Open Heavy Flavor Production at RHIC

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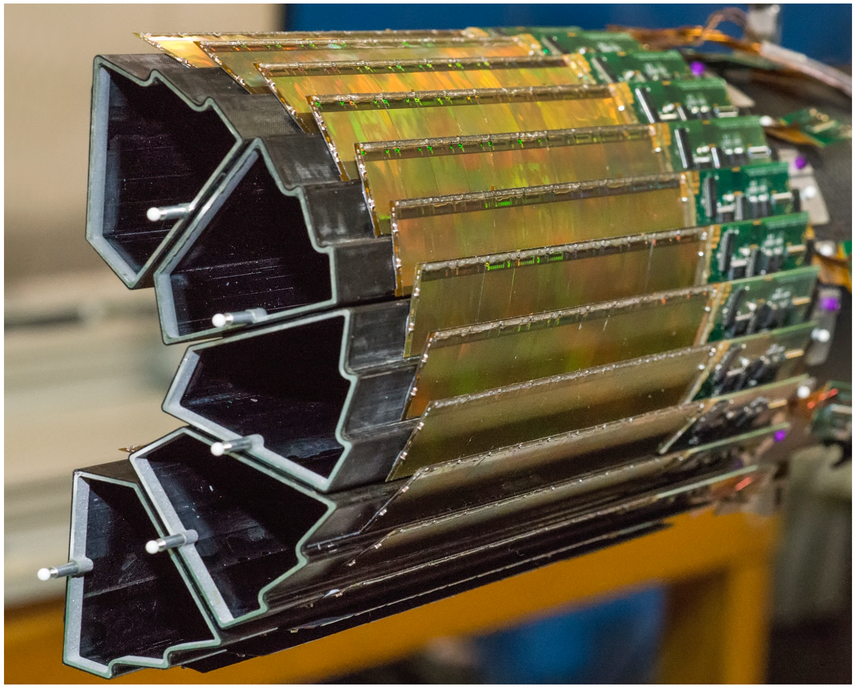
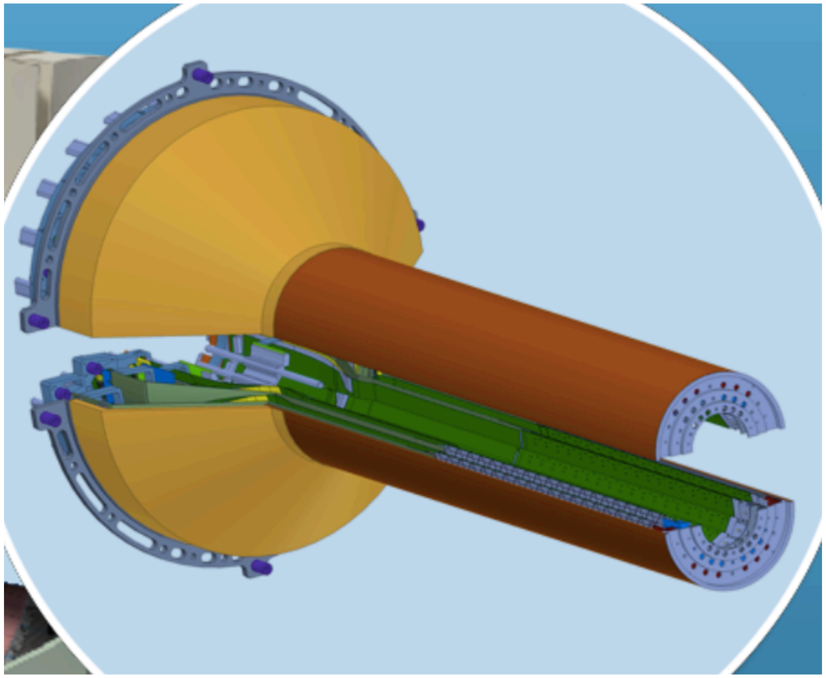
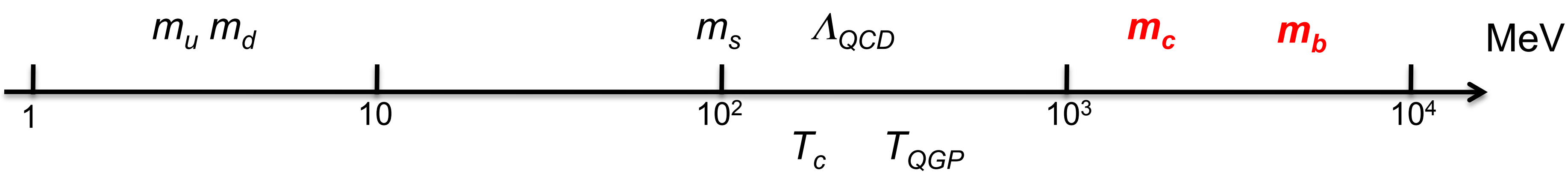


STAR PXL (2014-2016)



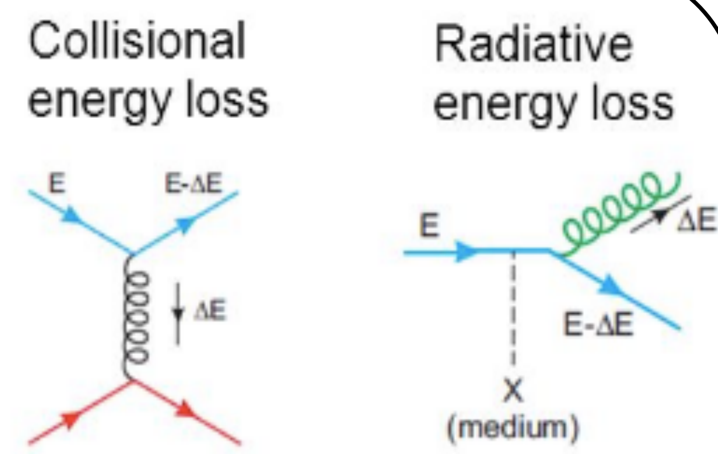
sPHENIX MVTX (2023+)

Uniqueness of Heavy Quarks in QCD



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

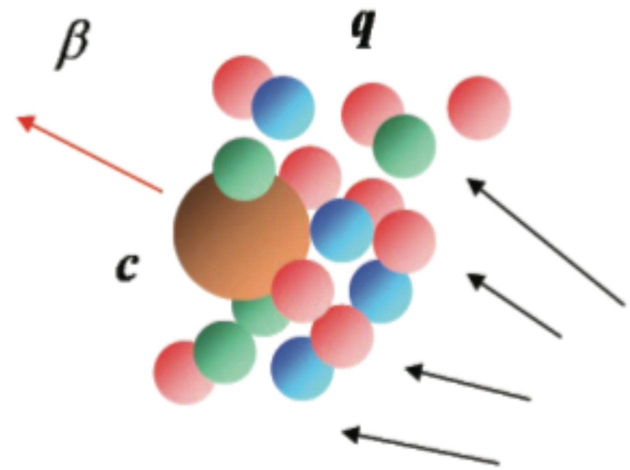
$m_{c,b} >> T_{QGP}$ *predominately created from initial hard scatterings*



Heavy quarks

- sensitive to

different energy loss mechanisms



When $M_{HQ} >> T$, $M_{HQ} >> gT$

"Brownian" motion

→ Langevin simu.

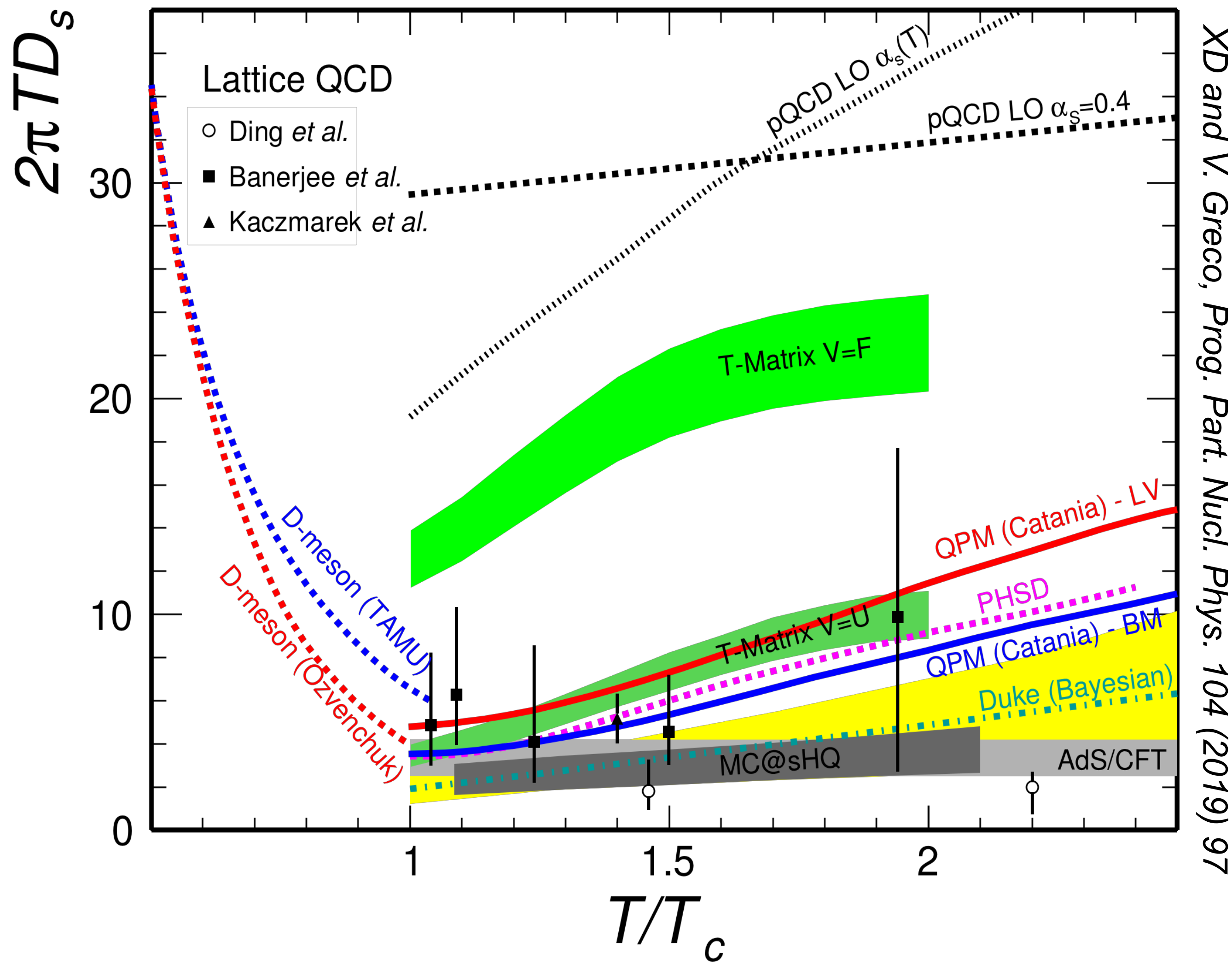
$$\frac{dp^i}{dt} = -\eta_D p^i + \xi^i(t),$$

Heavy quark transport – to probe QGP with comprehensive p_T coverage

- unique insights to both perturbative and non-perturbative regimes

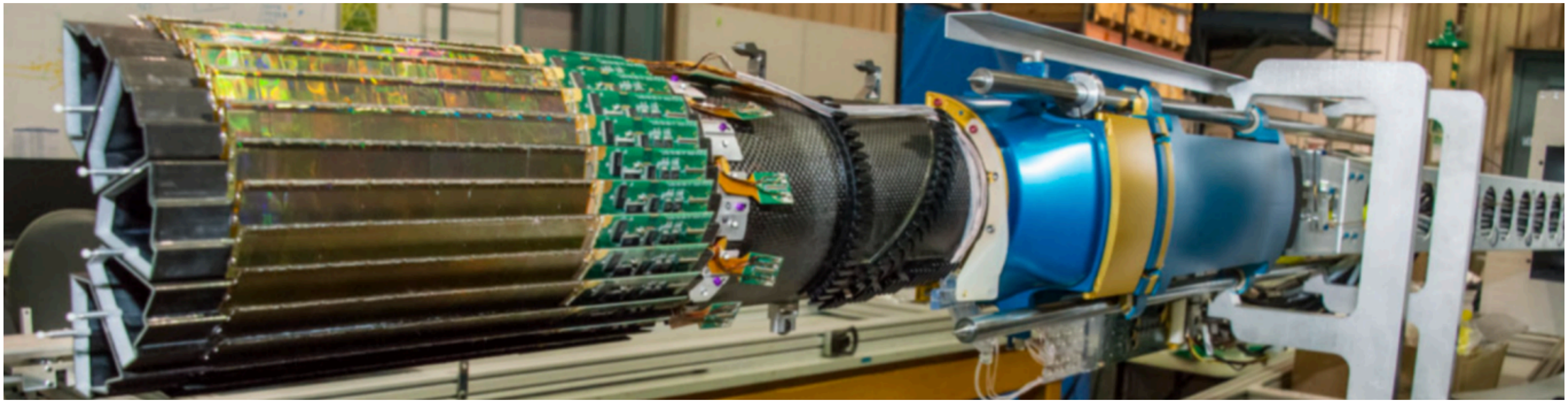
Physics Goals of Heavy Quark Measurements in HIC

$$D_s = \frac{T}{M_Q \eta_D (p=0)} \qquad D_s(2\pi T) \sim \eta / s \sim \sigma_{EM} / T$$



Wide momentum coverage, particularly down to low p_T, is crucial!

STAR Heavy Flavor Tracker

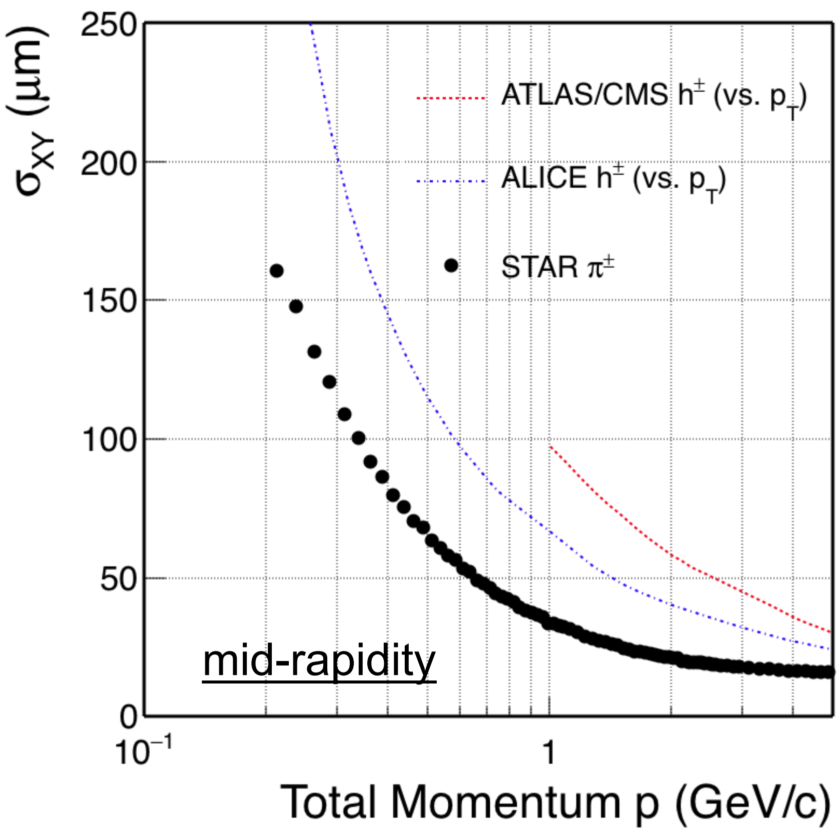


Detector	Radius (cm)	Pitch Size R/φ - Z (μm - μm)	Thickness
Silicon **S**trip **D**etector	22	95 / 40000	1% X_0
Intermediate **S**ilicon **T**racker	14	600 / 6000	1.3%X_0
PiXeL	8	**20.7 / 20.7**	0.5%X_0
	2.8	**20.7 / 20.7**	**0.4%X_0** *

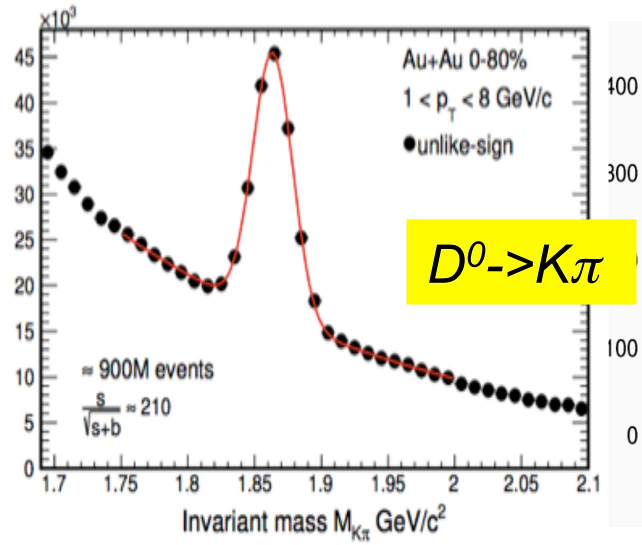
** 0.5%X_0 in Run14*

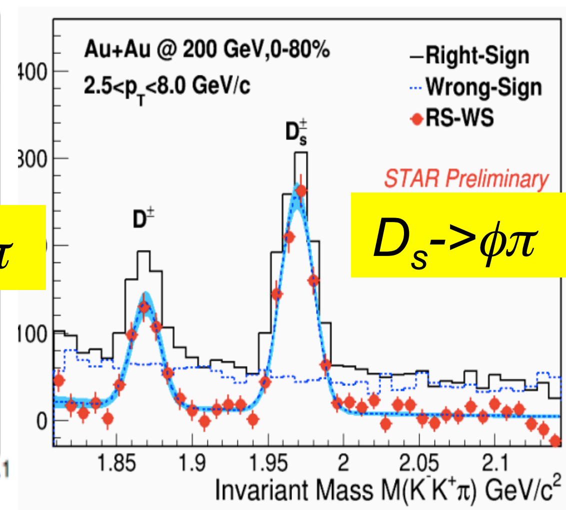
- Ultimate position resolution and solid mechanical support
- Thin detector material for superior pointing resolution over a broad p_T region

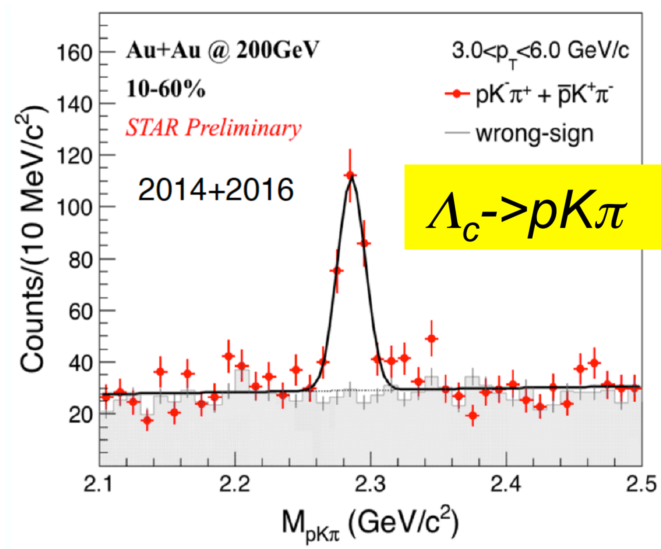
Pixel Detector Performance



Exclusive reconstruction of HF hadrons in heavy-ion collisions

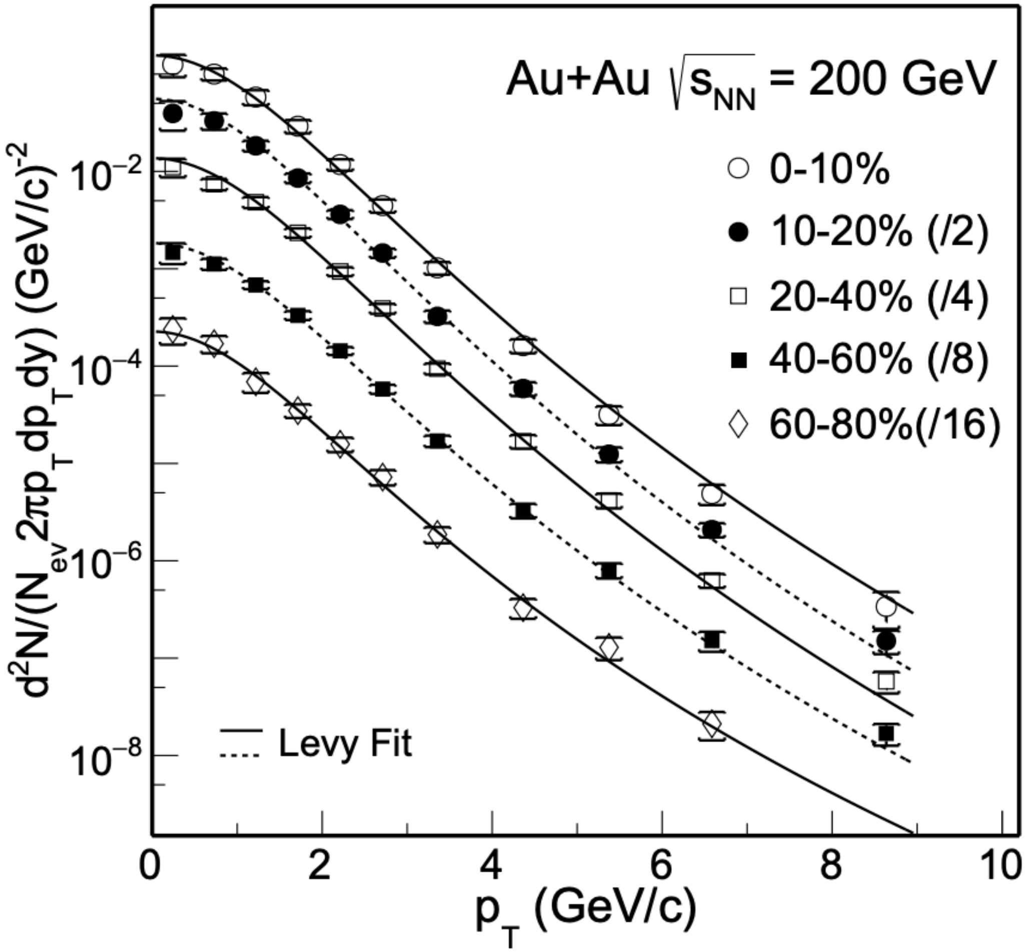


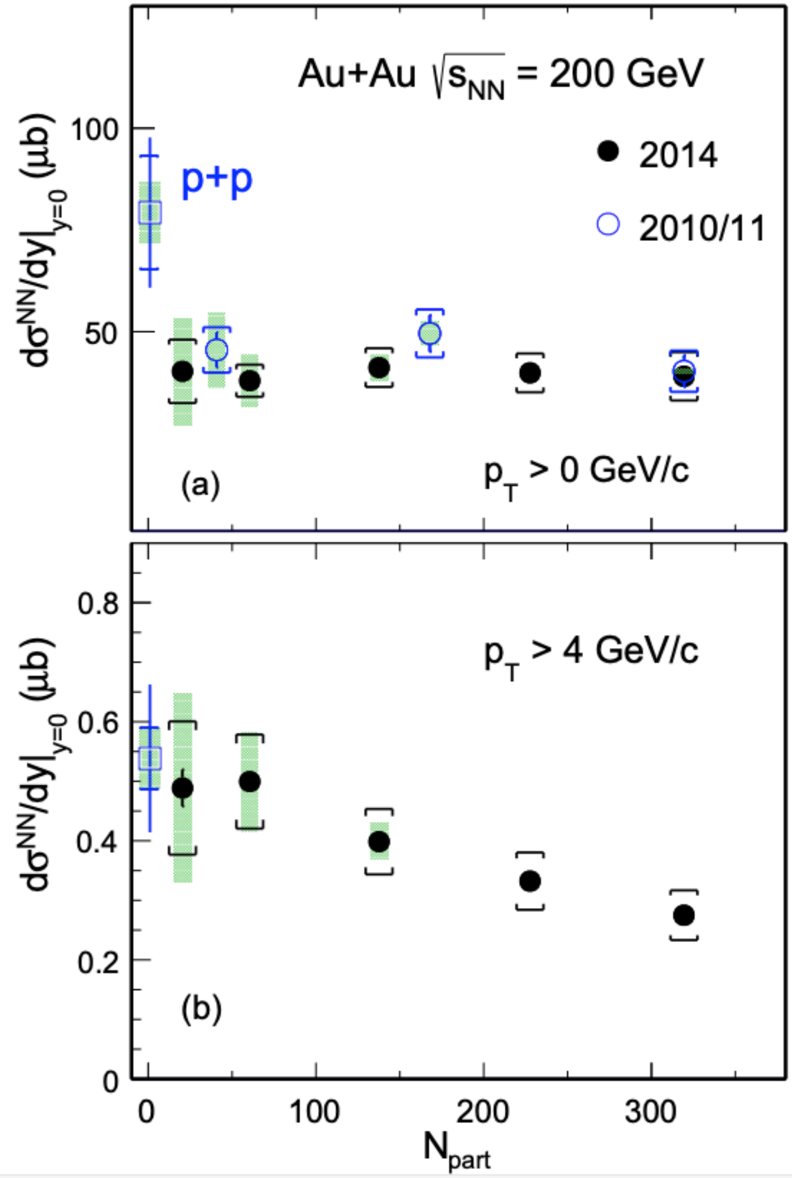




STAR	30 μm @ 1 GeV/c (p)
ALICE	70 μm @ 1 GeV/c (p_T)
ATLAS/CMS	100 μm @ 1 GeV/c (p_T)

