Hall C and EIC Deuteron simulations

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Tensor SIDIS Workshop, Jefferson Laboratory

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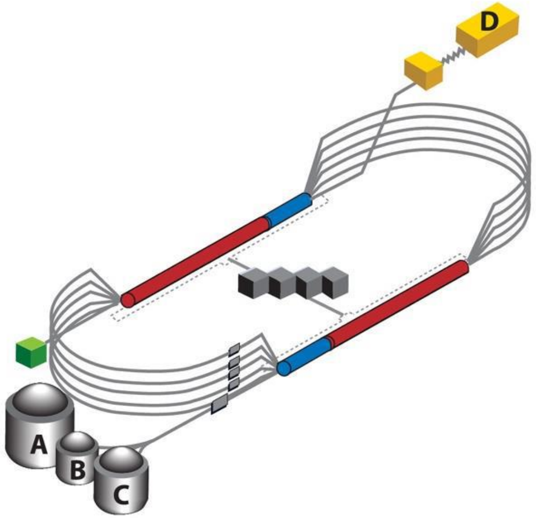
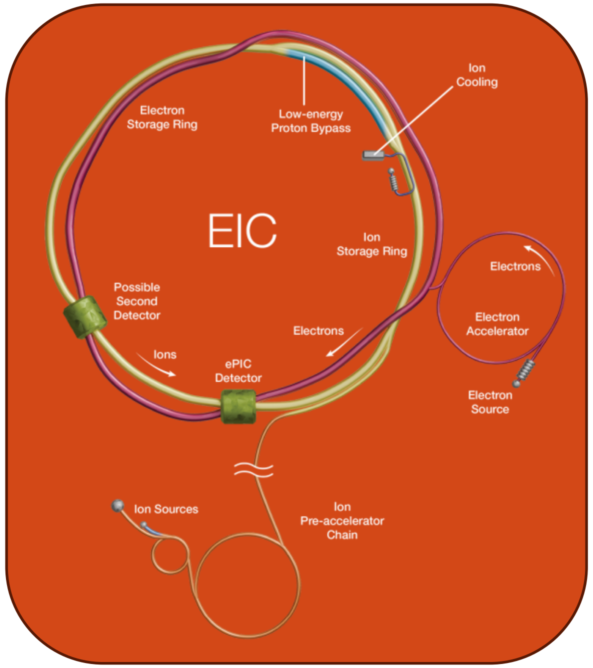
OVERVIEW

- Simulation framework for dedicated experiment for SIDIS on tensor polarized deuterons
  - Initial studies using SoLID framework
  - Full simulation framework status



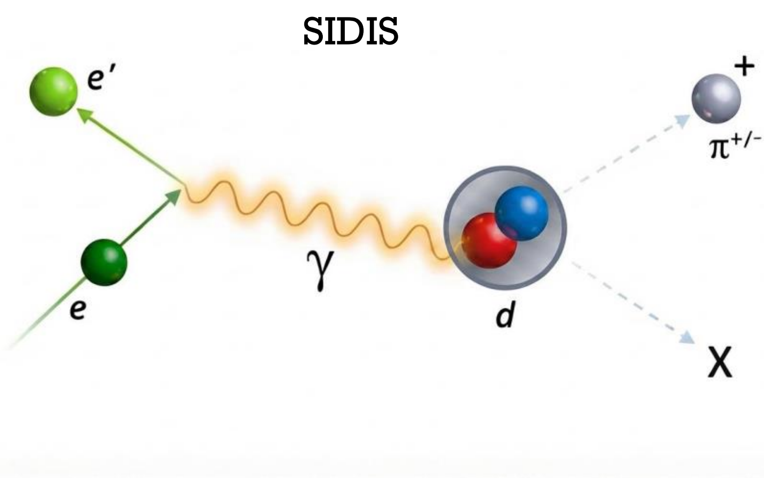
- Simulations for Tagged DIS (TDIS) at ePIC at Electron-Ion Collider (EIC)
  - TDIS simulations with unpolarized deuterons



3 HALL C SIMULATIONS

TENSOR SIDIS EXPERIMENT

- **Motivation:** Measurement of tensor polarized structure function $F_{U(LL),T}$ of deuteron
  - More details in David Ruth's presentation



$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h\,F_{UU}^{\cos\phi_h}$$

$$+\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} + \lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h\,F_{LU}^{\sin\phi_h}$$

vector

$$+S_{\parallel}\left[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right]$$

$$+S_{\parallel}\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h\,F_{LL}^{\cos\phi_h}\right]$$

tensor

$$+T_{\parallel\parallel}\Big[F_{U(LL),T} + \varepsilon F_{U(LL),L} + \sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h\,F_{U(LL)}^{\cos\phi_h}$$

$$+\varepsilon\cos(2\phi_h)\,F_{U(LL)}^{\cos 2\phi_h} + \lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h\,F_{L(LL)}^{\sin\phi_h}\Big]\Big\}.$$

TENSOR SIDIS EXPERIMENT

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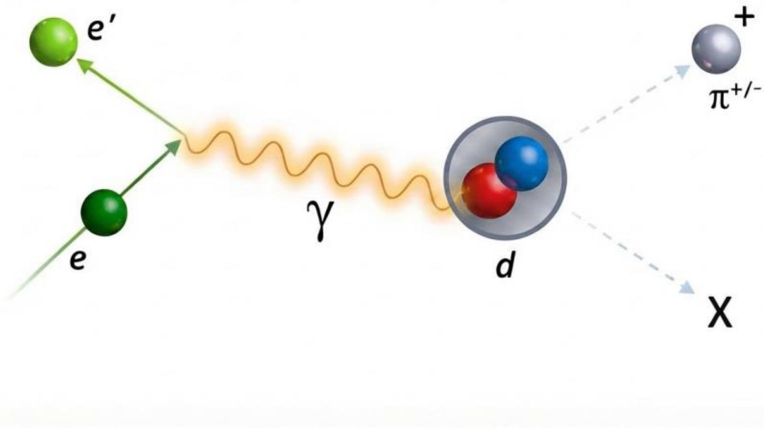
- **Experimental method:** Semi-inclusive DIS (SIDIS)

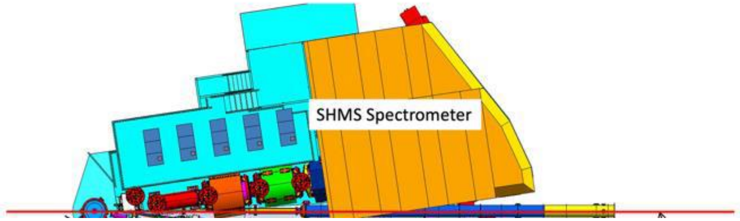
- **Experimental setup:**
  - Tensor polarized target at Hall C at JLab
  - Electron detection – SHMS
  - SIDIS hadron ($\pi^{\pm}$) detection – SBS

- **Simulation setup:**
  - Initial studies – SoLID simulation framework
  - Final simulations – Combination of Hall C (simc) and Hall A (g4sbs) simulation frameworks

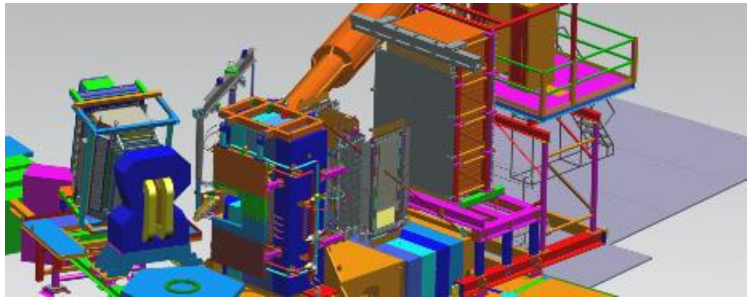
SIDIS



SHMS



SBS



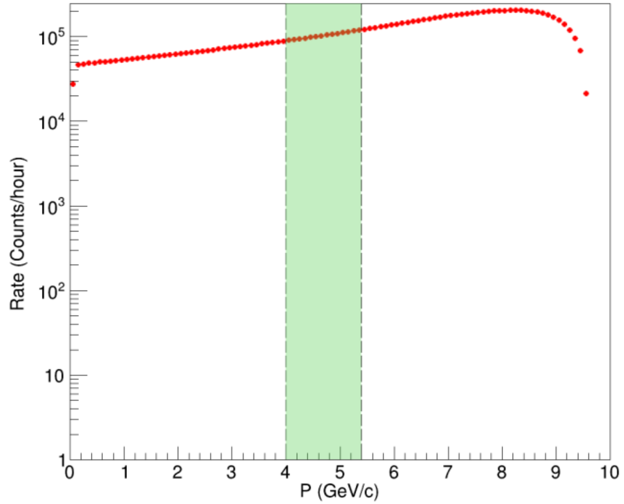
LIU, ET AL. SIMULATION SETUP

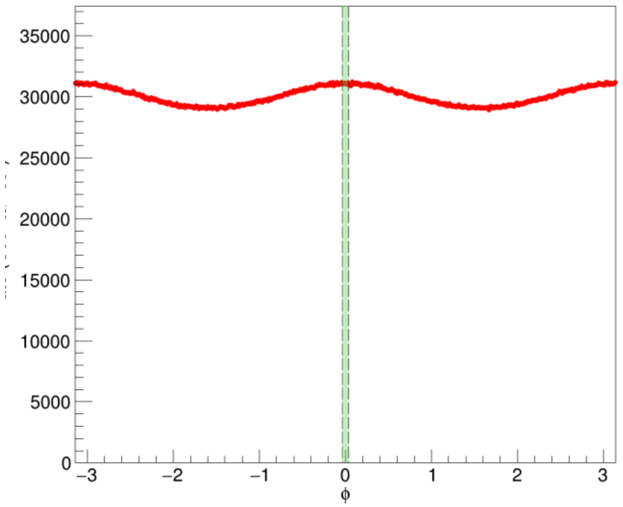
- Simulation based on SoLID SIDIS framework with cuts on kinematics of scattered electron and SIDIS hadron
  - Based on acceptance of SHMS and SBS

