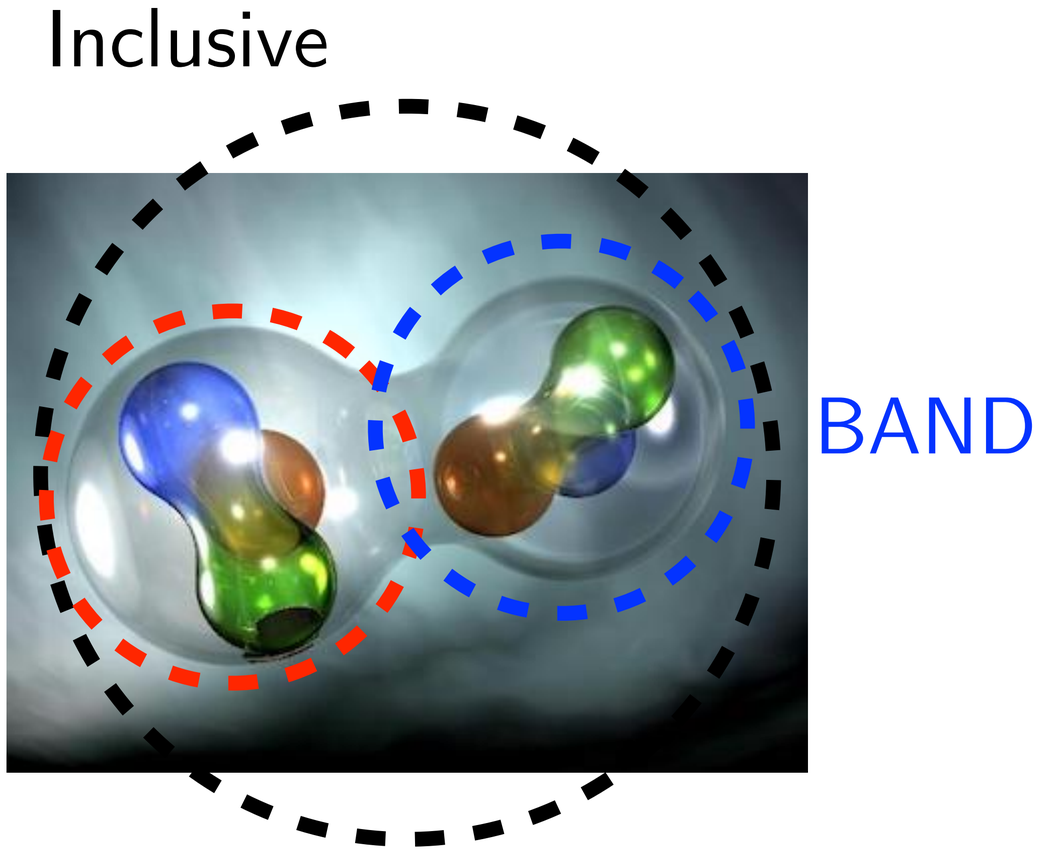
- 1 μA at 10.9 GeV
- Scattered electron to HMS/SHMS
- Recoil proton to LAD

LAD hardware

- Proton detection:
  - 5 panels of refurbished CLAS TOF scintillators
  - Proton ID using dE/dX vs. TOF
  - Proton momentum from TOF
- Proton vertexing:
  - Repurposed PRad GEMs
  - Active area 120 x 55 cm^2



LAD is critical cross check of tagged measurements



- Inclusive + BAND + LAD overconstrains deuterium
- BAND and LAD must show consistent modification of bound protons/neutrons
- Hope to achieve lower recoil momentum and angles than BAND
- Expected to run summer 2024

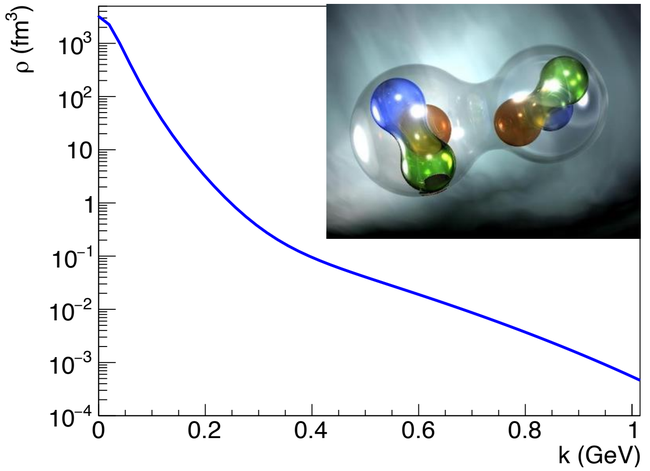
Tagged DIS is just getting started!