D^0 Meson Production in Au+Au Collisions

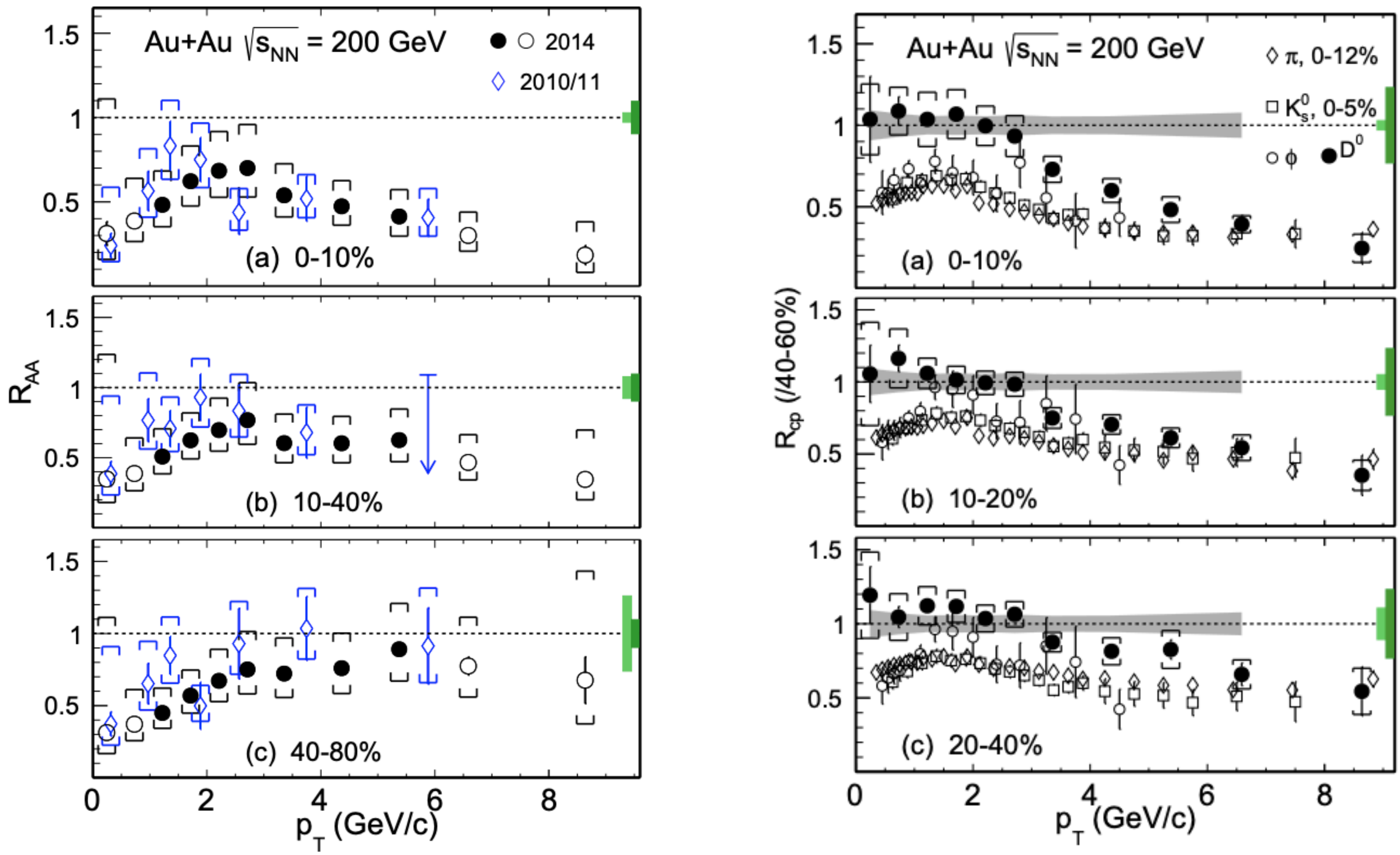




- D^0 p_T-integrated X-section in central Au+Au is smaller than that in p+p collisions
- D^0 int. X-section at p_T>4 GeV/c decreases from p+p to central Au+Au collisions

STAR, arXiv:1812.10224

Nuclear Modification Factors



R_{AA} <~1 in all p_T regions

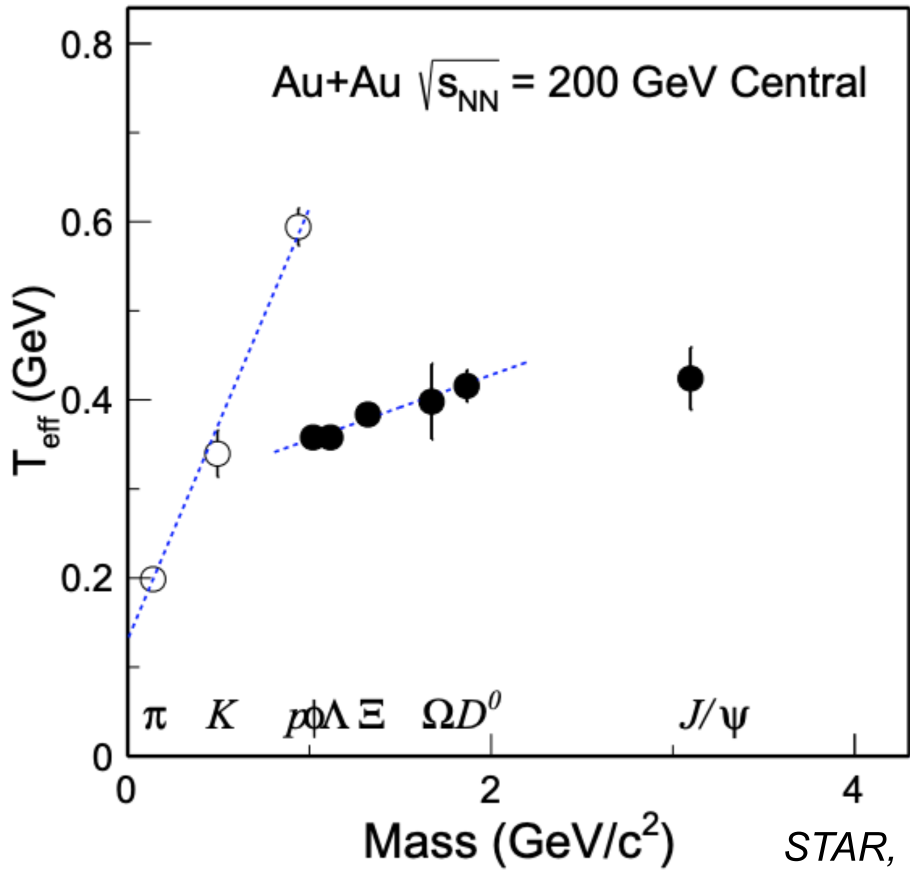
STAR, arXiv:1812.10224

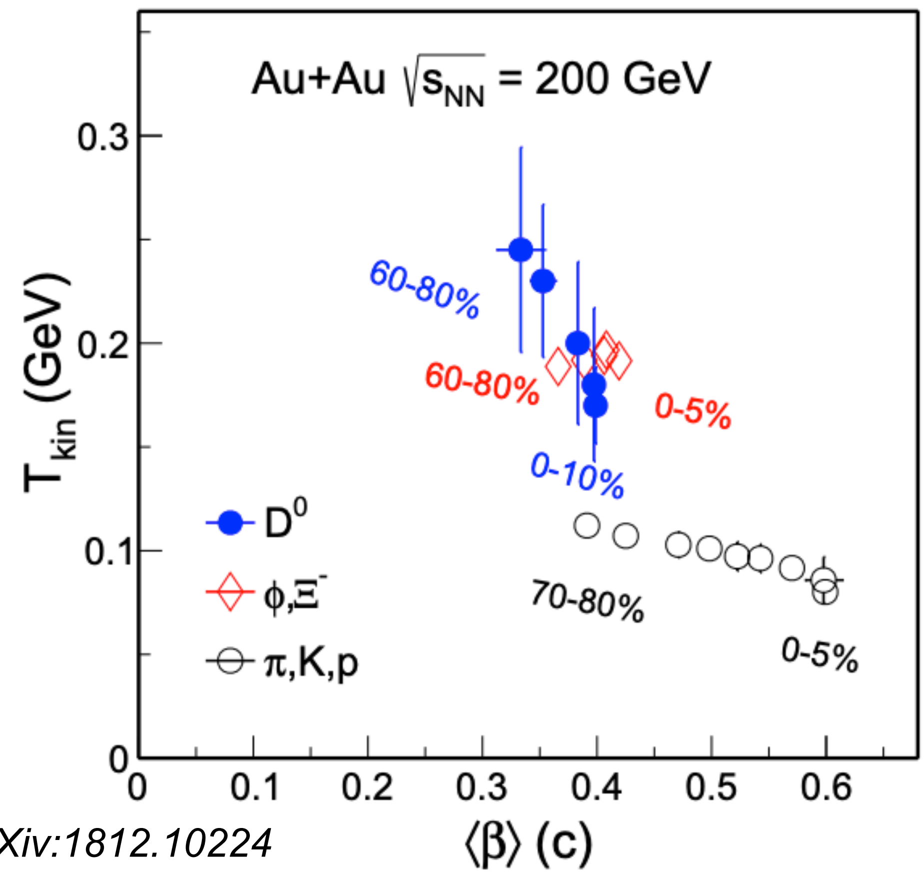
– *uncertainties dominated by p+p reference*

R_{cp} (X/40-60%) suppression at high p_T, smaller in semi-central collisions

- *$R_{cp}(D^0)$ ~ R_{cp} (ϕ) > $R_{cp}(\pi,K_s)$ at p_T <~ 6 GeV/c*
- *reasonably described by LBT/Duke models*

Charm Hadron Radial Flow





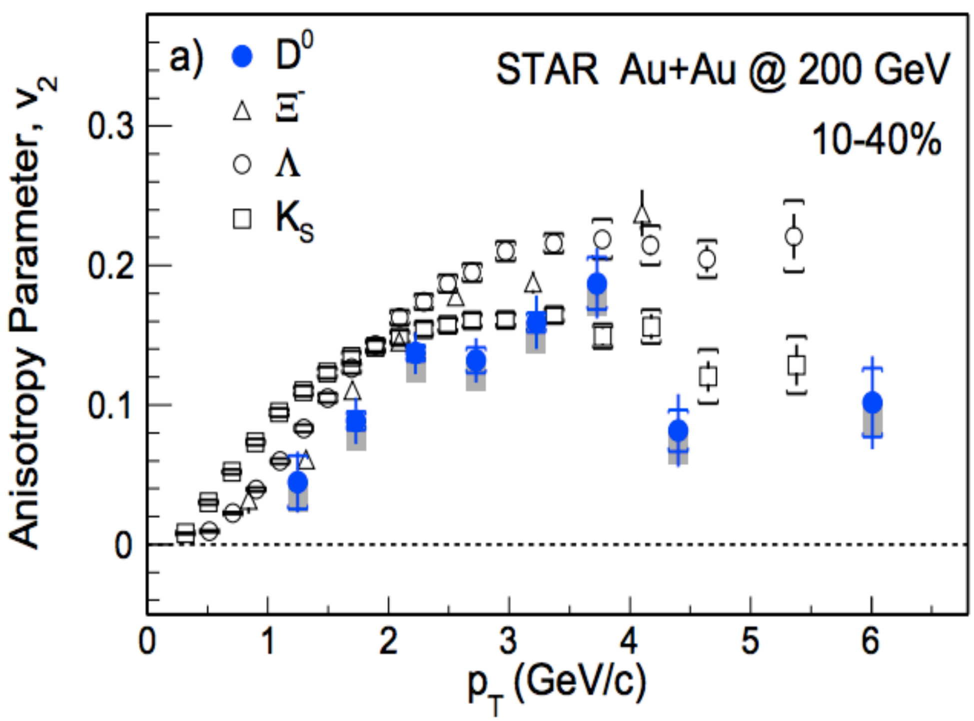
STAR, arXiv:1812.10224

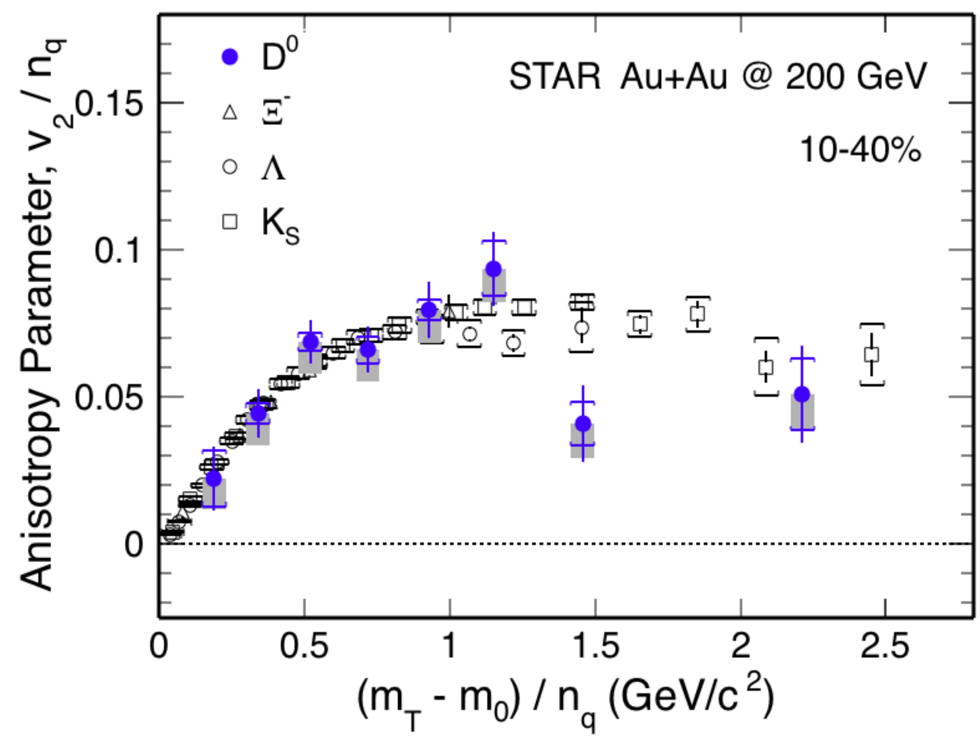
- T_{eff} slope parameter follows the same trend as multi-strange hadrons
- Blast-Wave model fits:

  $T_{kin}(D^0) \sim T_{kin}(\phi,\Xi) > T_{kin}(\pi,K,p)$ and $\beta(D^0) \sim \beta(\phi,\Xi) < \beta(\pi,K,p)$

  → Early freeze-out for D^0 mesons from the fireball

Charm Hadron v_2 at RHIC





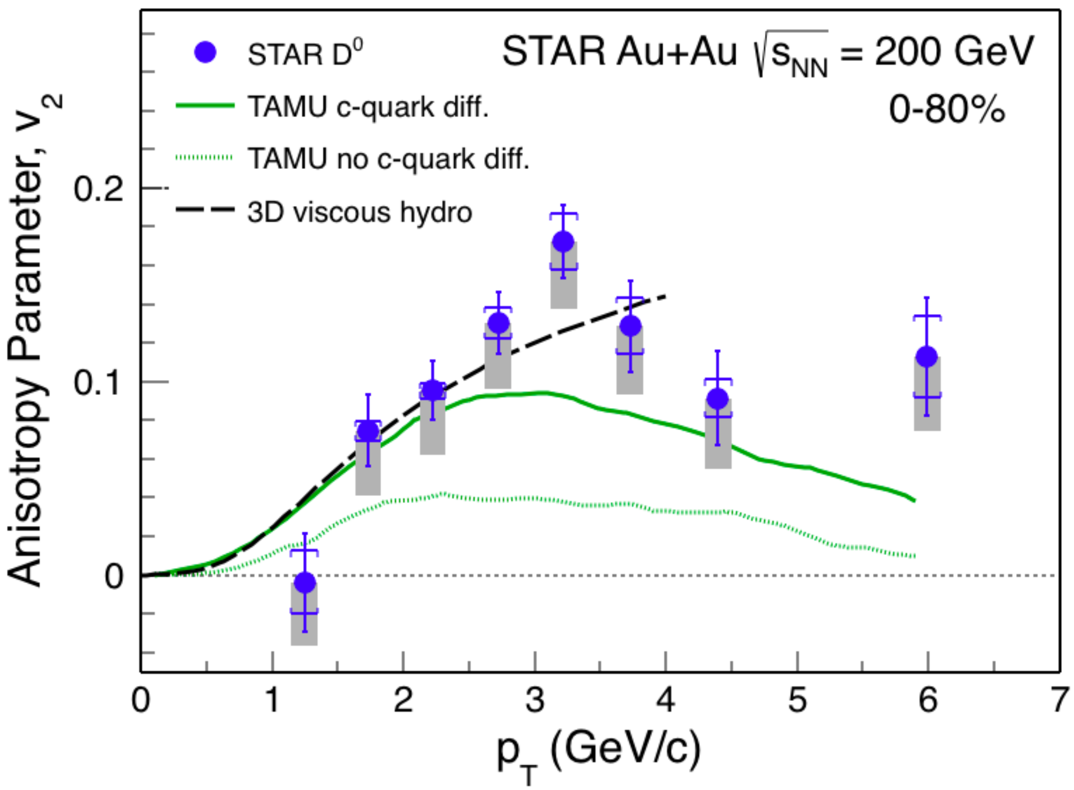
STAR, PRL 118 (2017) 212301

- 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

Charm Hadron v_2 Compared to Theory Models

STAR, PRL 118 (2017) 212301



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 x10^{-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

[1] **SUBATECH:** *Phys Rev C 90, 054909 (2014), Phys Rev C 92, 014910 (2015)*
[2] **TAMU:** *Phys Rev C 86, 014903 (2012), Phys Rev Lett 110, 112301 (2013)*
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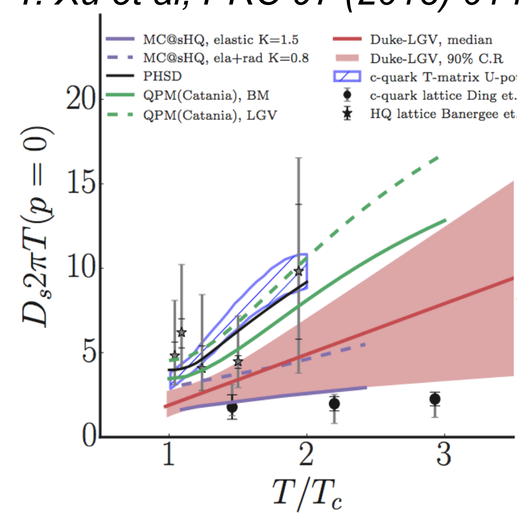
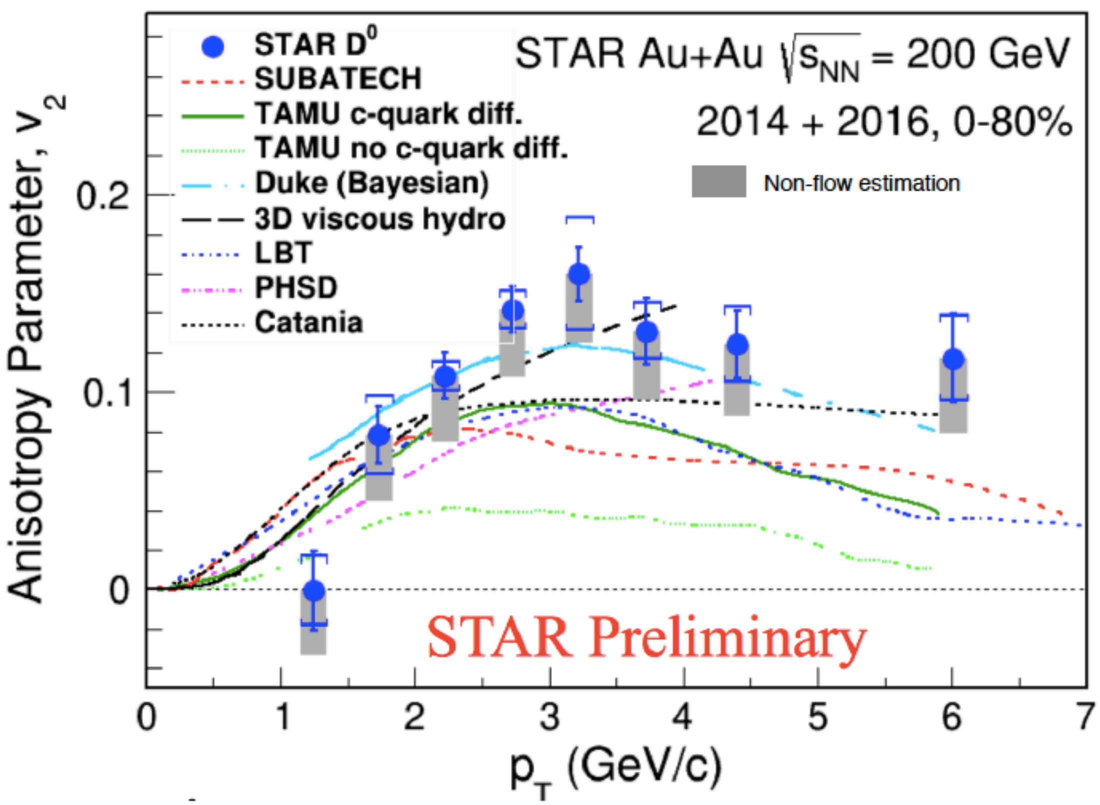
Bayesian analysis
Y. Xu et al, PRC 97 (2018) 014907



