

DIS2022

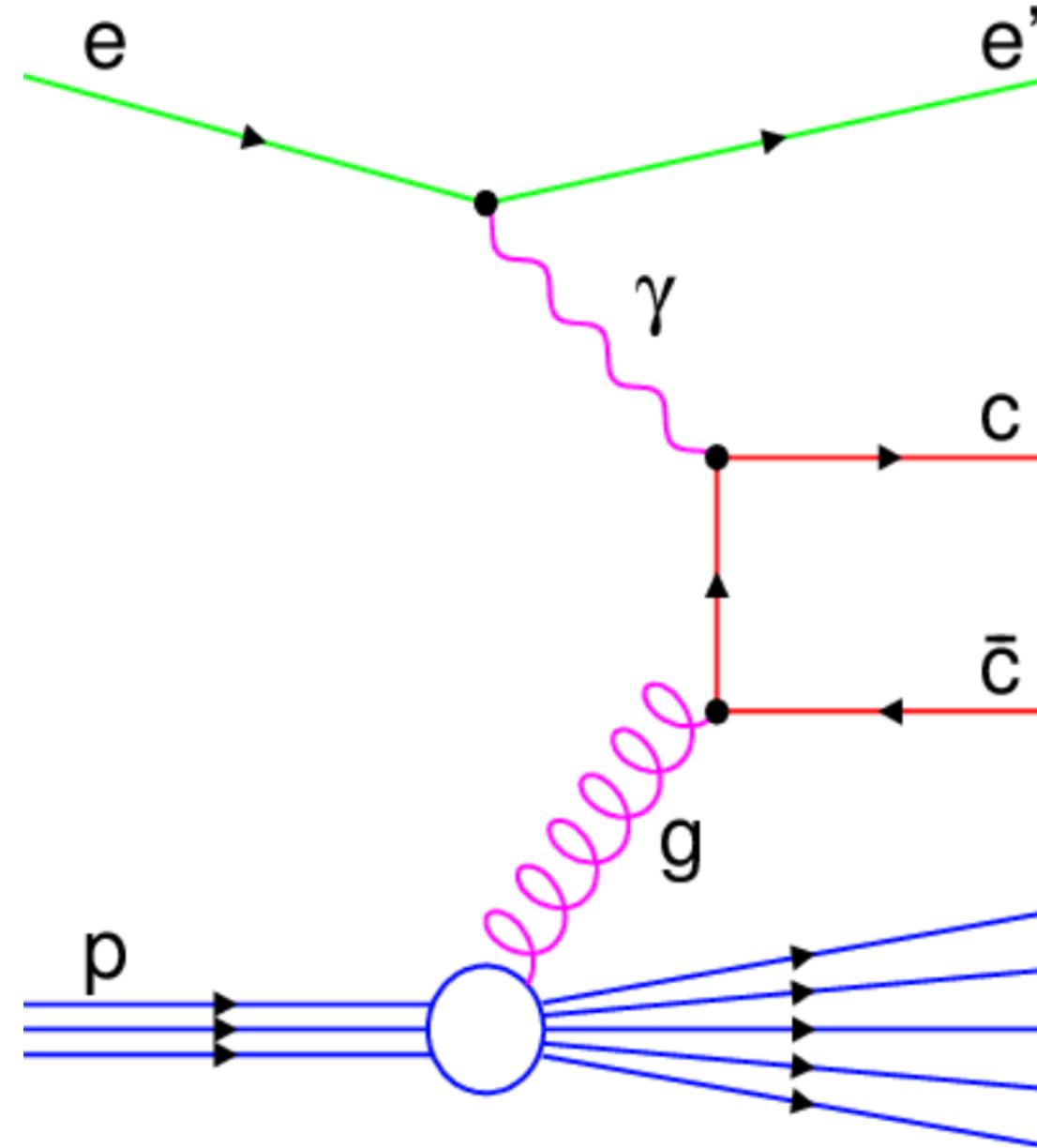
XXIX International Workshop on Deep-Inelastic Scattering and Related Subjects

Santiago de Compostela, 2-6 May 2022

Studying Gluon Distributions and Hadronization with Heavy Flavor Production at the Future Electron Ion Collider

Sooraj Radhakrishnan (for ATHENA Collaboration)
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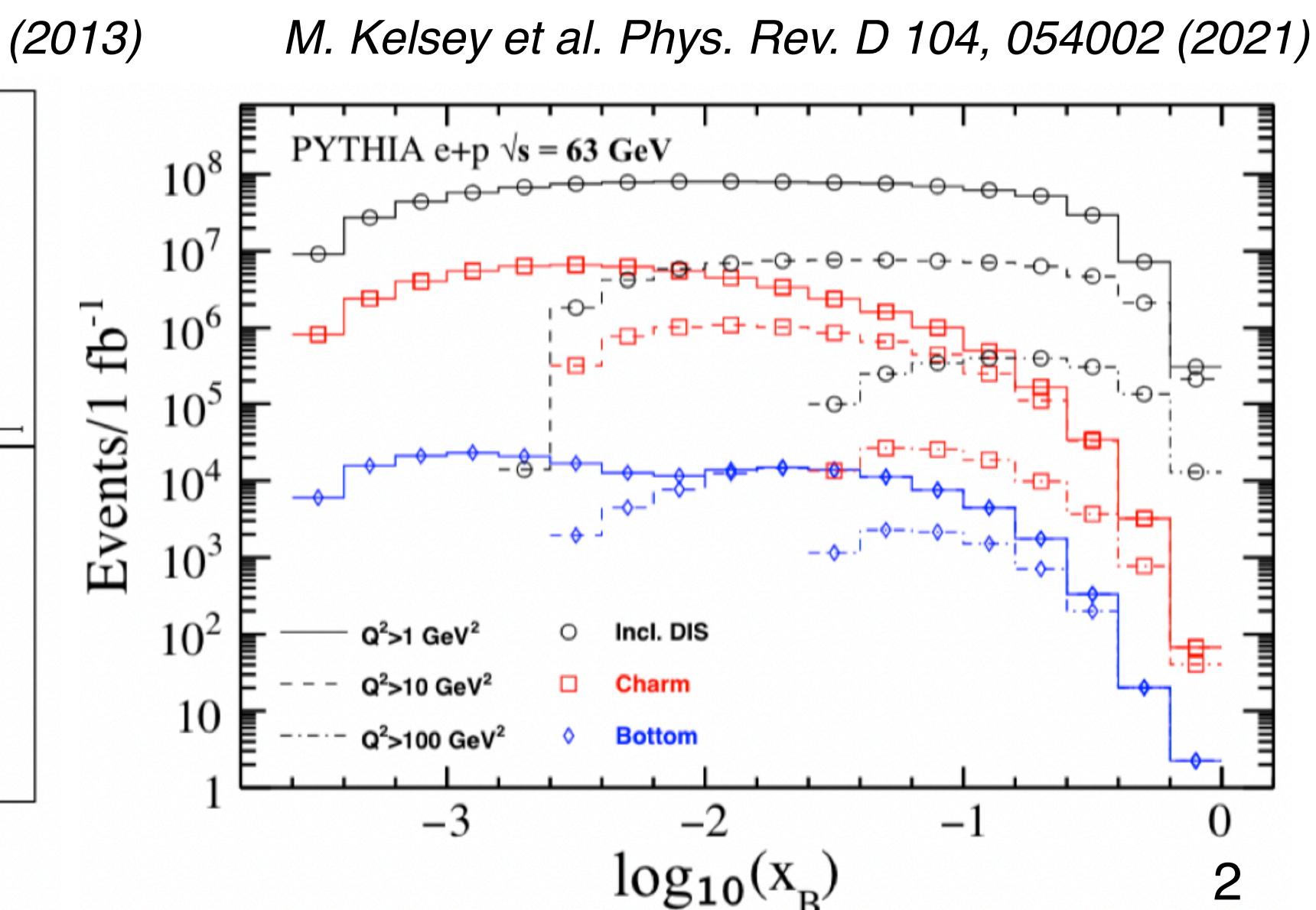
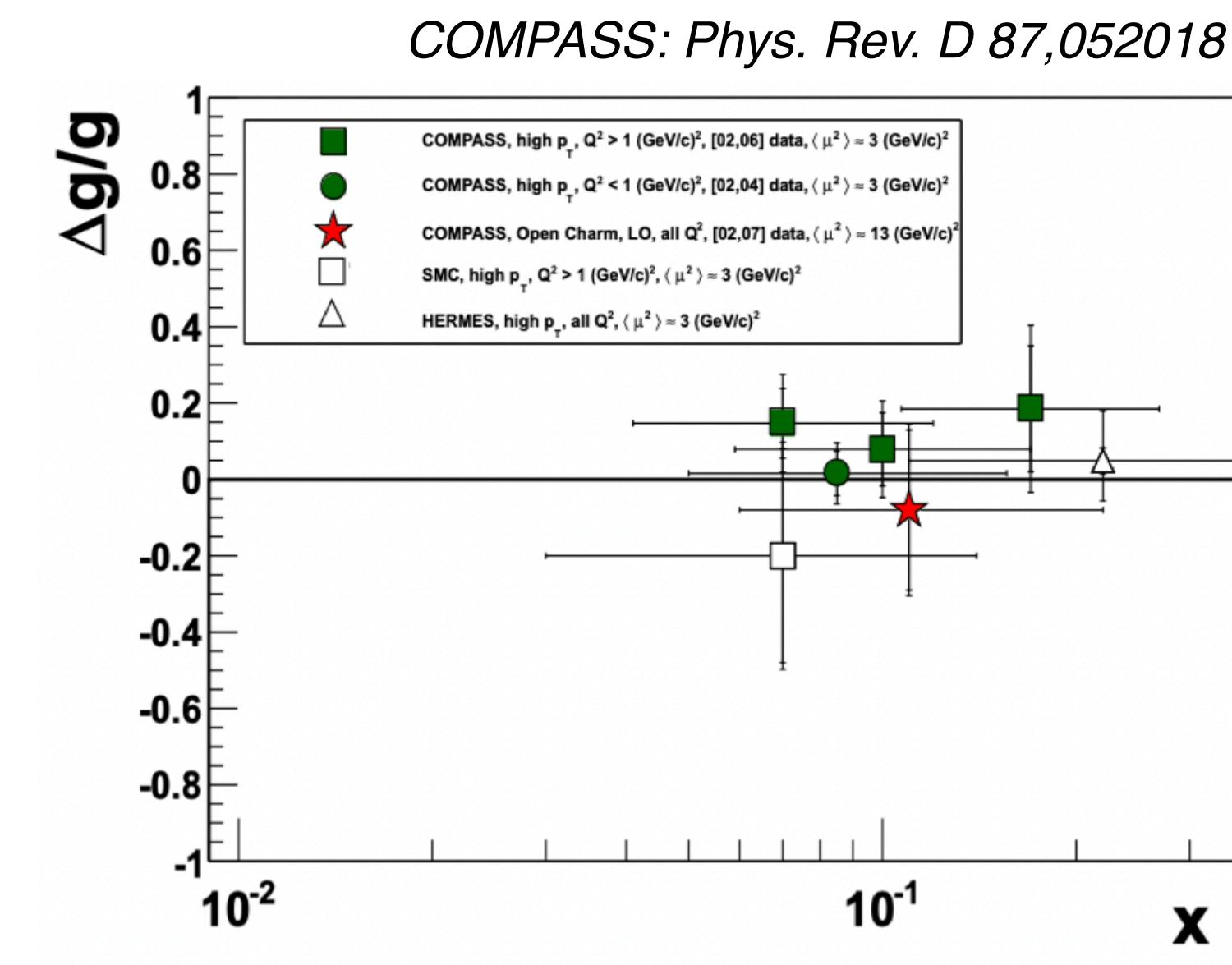
Heavy Quarks as Probes of Gluon Distributions



- Heavy quark production in DIS: leading order contribution from photon gluon fusion process
- Ideal to probe gluon distributions
- Can access heavy flavor production over a broad kinematic range at the EIC

- Will constrain gluon helicity, gluon nPDFs, gluon TMDs over a broad kinematic range, which are major focuses of EIC physics

EIC White Paper: arXiv:1212.1701 (2012)

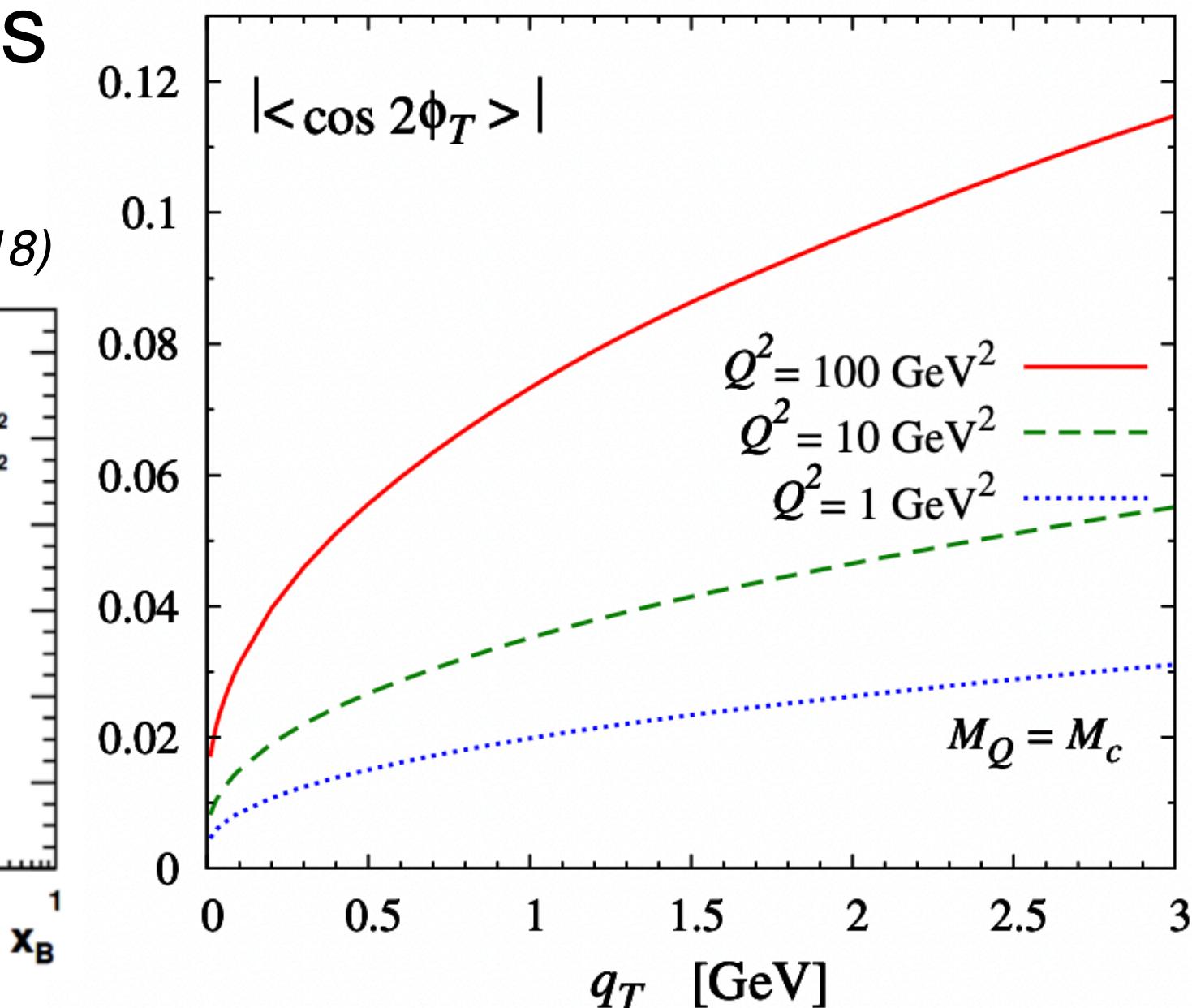
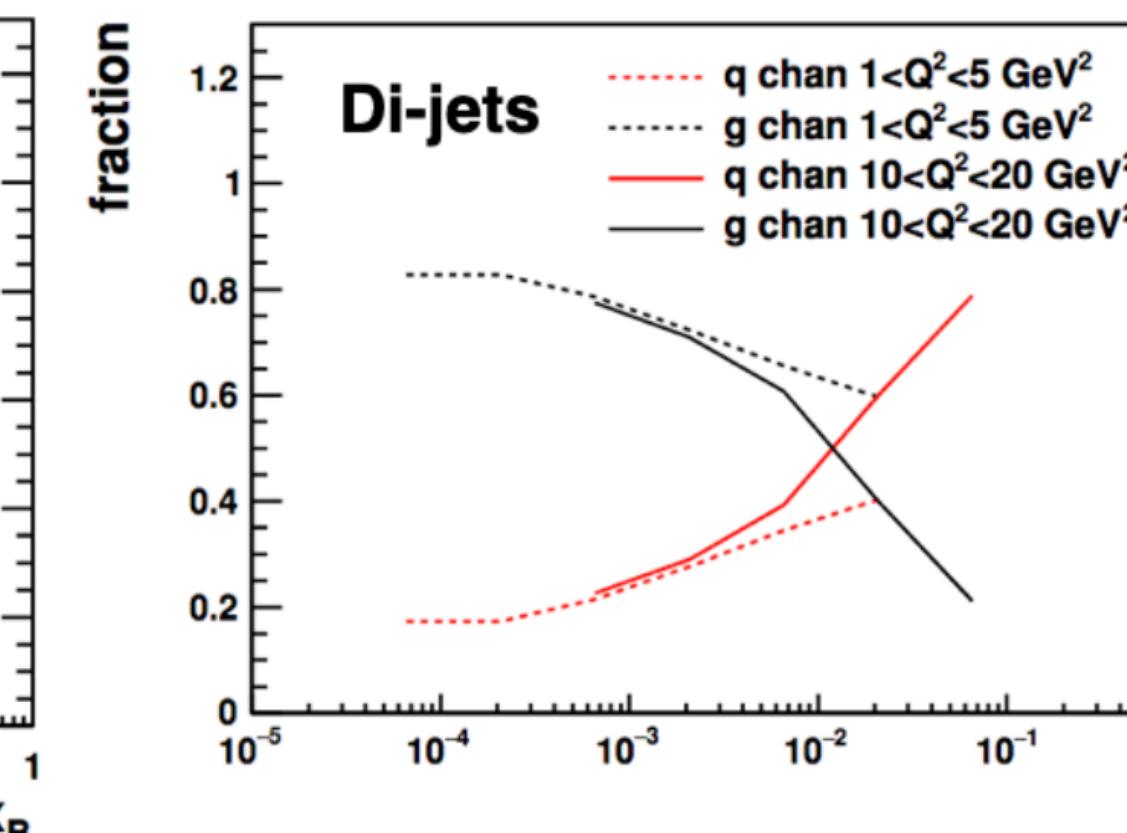
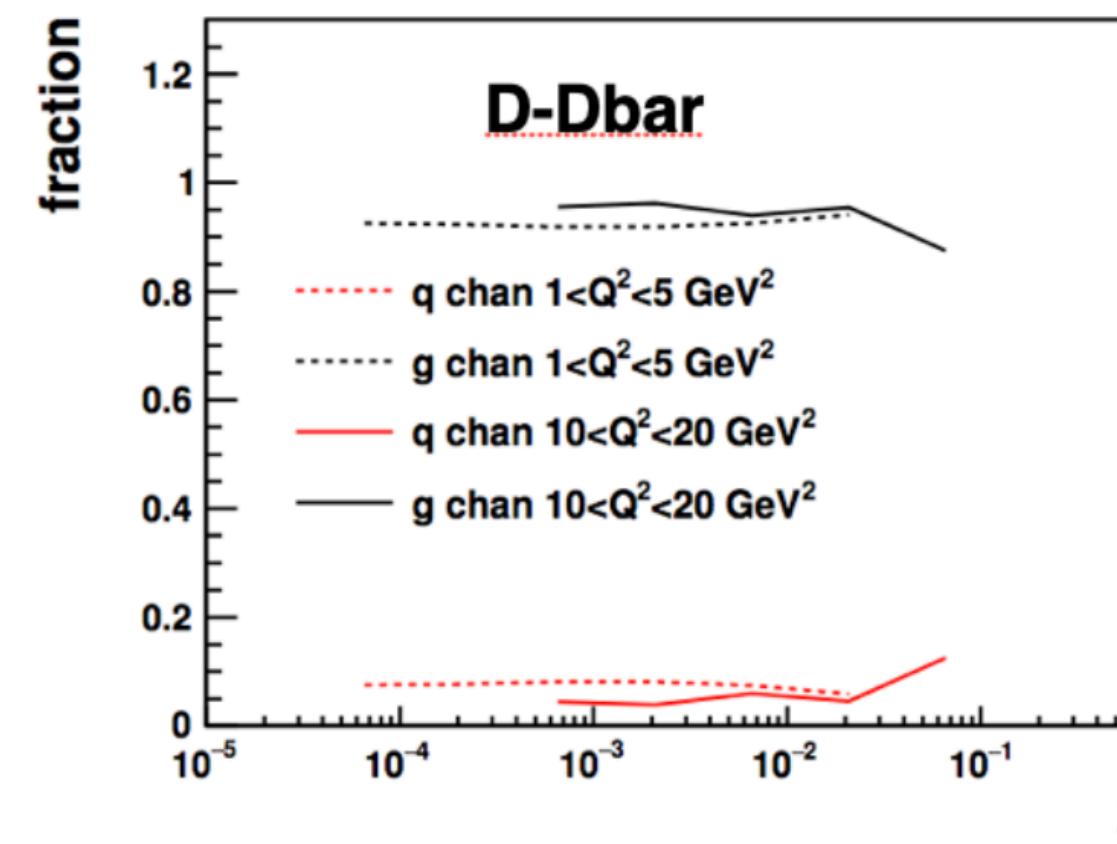


