Studies of Open Charm Hadron Reconstruction at the Electron-Ion Collider

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UC Consortium EIC Meeting Oct. 20-21 2020

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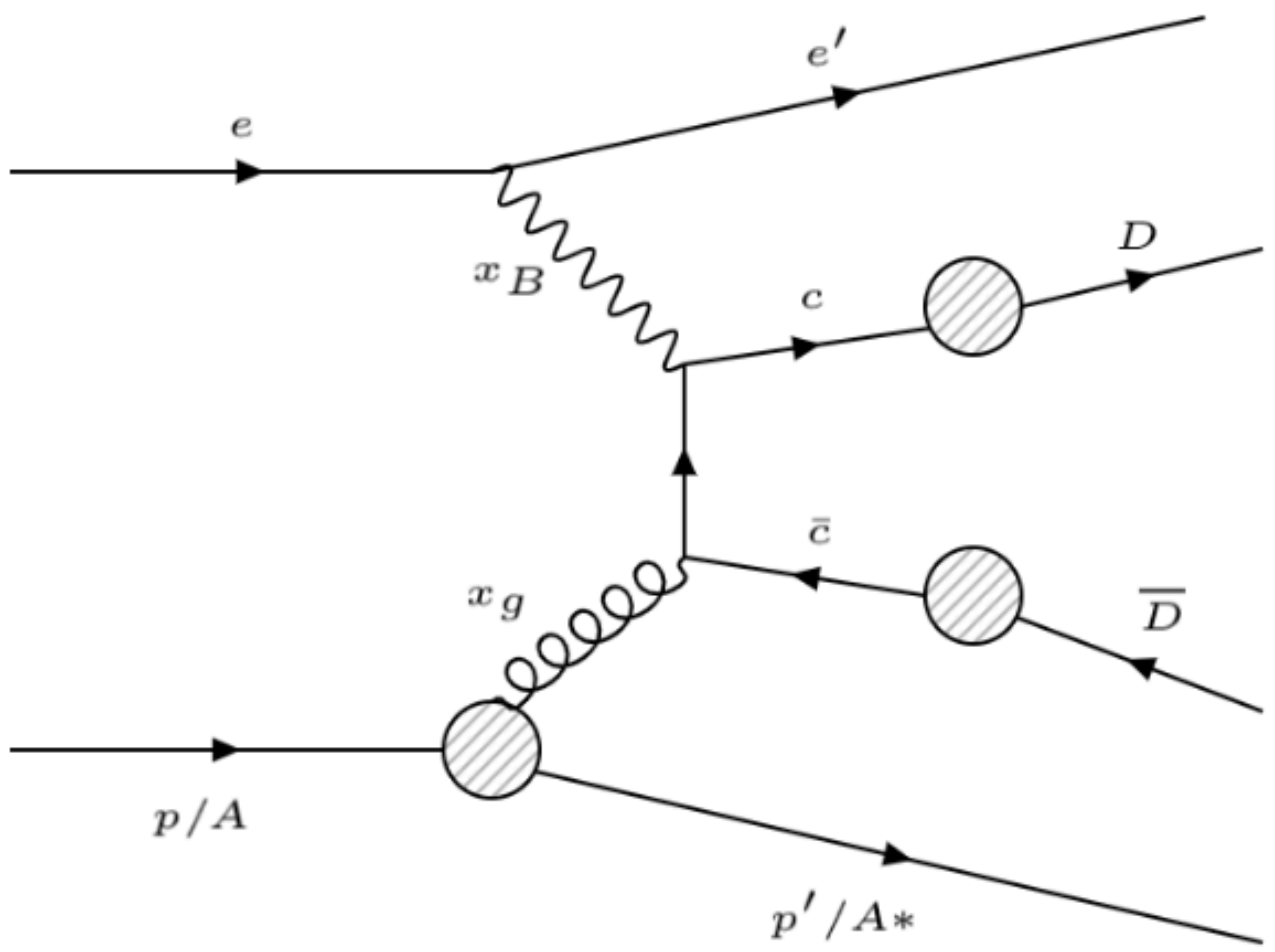
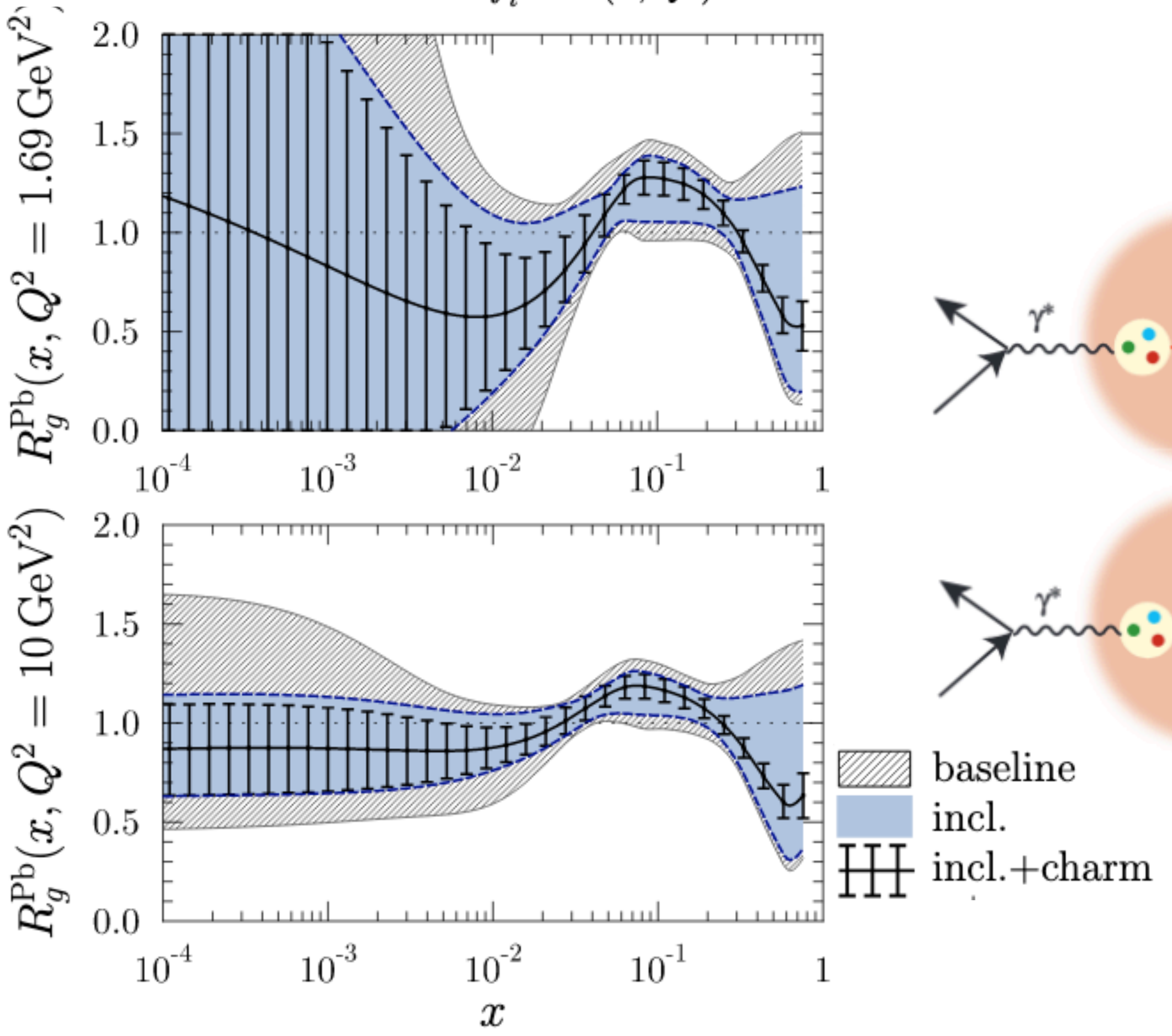
Thanks to E. Sichtermann and F. Yuan for additional useful discussions

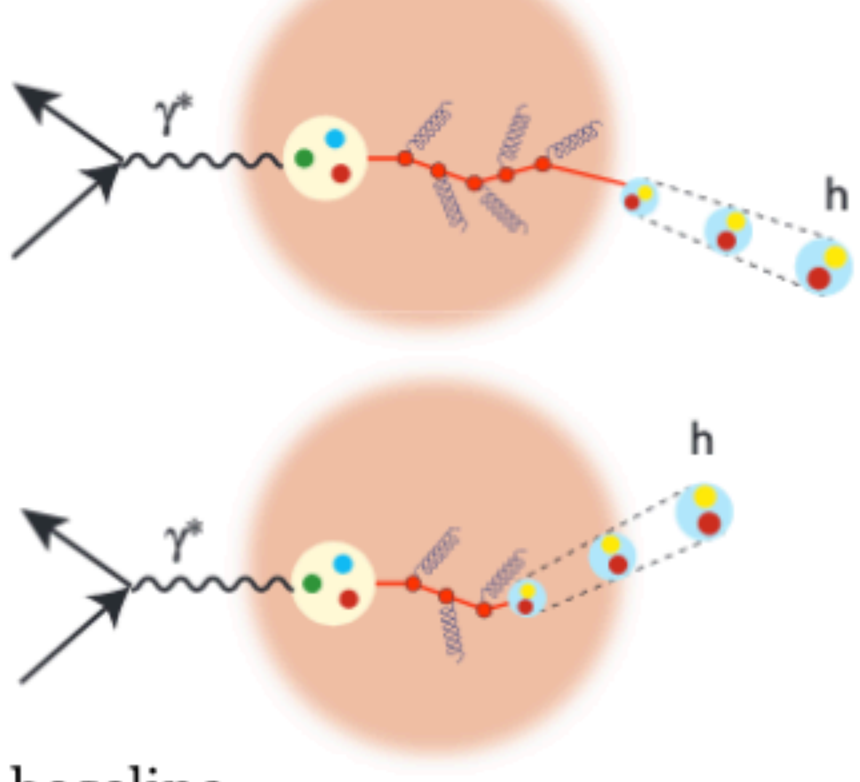
Introduction

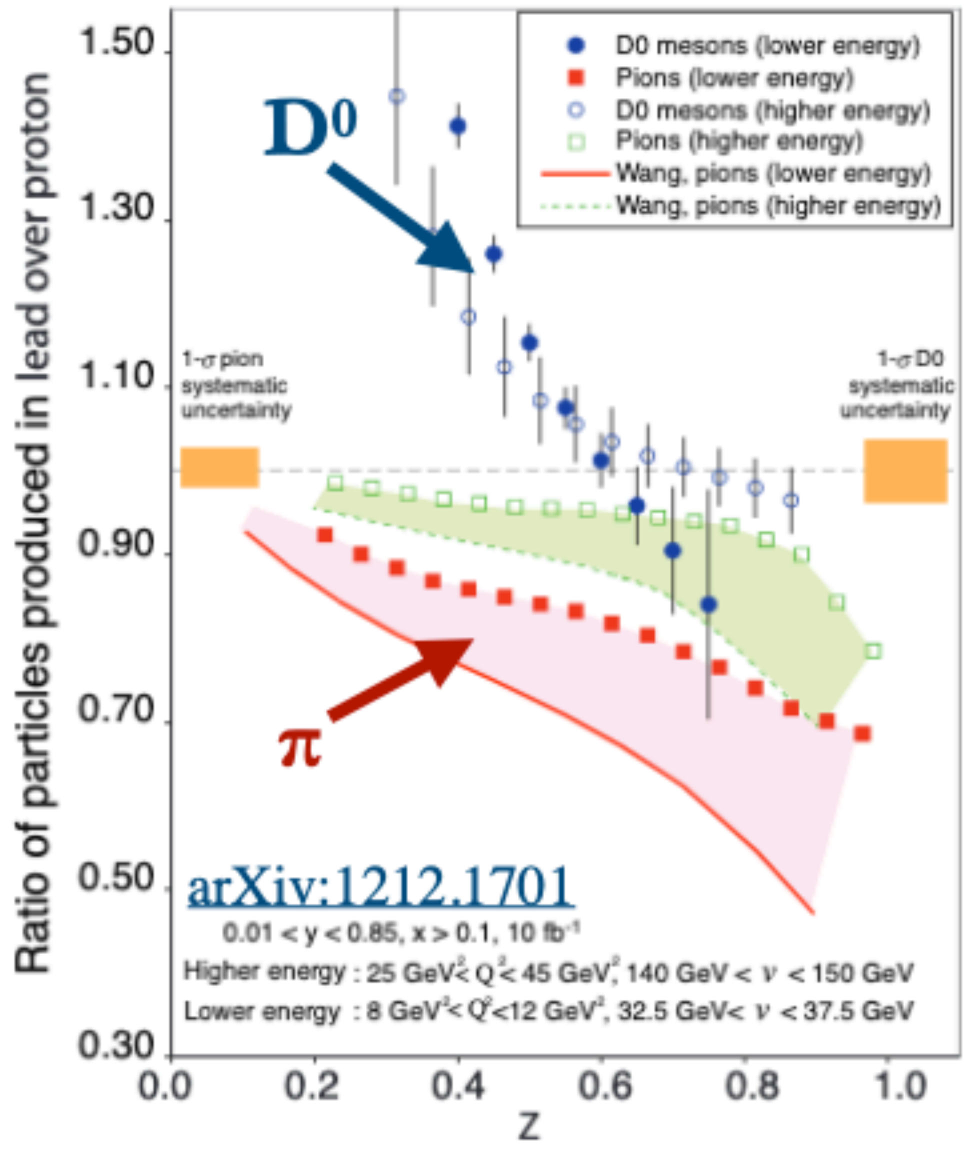
[1] E. Aschenauer et al. Phys. Rev. D96, 114005 (2017)
[2] E. Chudakov et al. Phys. Conf. Ser.770, 012042 (2016)



$$R_i(x, Q^2) \equiv \frac{f_i^{\mathrm{proton}/A}(x, Q^2)}{f_i^{\mathrm{proton}}(x, Q^2)}$$







Heavy-flavor quarks produced at leading-order via boson-gluon fusion

- Unique probe of gluon dynamics in the nucleon/nucleus (gluon (n)PDF, CNM effects, gluon Sivers, etc.)

