Tagged Deep Inelastic Scattering in eD Collisions at $10\text{x}130\ \text{GeV}^2$

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ePIC Physics Forum

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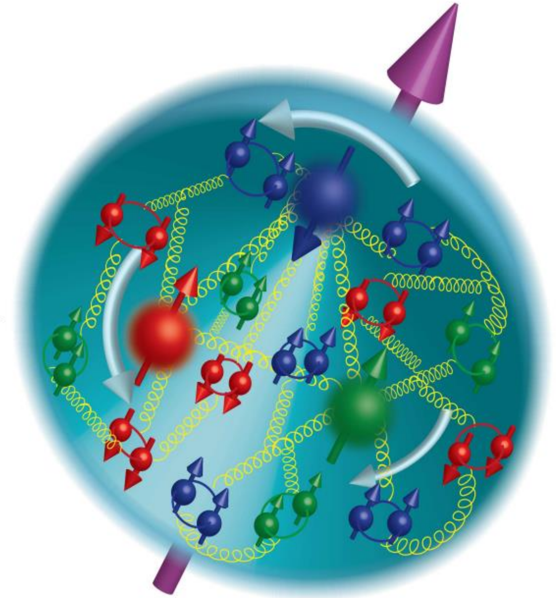
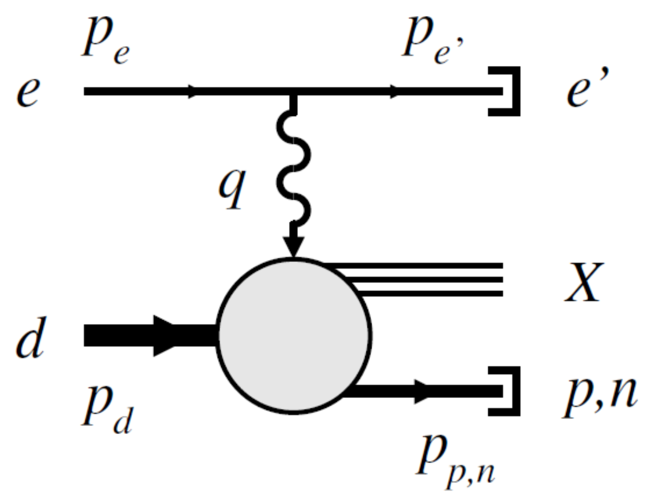
PHYSICS MOTIVATION

- **Main motivation:** Understanding of internal structure of neutrons and light nuclei
- **Neutron internal structure** vital for full understanding of nucleon internal structure and QCD
- Complementary measurement to study of internal structure of protons in traditional Deep Inelastic Scattering (DIS)
- **Main challenges:**
  - Neutrons are neutral and cannot be easily accelerated
  - Difficult to handle free neutrons



EXPERIMENTAL METHOD OVERVIEW

- **Possible experimental solution:** Tagged DIS (TDIS)
  - DIS on deuteron (d)
  - Measurement of the scattered electron and the spectator p or n
- **Challenges:**
  - Neutron is bound and not free, but we are interested in free n structure functions
  - Detection of the spectator p or n
- **Advantages:**
  - Straightforward, when spectators are successfully detected
  - Possible to measure p and cross-check with standard methods



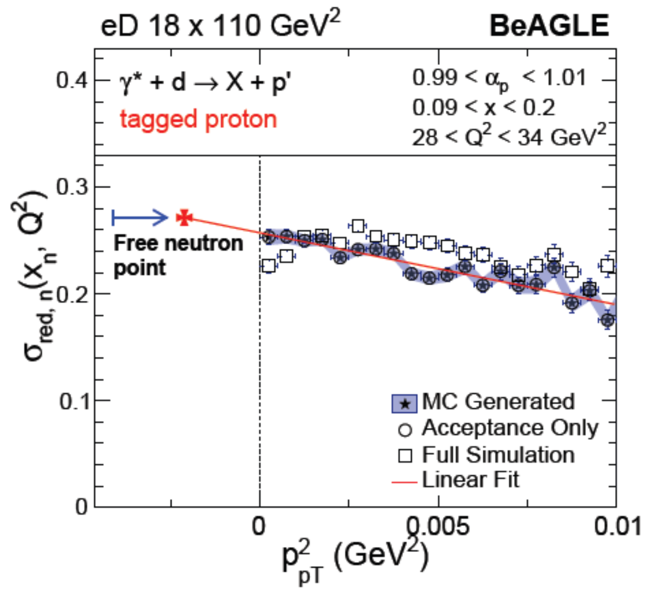
A. Jentsch, Z. Tu, Ch. Weiss: Phys. Rev. C **104**, 065205.

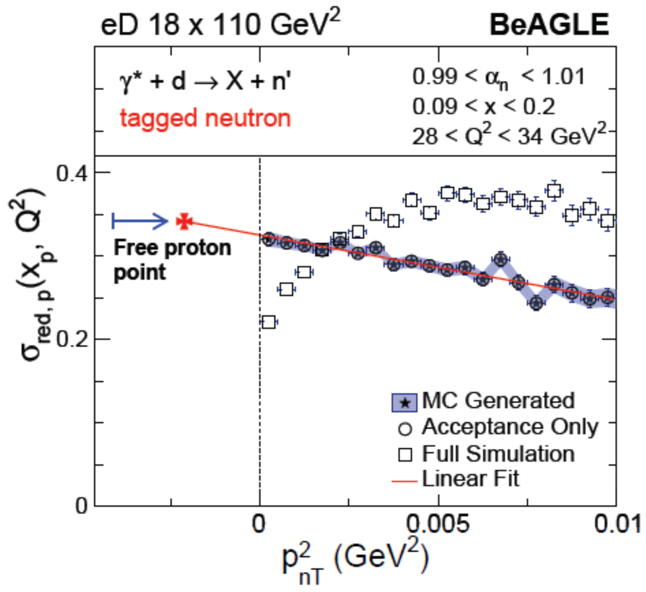
EXPERIMENTAL METHOD

- **Solution:**
  - Pole extrapolation for extraction of free neutron/proton structure

- Experimental method verified in previous publication by A. Jentsch, Z. Tu, and C. Weiss: [Phys. Rev. C **104**, 065205.]
  - Only using True MC information
  - Not using EICRecon, only manual smearing of MC
  - RC not used in the analysis

- **This analysis:**
  - Implementation of full TDIS framework using ePIC simulations
  - Using RC information from EICRecon with full efficiency and acceptance correction
  - More realistic estimate of systematic uncertainties
  - Projection of statistical uncertainties to early year EIC luminosity





A. Jentsch, Z. Tu, C. Weiss: [Phys. Rev. C **104**, 065205.]

VARIABLES USED IN ANALYSIS

- Scattered electron
  - $Q^2 = -q^2 = -\left(p_{e,beam} - p_{e,scat}\right)^2$
  - $x = \frac{Q^2}{P \cdot q}$
  - $x_{nucleon} = \frac{Q^2}{2P_{nucl} \cdot q} = \frac{x}{2-\alpha_p}$
- Kinematic variables
  - $y = \frac{p_d \cdot q}{p_d \cdot p_{e,beam}}$
  - $1 - \epsilon = \frac{y^2}{1+(1-y)^2}$
- Light-cone momentum fraction:
  - $\alpha_p \equiv \frac{2p_p^+}{p_d^+} = \frac{2\left(E_p + p_{z,p}\right)}{E_d + p_{z,d}}$
- Proton transfer momentum
  - $p_{T,p} = \sqrt{p_{x,p}^2 + p_{y,p}^2}$
- Fine structure constant
  - $\alpha_{em} = \frac{1}{137}$
- Luminosity and cross section
  - $L_{int} = \frac{N_{events}}{\sigma_{tot}}$
    - $\mathrm{mb} = 2.568\ \mathrm{GeV}^{-2}$
    - Cross section for eD at $10\mathrm{x}130\ \mathrm{GeV}^2$:
      - $\sigma_{tot} = 3.538 \cdot 10^{-4}\mathrm{mb}\ (en)$
      - $\sigma_{tot} = 3.707 \cdot 10^{-4}\mathrm{mb}\ (ep)$

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DEUTERON REDUCED CROSS SECTION

- Differential cross section on d can be written in terms of deuteron reduced cross ($\sigma_{red,d}$) section and photon flux:
  - $\mathrm{d}\sigma_d = Flux(x, Q^2) \times \sigma_{red,d} \times \mathrm{d}x\mathrm{d}Q^2 \frac{\mathrm{d}\phi_{e'}}{2\pi} [2(2\pi)^3]^{-1} \frac{\mathrm{d}\alpha_p}{\alpha_p} \frac{\mathrm{d}p_{T,p}^2}{2} \mathrm{d}\phi_p$

A. Jentsch, Z. Tu, C. Weiss: Phys. Rev. C **104**, 065205.
M. Strikman and C. Weiss: Phys. Rev. C **97**, 035209.
C. Weiss and W. Cosyn: Phys. Rev. C **102**, 065204.

