2022 RHIC/AGS ANNUAL USERS' MEETING

From RHIC to EIC

At the QCD Frontiers

This meeting will be held virtually.
June 7–10, 2022

Heavy Flavor at the EIC

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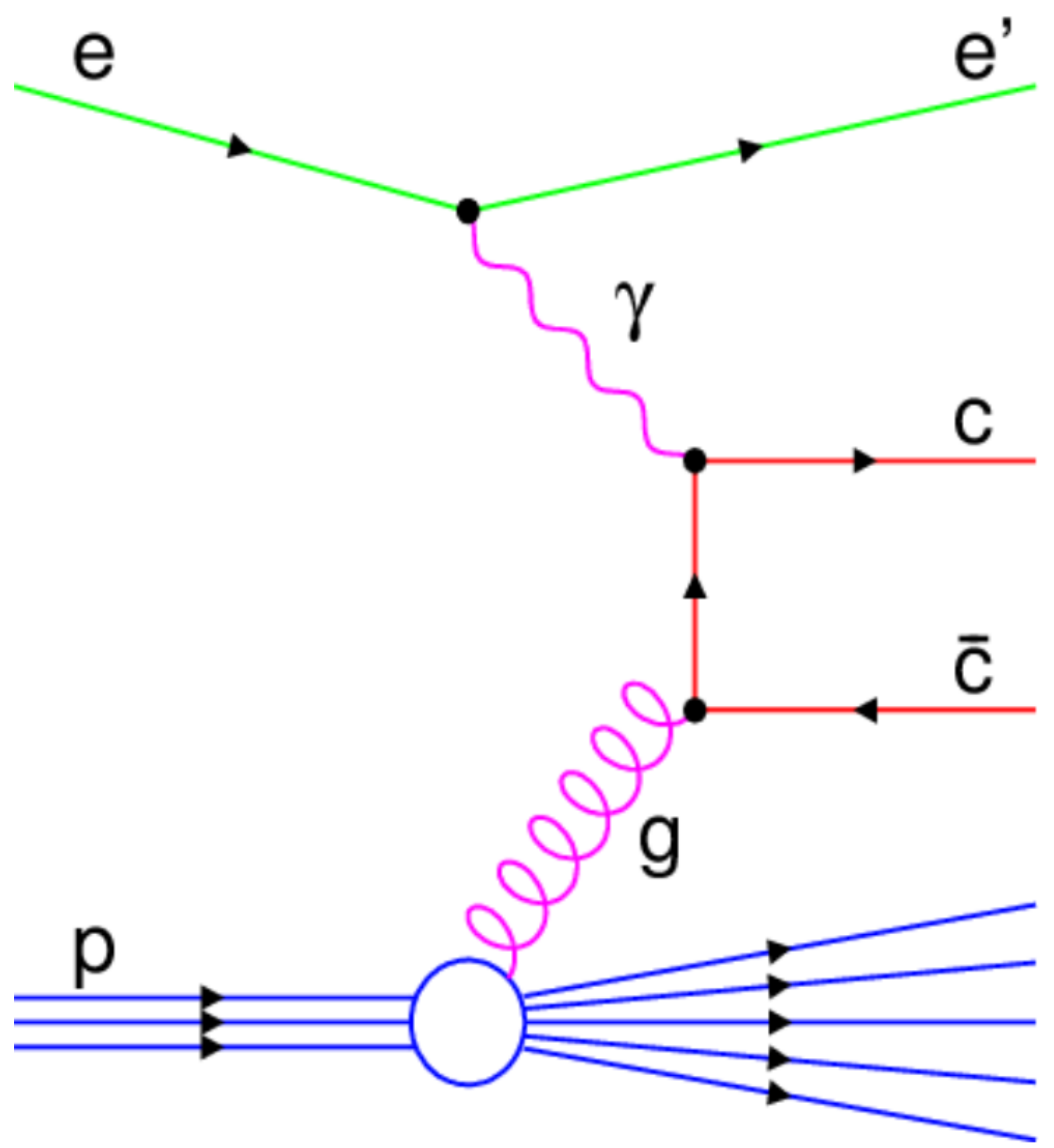
KENT STATE UNIVERSITY

BERKELEY LAB

Heavy Quarks as Probes of Gluon Distributions



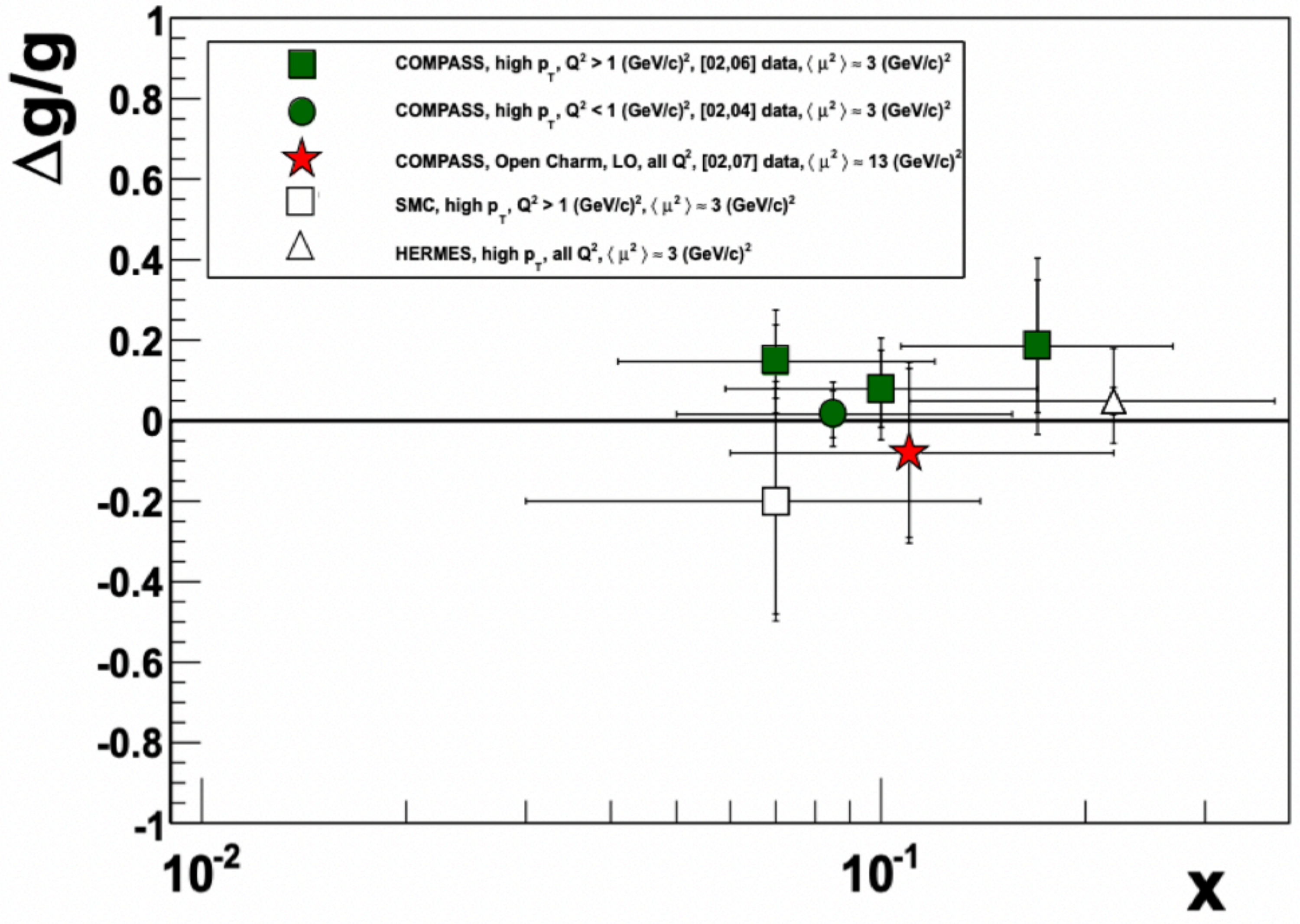
- Heavy quark production in DIS: leading order contribution from photon gluon fusion process
- Ideal to probe gluon distributions

- Can access heavy flavor production over a broad kinematic range at the EIC

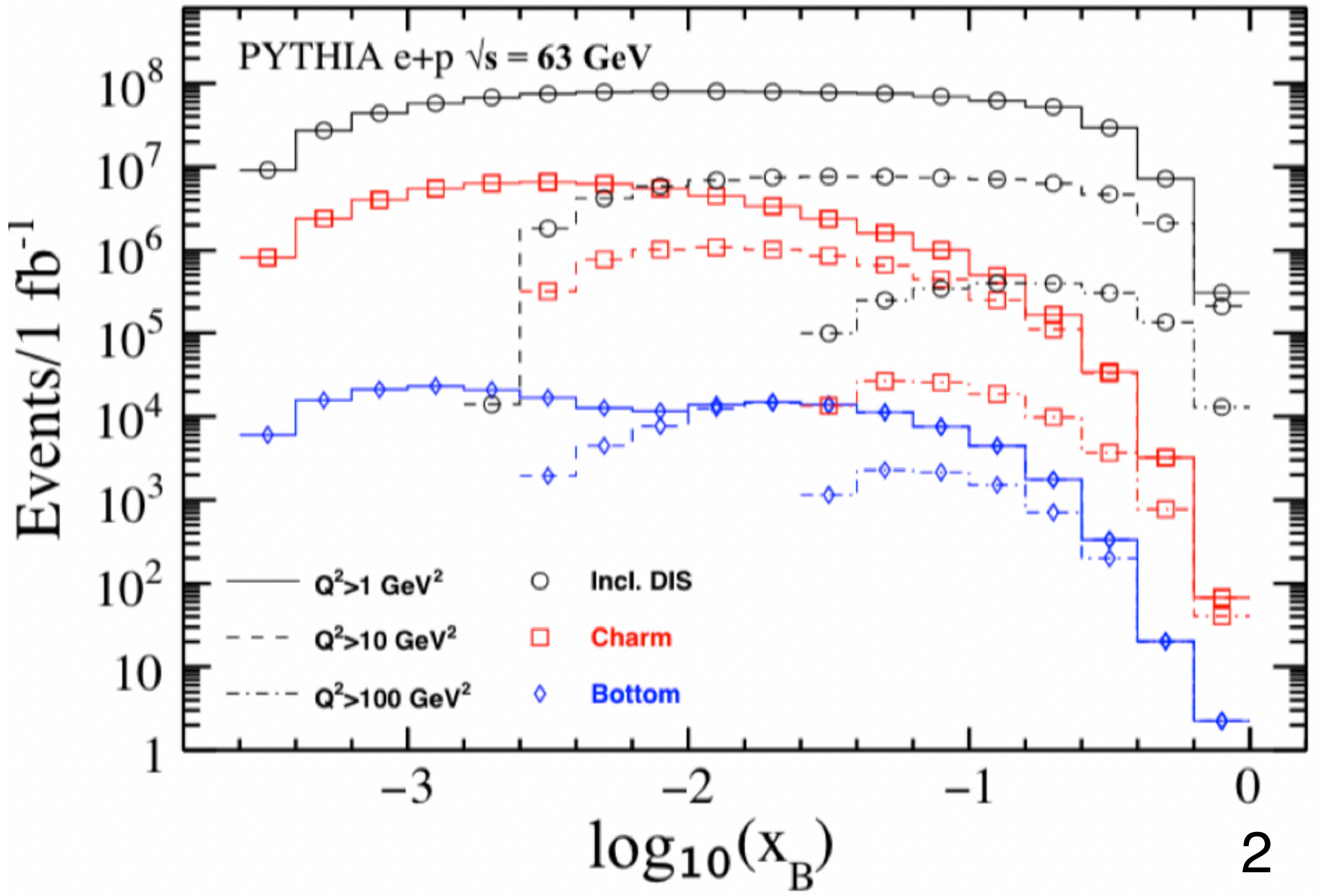
- Will constrain gluon helicity, gluon nPDFs, gluon TMDs over a broad kinematic range, which are major focuses of EIC physics

EIC White Paper: arXiv:1212.1701 (2012)

COMPASS: Phys. Rev. D 87,052018 (2013)



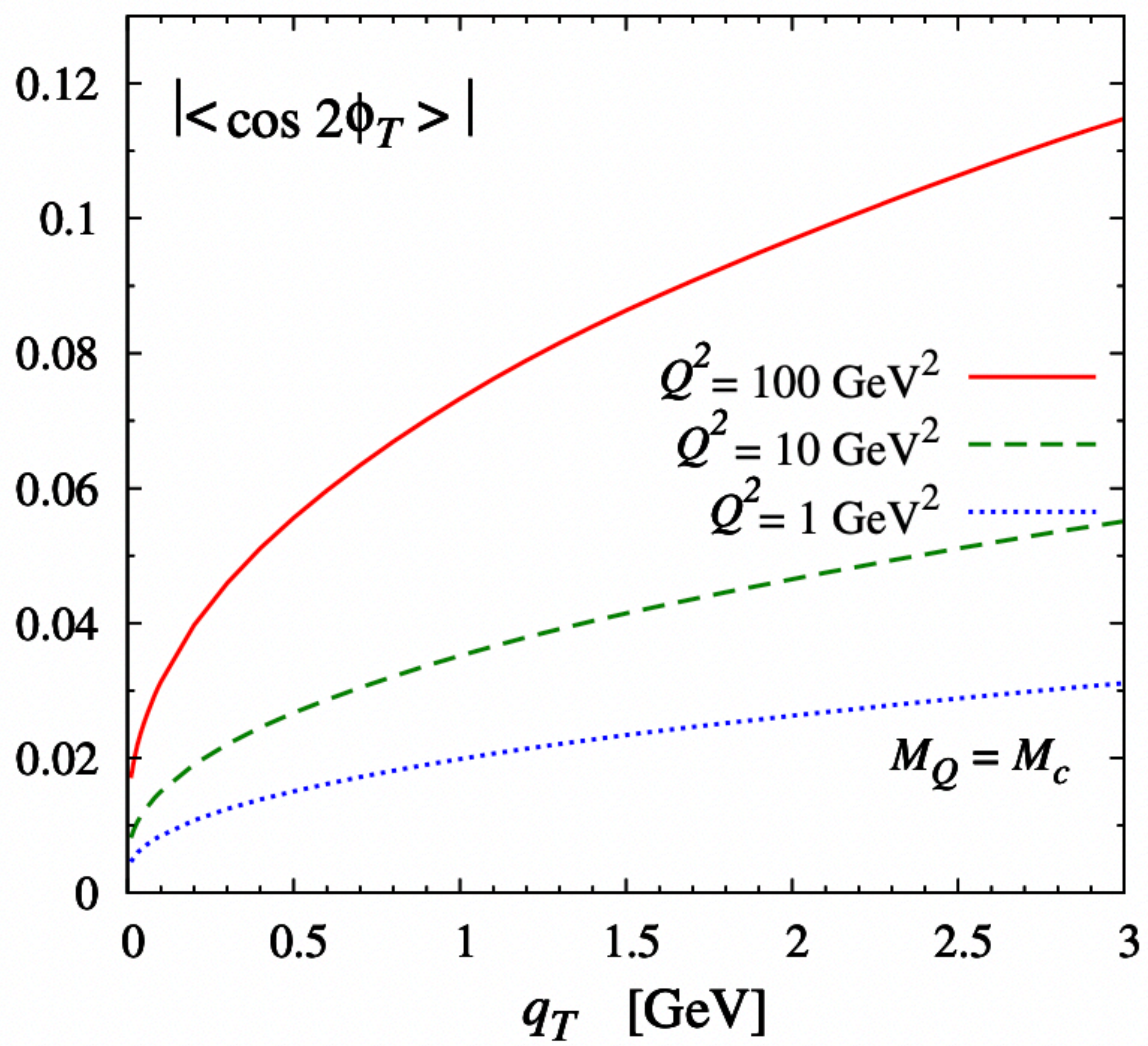
M. Kelsey et al. Phys. Rev. D 104, 054002 (2021)



Gluon TMDs and Hadronization

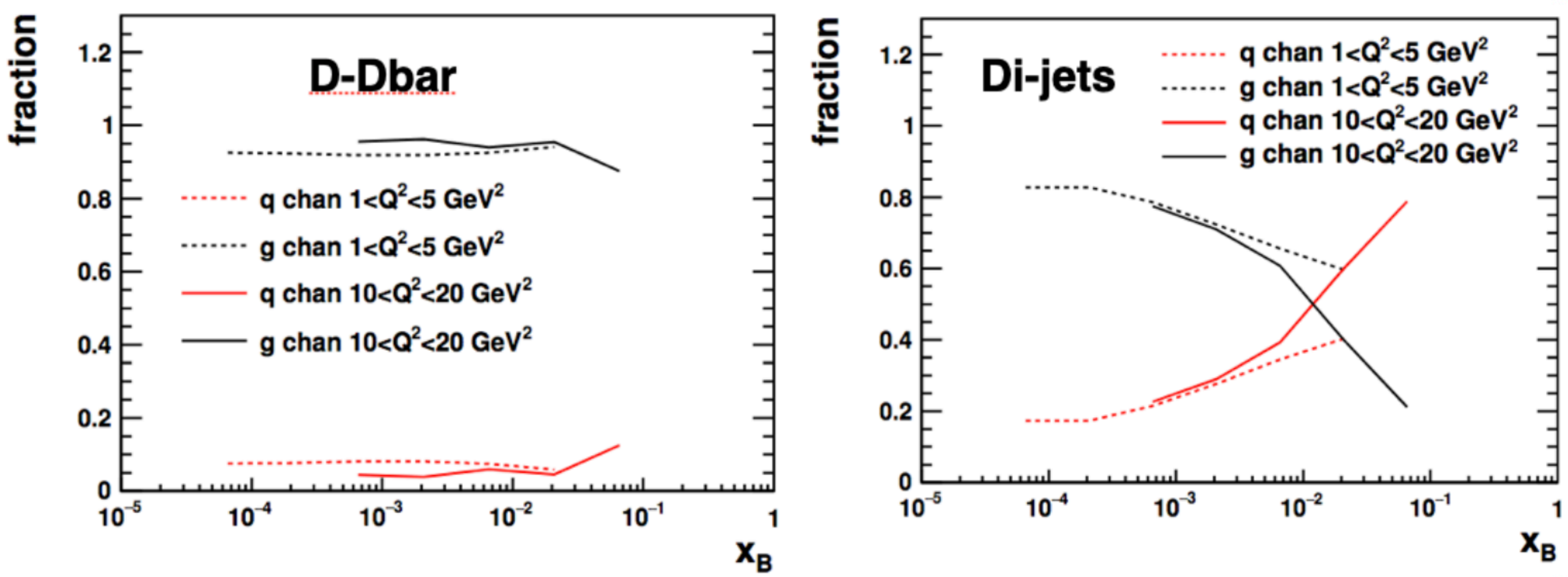
- Heavy flavor pair production ideal channel to probe gluon TMDs, eg: Sivers asymmetry, linearly polarized gluon TMDs

