Charm Production and Flow at RHIC

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Au+Au event display with STAR-HFT

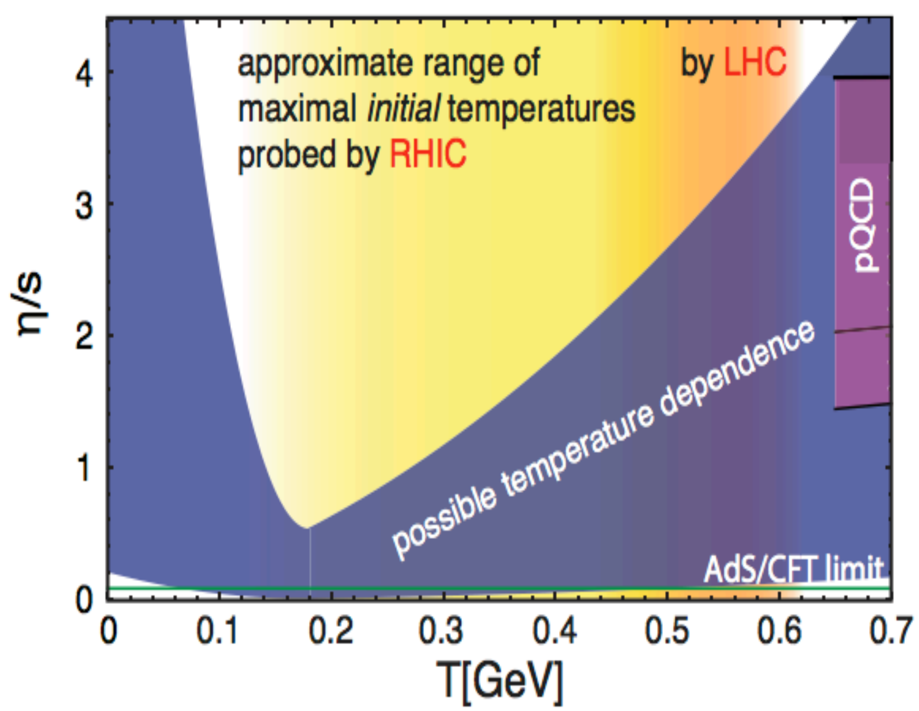
Outline

- Heavy Quarks - Uniqueness in Probing sQGP Properties
- Recent Experimental Achievements at RHIC
  - R_{AA} suppression - parton energy loss
  - Collectivity - sQGP transport coefficient
  - Hadrochemistry - hadronization
- Summary & Future Heavy Flavor Program at RHIC

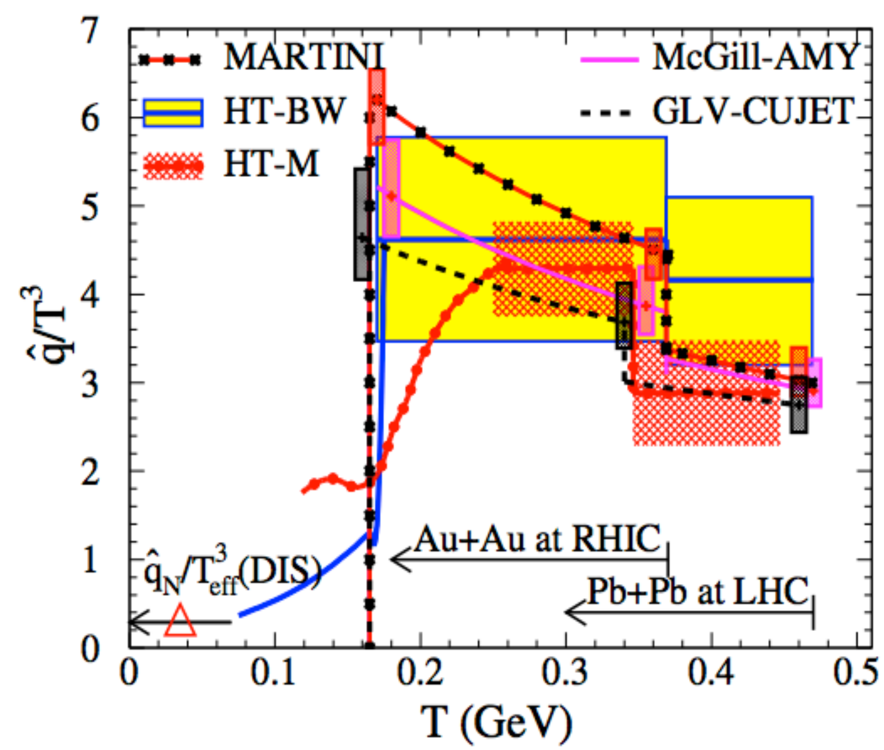
Quantitative Measure of sQGP

~2 ~6

p_T (GeV/c)



Hot QCD white paper - arXiv: 1502.02730



JET Coll., PRC 90 (2015) 014909

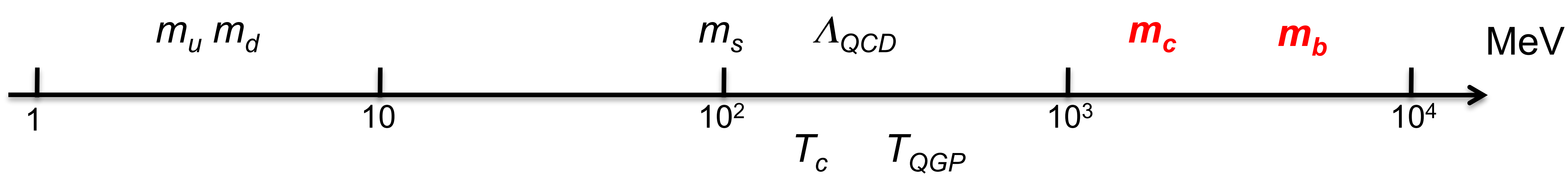
?

strongly coupled
hydrodynamics

weakly coupled
pQCD

What is the microscopic picture of "perfect fluid"?

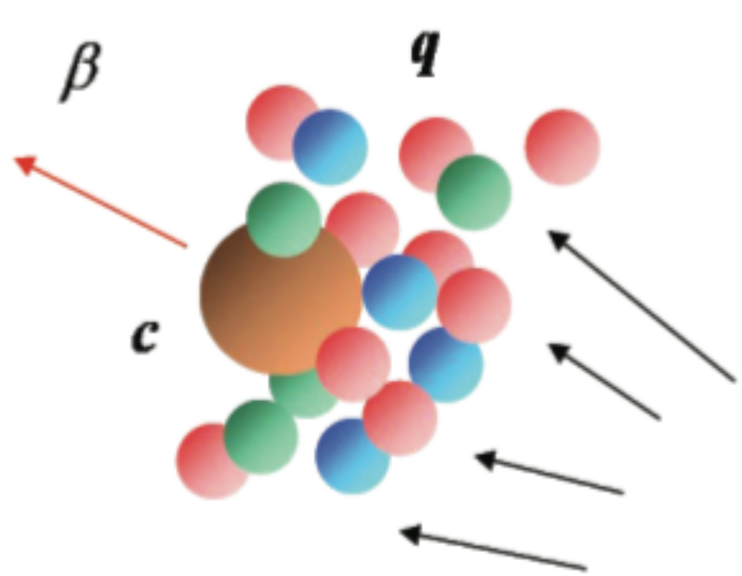
Uniqueness of Heavy Flavor Quarks



$m_{c,b} >> \Lambda_{QCD}$ *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. $$D = \frac{RT}{N_A 6\pi\eta a} = \frac{k_B T}{6\pi\eta a}$$

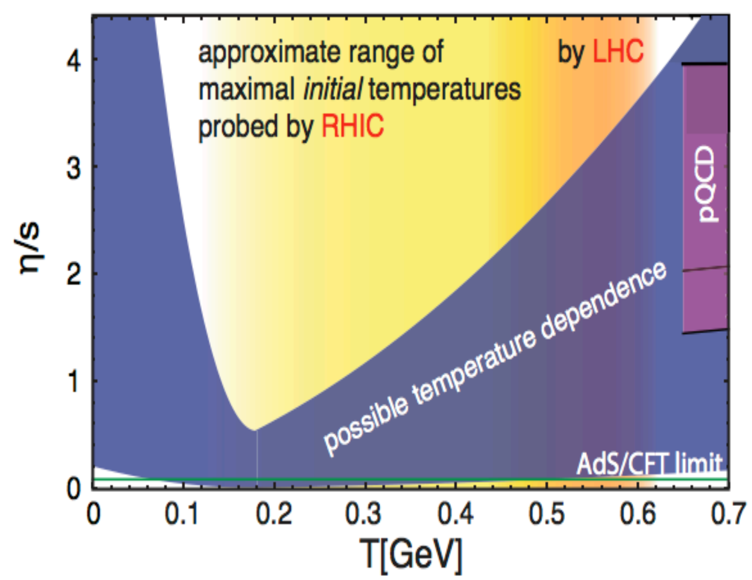
Heavy Flavor Quark Transport in sQGP

Langevin stochastic equation

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

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

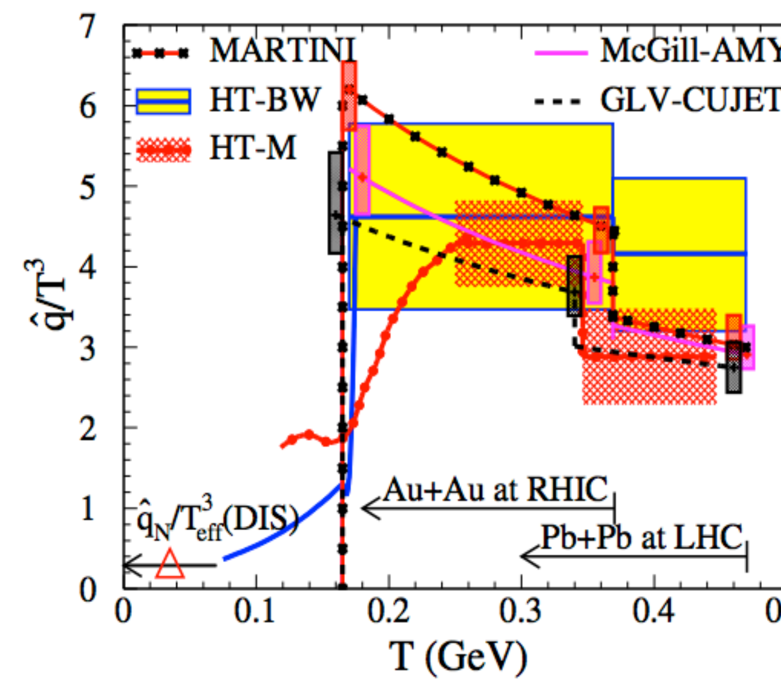
$$D_s \equiv \frac{\langle x^2(t)\rangle - \langle x^2(0)\rangle}{2dt} = \frac{t}{M\eta_D(p=0)}$$



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

ratio depends on the strong/weak coupling nature of QGP

R. Rapp and H. van Hees, 0903.1096



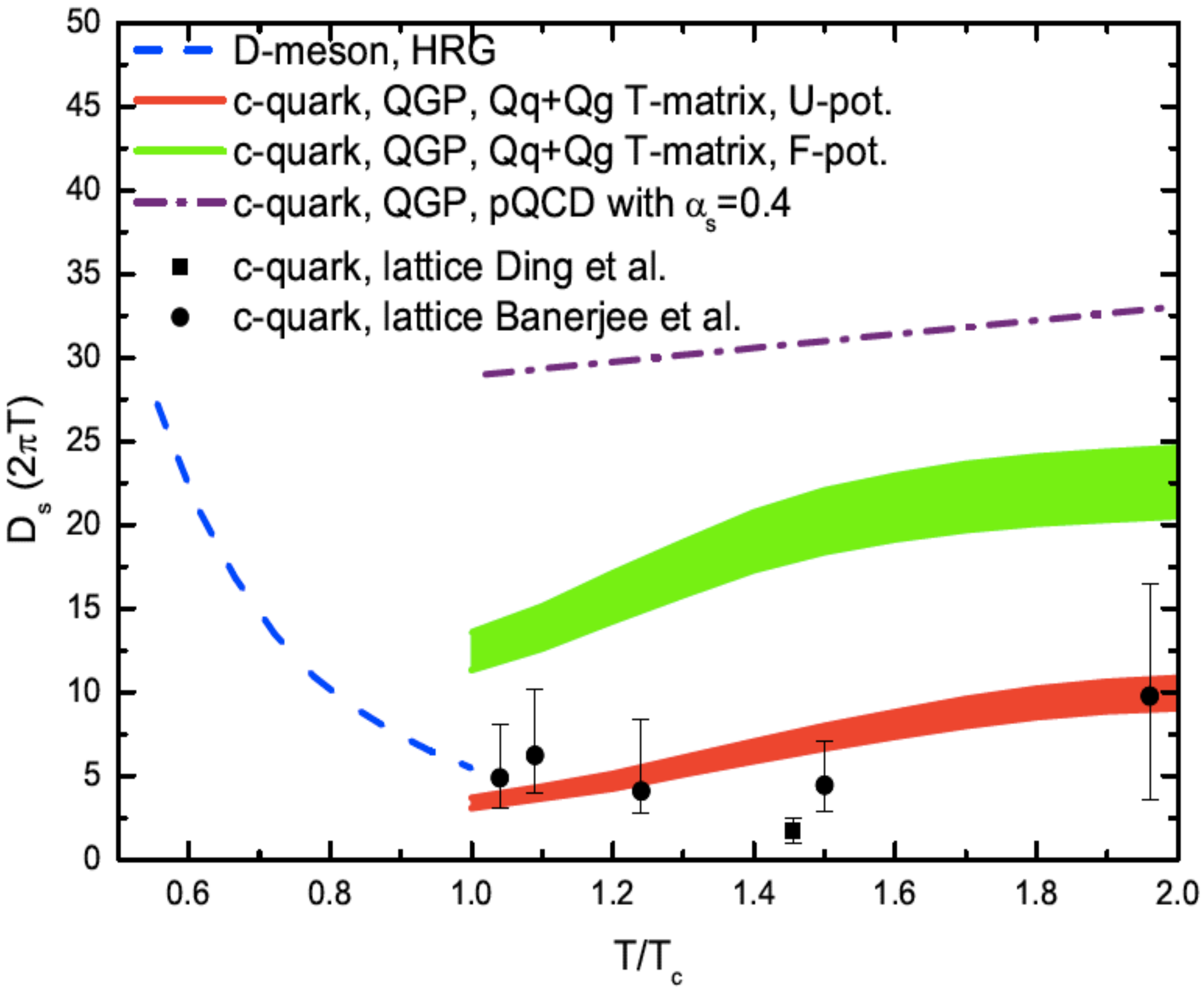
$$\hat{q} = \frac{\Delta p_T^2}{\lambda} = \frac{4D_p E_p}{p} \qquad 2\pi T D_S = \frac{8\pi T^3}{\hat{q}(p \to 0)}$$

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

To determine HQ diffusion coefficient

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

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

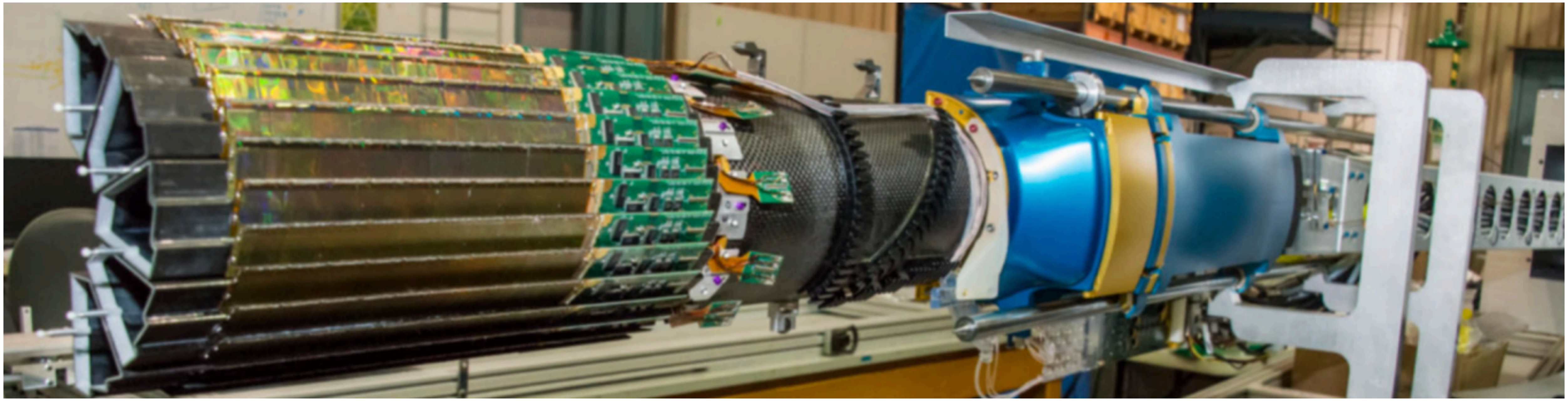
$$\Lambda_c^+ \rightarrow p K^- \pi^+ \qquad c\tau \sim 60\mu m$$

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*

STAR Heavy Flavor Tracker (HFT)



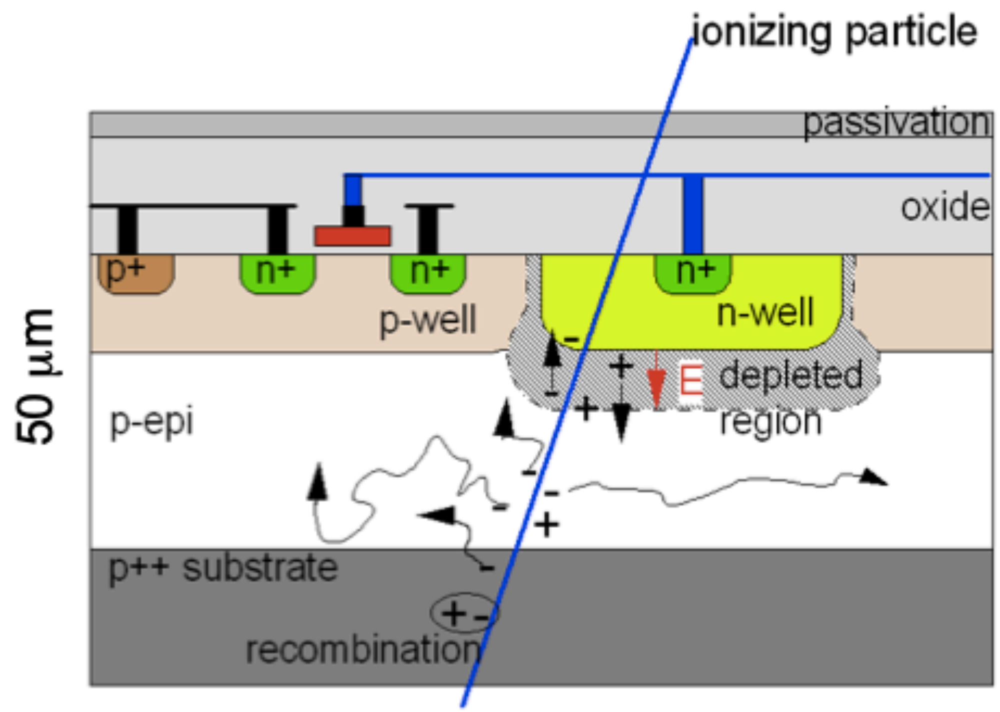
G. Contin et al, NIMA 907 (2018) 60

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 R&D

Monolithic Active Pixel Sensor (MAPS)

MAPS pixel cross-section (not to scale)



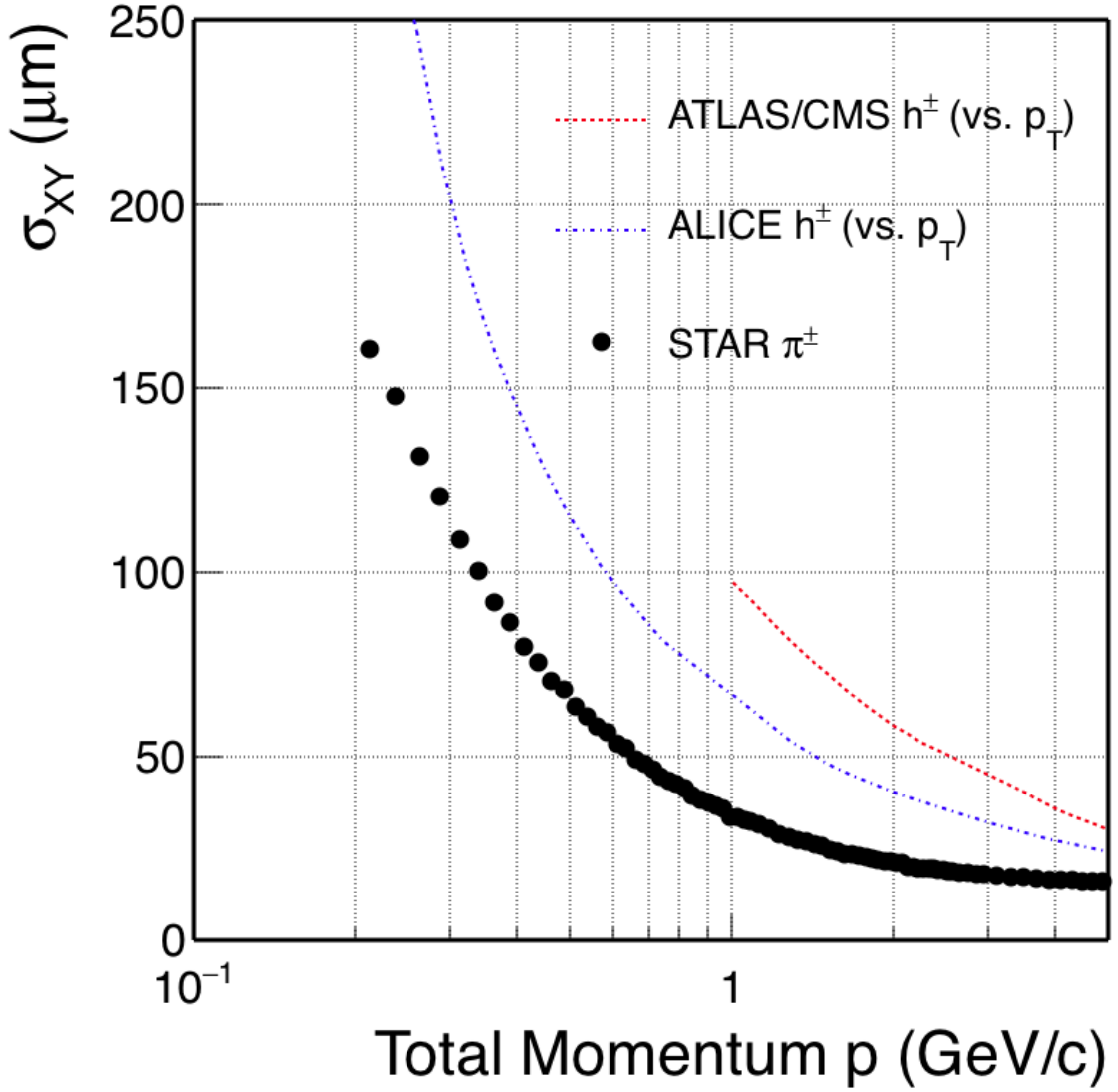
Properties:

- Standard commercial CMOS technology
- Sensor and signal processing are integrated in the same silicon wafer
- Signal is created in the low-doped epitaxial layer (typically ~10-15 µm) → MIP signal is limited to <1000 electrons
- Charge collection is mainly through thermal diffusion (~100 ns), reflective boundaries at p-well and substrate

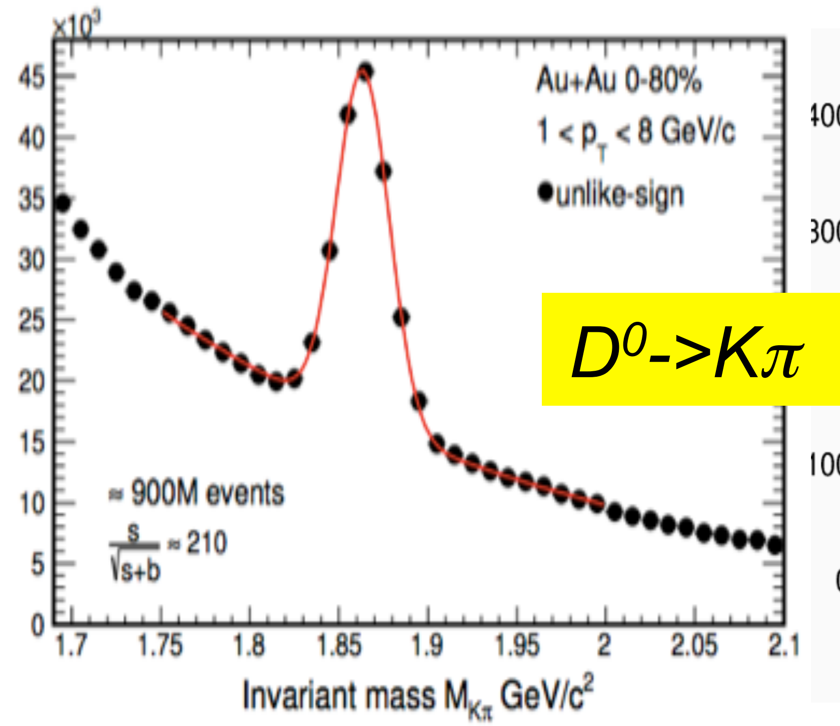
MAPS and competition	MAPS	Hybrid Pixel	CCD
Granularity	+	-	+
Small material budget	+	-	+
Readout speed	+	++	-
Radiation tolerance	+	++	-

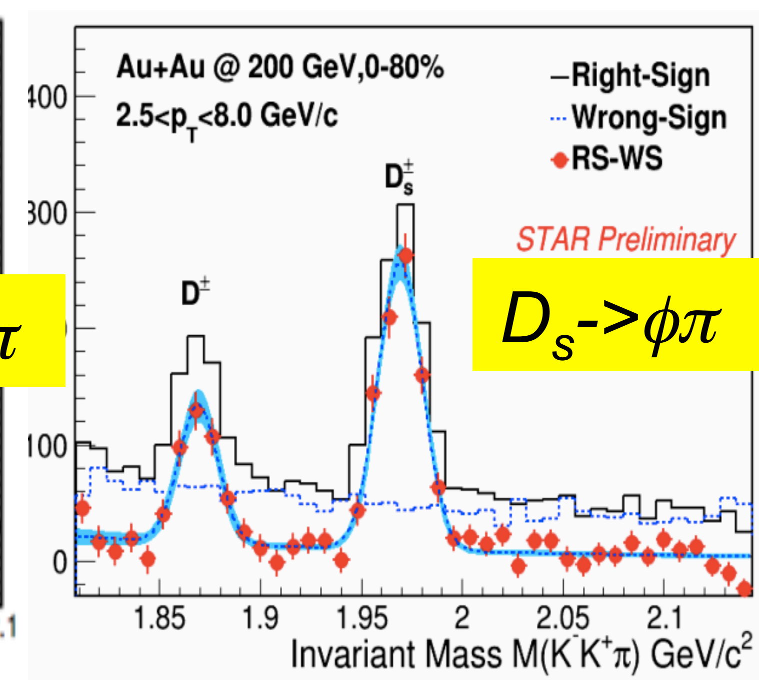
MAPS - particularly chosen for measuring HF hadron decays in heavy ion collisions

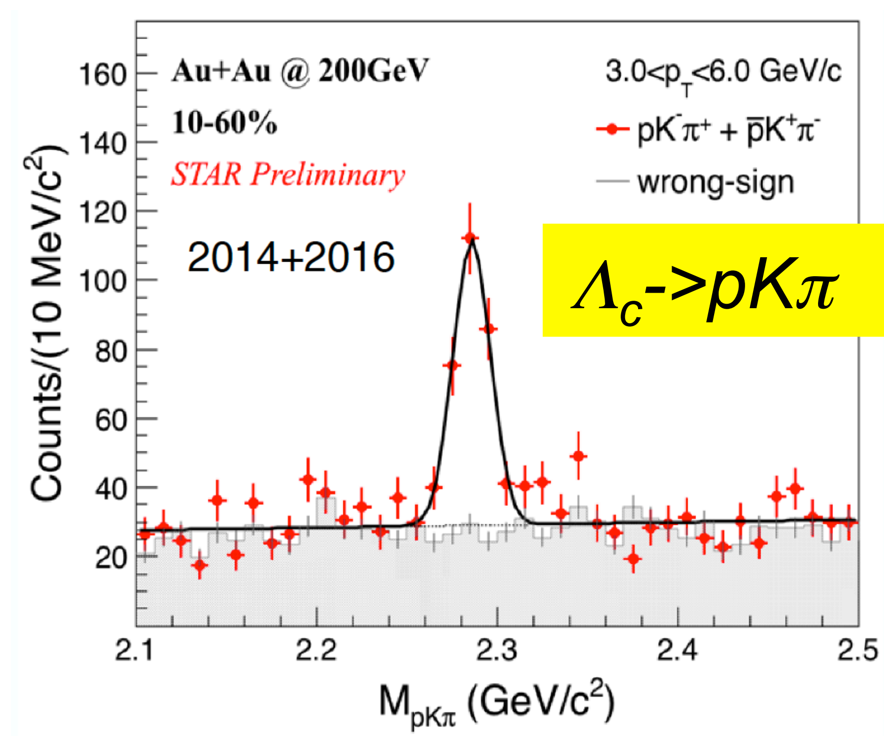
PXL Detector Performance



Exclusive reconstruction of HF hadrons in heavy-ion collisions







STAR	30 μm @ 1 GeV/c (p)
ALICE	70 μm @ 1 GeV/c (p_T)
ATLAS/CMS	100 μm @ 1 GeV/c (p_T)

R_{AA} Suppression → Parton Energy Loss

Collectivity → Transport parameter D_s

Hadrochemistry → Hadronization

R_{AA} Suppression → Parton Energy Loss

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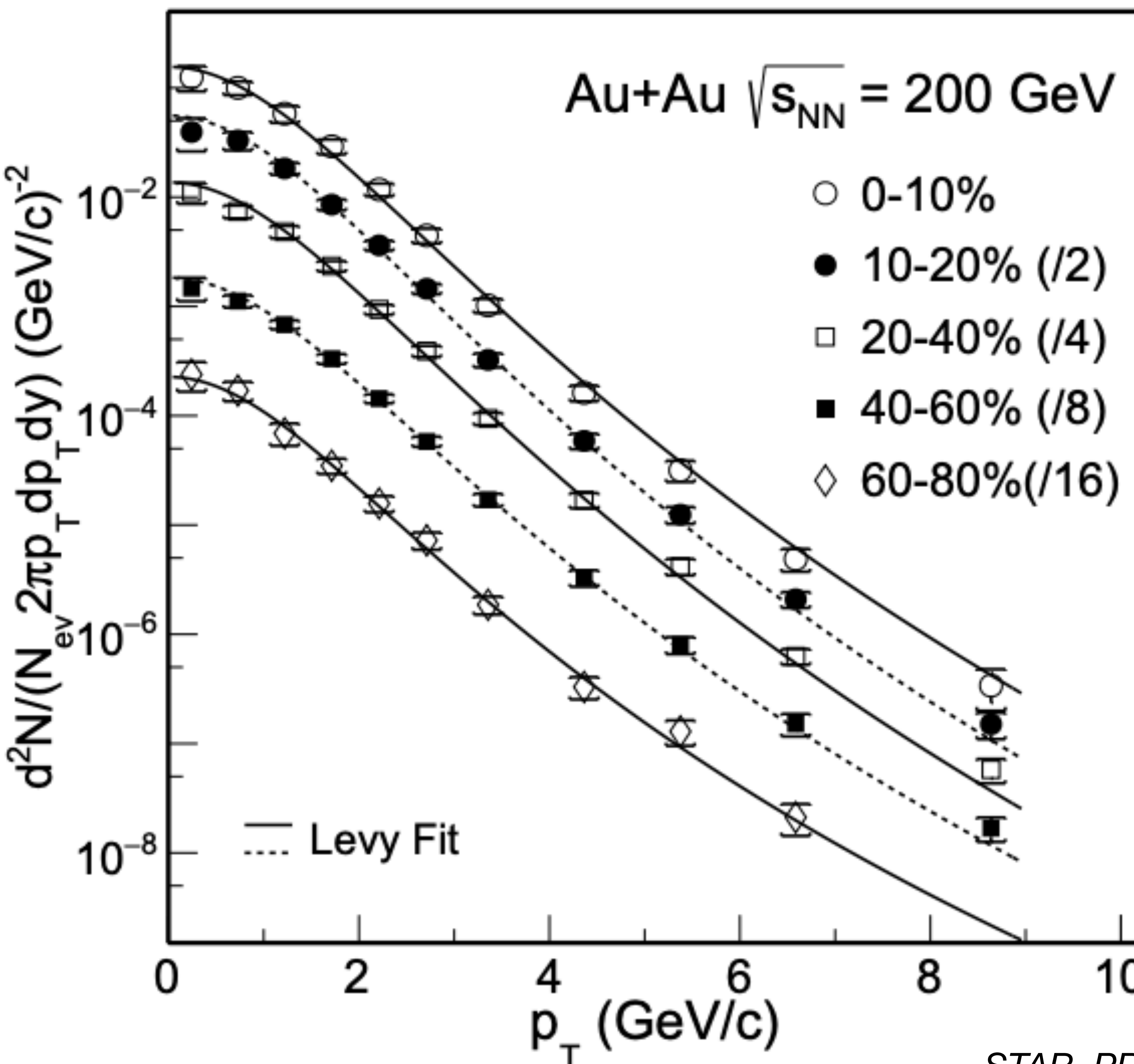
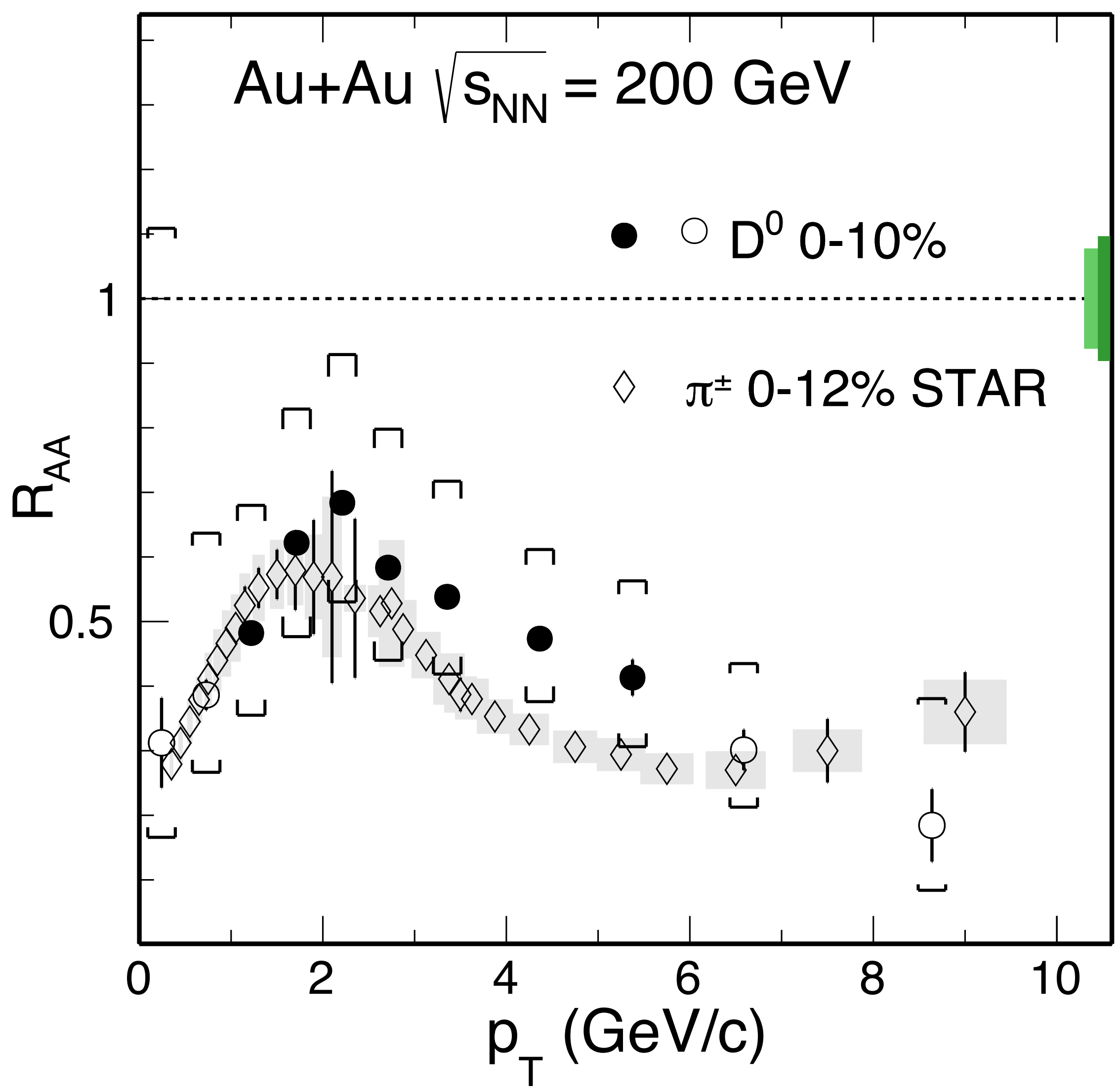
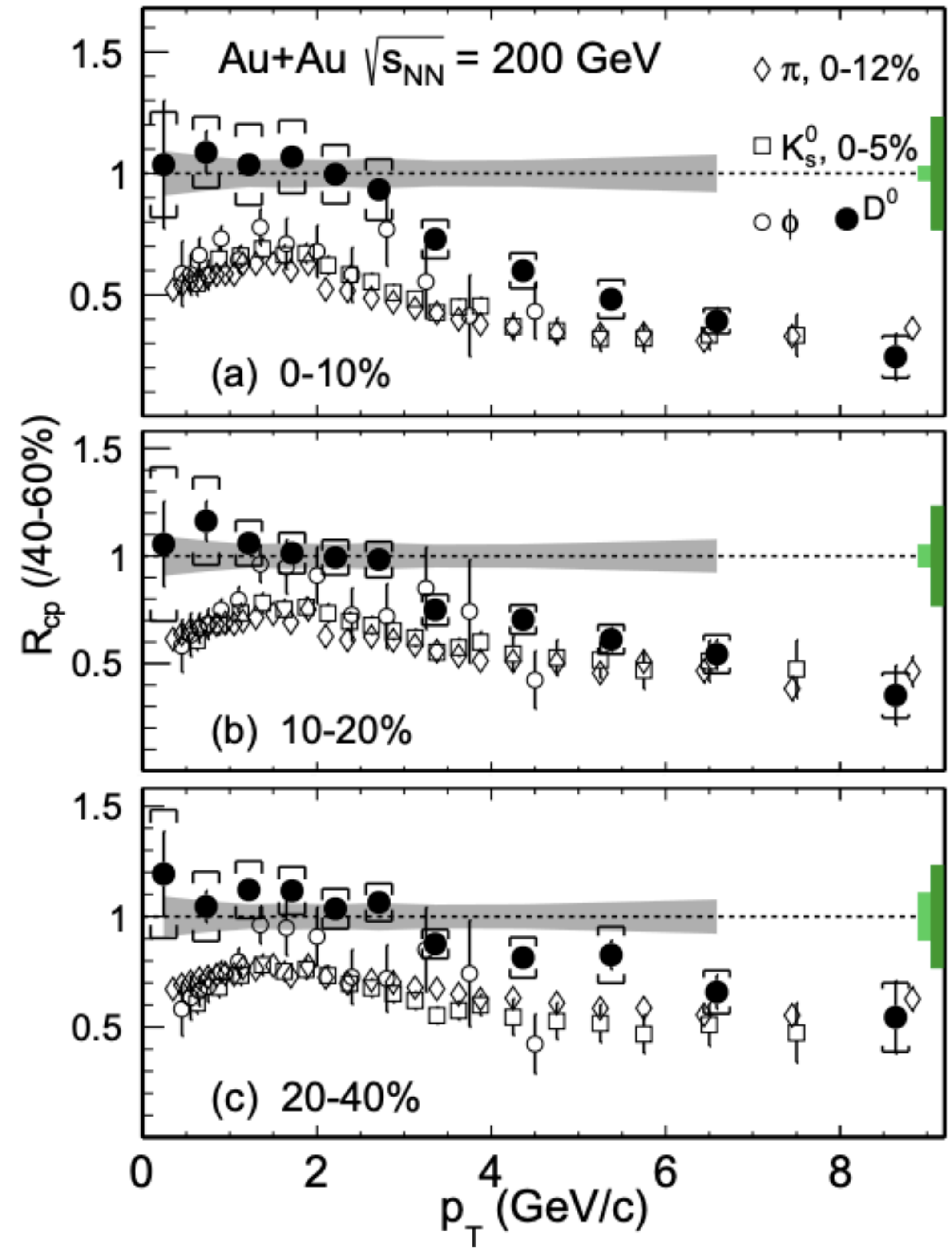
D^0 Meson p_T Spectra