Previous studies [1,2] have investigated charm production + constraints to gluon (n)PDF

- High-x_B charm production offers more constraint w.r.t. inclusive-only measurements

Goal to study charm hadron reconstruction with future EIC detector with precision vertex detectors

Outline

Fast simulation setup with PYTHIA 6 event generation

Validation with full GEANT-based simulation with all-Si tracker

Projections of charm reduced cross-sections & structure function F_2

Measurements of $D\overline{D}$ hadrons

[1] https://eic.github.io/software/pythia6.html

Fast Simulation Setup

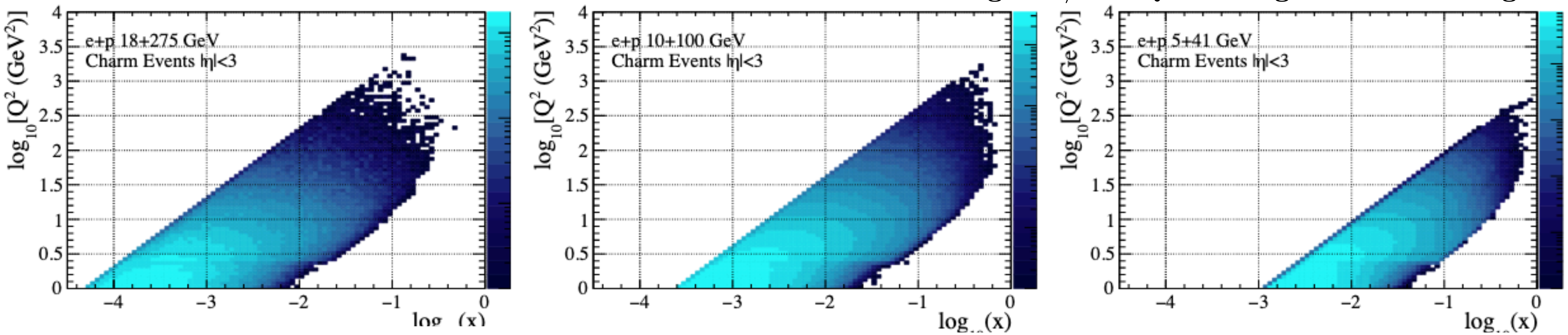
PYTHIA 6 Subprocesses

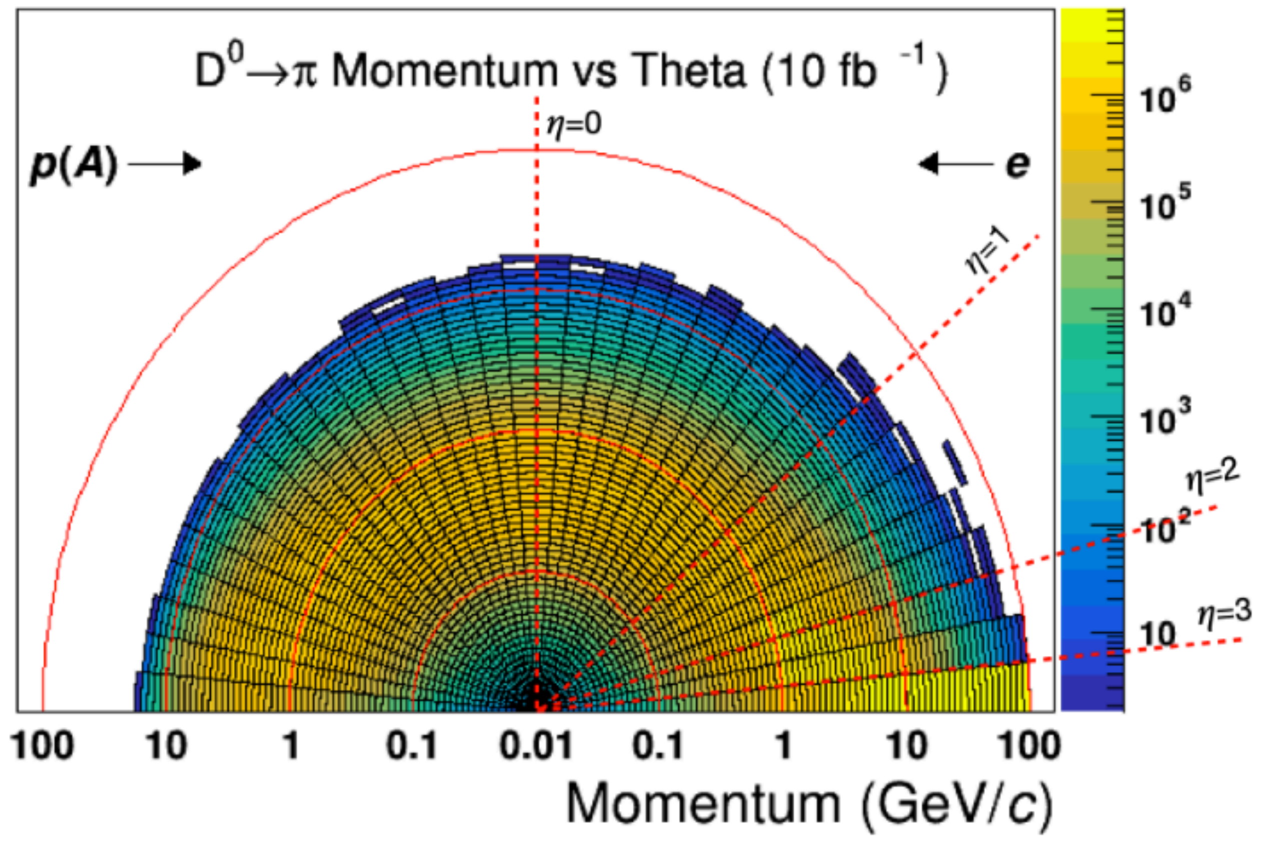
Subprocess	#	Description
soft VMD		
V N → V N	91	elastic VMD
V N → X N	92	single-diffractive VMD
V N → V X	93	single-diffractive VMD
V N → X X	94	double-diffractive VMD
V N → X	95	soft non-diffractive VMD low-pT
QCD 2→2		
	96	semihard QCD 2→2
RESOLVED (hard VMD and anomalous)		
qq → qq	11	QCD 2 → 2(q)
q qbar → q qbar	12	
q qbar → gg	13	
gq → gq	28	
qg → qg	28	QCD 2 → 2(g)
gg → q qbar	53	
gg → gg	68	
DIRECT		
γ*q → q	99	LO DIS
γ*T q → qg	131	(transverse) QCDC
γ*L q → qg	132	(longitudinal) QCDC
γ*T g → q qbar	135	(transverse) PGF
γ*L g → q qbar	136	(longitudinal) PGF

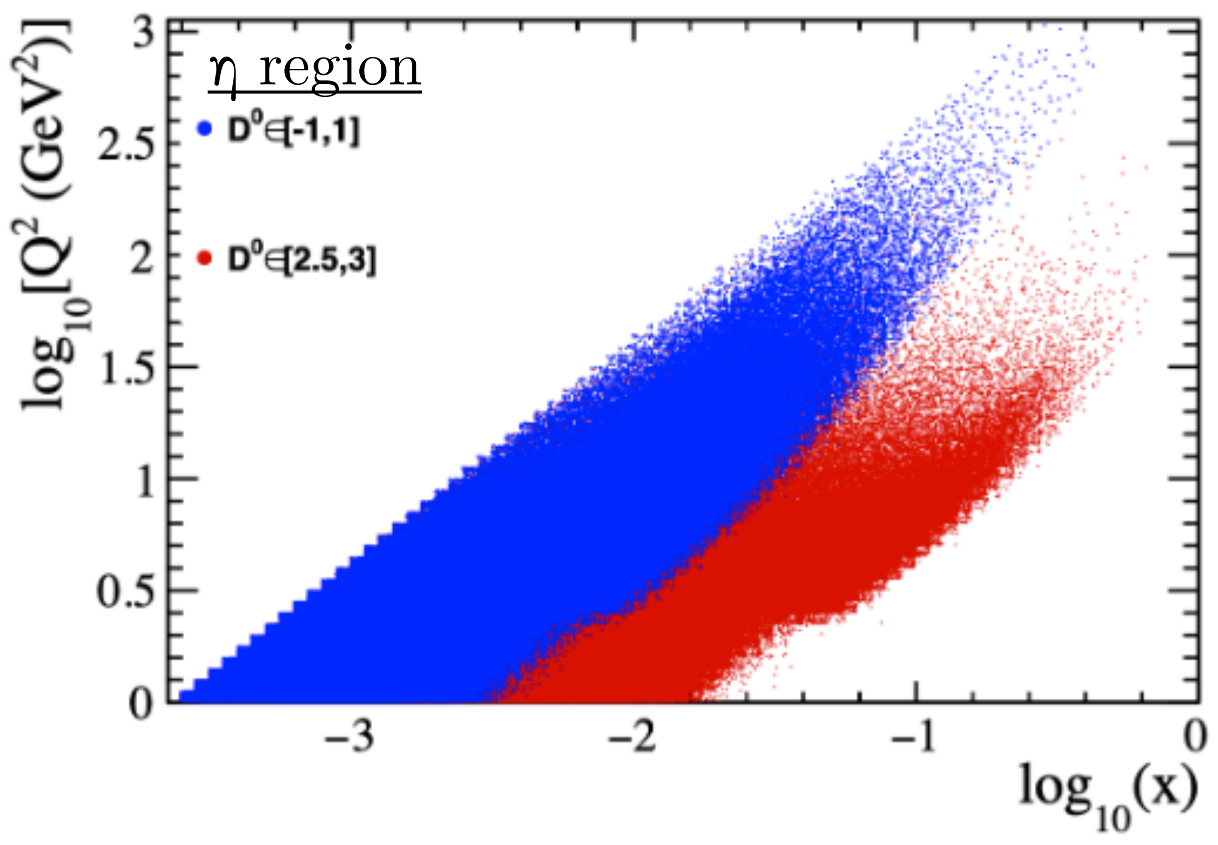
Electron-proton collisions generated with PYTHIA 6 with eRHIC tuning [1]

Kinematic coverage of charm events studied for various beam energy configurations

High x_B/low Q^2 coverage at lower energies







Fast Simulation Setup

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PYTHIA 6

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Electron-proton collisions generated with PYTHIA 6 with eRHIC tuning [1]

Kinematic coverage of charm events studied for various beam energy configuration

Final state hadrons smeared with momentum and position resolutions

Momentum 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	$0.1 \cdot p \oplus 2.0$

Position Resolution (Transverse)

η Region	Detector Matrix (μm)	LBNL (μm)
-3.0< η <-2.5	$30/p_T \oplus 40$	$30/p_T \oplus 10$
-2.5< η <-2.0	$30/p_T \oplus 20$	$30/p_T \oplus 10$
-2.0< η <-1.0	$30/p_T \oplus 20$	$25/p_T \oplus 10$
-1.0< η <1.0	$20/p_T \oplus 5$	$20/p_T \oplus 5$
1.0< η <2.0	$30/p_T \oplus 20$	$25/p_T \oplus 10$
2.0< η <2.5	$30/p_T \oplus 20$	$30/p_T \oplus 10$
2.5< η <3.0	$30/p_T \oplus 40$	$30/p_T \oplus 10$
3.0< η <3.5	$30/p_T \oplus 60$	N/A

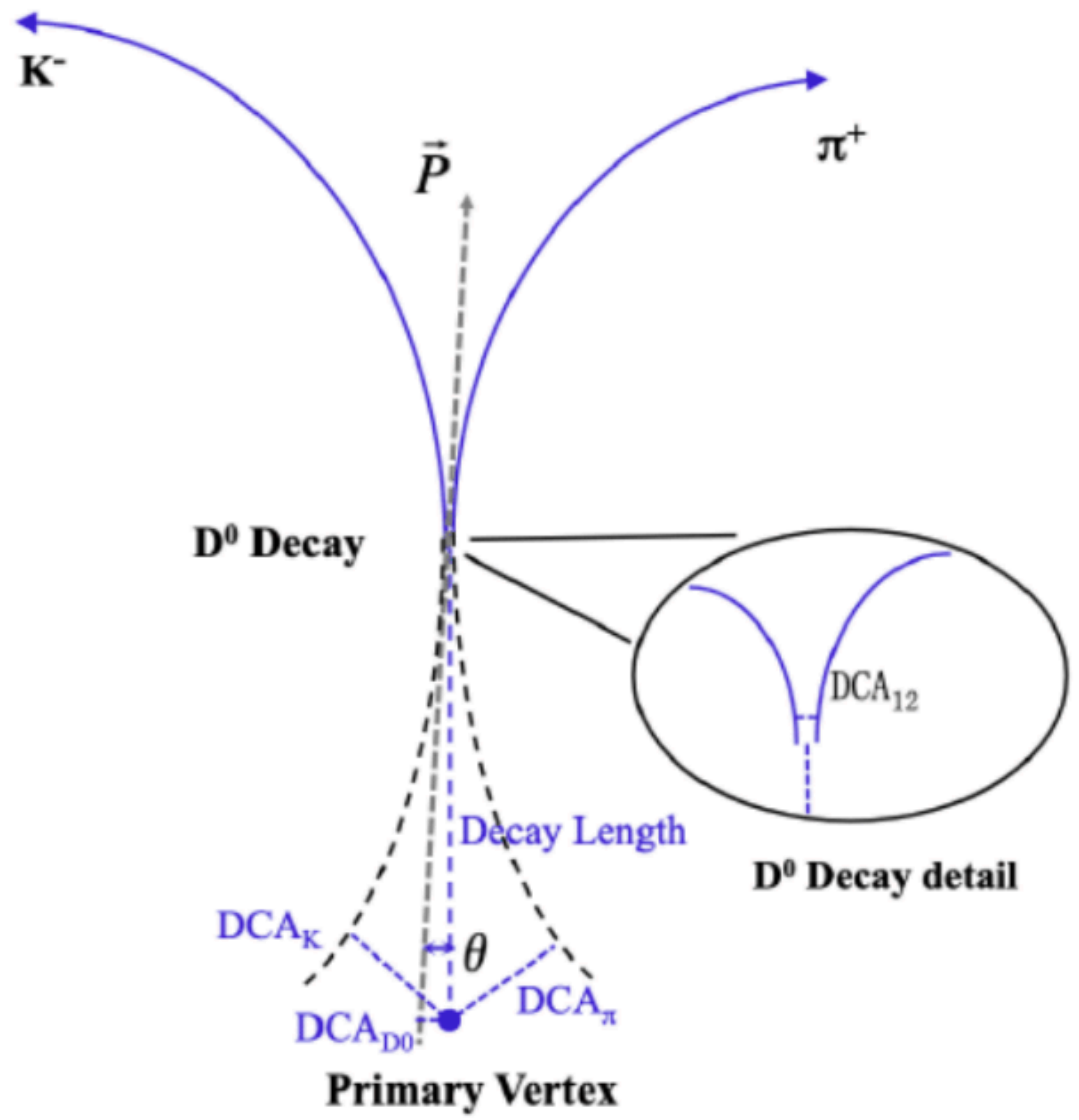
Two single track pointing resolution scenarios

