Overview of Open Heavy Flavor Results at RHIC and LHC

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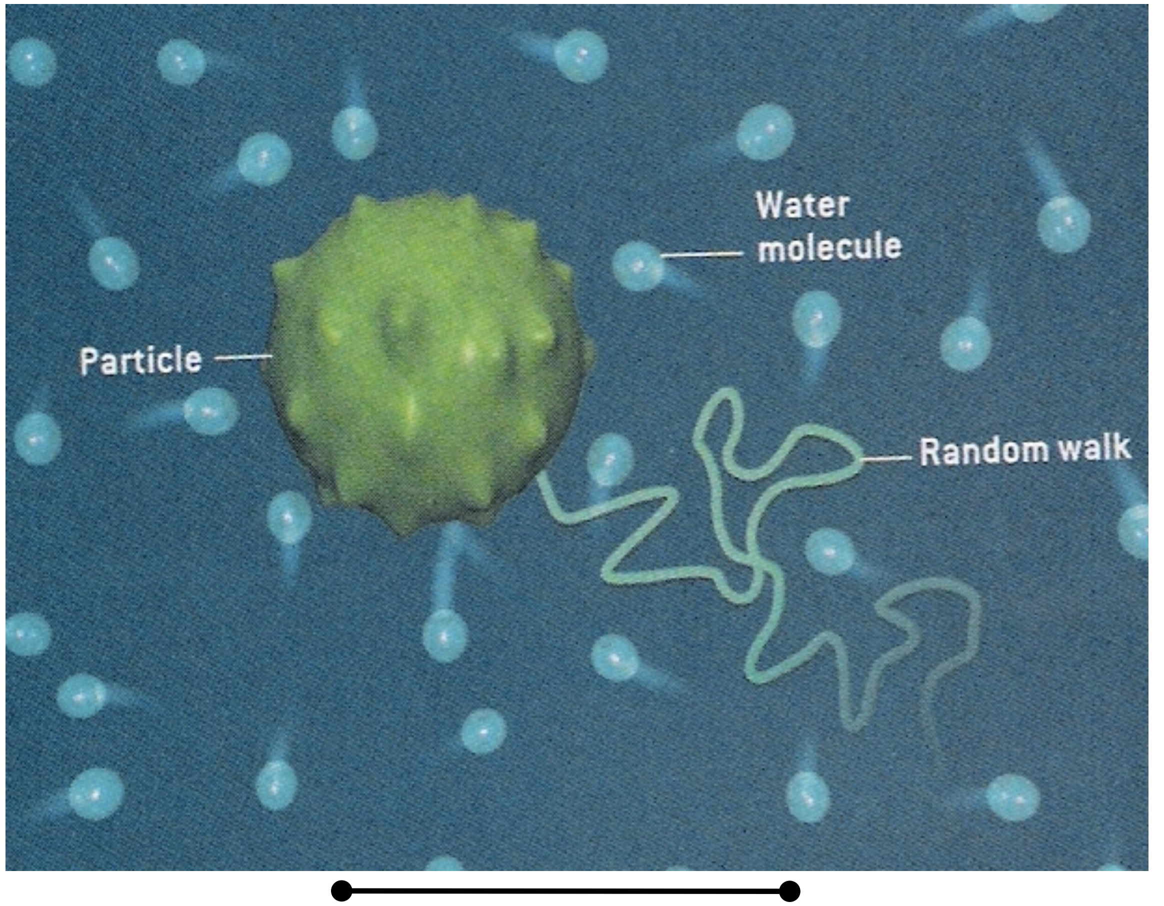
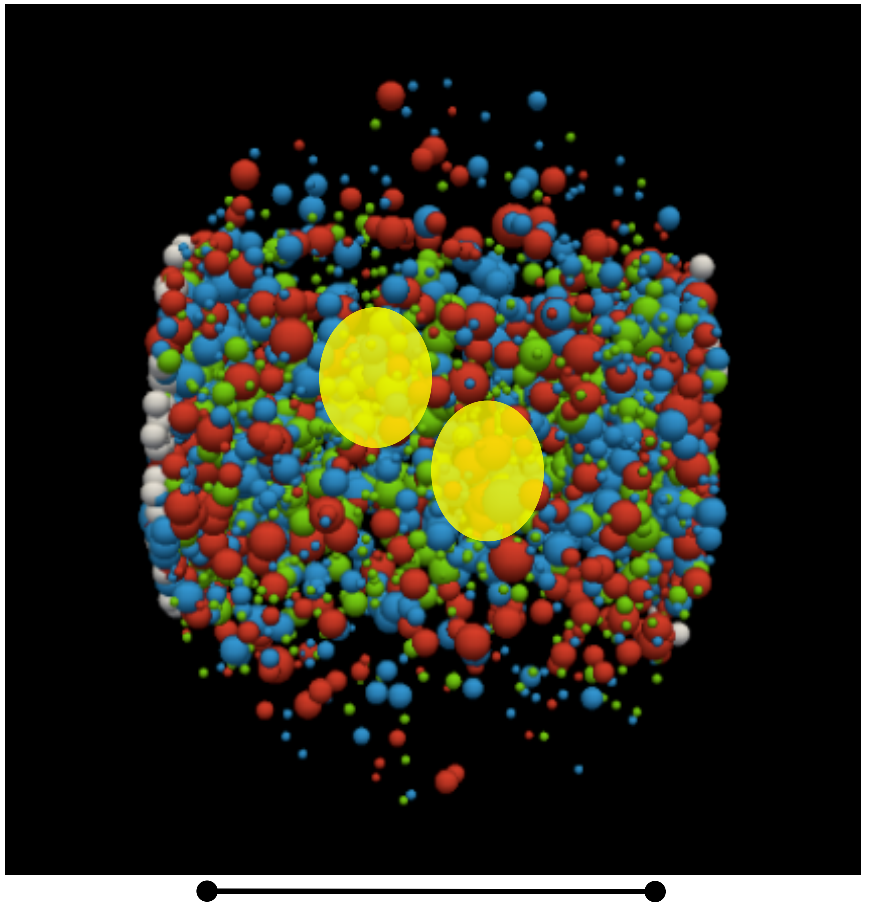
Lawrence Berkeley National Laboratory

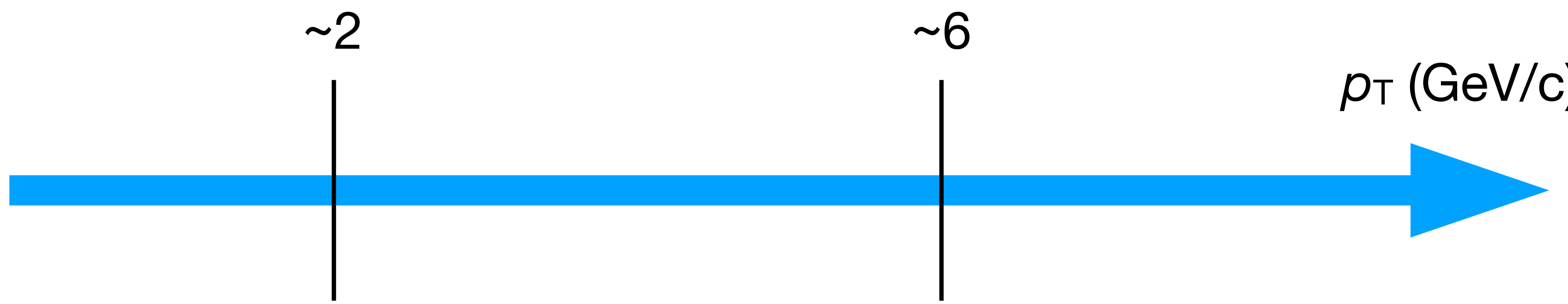


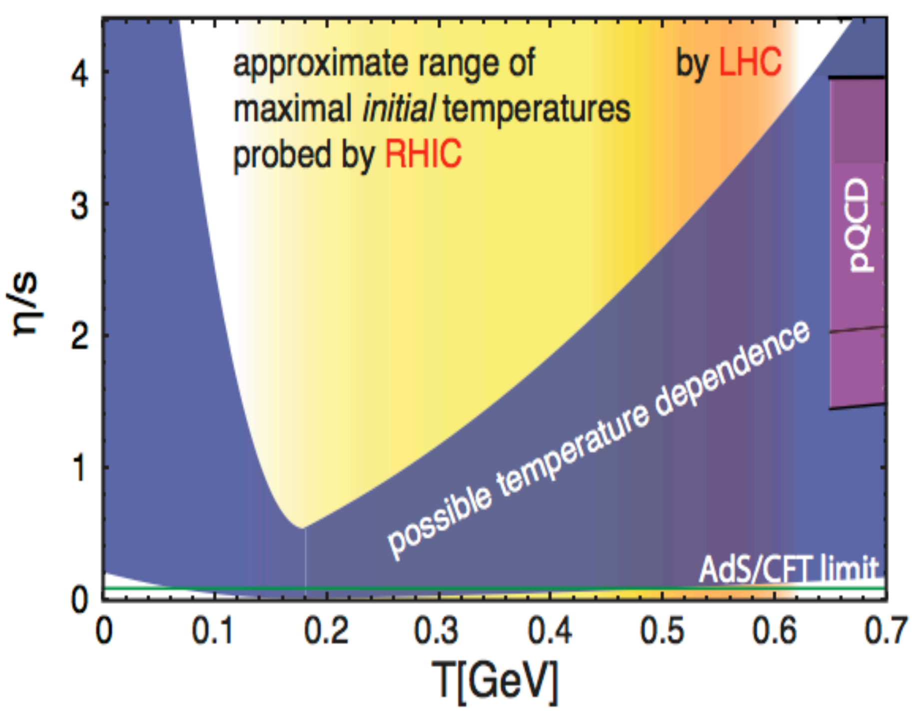
~ 10-100 nm



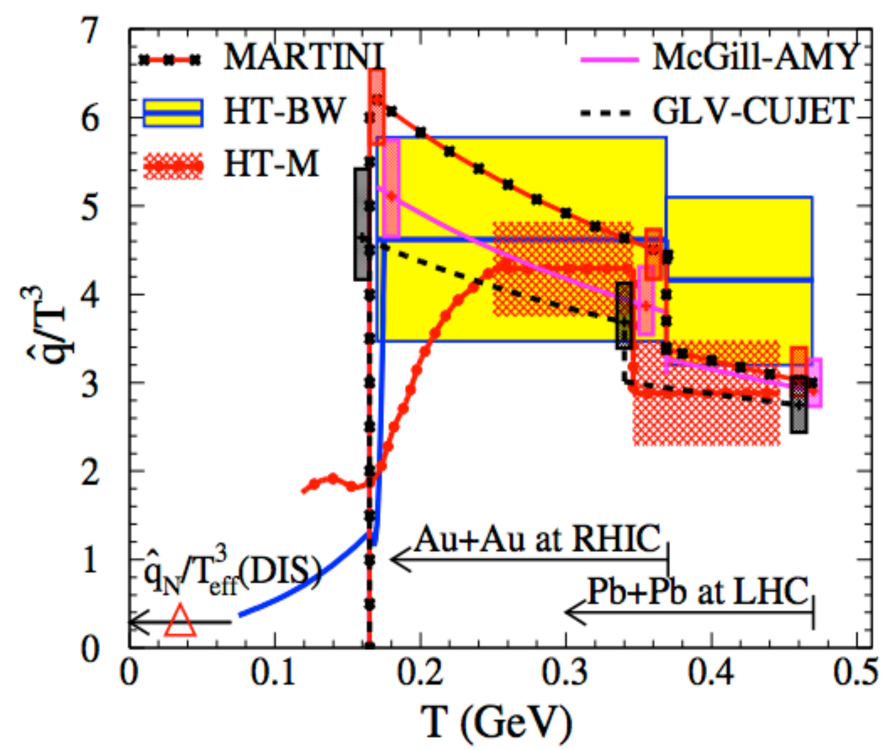
~10 fm

Quantitative Measure of QGP





Hot QCD white paper - arXiv: 1502.02730



JET Coll., PRC 90 (2015) 014909

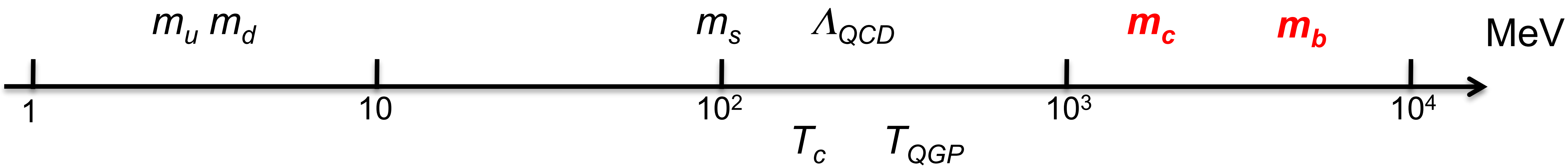
strongly coupled hydrodynamics

?

weakly coupled pQCD

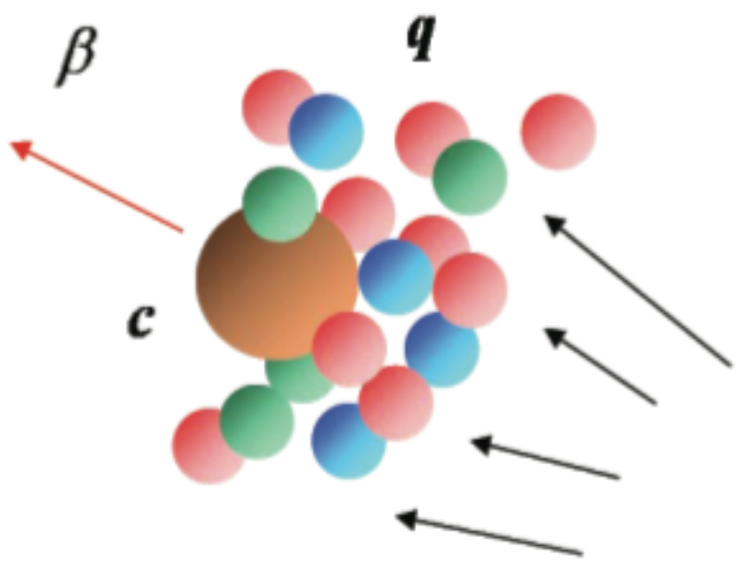
What is the microscopic picture of “perfect fluid”?

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



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

Langevin simu. for HQ diffusion in QGP

Diffusion Coefficients

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

ratio depends on the strong/weak coupling nature of QGP

R. Rapp and H. van Hees, 0903.1096

$$\hat{q} = \frac{\Delta p_T^2}{\lambda} = \frac{4 D_p E_p}{p}$$

gauge to disentangle 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

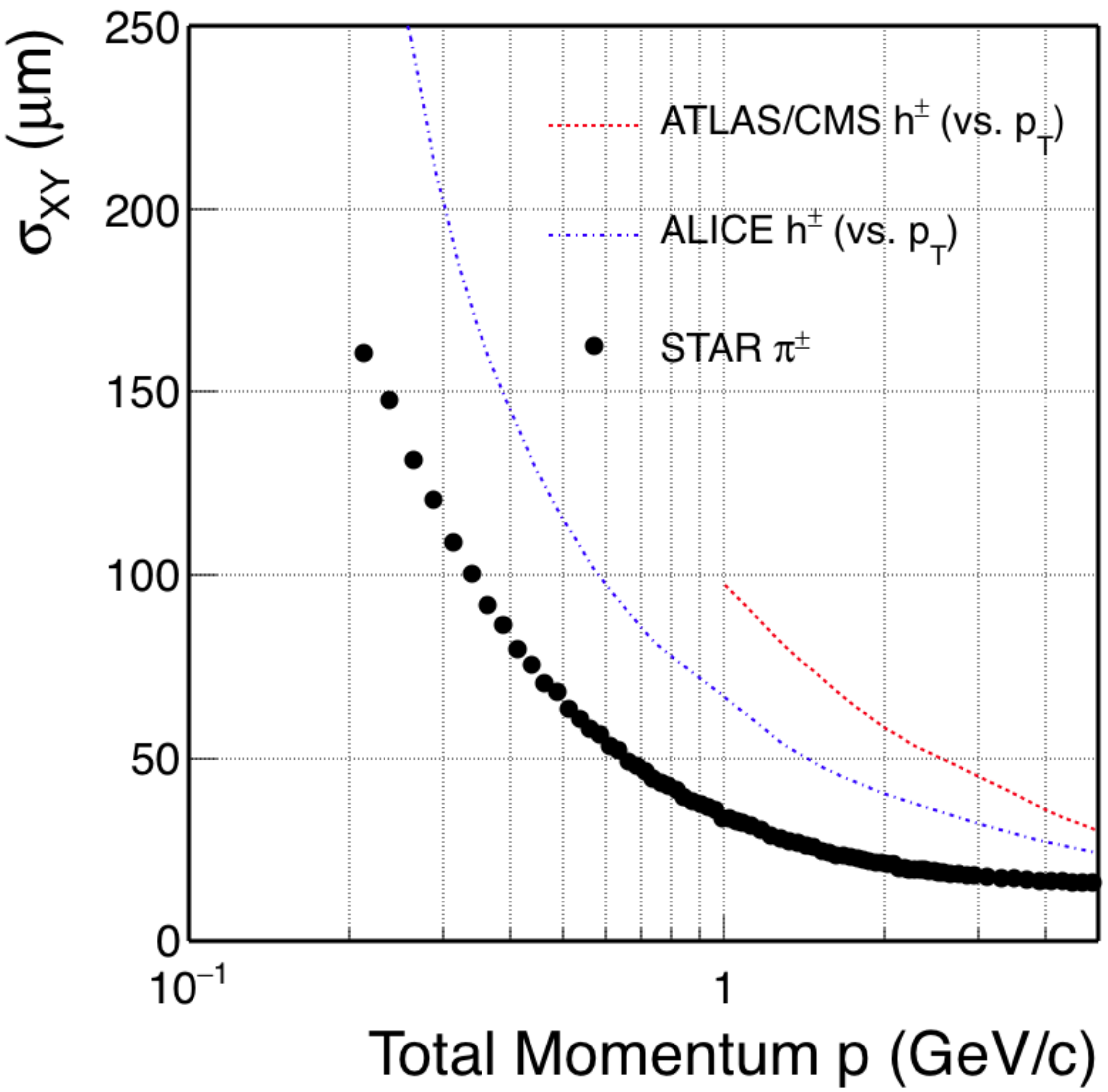
Key Instruments - Pixel Detector

	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	$1\%X_0$	$\sim1\%X_0$	$\sim1\%X_0$	$\sim1\%X_0$	$1\%X_0$	**$0.4\%X_0$**

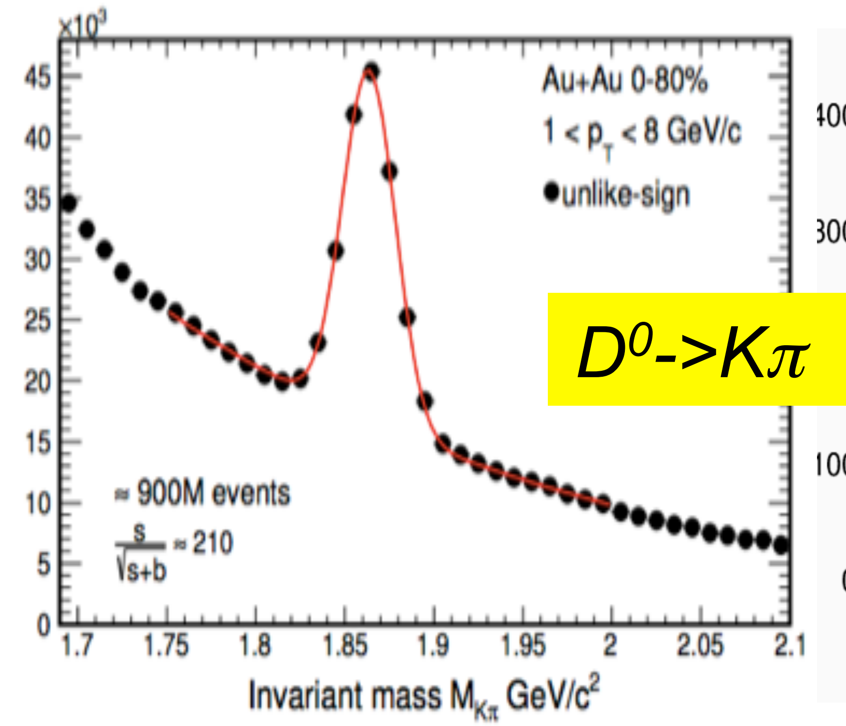
STAR Pixel – first application of **MAPS** technology in collider experiments
(MAPS - Monolithic Active Pixel Sensor)

