Charm and Bottom at EIC

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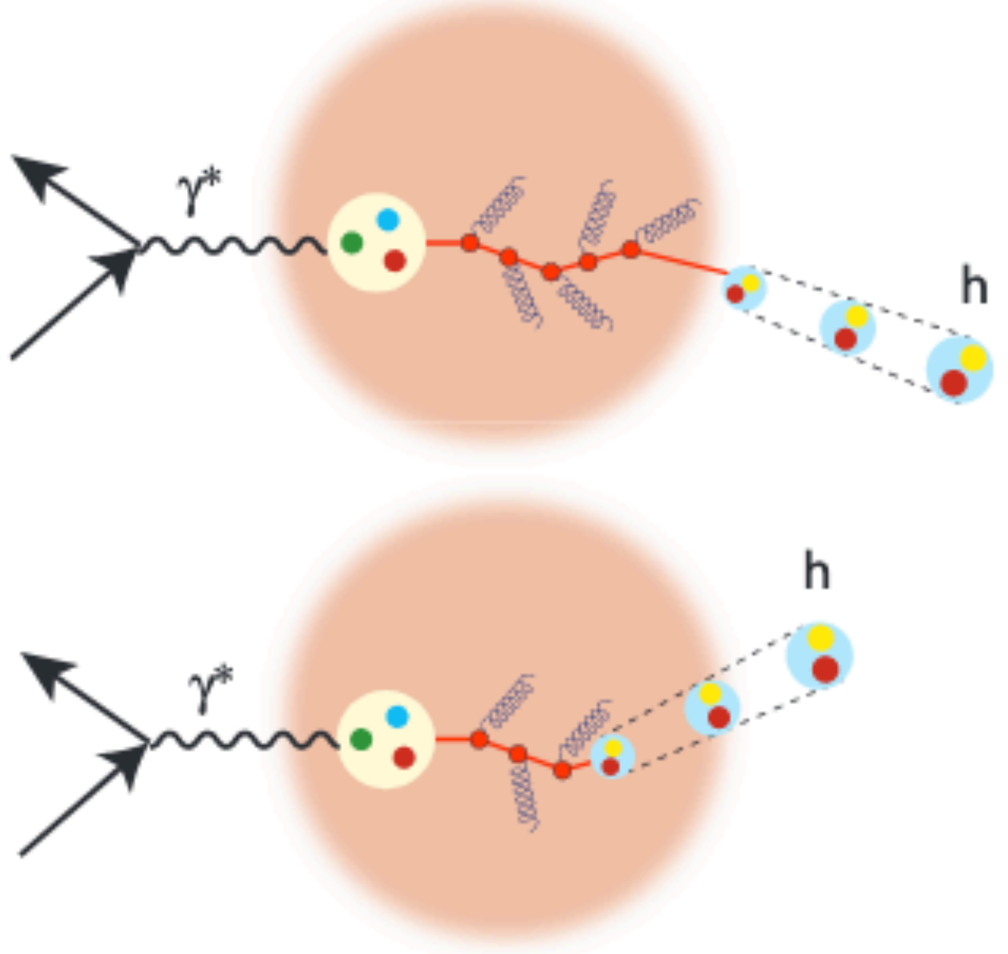
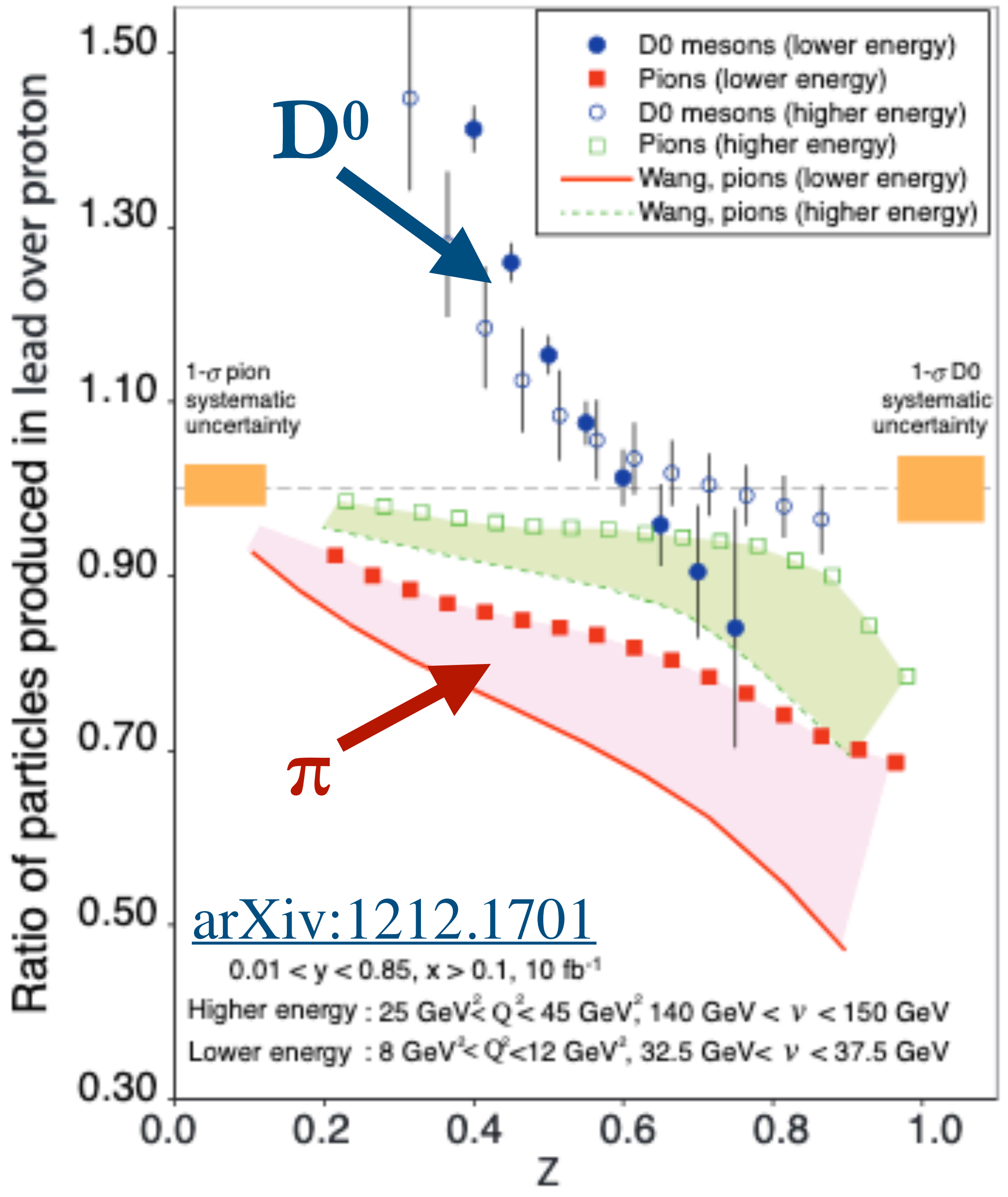
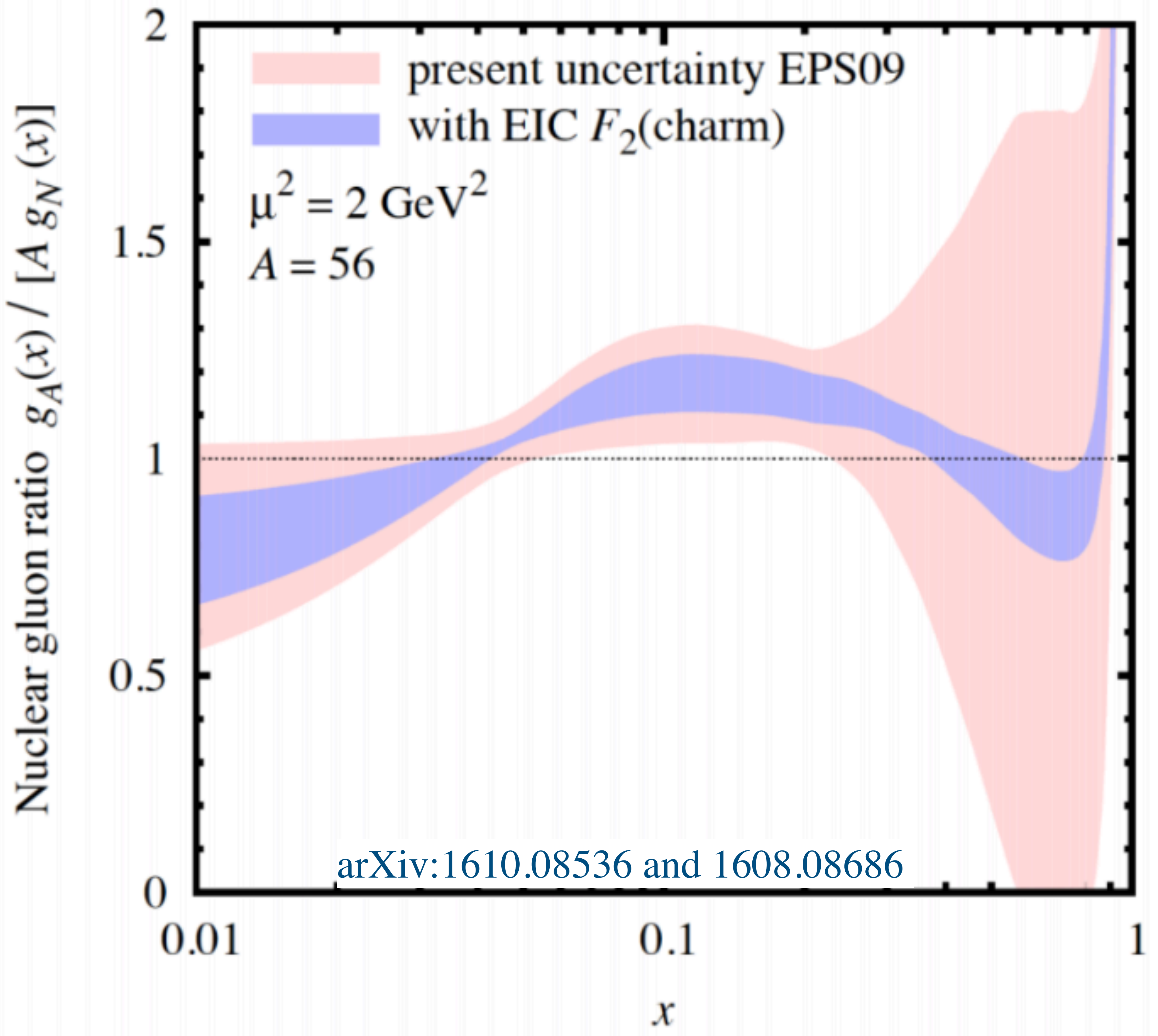
Heavy-Flavor in e-p(A) Collisions







- **Lots of interesting physics to do with heavy-flavor quarks**
  - Charm + bottom production
  - Cold nuclear matter effects; Charm+bottom hadronization
  - High-x charm production + improvement to gluon nPDF
  - Quarkonia production
  - Gluon contribution to nucleon spin

Outline

- PYTHIA setup
- Charm and bottom hadron distributions in e+p collisions
- Fast simulation setup + primary vertex (PV) reconstruction studies
- D^0 + B reconstruction studies
- Summary

PYTHIA 6.4 Setup

- **EIC tune provided by BNL group [(https://wiki.bnl.gov/eic/index.php/PYTHIA)](https://wiki.bnl.gov/eic/index.php/PYTHIA)**
- **Minimum $Q^2 = 1$ (GeV^2)**
- **No radiative corrections**
- **Simulated beam energies (in GeV):**
  - 18 e + 275 p
  - 10 e + 100 p
  - 5 e + 100 p
  - 5 e + 41 p
  - 18 e + 110 p
  - 10 e + 110 p