- High v_2 data precision offers stringent constraints to model calculations
- Sensitivity to sQGP transport parameter $\boldsymbol{2\pi TD_s}$ and its temperature dependence

Charm Hadron v_2 Compared to Theory Models

2014+2016 Dataset



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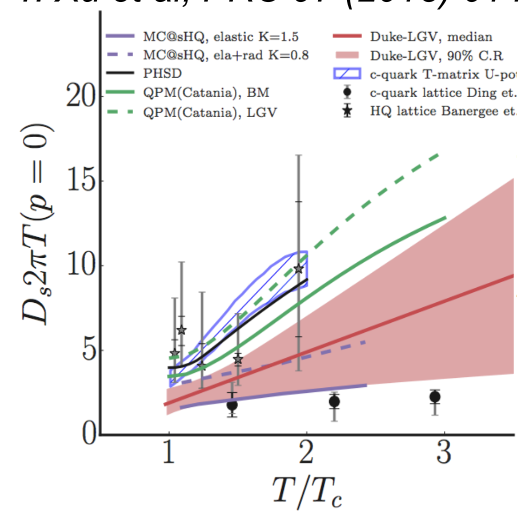
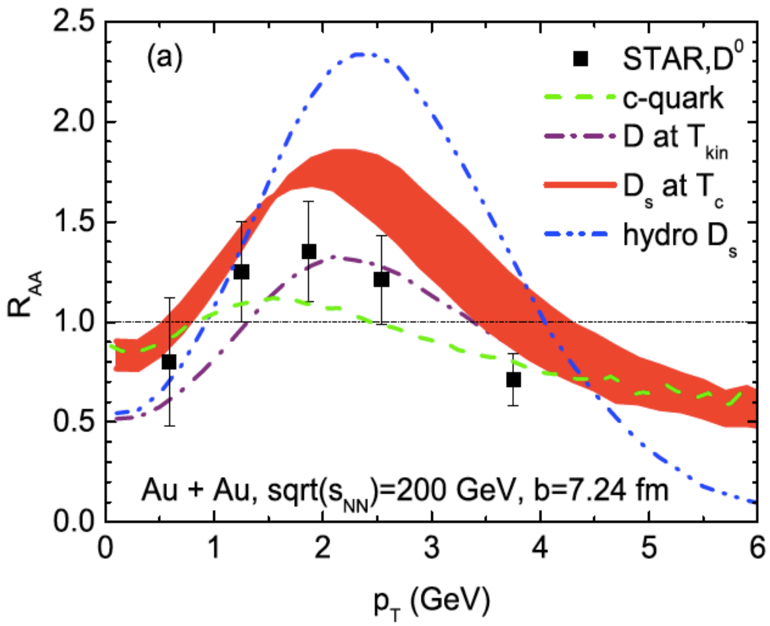
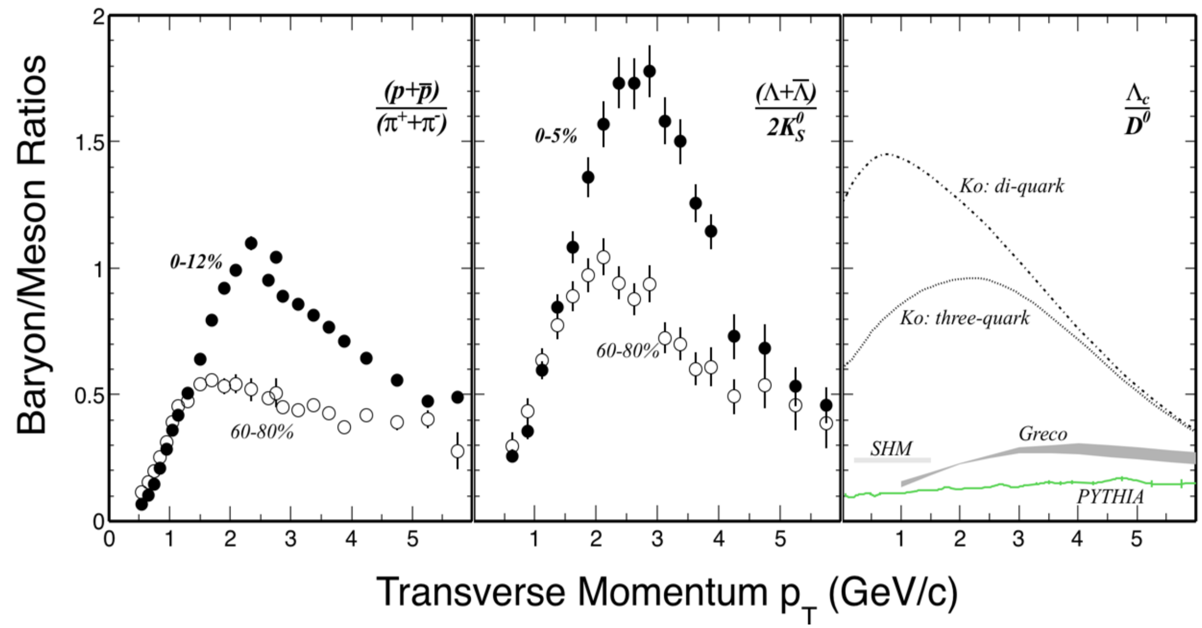


- High v_2 data precision offers stringent constraints to model calculations
- Sensitivity to sQGP transport parameter ***$2\pi TD_s$*** and its temperature dependence

Charm Quark Hadronization



H. Min et al. PRL 110,112301 (2013)



Ko model : Y. Oh, et.al. PRC 79,044905 (2009)

Greco model : S.Ghosh, et. al. PRD 90,054018 (2014)

Coalescence hadronization

Strangeness enhancement -> D_s enhancement

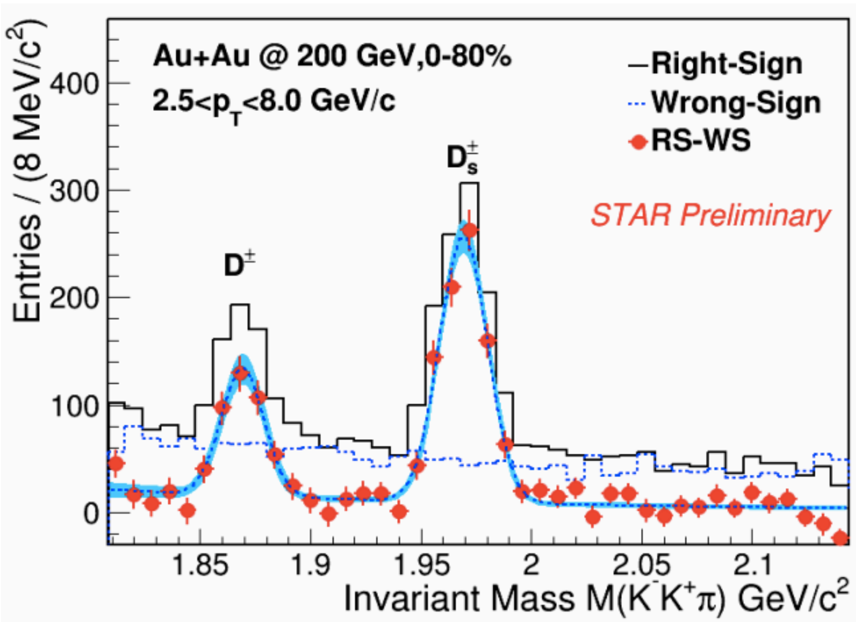
Baryon enhancement -> Λ_c enhancement

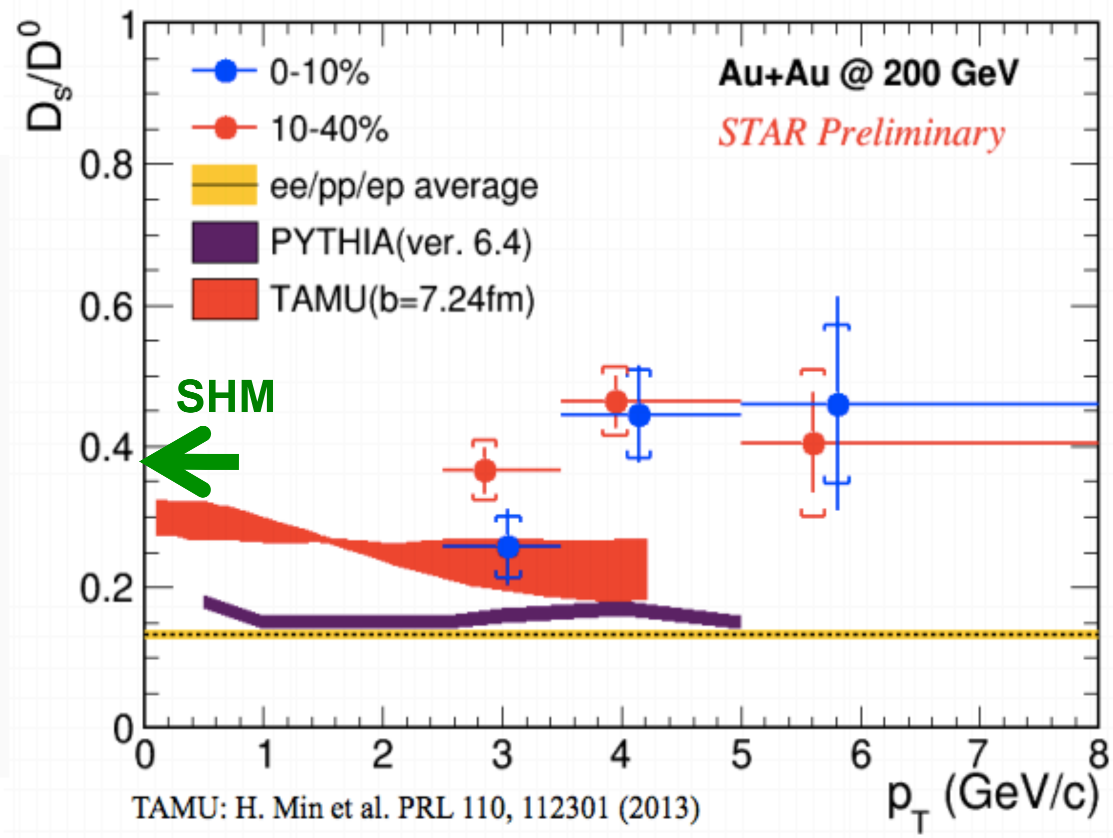
$$2\sigma_{c\bar{c}} = D^0 + D^+ + D_s^+ + \Lambda_c^+ \quad + \text{c.c.}$$

60.8% 24.0% 8.0% 6.2% *Lisovyi, et. al. EPJ C 76, 397 (2016)*

D_s Enhancement in Au+Au Collisions

$$D_s^+ \rightarrow \phi\pi^+ \rightarrow K^+K^-\pi^+$$

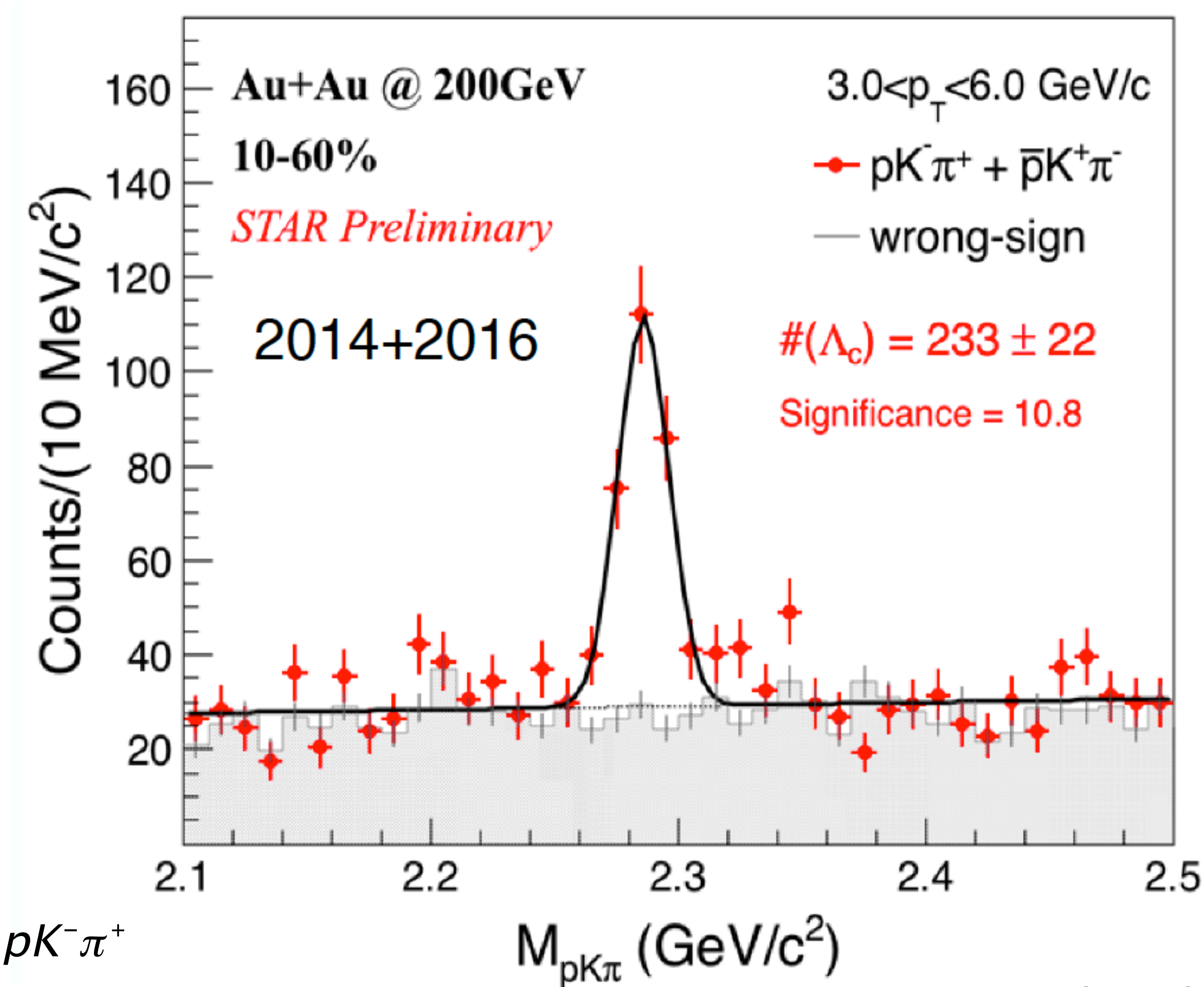




•Significant D_s/D^0 enhancement in mid-central Au+Au collisions w.r.t fragmentation baseline or p+p measurement

- Coalescence hadronization
- SHM predicts D_s/D^0 ratio ~ 0.35-0.40 (central) *Andronic et al., PLB 571 (2003) 36*

Λ_c Reconstruction in Au+Au collisions

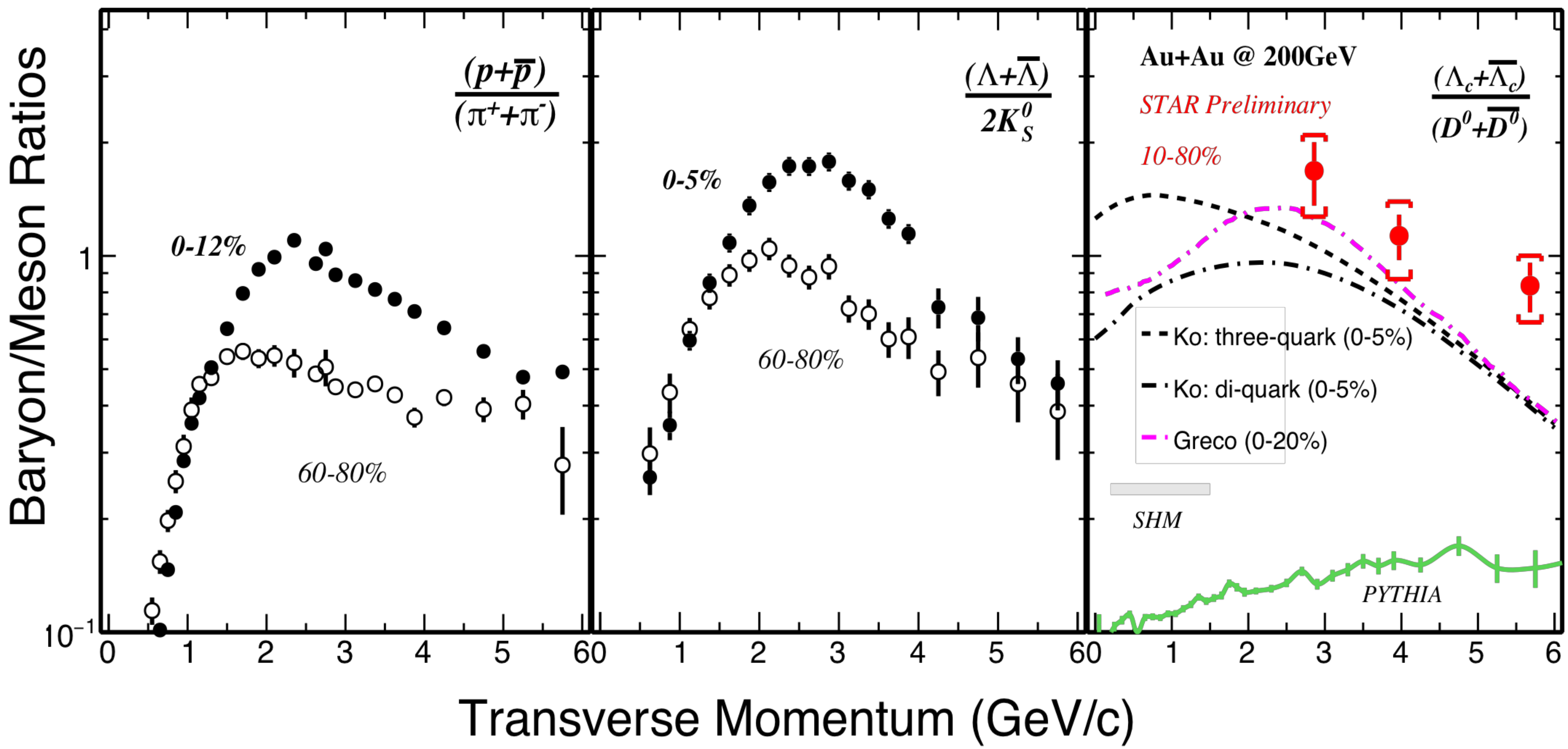


$\Lambda_c^+ \rightarrow pK^-\pi^+$

$c\tau = 60\mu m$

STAR, QM18

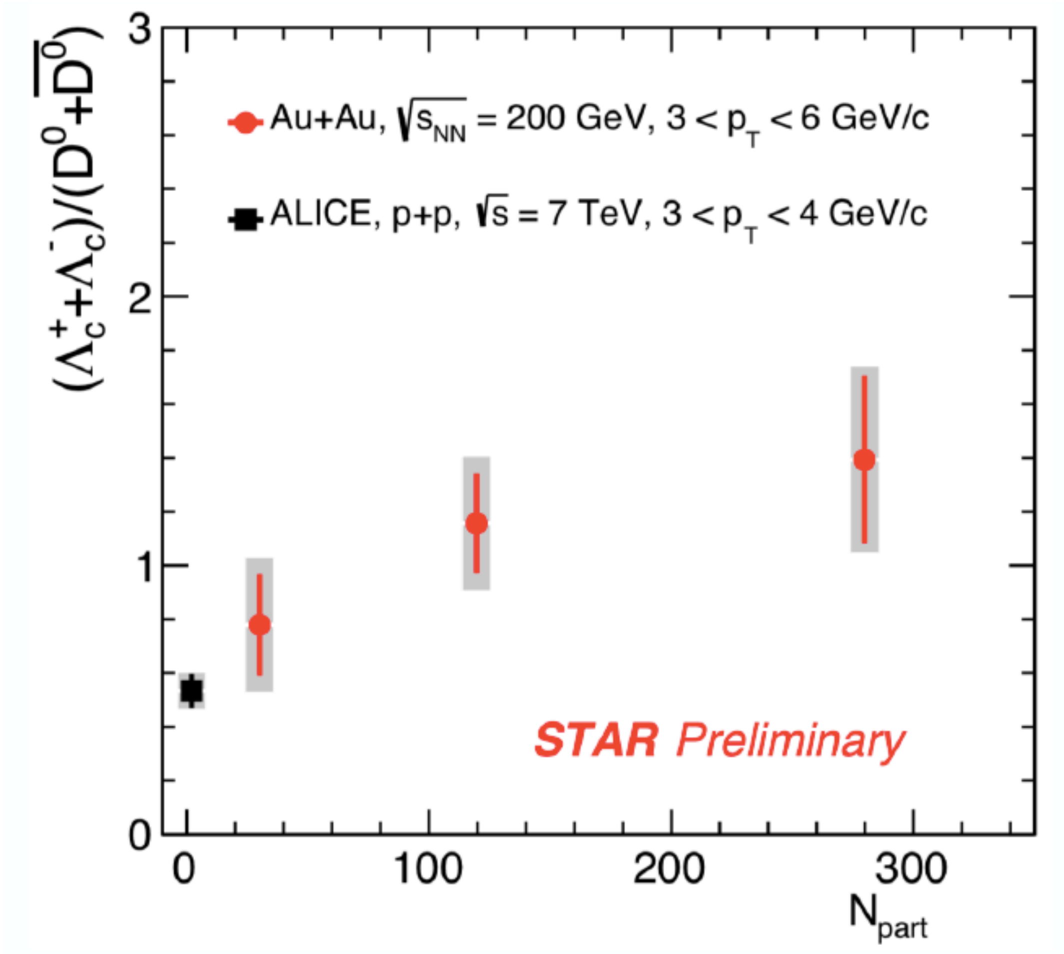
Λ_c Enhancement in Au+Au Collisions

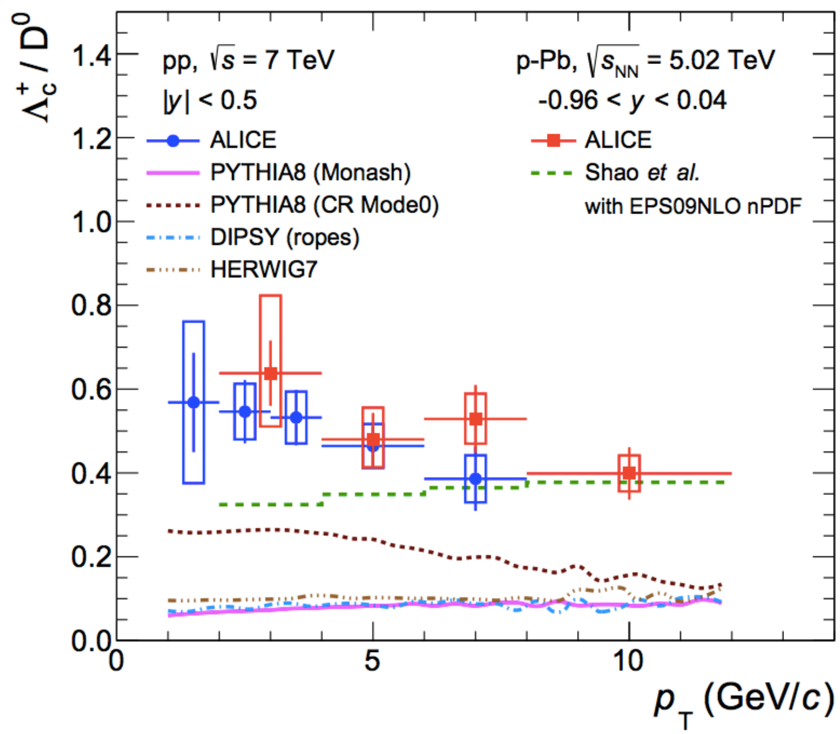


Ko model : Y. Oh, et.al. PRC 79 (2009) 044905; Greco model : S.Plumari, et. al. EPJC 78 (2018) 348

