# Nucleon structure with tagged DIS

Tyler Kutz
MIT/TAU

ECT* Workshop

*Short-distance nuclear structure and PDFs*

Trento, Italy
July 20, 2023

# Bound nucleons are modified...so what?

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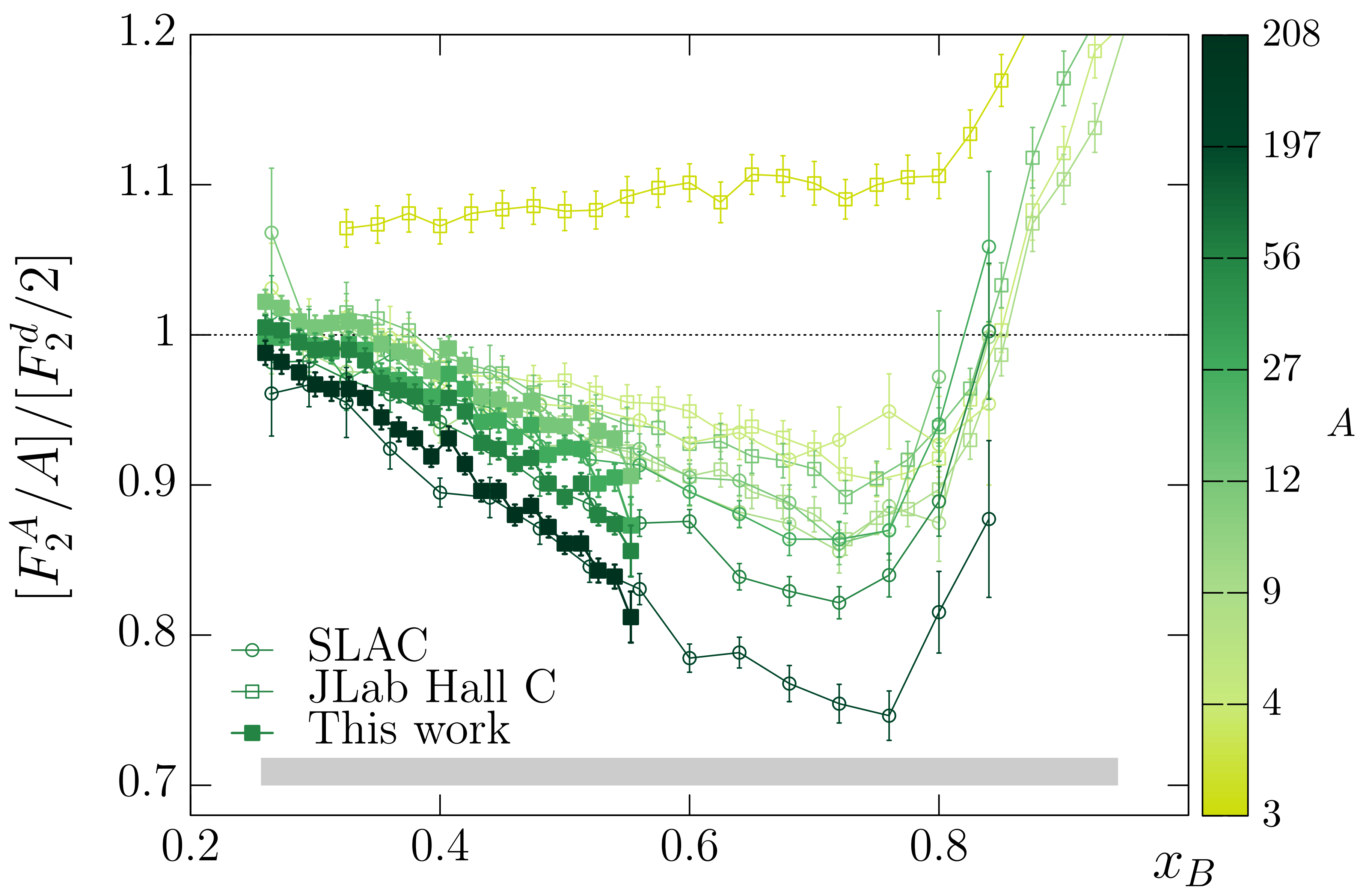
Fundamental:
What nucleons are modified?
What mechanism drives modification?



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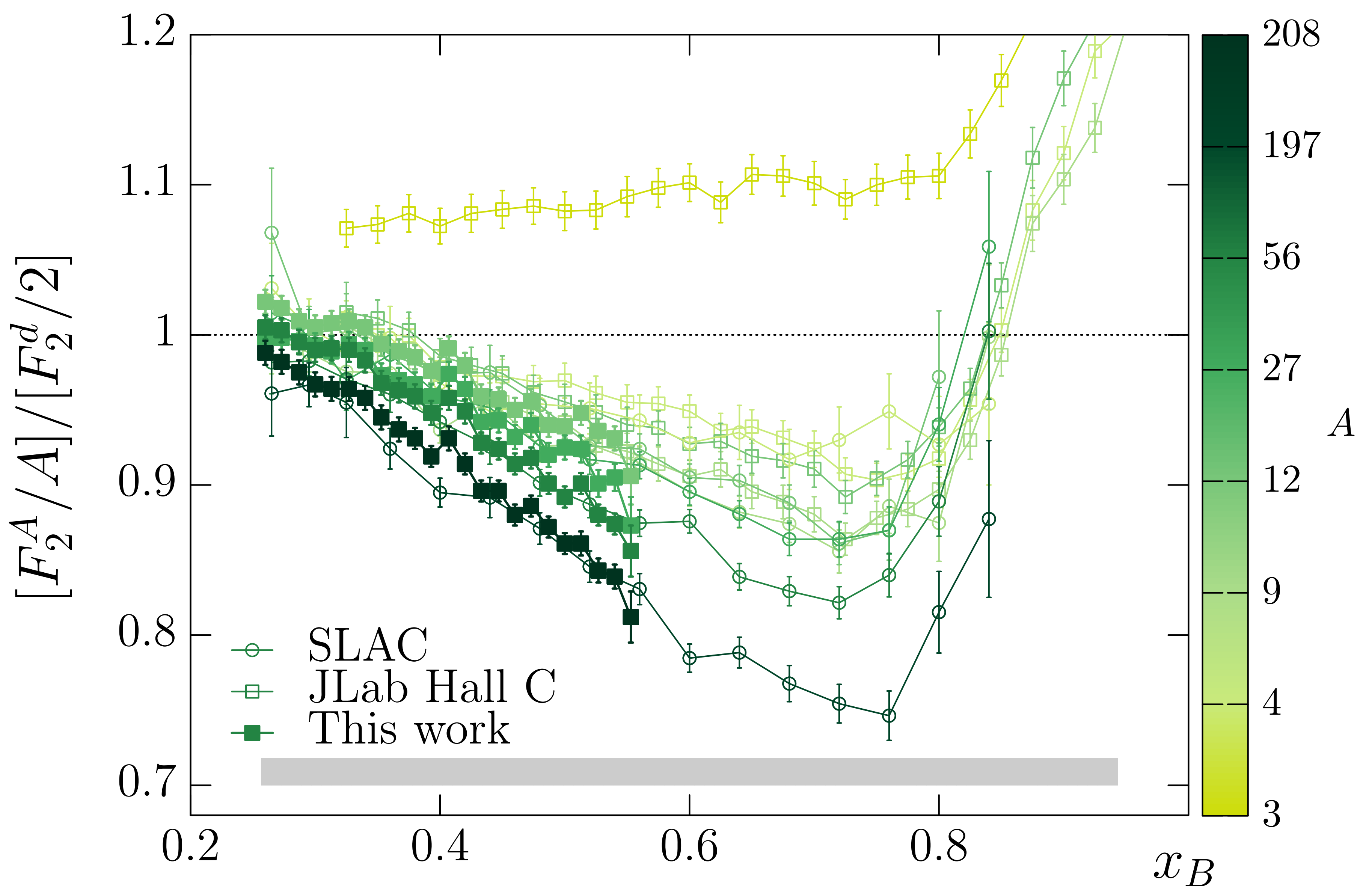
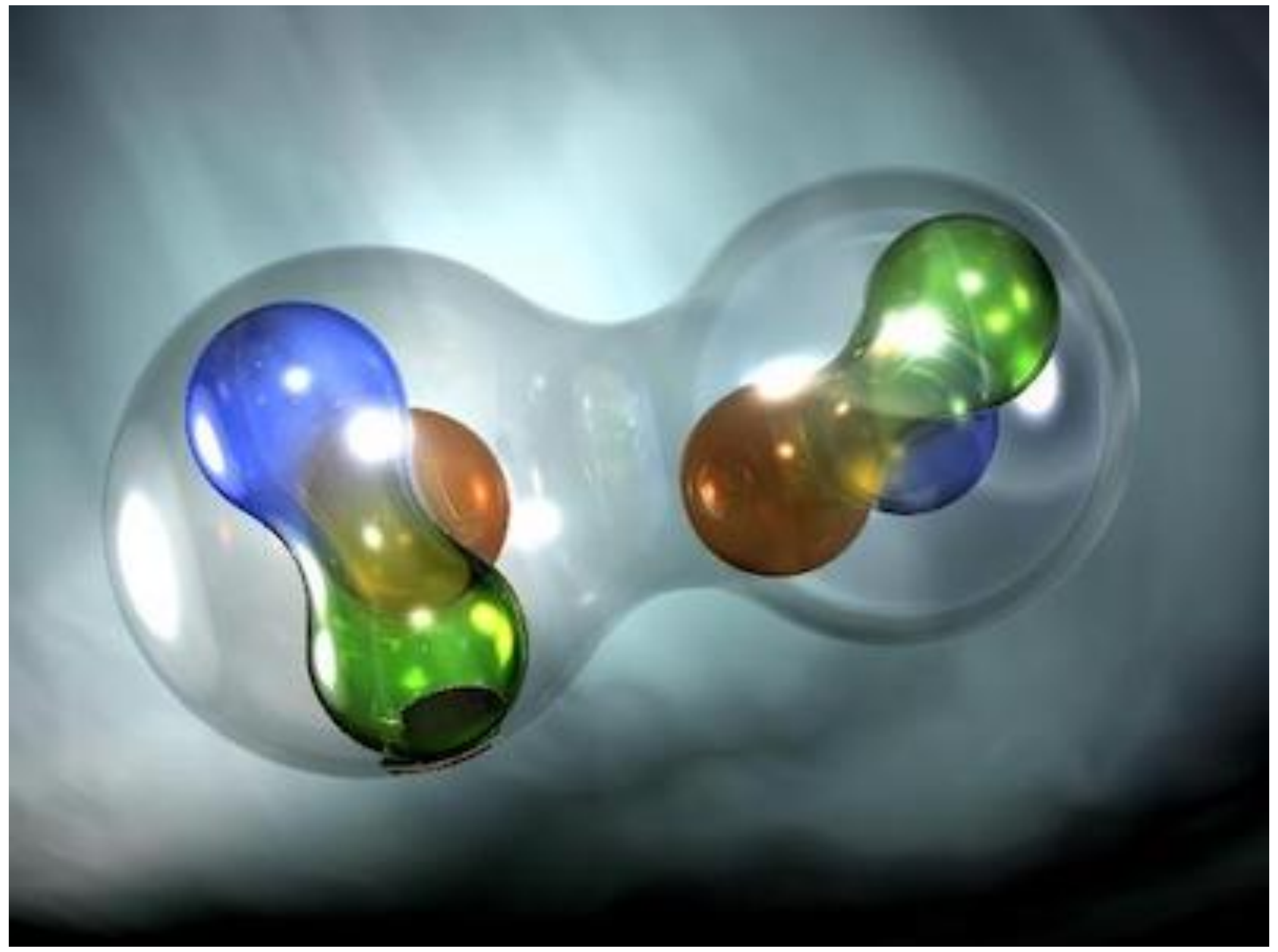
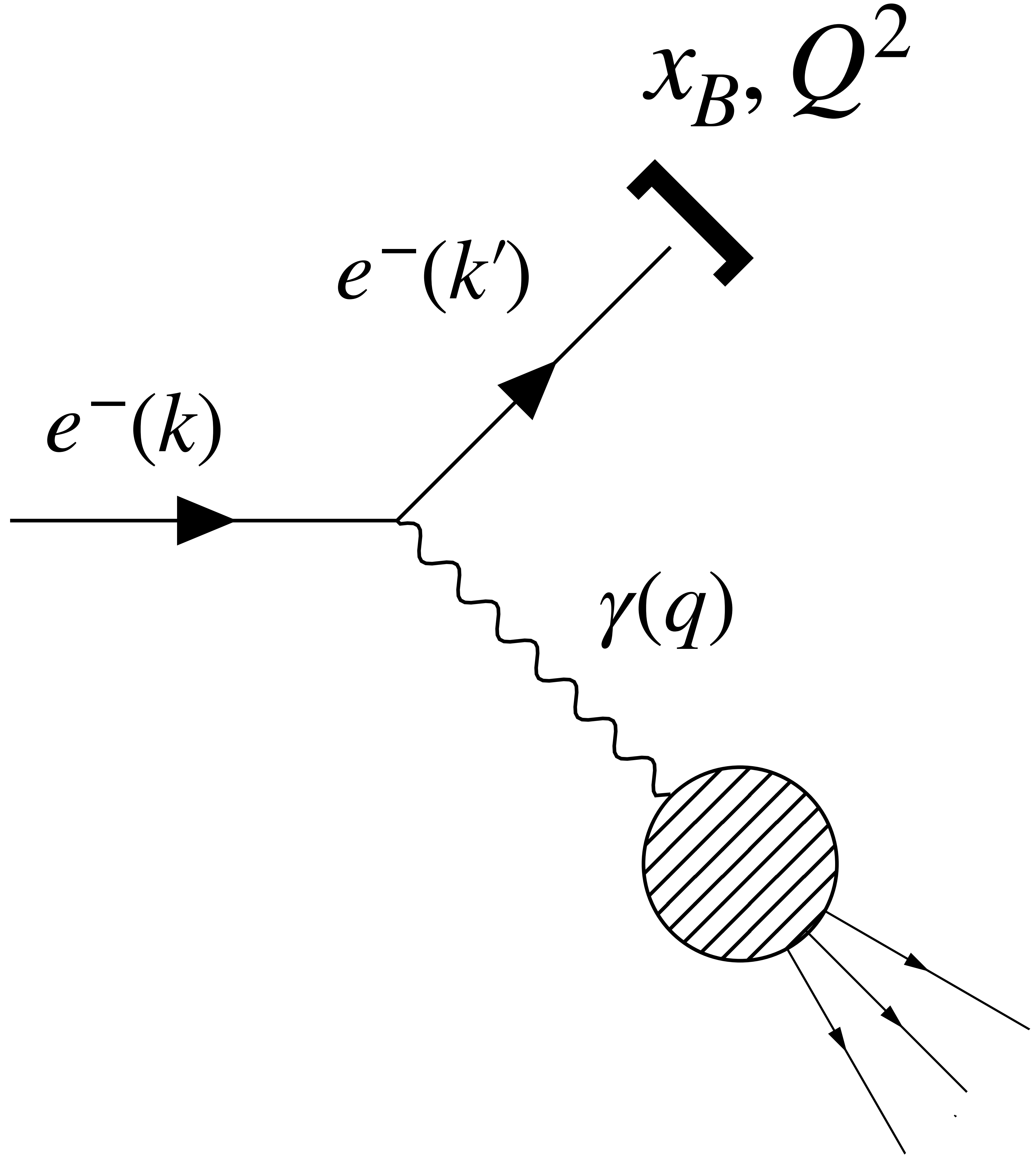



Practical:
What is the structure of the free neutron?



# Inclusive DIS gives average structure of nucleus




- Detect scattered electron

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

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

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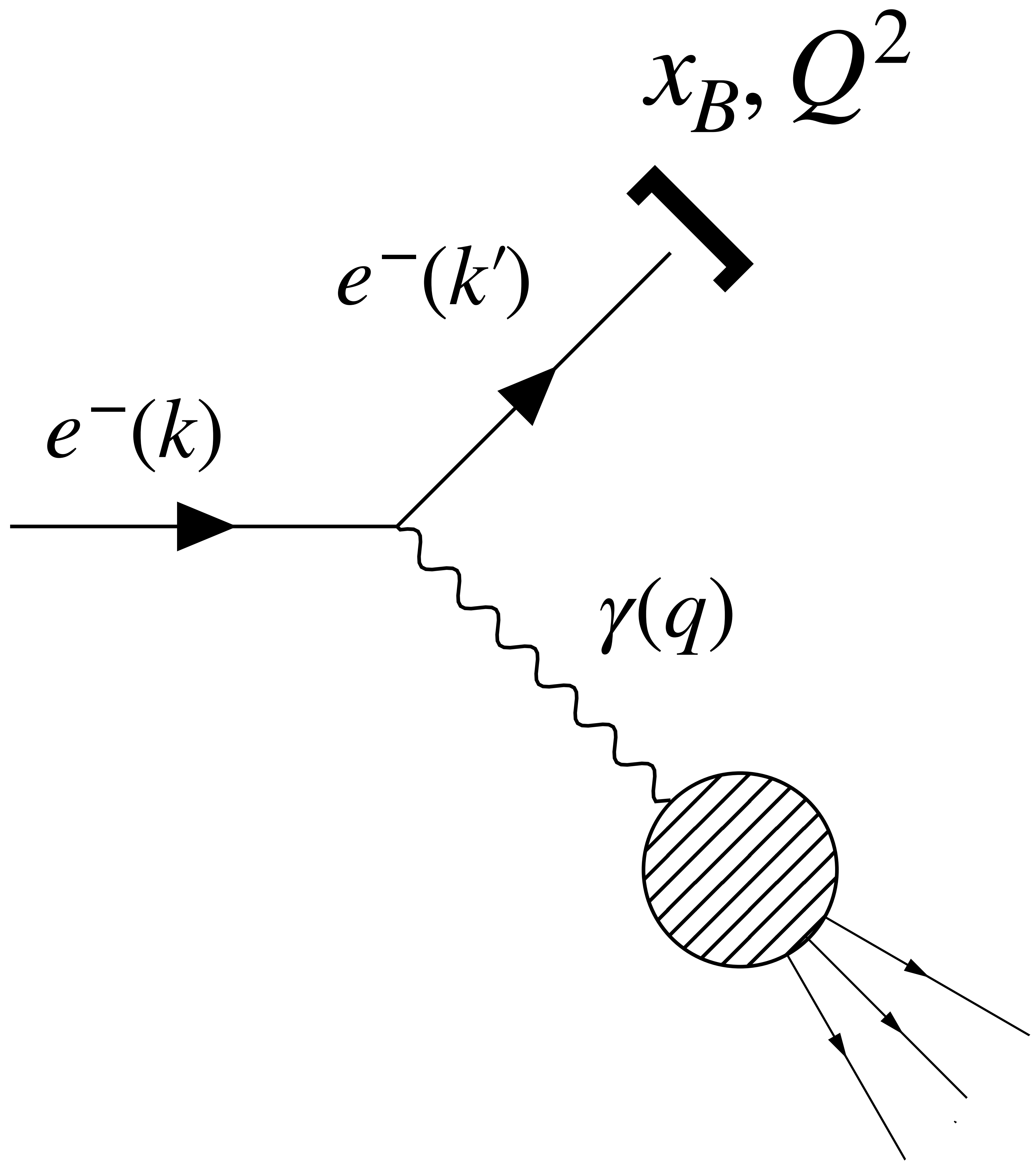


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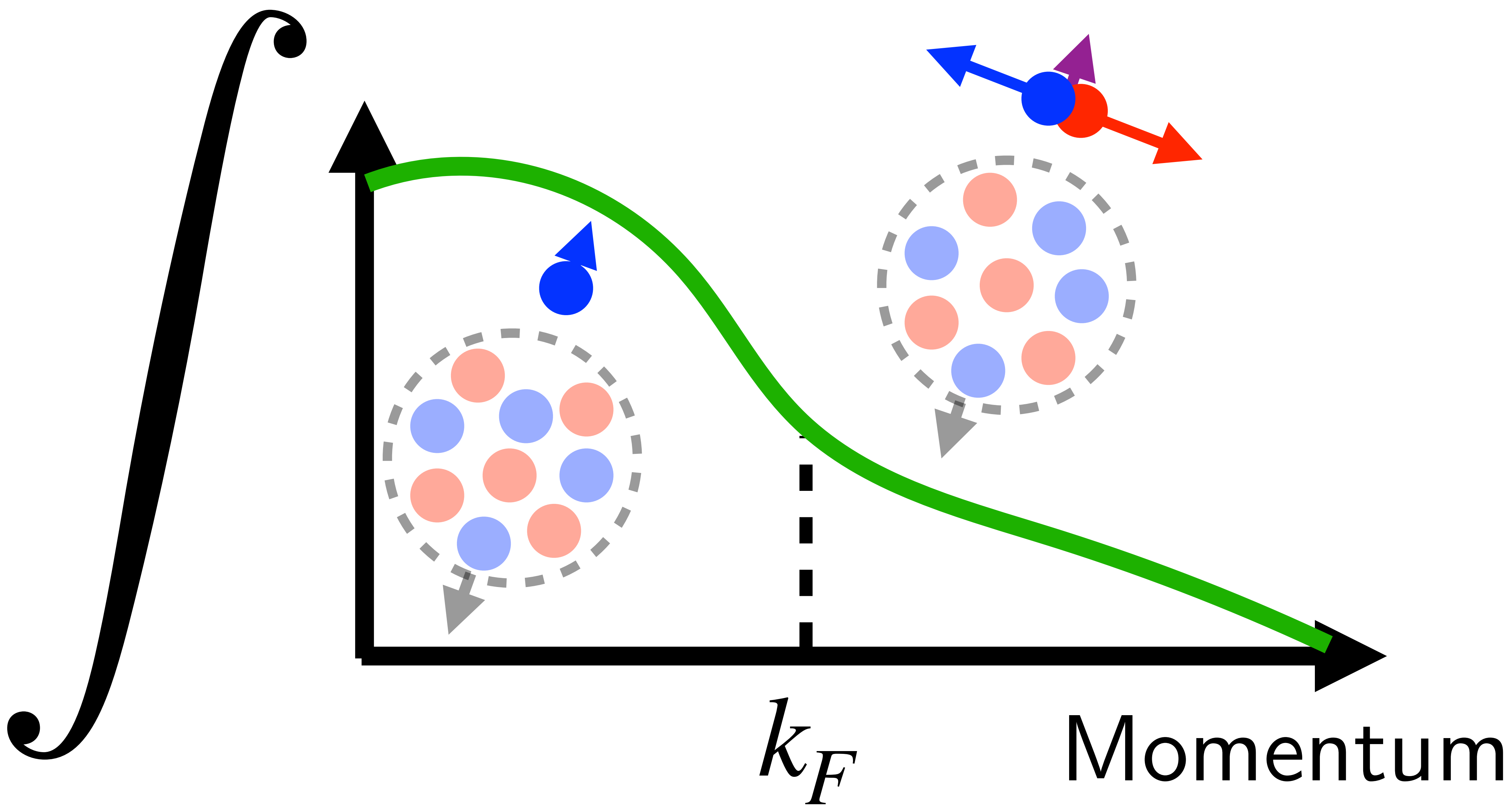
- Integrates over entire nucleus



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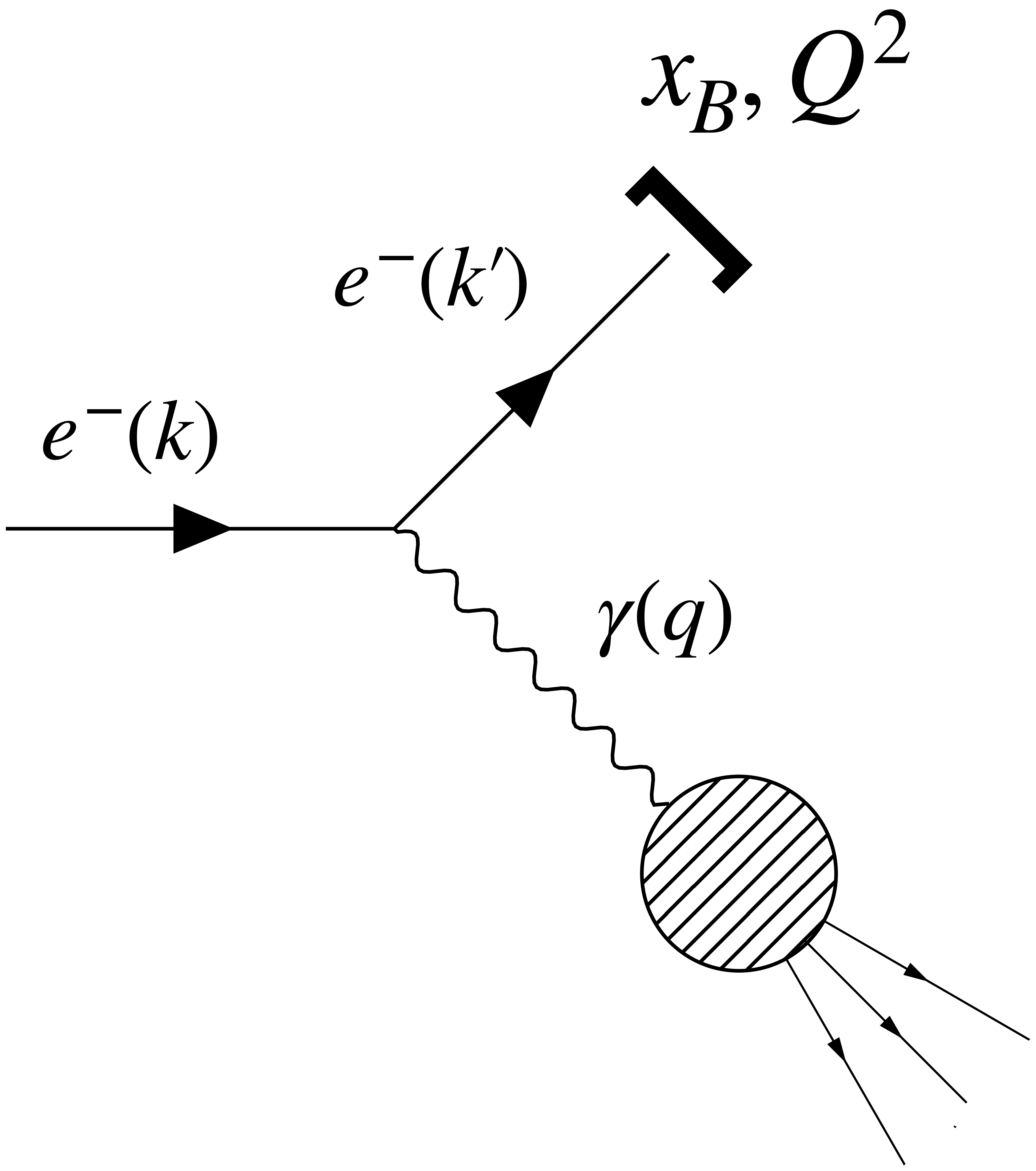
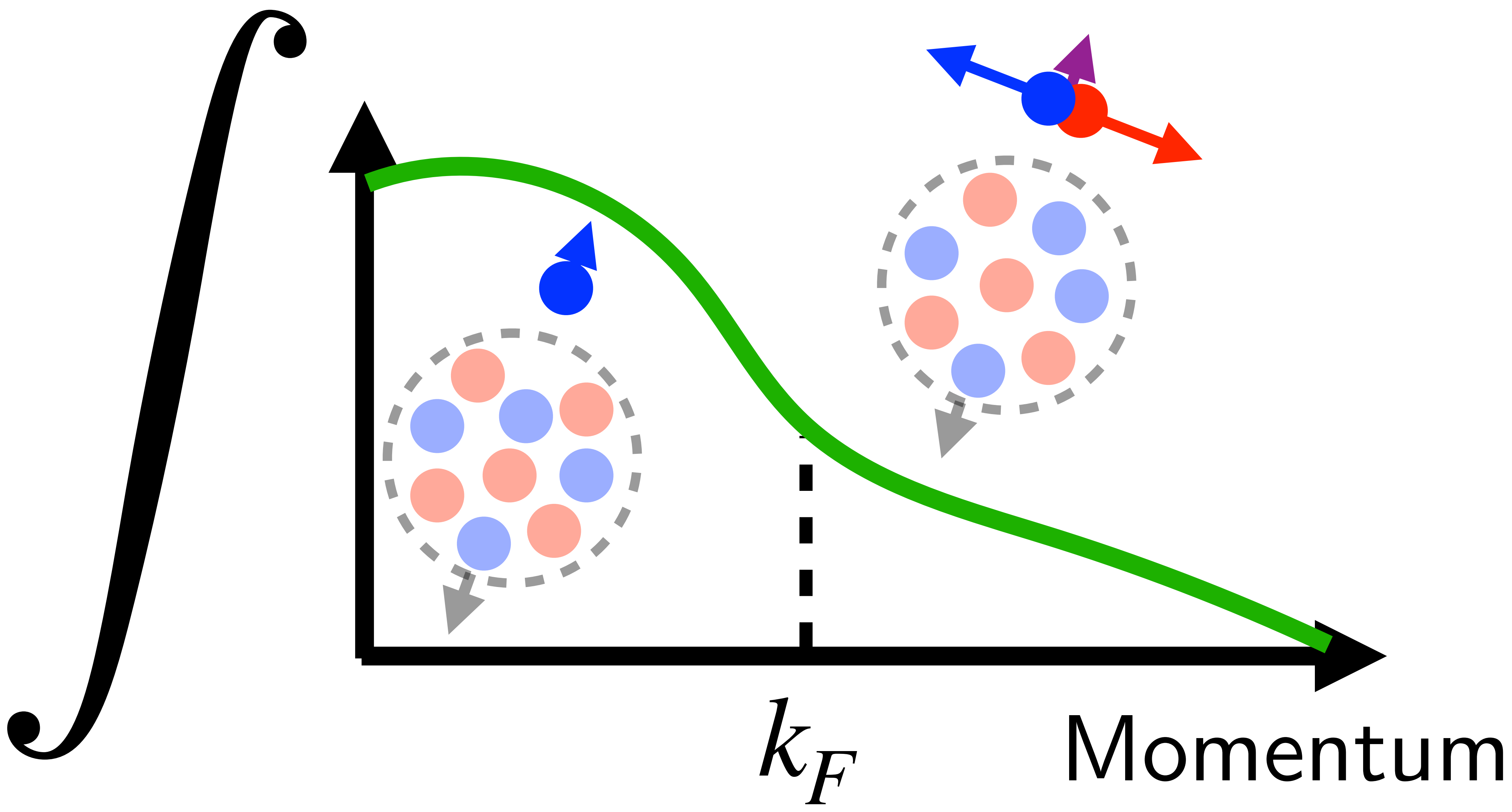