PID: Assumption of good K/π/p separation up to $p = 7(10)$ GeV/c

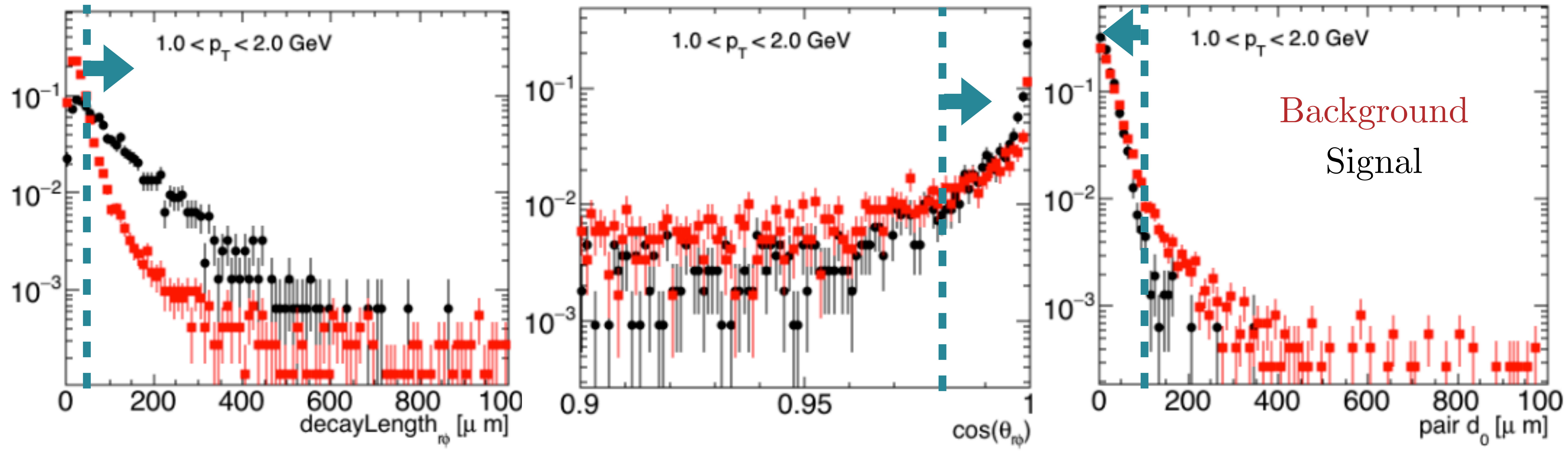
+Primary Vertex (PV) resolution (described later)

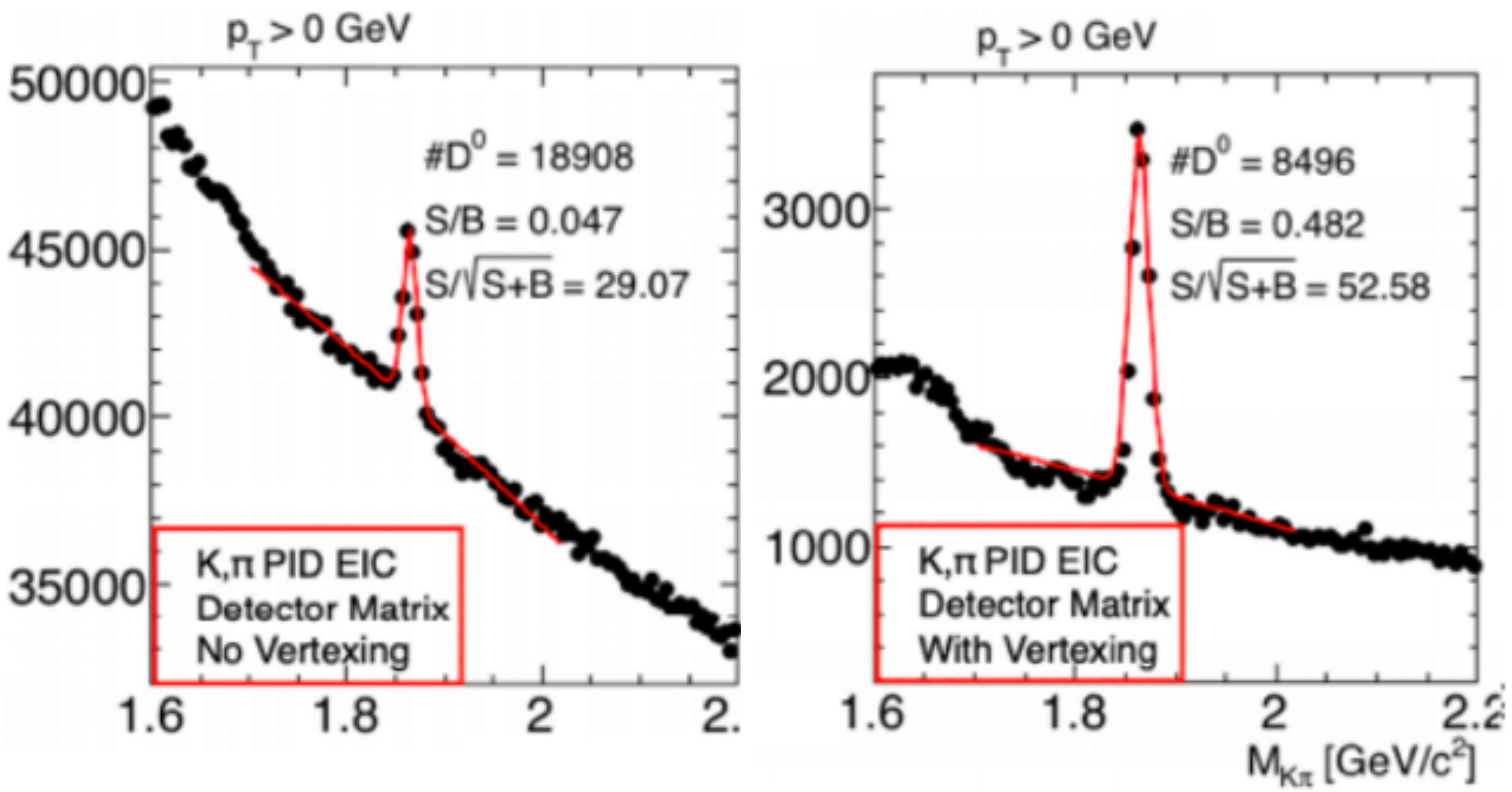
[1] https://eic.github.io/software/pythia6.html

D^0 Reconstruction with Vertexing



Detector Matrix Pointing Resolution





Topological reconstruction of $D^0 \rightarrow K\pi$

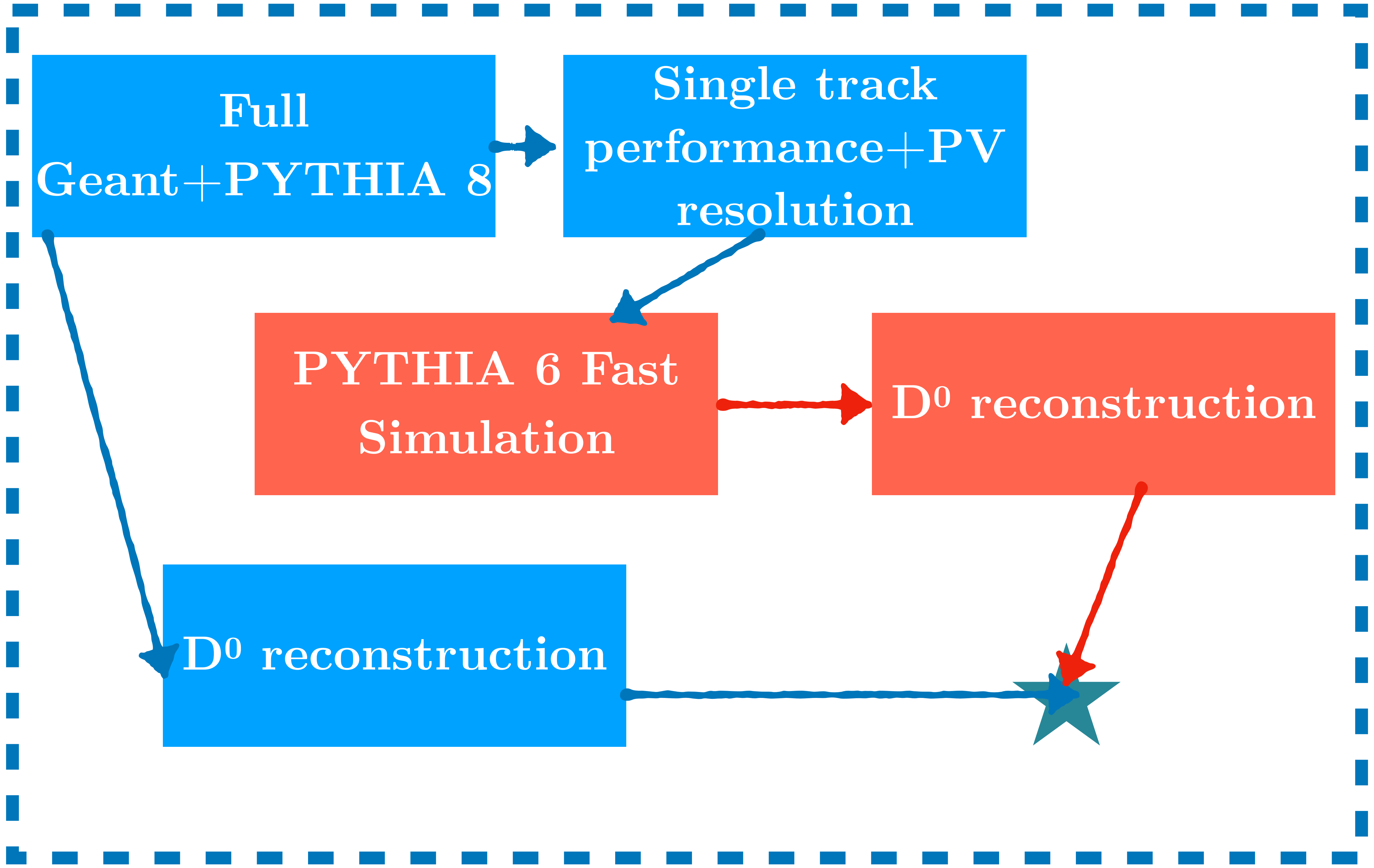
BKGs include combinatorial+partially reco. charm

Topological cuts increase integrated signal significance by 70%

- Not optimized to maximize significance+p_T dependence
- Other possible variables+longitudinal dimension

Full Simulation Validation

Reliability of D^0 reconstruction with fast simulation smearing evaluated using full GEANT4-based PYTHIA 8 simulation in Fun4All framework