STAR, PRC 99 (2019) 034908

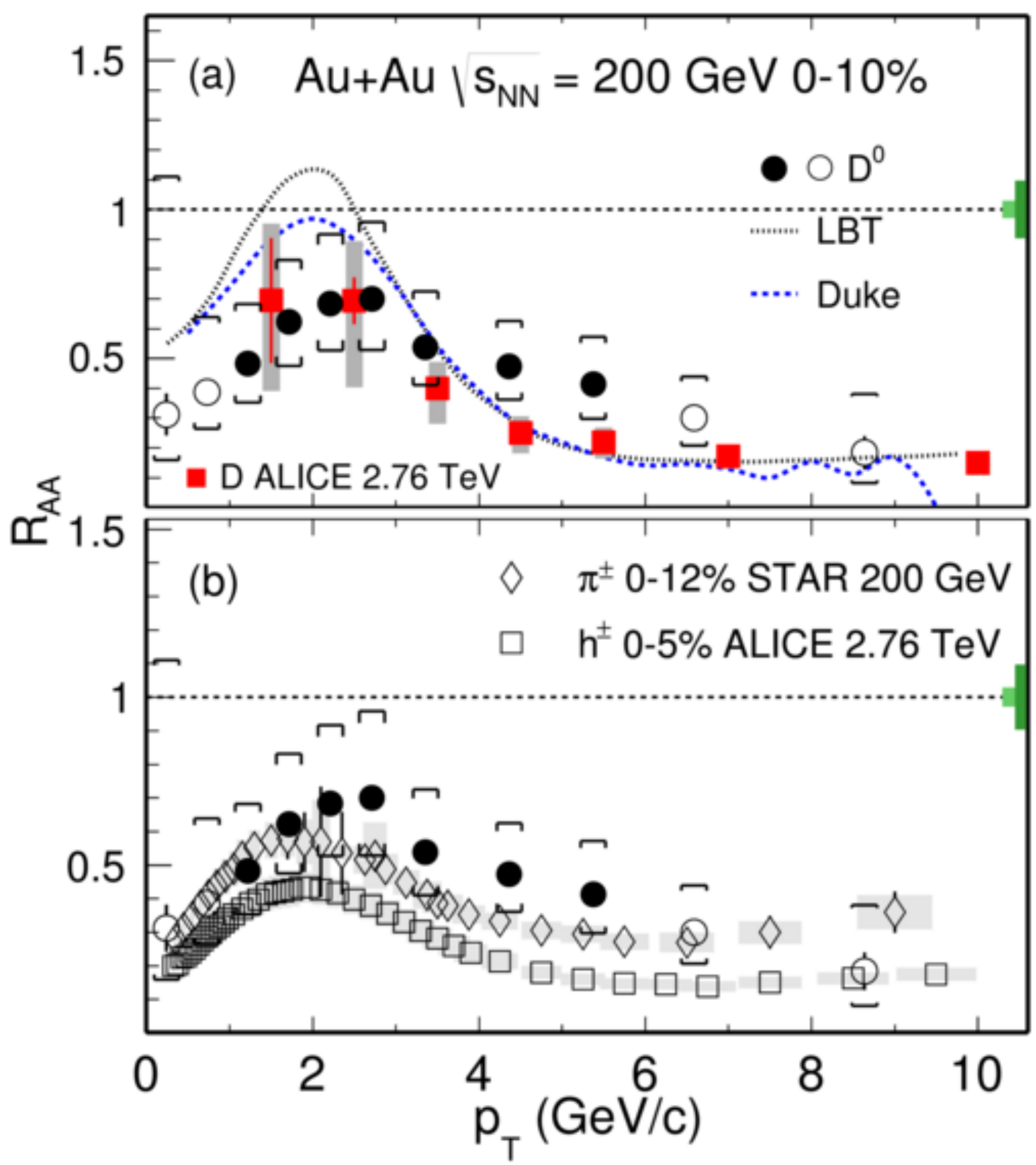
D^0 Meson R_{AA}/R_{CP} in A+A Collisions

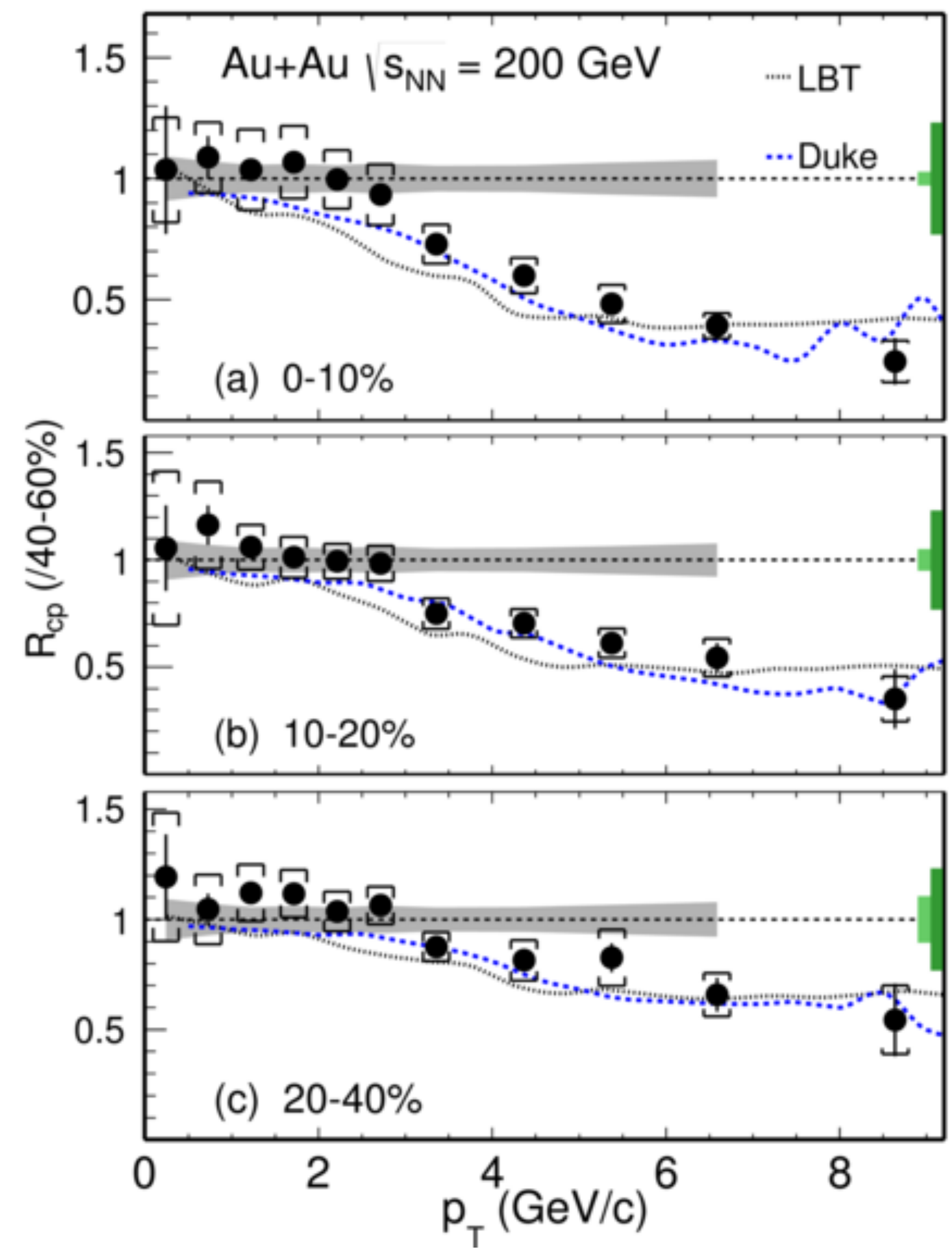




- $R_{AA}(D) \sim R_{AA}(h)$ at $p_T >$ ~4 GeV/c
  - significant charm quark energy loss in the QGP medium
  - importance of radiative and collisional energy loss

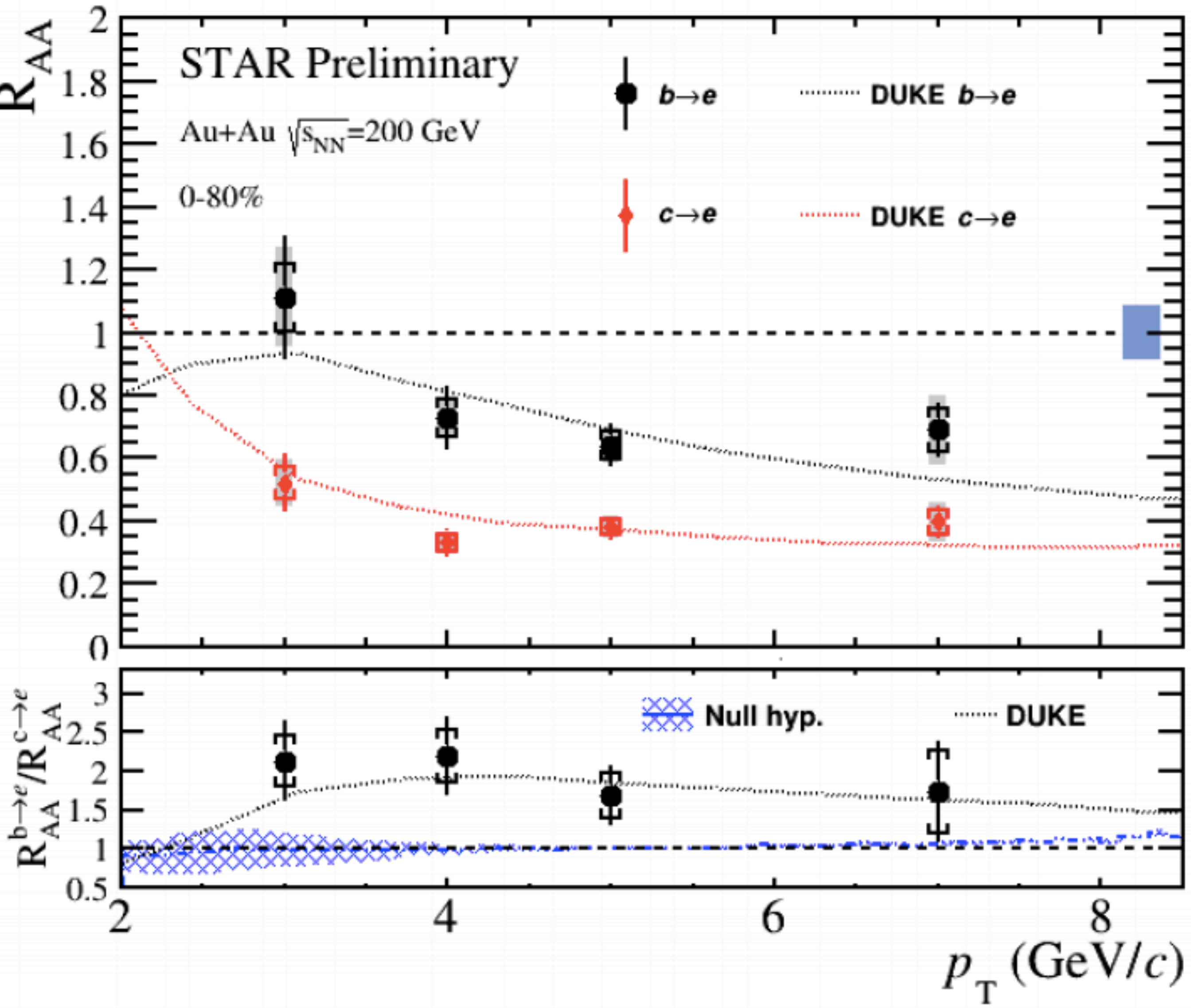
Comparison to Models



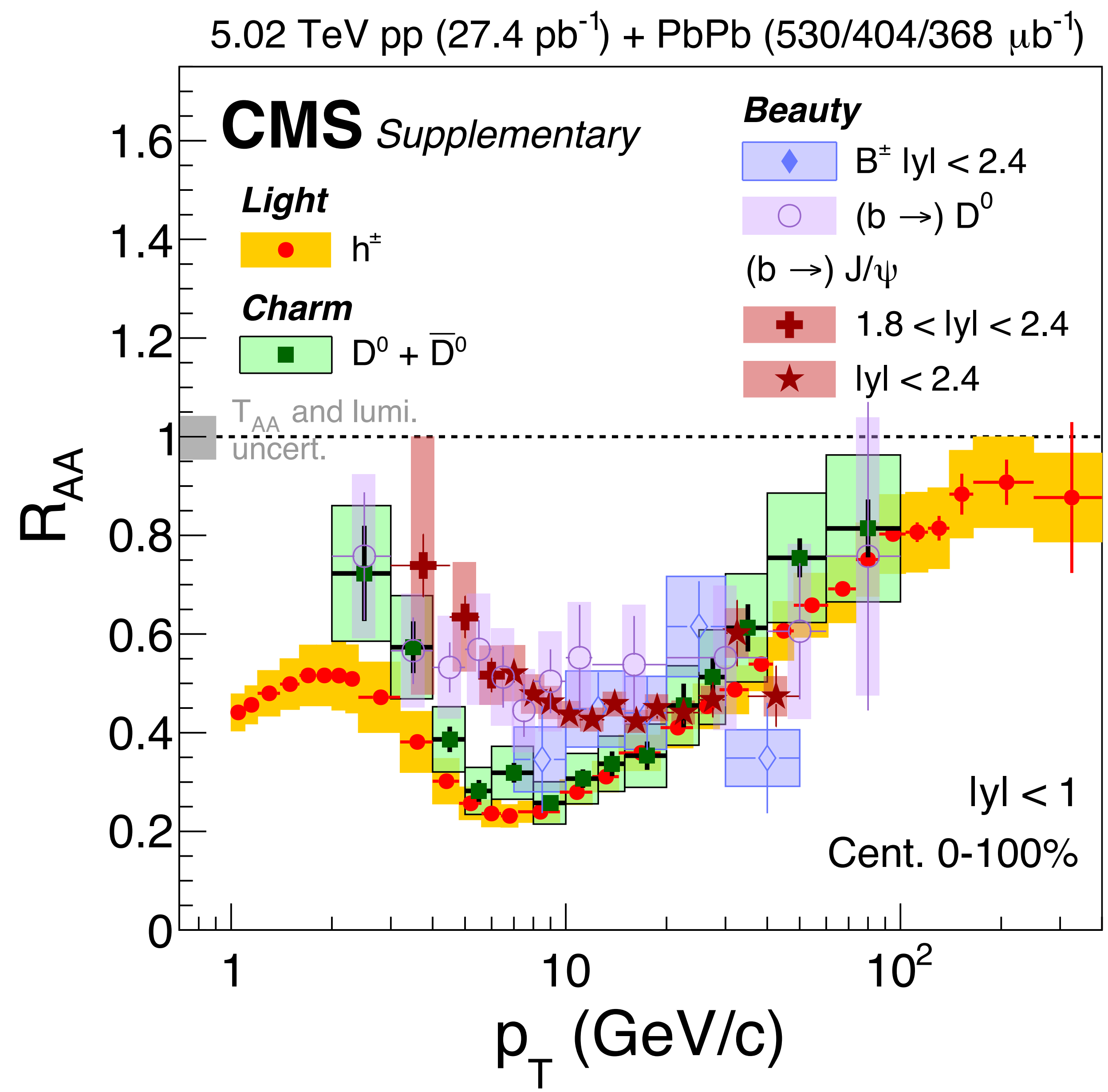


- Characteristic “flow” bump in R_{AA} qualitatively reproduced in model calculations

Bottom Suppression at Low p_T



STAR QM19



CMS, PRL 123 (2019) 022001

- LHC: $R_{AA}(J/\psi_B) \sim R_{AA}(D_B) > R_{AA}(D)$ at $p_T < 10$ GeV/c
- 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

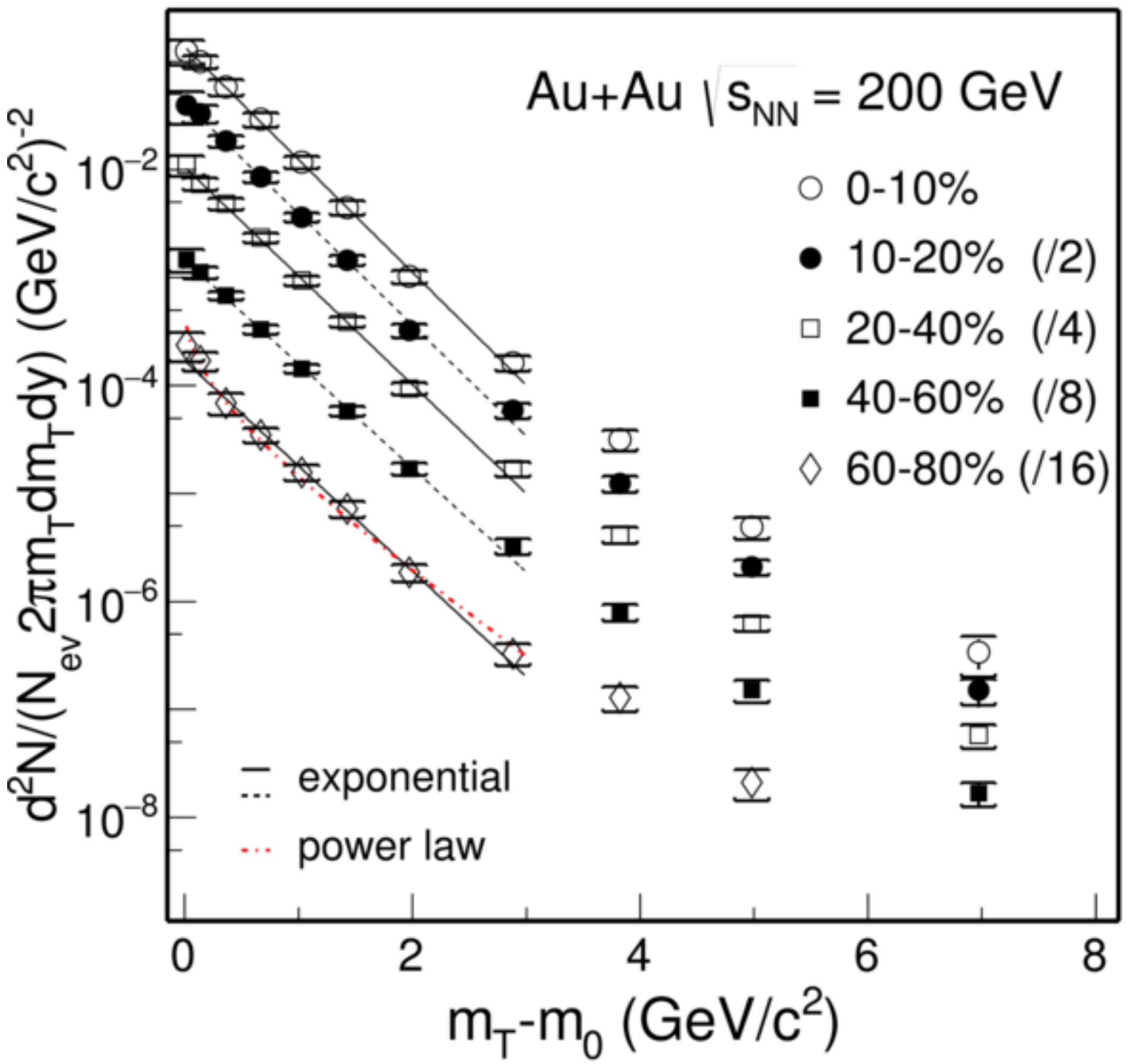
R_{AA} Suppression → Parton Energy Loss

Collectivity → Transport parameter D_s

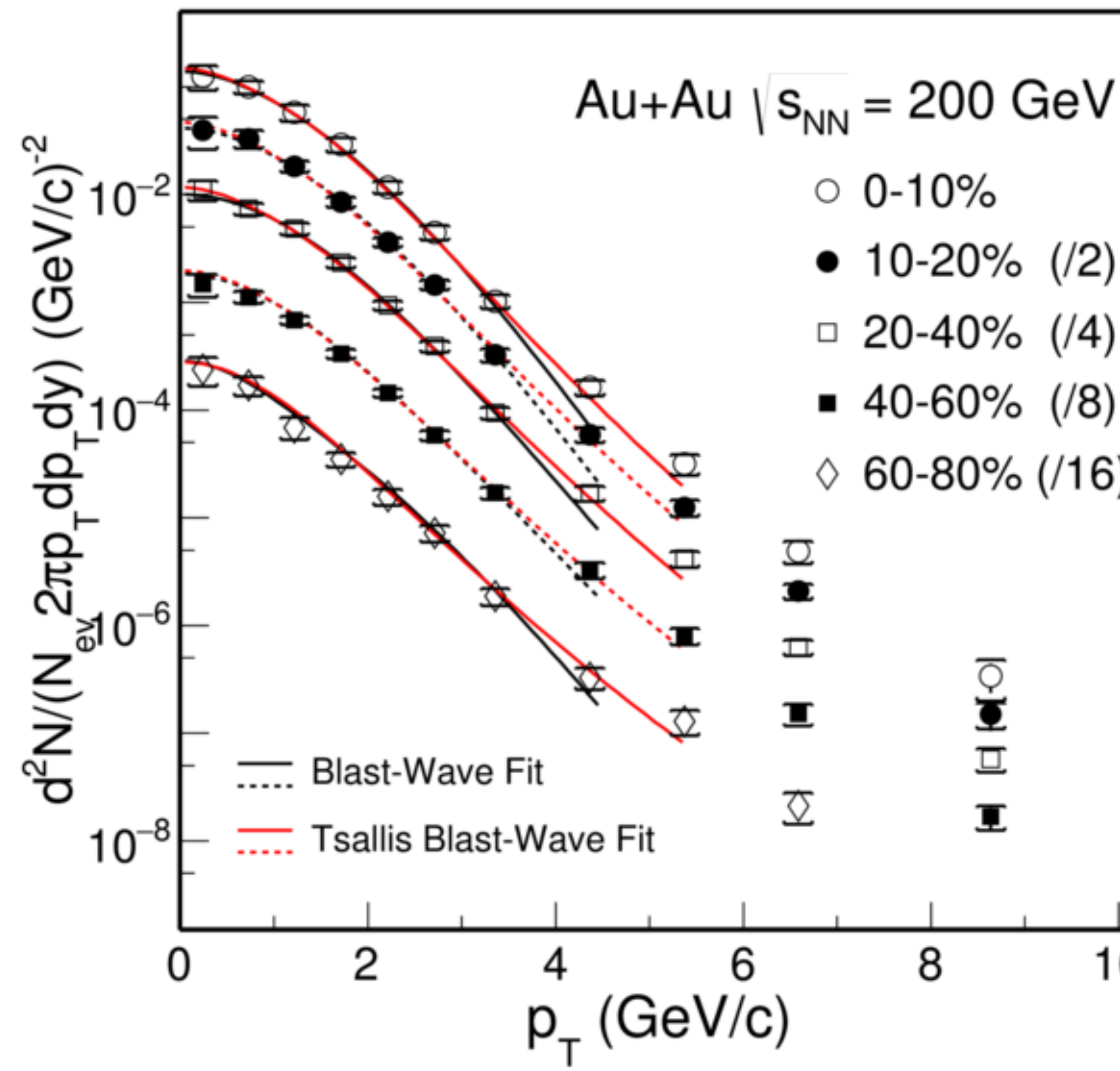
Hadrochemistry → Hadronization

Radial Flow

expo fit to m_T spectra

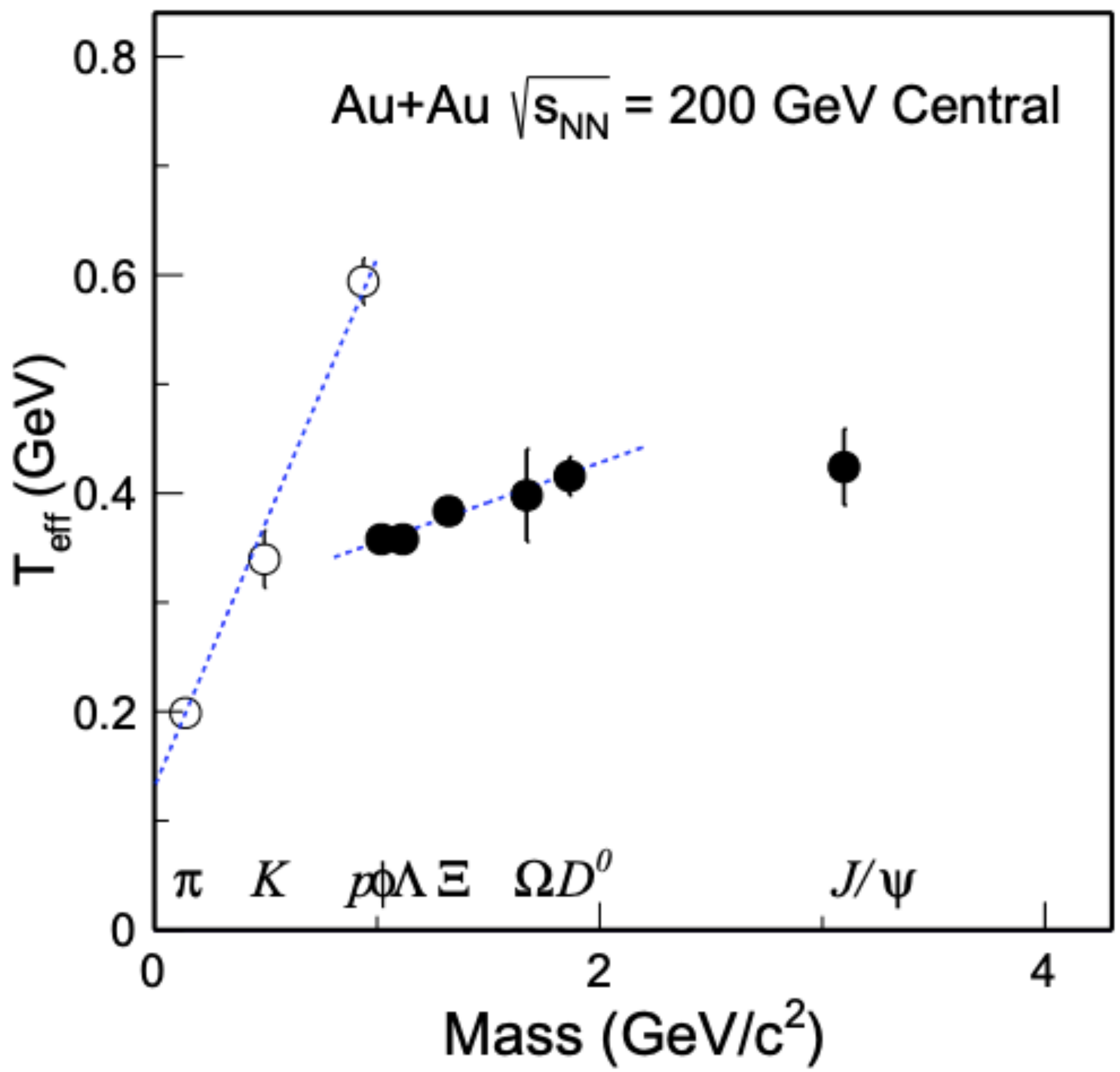


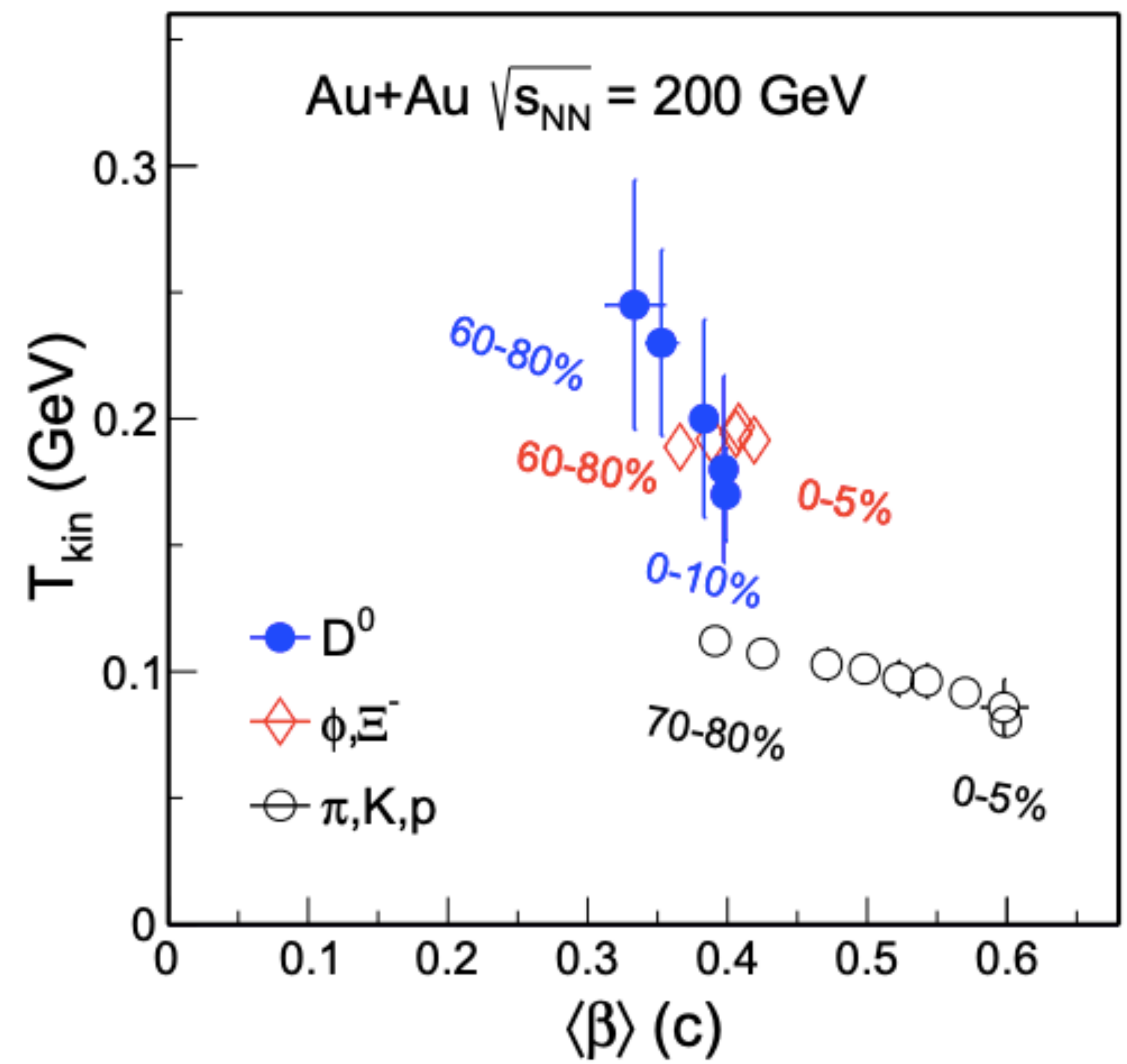
(Tsallis) Blast-Wave fits



STAR, PRC 99 (2019) 034908

D^0 Radial Flow

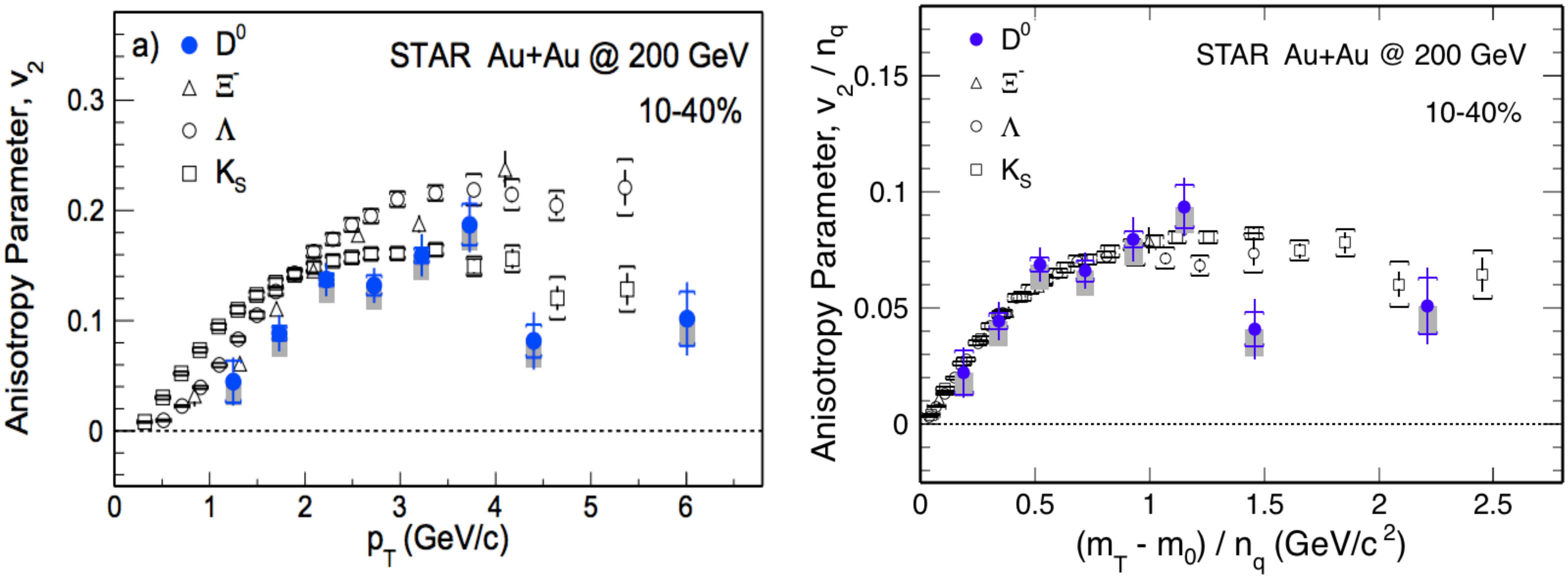




- T-slope parameter (expo fit to m_T spectra) follows the similar trend as other strange particles
- Similar to multi-strange harons, D^0 mesons kinetically freeze out earlier than light hadrons