- Detect scattered electron

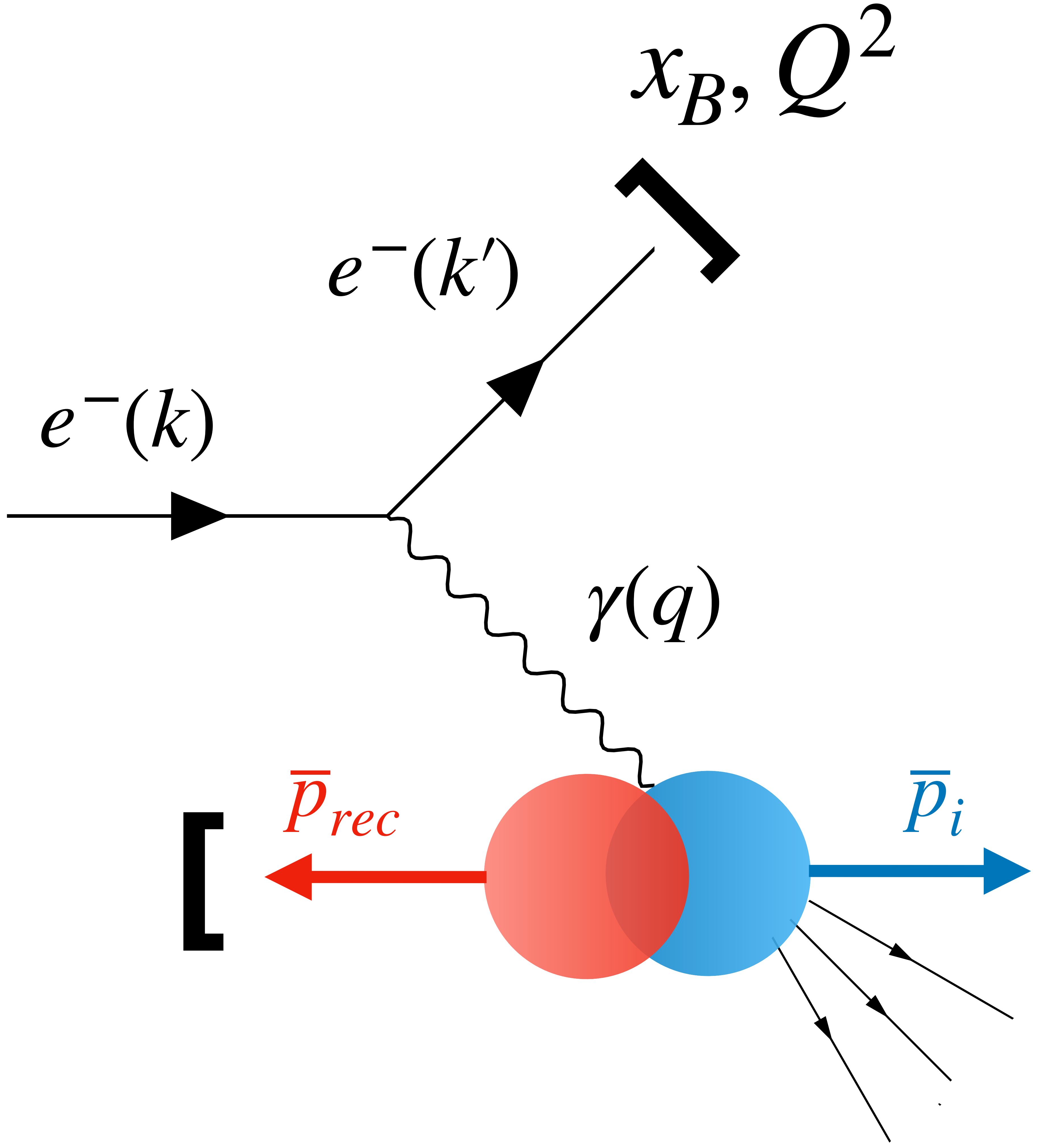
$$Q^2 = 2EE'(1 - \cos\theta)$$

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

- Integrates over entire nucleus
- Variables smeared by Fermi motion



# Tagged DIS can provide the remedy



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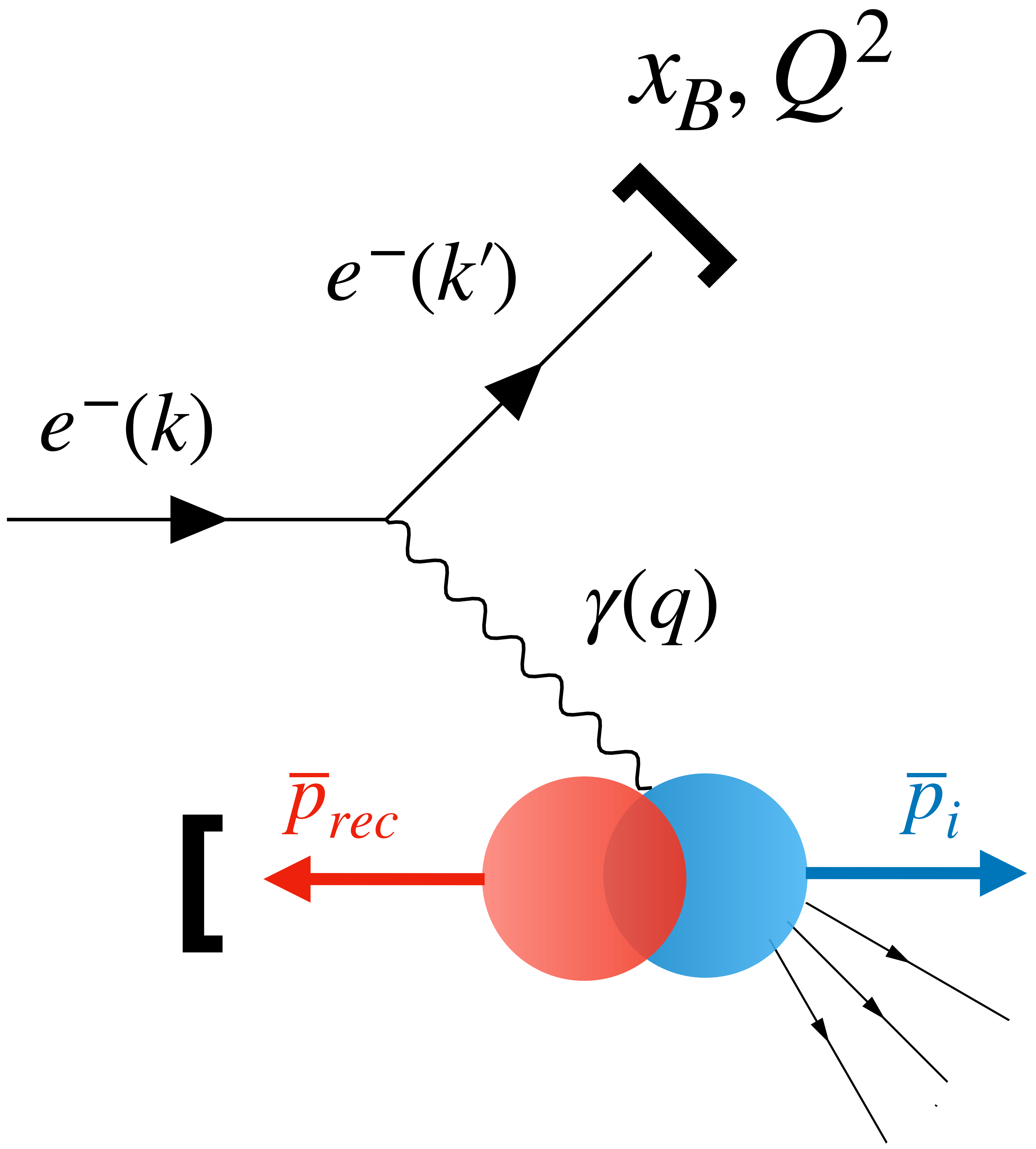


- Detect scattered electron *and* spectator nucleon

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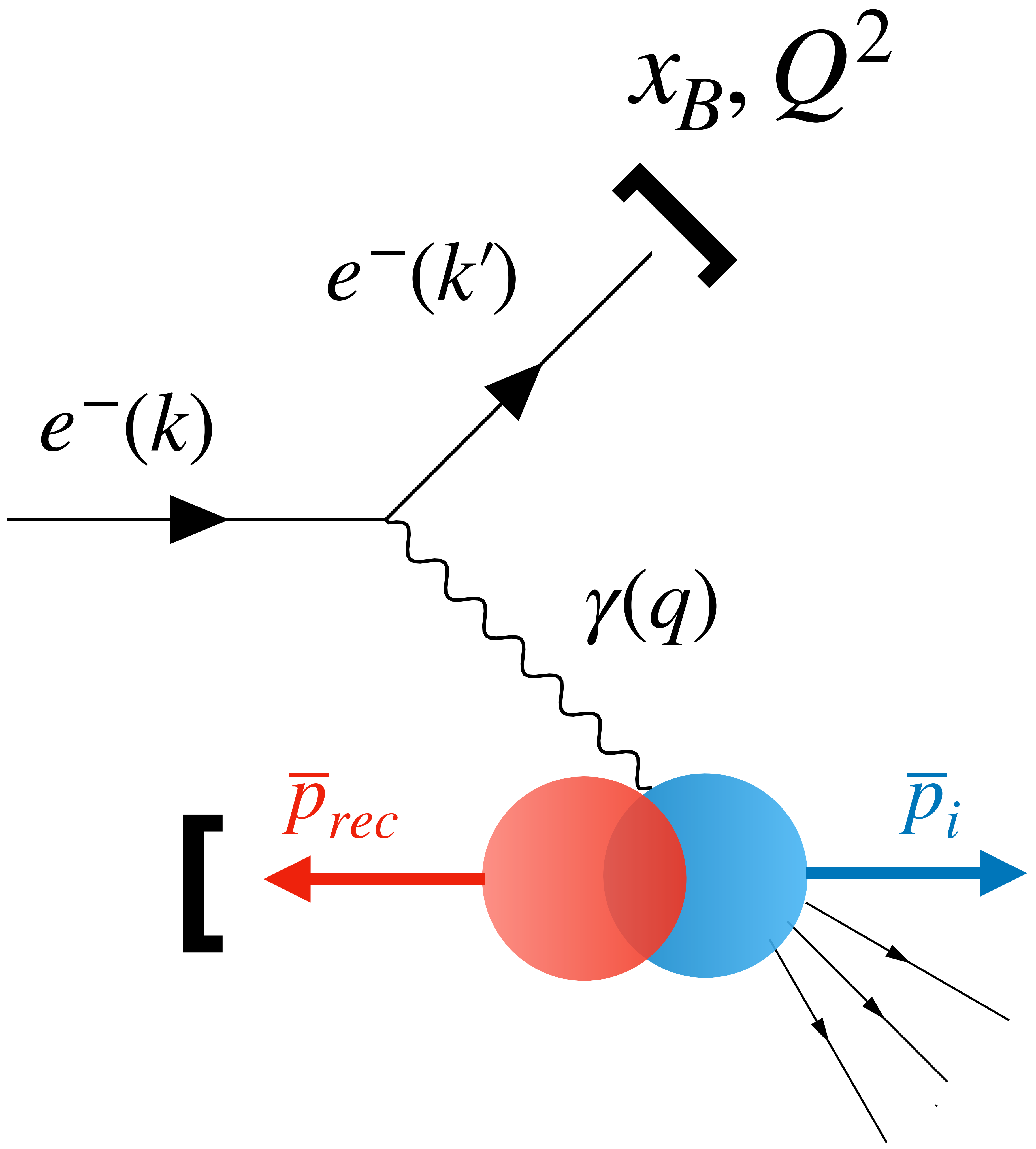
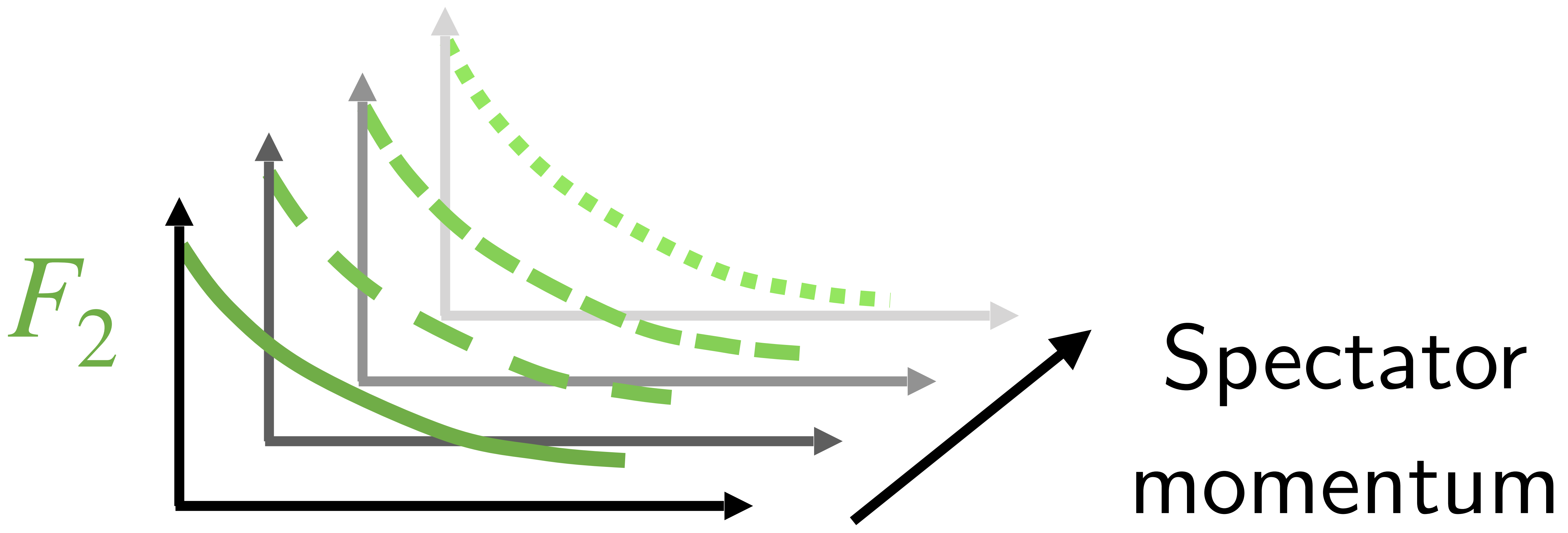



- Detect scattered electron *and* spectator nucleon
- Measure structure as function of nuclear state



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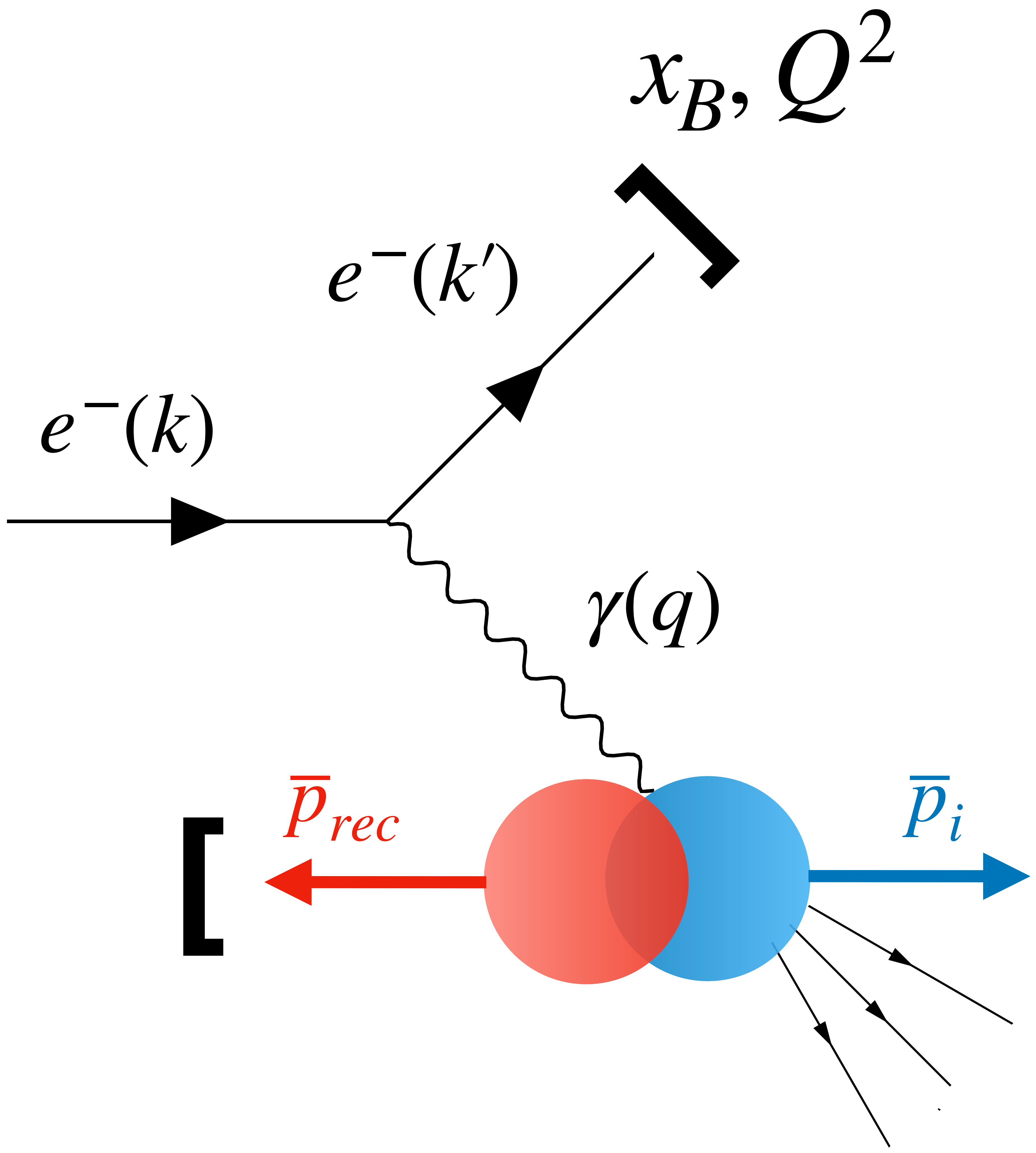


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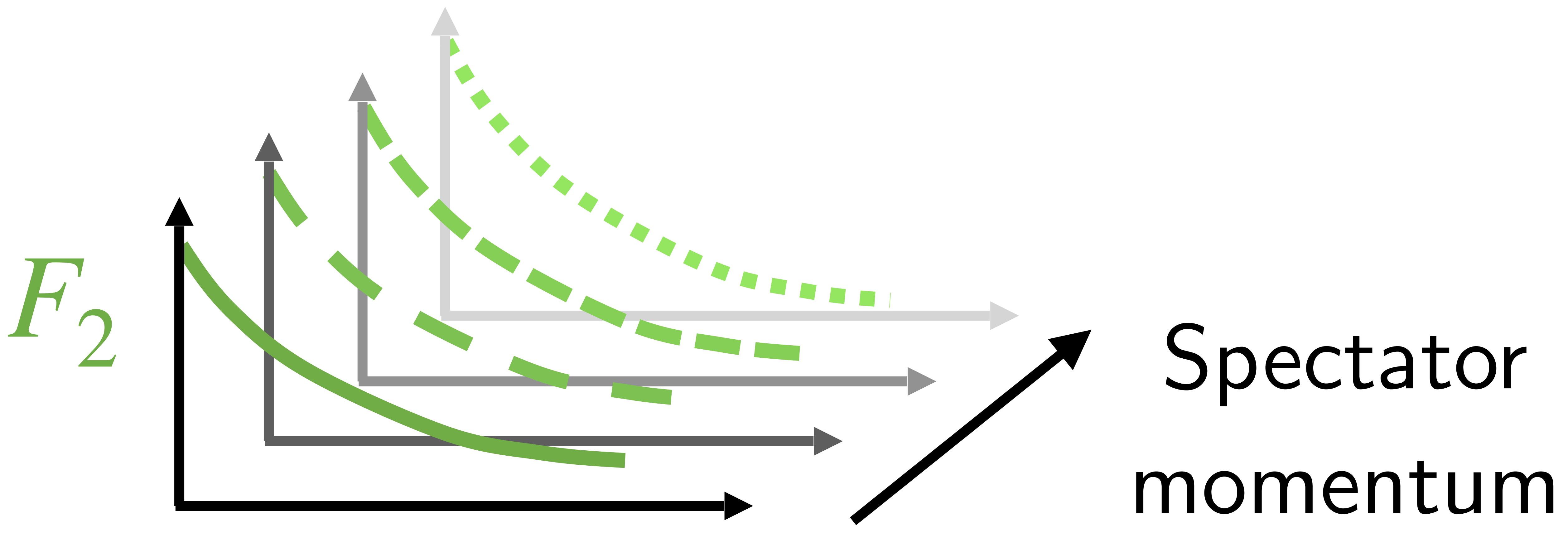


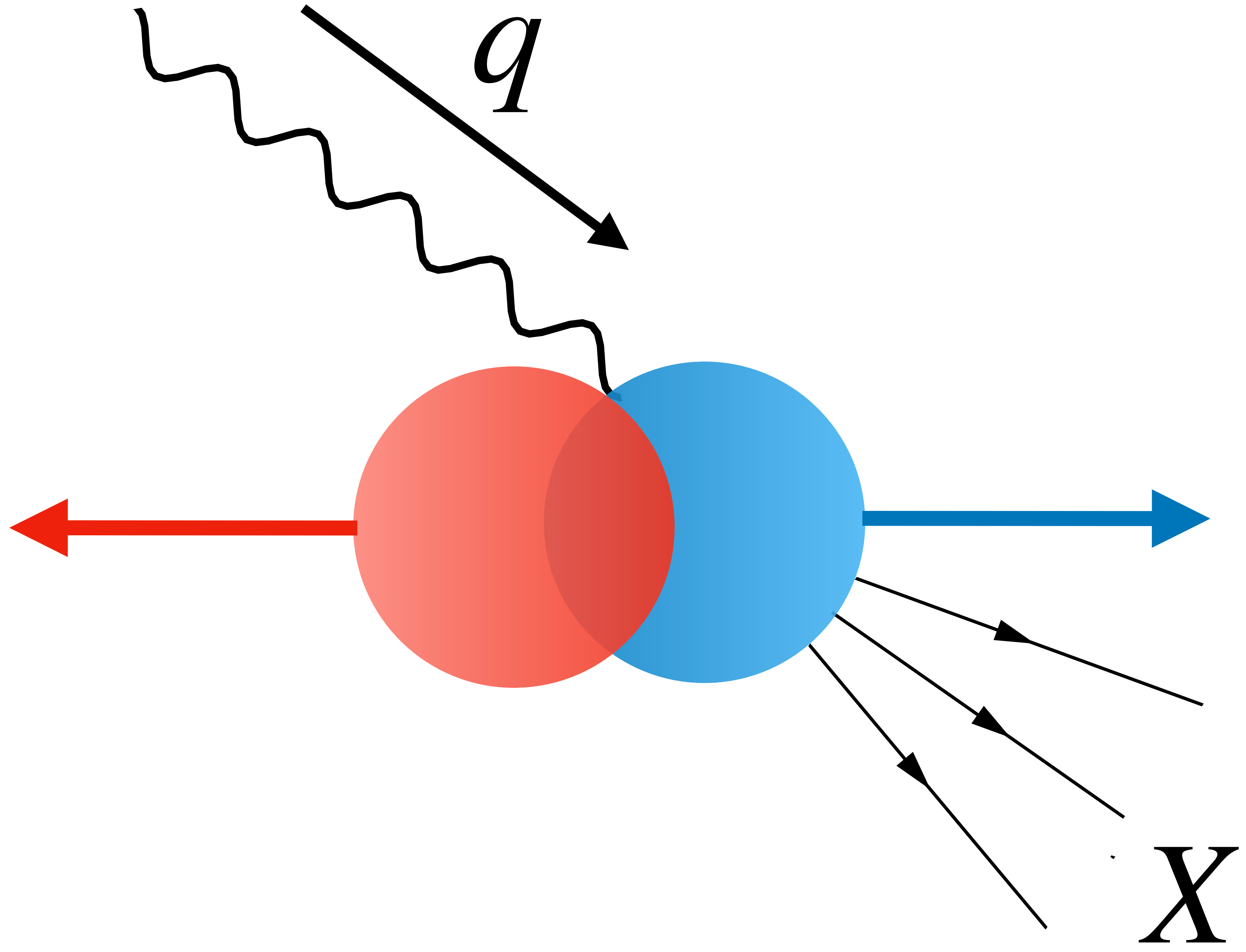

- Account for nucleon motion

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

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

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

# Mitigating final state interactions

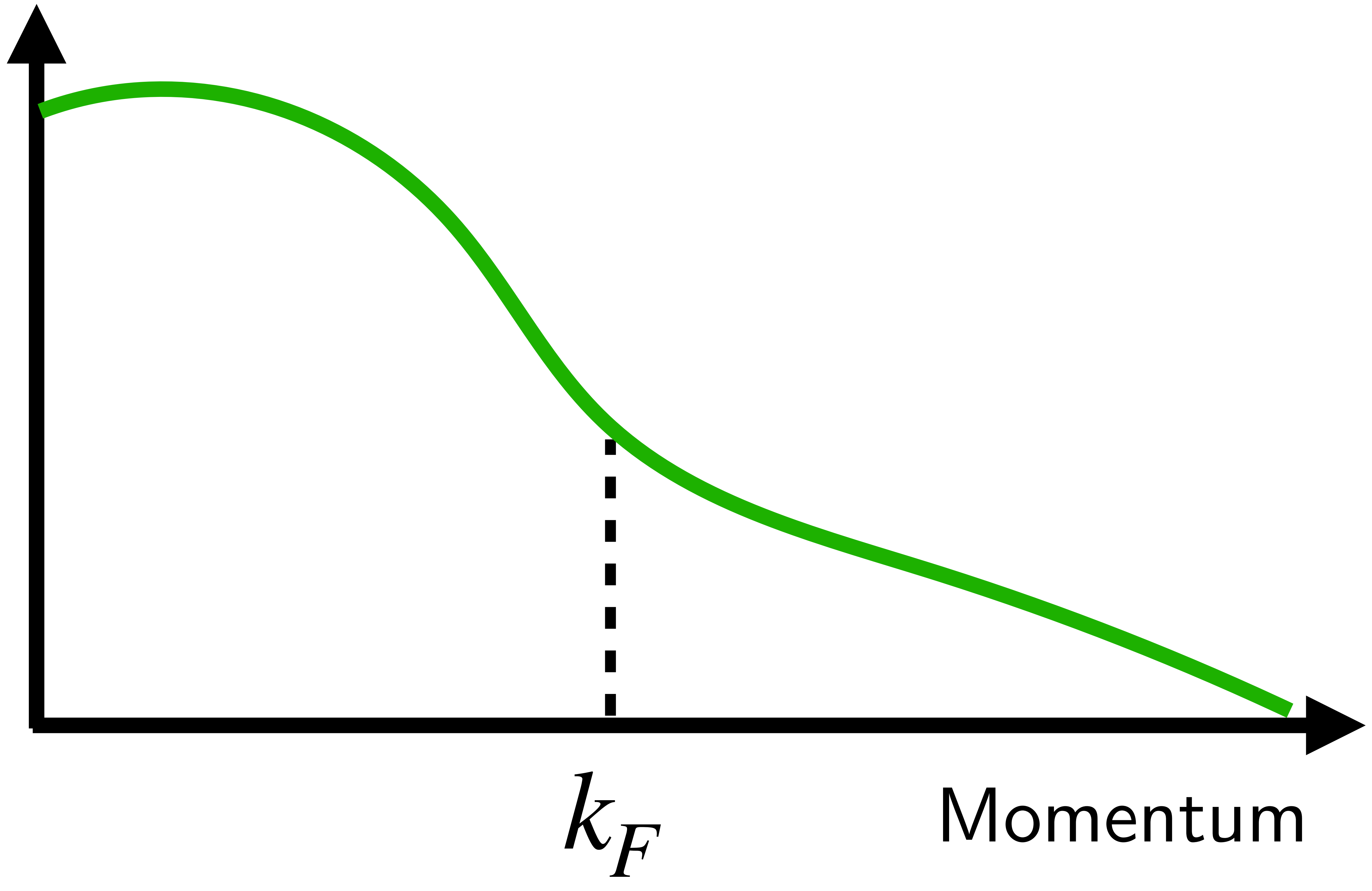



- Final state $X$ goes in direction of $q$

  → Look at backward-going spectators

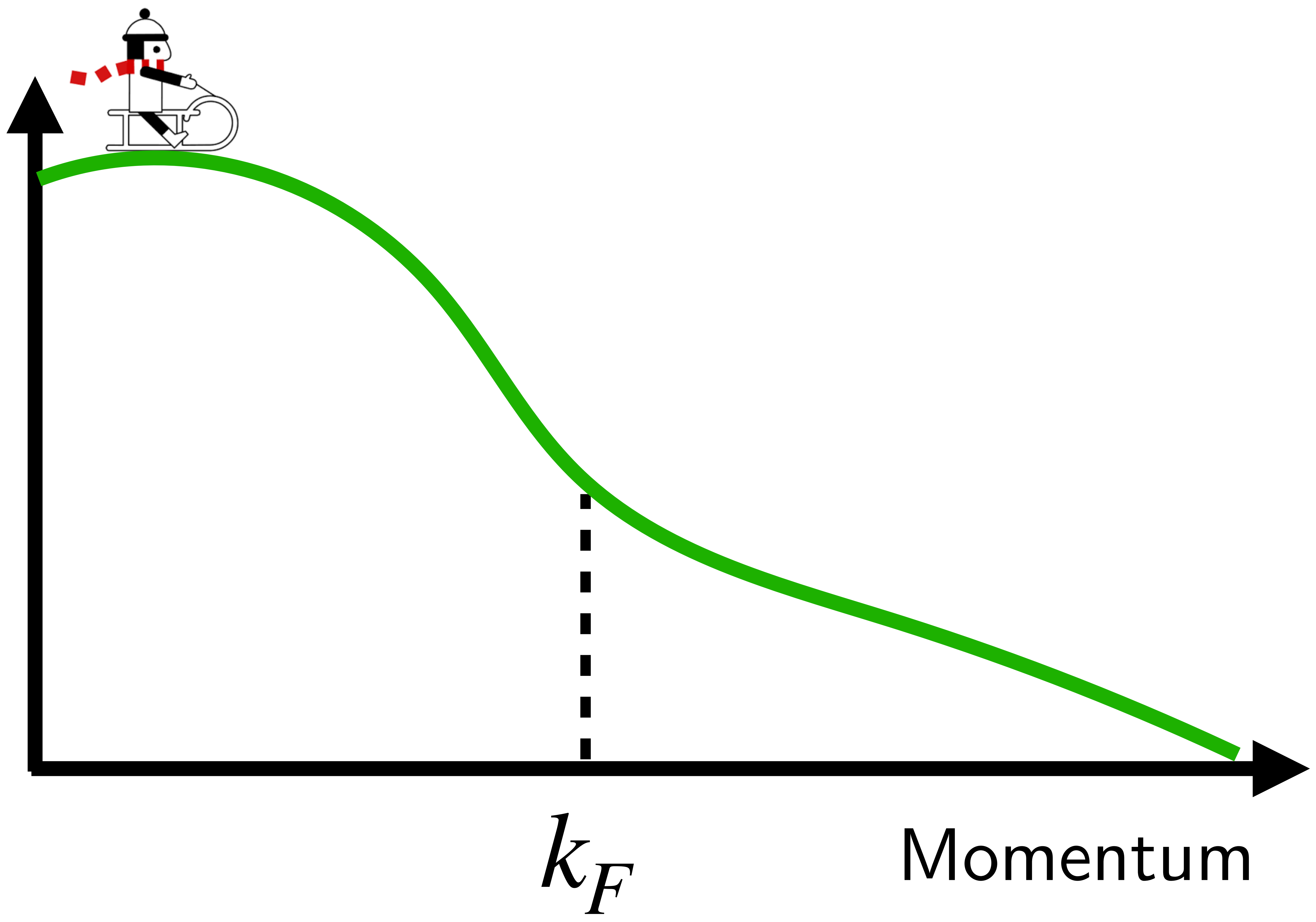
- FSI grows with $W'$, largely independent of $x'$ (?)

