

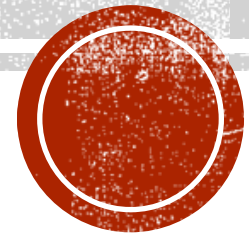
Tagged Deep Inelastic Scattering in eD Collisions at $10 \times 130 \text{ GeV}^2$

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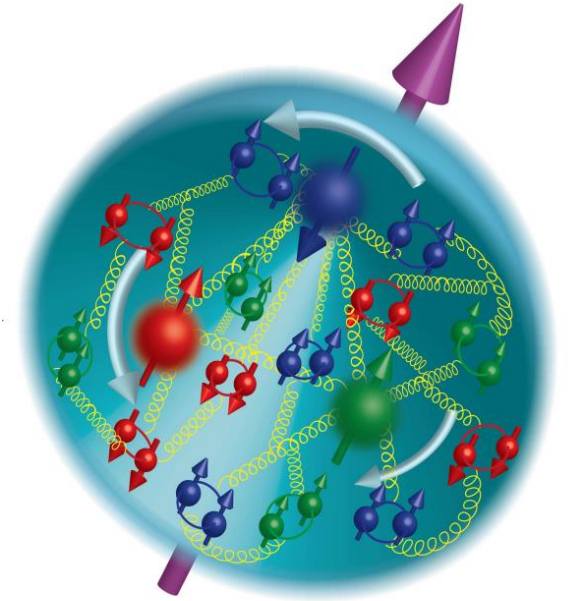
ePIC Collaboration Meeting, Glasgow

07/15/2026



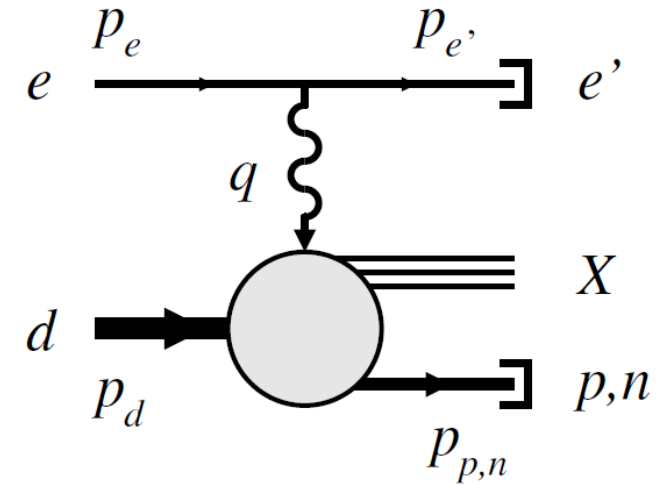
PHYSICS MOTIVATION

- **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.](#)

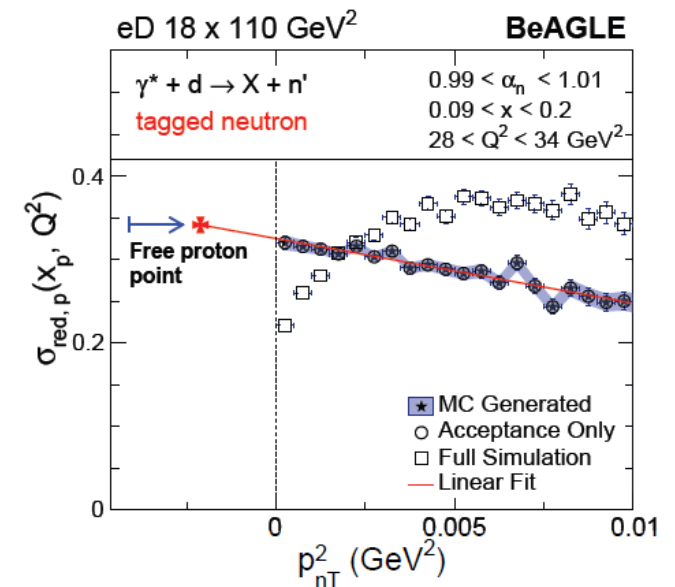
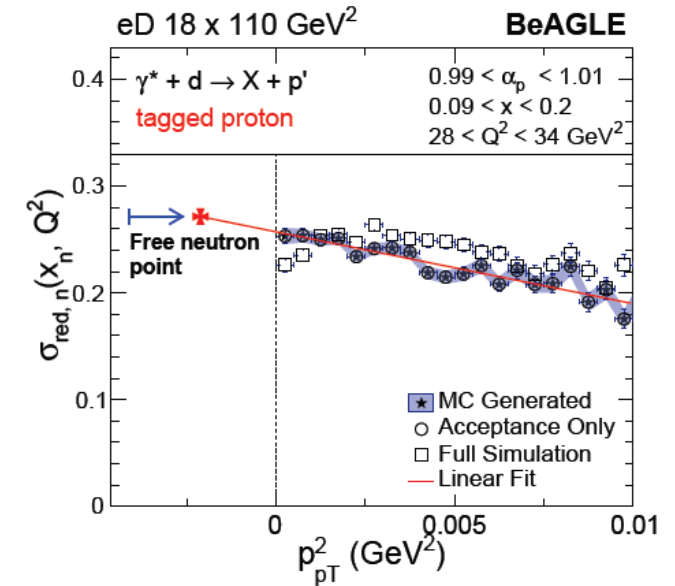
EXPERIMENTAL METHOD

■ 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



KINEMATIC VARIABLES

- Scattered electron

- $Q^2 = -q^2 = -(p_{e,beam} - p_{e,scat})^2$

- $x = \frac{Q^2}{P \cdot q}$

- $x_{nucleon} = \frac{Q^2}{2P_{nucl} \cdot q} = \frac{x}{2 - \alpha_p}$

- 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:

- $\alpha_p \equiv \frac{2p_p^+}{p_d^+} = \frac{2(E_p + p_{z,p})}{E_d + p_{z,d}}$

- 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

- $L_{int} = \frac{N_{events}}{\sigma_{tot}}$

- $\text{mb} = 2.568 \text{ GeV}^{-2}$

- Cross section for eD at $10 \times 130 \text{ GeV}^2$:

- $\sigma_{tot} = 3.538 \cdot 10^{-4} \text{ mb (en)}$

- $\sigma_{tot} = 3.707 \cdot 10^{-4} \text{ mb (ep)}$

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:

$$d\sigma_d = Flux(x, Q^2) \times \sigma_{red,d} \times dx dQ^2 \frac{d\phi_{e'}}{2\pi} [2(2\pi)^3]^{-1} \frac{d\alpha_p}{\alpha_p} \frac{dp_{T,p}^2}{2} d\phi_p$$

- Photon flux:

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

- Measured reduced cross section (integrated over $d\phi_p$)

$$\bar{\sigma}_{red,d} = \left(\frac{2.568}{L_{int}} \right) \frac{Q^4 x}{2\pi\alpha_{em}^2 [1+(1-y)^2]} \frac{[4(2\pi)^3] \alpha_p}{\Delta\alpha_p} \frac{dN}{\Delta x \Delta Q^2 \Delta p_{T,p}^2 2\pi}$$

▪ $\Delta x, \Delta Q^2, \Delta p_{T,p}^2, \Delta\alpha_p$ are bin widths

- Scattered electron
- Spectator proton/neutron
- Photon flux
- Luminosity

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.](#)

- 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:

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

- $\bar{\sigma}_{red,n}$ at the pole corresponds to a free n
 - $p_{pT}^2 \rightarrow -a_T^2$ 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

$$S_d(p_{pT}, \alpha_p)[pole] = \frac{R}{(p_{pT}^2 + a_T^2)}$$

- Position of pole

$$a_T^2 = m_N^2 - \alpha_p(2 - \alpha_p) \frac{M_d^2}{4}$$

- Residue of spectral function

$$R = 2\alpha_p^2 m_N \Gamma^2 (2 - \alpha_p)$$

$$\Gamma = 0.007885 \text{ GeV}$$

A. Jentsch, Z. Tu, C. Weiss: [Phys. Rev. C **104**, 065205.](#)
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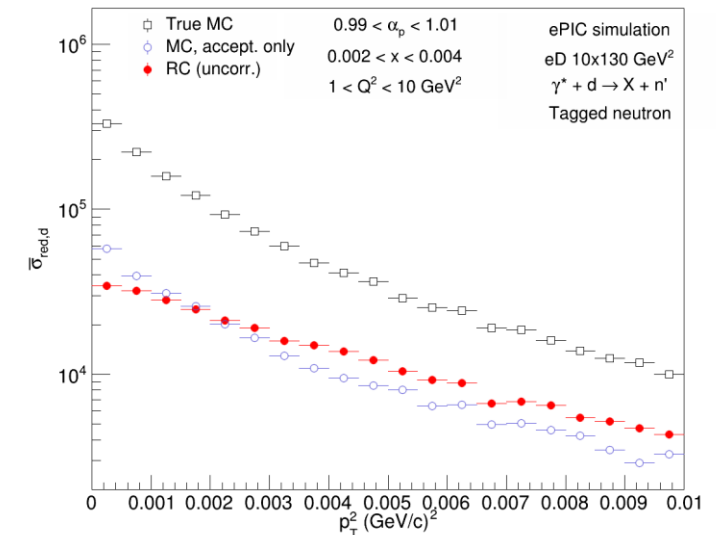
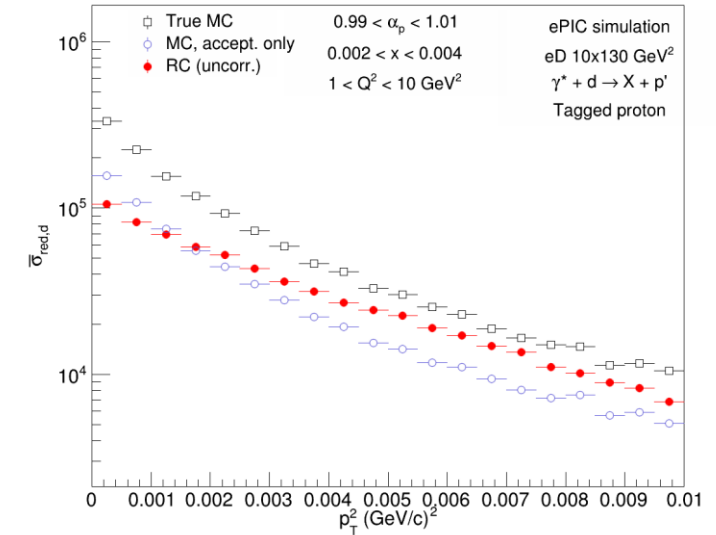
SIMULATION PRODUCTION

- BeAGLE generated eD collisions at $10 \times 130 \text{ GeV}^2$
- Simulation production overview:
 - Official simulation campaign 26.03.1
 - 20M events of eD $10 \times 130 \text{ GeV}^2$
 - 10M of en and 10M of ep
- Luminosity and cross section:
 - en : $\sigma_{tot} = 3.538 \cdot 10^{-4} \text{ mb}$, $L_{int} = N_{evt}/\sigma_{tot} = 10\text{M}/(3.538 \cdot 10^{-4} \text{ mb}) = 10\text{M}/(3.538 \cdot 10^8 \text{ fb}) = 0.028 \text{ fb}^{-1}$
 - ep : $\sigma_{tot} = 3.707 \cdot 10^{-4} \text{ mb}$, $L_{int} = 0.028 \text{ fb}^{-1}$ (same as en after rounding)
 - Total integrated luminosity (EICRecon): $L_{int} = 0.056 \text{ fb}^{-1}$
 - Expected luminosity for year 2: $L_{int} = 1.5 \text{ fb}^{-1}$
 - All statistical uncertainties projected to expected luminosity
- Note: eD collisions at $9 \times 130 \text{ GeV}^2$ sample currently in production



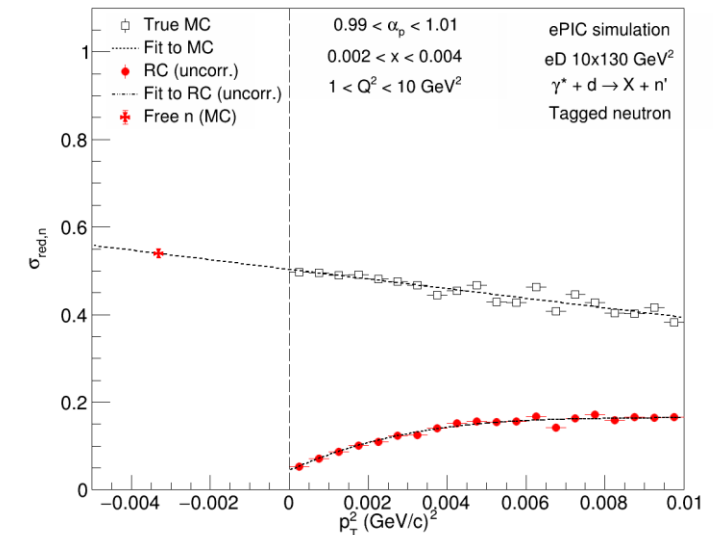
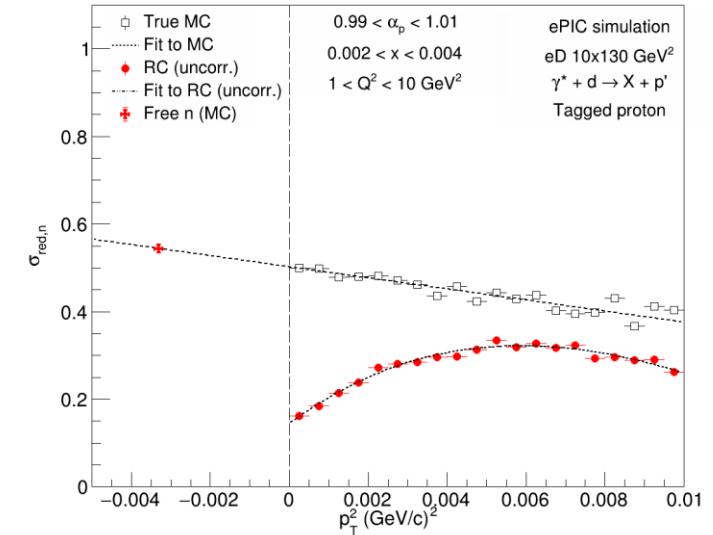
DEUTERON REDUCED CROSS SECTION

