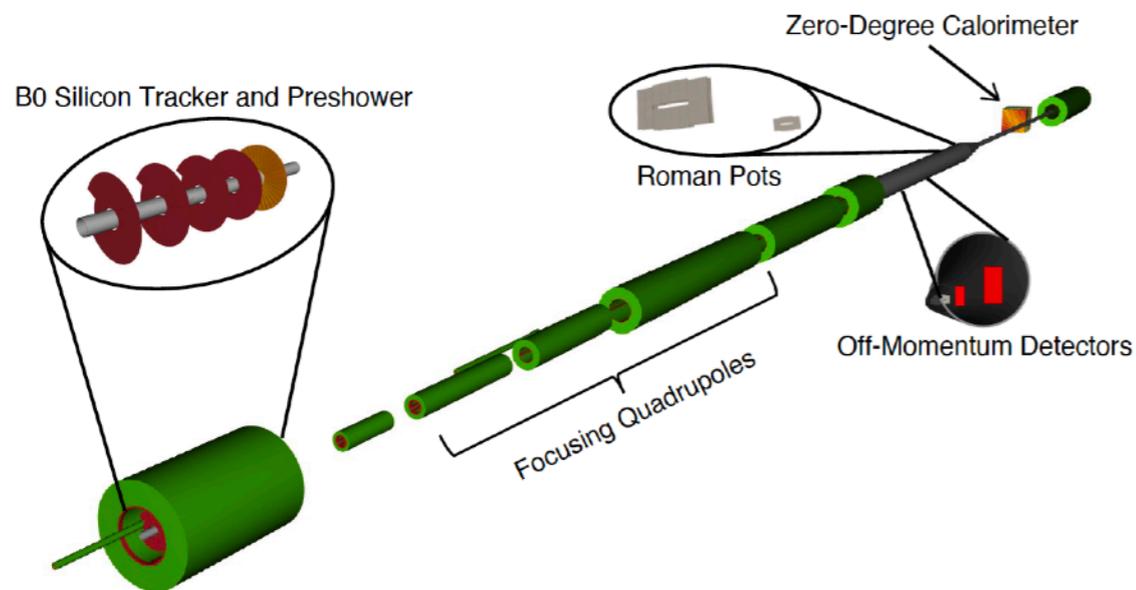


Spectator tagging with EIC far-forward detectors: Free and bound nucleon structure

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



Deuteron DIS with spectator tagging

Controlling the nuclear configuration
Variables, observables, structures

EIC far-forward detector

Physics \leftrightarrow 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

Based on

Physics/detector simulations

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

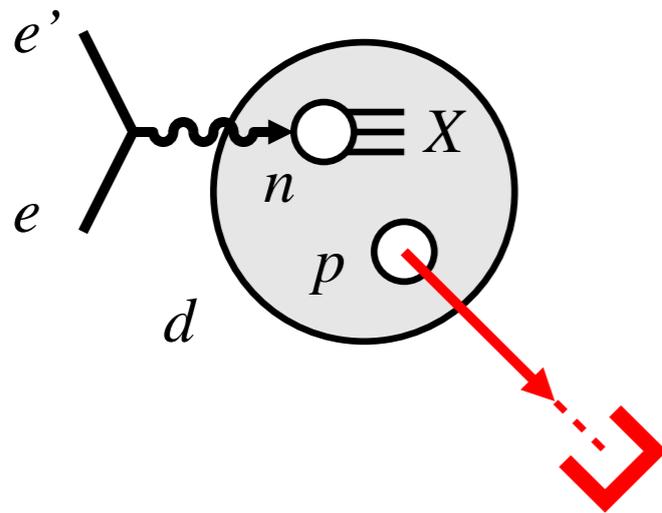
Jentsch, Strikman, Tu, CW, in progress

Theory development

Cosyn, Sargsian, Frankfurt, Strikman, CW

Detector design

Yellow Report + Updates



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

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

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

Electron-deuteron cross section

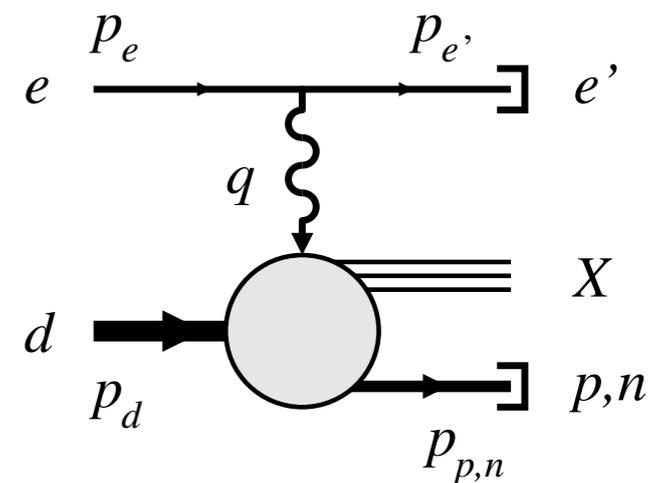
$$d\sigma(ed \rightarrow e'Xp) = \text{Flux}(x, Q^2) dx dQ^2 \frac{d\phi_{e'}}{2\pi} \times \sigma_{d,\text{red}}(x, Q^2; \alpha_p, p_{pT}, \phi_p) d\Gamma_p \quad \text{likewise for } p \rightarrow n$$