- Significant enhancement in Λ_c/D compared to PYTHIA/fragmentation baseline
- The Λ_c/D^0 ratio is compatible with light flavor baryon-to-meson ratios
- Consistent with coalescence + strong charm-medium coupling

Centrality Dependence of Λ_c/D^0 Enhancement





ALICE, JHEP 04 (2018) 108

Trend of larger Λ_c/D^0 ratio in more central collisions

- similar as light/strange hadrons - coalescence hadronization

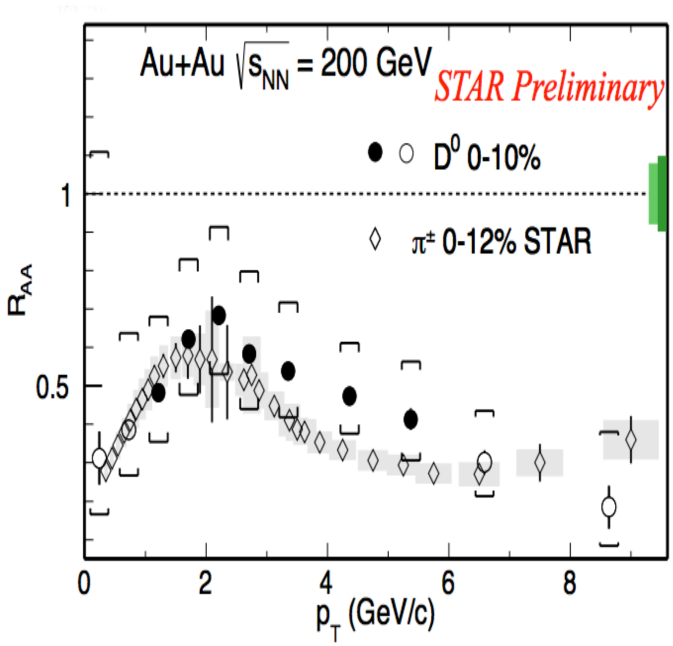
– $\Lambda_c/D^0 \sim 0.5$ in p+p/p+Pb collisions, not fully understood either

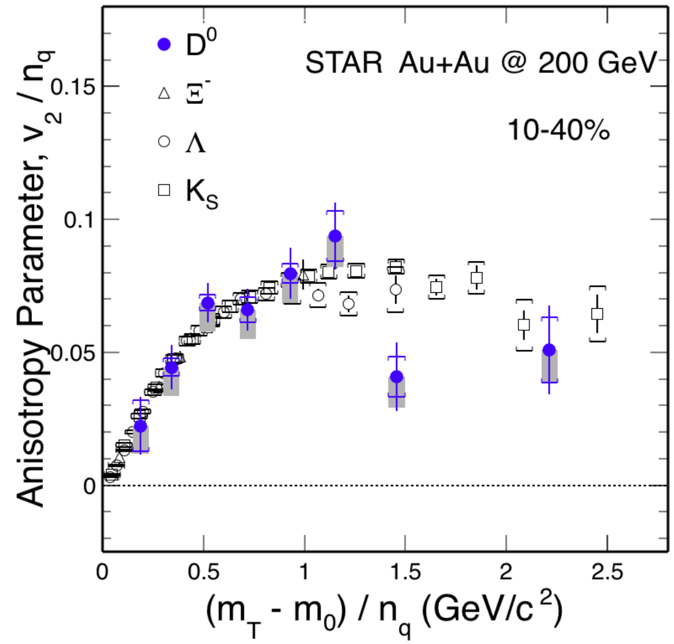
Total Charm Production Cross Section

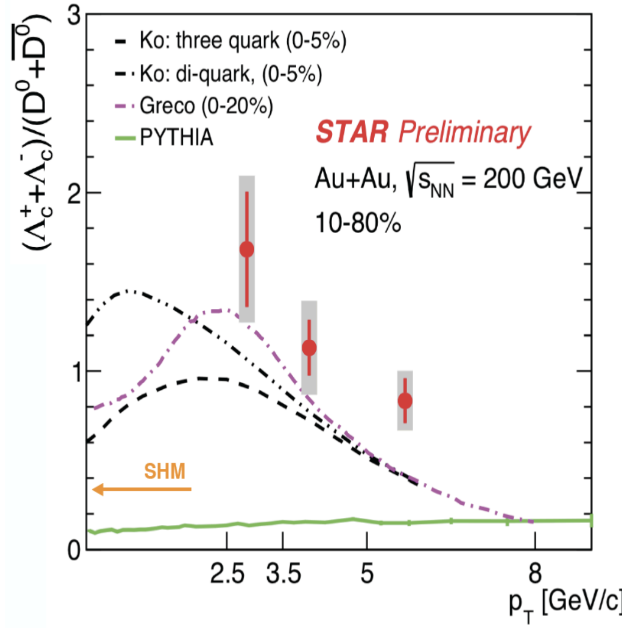
Charm Hadron		Cross Section dσ/dy (μb)
Au+Au 200 GeV (10-40%)	D^0	41 ± 1 ± 5
	D^+	18 ± 1 ± 3
	D_s^+	15 ± 1 ± 5
	Λ_c^+	78 ± 13 ± 28*
	Total	**152 ± 13 ± 29**
p+p 200 GeV	**Total**	**130 ± 30 ± 26**

Total charm X-section follows ~ N_{bin} scaling from p+p to Au+Au
However, charm hadron fractions are different from p+p to Au+Au collisions

Short Summary of Charm Measurements



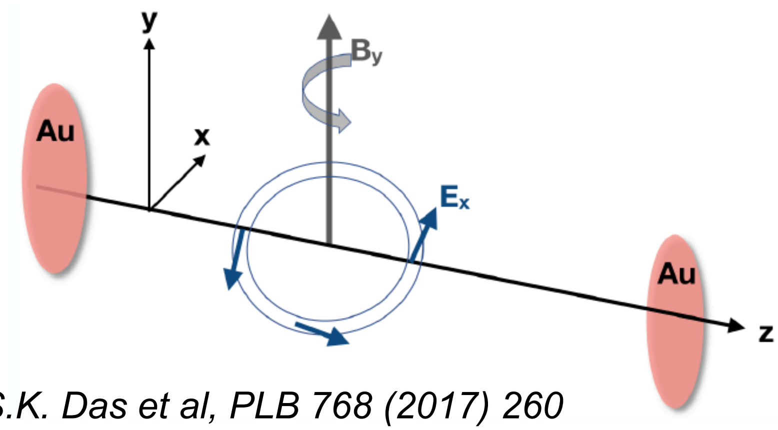




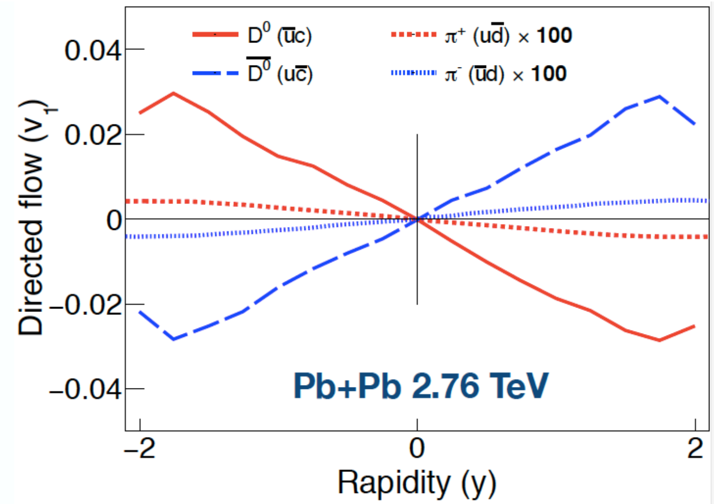
$R_{AA}(D) \sim R_{AA}(h)$	- charm quarks lose significant energy
$v_2(D) \sim v_2(h)$ vs. m_T	- charm quarks flow like light quarks
Λ_c/D^0 and D_s/D^0 enhancement	- coalescence hadronization

Evidence of charm quark flowing with the QGP

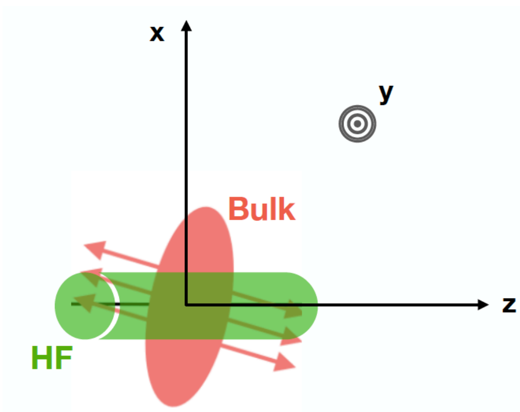
D^0 Directed Flow – New Directions



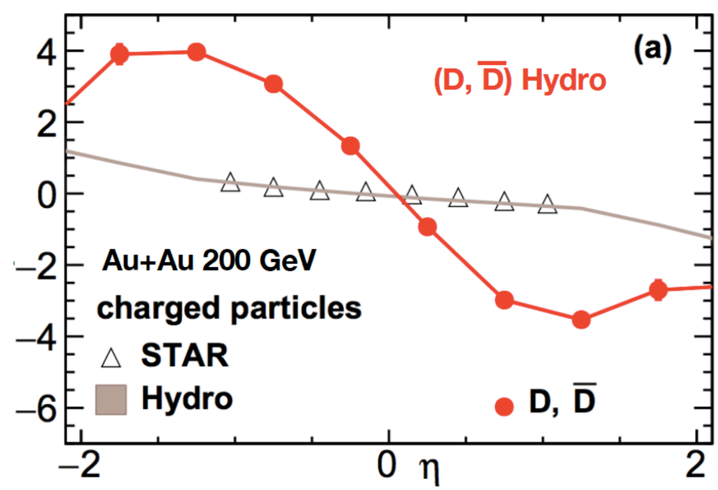
S.K. Das et al, PLB 768 (2017) 260



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



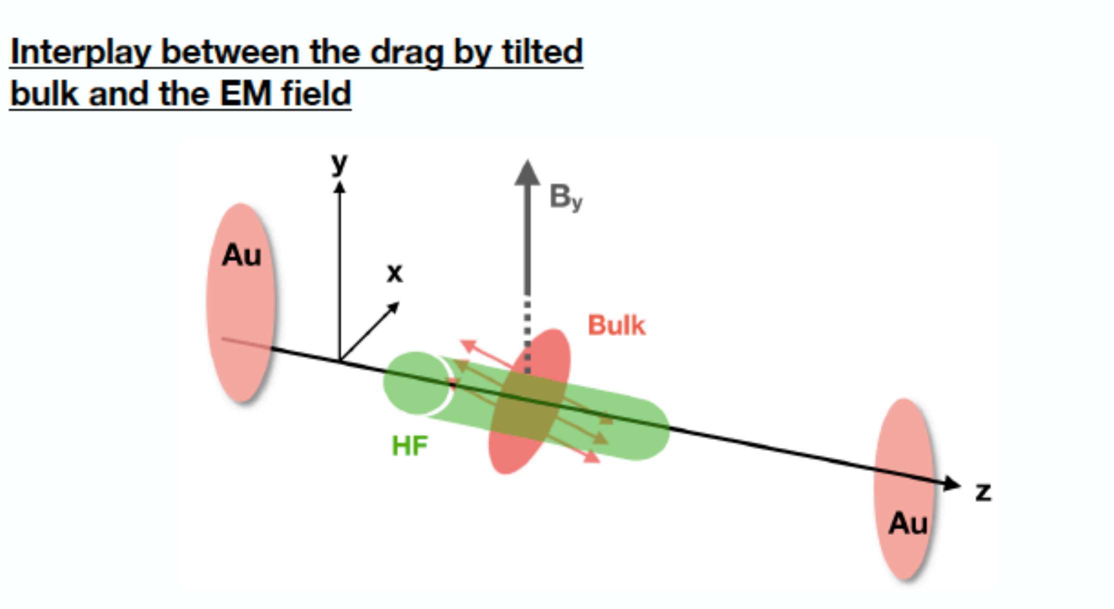
S. Chatterjee and P. Bożek, PRL 120 (2018) 192301

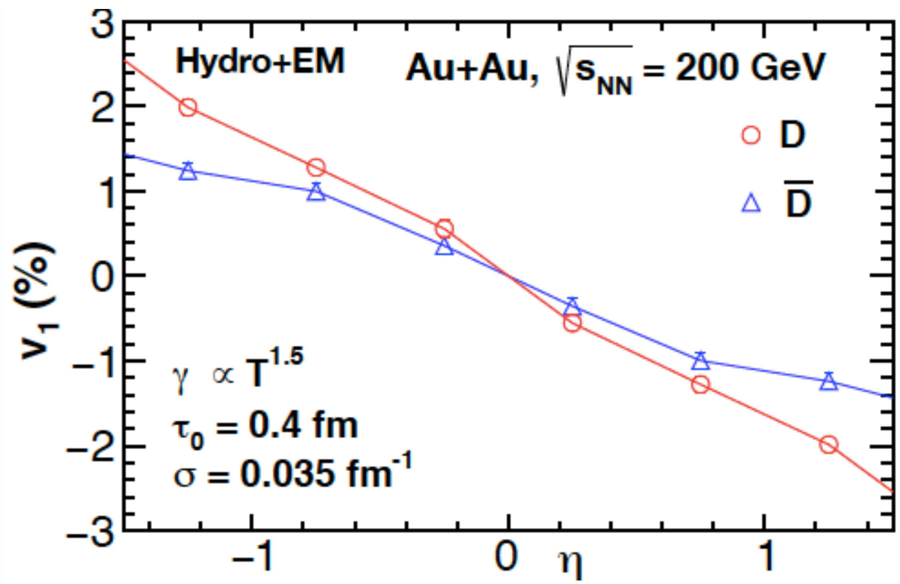


Tilted QGP + hydro -> dv_1/dy (D) = dv_1/dy (Dbar) >> dv_1/dy (h)

D^0 Directed Flow – Model Predictions

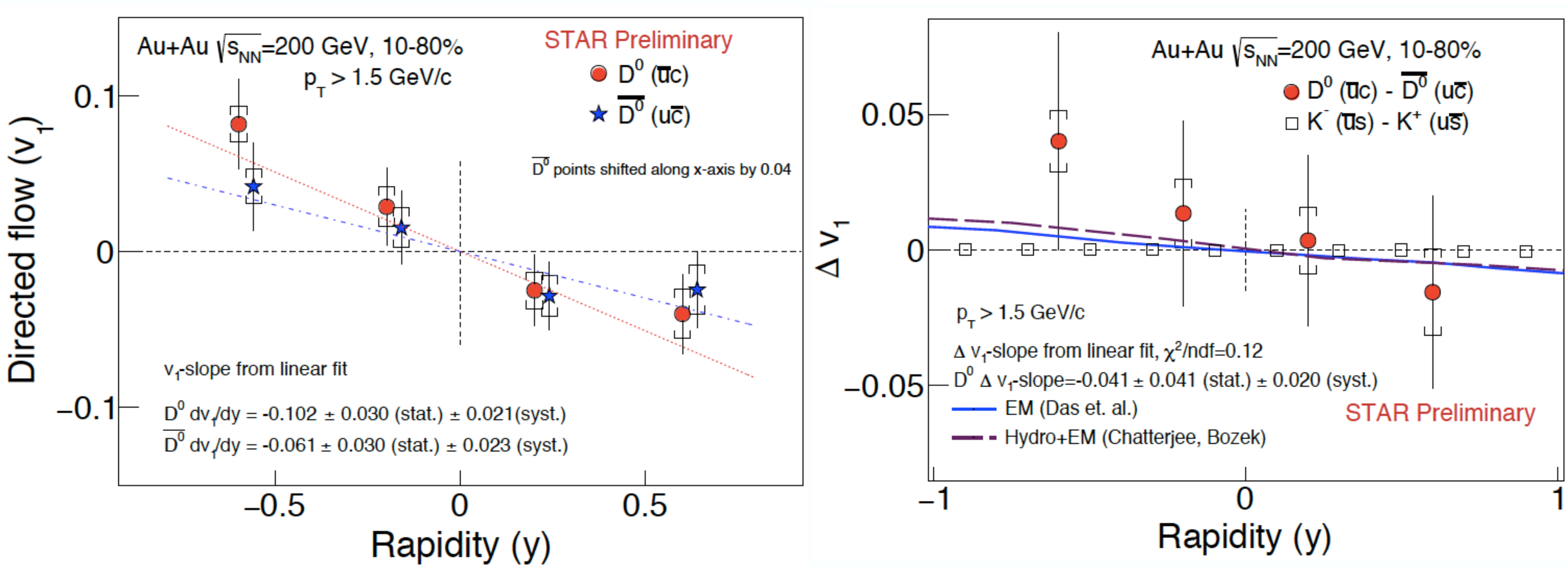
Two Effects Together





S. Chatterjee and P. Bożek, 1804.04893

Observation of D^0 Directed Flow



v_1-slope (D) >> v_1-slope (K)

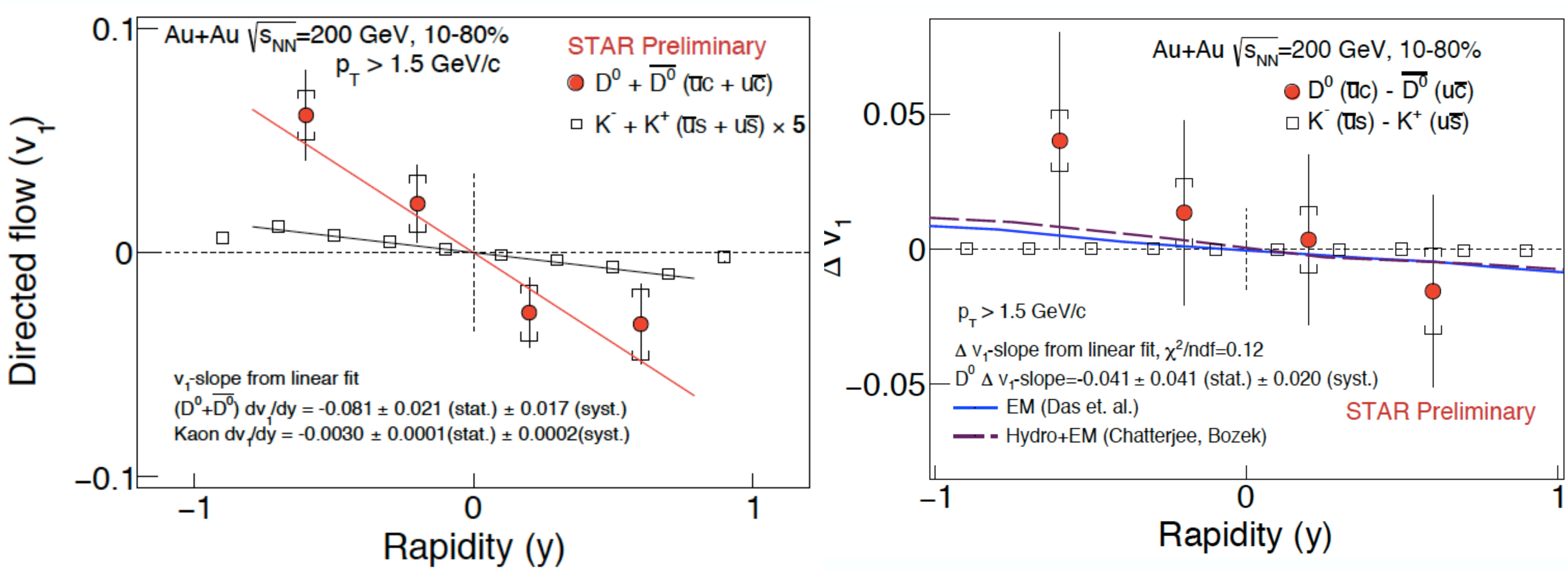
-> consistent with tilted QGP source + hydro evolution

