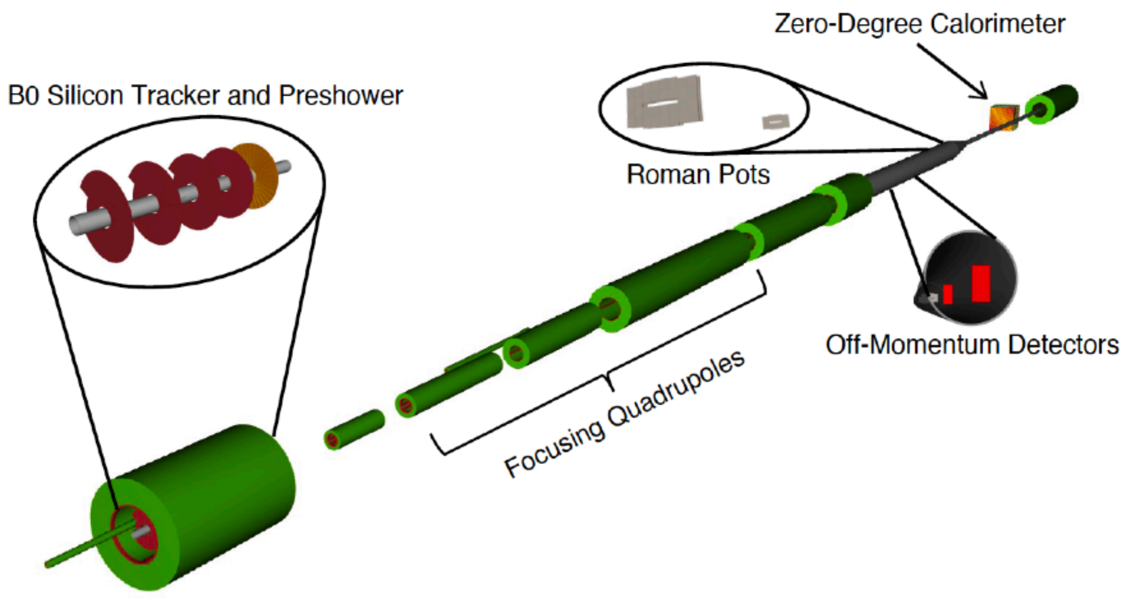
Spectator tagging with EIC far-forward detectors: Free and bound nucleon structure

C. Weiss (JLab), SRC Collaboration Meeting, MIT, 02-04 Aug 2022 [Webpage]

Jefferson Lab



Based on

Physics/detector simulations

Jentsch, Tu, CW, PRC 104, 065205 (2021)

Jentsch, Strikman, Tu, CW, in progress

Theory development

Cosyn, Sargsian, Frankfurt, Strikman, CW

Detector design

Yellow Report + Updates

Deuteron DIS with spectator tagging

Controlling the nuclear configuration

Variables, observables, structures

EIC far-forward detector

Physics ↔ detector variables

Subsystems, acceptance, resolution

Free neutron/proton structure $x \sim 10^{-2}$ - 10^{-1}

Pole extrapolation in spectator momentum

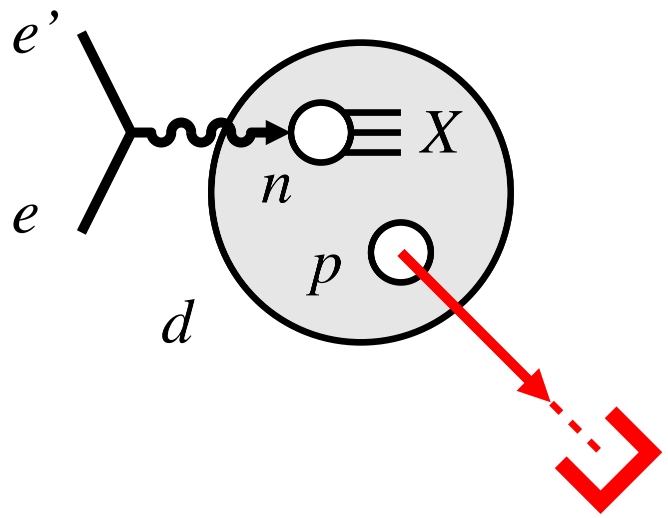
Uncertainties

Bound nucleon structure $x > 0.3$

EMC effect, off-shell dependence

Future directions

Tagging: Applications



$$e + d \to e' + X + p(n)$$

$$\alpha_p = \frac{E_p + p_p^z}{M_d}, \quad \mathbf{p}_{pT}$$

Control nuclear configuration in DIS process

Detection of spectator selects nuclear configuration:
Momentum $\leftrightarrow$ size, interactions, p or n

Free neutron structure: $p \sim$ few 10 MeV,
extrapolation to pole at $p^2 < 0$

Bound nucleon structure / EMC effect:
$p \sim$ 200-500 MeV

Spectator momentum variables

Light-cone momenta in γ^* direction ($\mathbf{q} \parallel$ z-axis)

Free neutron: $\alpha_p \sim 1 \pm$ few 0.01, $p_{pT} \sim$ few 10 MeV

Bound nucleon: $\alpha_{p,n} \sim 0.5 - 1.5$, $p_{pT} \sim$ 200-500 MeV

Tagging: Observables

Electron-deuteron cross section

$$d\sigma(ed \to e'Xp) \;=\; \text{Flux}(x, Q^2)\, dx dQ^2 \frac{d\phi_{e'}}{2\pi} \;\times\; \sigma_{d,\text{red}}(x, Q^2; \alpha_p, p_{pT}, \phi_p)\; d\Gamma_p$$

