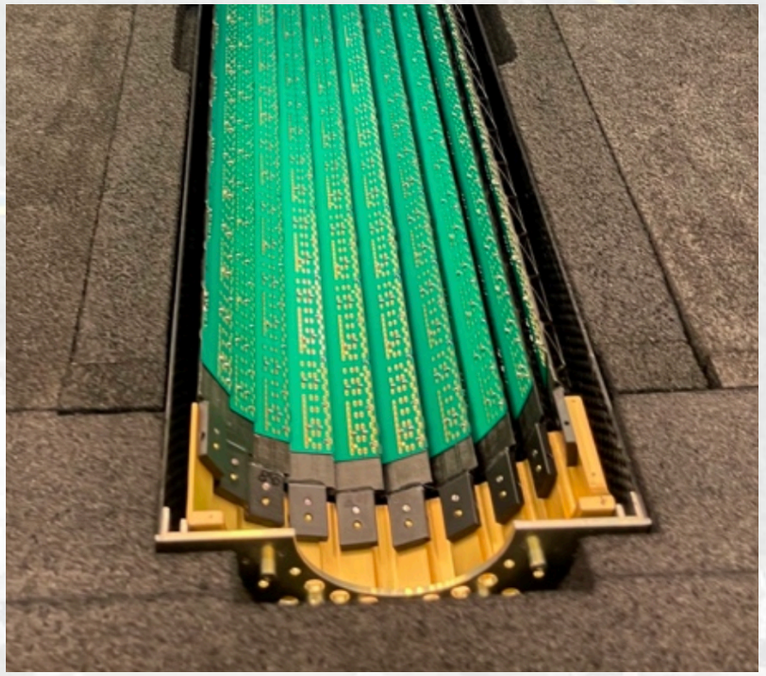
Heavy Flavor Production and Properties of sQGP at RHIC

Xin Dong (Lawrence Berkeley National Laboratory)

STAR HFT, summer 2014



sPHENIX MVTX, summer 2022

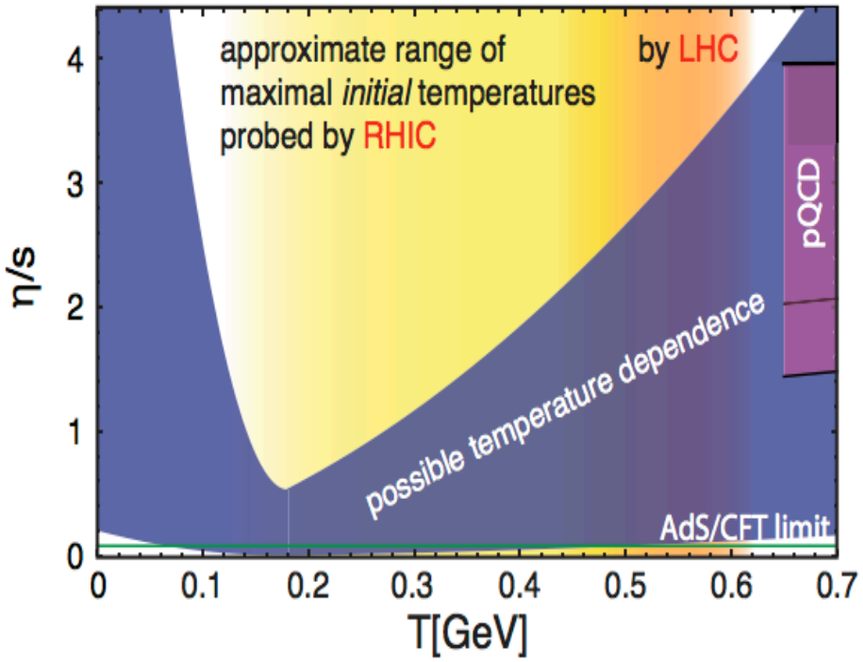
Outline

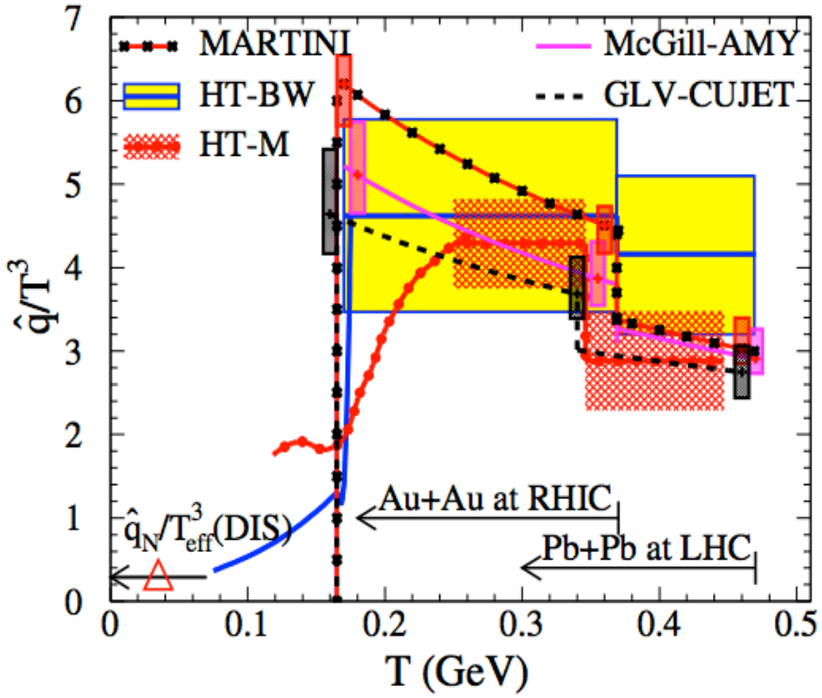
- Introduction:
  - Heavy quarks: microscopic characterization of sQGP
- Recent Heavy Flavor Results at RHIC
  - R_{AA} suppression - parton energy loss
  - Hadrochemistry - hadronization
  - Collectivity - sQGP transport coefficient
- Future Heavy Flavor Program at RHIC

QGP Emergent Properties

~2 ~6

p_T (GeV/c)





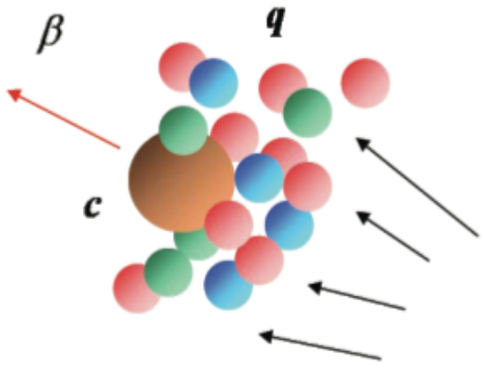
Hot QCD white paper - arXiv: 1502.02730

JET Coll., PRC 90 (2015) 014909

strongly coupled hydrodynamics ? weakly coupled pQCD

What is the microscopic picture of "perfect fluid"?

Heavy Flavor Quark Transport in QGP



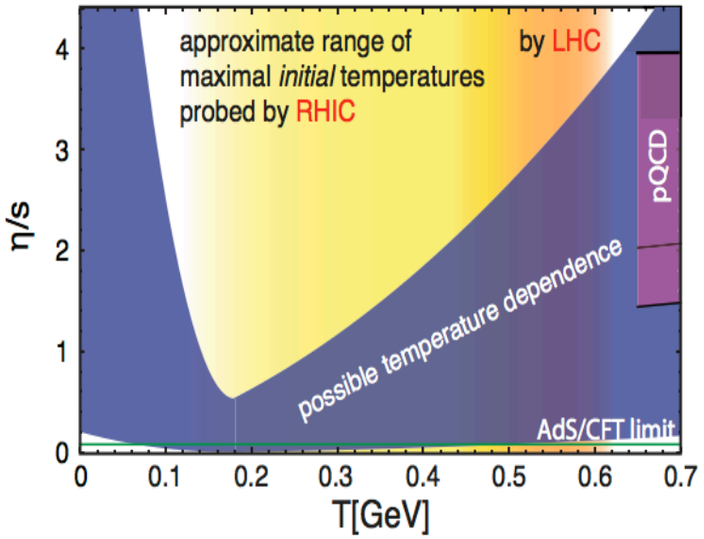
Femtoscopic "Brownian" motion

Langevin stochastic equation

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

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

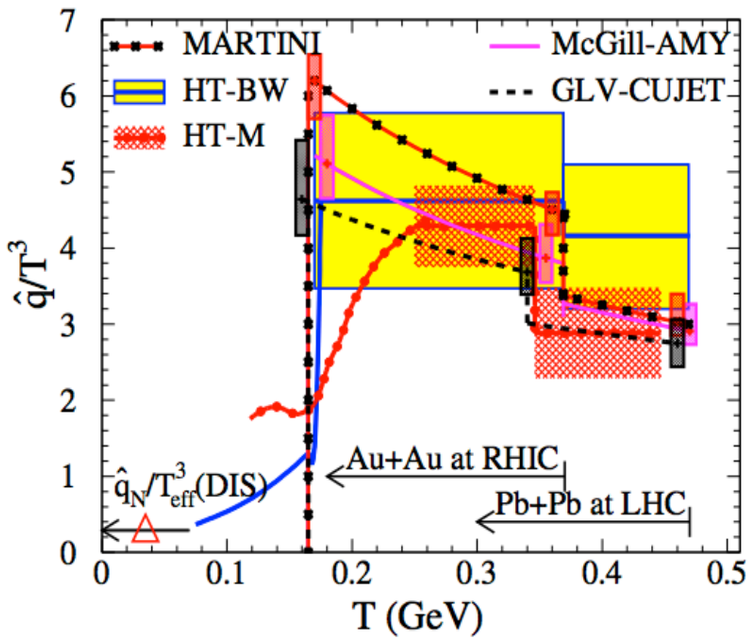
$$D_s \equiv \frac{\langle x^2(t)\rangle - \langle x^2(0)\rangle}{2dt} = \frac{t}{M\eta_D(p=0)}$$



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

ratio depends on the strong/weak coupling nature of QGP

R. Rapp and H. van Hees, 0903.1096



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

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

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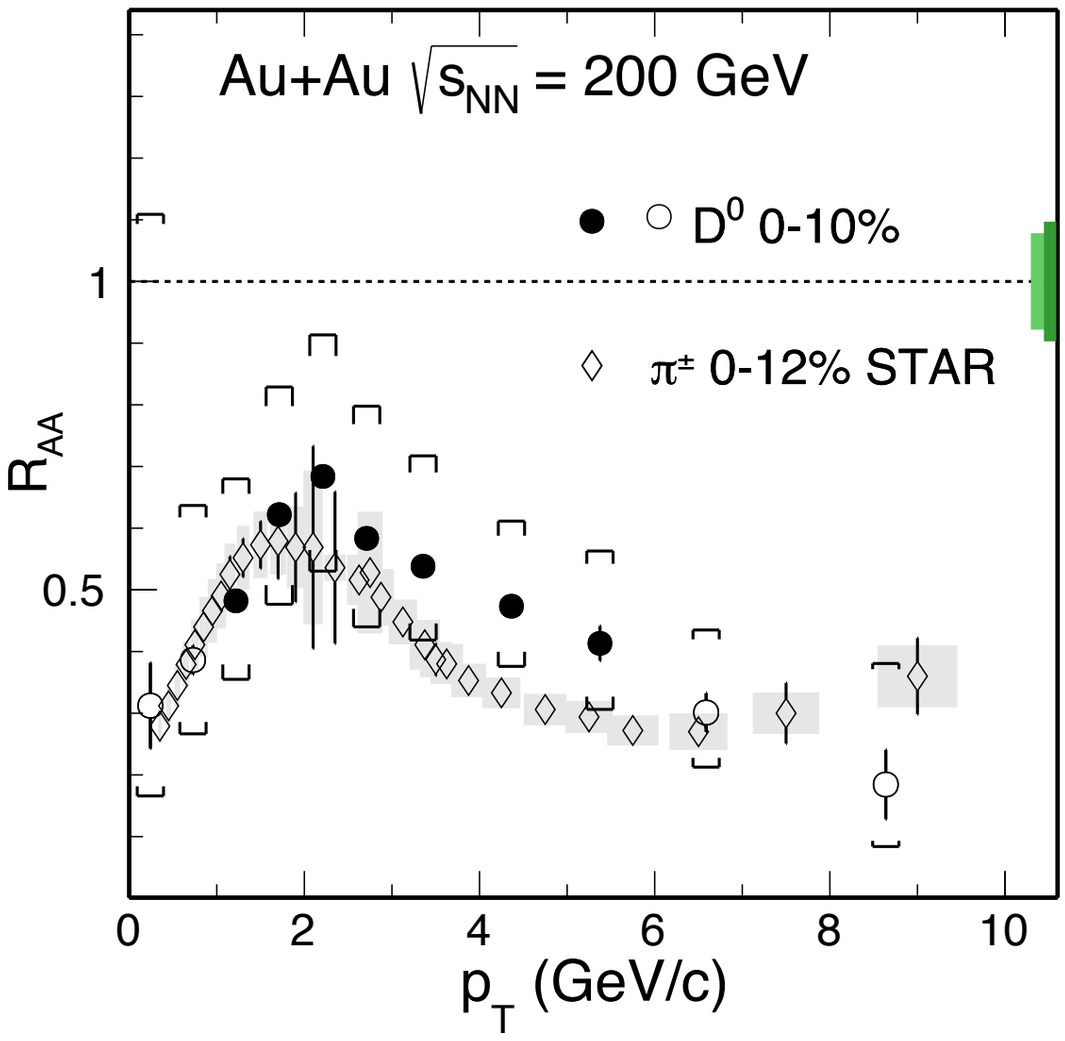
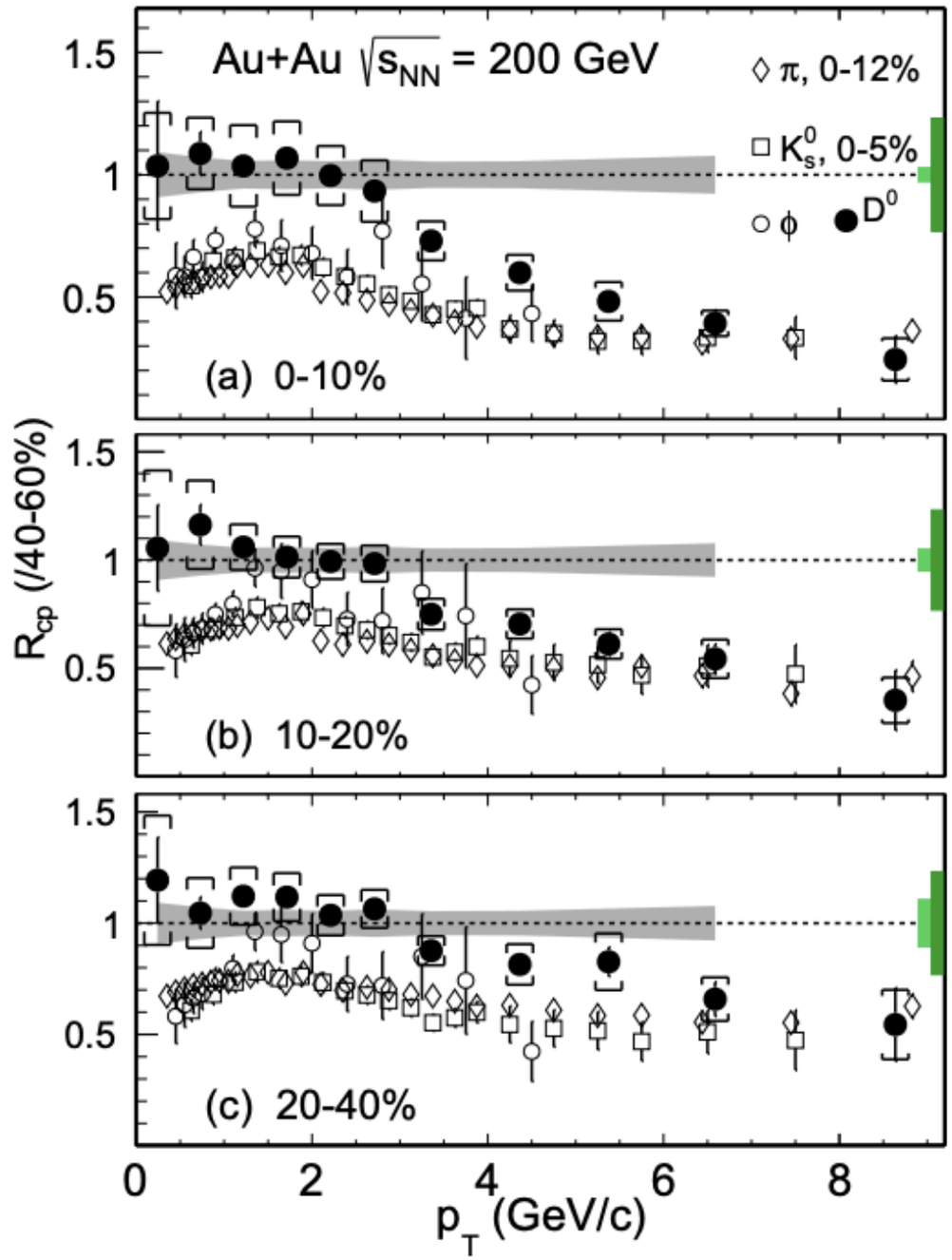
D^0 Meson R_{AA}/R_{CP} in A+A Collisions