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- Scattered electron
- Spectator proton/neutron
- Photon flux

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- Photon flux:
  - $Flux(x, Q^2) = \frac{2\pi\alpha_{em}^2 y^2}{Q^4(1-\epsilon)x} = \frac{2\pi\alpha_{em}^2[1+(1-y)^2]}{Q^4 x}$

- Scattered electron
- Spectator proton/neutron
- Photon flux
- Unit conversion

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- Measured reduced cross section (integrated over $\mathrm{d}\phi_p$)
  - $\bar{\sigma}_{red,d} = \left(\frac{2.568}{L_{int}}\right) \frac{Q^4 x}{2\pi\alpha_{em}^2[1+(1-y)^2]} \frac{[4(2\pi)^3]\alpha_p}{\Delta\alpha_p} \frac{\mathrm{d}N}{\Delta x \Delta Q^2 \Delta p_{T,p}^2 2\pi}$
    - $\Delta x,\ \Delta Q^2,\ \Delta p_{T,p}^2, \Delta\alpha_p$ are bin widths

- Full azimuthal coverage for electron
  - $(\Delta\phi_{e'}/2\pi) = 2\pi/2\pi = 1$
- Full azimuthal coverage for spectator
  - $\Delta\phi_p = 2\pi$

POLE EXTRAPOLATION METHOD

- Nucleon reduced cross section obtained by removing pole of deuteron spectral function:
  - $\bar{\sigma}_{red,n} = \frac{\bar{\sigma}_{red,d}(x,Q^2)}{[2(2\pi)^3]S_d(p_{pT},\alpha_p)[pole]}$

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- Deuteron spectral function
  - $S_d(p_{pT},\alpha_p)[pole] = \frac{R}{(p_{pT}^2+a_T^2)}$
  - Position of pole
    - $a_T^2 = m_N^2 - \alpha_p(2-\alpha_p)\frac{M_d^2}{4}$
  - Residue of spectral function
    - $R = 2\alpha_p^2 m_N \Gamma^2(2-\alpha_p)$

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- We can measure/calculate this
- External input from model/experiment
- Deuteron spectral function
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    - $R = 2\alpha_p^2 m_N \Gamma^2(2-\alpha_p)$
    - $\Gamma = 0.007885\ \text{GeV}$

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  - $\bar{\sigma}_{red,n} = \frac{\bar{\sigma}_{red,d}(x,Q^2)}{[2(2\pi)^3 \boxed{S_d(p_{pT},\alpha_p)[pole]}}$

- $\bar{\sigma}_{red,n}$ at the pole corresponds to a free n
  - $p_{pT}^2 \to -a_T^2$ which means negative (unphysical) p_{pT}^2

- Same measurement can be done for p
  - Cross check with proton F_2 extracted with traditional method
  - Can be used to select optimal deuteron spectral function

- We can measure/calculate this
- External input from model/experiment

- Deuteron spectral function
  - $S_d(p_{pT}, \alpha_p)[pole] = \frac{R}{(p_{pT}^2 + a_T^2)}$
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SIMULATION PRODUCTION

- BeAGLE generated eD collisions at $10\text{x}130\ \mathrm{GeV}^2$

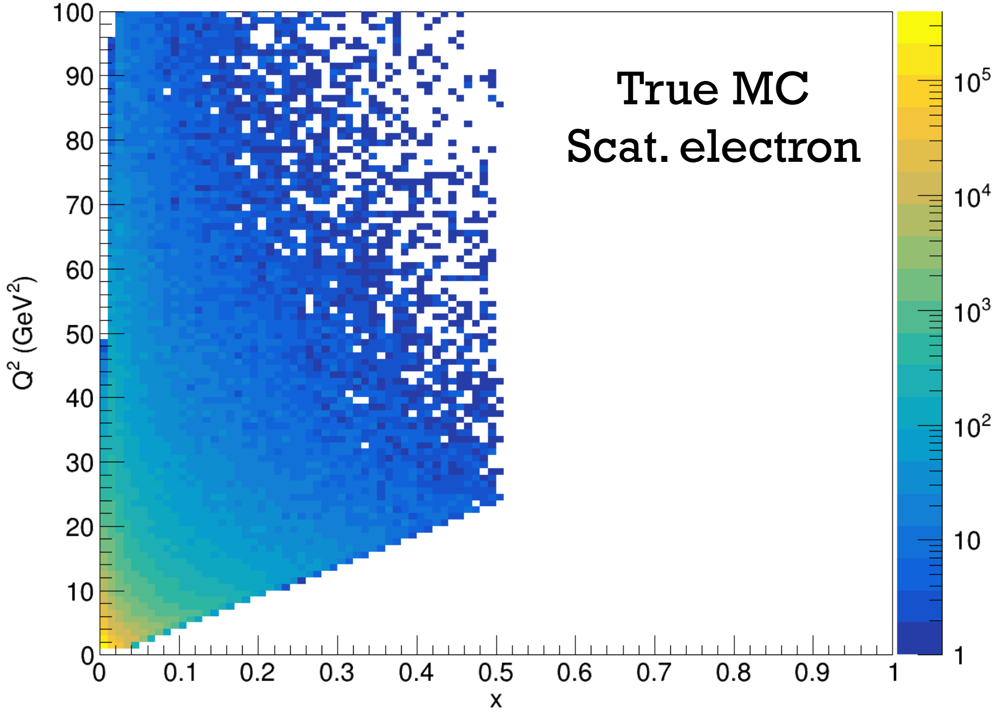
- Simulation production overview:
  - Official simulation campaign 26.03.1
  - 20M events of eD $10\text{x}130\ \mathrm{GeV}^2$
    - 10M of en and 10M of ep

- Luminosity and cross section:
  - en: $\sigma_{tot} = 3.538 \cdot 10^{-4}\mathrm{mb}$, $L_{int} = N_{evt}/\sigma_{tot} = 10\mathrm{M}/(3.538 \cdot 10^{-4}\mathrm{mb}) = 10\mathrm{M}/(3.538 \cdot 10^{8}\mathrm{fb}) = 0.028\ \mathrm{fb}^{-1}$
  - ep: $\sigma_{tot} = 3.707 \cdot 10^{-4}\mathrm{mb}$, $L_{int} = 0.028\ \mathrm{fb}^{-1}$ (same as en after rounding)
  - Total integrated luminosity (EICRecon): $L_{int} = 0.056\ \mathrm{fb}^{-1}$
  - Expected luminosity for year 2: $L_{int} = 1.5\ \mathrm{fb}^{-1}$
    - All statistical uncertainties projected to expected luminosity

- Note: eD collisions at $9\text{x}130\ \mathrm{GeV}^2$ sample currently in production

