Tracking Detector Requirements for Heavy Flavor Measurements at EIC

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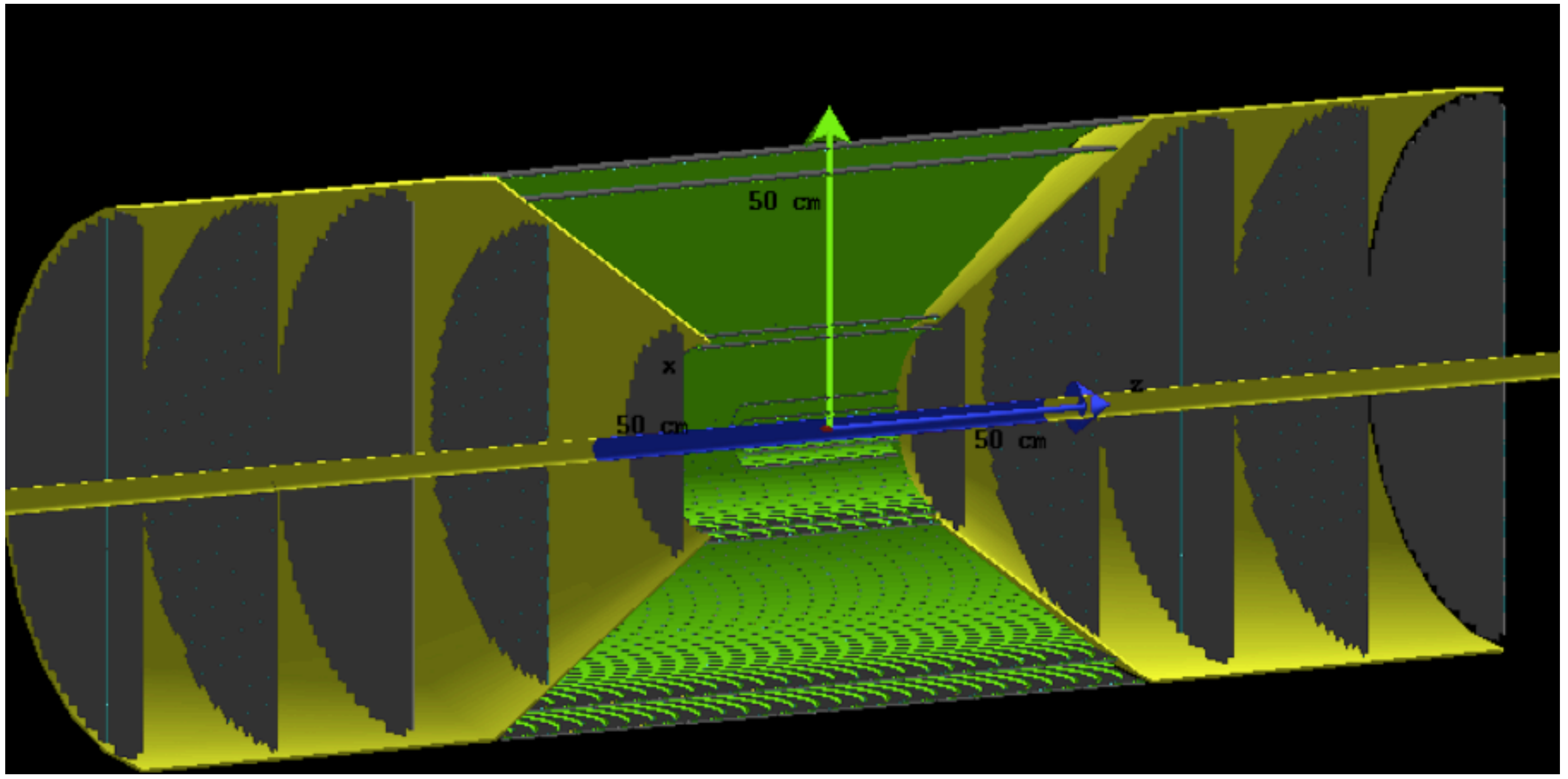
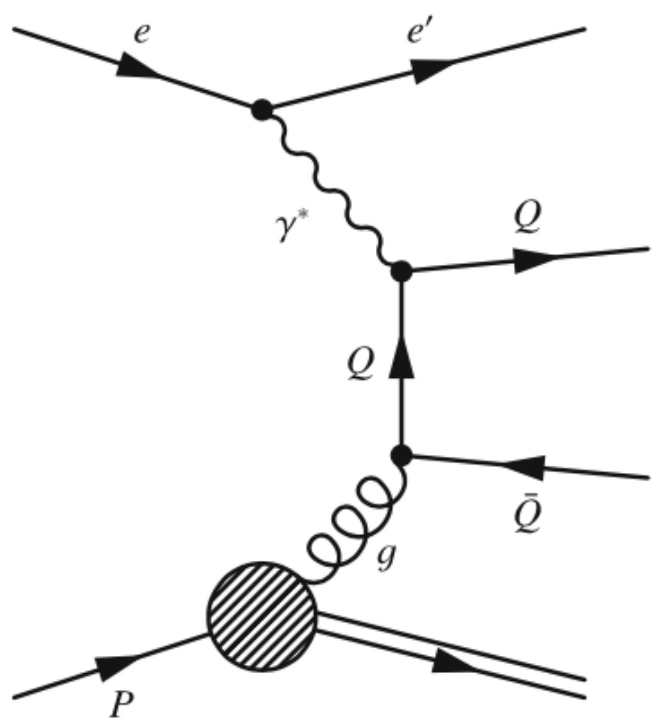
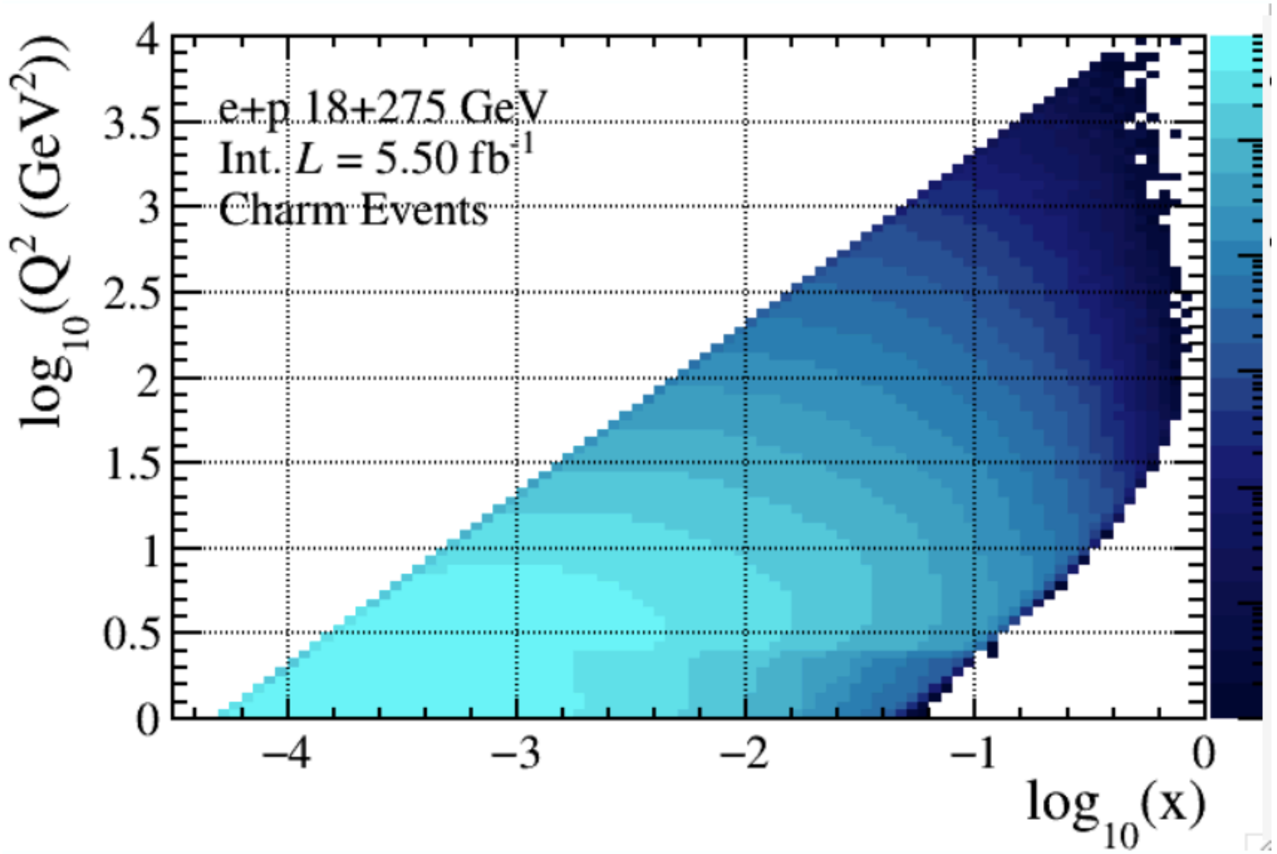


Courtesy of Rey Cruz Torres

Heavy Flavor to Probe Gluon Dynamics at EIC

- EIC is a machine for precision investigation of gluon dynamics in nucleon/nucleus
- Heavy flavor in NC channel - sensitive probe to initial gluons



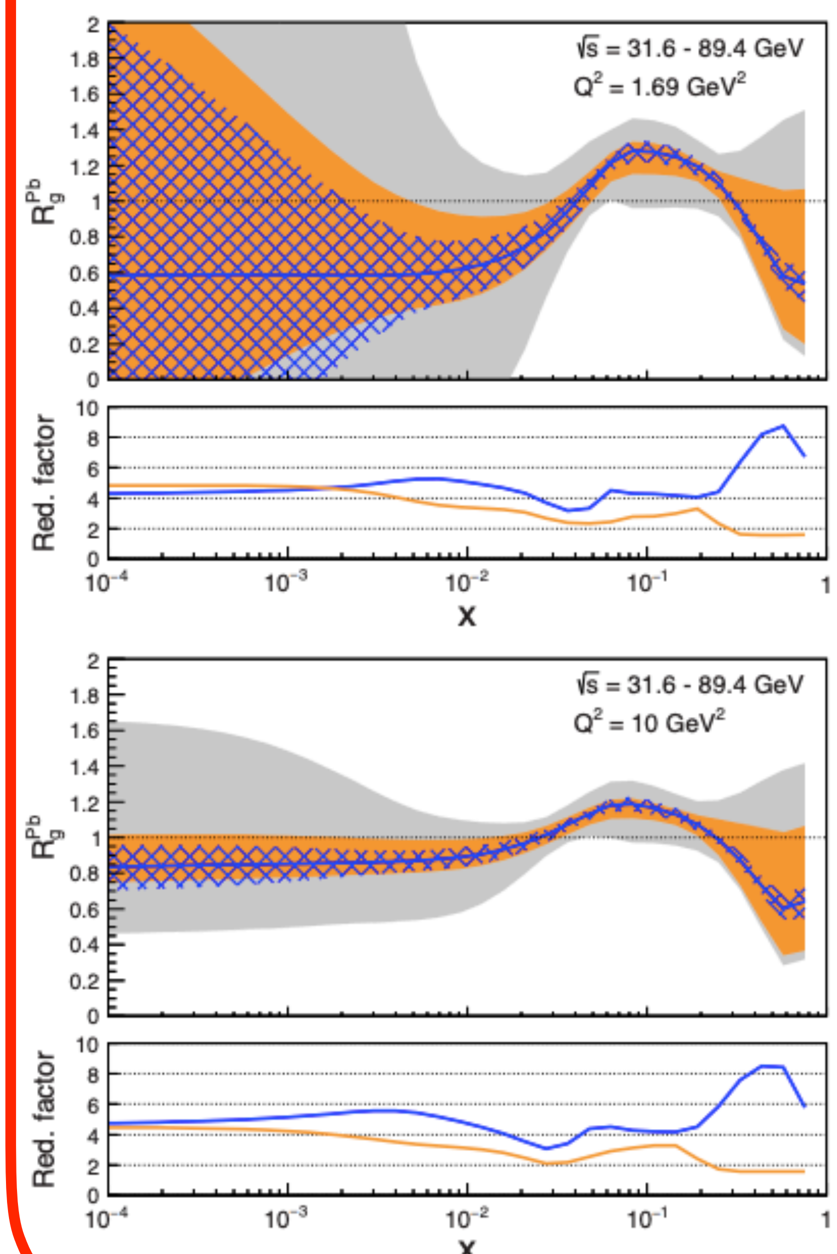


- ***Inclusive*** heavy flavor measurement in e+p/A to constrain *gluon (n)PDF*, particularly at high x region
- $D\overline{D}$ ***pair*** reconstruction to access *gluon TMDs*
- Heavy flavor hadron (***D***, Λ_c etc.) in e+p/A for *hadronization* and *CNM* effect
- Heavy flavor $\boldsymbol{A_{LL}}$ for *gluon spin* contribution
- **Quarkonia** threshold production for understanding *proton mass*

