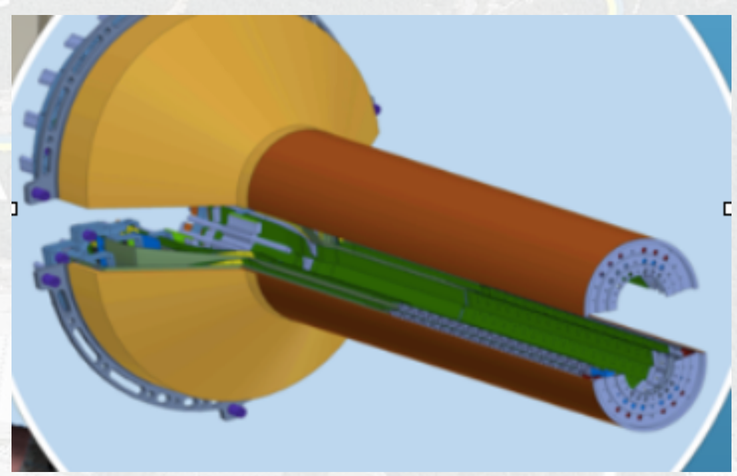
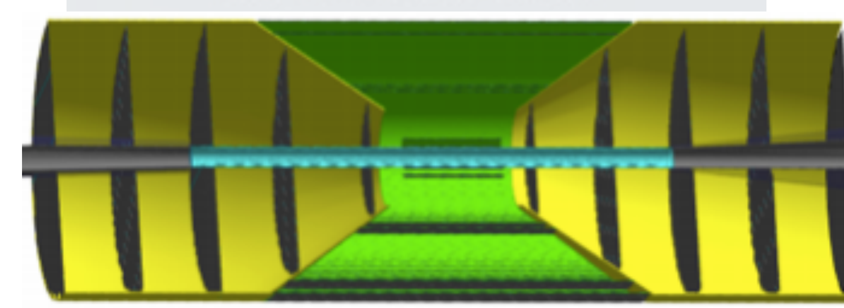
Heavy Flavor Measurements from RHIC to EIC

Xin Dong (Lawrence Berkeley National Laboratory)

STAR HFT



sPHENIX MVTX

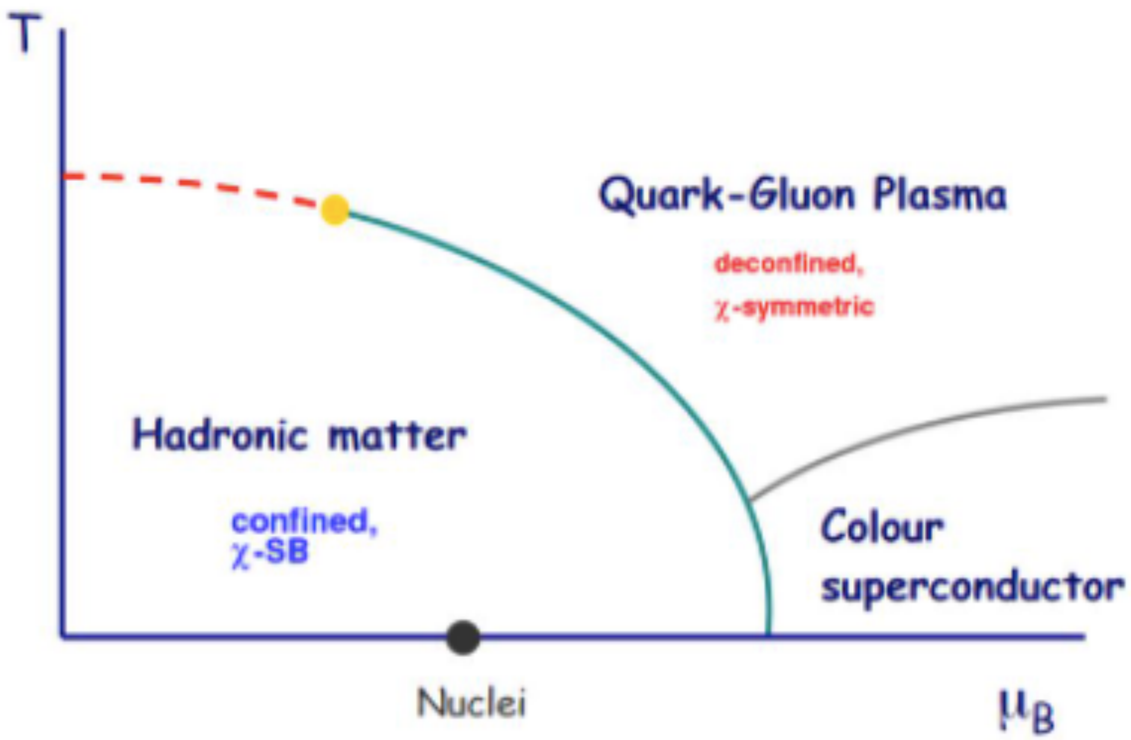


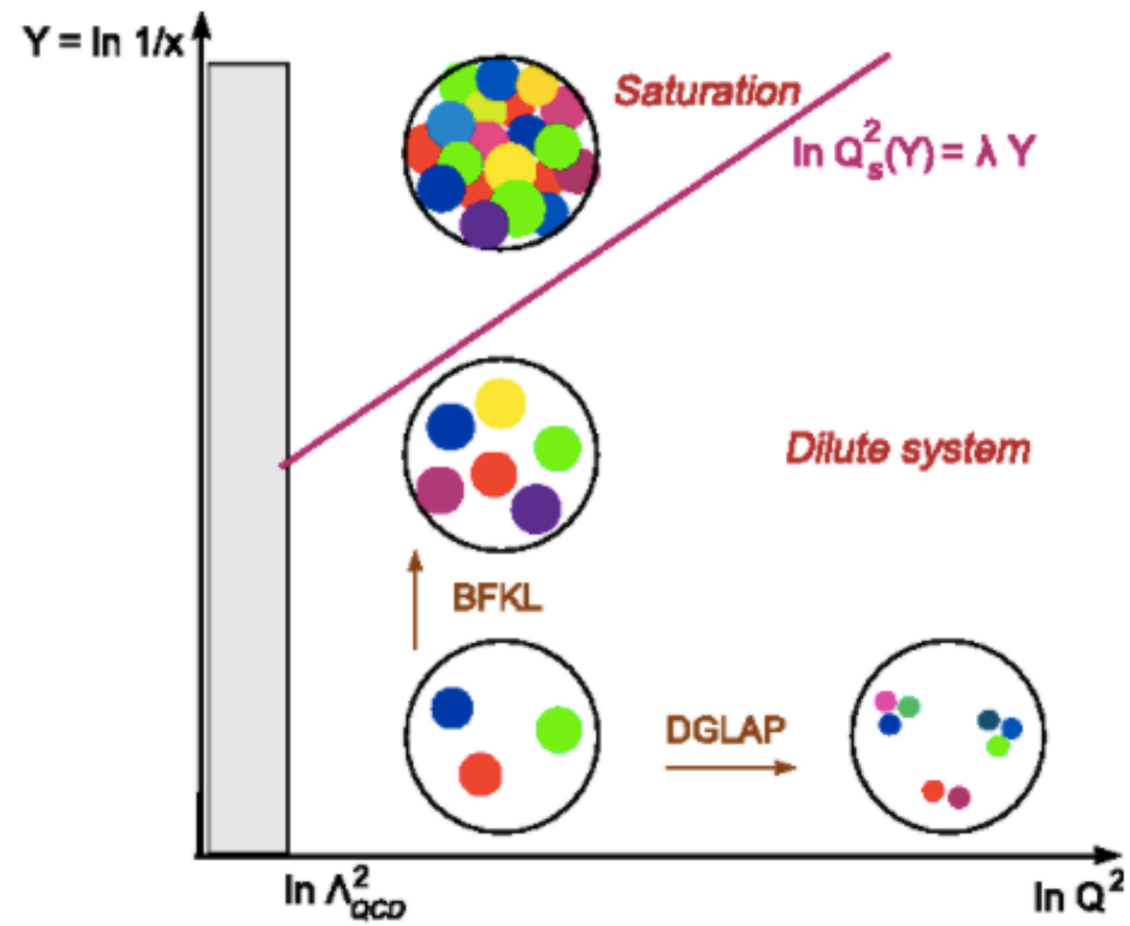
All Si-Tracker

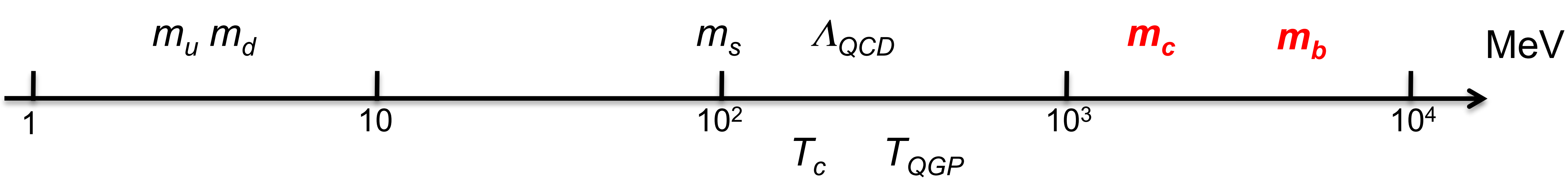
Outline

- Introduction
- Heavy flavors at RHIC to date (-2021)
  - *Quantifying QGP properties - Phase-I*
- Heavy flavors at RHIC in near future (2022 - 202x)
  - *Quantifying QGP properties - Phase-II*
  - *Glimpsing at gluon distributions in nucleon/nucleus*
- Heavy flavors at EIC (203x -)
  - *Scrutinizing gluon dynamics in nucleon/nucleus*
- Summary

Heavy Flavors: Unique Probes to Hot and Cold QCD



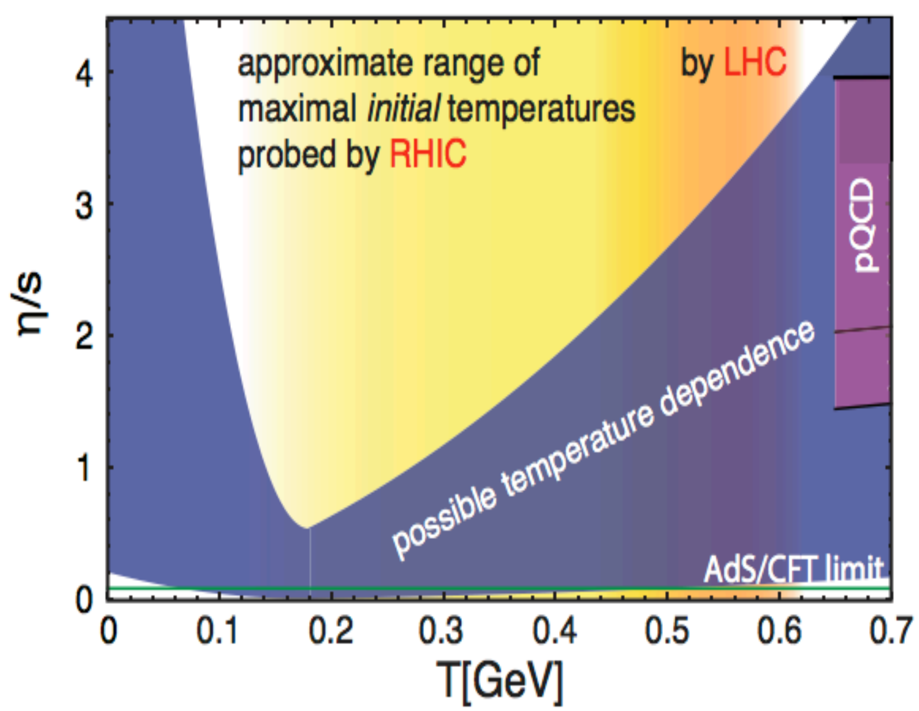




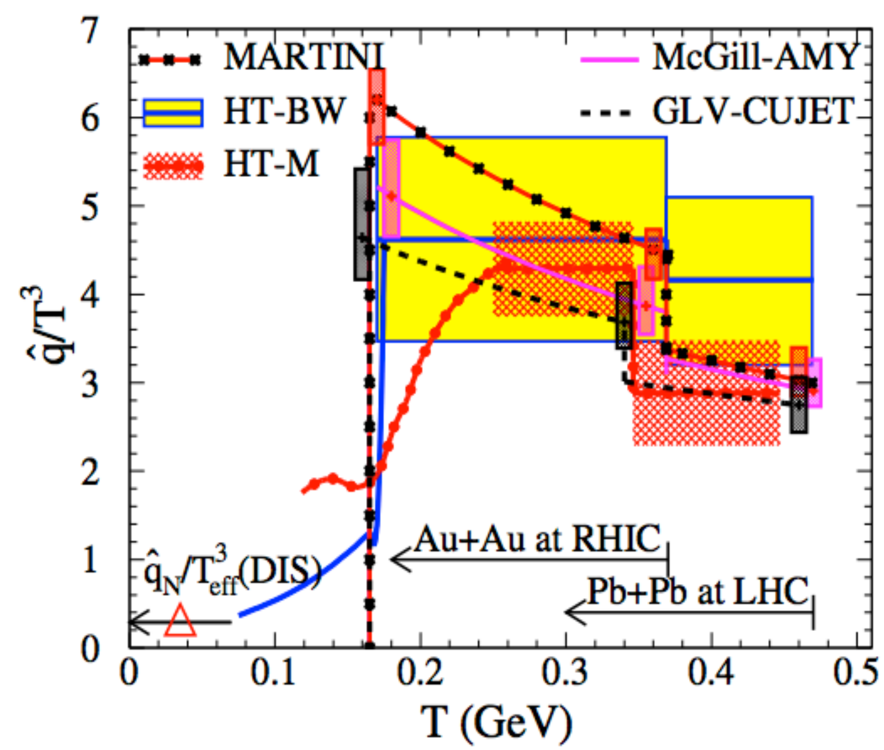
Hot QCD:	HFs retain QGP dynamics	- **microscopic structure of QGP**
Cold QCD:	HFs access to gluon dynamics	- **gluonic structure of nucleon/nucleus**

RHIC Mission: Quantitative Measure of QGP

~2 ~6 p_T (GeV/c)



Hot QCD white paper - arXiv: 1502.02730



JET Coll., PRC 90 (2015) 014909

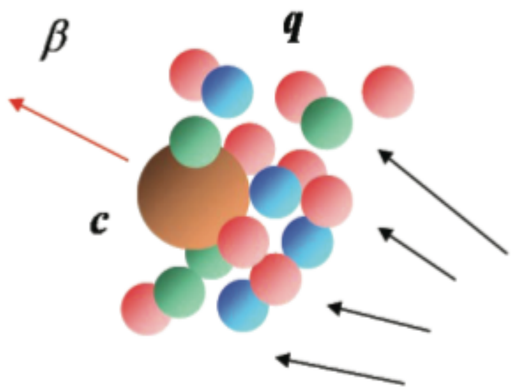
?

strongly coupled ⟷ weakly coupled

hydrodynamics pQCD

What is the microscopic picture of "perfect fluid"?

Heavy Flavor Quark Transport in QGP



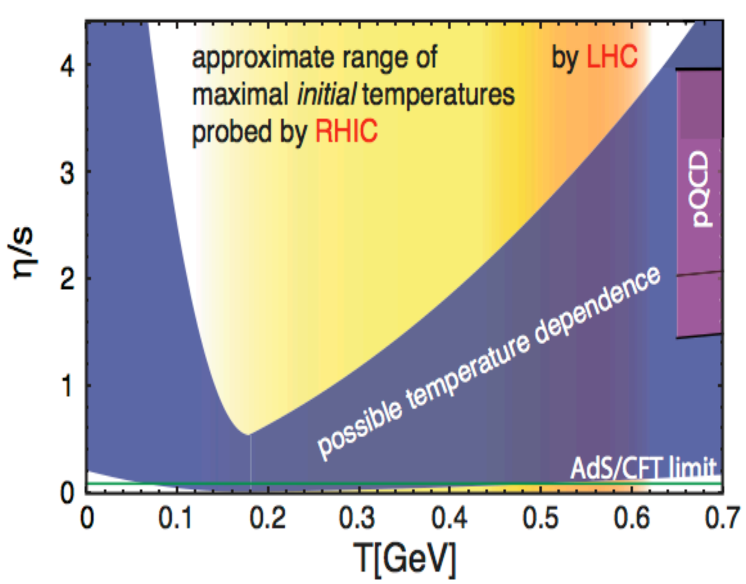
Femtoscopic "Brownian" motion

Langevin stochastic equation

$$\frac{d\vec{p}}{dt} = -\eta_D(p)\vec{p} + \vec{\xi}$$

$M_Q >> T$, $M_Q >> gT$

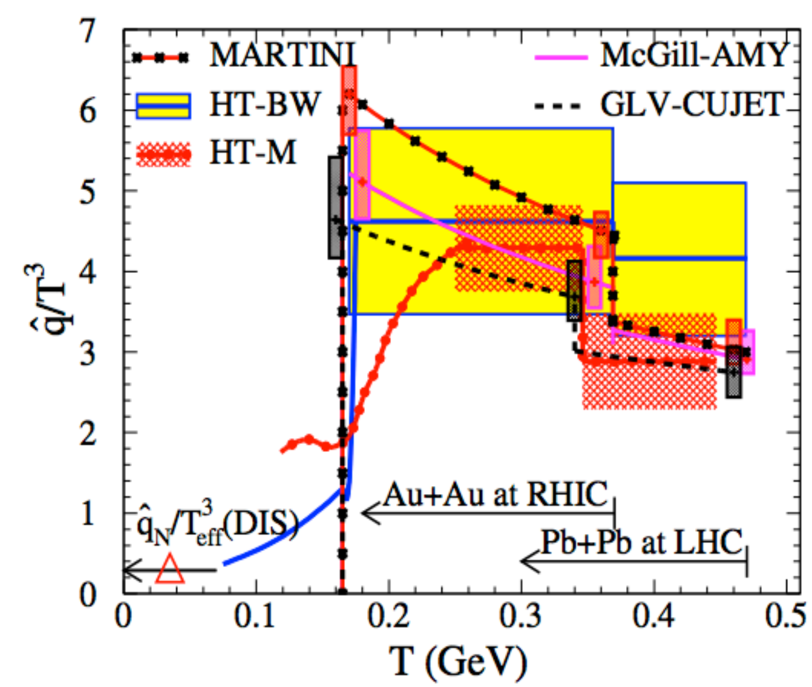
$$D_s \equiv \frac{\langle x^2(t)\rangle - \langle x^2(0)\rangle}{2dt} = \frac{t}{M\eta_D(p=0)}$$



$$D_s(2\pi T) \sim \eta/s$$

ratio depends on the strong/weak coupling nature of QGP

R. Rapp and H. van Hees, 0903.1096



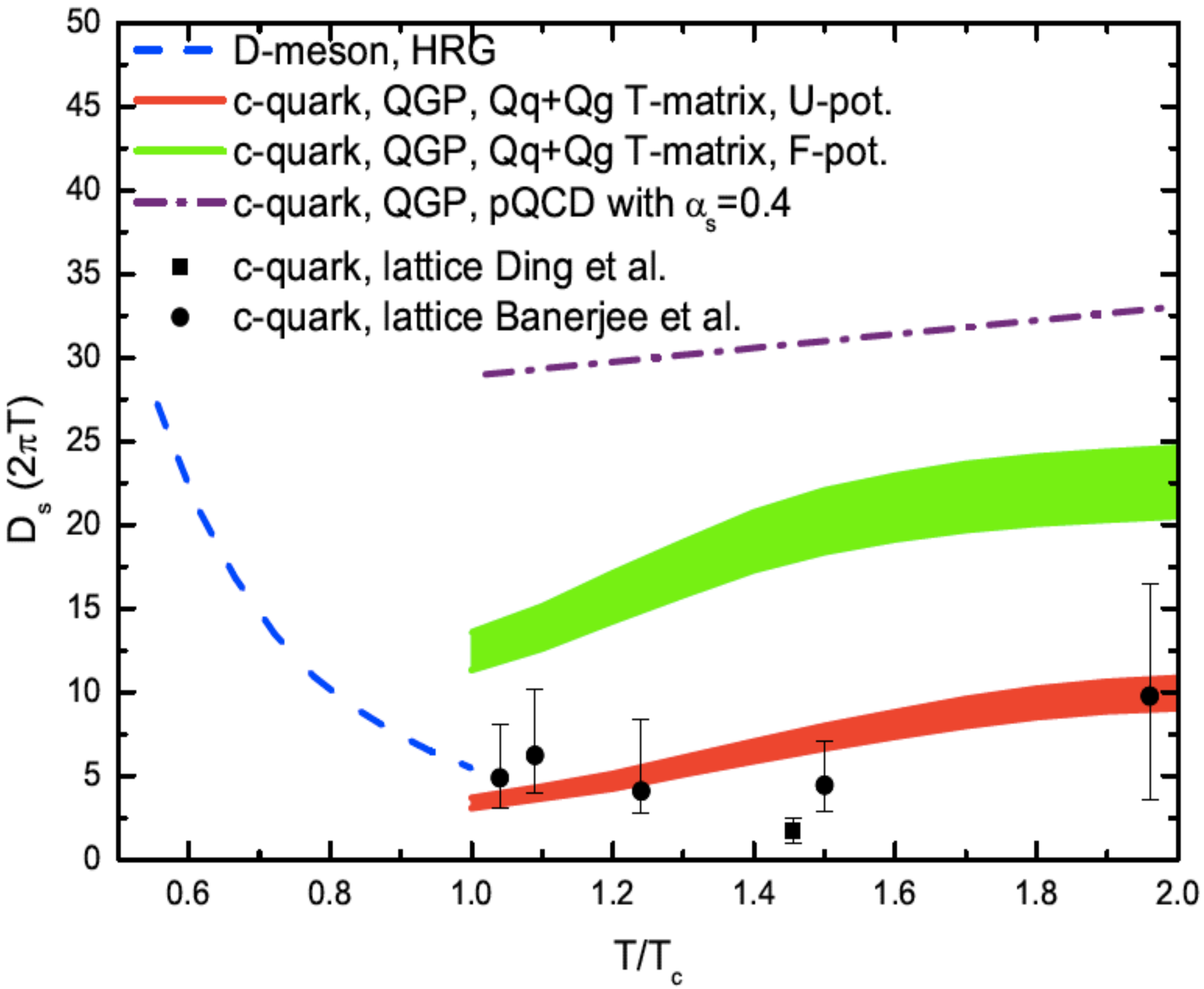
$$\hat{q} = \frac{\Delta p_T^2}{\lambda} = \frac{4D_p E_p}{p} \qquad 2\pi T D_S = \frac{8\pi T^3}{\hat{q}(p \to 0)}$$

collisional vs. radiative energy loss

Heavy quark transport – to probe QGP with comprehensive p_T coverage

- unique insights to both perturbative and non-perturbative regimes

Heavy Quark Diffusion Coefficient



HotQCD white paper - arXiv: 1502.02730

2015

- $2\pi T D_s$ ~ up to 30 @ T_c

To determine HQ diffusion coefficient

Precision measurement of D^0 production (R_{AA} and v_2), particularly at low p_T

$D^0 \rightarrow K^-\pi^+$ $\qquad c\tau \sim 123\mu m$

$\Lambda_c^+ \rightarrow pK^-\pi^+$ $\qquad c\tau \sim 60\mu m$

Big Challenge

Combinatorial background in heavy-ion collisions

Silicon pixel detector to separate secondary decay vertex
- *STAR* ***Heavy Flavor Tracker (HFT)*** *upgrade*
- *PHENIX VTX/FVTX upgrade*

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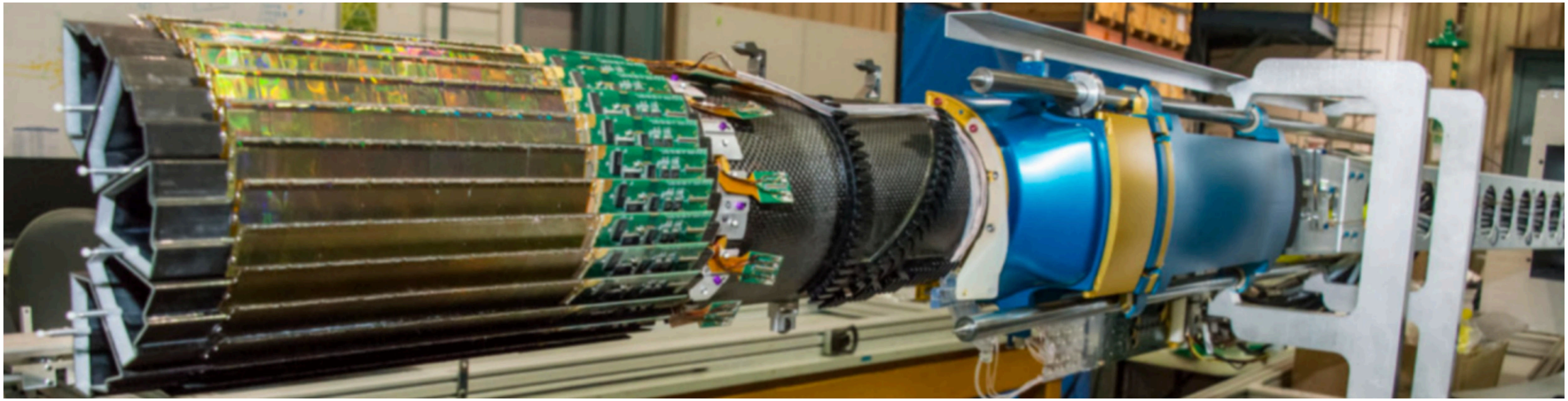
STAR Heavy Flavor Tracker (HFT)



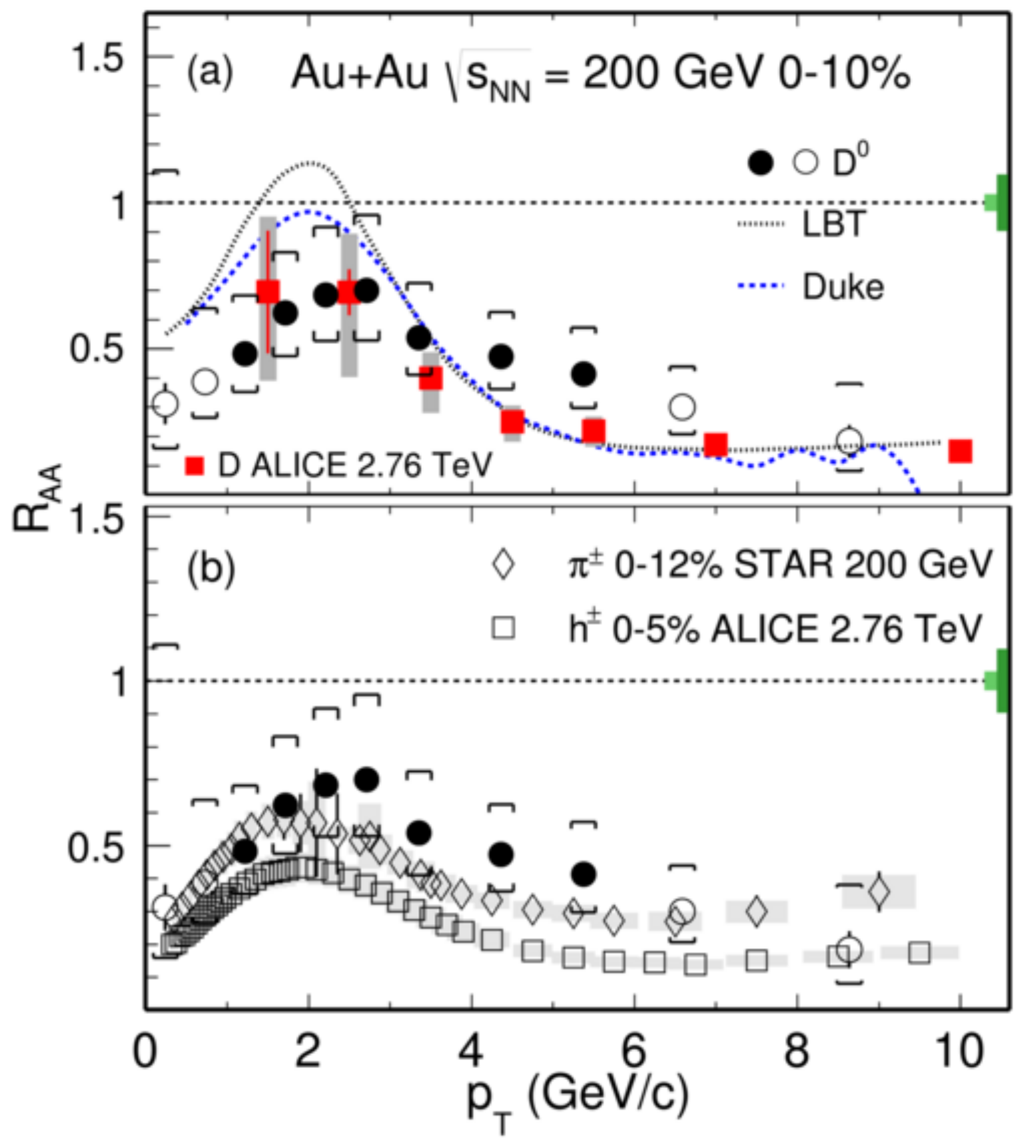
G. Contin et al, NIMA 907 (2018) 60

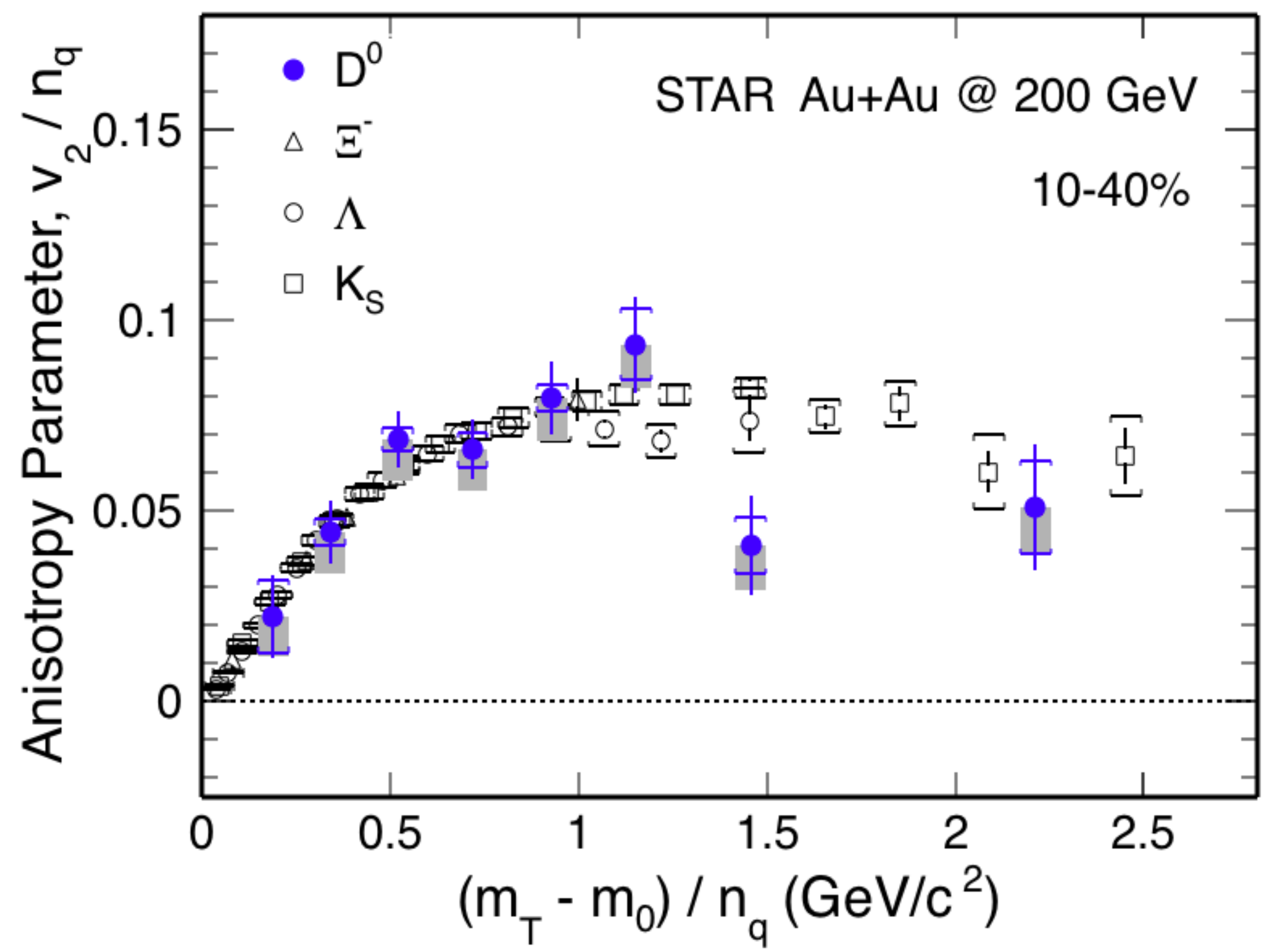
Detector	Radius (cm)	Pitch Size R/φ - Z (μm - μm)	Thickness
Silicon **S**trip **D**etector	22	95 / 40000	1% X_0
Intermediate **S**ilicon **T**racker	14	600 / 6000	1.3%X_0
Pi**X**e**L**	8	**20.7 / 20.7**	0.5%X_0
	2.8	**20.7 / 20.7**	**0.4%X_0** *

- First application of Monolithic Active Pixel Sensor (MAPS) at a collider experiment
- MAPS technology widely used/planned in NP experiments
  - ALICE ITS2/ITS3, sPHENIX MVTX, CBM MVD, EIC Si Tracker

D^0 Meson R_{AA}/R_{CP} in A+A Collisions

STAR, PRC 99 (2019) 034908

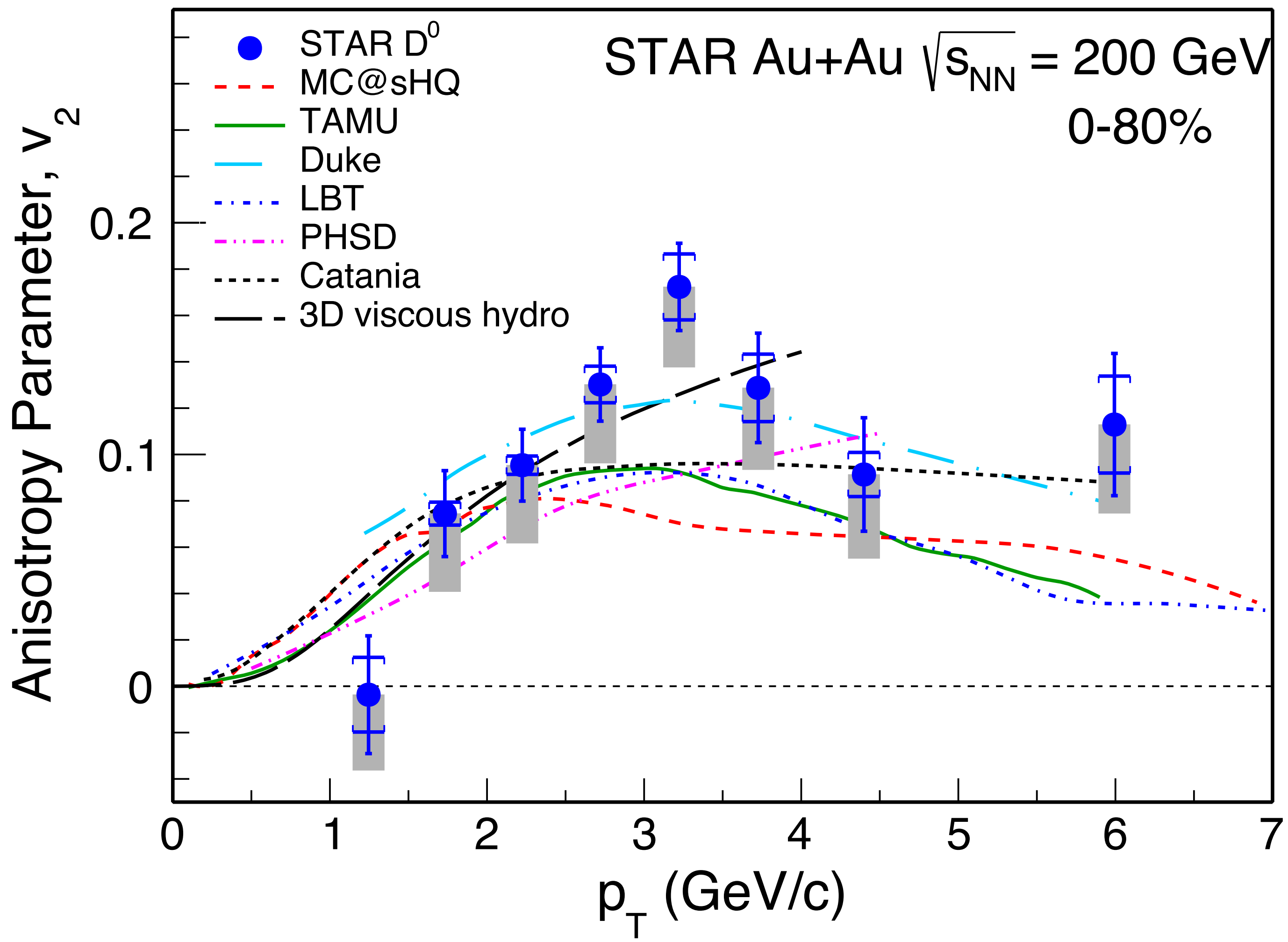




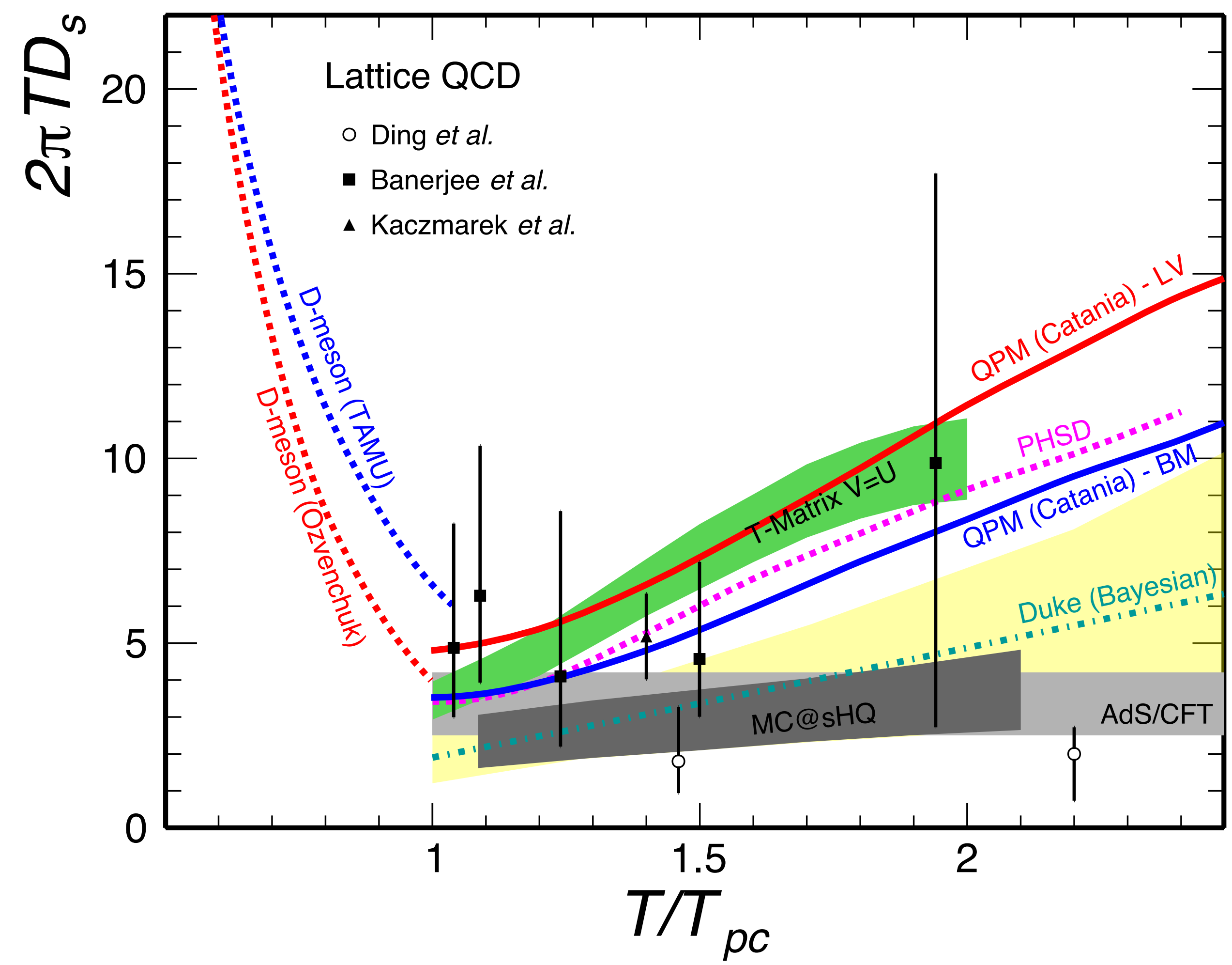
- $R_{AA}(D) \sim R_{AA}(h)$ at $p_T > \sim 4$ GeV/c
  - significant charm quark energy loss in the QGP medium
- v_2(D) follows the $(m_T - m_0)/n_q$ scaling as light hadrons

Evidence of charm quarks reaching local thermal equilibrium!

D^0 v_2 Compared with Models



STAR, PRL 118 (2017) 212301

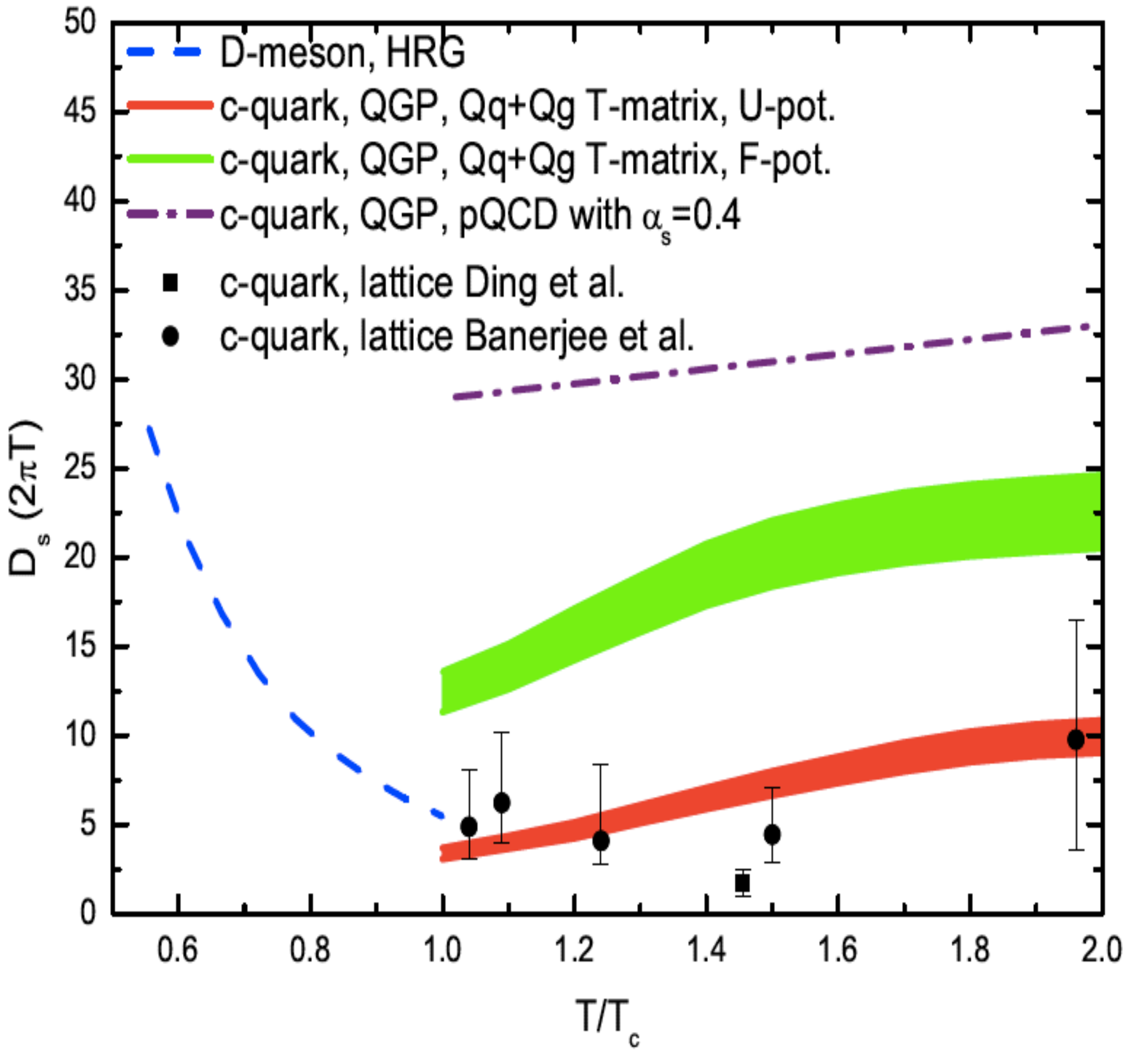


XD, Y-J Lee & R. Rapp, Ann. Rev. Nucl & Part. Sci. 69 (2019) 417

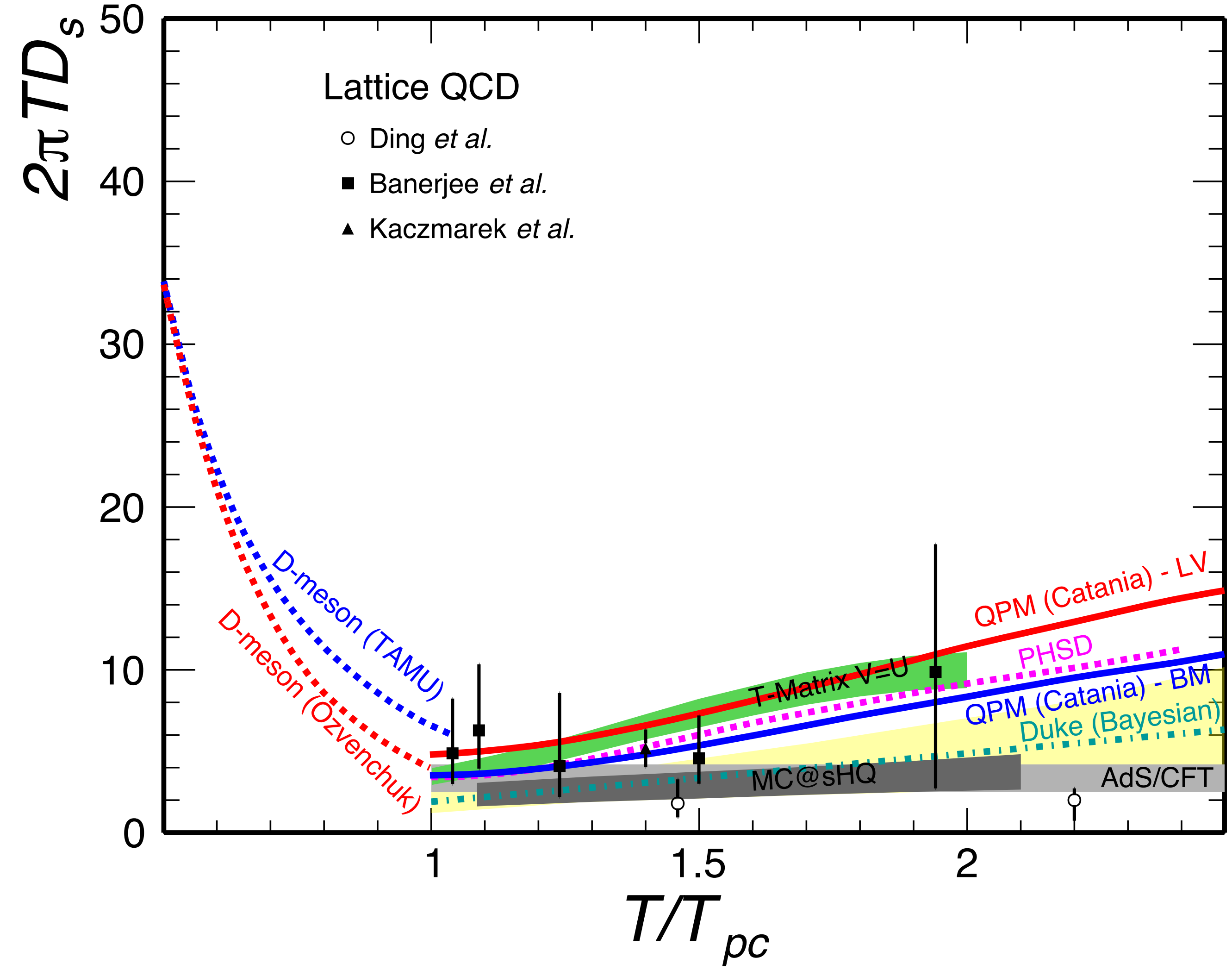
- State-of-the-art model calculations from various approaches reasonably describe D^0 meson v_2 data at RHIC
- Charm quark $2\pi TD_s$ **~ 2-5** at near T_c
  - consistent with quenched lattice calculations
  - larger uncertainty in temperature dependence

Charm Spatial Diffusion Coefficient

2015



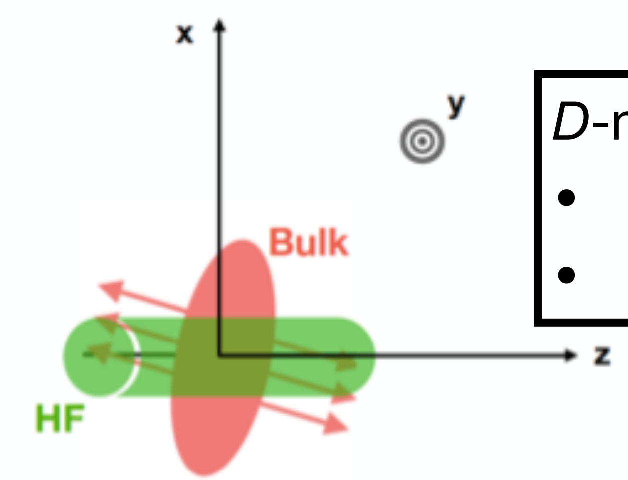
2019



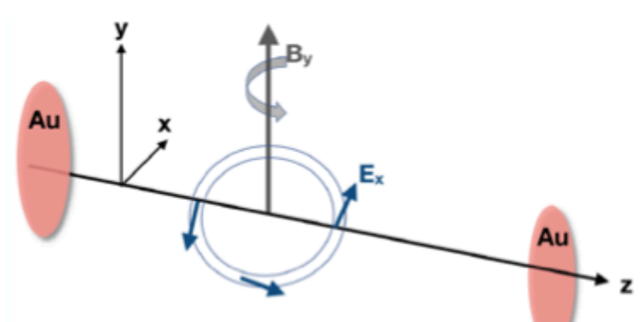
Strongly interacting QGP!