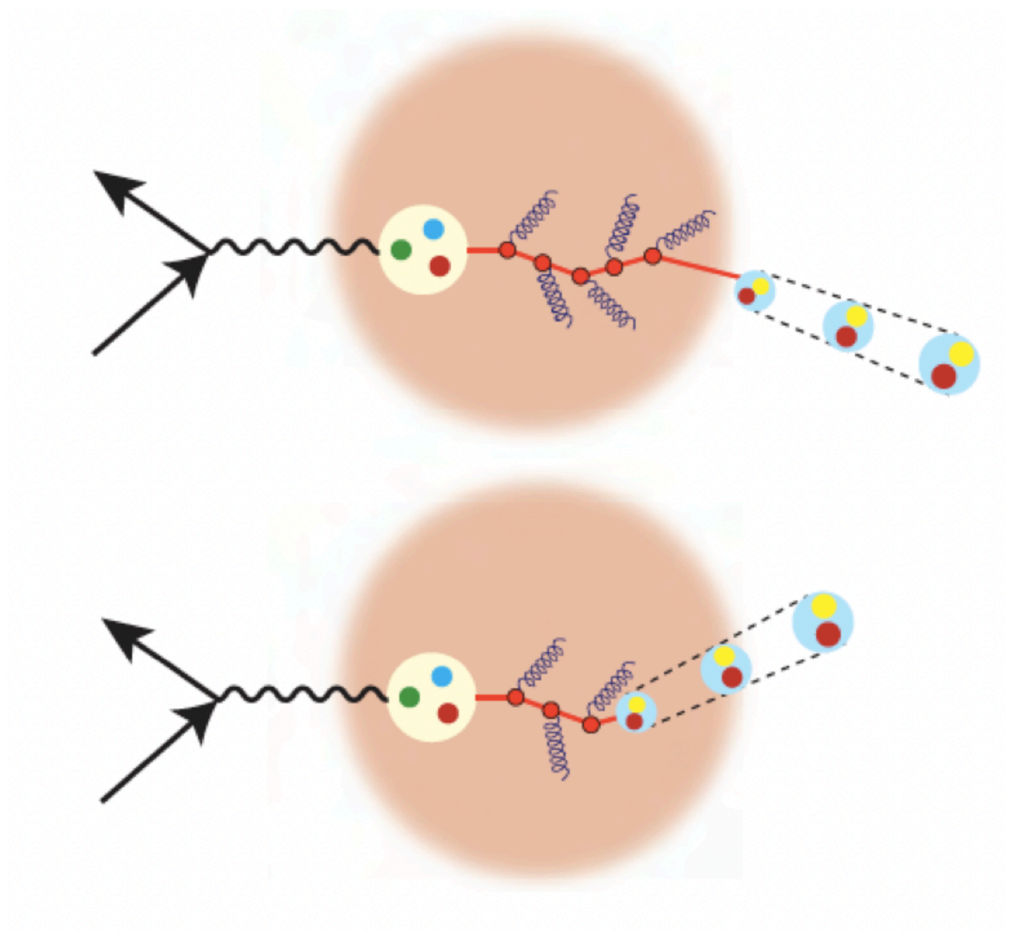
D. Boer et al. JHEP 08 (2016) 001



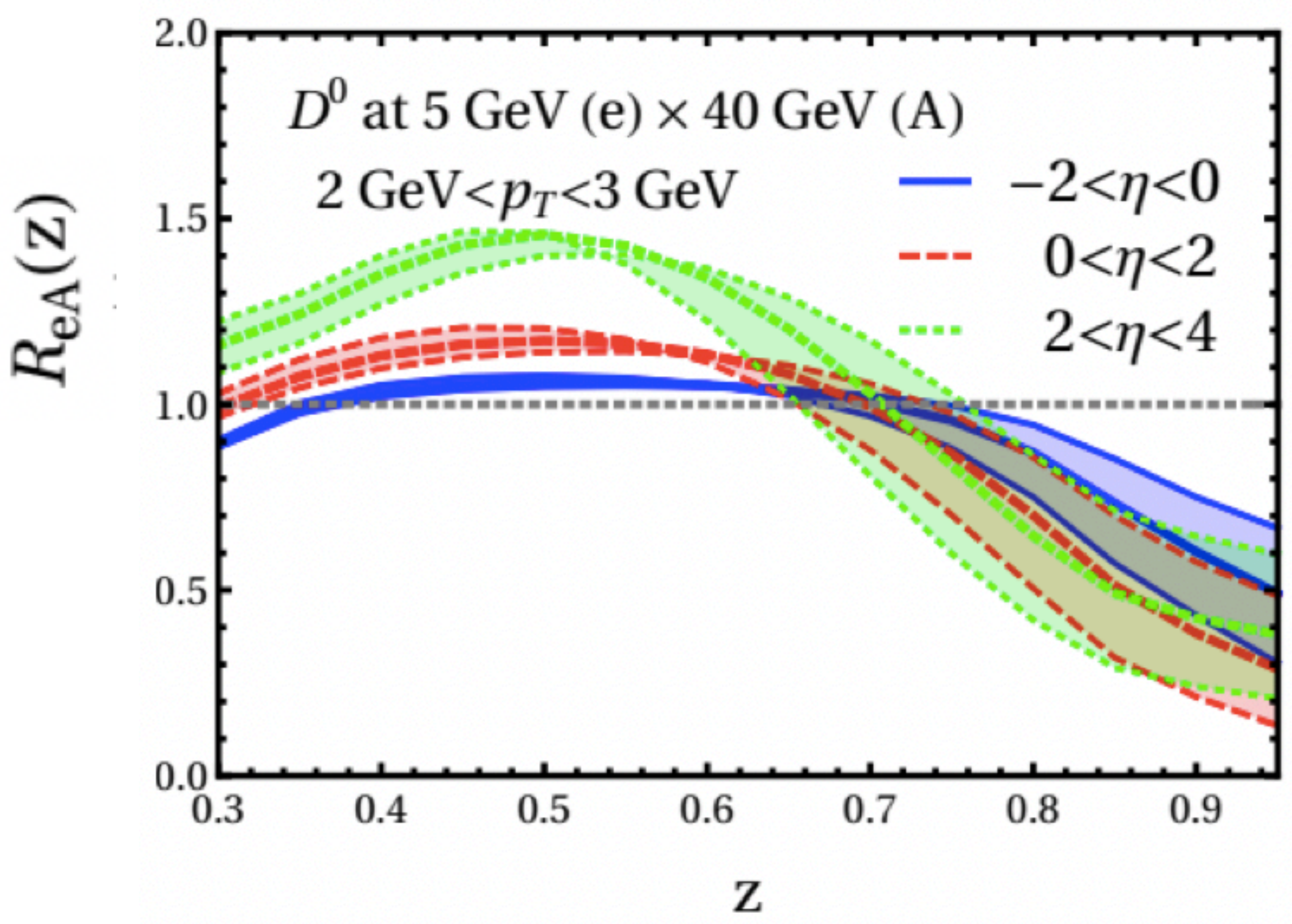
- Also, clean probes of gluon TMDs

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



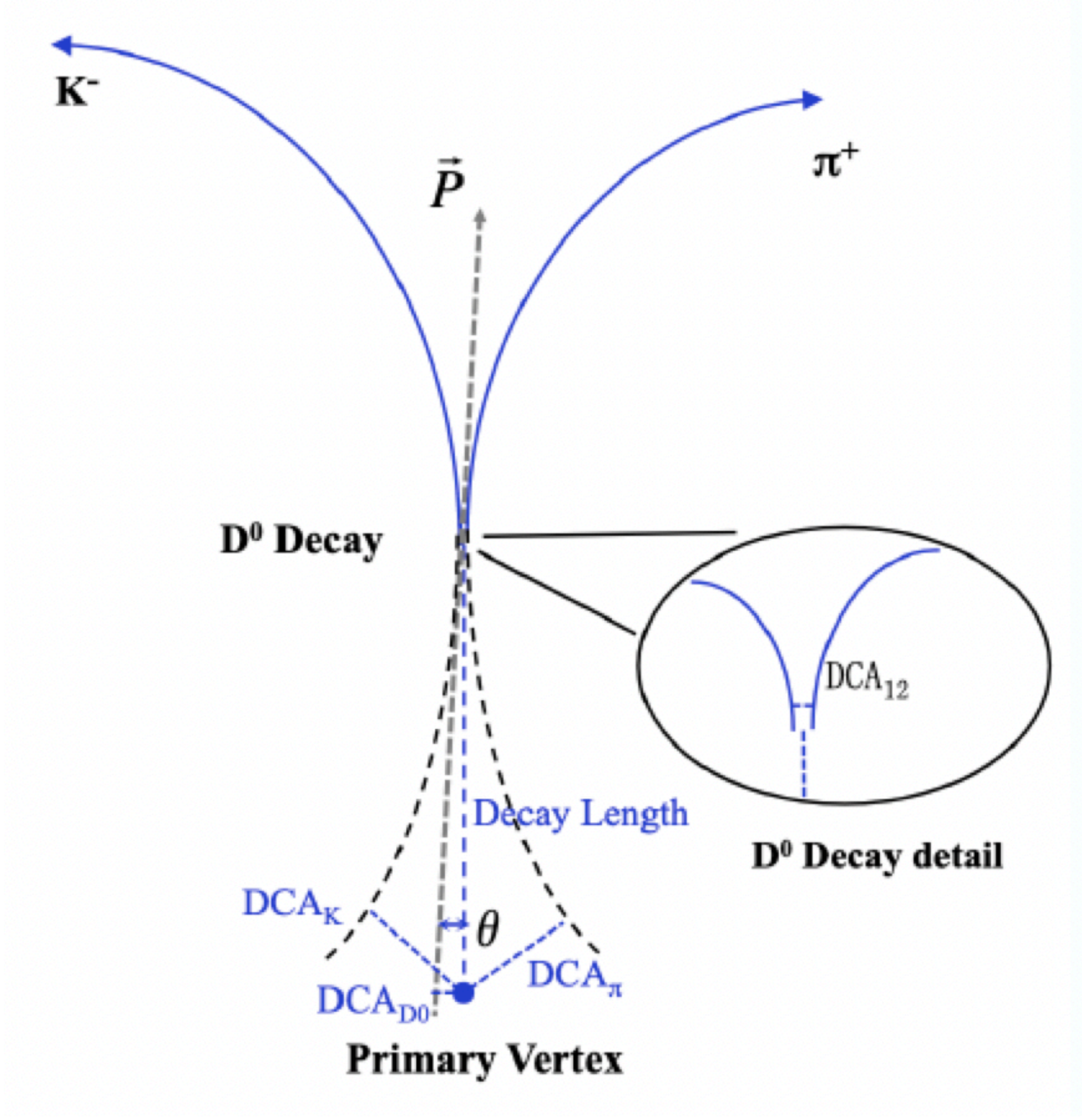


H. Liu et al. arXiv:2007.10994



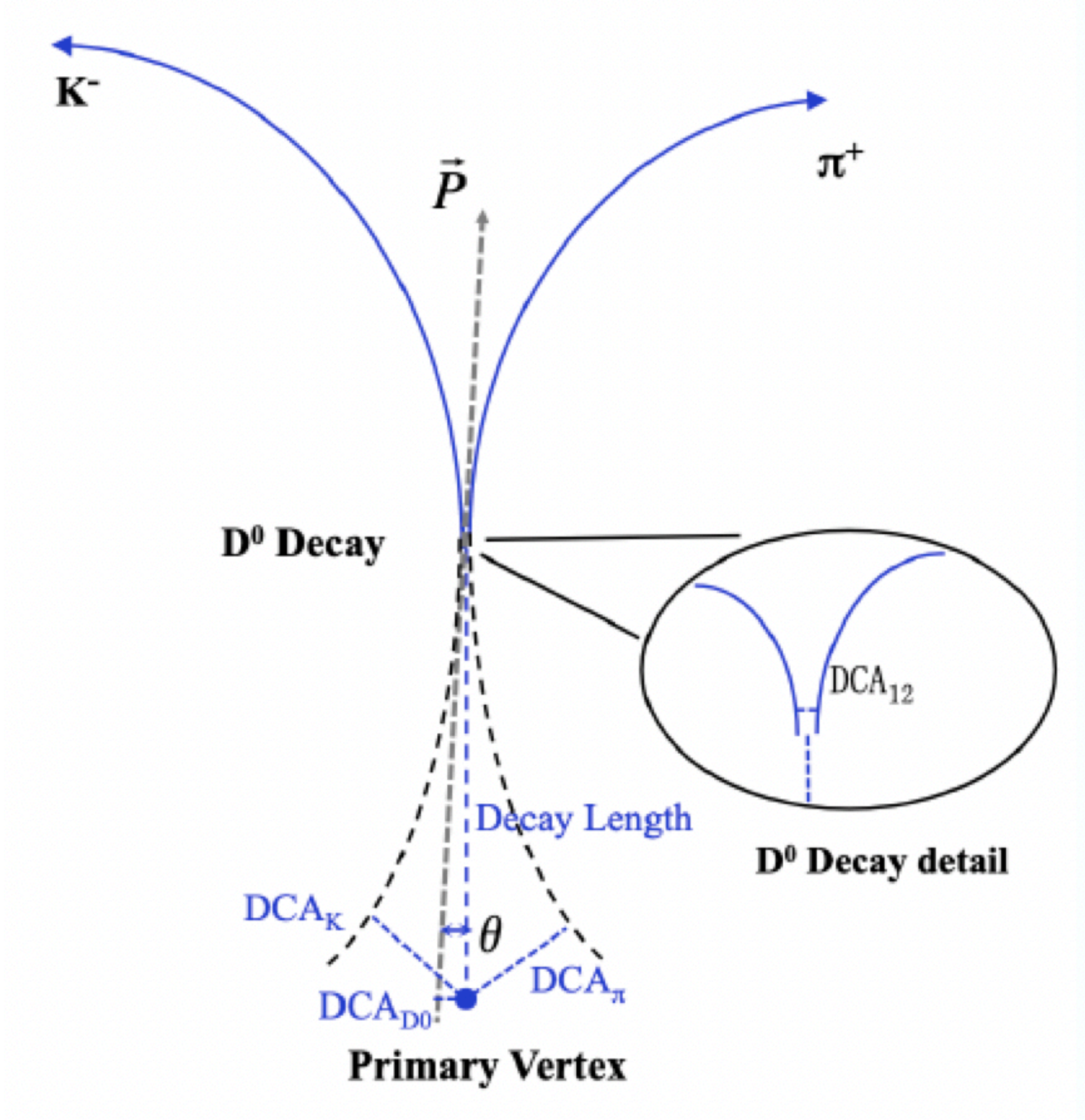
- Study Hadronization through modification of fragmentation in presence of nuclear matter

Heavy Flavor Reconstruction at EIC



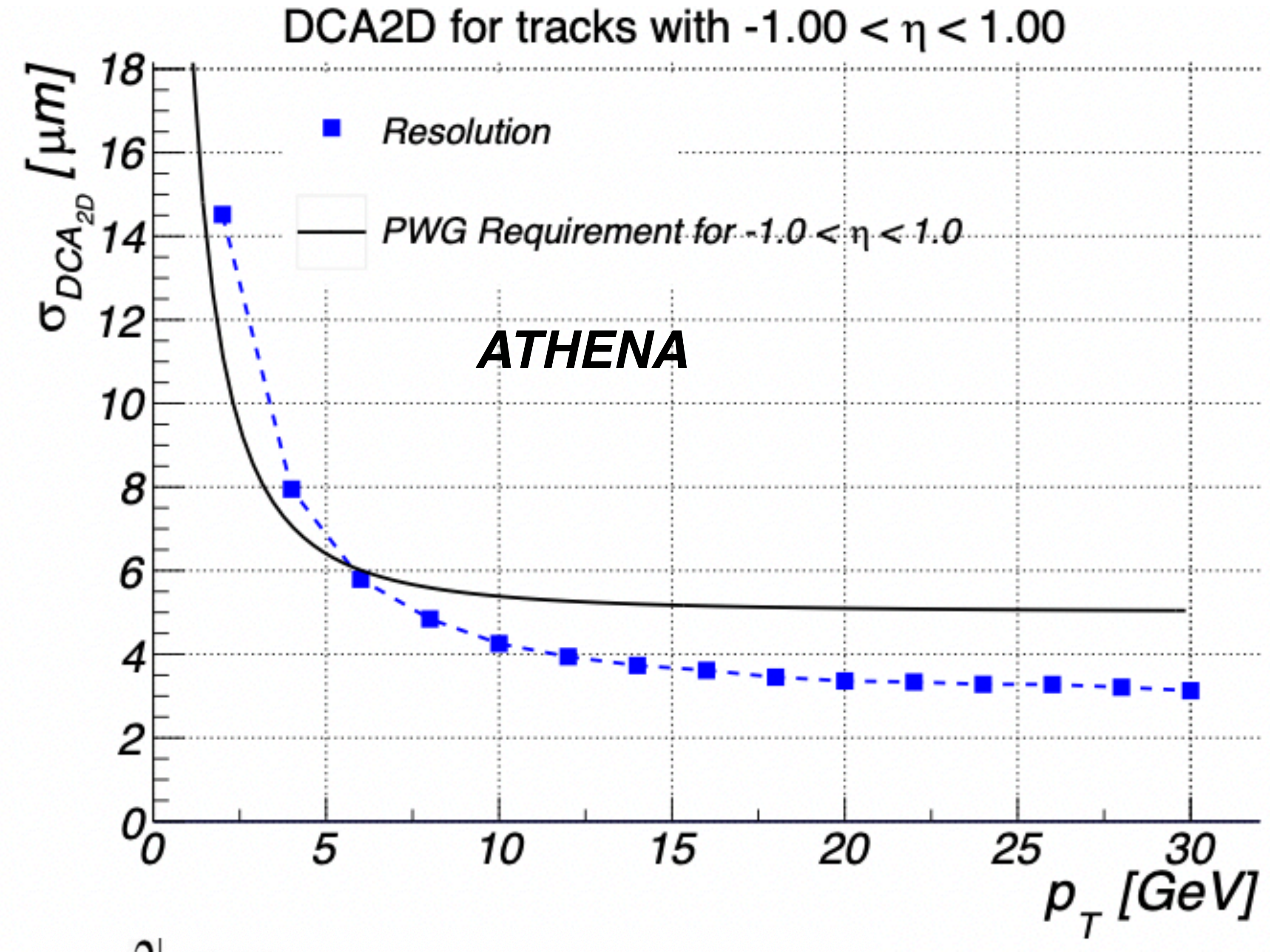
- Key for HF measurements: Tracking system with excellent track pointing resolution, good momentum resolution