  → Form ratios in $x'$


$k_F$
Momentum

**1. BoNuS**

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



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

Structure of high-momentum bound nucleons

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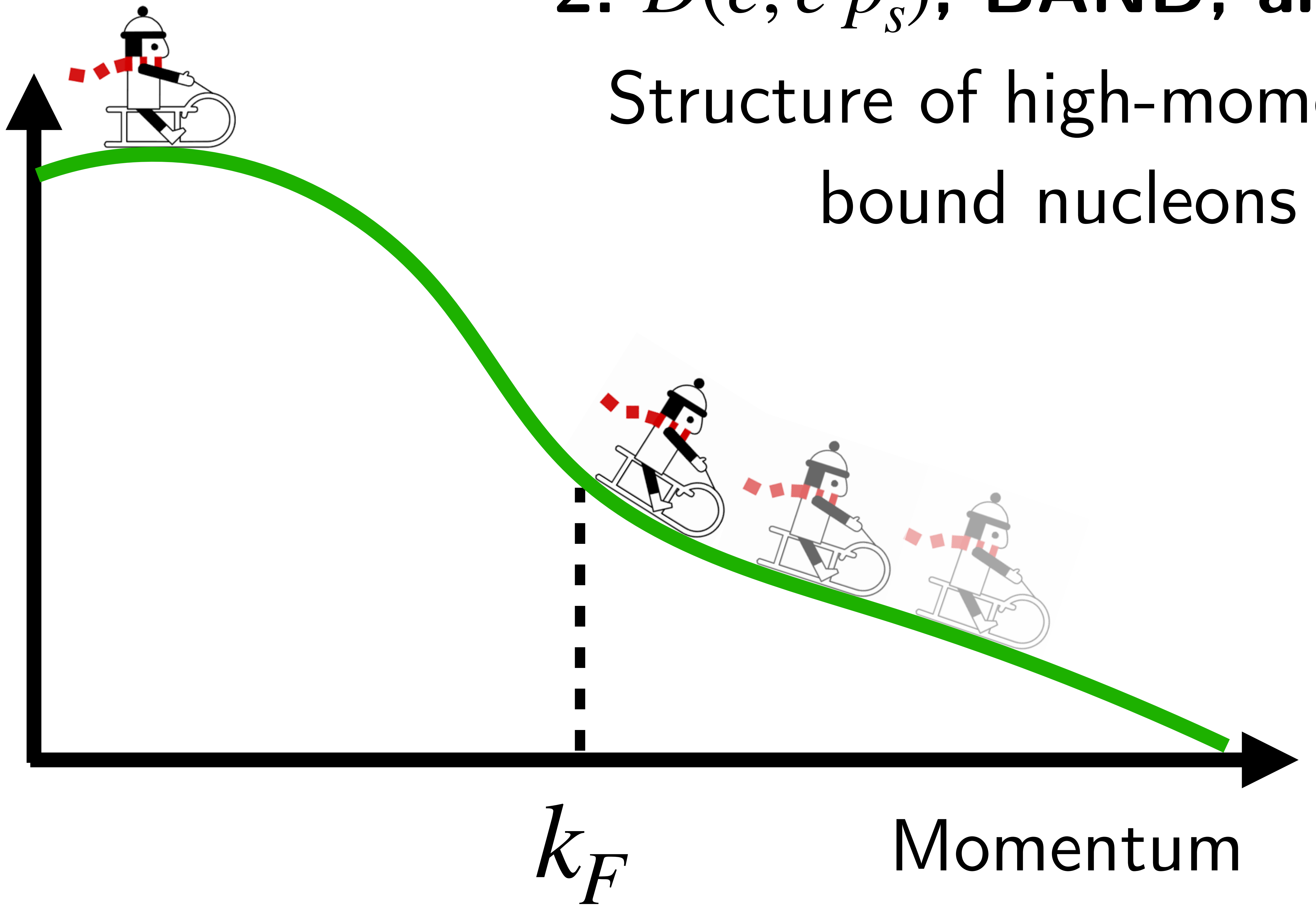

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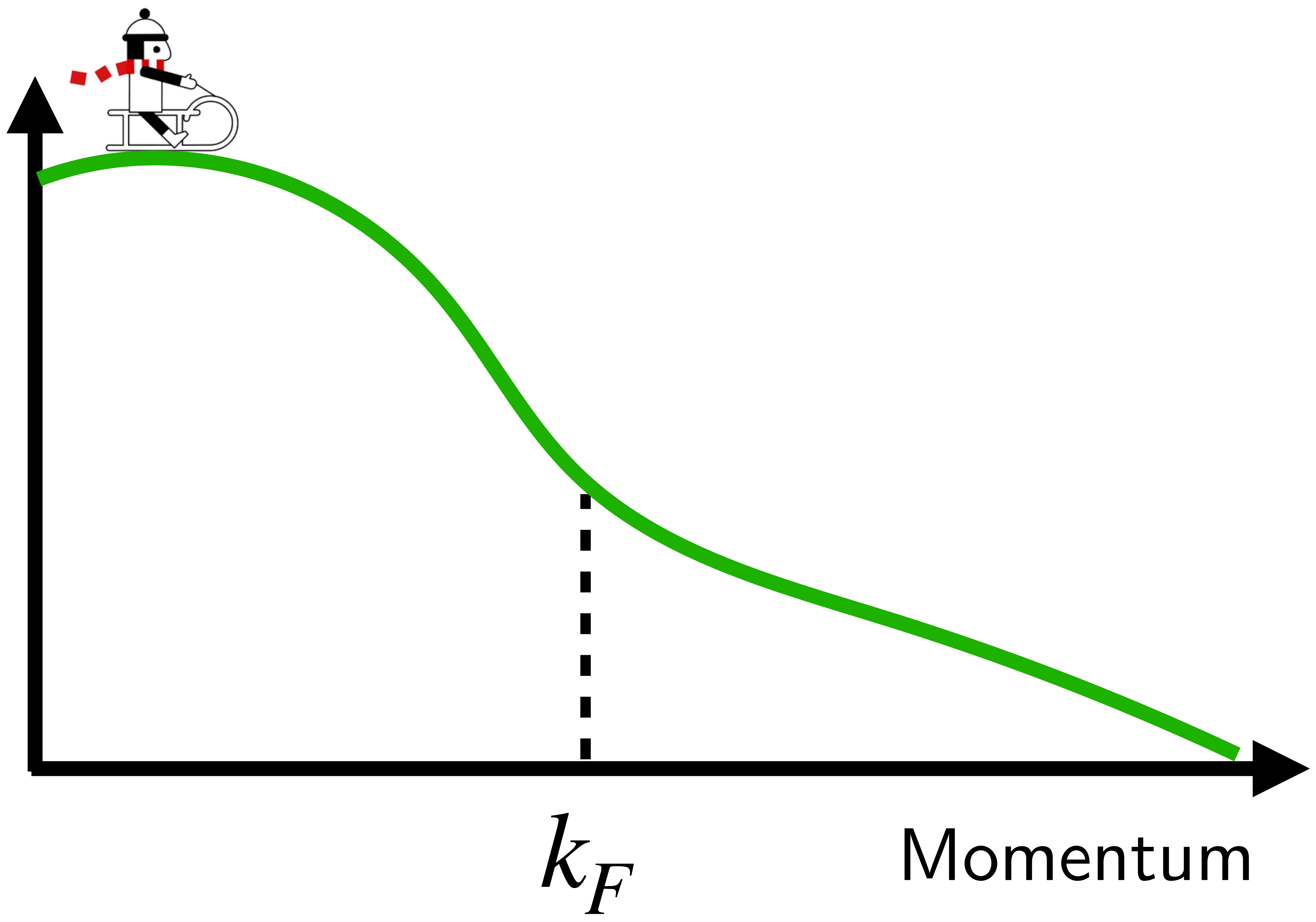
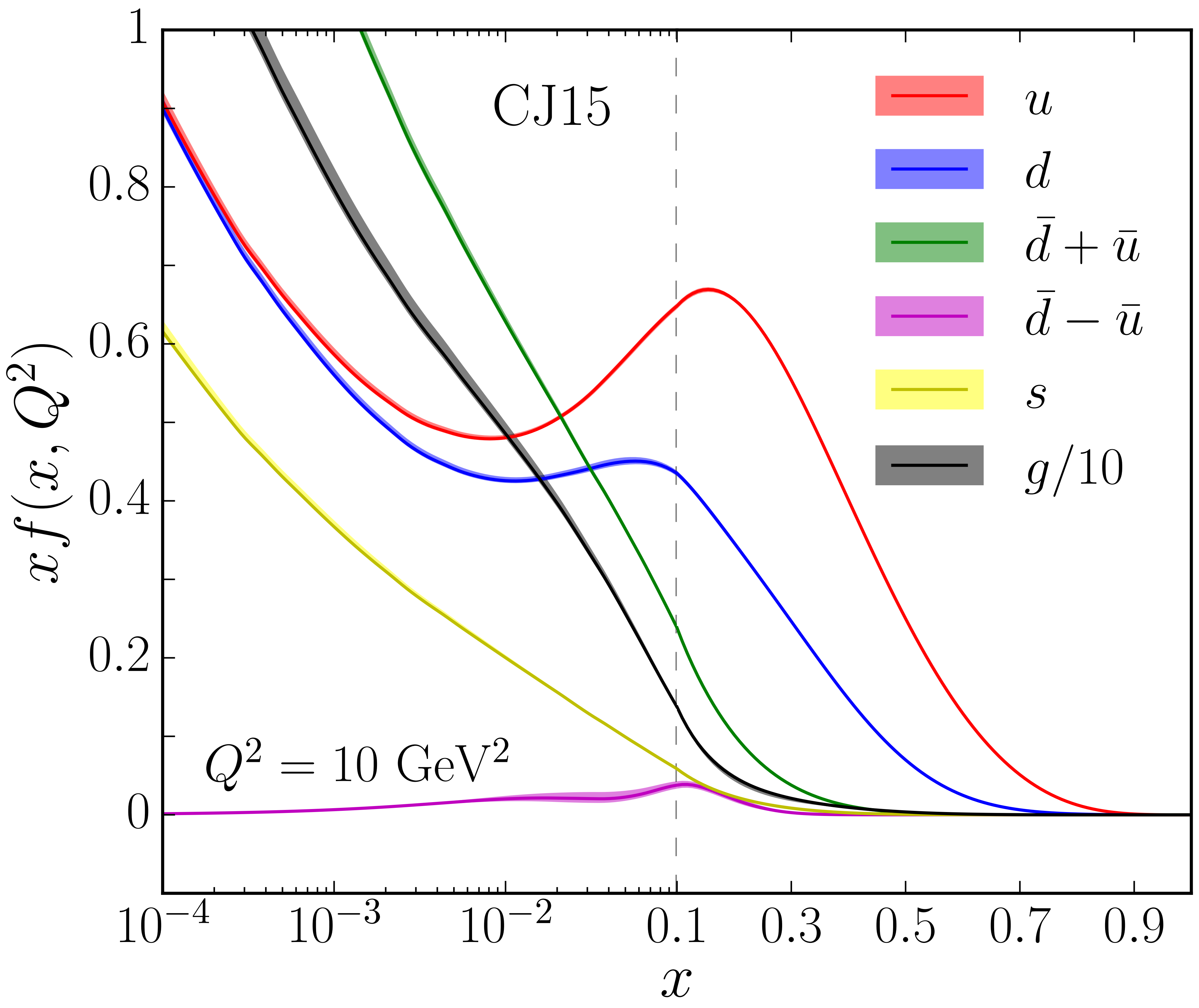


# Free structure function ratio $F_2^n/F_2^p$

- Limit of $d/u$ as $x_B \to 1$ sensitive to spin-flavor symmetry breaking mechanism
- Constraints on PDFs



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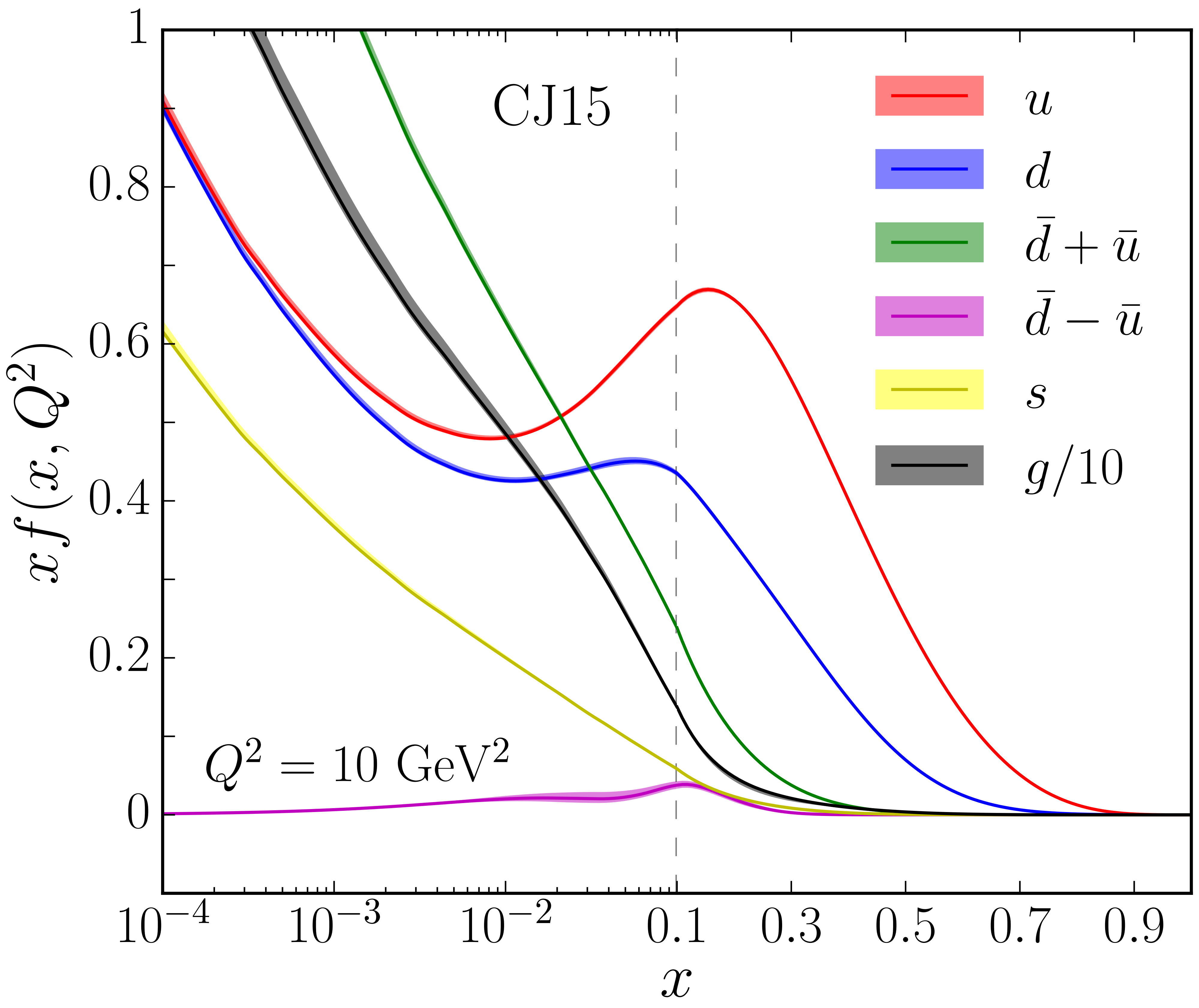
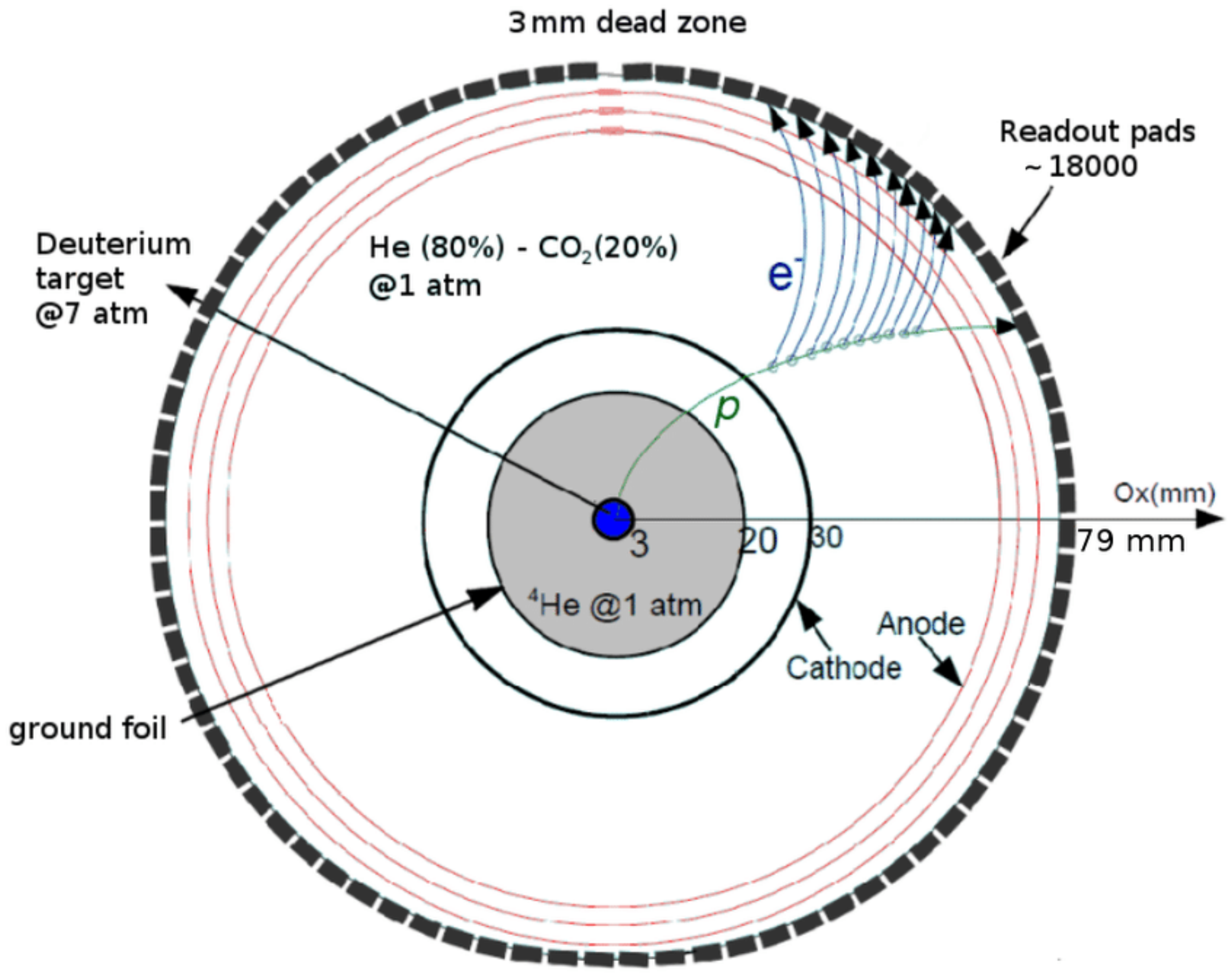



- Methods:
  - Extract from nuclear structure functions with nuclear corrections
  - Use tagged DIS to extract structure of barely-off-shell neutrons in deuterium

# 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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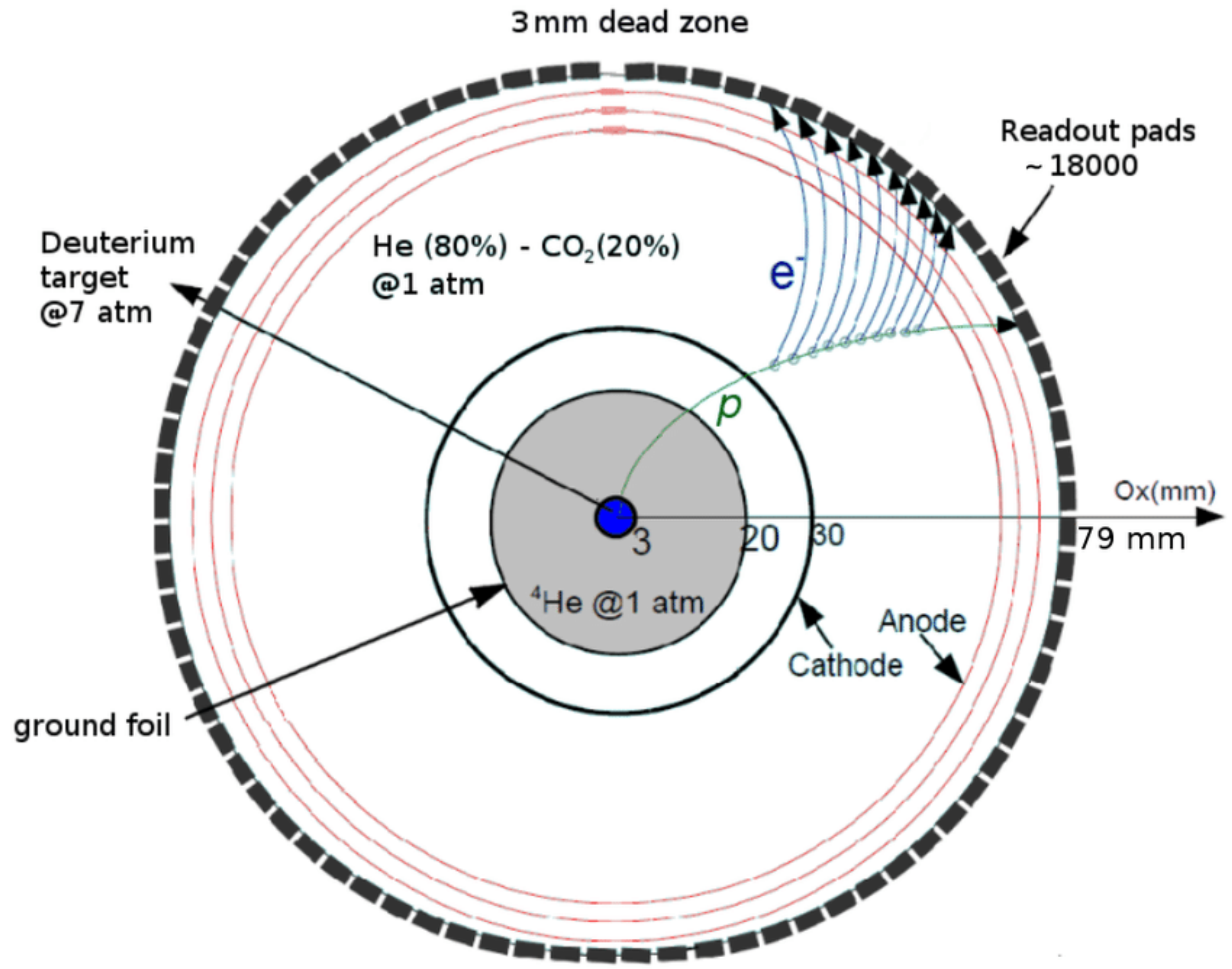
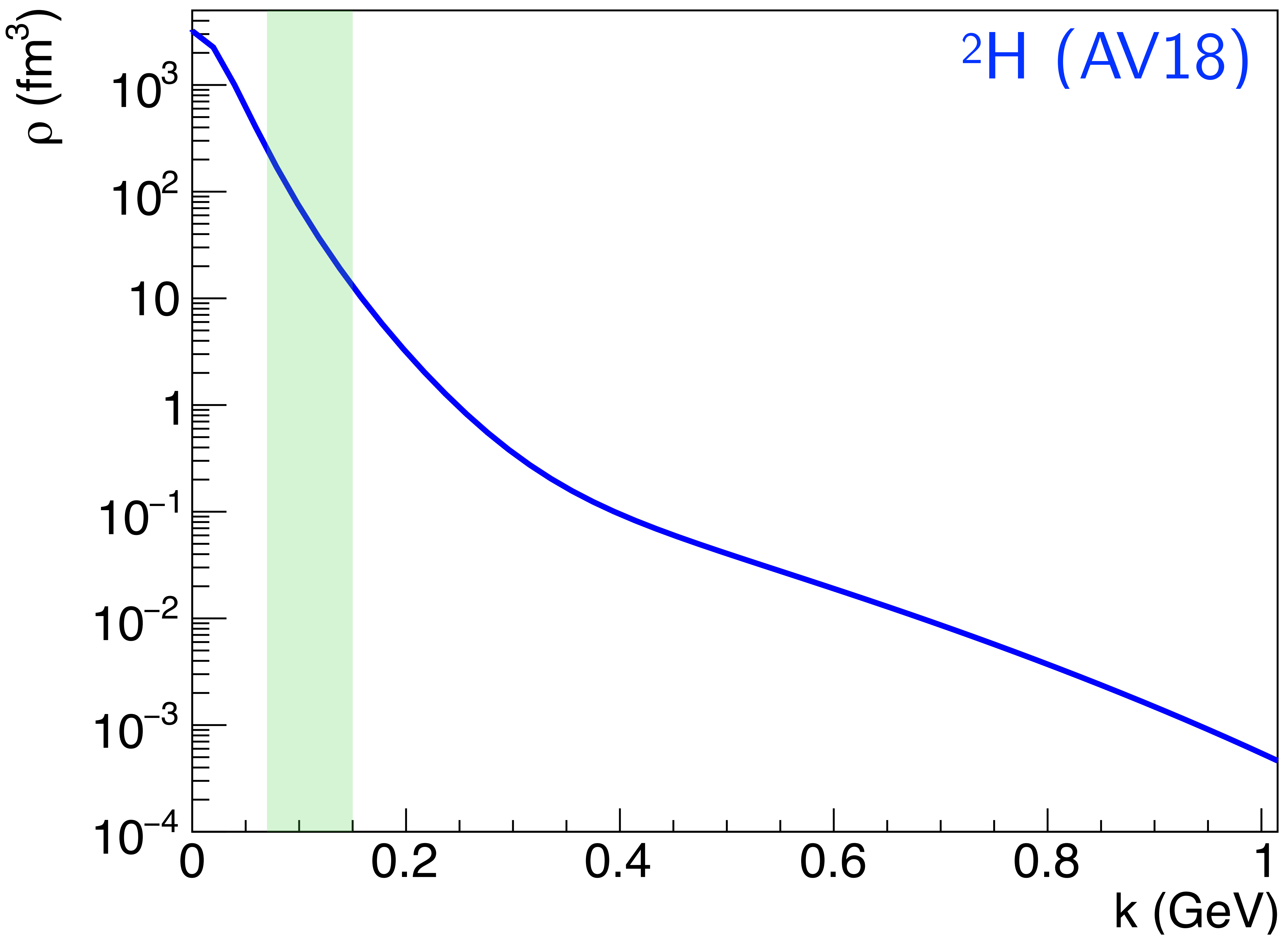
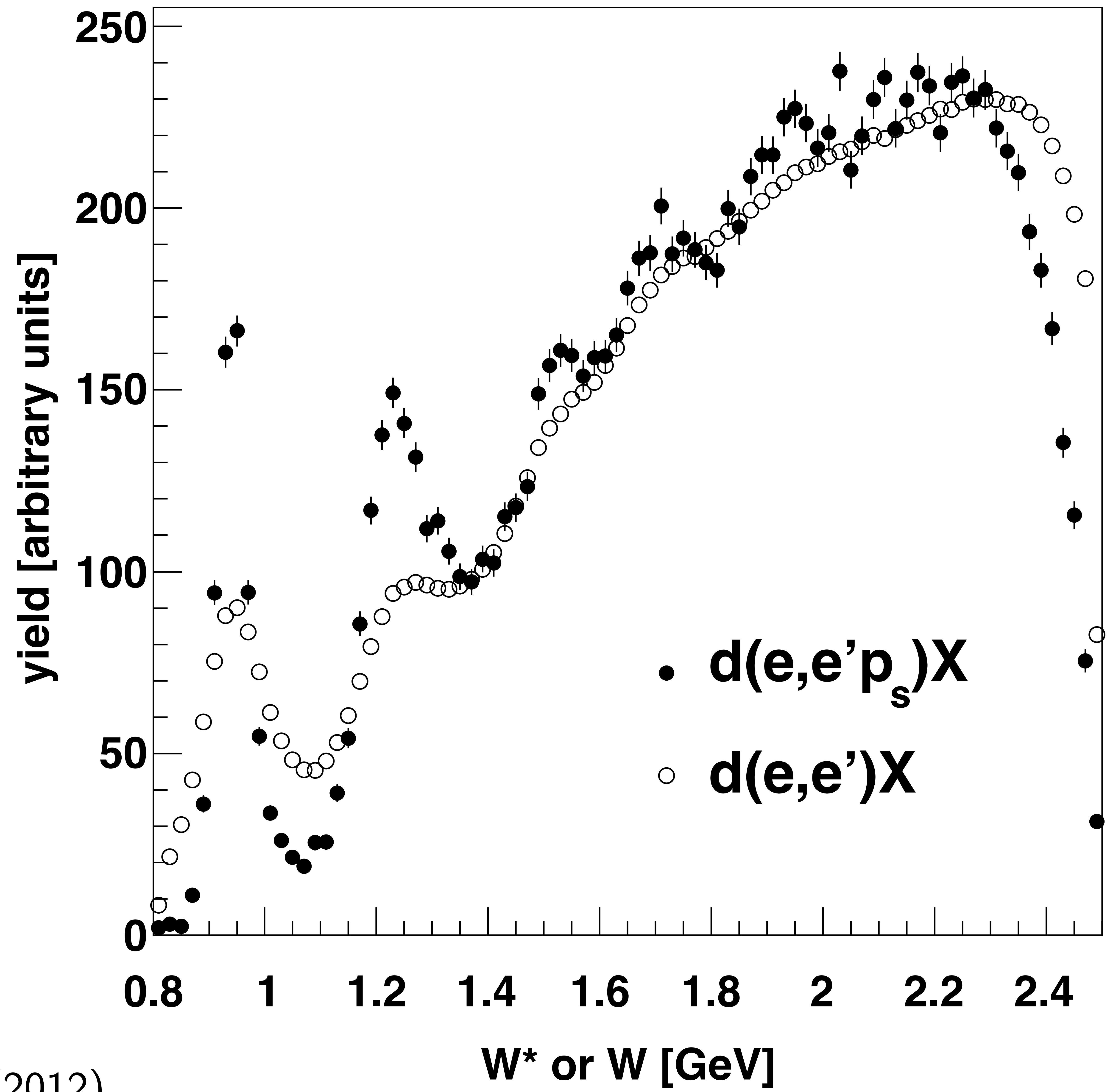


