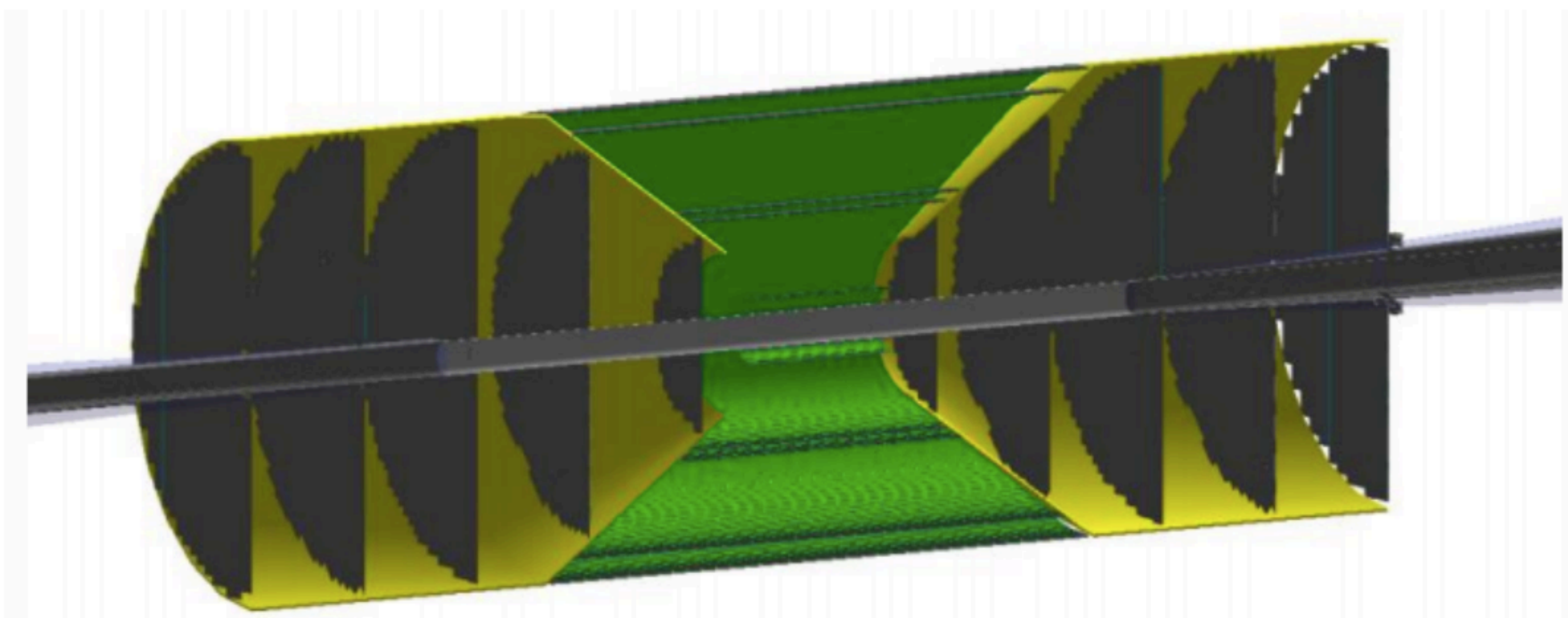
An All-Si Tracker for Heavy Flavor Measurements at EIC

Xin Dong (Lawrence Berkeley National Laboratory)



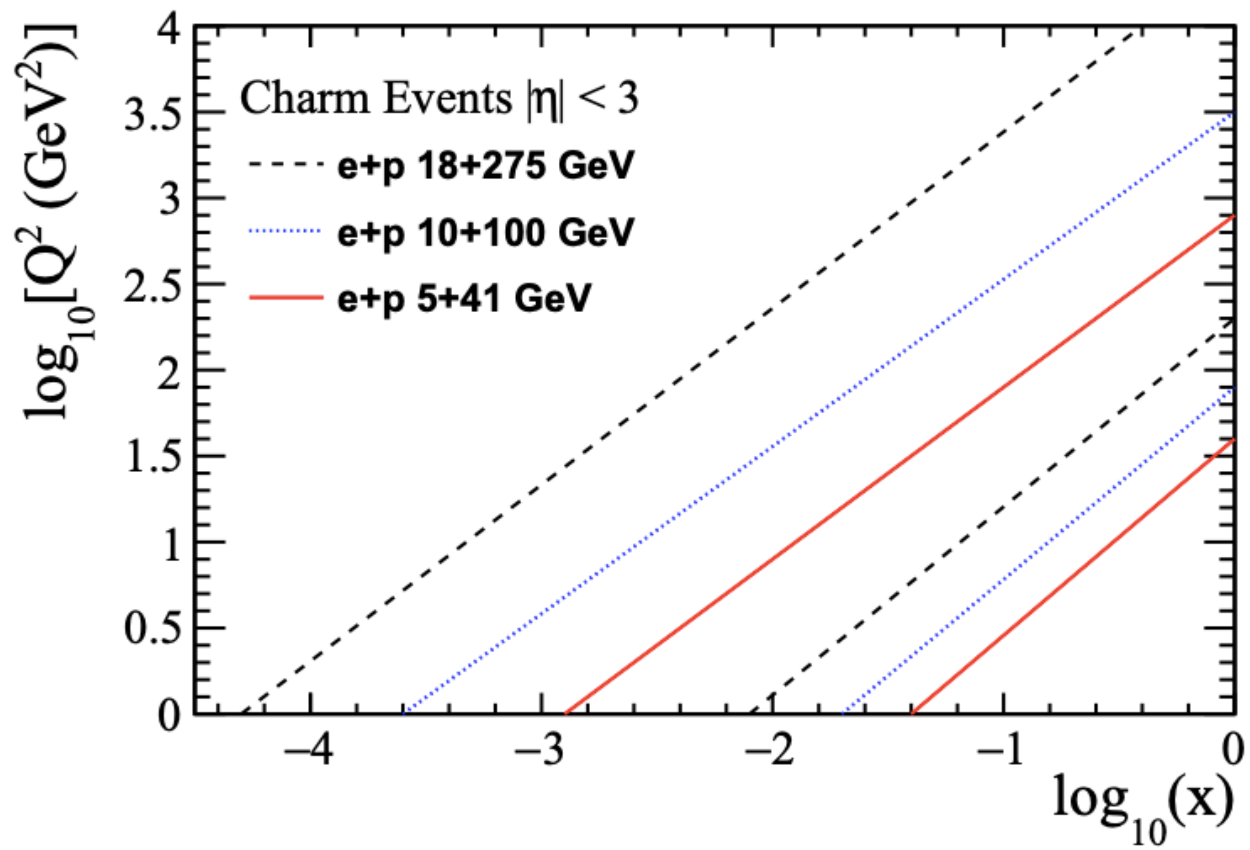
In collaboration with:
Reynier Cruz-Torres, Leo Greiner, Samuel Heppleman, Yuanjing Ji, Matthew Kelsey, Sooraj Radhakrishnan, Ernst Sichtermann, Lei Xia, Nu Xu, Feng Yuan, Yuxiang Zhao etc.

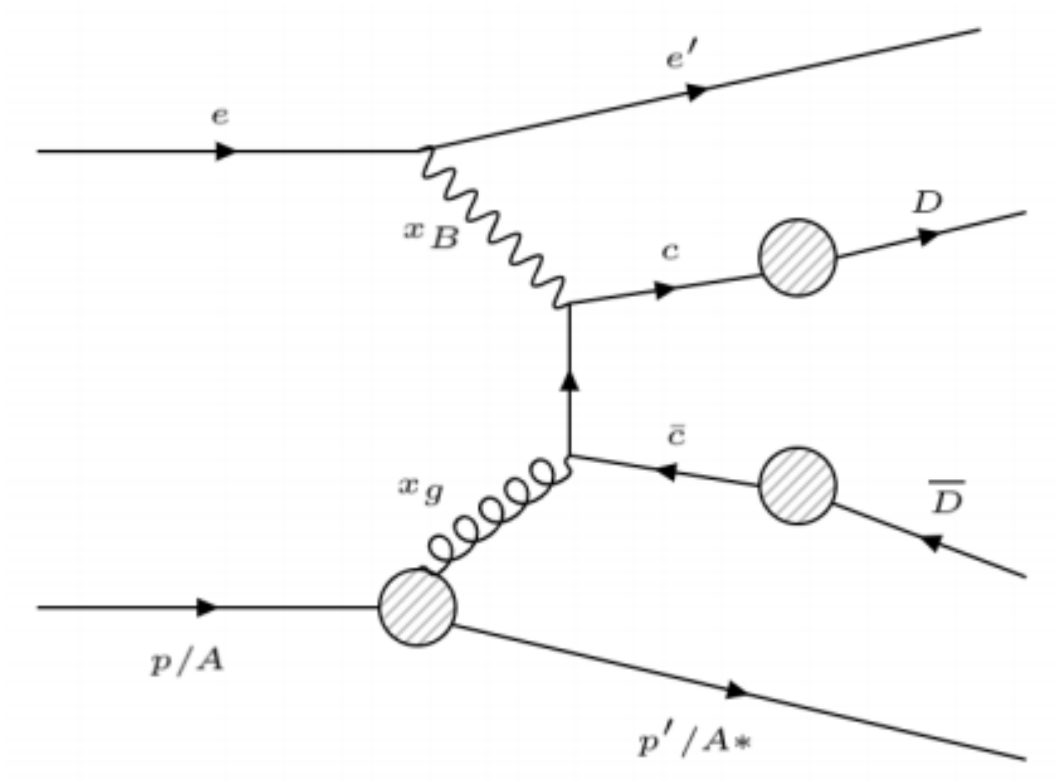
Outline

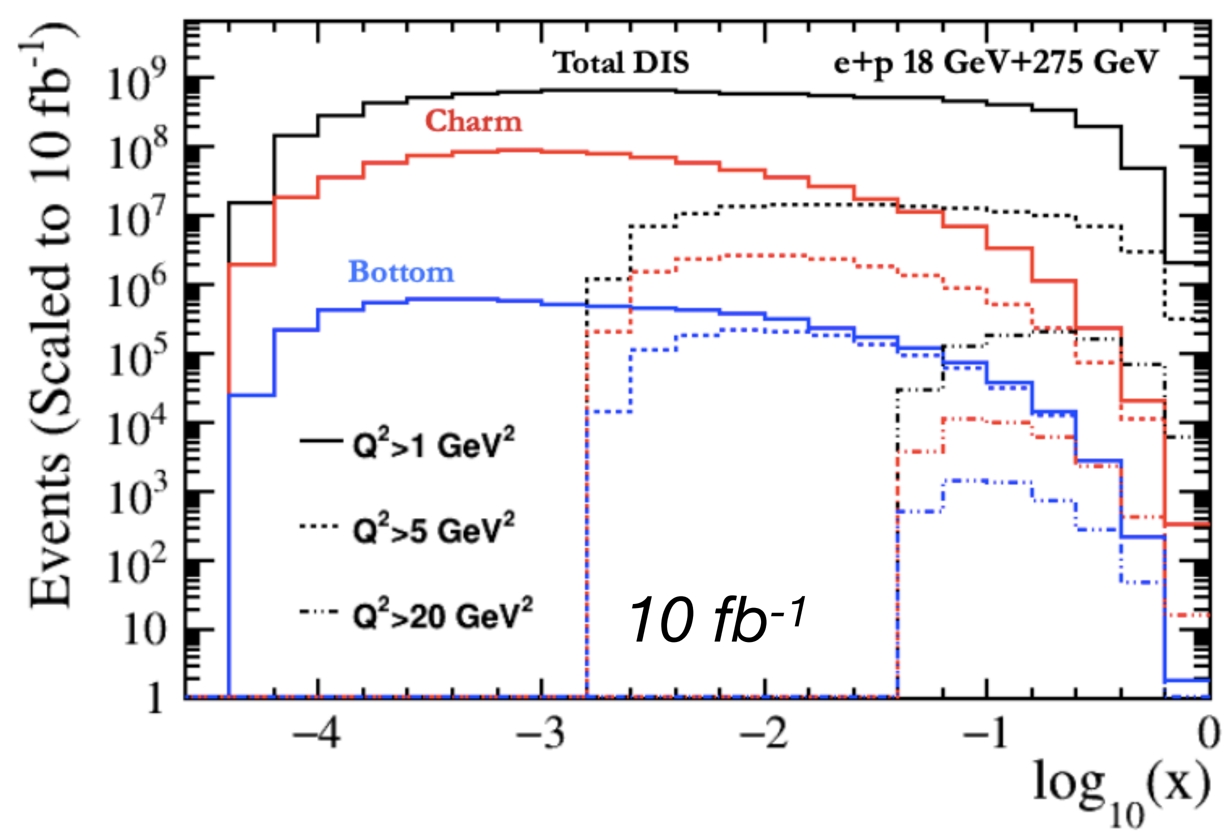
- Introduction and An All-Si Compact Tracker Concept
  - Introduction and kinematic distributions
  - An all-Si compact tracker and performance studies
- Physics Simulations on Heavy Flavor Measurements at EIC
  - Charm structure function $\rightarrow$ gluon (n)PDF
  - Charm double spin asymmetry $\rightarrow$ gluon helicity
  - $D\overline{D}$ pair azimuth distribution $\rightarrow$ gluon TMDs
  - Charm hadrochemistry $\rightarrow$ hadronization, CNM

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

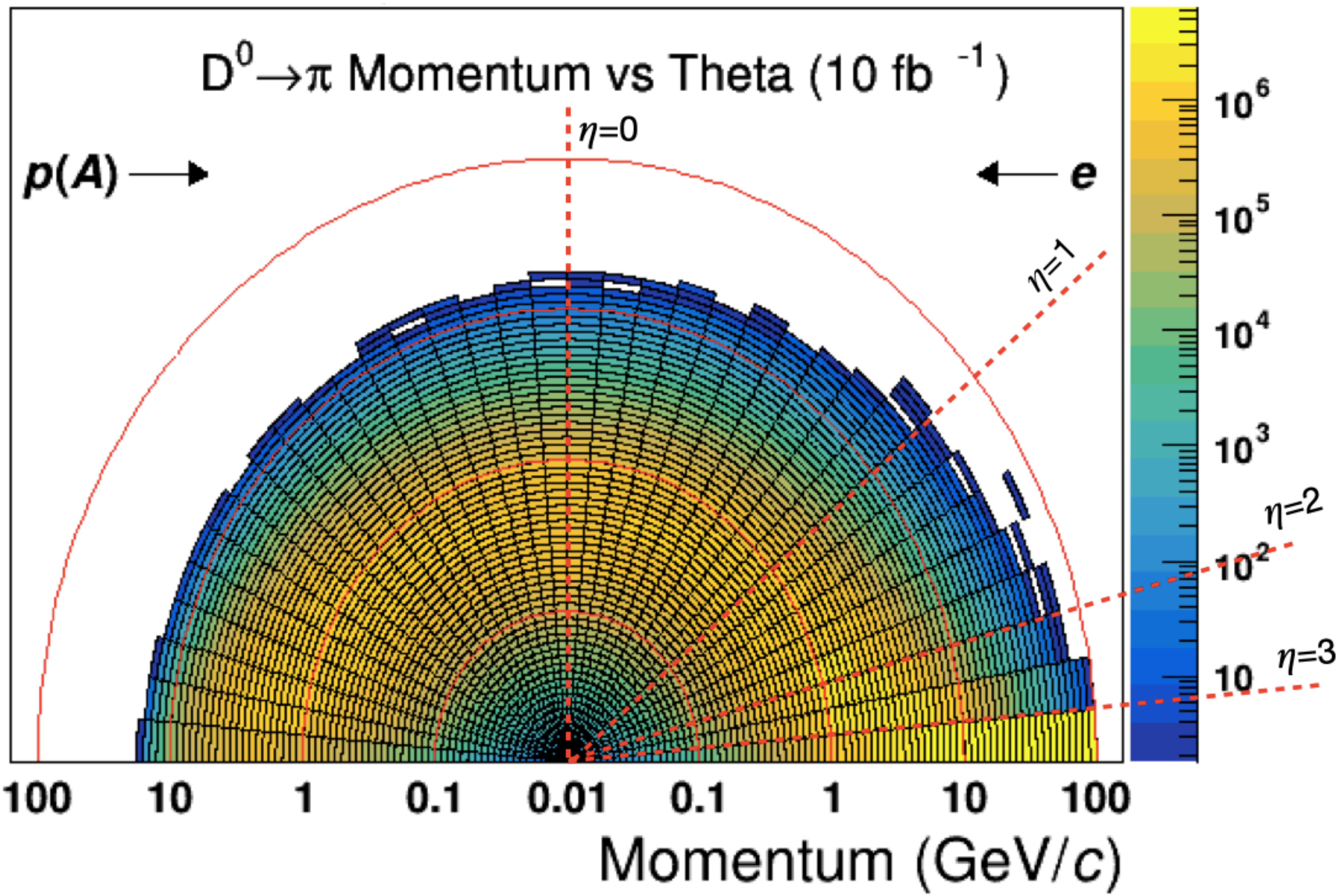






Kinematic Distributions

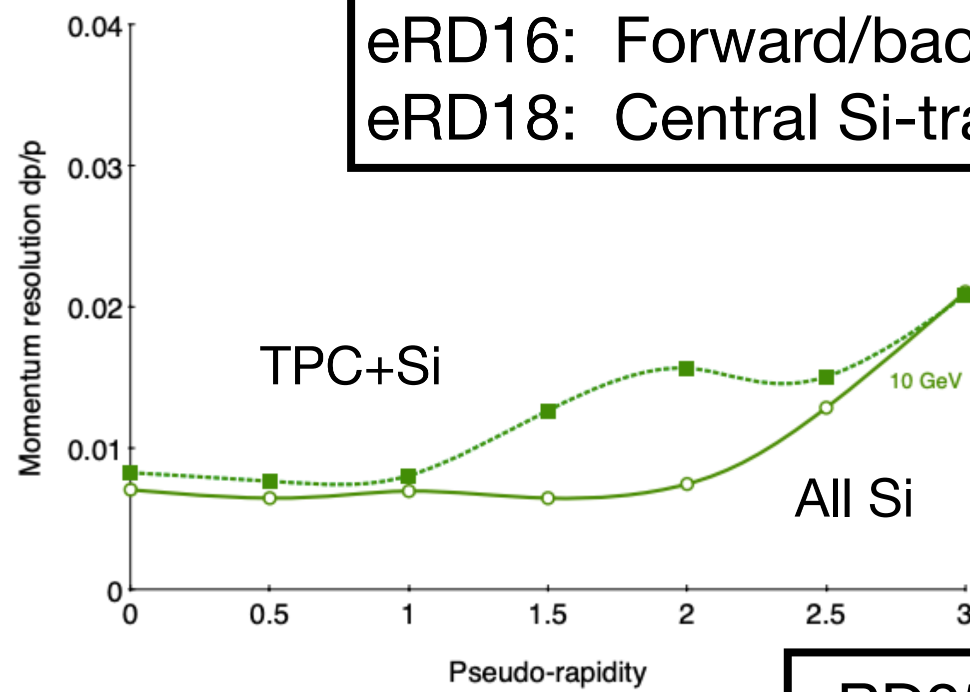
e + p   18 + 275   PYTHIA 6.4



Tracking Requirements and An All-Silicon Tracker Concept

Tracking Detector requirements:

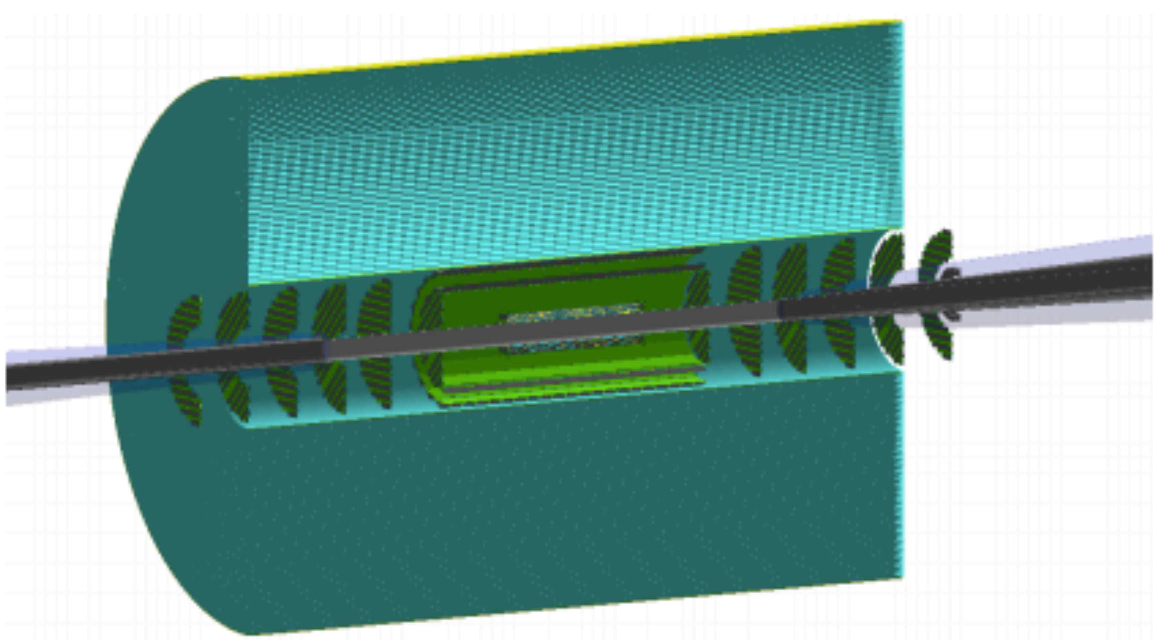
- Wide η coverage
- Thin detector material
- Decent momentum resolution
- Secondary vertex resolution



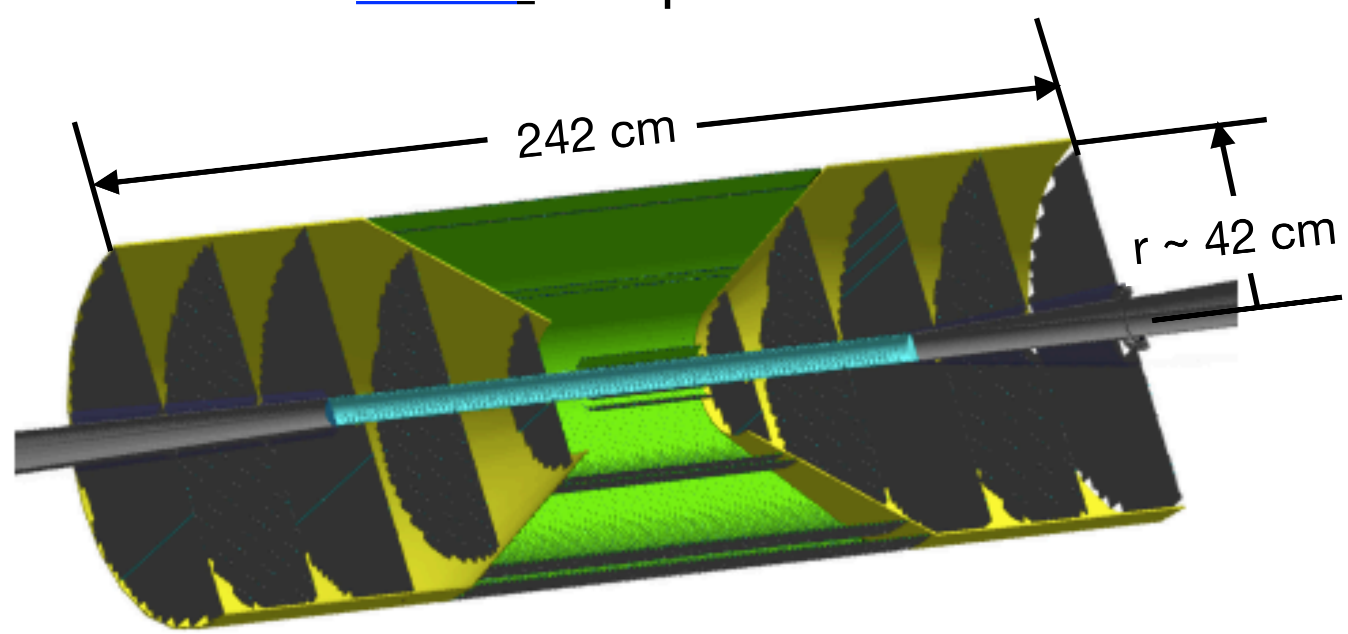
eRD16: Forward/backward Si-tracker
eRD18: Central Si-tracker