<u>All-Silicon Detector Concept</u>

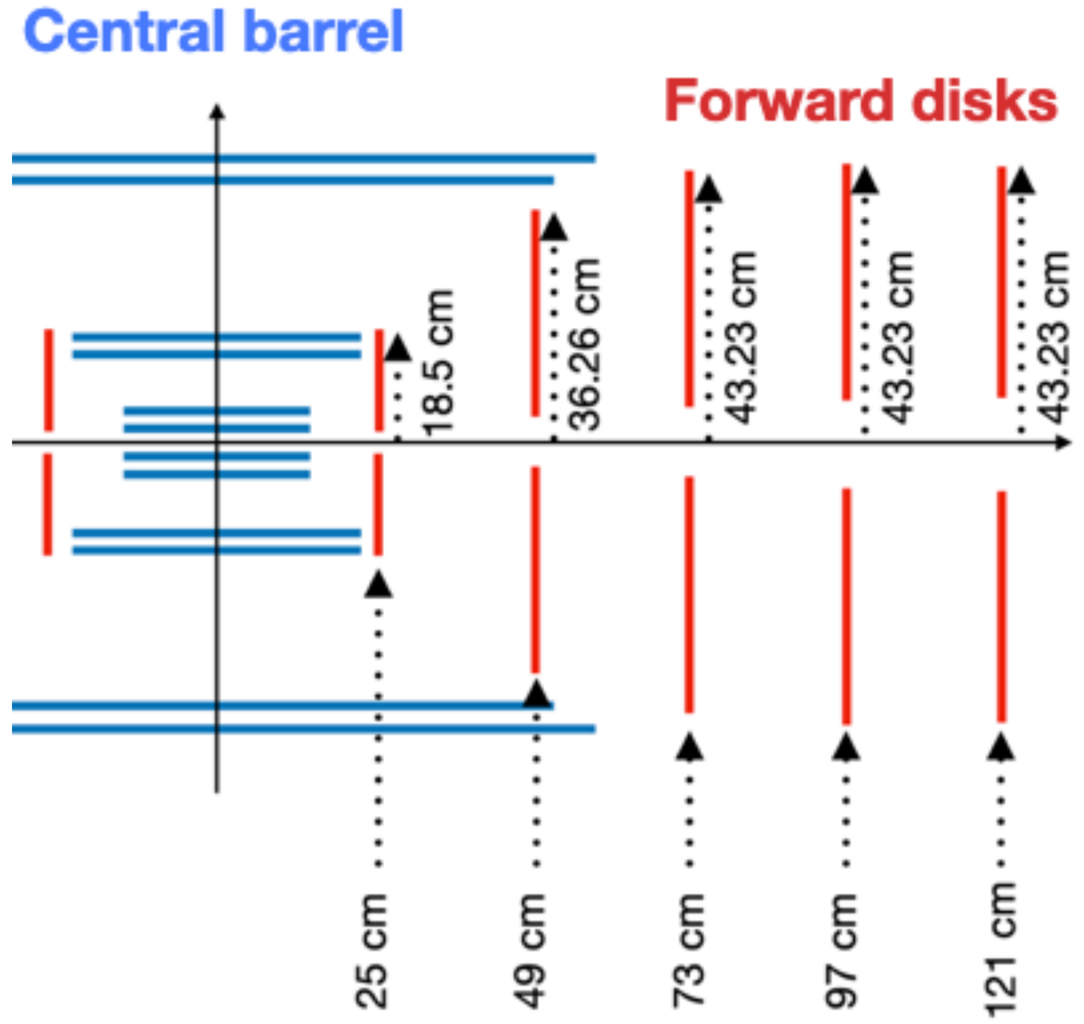
10 μm x 10 μm pixel devices

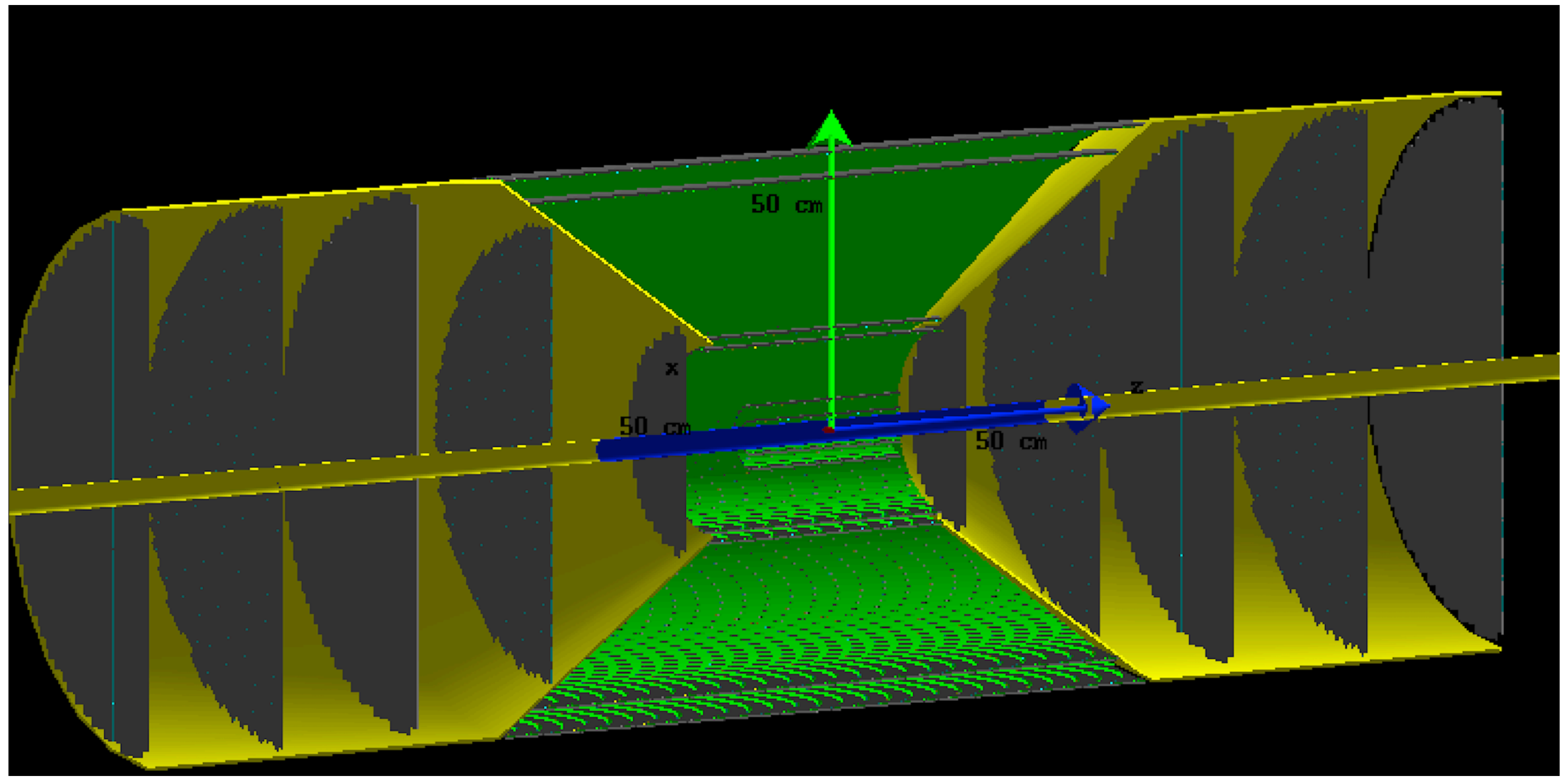
X/X0=0.3% per layer

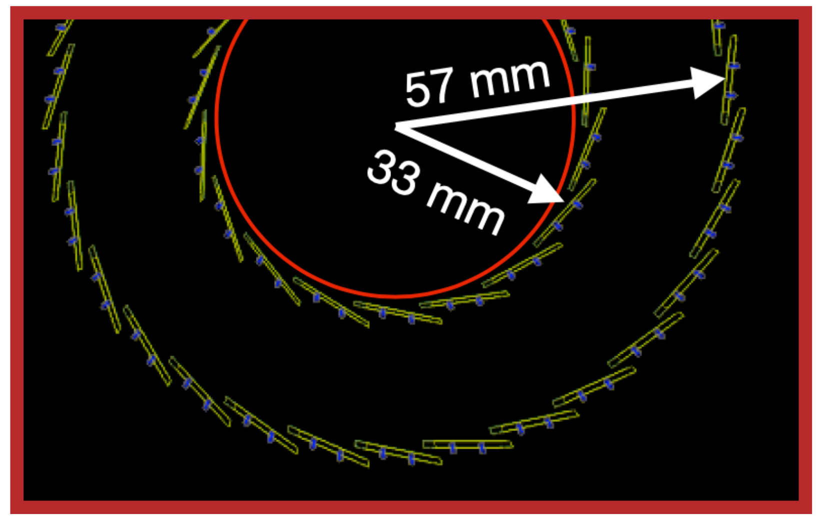
Beampipe r=3.1 cm

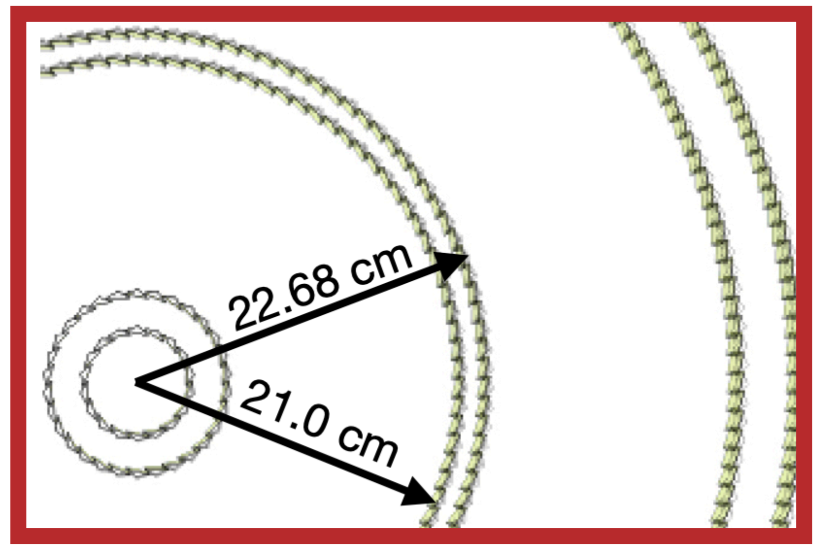
B = 3.0 T

Outer barrel r = 39, 42 cm



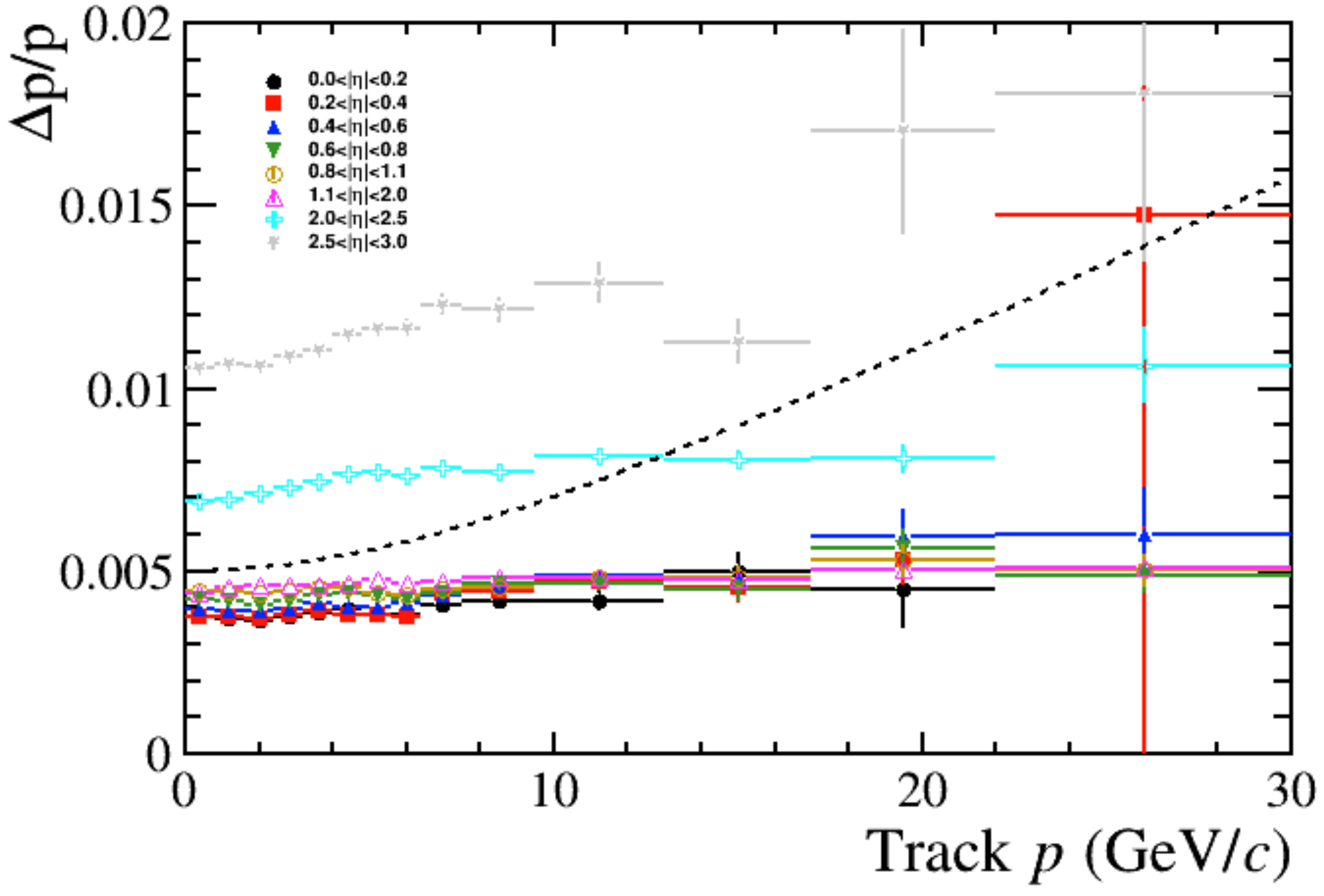


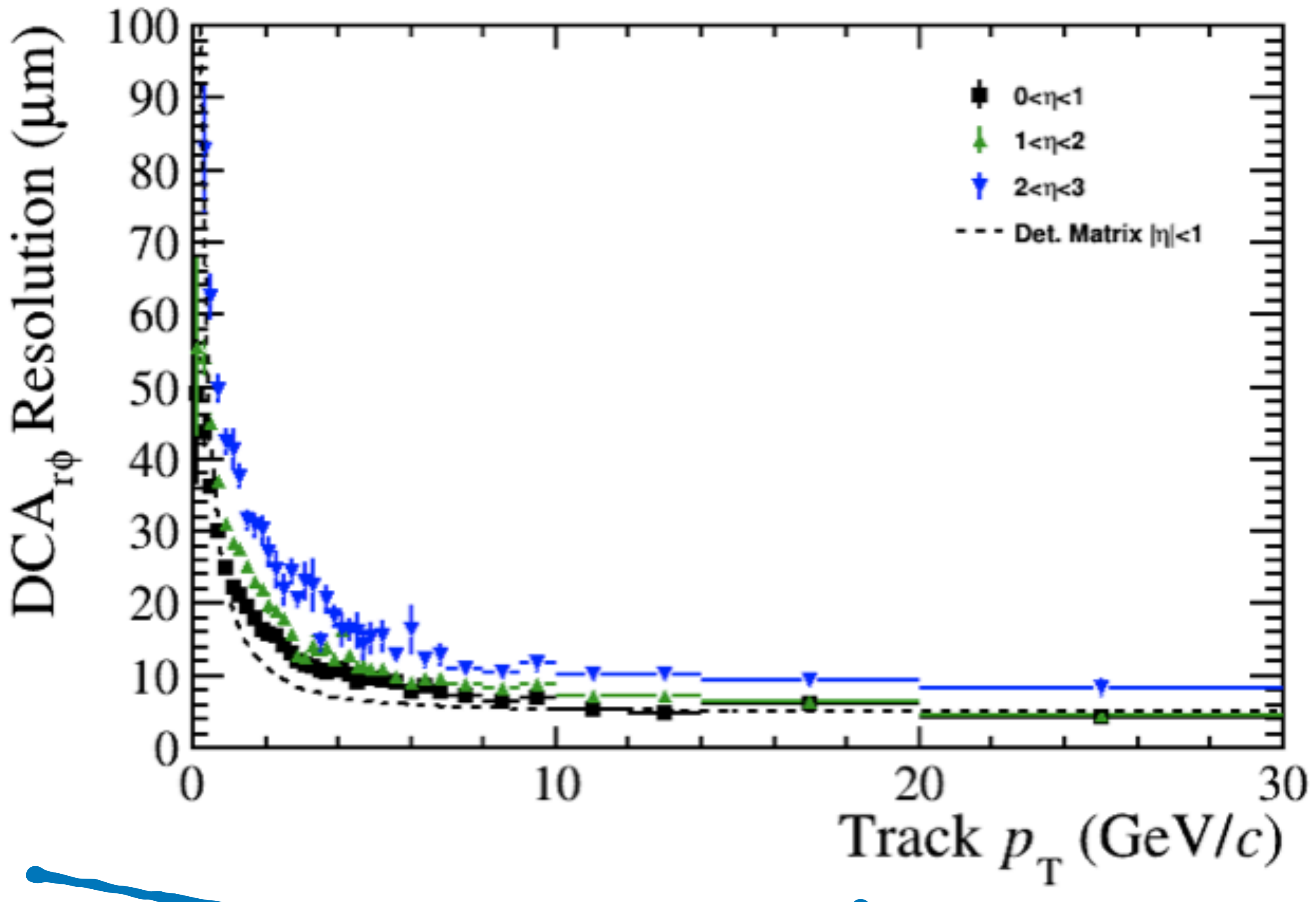


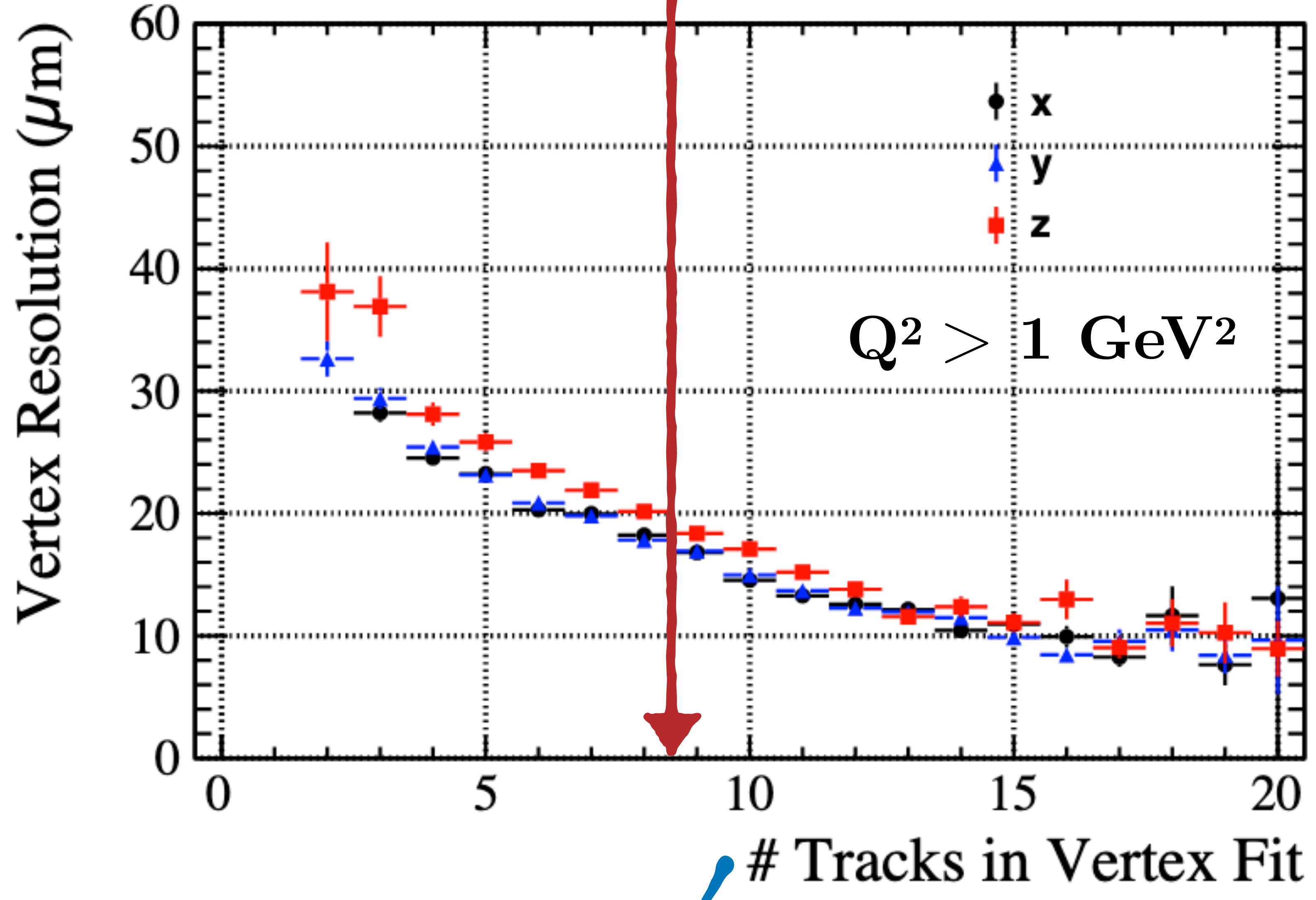


All-Si Performance