- (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 acceptor 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



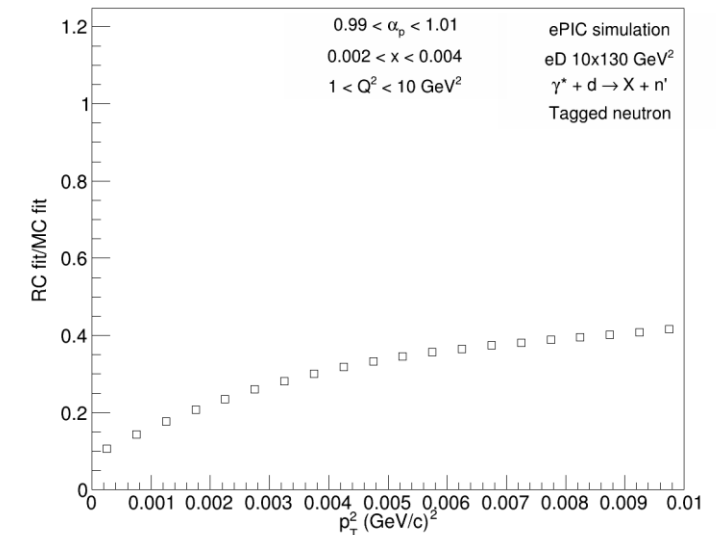
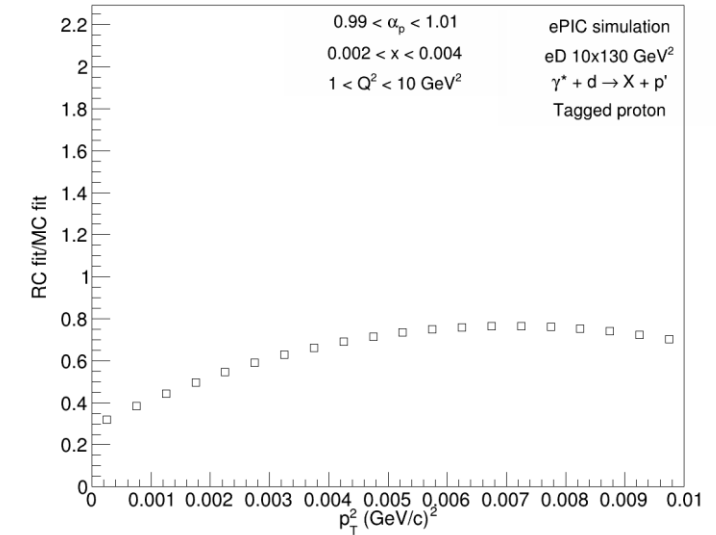
NUCLEON REDUCED CROSS SECTION – UNCORRECTED

- (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



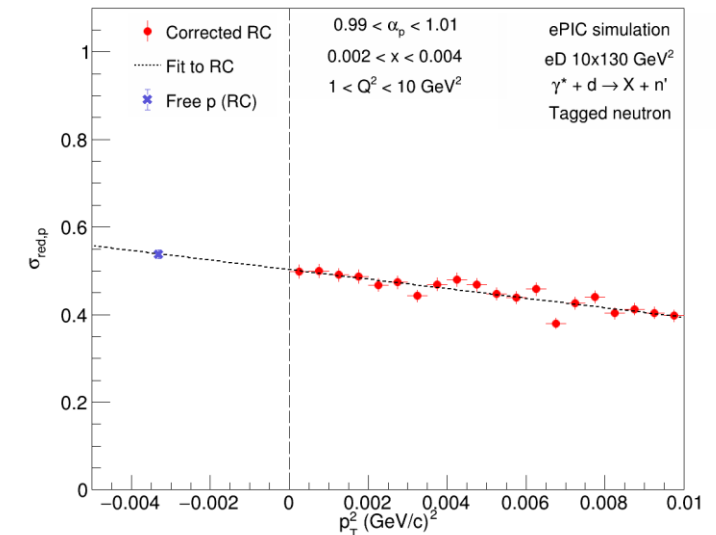
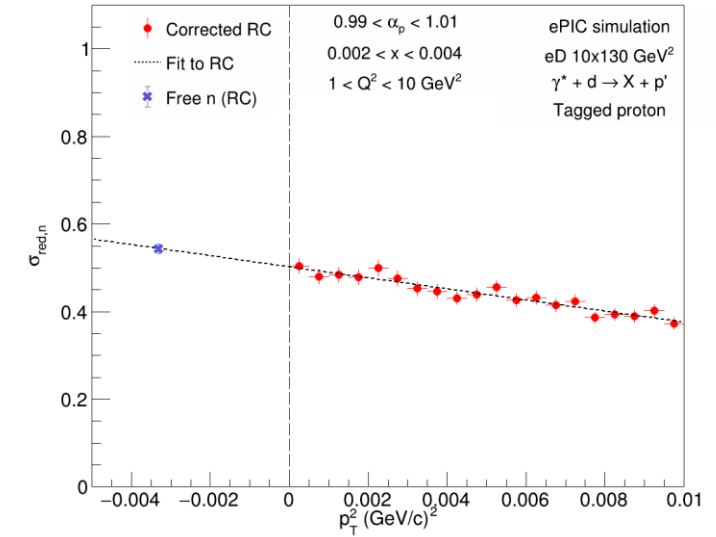
EFFICIENCY AND ACCEPTANCE

