

The 18th International Conference on
Strangeness in Quark Matter
10-15 June 2019, Bari (Italy)



Recent Heavy-Flavor Results from STAR

Guannan *XIE* (for the STAR Collaboration)

Lawrence Berkeley National Laboratory

June 10-15, 2019



Guannan Xie



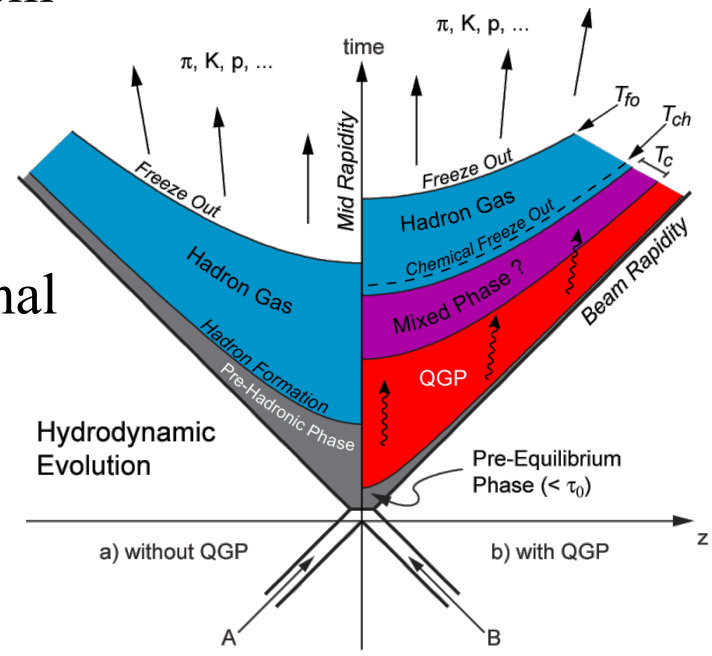


Contents

- Heavy quarks: $m_{c/b} \gg \Lambda_{\text{QCD}}, T_{\text{QGP(RHIC)}}$
 - 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 ($Q\bar{Q}$)
 - Dissociation : $Q\bar{Q}$ potential color-screened in the medium
 - Sequential melting : different quarkonia dissociate at different temperatures
 - Regeneration





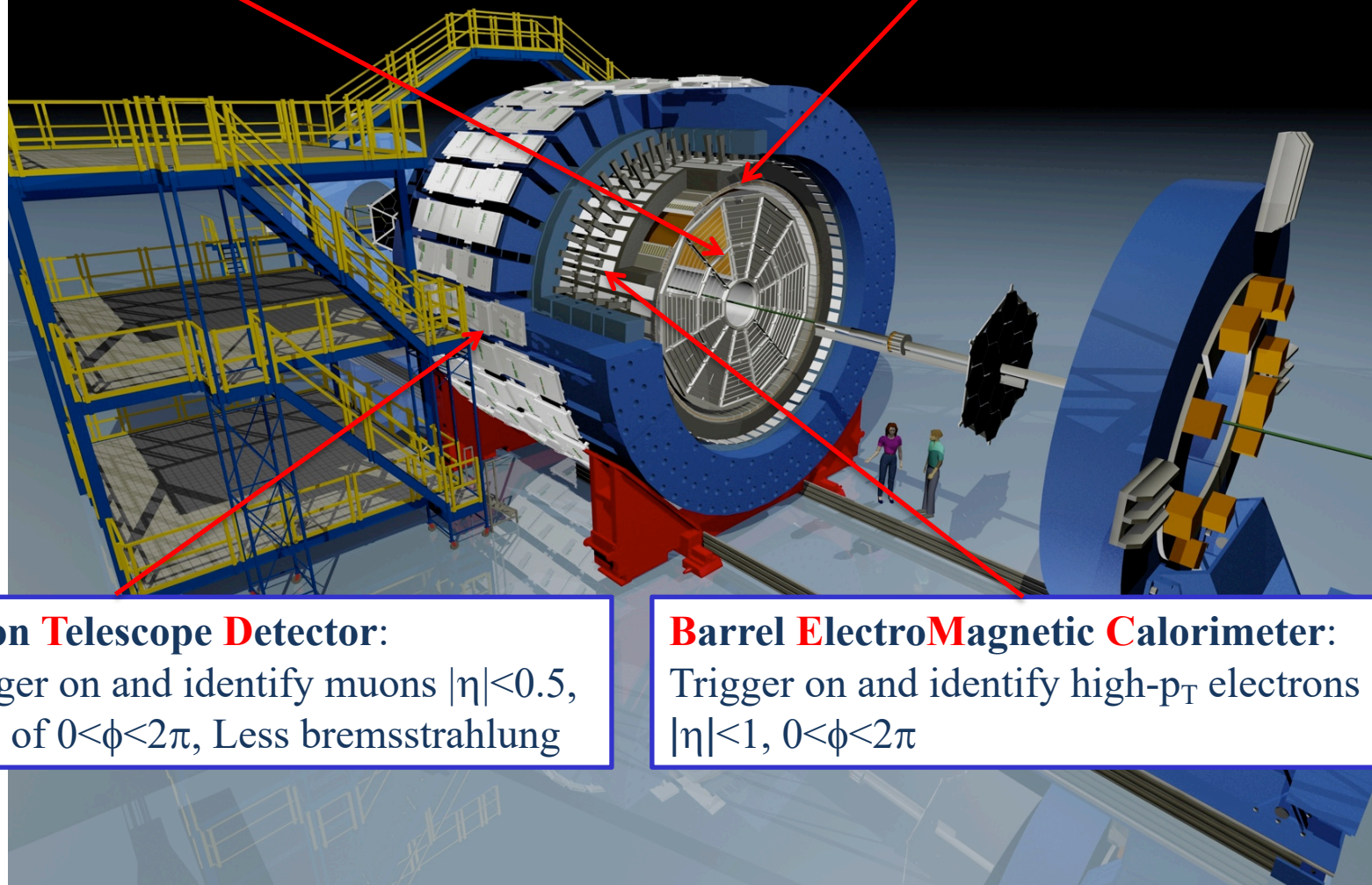
STAR Detector

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:

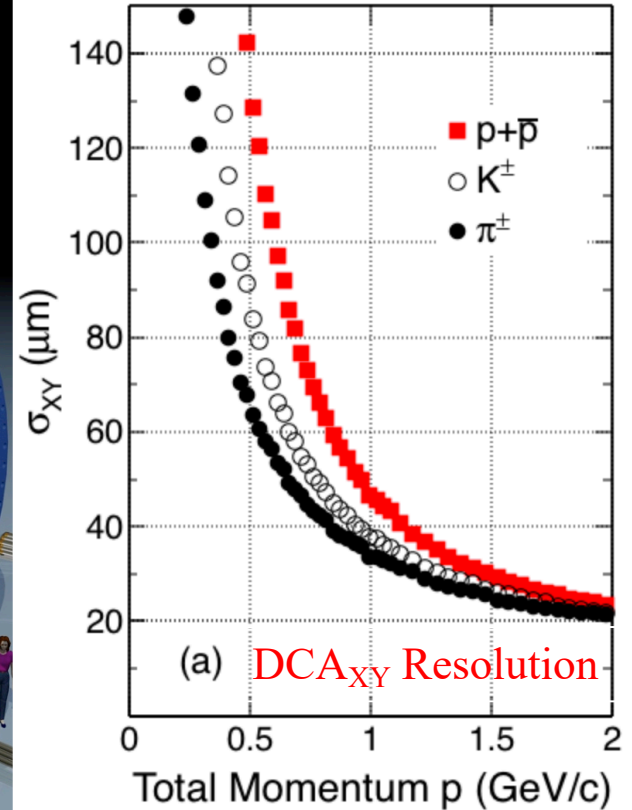
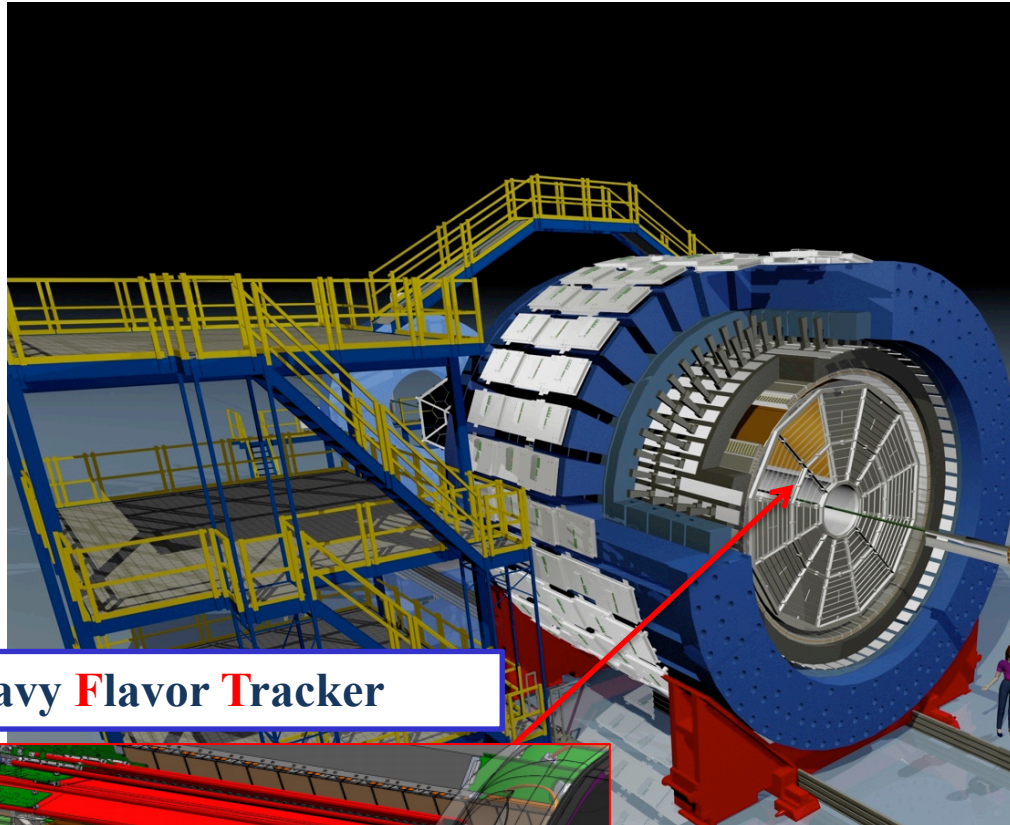
Trigger on and identify muons $|\eta| < 0.5$,
45% of $0 < \phi < 2\pi$, Less bremsstrahlung

Barrel ElectroMagnetic Calorimeter:

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

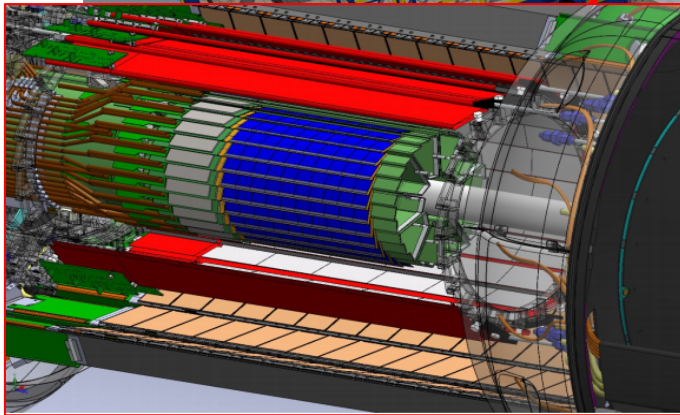


Heavy Flavor Tracker



Phys. Rev. C 99, (2019) 034908

Heavy Flavor Tracker



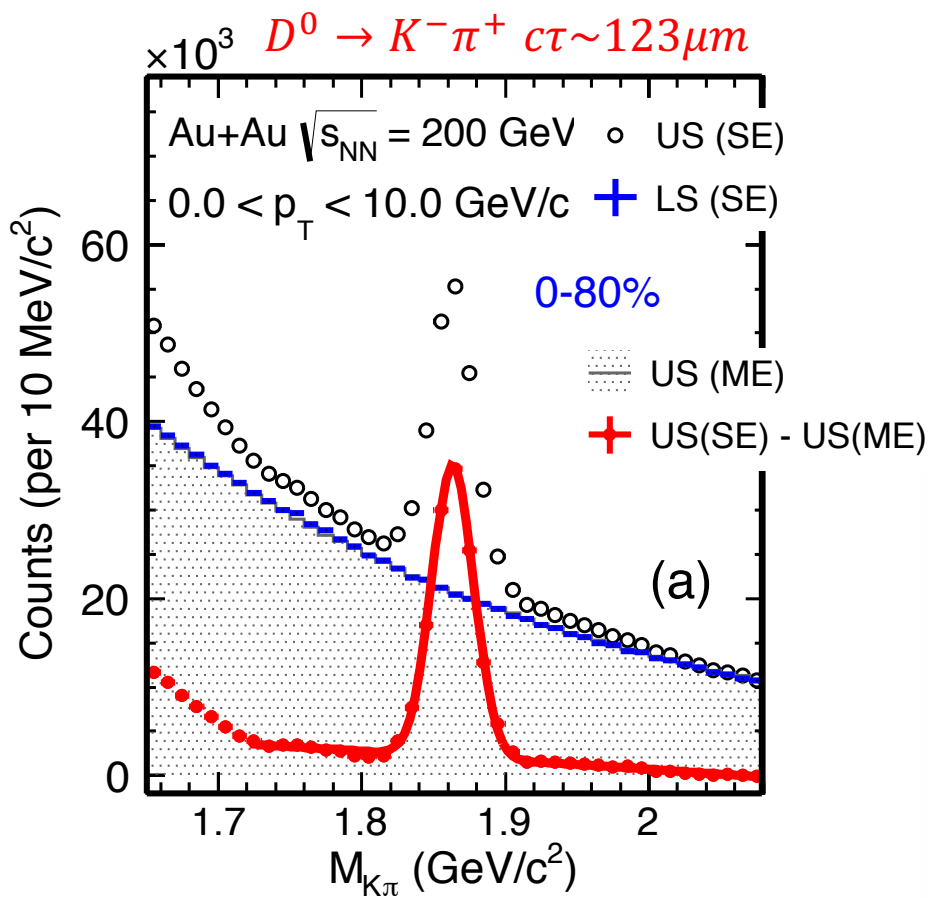
HFT: (2014-2016)