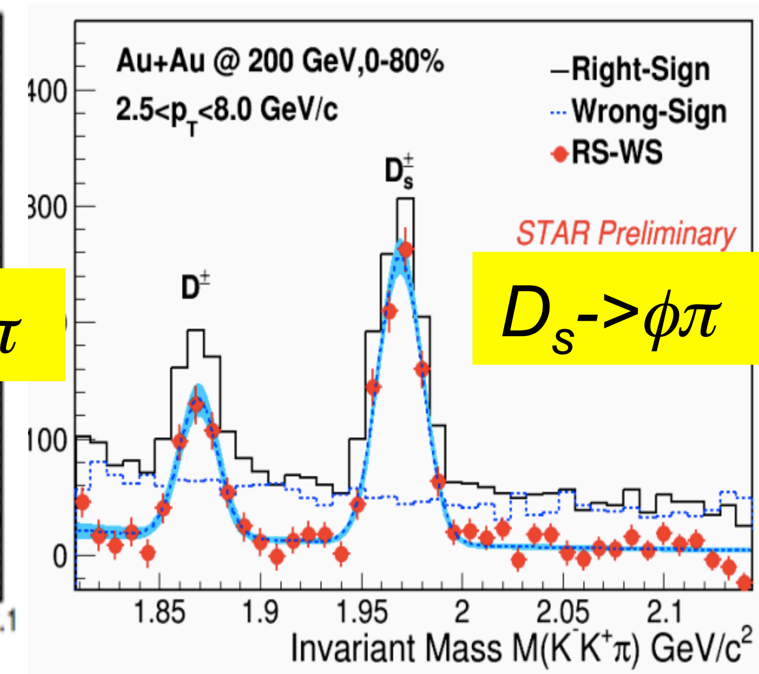
Next generation MAPS planed for future experiments:
ALICE ITS upgrade, sPHENIX MVTX
- to address the QGP medium properties
Also for CBM, EIC detector R&D

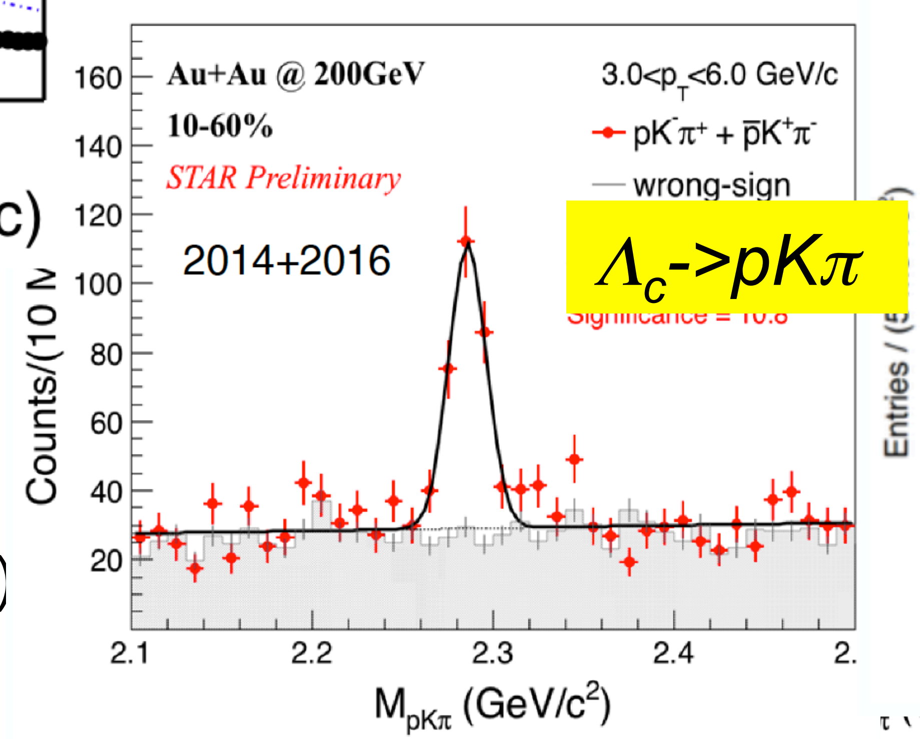
PXL Detector Performance

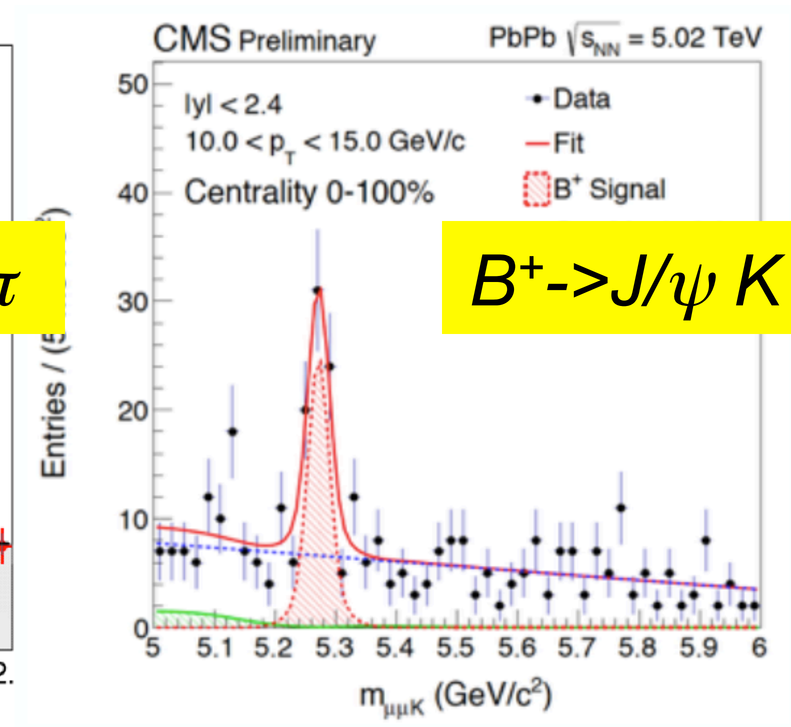


Exclusive reconstruction of HF hadrons in heavy-ion collisions





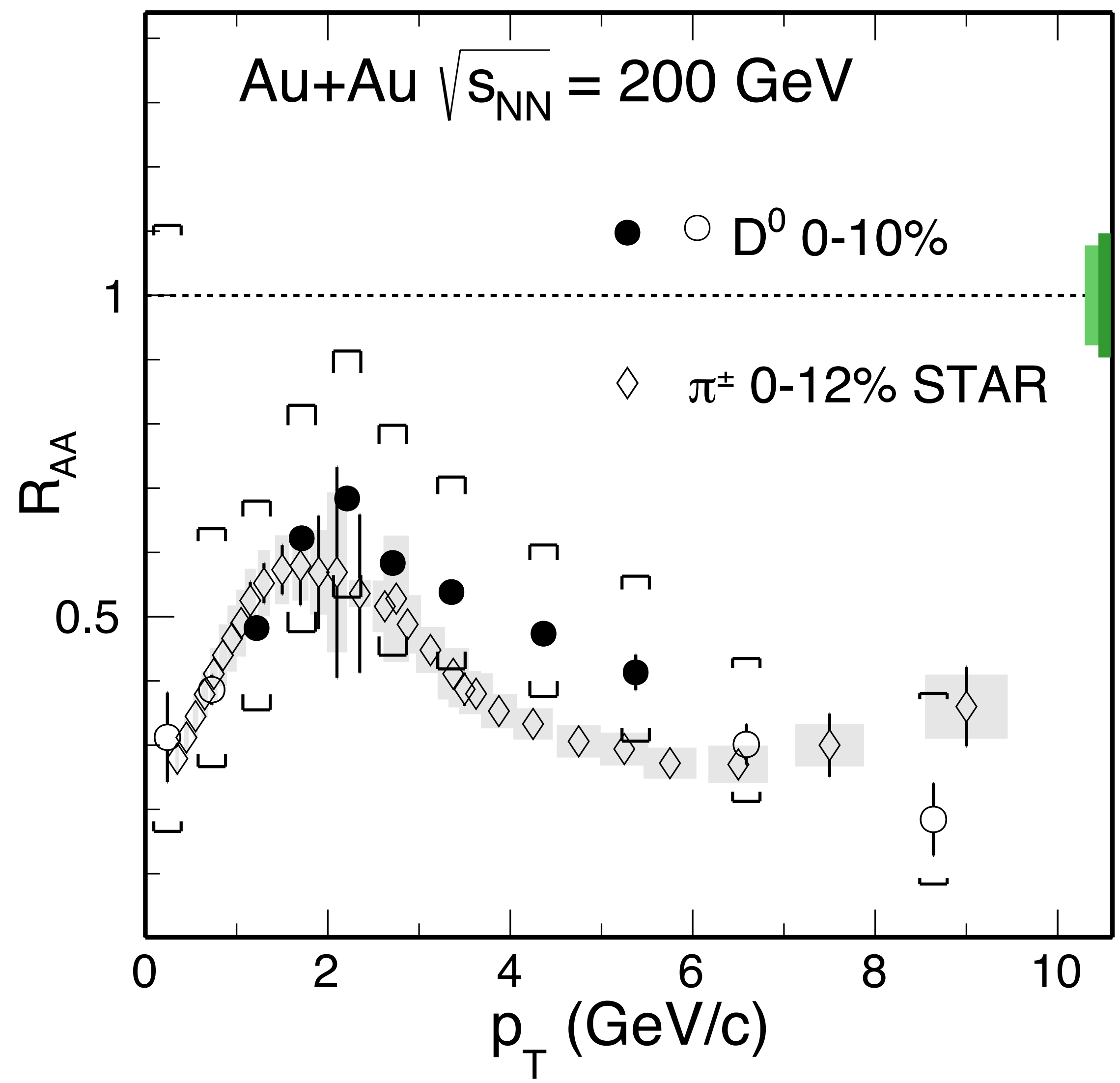




STAR	30 μm @ 1 GeV/c (p)
ALICE	70 μm @ 1 GeV/c (p_T)
ATLAS/CMS	100 μm @ 1 GeV/c (p_T)

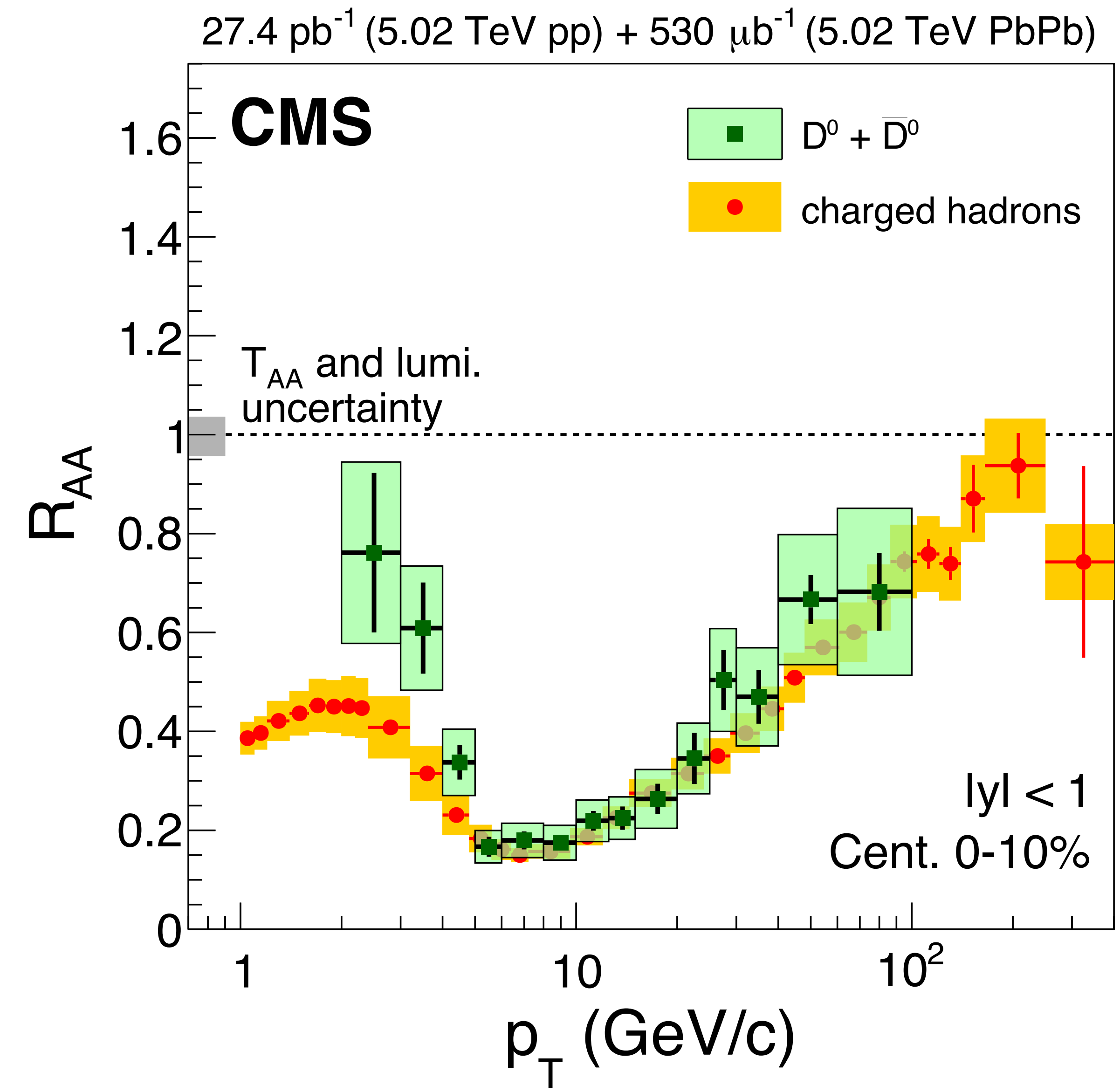
D^0 Meson R_{AA} in Central A+A Collisions