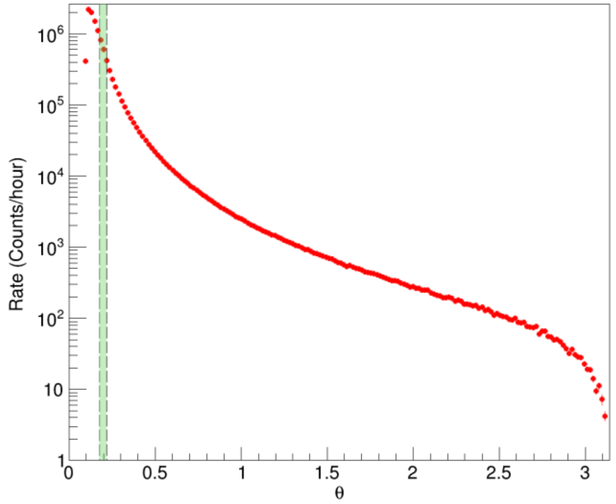
- Simulation setup:
  - Number of generated events: $8 \cdot 10^8$
  - Electron beam: 11 GeV
  - Target: D
    - Dilution from N is treated later in the simulation
  - Detected hadron: π^+

	$\boldsymbol{\theta}$ (deg)	$\boldsymbol{\phi}$ (deg)	$\boldsymbol{P}$ (GeV/$\boldsymbol{c}$)
Electron	$10.3 - 12.4$	$-2.87 - 2.87$	$4.0 - 5.4$
Hadron	$10 - 20$	$167 - 193$	$2.0 - 4.0$

Scattered electron







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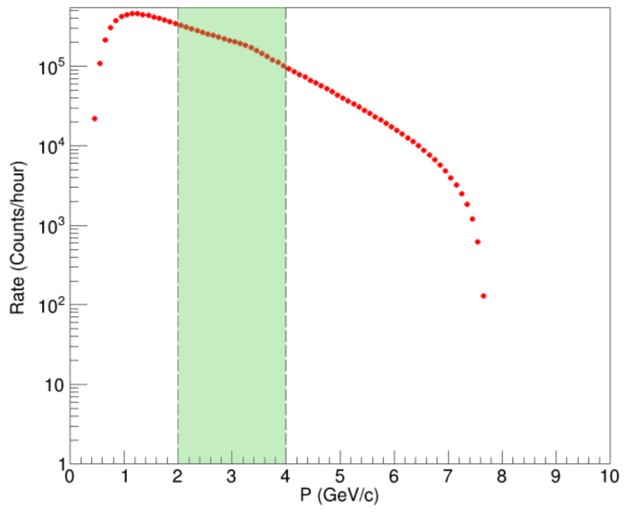
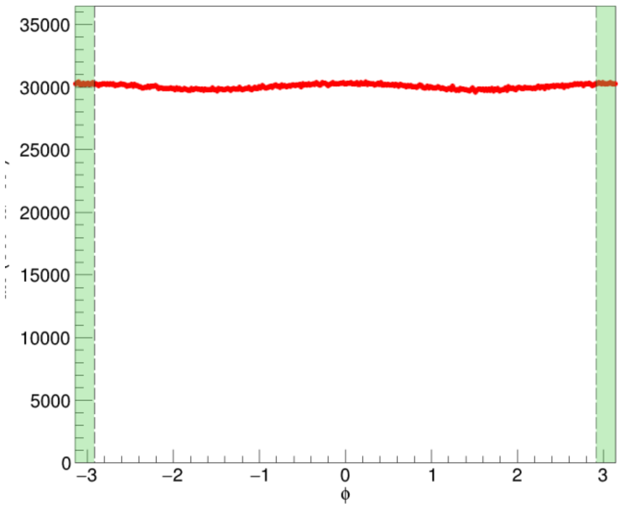
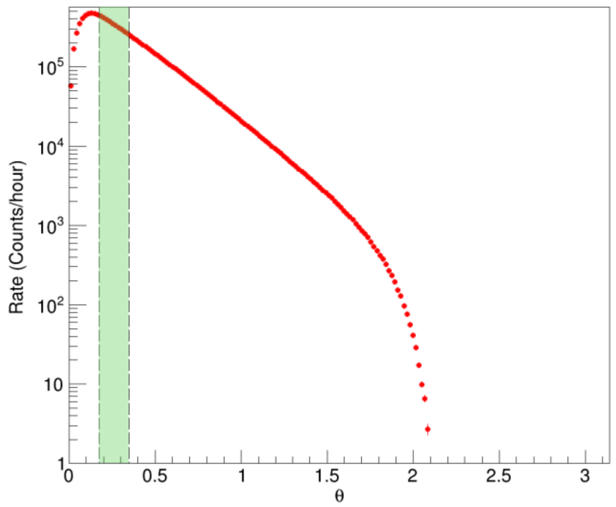
SIDIS $\pi^\pm$

