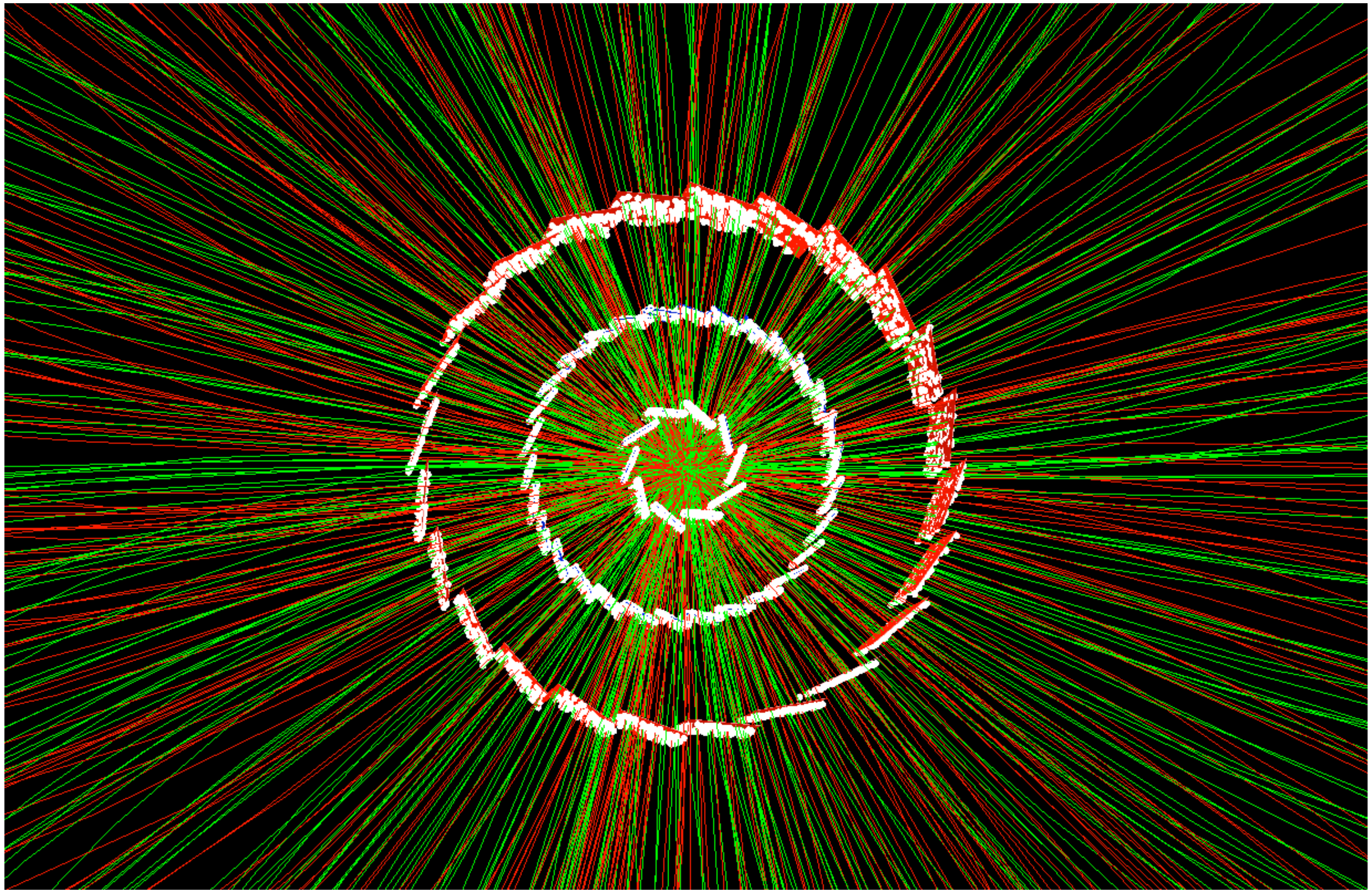
Open Heavy Flavor Production at RHIC

Xin Dong (Lawrence Berkeley National Laboratory)



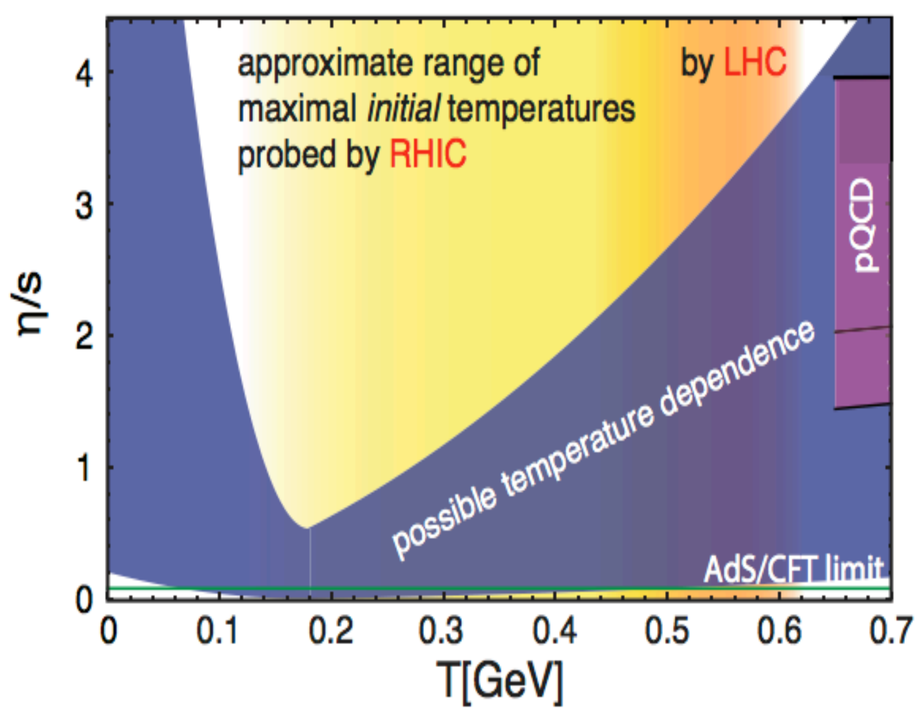
Au+Au event display with STAR-HFT

Outline

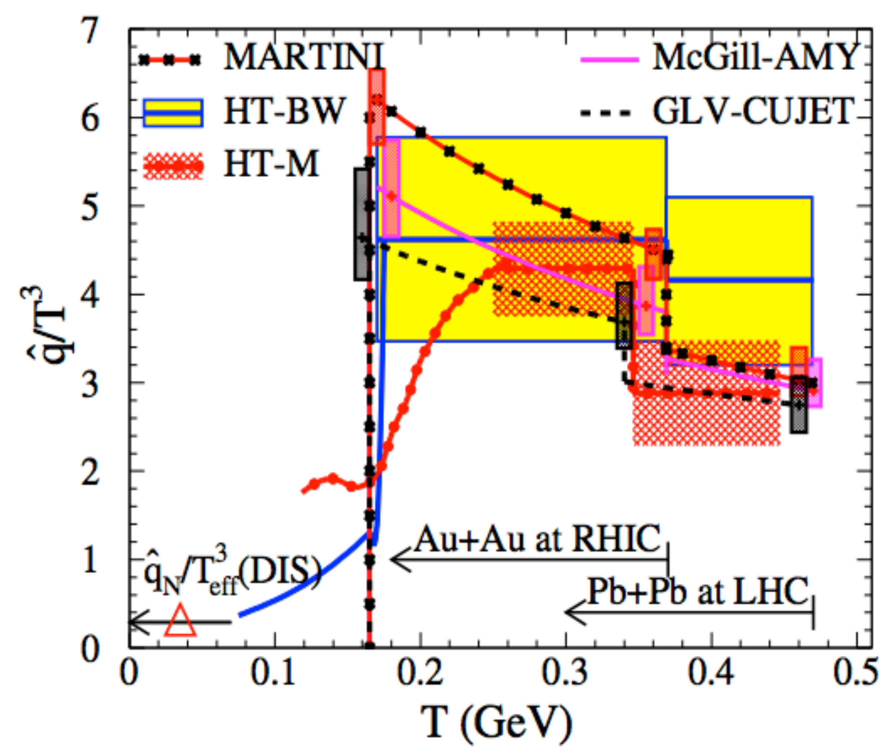
- Introduction:
  - Heavy Quarks: Unique Probe to Characterize sQGP
- Recent Heavy Flavor Results at RHIC
  - R_{AA} suppression - parton energy loss
  - Hadrochemistry - hadronization
  - Collectivity - sQGP transport coefficient
- Future Heavy Flavor Program at RHIC

QGP Emergent Properties

~2 ~6 p_T (GeV/c)



Hot QCD white paper - arXiv: 1502.02730



JET Coll., PRC 90 (2015) 014909

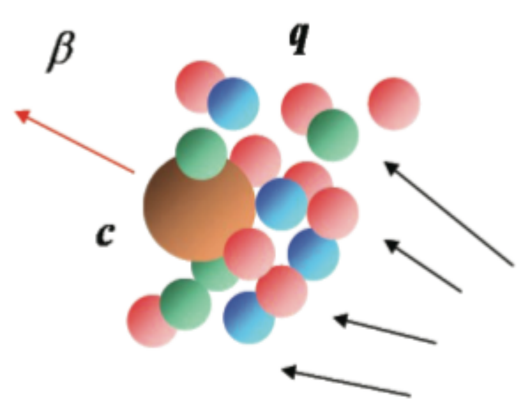
?

strongly coupled
hydrodynamics

weakly coupled
pQCD

What is the microscopic picture of "perfect fluid"?

Heavy Flavor Quark Transport in QGP



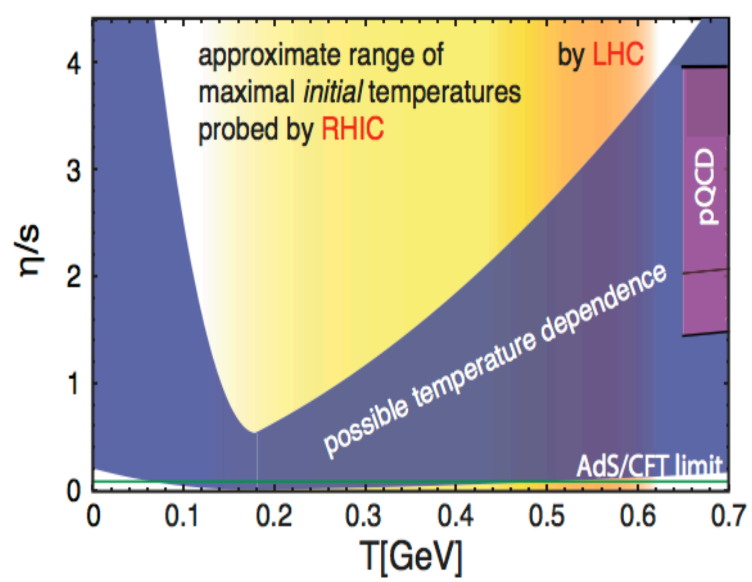
Femtoscopic "Brownian" motion

Langevin stochastic equation

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

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

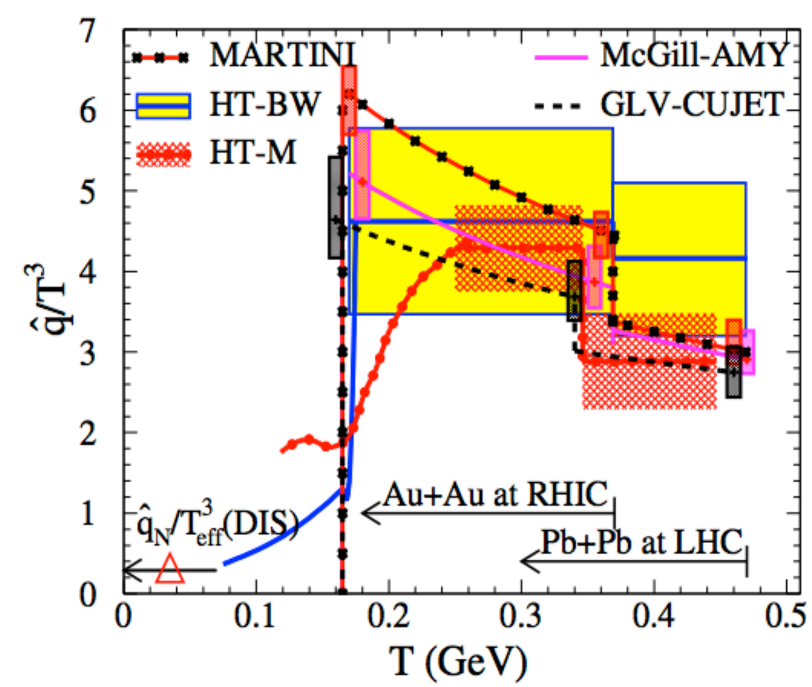
$$D_s \equiv \frac{\langle x^2(t)\rangle - \langle x^2(0)\rangle}{2dt} = \frac{t}{M\eta_D(p=0)}$$



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

ratio depends on the strong/weak coupling nature of QGP

R. Rapp and H. van Hees, 0903.1096



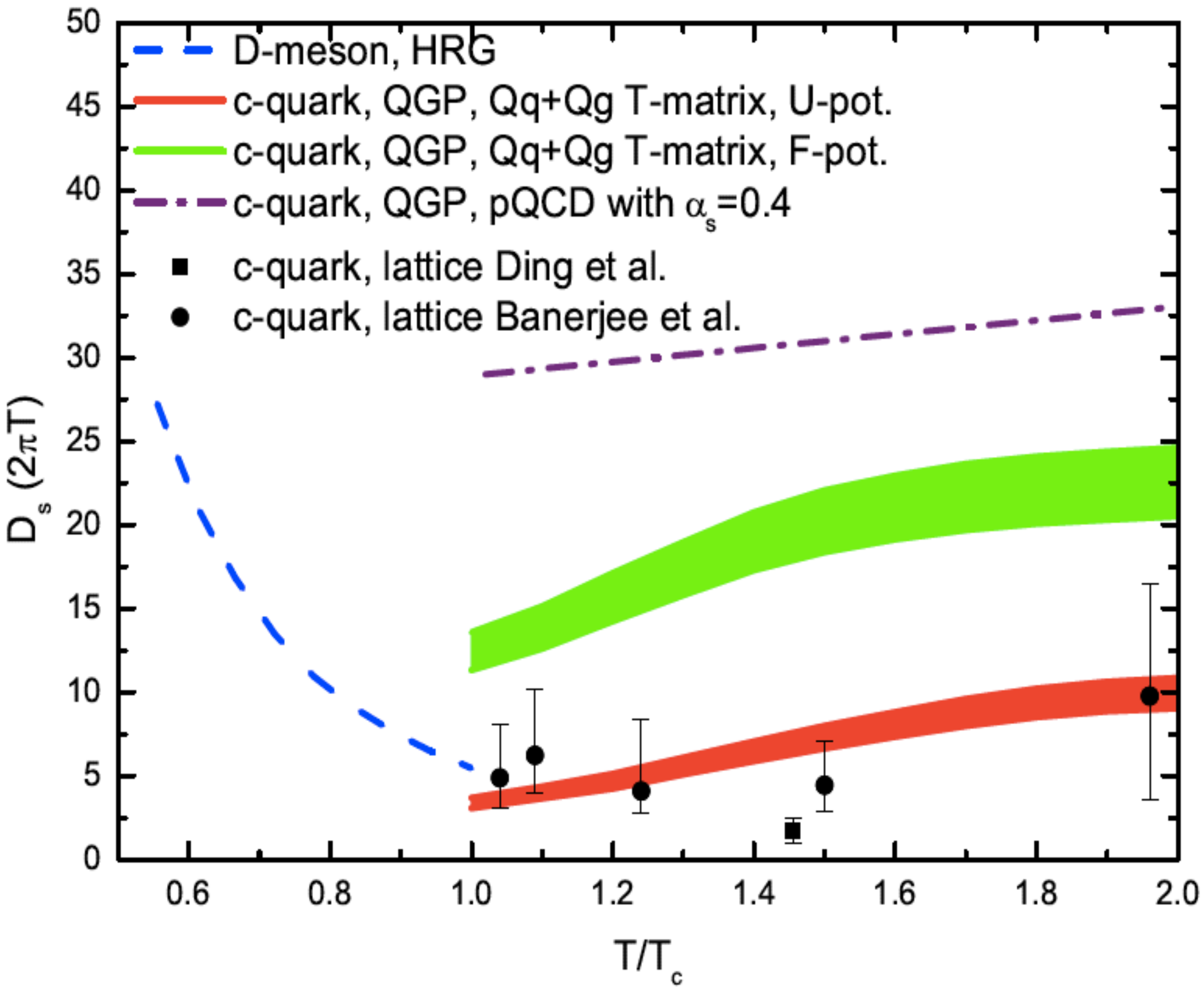
$$\hat{q} = \frac{\Delta p_T^2}{\lambda} = \frac{4D_pE_p}{p} \qquad 2\pi T D_S = \frac{8\pi T^3}{\hat{q}(p\to 0)}$$

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

<u>2015</u>

- $2\pi T D_s$ ~ 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

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

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

<u>Big Challenge</u>

Combinatorial background in heavy-ion collisions

Silicon pixel detector to separate secondary decay vertex!

Instrumentation

	ALICE	ATLAS	CMS	LHCb	PHENIX	STAR
Sensor tech.	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid	**MAPS**
Pitch size (μm^2)	50x425	50x400	100x150	200x200	50x425	**20x20**
Radius of first layer (cm)	3.9	5.1	4.4	N/A	2.5	2.8
Thickness of first layer	$1\%X_0$	$\sim1\%X_0$	$\sim1\%X_0$	$\sim1\%X_0$	$1\%X_0$	**$0.4\%X_0$**

STAR Pixel - first application of **MAPS** technology in collider experiments
Monolithic Active Pixel Sensor

Next generation MAPS sensor deployed for ALICE-ITS2, sPHENIX-MVTX upgrades

MAPS-based pixel detector planned for CBM, EIC tracker etc.

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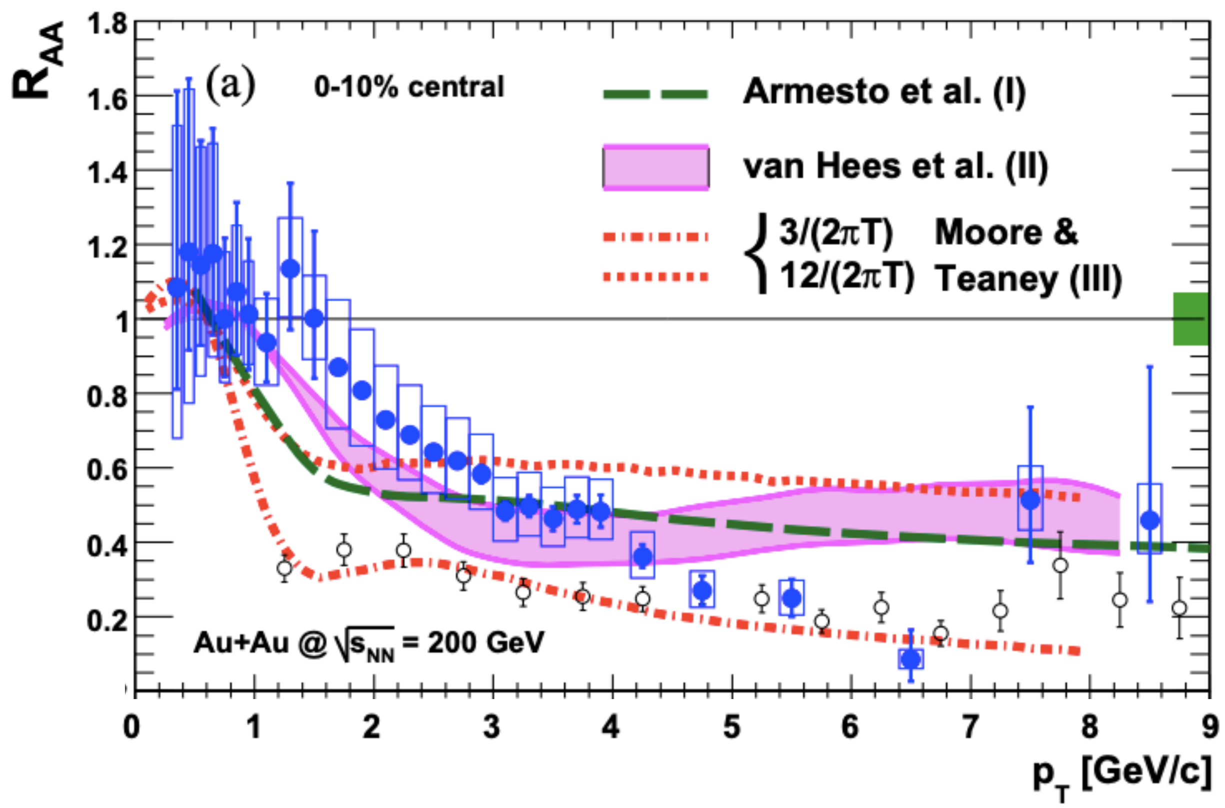
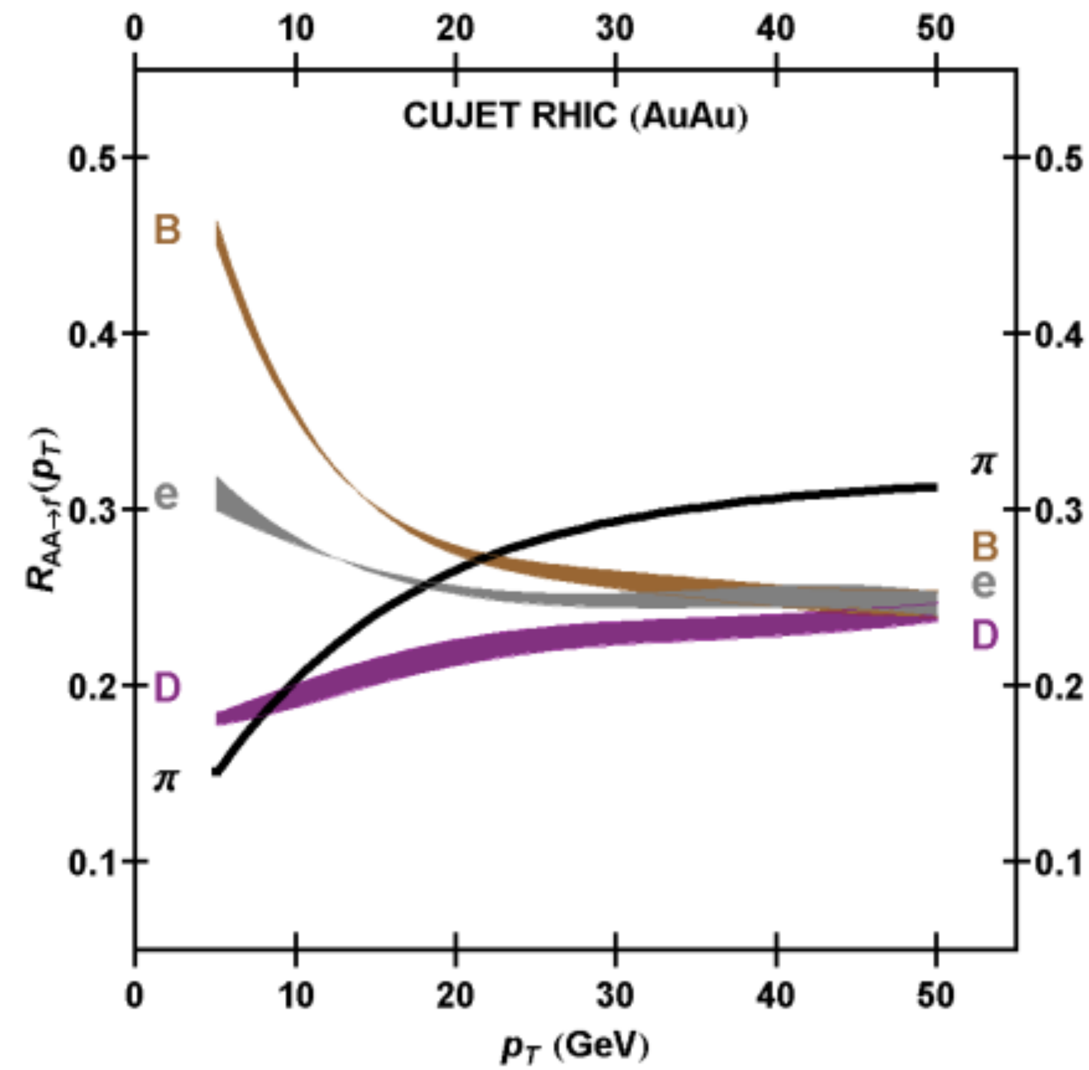
- Future Heavy Flavor Program at RHIC