RHIC



STAR, PRC 99 (2019) 034908

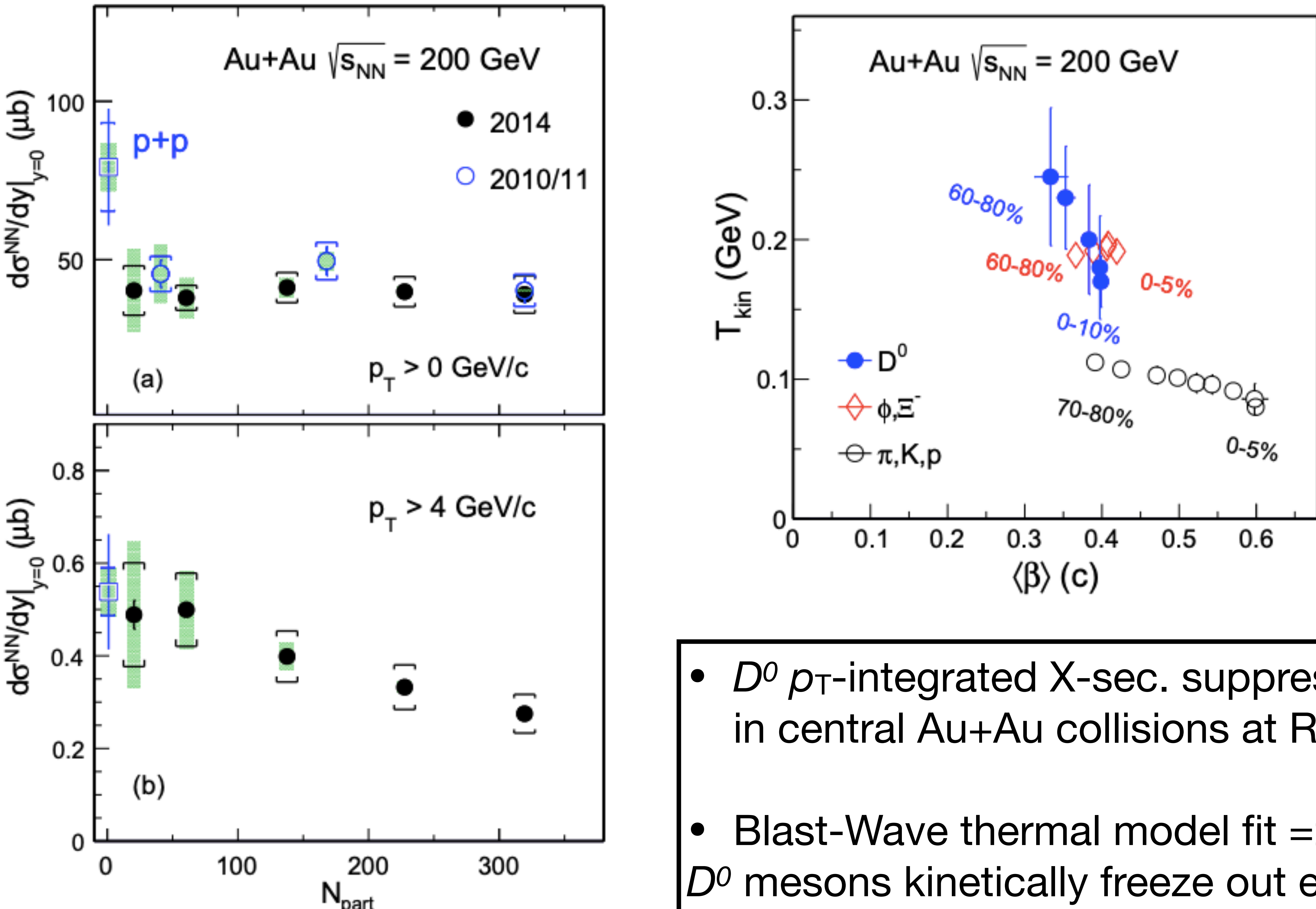
LHC



CMS, PLB 782 (2018) 474

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

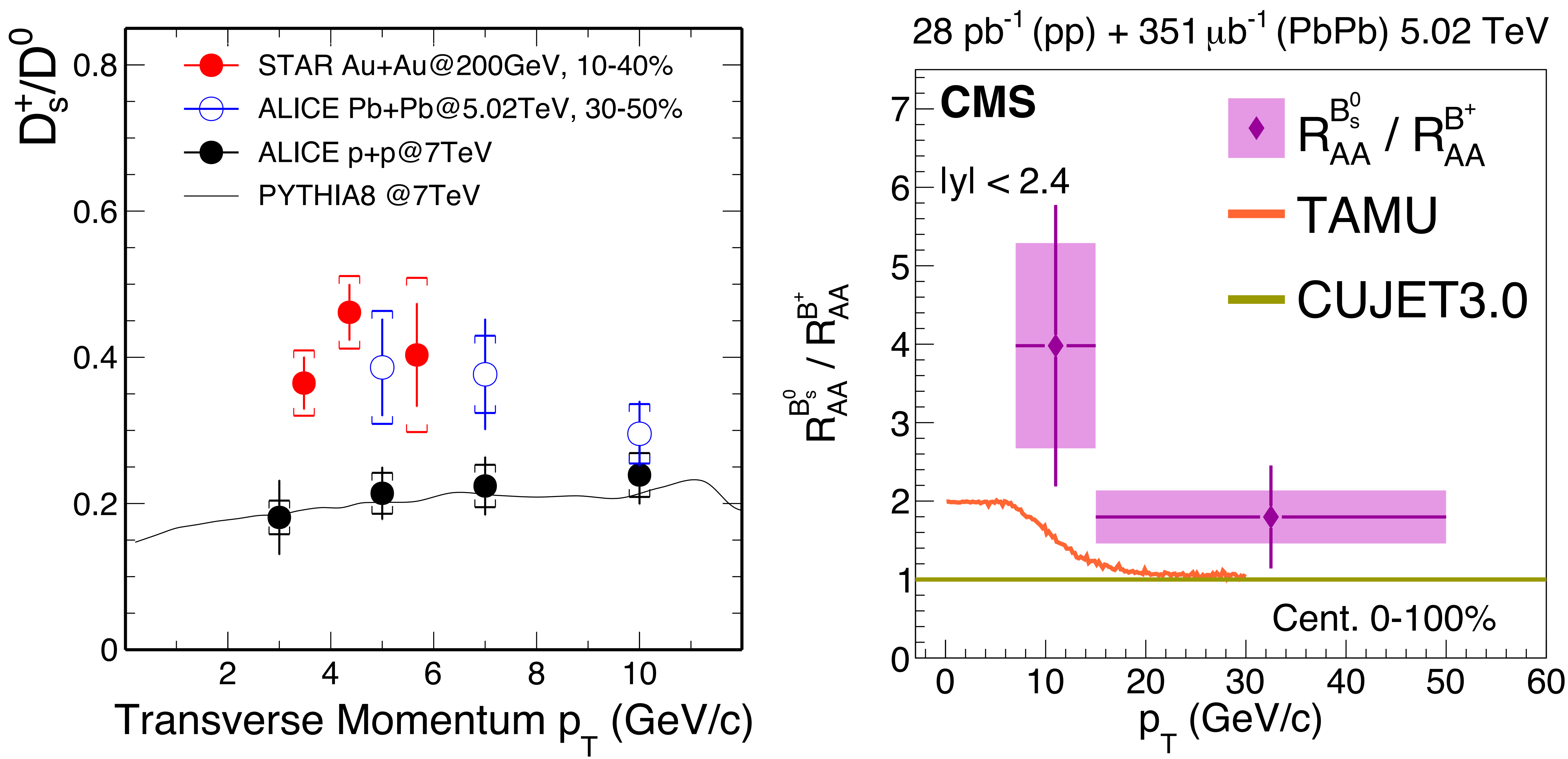
D^0 Total Cross Section and Radial Flow



- D^0 p_T-integrated X-sec. suppressed in central Au+Au collisions at RHIC
- Blast-Wave thermal model fit => D^0 mesons kinetically freeze out earlier than light flavor hadrons

STAR, PRC 99 (2019) 034908

Strange-Charm Meson Enhancement



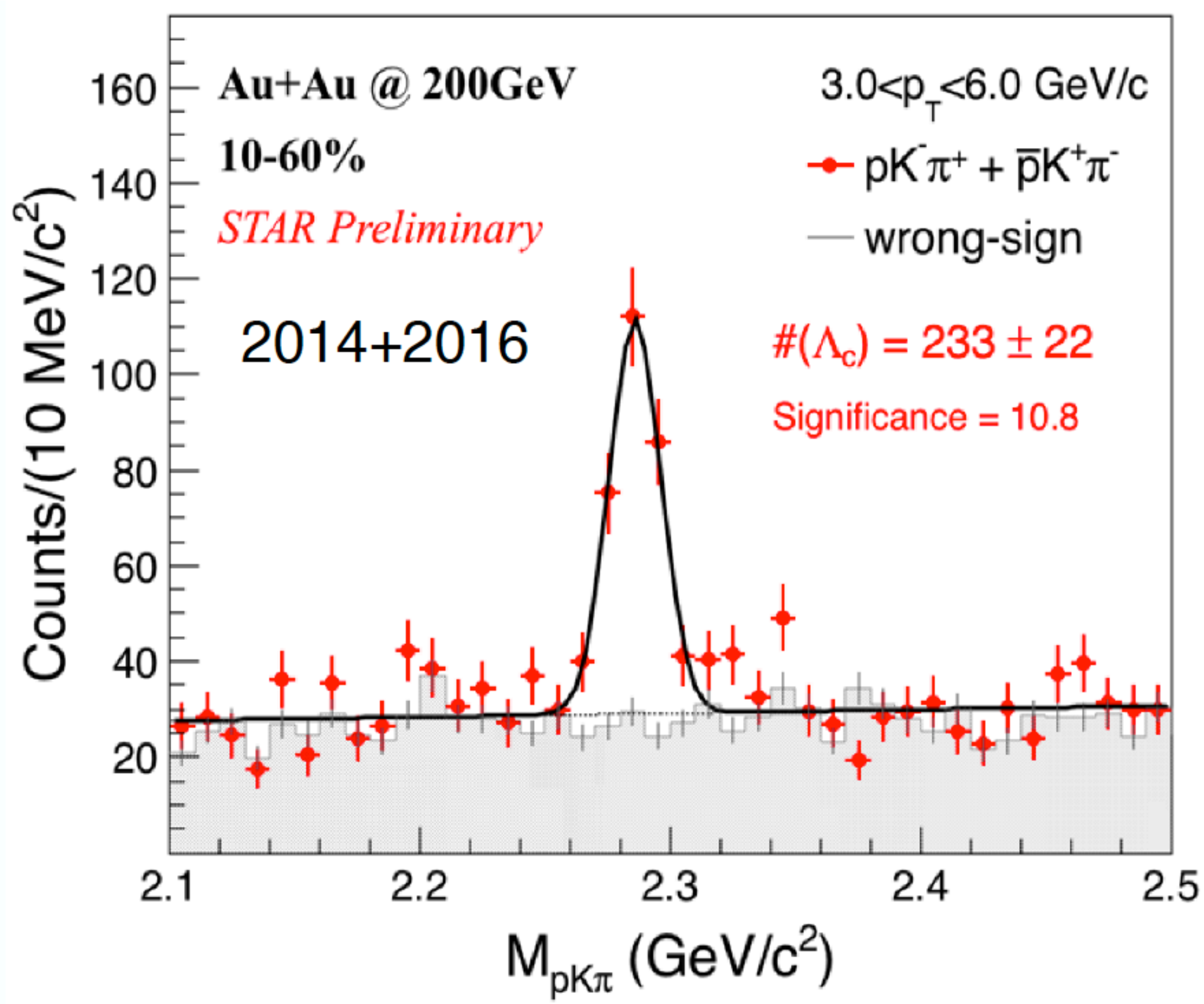
STAR, QM17; ALICE, JHEP 1810 (2018) 174; CMS-PAS-HIN-17-008

- Enhancement in D_s/D^0 ratio in A+A w.r.t to PYTHIA/pp baseline
  - Coalescence hadronization
  - Strangeness enhancement

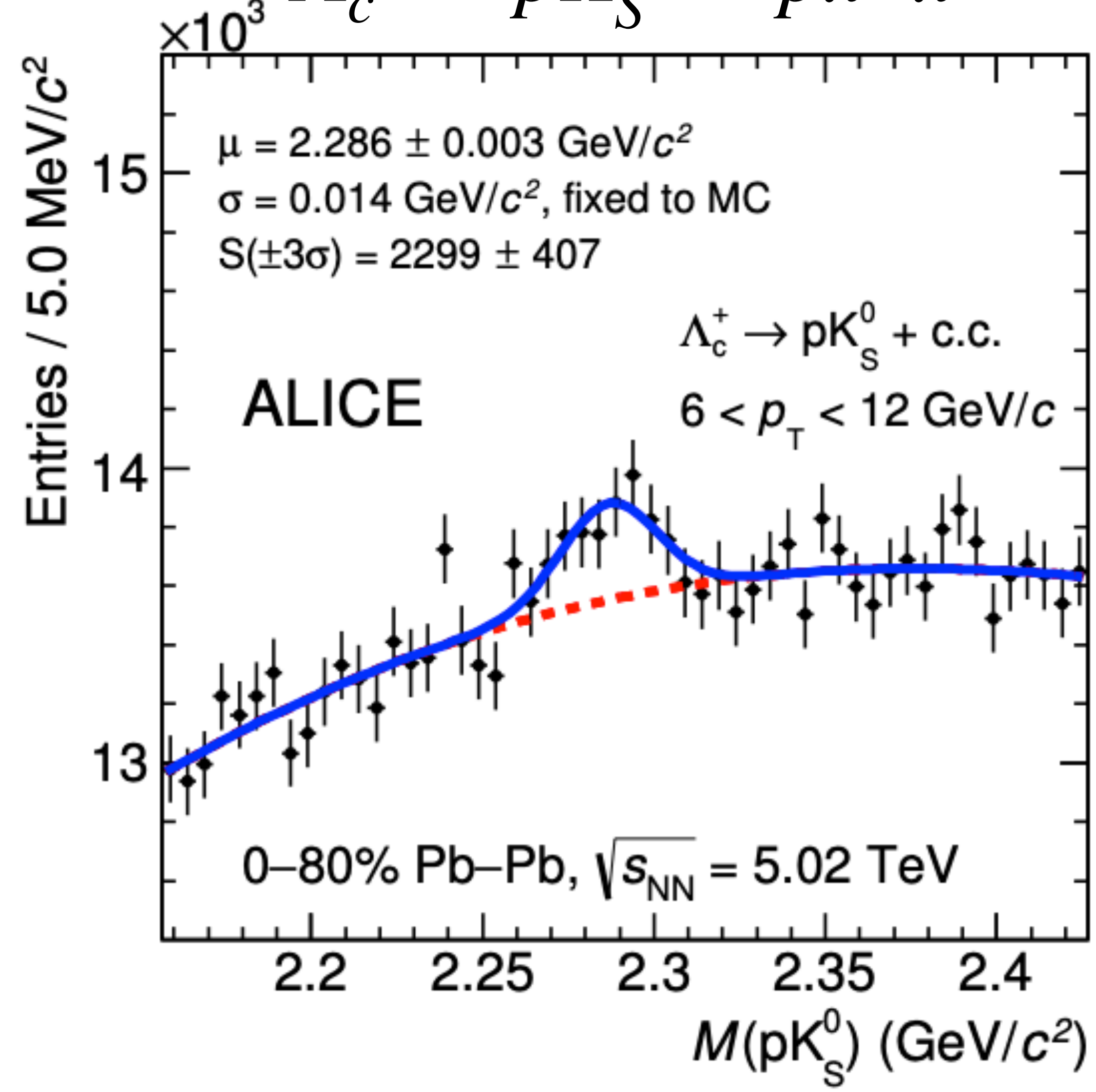
Λ_c Reconstruction in Heavy-Ion Collisions

$$c\tau = 60\mu m$$

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



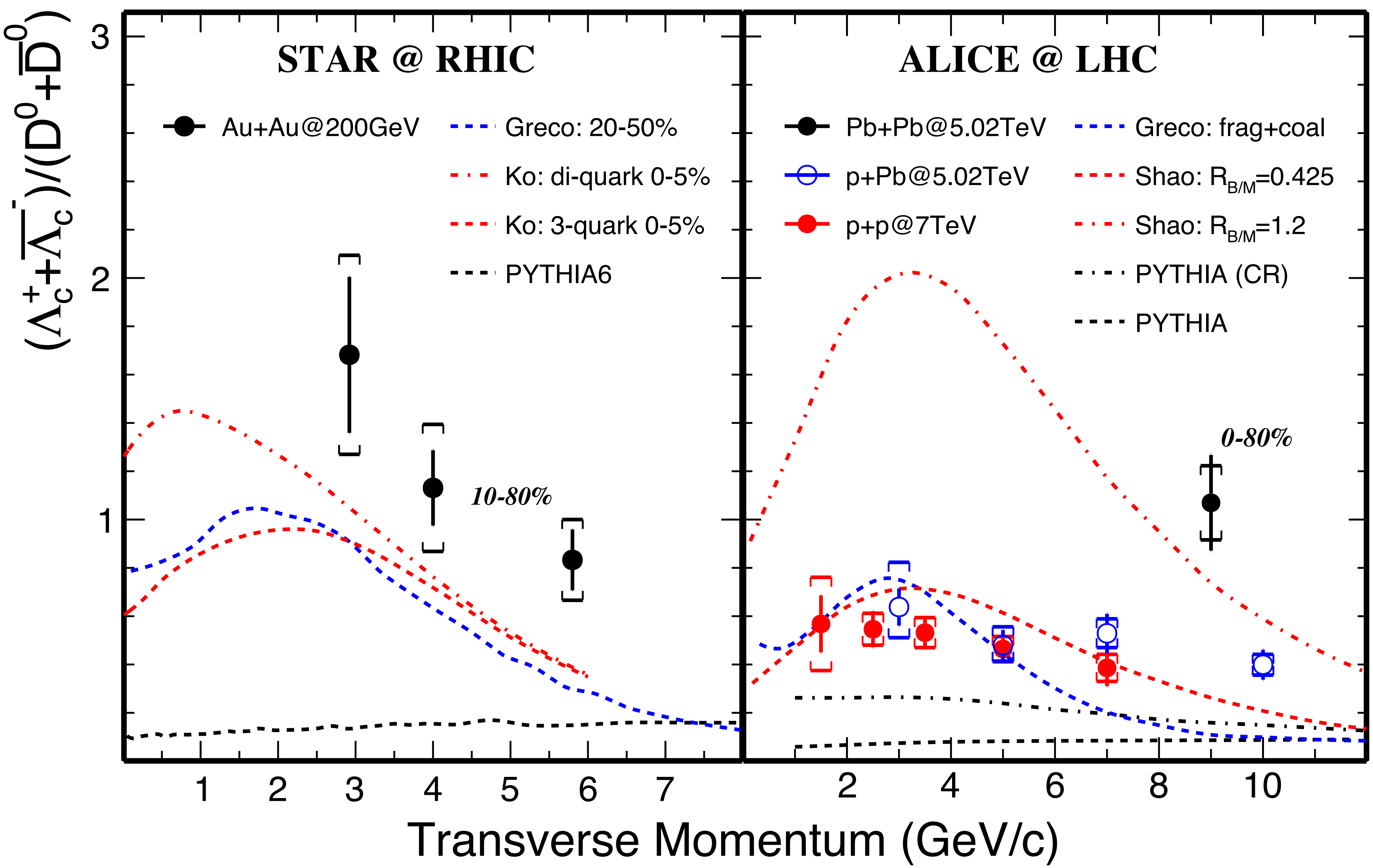
$\Lambda_c^+ \rightarrow pK_S^0 \rightarrow p\pi^+\pi^-$



STAR, QM18; ALICE, arXiv:1809.10922

Great experimental achievement in reconstructing charm baryon in heavy-ion collisions !

Charm Baryon Enhancement



STAR, QM18; ALICE, arXiv:1809.10922

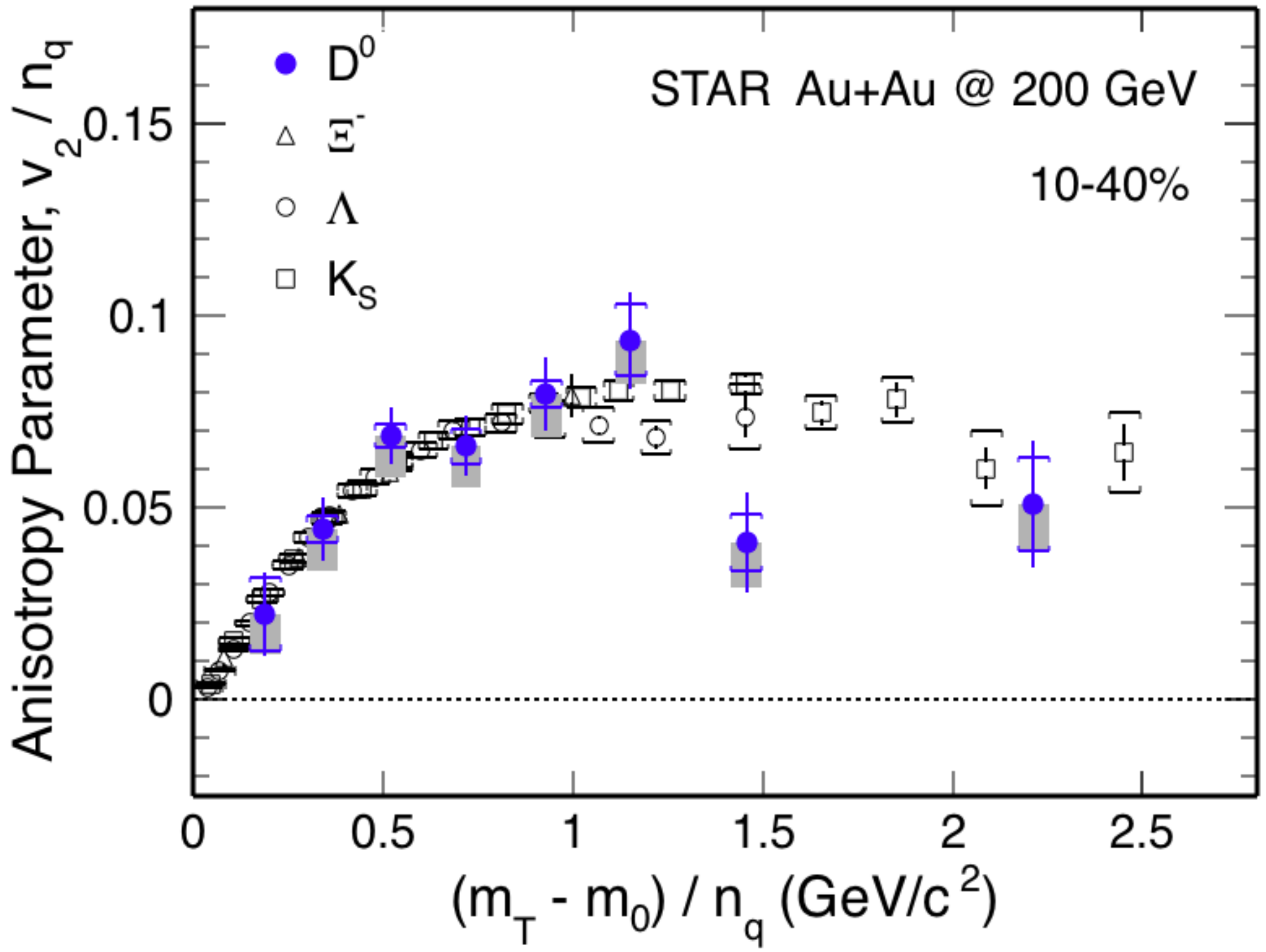
- Significant enhancement in Λ_c/D^0 ratio in A+A collisions w.r.t PYTHIA/p+p baselines
  - Coalescence hadronization