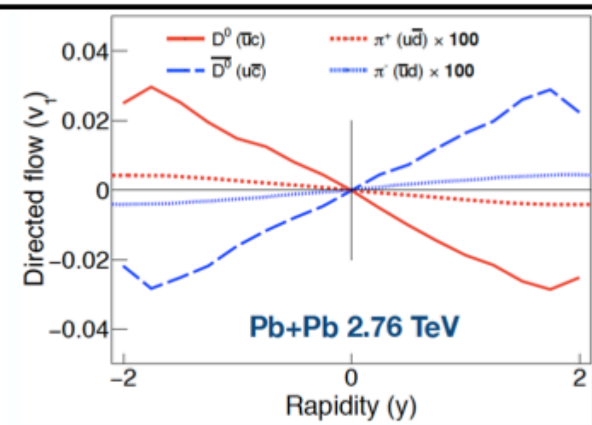
D^0 v_1 - sQGP Properties and Initial *B*-field

S. Chatterjee & P. Bozek, PRL 120 (2018) 192301



D-meson v_1 sensitive to
- geometry tilt of QGP source
- HQ diffusion coefficient $D_s(T)$

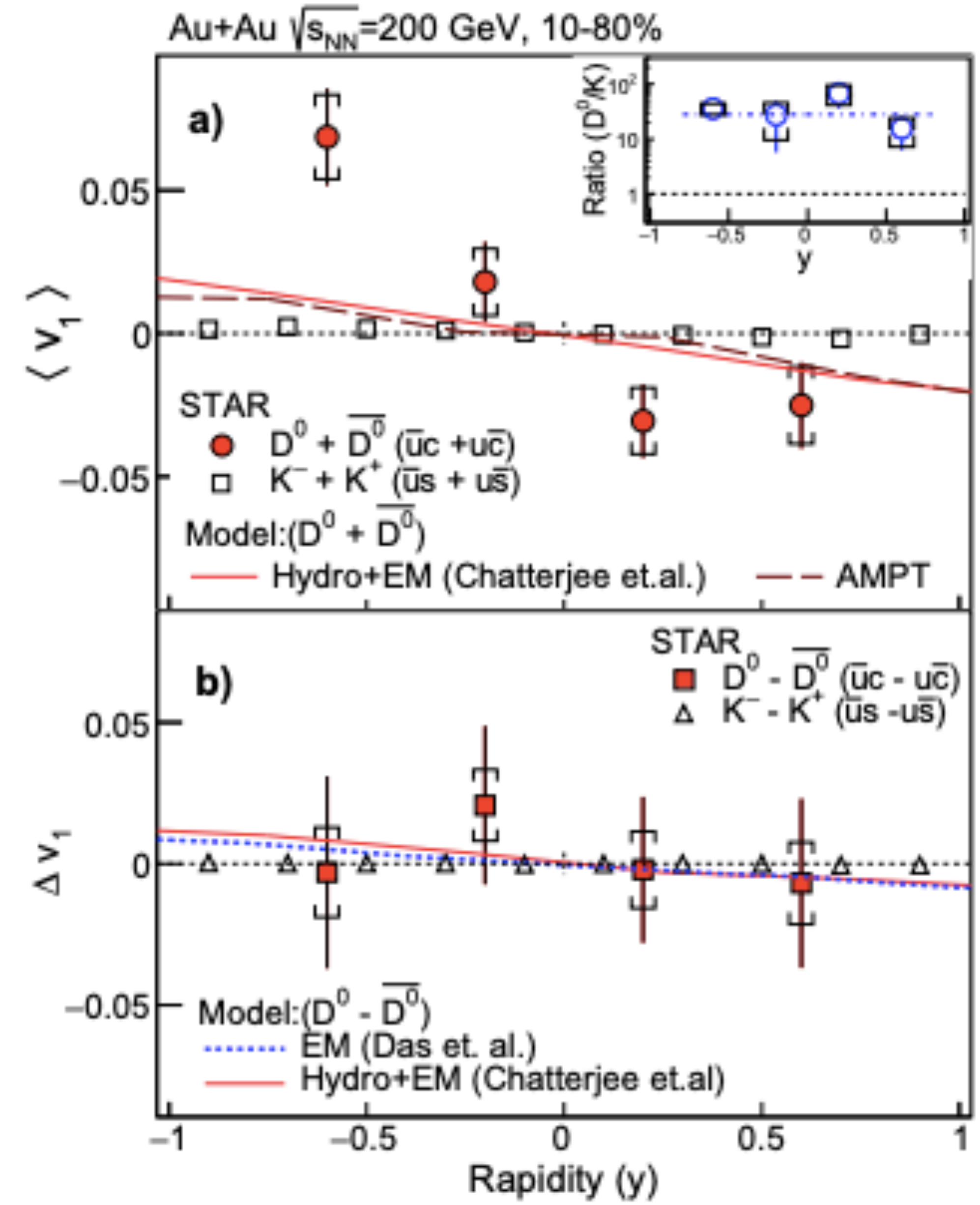




S.K. Das et al, PLB 768 (2017) 260

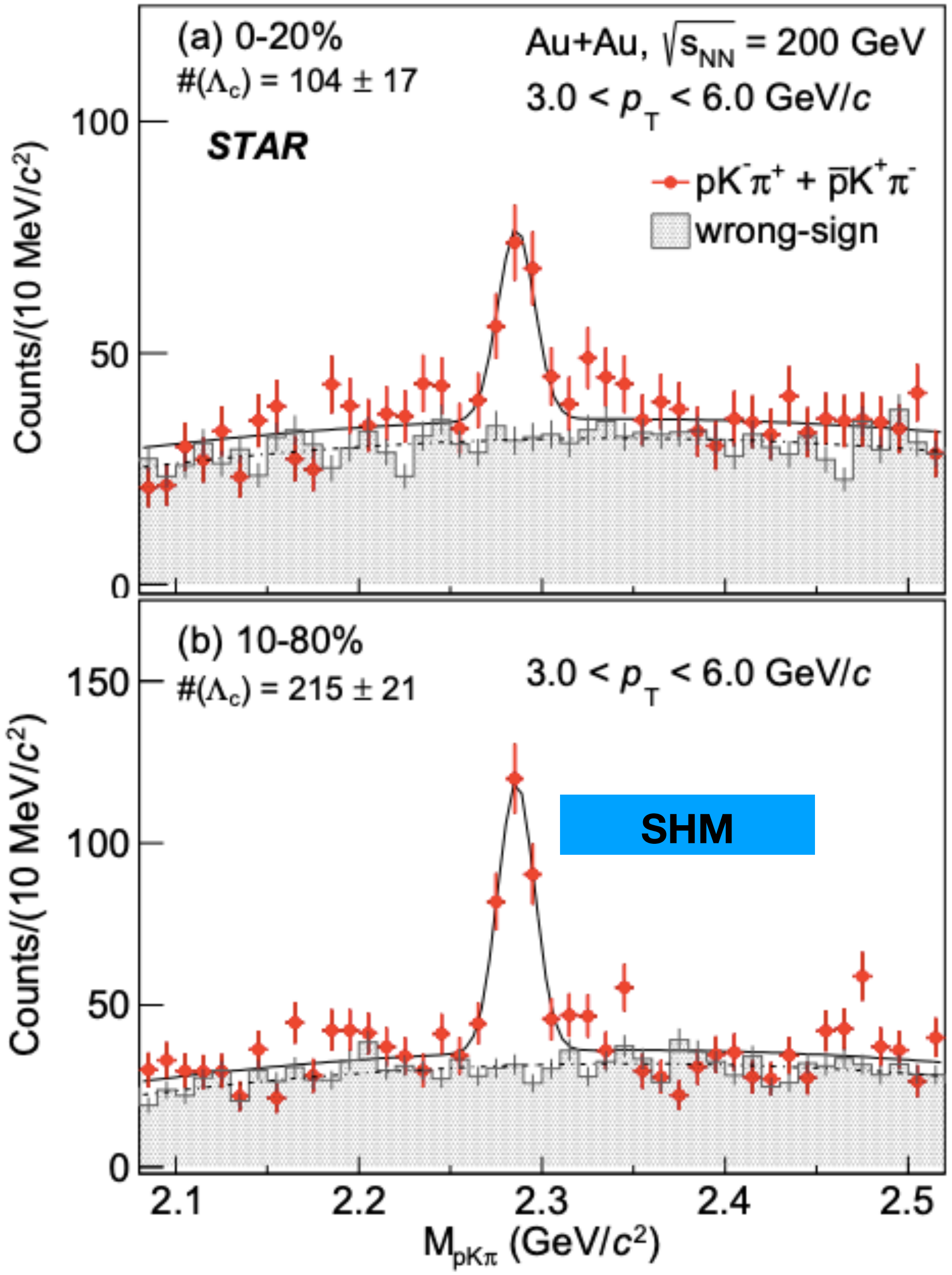
Strong B field in HIC -> $v_1(D) = -v_1(\text{Dbar})$, $v_1(h^+)-v_1(h^-)\sim 0$

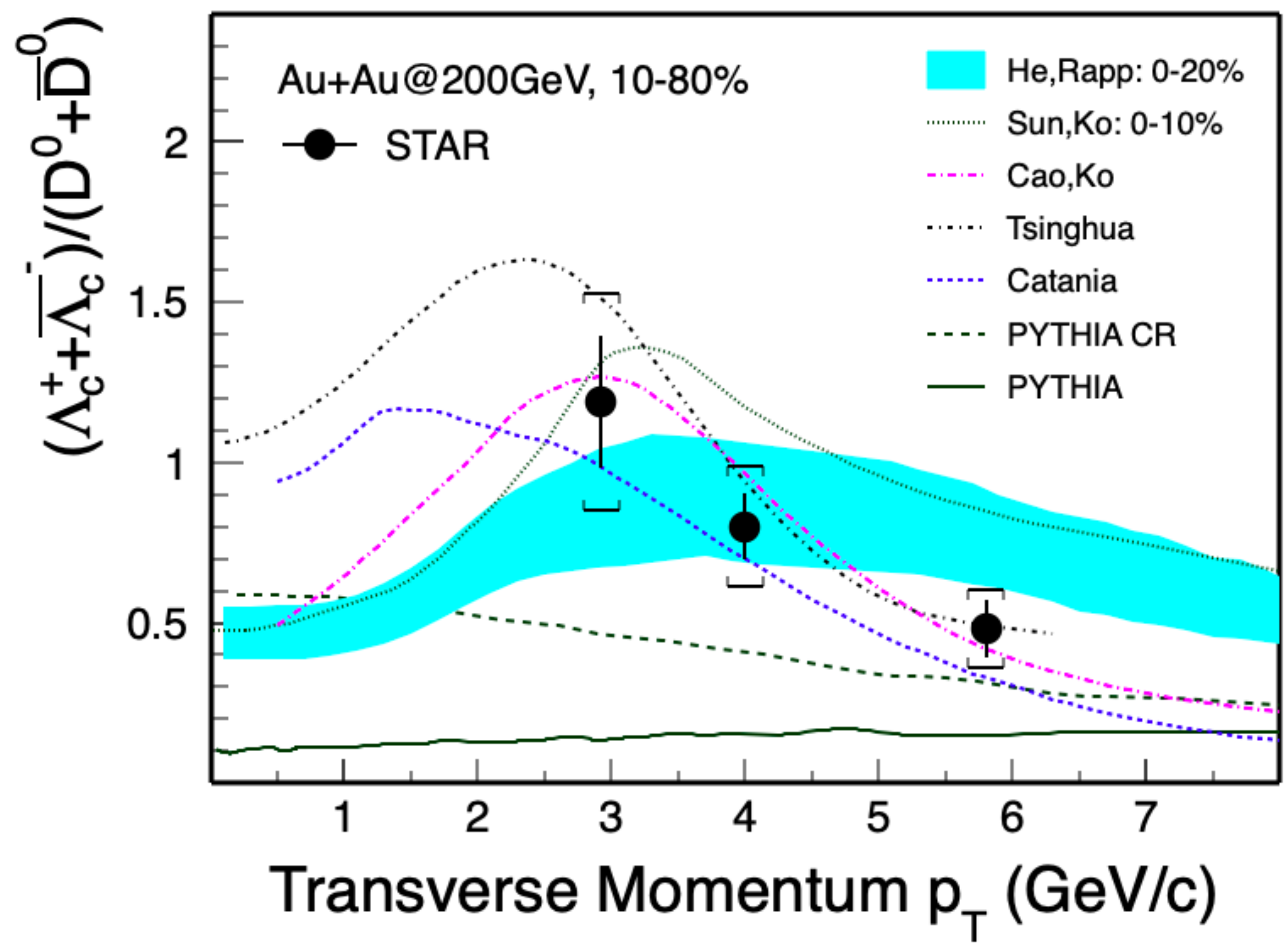
STAR, PRL 123 (2019) 162301



- $v_1(D) >> v_1(h)$
  - Constraints on T-dependence of HQ diffusion coefficient
- $v_1(D)$ - $v_1(\text{Dbar})$ - experimental uncertainty large
  - Need more precise measurement to access the B-field signal

Λ_c Reconstruction in Heavy-Ion Collisions

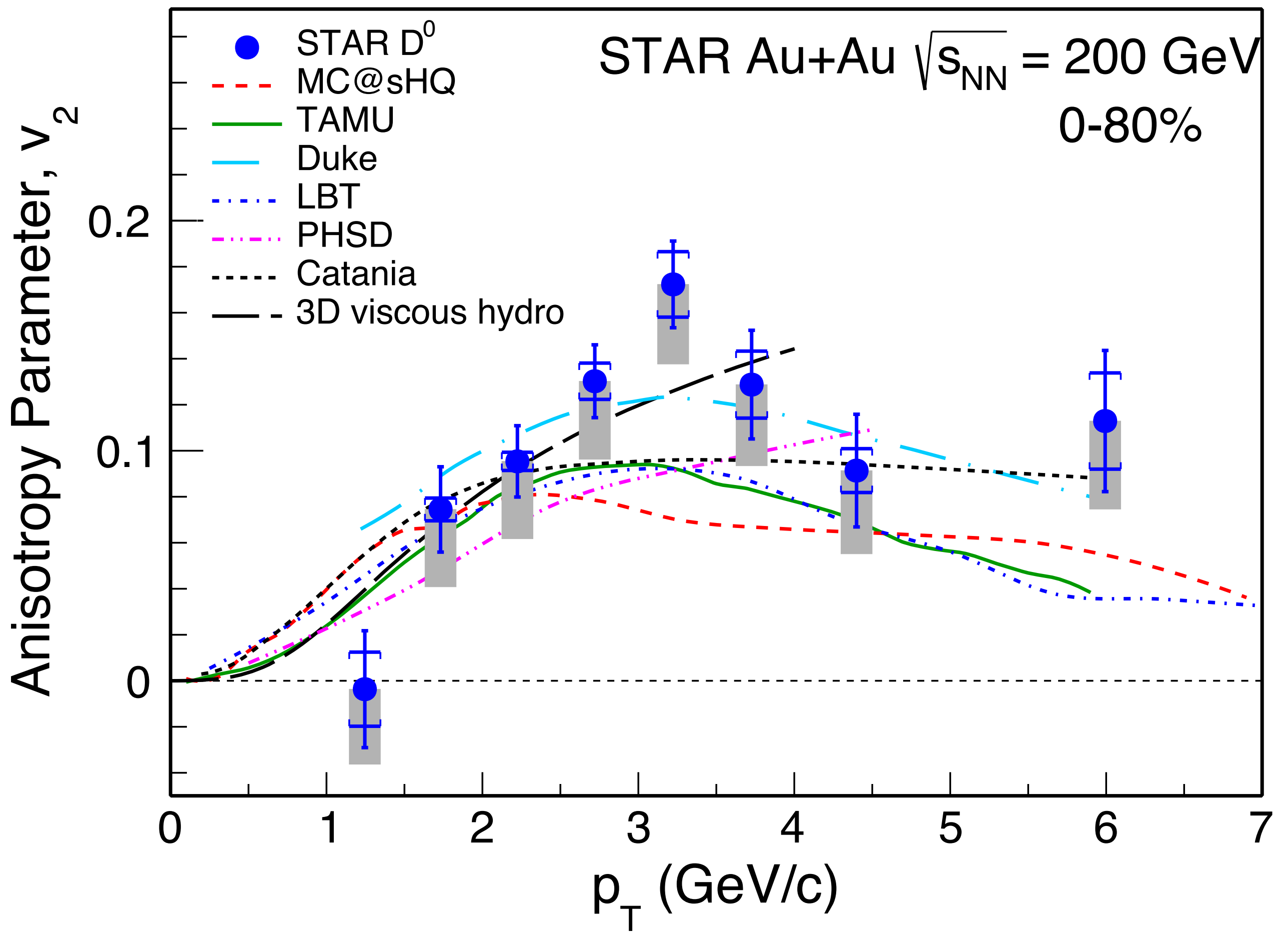


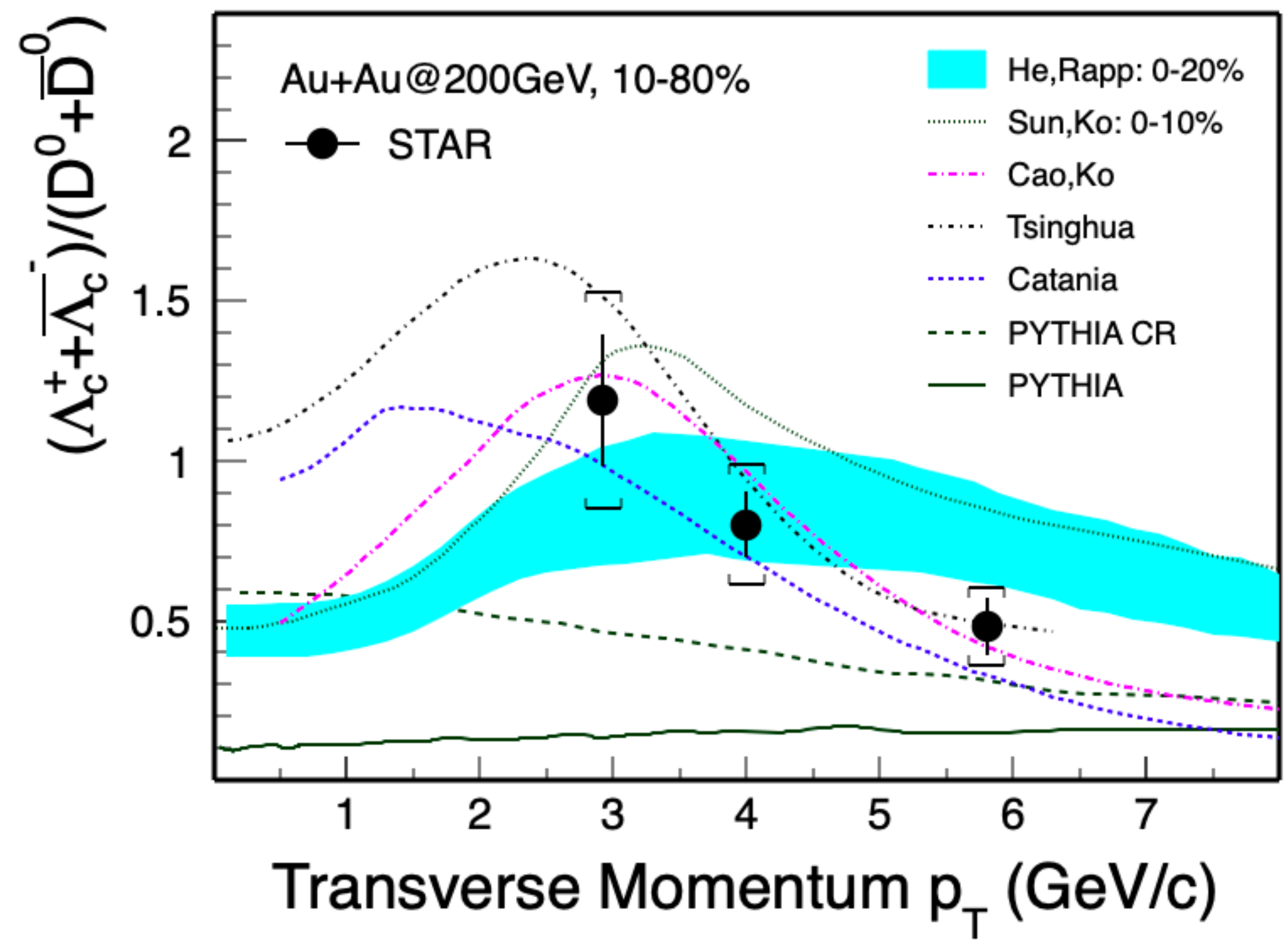


STAR, PRL 124 (2020) 172301

- Λ_c/D^0 ratio comparable to light/strange hadrons in A+A collisions
- Λ_c/D^0 enhancement w.r.t the PYTHIA predictions (w/ and w/o CR)
- Coalescence models qualitatively reproduce the large Λ_c/D^0 ratio

Summary I: Heavy Flavor at RHIC to-date





Significant charm hadron flow -> $2\pi TD_s$~ 2-5@T_c

-> T-dependence, *c* vs. *b* universality, relation to *η/s* etc.

Large D_s/D^0 and Λ_c/D^0 enhancement -> coalescence hadronization

-> precise heavy baryon, relation to color confinement

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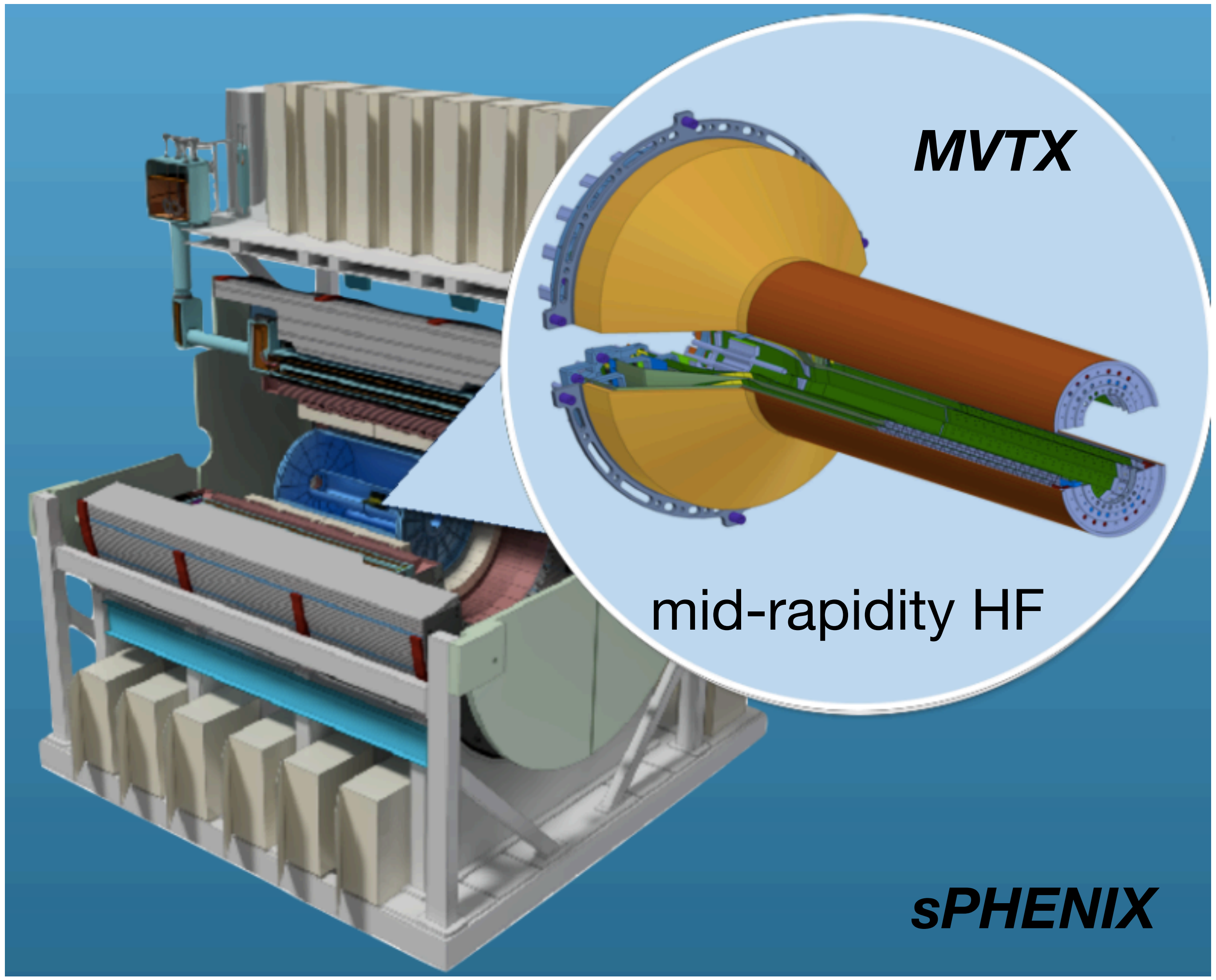
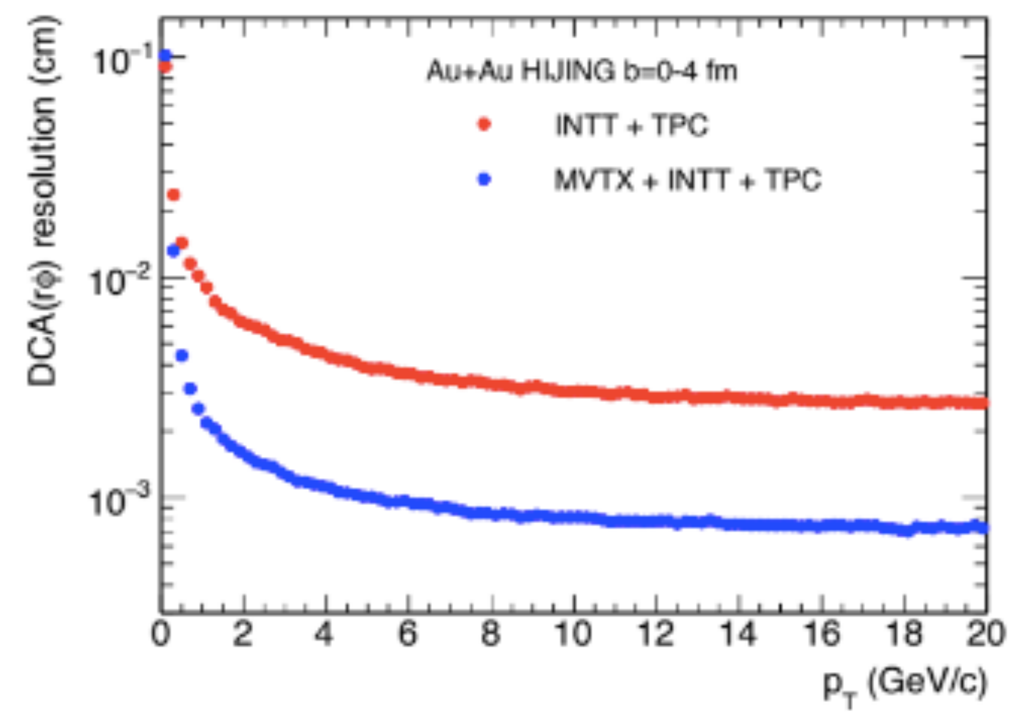
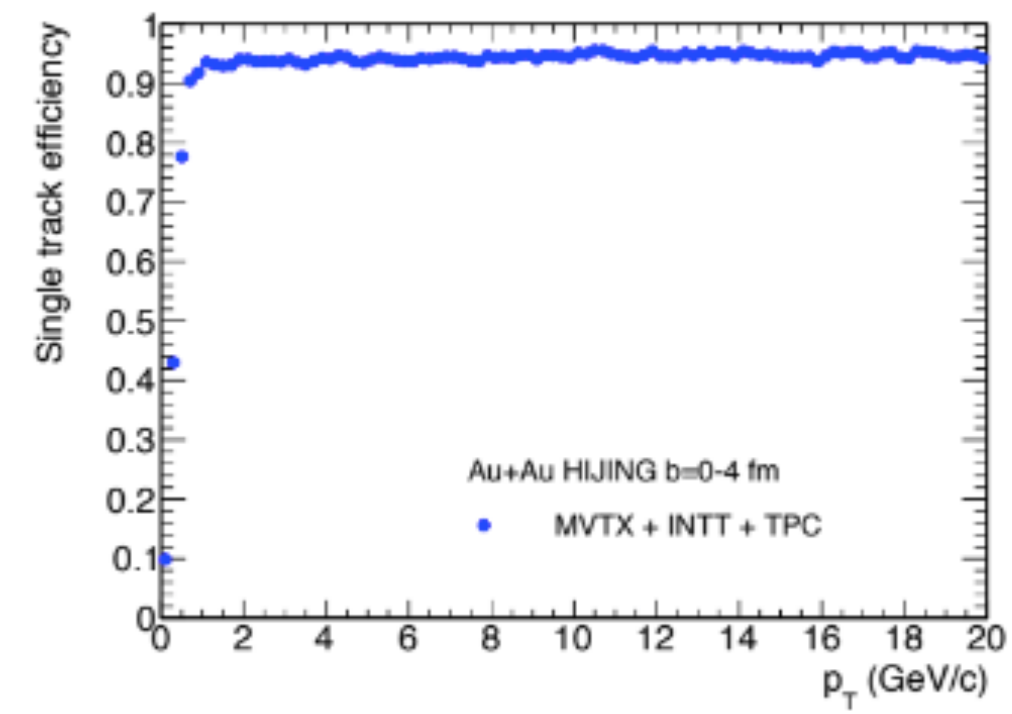
MAPS-based VTX (MVTX) @ sPHENIX

MVTX @ sPHENIX: Next generation fast MAPS detector (leveraging ALICE ITS2)





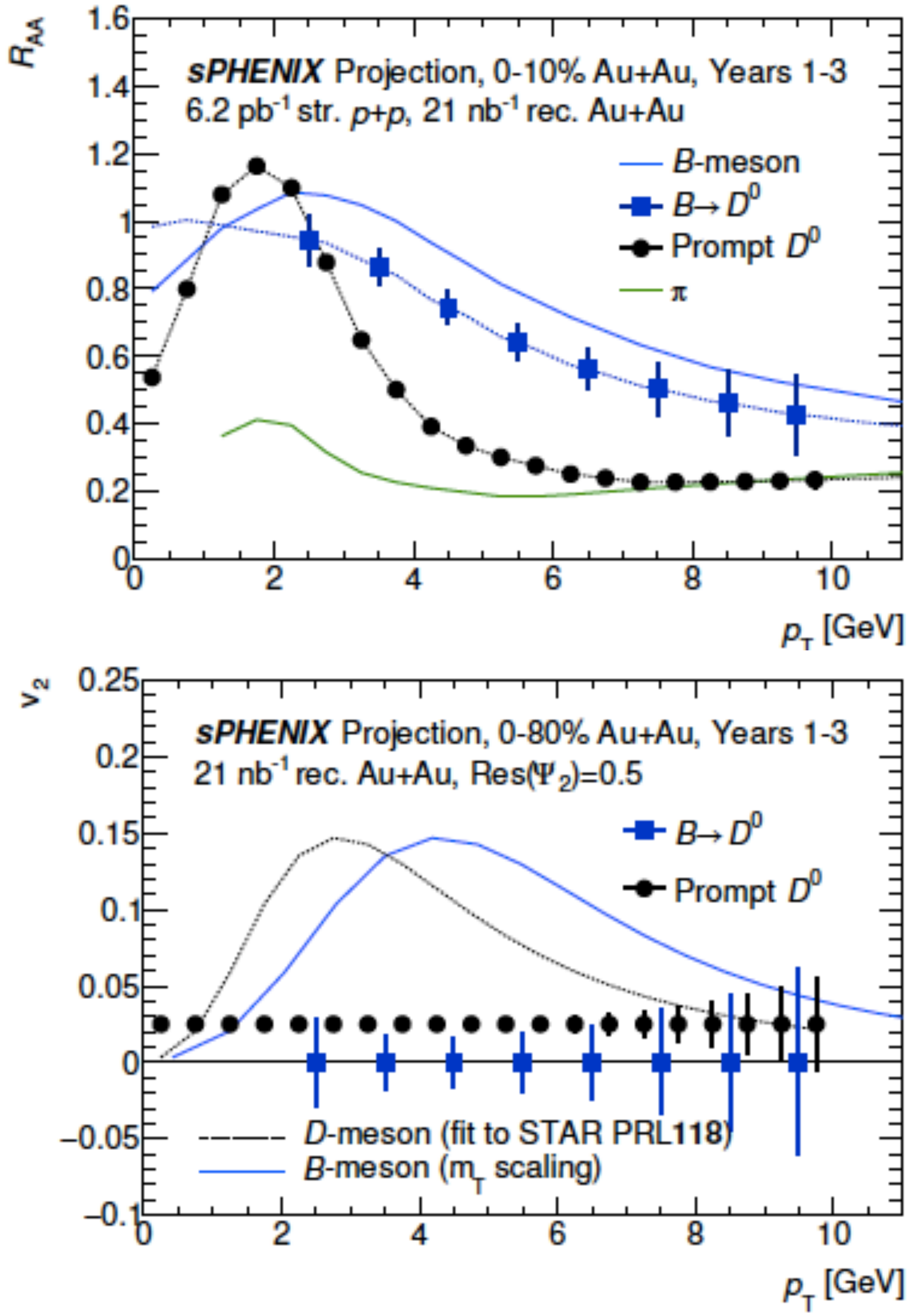


	HFT		MVTX
thickness	0.4% X_0	→	0.3% X_0
integration time	186 μs	→	< 10 μs

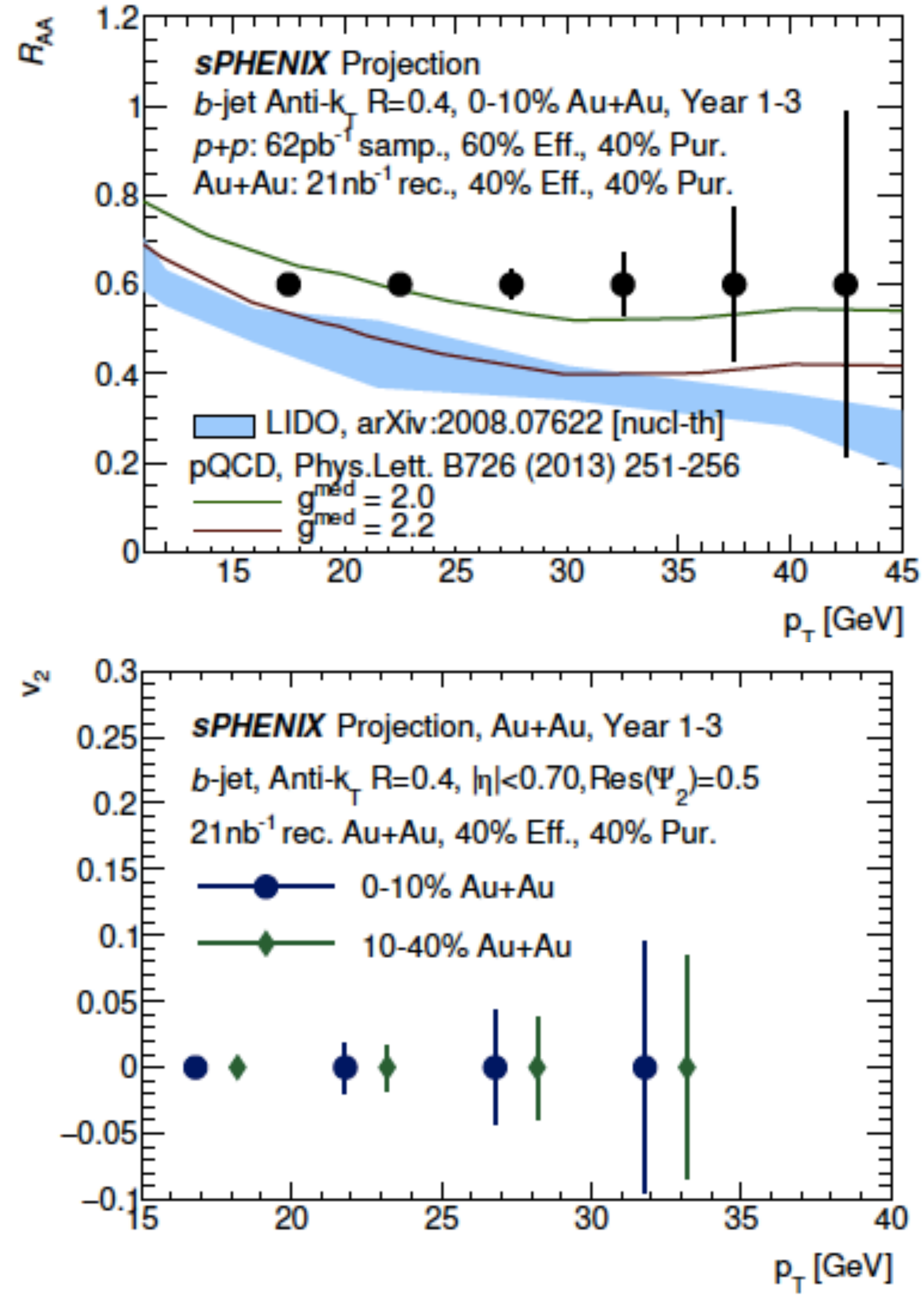
==> background reduced by > x10

Precision Measurement of Open-Bottom Production

B-meson via non-prompt D^0

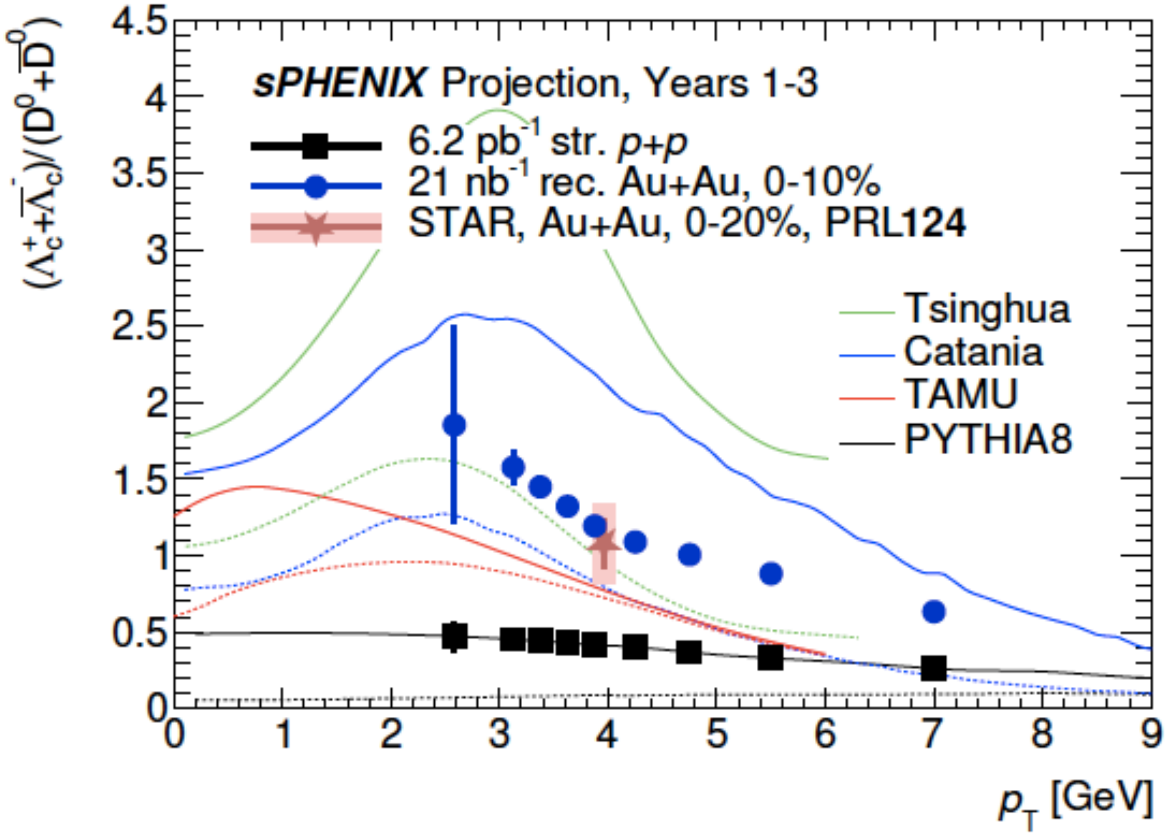


b-jet



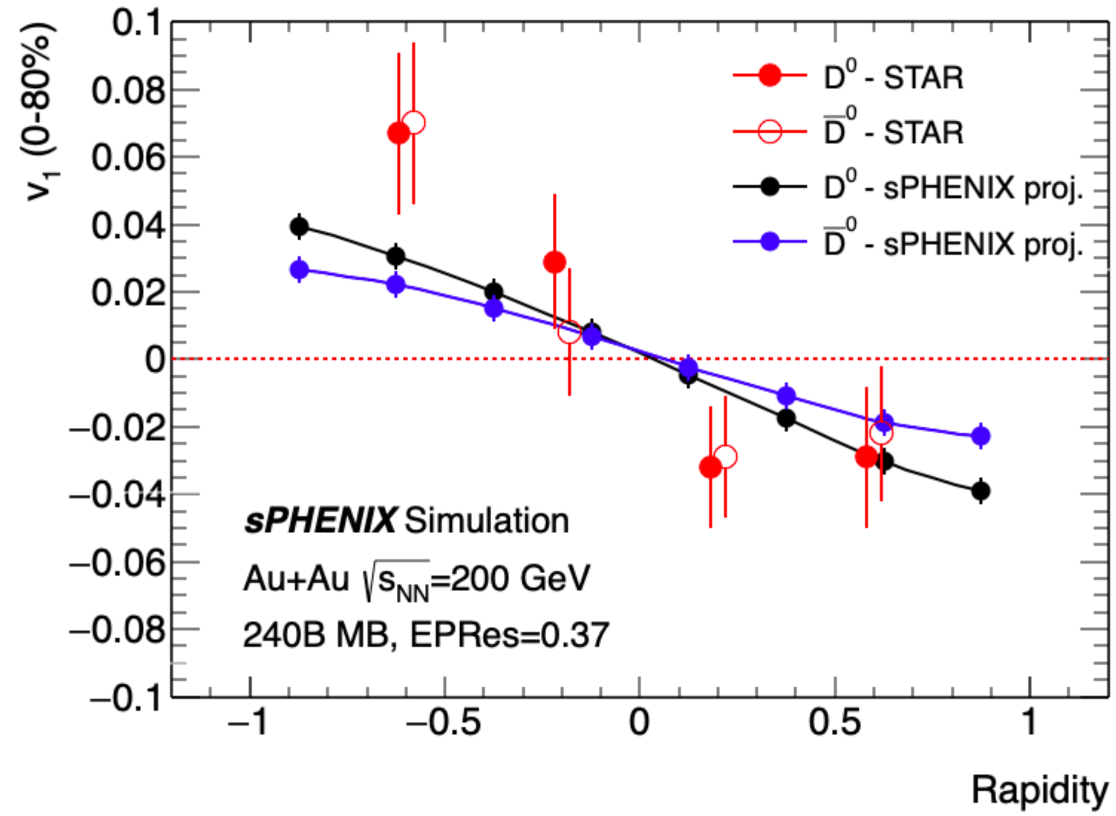
Fruitful Charm/Bottom Physics

Charm/Bottom Hadrochemistry



- Precise measurement of various charm hadrons (Λ_c^+,D_s^+)
- Enable access to open bottom hadrons (Λ_b, B_s etc)
- Detail investigation of charm baryon spectroscopy in p+p collisions

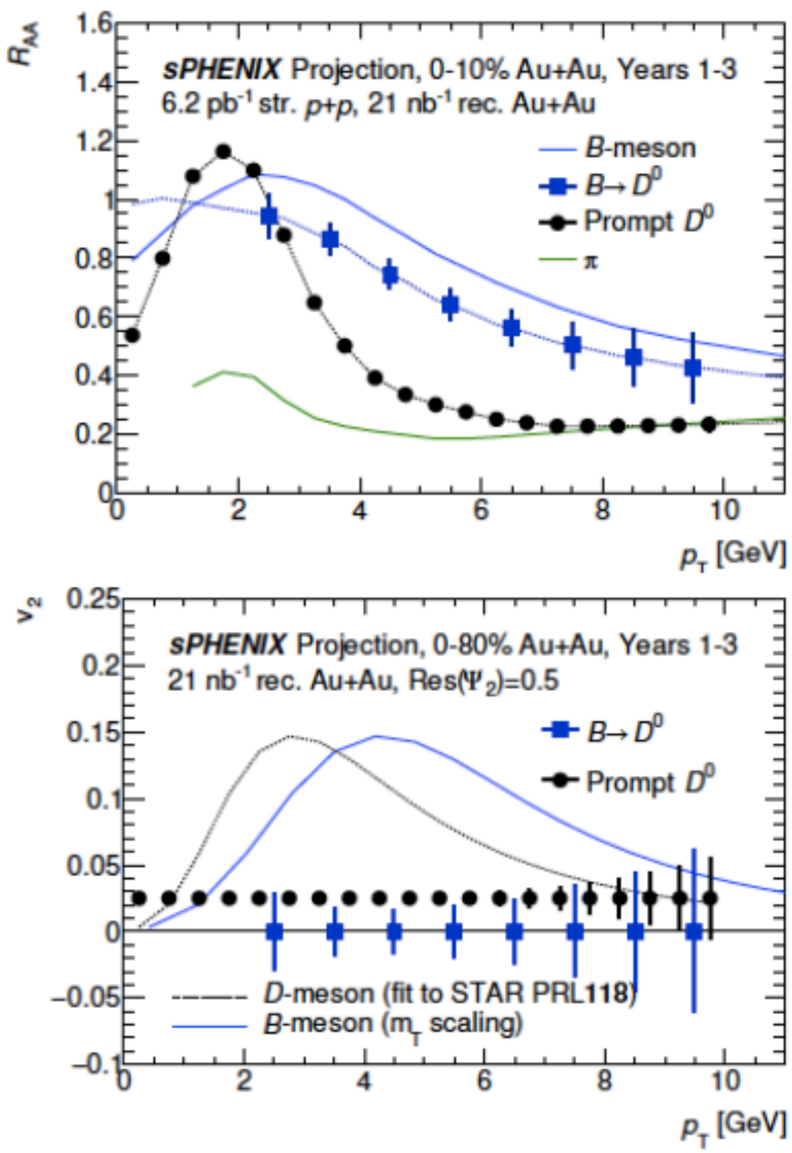
$D^0/\overline{D}^0$ v1 - $2\pi TD_s(T)$ / initial B-field

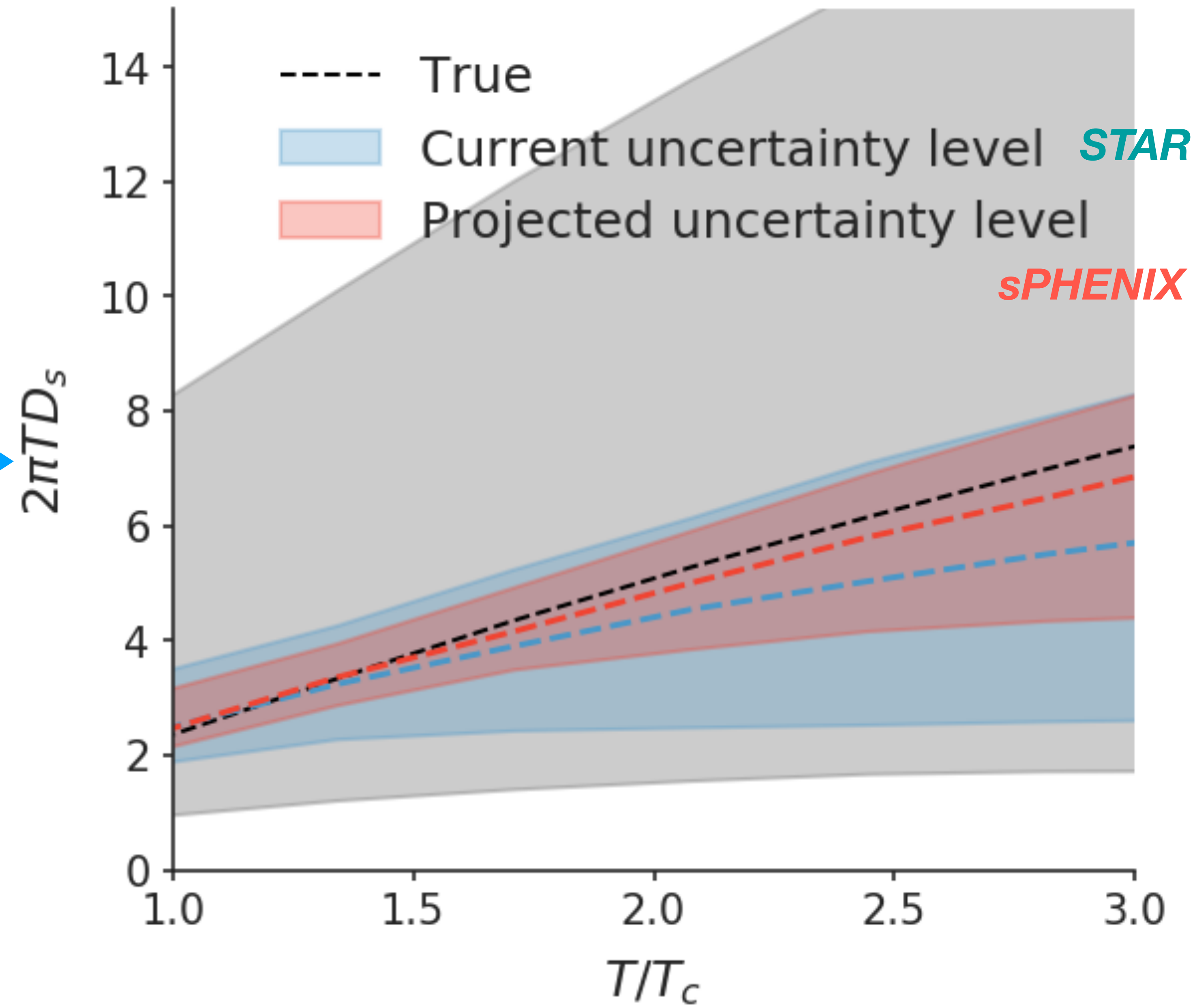


- $D^0/\overline{D}^0$ $\langle v_1 \rangle$
  - QGP longitudinal structure
  - temperature dependent $2\pi TD_s(T)$
- $D^0/\overline{D}^0$ Δv_1
  - unique access to initial B-field
  - sPHENIX proj. ~5σ given model predictions

Impact on Charm Diffusion Coefficient

Bayesian analysis to constrain HQ diffusion coefficient
- Weiyao Ke (Duke), HF Workshop, LBNL, 2019