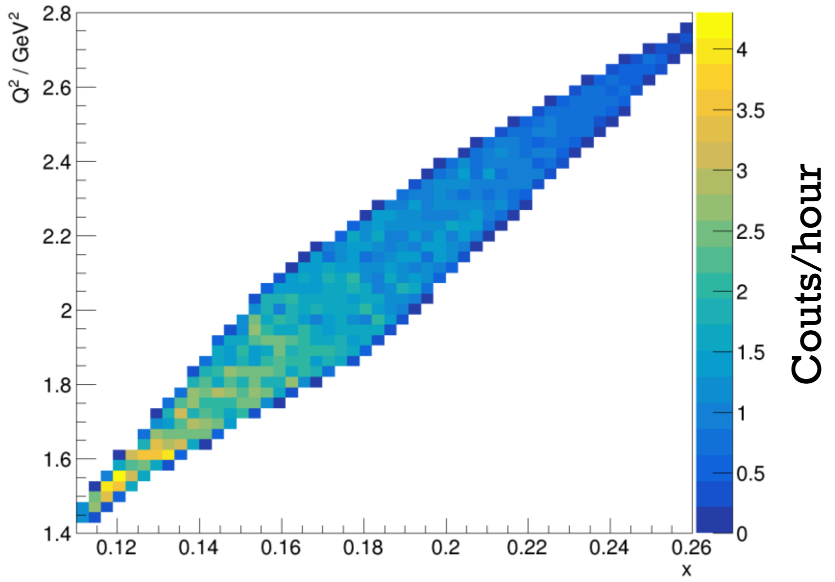


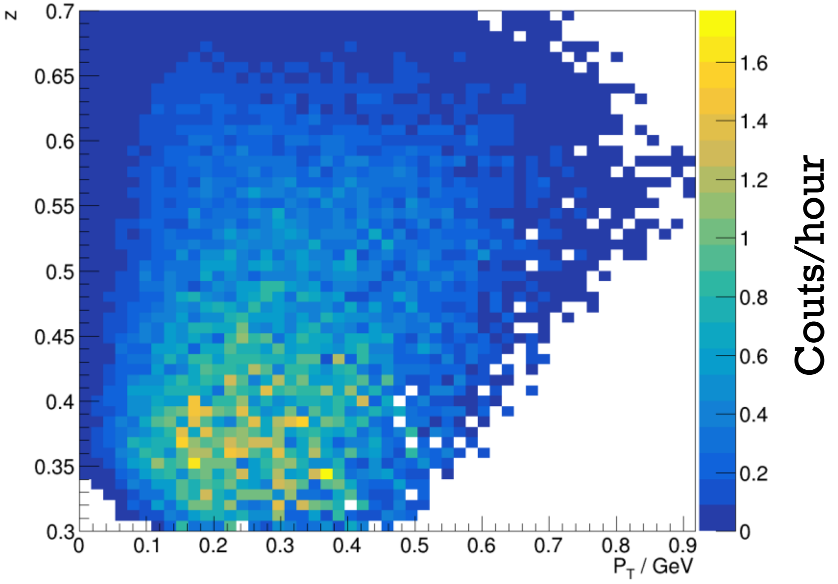




EXPECTED RATES

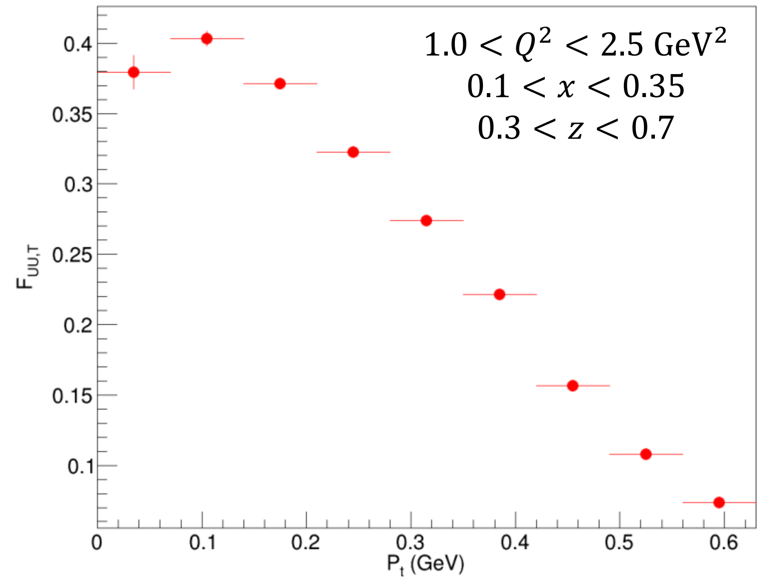
- Rate calculation (s^{-1}):
  - $R = \sum_i Weight_i \cdot L/nEvents_{gen}$
  - Sum over all generated events $nEvents_{gen}$
- Weight in SoLID framework:
  - $Weight = ds \cdot jacobian \cdot volume$
    - $ds = \frac{\alpha_{em}^2 y}{2xQ^2(1-\epsilon)} \frac{\gamma^2}{2x} F_{UU,T}$
    - $jacobial = 2P_t \frac{Q^2}{2x(P\cdot l)} \frac{1}{Q^2} = \frac{P_t}{x(P\cdot l)}$
    - $volume = \Delta x \Delta Q^2 \Delta z \Delta P_t \Delta\phi_h \Delta\phi_s$
- Luminosity scale:
  - $L/nEvents_{gen}$
  - $L = 10^9 \cdot 0.197327^2$ (units?), $nEvents_{gen} = 8 \cdot 10^8$
- Time of data taahing:
  - Base study for 1h: $t = 3600$ s
- Cross-checked with LOI

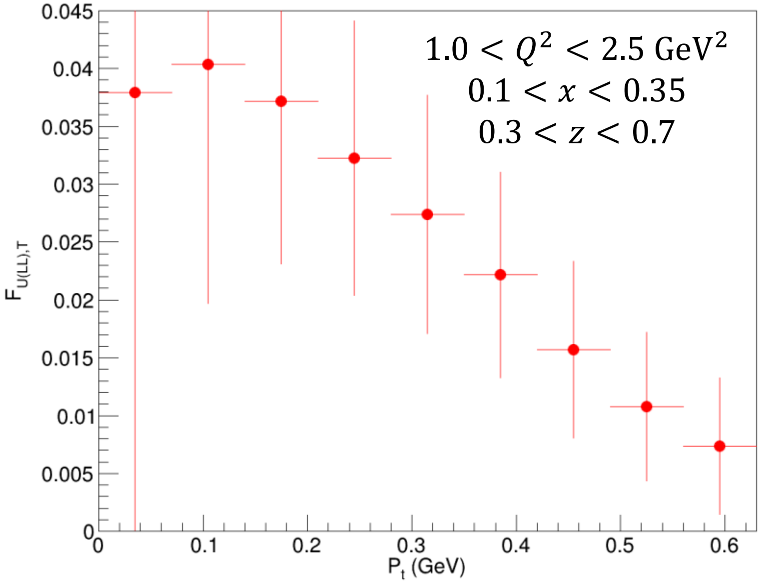




$F_{U(LL),T}$ PROJECTION

- (top) Projected $F_{UU,T}$ as a function of P_t directly from SoLID for 5 days of data taking
- (bottom) Projected $F_{U(LL),T}$ from $F_{UU,T}$ for 5 days of data taking
  - Assumption from LOI: $F_{U(LL),T}$ is 10% of $F_{UU,T}$
  - Polarization 30% (scale is 0.3^2)
  - Dilution 27% (scale is 0.27^2)
  - Additional 10% (fraction of polarized events)
- But this assumes that we measure cross-section, which we will not/cannot do in real experiment
- We are missing all detector effects





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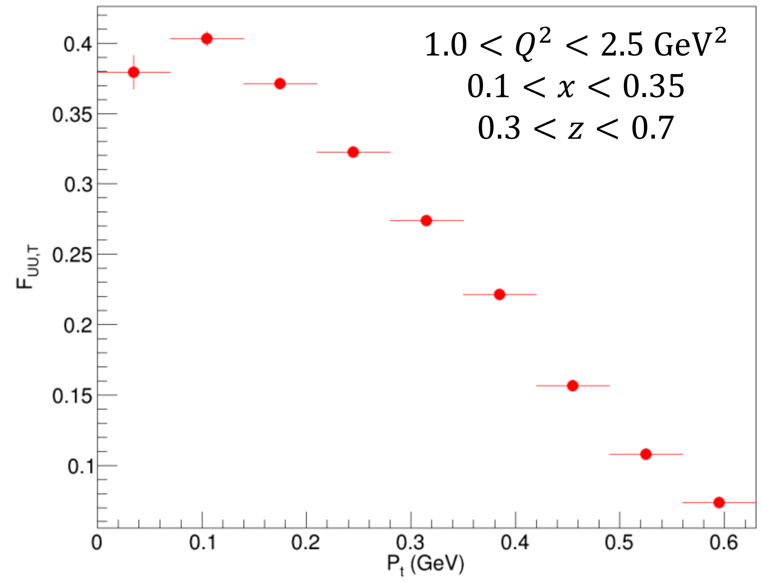
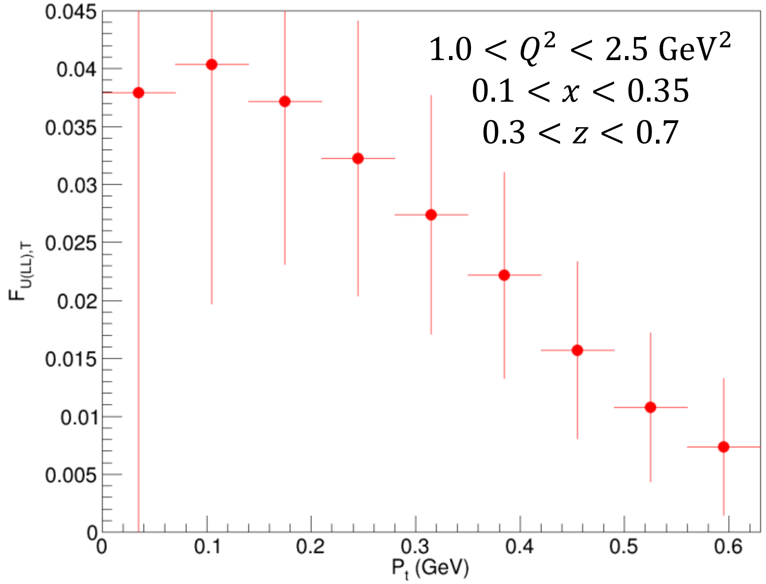
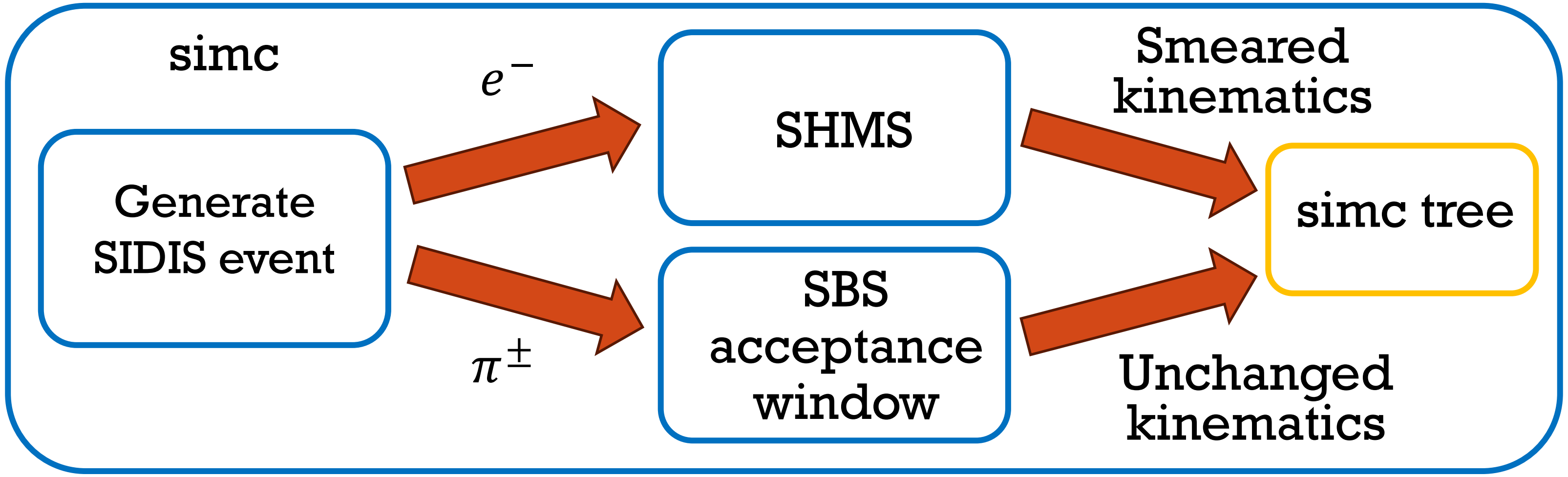
- But this assumes that we measure cross-section, which we will not/cannot do in real experiment
- We are missing all detector effects
- Working on full simulation combining simc and g4sbs