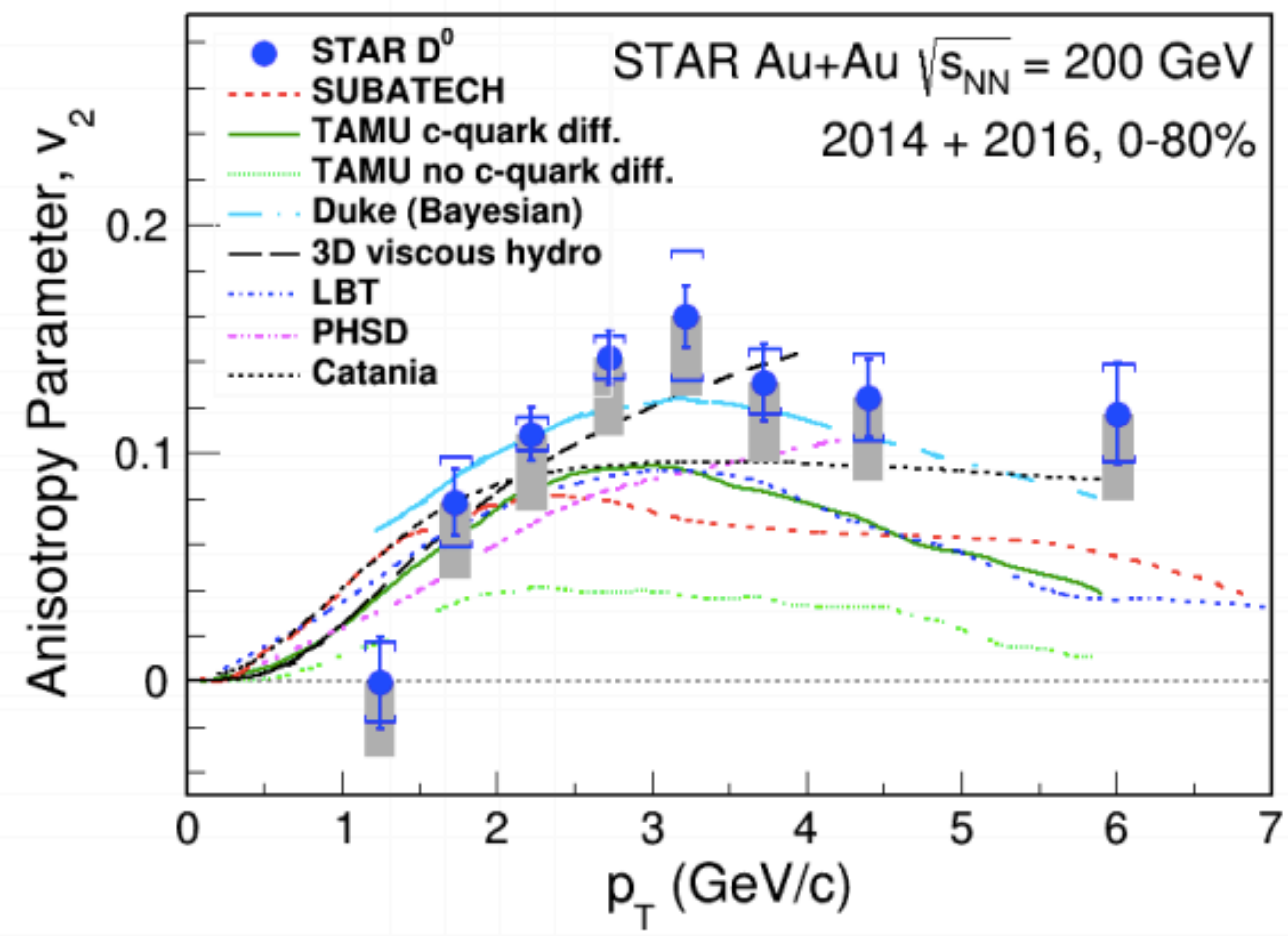
Total Charm Production Cross Section

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**

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

Charm Hadron v_2 at RHIC

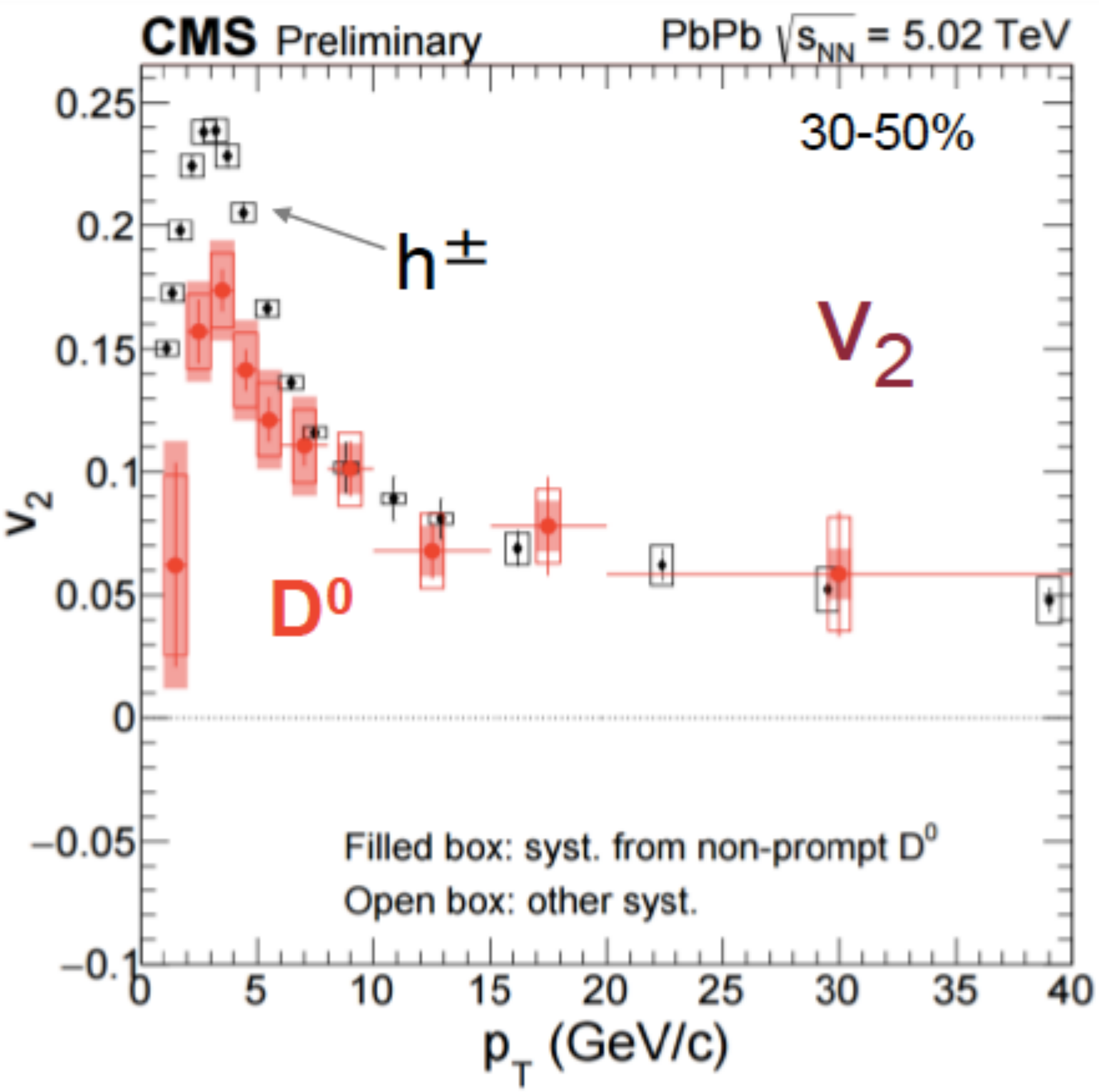


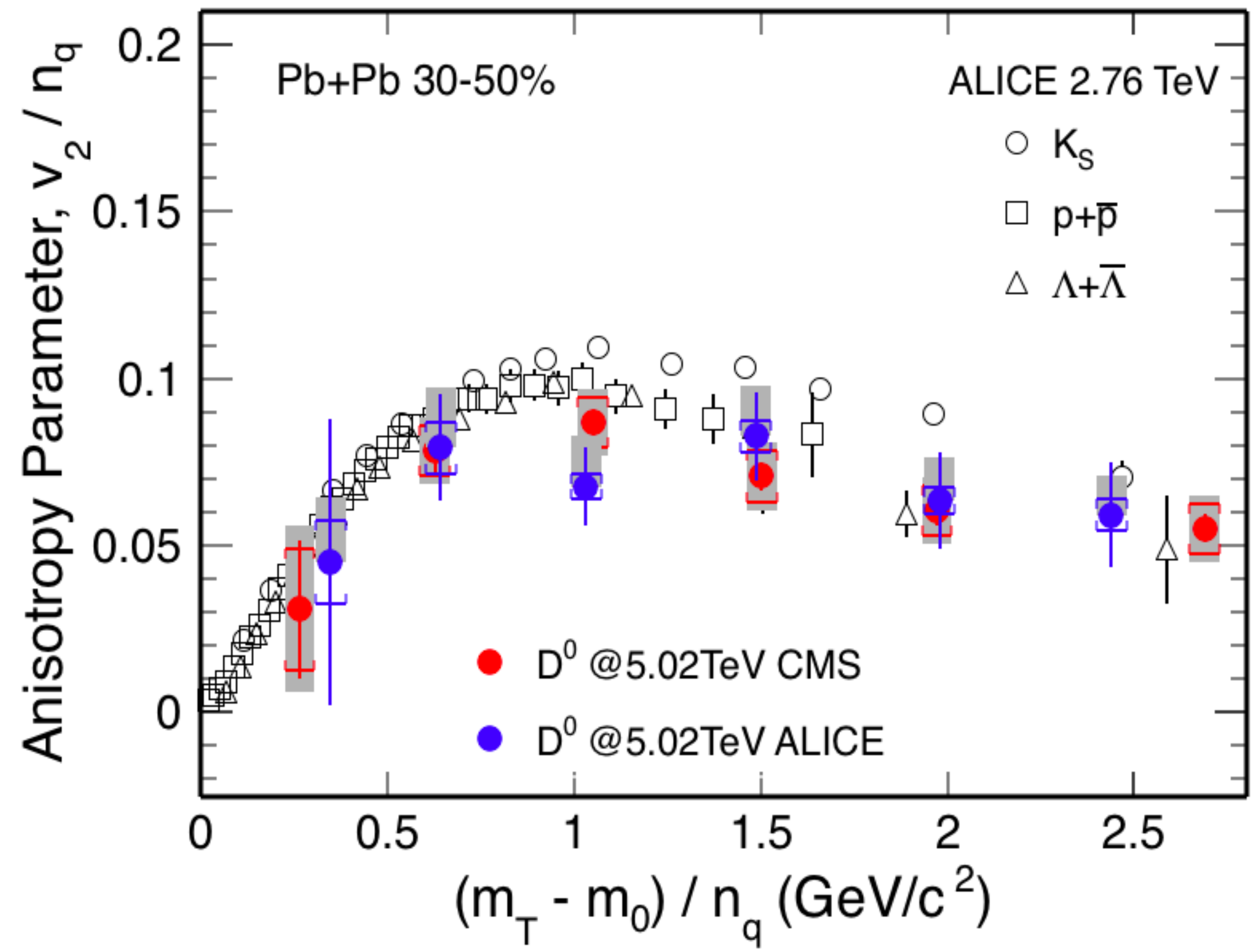


STAR, PRL 118 (2017) 212301; QM18

- Mass ordering at p_T < 2 GeV/c (hydrodynamic behavior)
- $v_2(D)$ follows the same $(m_T\text{-}m_0)$ scaling as light hadrons below 1 GeV/c^2
- Transport models including *c* diffusion in medium consistent with data

Charm Hadron v_2 at LHC

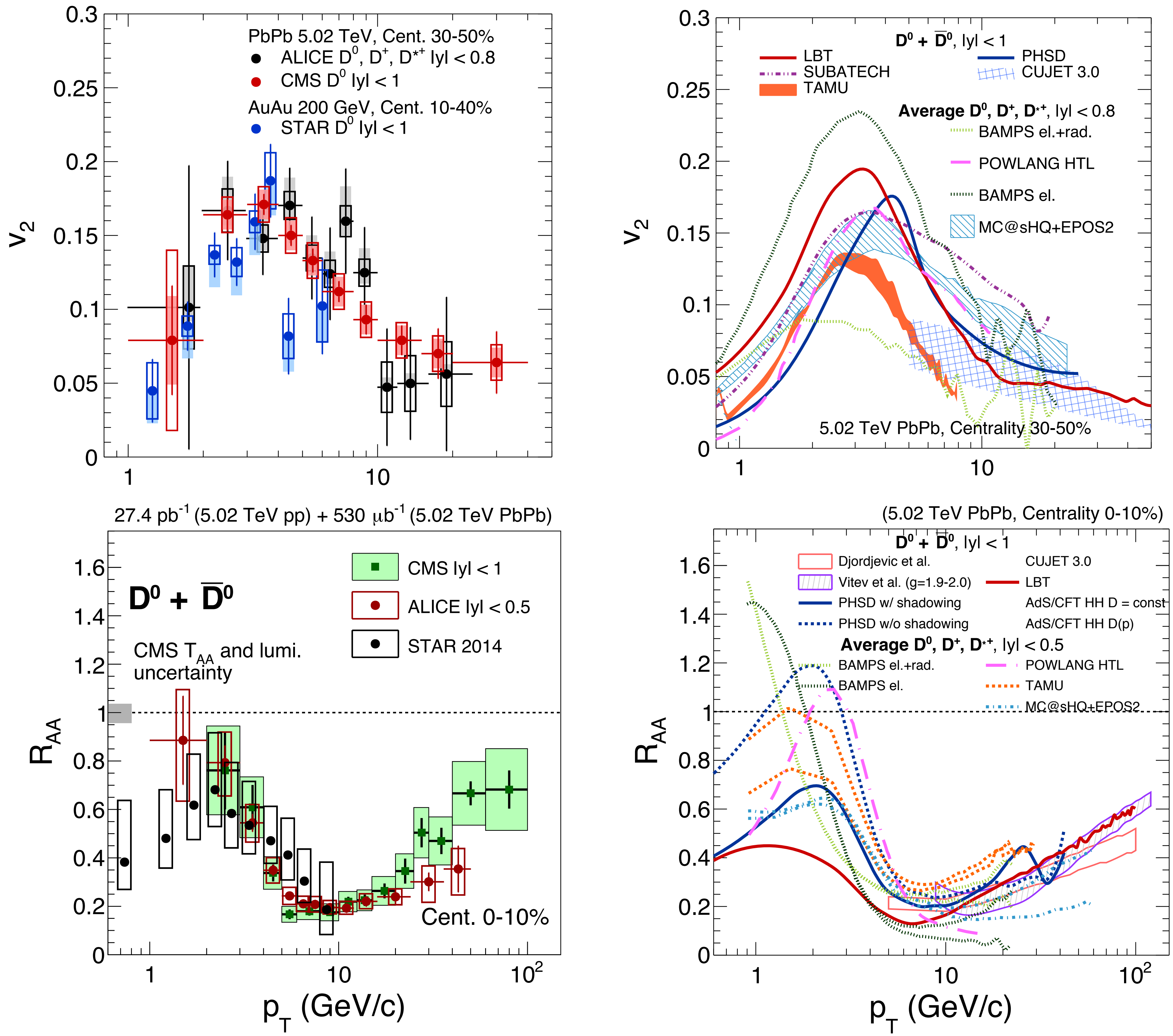




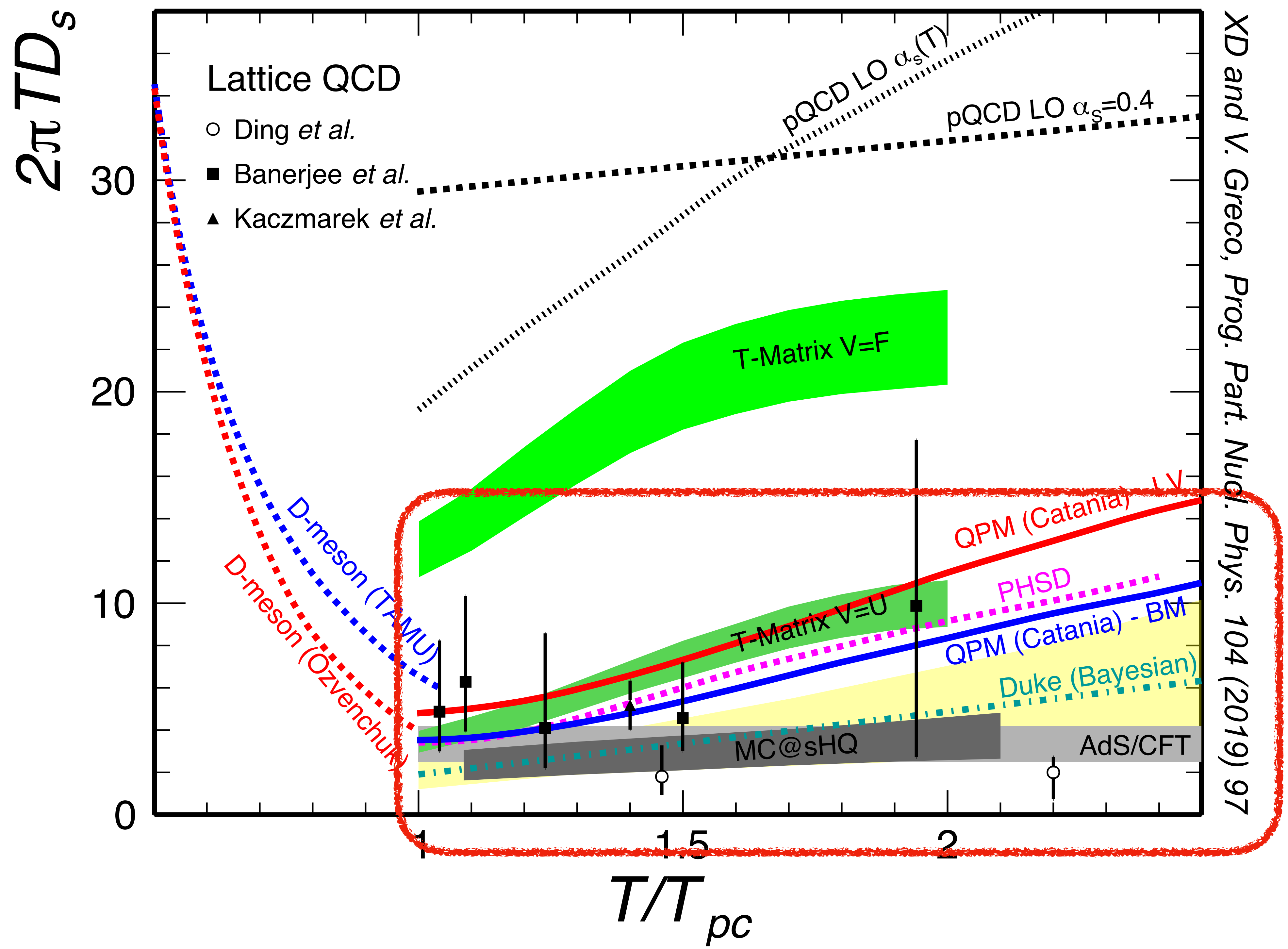
CMS, PRL 120 (2018) 202301; ALICE, PRL 120 (2018) 102301