- A Low-Energy Recoil Tracker (ALERT) with CLAS12 at JLab Hall B:
  - ^{3}H/^{3}He tagged DIS from ^{4}He
- TDIS-n at JLab Hall C:
  - BoNuS-style measurement of low-momentum neutrons in deuterium
- Tagging at EIC (beyond neutron spin structure)

Summary

Summary

- Tagged DIS allows measurements of parton structure sensitive to nuclear configuration
  - Study quasi-free nucleons to extract free neutron structure
  - Study highly virtual nucleons to probe origin of EMC effect



Summary

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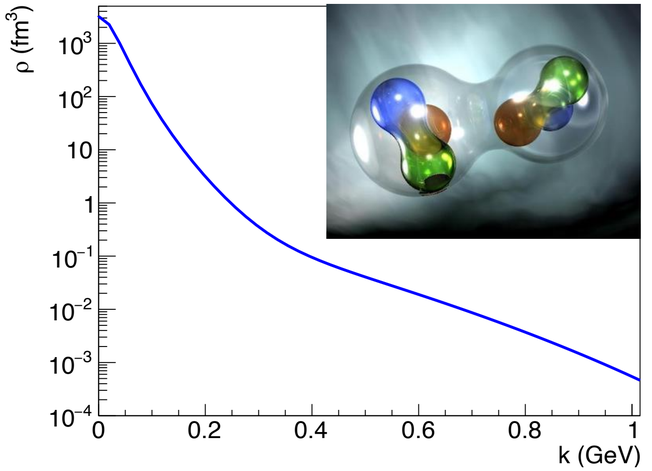
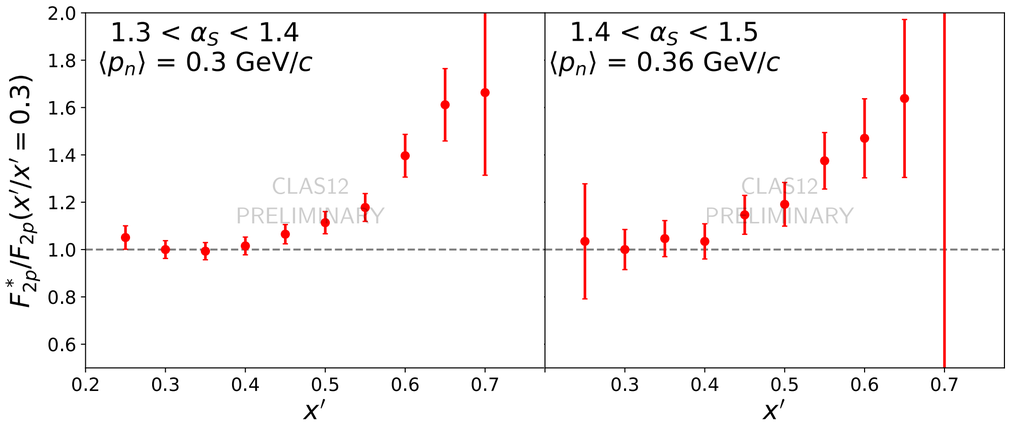
- Preliminary BAND/CLAS12 results show large modification of high-momentum protons in deuterium