eRD25: All-Si tracker

Hybrid: gas outer tracker + Si vertex



All-Si compact tracker



courtesy of H. Wennlof

Full Simulation with Fun4All

All-Silicon Detector Concept

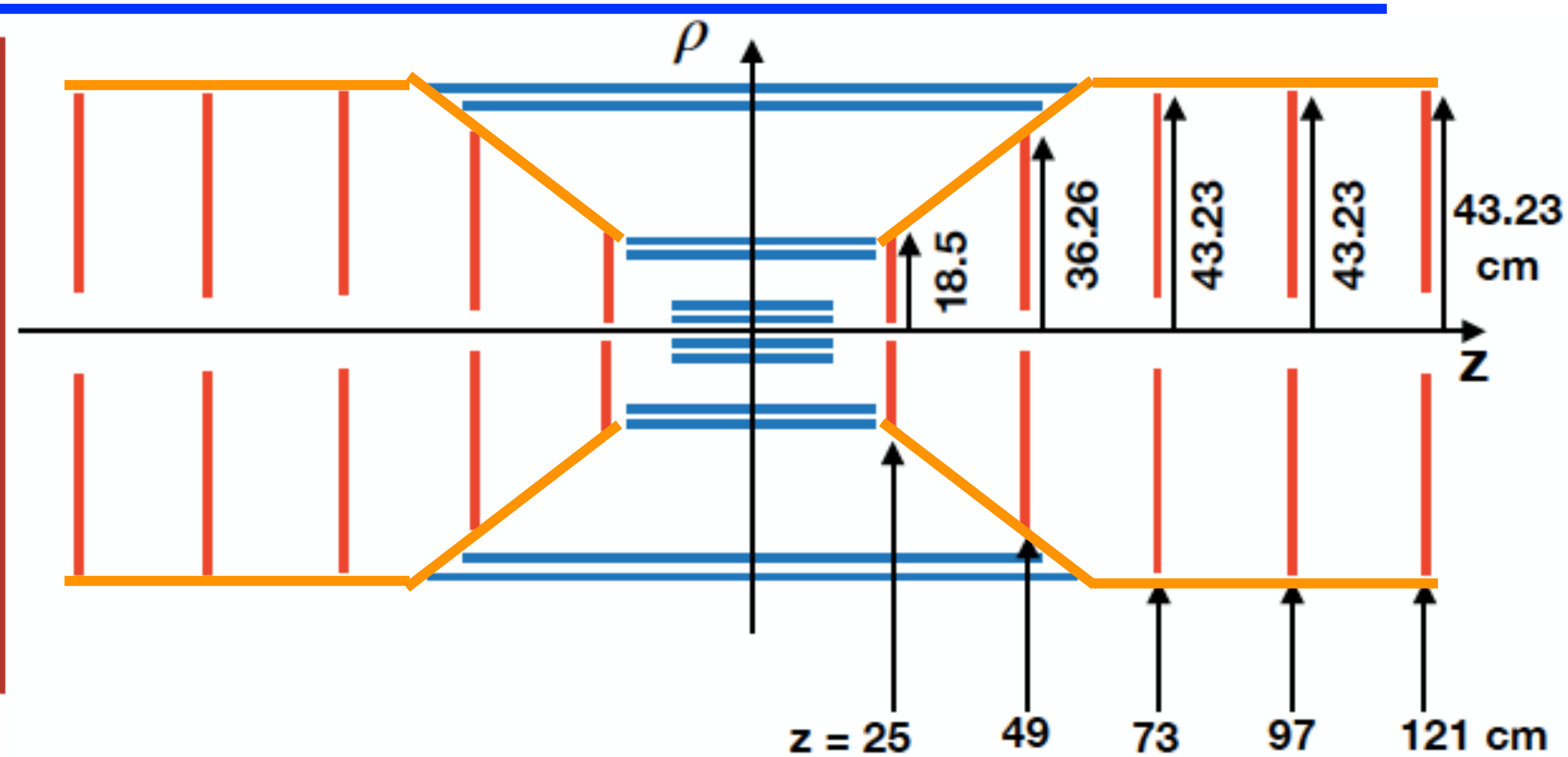
10 μm x 10 μm pixel devices

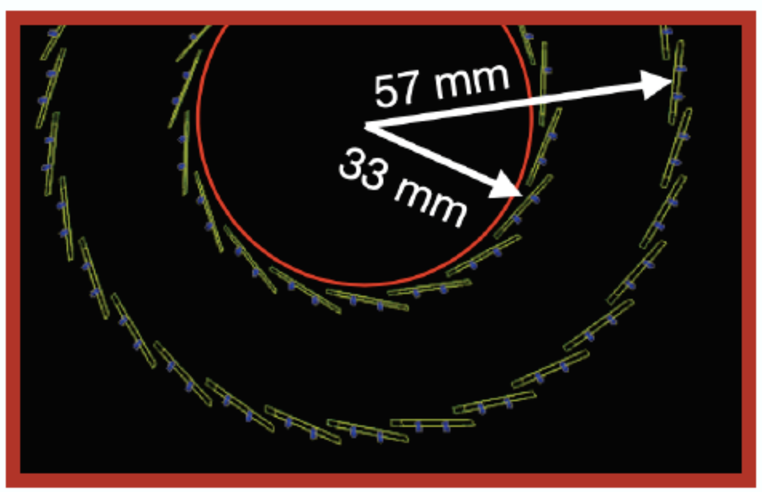
X/X0=0.3% per layer ← *ALICE-ITS2*

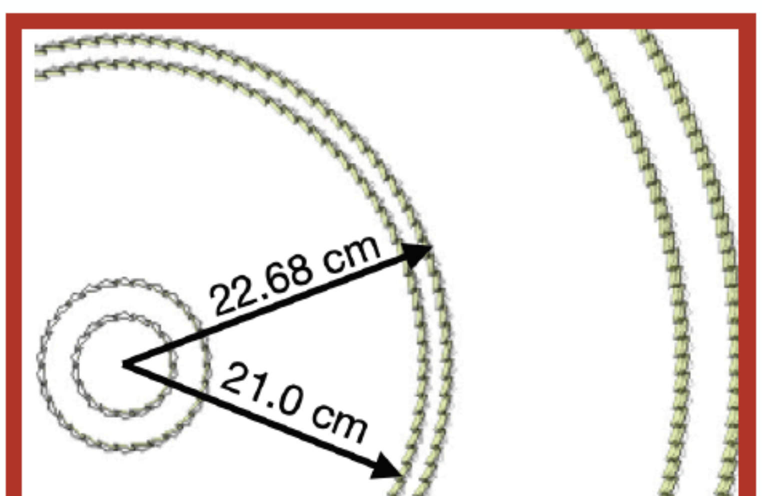
Beampipe r=3.1 cm

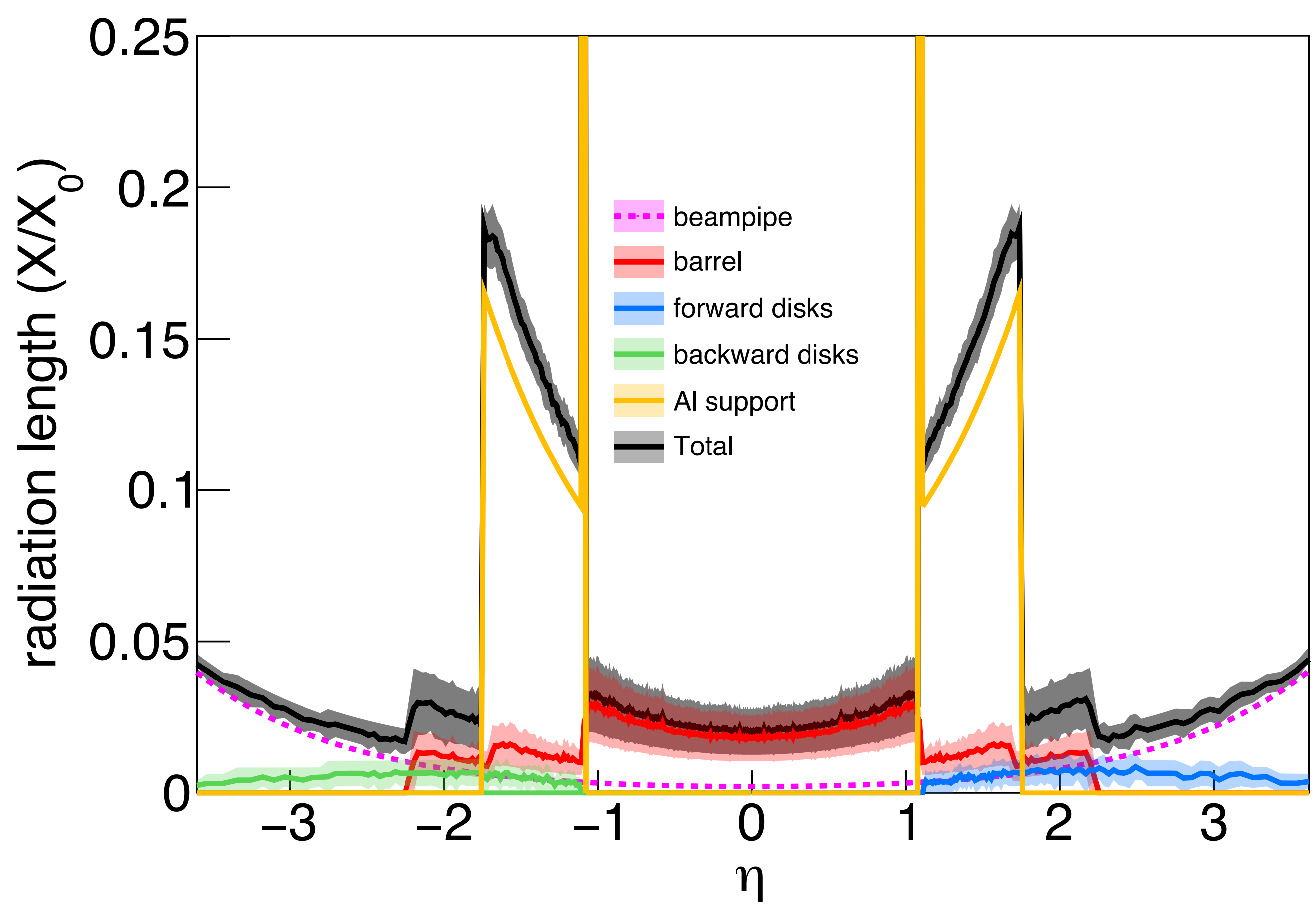
B = 3.0 T

Outer barrel r = 39, 42 cm





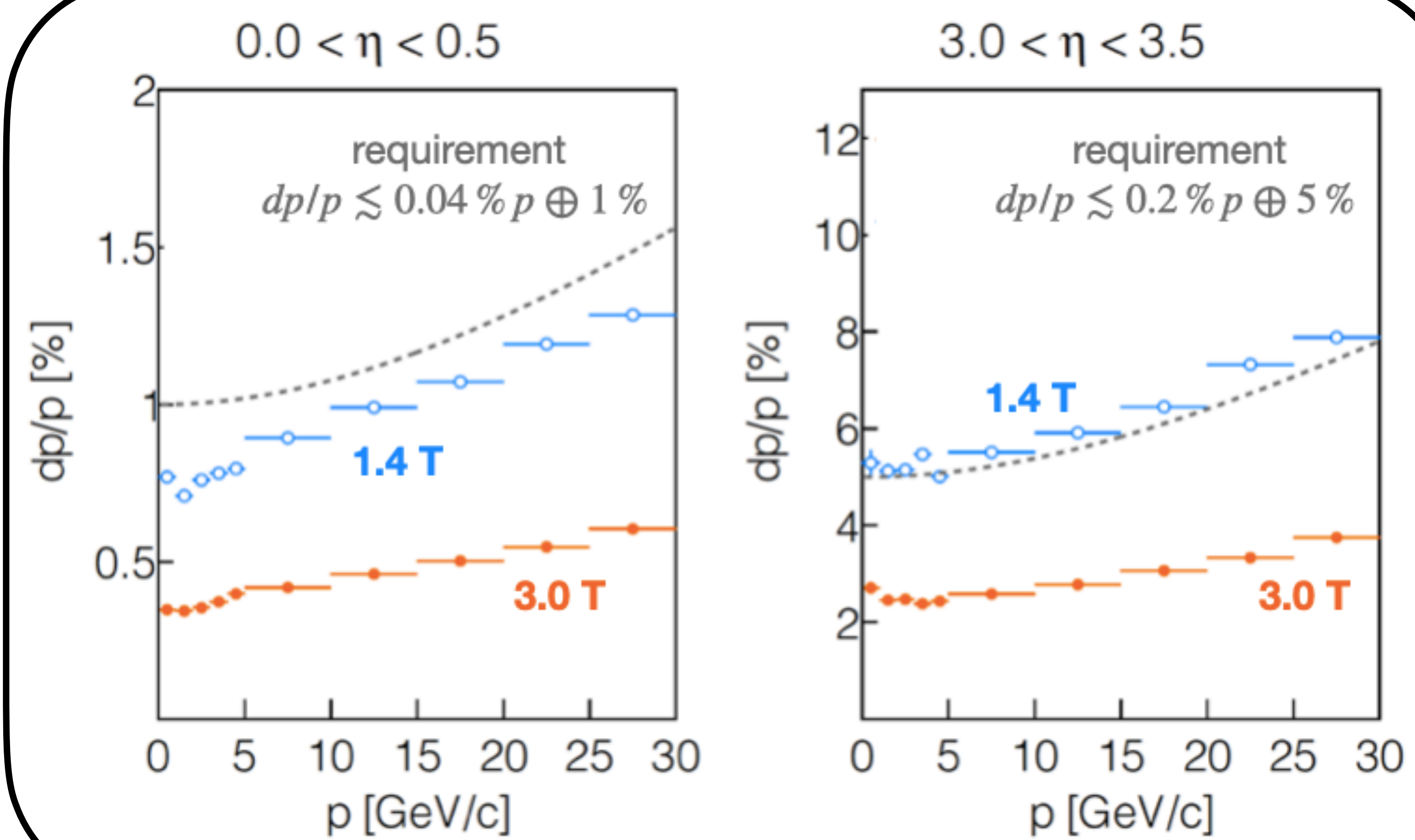




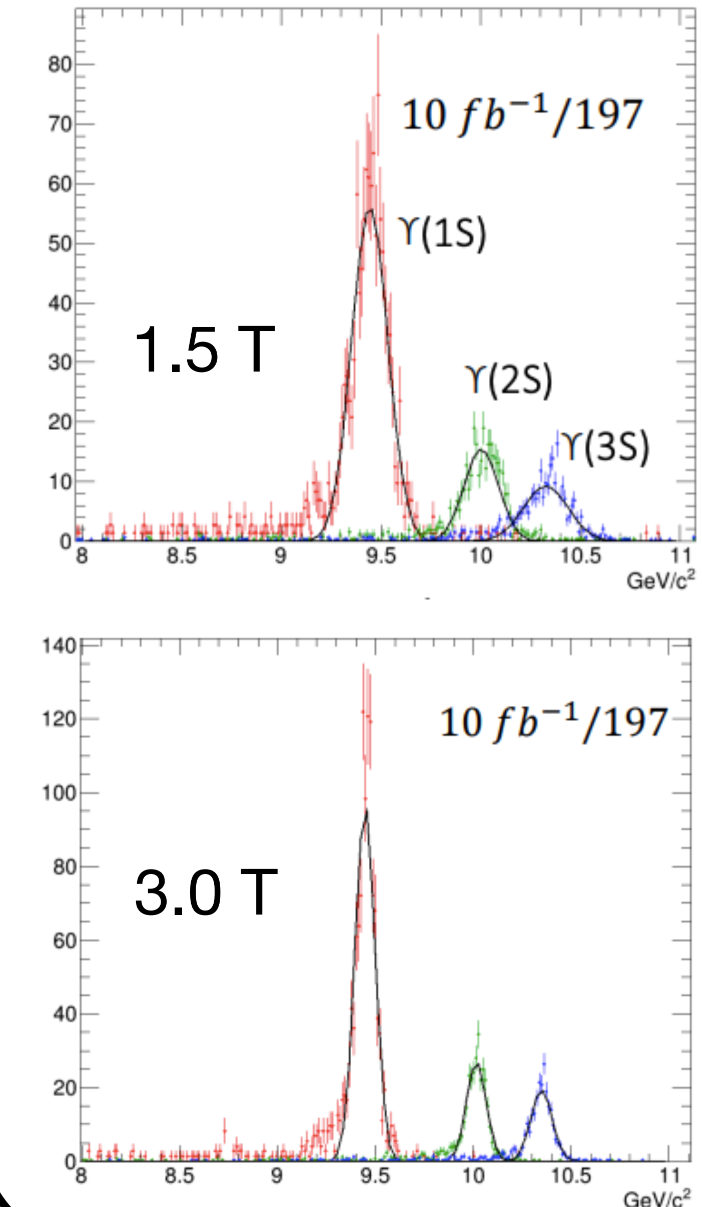
Momentum Resolution

π^-, 10 μm pixel, $X/X_0 = 0.3\%$

Full (Geant4) simulations

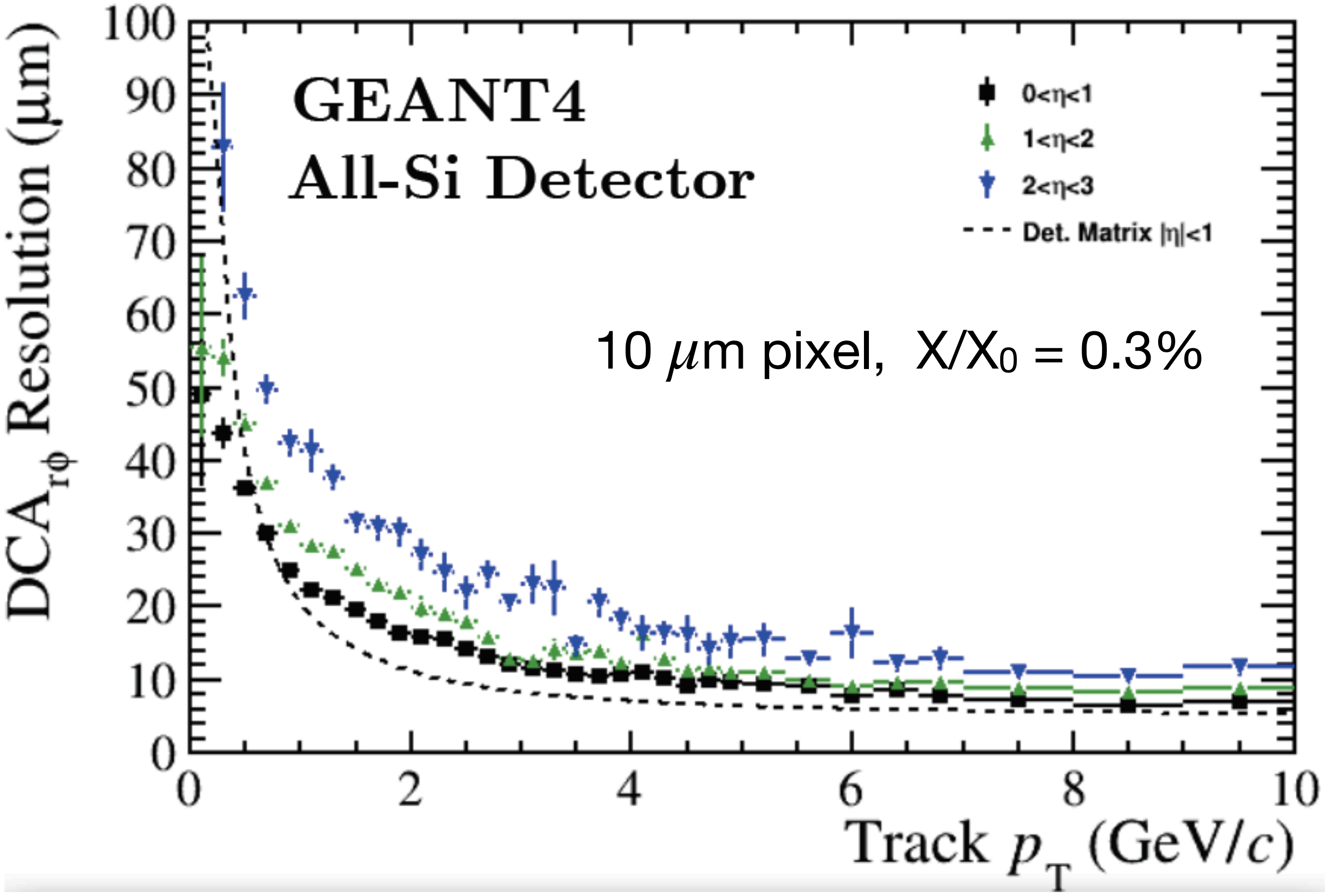


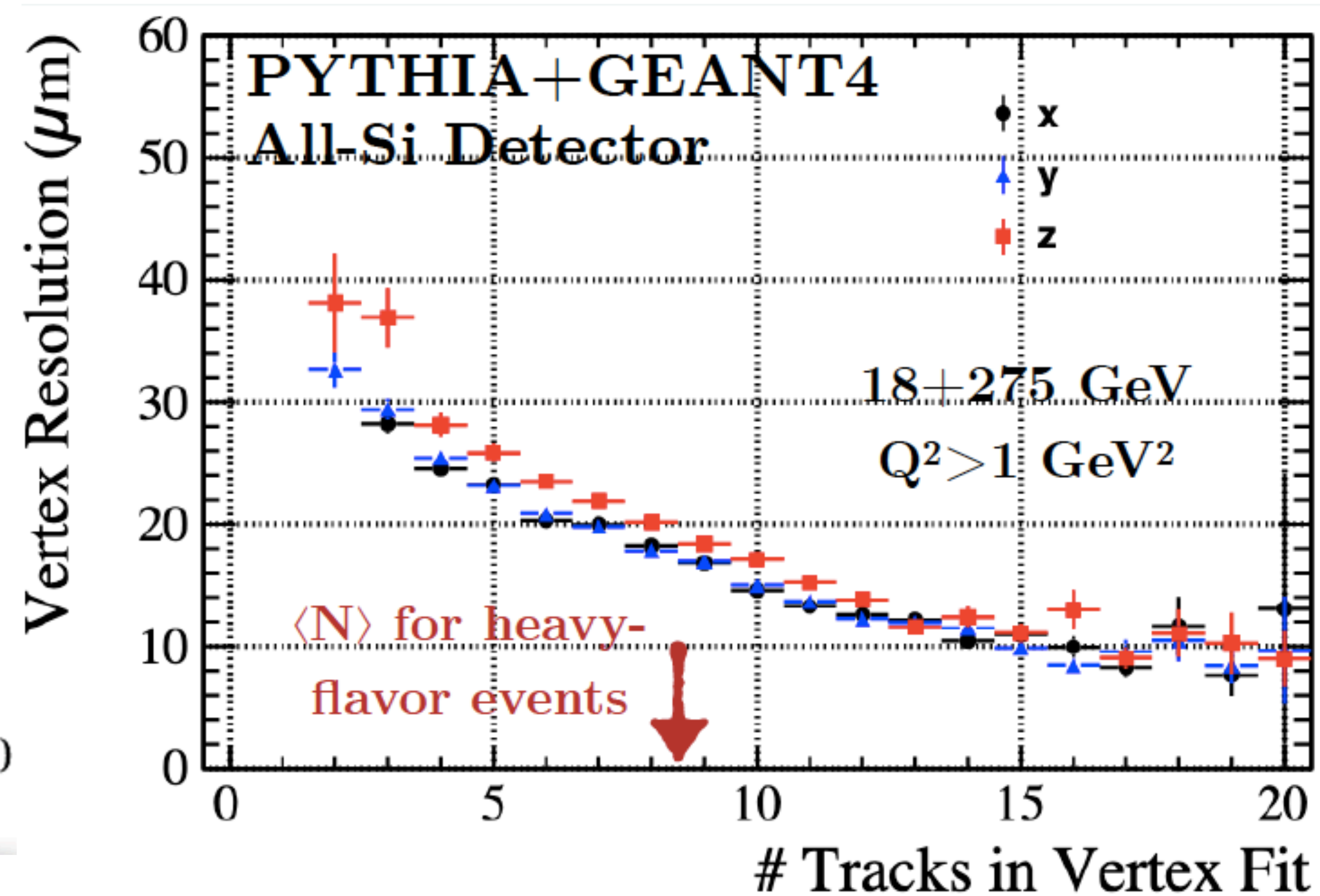
eSTARLight + All-Si



All-Si tracker offers a momentum resolution satisfying the physics requirement
- *superior momentum resolution with a 3T B-field*

Pointing & Vertex Resolution





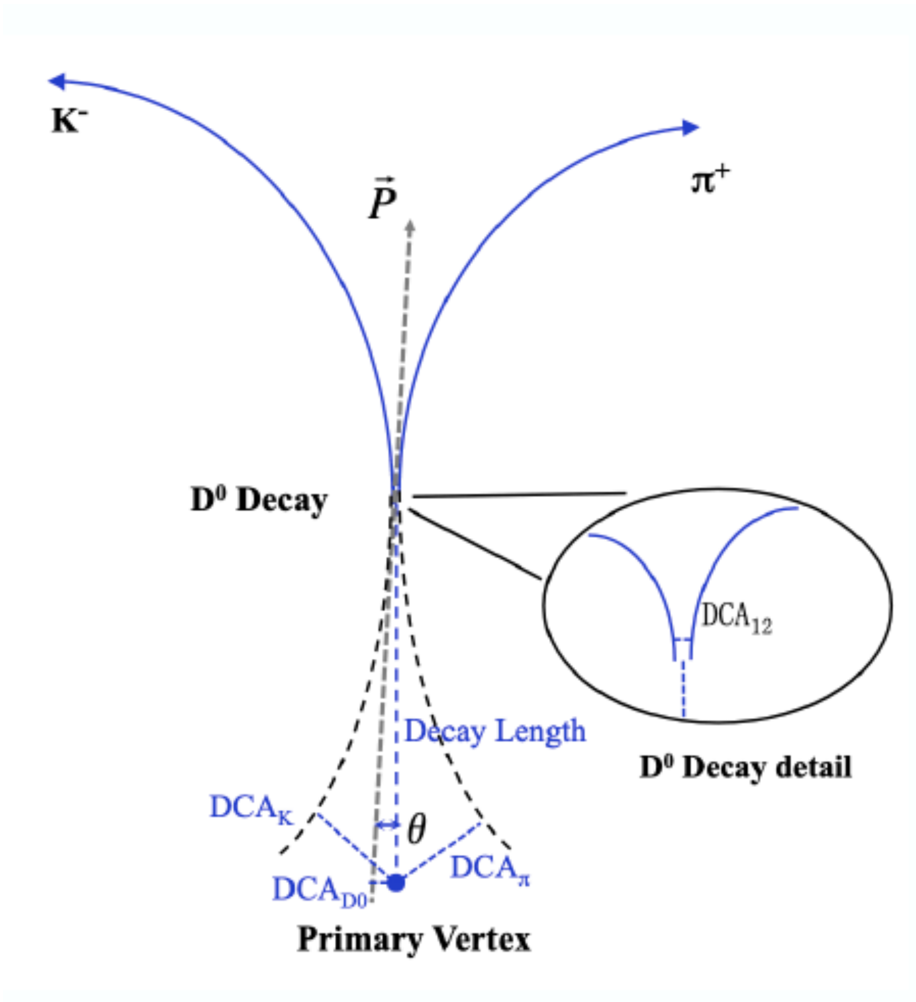
All-Si tracker pointing resolution: $\sigma_{r\phi} \sim 25\mu m$ @ 1 GeV/c ($|\eta|$<1)

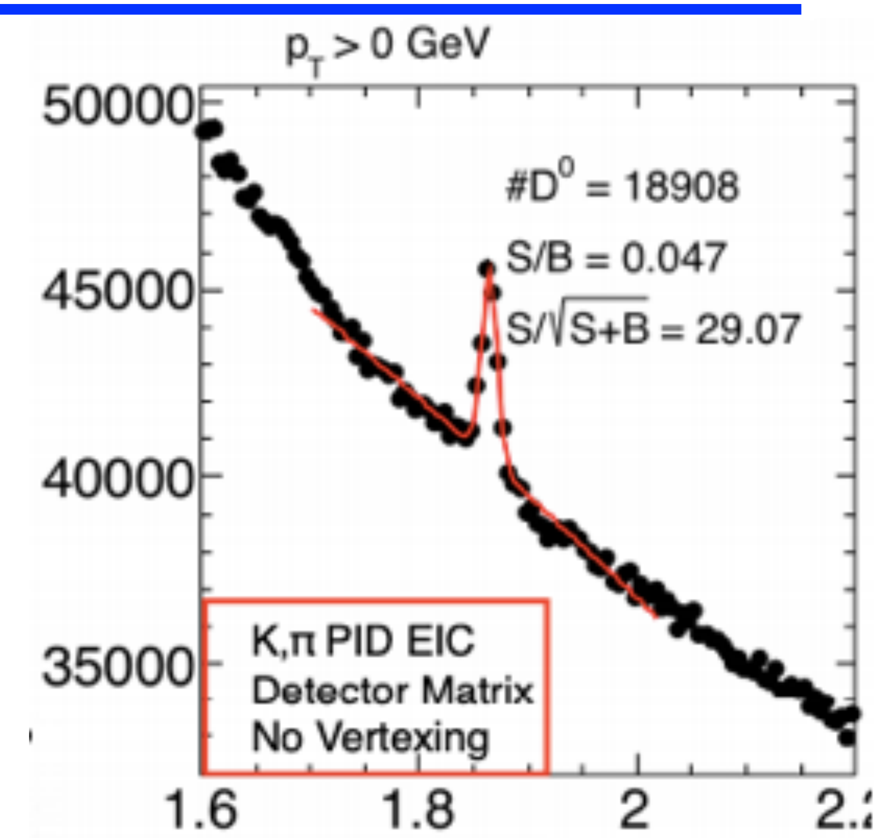
- slight/anticipated degradation at higher η

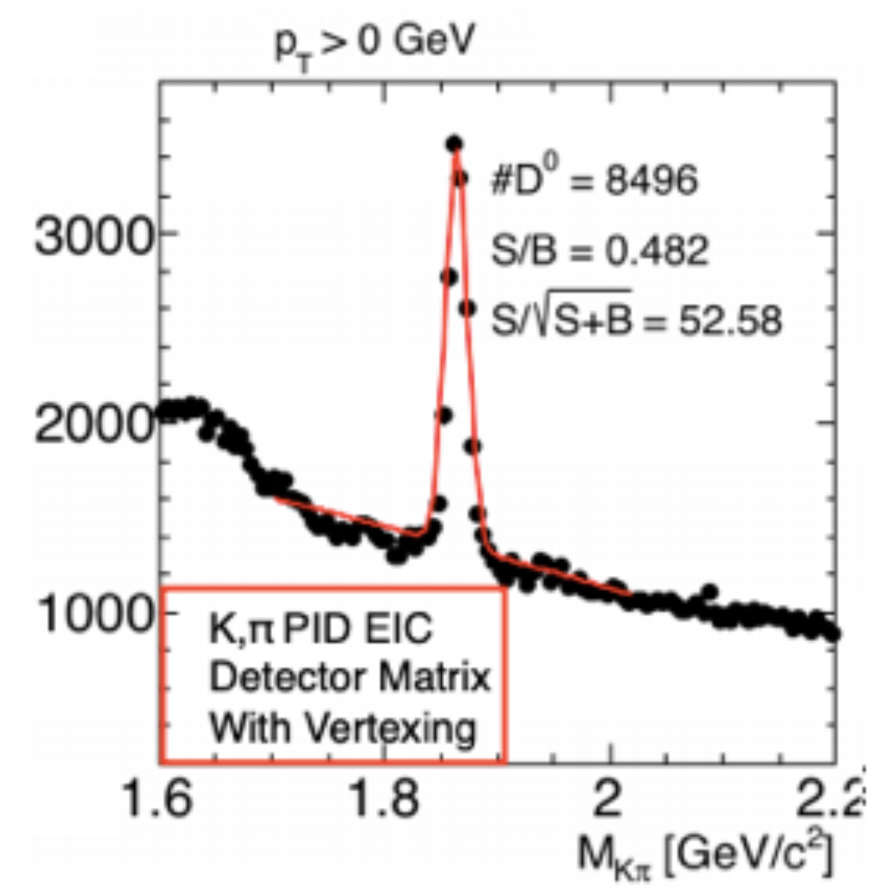
All-Si tracker vertexing resolution: $\sigma_{XYZ} < 20\mu m$ for HF events

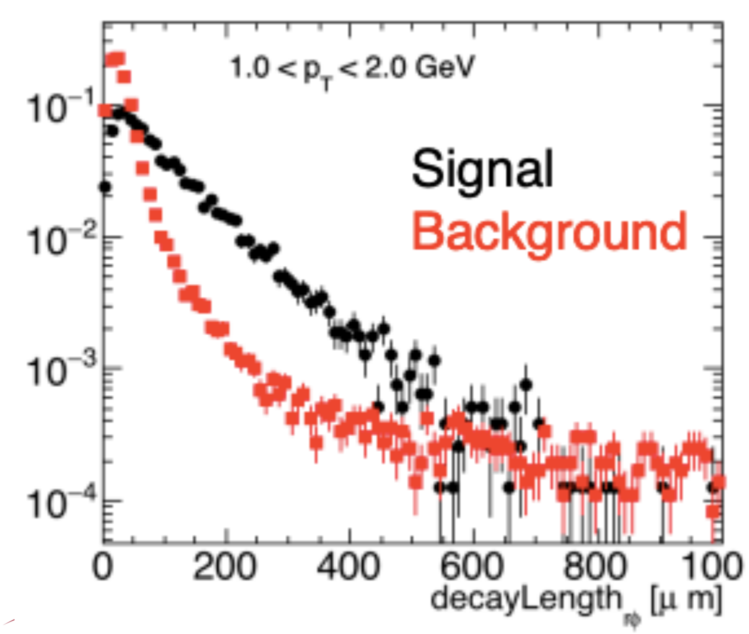
- Satisfying experimental requirements for reconstructing charm/bottom decays ($c\tau \sim$ 60-500 μm)

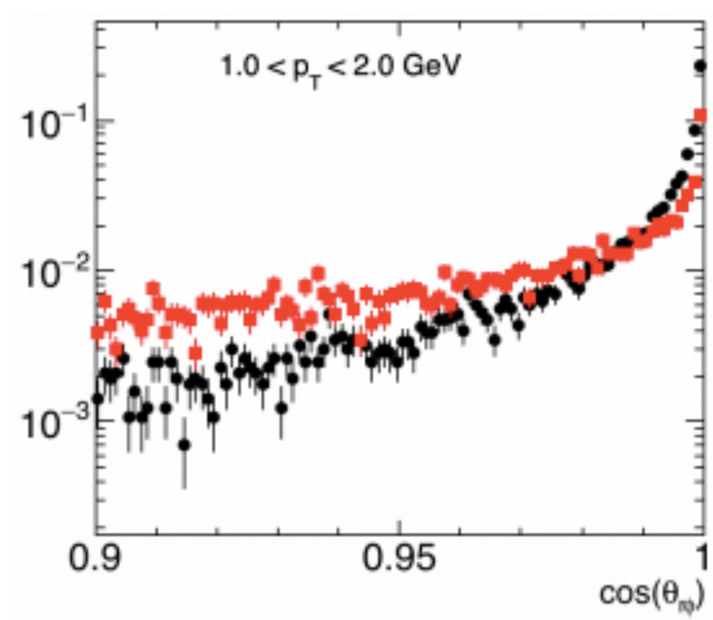
Topological Reconstruction of Heavy Flavor Decays







