Recent Heavy-Flavor Results from STAR

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Lawrence Berkeley National Laboratory

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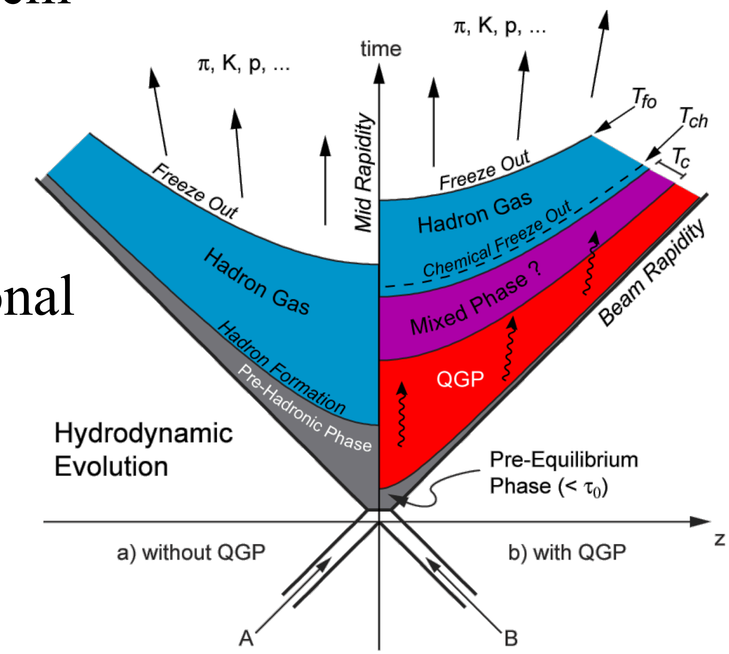
Contents

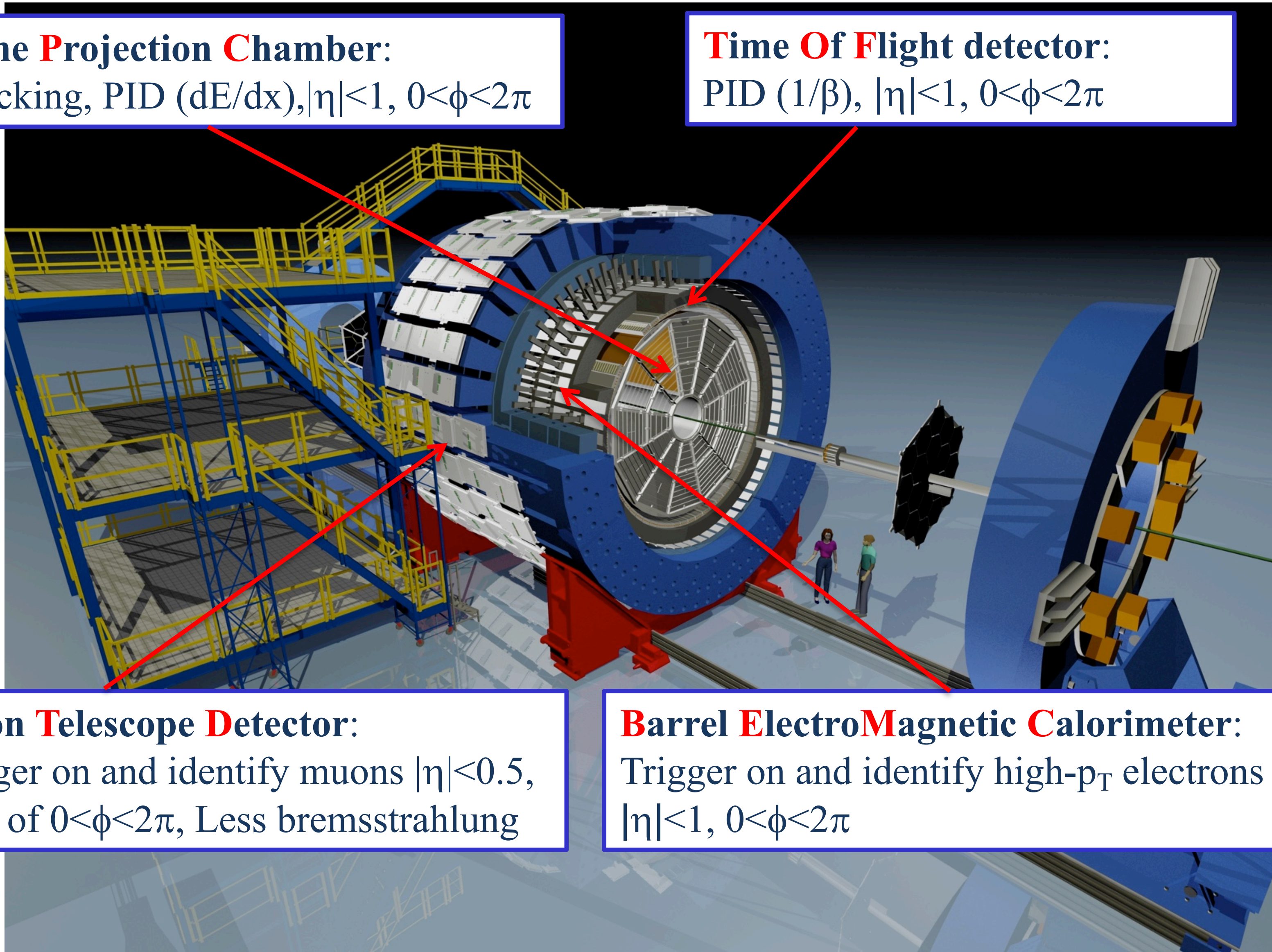
- Heavy quarks: $m_{c/b} >> \Lambda_{QCD}$, $T_{QGP(RHIC)}$
  - Produced early in heavy-ion collisions through hard scatterings
  - Experience the whole evolution of the system
    → good probe of medium properties



- Open heavy flavor ($Q\bar{q}, Qqq$)
  - In medium energy loss, radiative + collisional
    $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$
  - Charm quark diffusion, v_n
  - Hadronization mechanism, D_s, Λ_c^+

- Quarkonium ($Q\overline{Q}$)
  - Dissociation : $Q\overline{Q}$ potential color-screened in the medium
    - Sequential melting : different quarkonia dissociate at different temperatures
  - Regeneration

STAR Detector



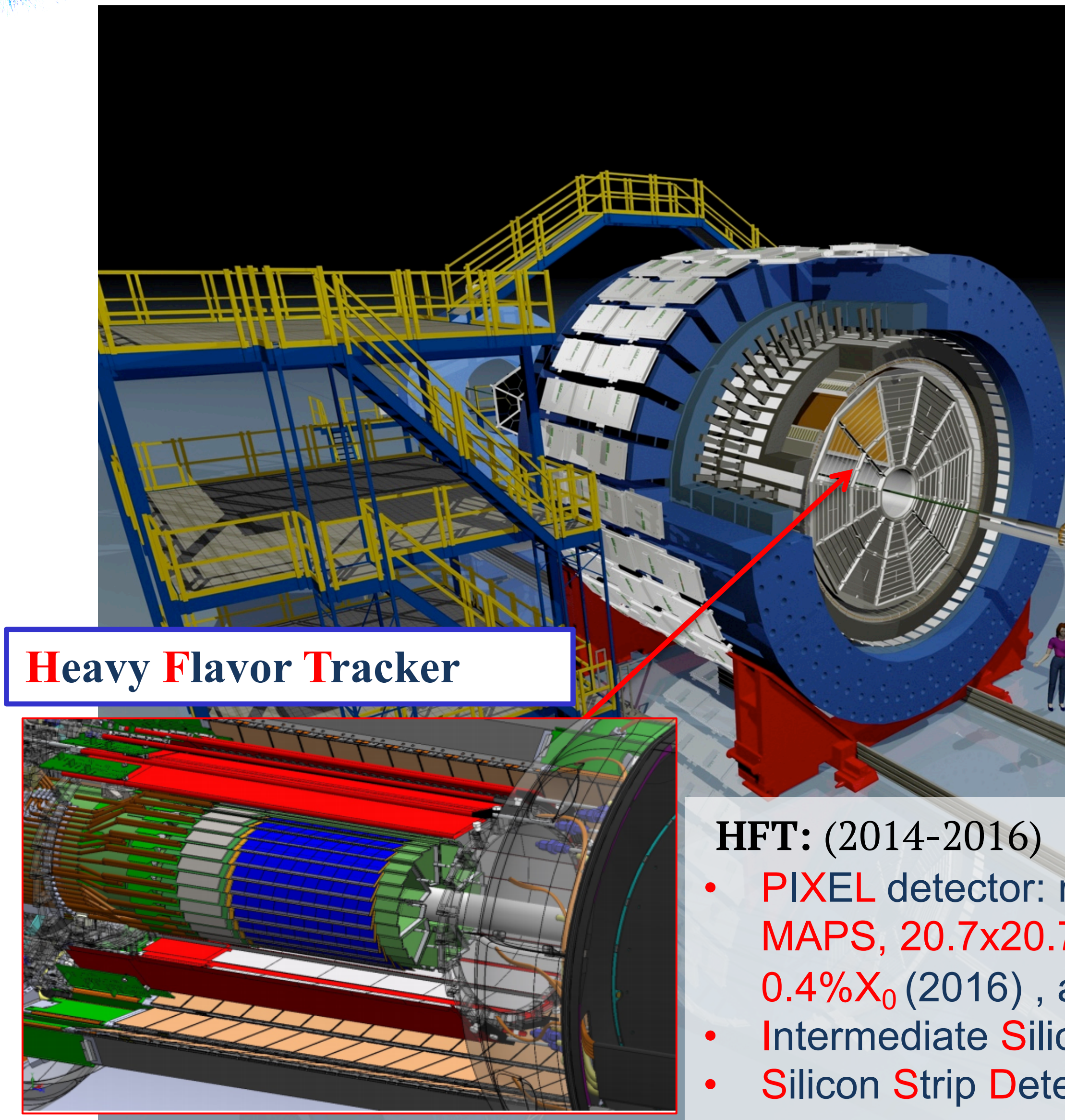
Time Projection Chamber:
Tracking, PID (dE/dx), $|\eta|<1$, $0<\phi<2\pi$

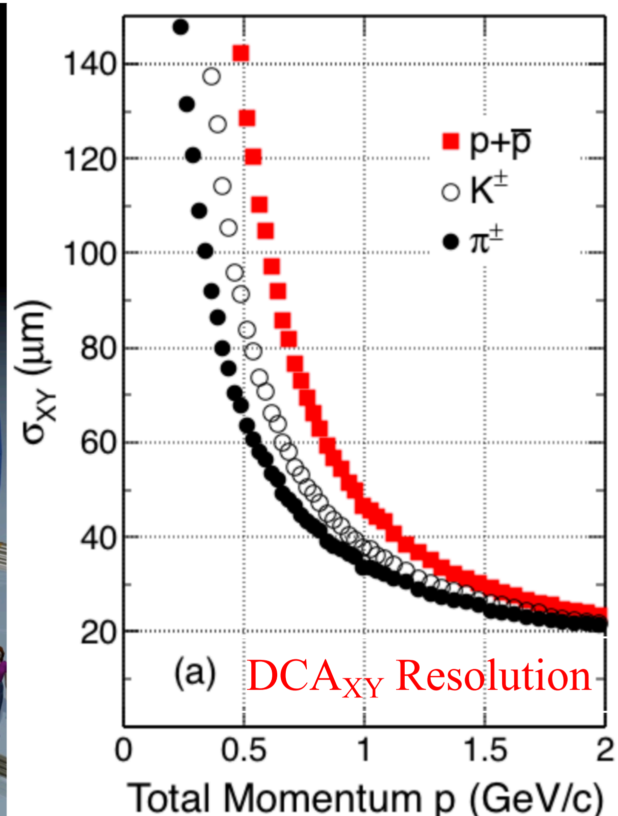
Time Of Flight detector:
PID ($1/\beta$), $|\eta|<1$, $0<\phi<2\pi$

Muon Telescope Detector:
Trigger on and identify muons $|\eta|<0.5$,
45% of $0<\phi<2\pi$, Less bremsstrahlung

Barrel ElectroMagnetic Calorimeter:
Trigger on and identify high-p_T electrons
$|\eta|<1$, $0<\phi<2\pi$

Heavy Flavor Tracker





Phys. Rev. C 99, (2019) 034908

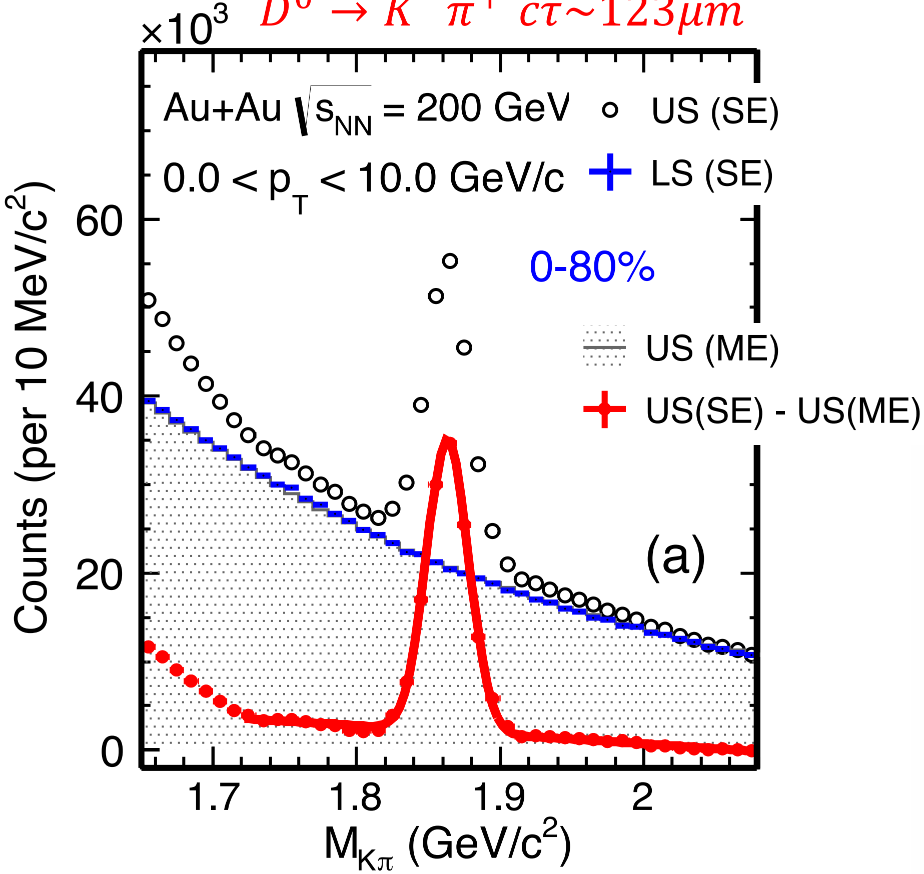
HFT: (2014-2016)

- PIXEL detector: r ~2.8 & 8 cm, MAPS, 20.7x20.7 μm^2, 0.5%X_0 (2014) 0.4%X_0 (2016) , air-cooled
- Intermediate Silicon Tracker: r ~14 cm
- Silicon Strip Detector: r ~22 cm

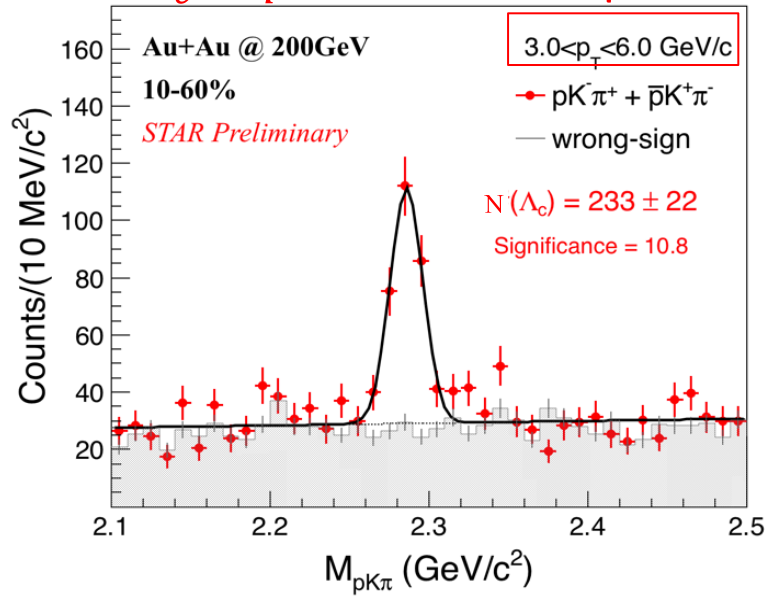
Open Charm Signals

Jan Vanek on June 11th Tue.