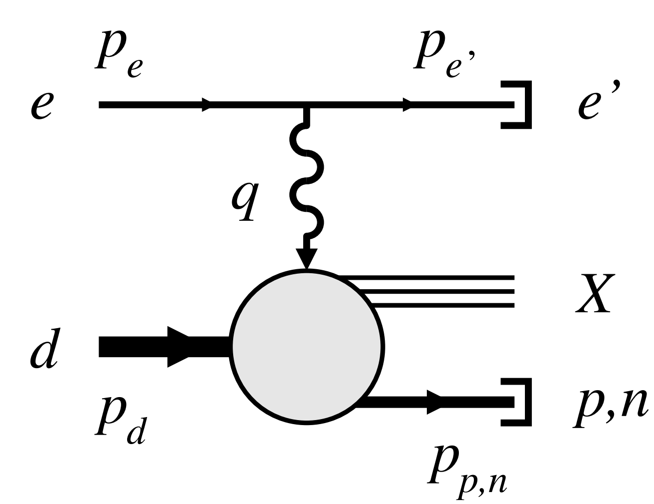
likewise for
$p \to n$

Reduced virtual photon cross section (no L/T separation)

$$\sigma_{d,\text{red}}(x, Q^2; \alpha_p, p_{pT}, \phi_p) = F_2(x, Q^2; \alpha_p, p_{pT}) + \epsilon F_L(x, Q^2; \alpha_p, p_{pT}) \;+\; \phi_p\text{-dep. structures}$$

DIS variables

$$x \;\equiv\; \frac{Q^2}{p_d q}, \quad 0 < x < 2 \qquad\qquad y \;\equiv\; \frac{p_d q}{p_d p_e}, \quad 0 < y < 1$$



Correspond to standard variables for DIS on nucleon with “nominal” momentum $p_d/2$

Tagging: Theory

Separate deuteron and nucleon structure → composite description
Use methods of light-front quantization [Frankfurt, Strikman 81+]

$$\sigma_{d,\text{red}}(x, Q^2; \alpha_p, p_{pT}) \;=\; S_d(\alpha_p, p_{pT}) \times \sigma_{n,\text{red}}(x_n, Q^2)$$

IA, here $\int d\phi_p$

+ initial-state modifications + final-state interactions

$$\sigma_{n,\text{red}}(x_n, Q^2) = F_{2n}(x_n, Q^2) + \epsilon F_{Ln}(x_n, Q^2)$$

reduced neutron cross section

$$x_n = \frac{x}{2 - \alpha_p}$$

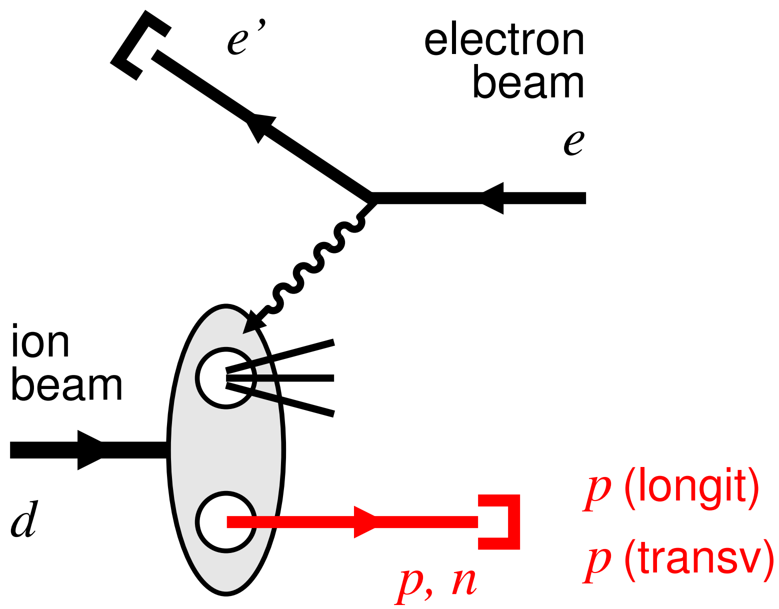
effective scaling variable in en DIS process

$\epsilon(en) = \epsilon(ed)$ + corrections $(1 - \alpha_p)^2 x^2 m^2 / Q^2$

same in en and ed process

Strategy: Use momentum dependence to eliminate/control initial-state modifications and final-state interactions

EIC: Spectator momentum variables



Detector variables

p_p(longit), p_p(transv) spectator momenta in detector

Boosted from rest frame in forward ion direction

$$\theta_p \equiv \frac{p_p(\text{transv})}{p_p(\text{longit})} \qquad x_{Lp} \equiv \frac{p_p(\text{longit})}{p_d(\text{beam})}$$

polar angle

momentum fraction = magnetic rigidity ratio

Relation to physics variables

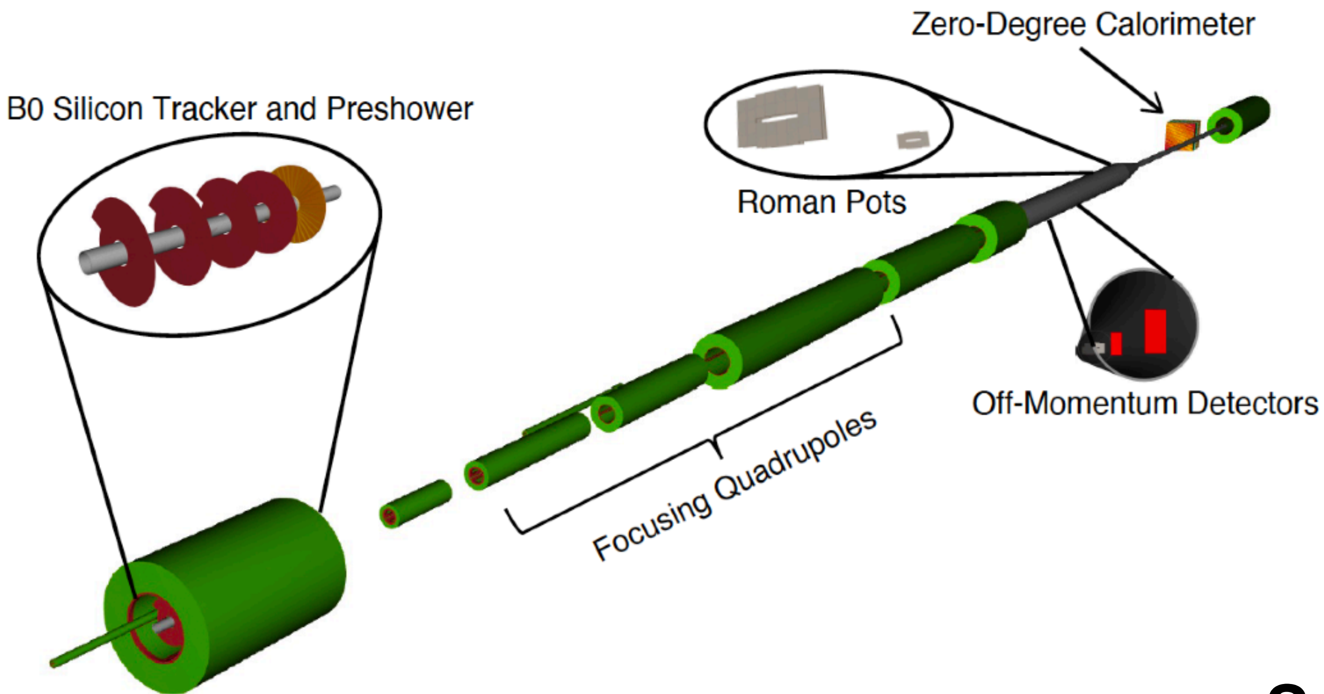
Forward ion direction generally different from virtual photon direction!