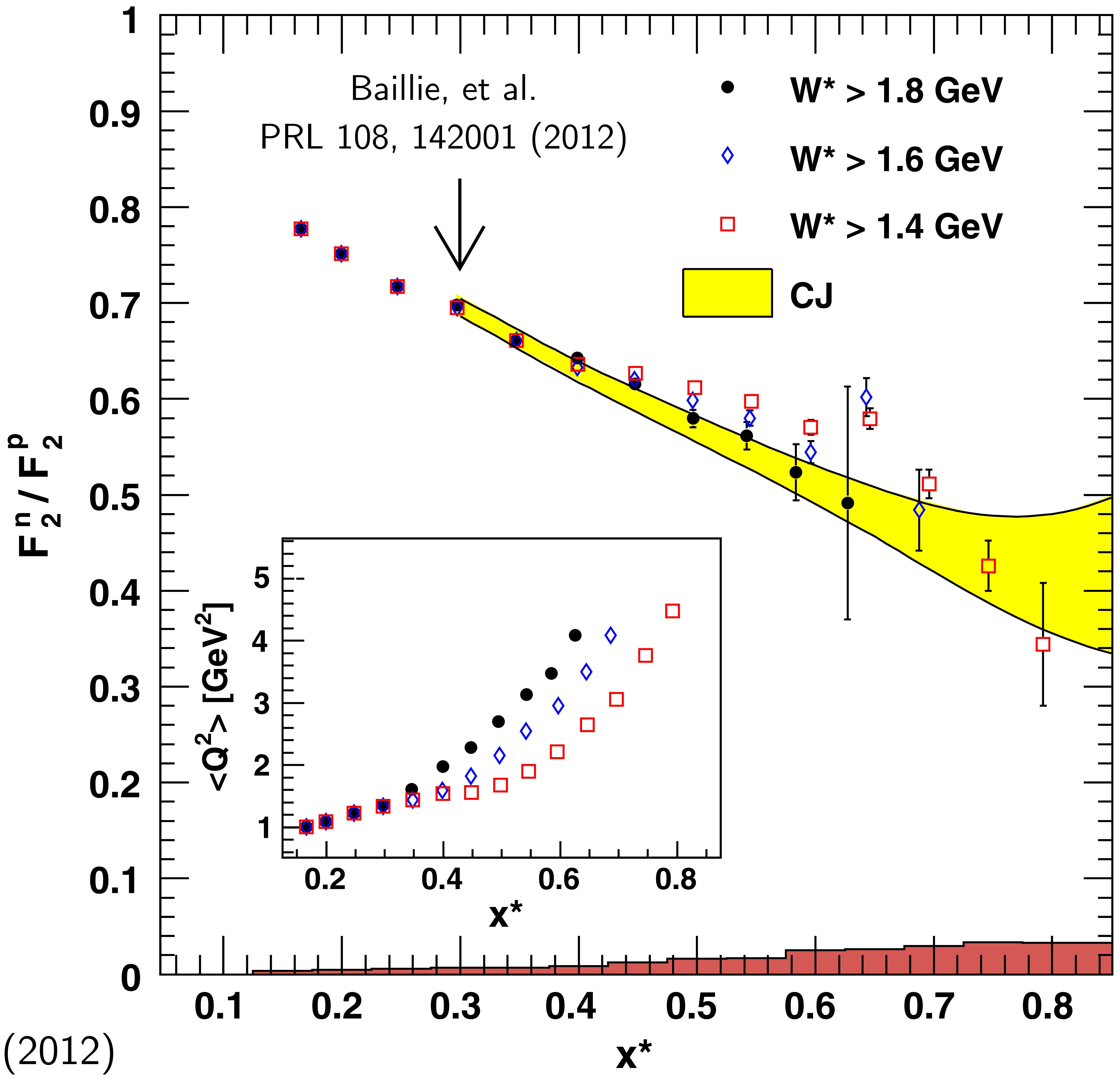



# BoNuS invariant mass with/without tagging




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

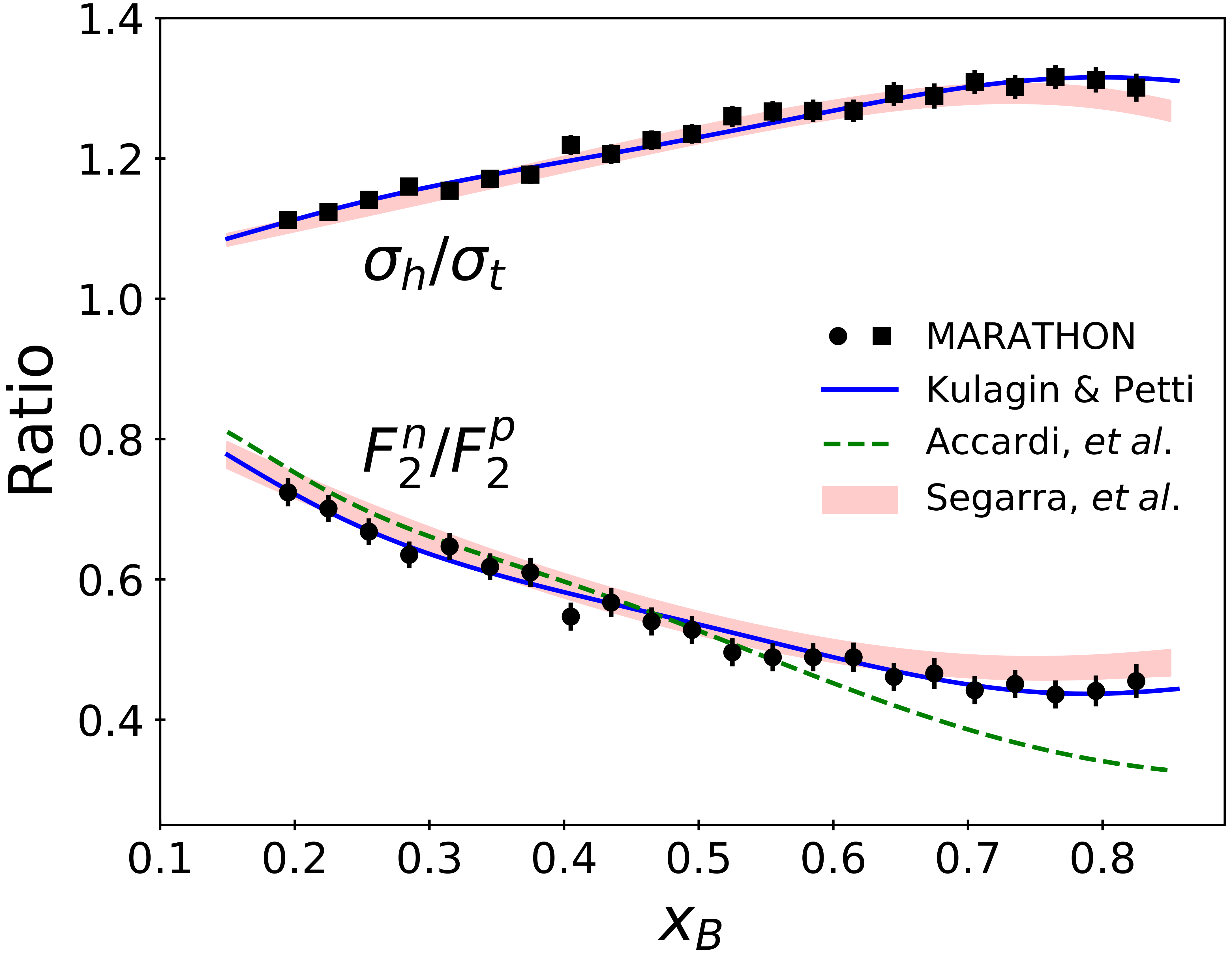
# BoNuS results

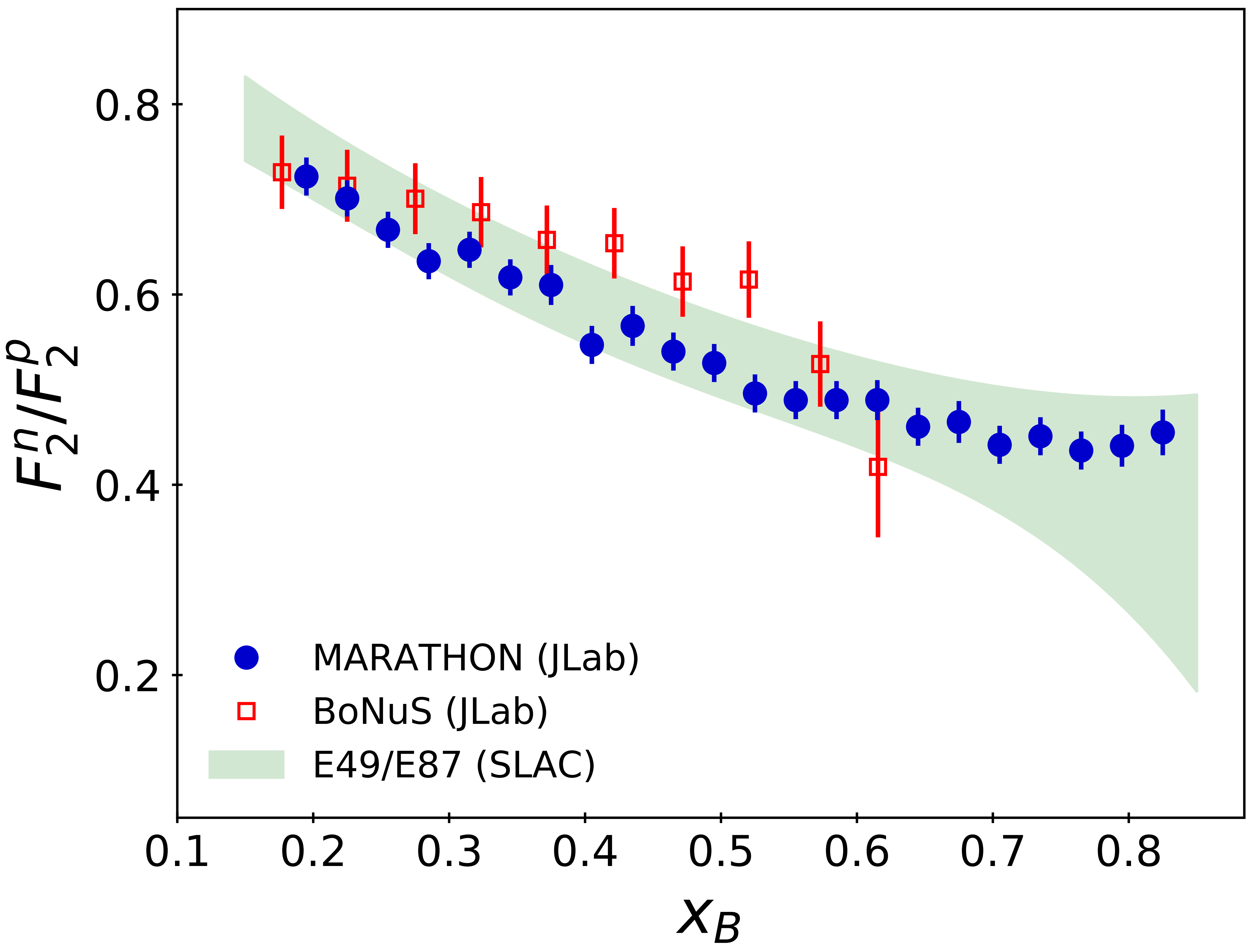



Baillie, et al. PRL 108, 142001 (2012)

# Compared to latest nuclear correction extraction

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

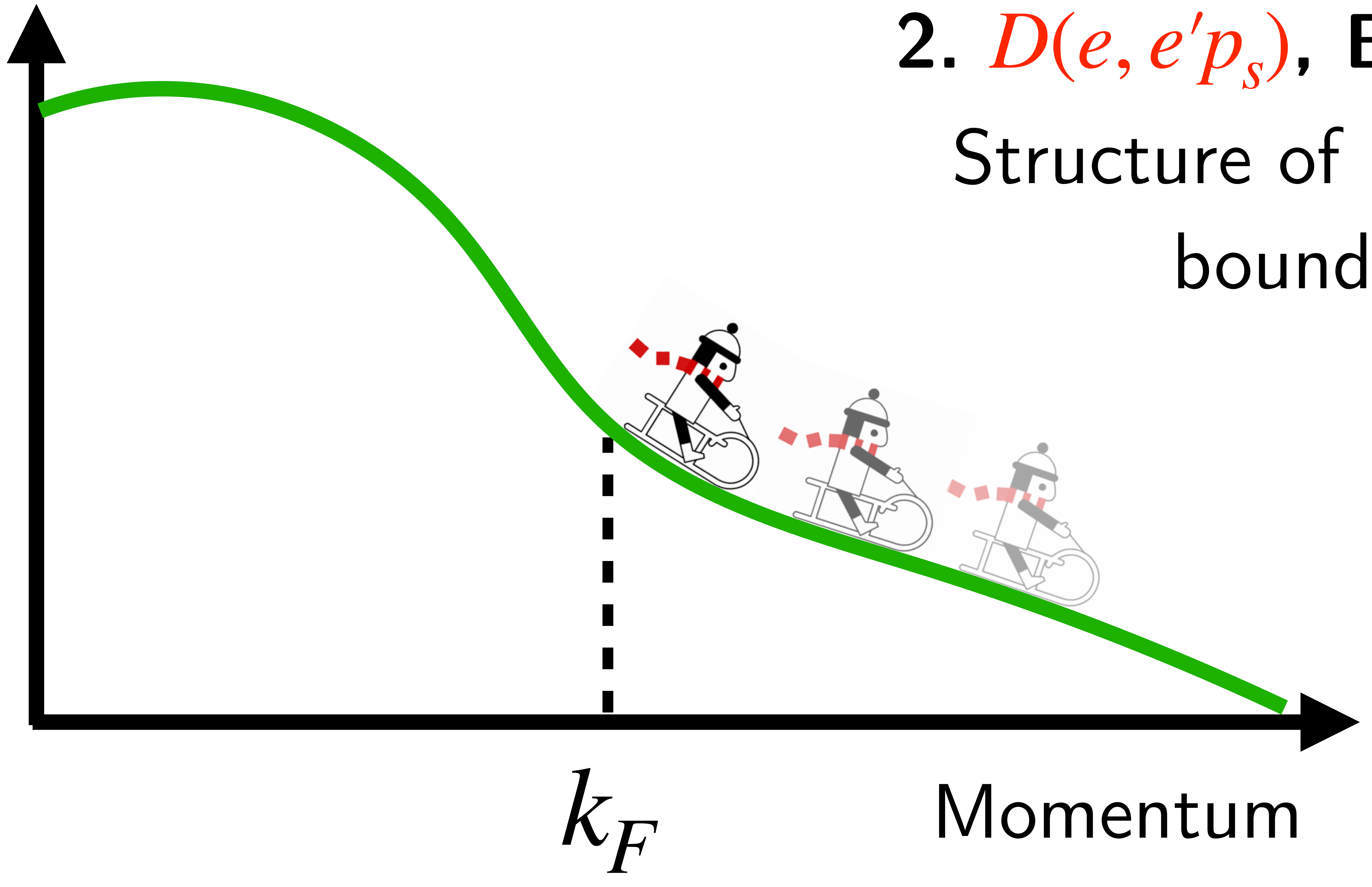


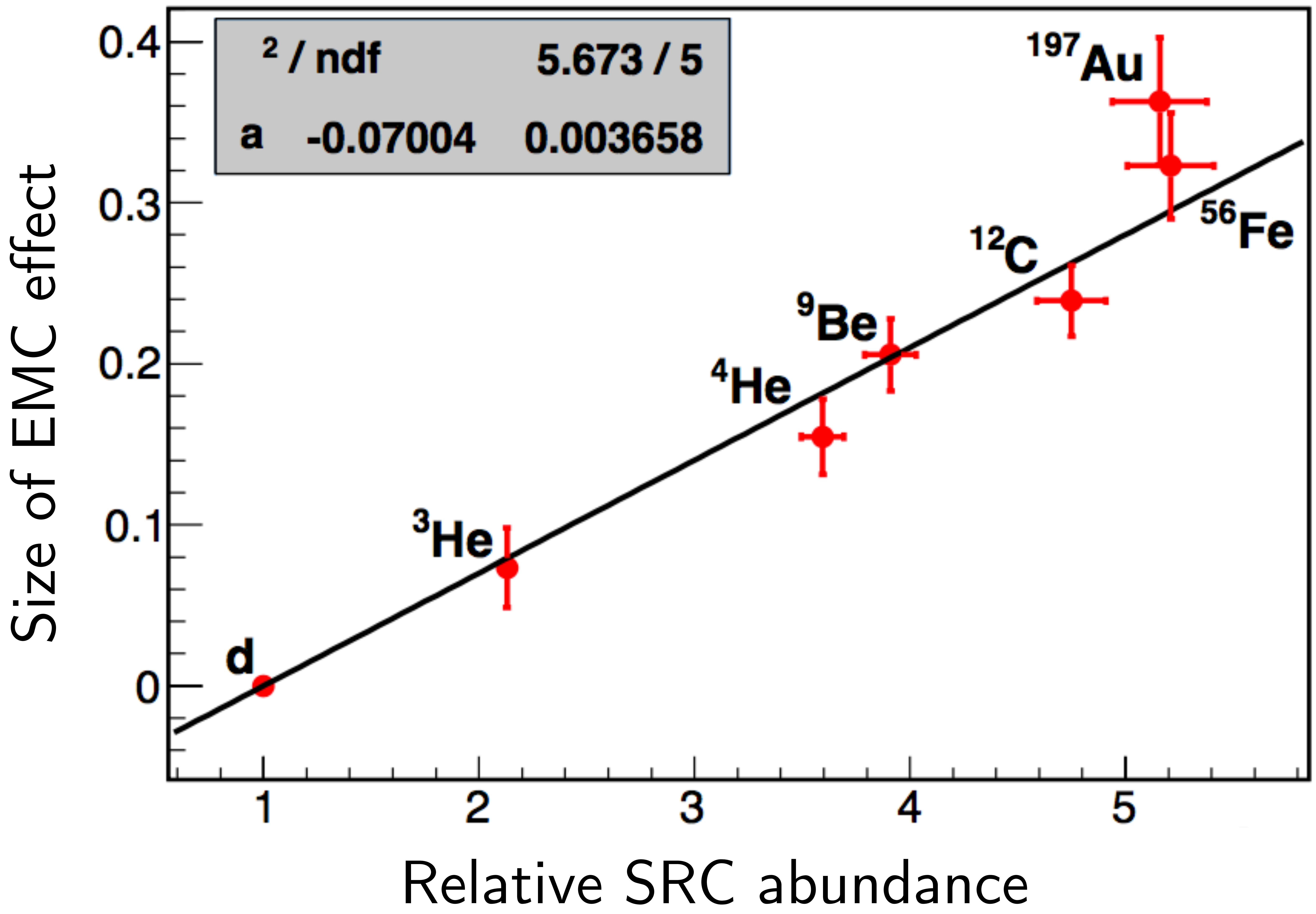

- MARATHON extraction from $^3$He/$^3$H ratio
- Only need to account for relative nuclear corrections in A = 3 nuclei

## 2. $D(e, e'p_s)$, **BAND, and LAD**

Structure of high-momentum bound nucleons

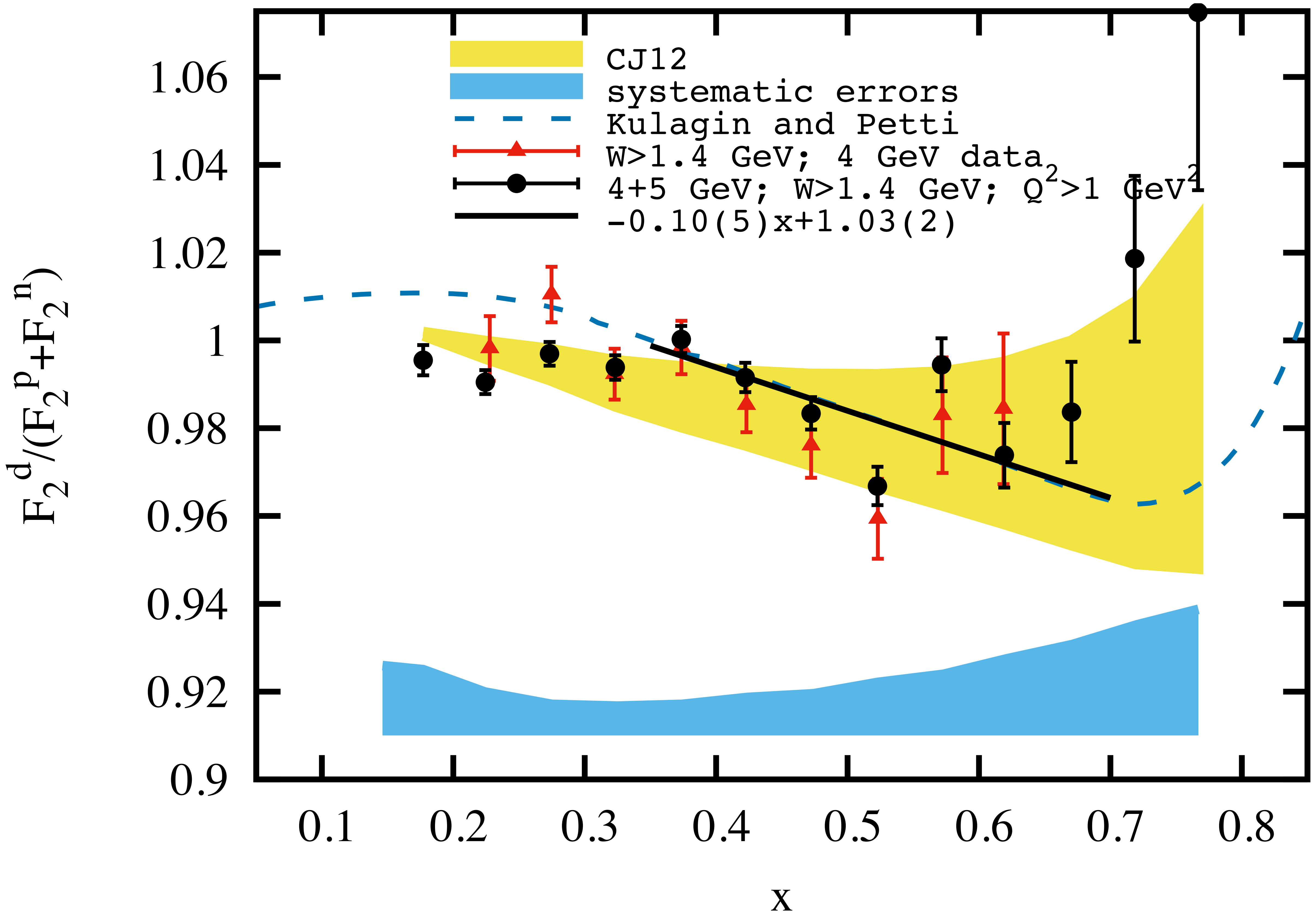


# SRC abundance and EMC magnitude are correlated



# Tagged DIS can definitively test SRC-EMC hypothesis

Griffioen *et al.*, PRC (2015)



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- EMC effect in deuterium is small

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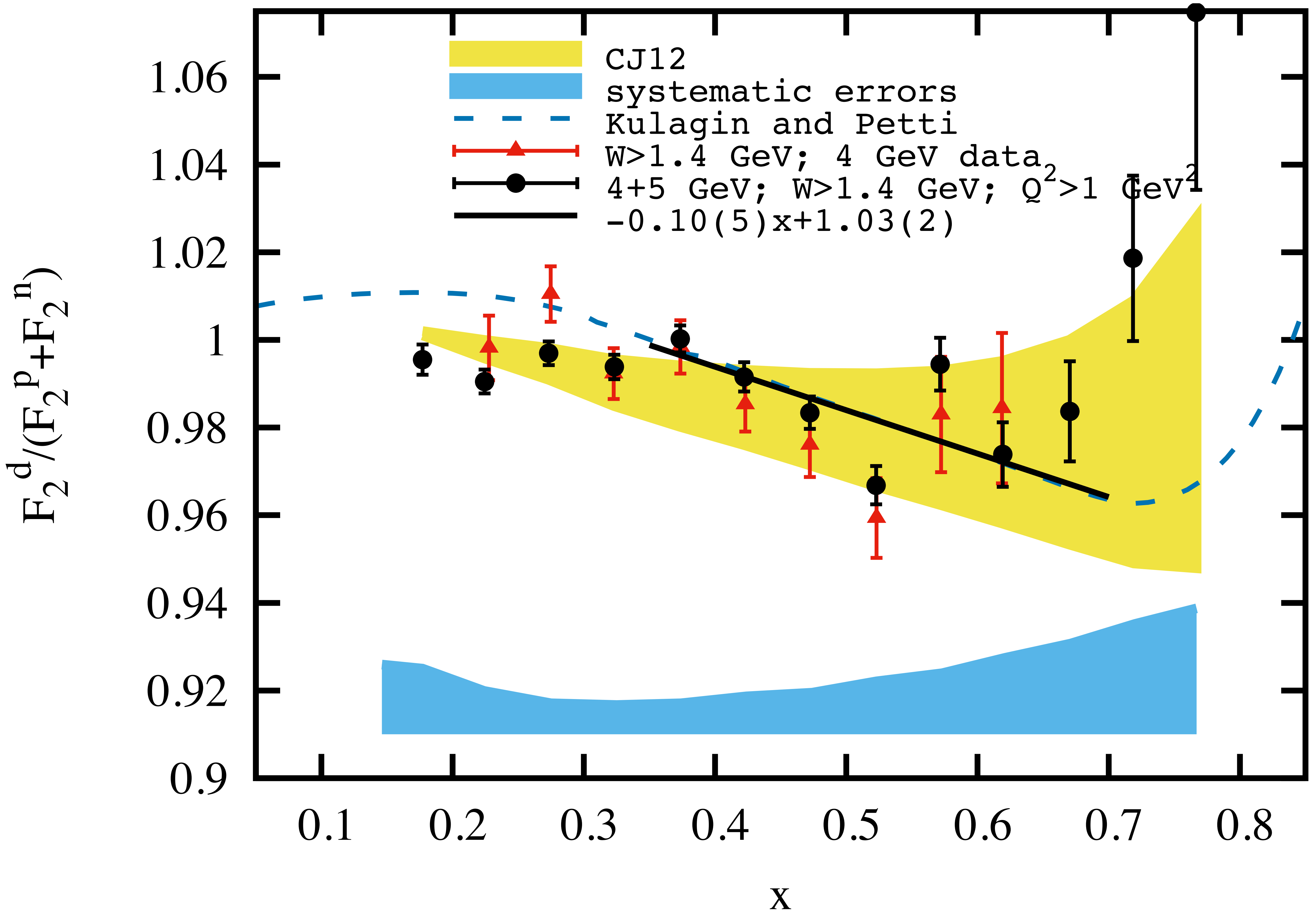
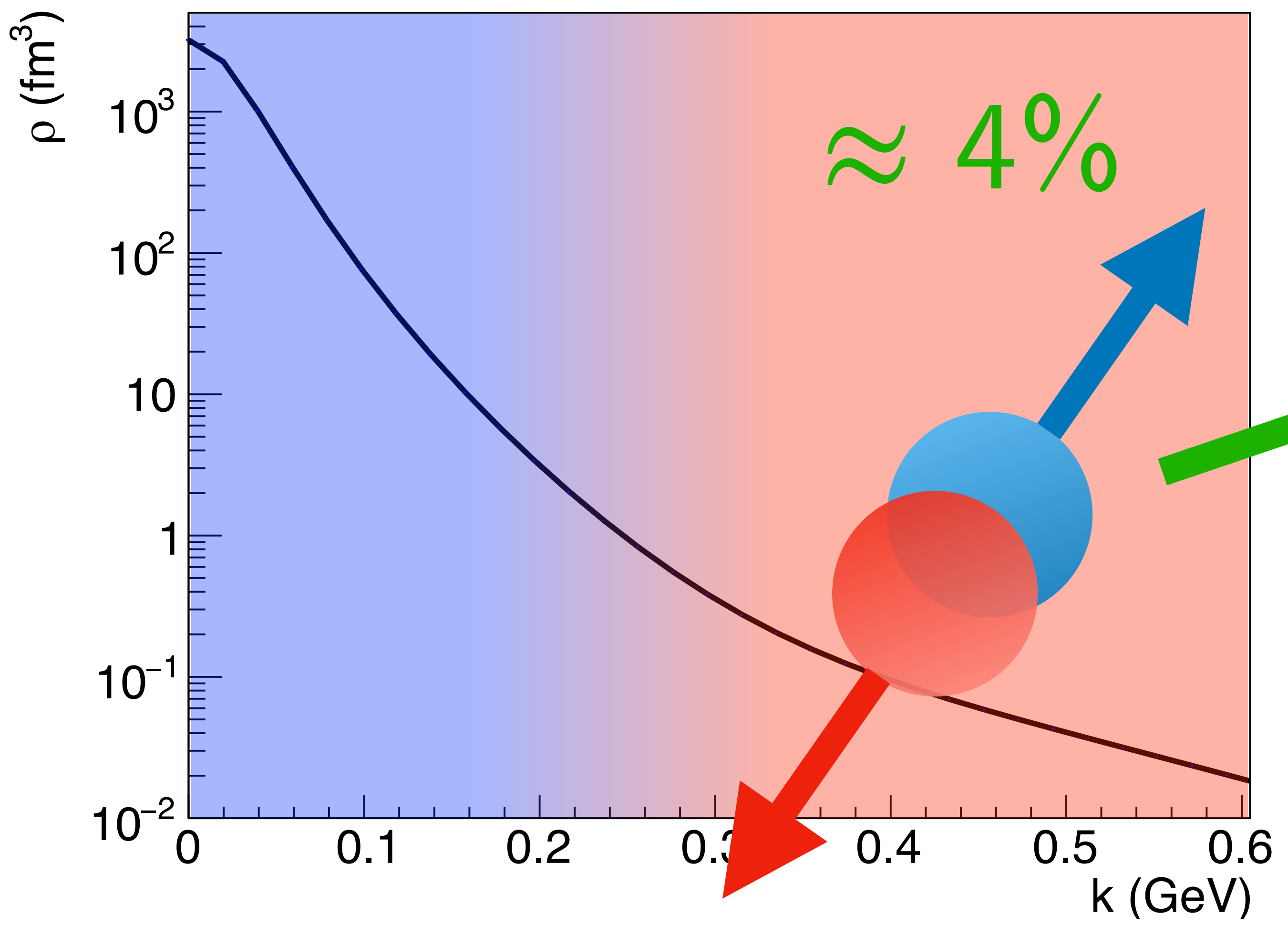


# Tagged DIS can definitively test SRC-EMC hypothesis

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

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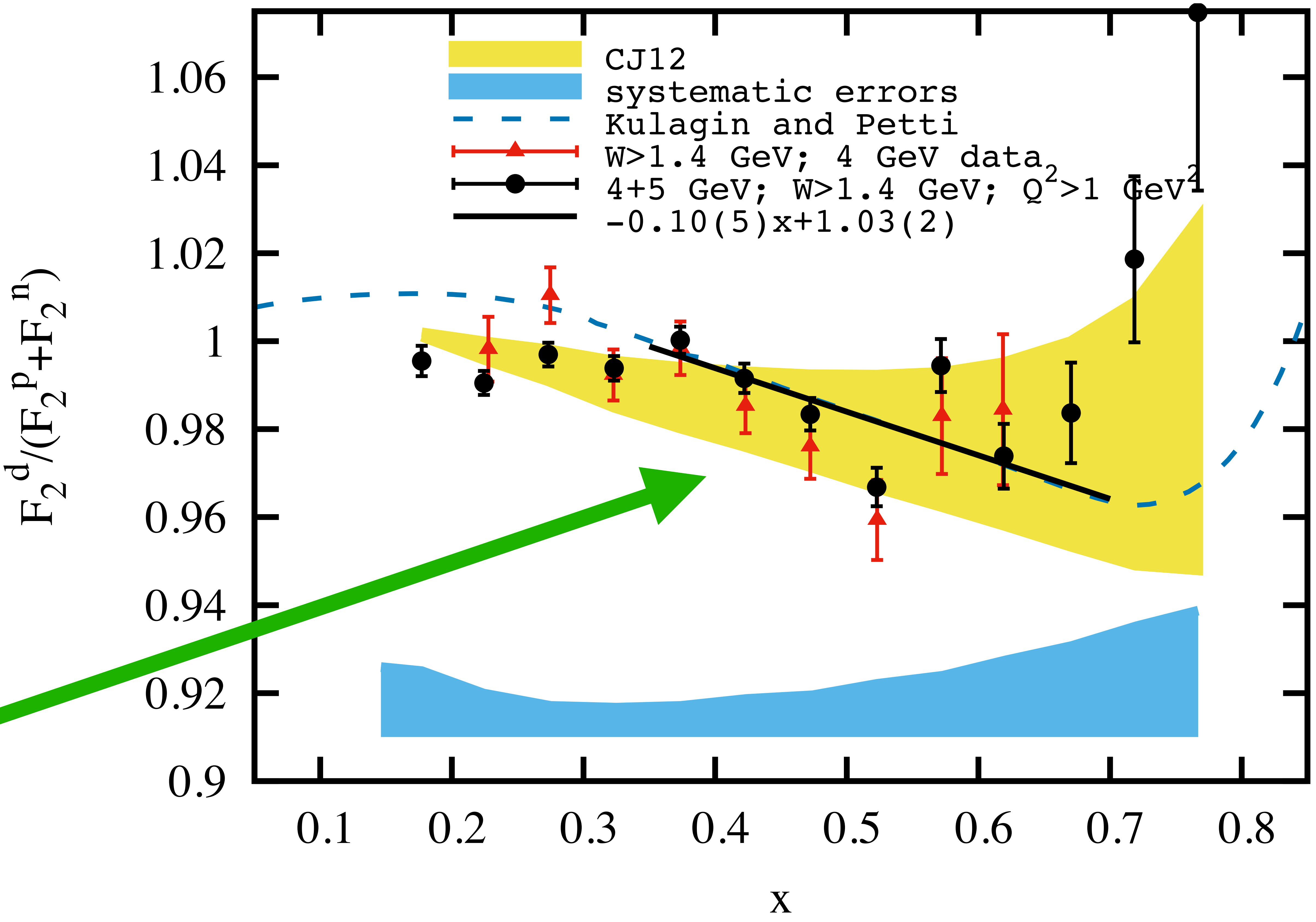
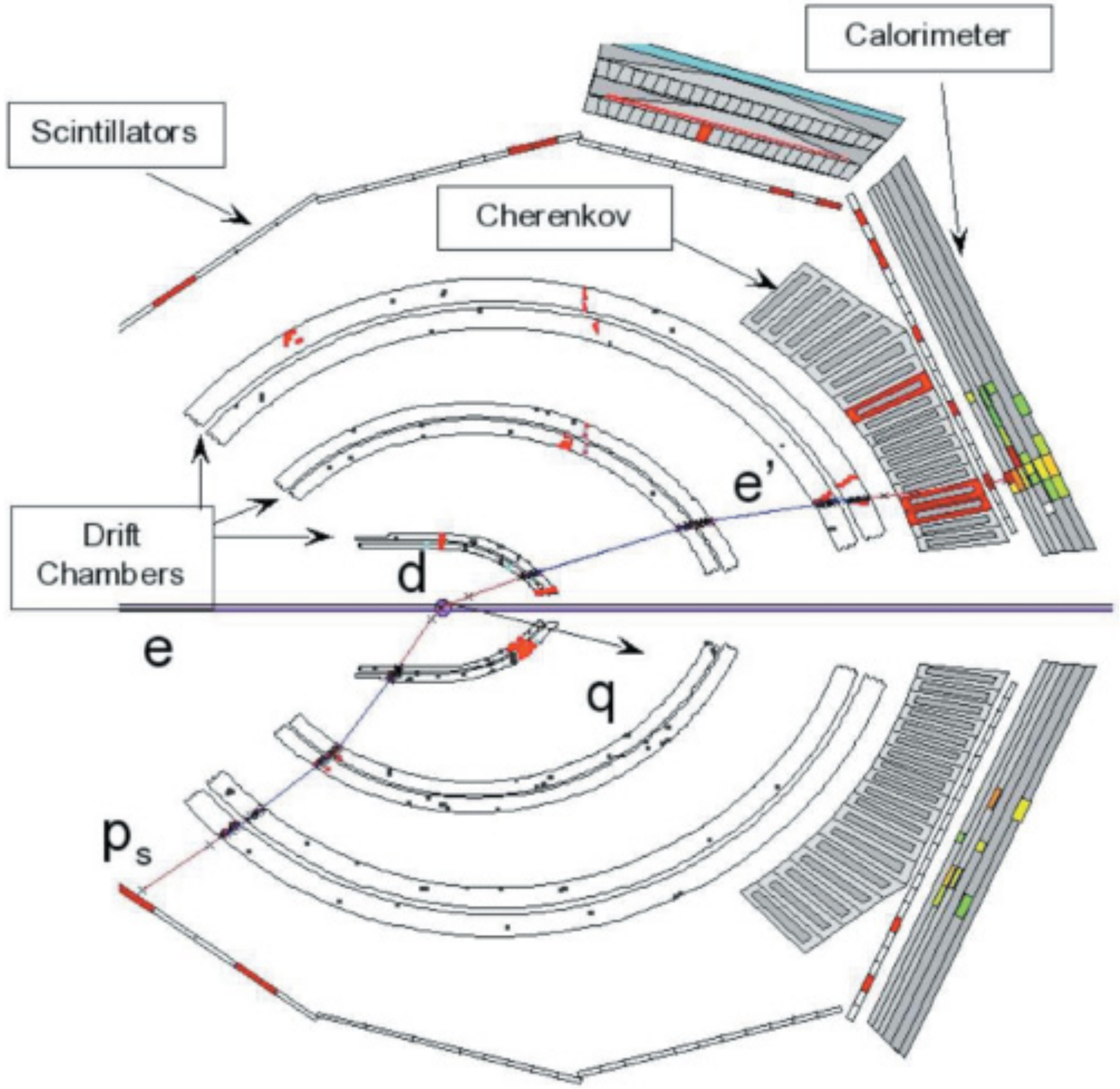