Physics Interests Utilizing Heavy Flavor Probes

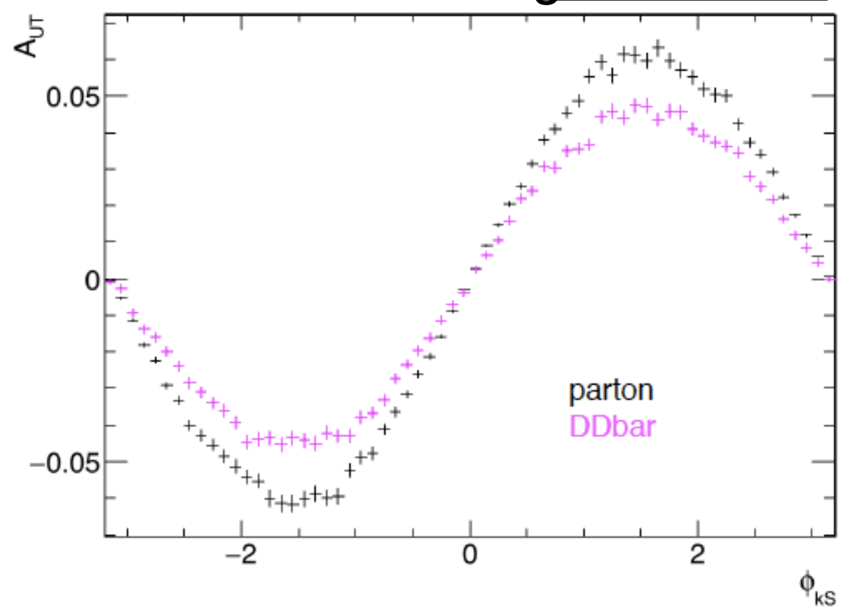
Gluon (n)PDF

$$R^A_{q,g}(x, Q^2) = \frac{f^A_{q,g}(x, Q^2)}{f^p_{q,g}(x, Q^2)}$$

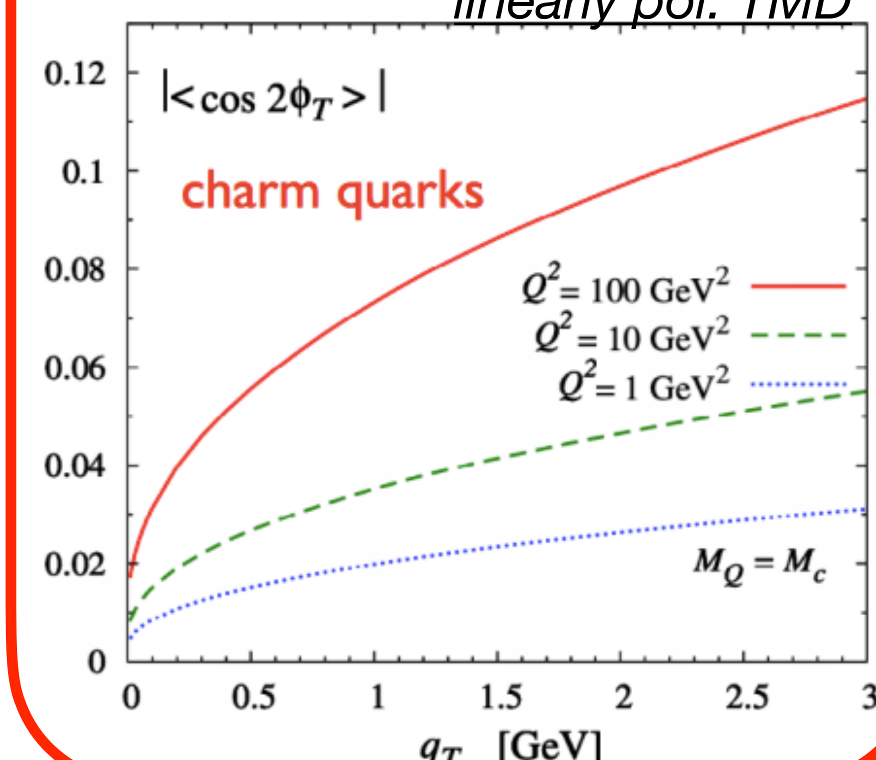


Gluon TMDs

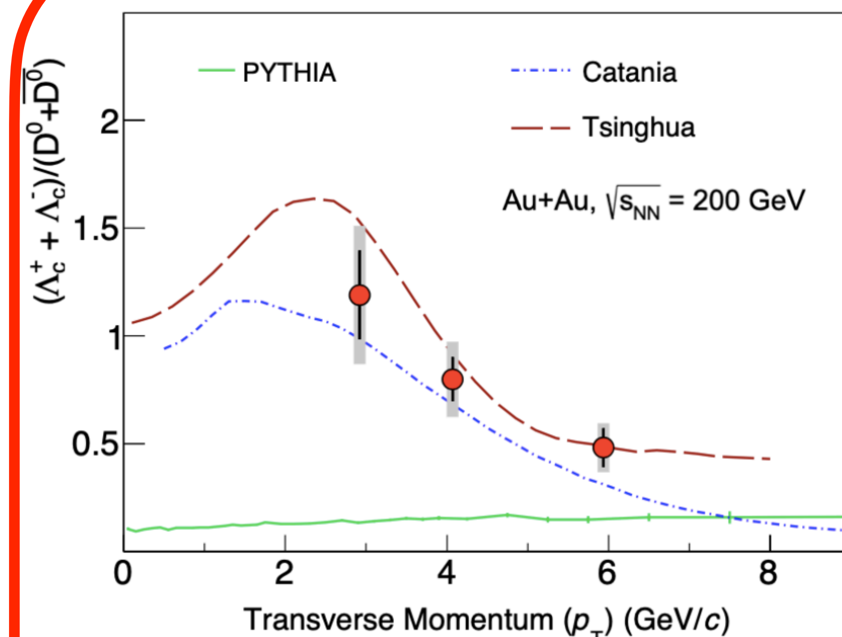
gluon Sivers

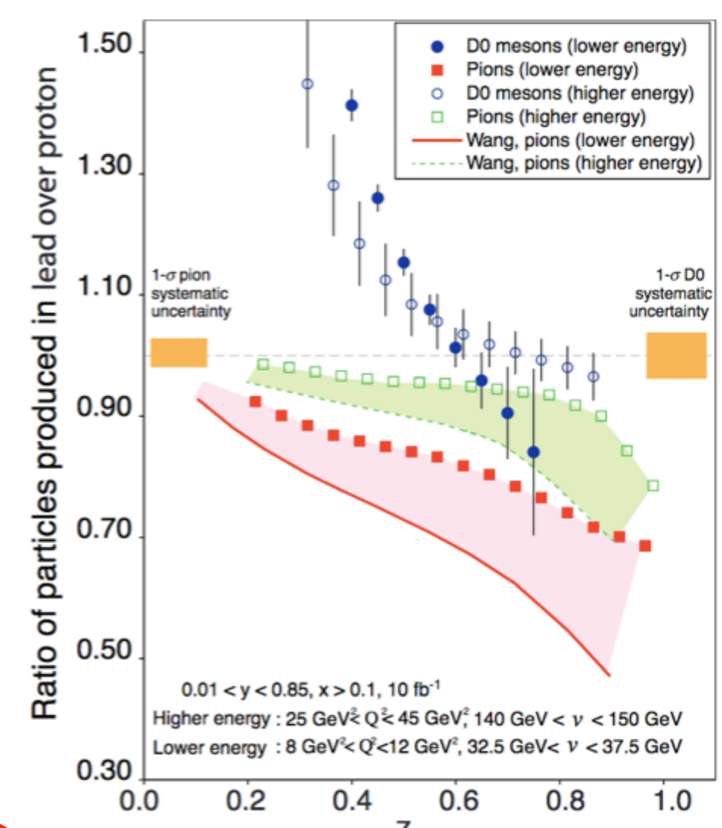


linearly pol. TMD



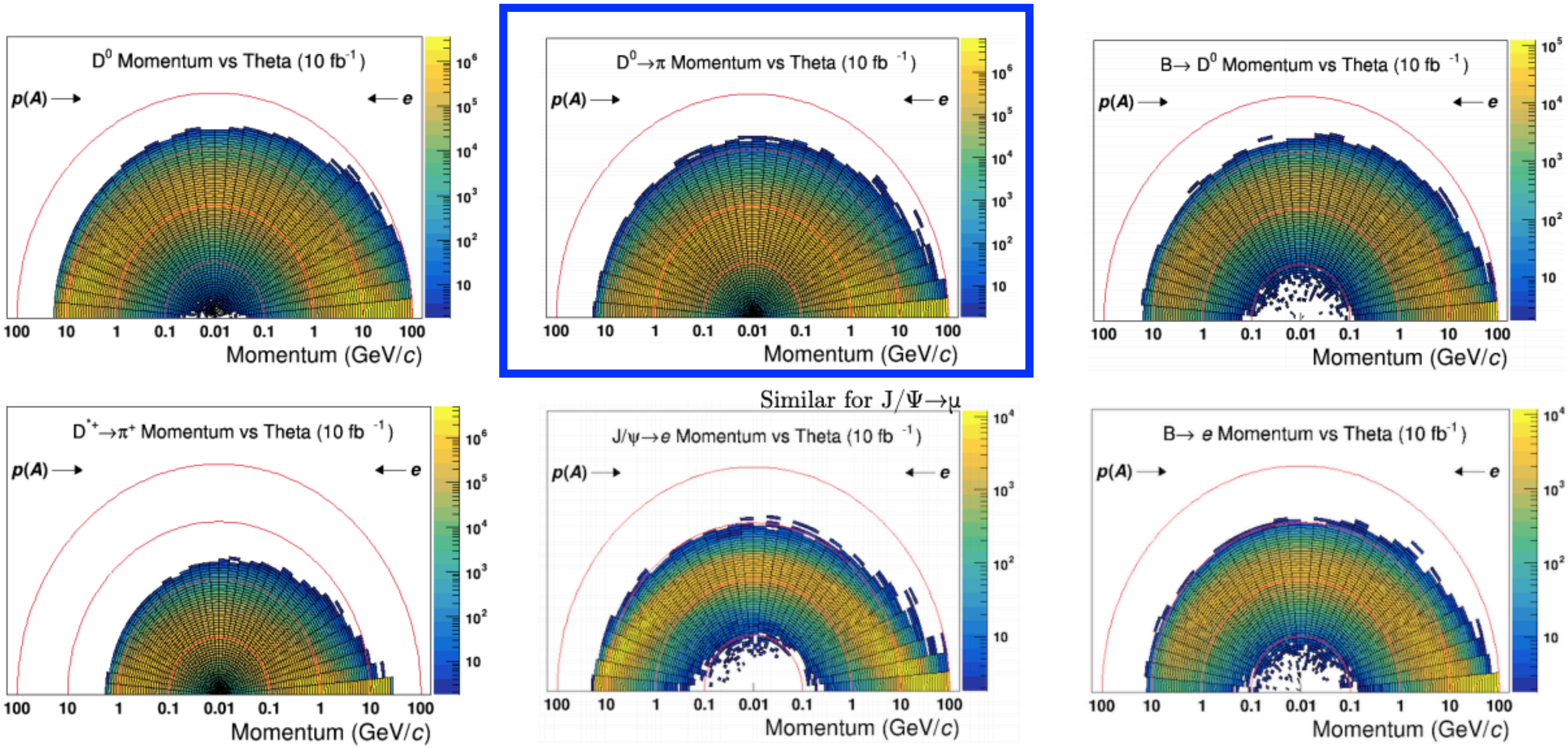
Hadronization/CNM



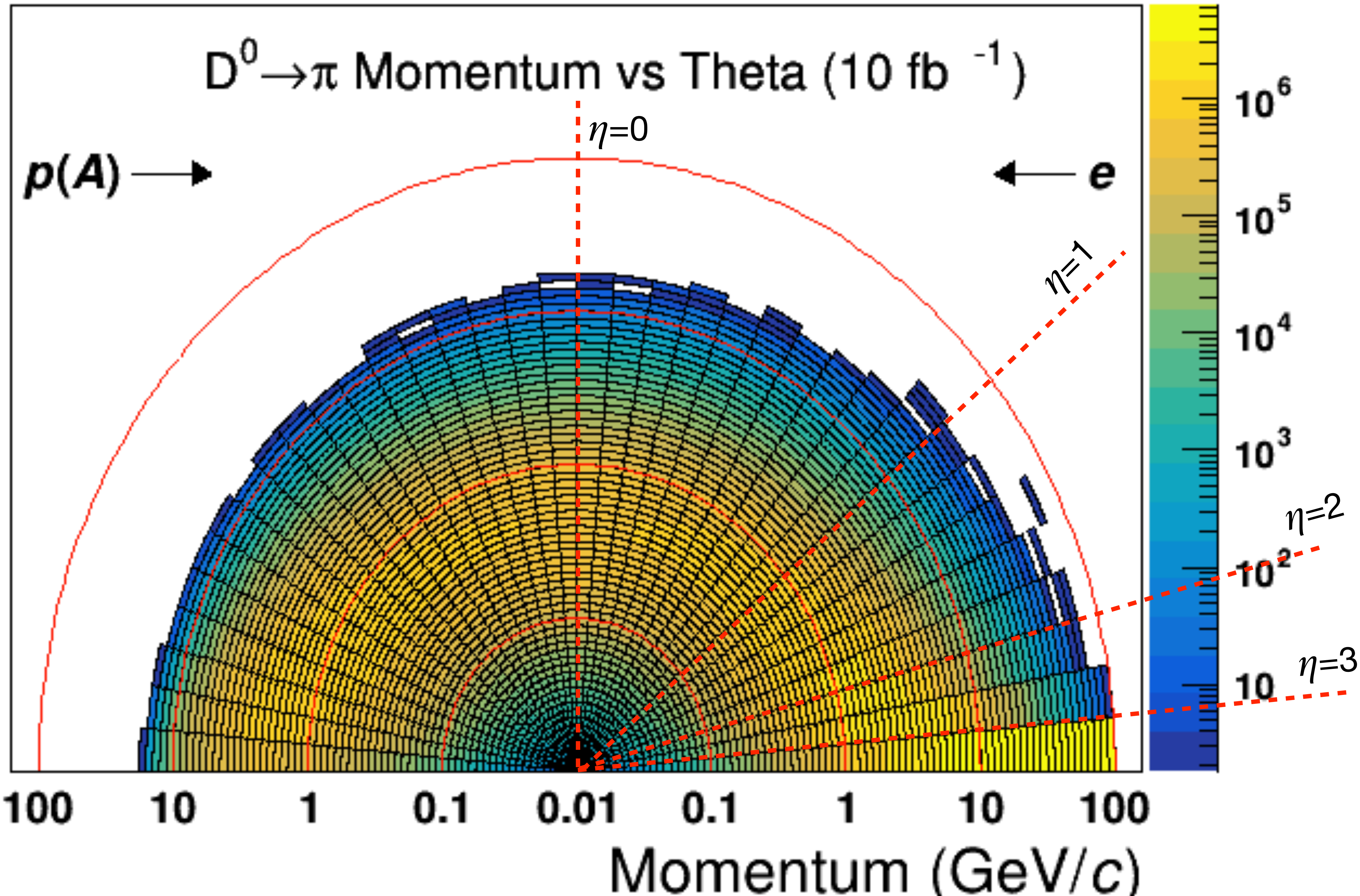


Kinematic Distributions

e + p 18 x 275 PYTHIA 6.4



Kinematic Distributions



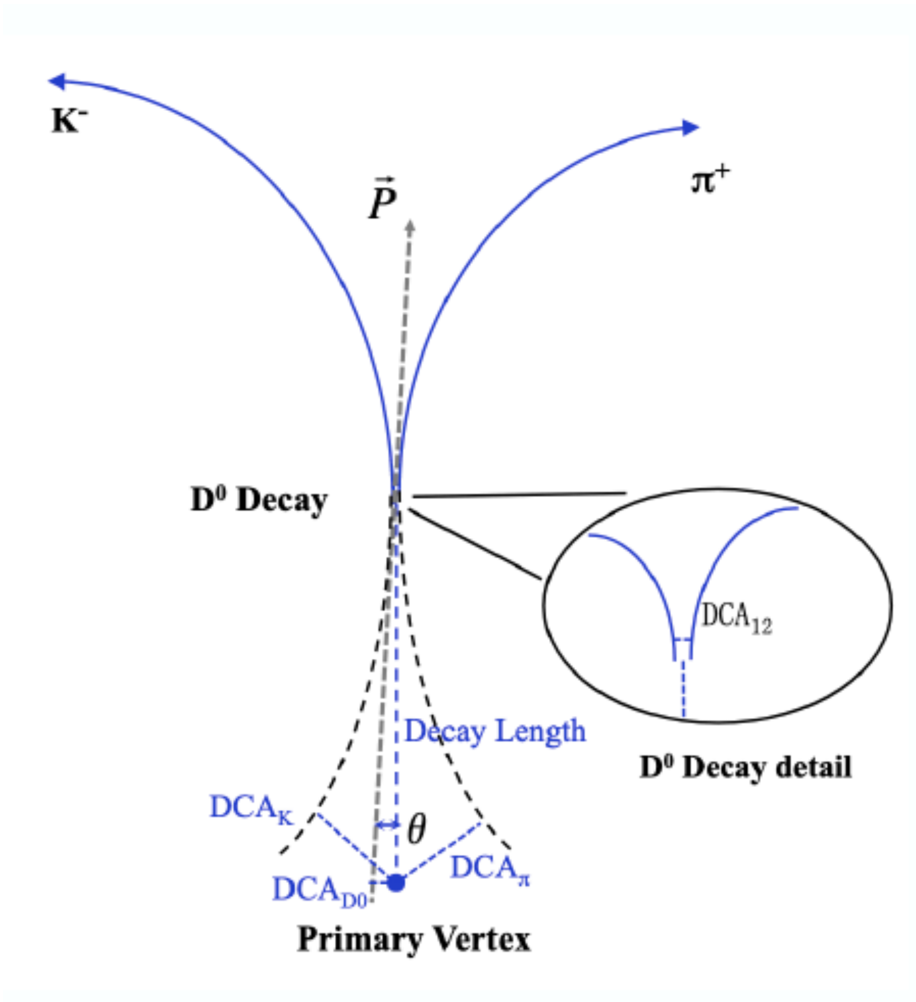
Fast Simulation w/ Default Detector Parameters