e-p program

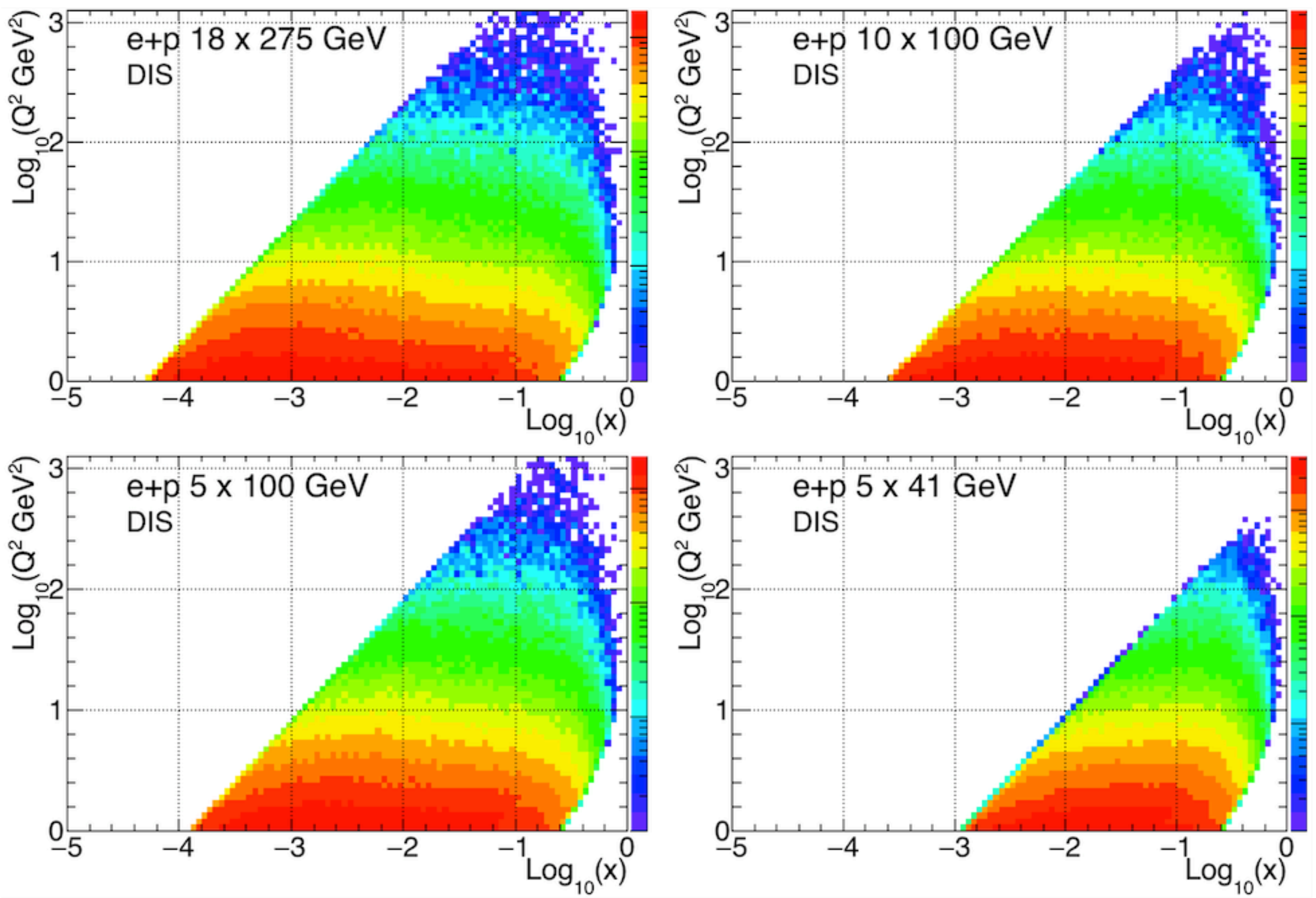
e-A program

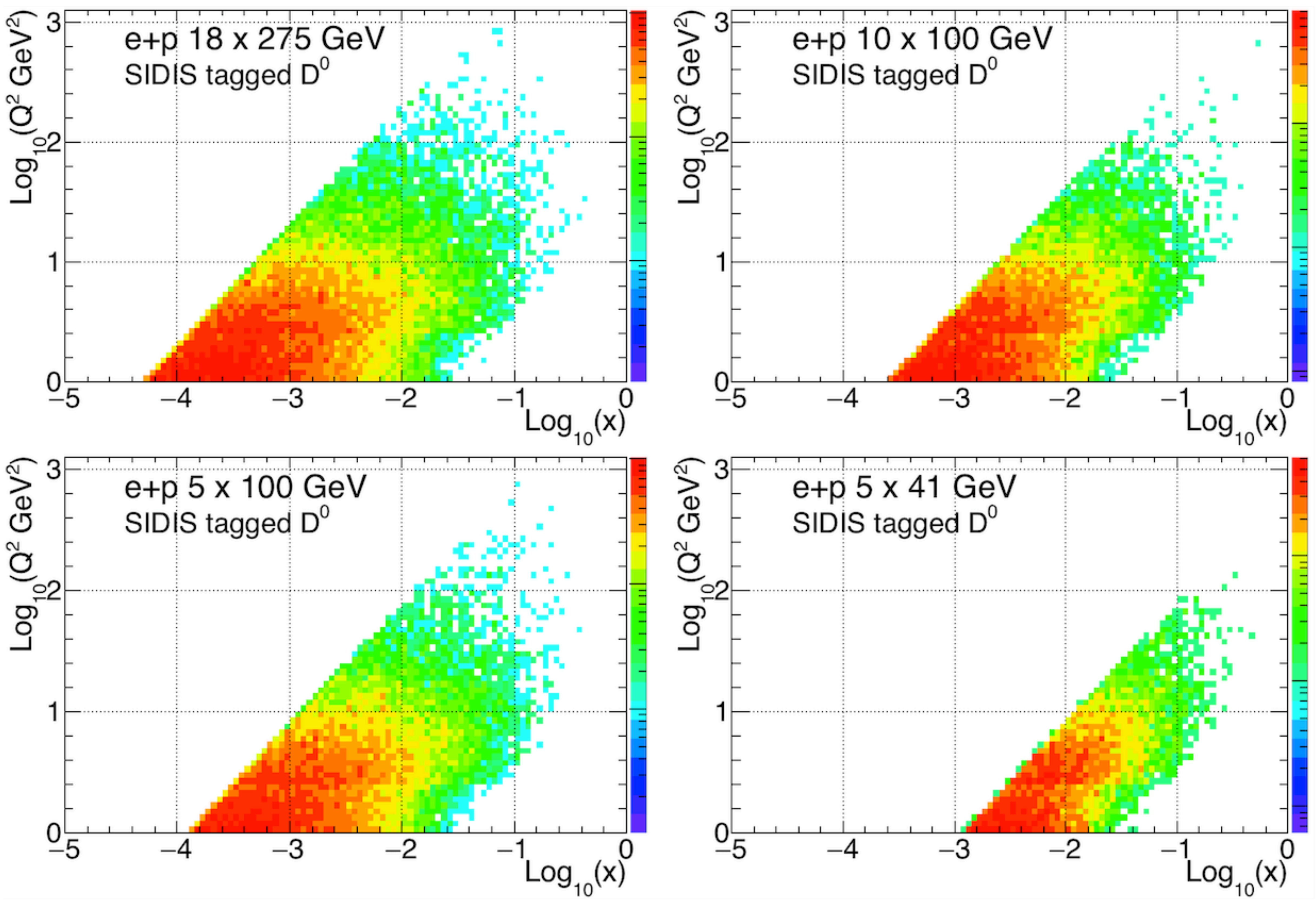
- **18 GeV e + 275 GeV p mostly highlighted here for heavy-flavor studies**

Subprocesses included

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

log(Q²) vs. log(x)



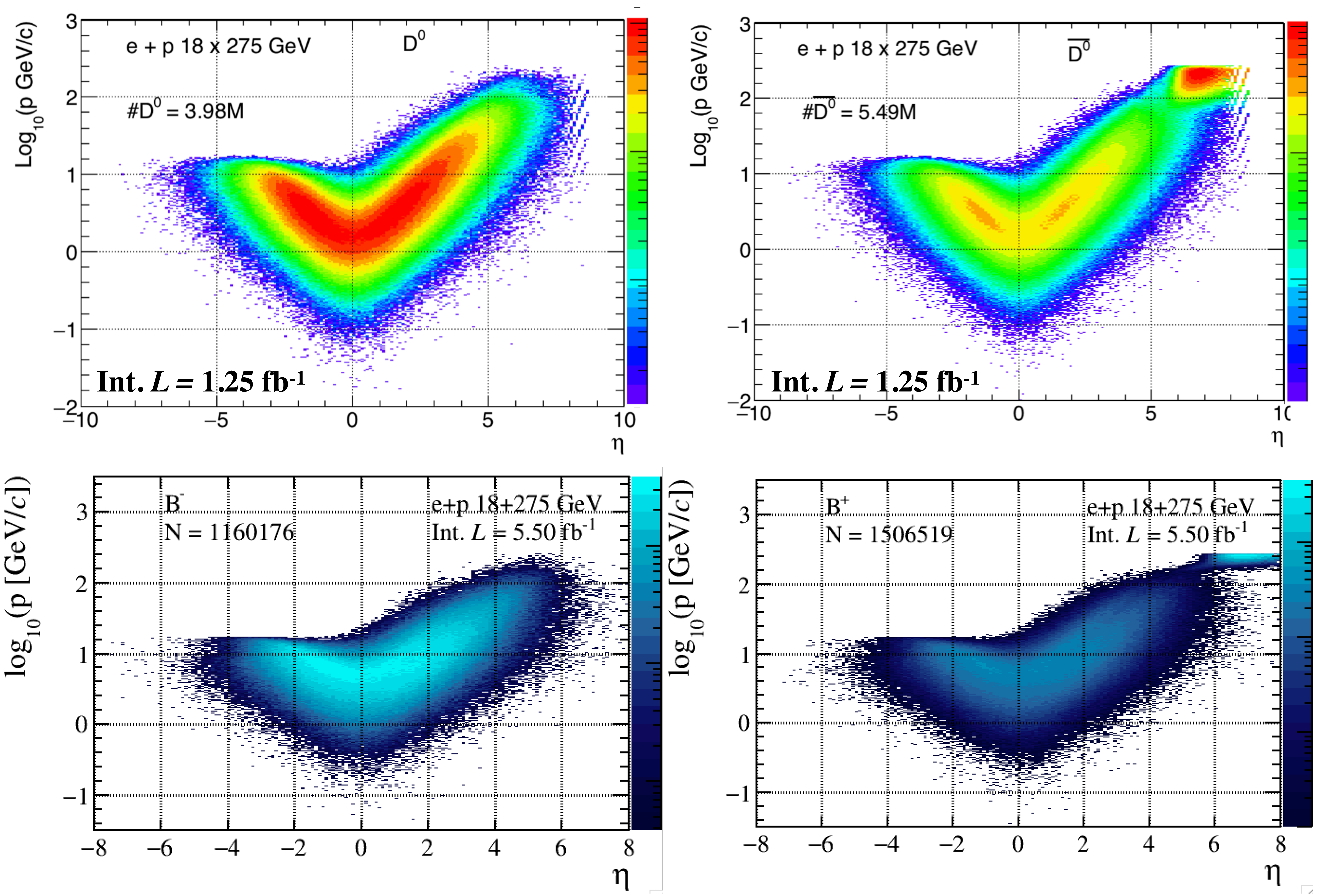


- Energies for electron + proton collision program

log(Q²) vs. log(x)

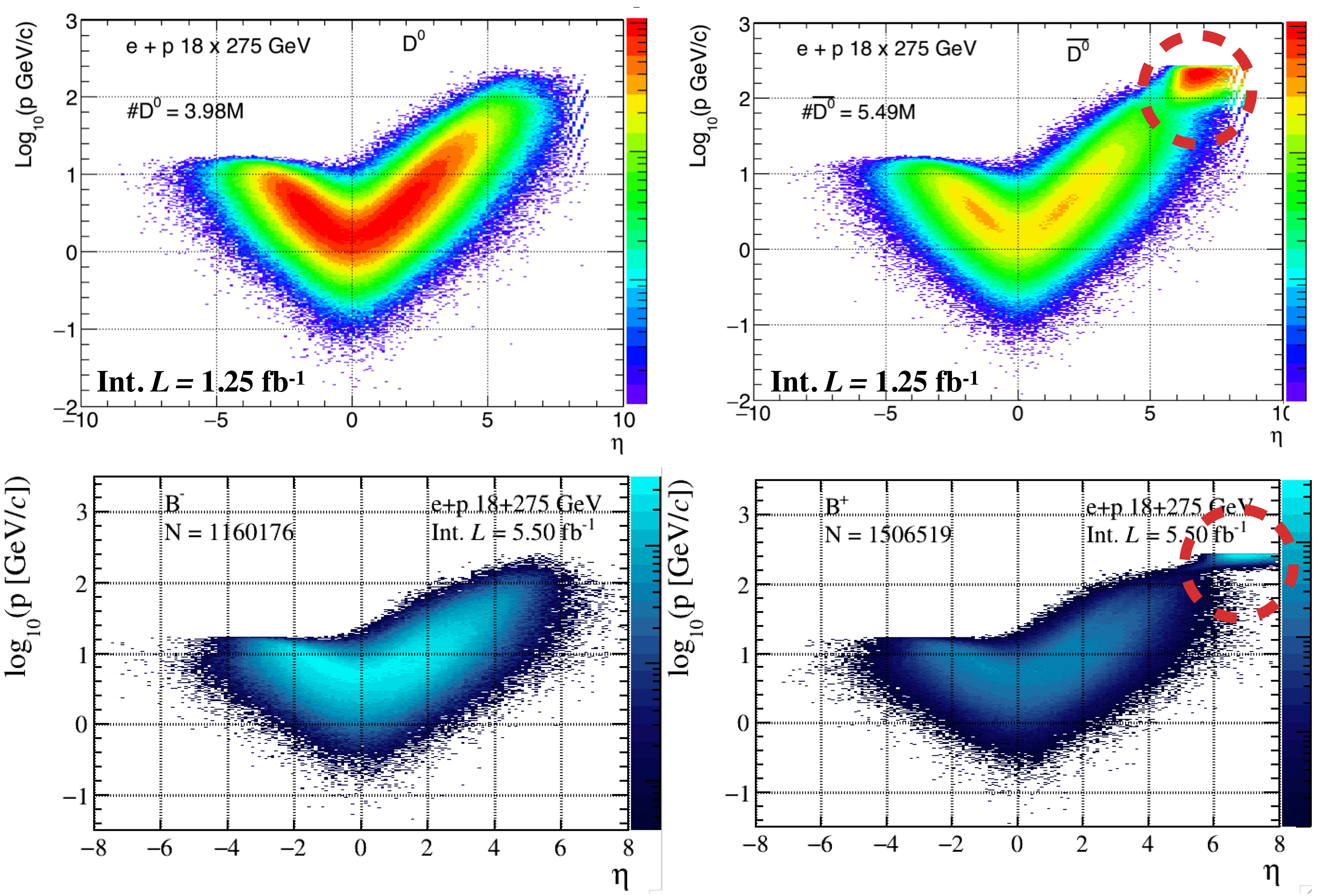
- **Comparisons between DIS and SIDIS with tagged charm or bottom hadron**

Heavy-Flavor Distributions



- Large portion of heavy-flavor hadrons produced within $|\eta|<3$
- Similar distributions for all heavy-flavor hadrons
- Standardized plots will soon follow

Heavy-Flavor Distributions



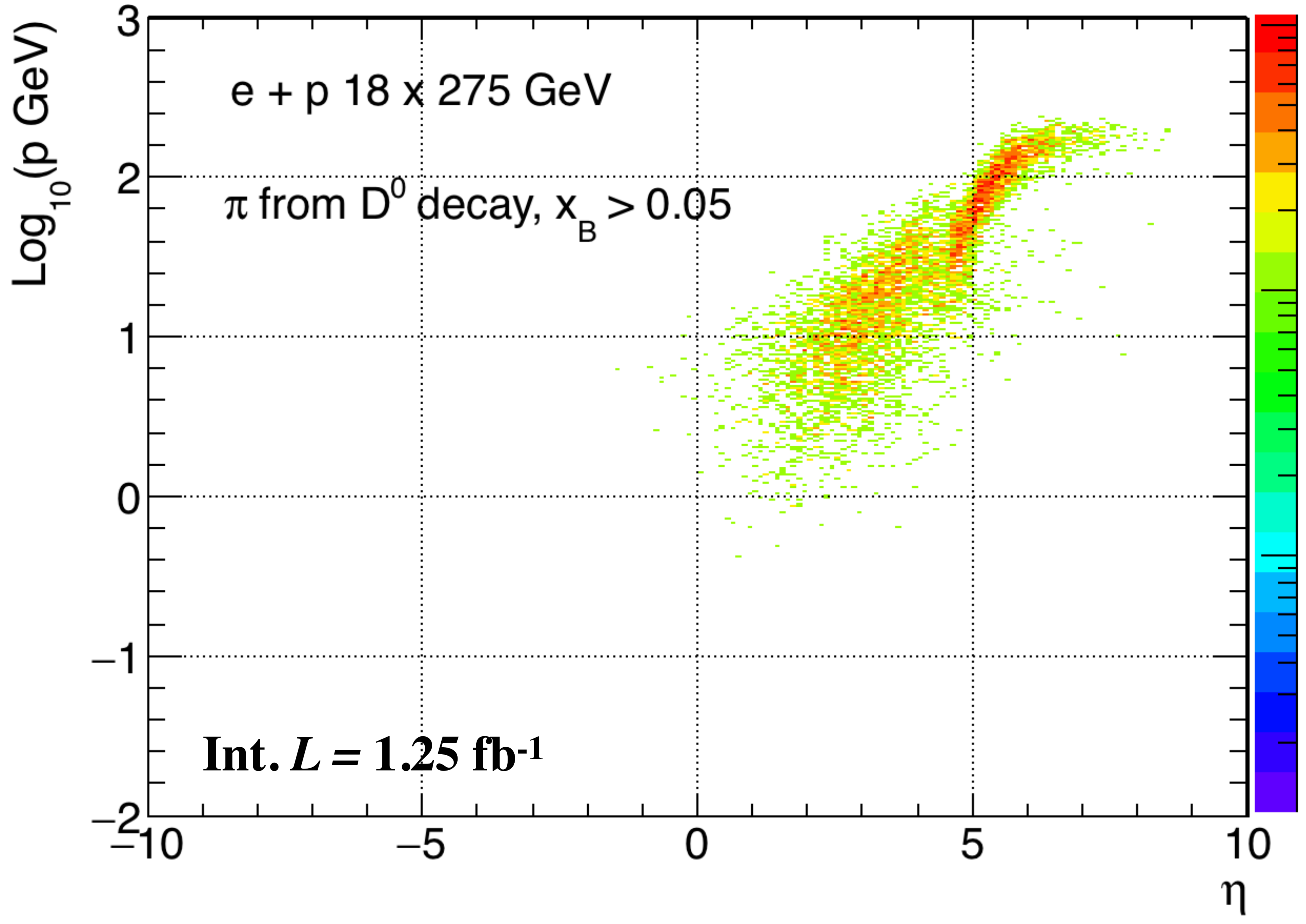
- **Large portion of heavy-flavor hadrons produced within $|\eta|<3$**
- **Similar distributions for all heavy-flavor hadrons**
- **Standardized plots will soon follow**