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

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



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

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

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

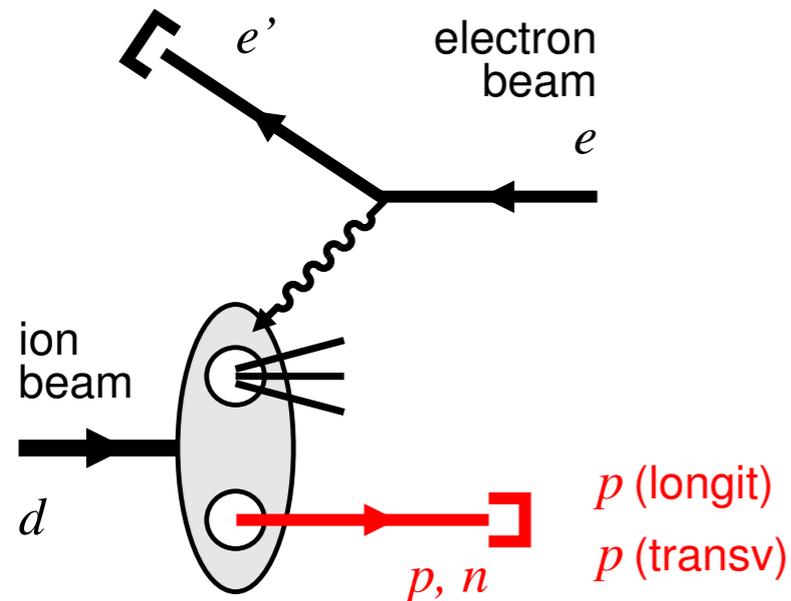
+ initial-state modifications + final-state interactions

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

$$x_n = \frac{x}{2 - \alpha_p} \quad \text{effective scaling variable in } en \text{ DIS process}$$

$$\epsilon(en) = \epsilon(ed) + \text{corrections } (1 - \alpha_p)^2 x^2 m^2 / Q^2 \quad \text{same in } en \text{ and } ed \text{ process}$$

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



Detector variables

$p_p(\text{longit}), p_p(\text{transv})$ spectator momenta in detector

Boosted from rest frame in forward ion direction

$$\theta_p \equiv \frac{p_p(\text{transv})}{p_p(\text{longit})}$$

polar angle

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

momentum fraction = magnetic rigidity ratio

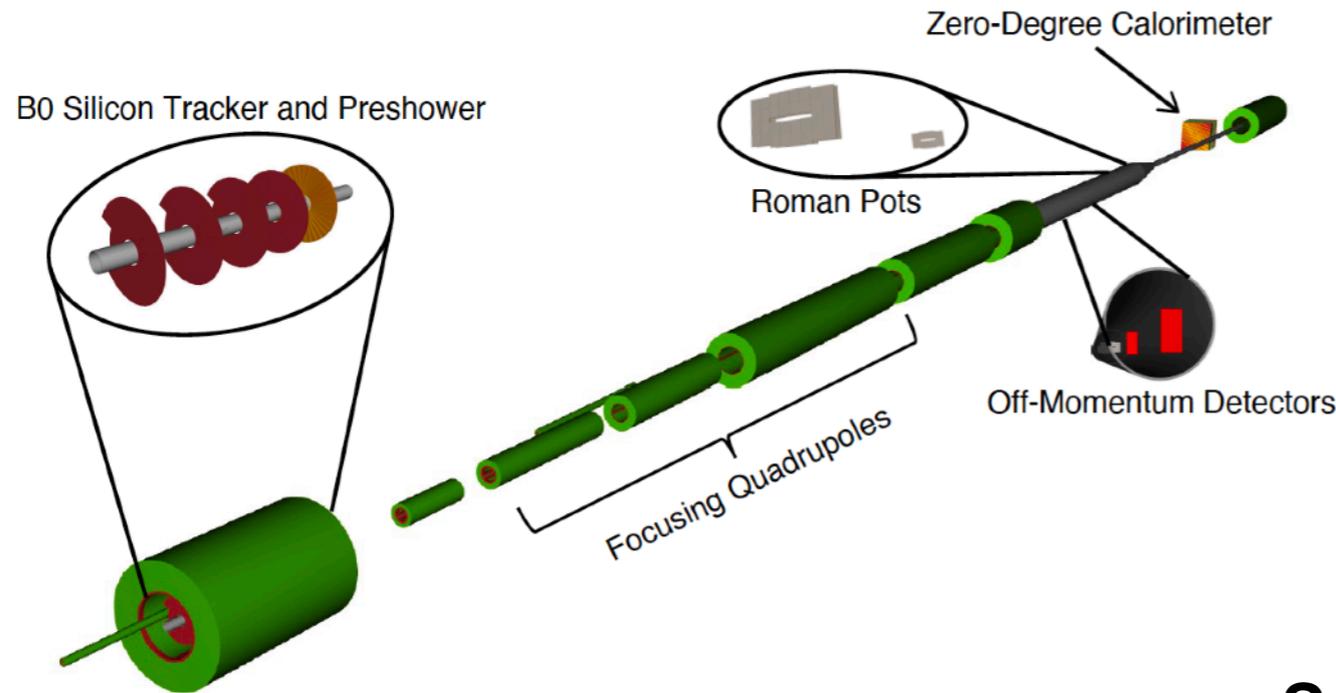
Relation to physics variables

Forward ion direction generally different from virtual photon direction!

