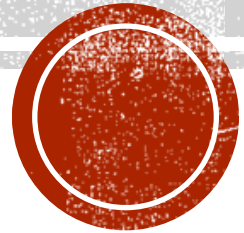
Deuteron Tagging



Jan Vanek

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ePIC Collaboration Meeting, BNL

01/23/2026

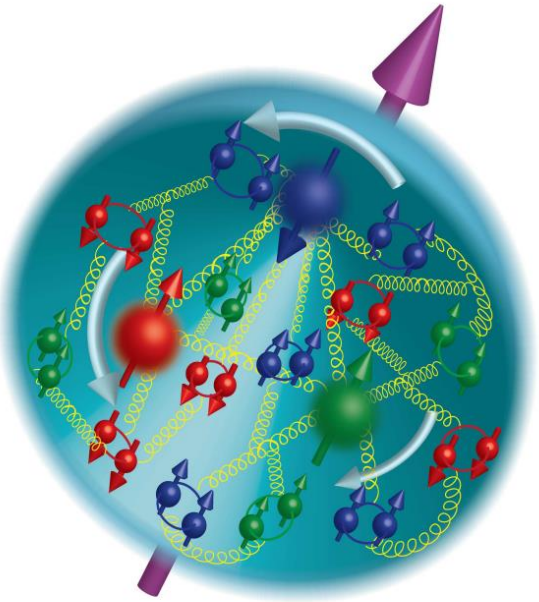
OVERVIEW

- Extraction of deuteron and neutron reduced cross section from HepMC and EICRecon simulation output
  - True MC information, without any beam or detector effects
  - Simulation setup:
    - eD DIS events at 10x130 GeV^2 (simulation by Alex Jentsch)
    - 500k events for tagged protons and 500k events for tagged neutrons
  - Goal:
    - Implementation of full TDIS framework on the new simulation sample
    - Reproduction results from A. Jentsch, Z. Tu, C. Weiss: Phys. Rev. C **104**, 065205
- Today:
  - Analysis overview
  - New results
    - New EICRecon simulation sample with full statistics (fix from last report)
    - Spectator proton tagging using reconstructed information from off-momentum detector
    - Spectator neutron tagging in HepMC

PHYSICS MOTIVATION

- Main motivation: Understanding of internal structure of nucleons

- Historically was studied via Deep Inelastic Scattering (DIS) on protons
  - Relatively experimentally easy as we can accelerate electrons or protons
  - Structure functions and Parton Distribution Functions (PDFs) of proton reasonably well known
  - Despite long experimental efforts, still many open questions:
    - Spin structure of nucleons, Transverse and Generalized PDFs…

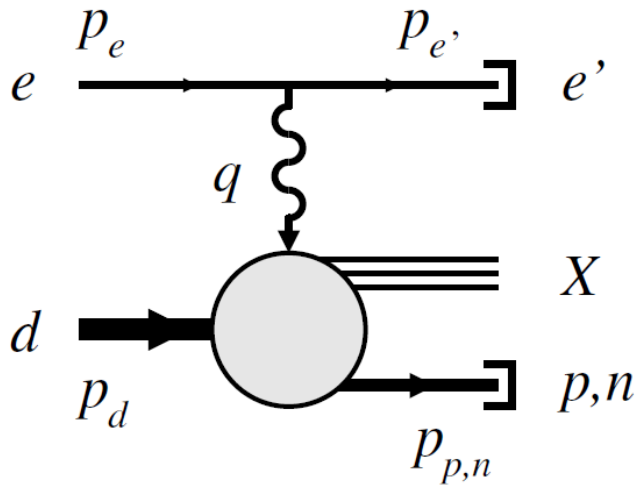


- We need also to need to measure **neutron internal structure** for full understanding of nucleon internal structure and QCD in general
  - Extraction of structure function F_2 of neutron

- Main challenges:
  - Neutrons are neutral and cannot be easily accelerated
  - Generally 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
    - Possible solution – pole extrapolation
  - Detection of the spectator p or n
    - Very difficult in fixed target experiments, as spectators have very low momentum and generally will stay in the target
    - Possible to measure at collider, such as the future Electron Ion Collider (EIC), as "target" is boosted
      - Still challenging, as spectators are very close to the hadron beam
- **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.

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:
  - $\mathrm{d}\sigma_d = Flux(x, Q^2) \times \sigma_{red,d} \times \frac{\mathrm{d}x}{2}\mathrm{d}Q^2 \frac{\mathrm{d}\phi_{e'}}{2\pi}[2(2\pi)^3]^{-1}\frac{\mathrm{d}\alpha_p}{\alpha_p}\frac{\mathrm{d}p_{T,p}^2}{2}\mathrm{d}\phi_p$
- Photon flux:
  - $Flux(x, Q^2) = \frac{2\pi\alpha_{em}^2 y^2}{Q^4(1-\epsilon)x} = \frac{2\pi\alpha_{em}^2[1+(1-y)^2]}{Q^4 x}$
- Deuteron reduced cross section
  - $\sigma_{red,d} = \frac{1}{Flux}\frac{\mathrm{d}\sigma_d}{\mathrm{d}x\mathrm{d}Q^2(d\phi_{e'}/2\pi)\mathrm{d}\Gamma_p}$, where $\mathrm{d}\Gamma_p = [2(2\pi)^3]^{-1}\frac{\mathrm{d}\alpha_p}{\alpha_p}\frac{\mathrm{d}p_{T,p}^2}{2}\mathrm{d}\phi_p$
- Measured reduced cross section (integrated over $\mathrm{d}\phi_p$)
  - $\bar{\sigma}_{red,d} = \left(\frac{2.568}{L_{int}}\right)\frac{Q^4 x}{2\pi\alpha_{em}^2[1+(1-y)^2]}\frac{[4(2\pi)^3]\alpha_p}{\Delta\alpha_p}\frac{\mathrm{d}N}{\Delta x\Delta Q^2\Delta p_{T,p}^2}$
    - $\Delta x,\ \Delta Q^2,\ \Delta p_{T,p}^2, \Delta\alpha_p$ are bin widths