# $D(e, e'p_s)$

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



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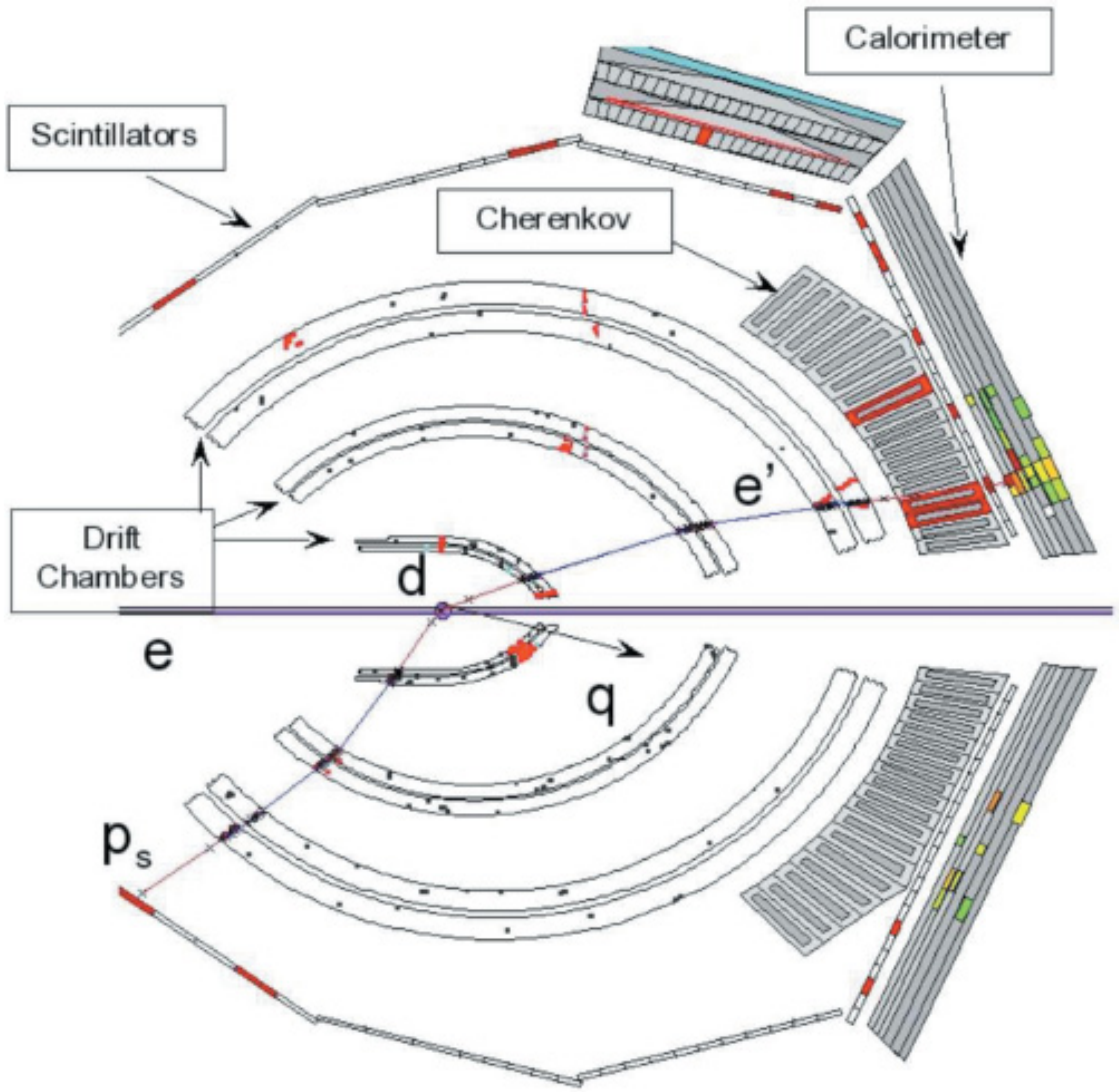
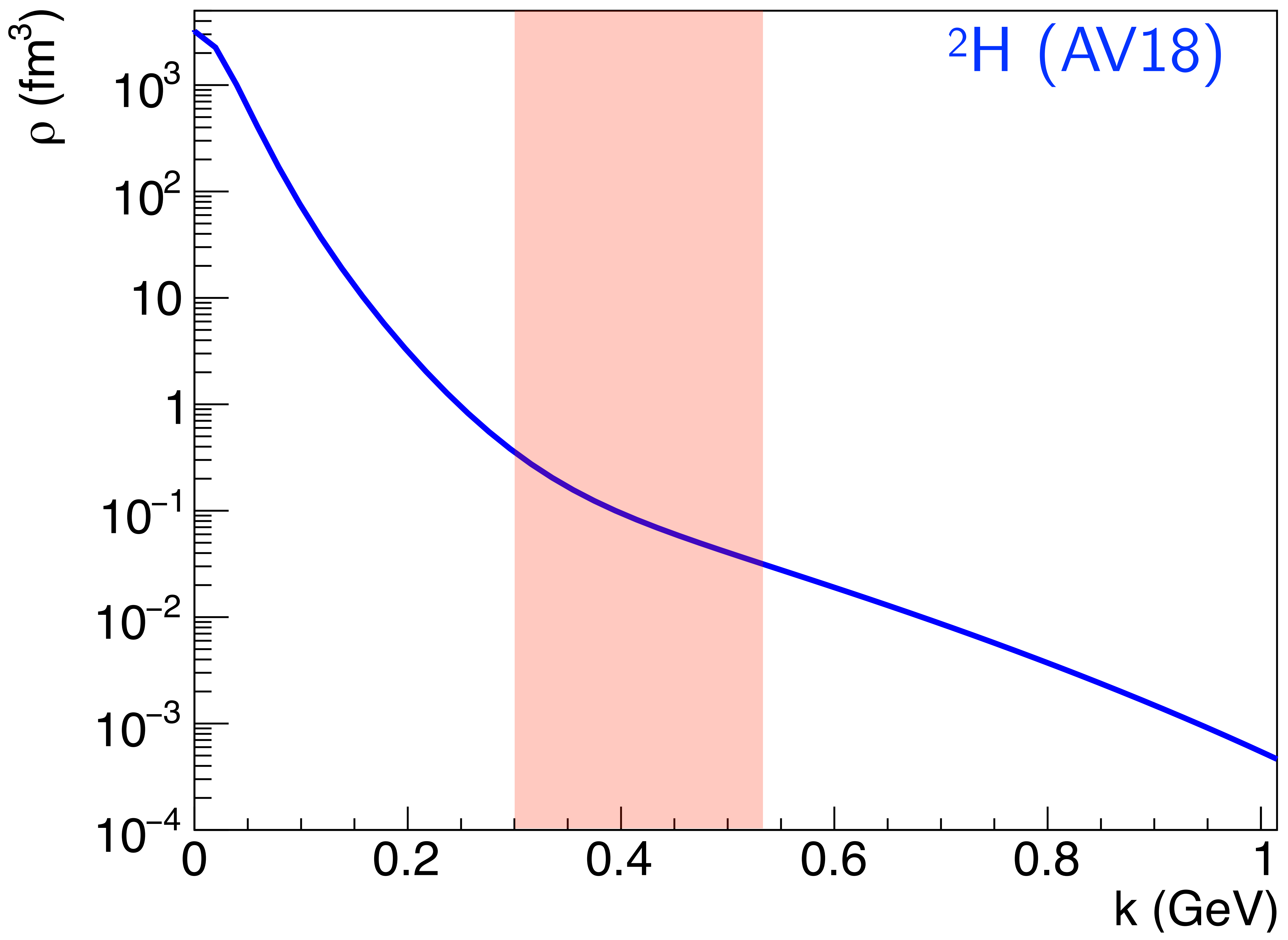
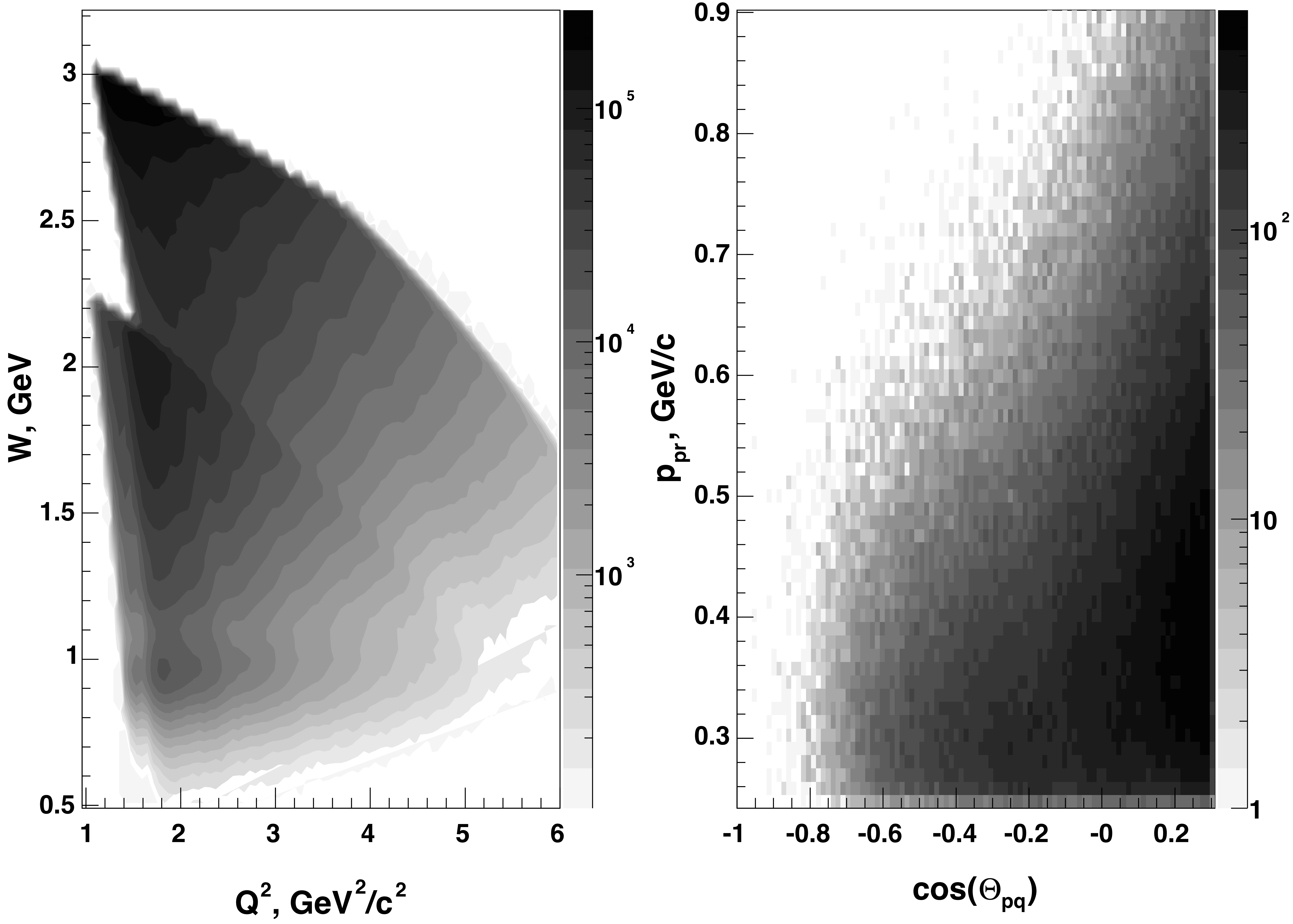


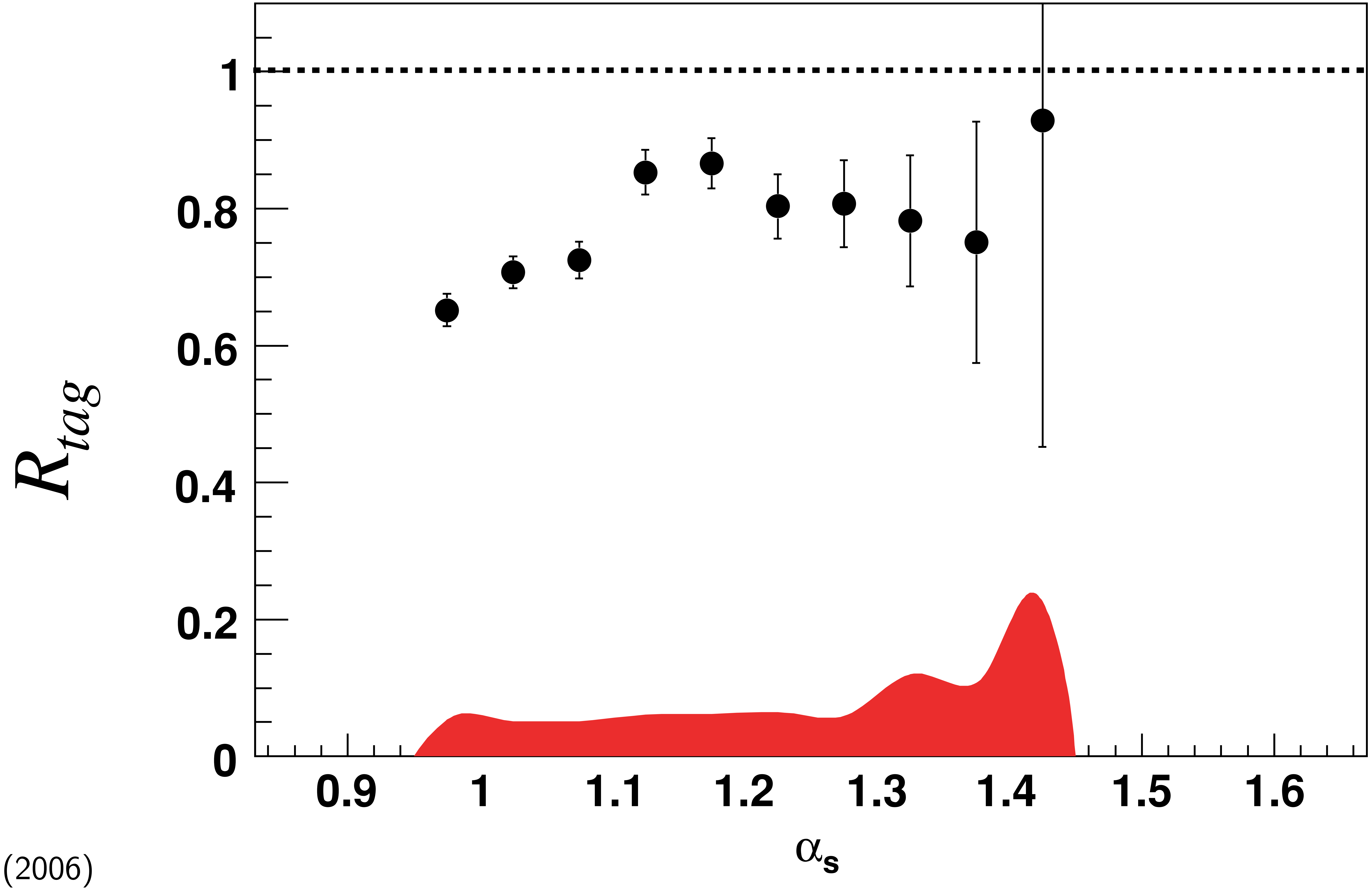
# $D(e, e'p_s)$ kinematic coverage was limited




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

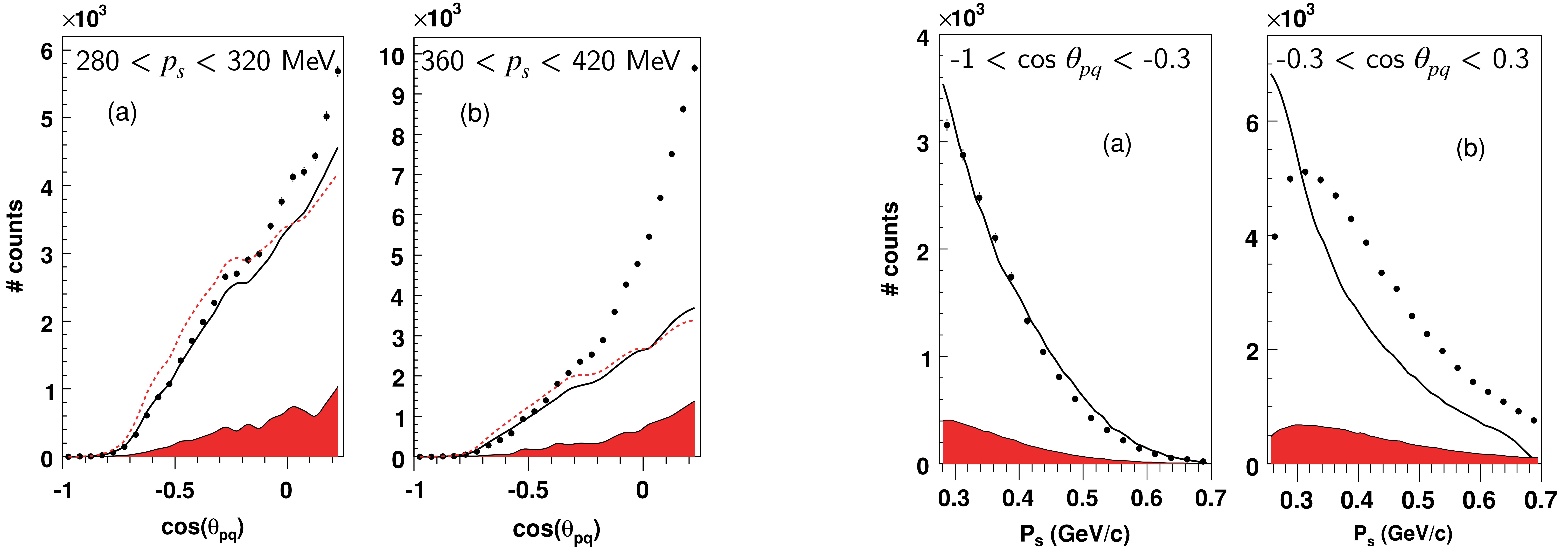
# $D(e, e'p_s)$ results

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




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

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

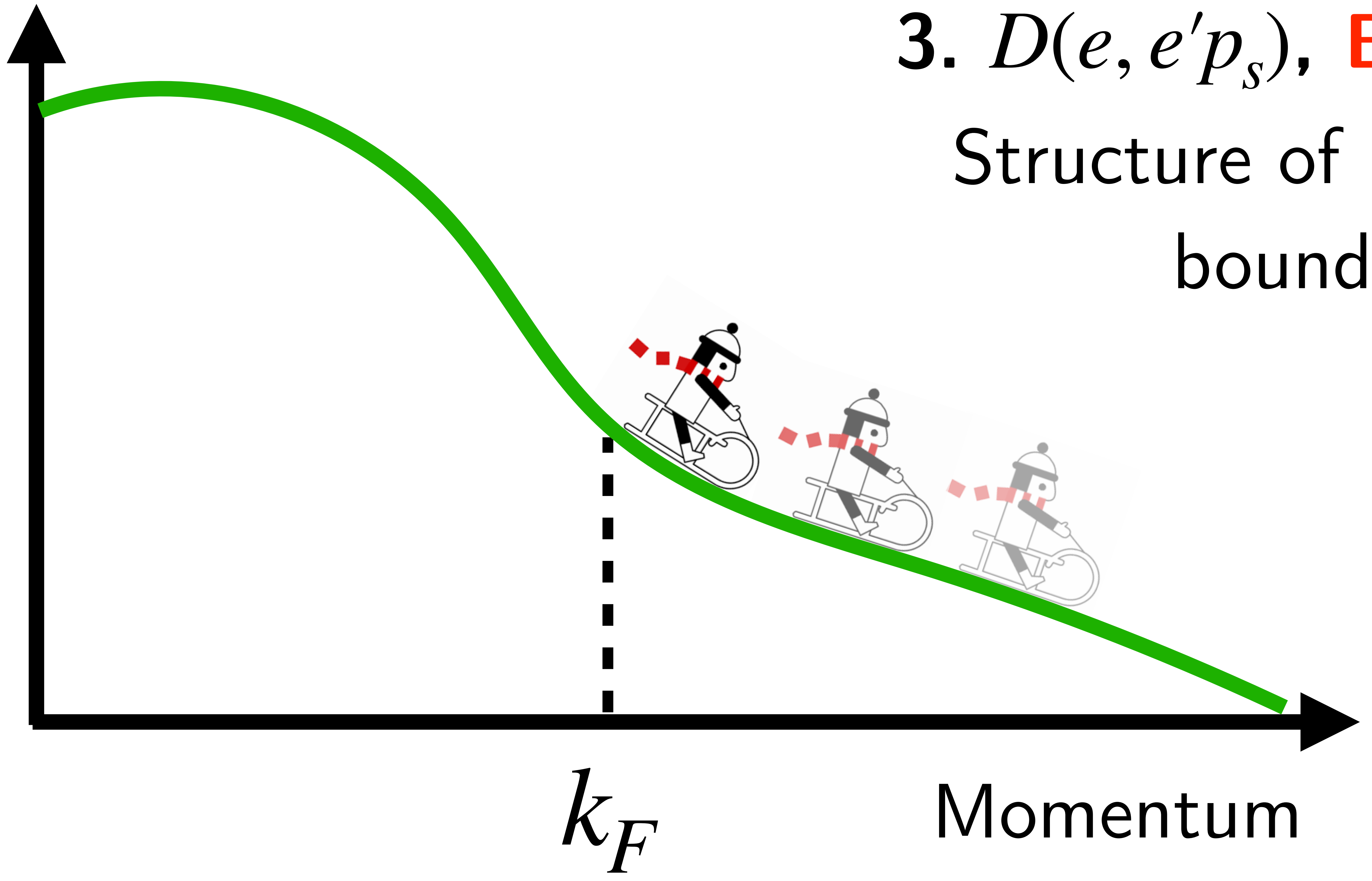



- Good agreement between data and PWIA at backward angles
- Enhancement in data (due to FSI?) at perpendicular angles

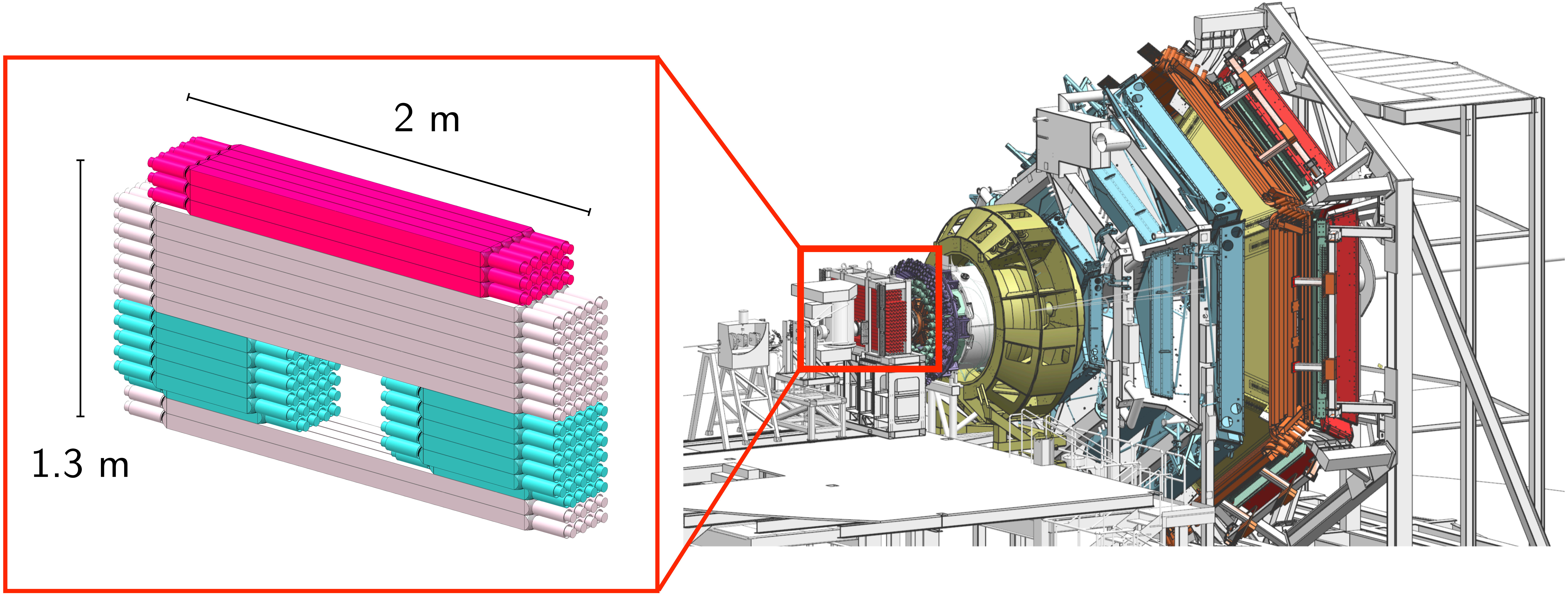
Klimenko, et al. PRC 73, 035212 (2006)

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

Structure of high-momentum bound nucleons



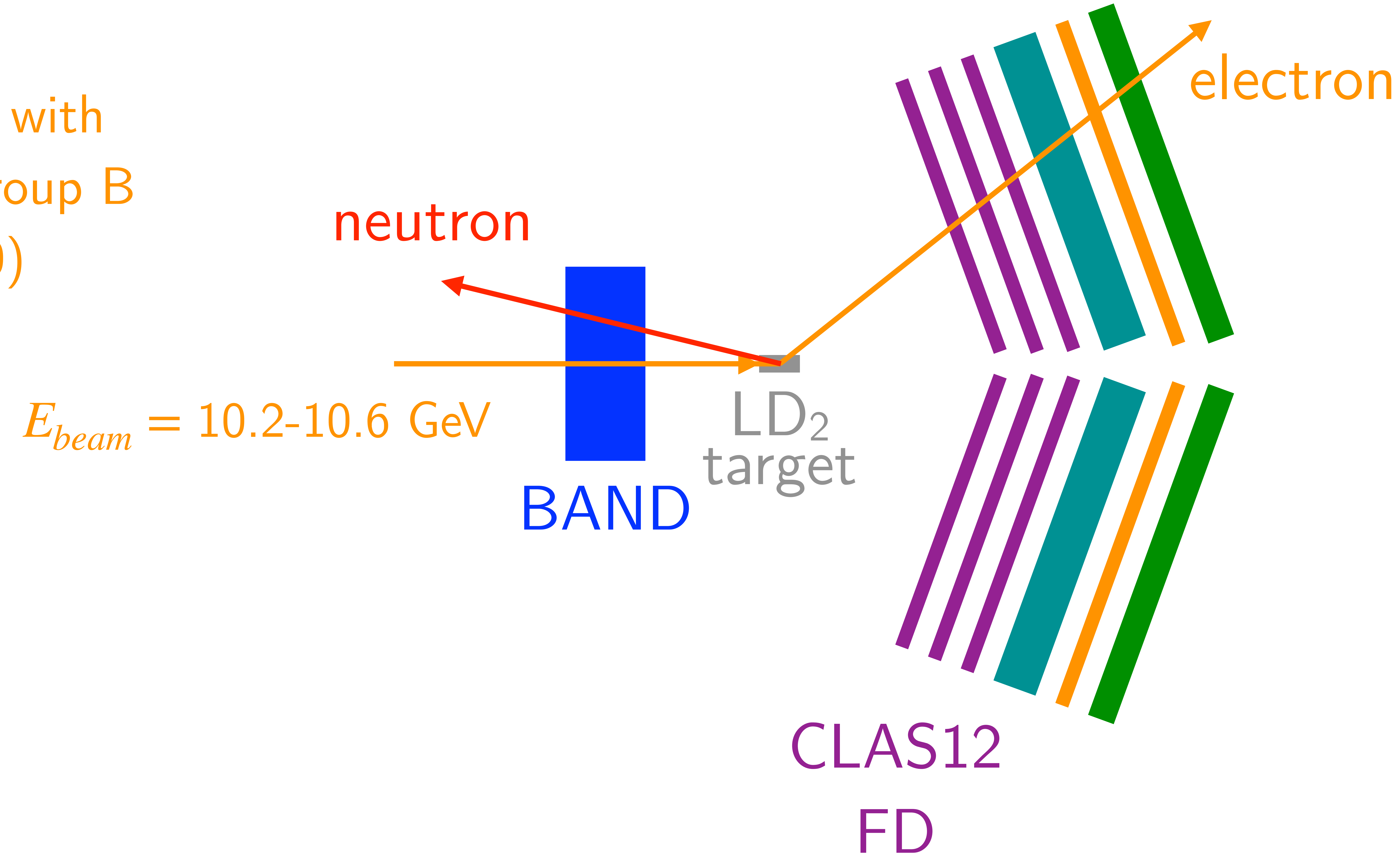
# BAND (Backward Angle Neutron Detector)