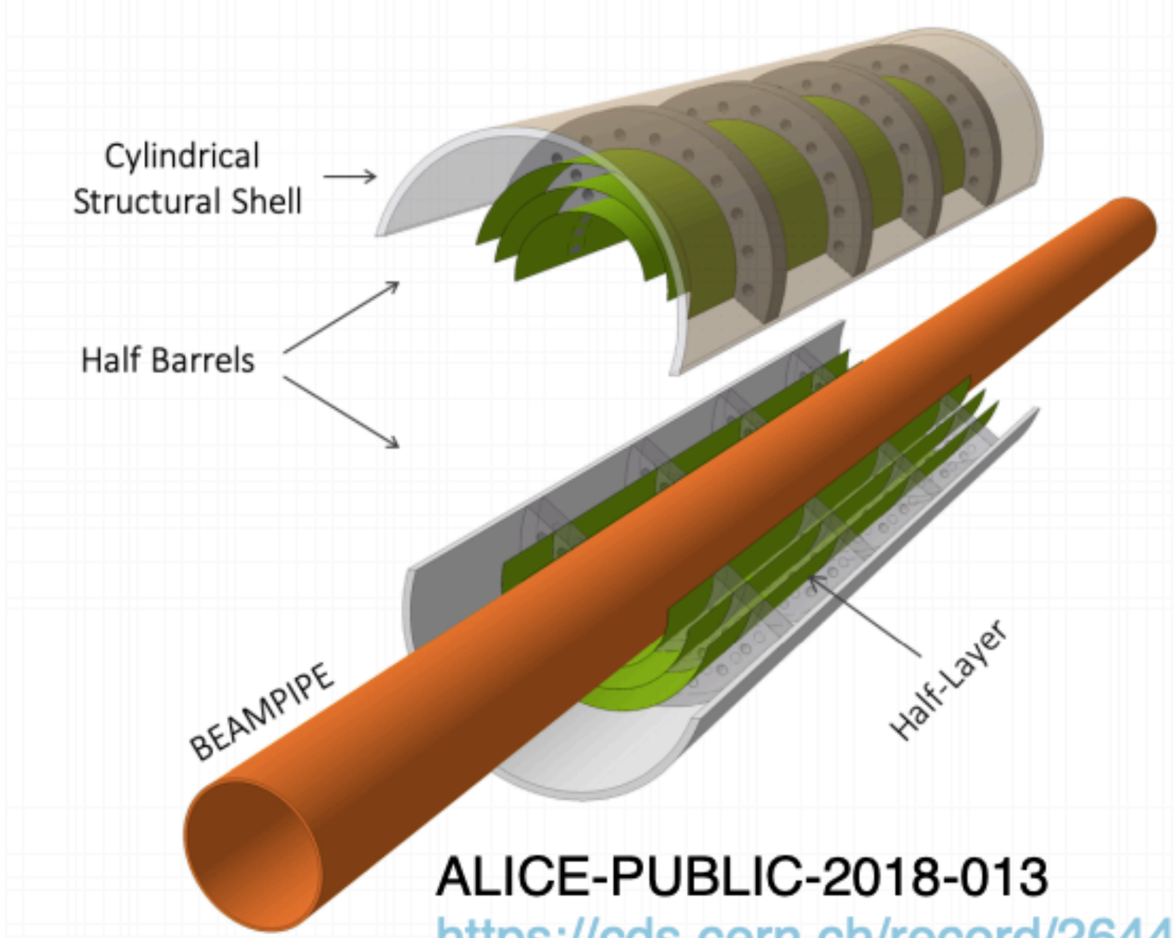




Ultra-thin Fine-pitch MAPS Technology

ALICE ITS3 aims for 65nm MAPS with extremely low mass

- $O(10 \times 10\ \mu m)$
- 20-40 μm-thick (0.05% X_0)
- stitched, bendable, self-support
- low power consumption (<20mW/cm^2)
- short integration time (~200 ns)



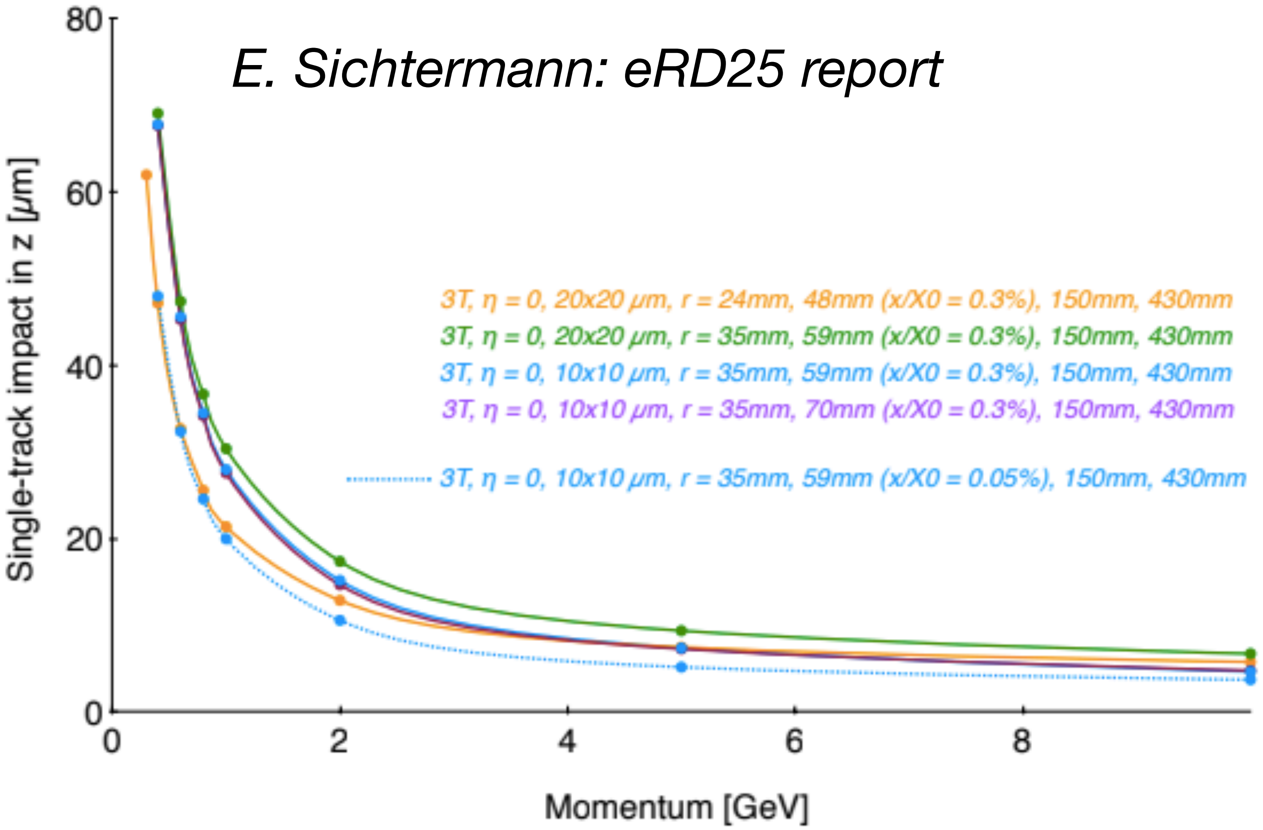
ALICE-PUBLIC-2018-013
https://cds.cern.ch/record/2644611

very attractive for vertex layers of EIC experiments

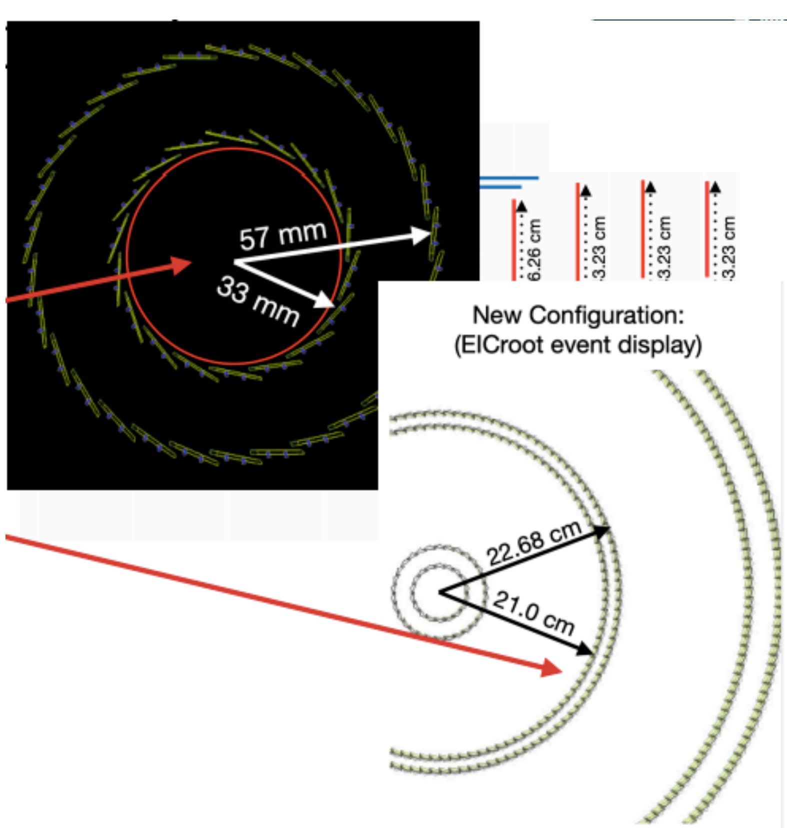
EIC Silicon Consortium

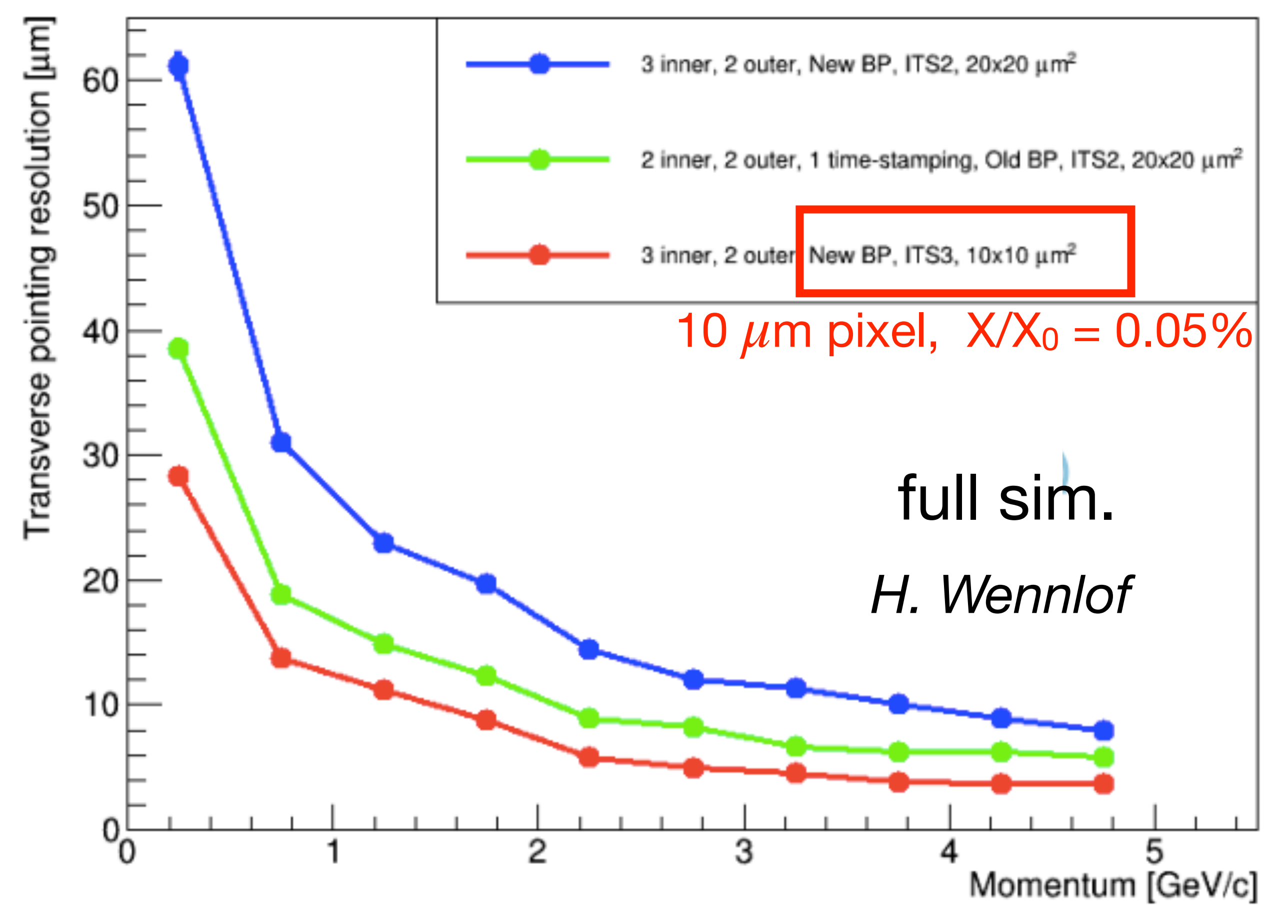
- joining and leveraging ITS3 sensor R&D for EIC detector
- other R&D associated with services, support, readout etc.

Benefits of Ultra-thin Fine-pitch MAPS Detector



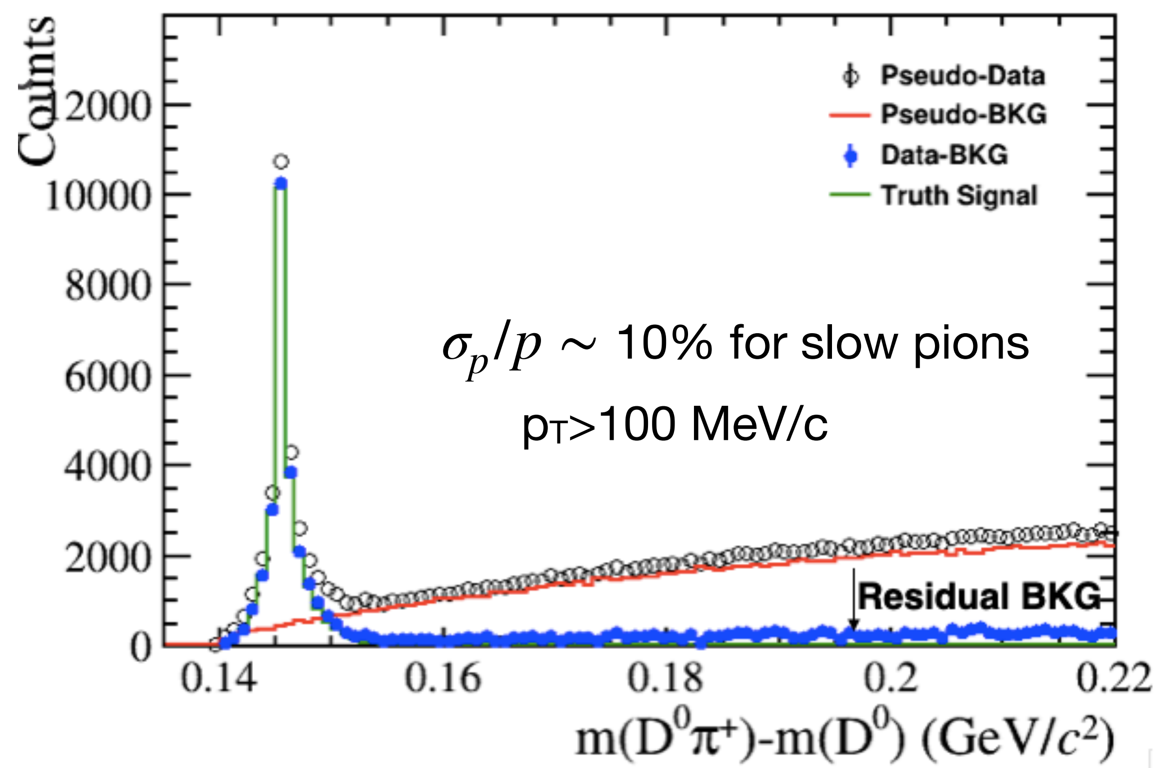
A larger beampipe leads to worsening of pointing resolution
- high mom region can be recovered with smaller pitch design (10x10 μm^2)
- low mom region can only be recovered with ultra-thin detector design (0.05%X_0)

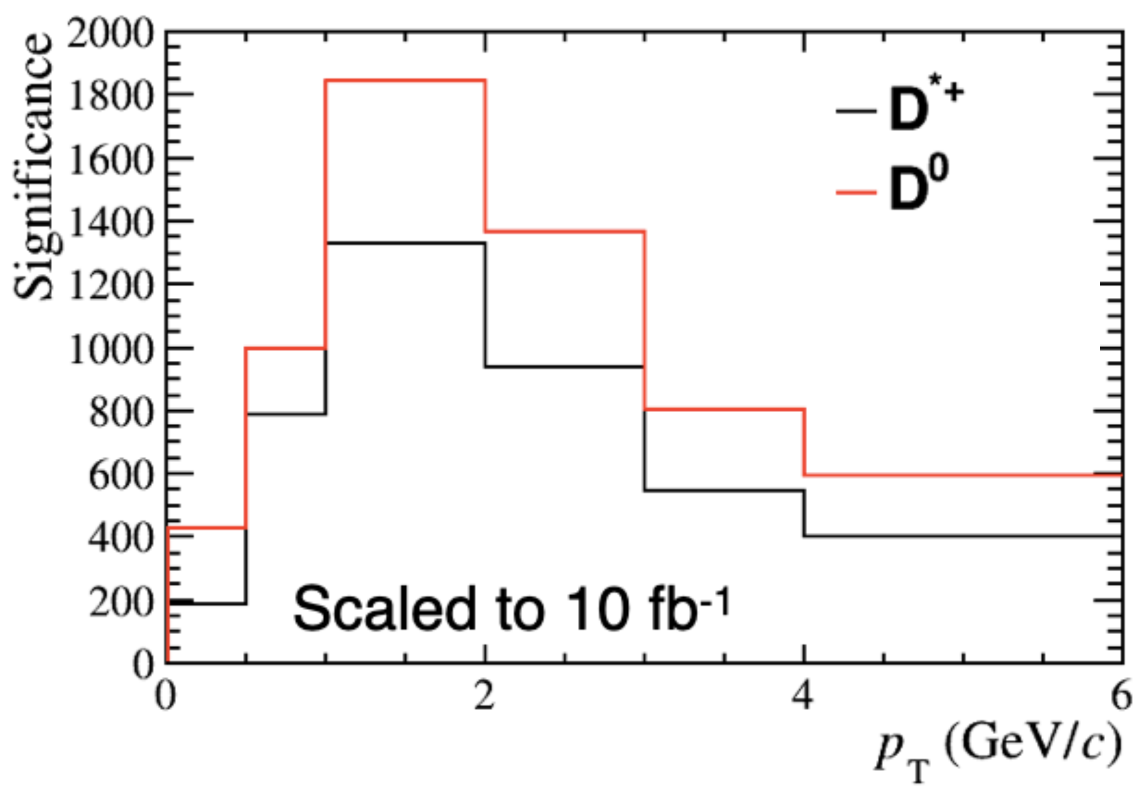


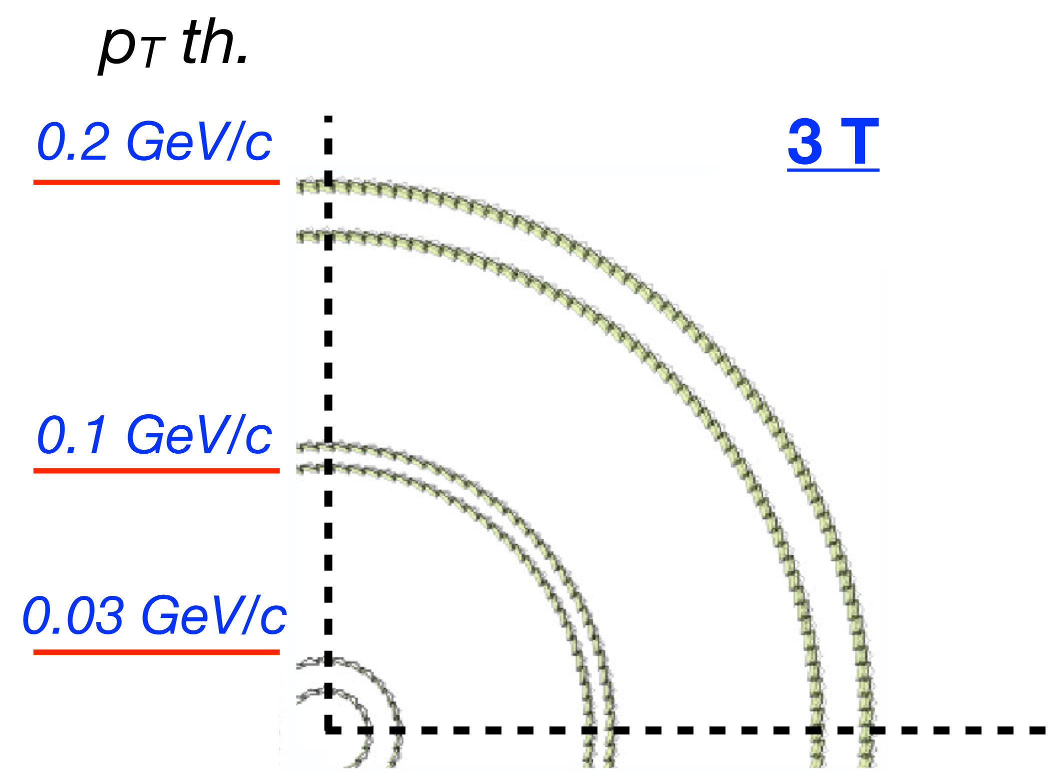


Low-p$_T$ Cut-off and D* Reconstruction

$D^{*+} \rightarrow D^0\pi^+$ $\quad$ $c \rightarrow D^{*+}$ (~24%)







- D^{*+} can be a viable channel
- Inner vertex layer optimization
  - *a third layer for redundancy + low p$_T$ acceptance*

- Introduction and An All-Si Compact Tracker Concept
  - Introduction and kinematic distributions
  - An all-Si compact tracker and performance studies
- Physics Simulations on Heavy Flavor Measurements at EIC
  - Charm structure function $\rightarrow$ gluon (n)PDF
  - Charm double spin asymmetry $\rightarrow$ gluon helicity
  - $D\overline{D}$ pair azimuth distribution $\rightarrow$ gluon TMDs
  - Charm hadrochemistry $\rightarrow$ hadronization, CNM

Detector Resolution Parametrization for Physics Simulation

Momentum Resolution (DM)

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	$0.1 \cdot p \oplus 2.0$

Pointing Resolution

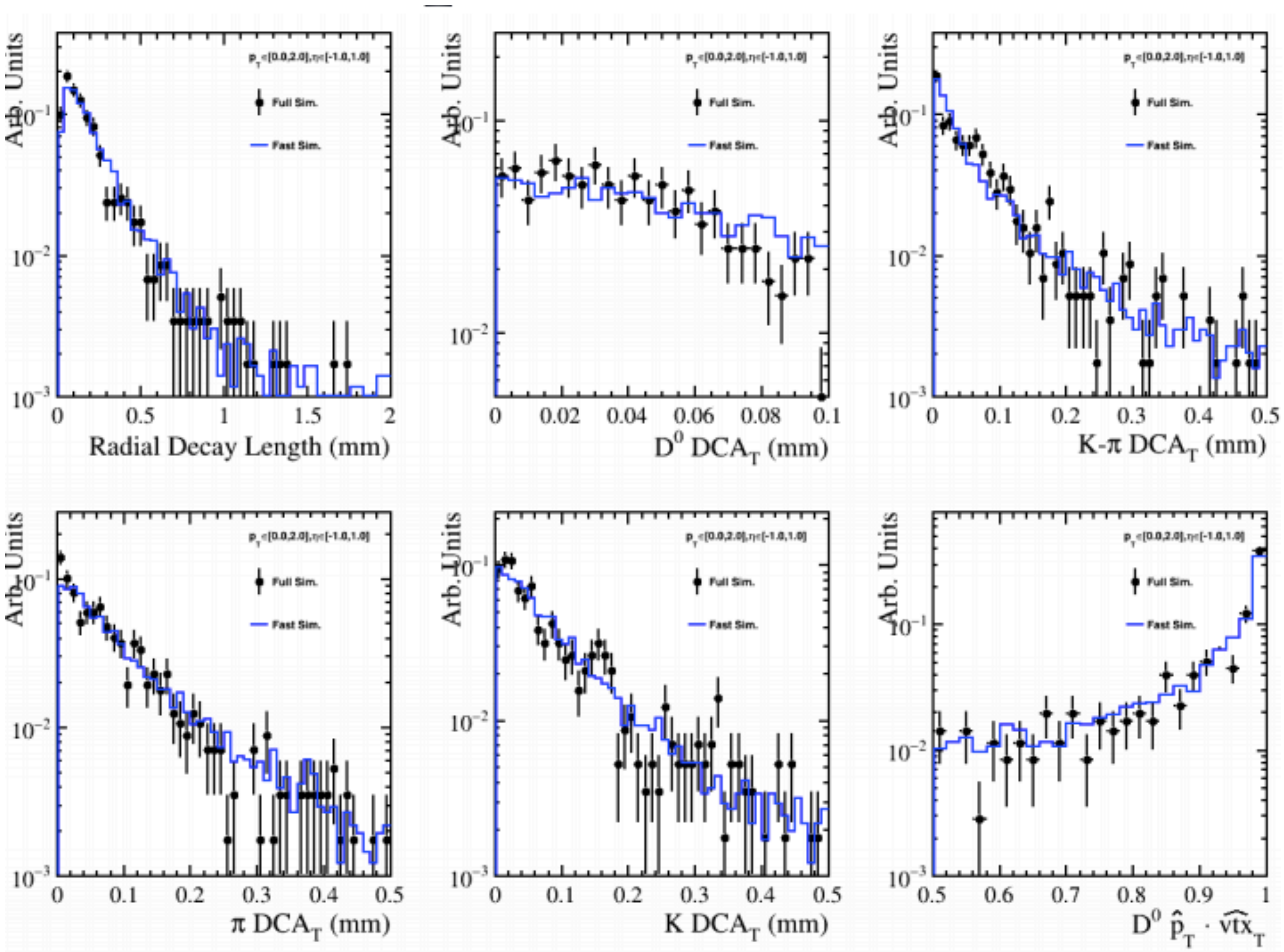
η Region	Detector Matrix (μm)	Stringent (μm)
-3.0< η <-2.5	$30/p_T \oplus 40$	$30/p_T \oplus 10$
-2.5< η <-2.0	$30/p_T \oplus 20$	$30/p_T \oplus 10$
-2.0< η <-1.0	$30/p_T \oplus 20$	$25/p_T \oplus 10$
-1.0< η <1.0	$20/p_T \oplus 5$	$20/p_T \oplus 5$
1.0< η <2.0	$30/p_T \oplus 20$	$25/p_T \oplus 10$
2.0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

PID criteria follows the Detector Matrix table guidance

(K/π 3σ separation up to 7 GeV/c within $|\eta|$<1)

- Charm and bottom reconstruction using fast simulation smearing of PYTHIA 6.4 output
- Momentum and pointing resolutions taken from detector matrix page as baseline
  - *A more stringent pointing resolution also used for comparison*

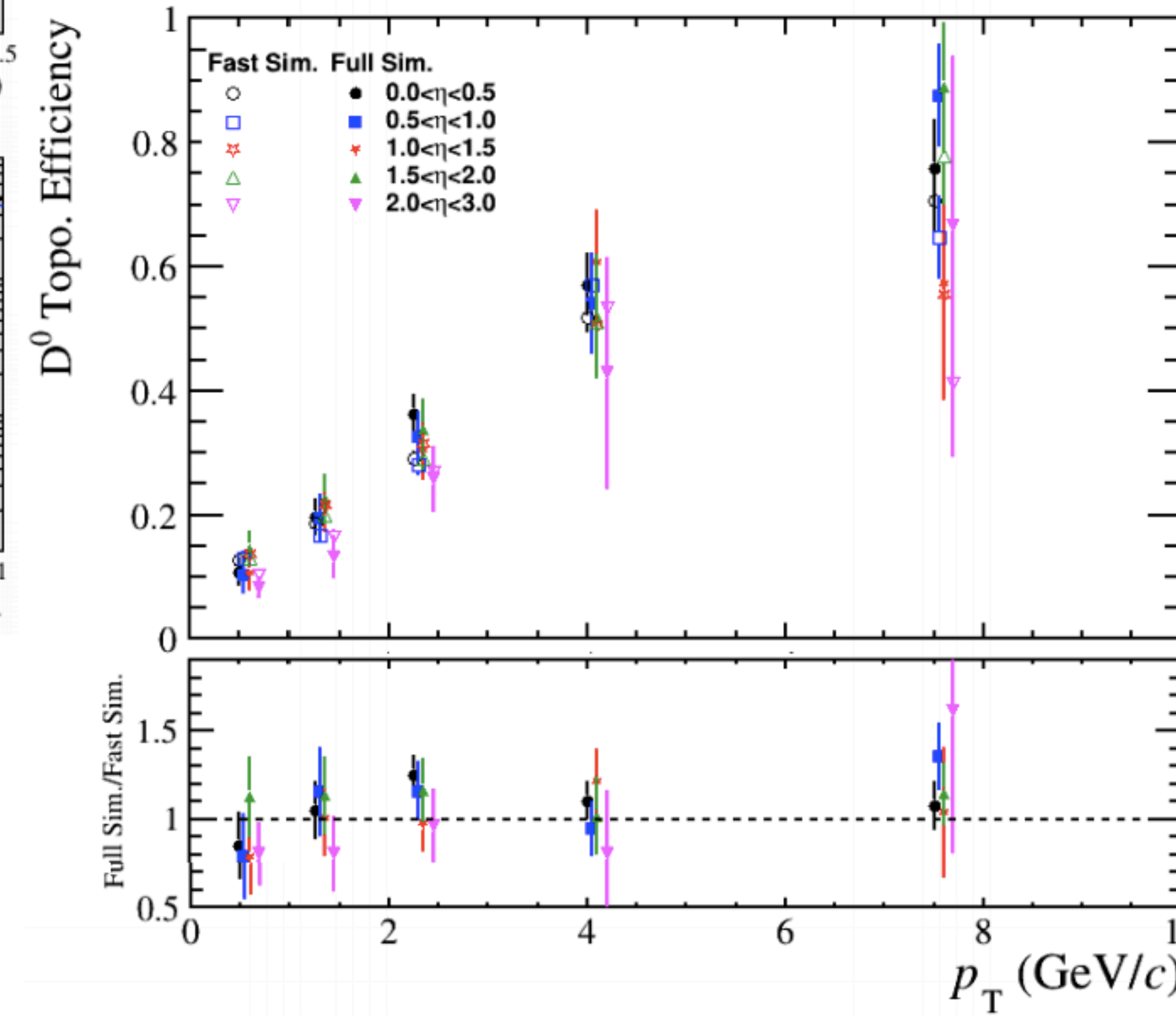
Validation of Fast Simulation w/ Fun4All