In non-exceptional DIS kinematics ($x \ll 1,\ Q^2 \ll Q^2_{\text{max}}$) directions are close

$$\theta_p \approx \frac{2p_{pT}}{\alpha_p p_d} \qquad x_{Lp} \approx \frac{\alpha_p}{2}$$

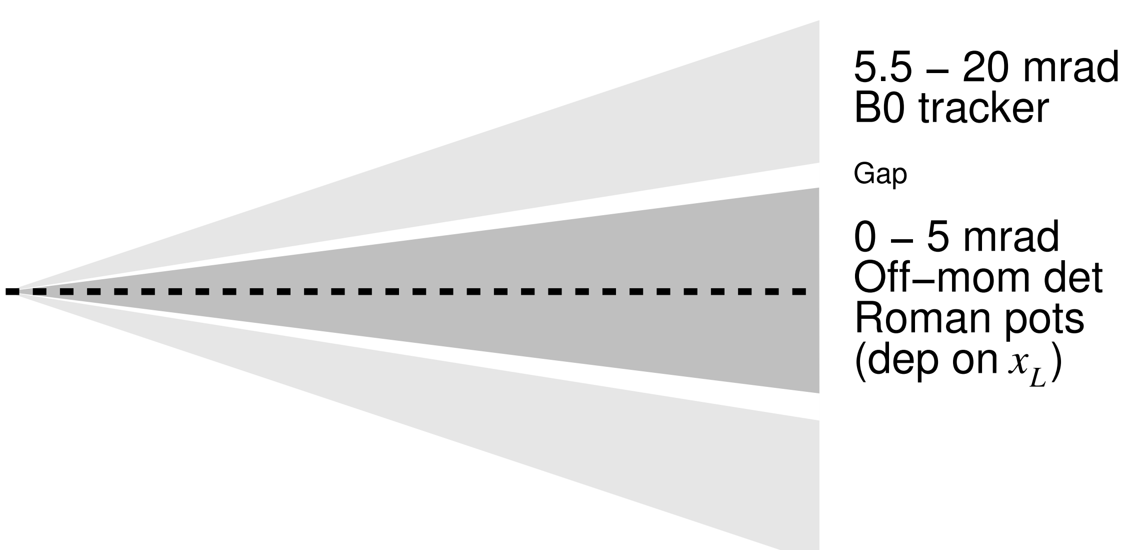
simple relation between physics and detector variables

EIC: Far-forward detectors



Magnetic spectrometer and detectors for charged particles, integrated in accelerator optics, several subsystems