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

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

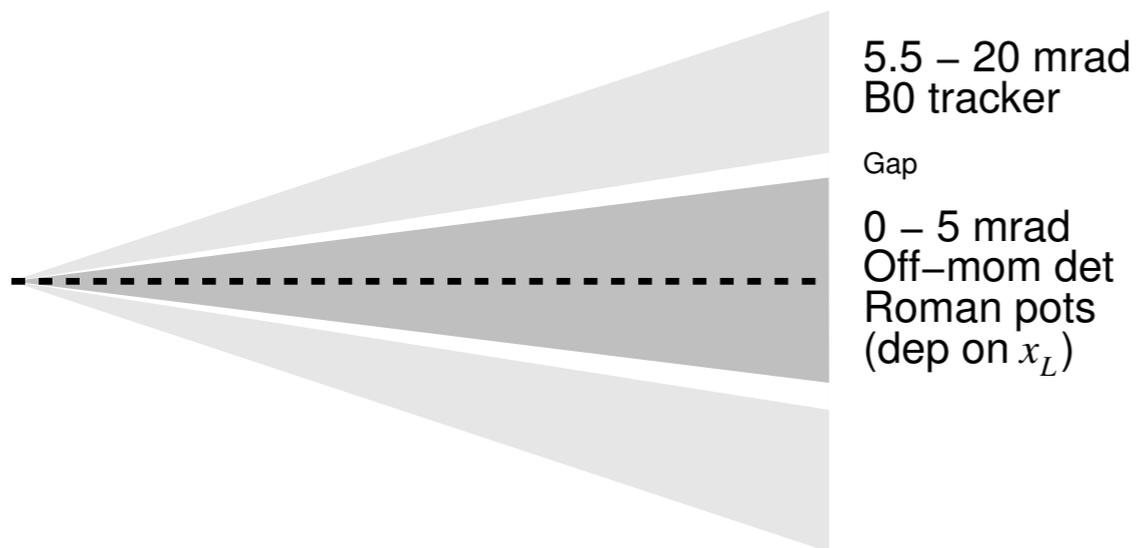
simple relation between physics and detector variables



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

Zero-degree calorimeter for neutrals

Subsystems used in spectator tagging

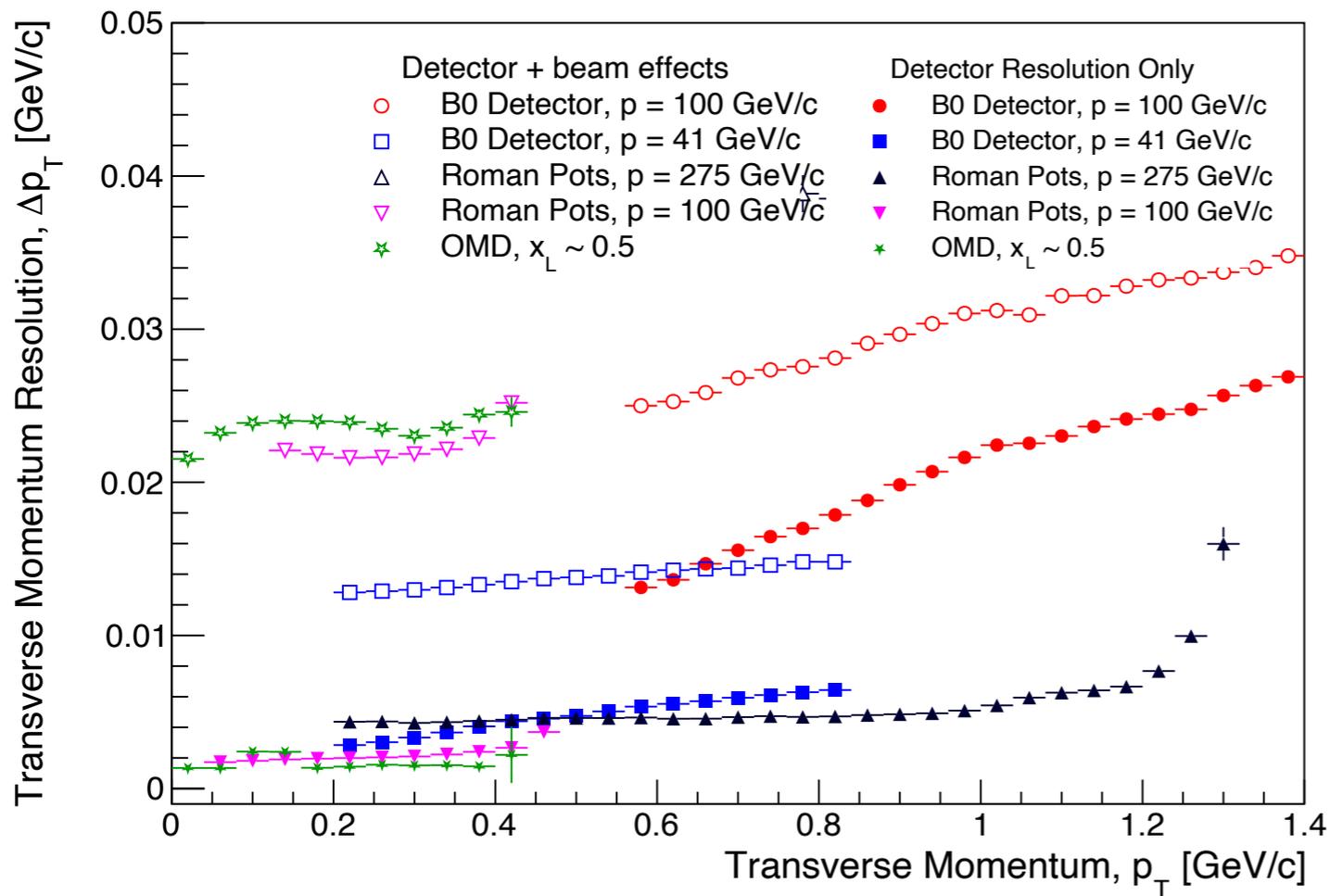


Proton acceptance = function(θ, x_L)