Radial Decay Vertex>0.04 mm

K-π DCA$_T$<0.15 mm

cos(D0 pointing angle)>0.98

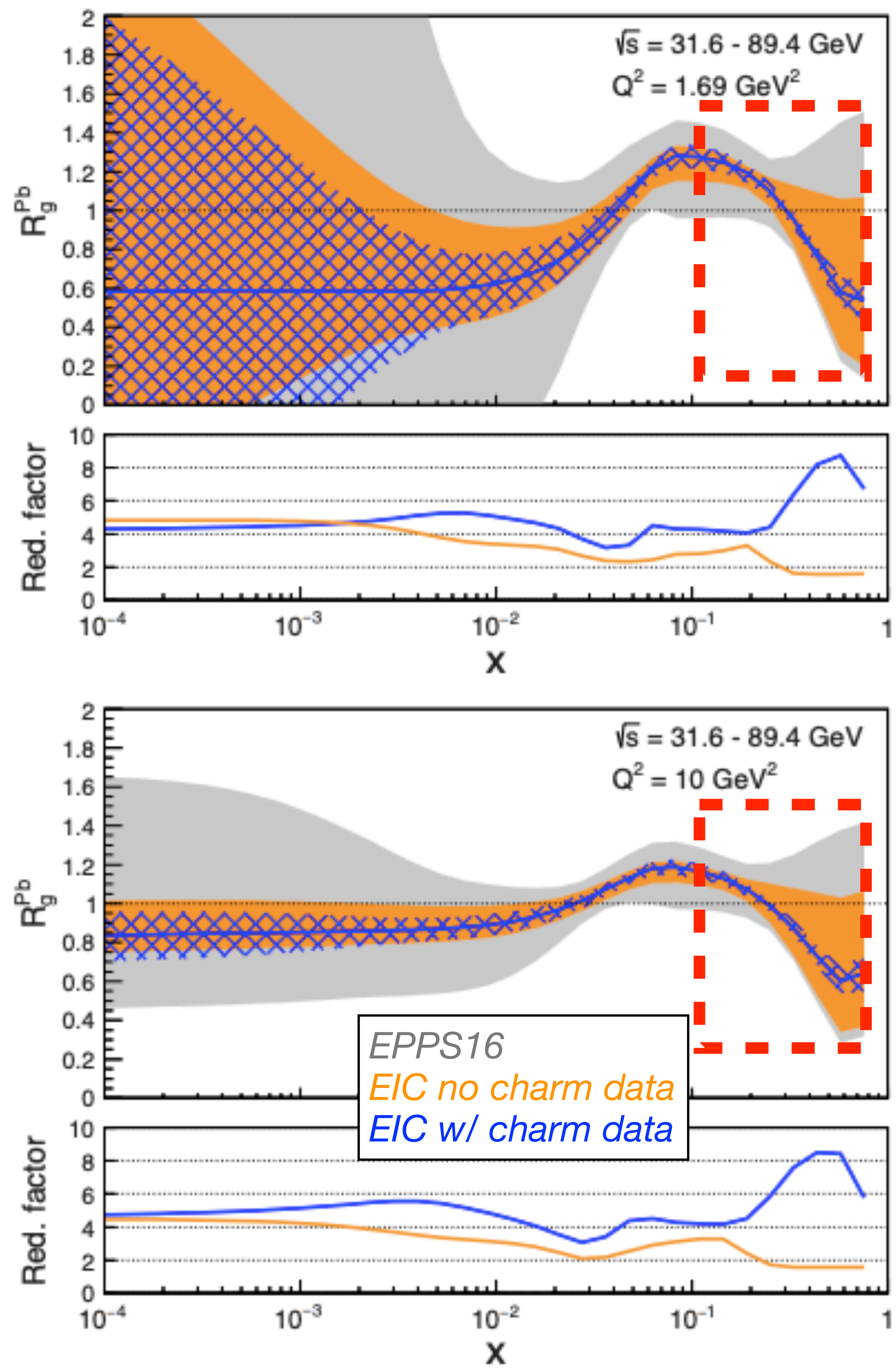


Fast simulation reproduces all topological distributions and D^0 efficiency !

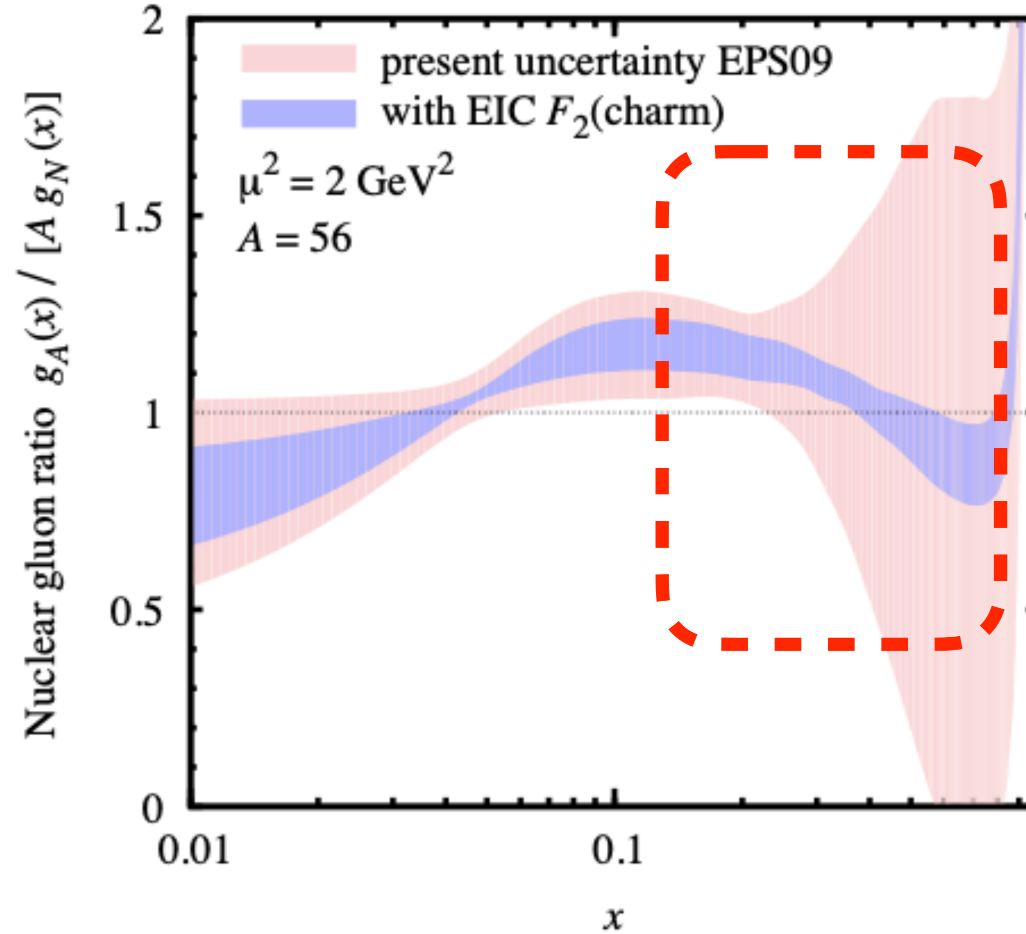
Inclusive Charm -> Gluon nPDF at High x

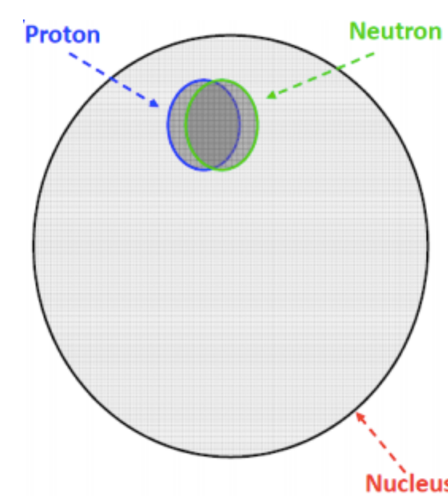
$R_g^{Pb} = f_g^{Pb}(x,Q^2)/f_g^p(x,Q^2)$

E.C. Aschenauer et al, 1708.01527



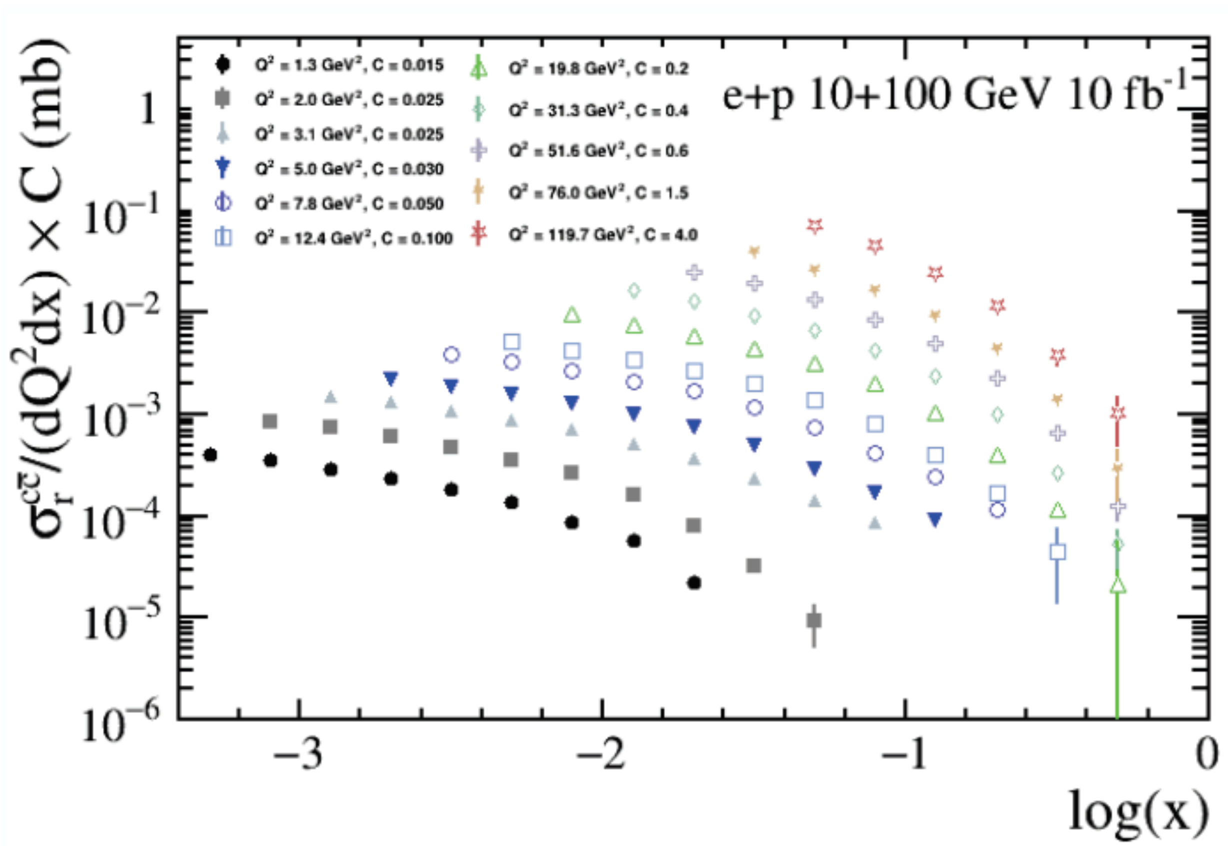
E. Chudakov et al, 1610.08536

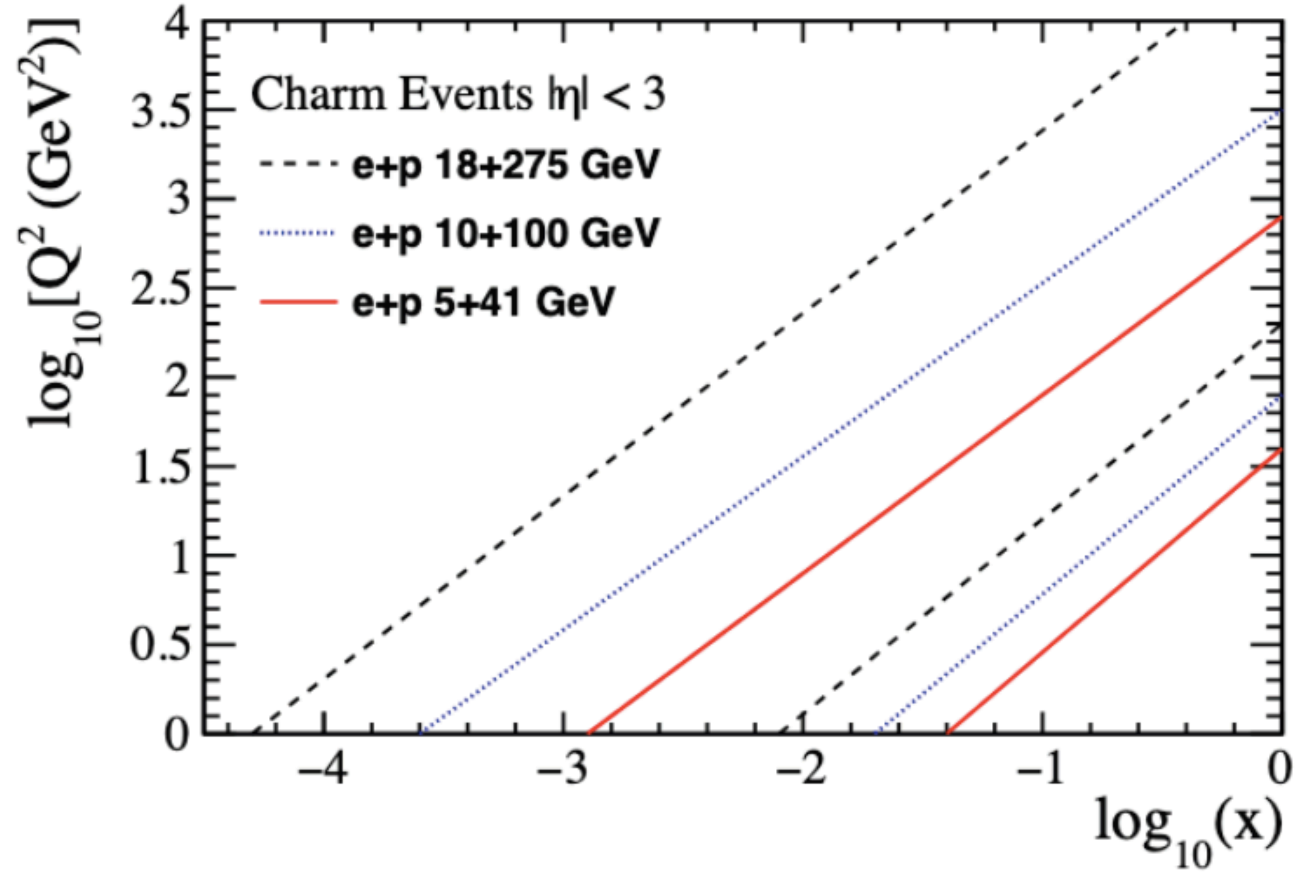




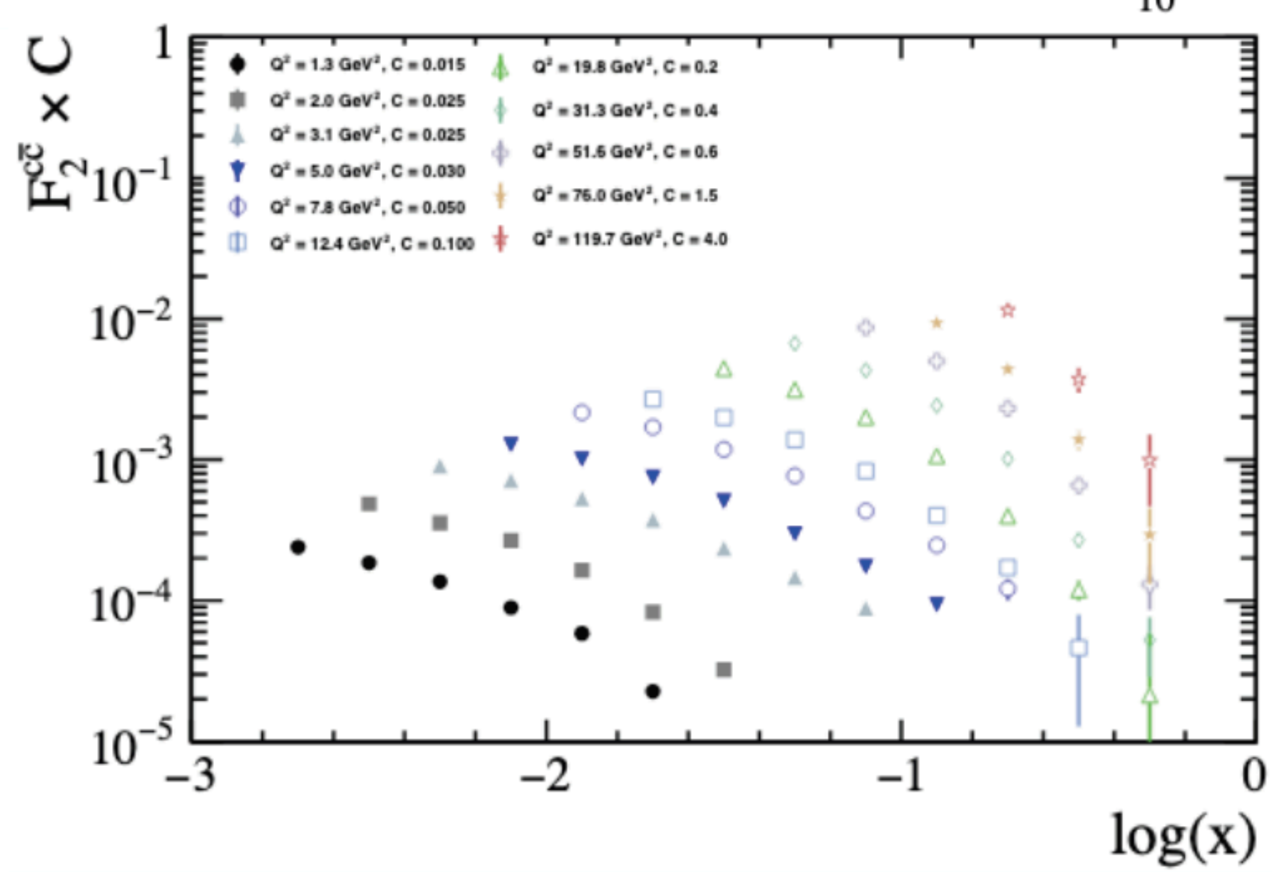
gluon probe to
short range correlation
at “EMC” region

Charm Structure Function $F_2^{c\bar{c}}$

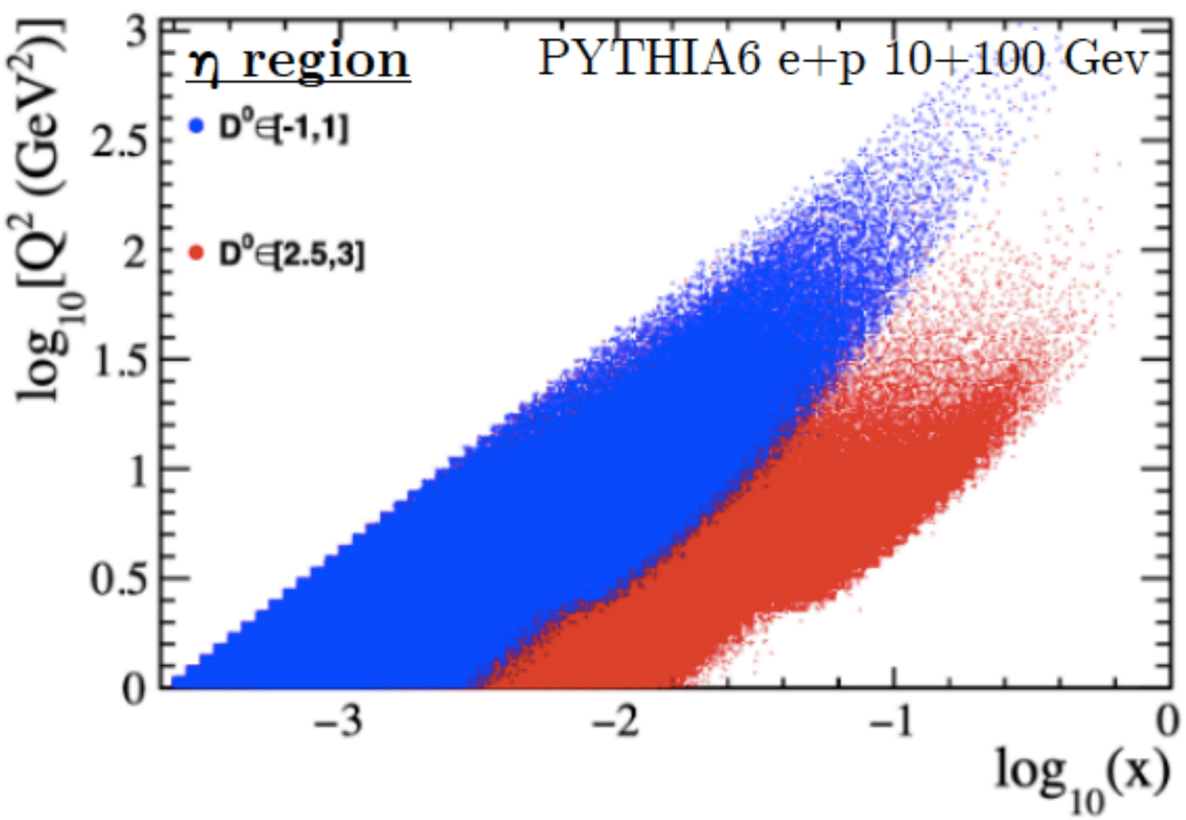


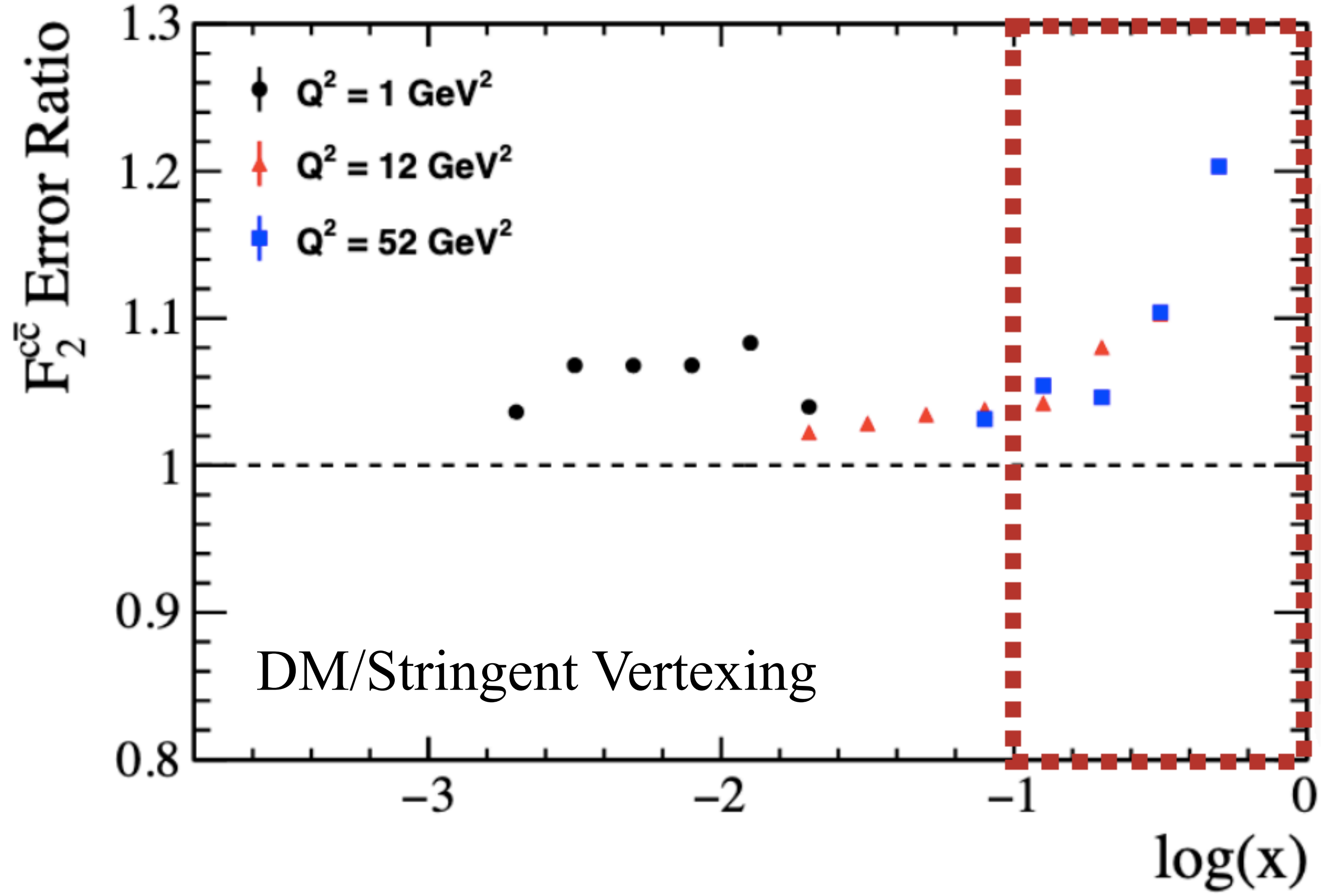


- Linear fit to $\sigma_r^{c\bar{c}}$ at 10+100 and 5+41 GeV e+p data, 10 fb^{-1} each
- Extend HERA measurement to high x region (x_B>0.1)



Charm Structure Function $F_2^{c\bar{c}}$





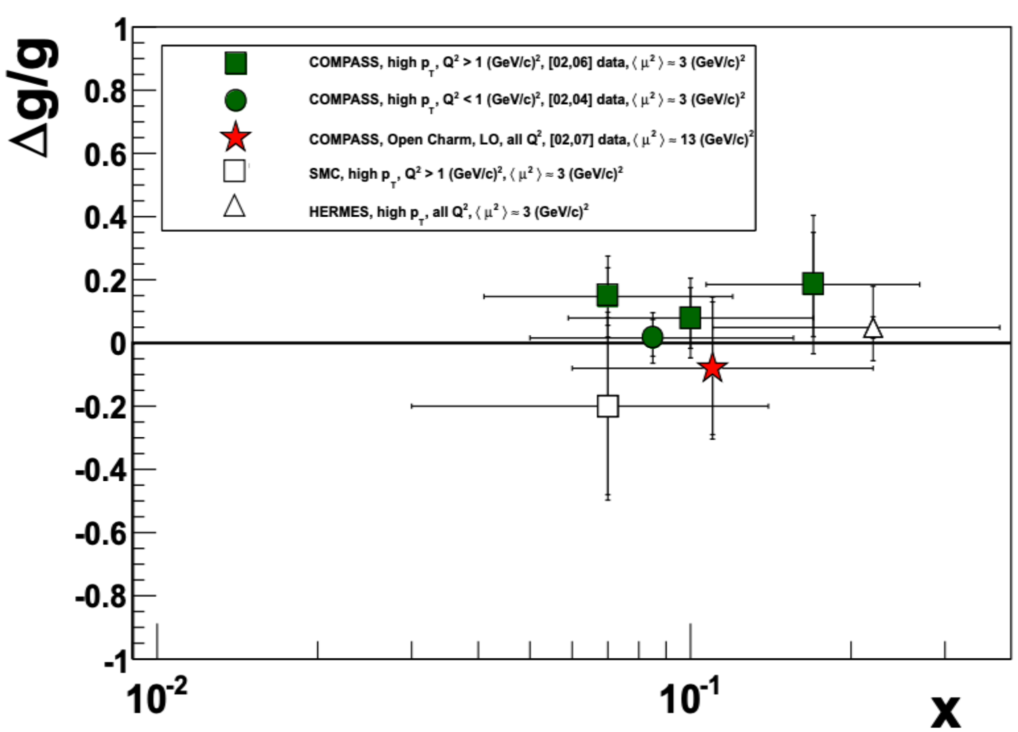
- Charm hadrons from high x_B more populated at higher η region
- More stringent tracking scenario improves uncertainties by 10-20% at x_B>0.1
- QCD analysis needed to evaluate the impact on gluon (n)PDFs