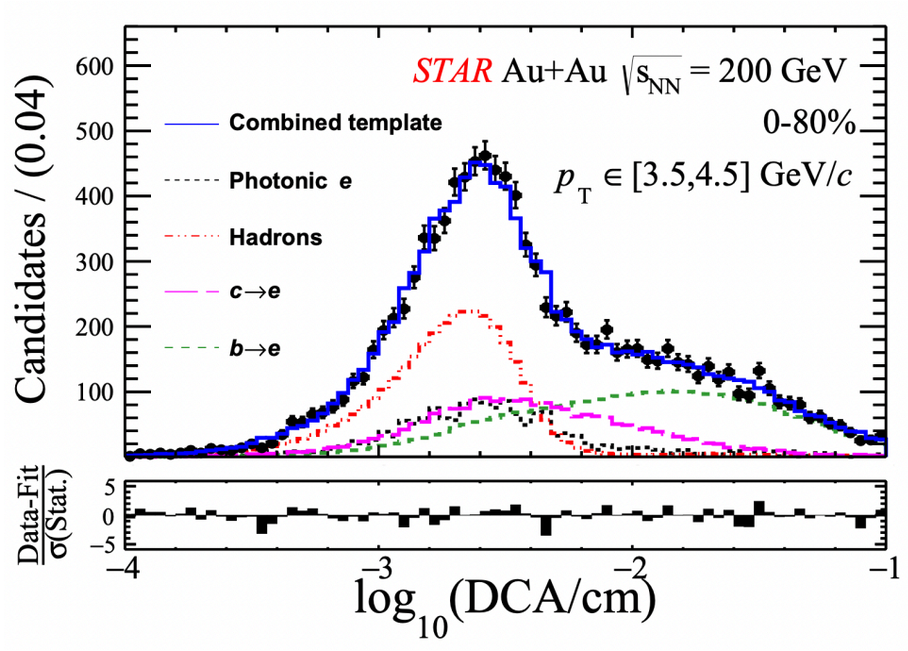


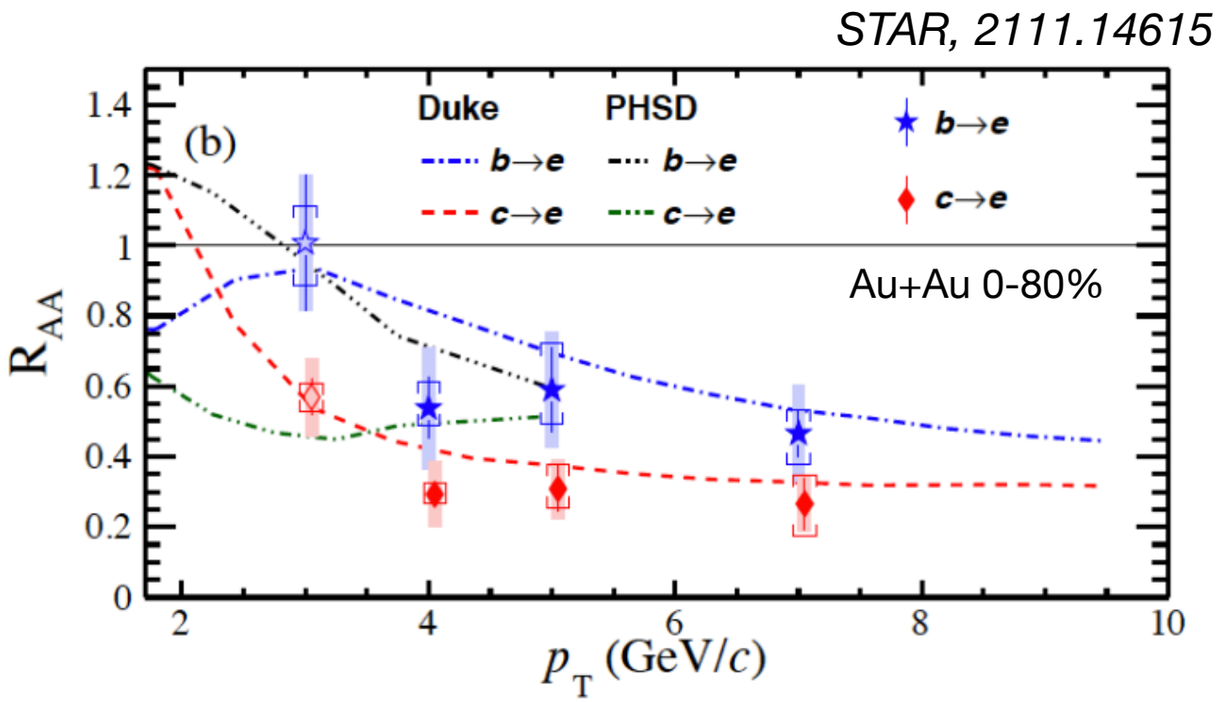
STAR, PRC 99 (2019) 034908

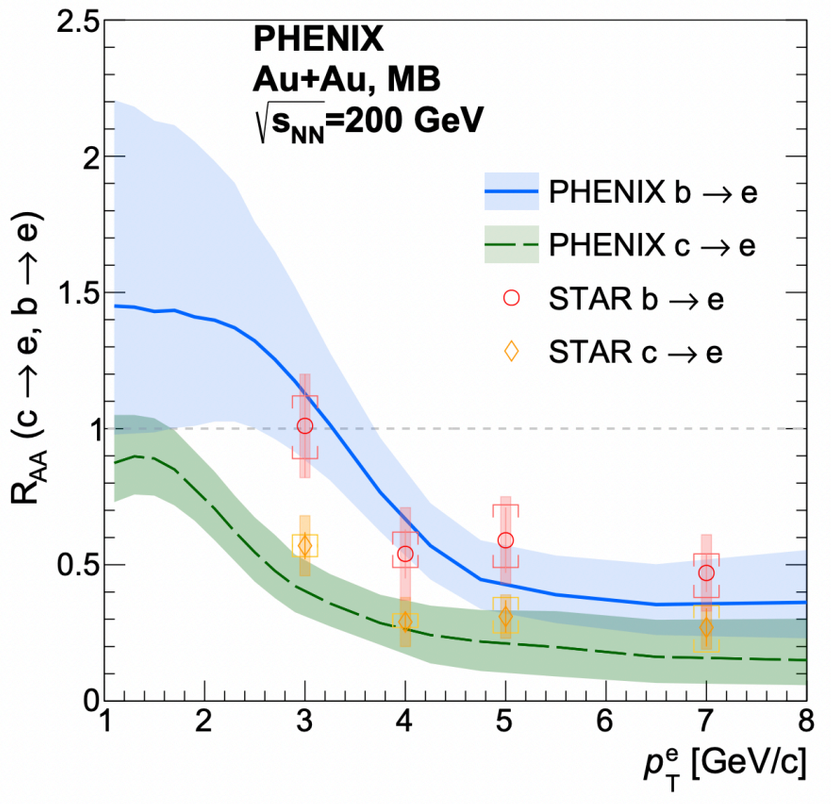


- $R_{AA}(D) \sim R_{AA}(h)$ at $p_T > \sim 4$ GeV/c
  - significant charm quark energy loss in the QGP medium
  - importance of radiative and collisional energy loss

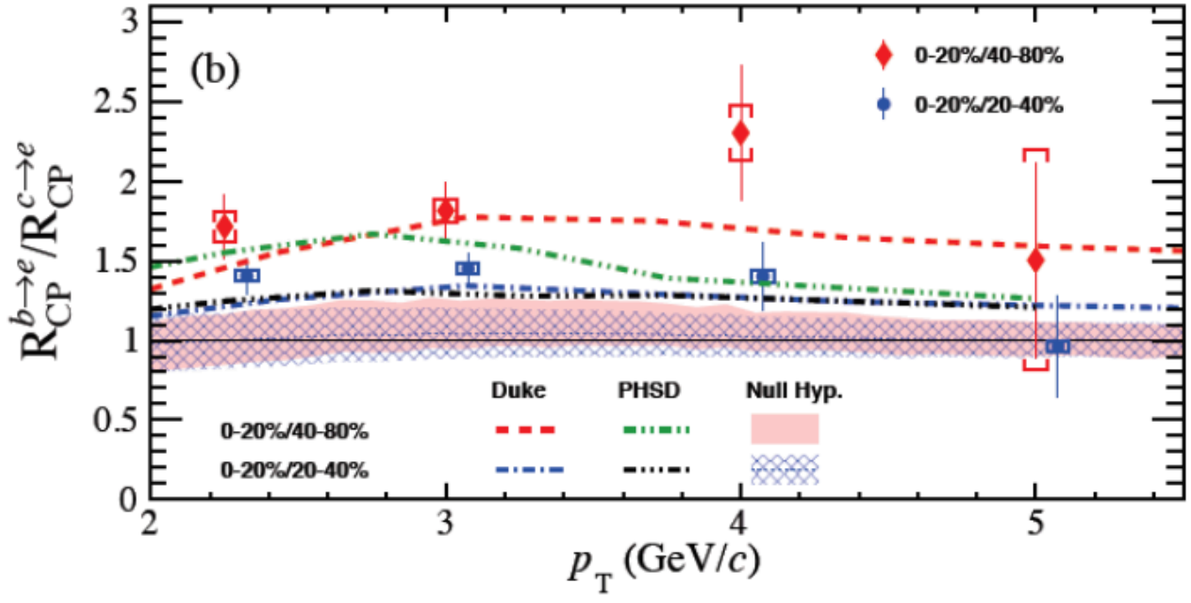
Bottom Suppression







PHENIX, 2203.17058



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

  mass hierarchy of parton energy loss

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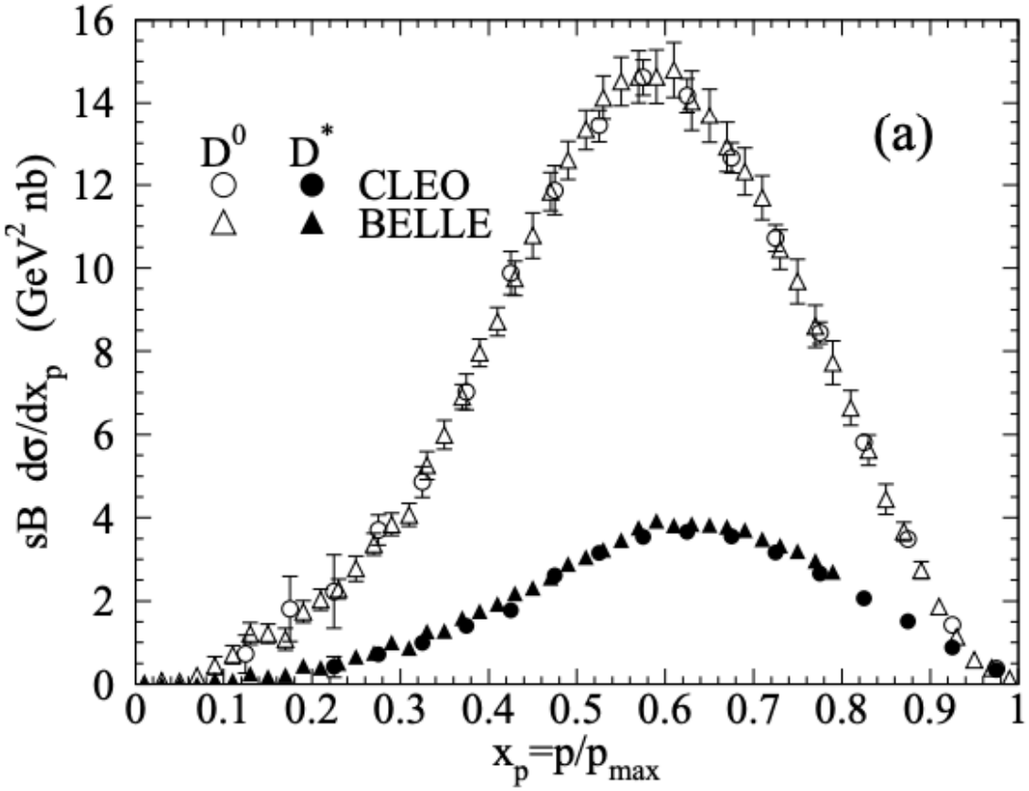
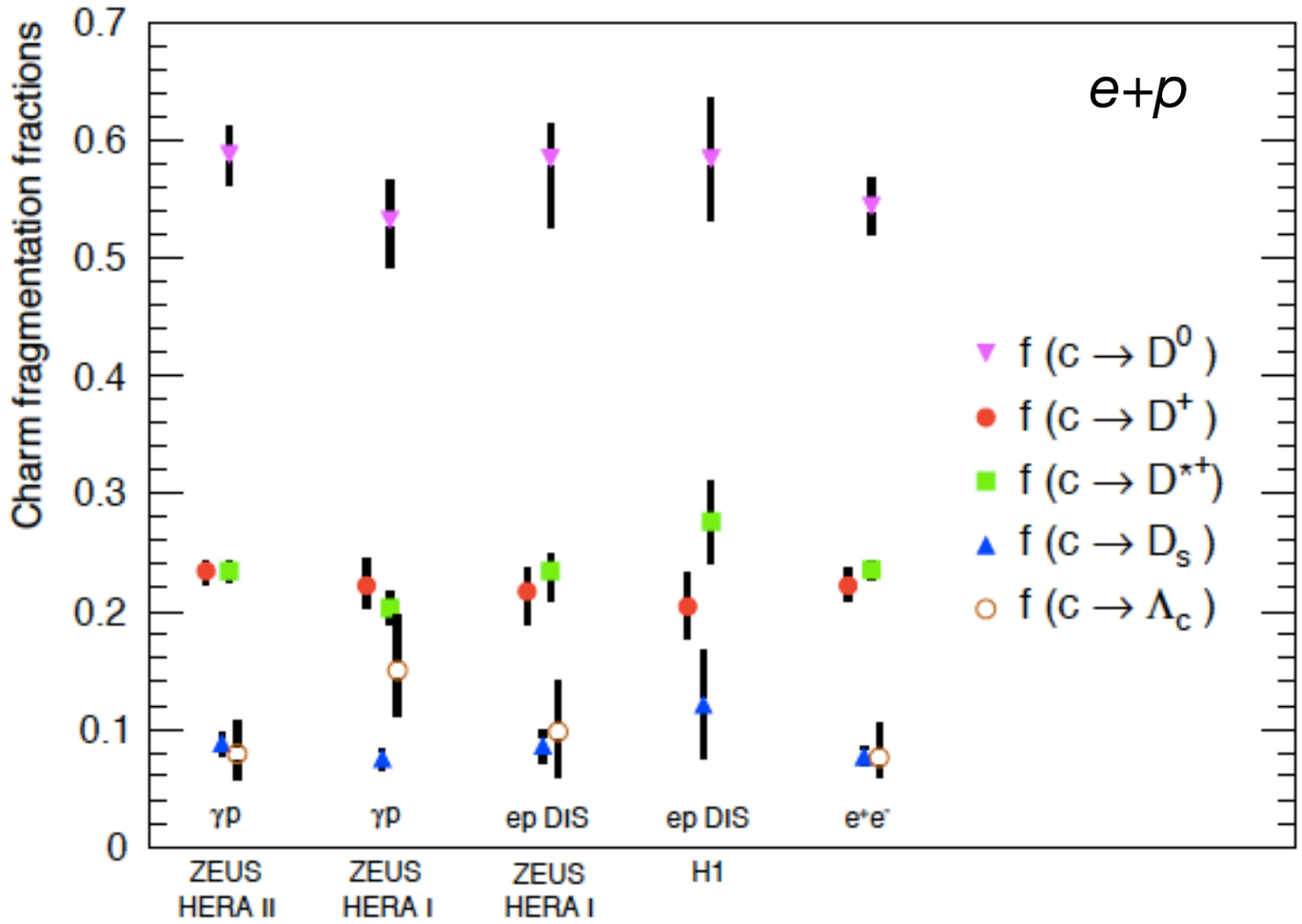
Charm Hadrochemistry in ee/ep

fragmentation measured in ee



PDG 2018



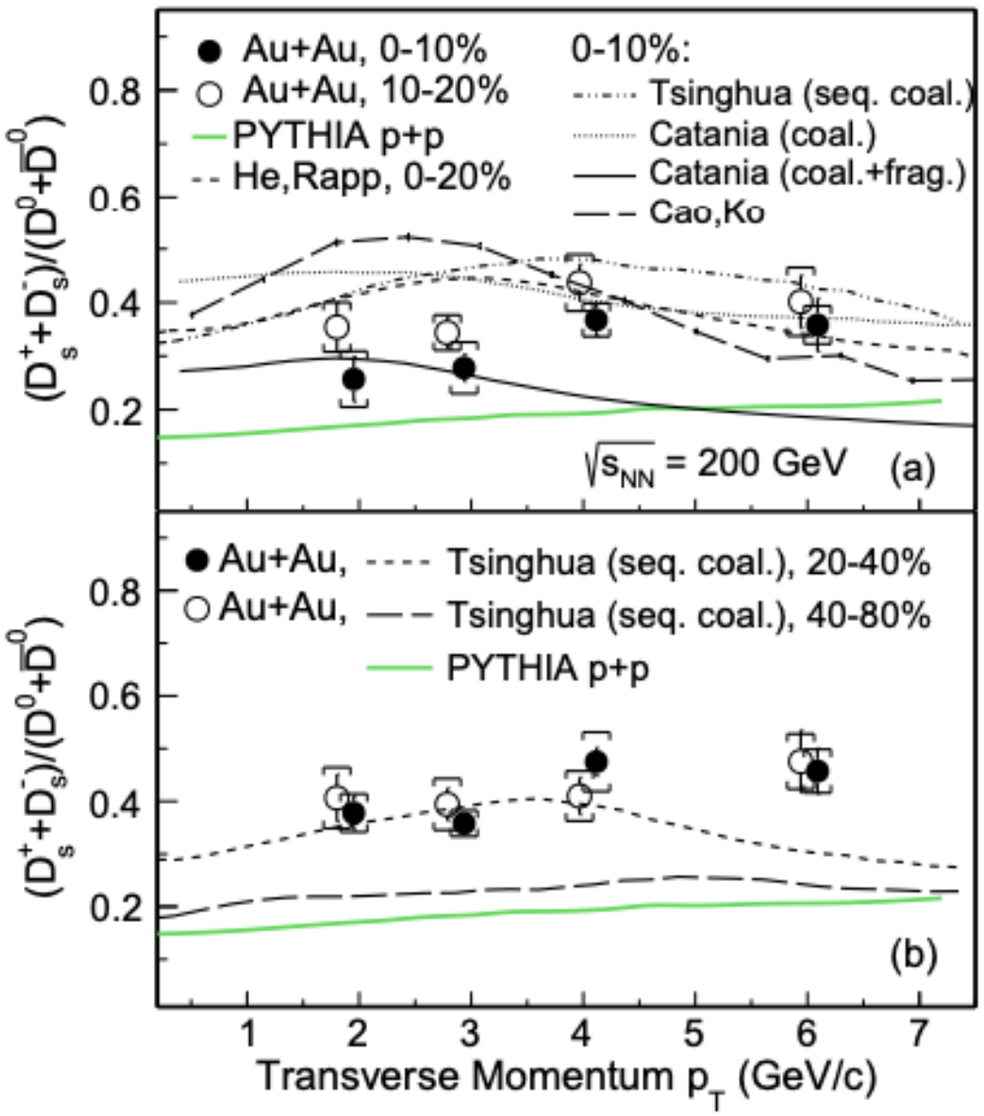
ZEUS, JHEP 1309 (2013) 058

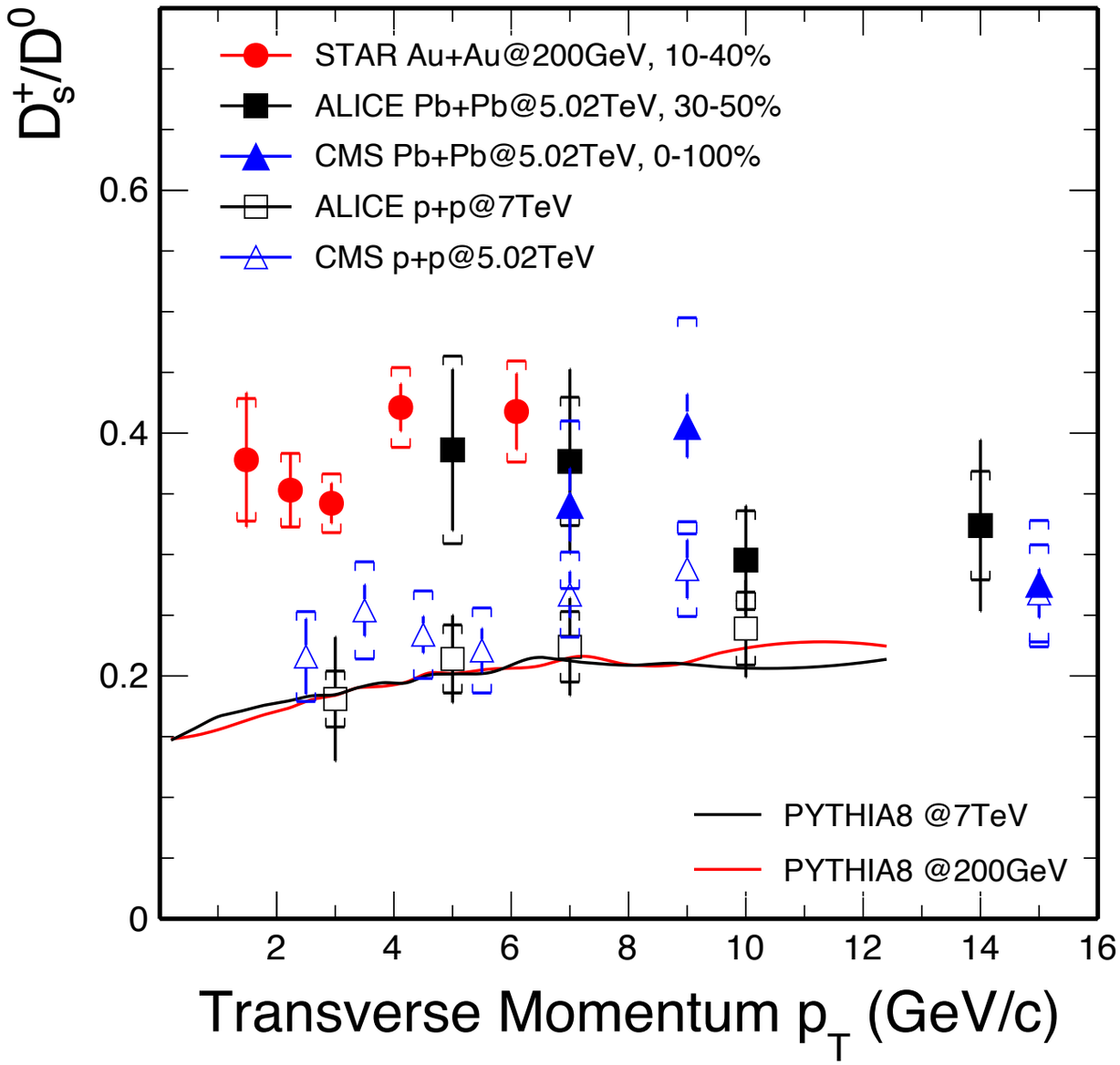
$$2\sigma_{c\bar{c}} = D^0 + D^+ + D_s^+ + \Lambda_c^+ \quad + \text{c.c.}$$