- **PIXEL** detector: $r \sim 2.8$ & 8 cm, **MAPS**, $20.7 \times 20.7 \mu\text{m}^2$, $0.5\% X_0$ (2014) $0.4\% X_0$ (2016), air-cooled
- Intermediate **Silicon Tracker**: $r \sim 14$ cm
- **Silicon Strip Detector**: $r \sim 22$ cm

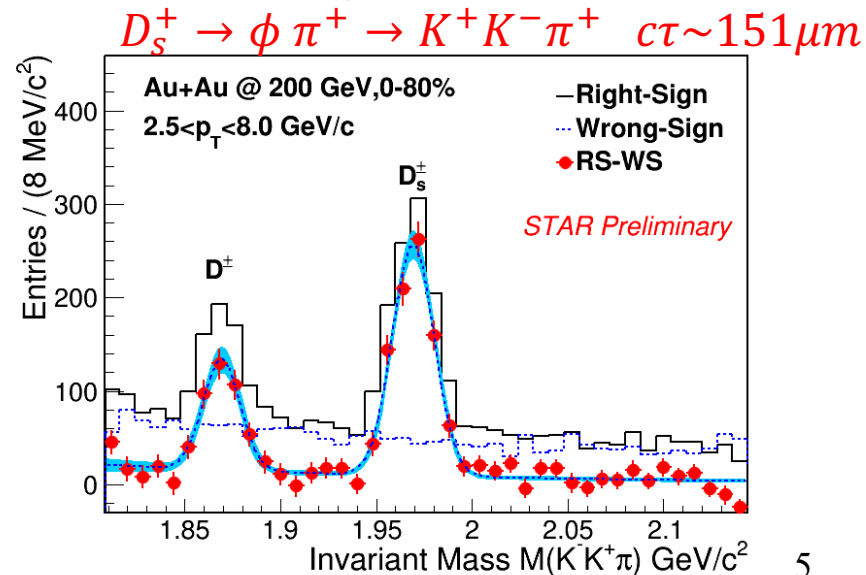
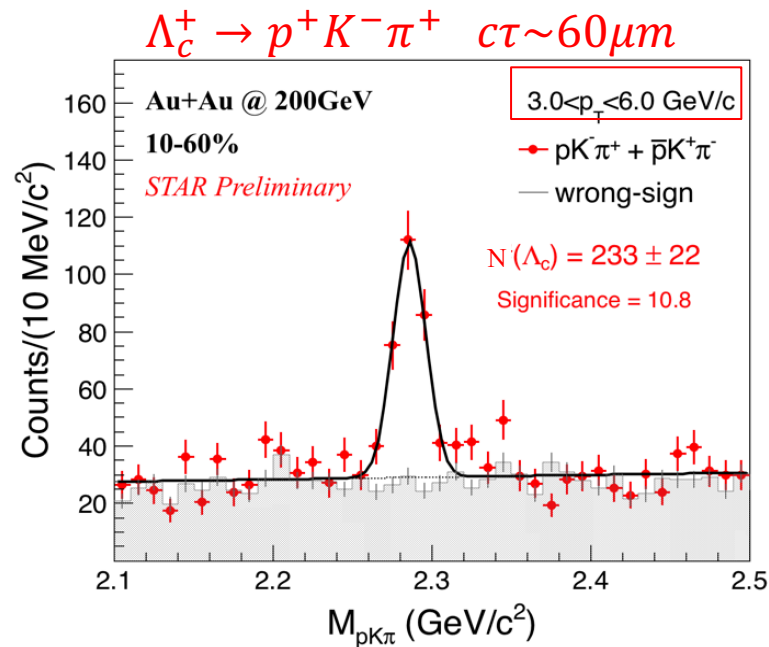


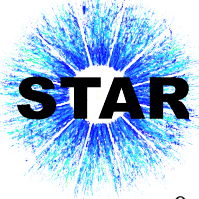
Open Charm Signals

Jan Vanek on June 11th Tue.



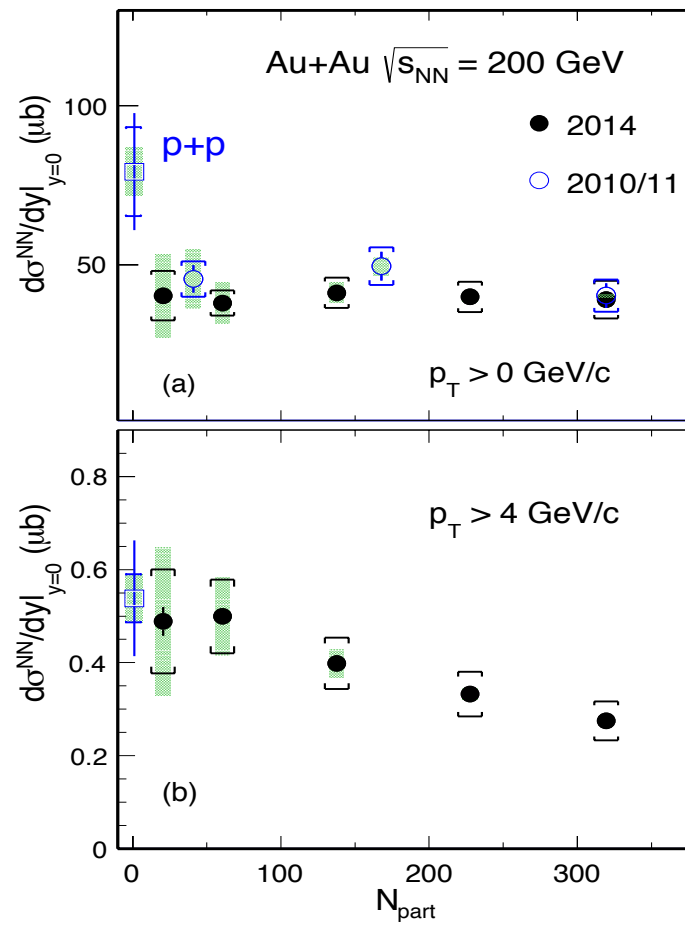
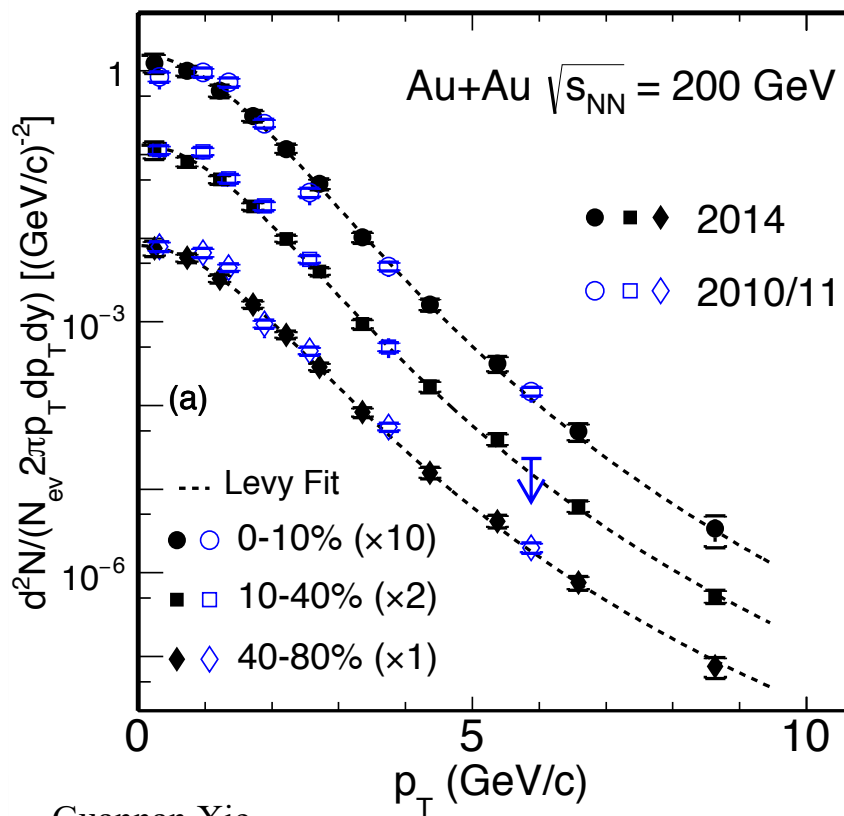
Guannan Xie





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.

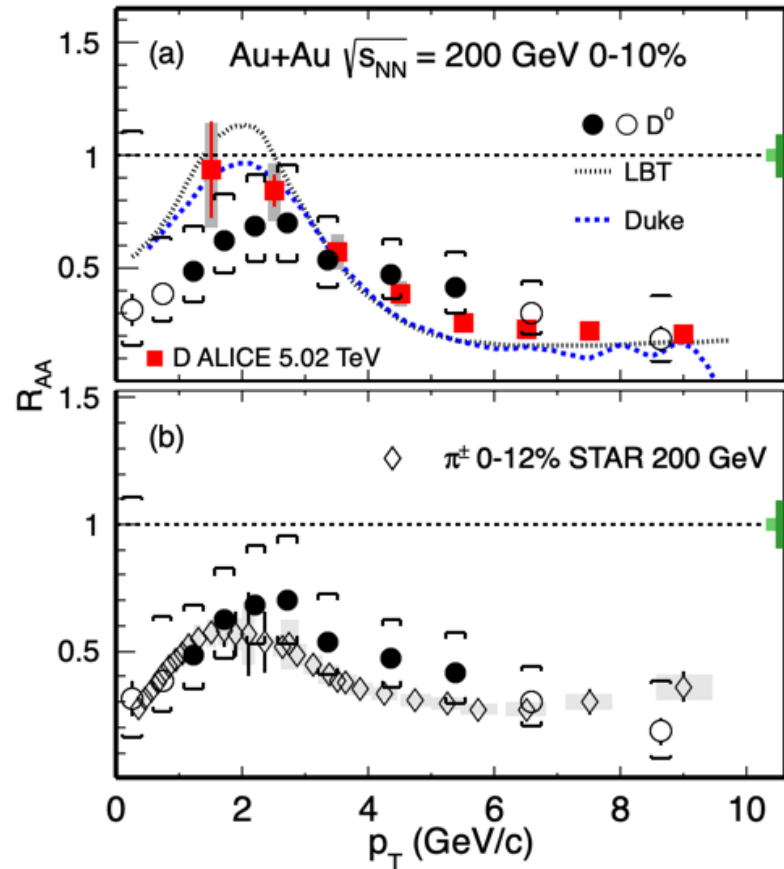
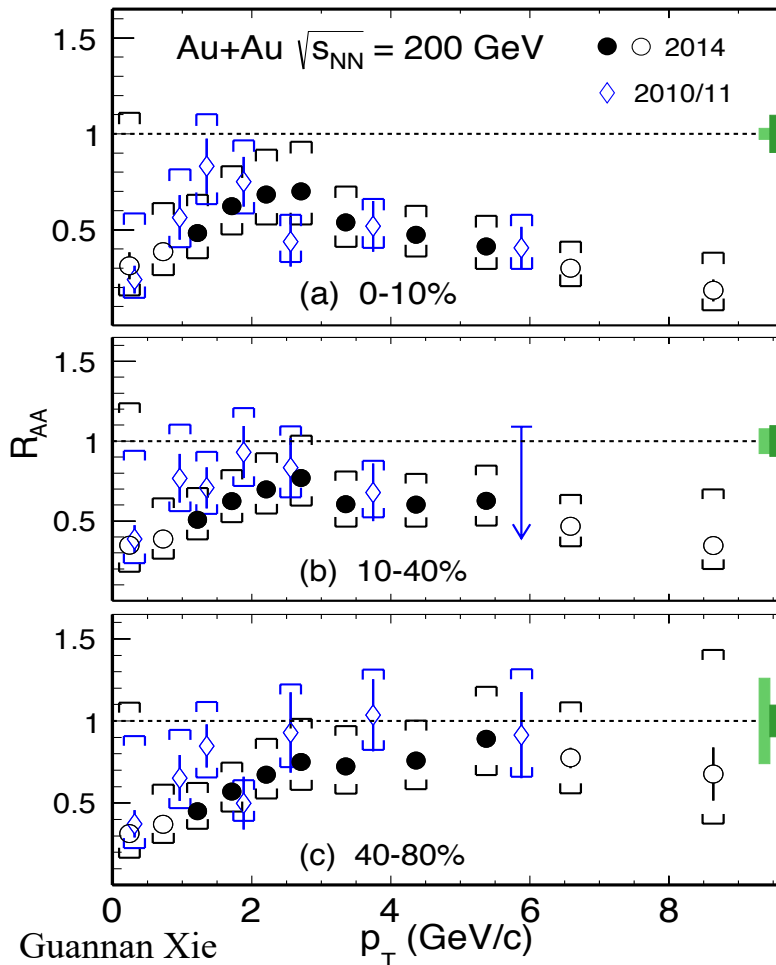


Phys. Rev. C 99, (2019) 034908
Phys. Rev. Lett. 121, (2018) 229901
Phys. Rev. D 86, (2012) 072013.