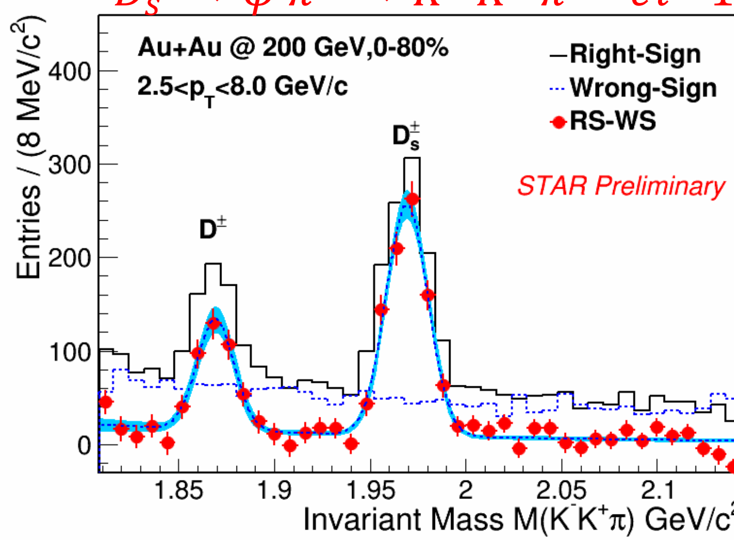
$D^0 \rightarrow K^- \pi^+ \;\; c\tau \sim 123 \mu m$



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

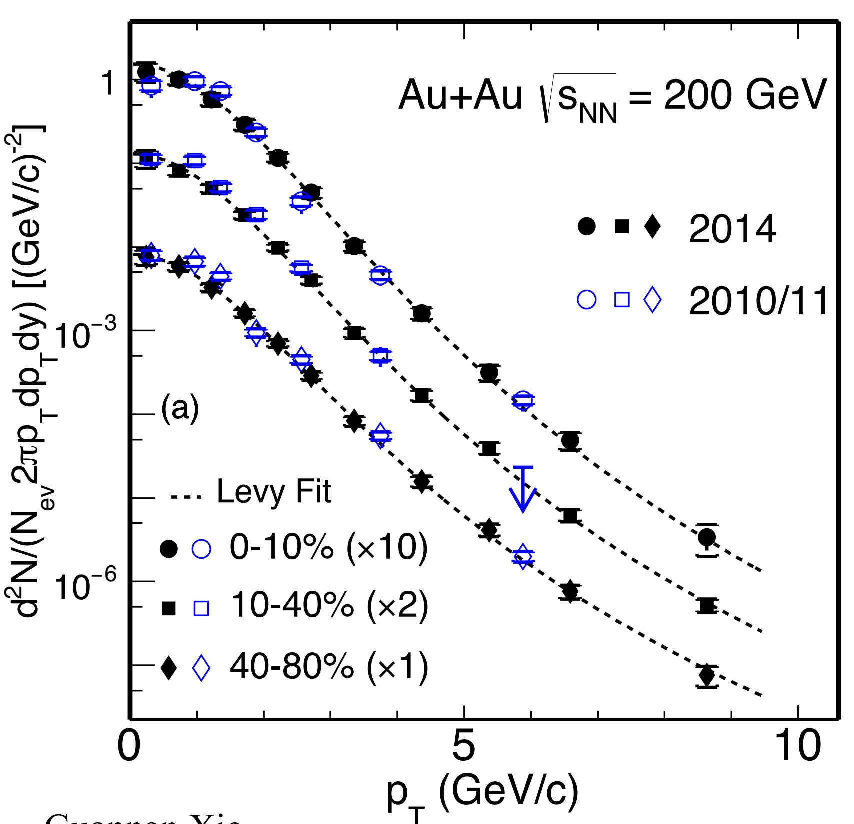


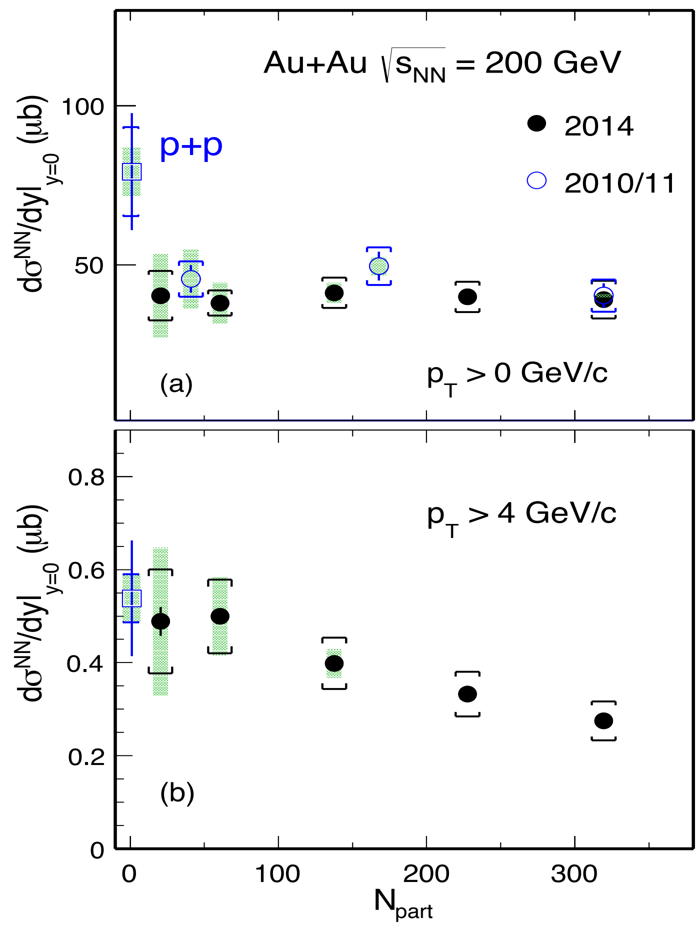
$D_s^+ \rightarrow \phi\, \pi^+ \rightarrow K^+ K^- \pi^+ \;\; c\tau \sim 151 \mu m$



D^0 p_T Spectra

- D^0 measurement was much improved with the help of HFT
  - A factor of >15, in terms of significance
- p_T-integrated D^0 cross-section is nearly independent of centrality, and smaller than in p+p collisions. However, for p_T > 4 GeV/c it increases towards peripheral collisions.

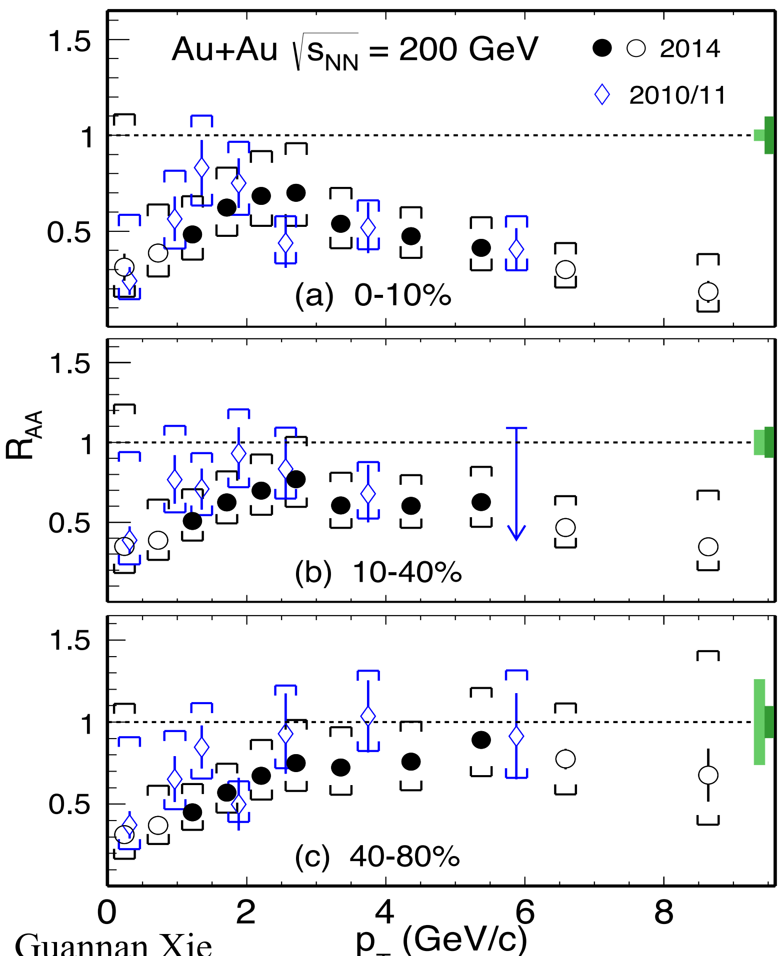


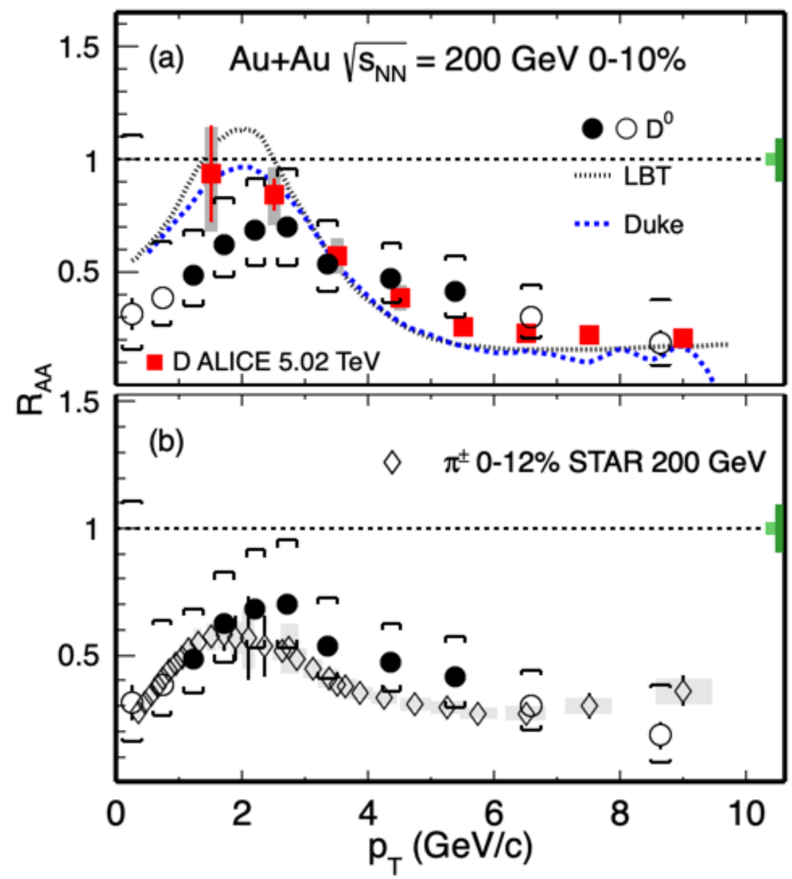


Phys. Rev. C 99, (2019) 034908
Phys. Rev. Lett. 121, (2018) 229901
Phys. Rev. D 86, (2012) 072013.

D^0 R_{AA}

- $R_{AA} < 1$ in the 0-10% centrality interval for all p_T
- Suppression at high p_T increases towards more central collisions
- Similar suppression trend as D-mesons at LHC and high-p_T pions at RHIC

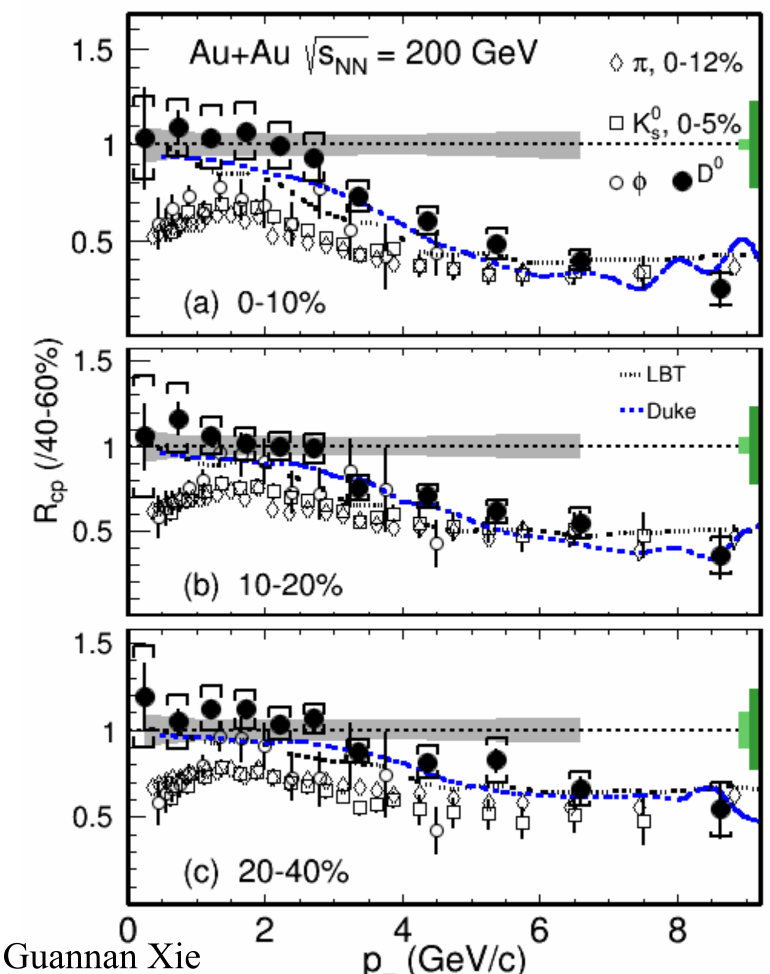


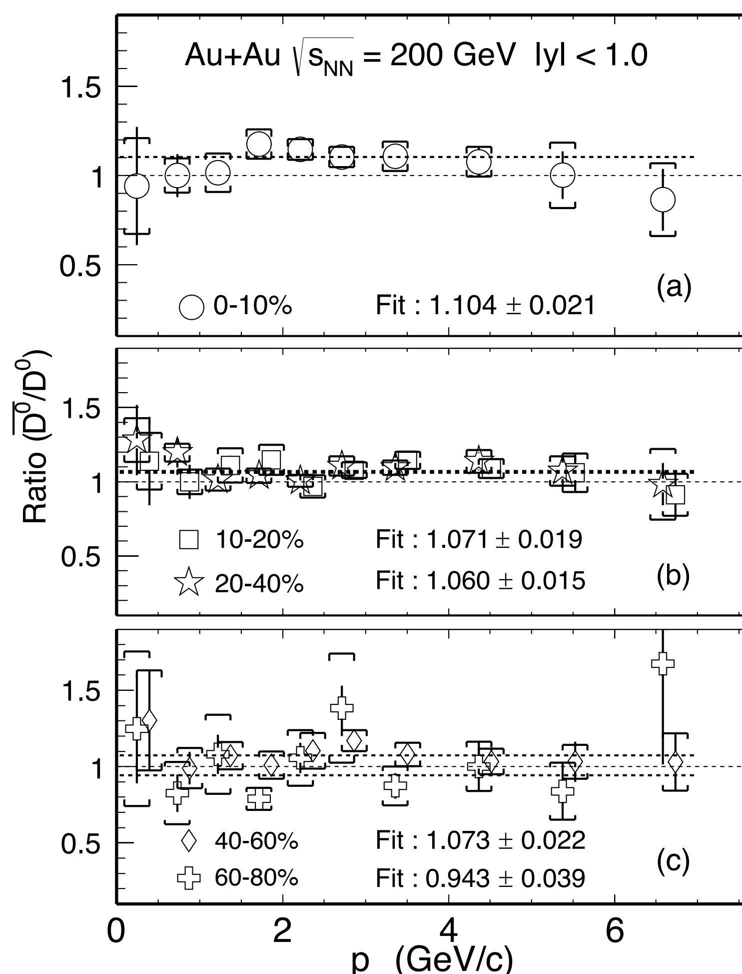


STAR:Phys. Lett. B 655 (2007) 104, Phys. Rev. C 99, (2019) 034908
ALICE: JHEP 1810 (2018) 174,
LBT: Phys. Rev. C 94 (2016) 014909 +private comm.
DUKE: PRC 92 (2015) 024907+private comm.

D^0 R_{CP} and $\overline{D^0}/D^0$ Ratio

- Significant suppression at high p_T .
- Reasonable agreement with theoretical calculations
- $\overline{D^0}/D^0$ ratio is larger than 1, possibly due to finite baryon density





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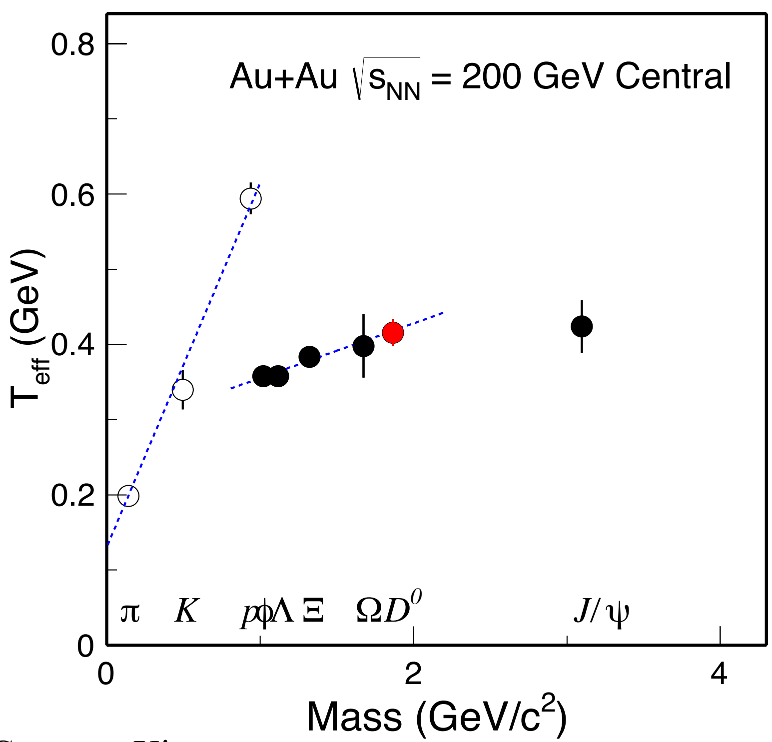
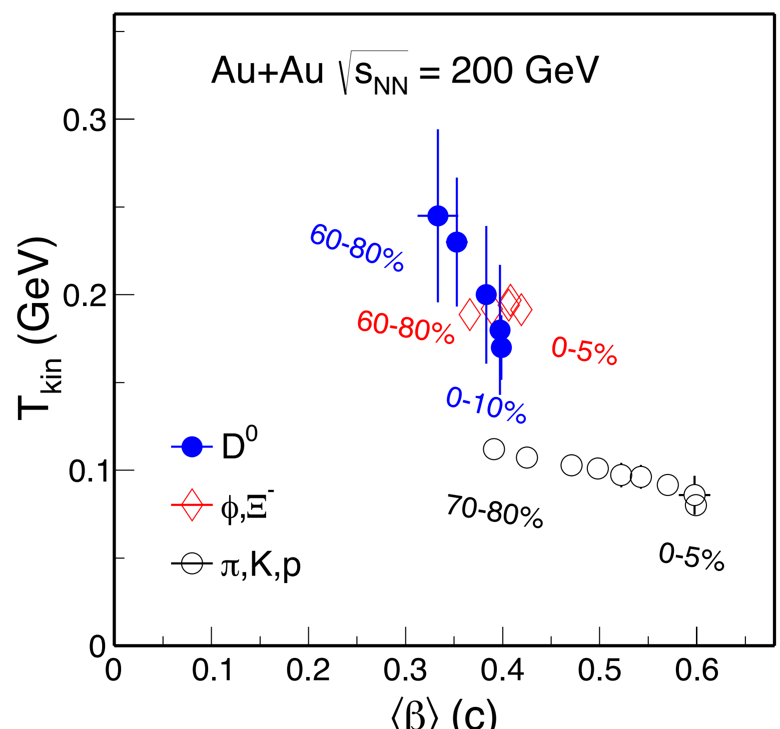
D^0 Radial Flow

- Exponential fit to the m_T spectra : collective behavior, T_{eff} slope parameter follows the same trend as multi-strange hadrons
- Blast Wave fits (p_T < 5 GeV/c) :
  $T_{kin}(\boldsymbol{D^0}) \sim T_{kin}(\phi,\Xi) > T_{kin}(\pi,K,p)$ and $\beta(\boldsymbol{D^0}) \sim \beta(\phi,\Xi) < \beta(\pi,K,p)$
  → suggests earlier freeze-out of $\boldsymbol{D^0}$ compared to light-flavor hadrons.