- Scattered electron
- Spectator proton + struck deuteron
- Photon flux

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
  - $\Delta\phi_p = 2\pi$
  - We are also integrating over full 2π

POLE EXTRAPOLATION METHOD

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

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

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

- Solution is to experimentally measure $\sigma_{red,n}$ as a function of p_{pT}^2 for small positive values and extrapolate to the pole
  - We are using DIS on bound n to extract F_2 of free n

- 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

- Deuteron spectral function
  - $S_d(p_{pT},\alpha_p)[pole] = \frac{R}{\left(p_{pT}^2+a_T^2\right)^2}$
  - Position of pole
    - $a_T^2 = m_N^2 - \alpha_p(2-\alpha_p)\frac{M_d^2}{4}$
    - Extrapolation done for $\alpha_p = 1$
  - Residue of spectral function
    - $R = 2\alpha_p^2 m_N \Gamma^2(2-\alpha_p)$
    - $\Gamma^2 = 0.007885$ GeV

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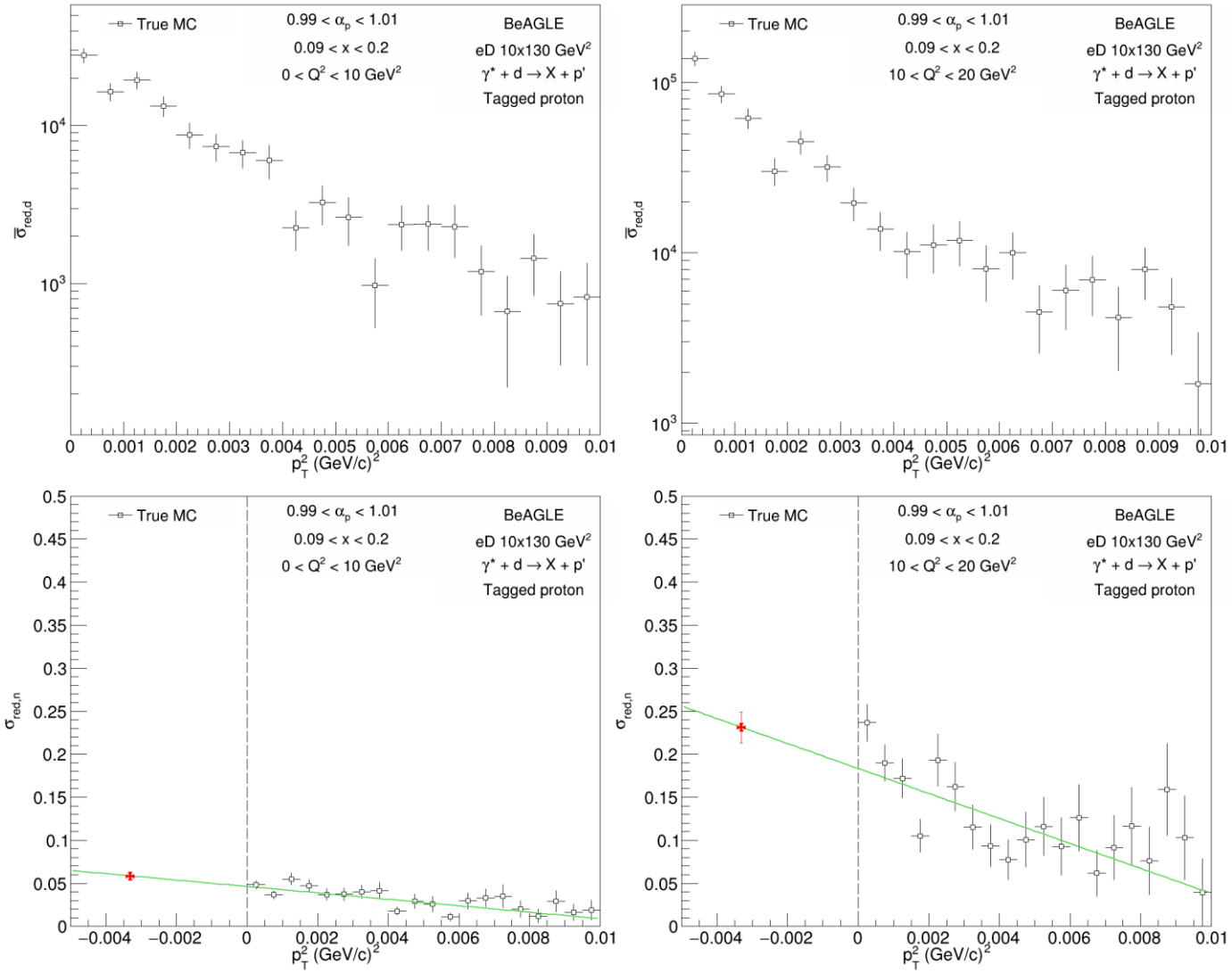
TAGGED PROTON – BeAGLE

- (top) Deuteron reduced cross section in BeAGLE calculated using tagged protons
- (bottom) Neutron reduced cross section in BeAGLE calculated using tagged protons
  - Red point is extrapolated to pole
- Minor updates since last time shown:
  - Selecting only events with one proton in spectator region
  - Added $|\eta| < 5.5$ cut
    - To match and compare to cuts in EICRecon