$D^0 R_{AA}$

- $R_{AA} < 1$ 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

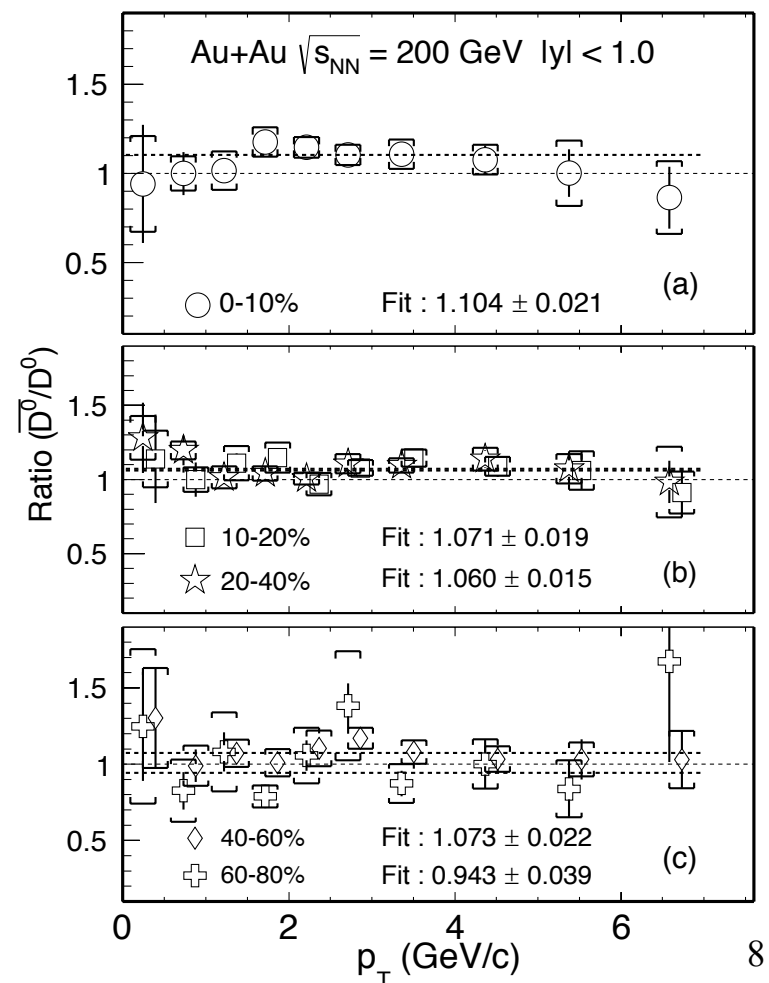
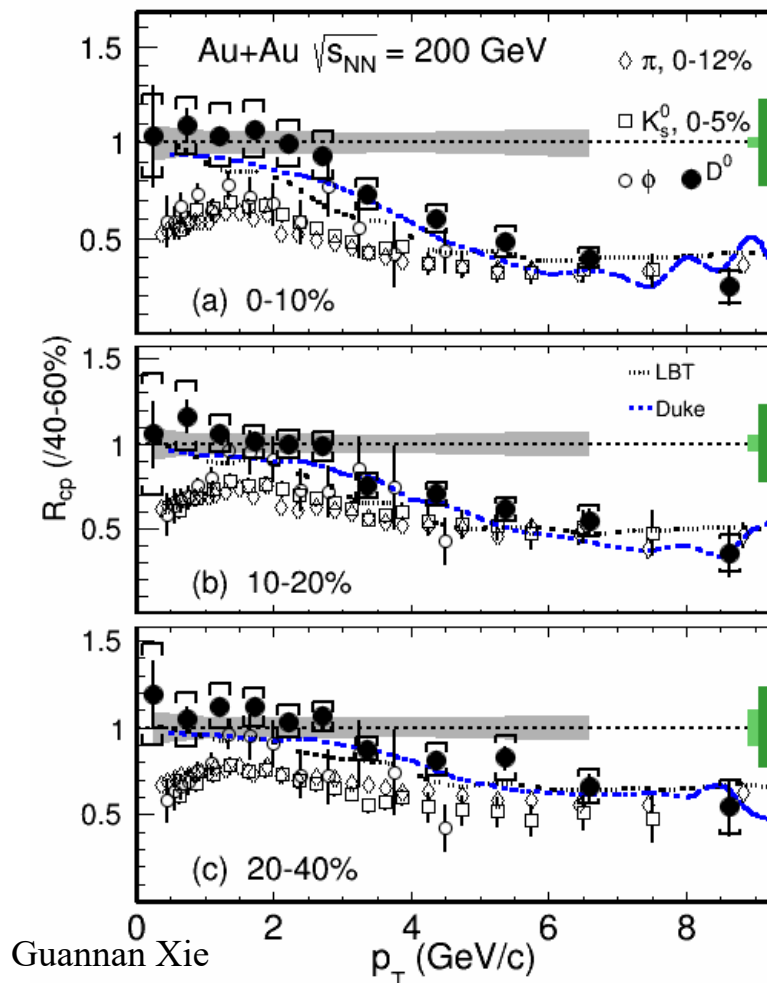


STAR: Phys. Lett. B 655 (2007) 104, Phys. Rev. C 99, (2019) 034908
 ALICE: JHEP 1810 (2018) 174,
 LBT: Phys. Rev. C 94 (2016) 014909 + private comm.
 DUKE: PRC 92 (2015) 024907 + private comm.



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

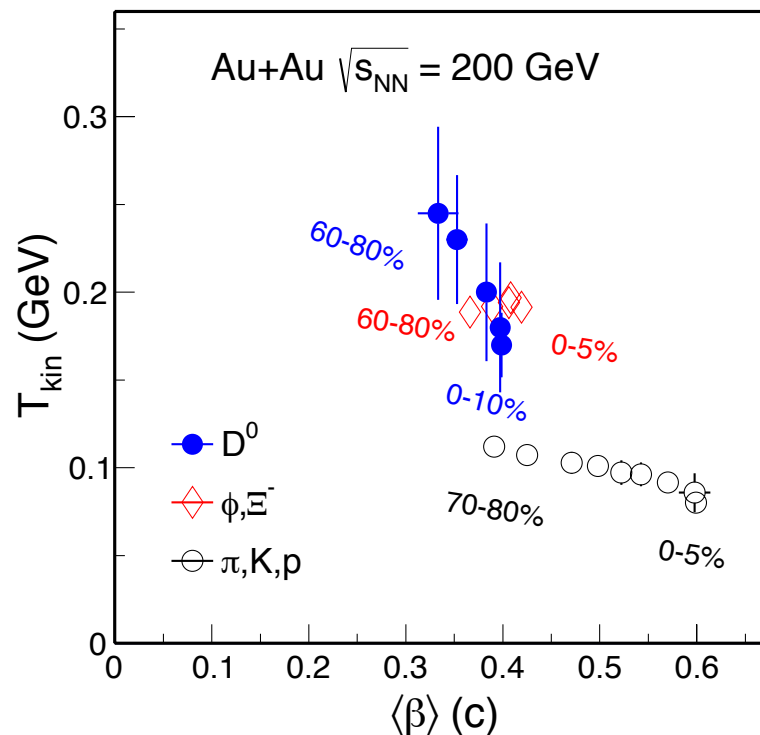
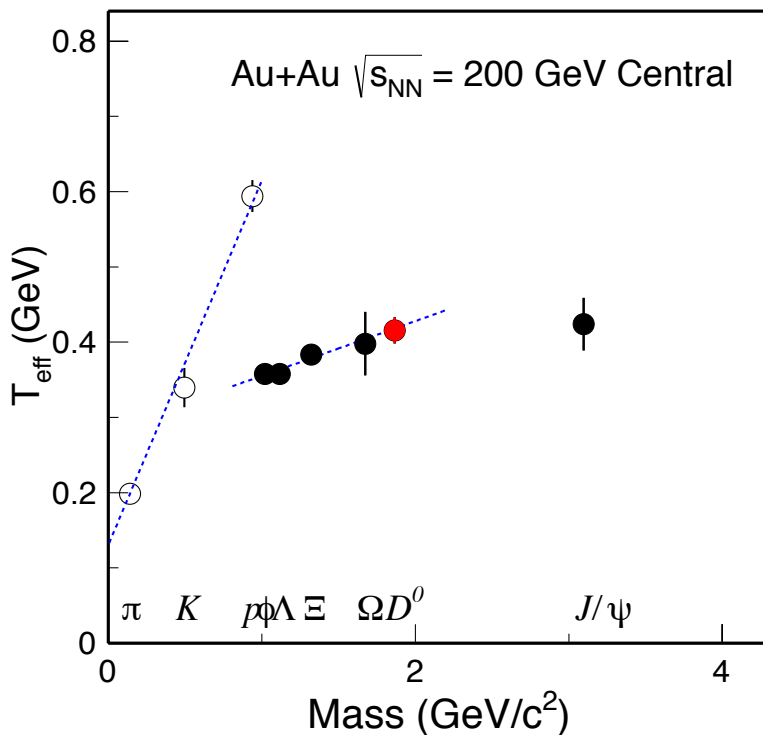




D^0 Radial Flow

- 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) :
 $T_{\text{kin}}(D^0) \sim T_{\text{kin}}(\phi, \Xi) > T_{\text{kin}}(\pi, K, p)$ and $\beta(D^0) \sim \beta(\phi, \Xi) < \beta(\pi, K, p)$
 → suggests earlier freeze-out of D^0 compared to light-flavor hadrons.