$T_{eff} = T_{fo} + m_0 \langle \beta_T \rangle^2$

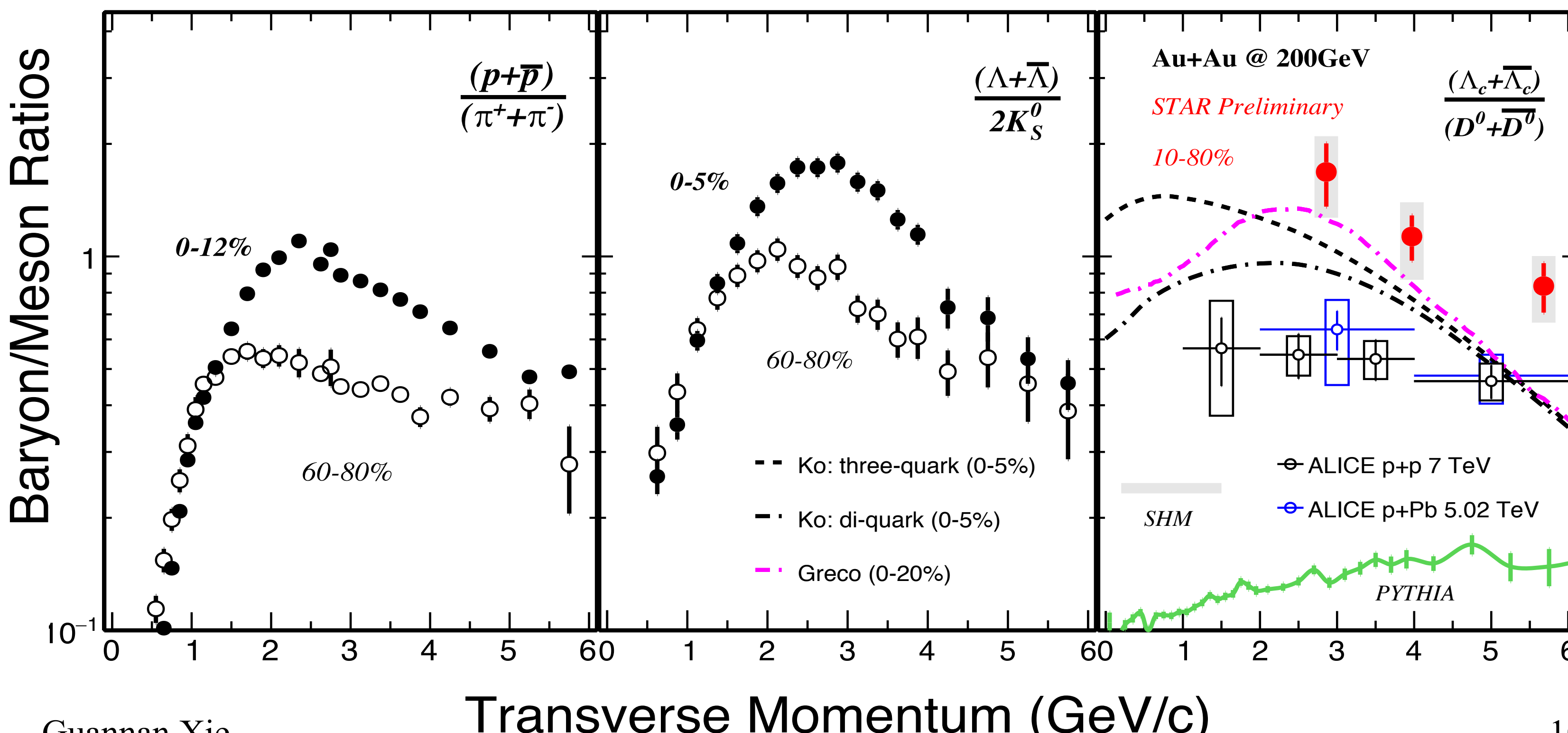




Phys. Rev. C 99, (2019) 034908

Λ_c/D^0 : p_T Dependence

- Significant enhancement of Λ_c/D^0 compared to PYTHIA/fragmentation baseline and p+p, p+Pb at LHC
- The Λ_c/D^0 ratio is comparable with light flavor baryon-to-meson ratios
- Consistent with charm quark hadronization via coalescence
  -- higher than model predictions, particularly at higher p_T

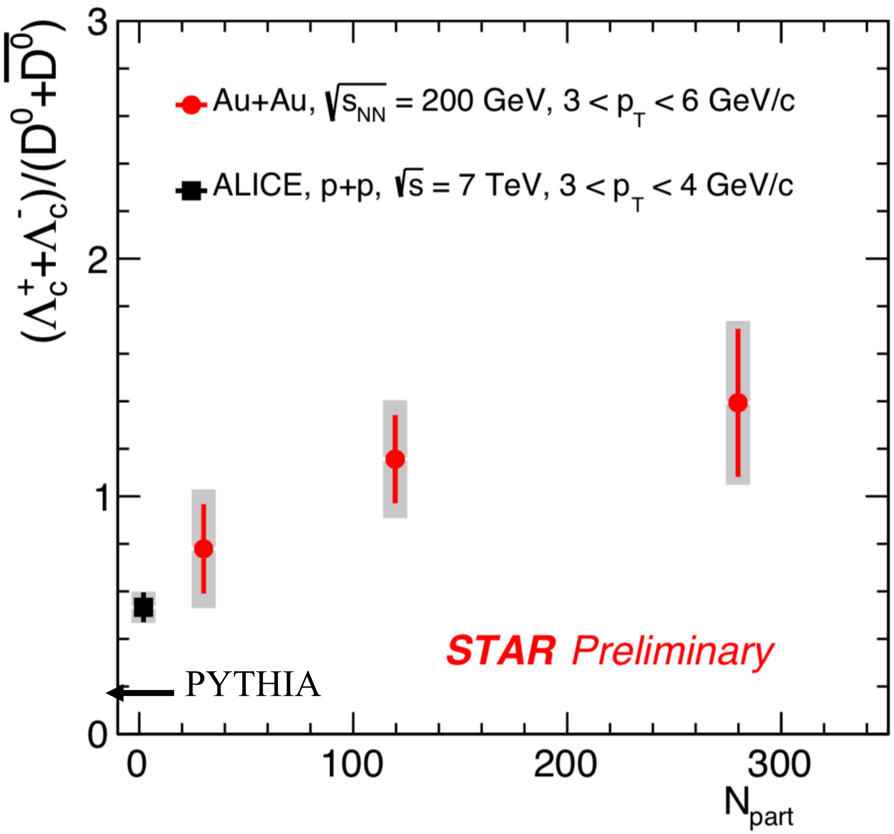


Ko: PRC 79 (2009) 044905 Greco: Eur.Phys.J.C (2018) 78:348
SHM: PRC 79 (2009) 044905 ALICE: JHEP 04 (2018) 108

Guannan Xie

Λ_c/D^0 : Centrality Dependence

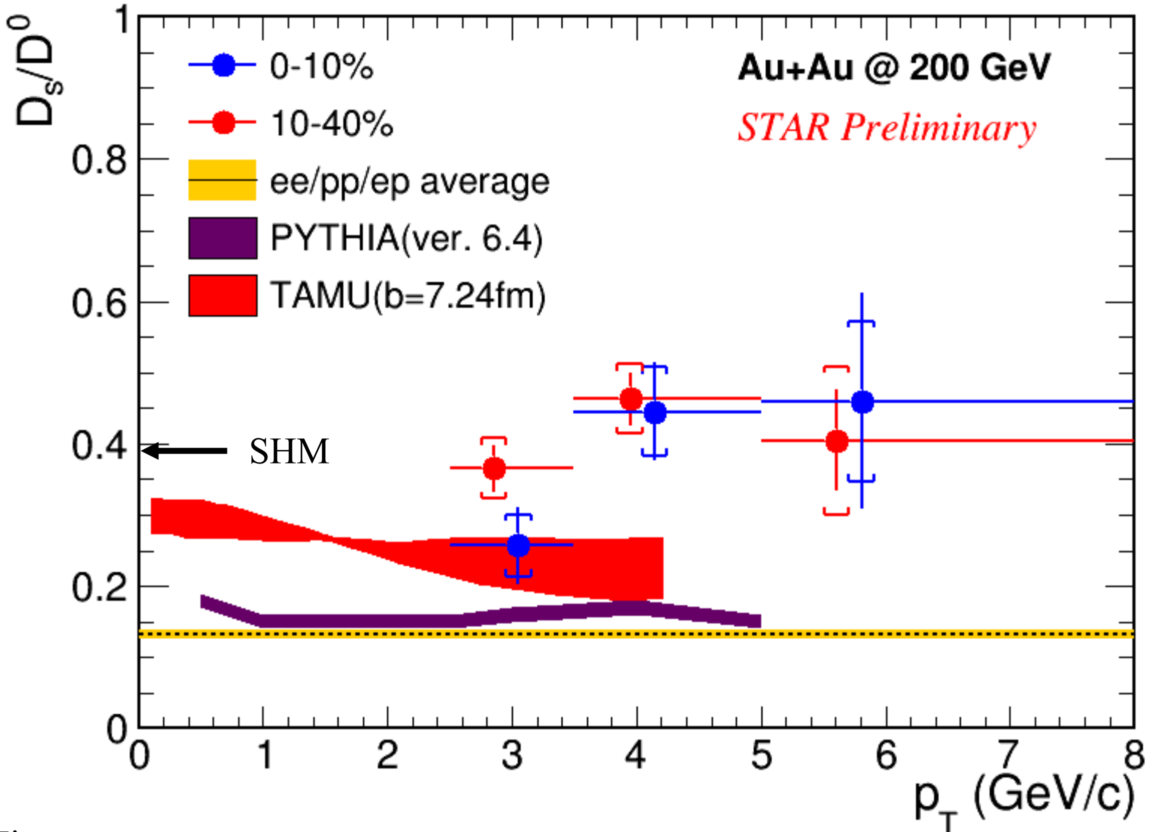
- Trends of Λ_c/D^0 ratio increases from peripheral to central collisions
- Ratio for peripheral Au+Au comparable with p+p value at 7 TeV



ALICE: JHEP 04 (2018) 108

D_s/D^0 Enhancement

- Strong D_s/D^0 enhancement observed in central A+A collisions w.r.t fragmentation baseline
  - Strangeness enhancement and coalescence hadronization
- Enhancement is larger than p+p, PYTHIA predictions

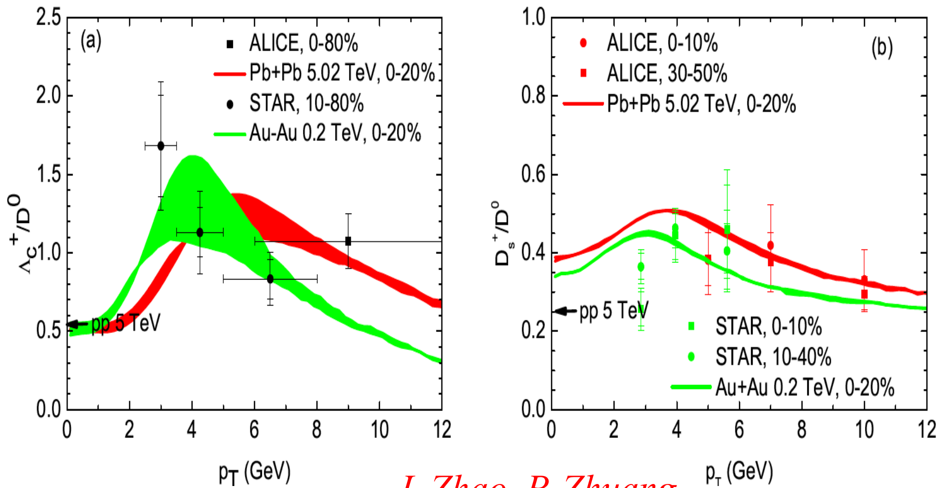


ep/pp/ep avg: M Lisovyi, et. al. EPJ C 76, (2016) 397
TAMU: H. Min et al. PRL 110, (2013) 112301
SHM: A. Andronic et al., PLB 571 (2003) 36

Recent Model Predictions

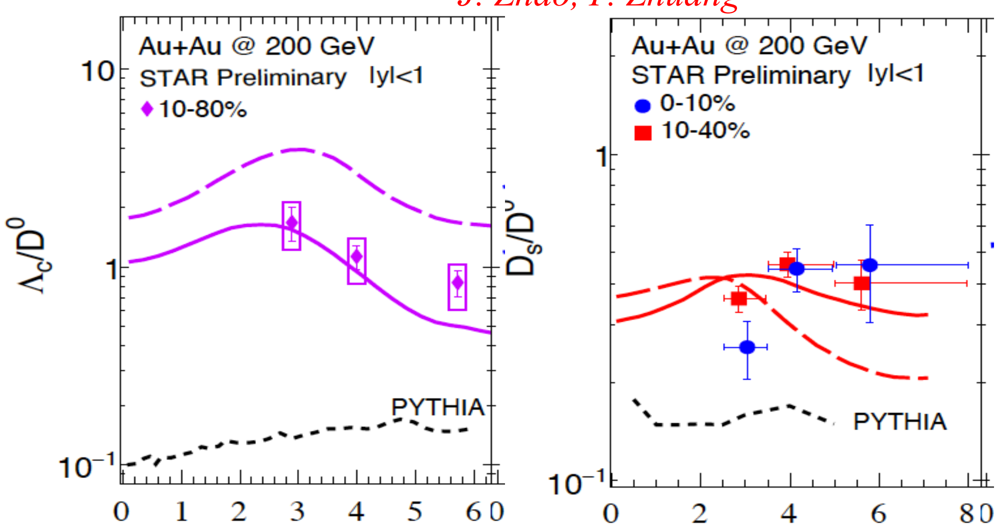
- Recent model predictions developed fast

M.He, R. Rapp

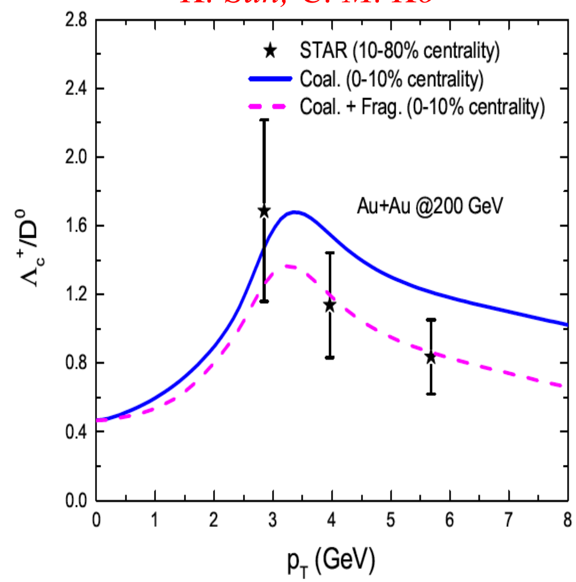


M. He and R. Rapp arXiv:1905.09216
K. Sun, C. M. Ko, etc. arXiv:1905.09774
J. Zhao, P. Zhuang, etc arXiv:1805.10858

J. Zhao, P. Zhuang



K. Sun, C. M. Ko



Total Charm Cross-section

- Total charm cross-section is extracted from the various charm hadron measurements

-- D^0 yields are measured down to zero p_T
-- For $D^{+/-}$ and D_s, Levy function fits to measured spectra are used for extrapolation.
-- For Λ_c, fits of three models to data are used and differences are included in systematics

Charm Hadron		Cross Section dσ/dy (μb)
AuAu 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**
pp 200 GeV	**Total**	**130 ± 30 ± 26**