R_{AA} Suppression - Heavy Quark Energy Loss

PHENIX, PRL 98 (2007) 172301

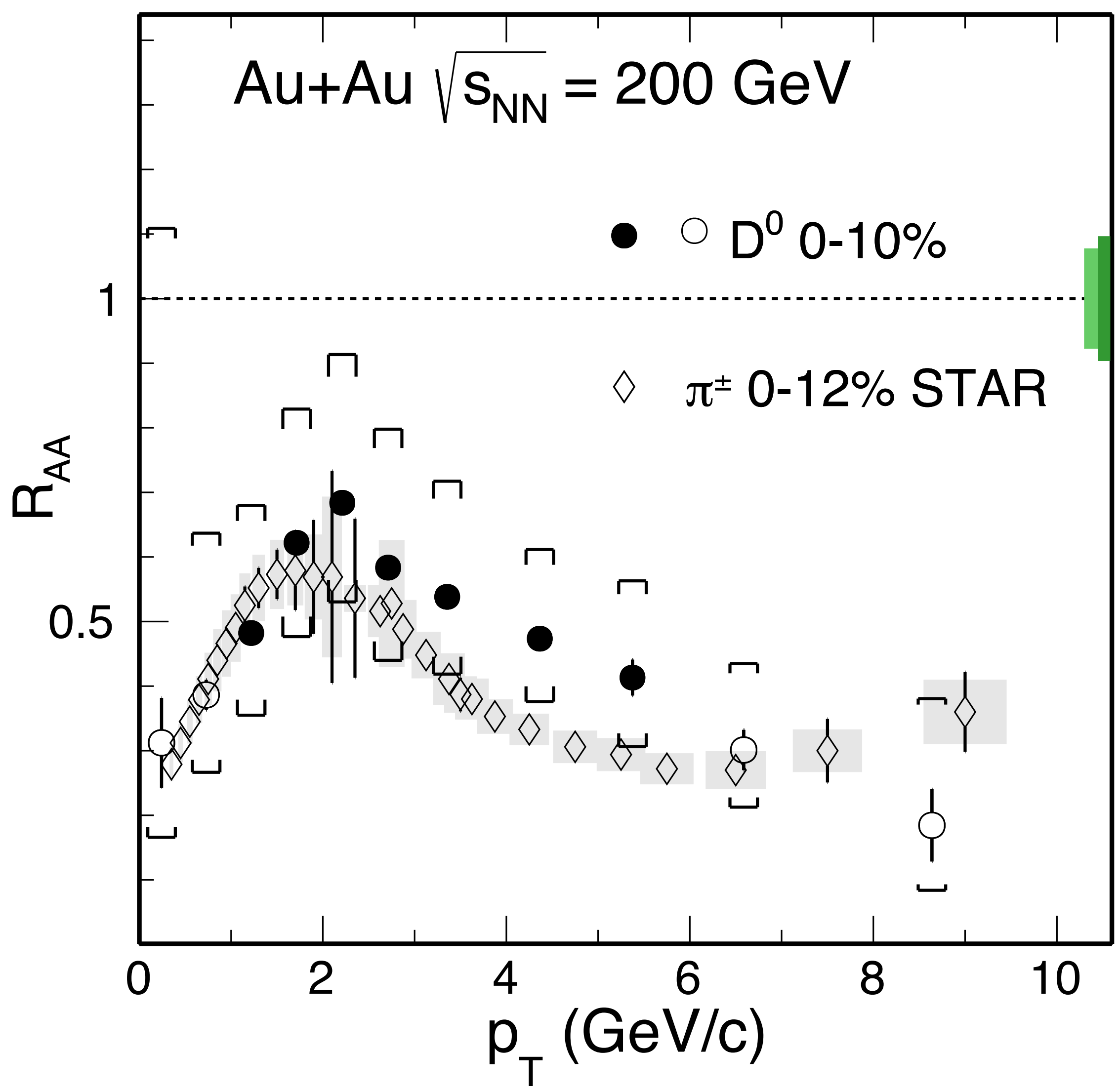


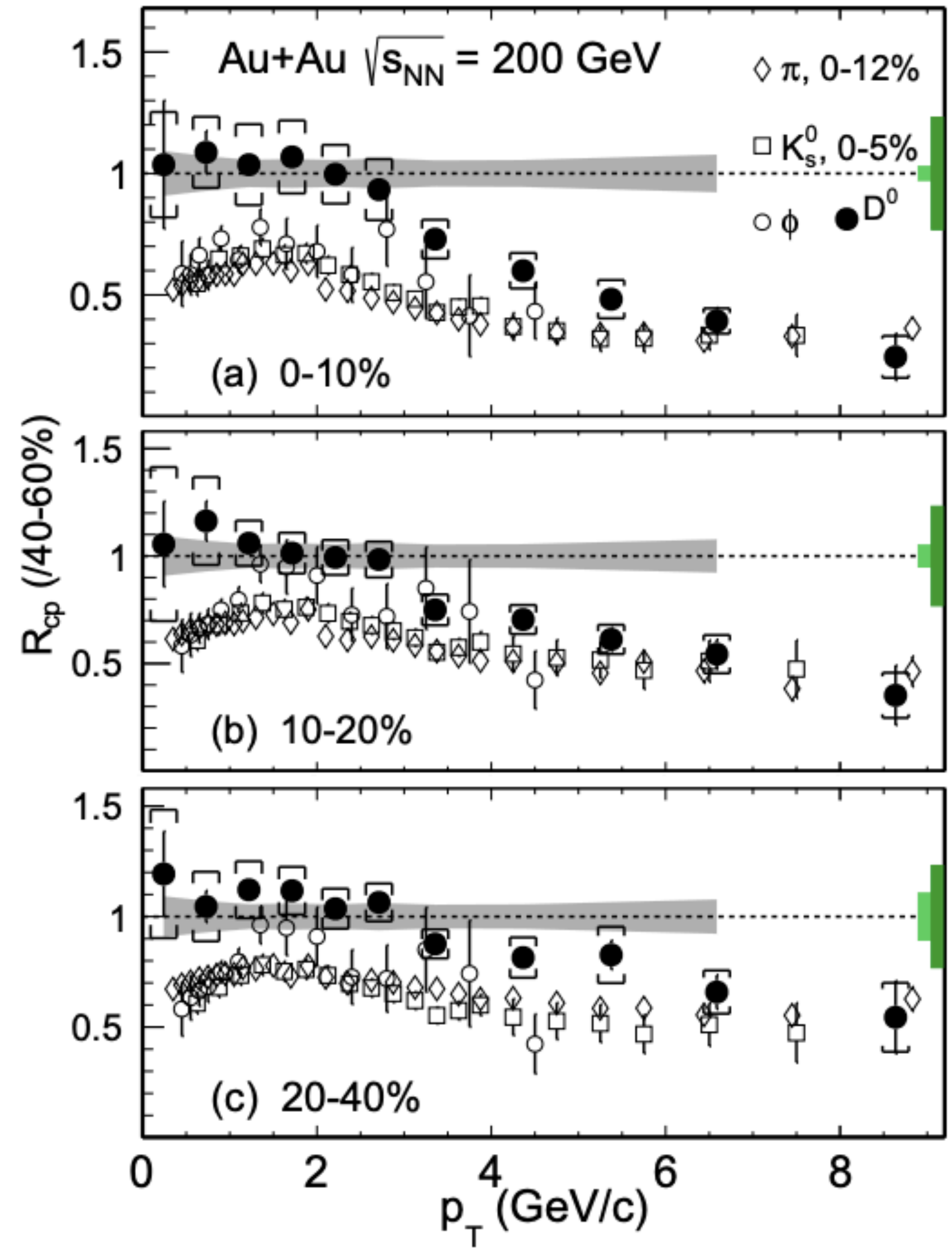
A. Buzzatti and M. Gyulassy, PRL 108 (2012) 022301



- Strong suppression of heavy flavor electrons reveals the importance of collisional energy loss
  - complication: mixed contributions from various HF hadrons
- pQCD predicts the energy loss mass hierarchy $\Delta E_q > \Delta E_c > \Delta E_b$
  - hadron R_{AA} pattern complicated by initial spectrum, fragmentation etc.

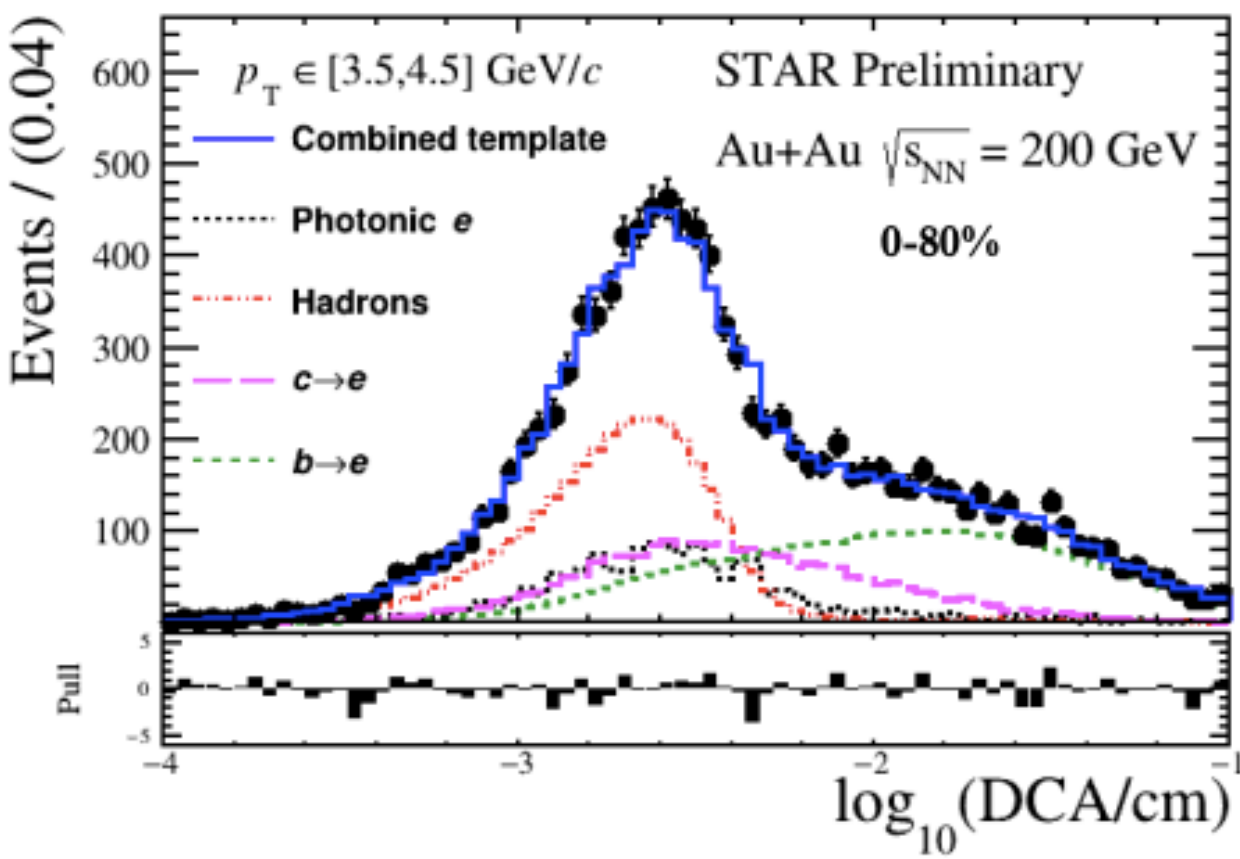
D^0 Meson R_{AA}/R_{CP} in A+A Collisions

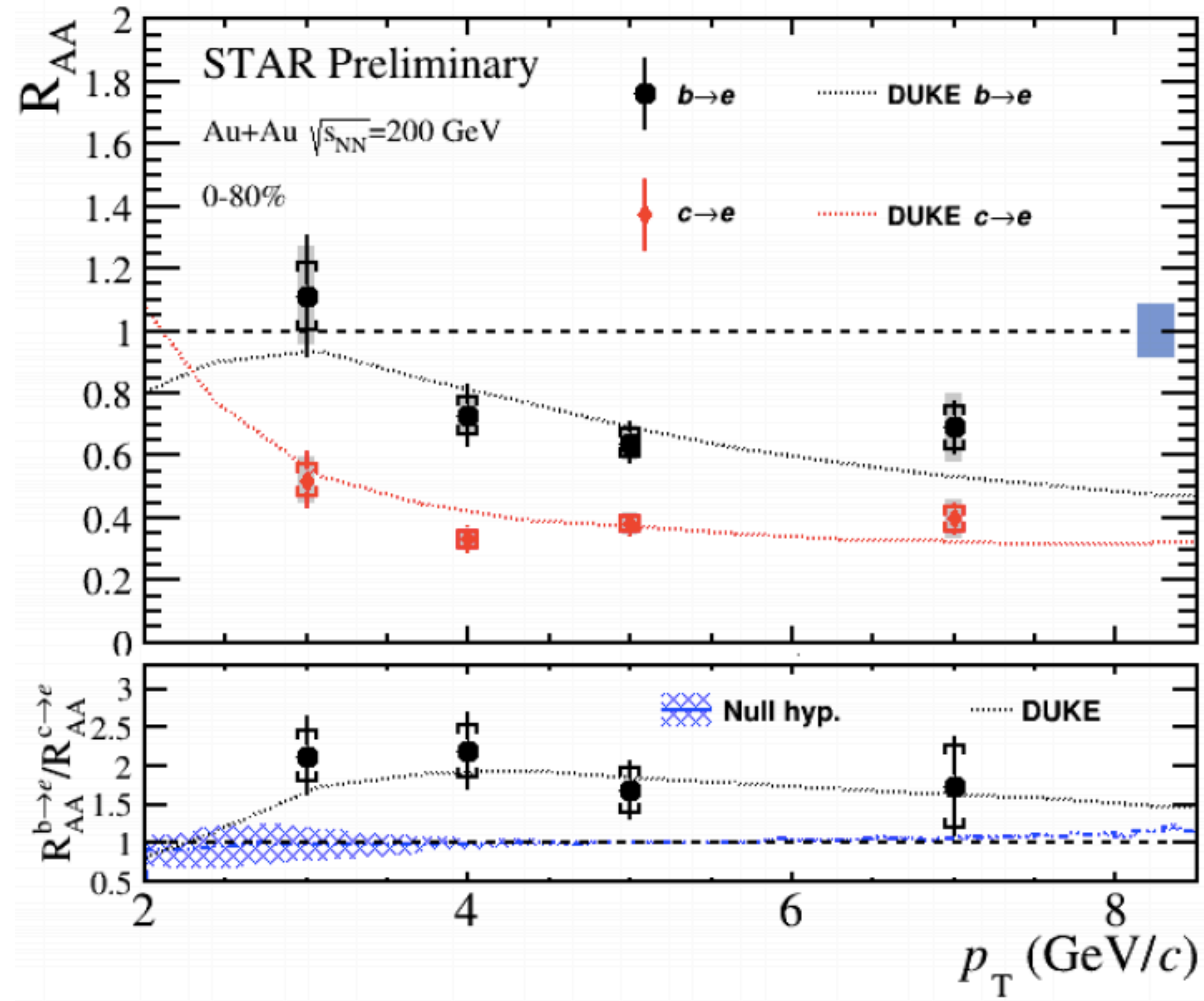




- $R_{AA}(D)$ ~ $R_{AA}(h)$ at p_T > ~4 GeV/c
  - significant charm quark energy loss in the QGP medium
  - importance of radiative and collisional energy loss

Bottom Suppression





STAR QM19

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

  Evidence of mass hierarchy of parton energy loss

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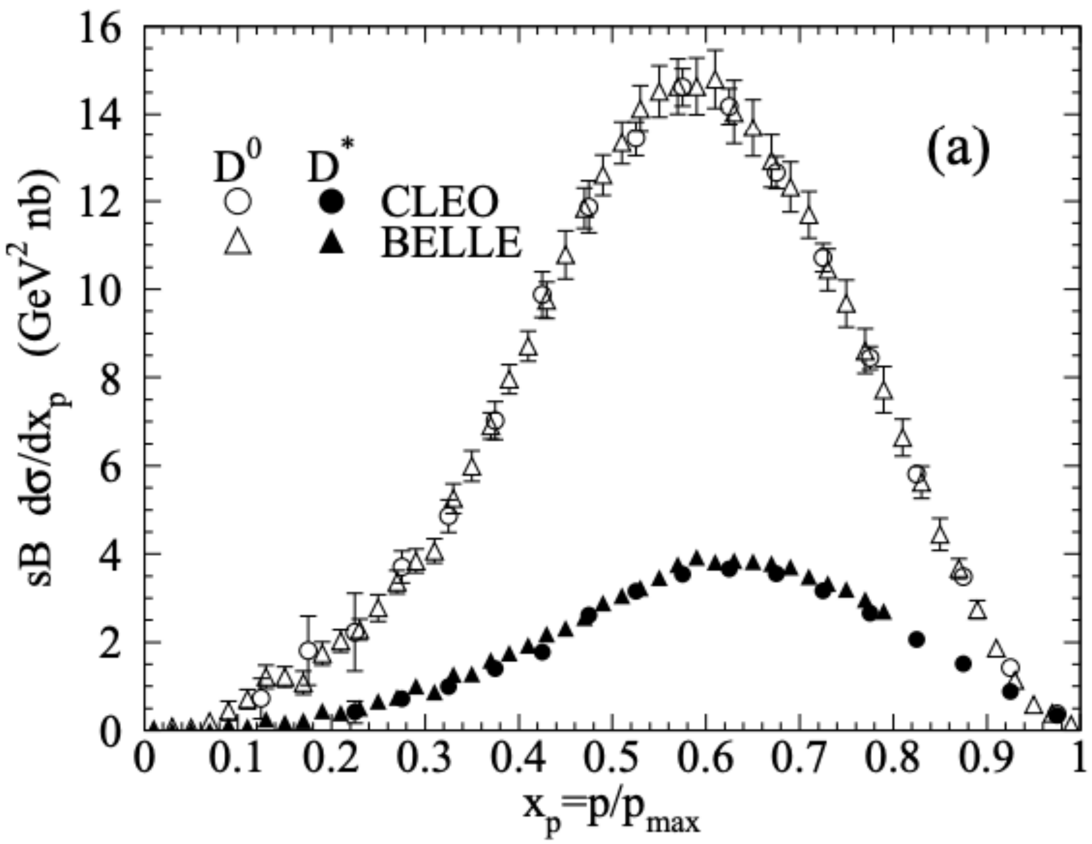
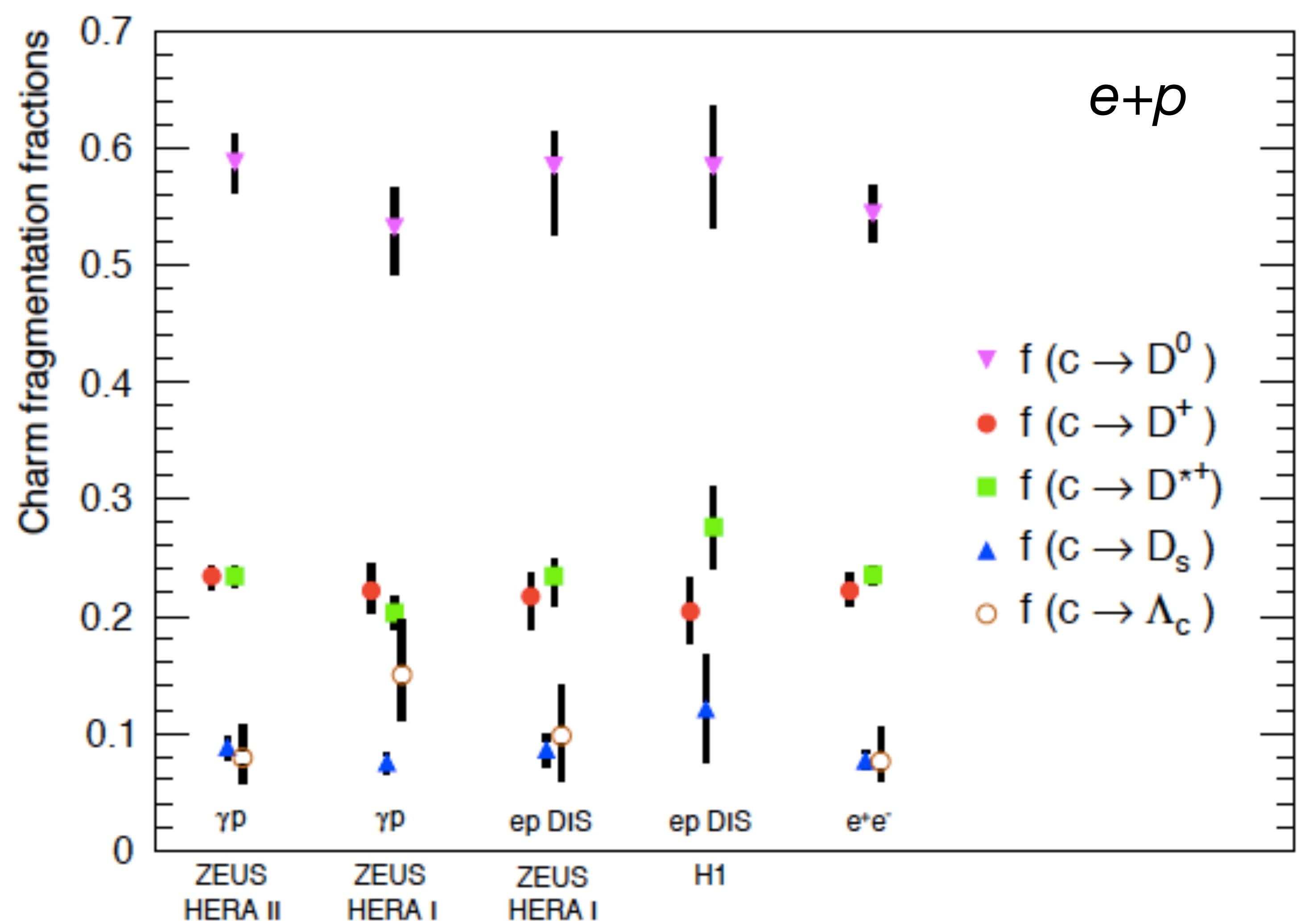
Charm Hadrochemistry in ee/ep

fragmentation measured in ee



PDG 2018



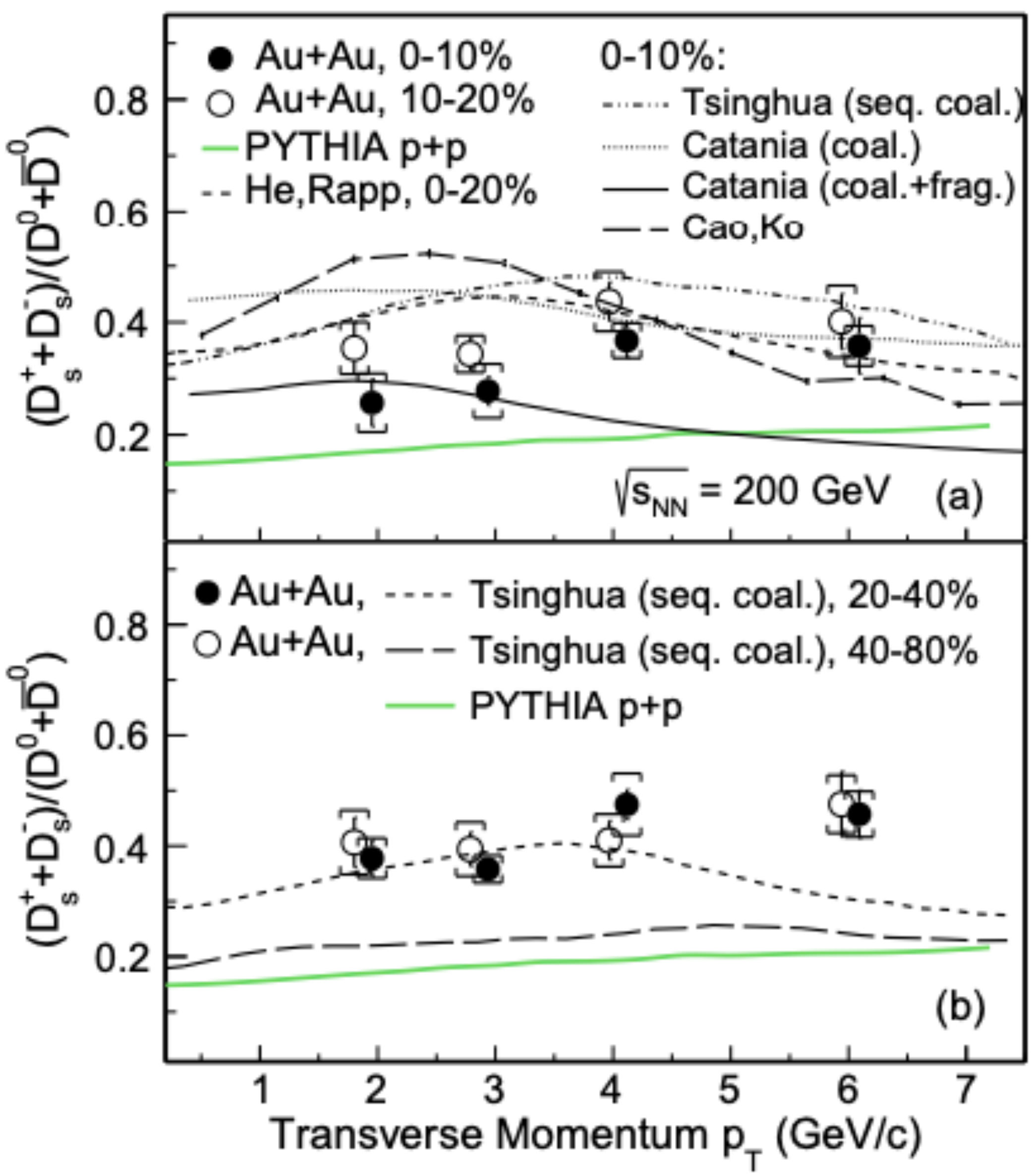
ZEUS, JHEP 1309 (2013) 058

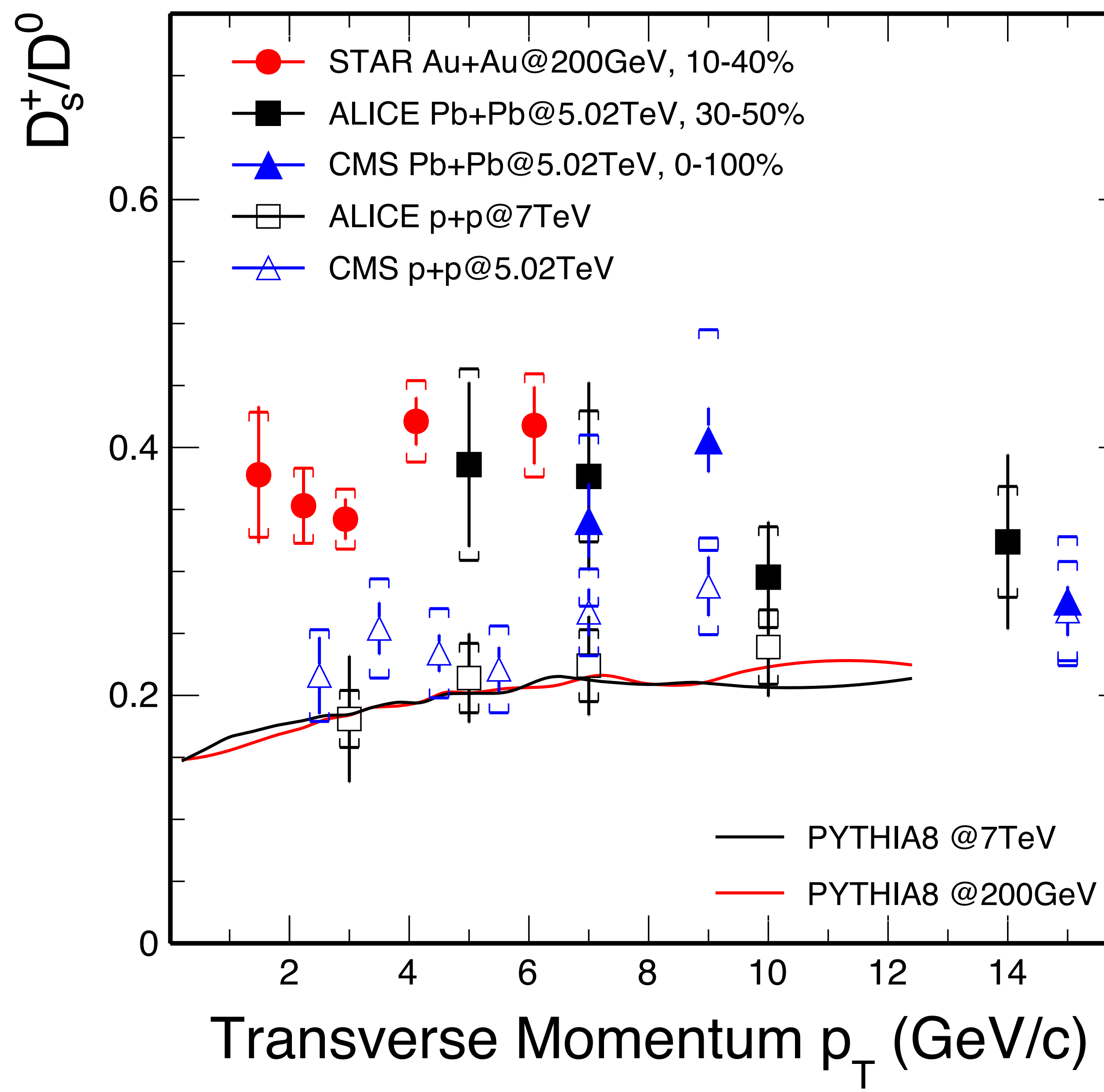
$$2\sigma_{c\bar{c}} = D^0 + D^+ + D_s^+ + \Lambda_c^+ \quad + \text{c.c.}$$