SCATTERED ELECTRON FINDING – MC

- Find electron which has the beam electron as a parent



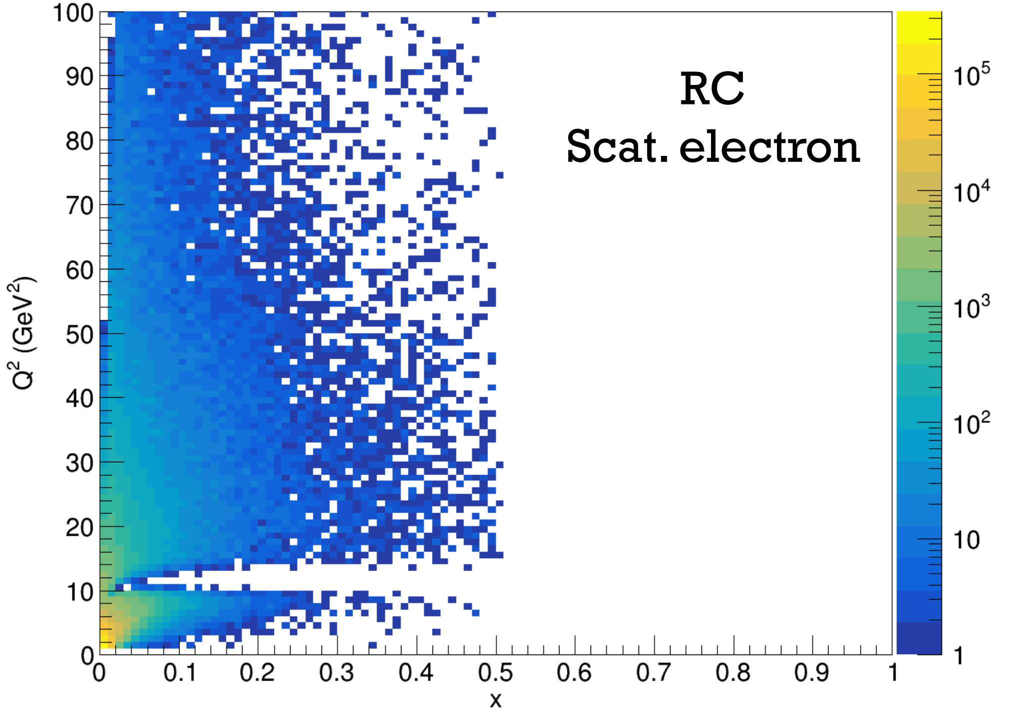
SCATTERED ELECTRON FINDING – RC

- Find negative charged track with well matched nECAL or bECAL cluster with $0.8 < E/p < 1.2$

- If more such cluster-track pairs are found, select the one with the highest momentum

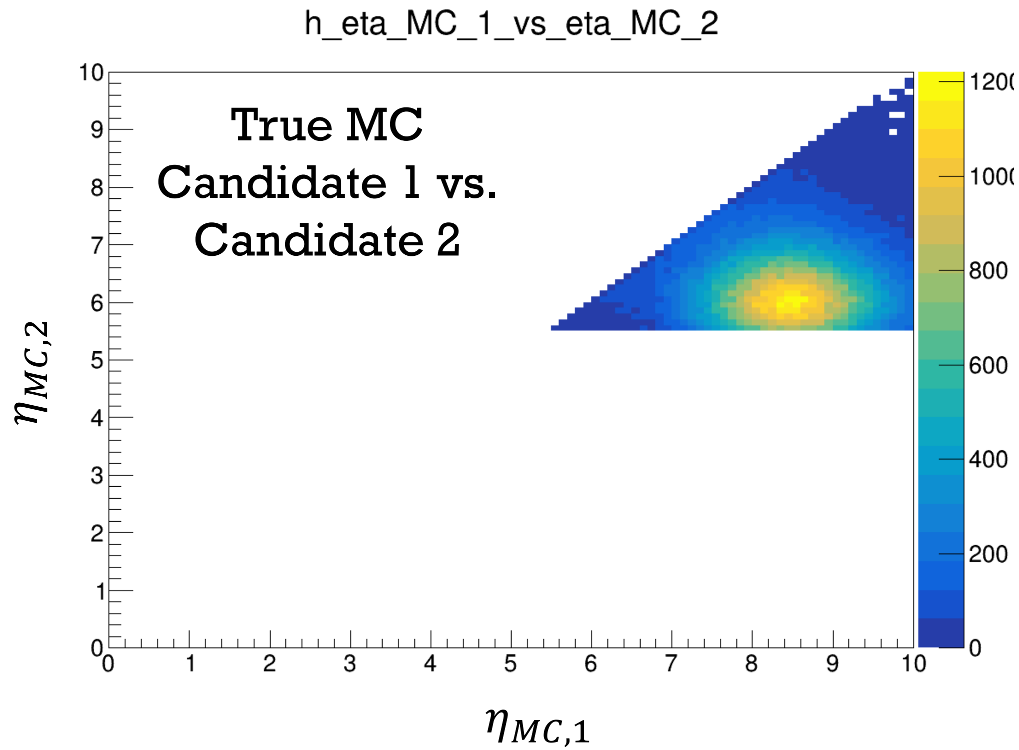
- Correct momentum magnitude using energy deposition in ECAL
  - Verified that this method provides better (x, Q^2) distribution and MC vs. RC for scattered electron kinematics

- Main source of efficiency drop in final cross sections



SPECTATOR SELECTION – MC

- EICRecon does not have direct spectator tagging
  - Selection based only on spectator kinematics
- Find final state True MC proton/neutron with $\eta > 5.5$
  - Some events have 2 such protons/neutrons
  - One is the spectator
  - Second one is from DIS process – don't want this one
- If 2 MC spectator candidates are in one event, take the one with larger η as spectator
  - Based on $\eta_{MC,1}$ vs. $\eta_{MC,2}$ distribution for such events (shown here)
- Method cross-checked with BeAGLE simulation



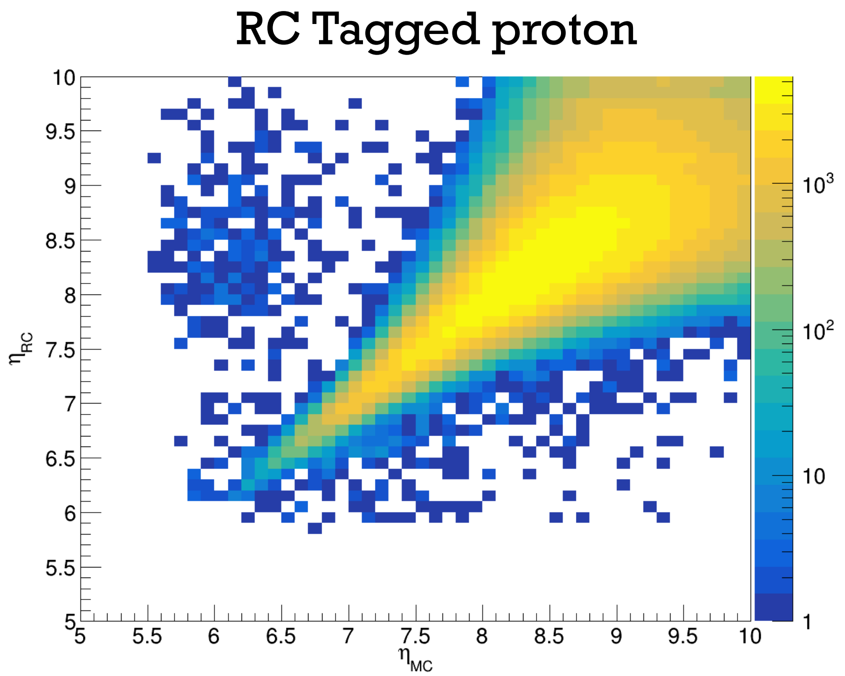
Pseudorapidity of far-forward protons in events with 2 such protons

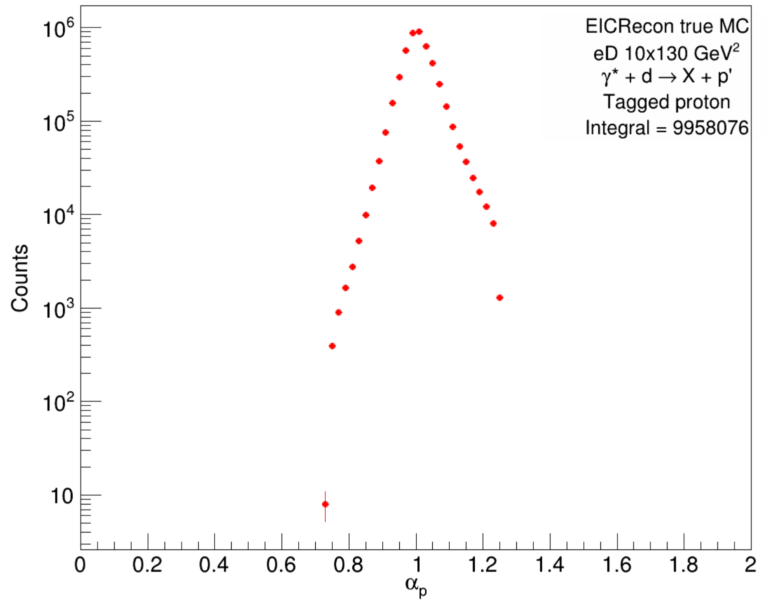
SPECTATOR SELECTION – RC

- Accept all events with well reconstructed candidate in OMD or ZDC

- If 2 candidates are found (rare), use the one with larger η as spectator

- Selecting only spectators with light cone momentum fraction: $0.99 < \alpha_p < 1.01$
  - $\alpha_p \equiv \frac{2p_p^+}{p_d^+} = \frac{2(E_p + p_{z,p})}{E_d + p_{z,d}}$