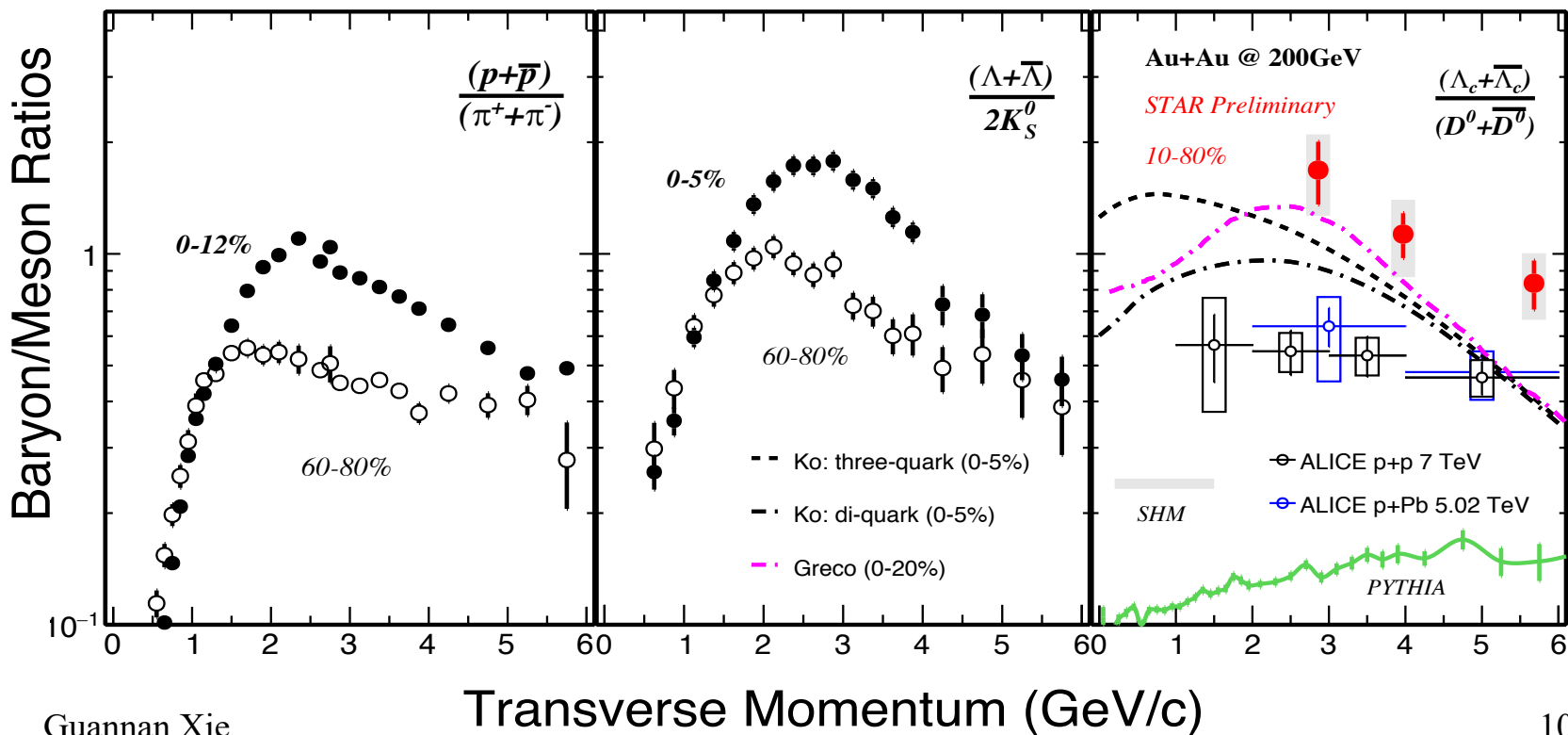
$$T_{\text{eff}} = T_{\text{fo}} + m_0 \langle \beta_T \rangle^2$$





Λ_c/D^0 : p_T Dependence

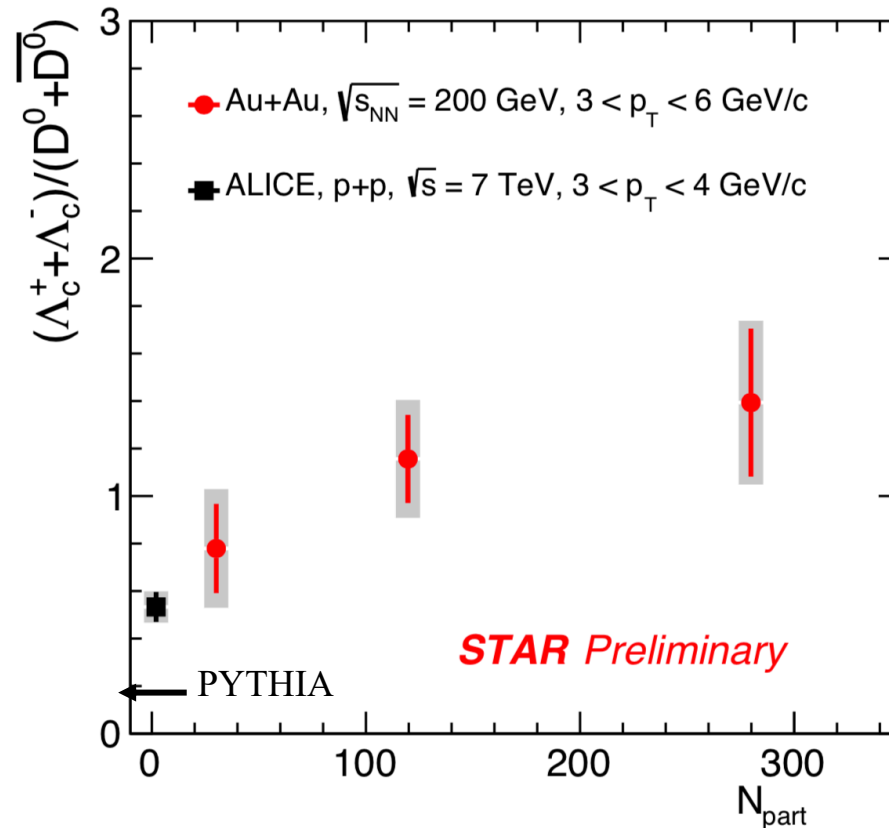
- Significant enhancement of Λ_c/D^0 compared to PYTHIA/fragmentation baseline and p+p, p+Pb at LHC
- The Λ_c/D^0 ratio is comparable with light flavor baryon-to-meson ratios
- Consistent with charm quark hadronization via coalescence
 - higher than model predictions, particularly at higher p_T





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

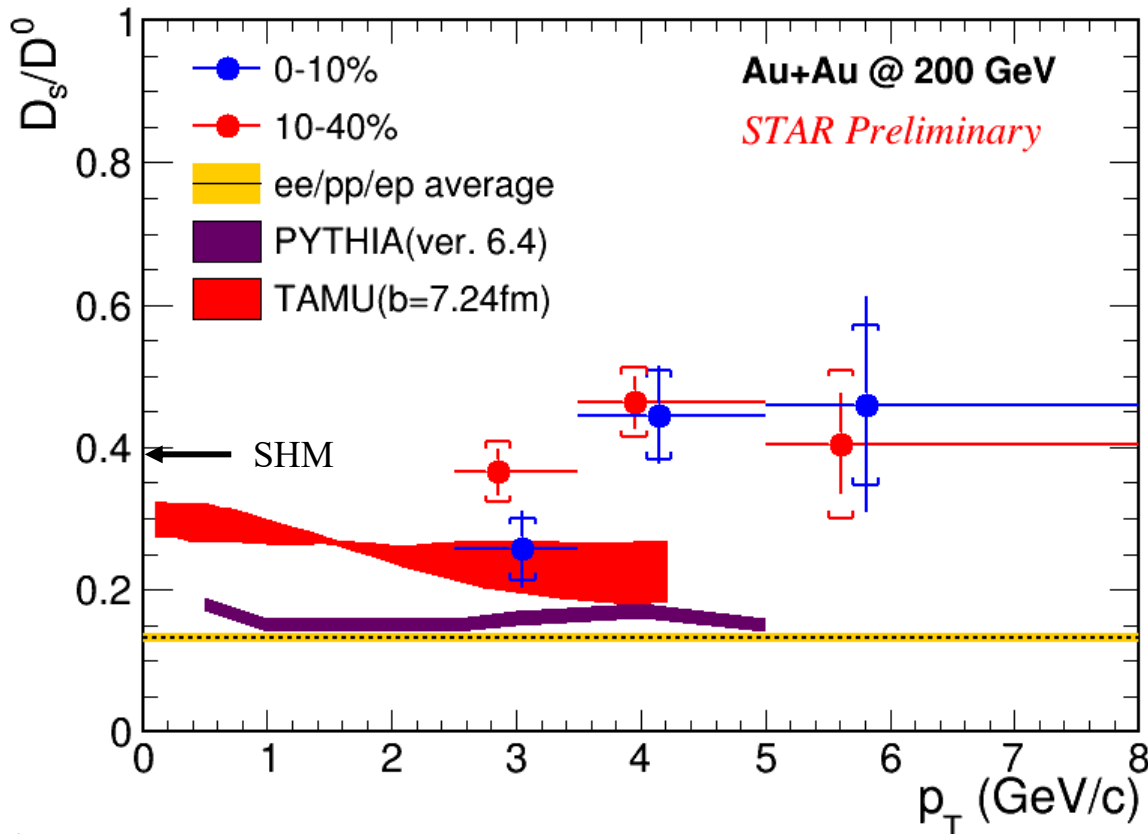


ALICE: JHEP 04 (2018) 108



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



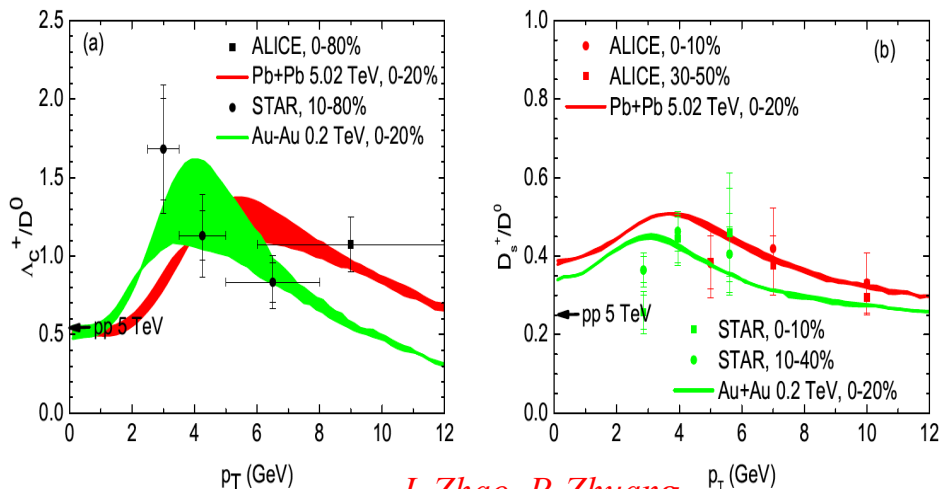
ep/pp/ep avg.: M Lisovsky, et al. EPJ C 76, (2016) 397
TAMU: H. Min et al. PRL 110, (2013) 112301
SHM: A. Andronic et al., PLB 571 (2003) 36



Recent Model Predictions

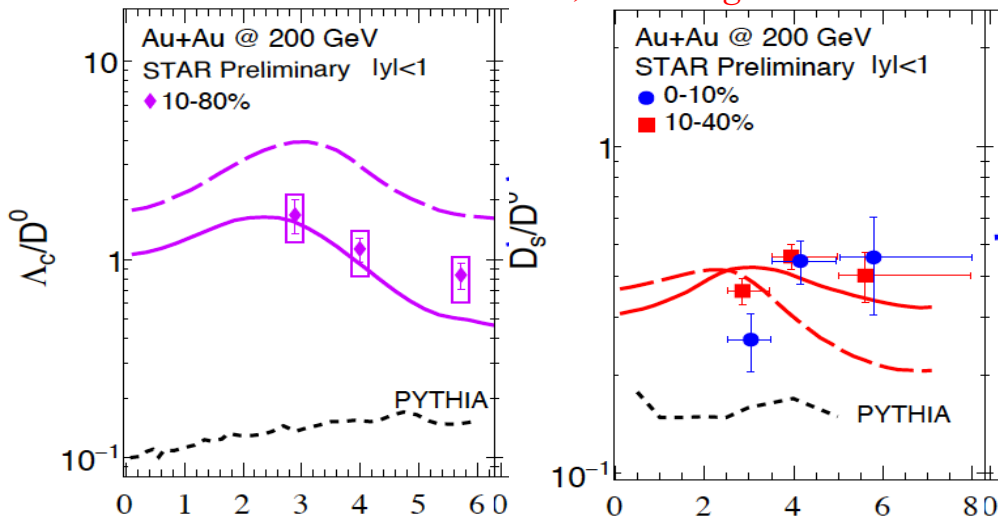
- Recent model predictions developed fast

M. He, R. Rapp

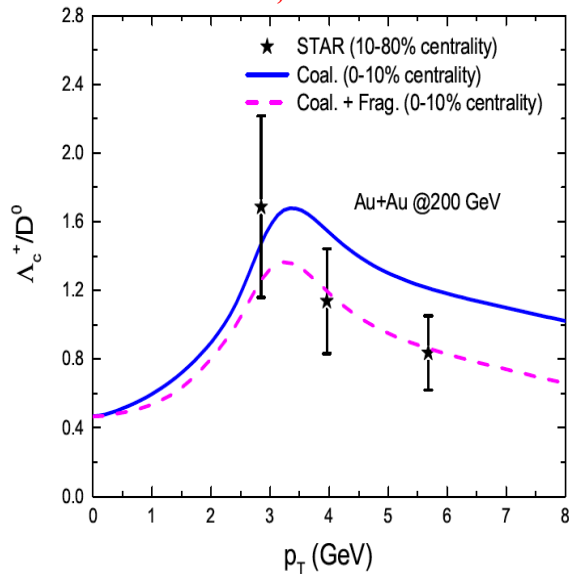


M. He and R. Rapp arXiv:1905.09216
K. Sun, C. M. Ko, etc. arXiv:1905.09774
J. Zhao, P. Zhuang, etc arXiv:1805.10858

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 $d\sigma/dy$ (μb)
AuAu 200 GeV (10-40%)	D^0	$41 \pm 1 \pm 5$
	D^+	$18 \pm 1 \pm 3$
	D_s^+	$15 \pm 1 \pm 5$
	Λ_c^+	$78 \pm 13 \pm 28^*$
	Total	$152 \pm 13 \pm 29$
pp 200 GeV	Total	$130 \pm 30 \pm 26$