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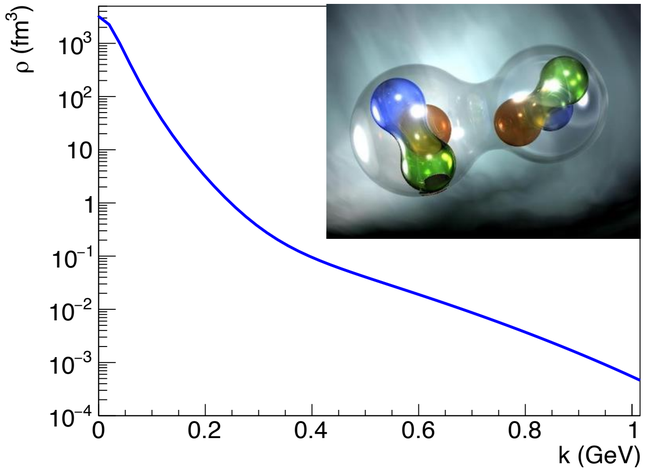
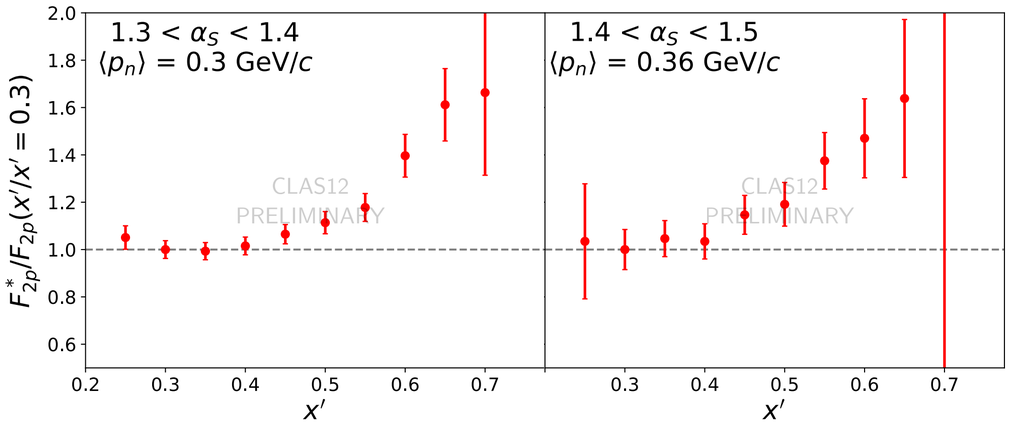
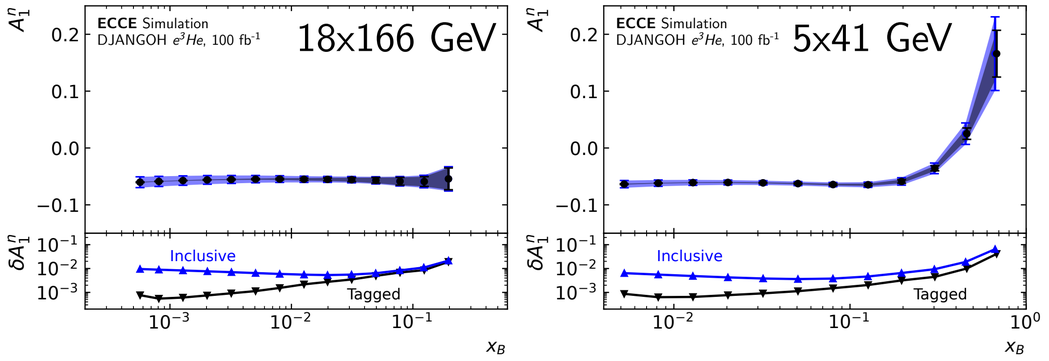
  - Study quasi-free nucleons to extract free neutron structure
  - Study highly virtual nucleons to probe origin of EMC effect
- Preliminary BAND/CLAS12 results show large modification of high-momentum protons in deuterium
- Rich tagged DIS program developing for JLab and EIC







Questions?


THAT CONCLUDES MY TWO-HOUR PRESENTATION. ANY QUESTIONS?
www.dilbert.com scottadams@aol.com
DID YOU INTEND THE PRESENTATION TO BE INCOMPREHENSIBLE, OR DO YOU HAVE SOME SORT OF RARE "POWERPOINT" DISABILITY?
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ARE THERE ANY QUESTIONS ABOUT THE CONTENT?
THERE WAS CONTENT?