60.8% 24.0% 8.0% 6.2%

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

D_s^+/D^0 Enhancement in Heavy Ion Collisions

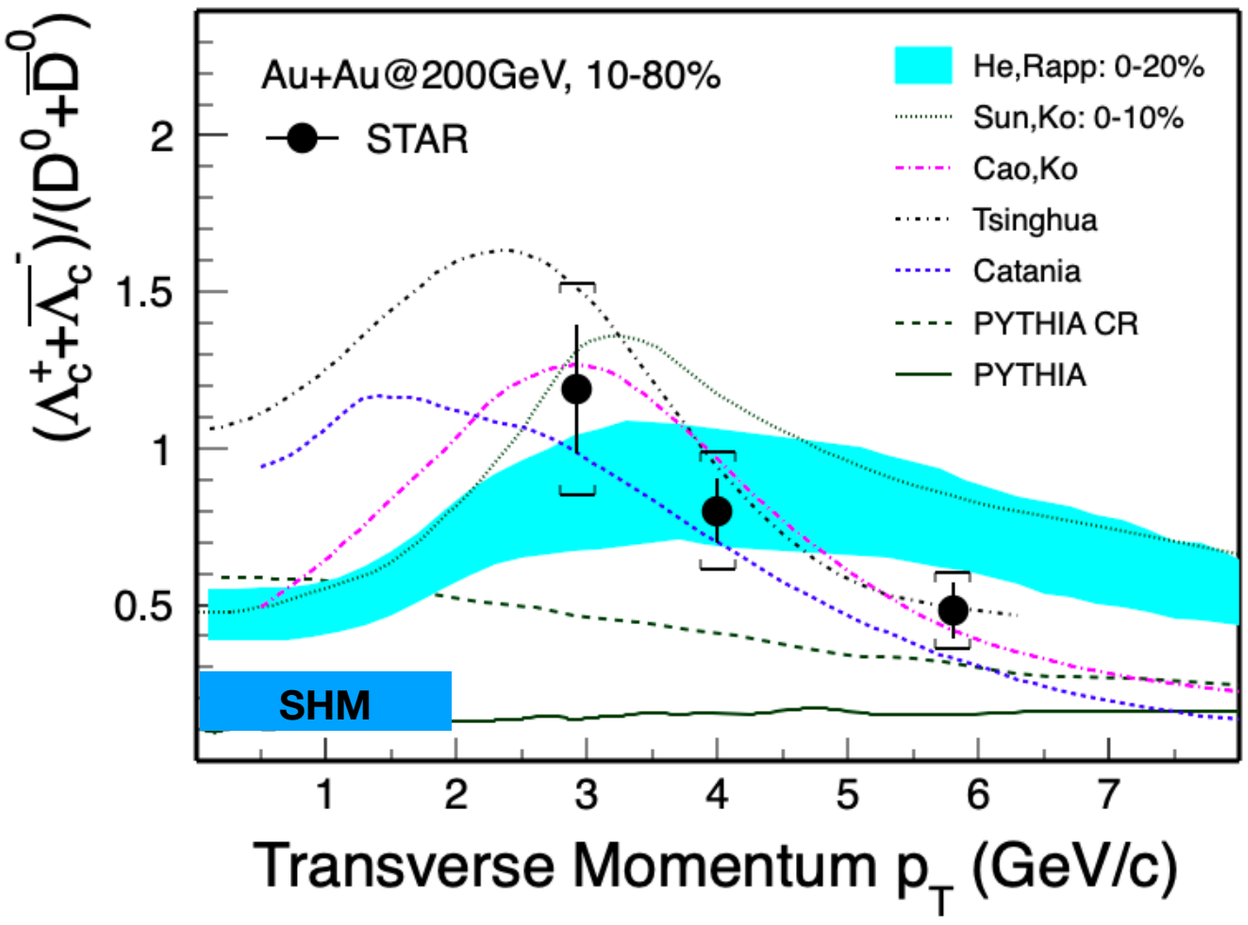


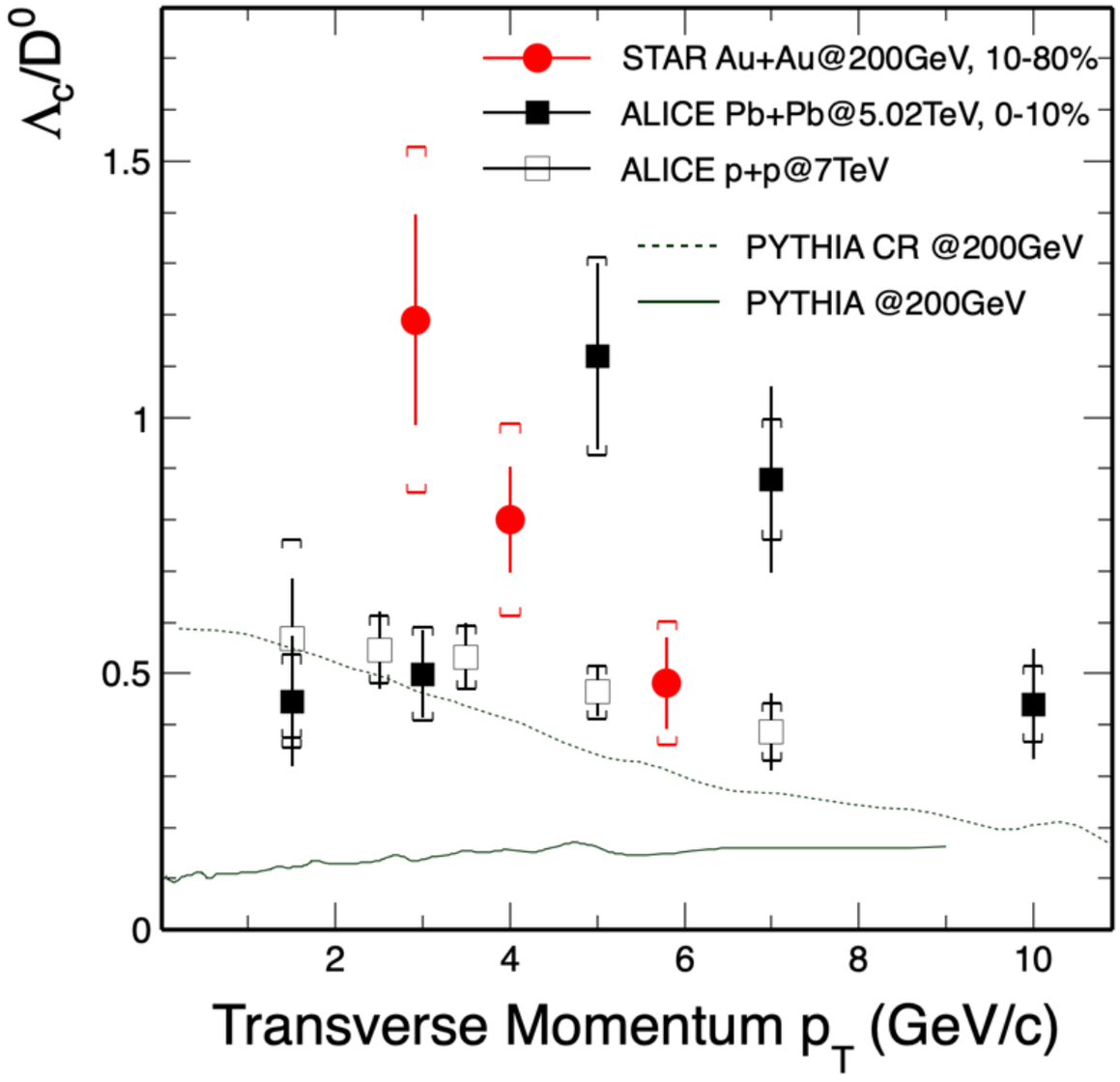


STAR, PRL 127 (2021) 092301, CMS, PAS-HIN-18-017
ALICE, JHEP 1810 (2018) 174, EPJC77 (2017) 550

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

Λ_c^+/D^0 Enhancement in Heavy Ion Collisions





STAR, PRL 124 (2020) 172301
ALICE, JHEP 04 (2018) 108, 2112.08156
CMS, PLB 803 (2020) 135328

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

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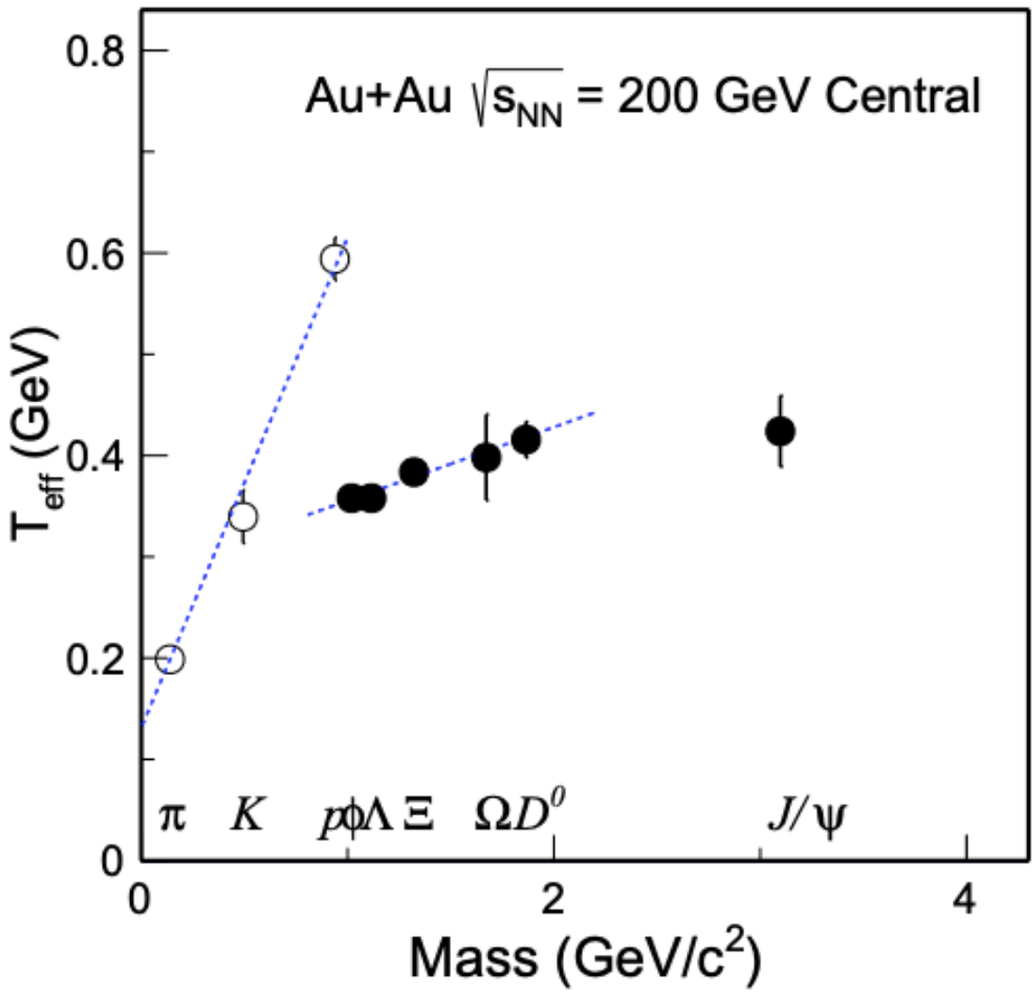
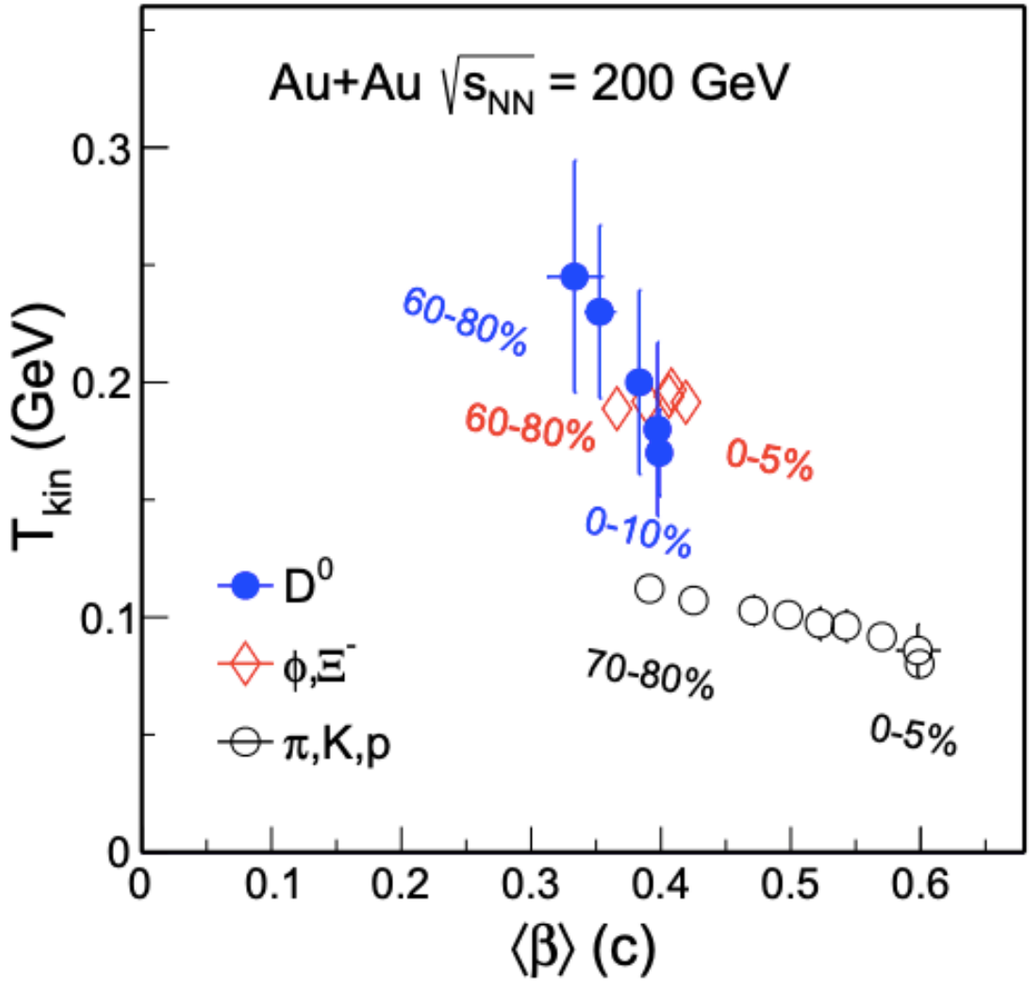
D^0 Radial Flow

m_T exponential fits



(Tsallis) Blast-Wave fits

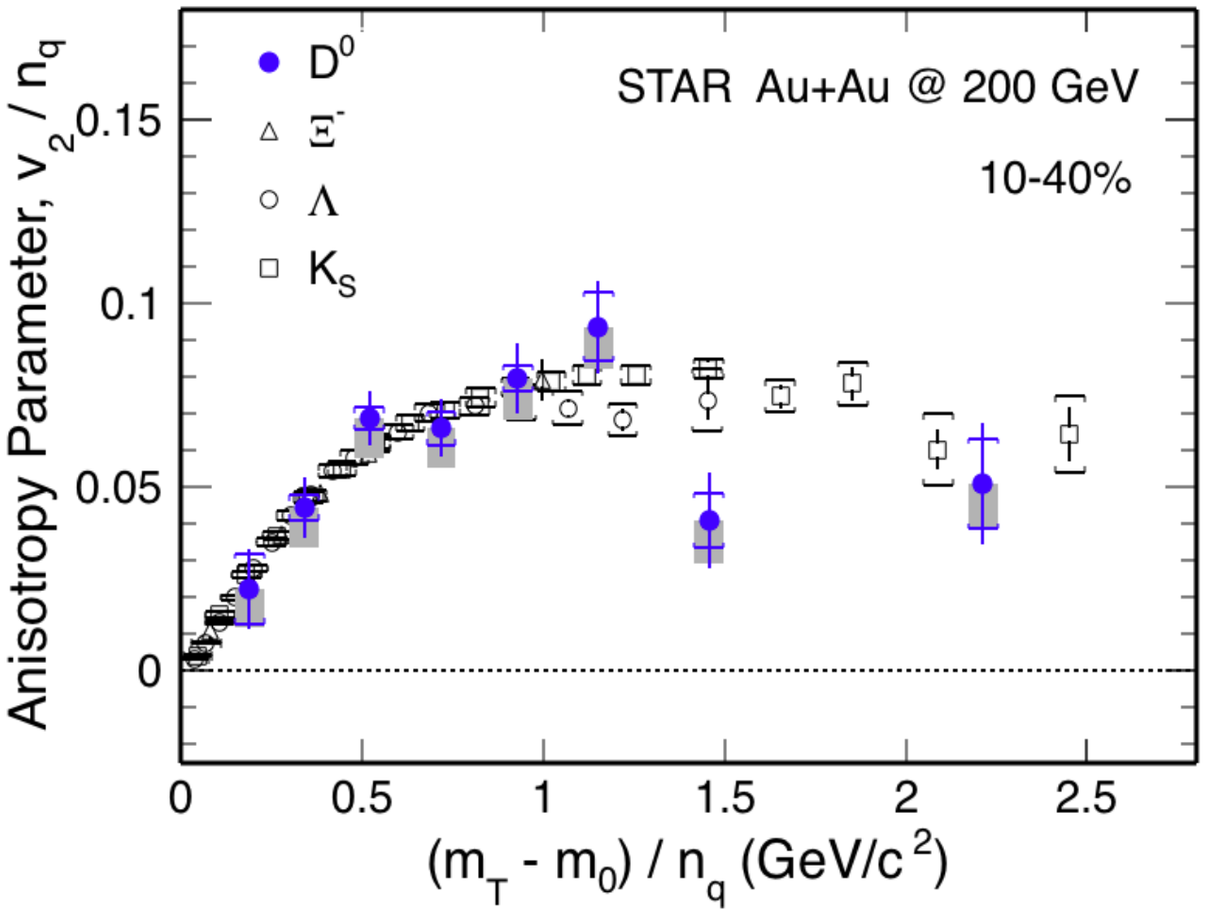


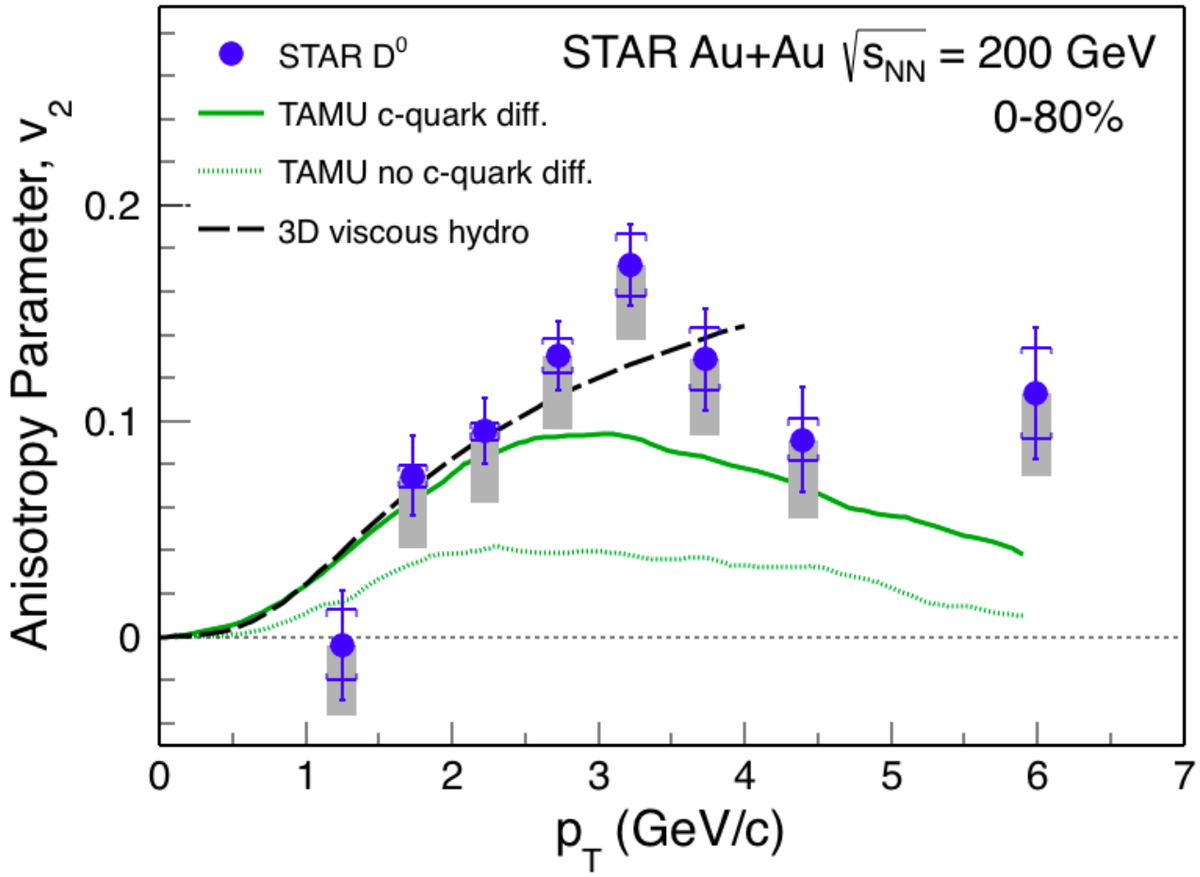
- T-slope parameter (expo fit to m_T spectra) follows the similar trend as other strange particles
- Similar to multi-strange hadrons, D^0 mesons kinetically freeze out earlier than light hadrons