FULL SIMULATION SETUP



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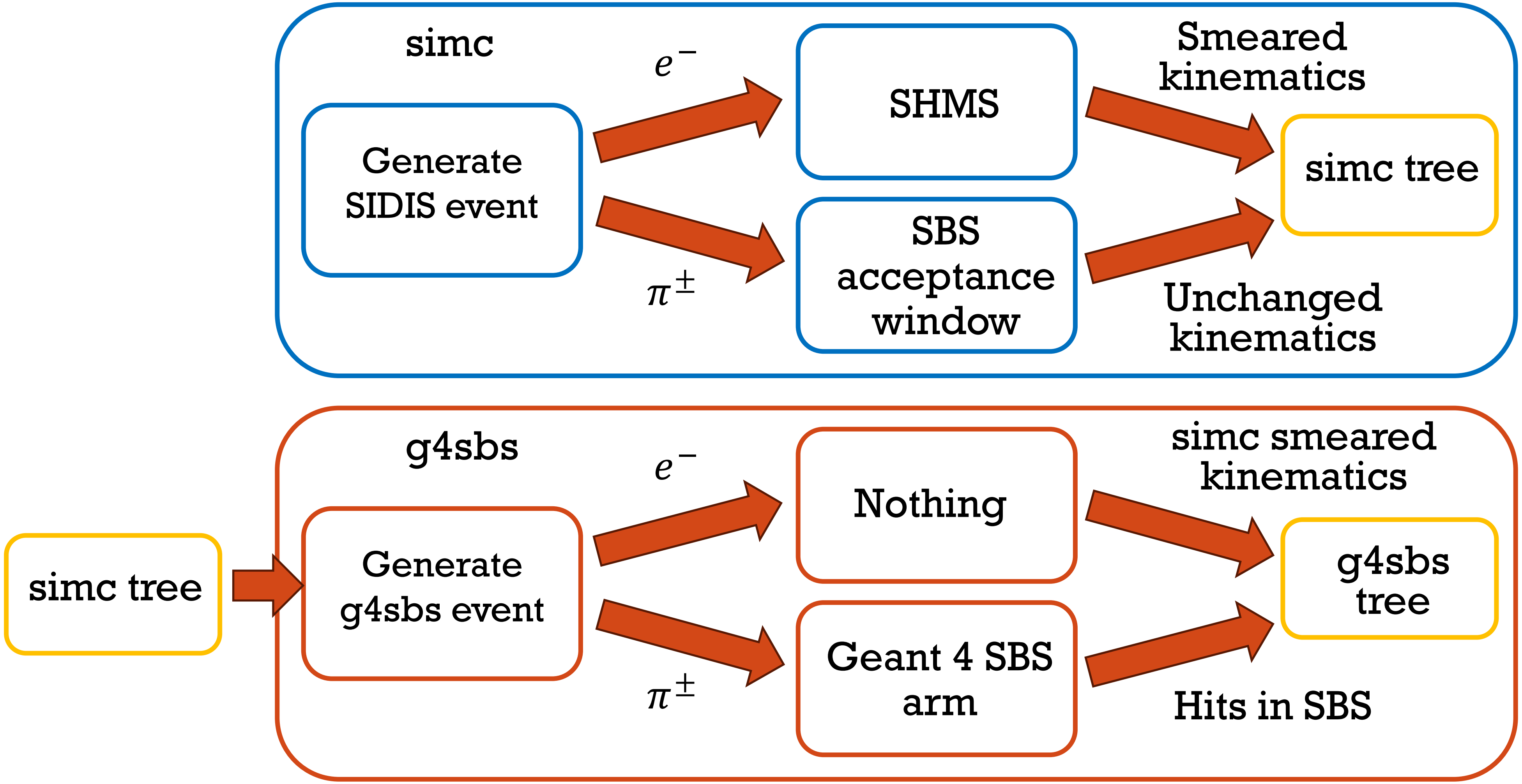

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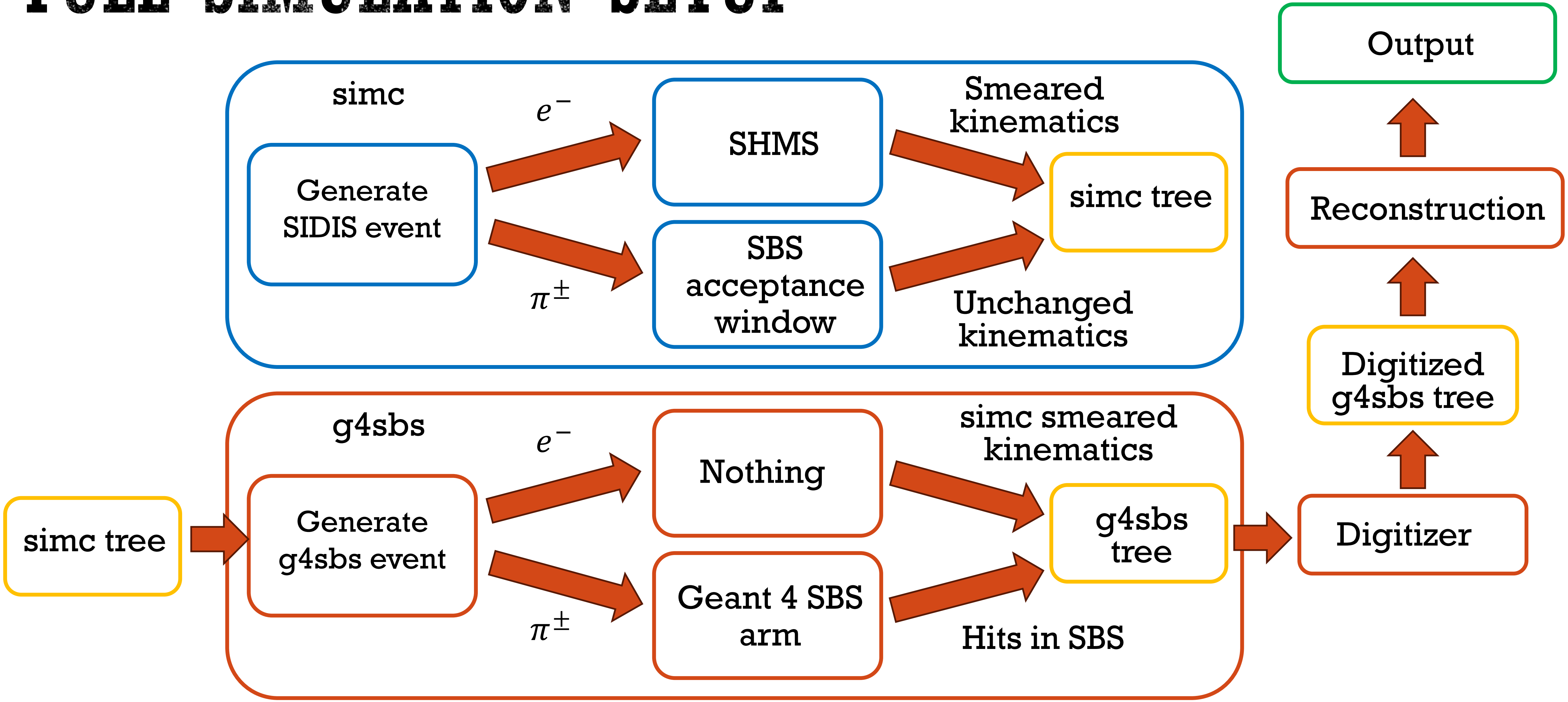
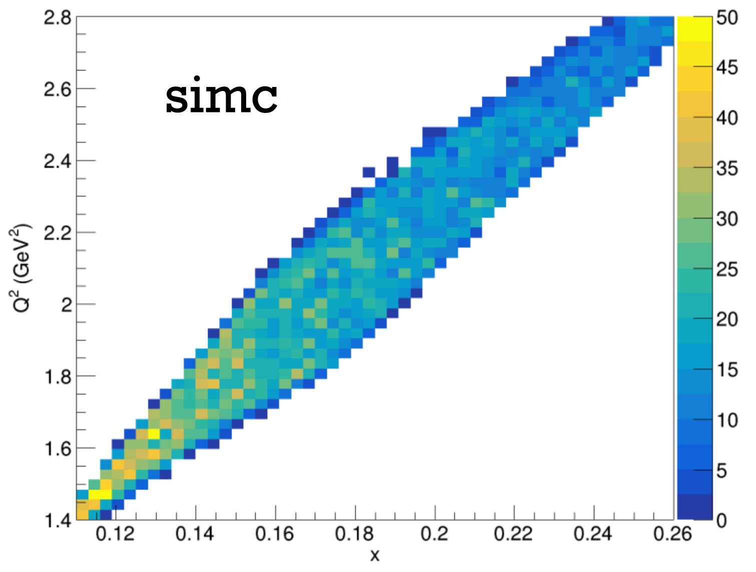
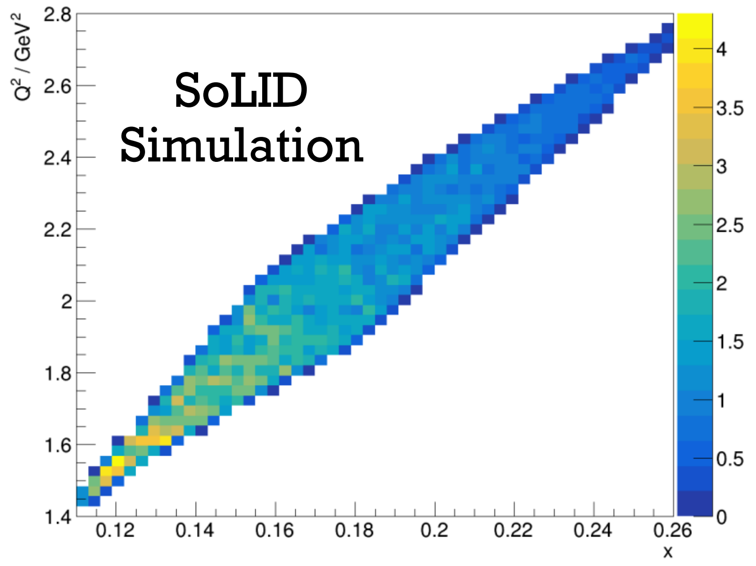