Zero-degree calorimeter for neutrals

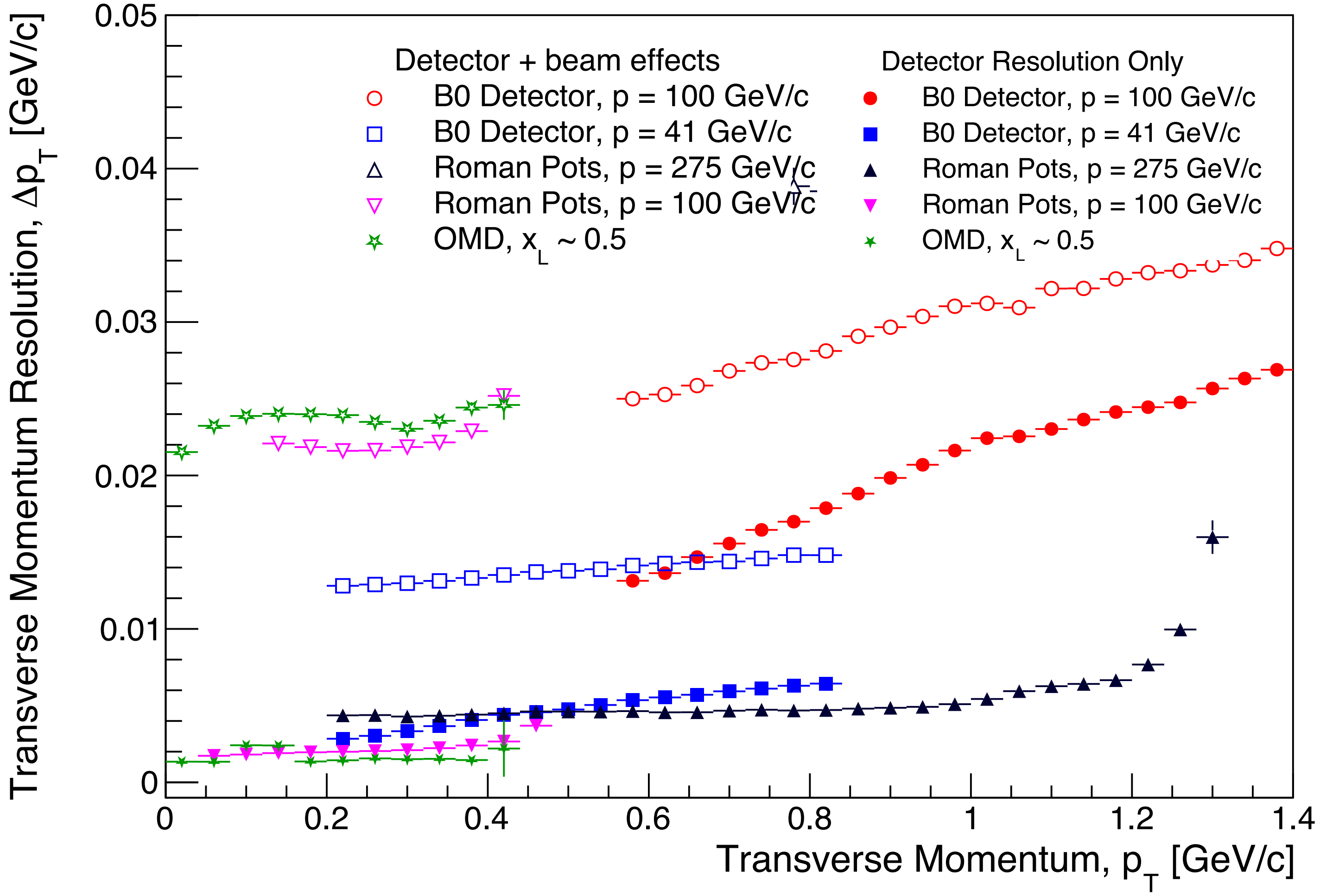


Proton acceptance = function(θ, x_L)

Subsystems used in spectator tagging

Protons	$\theta < 5$ mrad $0.2 < x_L < 0.6$	Off-mom detectors	Used in free neutron
Protons	$\theta < 5$ mrad $x_L > 0.6$	Roman Pots	Bound nucleon/EMC
Protons	$5.5 < \theta < 20$ mrad	B0 tracker	Bound nucleon/EMC
Neutrons	$\theta < 4$ mrad	ZDC	

EIC: Momentum resolution



Summary prepared by A. Jentsch

Proton momentum resolution

Simulations include detector resolution and beam effects: angular divergence, crabbing rotation, vertex smearing

Details depends on kinematics: Beam energy, subsystems used

Transverse momentum resolution achieved $\Delta p_T \sim$ 20 MeV at low p_T

Longitudinal momentum resolution typically $\alpha_p/\alpha_p \lesssim$ 5%, significantly better for $\alpha_p \sim 1$

Figures in supplement

Neutron momentum resolution

$$\frac{\Delta E}{E} = \frac{50\,\%}{\sqrt{E}} \oplus 5\,\% \qquad \frac{\Delta\theta}{\theta} = \frac{3\,\mathrm{mrad}}{\sqrt{E}}$$

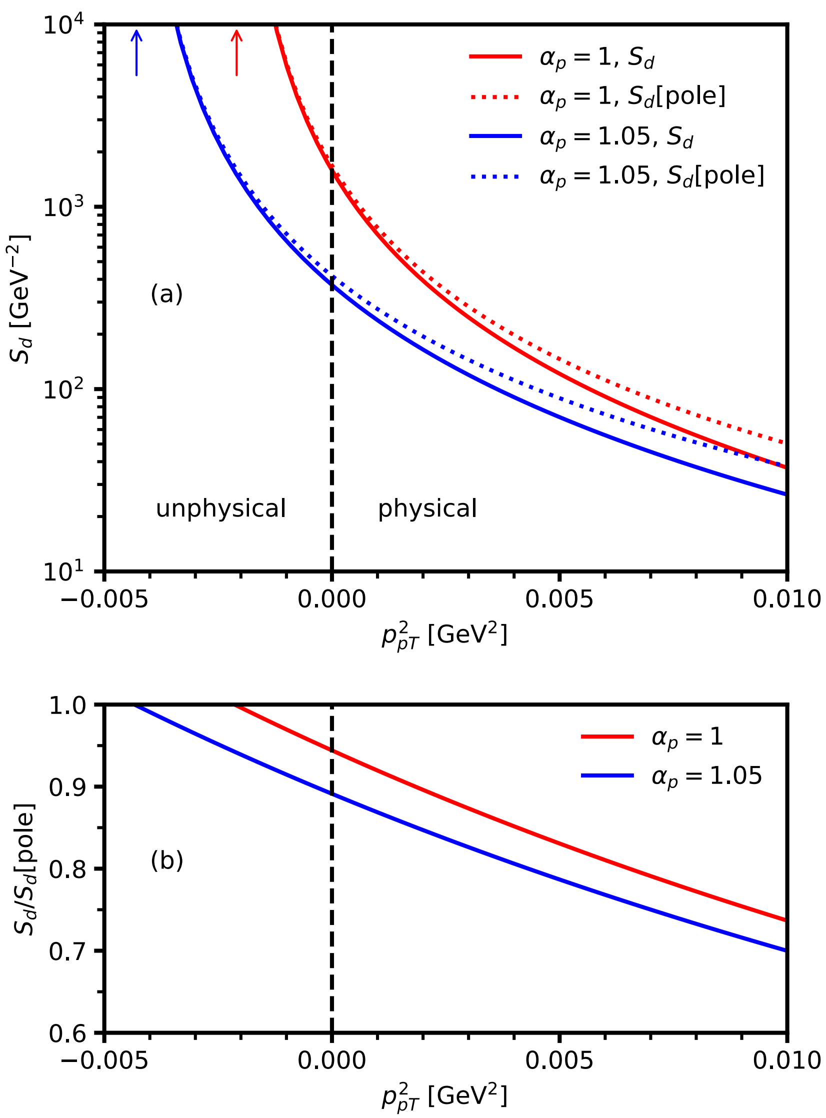
with present ZDC design

Free nucleon: Pole extrapolation

$$\sigma_{d,\text{red}} = S_d(\alpha_p, p_{pT})\, \sigma_{n,\text{red}}(x_n, Q^2)$$