  - collectivity from partonic stage interactions

D^0 Meson v_2 in A+A Collisions

STAR, PRL 118 (2017) 212301

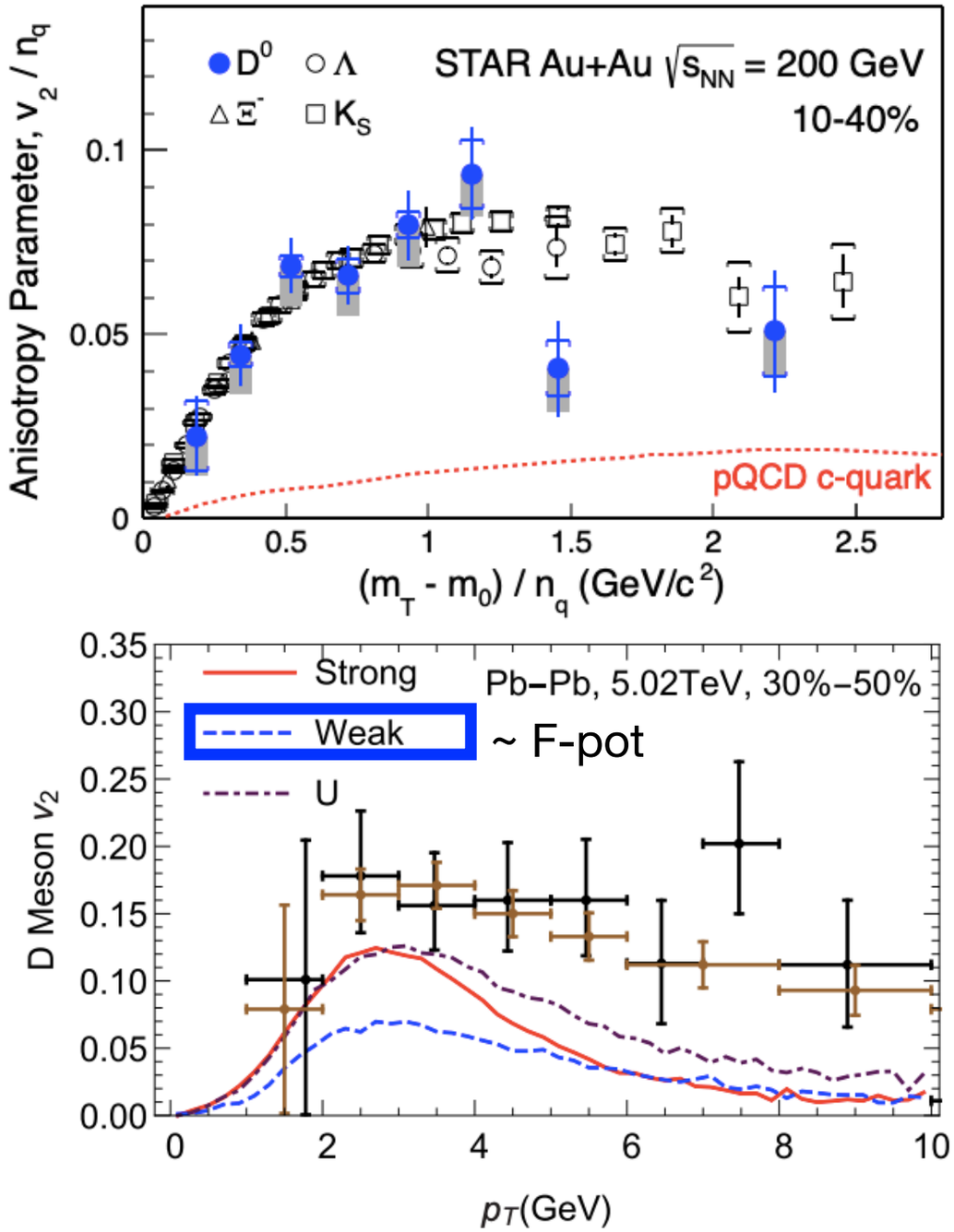




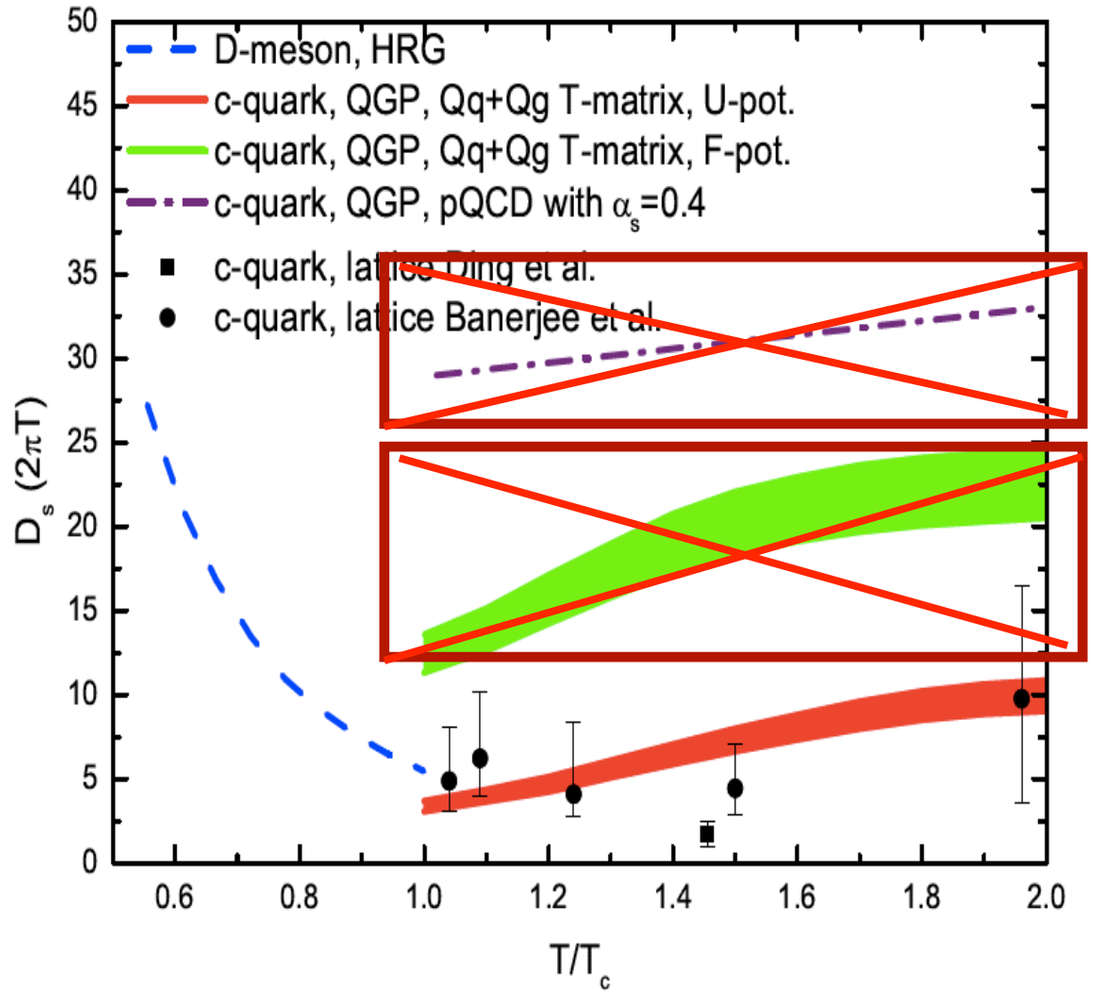
- v_2(D) follows the $(m_T-m_0)/n_q$ scaling as light hadrons

  Evidence of charm quarks reaching local thermal equilibrium!
- 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^0 v_2 Compared with Model Calculations

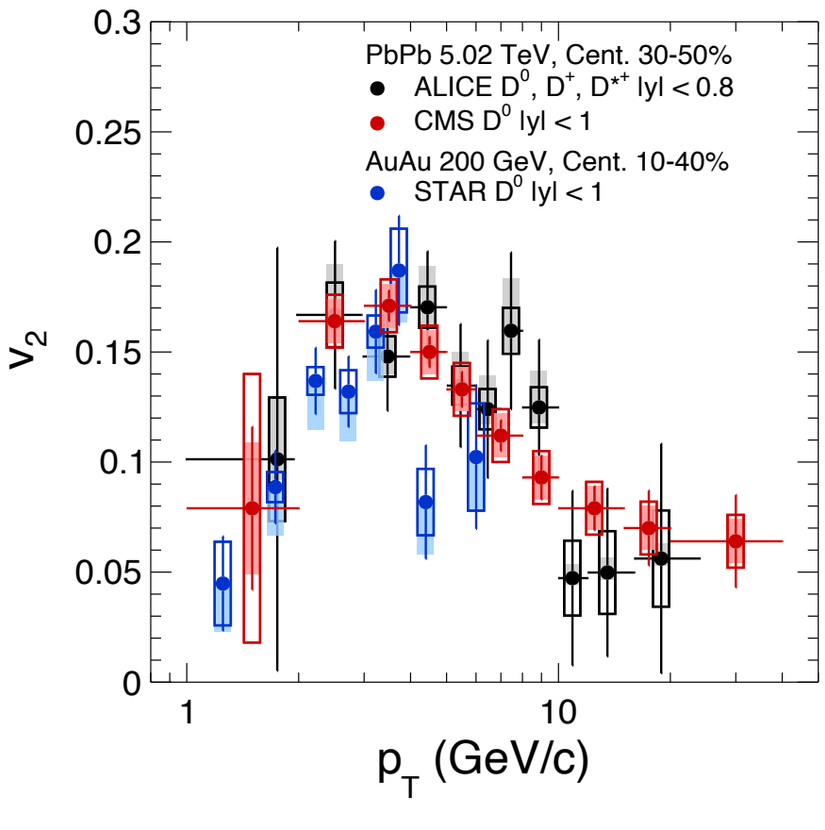


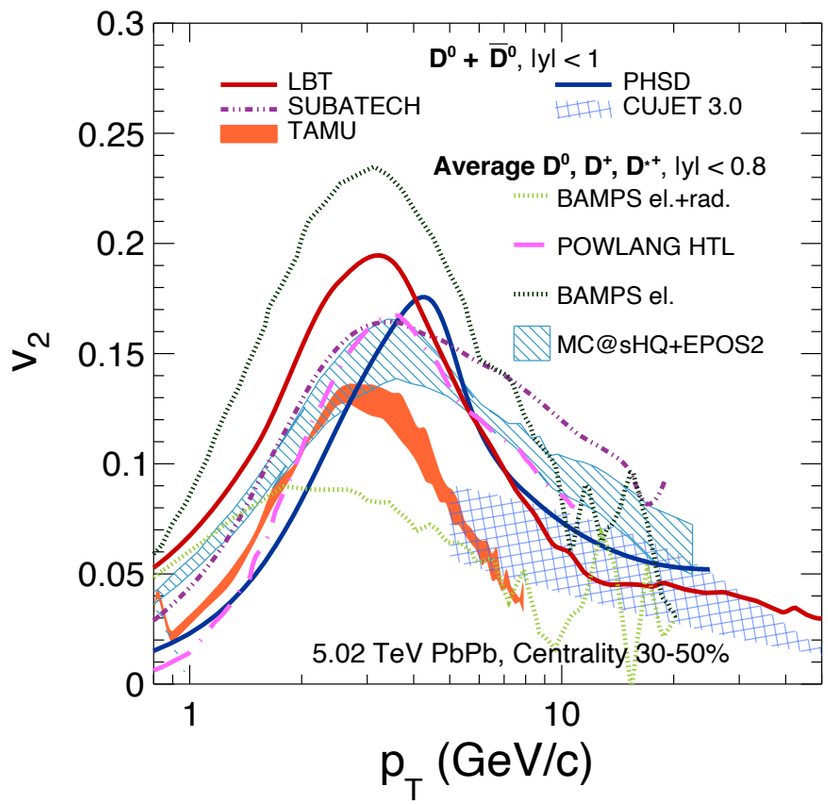
pQCD c-quark (b=7fm):
R. Rapp & H. van Hees, arXiv: 0903.1096
T-Matrix with F-pot:
S. Liu et al, PRC 99 (2019) 055201

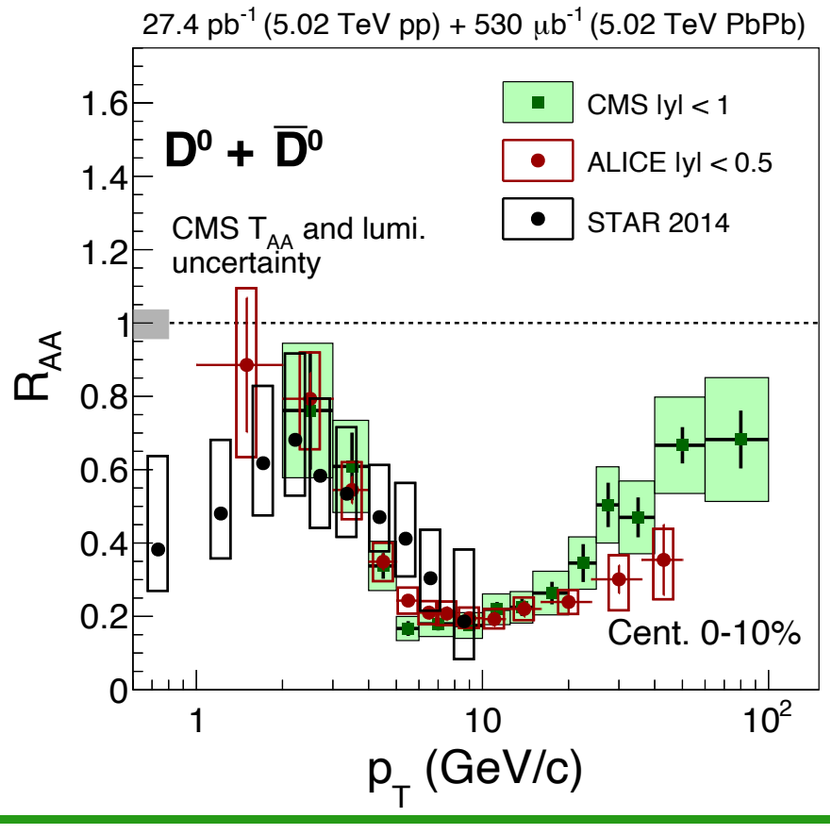


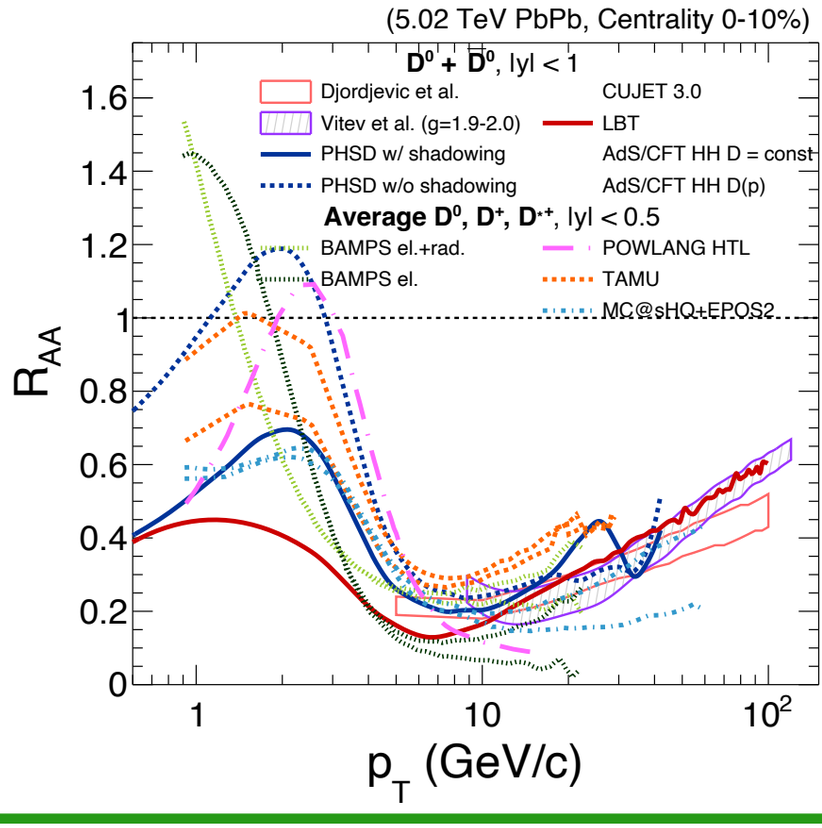
- pQCD calculation and T-Matrix with F-pot. cannot reproduce the data
  - *heavy quarkonium R_{AA} data disfavors F-pot.*