FULL SIMULATION STATUS

- simc
  - Implemented tensor SIDIS framework
  - Proper setup/input file, once everything else is set
  - Cross section calculation: SoLID vs. simc
    - See Nathaly's talk
- g4sbs
  - Geant simulation implemented
  - Tested digitization with new setup
  - Working on reconstruction
  - Proper setup/input file to Geant, once everything else is set

- Implement full tensor SIDIS simulation analysis with new framework
  - Last step, once everything above is worked out

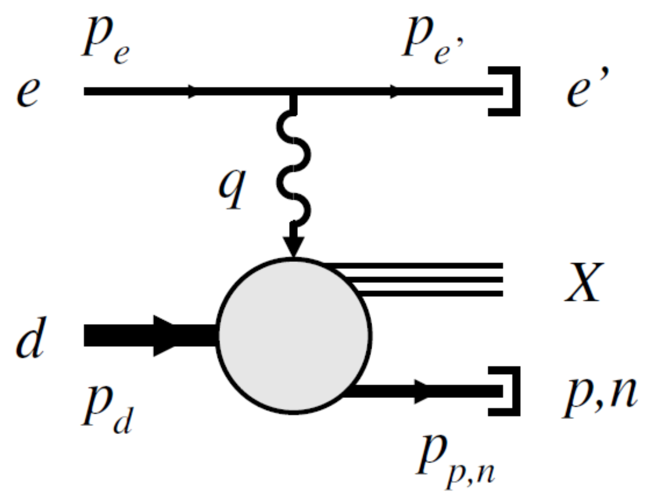




TDIS AT EIC

EXPERIMENTAL METHOD OVERVIEW

- **Tagged DIS (TDIS)**
  - DIS on deuteron (d)
  - Measurement of the scattered electron and the spectator p or n
- **Physics motivation**
  - Next talk by Wim Cosyn
- **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
    - Hard in fixed target experiments
    - **Relatively easy at collider – EIC**
- **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:
  - $\mathrm{d}\sigma_d = Flux(x, Q^2) \times \sigma_{red,d} \times \frac{\mathrm{d}x}{2} \mathrm{d}Q^2 \frac{\mathrm{d}\phi_{e'}}{2\pi} [2(2\pi)^3]^{-1} \frac{\mathrm{d}\alpha_p}{\alpha_p} \frac{\mathrm{d}p_{pT}^2}{2} \mathrm{d}\phi_p$
- We can get the n reduced cross section ($\sigma_{red,n}$) from the d reduced cross section and pole of d spectral function
  - $\sigma_{red,n} = \frac{\sigma_{red,d}(x,Q^2)}{[2(2\pi)^3] S_d(p_{pT},\alpha_p)[pole]}$
  - And similarly for proton reduced cross section

- Light-cone momentum fraction:
  - $\alpha_p \equiv \frac{2p_p^+}{p_d^+} = \frac{2(E_p+p_{z,p})}{M_d+p_{z,d}}$
- Proton transfer momentum
  - $p_{pT} = \sqrt{p_{x,p}^2 + p_{y,p}^2}$

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.