*** derived using Λ_c^+/D^0 ratio in 10-80%**

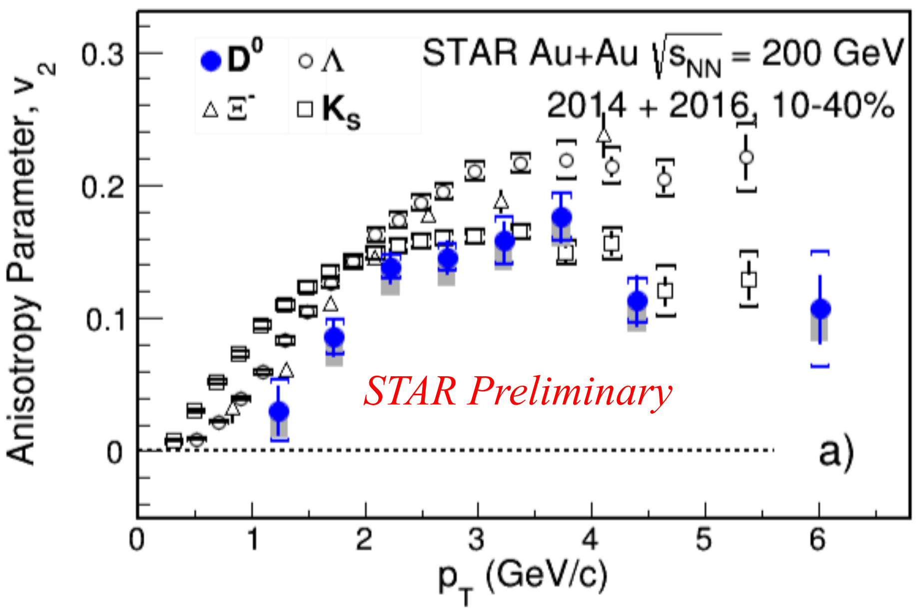
- Total charm cross-section per nucleon-nucleon collision is consistent with p+p value within uncertainties, but redistributed among different charm hadron species

D^0 Elliptic Flow

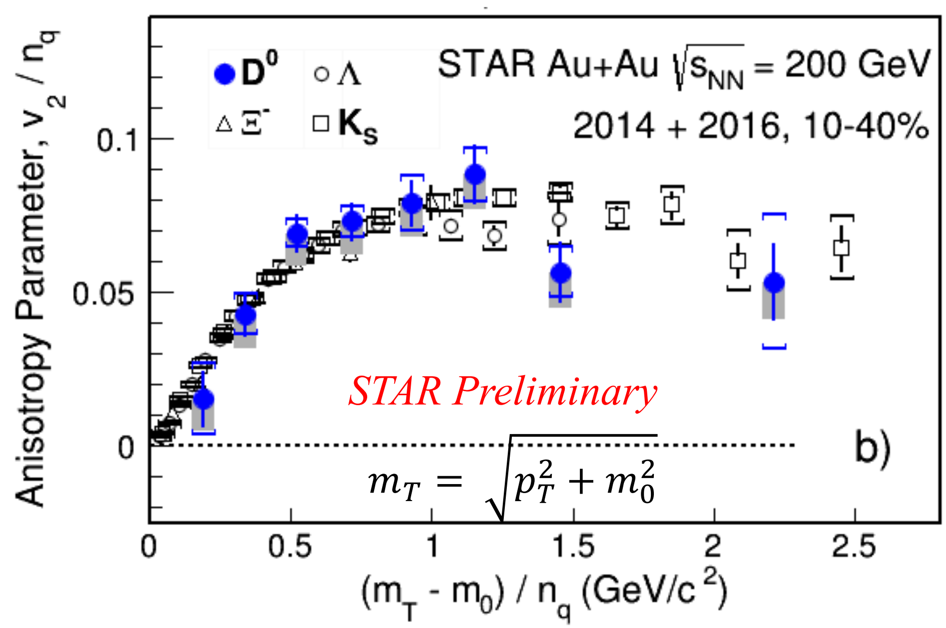
- Mass ordering at p_T < 2 GeV/c (hydrodynamic behavior)
- $v_2(D^0)$ follows the $(m_T - m_0)$ NCQ scaling as light flavor hadrons below 1 GeV/c^2

  → Evidence of charm quarks flowing with the medium

2014 +2016 Dataset



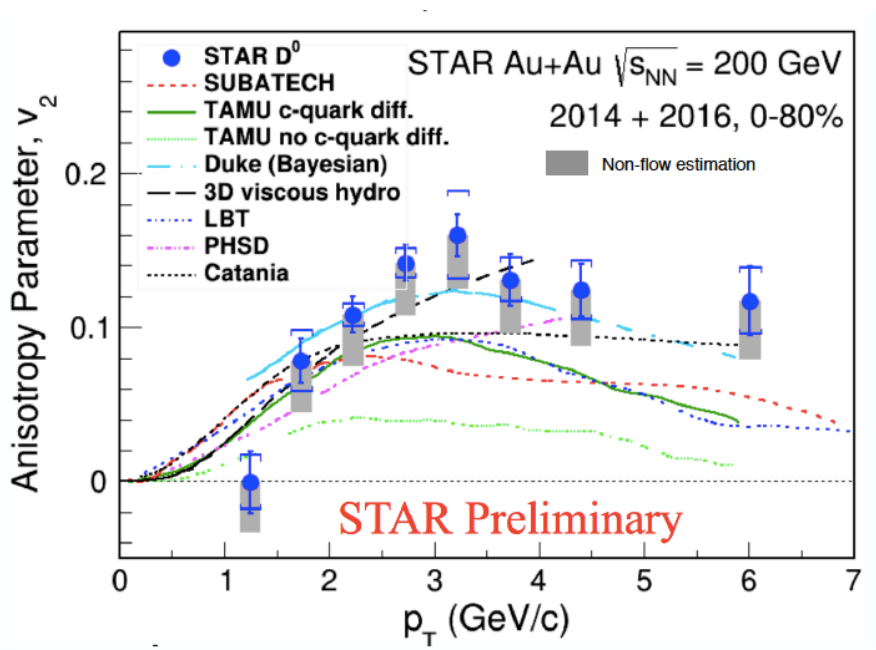
2014 data, Phys. Rev. Lett. 118, (2017) 212301

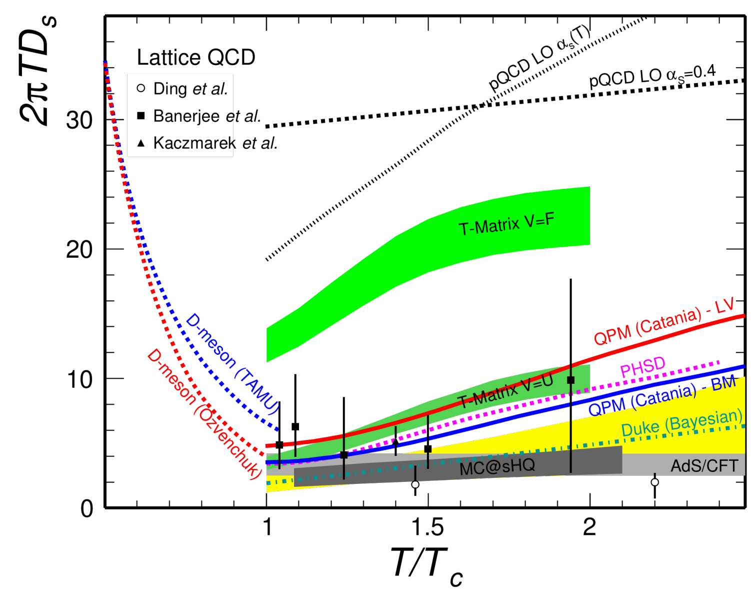


D^0 Elliptic Flow

- High precision of v_2 data offers stringent constraints to model calculations. Transport models with charm quark diffusion in the medium can describe the data
- Sensitivity to charm diffusion coefficient $2\pi TD_s$ and its temperature dependence

2014+2016 Dataset



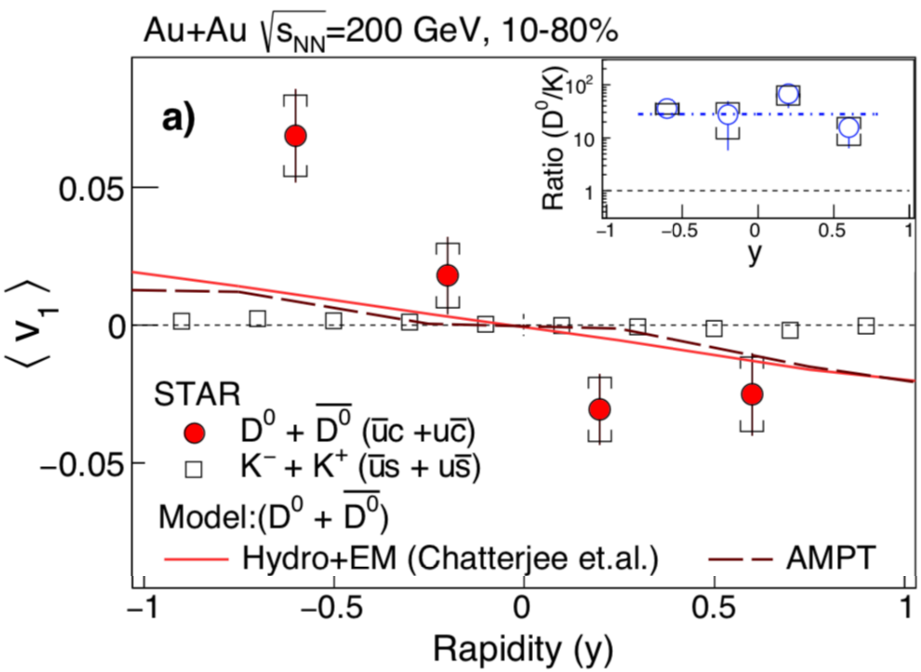


X. Dong and V. Greco, Progress in Particle and Nuclear Physics, 104 (2019) 97
[1] SUBATECH: Phys Rev C 90, 054909 (2014), Phys Rev C 92, (2015) 014910
[2] TAMU: Phys Rev C 86, (2012) 014903 Phys Rev Lett 110, (2013) 112301 [3] Duke: Phys Rev C 92, (2015) 024907 [4] 3D viscous hydro: Phys Rev C 86, (2012) 024911 [5] LBT: Phys Rev C 94, (2016) 014909 [6] PHSD: Phys ReV 90, (2014) 051901 , Phys ReV 90, (2014) 051901 [7] Catania: Phys ReV 96, (2017) 044905

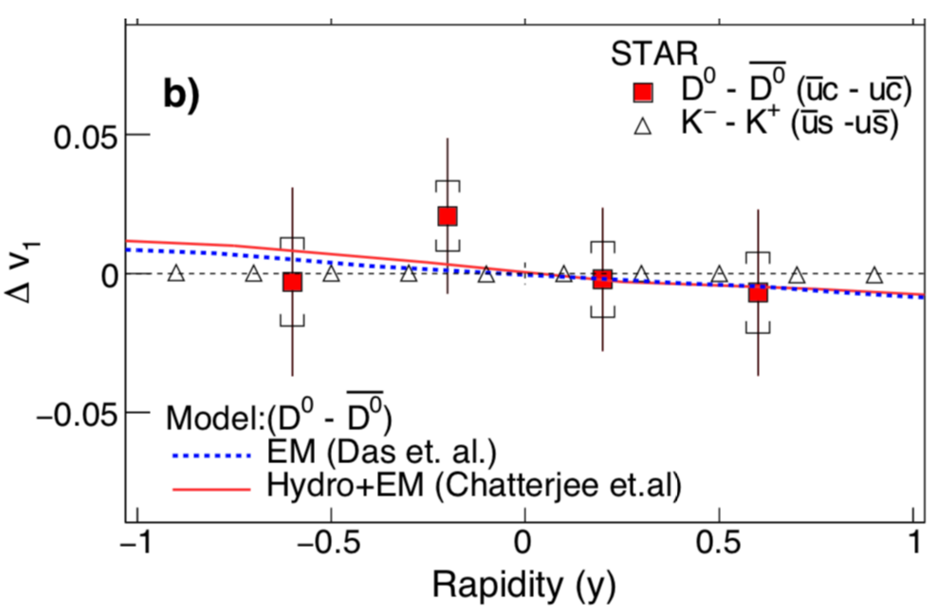
D^0 Directed Flow (v_1)

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

- Charm quarks interact with bulk medium → $\boldsymbol{D^0}$ v_1 sensitive to the initial tilt of the source (bulk) *S. Chatterjee and P. Bożek, PRL 120 (2018) 192301*
- Charm and anti-charm quarks can be deflected differently by the initial EM field → difference between $\boldsymbol{D^0}$ and $\overline{\boldsymbol{D^0}}$ v_1 sensitive to EM field
- First observation of non-zero (negative) $\boldsymbol{D^0}$($\overline{\boldsymbol{D^0}}$) v_1 slope, much larger than that of kaons $D^0 + \overline{\boldsymbol{D^0}}$ $dv_1/dy = -0.081 \pm 0.021(stat) \pm 0.017(sys)$
- More precise data are needed for Δv_1 $d\Delta v_1/dy = -0.041 \pm 0.041(stat) \pm 0.020(sys)$

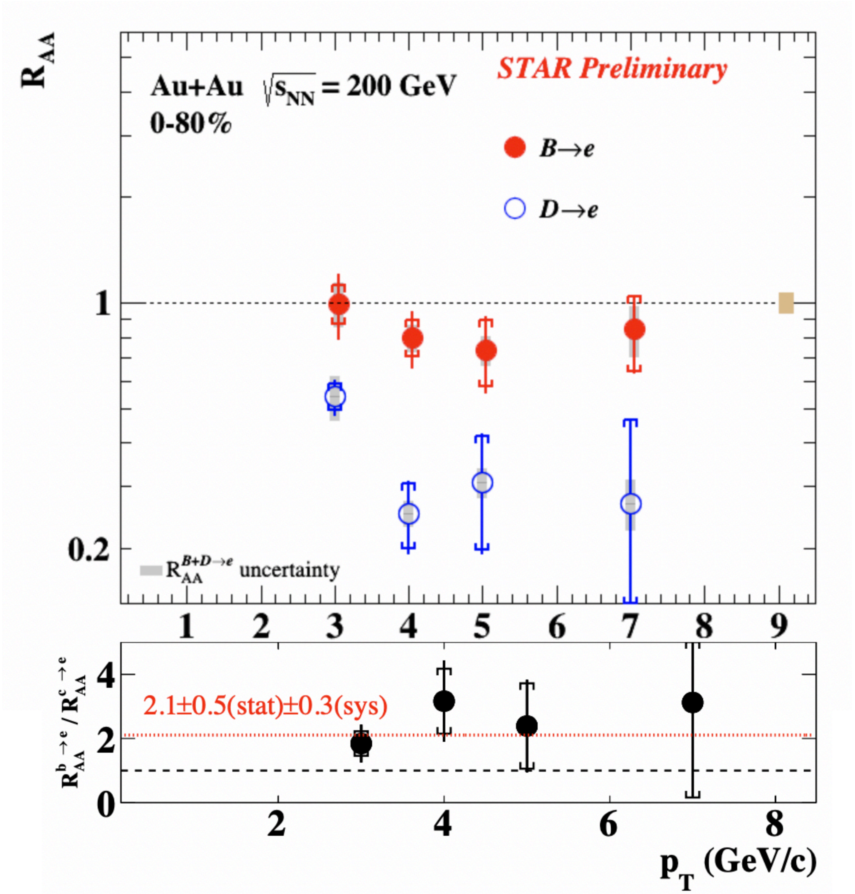


STAR, arXiv:1905.02052



Charm to Bottom Through Single e Channel

- Strong interaction of charm with the medium. How about bottom?
- Impact parameter method to separate c/b→electrons
- Indication of less suppression for *B*→*e* than *D*→*e* (~2 σ): consistent with $\Delta E_c > \Delta E_b$. Measurements with improved precision on the way



Quarkonium Signals

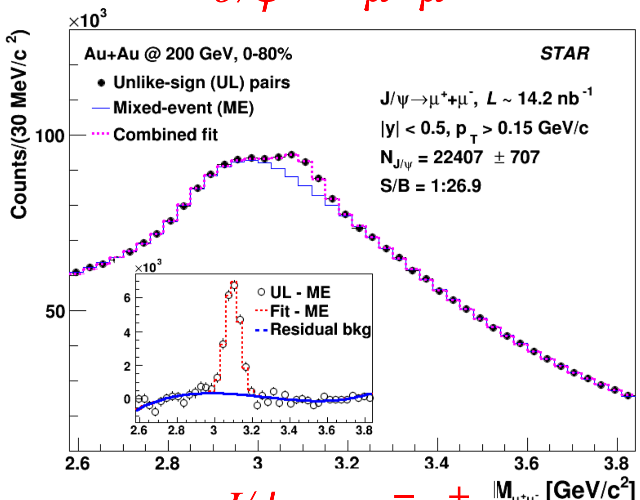
Te-Chuan Huang on June 13th Thu.