Gluon TMDs and Hadronization

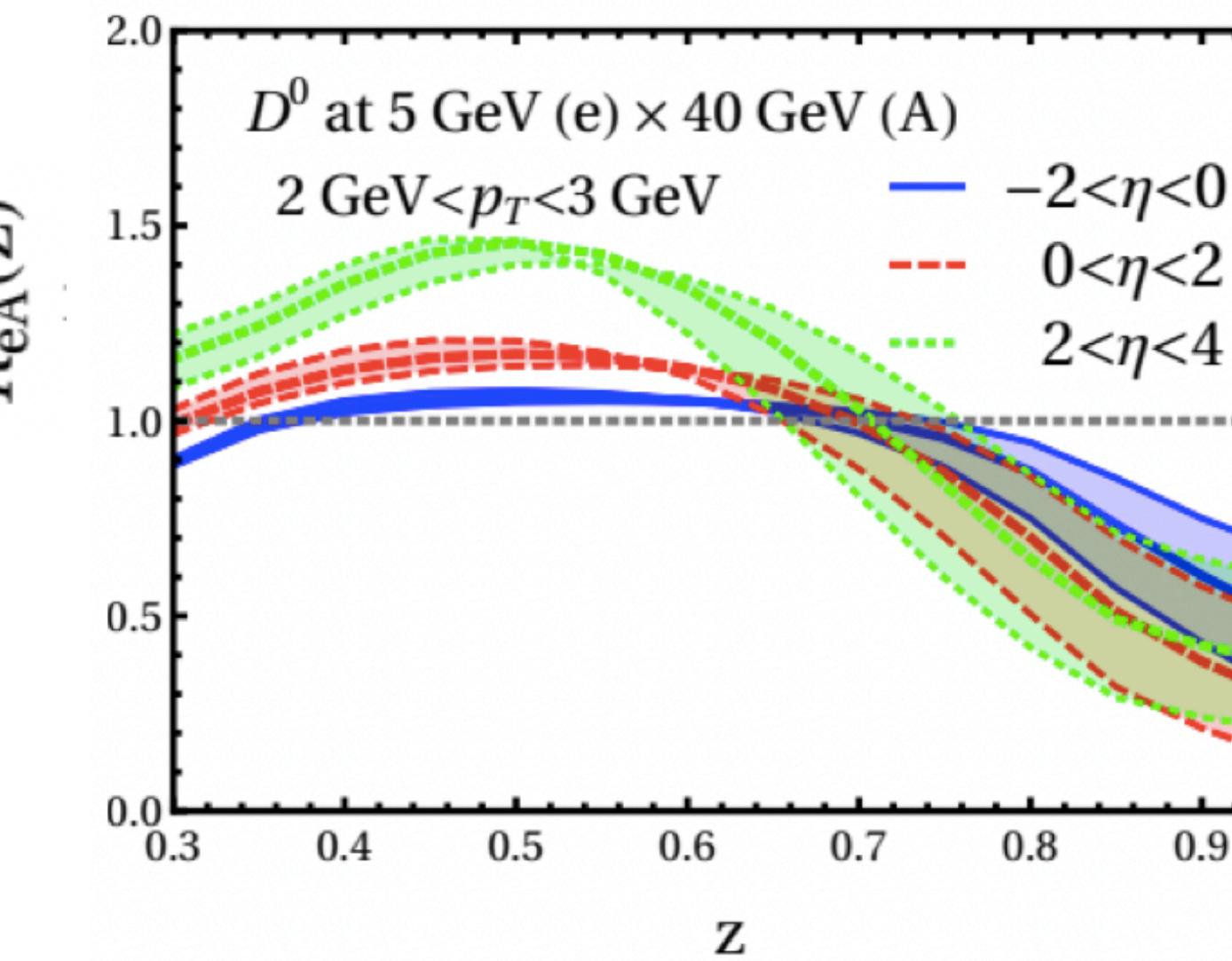
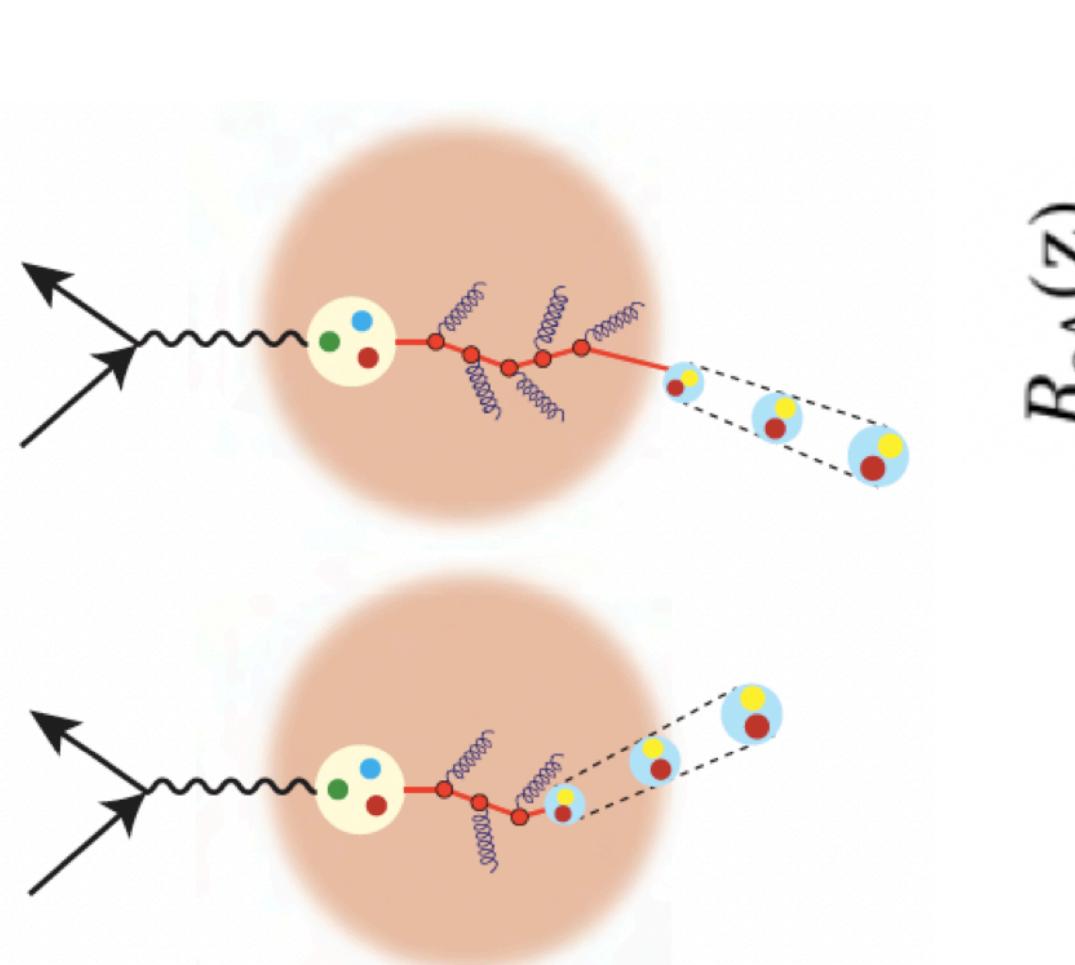
- Heavy flavor pair production ideal channel to probe gluon Sivers asymmetry, linearly polarized gluon TMDs
- Also, clean probes of gluon TMDs

D. Boer et al. JHEP 08 (2016) 001

L. Zheng et al. Phys. Rev. D 98, 034011 (2018)

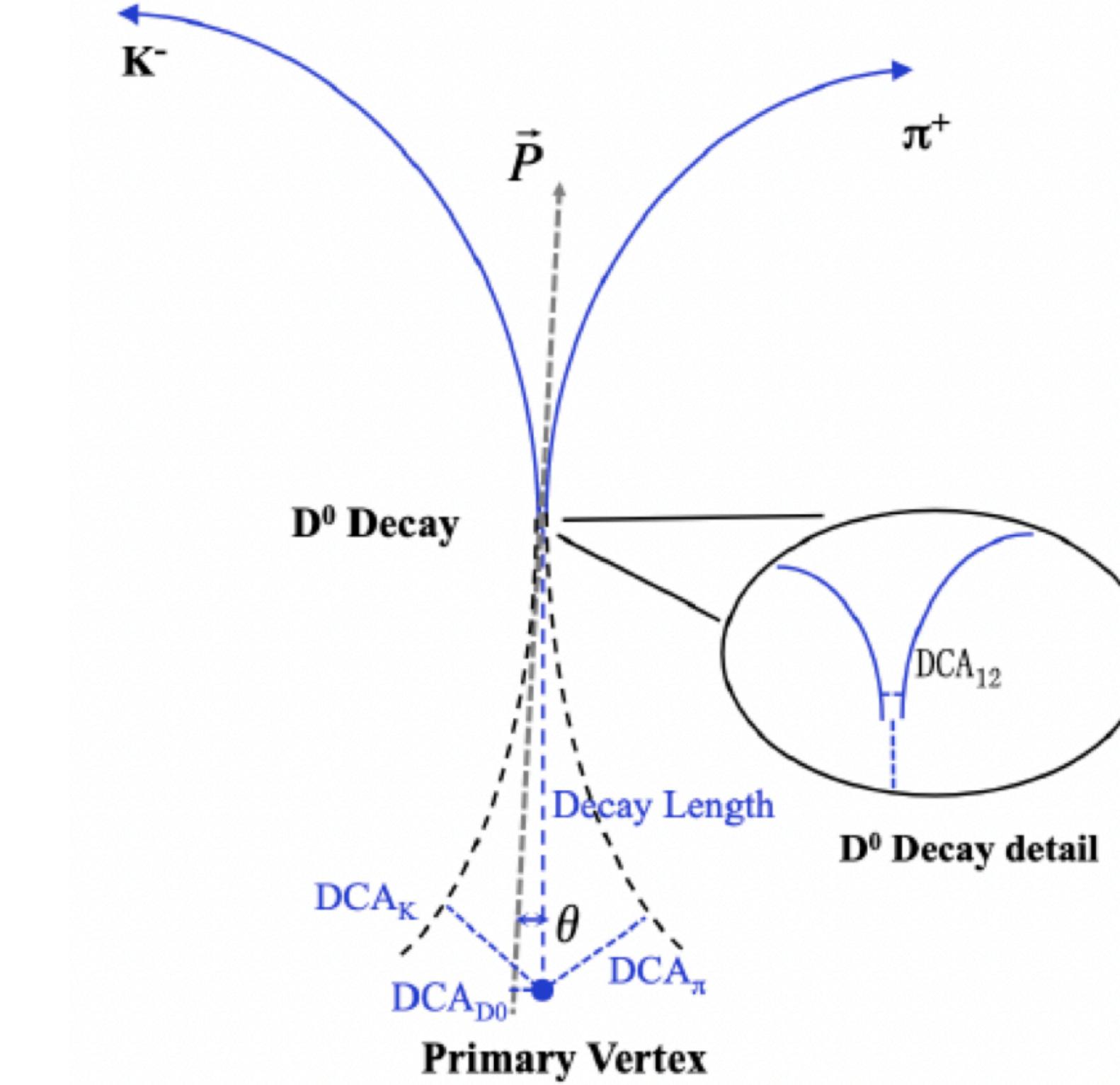


H. Liu et al. arXiv:2007.10994



- Study Hadronization through modification of fragmentation in presence of nuclear matter

Heavy Flavor Reconstruction at EIC

- 

\bar{P}

π^+

$\bar{\kappa}^-$

D^0 Decay

Decay Length

D^0 Decay detail

DCA_K

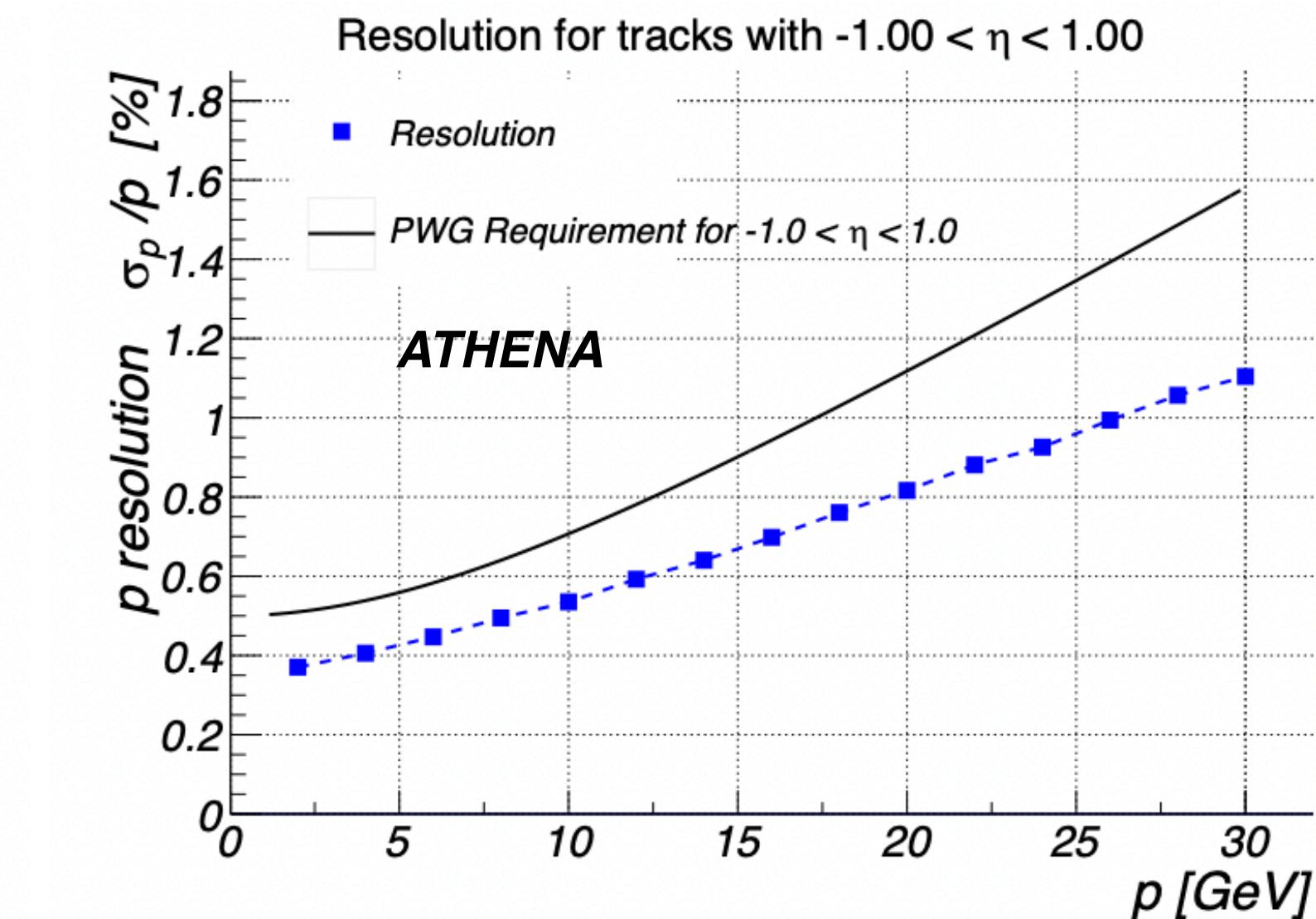
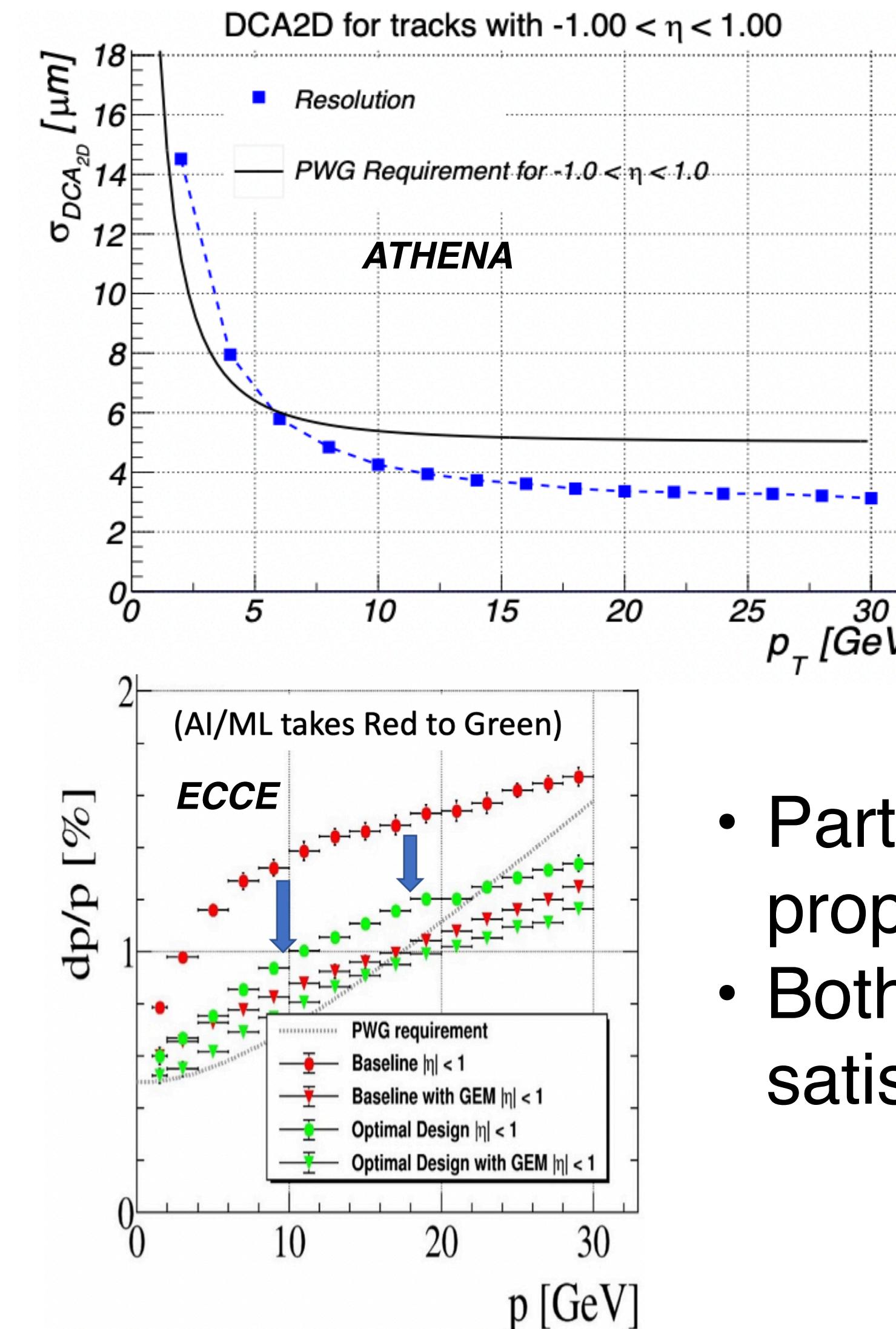
DCA_{D^0}

θ

DCA_π

Primary Vertex
- Key for HF measurements: Tracking system with excellent track pointing resolution, good momentum resolution