-> offer constraints on longitudinal structure of medium properties

No significant difference between v_1(D) and v_1(Dbar)

-> Need more statistics to ping down the magnetic field strength

Observation of D^0 Directed Flow



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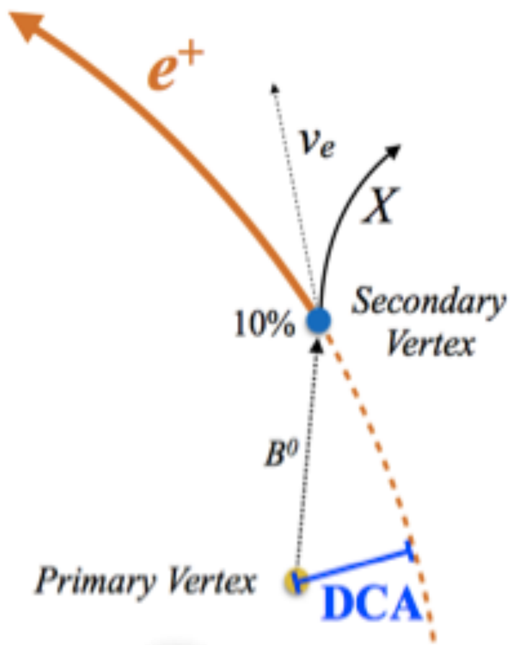
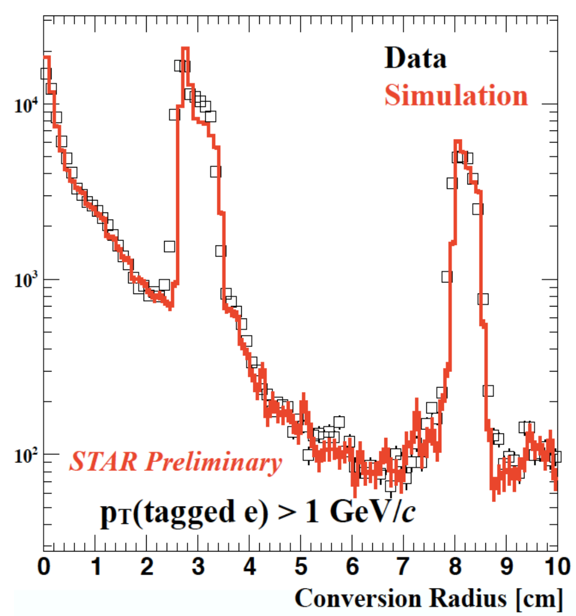
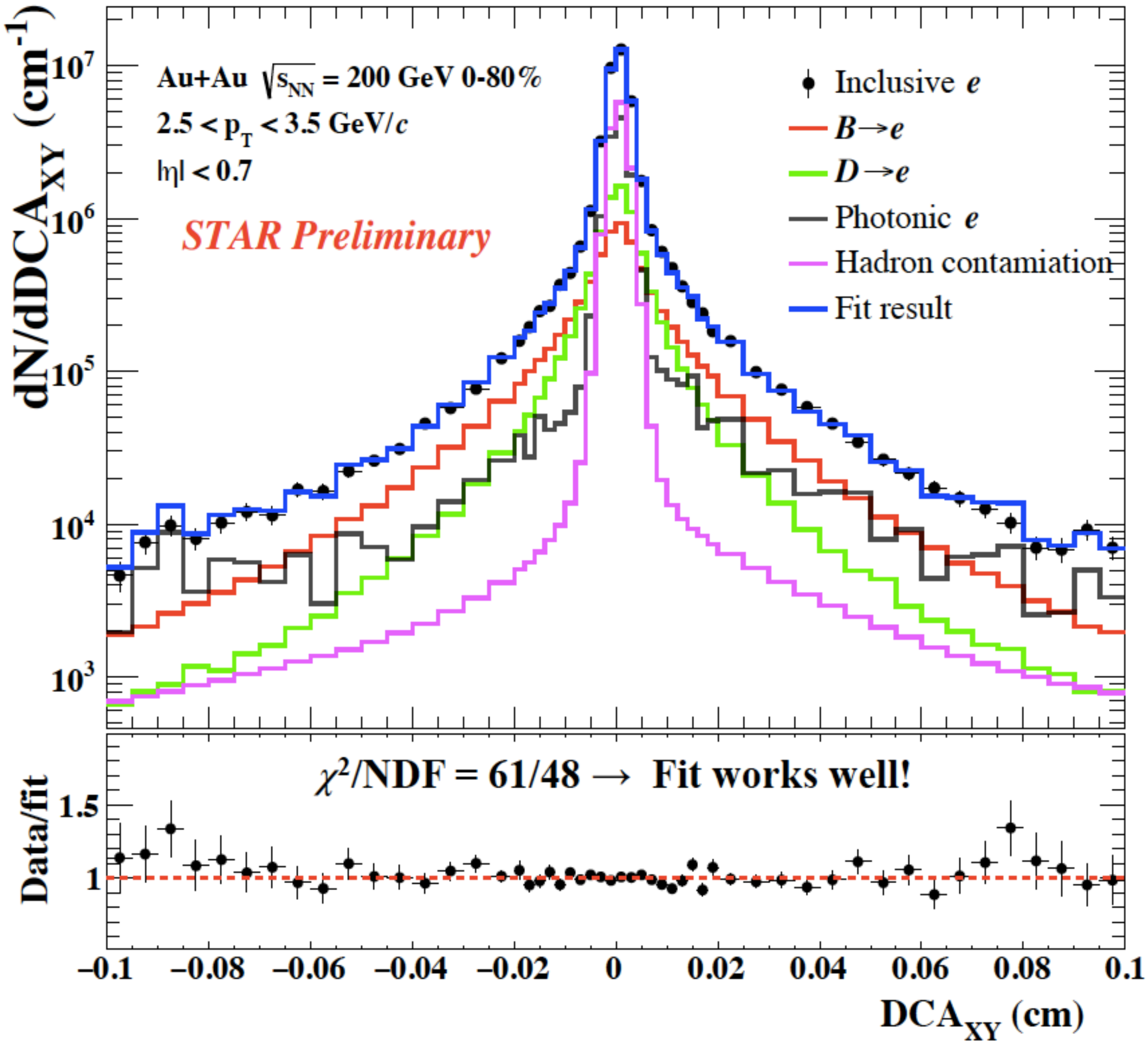
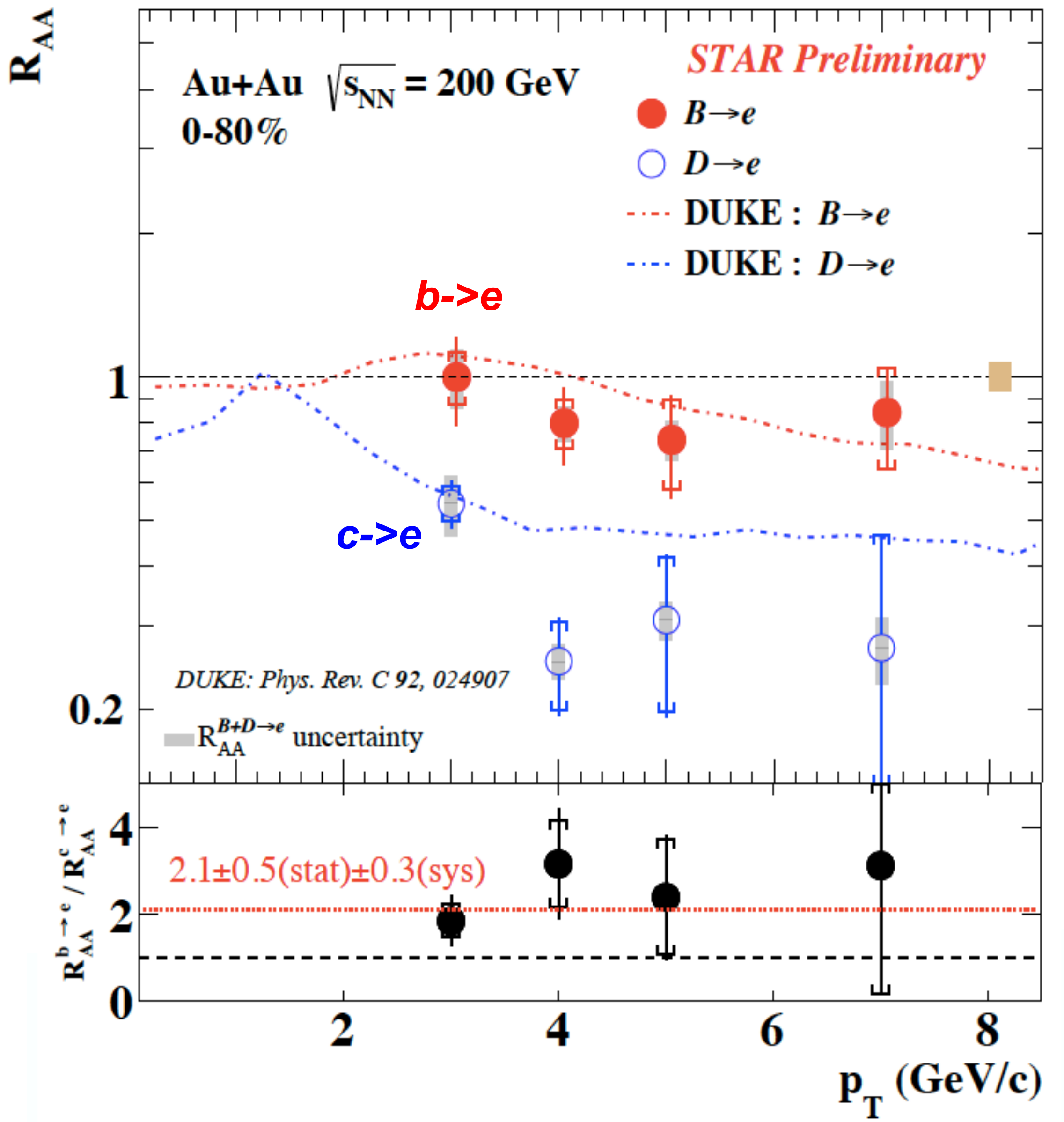
Attempt to Measure Bottom – Single Electrons







Charm/bottom Separation in Single Electron Channel



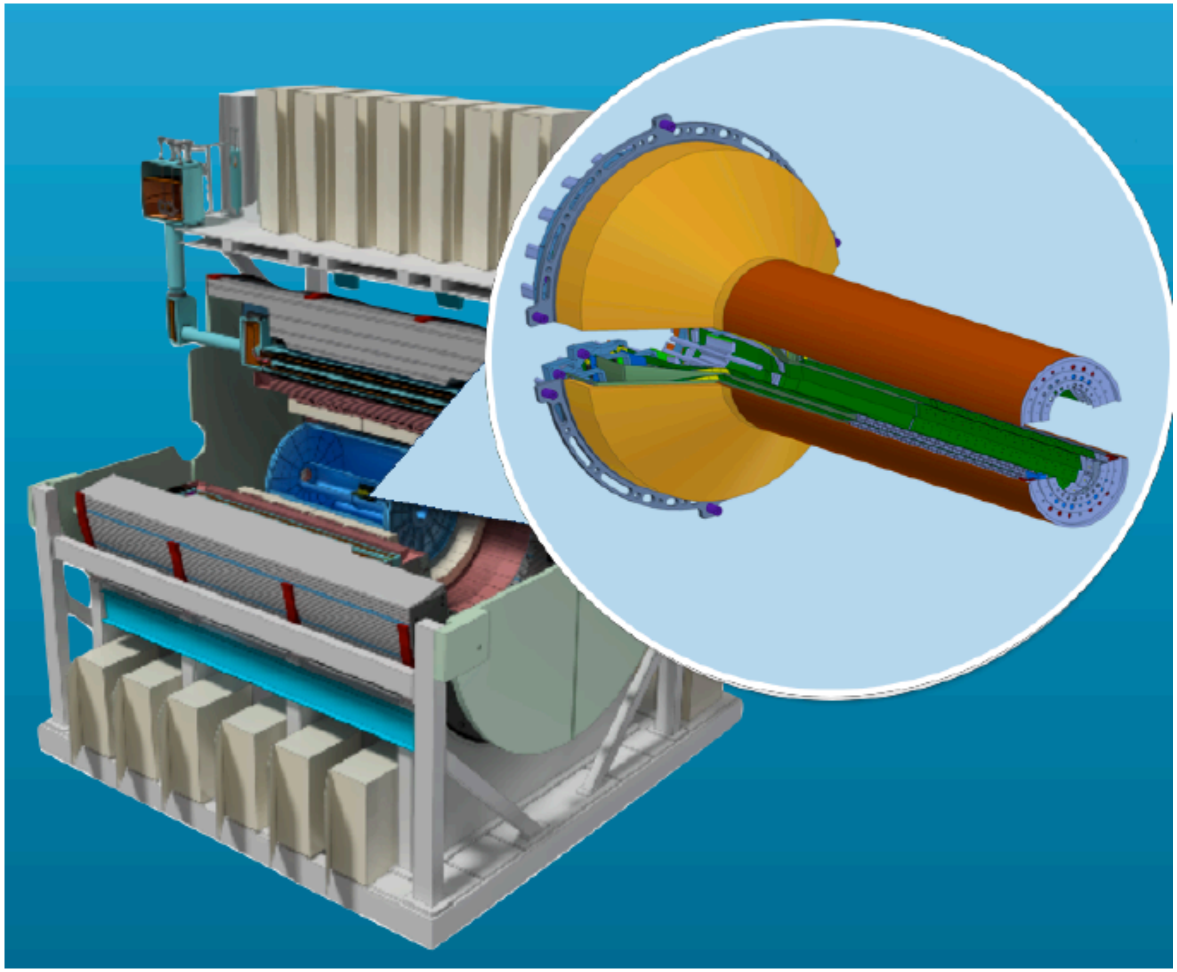
STAR, QM17

Impact parameter method to separate c/b electrons and non-prompt D^0, J/ψ

- $R_{AA}(e_B) < R_{AA}(e_D)$ at 3 – 8 GeV/c (2σ)

hint of mass hierarchy of parton energy loss

sPHENIX

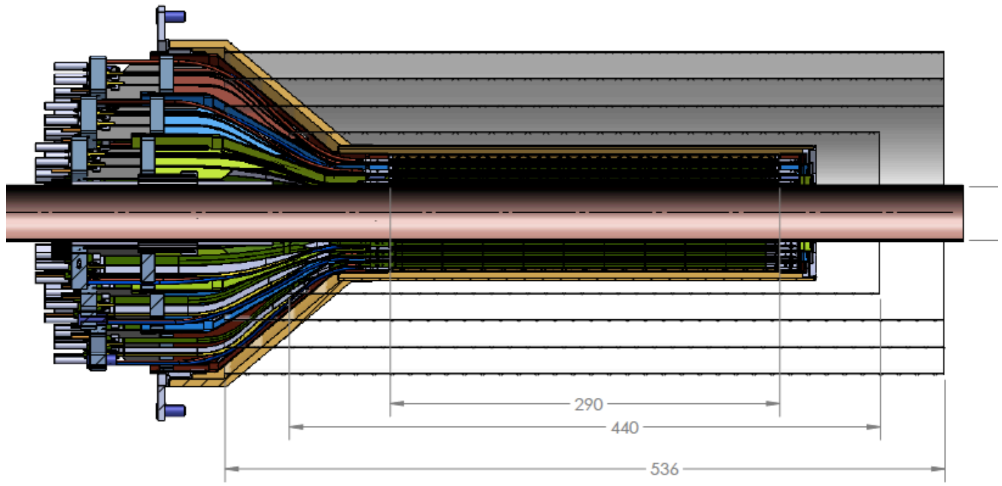


sPHENIX

next generation fast detector for jet, Upsilon and HF measurements

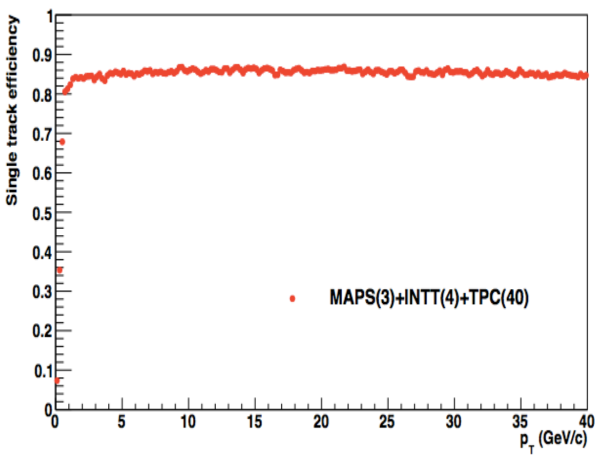
- >15kHz DAQ rate (x10 faster than STAR)
- a total of 240 billion MB events (x100 larger than STAR HFT data)

MVTX: Features and Performance

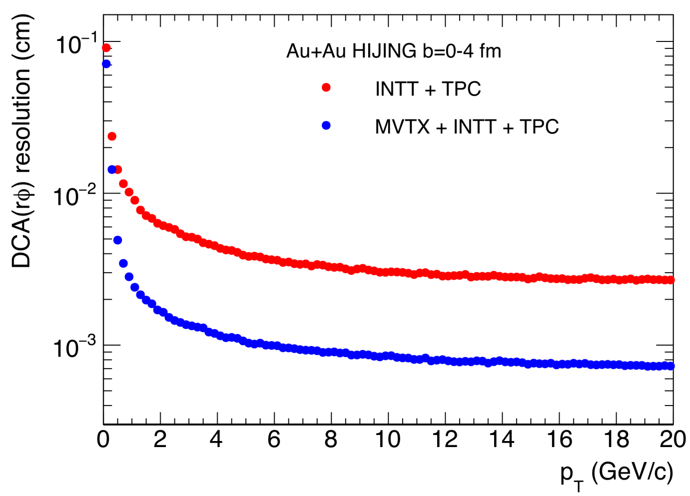


MAPS-based silicon VerTeX detector
- next generation MAPS sensors
- utilize ALICE ITS upgrade design
- 28x28 um pitch size
- **0.3%X_0** per layer
- **<10 us** integration time
  (x20 faster than STAR PXL)

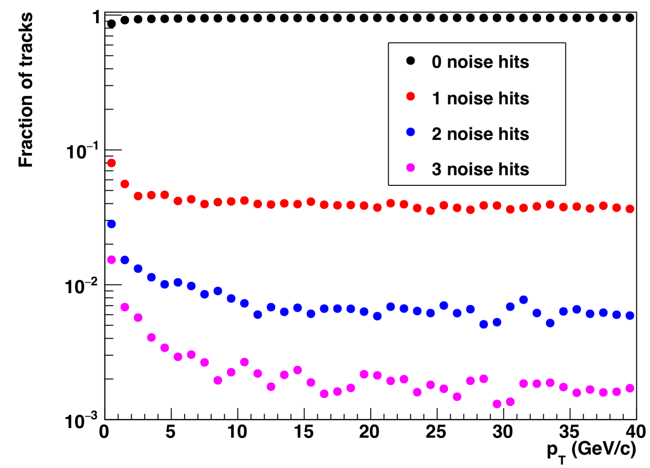
Full GEANT + tracking simulation for sPHENIX



high tracking efficiency



superior pointing resolution

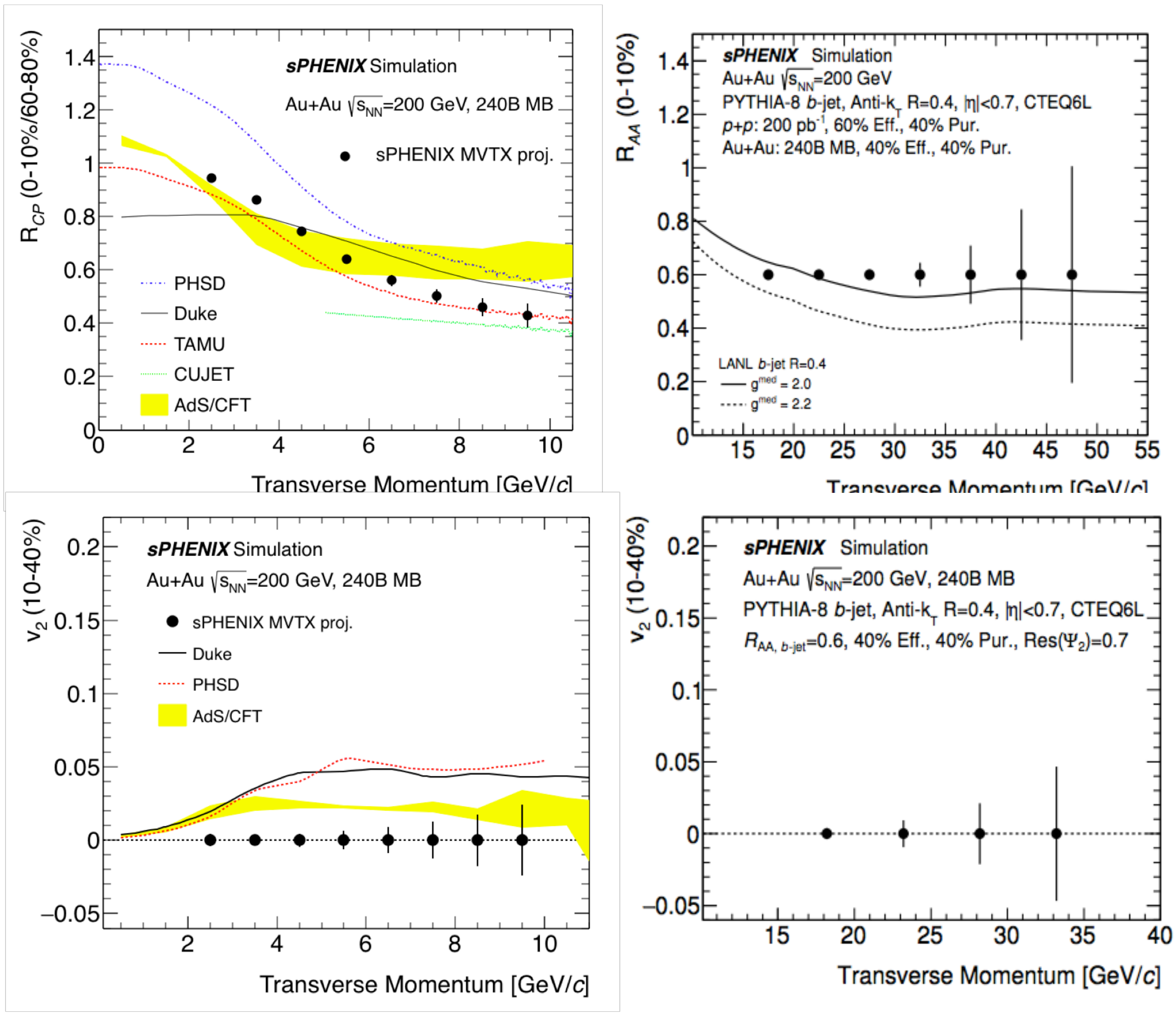


low fake rate

Projections on Open Bottom Physics with sPHENIX

Precision open bottom measurements over a broad momentum range

- mass/flavor dependence of parton energy loss
- precision determination of heavy quark diffusion coefficient