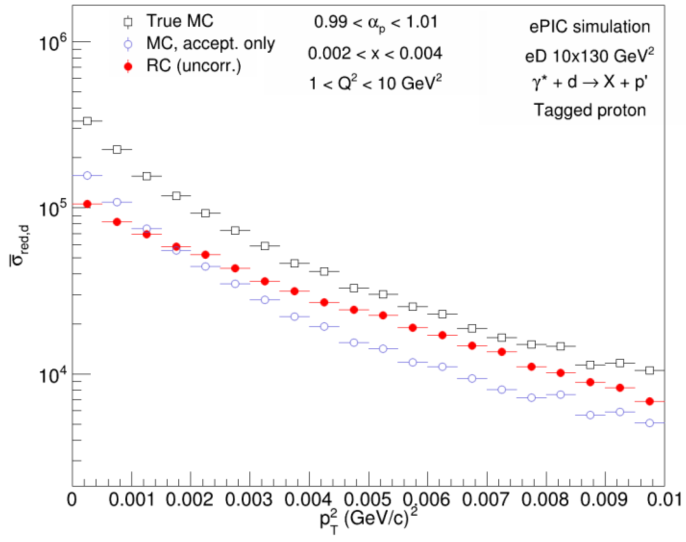


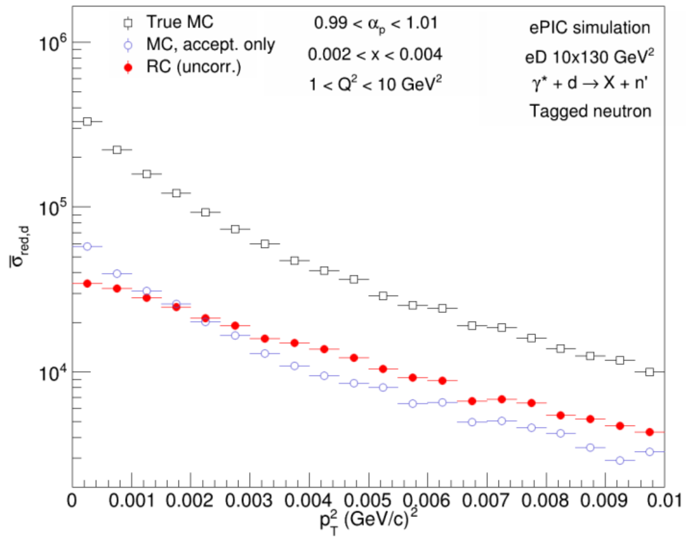
DEUTERON REDUCED CROSS SECTION

- (top) Deuteron reduced cross section in EICRecon calculated using **tagged protons**
- (bottom) Deuteron reduced cross section in EICRecon calculated using **tagged neutrons**

- Comparison of True MC (black), acceptance only MC (blue), and RC (red)
  - Acceptance only = MC distribution for accepter RC events
    - Reflects only efficiency loss, but not bin migration that changes p_T^2
    - Acc. Only/True MC largely p_T^2 independent, within statistical precision

- Substantial overall efficiency loss dominated by electron finding algorithm



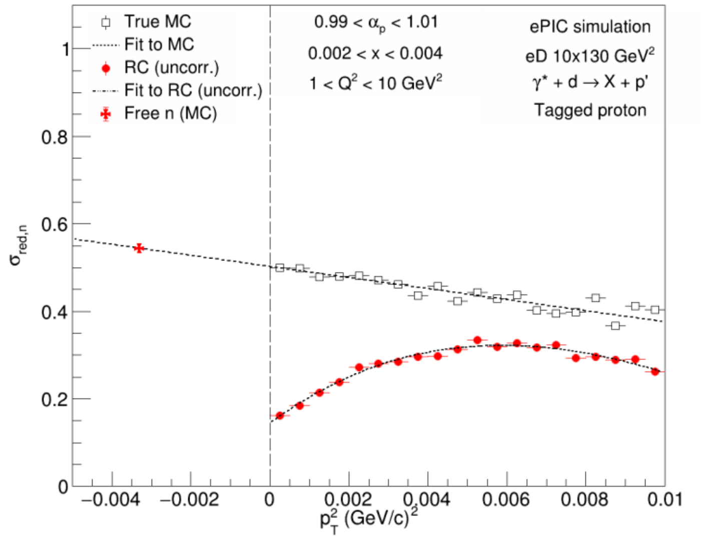


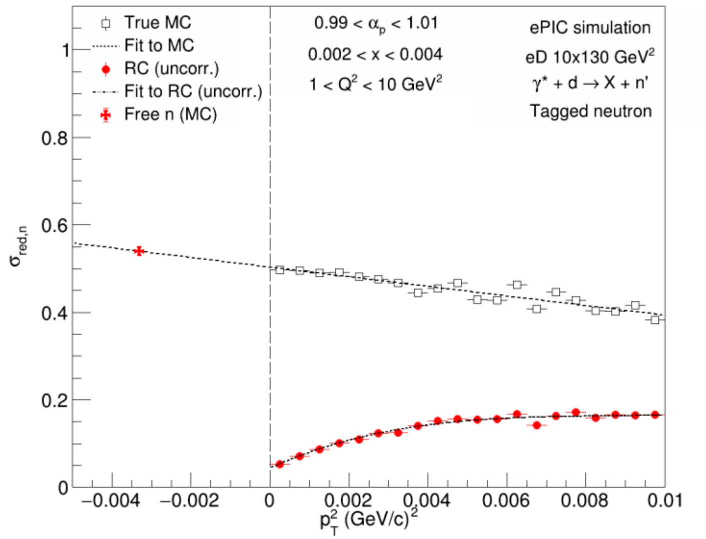
NUCLEON REDUCED CROSS SECTION – UNCORRECTED

- (top) **Neutron** reduced cross section in EICRecon
- (bottom) **Proton** reduced cross section in EICRecon

- True MC fitted with linear function
  - Extrapolation uncertainty from 1σ confidence interval of the fit
- RC fitted with 3rd order polynomial
  - Tried also 4th order polynomial
    - Gives the same result within statistical precision

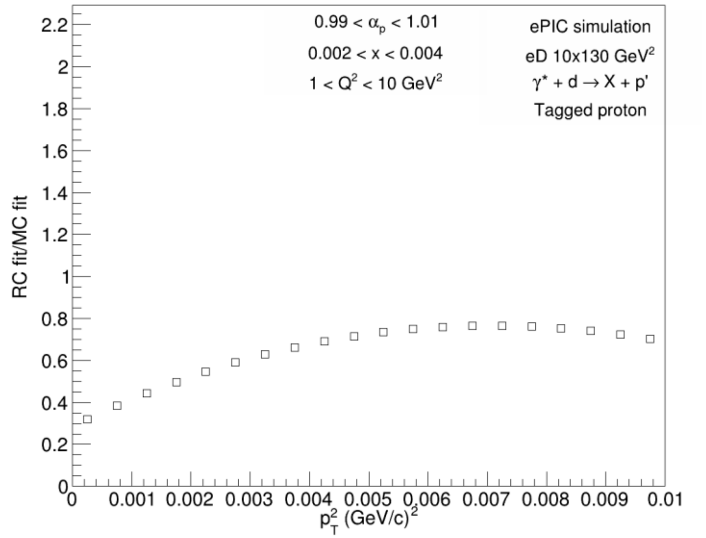
- Not showing acceptance only
  - Pole removal for acceptance only is difficult for matched MC events, as matching $\alpha_{p,MC}$ is not constrained due to contamination

