Probing gluon TMDs with reconstructed and tagged heavy flavor hadron pairs at the EIC

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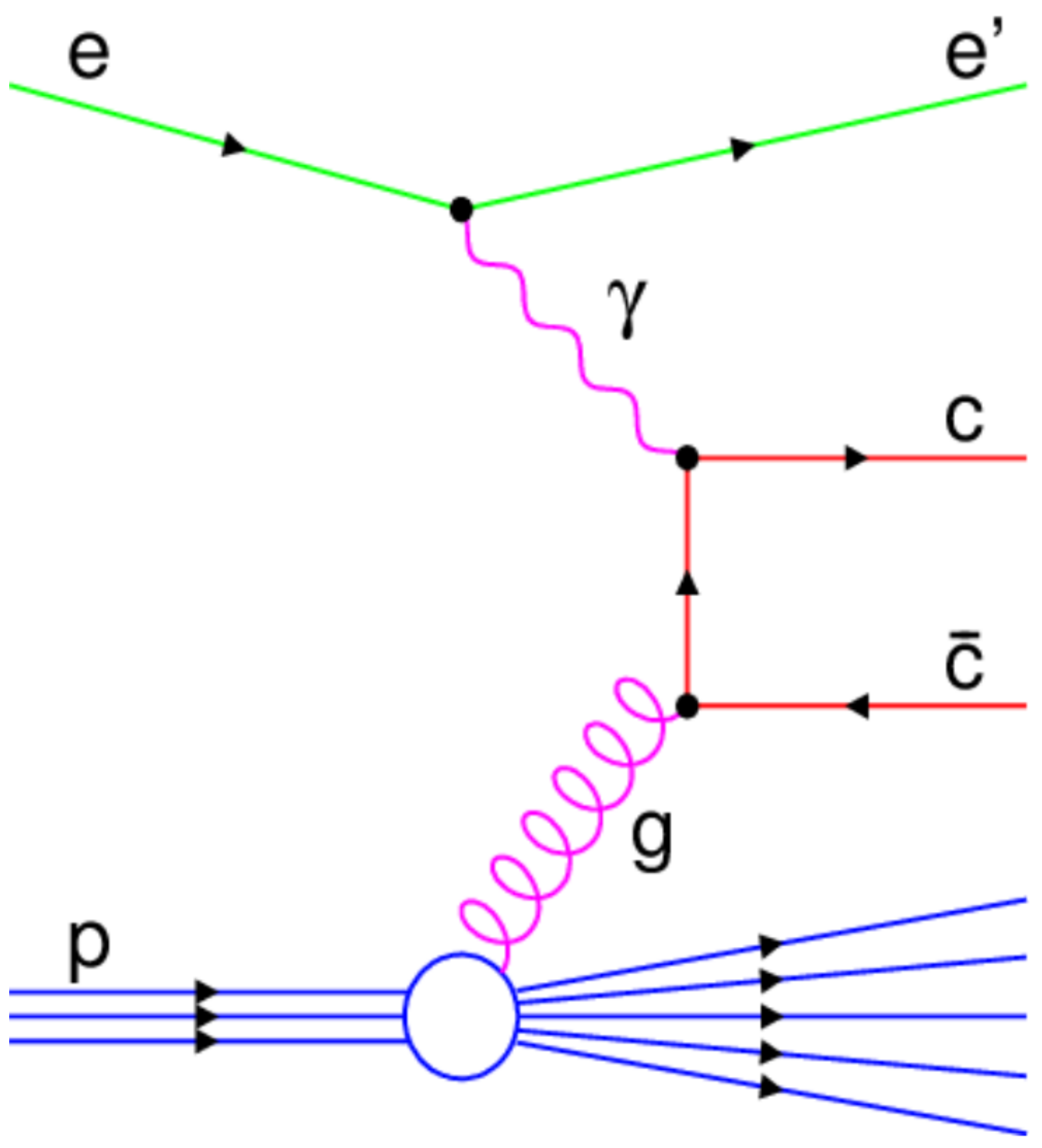
Outline

- Introduction
- Simulation setup
- Uncertainty projections on transverse asymmetries with exclusive reconstruction
- Heavy flavor tagging at the EIC
- Uncertainty projections with tagged HF hadrons
- Summary

Heavy Quark Pairs as Probes of Gluon TMD

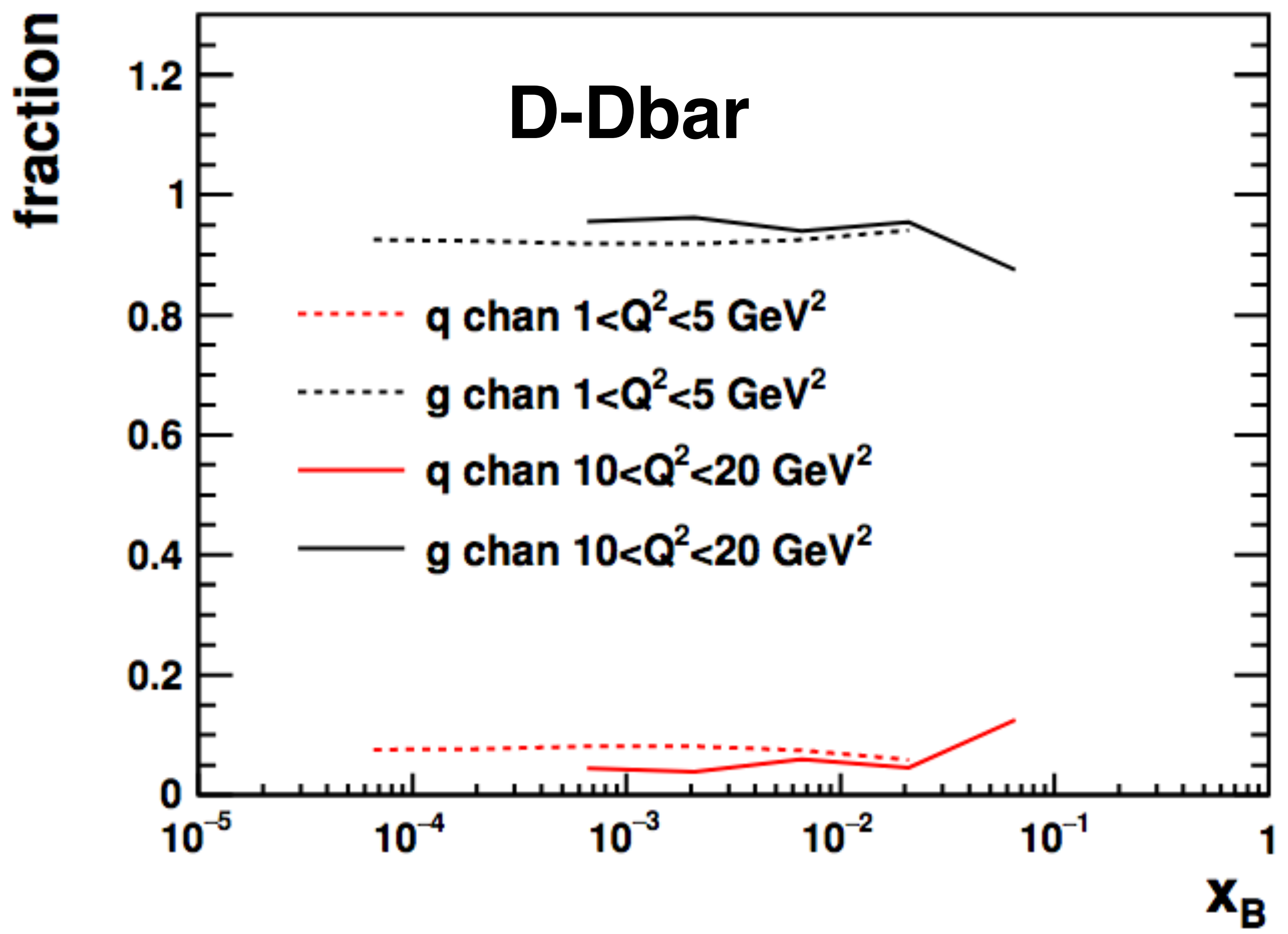


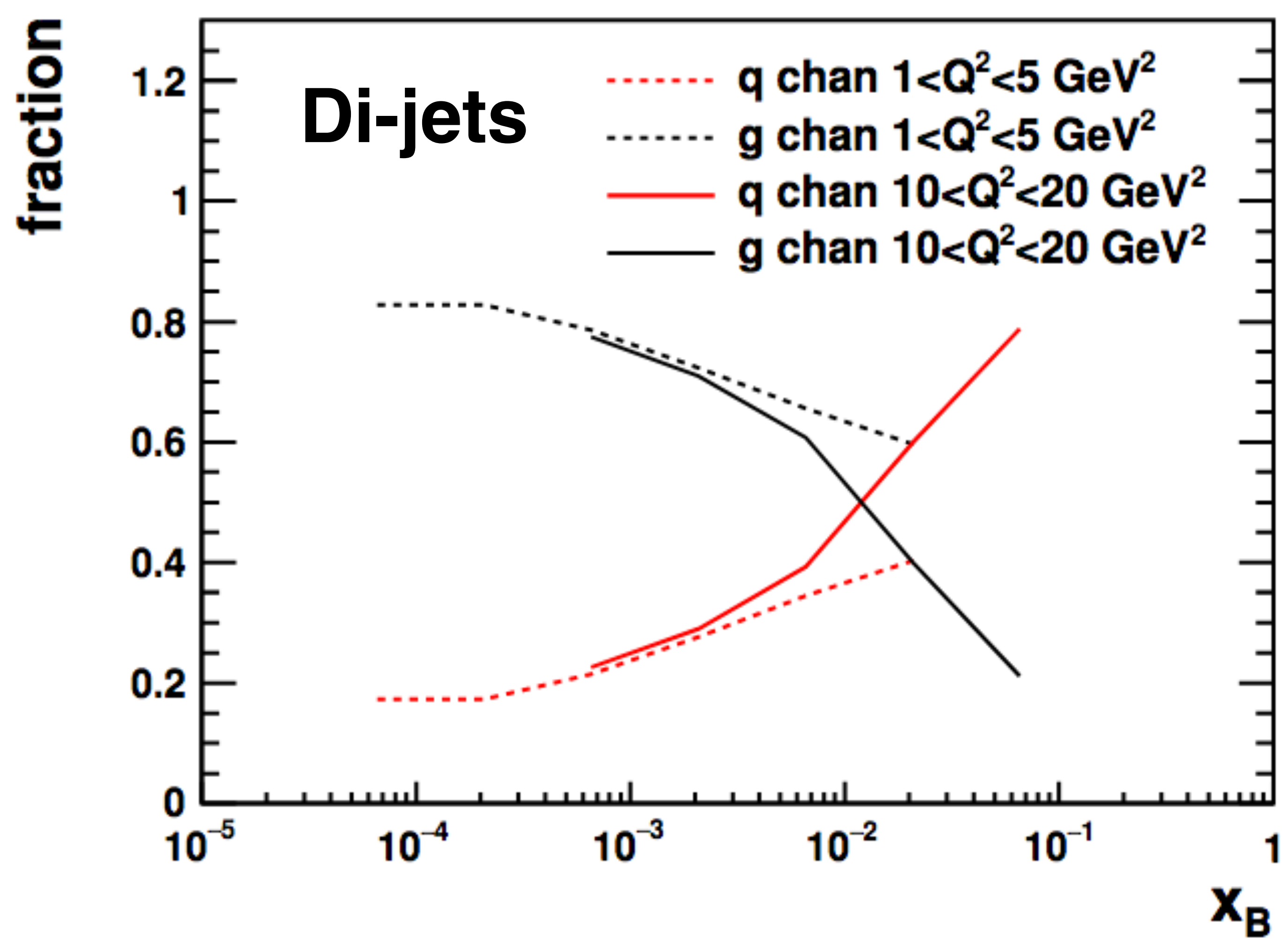
- Heavy quark production in DIS: leading order contribution from photon gluon fusion process
- Ideal to probe gluon distributions

- HQ pair production sensitive to the transverse momentum of the gluons
- Possibility to study gluon TMDs by reconstructing heavy hadron pairs at the EIC
- Gluon TMDs currently poorly constrained by experiments

- Unique sensitivity to gluon TMDs at high x_B, complementary to di-jets/di-hadrons at low x_B

L.Zheng et.al PhysRevD.98.034011





Heavy Quark Pairs as Probes of Gluon TMD

- Sivers function - correlation between proton spin and transverse momentum of parton
- Can be accessed in transversley polarized e+p (e+A) collisions

- Contributes the measured transverse single spin asymmetry

$$A_{UT}(\phi_{kS}, k_T) = \frac{d\sigma^{\uparrow}(\phi_{kS}, k_T) - d\sigma^{\downarrow}(\phi_{kS}, k_T)}{d\sigma^{\uparrow}(\phi_{kS}, k_T) + d\sigma^{\downarrow}(\phi_{kS}, k_T)} \propto \frac{\Delta^N f_{g/p^{\uparrow}}(x, k_{\perp})}{2 f_{g/p}(x, k_{\perp})},$$

Sivers previous studies: L.Zheng et.al PhysRevD.98.034011

- TMD of linearly polarized gluons - important in determining axial charge distributions in the initial stage and thus to the chiral magnetic effects in heavy-ion collisions