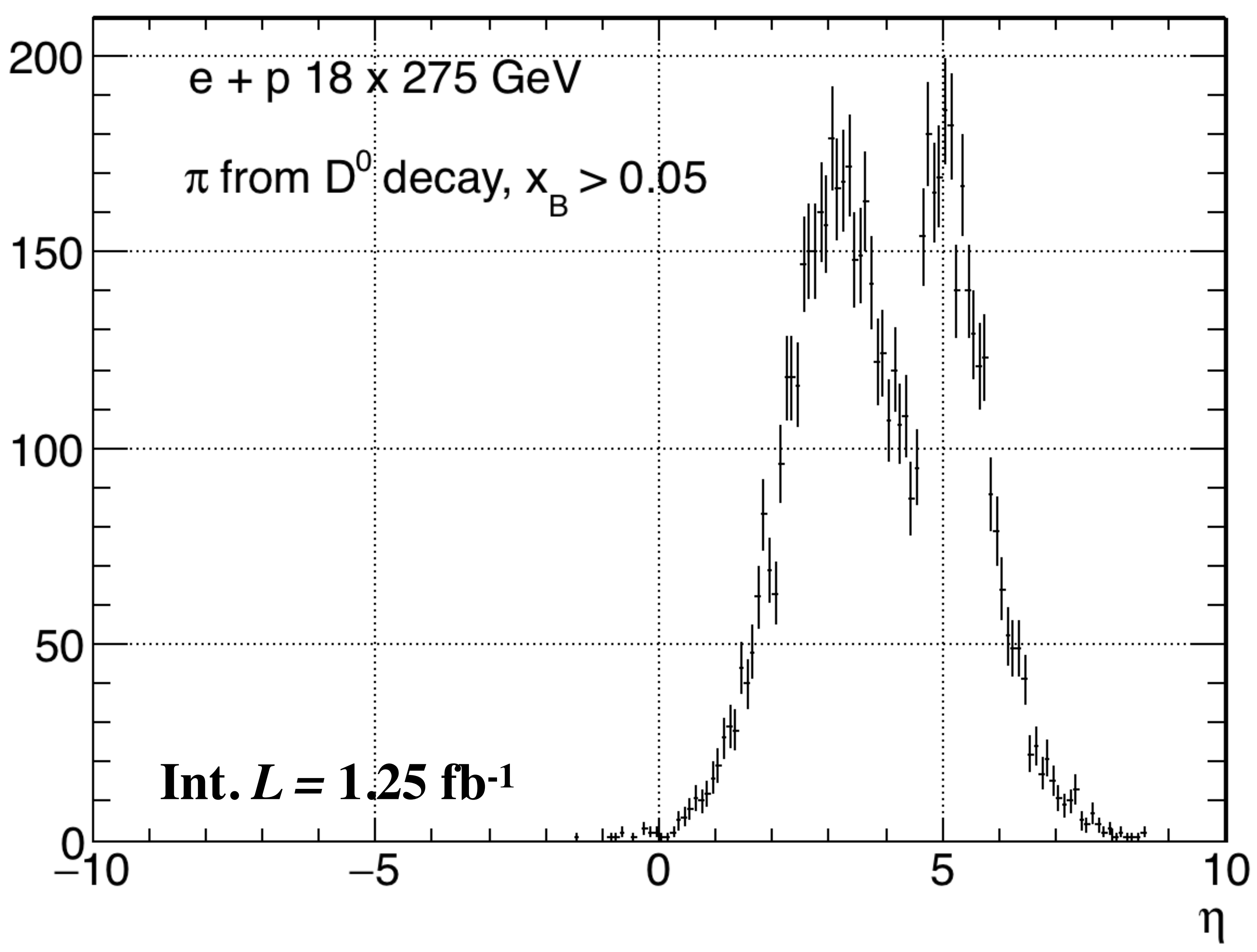
- **Forward peak attributed to LO DIS ($\gamma+q\rightarrow q$) process in PYTHIA**
- **Recombination with beam remnants ($b\bar{u}$ vs. $\bar{b}u$)? Feature of PYTHIA?**

Heavy-Flavor Decay Distributions

- Charm and bottom decay products within $|\eta|<3$
- Similar distributions for other charm hadron decays and $B\rightarrow D^+$/Lepton decays

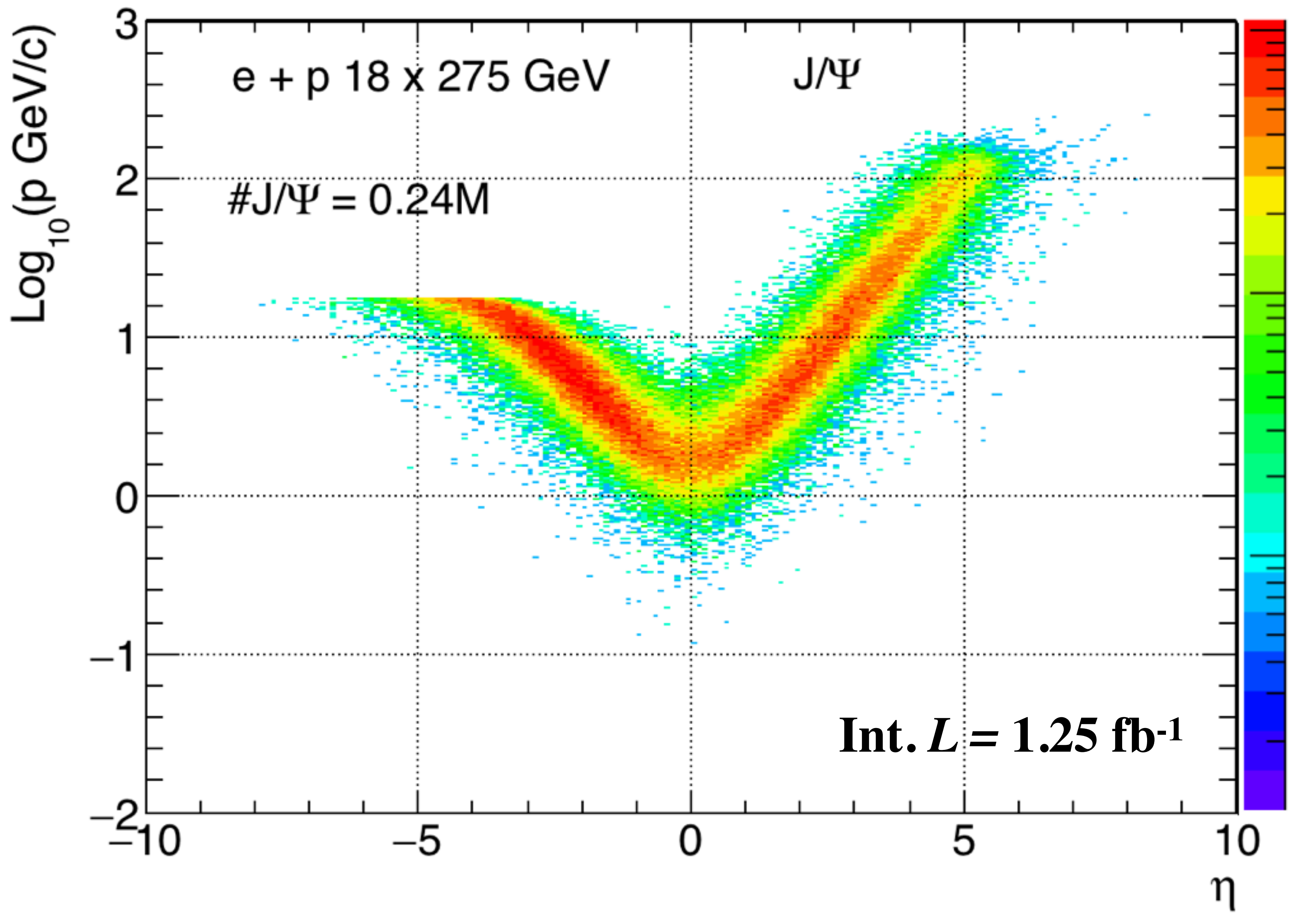
High-x Charm Production

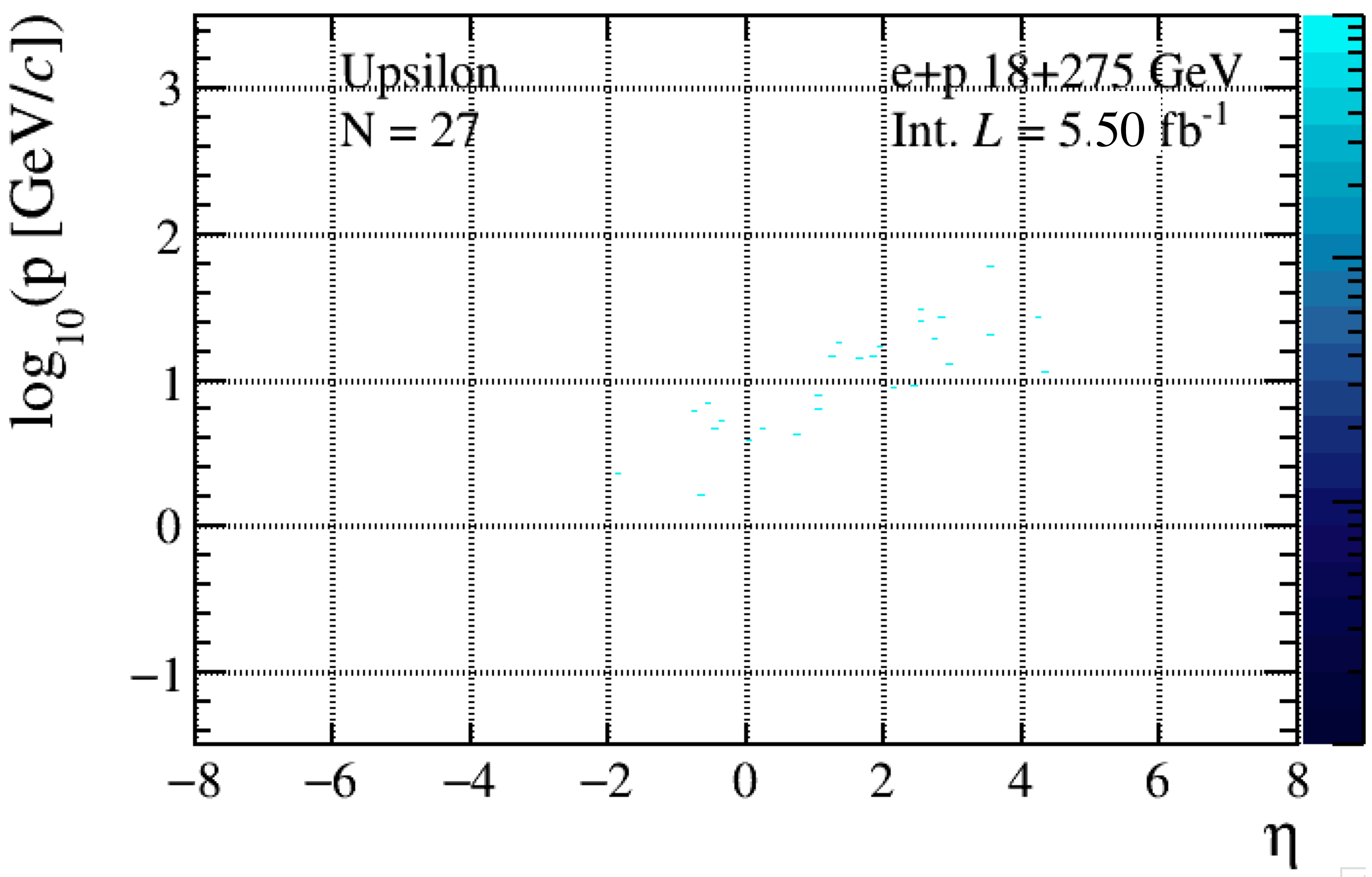




- **High-x charm production (x_B>0.05) decay products mostly populating the forward region**
- **Peaks around η~2; Second peak from beam remnant contributions at η~4**
- **Mean momentum ~10 GeV/c**

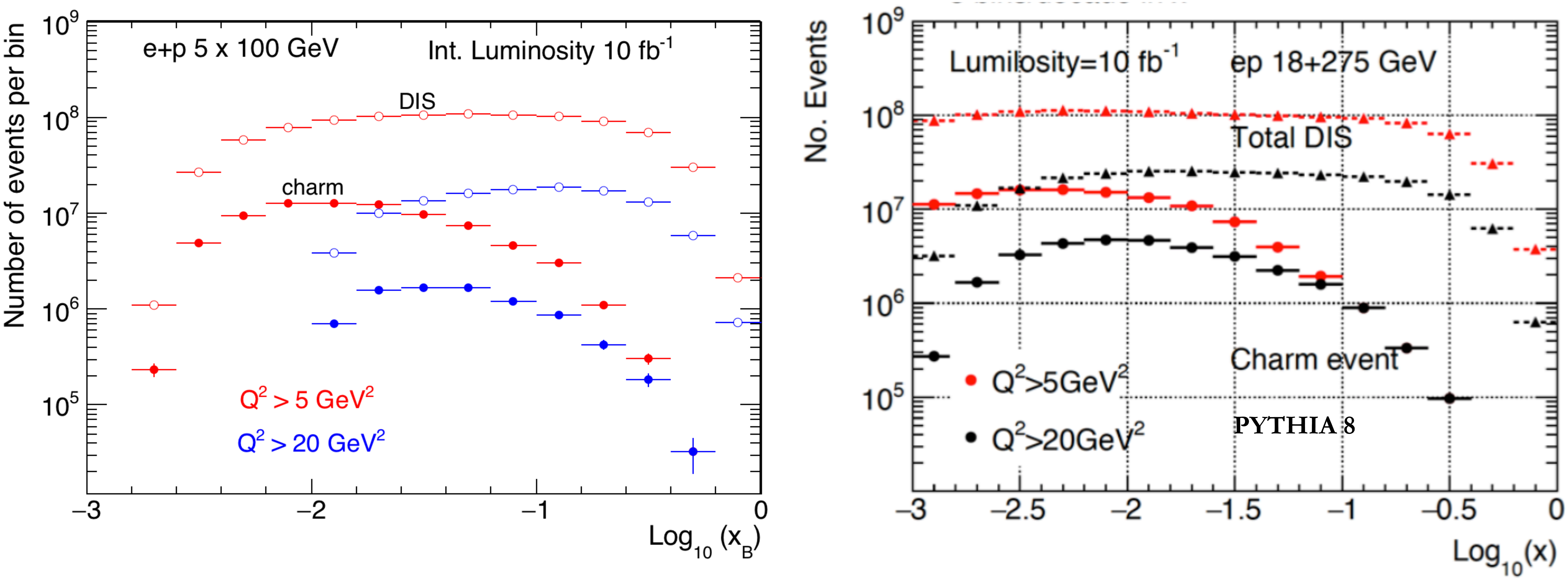
Quarkonia Distributions





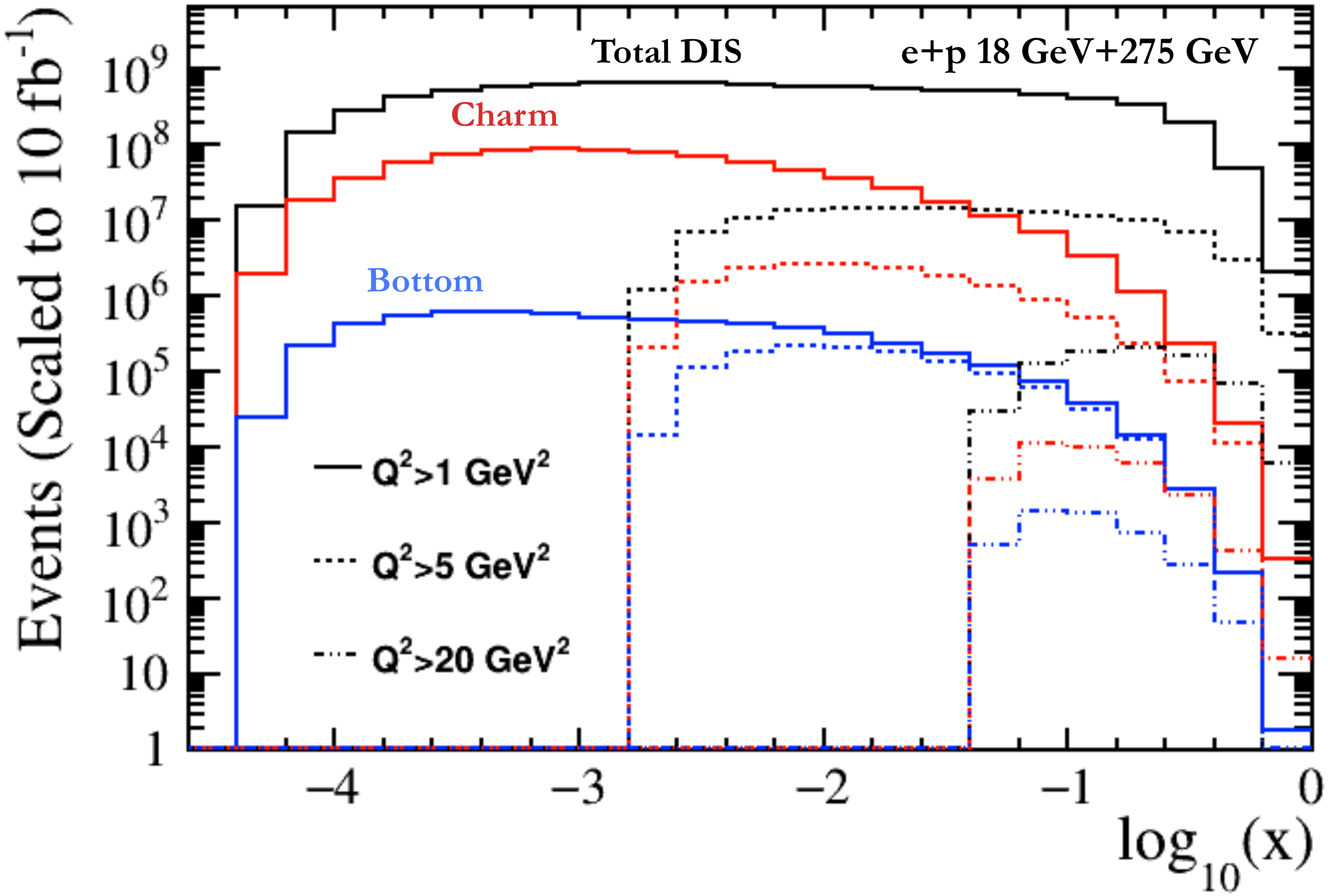
- **J/ψ production O(1%) of all charm events and is slightly peaked in the forward region**
- **Upsilon production surprisingly low; Still under investigation**