⟨N⟩ for heavy-flavor events







Sub-percent momentum resolution

Comparable pointing resolution to detector matrix parameterization

Primary vertex resolution on the order of 20 μm for heavy-flavor events

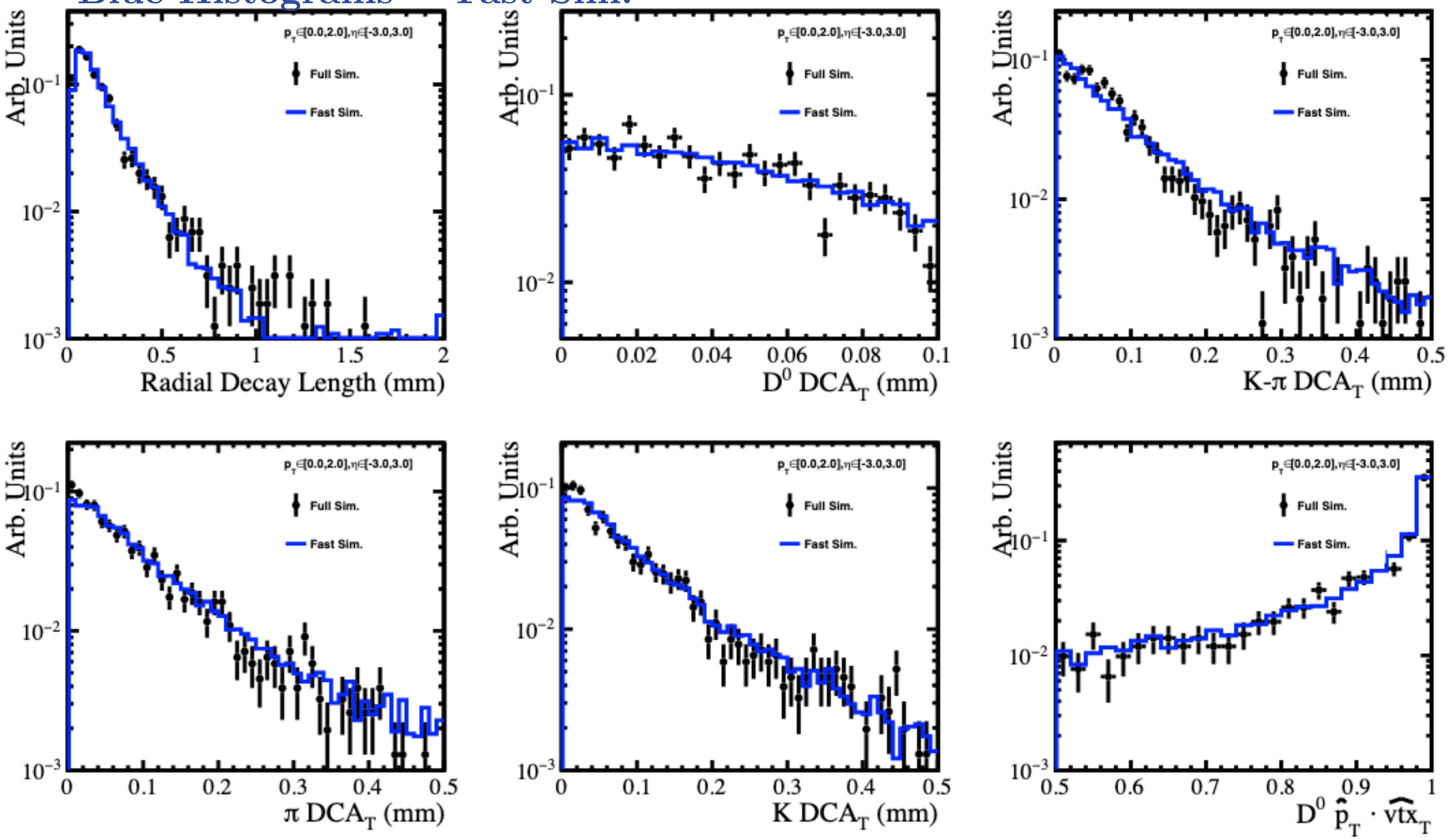
Pythia6 Fast Simulation

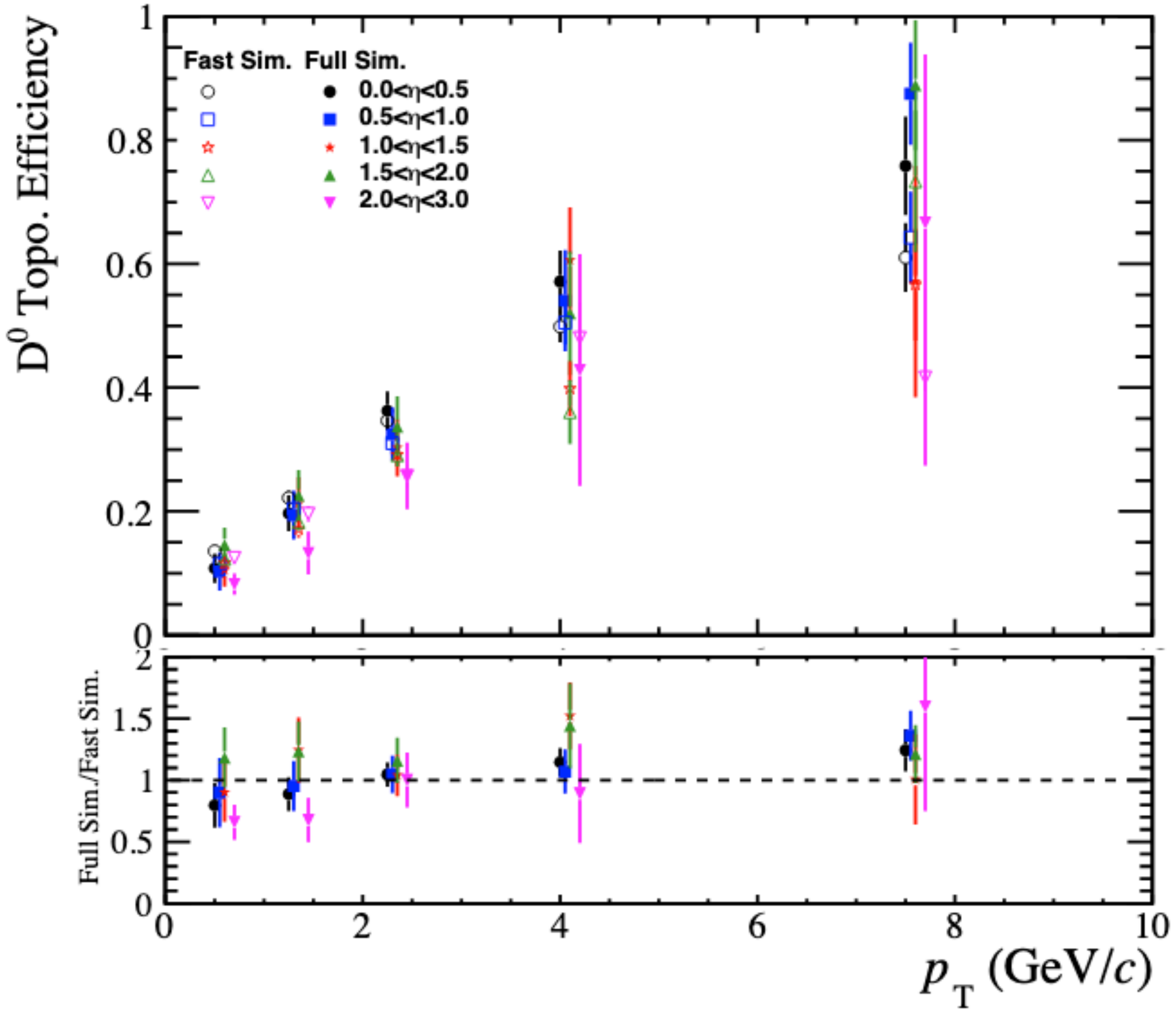
Plus pseudo-tracking efficiency to keep things consistent and assumption of perfect PID

Full vs. Fast Simulation

Data Points = Full Sim.