Summary of D^0 v_2 and R_{AA} at RHIC and LHC



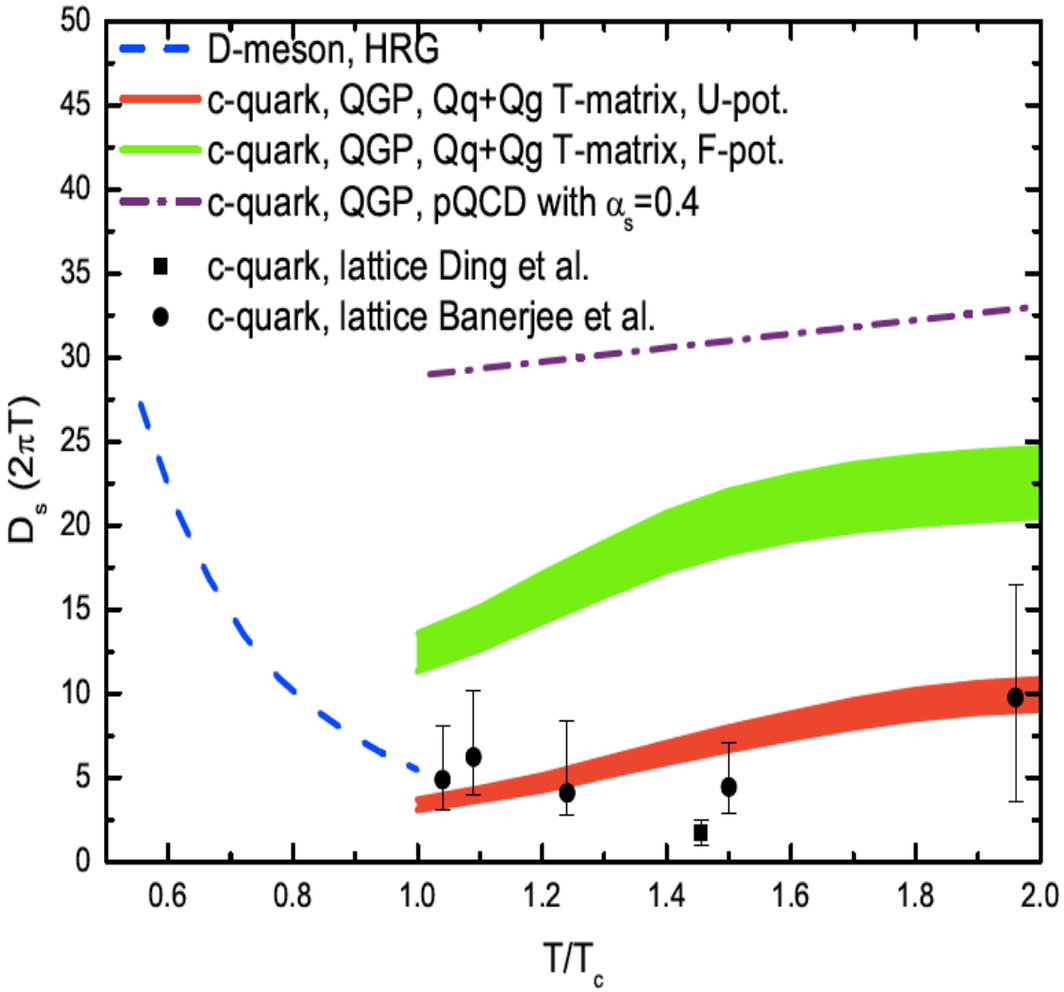




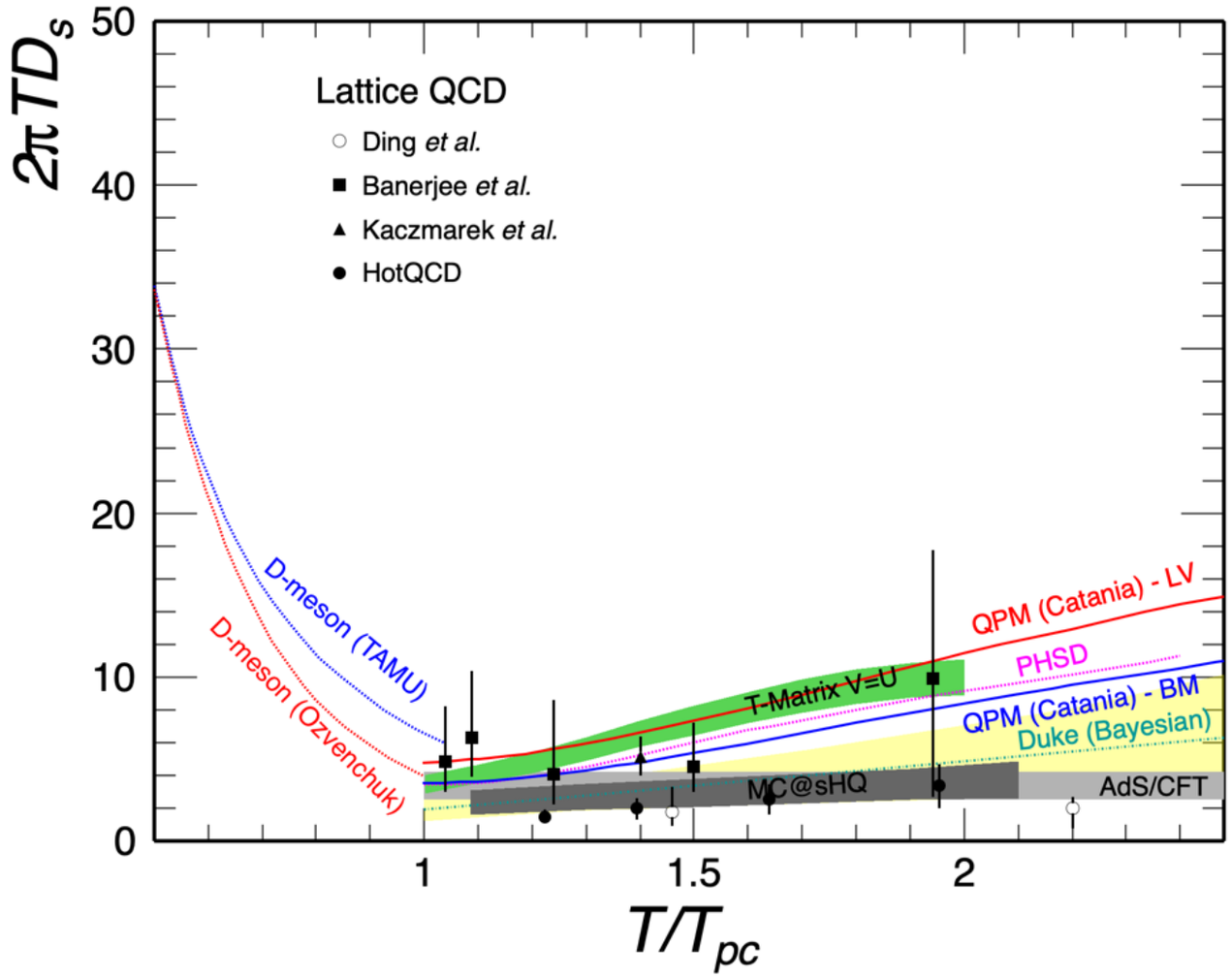


Charm Spatial Diffusion Coefficient

2015



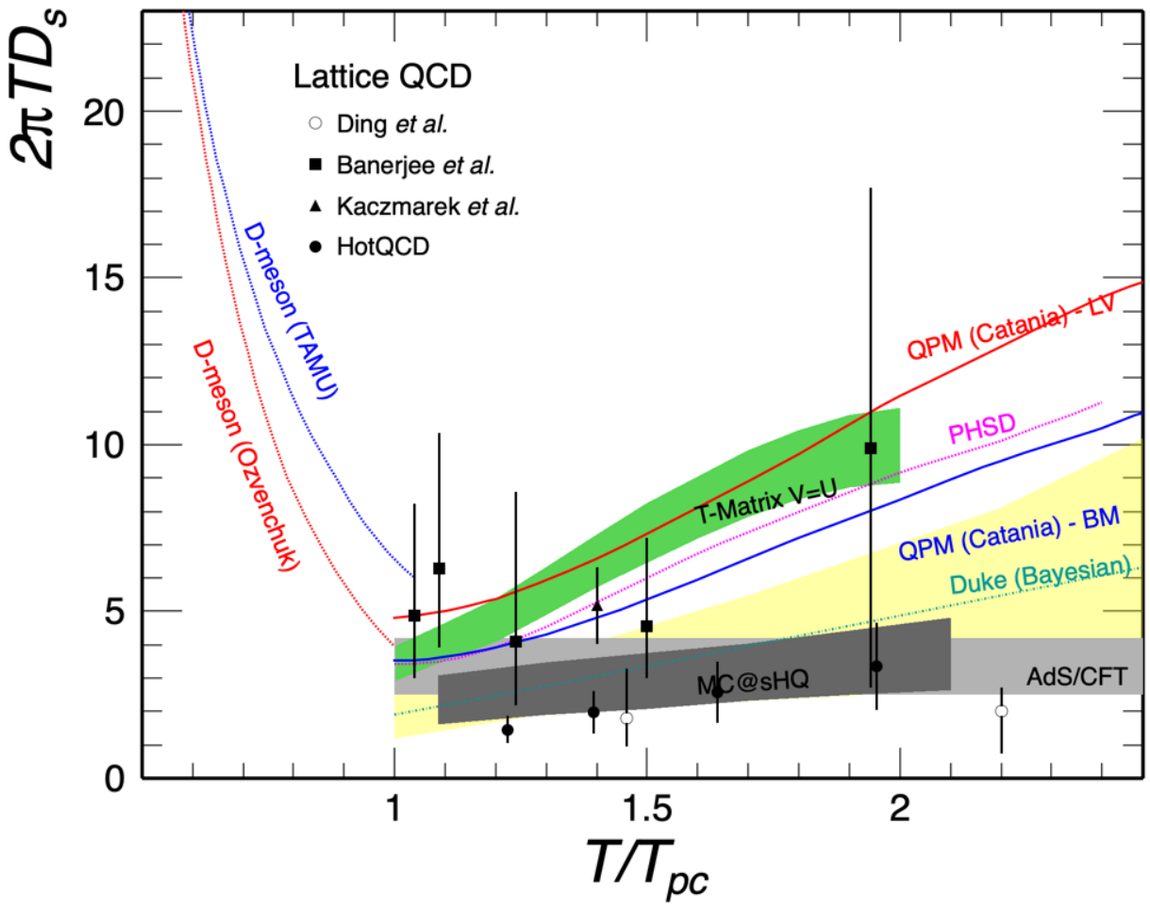
2019

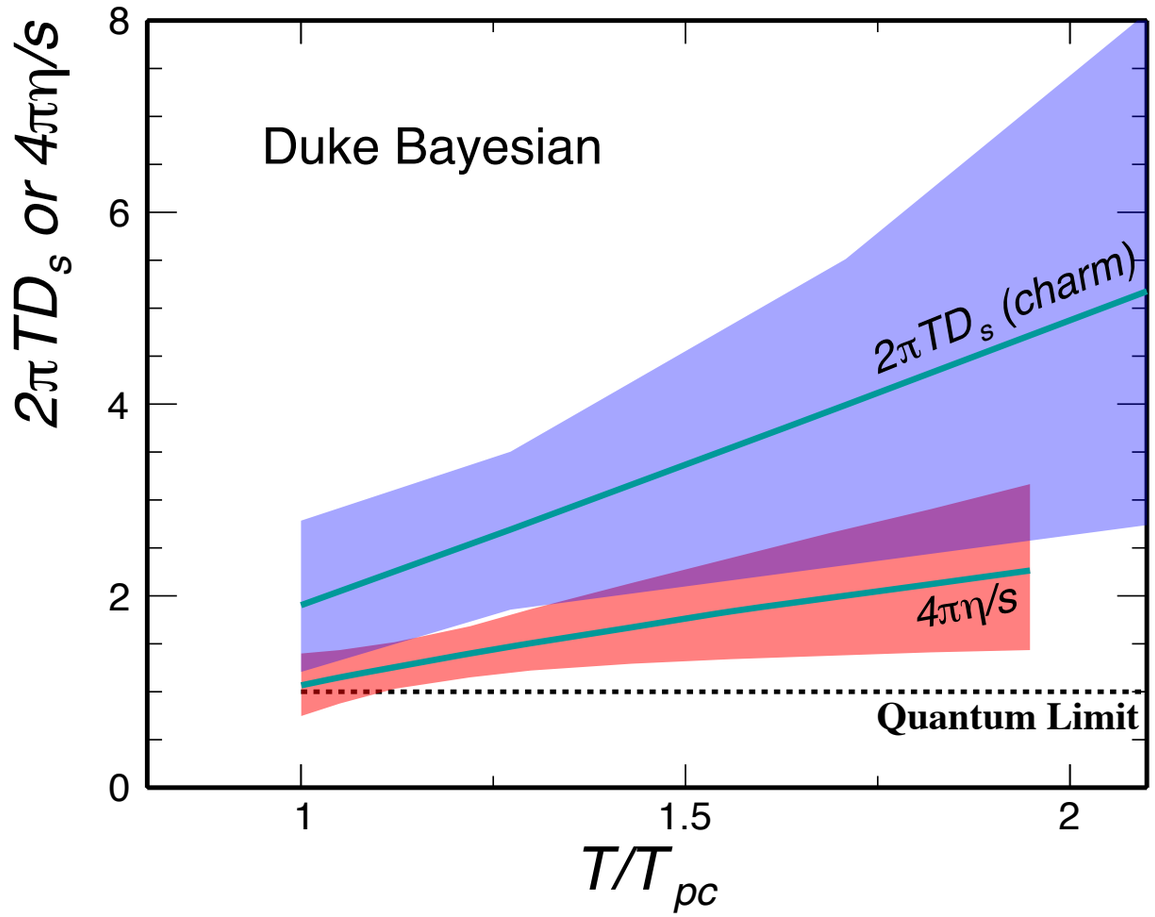


XD, Y-J Lee & R. Rapp, Ann. Rev. Nucl & Part. Sci. 69 (2019) 417
HotQCD, 2022

Strongly interacting QGP!

sQGP Transport Parameters





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

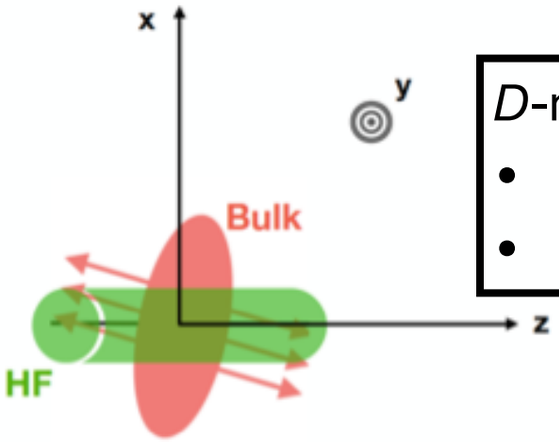
η/s: *J. Bernhard et al, Nature Physics 115 (2019) 1113*

- Charm quark $2\pi TD_s$ **~ 2-5** at near T_c
  - consistent with quenched lattice calculations

momentum/temperature dependence? charm vs. bottom universality?

D^0 v_1 - T-dependent sQGP Properties

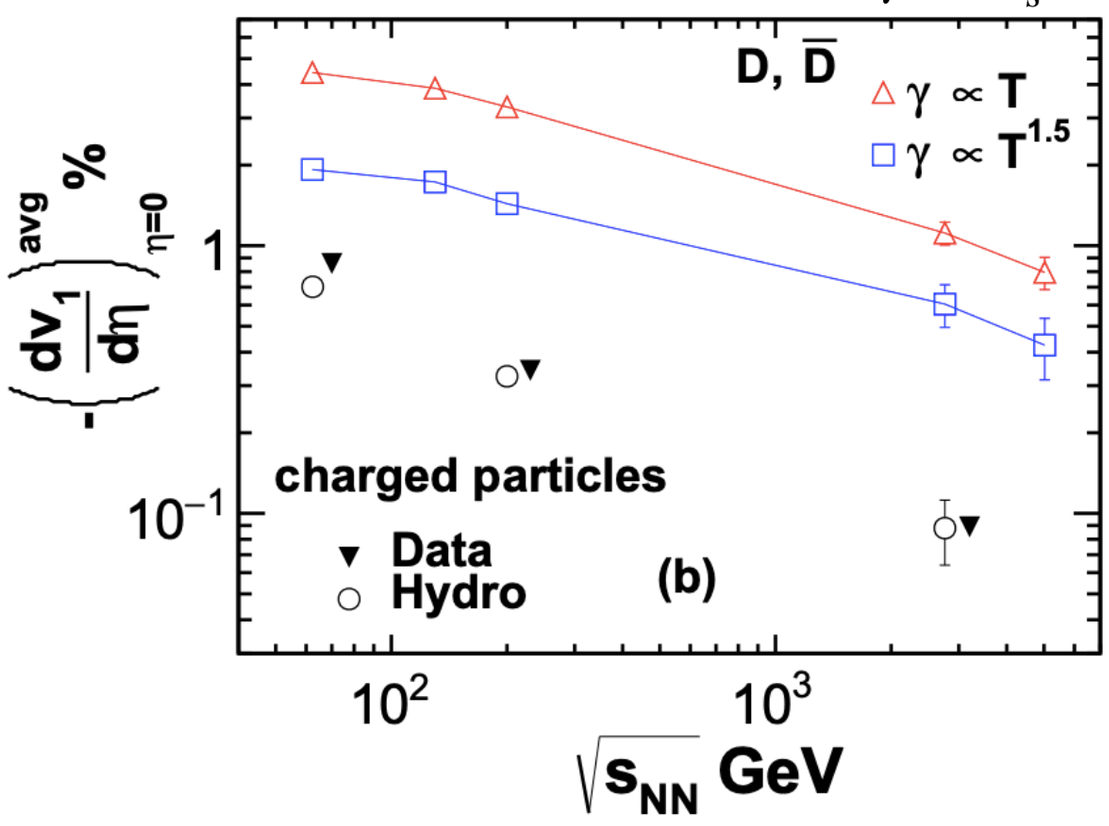
S. Chatterjee & P. Bozek, PRL 120 (2018) 192301



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

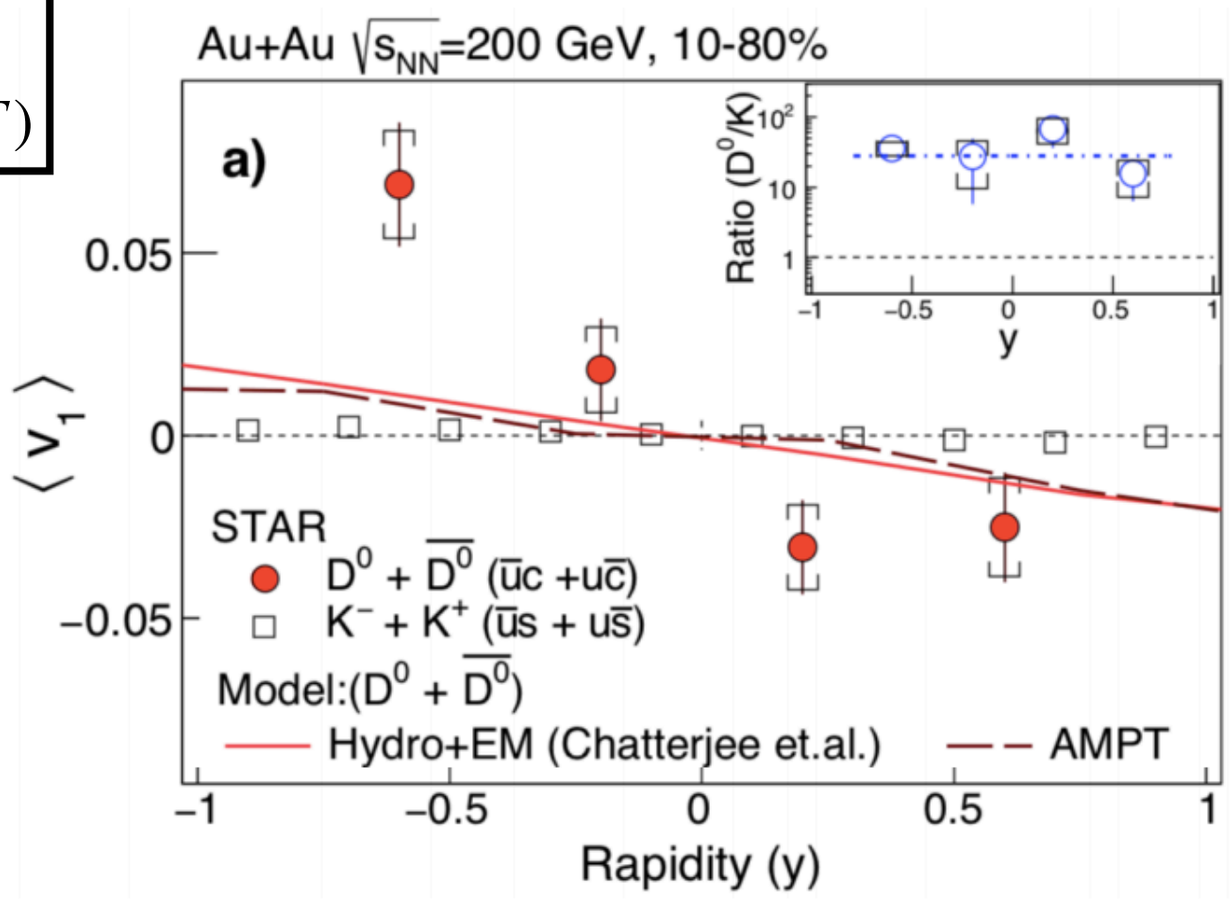
Hydro model

$\gamma = D_s/ET$



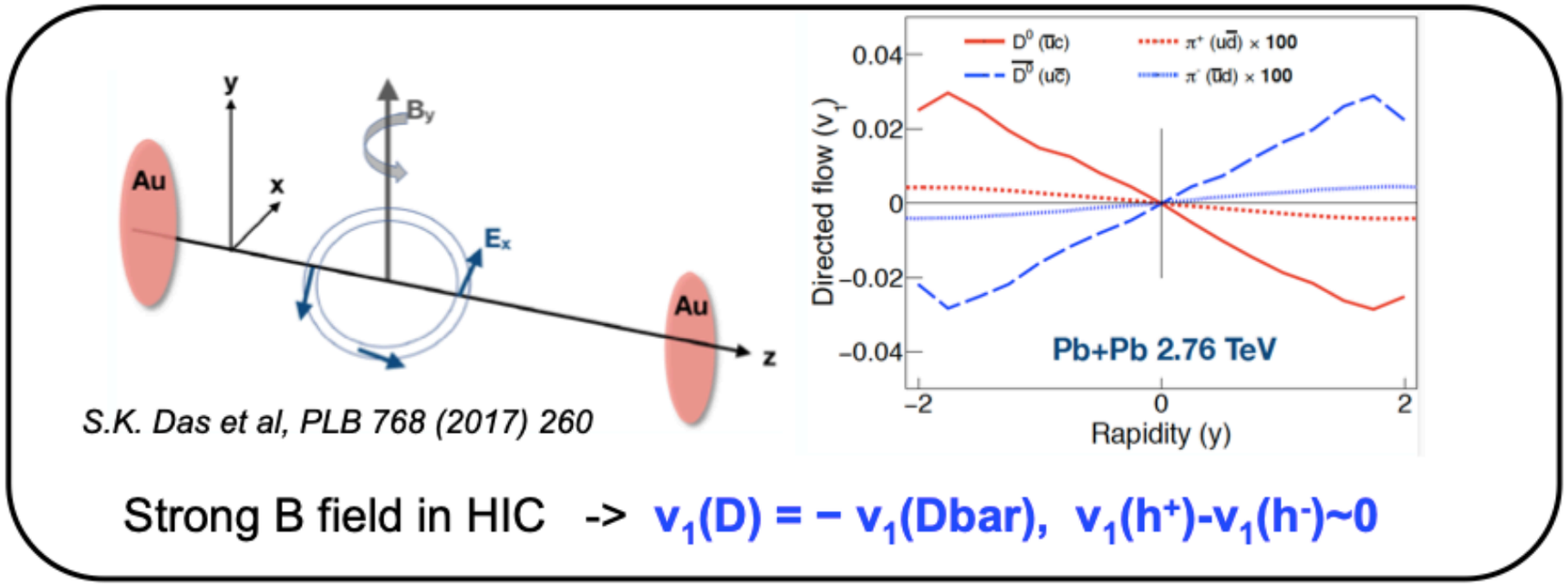
S. Chatterjee & P. Bozek, PLB 798 (2019) 134955