Accessing Gluon Dynamics with (polarized) p+p

***D*-meson *A*_{*LL*}**

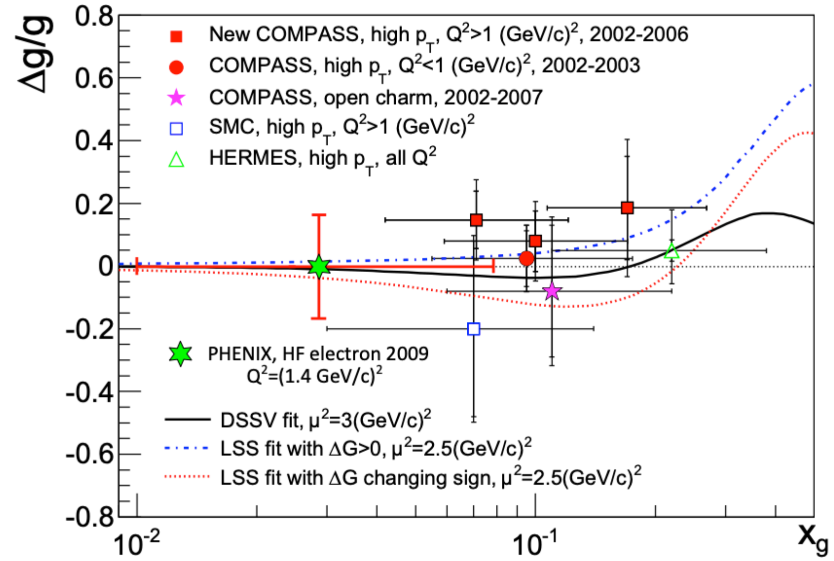
- Gluon helicity distribution

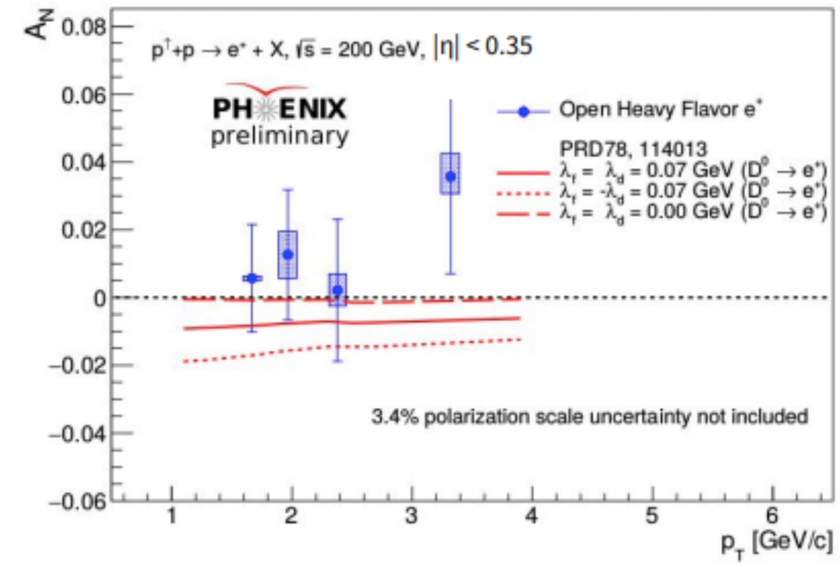
***D*-meson *A*_{*N*}**

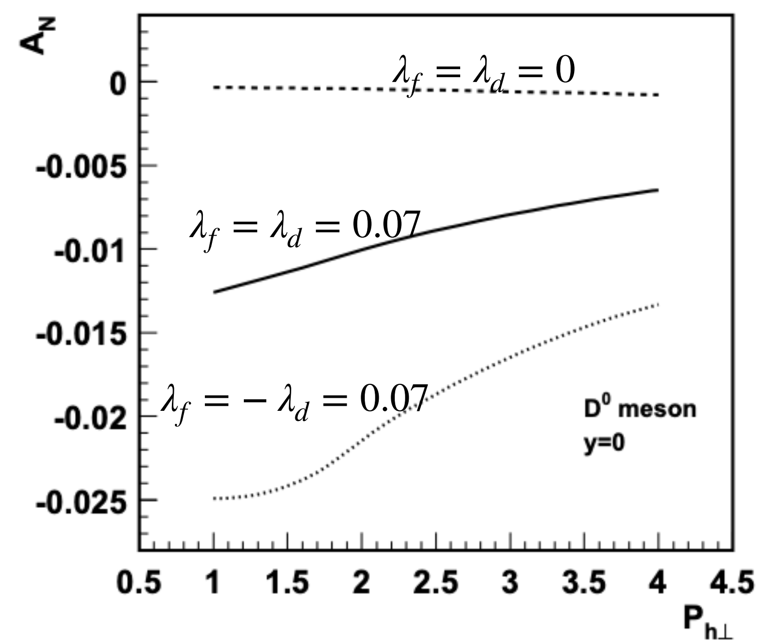
- twist-3 tri-gluon correlation / gluon Sivers function

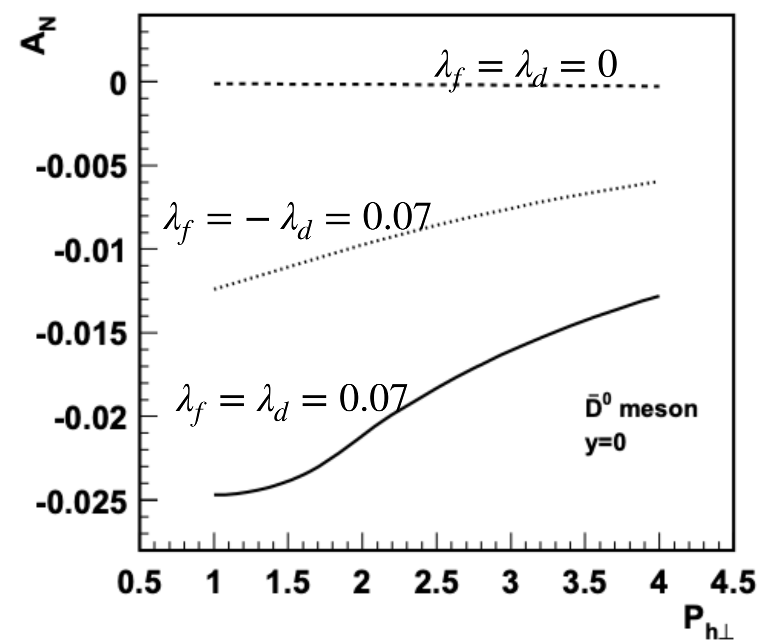
$$A_N(c) \neq A_N(\bar{c})$$

PHENIX, PRD 87 (2013) 012011, DIS 2021







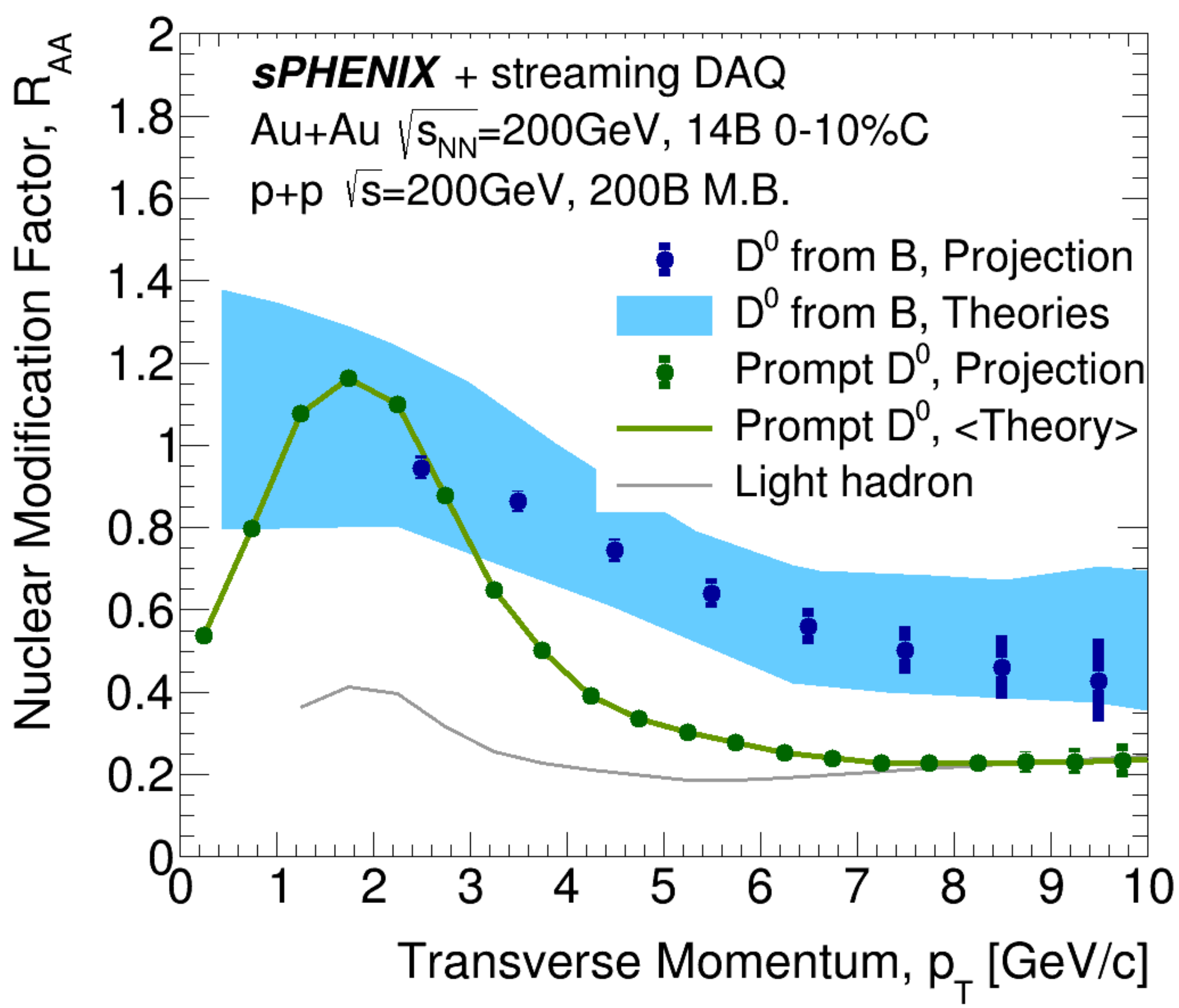


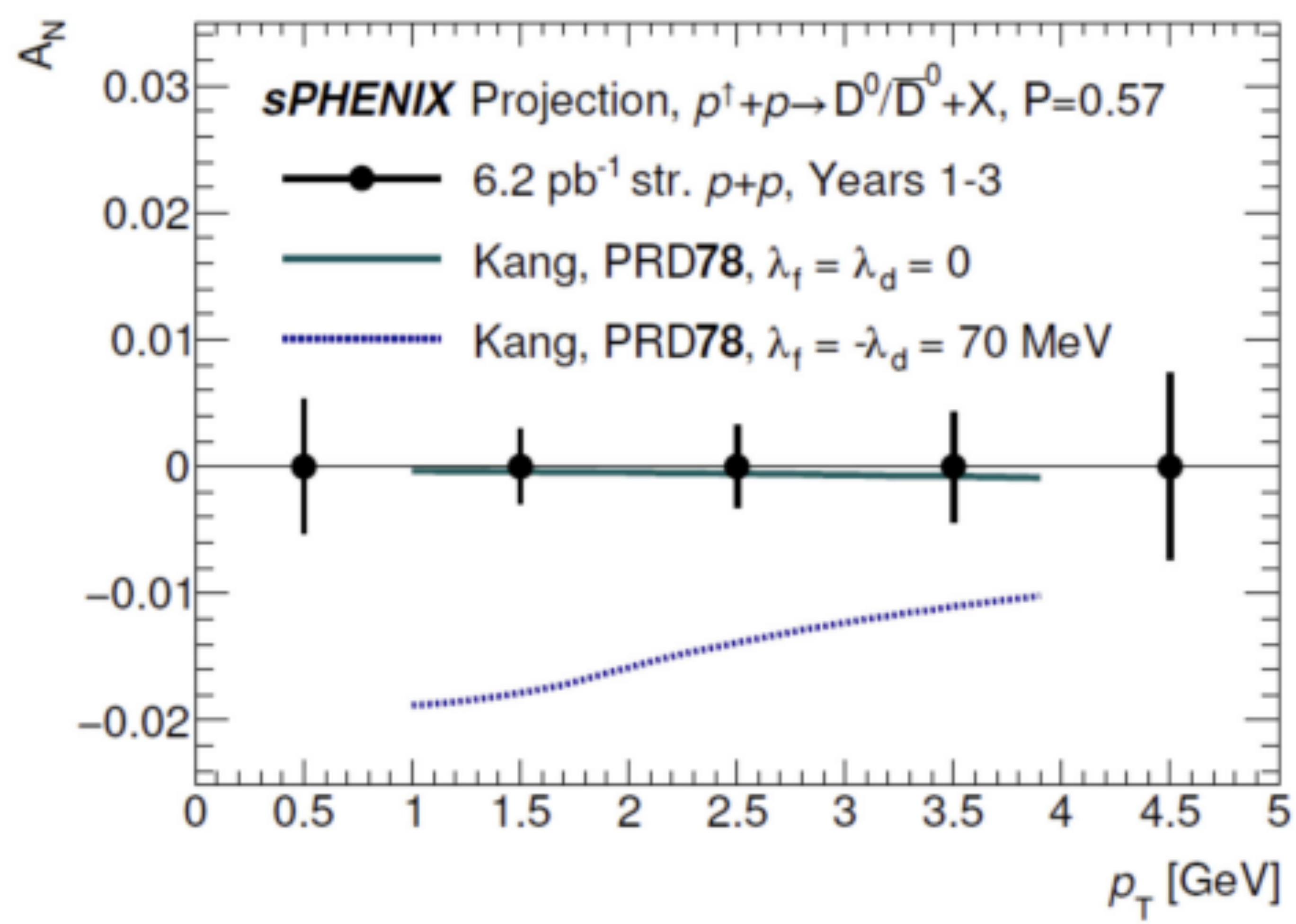
Z.B. Kang et al, PRD 78 (2008) 114013

*D** without secondary vertexing
sPHENIX: 0.8 trillion -> 450σ (320σ each charge sign)
*D*⁰ with secondary vertexing
utilizing secondary topology to improve signal significance

Streaming DAQ for HF Program in p+p

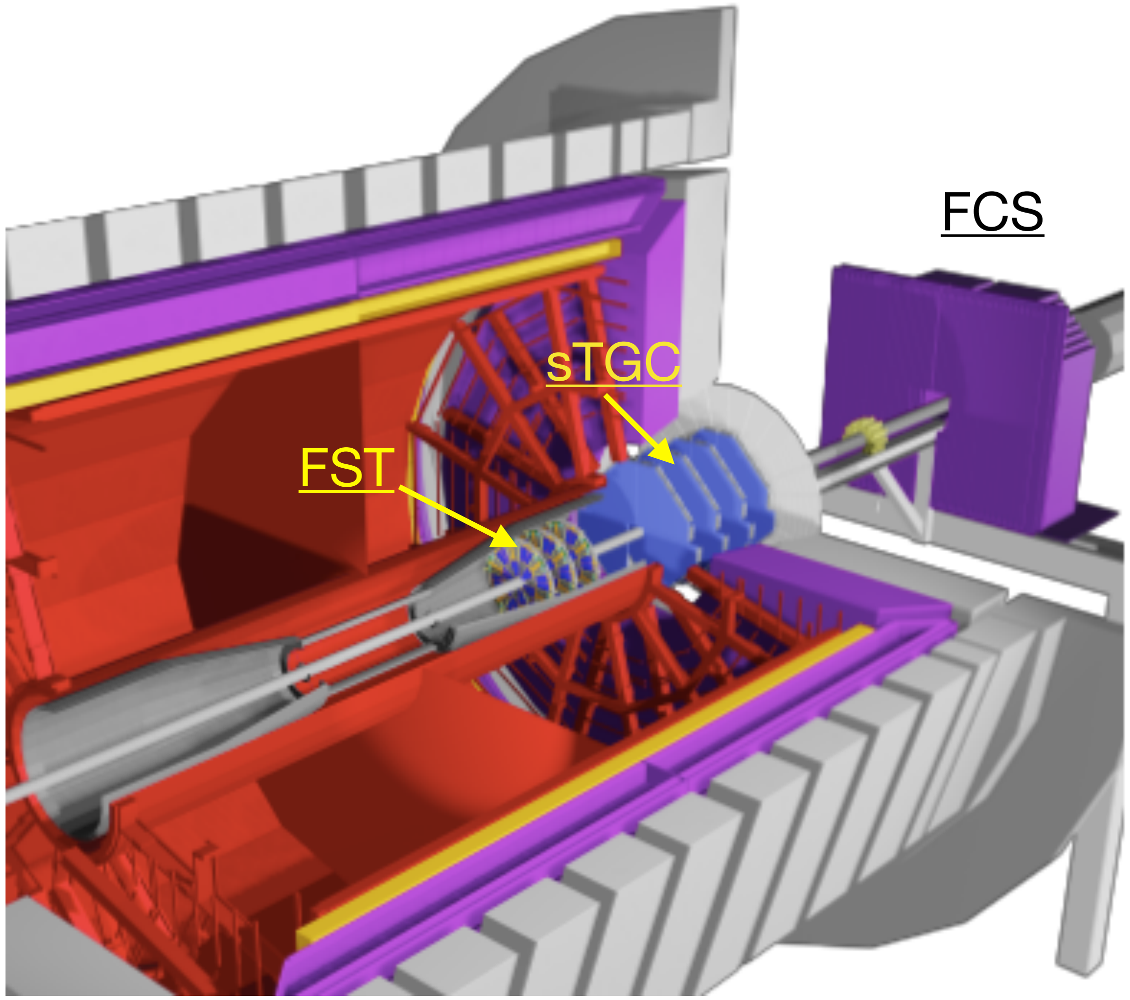
Streaming recording 10% of all M.B. p+p collisions in 2024
- xO (500) improve compared to the triggered mode
- critical for low p_T charm/bottom hadron measurements for R_{AA} reference
- enable high statistics measurements of D-meson A_N, A_{LL} etc.





sPH-TRG-2021-001

Opportunities with STAR Forward Upgrades



Forward tracking + calorimeters

$2.5 < |\eta| < 4.0$

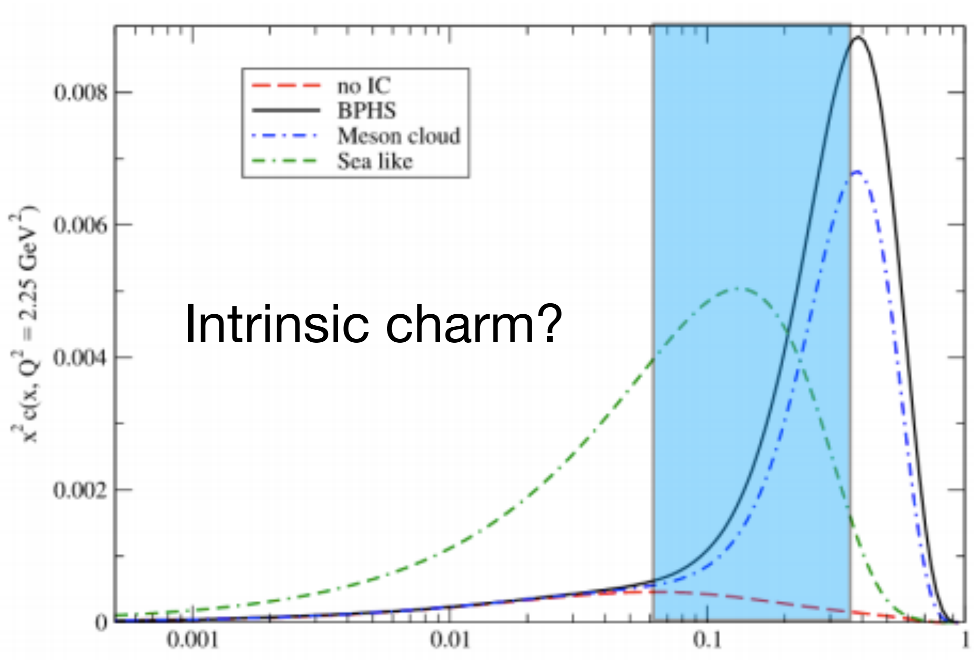
$$x_p \approx \frac{p_T}{\sqrt{s}} e^y$$

low x reach: 10^{-4}

high x reach: ~0.05 - 0.5

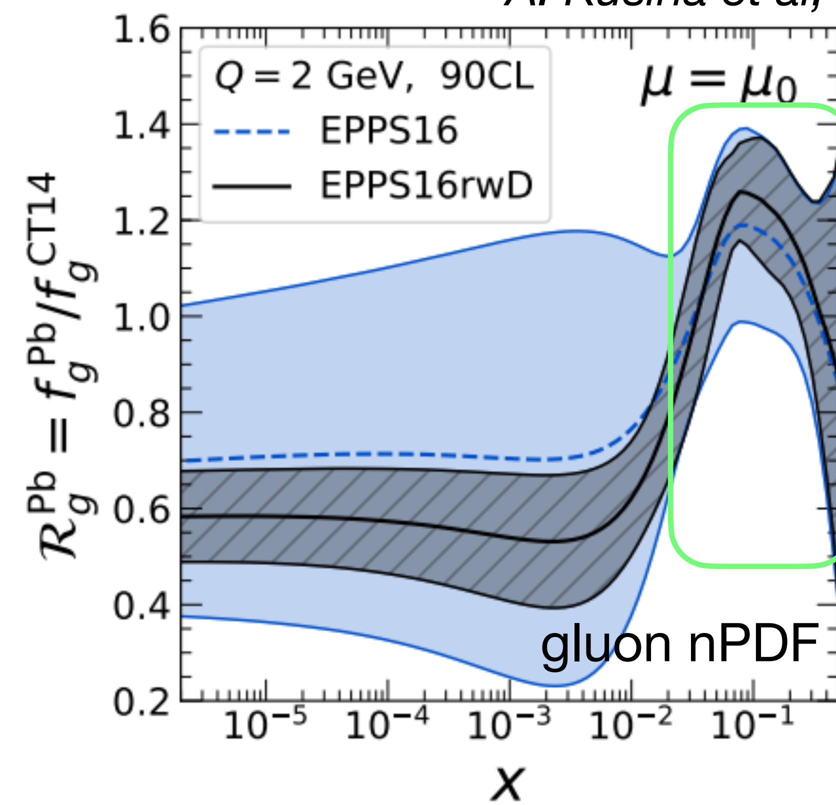
Heavy flavors: cleaner probe to gluon distributions in nucleon/nucleus

- trigger capabilities?
- secondary vertex? or D^*?



V.P. Gonçalves et al, NPA 842 (2010) 59

A. Kusina et al, 2012.11462



STAR Forward Upgrade Opportunity

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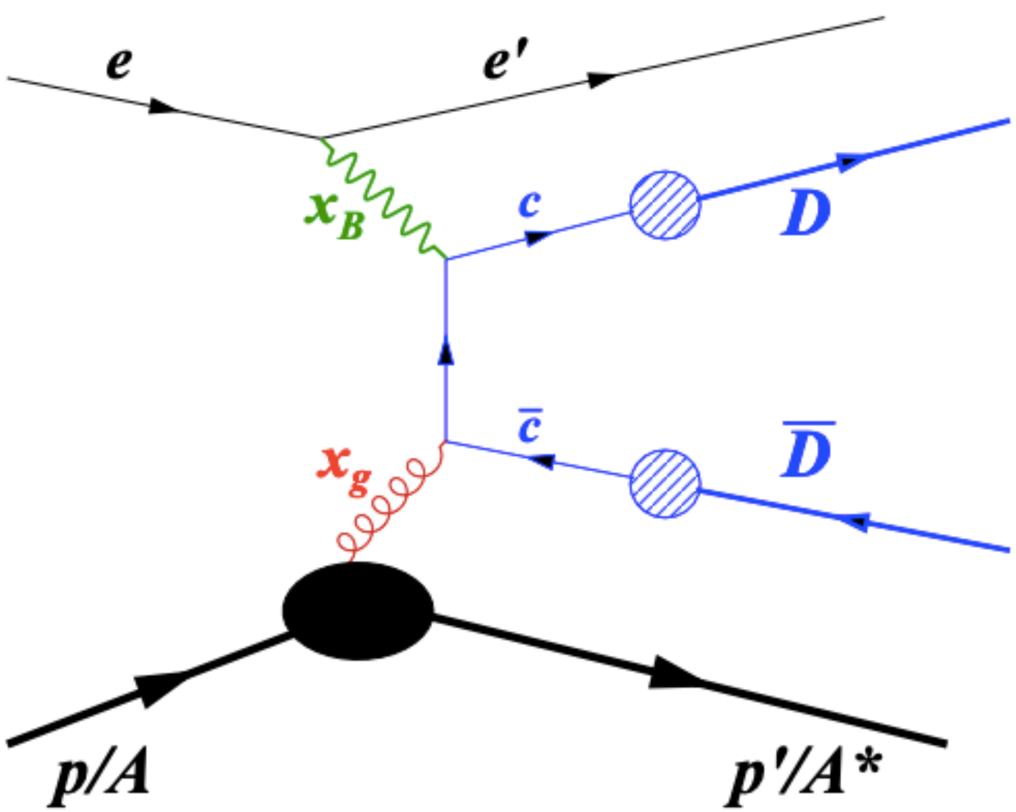
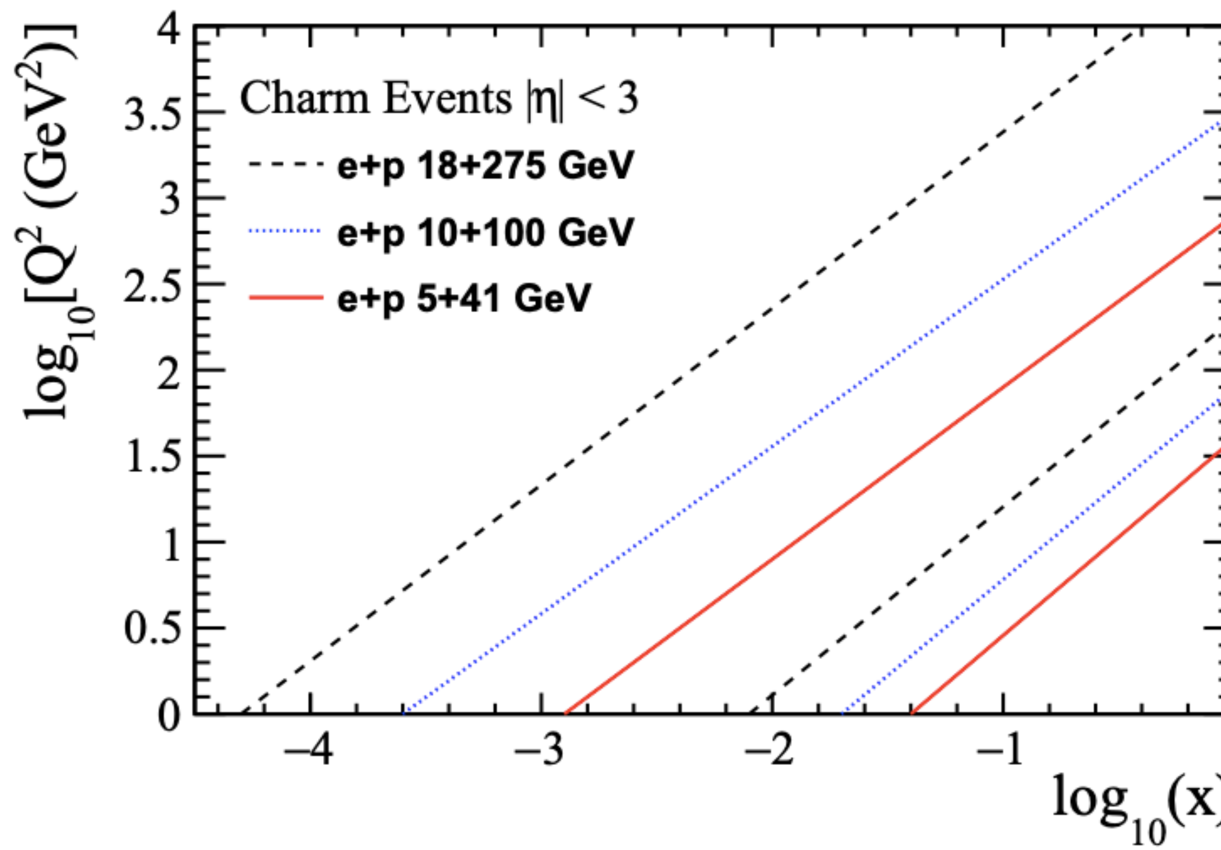
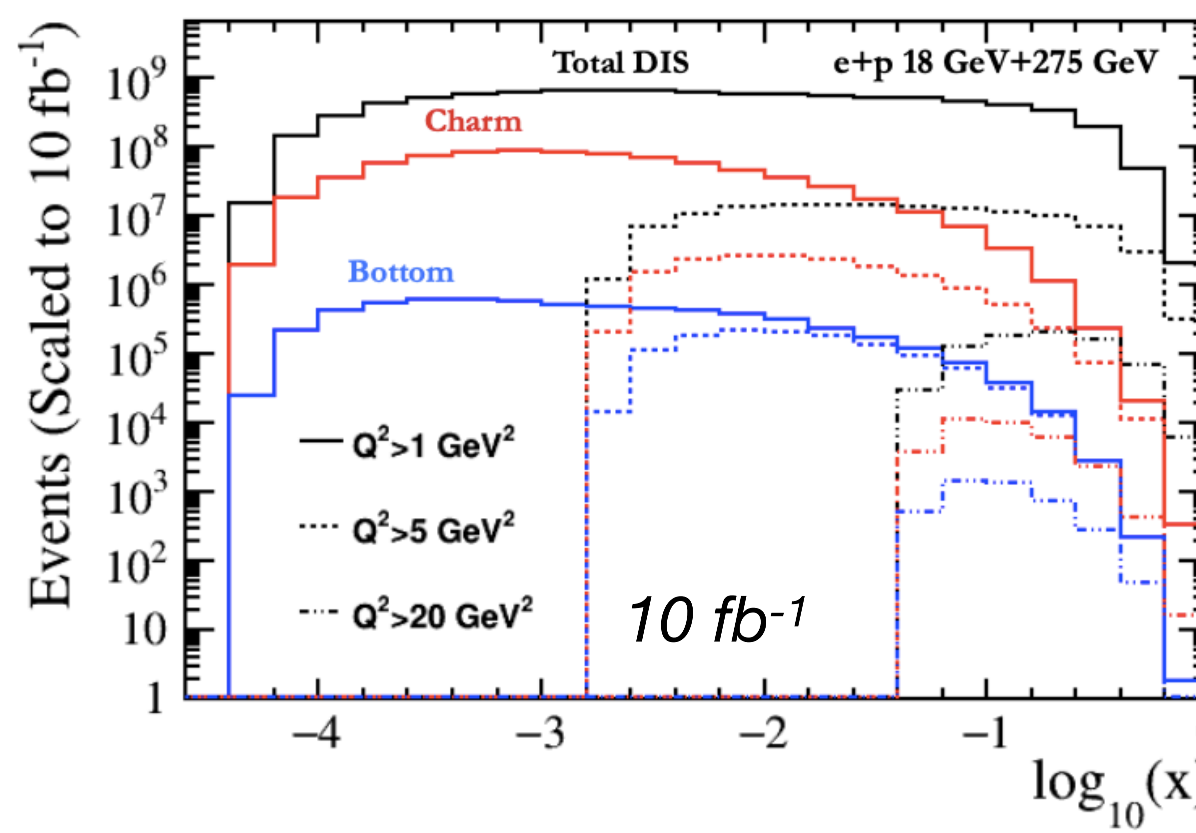
Heavy Flavors at EIC

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

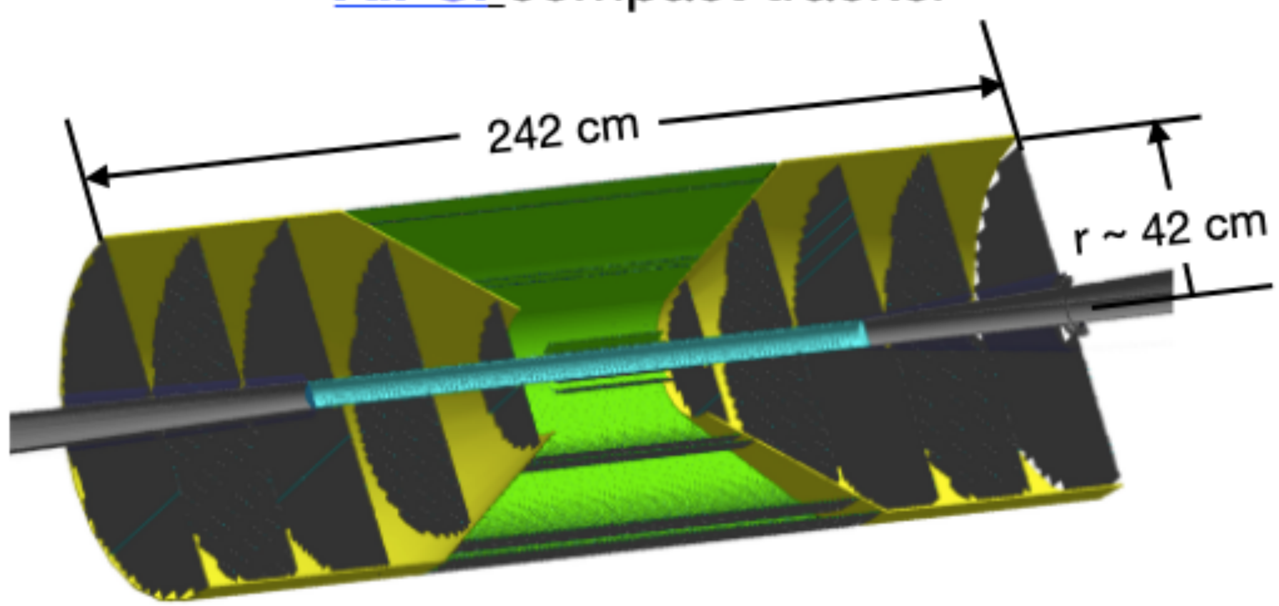




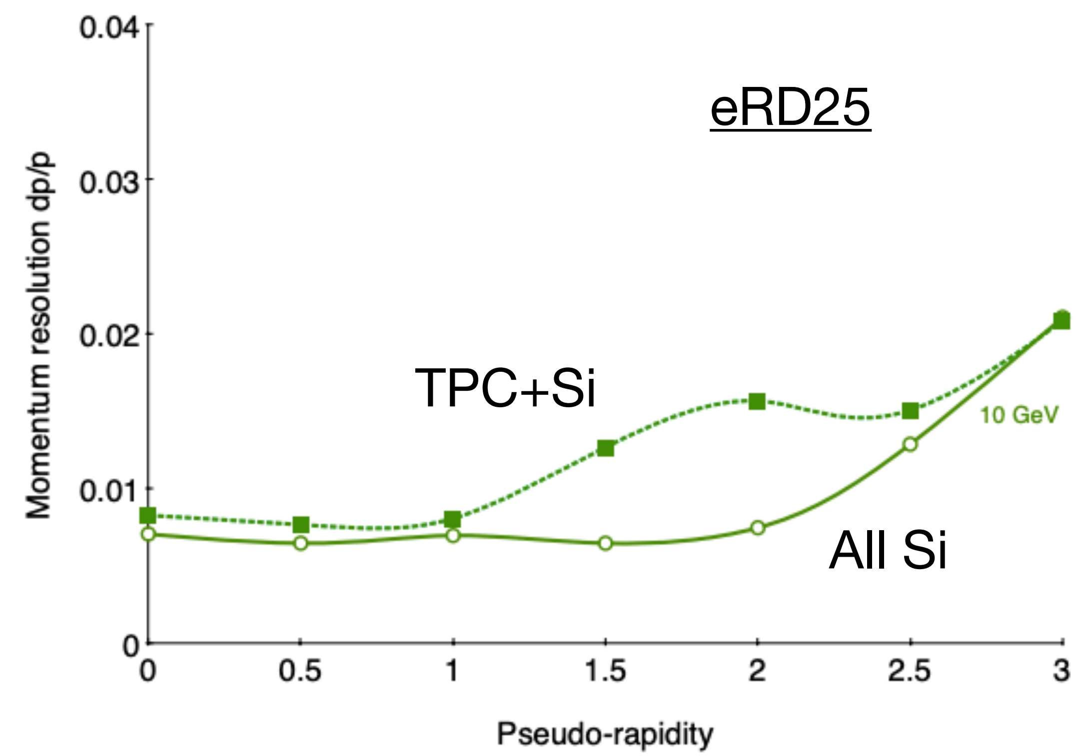


An All-Silicon Tracker Based on Ultra-Thin MAPS

All-Si compact tracker

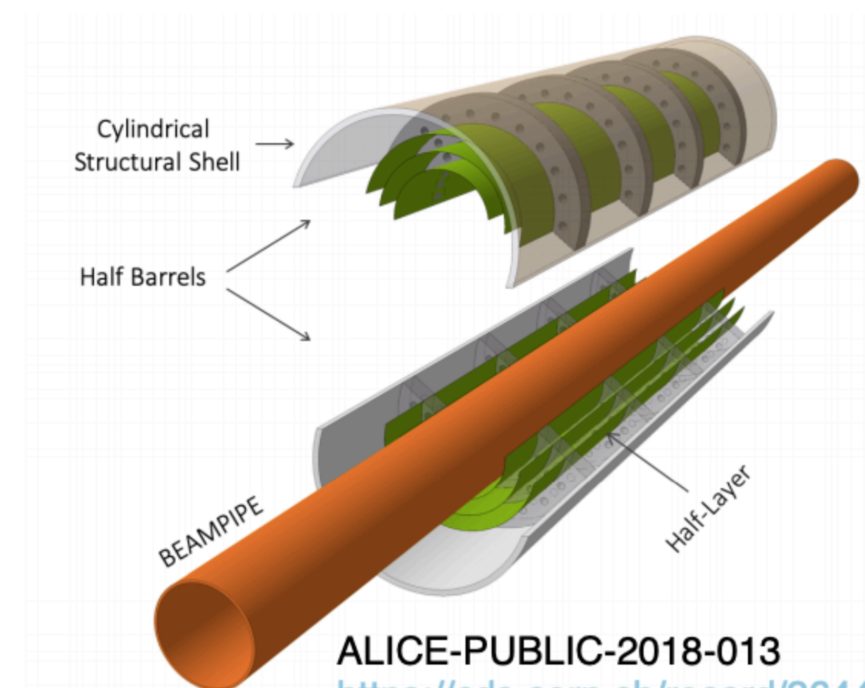


arXiv: 2102.08337



ALICE ITS3 aims for 65nm MAPS with extremely low mass

- O(10x10 μm)
- 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

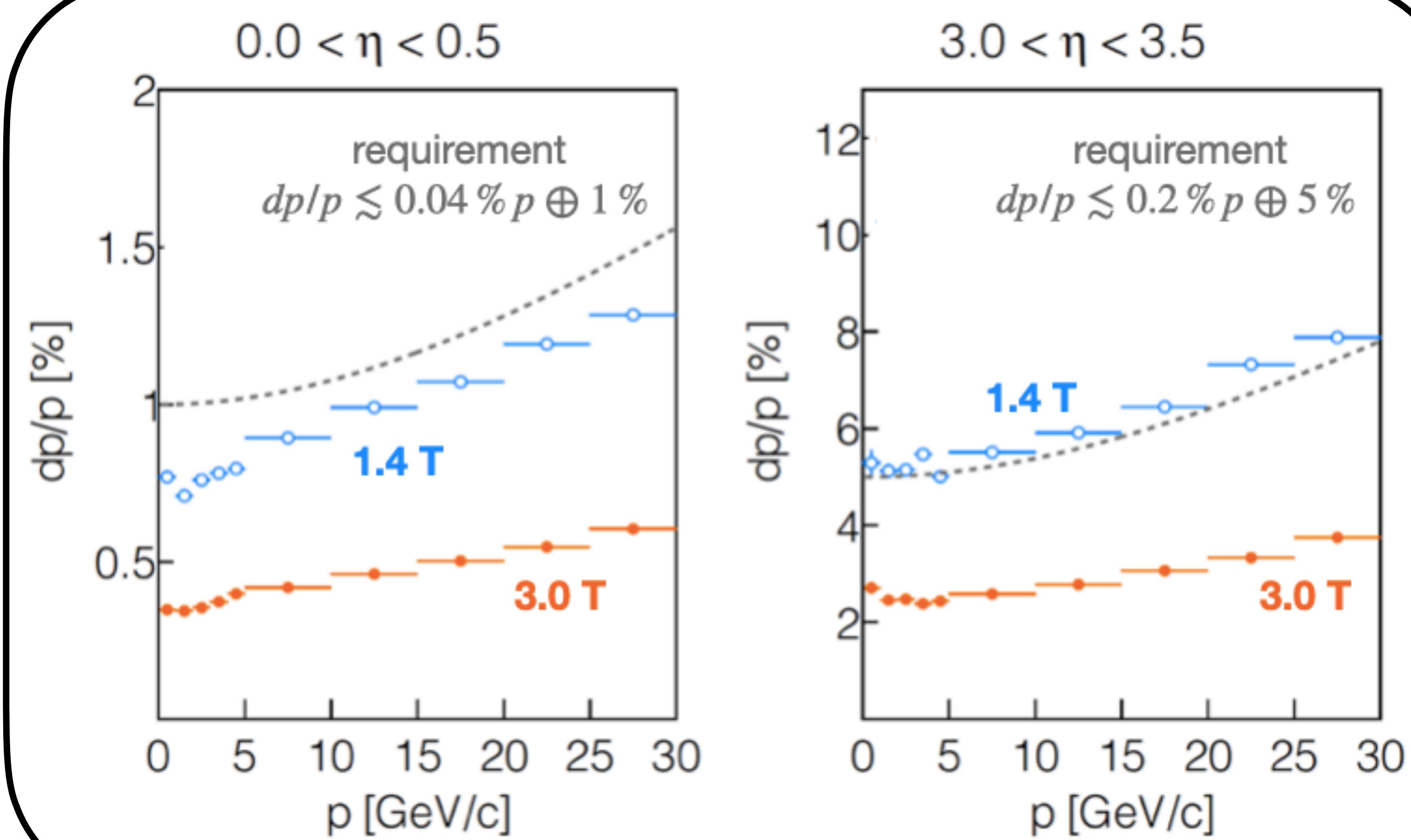
EIC Silicon Consortium

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

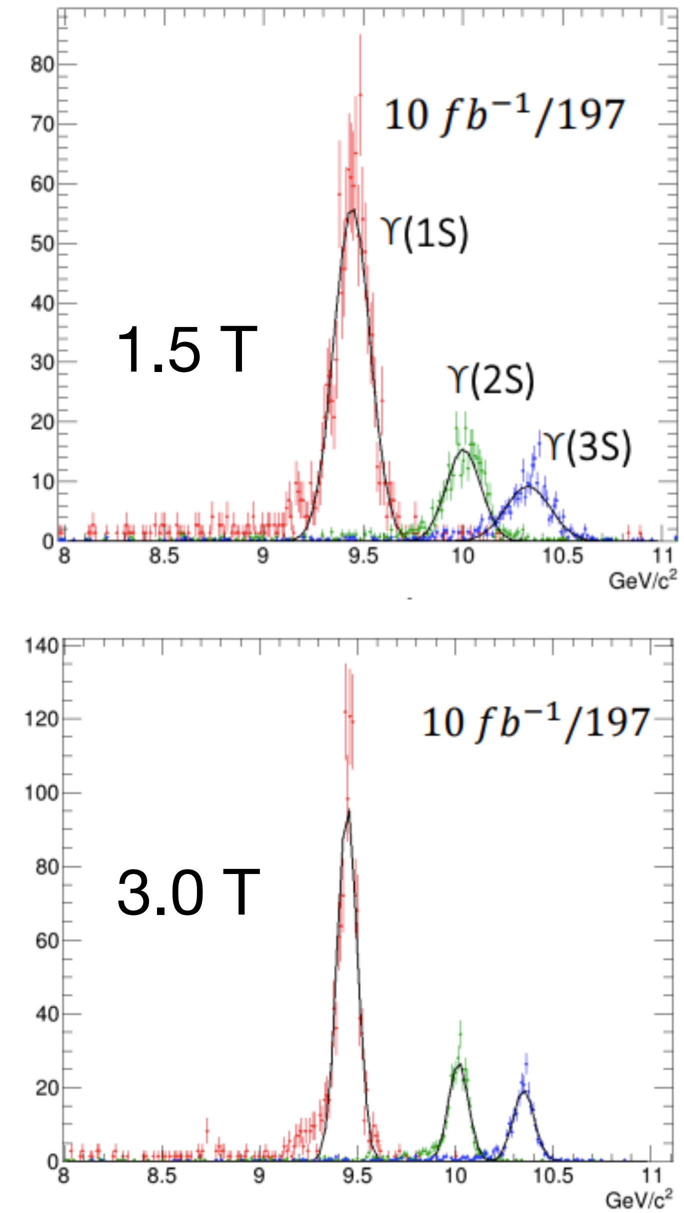
Momentum Resolution

π^-, 10 μm pixel, $X/X_0 = 0.3\%$

Full (Geant4) simulations



eSTARLight + All-Si

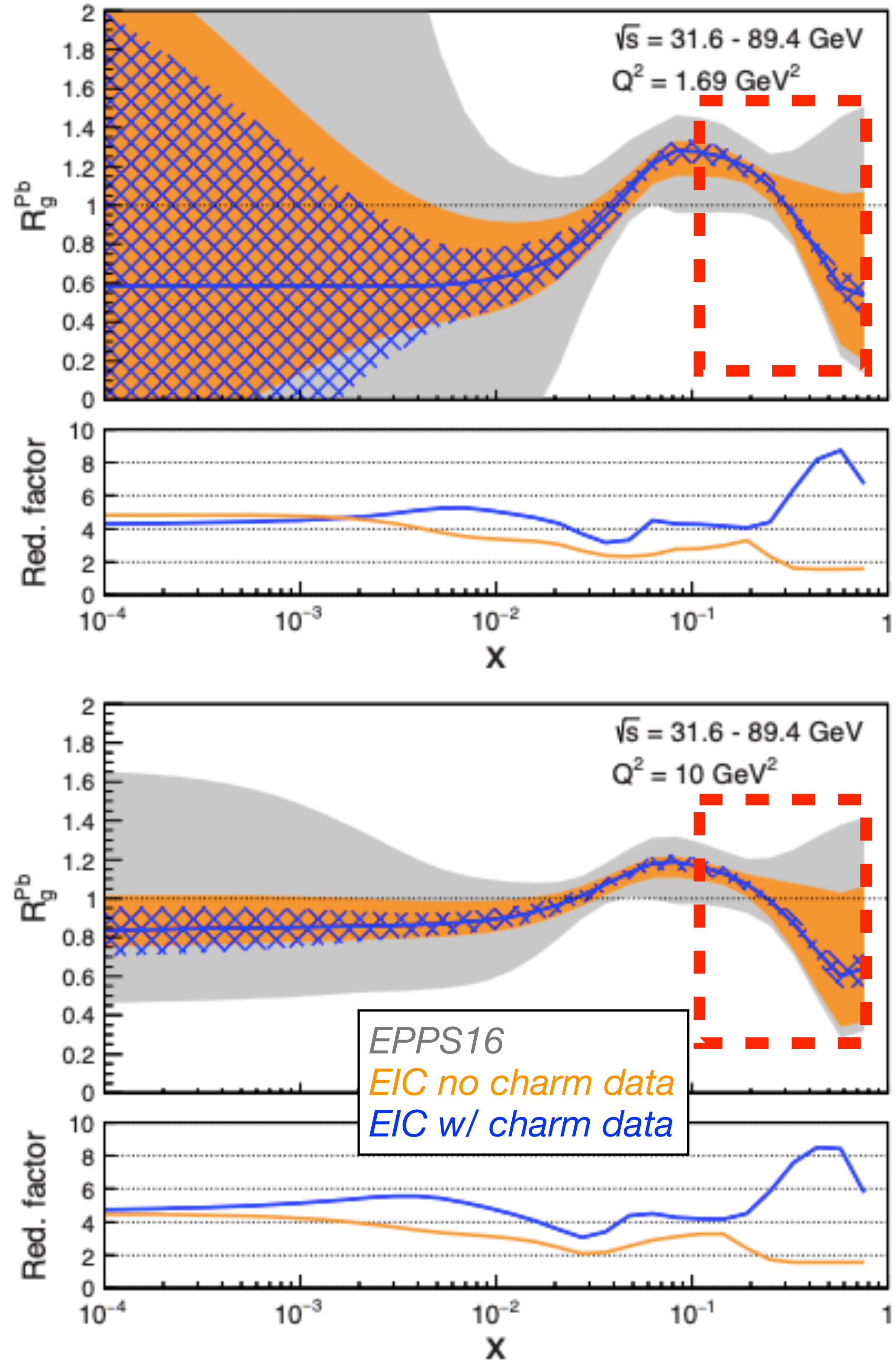


All-Si tracker offers a momentum resolution satisfying the physics requirement

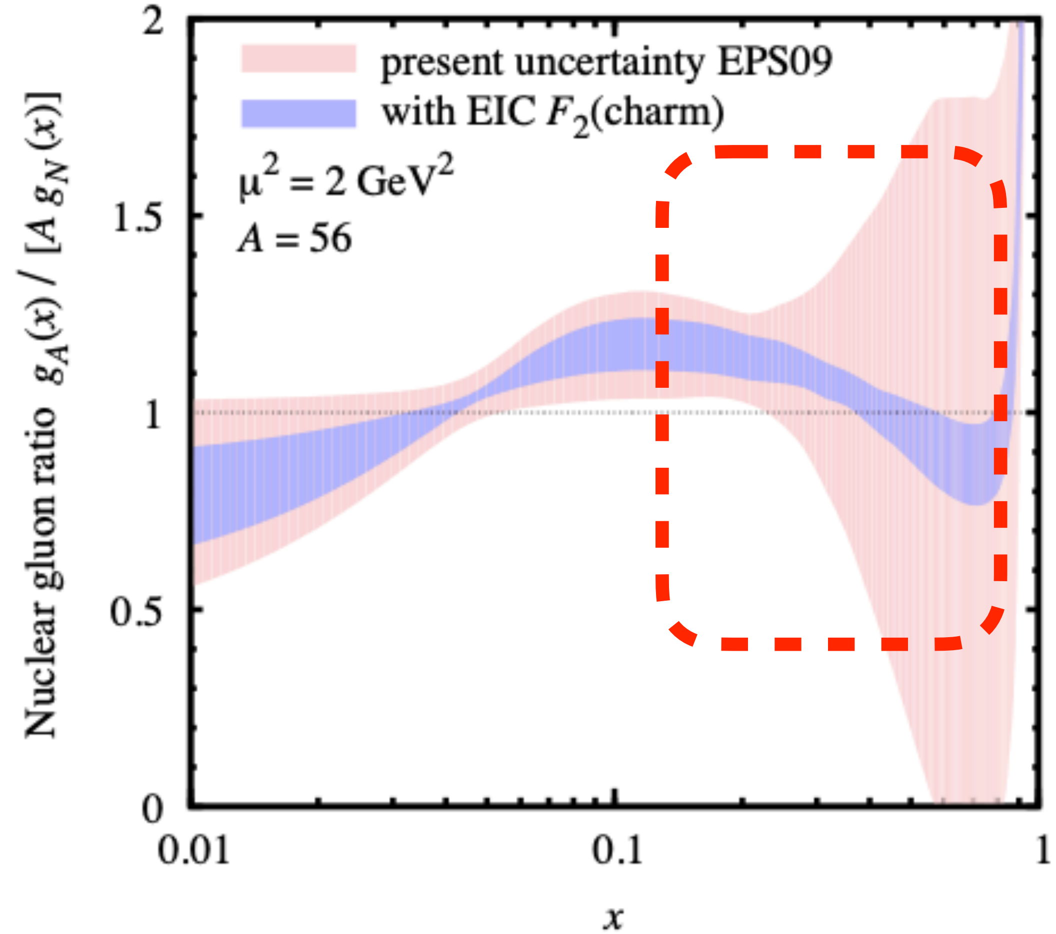
Inclusive Charm -> Gluon nPDF at High x

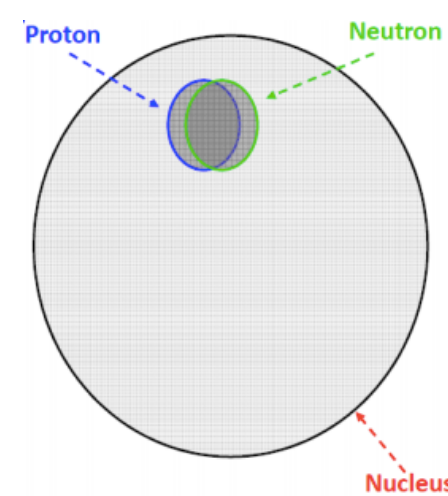
$R_g^{Pb} = f_g^{Pb}(x, Q^2)/f_g^p(x, Q^2)$