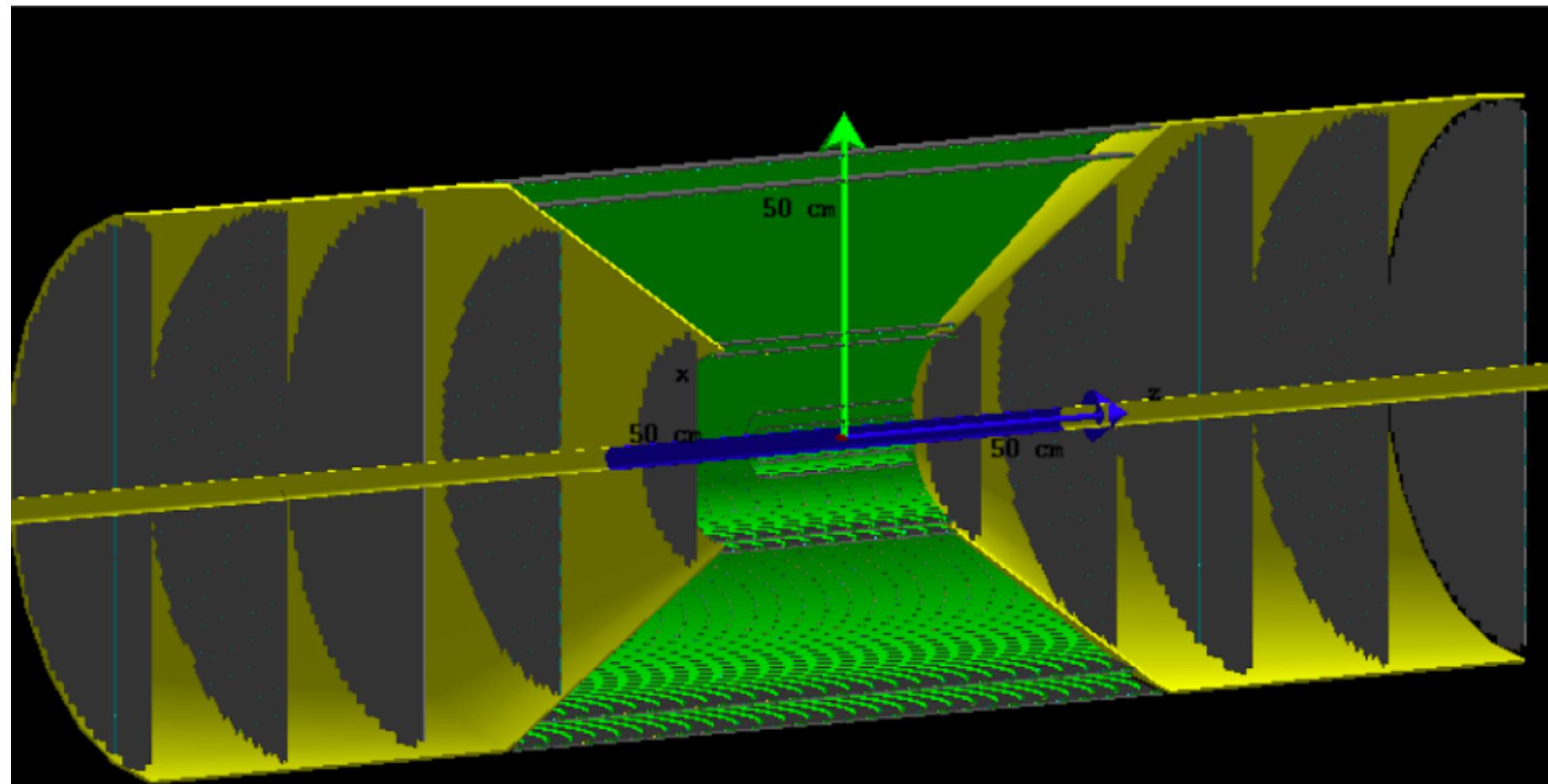
- MAPS based inner tracking and vertexing system required for excellent track pointing and momentum resolutions



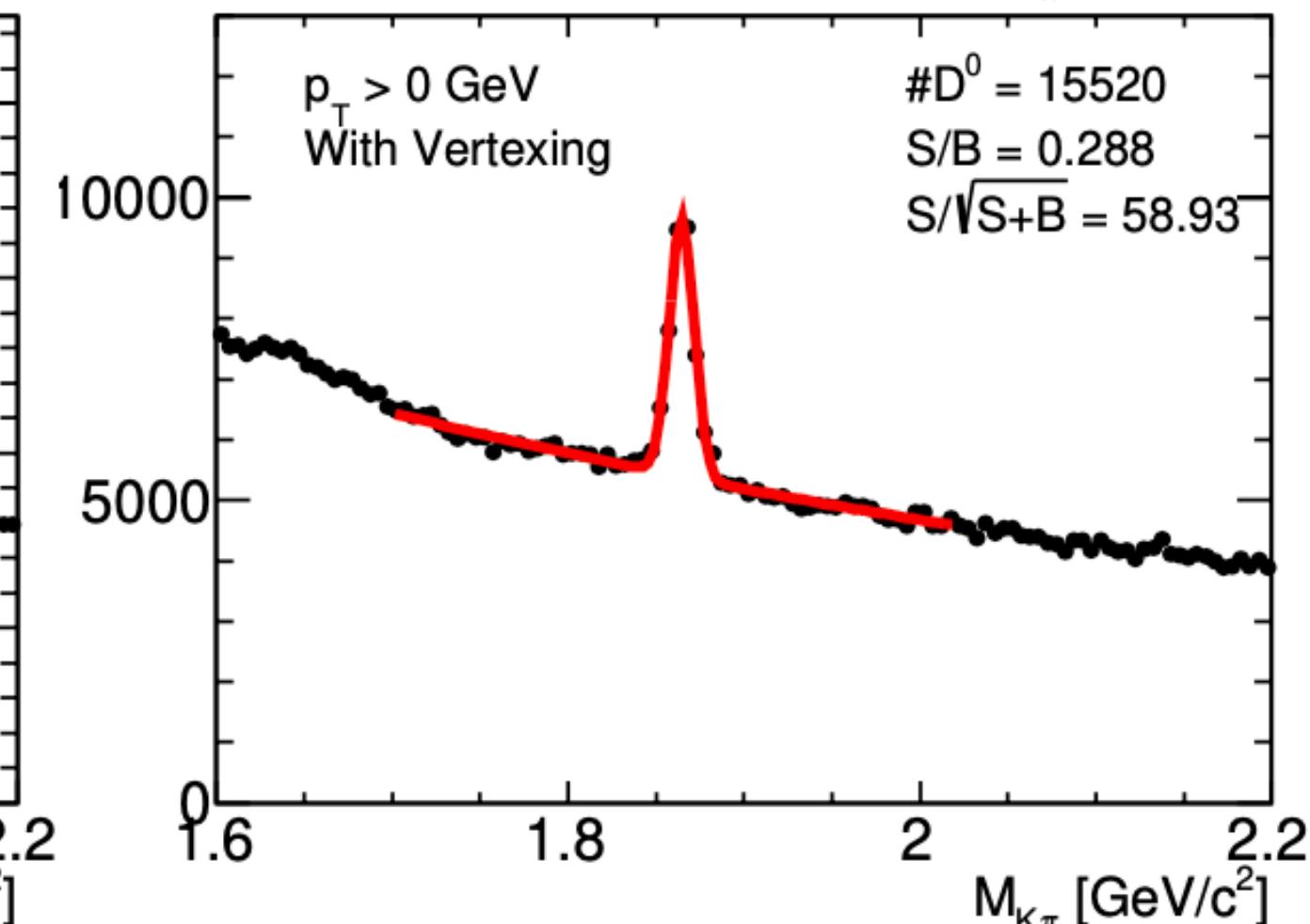
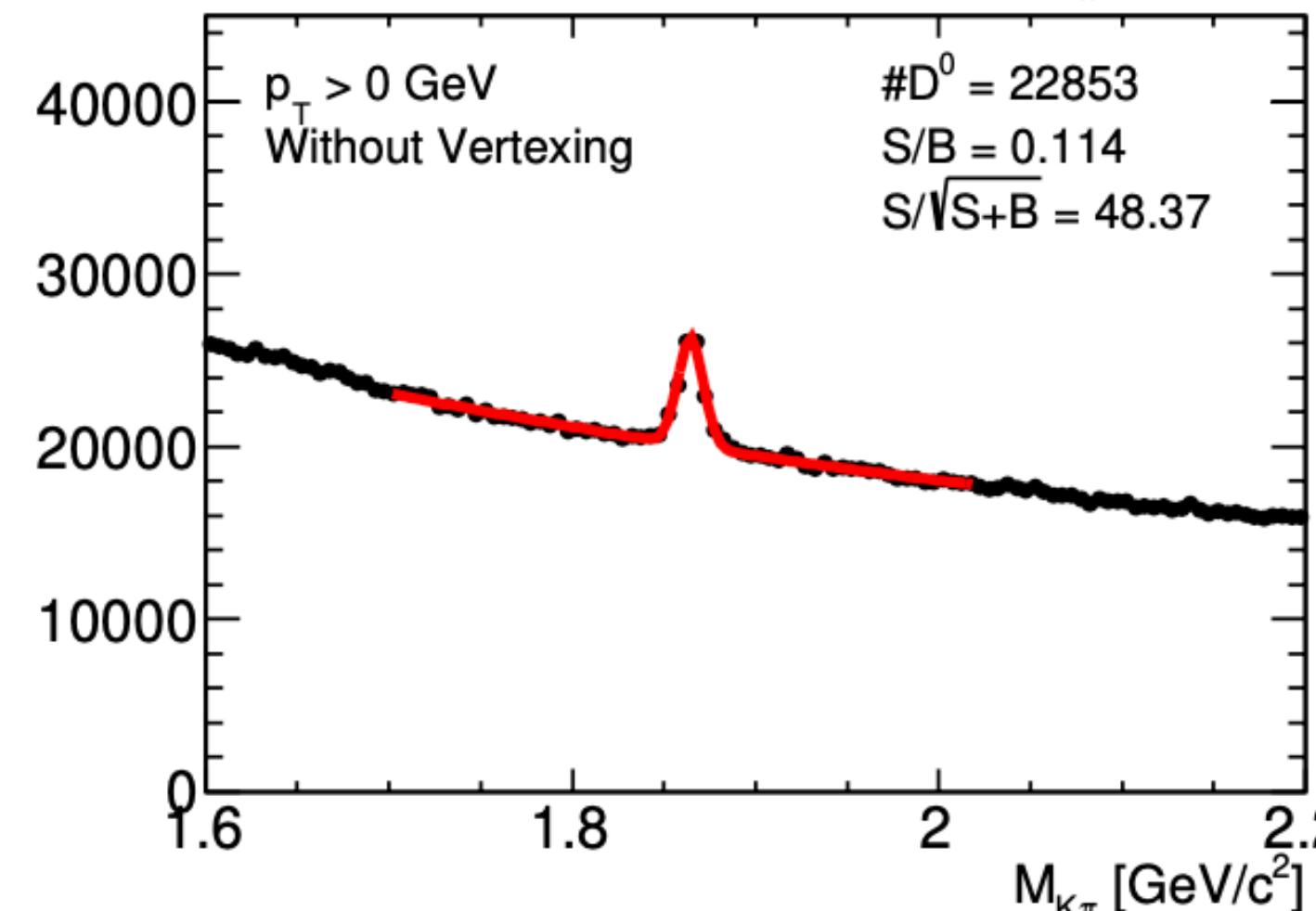
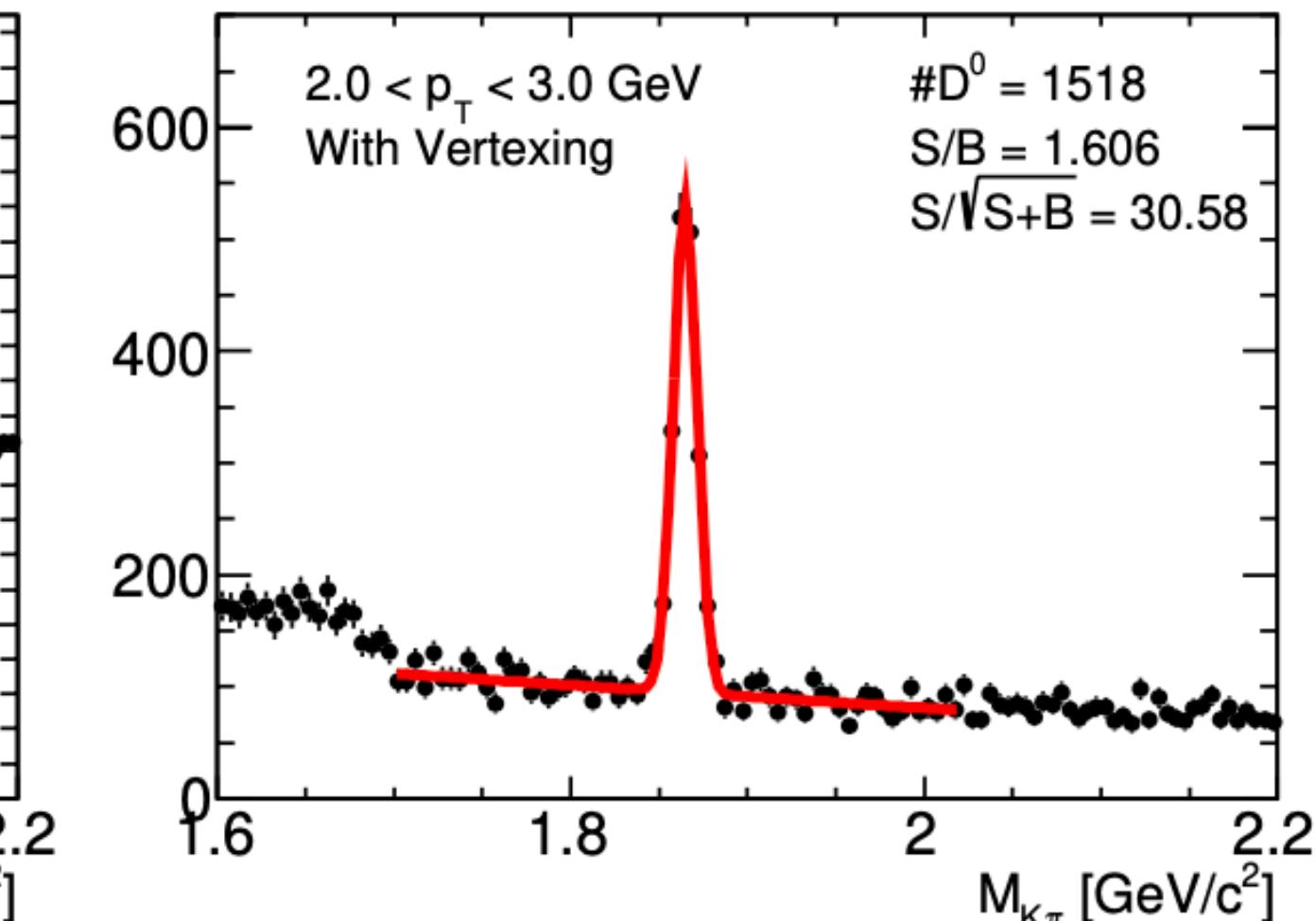
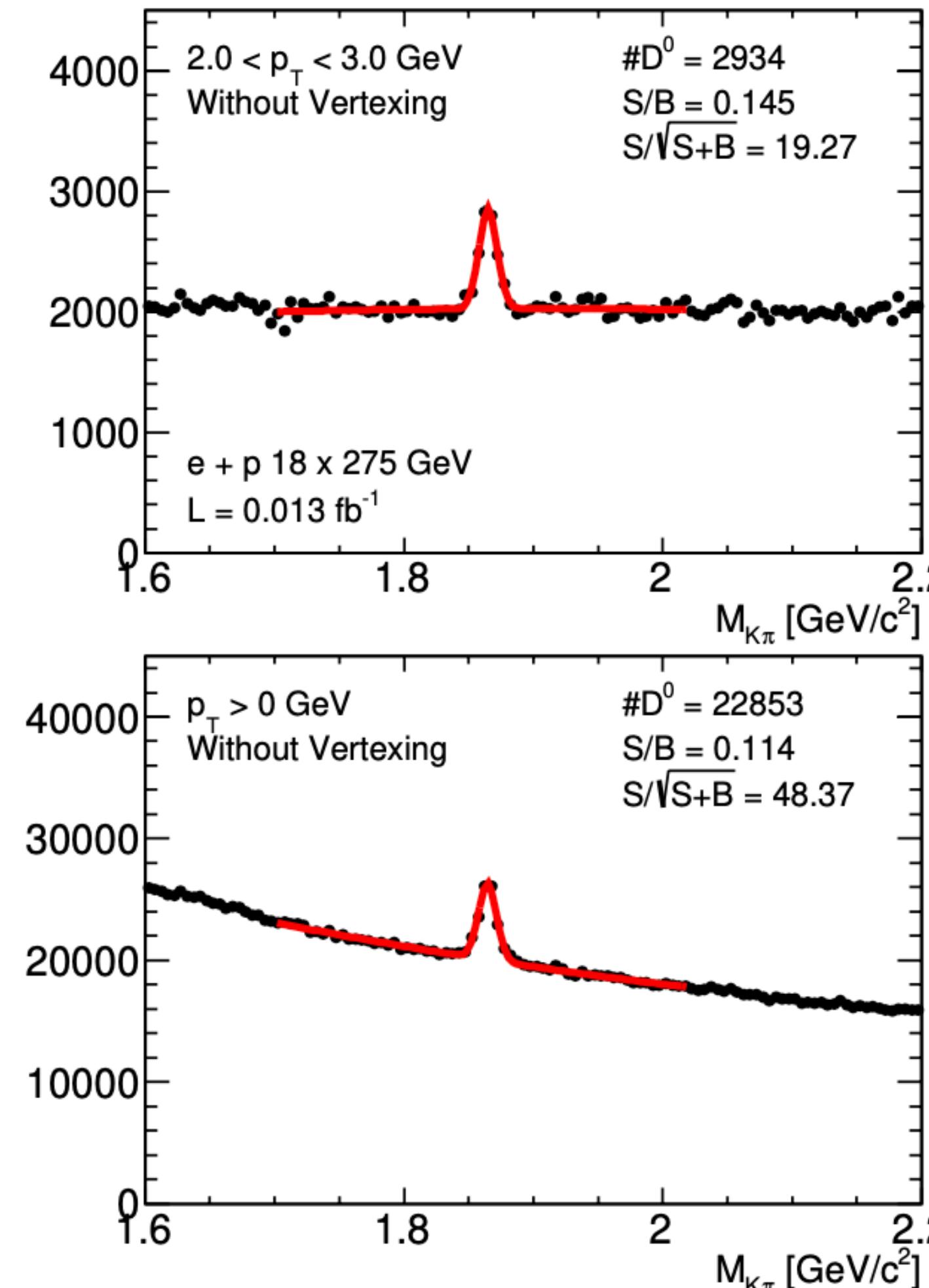
- Part of both ATHENA and ECCE proposals
- Both can provide resolutions satisfying YR requirements

Plots from EIC UG meeting August 2021

EIC Simulation Setup



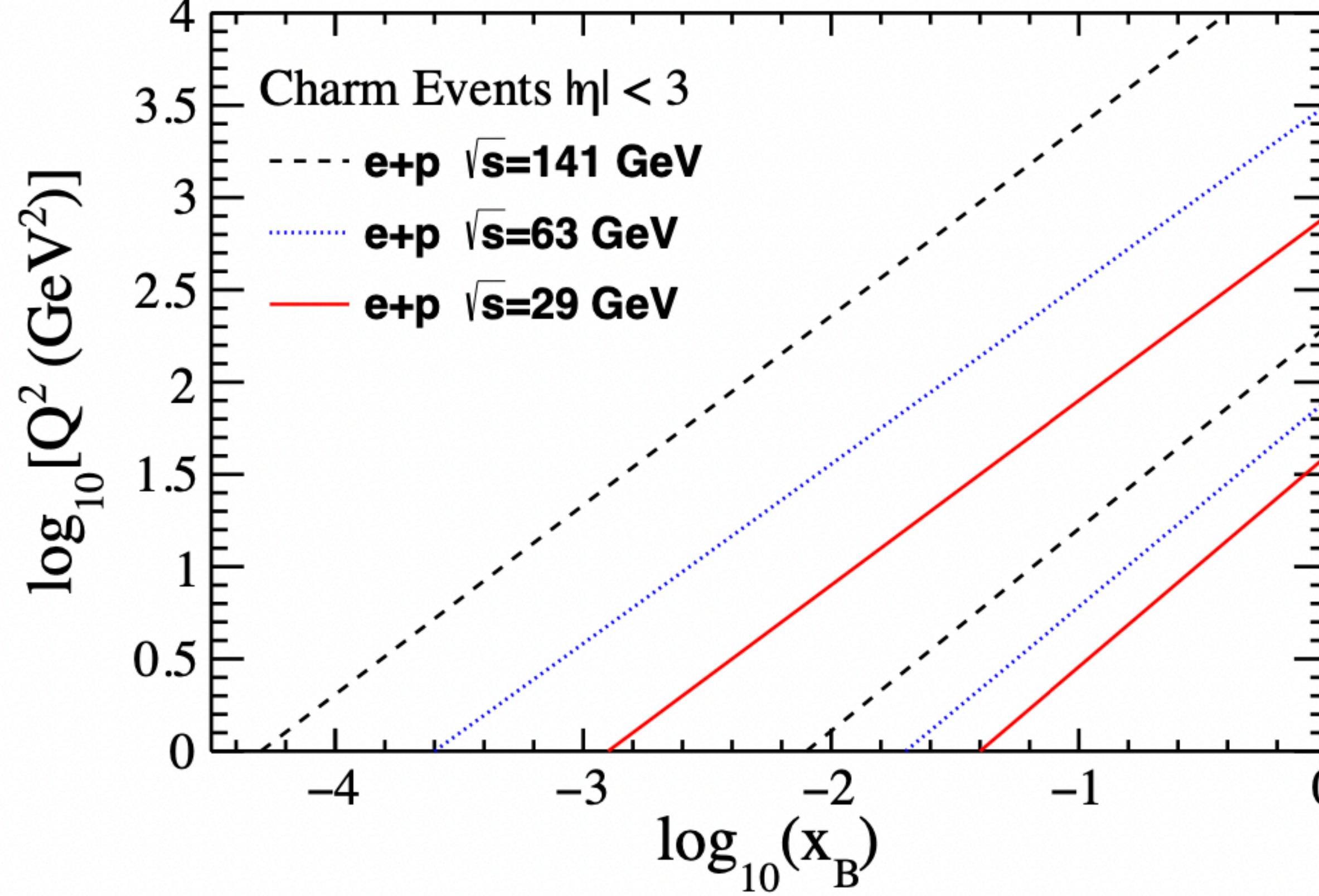
- Pythia6 EIC tune
- All-silicon tracker design composed of MAPS sensors
- 3x2 barrel layers within $|\eta| < 1$; five disks in forward and backward regions each, with coverage $1 < |\eta| < 3$
- Tracking specifications as in EIC YR
Det.Matrix: *arXiv:2102.08337*