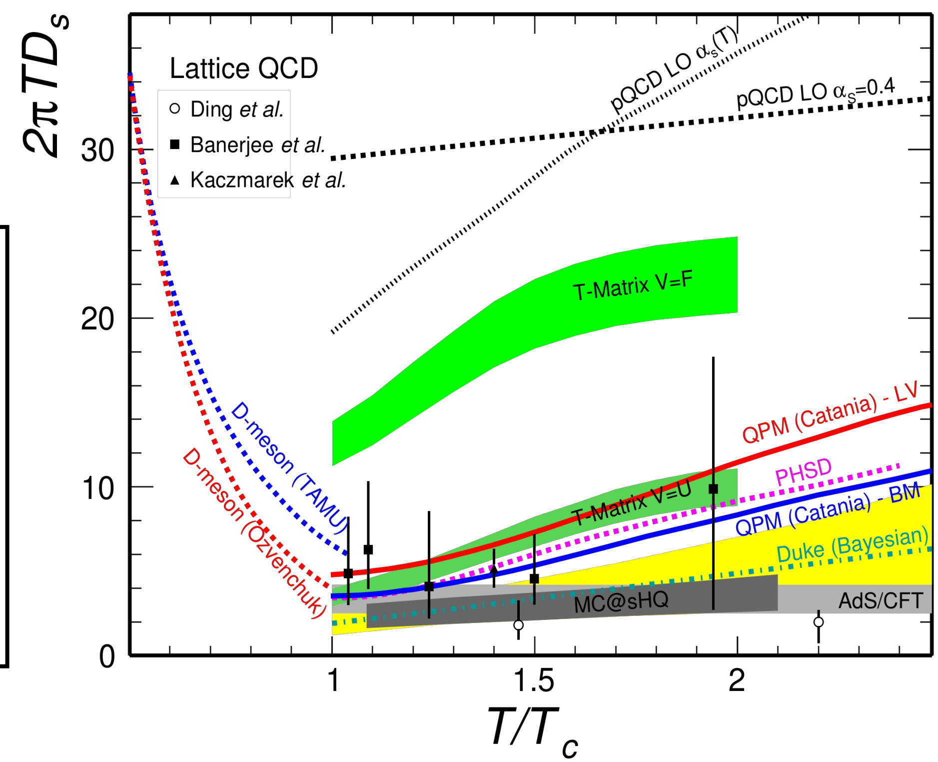


Prospective Heavy Flavor Program in Future

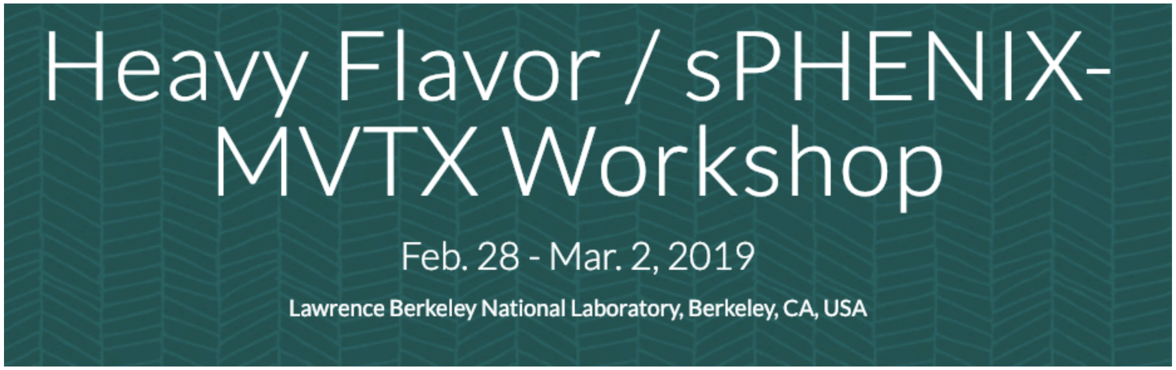
	2014	2015	2016	2017	2018	2019	2020	2021	2022+
RHIC	HF Phase-I			pp	CME	BES-II			HF Phase-II
LHC	LS1	Run-2				LS2		Run-3	

RHIC HF Phase-II / LHC Run-3
@ 2021+

- Precision open bottom measurements over a broad momentum range
- Heavy flavor baryon and correlations



HF/sPHENIX-MVTX Workshop at LBNL



https://sites.google.com/lbl.gov/hfmvtxlbnl2019/

Backups

Key Instruments – Pixel Silicon Detector

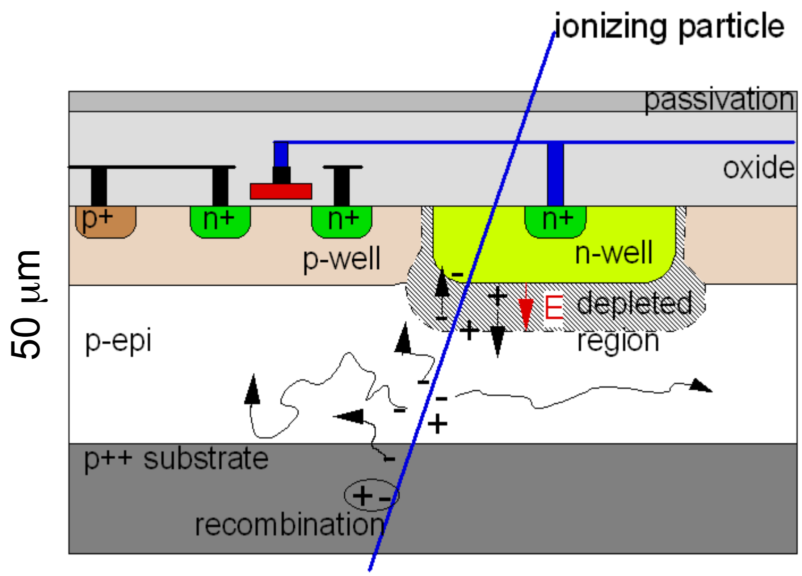
	ALICE	ATLAS	CMS	LHCb	PHENIX	STAR
Sensor tech.	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid	**MAPS**
Pitch size (μm^2)	50x425	50x400	100x150	200x200	50x425	**20x20**
Radius of first layer (cm)	3.9	5.1	4.4	N/A	2.5	2.8
Thickness of first layer	$1\%X_0$	$\sim1\%X_0$	$\sim1\%X_0$	$\sim1\%X_0$	$1\%X_0$	**$0.4\%X_0$**

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

Monolithic Active Pixel Sensors (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

Experimental Methods

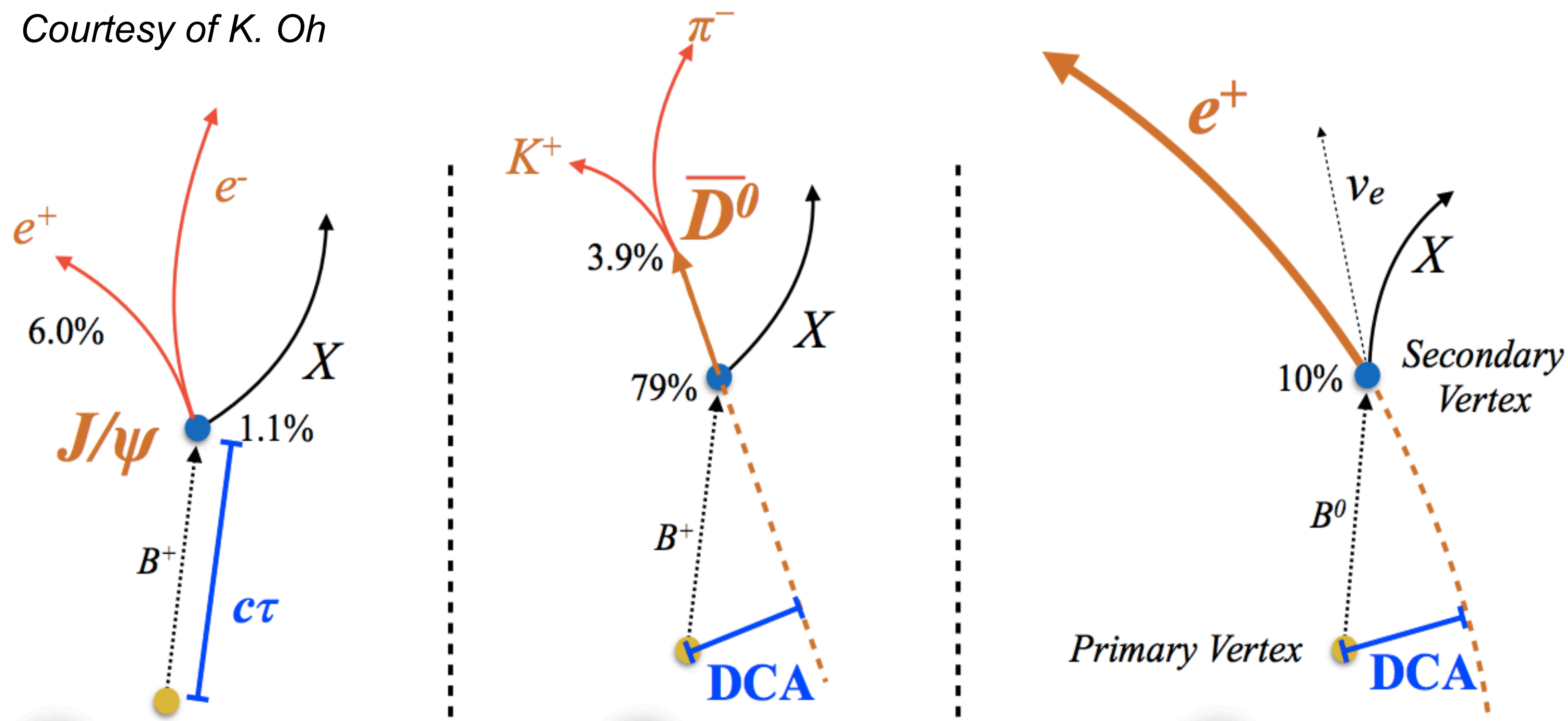
Hadron	Abundance (fragmentation)	cτ (μm)
D^0	56%	123
D^+	24%	312
D_s	10%	150
Λ_c	10%	60
B^+	40%	491
B^0	40%	456

1) Secondary vertex reconstruction
   e.g. $D^0 \to K\pi$, $\Lambda_c \to pK\pi$

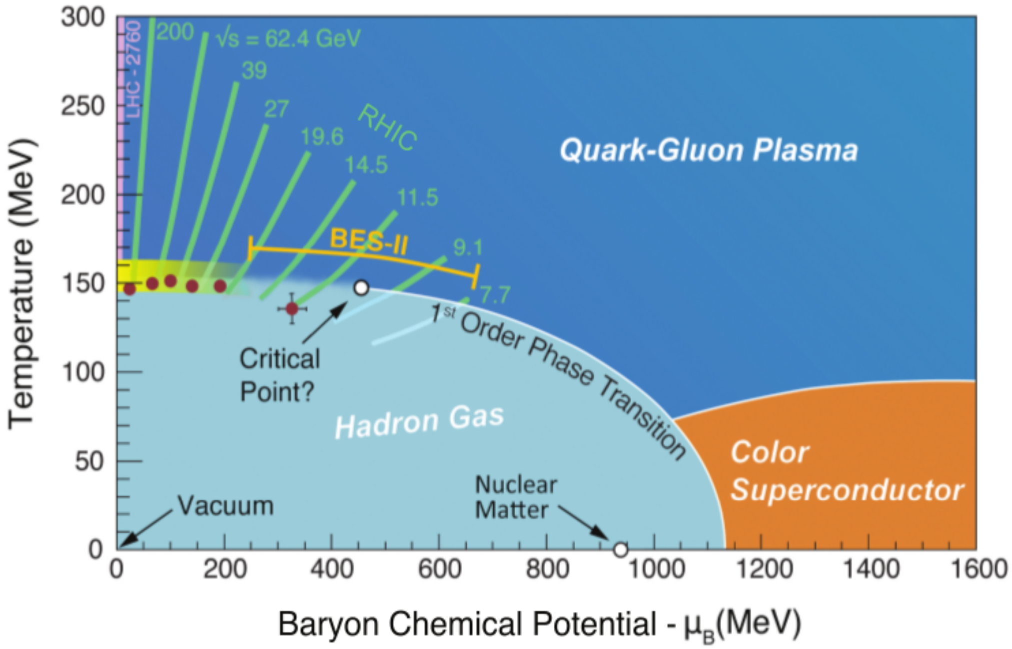
2) Inclusive impact parameter method
   e.g. $D/B \to e$, $B \to D$, $B \to J/\psi$ …

Precision silicon vertex tracker is crucial, particularly in high multiplicity heavy-ion collisions

Courtesy of K. Oh



Quantitative Measure of QGP

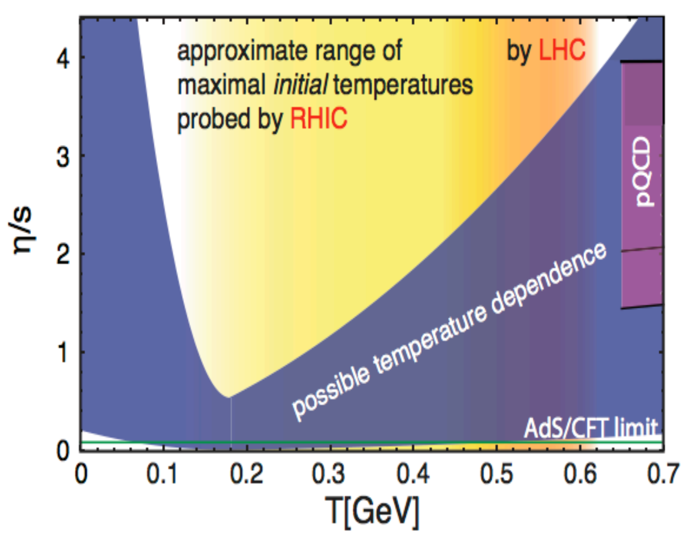


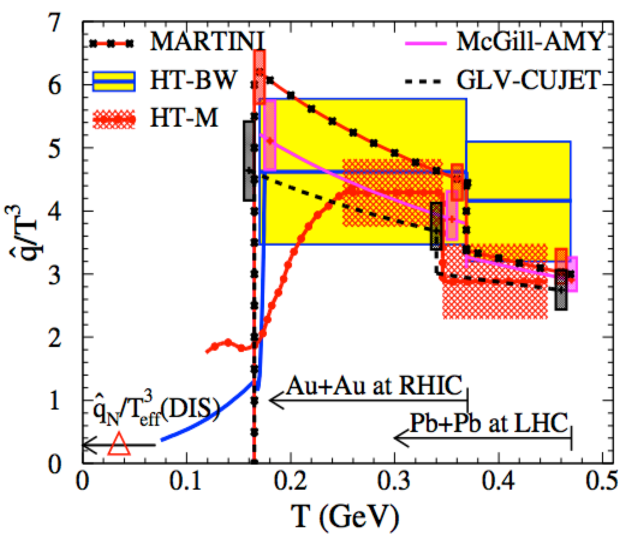
At top RHIC and LHC energies:

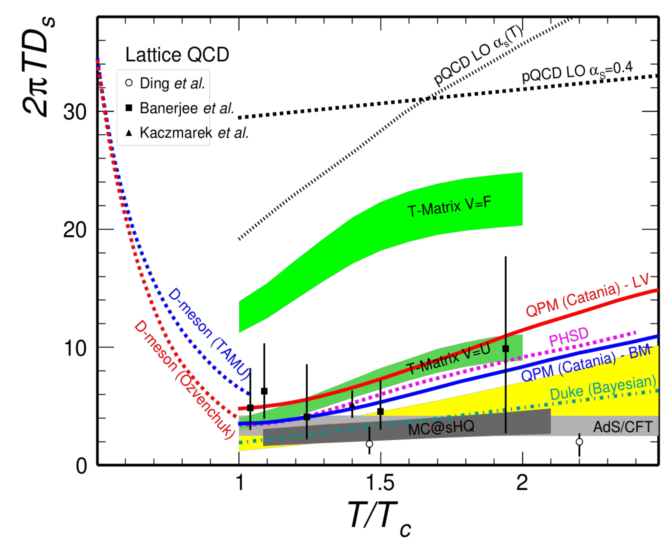
To precisely determine (temperature dependence of) **emergent** QCD transport parameters in QGP

- ***η/s*** - *gluons*
- ***q-hat*** - *high energy partons*
- ***D_s*** - *heavy quarks*
- …

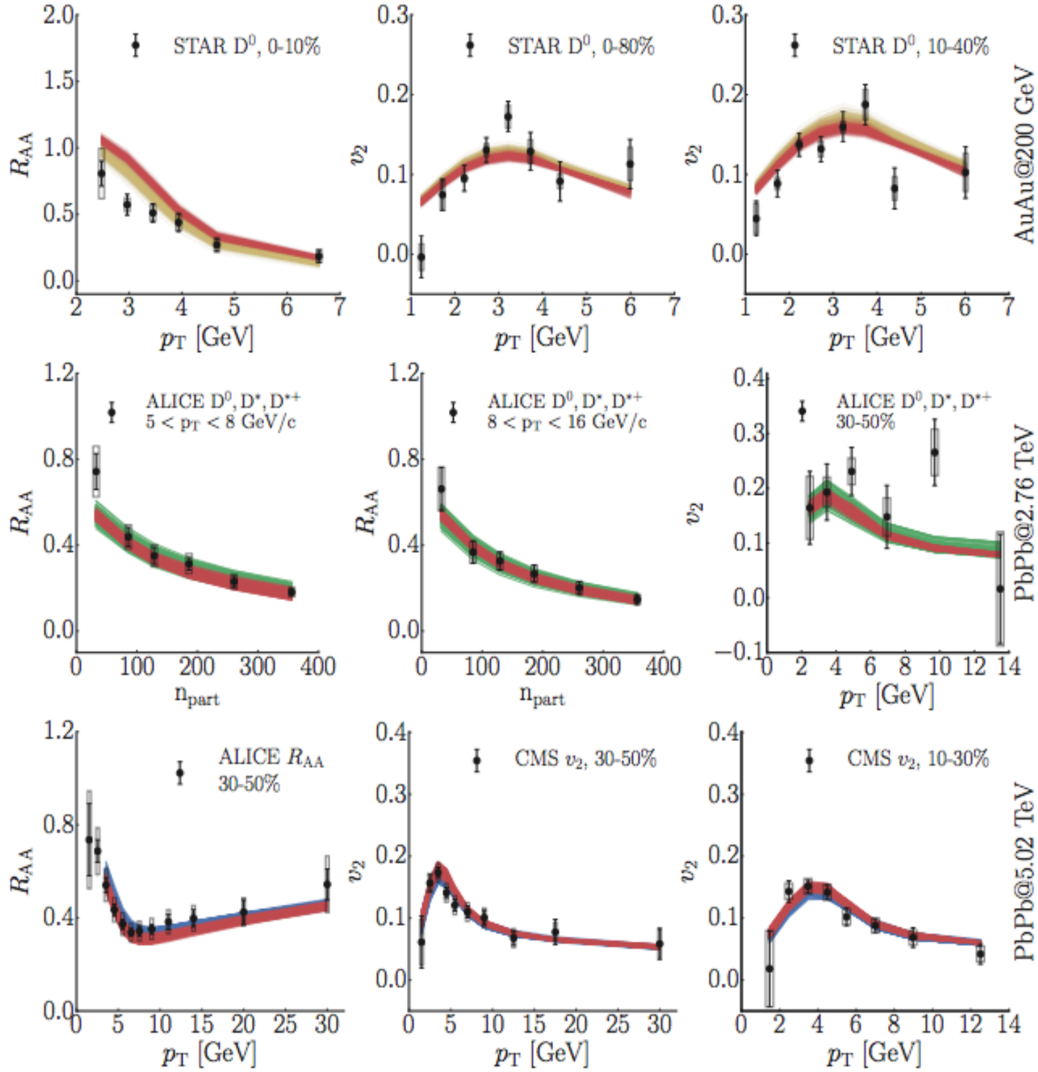
JET Coll., PRC 90 (2015) 014909
Hot QCD white paper - arXiv: 1502.02730



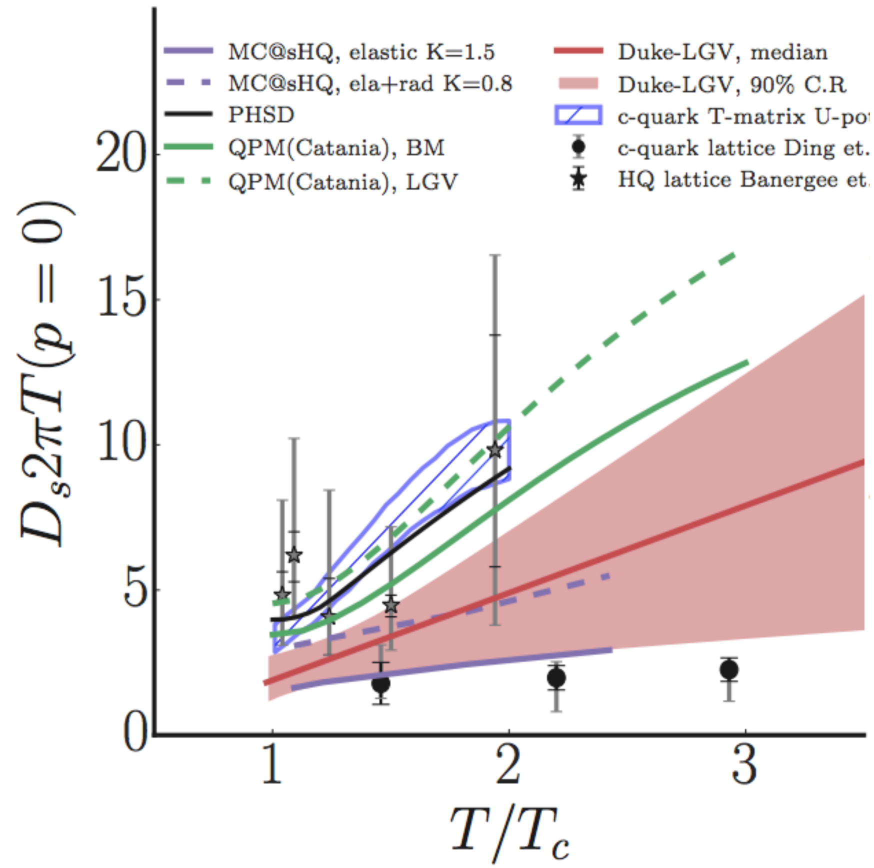




Bayesian Analysis to Extract HQ Diffusion Coefficient



Bayesian analysis based on Duke model:
Langevin + Hydro



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

Open question: Charm heavy enough ? (as compared to medium interactions)

-> Go Heavier !!!