T. Lappi, S. Schlichting Phys Rev D. 97. 034034 (2017)

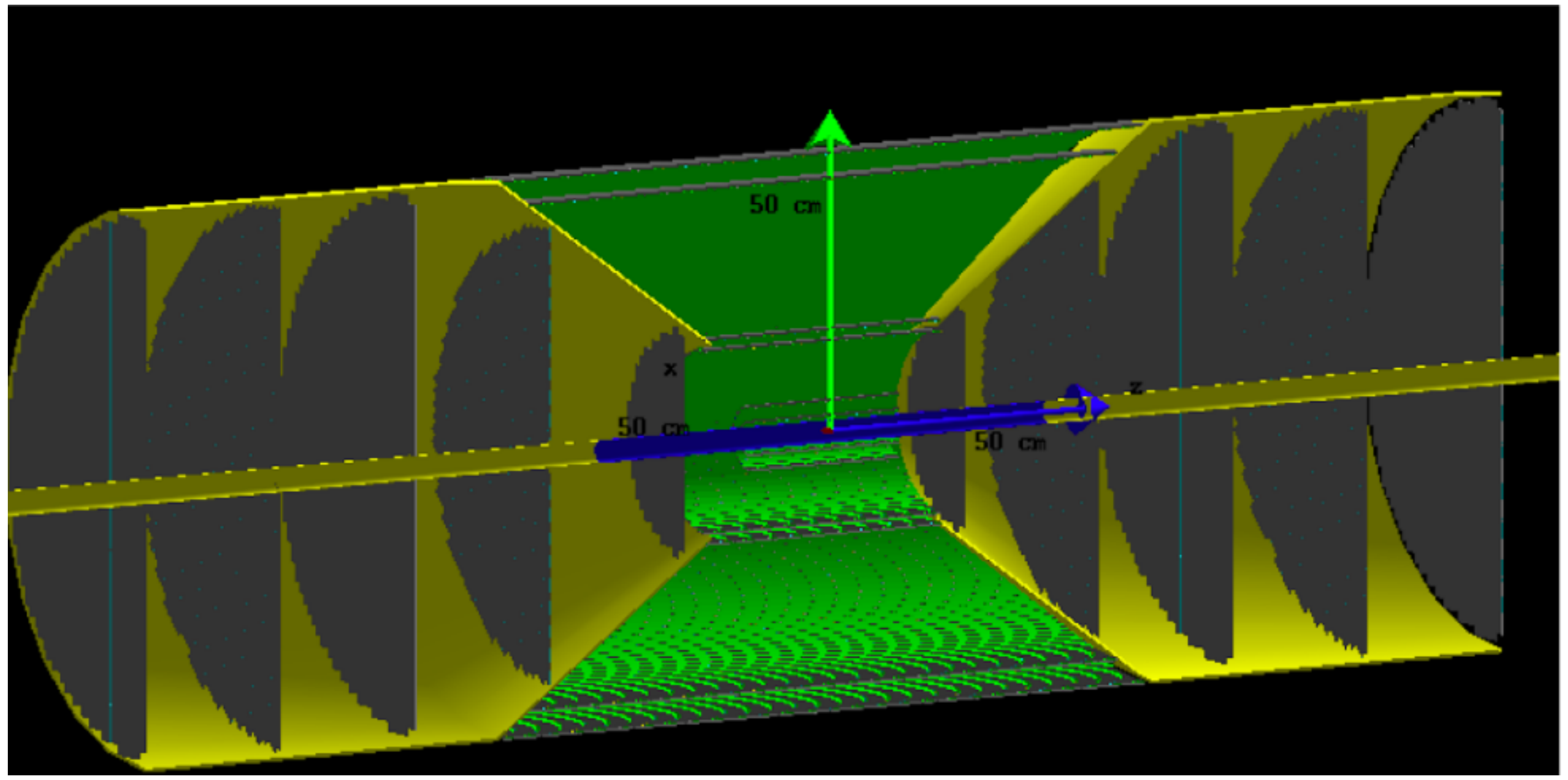
- Can be accessed in unpolarized e+p (e+A) collisions

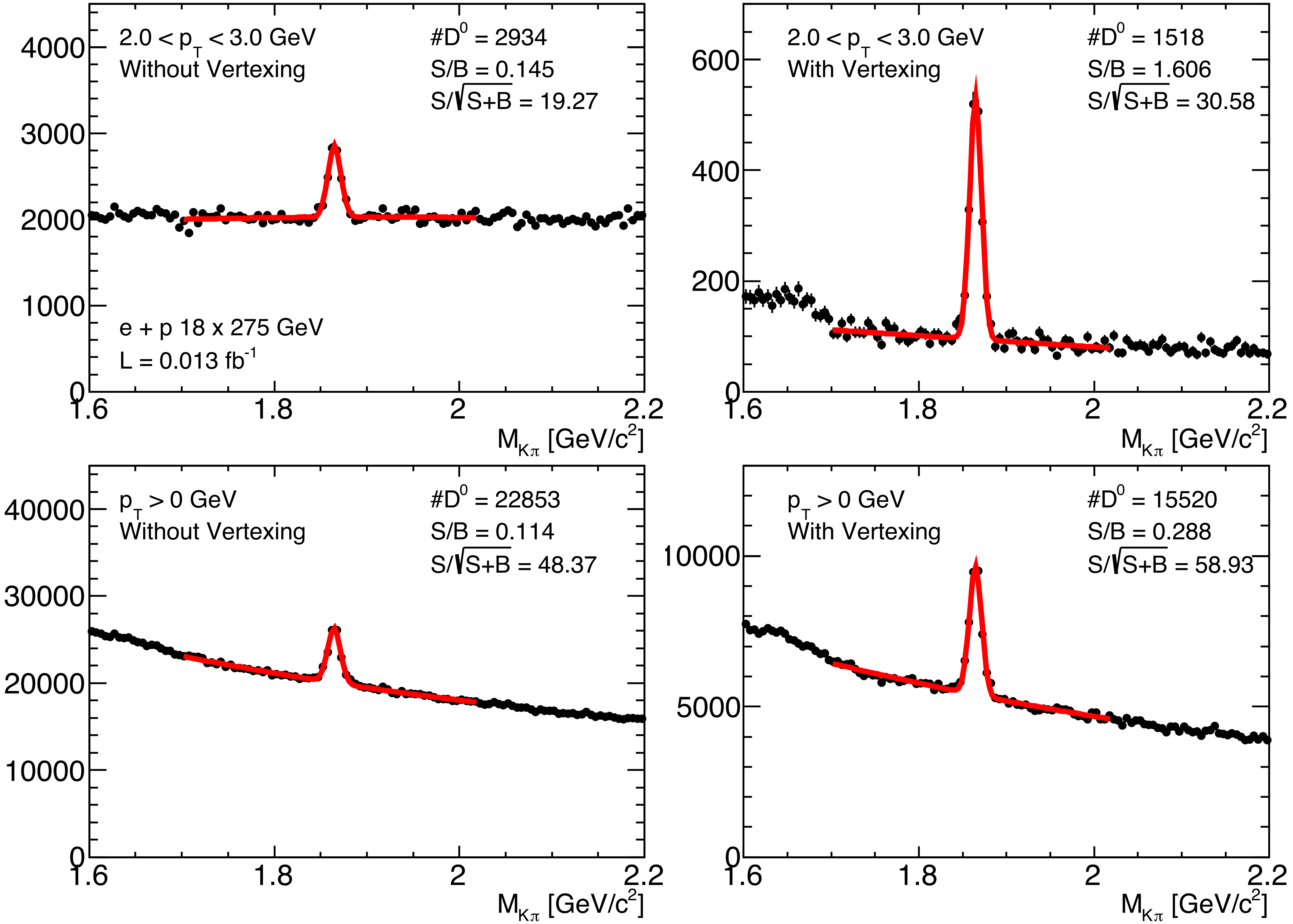
$$|\langle \cos 2\phi_T \rangle| = \frac{\boldsymbol{q}_T^2}{2M^2} \frac{\left|h_1^{\perp g}(x, \boldsymbol{p}_T^2)\right|}{f_1^g(x, \boldsymbol{p}_T^2)} \frac{\left|\mathcal{B}_0^{eg \to eQ\bar{Q}}\right|}{\mathcal{A}_0^{eg \to eQ\bar{Q}}}$$

ϕ_T - azimuthal angle of the HQ hadron pair momentum

LP TMD Signal projections: Daniël Boer EIC YR WG presentation

PYTHIA and EIC Simulation Setup

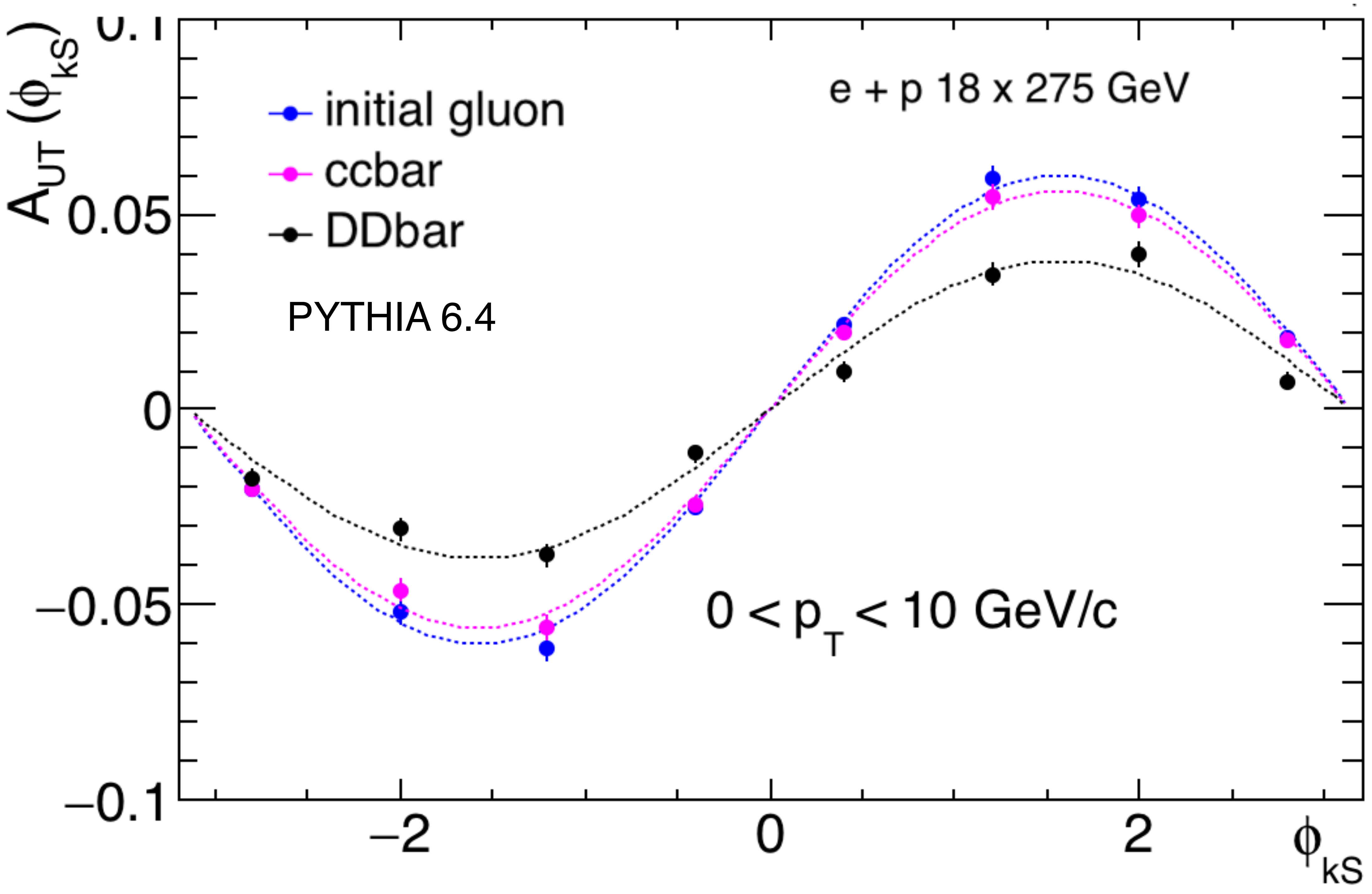


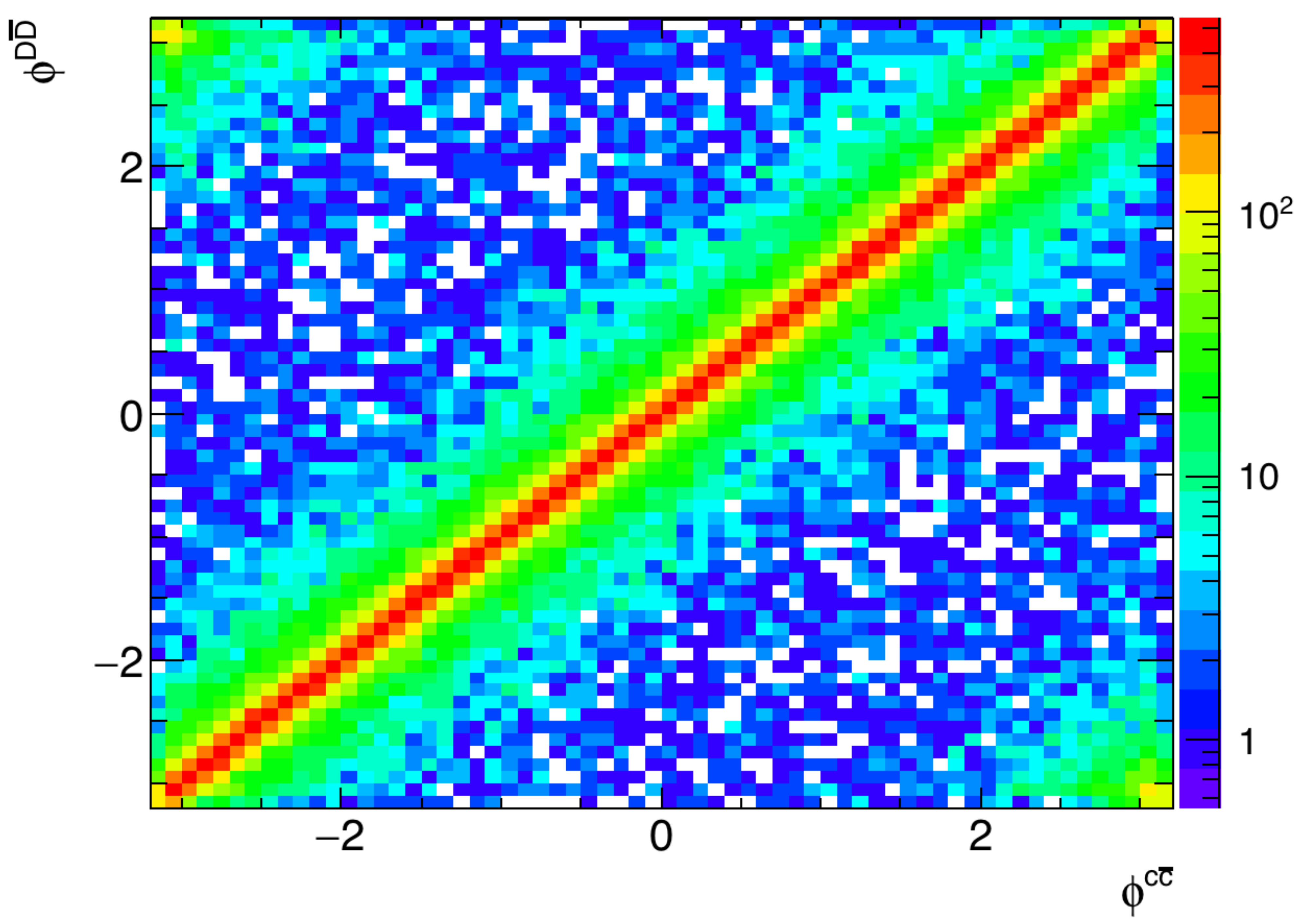


- Pythia6 EIC tune (https://eic.github.io/software pythia6.html)
- All-silicon tracker design composed of MAPS sensors
- 3x2 barrel layers within $|\eta| < 1$
- Five disks in forward and backward regions each, with coverage $1<|\eta|<3$
- Tracking specifications as in EIC YR Det.Matrix: *arXiv:2102.08337*