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

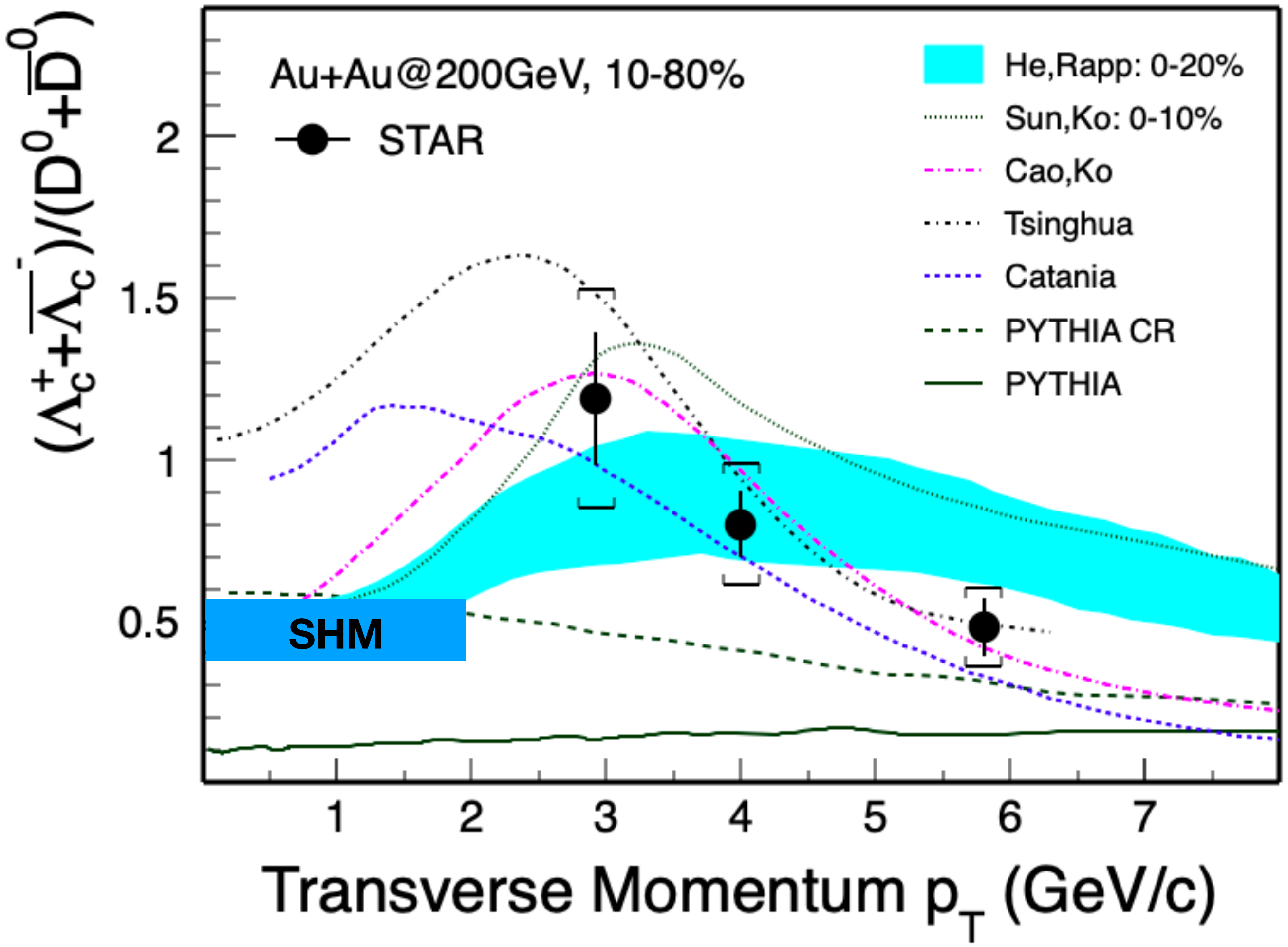


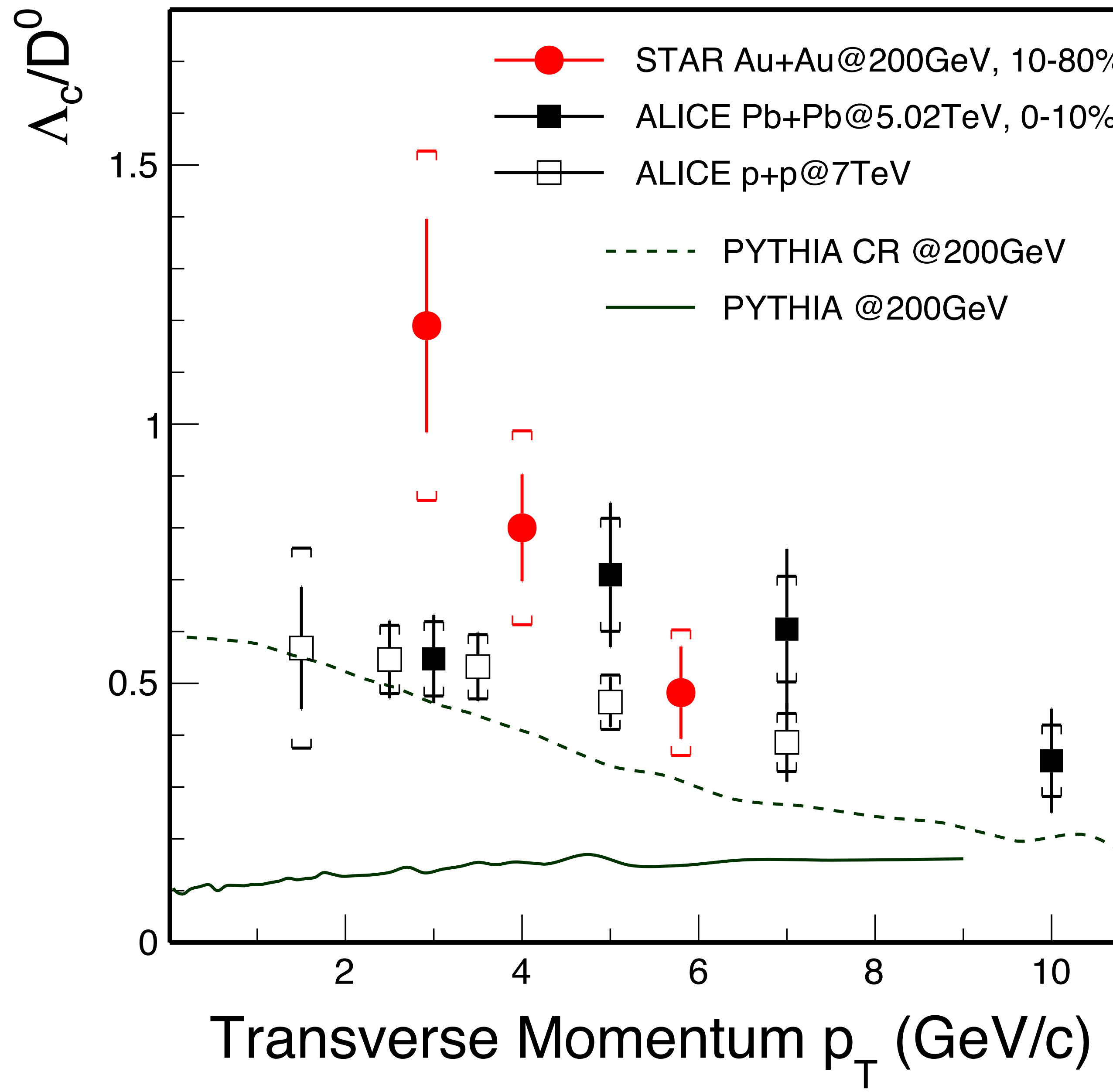


STAR, PRL 127 (2021) 092301, CMS, PAS-HIN-18-017
ALICE, JHEP 1810 (2018) 174, EPJC77 (2017) 550

- 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

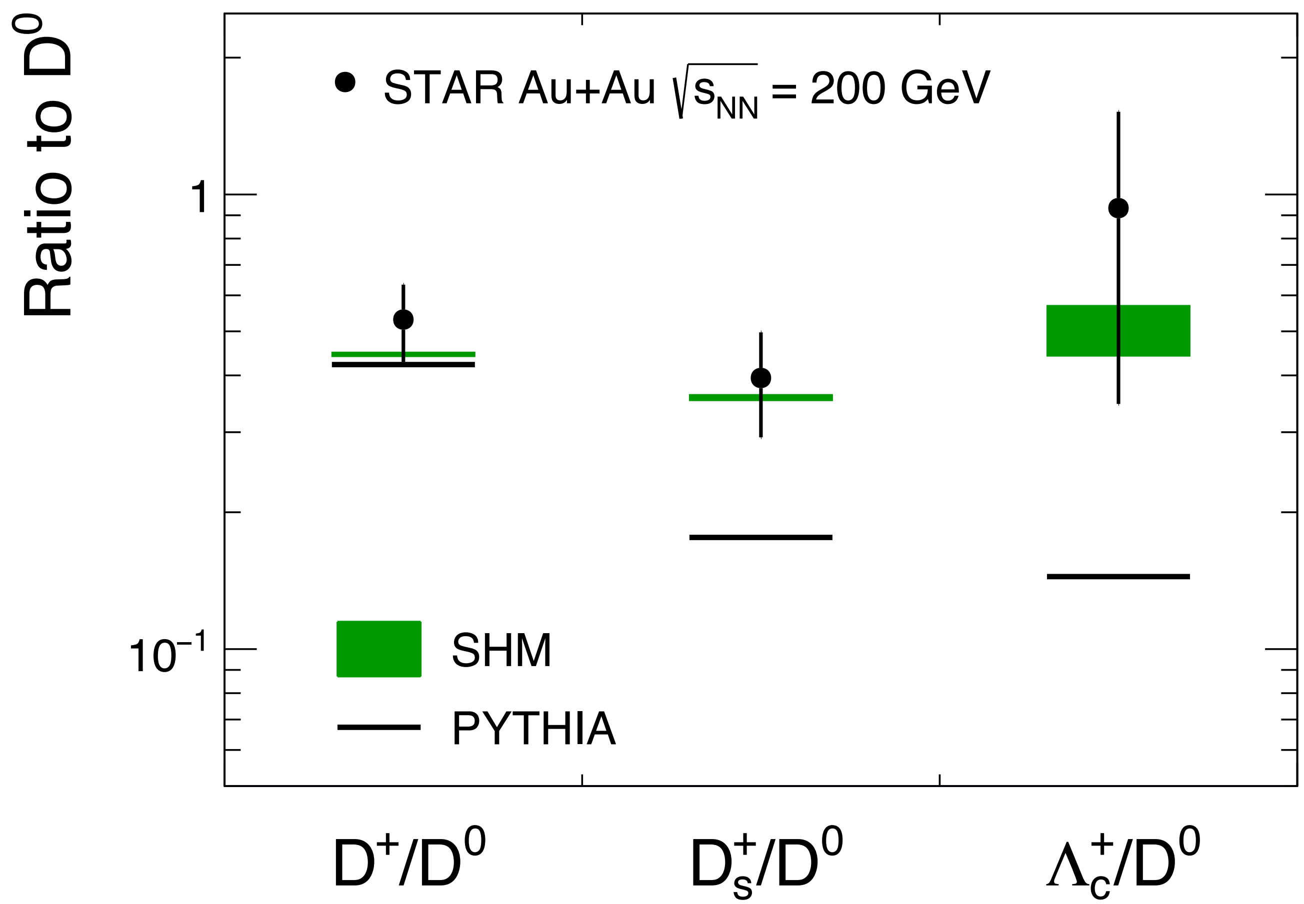




STAR, PRL 124 (2020) 172301
ALICE, JHEP 04 (2018) 108, QM19
CMS, PLB 803 (2020) 135328

- 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

Charm Hadrochemistry



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%*

SHM: THERMUS calculations
chemical FO parameters from the fit to light/strange hadrons

at RHIC top energy

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

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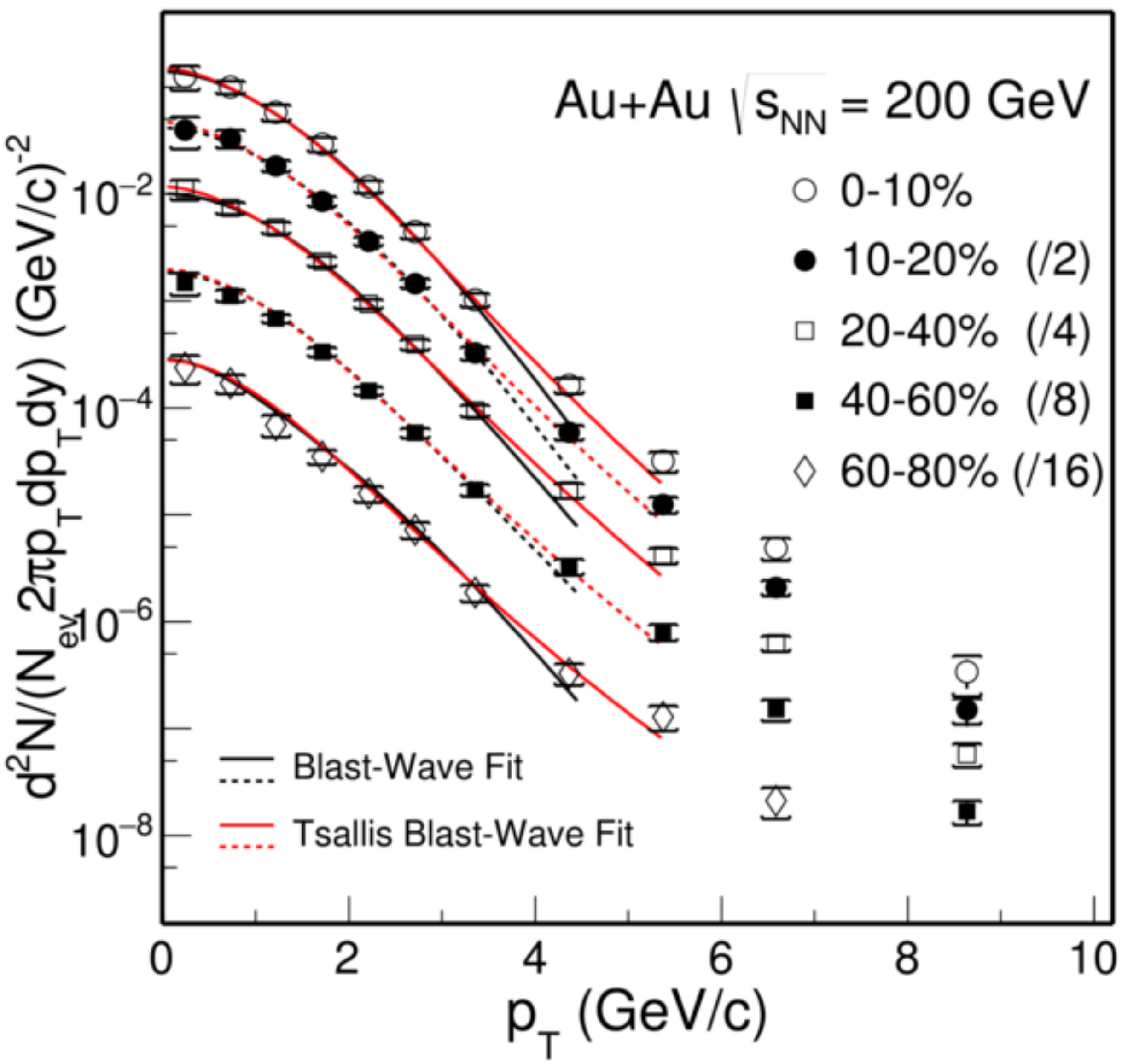
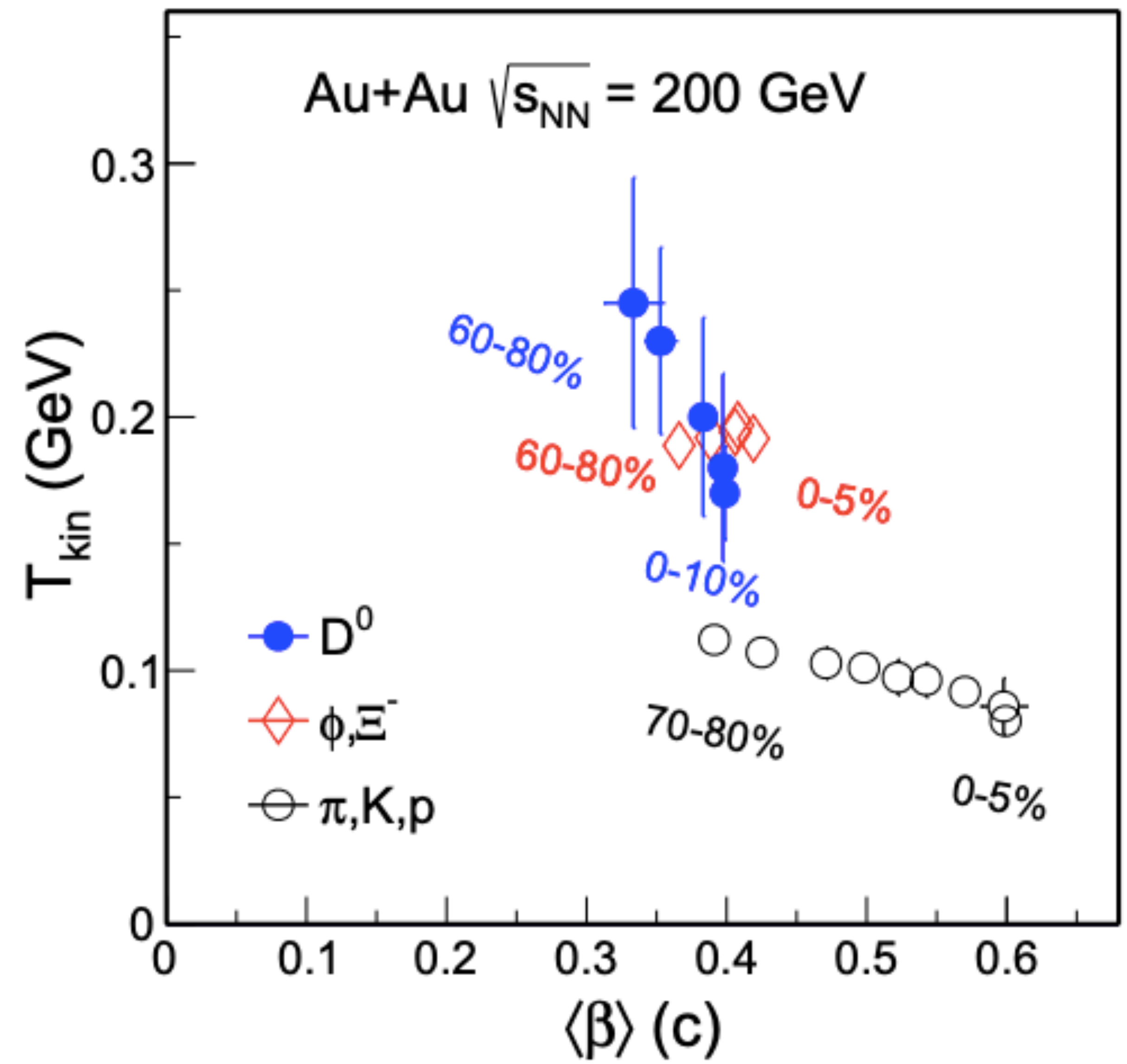
Collectivity - Radial Flow

(Tsallis) Blast-Wave fits



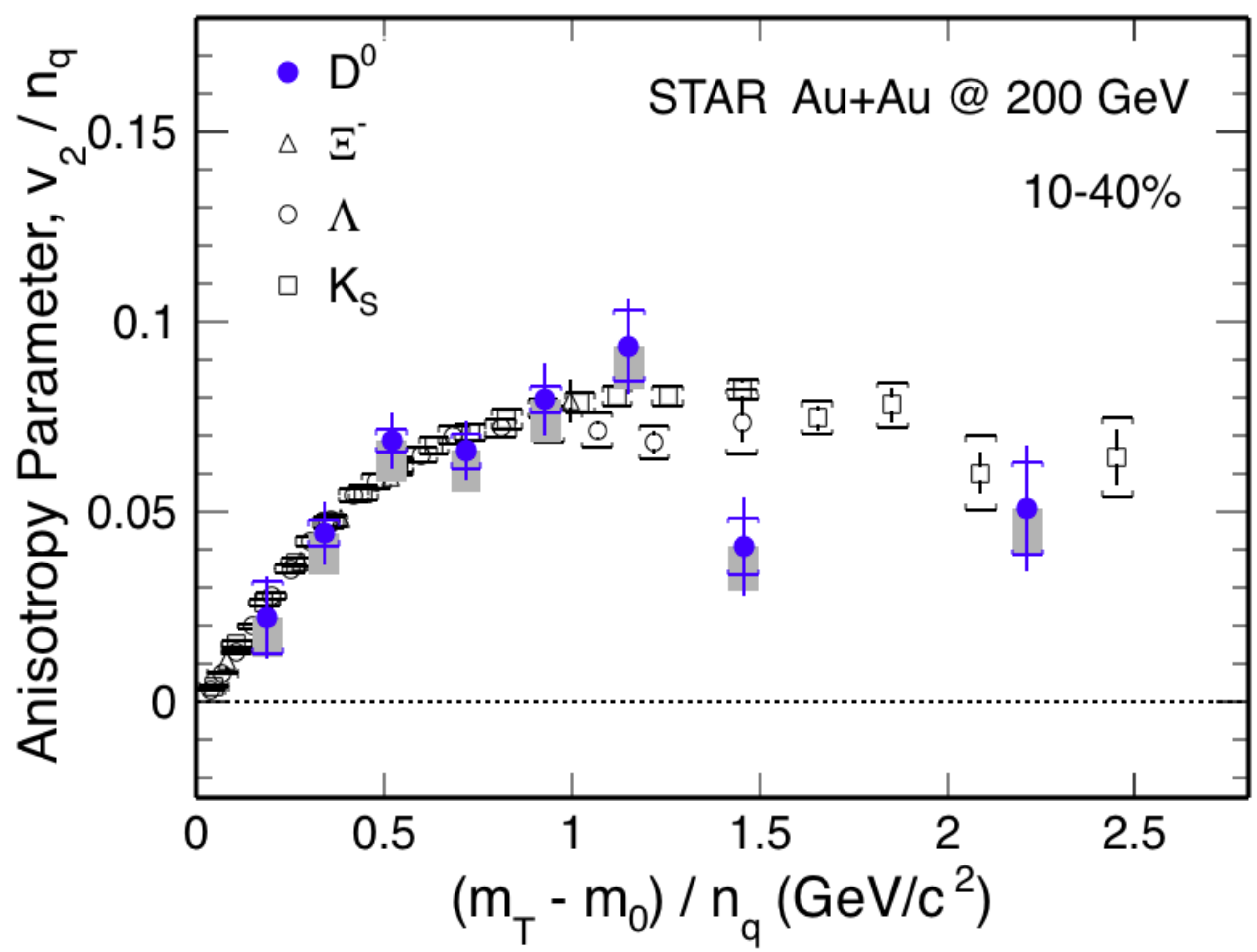


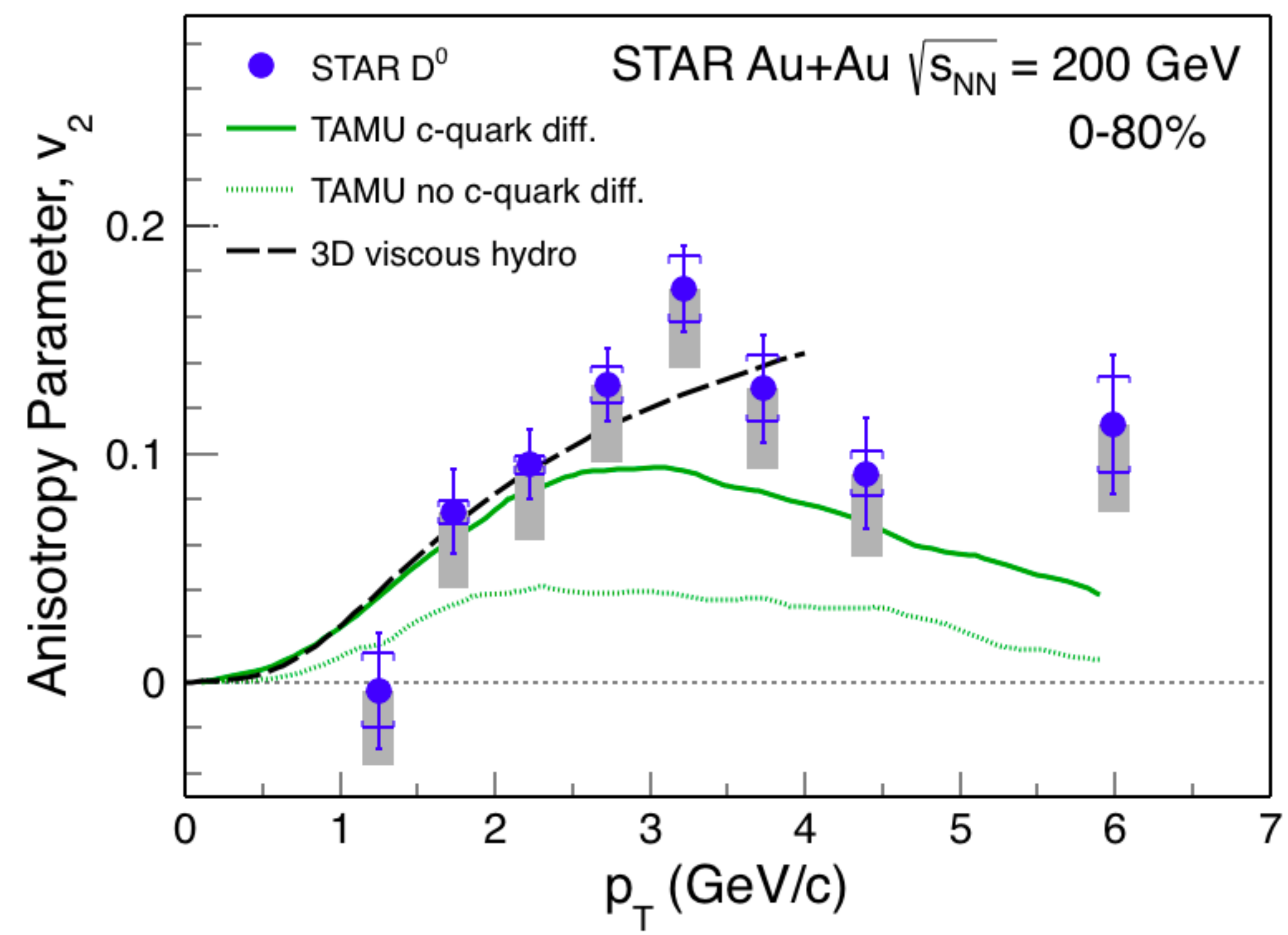
STAR, PRC 99 (2019) 034908

- Blast-wave model fit: similar to multi-strange harons, 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