- 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



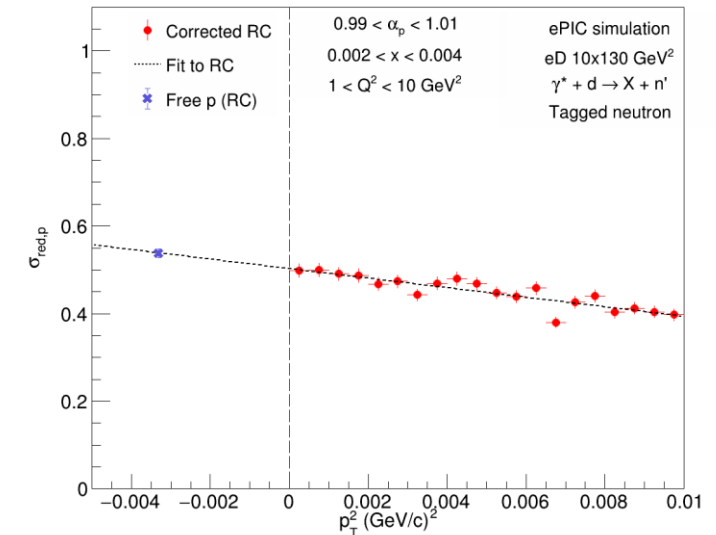
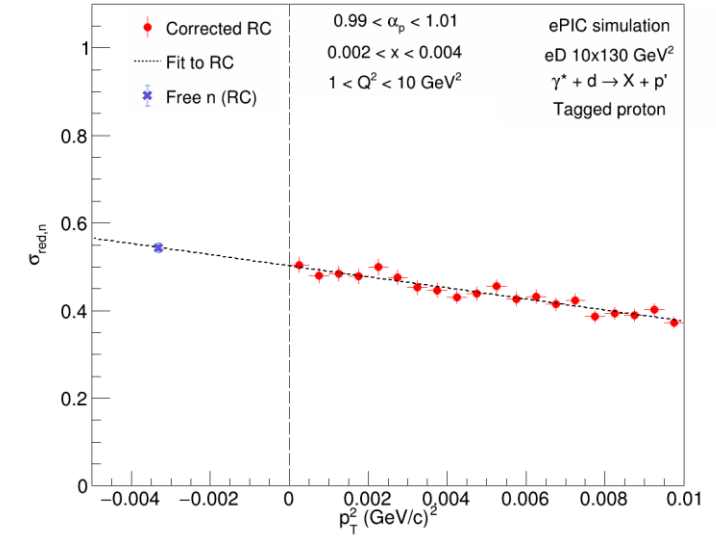
SYSTEMATIC UNCERTAINTIES

■ 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).

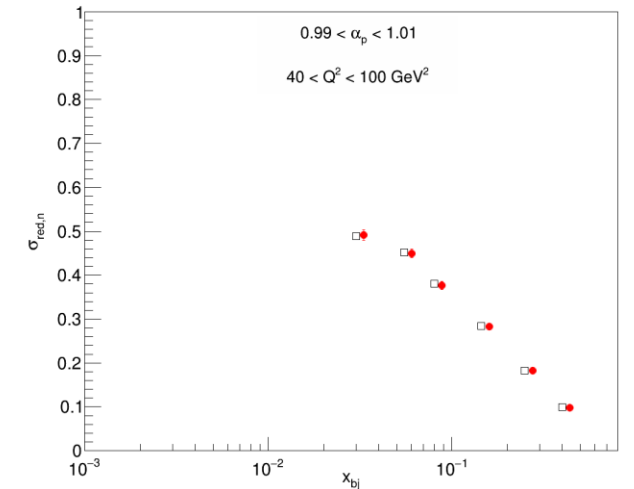
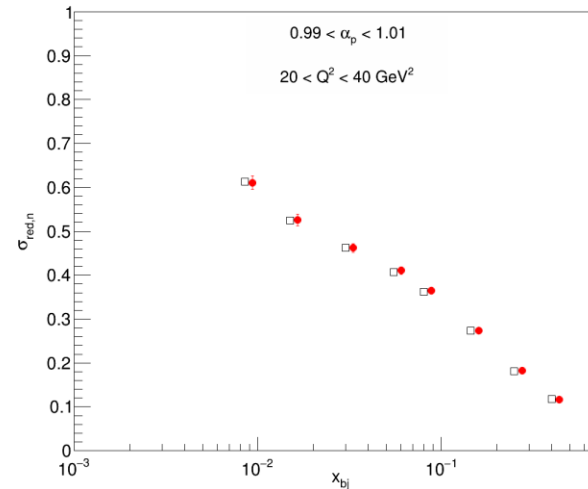
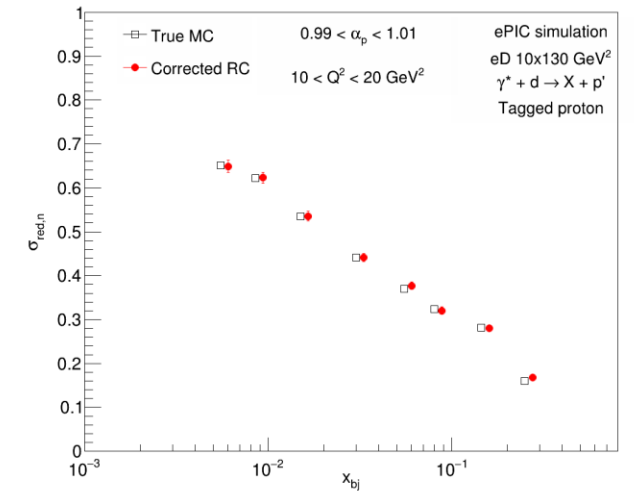
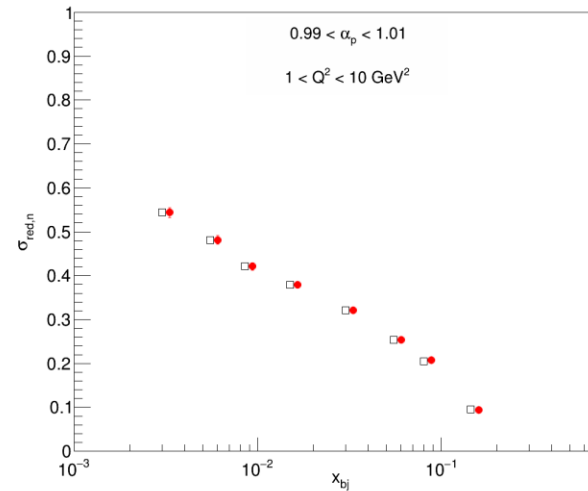
■ Total systematic uncertainty:

$$\sigma_{sys} = \sqrt{\sigma_{lumi}^2 + \sigma_{th}^2 + \sigma_{beam}^2 + \sigma_{n/p}^2}$$