Charm Production Rate



- **Total charm cross-section w.r.t. total DIS comparable between PYTHIA 6 and 8**
- **Note different collisional energies**
- **Similar to previous studies in arXiv:1608.08686 + arXiv:1610.08536**

Bottom Production Rate



- Bottom cross-section roughly 10% of charm for Q^2>5 GeV^2

Fast Simulation Setup

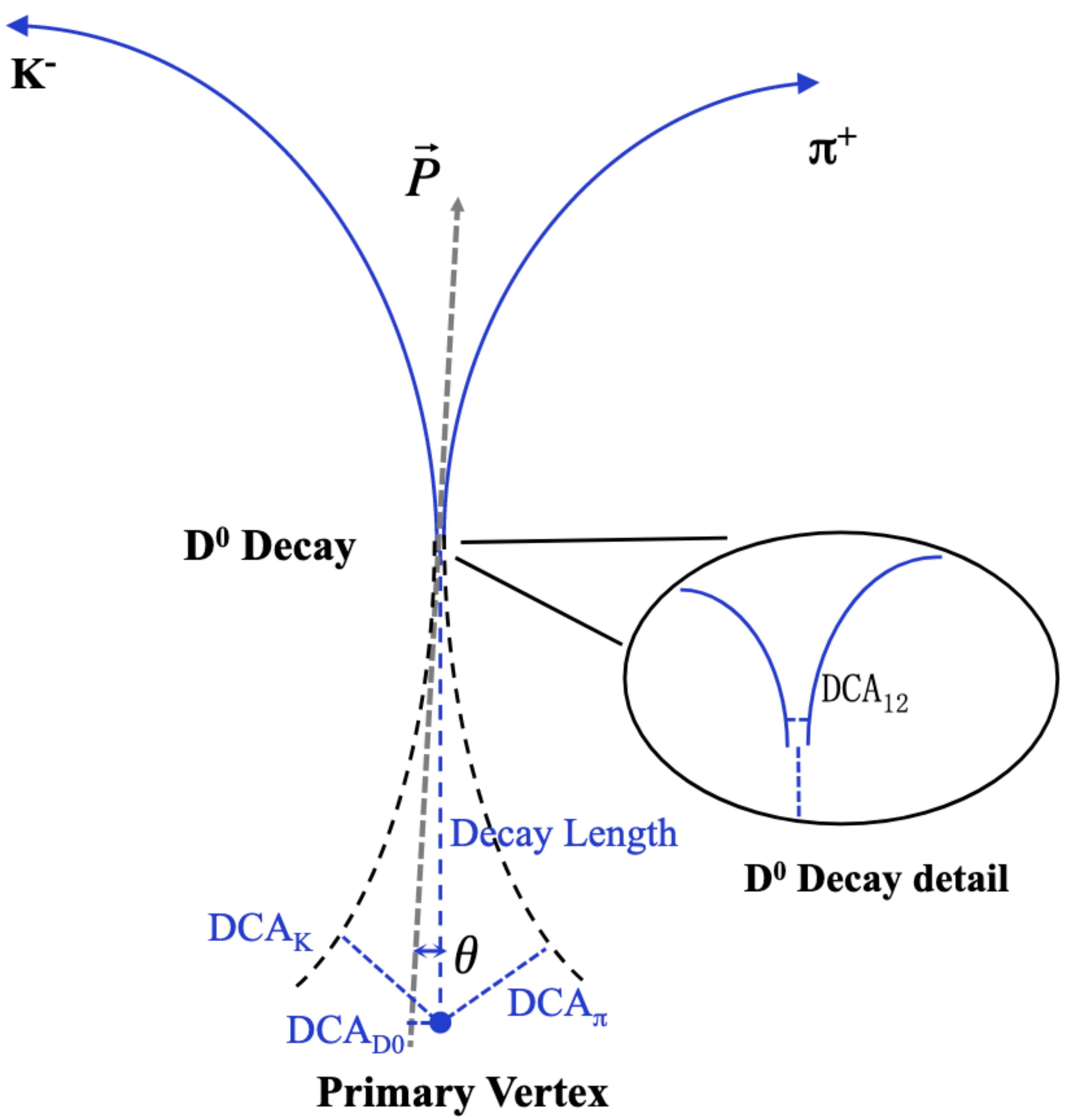
η	Nomenclature			Tracking: Resolution	Tracking: Allowed X/X_0	Tracking: Si-Vertex	Electrons: Resolution σ_E/E	Electrons: PID	$\pi/K/p$: p-Range (GeV/c)	$\pi/K/p$: Separation
-6.9 to -5.8	↓ p/A	Auxiliary Detectors	low-Q2 tagger	σ_θ/θ < 1.5%; 10-6 < Q2 < 10-2 GeV2						
...										
-4.5 to -4.0			Instrumentation to separate charged particles from photons				2%/√E			
-4.0 to -3.5								π suppression up to 1:10^4	≤ 7 GeV/c	≥ 3 σ
-3.5 to -3.0		Central Detector	Backward Detector	σ_p/p ~ 0.1%⊕0.5%	~5% or less X	TBD				
-3.0 to -2.5										
-2.5 to -2.0				σ_p/p 0.1%⊕0.5%			2%/√E			
-2.0 to -1.5				σ_p/p 0.05%⊕0.5%			7%/√E			
-1.5 to -1.0							7%/√E			
-1.0 to -0.5			Barrel	σ_p/p ~0.05%×p+0.5%		σ_{xyz} ~ 20 μm, $d_0(z)$ ~$d_0(r\Phi)$ ~ 20/p_TGeV μm + 5 μm	(10-12)%/√E		≤ 5 GeV/c	
-0.5 to 0.0										
0.0 to 0.5										
0.5 to 1.0										
1.0 to 1.5			Forward Detectors	σ_p/p ~0.05%×p+1.0%		TBD			≤ 8 GeV/c	
1.5 to 2.0										
2.0 to 2.5									≤ 20 GeV/c	
2.5 to 3.0				σ_p/p ~ 0.1%×p+2.0%						
3.0 to 3.5									≤ 45 GeV/c	
3.5 to 4.0	↑ e	Auxiliary Detectors	Instrumentation to separate charged particles from photons							
4.0 to 4.5										
...			Neutron Detection							
> 6.2			Proton Spectrometer	$\sigma_{intrinsic}(\|t\|)/\|t\|$ < 1%; Acceptance: 0.2 < p_t < 1.2 GeV/c						

https://physdiv.jlab.org/DetectorMatrix/

- Charm and bottom reconstruction studied using fast simulation smearing of PYTHIA 6.4 output
- Momentum and pointing resolutions taken from detector matrix page as baseline (focusing on central detector $|\eta|<3$)
- Working assumptions: Perfect tracking and PID, and central transverse pointing resolution extends to $|\eta|<3$

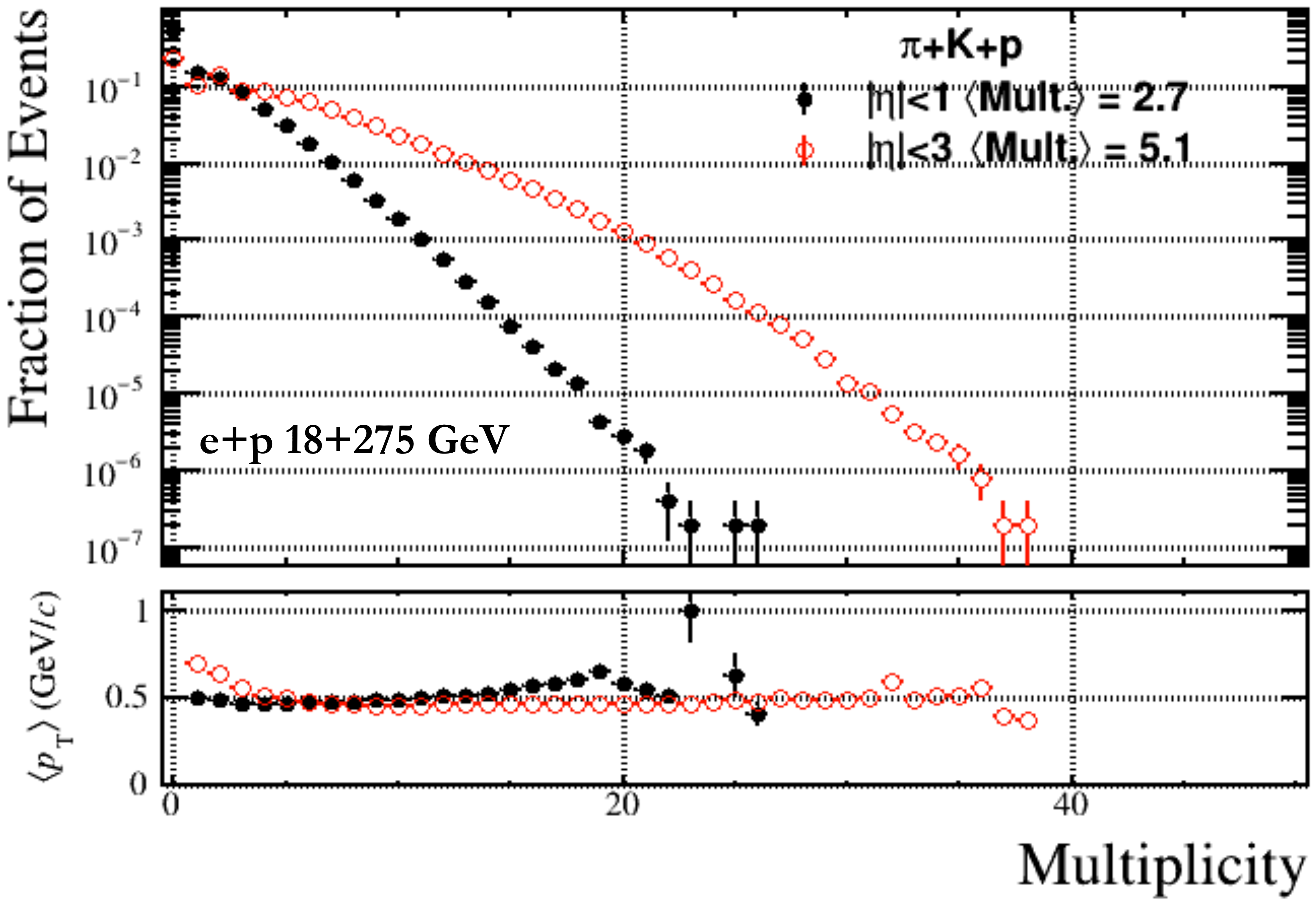
Studies of Primary Vertex Resolution

- **Charm and bottom reconstruction significantly effected by PV resolution**
  - e-p(A) environment more difficult than p(A)-p(A)
- **Primary vertex fitter**
  - Charged π, K, and p within |η|<1 (or 3) smeared with fast-sim setup
  - Least-squares fit of vertex x-y using using a seed of x=y=0
  - Reasonable starting point assuming constraint from electron beam profile (σ~20 μm)
  - Second vertex z fit with seed = average particle z DCA)