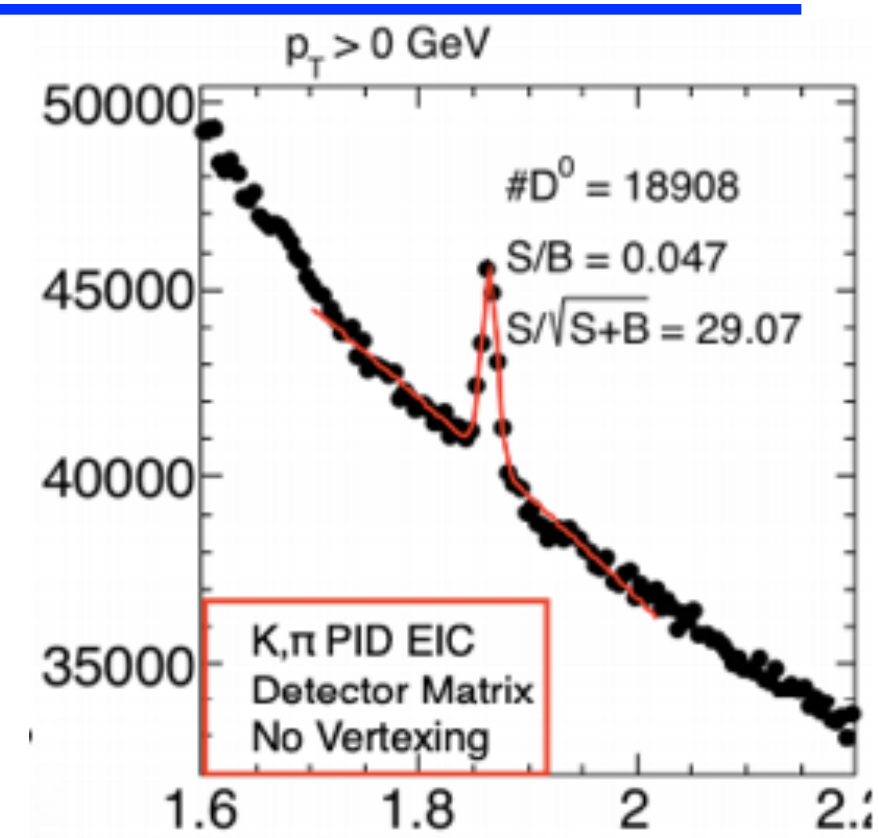
η	Nomenclature			Tracking			Electrons		π/K/p	
				Resolution	Allowed X/X_0	Si-Vertex	Resolution σ_E/E	PID	p-Range (GeV/c)	Separation
-3.5 to -3.0		Central Detector	Backward Detector	$\sigma_p/p \sim 0.1\% \oplus 0.5\%$	~5% or less X	TBD	[illegible]	π suppression up to 1:10^4	≤ 7 GeV/c	≥ 3 σ
-3.0 to -2.5										
-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	

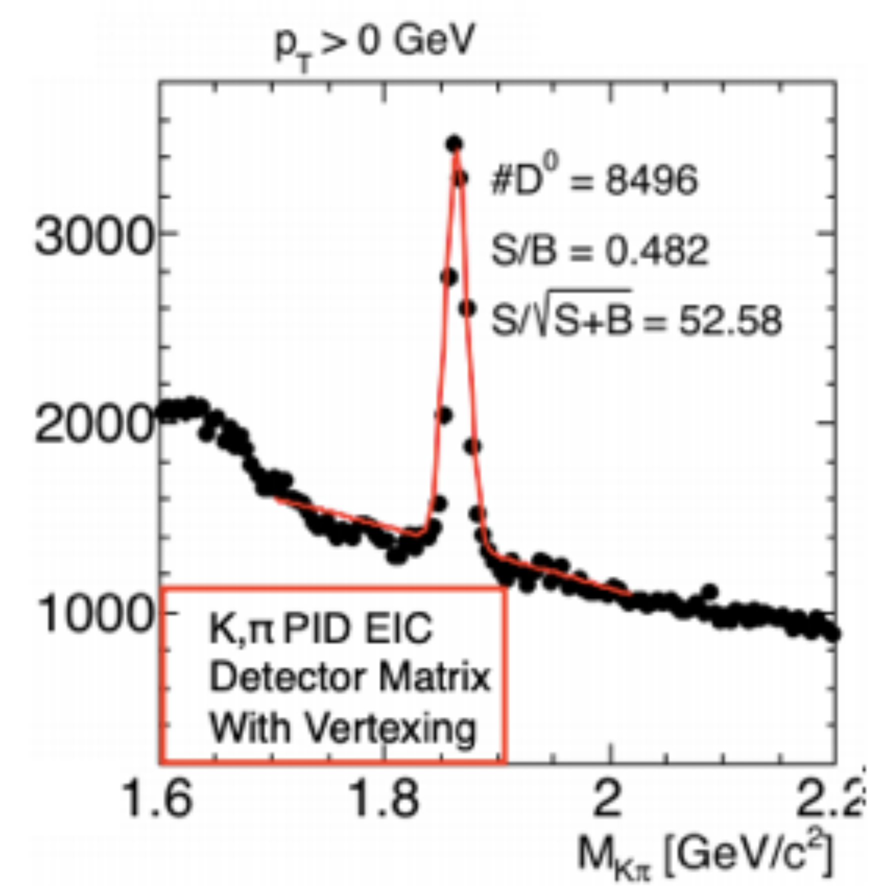
$$\sigma_{XYZ} \sim 20\ \mu m$$
$$d_0(z) \sim d_0(r\phi) = 20/p_T \oplus 5\mu m$$

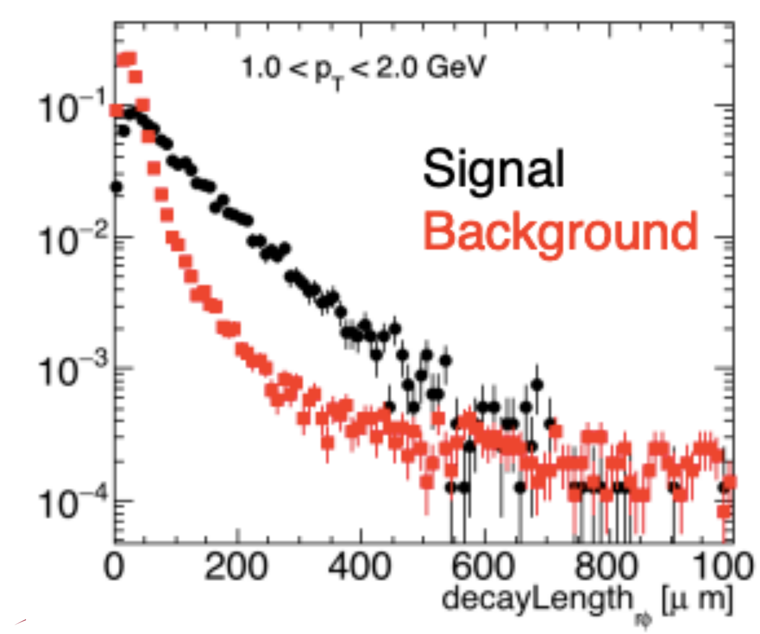
- Charm and bottom reconstruction using fast simulation smearing of PYTHIA 6.4 output
- Momentum and pointing resolutions taken from detector matrix page as baseline
  - central transverse pointing resolution extends to $|\eta|<3$

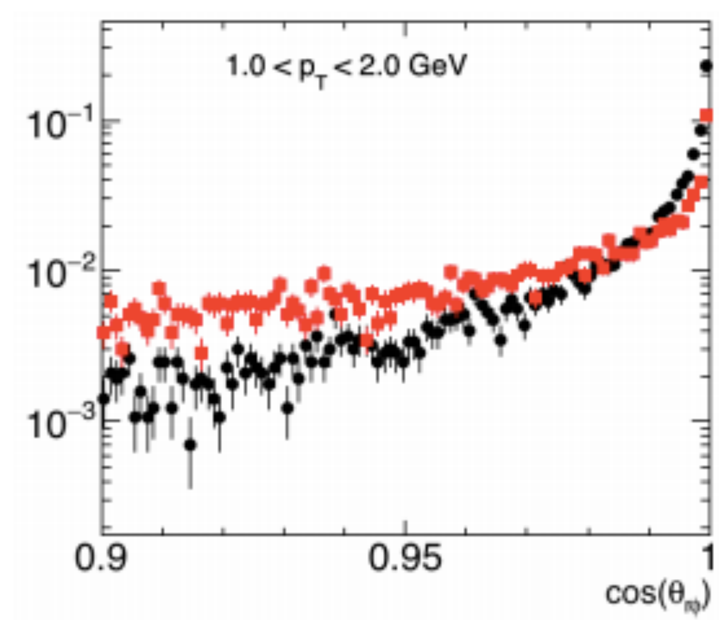
Topological Reconstruction of Heavy Flavor Decays





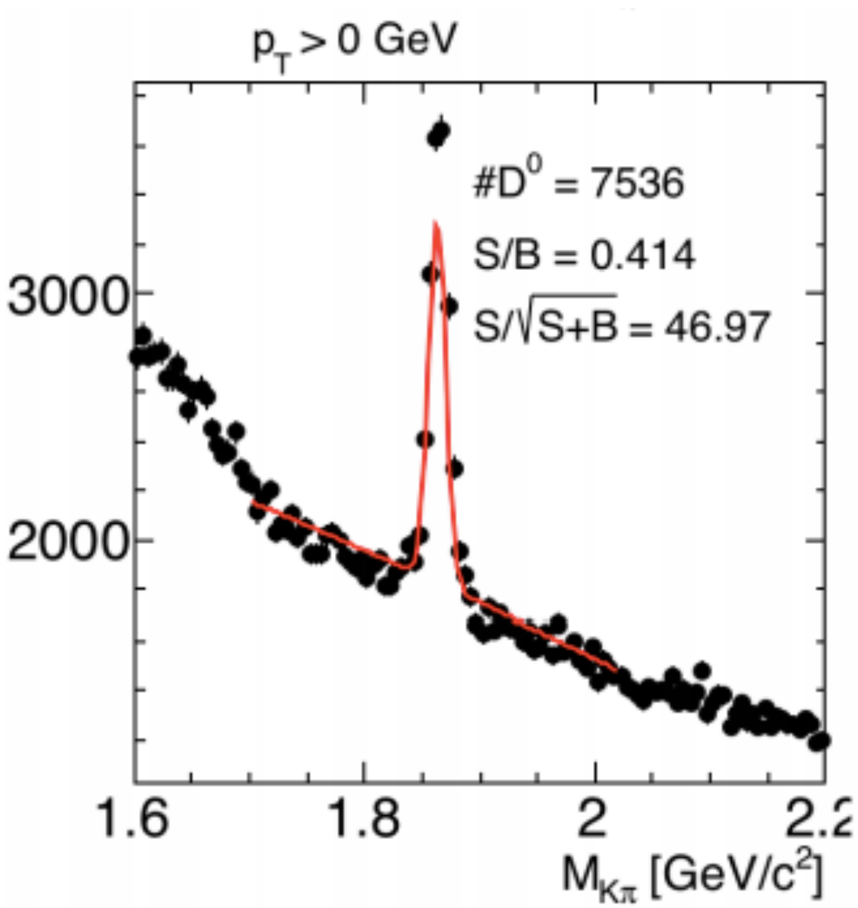






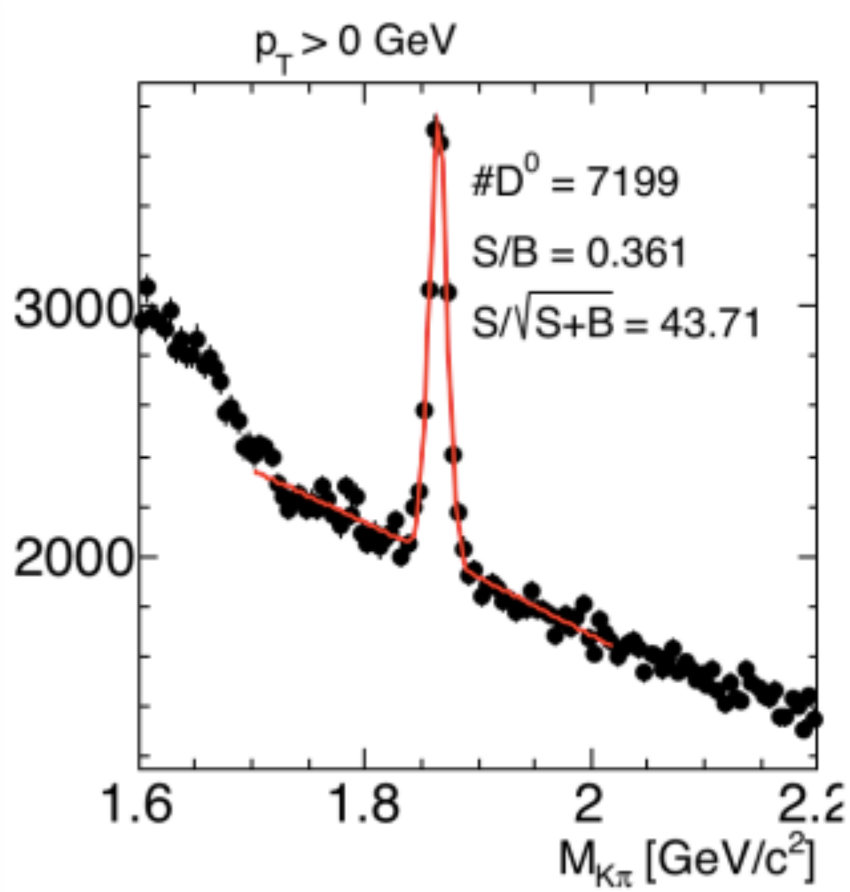
Impact of Pointing Resolution on D⁰ Significance