- 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

Charm Hadron v_2 and R_{AA}



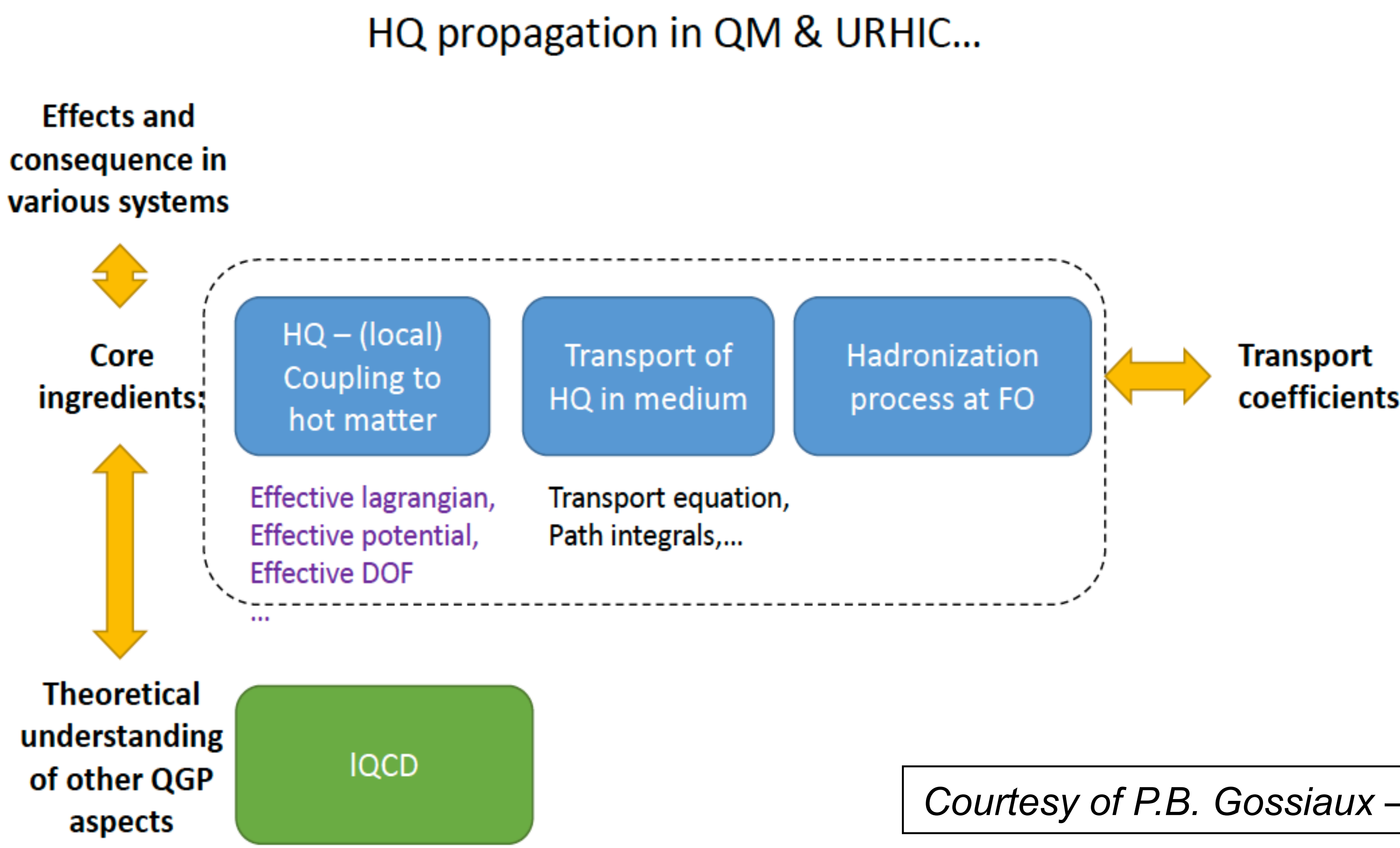
Current Knowledge of HQ Diffusion Coefficient



$2\pi TD_s$ **~ 2-5 at T_c**

Next: temperature dependence? charm vs. bottom universality?

Towards Precision Determination of D_s



Courtesy of P.B. Gossiaux – QM18

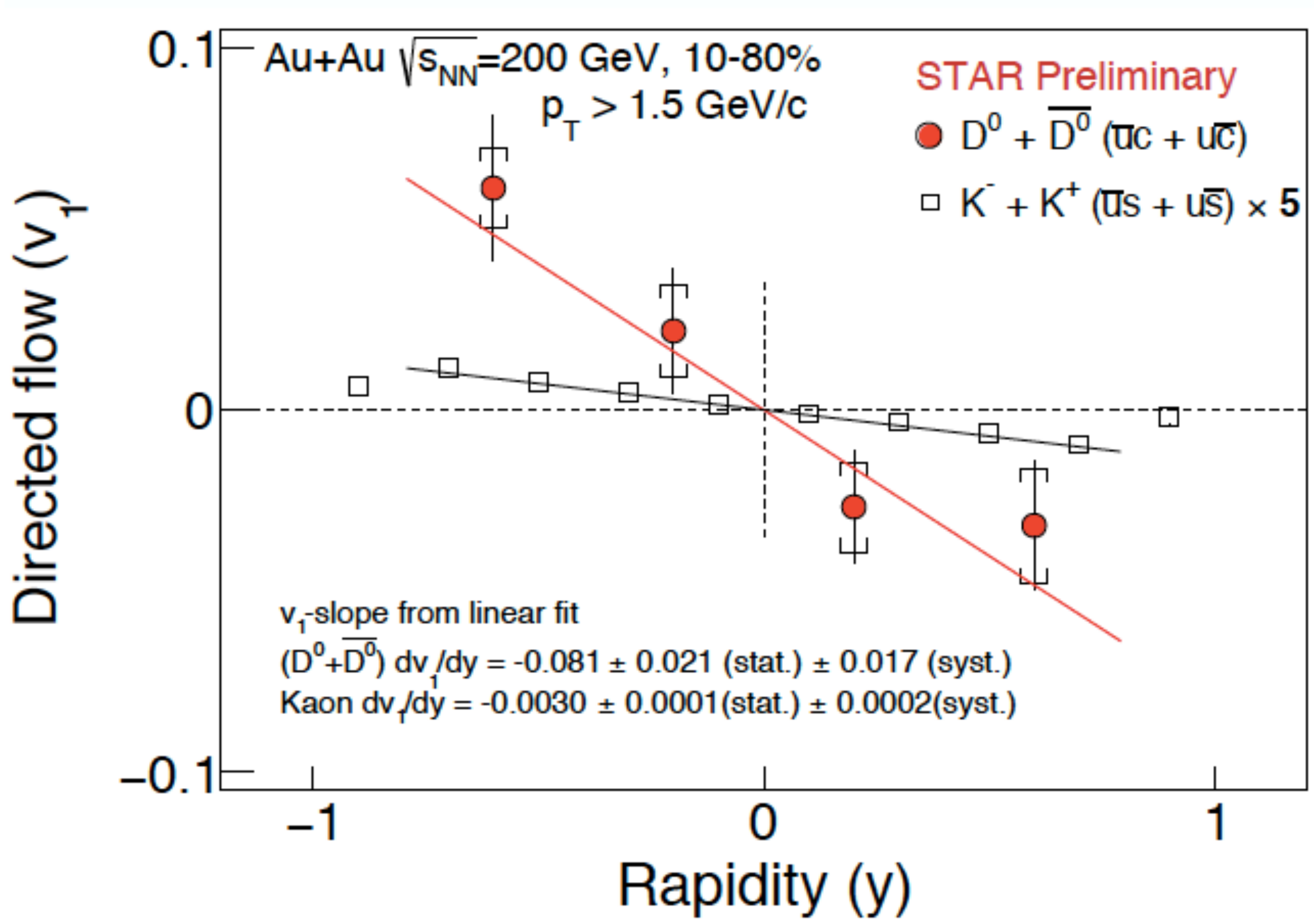
Rapid developments among theorists to resolve/understand trivial/non-trivial differences between different models

EMMI Rapid Reaction Task Force - *R. Rapp et al., 1803.03824*

Jet-HQ Working Group - *S.S. Can et al., 1809.07894*

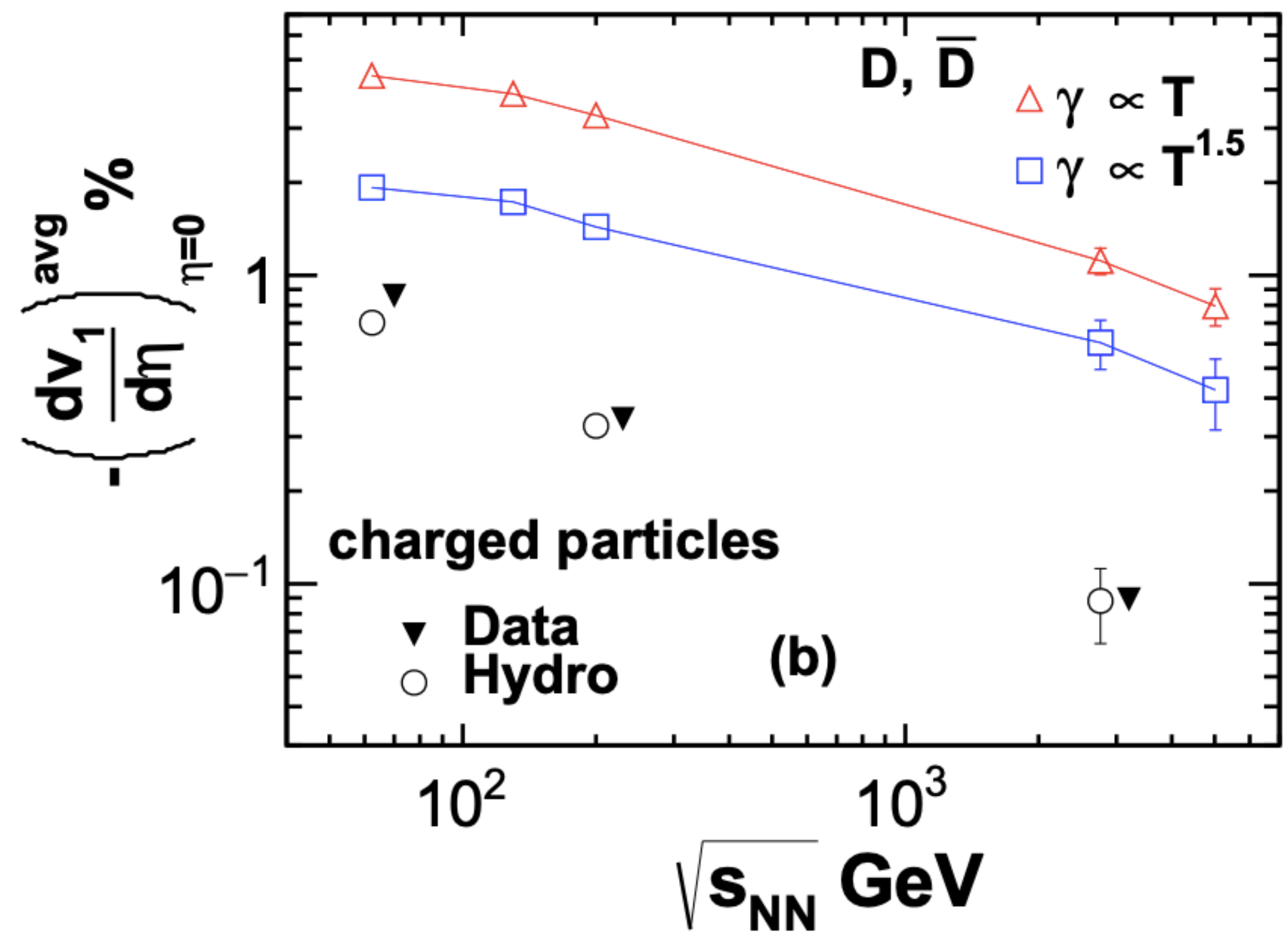
D^0 v_1 - New Insight to QGP Properties

Data



STAR, QM18

Hydro Model



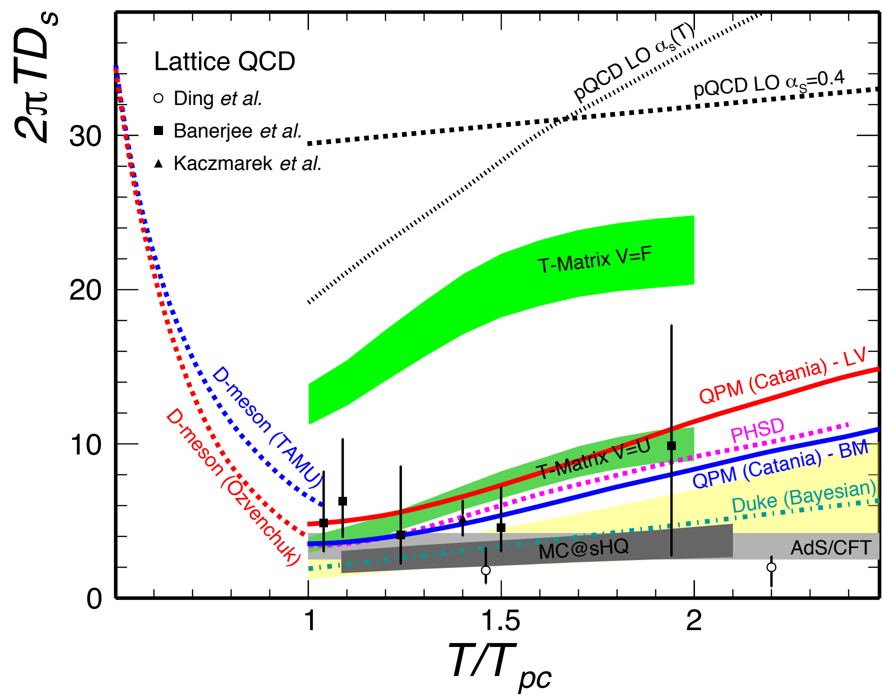
Chatterjee & Bozek, 1804.04893

D-meson v_1 sensitive to

- T dependence of HQ diffusion coefficient
- geometry tilt of the QGP source
- Initial magnetic field ($D/\overline{D}$ v_1 difference)

Bottom Quark: Cleaner Measure of HQ Diffusion

Is charm quark heavy enough?