Protons	$\theta < 5$ mrad $0.2 < x_L < 0.6$	Off-mom detectors
Protons	$\theta < 5$ mrad $x_L > 0.6$	Roman Pots
Protons	$5.5 < \theta < 20$ mrad	B0 tracker
Neutrons	$\theta < 4$ mrad	ZDC

Used in free neutron

Bound nucleon/EMC



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

$$\frac{\Delta E}{E} = \frac{50\%}{\sqrt{E}} \oplus 5\%$$

$$\frac{\Delta\theta}{\theta} = \frac{3 \text{ mrad}}{\sqrt{E}}$$

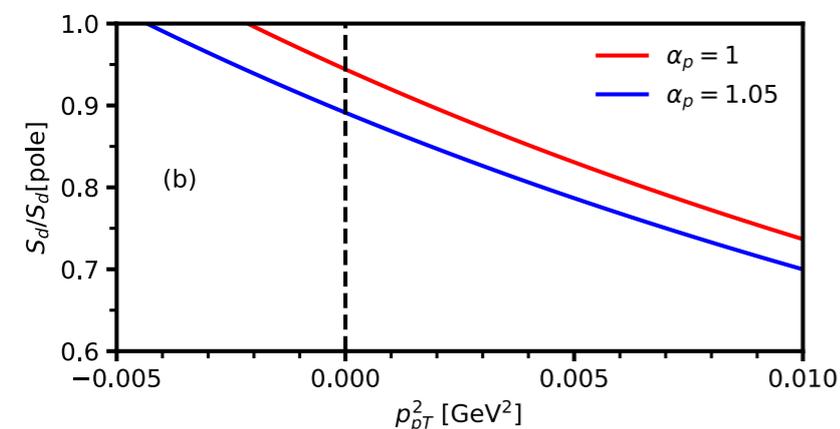
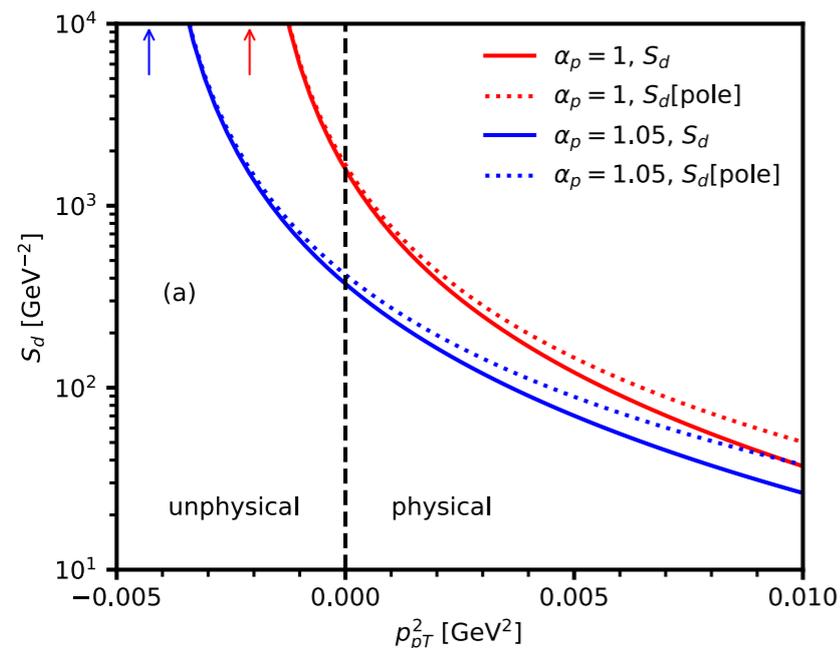
with present ZDC design