- Signal significance improves greatly with vertexing cuts

Correlations between Partonic and Hadronic Stages

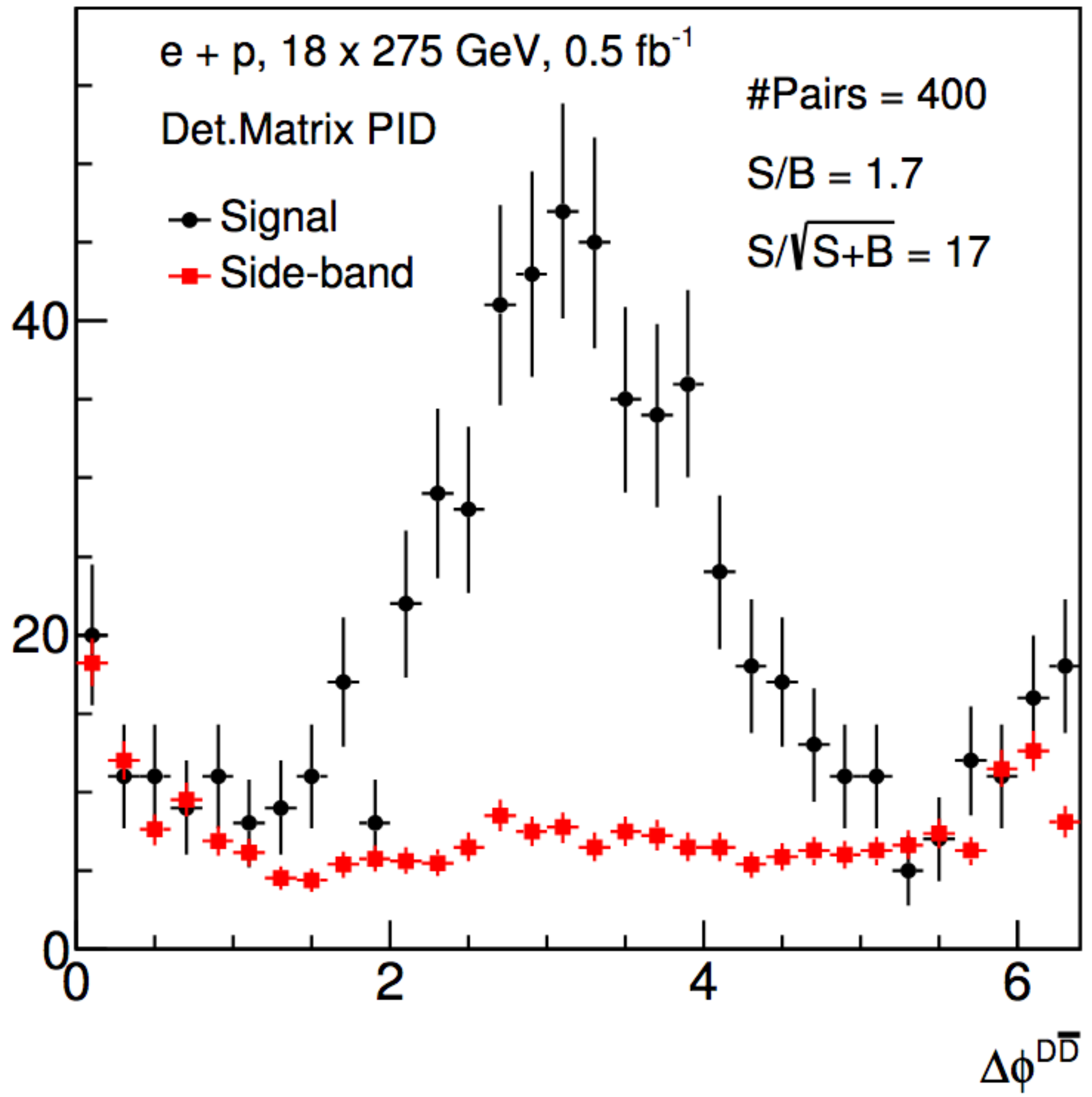




- Hadronization doesn't cause much decorrelation in angular distributions
- Azimuthal correlations are preserved to the final state

Input A_{UT} corresponding to 10% of the positivity bound from L.Zheng et.al PhysRevD.98.034011

D^0 Meson Pair Reconstruction



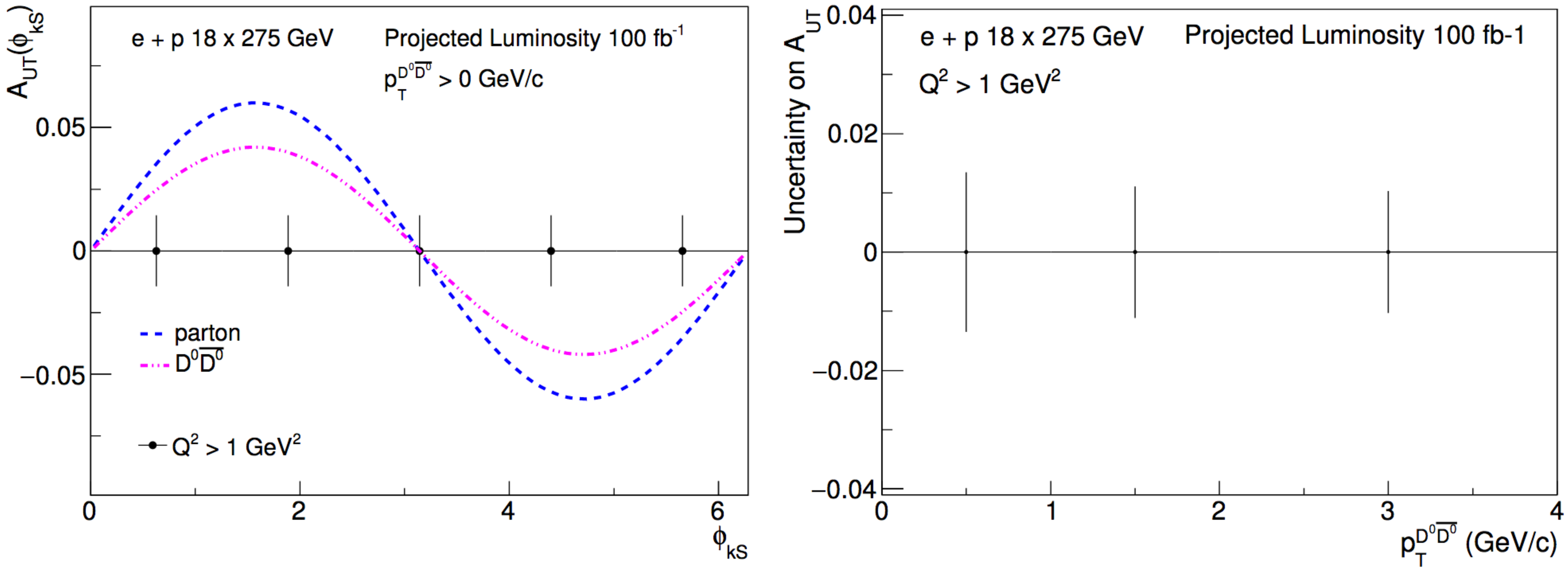
Signal: Unlike sign Kπ pairs within 3σ of D^0 mass peak

Background: Unlike sign Kπ pairs outside 6σ of D^0 mass peak

Daughter tracks kinematic cuts:
$p_T > 0.2$ GeV/c
$|\eta| < 3.0$

- Good signal to background ratio and signal significance for D meson pair reconstruction

Statistical Uncertainty Projections



Signal projections from:

Sivers:
L.Zheng et.al PhysRevD. 98.034011

LP TMD:
Daniël Boer EIC YR WG presentation

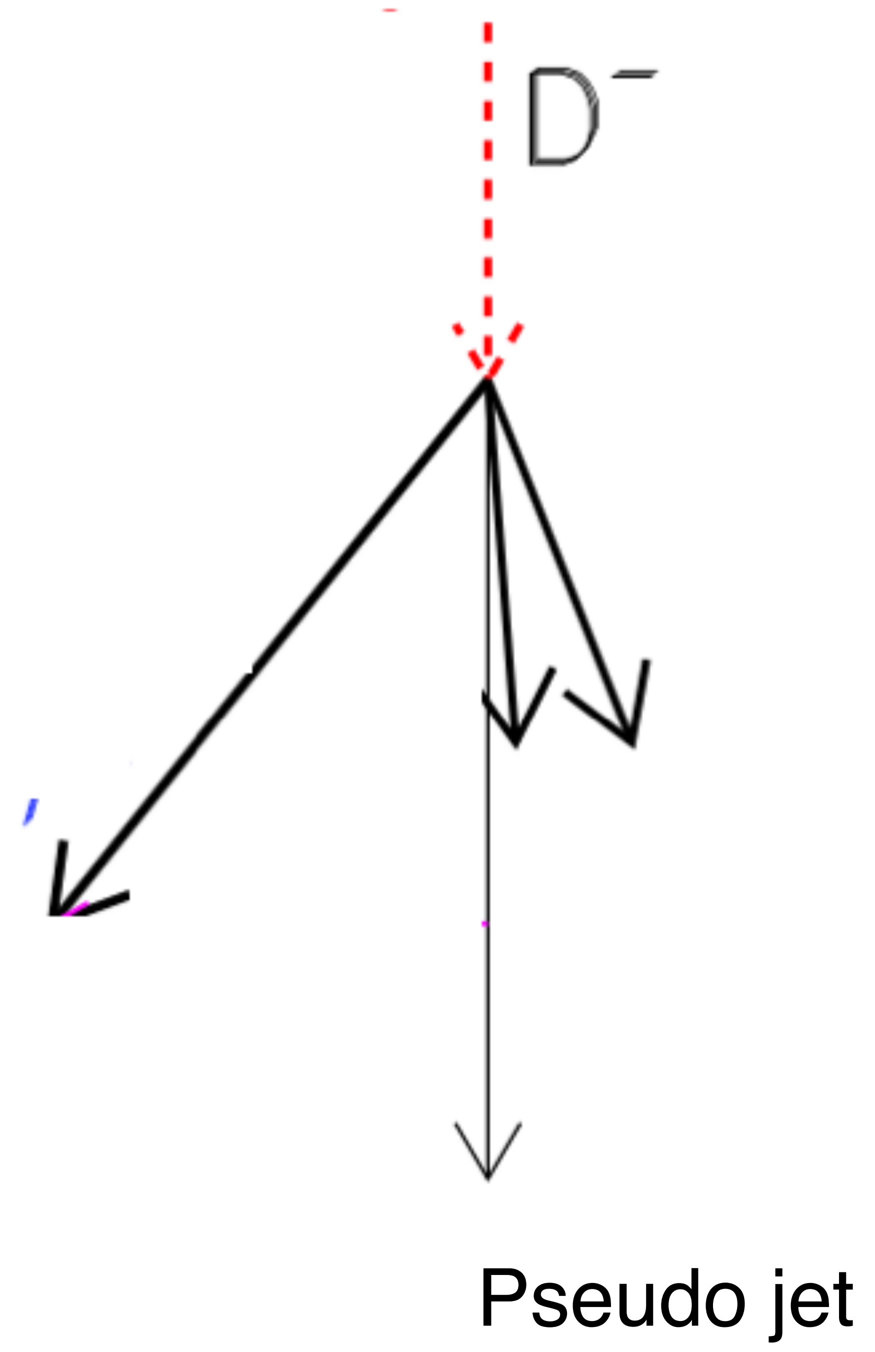
- Uncertainty projections vs phi and p_T
- Projected uncertainty on <A_{UT}> is 0.6% (7σ for a signal of 10% positivity bound). Proton beam polarization of 70% is assumed
- Projected uncertainty on <cos(2ϕ)> is 0.4%

Heavy Flavor Tagging

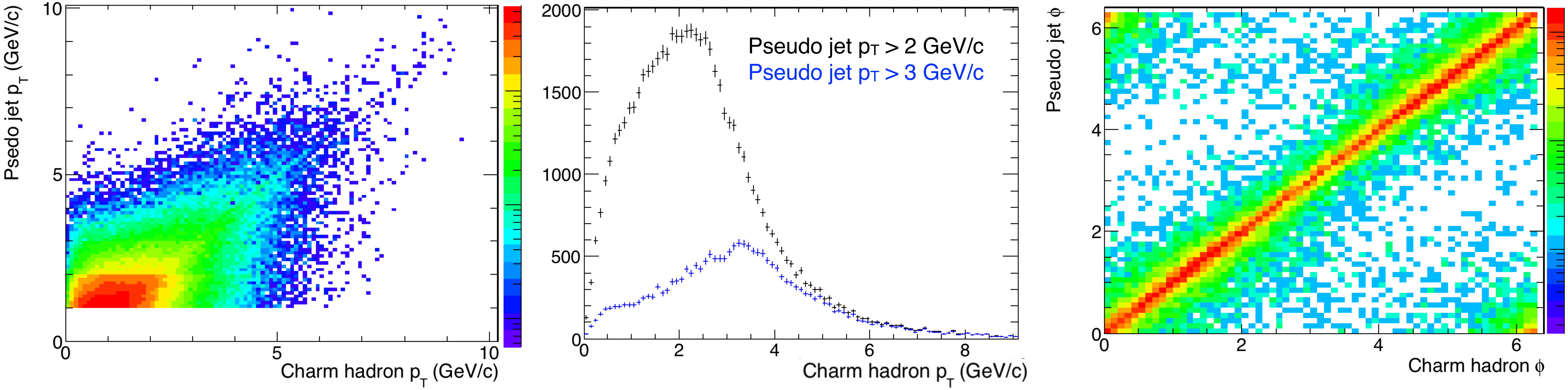
- Exclusive reconstruction suffers from low branching ratios, ~3% for $D^0 \longrightarrow K\pi$
- So can access only <1% of all D meson pairs even with a perfect detector
- Can we tag HF hadrons (or jets) with good efficiency and purity?