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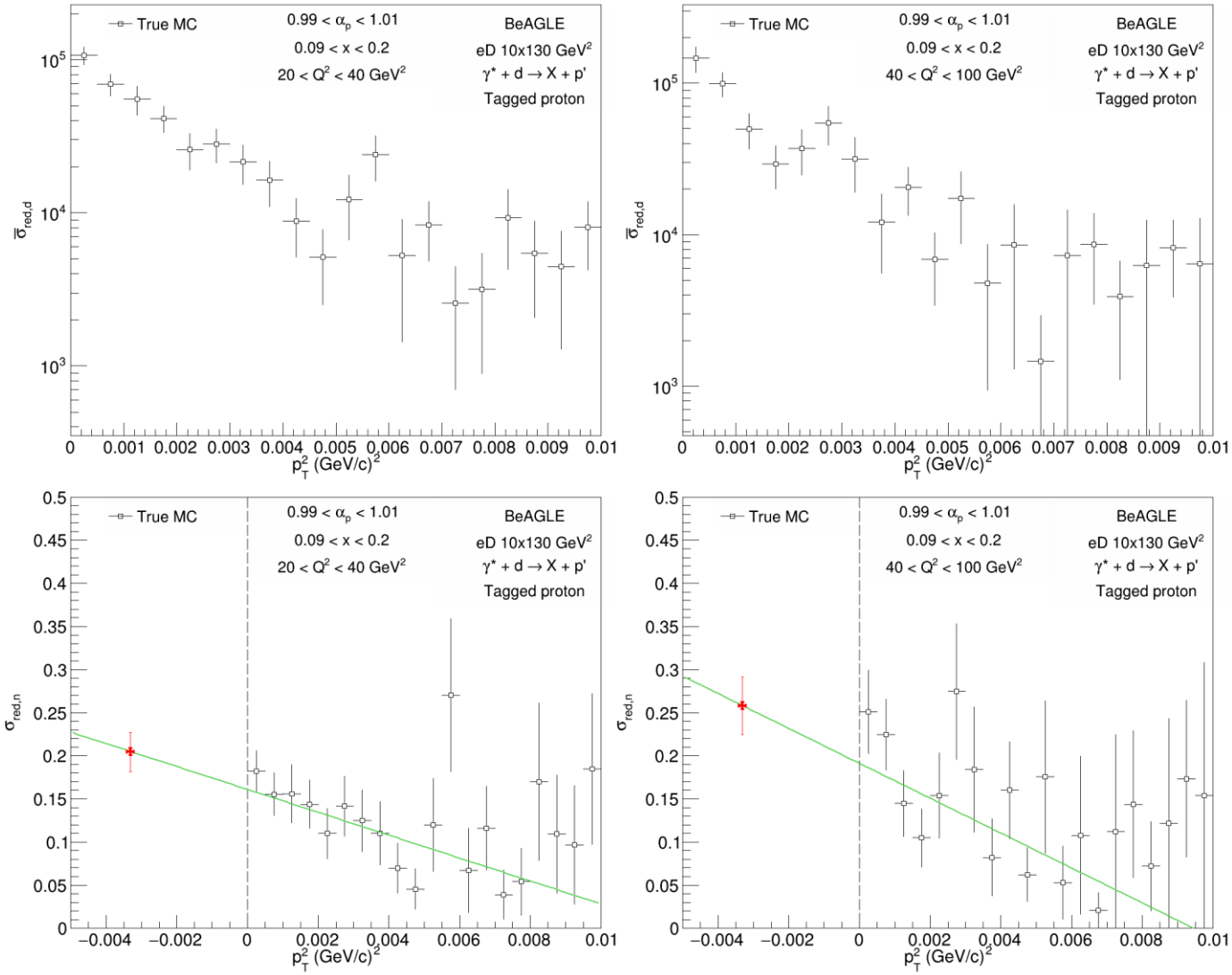

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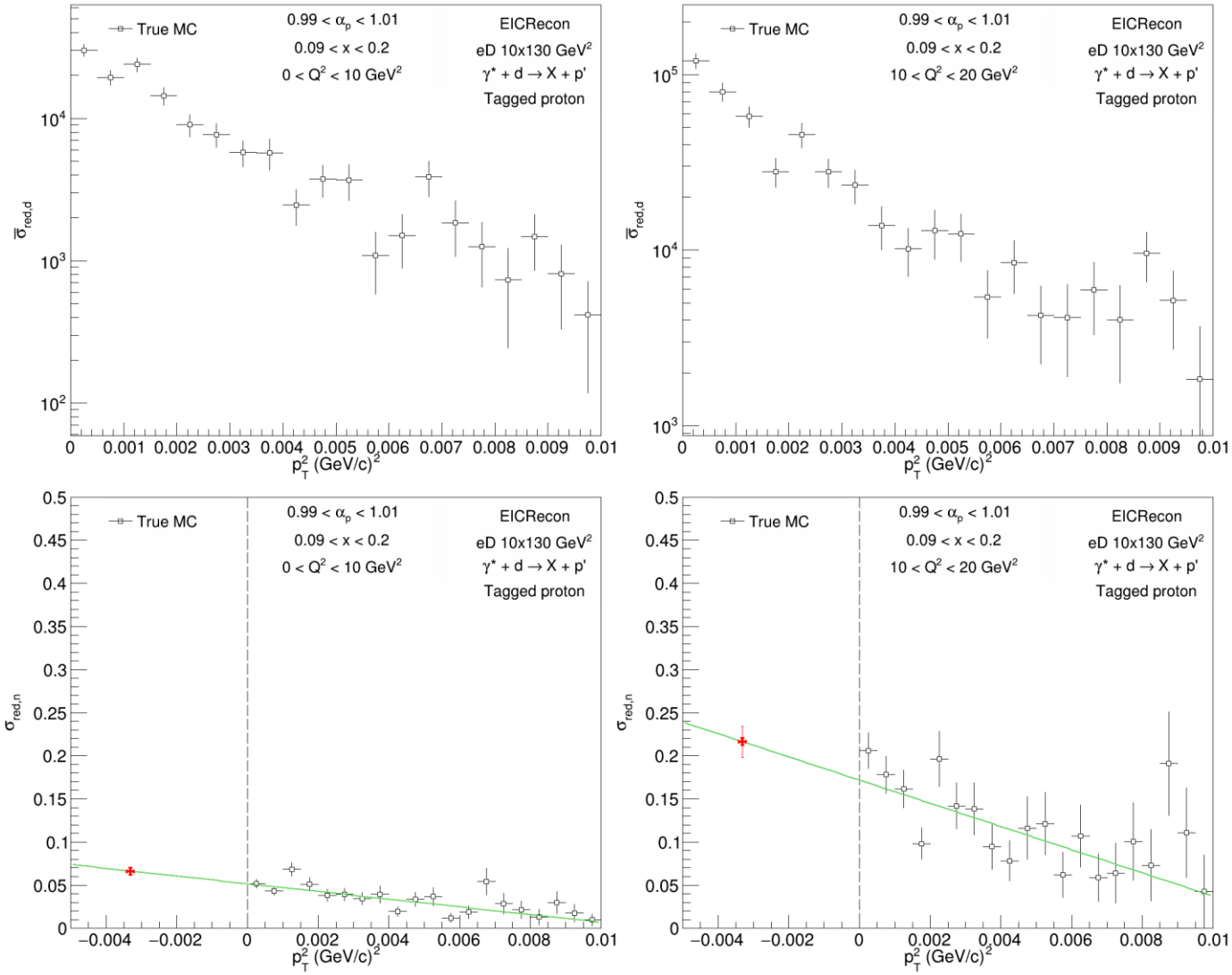