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

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

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



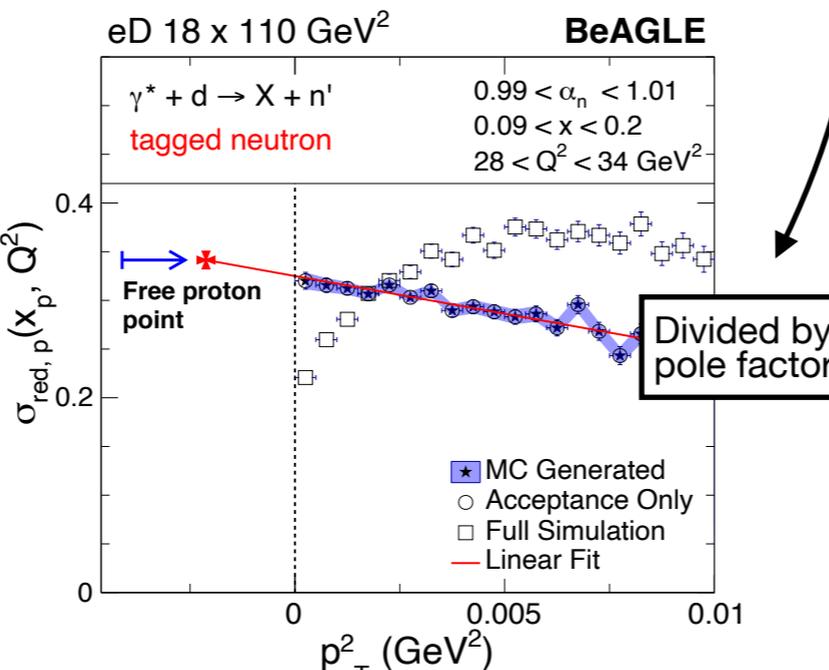
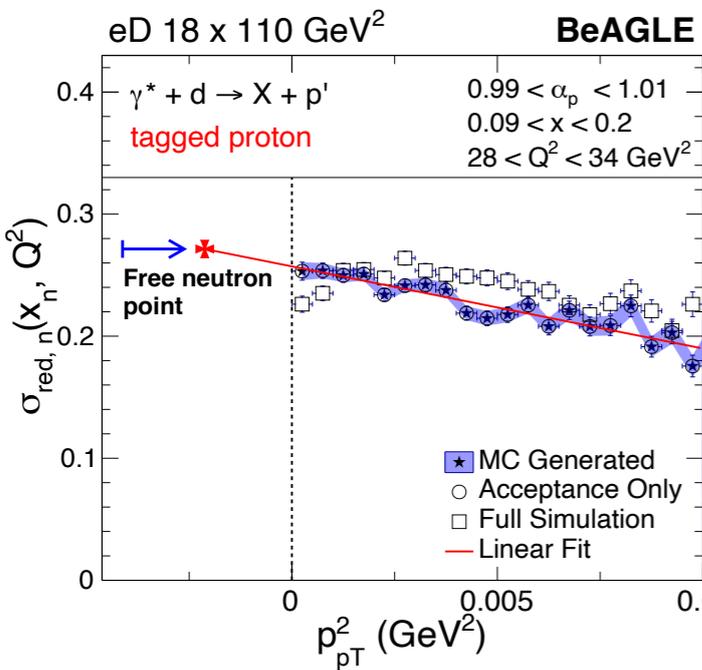
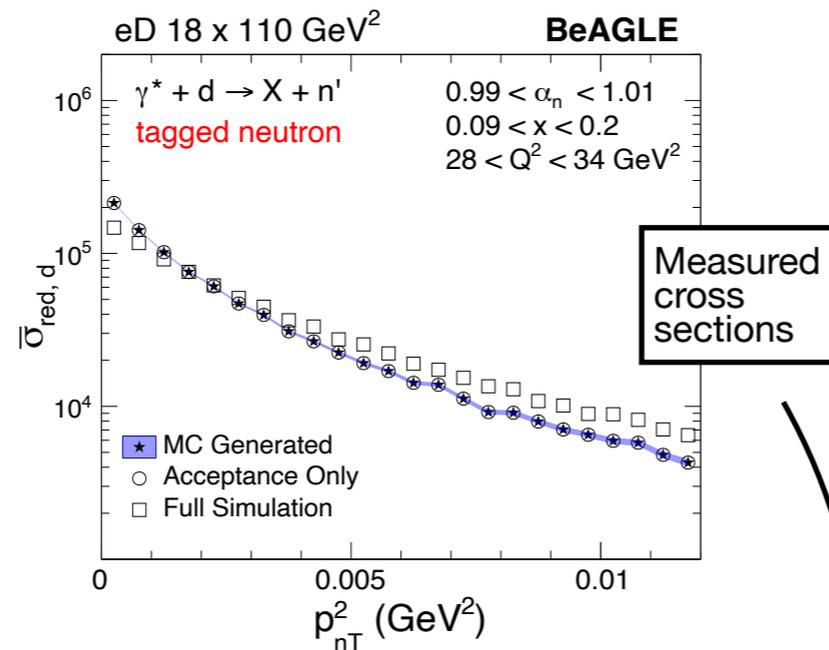
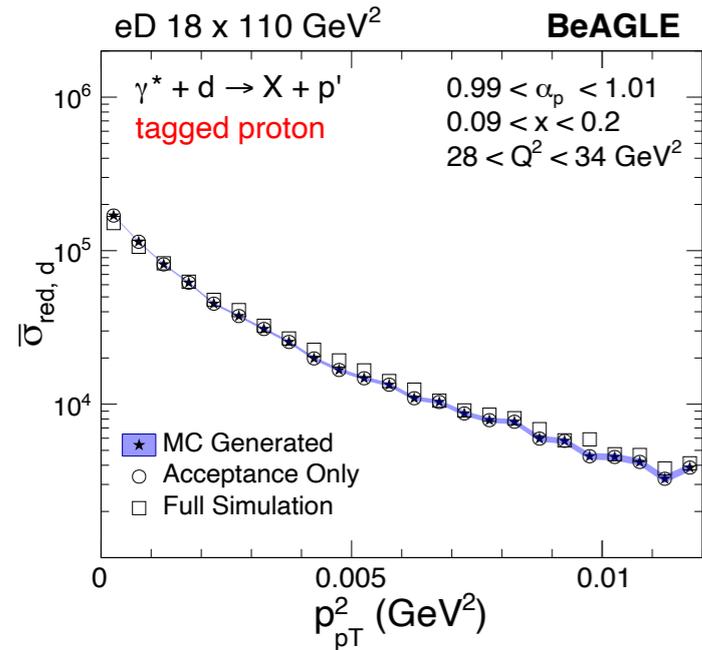
Extraction procedure

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!