J/ψ: Large cross section at RHIC energy, interplay of several effects

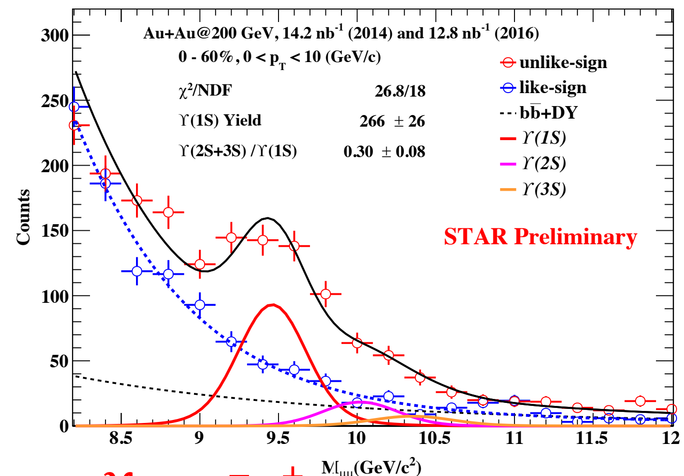
ϒ: A cleaner probe at RHIC, small production cross section

arXiv:1905.13669 , submitted to P.L.B

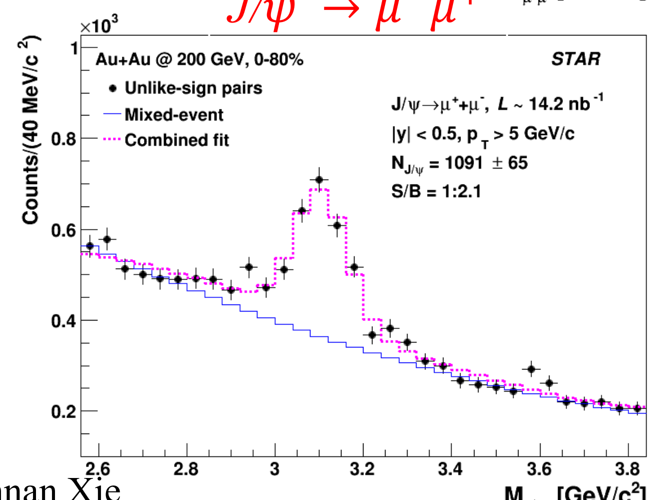
$J/\psi \rightarrow \mu^- \mu^+$



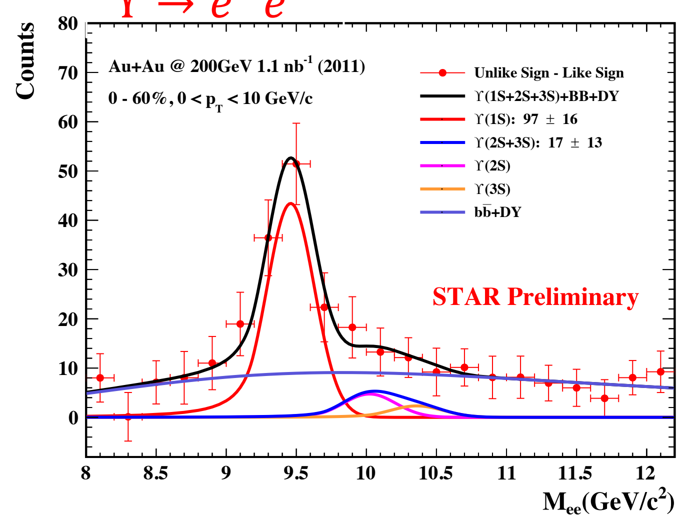
$\Upsilon \rightarrow \mu^- \mu^+$



$J/\psi \rightarrow \mu^- \mu^+$



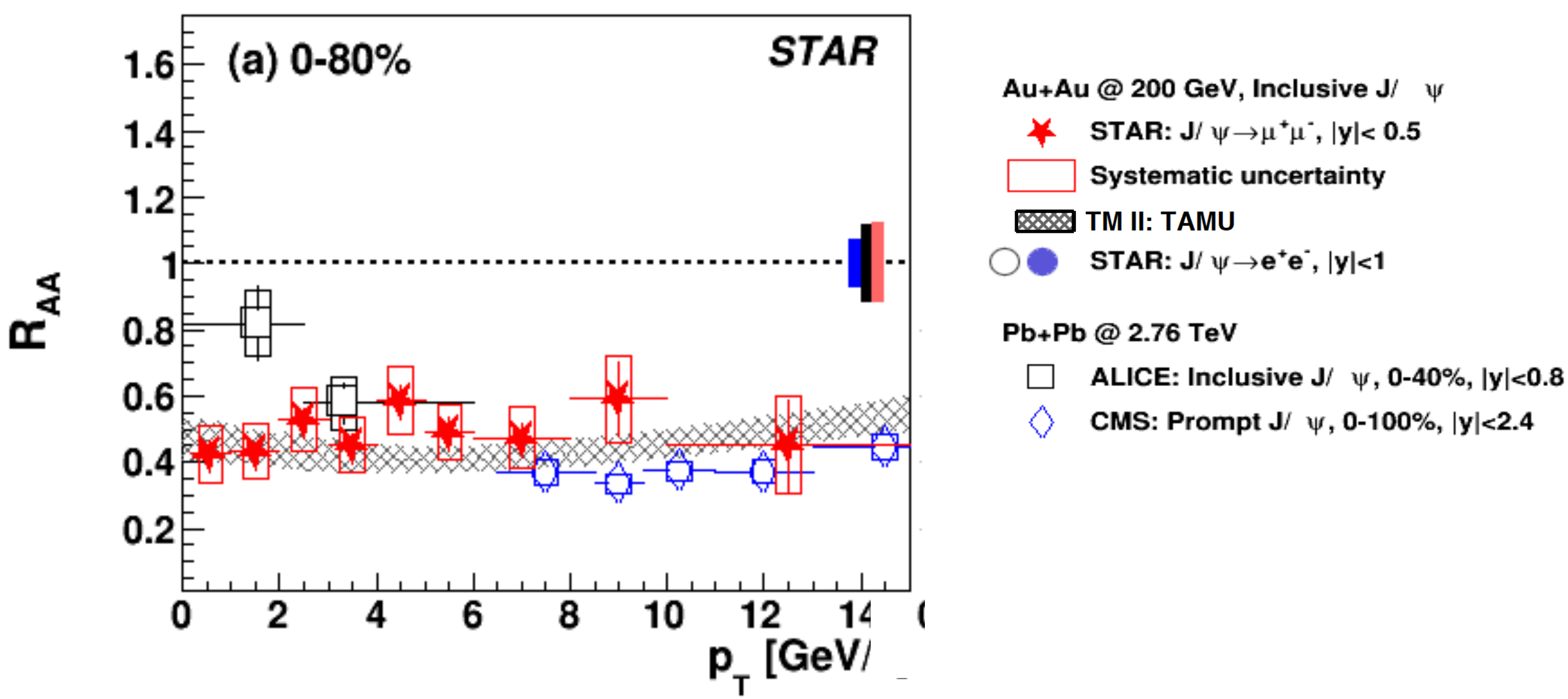
$\Upsilon \rightarrow e^- e^+$



J/ψ R_{AA} vs. p_T

- Suppressed for a wide kinematic range
- Low p_T : regeneration
- High p_T : initial production

Inclusive J/ψ from STAR



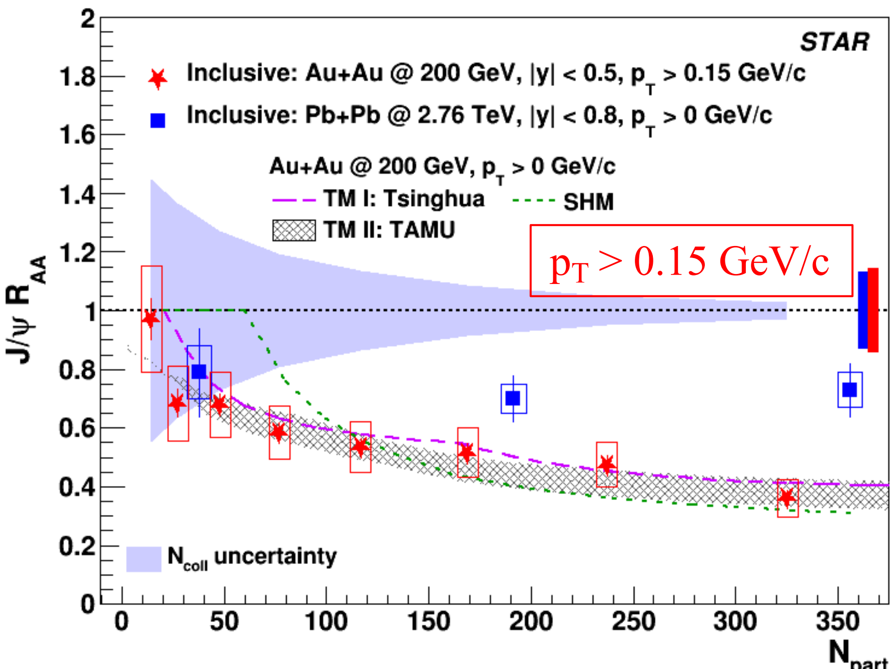
arXiv:1905.13669 submitted to P.L.B; ALICE : PLB 734 (2014) 314
PHENIX : PRL 98 (2007) 232301; CMS: JHEP 05 (2012) 063.
Model II at RHIC: PRC 82 (2010) 064905

J/ψ R_{AA} vs. Centrality

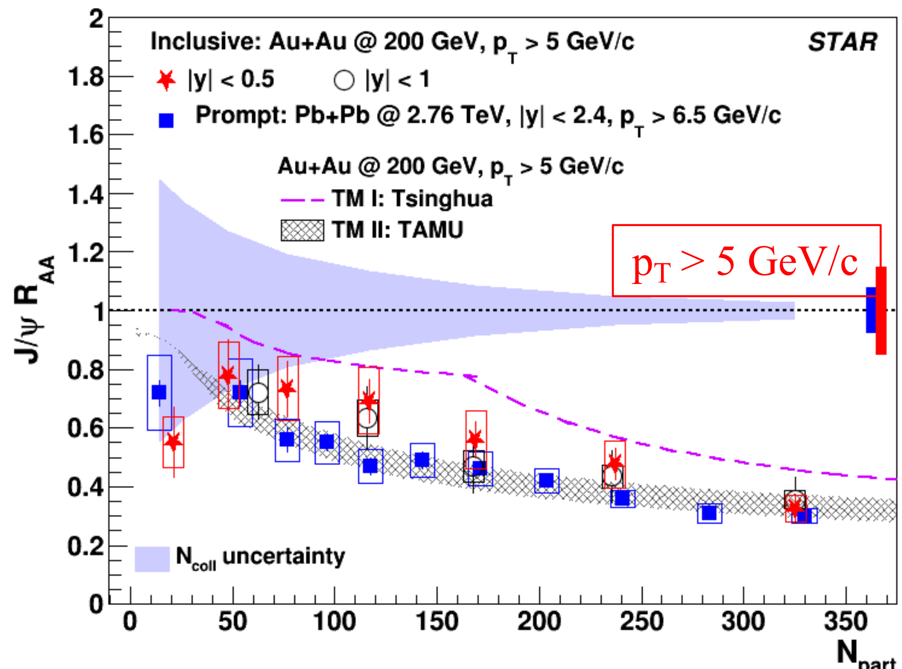
- Both, low and high p_T, R_{AA} decreases from peripheral to central collisions
- Low p_T : more suppressed at RHIC in central and semi-central
  → Less regeneration due to lower charm production
- High p_T : hint of systematically less suppression at RHIC for semi-central
  → Probably stronger dissociation at LHC due to high temperature

ALICE : PLB 734 (2014) 314, CMS: JHEP 05 (2012) 063

arXiv:1905.13669 , submitted to P.L.B



Inclusive J/ψ from STAR

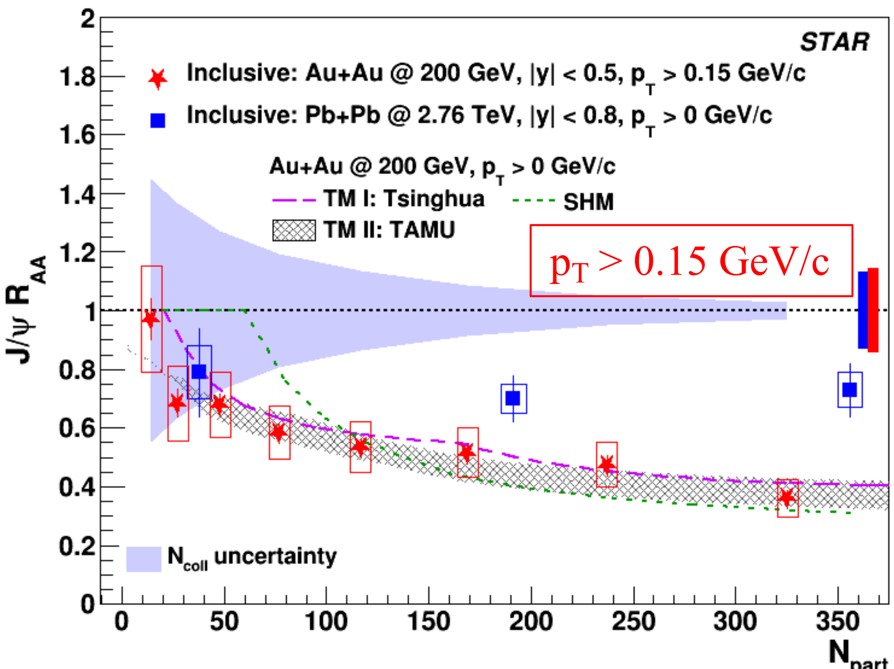


J/ψ R_{AA} comparison with models

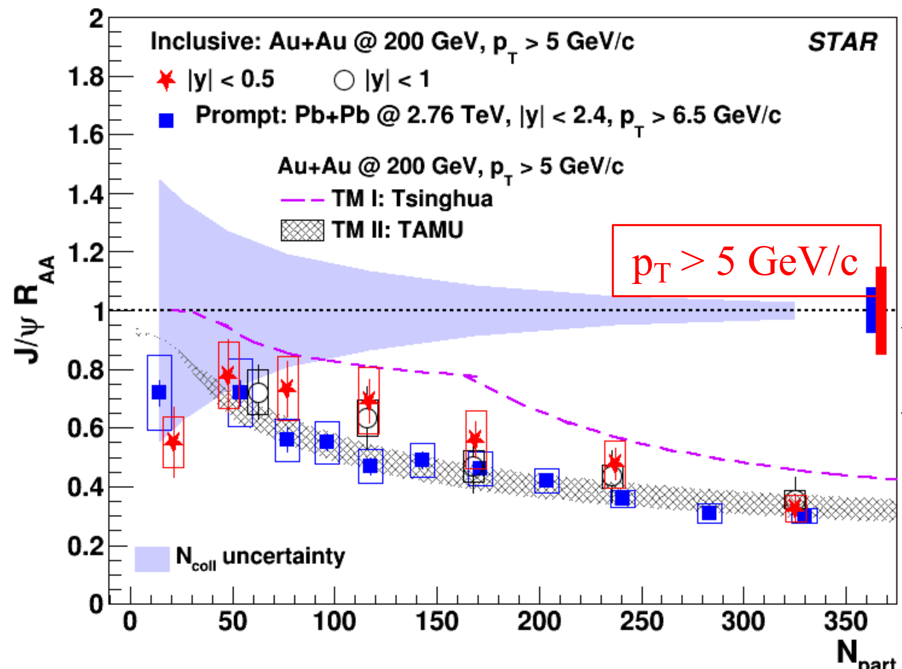
- Low p_T : both models can describe centrality dependence at RHIC
- High p_T : the data lay mostly between the two model calculations

Model I at LHC: PRC 89 (2014) 054911 ; Model II at RHIC: PRC 82 (2010) 064905; Model II at LHC: NPA 859 (2011) 114

arXiv:1905.13669 , submitted to P.L.B

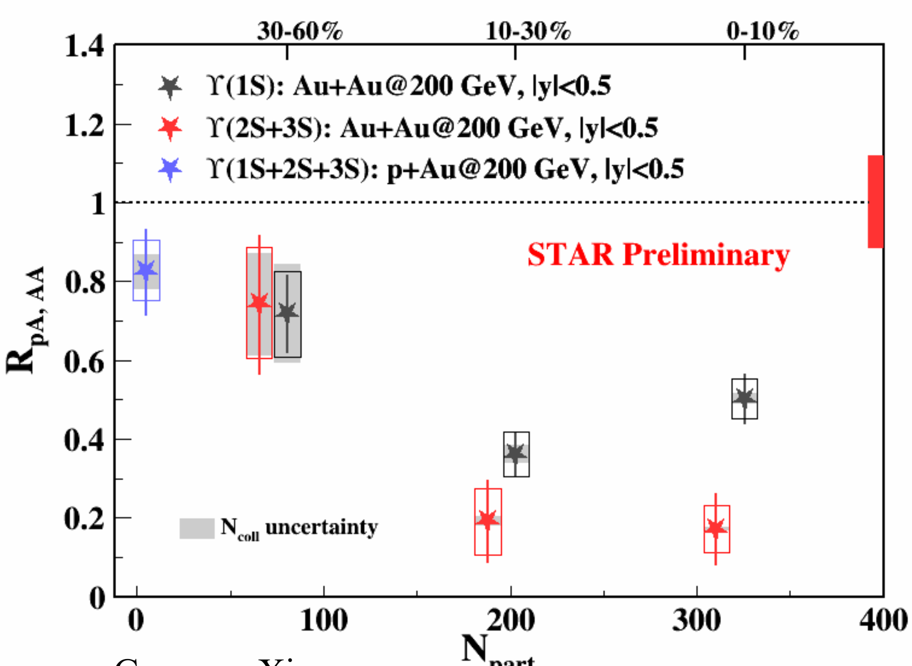


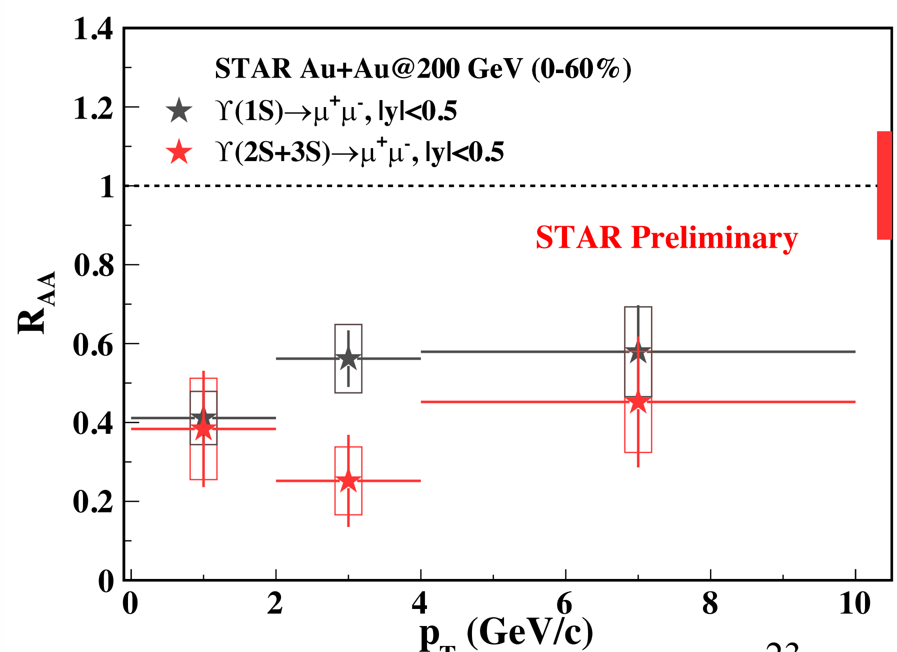
Inclusive J/ψ from STAR



ϒ(1S) vs. ϒ(2S+3S)