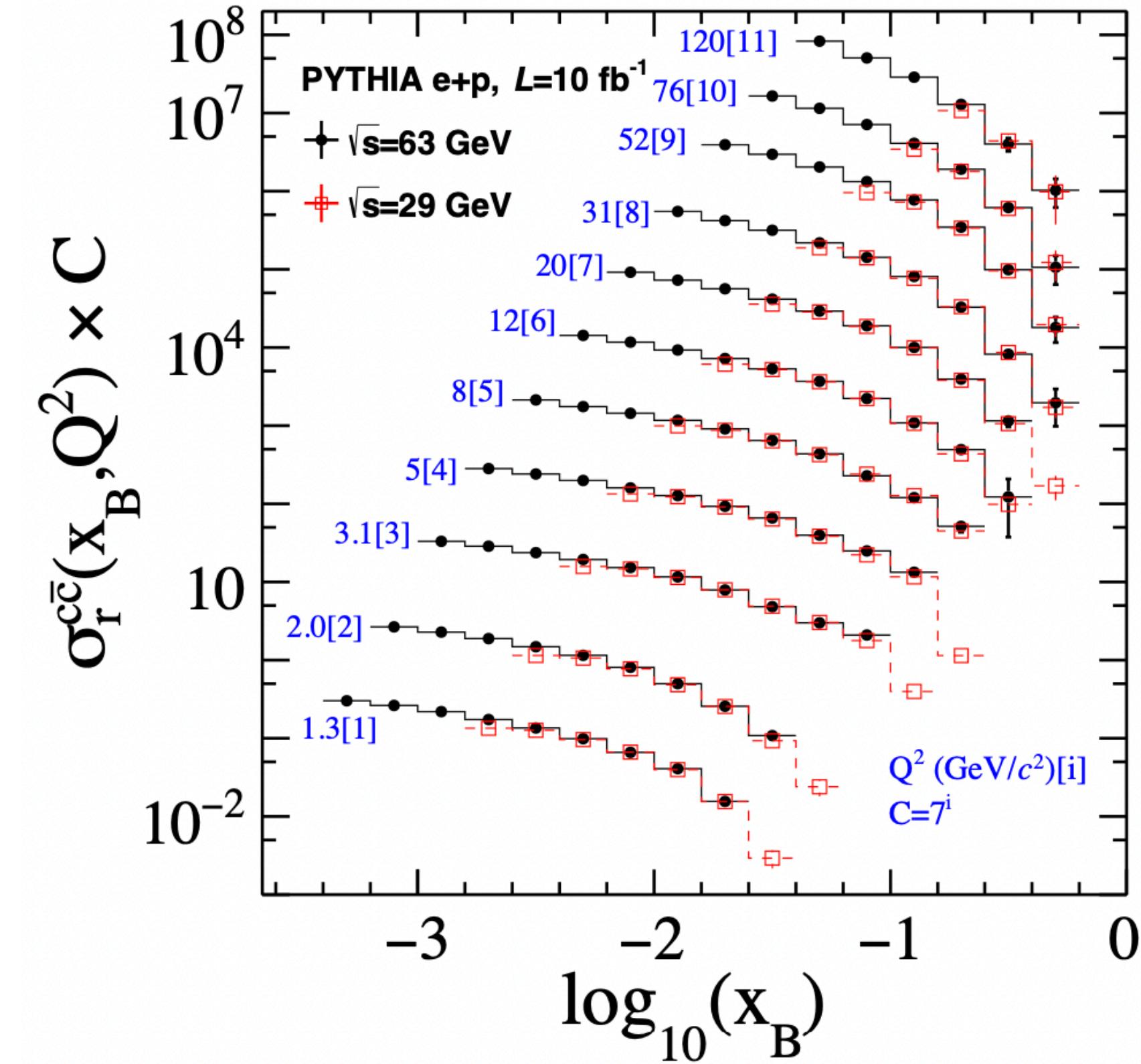
- Signal significance improves greatly with vertexing cuts

Simulation Results

Charm Cross-section and Gluon nPDF



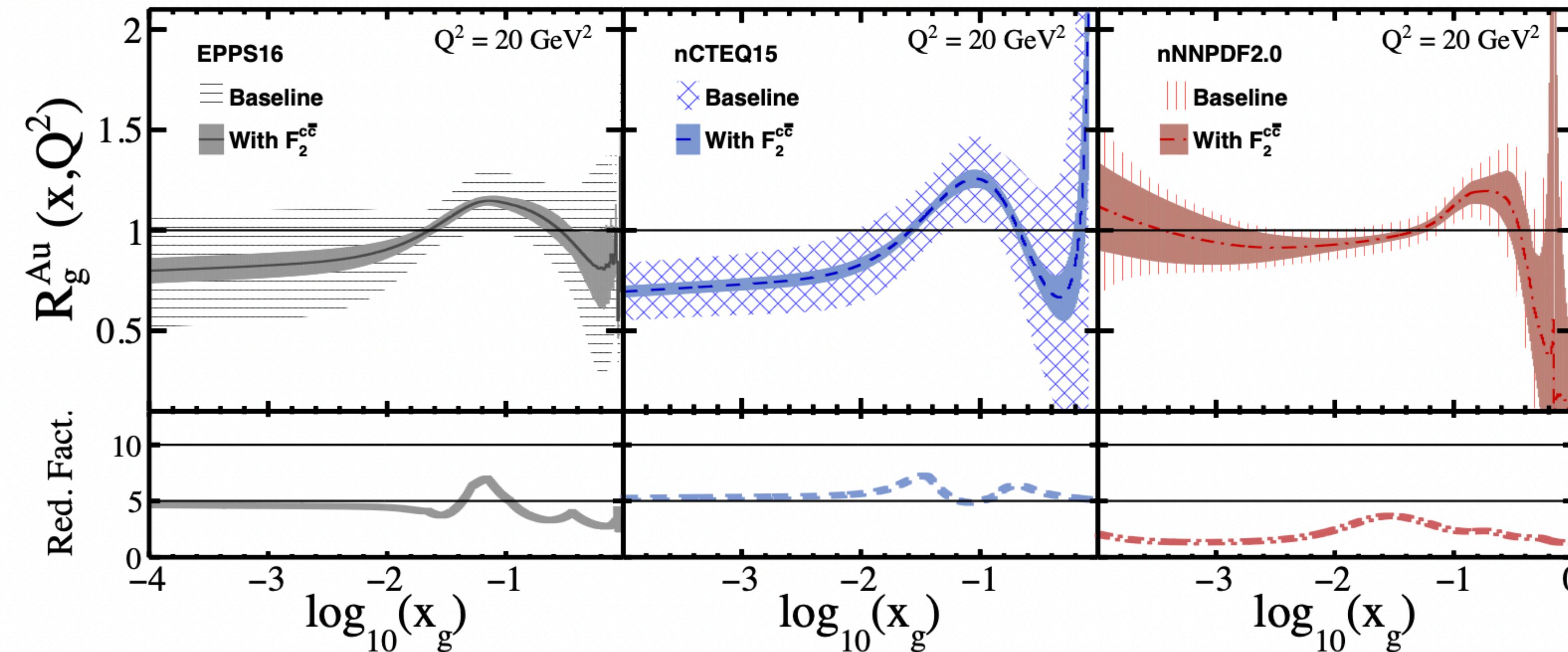
$$\sigma_r^{c\bar{c}}(x_B, Q^2) = F_2^{c\bar{c}}(x_B, Q^2) - \frac{y^2}{Y^+} F_L^{c\bar{c}}(x_B, Q^2)$$



For more details see: Phys. Rev. D 104, 054002 (2021)

- x_B - Q^2 coverage and statistical uncertainty projections for charm cross-section at EIC
- Excellent precision over a broad kinematic range. Higher x_B coverage with lower collision energies

Charm Cross-section and Gluon nPDF



For more details see: *Phys. Rev. D* 104, 054002 (2021)

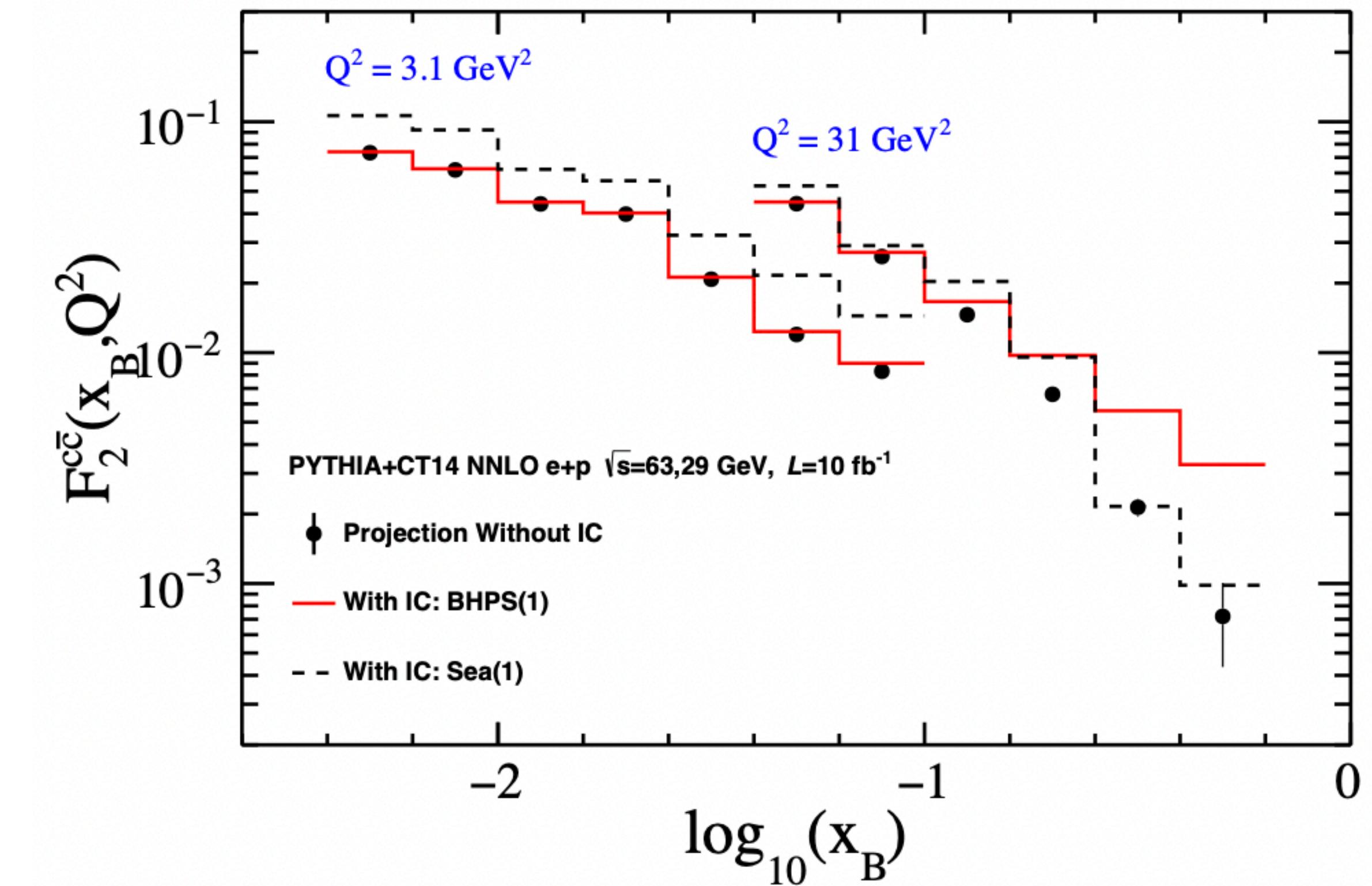
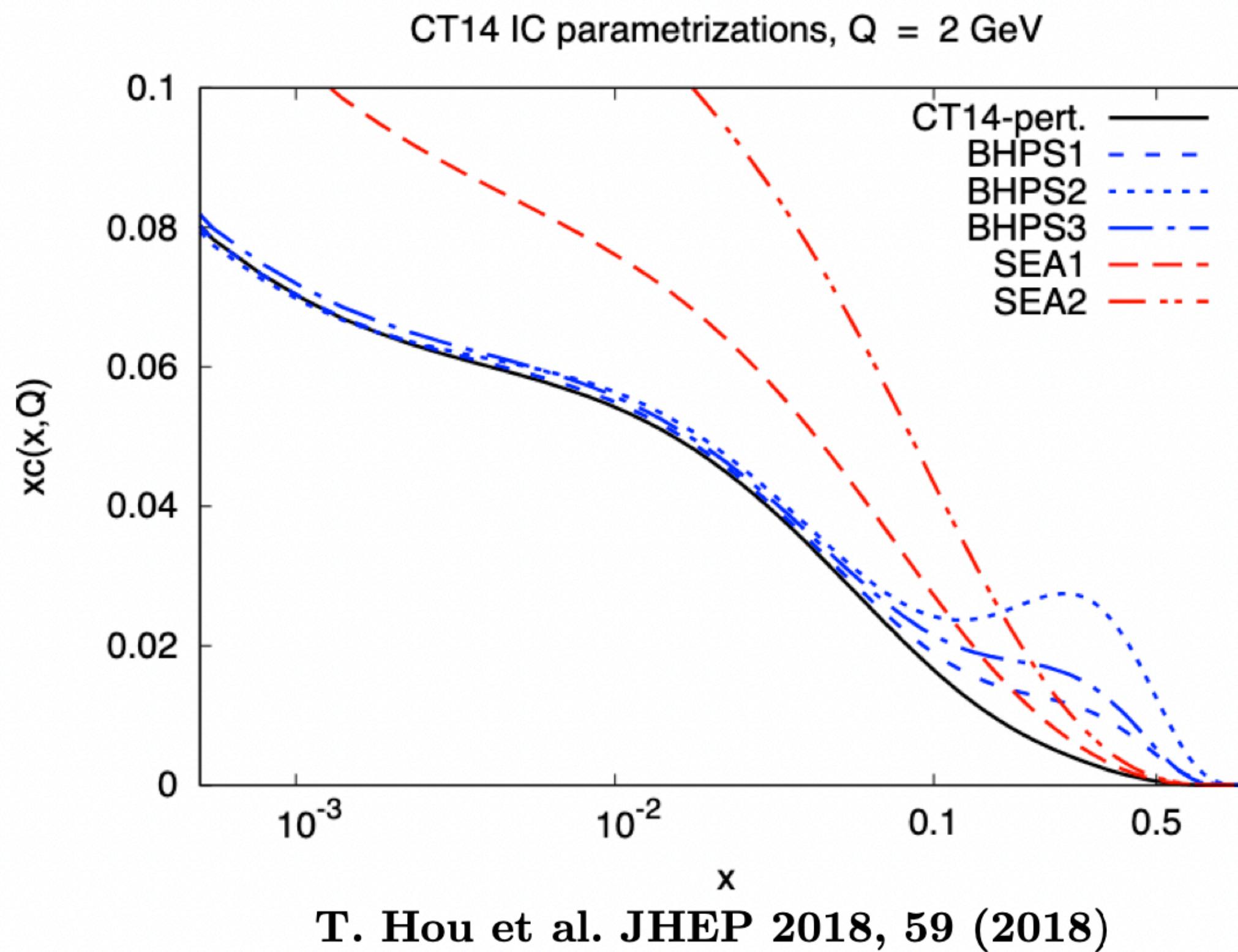
- Impact of EIC charm data evaluated by reweighting of pdfs
- Significant reduction in uncertainties with EIC data, particularly at large x_B
- Impact similar across different nPDF fits studied

$$f_k = f_0 + \sum_i \left(\frac{f_{i,+} + f_{i,-}}{2} \right) r_{k,i}$$

$$w_k = \frac{\exp[-\chi_k^2/2]}{\frac{1}{N_{rep}} \sum_k \exp[-\chi_k^2/2]}$$

$$f_{new} = f_0 + \sum_i \left(\frac{f_{i,+} + f_{i,-}}{2} \right) \left[\frac{1}{N_{rep}} \sum_k w_k r_{k,i} \right]$$

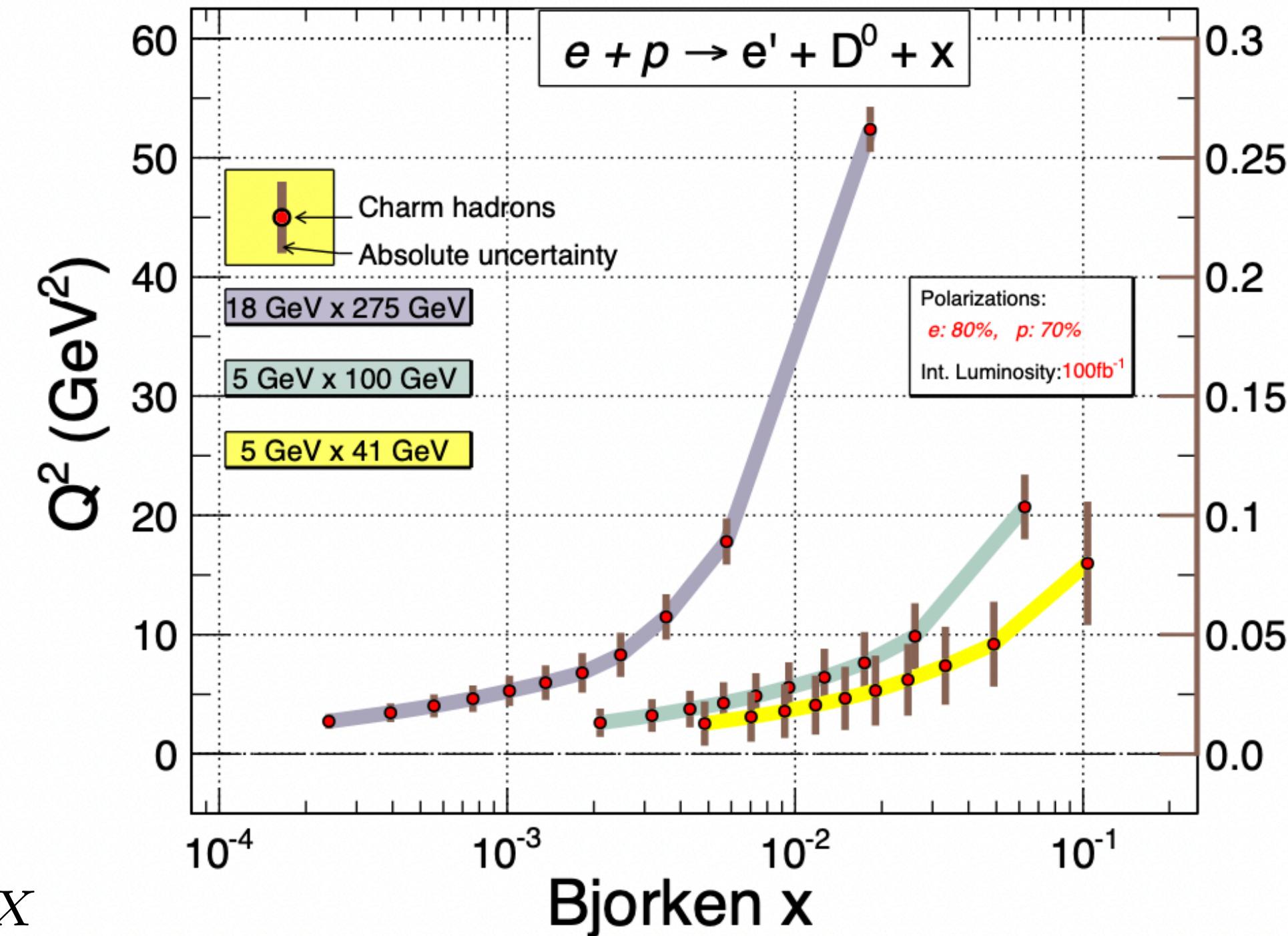
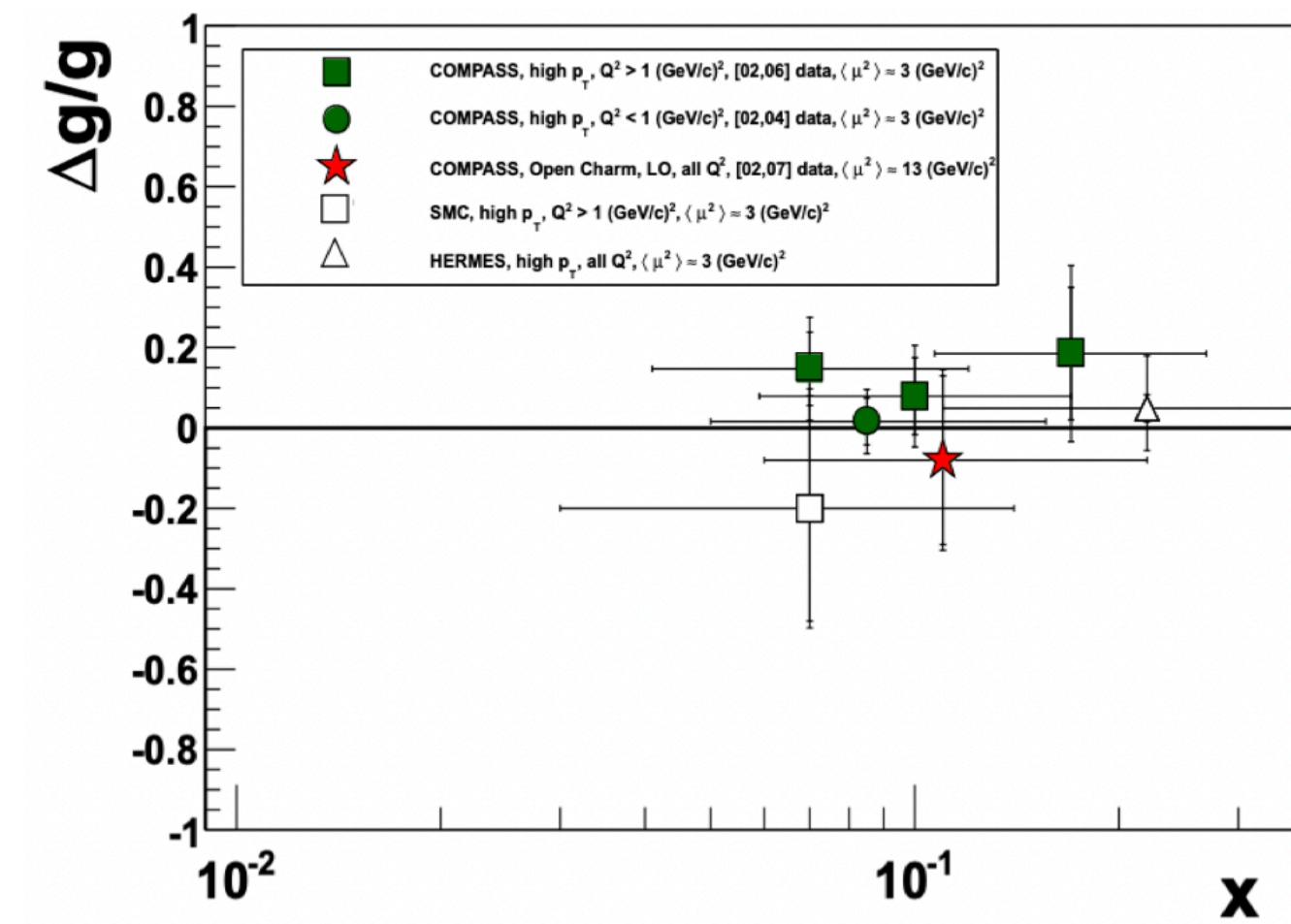
Impact of Intrinsic Charm in Proton