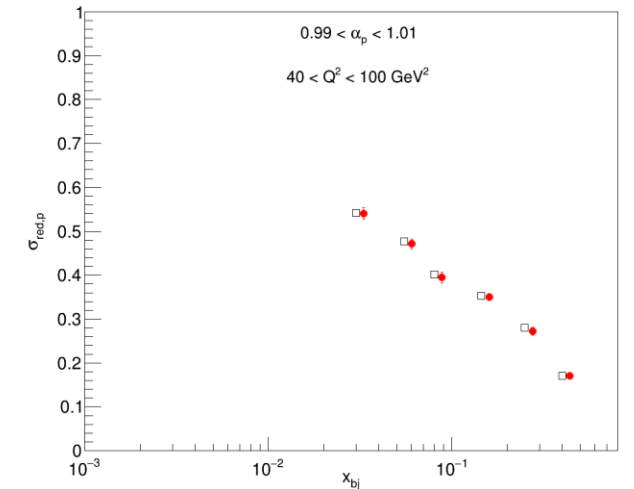
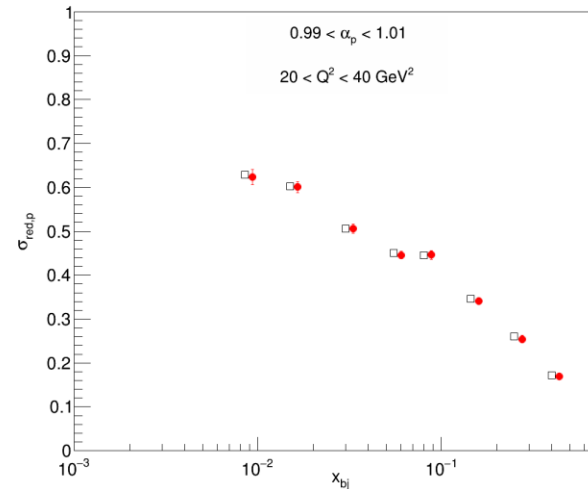
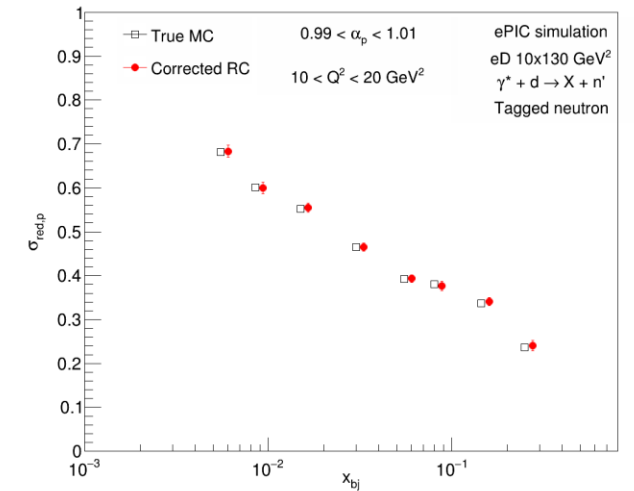
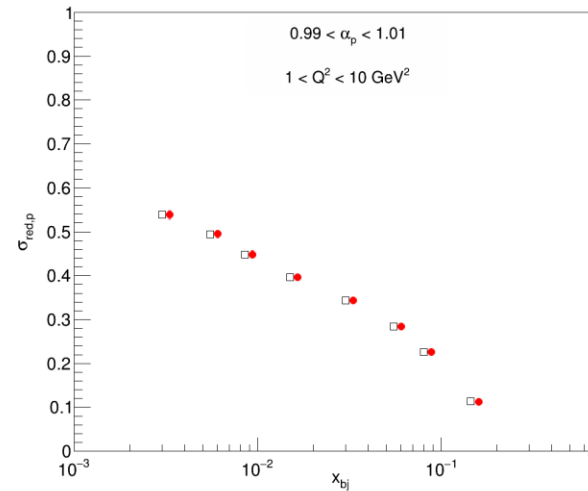
NEUTRON REDUCED CROSS SECTION VS. x_{bj}

- 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



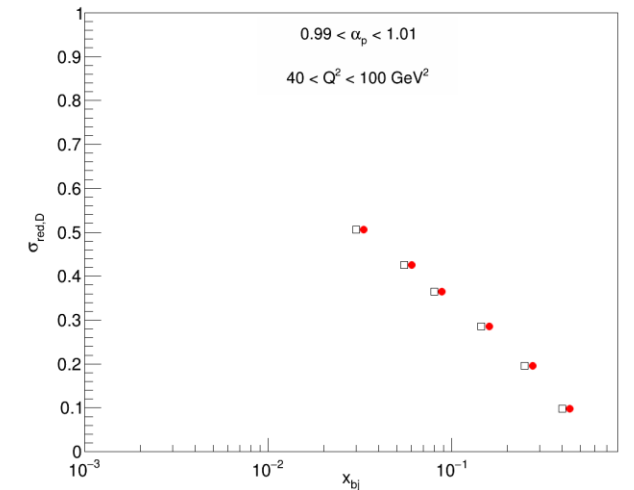
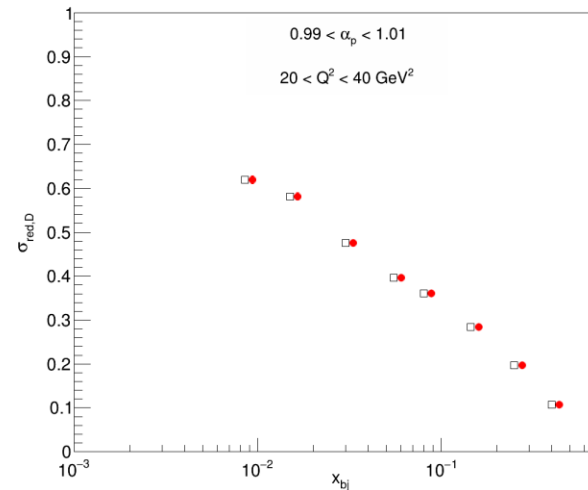
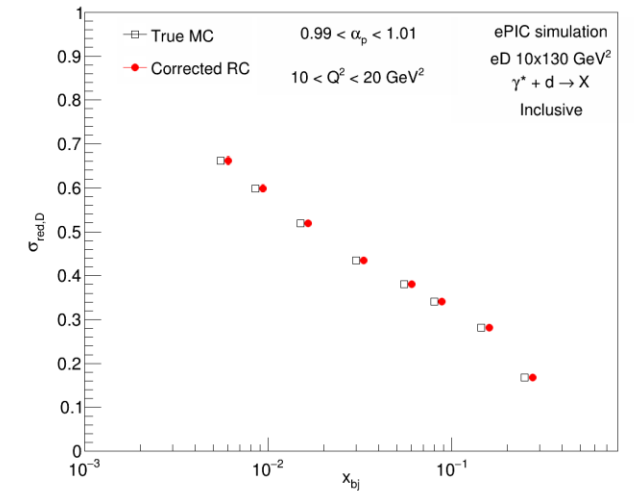
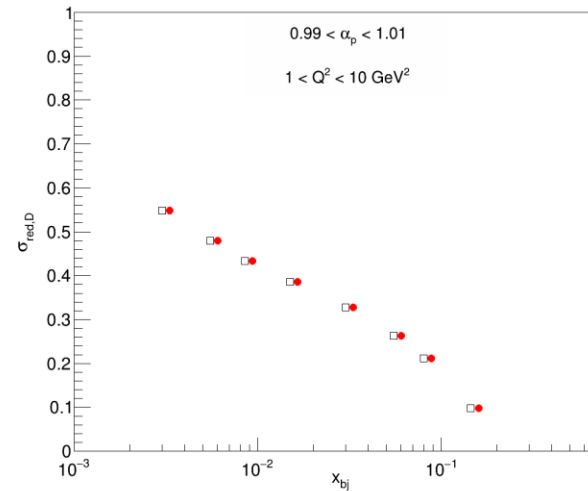
PROTON REDUCED CROSS SECTION VS. x_{bj}