Go Heavier - Open Bottom Production

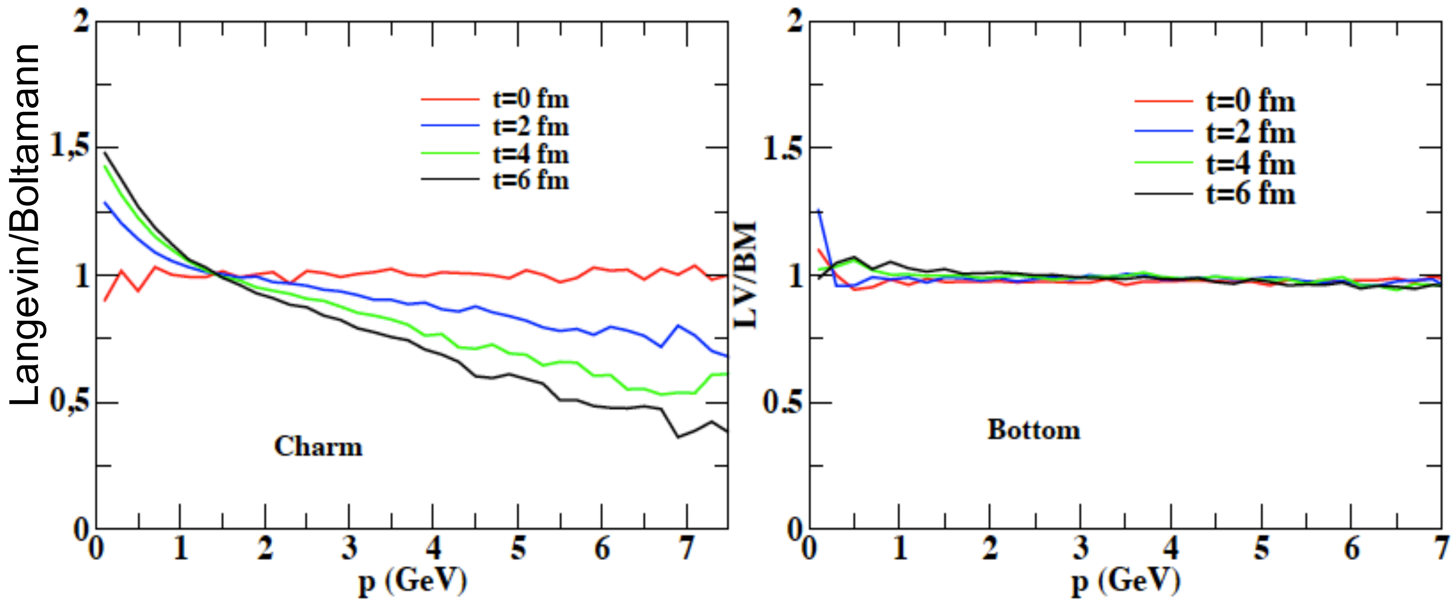
Open bottom production over a wide range of momentum

Mass/Flavor dependence of parton energy loss

Cleanest probe to quantify medium transport properties – e.g. ***D_{HQ}***

Total bottom yield for precision interpretation of Upsilon suppression

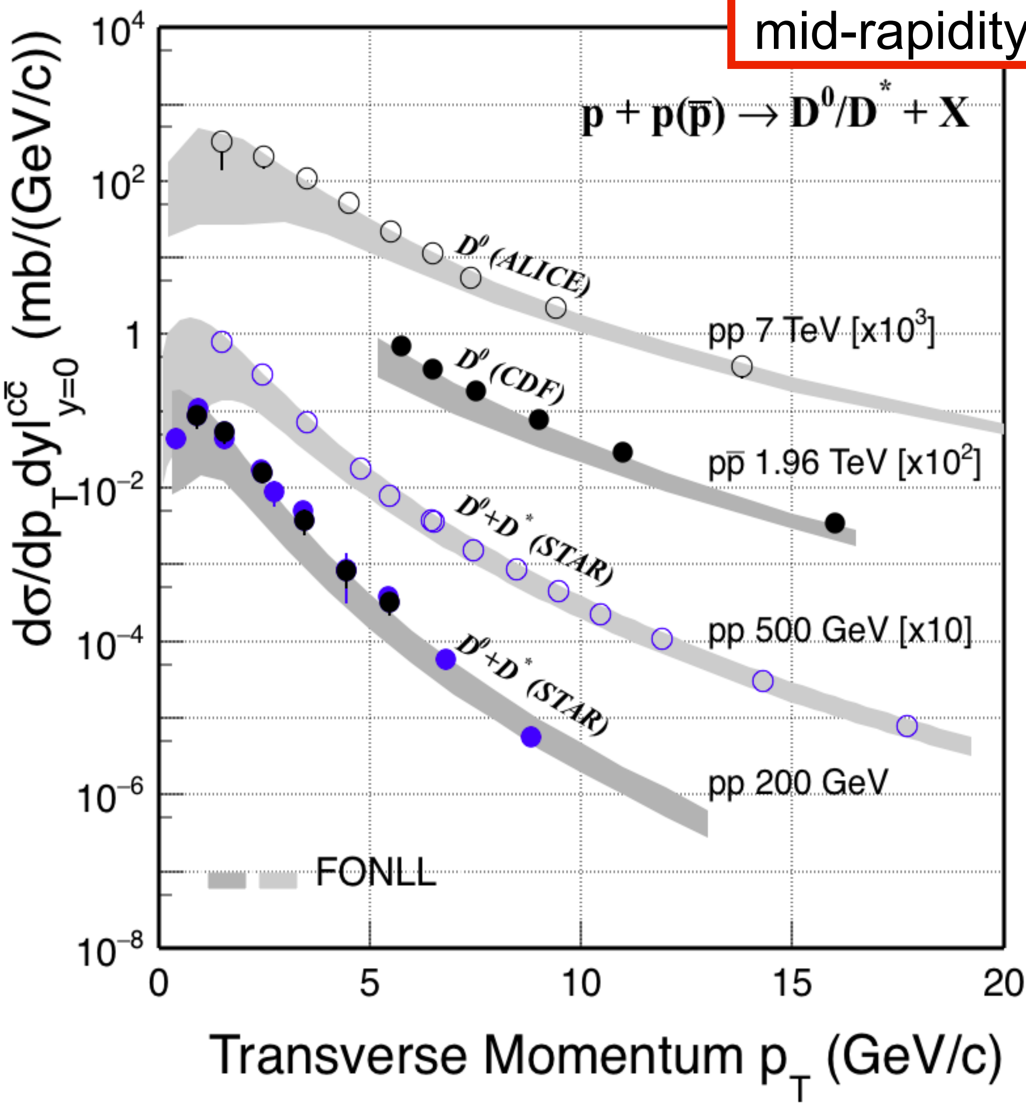
Das et al., PRC 90 (2014) 044901



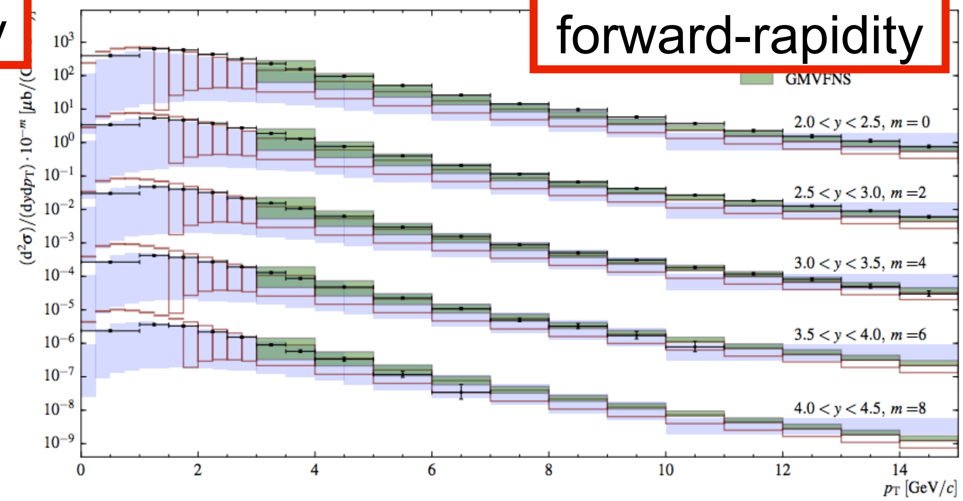
Is charm heavy enough? Sizable correction to the Langevin approach for charm - may limit the precision in determining ***D_{HQ}***

Charm Production in p+p Collisions

0.2-7 TeV
mid-rapidity



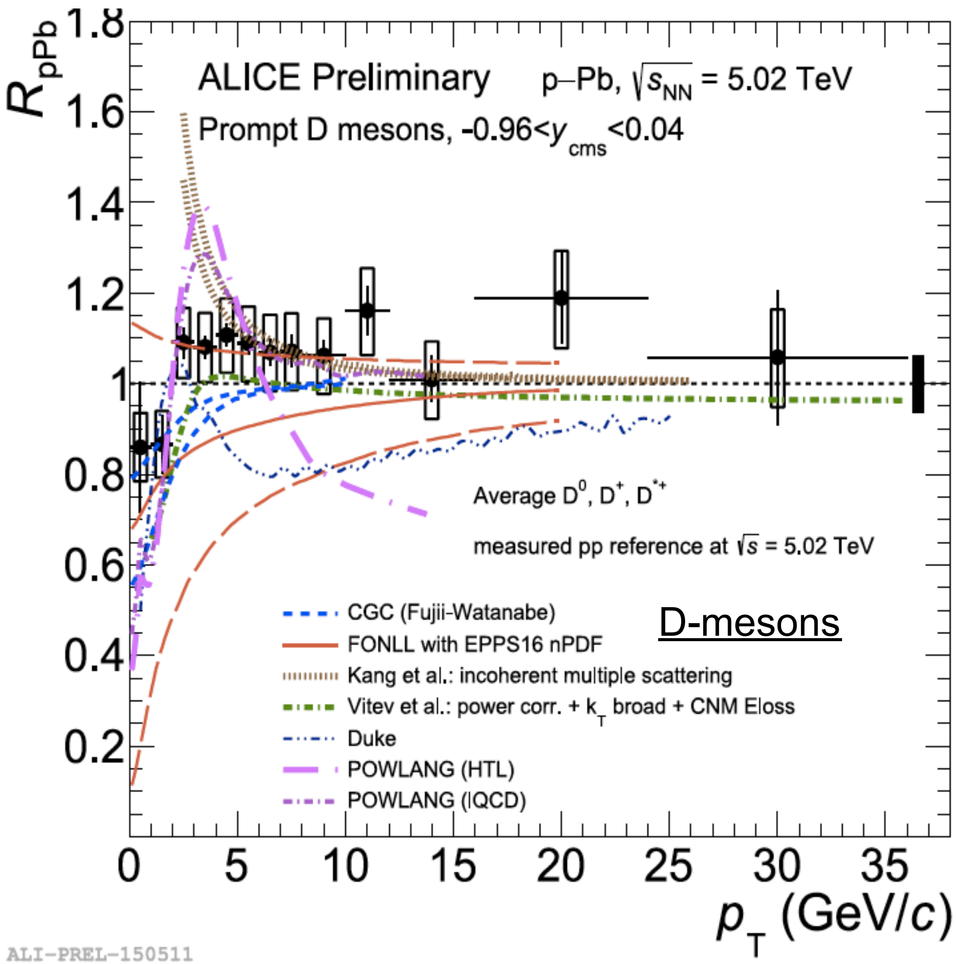
13 TeV
forward-rapidity

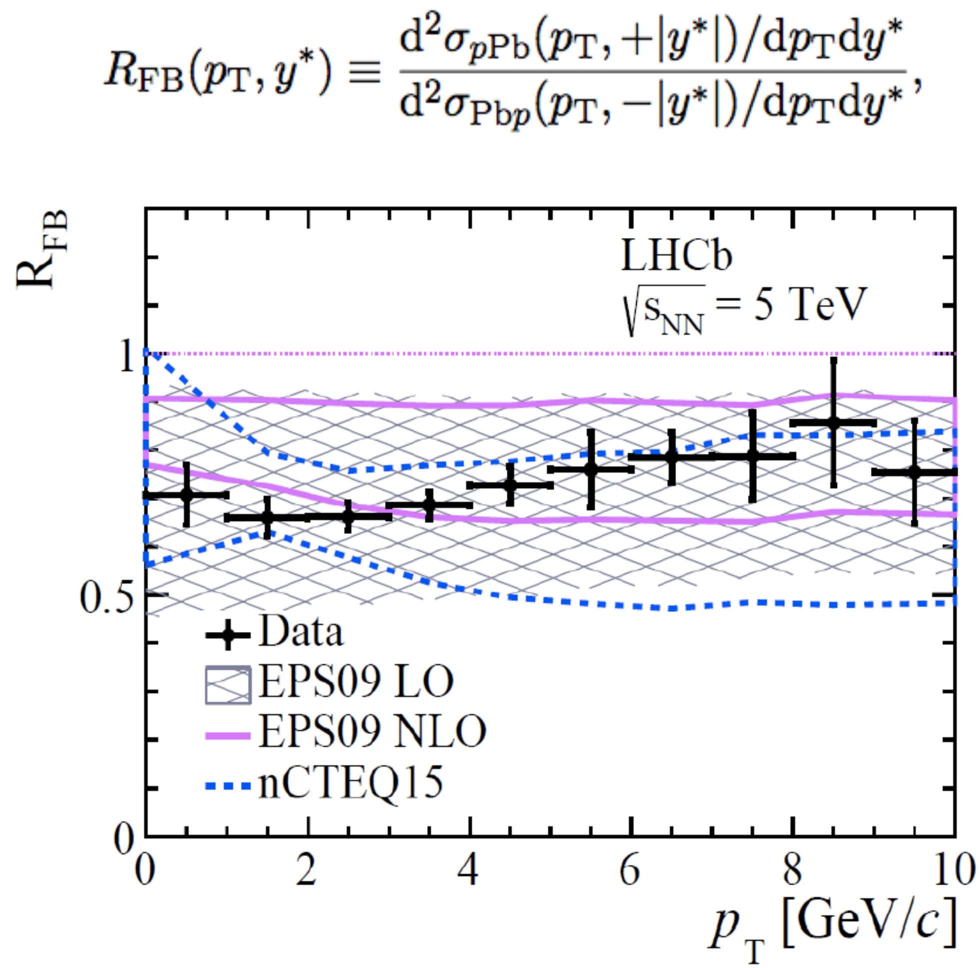


STAR, PRD 86 (2012) 072013, QM14
CDF, PRL 91 (2003) 241804
ALICE, JHEP 01(2012) 128, arXiv: 1702.00766
LHCb, JHEP 03 (2016) 159, 09 (2016) 013

- Charm hadron spectra well described by pQCD FONLL
  - data prefer upper bounds of FONLL calculations

p+A to Constrain Cold Nuclear Matter Effects





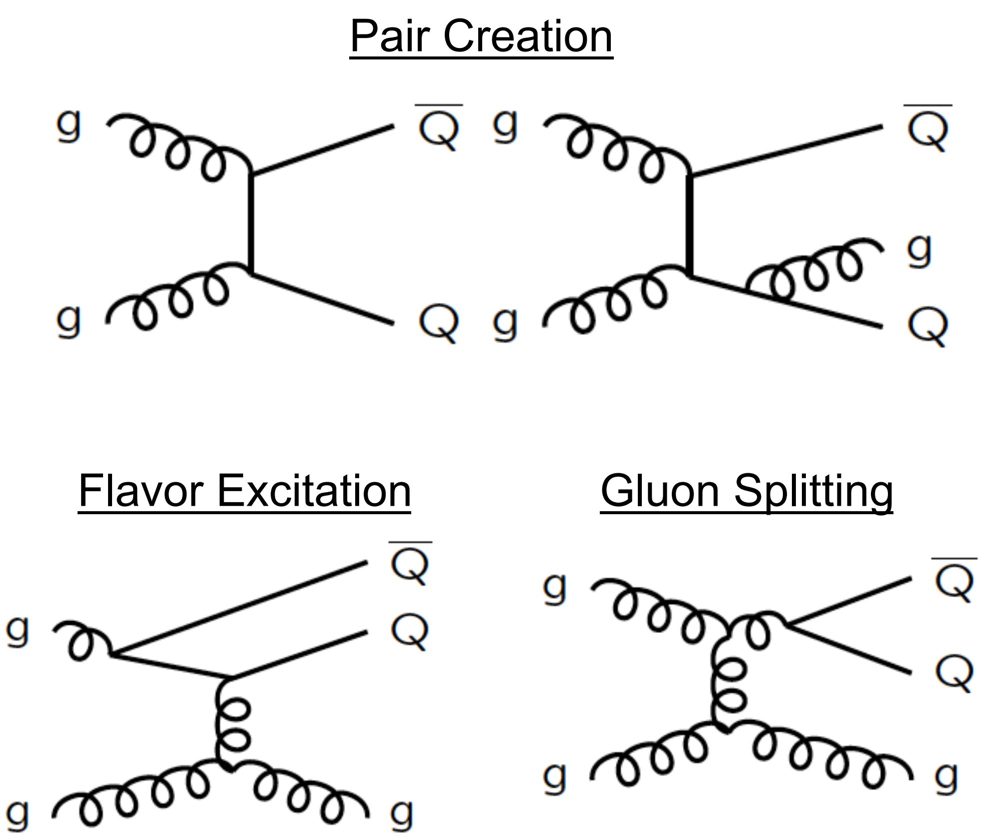
ALICE, PRC 94 (2016) 054908, QM18; LHCb, JHEP 10 (2017) 090

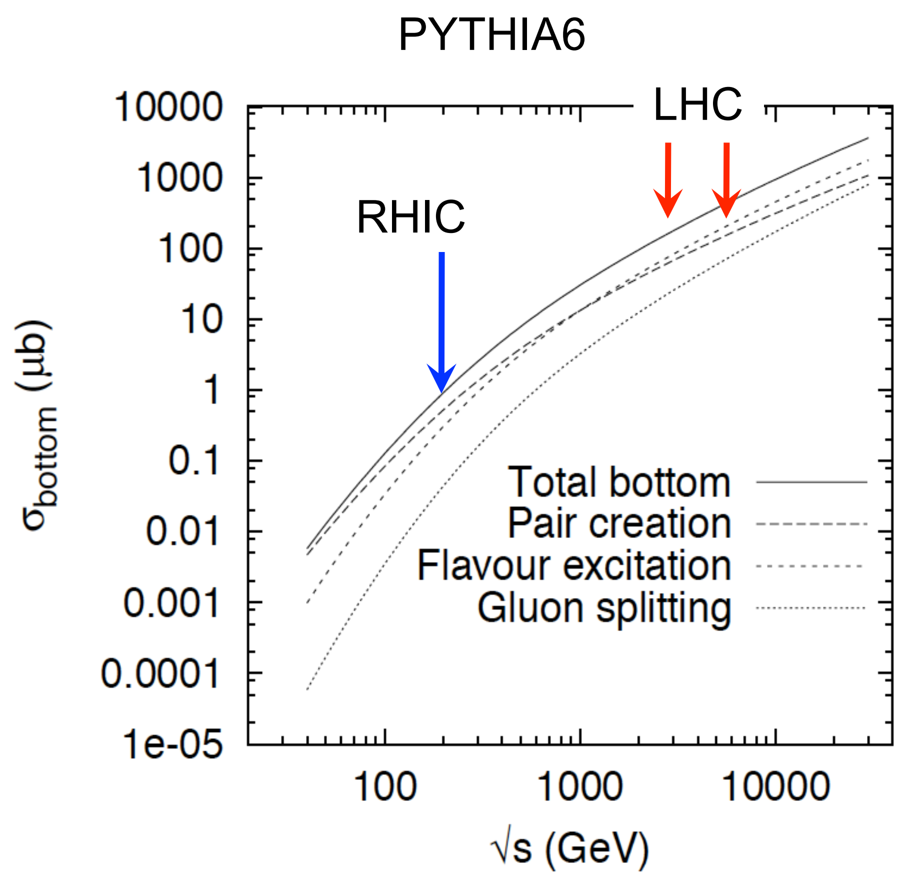
pQCD+nPDF / models with CNM effects describe R_{pPb} at mid-rapidity and F/B asymmetry reasonably well.