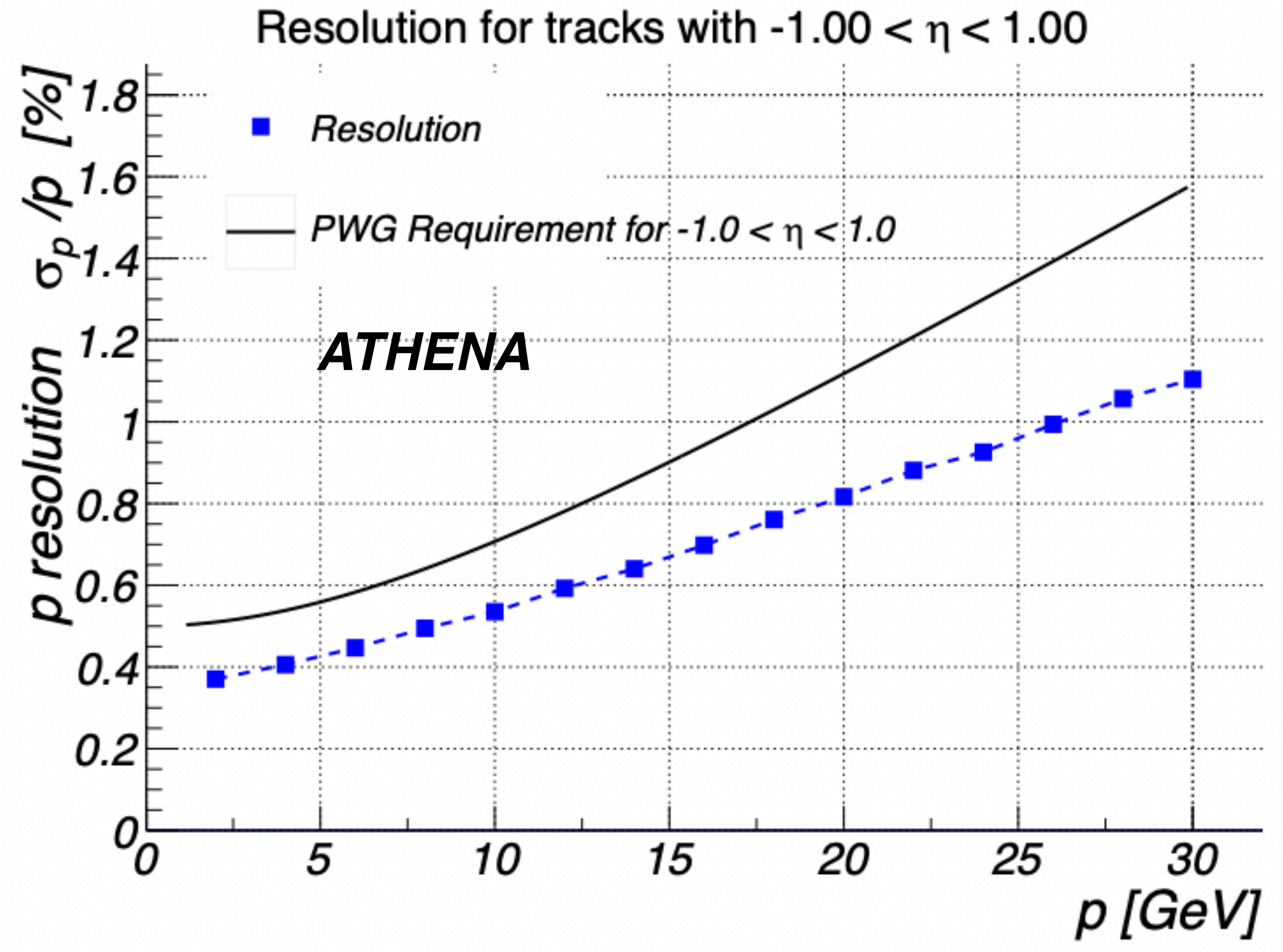
Heavy Flavor Reconstruction at EIC

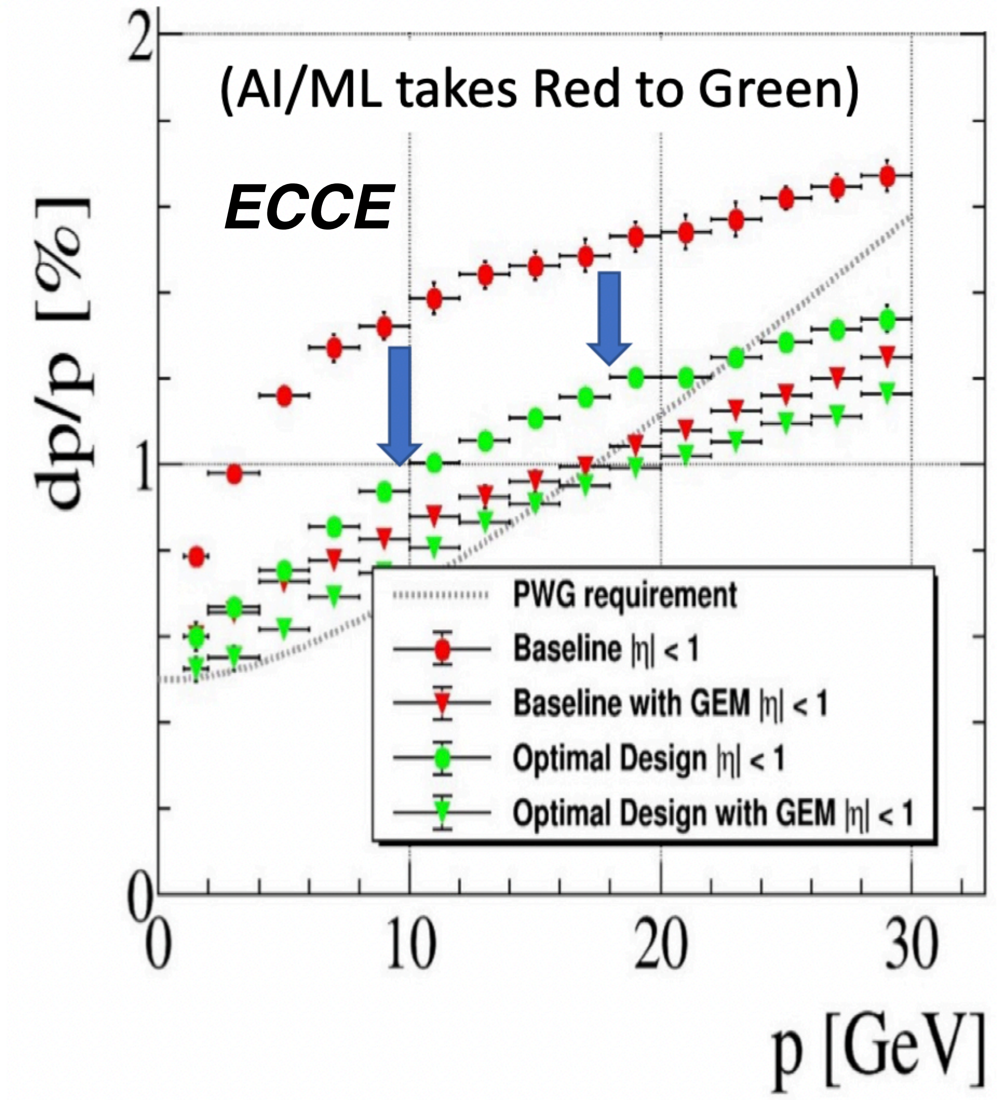


- Key for HF measurements: Tracking system with excellent track pointing resolution, good momentum resolution

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



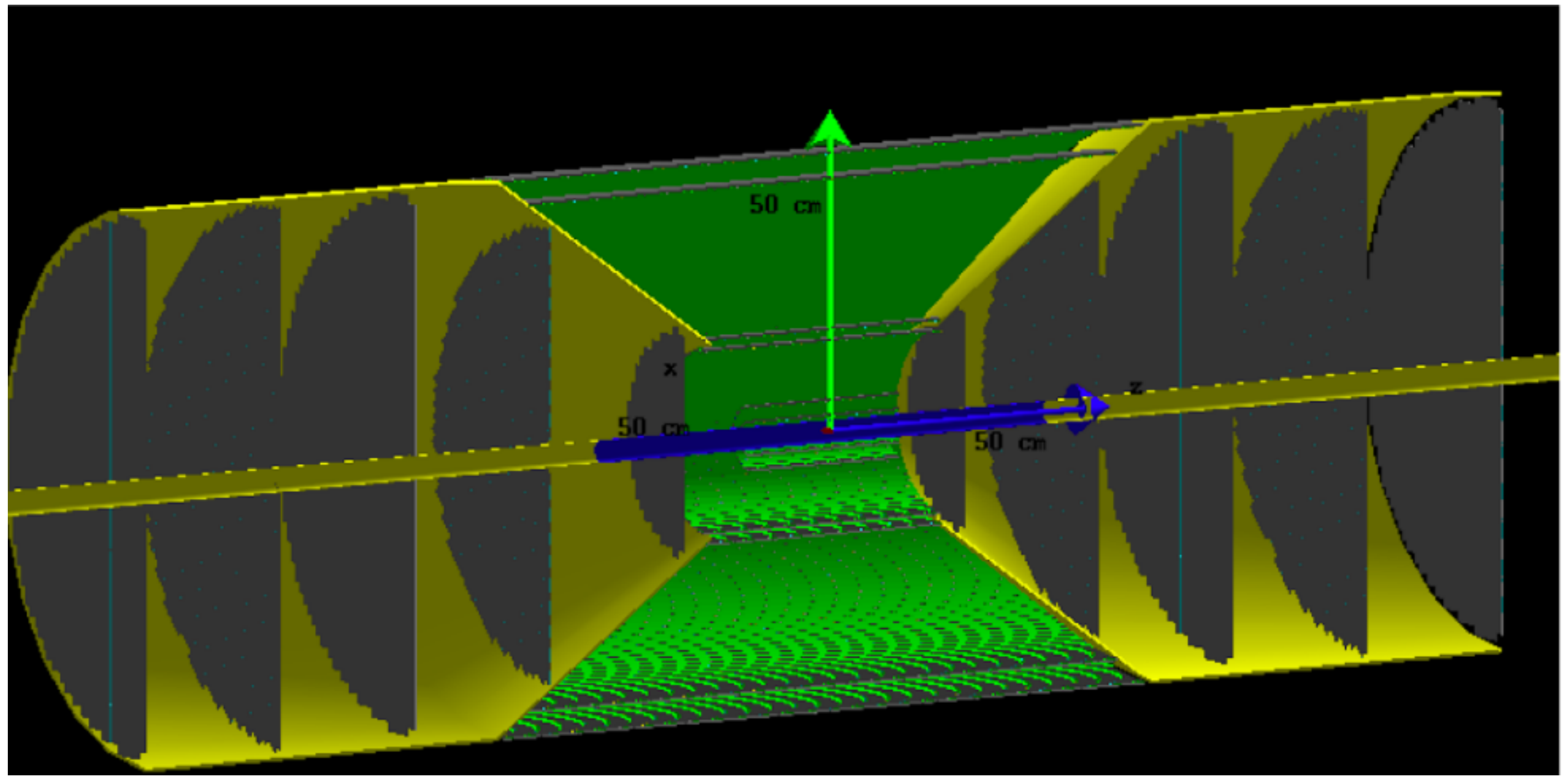


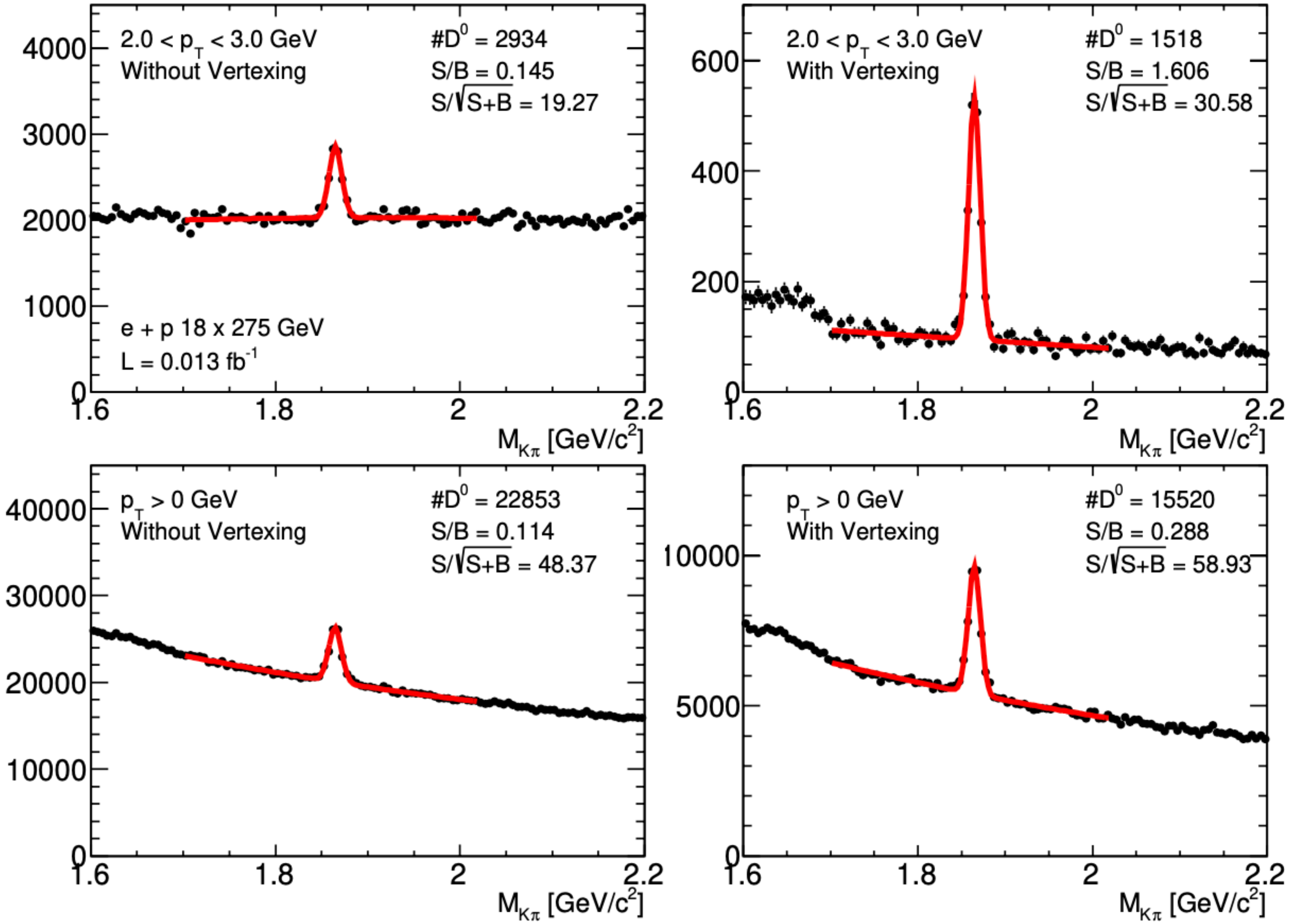


- Part of both ATHENA and ECCE proposals
- Both can provide resolutions satisfying YR requirements

Plots from EIC UG meeting August 2021

EIC Simulation Setup



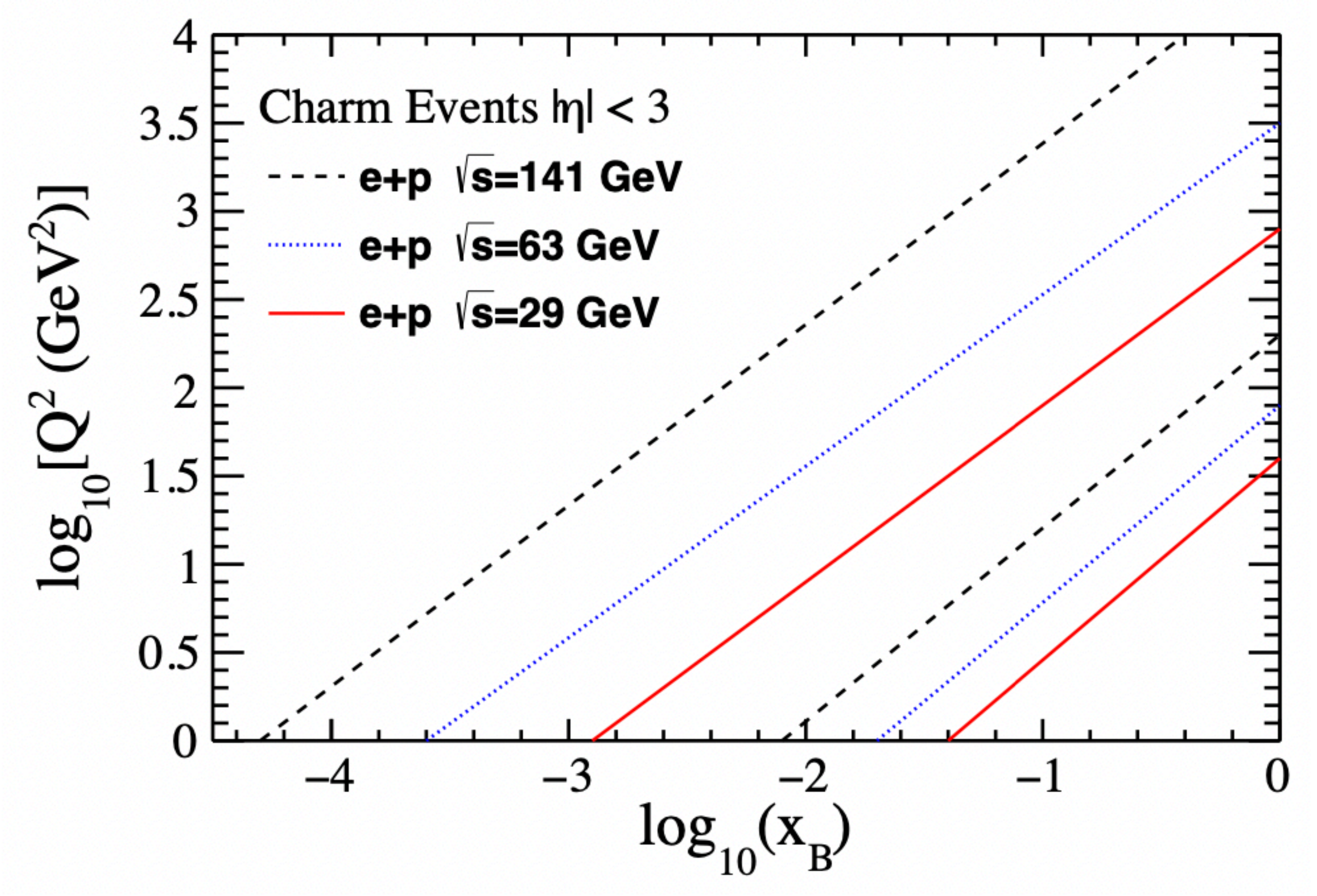


- Pythia6 EIC tune
- All-silicon tracker design composed of MAPS sensors
- 3x2 barrel layers within $|\eta| < 1$; five disks in forward and backward regions each, with coverage $1<|\eta|<3$
- Tracking specifications as in EIC YR Det.Matrix: *arXiv:2102.08337*