- 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



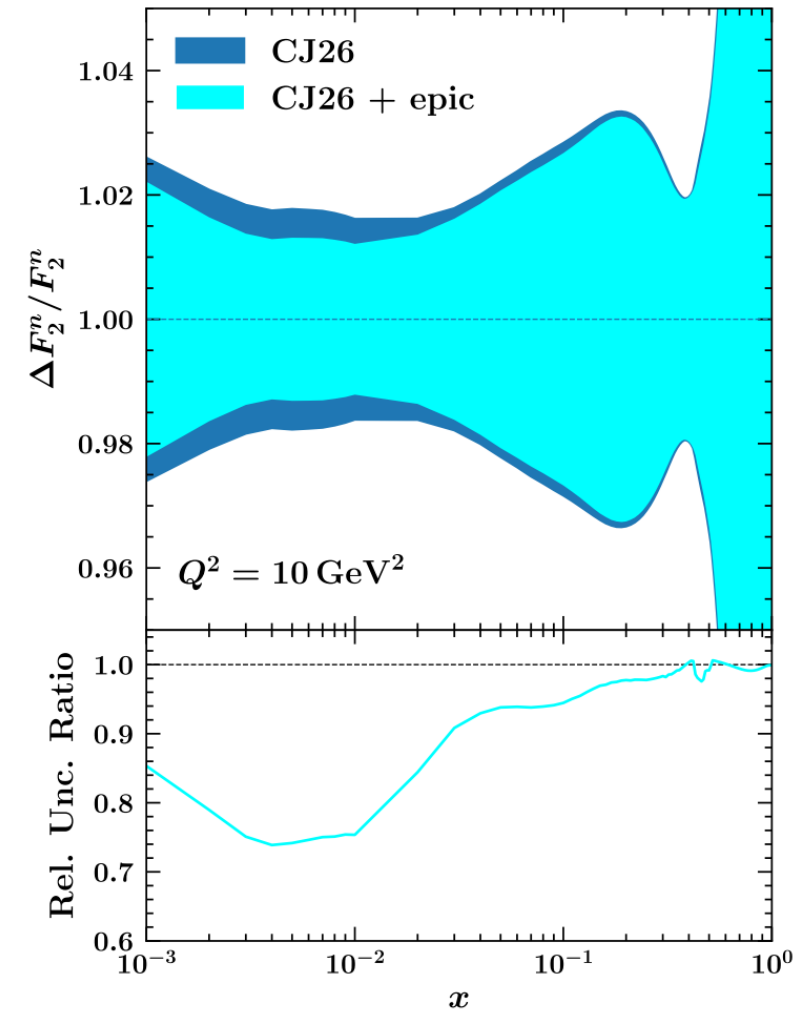
DEUTERON REDUCED CROSS SECTION VS. x_{bj}

- 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



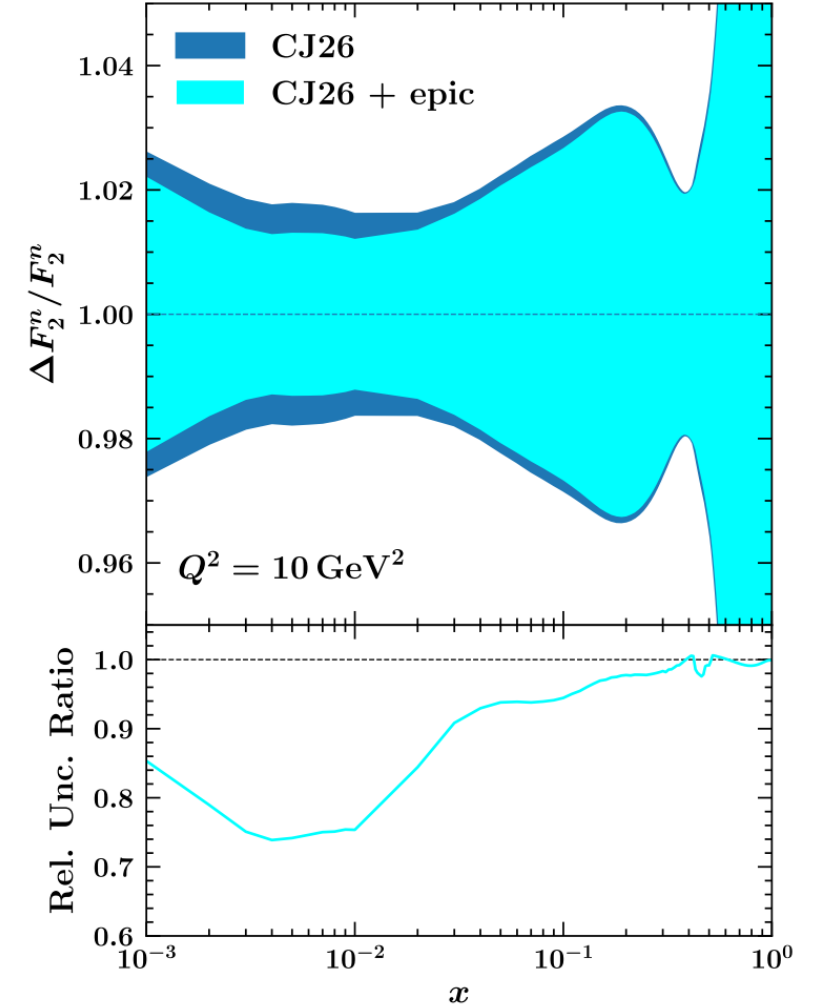
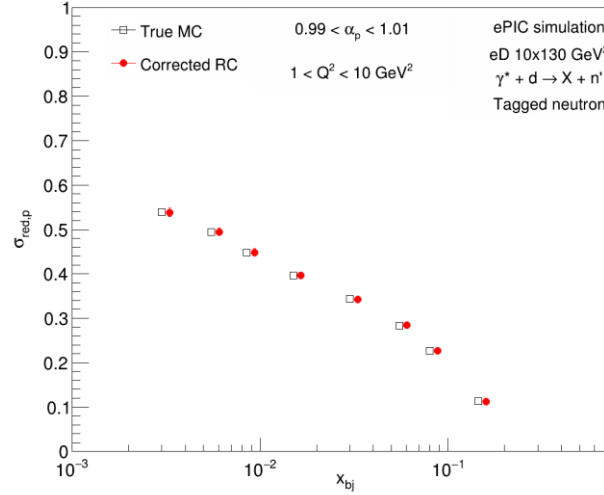
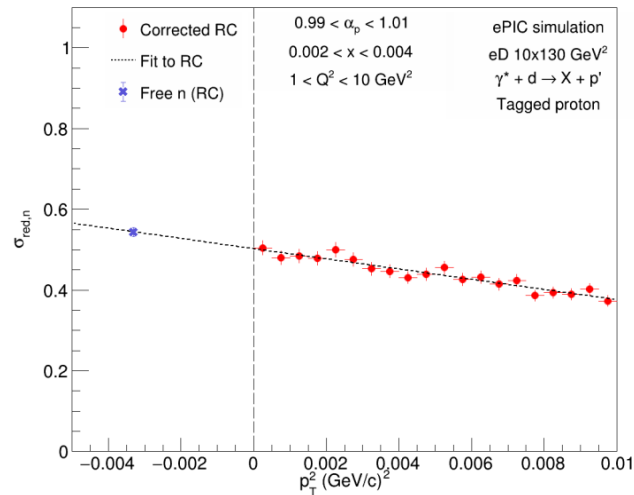
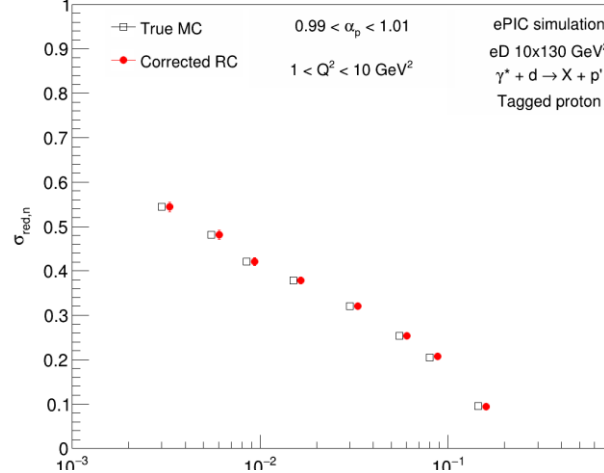
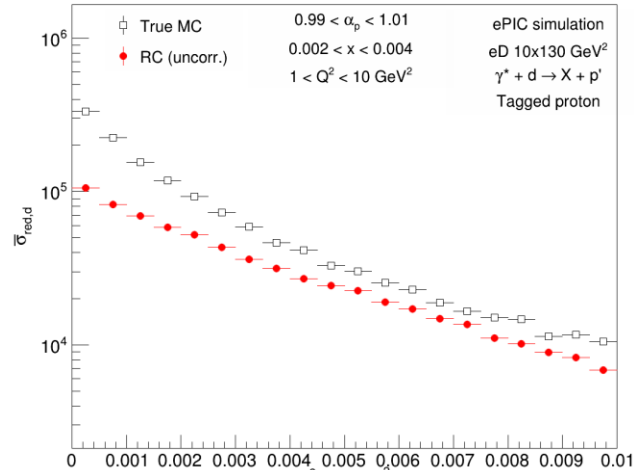
RESULT FOR ESR