STAR, PRL 123 (2019) 162301



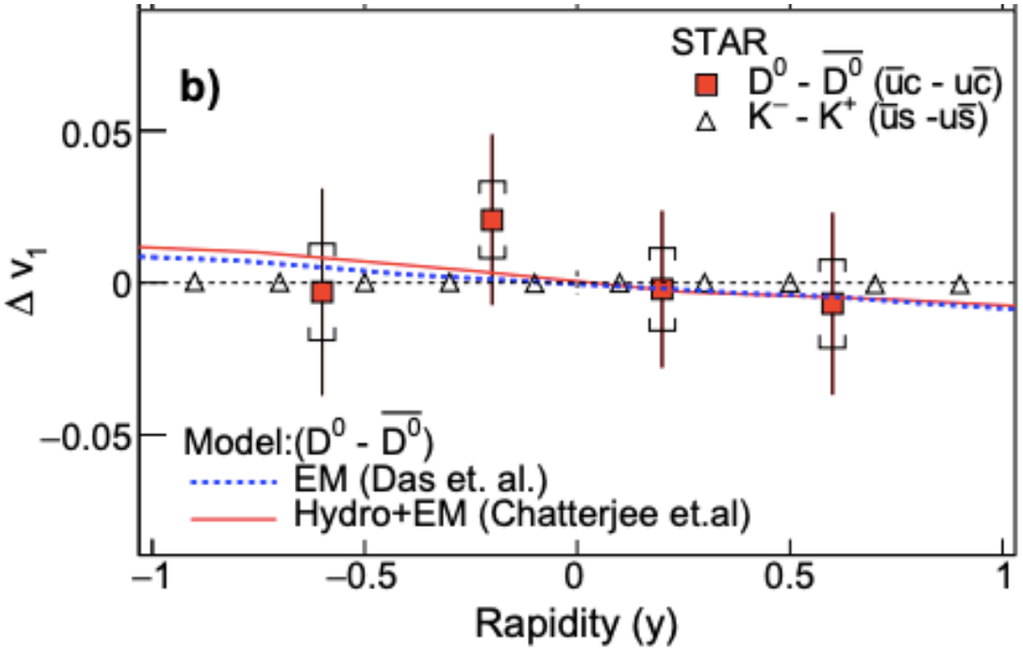
- $v_1(D) \gg v_1(h)$
  - Constraints on T-dependence of HQ diffusion coefficient

$D^0/\overline{D}^0$ v_1 difference - Access to Initial B Field

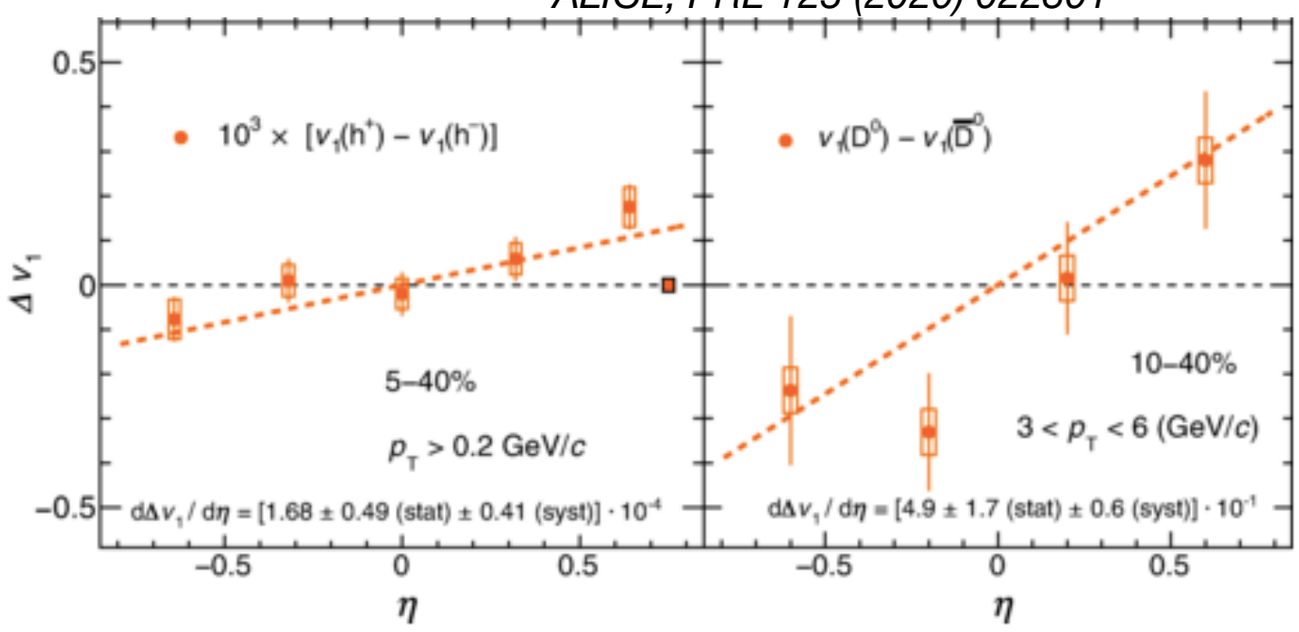


Strong B field in HIC -> $v_1(D) = -v_1(\overline{D})$, $v_1(h^+)-v_1(h^-)\sim 0$

STAR, PRL 123 (2019) 162301

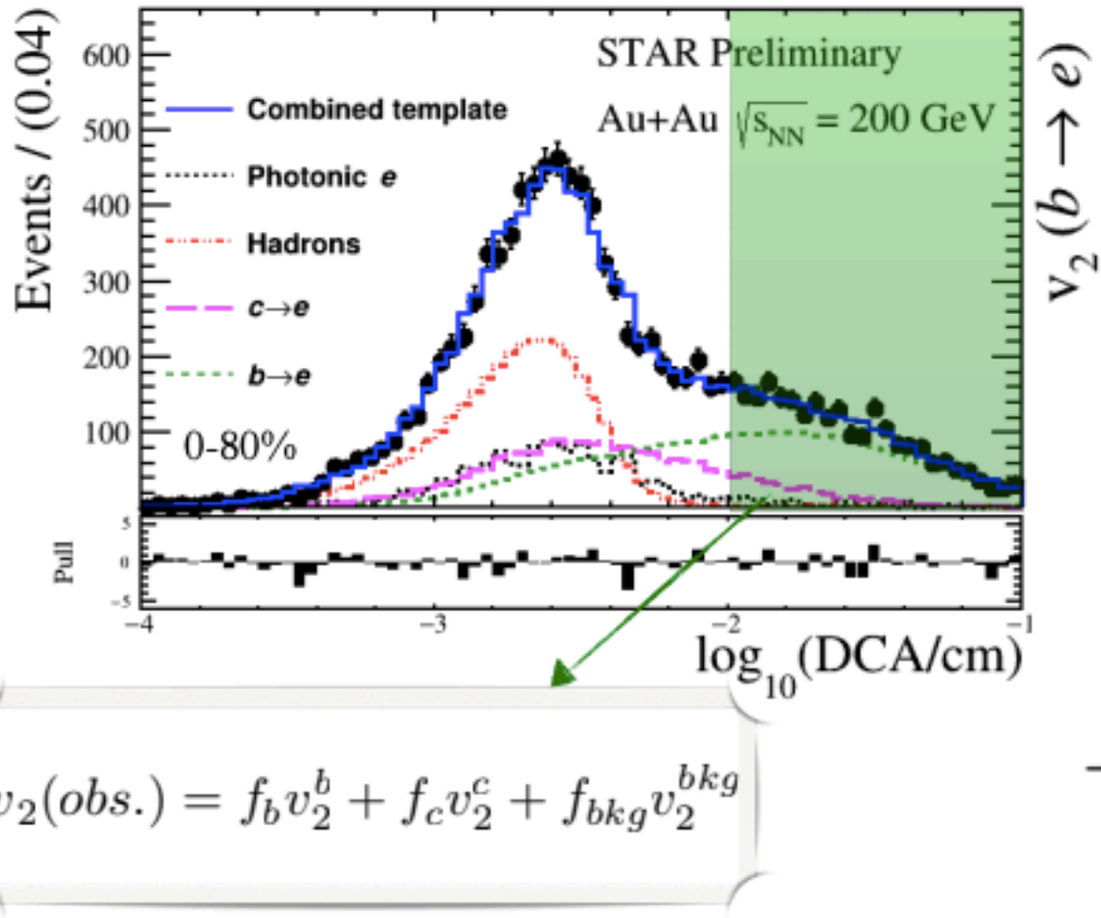


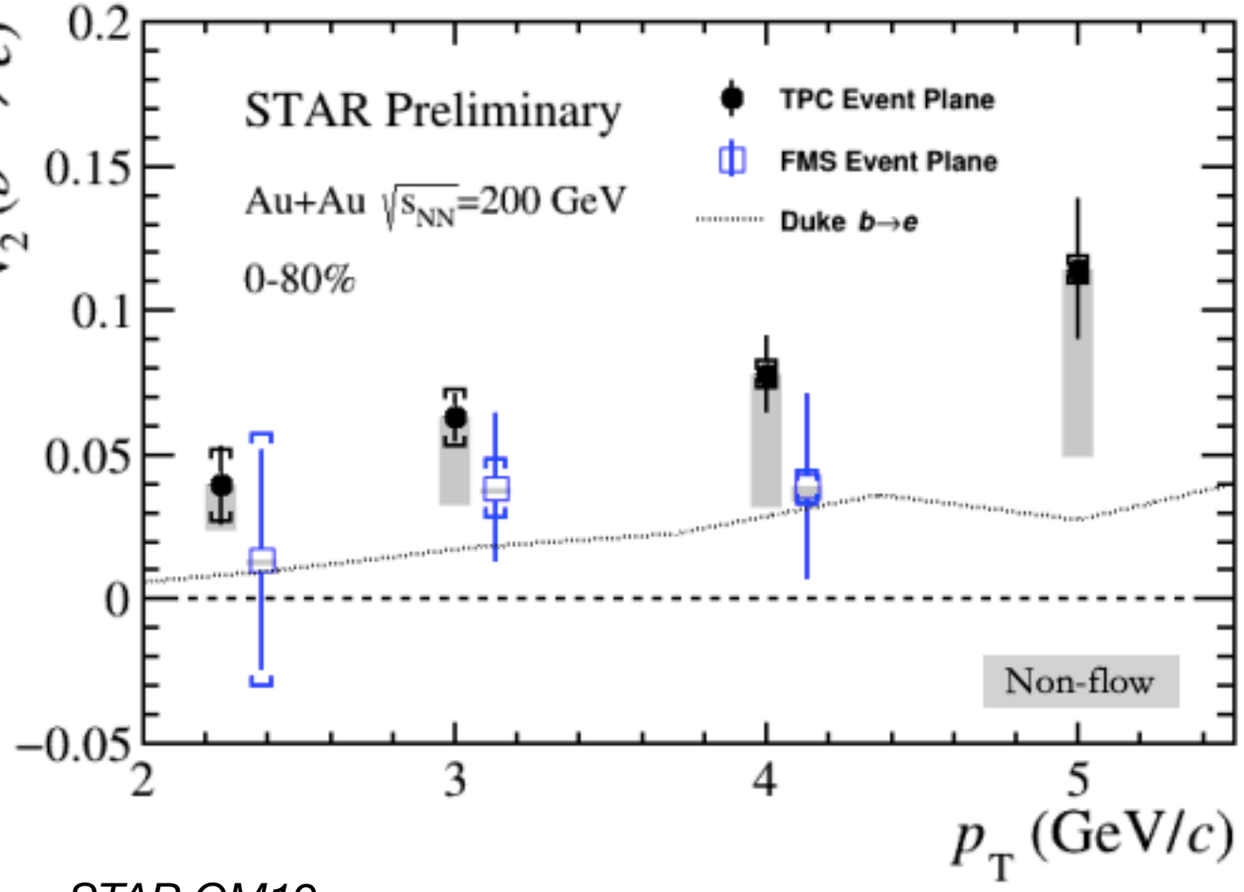
ALICE, PRL 125 (2020) 022301



STAR: inconclusive due to experimental uncertainty
ALICE: significant difference, however, opposite sign w.r.t the prediction
→More detailed investigation needed for better understanding

First Look at the Bottom v_2





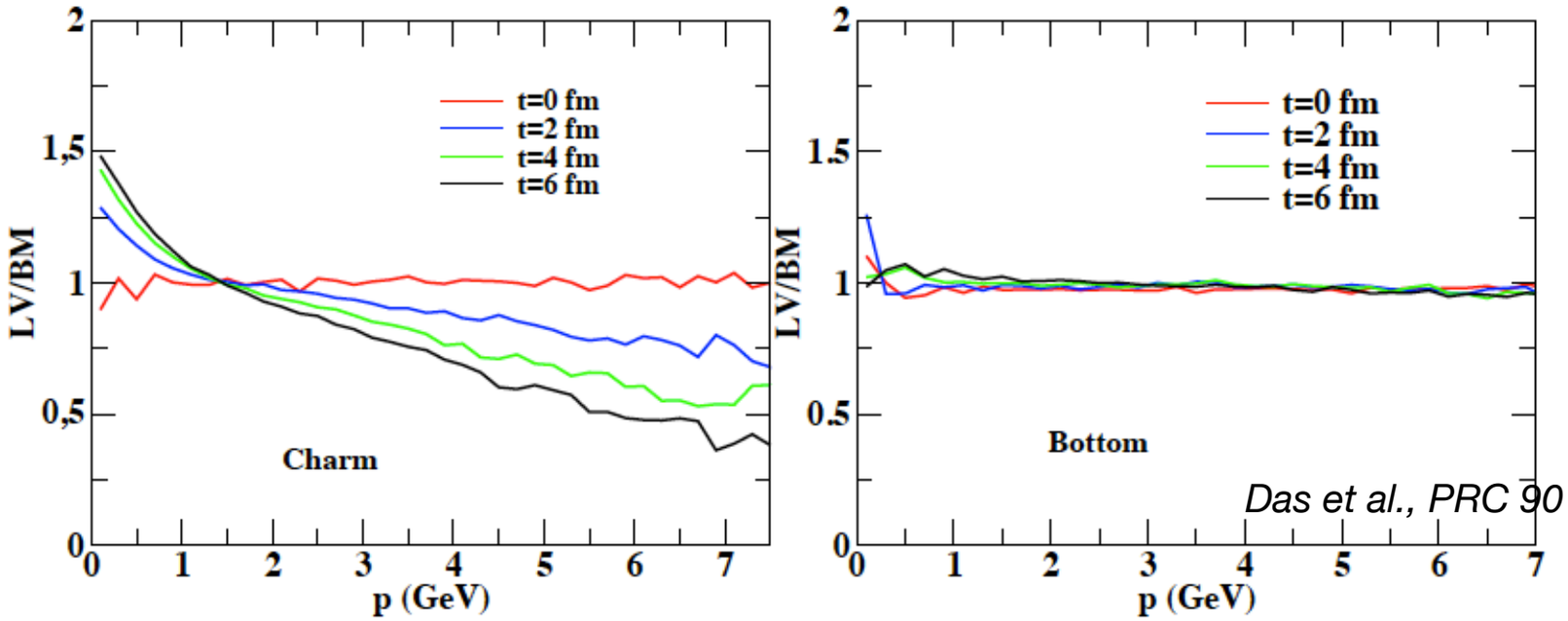
STAR QM19

- TPC and FMS ($2.5 < \eta < 4.0$) methods provide consistent results

  Evidence of non-zero bottom v_2 (3.4σ)

Towards Precision Constraints of HQ Diffusion Coefficient

Why bottom quarks? Sizable correction in Langevin approach for c-quarks



Das et al., PRC 90 (2014) 044901

Theoretical Collaboration

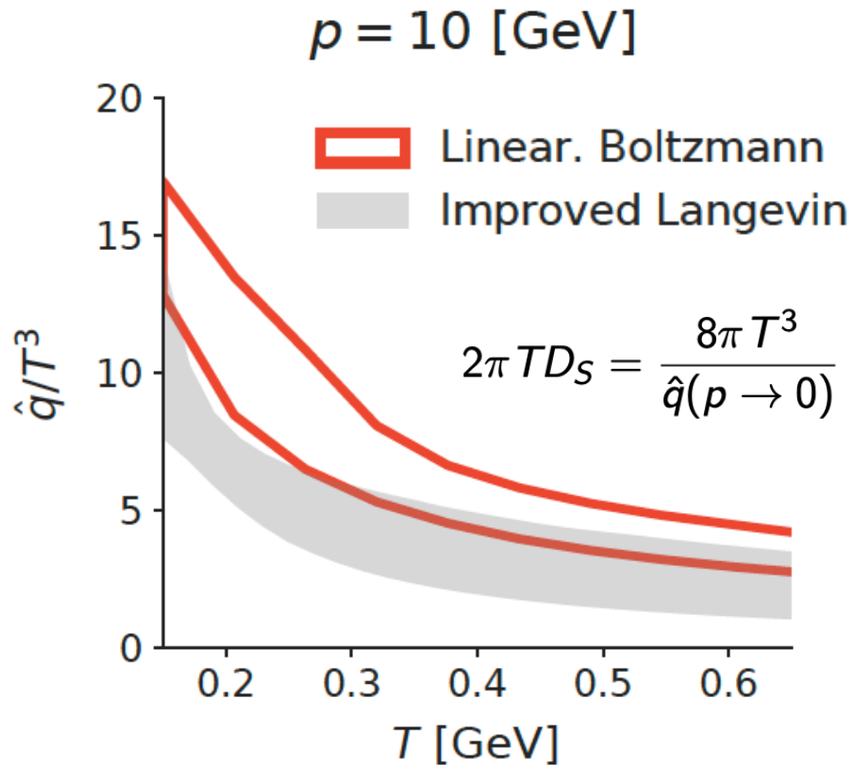
To resolve/understand trivial/non-trivial differences between different models