- Signal significance improves greatly with vertexing cuts

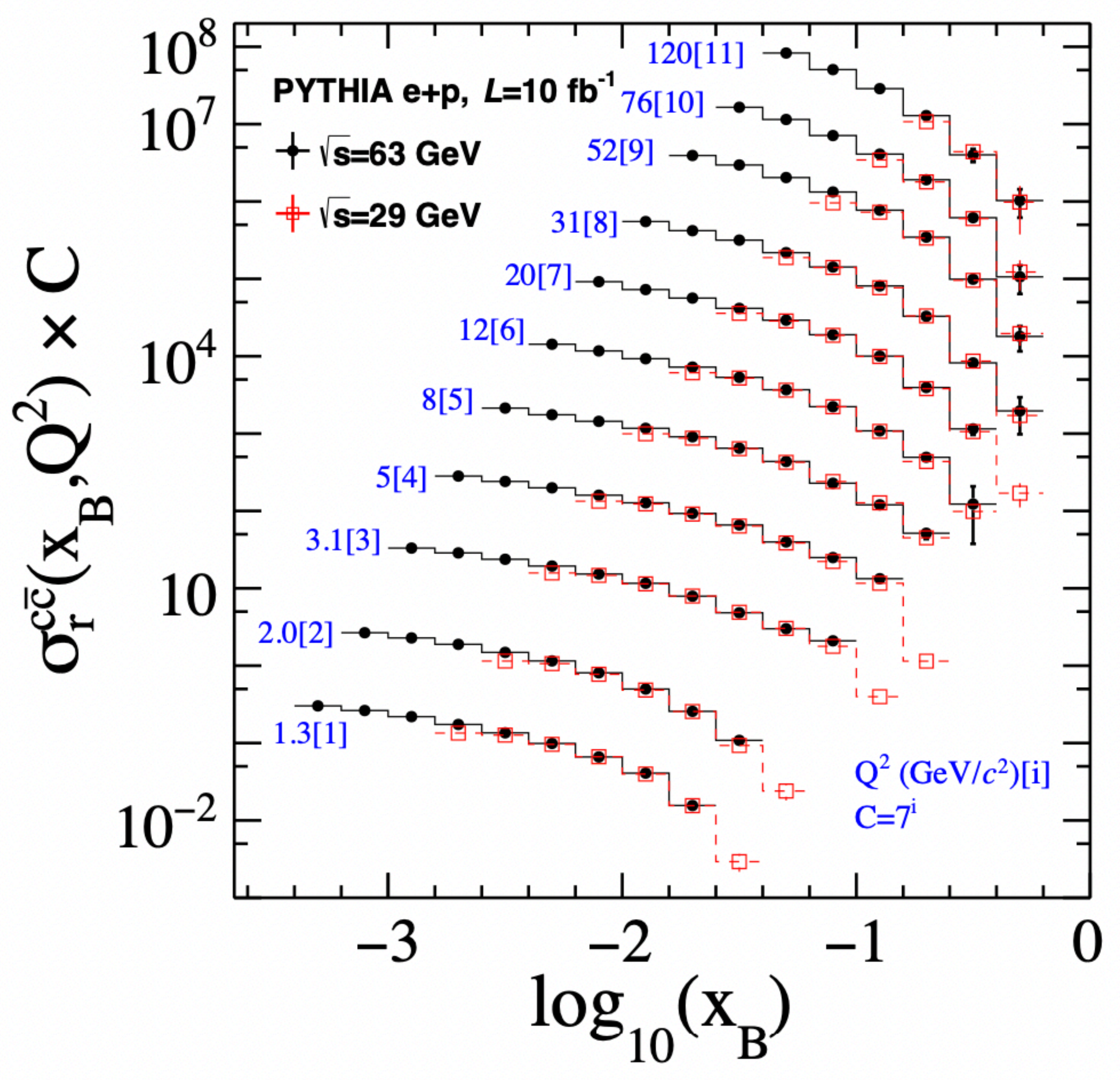
Simulation Results

Charm Cross-section and Gluon nPDF



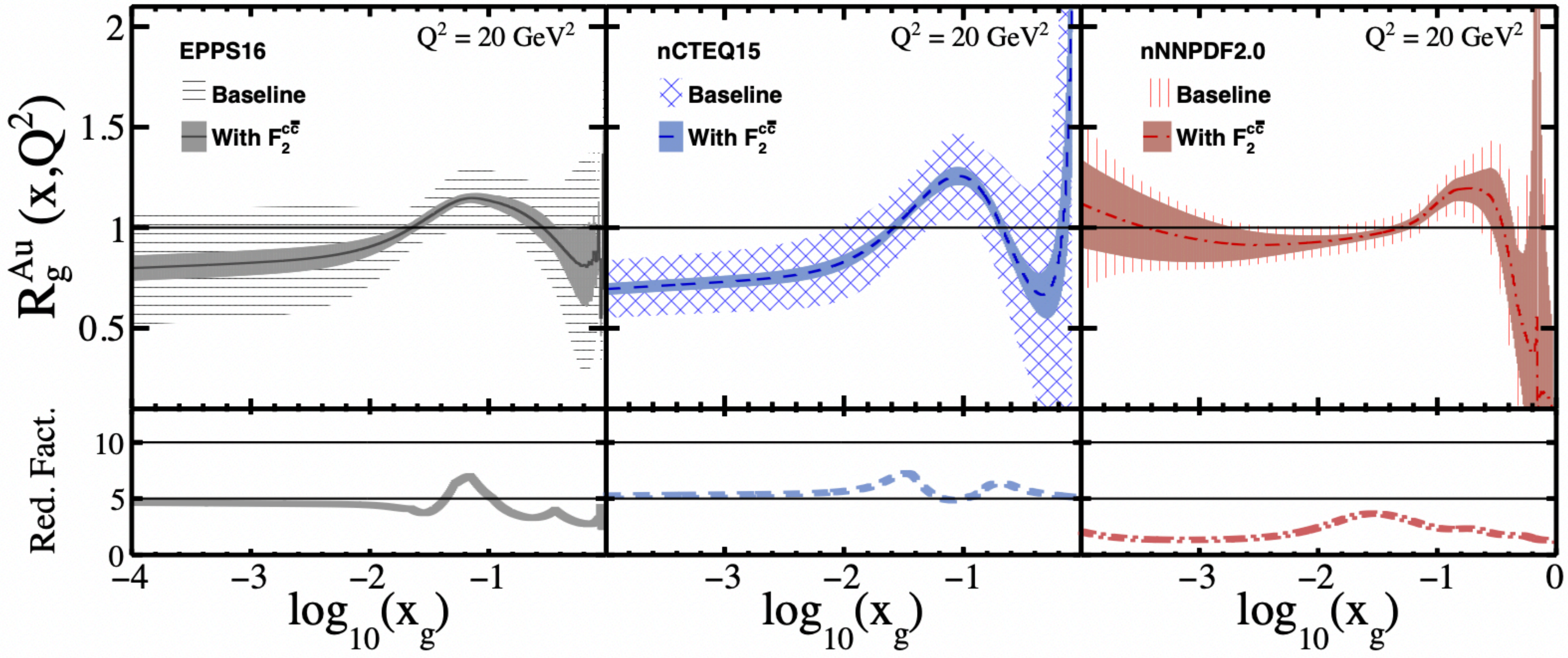
For more details see: Phys. Rev. D 104, 054002 (2021)

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



- 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



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

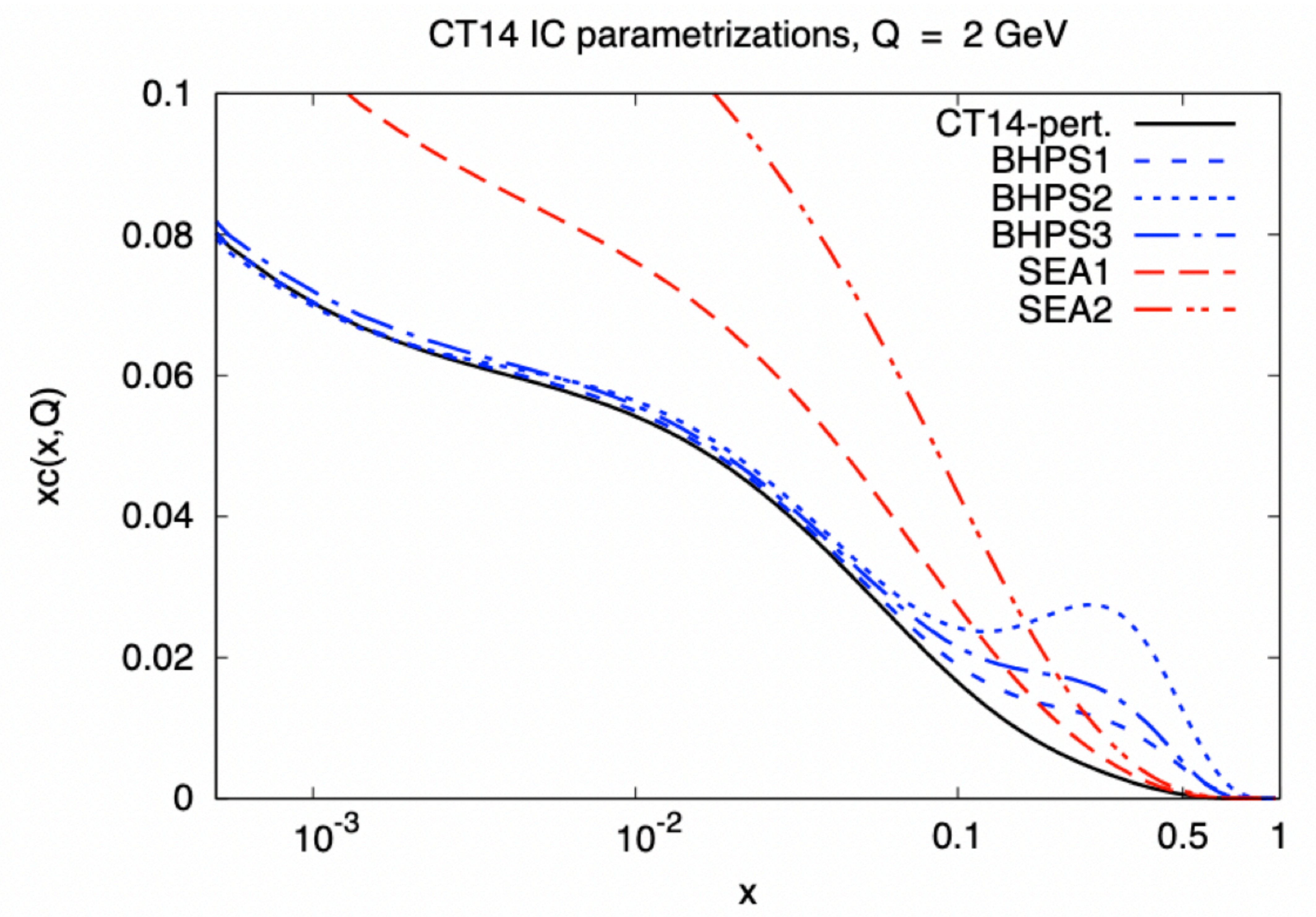
$$w_k = \frac{exp[-\chi_k^2/2]}{\frac{1}{N_{rep}} \sum_k exp[-\chi_k^2/2]}$$

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

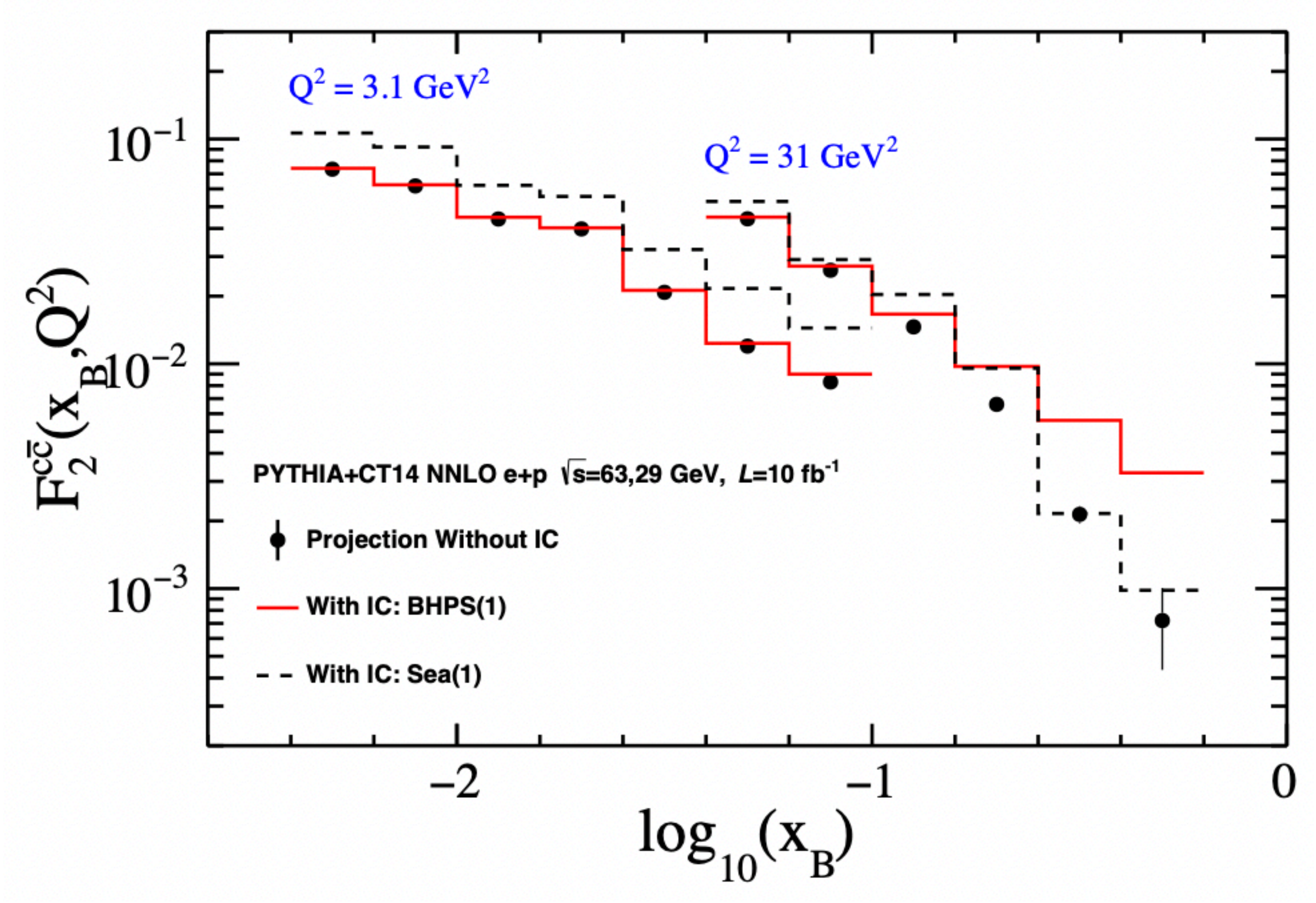
For more details see: Phys. Rev. D 104, 054002 (2021)

- 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
- Important to constrain shadowing, anti-shadowing and at high x, possible gluonic EMC effects

Impact of Intrinsic Charm in Proton



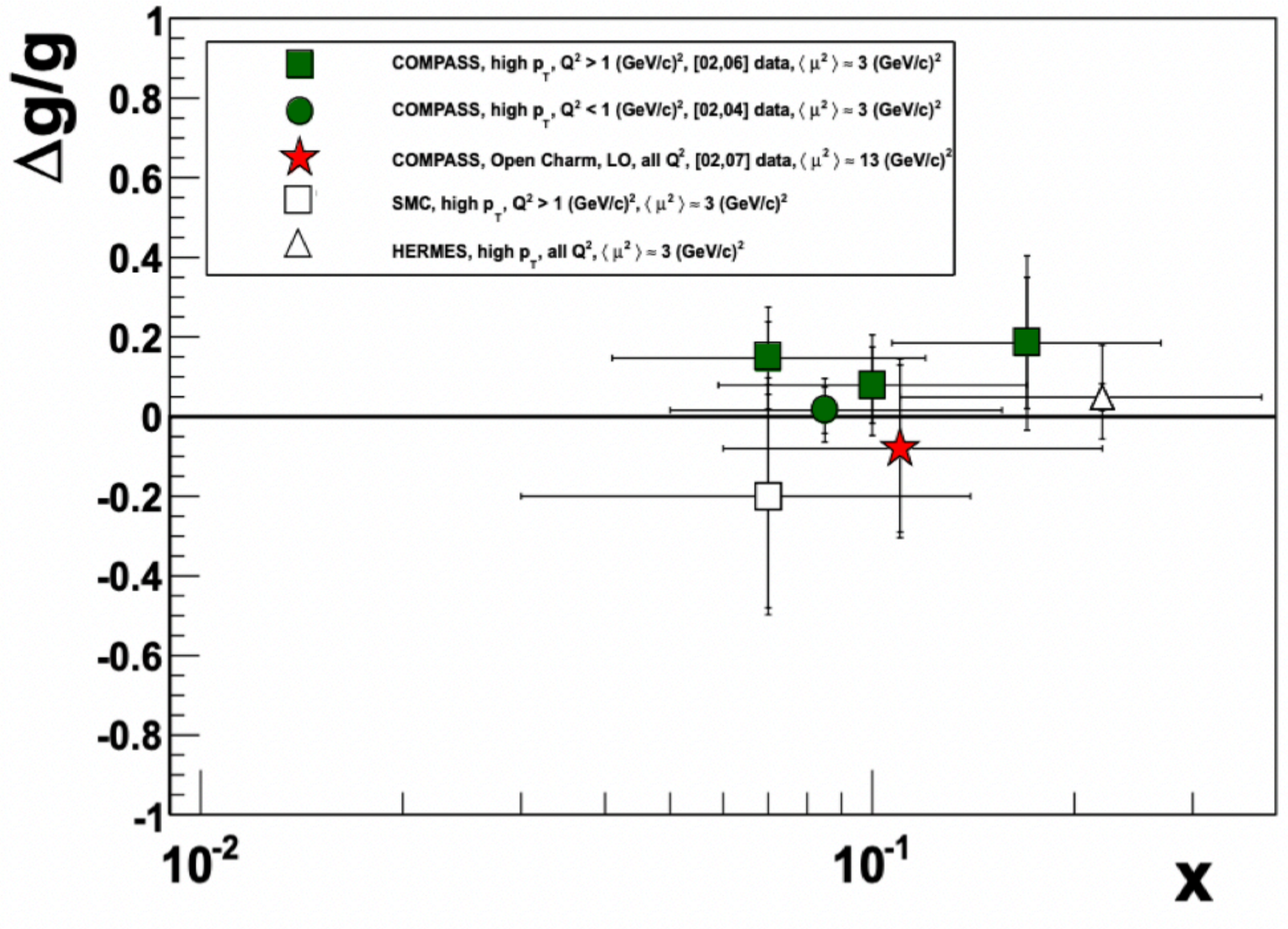
T. Hou et al. JHEP 2018, 59 (2018)

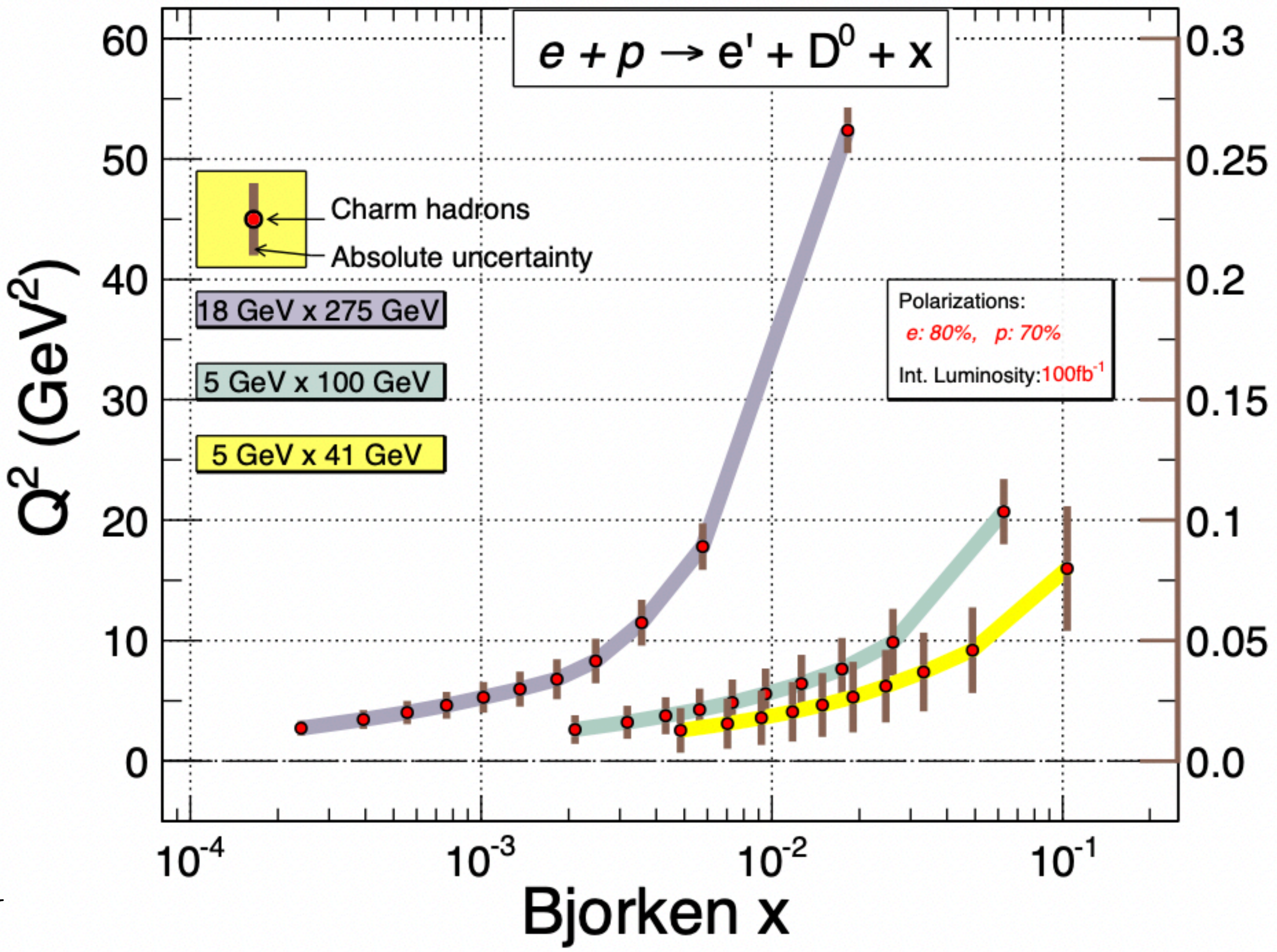


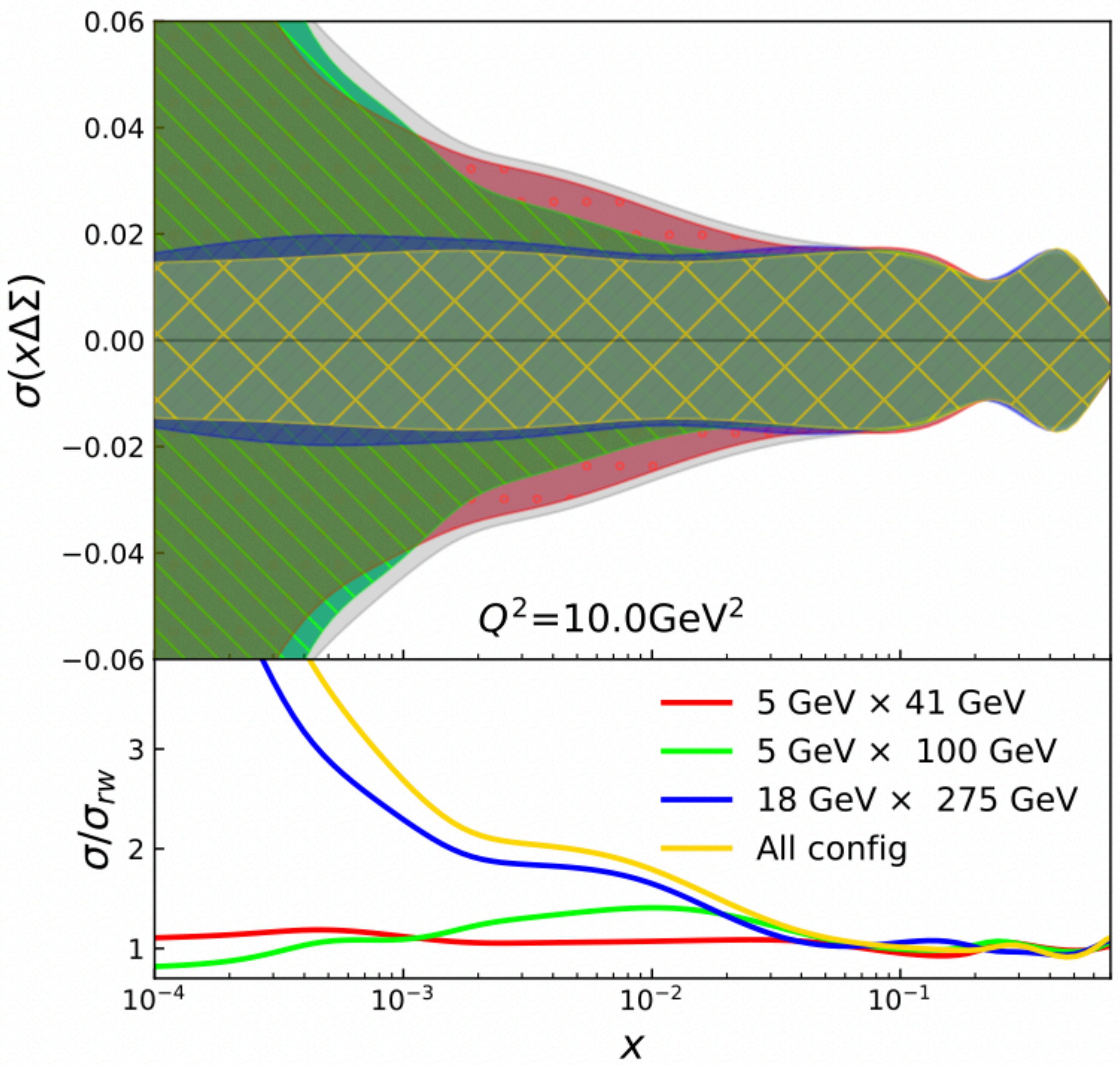
For more details see: Phys. Rev. D 104, 054002 (2021)