- Use Fastjet package for clustering
- Anti-k_T jets with R = 1.0
- Looking at reconstructed pseudo jets with $p_{T,jet} > 1.0$ GeV/c; track $p_T > 0.2$ GeV/c
- For truth tagging, if a HF decay track is present in a pseudo jet, tag it HF jet

- Simulation set up same as for exclusive reconstruction study

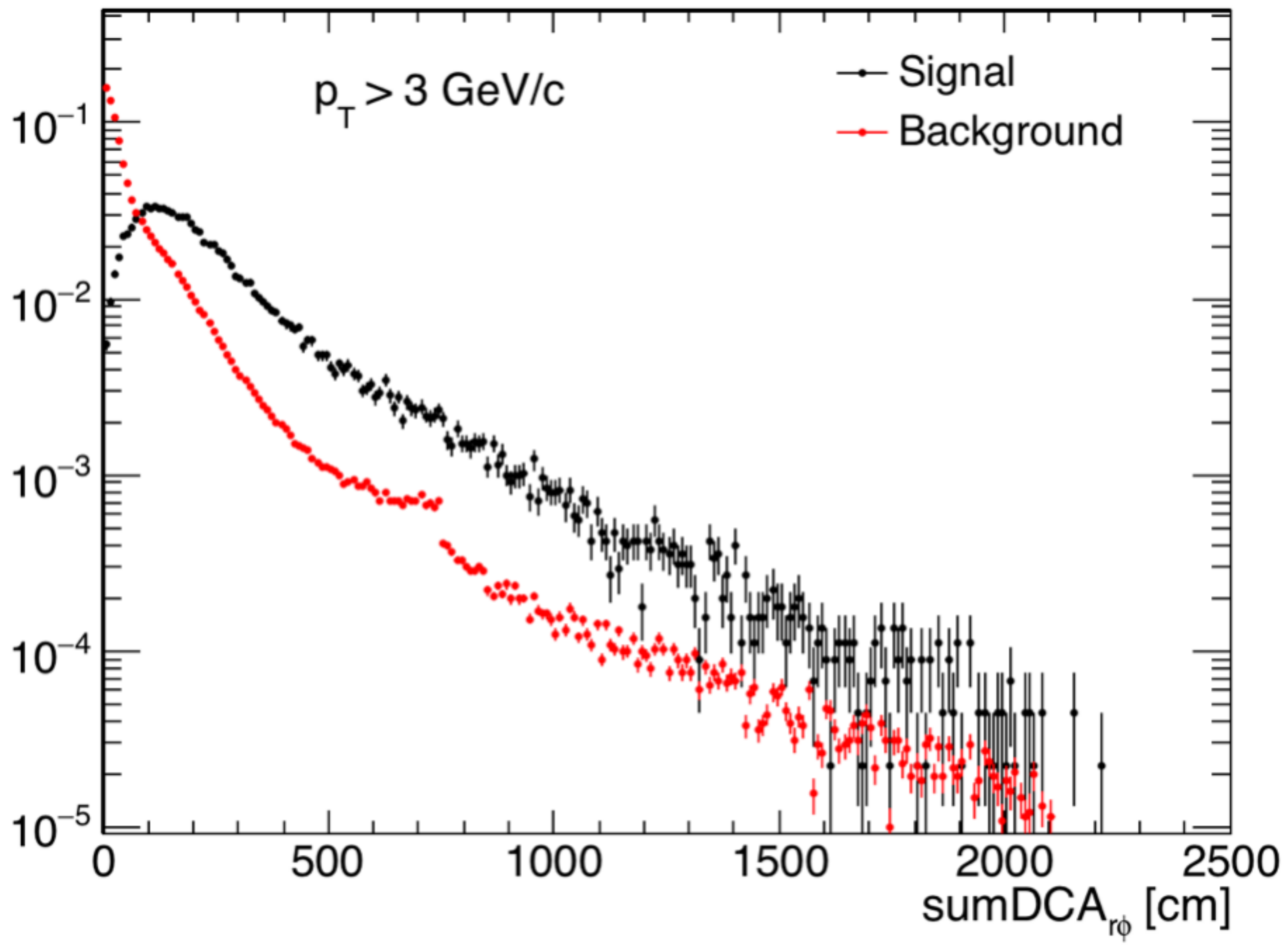


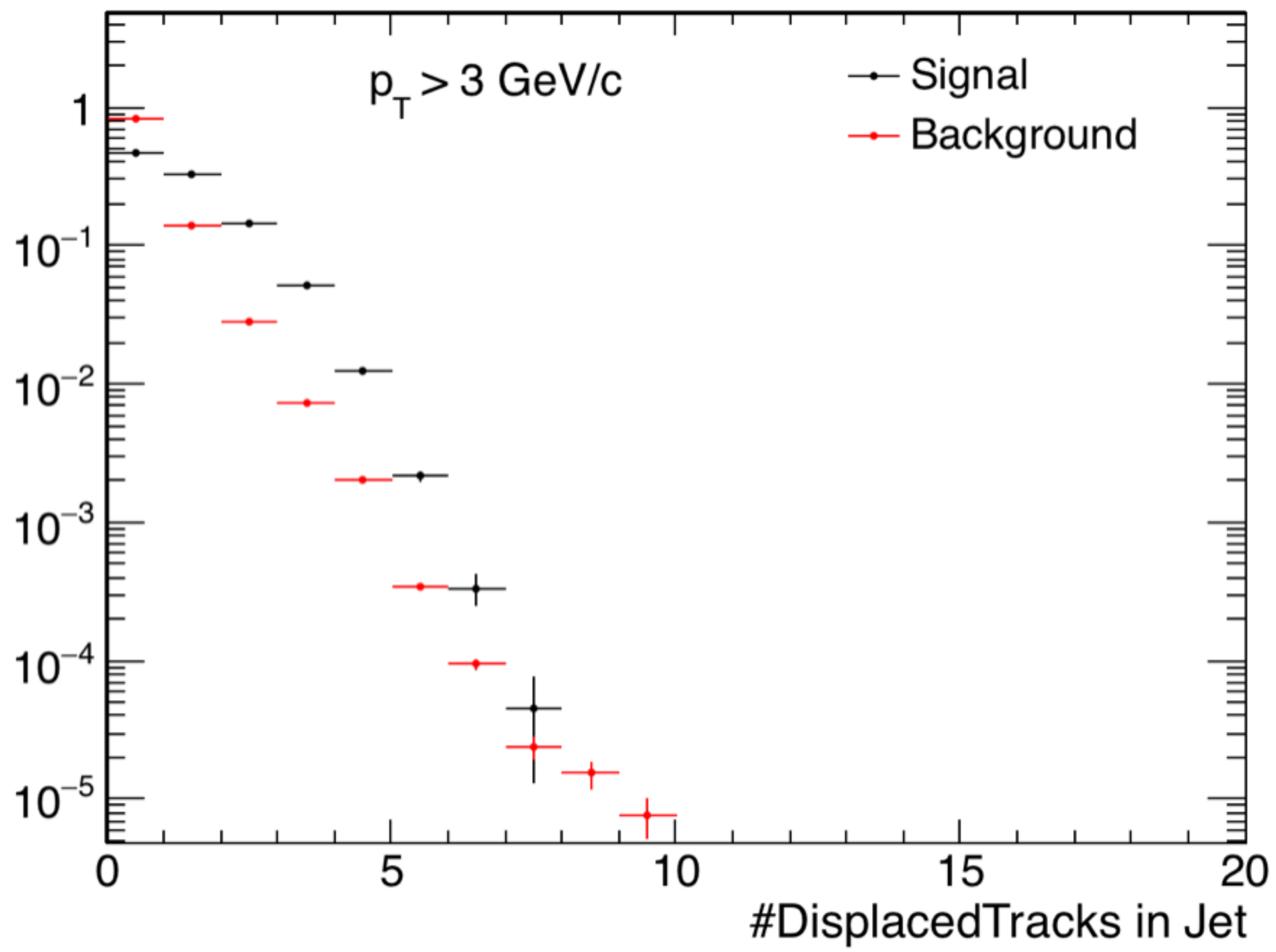
Correlations with Truth



- Very good correlation between truth and reconstructed variables
- Good correlation in p_T above pseudo jet p_T 2 GeV/c
- Azimuthal angles tightly correlated

Topological Tagging of HF Decays

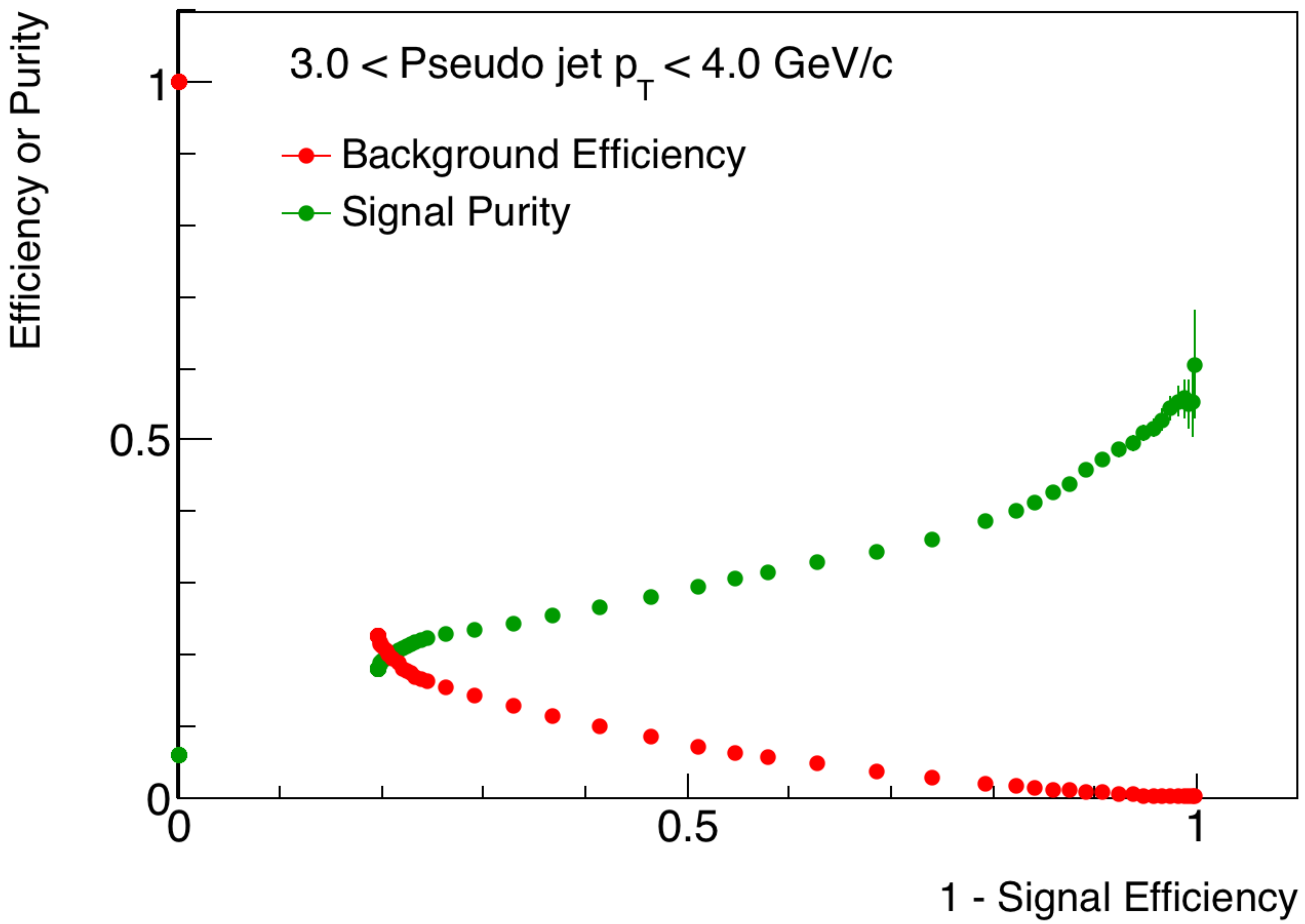


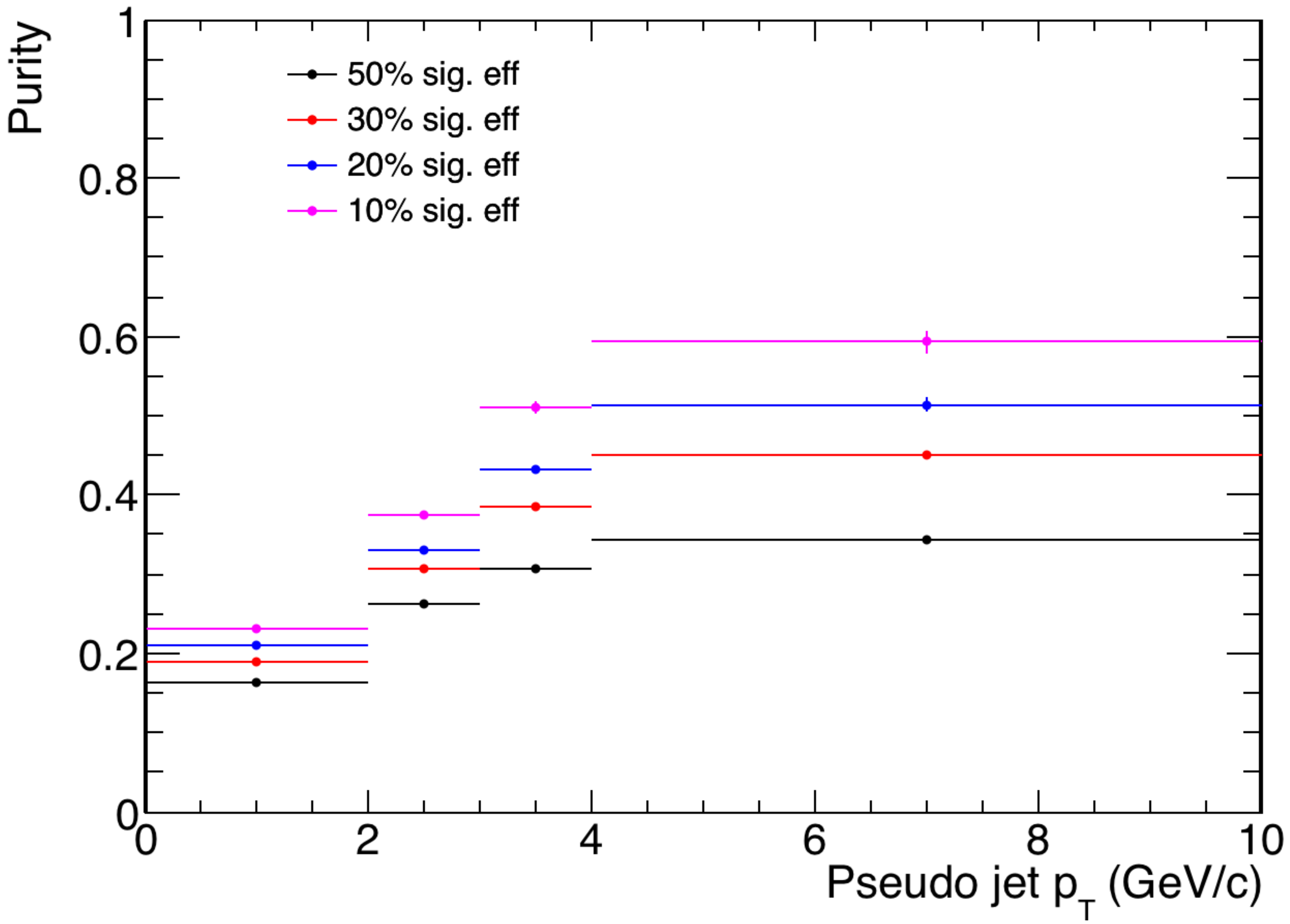


- All topological variables in the transverse plane

- Variables used for tagging
  - Sum DCA of 3 most displaced tracks
  - DCA of most displaced track
  - Number of displaced tracks with a minimum DCA cut
  - Avg pair DCA of 3 most displaced tracks
- Combined using Boosted Decision Trees