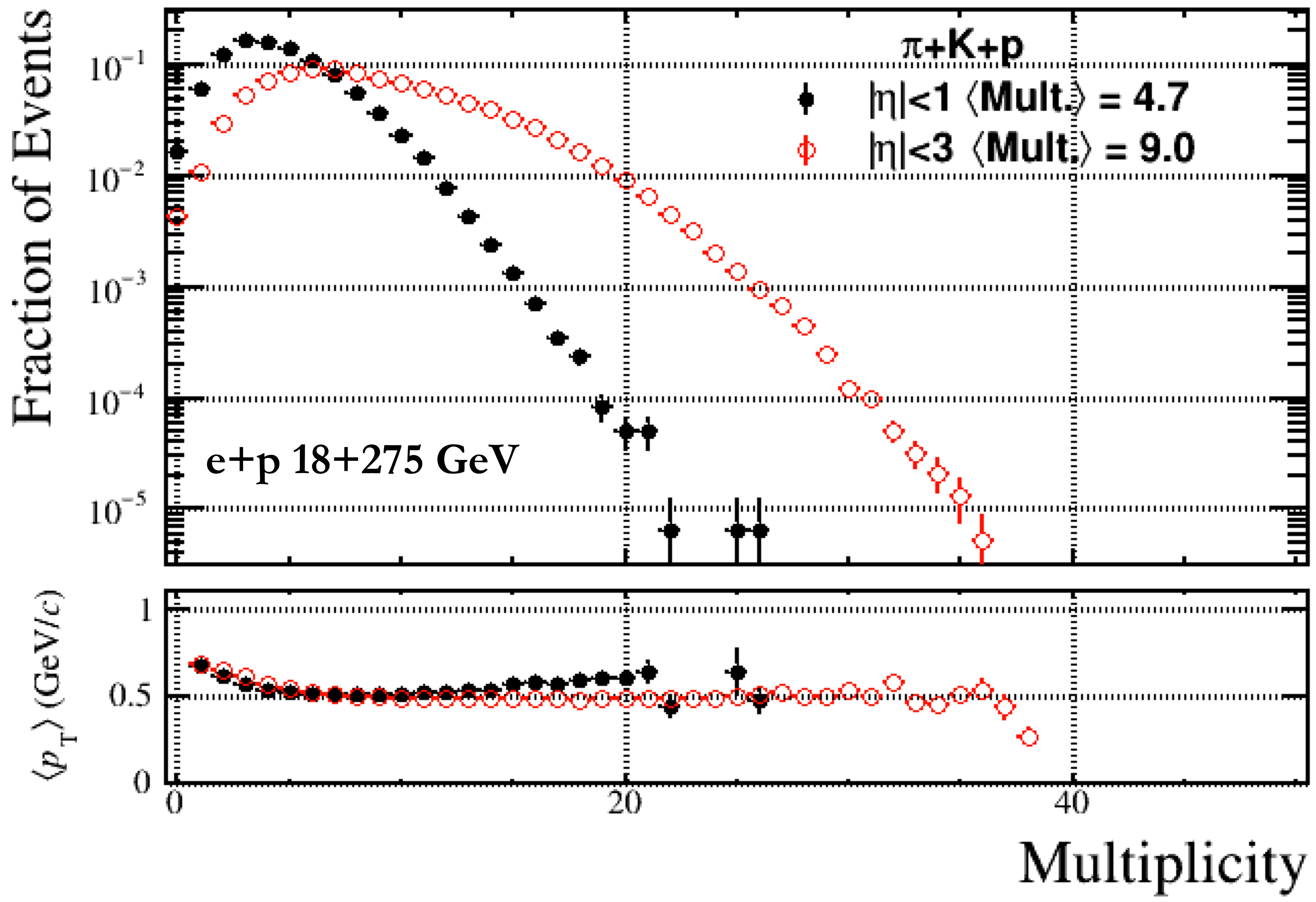


Track Multiplicity

All DIS Events



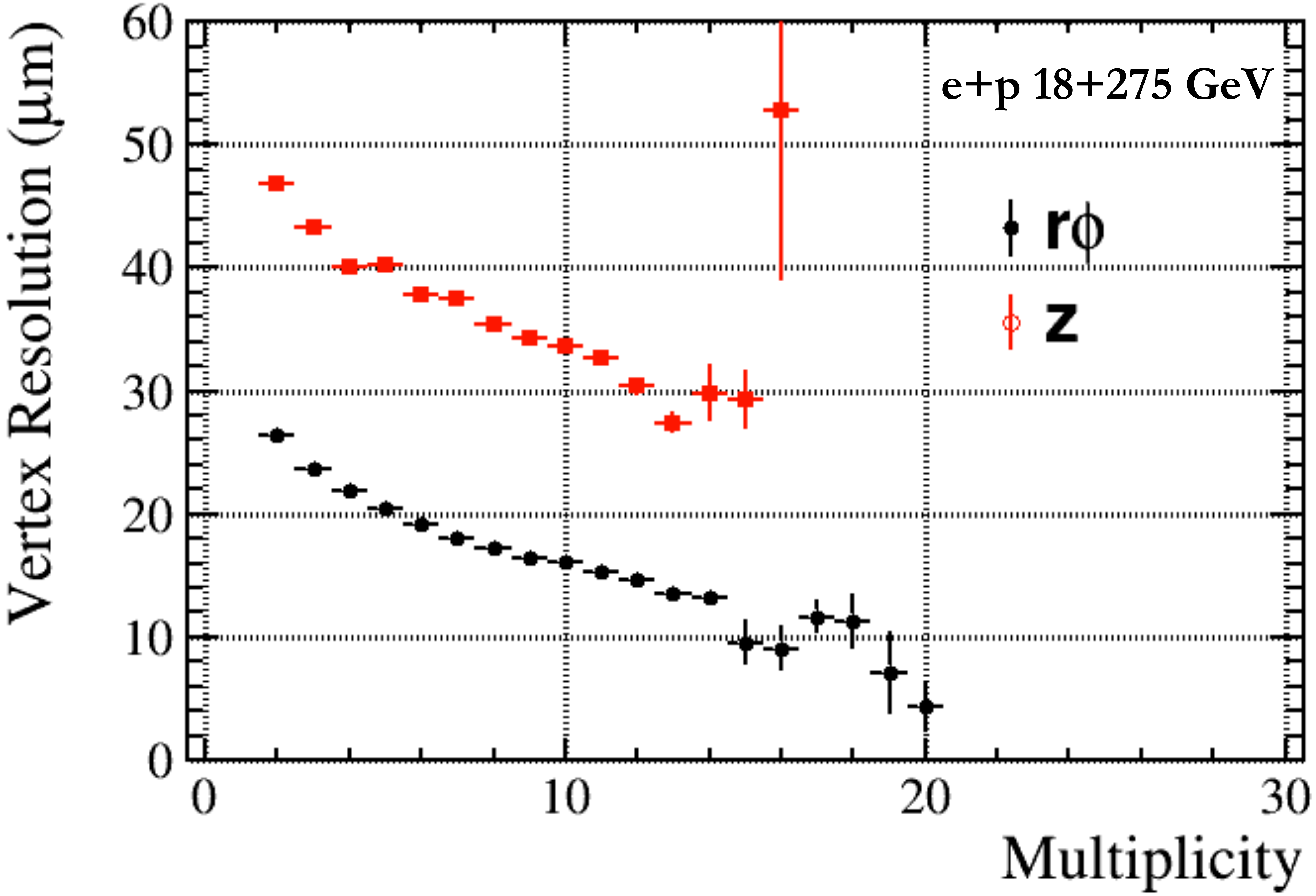
HF-Tagged Events



- **Average multiplicity higher larger rapidity window**
- **Multiplicity higher in heavy-flavor tagged events (note not removing HF daughters)**

*Averages exclude mult.=0 case

Primary Vertex Resolution



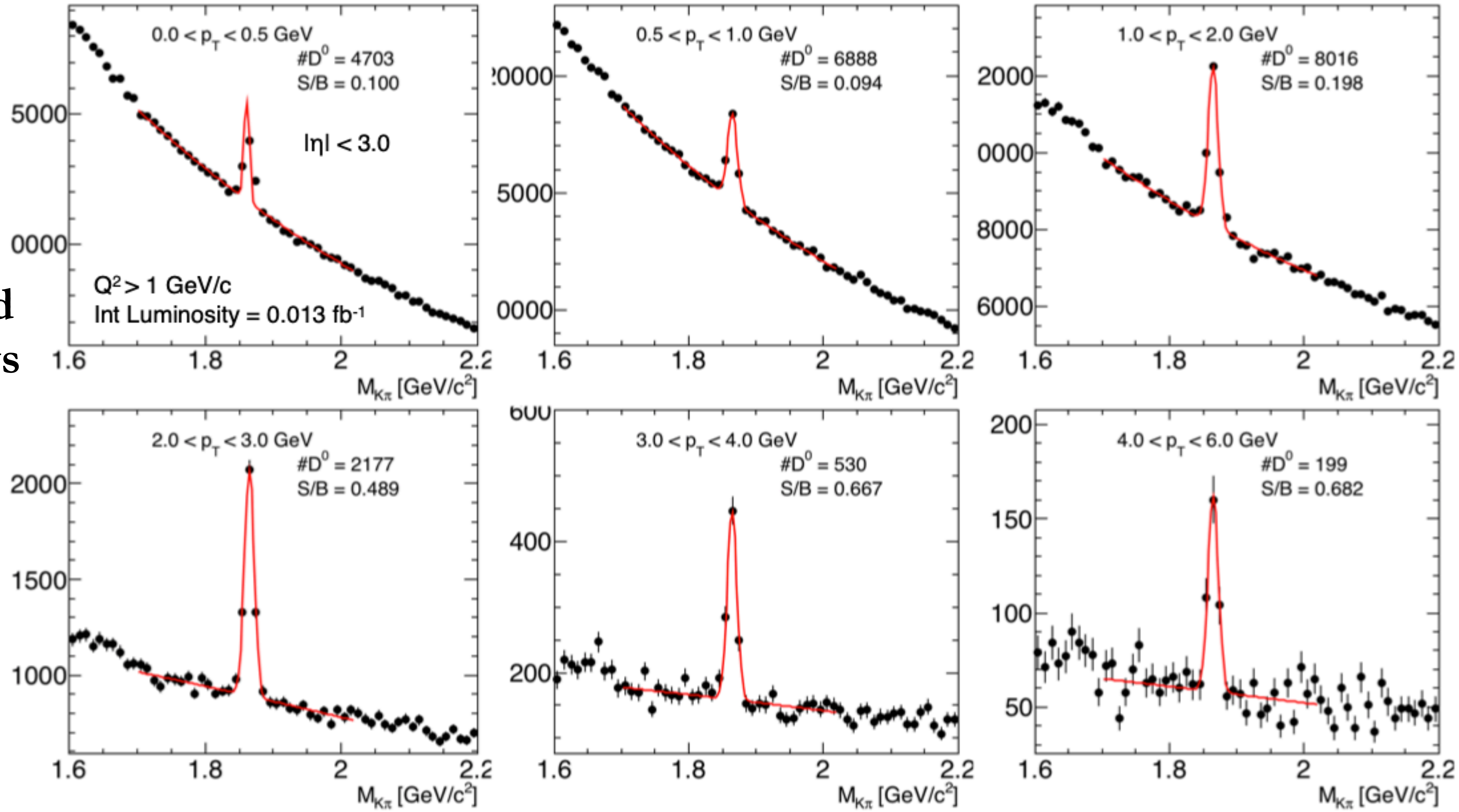
rφ position fit with all tracks in |η|<3

z position fit with all tracks in |η|<1

- **Vertex z resolution worse due to fitting routine (i.e., z-dimension resolution inflated by rφ uncertainty)**
- **Average vertex rφ resolution for HF tagged events (⟨mult.⟩~9): ~16 μm**

D^0 Reconstruction

- **All Kπ pairs taken from PYTHIA output (no vertex requirement)**
- **Background from combinatorial and partially reconstructed charm decays**
- **Good S/B compared to hadron-hadron collisions**
  - p+p (1/100 @ √s= 200 GeV)
  - A+A (1/10000 @ $\sqrt{s_{NN}}$= 200 GeV)

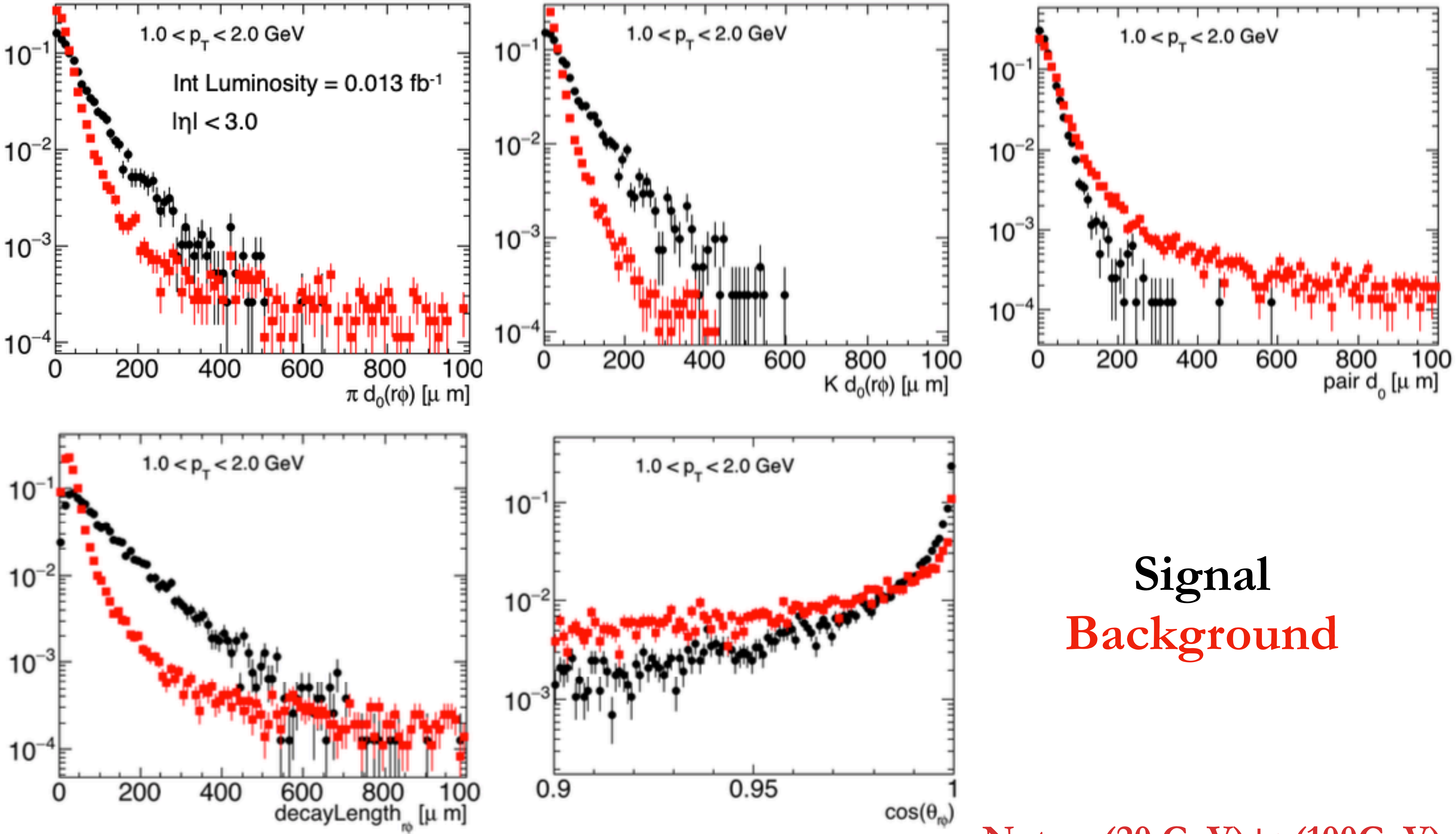


Note: e(20 GeV)+p(100GeV)

D^0 Topological Variables

D^0 p_T range of 1-2 GeV/c for example

- Only transverse impact parameters (d_0) looked at
- Possibility to add longitudinal dimension for additional improvement
- Using a rφ vertex resolution of 20 μm

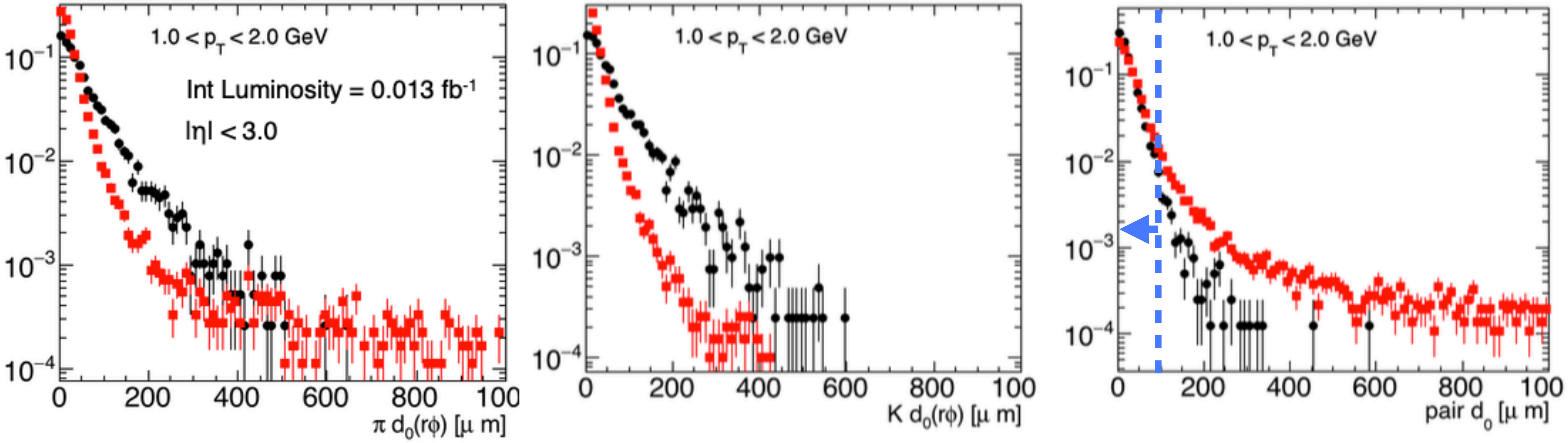


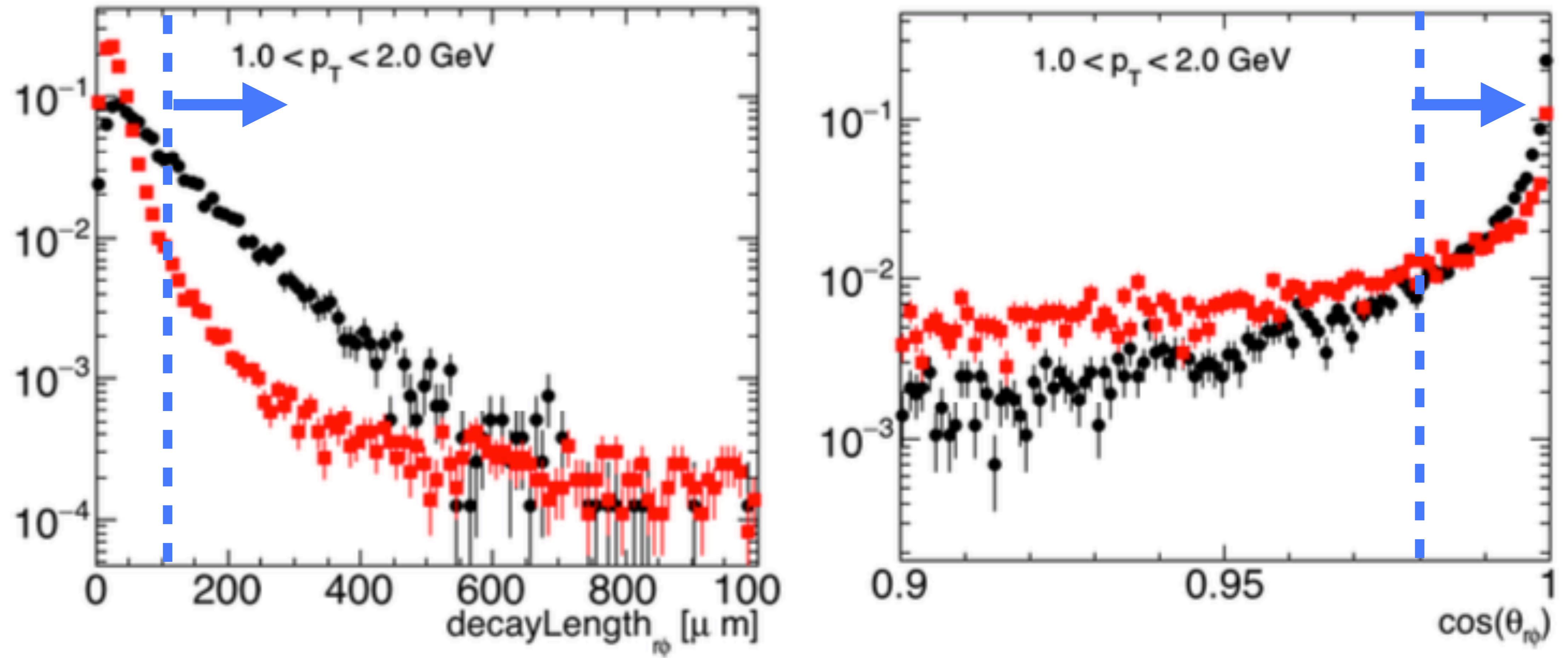
Note: e(20 GeV)+p(100GeV)