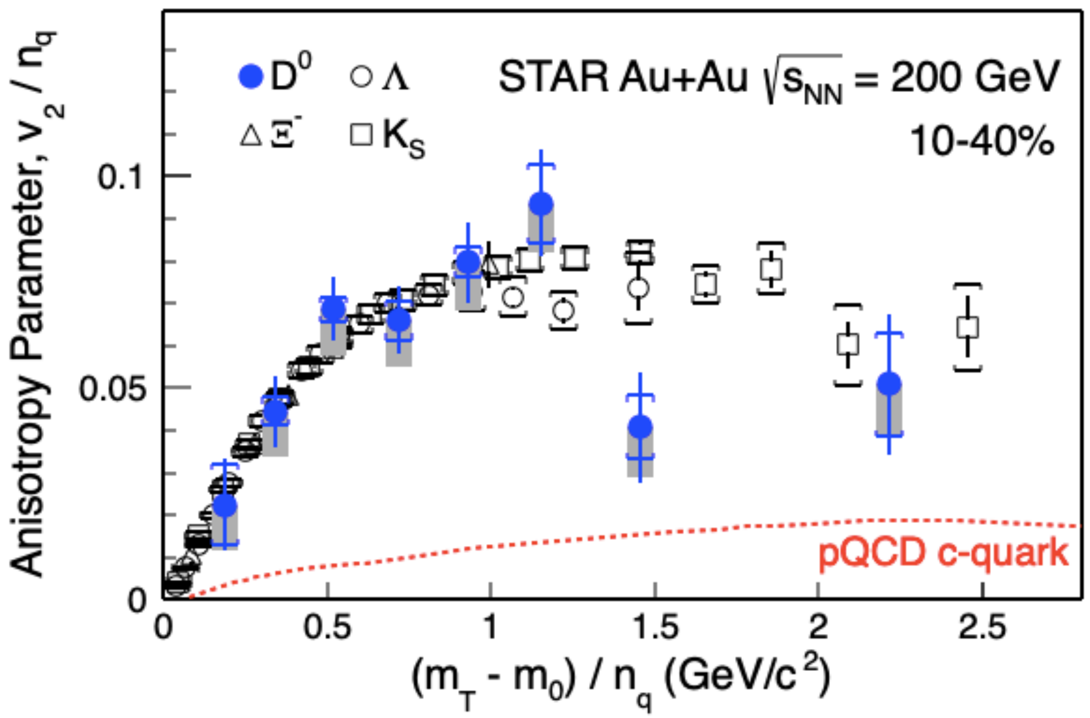


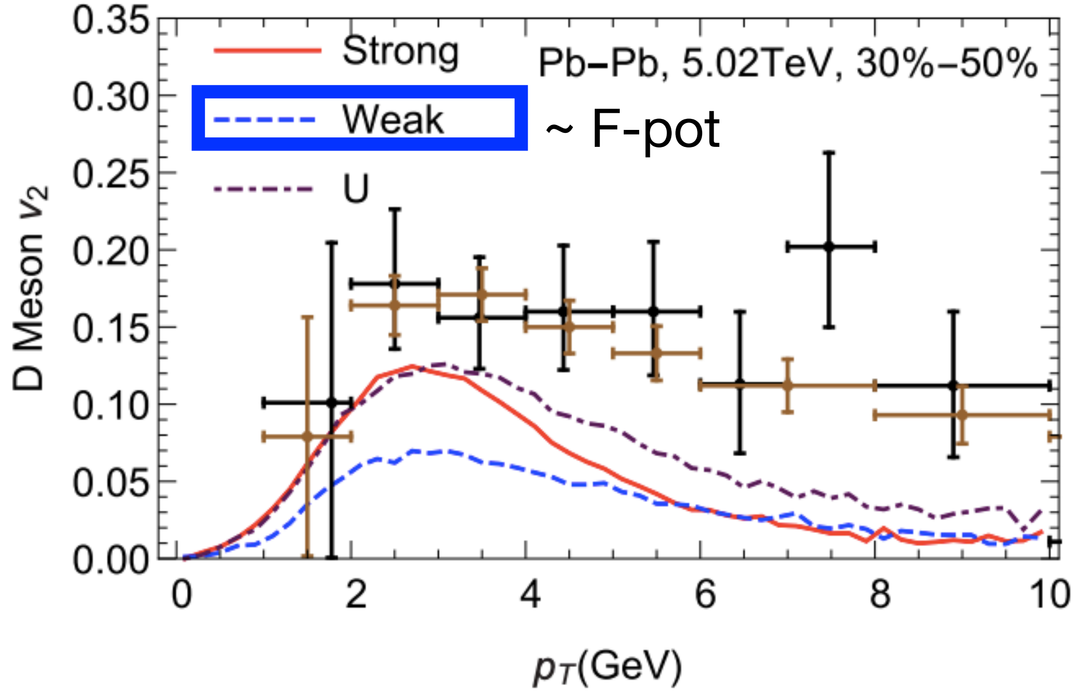


- v_2(D) follows the $(m_T - m_0)/n_q$ scaling as light hadrons

  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



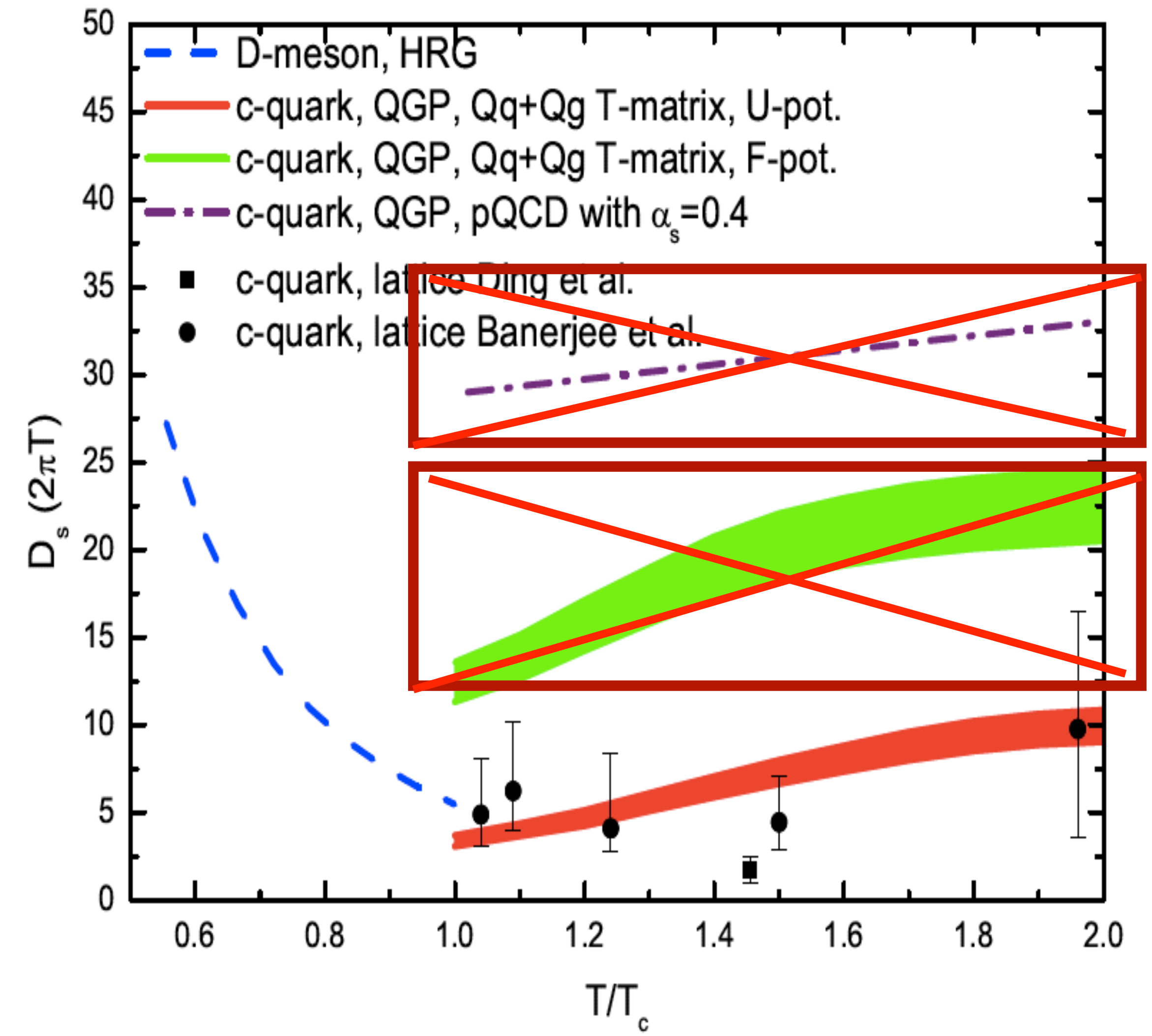


pQCD c-quark (b=7fm):

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

T-Matrix with F-pot:

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

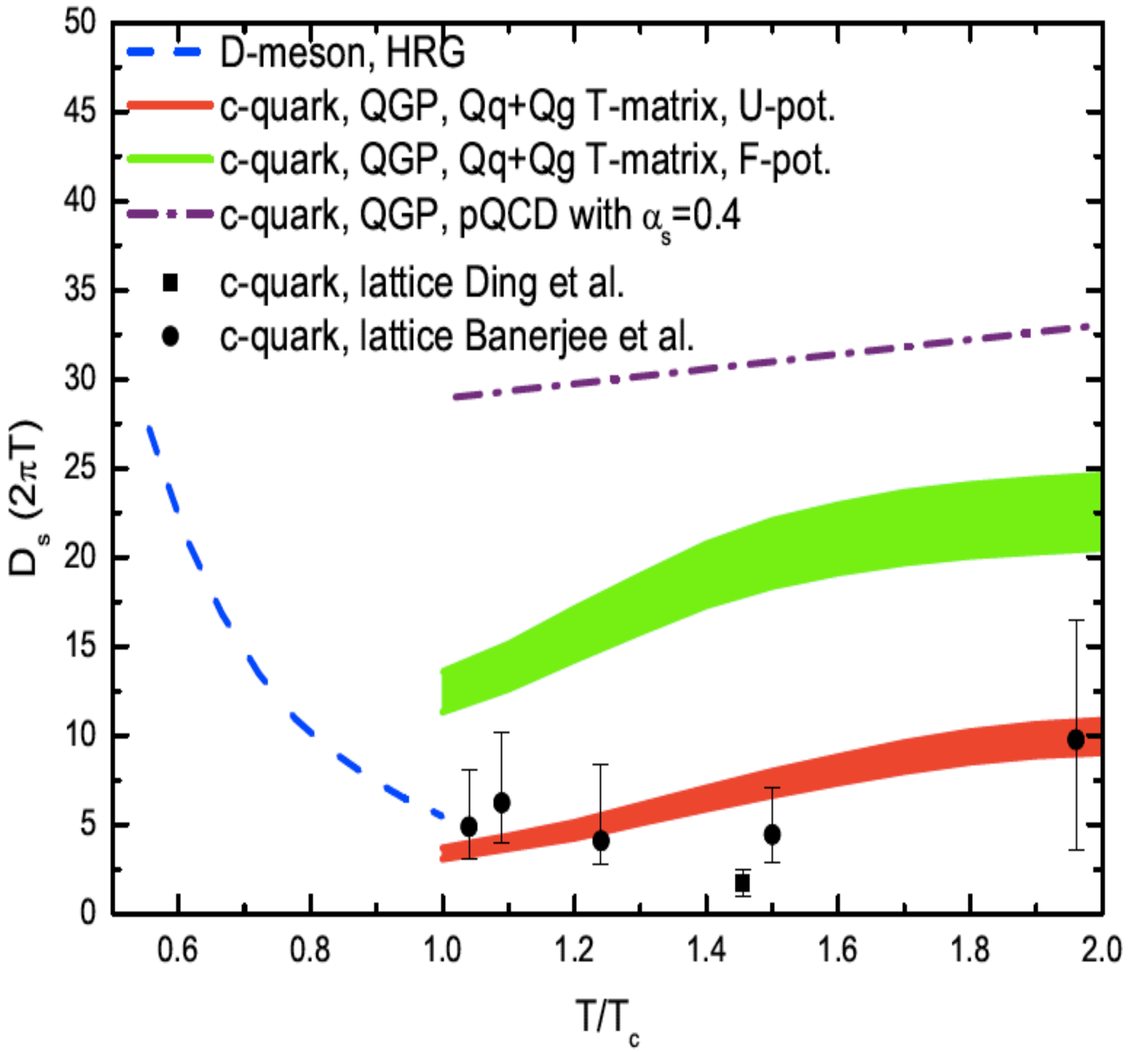


- pQCD calculation and T-Matrix with F-pot. cannot reproduce the data

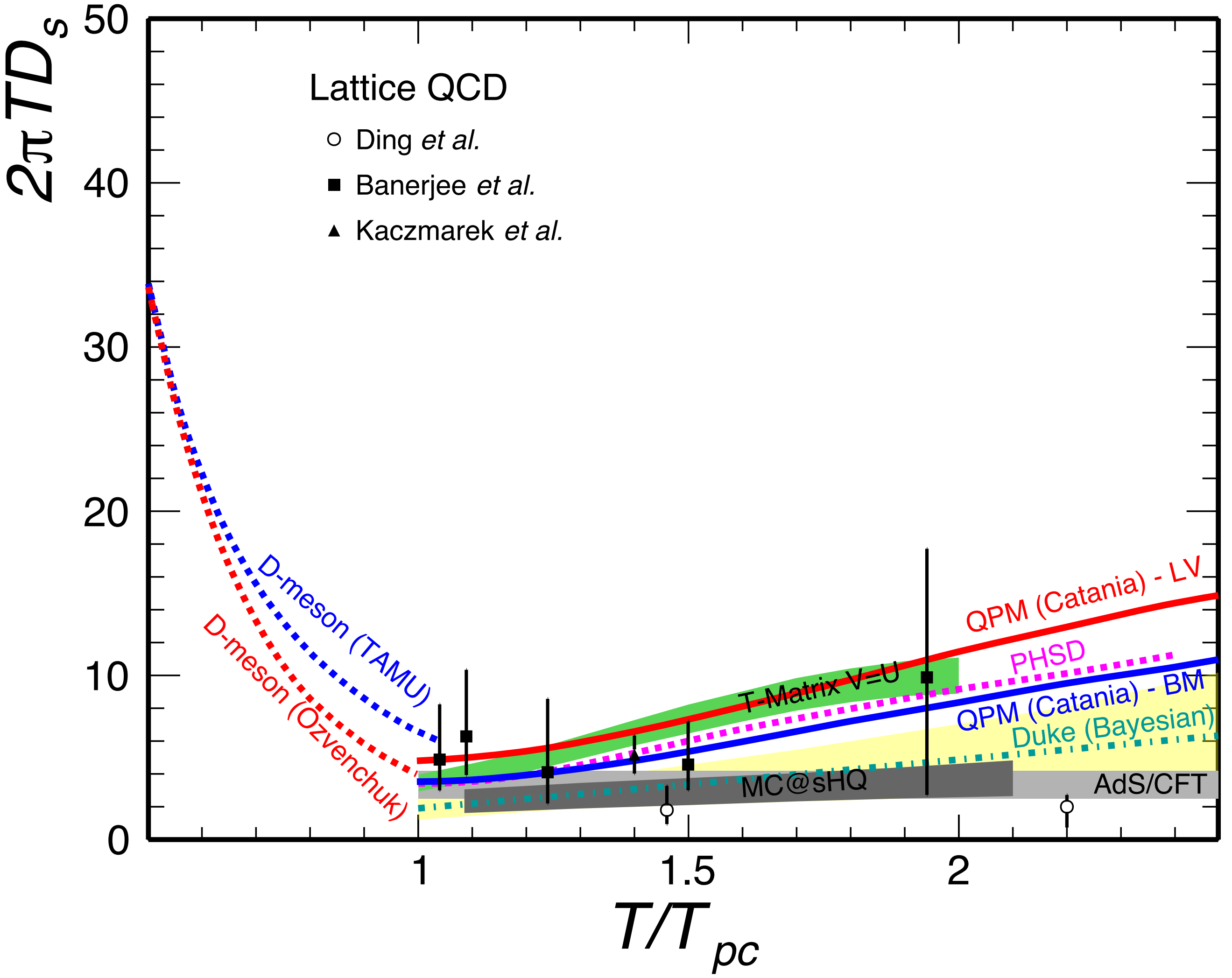
  - heavy quarkonium R_{AA} data disfavors F-pot.

Charm Spatial Diffusion Coefficient

2015



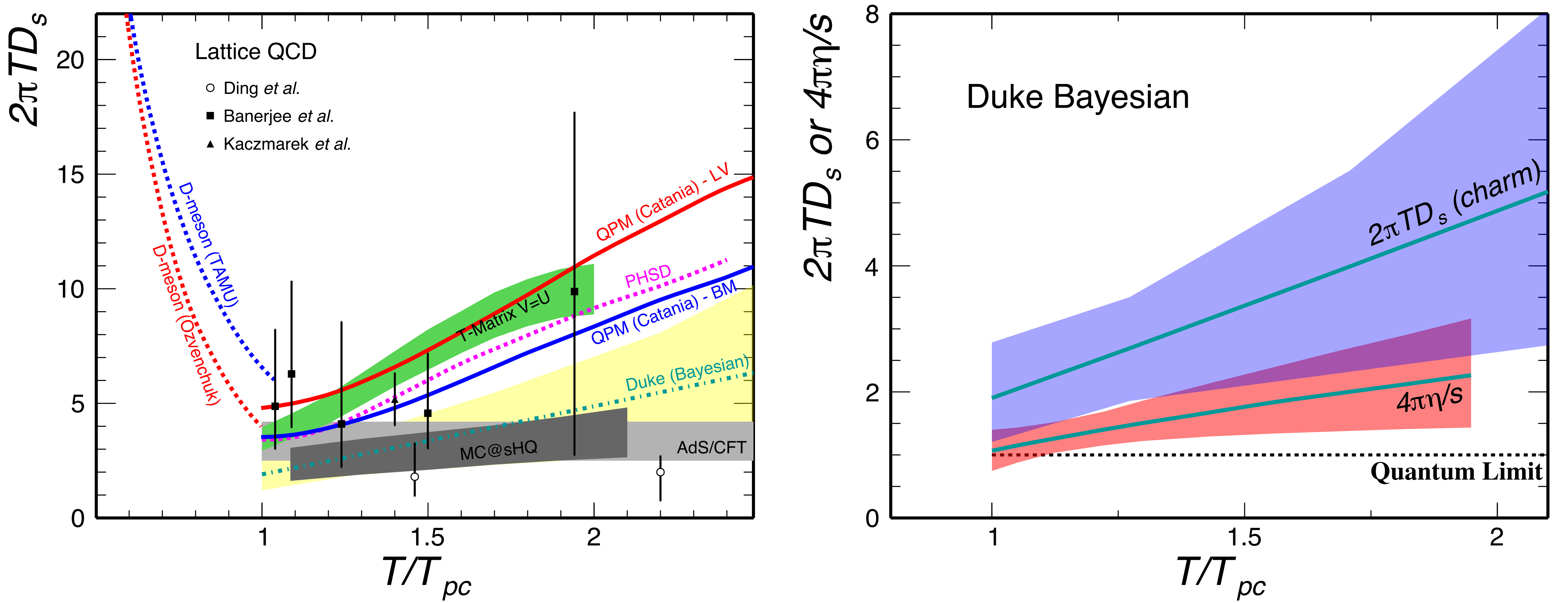
2019



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

Strongly interacting QGP!

sQGP Transport Parameters



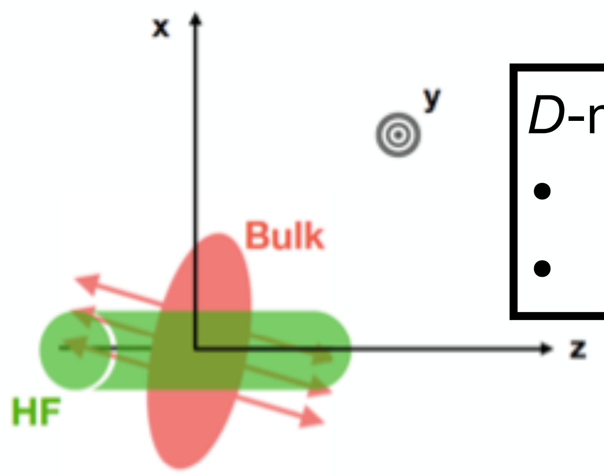
$2\pi TD_s$: *Y. Xu et al, PRC 97 (2018) 014907*
η/s: *J. Bernhard et al, Nature Physics 115 (2019) 1113*