  - collectivity from partonic stage interactions

D^0 v_2 at RHIC

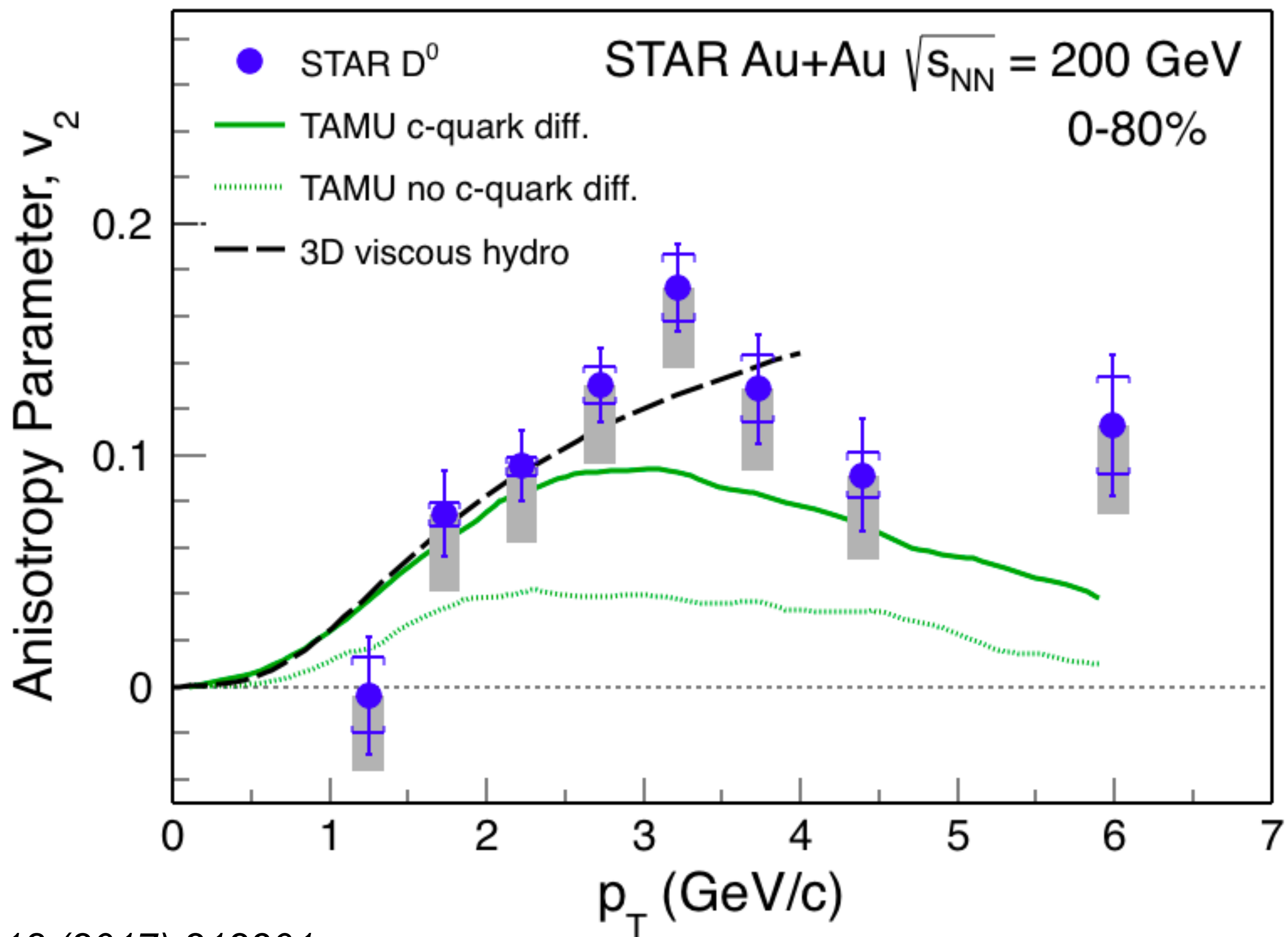


STAR, PRL 118 (2017) 212301

- Mass ordering at p_T < 2 GeV/c (hydrodynamic behavior)
- v_2(D) follows the (m_T-m_0) NCQ scaling as light hadrons below 1 GeV/c^2

Evidence of charm quarks flowing with the medium

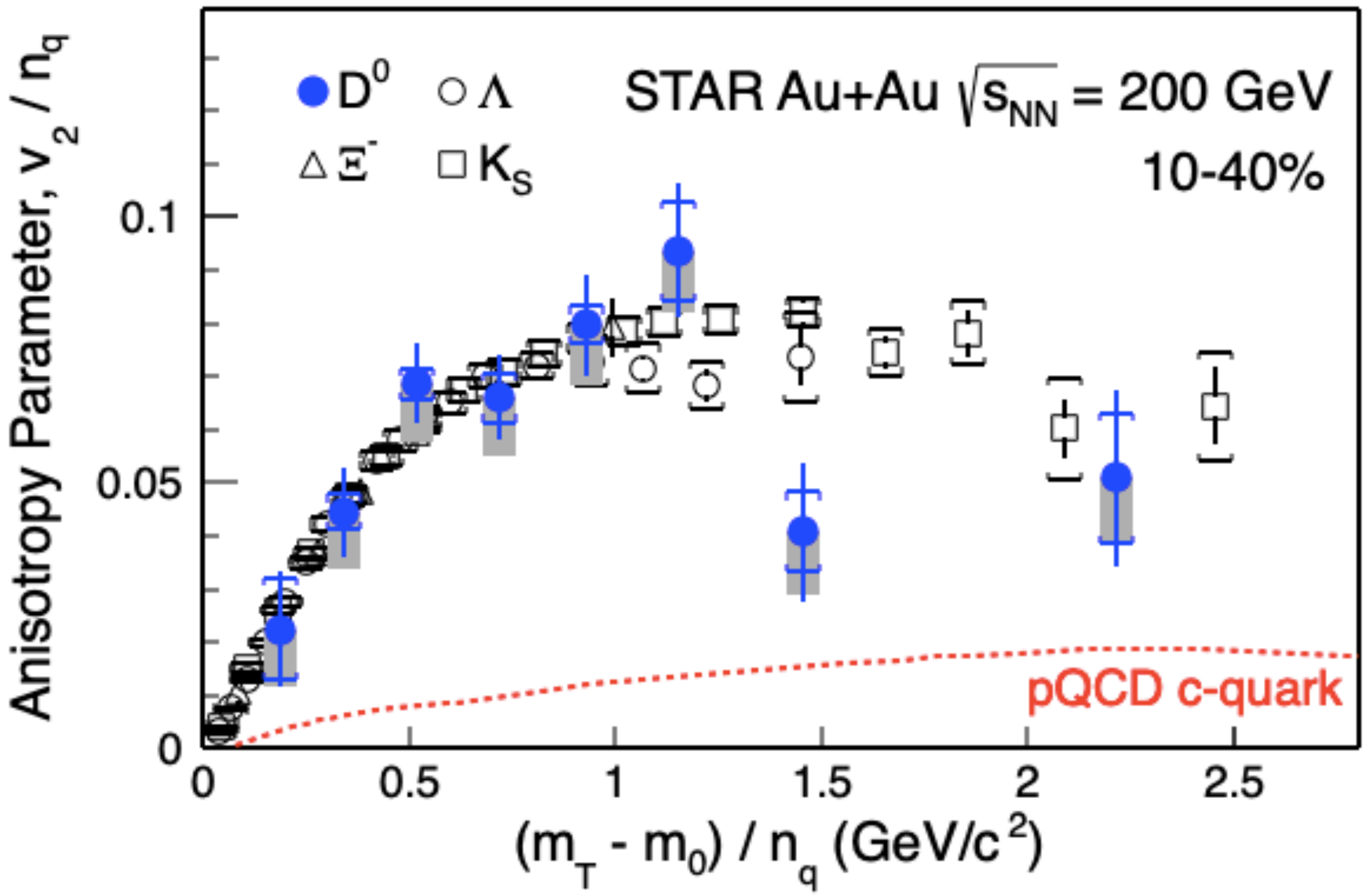
D^0 v_2 Compared with Models



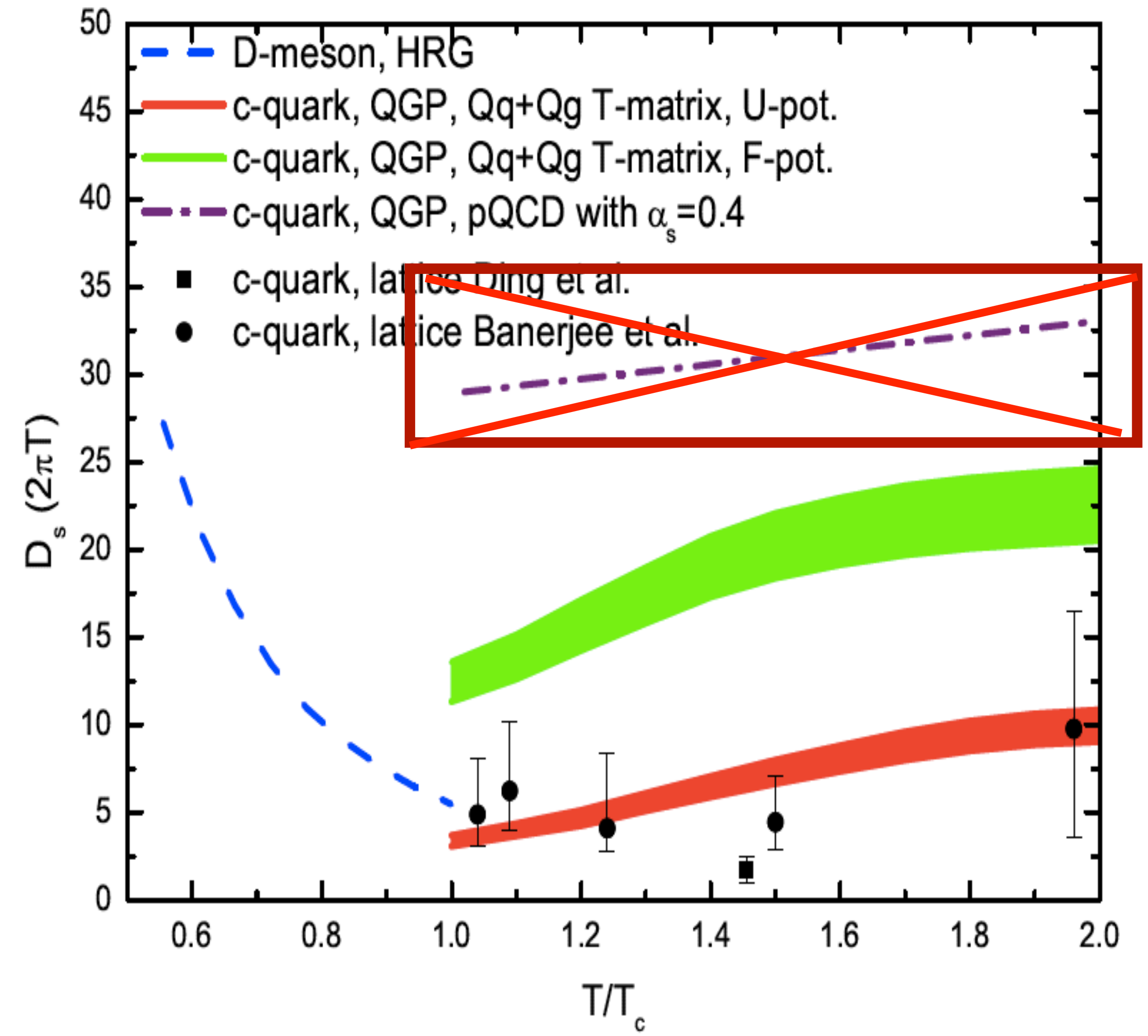
STAR, PRL 118 (2017) 212301

- 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^0 v_2 Compared with pQCD Calculation

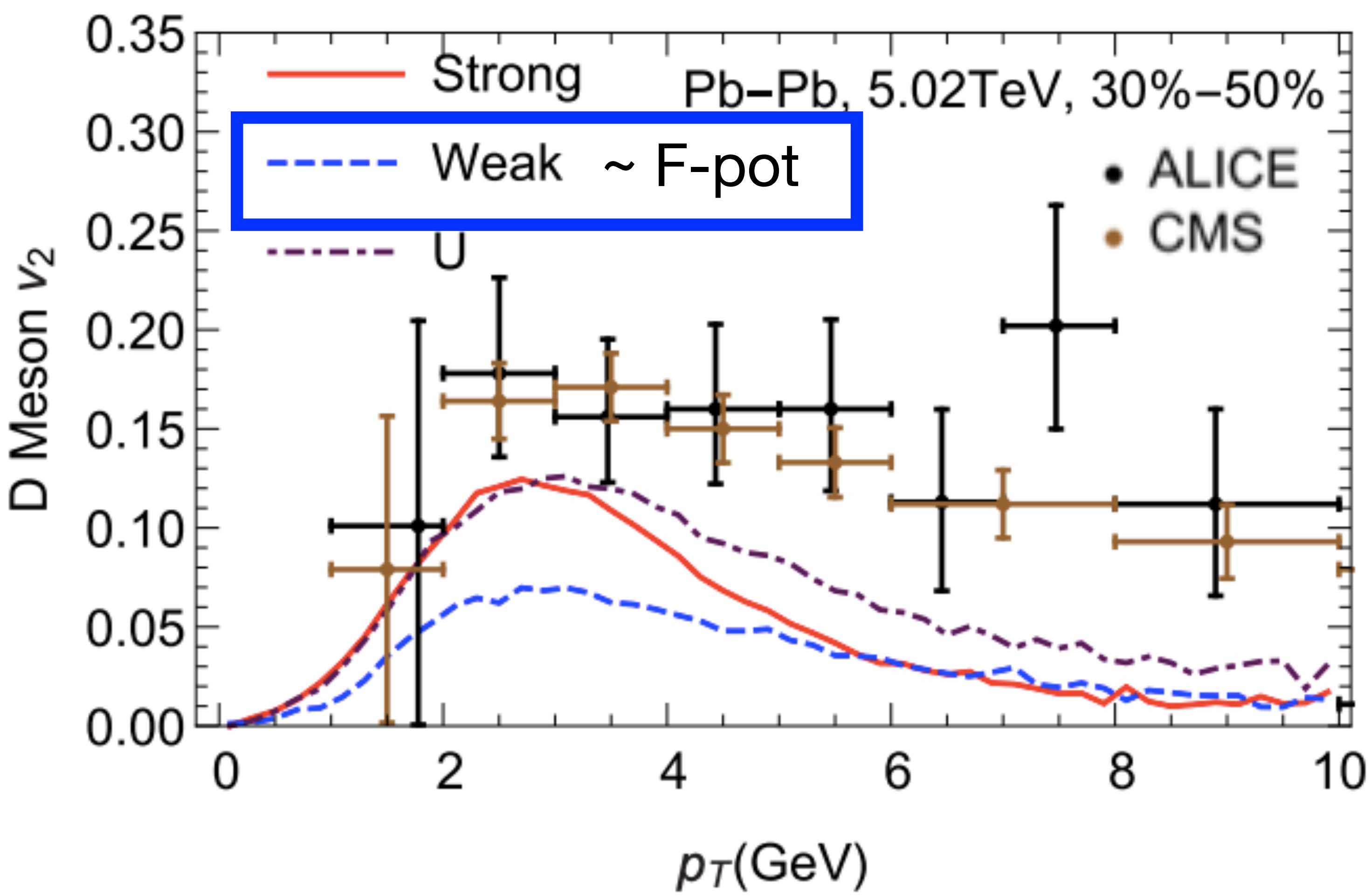


STAR data: PRL 118 (2017) 121301
pQCD c-quark (b=7fm):
R. Rapp & H. van Hees, arXiv: 0903.1096

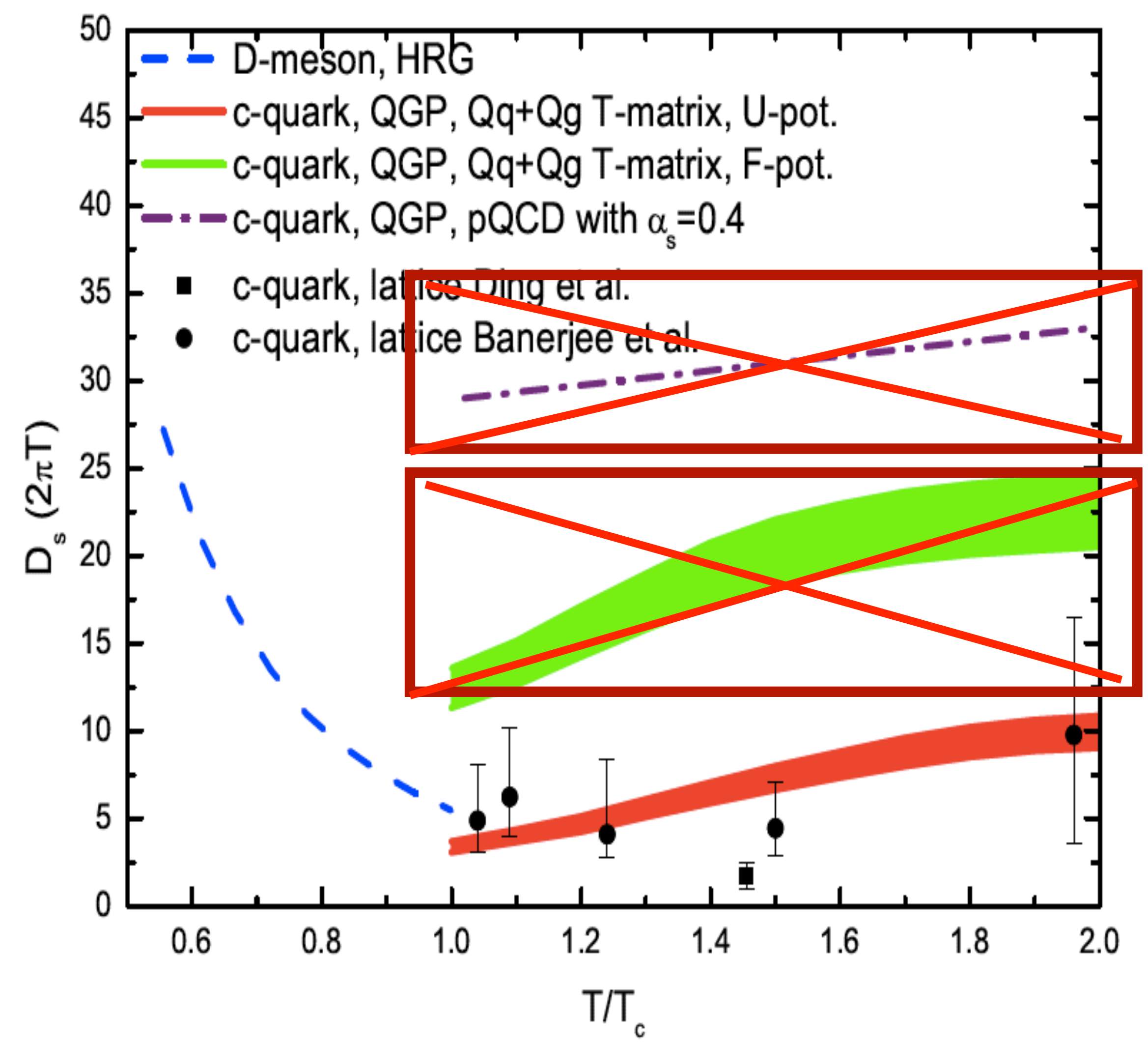


- pQCD calculation with high $2\pi TD_s$ yield a very small charm quark v_2 - cannot reproduce the data

D^0 v_2 Compared with T-Matrix F-pot./Weak pot.



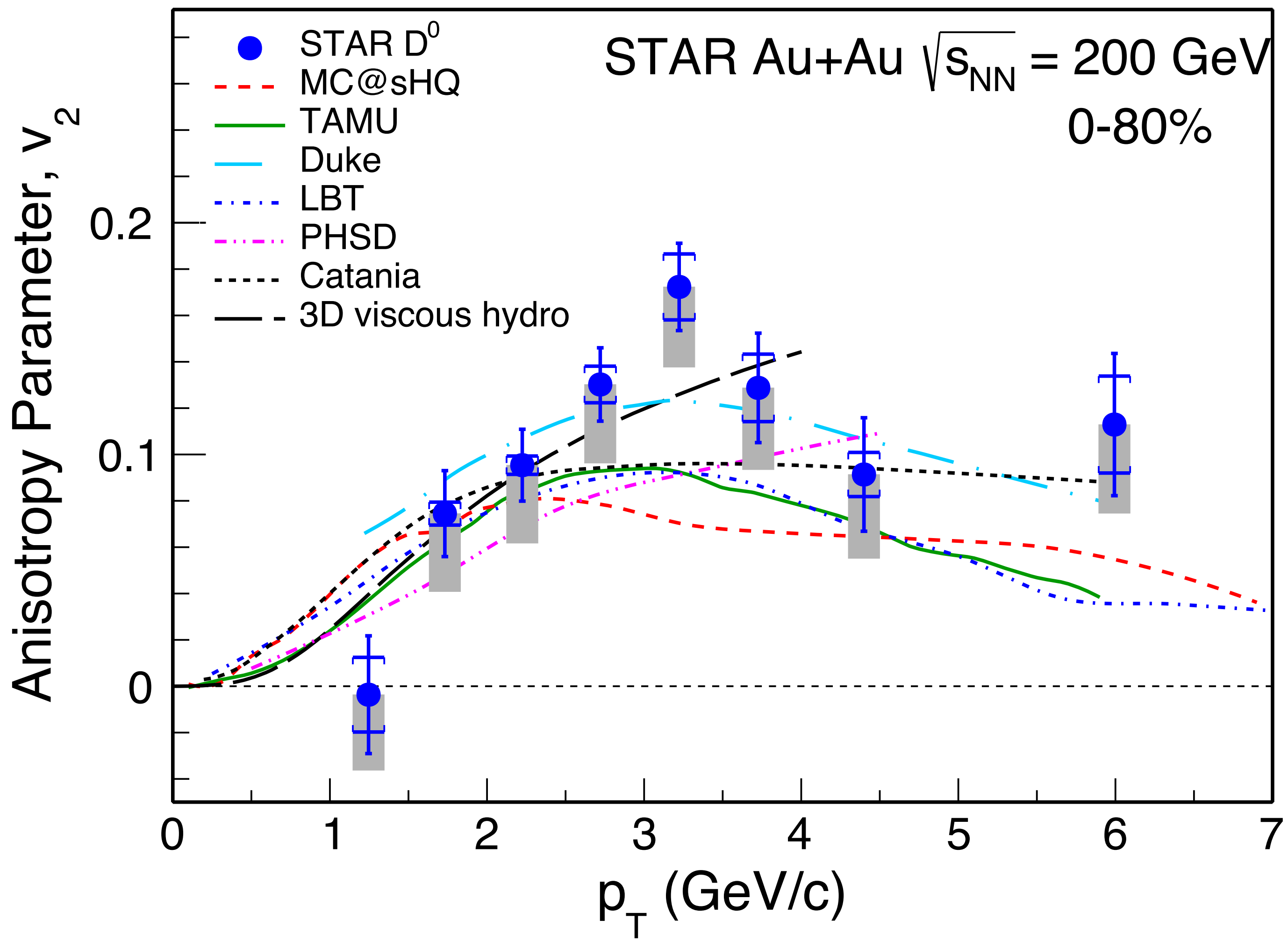
S. Liu et al, PRC 99 (2019) 055201



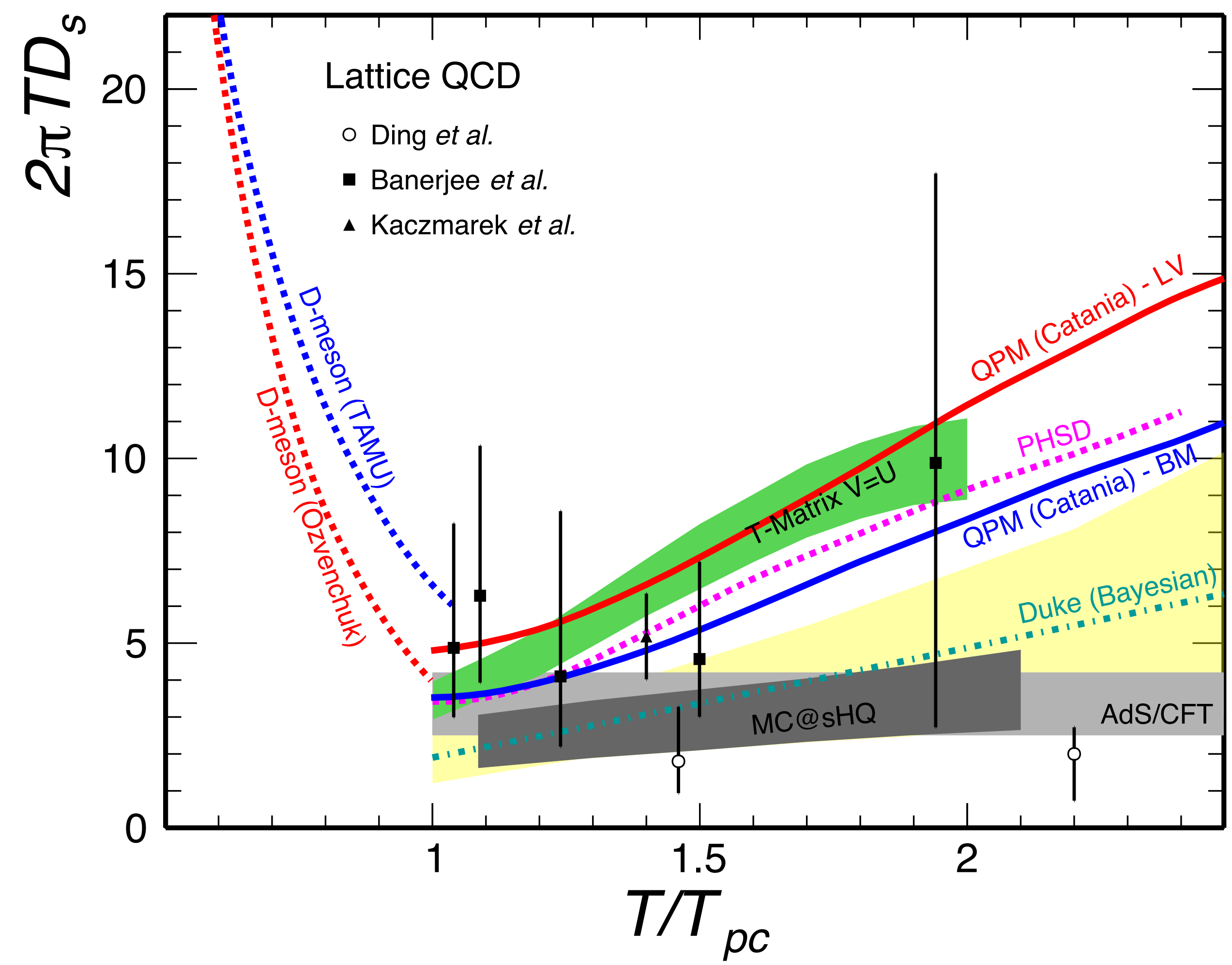
- T-Matrix with F-pot./weak-pot. underpredicts D-meson v_2

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

D^0 v_2 Compared with Models



STAR, PRL 118 (2017) 212301

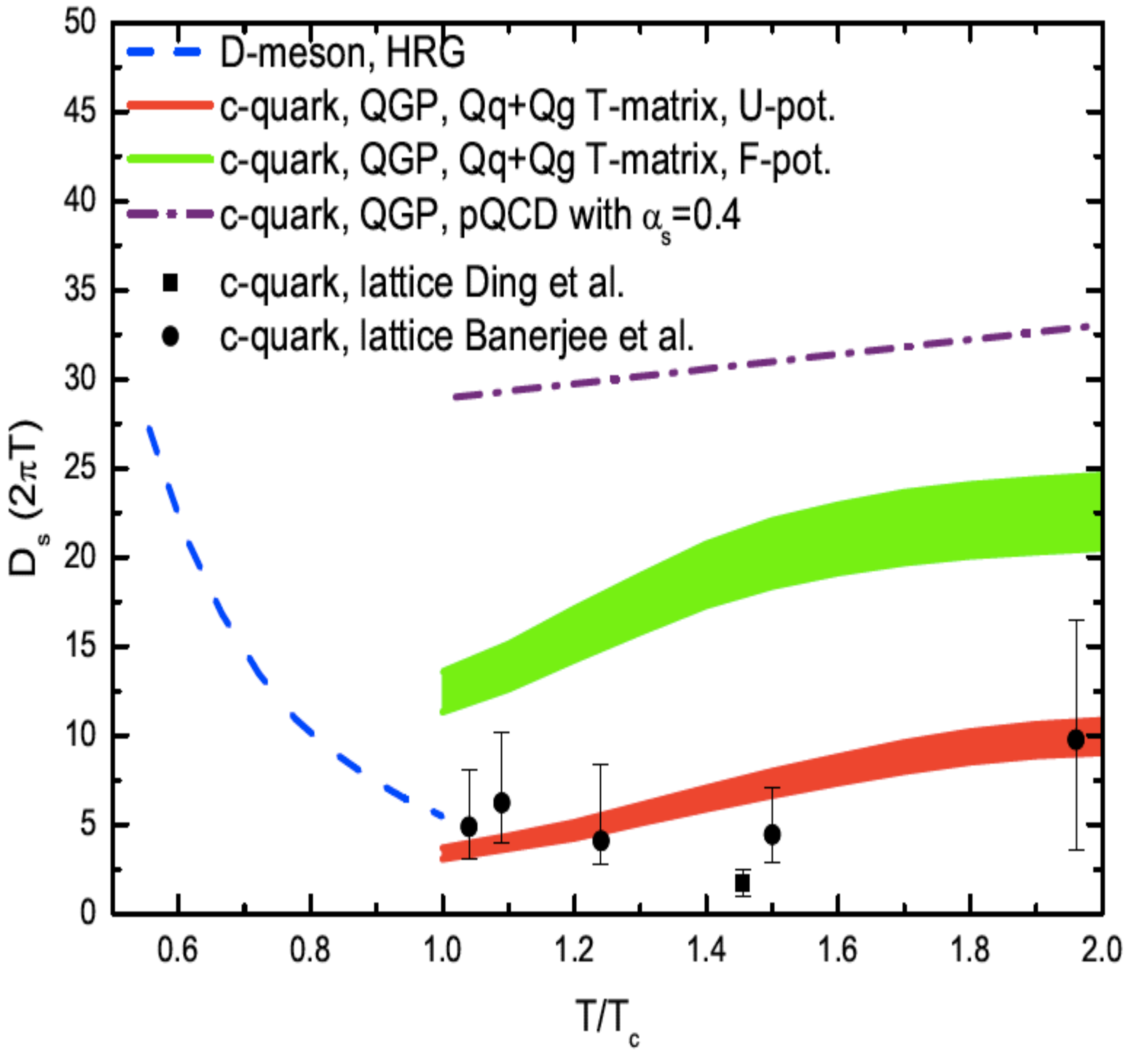


XD, Y-J Lee & R. Rapp, Ann. Rev. Nucl & Part. Sci. 69 (2019) 417

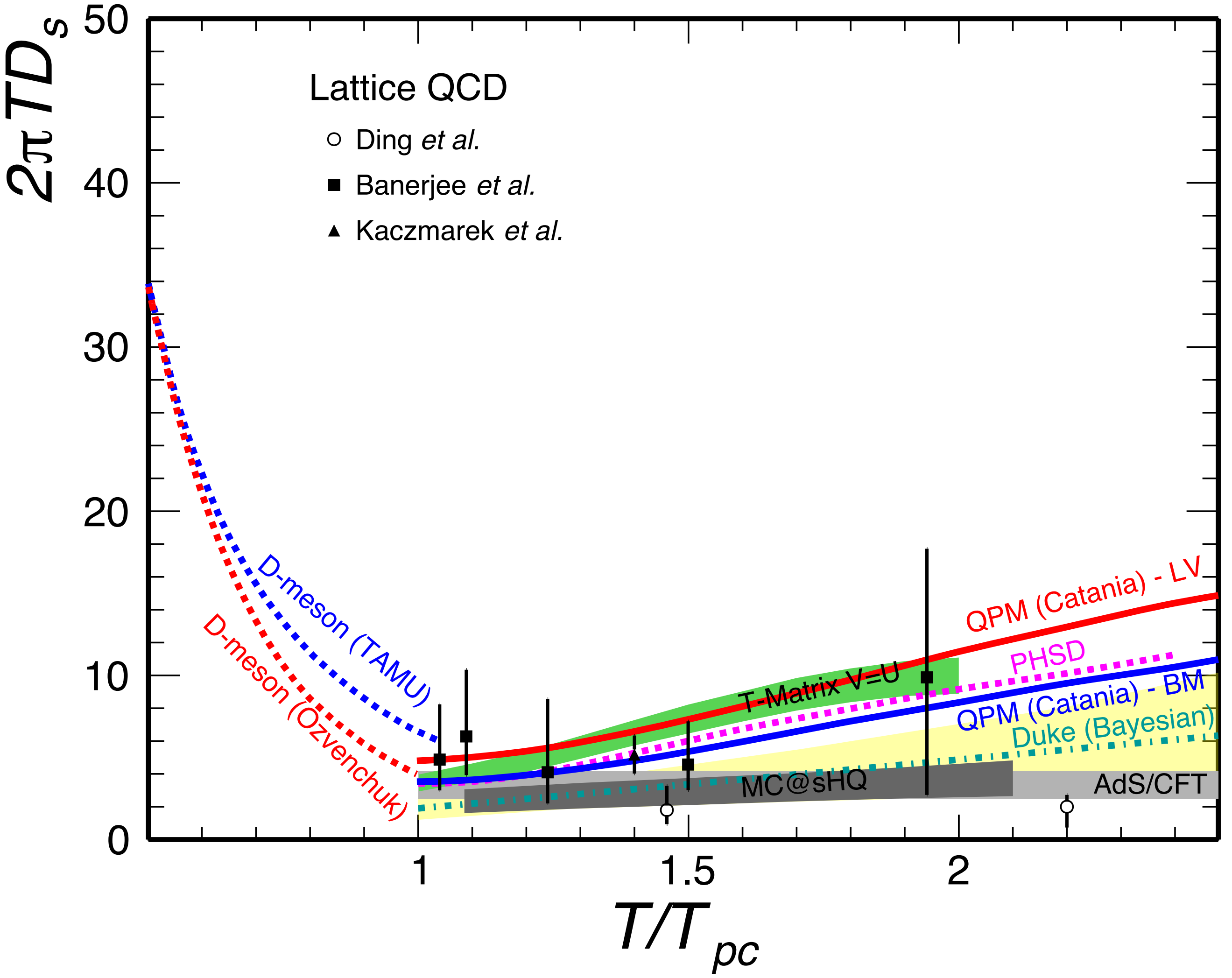
- State-of-the-art model calculations from various approaches reasonably describe D^0 meson v_2 data at RHIC
- Charm quark $2\pi TD_s$ **~ 2-5** at near Tc
  - consistent with quenched lattice calculations
  - larger uncertainty in temperature dependence

Charm Spatial Diffusion Coefficient

2015



2019

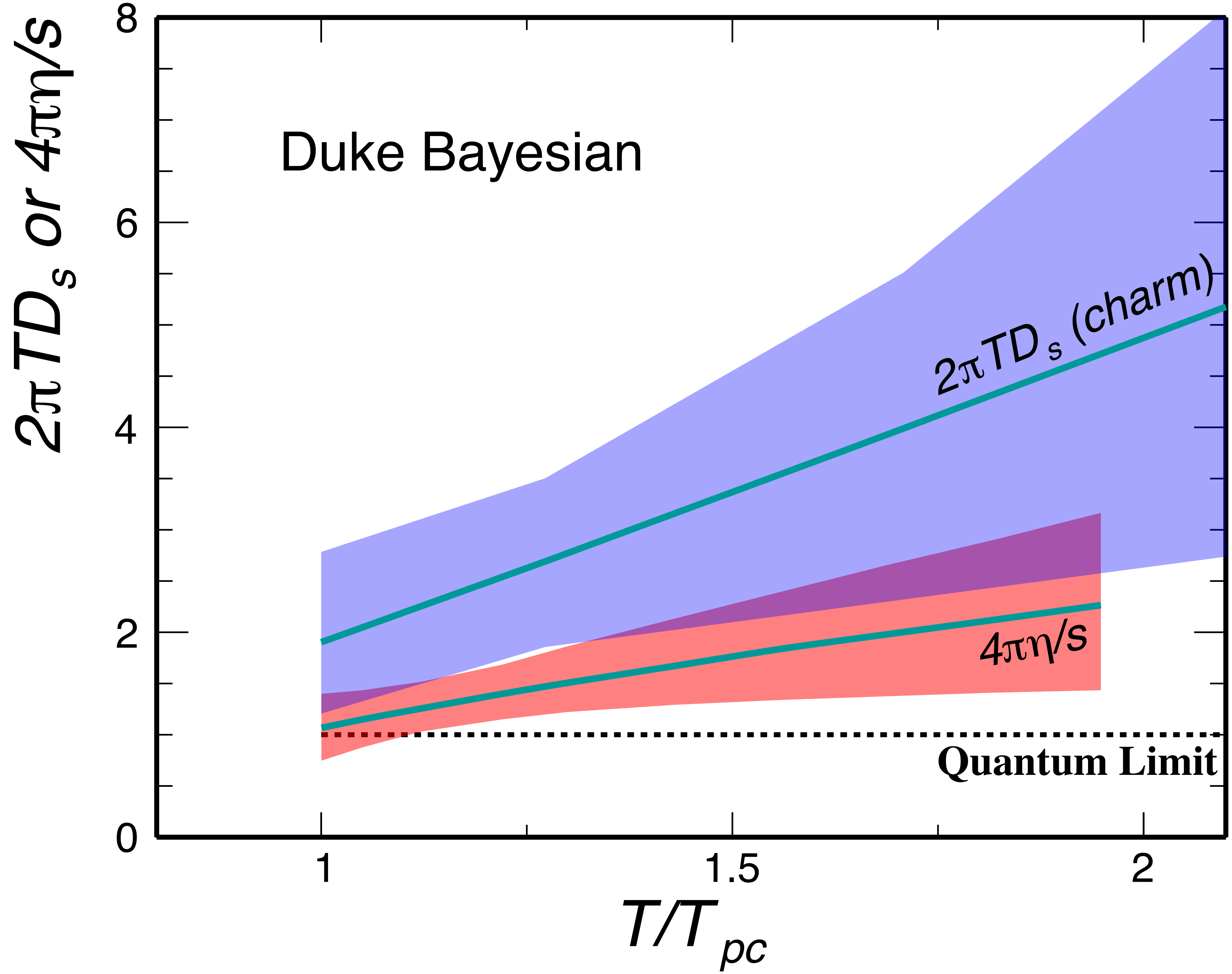


Strongly interacting QGP!