D^0 Topological Variables

- Only transverse impact parameters (d_0) looked at
- Possibility to add longitudinal dimension for additional improvement
- Using a rφ vertex resolution of 20 μm
  - "By-eye" cuts chosen:
    - $\cos(\theta_{r\varphi}) > 0.98$
    - dL > 40 μm
    - pair d0 < 150 μm
  - No optimization or p_T dependence

<u>D^0 p_T range of 1-2 GeV/c for example</u>





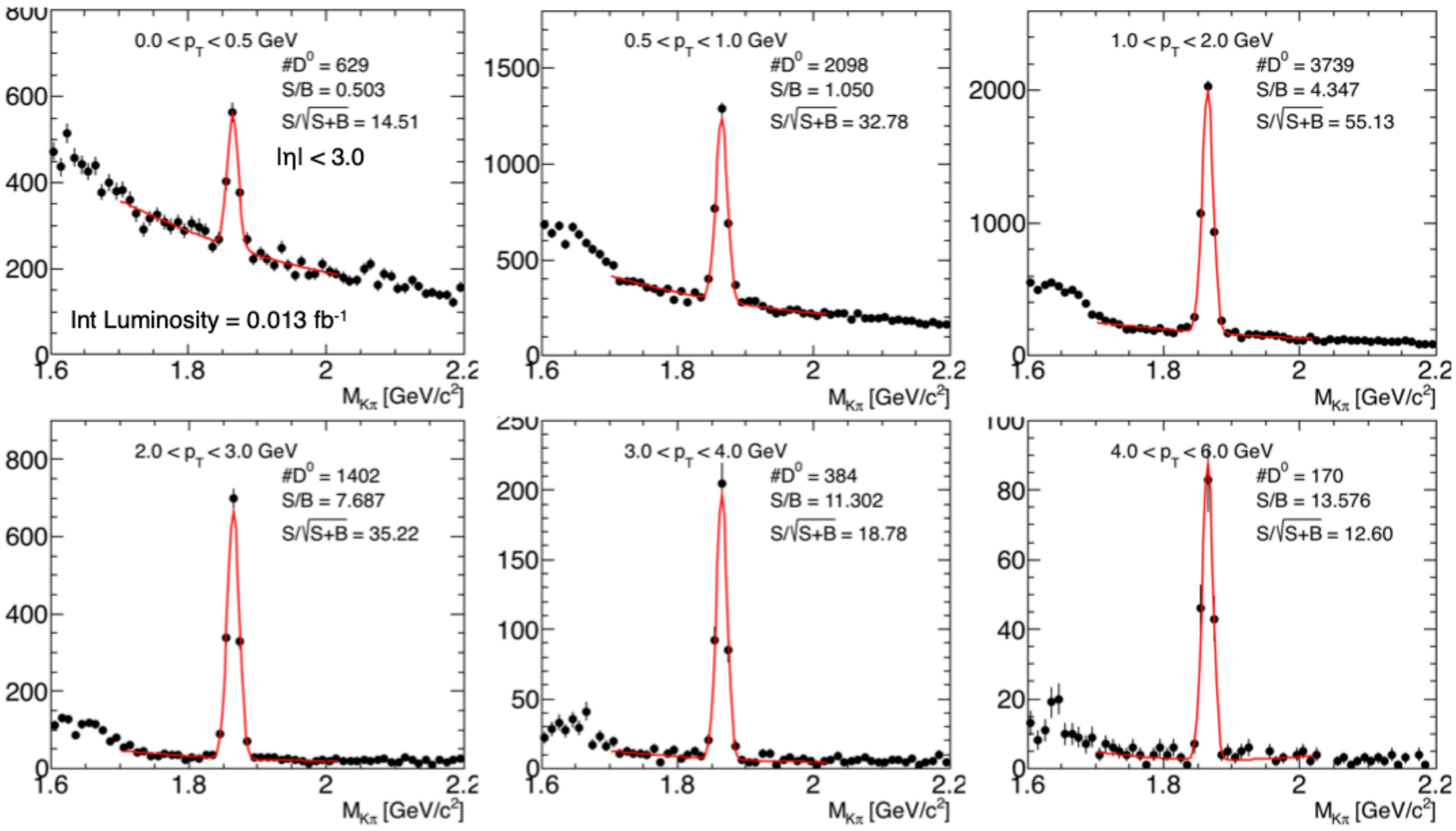
Signal

Background

Note: e(20 GeV)+p(100GeV)

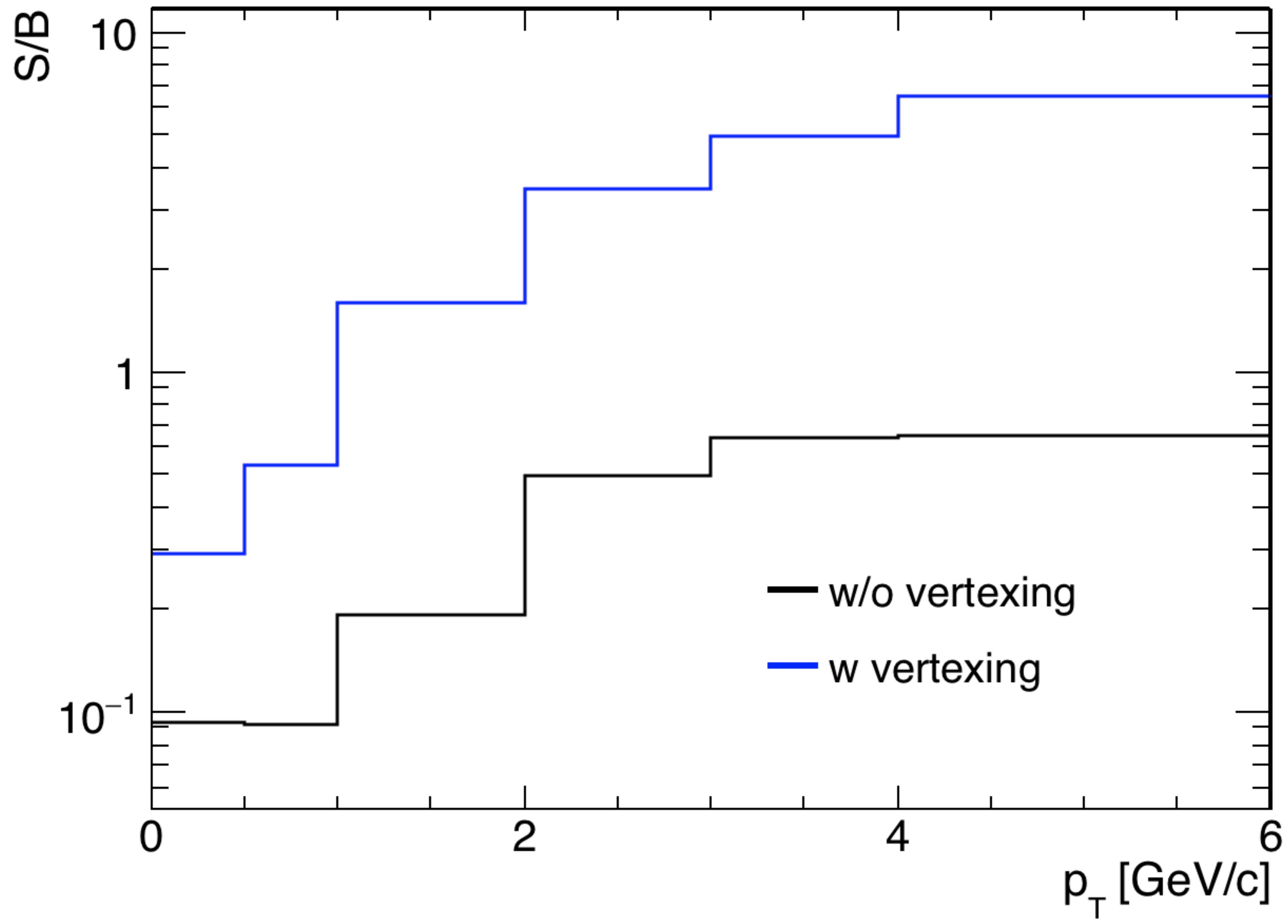
D^0 Reconstruction w/ Vertexing

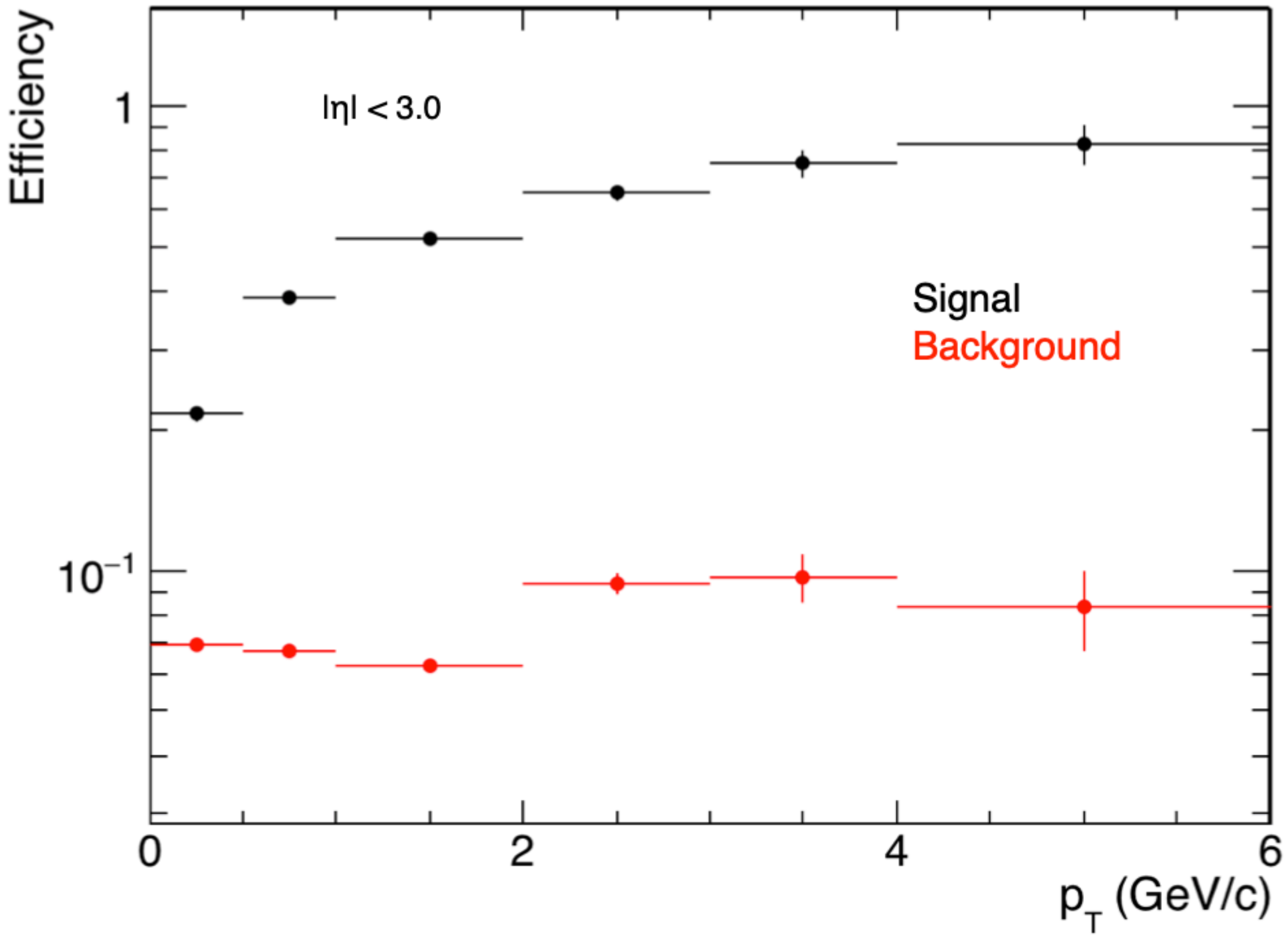
- Significant reduction of background and improvement of signal significance
- Room for additional improvement with optimization and incorporating longitudinal dimension on topological variables



Note: e(20 GeV)+p(100GeV)

D^0 S/B and Efficiency



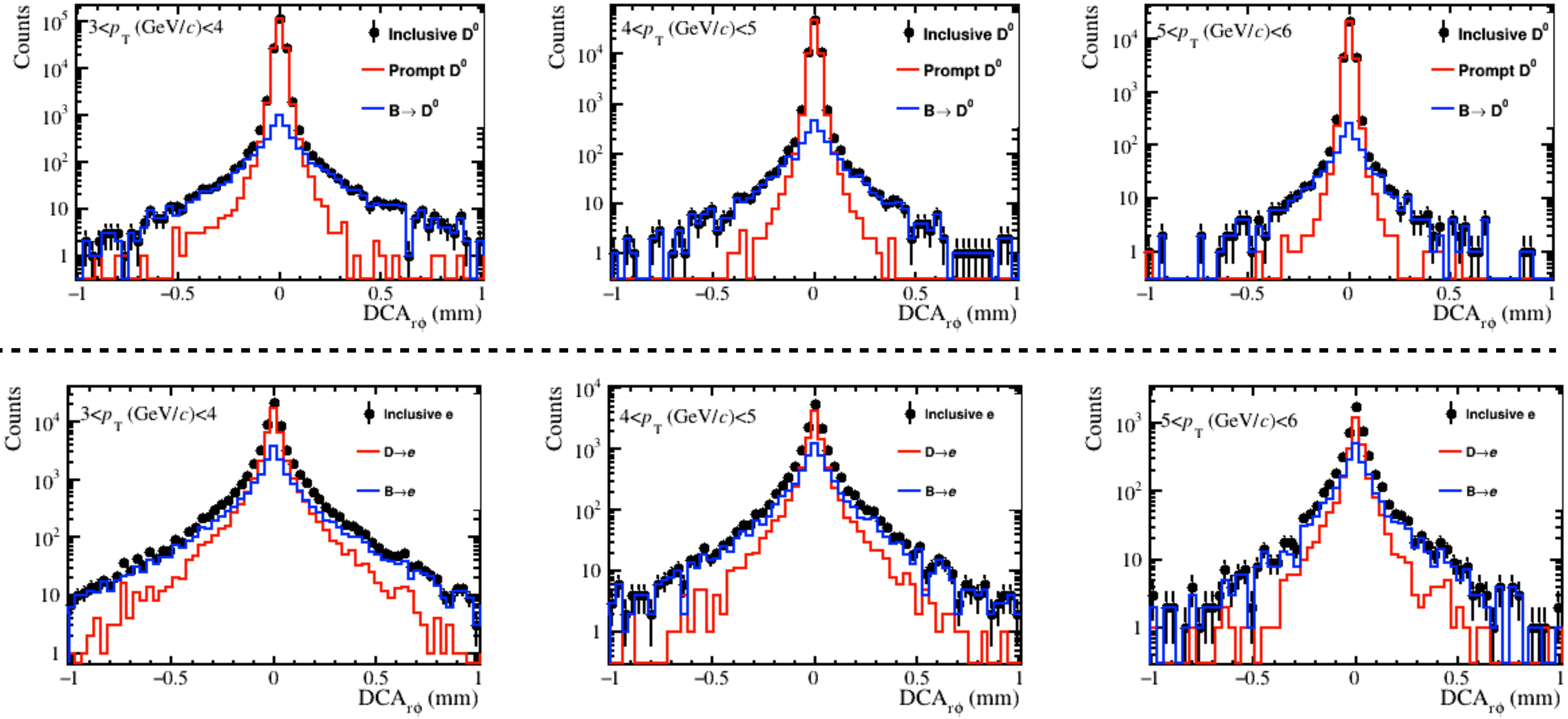


- **Reiterating nice improvement of *D^0* S/B with vertexing**
  - Factor of 10(2) for high(low) p_T
- **Modest signal efficiency with "by-eye" cuts**