- 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



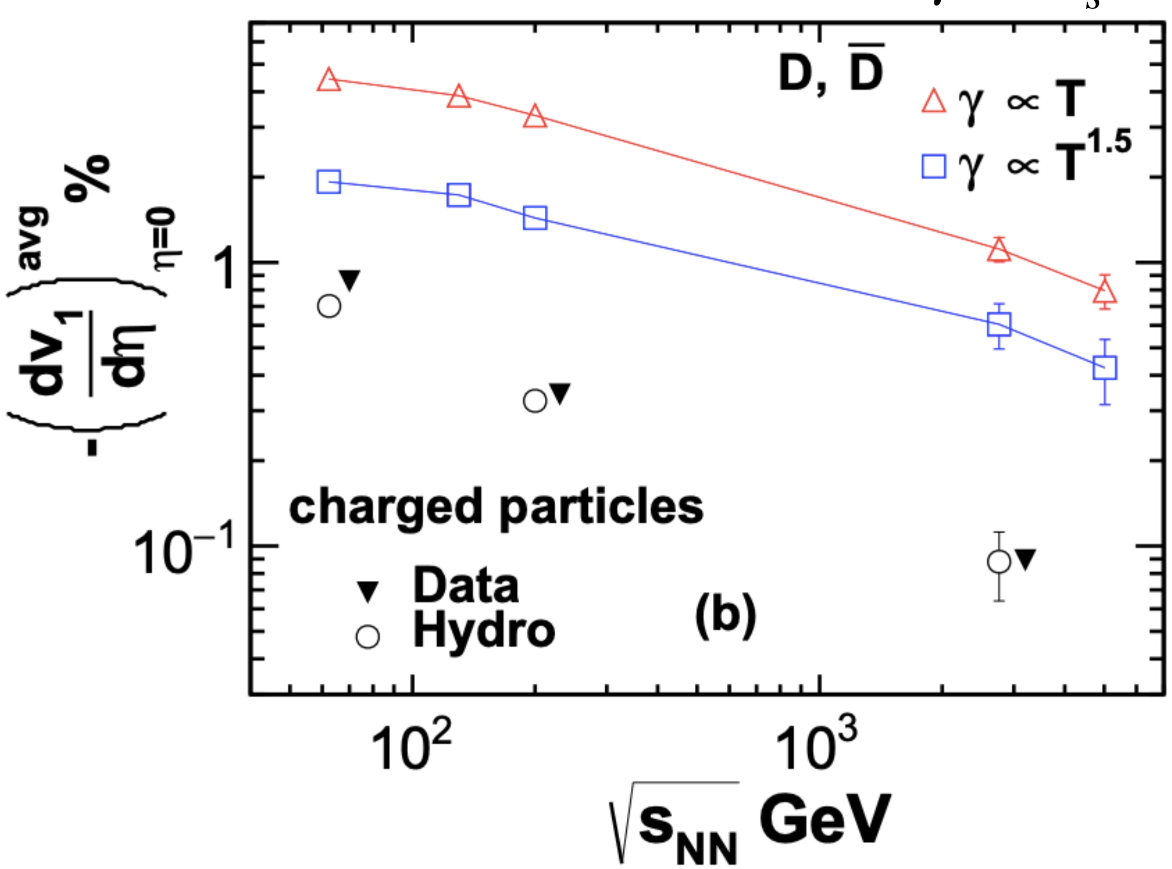
D-meson v_1 sensitive to

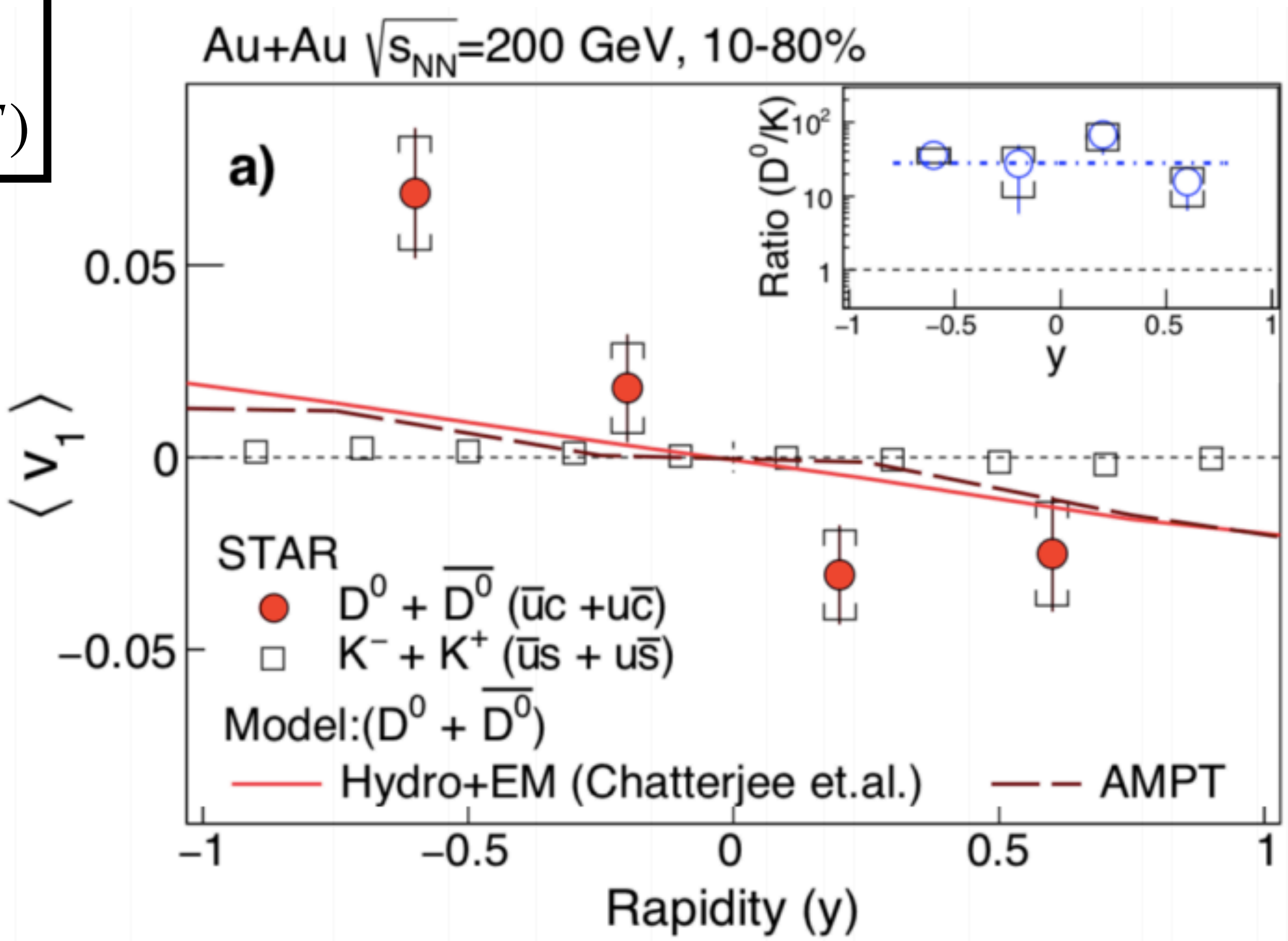
- geometry tilt of QGP source
- HQ diffusion coefficient $D_s(T)$

STAR, PRL 123 (2019) 162301

Hydro model

$\gamma = D_s/ET$

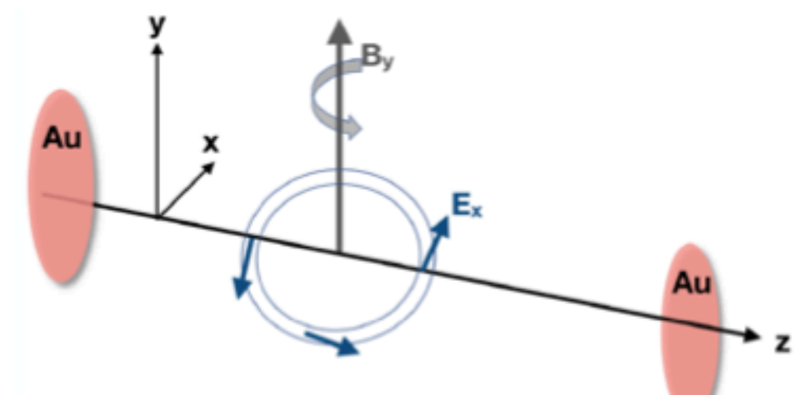




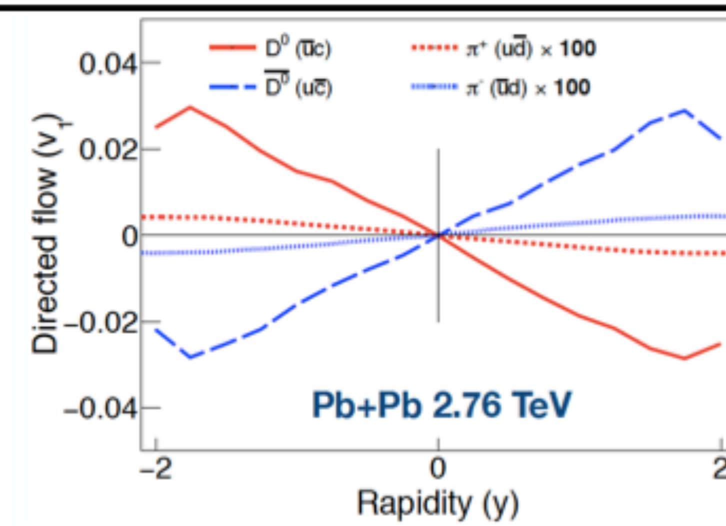
- $v_1(D) \gg v_1(h)$
  - Constraints on T-dependence of HQ diffusion coefficient

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

$D^0/\overline{D}^0$ v₁ difference - Access to Initial B Field

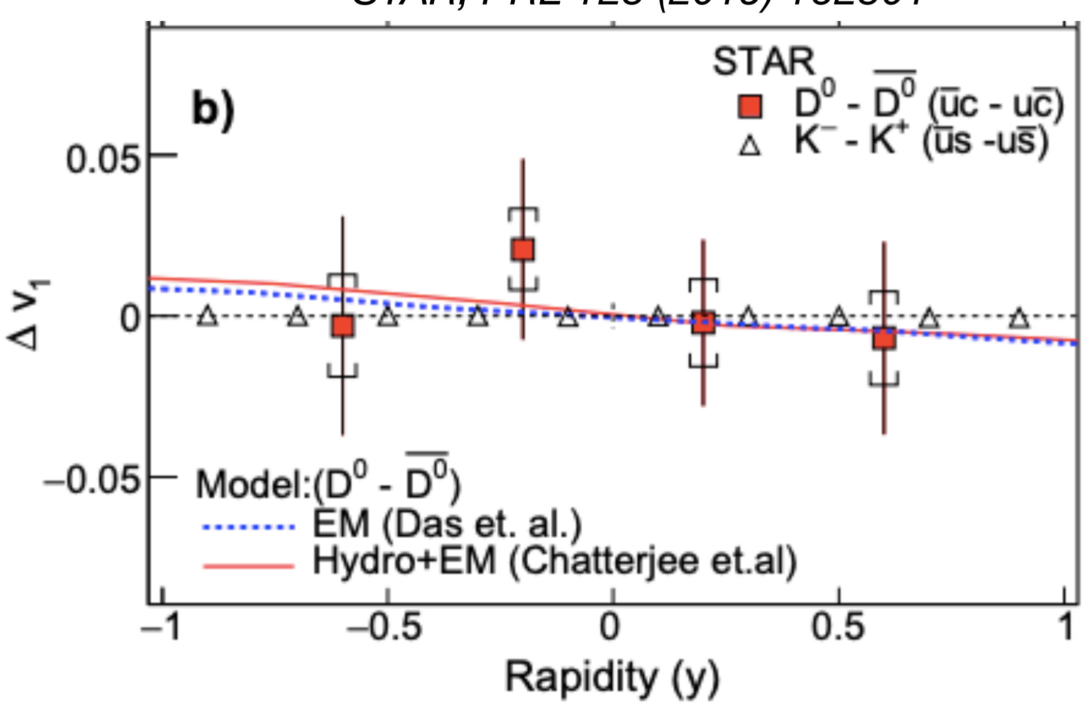


S.K. Das et al, PLB 768 (2017) 260

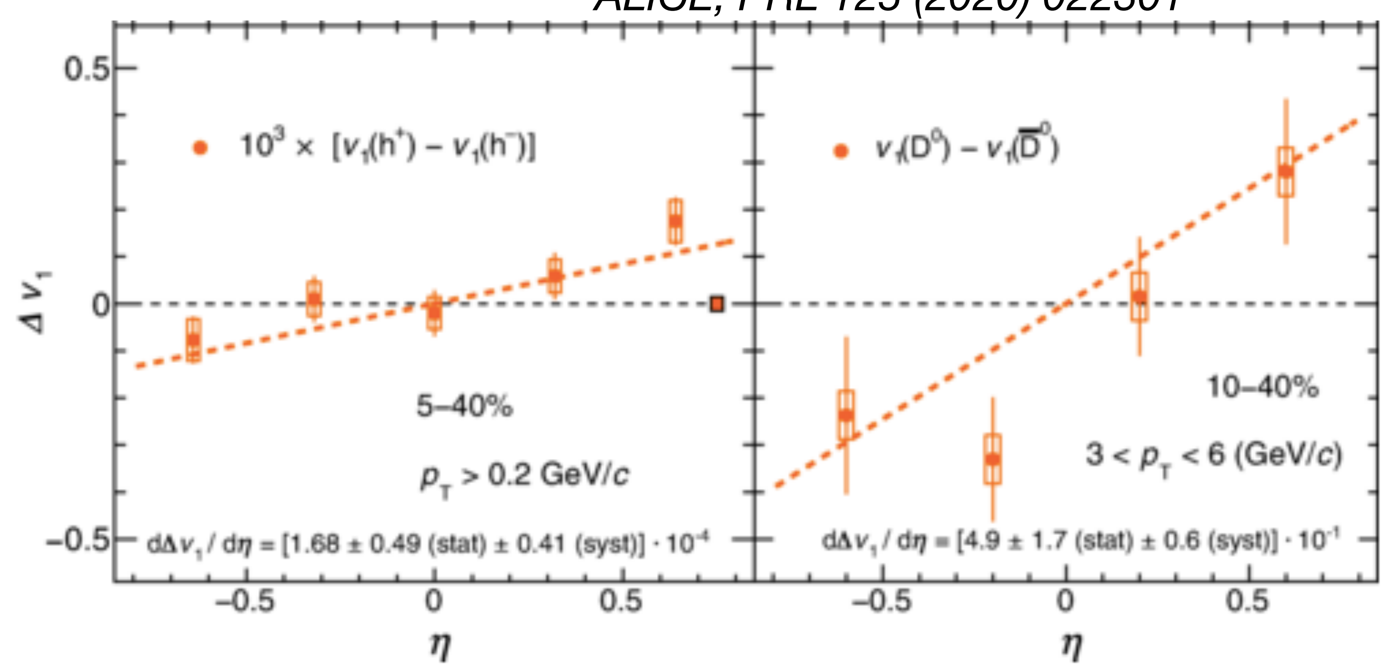


Strong B field in HIC -> $v_1(D) = -v_1(\mathrm{Dbar})$, $v_1(h^+)-v_1(h^-)\sim 0$

STAR, PRL 123 (2019) 162301

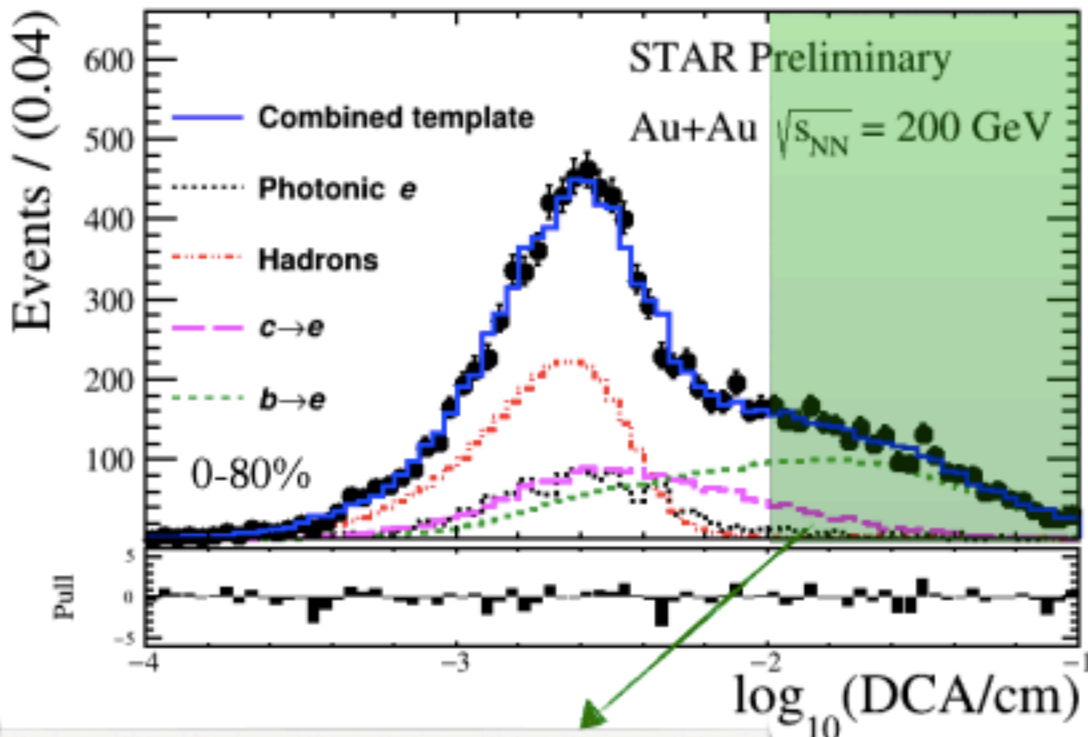


ALICE, PRL 125 (2020) 022301

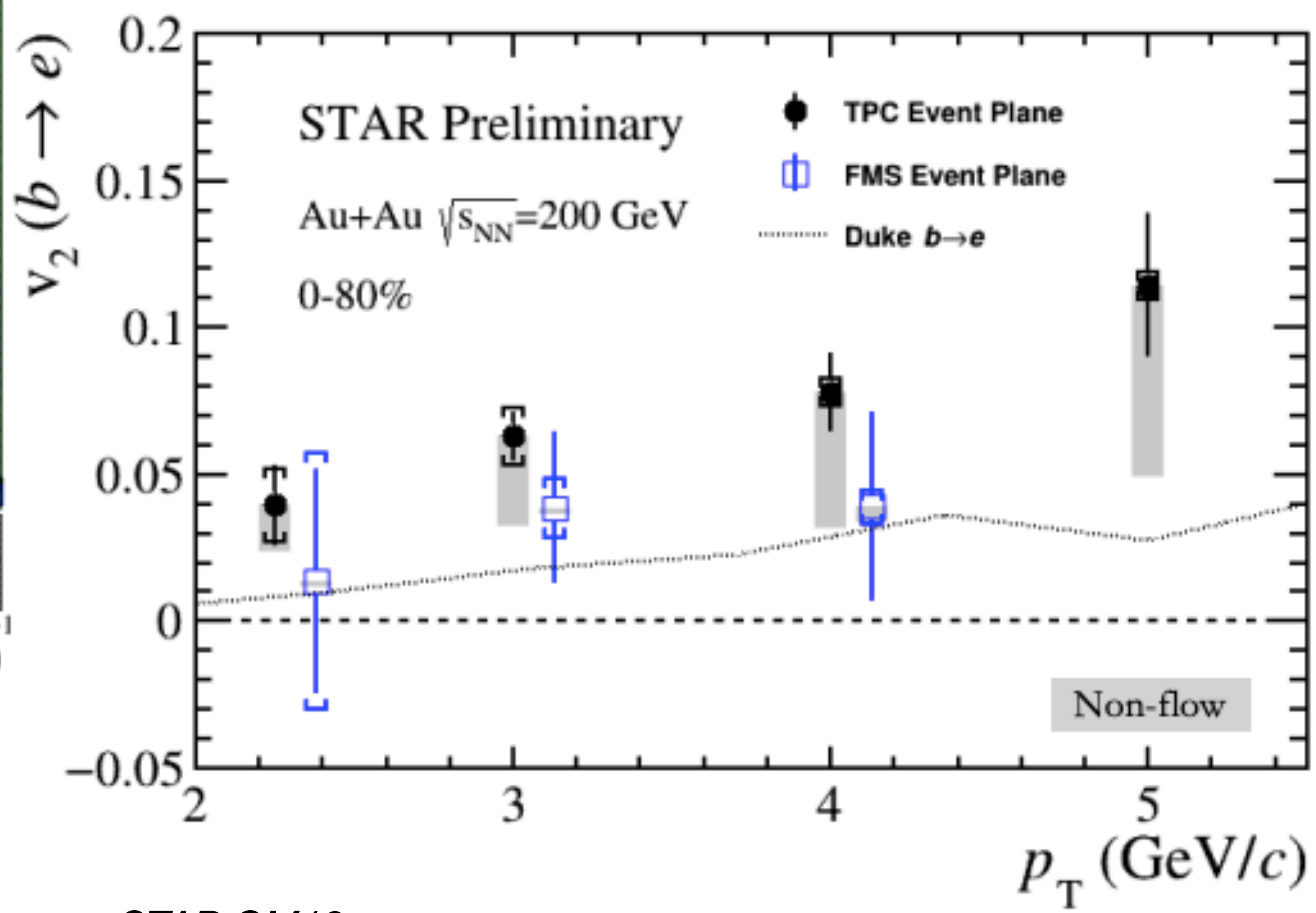


STAR: inconclusive due to experimental uncertainty
ALICE: significant difference, however, opposite sign w.r.t the prediction
→More detailed investigation needed for better understanding

First Look at the Bottom v_2



$$v_2(obs.) = f_b v_2^b + f_c v_2^c + f_{bkg} v_2^{bkg}$$



STAR QM19

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

  Evidence of non-zero bottom v_2 (3.4σ)

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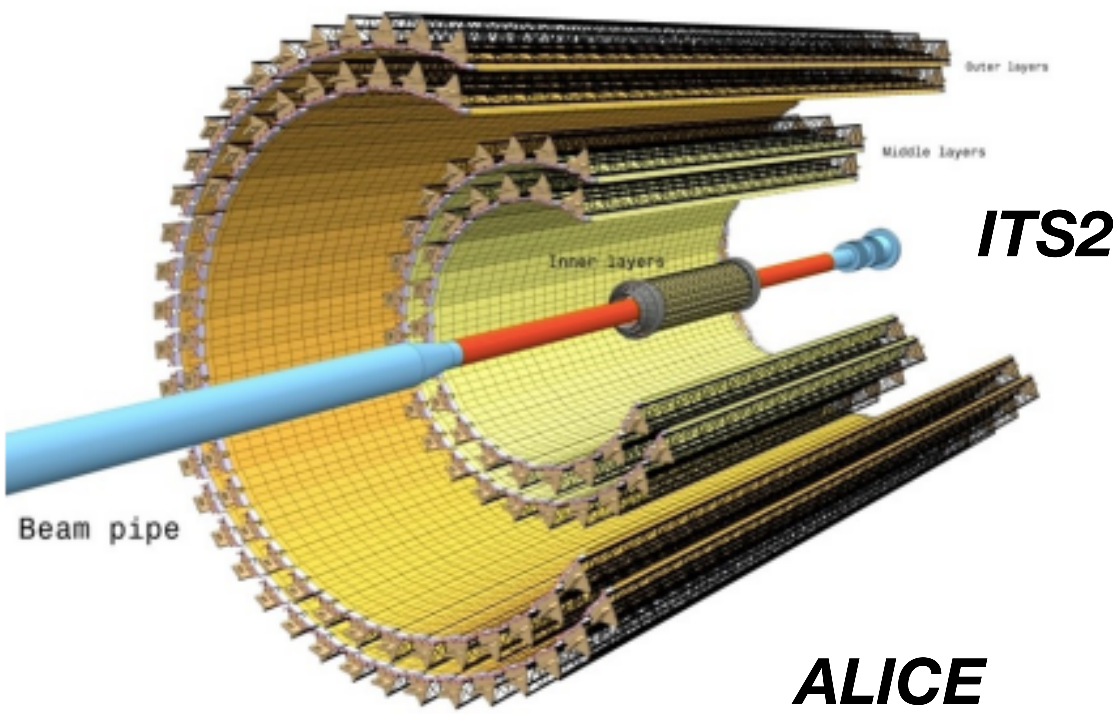
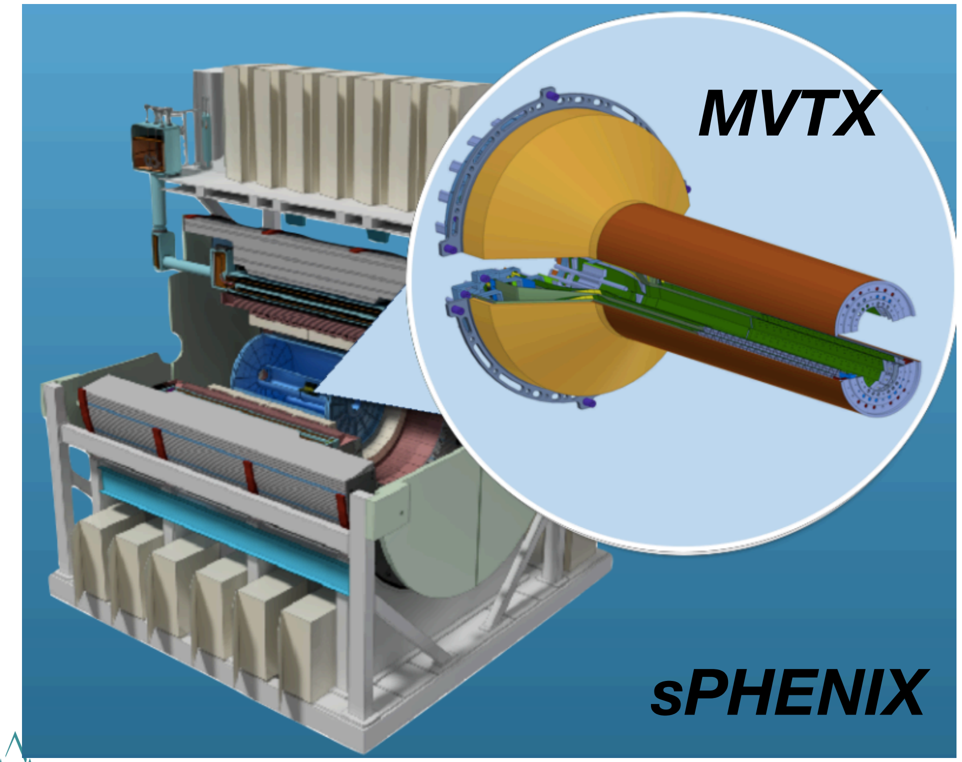
ALICE-ITS2 and sPHENIX MVTX