- 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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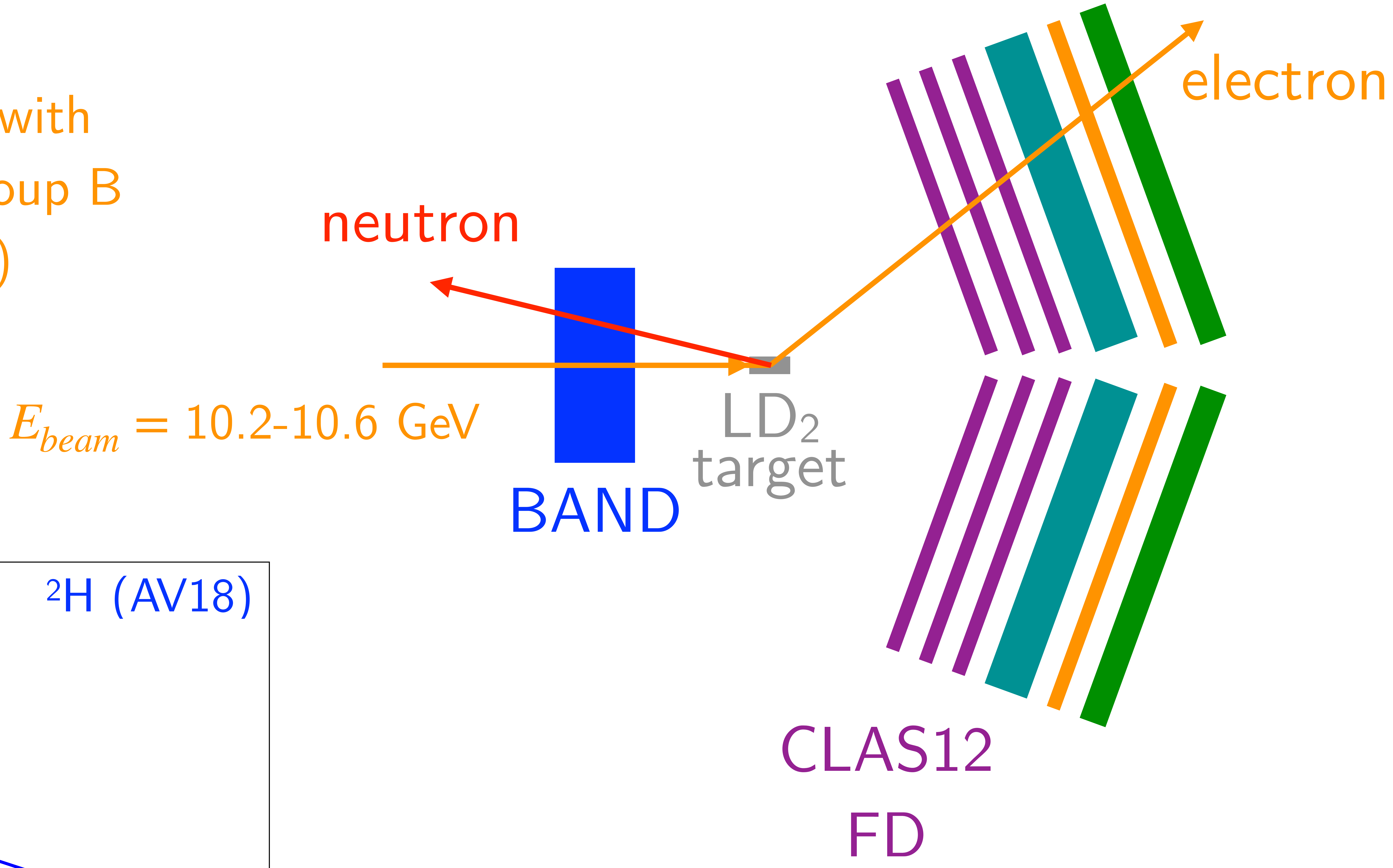
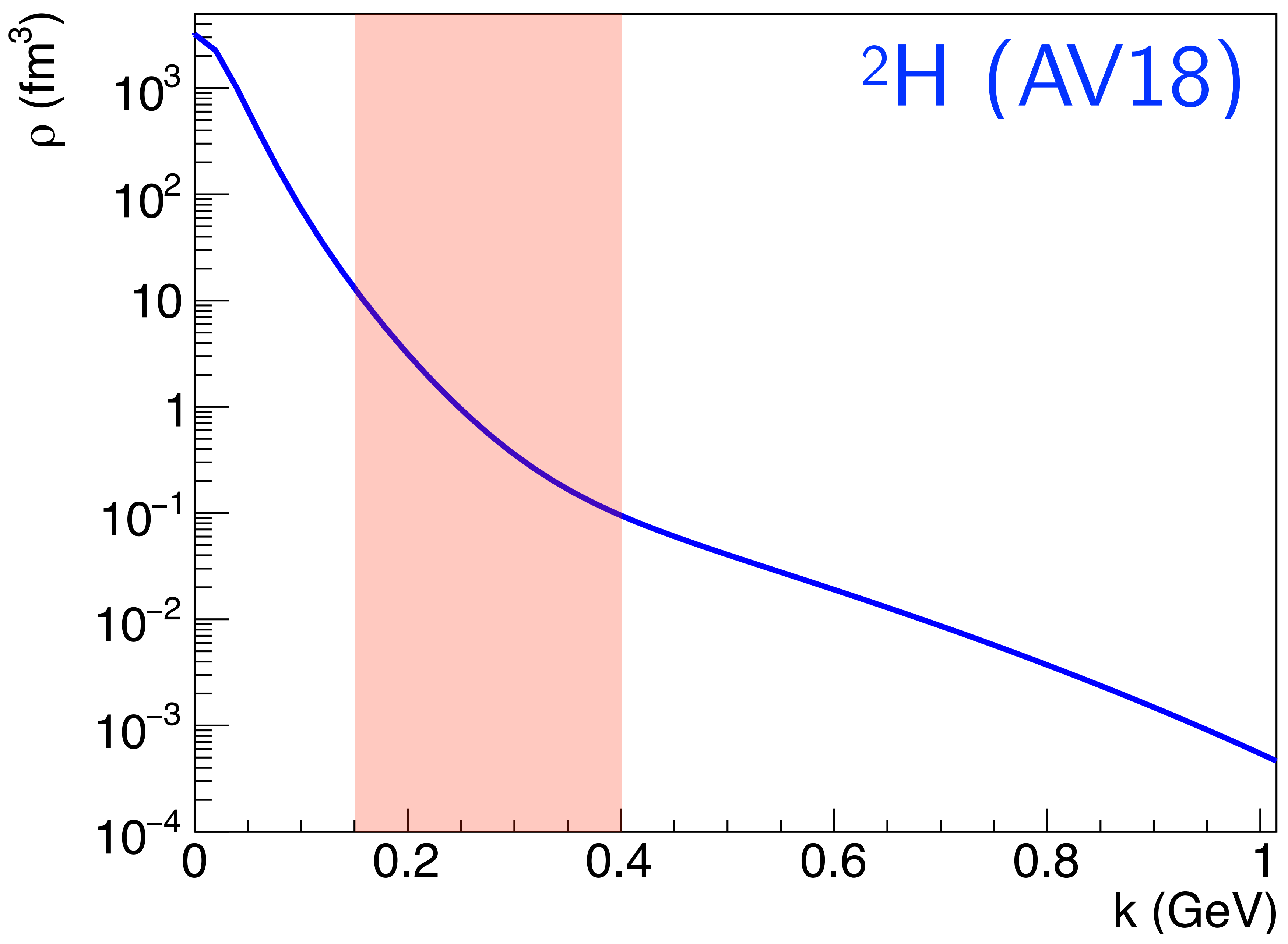


# BAND analysis team


Efrain Segarra


Florian Hauenstein


Jackson
Pybus


Natalie
Wright


Jason
Phelan


Sara
Ratliff

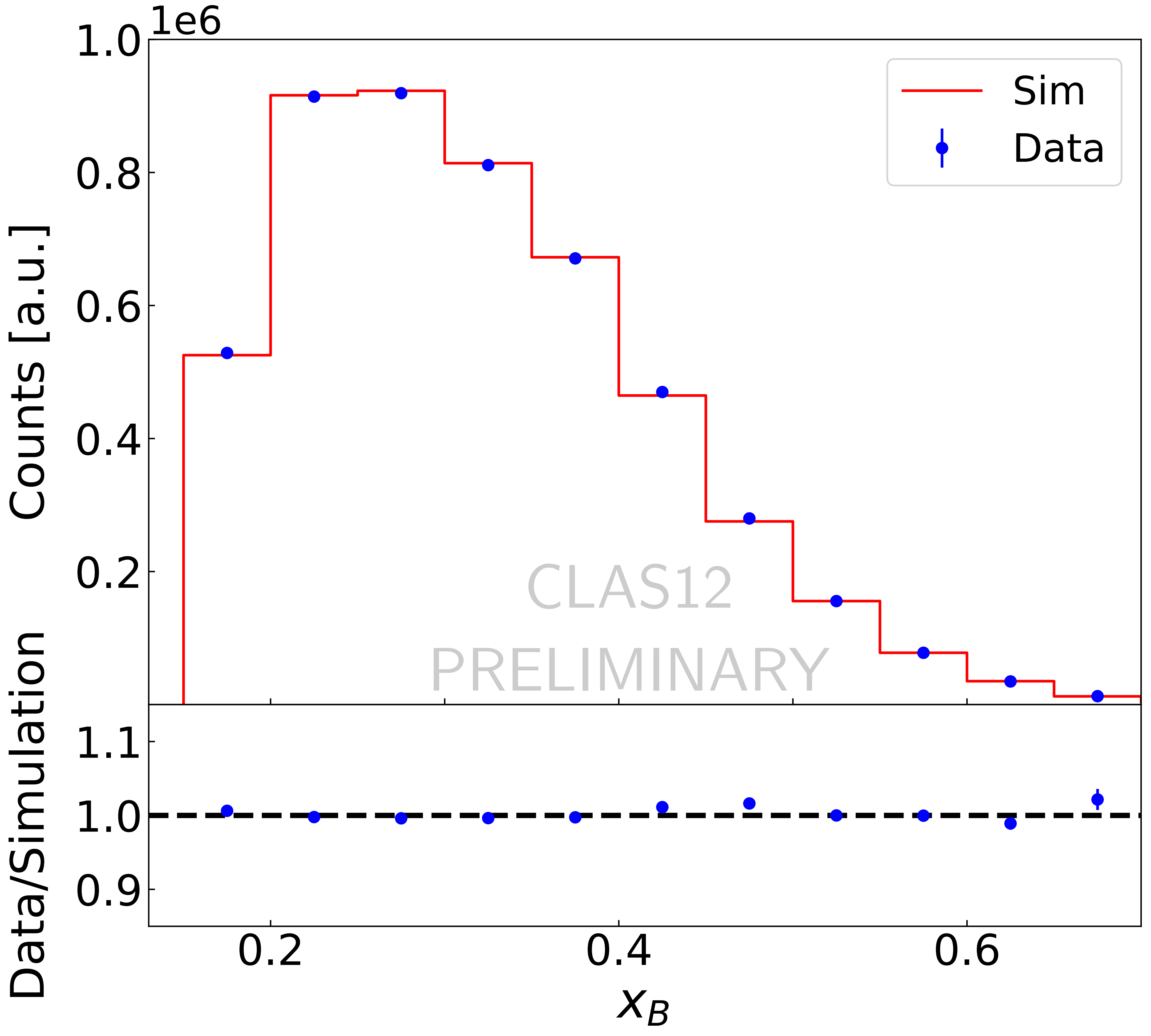
# Theory calculation for tagged DIS

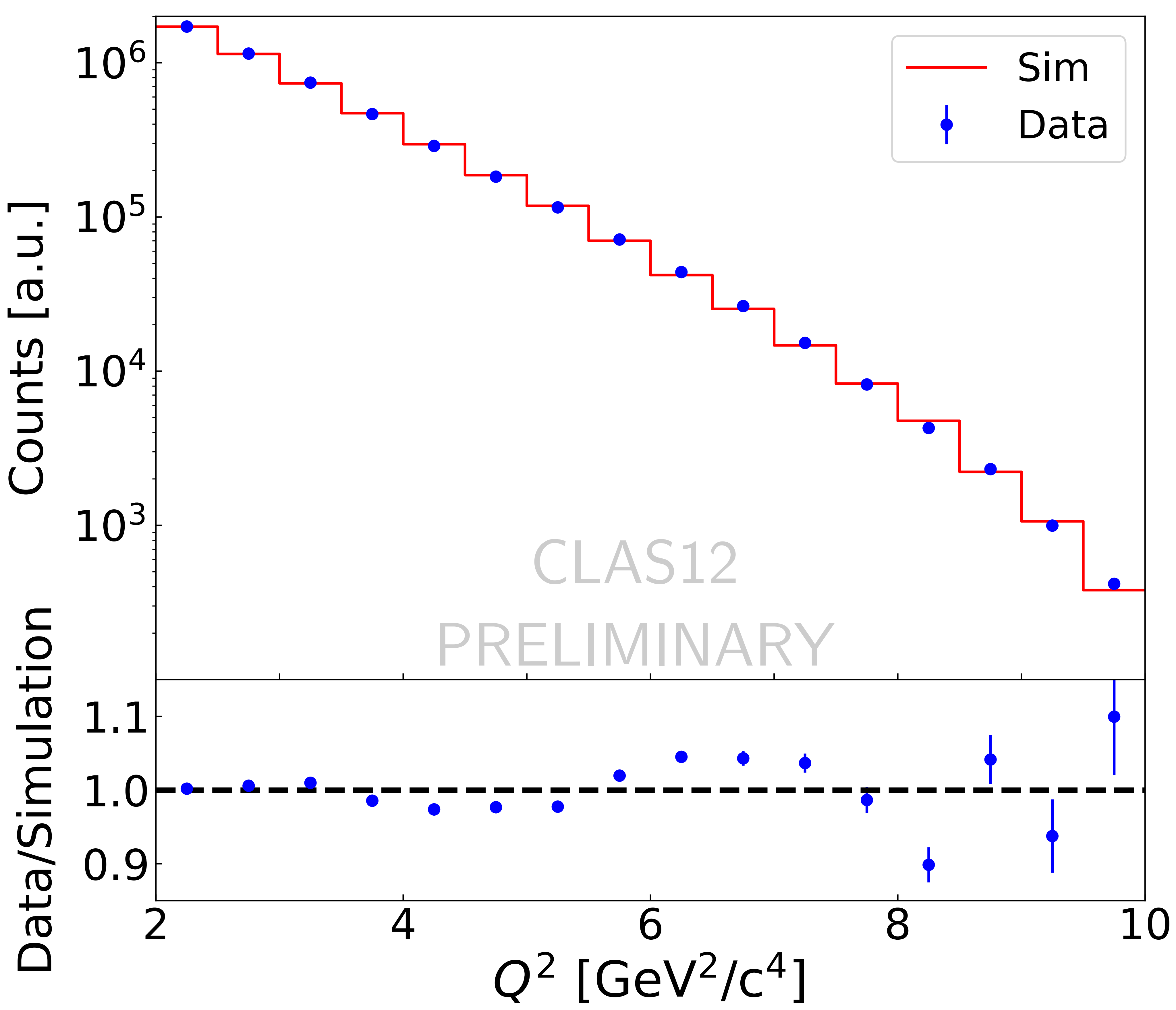
- Cross section model by M. Strikman & C. Weiss (PRC 97, 035209 (2018):

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

- 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

# Inclusive DIS results




$Q^2 > 2$ GeV2.

$W^2 > 4$ GeV2.

$y < 0.7$

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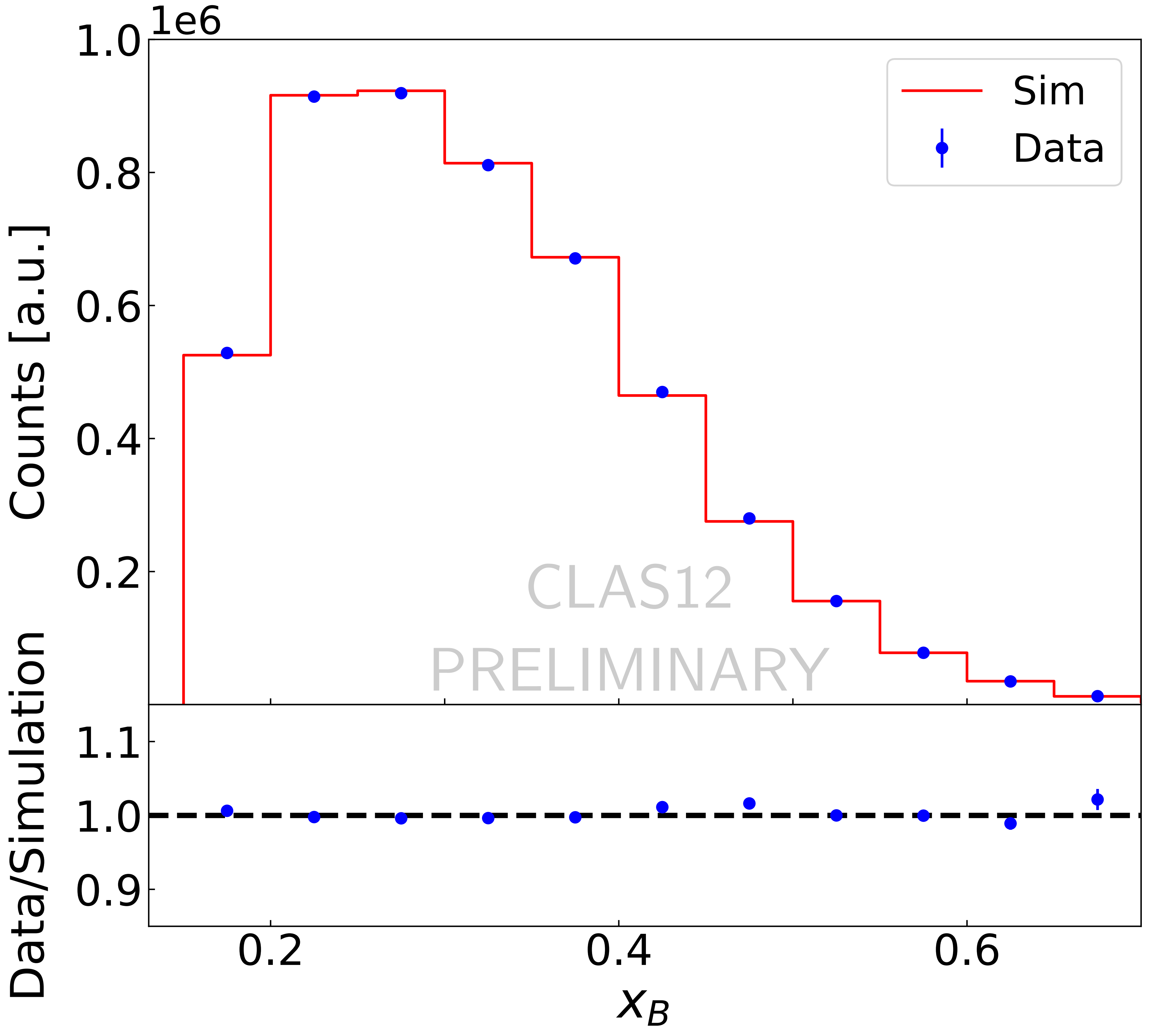


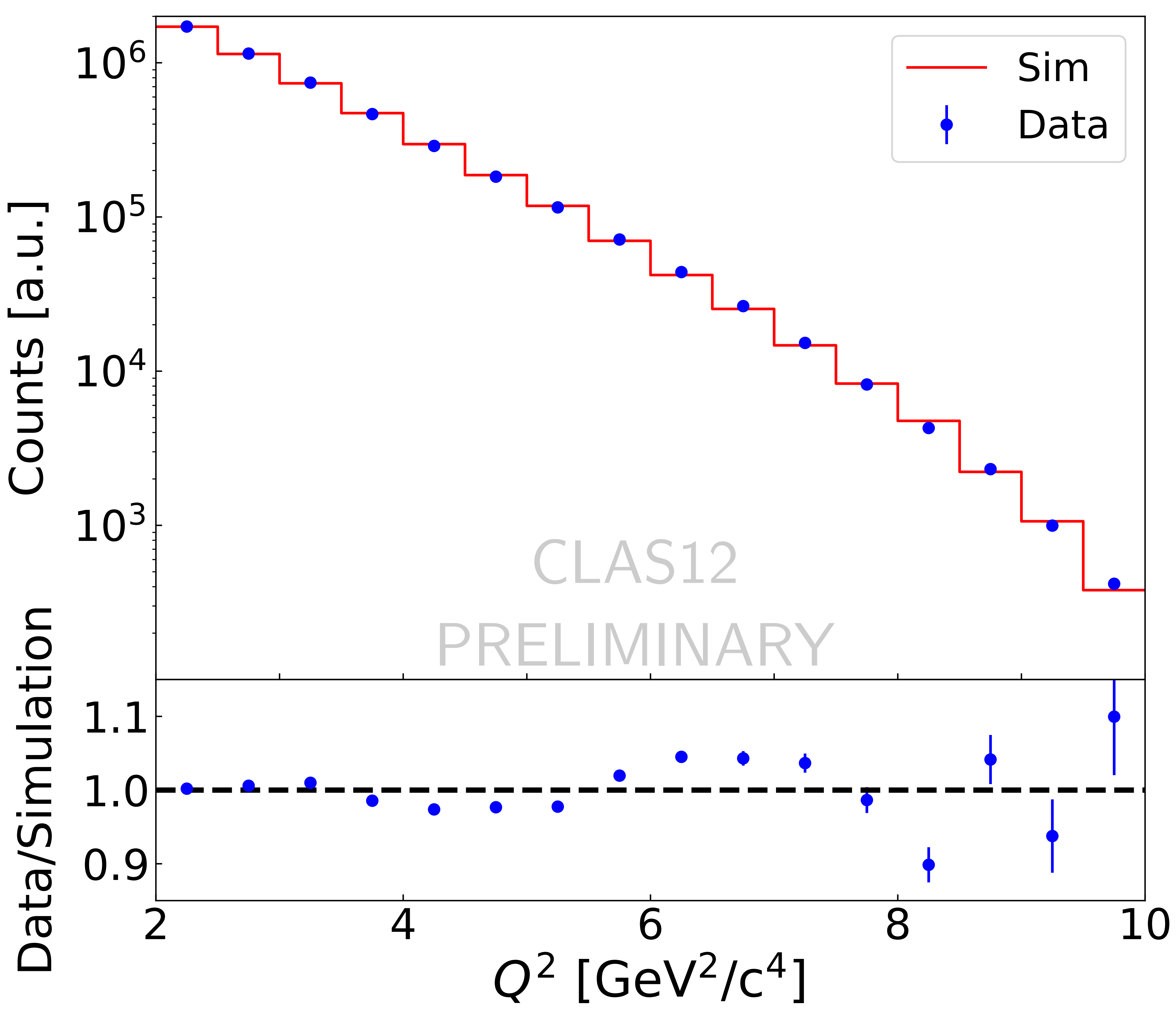


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✓ Validates simulation of electron in CLAS12

# 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 $\alpha_S$

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- Form double ratio for bins in $\alpha_S$
- Ratio gives cancellation of systematics

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

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- Form double ratio for bins in $\alpha_S$
- Ratio gives cancellation of systematics
- Choose to normalize to $x'_0 = 0.3$
- Sensitive to ratio of bound to free proton structure

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

# Tagged DIS

$E_{dep} > 10$ MeVee

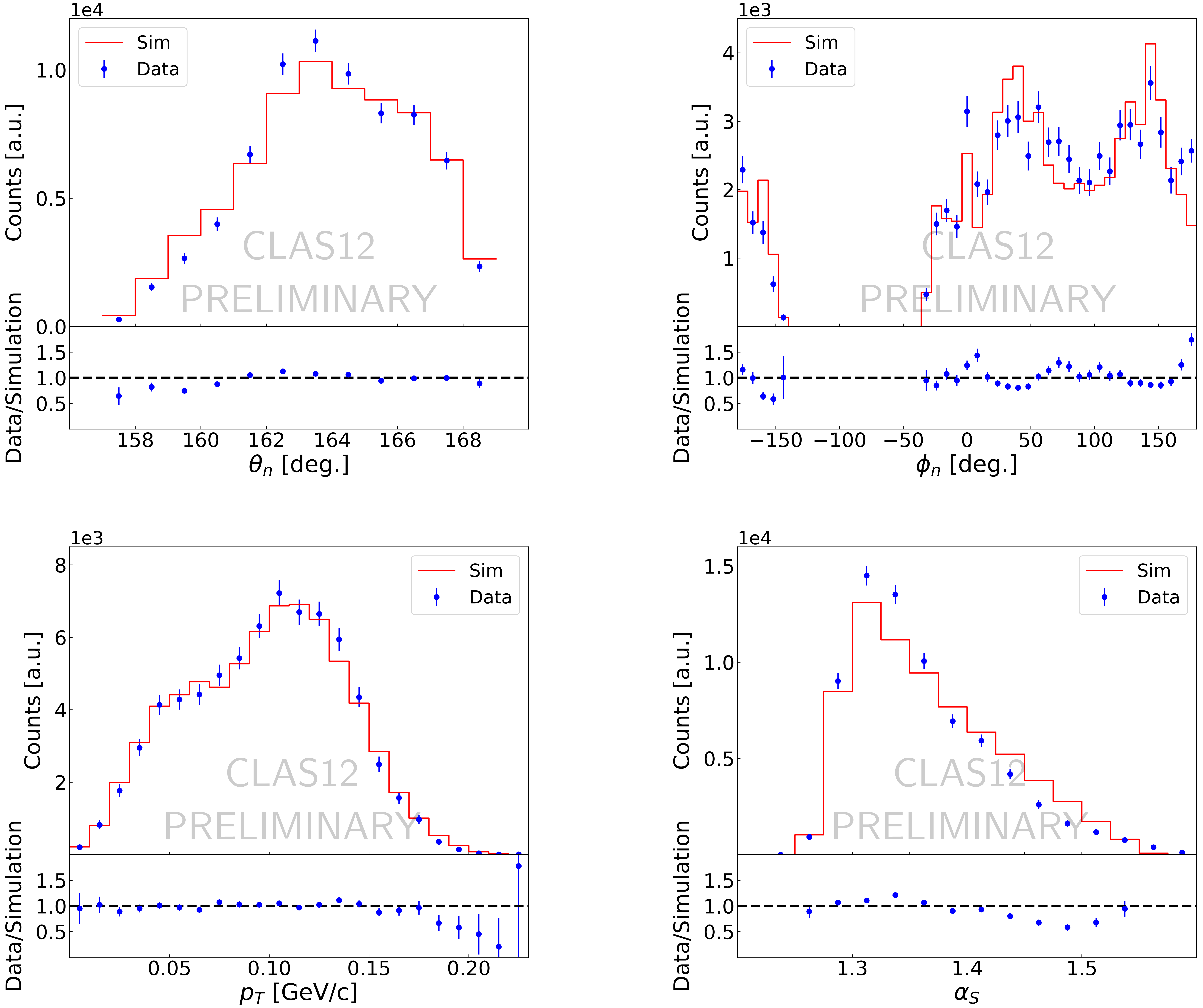
$p_n > 0.25$ GeV

$\theta_n < 168.5°$

$W' > 1.8$ GeV

$\alpha_s > 1.2$

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



# BAND invariant mass with/without tagging

(2 GeV deuterium data from RG-M)

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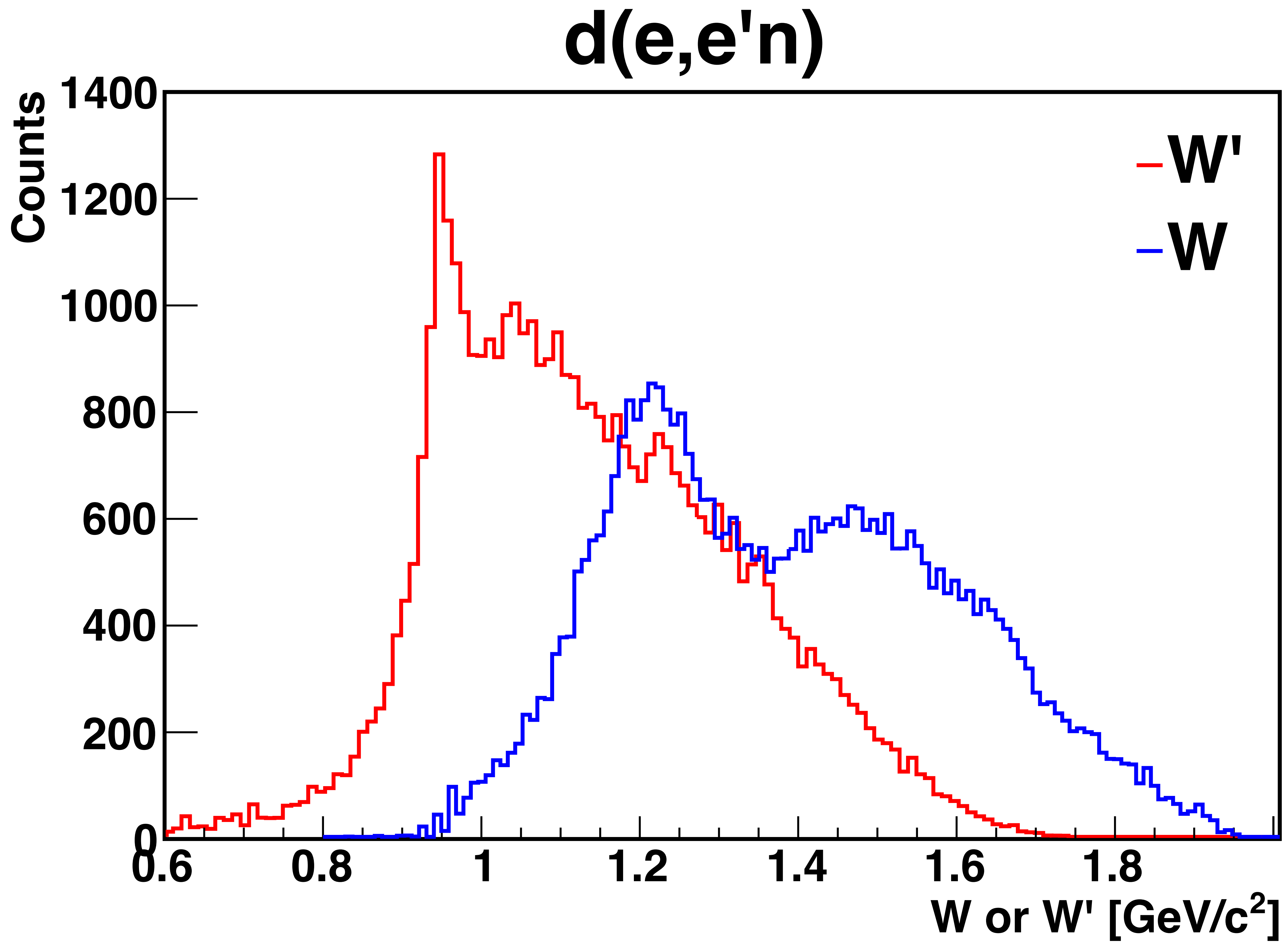
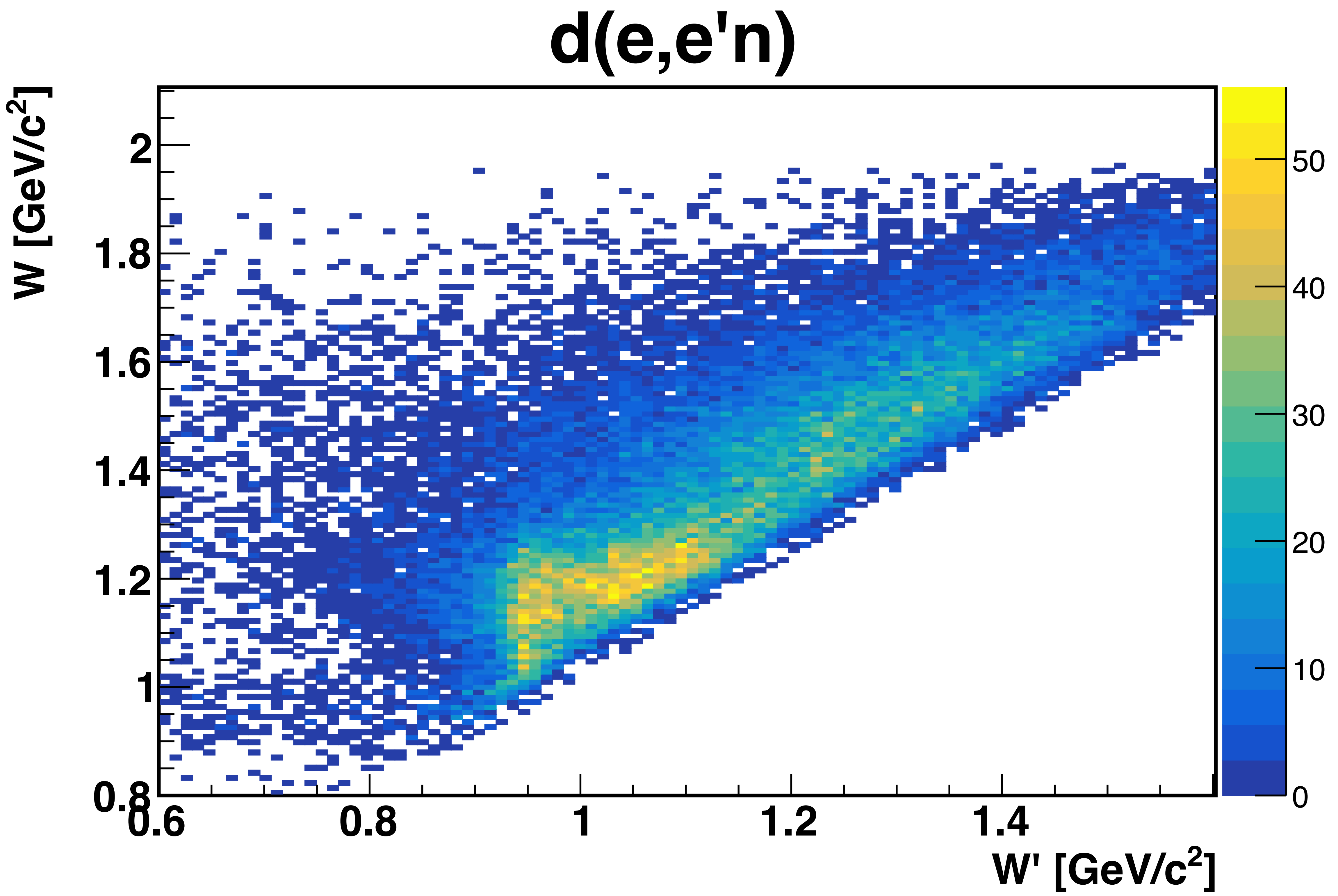
- Two big differences from BoNuS:
  - Higher spectator momentum
  - Larger range in spectator momentum