DEUTERON REDUCED CROSS SECTION

- Scattered electron
- Spectator proton
- Photon flux

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POLE EXTRAPOLATION METHOD

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- $\sigma_{red,n}$ at the pole corresponds to a free n
  - $p_{pT}^2 \rightarrow -\alpha_T^2$ 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
  - $S_d(p_{pT}, \alpha_p)[pole] = \frac{R}{(p_{pT}^2+a_T^2)}$
  - 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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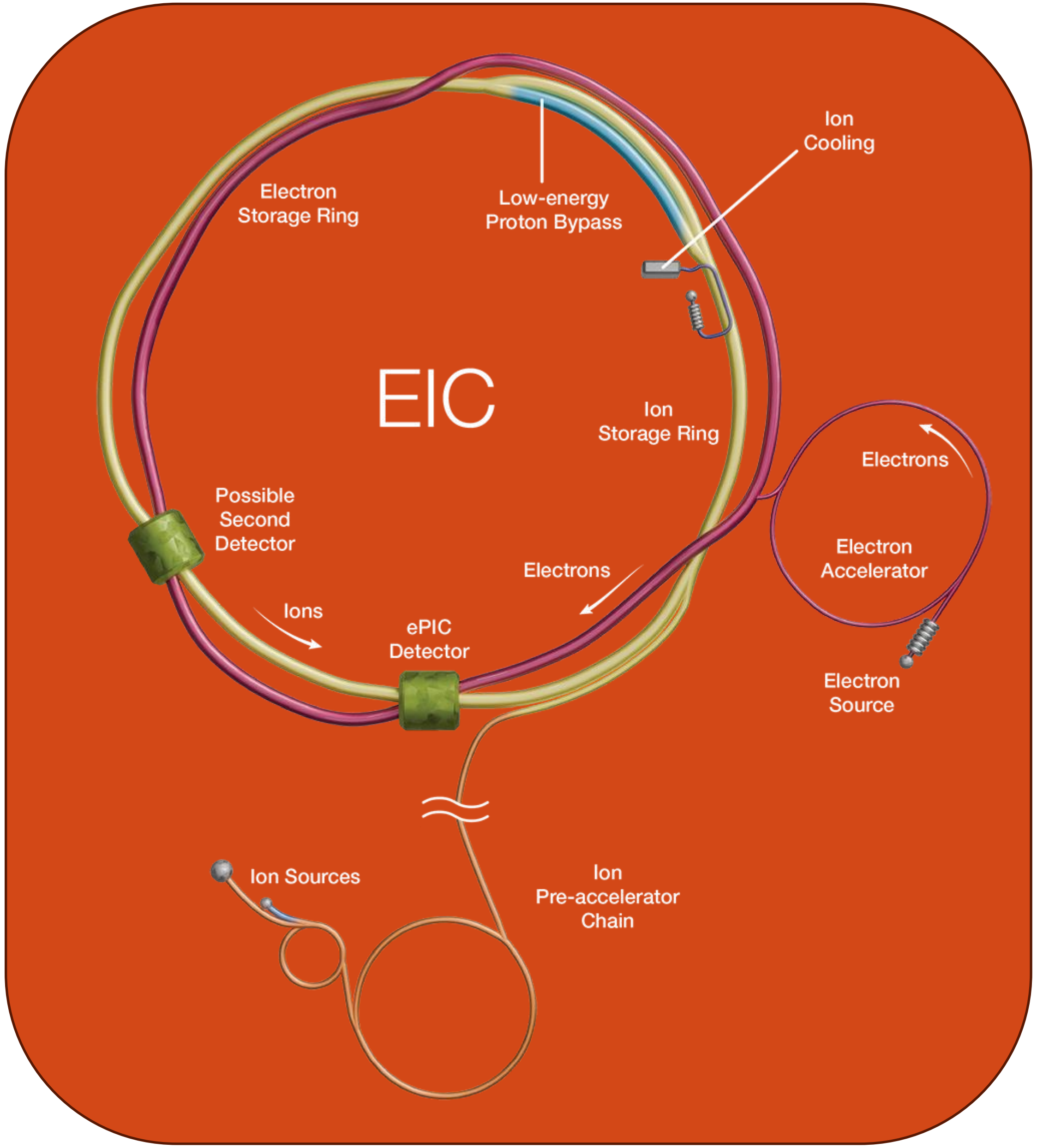
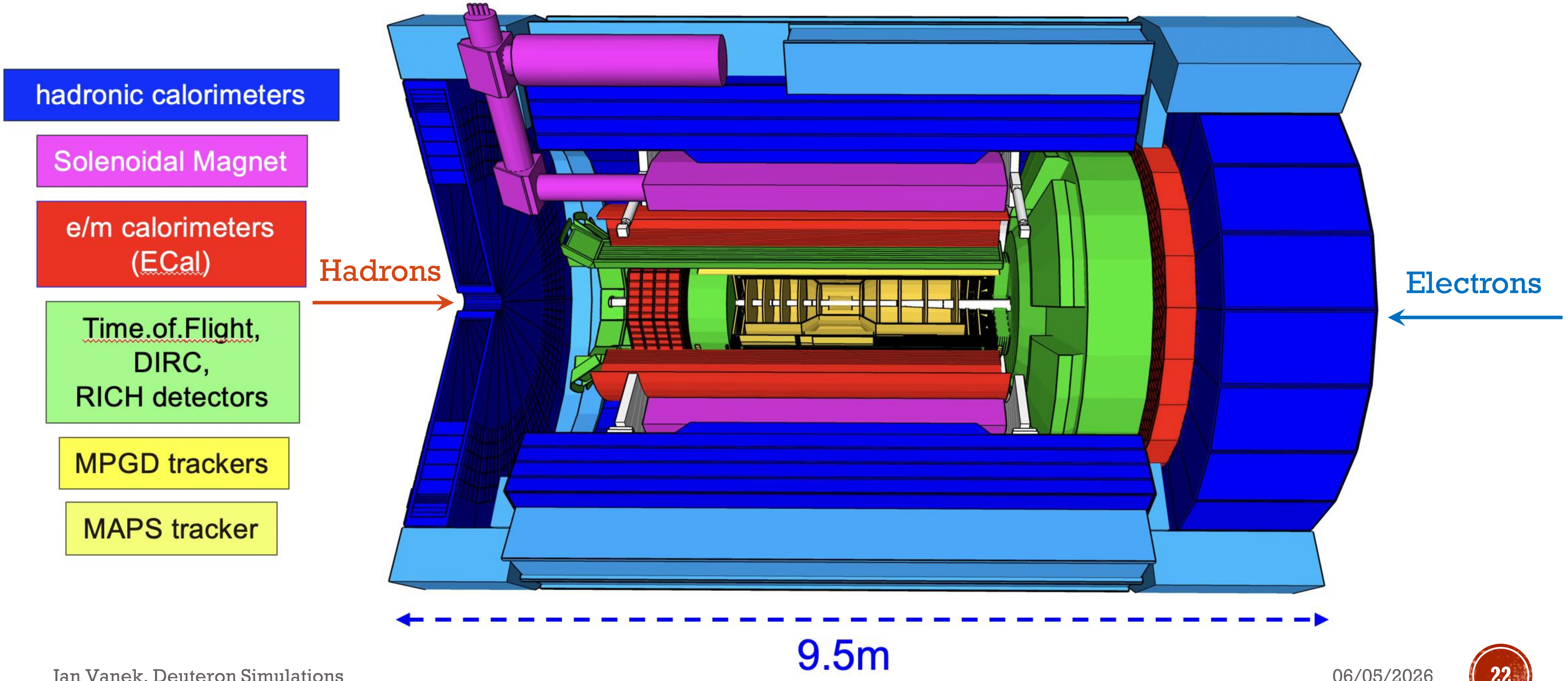
ELECTRON-ION COLLIDER

- Electron-Ion Collider (EIC) will be built in Brookhaven National Laboratory in the place of current Relativistic Heavy Ion Collider (RHIC)
- Hadron ring:
  - Upgrade of one of the existing RHIC rings
  - Possibility to accelerate wide range of hadrons
    - Protons, light nuclei (d, ^{3}He…), heavy nuclei (^{197}Au, ^{238}U…)
  - Protons and some light nuclei can be polarized
  - Large range of energies
    - From 41 GeV to 275 GeV for protons
- Electron ring:
  - Longitudinally polarized electrons
  - Continuous operation
    - One electron bunch replaced every second
  - Wide range of energies
    - From 8 GeV to 18 GeV