For more details see: Phys. Rev. D 104, 054002 (2021)

- Question of intrinsic charm in proton still an open one, different models
- EIC charm data will have sufficient precision to distinguish between different scenarios

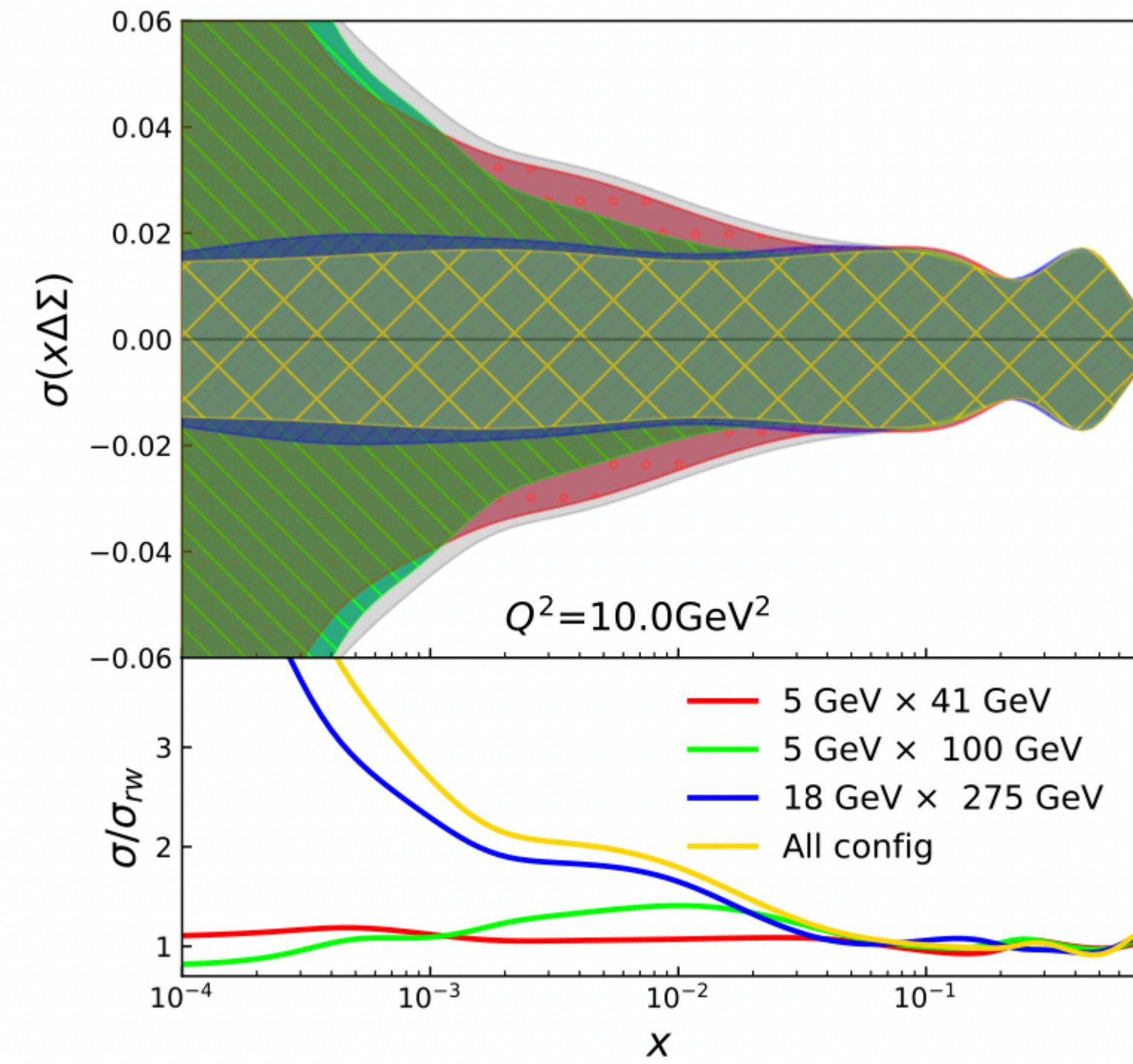
Impact on Gluon Helicity



$$A_1^c \equiv \frac{1}{D(y)} A_{LL}^{\vec{e} + \vec{p} \rightarrow e' + D^0 + X}$$

$$= \frac{1}{D(y)} \frac{1}{P_e P_p} \frac{N + + - N + -}{N + + + N + -}$$

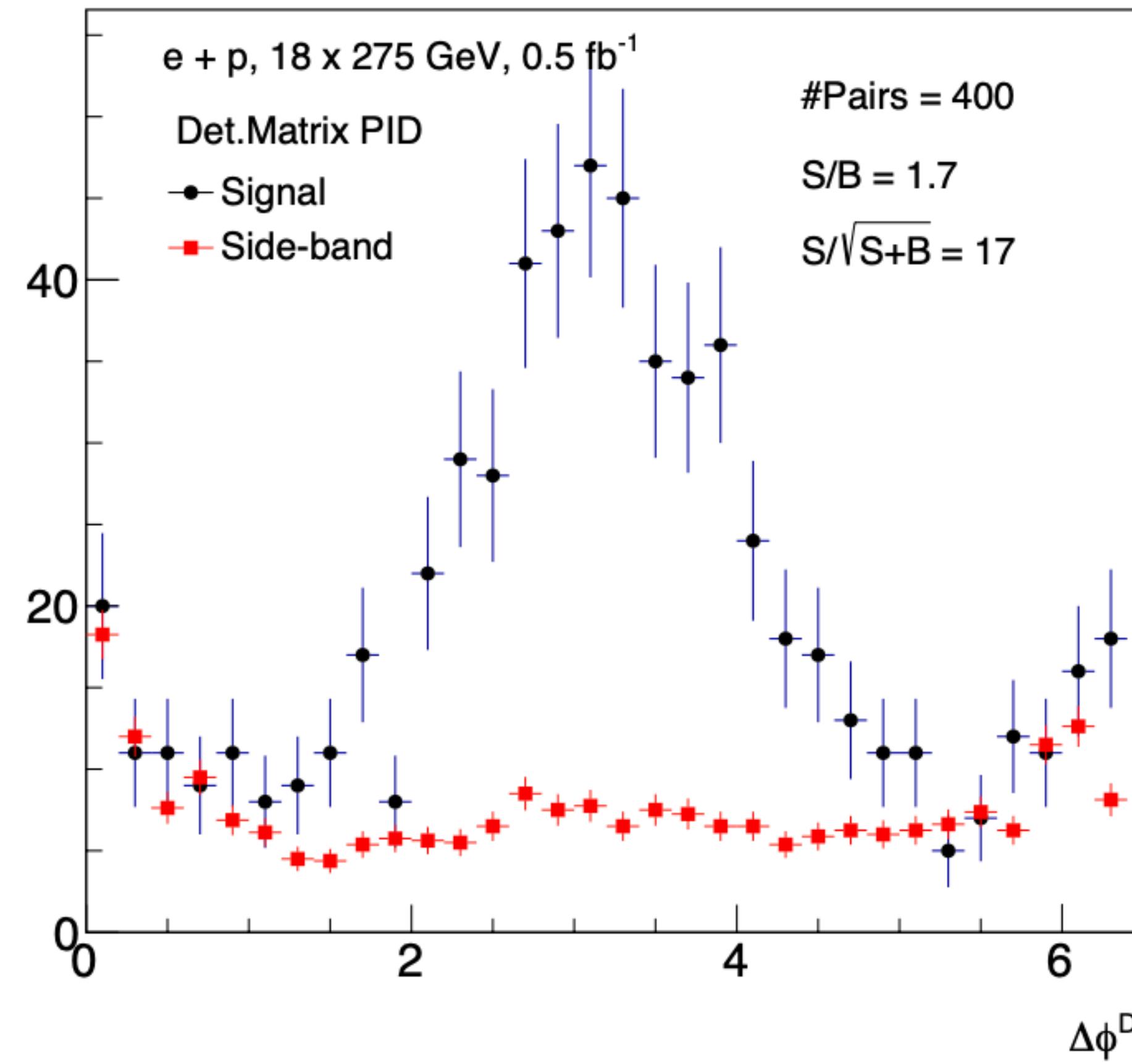
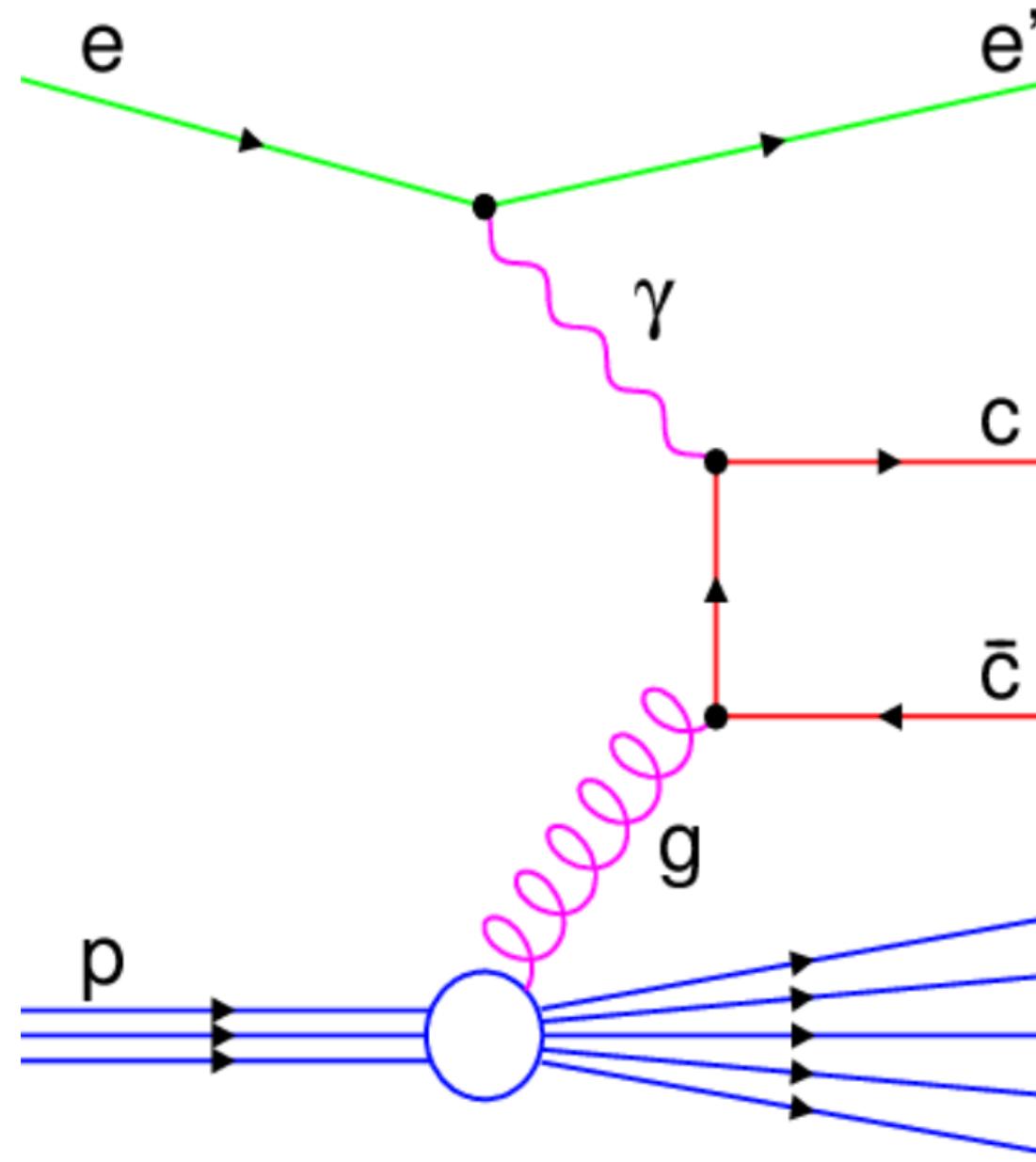
$$\propto \hat{a}_{LL} \frac{\Delta g}{g}$$



For more details see: Phys. Rev. D.104.114039 (2021)
Also EIC YR: arXiv:2103.05419

- Access to $\Delta g/g$ over a broad kinematic range
- Impact on gluon helicity distributions evaluated through pdf reweighting