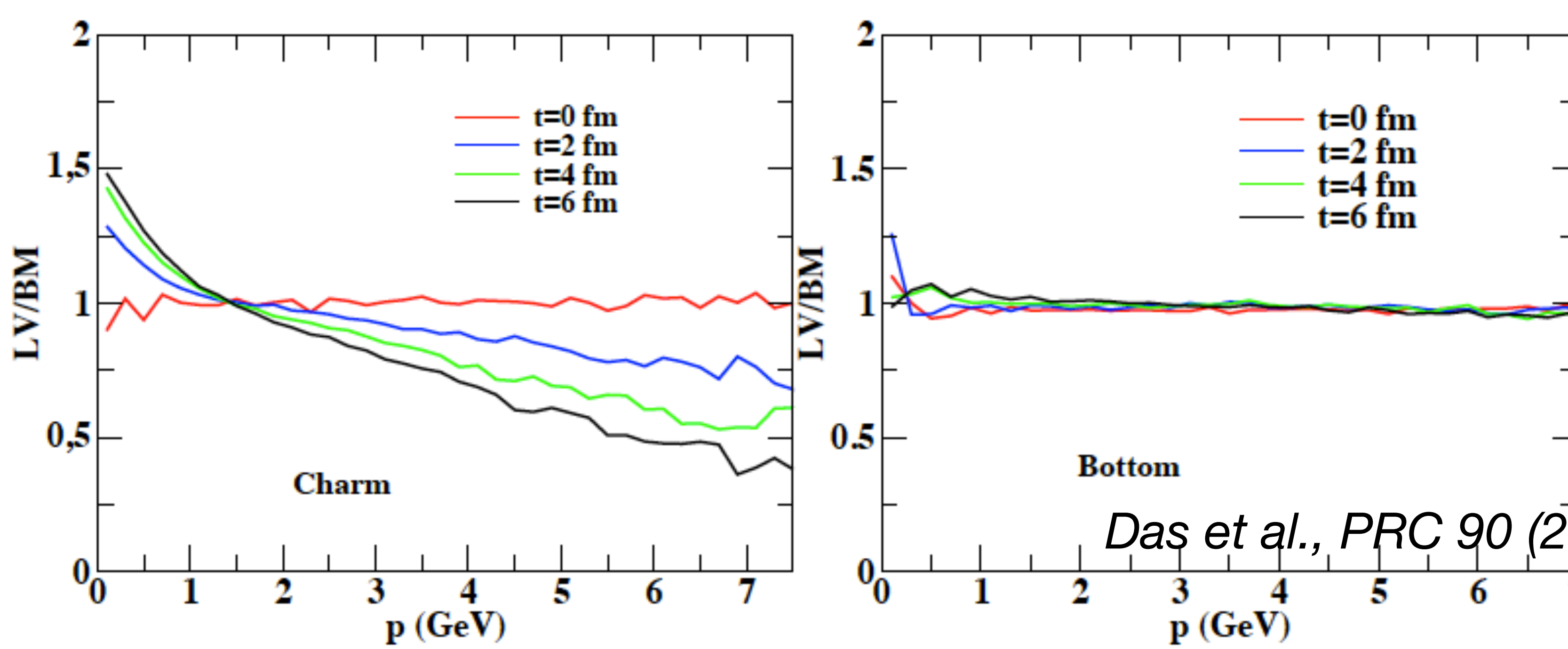


$2\pi TD_s \sim 2-5$ @ T_c

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

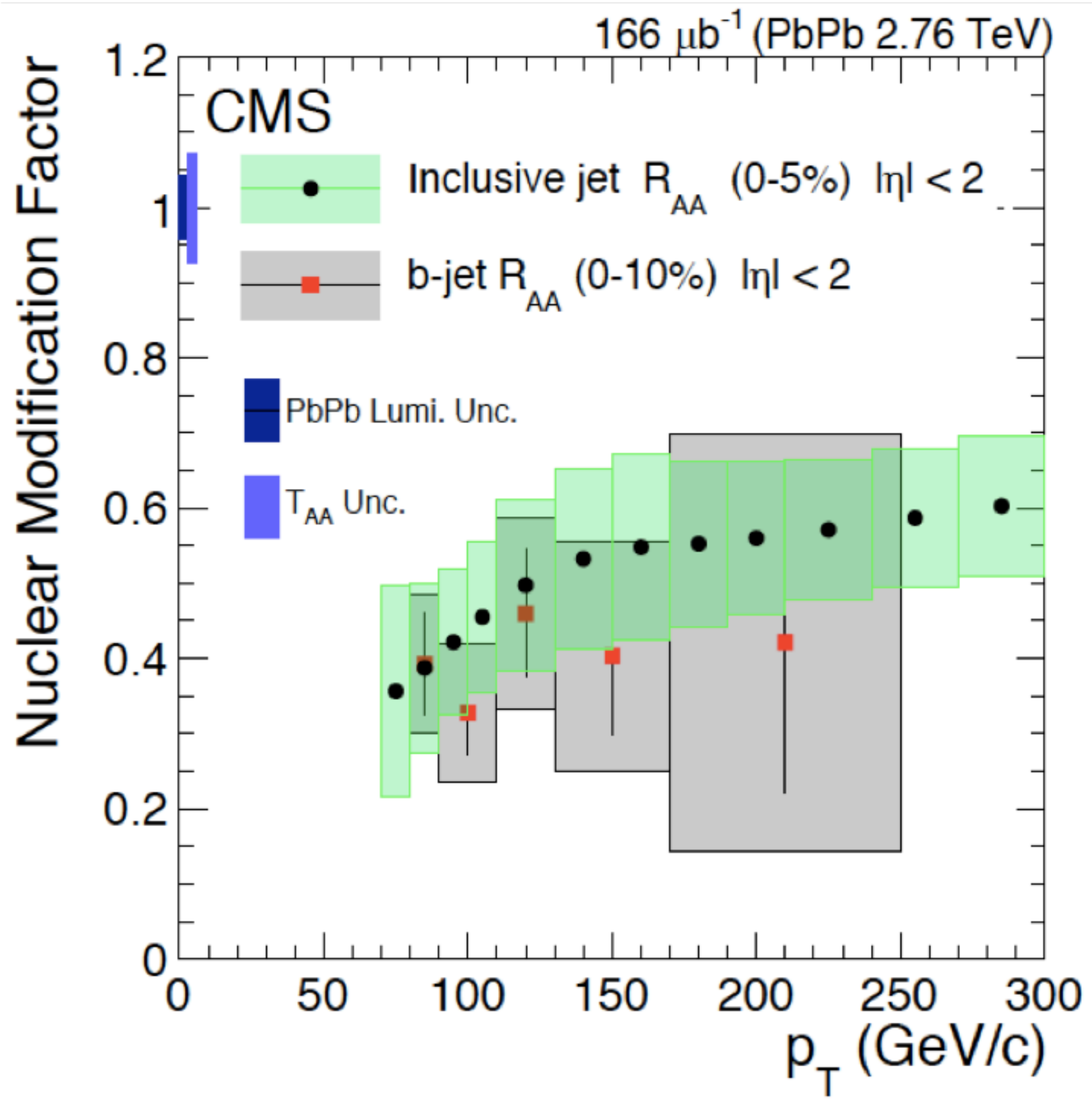
- comparable to charm quark mass

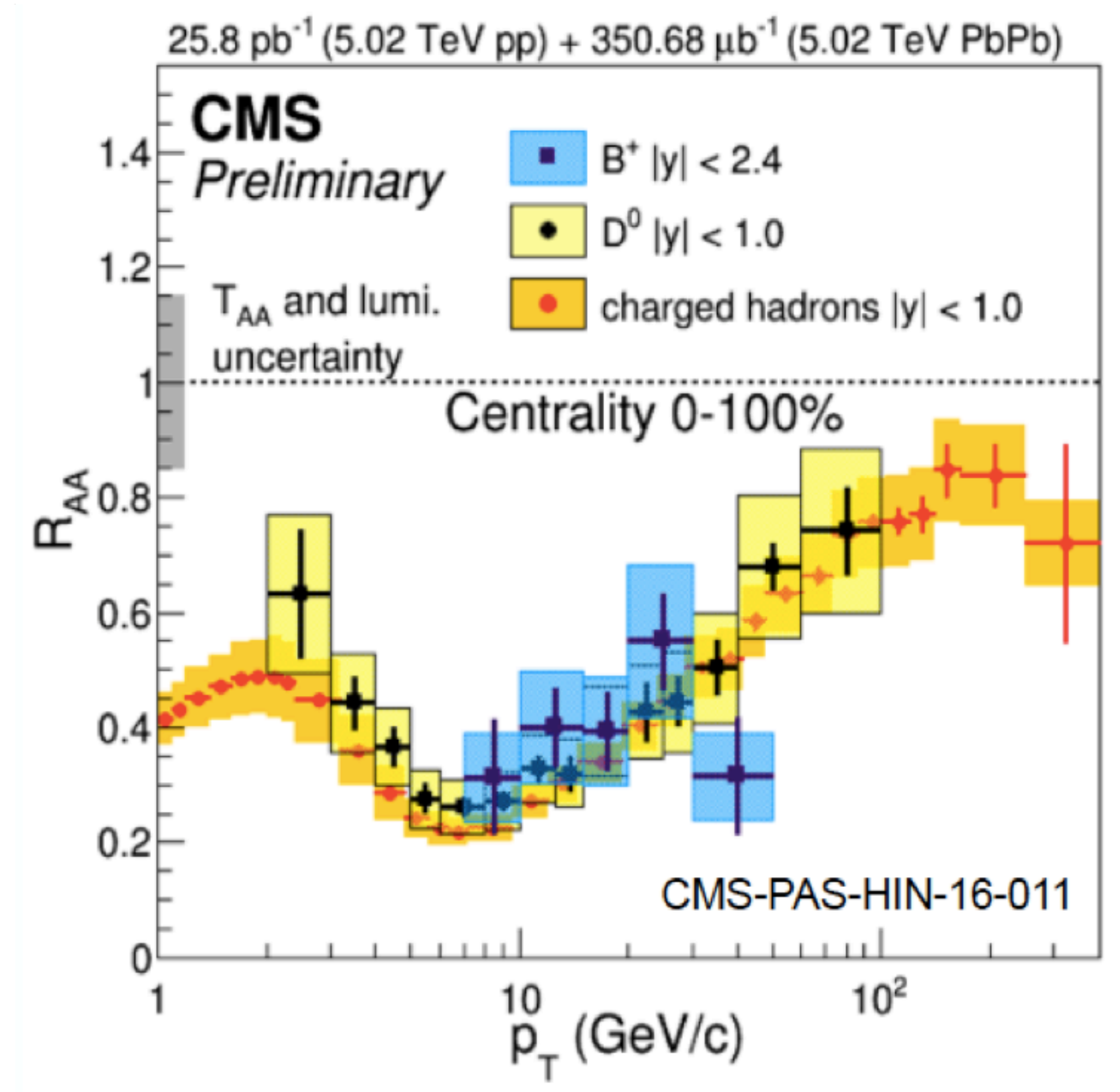
Sizable correction to Langevin approach for charm quarks



Das et al., PRC 90 (2014) 044901

b-jet and B+ Hadron at High p_T



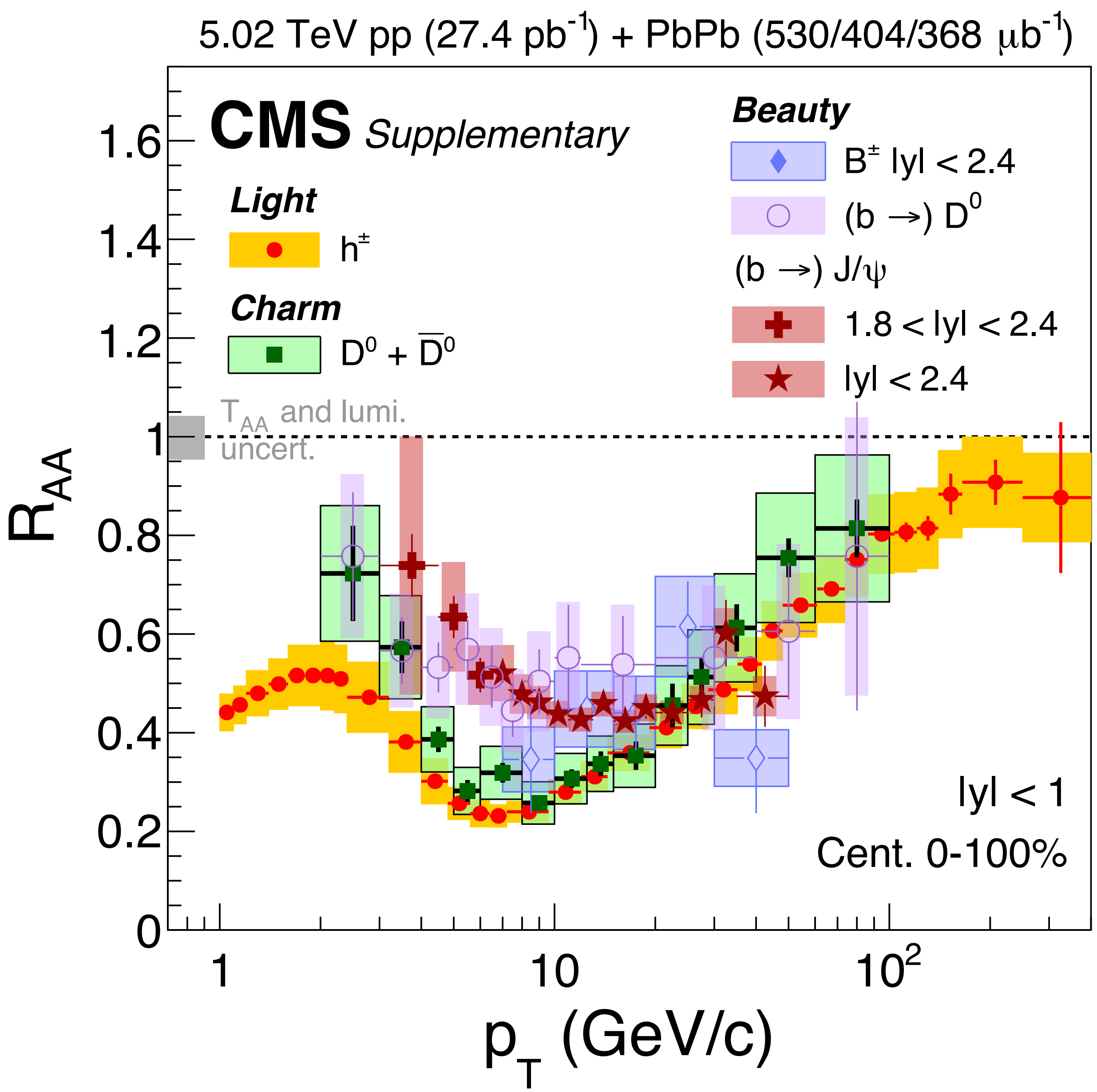


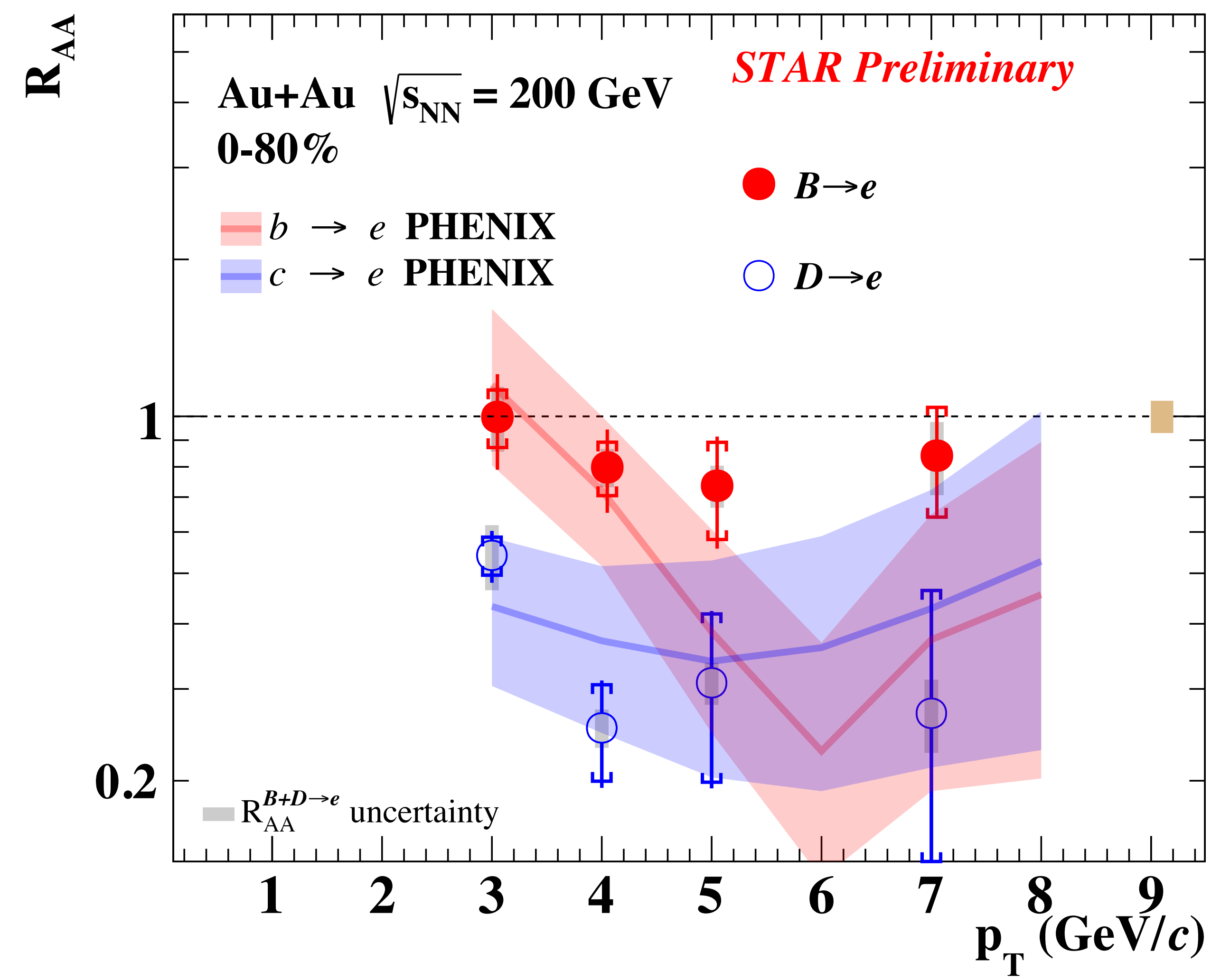
CMS, PRL 113 (2014) 132301, PRL 119 (2017) 152301

- R_{AA}(*b*-jet) ~ R_{AA}(incl. jet) at p_T > 70 GeV/c
- $R_{AA}(B^+)$ ~ R_{AA}(D) ~ R_{AA}(h) at p_T > 10 GeV/c

  mass hierarchy ? -> going to lower p_T

Bottom Suppression at Low p_T



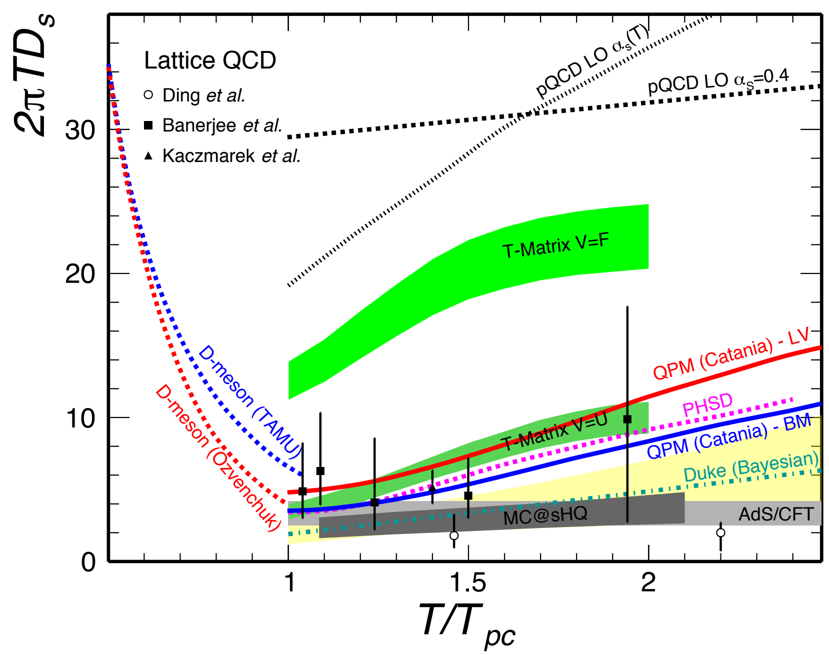


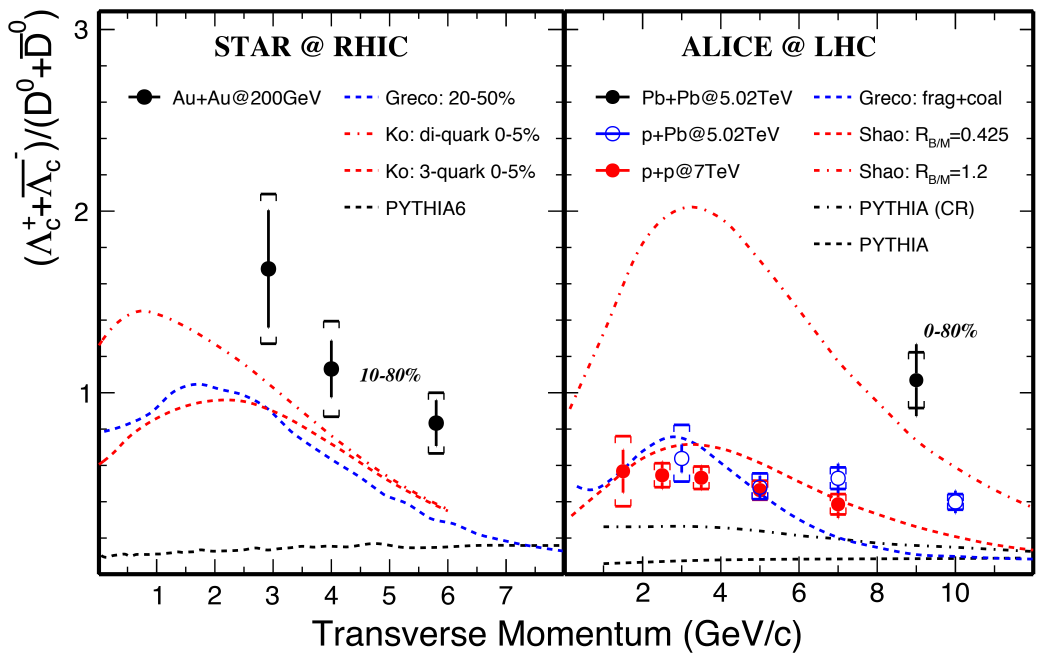
CMS, arXiv:1810.11102; STAR/PHENIX QM17

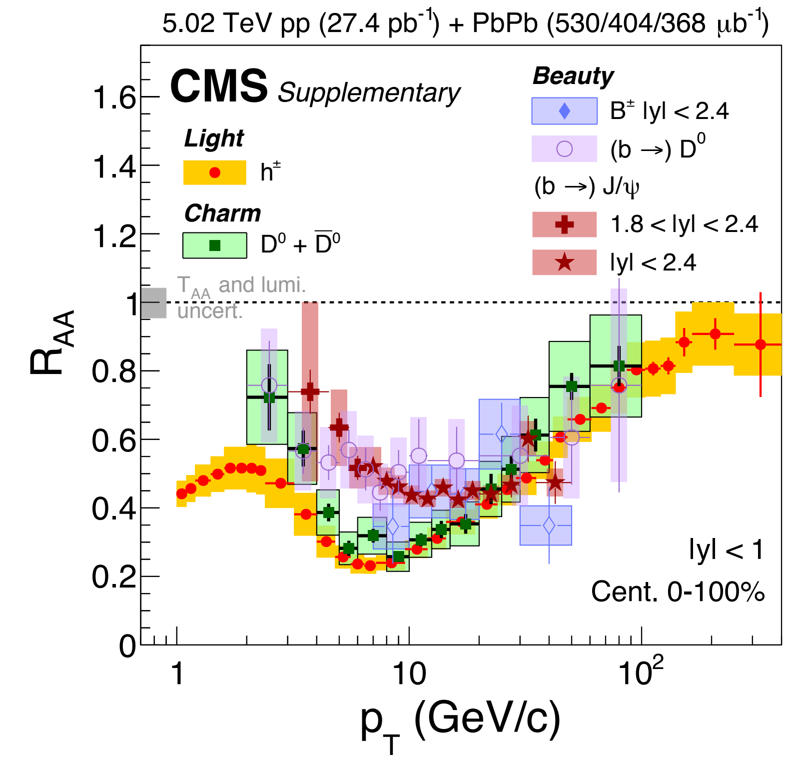
- LHC: $R_{AA}(J/\psi_B) \sim R_{AA}(D_B) > R_{AA}(D)$ at $p_T < 10$ GeV/c
- RHIC: $R_{AA}(e_B) < R_{AA}(e_D)$ at 3–8 GeV/c (2σ)

Mass hierarchy of parton energy loss

Summary







Significant charm hadron flow -> $2\pi TD_s \sim$ 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

$R_{AA}(B) > R_{AA}(D)$ at low p_T; ~ $R_{AA}(D)$ at high p_T -> mass hierarchy of energy loss