- 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



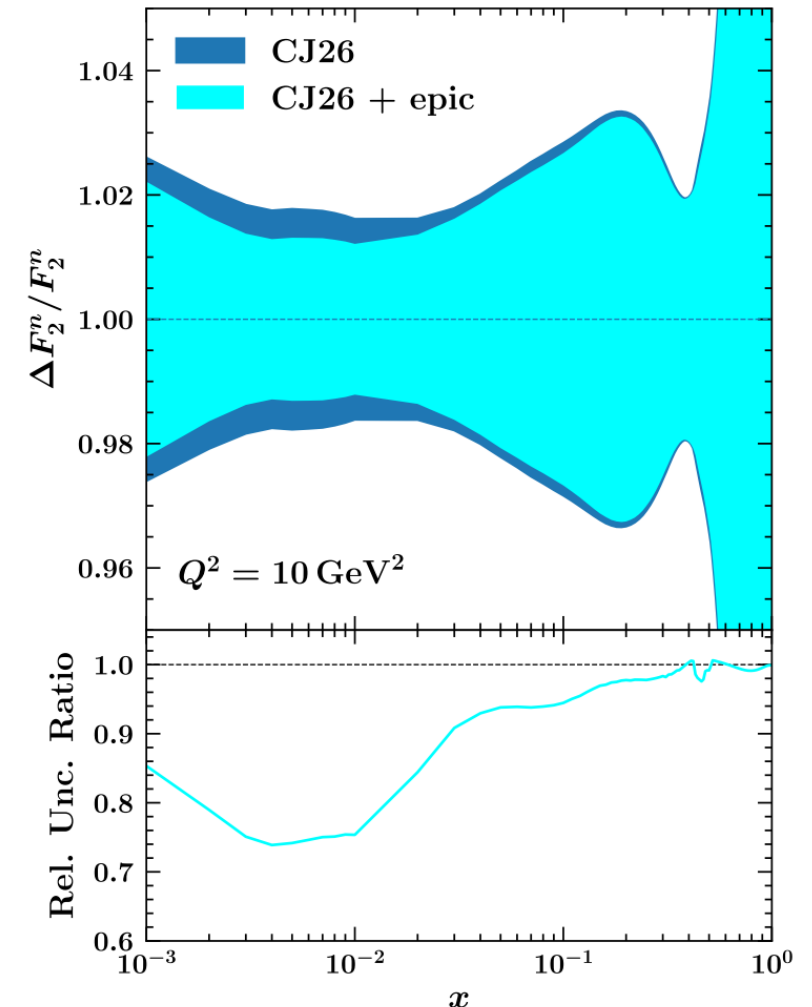
FIGURES FOR NIM PAPER

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



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**
- **Results approved in Physics Forum on 07/07/2026**
- **Outlook:** TDIS with polarized deuterons
 - Polarized structure of deuterons