* 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

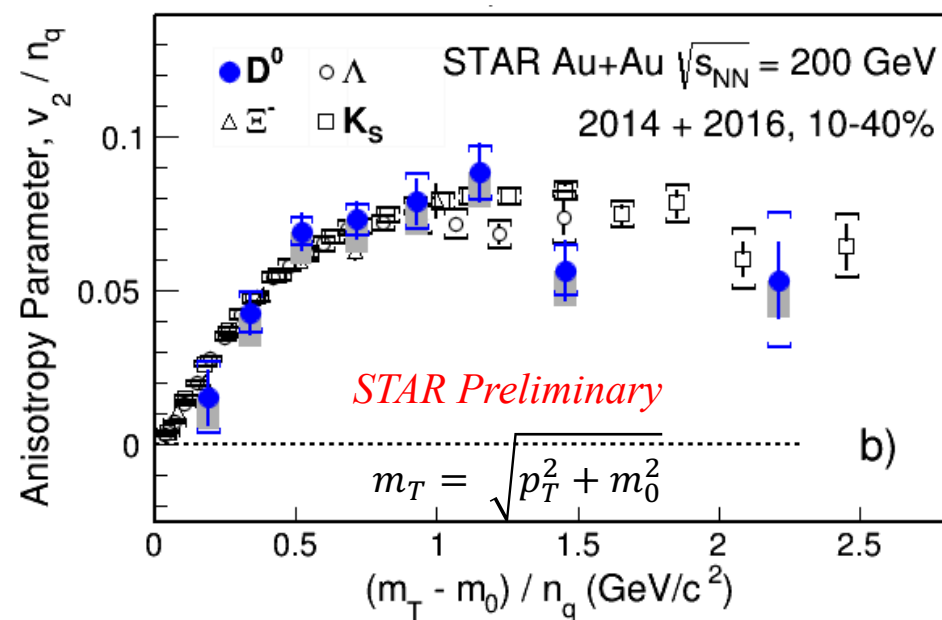
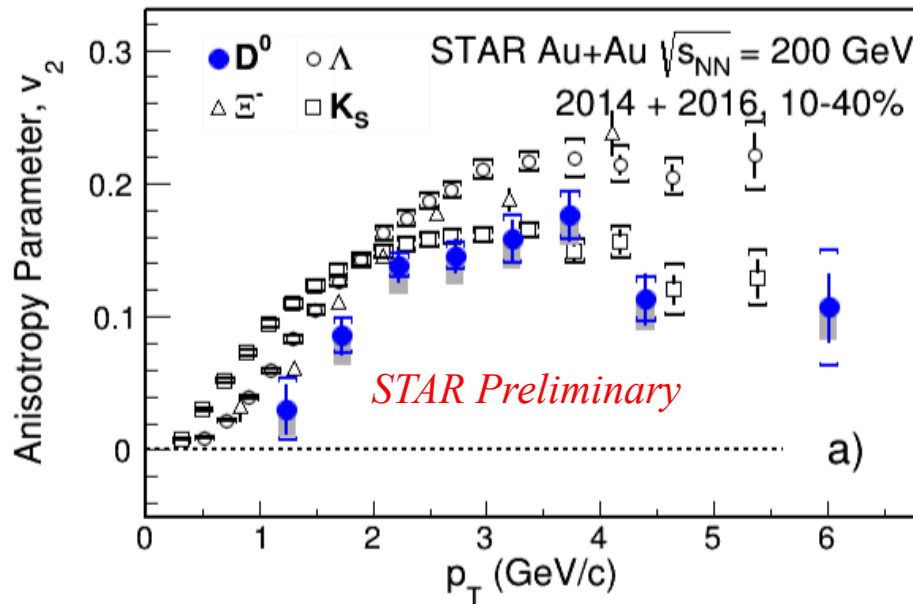


D^0 Elliptic Flow

- 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/c²
→ Evidence of charm quarks flowing with the medium

2014 +2016 Dataset

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

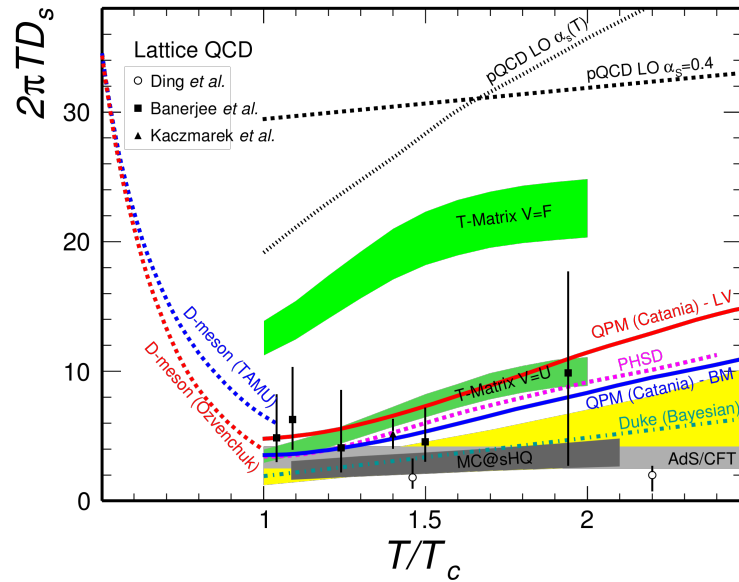
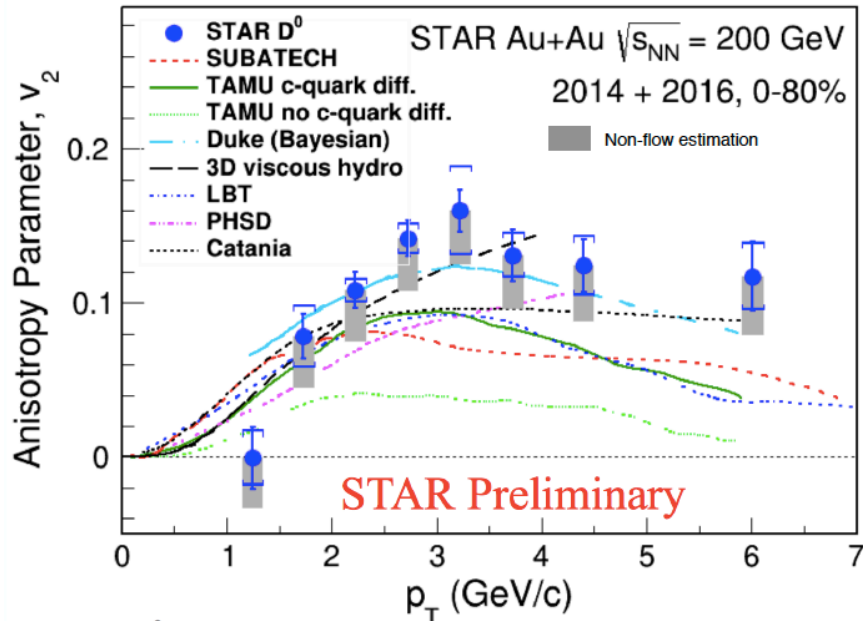




D^0 Elliptic Flow

- 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 $\rightarrow D^0 v_1$ sensitive to the initial tilt of the source (bulk)

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

- Charm and anti-charm quarks can be deflected differently by the initial EM field \rightarrow difference between D^0 and $\overline{D^0} v_1$ sensitive to EM field

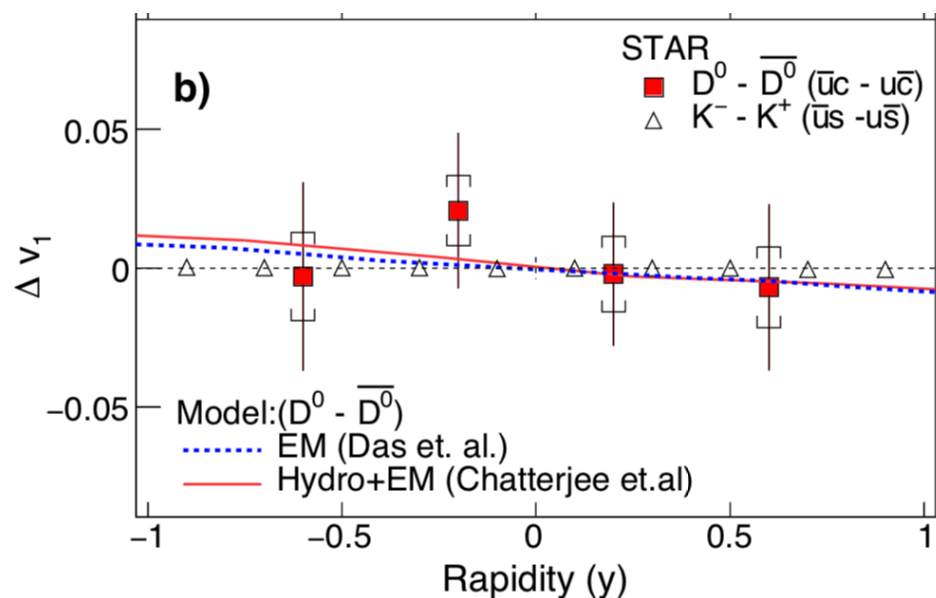
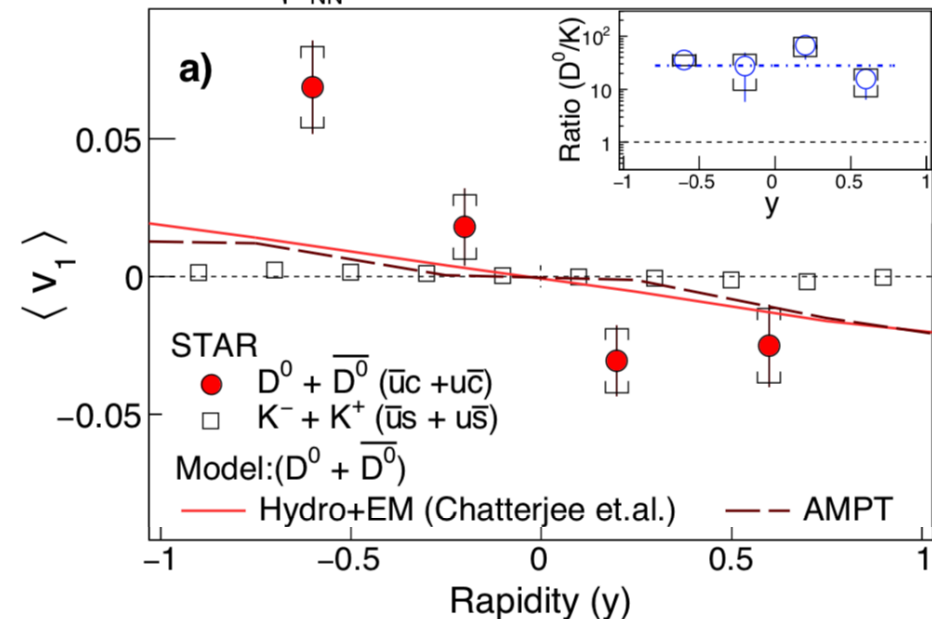
- First observation of non-zero (negative) $D^0(\overline{D^0}) v_1$ slope, much larger than that of kaons

$$D^0 + \overline{D^0} dv_1/dy = -0.081 \pm 0.021(stat) \pm 0.017(sys)$$

- More precise data are needed for Δv_1 $d\Delta v_1/dy = -0.041 \pm 0.041(stat) \pm 0.020(sys)$