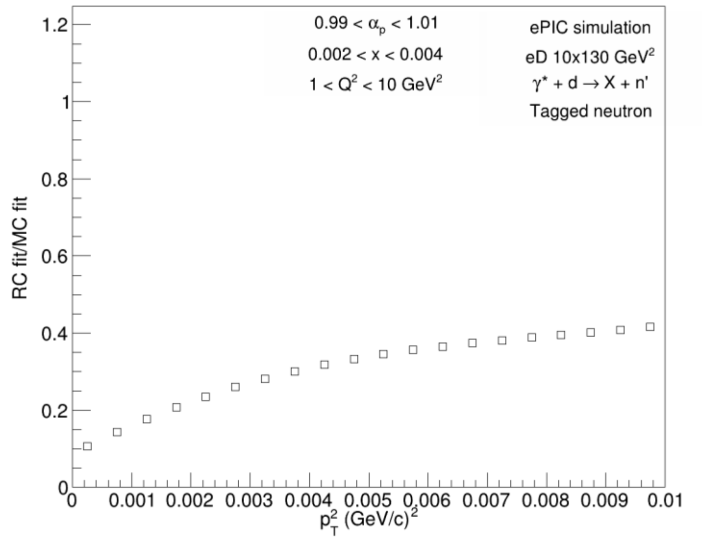




EFFICIENCY AND ACCEPTANCE

- Efficiency and bin migration correction done using ratio of MC and RC **fit functions** to nucleon reduced cross section
  - $Eff. = RC\ fit/MC\ fit$
  - Functions evaluated at histogram bin centers
- Efficiency then applied back to RC reduced cross section point-by-point



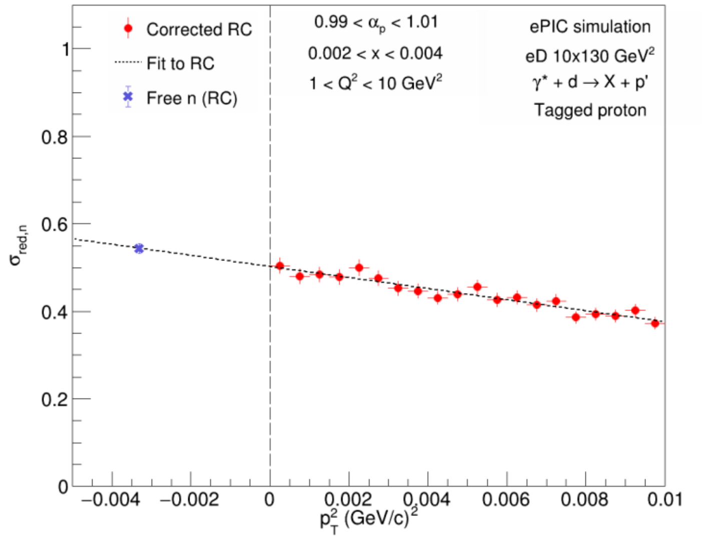


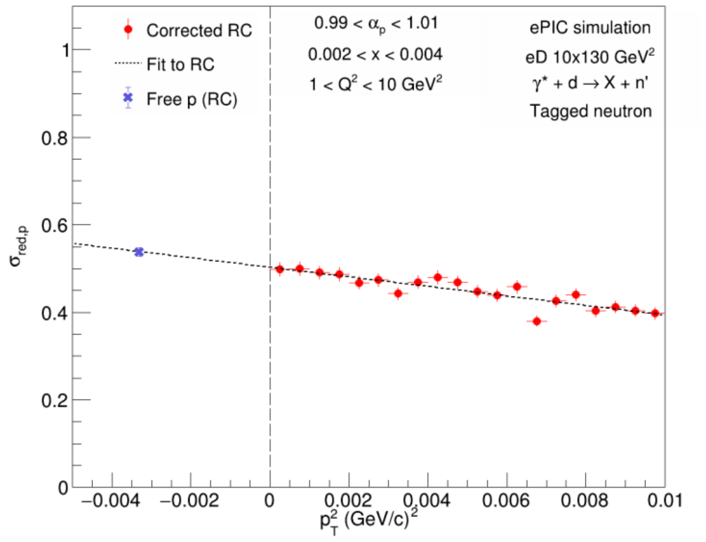
NUCLEON REDUCED CROSS SECTION – CORRECTED

- (top) Fully corrected **neutron** reduced cross section in EICRecon
- (bottom) Fully corrected **proton** reduced cross section in EICRecon

- Error bars are total systematic uncertainties:
  - $\sigma_{tot} = \sqrt{\sigma_{stat}^2 + \sigma_{sys}^2}$
  - Details about systematic uncertainty in next slide

- Extrapolation uncertainty from 1σ confidence interval of the fit to distribution with combined uncertainties

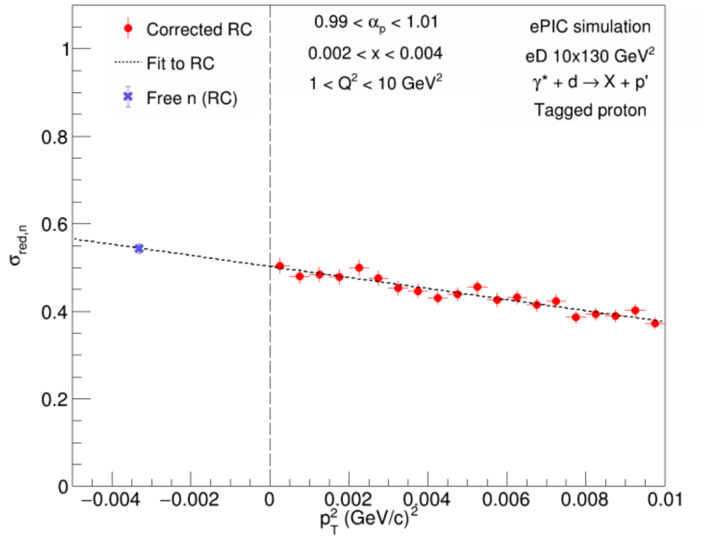


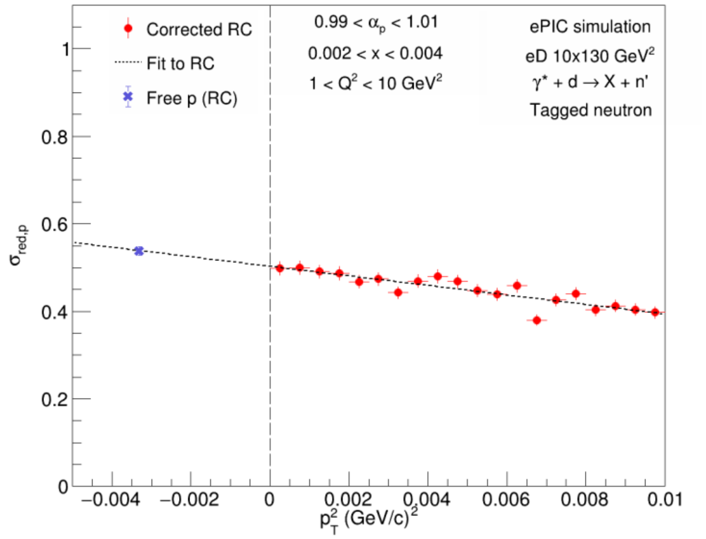


SYSTEMATIC UNCERTAINTIES

- Sources of systematic uncertainties:
  - **Luminosity:** $\sigma_{lumi} = 1.5\ \%$
    - From YR and current discussions
  - **Theory/extrapolation:** $\sigma_{th} = 2\ \%$
    - From original paper
      - A. Jentsch, Z. Tu, C. Weiss: Phys. Rev. C **104**, 065205.
  - **Beam effects:** $\sigma_{beam} = 1.5\ \%$
    - Crossing angle, angular divergence, beam momentum spread
    - Based on values cited by ATLAS or HERA
      - ATLAS Collaboration, The European Physical Journal C 83 (2023).
      - HERA Collaboration, Nuclear Physics B 816, 1–61 (2009).
  - **Proton reconstruction:** $\sigma_p = 2\ \%$
    - Uncertainty of the transport matrix
    - Based on values cited by ATLAS
      - ATLAS Collaboration, The European Physical Journal C 83 (2023).
  - **Neutron reconstruction:** $\sigma_n = 1\ \%$
    - Uncertainty of the primary vertex resolution
    - Based on values cited by HERA and ePIC Roman Pot studies
      - HERA Collaboration, Nuclear Physics B 816, 1–61 (2009).