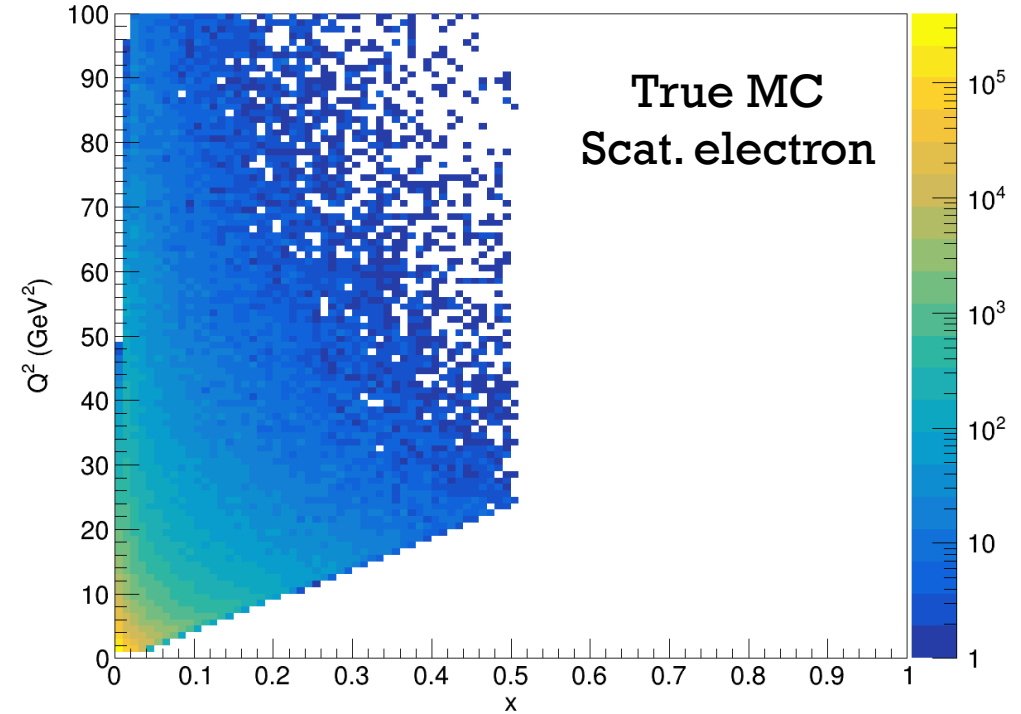
**THANK YOU FOR
ATTENTION**



BACKUP

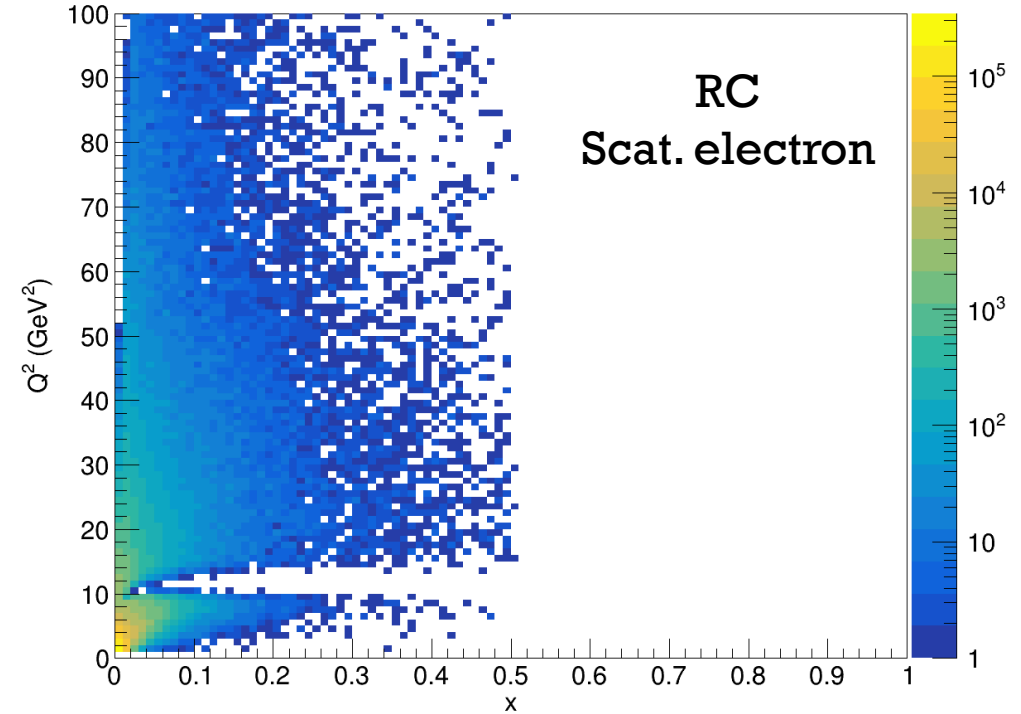
SCATTERED ELECTRON FINDING — MC

- Find electron which has the beam electron as a parent



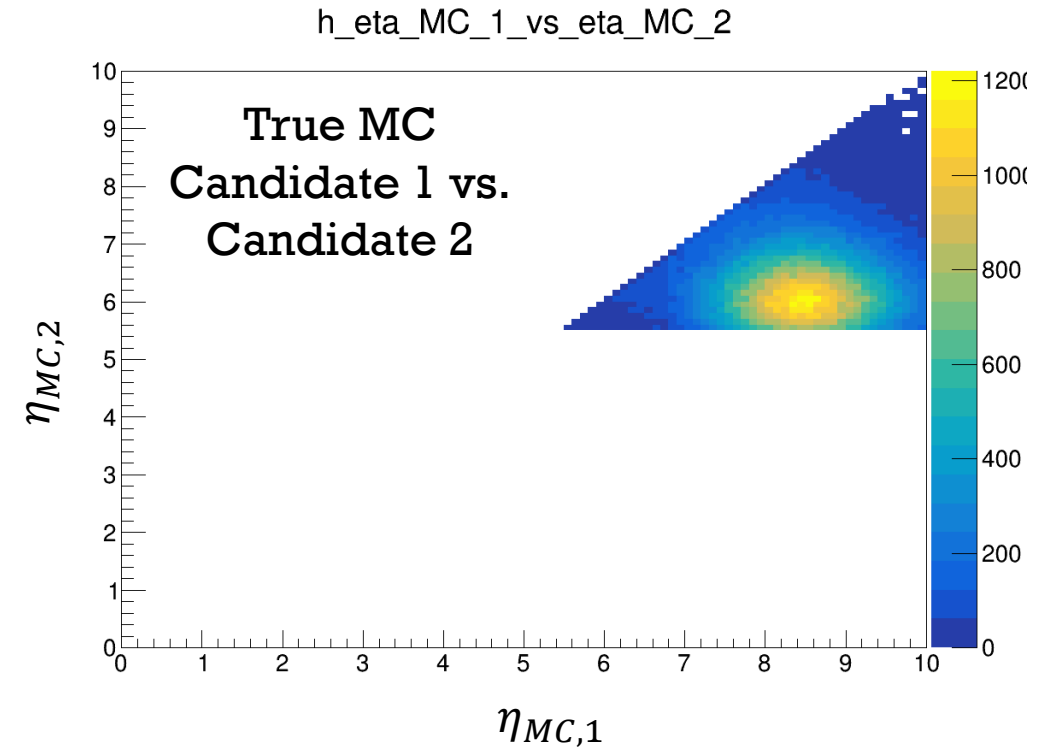
SCATTERED ELECTRON FINDING — RC

- 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: $0.99 < \alpha_p < 1.01$
 - $\alpha_p \equiv \frac{2p_p^+}{p_d^+} = \frac{2(E_p + p_{z,p})}{E_d + p_{z,d}}$

RC Tagged proton