$2\pi TD_s$ 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*



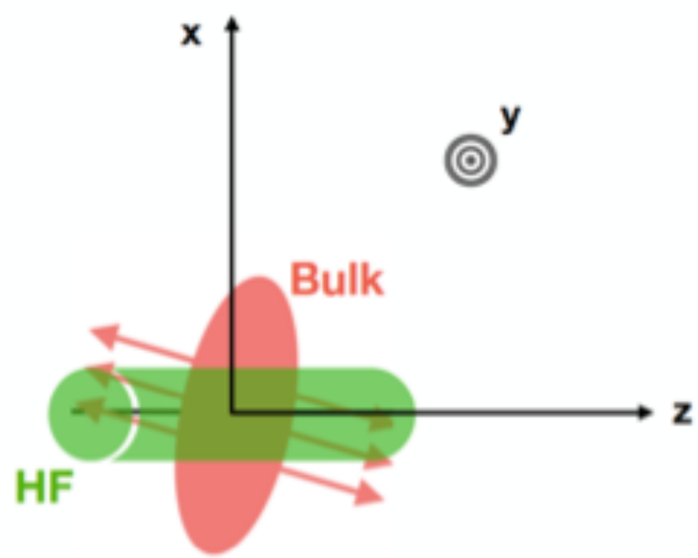
charm vs. bottom universality? momentum/temperature dependence?

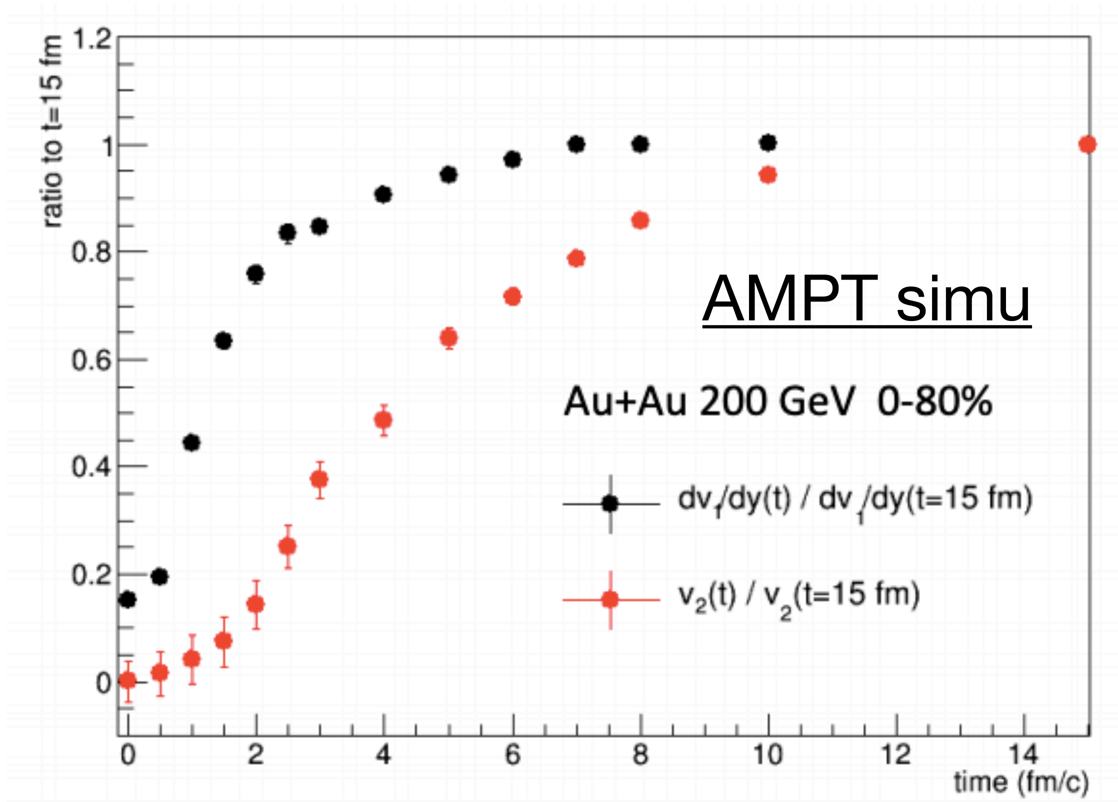
D^0 v_1 - New Insight to sQGP Properties

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

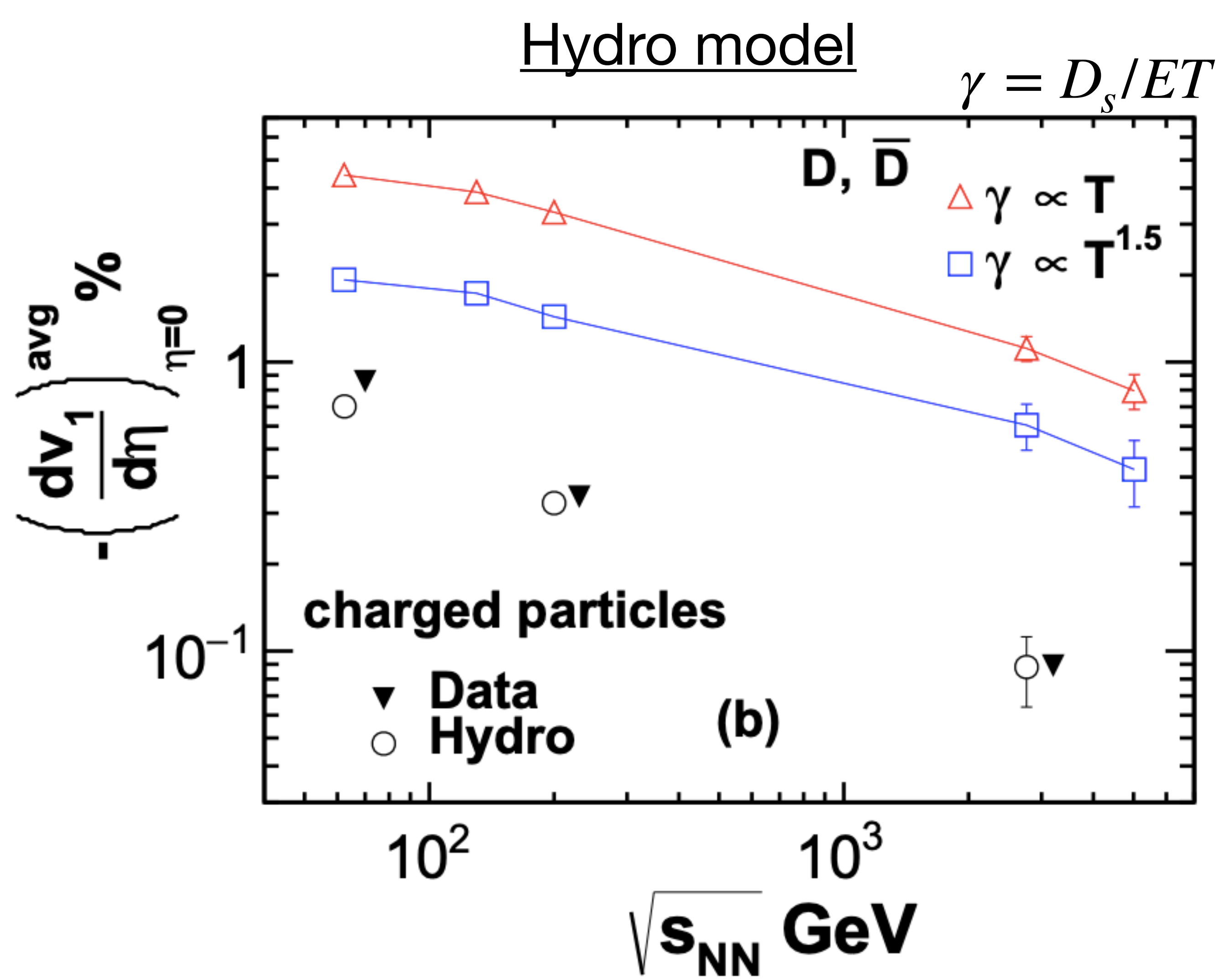
D-meson v_1 sensitive to

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



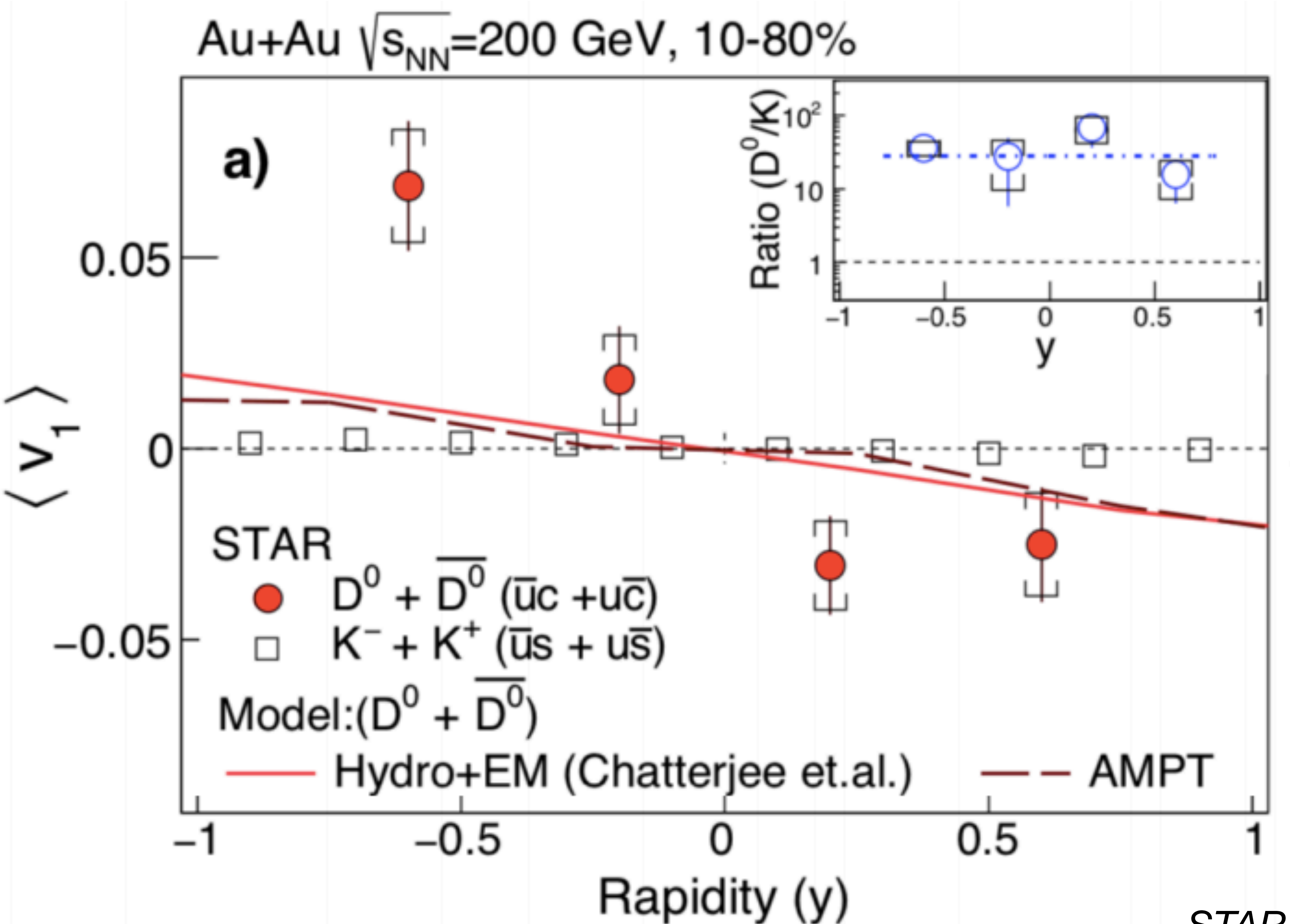


X. Ju, DNP 2019



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

D^0 v_1 - New Insight to sQGP Properties

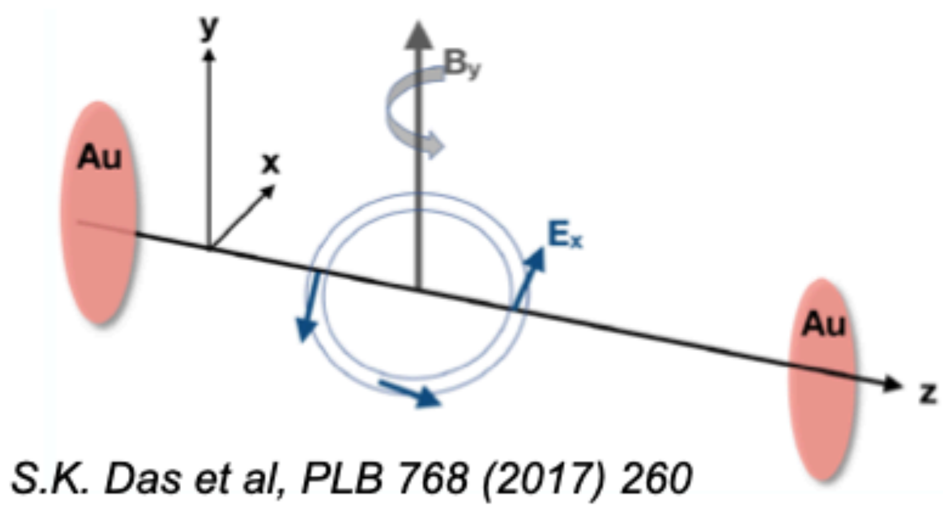


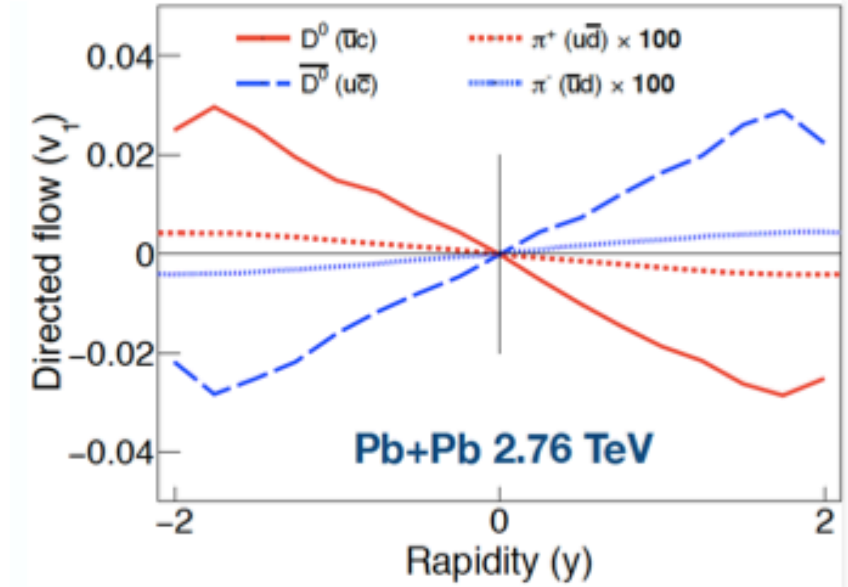
STAR, PRL 123 (2019) 162301

$$v_1(D) \gg v_1(h)$$

- Originated from initial tilted source + HQ diffusion in sQGP
- Constraints on T-dependence of HQ spacial diffusion coefficient?
  - Need theory model calculations

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



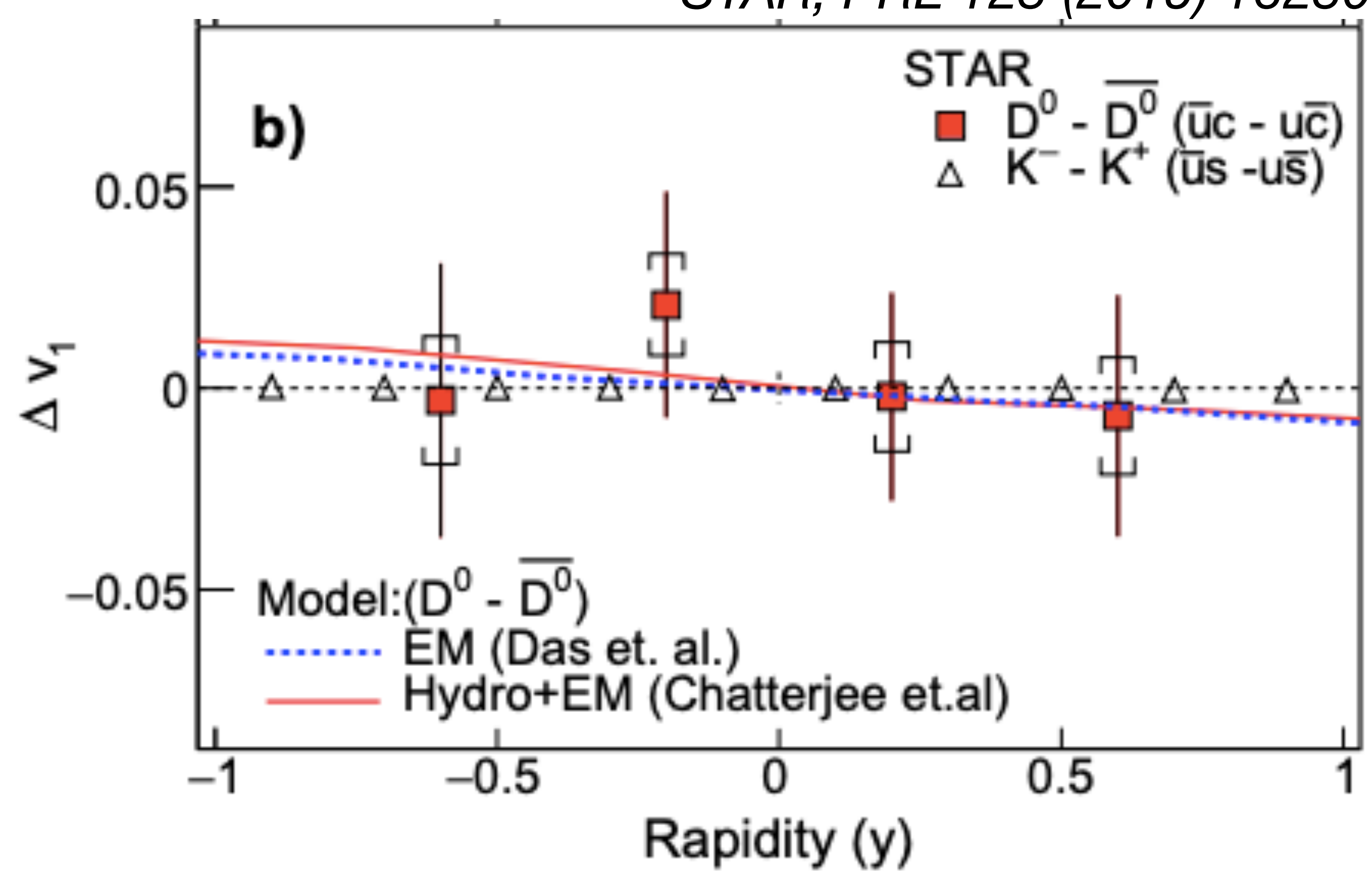


Strong B field in HIC -> $v_1(D) = - v_1(Dbar)$, $v_1(h^+)-v_1(h^-)\sim 0$

STAR, PRL 123 (2019) 162301

Current experimental uncertainty >> predicted signal

More precise measurements are required in order to access the initial B field signal



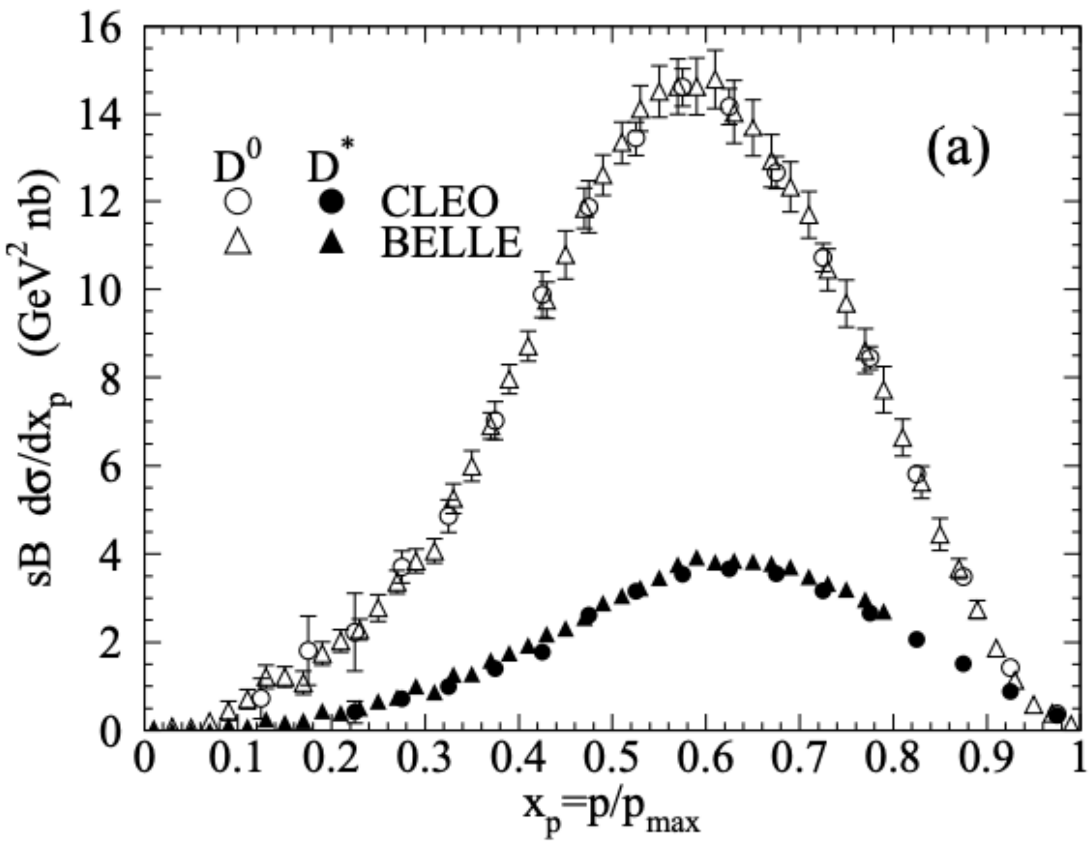
R_{AA} Suppression → Parton Energy Loss

Collectivity → Transport parameter D_s

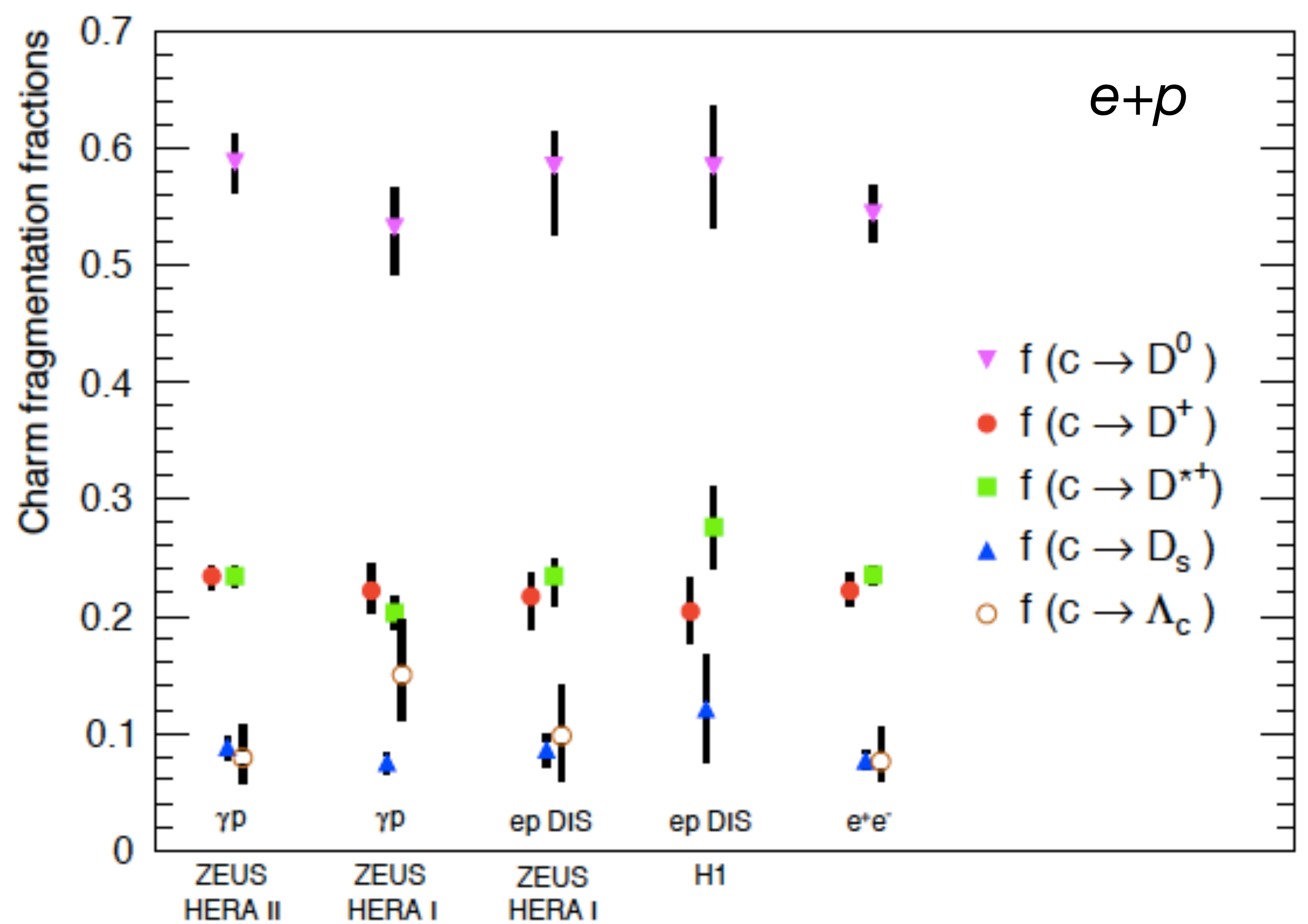
Hadrochemistry → Hadronization

Charm Hadrochemistry in ee/ep

fragmentation measured in ee



PDG 2018



ZEUS, JHEP 1309 (2013) 058

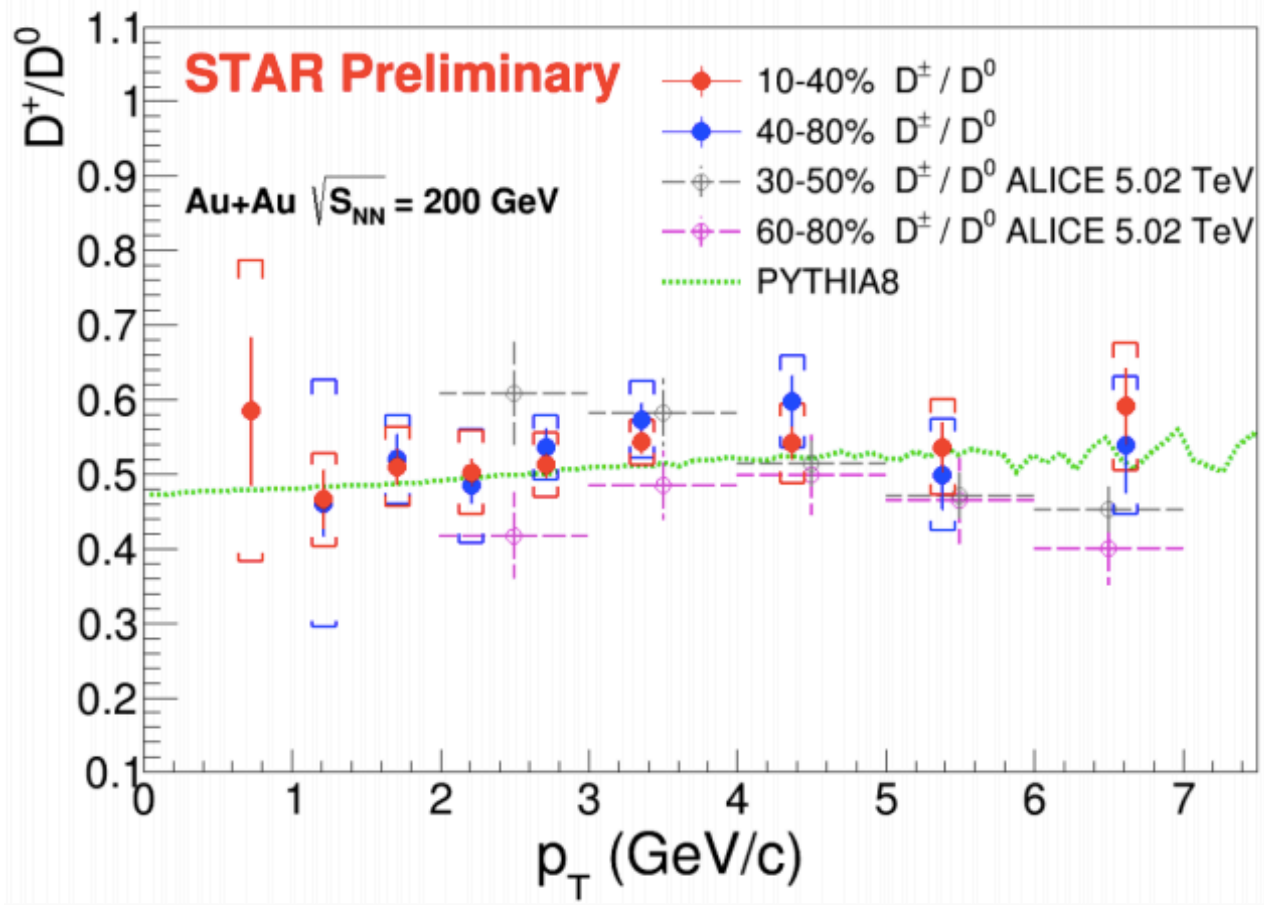
$$2\sigma_{c\bar{c}} = D^0 + D^+ + D_s^+ + \Lambda_c^+ \quad + \text{c.c.}$$