-> transition between collisional vs. elastic energy loss

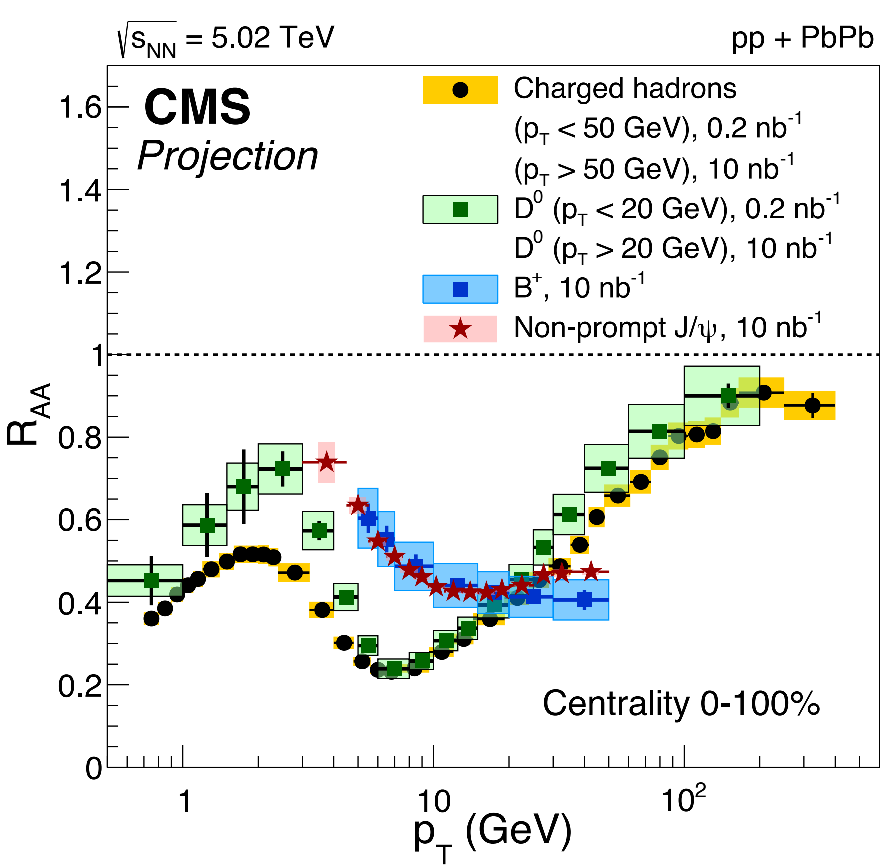
Prospective Heavy Flavor Program in Future

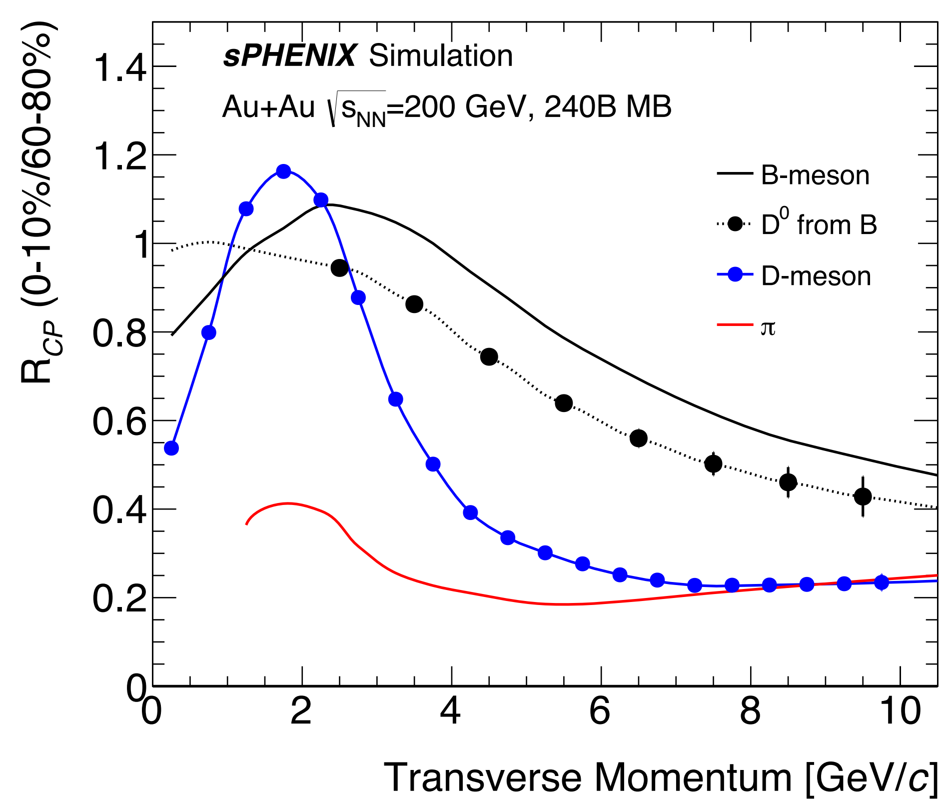
	2014	2015	2016	2017	2018	2019	2020	2021	2022+
RHIC	HF Phase-I			pp	CME	BES-II			HF Phase-II
LHC	LS1	Run-2				LS2		Run-3	

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

Precision open bottom

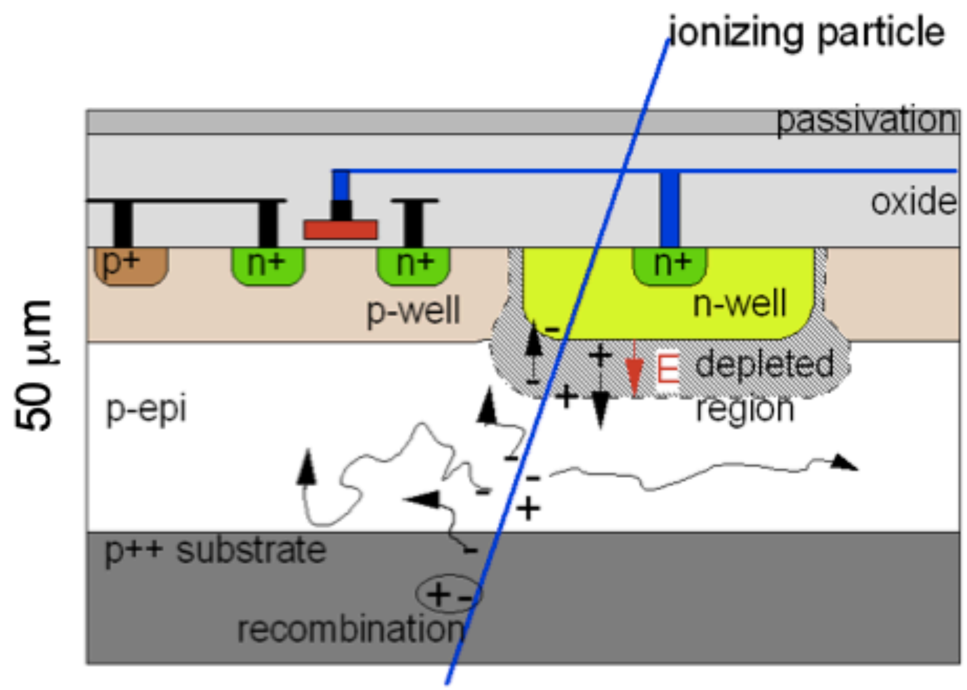
Heavy flavor baryons and correlations





Monolithic Active Pixel Sensor (MAPS)

MAPS pixel cross-section (not to scale)



Properties:

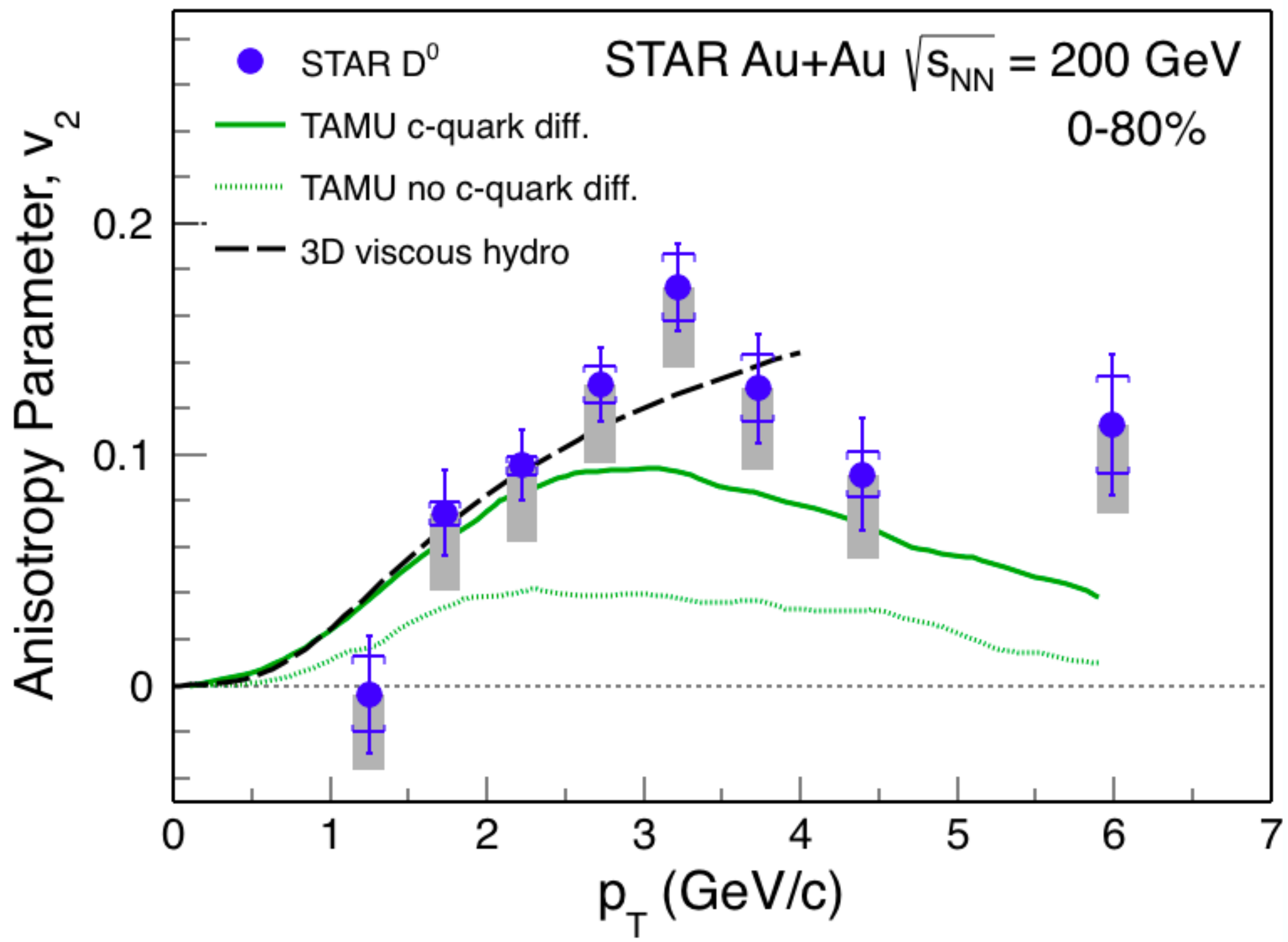
- Standard commercial CMOS technology
- Sensor and signal processing are integrated in the same silicon wafer
- Signal is created in the low-doped epitaxial layer (typically ~10-15 µm) → MIP signal is limited to <1000 electrons
- Charge collection is mainly through thermal diffusion (~100 ns), reflective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

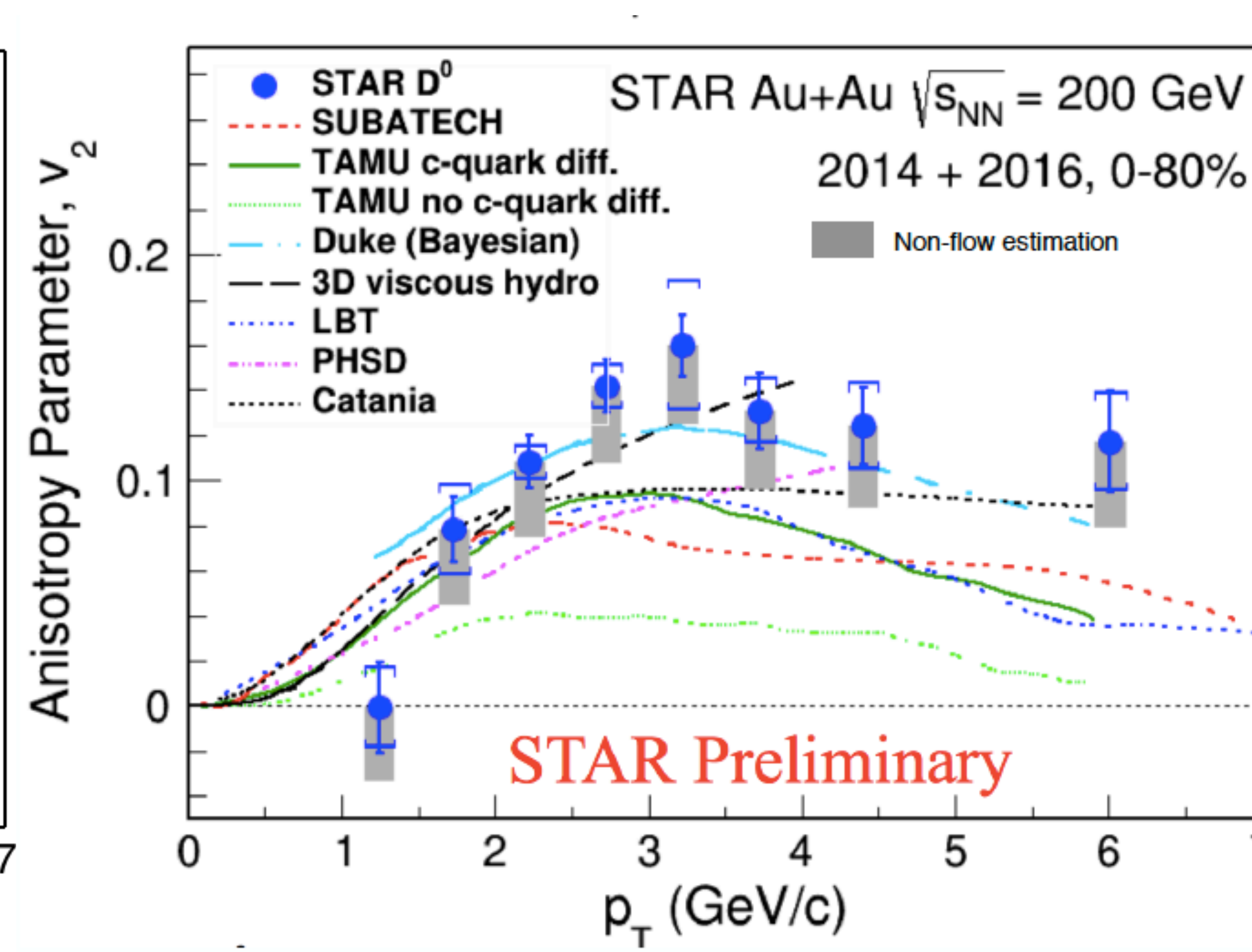
MAPS and competition	MAPS	Hybrid Pixel	CCD
Granularity	+	-	+
Small material budget	+	-	+
Readout speed	+	++	-
Radiation tolerance	+	++	-