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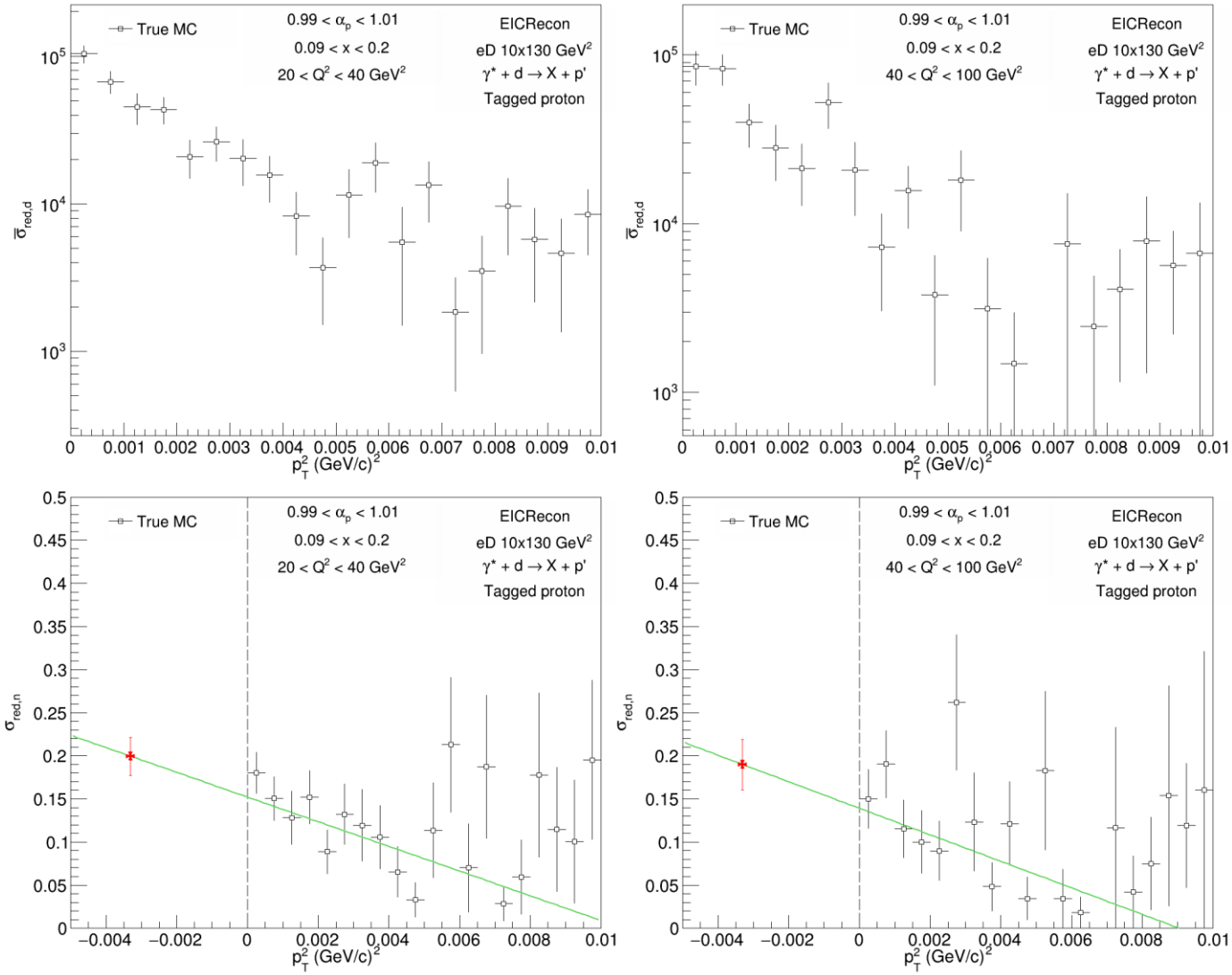