$\sigma \sim 20\mu m$ @ 1 GeV/c



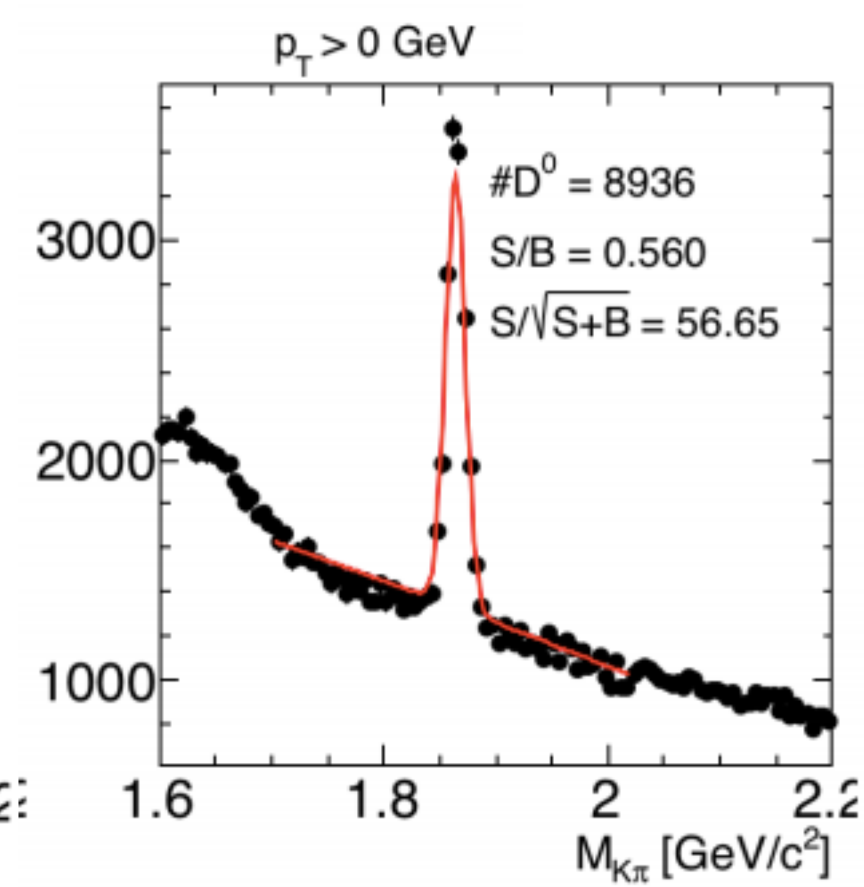
D⁰ significance

$\sigma \sim 30\mu m$ @ 1 GeV/c



-10%

$\sigma \sim 10\mu m$ @ 1 GeV/c

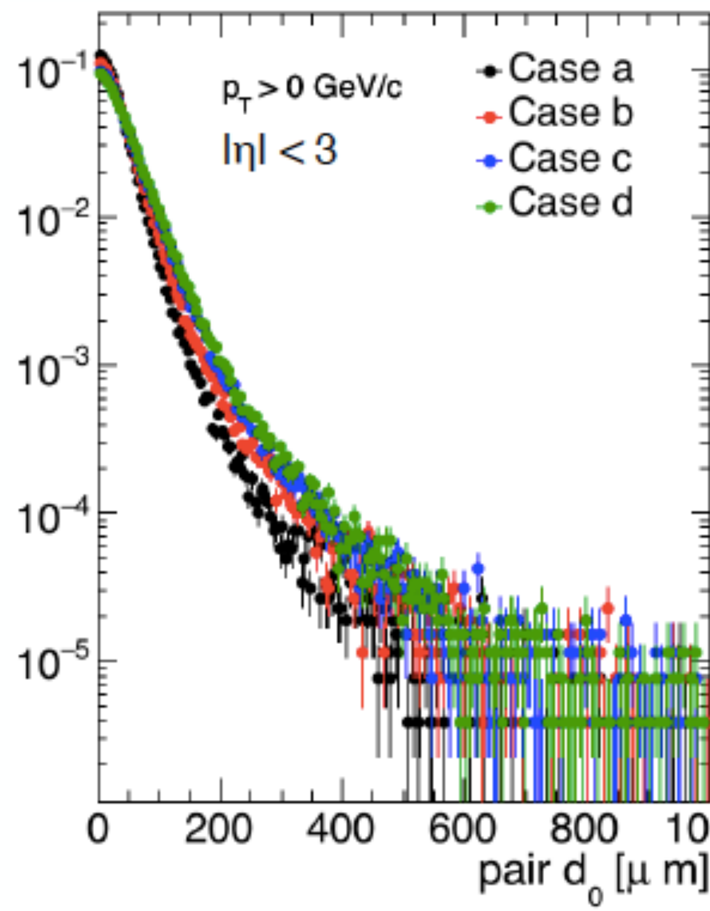


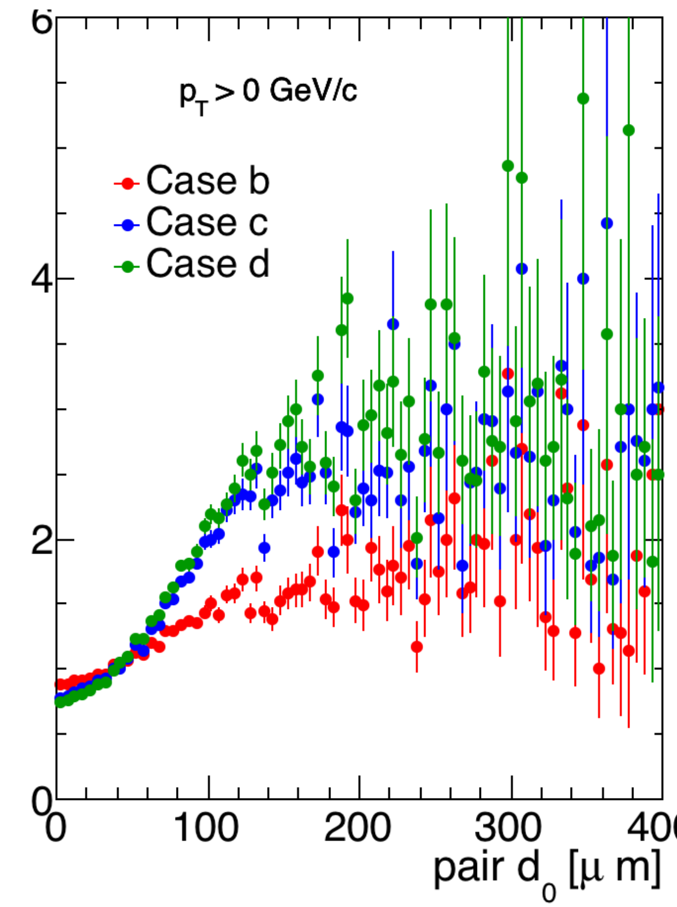
+20%

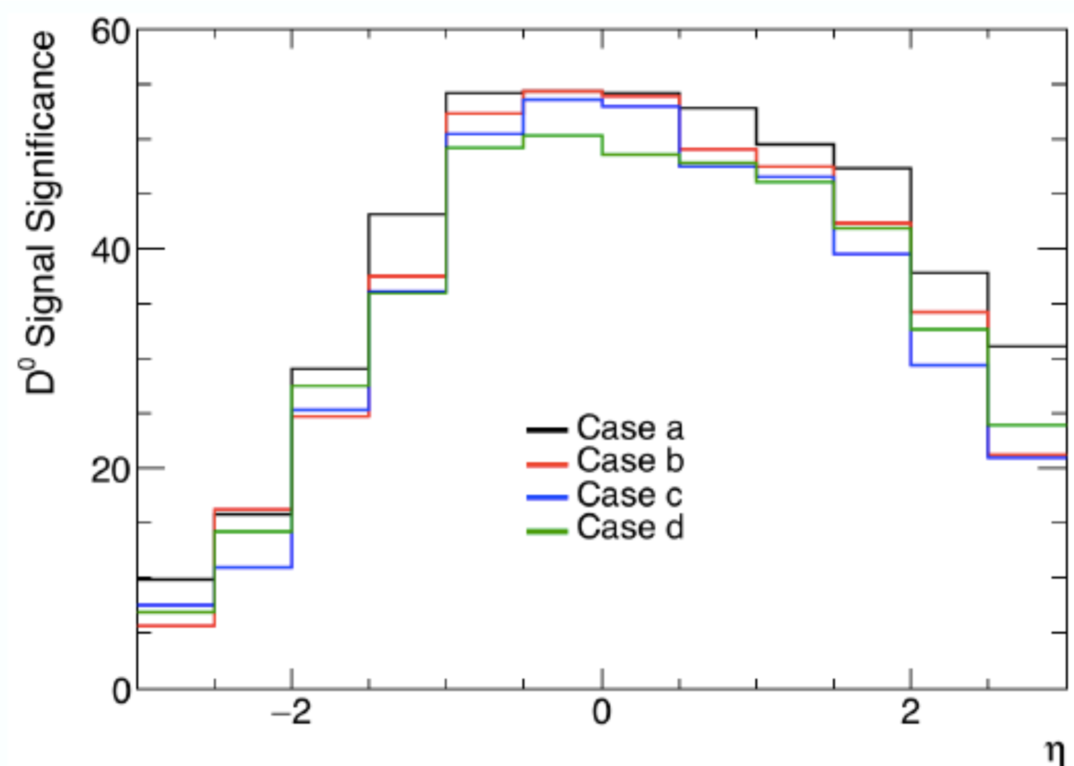
- vertex res. assumed to be 20 μm

Comparison between Different Scenarios

- Case a:
  - $20/p_T + 5$ at all η
- Case b (proposed by LBNL):
  - $20/p_T + 5$ for $0 < |\eta| < 1$
  - $25/p_T + 10$ for $1 < |\eta| < 2$
  - $30/p_T + 10$ for $2 < |\eta| < 3$
- Case c (proposed by LANL):
  - $25/p_T$ for $0 < |\eta| < 1$
  - $30/p_T + 20$ for $1 < |\eta| < 2$
  - $30/p_T + 40$ for $2 < |\eta| < 3$
- Case d:
  - $30/p_T + 5$ at all η





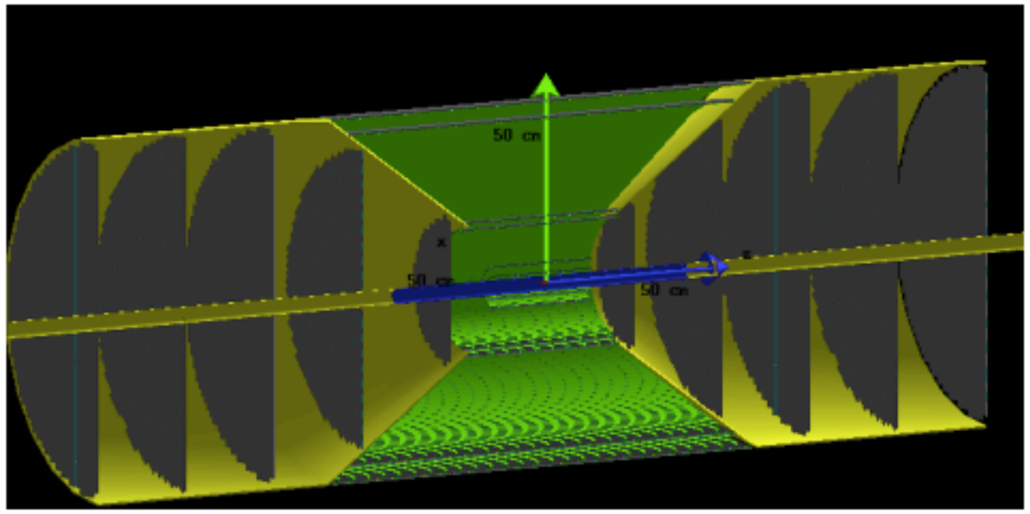


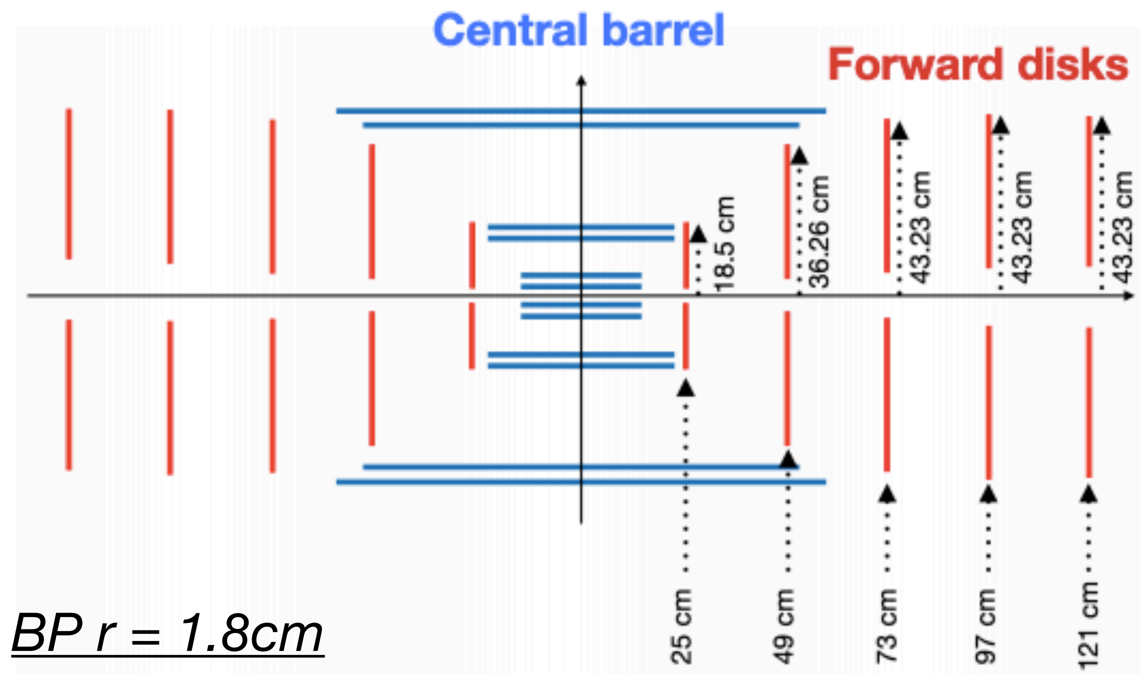
<u>Case b vs. Case c</u>

- 10% reduction in D^0 significance in forward region (2<eta<2.5)