60.8% 24.0% 8.0% 6.2%

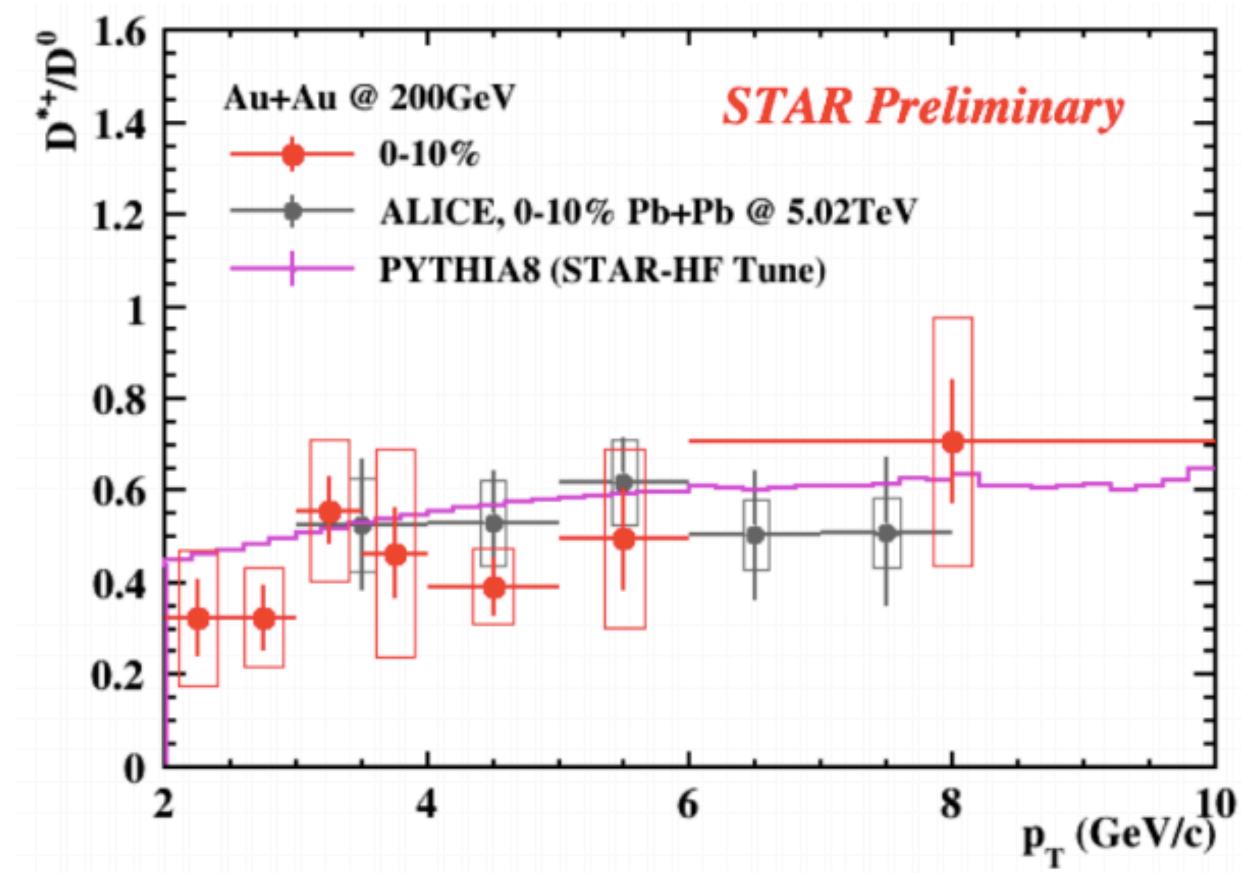
Lisovyi, et. al. EPJ C 76 (2016) 397

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

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

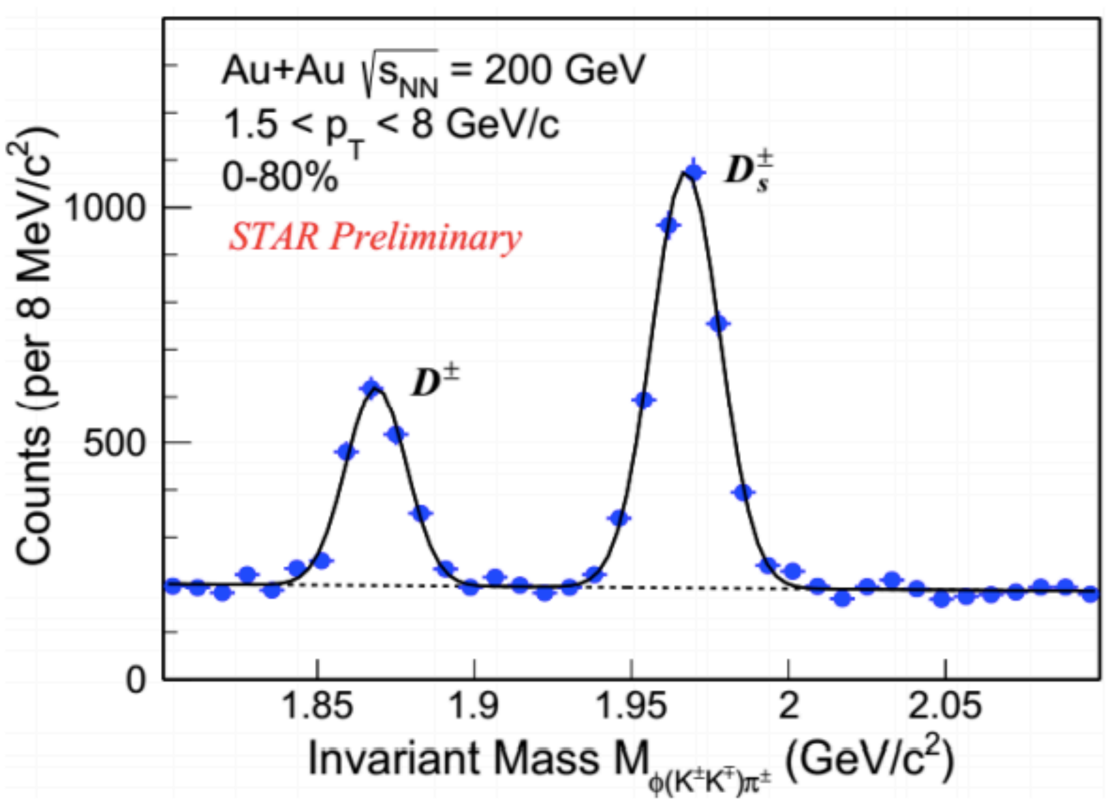


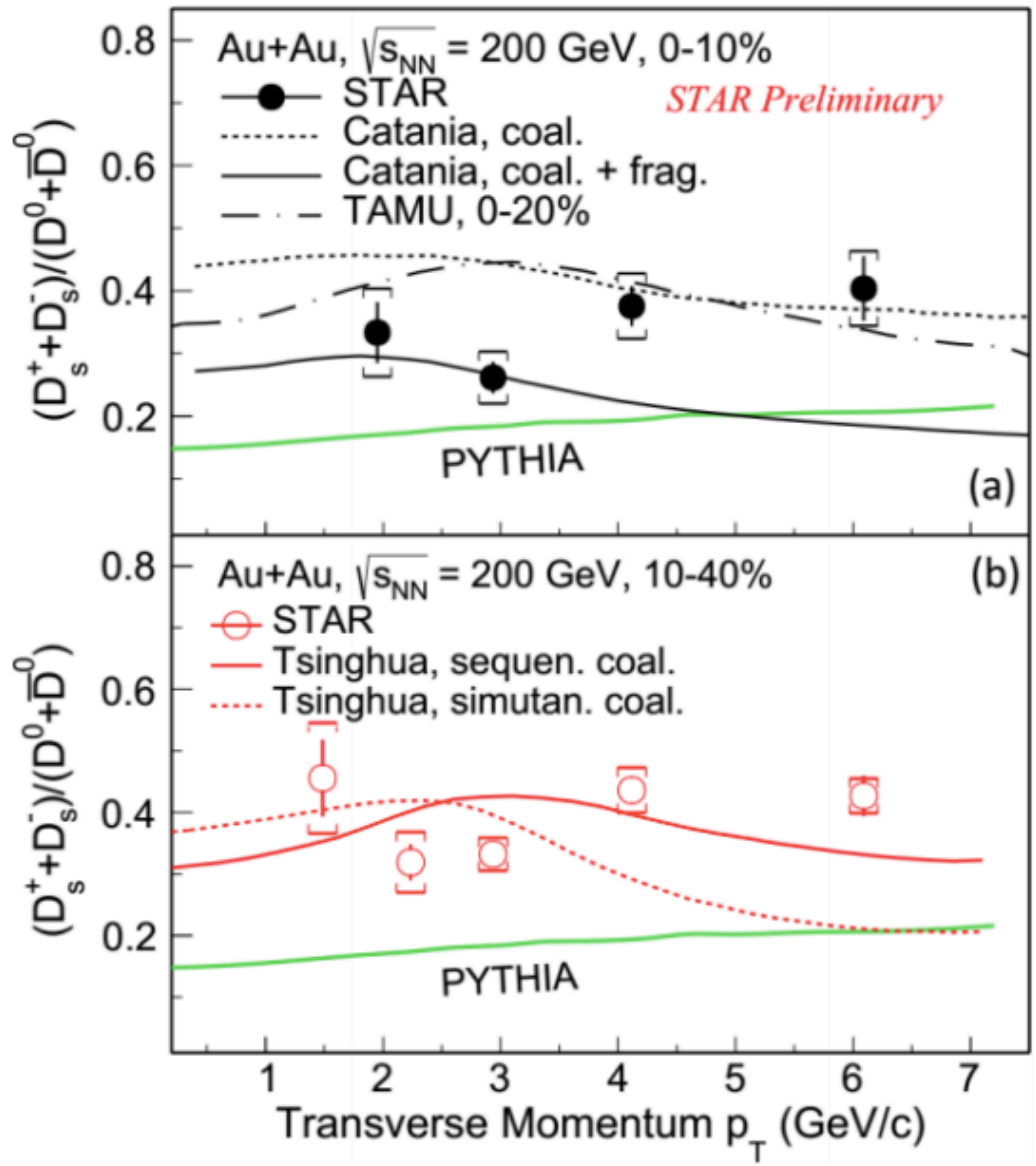
$D^{*+} \rightarrow D^0\pi^+ \rightarrow K^-\pi^+\pi^+$



- 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

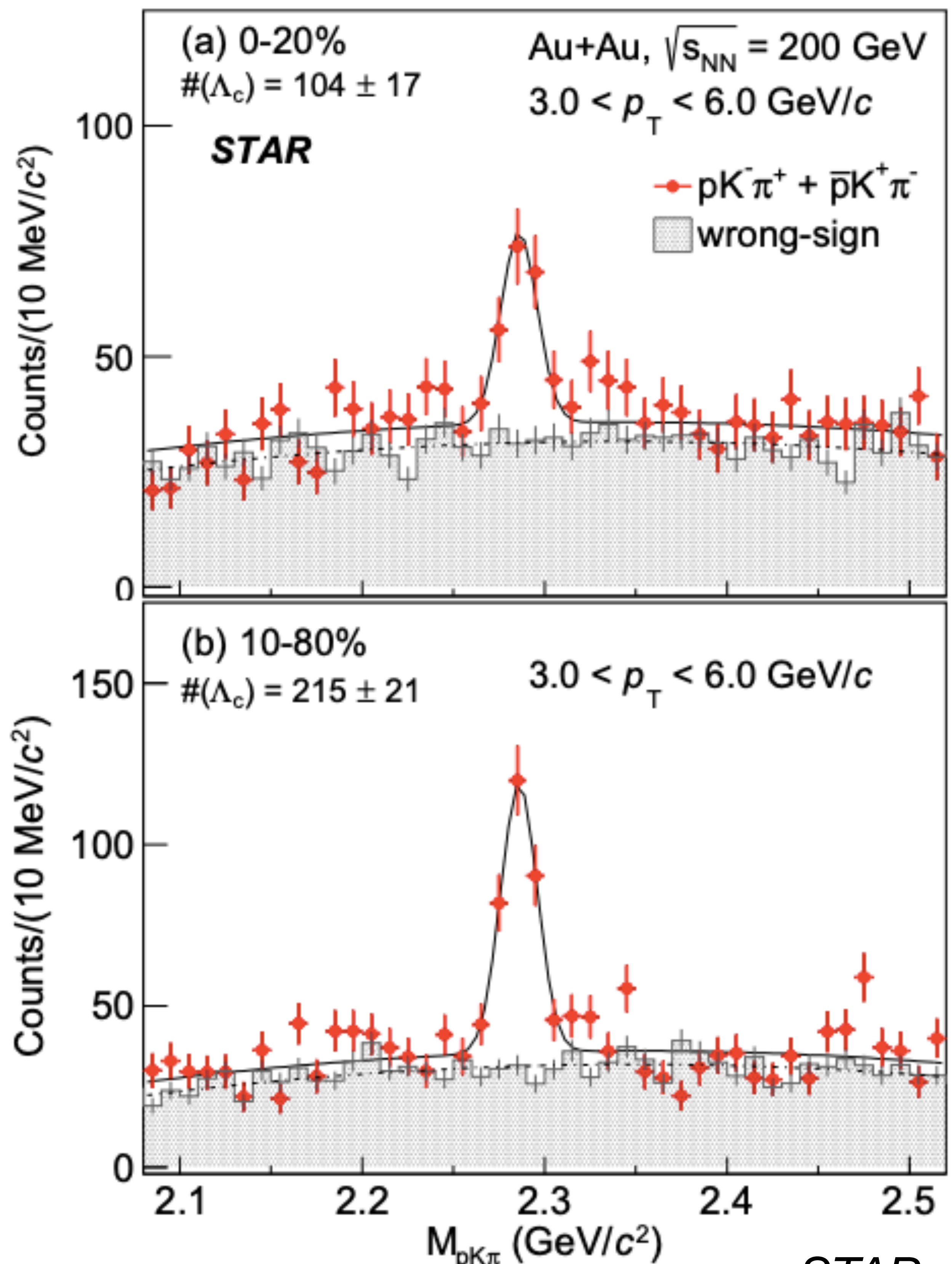




STAR, HP 2020

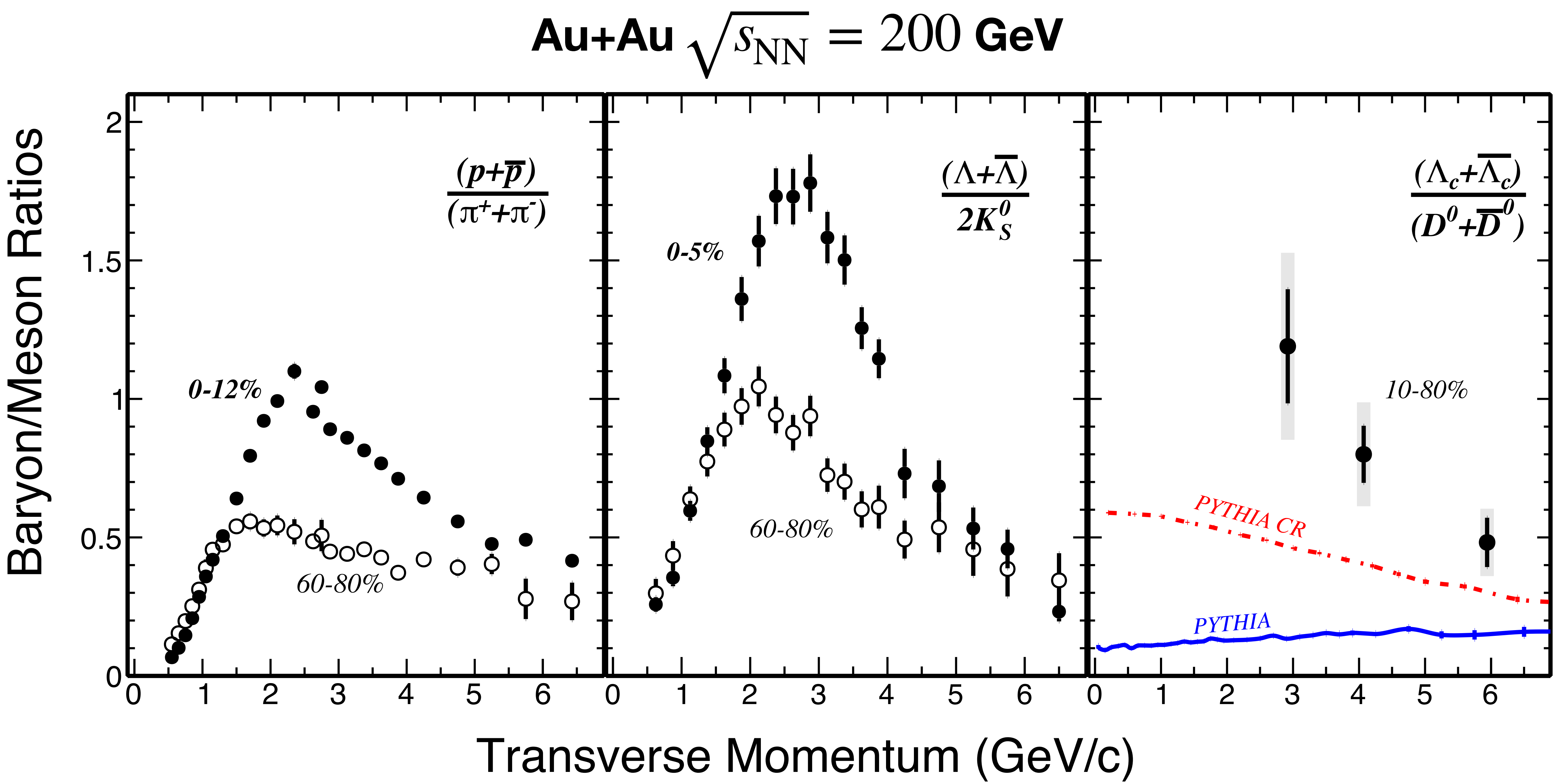
- D_s^+/D^0 significantly higher than fragmentation baseline calculated from PYTHIA
- Models with coalescence hadronization + strangeness enhancement qualitatively reproduce the data

Λ_c Reconstruction in Heavy-Ion Collisions



STAR, PRL 124 (2020) 172301

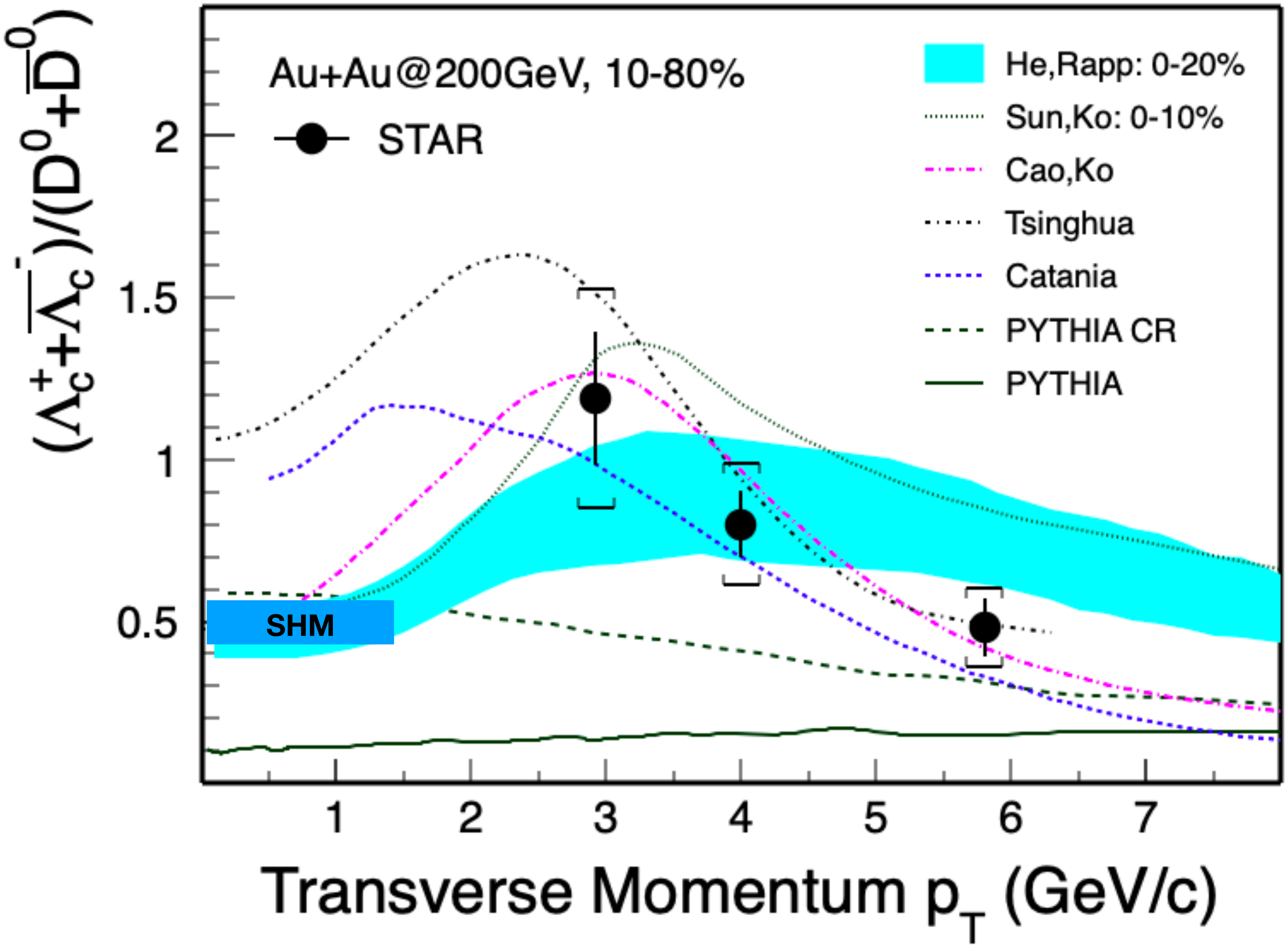
Baryon-to-Meson Ratios in Au+Au Collisions



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)

Λ_c Enhancement Compared to Models

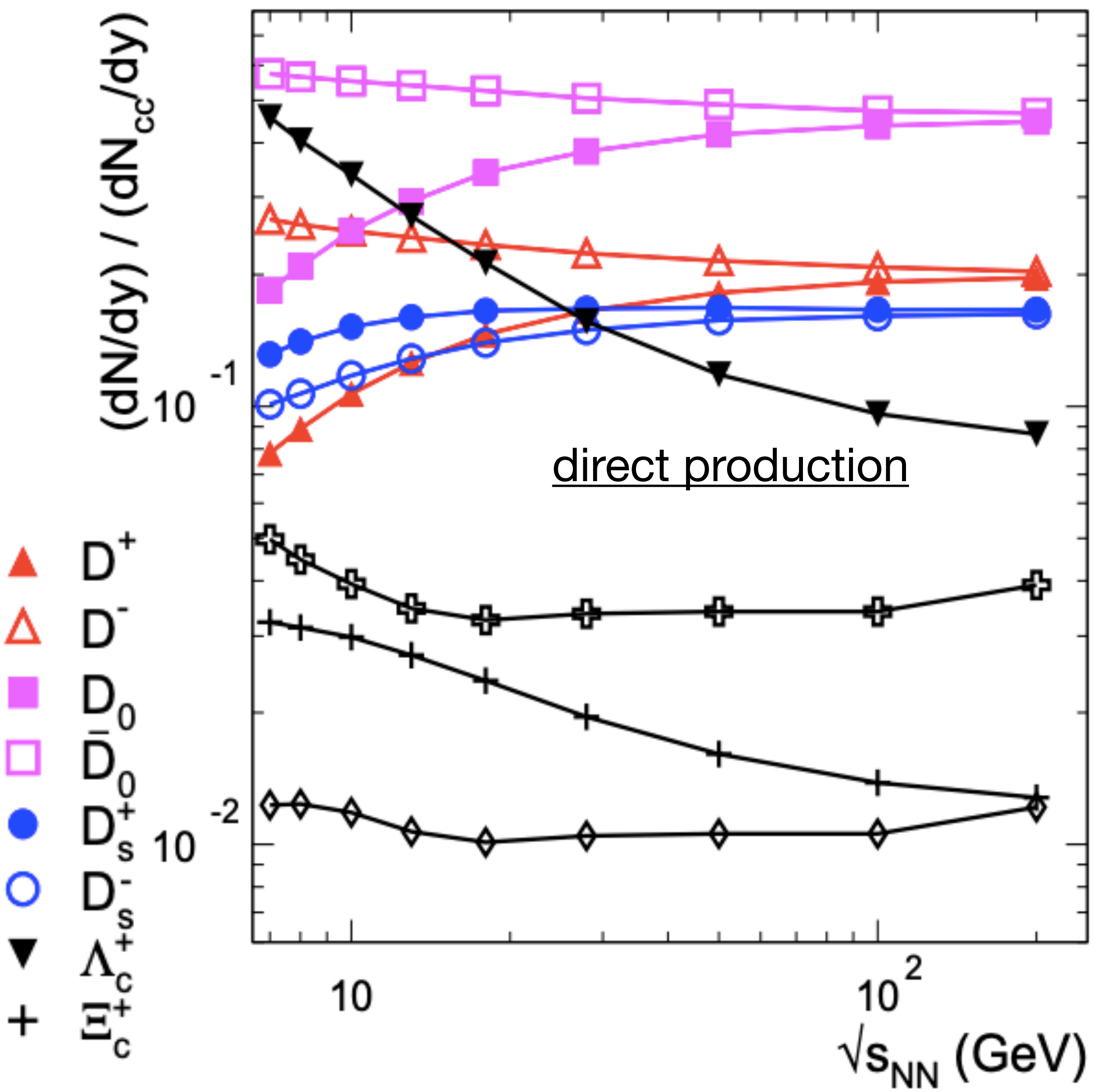


STAR, PRL 124 (2020) 172301

- Coalescence models qualitatively reproduce the large Λ_c/D^0 ratio

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

Total Charm Production Cross Section

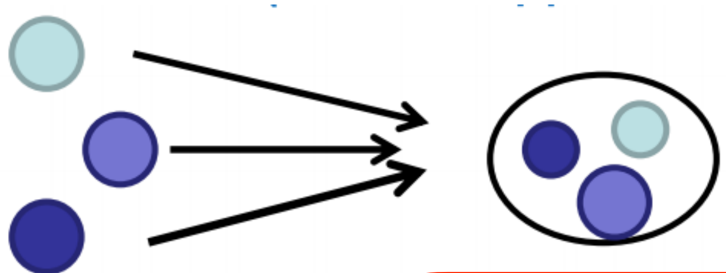
Charm Hadron		Cross Section dσ/dy (μb)
Au+Au 200 GeV (10-40%)	D^0	41 ± 1 ± 5
	D^+	18 ± 1 ± 3
	D_s^+	15 ± 1 ± 5
	Λ_c^+	78 ± 13 ± 28*
	Total	**152 ± 13 ± 29**
p+p 200 GeV	**Total**	**130 ± 30 ± 26**

** extracted from 10-80%*

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

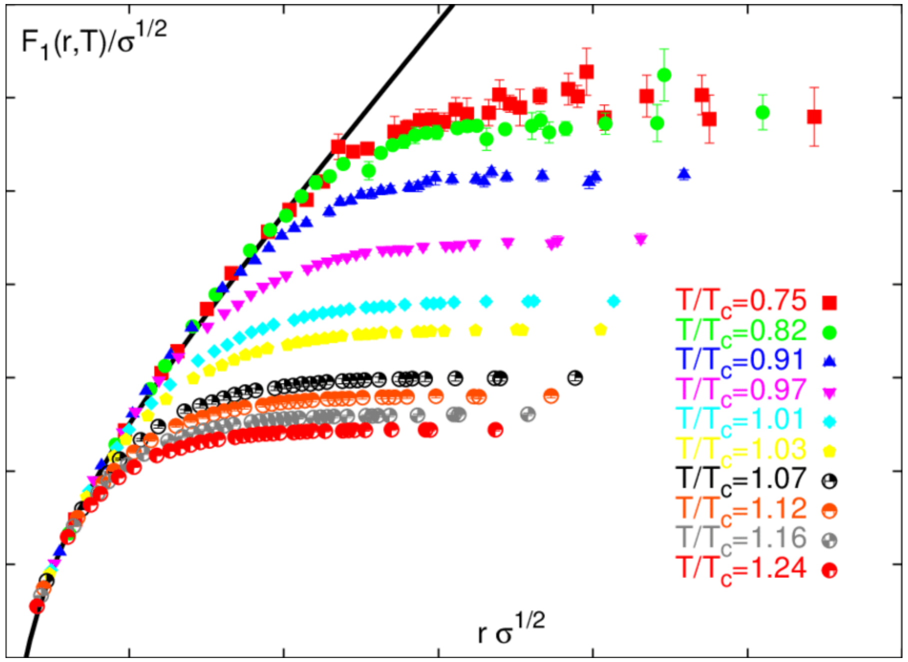
Connection to Confinement/sQGP Properties?

Coalescence

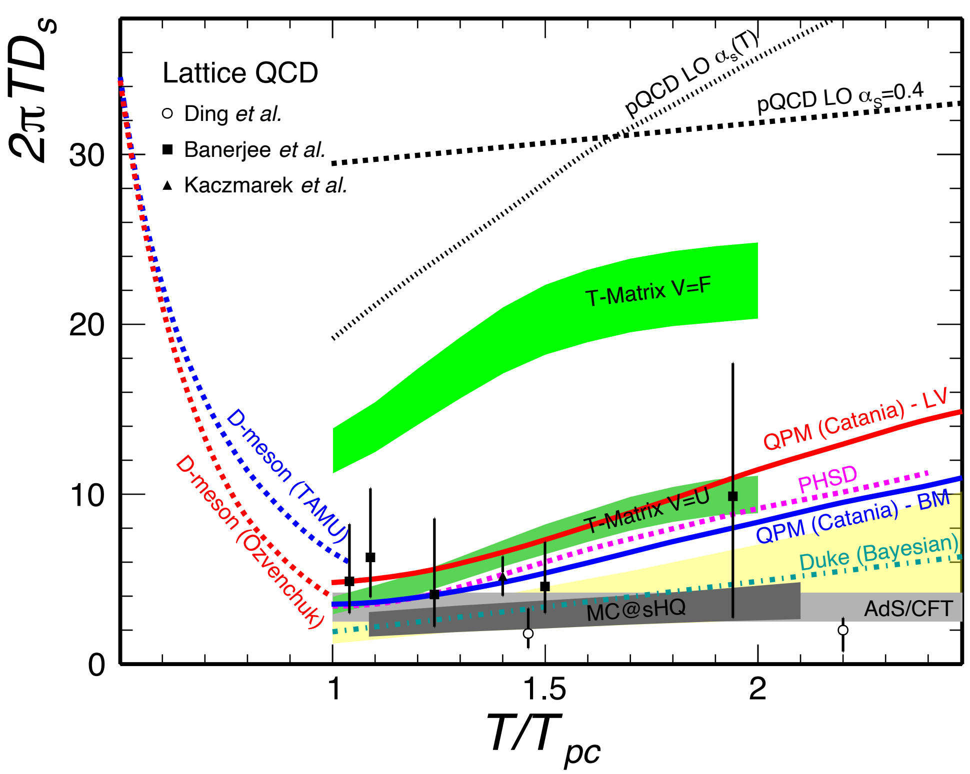


$$N_c = g_c \int \left(\prod_{i=1}^{N} \mathrm{d}N_i\right) \rho_c^W(x_1, ..., x_N; p_1, ..., p_N)$$

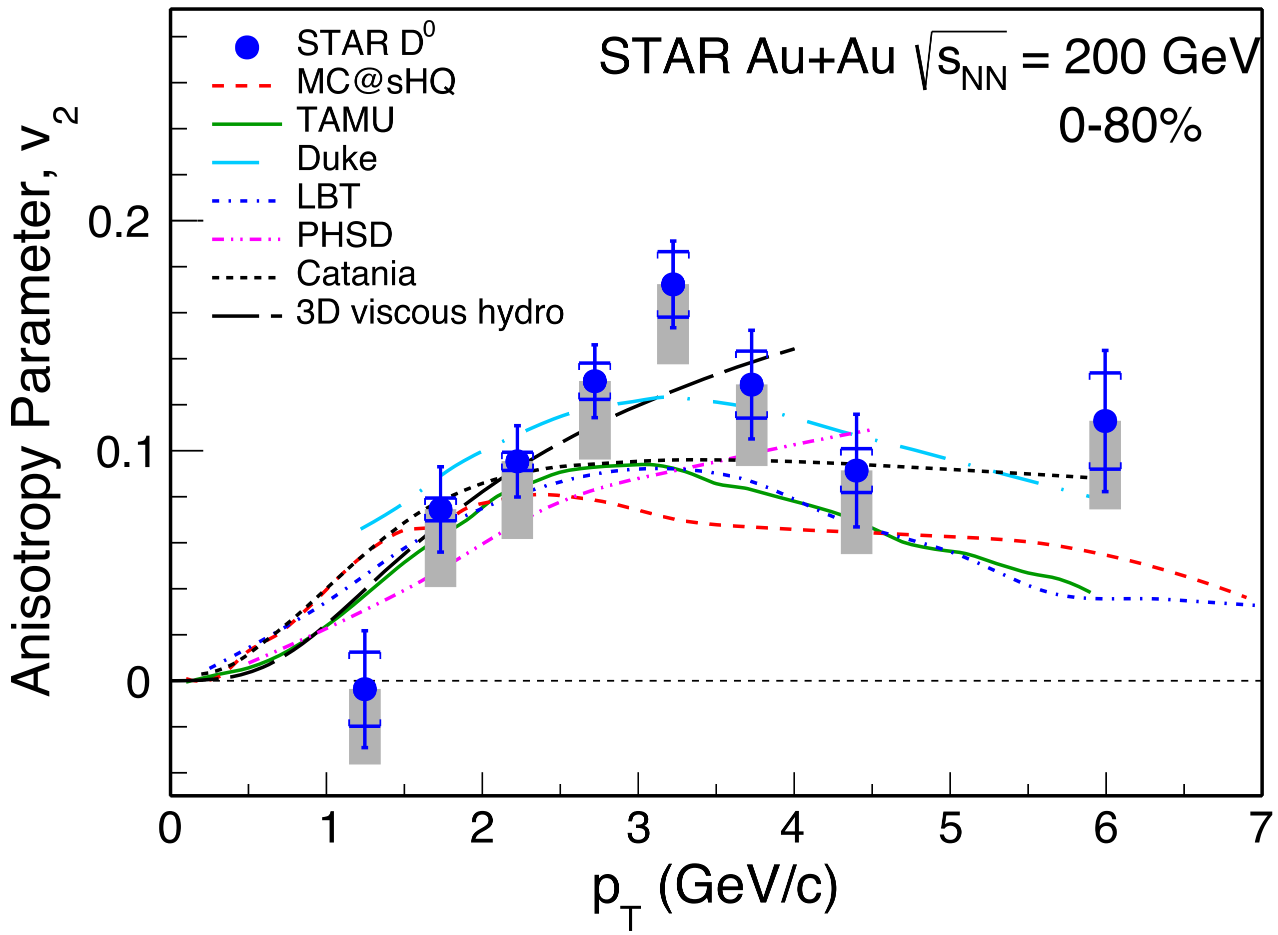
Confinement

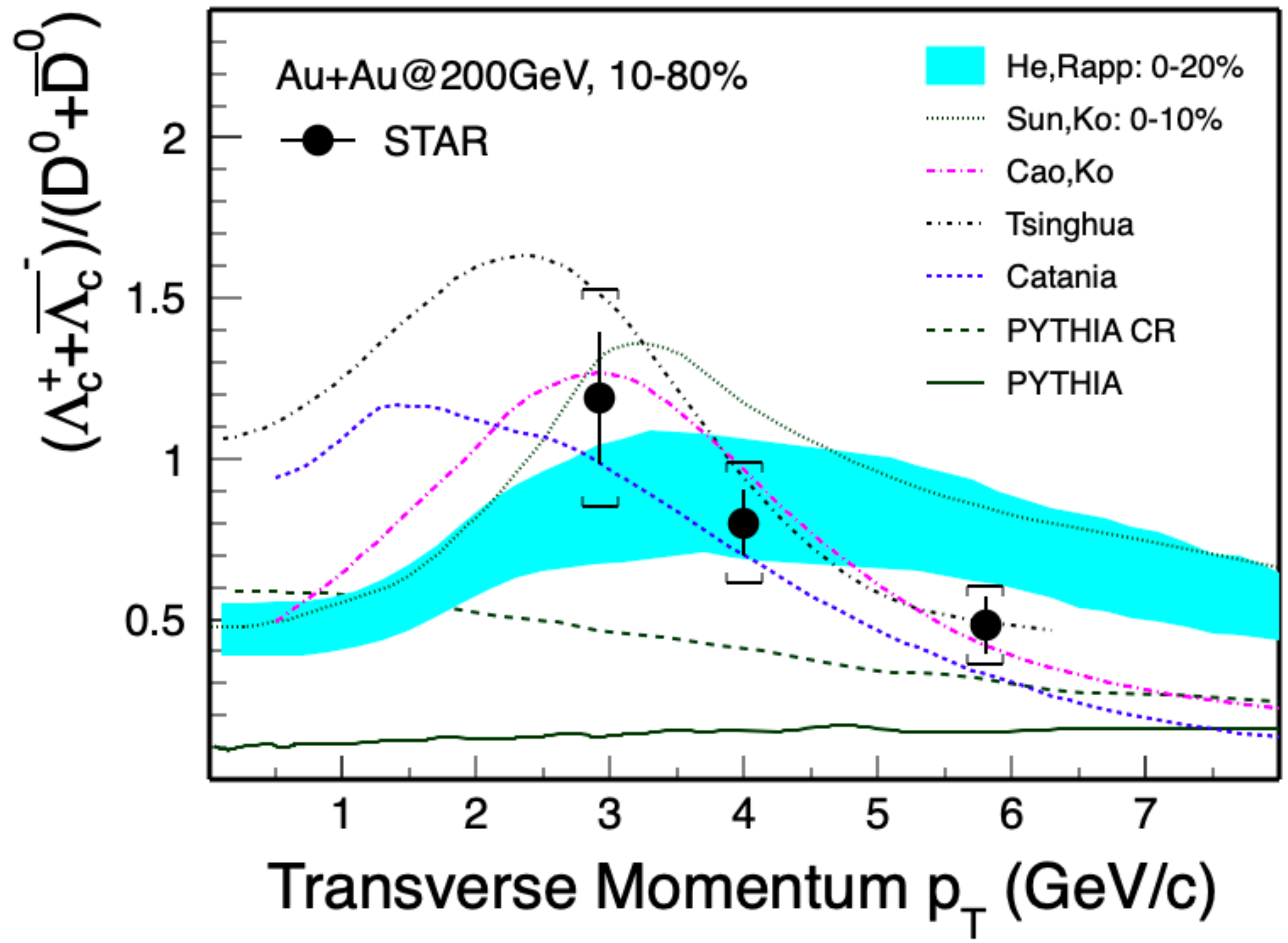


sQGP



Summary





Significant charm hadron flow -> $2\pi T D_s \sim$ 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