Tagged cross section measured with excellent coverage

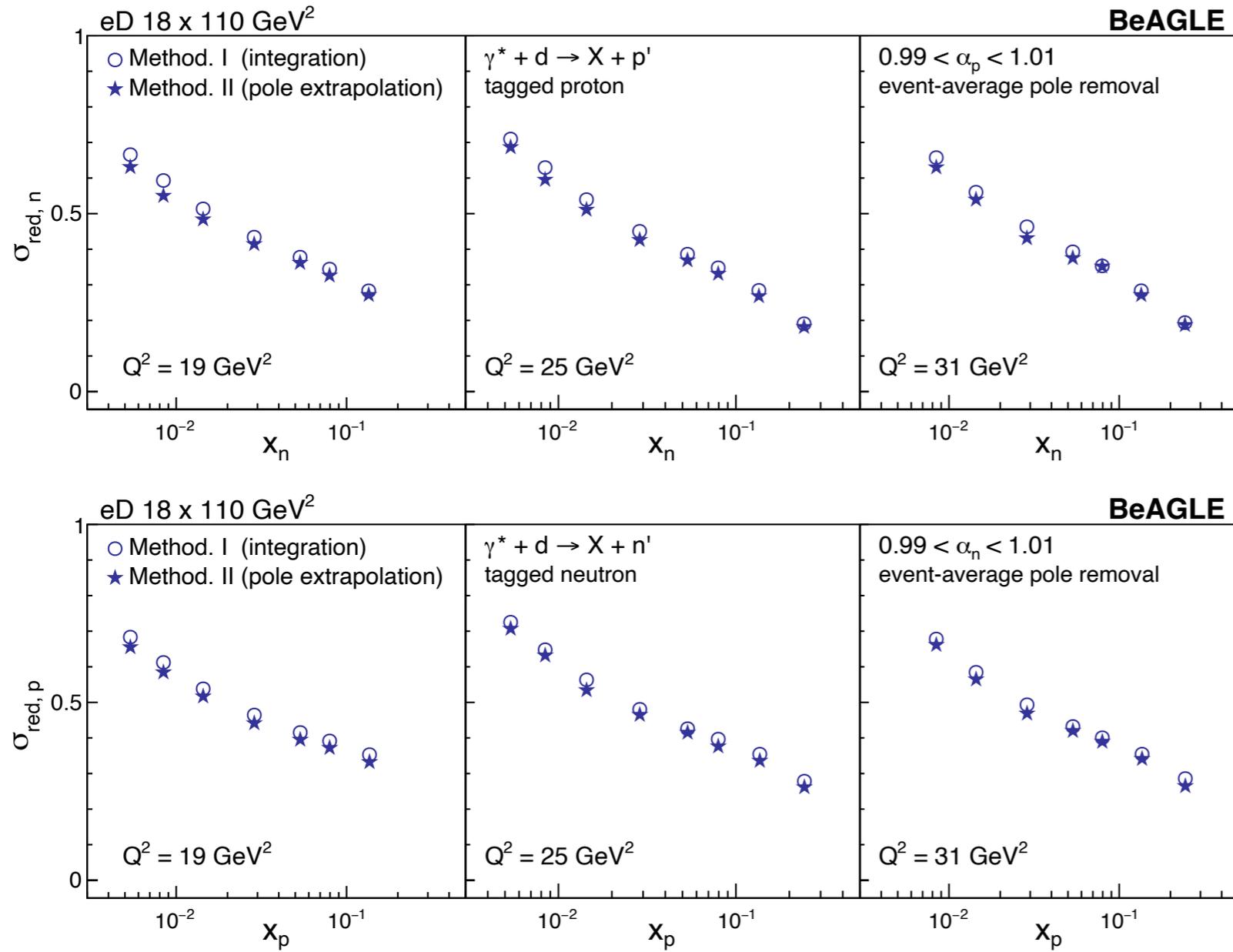
Significant uncertainties in evaluation of pole factor due to p_T resolution

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



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

Validation of pole extrapolation results by comparison with input model

Basic assumption: Initial-state modification proportional to 4-dim virtuality of active nucleon = function of spectator momentum in tagged DIS

[Frankfurt, Strikman 1988]

$$p_n^2 - m^2 = (p_d - p_p)^2 - m^2 = \text{function}(\alpha_p, p_{pT}) \equiv V(\alpha_p, p_{pT}) \quad [\text{same for } p \leftrightarrow n]$$