E.C. Aschenauer et al, 1708.01527



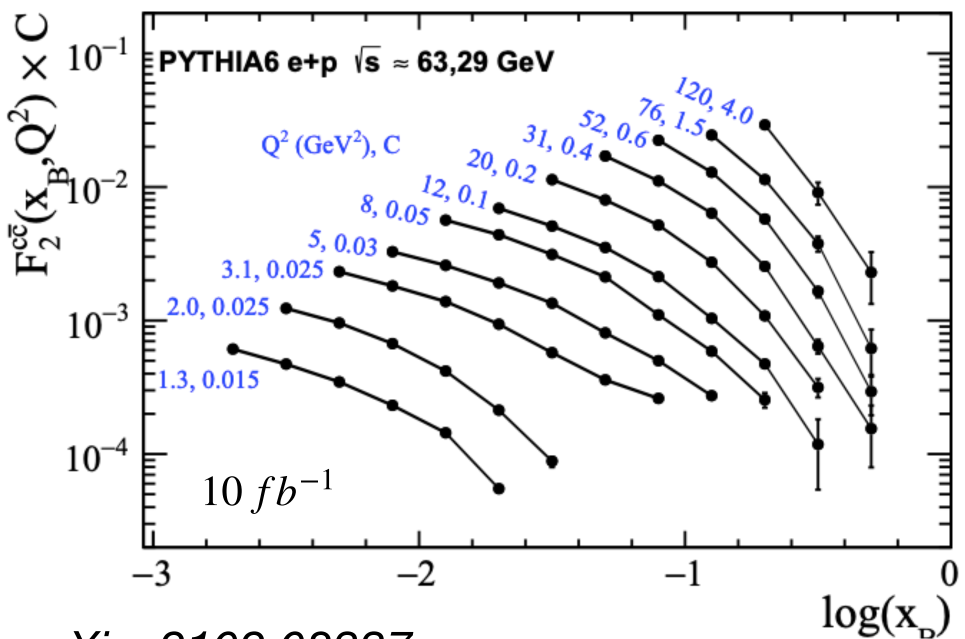
E. Chudakov et al, 1610.08536





gluon probe to
short range correlation
at “EMC” region

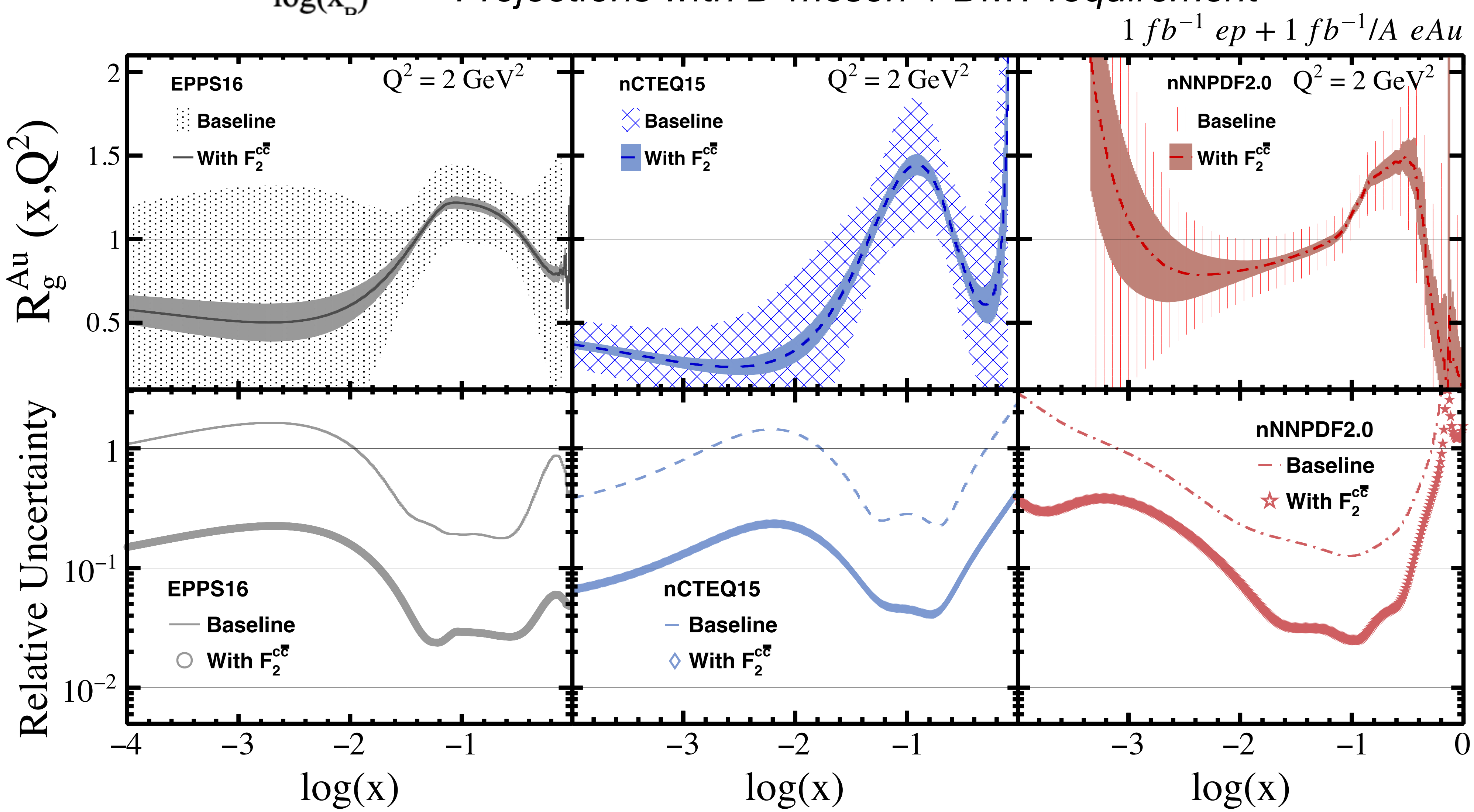
Charm Structure Function $F_2^{c\bar{c}}$ and Gluon nPDF



arXiv: 2102.08337

- Linear fit to $\sigma_r^{c\bar{c}}$ at 10+100 and 5+41 GeV e+p
- Extend HERA measurement to high x region
- Significant impact on gluon nPDF with ep/eA, especially at high x region

Projections with D-meson + DMT requirement



Gluon Helicity $\Delta g/g$

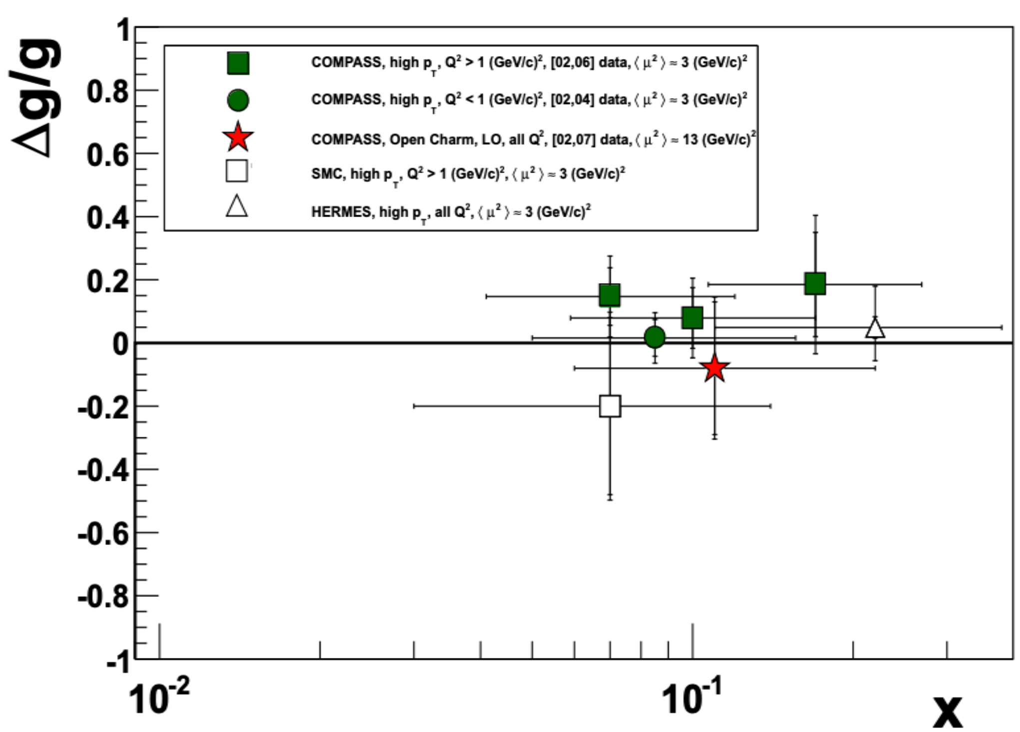
Understanding proton spin is one of the EIC science goals

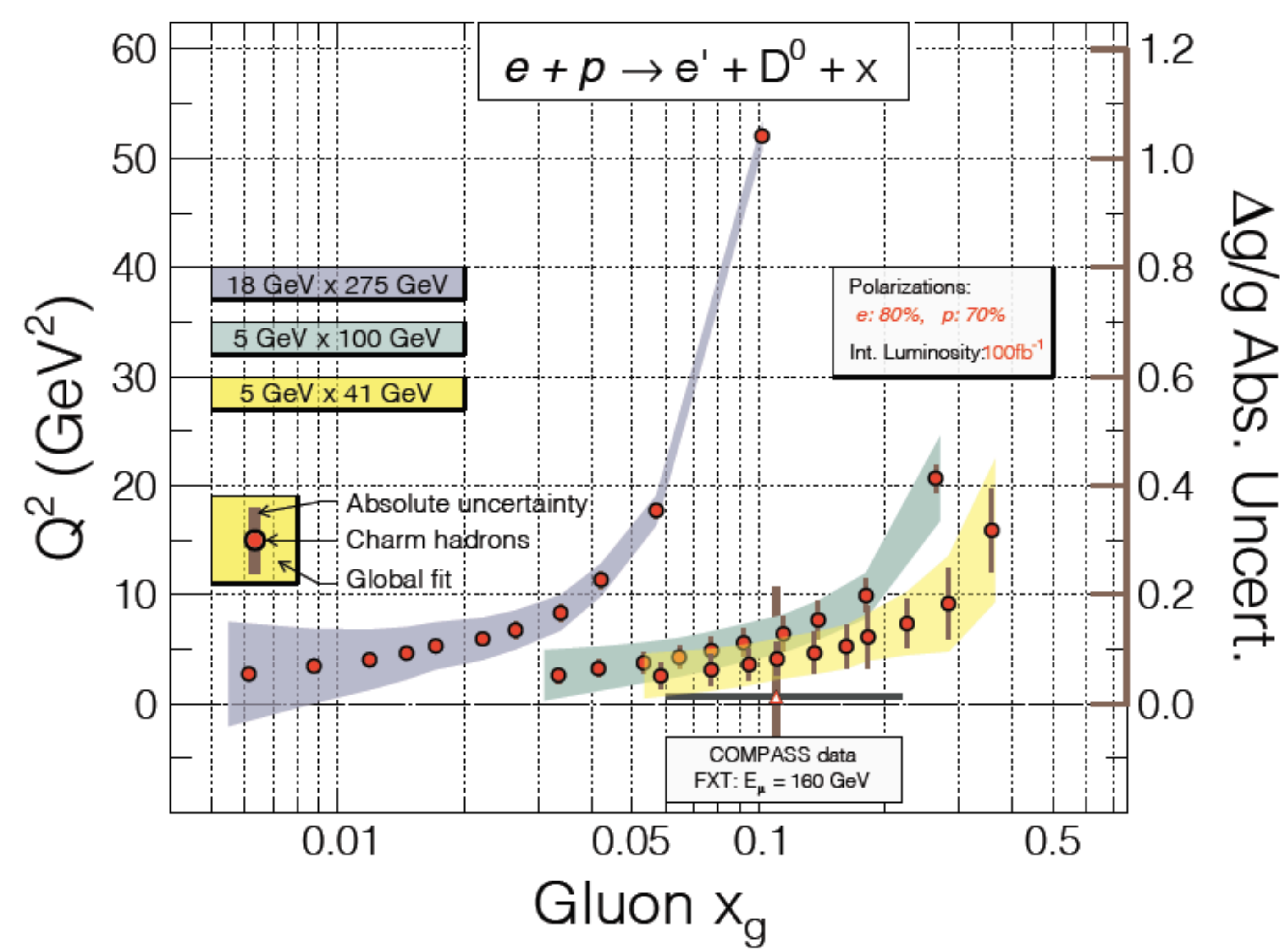
HF - better sensitivity to the gluon dynamics
- complementary to the inclusive measurement
- direct access to $\Delta g/g$ LO $A_{LL} \propto \hat{a}_{LL} \times \Delta g/g$

data placed at each measured (x_g, Q^2) position

error bars - uncertainty of A_{LL}

COMPASS data from open charm





arXiv: 2102.08337, EIC YR 2021

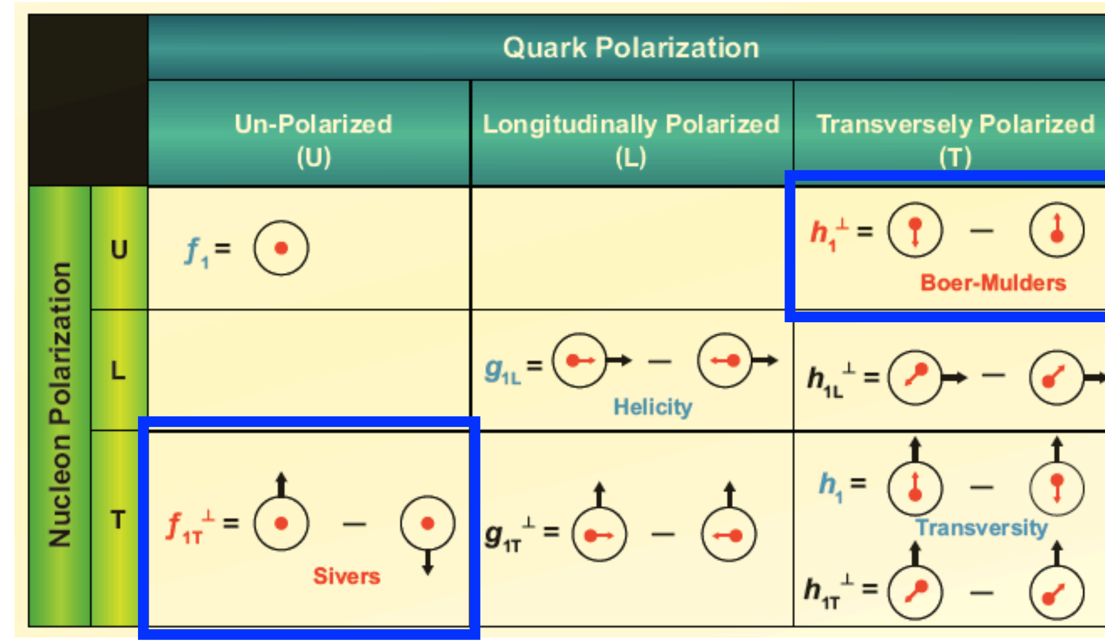
$D\overline{D}$ Pair - Probe Gluon TMDs

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

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

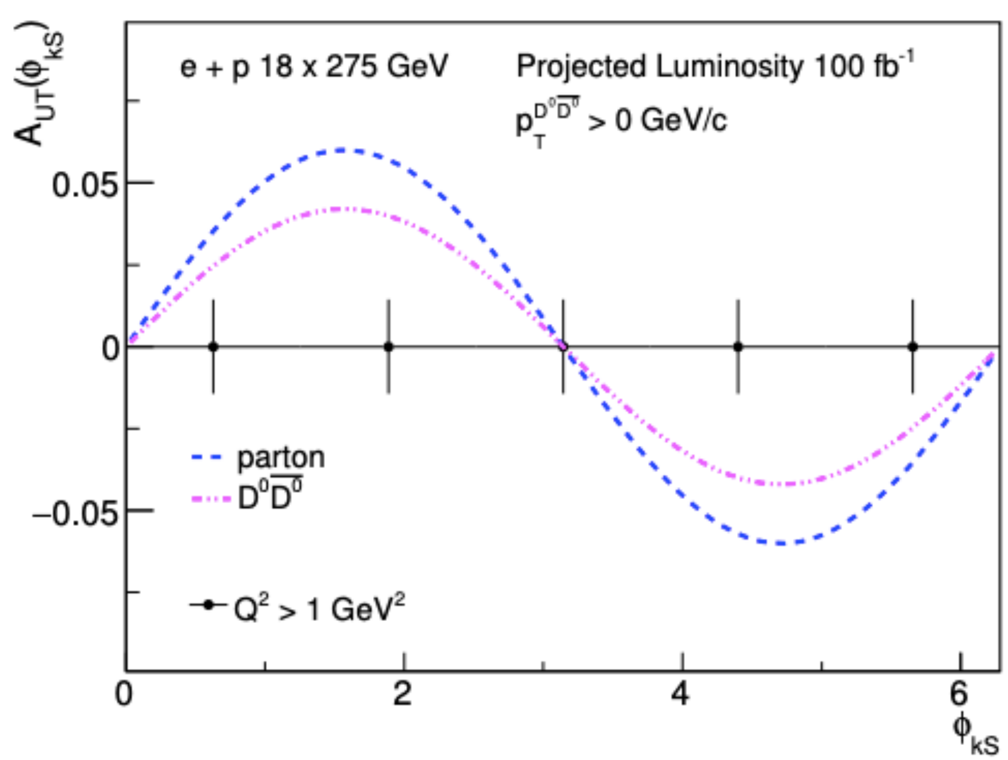
Charm hadron pair in unpolarized exp.
- linearly polarized Boer-Mulders function

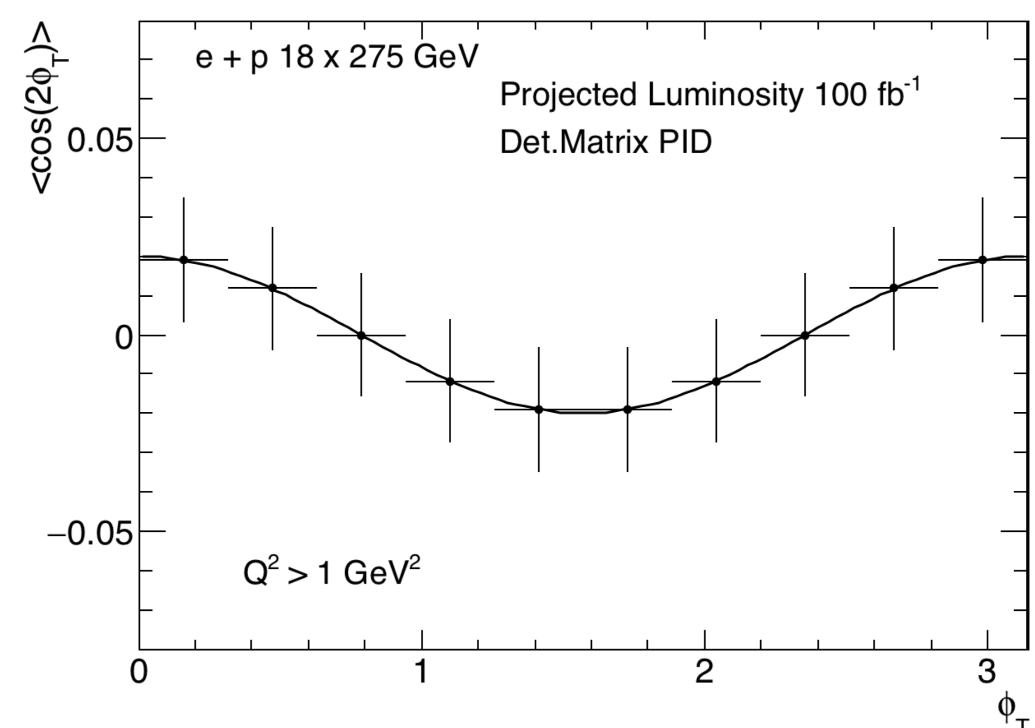
D. Boer et. al., JHEP 08 (2016) 001



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

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

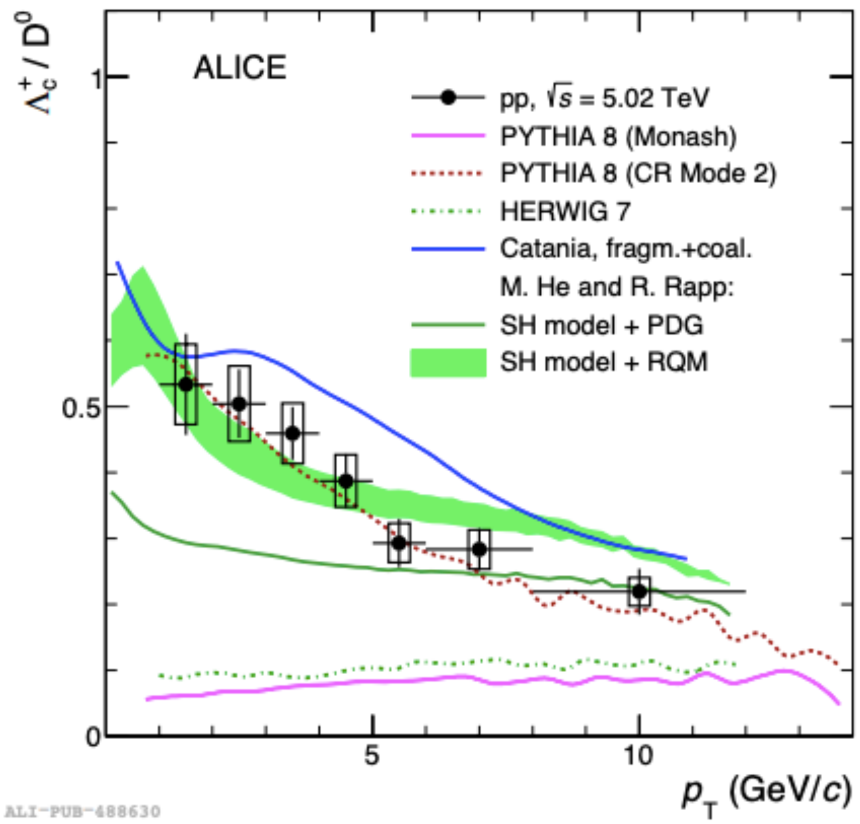


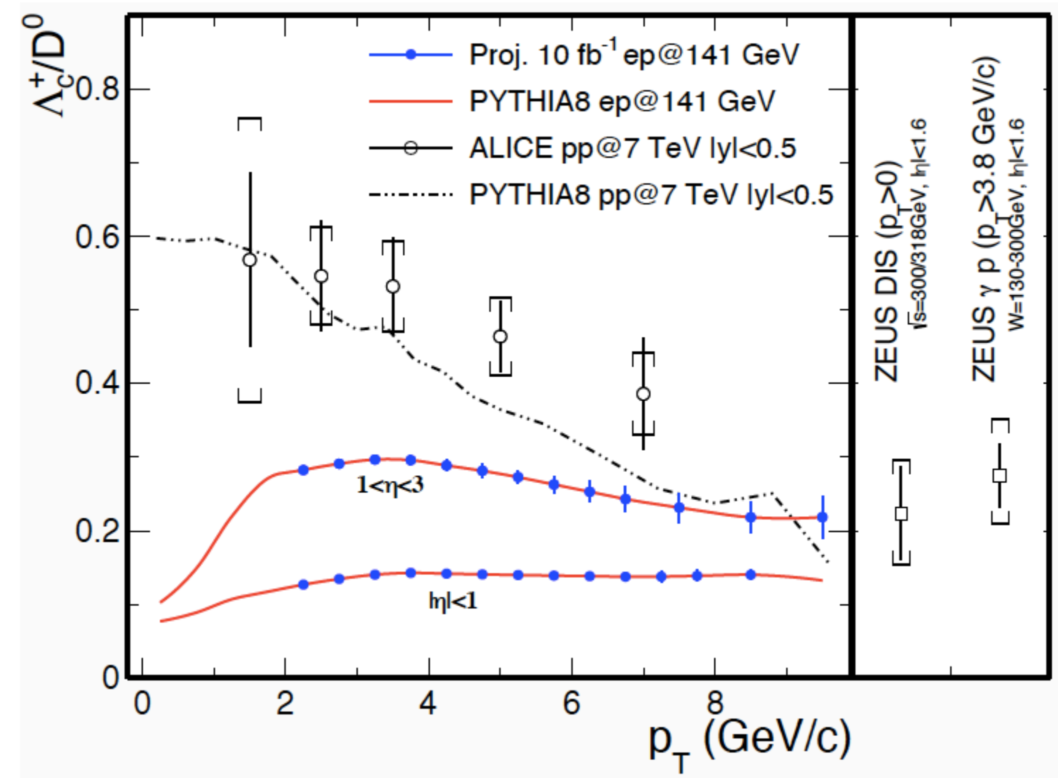


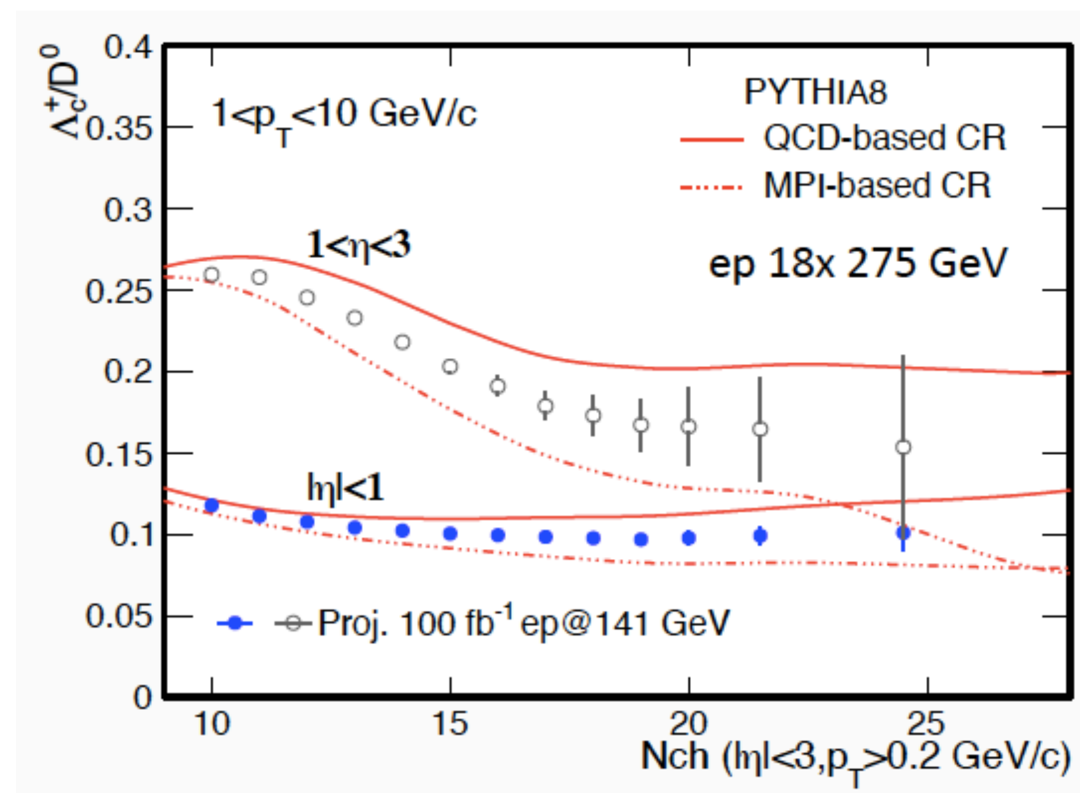
- ~0.4% projected uncertainty on both A_{UT} and $\cos(2\phi_T)$ with 100 fb^{-1}

Charm Hadrochemistry for Hadronization

arXiv: 2102.08337



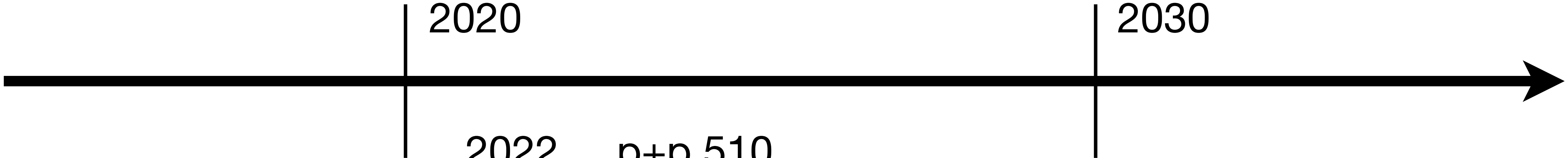




Systematic measurement of Λ_c^+ in ep, pp and AA collisions to understand charm baryon production and hadronization

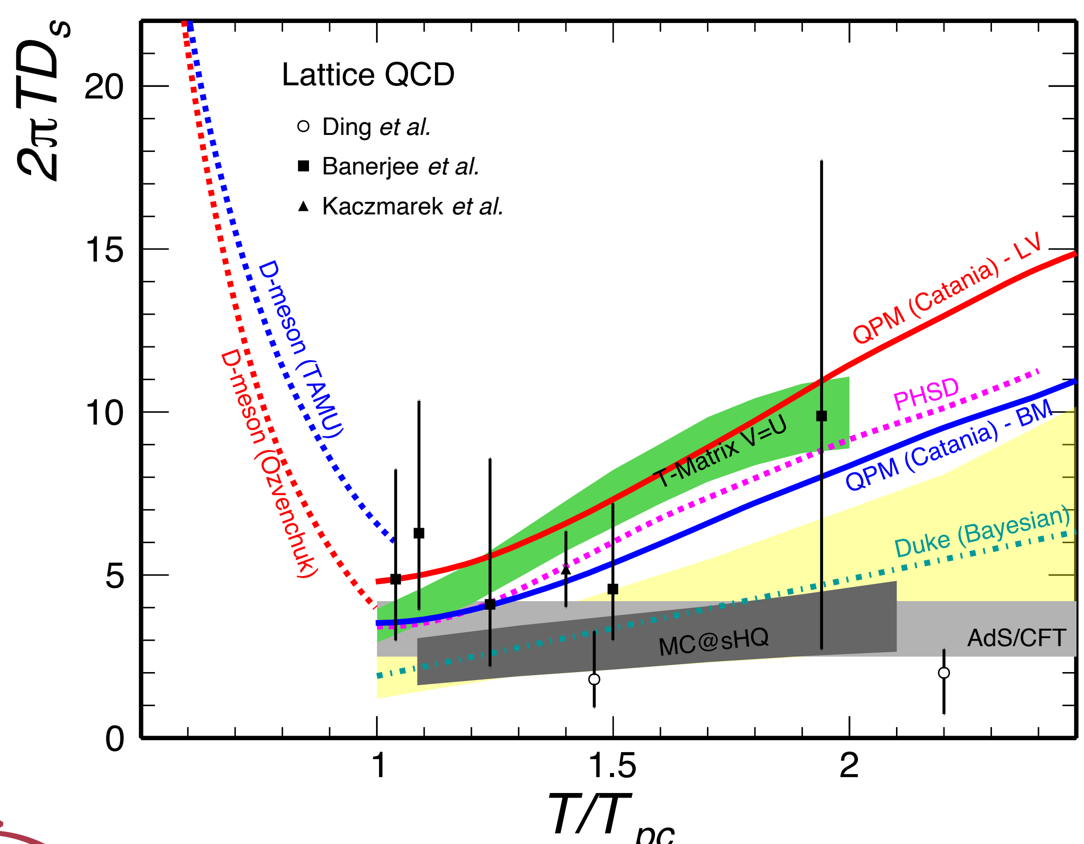
- multi-differential (p_T, multiplicity etc) measurements
- new opportunities: other charm baryons, Λ_c^+ spin transfer etc.

Summary

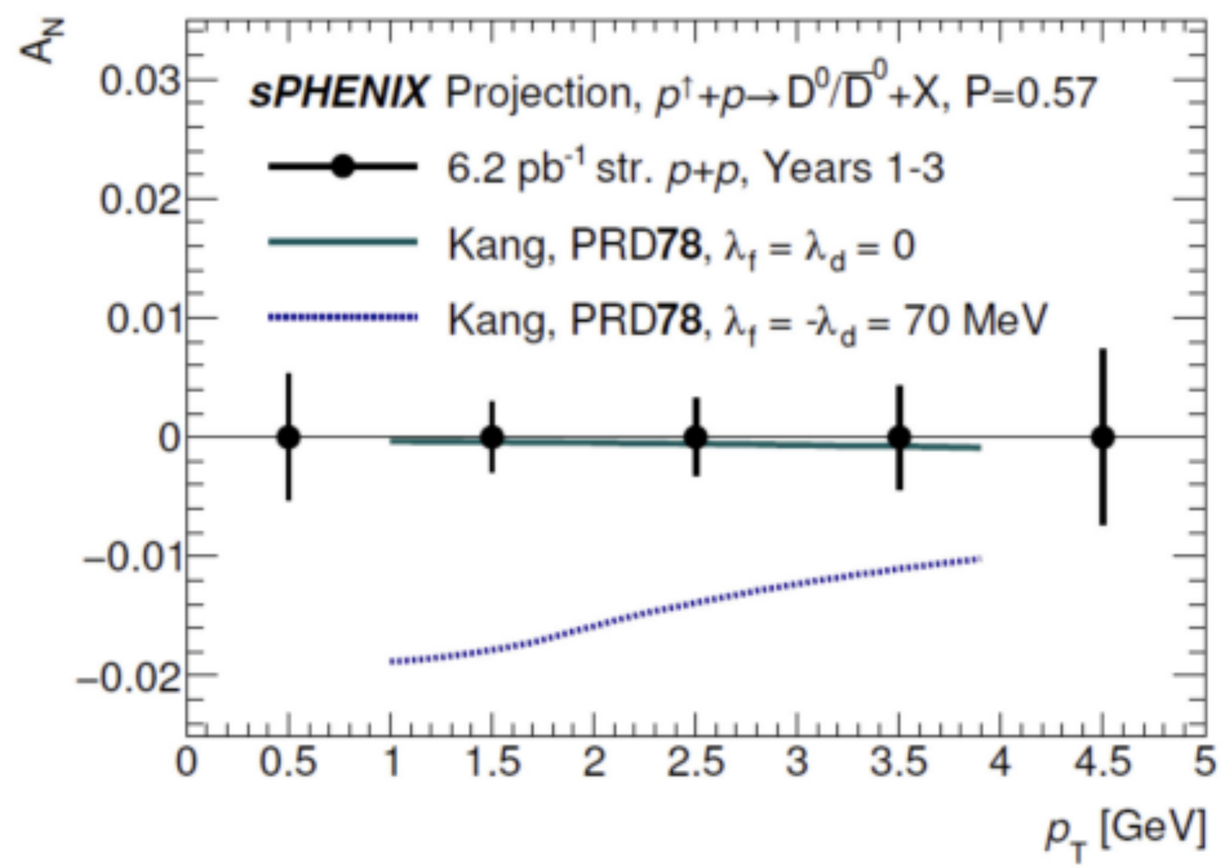


2022	p+p 510
2023	Au+Au 200
2024	p+p 200
	p+Au 200
2025	Au+Au 200

Quantifying QGP Properties



Glimpsing at gluon distributions in p/A

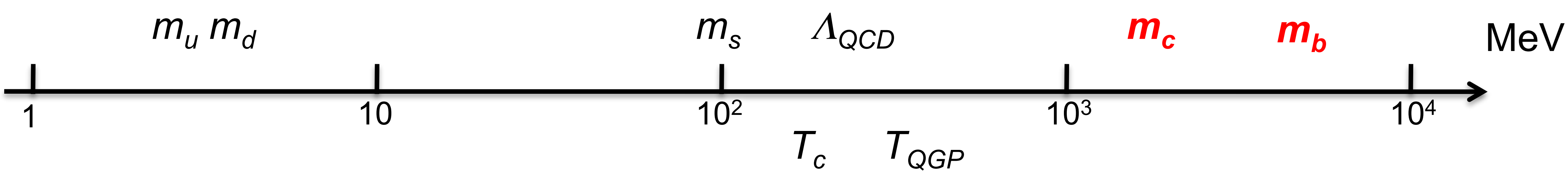


Acknowledgements

J. Bielcik, X. Chen, G. Contin, R. Cruz-Torres, C. Fu, V. Greco, L. Greiner, Y. Guo, M. Gyulassy, L. He, H. Huang, J. Huang, Y.F. Hong, B. Jacak, Y. Ji, X.Y. Ju, M. Kelsey, Y.J. Lee, Y. Liang, M.X. Liu, M. Lomnitz, L. Ma, S. Margetis, S. Mizuno, M. Mustafa, Md Nasim, G. Odyniec, K. Oh, H. Qiu, S. Radhakrishnan, R. Rapp, H.G. Ritter, A. Schmah, S. Shi, E. Sichtermann, M. Simko, S. Singha, X.M. Sun, Z.B. Tang, J. Thaeder, J. Thomas, J. Vanek, F. Videbaek, F. Wang, Y.P. Wang, H. Wieman, L. Xia, G. Xie, W. Xie, N. Xu, Z. Xu, Z. Ye, F. Yuan, Y.F. Zhang, Y.X. Zhao, L. Zhou …

Backup

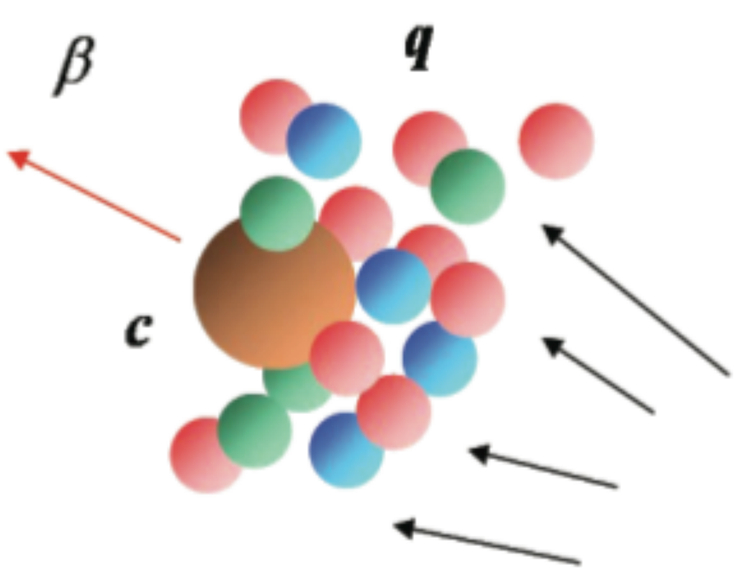
Uniqueness of Heavy Flavor Quarks



$m_{c,b} >> \Lambda_{QCD}$ *amenable to perturbative QCD*

$m_{c,b} >> T_{QGP}$ *predominately created from initial hard scatterings*

"Brownian" motion



$M_Q >> T$, $M_Q >> gT$

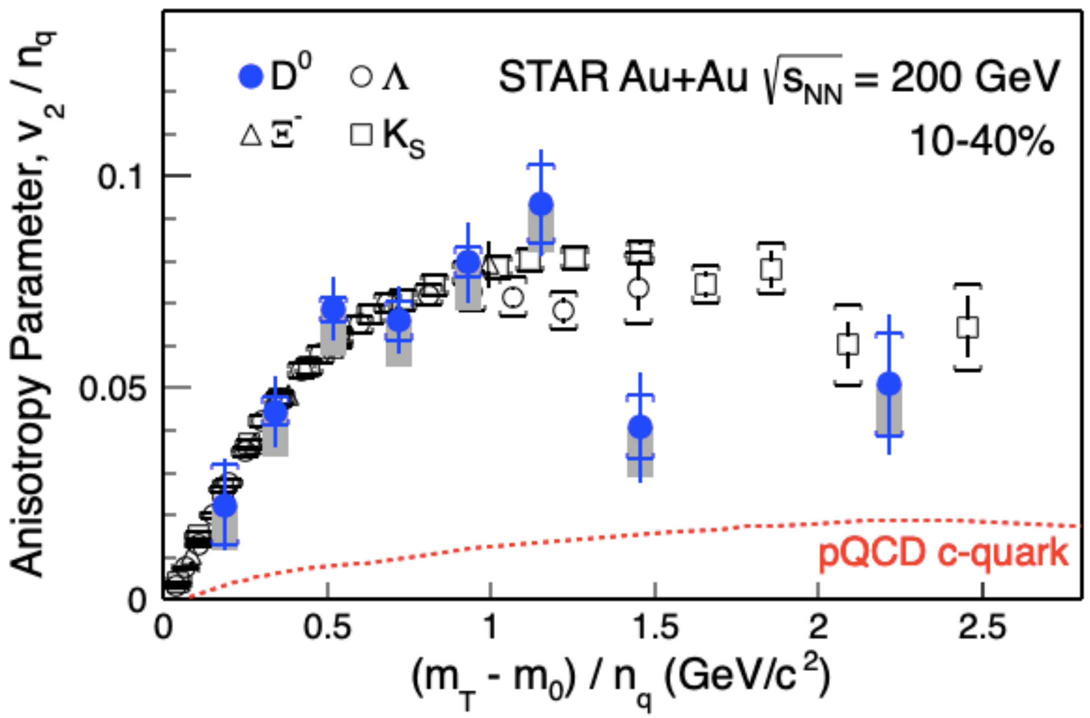
Diffusion Equation

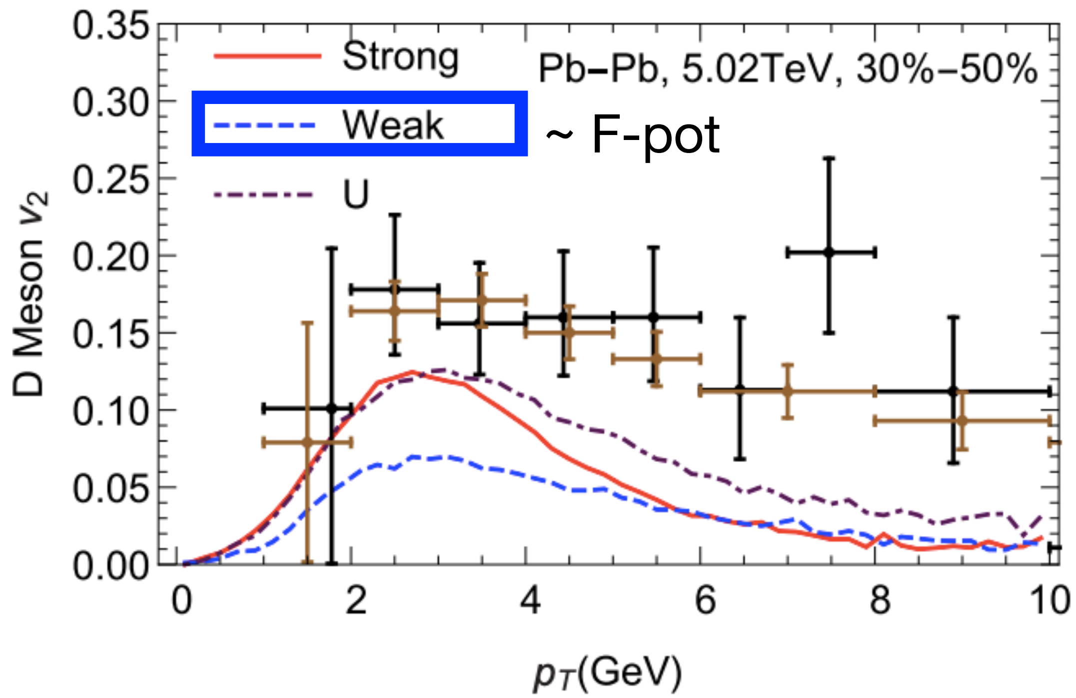
$$\frac{\partial \rho}{\partial t} = D\frac{\partial^2 \rho}{\partial x^2} \qquad \langle x^2(t)\rangle - \langle x^2(0)\rangle \sim Dt$$

D or D$_s$ - spacial diffusion coefficient

- used to reveal medium substructures
- e.g. $$D = \frac{RT}{N_A 6\pi\eta a} = \frac{k_B T}{6\pi\eta a}$$

D^0 v_2 Compared with pQCD Calculation

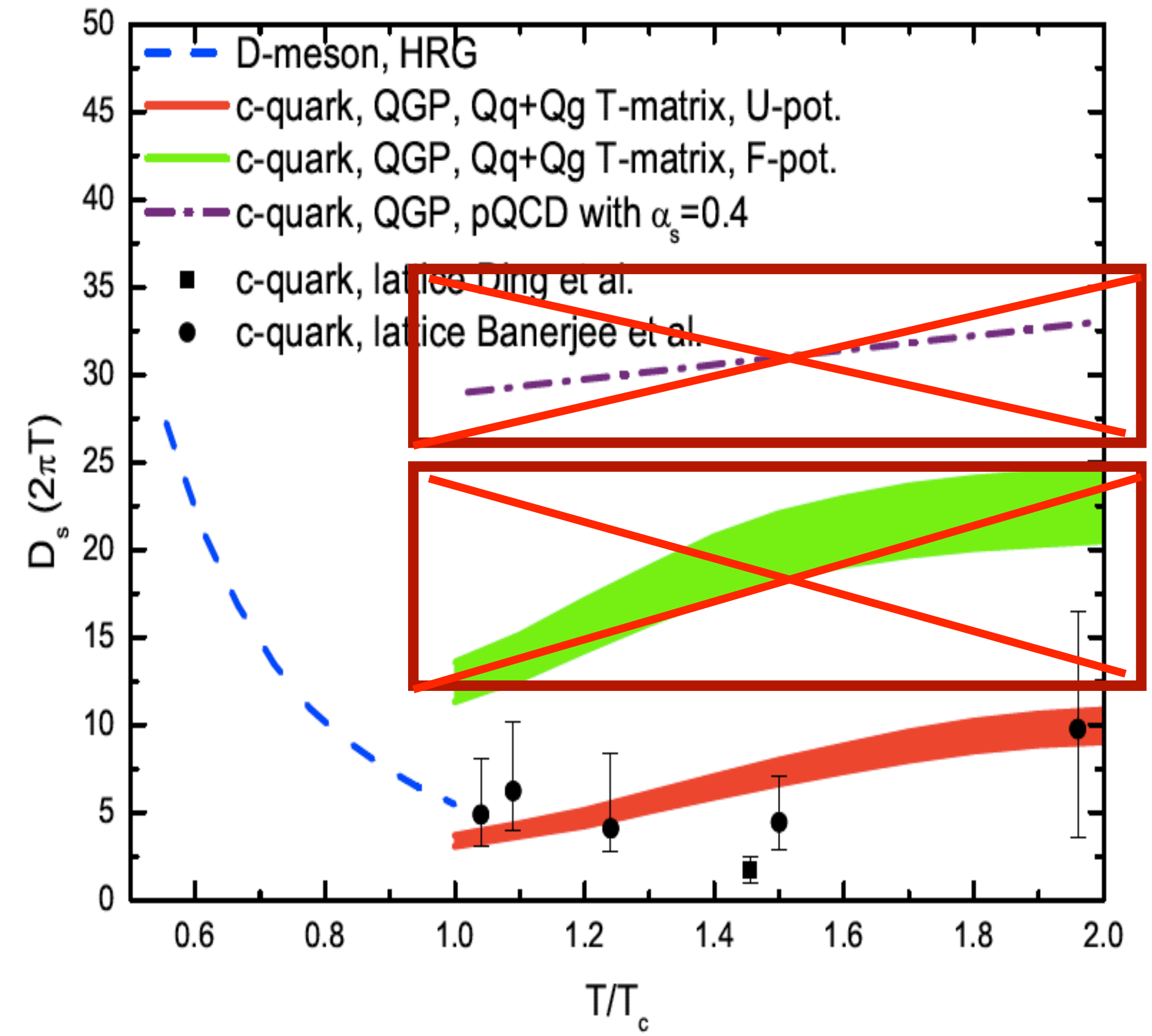




pQCD c-quark (b=7fm):