- 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







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

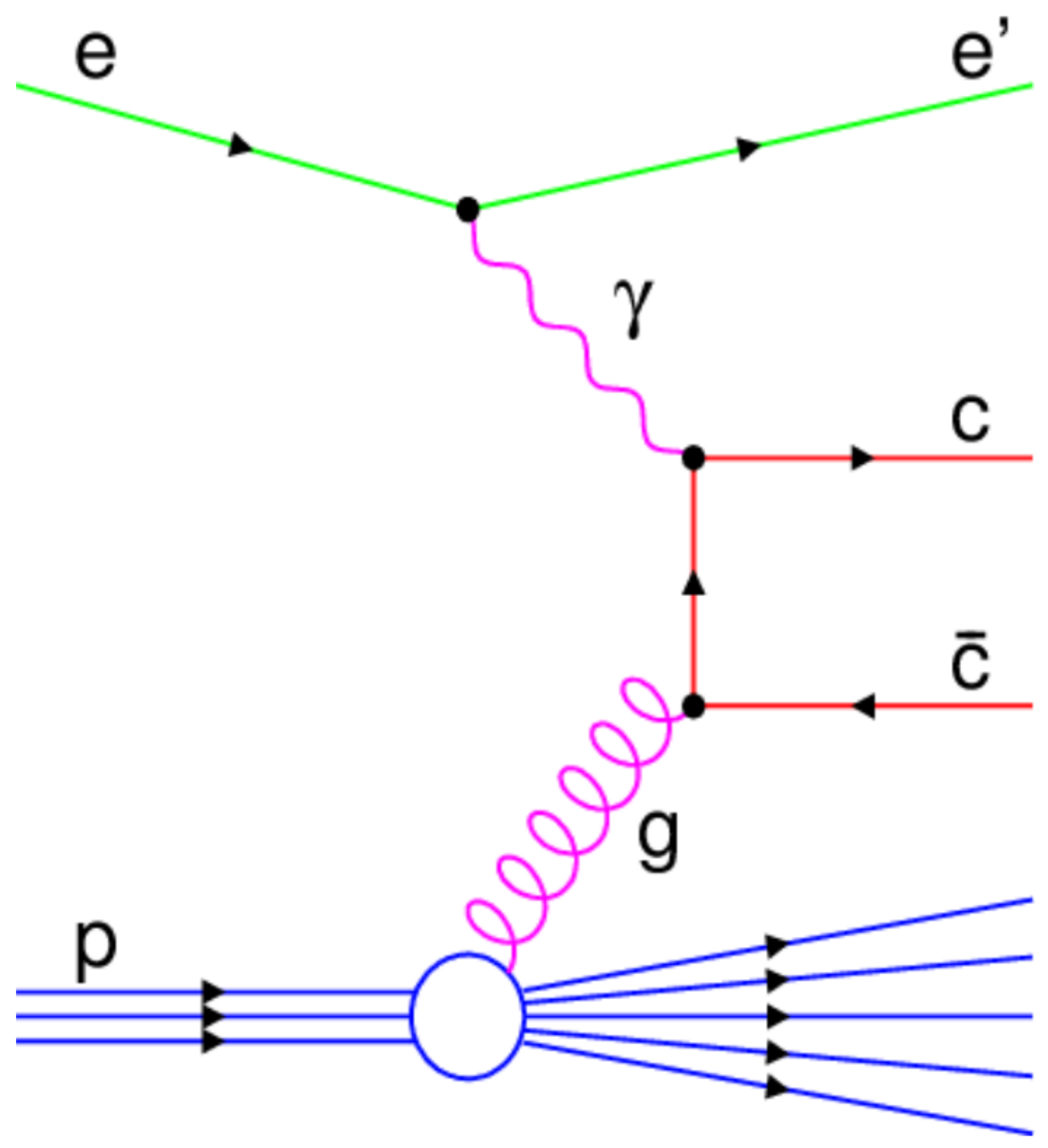
$$A_1^c \equiv \frac{1}{D(y)} A_{LL}^{\vec{e}+\vec{p}\rightarrow e'+D^0+X}$$

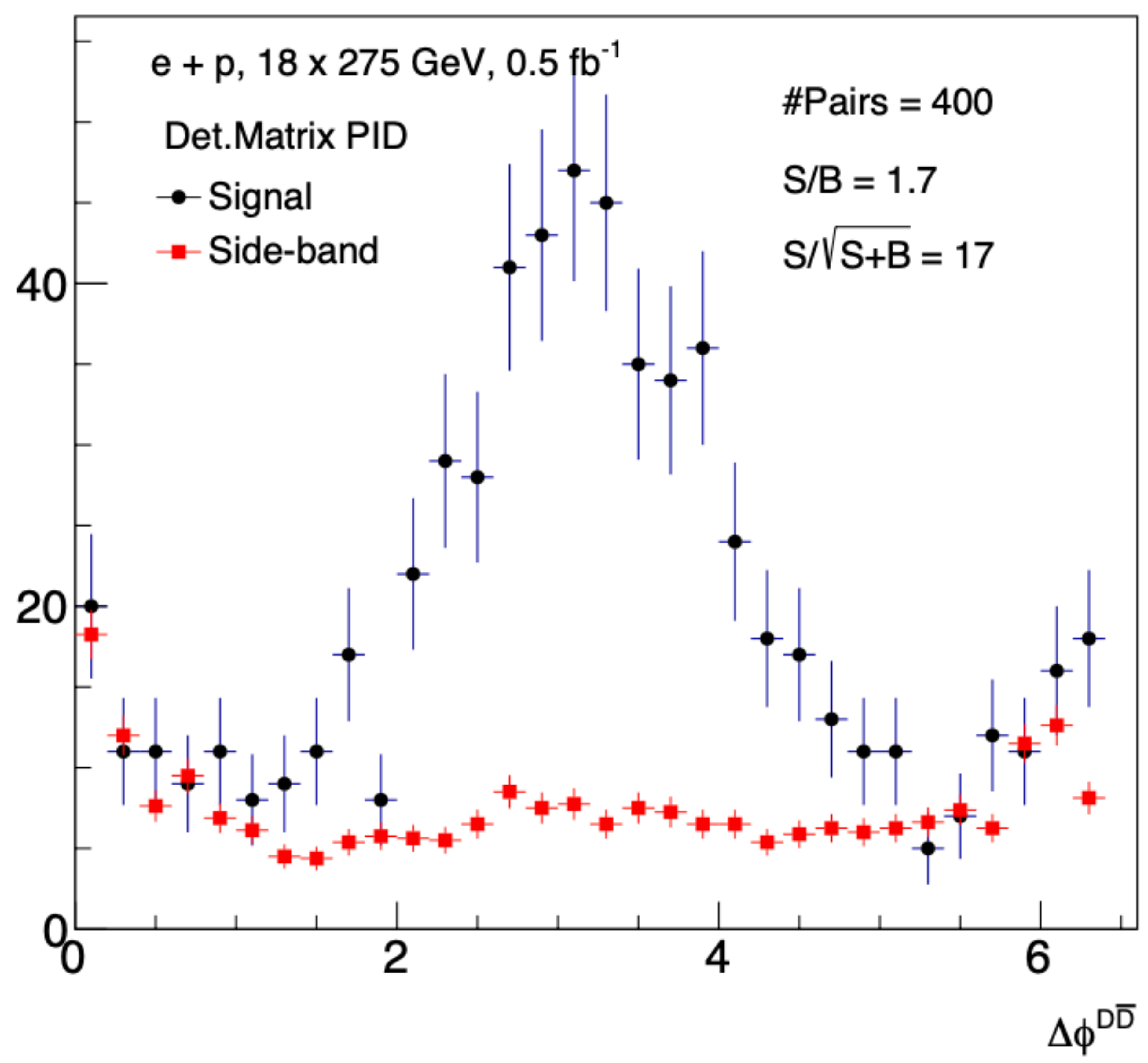
$$= \frac{1}{D(y)} \frac{1}{P_e P_p} \frac{N++-N+-}{N+++N+-}$$

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

- Access to Δg/g over a broad kinematic range
- Impact on gluon helicity distributions evaluated through pdf reweighing

D^0 Meson Pair Reconstruction





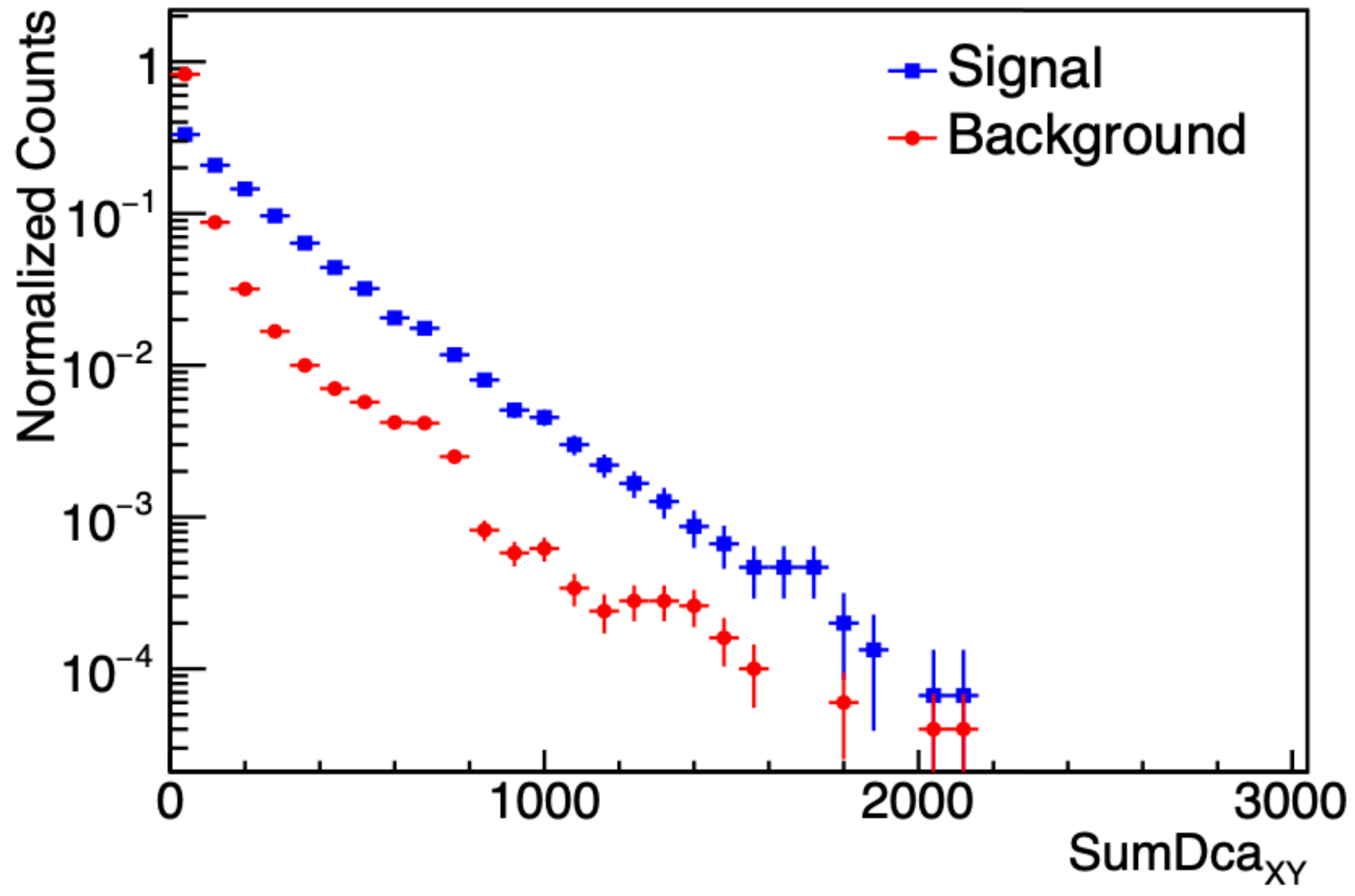
Signal: Unlike sign Kπ pairs within 3σ of D^0 mass peak

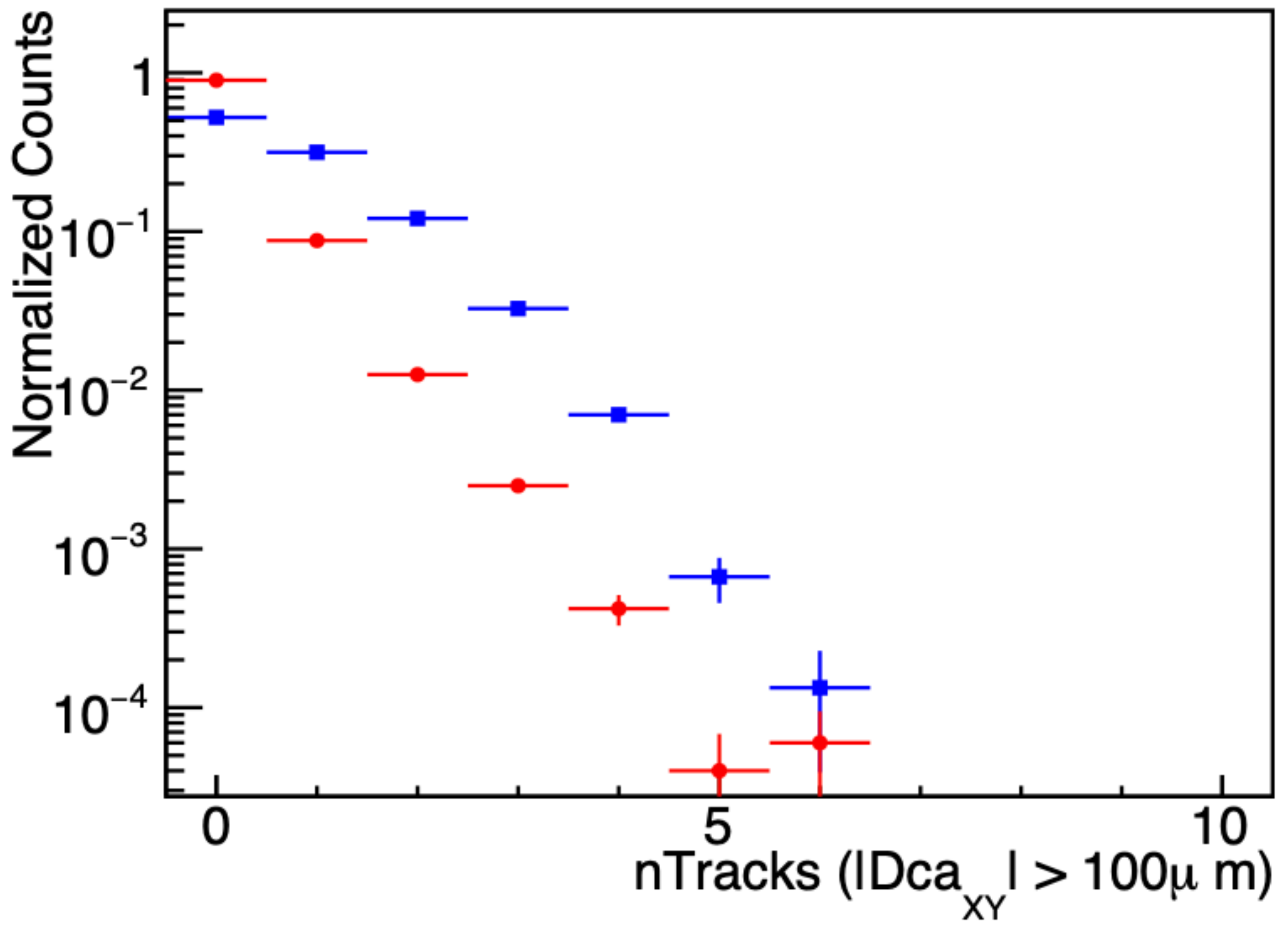
Background: Unlike sign Kπ pairs within 6 to 12σ on either side of D^0 mass peak