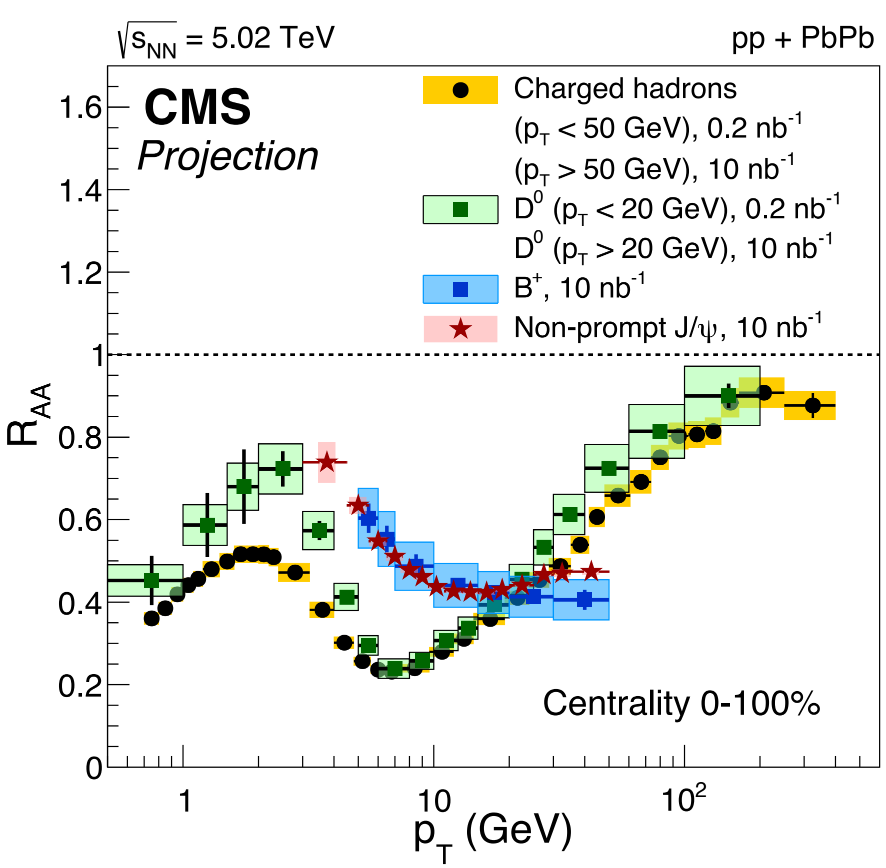
Prospective Heavy Flavor Program in Future

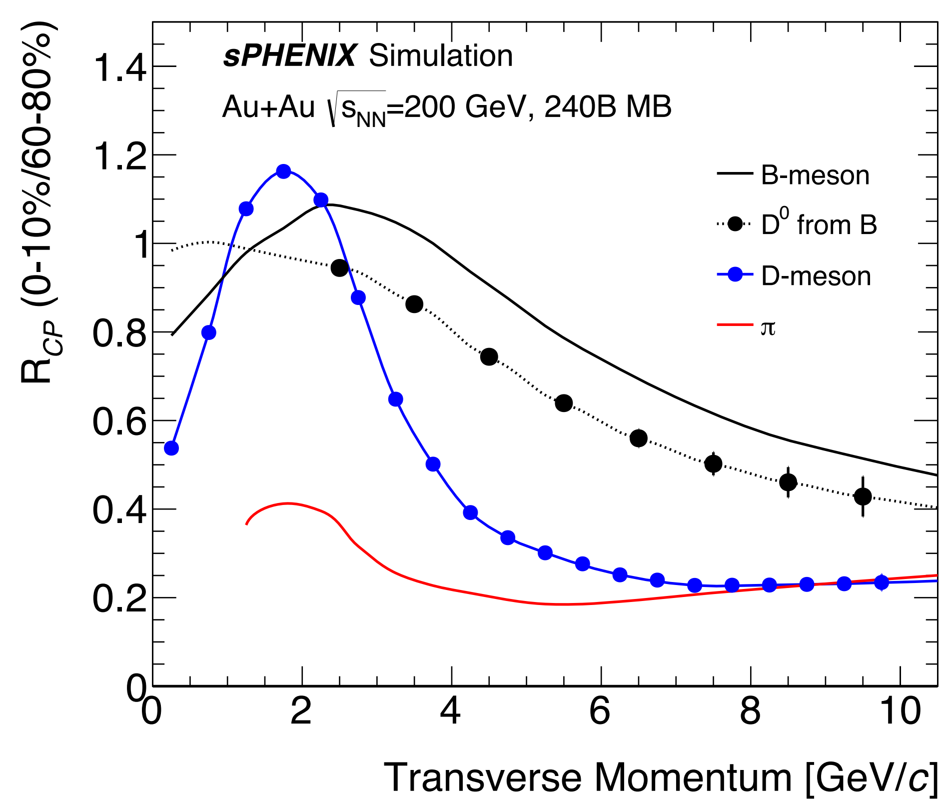
	2014	2015	2016	2017	2018	2019	2020	2021	2022+
RHIC	HF Phase-I			pp	CME	BES-II			HF Phase-II
LHC	LS1	Run-2				LS2		Run-3	

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

Precision open bottom

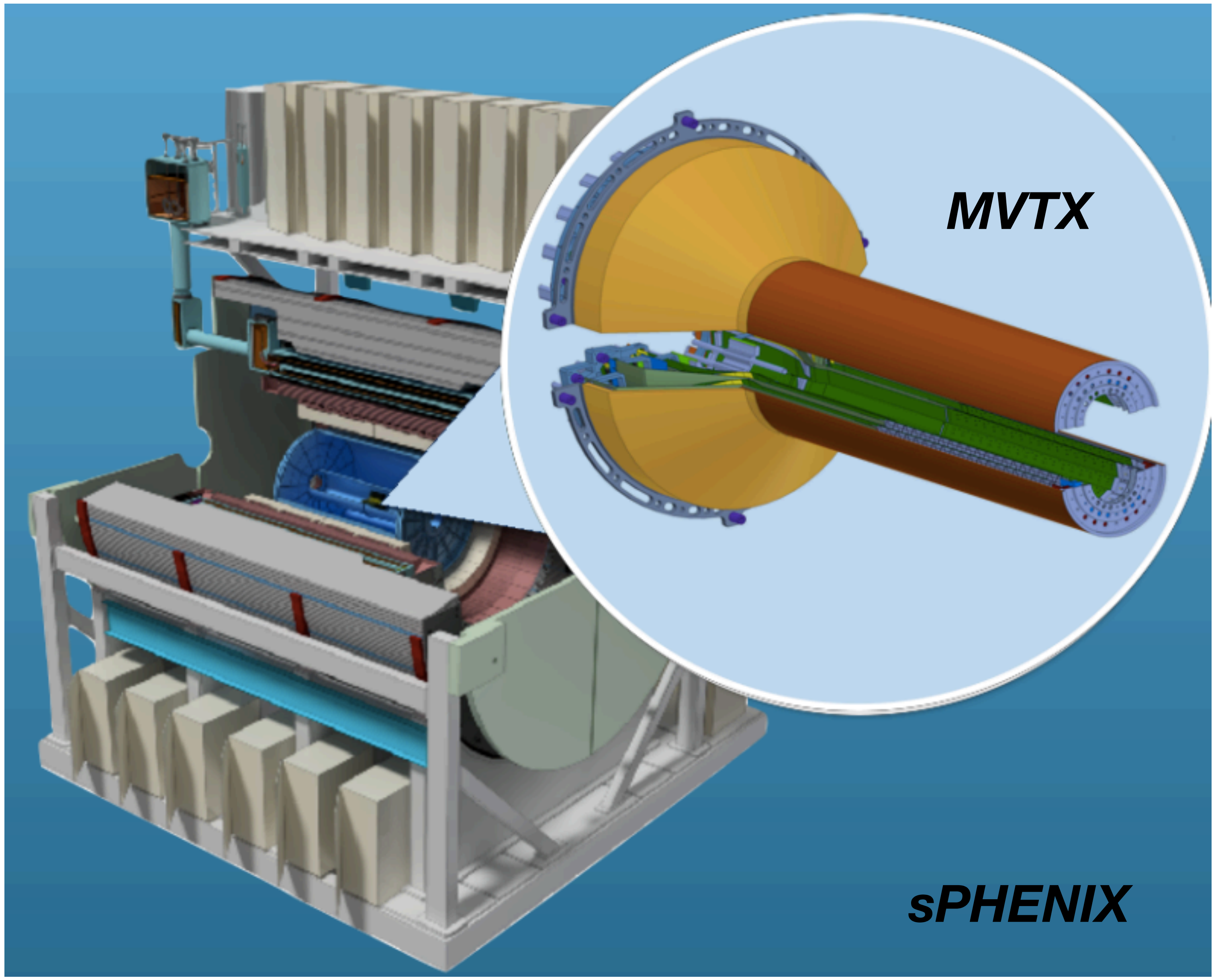
Heavy flavor baryons and correlations





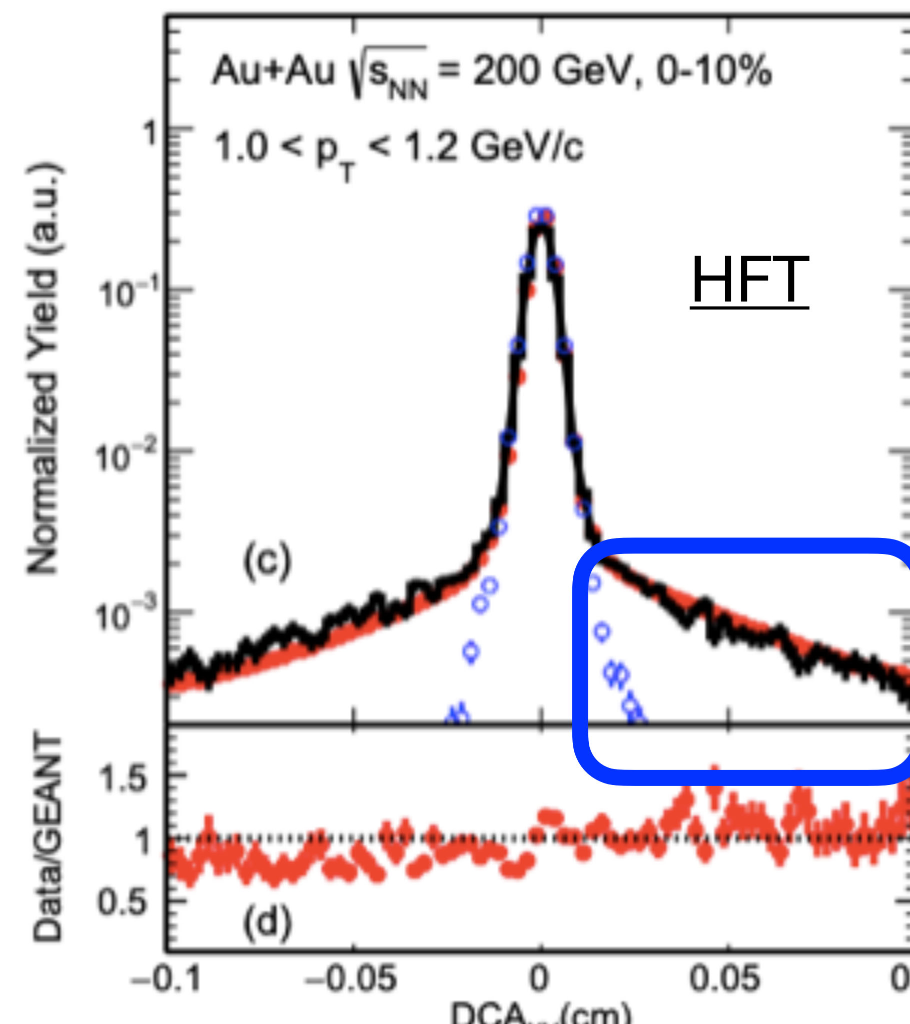
MAPS-based VTX (MVTX) @ sPHENIX

sPHENIX: dedicated fast detector for hard probes at RHIC (data taken: 2023-)



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

==> background reduced by > x10

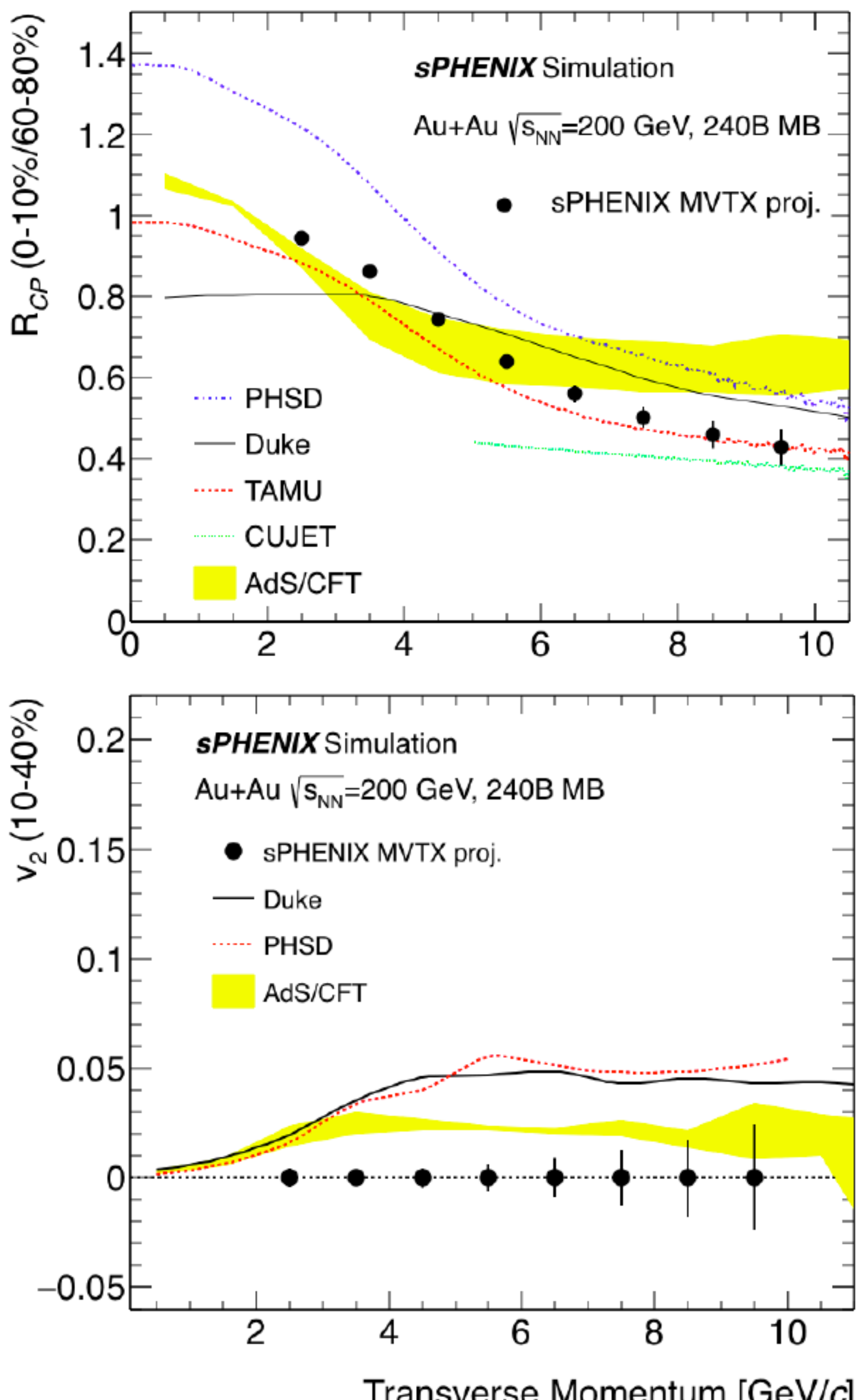


DAQ rate ~ 15 kHz (x7-10 faster than STAR)
Collision rate ~ 200 kHz (x 3-4 higher than 2016)

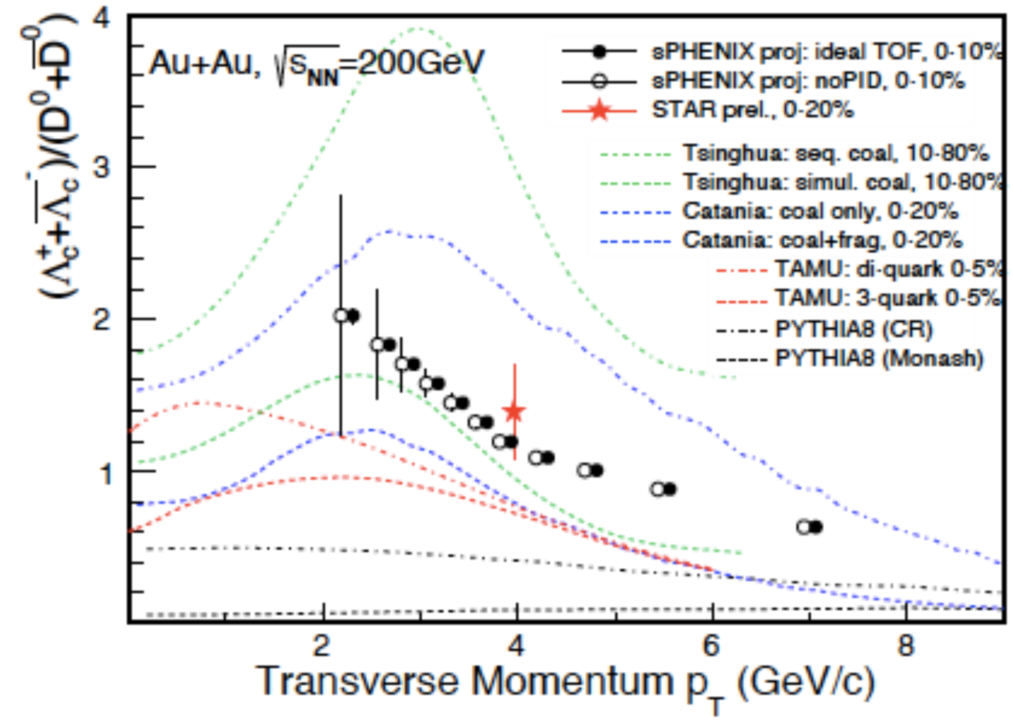
Future sPHENIX Heavy Flavor Program

Open bottom R_{AA} and v_2

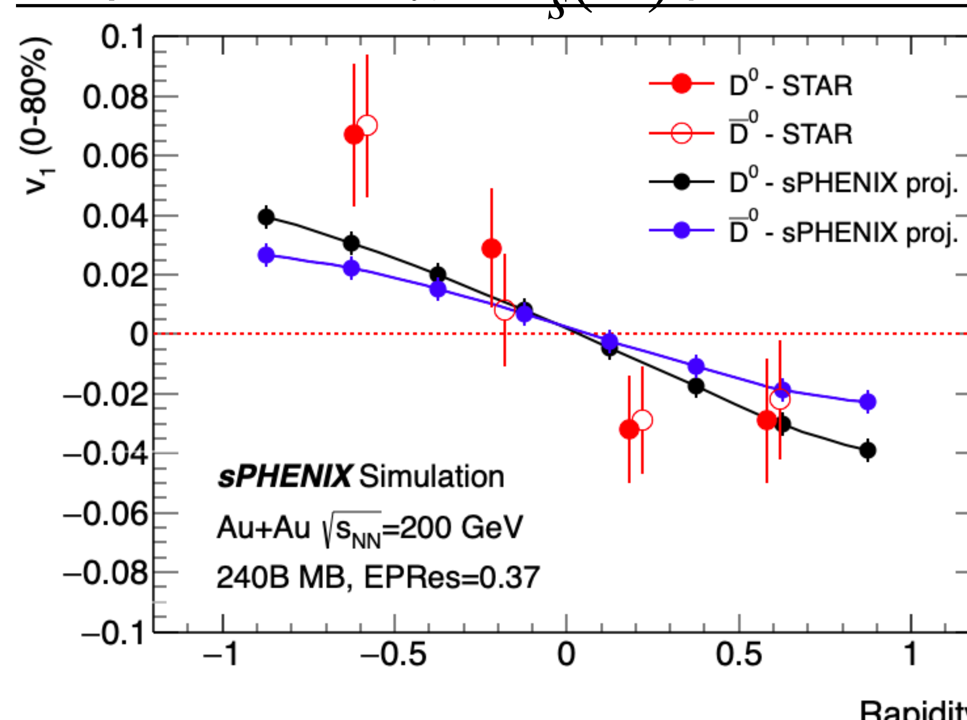
– HQ (c/b) diffusion coefficients



Λ_c/Λ_b production - hadronization

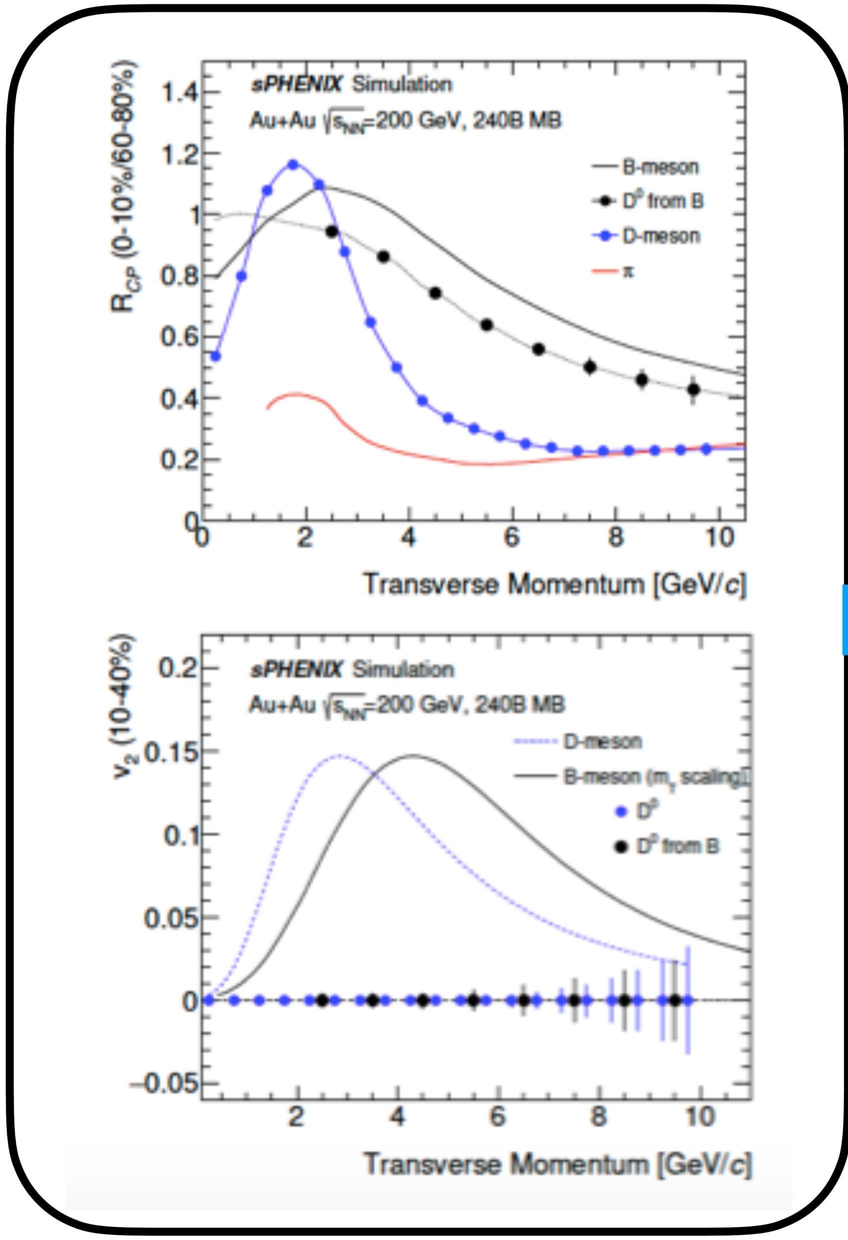


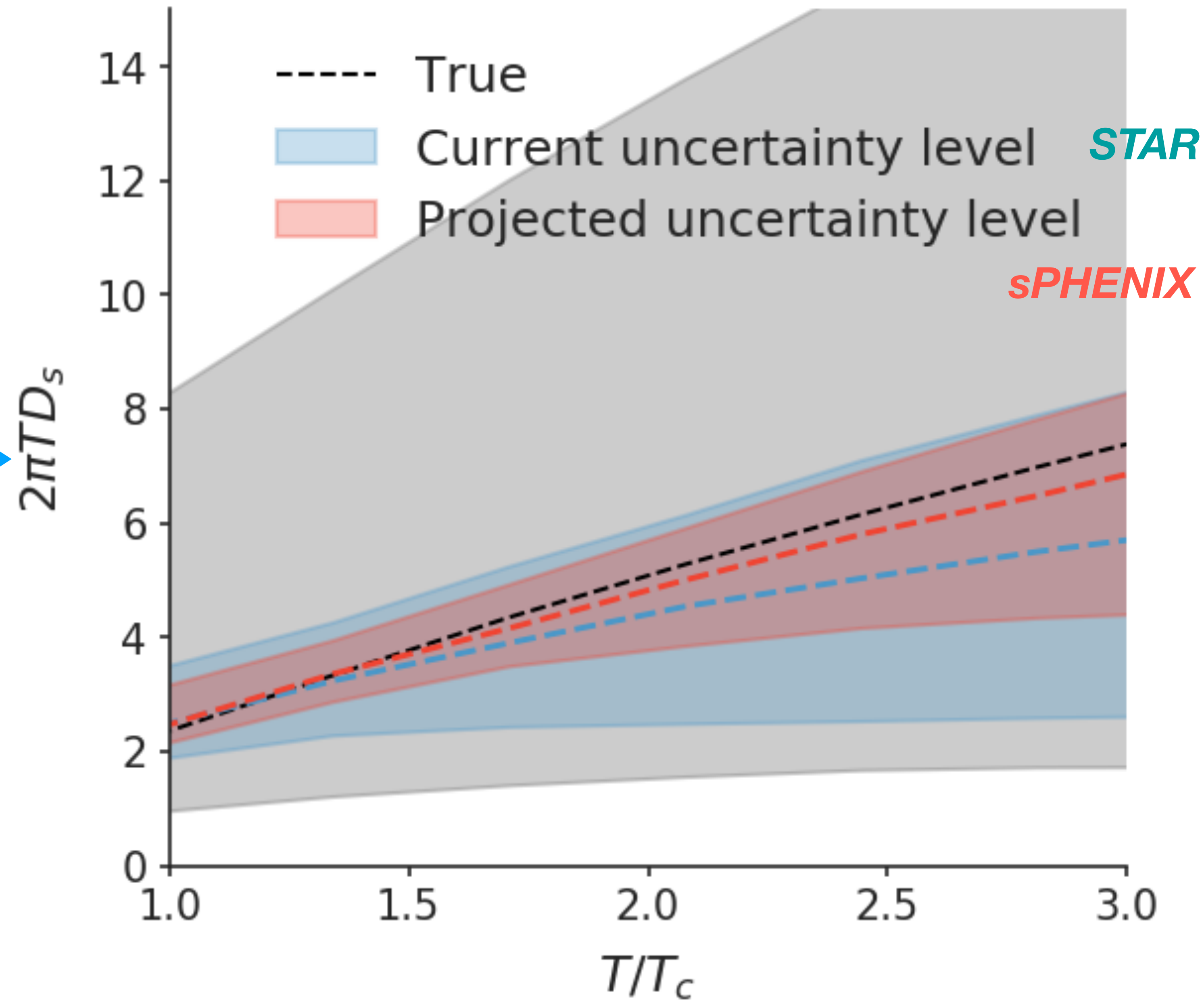
$D^0/\overline{D}^0$ v1 - $2\pi TD_s(T)$ / initial B-field



Impact on Charm Diffusion Coefficient

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





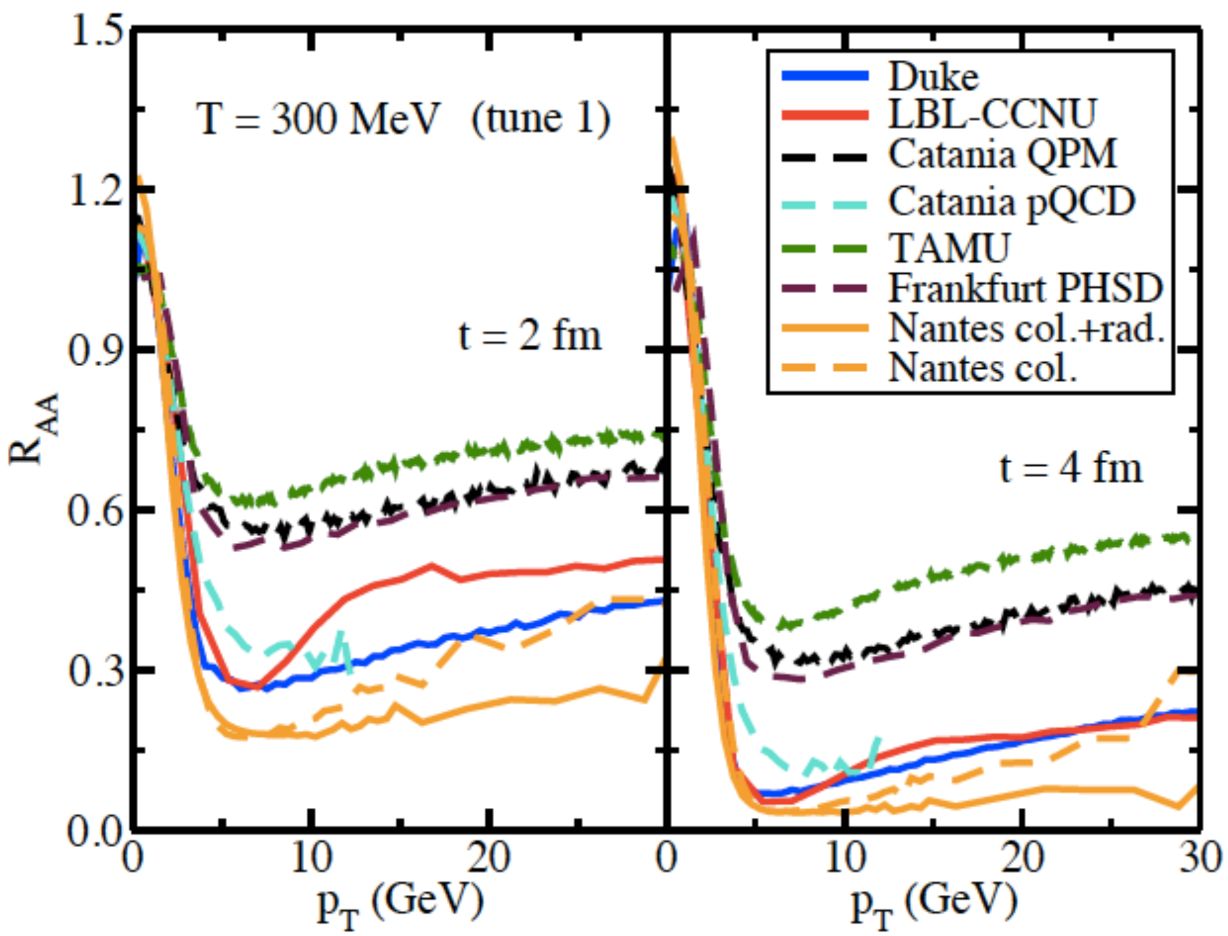
Theory Uncertainties

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*

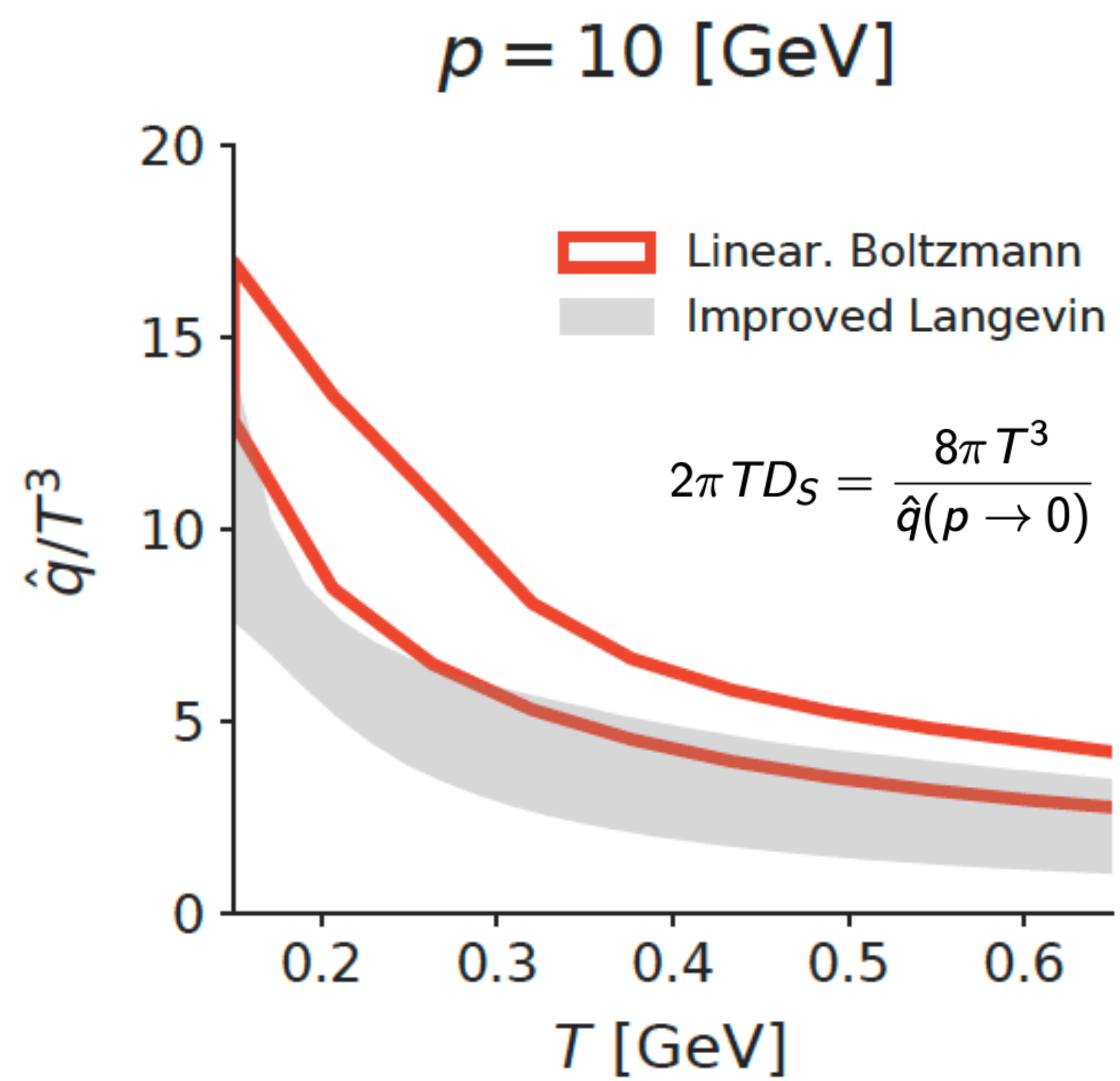
Jet-HQ Working Group - *S.S. Cao et al., PRC 99 (2019) 054907*

R_{AA} of charm quark in a static medium



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

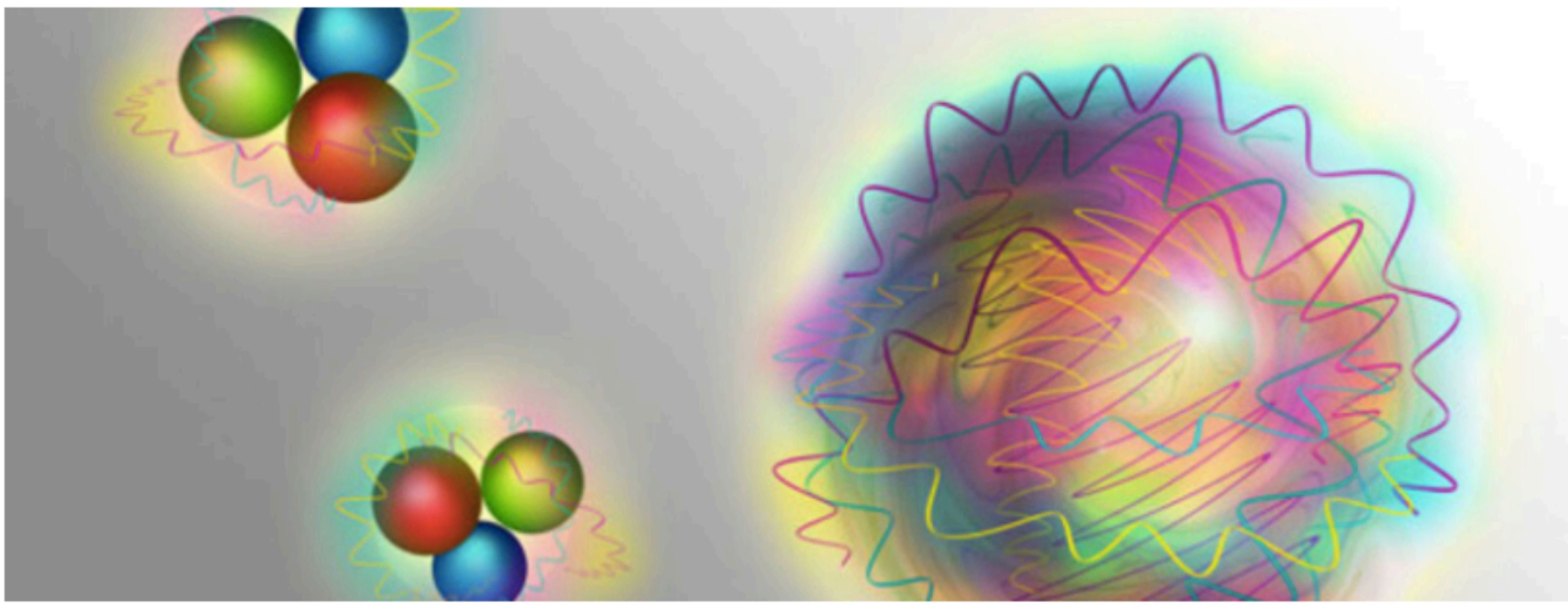
S.S. Cao et al., PRC 99 (2019) 054907



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

ECT*
EUROPEAN CENTRE
FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS
FONDAZIONE BRUNO KESSLER

HEAVY-FLAVOR TRANSPORT IN QCD MATTER



26 April 2021 — 30 April 2021

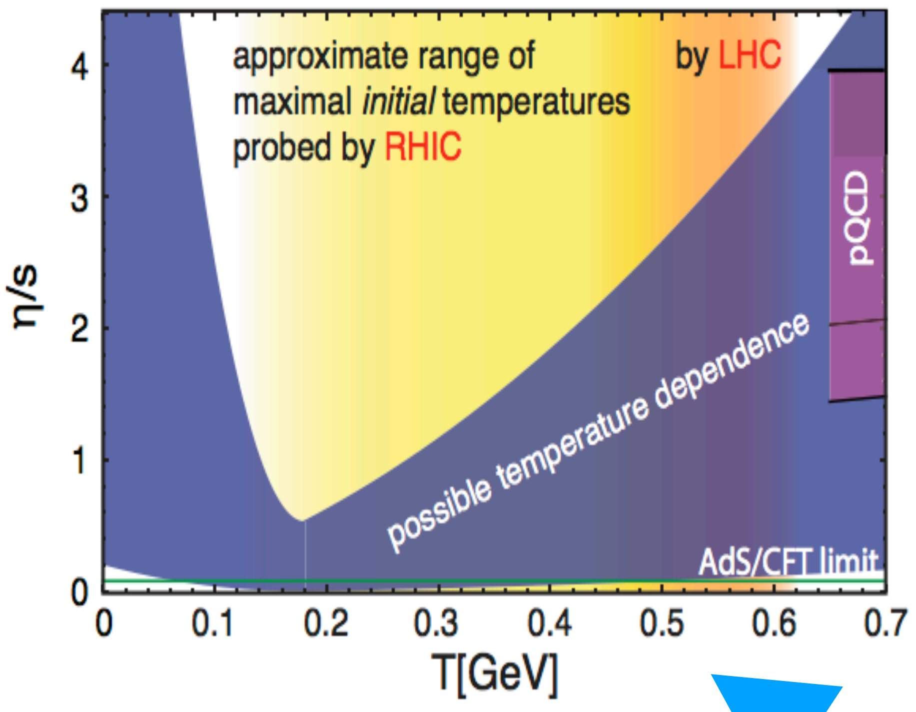
(was scheduled on Feb. 24-28, 2020)