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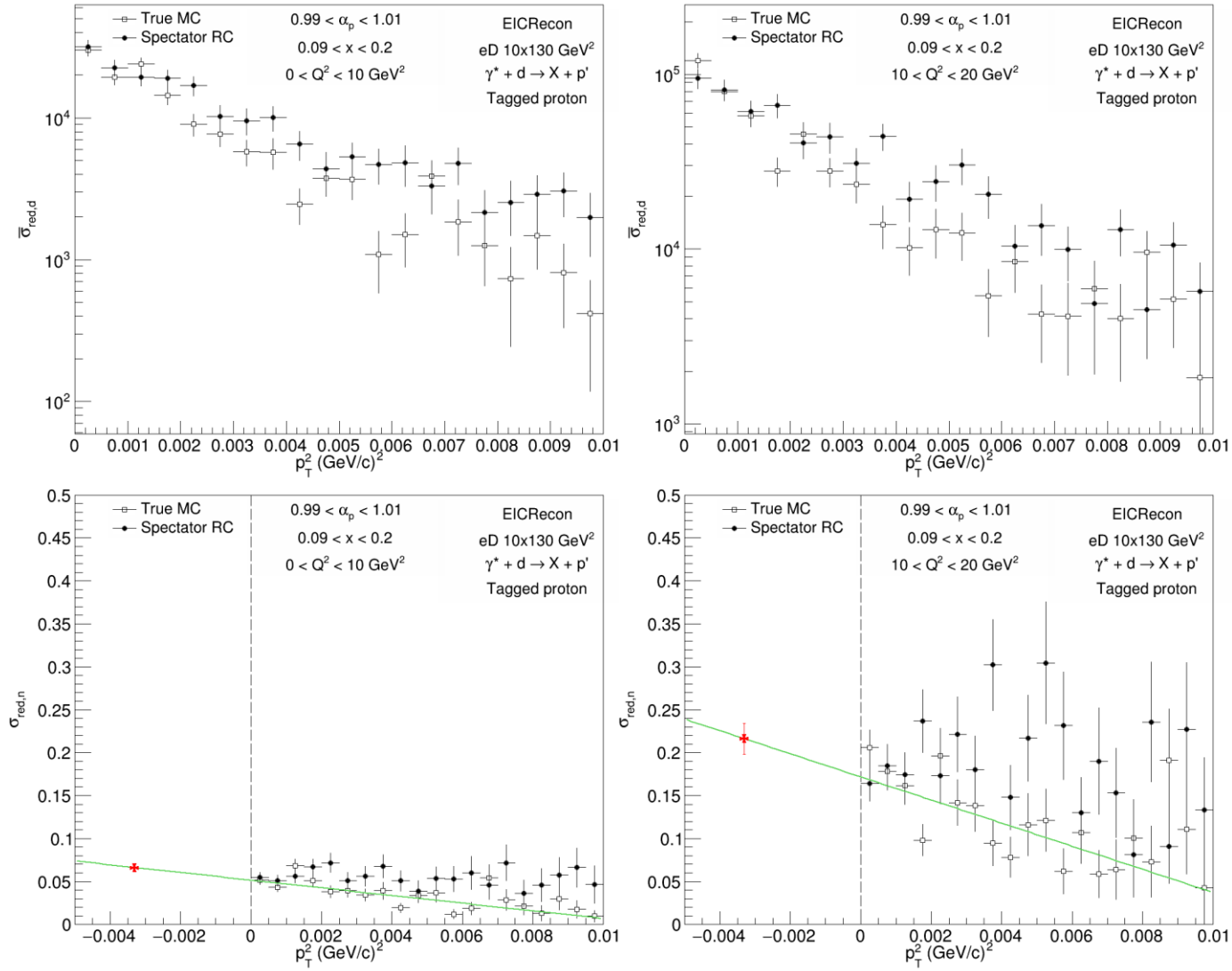

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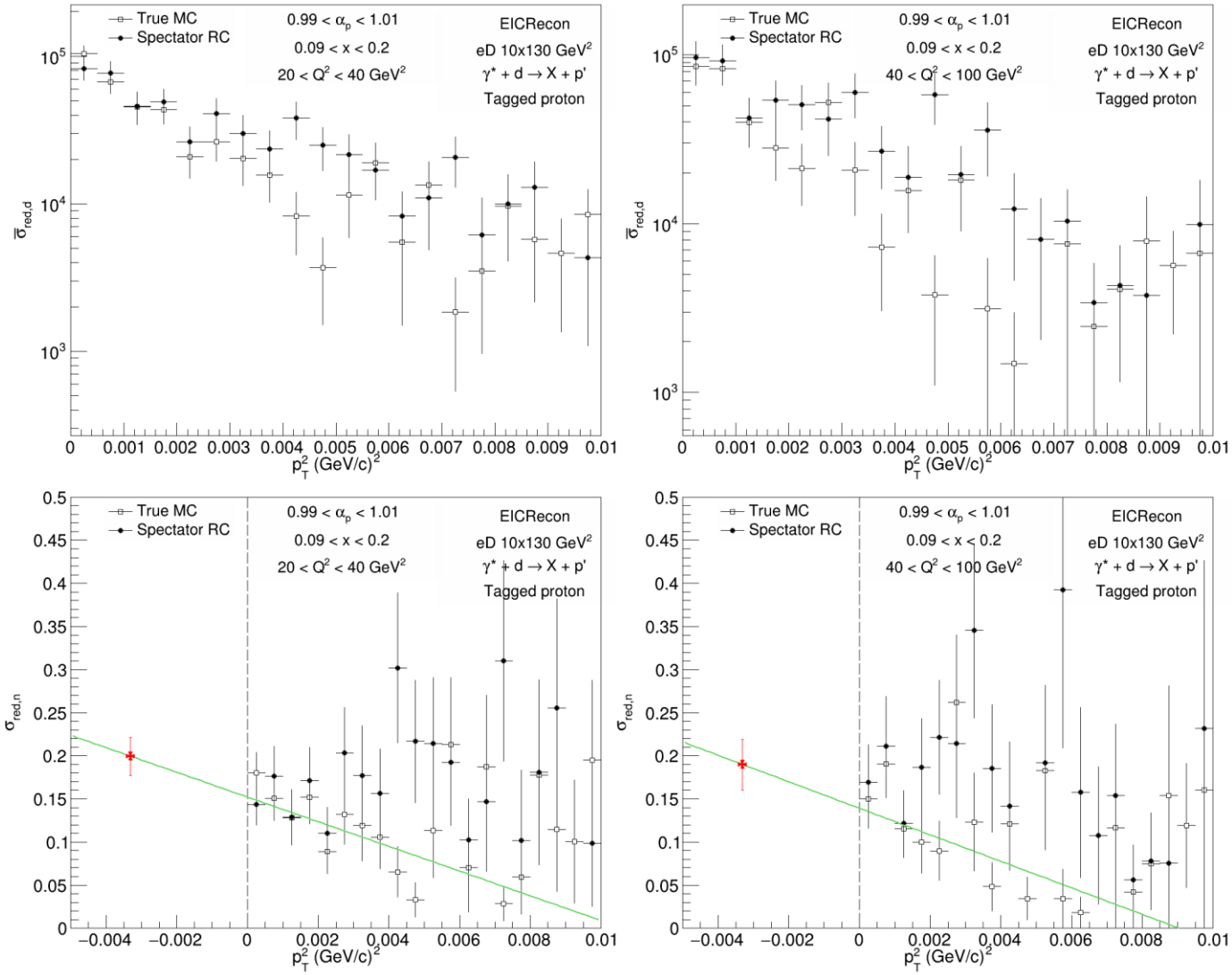