# BAND invariant mass with/without tagging

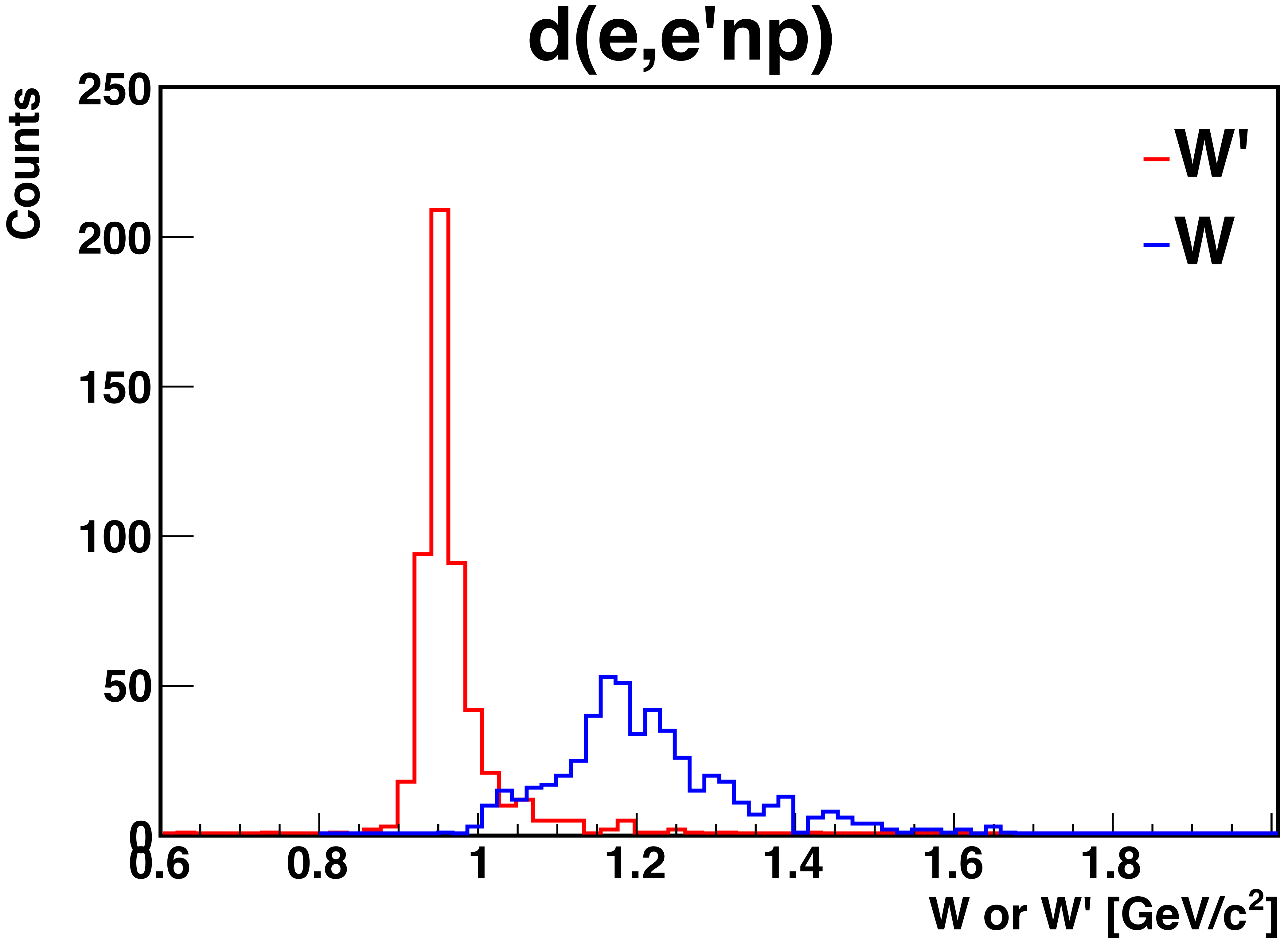
(2 GeV deuterium data from RG-M)

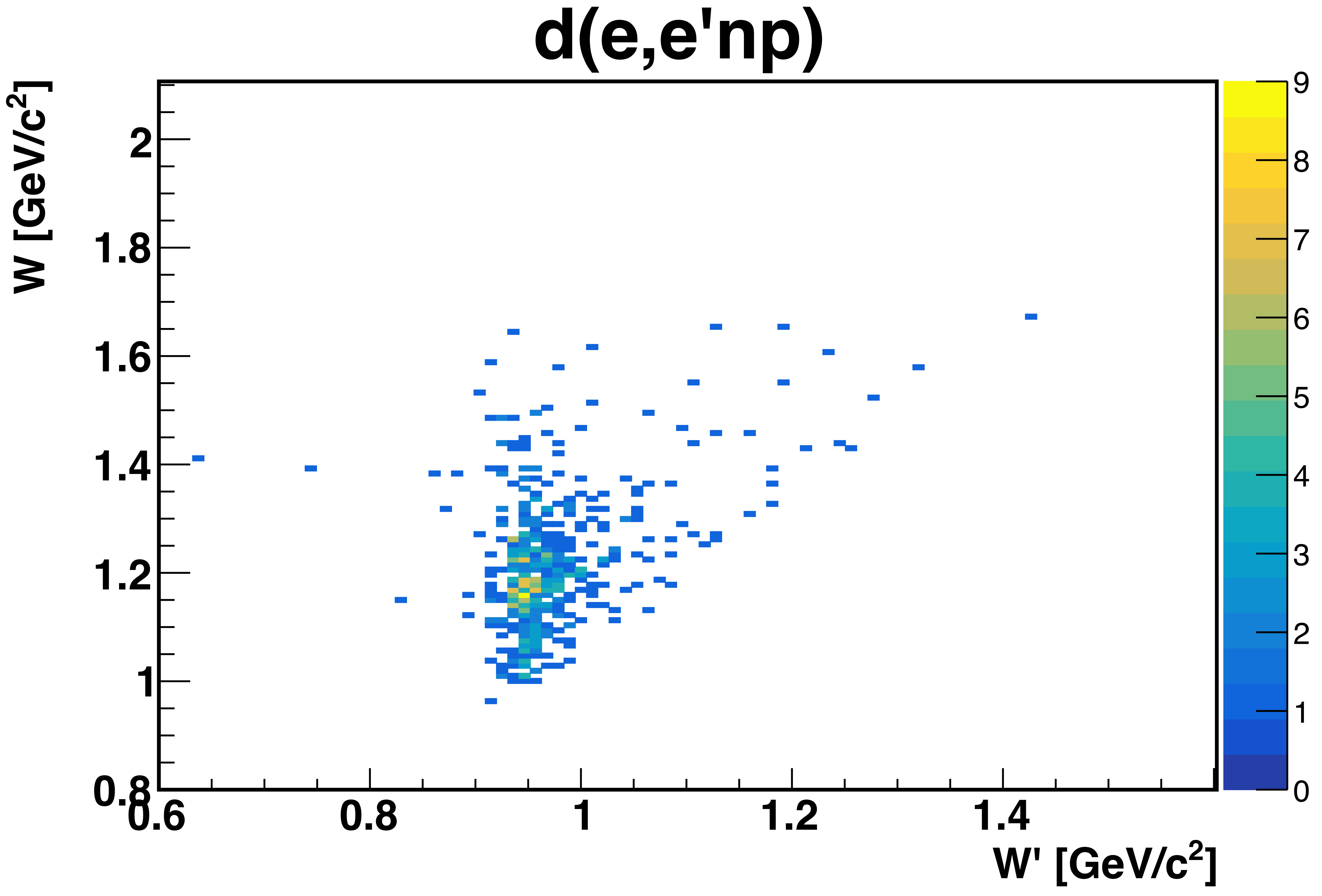


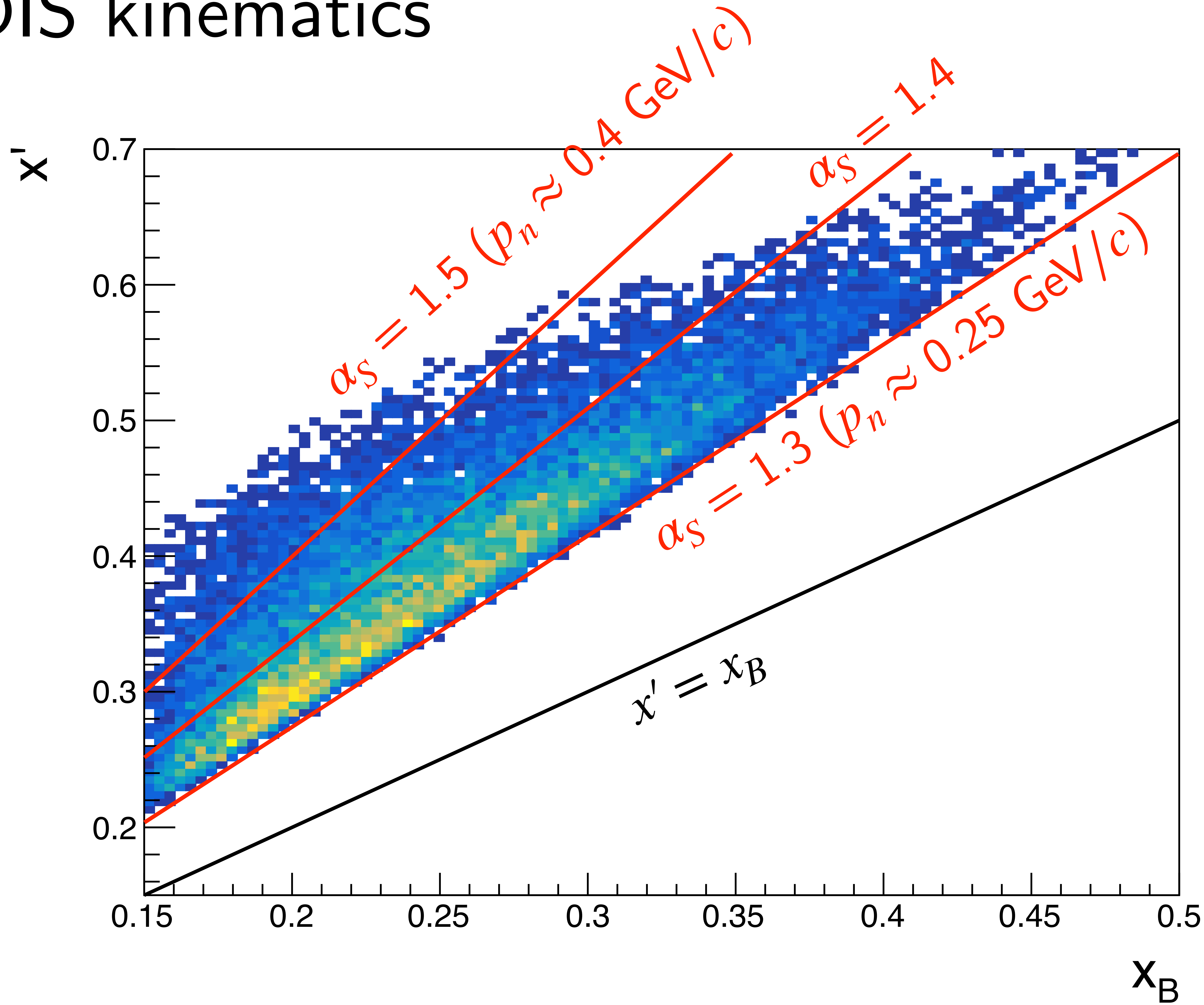
# BAND invariant mass with/without tagging

(2 GeV deuterium data from RG-M)

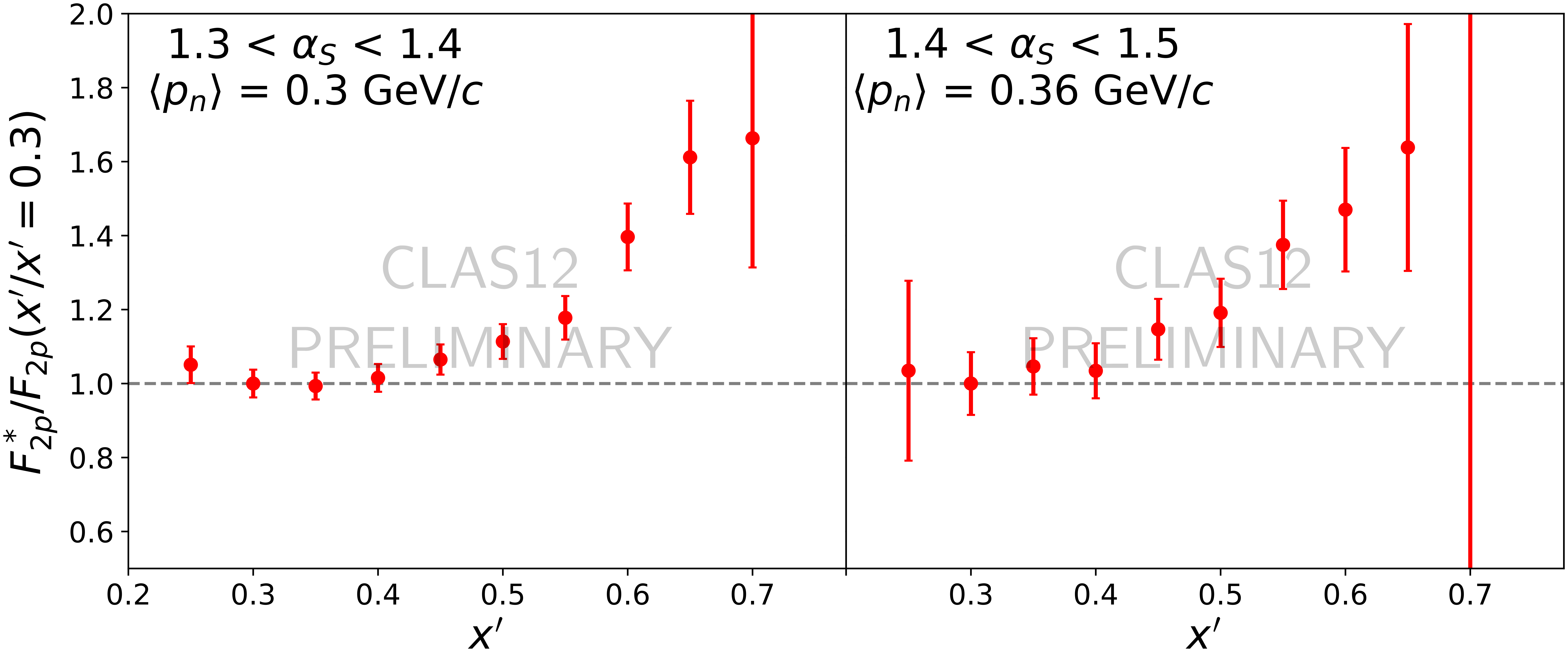


# Tagged DIS kinematics

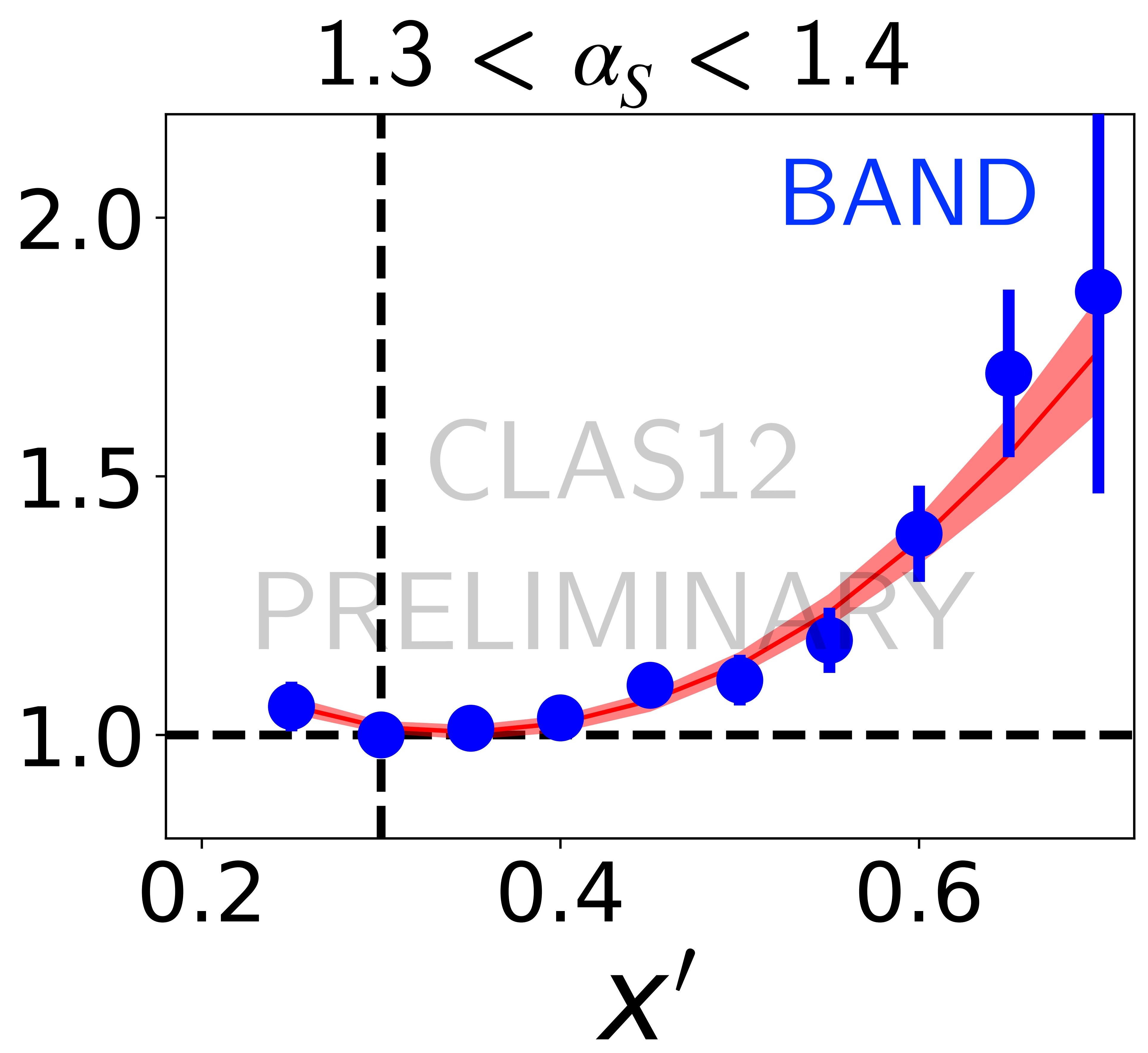


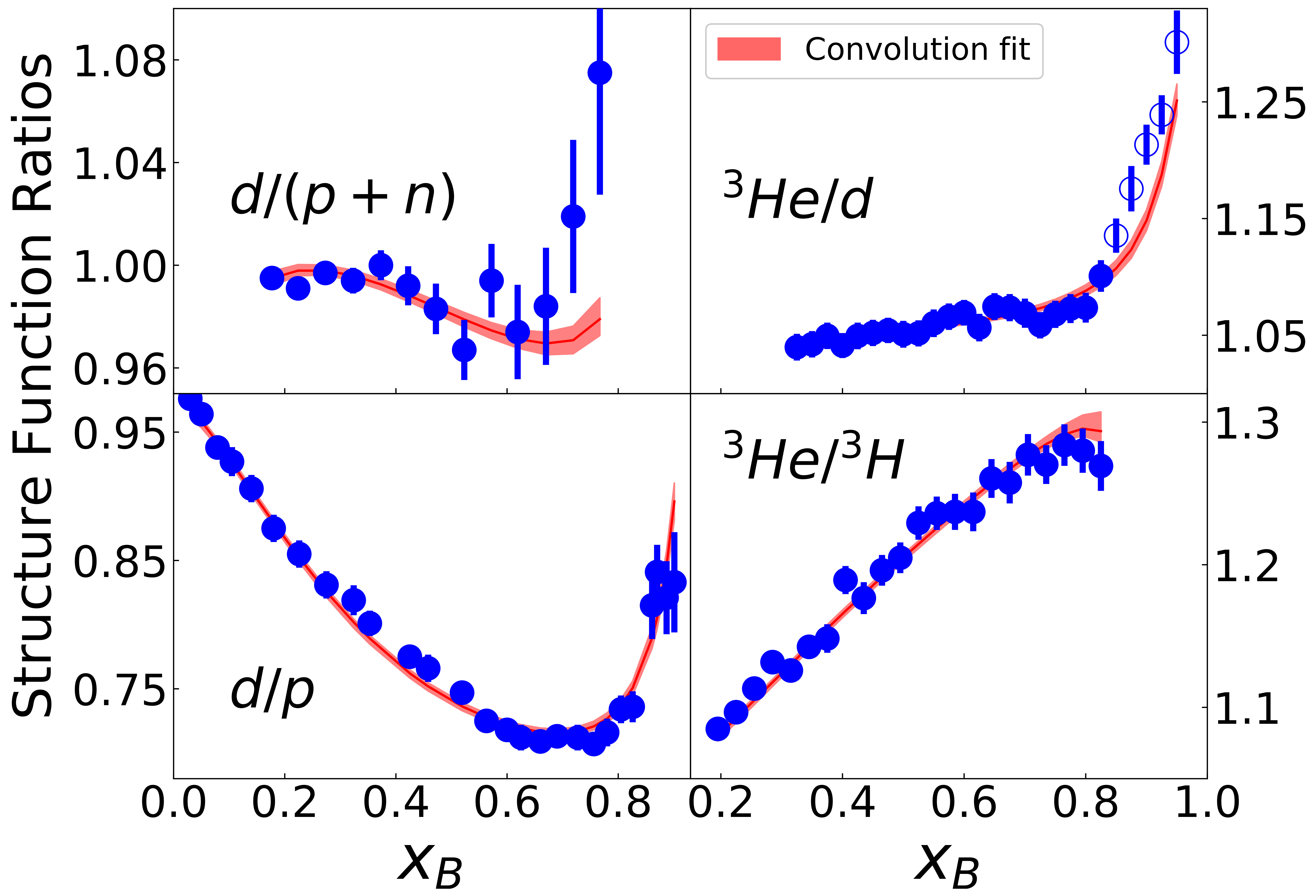
# Tagged DIS double ratio




Large, $x'$-dependent effect in high-$\alpha_S$ protons

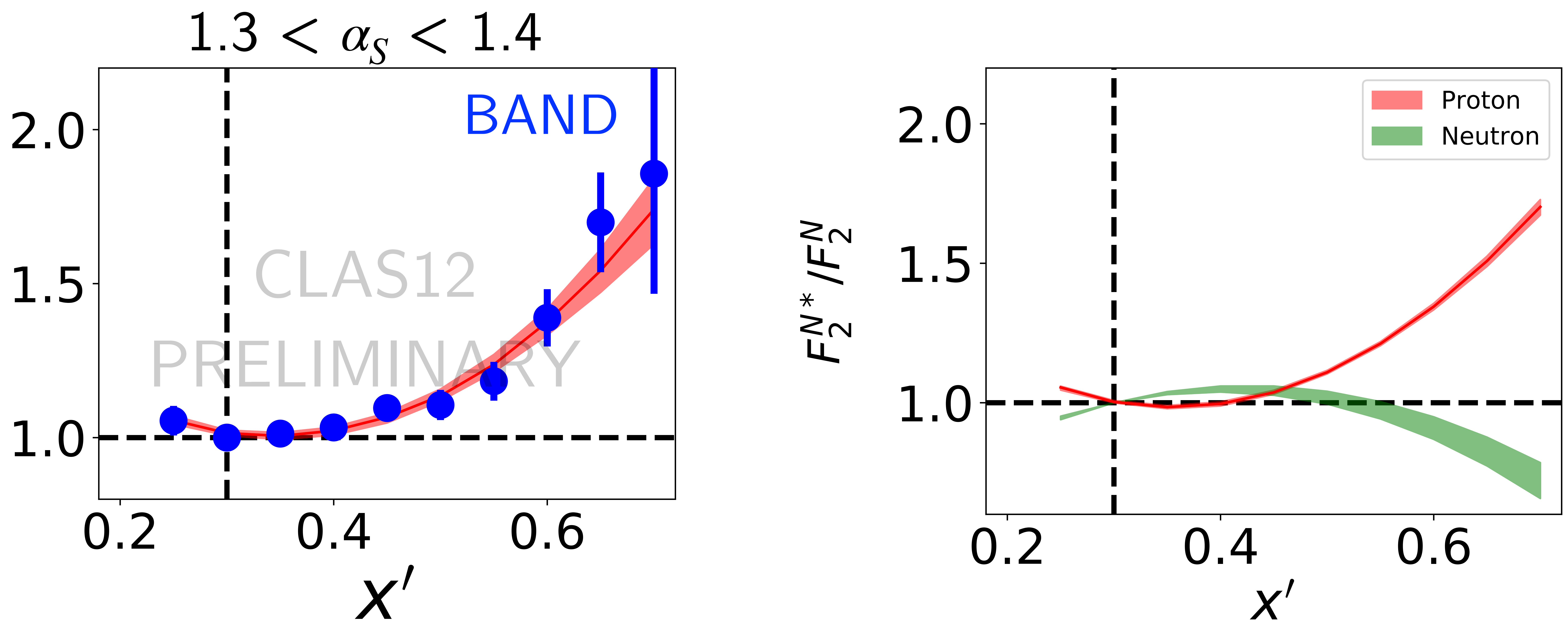
# Result consistent with inclusive measurements of light nuclei...