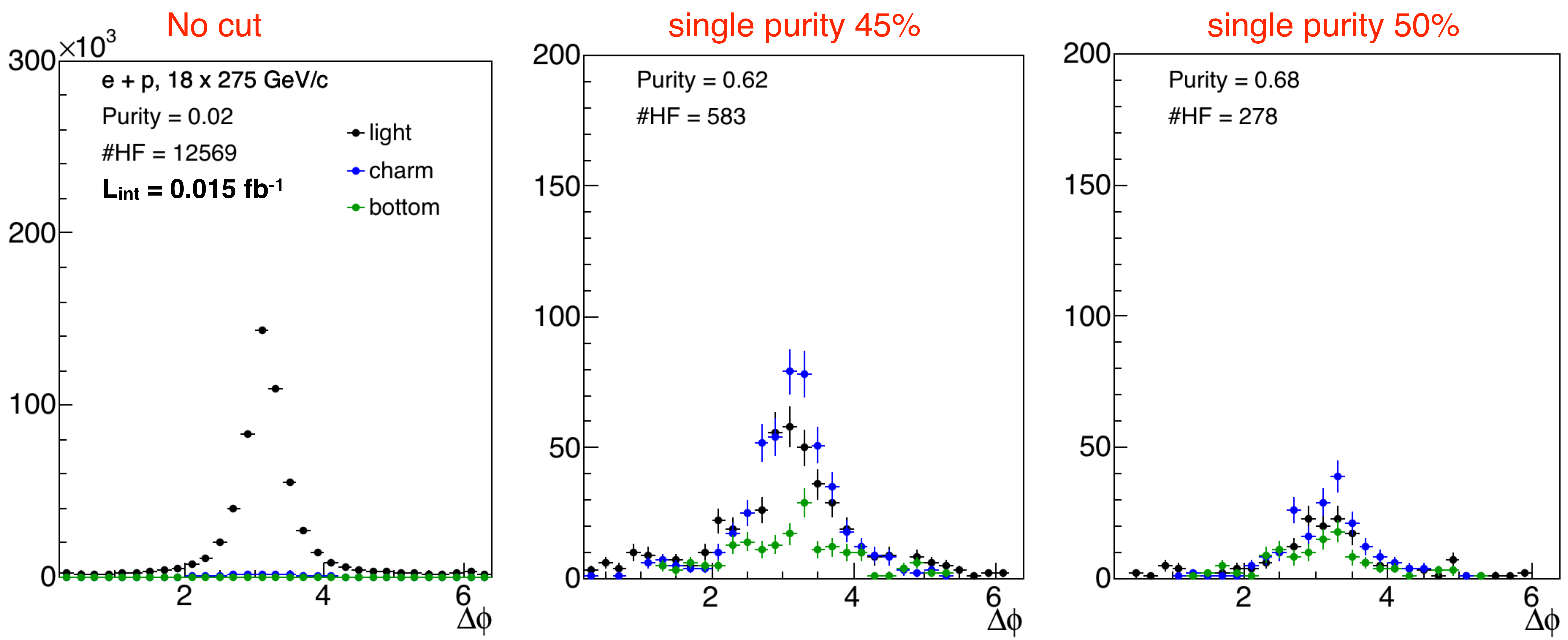
Tagging Performance





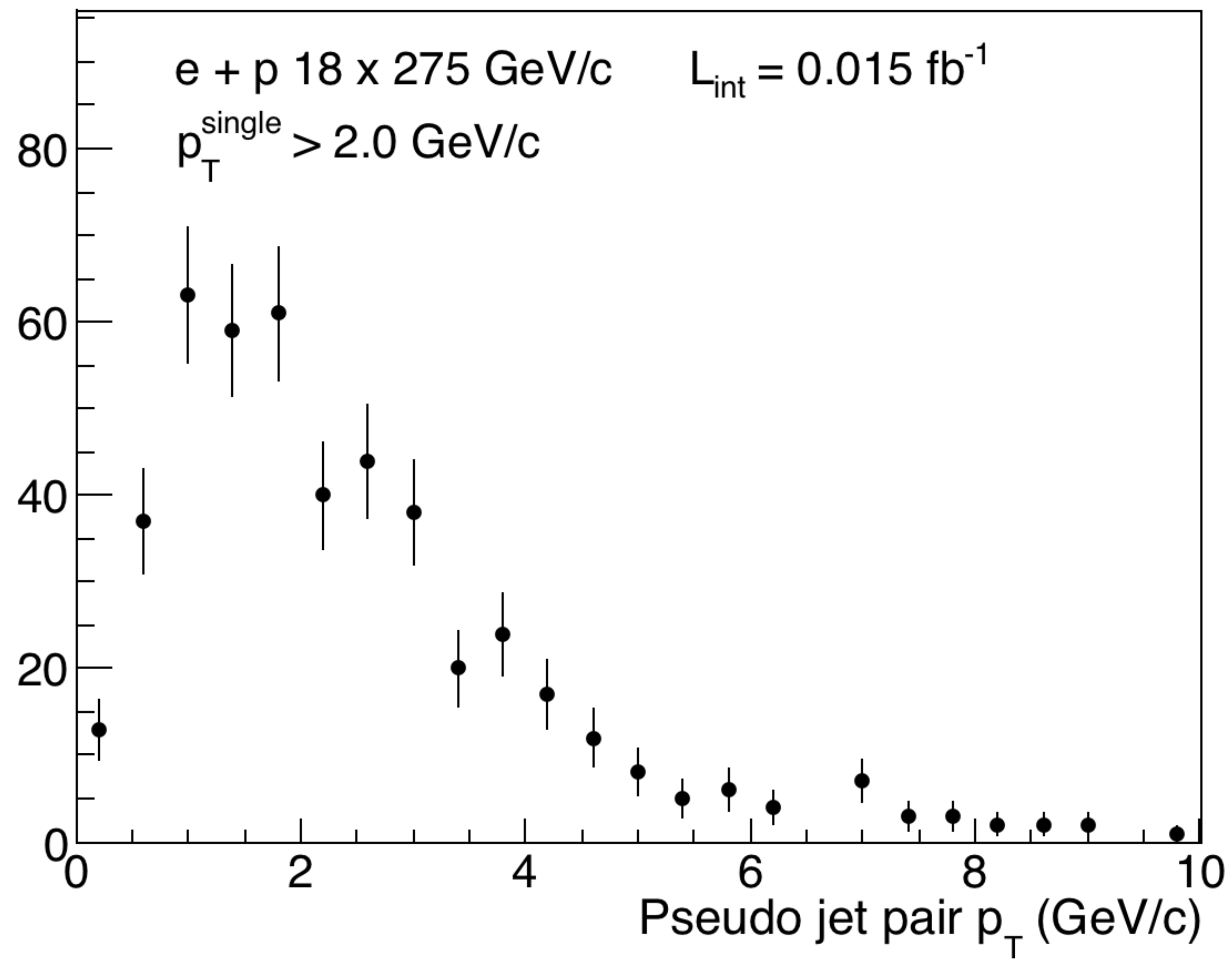
- Above 50% purity for $p_T > 3$ GeV/c with ~20% signal efficiency
- Signal purity improves significantly compared to without tagging cuts

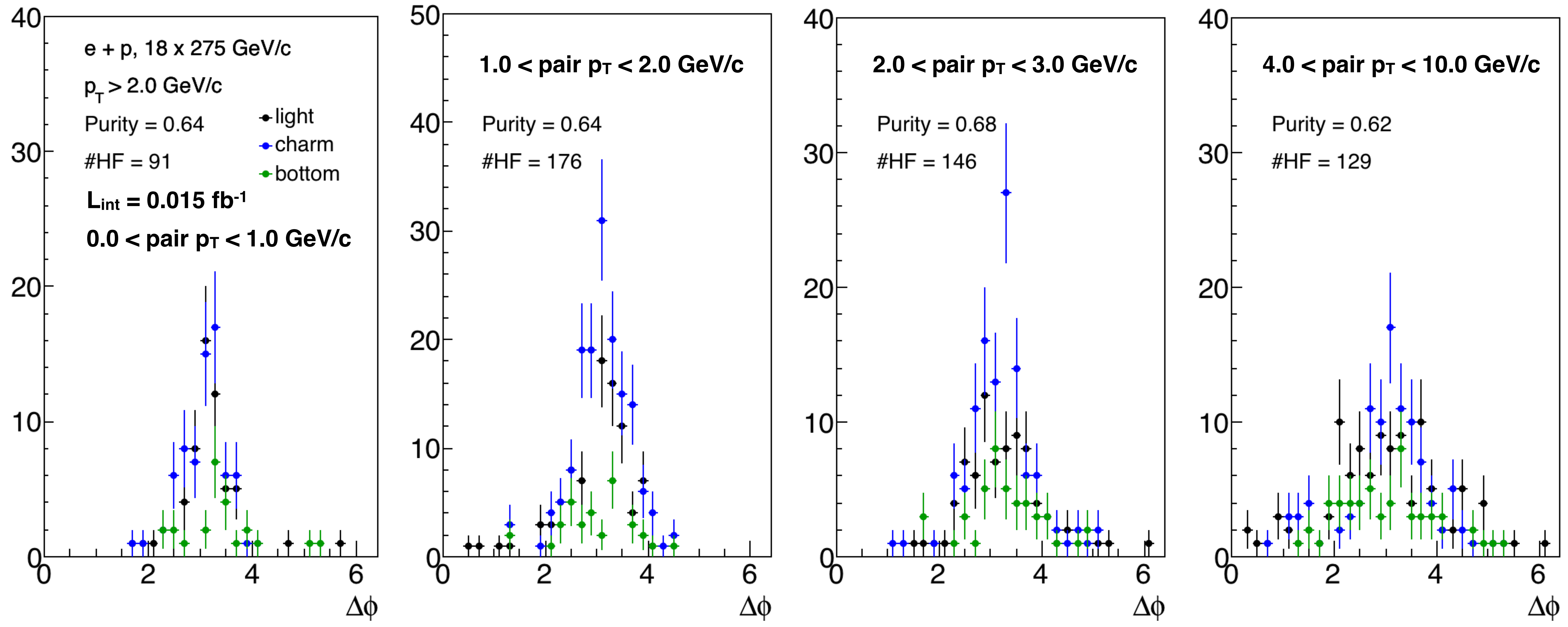
Tagged HF Pair



- Proportion of HF hadron pairs cain be significantly improved by tagging
- Purity increases from ~2% to ~70%