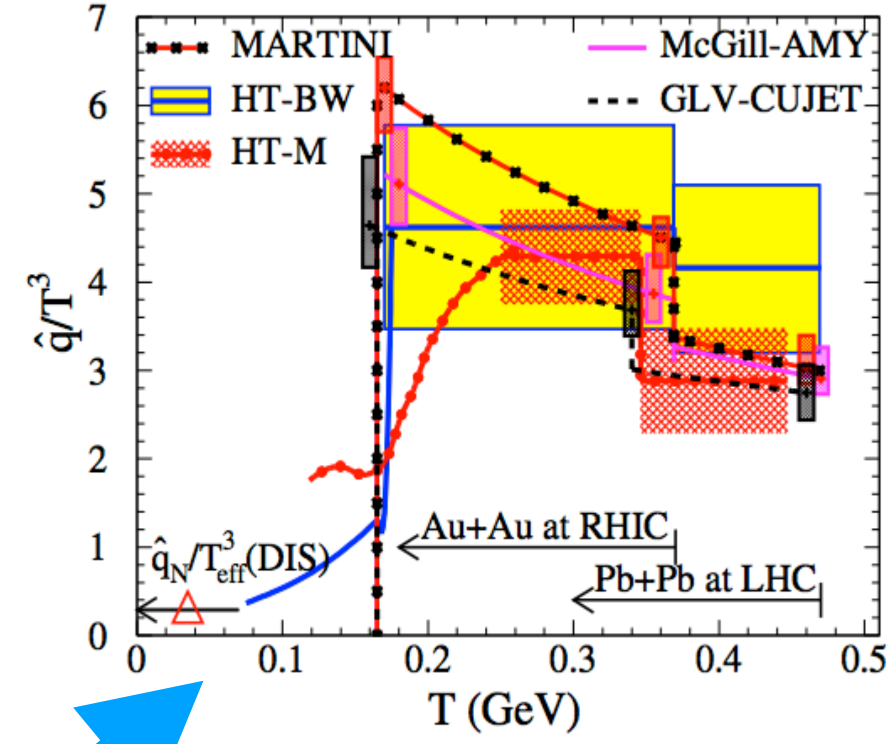
ECT* - Villa Tambosi

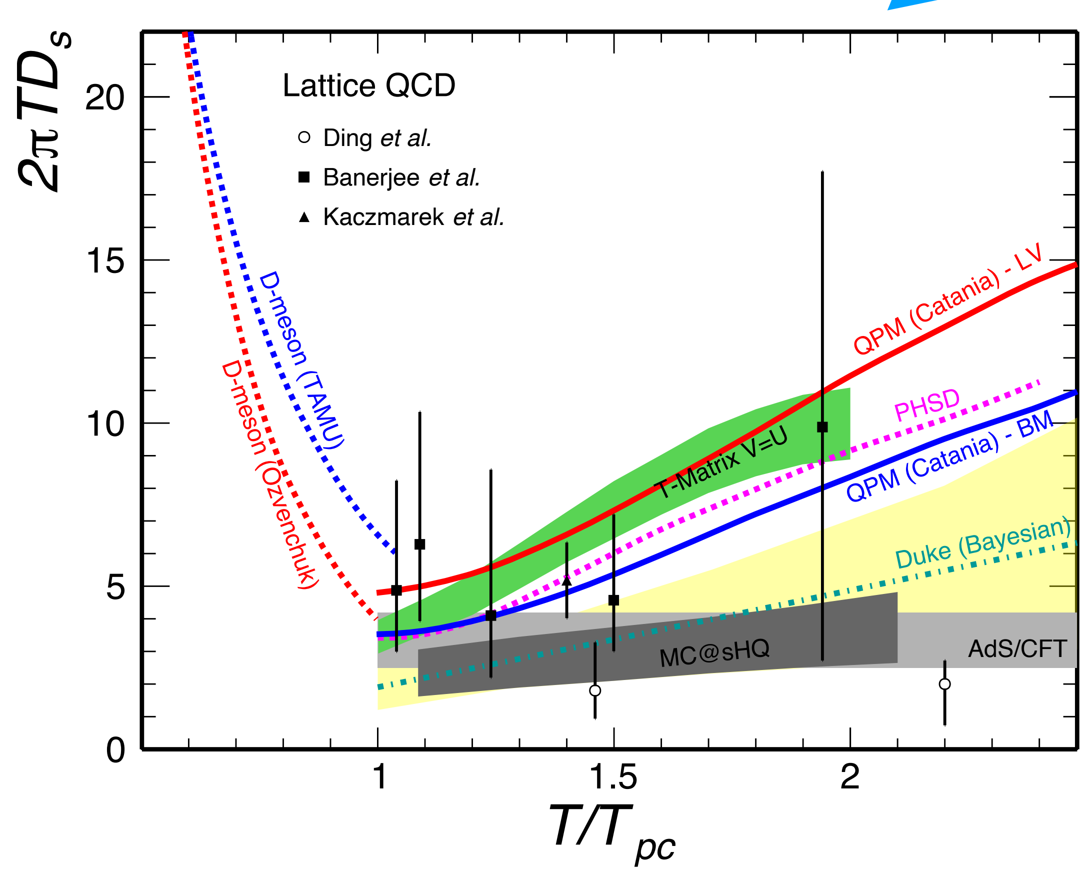
Strada delle Tabarelle, 286

Trento - Italy

Quantitative Measure of sQGP







Backup

Molecule Diffusion and Einstein's Theory

A

BRIEF ACCOUNT

OF

MICROSCOPICAL OBSERVATIONS

Made in the Months of June, July, and August, 1827,

ON THE PARTICLES CONTAINED IN THE POLLEN OF PLANTS;

AND

ON THE GENERAL EXISTENCE OF ACTIVE MOLECULES

IN ORGANIC AND INORGANIC BODIES.

BY

ROBERT BROWN,

F.R.S., HON. M.R.S.E. AND R.I. ACAD., V.P.L.S.,

MEMBER OF THE ROYAL ACADEMY OF SCIENCES OF SWEDEN, OF THE ROYAL SOCIETY OF DENMARK, AND OF THE IMPERIAL ACADEMY NATURÆ CURIOSORUM; CORRESPONDING MEMBER OF THE ROYAL INSTITUTES OF FRANCE AND OF THE NETHERLANDS, OF THE IMPERIAL ACADEMY OF SCIENCES AT ST. PETERSBURG, AND OF THE ROYAL ACADEMIES OF PRUSSIA AND BAVARIA, ETC.

5. ***Über die von der molekularkinetischen Theorie der Wärme geforderte Bewegung von in ruhenden Flüssigkeiten suspendierten Teilchen; von A. Einstein.***

In dieser Arbeit soll gezeigt werden, daß nach der molekularkinetischen Theorie der Wärme in Flüssigkeiten suspendierte Körper von mikroskopisch sichtbarer Größe infolge der Molekularbewegung der Wärme Bewegungen von solcher Größe ausführen müssen, daß diese Bewegungen leicht mit dem Mikroskop nachgewiesen werden können. Es ist möglich, daß die hier zu behandelnden Bewegungen mit der sogenannten „Brownschen Molekularbewegung" identisch sind; die mir erreichbaren Angaben über letztere sind jedoch so ungenau, daß ich mir hierüber kein Urteil bilden konnte.

Wenn sich die hier zu behandelnde Bewegung samt den für sie zu erwartenden Gesetzmäßigkeiten wirklich beobachten läßt, so ist die klassische Thermodynamik schon für mikroskopisch unterscheidbare Räume nicht mehr als genau gültig anzusehen und es ist dann eine exakte Bestimmung der wahren Atomgröße möglich. Erwiese sich umgekehrt die Voraussage dieser Bewegung als unzutreffend, so wäre damit ein schwerwiegendes Argument gegen die molekularkinetische Auffassung der Wärme gegeben.

§ 1. Über den suspendierten Teilchen zuzuschreibenden osmotischen Druck.

Im Teilvolumen V^* einer Flüssigkeit vom Gesamtvolumen V seien z-Gramm-Moleküle eines Nichtelektrolyten gelöst. Ist das Volumen V^* durch eine für das Lösungsmittel, nicht aber für die gelöste Substanz durchlässige Wand vom reinen Lösungs-

Robert Brown, 1827

Albert Einstein, 1905

- Brownian Motion – jittery motion of pollen grains in water
- Einstein's 1905 paper mathematically explained the Brownian motion

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

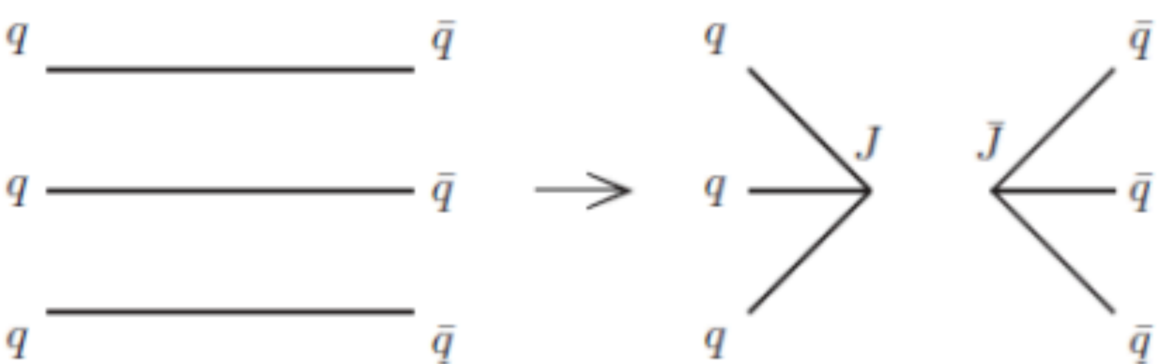
D – diffusion coefficient

- Validated by Jean Perrin's experiment in 1909 (awarded Nobel Prize in 1926)

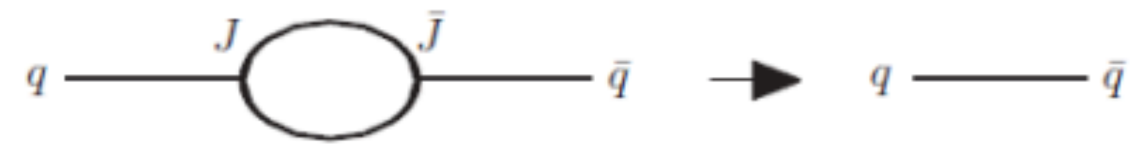
Color Reconnection in PYTHIA 8.2

(a) Type I: ordinary dipole-style reconnection

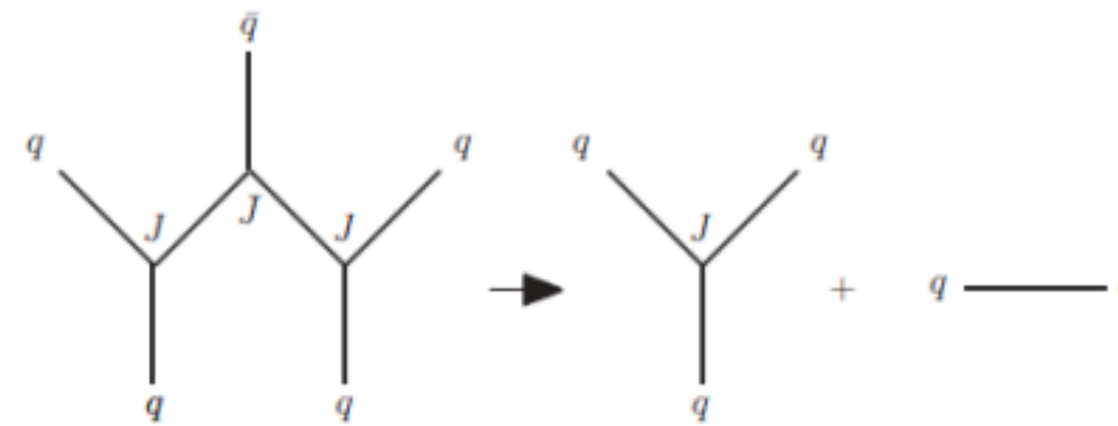
(b) Type II: junction-style reconnection



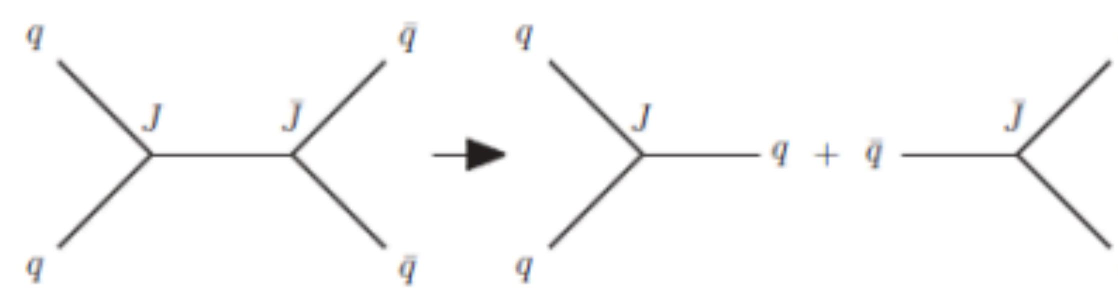
(c) Type III: baryon-style junction reconnection



(a) Doubly-connected $J\bar{J}$ system



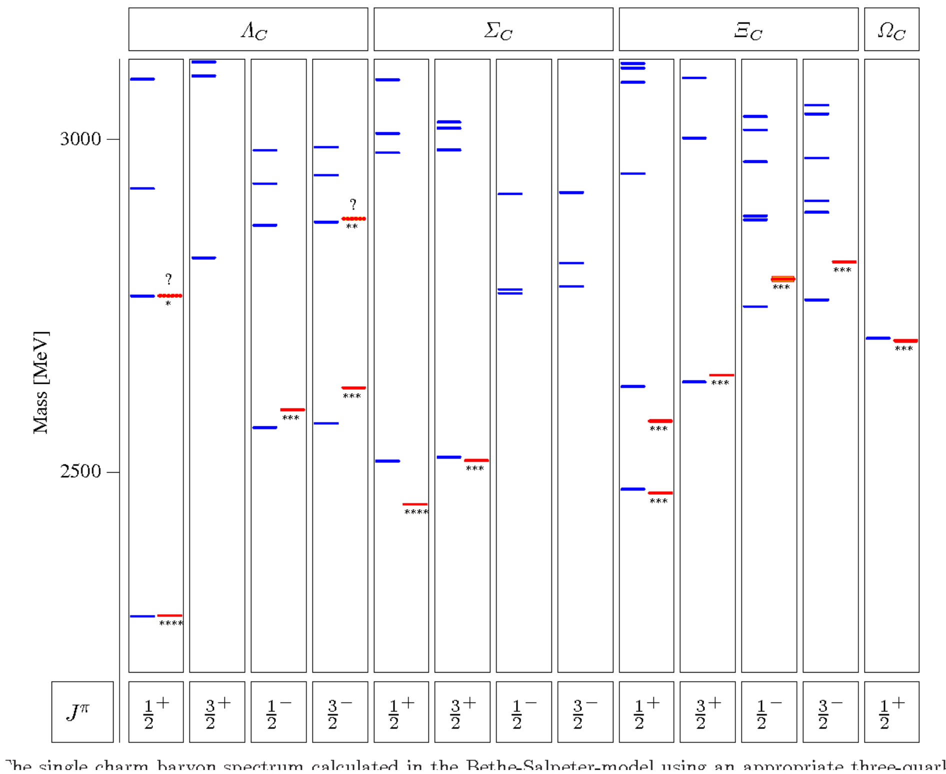
(b) Multiple $J\bar{J}J\cdots$ Connections



(c) A single $J\bar{J}$ Connection

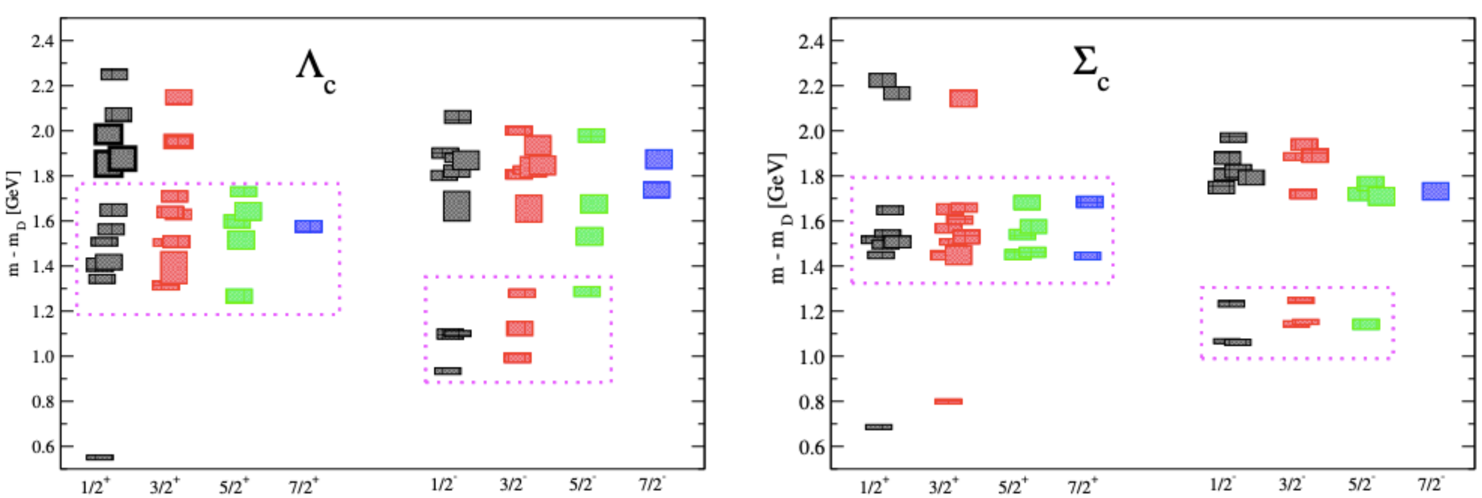
Missing Charm Baryon Resonances

Quark Model predictions



S. Migura et al, EPJA 28 (2006) 41

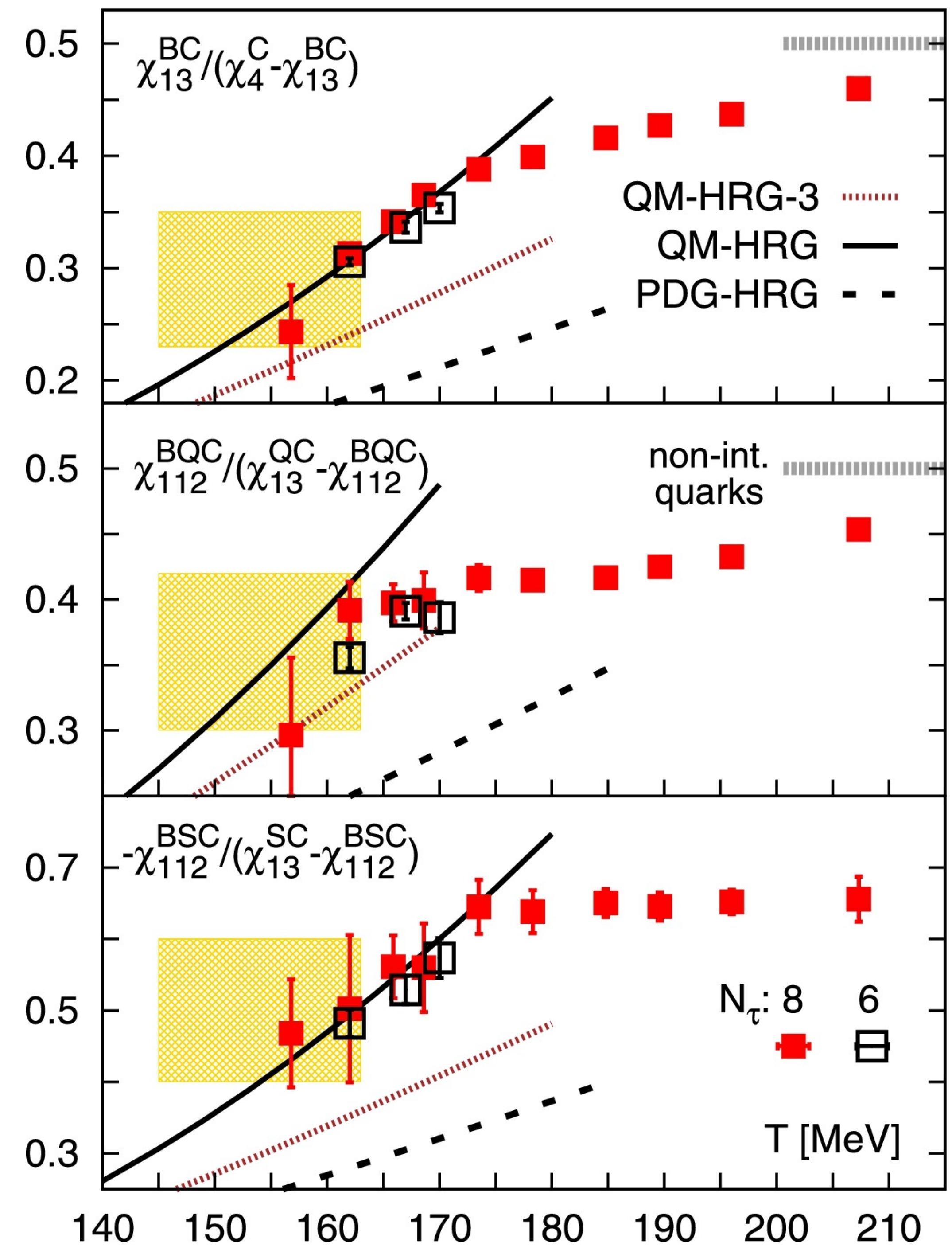
Lattice QCD predictions



(a) (b)

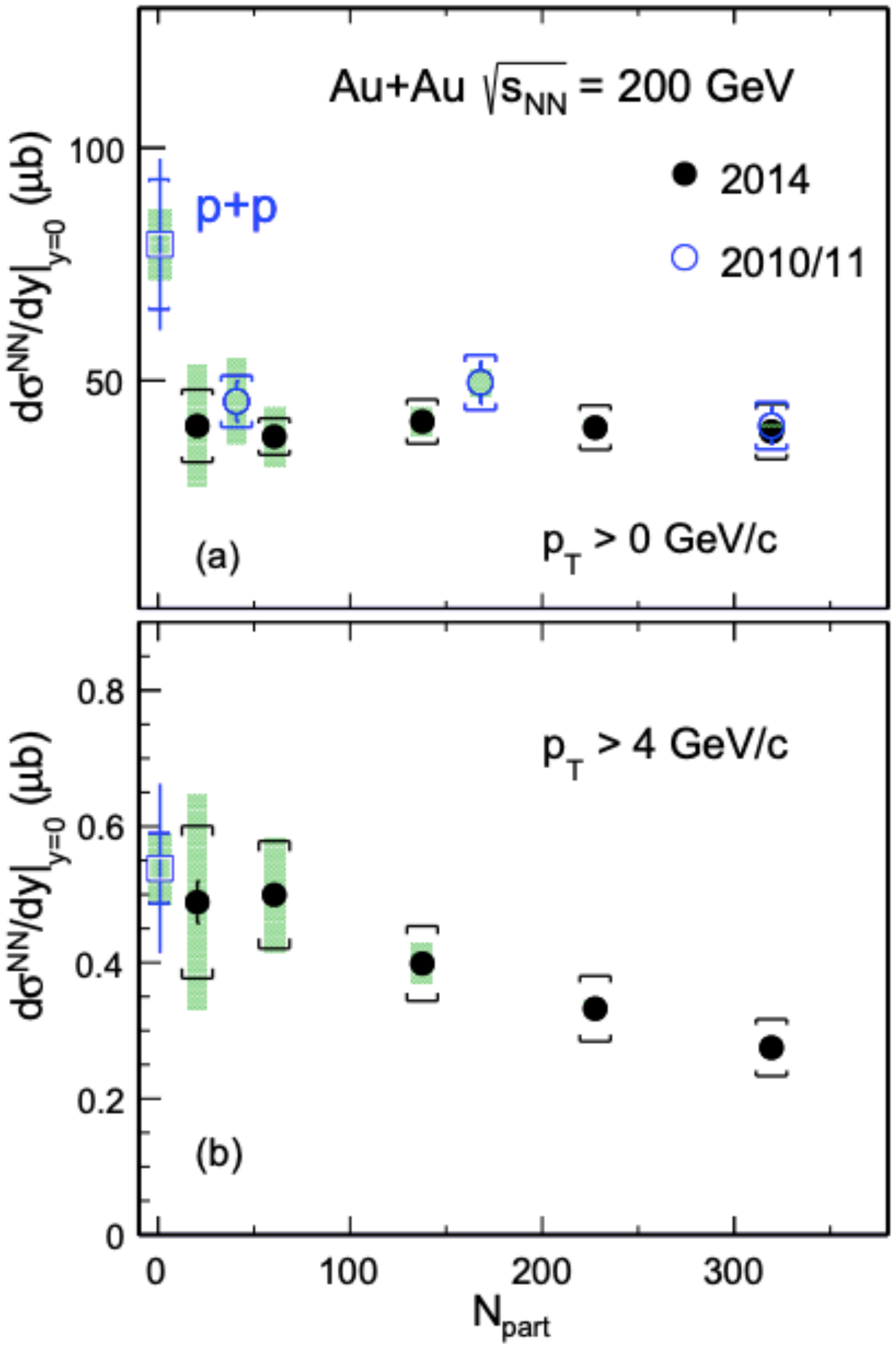
M. Padmanath et al, arXiv: 1311.4806

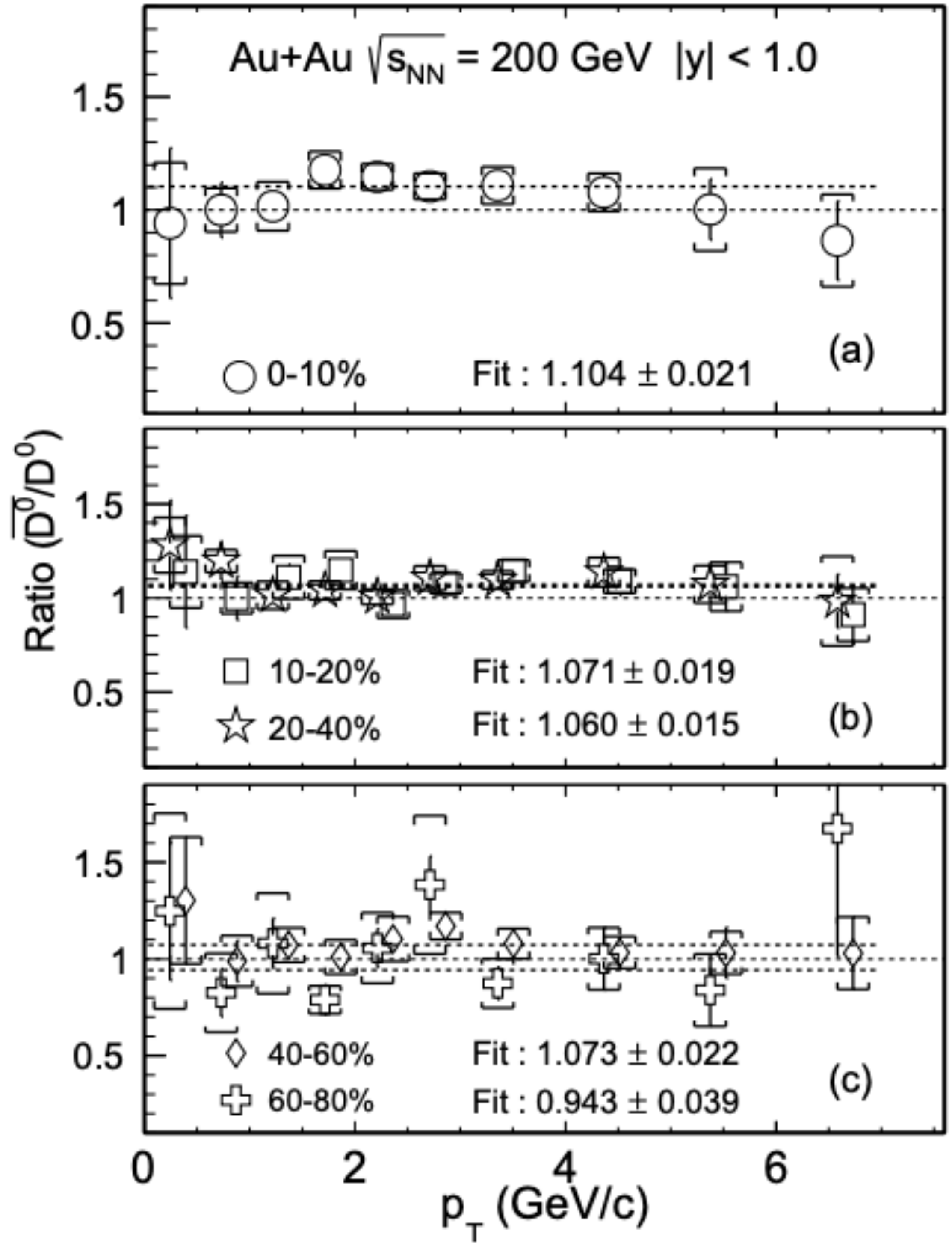
Lattice QCD - Thermodynamics



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

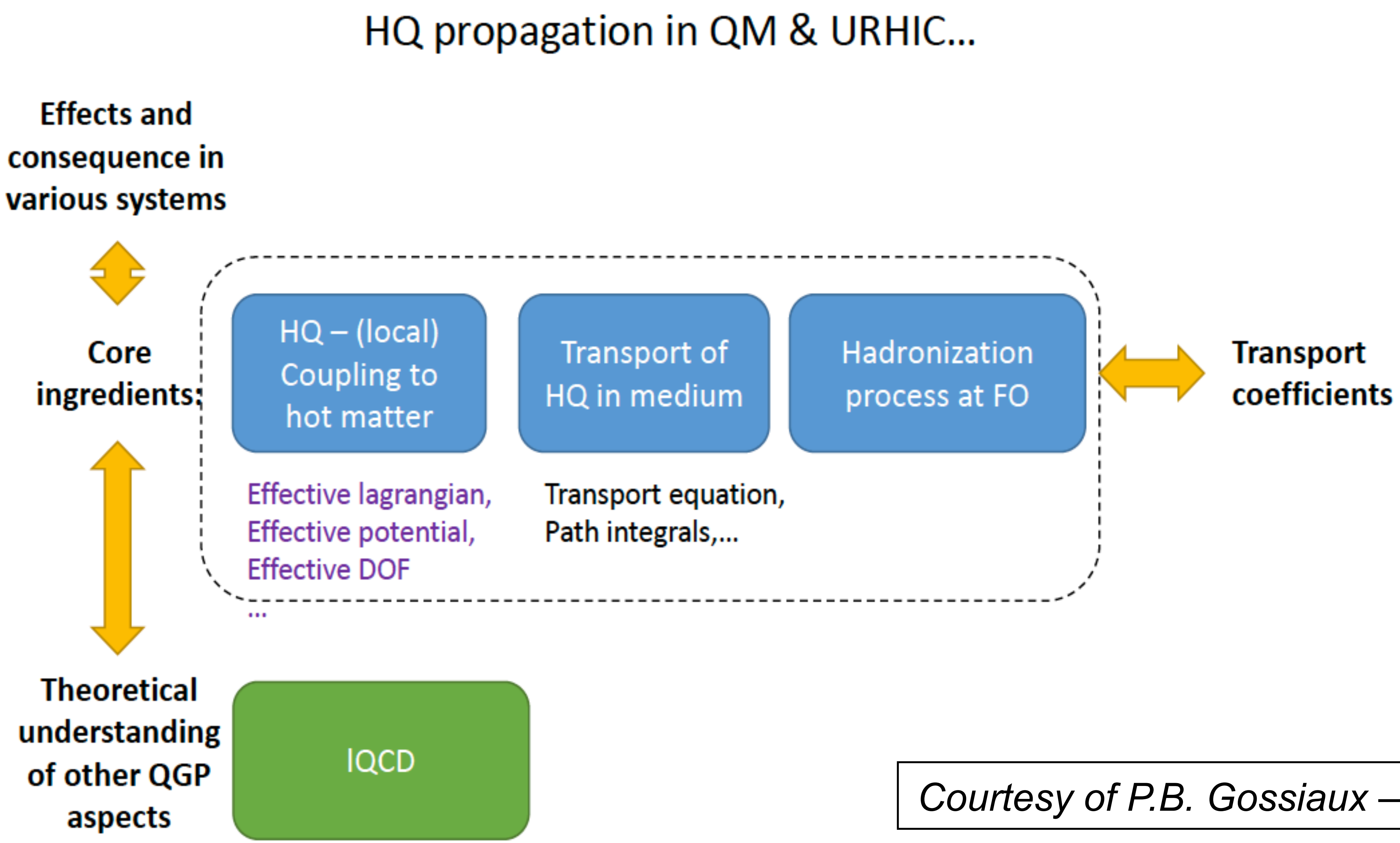
D^0 Total Cross Section and Radial Flow





- *D^0 p_T*-integrated X-sec. suppressed in central Au+Au collisions
- *D^0bar/D^0* > 1 (small deviation but significant)

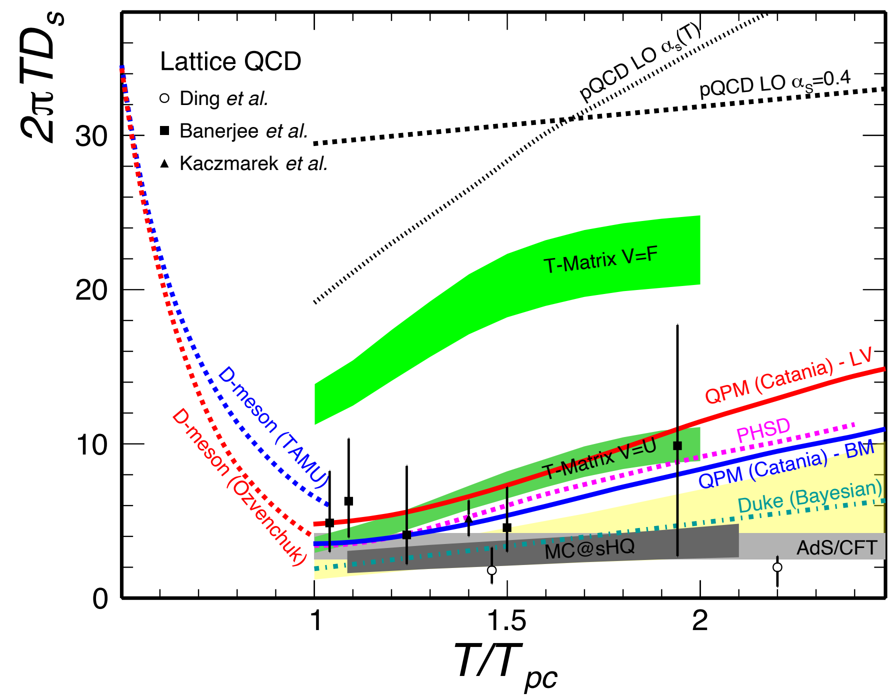
Modeling of HQ Propagation in sQGP



Courtesy of P.B. Gossiaux – QM18

Bottom Quark: Cleaner Measure of HQ Diffusion

Is charm quark heavy enough?