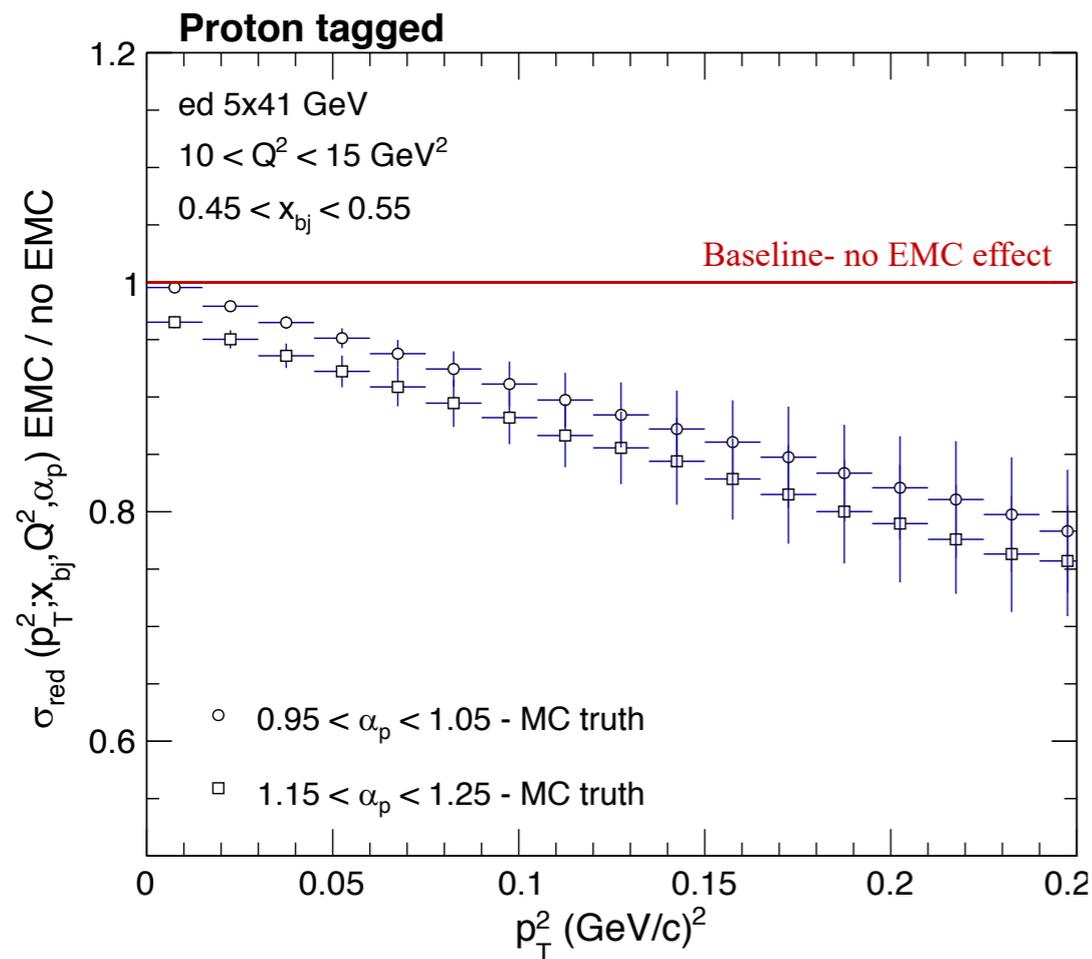
$$F_{2n}(x, Q^2; \alpha_p, p_{pT})[\text{bound}] = \left[1 + \frac{V(\alpha_p, p_{pT})}{\langle V \rangle} f(x) \right] F_{2n}(x, Q^2)[\text{free}]$$

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



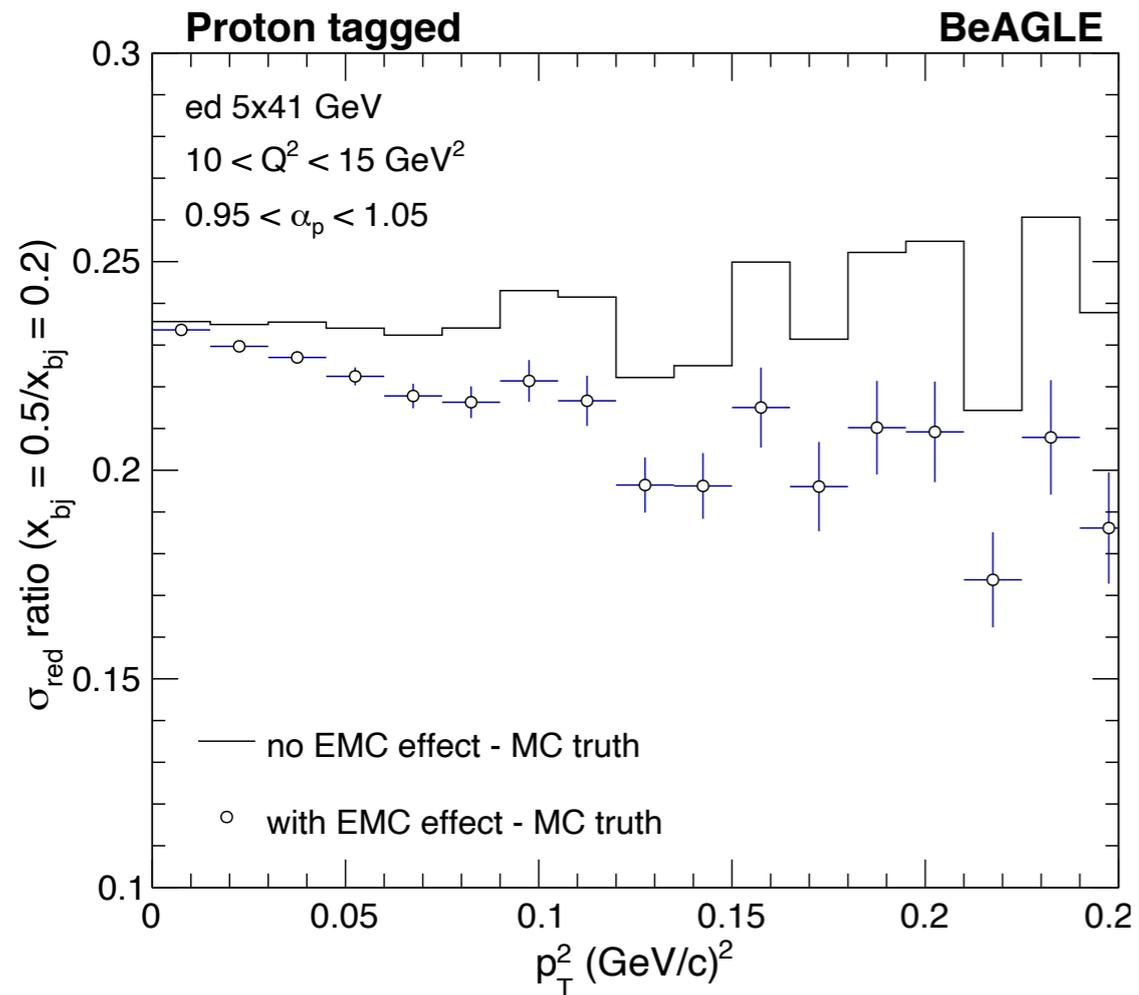
Comparison of reduced cross section measurement with/without EMC effect