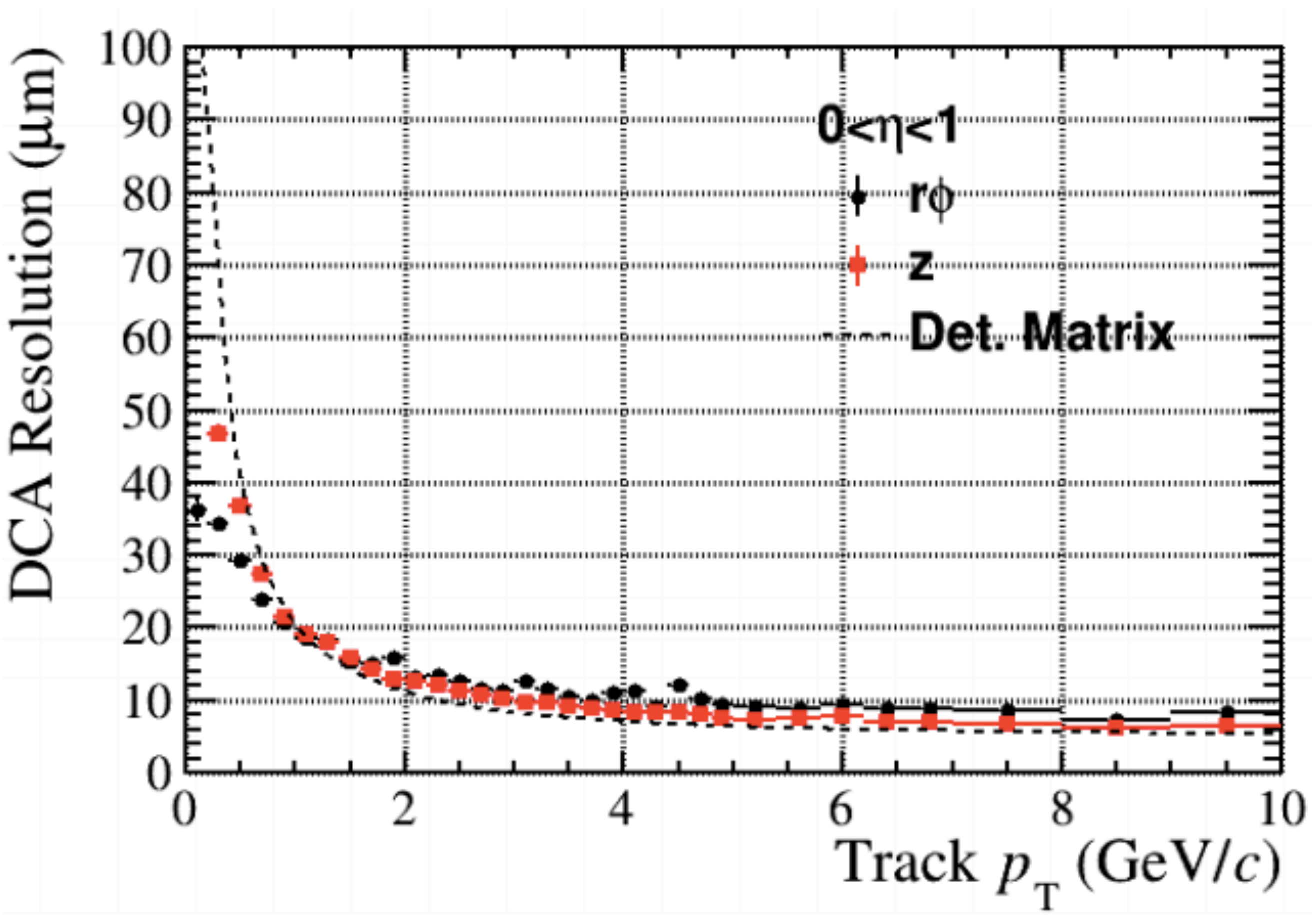
Full All-Si Detector Simulation in Fun4All

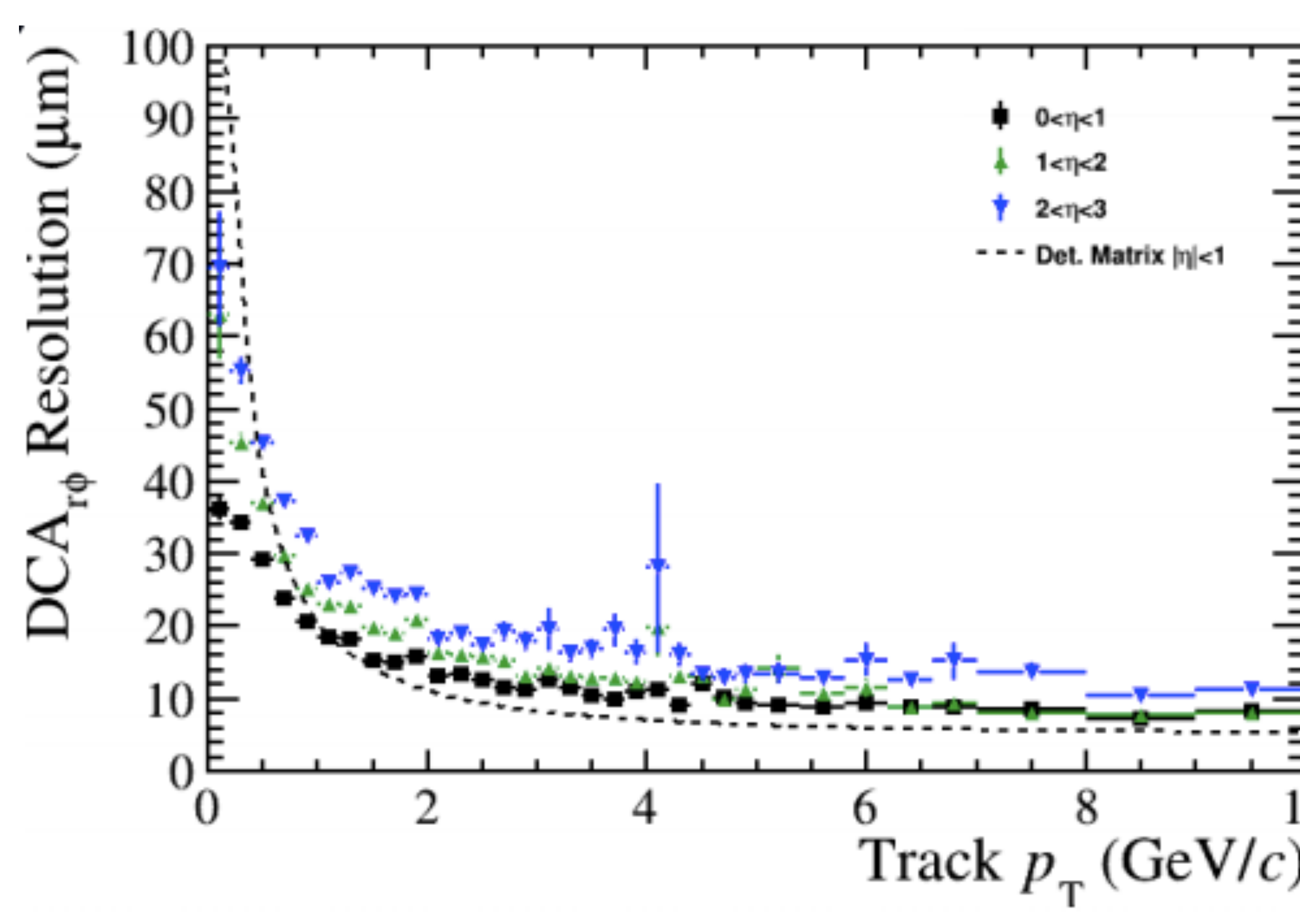
3T, beampipe + support cone included, 20x20 um





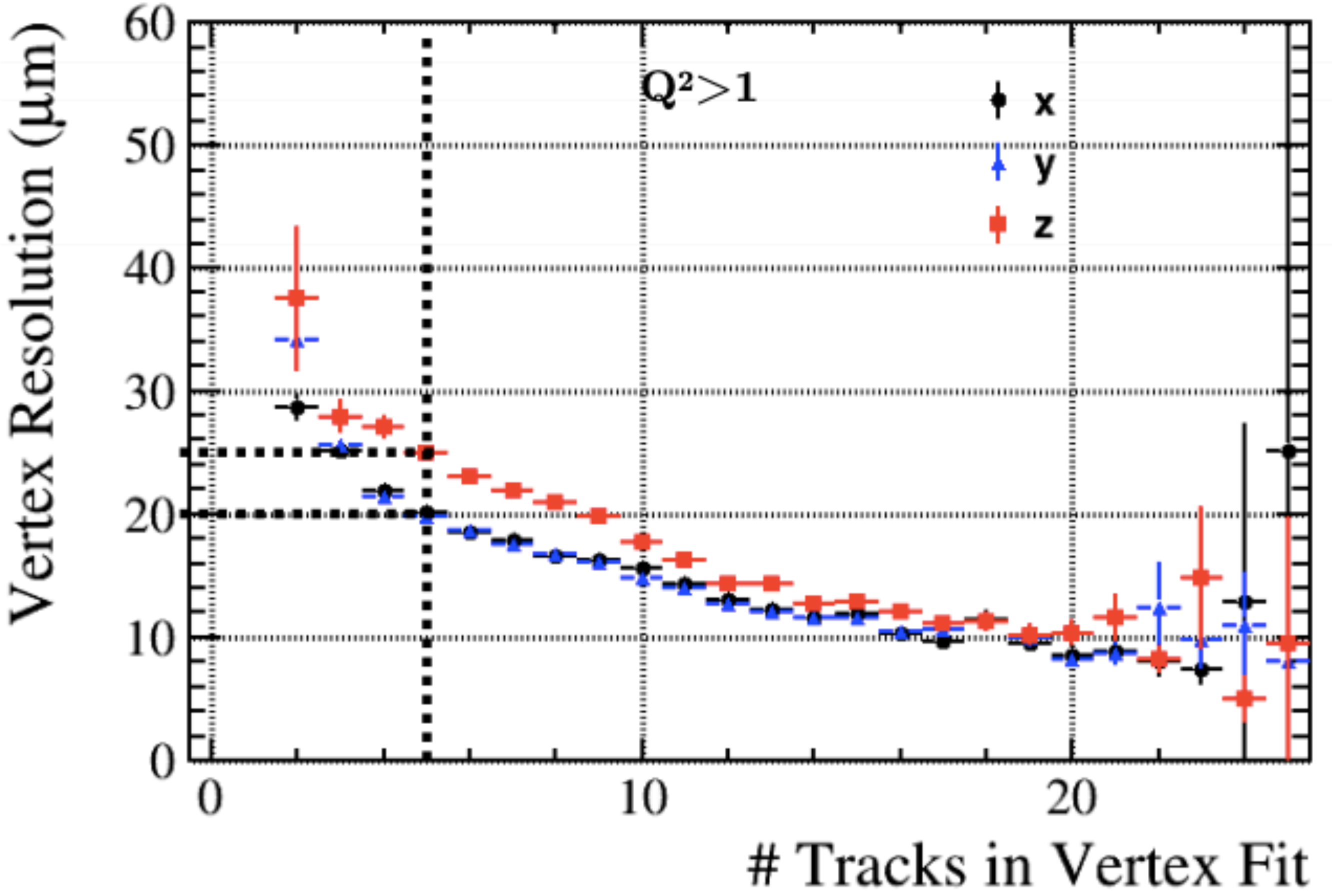
BP r = 1.8cm



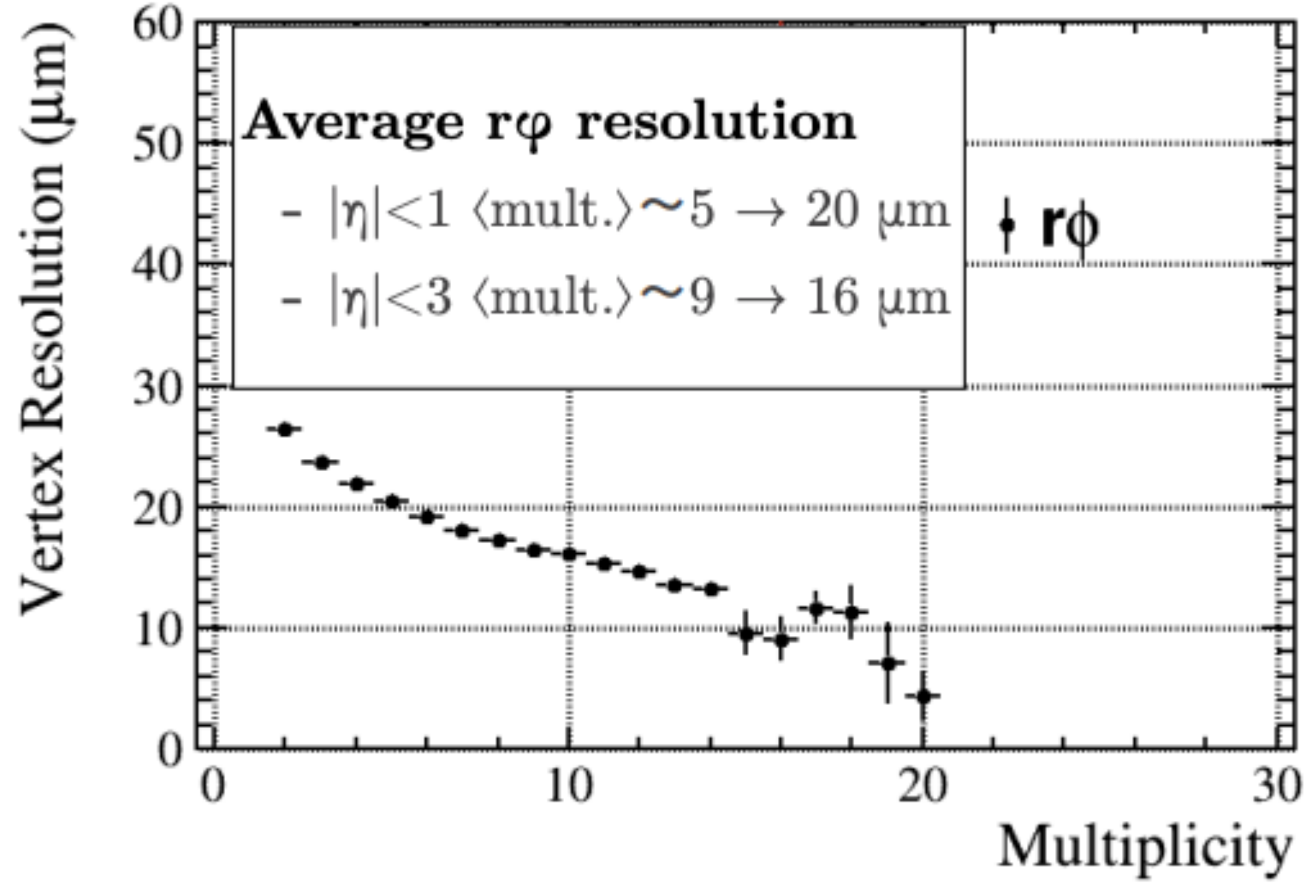


Vertex Resolution

Full Simulation



PV Fitter from Fast Simulation



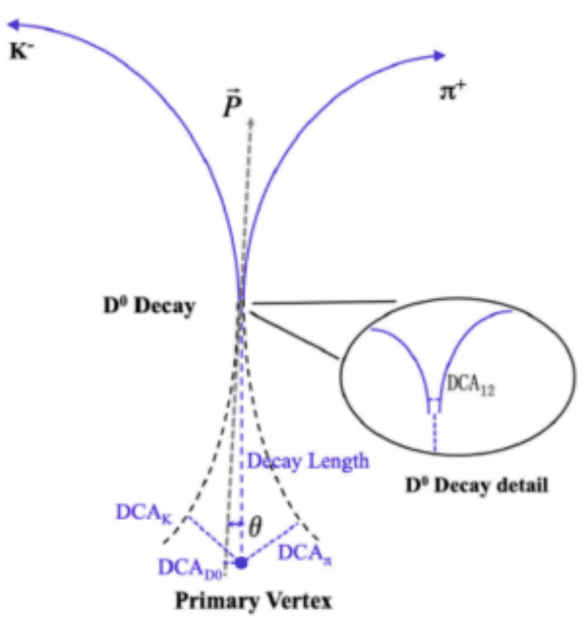
- Vertex res: $\sigma_{X,Y} \sim 20\mu m$ at <Mult> ~ 5
- Reproduced by both full and fast simulation studies