- **Total systematic uncertainty:**
  - $\sigma_{sys} = \sqrt{\sigma_{lumi}^2 + \sigma_{th}^2 + \sigma_{beam}^2 + \sigma_{n/p}^2}$

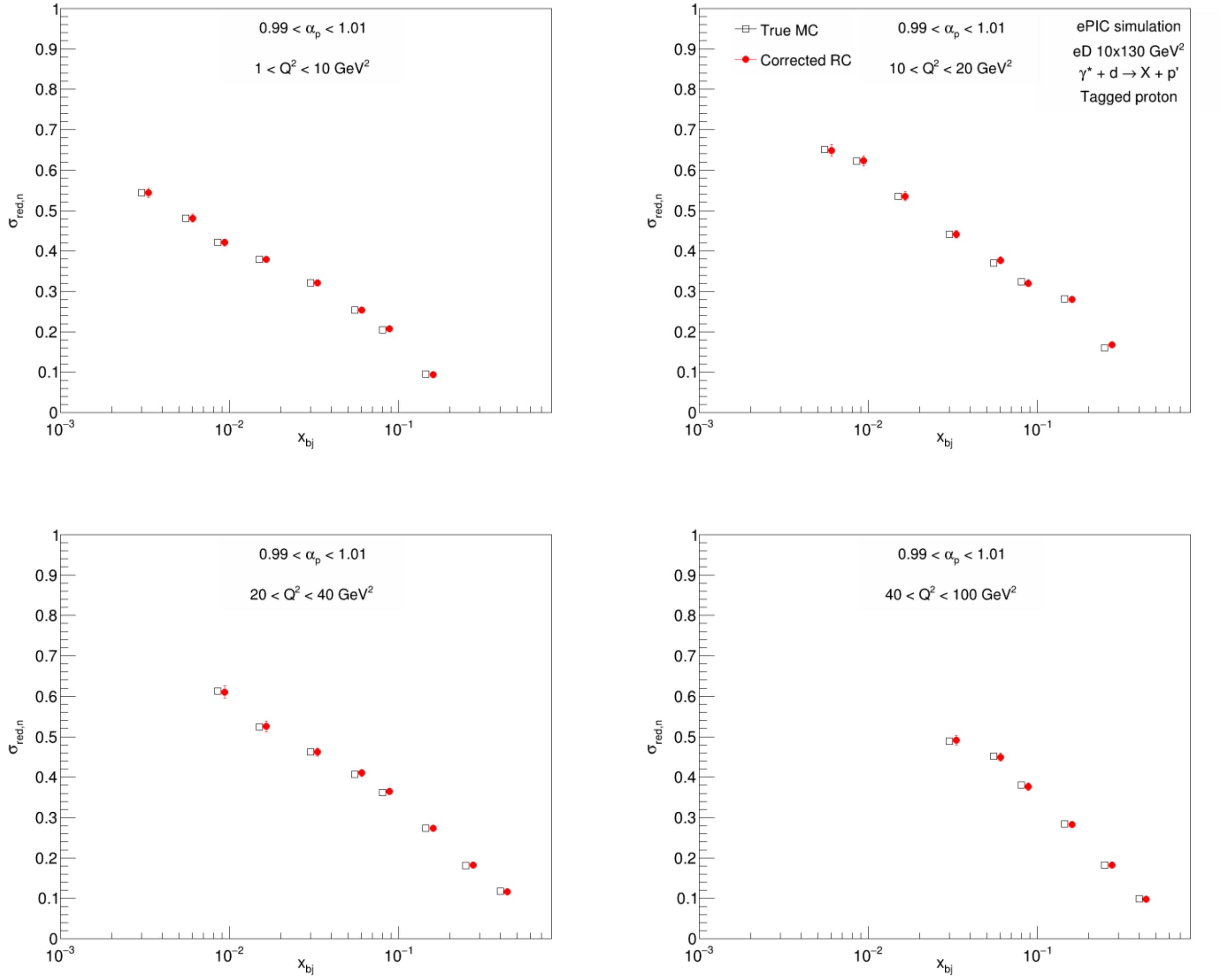




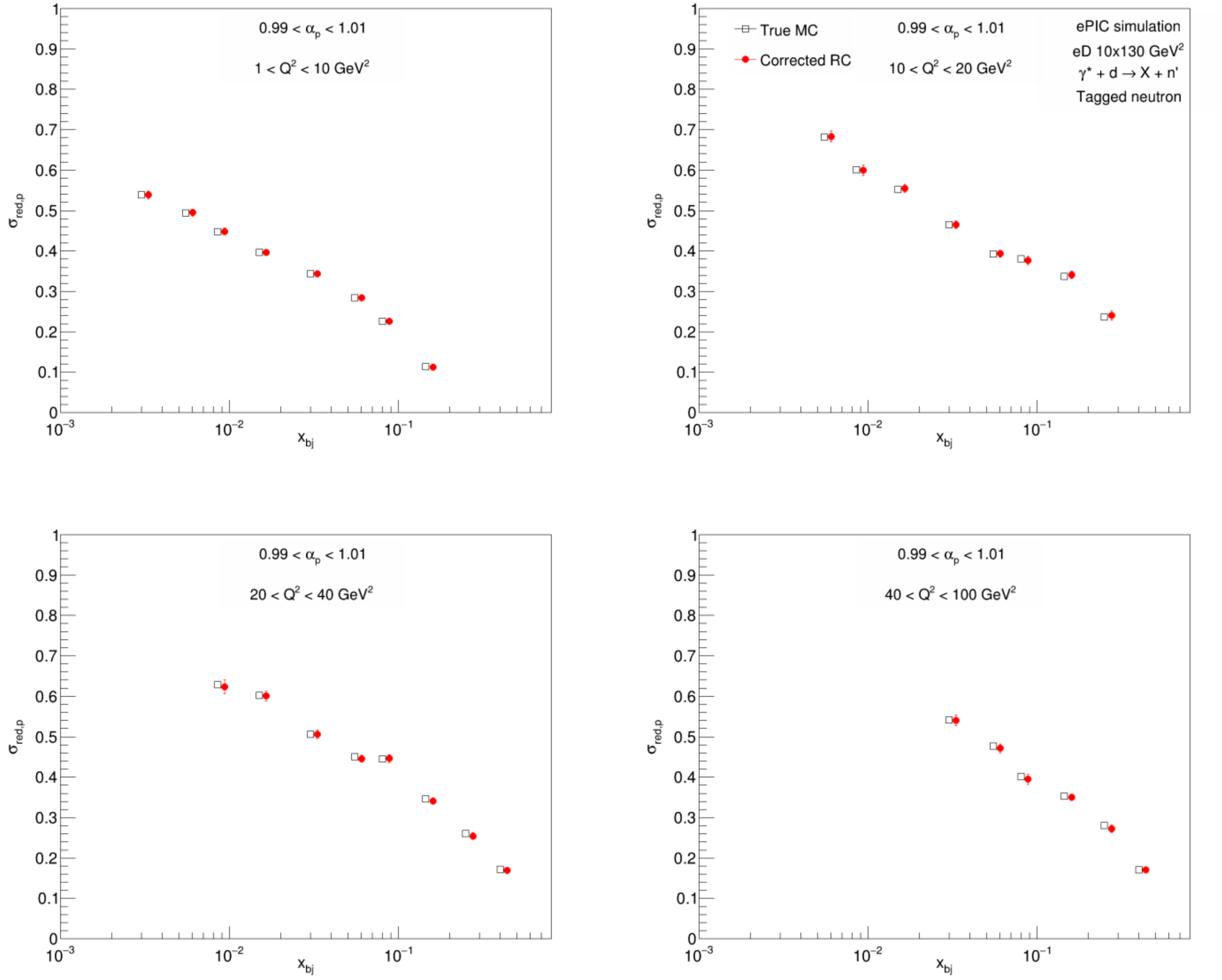
NEUTRON REDUCED CROSS SECTION VS. x_{bj}

- Comparison of the True MC and RC **neutron** reduced cross sections in bins of (x_{bj}, Q^2)

- Uncertainties dominated by systematics
  - Statistical uncertainties negligible even in early years of running the EIC