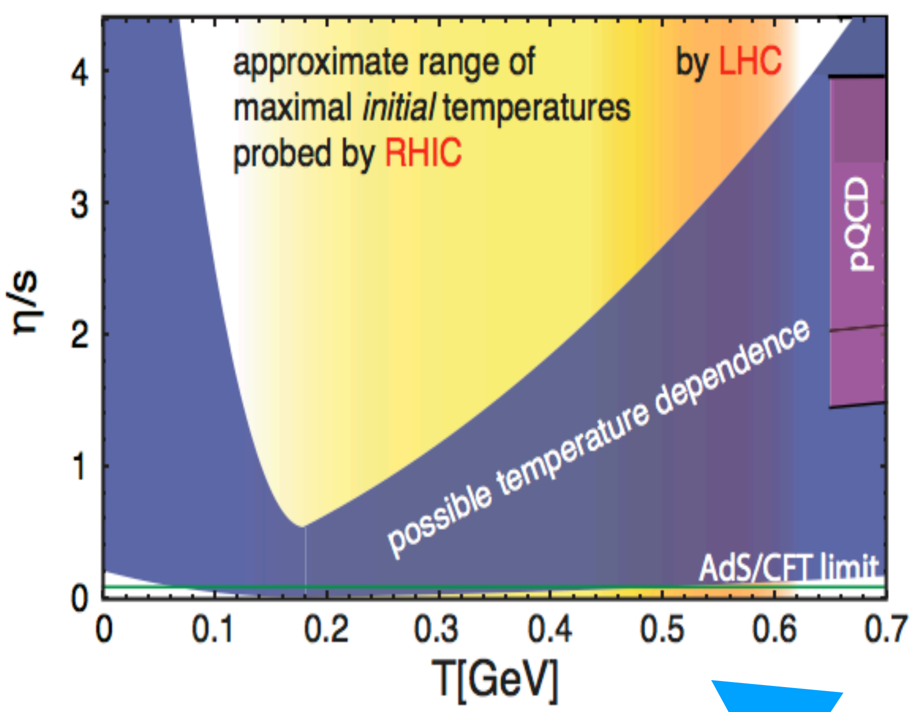
R. Rapp & H. van Hees, arXiv: 0903.1096

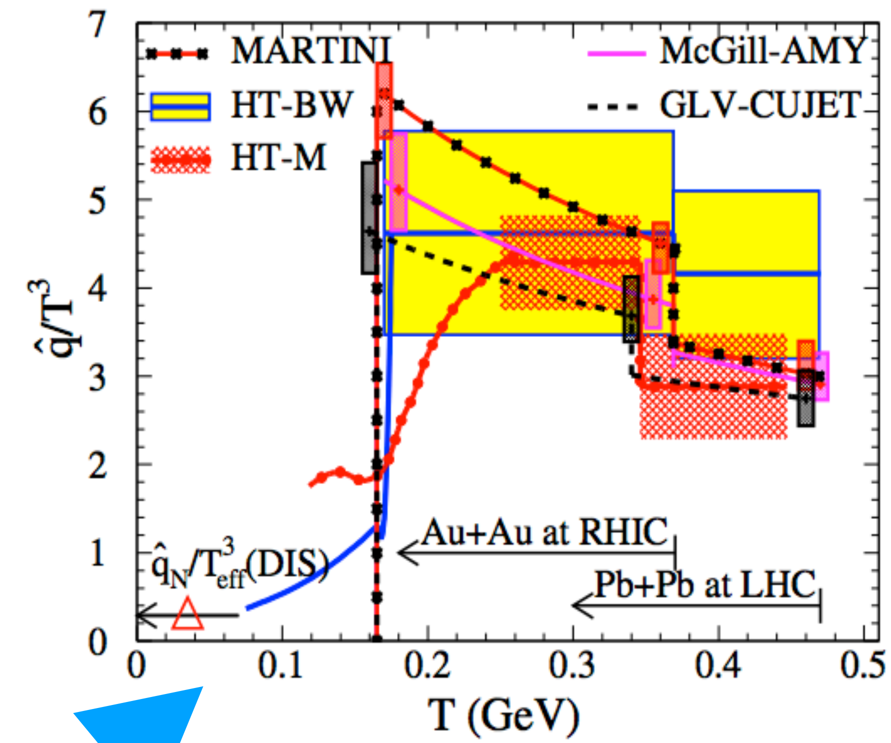
S. Liu et al, PRC 99 (2019) 055201

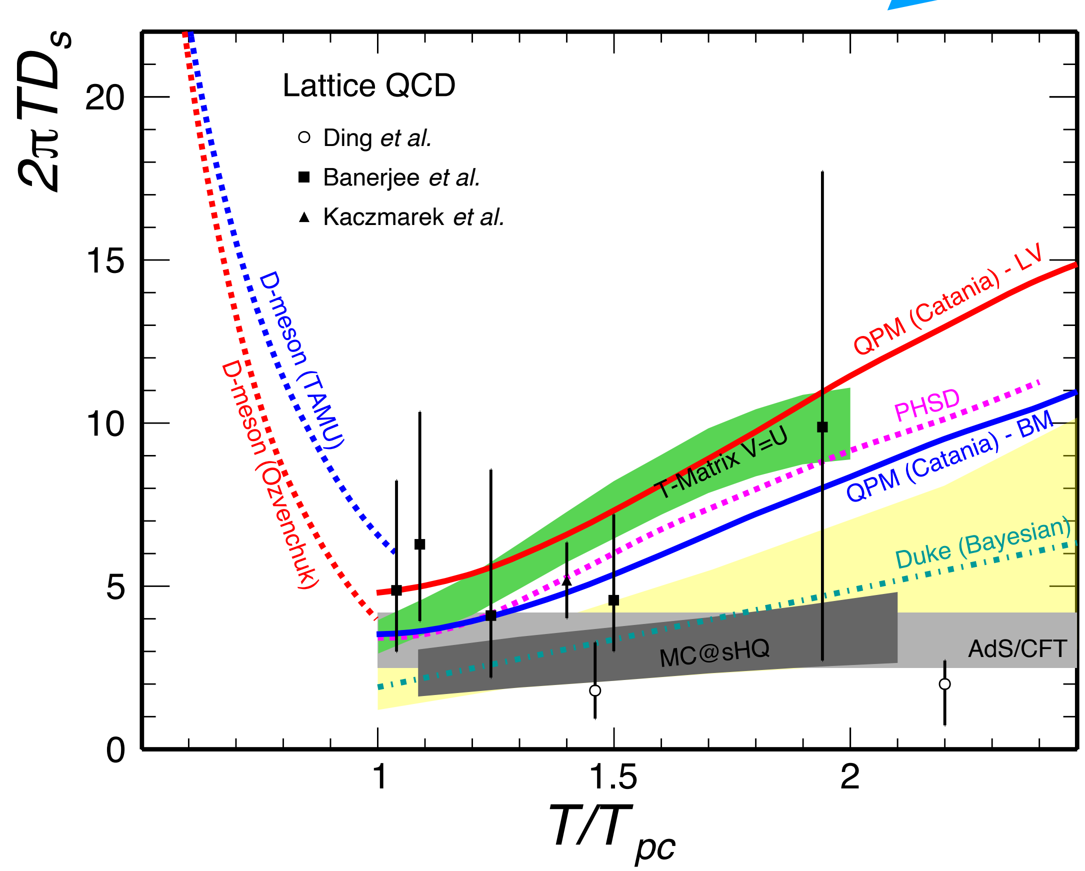


- pQCD calculation and T-Matrix with F-pot. cannot reproduce the data

Quantitative Measure of QGP



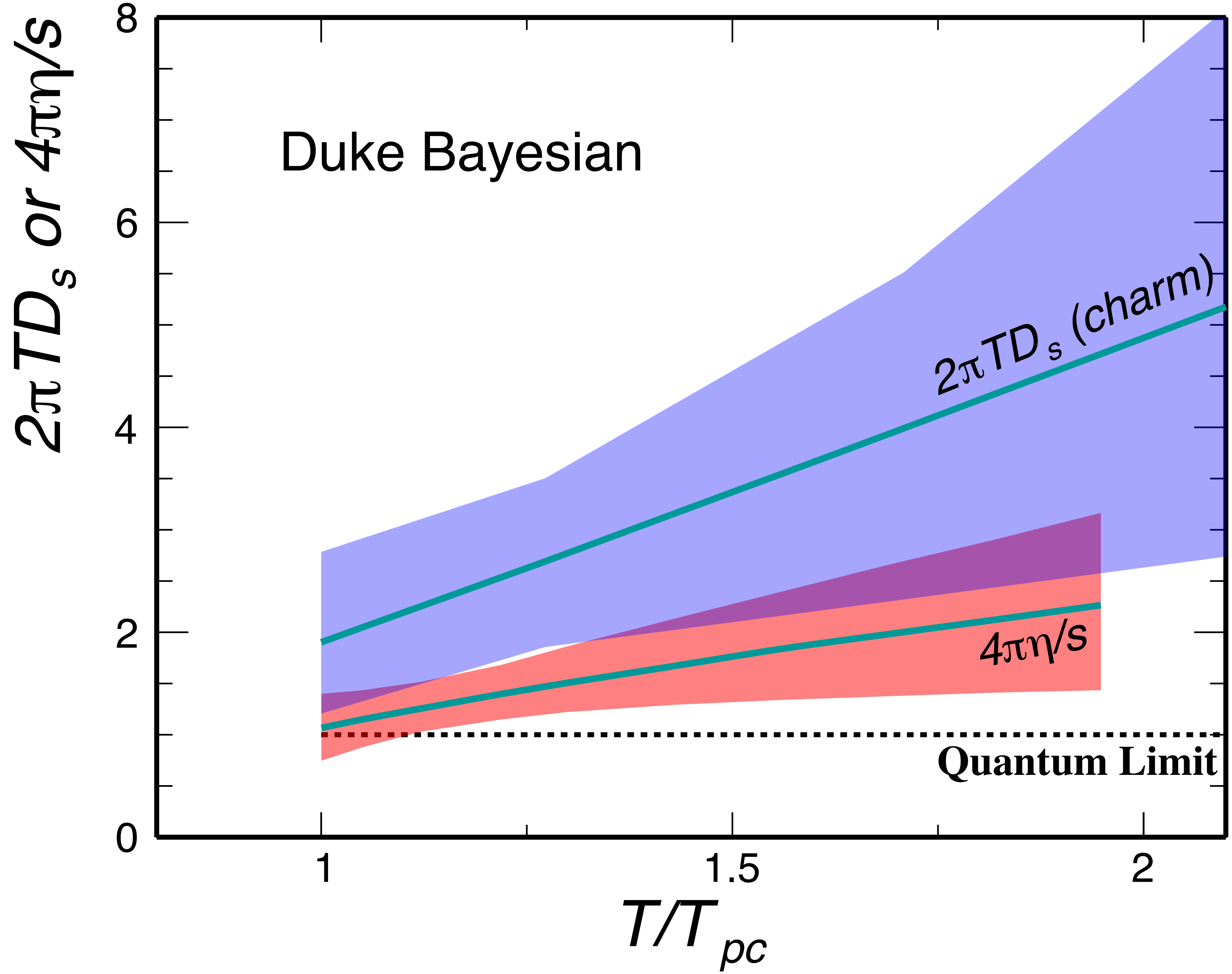




$2\pi TD_s$ vs. $4\pi\eta/s$

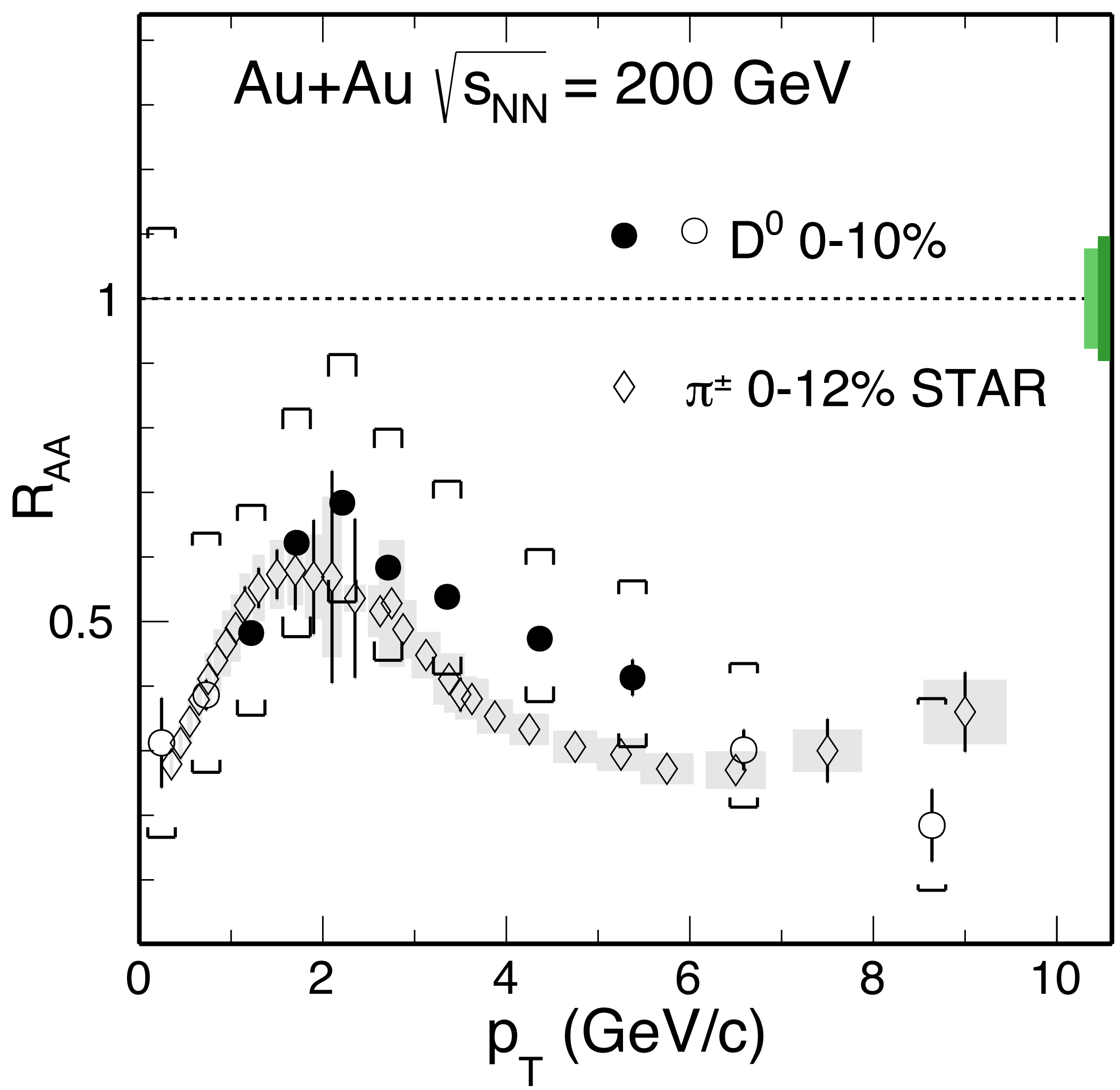
$2\pi TD_s$: *Y. Xu et al, PRC 97 (2018) 014907*

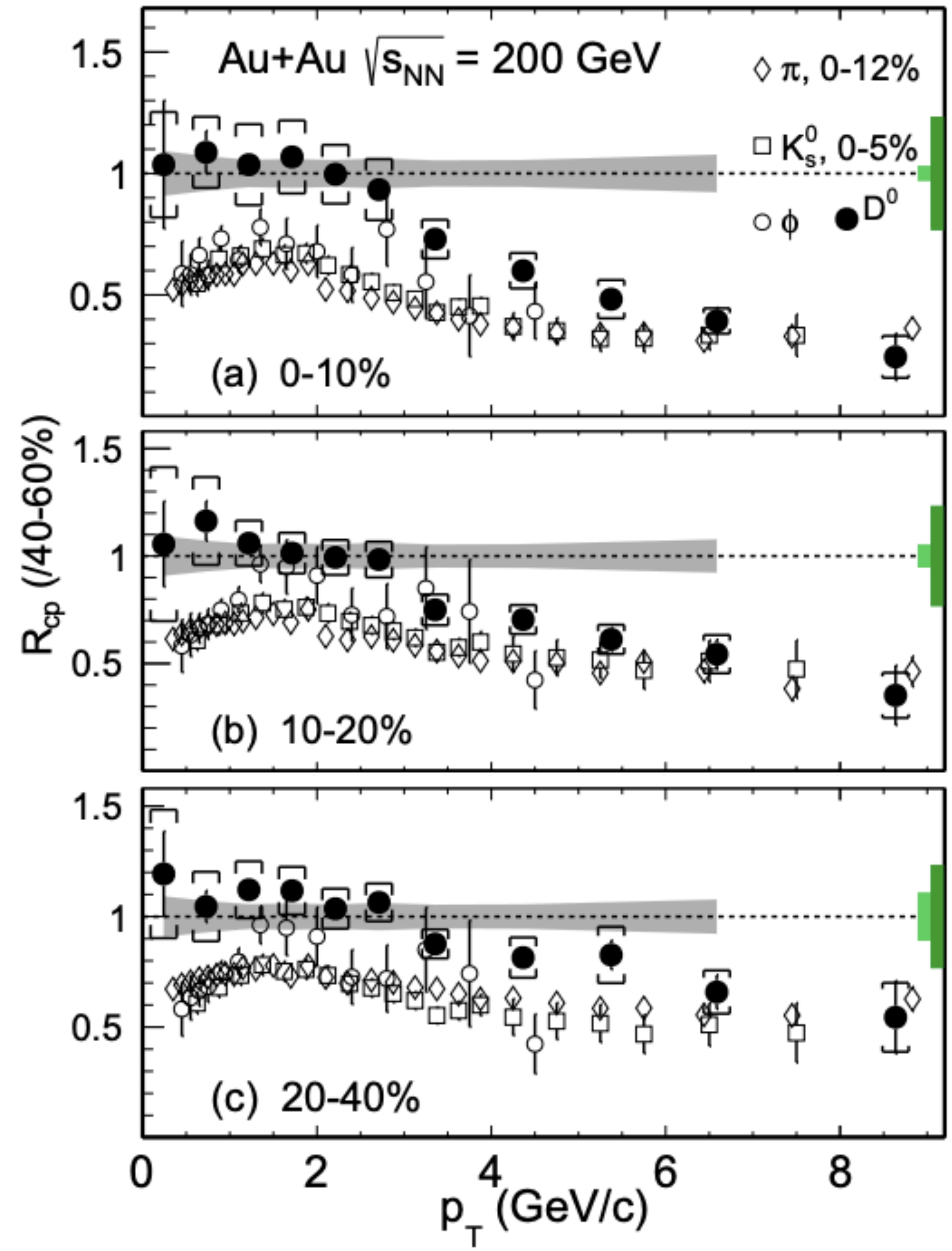
η/s: *J. Bernhard et al, Nature Physics 115 (2019) 1113*



charm vs. bottom universality? momentum/temperature dependence?

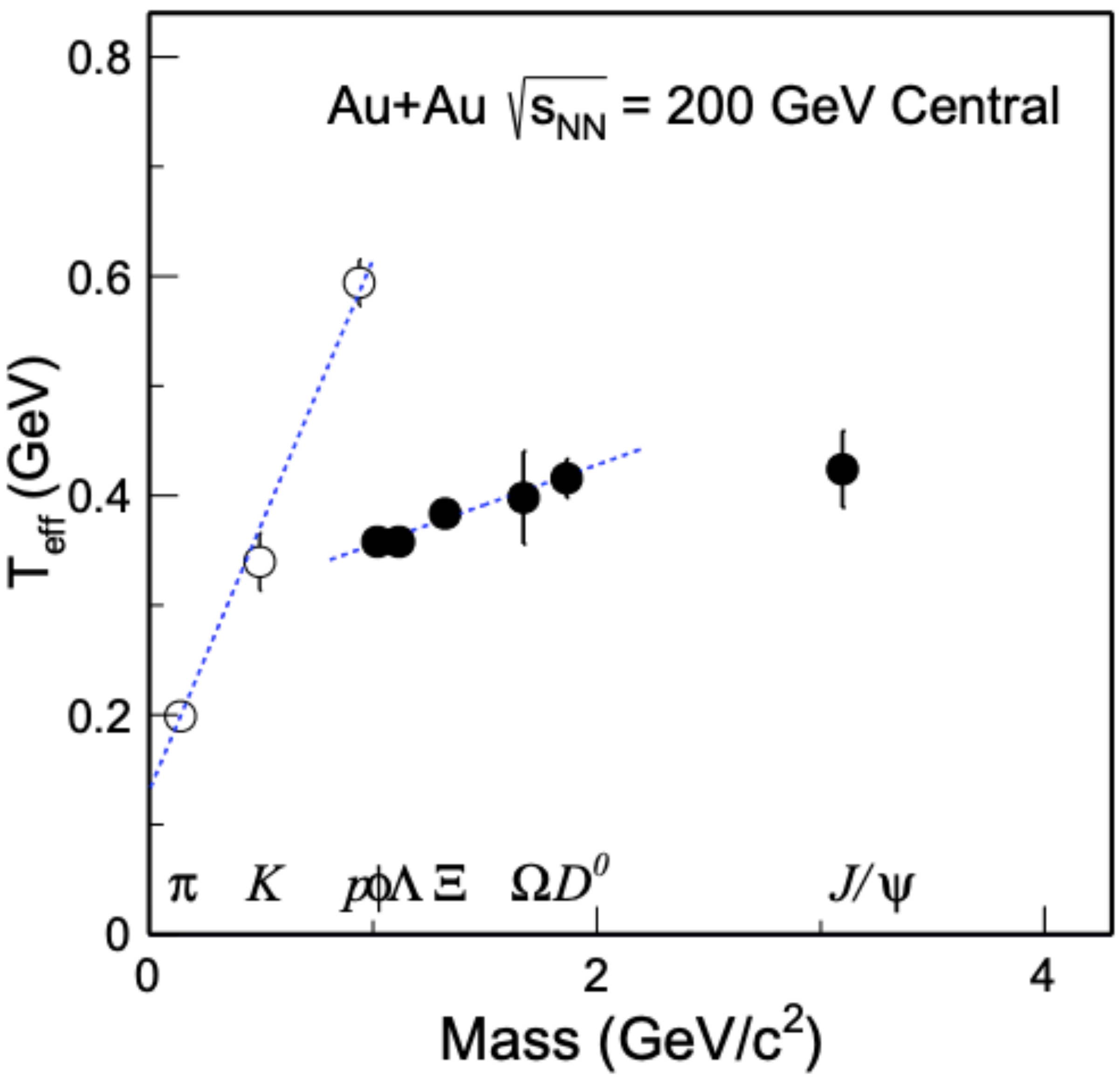
D^0 Meson R_{AA}/R_{CP} in A+A Collisions

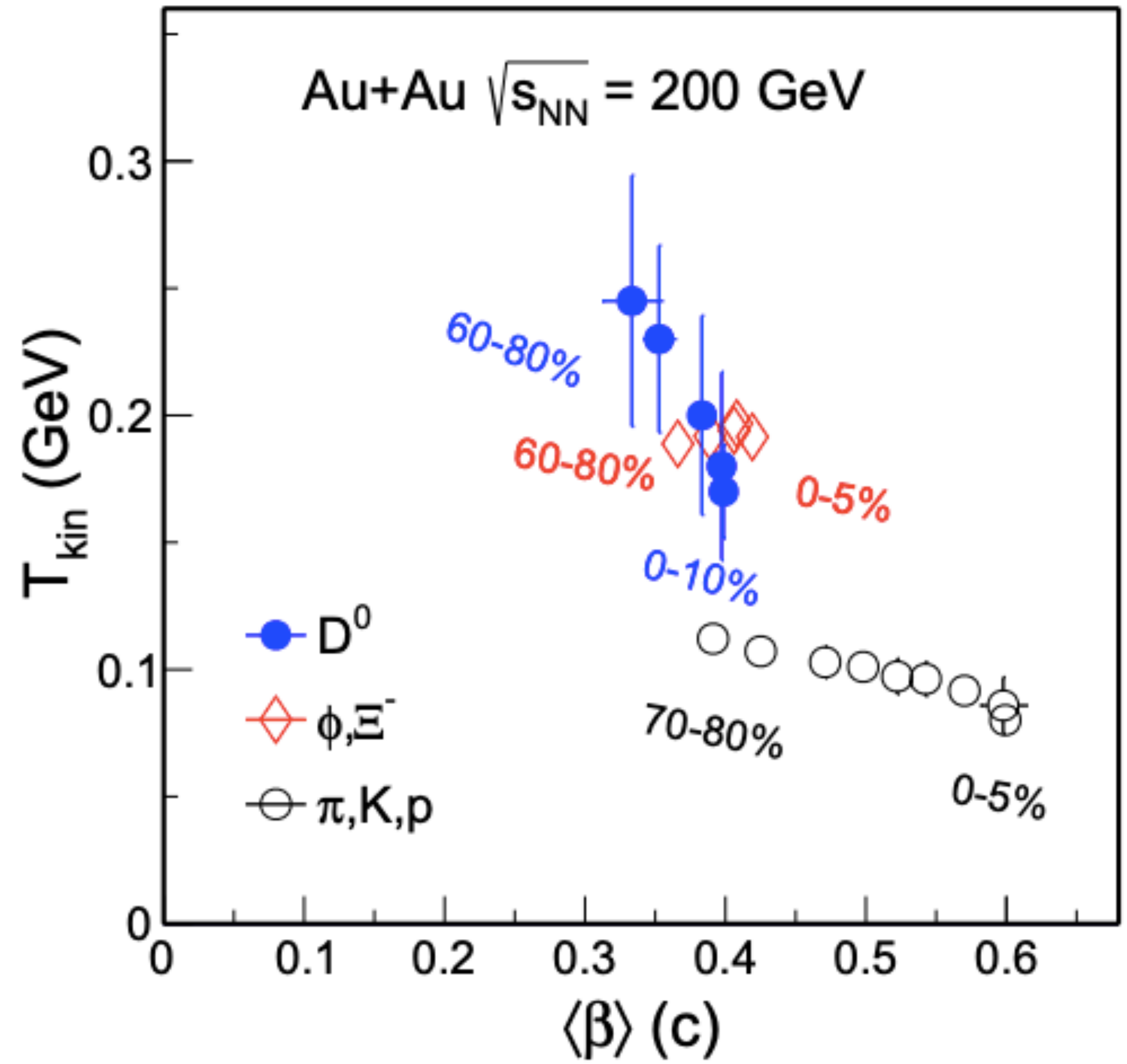




- $R_{AA}(D) \sim R_{AA}(h)$ at $p_T >$ ~4 GeV/c
  - significant charm quark energy loss in the QGP medium
  - importance of radiative and collisional energy loss

D^0 Radial Flow

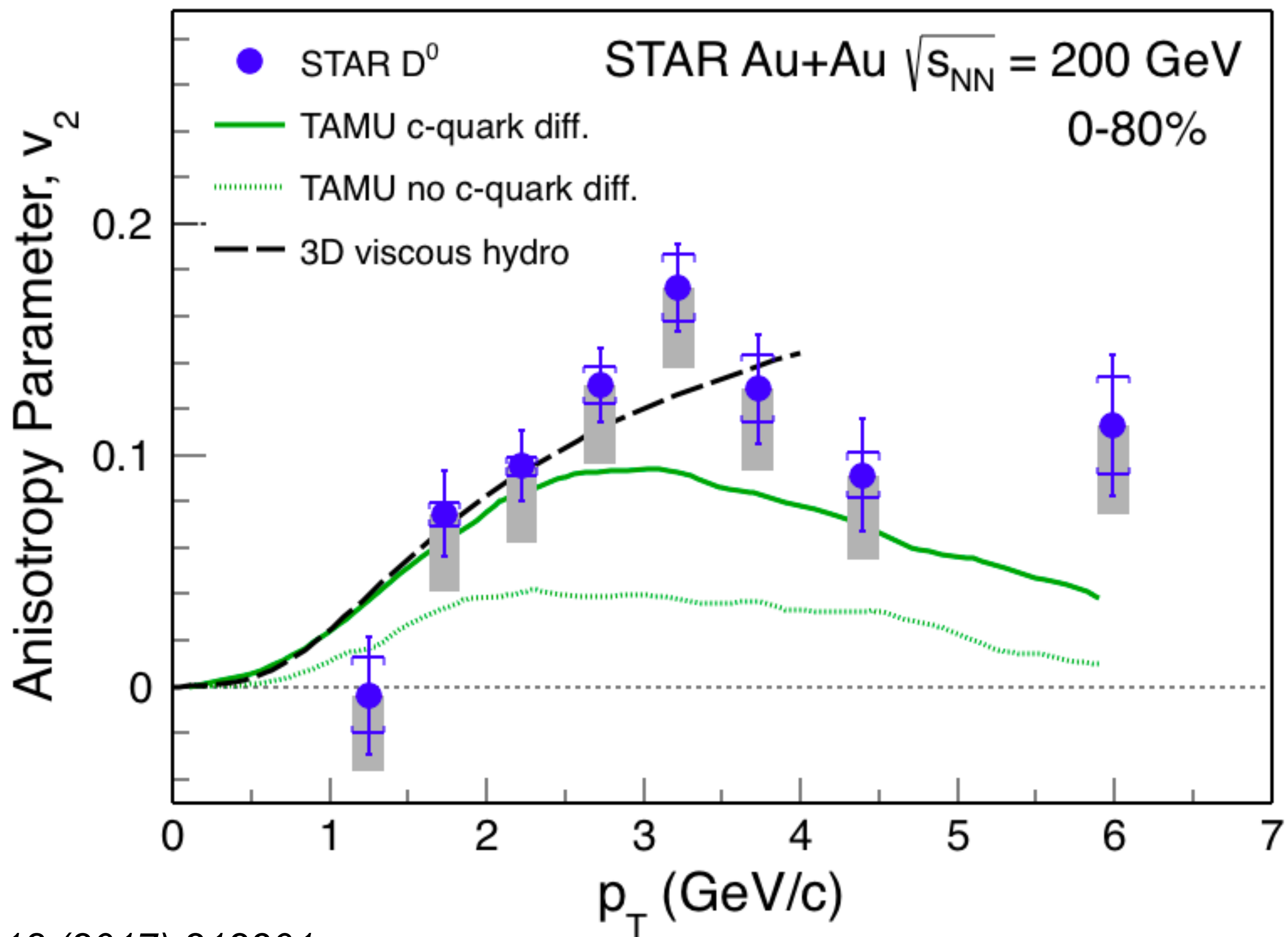




- T-slope parameter (expo fit to m_T spectra) follows the similar trend as other strange particles
- Similar to multi-strange hadrons, D^0 mesons kinetically freeze out earlier than light hadrons

  \- collectivity from partonic stage interactions

D^0 v_2 Compared with Models

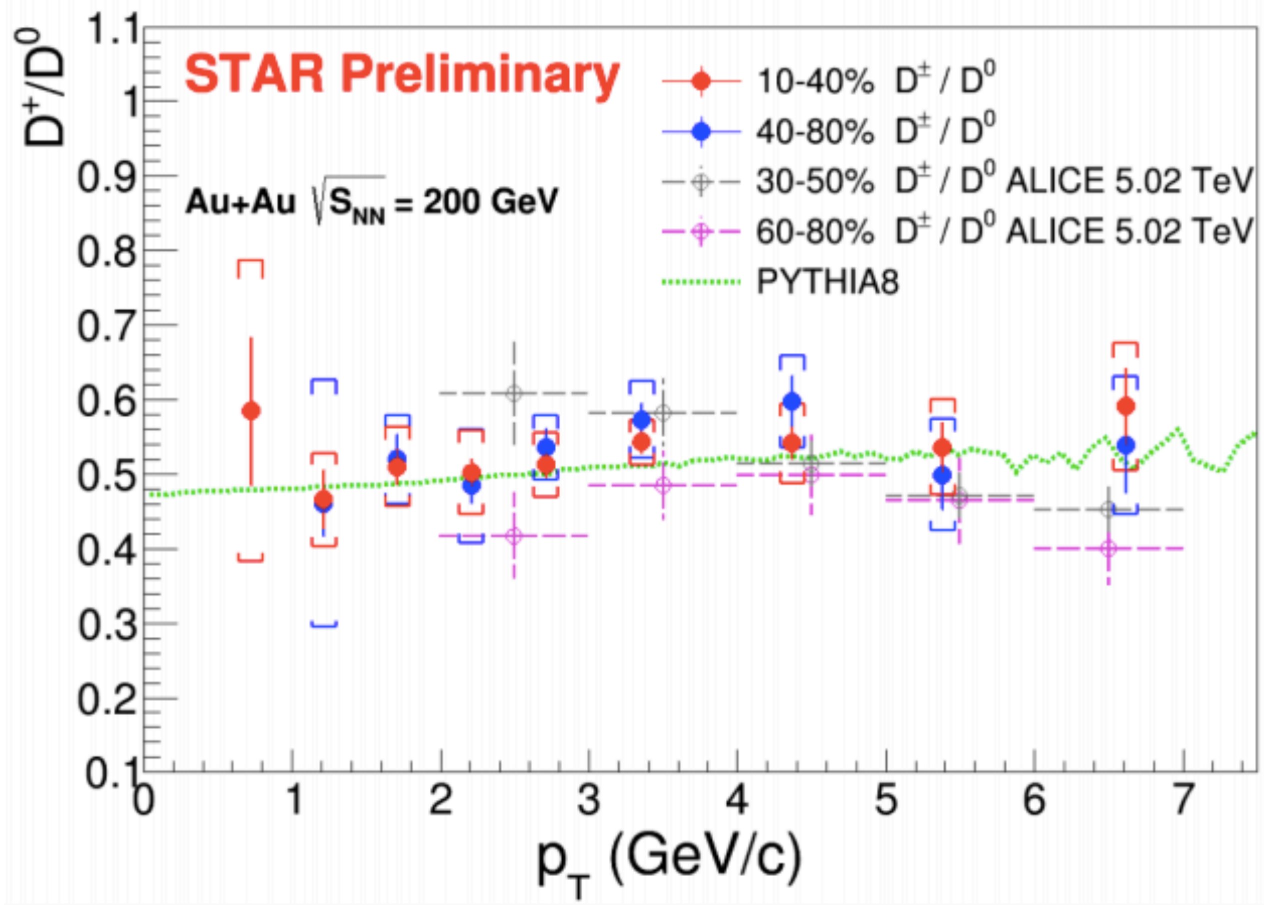


STAR, PRL 118 (2017) 212301

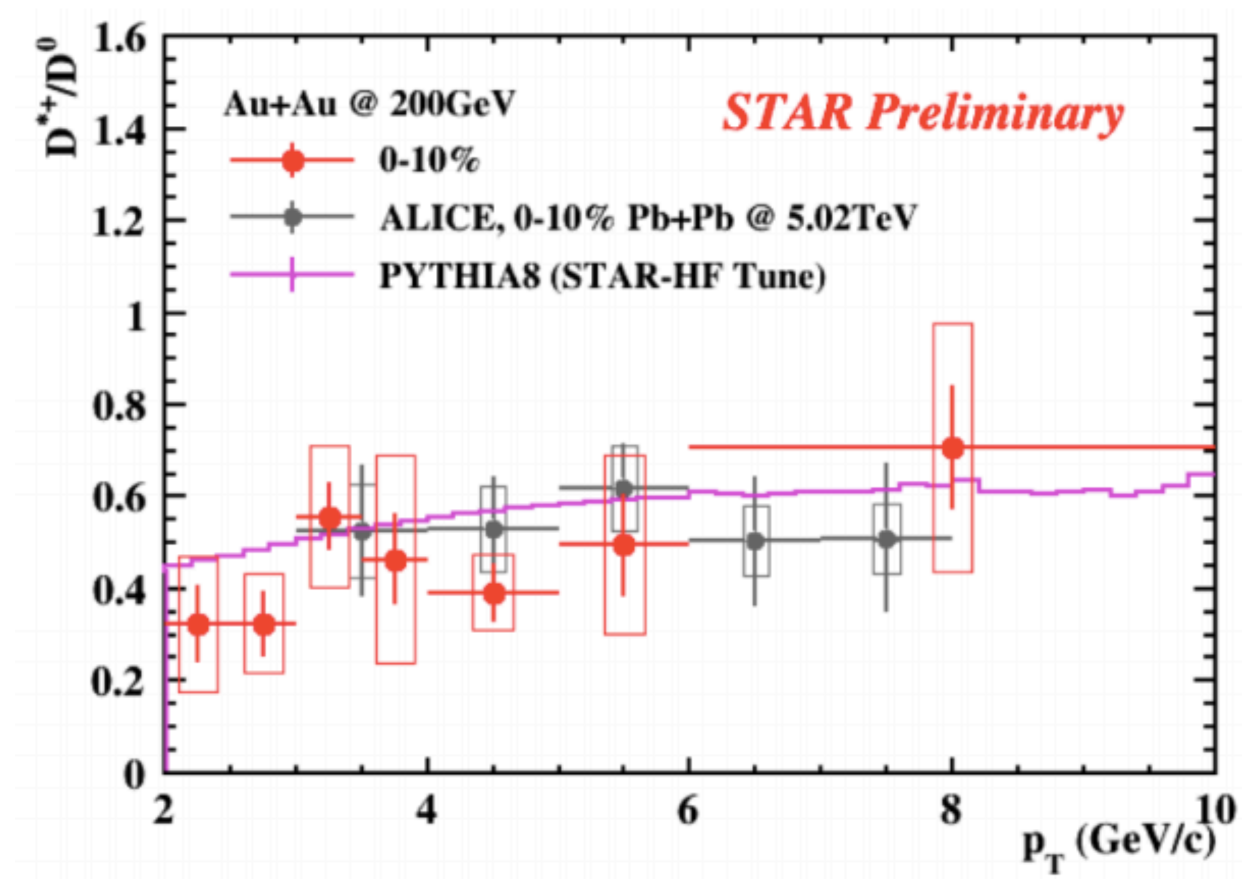
- Large D^0 v_2 ordinated from charm quark diffusion in QGP
- 3D viscous hydro consistent with D^0 v_2 data up to 4 GeV/c

D^+ and D^{*+} Production in Au+Au Collisions

$D^+ \rightarrow K^-\pi^+\pi^+$

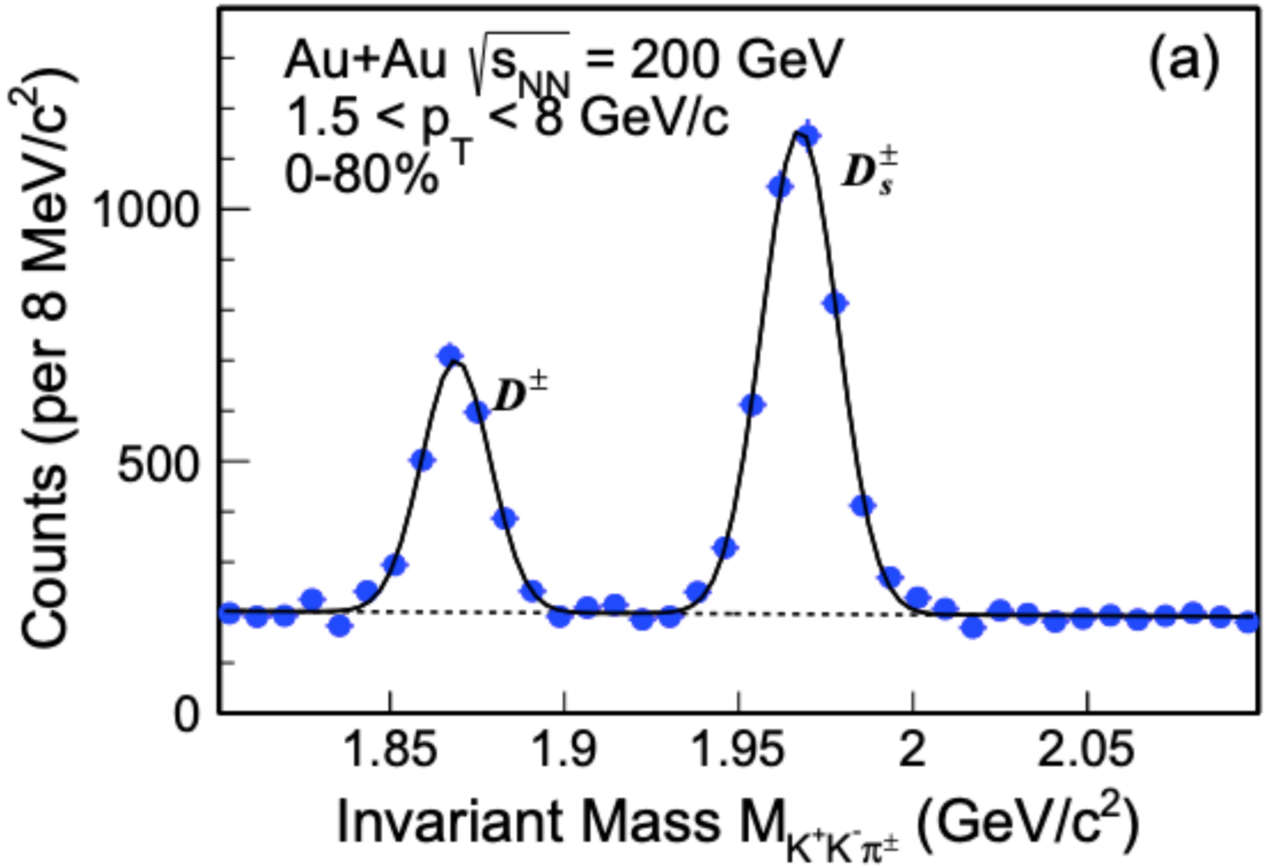


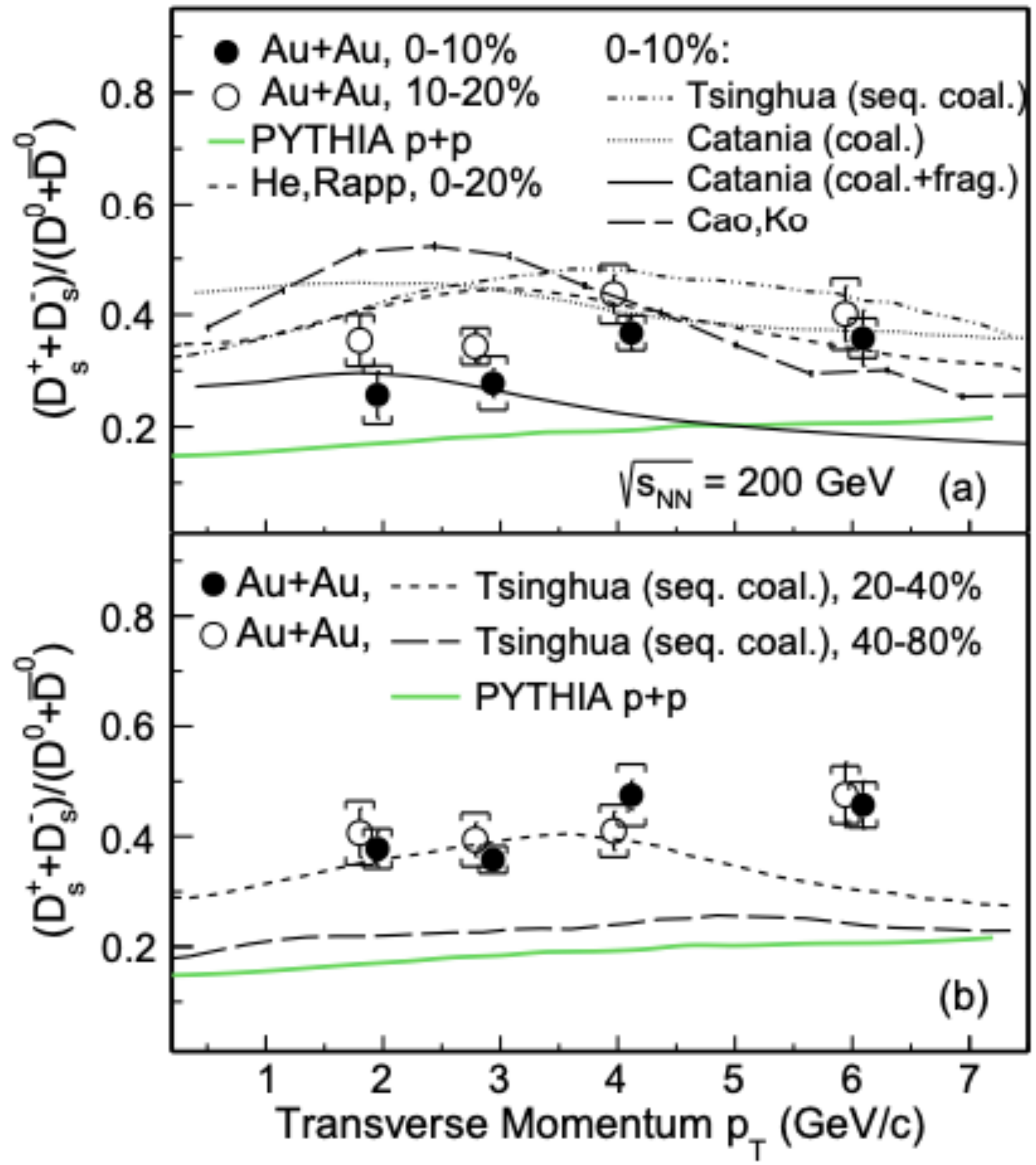
$D^{*+} \rightarrow D^0\pi^+ \rightarrow K^-\pi^+\pi^+$



- D^+/D^0, D^*/D^0 ratios consistent with PYTHIA model calculations
- No significant modification to charm-light meson production in A+A collisions

D_s^+/D^0 Enhancement in Au+Au Collisions



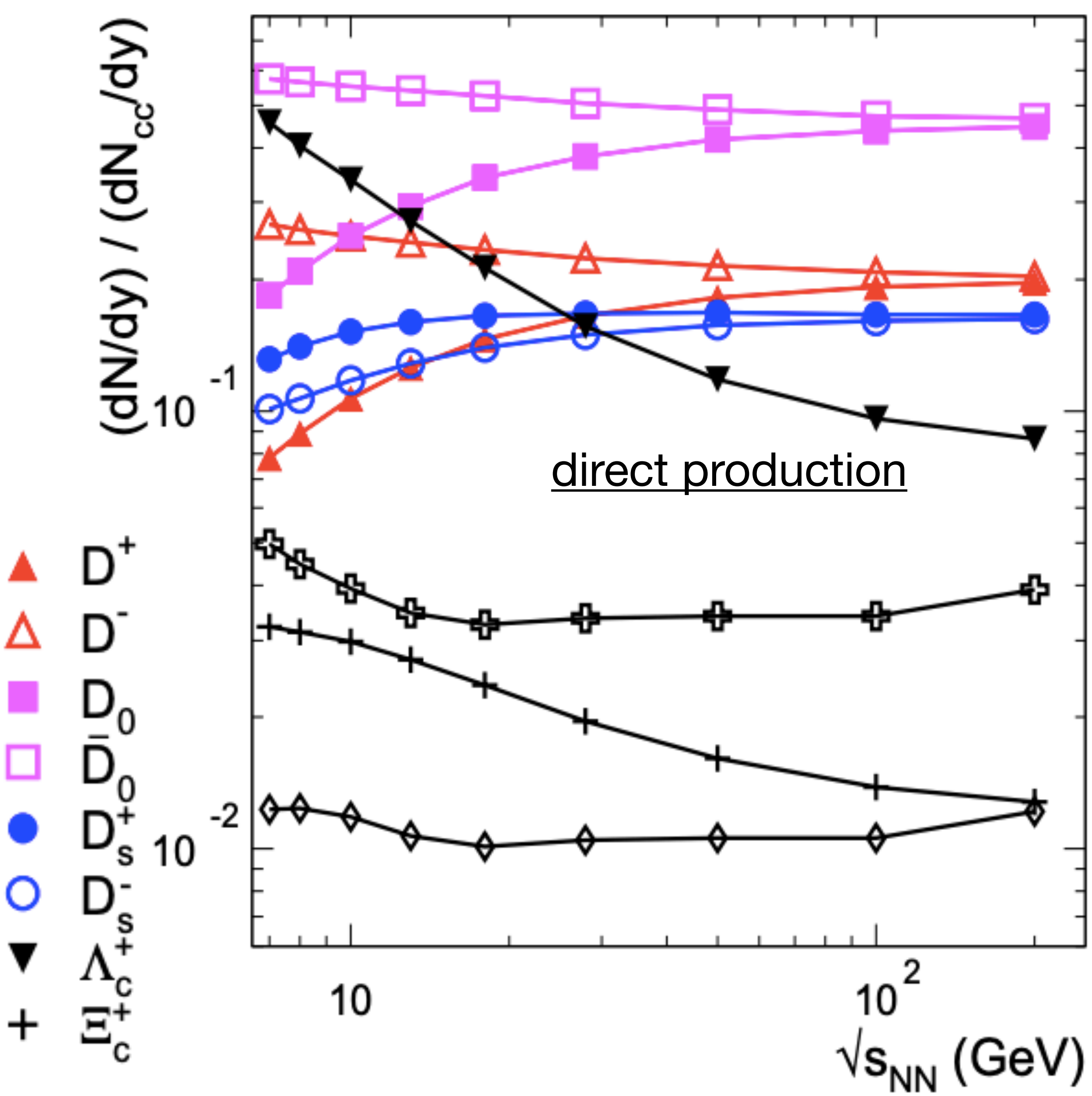


- D_s^+/D^0 significantly higher than fragmentation baseline calculated from PYTHIA
- Models with coalescence hadronization + strangeness enhancement qualitatively reproduce the data

STAR, arXiv: 2101.11793

Statistical Hadronization

$$n_i = \frac{d_i}{2\pi^2} m_i^2 T_H K_2\left(\frac{m_i}{T_H}\right)$$



A. Andronic et al., arXiv:0710.1851

Feeddown contribution to Λ_c

r_i	D^+/D^0	D^{*+}/D^0	D_s^+/D^0	Λ_c^+/D^0
PDG(170)	0.4391	0.4315	0.2736	0.2851
PDG(160)	0.4450	0.4229	0.2624	0.2404
RQM(170)	0.4391	0.4315	0.2726	0.5696
RQM(160)	0.4450	0.4229	0.2624	0.4409

M. He & R. Rapp, PLB 795 (2019) 117

SHM: $\Lambda_c/D^0 \sim$ 0.25-0.3 (PDG states)

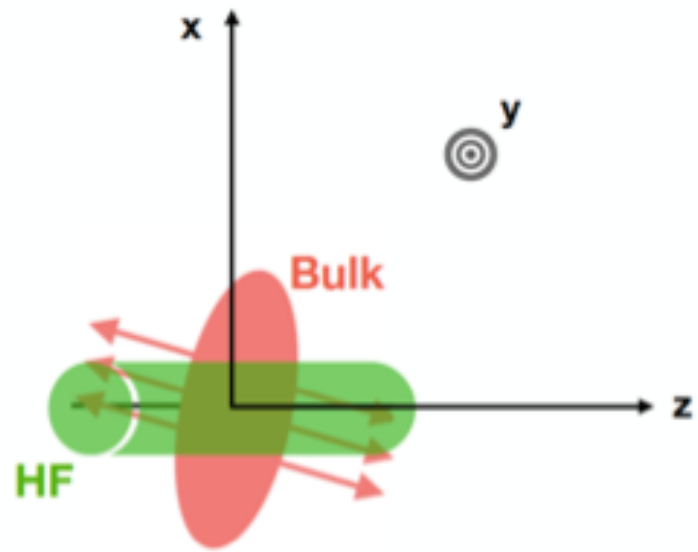
However, ratio can be doubled when including charm baryon resonances

- existence of unmeasured charm baryon resonances supported by Lattice QCD calculation

A. Bazavov et al, PLB 737 (2014) 210

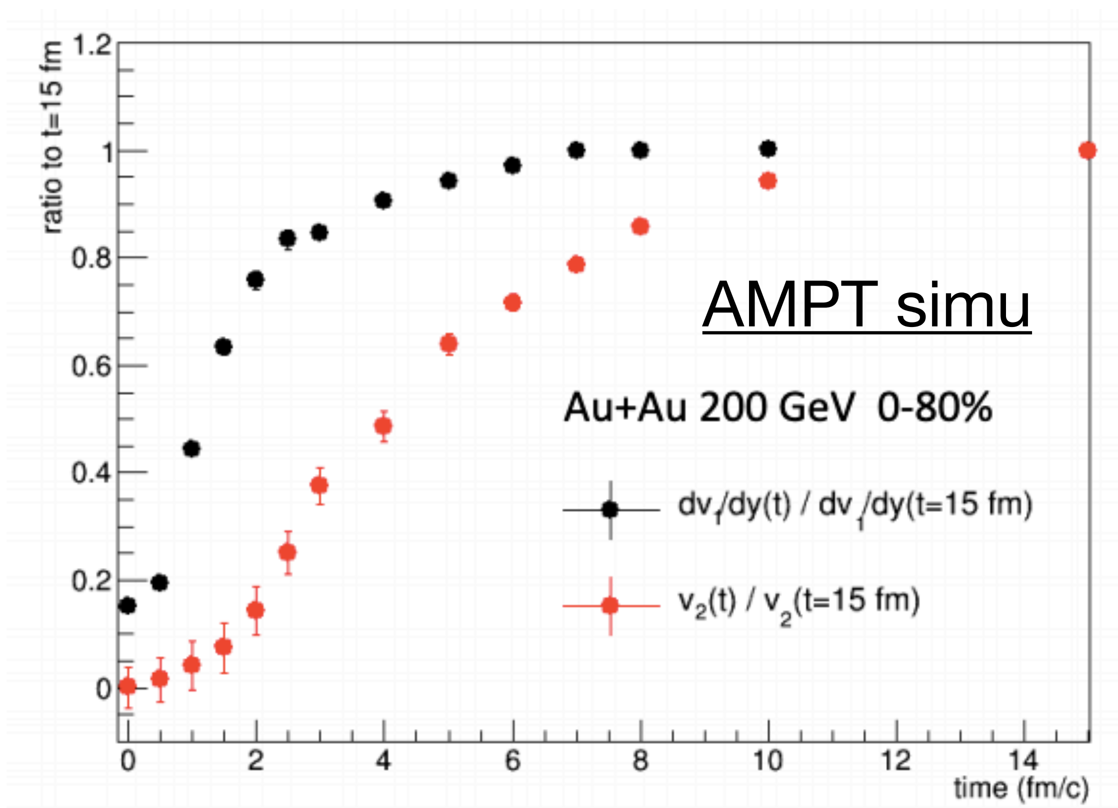
D^0 v_1 - New Insight to sQGP Properties