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

See Xiangming Sun's talk (Sun.) for more applications

D^0 v_2 Compared with Models

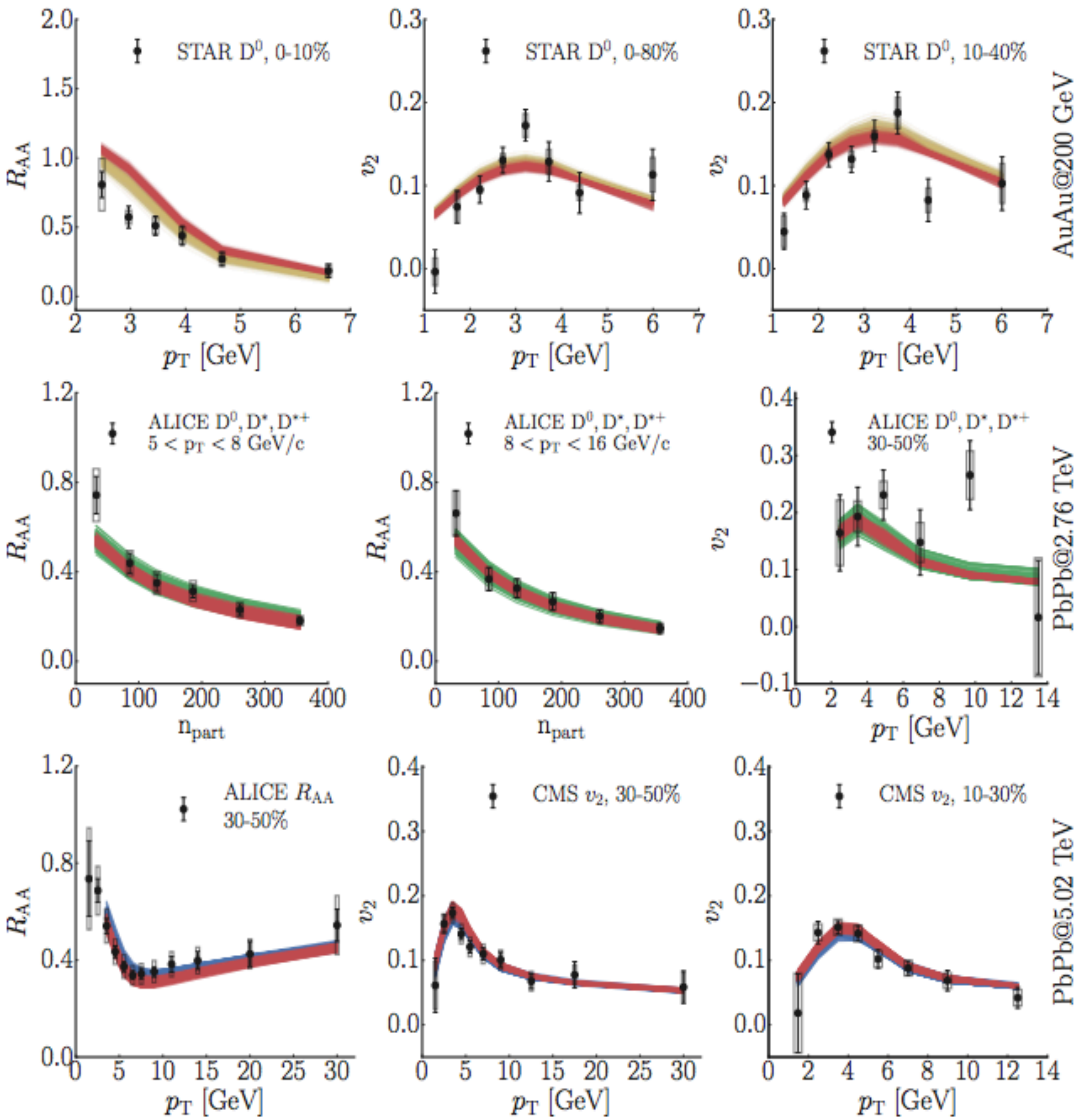




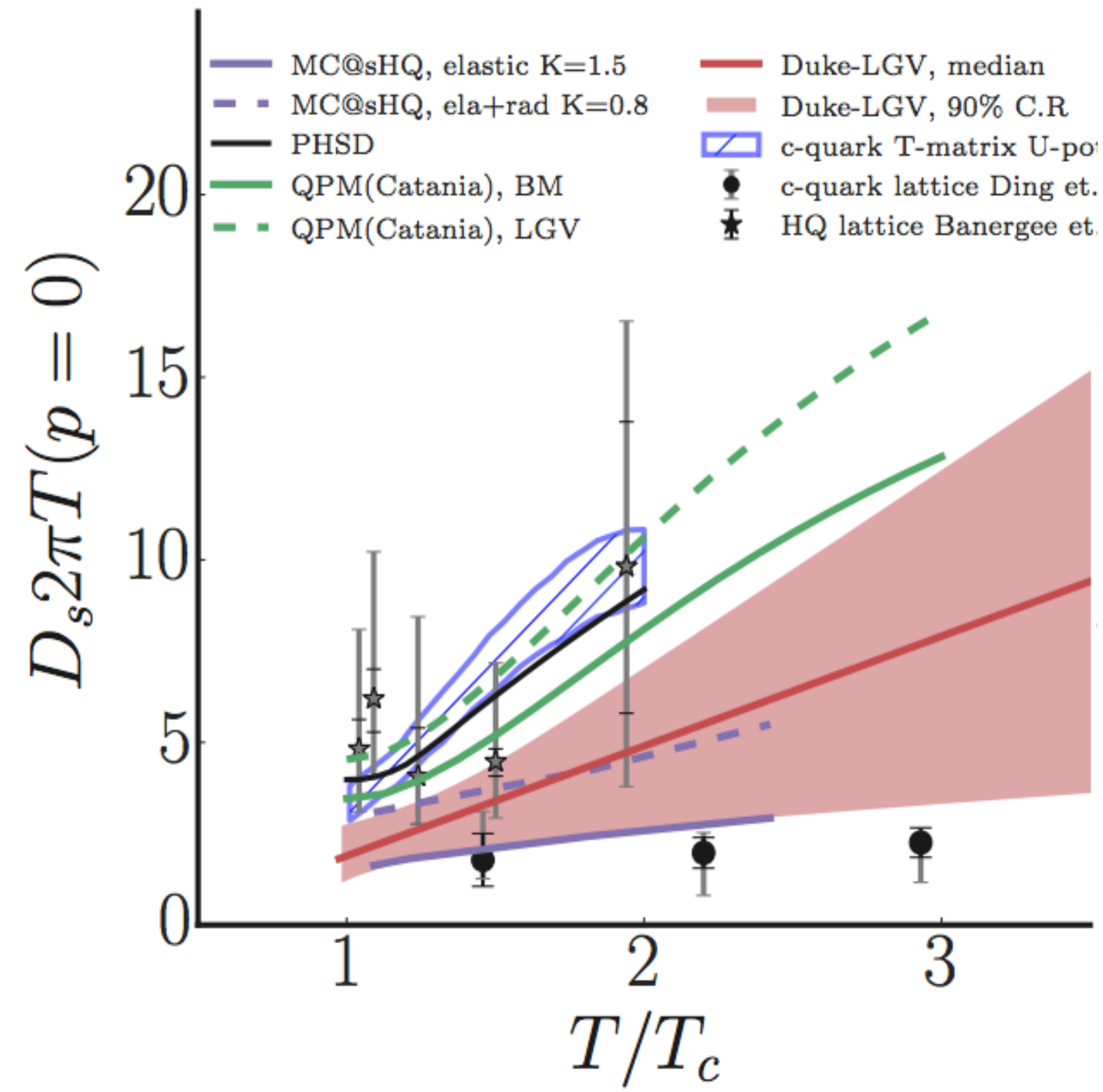
Compared Models	x2/NDF	p-value
SUBATECH [1]	17.3/8	0.026
TAMU c quark diff. [2]	12.0/8	0.15
TAMU no c quark diff. [2]	33.7/8	4.5×10^{-5}
Duke (Bayesian) [3]	8.5/8	0.39
3D viscous hydro [4]	3.7/6	0.71
LBT [5]	13.3/8	0.10
PHSD [6]	8.7/7	0.27
Catania [7]	9.7/8	0.29

- D^0 v_2
  <-> Charm quark diffusion in QGP
- Provide strong constraints to model calculations

Bayesian Analysis to Extract HQ Diffusion Coefficient



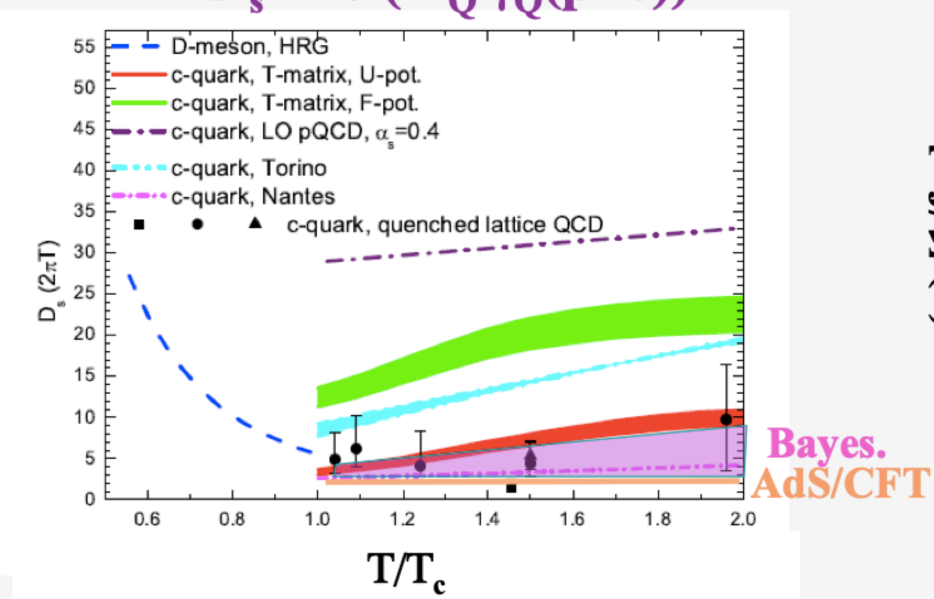
Bayesian analysis based on Duke model:
Langevin + Hydro

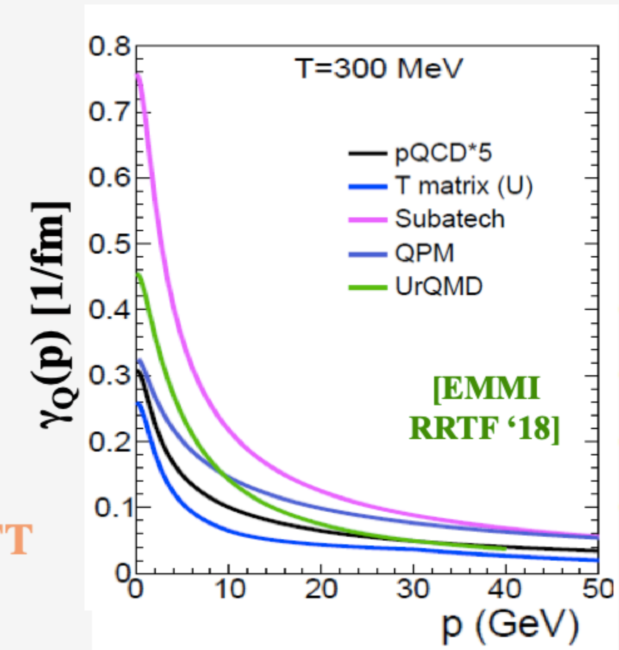


Y. Xu et al, PRC 97 (2018) 014907

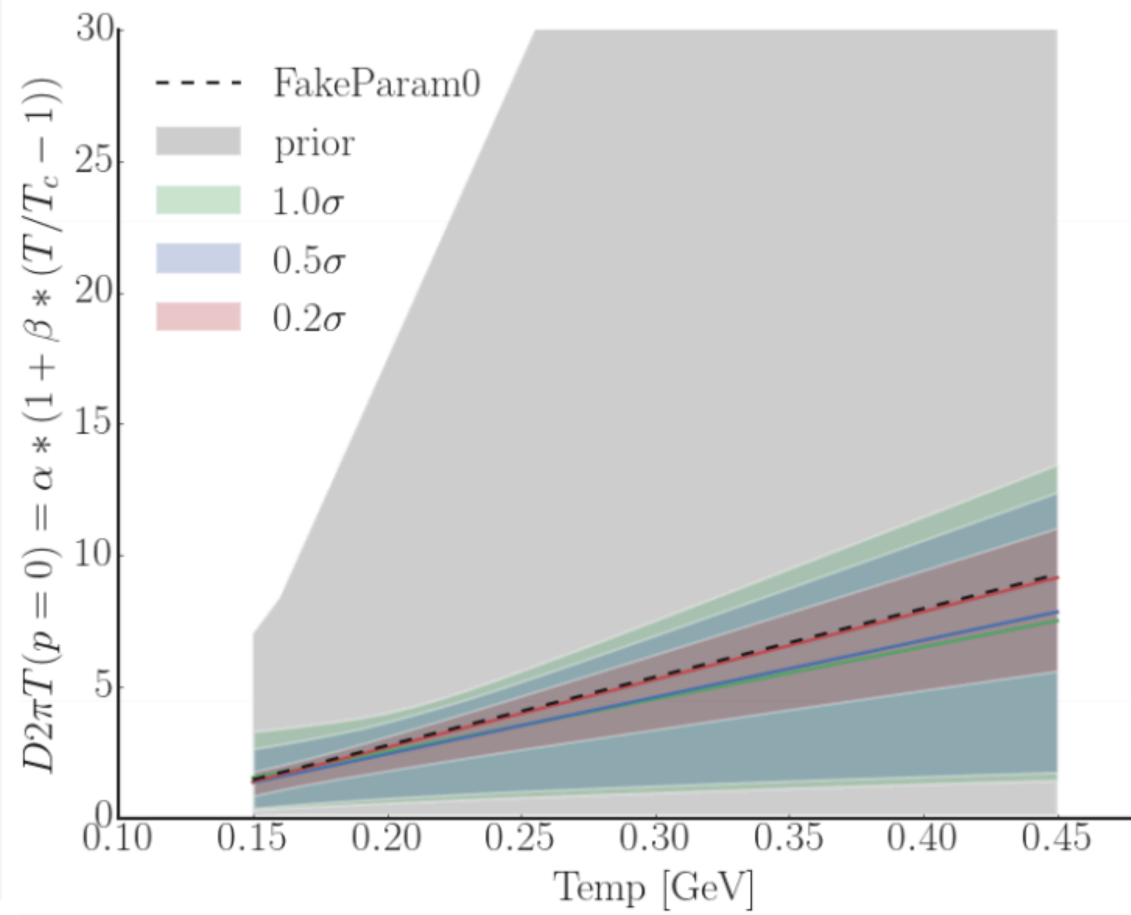
HQ Diffusion Coefficient

$\mathcal{D}_s = T / (m_Q \gamma_Q(p=0))$





- suggests minimum of $\mathcal{D}_s(2\pi T) \sim$ 2-4 near T_{pc}
- scatt. rate: $\Gamma_{coll} \sim 3/\mathcal{D}_s \sim 1$ GeV – no light quasi-particles!
- T- and p-dependence reflect core property of QCD



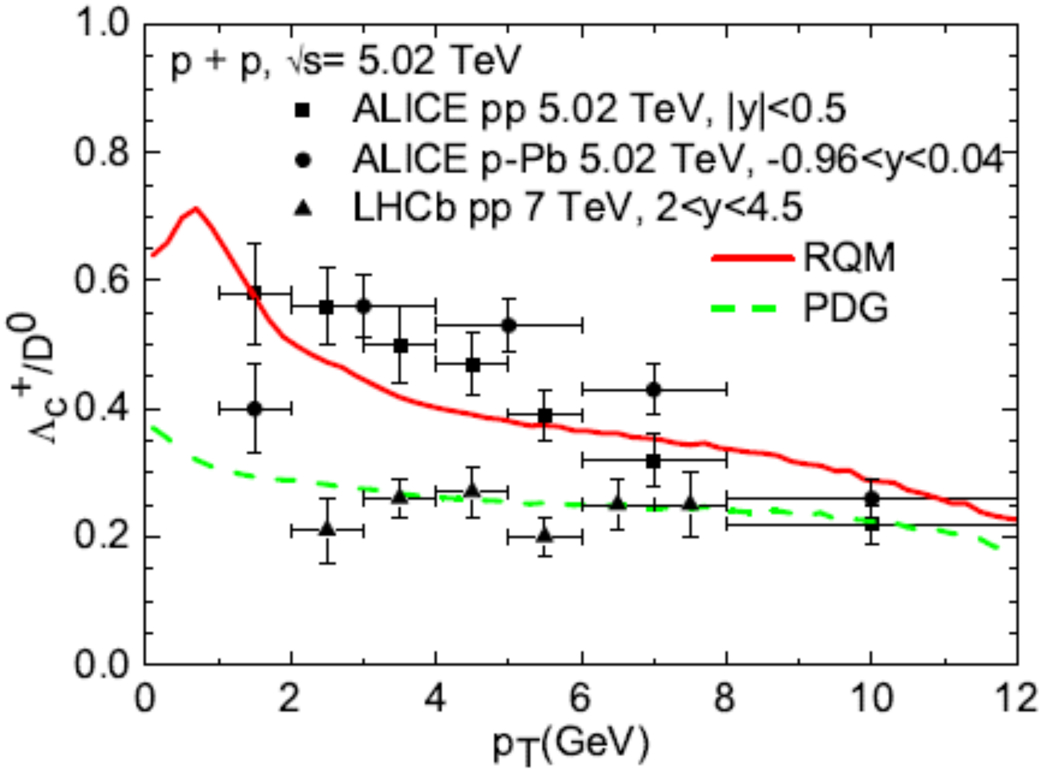
R. Rapp, HF workshop@LBNL

W. Ke, Bayesian projection

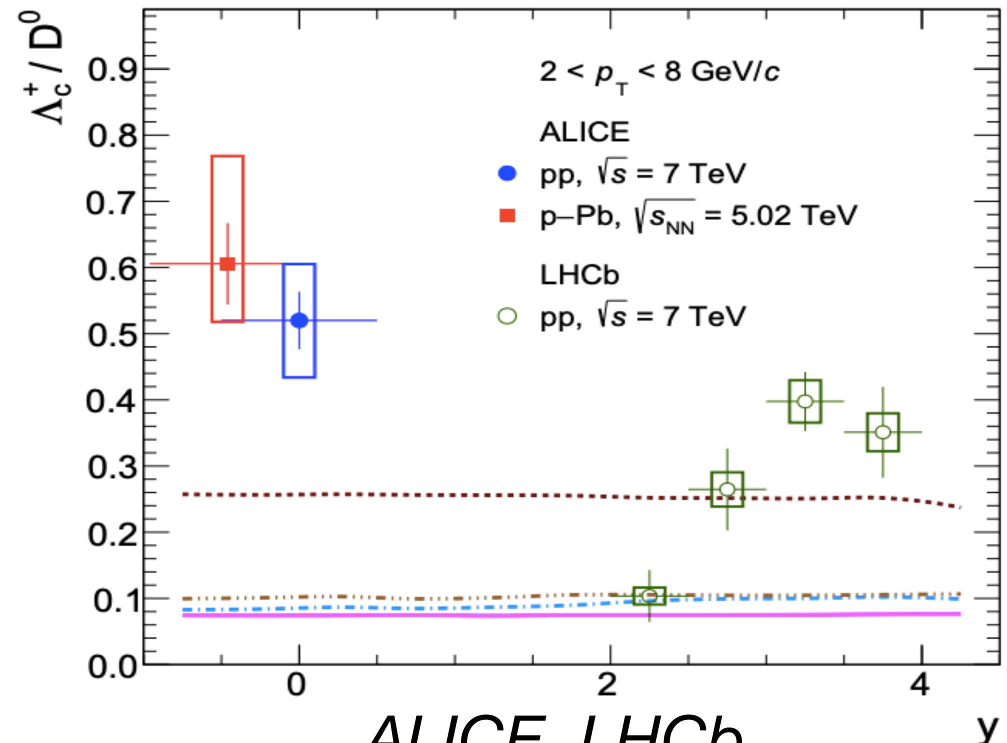
What is the p- and T- dependence of HQ diffusion coefficient?

How will bottom measurement help determine HQ diffusion coefficient?

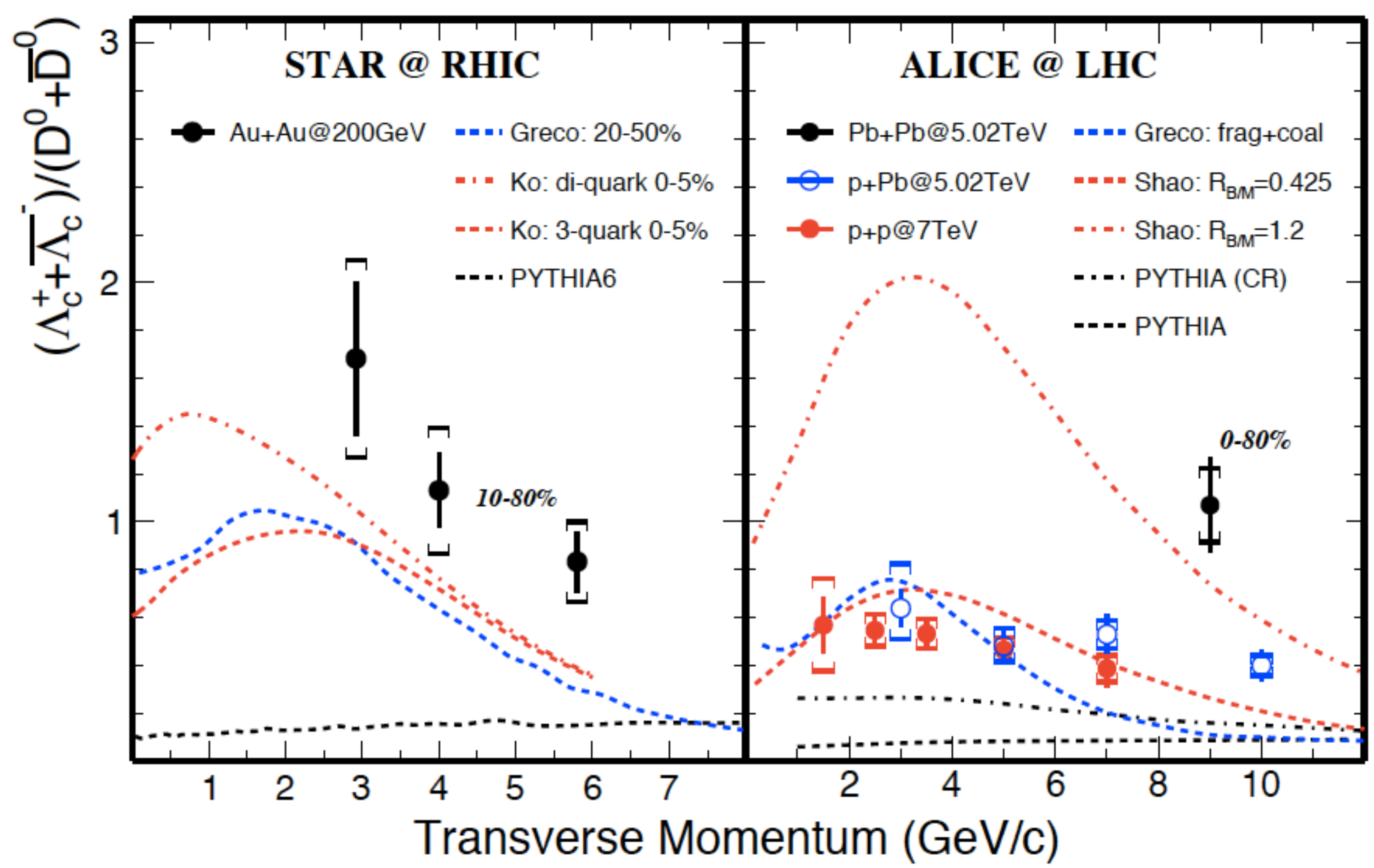
Λ_c Baryon



He and Rapp, 1902.08889



ALICE, LHCb



Does Λ_c yield go beyond SHM limit?