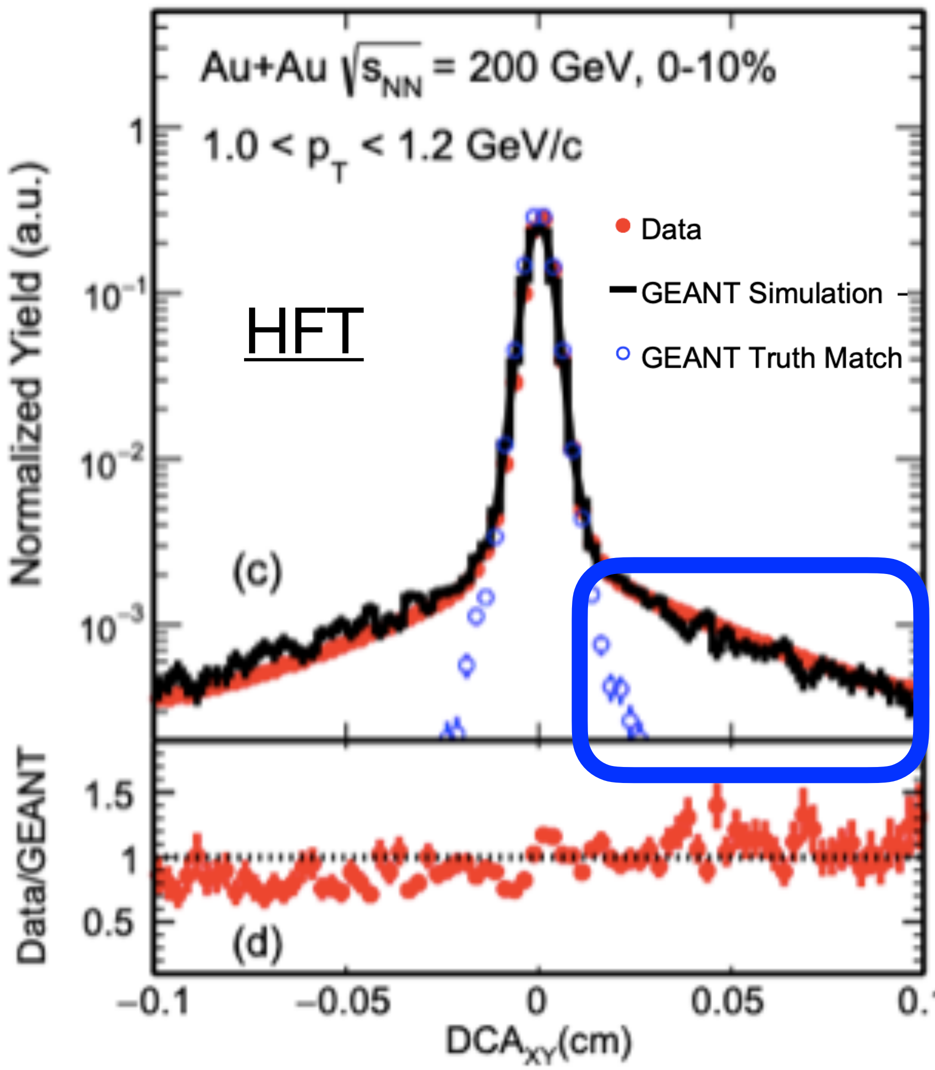


Next generation fast MAPS detector

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

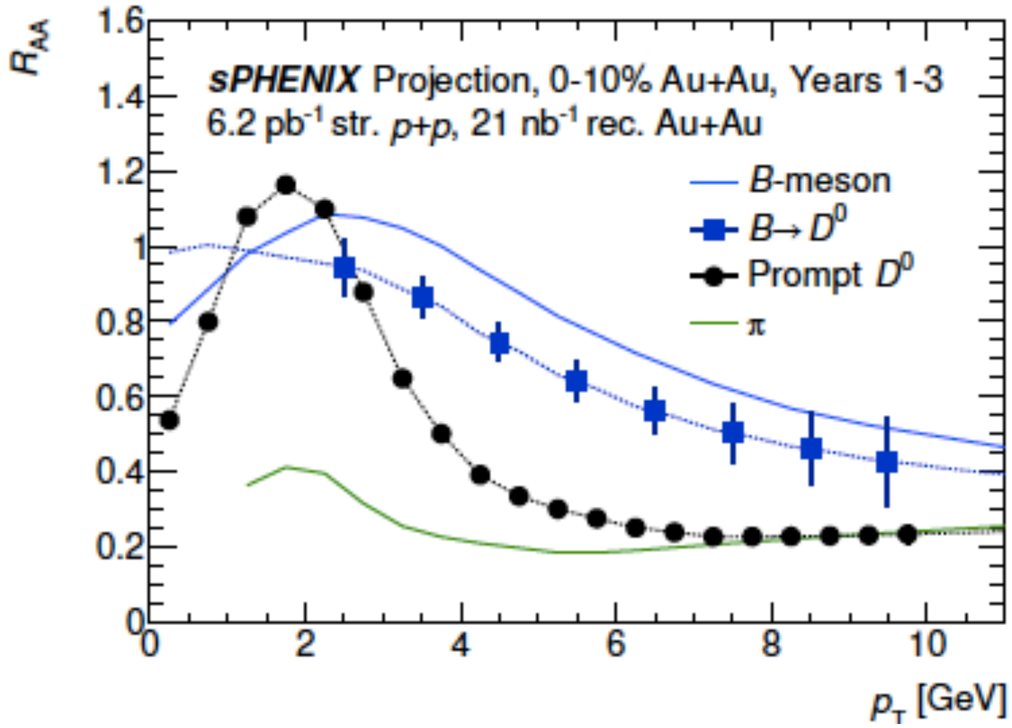
==> background reduced by > x10

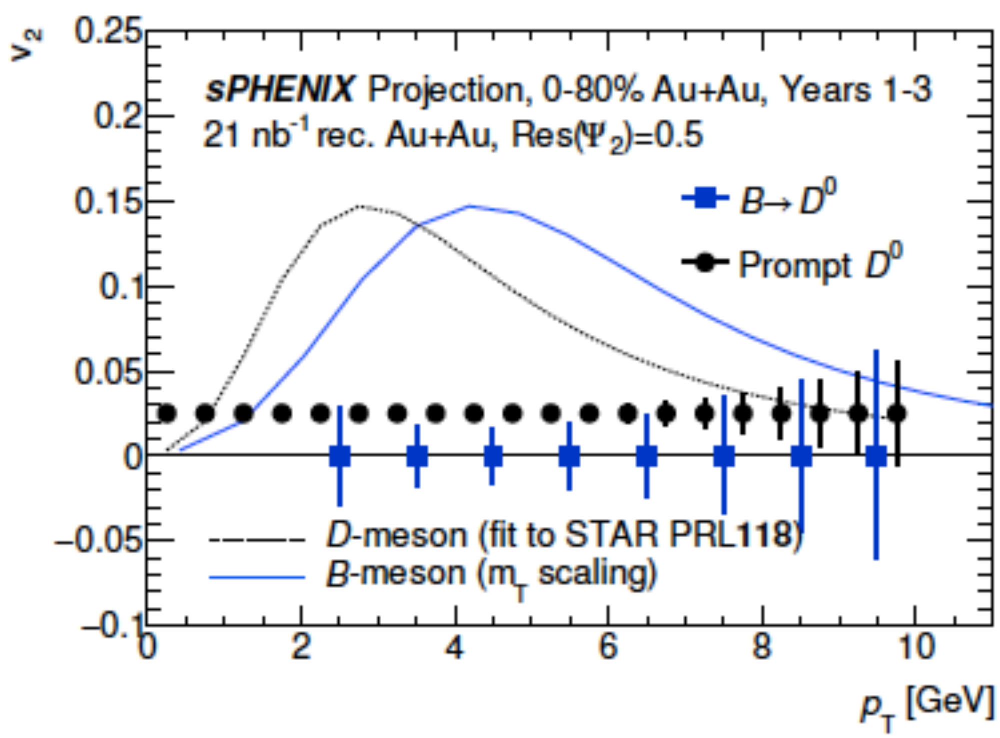




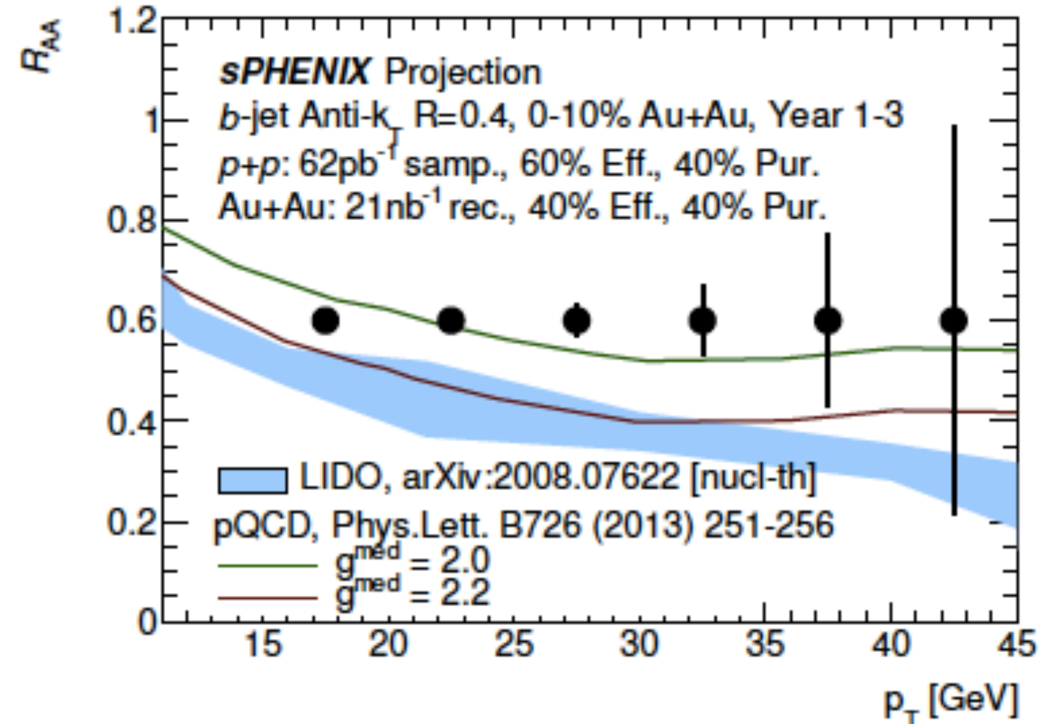
Precision Measurement of Open-Bottom at RHIC

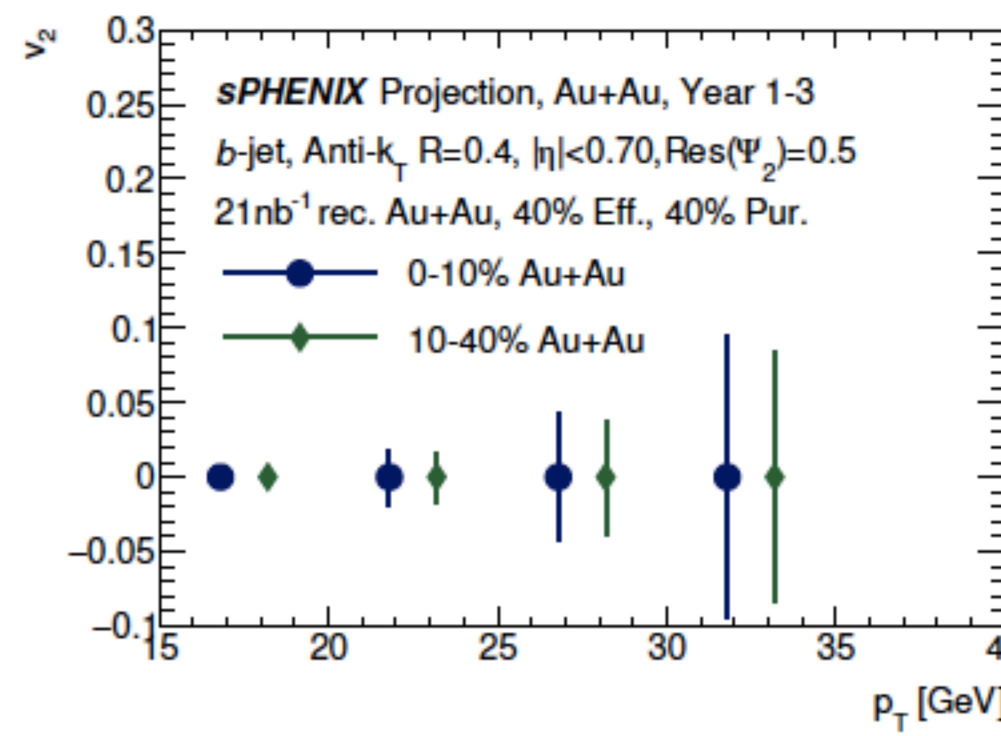
B-meson via non-prompt D^0





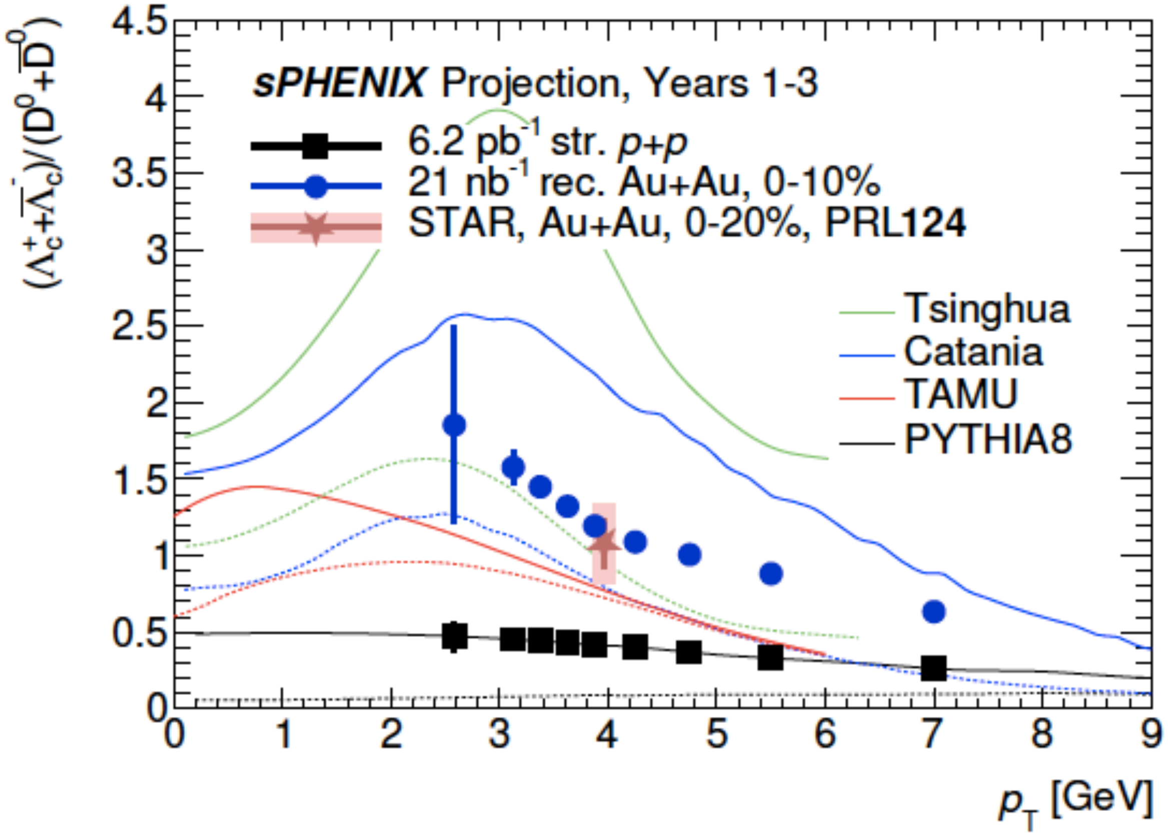
b-jet





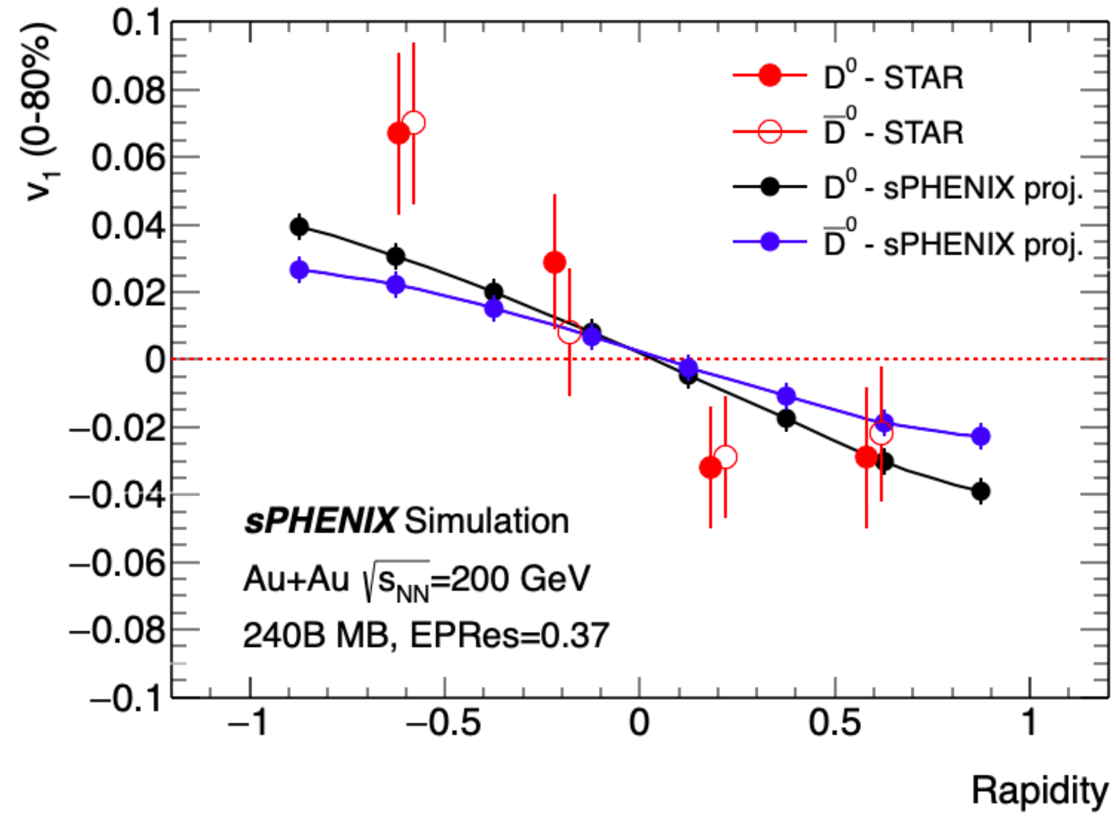
Fruitful Charm/Bottom Physics

Charm/Bottom Hadrochemistry



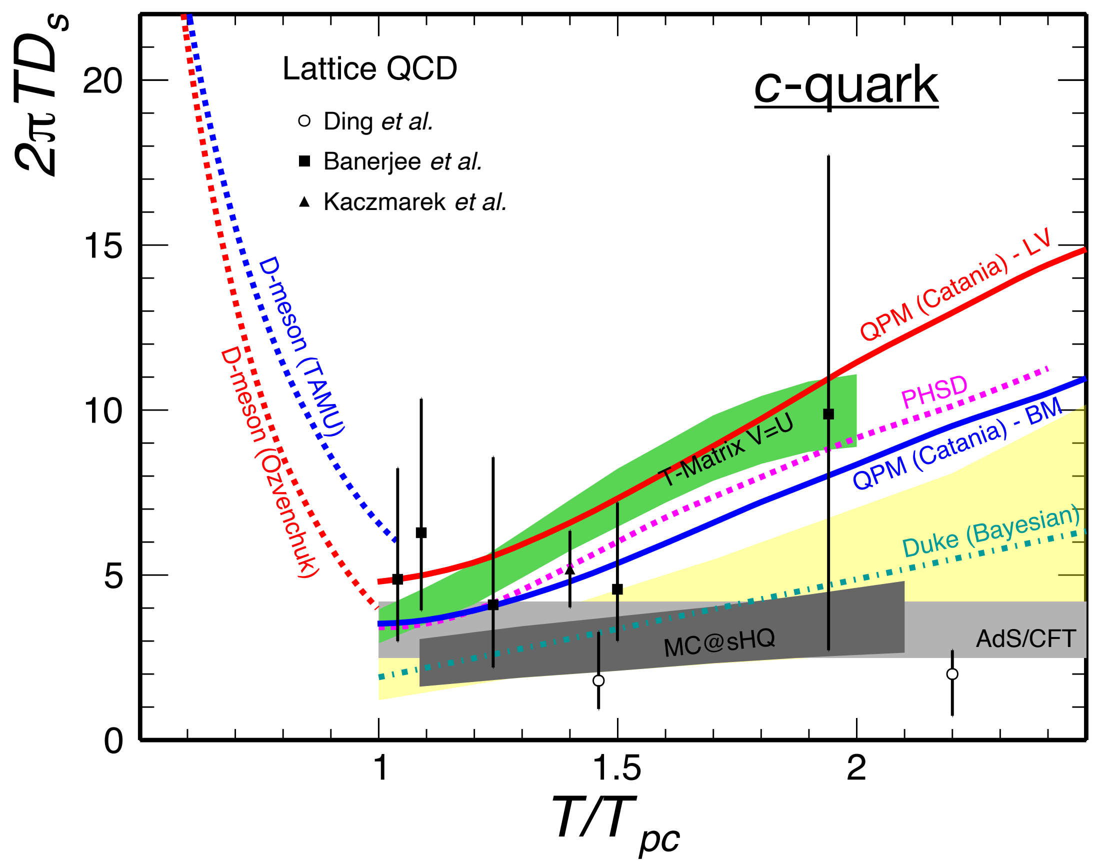
- Precise measurement of various charm hadrons (Λ_c^+,D_s^+)
- Enable access to open bottom hadrons (Λ_b, B_s etc)
- Detail investigation of charm baryon spectroscopy in p+p collisions

$D^0/\overline{D}^0$ 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

Summary



<u>charm quarks in medium</u>

- significant energy loss
- significant collectivity
- coalescence hadronization

- $2\pi TD_s$ **~ 2-5 @ T$_c$**

	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: MVTX@sPHENIX, ITS2@ALICE,
Precision open bottom
Heavy flavor baryons and correlations

Backup

Uniqueness of Heavy Flavor Quarks

m_u m_d — m_s — Λ_{QCD} — m_c — m_b — MeV

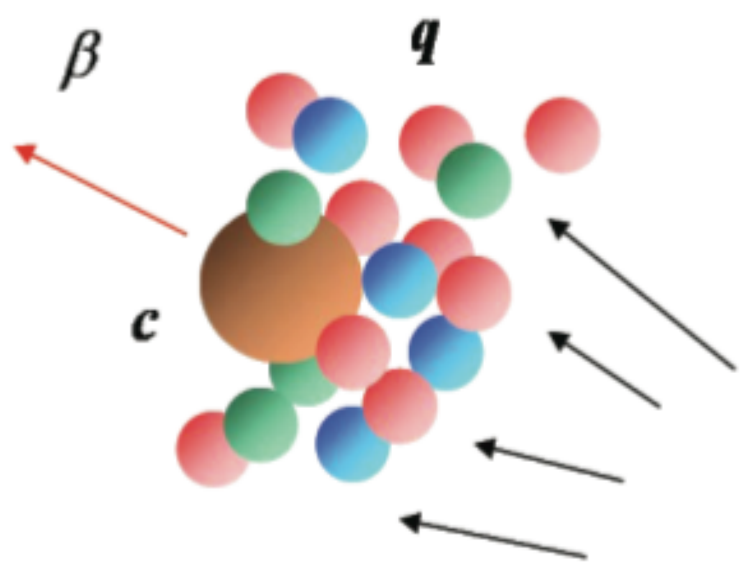
1 — 10 — 10^2 — 10^3 — 10^4

T_c — T_{QGP}

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

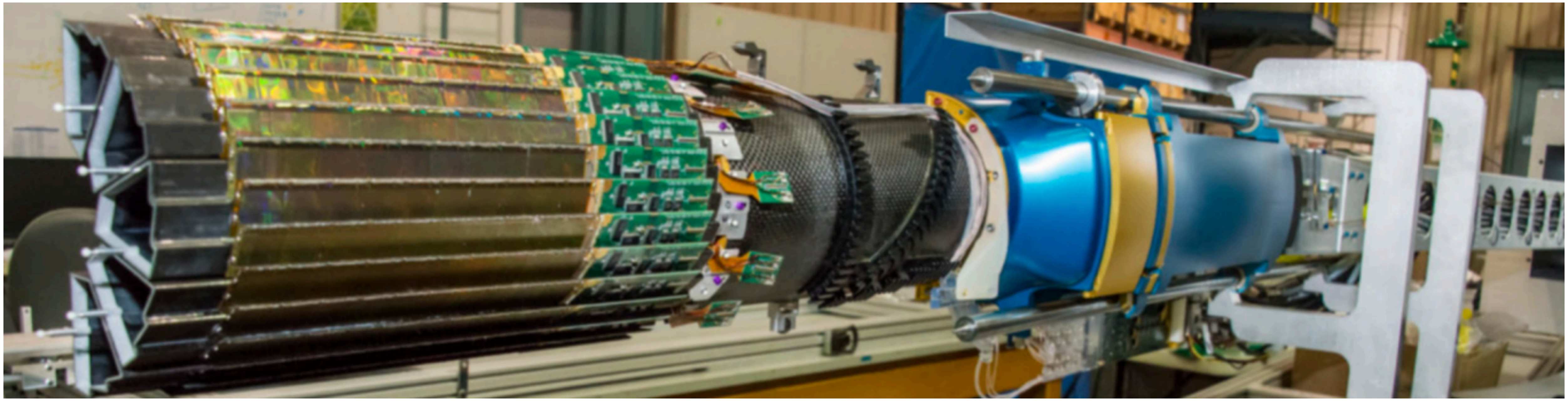
$$\frac{\partial \rho}{\partial t} = D\frac{\partial^2 \rho}{\partial x^2} \qquad \langle x^2(t)\rangle - \langle x^2(0)\rangle \sim Dt$$

D or D_s - spacial diffusion coefficient

- used to reveal medium substructures
- e.g.

$$D = \frac{RT}{N_A 6\pi\eta a} = \frac{k_B T}{6\pi\eta a}$$

STAR Heavy Flavor Tracker (HFT)