- Combined results from two decay channels (e^+e^-&$\mu^+\mu^-$) from STAR
- Indication of more suppression towards central collisions
- No clear p_T dependence
- ϒ(2S+3S) more suppressed than ϒ(1S) in 0-10% central collisions
  → consistent with "sequential melting" expectation

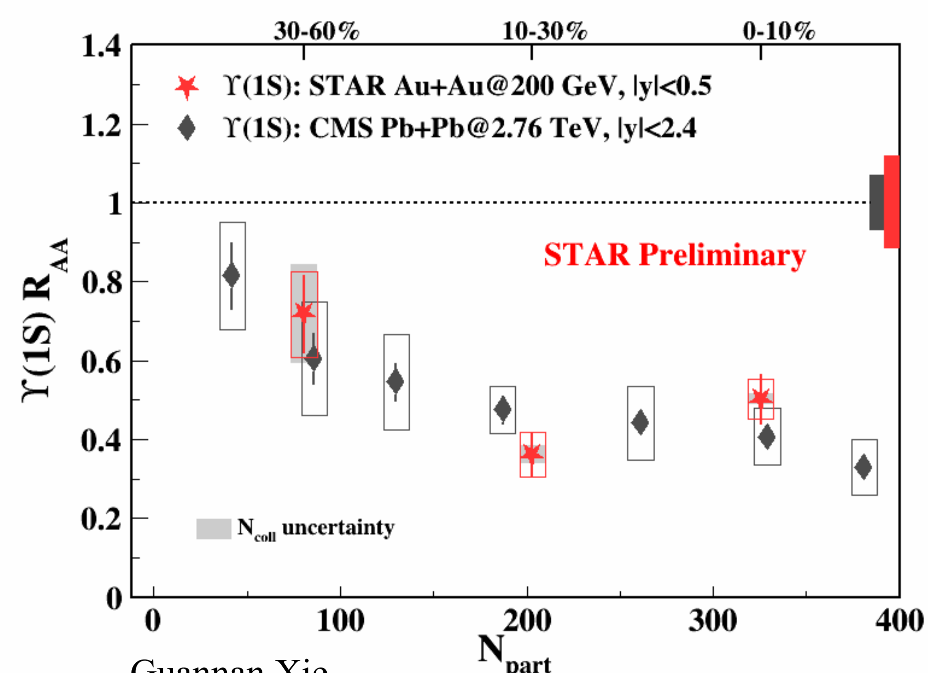


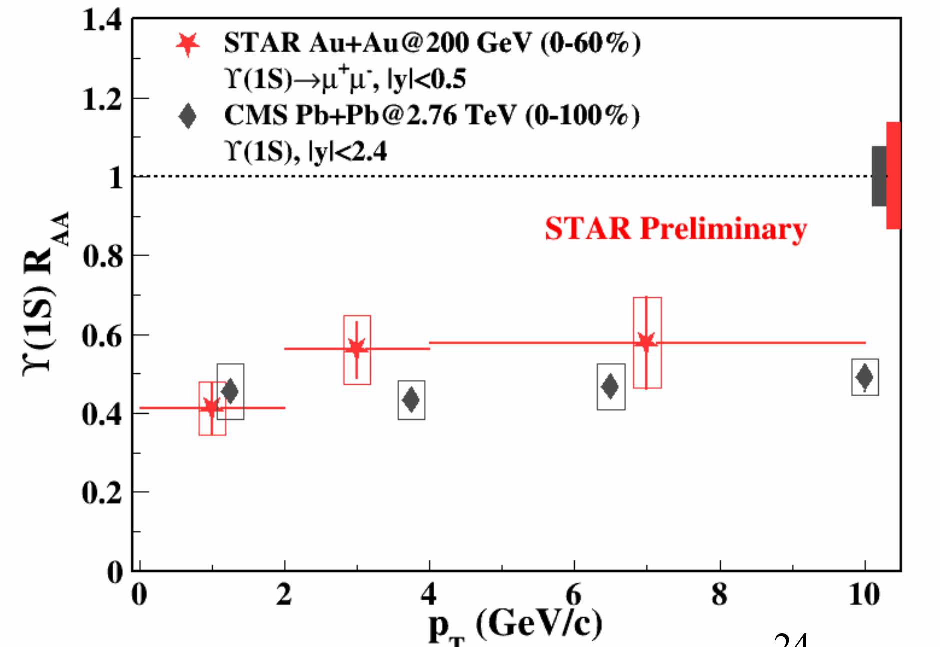


Υ(1S)

- Combined results from two decay channels (e^+e^-&$\mu^+\mu^-$) from STAR
- Indication of more suppression towards central collisions
- No strong p_T dependence
- Suppression level is similar at RHIC and the LHC:
  - CNM /pfgeffect
  - Suppression of excited Υ states

CMS, PLB 770 (2017) 357

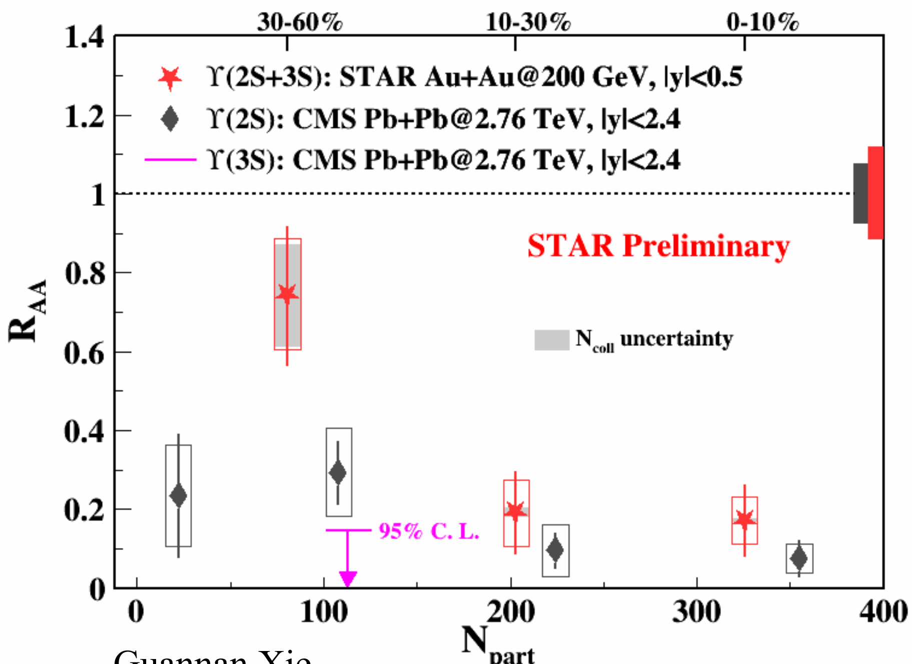


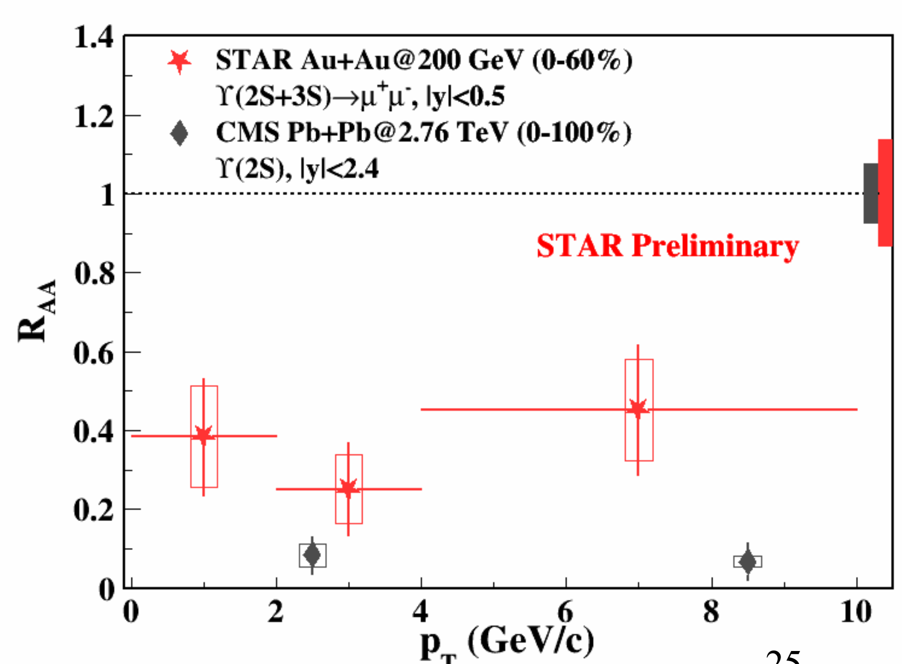


Υ(2S+3S)

- Indication of more suppression towards central collisions
- No clear p_T dependence
- More suppressed than Υ(1S) in 0-10% central collisions
  → consistent with "sequential melting" expectation
- Indication of STAR values higher than LHC in peripheral collision
  - less suppression at RHIC?

CMS, PLB 770 (2017) 357



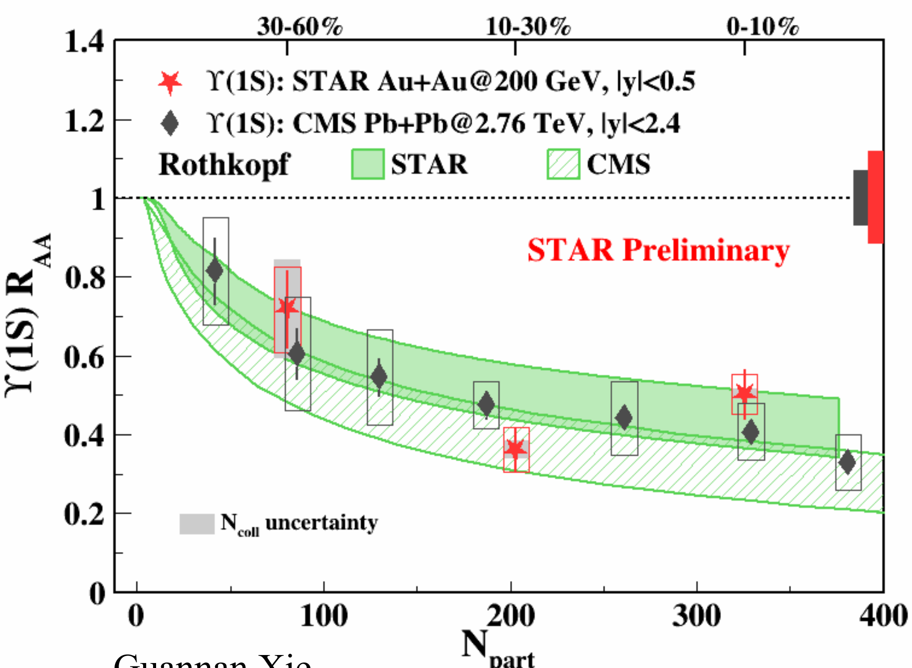


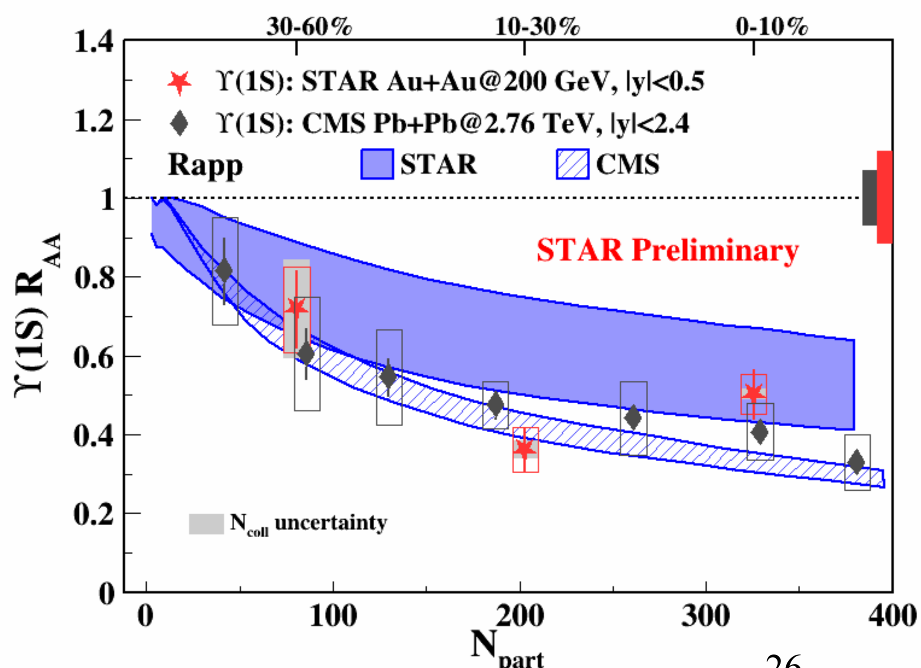
Guannan Xie

Comparison with Models: $\Upsilon(1S)$

- Both models show good agreement with data for $\Upsilon(1S)$
  - KSU: Complex potential (lattice QCD); No CNM or regeneration
  - TAMU: T-dependent binding energy; Includes CNM and regeneration

KSU： B. Krouppa, A. Rothkopf, and M. Strickland, PRD 97, (2018) 016017
TAMU： X. Du, M. He, and R. Rapp, PRC 96, (2017) 054901

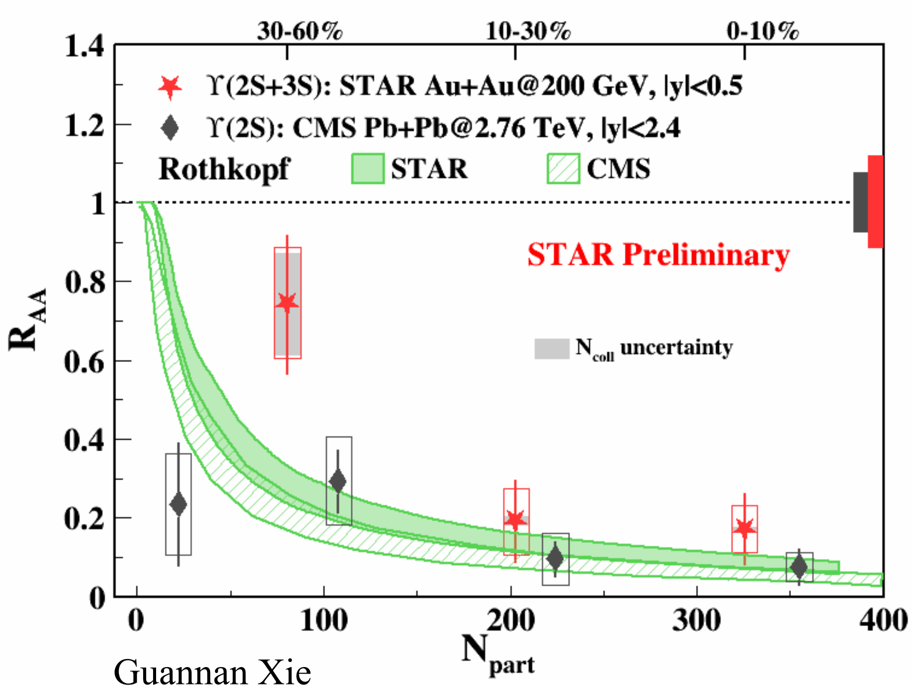


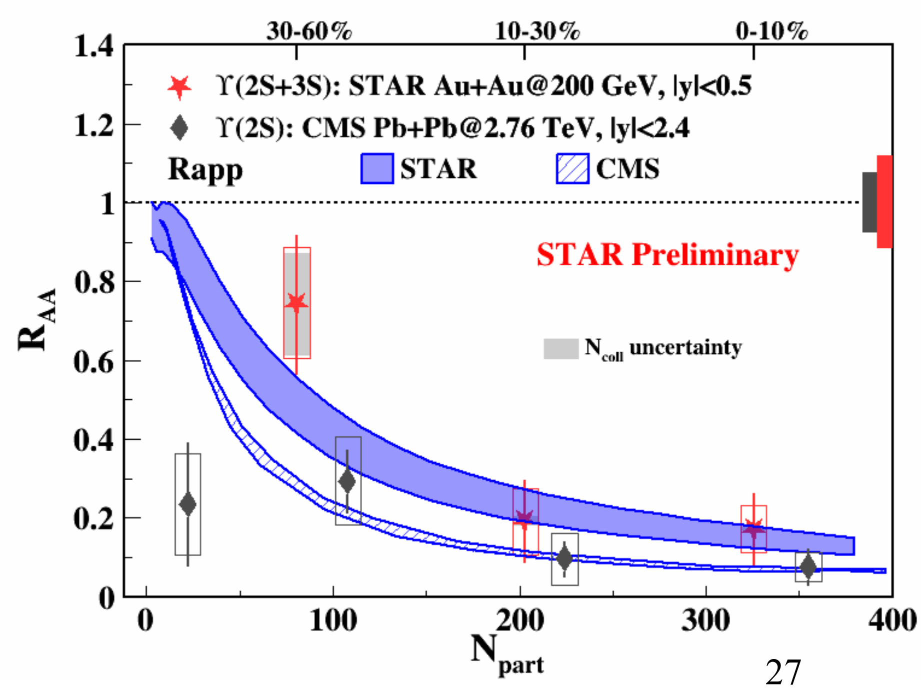


Comparison with Models: ϒ(2S+3S)