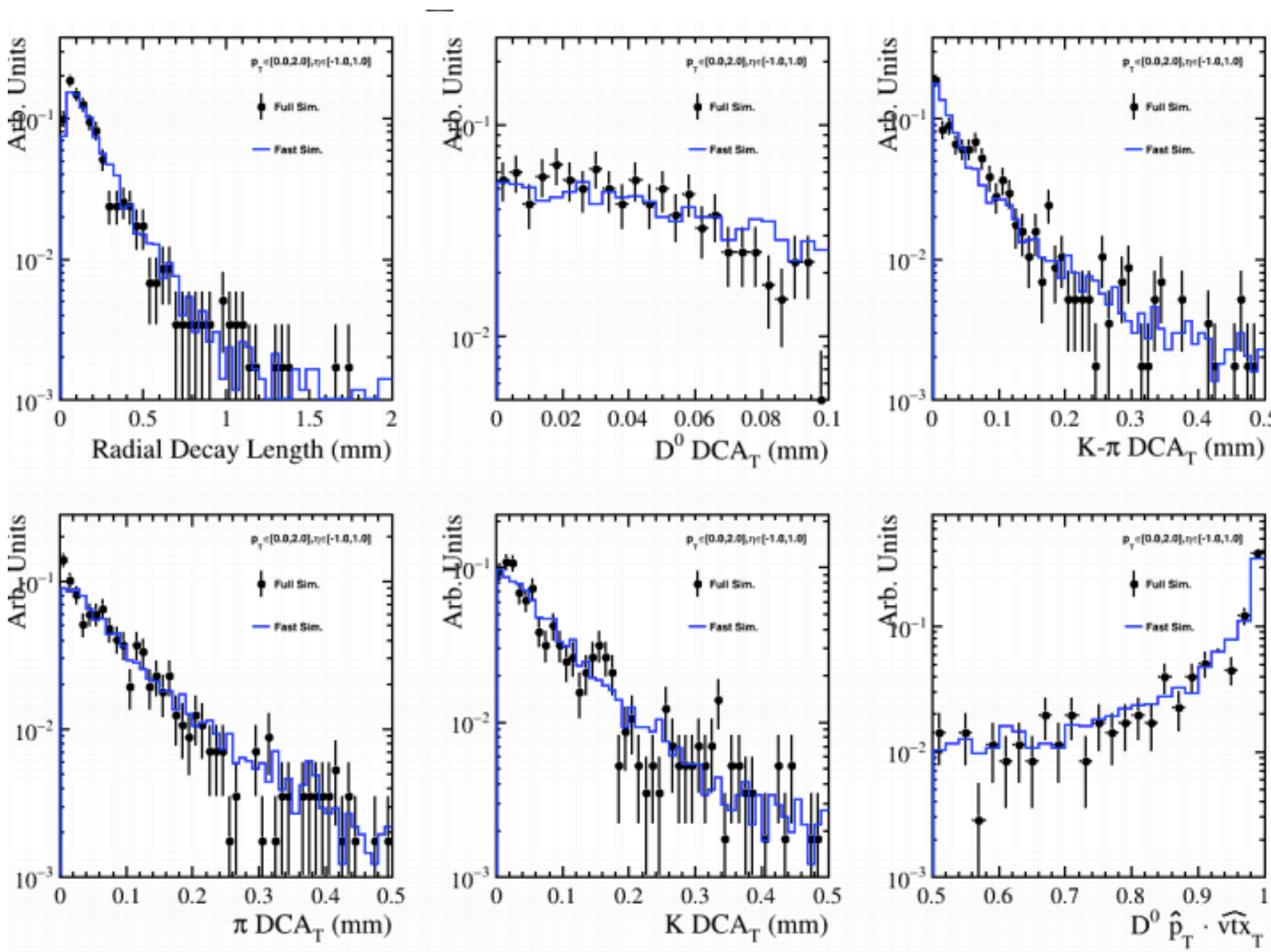
Validation of Fast Simulation w/ Fun4All

D^0 signal significance improved by cutting on topological variables

- https://indico.bnl.gov/event/8494/contributions/37480/attachments/28030/43019/EIC_HFJETYRWG_SR_2.pdf

Good agreement at η in [-1,1] (same for all η windows)





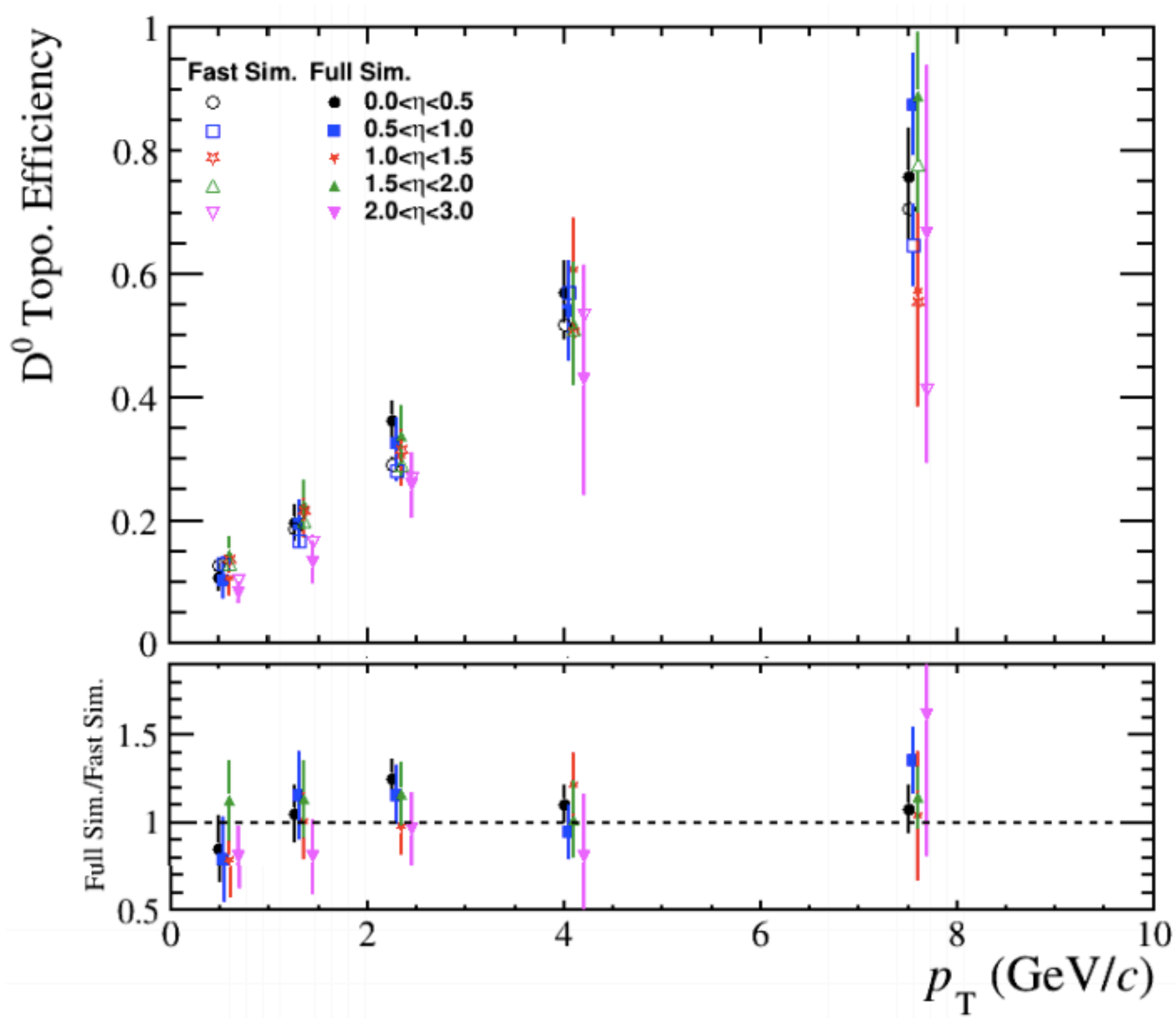
Fast simulation reproduces all topological distributions !

Validation of Fast Simulation w/ Fun4All

Radial Decay Vertex>0.04 mm

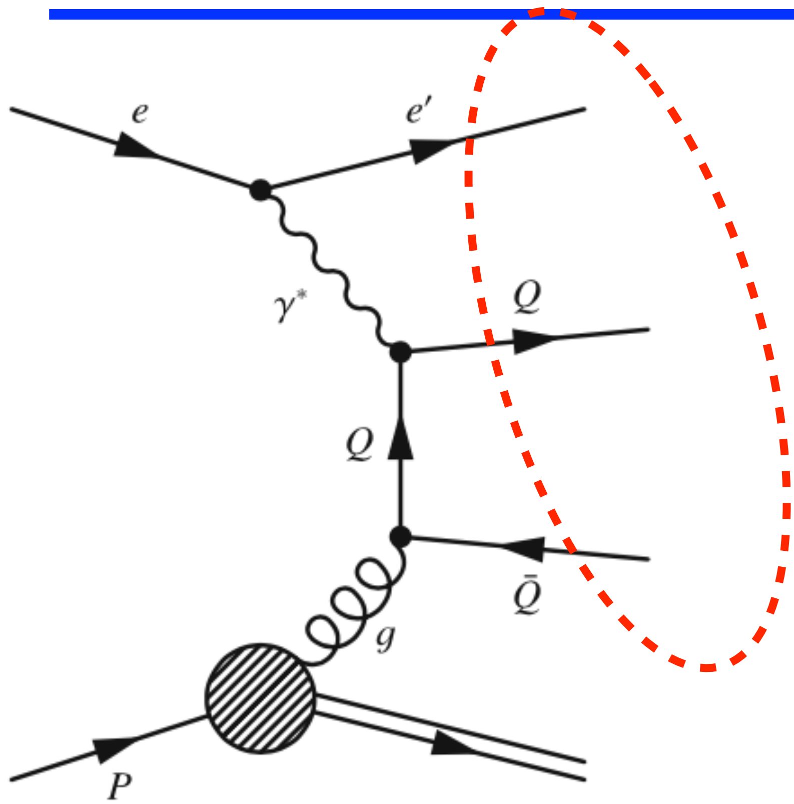
K-π DCA_T<0.15 mm

cos(D0 pointing angle)>0.98



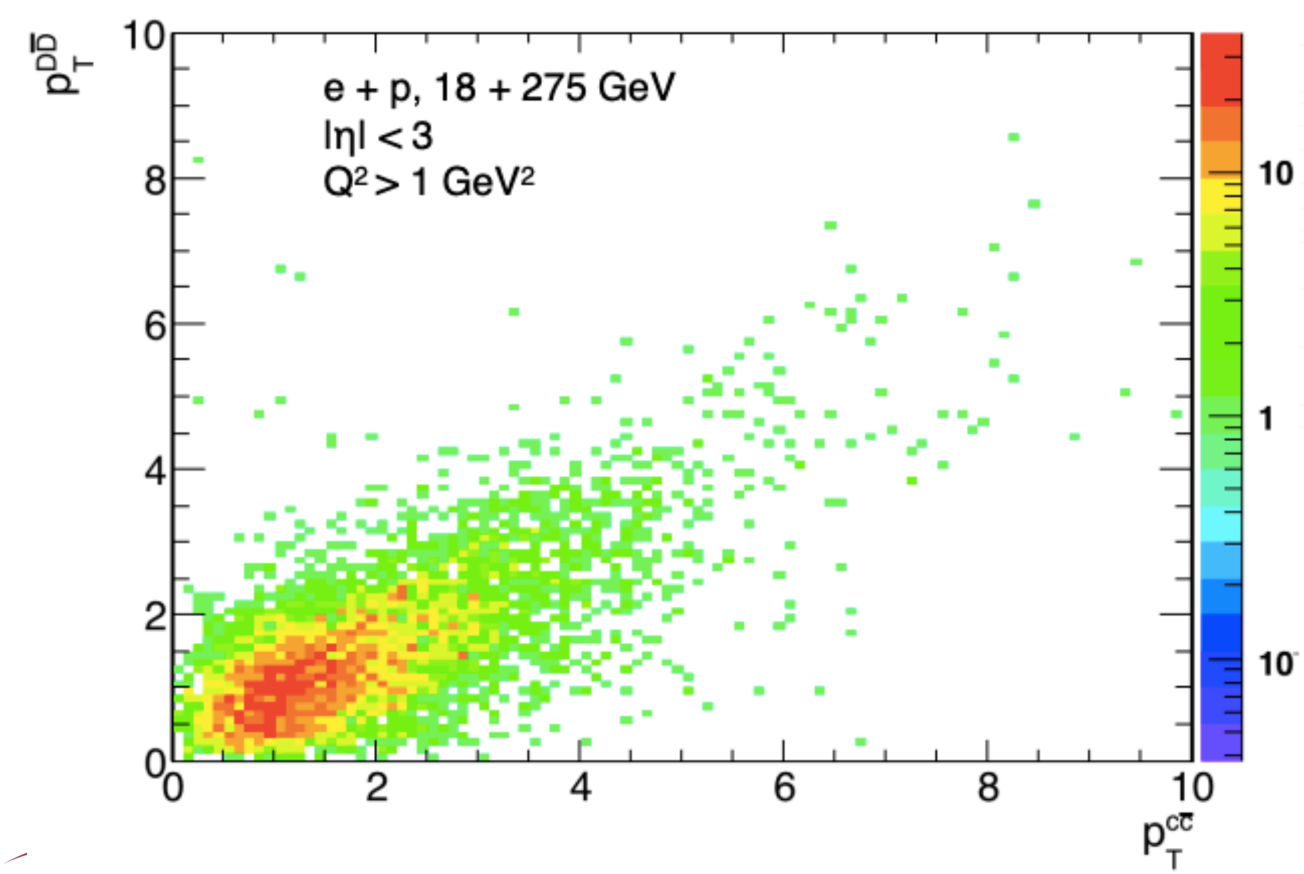
Fast simulation reproduces the D^0 efficiency in full simulation!