+ modifications/interactions

$$S_d[\text{pole}] = \frac{C}{(p_{pT}^2 + a_T^2)^2}$$



Noninteracting pn configurations (size $\rightarrow \infty$) can be reached by analytic continuation in spectator momentum [Sargsian, Strikman 2005]

“Free nucleon pole” of spectral function: Universal feature, position and residue known
Bethe-Peierls radius, asymptotic S-wave normalization

Extraction procedure

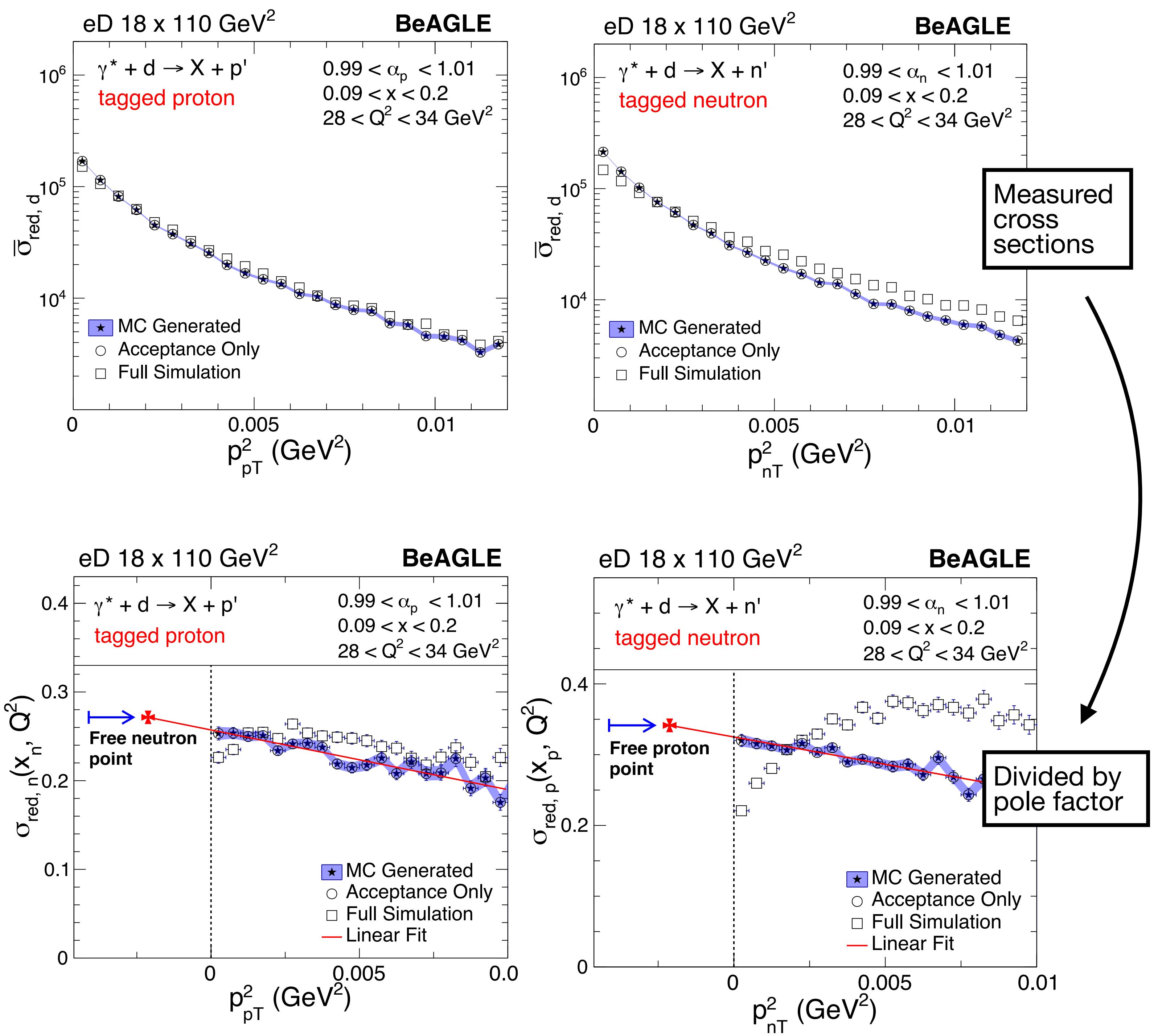
Measure proton-tagged cross section at fixed α_p as function of $p_{pT}^2 > 0$

Divide data by pole term of spectral function evaluated at experimental p_{pT}^2

Extrapolate to pole position $p_{pT}^2 \rightarrow -a_T^2 < 0$

Experimentally challenging: Functions depend strongly on p_{pT} — resolution!

Free nucleon: EIC simulations



Jentsch, Tu, CW, PRC 104, 065205 (2021)