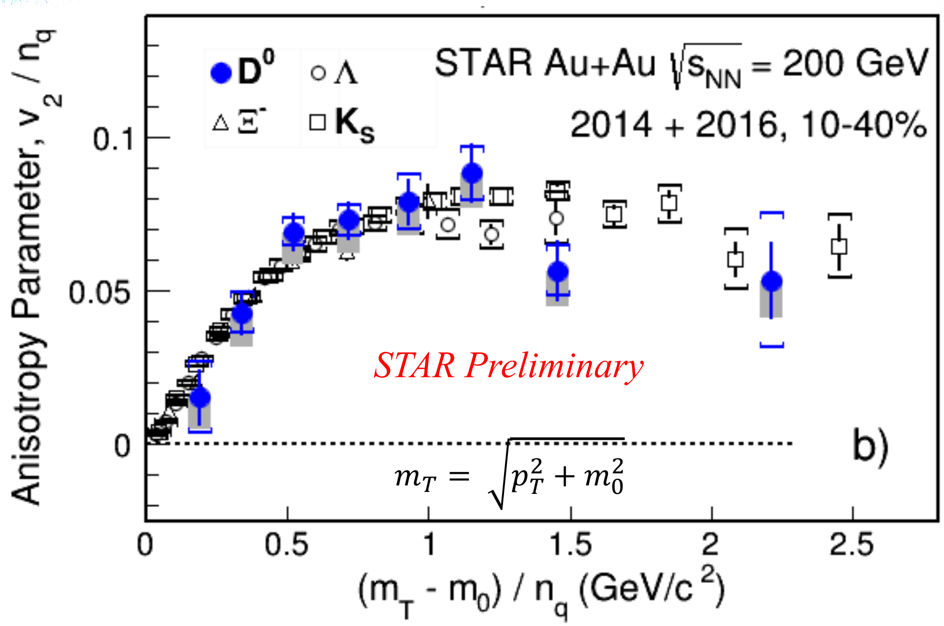
- Both models consistently describe RHIC and LHC excited ϒ states suppression in semi-central and central collisions
  - KSU model is lower than data in 30-60% centrality

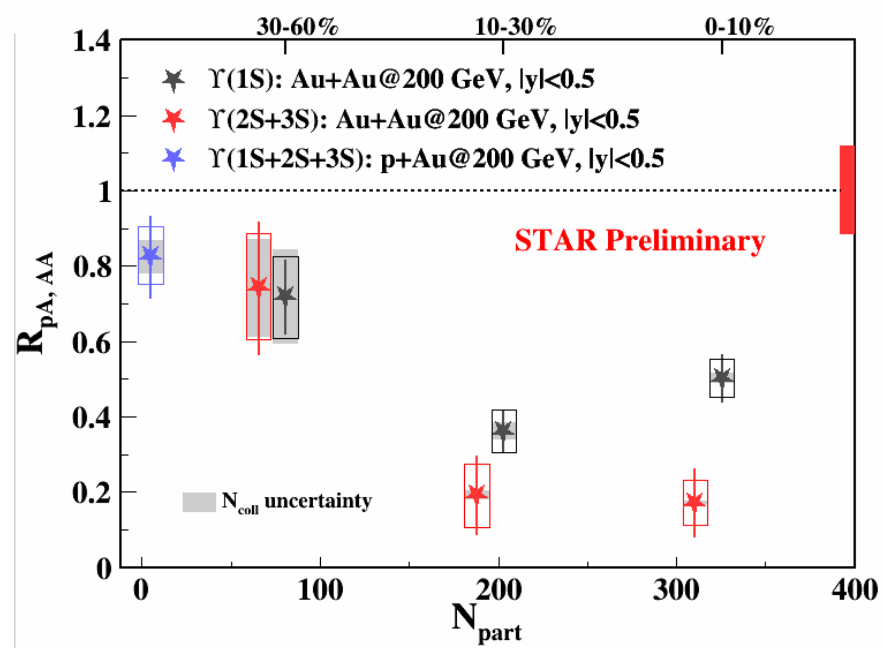
KSU： B. Krouppa, A. Rothkopf, and M. Strickland, PRD 97, (2018) 016017
TAMU： X. Du, M. He, and R. Rapp, PRC 96, (2017) 054901





Summary

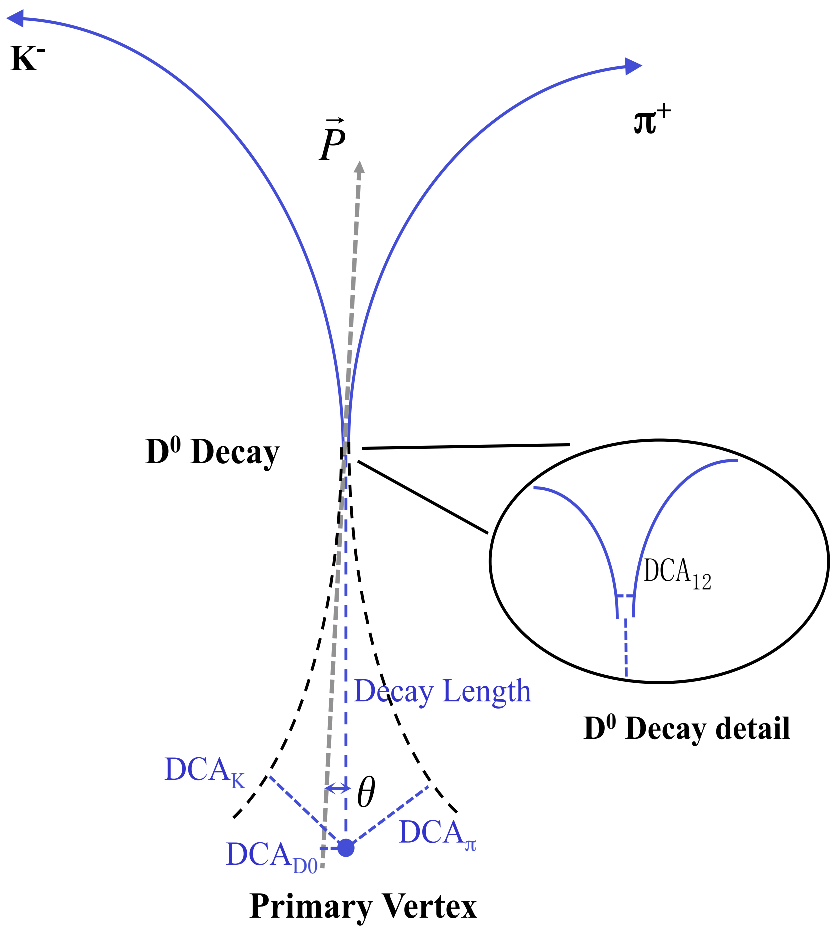




- Open heavy flavor
  - Significant collective behavior for charm → charm quark diffusion in medium
  - Hint of $R_{AA}(b \rightarrow e) > R_{AA}(c \rightarrow e)$ → mass hierarchy
  - $D_s/D^0 and\ \Lambda_c^+/D^0$ enhancement → coalescence hadronization
- Quarkonium
  - Strong suppression of J/ψ at high p_T in central collision → dissociation
  - Low p_T J/ψ R_{AA} at RHIC lower than the LHC → regeneration
  - ϒ(2S+3S) more suppressed than ϒ(1S) in central collision → sequential melting

Back up

Topological Reconstruction



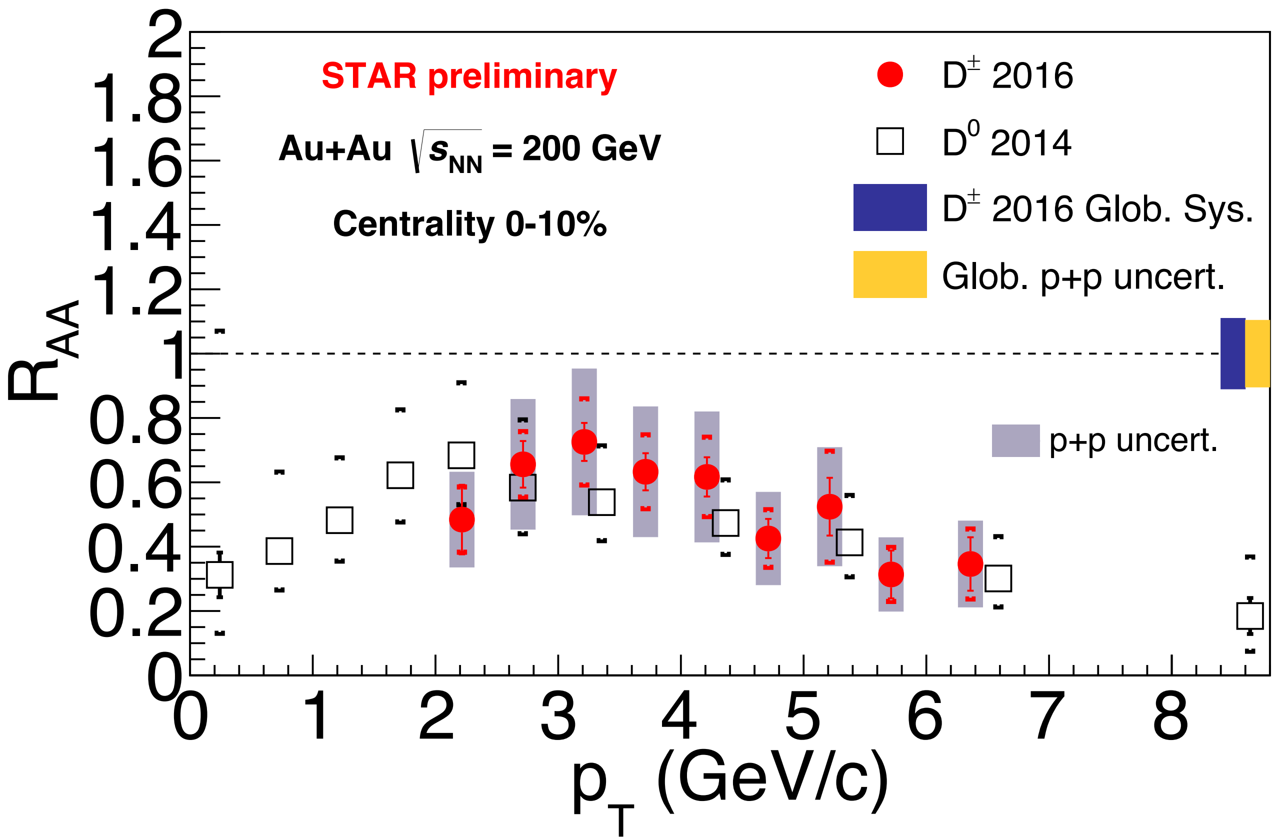
- Direct topological reconstruction through hadronic channels

$$D^0(\overline{D^0}) \rightarrow K^{\mp}\pi^{\pm}$$
$$\Lambda_c^+ \rightarrow pK^-\pi^+$$
$$D_s^+ \rightarrow \phi(1020)\pi^+ \rightarrow K^+K^-\pi^+$$

- With HFT: greatly reduced combinatorial background
- Topological cuts optimized by TMVA (Toolkit for Multi Variate Analysis)

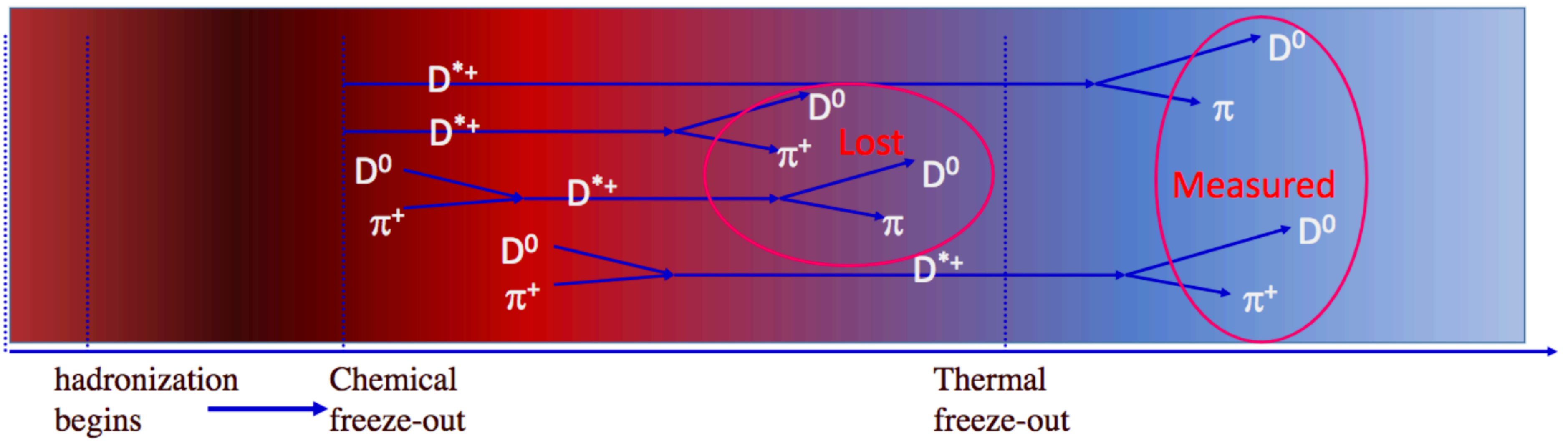
$D^{+/-}$ R_{AA}

- Similar suppression for D^0 and $D^{+/-}$
- Spectra measurement is important for the total charm cross-section



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

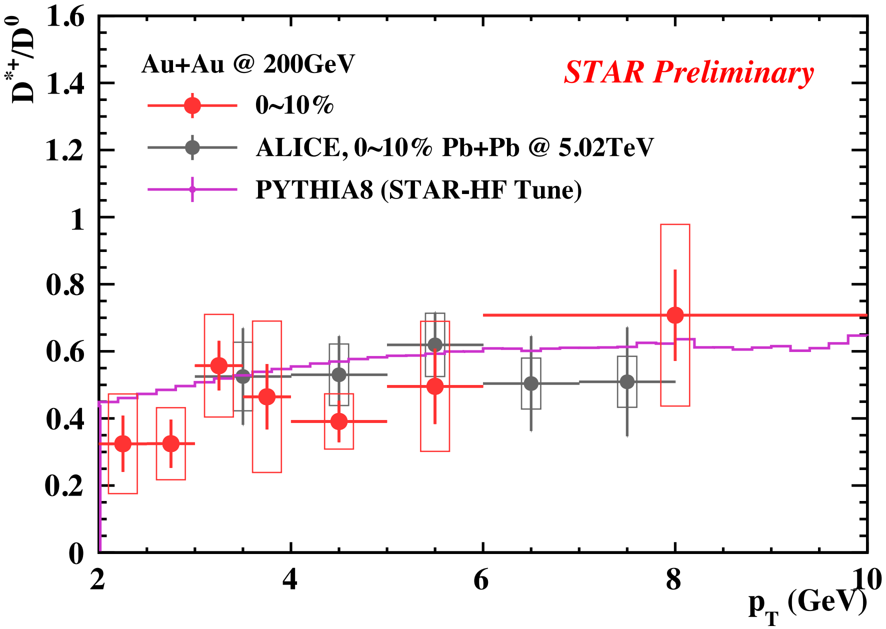
- D^{*+} feeds down to D^0 yields $D^{*+} \rightarrow D^0 + \pi^+_{soft}$
- Possible hot medium effects :
  - D^{*+} life time could become shorter in hot medium
  - Re-scattering can lead to loss of yield

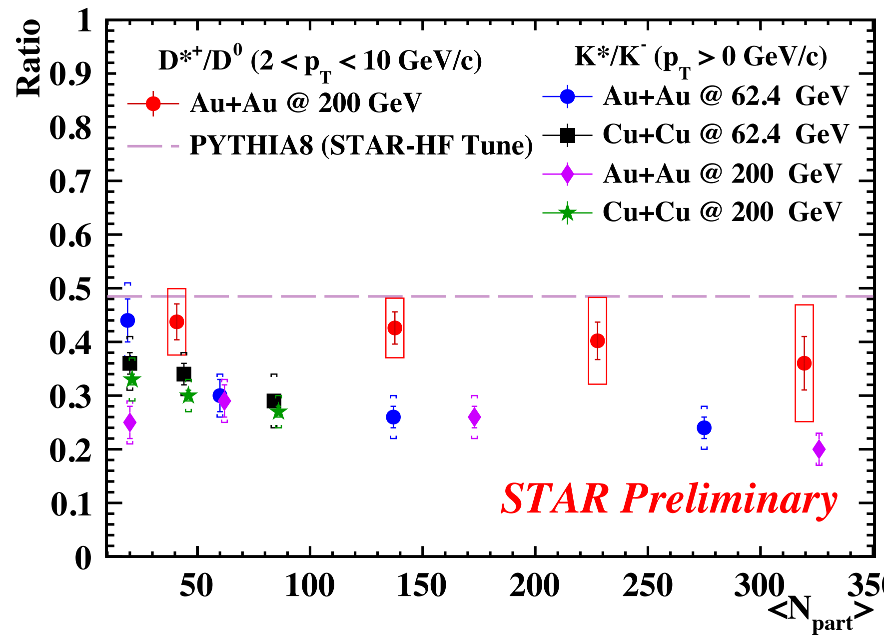


Shuai Y. F. Liu and Ralf Rapp. Phys. Rev. C 97 (2018) 034918.