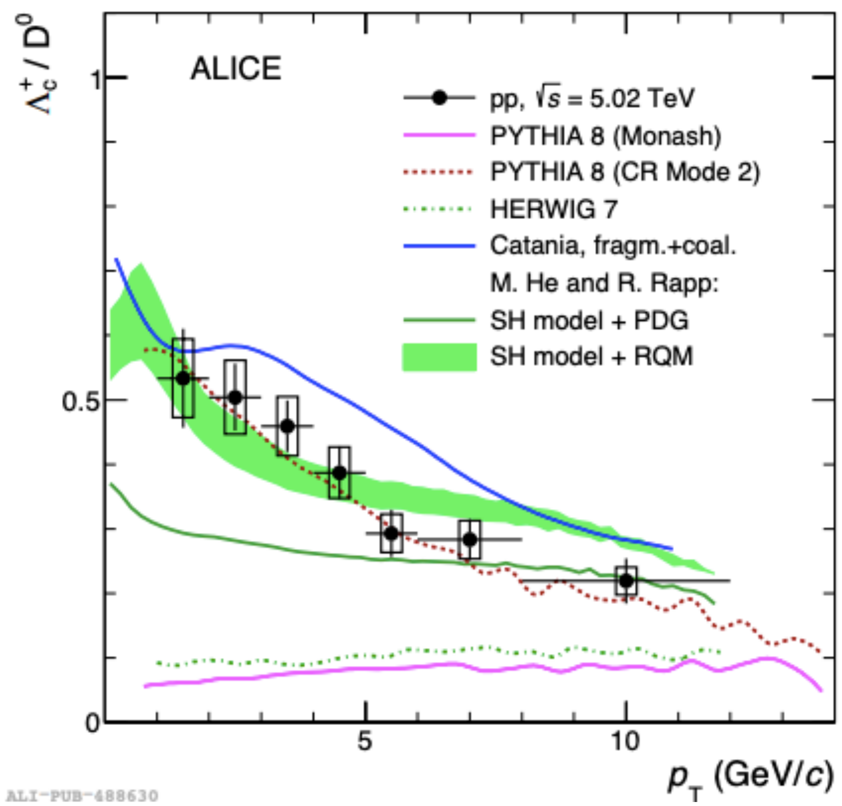


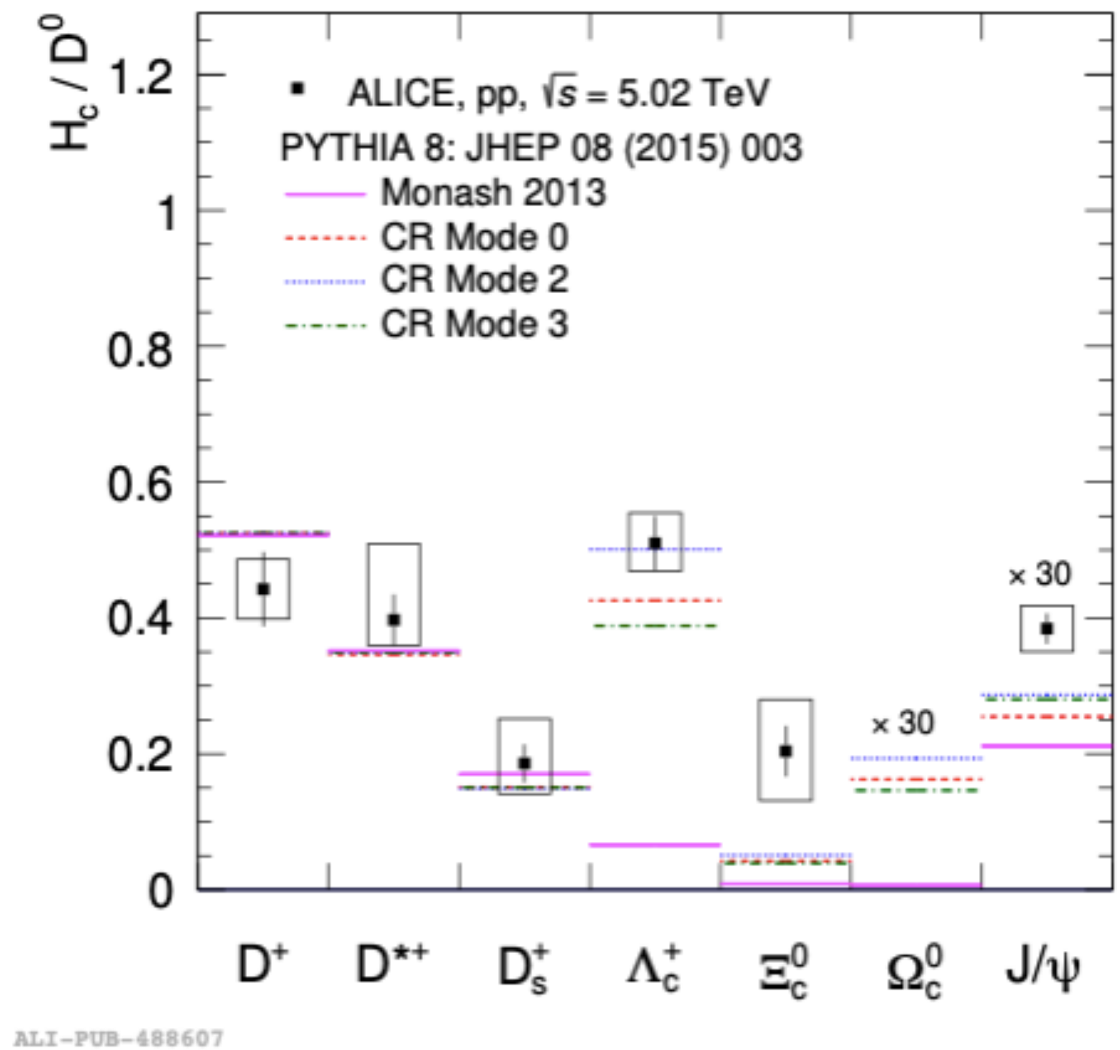
G. Contin et al, NIMA 907 (2018) 60

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** *

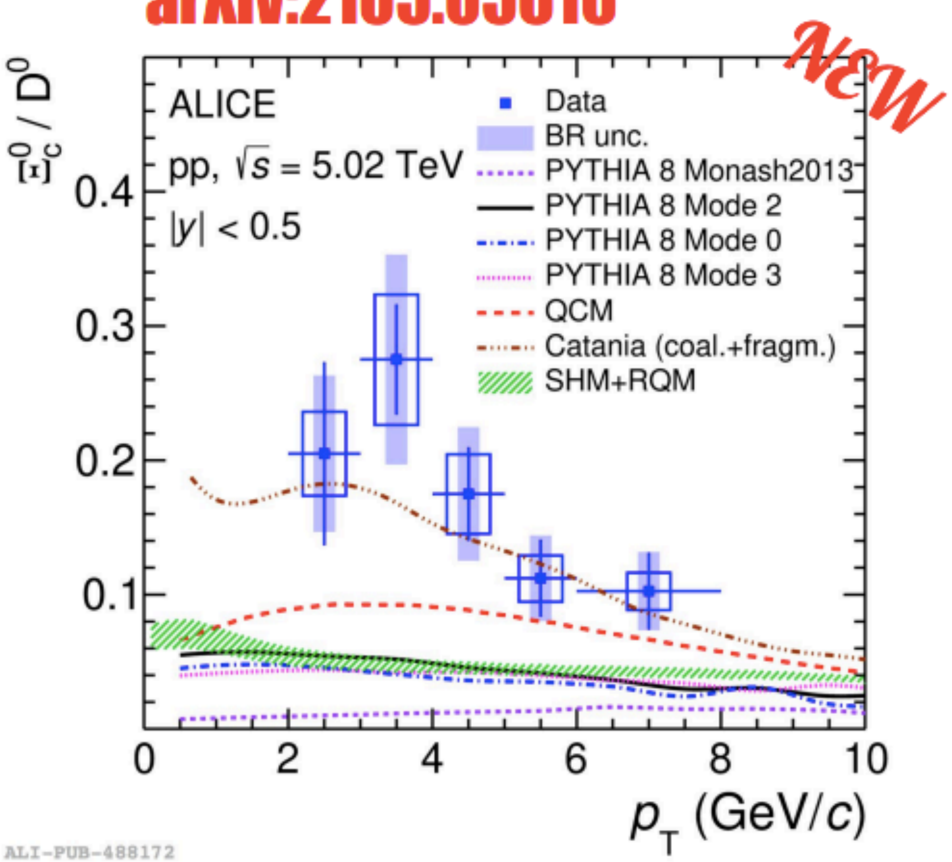
- First application of Monolithic Active Pixel Sensor (MAPS) at a collider experiment
- MAPS technology widely used/planned in NP experiments
  - ALICE ITS2/ITS3, sPHENIX MVTX, CBM MVD, EIC Si Tracker

Charm Baryons in p+p Collisions





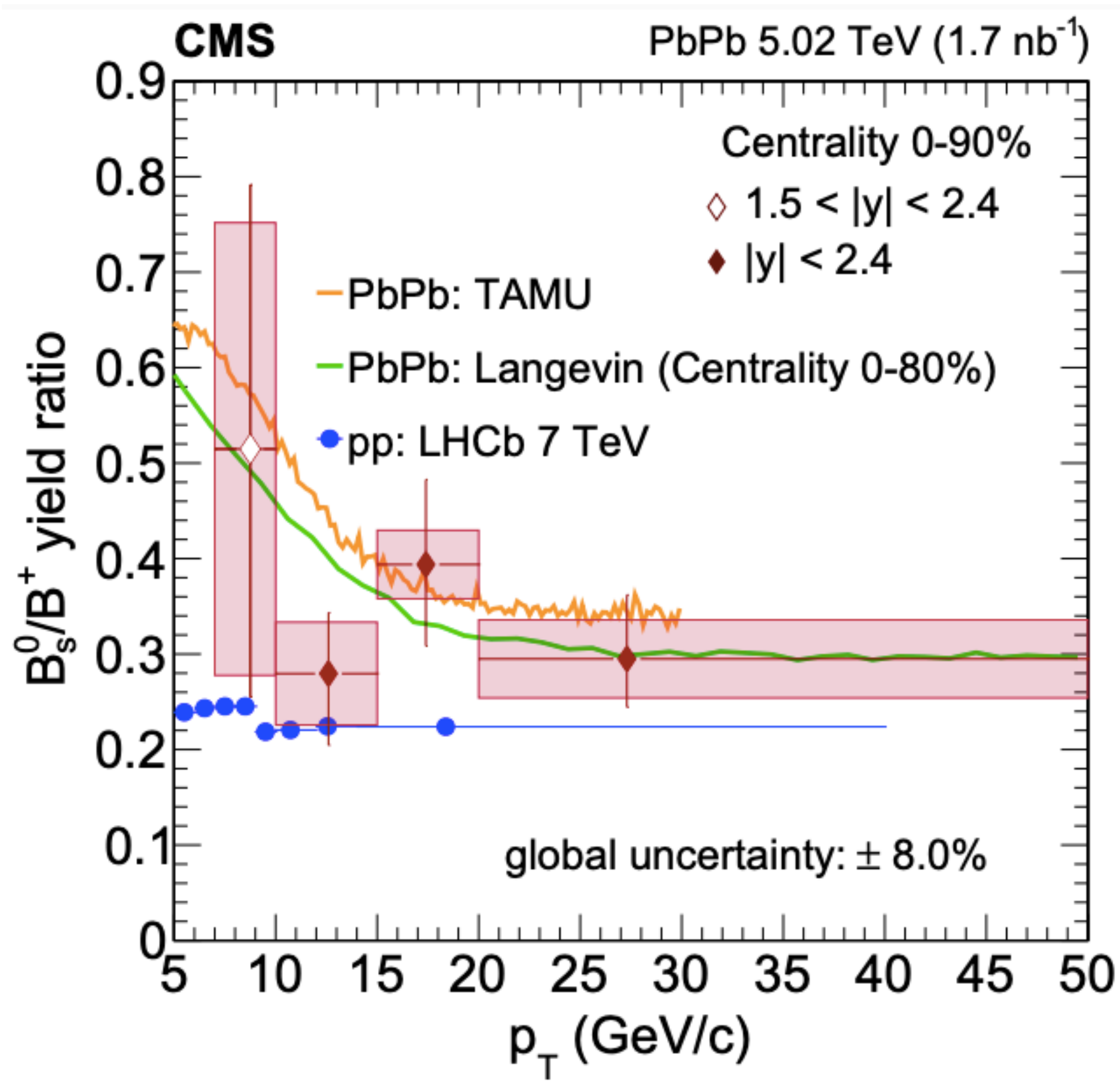
arXiv:2105.05616



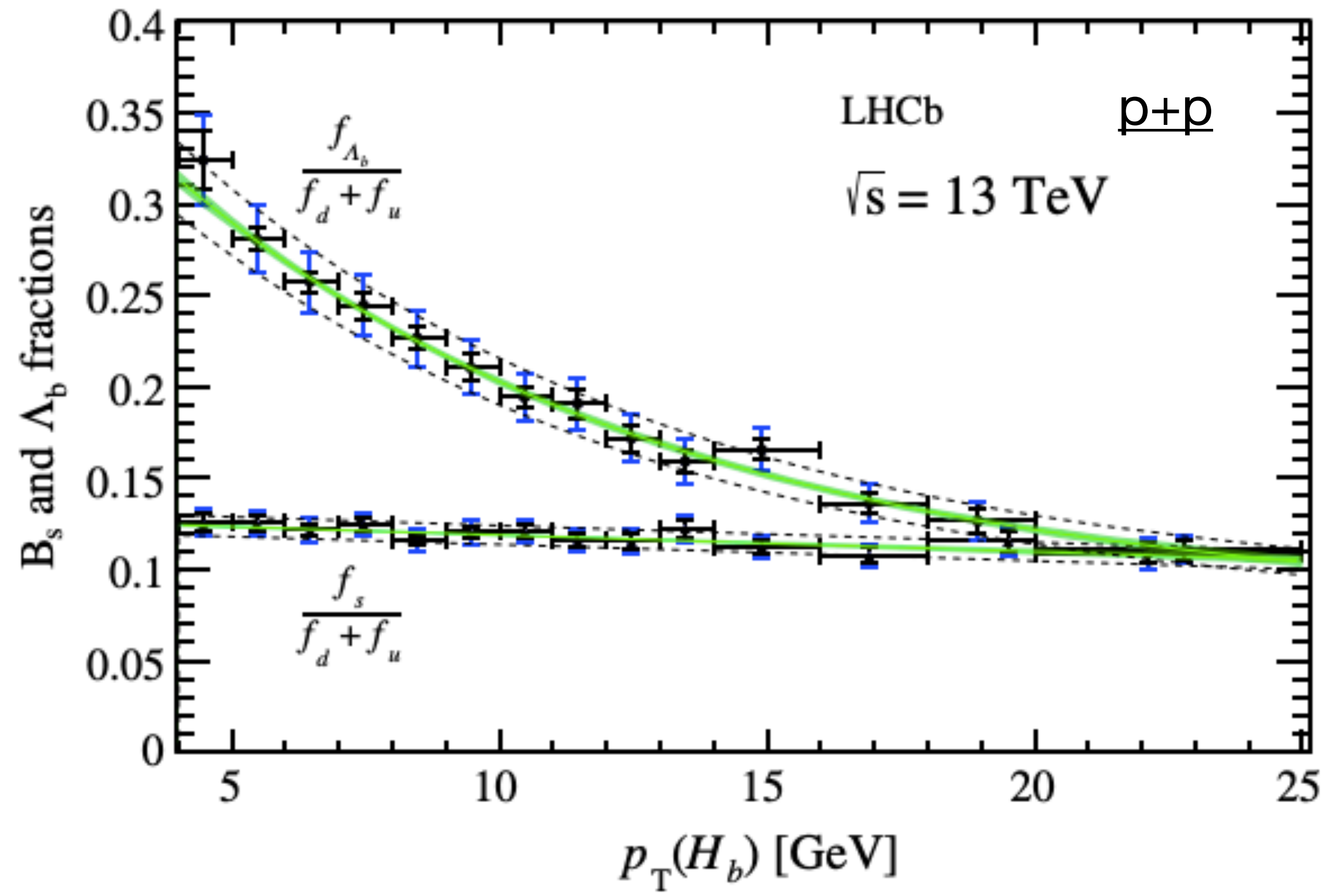
- Λ_c/D in p+p > Λ_c/D in ee/ep at LHC
  - PYTHIA with CR + baryon junction agrees with data
- New Ξ_c/D ratio > PYTHIA tune

More detail investigation on charm baryon production mechanism in hadronic collisions
Charm baryon to total charm cross section in p+p?

Bottom Quark Hadronization



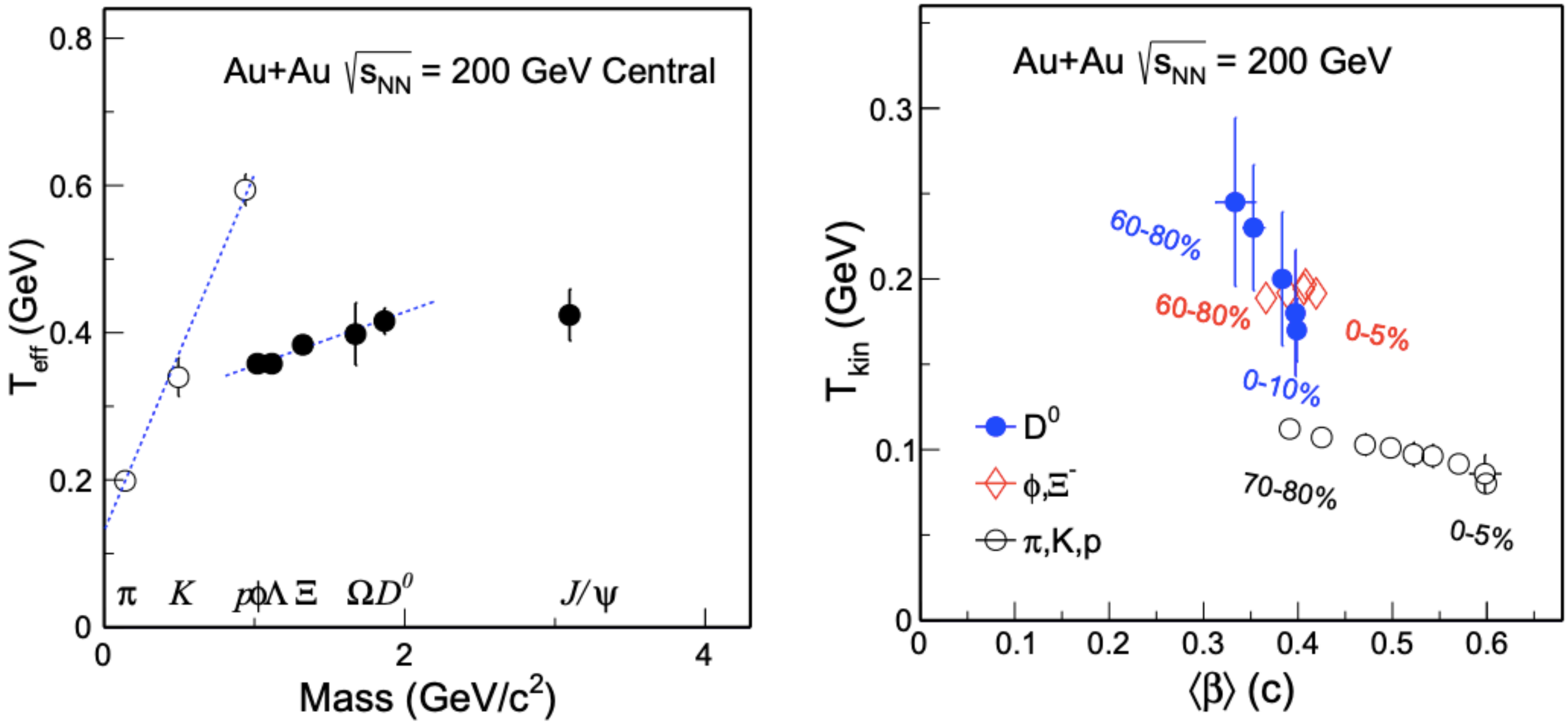
CMS arXiv:2109.01908



LHCb, PRD 100 (2019) 031102

- Hint of B_s/B^+ enhancement in PbPb collisions
  - coalescence hadronization for bottom quarks in QGP
  - better precision to constrain the bottom hadronization
- Λ_b/B ratio enhanced at low pT in p+p - similar to Λ_c/D
  - more investigation to understand HQ baryon states production

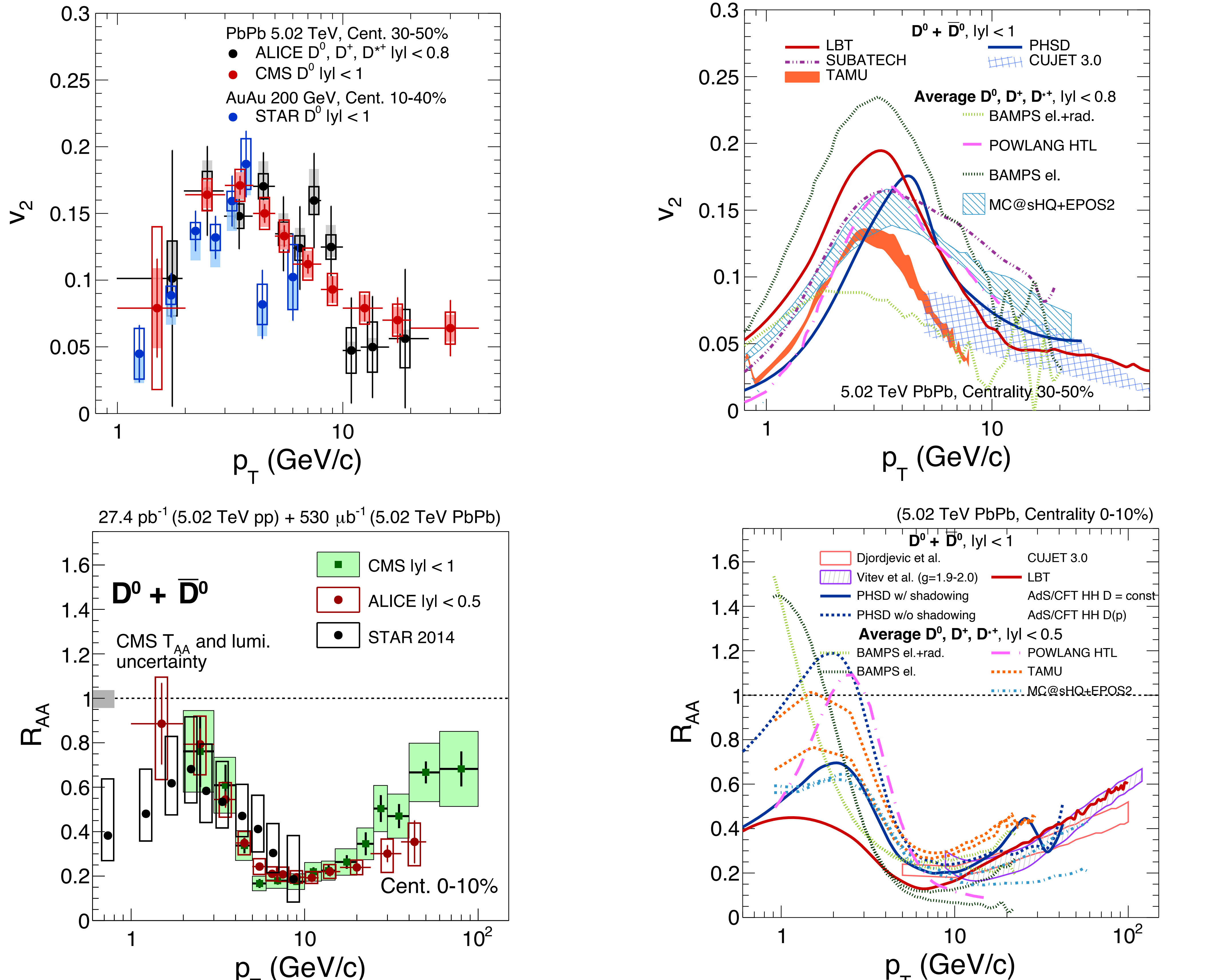
D^0 Radial Flow



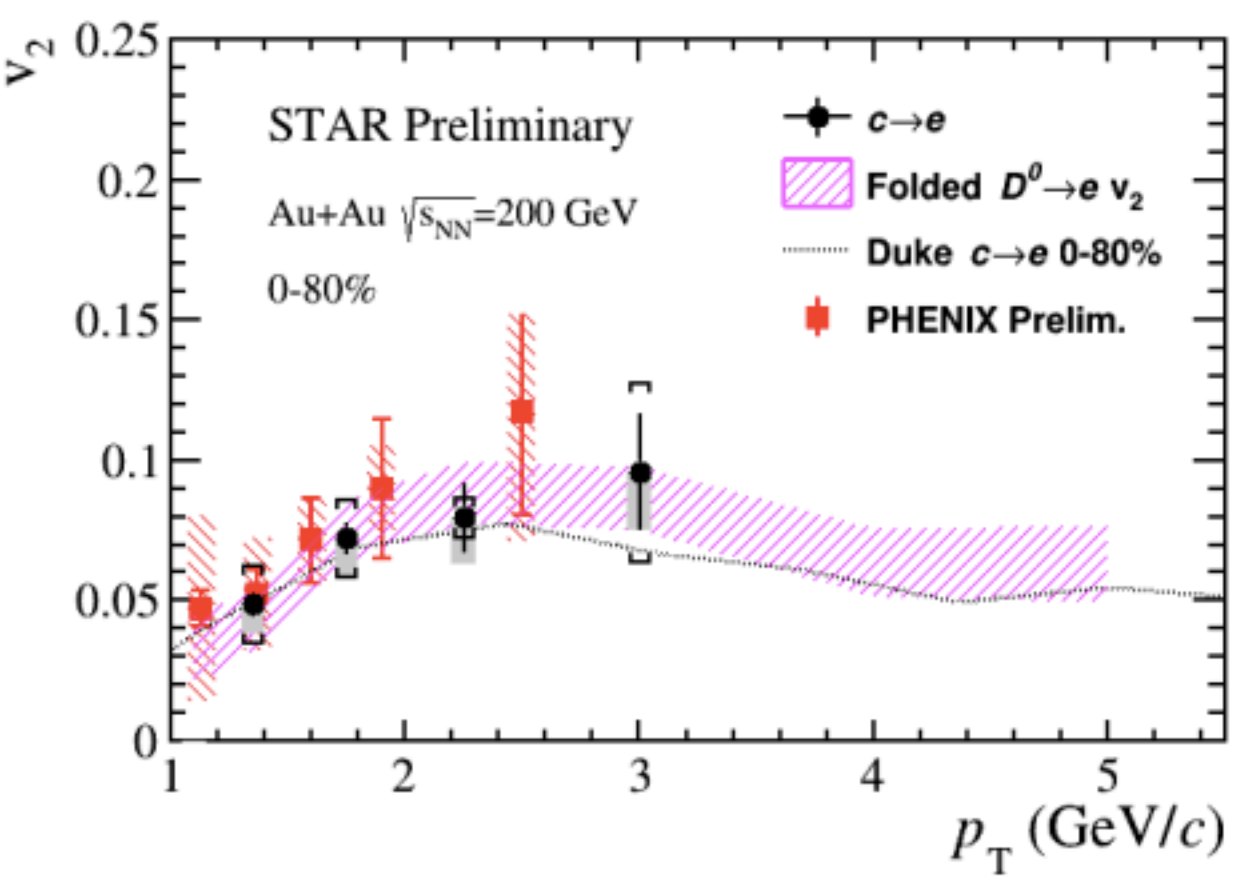
- T-slope parameter (expo fit to m_T spectra) follows the similar trend as other strange particles
- Similar to multi-strange hadrons, *D^0* mesons kinetically freeze out earlier than light hadrons