Gluon Helicity $\Delta g/g$

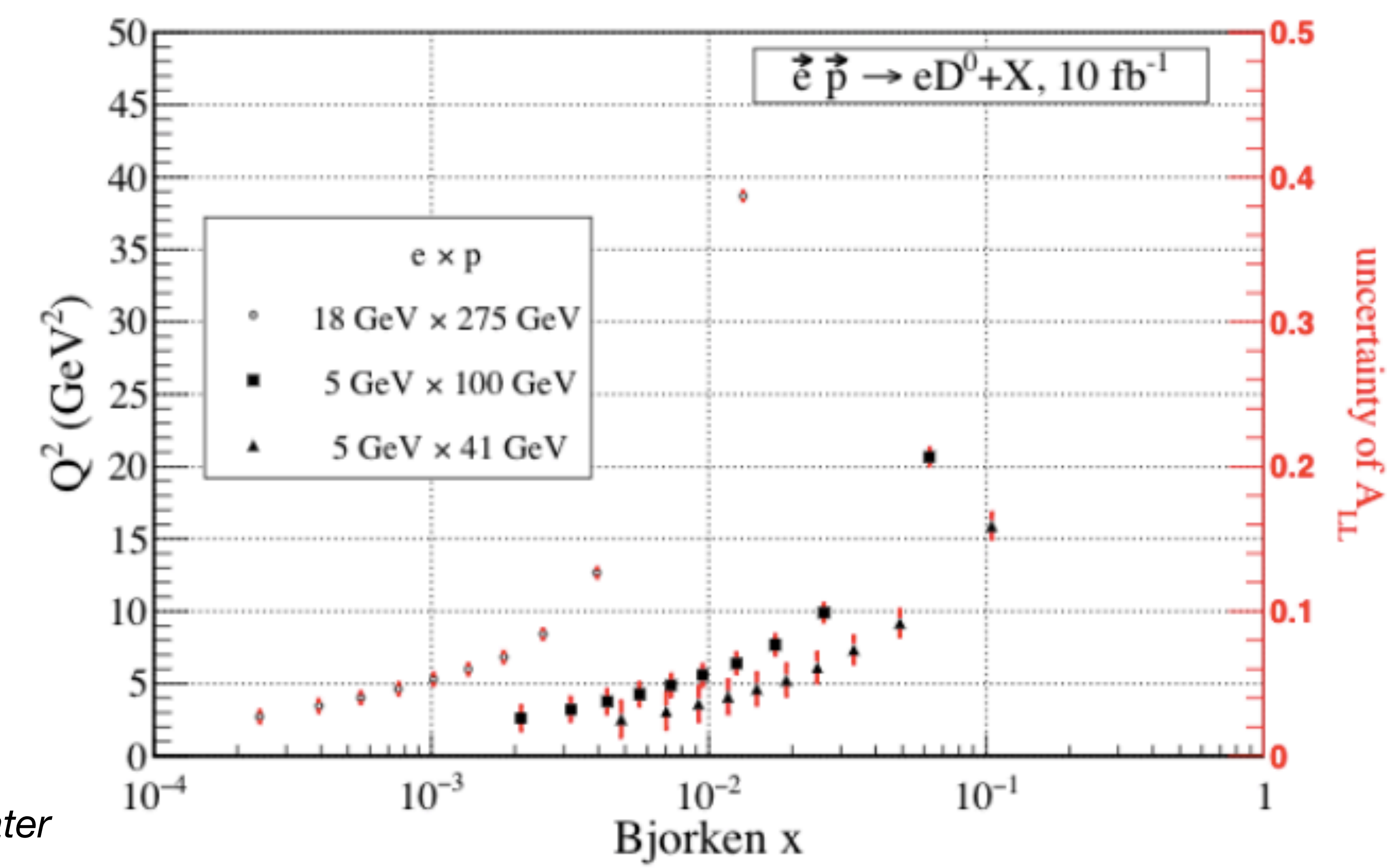
Understanding proton spin is one of the EIC science goals

HF - better sensitivity to the gluon dynamics
- complementary to the inclusive measurement
- direct access to $\Delta g/g$ LO $A_{LL} \propto \hat{a}_{LL} \times \Delta g/g$

COMPASS data from open charm



data placed at each measured (x_B, Q^2) position
error bars - uncertainty of A_{LL}

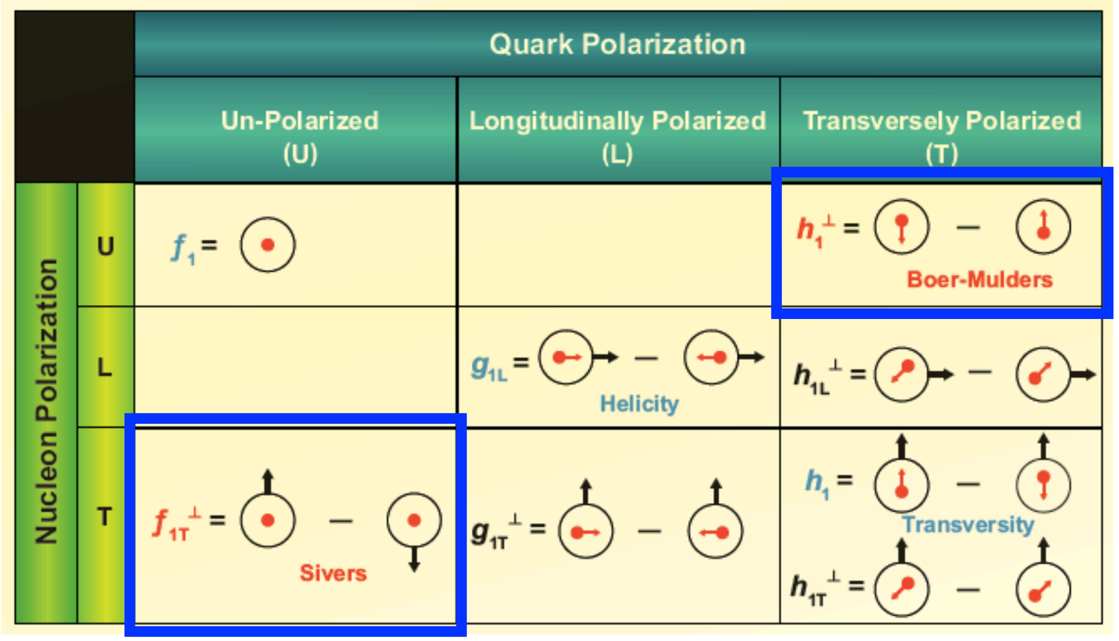


see Yuxiang Zhao's presentation later

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

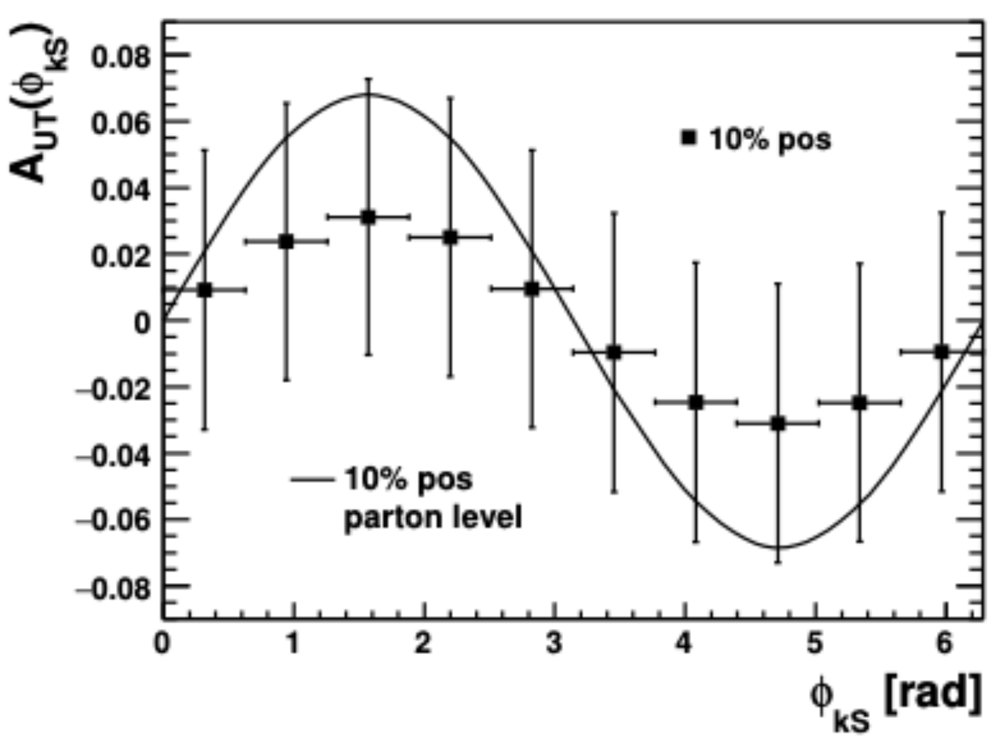
Charm hadron pair in transverse polarized exp.
- gluon Sivers functions

Charm hadron pair in unpolarized exp.
- linearly polarized Boer-Mulders function

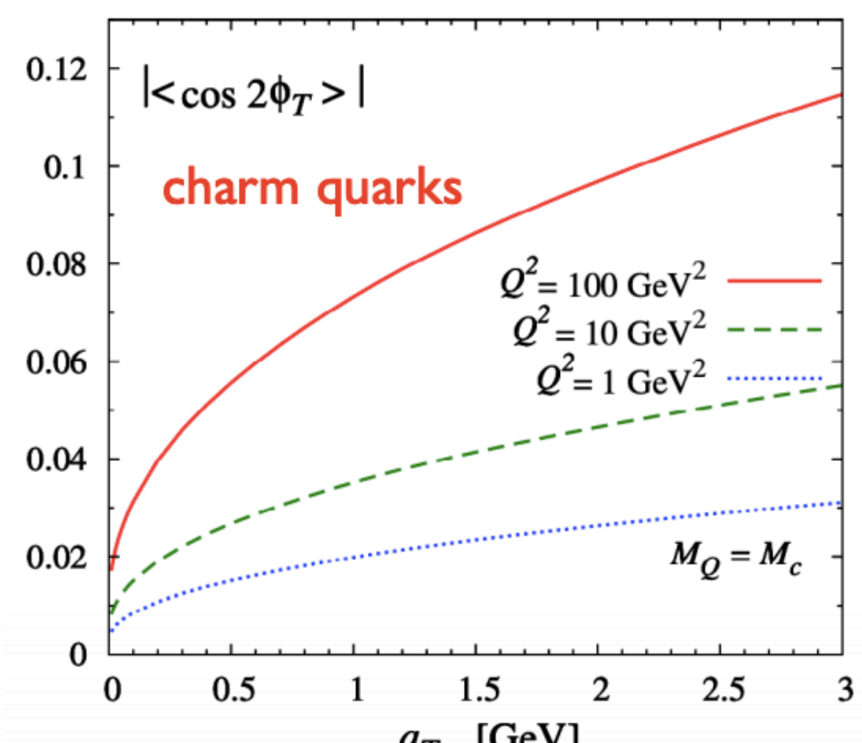


$$A_{UT}(\phi_{kS}, k_T) = \frac{d\sigma^\uparrow(\phi_{kS}, k_T) - d\sigma^\downarrow(\phi_{kS}, k_T)}{d\sigma^\uparrow(\phi_{kS}, k_T) + d\sigma^\downarrow(\phi_{kS}, k_T)} \propto \frac{\Delta^N f_{g/p^\uparrow}(x, k_\perp)}{2 f_{g/p}(x, k_\perp)},$$

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



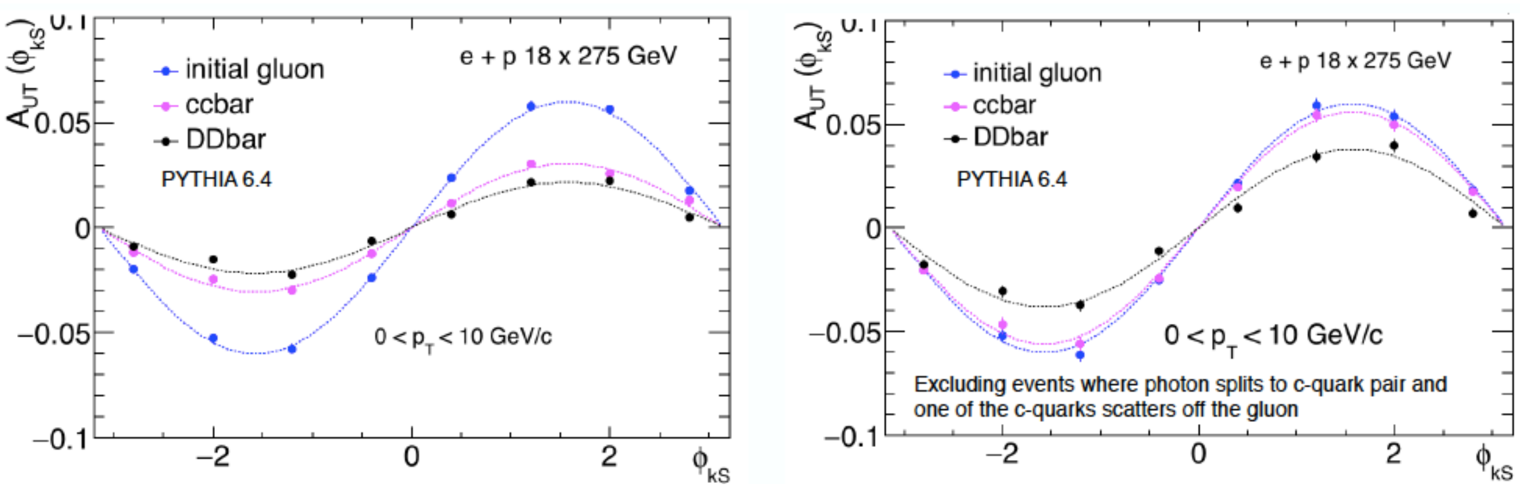
L. Zheng et. al., PRD 98 (2018) 034011

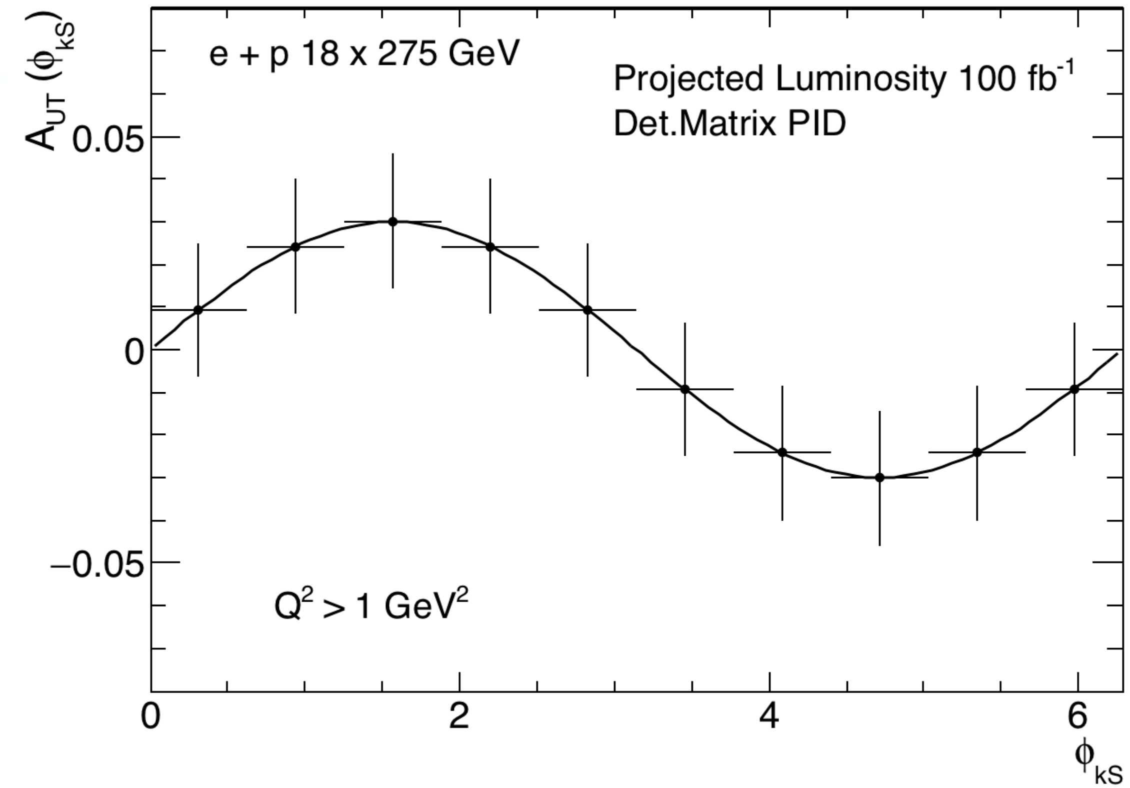


D. Boer et. al., JHEP 08 (2016) 001

Projection on Gluon Sivers Function

PYTHIA6 Simulation

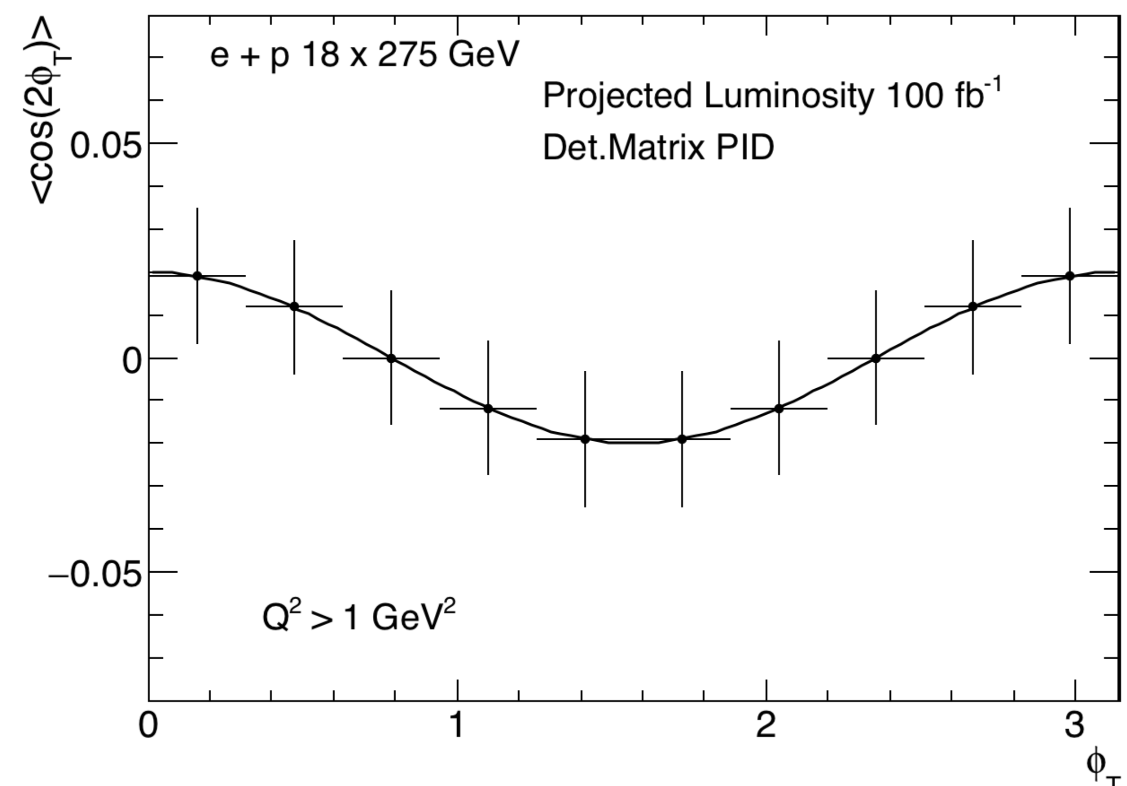




- PYTHIA simulation shows a small impact on $D\overline{D}$ angular correlation

  - larger dilution due to process selection - under investigation

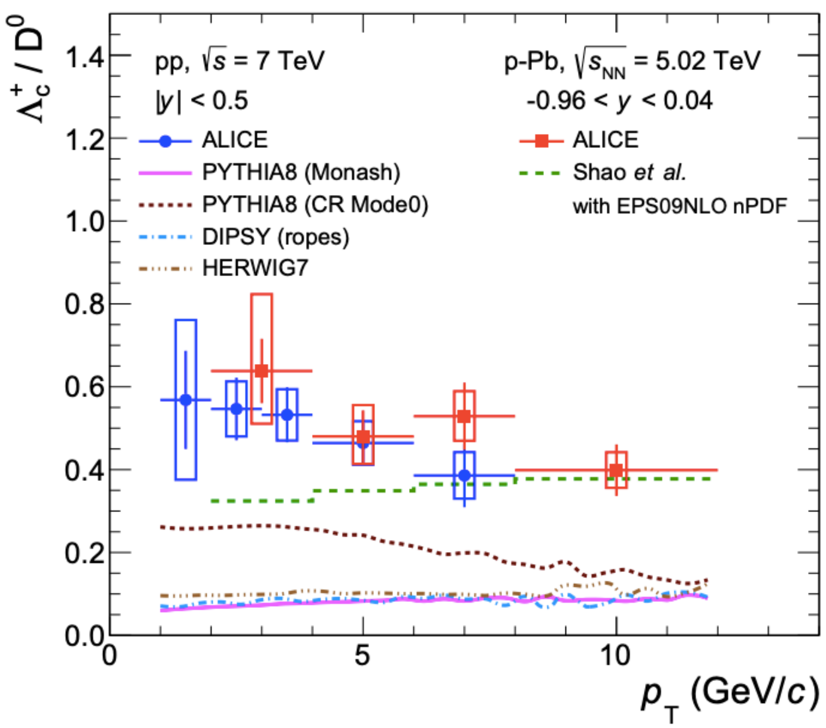
- ~0.4% projected uncertainty on both A_{UT} and $\cos(2\phi_T)$ with 100 fb^{-1}
  - same input asymmetry assumed as in *L. Zheng et al., PRD 98 (2018) 034011*



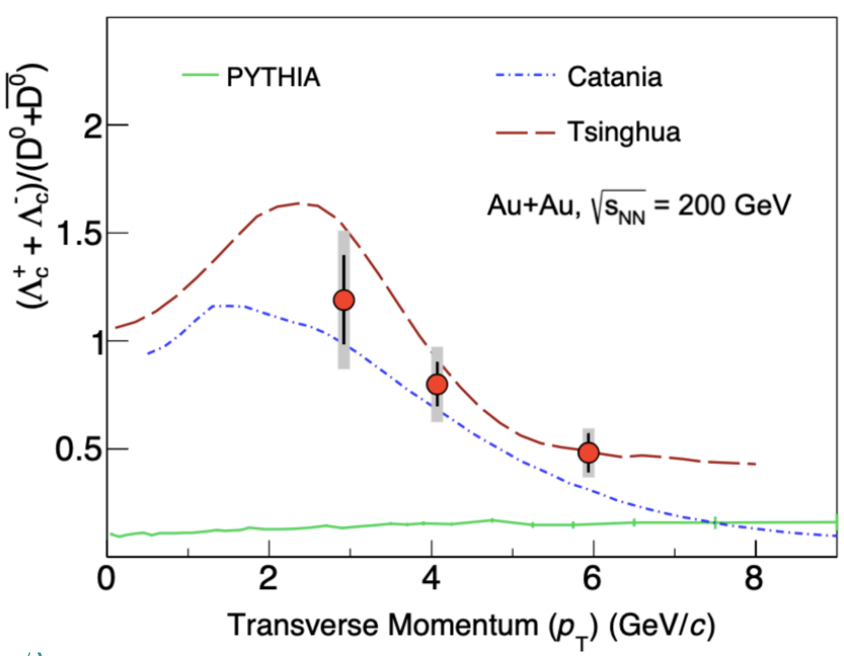
Hadronization and CNM

Charm hadrochemistry

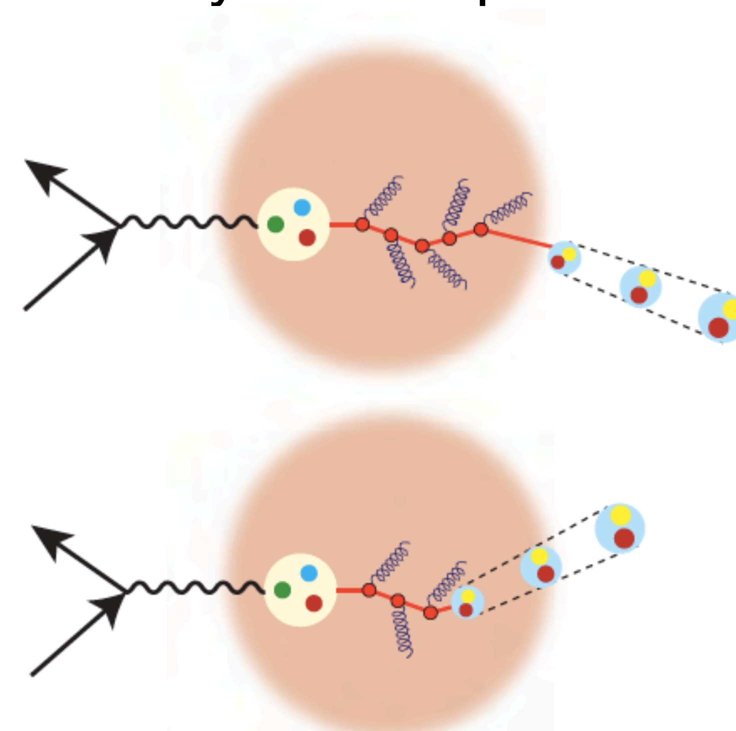
ALICE, JHEP 04 (2018) 108



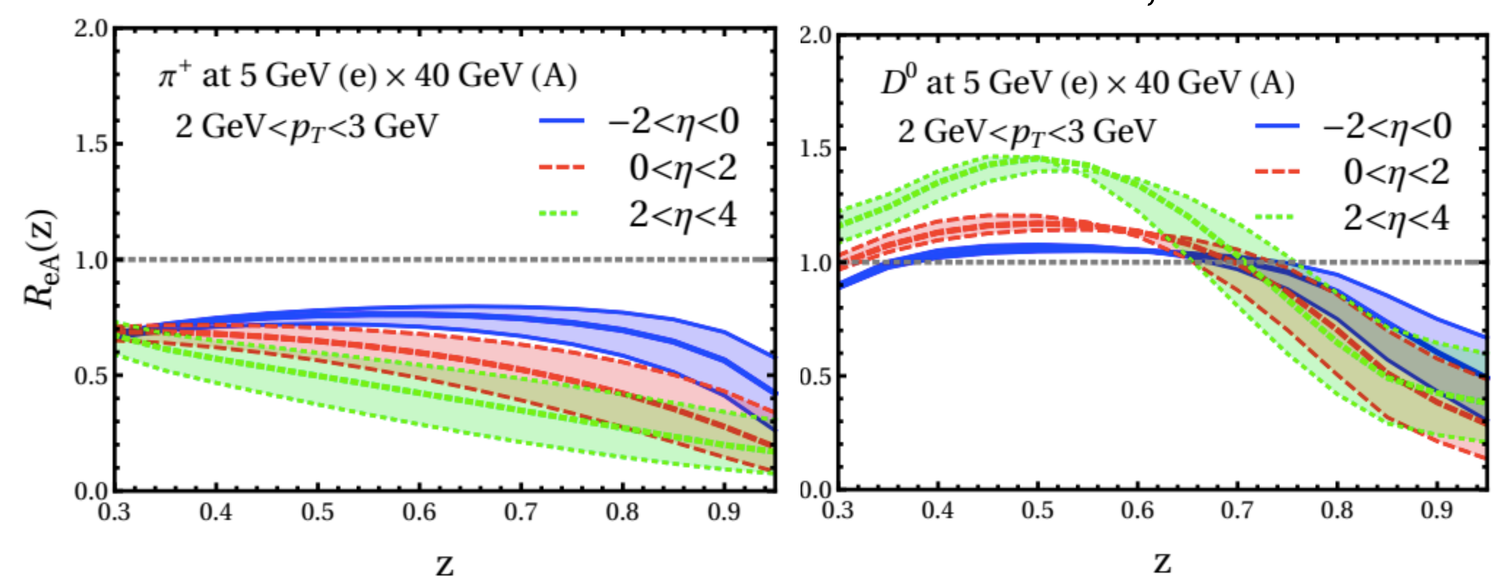
STAR, PRL 124 (2020) 172301



Cold Nuclear Matter Effect on light/heavy hadron production



H. Liu et. al., 2007.10994

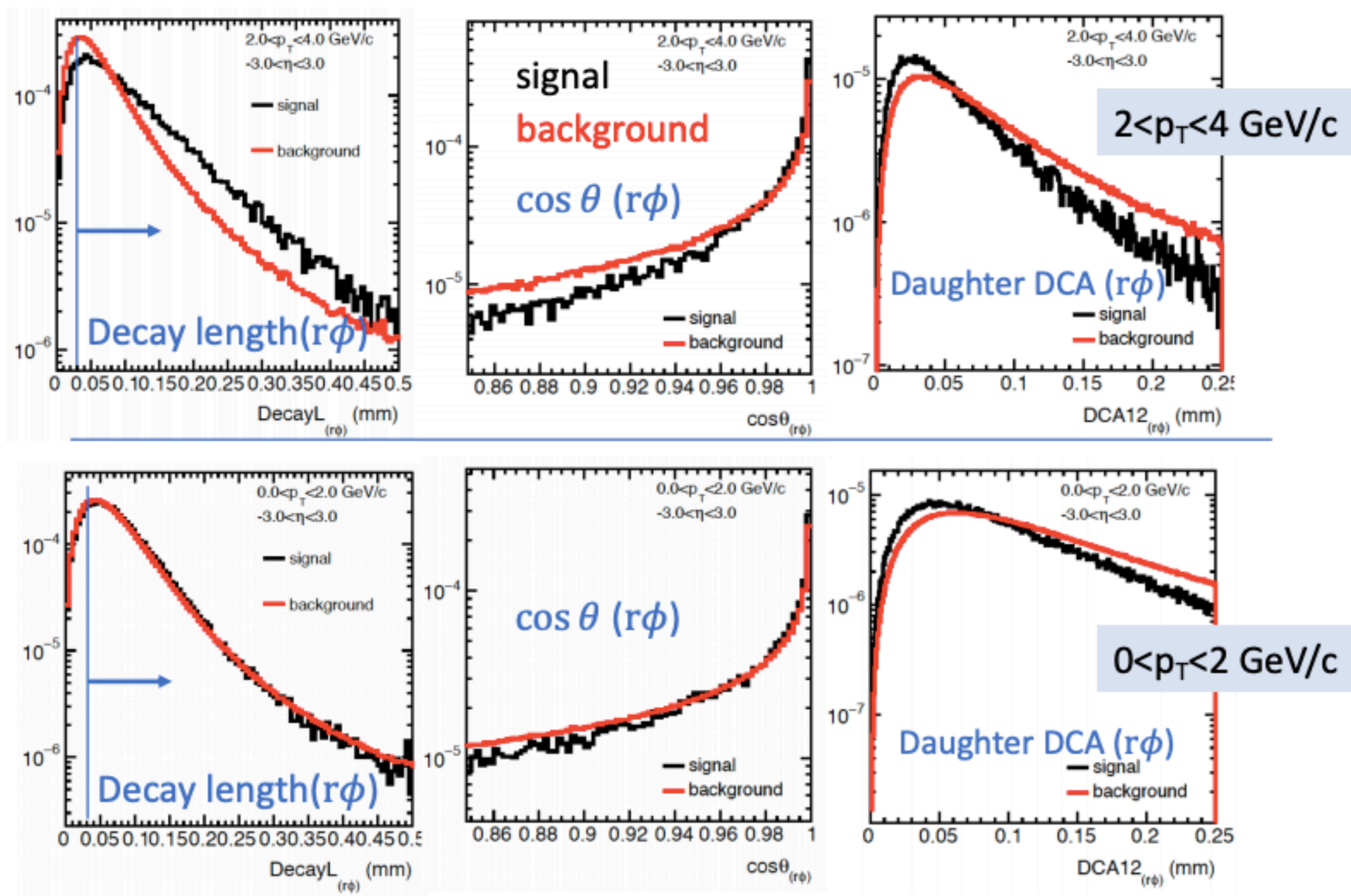


Λ_c^+ Reconstruction

Systematic measurement of Λ_c^+ in ep, pp and AA collisions to understand charm baryon production and hadronization