$B \rightarrow D^0/e$ Reconstruction

B→D0

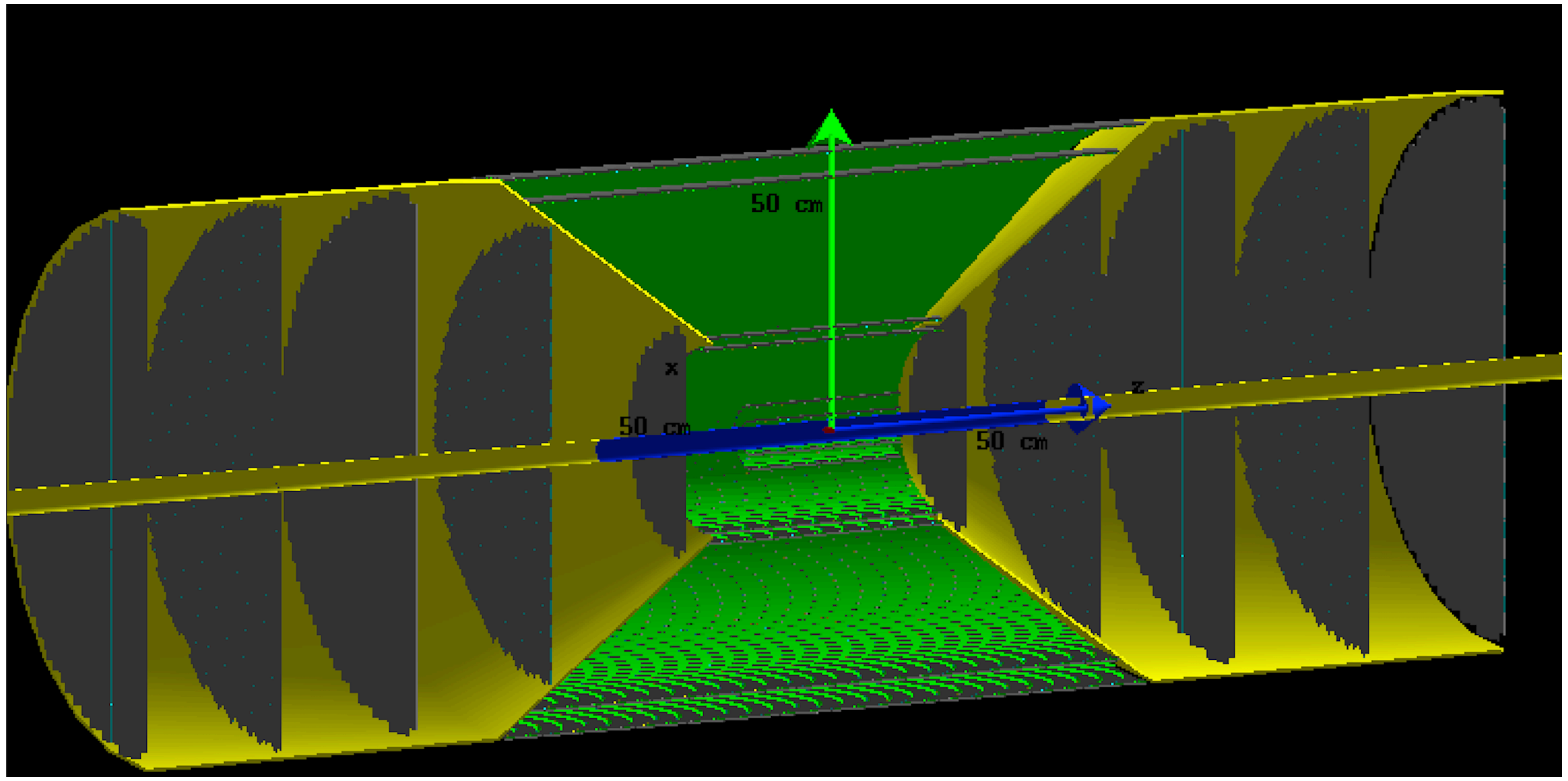
B→e

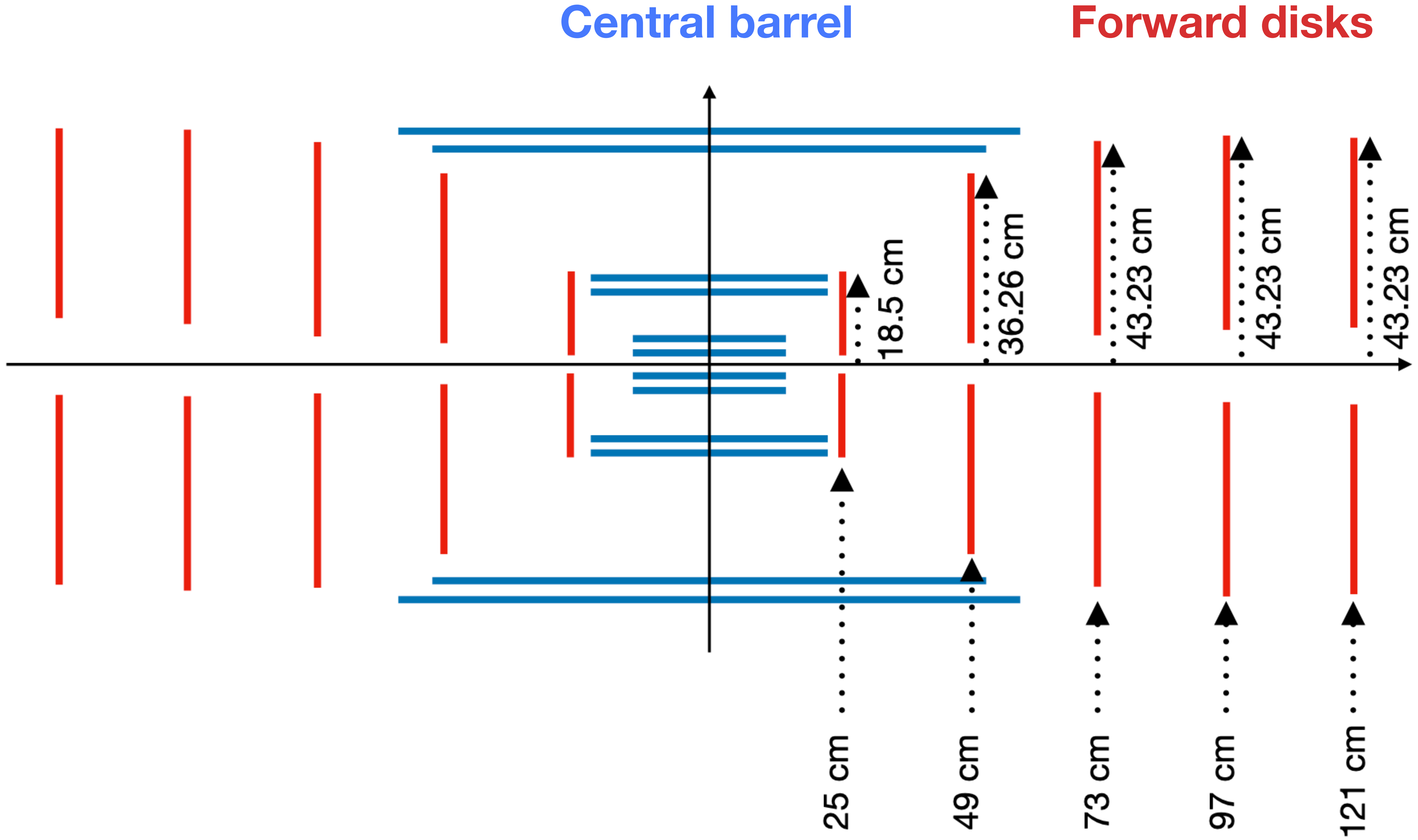


e+ p (18+275 GeV)
5.5 fb^{-1}
$|\eta|<1$

- Using distance-of-closest approach of D^0/e candidates w.r.t. PV to separate prompt D and B decays
- Good separation of prompt and $B \rightarrow D^0/e$

All-Silicon Detector Concept





- **Six barrel pixel layers + five forward pixel disks provide tracking up to $|\eta|=4$**
- **From open heavy-flavor perspective, all-silicon detector better suited**
  - Better pointing resolution, good $\delta p/p$ > 5GeV/c, etc.

➡ Factor of 2-3 increase of statistics with $|\eta|<1\rightarrow3$
➡High-x charm production at $\eta\sim2$, $\langle p\rangle=10$ GeV/c

Summary

- We have studied charm and bottom kinematics in PYTHIA 6.4 and 8 simulations
- Charm and bottom hadron reconstruction studied using a fast simulation guided by (evolving) detector performance parameters
- Current tracking performance essential for open HF measurements; Good forward tracking will improve charm+bottom precision

To-do

- Further studies of tracking performance + PV vertex resolution and impact on heavy-flavor reconstruction with updated detector concepts
- Standardized acceptance plots
- Projections on physics observables (e.g., nPDF uncertainty)