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 $\sim 25 \text{ fb}^{-1}$ ed 5x41 GeV



Ratio observables can reduce/minimize FSI effects

$$\frac{\sigma_{\text{red}}(x = 0.5; \alpha_p, p_{pT})}{\sigma_{\text{red}}(x = 0.2; \alpha_p, p_{pT})} \quad \text{relative reduction from EMC effect}$$

Statistical uncertainties visible

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

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 \propto 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

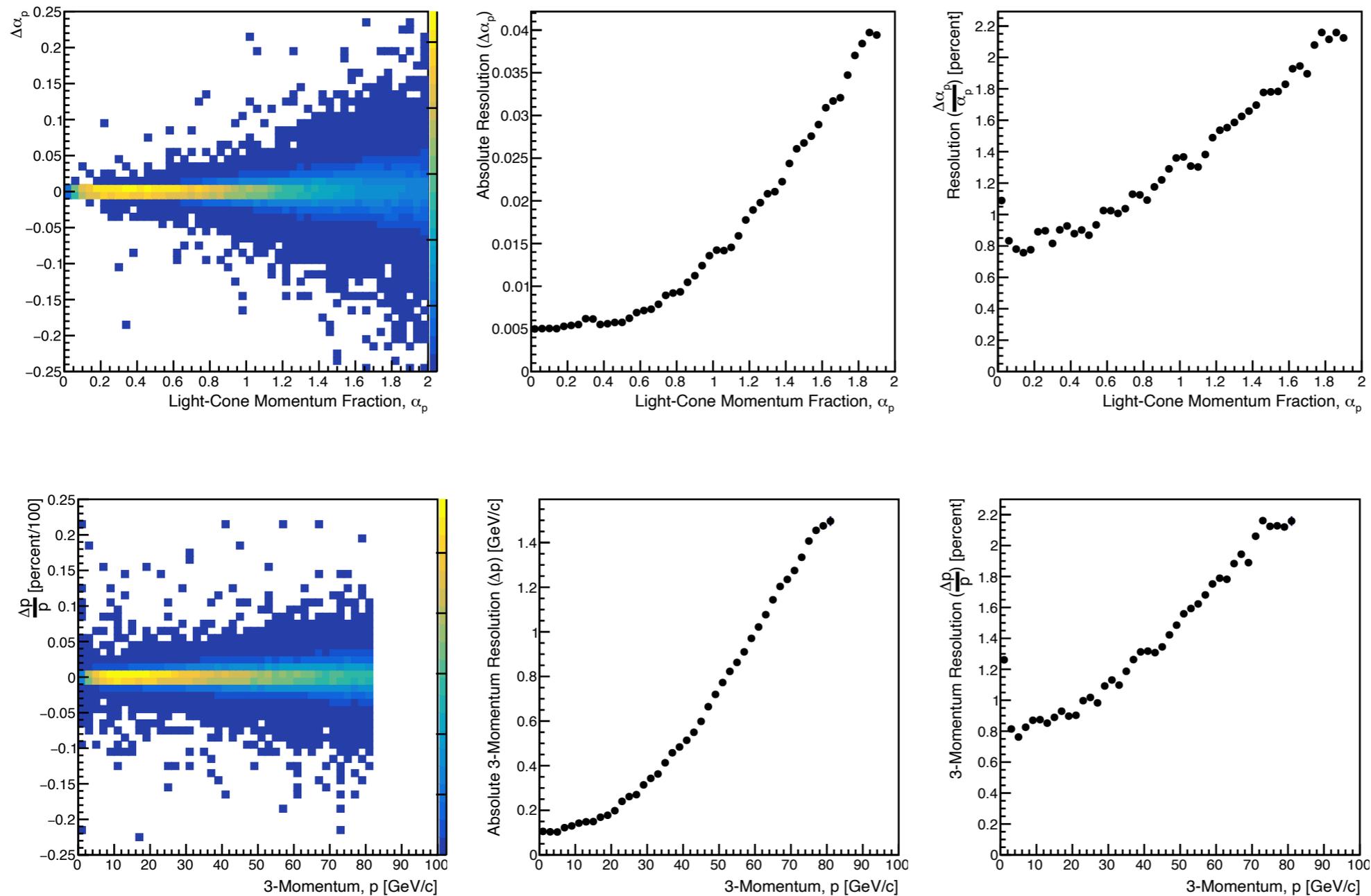
On-going/planned detector developments that would improve spectator tagging capabilities:

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 angular resolution to improve neutron resolution to level comparable to protons

- 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



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