D^{*+}/D^0 Ratio in Au+Au Collisions

- D^{*+}/D^0 ratio in Au+Au collisions at 200 GeV is consistent with PYTHIA and with ALICE data at higher p_T.
- Ratio of the integrated yields shows no strong centrality dependence



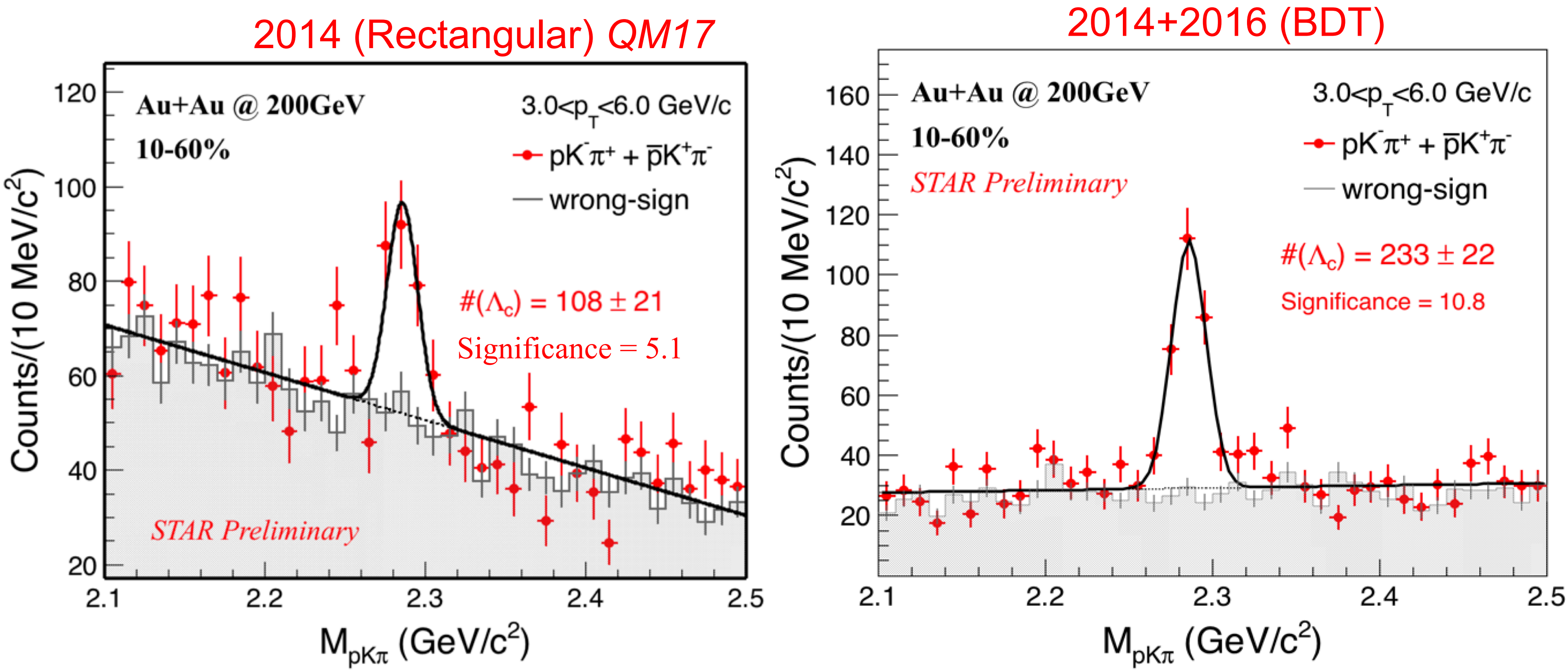


K/K, Phys. Rev. C (2011) 84. 034909.*
ALICE Collaboration, arXiv:1804.09083.

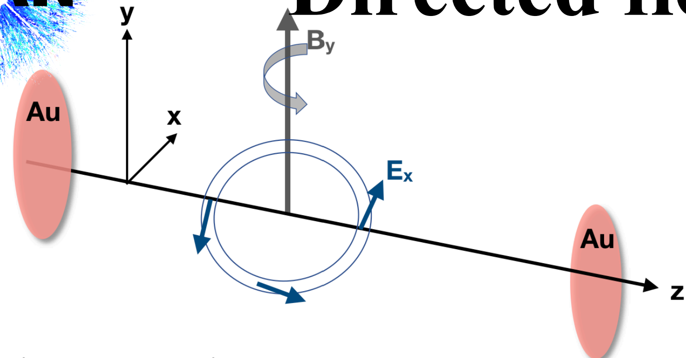
Λ_c Reconstruction

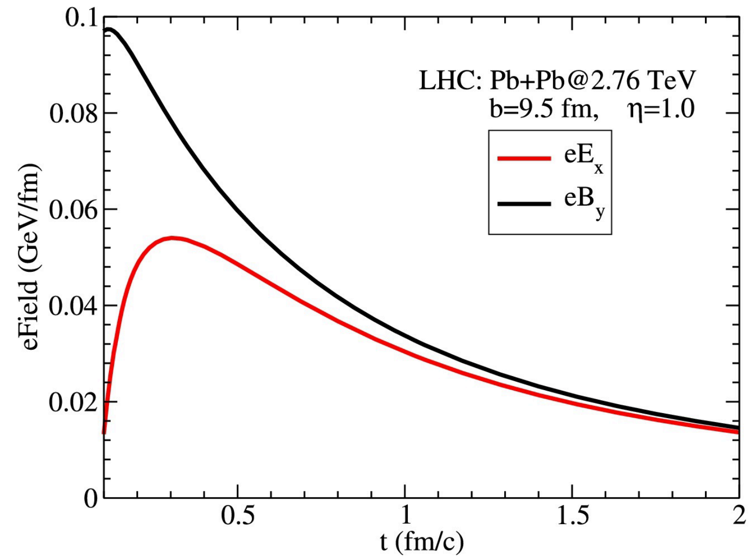
- More than 50% improvement in signal significance with TMVA BDT
- Also new data from 2016

→ Effectively 4x more data

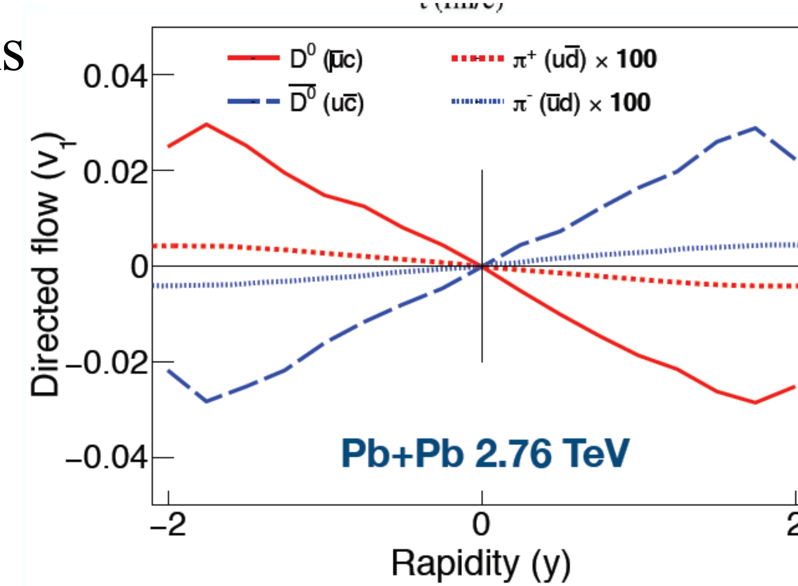


Directed flow (v1) due to EM fields

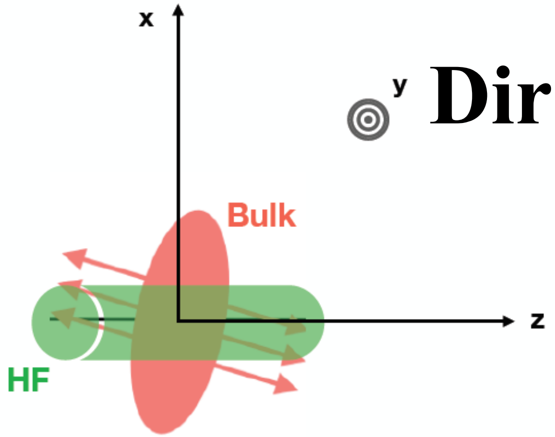




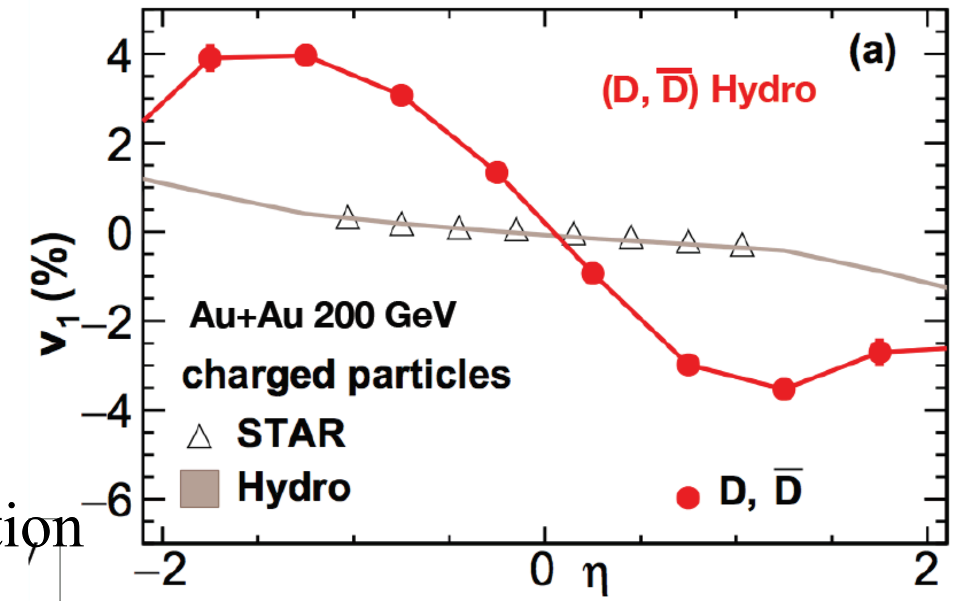
- The moving spectators can produce enormously large electromagnetic field (eB ~ 10^{18} G at RHIC)
- Due to early production of heavy quarks ($\tau_{CQ} \sim 0.1$ fm/c) positive and negative charm quarks (CQs) can get deflected by the initial EM force
- D^0 and D^0 v_1 can offer insight into the early time EM fields



Das et. al., Phys Lett B 768, 260 (2017)



Directed flow (v1) due to hydro



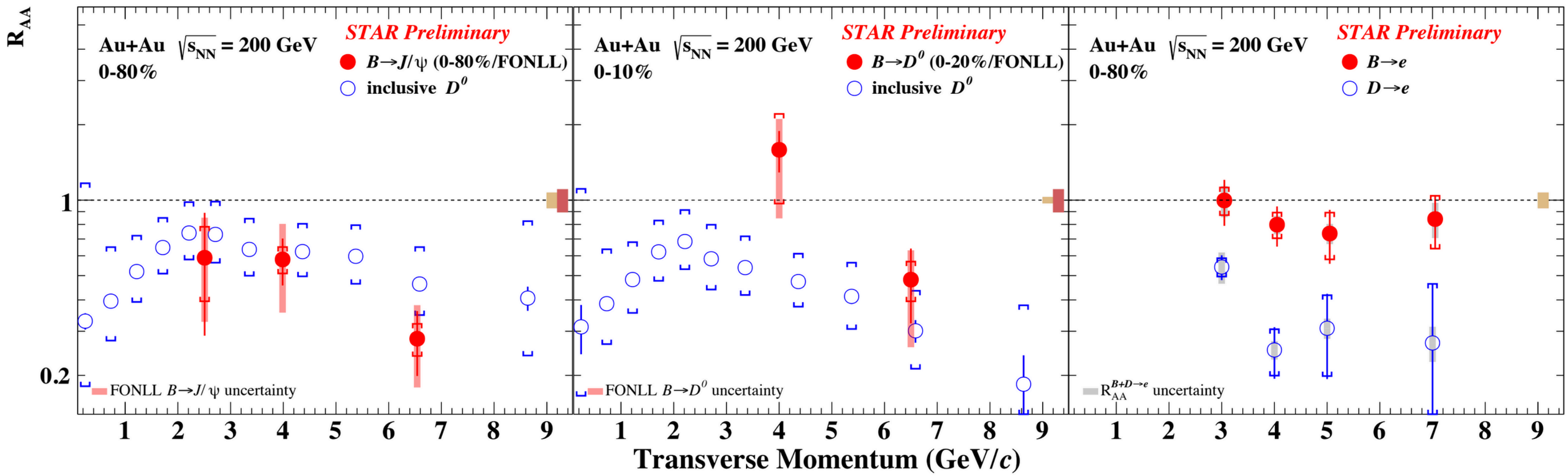
Chatterjee, Bozek:
Phys Rev Lett 120, 192301 (2018)

- Heavy quarks are produced according to Ncoll density: symmetric in rapidity
- At non-zero rapidity, CQs production points are shifted from the bulk
- This can induce larger v_1 in CQs than light flavors
- Magnitude of CQ v_1 depends on the drag parameter used in this model

→ $(v_1\text{-slope})_{CQ}$ >> $(v_1\text{-slope})_{LQ}$ CQs much more sensitive to the initial tilt than the charged hadrons

B Study from Non-prompt J/ψ & D^0 & e

- Strong interaction of charm with the medium. How about bottom?
- Strong suppression for $B \rightarrow J/\psi$ and D^0 at high p_T.
- Indication of less suppression for $B \rightarrow e$ than $D \rightarrow e$ (~2 σ): consistent with $\Delta E_c > \Delta E_b$. Measurements with improved precision on the way

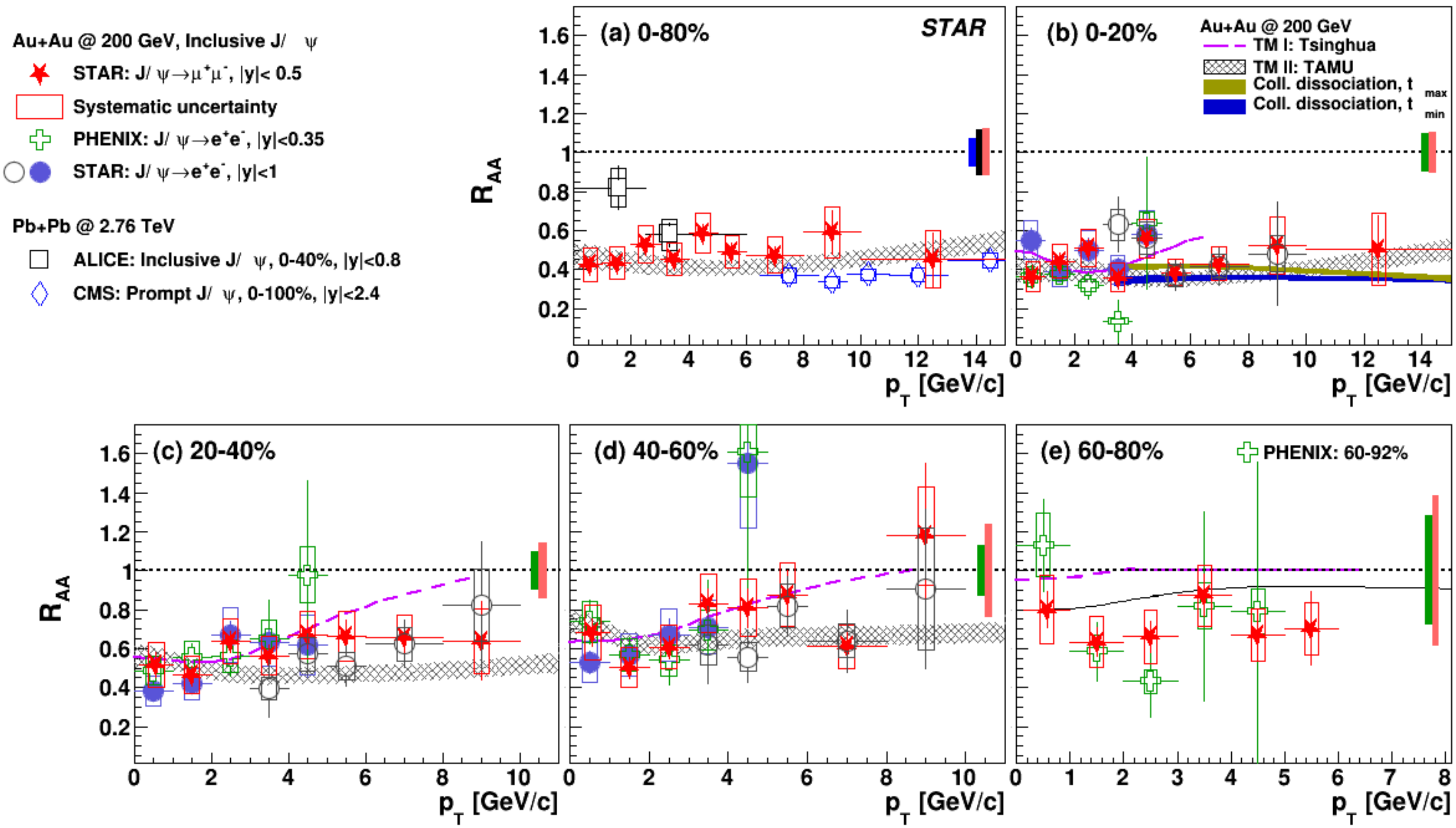


$$R_{AA}^{B\rightarrow J/\psi} = \frac{f_{Au+Au}^{B\rightarrow J/\psi}(data)}{f_{p+p}^{B\rightarrow J/\psi}(theory)} R_{AA}^{inc.\ J/\psi}(data) \quad R_{AA}^{B\rightarrow D^0} = \frac{1}{<N_{coll}>} \frac{f_{Au+Au}^{B\rightarrow D^0} \times dN_{Au+Au}^{incl.\ D^0}/dp_T}{dN_{FONLL}^{B\rightarrow D^0}/dp_T}$$

$$R_{AA}^{B\rightarrow e} = \frac{f_{Au+Au}^{B\rightarrow e}(data)}{f_{p+p}^{B\rightarrow e}(data)} R_{AA}^{inc.\ e}(data) \quad R_{AA}^{D\rightarrow e} = \frac{1-f_{Au+Au}^{B\rightarrow e}(data)}{1-f_{p+p}^{B\rightarrow e}(data)} R_{AA}^{inc.\ e}(data)$$

R_{AA} references (data vs. theory) are different for comparisons. The decay kinematics needs to be unfolded for different channels.

J/ψ R_{AA} vs. p_T



arXiv:1905.13669 submitted to P.L.B; ALICE : PLB 734 (2014) 314
PHENIX : PRL 98 (2007) 232301; CMS: JHEP 05 (2012) 063