EMMI Rapid Reaction Task Force

- R. Rapp et al., NPA 979 (2018) 21

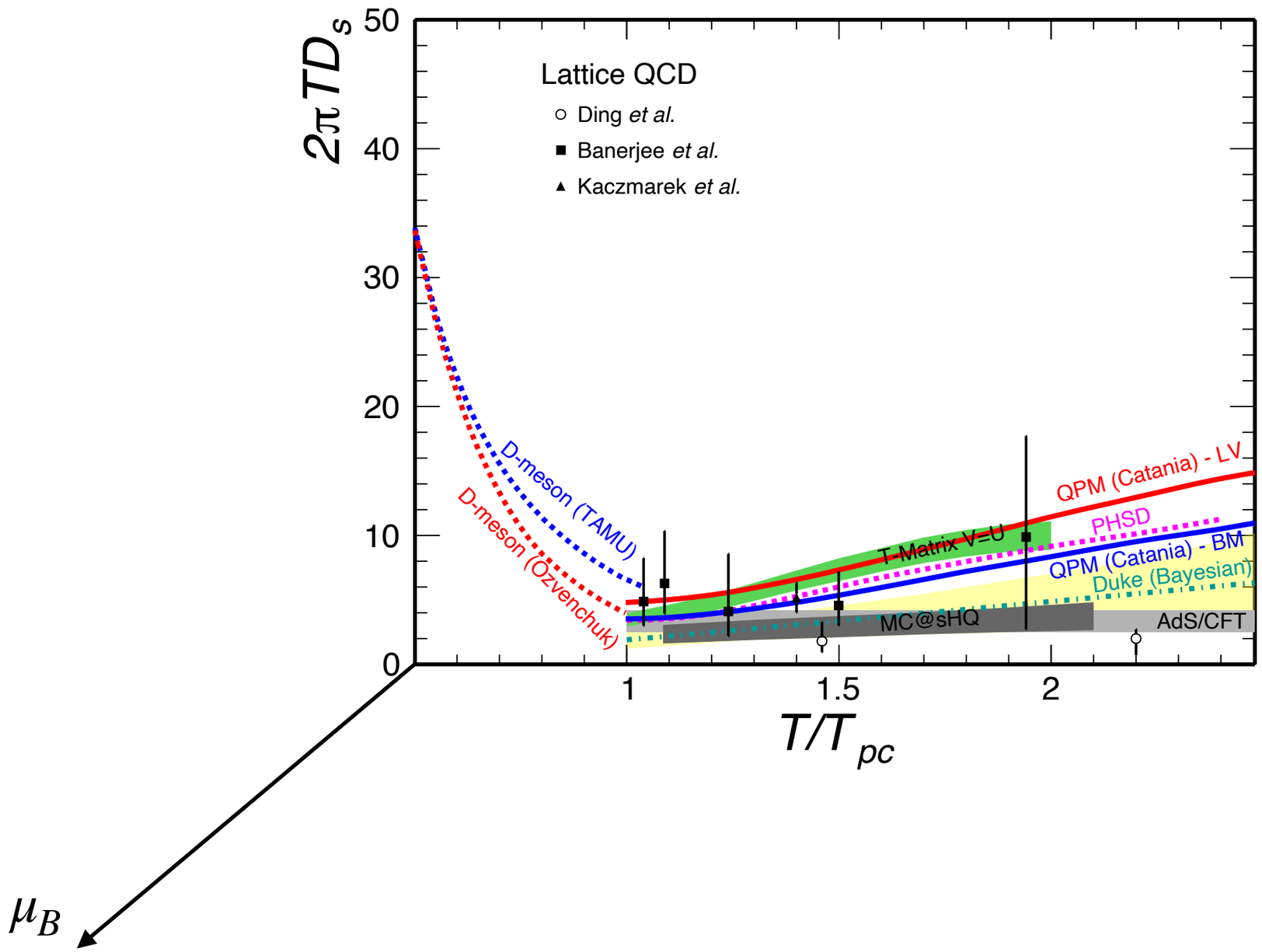
Jet-HQ Working Group

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

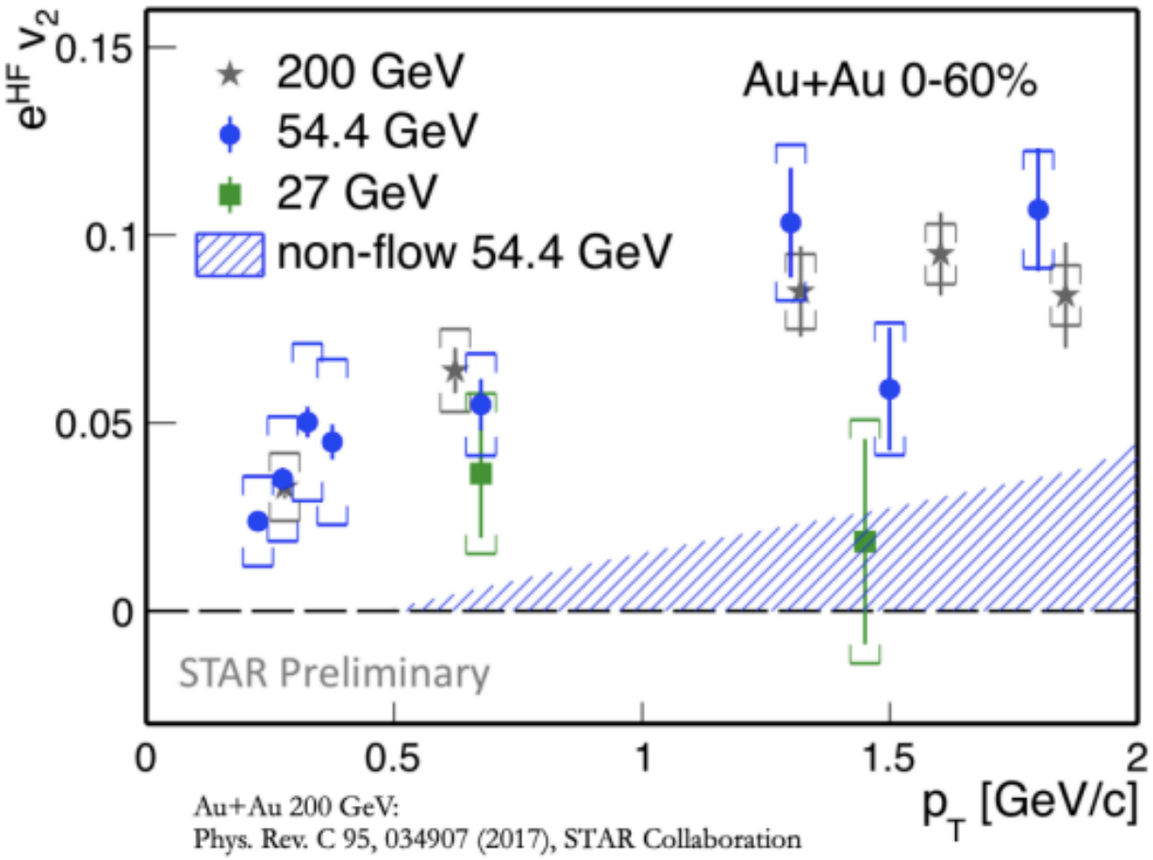


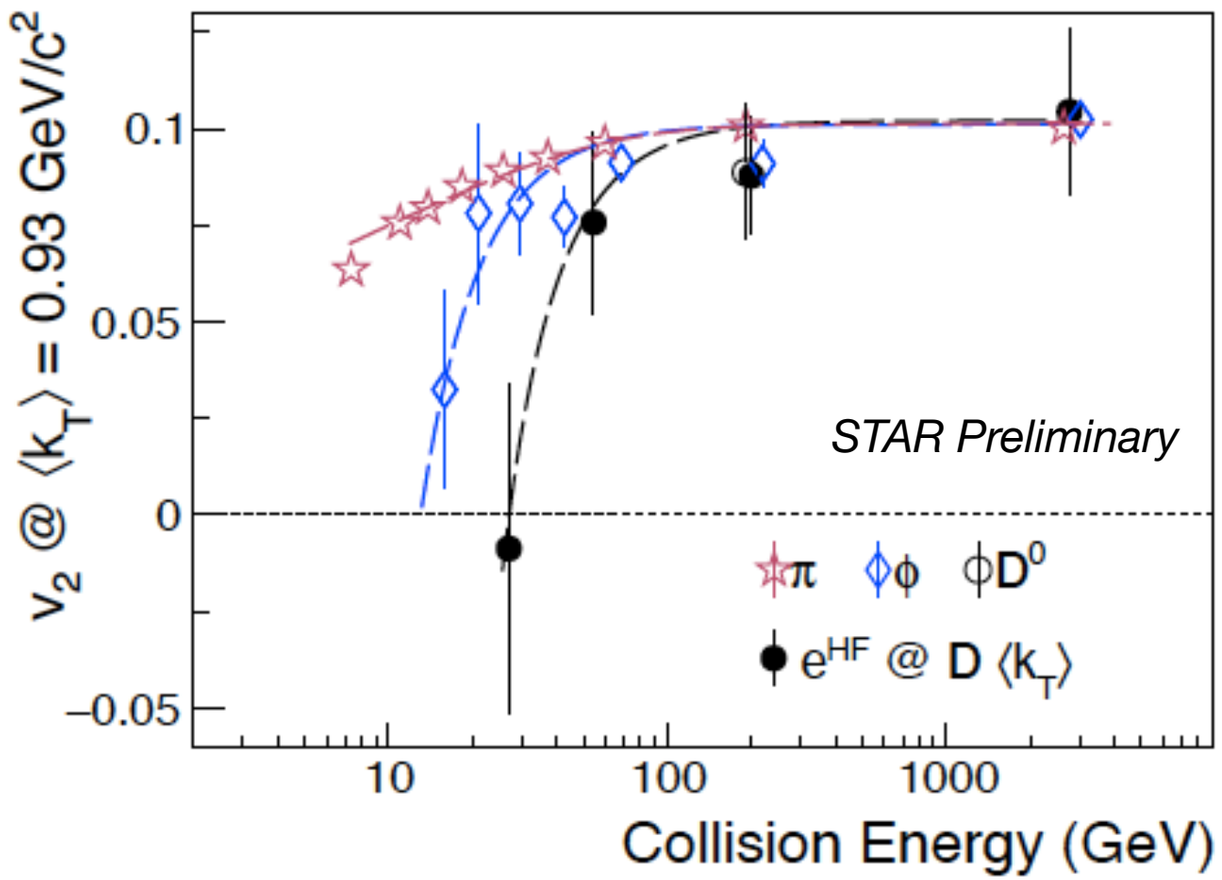
W.Y. Ke et al., PRC 98 (2018) 064901

μ_B Dependence of QGP Properties



Energy Dependent Heavy Flavor Electron v_2





STAR, HP 2020

- Comparable HF electron v_2 at 54.4 GeV w.r.t. that at 200 GeV
- Hint of zero HF electron v_2 at 27 GeV
  - more precise measurements are needed for better understanding
  - help constrain on μ_B-dependent $2\pi TD_s$

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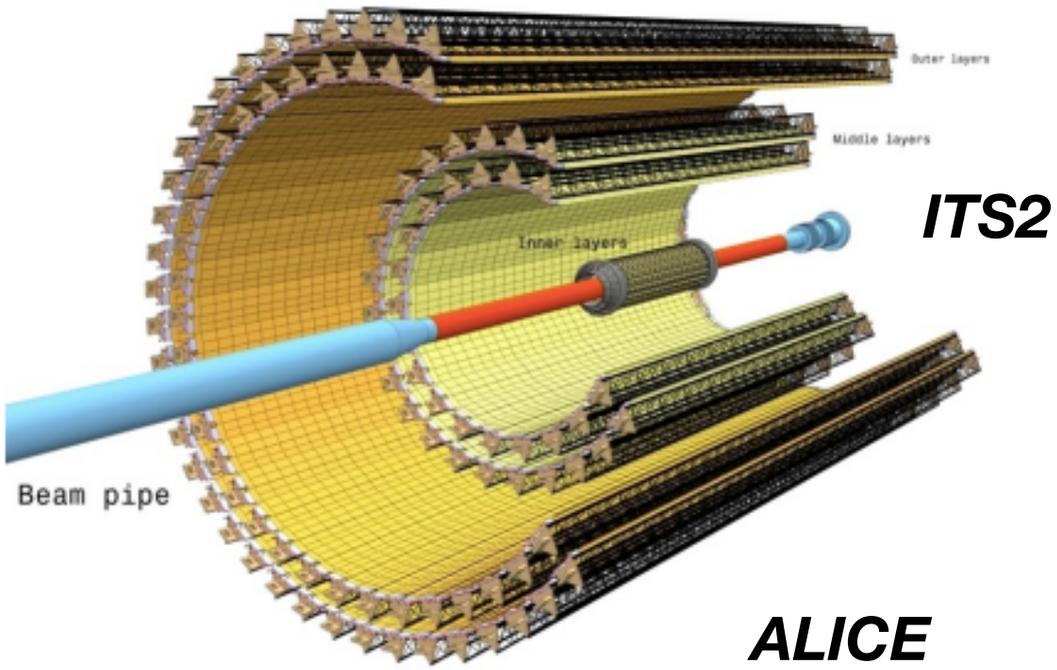
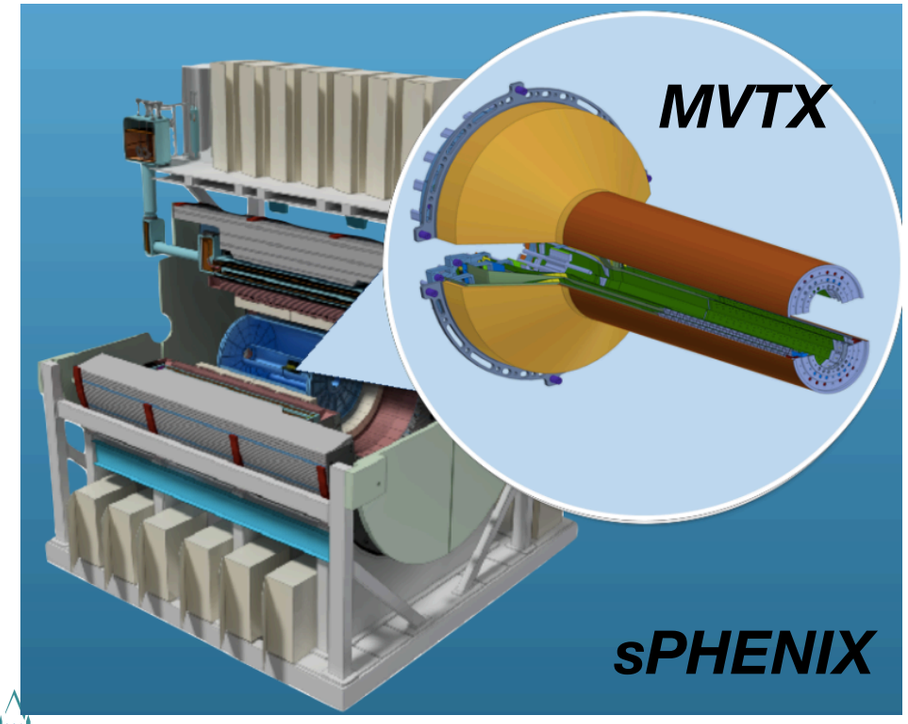
  - Heavy Quarks: Unique Probe to Characterize sQGP
- Recent Heavy Flavor Results at RHIC
  - R_{AA} suppression - parton energy loss
  - Hadrochemistry - hadronization
  - Collectivity - sQGP transport coefficient
- Future Heavy Flavor Program at RHIC

ALICE-ITS2 and sPHENIX MVTX



ITS2

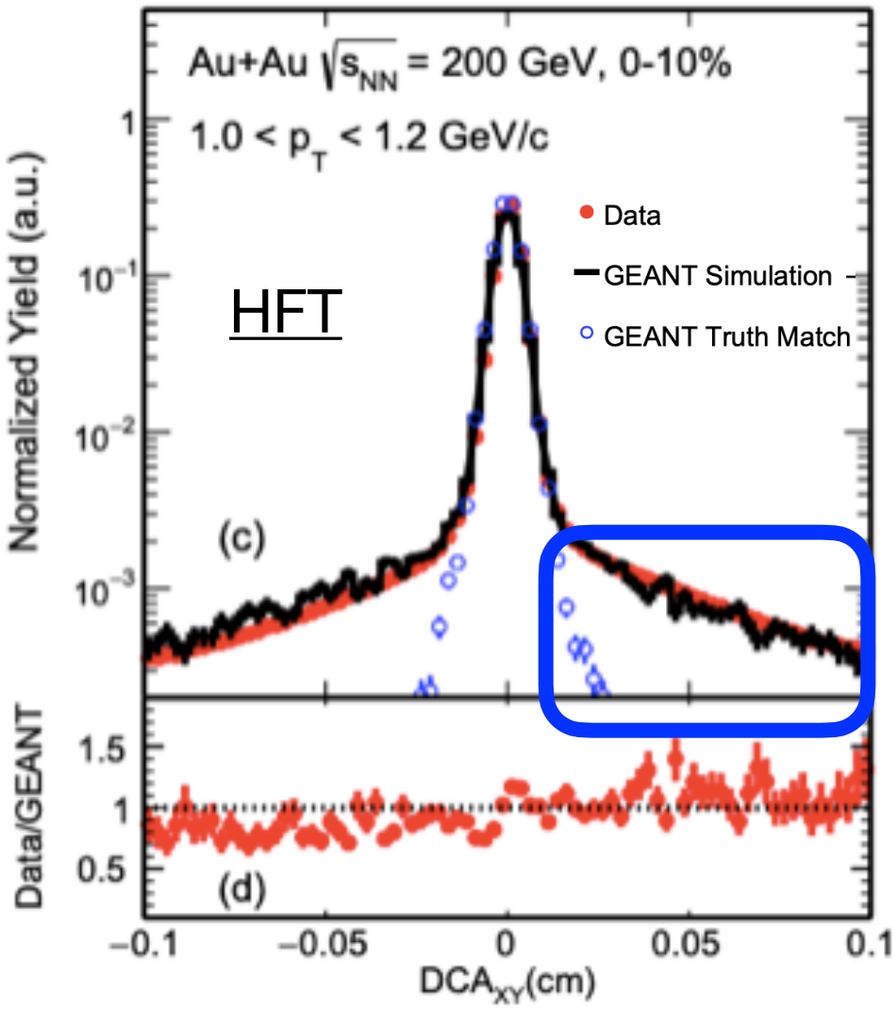
ALICE



Next generation fast MAPS detector

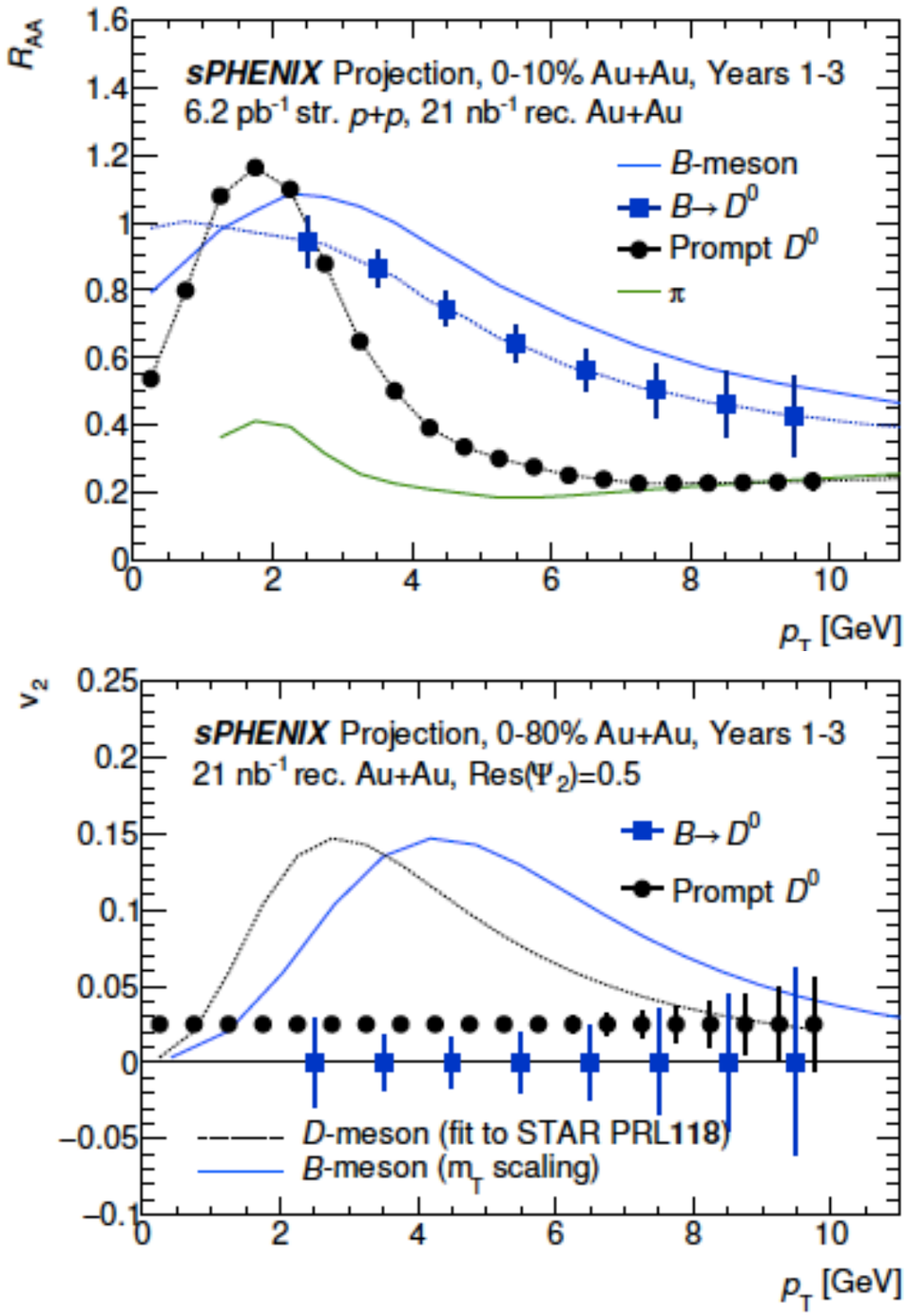
	HFT	ITS2/MVTX
thickness	0.4% X_0 →	0.3% X_0
integration time	186 μs →	$< 10\ \mu s$