Tagged cross section measured with excellent coverage

Significant uncertainties in evaluation of pole factor due to p_T resolution

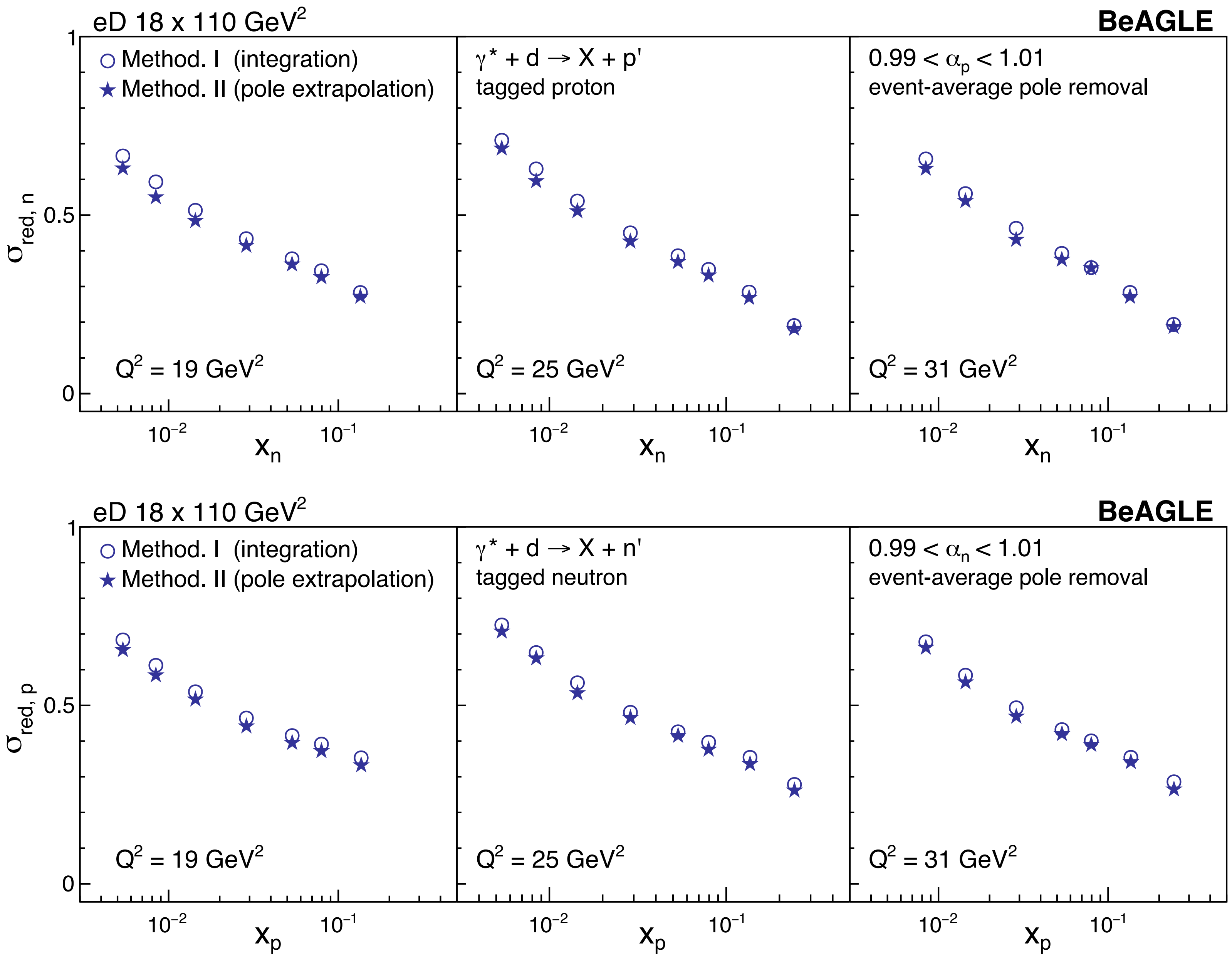
Pole factor evaluated in event-averaged analysis (binned in p_T^2) to allow for correction of resolution effects (unfolding)

Uncertainties analyzed, results validated by comparison with input

Pole extrapolation realistic for proton spectator, exploratory for neutron spectator

Final uncertainties depend on ability to correct for resolution

Free nucleon: EIC simulations



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Validation of pole extrapolation results by comparison with input model

Bound nucleon: Tagged EMC effect

Basic assumption: Initial-state modification proportional to 4-dim virtuality of active nucleon = function of spectator momentum in tagged DIS
[Frankfurt, Strikman 1988]

$$p_n^2 - m^2 \;=\; (p_d - p_p)^2 - m^2 \;=\; \text{function}(\alpha_p, p_{pT}) \;\equiv\; V(\alpha_p, p_{pT})$$

[same for $p \leftrightarrow n$]

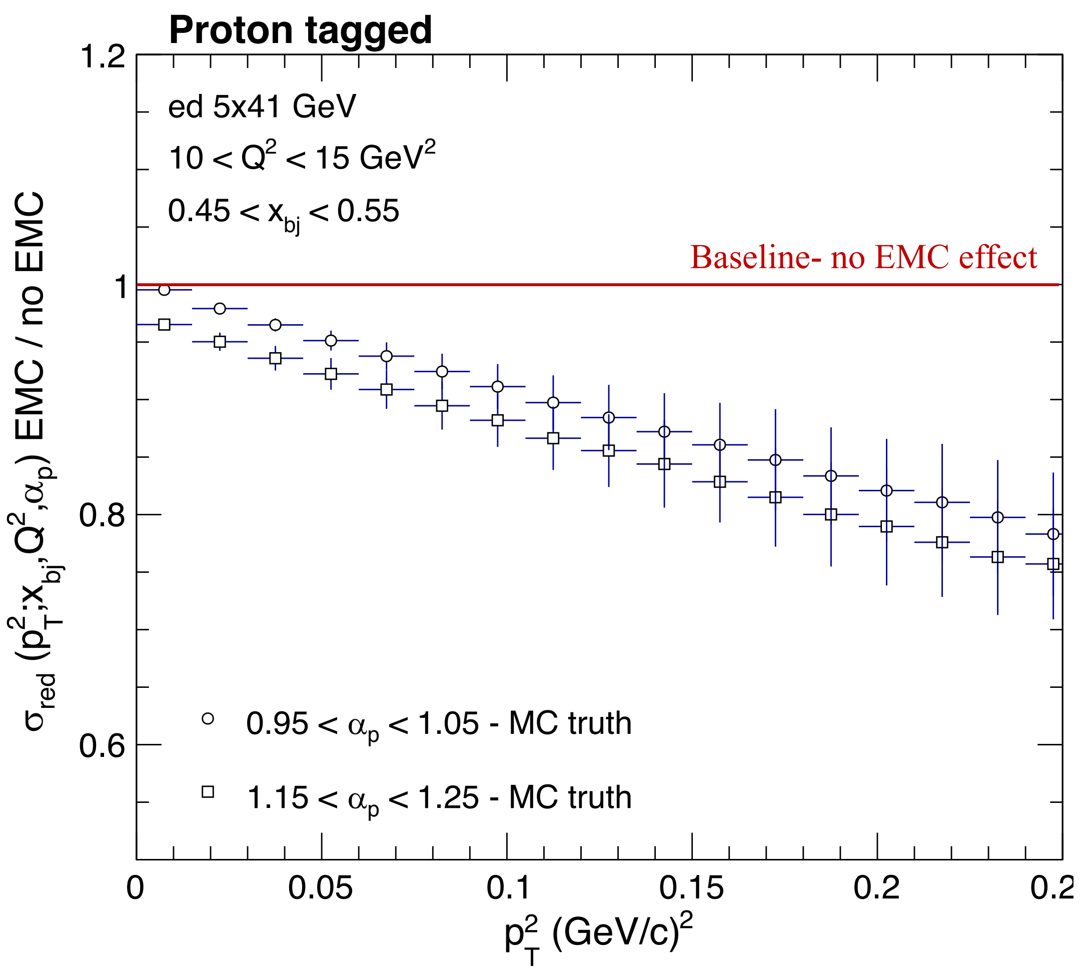
$$F_{2n}(x, Q^2; \alpha_p, p_{pT})[\text{bound}] \;=\; \left[1 + \frac{V(\alpha_p, p_{pT})}{\langle V \rangle} f(x) \right] F_{2n}(x, Q^2)[\text{free}]$$