Au+Au $\sqrt{s_{NN}}=200$ GeV, 10-80%

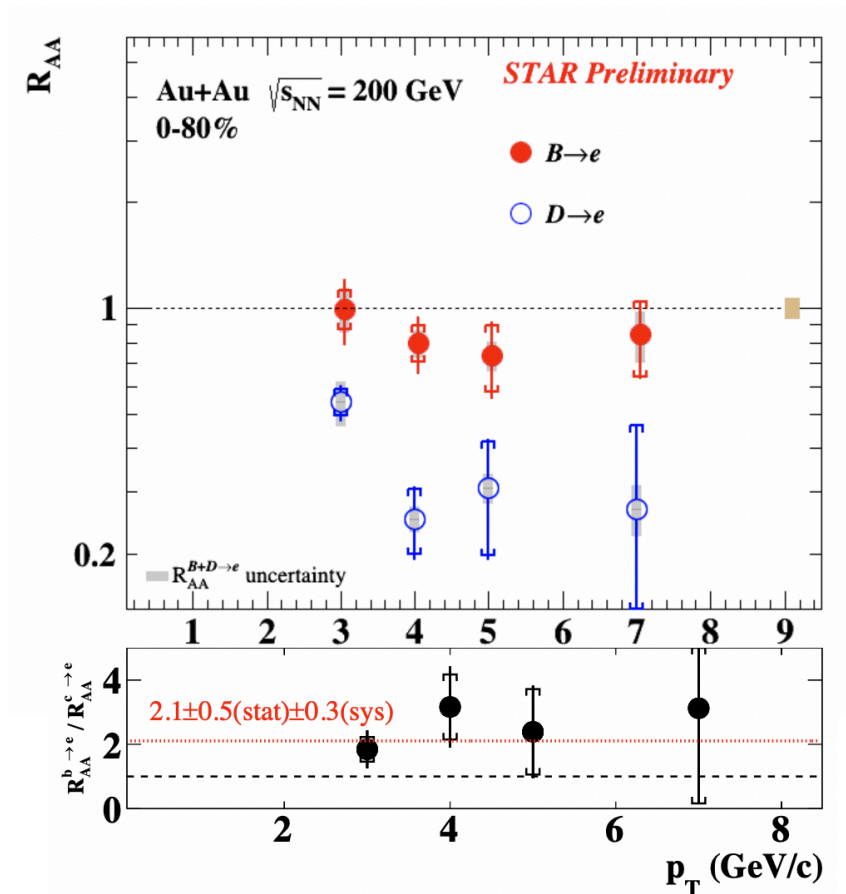
STAR, arXiv:1905.02052





Charm to Bottom Through Single e Channel

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





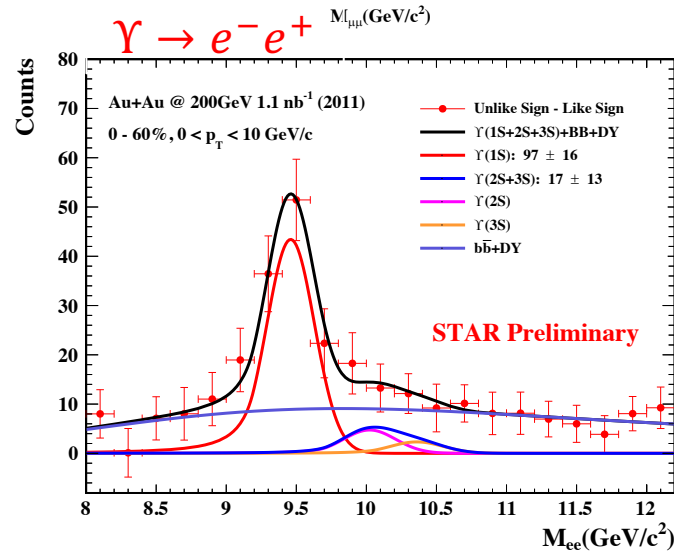
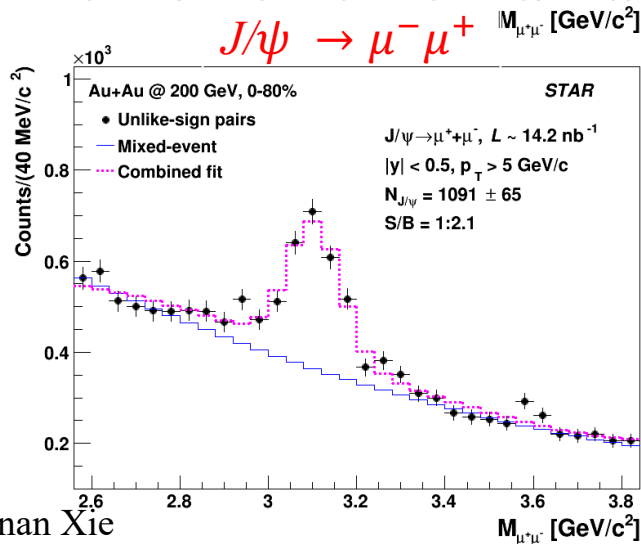
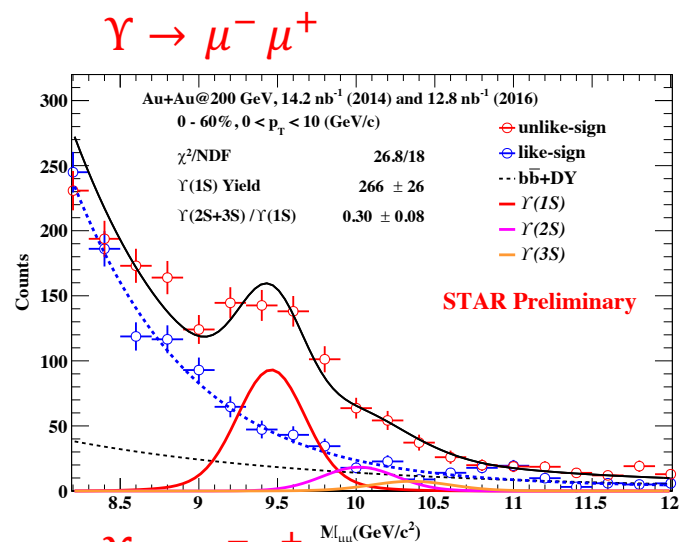
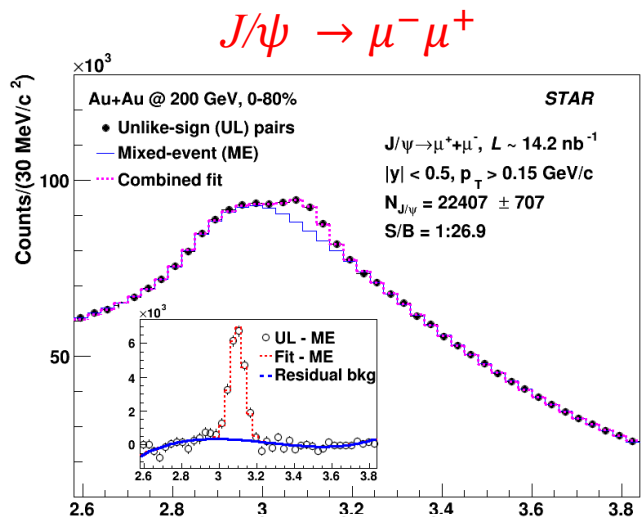
Quarkonium Signals

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

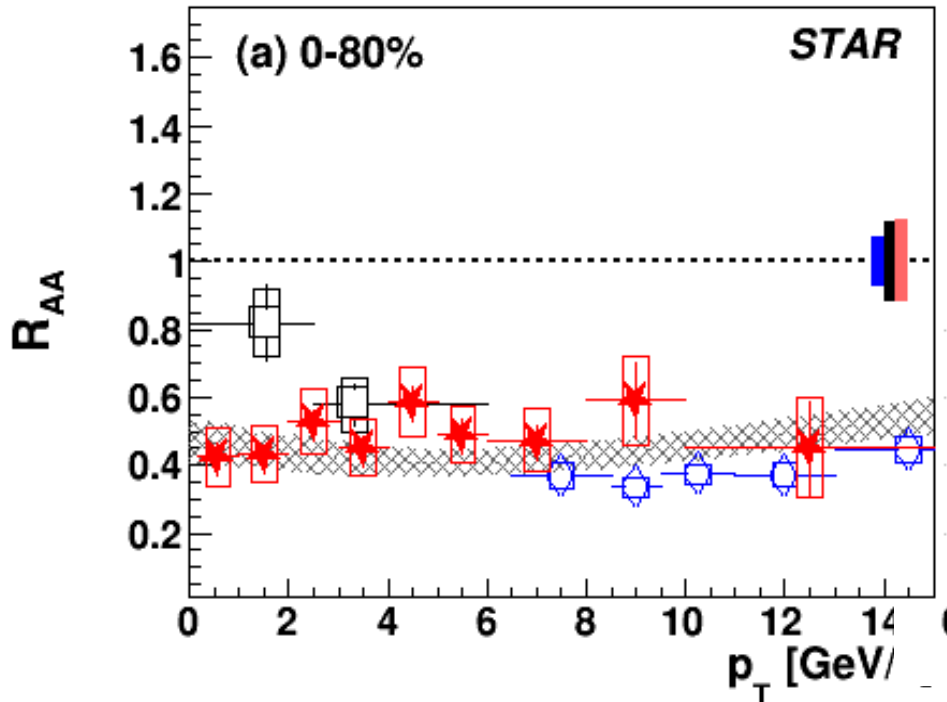




J/ψ R_{AA} vs. p_T

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

Inclusive J/ψ from STAR



- Au+Au @ 200 GeV, Inclusive J/ψ
- ★ STAR: $J/\psi \rightarrow \mu^+\mu^-$, $|y| < 0.5$
 - Systematic uncertainty
 - ▨ TM II: TAMU
 - ● STAR: $J/\psi \rightarrow e^+e^-$, $|y| < 1$
- Pb+Pb @ 2.76 TeV
- ALICE: Inclusive J/ψ , 0-40%, $|y| < 0.8$
 - ◇ CMS: Prompt J/ψ , 0-100%, $|y| < 2.4$

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



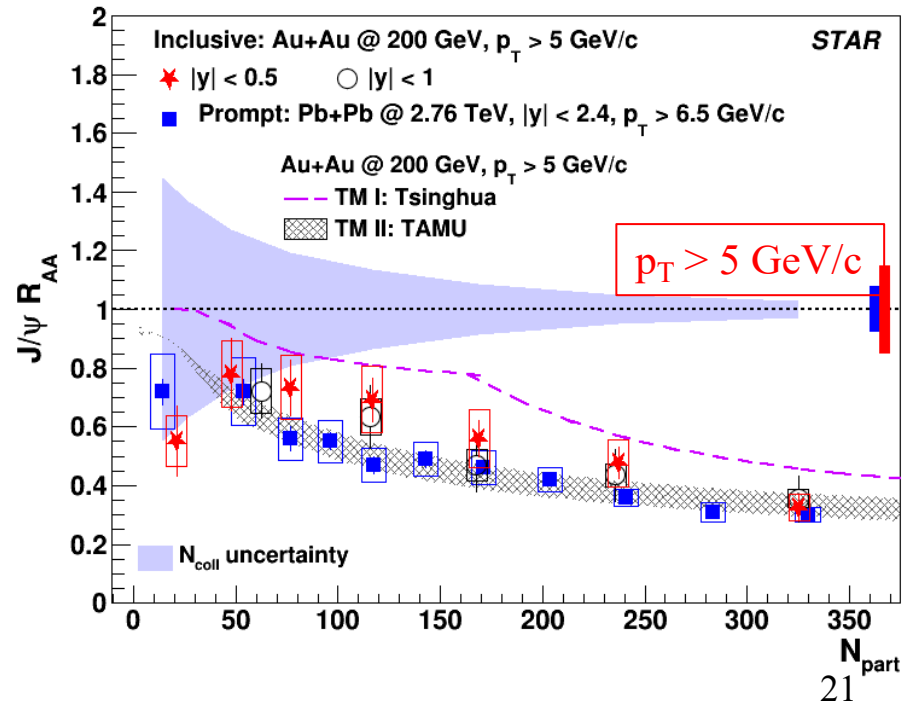
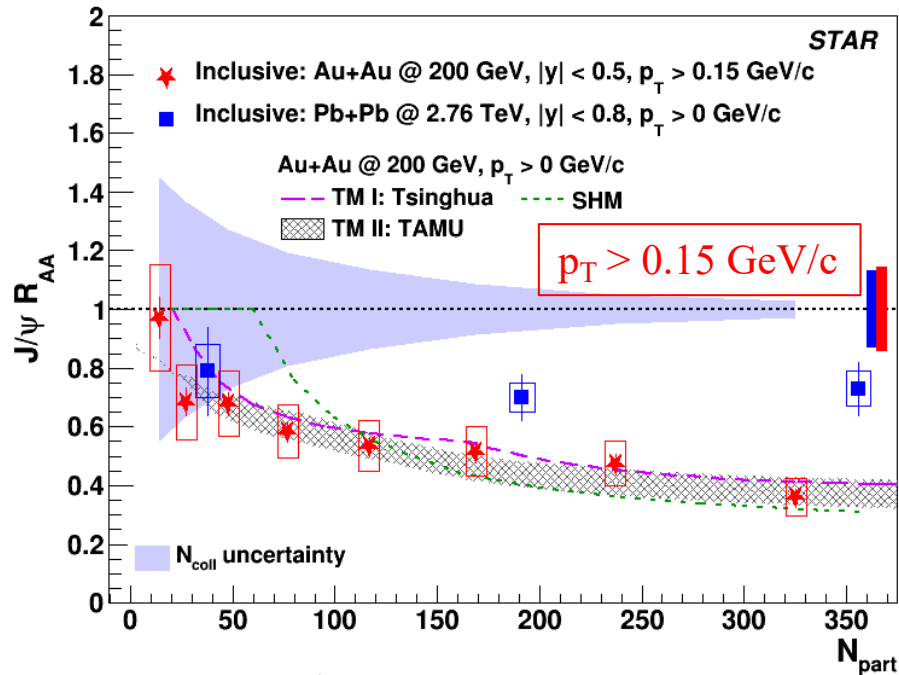
J/ψ R_{AA} vs. Centrality