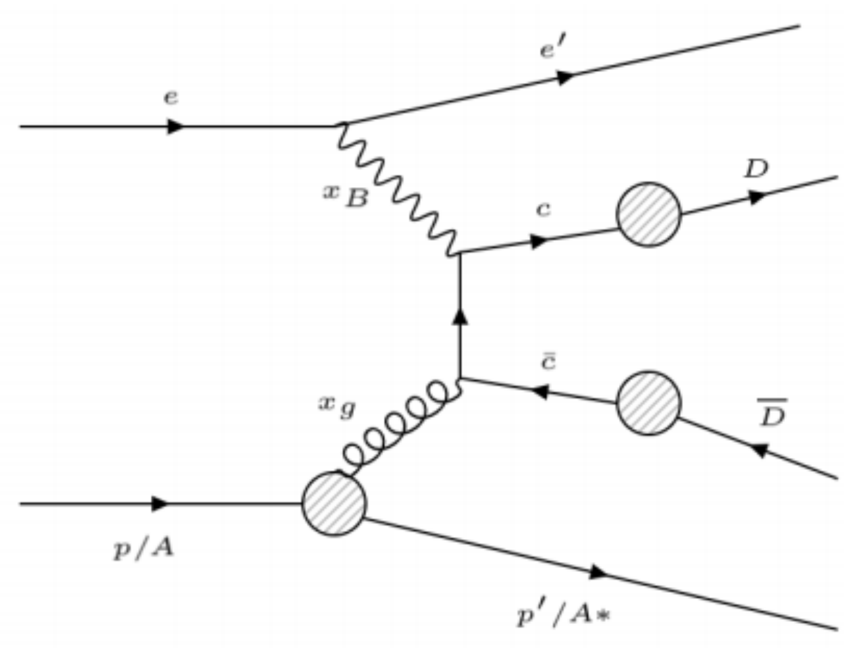
$\Lambda_c^+ \rightarrow pK^-\pi^+$

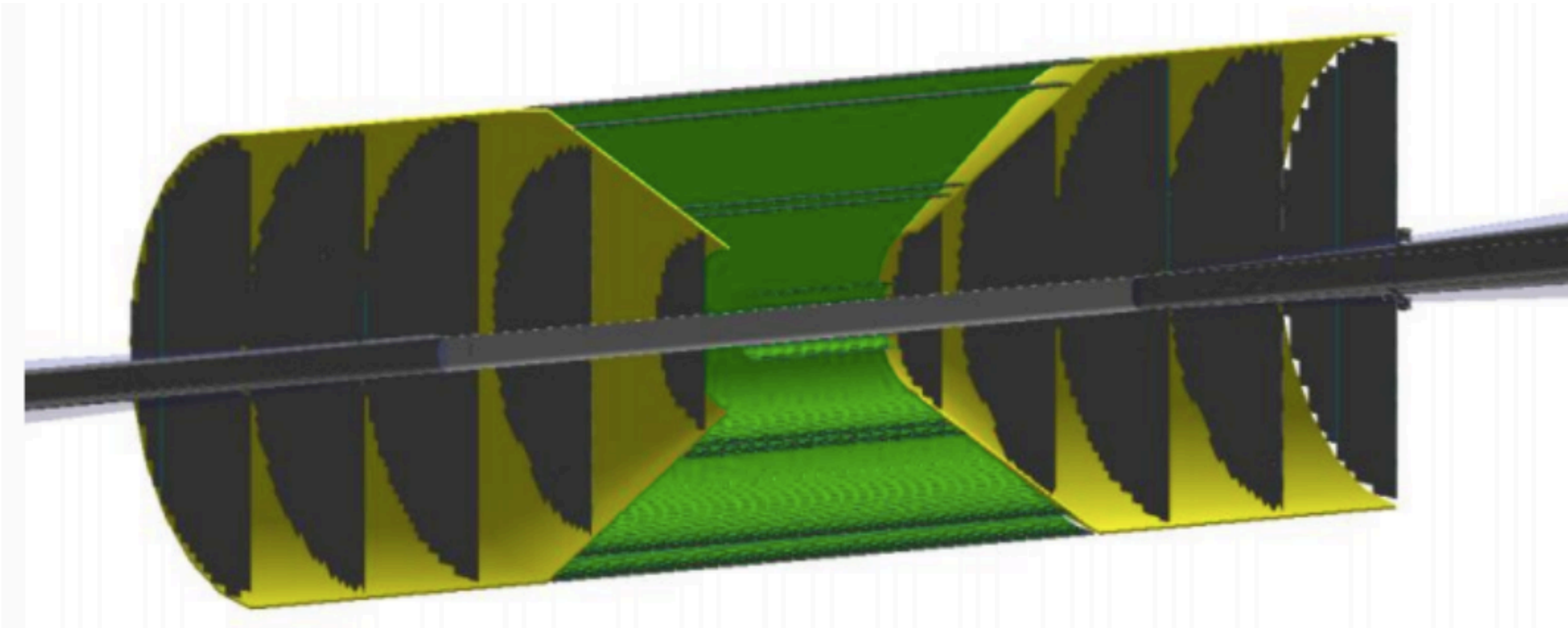
$c\tau \sim 60\mu m$



Decent S/B separation for Λ_c^+ at p_T> 2 GeV/c (potential challenging at lower p_T)

Summary



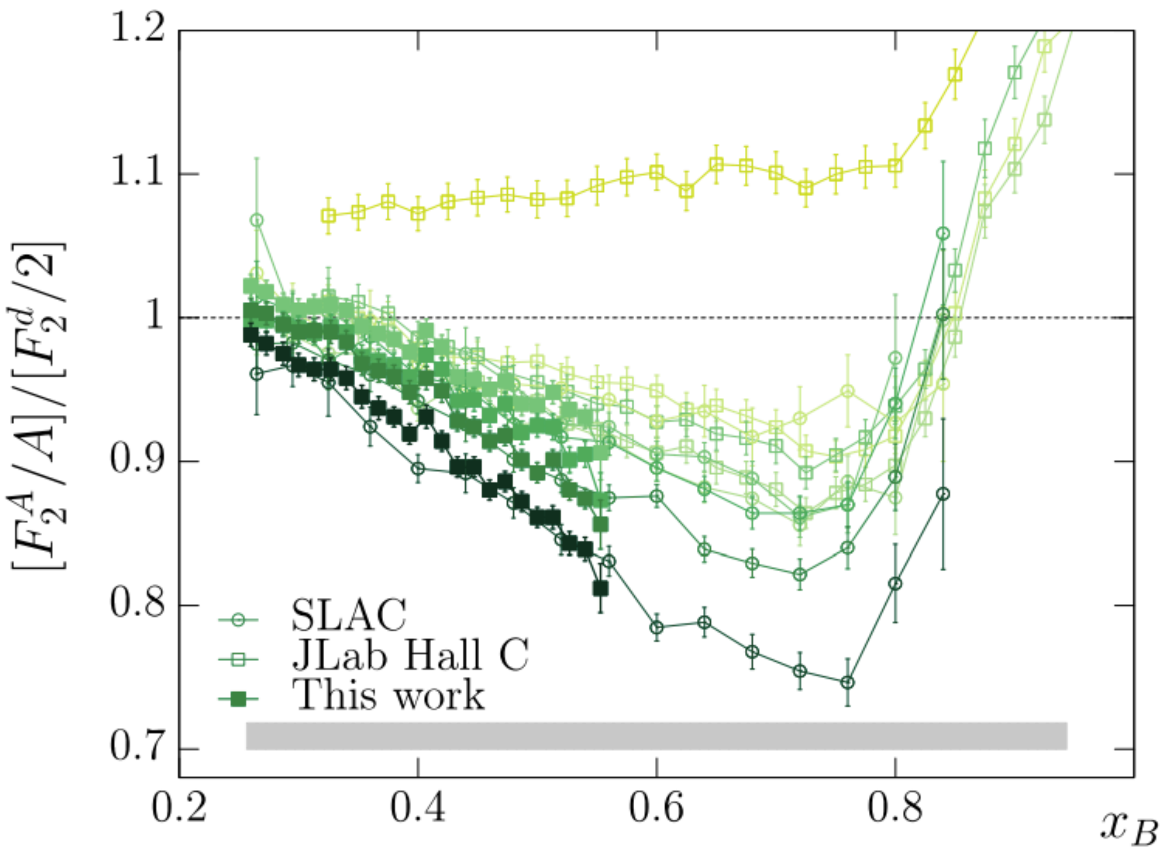


- EIC is a precision QCD machine! Heavy flavor measurements offer unique sensitivity to study gluon dynamics in QCD.

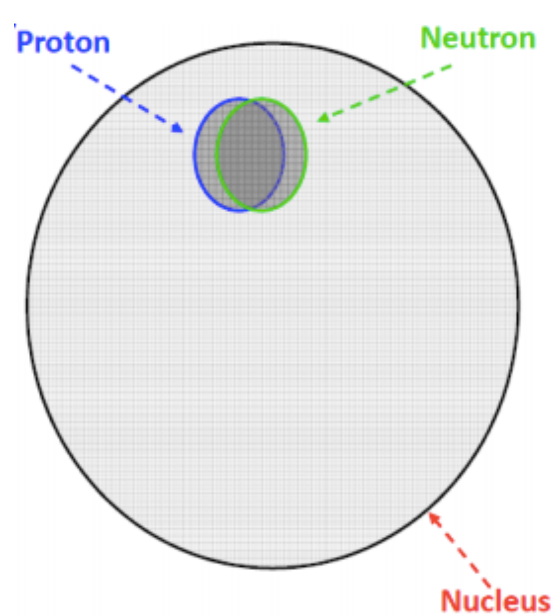
- An all-Si compact tracker satisfies momentum/pointing/vertexing requirements and enables these precision heavy flavor measurements.
  - *Ultra-thin fine-pitch MAPS detector is essential!*

Backup

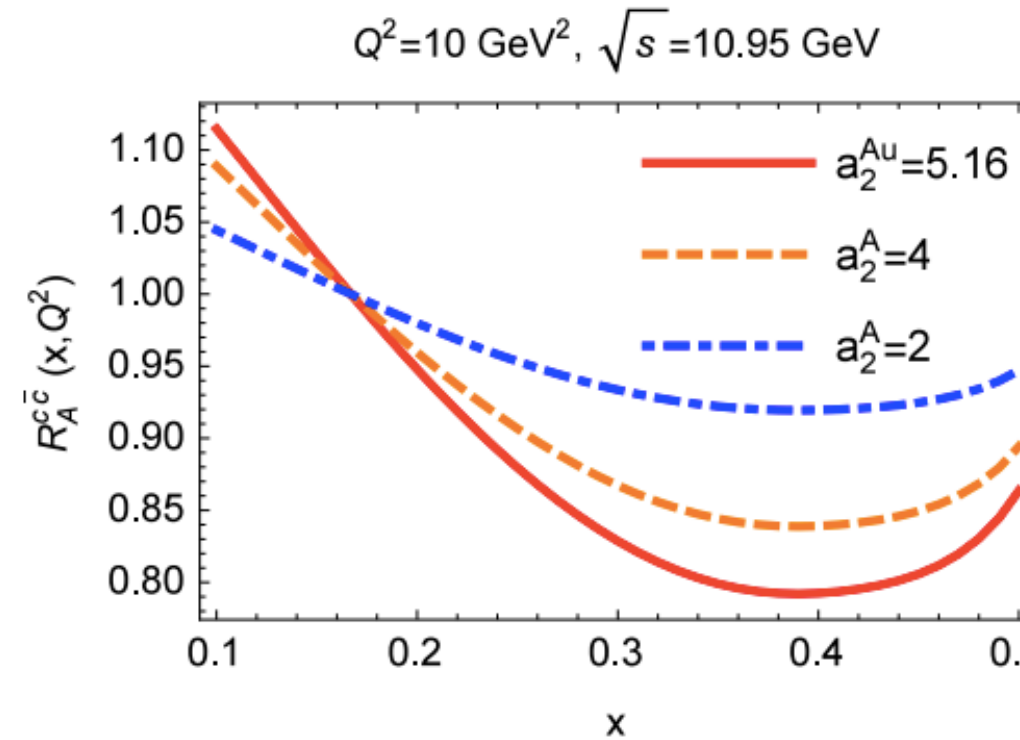
EMC <-> Short-Range Correlation

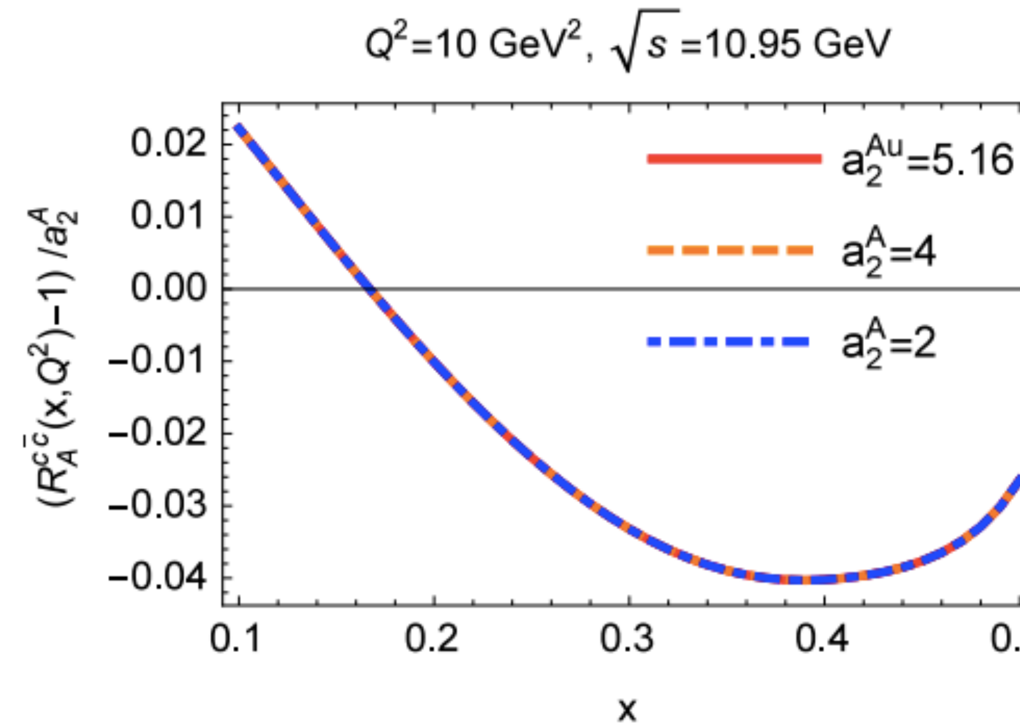


EMC effect at large x <-> SRC-np

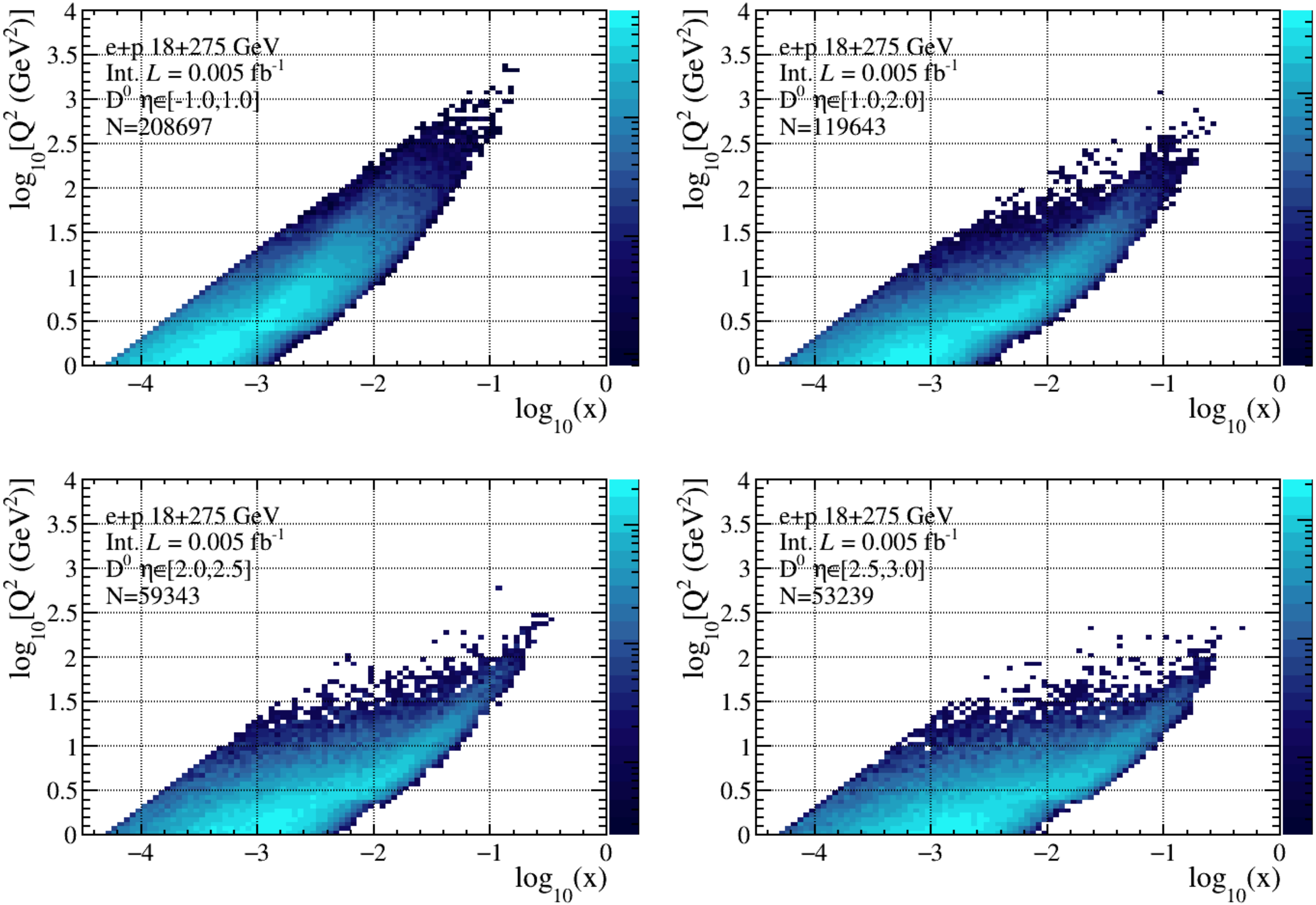


charm -> gluon probe to SRC



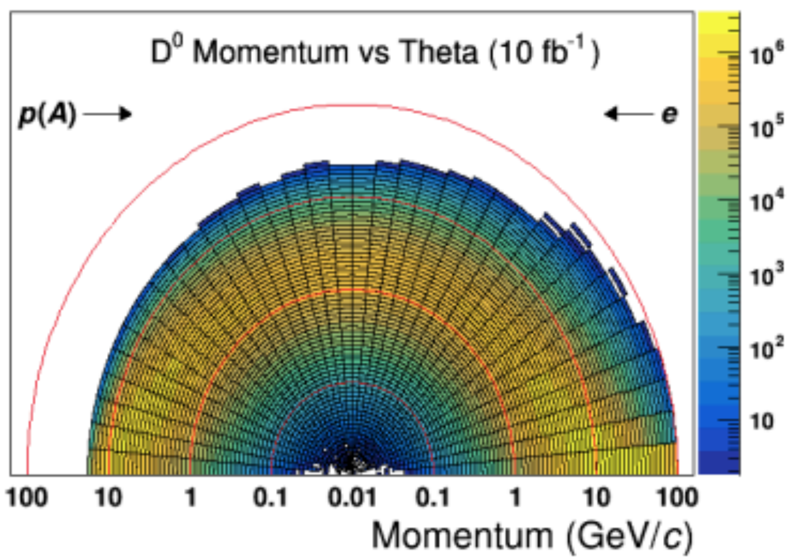


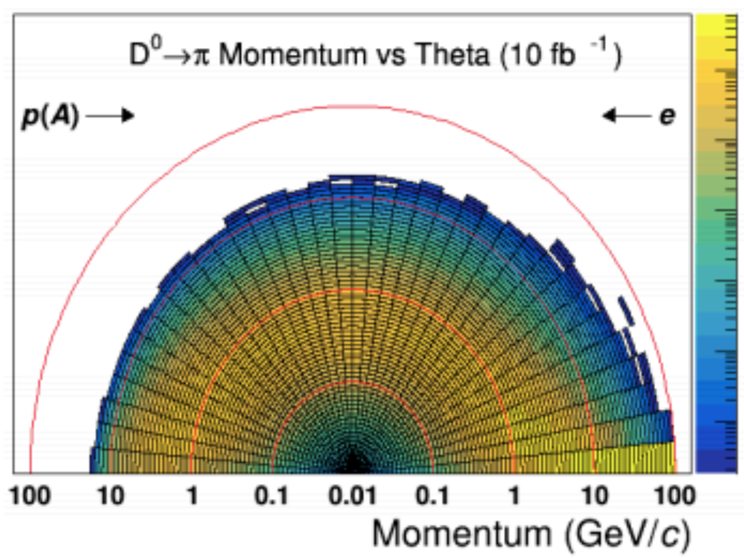
J. Xu and F. Yuan, PLB 801 (2019) 135187

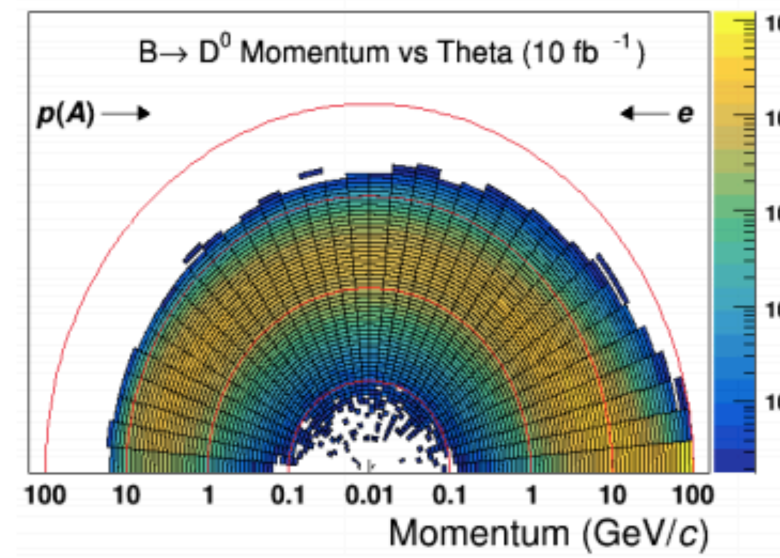

e+p 18+275 GeV
Int. L = 0.005 fb^{-1}
D^0 η∈[-1.0,1.0]
N=208697
e+p 18+275 GeV
Int. L = 0.005 fb^{-1}
D^0 η∈[1.0,2.0]
N=119643
e+p 18+275 GeV
Int. L = 0.005 fb^{-1}
D^0 η∈[2.0,2.5]
N=59343
e+p 18+275 GeV
Int. L = 0.005 fb^{-1}
D^0 η∈[2.5,3.0]
N=53239
$\log_{10}[Q^2$ (GeV^2)]
$\log_{10}$(x)
0
0.5
1
1.5
2
2.5
3
3.5
4
−4
−3
−2
−1
0