S. Chatterjee & P. Bozek, PRL 120 (2018) 192301



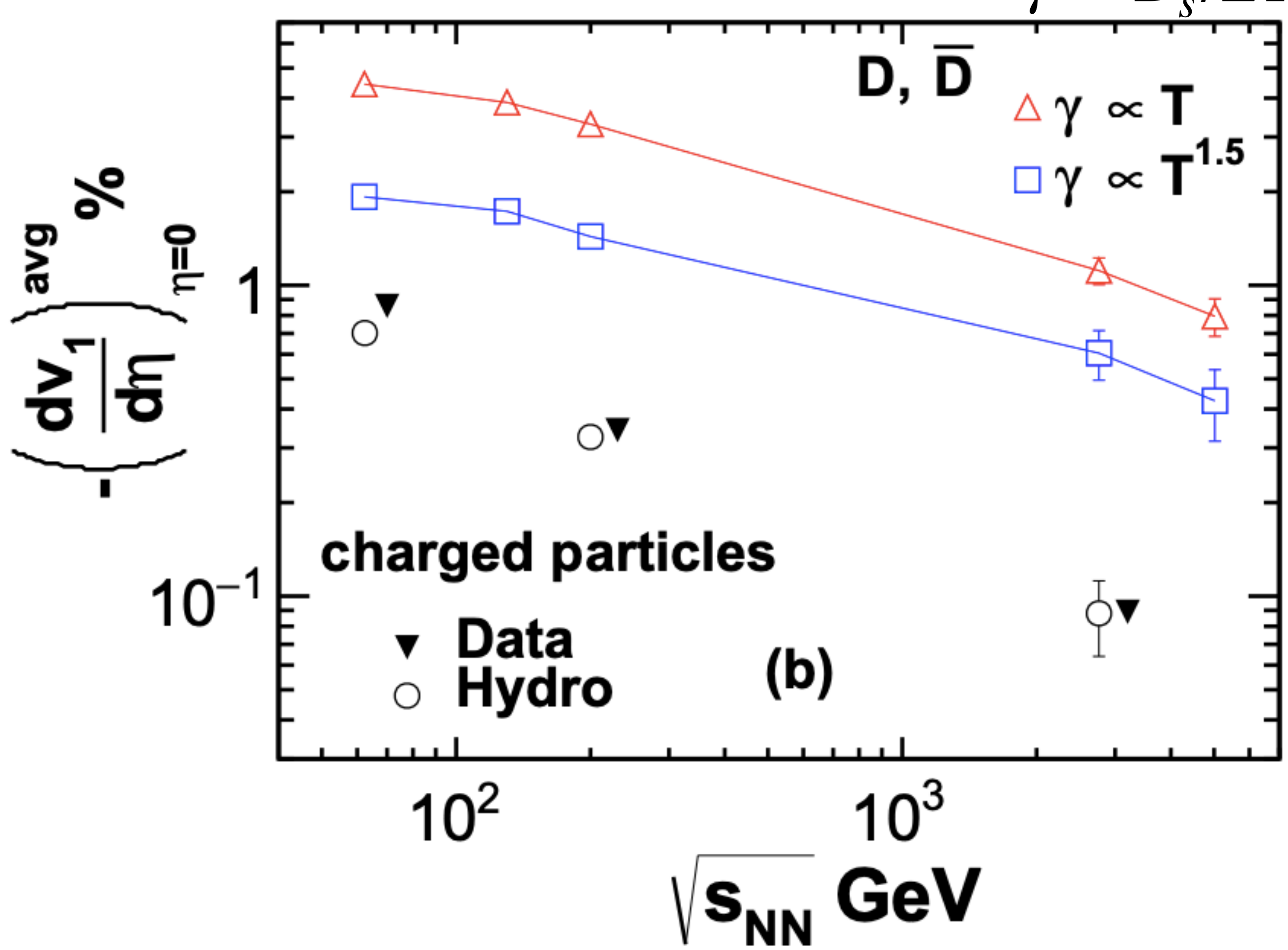
D-meson v_1 sensitive to

- geometry tilt of QGP source
- HQ diffusion coefficient $D_s(T)$



Hydro model

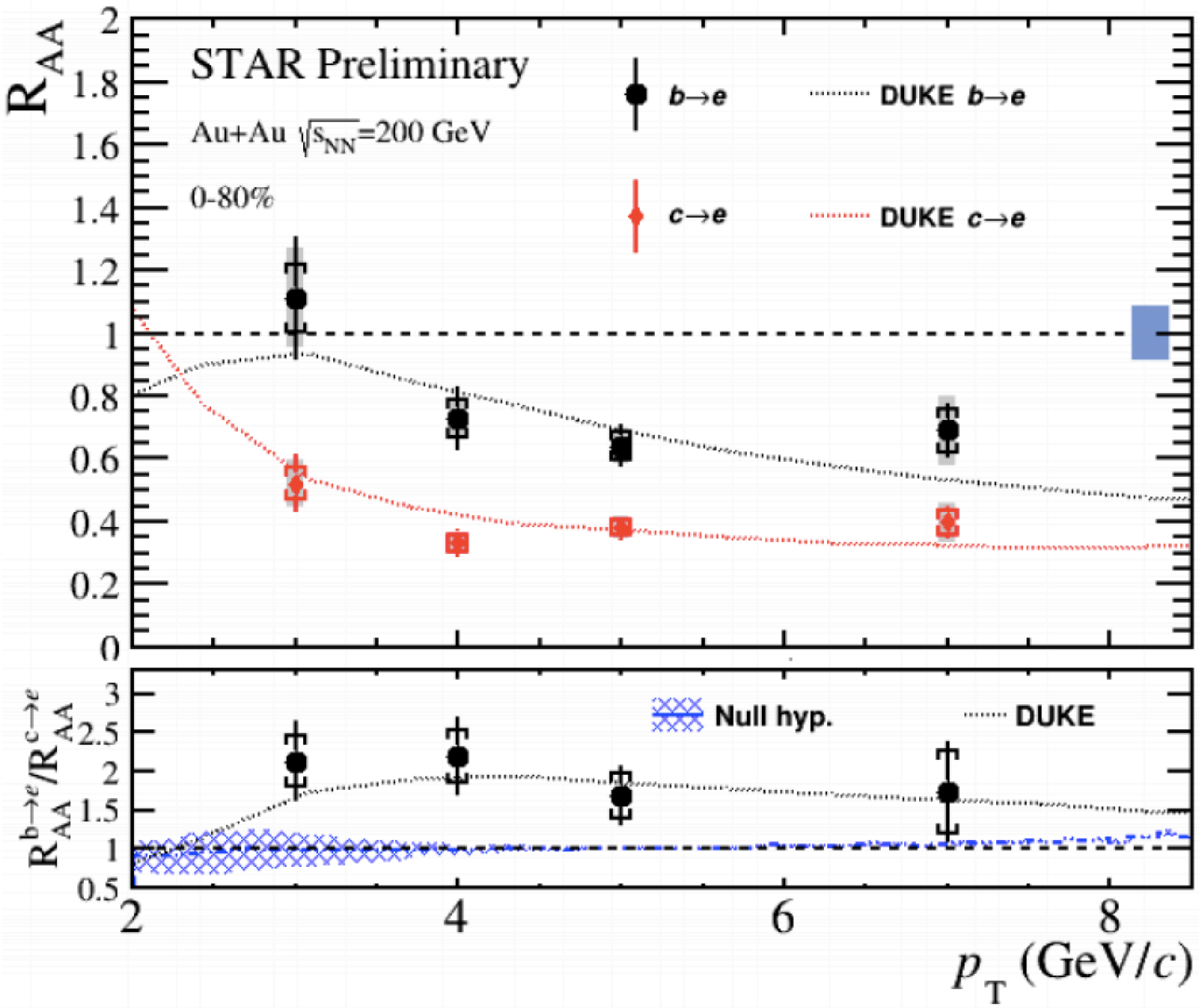
$\gamma = D_s / ET$



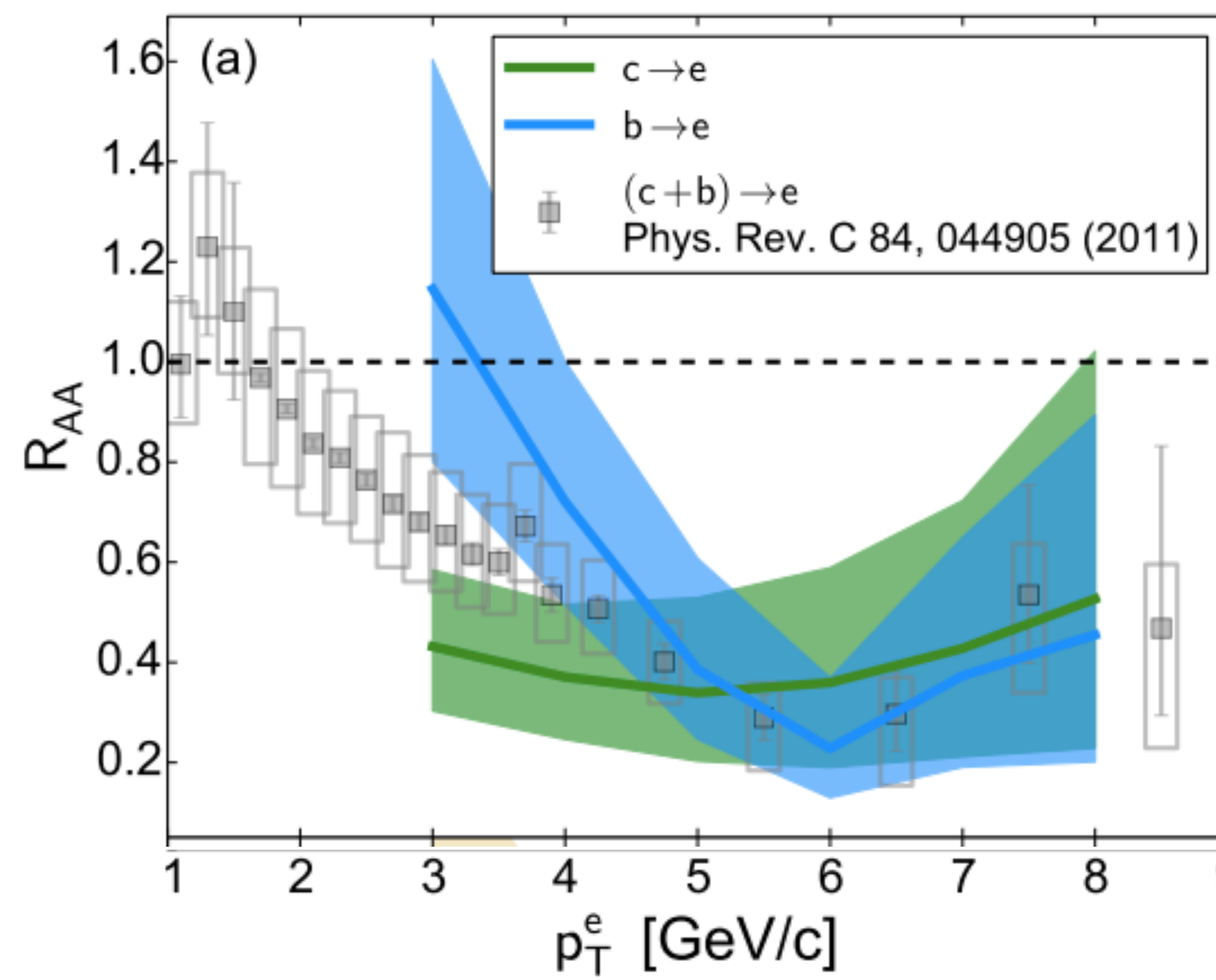
X. Ju, DNP 2019

S. Chatterjee & P. Bozek, PLB 798 (2019) 134955

Bottom Suppression at Low p_T



STAR QM19



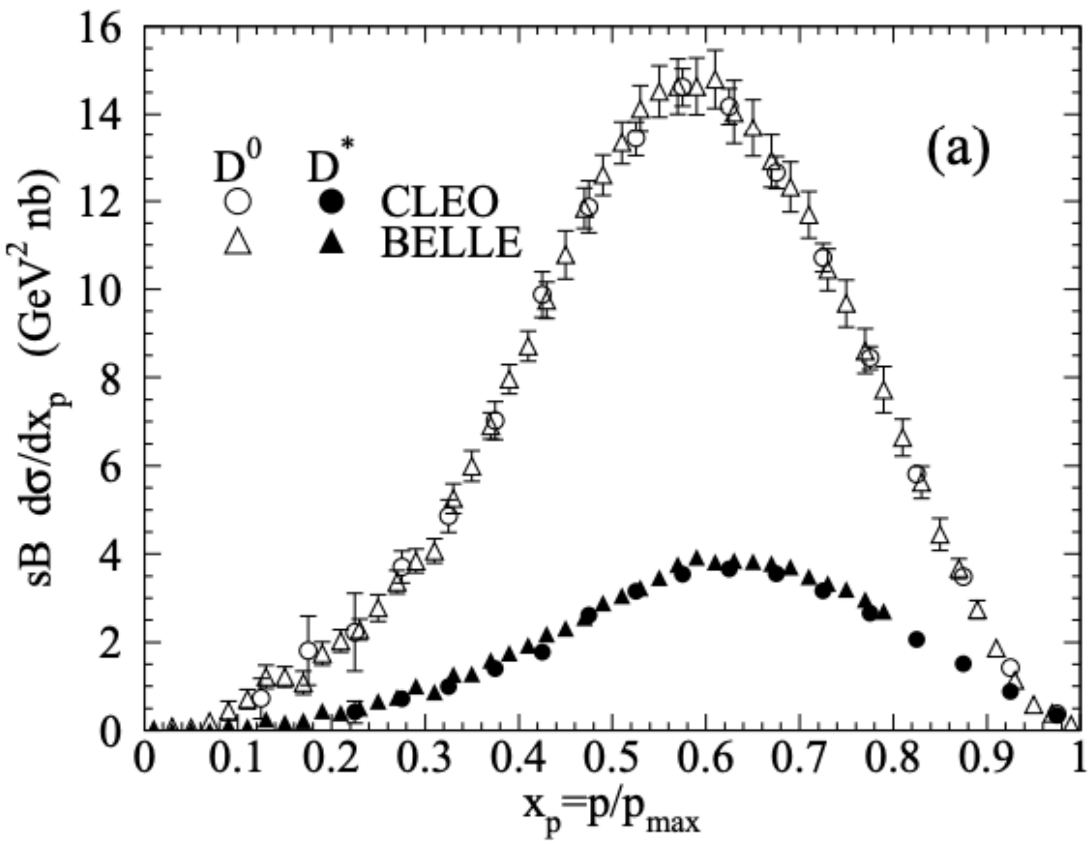
PHENIX, PRC 93 (2016) 034904

- RHIC: $R_{AA}(e_B) < R_{AA}(e_D)$ at 3–8 GeV/c (3σ)

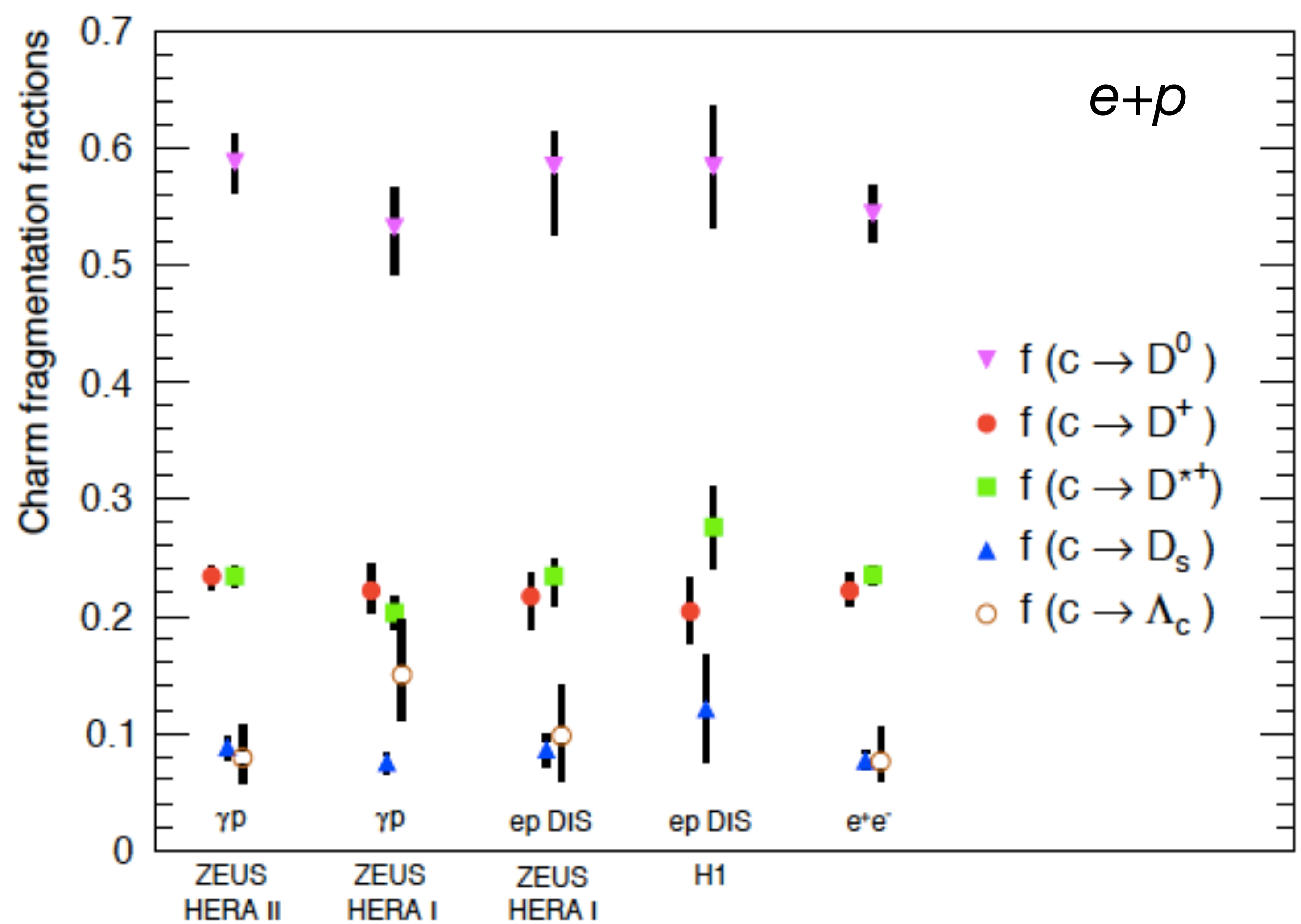
  Evidence of mass hierarchy of parton energy loss

Charm Hadrochemistry

fragmentation measured in ee



PDG 2018



ZEUS, JHEP 1309 (2013) 058

$$2\sigma_{c\bar{c}} = D^0 + D^+ + D_s^+ + \Lambda_c^+ \quad + \text{c.c.}$$

60.8% 24.0% 8.0% 6.2%

Lisovyi, et. al. EPJ C 76 (2016) 397

Total Charm Production Cross Section

Charm Hadron		Cross Section dσ/dy (μb)
Au+Au 200 GeV (10-40%)	D^0	41 ± 1 ± 5
	D^+	18 ± 1 ± 3
	D_s^+	15 ± 1 ± 5
	Λ_c^+	78 ± 13 ± 28*
	Total	**152 ± 13 ± 29**
p+p 200 GeV	**Total**	**130 ± 30 ± 26**

** extracted from 10-80%*

- Total charm cross section follows ~ N_{bin} scaling from p+p to Au+Au
- However, charm hadrochemistry changes considerably!

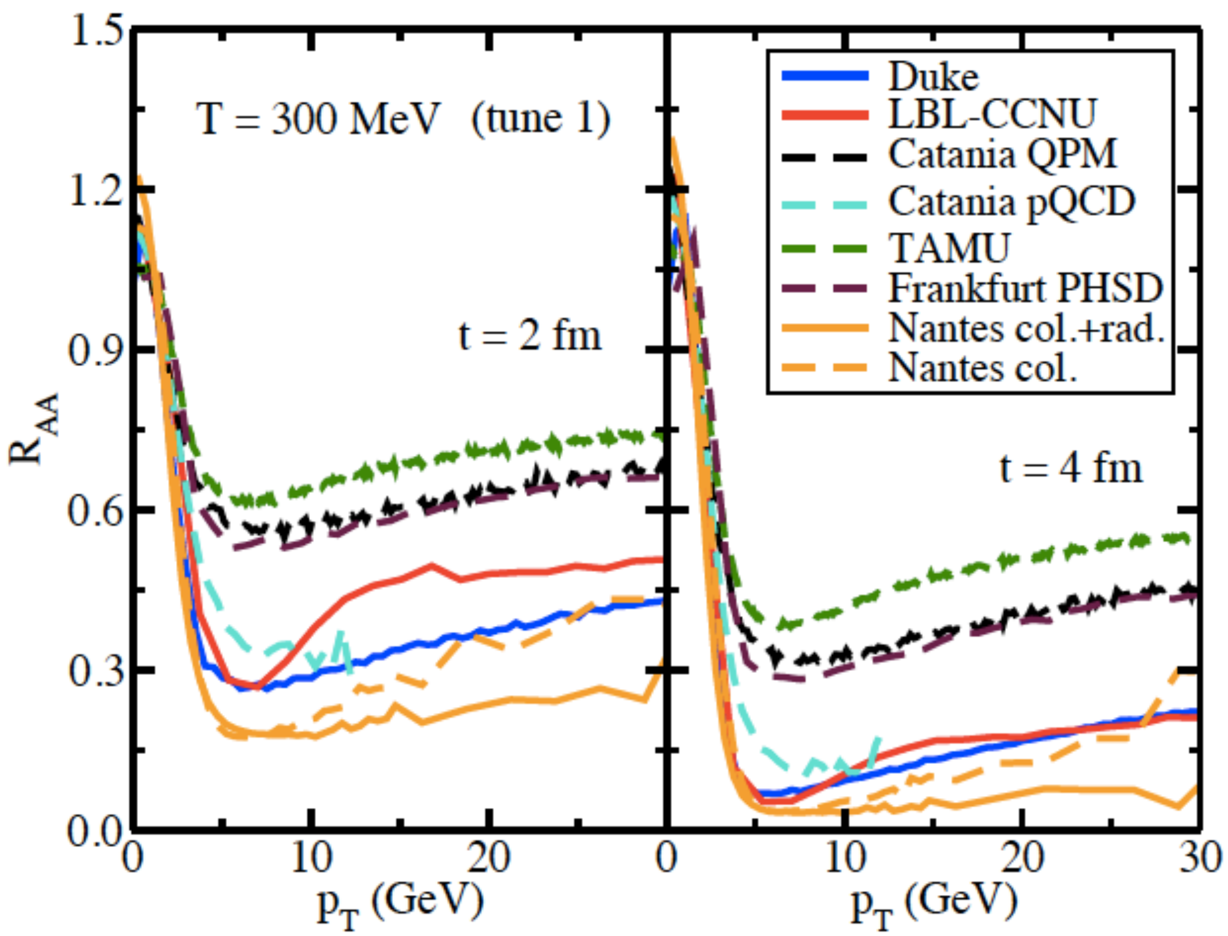
Theory Uncertainties

Rapid developments among theorists to resolve/understand trivial/non-trivial differences between different models

EMMI Rapid Reaction Task Force - *R. Rapp et al., NPA 979 (2018) 21*

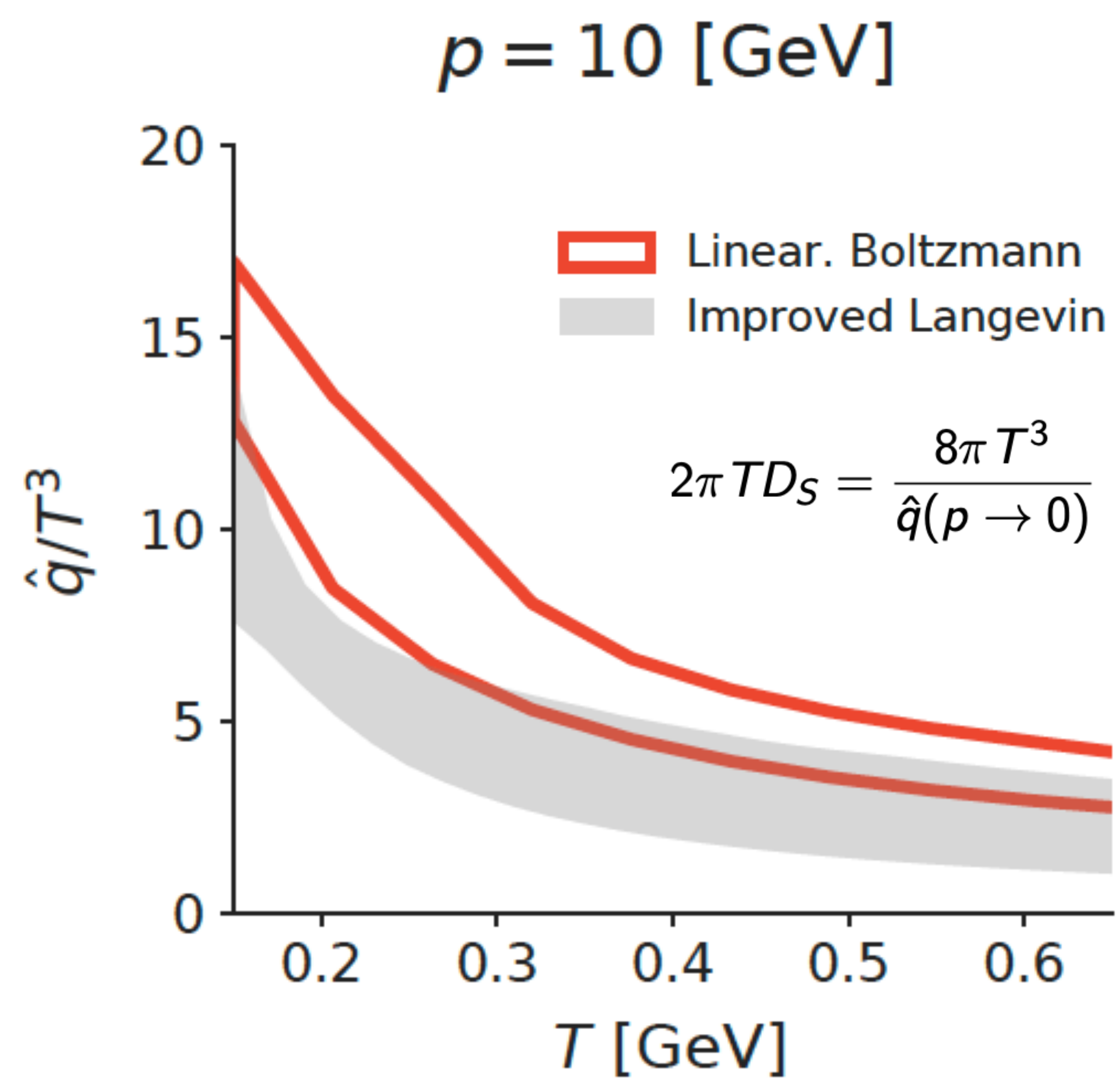
Jet-HQ Working Group - *S.S. Cao et al., PRC 99 (2019) 054907*

R_{AA} of charm quark in a static medium



all models in their full calculations reproduce experimental R_{AA}

S.S. Cao et al., PRC 99 (2019) 054907



W.Y. Ke et al., PRC 98 (2018) 064901

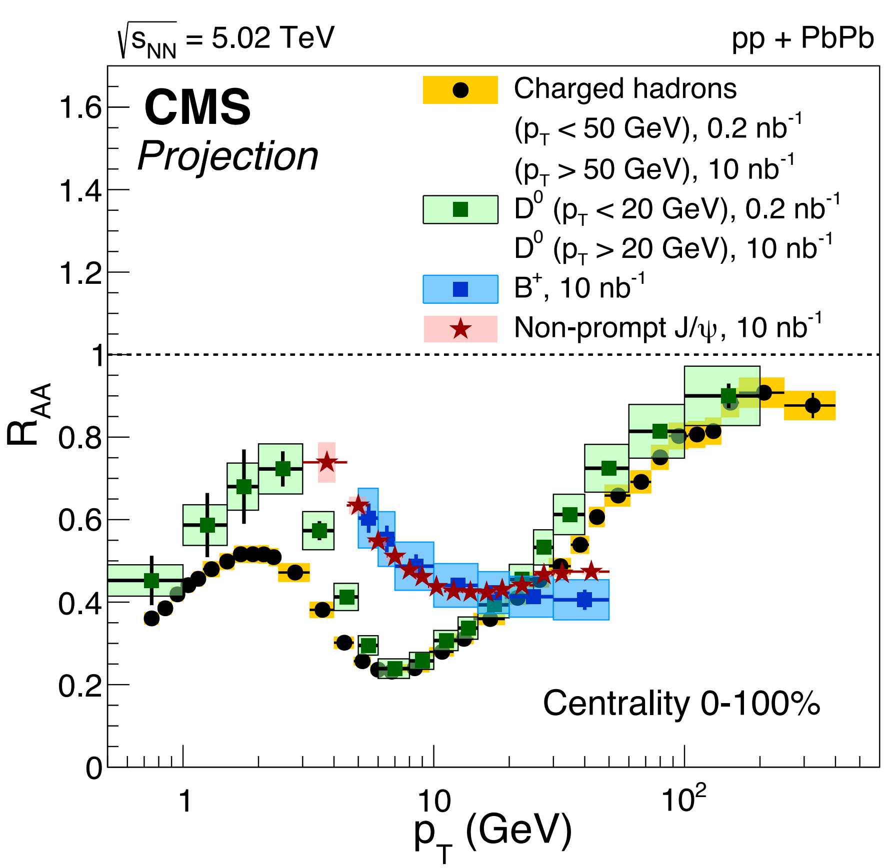
Heavy Flavor Program at RHIC

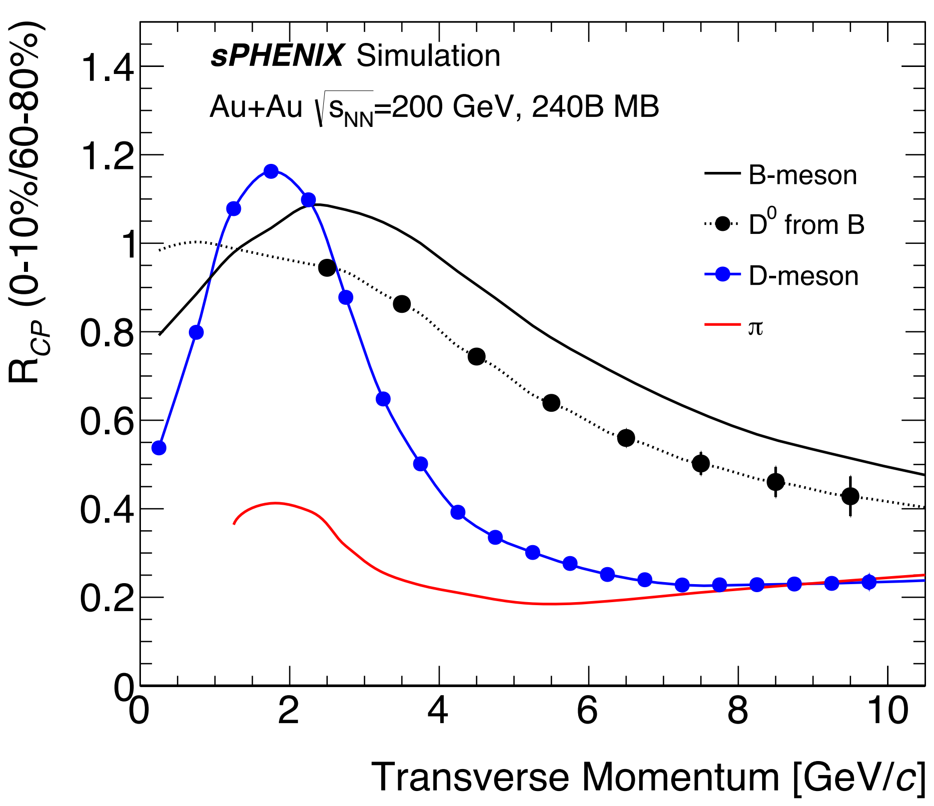
	2014	2015	2016	2017	2018	2019	2020	2021	2022+
RHIC	HF Phase-I			pp	CME	BES-II			HF Phase-II
LHC	LS1	Run-2				LS2		Run-3	

Next generation MAPS pixel detectors: ITS2@ALICE, MVTX@sPHENIX

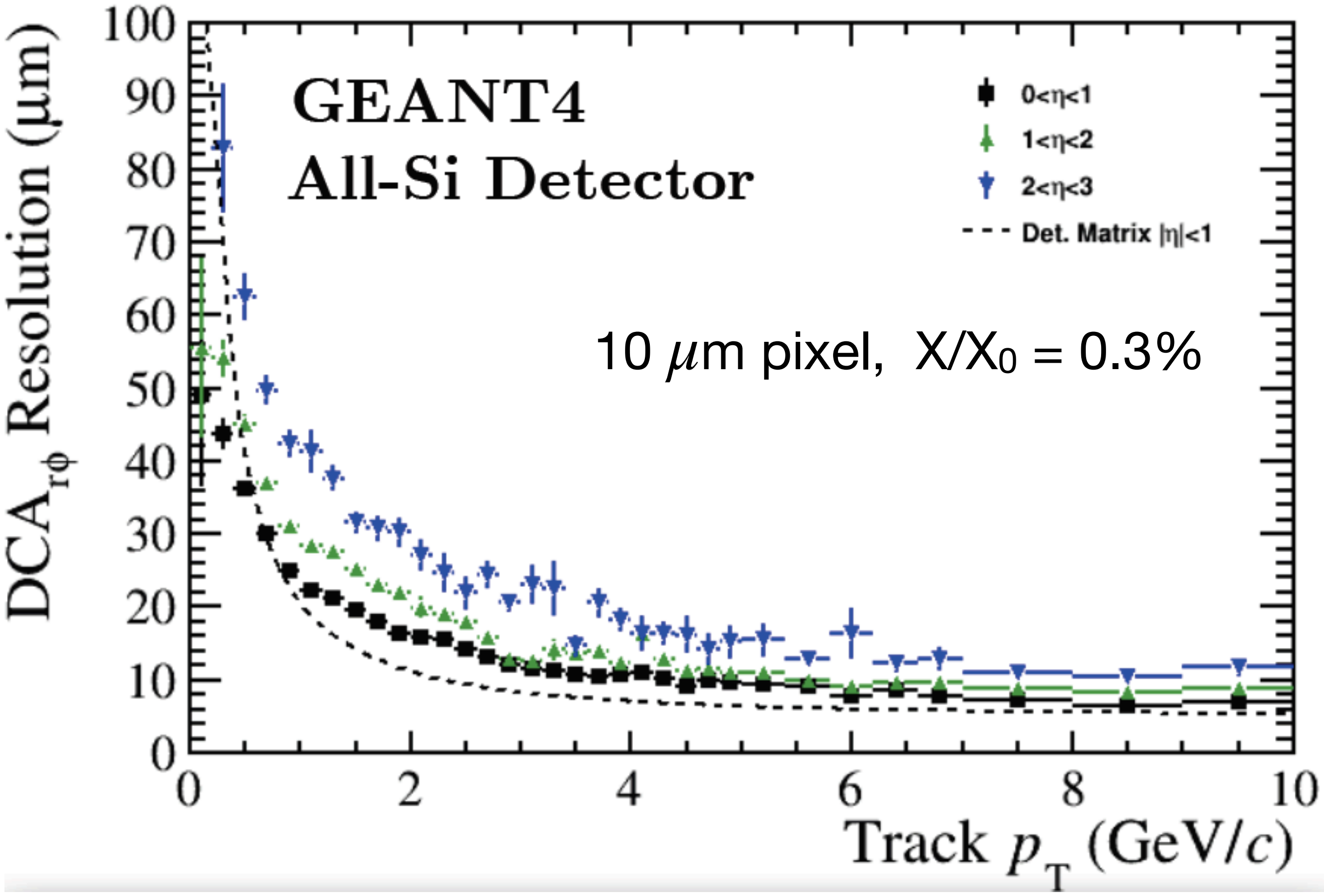
Precision open bottom

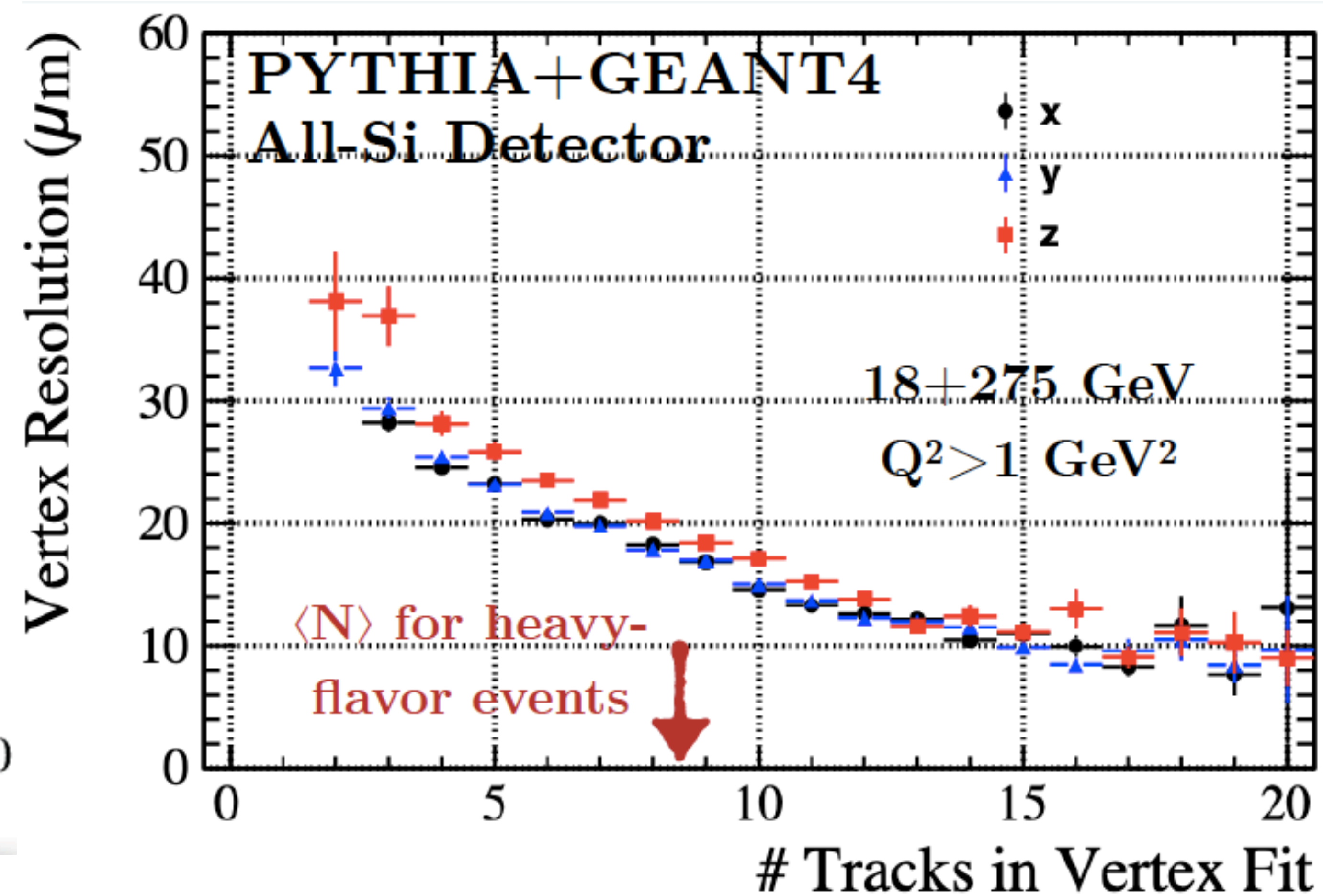
Heavy flavor baryons and correlations





Pointing & Vertex Resolution





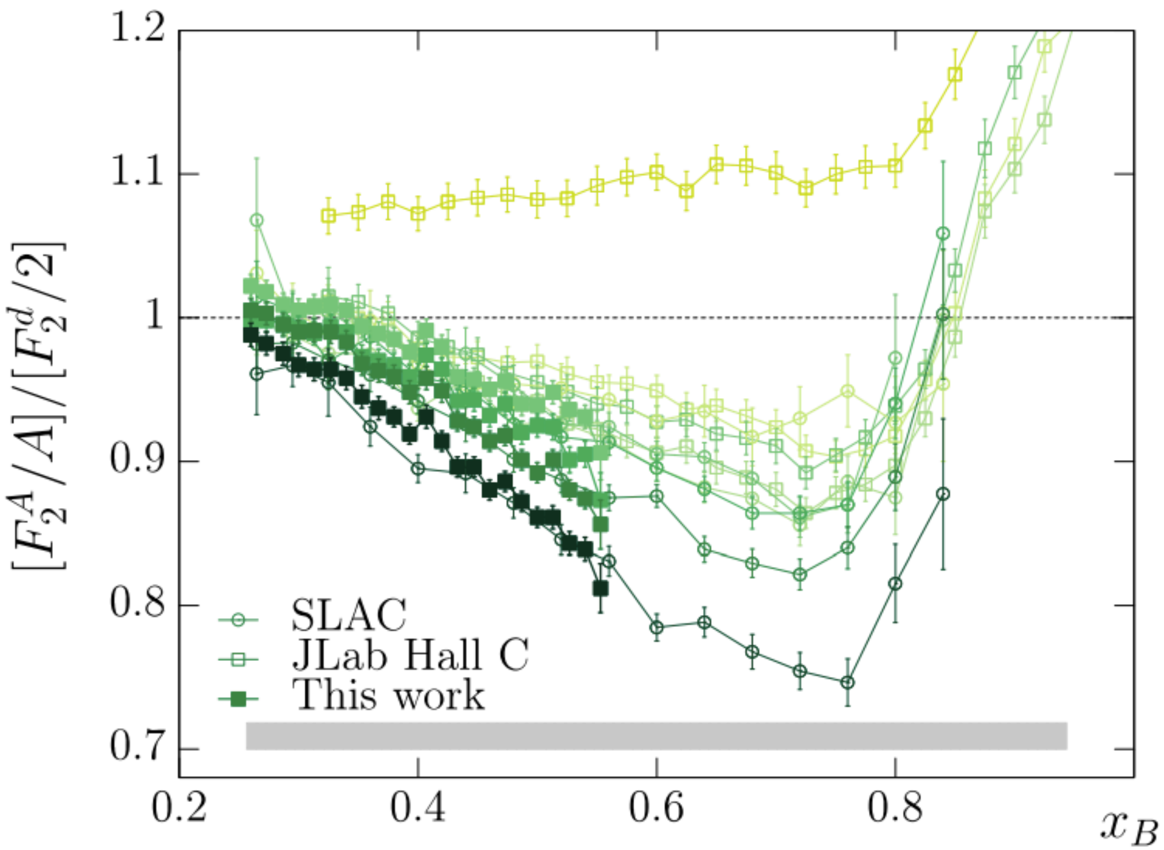
All-Si tracker pointing resolution: $\sigma_{r\phi} \sim 25\mu m$ @ 1 GeV/c ($|\eta|$<1)

- slight/anticipated degradation at higher η

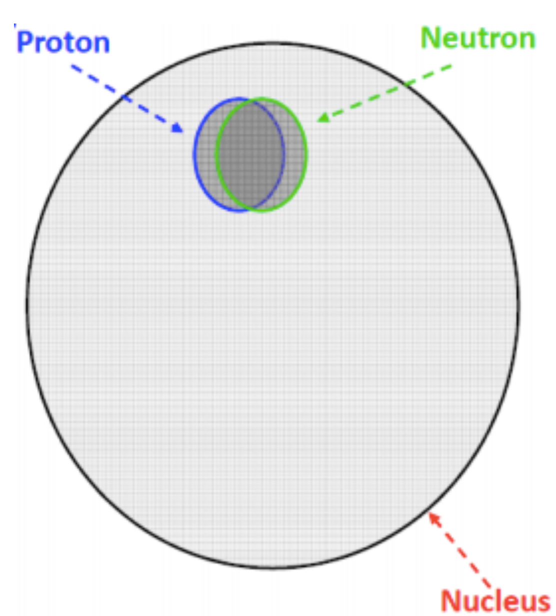
All-Si tracker vertexing resolution: $\sigma_{XYZ} < 20\mu m$ for HF events

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

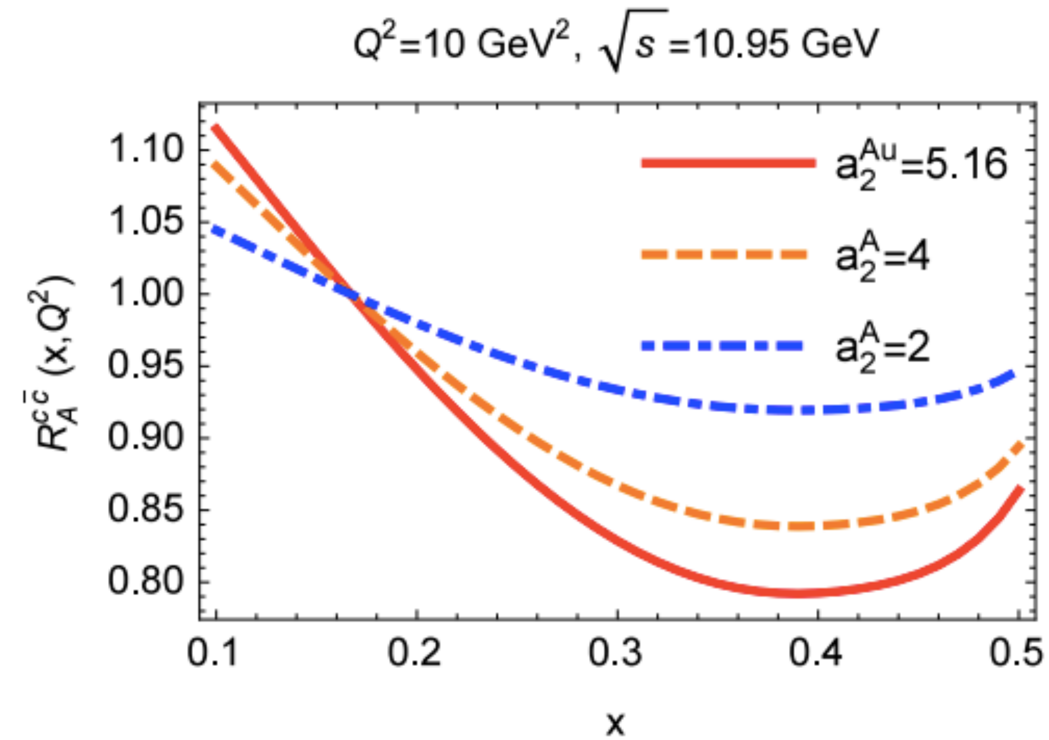
EMC <-> Short-Range Correlation

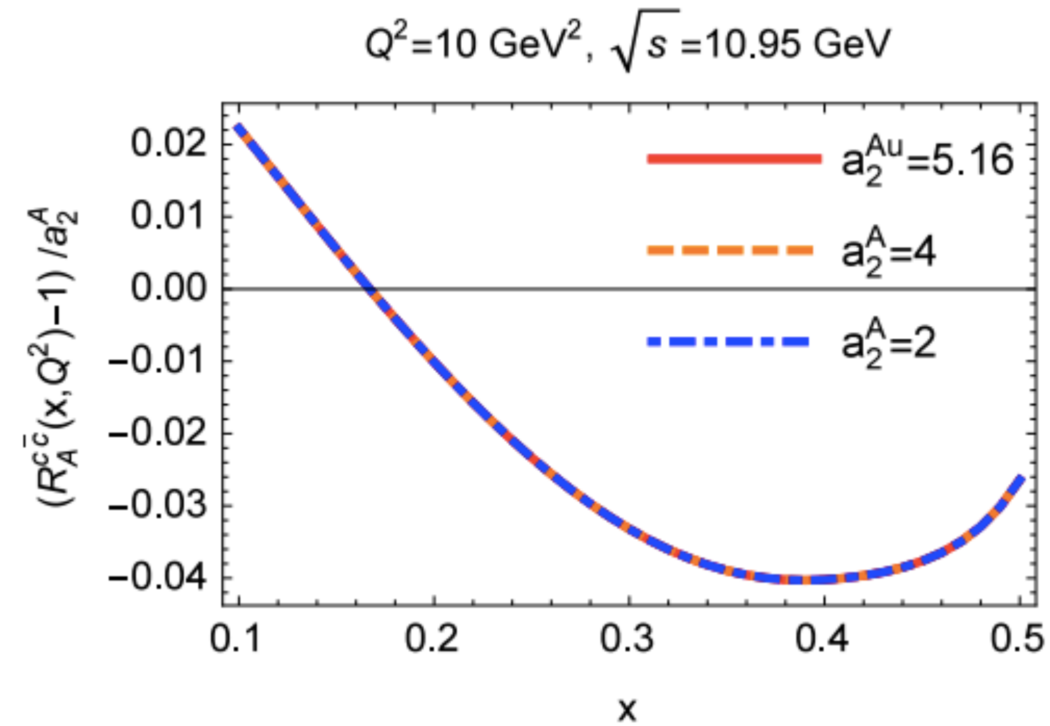


EMC effect at large x <-> SRC-np



charm -> gluon probe to SRC

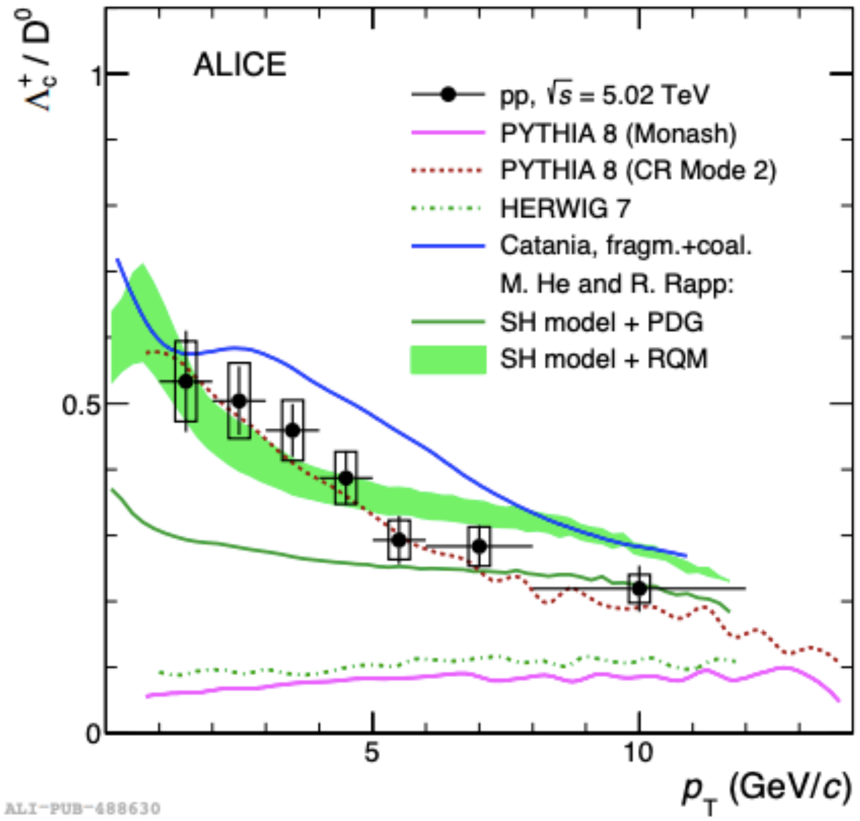




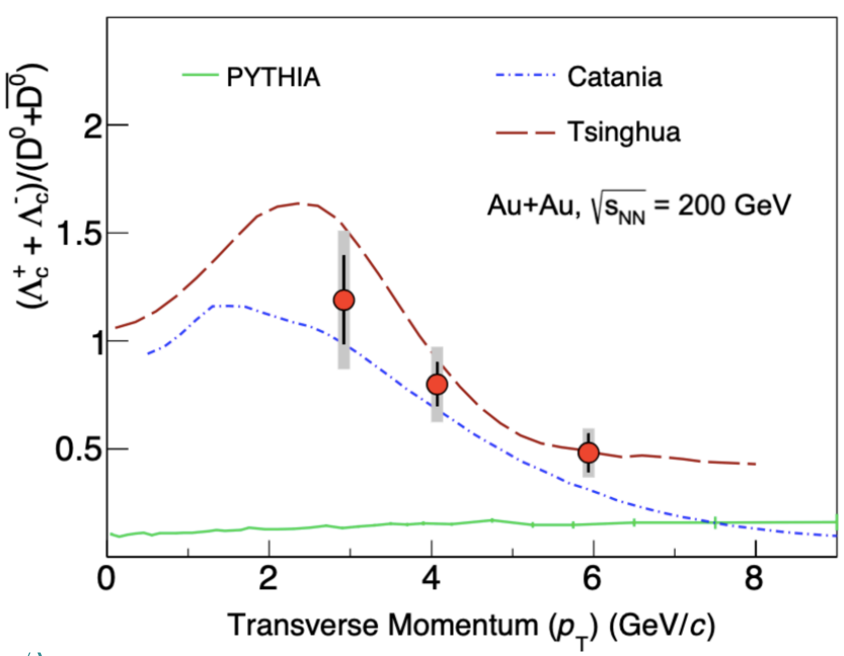
J. Xu and F. Yuan, PLB 801 (2019) 135187