Uniqueness at RHIC

Uniqueness at RHIC

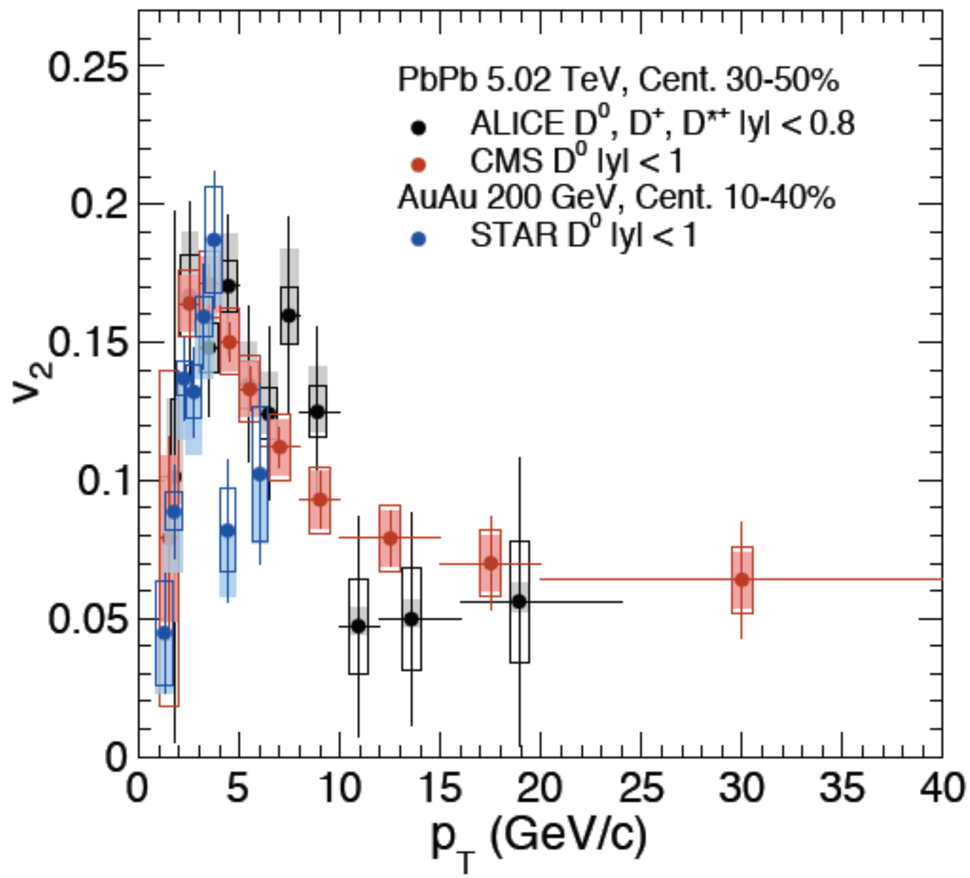
- dominated by pair creation, clean interpretation for experimental results

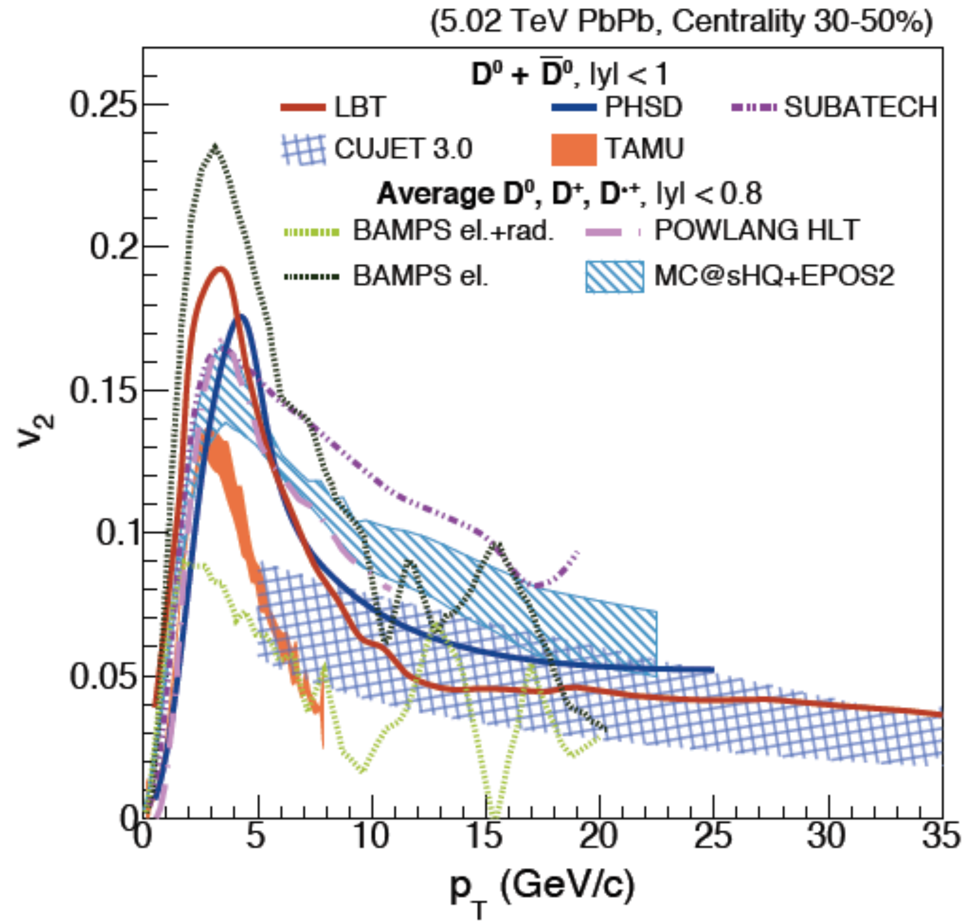




T. Sjostrand, EPJC17 (2000) 137

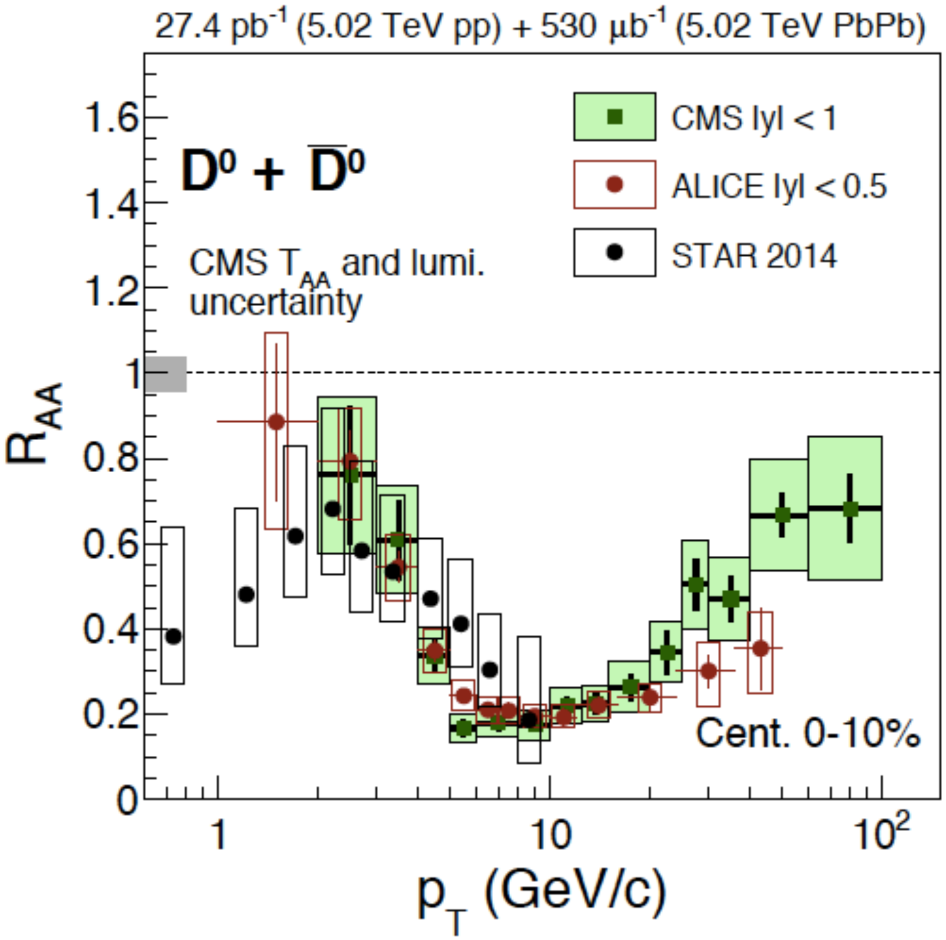
Compilation of D v_2 data from RHIC and LHC

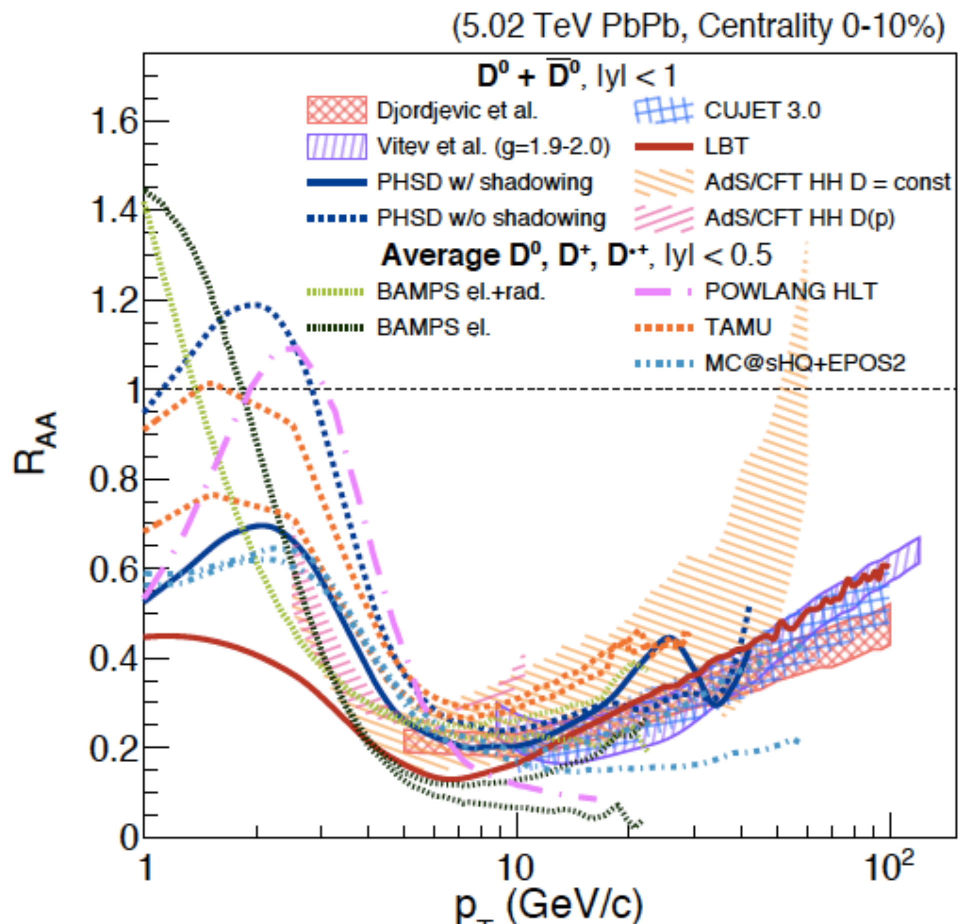




Courtesy: Y.J. Lee

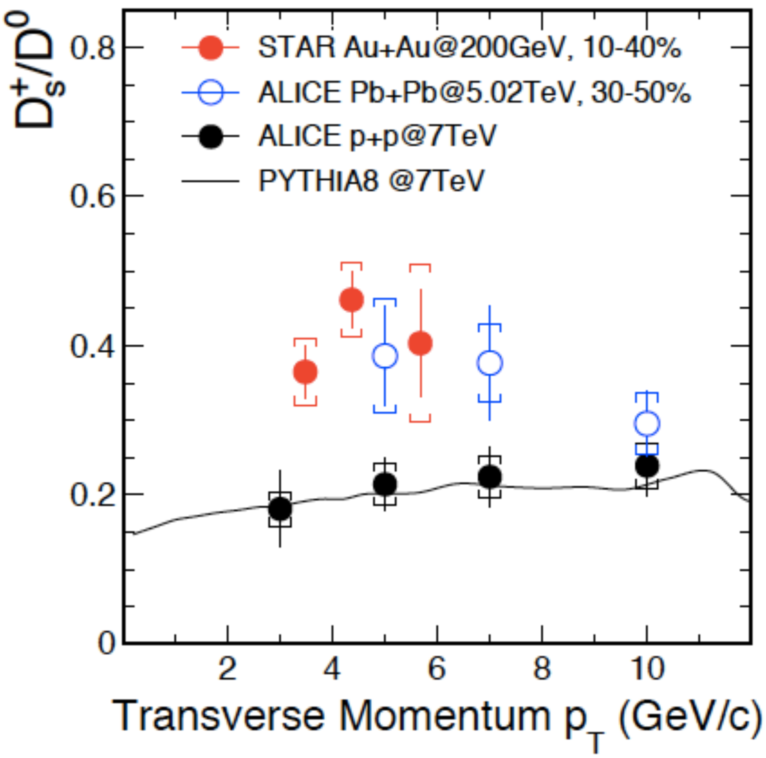
Compilation of D R_{AA} data from RHIC and LHC

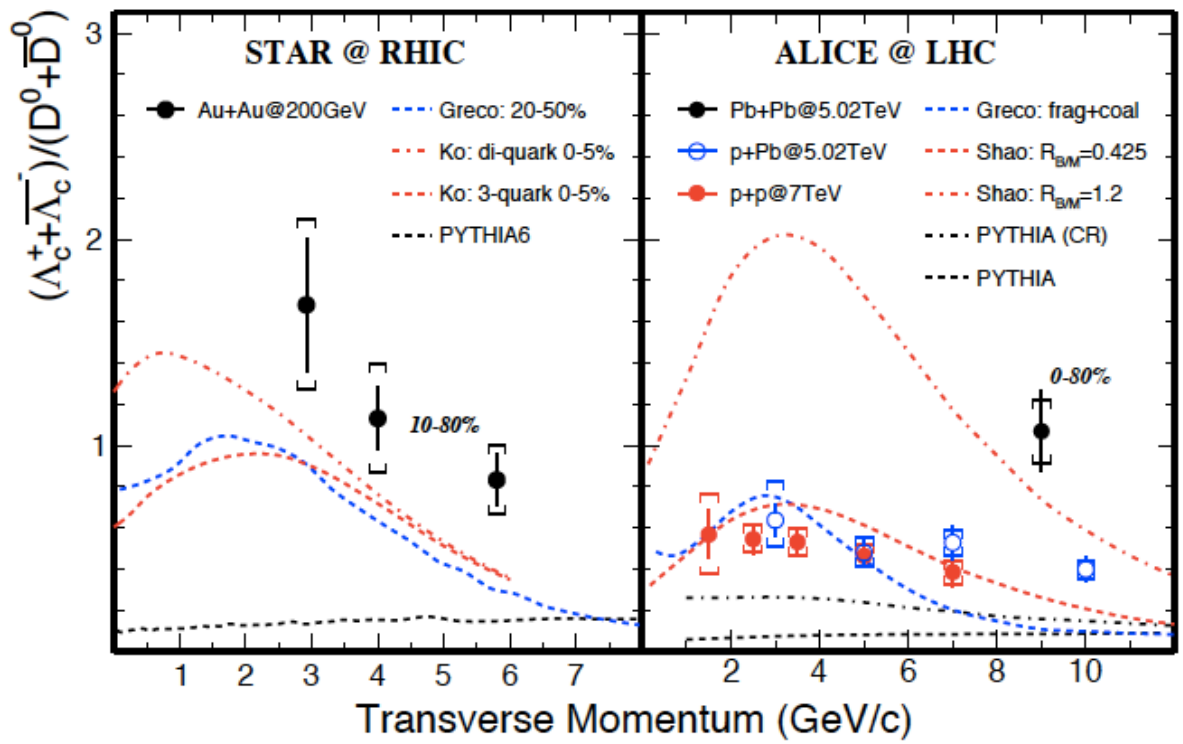




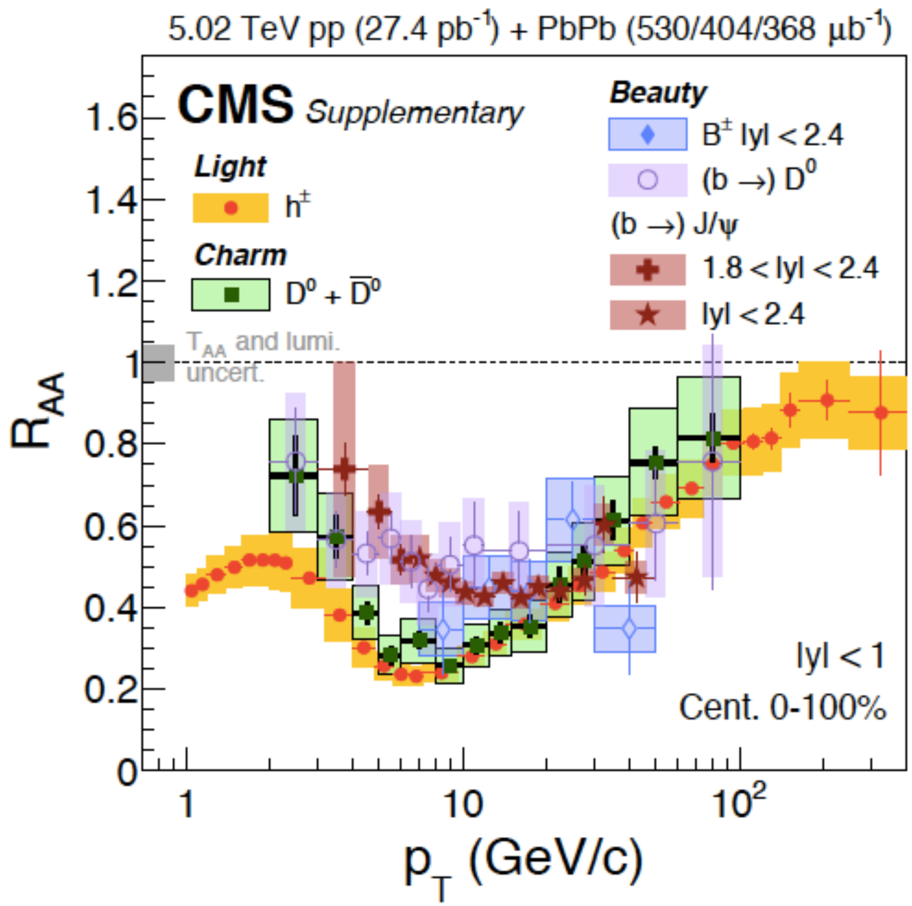
Courtesy: Y.J. Lee

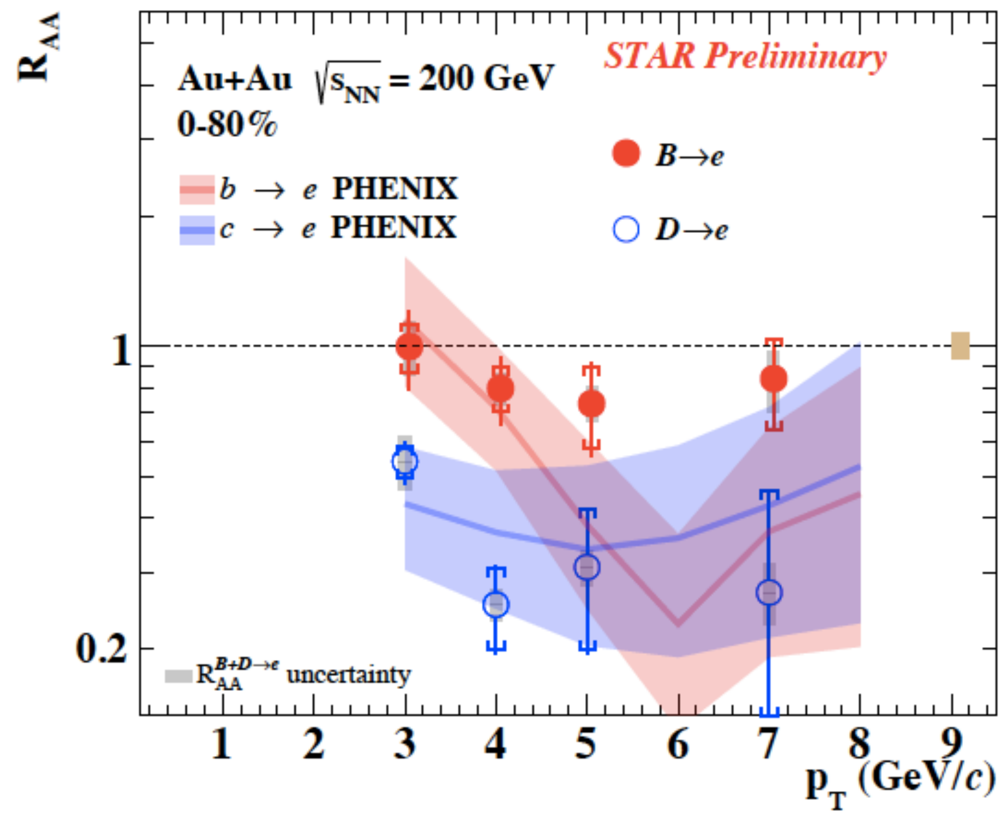
D_s/D^0 and Λ_c/D^0 from RHIC and LHC



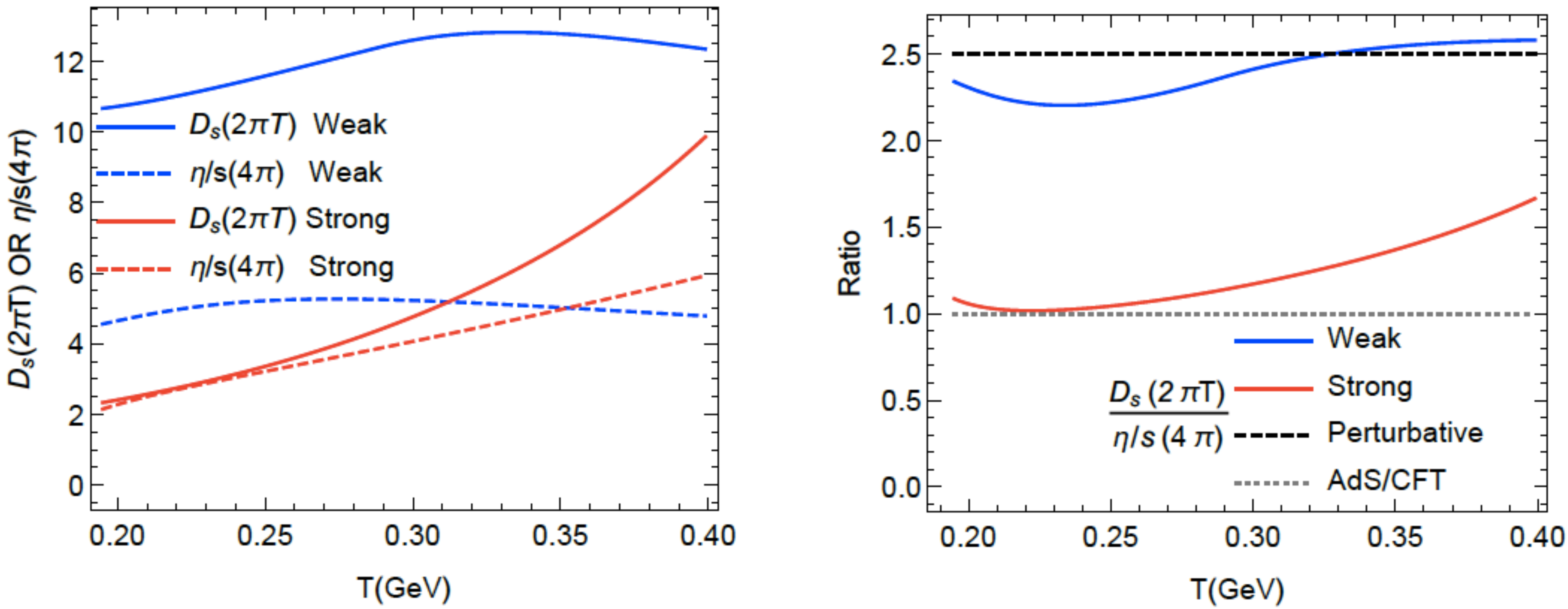


Compilation of Bottom R_{AA} from RHIC and LHC





Heavy Quark Diffusion and η/s



R. Rapp et al. 1803.03824