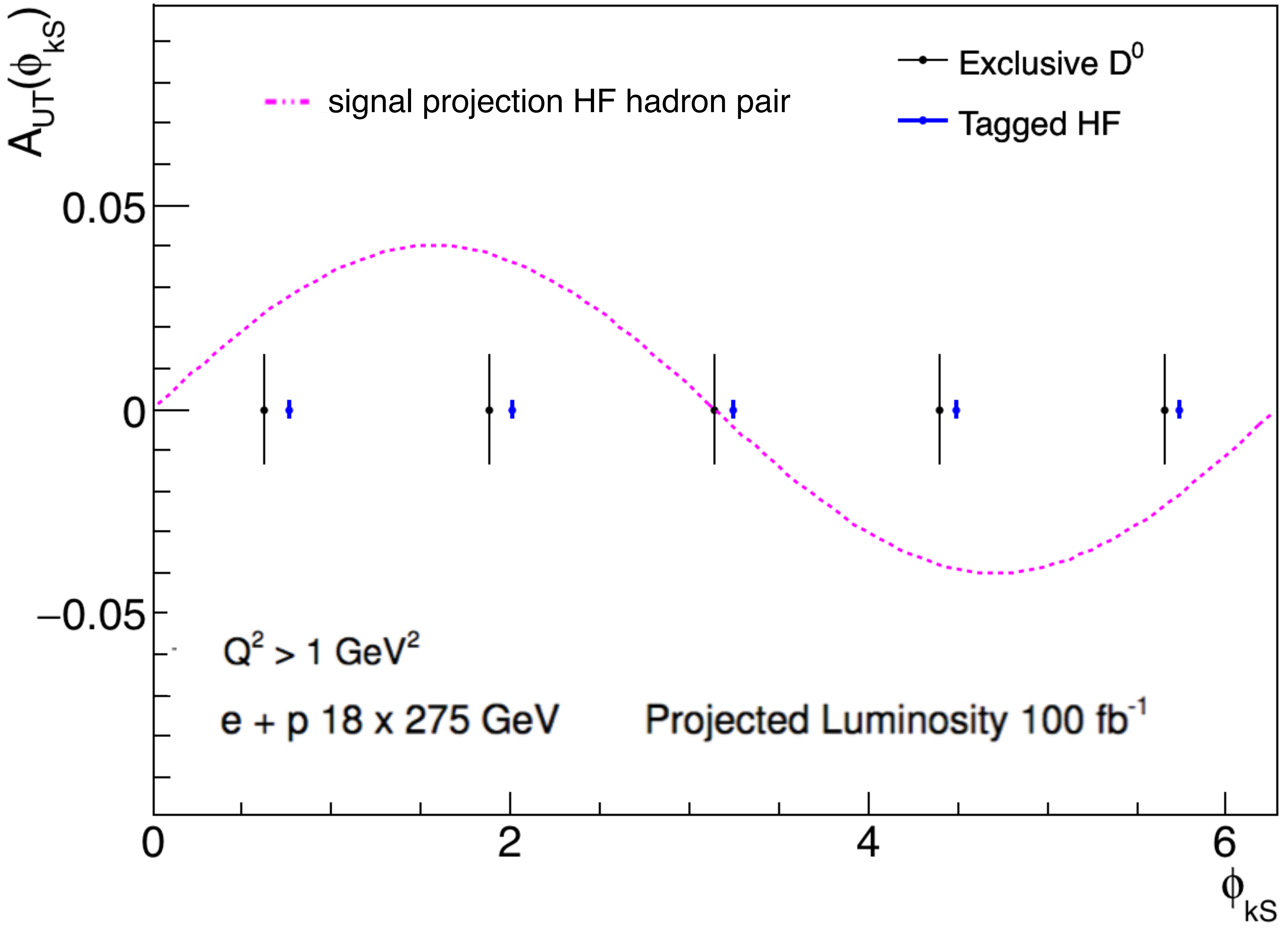
Tagged HF Pair Kinematics

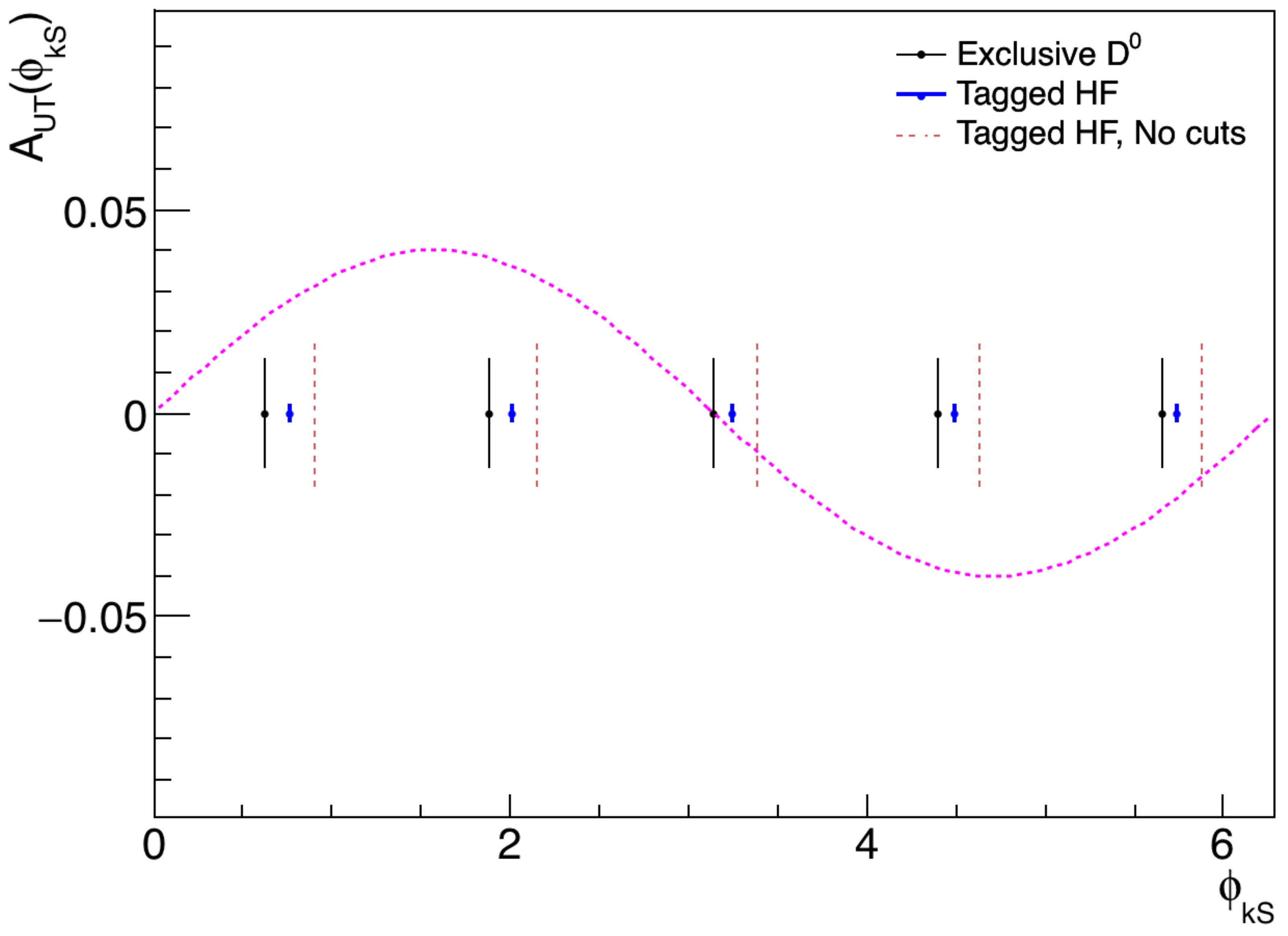




- Can cover pair p_T down to zero, good purity in all pair p_T ranges

Uncertainty projections





- About a factor of 6 reduction in uncertainties

- $A_{UT}^{meas} = (N_{hf}A_{UT}^{hf} + N_{ch}A_{UT}^{ch})/(N_{hf} + N_{ch})$
- Gluon contribution to A_{UT}^{hf} much larger than for A_{UT}^{ch}. Quark contribution to either is small
- Since A_{UT}^{ch} is small and purity is large (~70%), ignore the second term on numerator
- $A_{UT}^{meas} = (N_{hf}A_{UT}^{hf})/(N_{hf} + N_{ch})$; $A_{UT}^{hf} = A_{UT}^{meas}$/purity/Polarization
- Uncertainty on A_{UT}^{hf} = Uncertainty on A_{UT}^{meas}/purity/Polarization

Summary and Outlook

- Heavy quark pair production offers an unique opportunity to study gluon TMDs at the EIC
- An all-silicon tracking detector design with MAPS allows good secondary vertex resolution - crucial for charm hadron reconstruction and tagging

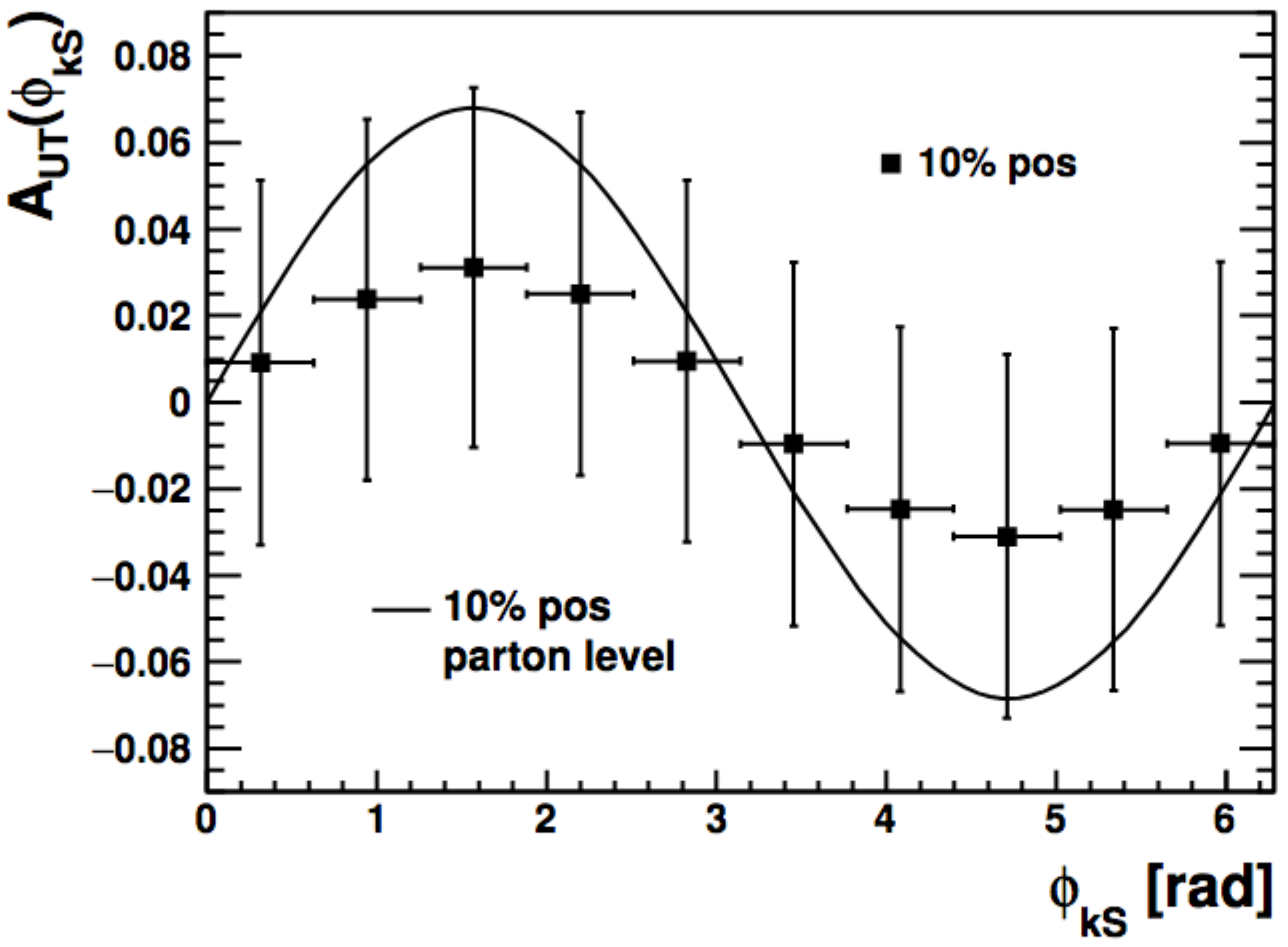
- Exclusive reconstruction: Projected uncertainty on $\langle A_{UT} \rangle \sim 0.6\%$

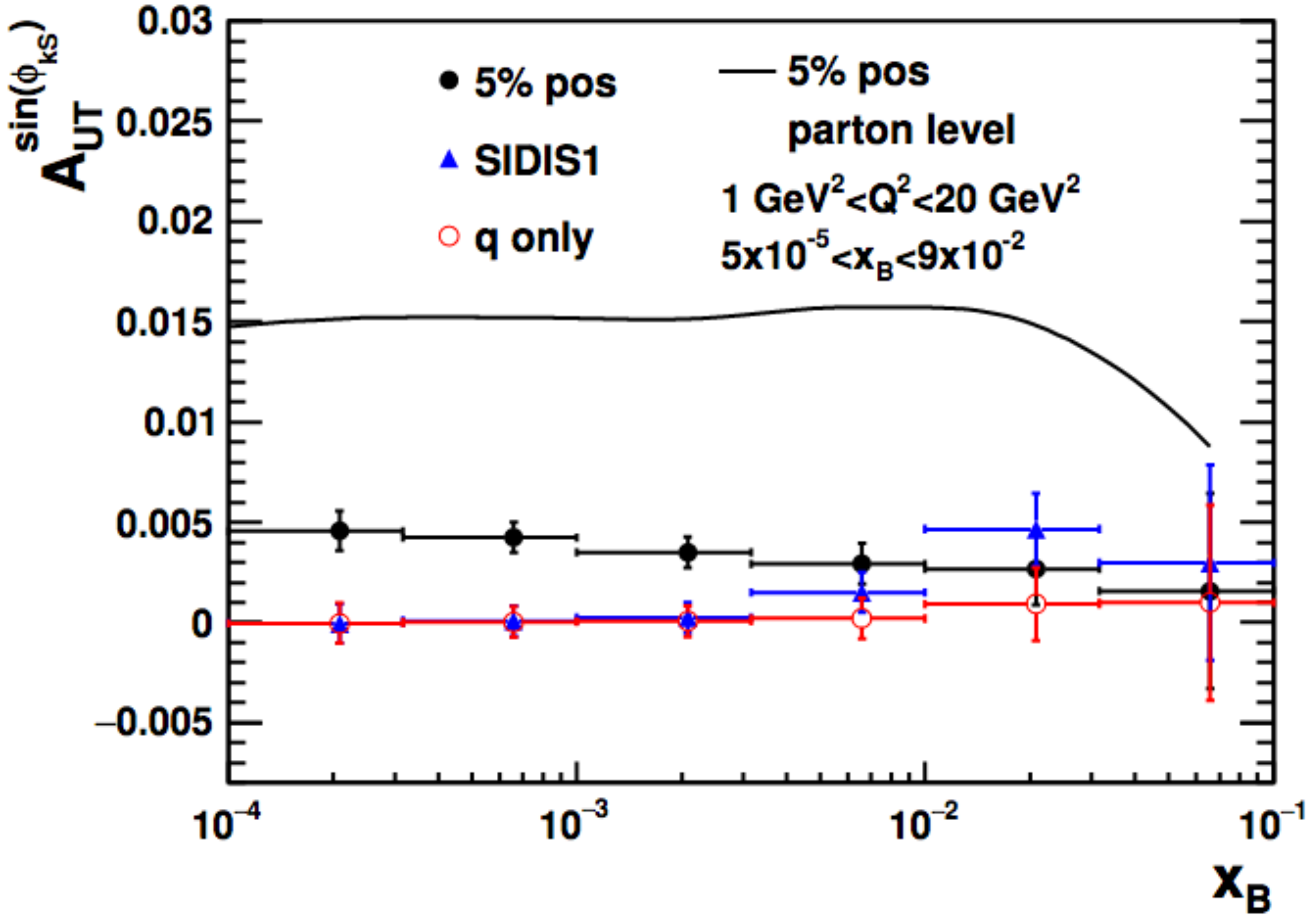
- Topological tagging of HF hadron decays can be done with good purity and efficiency
- HF pair signal purity can be improved substantially, from ~2% to ~70%
- Uncertainty projections on $\langle A_{UT} \rangle$ reduce by a factor of 6 compared to exclusive reconstruction