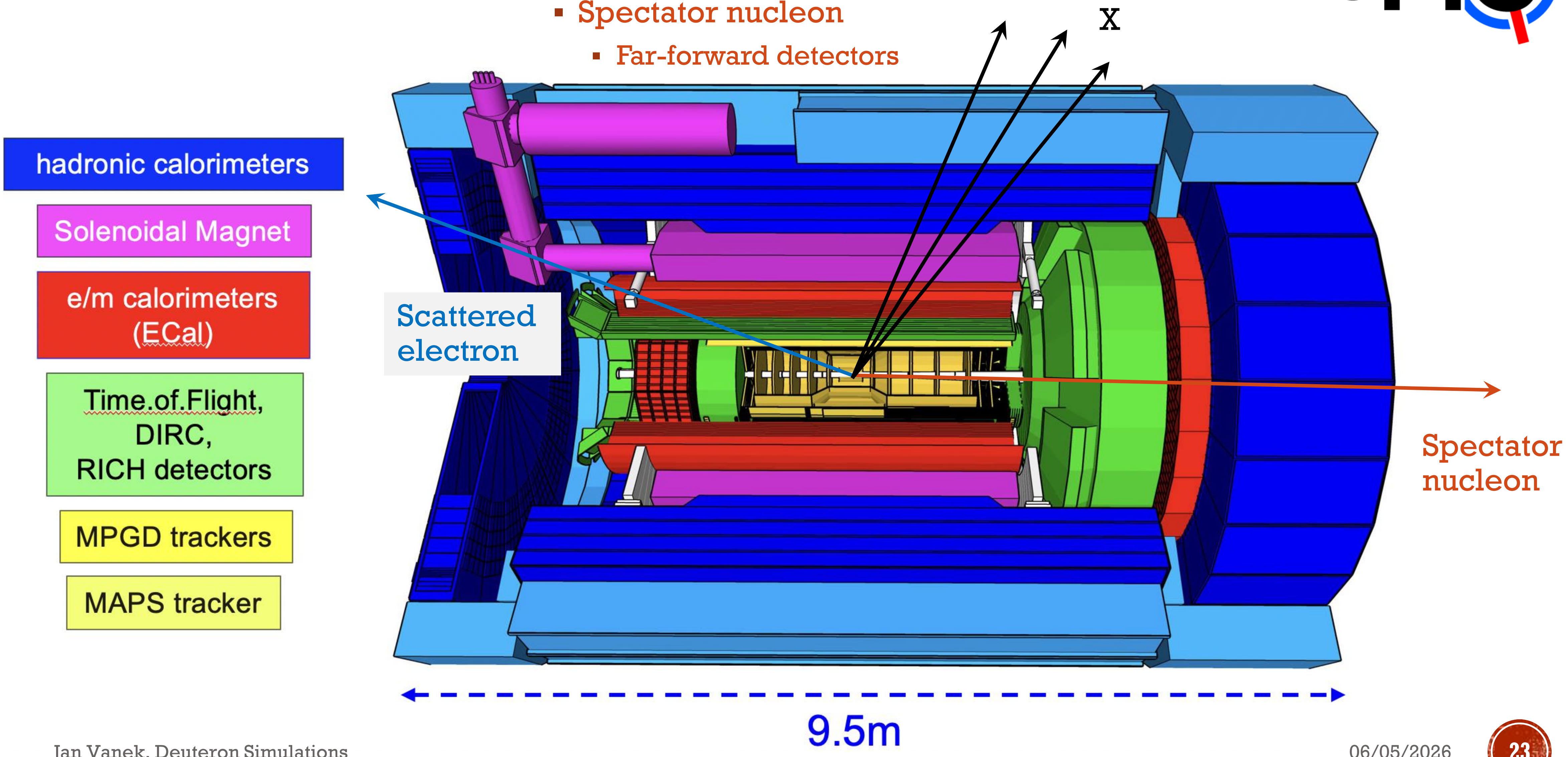


ePIC DETECTOR



ePIC DETECTOR

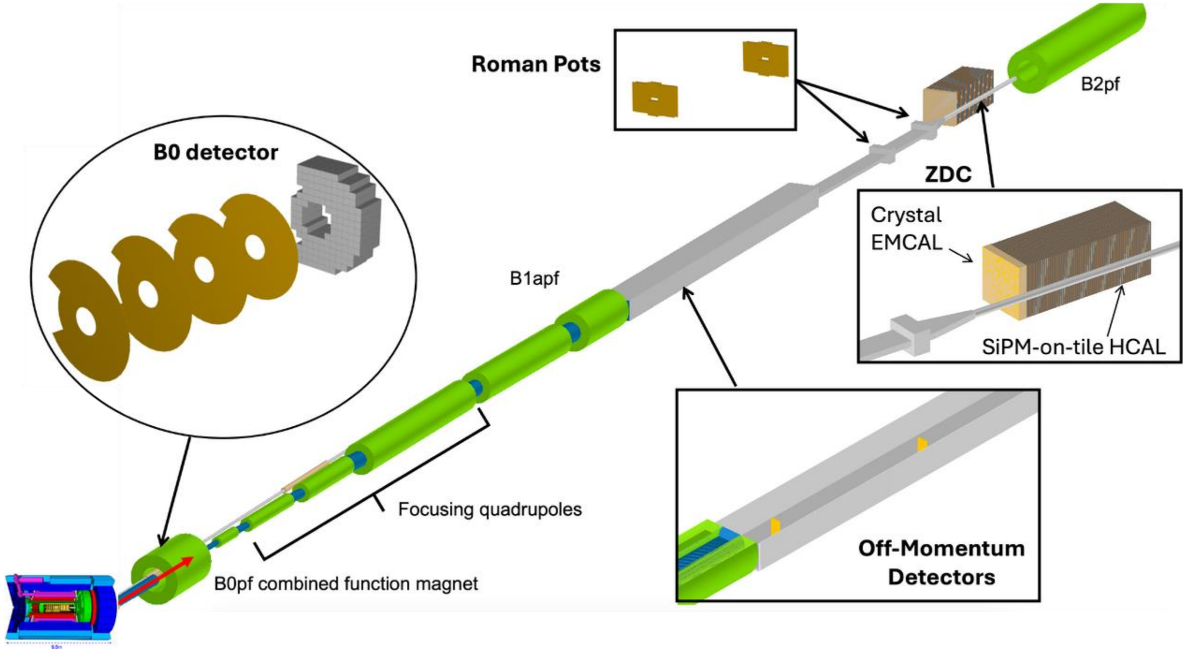
- What do we need for TDIS?
  - Scattered electron
    - Central barrel detectors
  - Spectator nucleon
    - Far-forward detectors



ePIC DETECTOR – FAR FORWARD

- Far-forward detector system for ePIC is designed to capture spectator hadrons which are very close to the beam

Detector	Hadron	Acceptance [mrad]
B0 Tracker	p	5.5-20.0
Off-momentum det.	p	0.0-5.0
Roman Pots	p	0.0-5.0
Zero Degree Calorimeter	n	0.0-4.0



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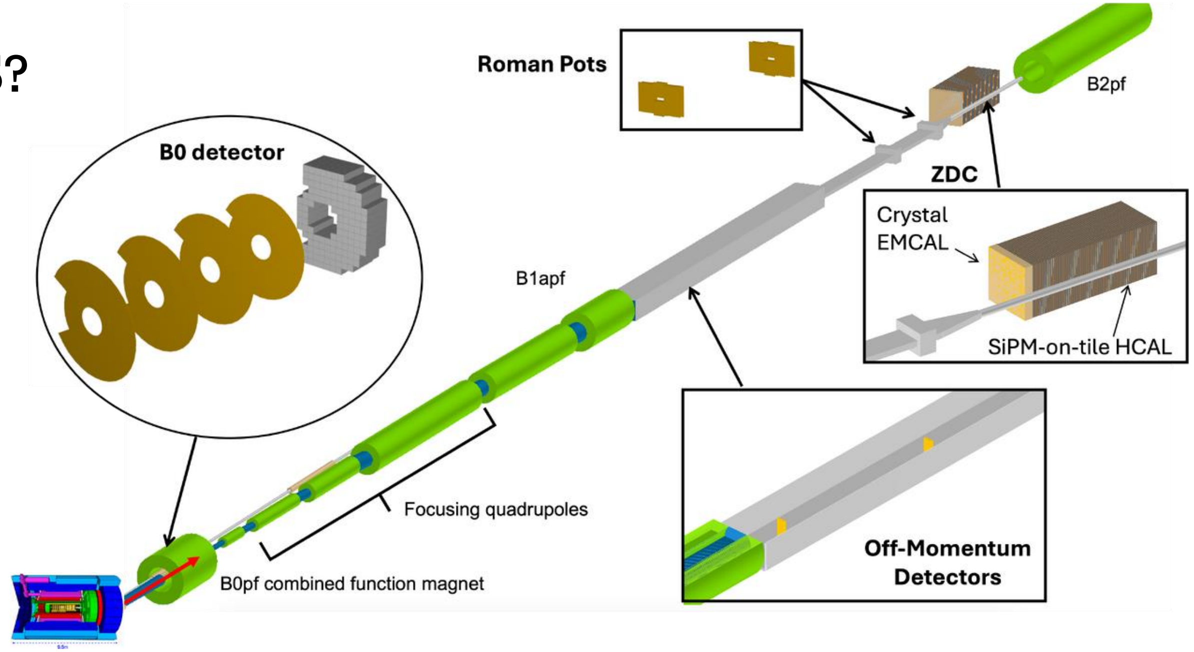
- What do we need for TDIS?
  - Off-momentum detector
    - Protons with ~ $^1/_2$ of beam energy
  - ZDC
    - Spectator neutrons



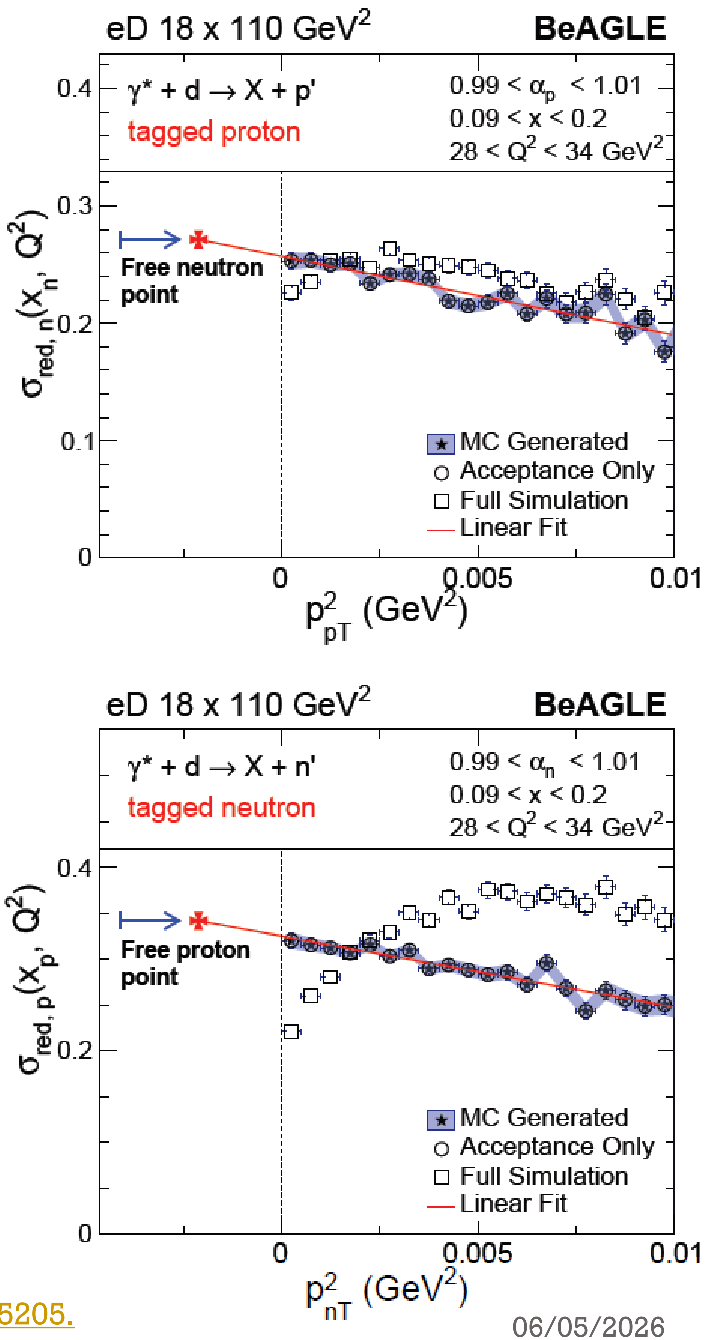
SIMULATION TOOLS

- **Event generator:** BeAGLE
  - **B**enchmark **eA G**enerator for **LE**ptoproduction
  - Key parts for deuteron simulation – PYTHIA 6.4 and deuteron light-front spectral function
- **Detector simulations:** Full simulation using GEANT4
- **Reconstruction:** Transport matrix to calculate spectator momentum at interaction point from momentum at the detector
  - Currently tuned only to spectators with energy very close to $^1/_2$ of beam energy