Hadronization and CNM

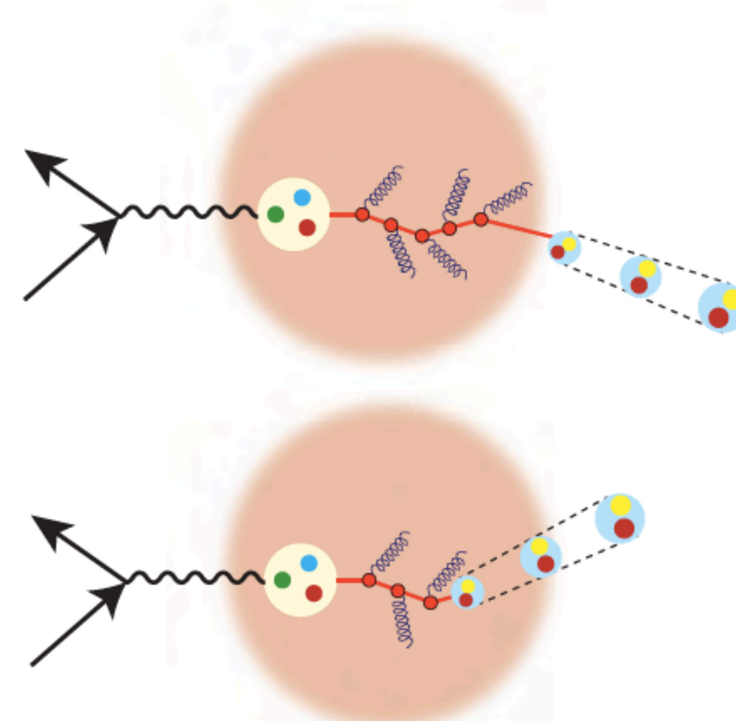
Charm hadrochemistry



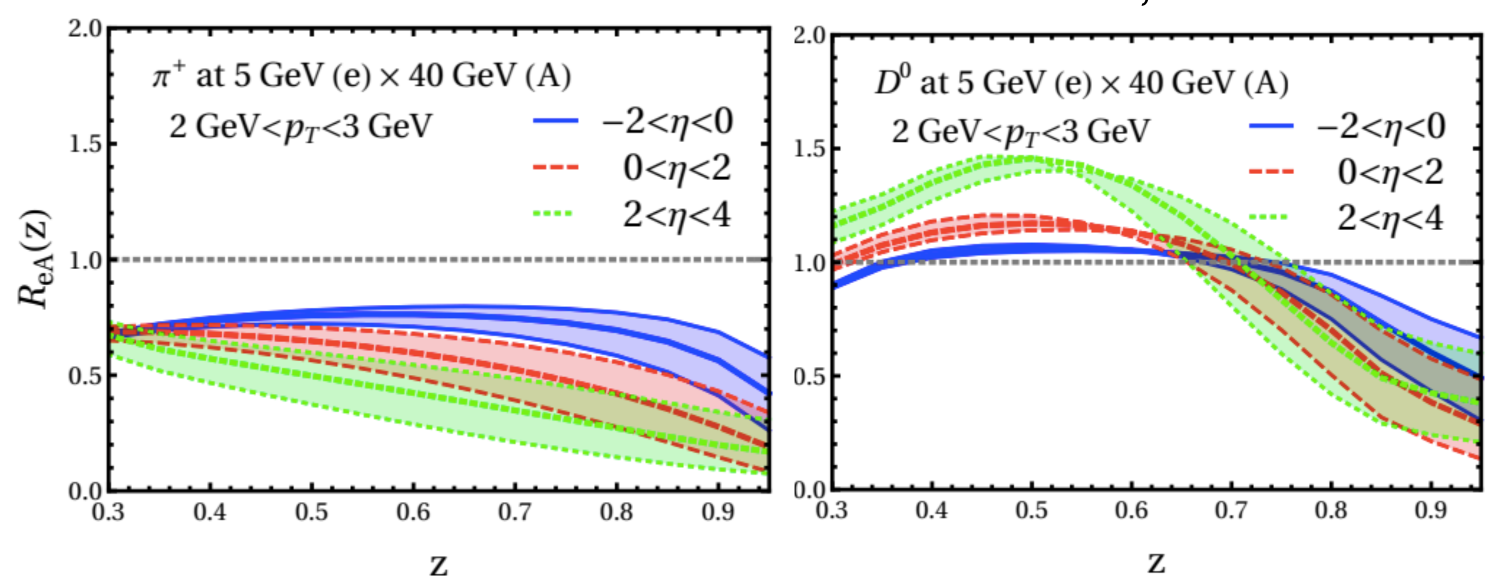
STAR, PRL 124 (2020) 172301



Cold Nuclear Matter Effect on
light/heavy hadron production



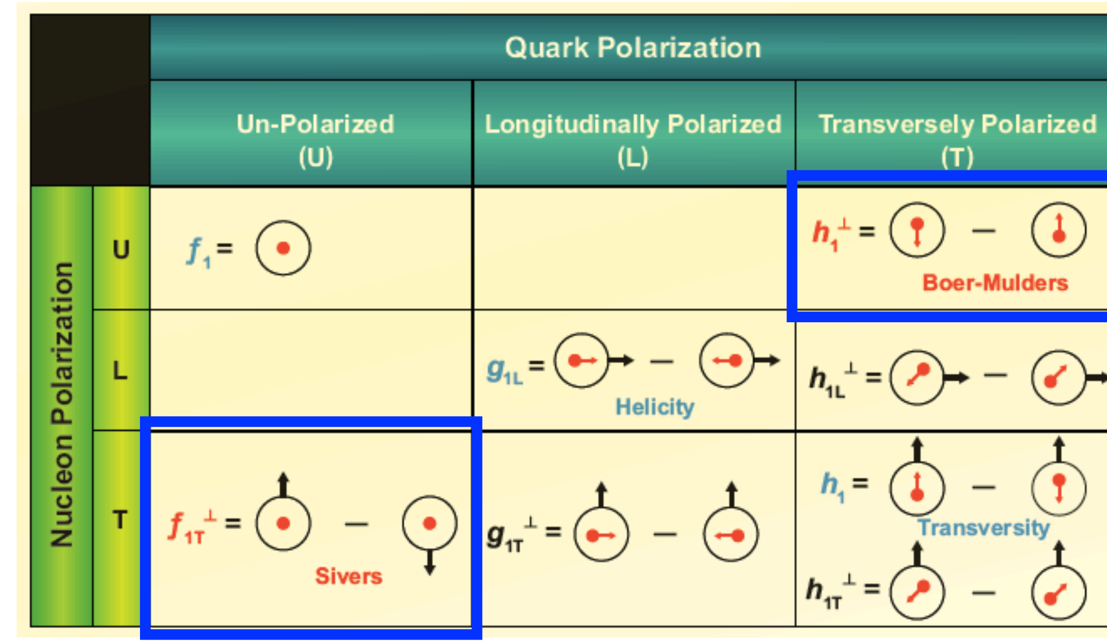
H. Liu et. al., 2007.10994



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

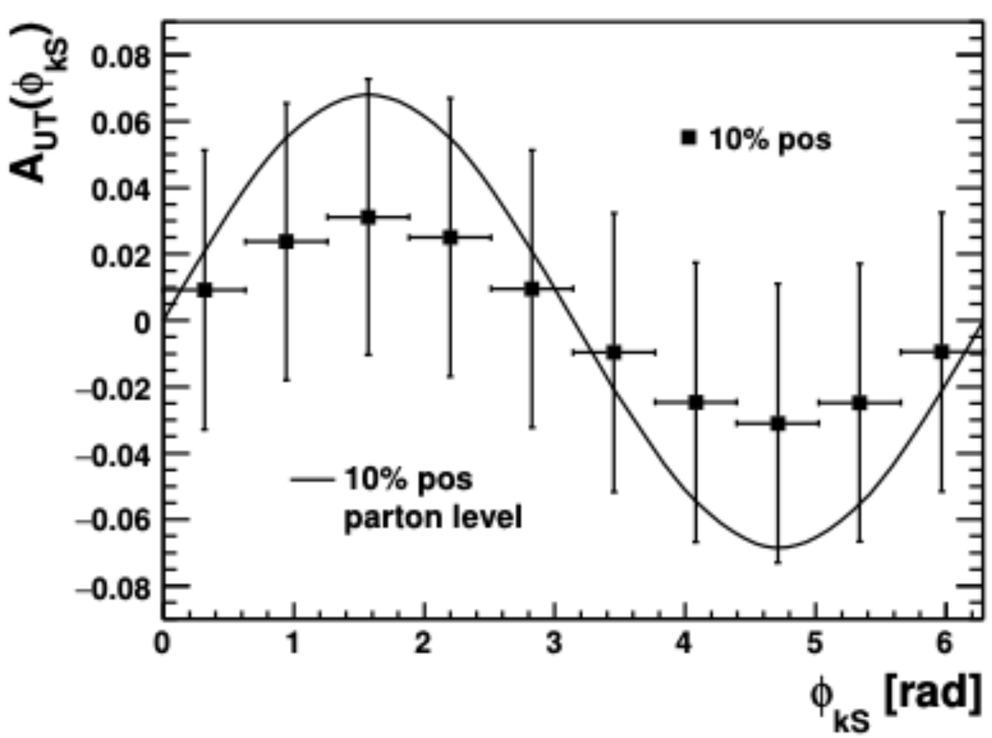
Charm hadron pair in transverse polarized exp.
- gluon Sivers functions

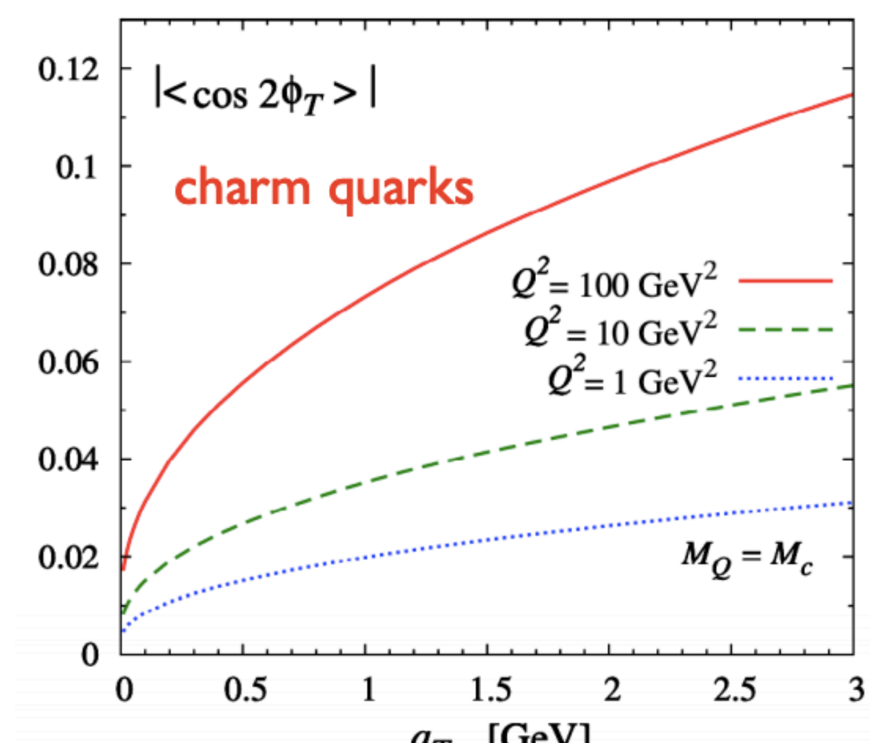
Charm hadron pair in unpolarized exp.
- linearly polarized Boer-Mulders function



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

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



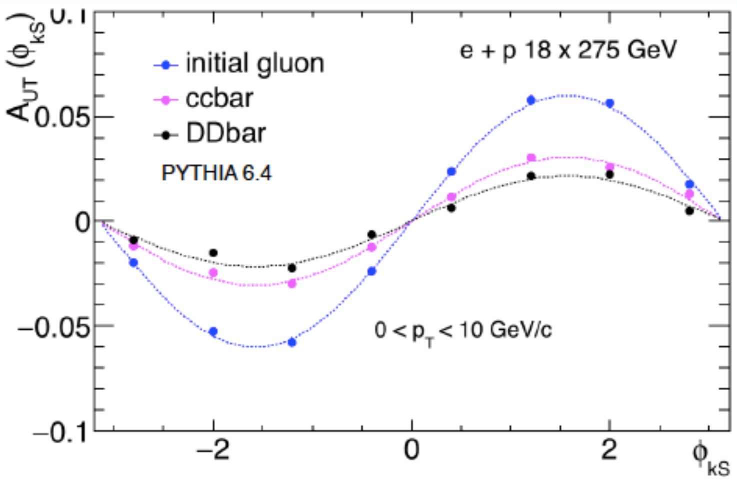


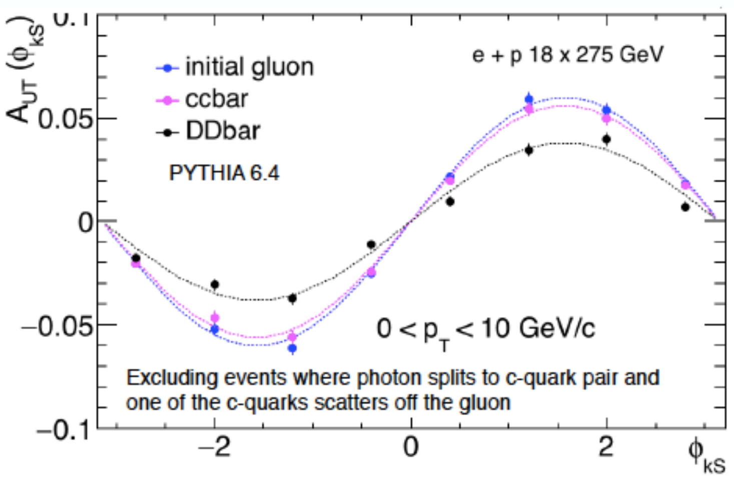
L. Zheng et. al., PRD 98 (2018) 034011

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

Projection on Gluon Sivers Function

PYTHIA6 Simulation



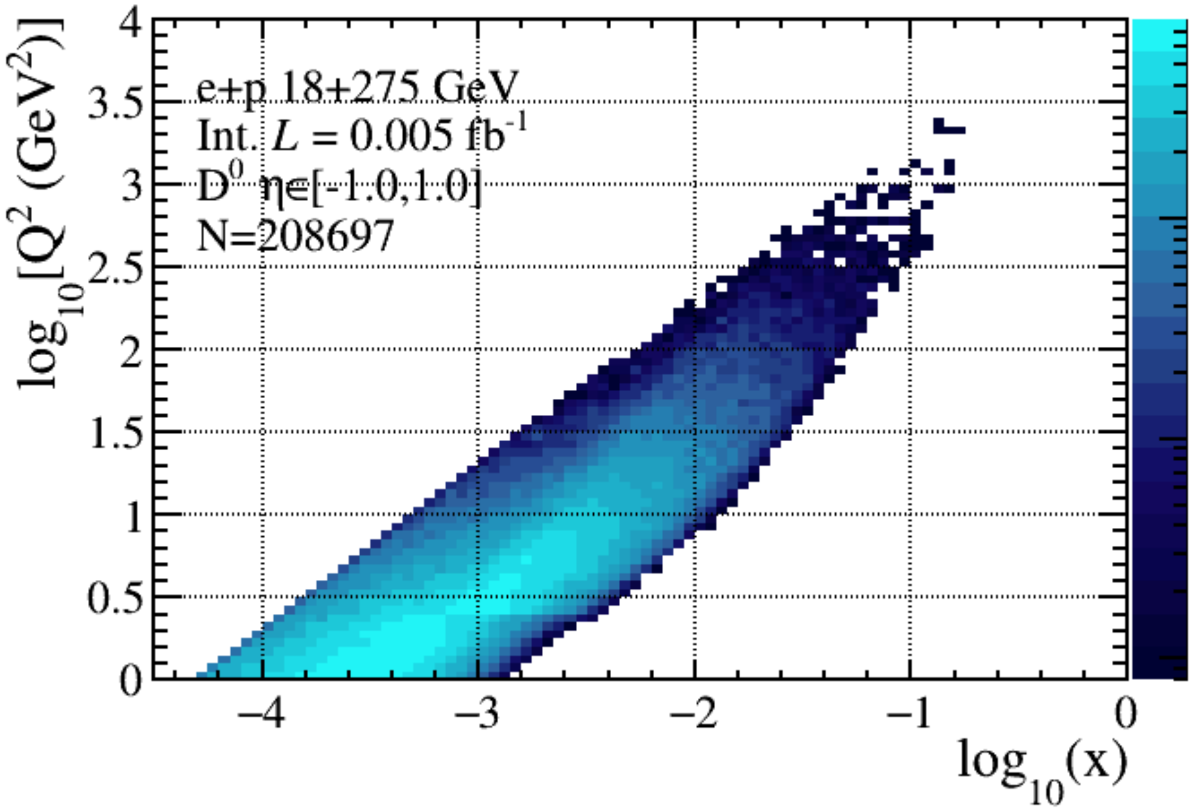


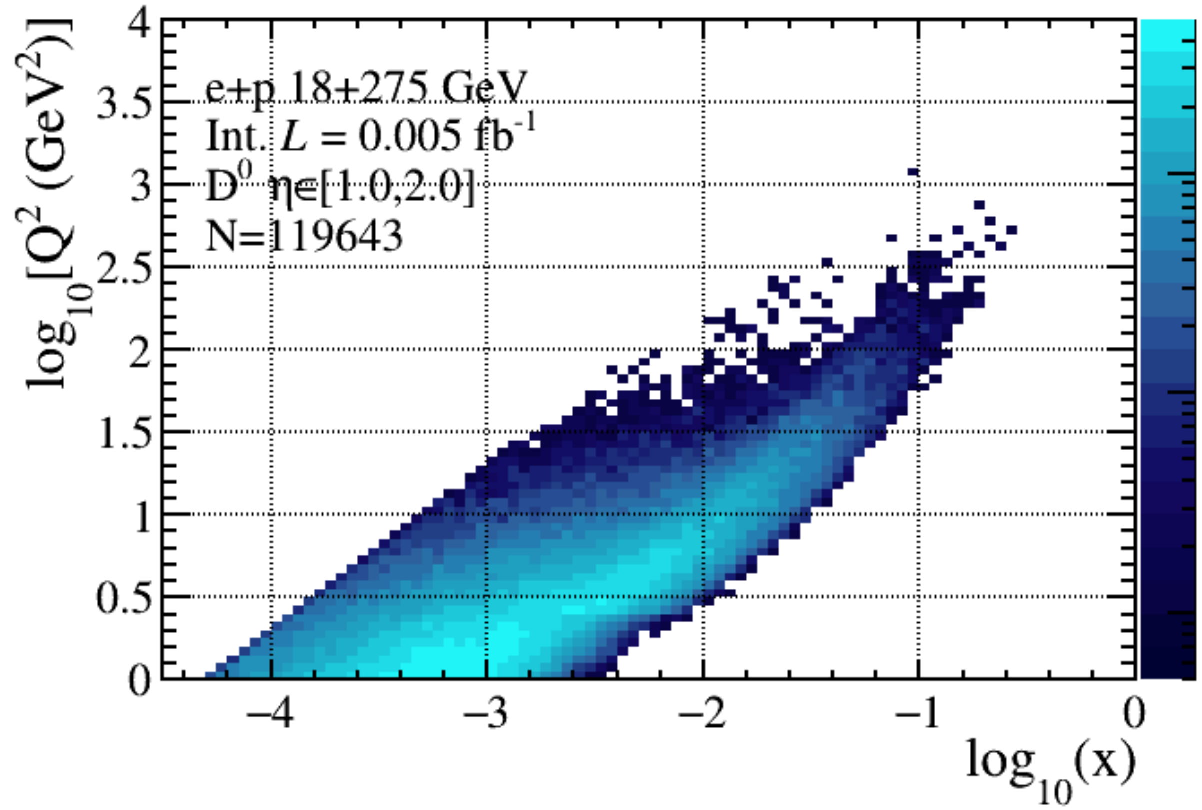
- PYTHIA simulation shows a small impact on $D\overline{D}$ angular correlation

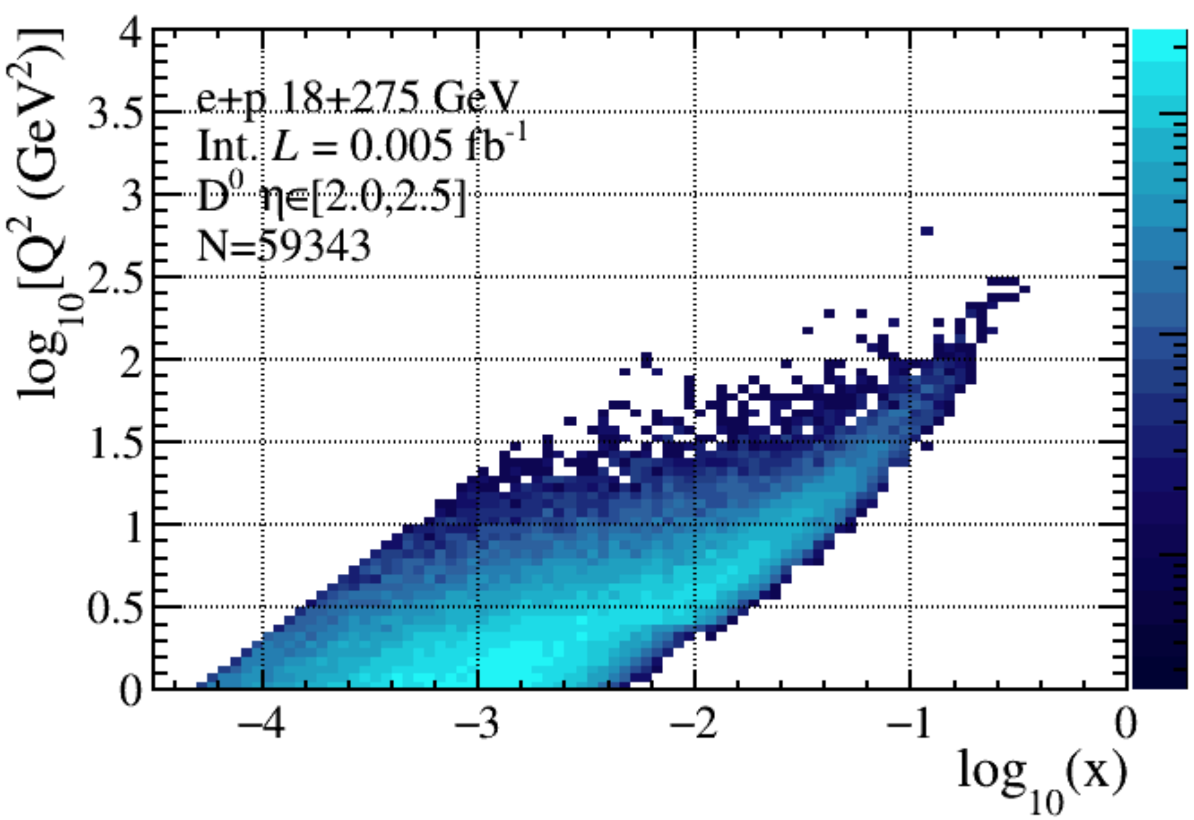
  - larger dilution due to process selection - under investigation

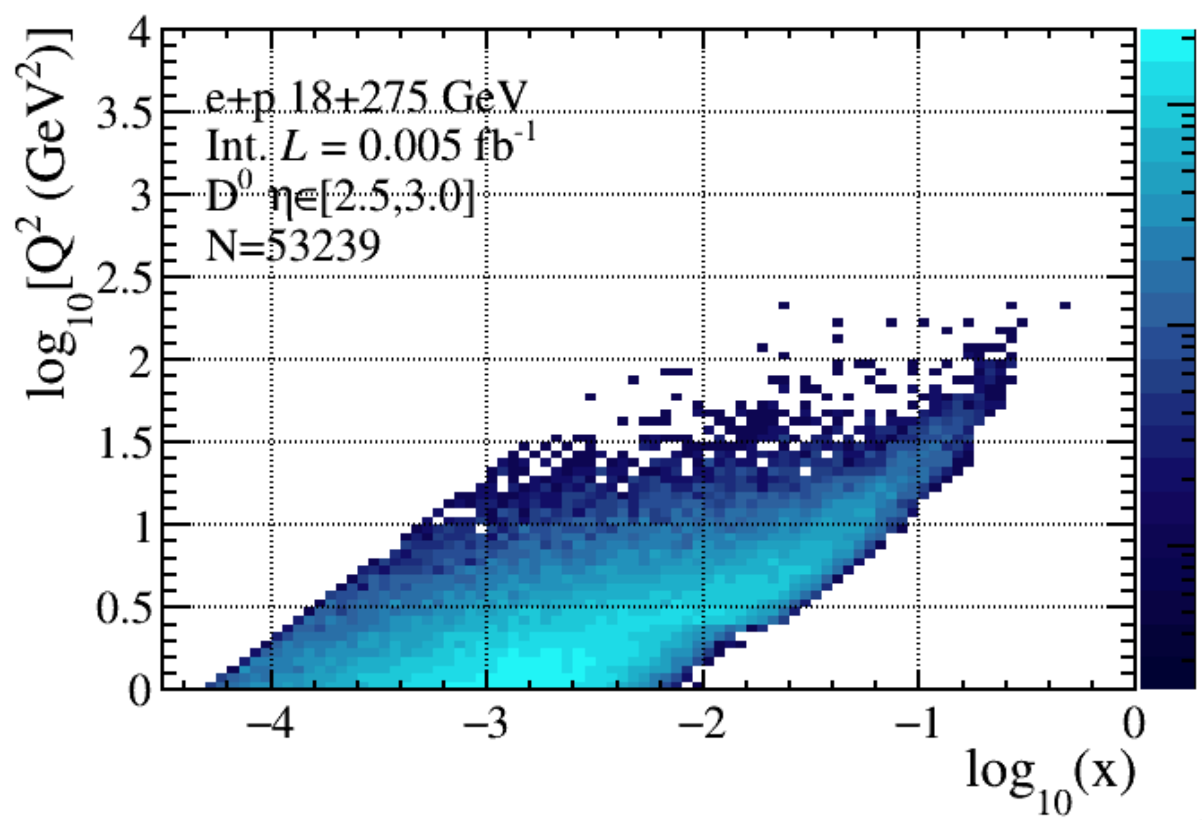
  - same input asymmetry assumed as in *L. Zheng et al., PRD 98 (2018) 034011*

arXiv: 2102.08337, EIC YR 2021


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

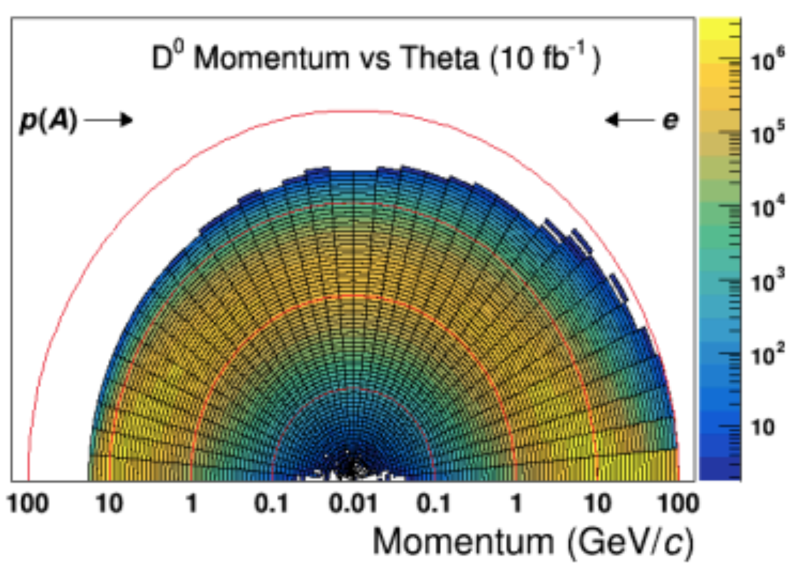

e+p 18+275 GeV
Int. L = 0.005 fb^{-1}
D^0 $\eta \in [1.0,2.0]$
N=119643
$\log_{10}[Q^2 (GeV^2)]$
$\log_{10}(x)$
4
3.5
3
2.5
2
1.5
1
0.5
0
−4
−3
−2
−1
0

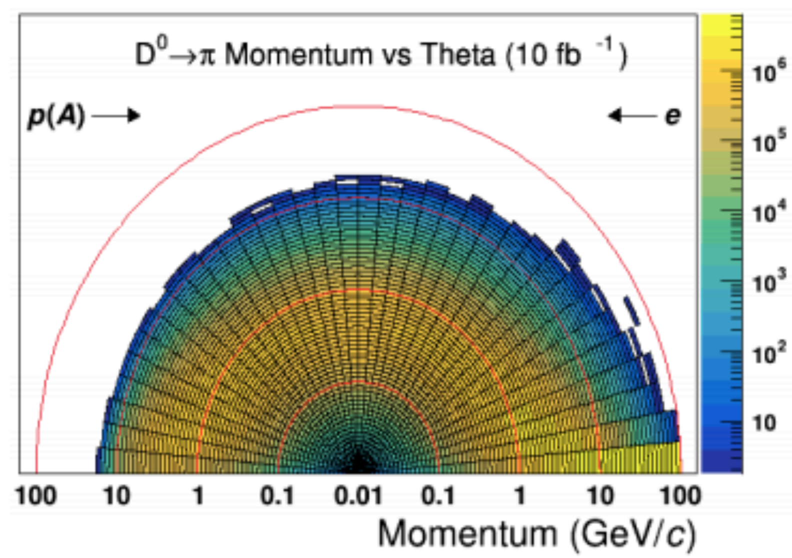

e+p 18+275 GeV
Int. L = 0.005 fb^{-1}
D^0 $\eta \in [2.0,2.5]$
N=59343
$\log_{10}[Q^2 (GeV^2)]$
$\log_{10}(x)$
4
3.5
3
2.5
2
1.5
1
0.5
0
−4
−3
−2
−1
0

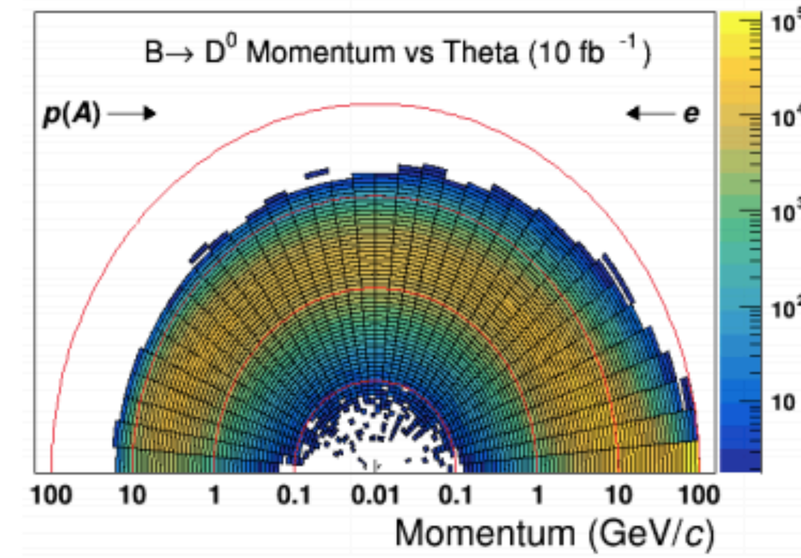

e+p 18+275 GeV
Int. L = 0.005 fb^{-1}
D^0 $\eta \in [2.5,3.0]$
N=53239
$\log_{10}[Q^2 (GeV^2)]$
$\log_{10}(x)$
4
3.5
3
2.5
2
1.5
1
0.5
0
−4
−3
−2
−1
0

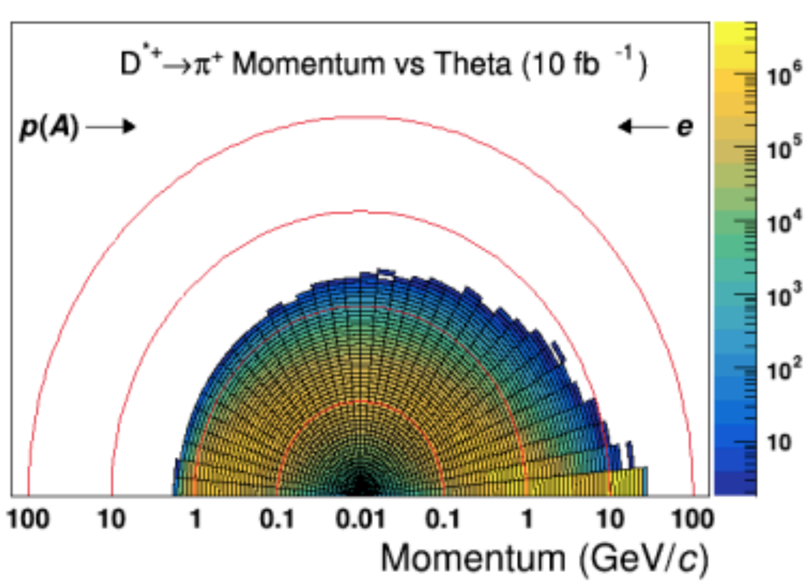
Kinematic Distributions

e + p 18 x 275 PYTHIA 6.4

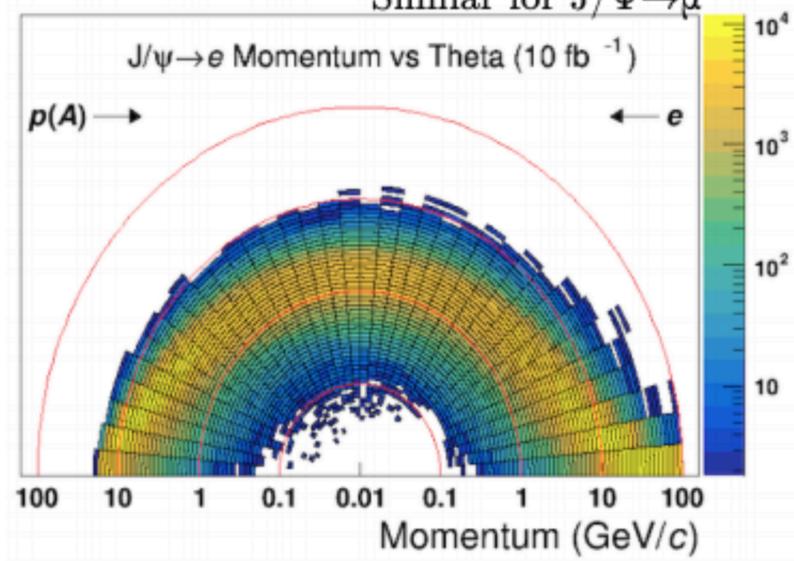


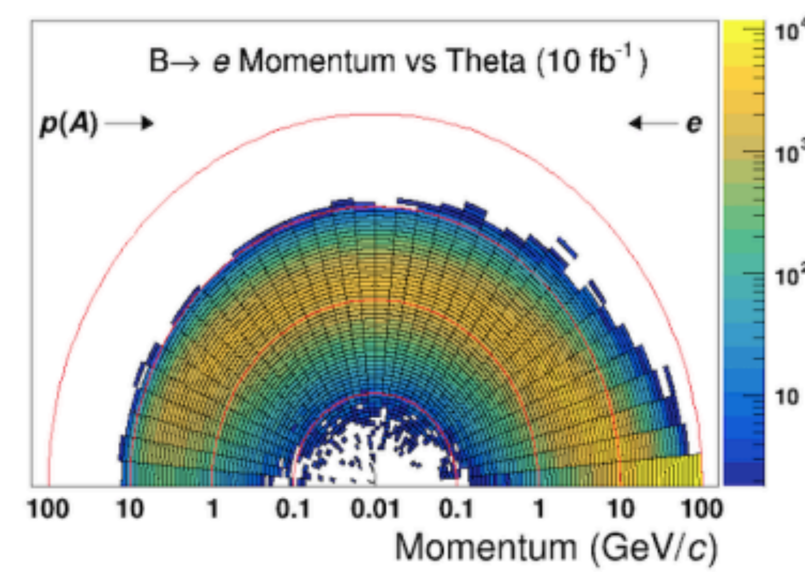






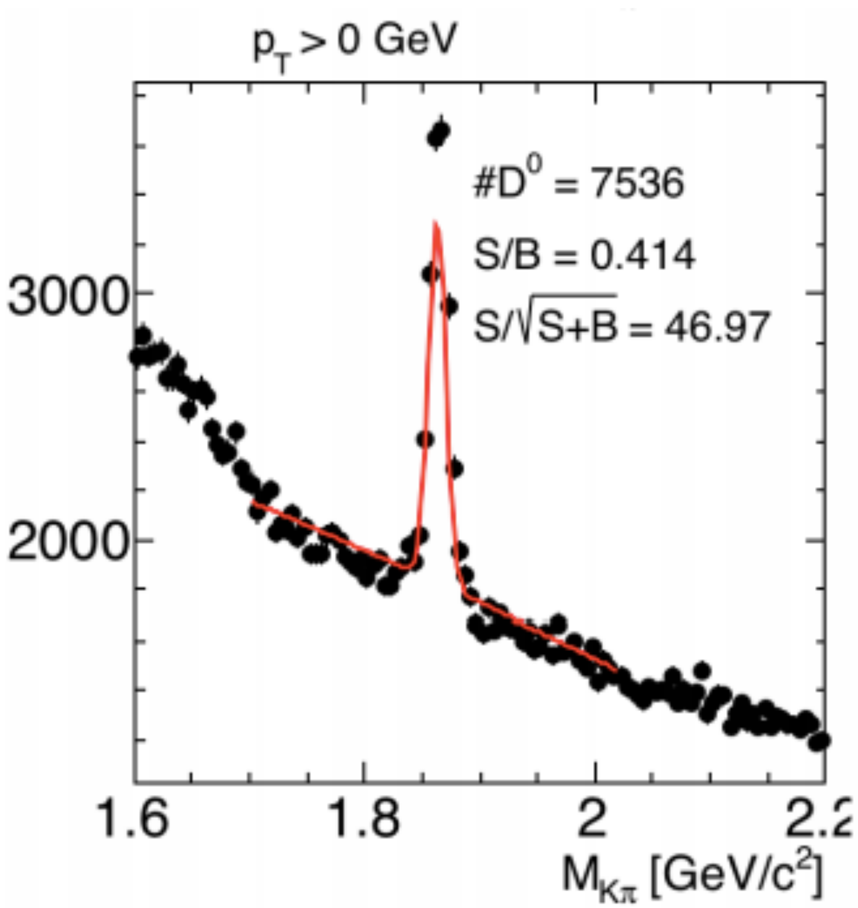
Similar for $J/\Psi \rightarrow \mu$





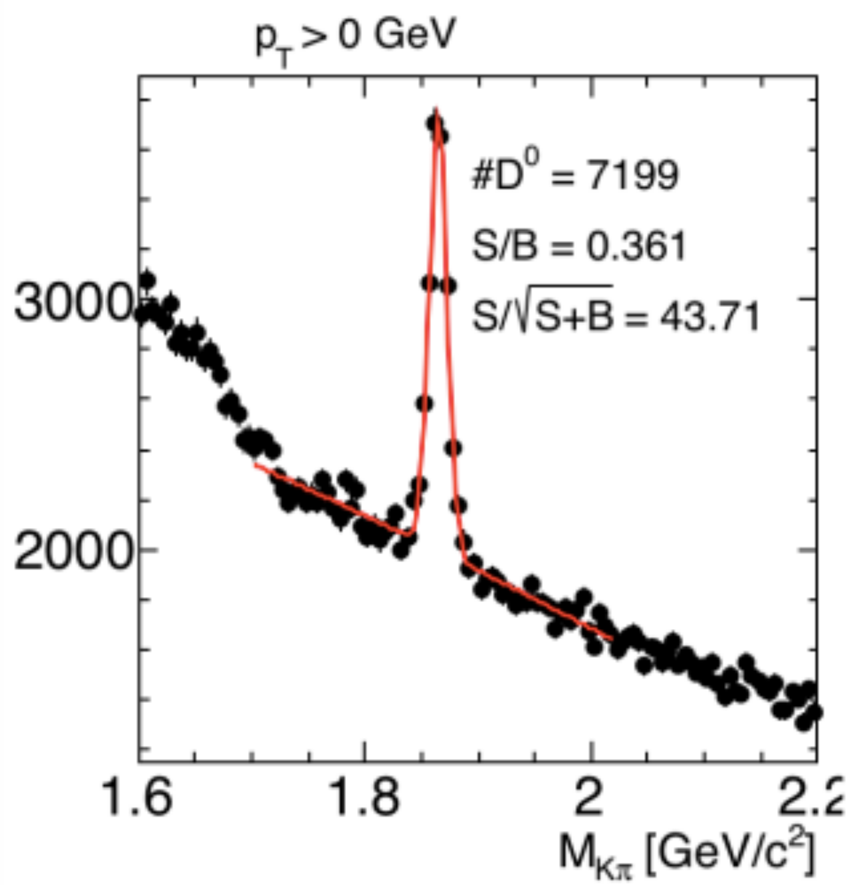
Impact of Pointing Resolution on D^0 Significance