- Will allow first direct measurements of gluon TMDs
- Pair tagging with good purity will benefit gluon transverse momentum dependent measurements

Back Up

Uncertainty projections

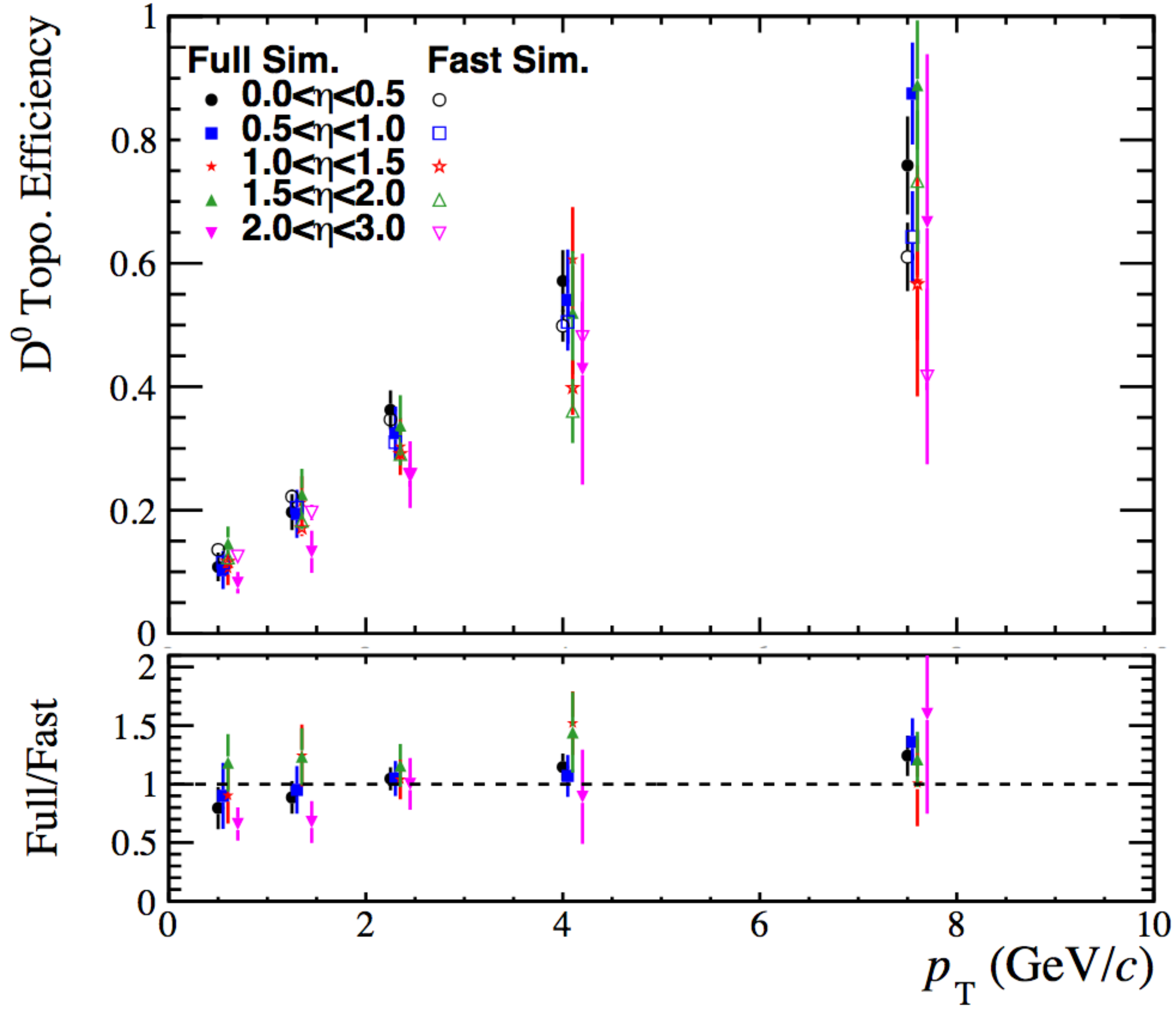




L.Zheng et.al
PhysRevD.98.034011

- Quark contribution to A_{UT} is small
- Gluon contribution (assuming 10 or 5% of positivity bound) is large for charm hadrons (~3%)
- Gluon contribution is smaller for charged hadrons (~0.7% at x_B = 0.005)

D Meson Topological Cut Efficiency



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

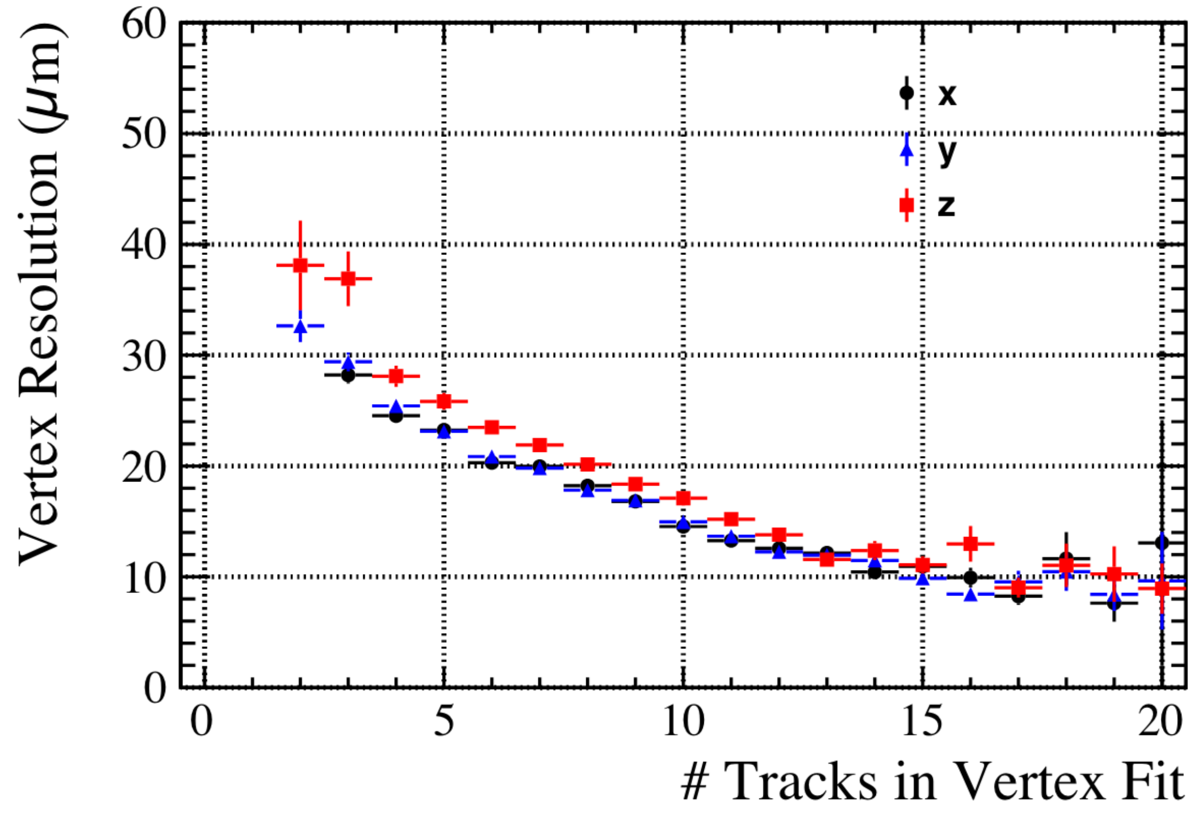
Position resolution

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	$30/p_T \oplus 60$

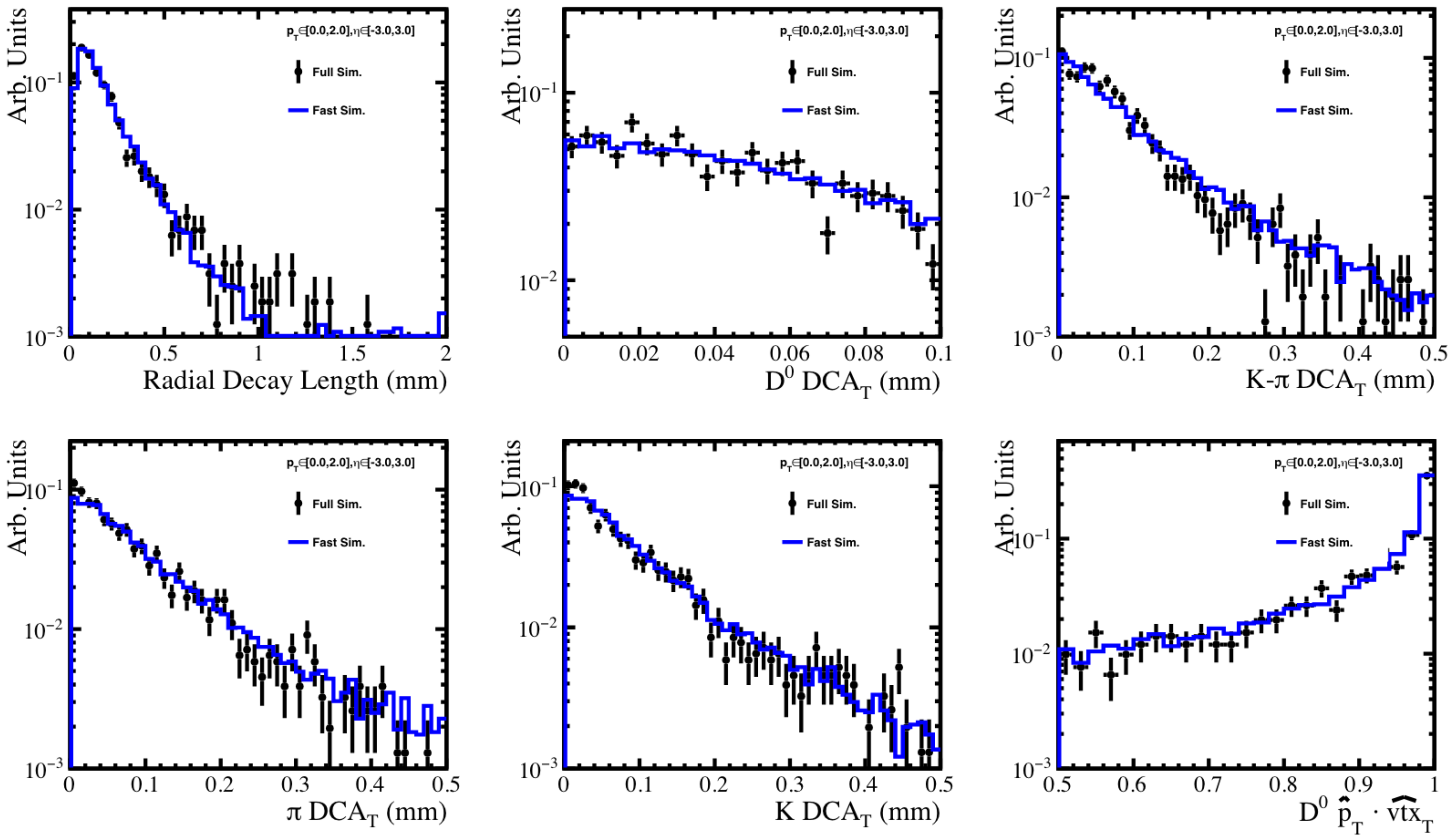
Mom resolution

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	$0.1 \cdot p \oplus 2.0$

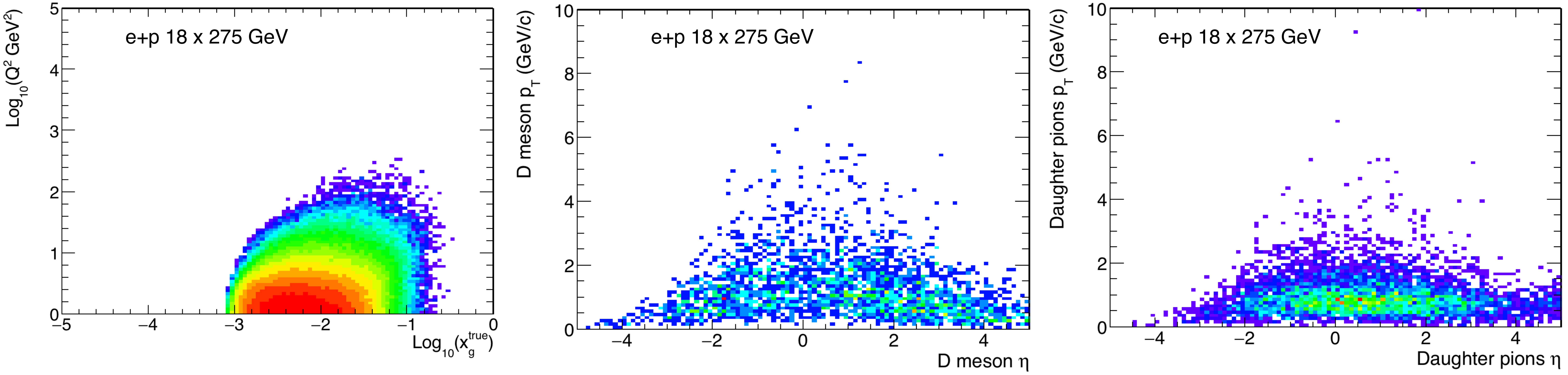
- Primary vertex resolution taken from full simulation