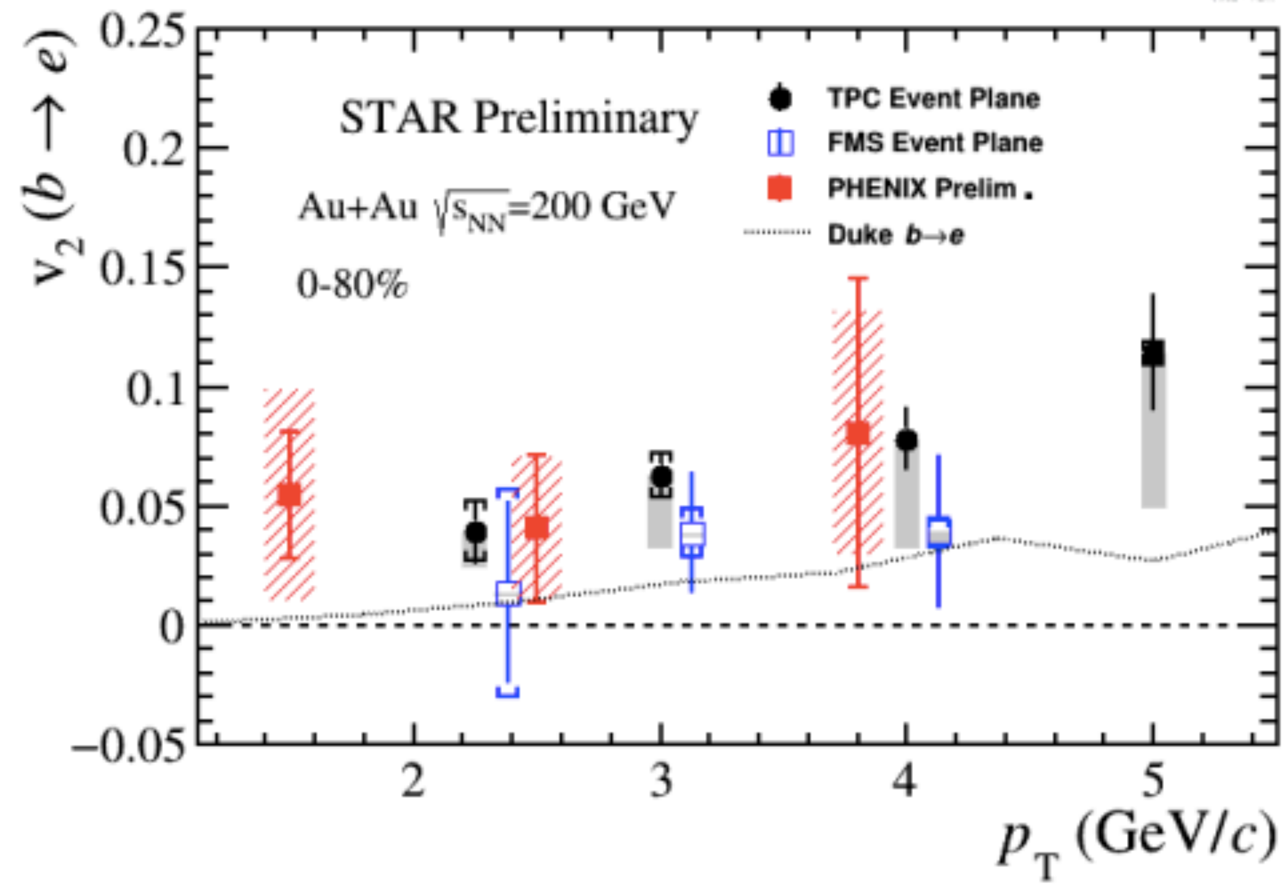
  \- collectivity from partonic stage interactions

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



Comparison with PHENIX Measurements

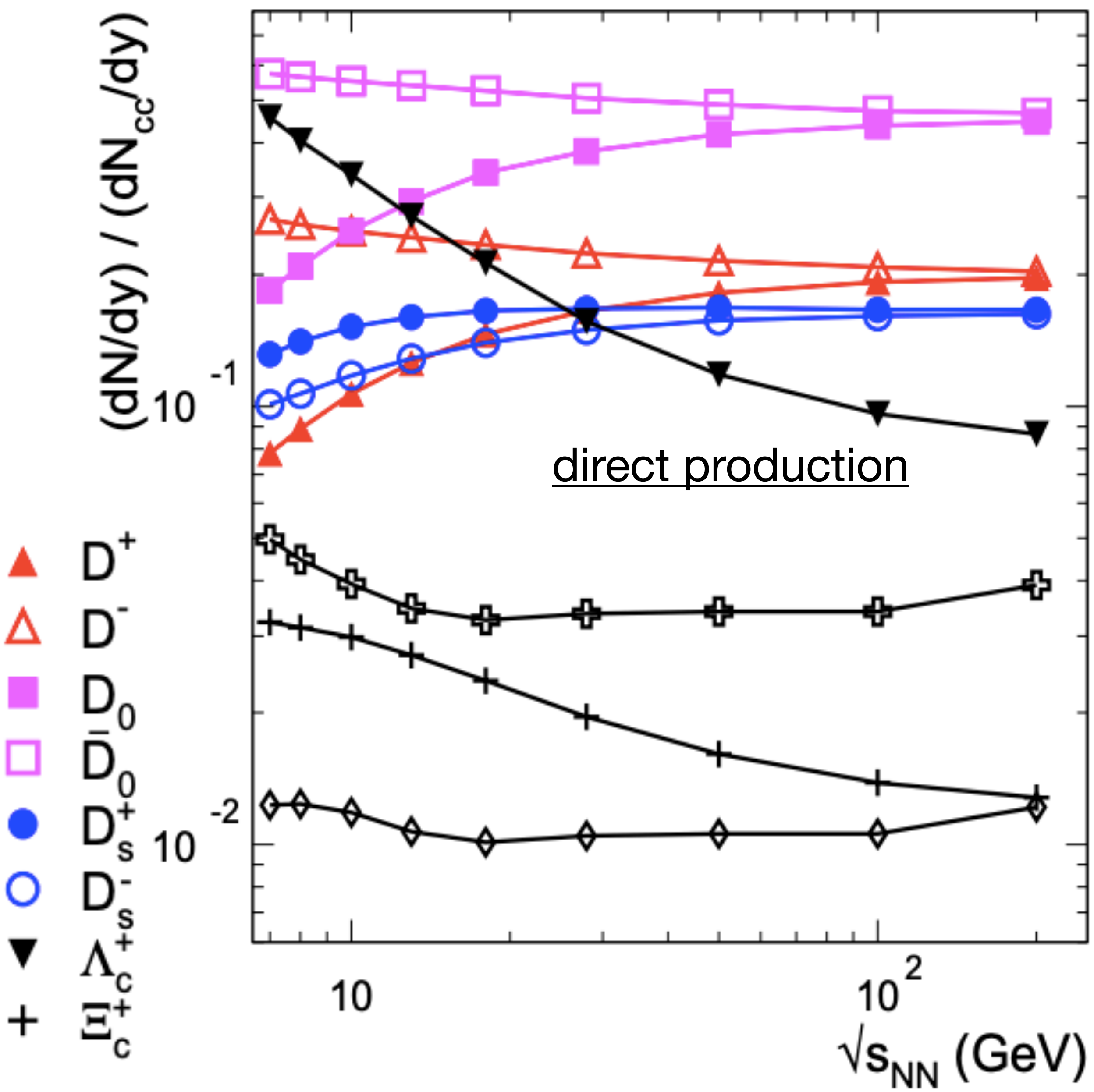




Consistent with PHENIX data with much improved precision

Statistical Hadronization

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



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

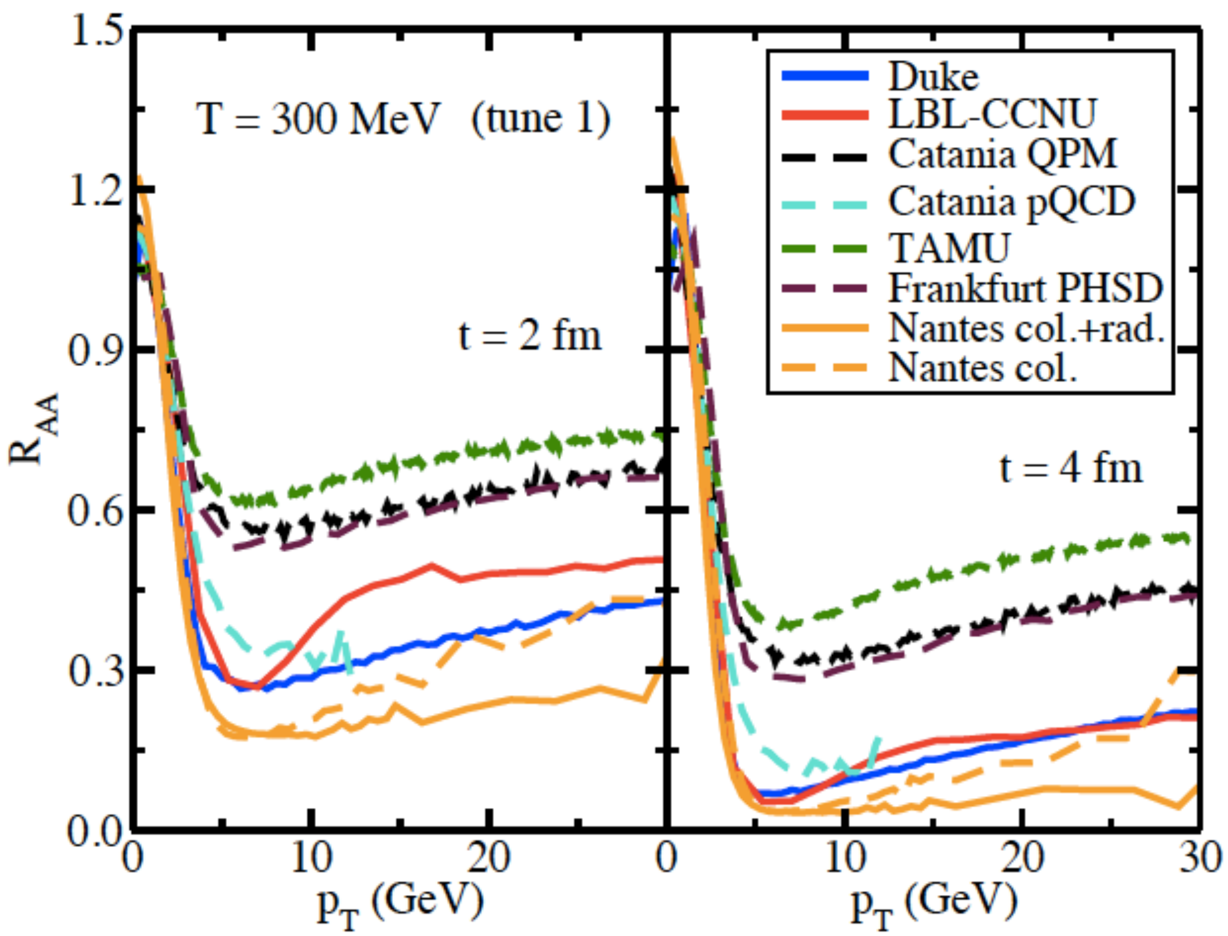
Theory Uncertainties

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*

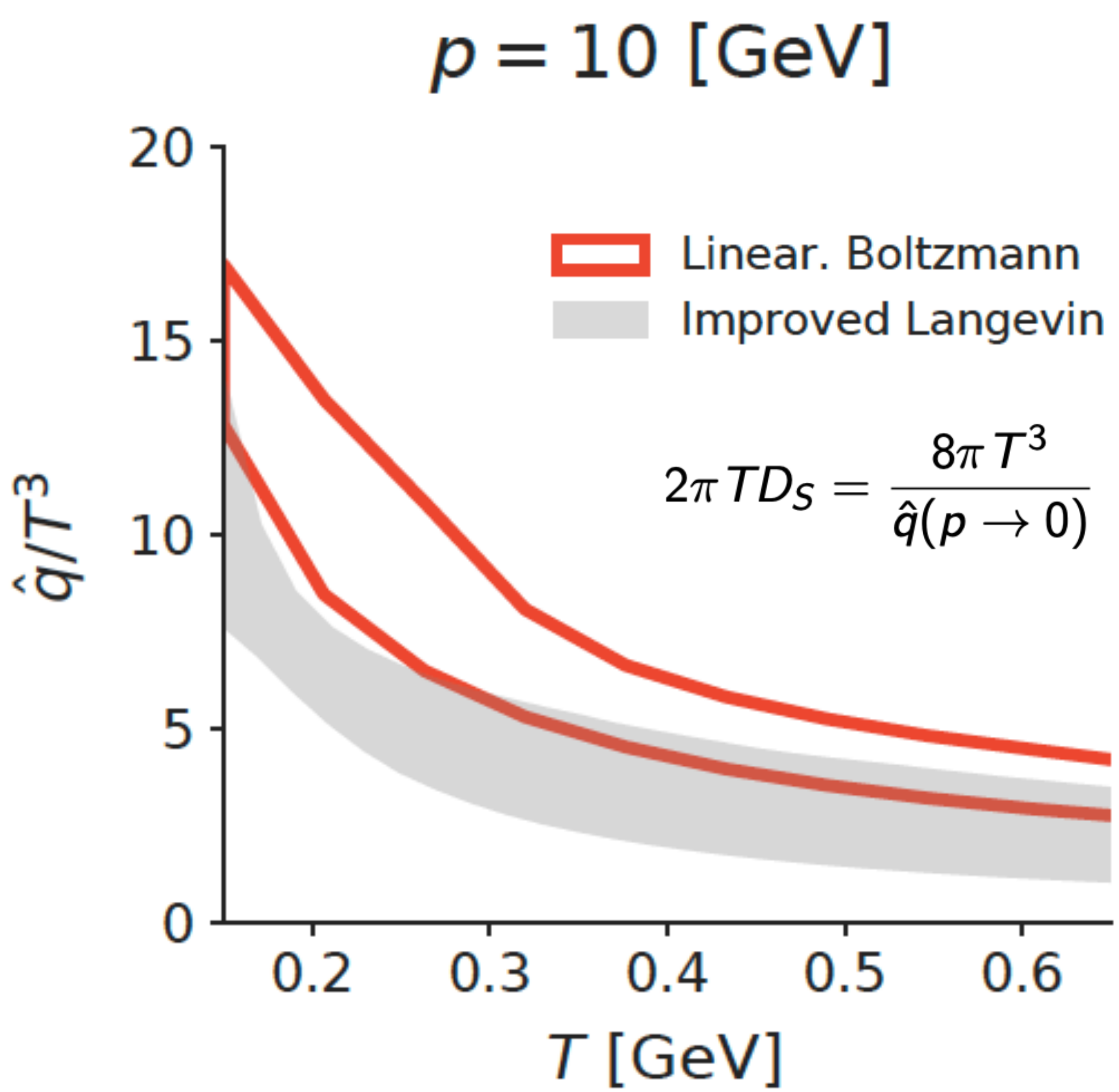
Jet-HQ Working Group - *S.S. Cao et al., PRC 99 (2019) 054907*

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

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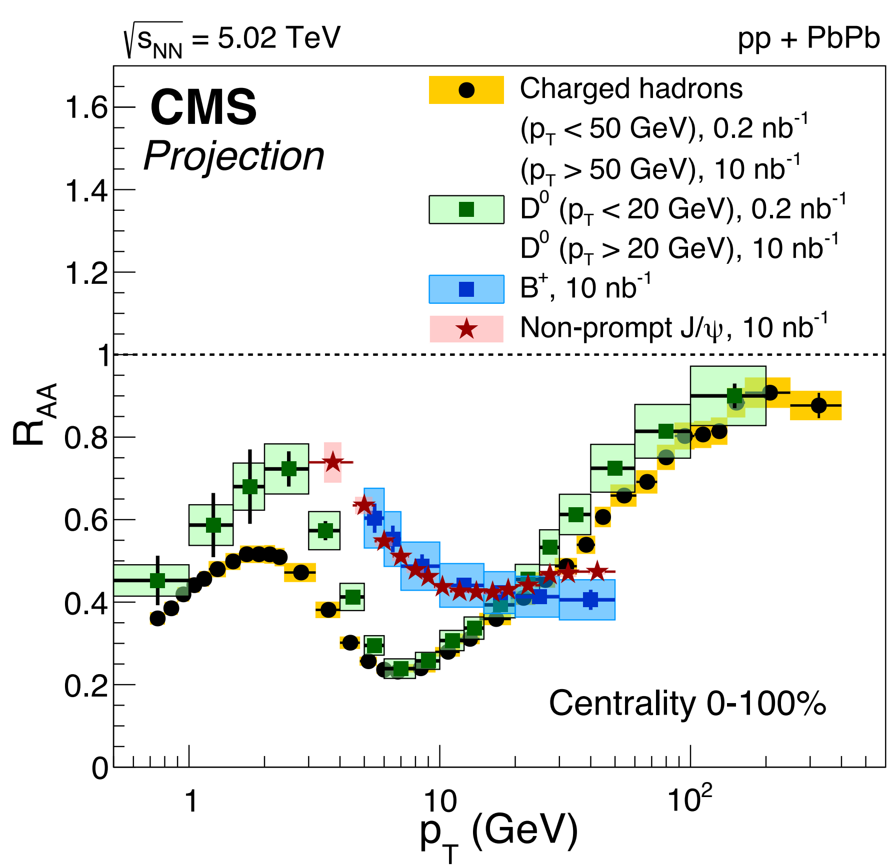
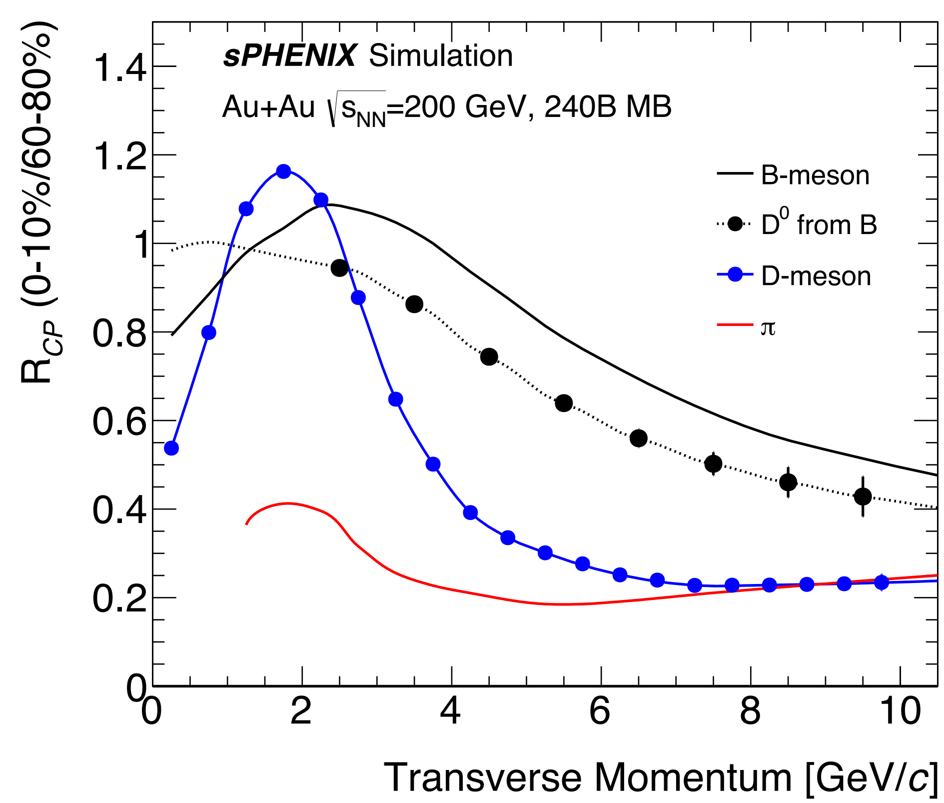
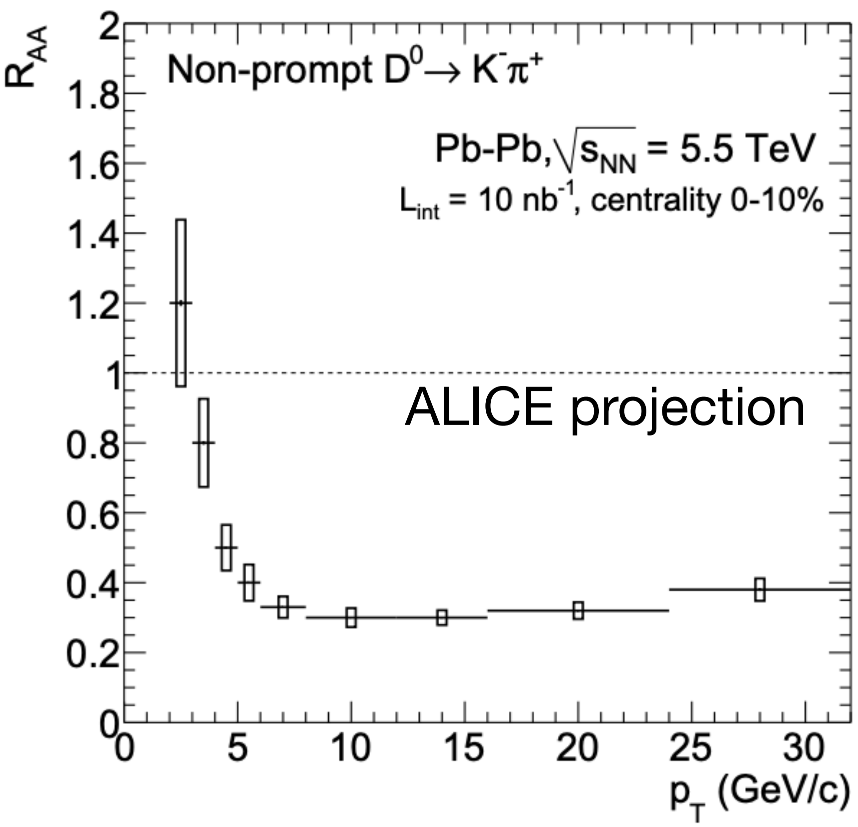
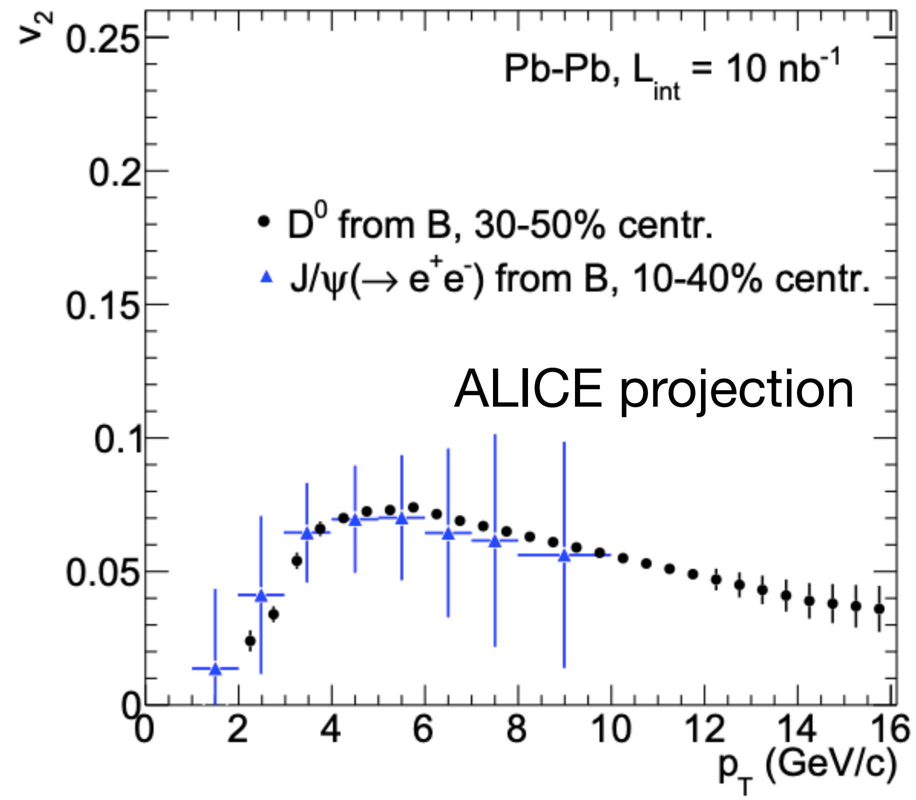
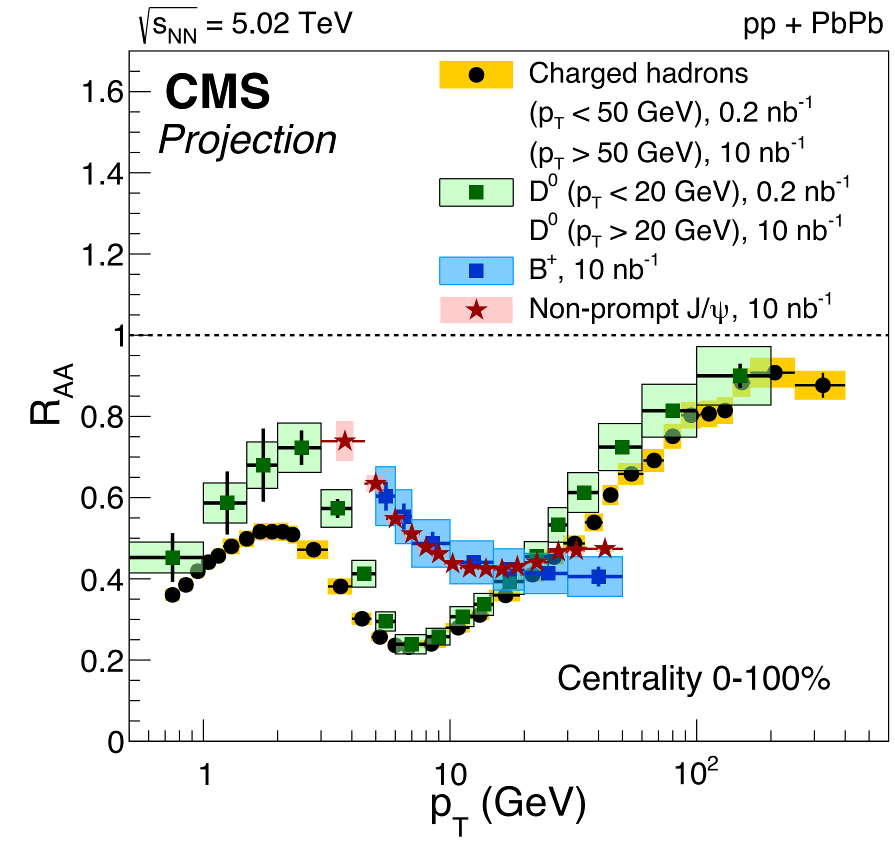




LHC Projections and HF Program in Near Future







RHIC (2023 -) and LHC Run3 (2022 -)

Precision measurement of charm/bottom R_{AA} and v_2, and hadrochemistry

- parton energy loss (transition between collisional vs. radiative)
- charm/bottom quark spacial diffusion coefficient
- charm/bottom quark hadronization

HQ correlations, HQ-in-jet etc.

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 |