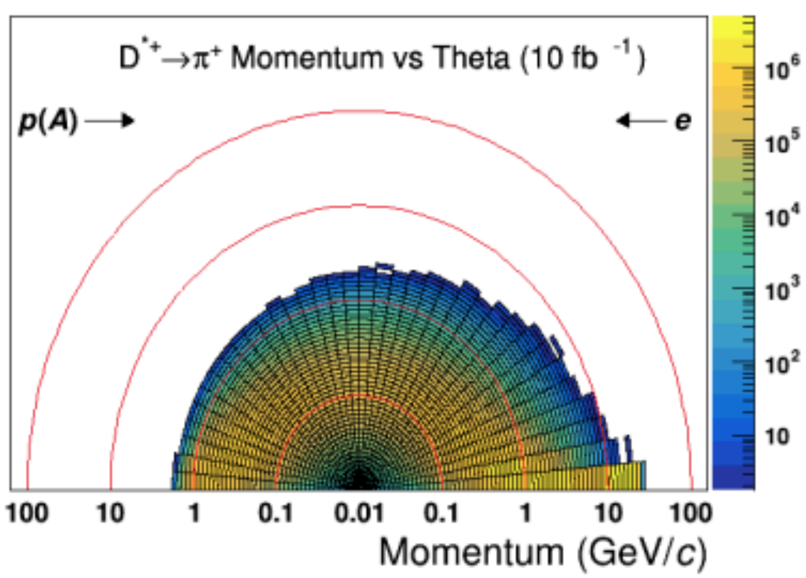
Kinematic Distributions

e + p 18 x 275 PYTHIA 6.4

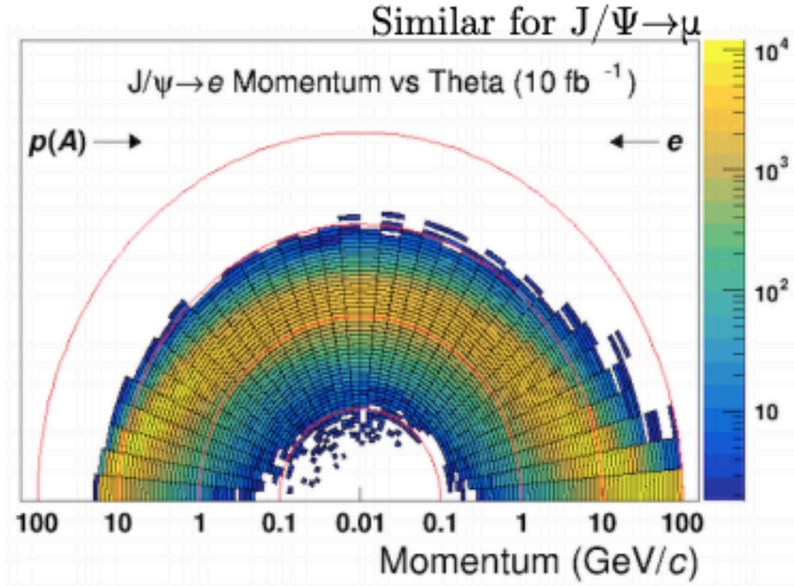


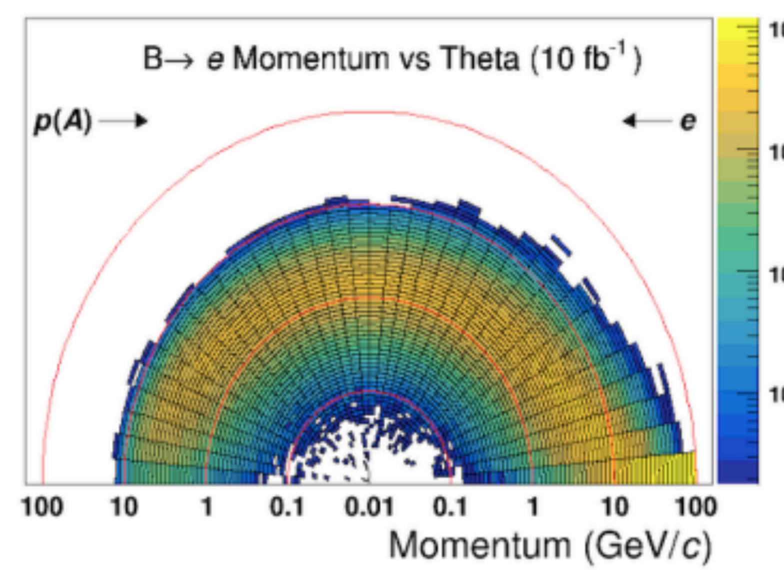






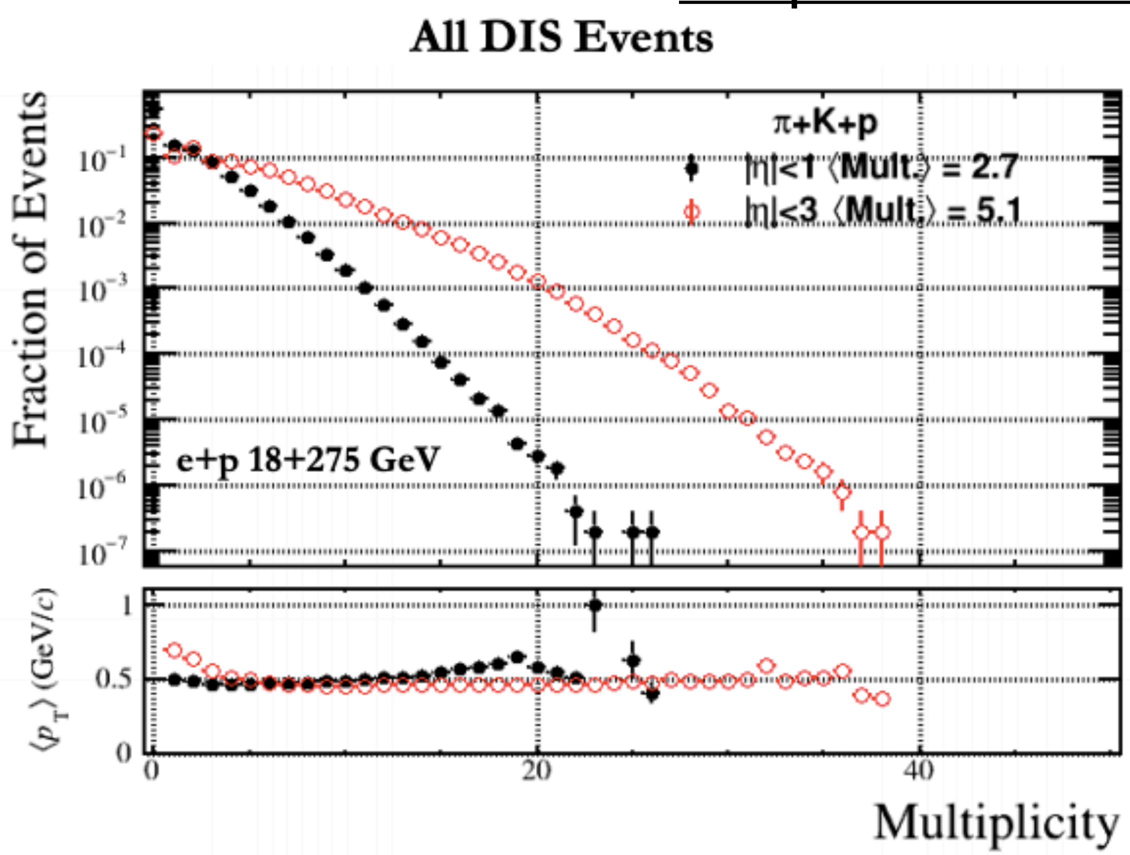
Similar for $J/\Psi \to \mu$

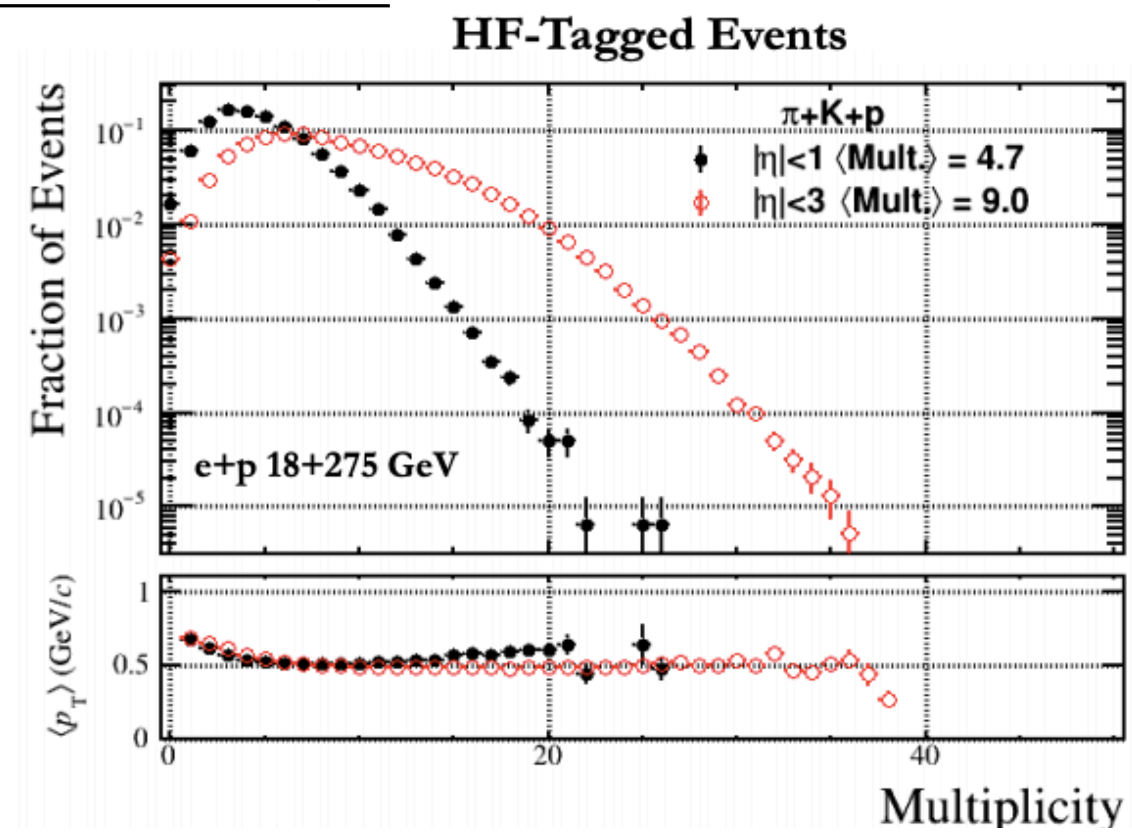


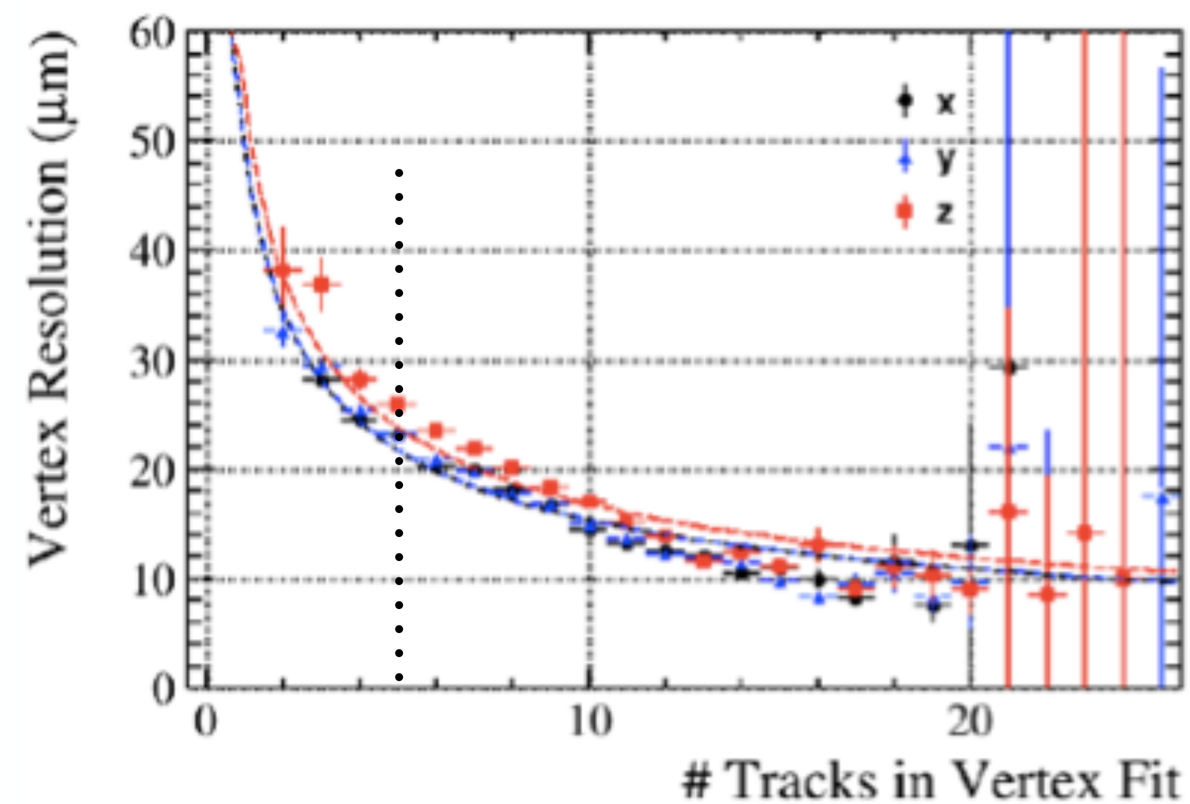


Primary Vertex Resolution

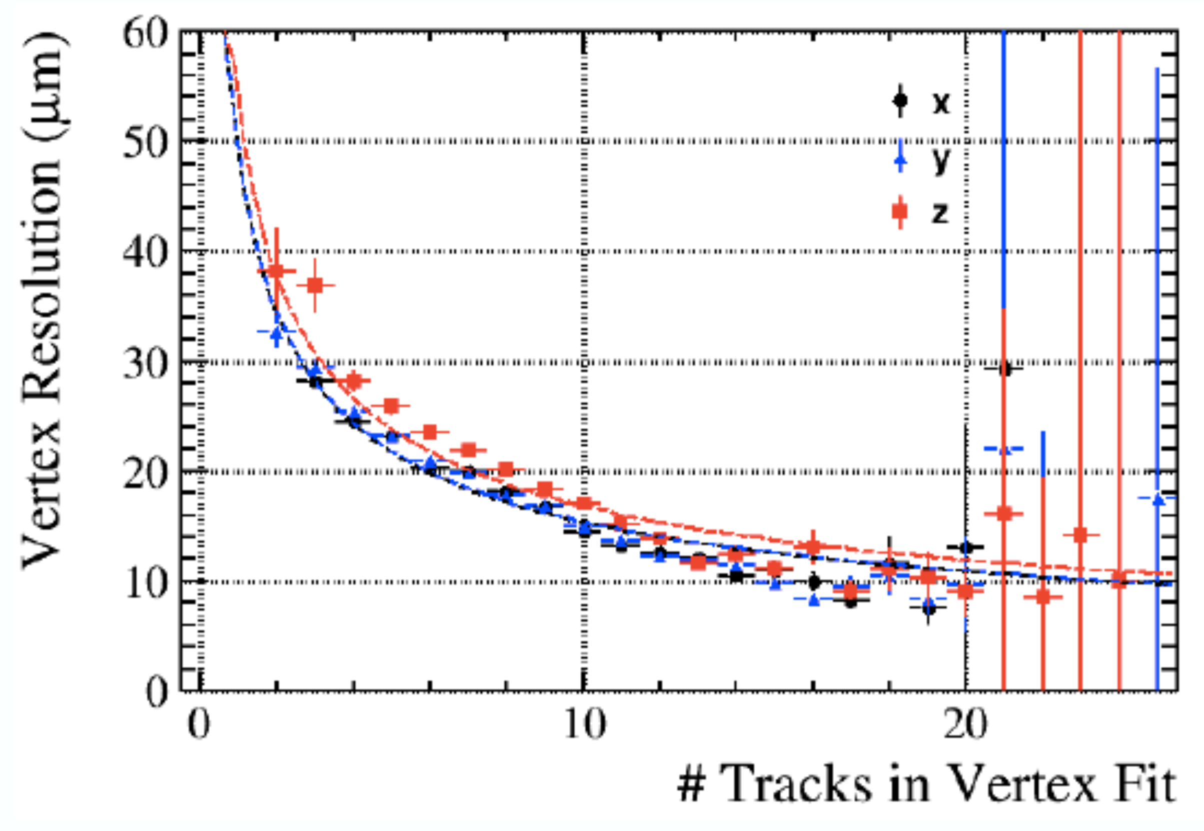
e + p   18 x 275   PYTHIA 6.4

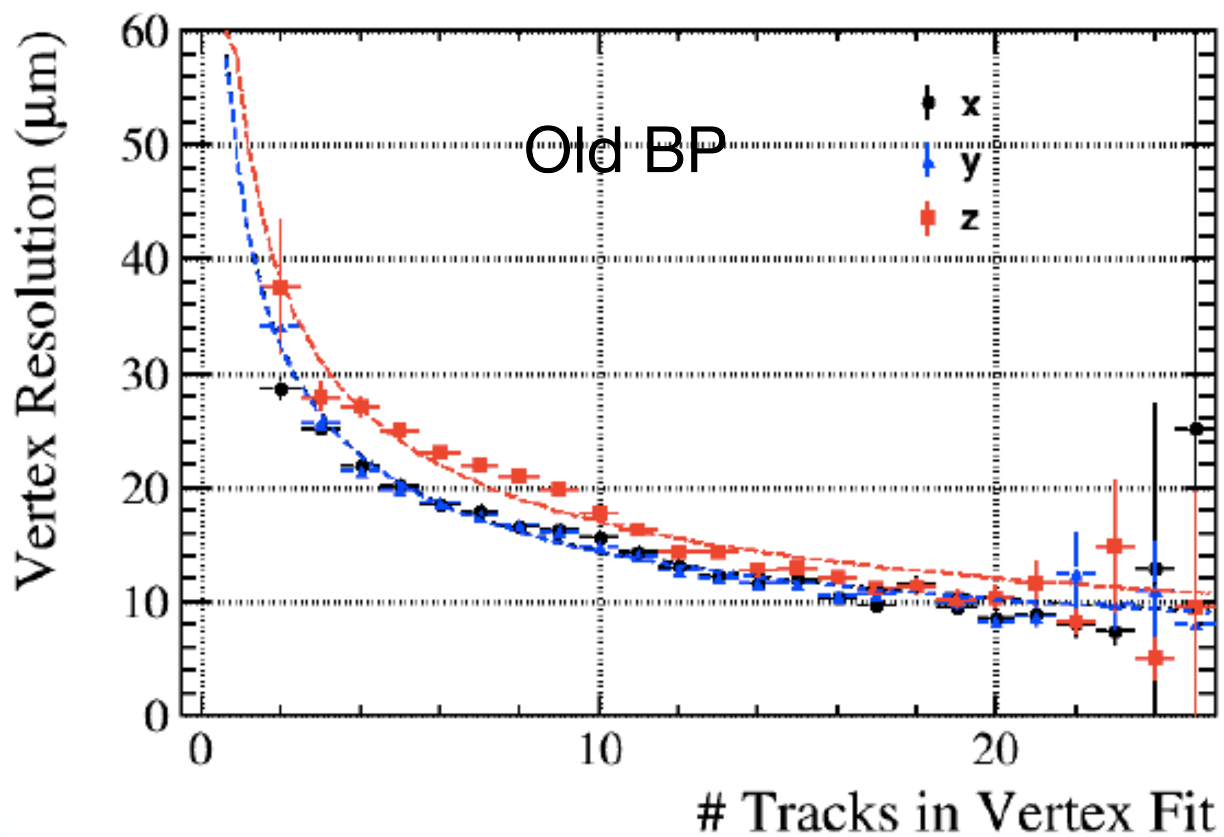




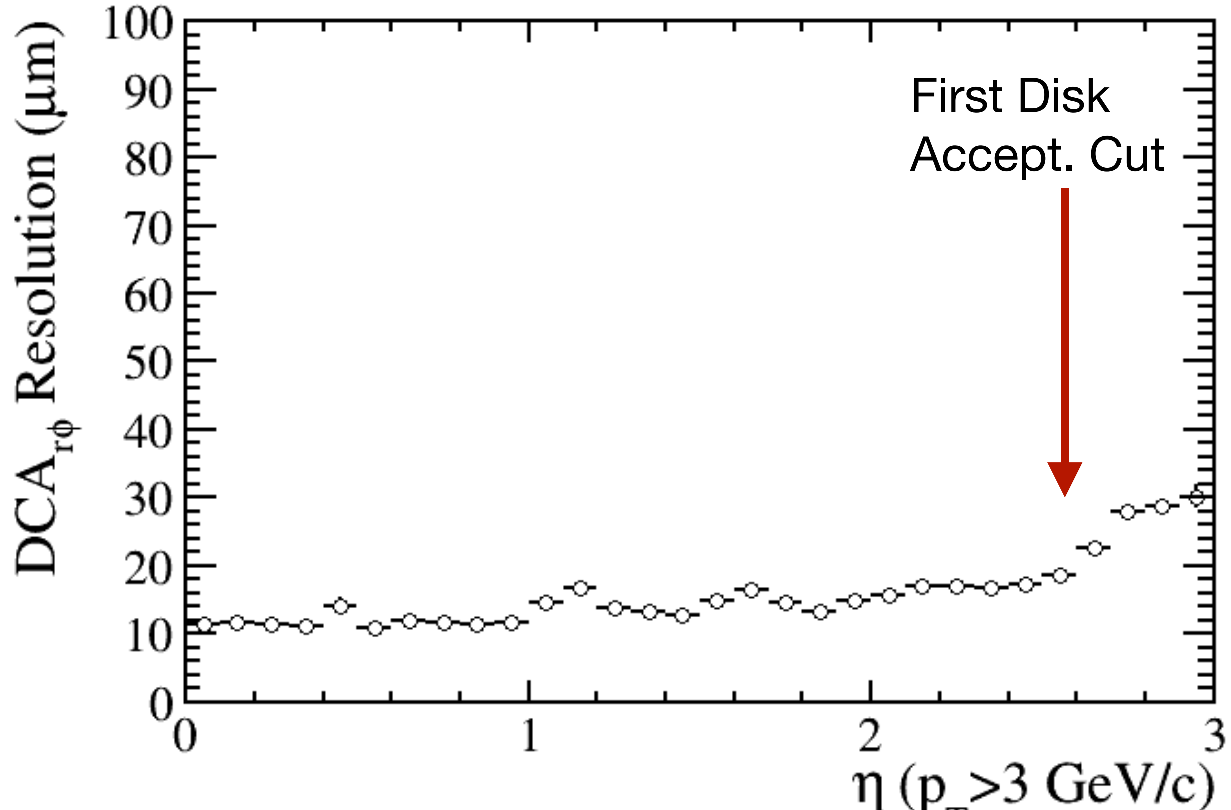


Full Simulation w/ New Beam Pipe



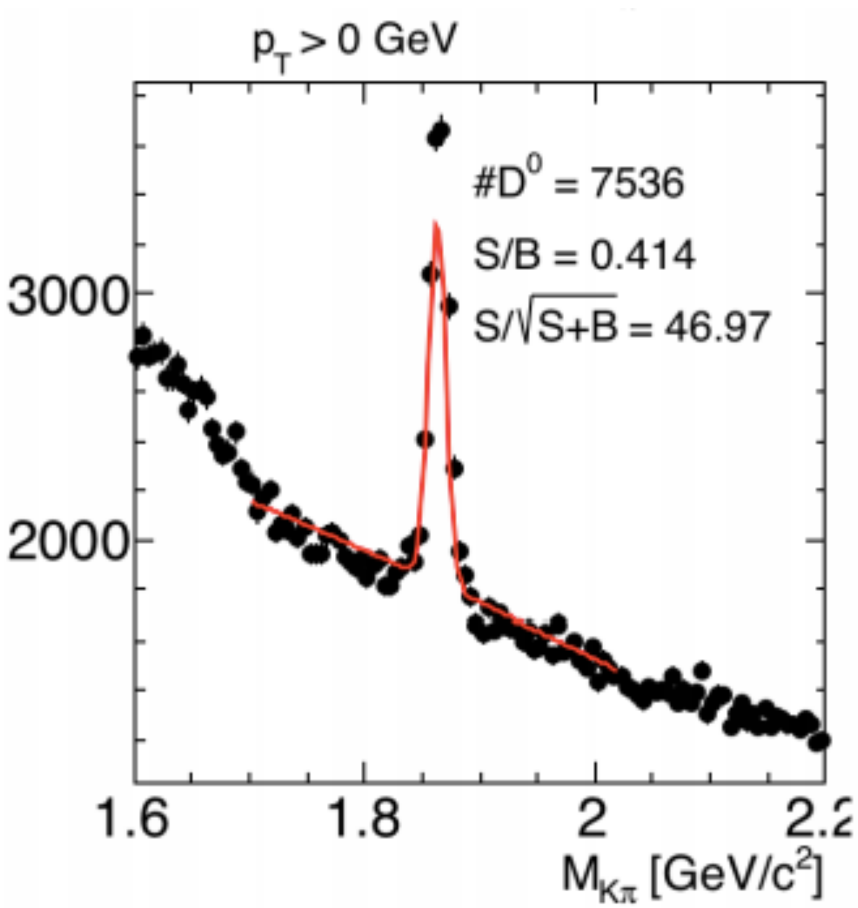


New BP



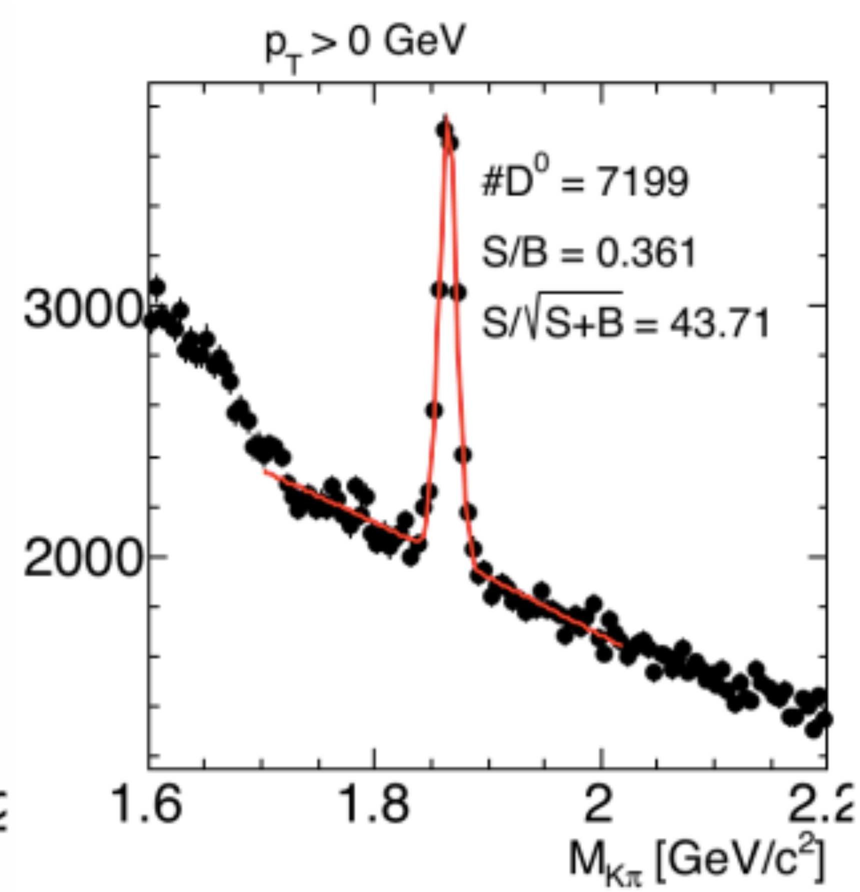
Impact of Pointing Resolution on D^0 Significance