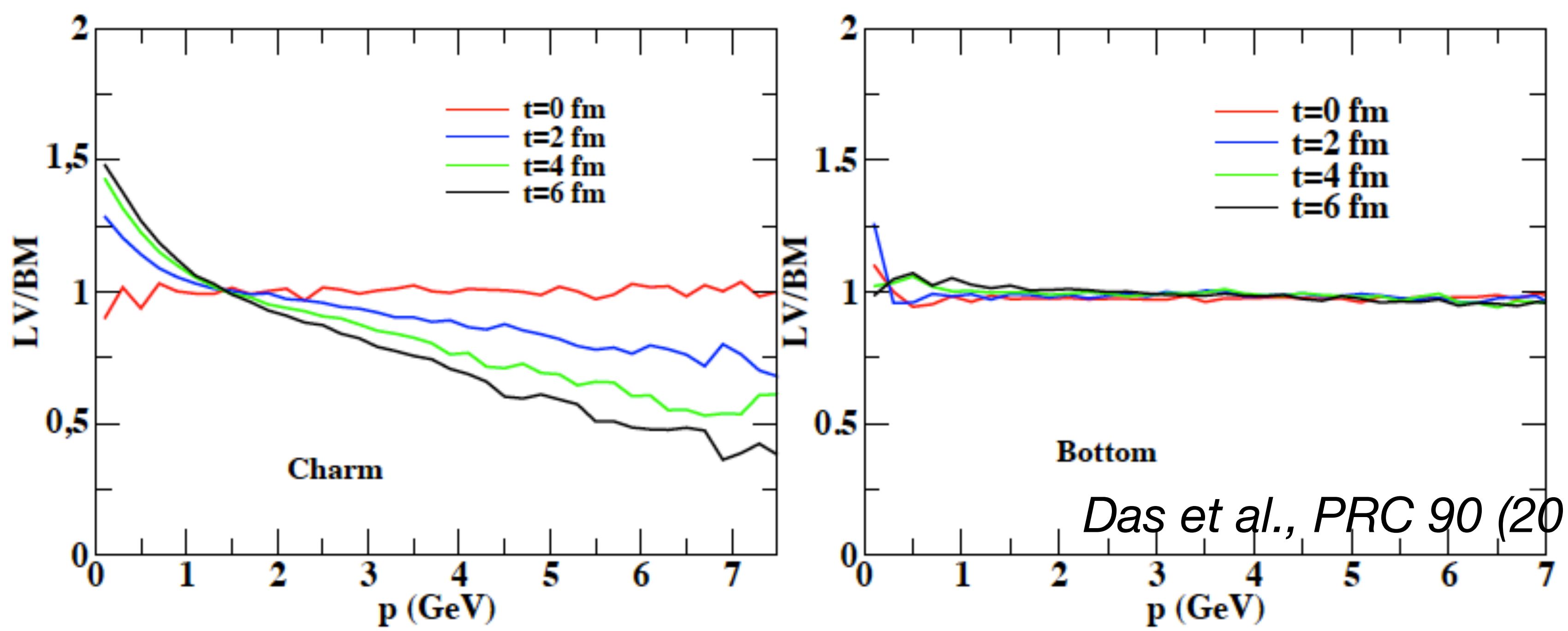


$2\pi TD_s \sim 2 - 5$ @ T_c

scattering rate: $\Gamma_{coll} \sim 3 / \mathcal{D}_s \sim 1$ GeV

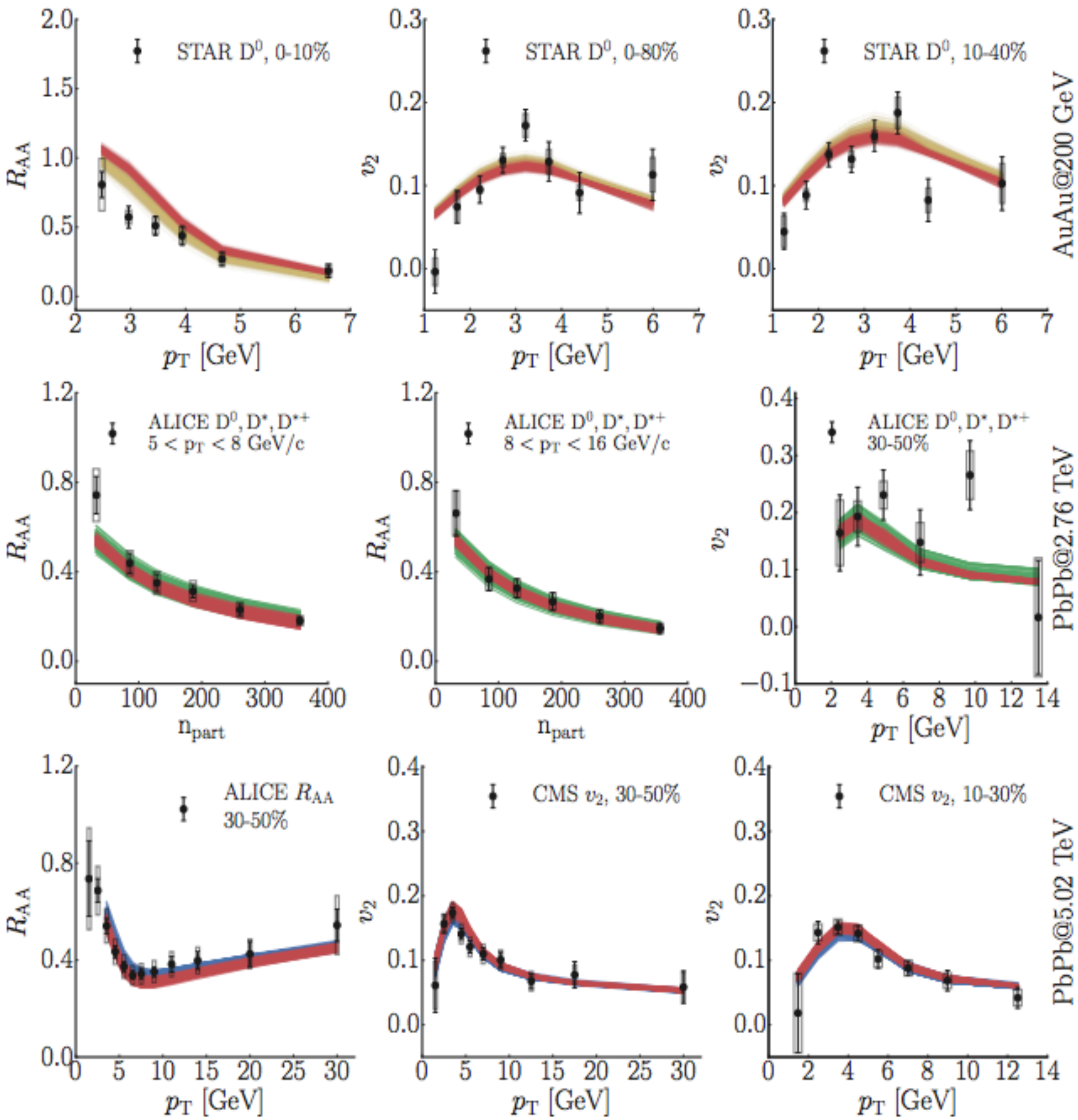
- comparable to charm quark mass

Sizable correction to Langevin approach for charm quarks

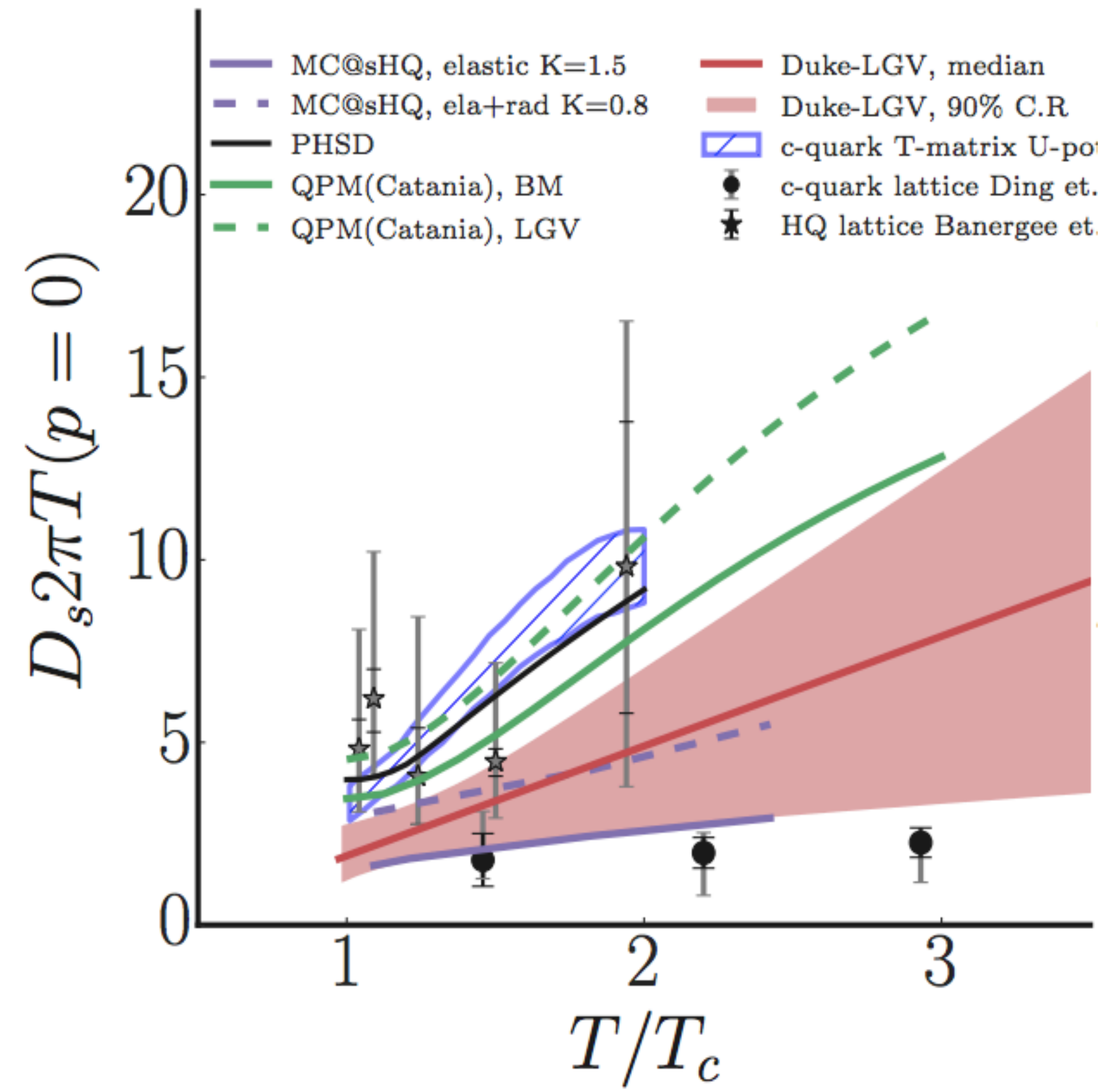


Das et al., PRC 90 (2014) 044901

Bayesian Analysis to Extract HQ Diffusion Coefficient

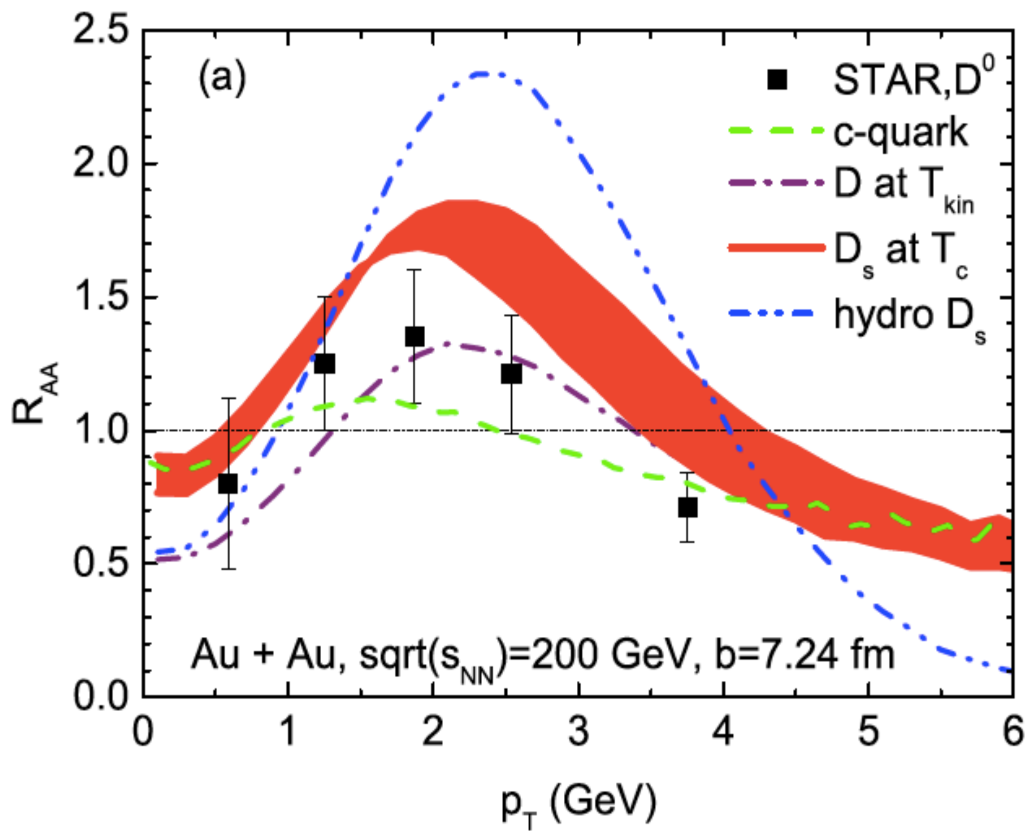


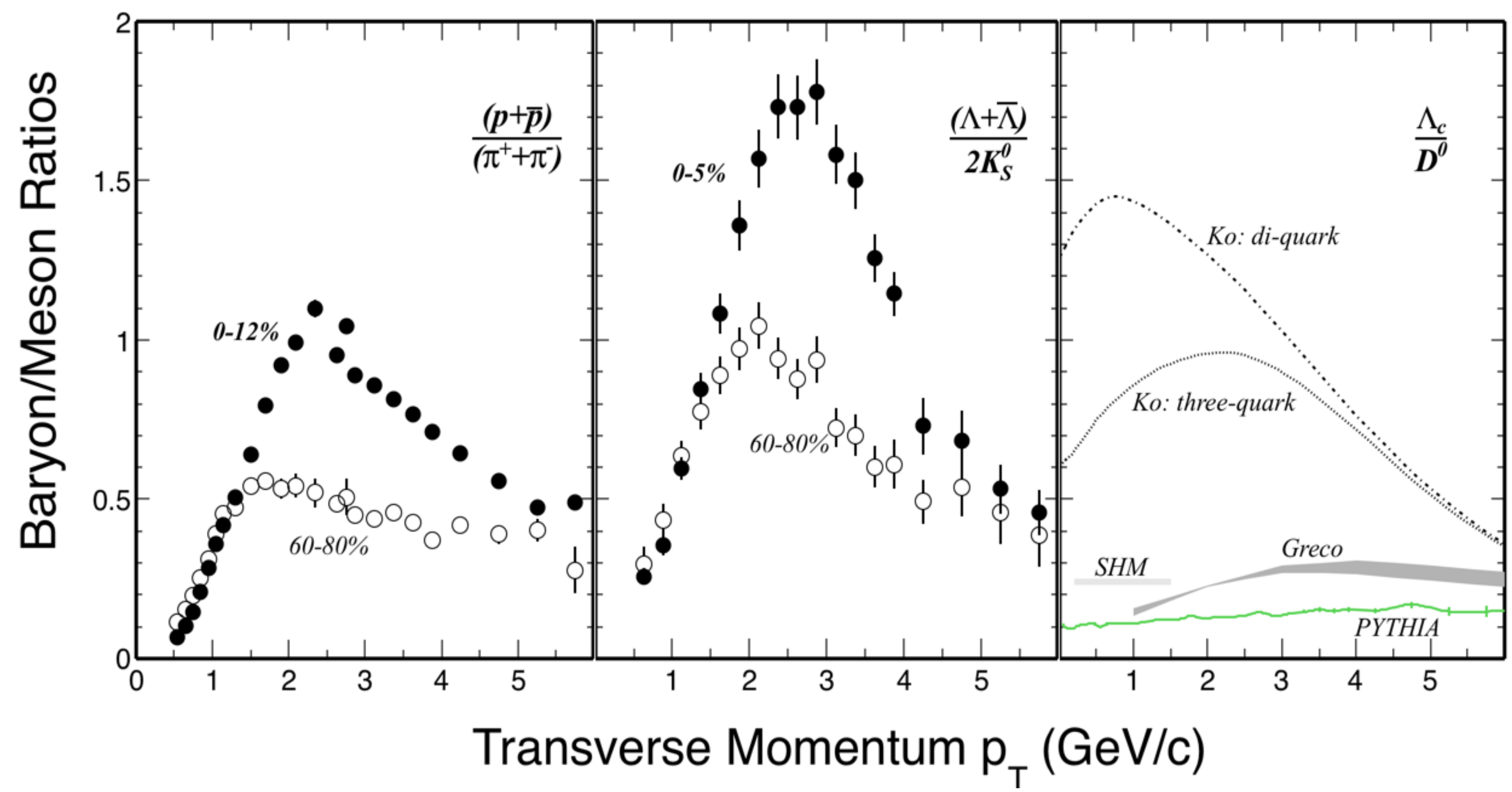
Bayesian analysis based on Duke model:
Langevin + Hydro



Y. Xu et al, PRC 97 (2018) 014907

Coalescence Hadronization





Coalescence hadronization

Strangeness enhancement -> D_s enhancement

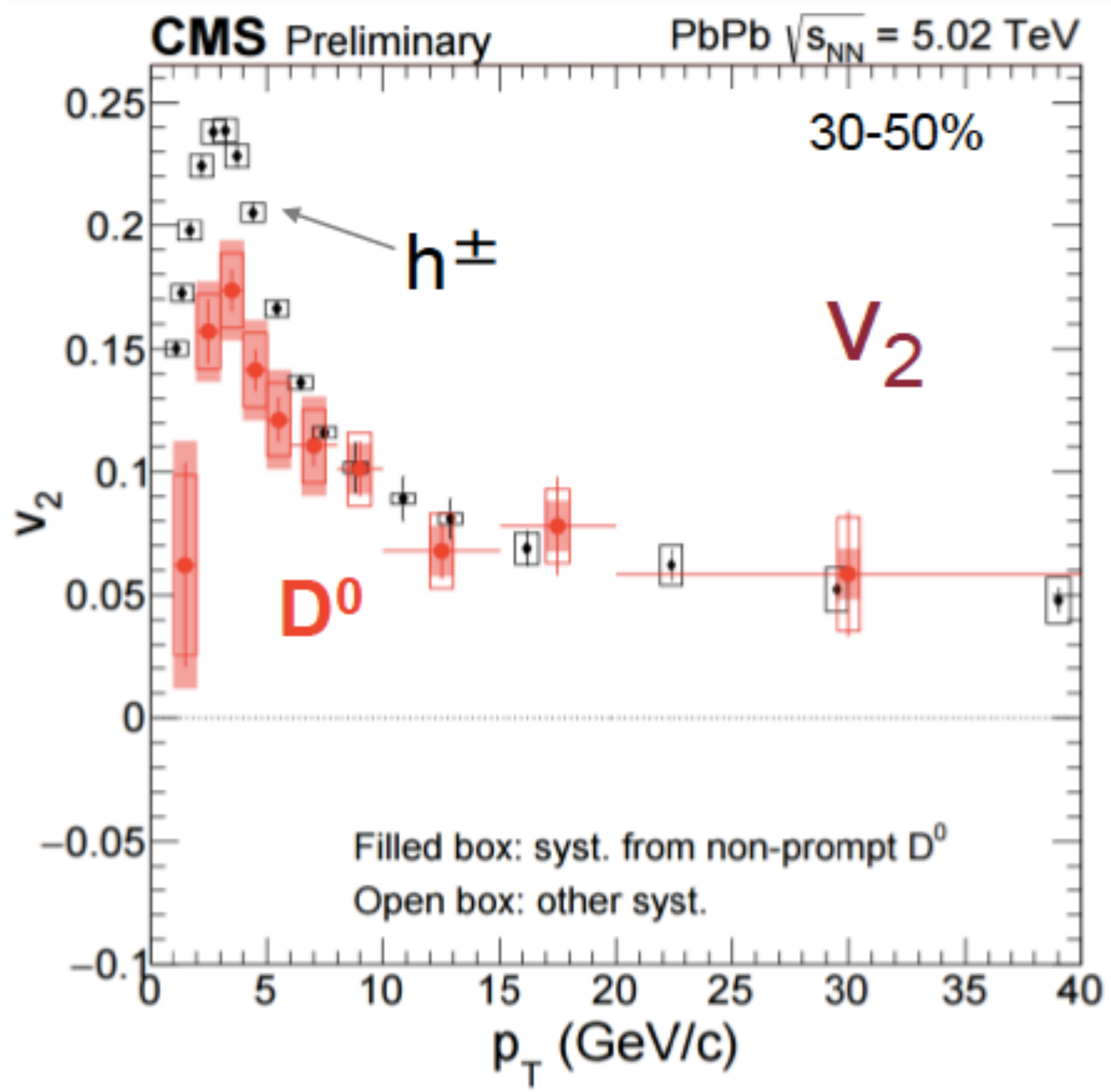
Baryon enhancement -> Λ_c enhancement

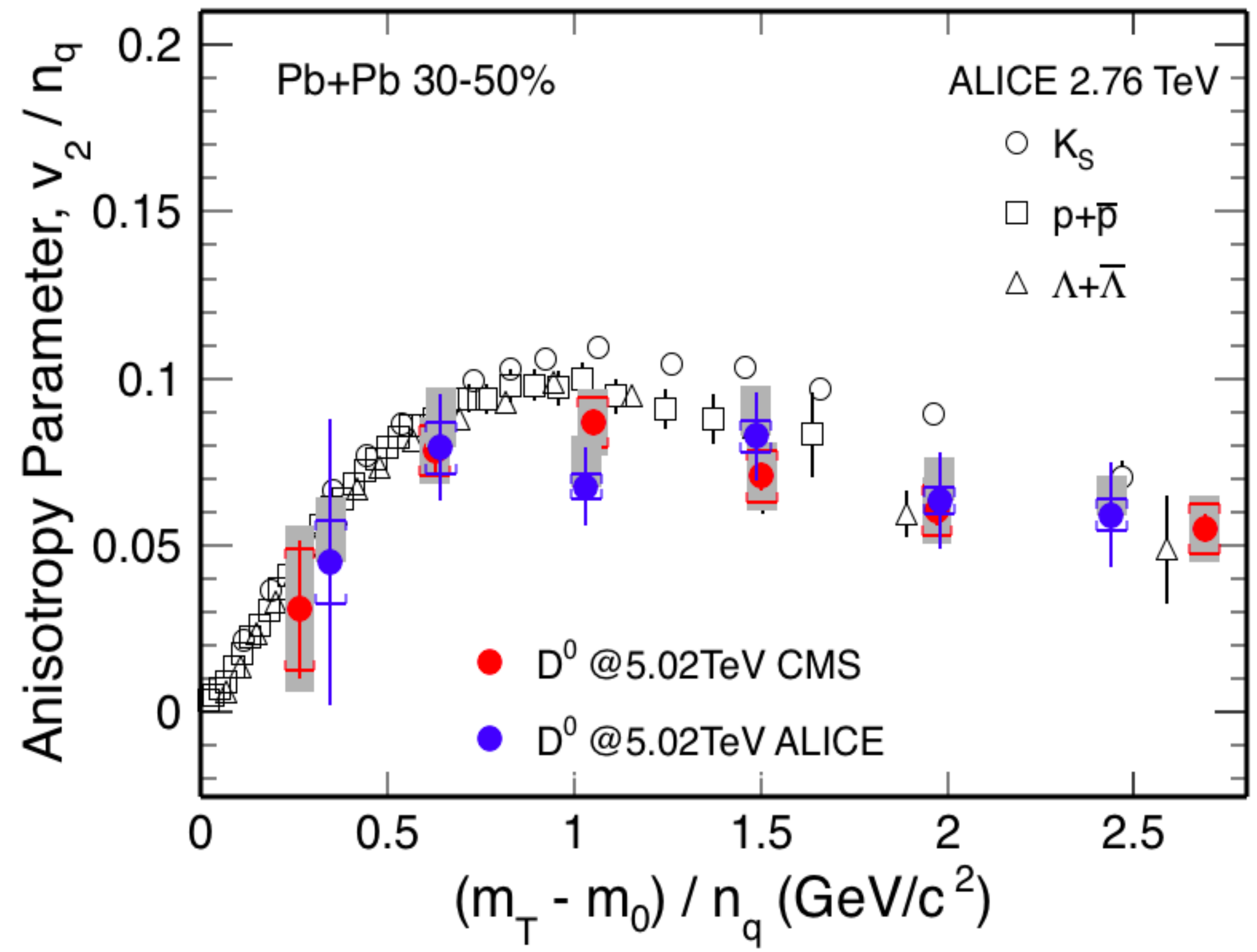
Uniqueness of using HQ to study hadronization:

produced through initial hard scatterings

-> identity preserved through medium evolution

Charm Hadron v_2 at LHC

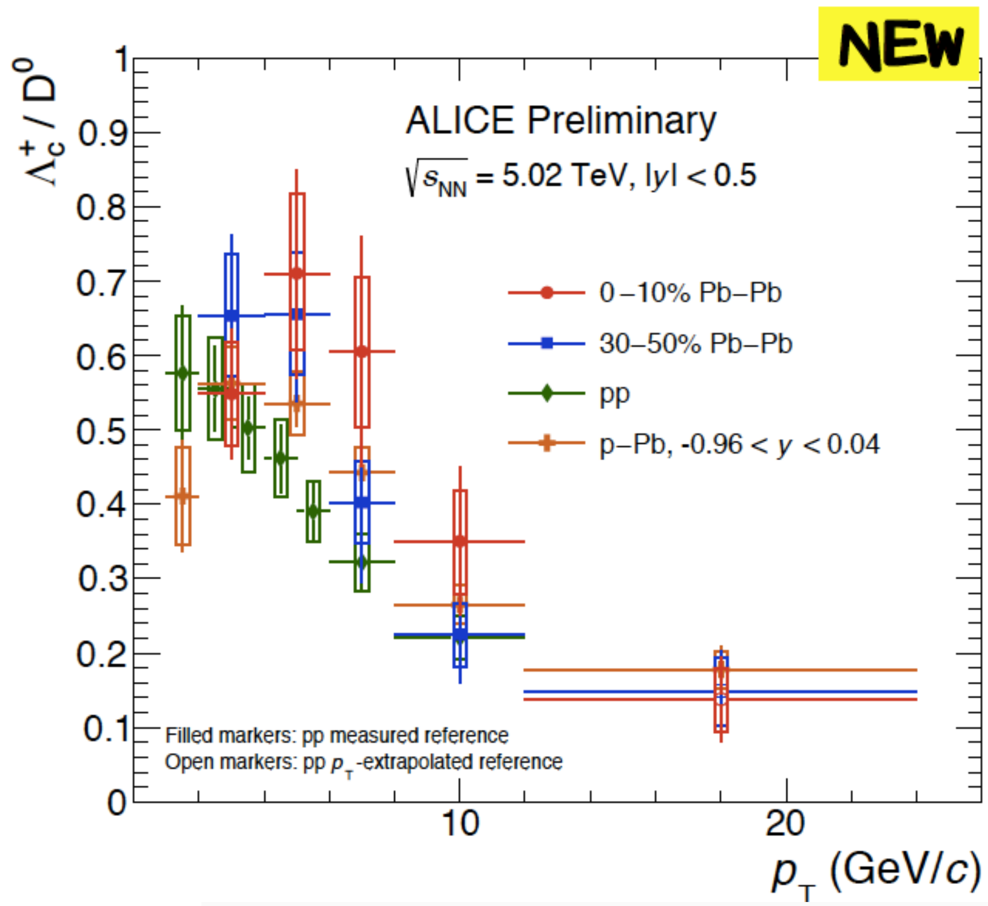


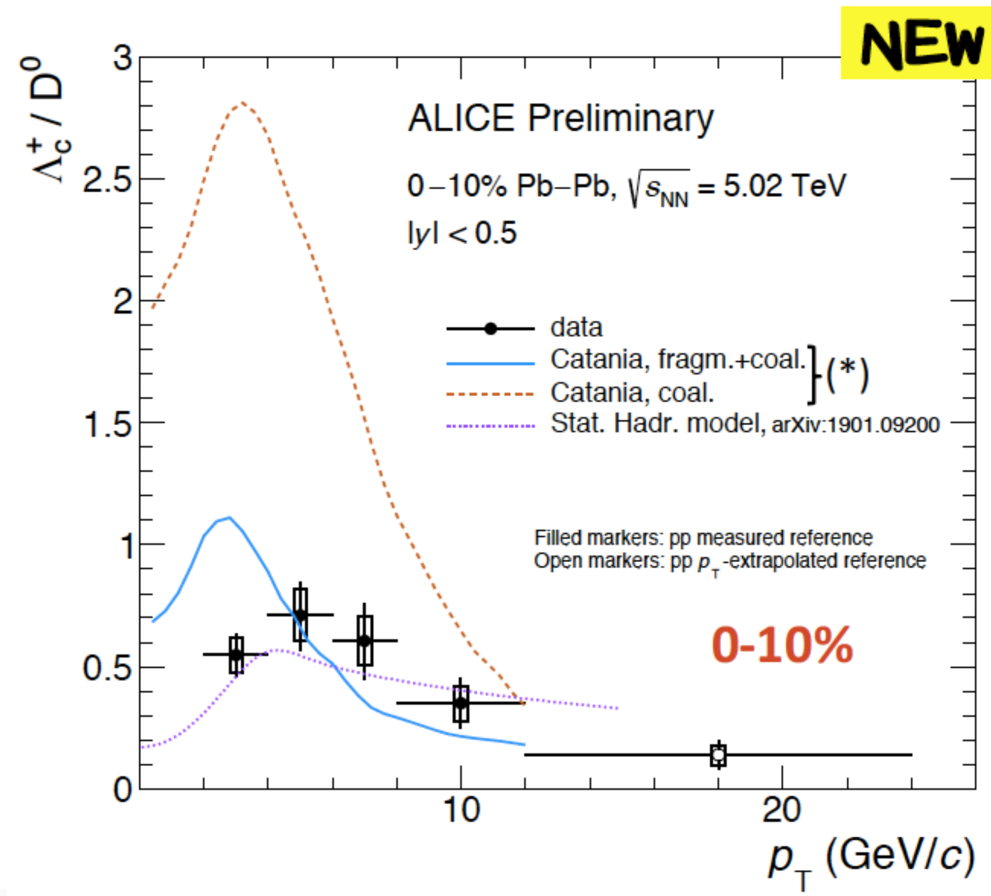


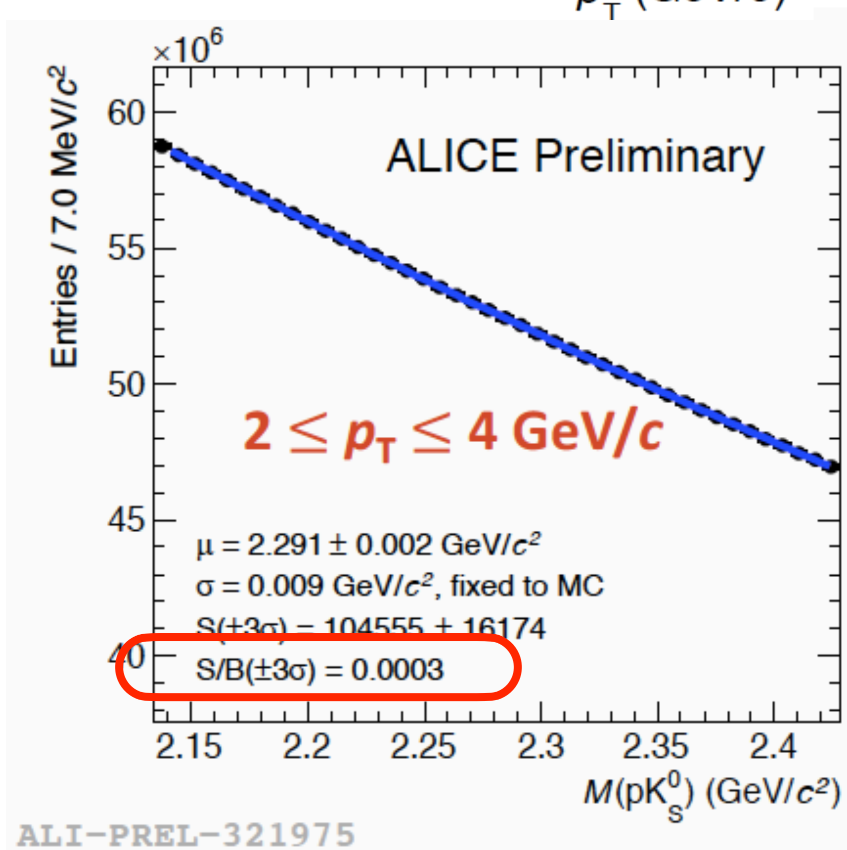
CMS, PRL 120 (2018) 202301; ALICE, PRL 120 (2018) 102301

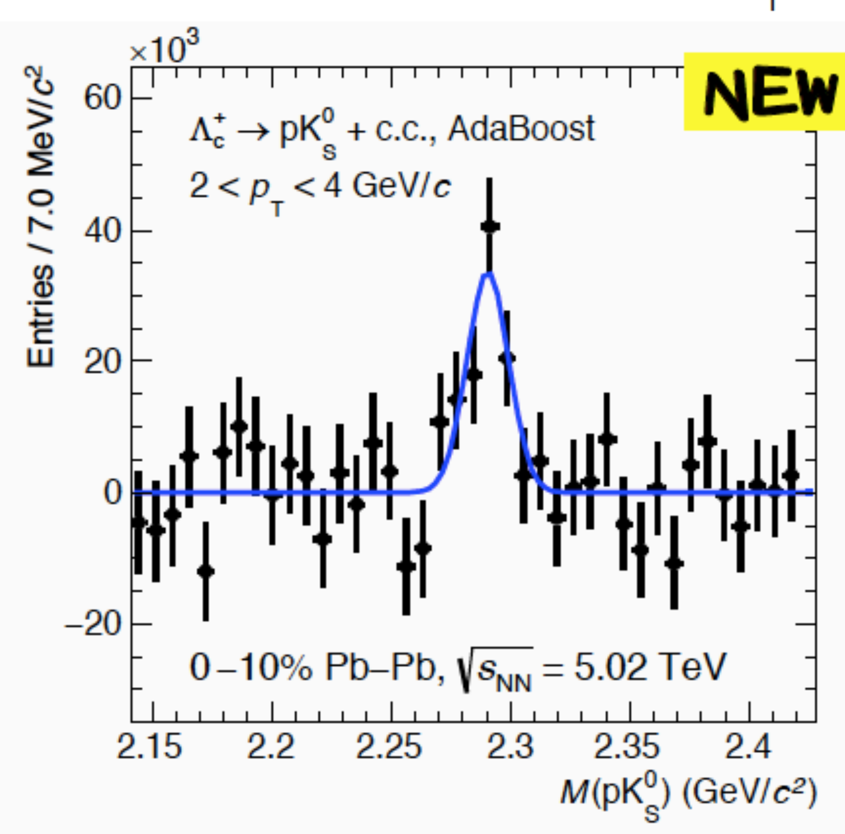
- Significant *D*-meson v_2 at 5.02 TeV Pb+Pb collisions
- D^0 v_2 follows the same trend as light hadrons at LHC

New Λ_c Result in Pb+Pb









Brief Summary of Charm Hadron v_2 and R_{AA}