D⁰ Meson Pair Reconstruction



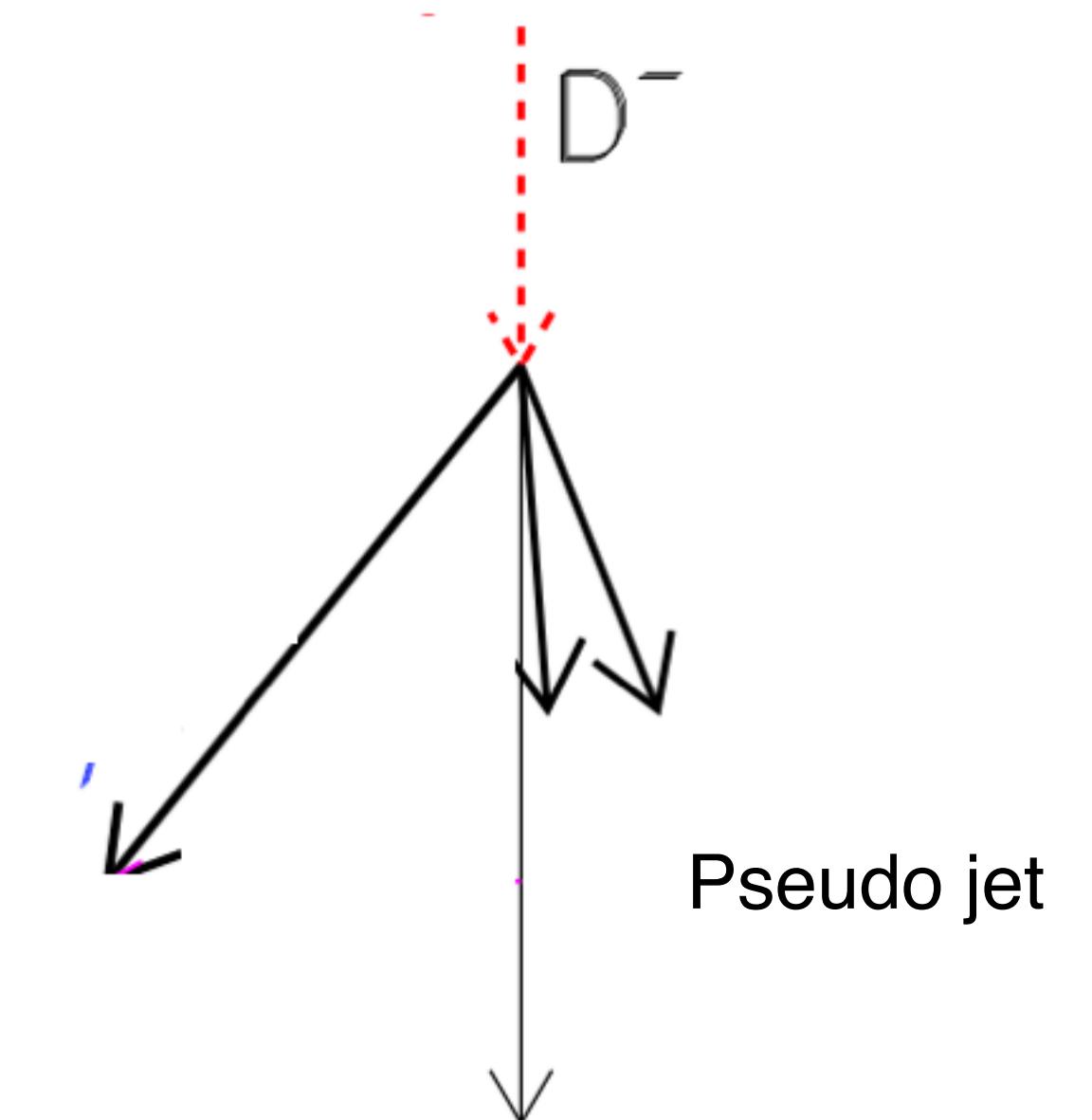
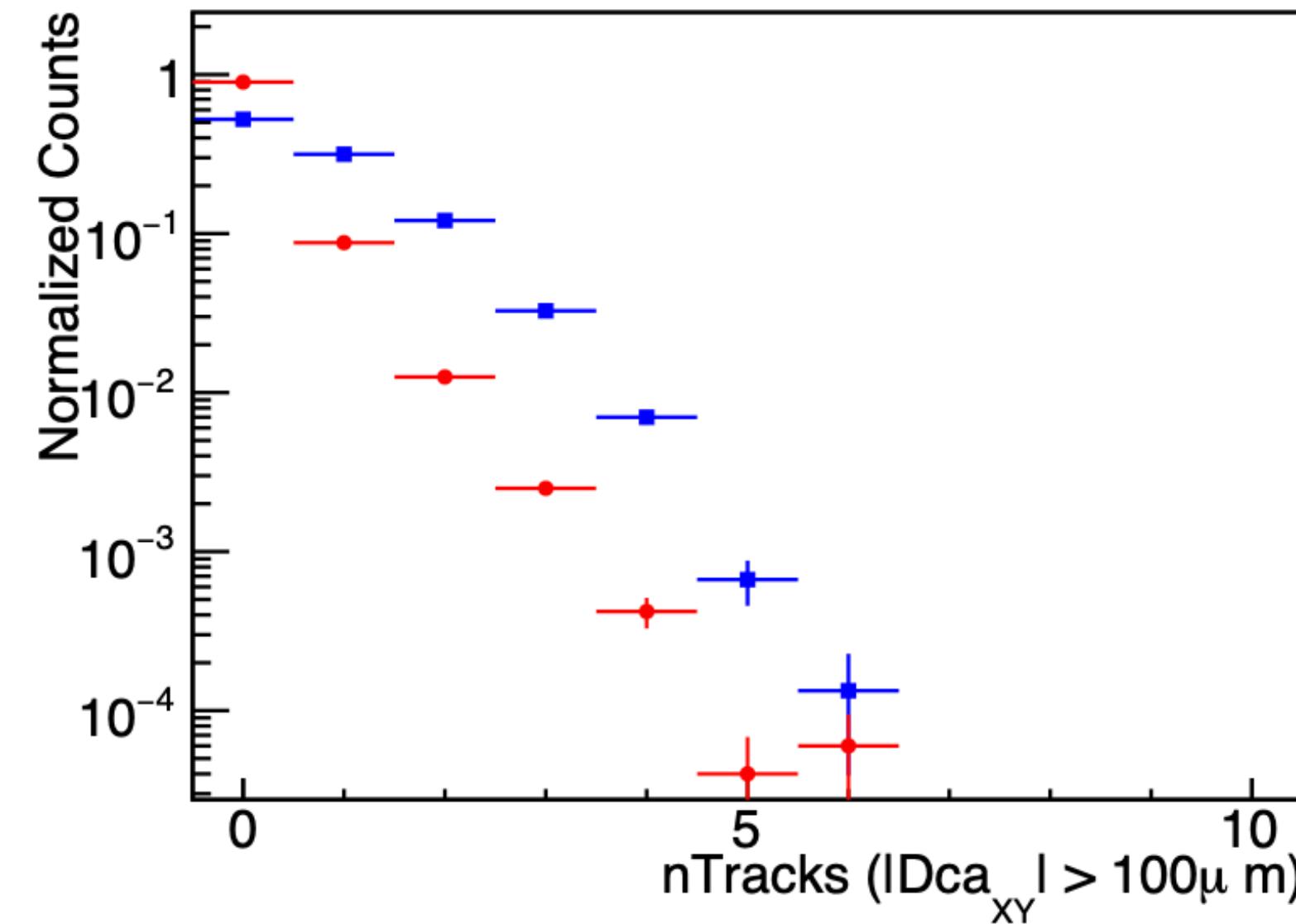
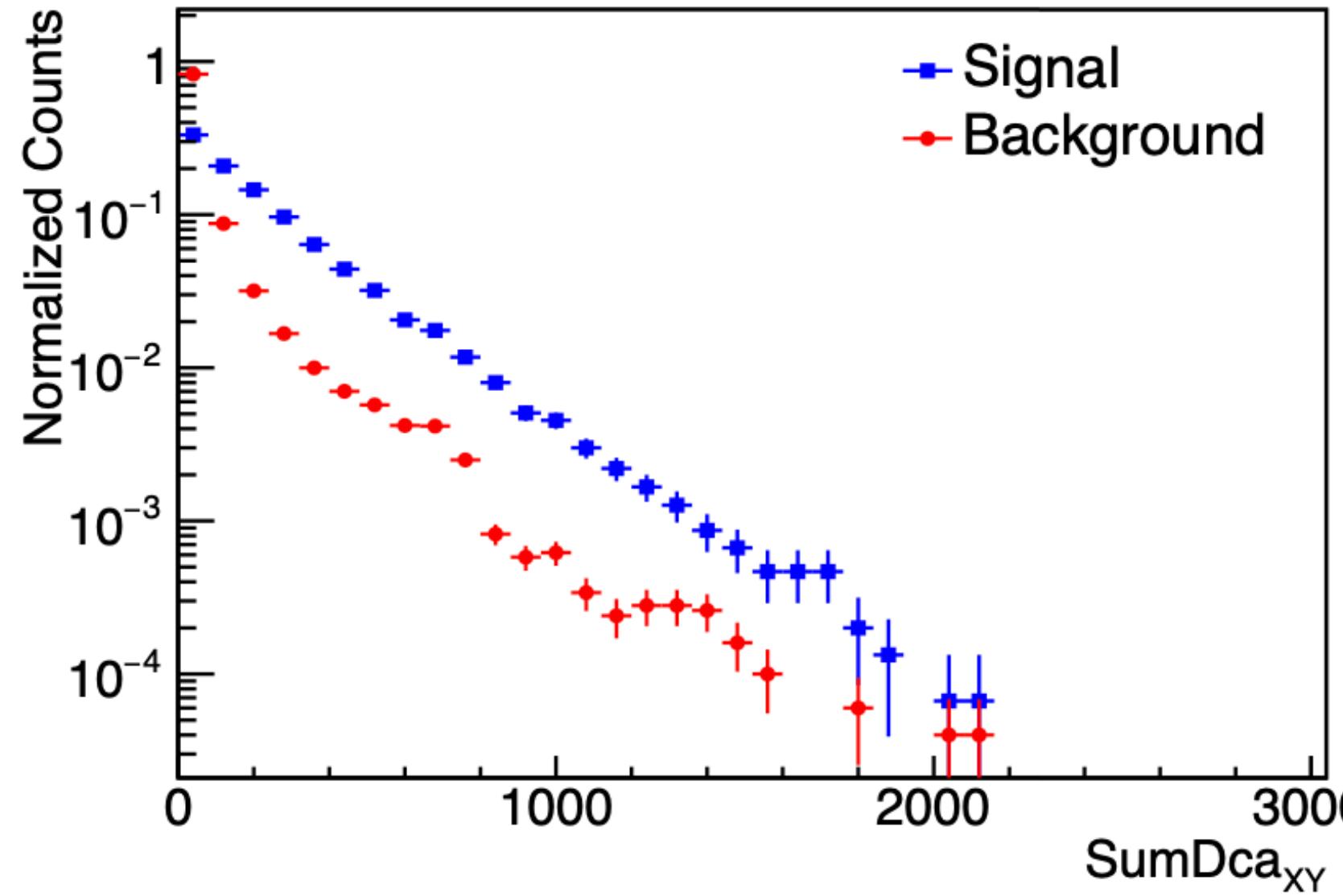
Signal: Unlike sign $K\pi$ pairs within 3σ of D^0 mass peak

Background: Unlike sign $K\pi$ pairs within 6 to 12σ on either side of D^0 mass peak

- Heavy flavor hadron pair reconstruction gives access to gluon transverse kinematics
—> direct probes of gluon TMDs
- Good signal to background ratio and signal significance for D meson pair reconstruction

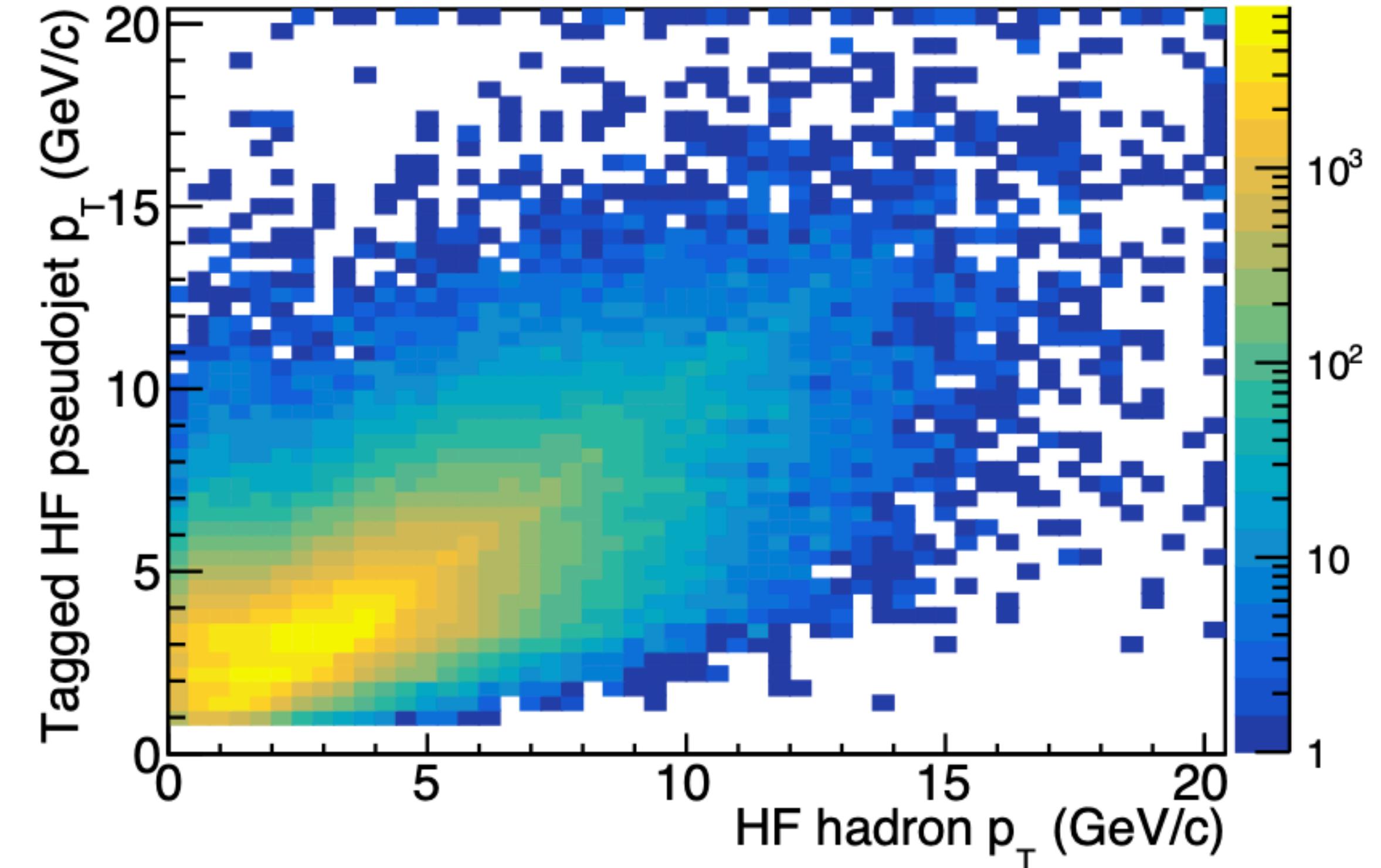
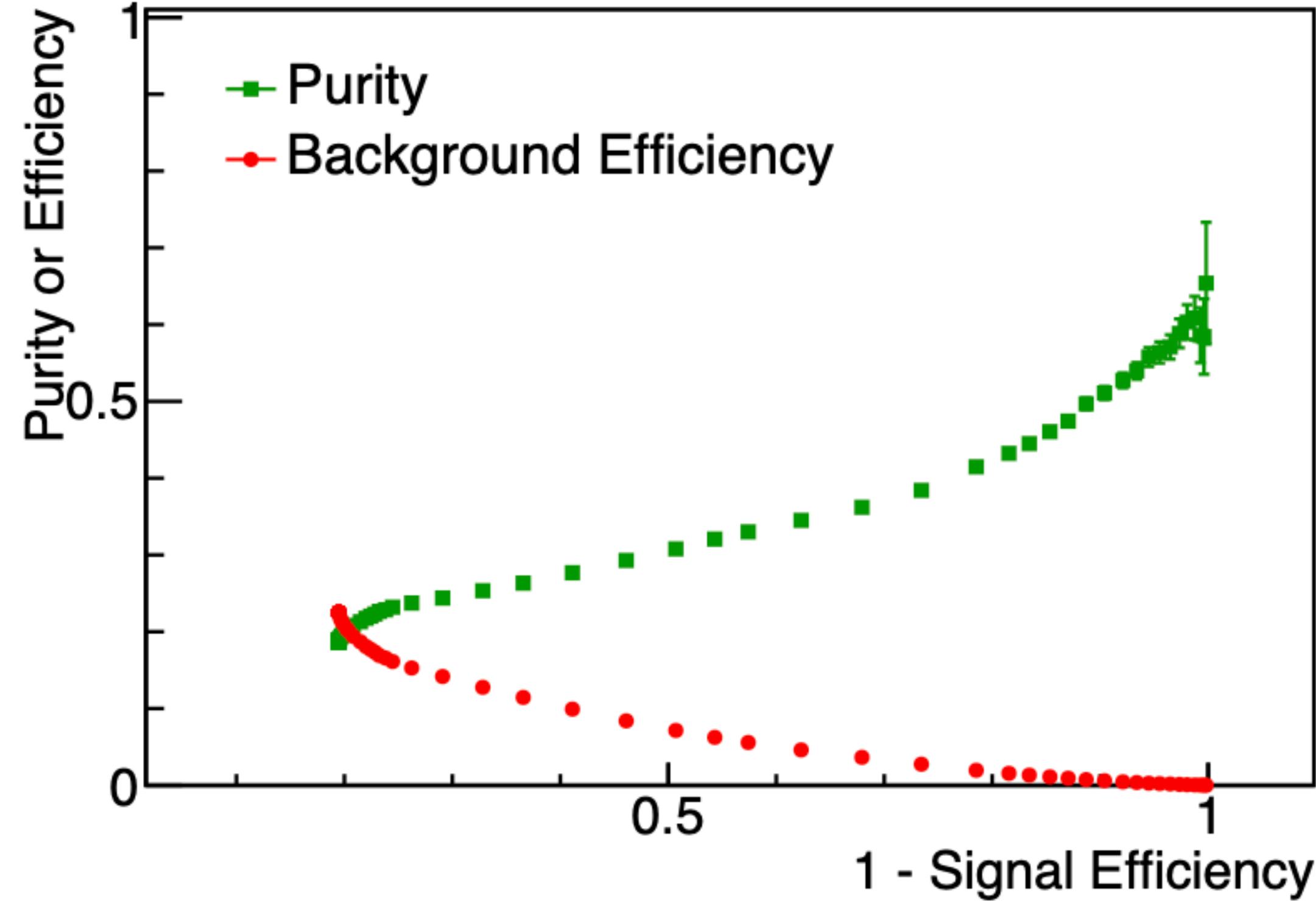
Heavy Flavor Tagging

- Exclusive reconstruction suffers from low branching ratios, ~3% for $D^0 \rightarrow K\pi$
- Utilize HF hadron decay topology to tag heavy flavor hadrons



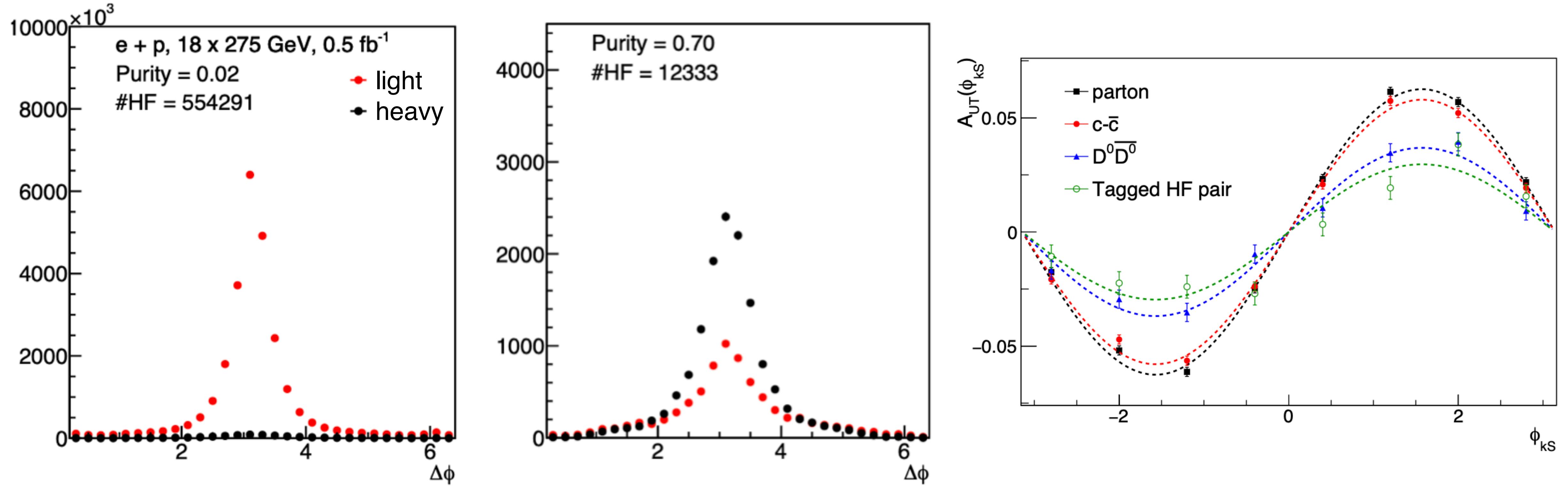
- Used Fastjet package for clustering, Anti- k_T with $R = 1.0$
- Construct topological variables for jets from constituent tracks. Excellent signal to background separation
- Different jet variables combined using Boosted Decision Trees
- Truth tagging: if parent HF hadron momentum falls within jet cone, tag it HF jet

Heavy Flavor Tagging Performance



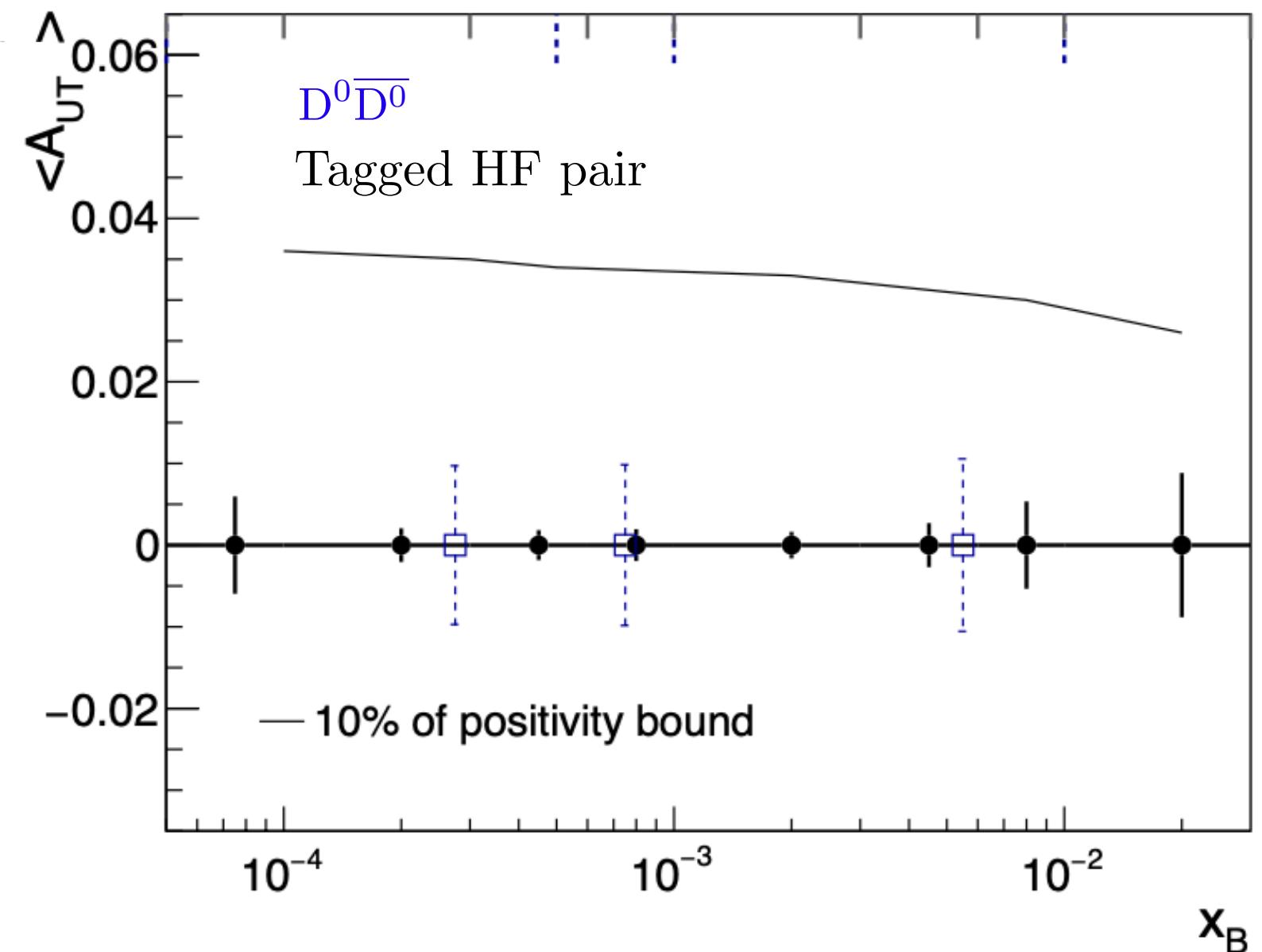
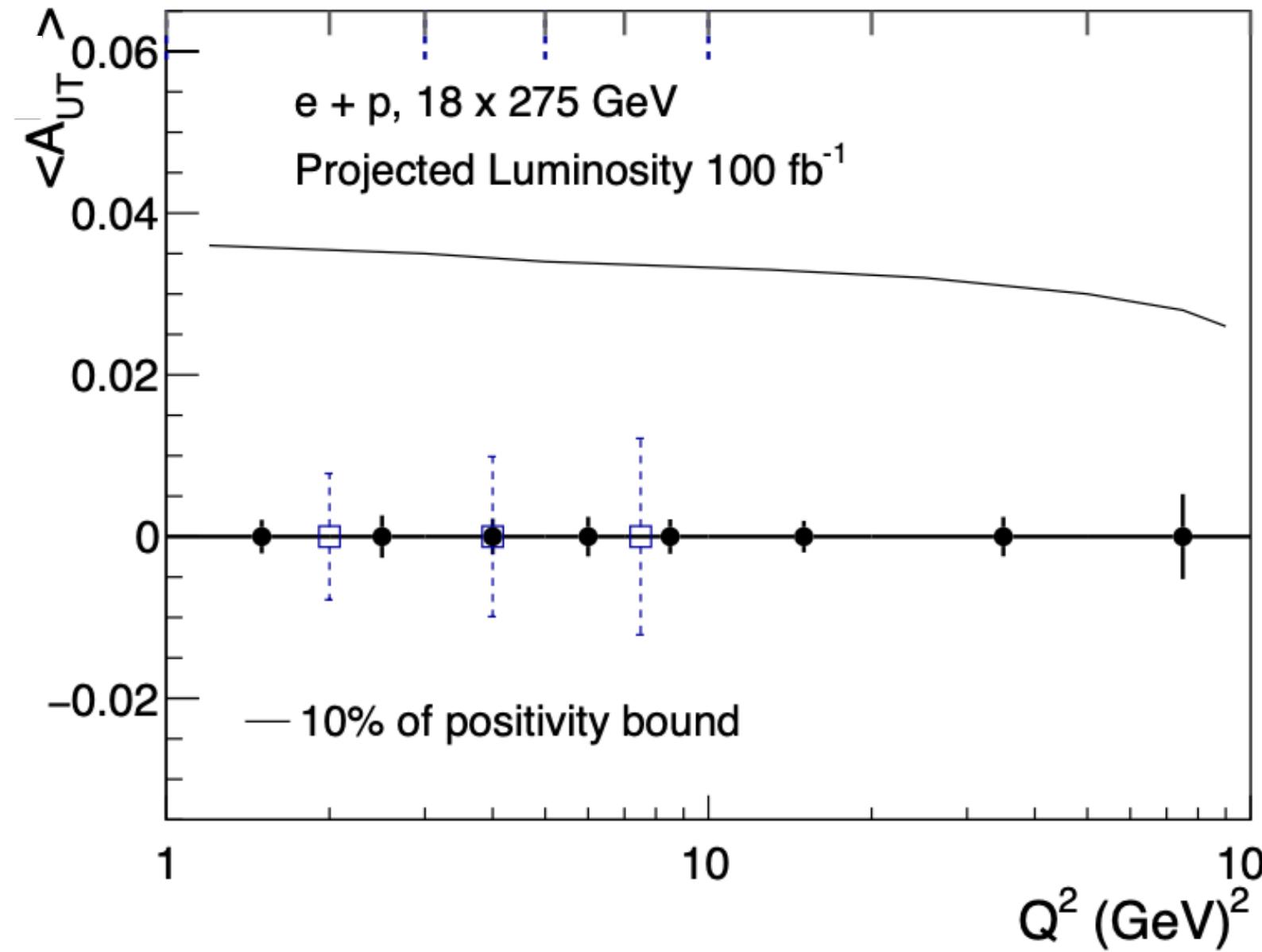
- About 60% purity at 10% signal efficiency for single jet tagging
- Good correlation between reconstructed jet and hadron momenta