==> background reduced by > x10

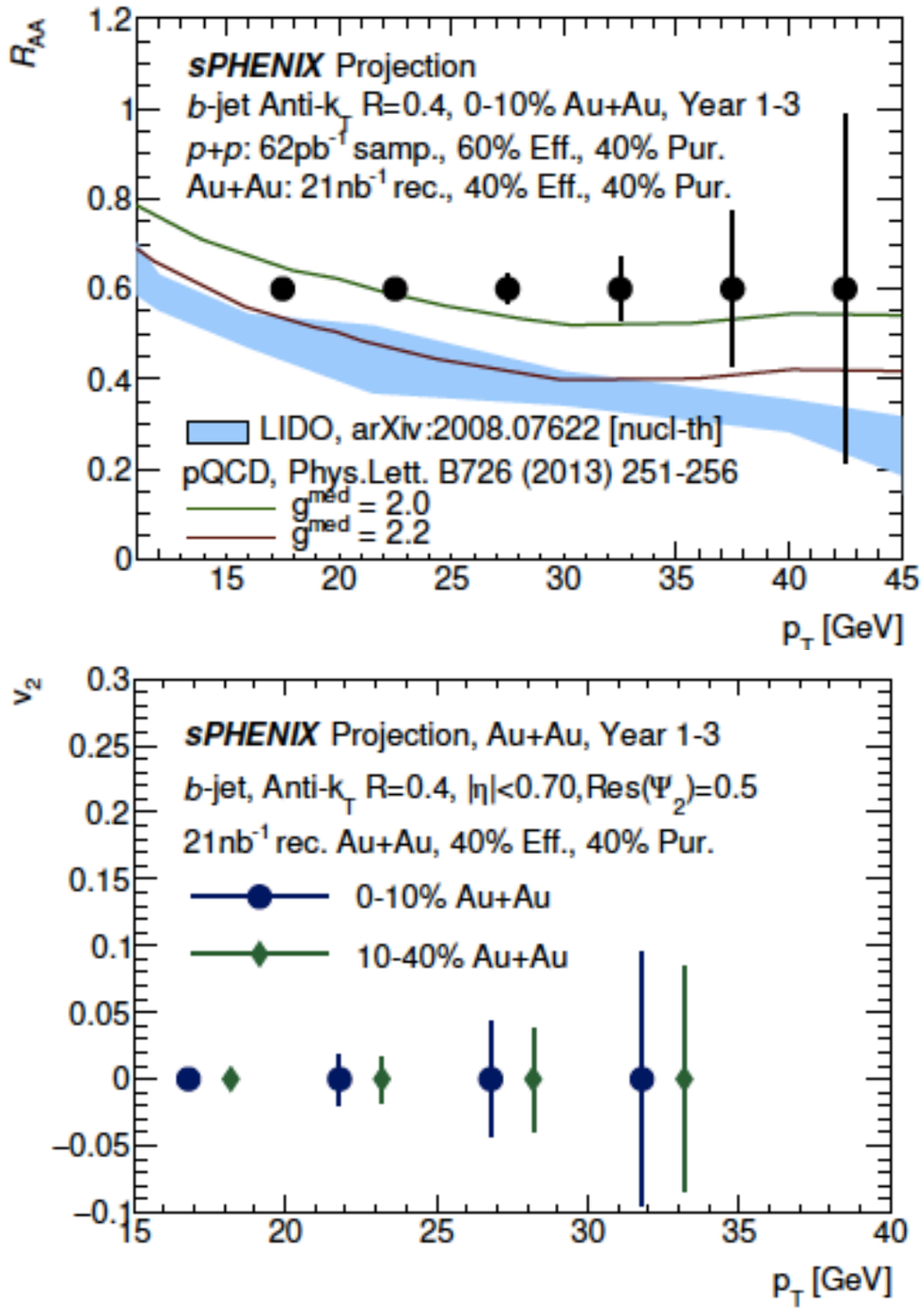


Precision Measurement of Open-Bottom at RHIC

B-meson via non-prompt D^0

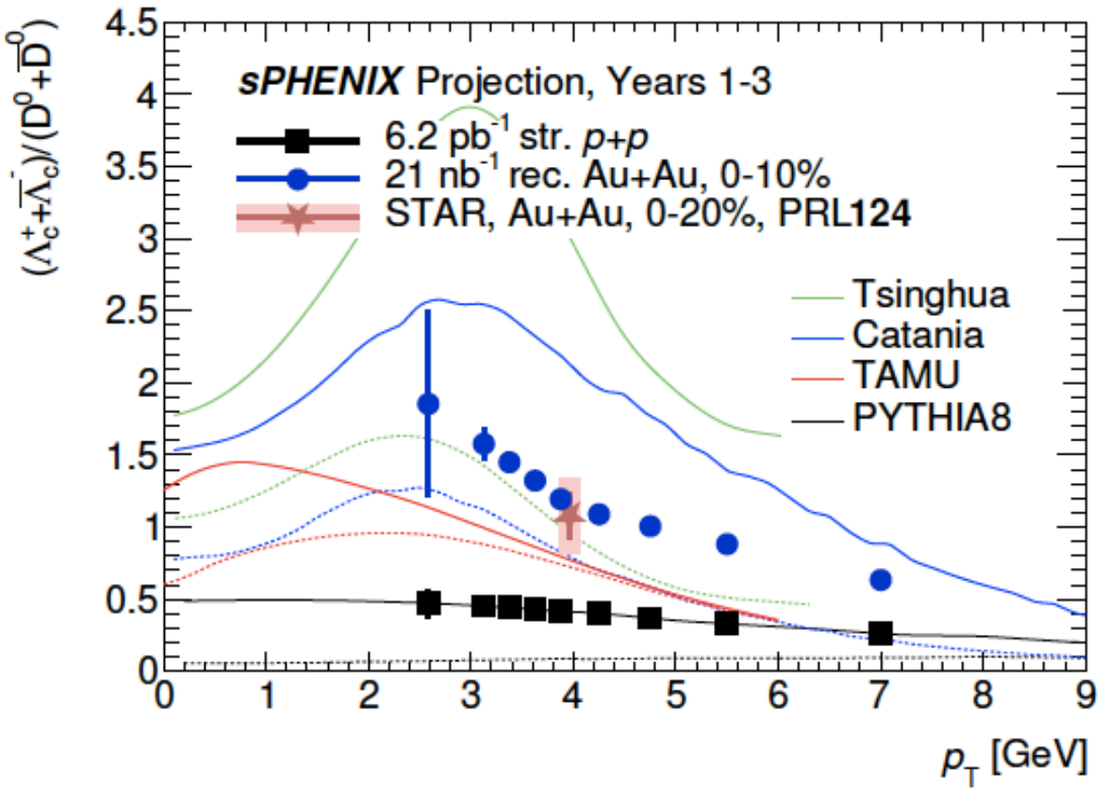


b-jet



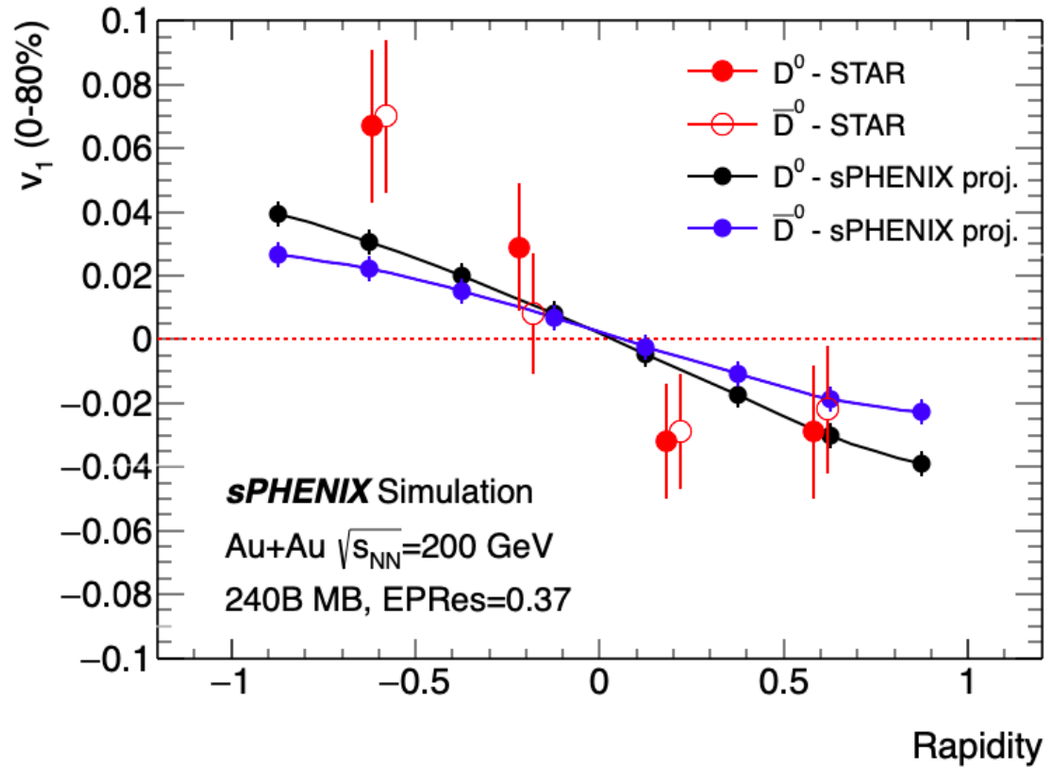
Fruitful Charm/Bottom Physics

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

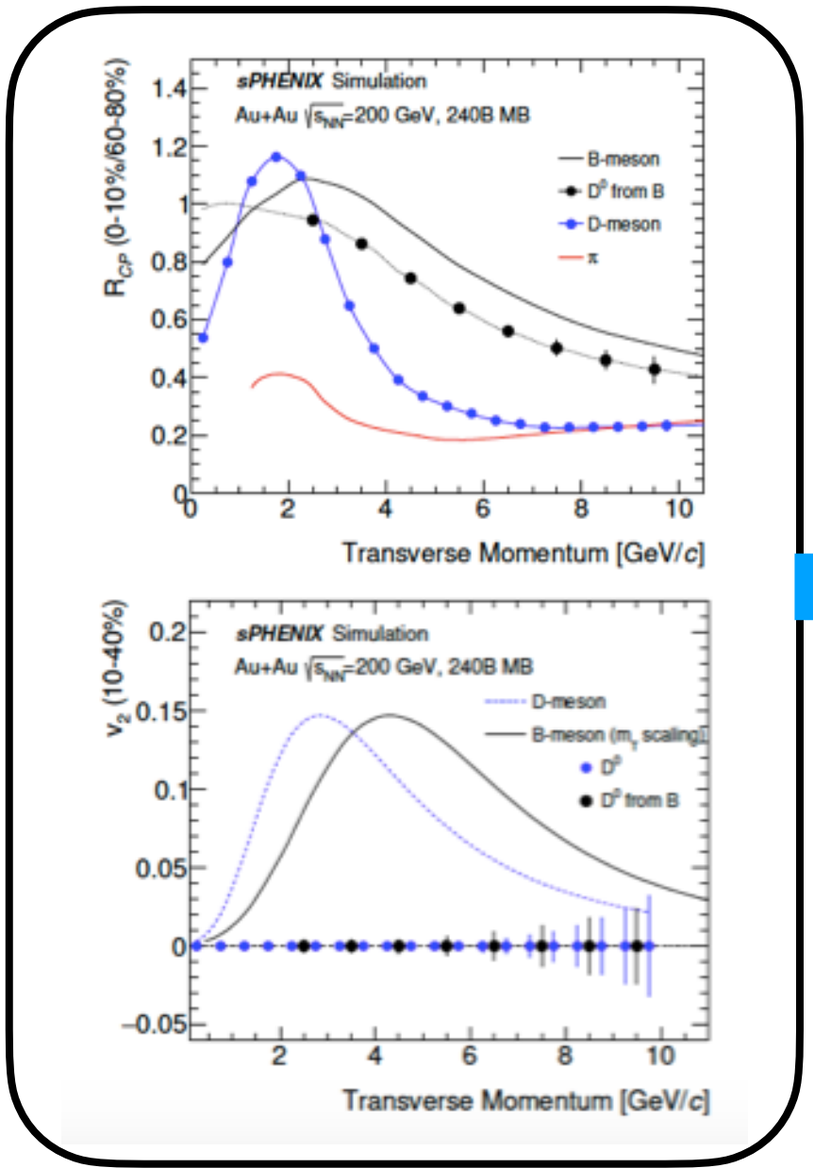
$D^0/\overline{D}^0$ v_1 - $2\pi TD_s(T)$ / initial B-field

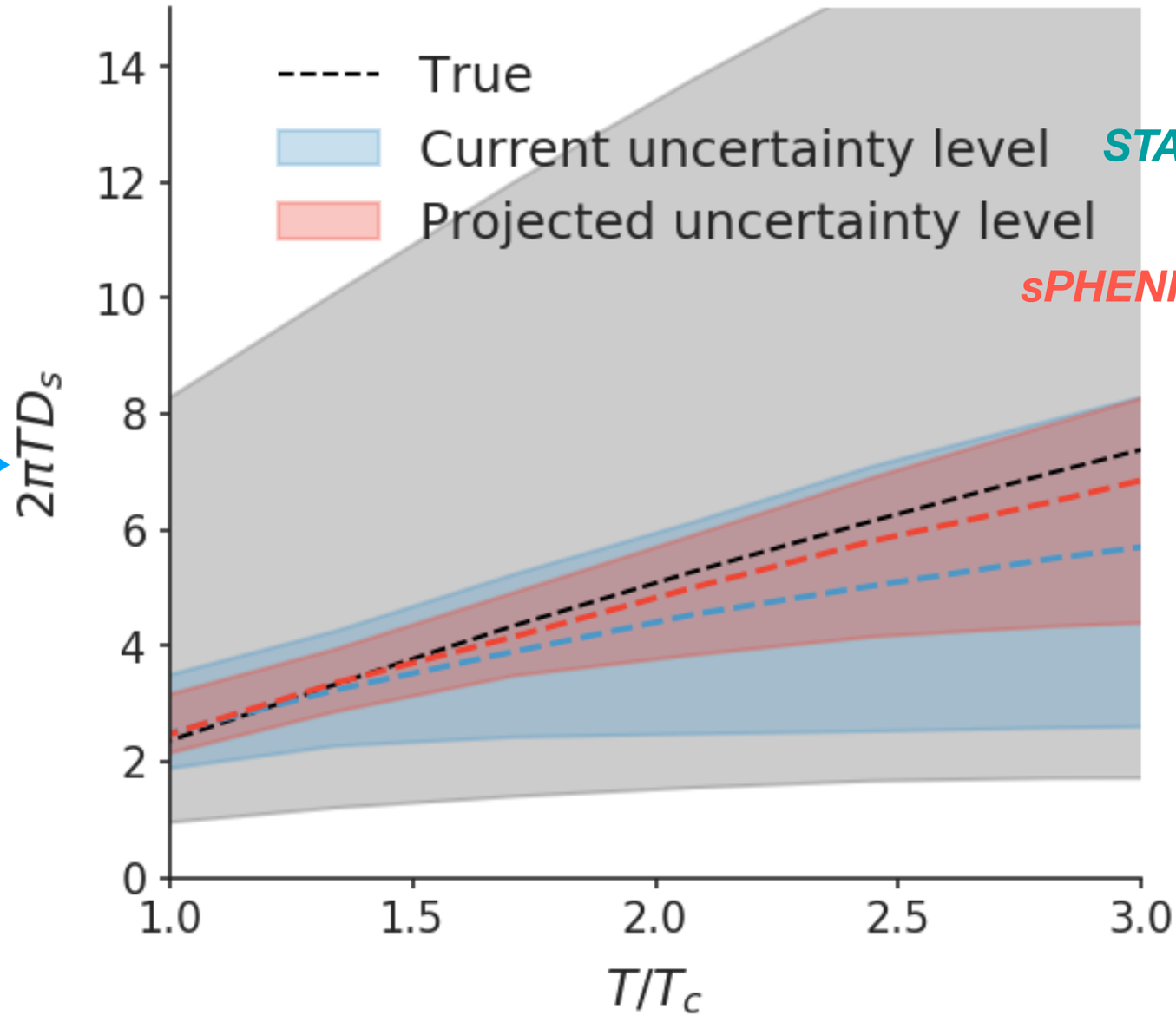


- $D^0/\overline{D}^0$ $\langle v_1 \rangle$
  - QGP longitudinal structure
  - temperature dependent $2\pi TD_s(T)$
- $D^0/\overline{D}^0$ Δv_1
  - unique access to initial B-field
  - sPHENIX proj. ~5σ given model predictions

Impact on Charm Diffusion Coefficient

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





RHIC/LHC Complementarity for HF Programs in 202x

	RHIC sPHENIX	LHC ALICE	LHC ATLAS/CMS
Charm X-sec		+	+
Bottom X-sec		++	++
b->c feeddown	+		
Gluon splitting	+		
Running Time	+		
DCA Res	+	+	
Mom Res			+
PID		+	
Jet E Res			+
Rapidity Coverage			+

Summary

	2014-2016	2017-2021	2022	2023	2024	2025+
RHIC	STAR/HFT charm			sPHENIX/MVTX bottom, Λ_c, correlations		
LHC		ALICE/ITS Run2		ALICE/ITS2 Run3		

STAR/HFT:

- $R_{AA}(D) \sim R_{AA}(h)$, $v_2(D) \sim v_2(h)$
- significant D_s/D^0 and Λ_c/D^0 enhancement
- charm quark diffusion coefficient: **2-5 @ T_c**

sPHENIX/MVTX:

- precision measurements of $R_{AA}(B)$ and $v_2(B)$
- bottom/charm hadrochemistry
- bottom/charm heavy quark diffusion coefficient