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

- 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

arXiv:1905.13669 , submitted to P.L.B

Inclusive J/ψ from STAR



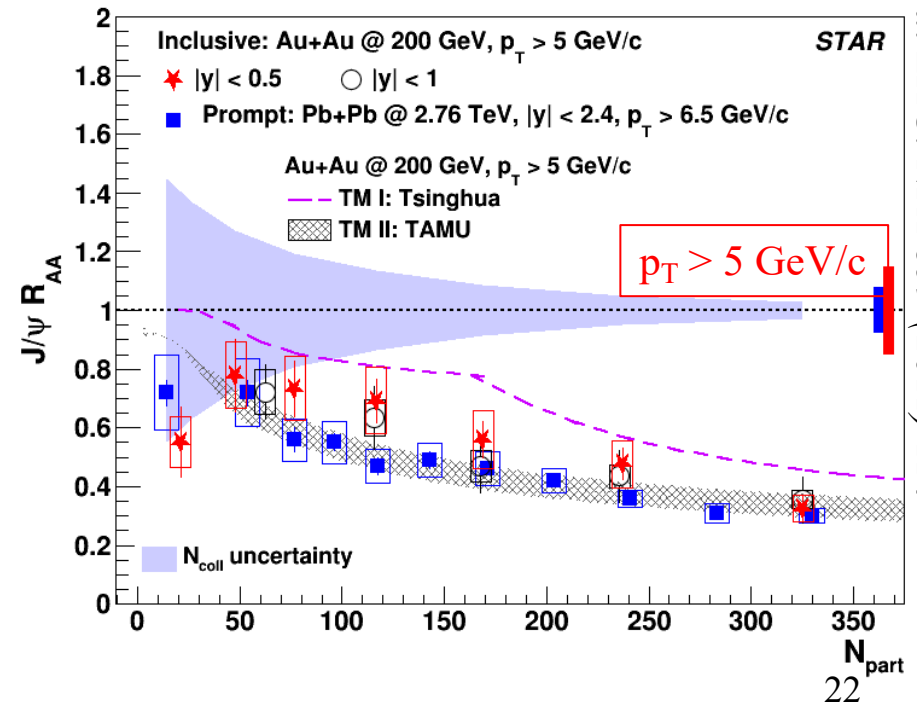
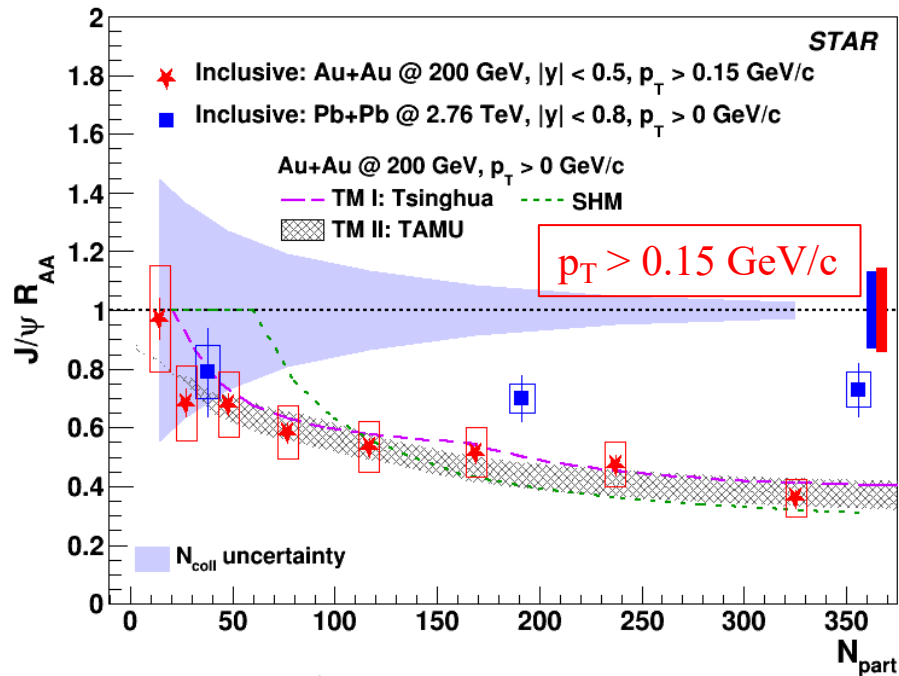


J/ψ R_{AA} comparison with models

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

arXiv:1905.13669 , submitted to P.L.B

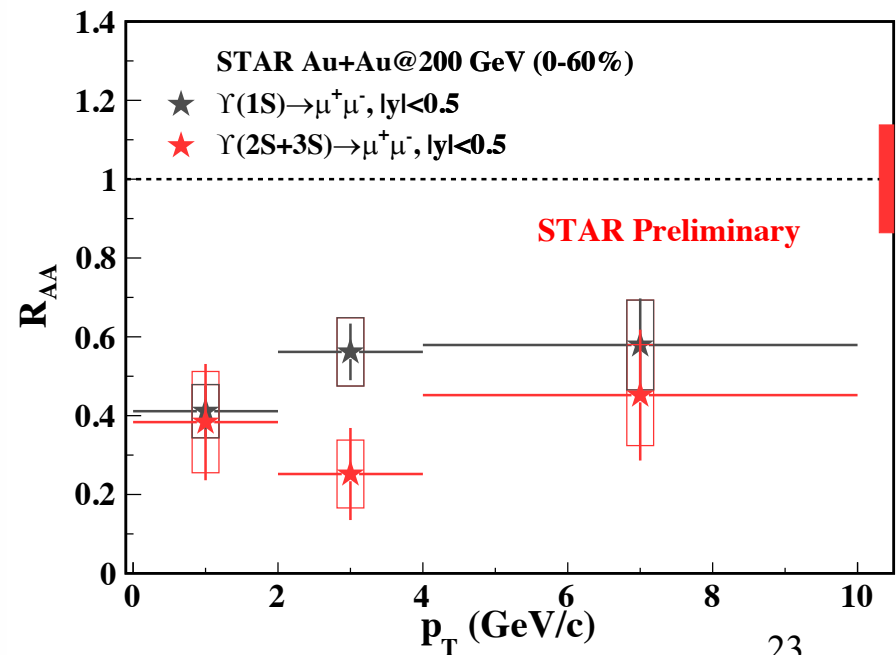
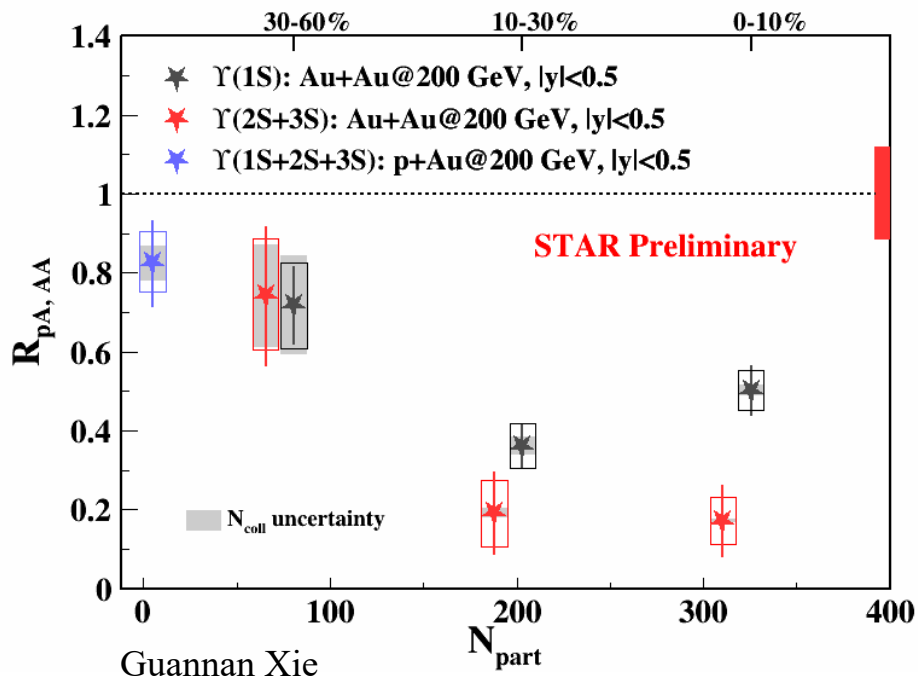
Inclusive J/ψ from STAR





$\Upsilon(1S)$ vs. $\Upsilon(2S+3S)$

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

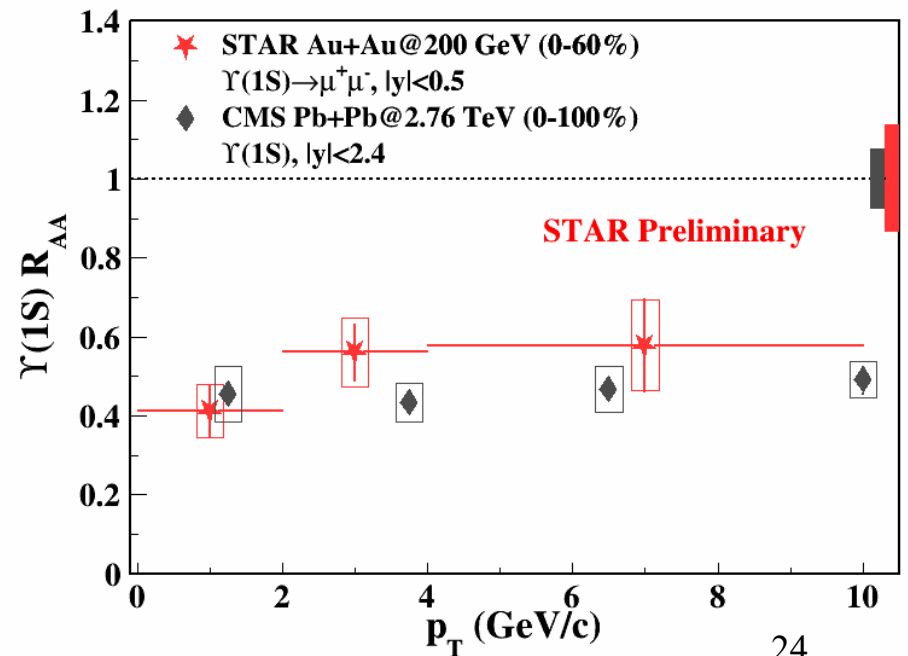
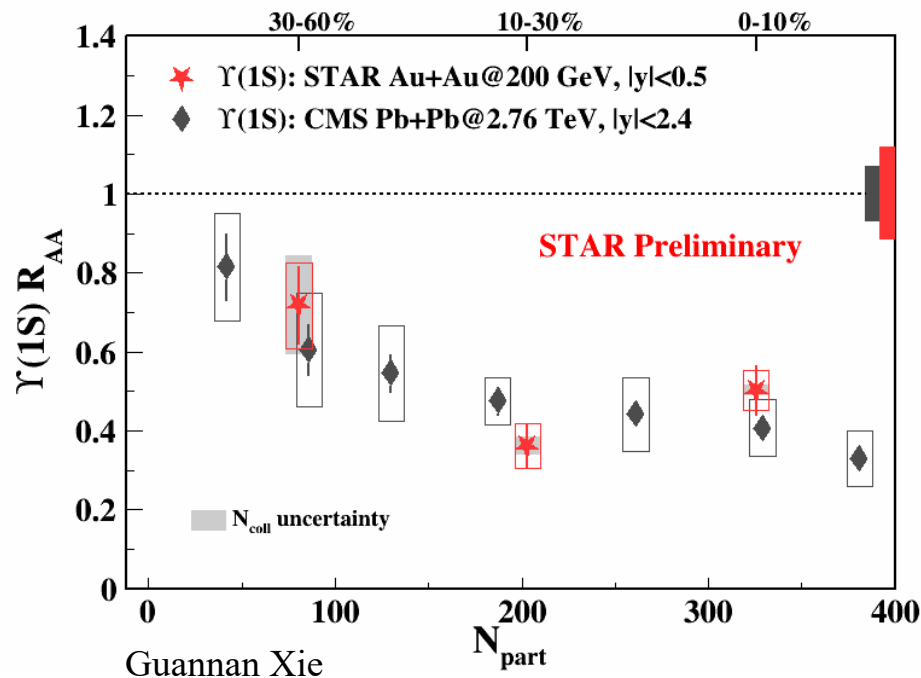