Blue Histograms = Fast Sim.





Good agreement between full and fast simulation distributions

Consistent efficiency after applying same default cuts

Validation of fast simulation procedure

Reduced Charm Hadron Cross-Section

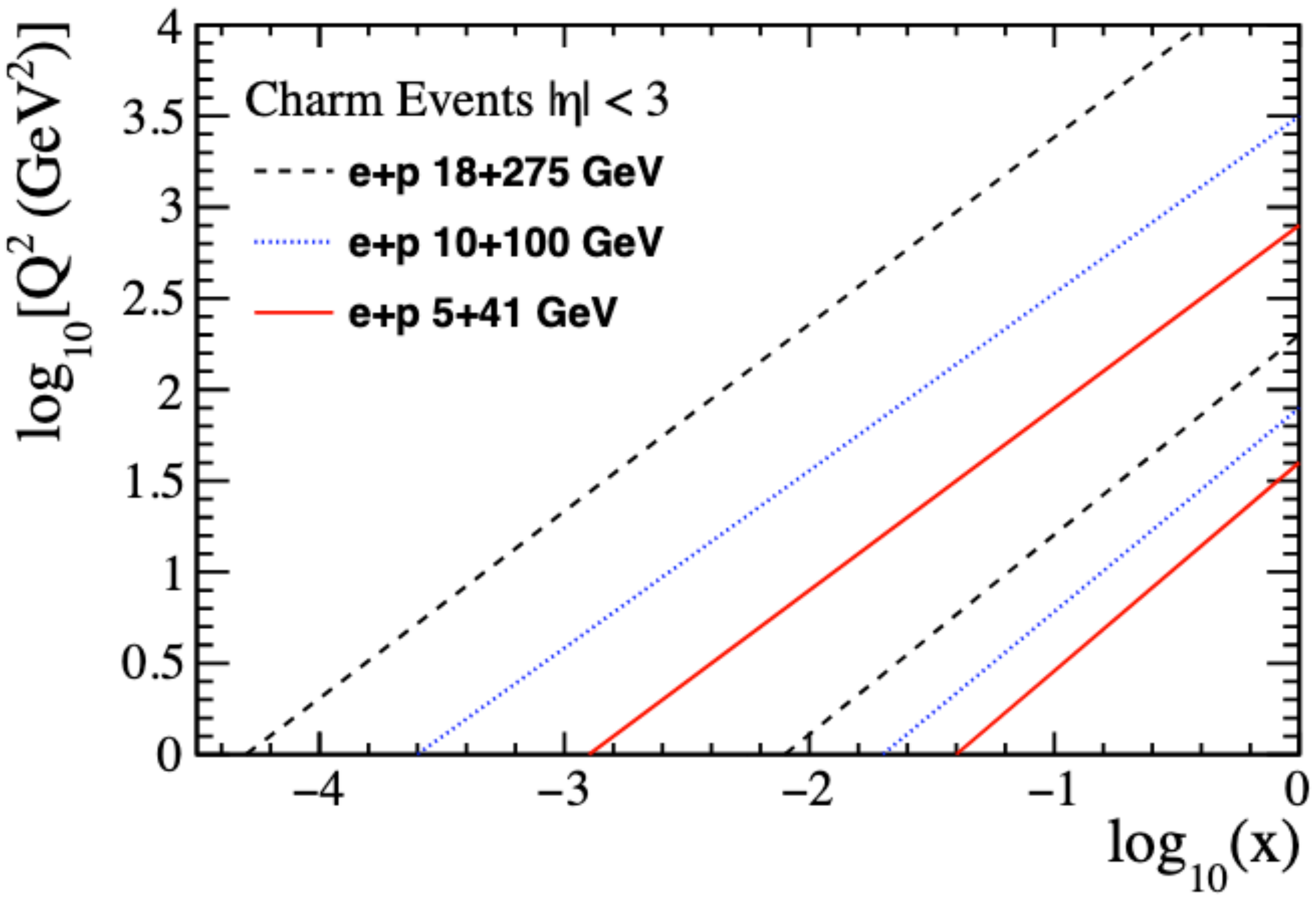
10x100 GeV and 5x41 GeV energies simulated

- Maximize high-x_B reach for charm F_2
- Scale yield to 10 fb^{-1} per energy as baseline

Nominal fast smearing routine (mom., pos., and PV resolutions, and track eff.)

D^0 truth candidates counted within mass peak after all selections

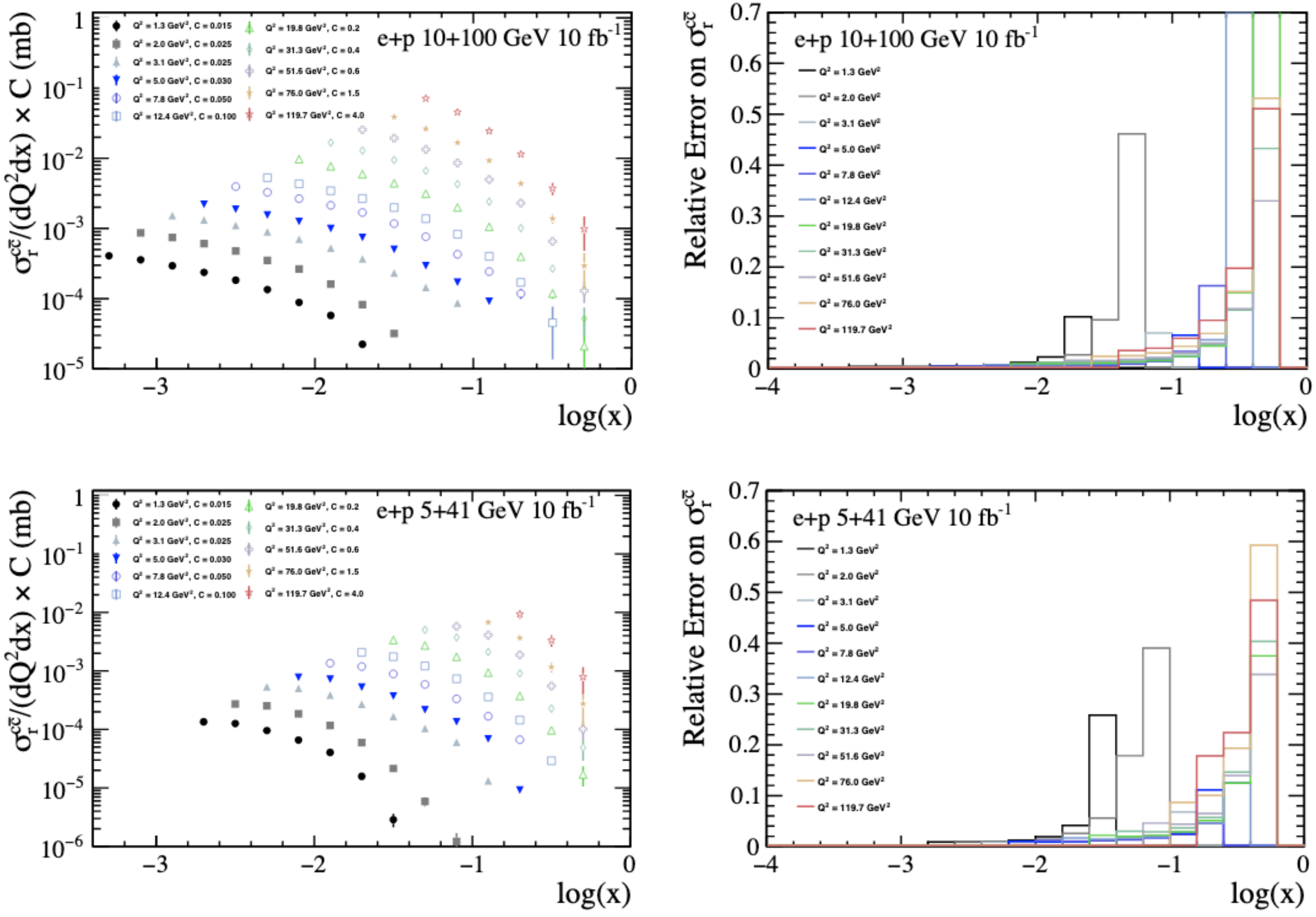
- Note: same counting for all backgrounds to derive signal significance



$$\sigma_r(x, Q^2) = \frac{dN(D^0 + \bar{D}^0)/2}{\mathcal{L} \cdot \varepsilon \cdot \mathcal{B}(D^0 \to K\pi) \cdot f(c \to D^0) \cdot \mathrm{d}x\mathrm{d}Q^2} \times \frac{xQ^4}{2\pi\alpha^2[1 + (1-y)^2]}$$

Reduced Charm Hadron Cross-Section

Uncertainties calculated directly from signal significance only



Charm Structure Function F_2

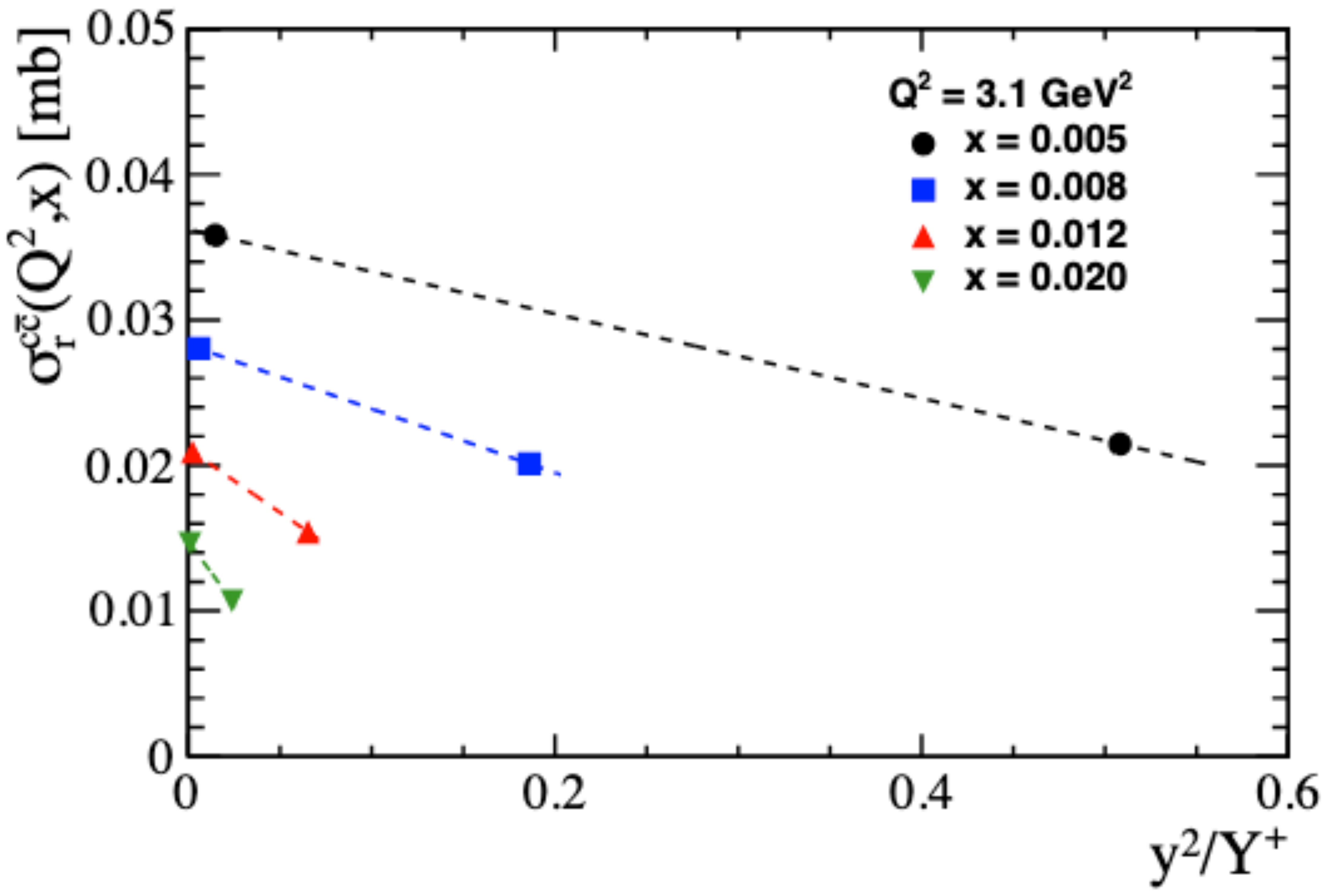
$$\sigma_r^{c\bar{c}}(Q^2,x) = F_2(Q^2,x) + \frac{y}{Y^+} F_L(Q^2,x), \;\; Y^+ = 1 + (1-y)^2$$