PROTON REDUCED CROSS SECTION VS. x_{bj}



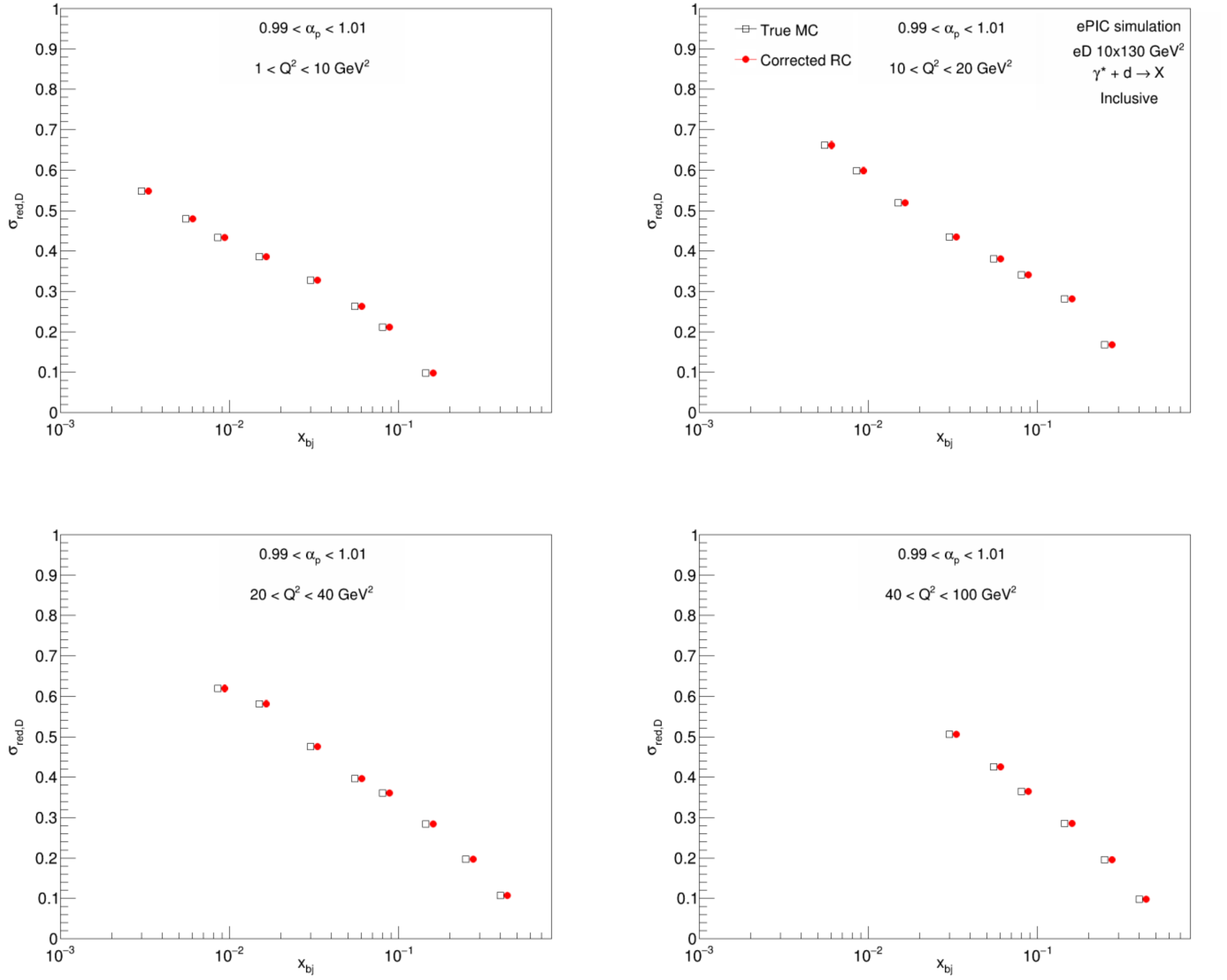
- Comparison of the True MC and RC **proton** reduced cross sections in bins of (x_{bj}, Q^2)

- Uncertainties dominated by systematics
  - Statistical uncertainties negligible even in early years of running the EIC

DEUTERON REDUCED CROSS SECTION VS. x_{bj}

- Comparison of the True MC and RC **inclusive deuteron** reduced cross sections in bins of (x_{bj}, Q^2)

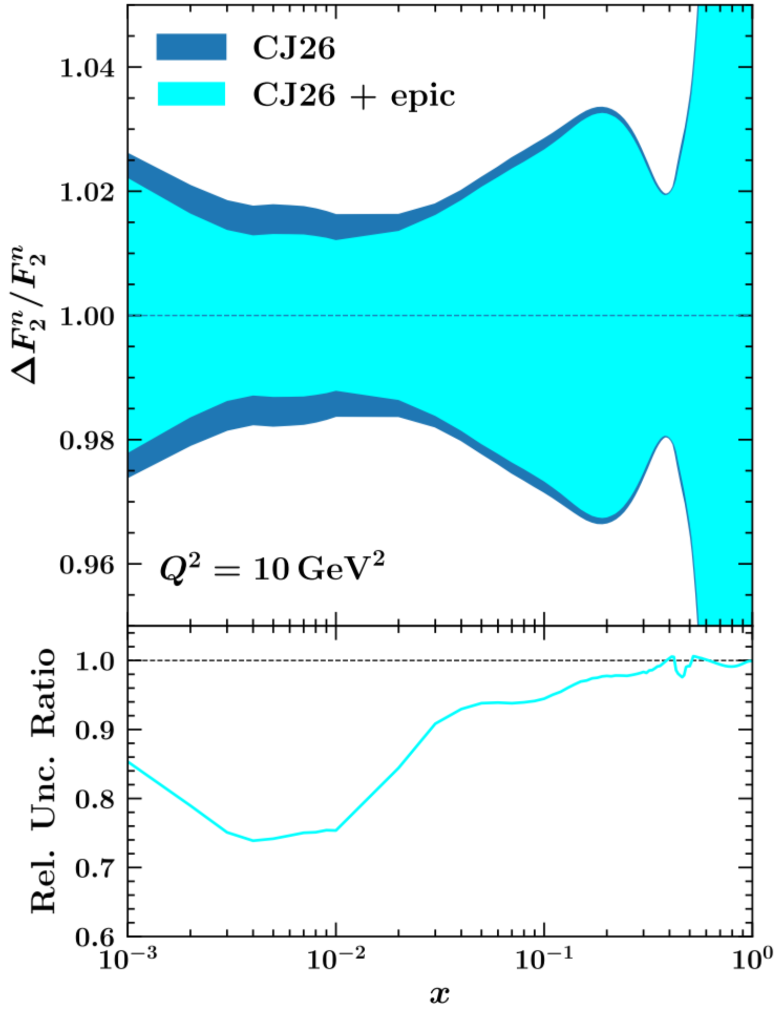
- Used primarily for calculations by our theory colleagues for ESR



RESULT FOR ESR

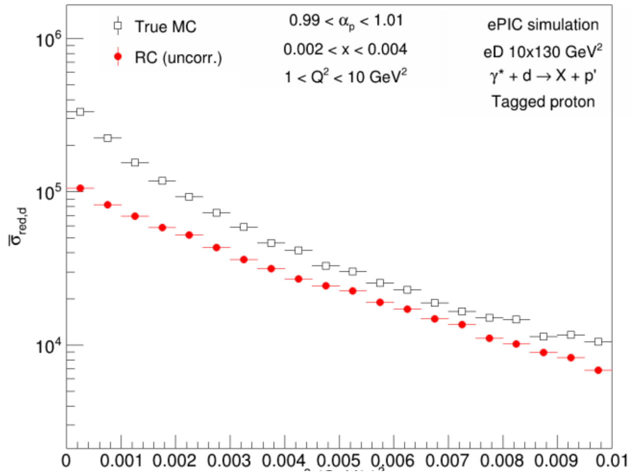
- Impact study demonstrating uncertainty reduction on neutron structure function F_2^n after using TDIS pseudo-data from ePIC
  - Expected $\sim 20\%$ uncertainty reduction for $10^{-3} < x < 10^{-2}$

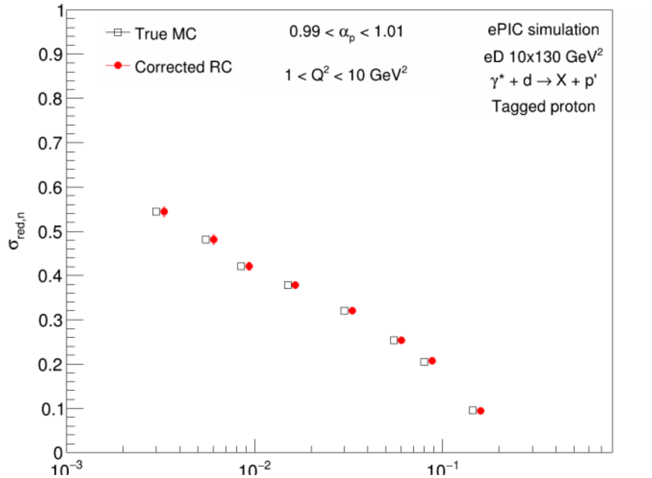
- Calculation by Matteo Cerutti and Alberto Accardi