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  - $a_T^2 = m_N^2 - \alpha_p(2-\alpha_p)\frac{M_d^2}{4}$
- Different result for proton reduced cross section than in original paper
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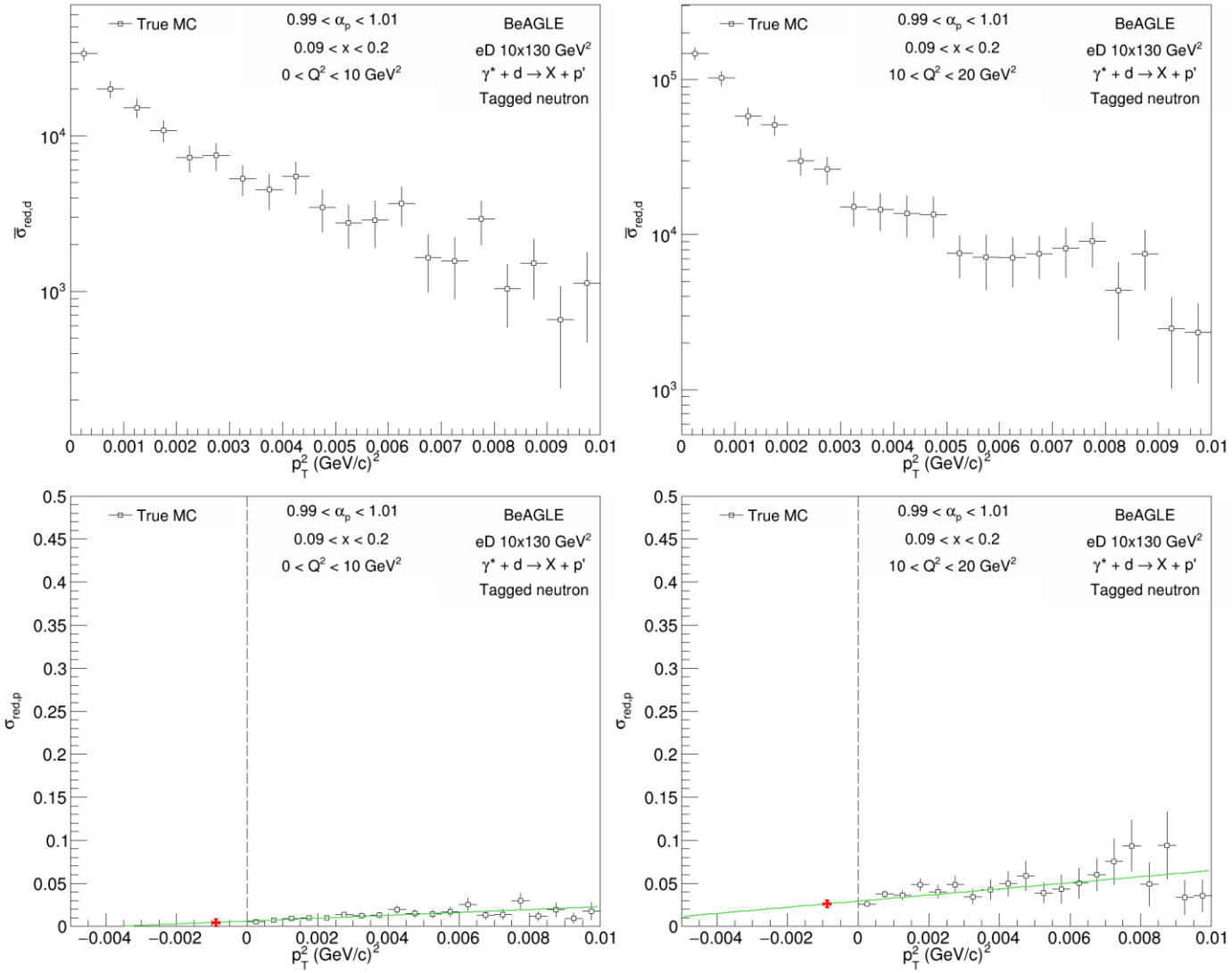