At fixed Q^2 and x_B σ_r behaves linearly vs. y/Y^+

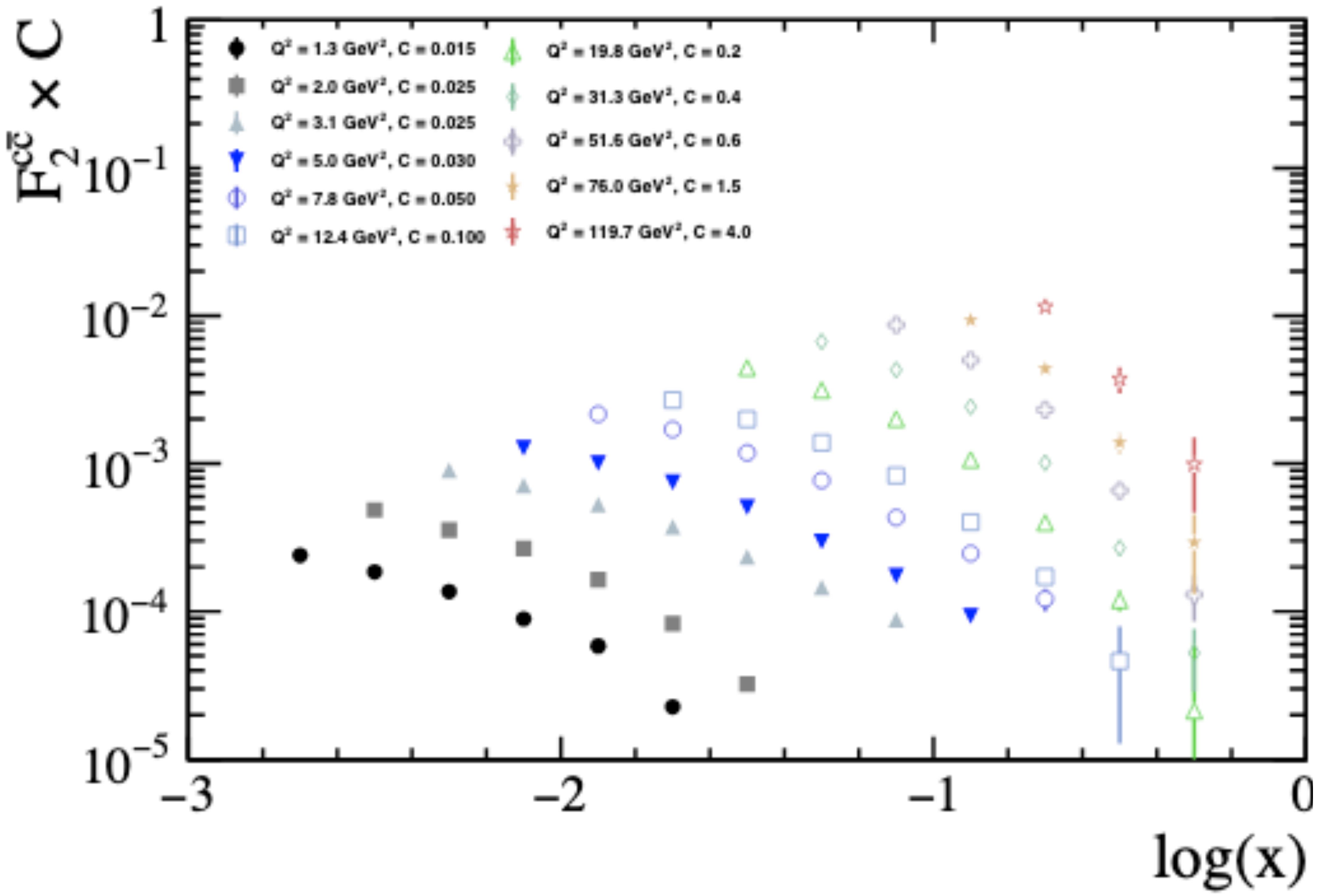
- Motivation for good (Q2,x) overlap at two c.o.m. energies

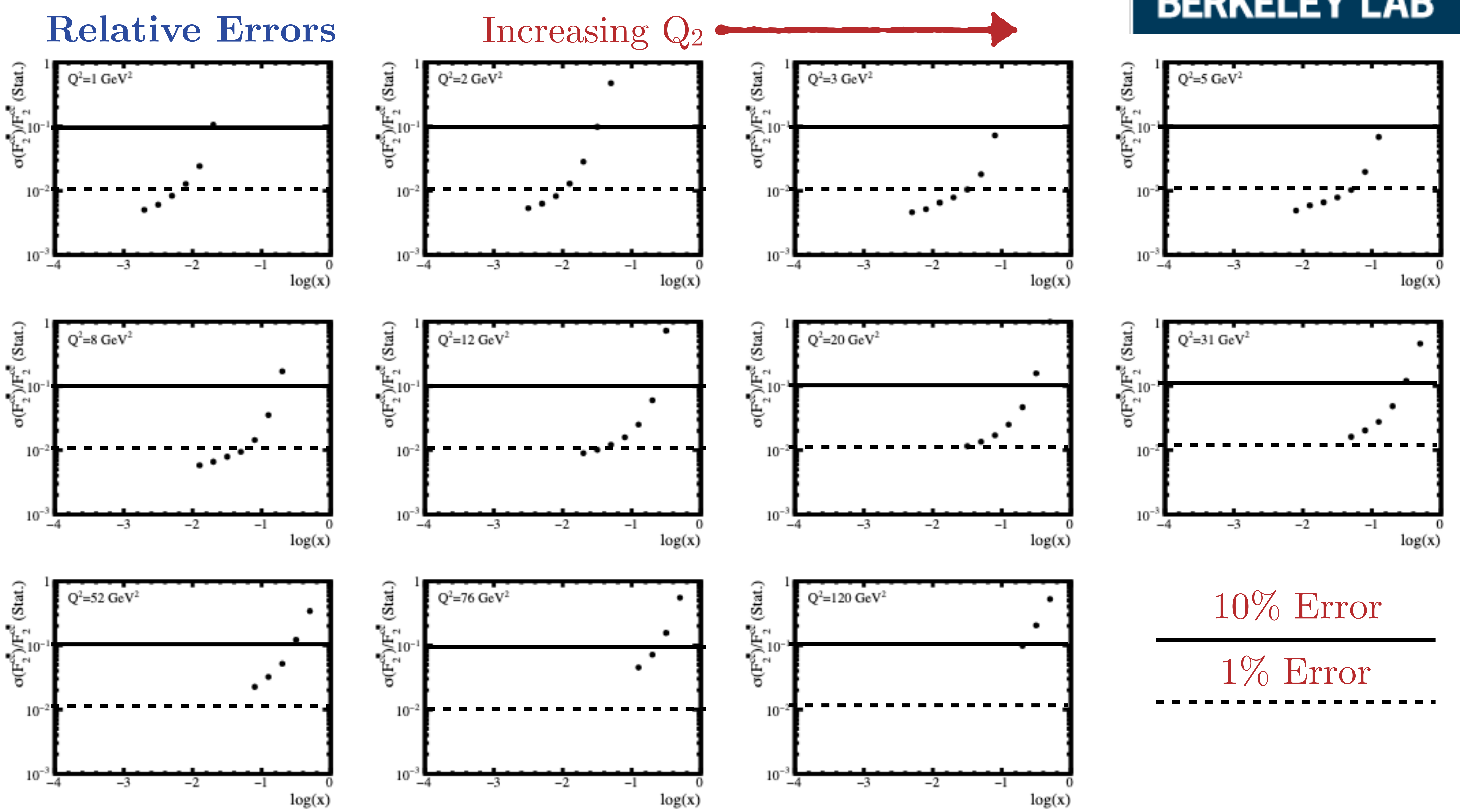
Integrated L=10 fb^{-1} used for each energy

- Largest y-axis constraint from higher-energy value



Charm Structure Function F_2



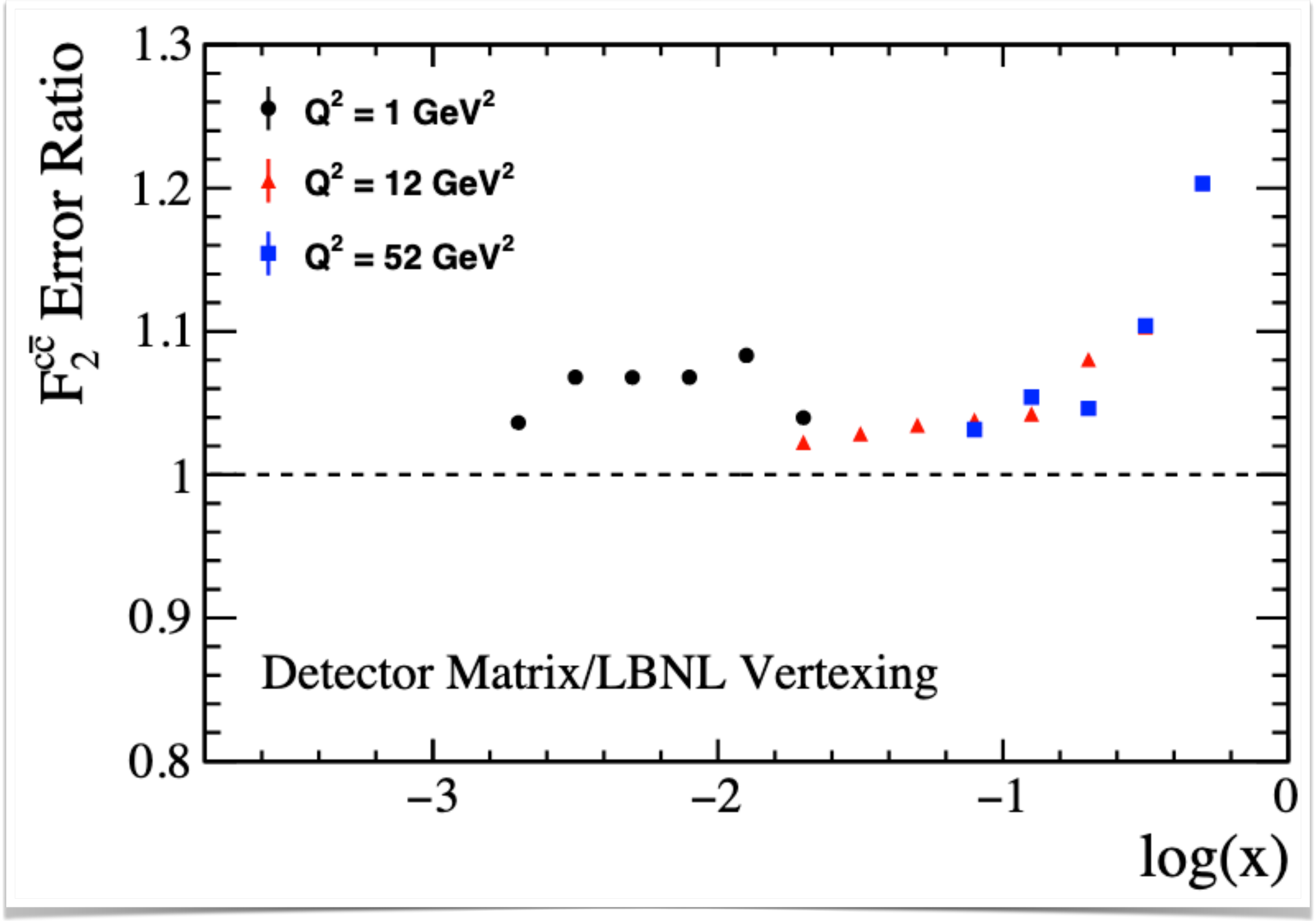


Uncertainties dominated by higher-energy cross-section

- Reduced 5x41 GeV by factor of ten → small impact on F_2
- Reduced 10x100 GeV by factor of two → almost √2 increase in uncert.