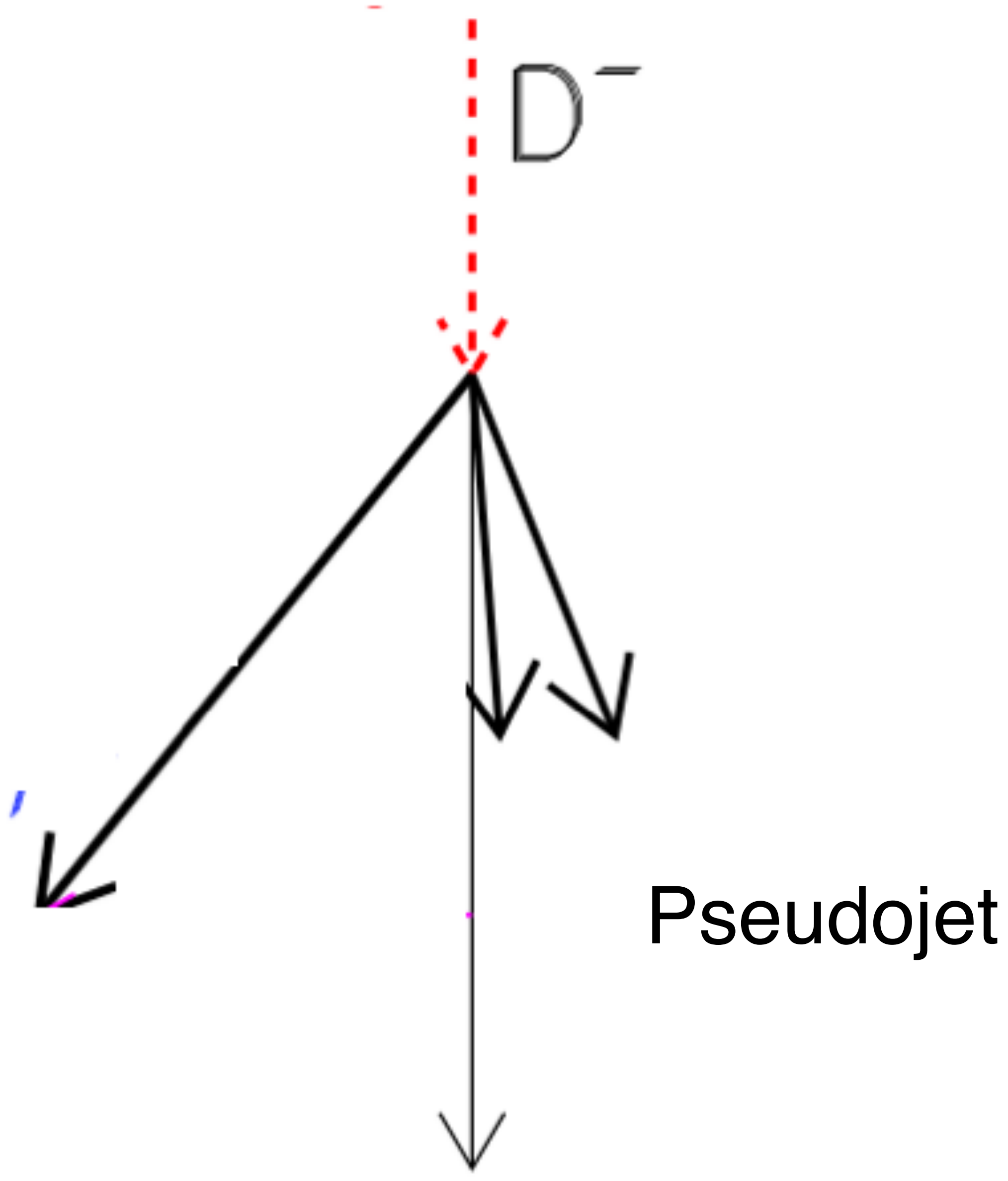
- Heavy flavor hadron pair reconstruction gives access to gluon transverse kinematics —> direct probes of gluon TMDs
- Good signal to background ratio and signal significance for D meson pair reconstruction

Heavy Flavor Tagging

- Exclusive reconstruction suffers from low branching ratios, ~3% for D^0 —> Kπ
- Utilize HF hadron decay topology to tag heavy flavor hadrons

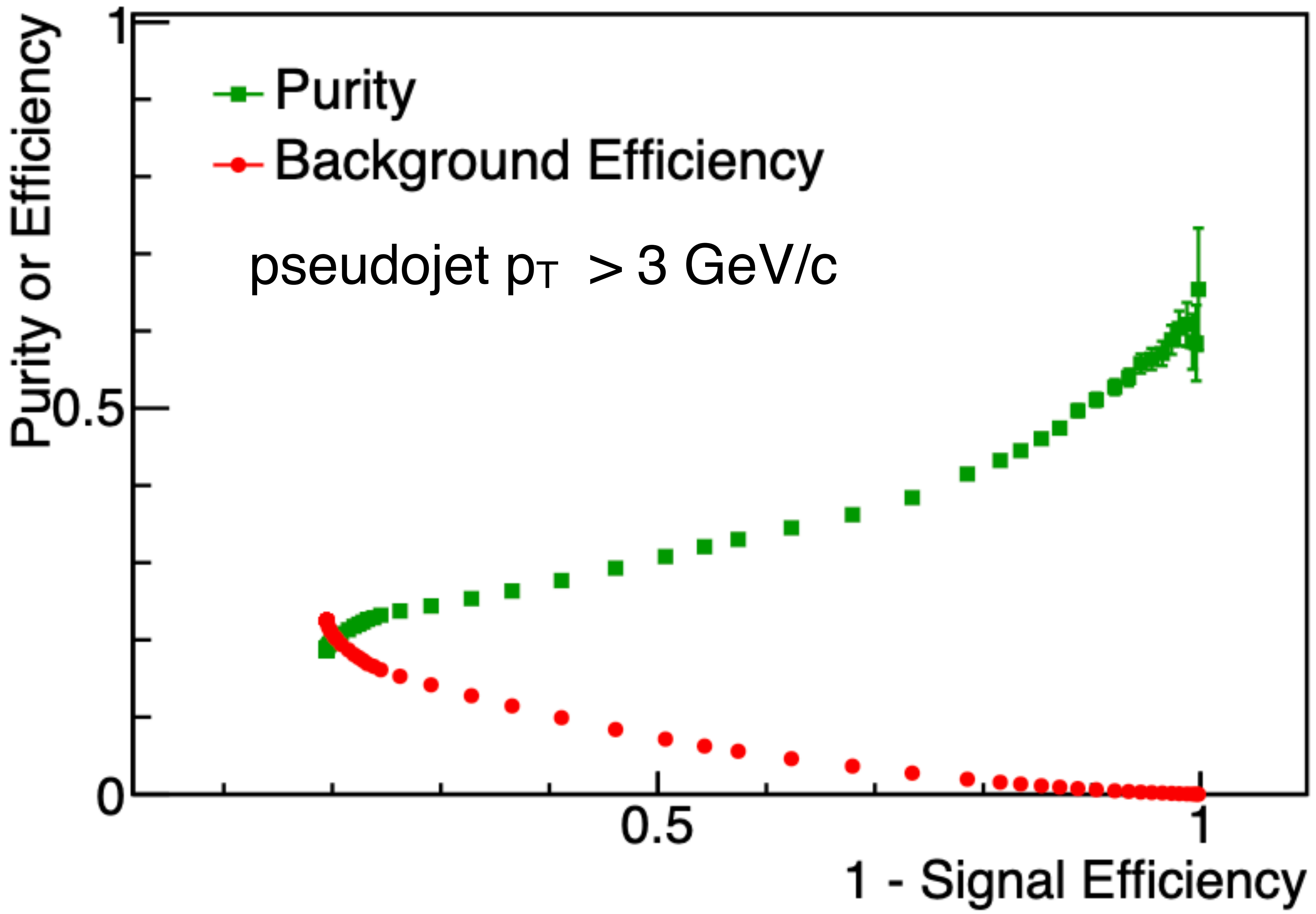


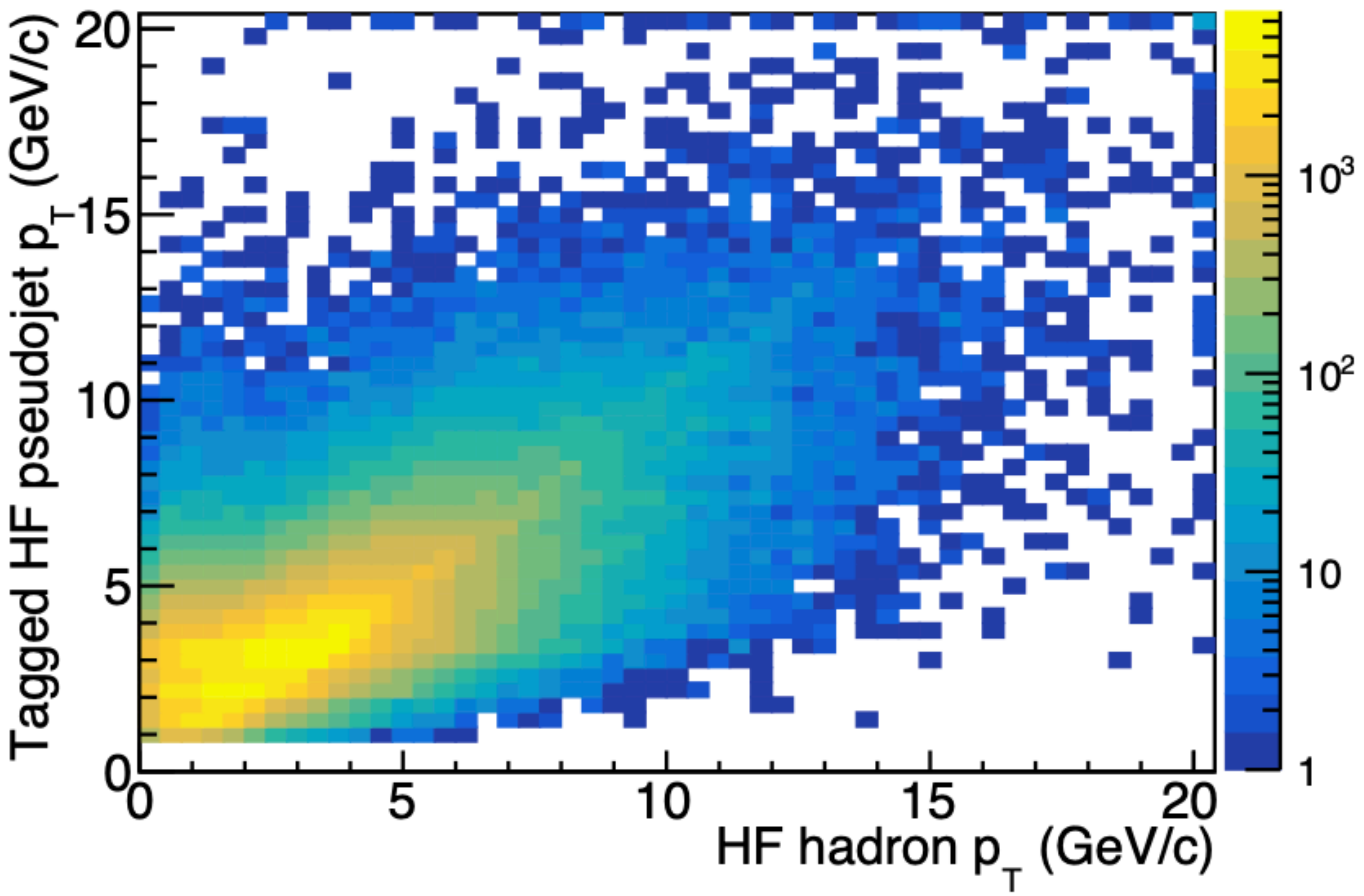




- Used Fastjet package for clustering, Anti-k_T with R = 1.0
- Construct topological variables for jets from constituent tracks. Excellent signal to background separation
- Different jet variables combined using Boosted Decision Trees
- Truth tagging: if parent HF hadron momentum falls within jet cone,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

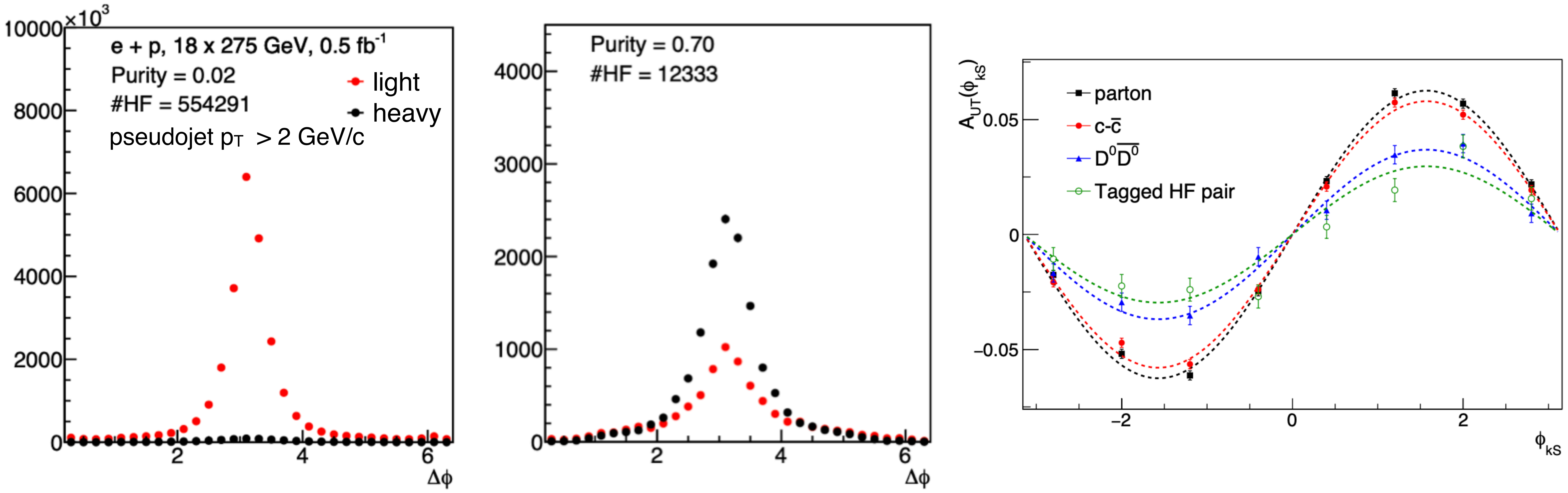
Heavy Flavor Tagging Performance





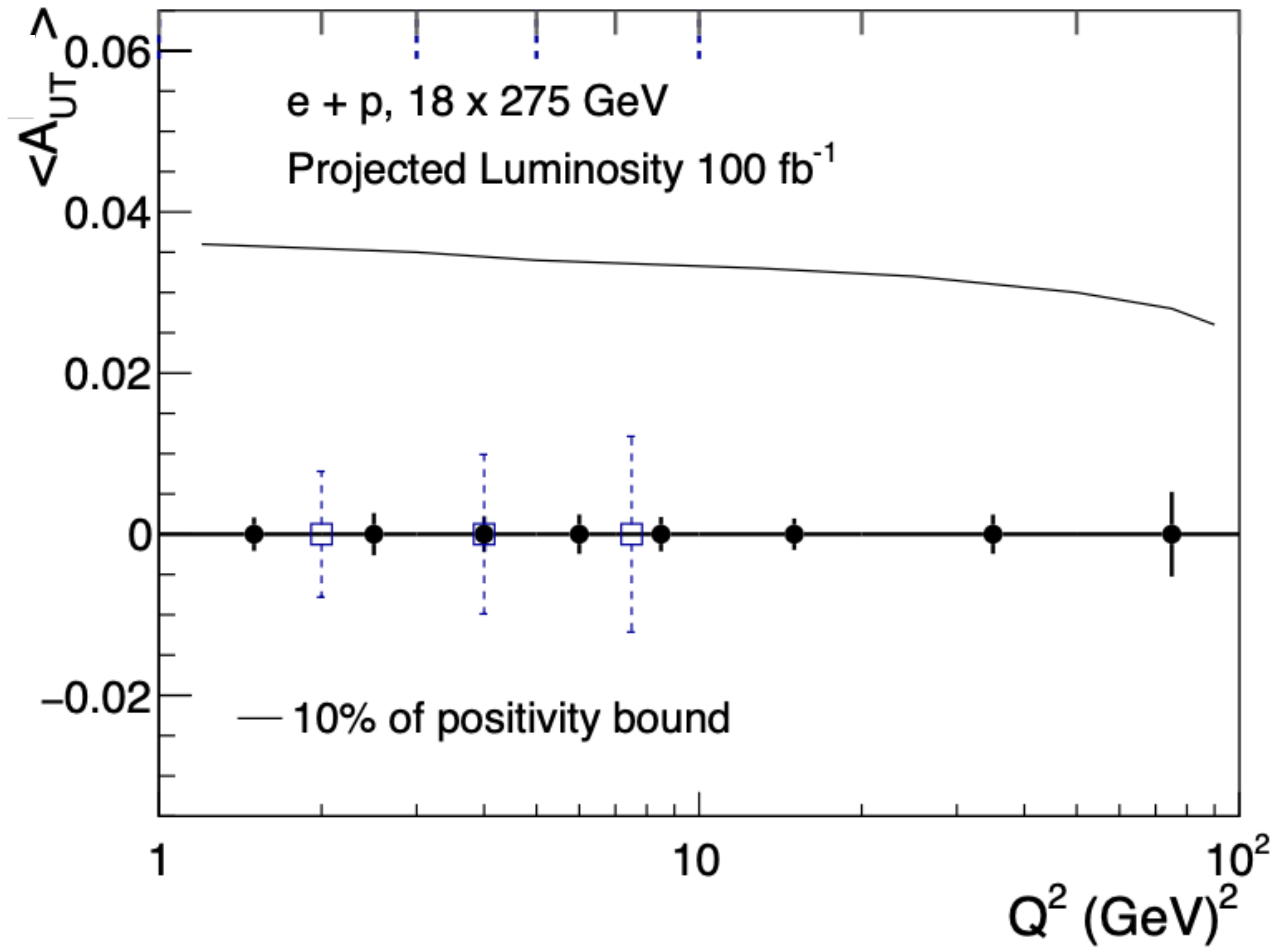
- About 60% purity at 10% signal efficiency for single jet tagging
- Good correlation between reconstructed jet and hadron momenta

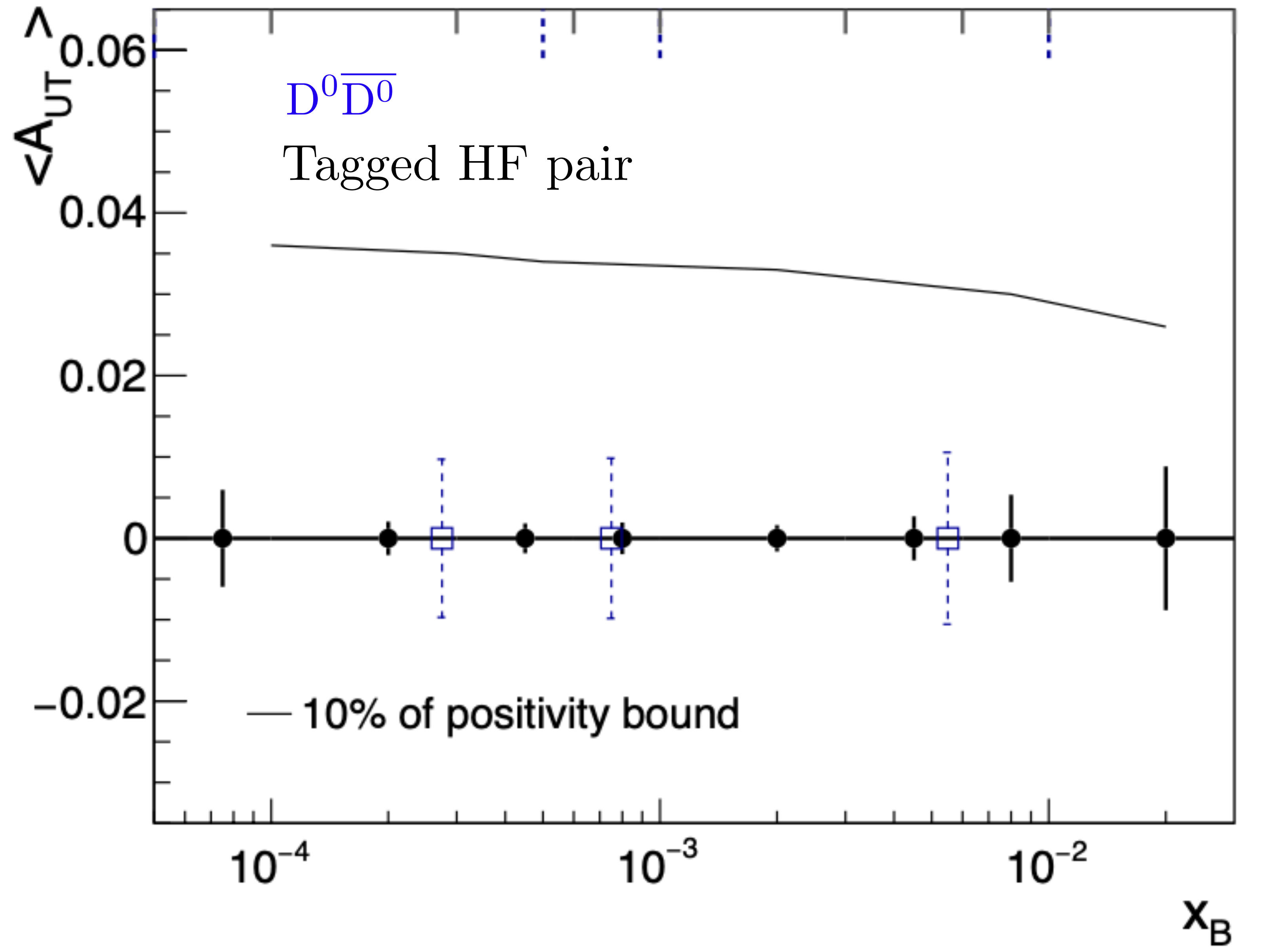
Heavy Flavor Tagging Performance



- 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





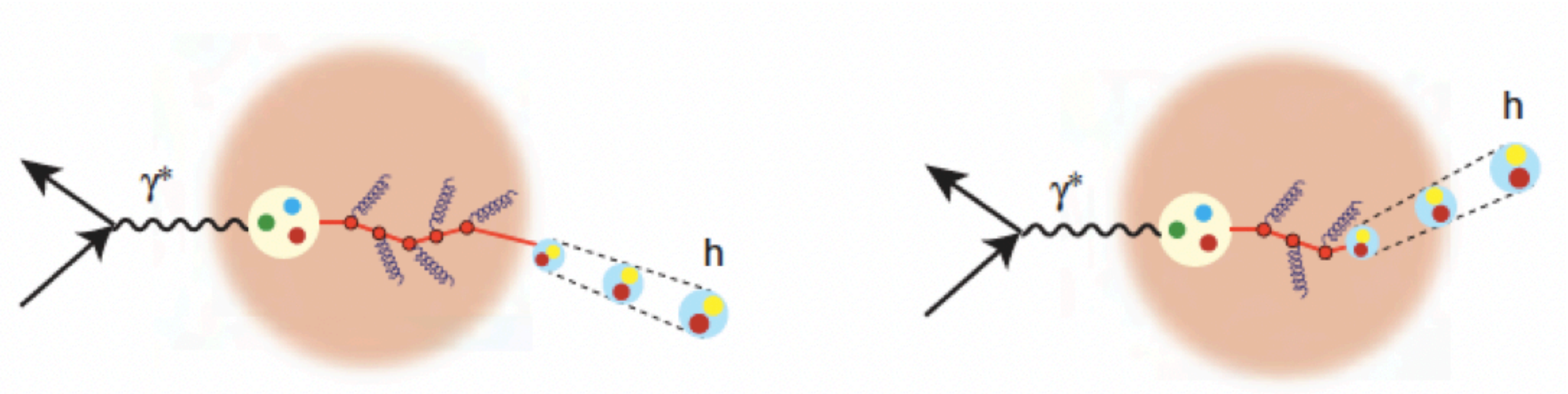
- For gluon Sivers asymmetry:
  Statistical uncertainty projections for transverse SSA A_{UT} with tagged HF pair:
  $$\delta A_{UT}^{HF} = \delta A_{UT}^{measured}/\text{purity}/\text{Polarization}$$