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



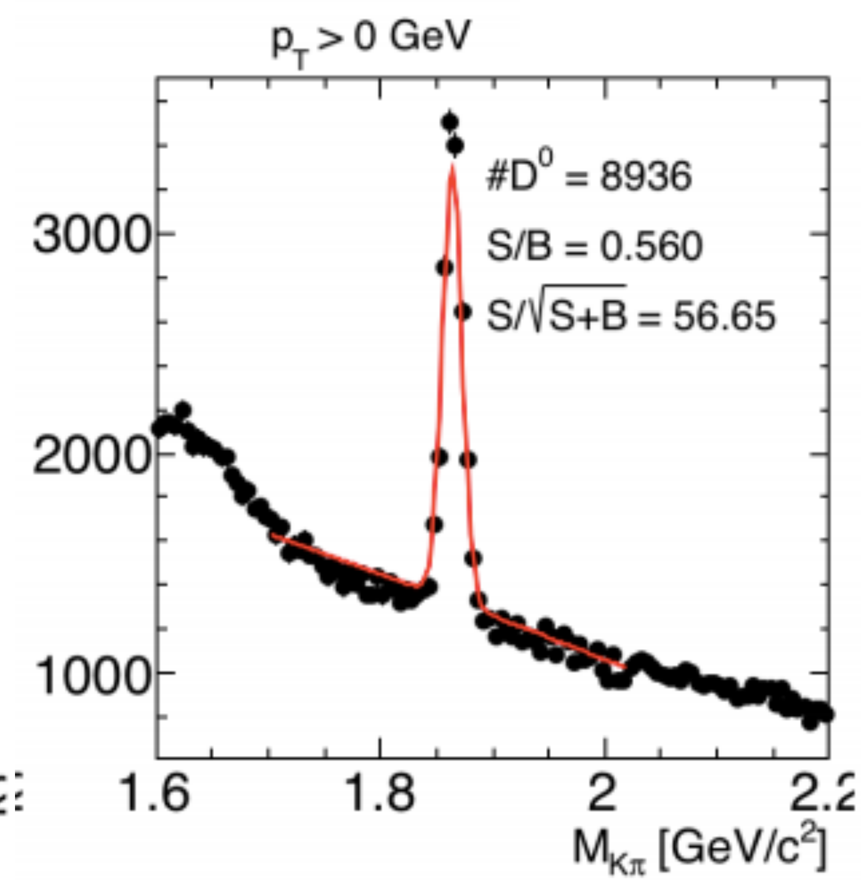
D^0 significance

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



-10%

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



+20%

- vertex res. assumed to be 20 μm

Full Simulation with Fun4All

All-Silicon Detector Concept

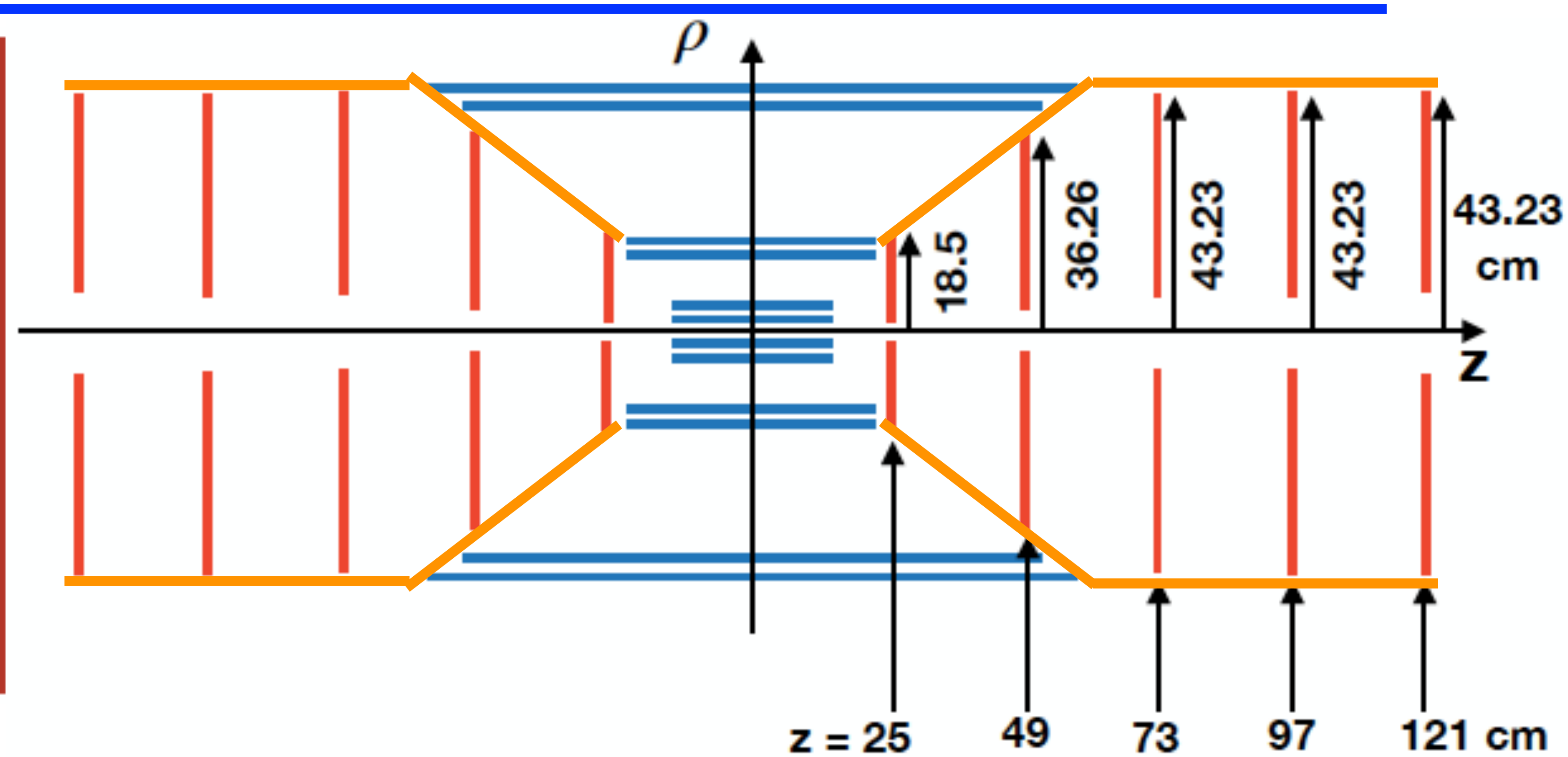
10 μm x 10 μm pixel devices

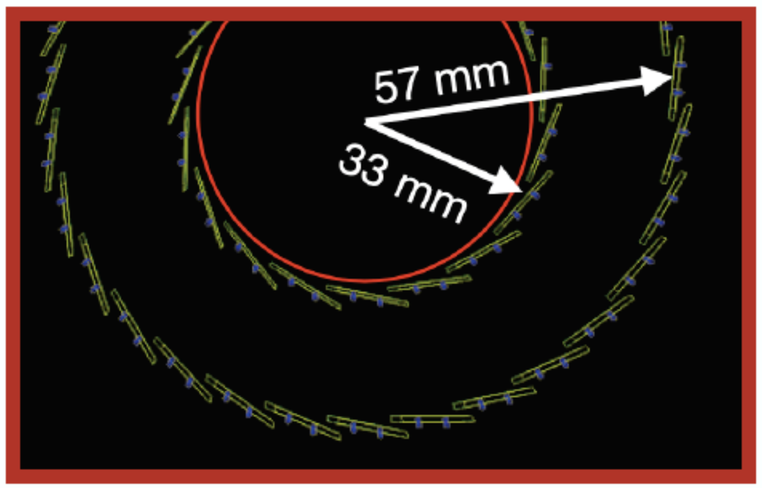
X/X0=0.3% per layer ← *ALICE-ITS2*

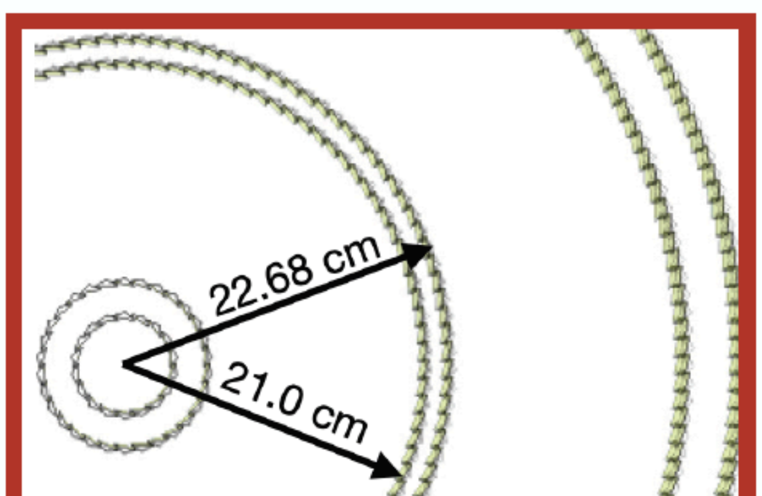
Beampipe r=3.1 cm

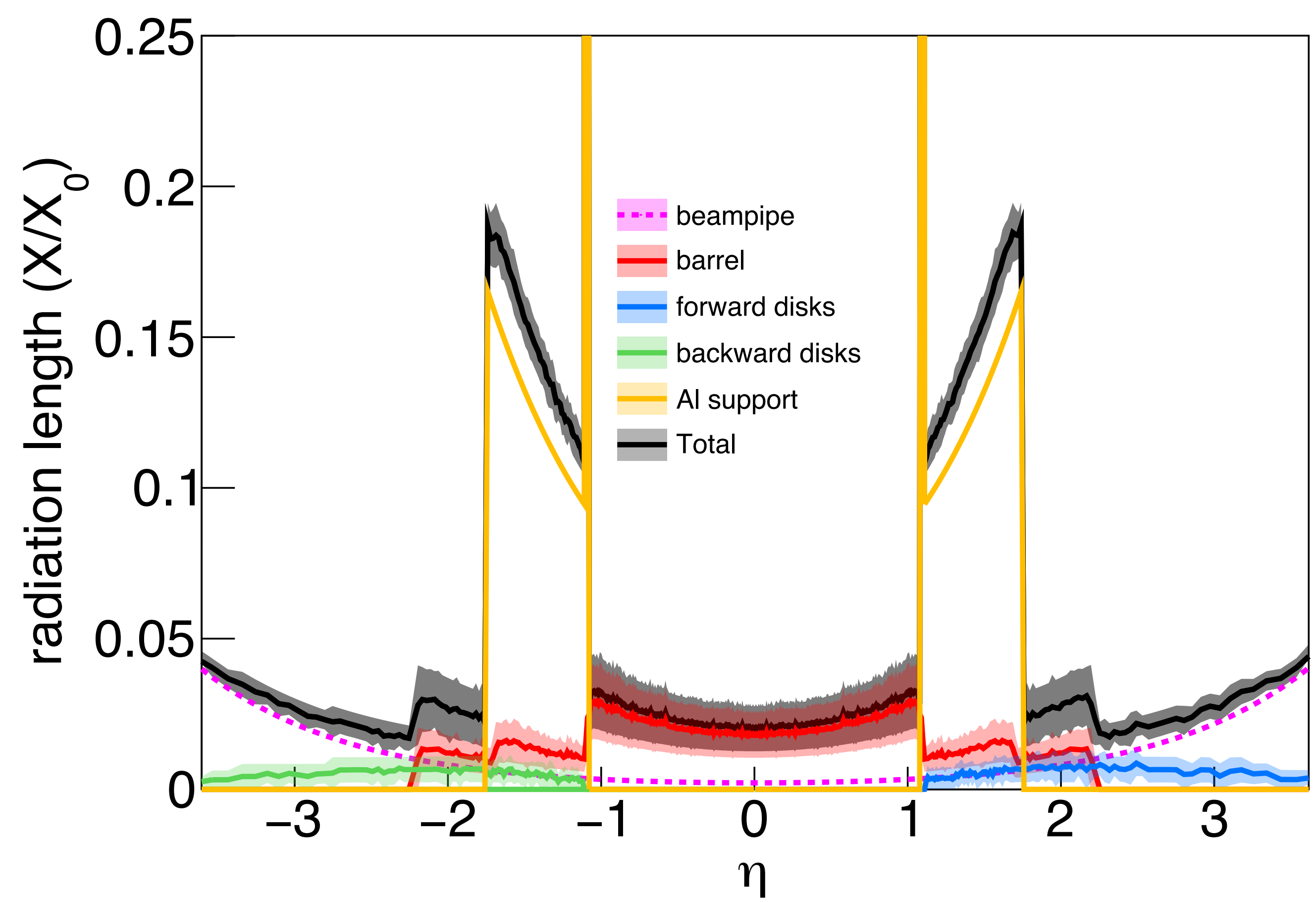
B = 3.0 T

Outer barrel r = 39, 42 cm

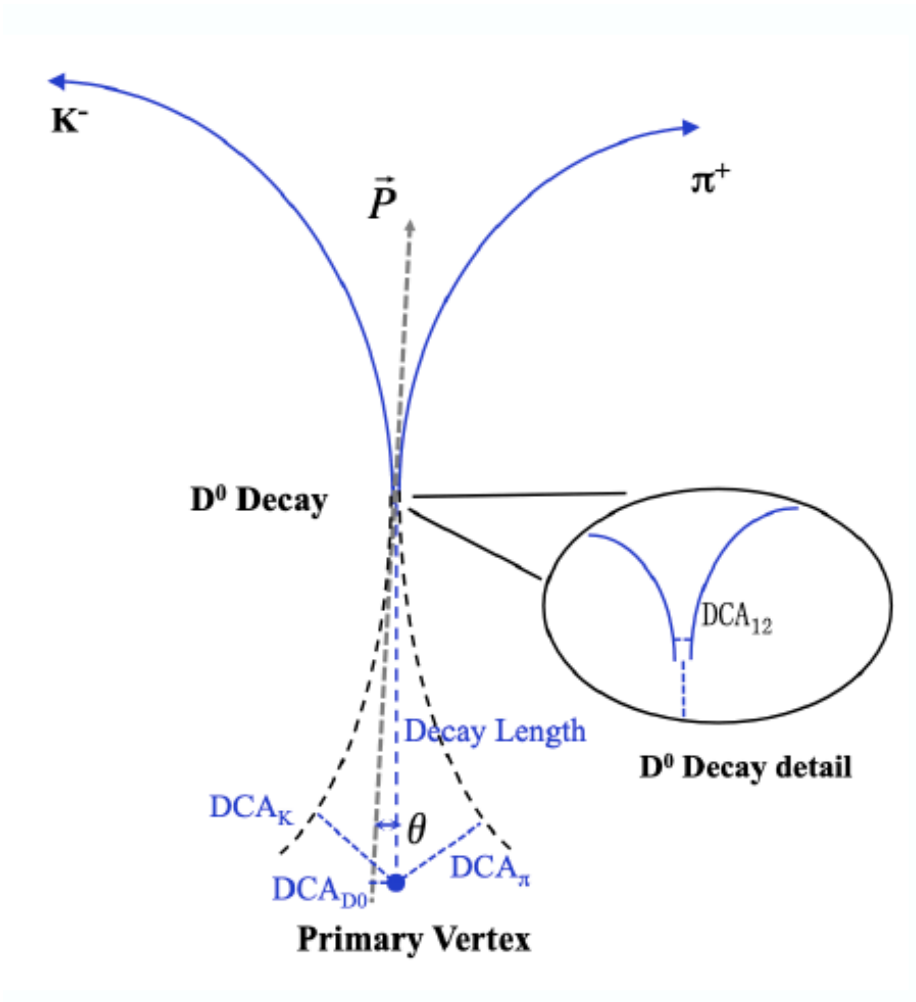


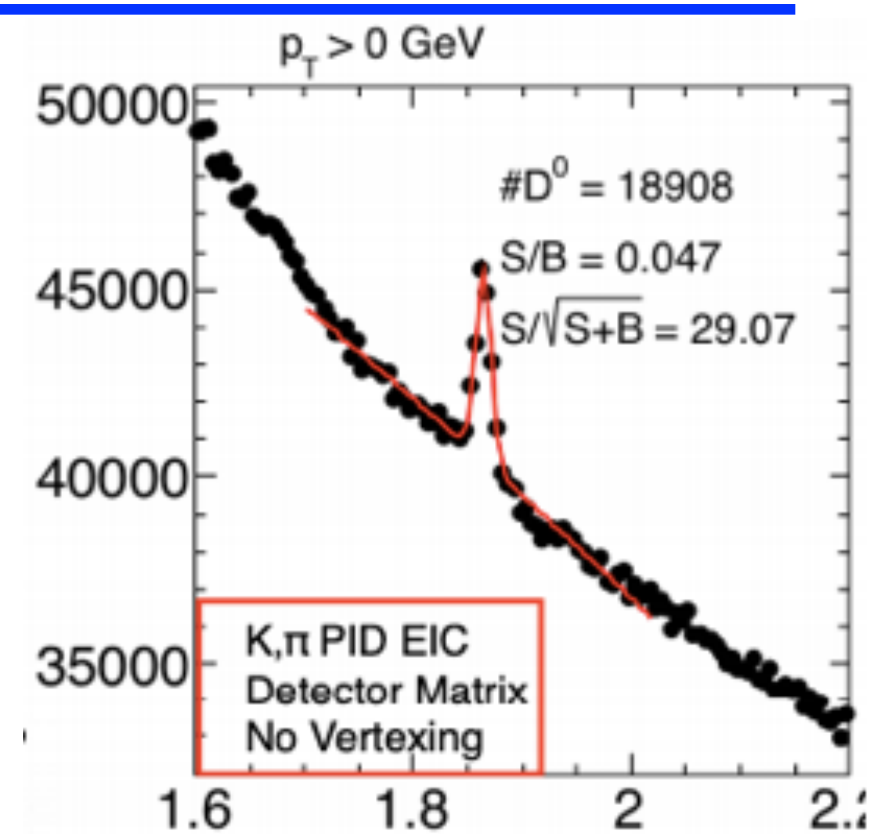


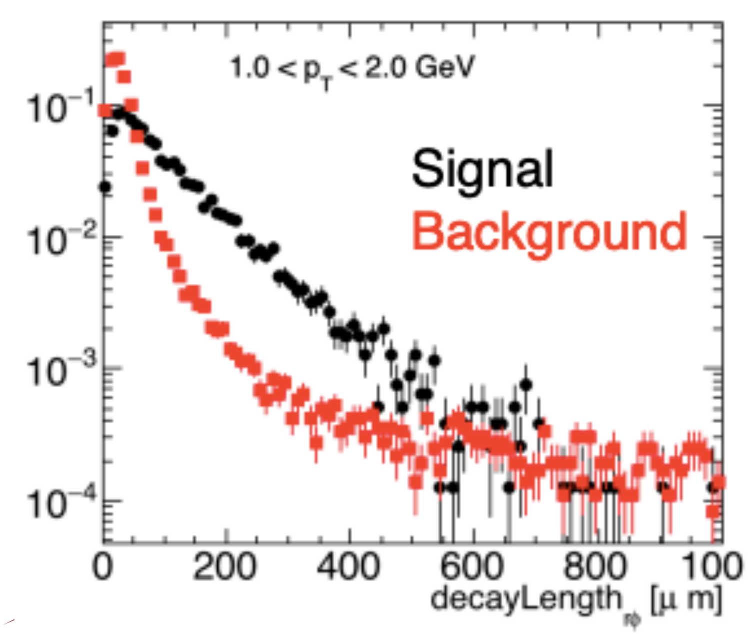


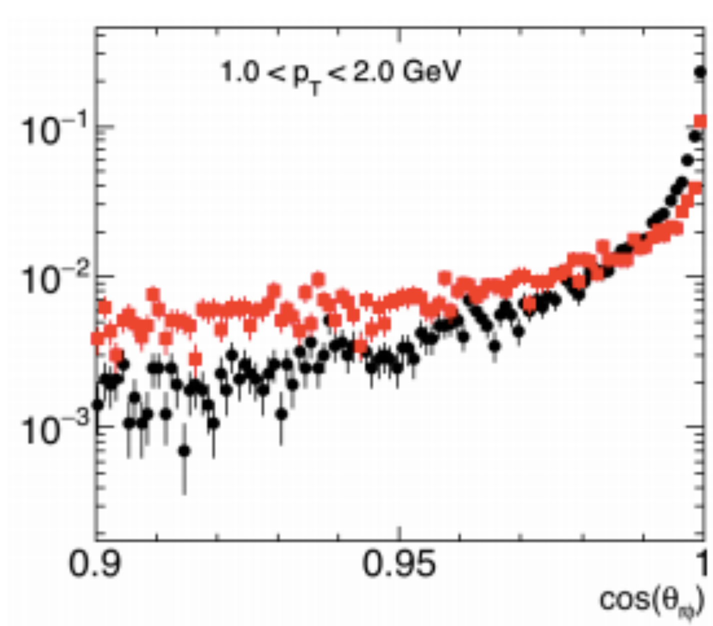


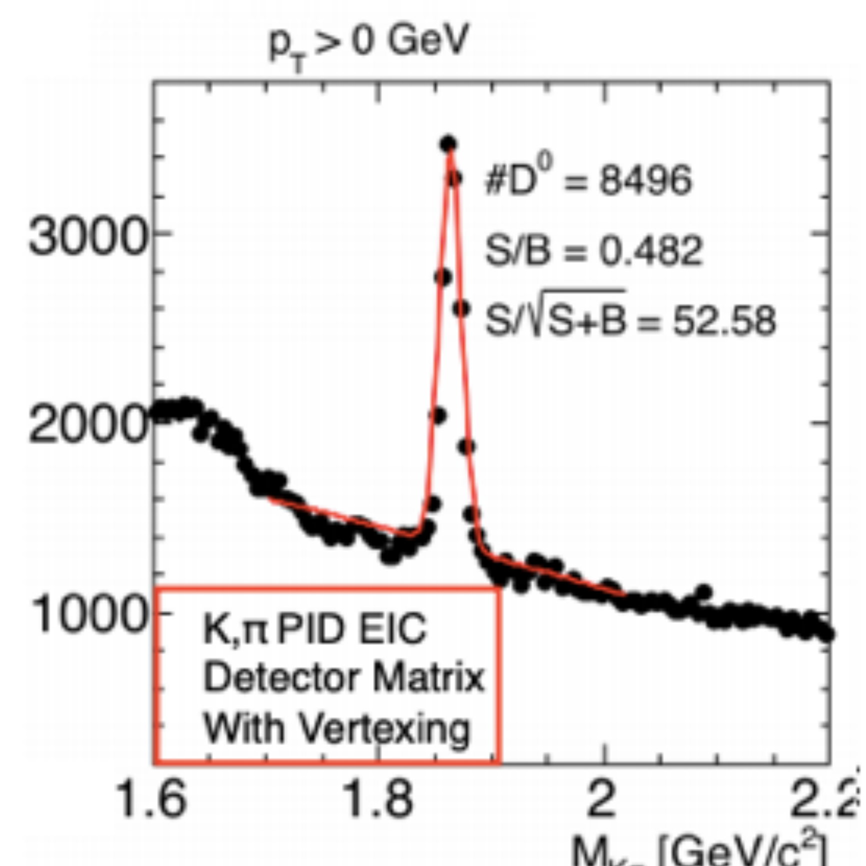
Topological Reconstruction of Heavy Flavor Decays









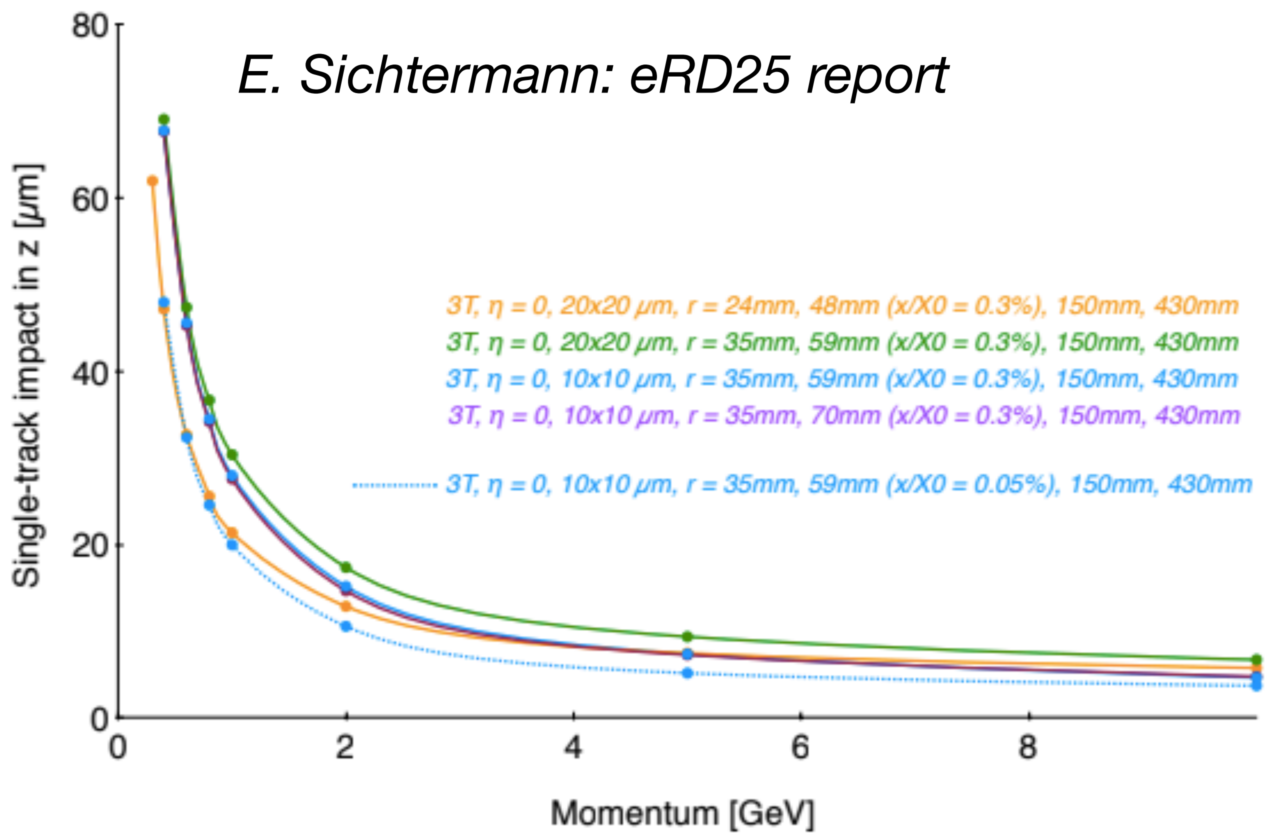


Specifications

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

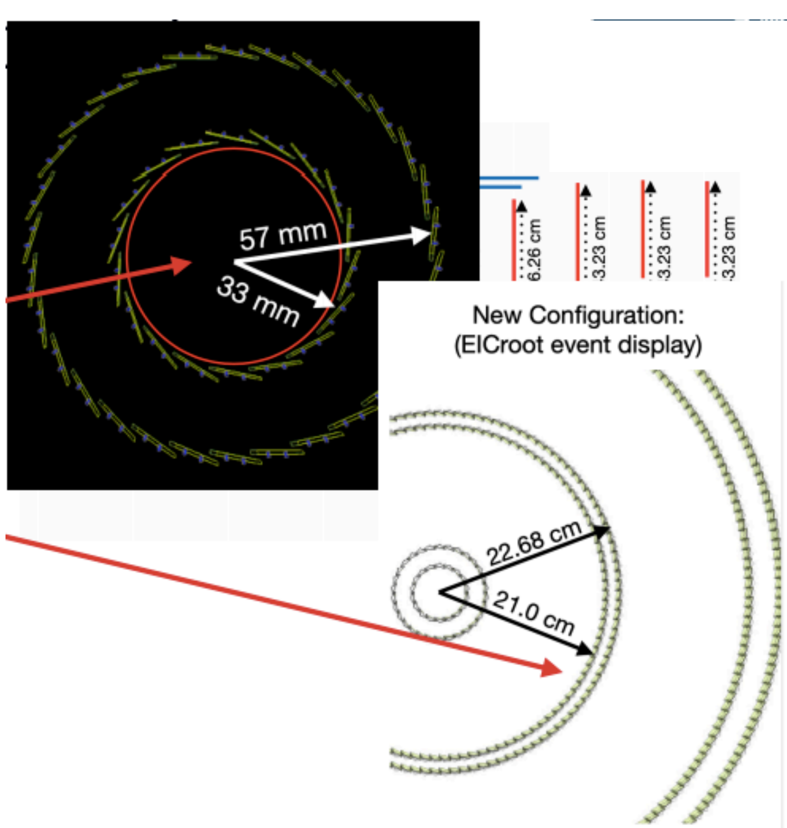
M. Mager | ITS3 kickoff | 04.12.2019 |

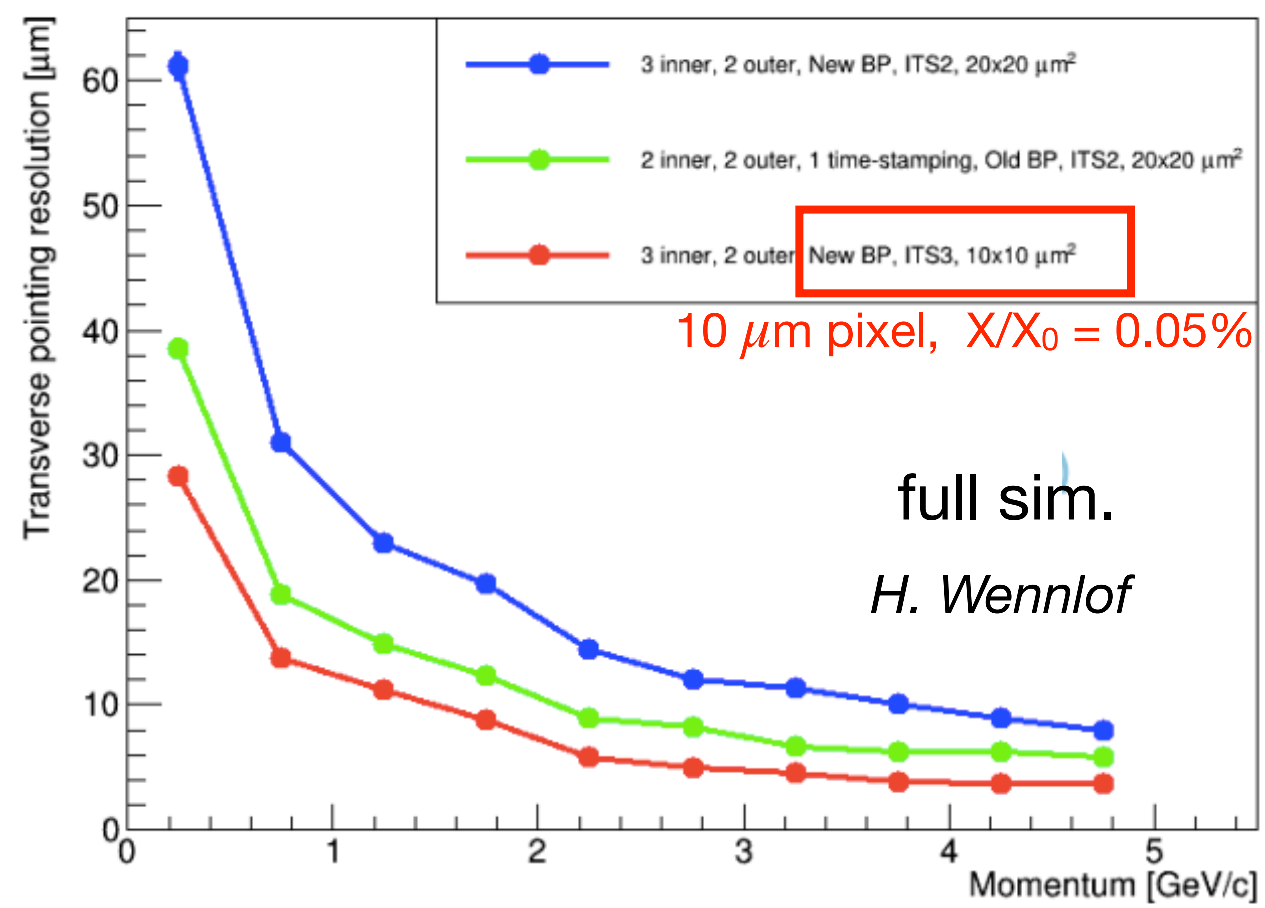
Benefits of Ultra-thin Fine-pitch MAPS Detector



A larger beampipe leads to worsening of pointing resolution

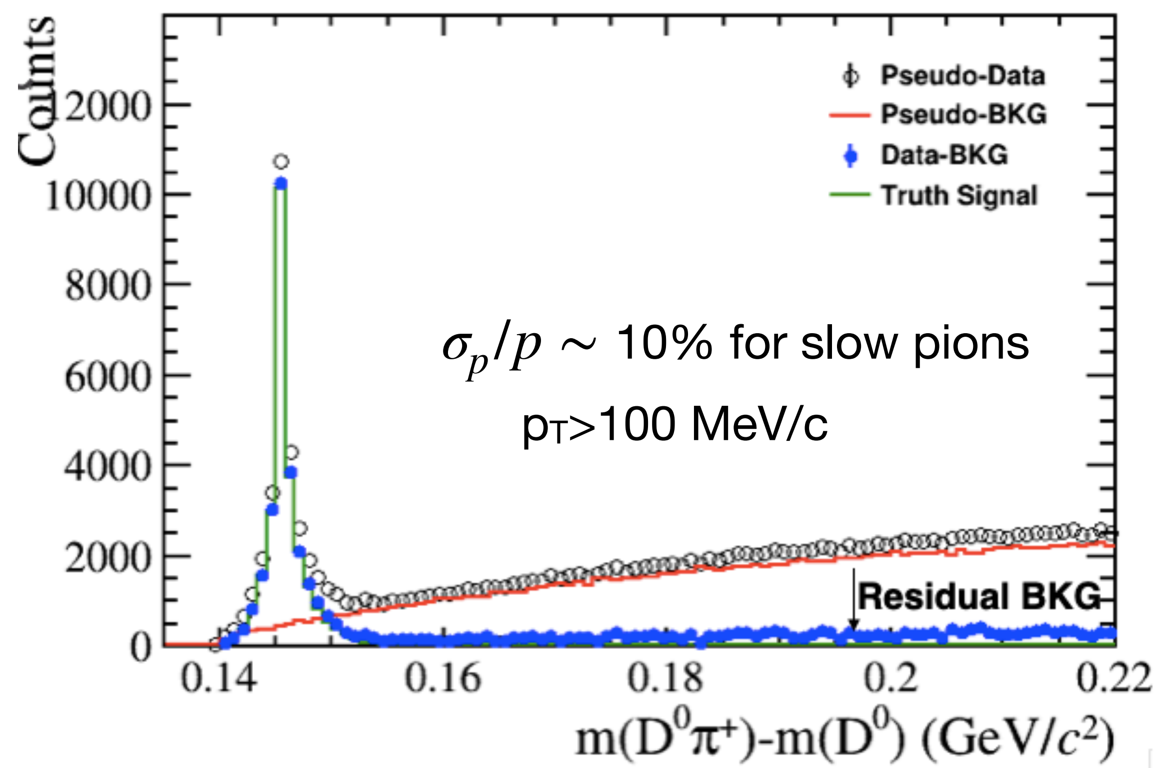
- high mom region can be recovered with smaller pitch design (10x10 μm^2)
- low mom region can only be recovered with ultra-thin detector design (0.05%X_0)

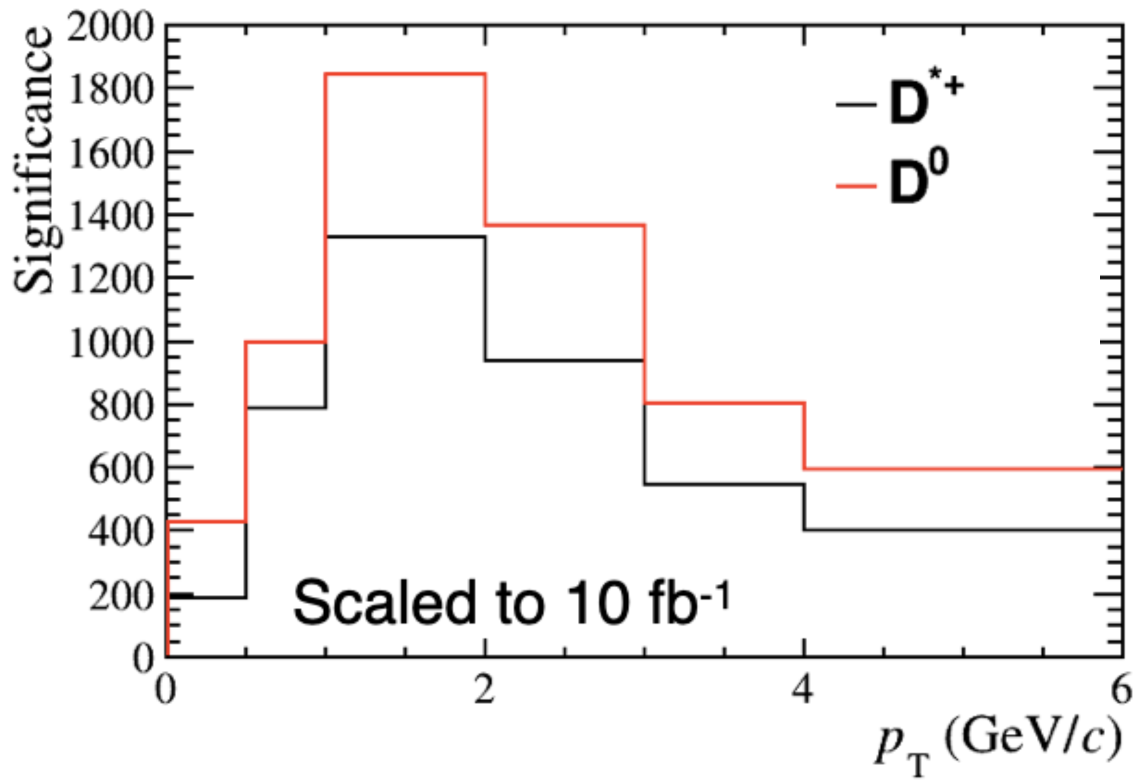


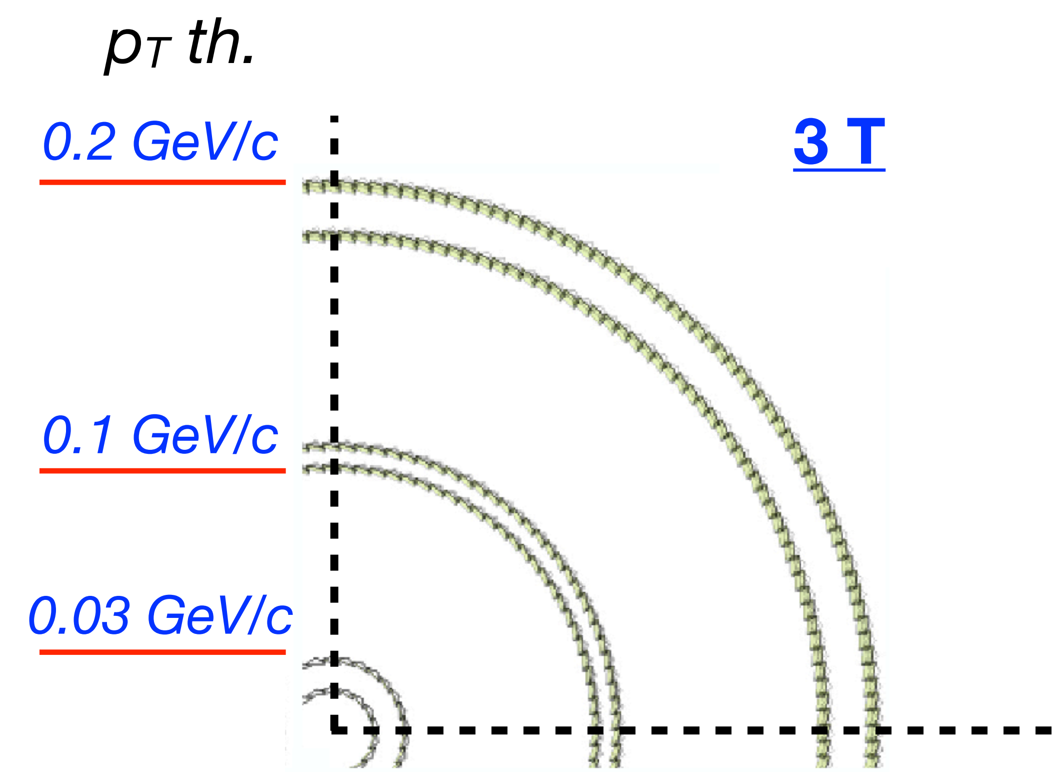


Low-p_T Cut-off and D* Reconstruction

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



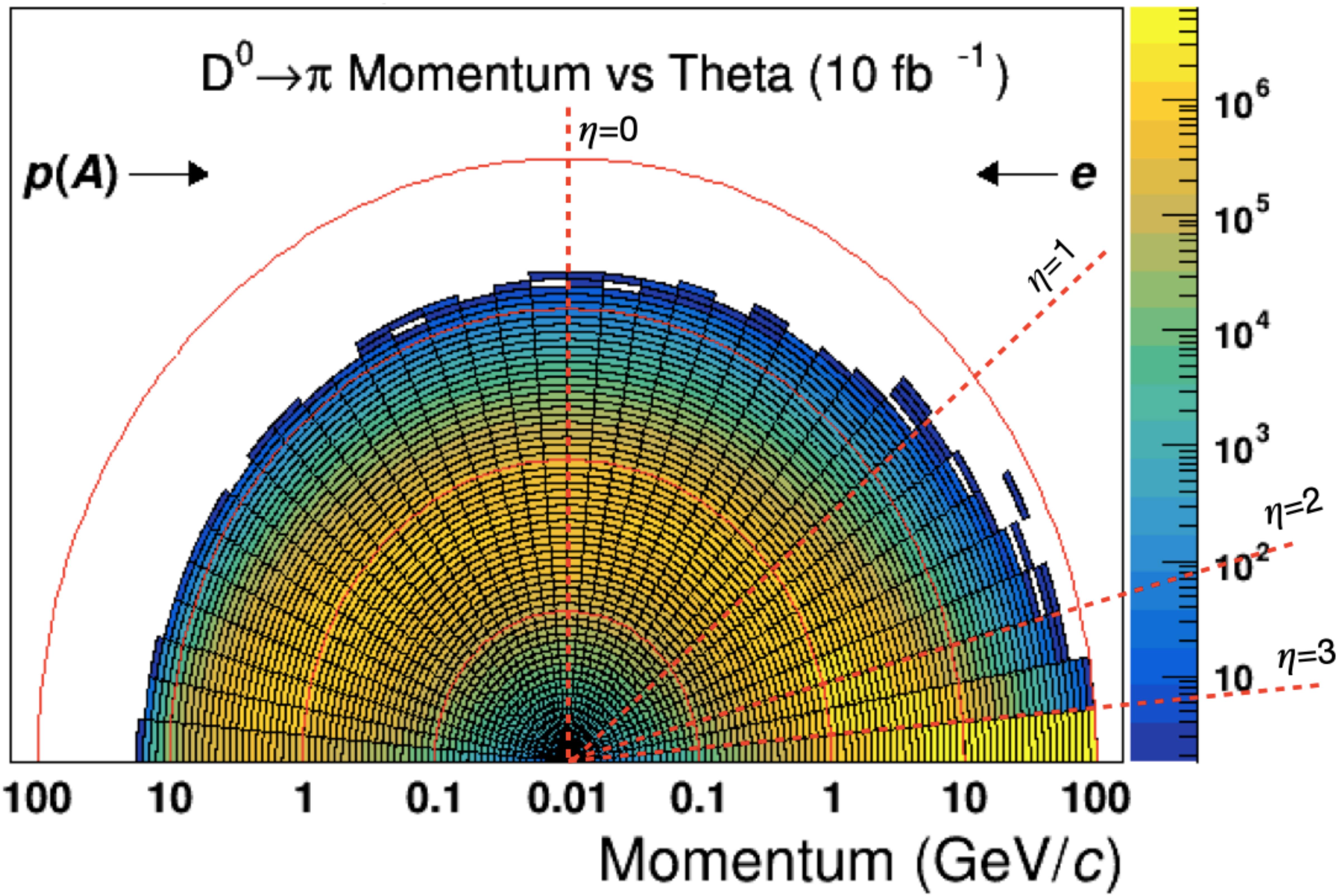




- D^{*+} can be a viable channel
- Inner vertex layer optimization
  - *a third layer for redundancy + low p_T acceptance*

Kinematic Distributions

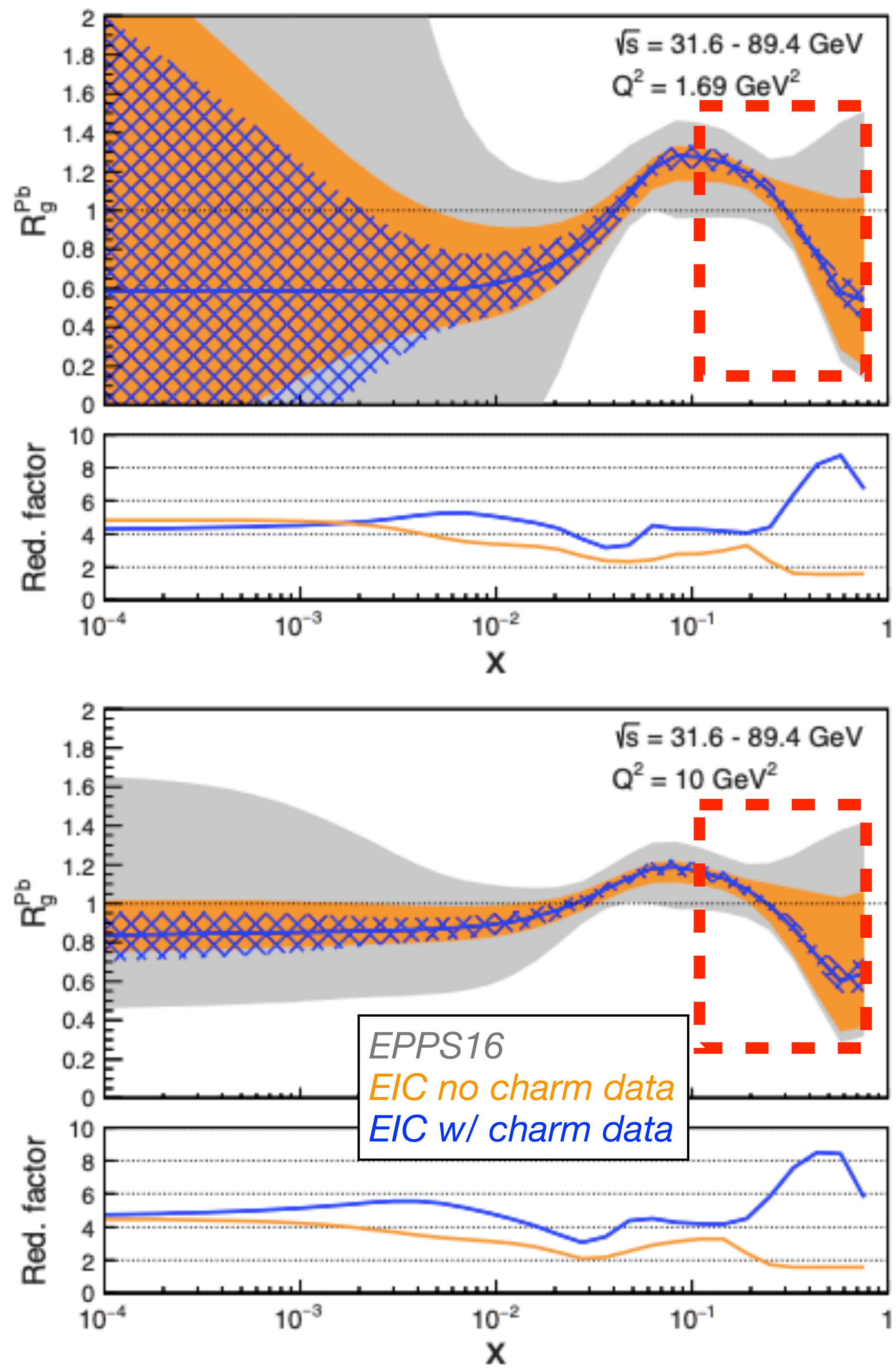
e + p 18 + 275 PYTHIA 6.4



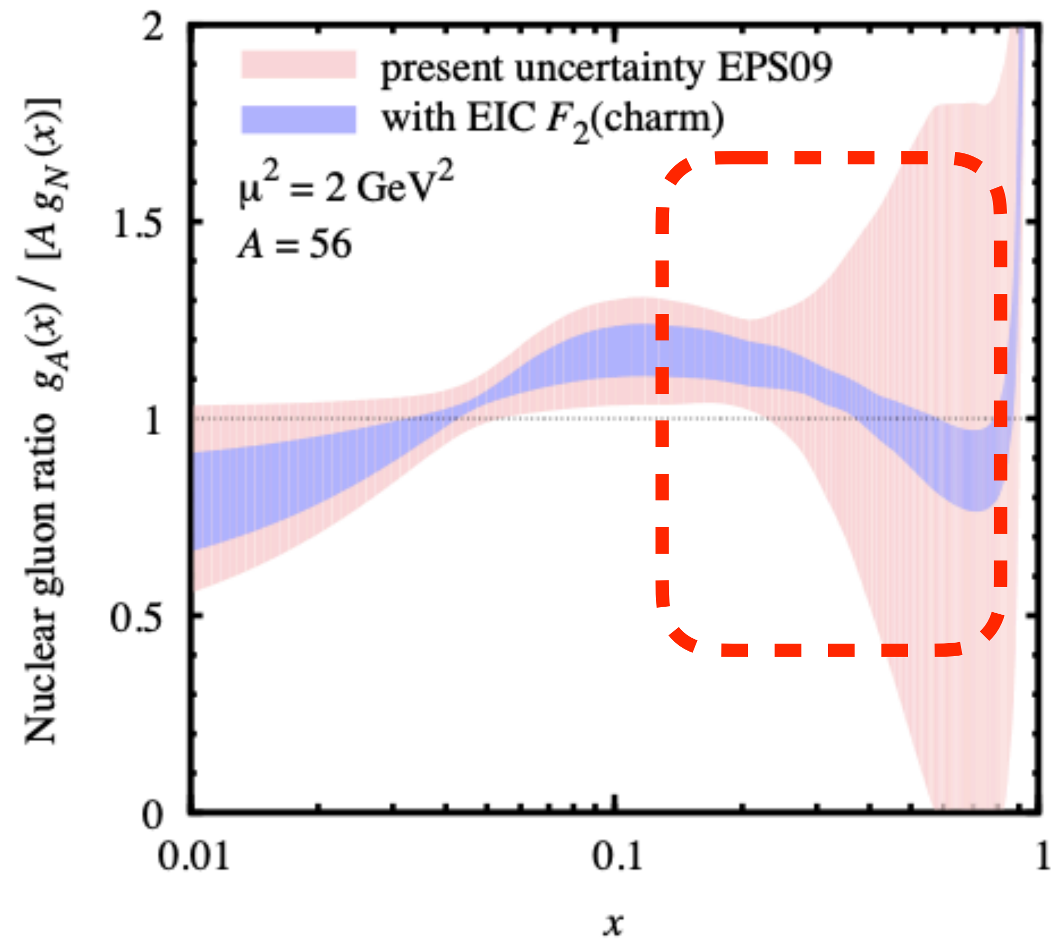
Inclusive Charm -> Gluon nPDF at High x

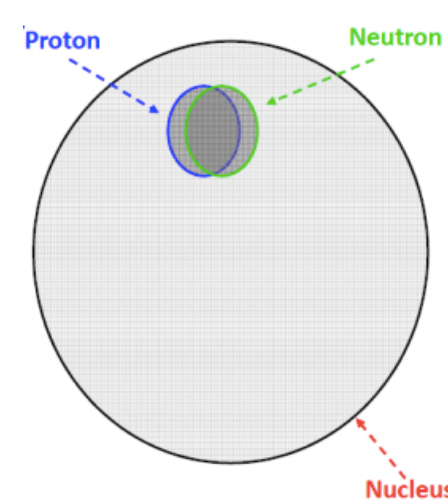
$R_g^{Pb} = f_g^{Pb}(x, Q^2)/f_g^p(x, Q^2)$

E.C. Aschenauer et al, 1708.01527



E. Chudakov et al, 1610.08536





gluon probe to short range correlation at "EMC" region

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	$0.1 \cdot p \oplus 2.0$

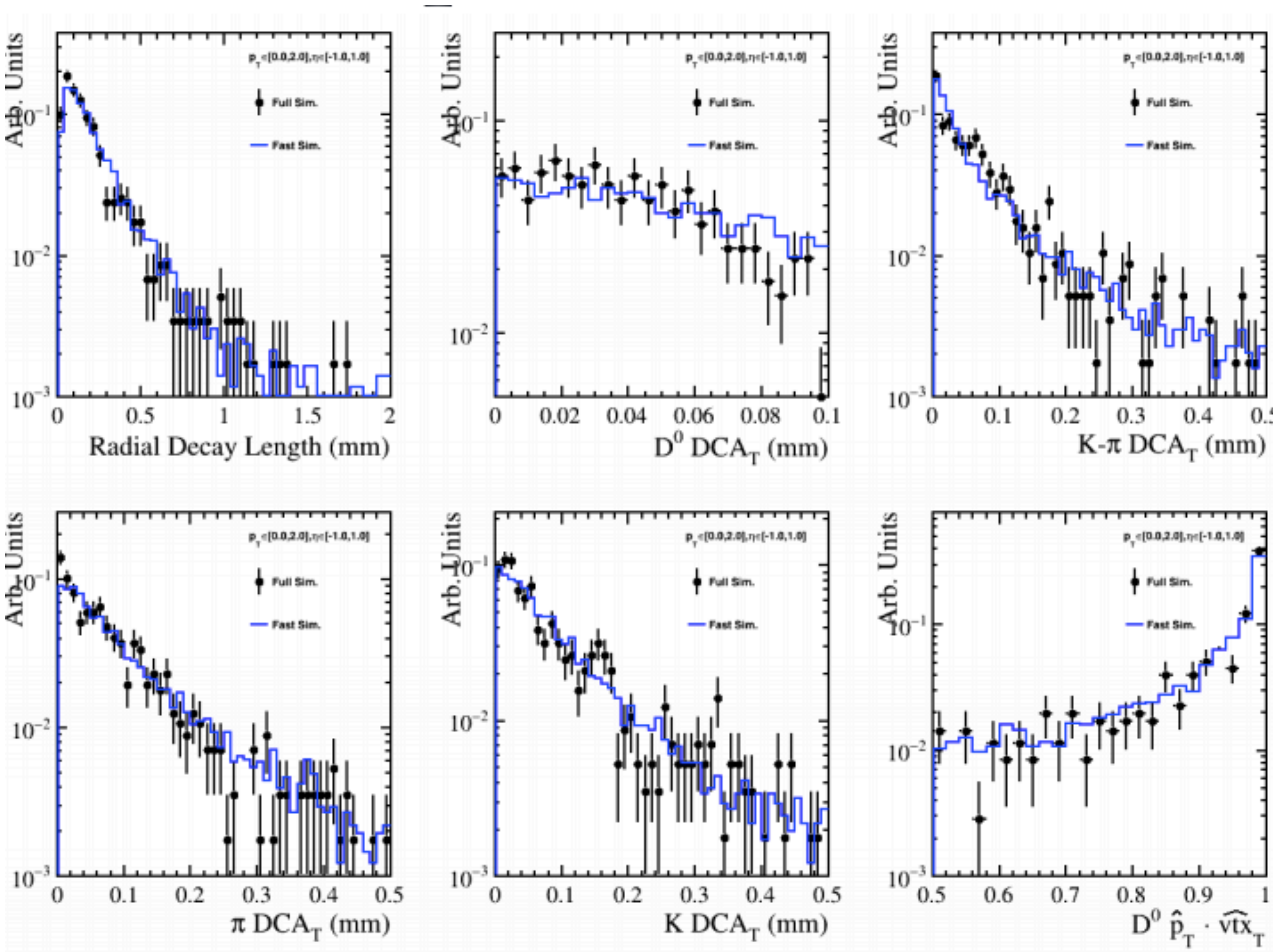
Pointing Resolution

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*

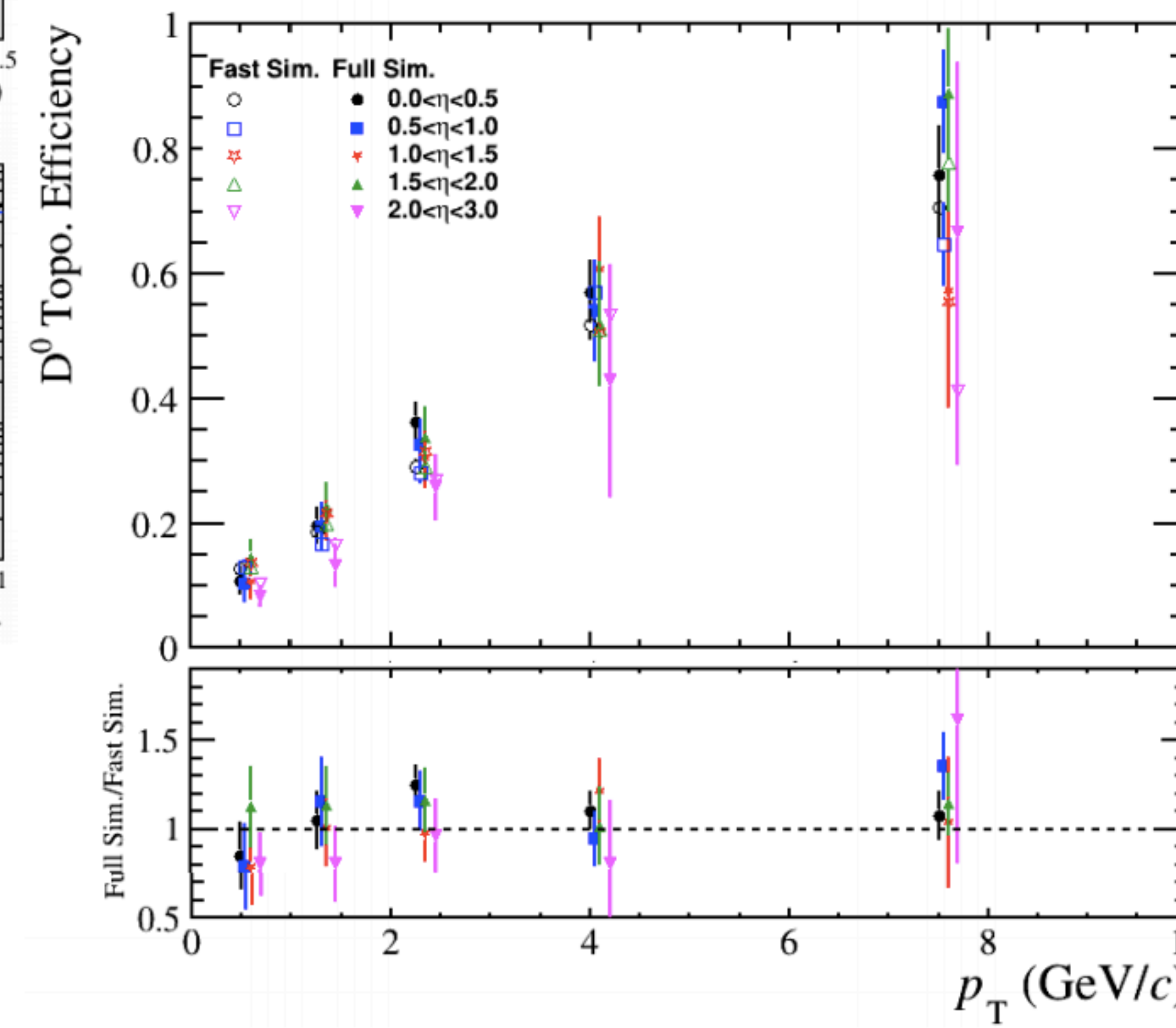
Validation of Fast Simulation w/ Fun4All



Radial Decay Vertex>0.04 mm

K-π DCA_T<0.15 mm

cos(D0 pointing angle)>0.98



<u>Fast simulation reproduces all topological distributions and D^0 efficiency !</u>