Model parameters fixed by inclusive EMC effect data ($0.3 < x < 0.7$) and "average virtuality" $\langle V \rangle_A$ from nuclear structure calculations
[Ciofi degli Atti, Frankfurt, Kaptari, Strikman 2007]

Minimal model. Includes possibility that EMC effect generated by SRCs, but not limited to it. Alternative to GCF

Challenge: Separate initial-state modifications from final-state interactions in tagged DIS measurements

Bound nucleon: EIC simulations



Comparison of reduced cross section measurement with/without EMC effect

Baseline for expected modification

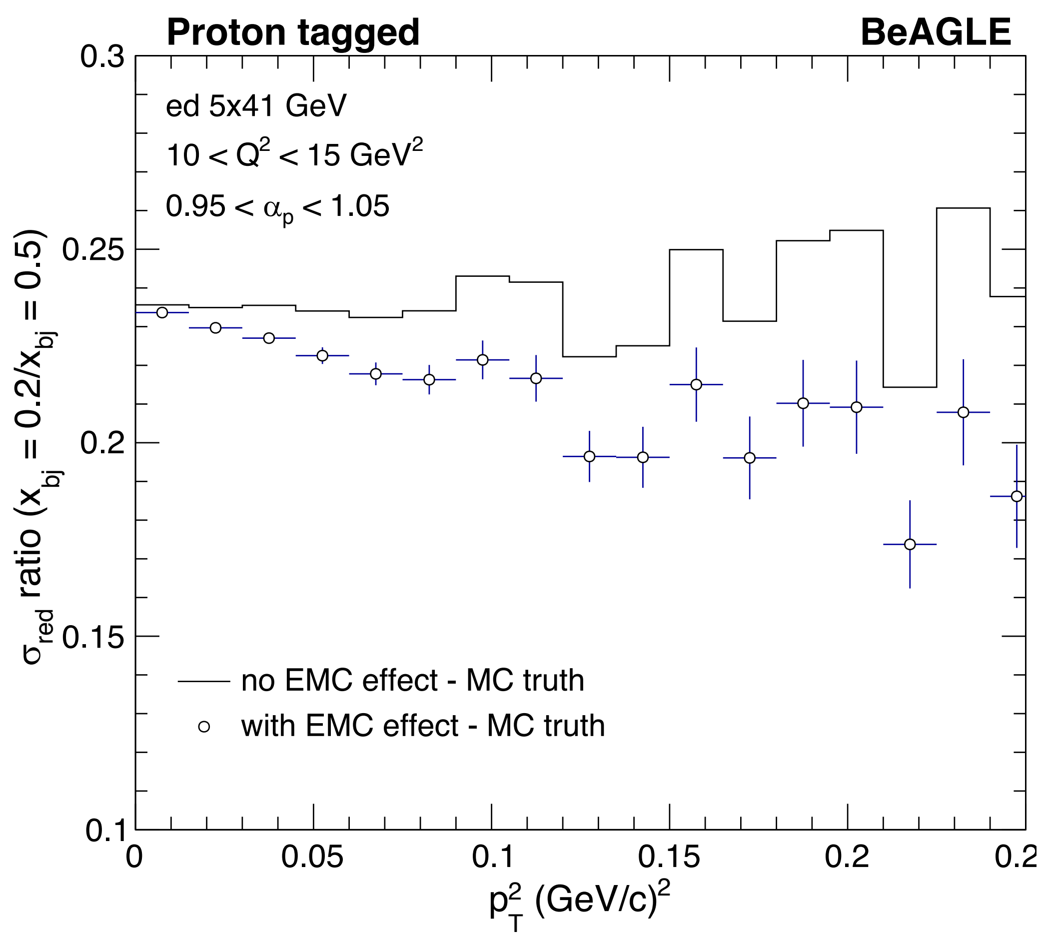
Statistical errors visible: Large x, exceptional configurations in deuteron

Here: Physics model does not include FSI. Need strategy that accounts for FSI

BeAGLE simulation, 10^9 events ~ 25 fb^{-1}
ed 5x41 GeV

Jentsch, Strikman, Tu, CW, DIS2022

Bound nucleon: EIC simulations



Jentsch, Strikman, Tu, CW, DIS2022

Ratio observables can reduce/minimize FSI effects

$$\frac{\sigma_{\text{red}}(x = 0.5; \alpha_p, p_{pT})}{\sigma_{\text{red}}(x = 0.2; \alpha_p, p_{pT})}$$

relative reduction from EMC effect

Statistical uncertainties visible

Shows some power to verify virtuality dependence, needs to be optimized

Extensions: Tagging with EIC

Azimuthal angle-dependent structures in spectator tagging
Unpolarized: $\cos\phi_p, \cos 2\phi_p$
Polarized electron: $A_{LU} \sim \sin\phi_p$, T-odd response function ∝ FSI
Far-forward detection not ϕ_p-symmetric due to crossing angle, beam profile, crab rotation