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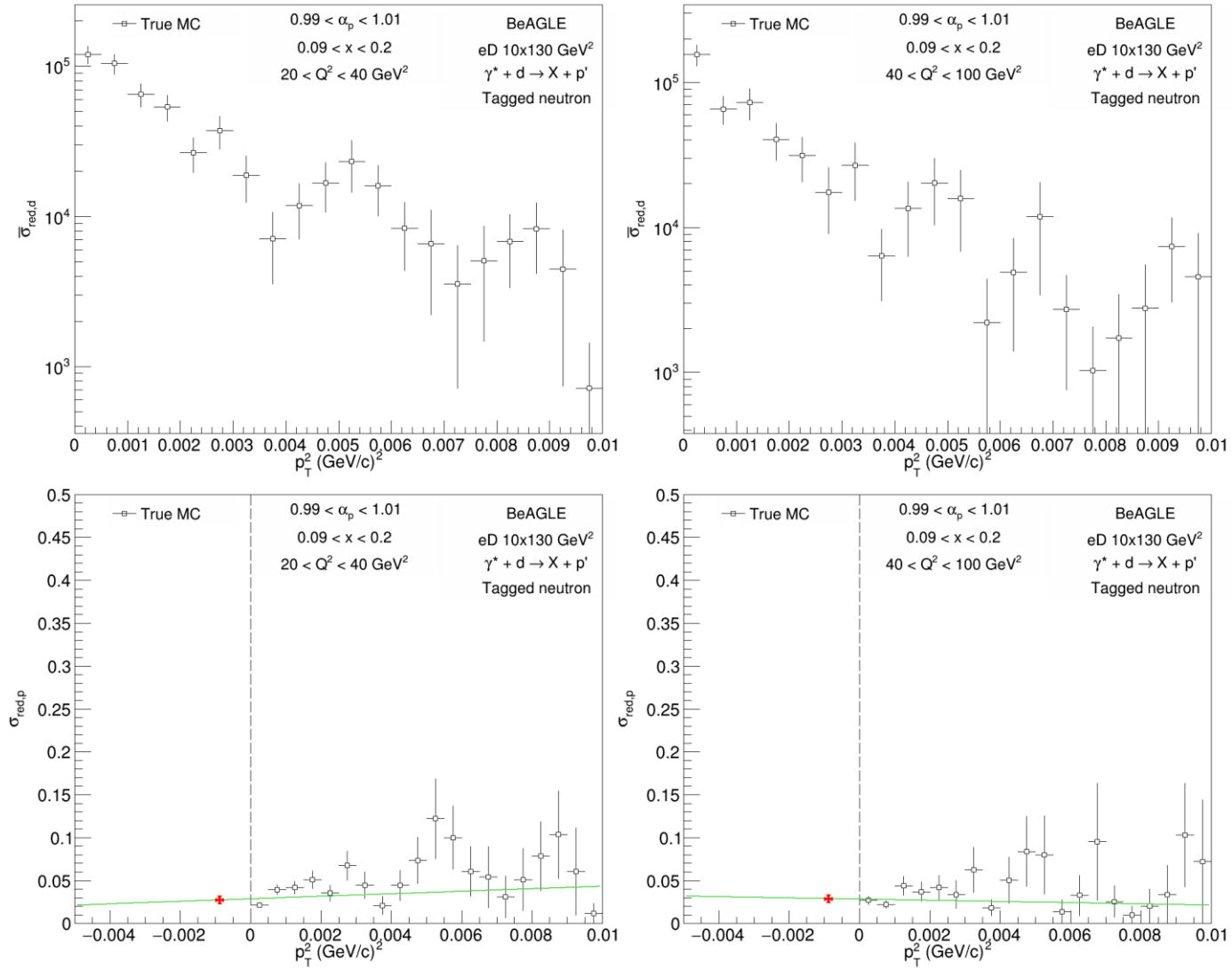

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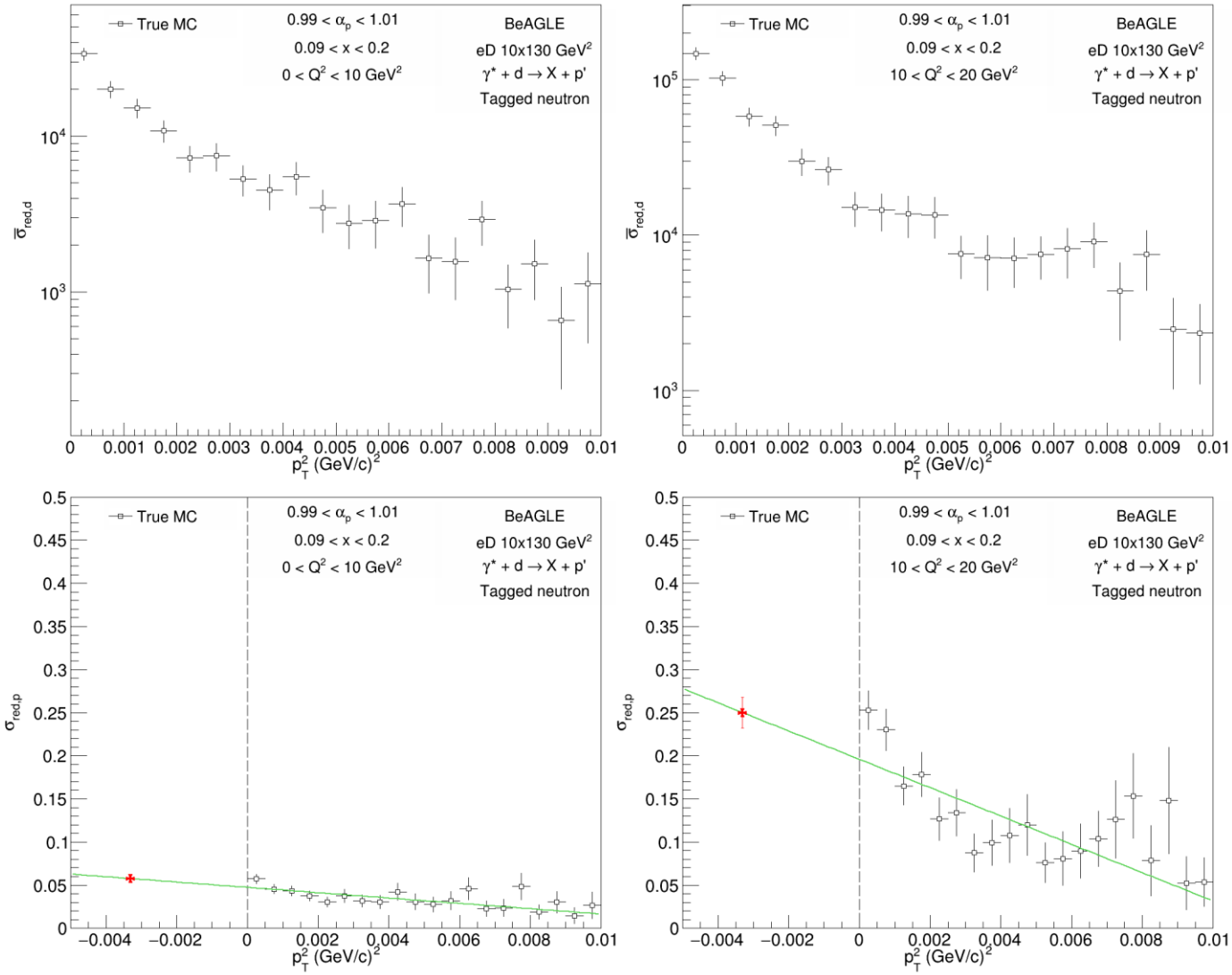