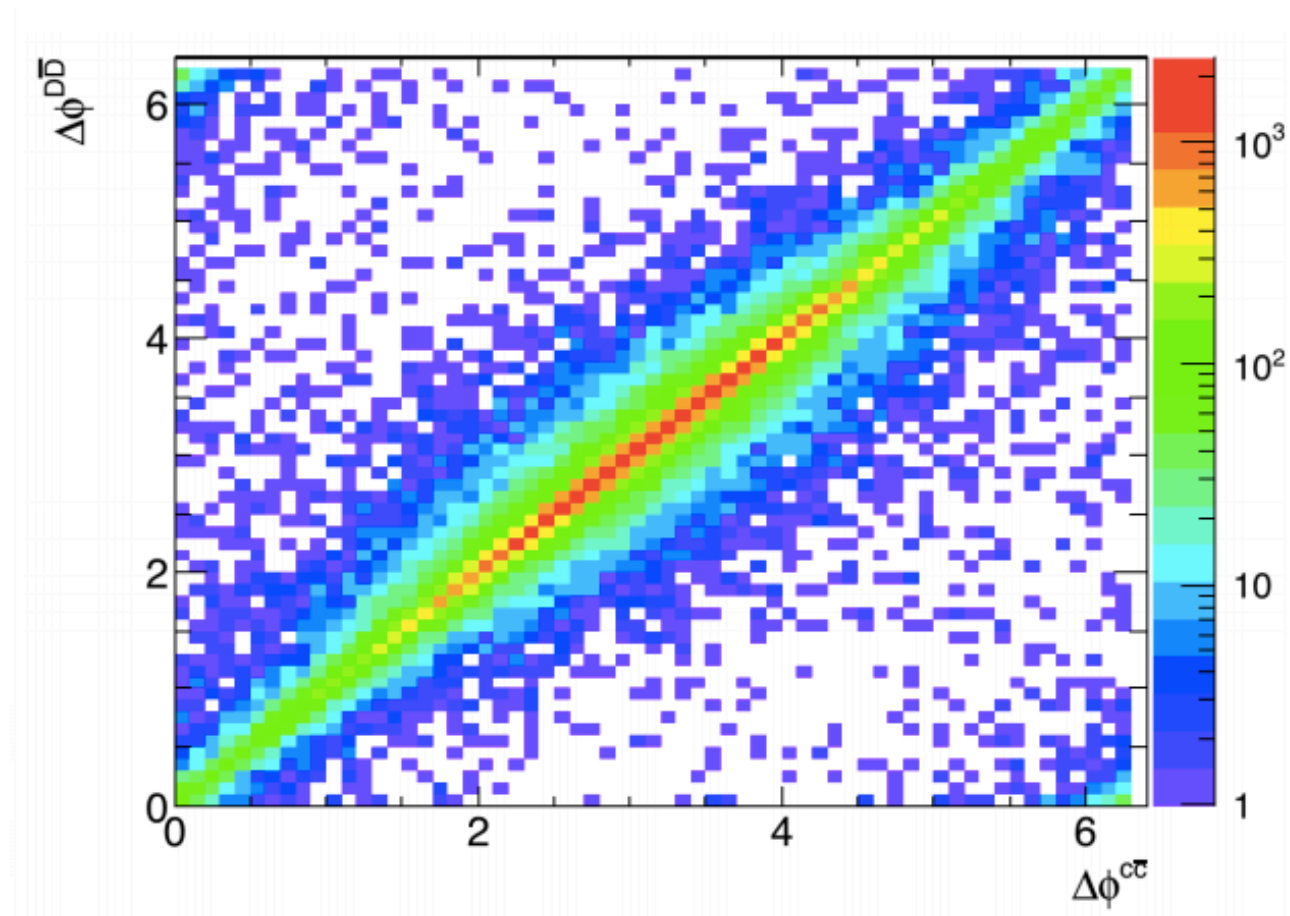
$D\overline{D}$ Pair - Probe Gluon TMDs



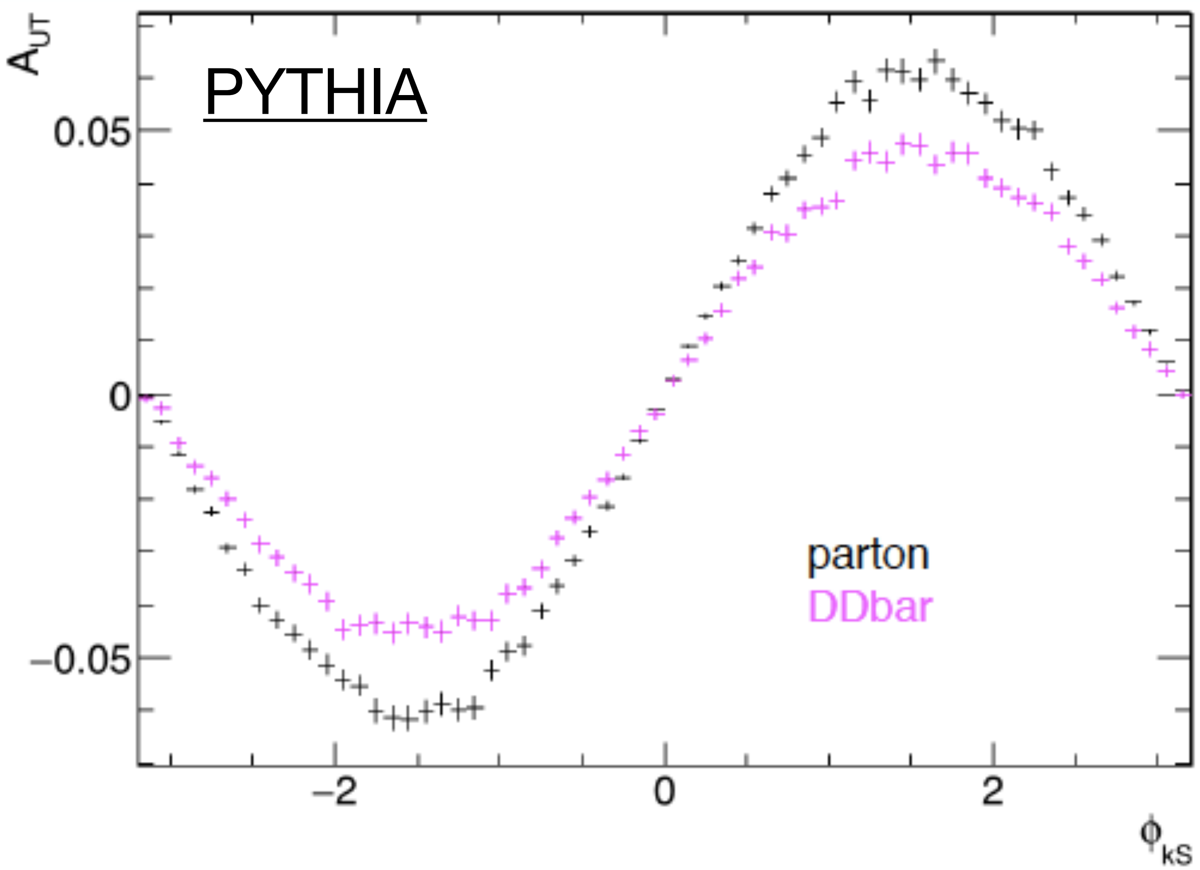
Charm hadron pair in transverse polarized exp.
- gluon Sivers functions

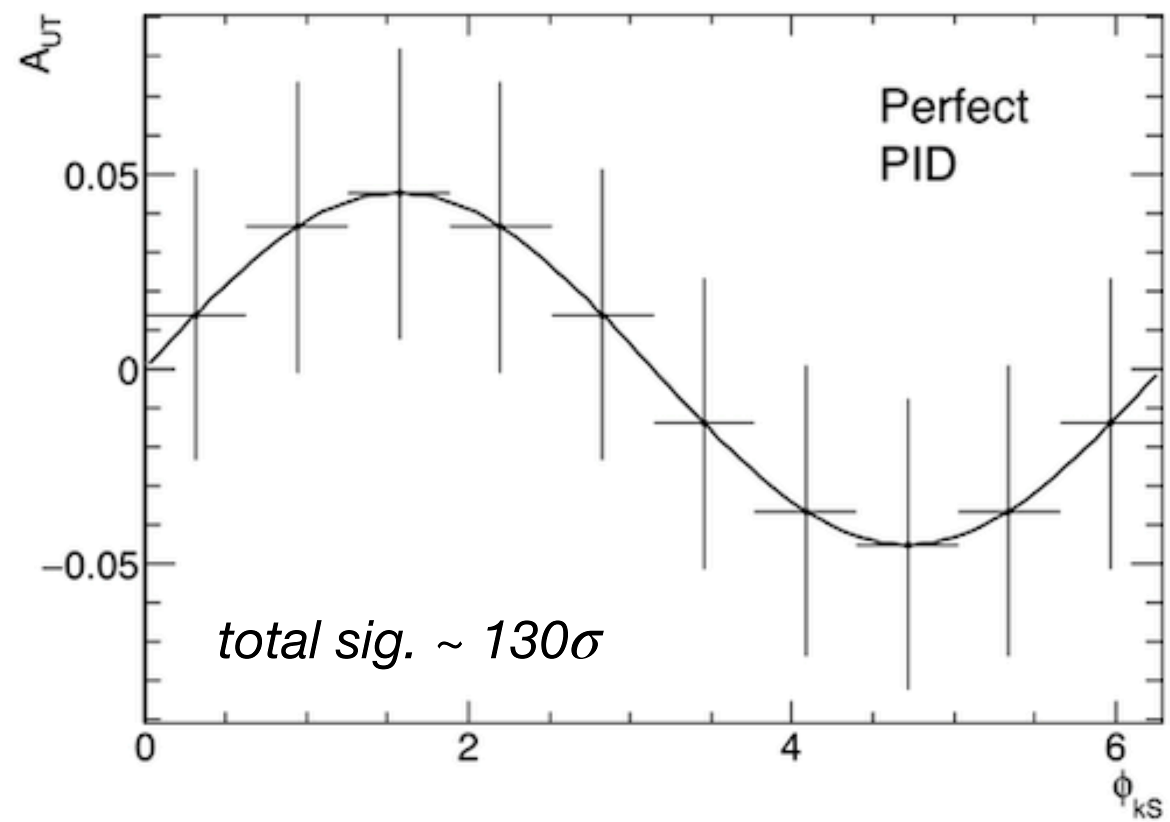
Charm hadron pair in unpolarized exp.
- linearly polarized TMD function