Heavy Flavor Tagging Performance



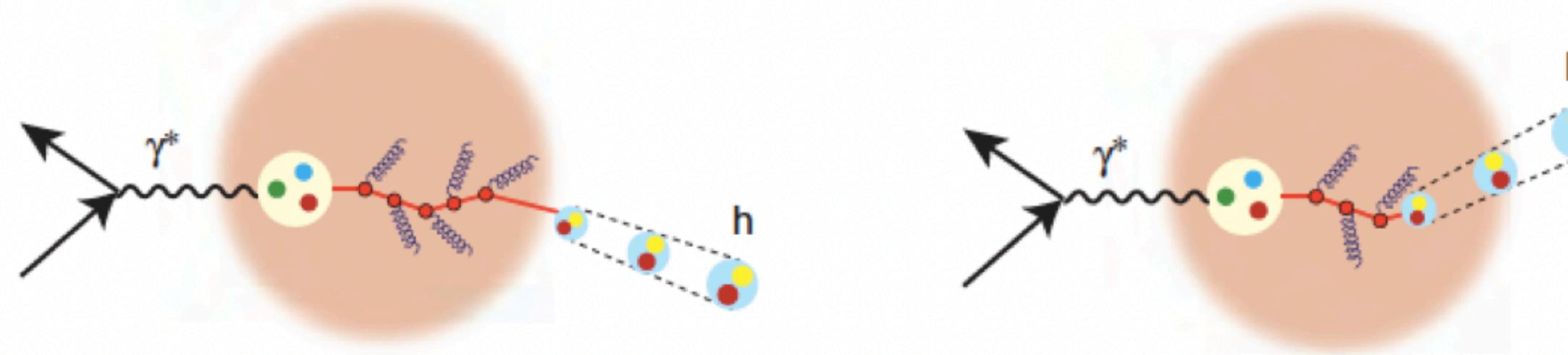
- Purity for HF pair selection improves from 2% to 70% with topological selection
- Gains substantially in statistics
- Initial transverse SSA at gluon level is preserved at final hadron level and for tagged HF jet pairs. Dilution of signal, ~50%

Projections for gluon TMD measurements

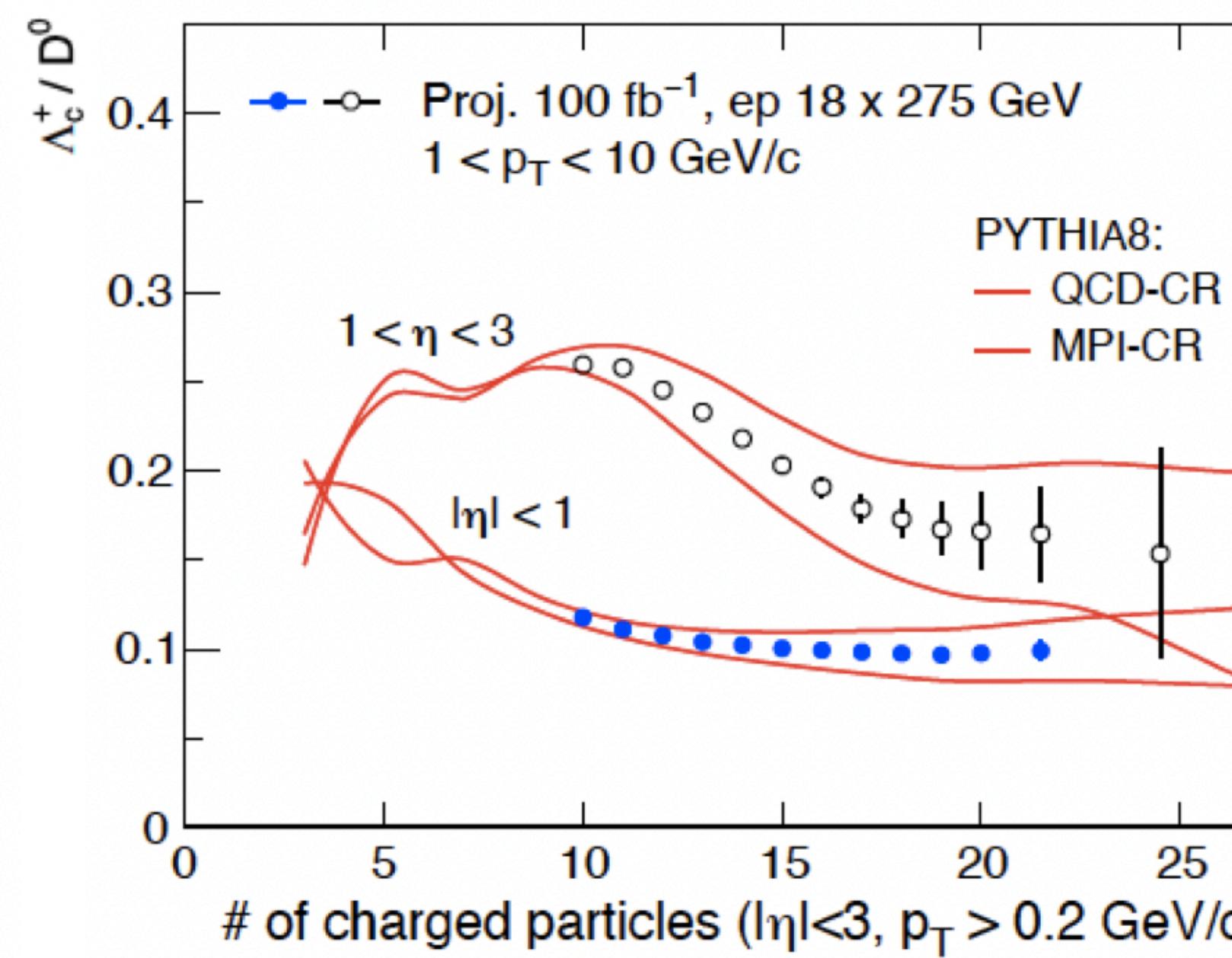
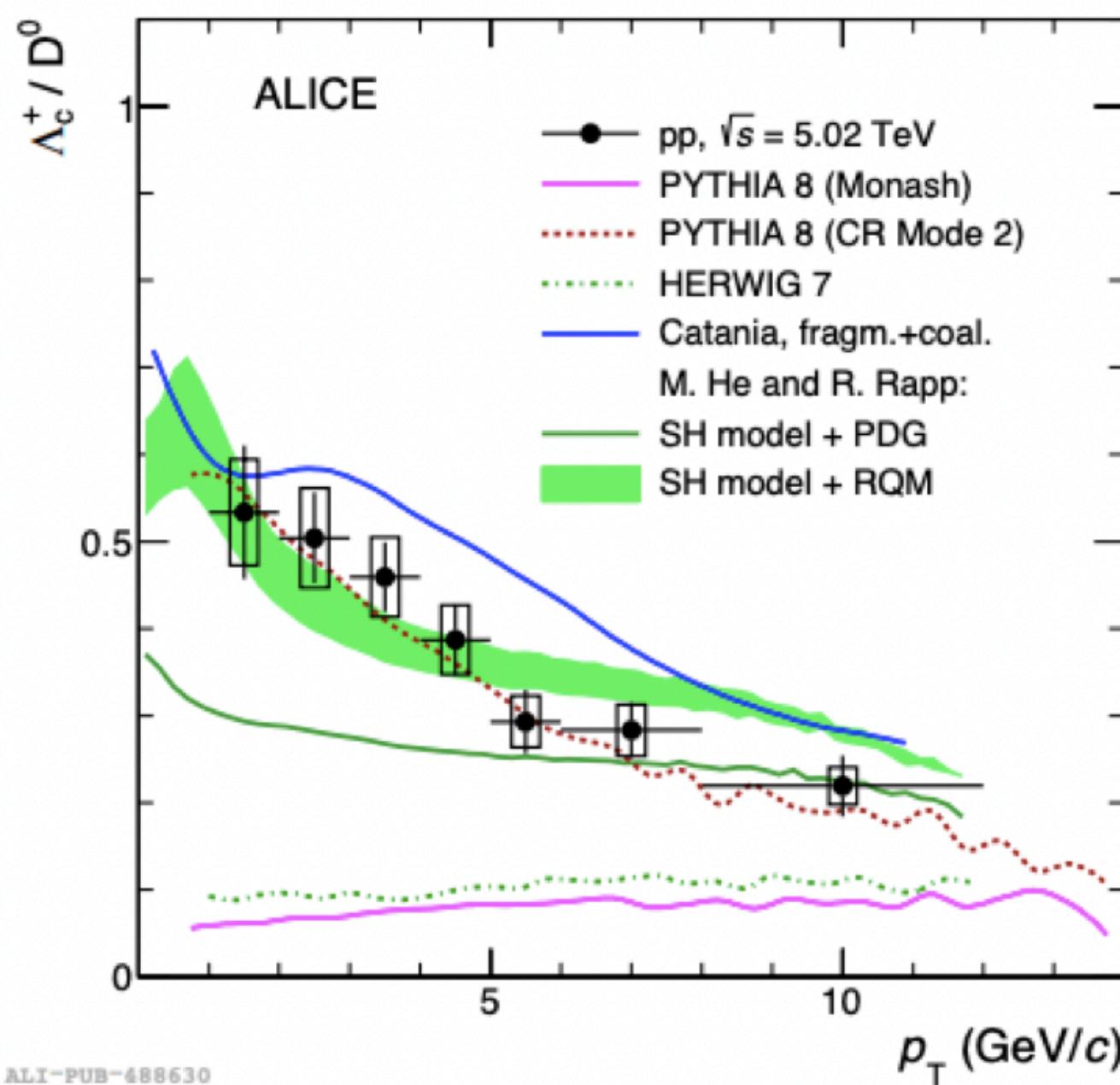
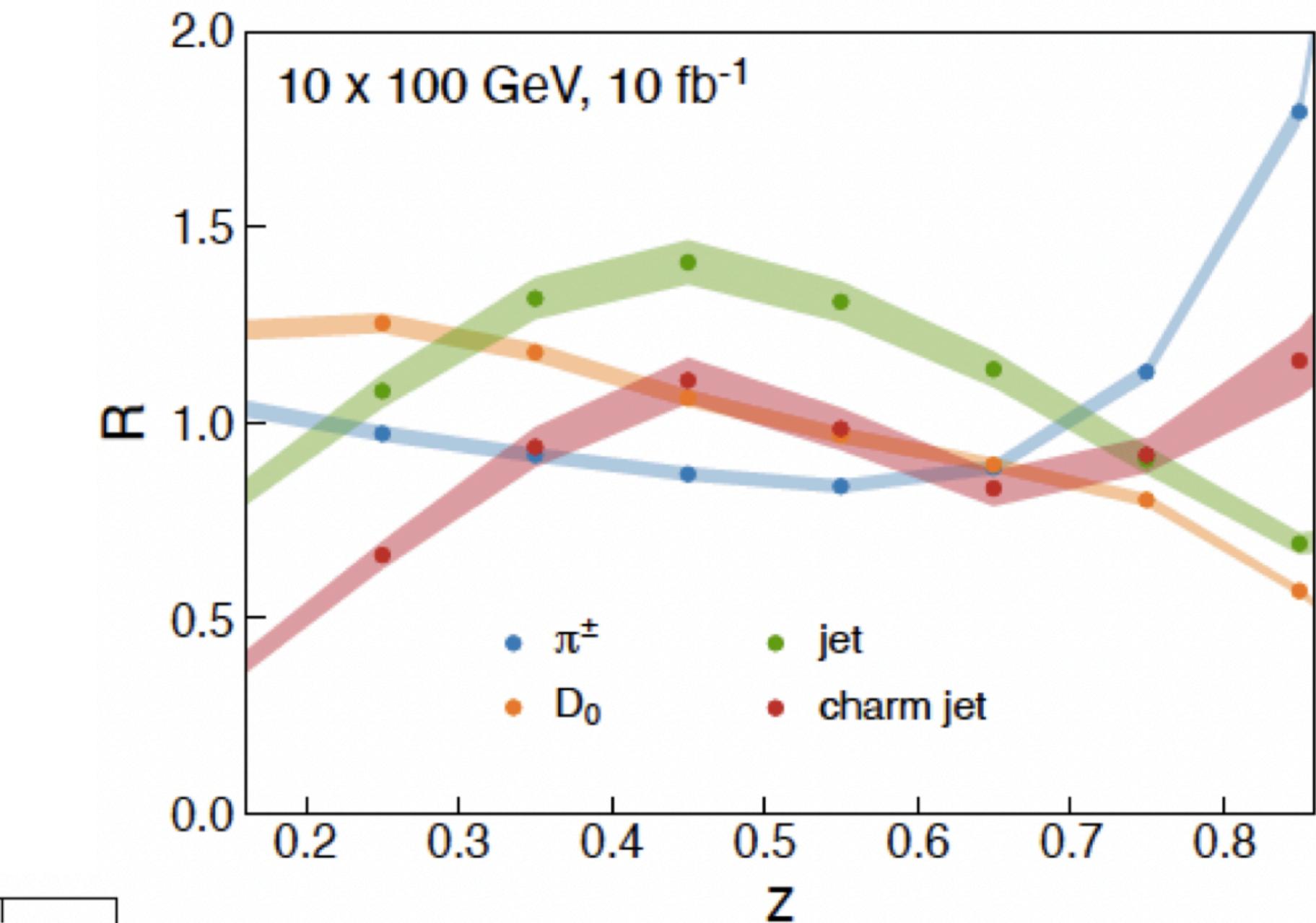


- For gluon Sivers asymmetry:
Statistical uncertainty projections for transverse SSA A_{UT} with tagged HF pair:
$$\delta A_{UT}^{HF} = \delta A_{UT}^{\text{measured}} / \text{purity} / \text{Polarization}$$
- Far improved (nearly an order of magnitude) improved precision for A_{UT}^{HF} measurements with tagged HF compared to using D \bar{D}
- Linearly polarized gluon TMD can also be measured using transverse anisotropy. Similar error bars, but without dilution from polarization
- Tagging can significantly help other measurements also: other gluon TMDs, interactions with nuclear matter etc

Study hadronization using HF hadrons



- Can study hadronization through modification of fragmentation in presence of nuclear matter
- Good precision for HF measurements



- Systematic study of production of charm baryon states to understand different hadronization schemes

Summary and Outlook

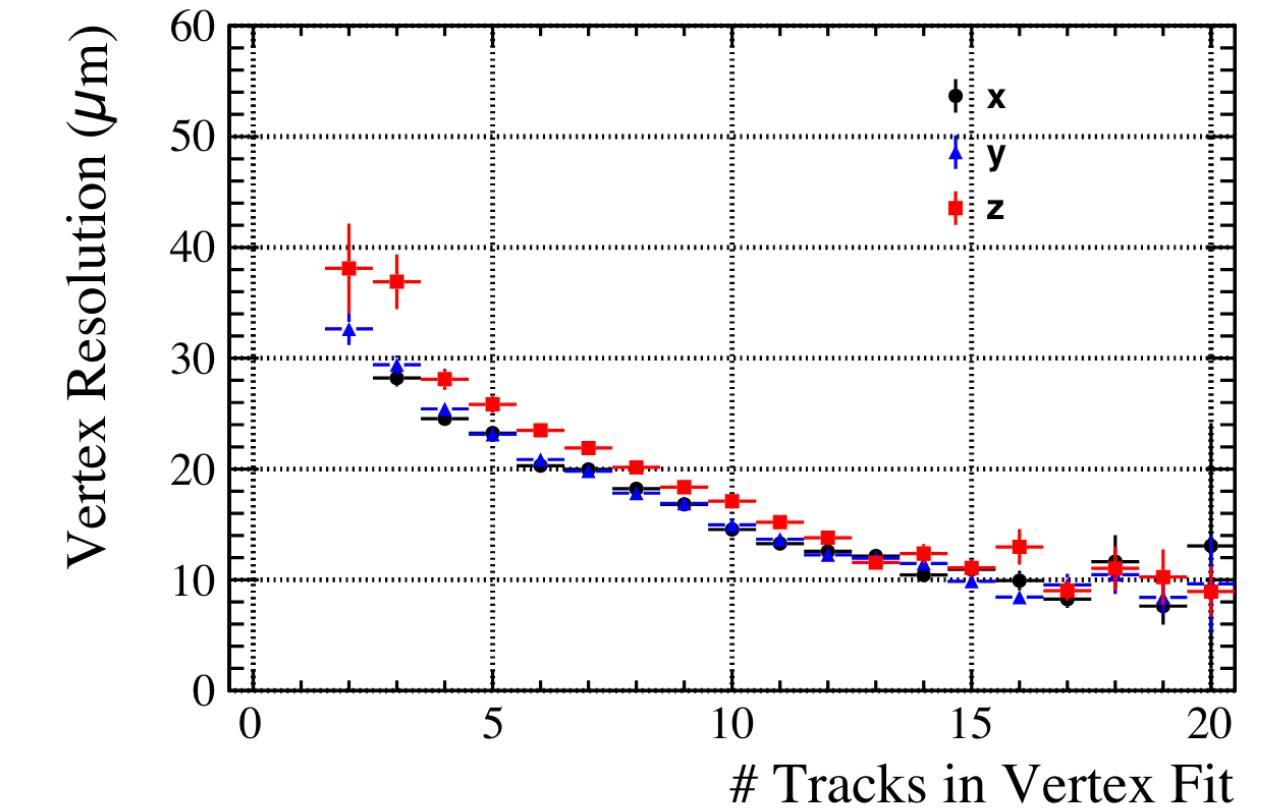
- Heavy quark production offers a clean channel to study gluon distributions at the EIC
- A MAPS-based silicon tracker experiment at EIC will enable precision measurements
 - Significantly improves constraints on gluon nPDFs, gluon helicity distributions, intrinsic charm PDF and gluon TMDs with EIC data
- Topological tagging of HF hadron decays can be done with good purity and efficiency
 - HF pair signal purity can be improved substantially, from $\sim 2\%$ to $\sim 70\%$
 - Improves precision of gluon TMD measurements using HF substantially
- High precision for HF measurements allows study of hadronization through fragmentation modification and heavy flavor baryon measurements