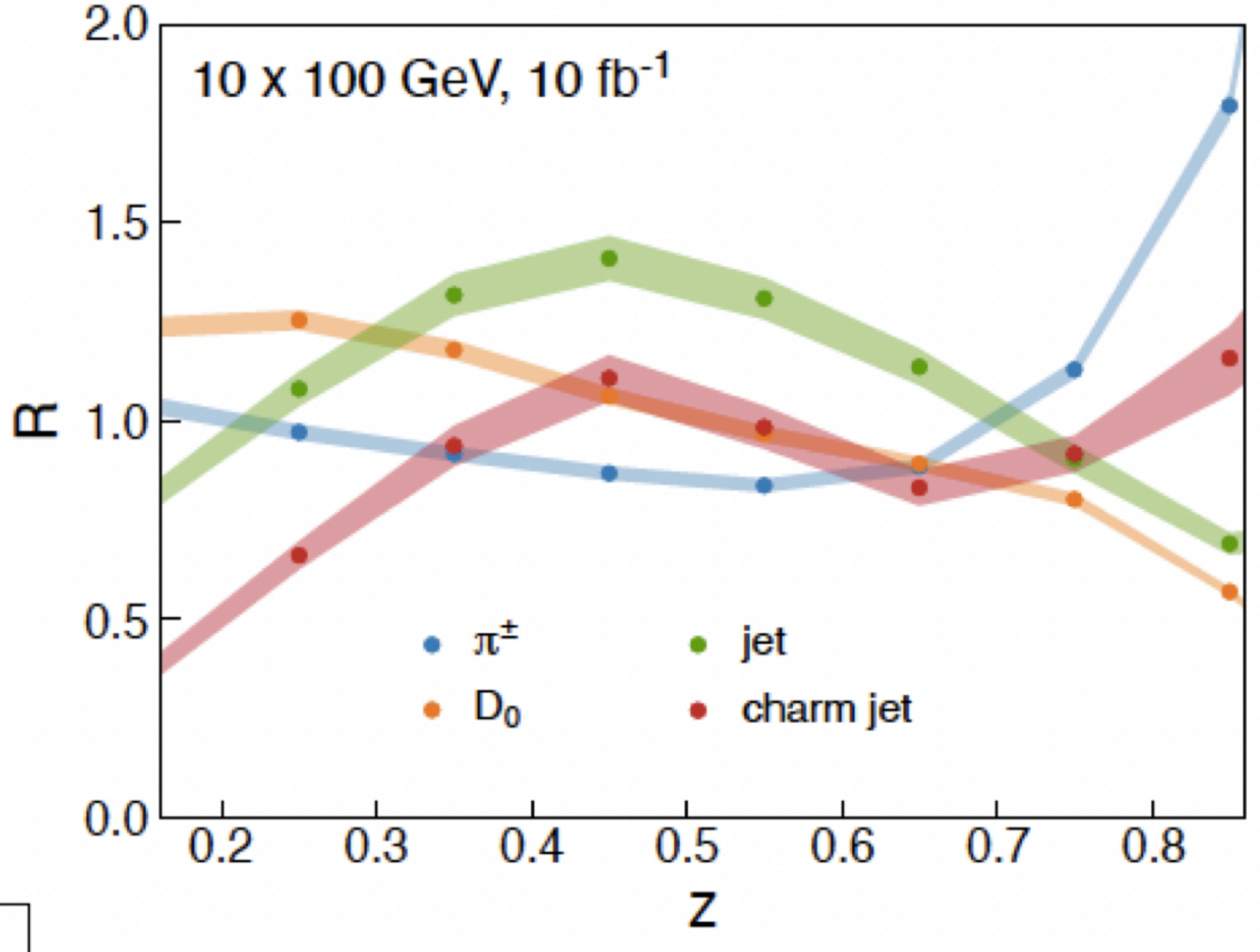
- Far improved (nearly an order of magnitude) improved precision for A_{UT}^{HF} measurements with tagged HF compared to using DDbar

- Linearly polarized gluon TMD can also be measured using transverse anisotropy. Similar error bars, but without dilution from polarization

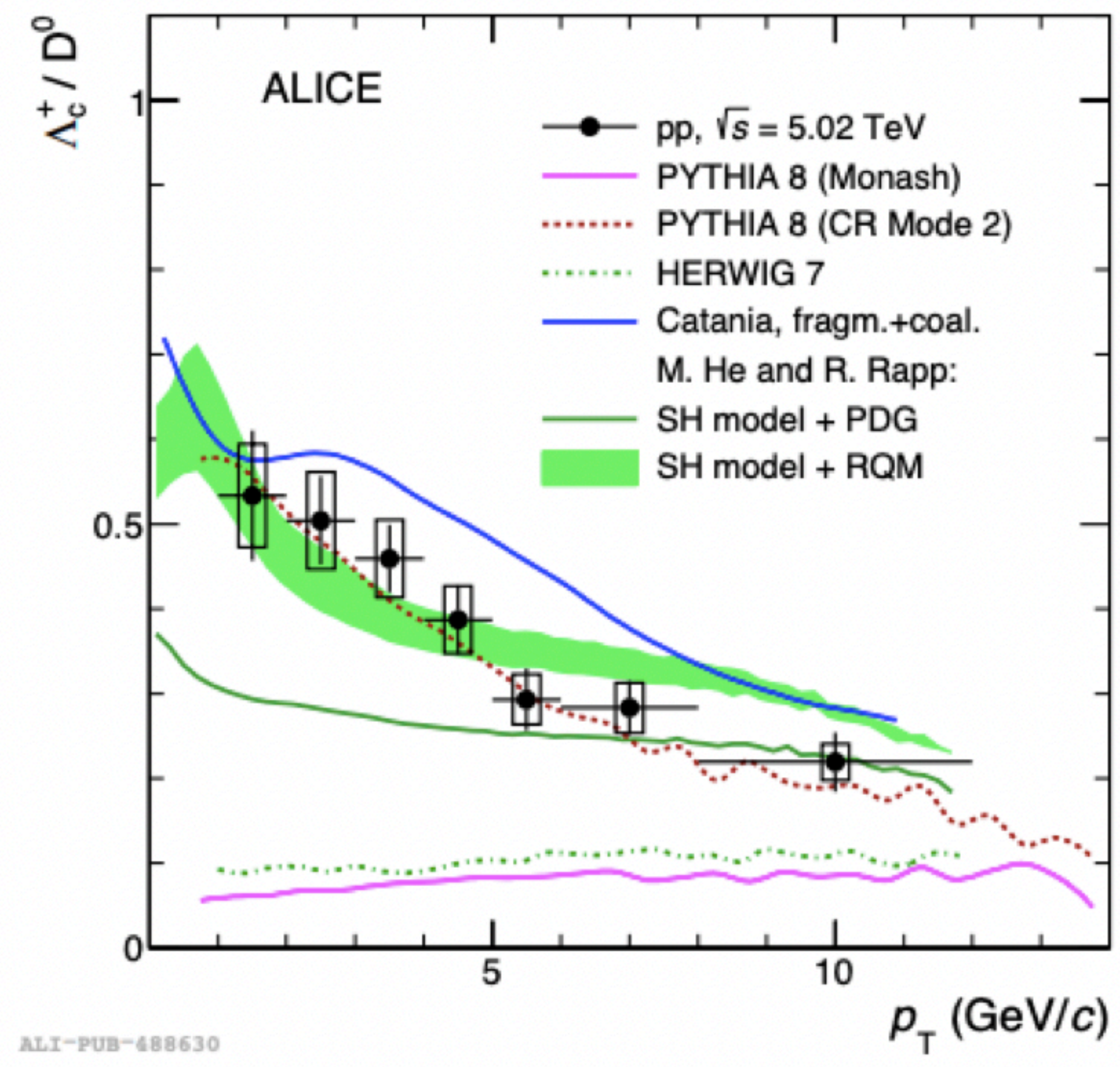
- Tagging can significantly help other measurements also: other gluon TMDs, interactions with nuclear matter etc

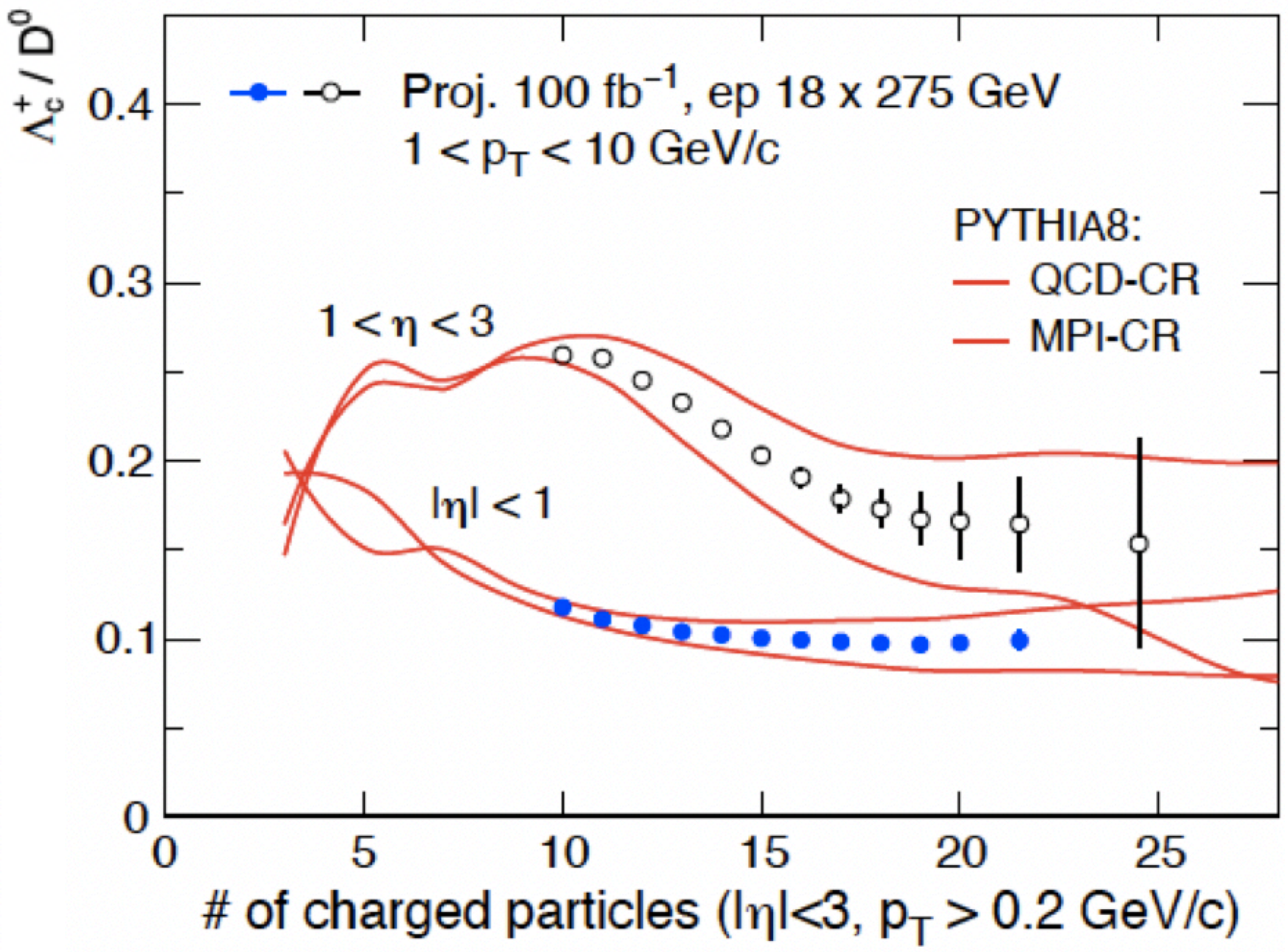
Study hadronization using HF hadrons





- 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 ~2% to ~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