- Fast simulation performance was validated using full simulation



D Meson Pair Kinematics

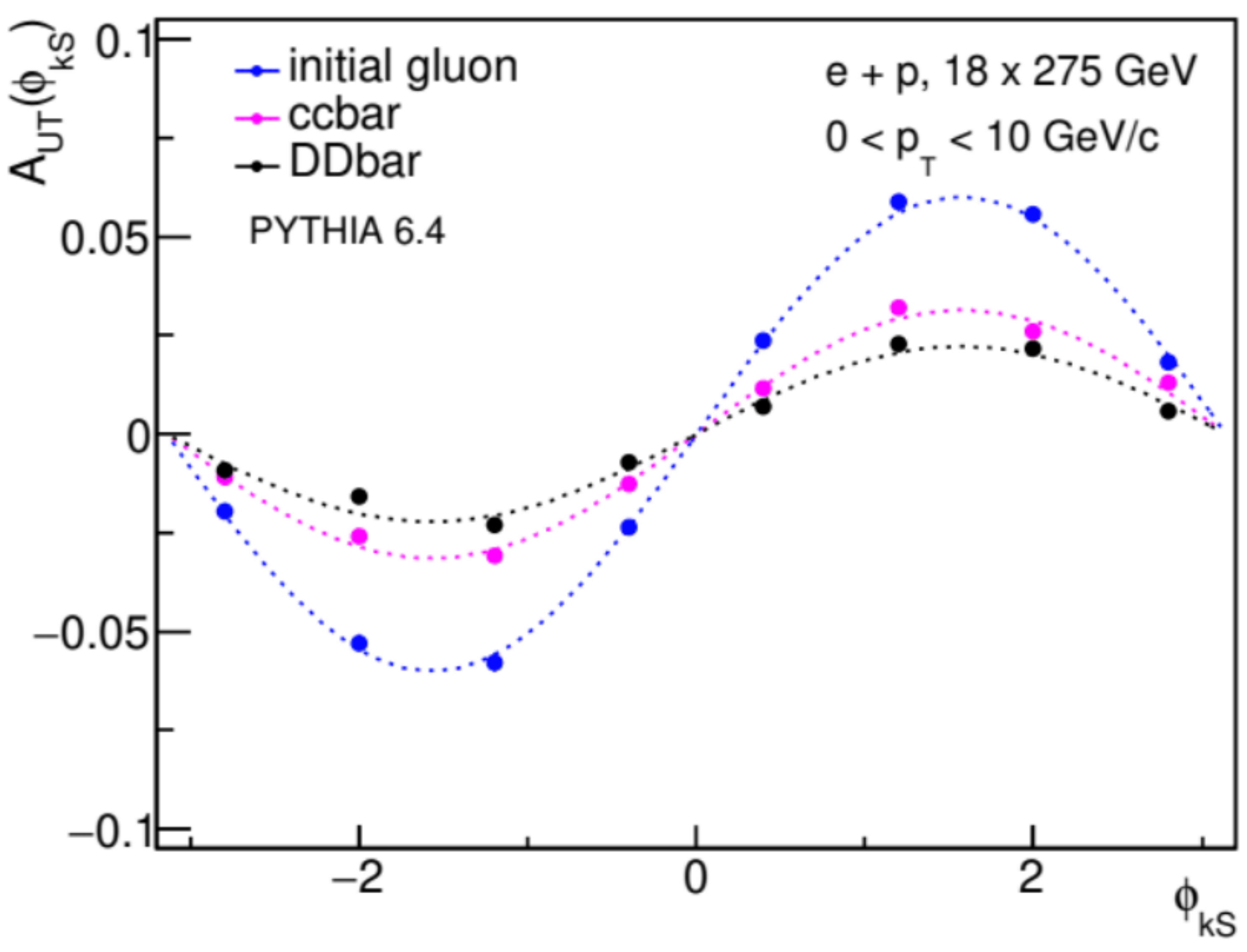


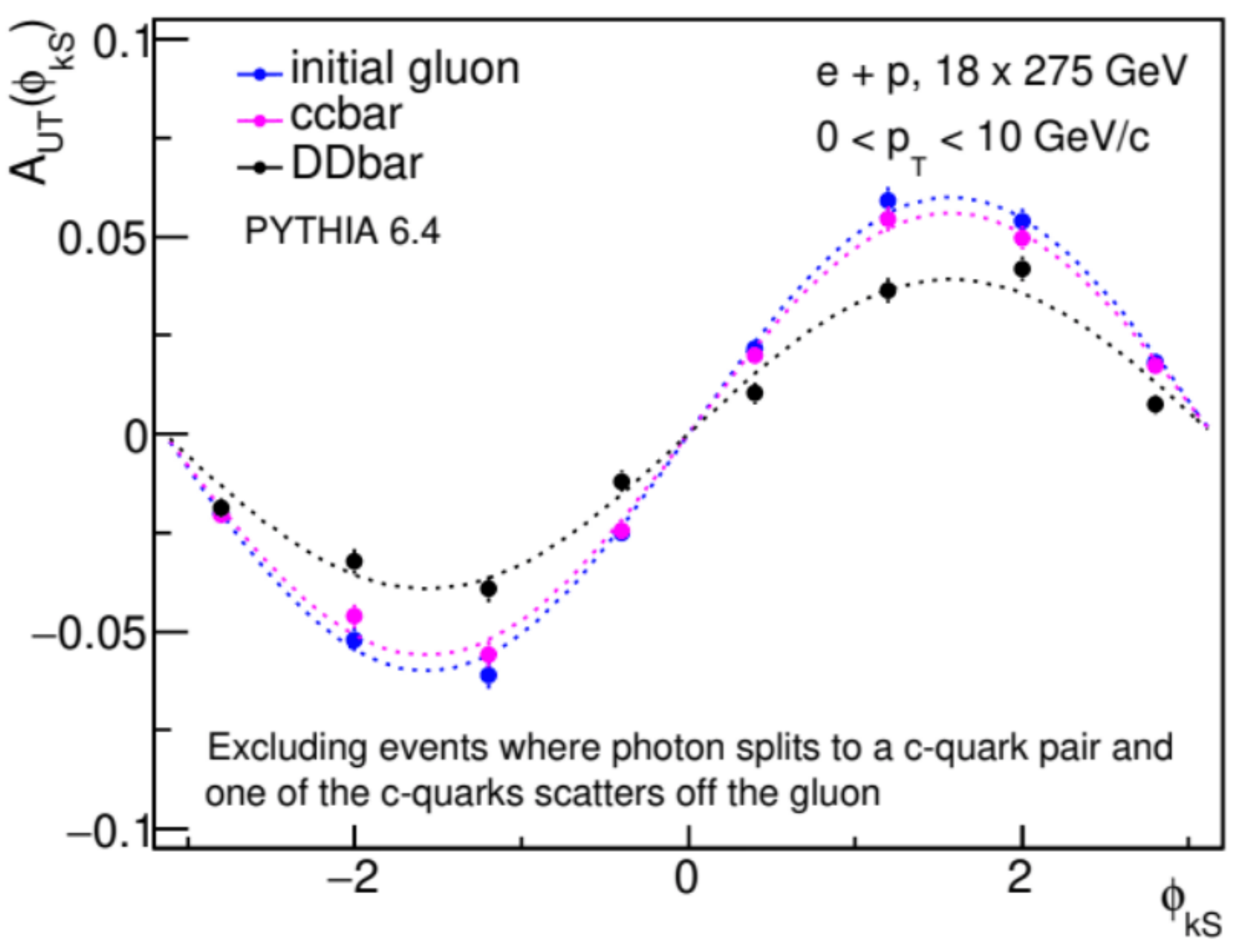
z-axes in log scale

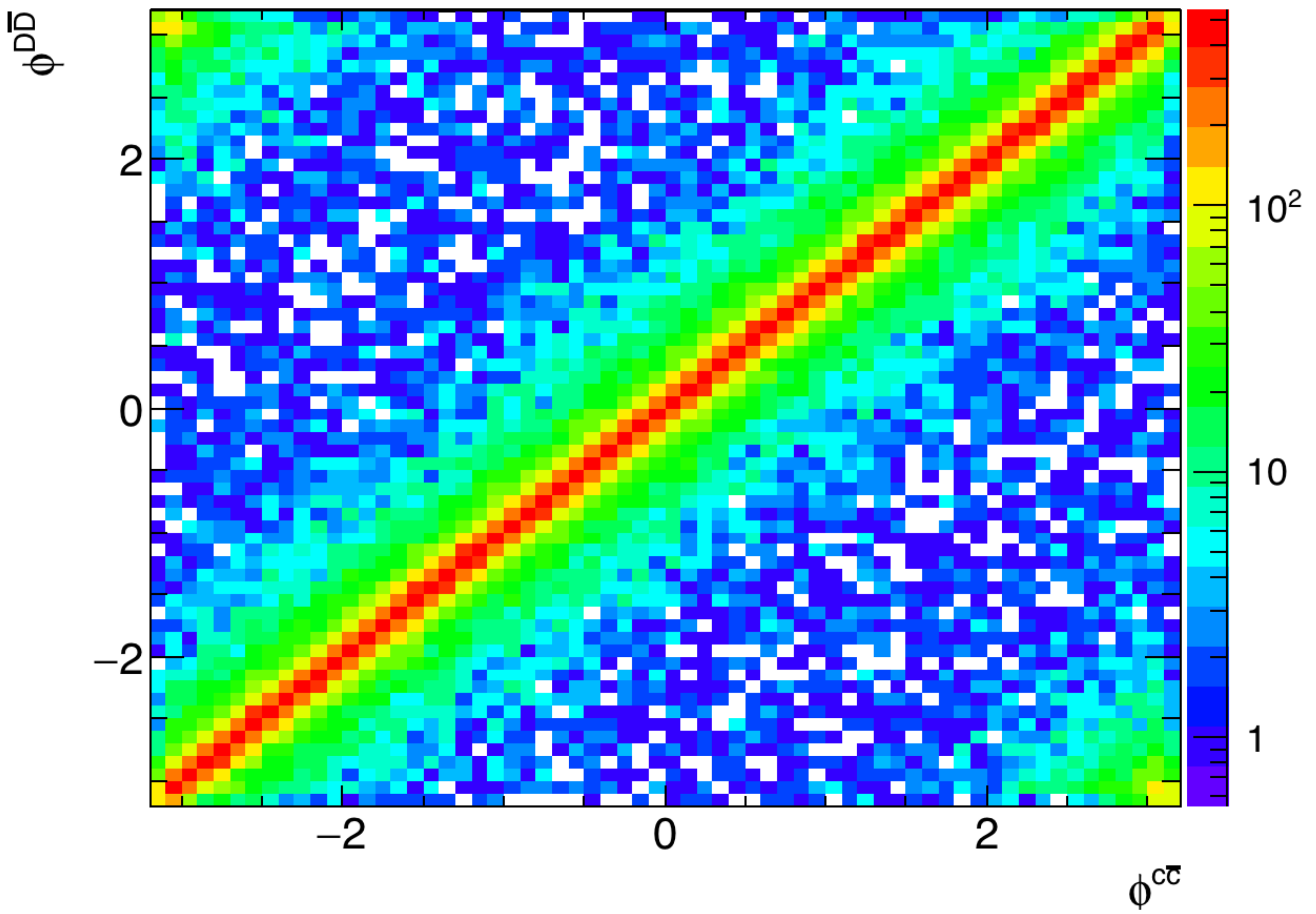
- Parton x reach in the range 0.001 < x 0.1

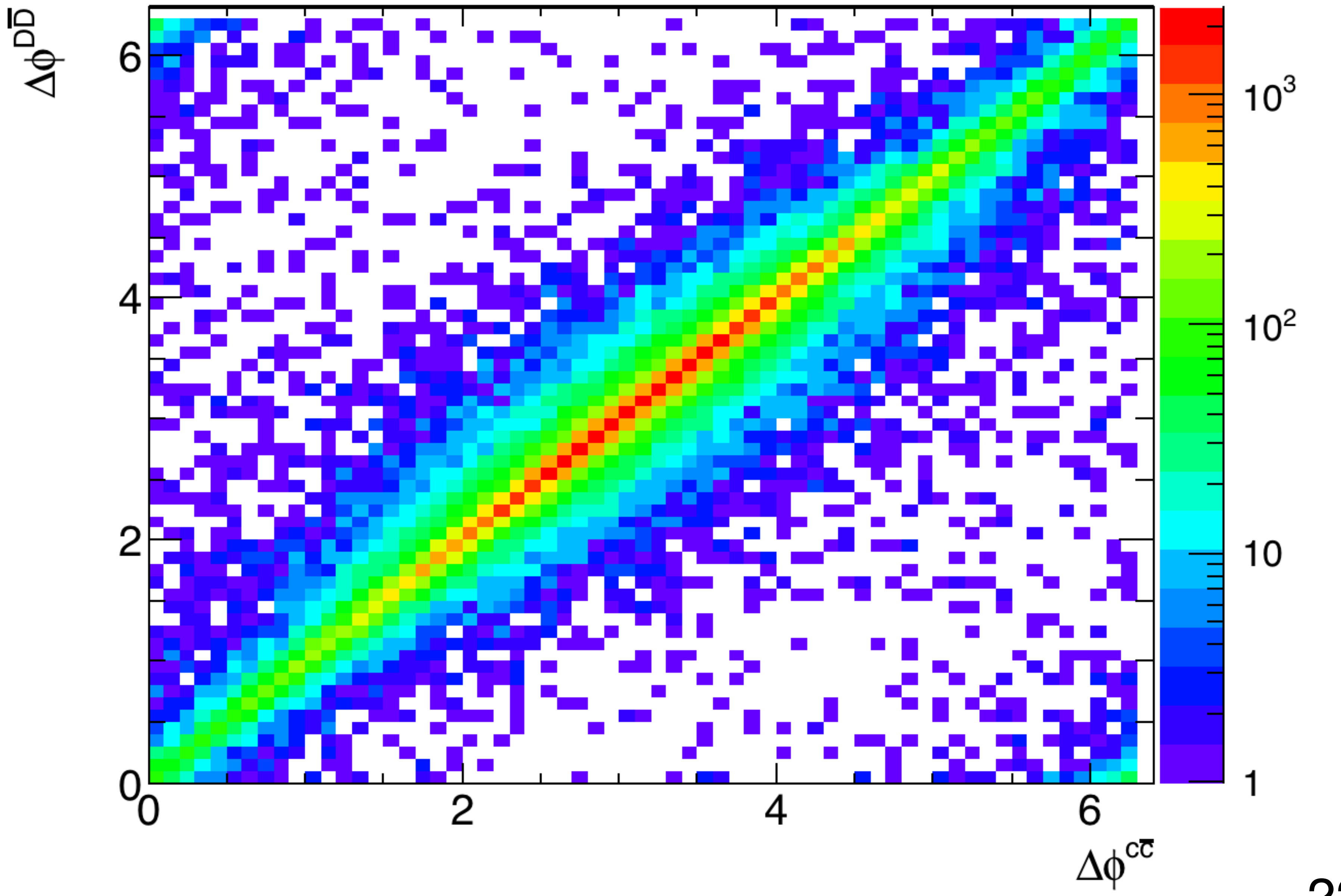
- D mesons and decay daughters in D meson pair events have low p_T (<~ 5 GeV/c)
- Acceptance of daughter tracks mostly within $|\eta| < 3$, within detector coverage

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