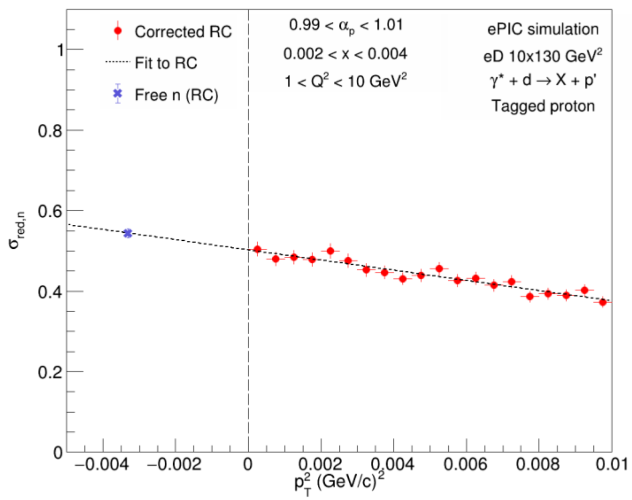


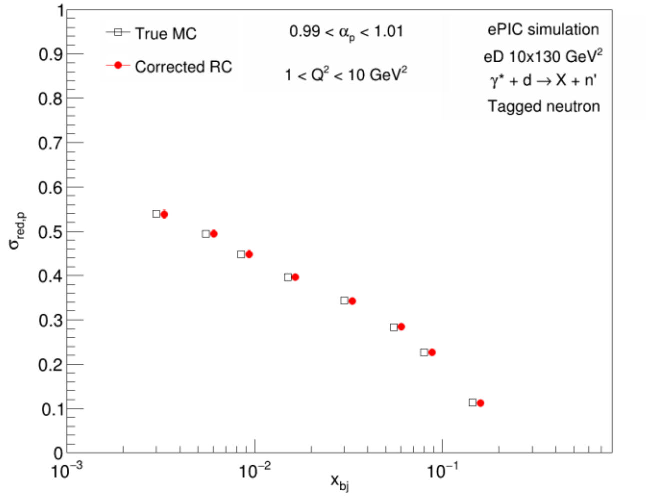
FIGURES FOR NIM PAPER

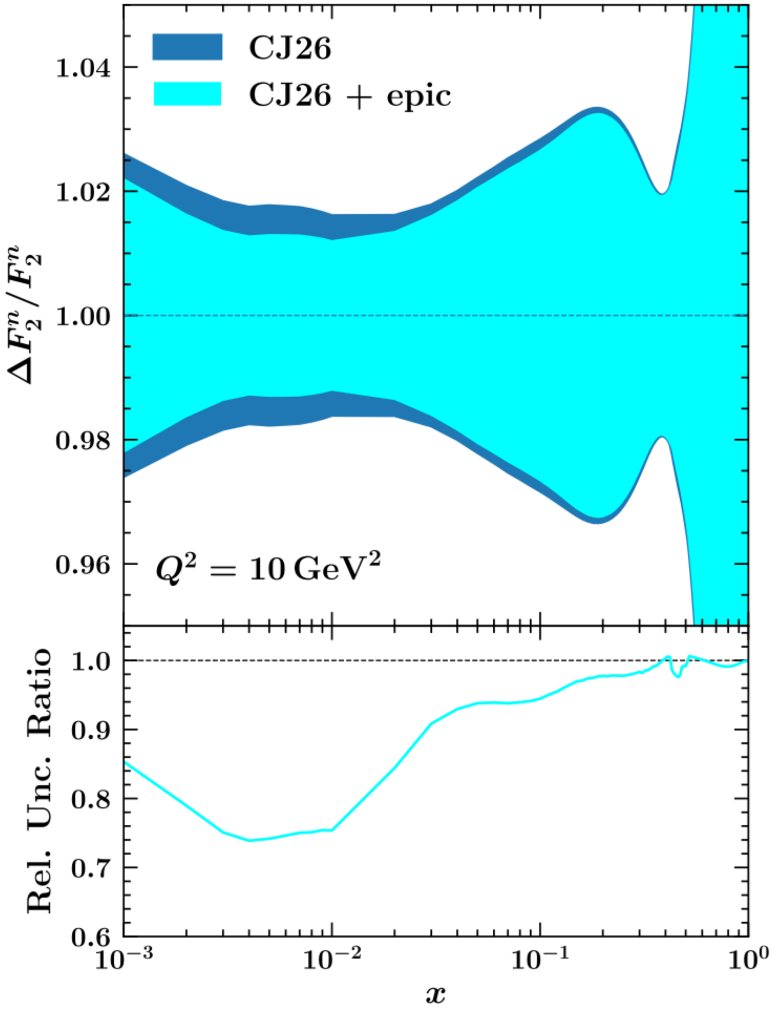
- To demonstrate the procedure, we will focus only on the first Q^2 bin ($1 < Q^2 < 10$ GeV^2)





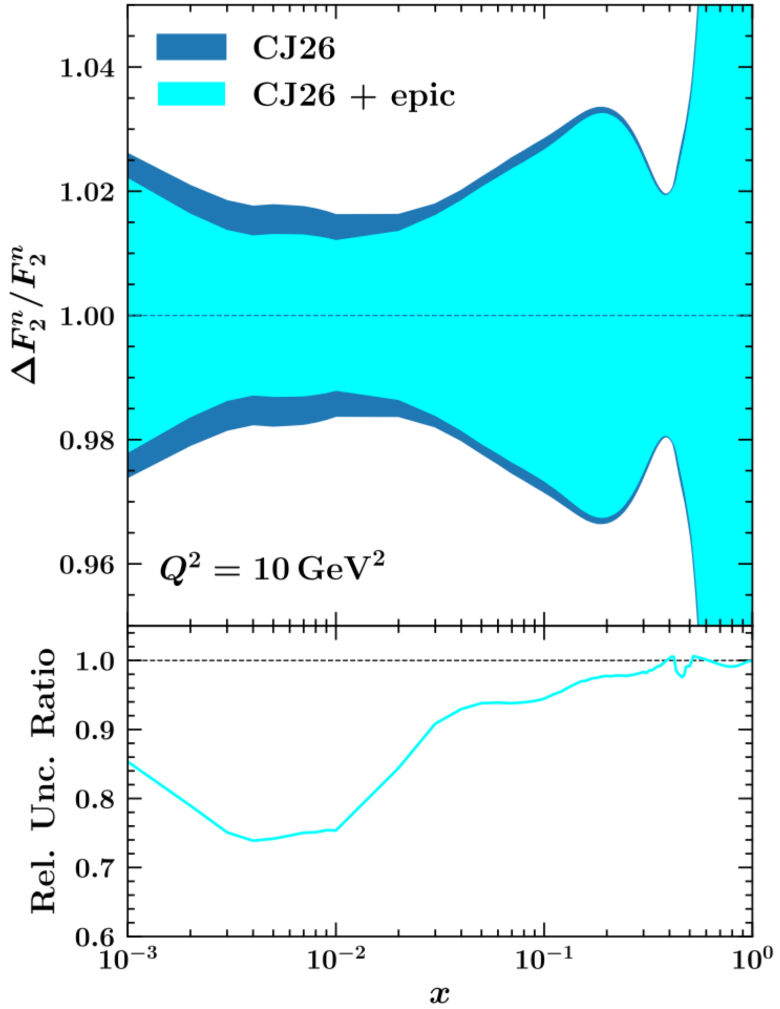






SUMMARY

- The results clearly demonstrate feasibility of measurement of TIDS in eD collisions in early years of the EIC
- The expected luminosity will be more than sufficient to have small or negligible statistical uncertainties
- Final uncertainty will be dominated by systematic uncertainty
- **Even with our conservative systematic uncertainty estimate, this measurement will have significant impact, even with luminosity in the early EIC years**
- **Outlook:** TDIS with polarized deuterons
  - Polarized structure of deuterons



THANK YOU FOR ATTENTION