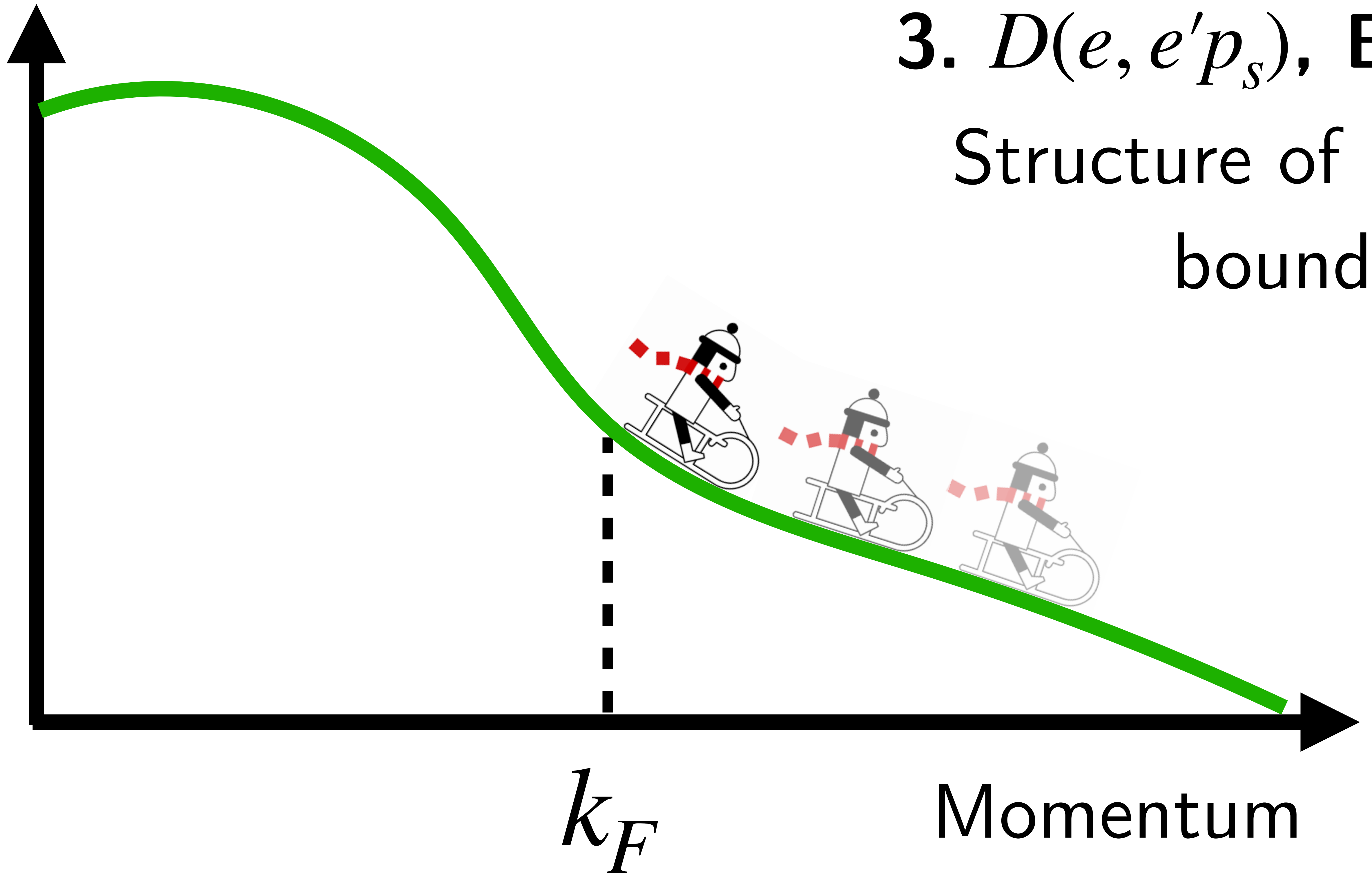



$$F_2^A(x_B) = \frac{1}{A}\int_{x_B}^{A}\frac{d\alpha}{\alpha}\int_{-\infty}^{0} dv\, F_2^p(x')\left[Z\rho_p(\alpha,v) + N\rho_n(\alpha,v)\frac{F_2^n(x')}{F_2^p(x')}\right]\times\left(1 + v\, f^{os}(x')\right)$$

# …and gives a prediction for bound *neutron* structure!

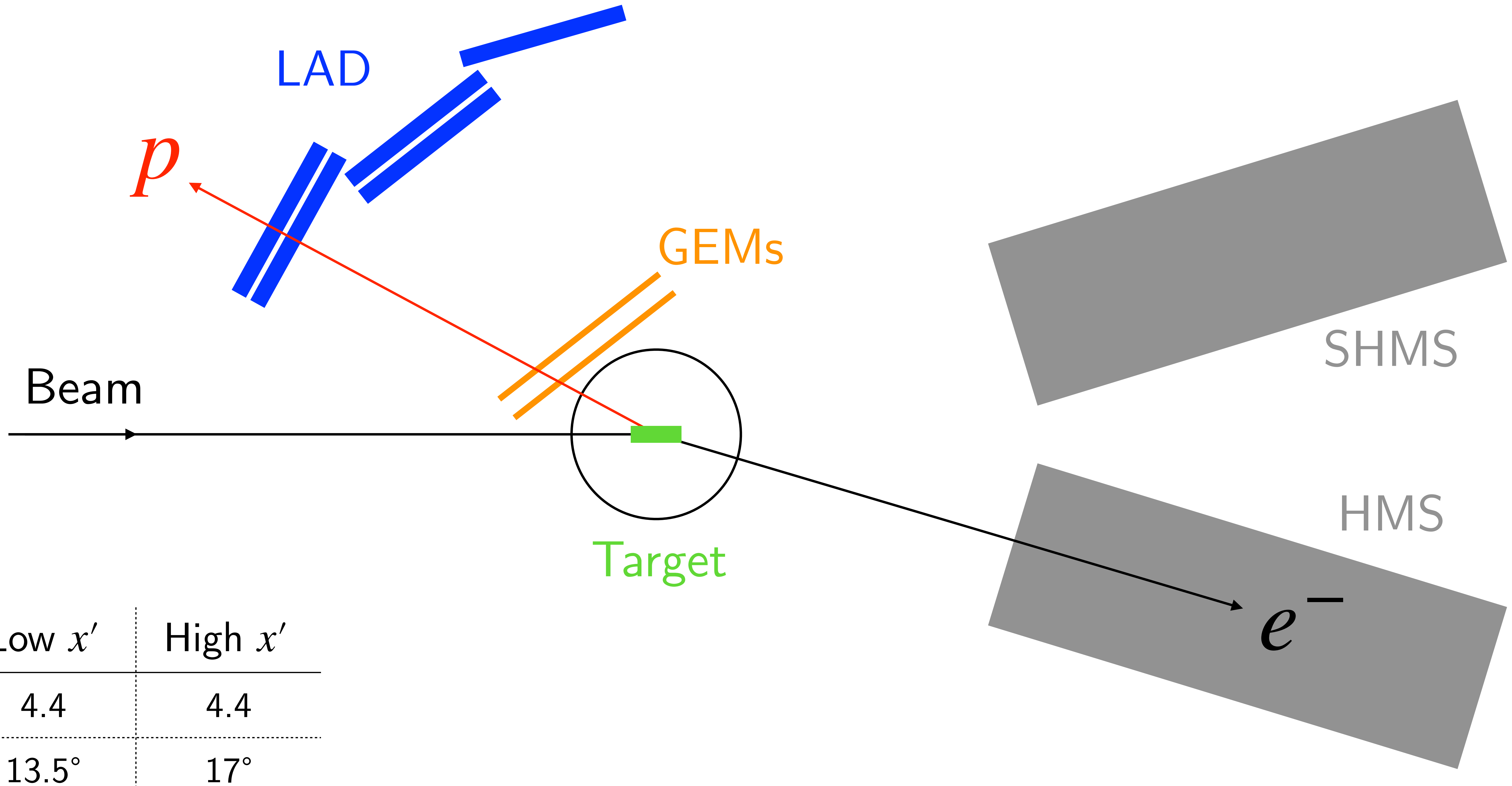





**3.** $D(e, e'p_s)$**, BAND, and LAD**

Structure of high-momentum bound nucleons

# Large Angle Detector (LAD) in Hall C

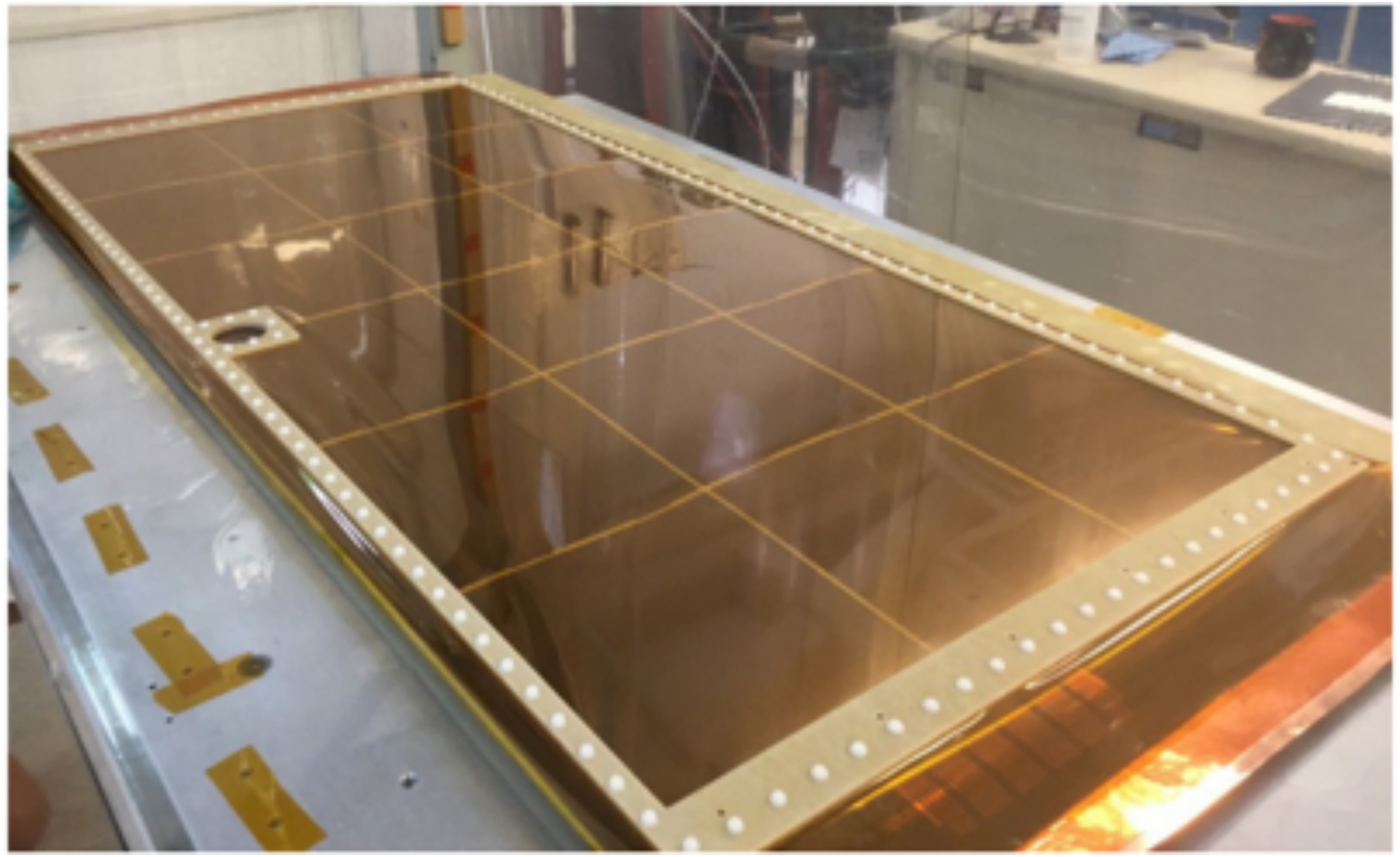



| | Low $x'$ | High $x'$ |
|---|---|---|
| $E'$ (GeV) | 4.4 | 4.4 |
| $\theta_e$ | 13.5° | 17° |
| $Q^2$ (GeV$^2$) | 2.7 | 4.2 |
| $x_B$ | 0.22 | 0.34 |

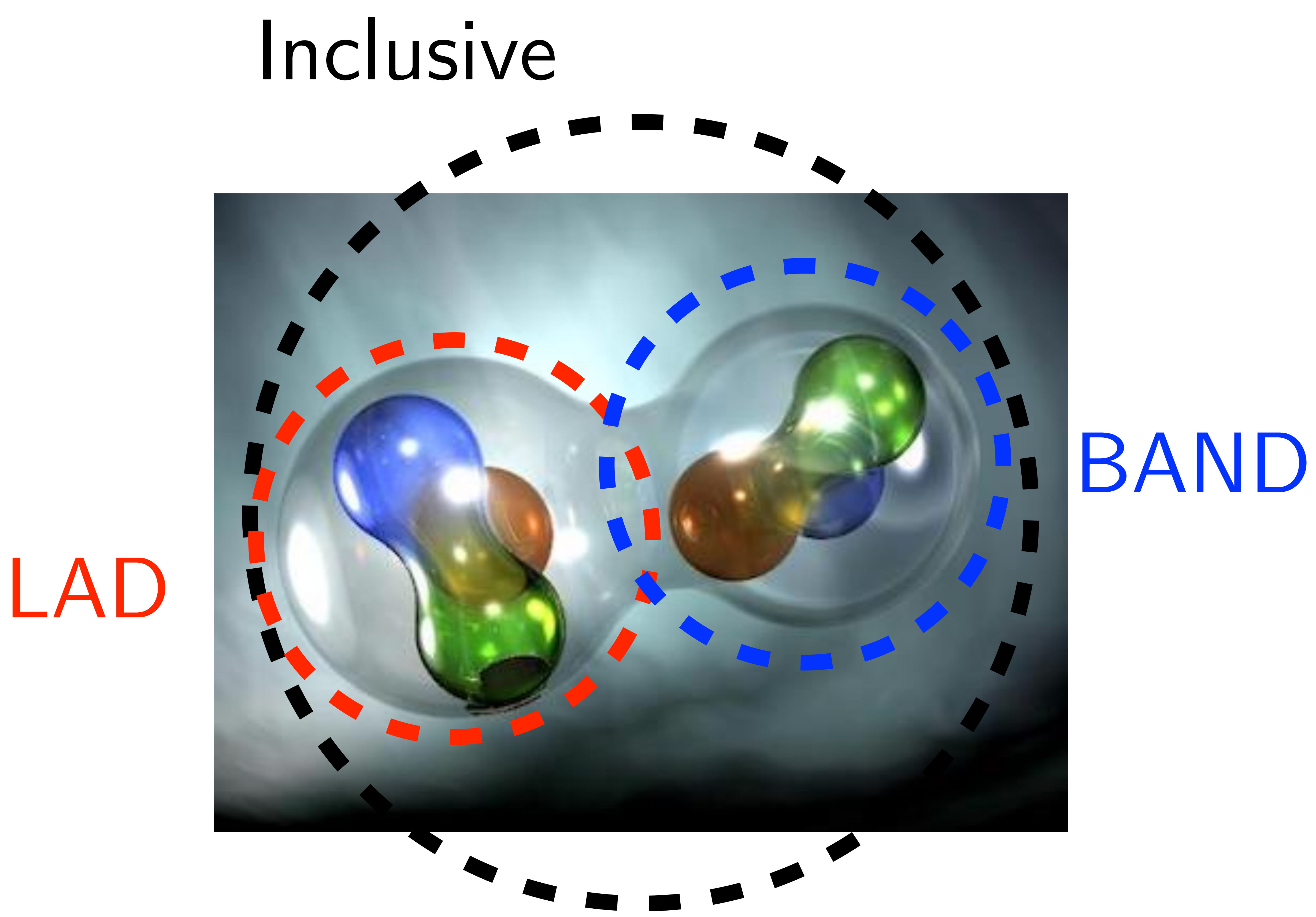
- 1 $\mu$A at 10.9 GeV
- Scattered electron to HMS/SHMS
- Recoil proton to LAD

# 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



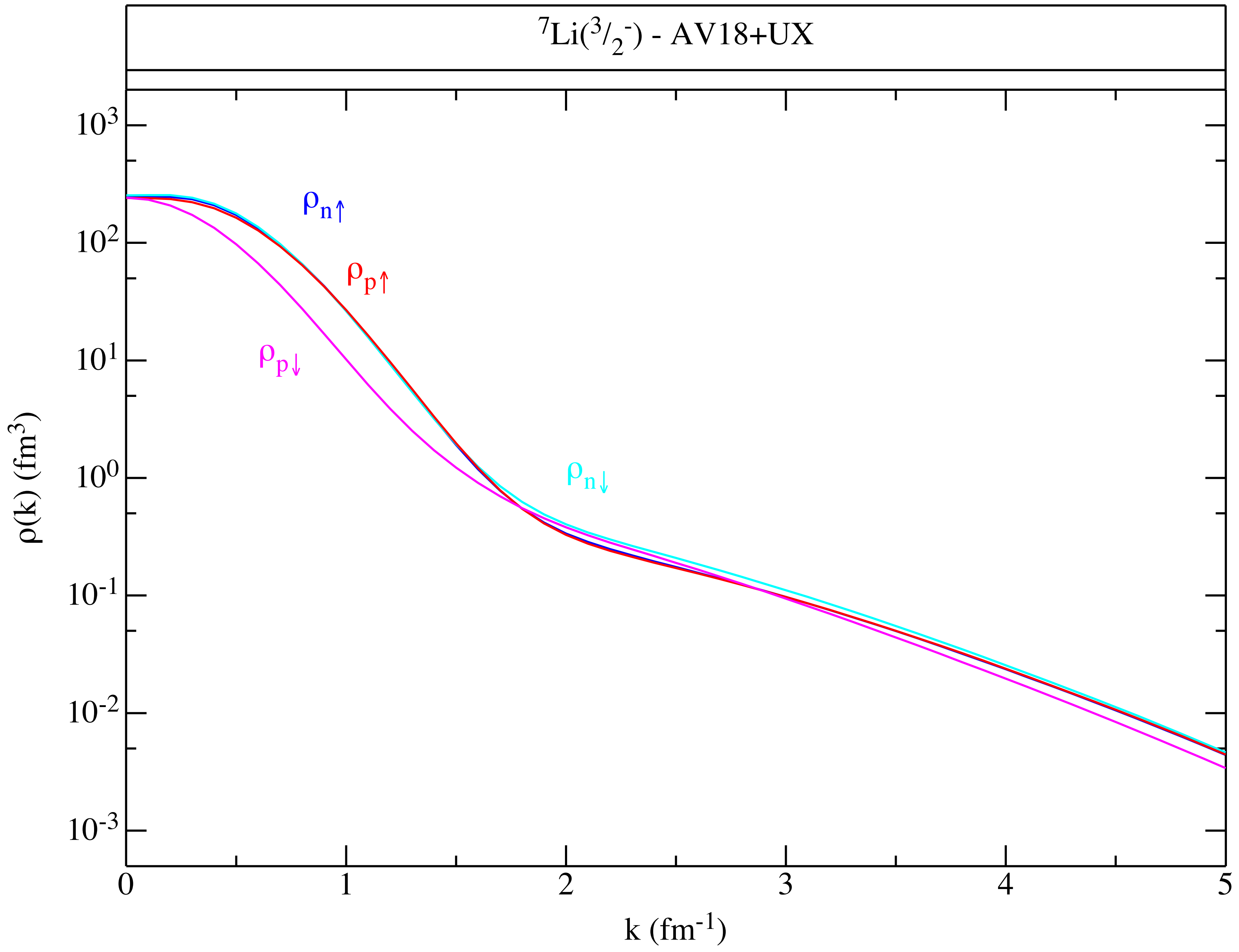

- Inclusive + BAND + LAD overconstrains deuterium
- BAND and LAD must show consistent modification of bound protons/neutrons
- Hope to achieve lower recoil momentum and angles than BAND
- On JLab schedule to start July 2024

# Tagged DIS is just getting started!

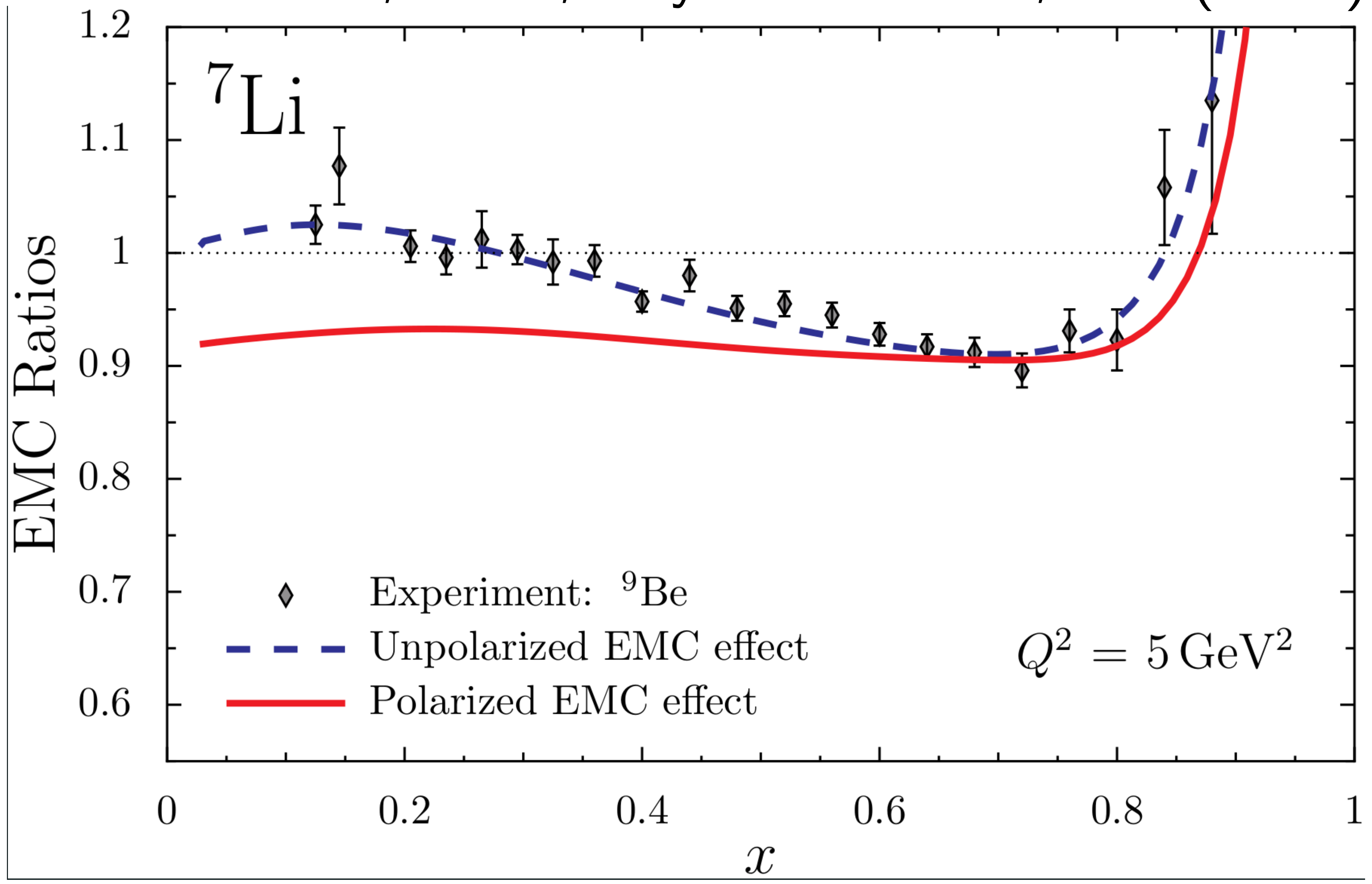
- A Low-Energy Recoil Tracker (ALERT) with CLAS12 at JLab Hall B:
  - $^3$H/$^3$He tagged DIS from $^4$He
- TDIS-n at JLab Hall C:
  - BoNuS-style measurement of low-momentum neutrons in deuterium
- Tagging at EIC

# SRC-EMC connection can also be tested by polarized EMC measurements

- Polarized measurements can distinguish mean-field and SRC effects
  - Small net polarization for high-momentum nucleons (small pEMC)
  - Mean-field calculations predict pEMC $\geq$ EMC




I. Cloët, *et al.*, Phys.Lett.B 642, 210 (2006)



# Summary

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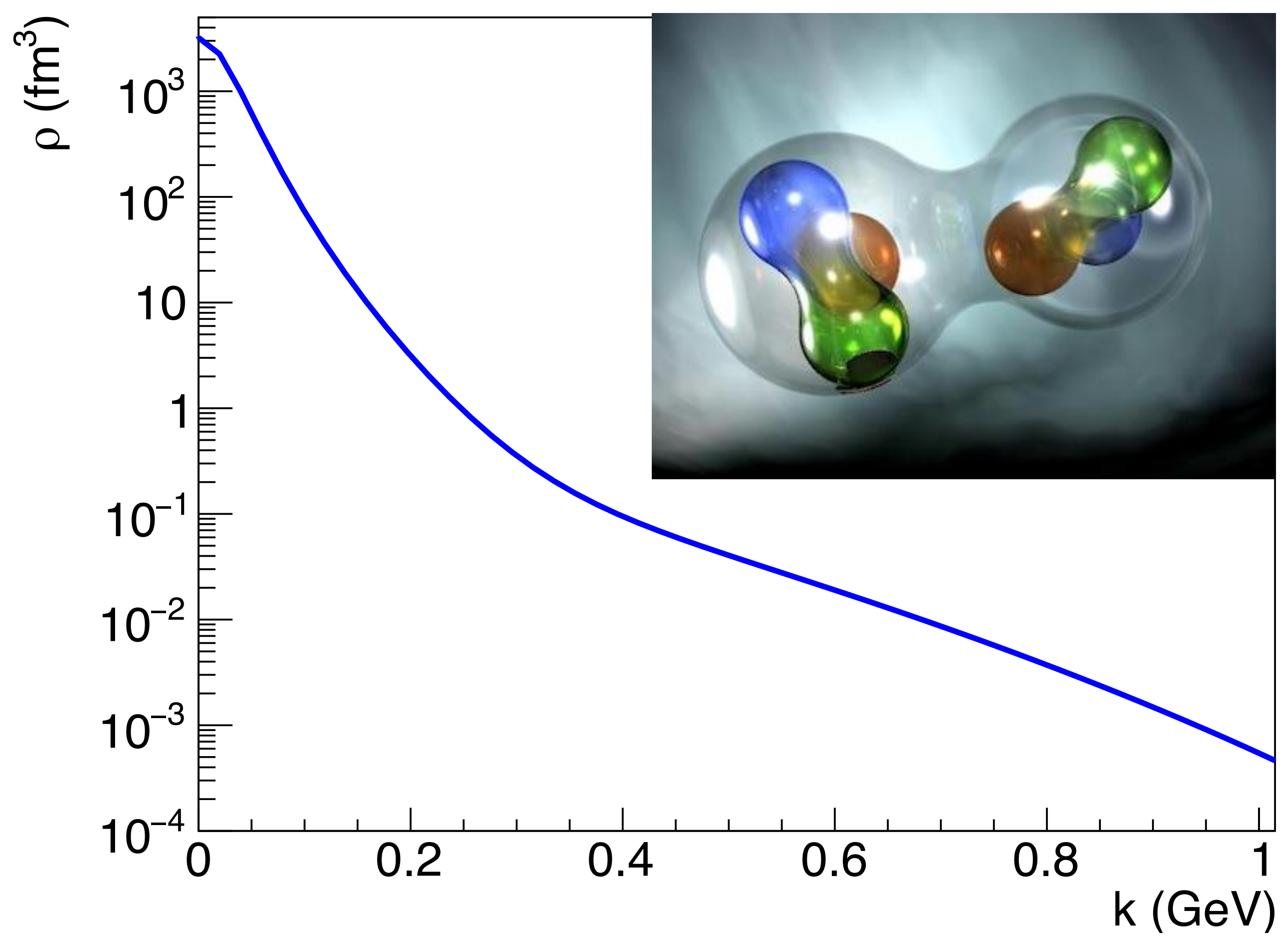
- Tagged DIS allows measurements of parton structure sensitive to nuclear configuration
  - Study quasi-free nucleons to extract free neutron structure
  - Study highly virtual nucleons to probe origin of EMC effect



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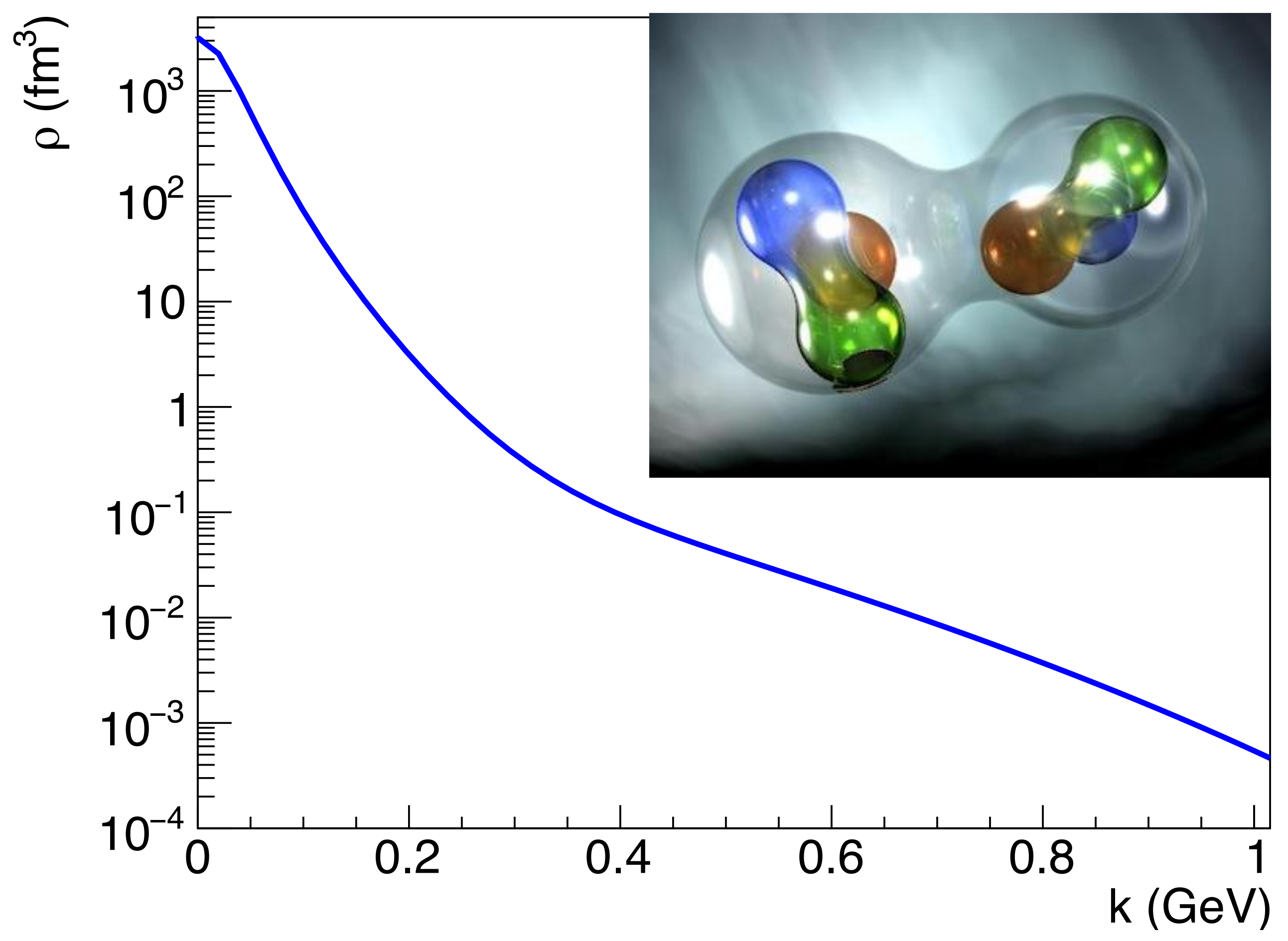


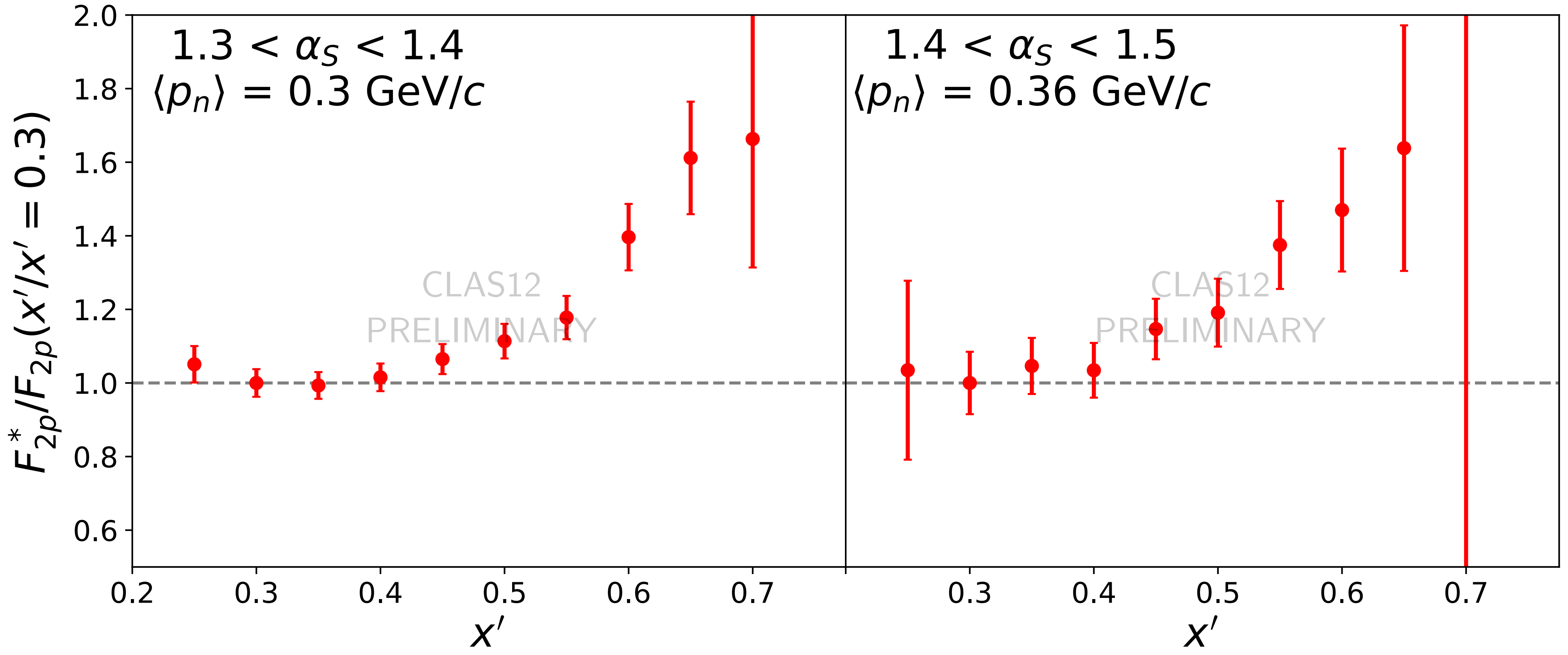

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    - Study quasi-free nucleons to extract free neutron structure
    - Study highly virtual nucleons to probe origin of EMC effect
- Preliminary BAND/CLAS12 results show large modification of high-momentum protons in deuterium
- Rich tagged DIS program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