Tagged DIS at small x: Diffractive scattering, nuclear shadowing, interplay with coherent nuclear scattering
Guzey, Strikman, CW, in progress

Tagged DIS with polarized deuteron: Vector and tensor polarization
Frankfurt, Strikman 1983. Cosyn, CW, 2018/2019

Spectator nucleon tagging + semi-inclusive π/K in current fragmentation: Flavor separation, FSI
Recent discussions

Tagging in exclusive processes on nucleon, e.g. deeply-virtual Compton scattering DVCS

Tagged DIS with $A > 2$: Theory much more complex IA + FSI
3He: Friscic et al 2021

Extensions: Far-forward detector development

On-going/planned detector developments that would improve spectator tagging capabilities:

Refine momentum reconstruction with Off-momentum Detectors and Roman Pots
to better account for longitudinal momentum dependence

Study possibilities for improving ZDC design energy and and angular resolution
to improve neutron resolution to level comparable to protons

Summary

- EIC will enable program of spectator tagging experiments with deuteron

  Unique physics: Free nucleon, nuclear modifications, diffraction/shadowing

  Driving far-forward detector development

- Free nucleon structure from on-shell extrapolation

  Spectator momentum resolution is main limiting factor

  Proton tagging: p_{pT} res limited by beam divergence, pole extrapolation accuracy $\sim$ few %

  Neutron tagging: p_{nT} and α_n resolution limited by ZDC

- Bound nucleon structure / tagged EMC effect

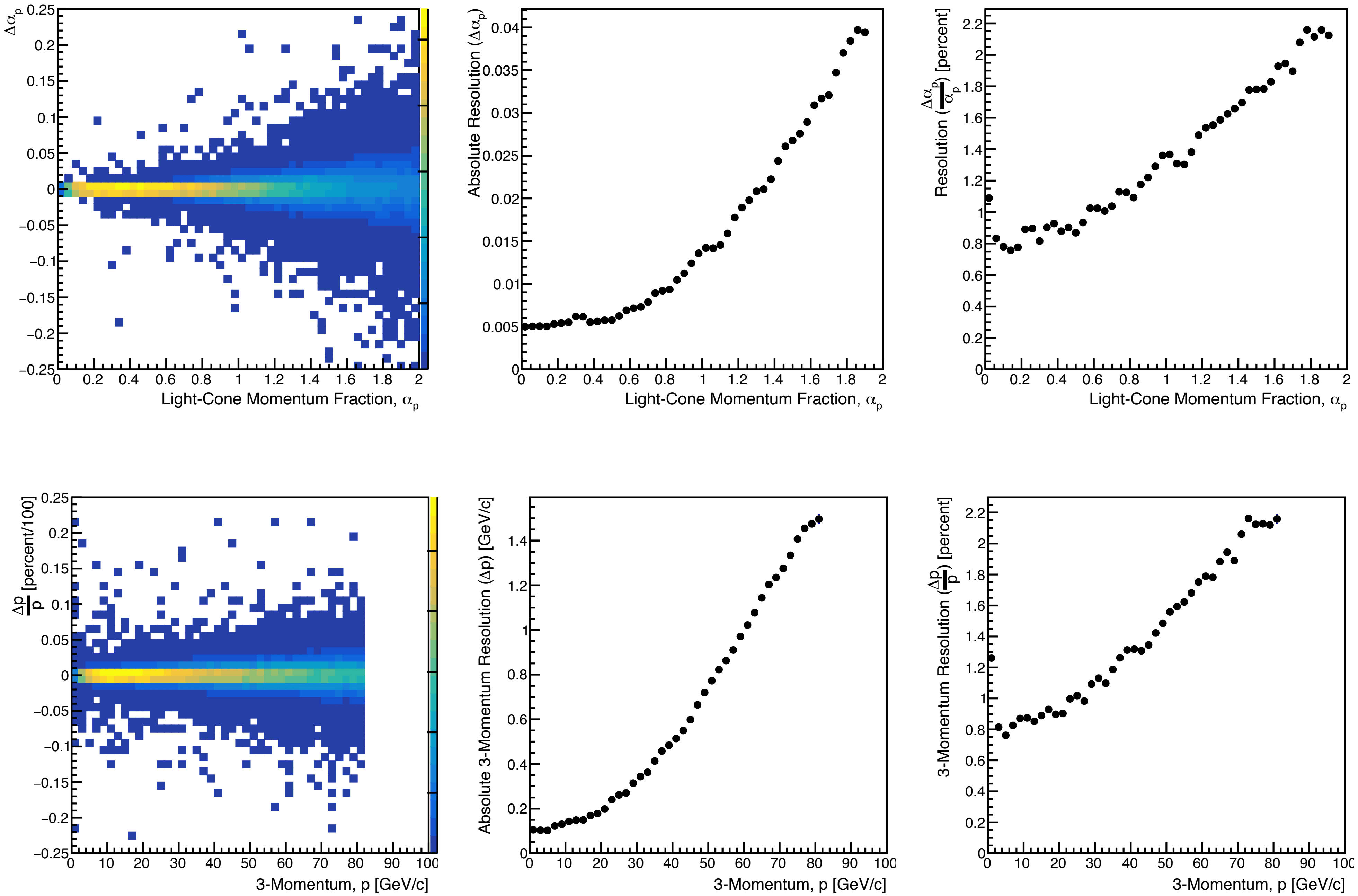
  Statistics becomes limiting factor at large x and large spectator momenta

  Challenge to separate initial-state modifications from FSI — observables, analysis?

- Many opportunities for collaborating in theory, simulations, development

Supplementary material

EIC: Longitudinal momentum resolution



Longitudinal momentum resolution for protons with EIC far-forward detector
Summary using all subsystems [Prepared by A. Jentsch]