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



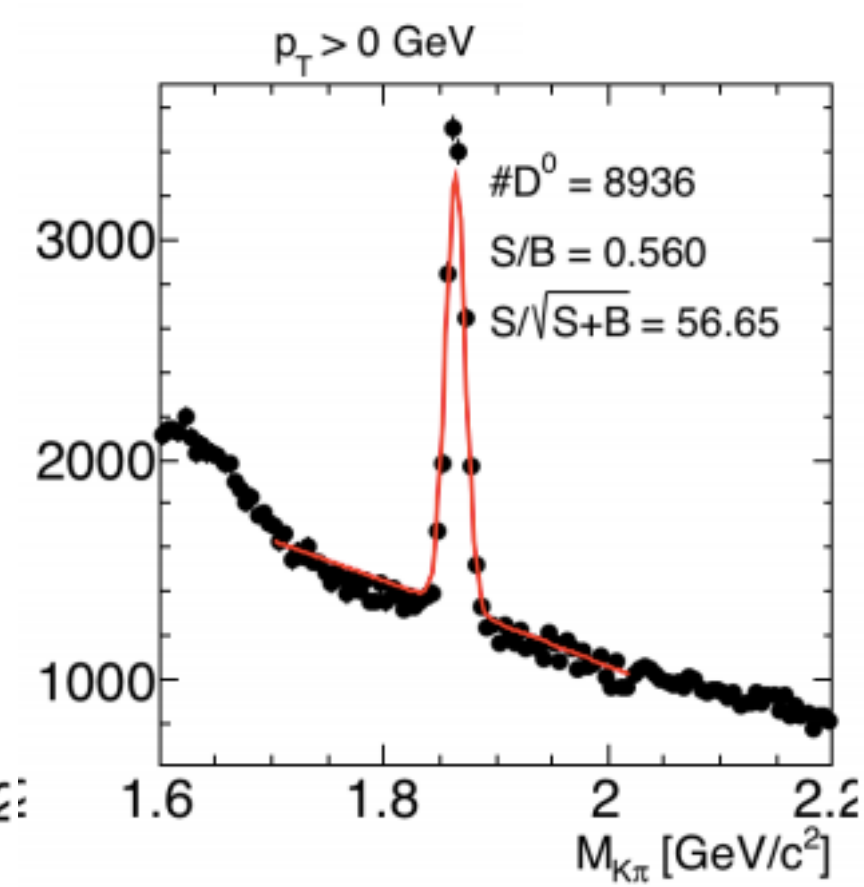
D^0 significance

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



-10%

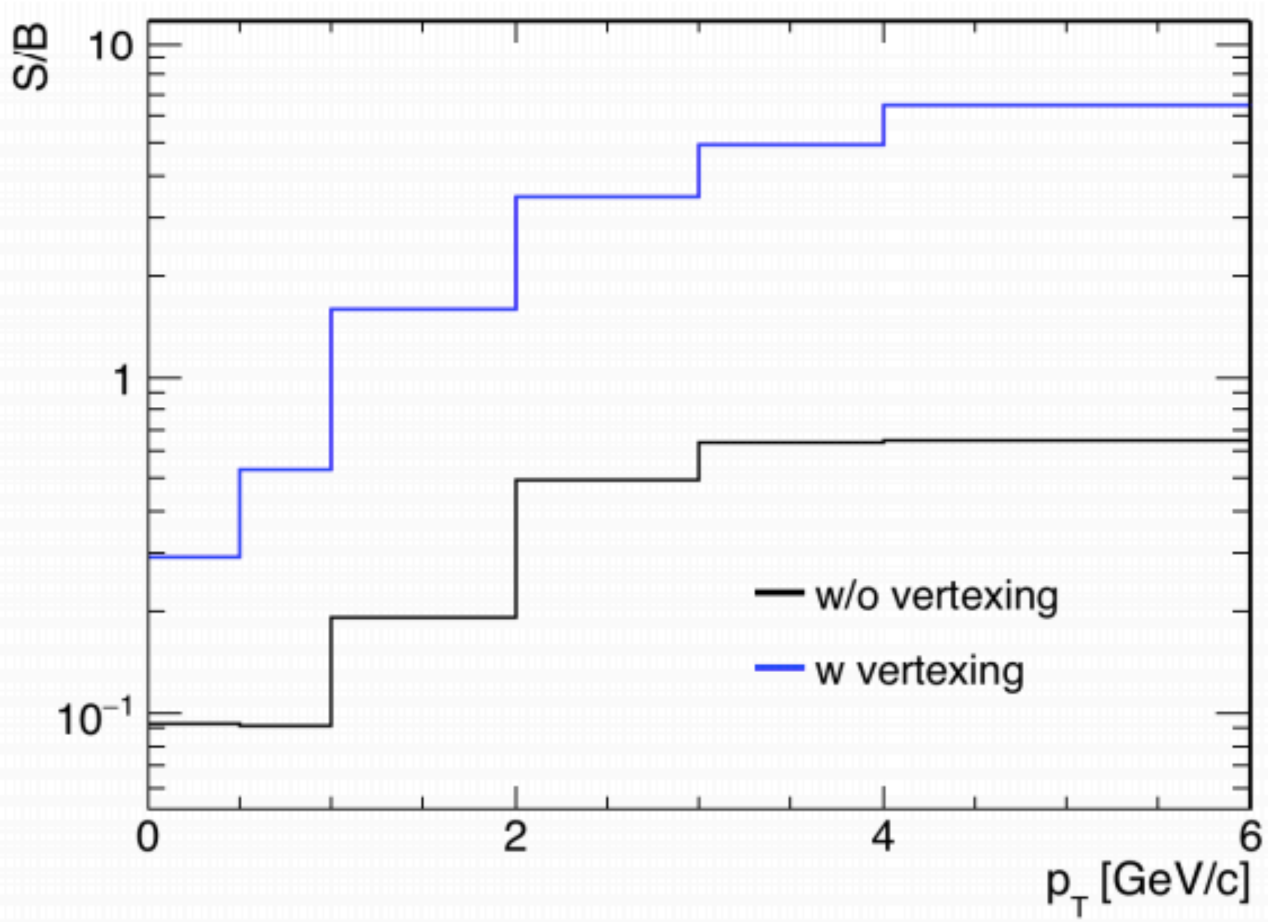
$\sigma \sim 10\mu m$ @ 1 GeV/c

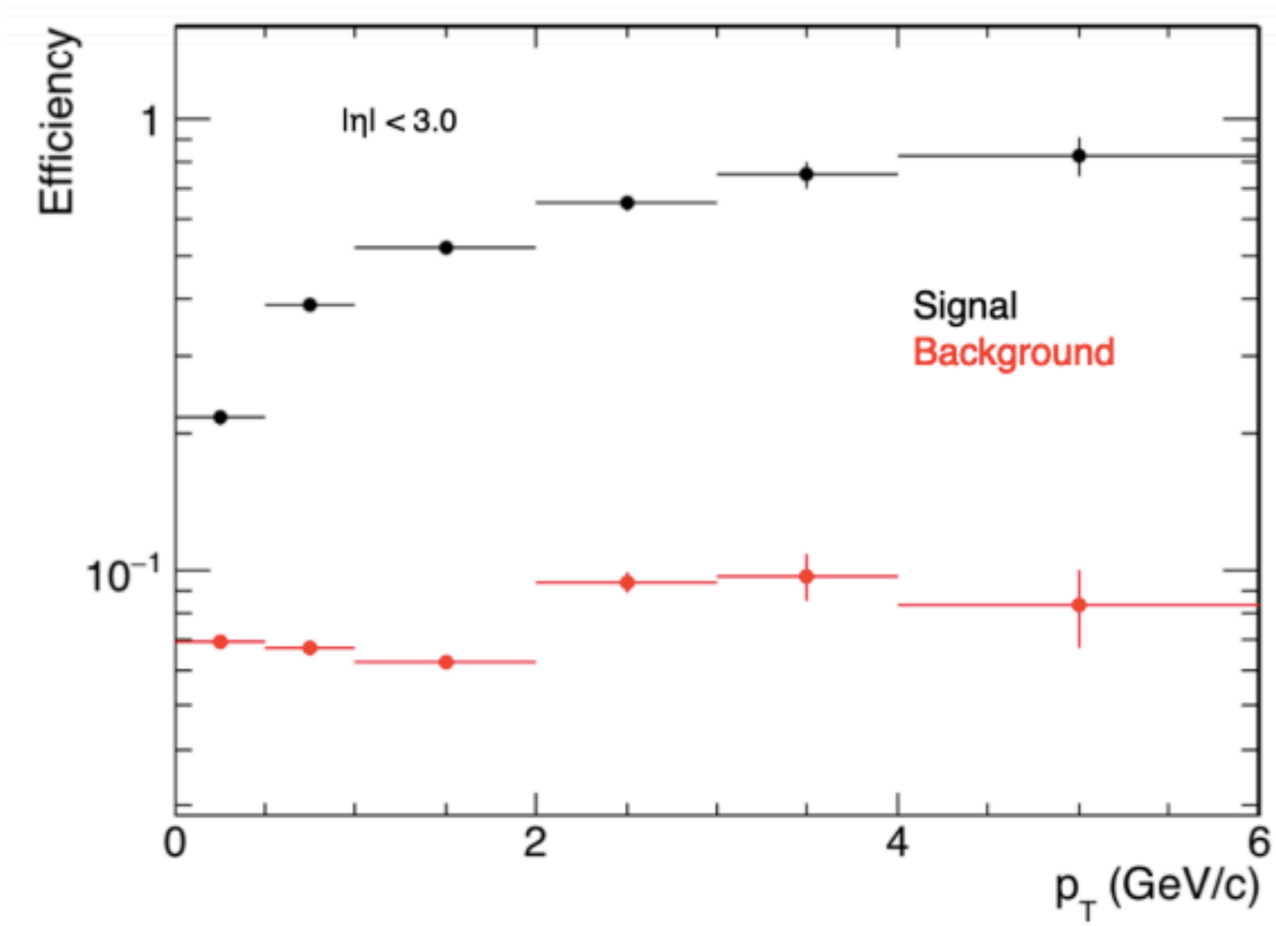


+20%

- vertex res. assumed to be 20 μm

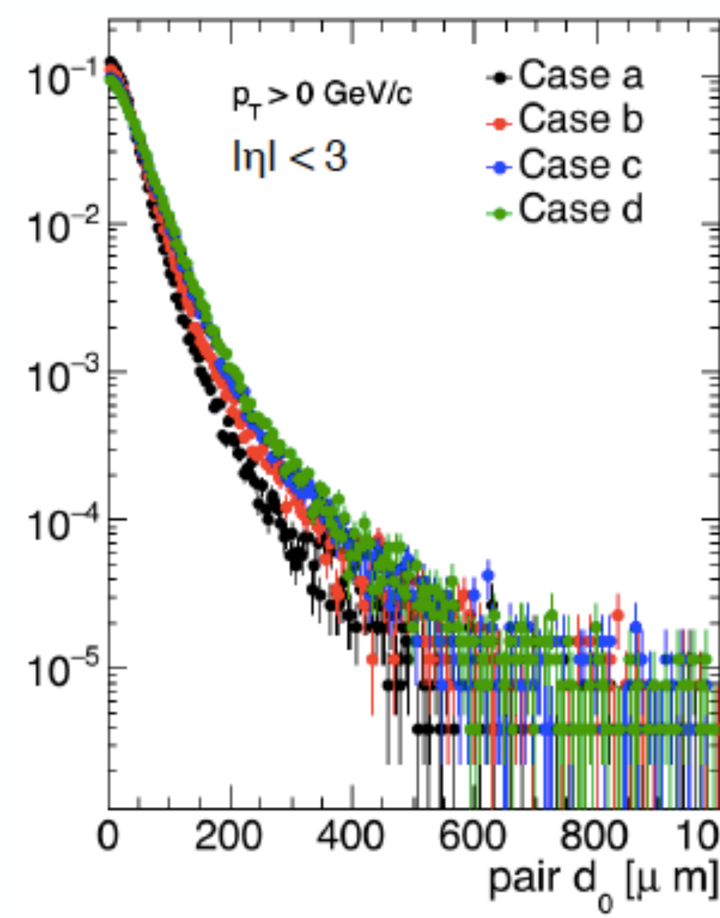
D^0 Topological Reconstruction

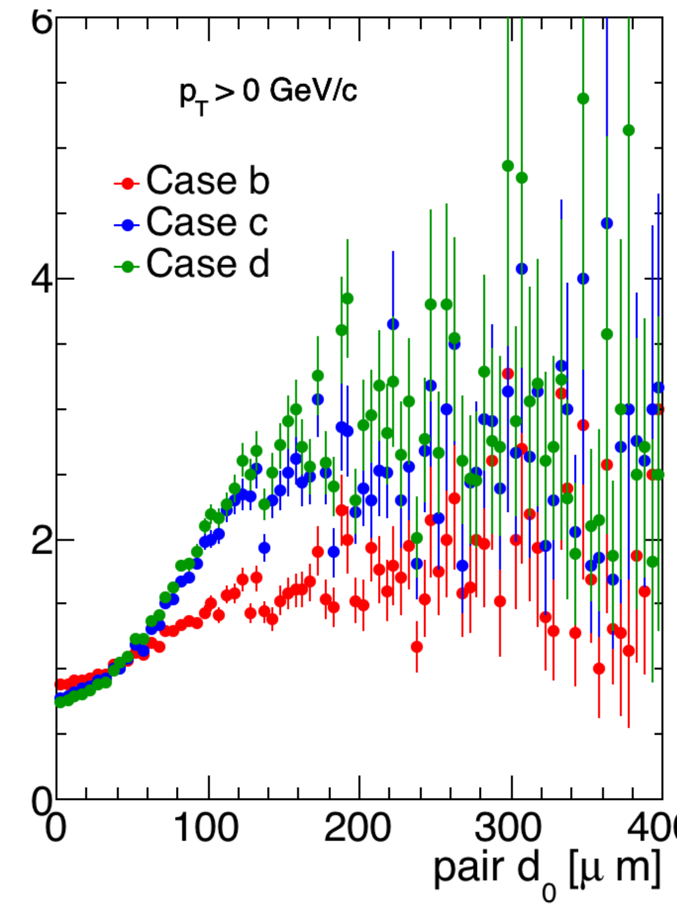


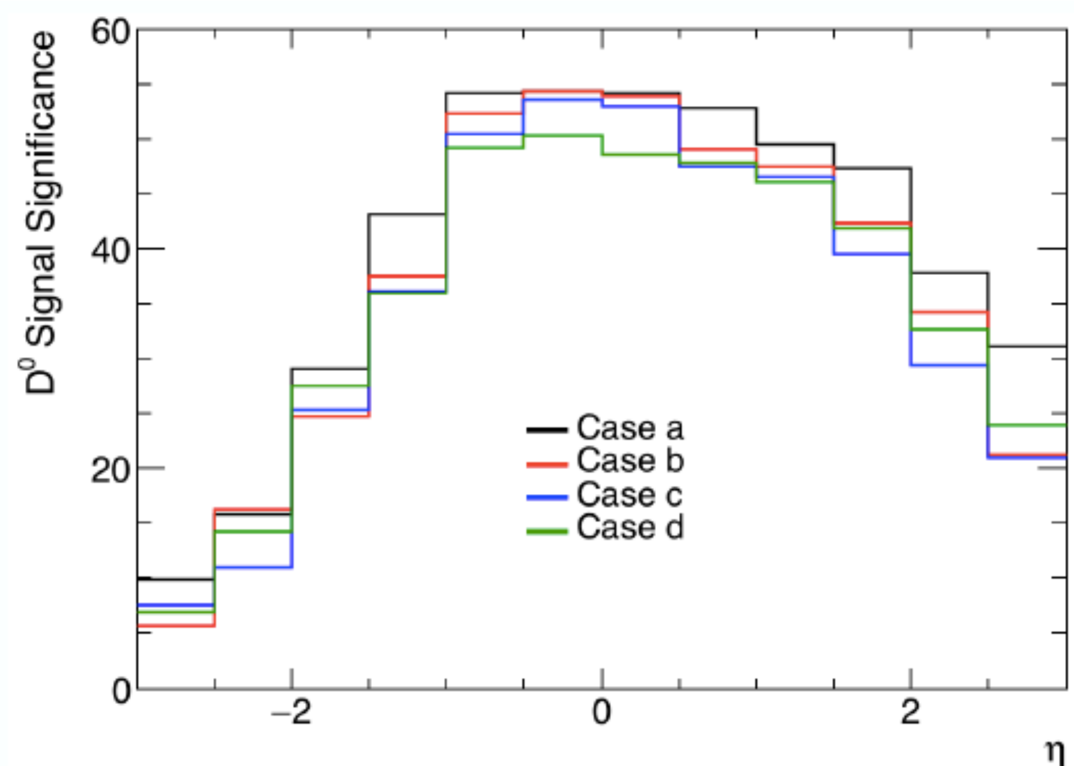


Comparison between Different Scenarios

- 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



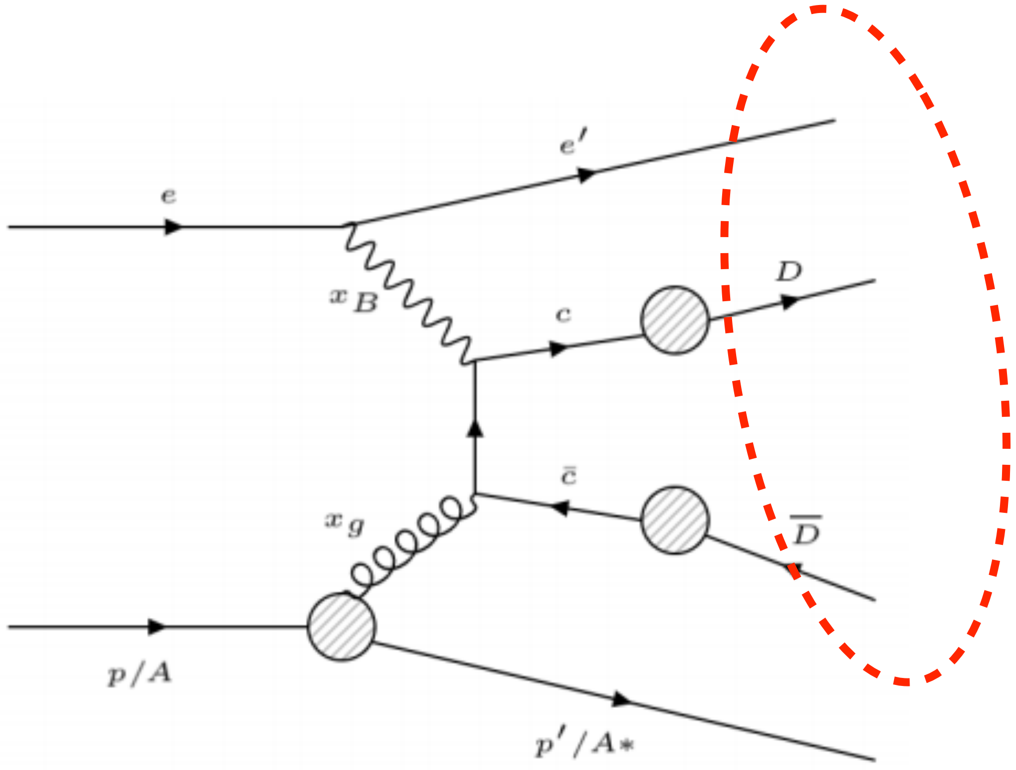




<u>Case b vs. Case c</u>

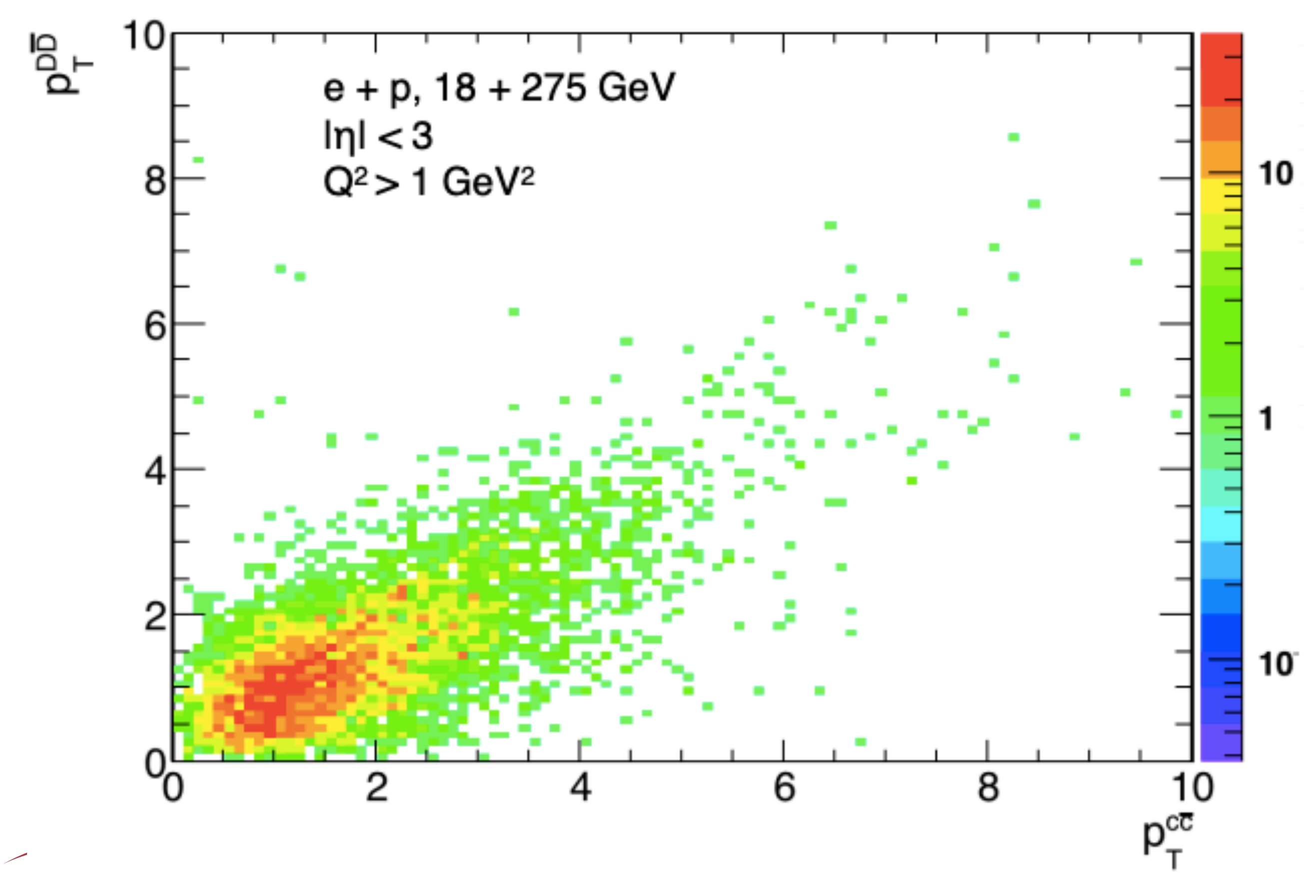
- 10% reduction in D^0 significance in forward region (2<eta<2.5)

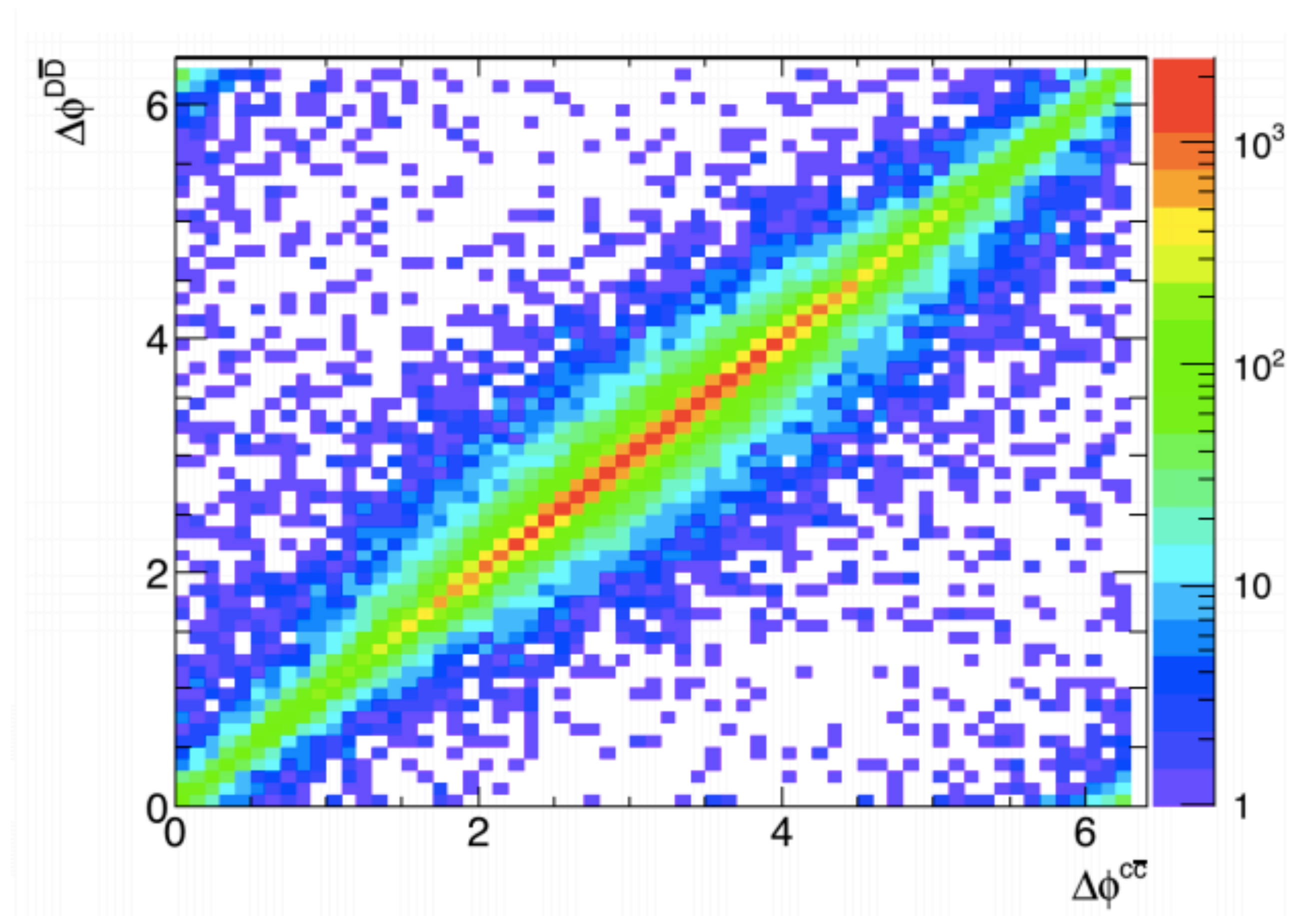
$D\overline{D}$ Pair - Probe Gluon TMDs



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

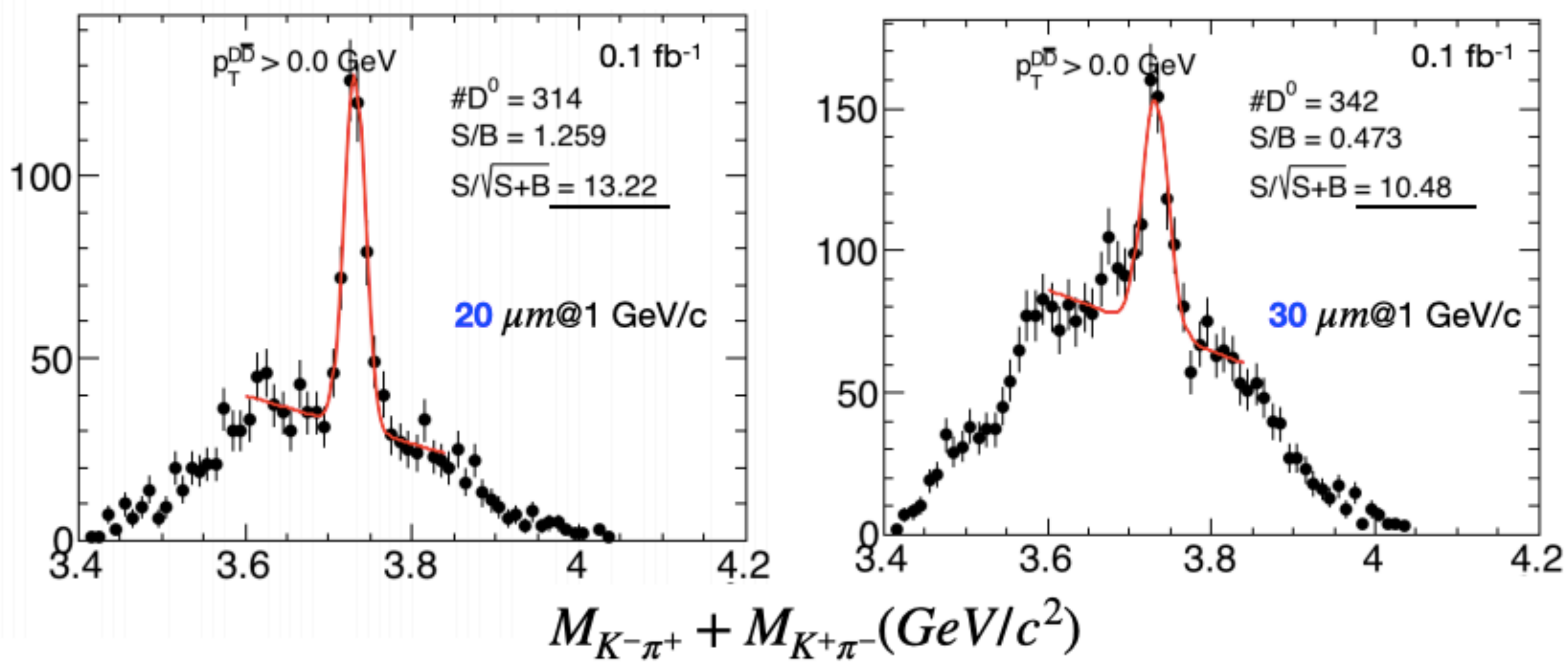
Charm hadron pair in unpolarized exp.
- linearly polarized TMD function





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

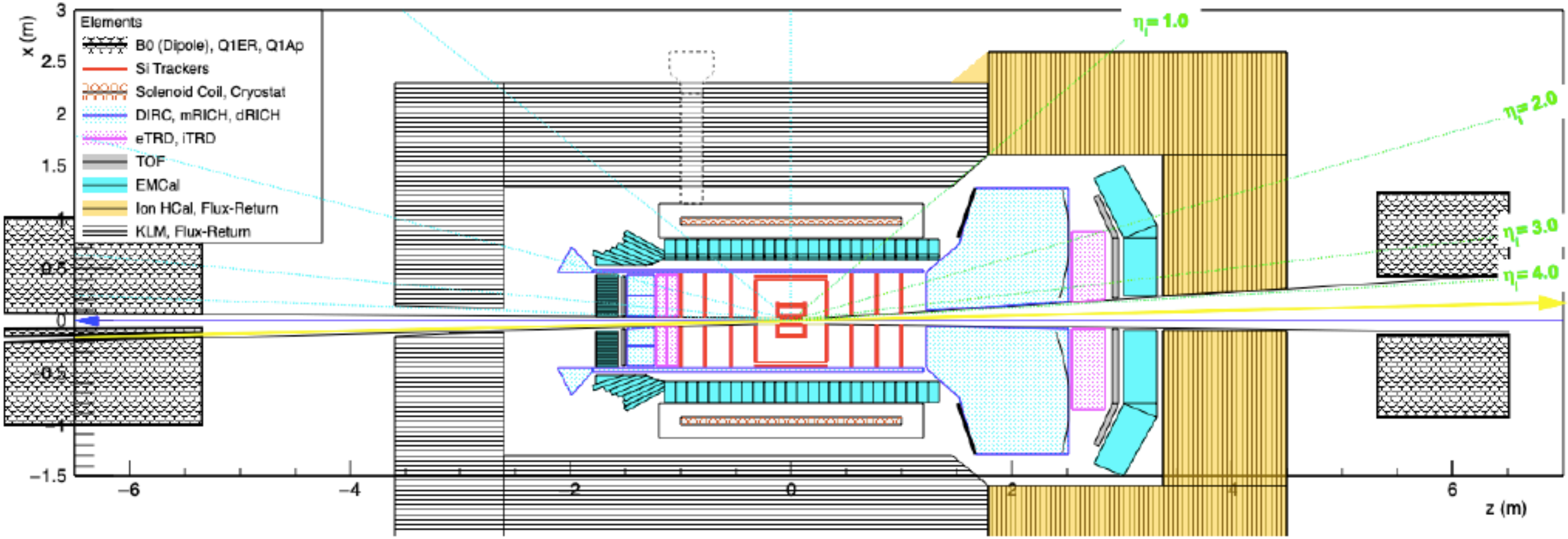


- $\Lambda_c^+ \to pK^-\pi^+$ ($c\tau$~60μm)
  - extremely short lifetime, multi-prong decay → critical requirement on single track pointing resolution

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

All-Si Tracker → Full Compact Detector at EIC

P. Nadel-Turonski, CFNS Seminar Oct. 8, 2020



- A general purpose compact detector can be built based on the all-Si tracker
- The all-Si compact tracker frees more space for other detectors (e.g. PID detector)

Specifications

ALICE

Parameter	ALPIDE (existing)	Wafer-scale sensor (this proposal)
Technology node	180 nm	65 nm
Silicon thickness	50 µm	20-40 µm
Pixel size	27 x 29 µm	O(10 x 10 µm)
Chip dimensions	1.5 x 3.0 cm	scalable up to 28 x 10 cm
Front-end pulse duration	~ 5 µs	~ 200 ns
Time resolution	~ 1 µs	< 100 ns (option: <10ns)
Max particle fluence	100 MHz/cm^2	100 MHz/cm^2
Max particle readout rate	10 MHz/cm^2	100 MHz/cm^2
Power Consumption	40 mW/cm^2	< 20 mW/cm^2 (pixel matrix)
Detection efficiency	> 99%	> 99%
Fake hit rate	< 10^{-7} event/pixel	< 10^{-7} event/pixel
NIEL radiation tolerance	~3 x 10^{13} 1 MeV n_{eq}/cm^2	10^{14} 1 MeV n_{eq}/cm^2
TID radiation tolerance	3 MRad	10 MRad

M. Mager | ITS3 kickoff | 04.12.2019 |

	ALPIDE		MALTA
Experiment	ALICE ITS (inner/outer layers)		ATLAS ITk pixel Phase II (outermost layer)
Technology	TJ 180 nm CIS	*65nm*	TJ 180 nm CIS modified
Substrate resistivity [kOhm cm]	> 1 (epi-layer 18-25 um)		
Collection electrode	small		
Detector capacitance [fF]	<5		
Chip size [cm x cm]	1.5 x 3		2 x 2
Pixel size [um x um]	**28 x 28**	*O(10x10)*	**36.4 x 36.4**
Peaking time [ns]	**2×10^3**		**20 – 50**
Time resolution [ns]	**N/A**	*~100*	**< 5**
Particle rate [kHz/mm^2]	10		10^3
Readout architecture	Asynchronous		
Analogue power [mW/cm^2]	**5.4**		**~ 70**
Digital power [mW/cm^2]	**31.5/14.8**		**2.5 (0.84 MHz/mm^2) 79.6 (27.2 MHz/mm^2) (matrix only)**
Total power [mW/cm^2]	**36.9/20.2**	*<20*	**~70 – 150 depending on rate**
NIEL [1MeV n_{eq}/cm^2]	1.7×10^{13}	*10^{14}*	$> 1.0 \times 10^{15}$
TID [Mrad]	2.7	*10*	100