Momentum resolution

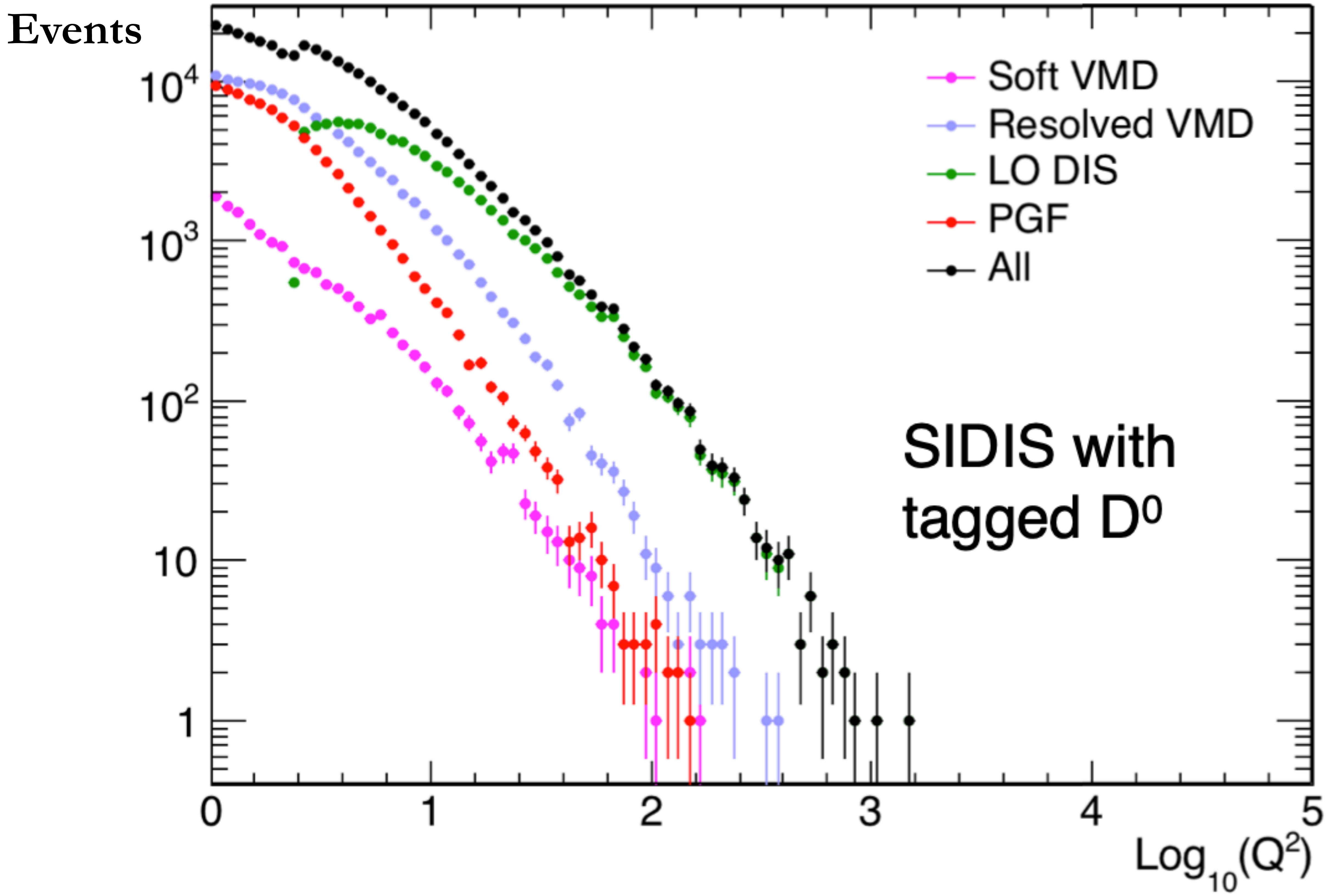
σ_p/p ~$0.05\% \times p + 0.5\%$

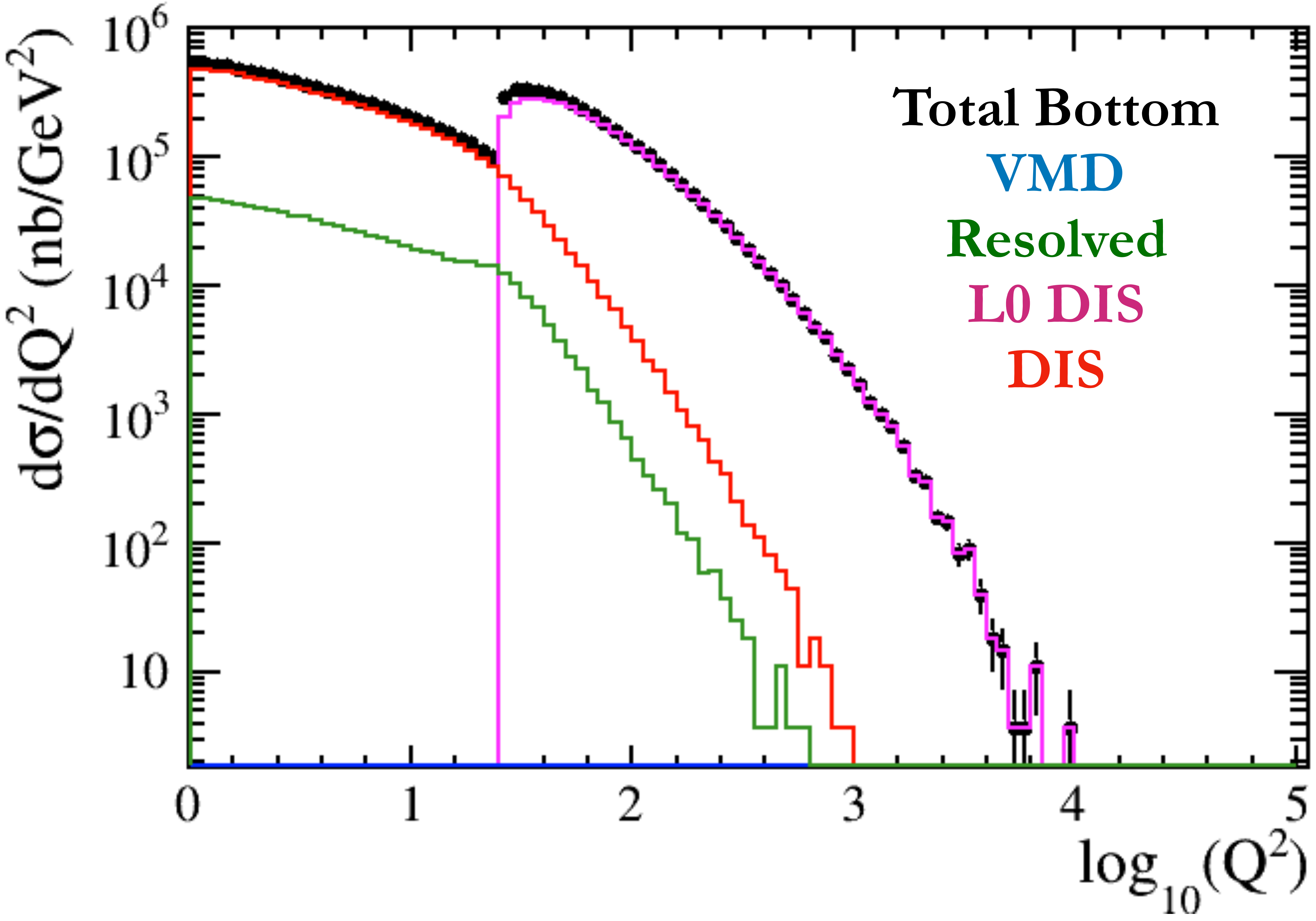
Pointing resolution $|\eta|<1$

$d_0(z)$ ~$d_0(r\Phi)$ ~ $20/p_T$GeV μm + 5 μm

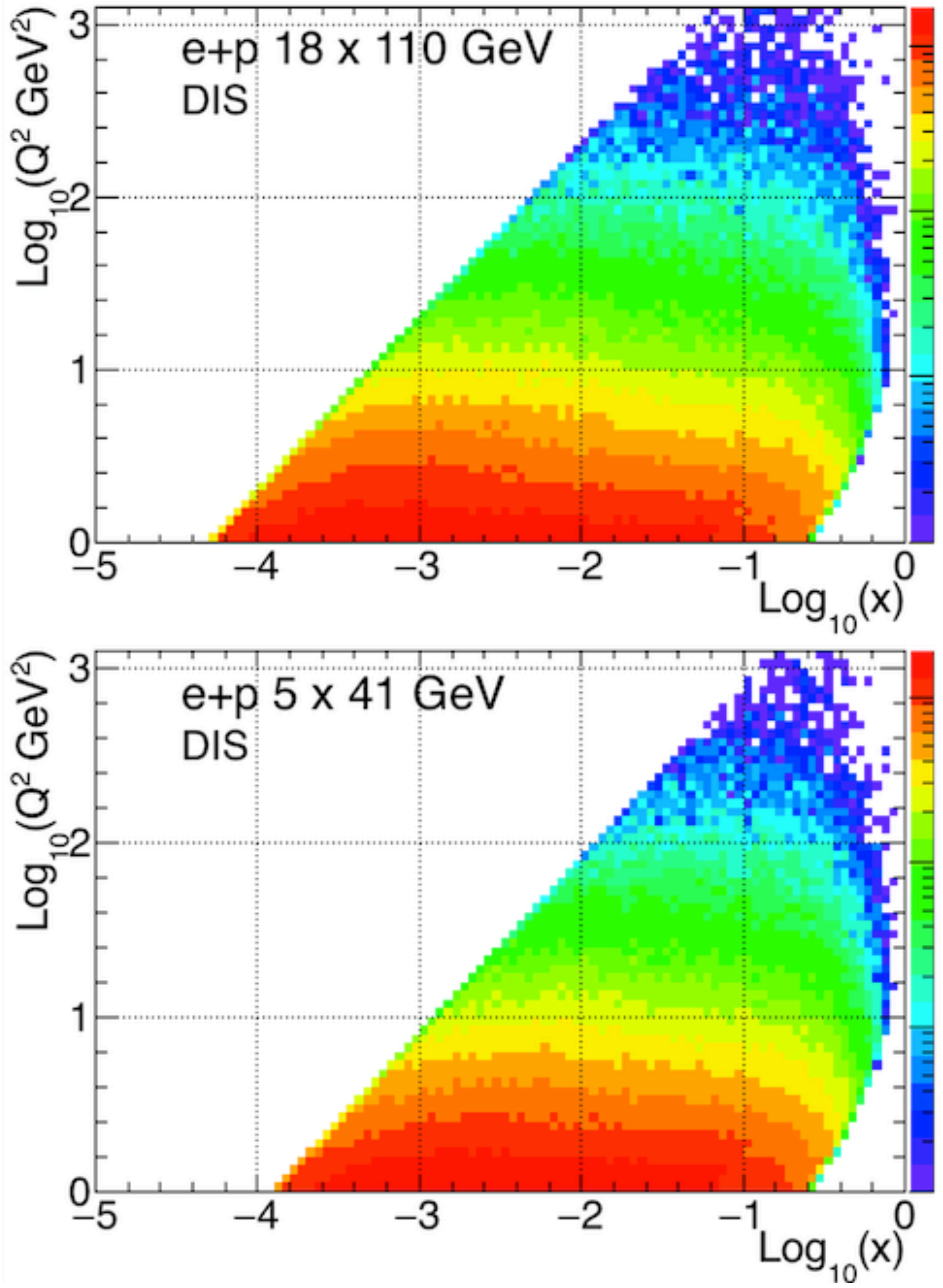
Backup slides follow

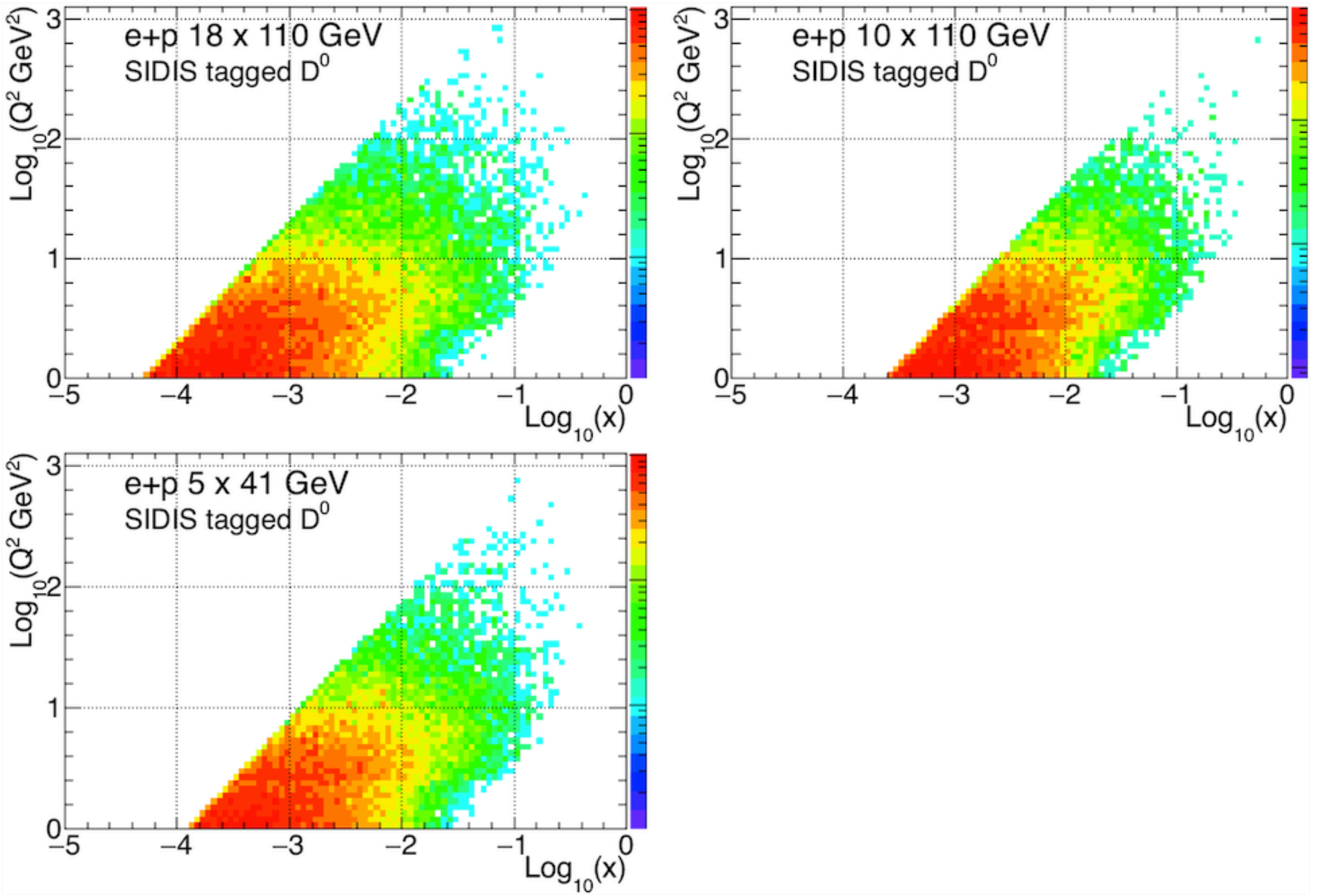
PYTHIA Processes to c/b X-Section





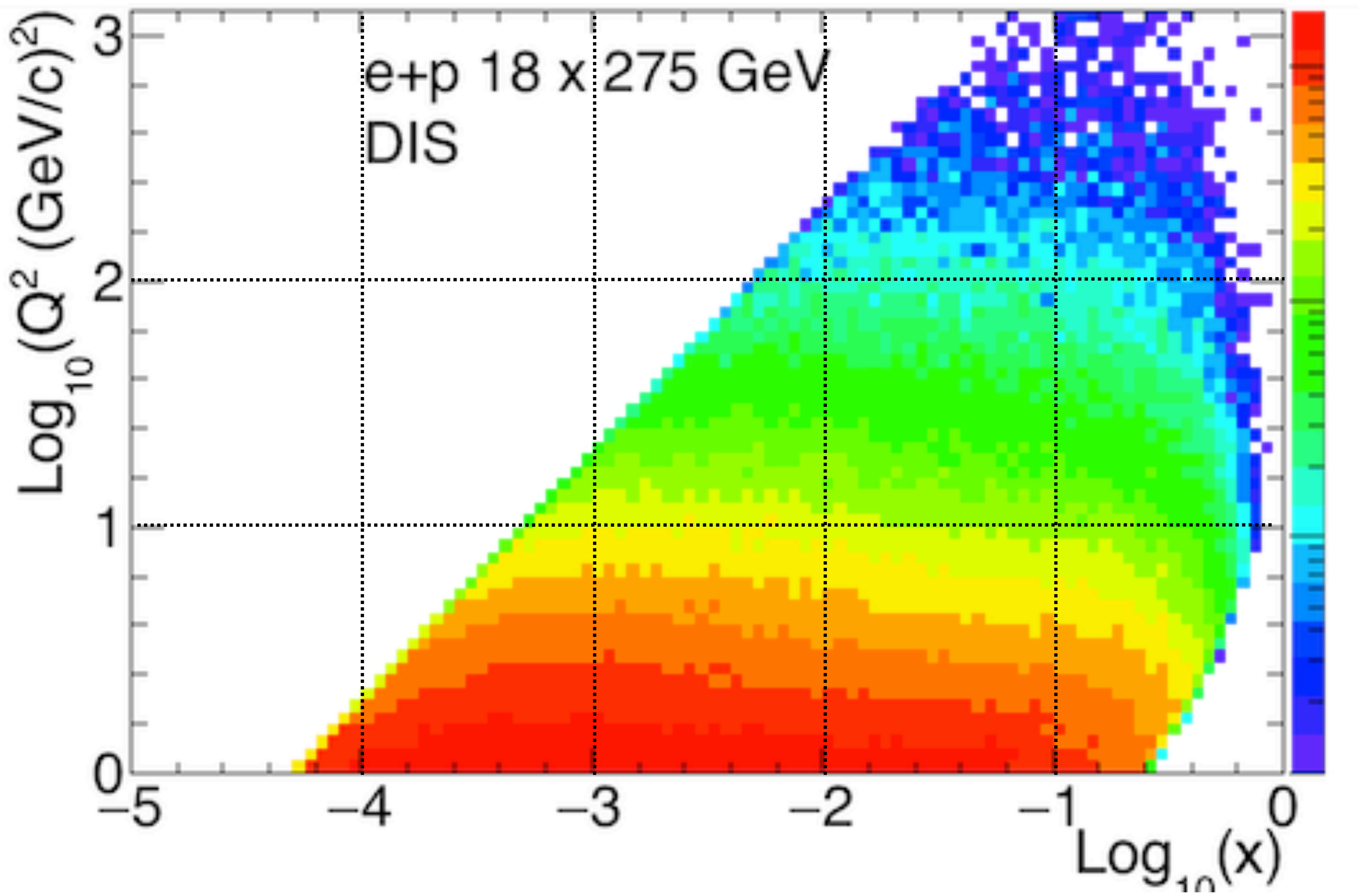
log(Q²) vs. log(x)

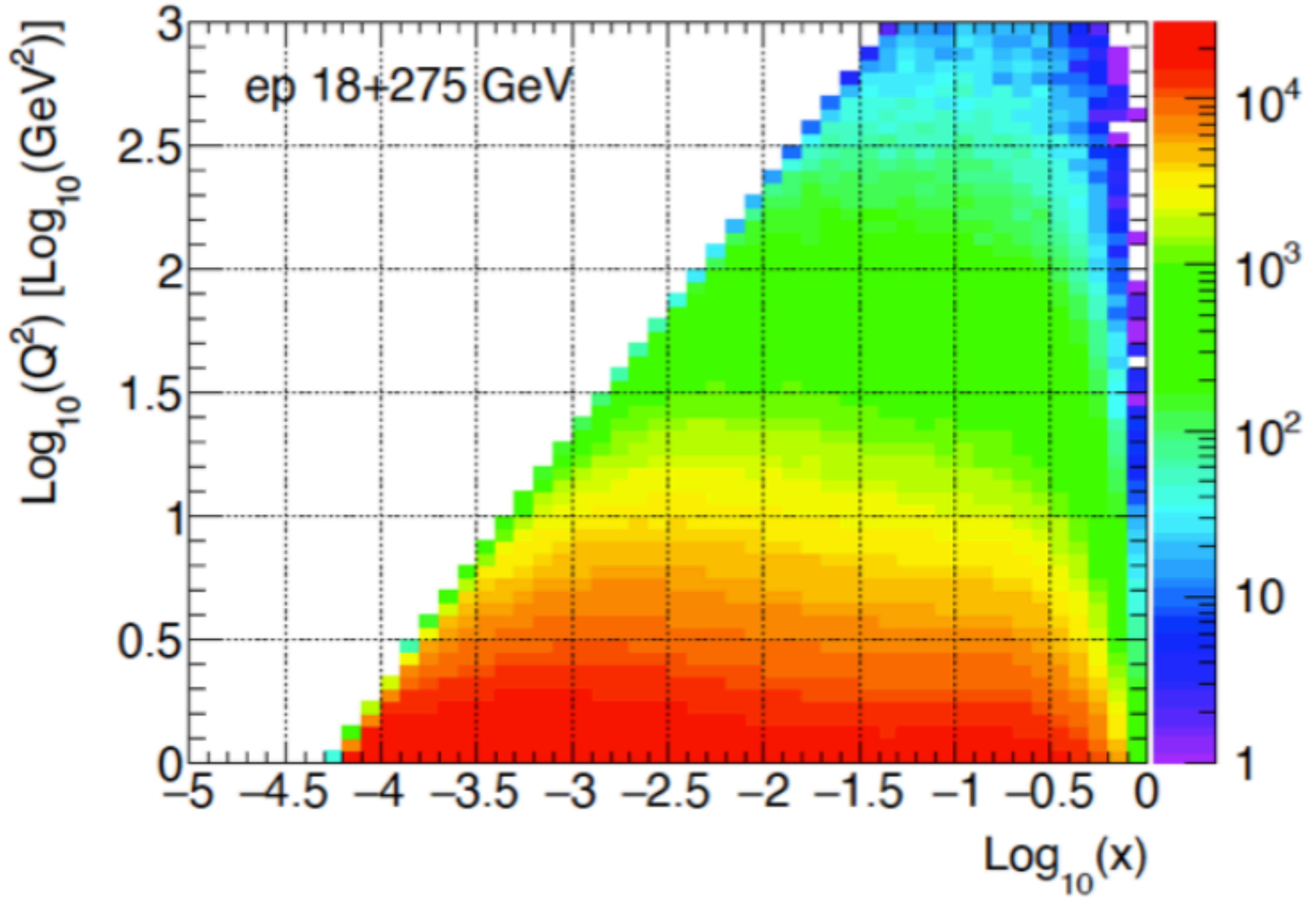




- **Energies for electron + ion collision program**

PYTHIA 6 vs. 8





- **Similar Q2 and x reach for both PYTHIA 6 and 8 (note statistics are different in each plot)**