Back Up

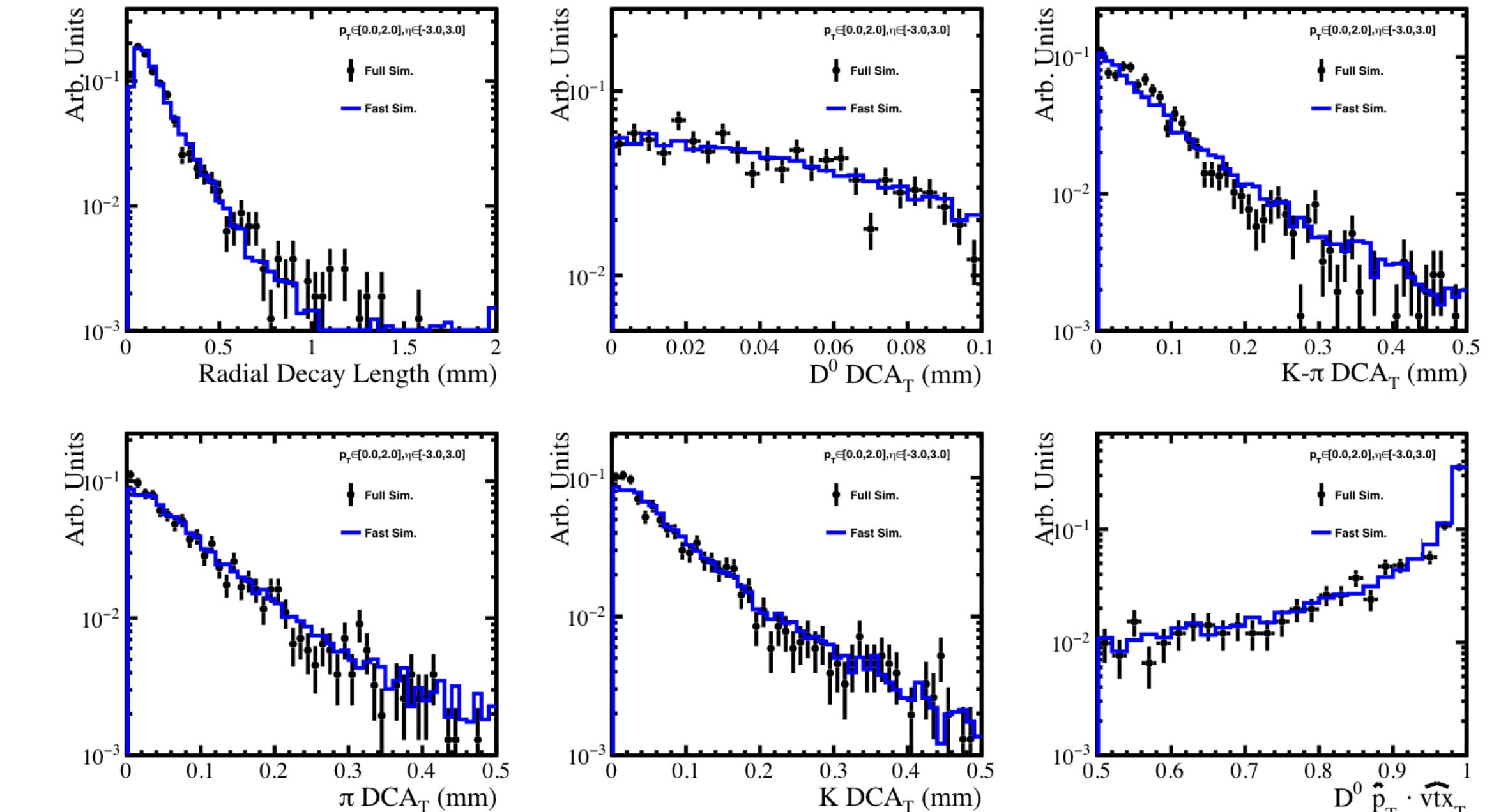
Fast Simulation Setup

- Detector responses implemented through a fastsimulation with parametrized position and momentum resolutions - for sufficient statistics
- Parameterizations taken from the current EIC detector matrix
- Full simulation studies and fastsim validation: See Rey's and Matt's talks

- Primary vertex resolution taken from full simulation



- Fast simulation performance was validated using full simulation



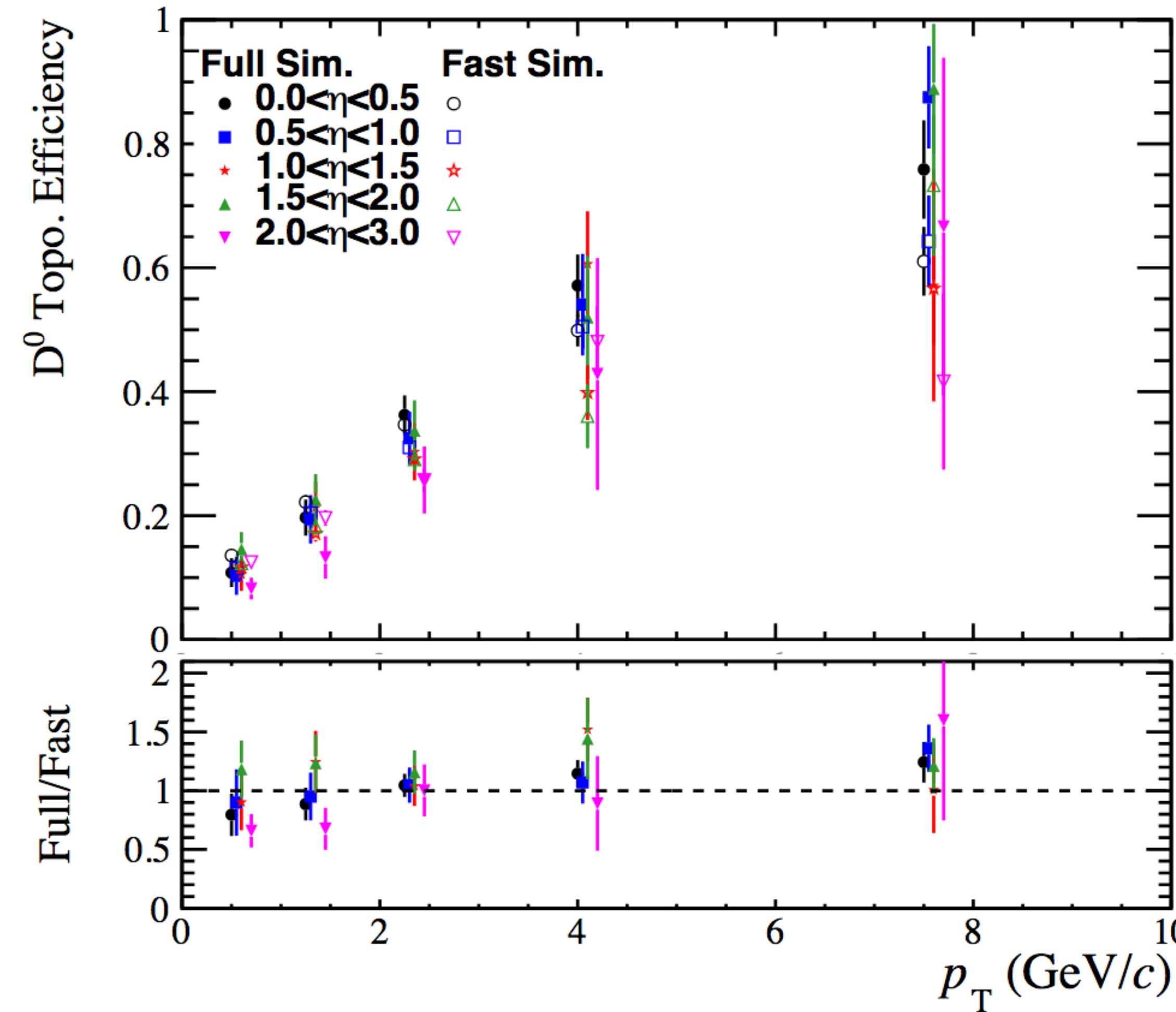
Position resolution

η Region	Detector Matrix (μm)
$-3.0 < \eta < -2.5$	$30/p_T \oplus 40$
$-2.5 < \eta < -2.0$	$30/p_T \oplus 20$
$-2.0 < \eta < -1.0$	$30/p_T \oplus 20$
$-1.0 < \eta < 1.0$	$20/p_T \oplus 5$
$1.0 < \eta < 2.0$	$30/p_T \oplus 20$
$2.0 < \eta < 2.5$	$30/p_T \oplus 20$
$2.5 < \eta < 3.0$	$30/p_T \oplus 40$
$3.0 < \eta < 3.5$	$30/p_T \oplus 60$

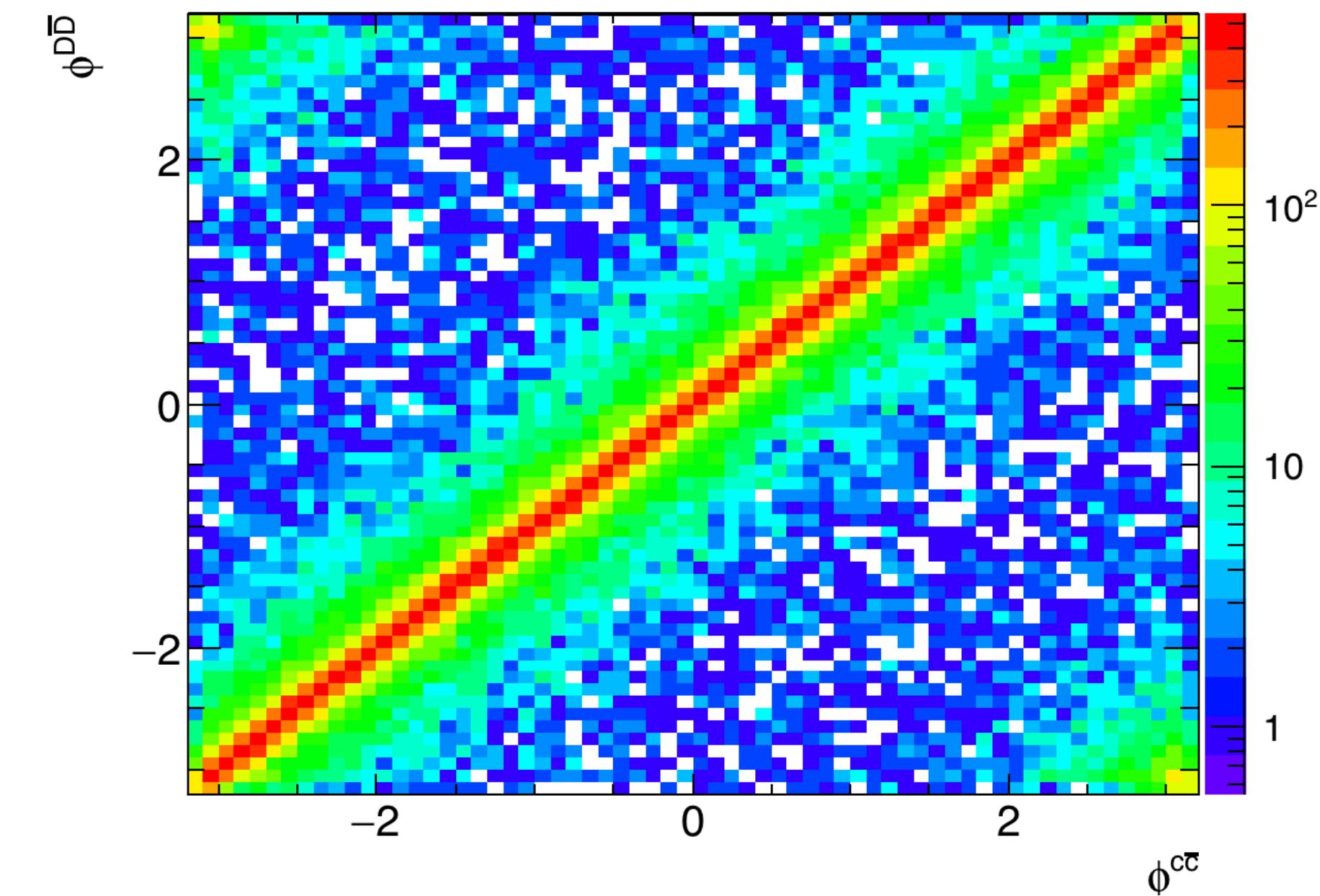
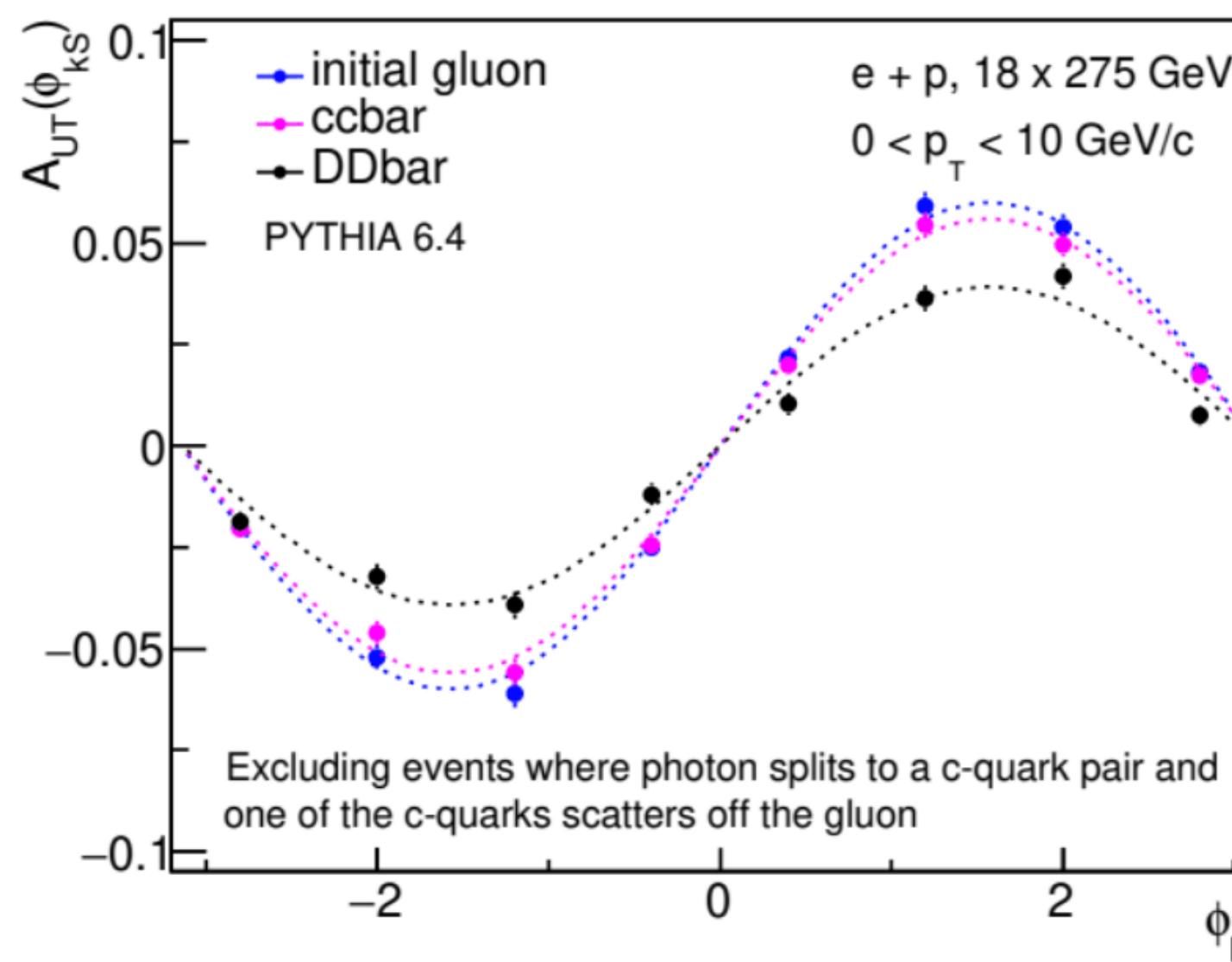
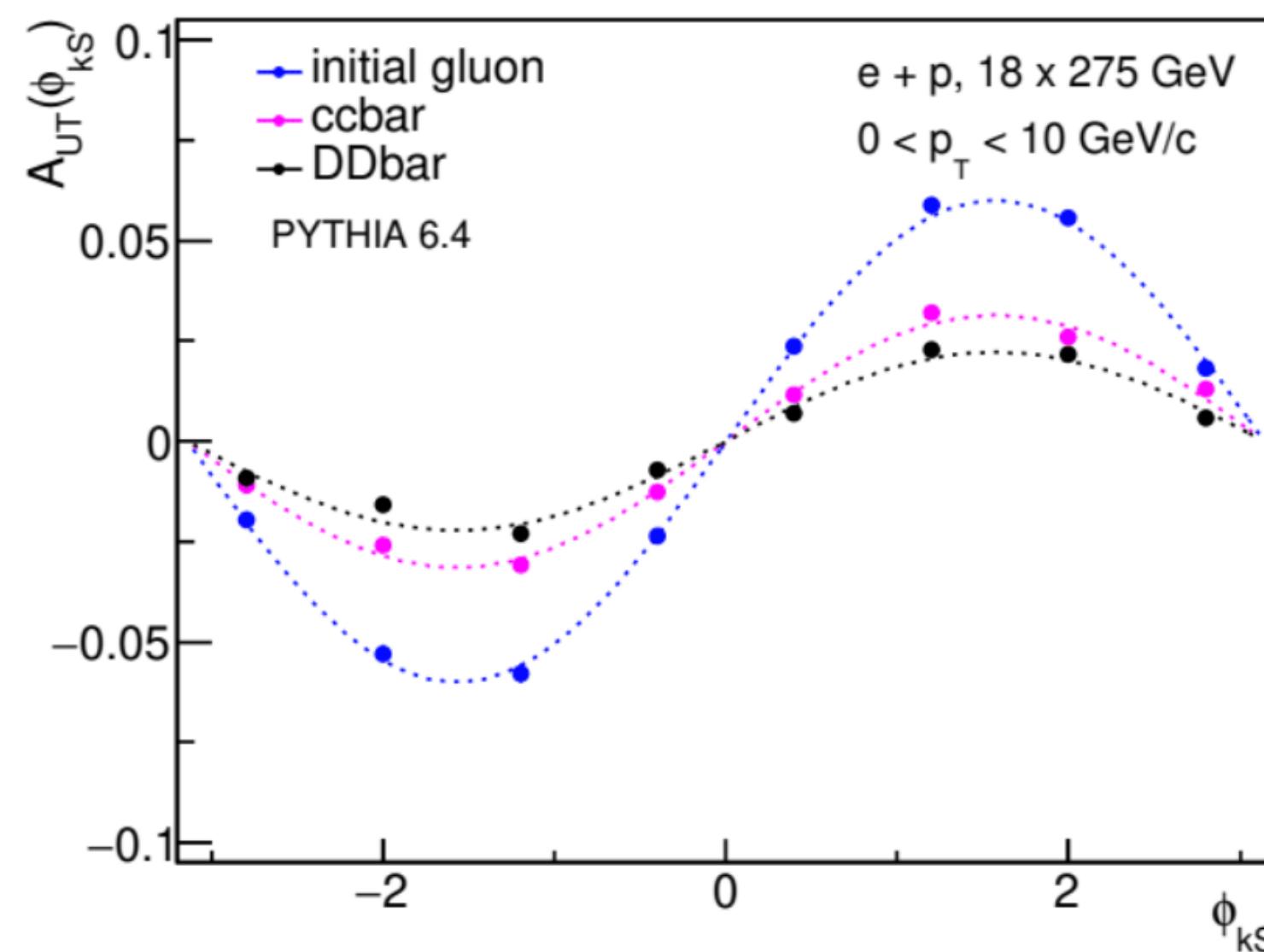
Mom resolution

η Region	Resolution (%)
$-3.5 < \eta < -2.5$	$0.1 \cdot p \oplus 0.5$
$-2.5 < \eta < -2.0$	$0.1 \cdot p \oplus 0.5$
$-2.0 < \eta < -1.0$	$0.05 \cdot p \oplus 0.5$
$-1.0 < \eta < 1.0$	$0.05 \cdot p \oplus 0.5$
$1.0 < \eta < 2.5$	$0.05 \cdot p \oplus 1.0$
$2.5 < \eta < 3.5$	$0.1 \cdot p \oplus 2.0$

D Meson Topological Cut Efficiency



Correlations between Partonic and Hadronic Stages



- Hadronization doesn't cause much decorrelation in angular distributions
- Stronger dilution in PYTHIA going from initial gluon to ccbar - but not seen in events where PYTHIA doesn't split photon to