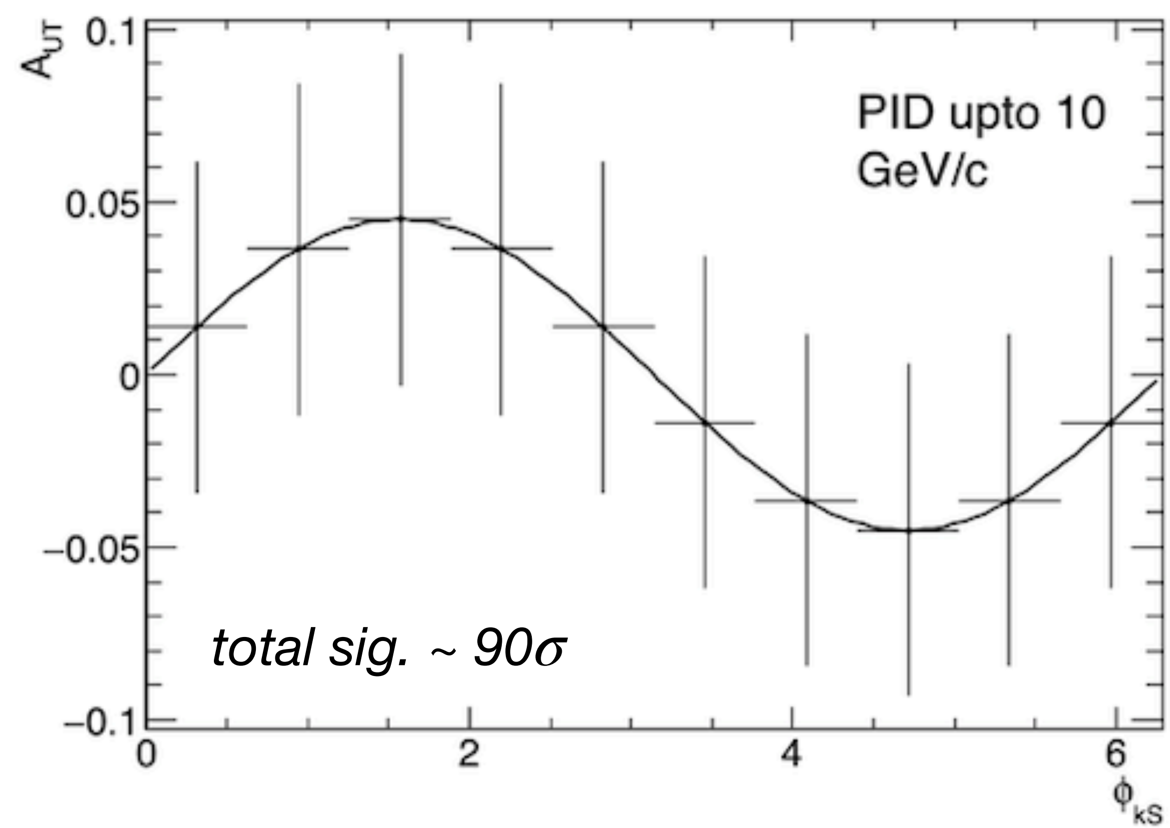




Projection on Gluon Sivers Function





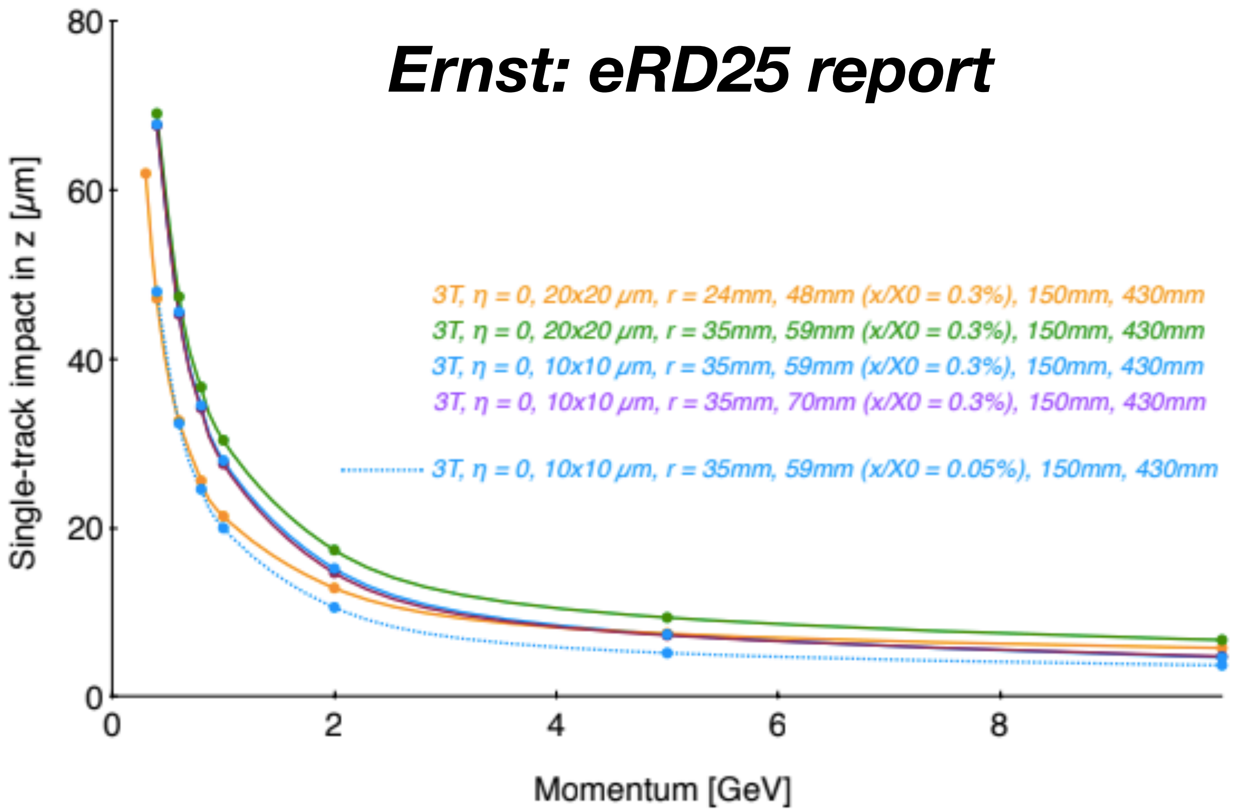


- Total statistics populated to each ϕ_{kS} bin
- Significance: 130 and 90 respectively
  - uncert. on A_{UT}: 0.008, 0.011
  - Comparable to early BNL group studies
    - *L. Zheng et al., PRD 98 (2018) 034011*

$\langle x_B \rangle \sim 0.005$

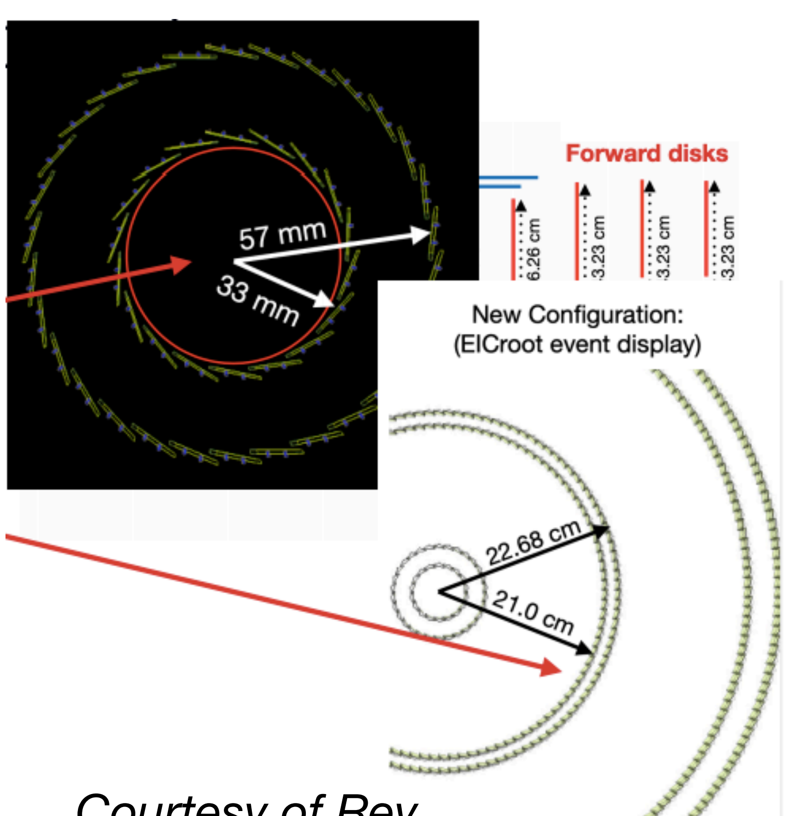
$\langle Q^2 \rangle \sim 2.7$ GeV^2

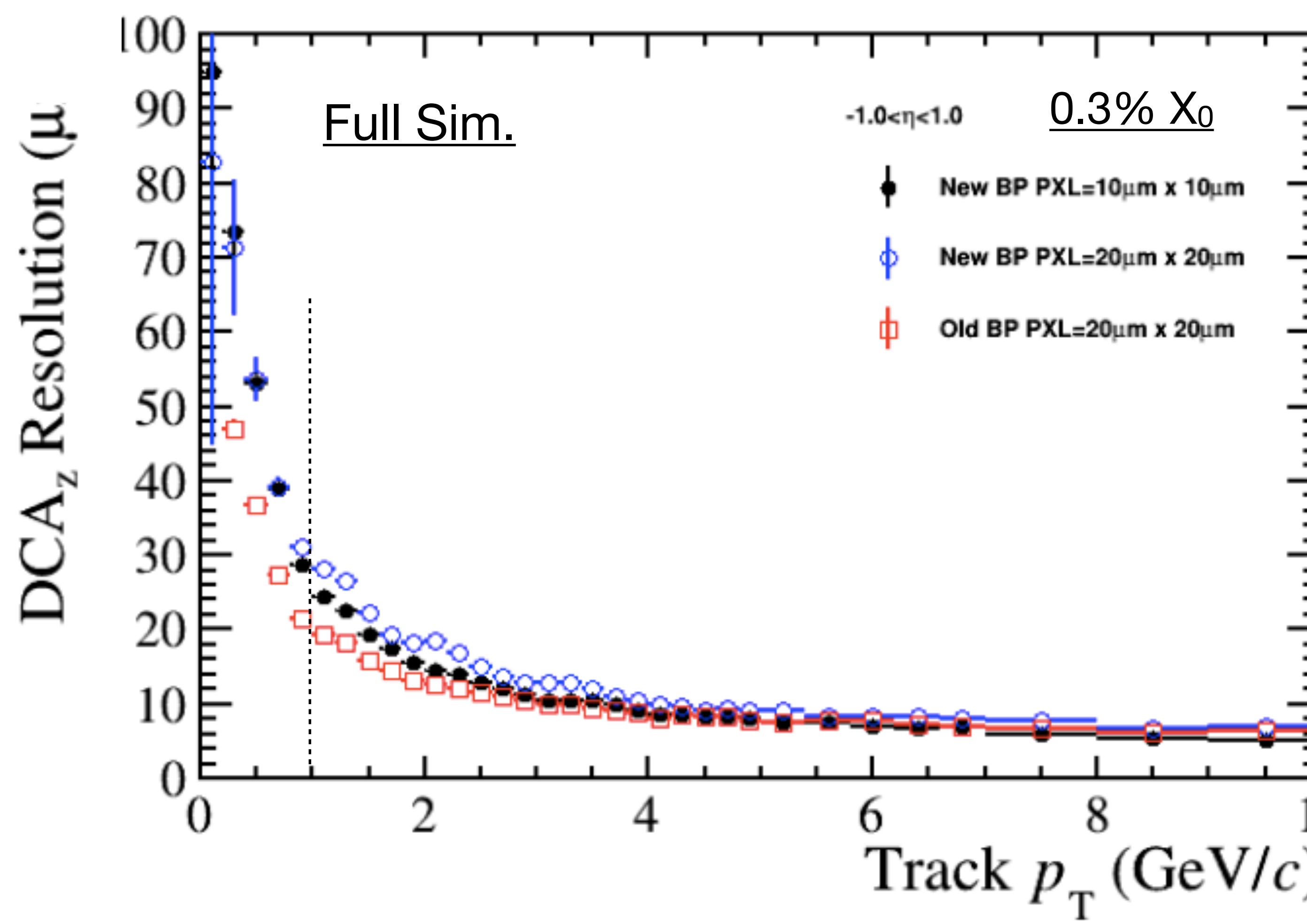
Impact of A Larger Beam-pipe



A larger beampipe leads to worsening of pointing resolution

- high mom region can be recovered with smaller pitch design (10x10 μm^2)
- low mom region can only be recovered with ultra-thin detector design (0.05%X_0)

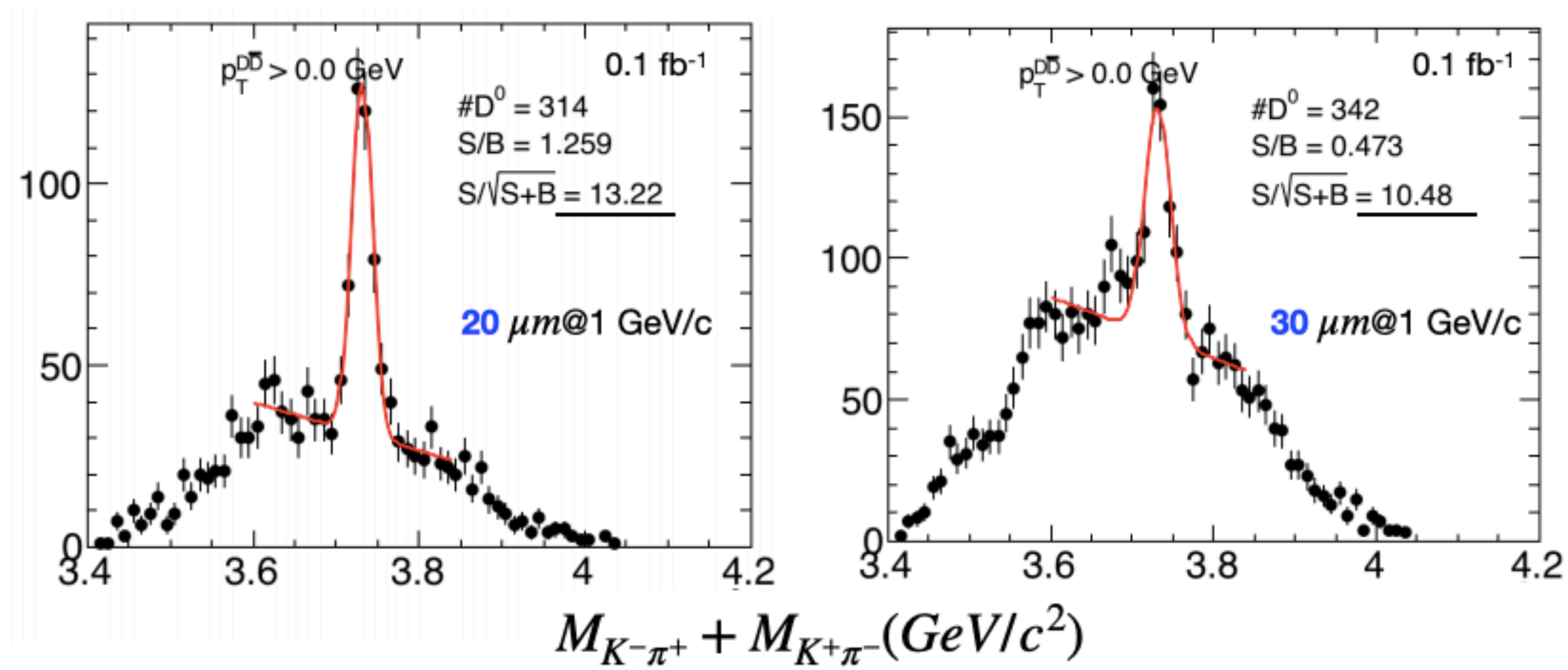




Courtesy of Rey

Benefits of Ultra-thin Fine-pitch MAPS Detector

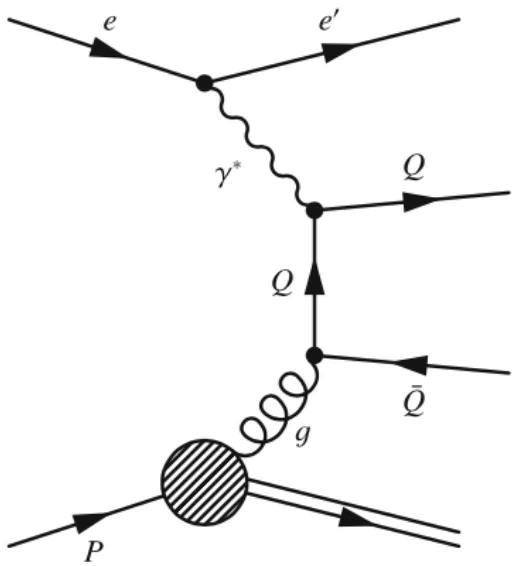
- $D - \overline{D}$ pair reconstruction
  - res. 30->20 μm
    - significance improved by 20%
    - S/B ratio improved by x2.5



- $\Lambda_c^+ \rightarrow pK^-\pi^+$ ($c\tau$~60μm)
  - extremely short lifetime, multi-prong decay → critical requirement on single track pointing resolution (simu. to be followed up)

- D^0 in the forward region, more sensitive to high x region
  - charm measurement can have the most significant impact on gluon (n)PDF

Summary



Physics Interests:

- ***Inclusive*** HF -> *gluon (n)PDF*
- $D-\overline{D}$ ***pair*** -> *gluon TMDs*
- ***D***, Λ_c -> *hadronization* and *CNM*

- EIC is a precision QCD machine!
- One should aim for the best detector performance in order to accomplish these precise measurements on heavy flavor observables (and others).
- Ultra-thin fine-pitch MAPS detector is essential!

Backup

Agreed Requirements within Physics Working Group

Eta Bin	Pointing Resolution
[-2.5, -1.0]	$\sigma_{XY} \sim 30/p_T \oplus 20\mu m$
[-1.0, 1.0]	$\sigma_{XY} \sim \sigma_Z \sim 20/p_T \oplus 5\mu m$
[1.0, 2.5]	$\sigma_{XY} \sim 30/p_T \oplus 20\mu m$
[2.5, 3.0]	$\sigma_{XY} \sim 30/p_T \oplus 40\mu m$
[3.0, 3.5]	$\sigma_{XY} \sim 30/p_T \oplus 60\mu m$

Full Simulation w/ New Beam Pipe