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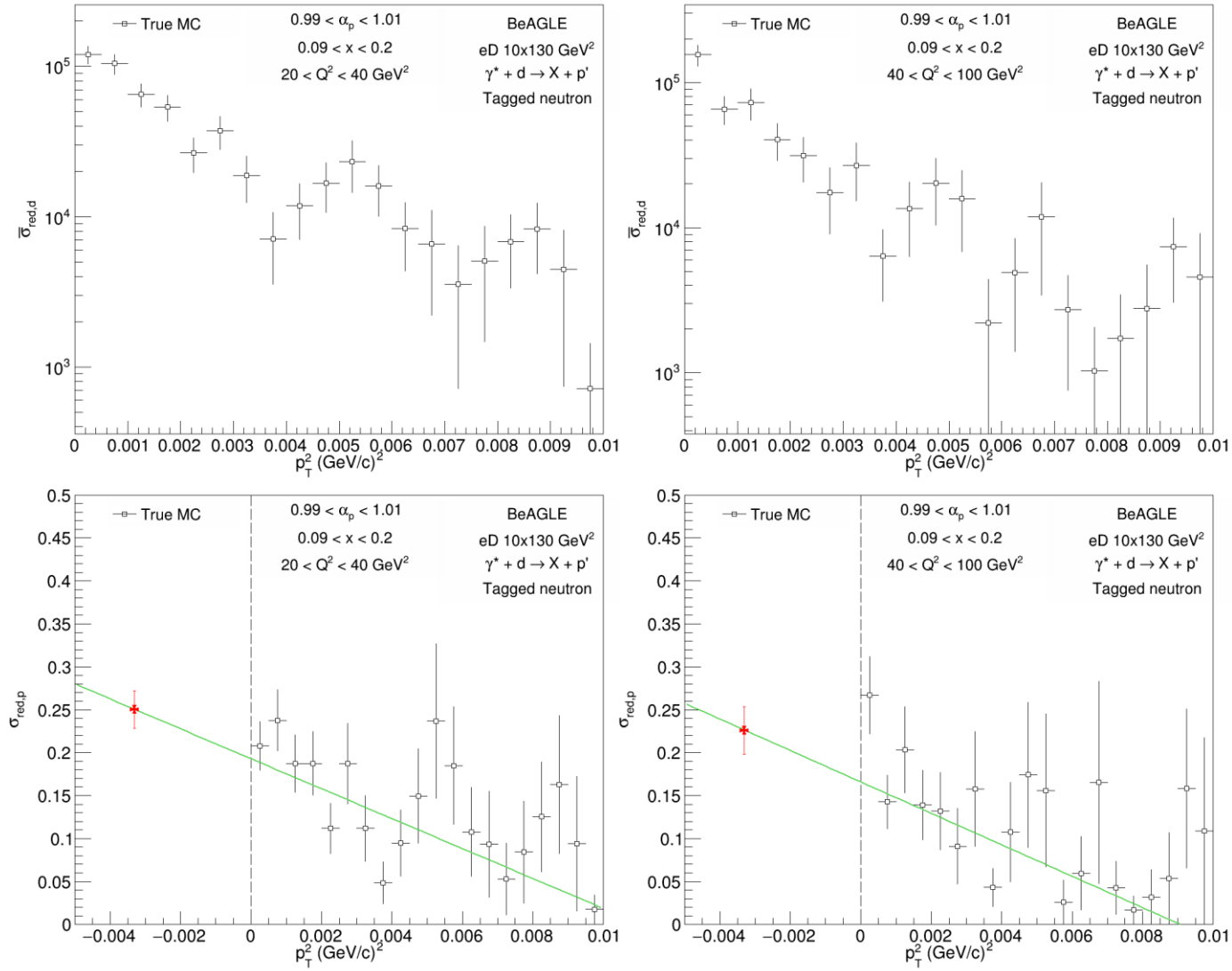

SUMMARY AND OUTLOOK

- Fully implemented TDIS framework for tagged protons for true MC from both BeAGLE and EICRecon
  - True MC information from BeAGLE and EICRecon appear to be consistent
- Added RC level information for spectator protons in EICRecon
  - First iteration of adding RC level information only using RC level information from off-momentum detectors
- Started with implementation of framework for tagged neutrons
  - Open questions about correct reduced cross section calculation
  - After discussion with Alex – will/should use average nucleon mass in a_T^2 calculation
- To-do/outlook:
  - Update a_T^2 calculation using average nucleon mass
  - Add full RC level framework, including scattered electron to tagged protons
  - Finalize tagged neutron framework
  - Cross-check with original simulation used for results in original publication

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

BACKUP

VARIABLES

- 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
  - $L_{int} = \frac{N_{events}}{\sigma_{tot}} = \frac{N_{events}}{4.5 \cdot 10^{-5}\text{mb}}$
    - $\text{mb} = 2.568\ \text{GeV}^{-2}$