Wan Chang, Elke-Caroline Aschenauer, Mark D. Baker, Alexander Jentsch, Jeong-Hun Lee, Zhoudunming Tu, Zhongbao Yin, and Liang Zheng: Phys. Rev. D **106**, 012007.

PREVIOUSLY PUBLISHED RESULTS

- Reduced cross section of n (top) and p (bottom) extracted from MC eD collisions at $18 \times 110\ \mathrm{GeV}^2$
  - MC Generated
    - True MC level information, without any acceptance effects
  - Acceptance only
    - Only detector acceptance is considered
    - Here basically identical to true MC as for the class of true MC events used, all spectator n and p hit the corresponding far-forward detector and efficiency is assumed to be 100%
  - Full Simulation
    - Detector and efficiency effect are considered with manual smearing (no full detector simulations)
- Pole extrapolation
  - Fit to the true MC as a proof of concept
  - Works well for true MC
  - More challenging for full simulation

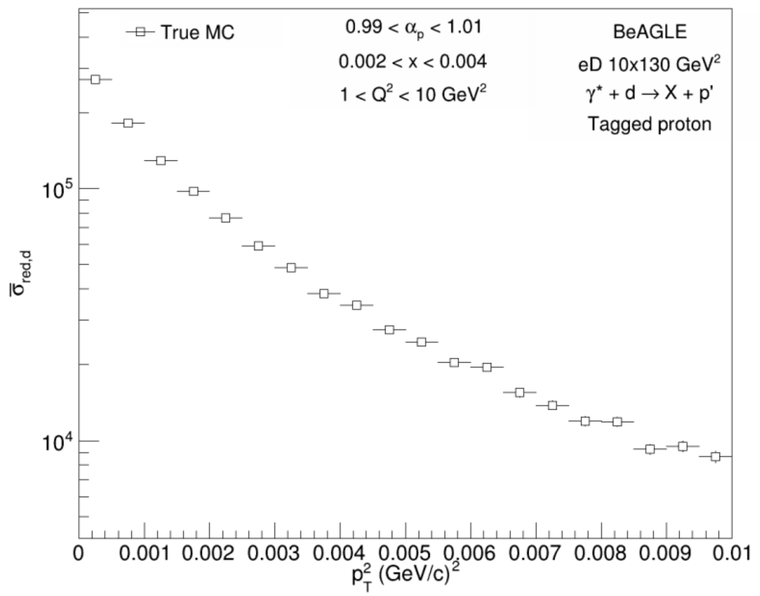


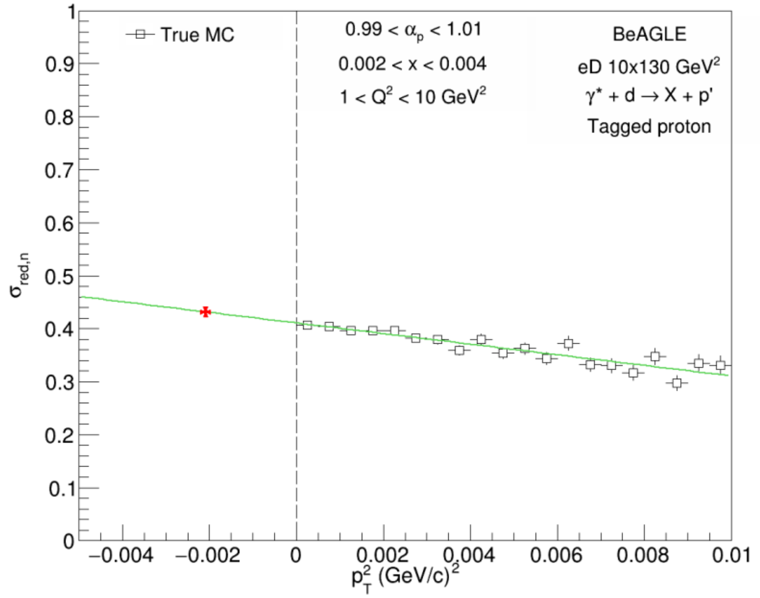
A. Jentsch, Z. Tu, Ch. Weiss: Phys. Rev. C **104**, 065205.

CURRENT STATUS

- Developed TDIS analysis framework using full ePIC simulation framework
  - Includes full detector simulations
  - Acceptance and efficiency correction
  - Estimate of systematic uncertainties

- **My involvement:**
  - Validation and checks of the new setup and cross-checks with the original results from previous slide
  - Developed methods of signal extraction from Full Simulation level information
    - Cannot show results here, only generator level distributions
  - **New results to be approved for public release soon and will be published in EIC early science overview publication**

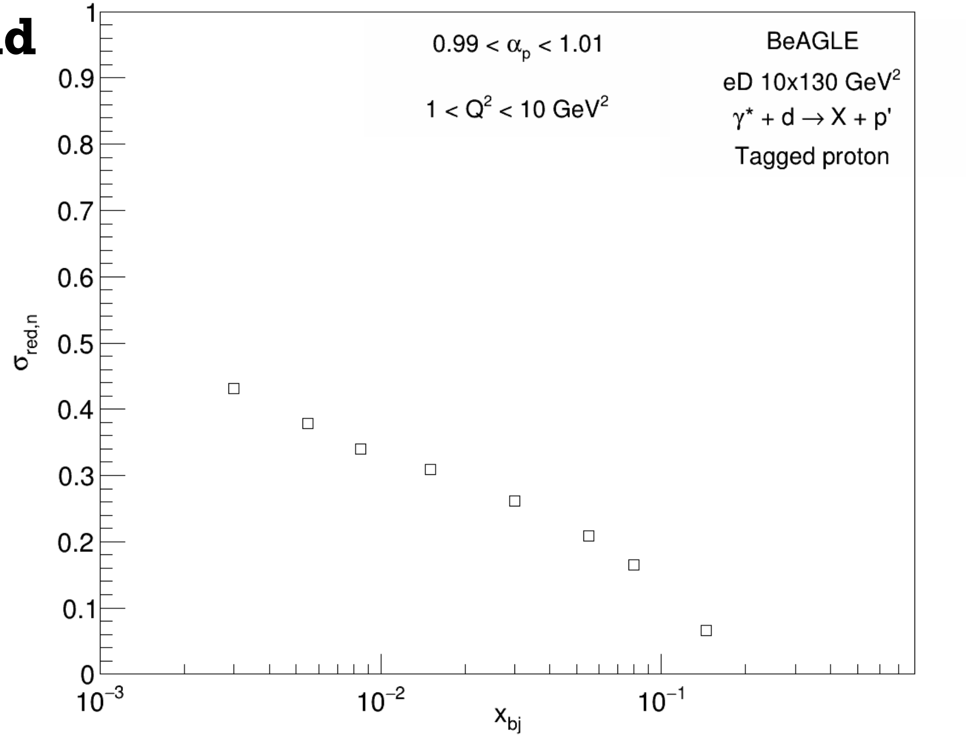




OUTLOOK

- **Extension of unpolarized analysis to polarized deuterons**

- **Study of polarized internal structure of the deuteron and of nucleons**
  - New theoretical framework to extract polarized structure functions:
    - W. Cosyn, C. Weiss, Semi-inclusive deep-inelastic scattering on a polarized spin-1 target. I. Cross section and spin observables, arXiv:2603.23699 [hep-ph]
    - W. Cosyn, C. Weiss, Semi-inclusive deep-inelastic scattering on a polarized spin-1 target. II. Deuteron and spectator nucleon tagging, arXiv:2603.23700 [hep-ph]



- **This study will be vital for justification of polarized deuteron beam program at EIC**
  - Deuteron beam polarization is difficult and expensive and thus needs strong physics motivation

THANK YOU FOR ATTENTION