Full QCD analysis needed for gluon PDF

Comparison of Tracking Scenarios



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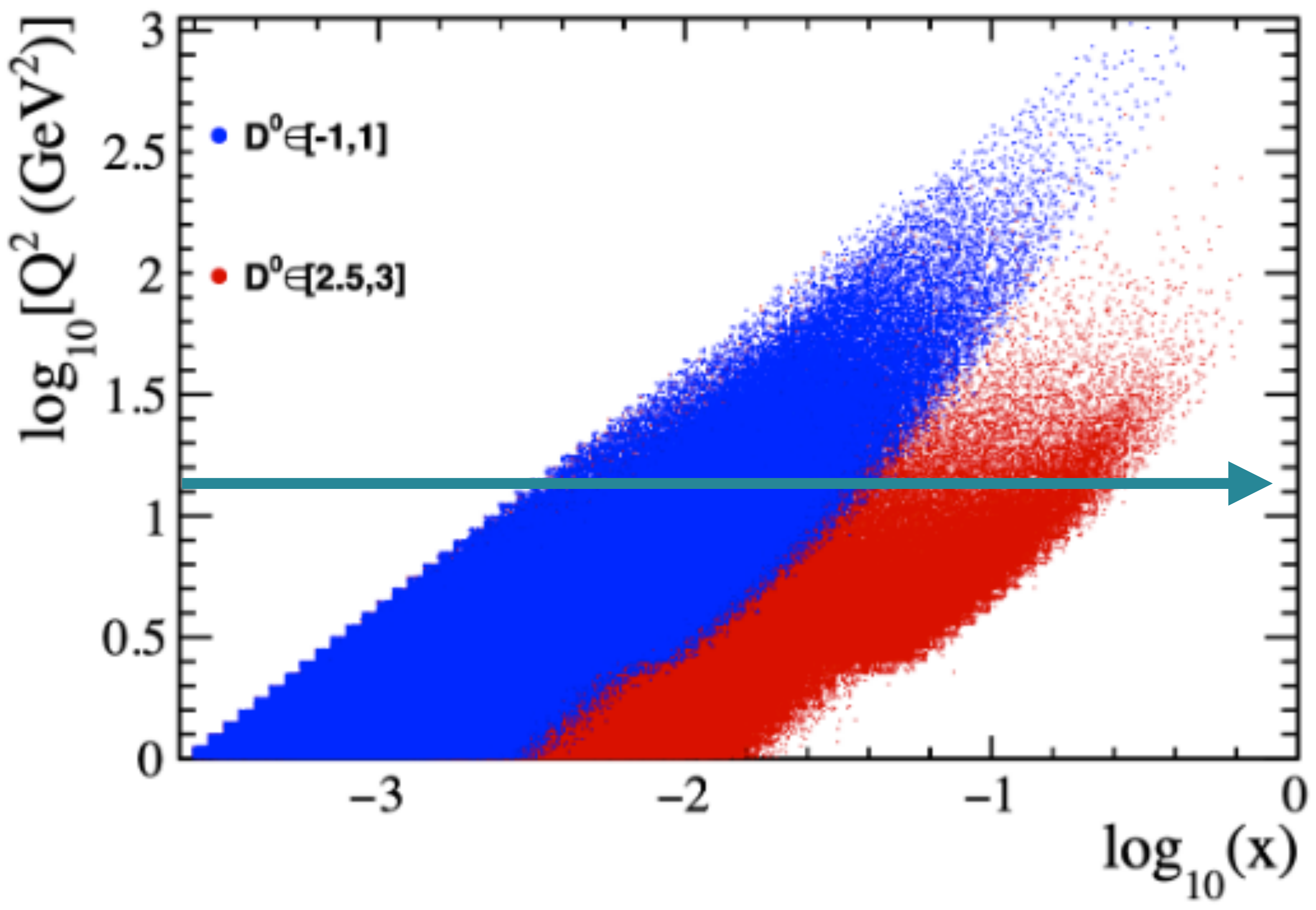
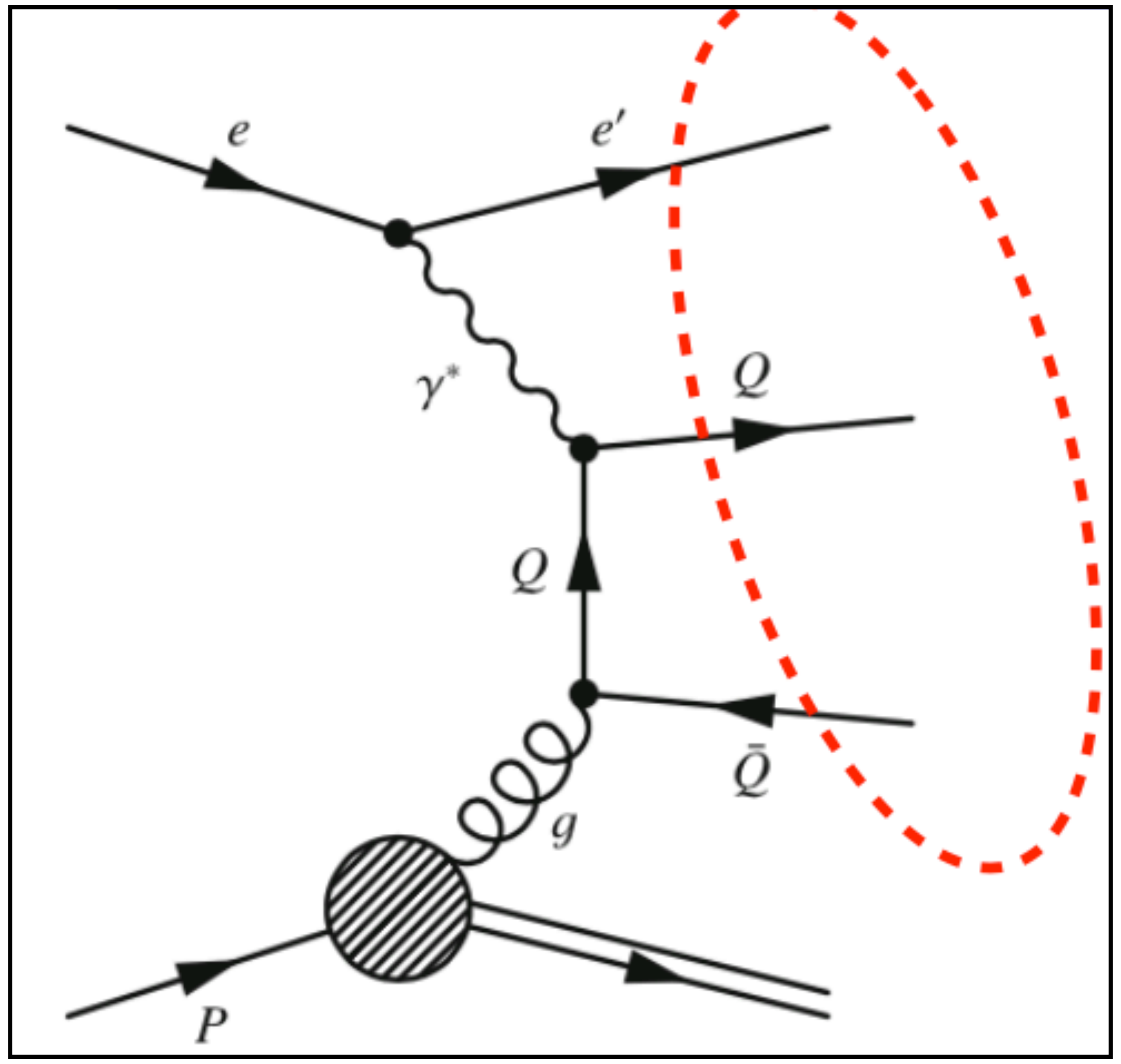


Trend vs. log(x) reflective of D^0 η distribution at fixed Q^2

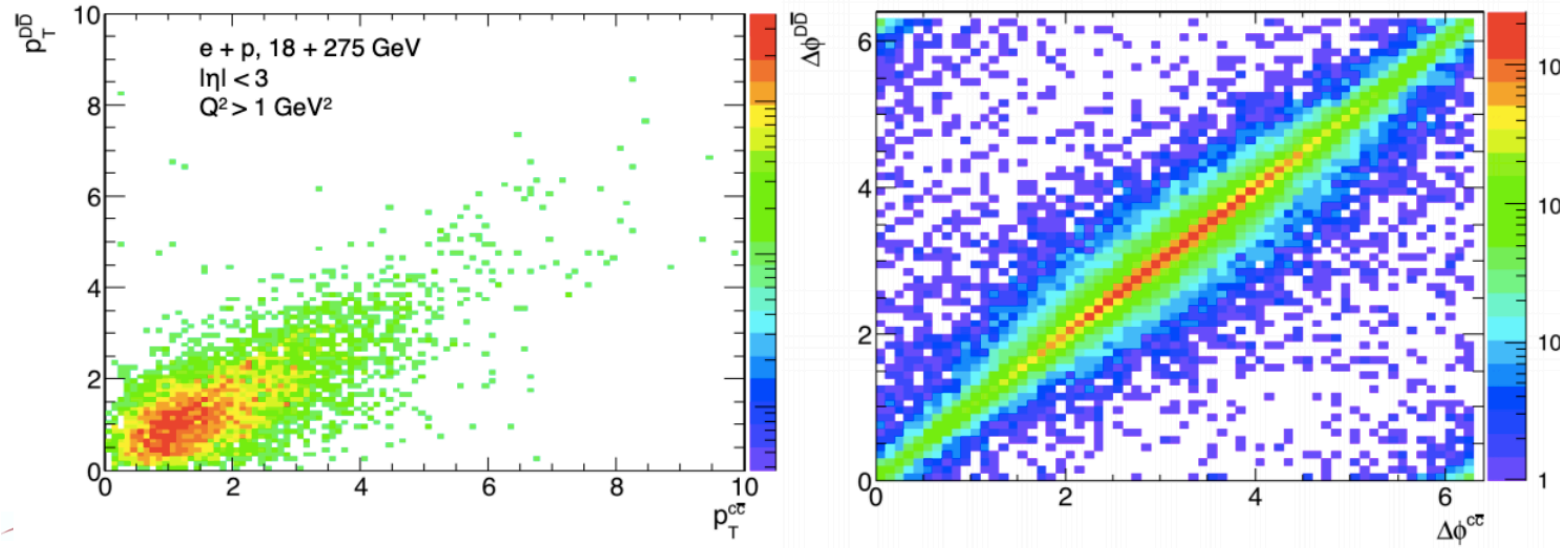
$D\bar{D}$ Hadron Pairs Reconstruction



Reconstructed charm hadron pair+scattered electron

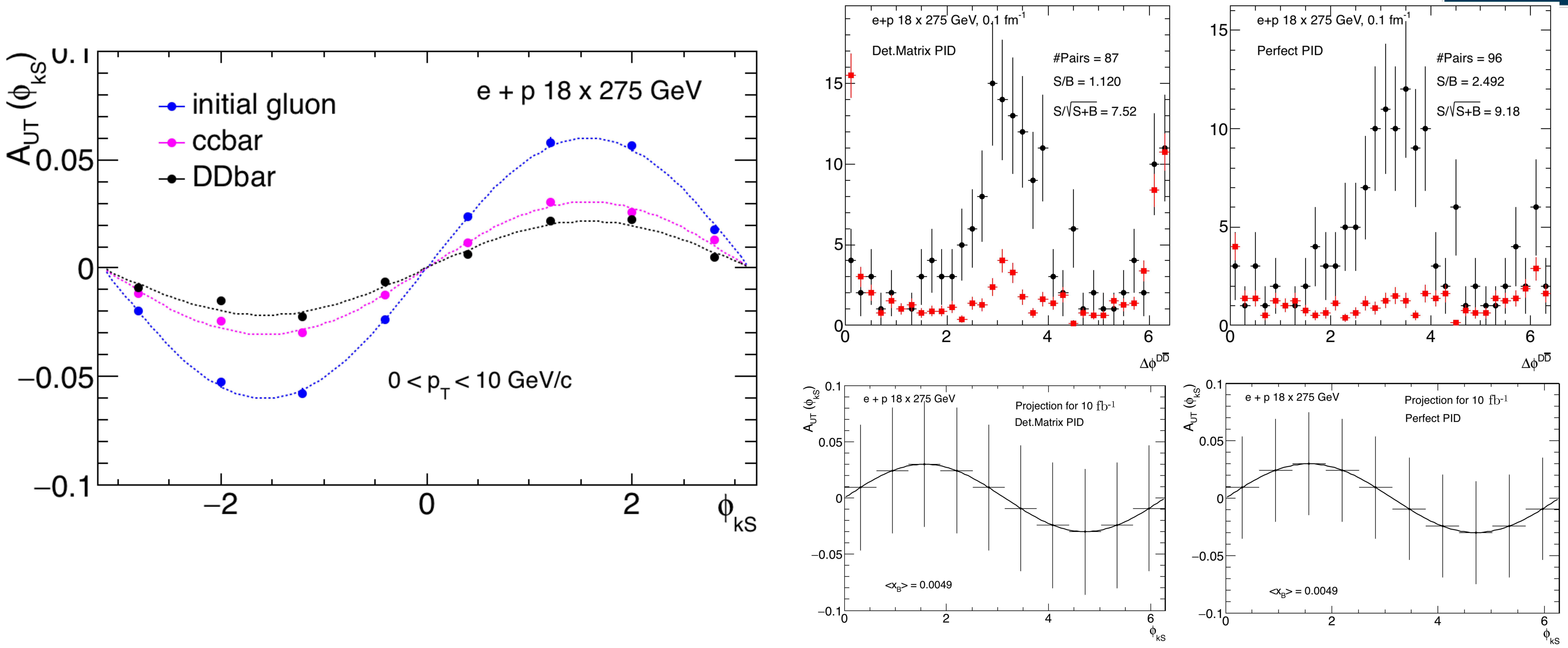
→ Access to full gluon kinematics

- Sensitive to gluon Sivers function in polarized collisions
- Sensitive to linearly polarized TMD function in unpolarized collisions



Preservation of charm di-quark kinematics through hadronization

Projection on Gluon Sivers Function



Dilution predominately from gluon→$c\bar{c}$ step; good signal preservation in hadronization process

- Studies of p_T dependent dilution ongoing

Projected Sivers asymmetry coefficient 4σ for 6% signal; 2σ for 3% signal

Summary

➡Studied the production kinematics and reconstruction of charm hadrons in e-p collisions using PYTHIA 6

➡Verified the reliability of fast simulation smearing using a full GEANT4-based simulation

➡Calculated reduced cross sections for charm hadrons and charm structure function F_2

➡Joint effort with theory groups to study impact on gluon (n)PDFs

➡Studies of $D\bar{D}$ reconstruction and projection for gluon Sivers function

Backup Slides Follow

PYTHIA 8 Setup

Electron-proton collisions generated using PYTHIA 8

- 18 GeV electrons on 275 GeV protons

Full Geant4 simulation using the Fun4All framework

```
Beams:idA = 2212     ! first beam, p = 2212, pbar = -2212
Beams:idB = 11       ! second beam, e = 11, ebar = -11
Beams:eA = 275       ! proton beam 275 GeV/c
Beams:eB = 18        ! electron beam 18 GeV/c
Beams:frameType=2    ! beams are back-to-back, but with different energies
! Settings related to output in init(), next() and stat()
Init:showChangedSettings = on
Main:timesAllowErrors=900000
Next:numberShowInfo = 1             ! print event information n times
! PDF
#PDF:pSet = 7 ! CTEQ6L, NLO alpha_s(M_Z) = 0.1180.
Tune:preferLHAPDF = 2
Tune:pp=14 #default one

MultipartonInteractions:pT0Ref=3
PDF:lepton=off
PhaseSpace:mHatMin=0.
# PhaseSpace:mHatMin=0.
PhaseSpace:pTHatMinDiverge=0.5
SpaceShower:dipoleRecoil=on
SpaceShower:pTmaxMatch=2
TimeShower:QEDshowerByL = off

PhotonCollision:all=on
PhotonParton:all=on
PromptPhoton:all=on
WeakBosonExchange:all=on
WeakSingleBoson:all=on
WeakDoubleBoson:all=on
#should not open the following
HardQCD:all=on
# # SoftQCD:elastic=on
# # SoftQCD:nonDiffractive=on
# # Diffraction
Diffraction:doHard=on
Charmonium:all=on
Bottomonium:all=on
# PhaseSpace:pTHatMin = 1
# PhaseSpace:pTHatMax = 2
PhaseSpace:Q2Min=1

Random:setSeed = on
Random:seed = 0

PDF:extrapolate = on
```

Full Simulation Tracking Efficiency