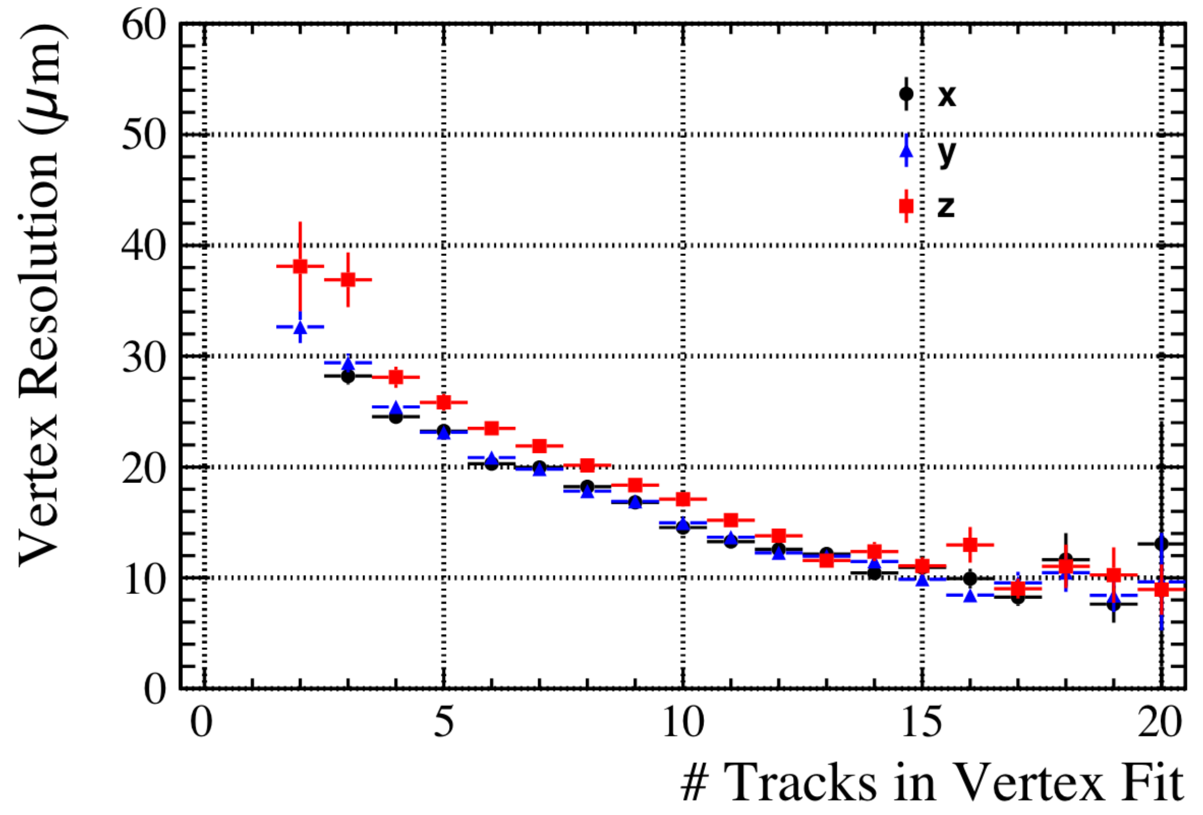
Position resolution

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

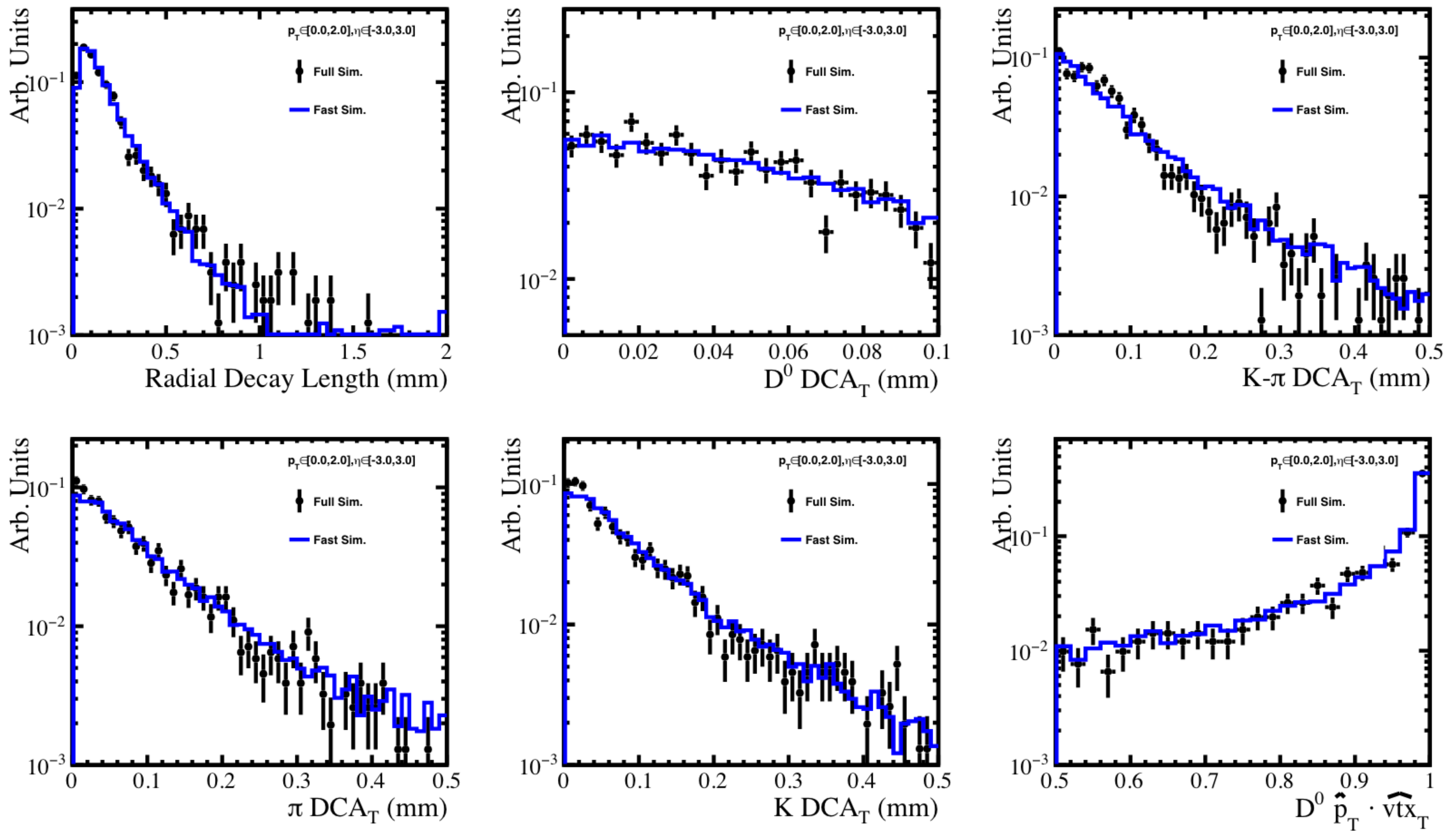
Mom resolution

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

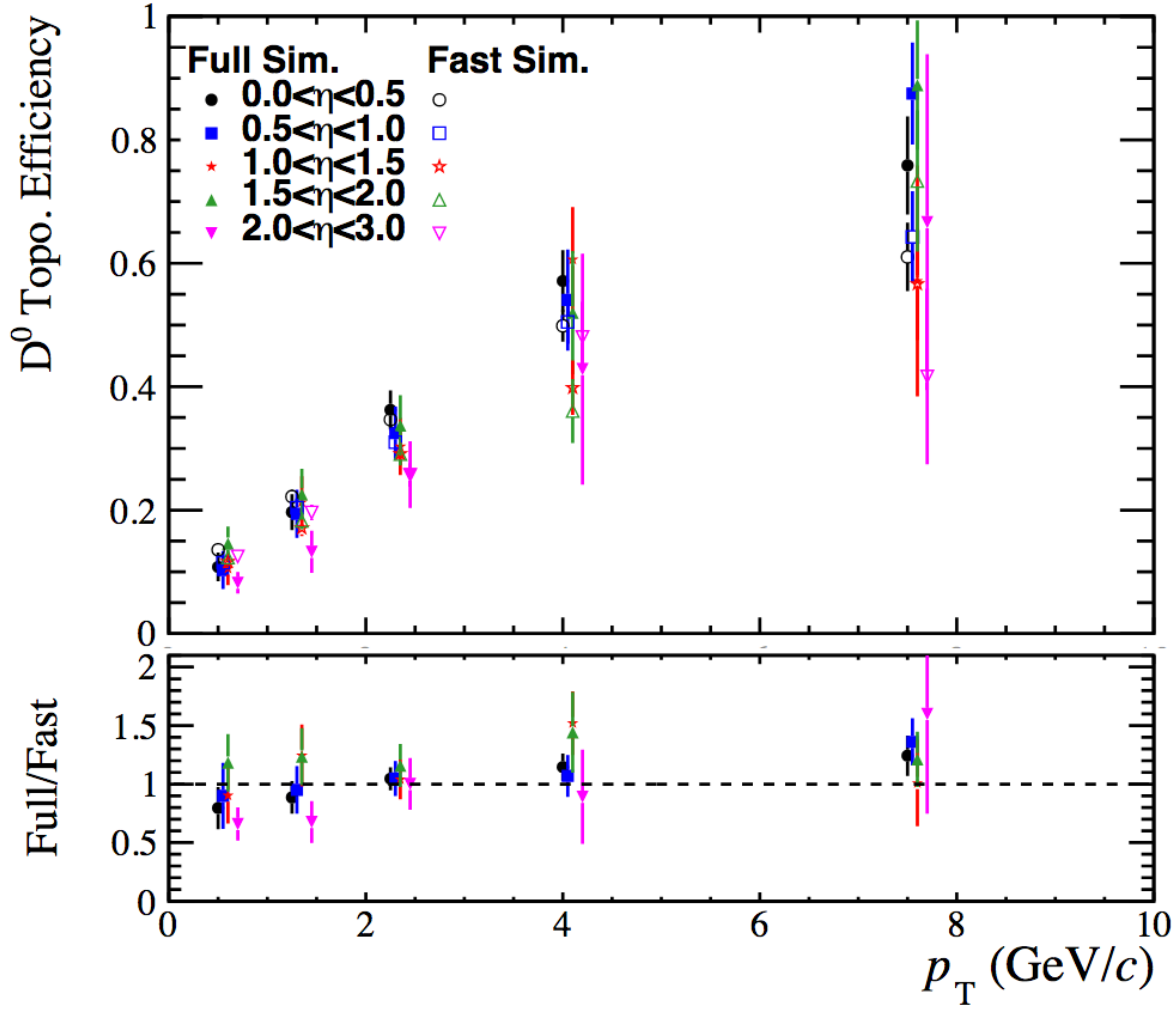
- Primary vertex resolution taken from full simulation



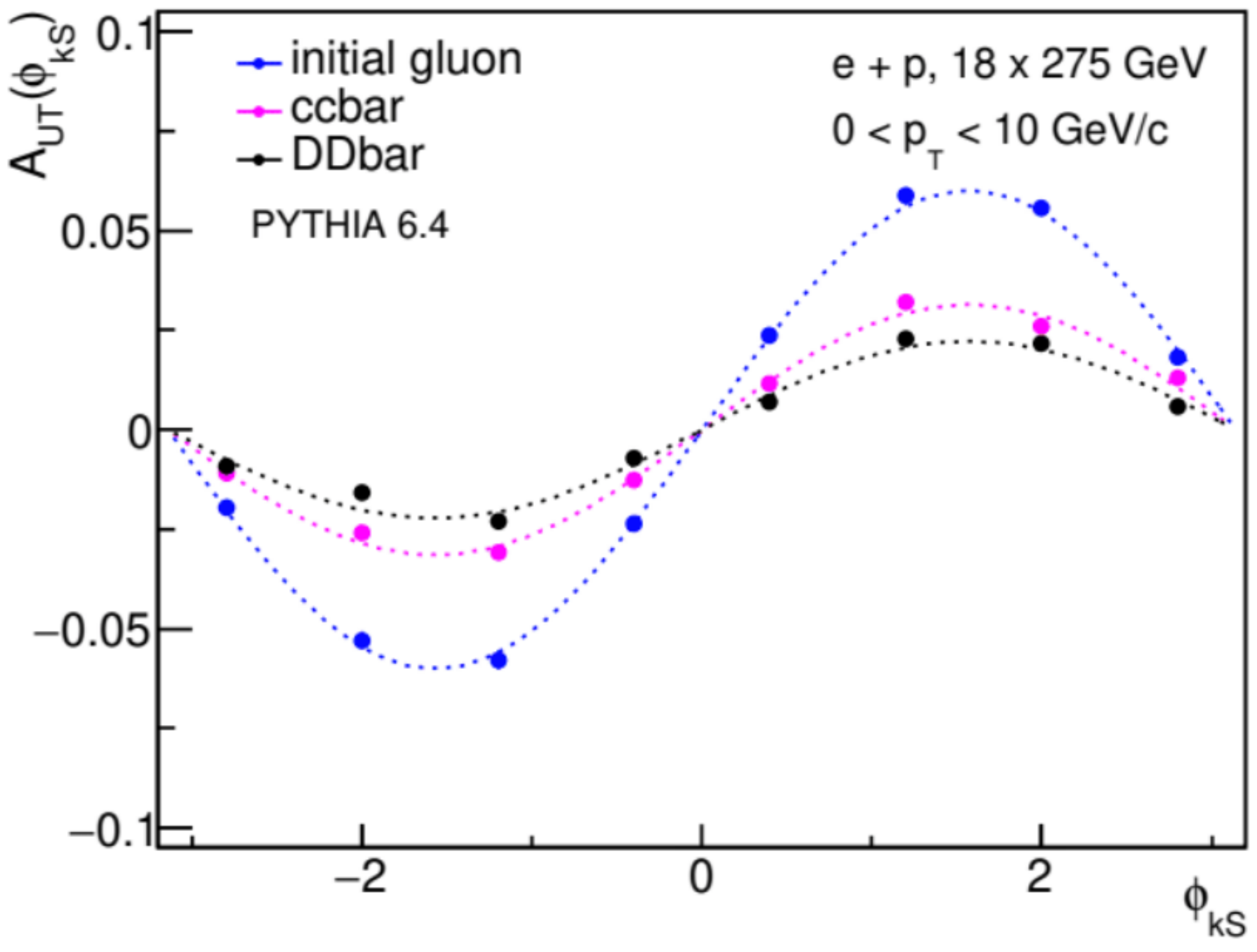
- Fast simulation performance was validated using full simulation

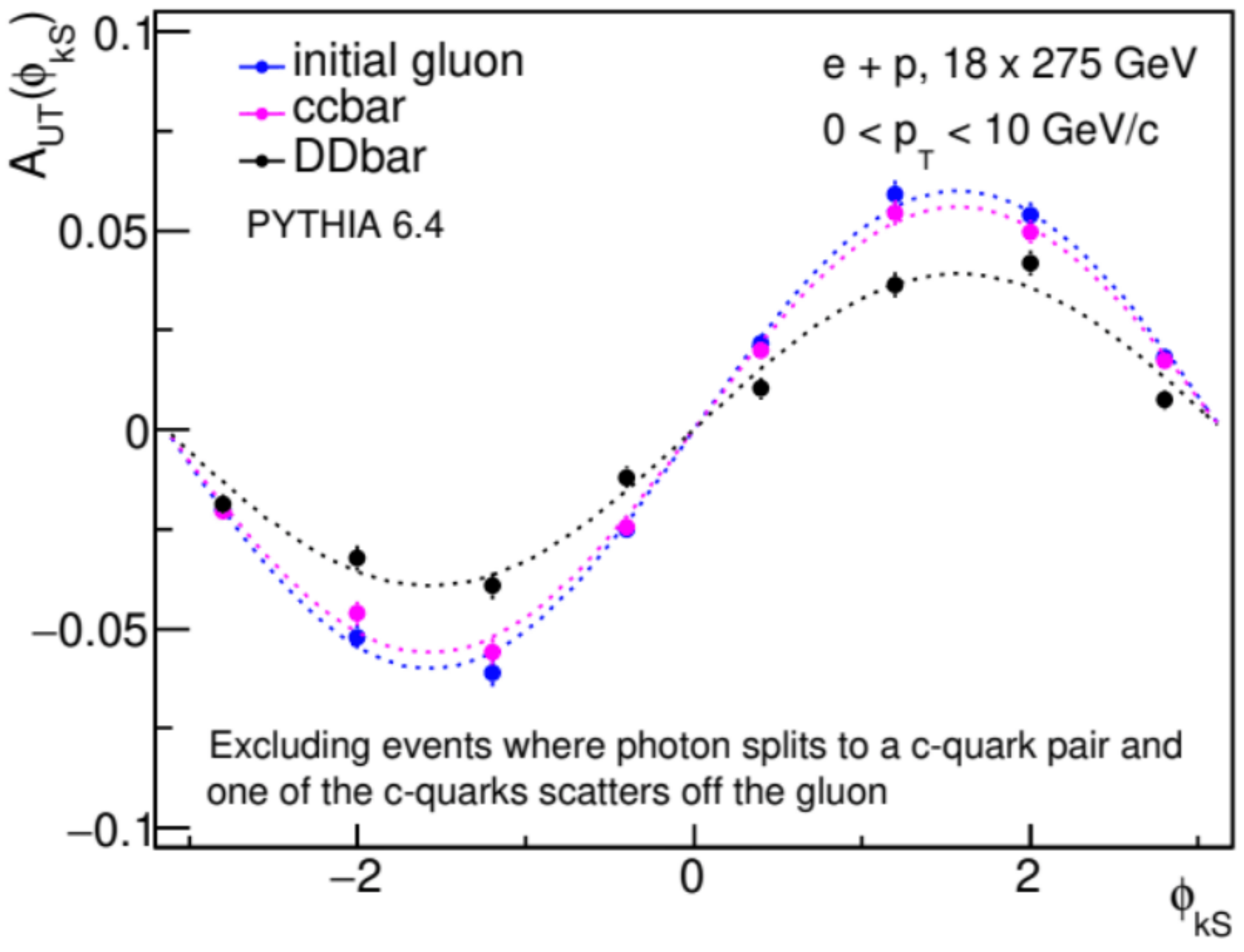


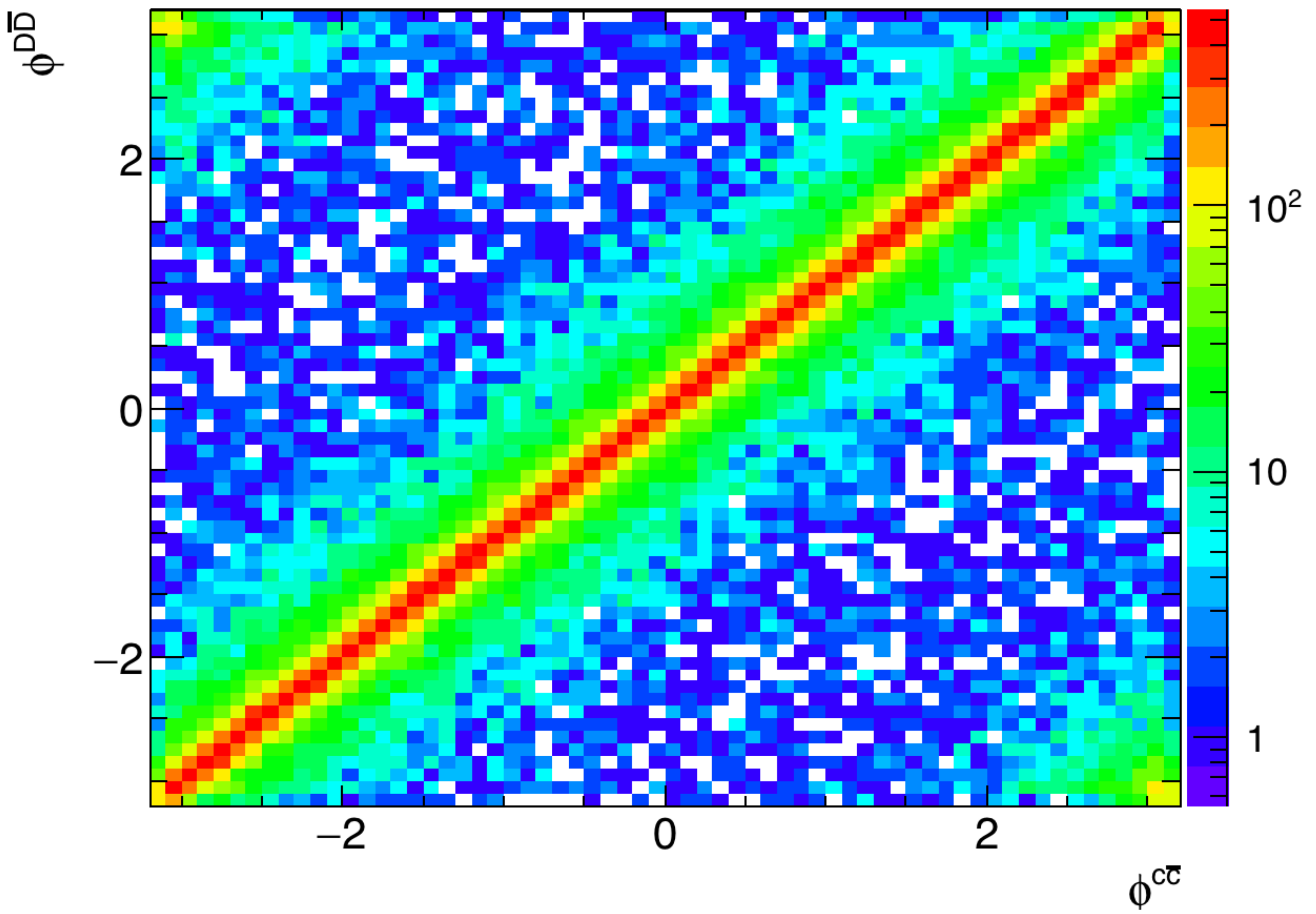
D Meson Topological Cut Efficiency

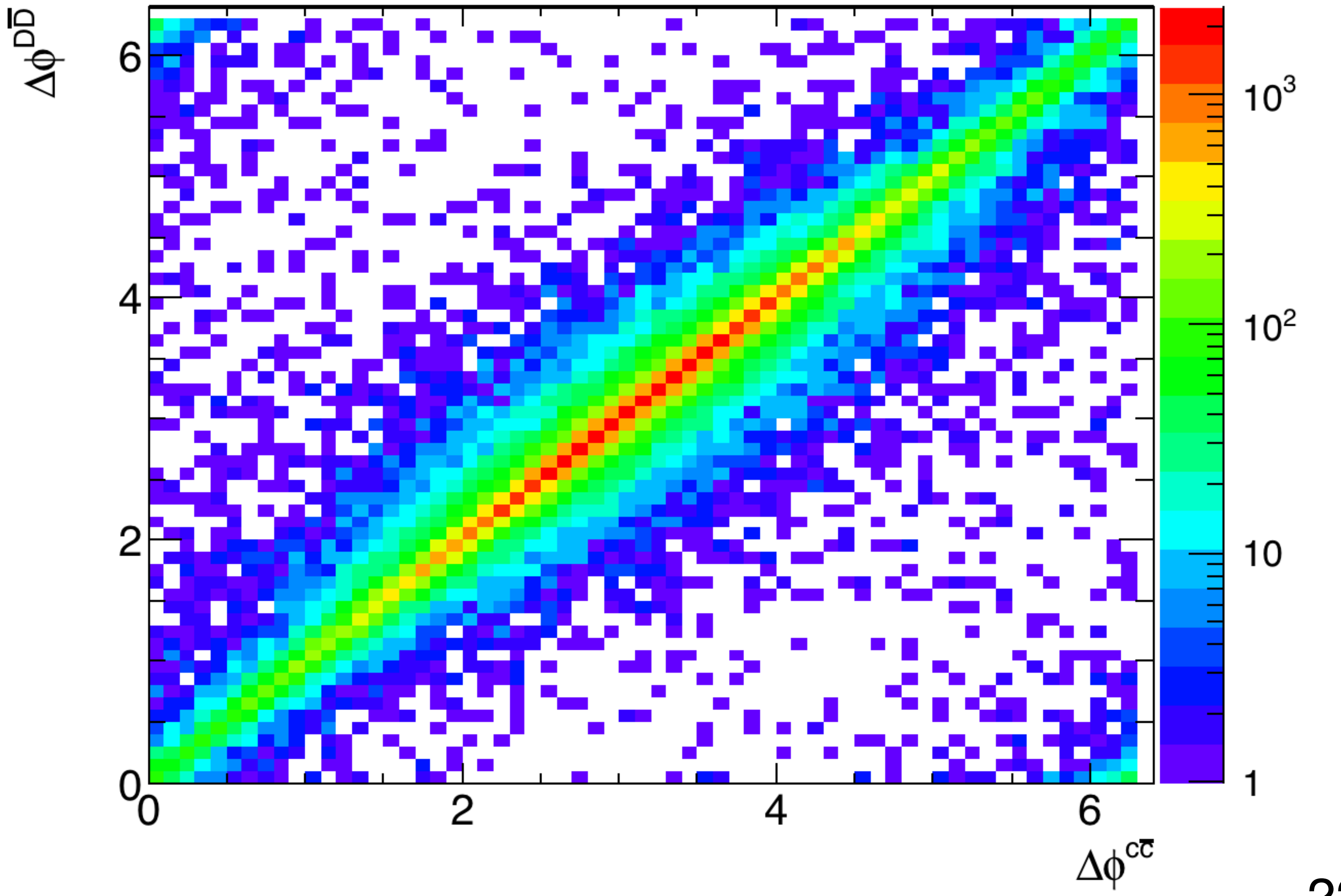


Correlations between Partonic and Hadronic Stages









- 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