$\Upsilon(1S)$

- 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 effect
 - Suppression of excited Υ states

CMS, PLB 770 (2017) 357

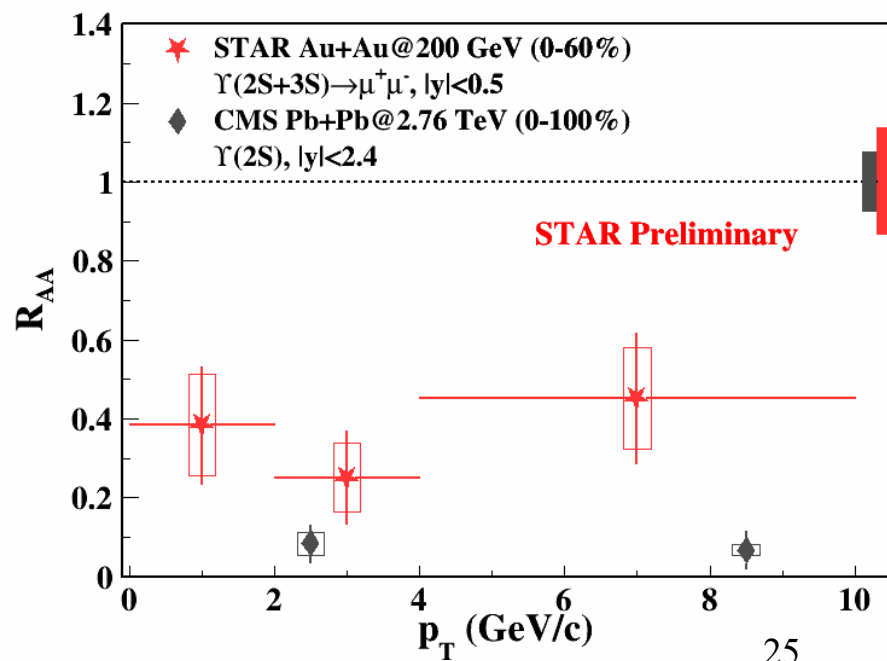
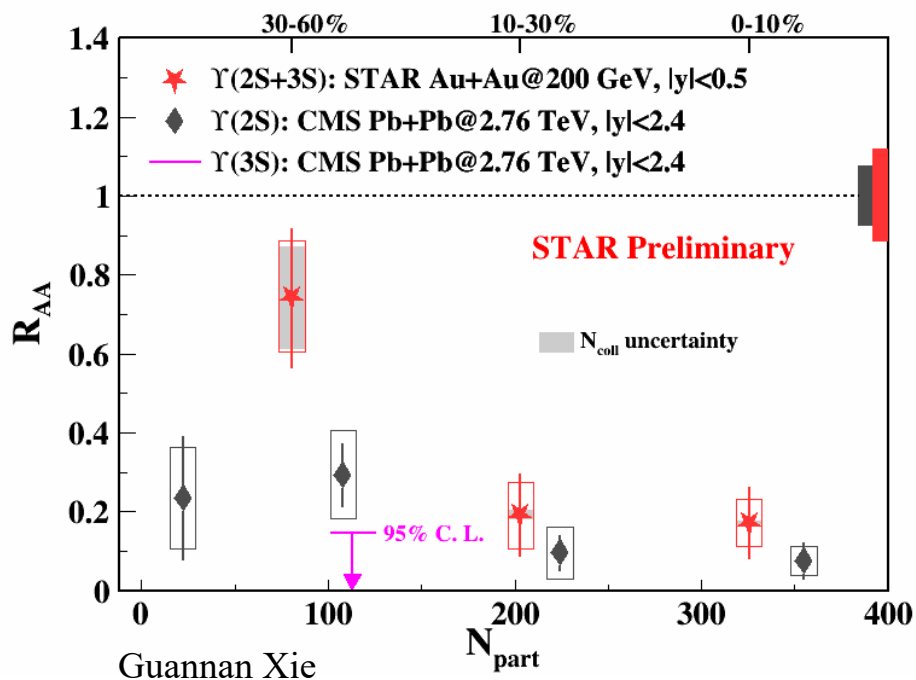




$\Upsilon(2S+3S)$

- Indication of more suppression towards central collisions
- No clear p_T dependence
- More suppressed than $\Upsilon(1S)$ 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



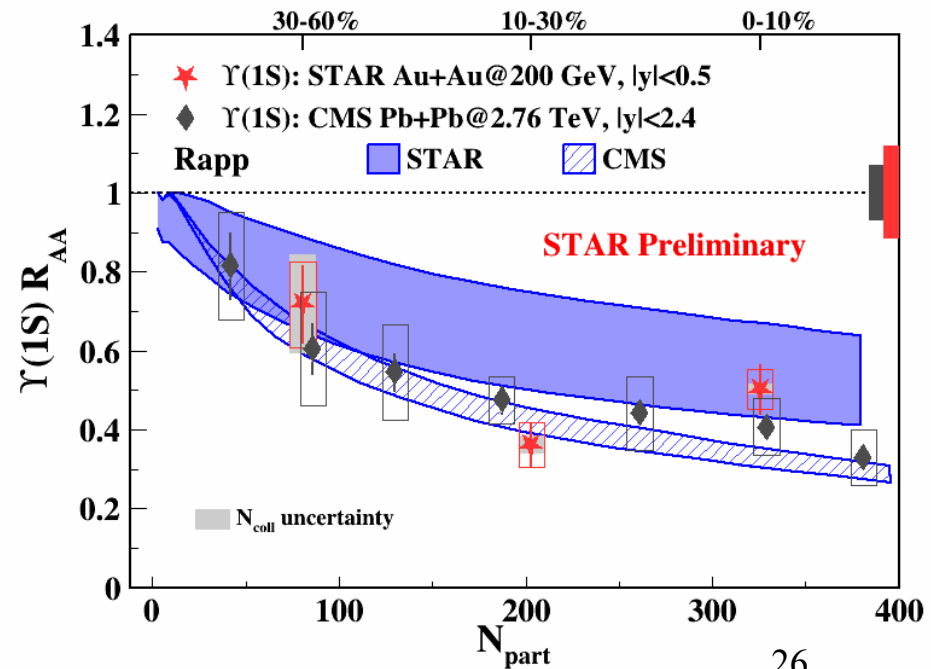
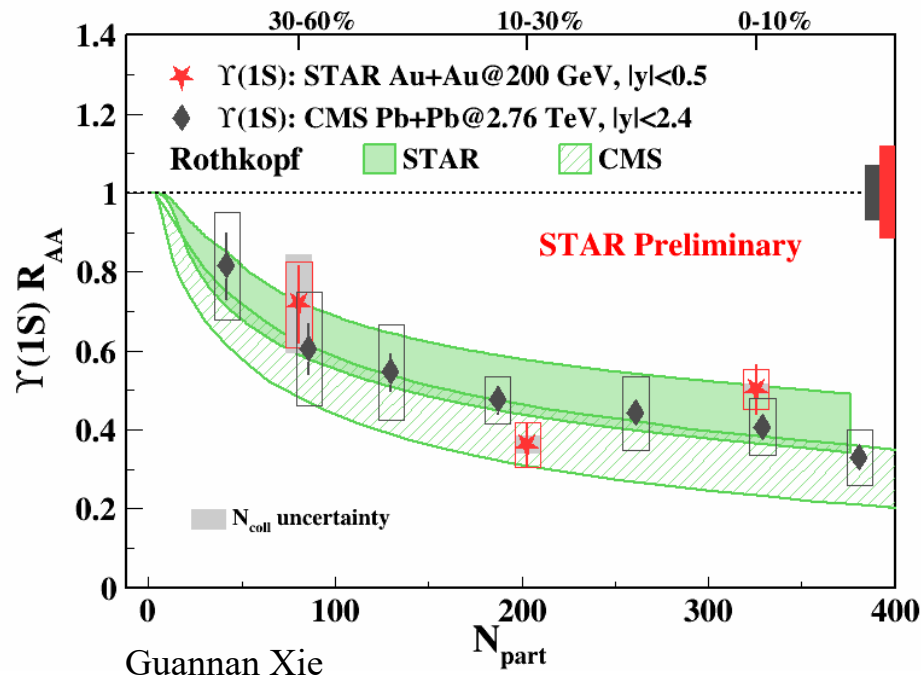


Comparison with Models: $\Upsilon(1S)$

- 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

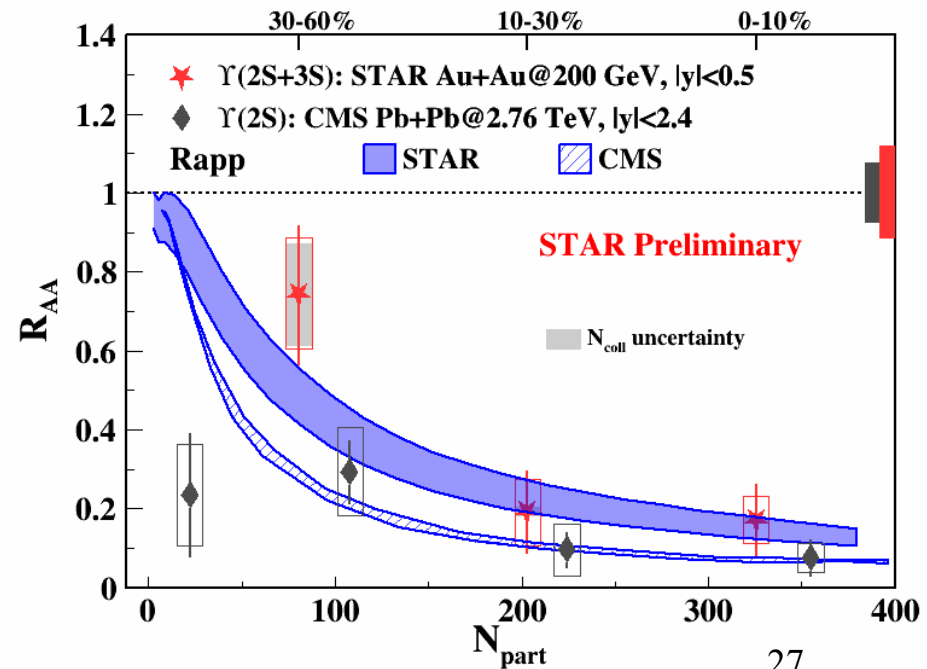
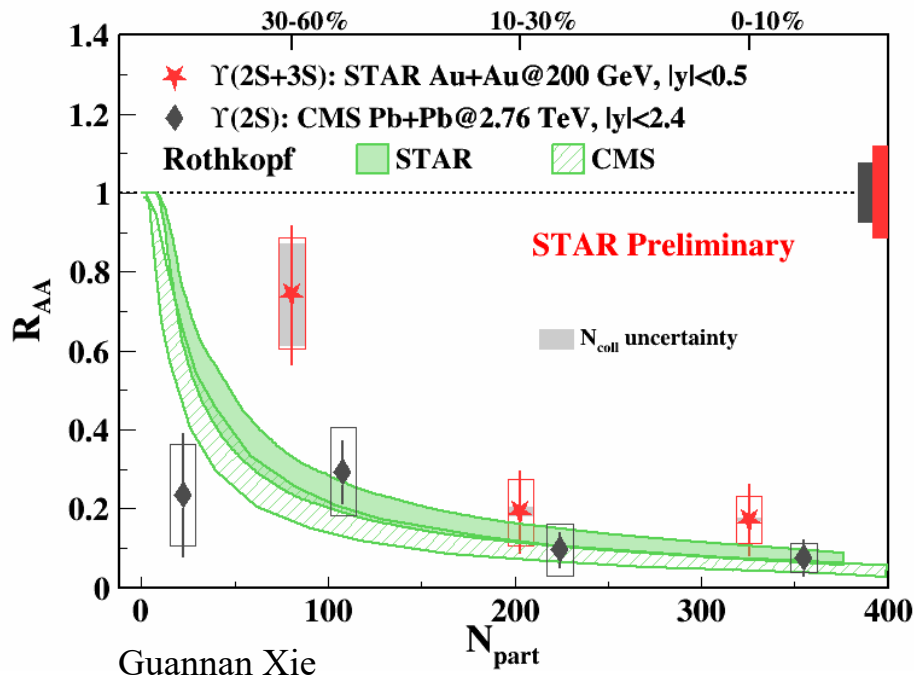




Comparison with Models: $\Upsilon(2S+3S)$

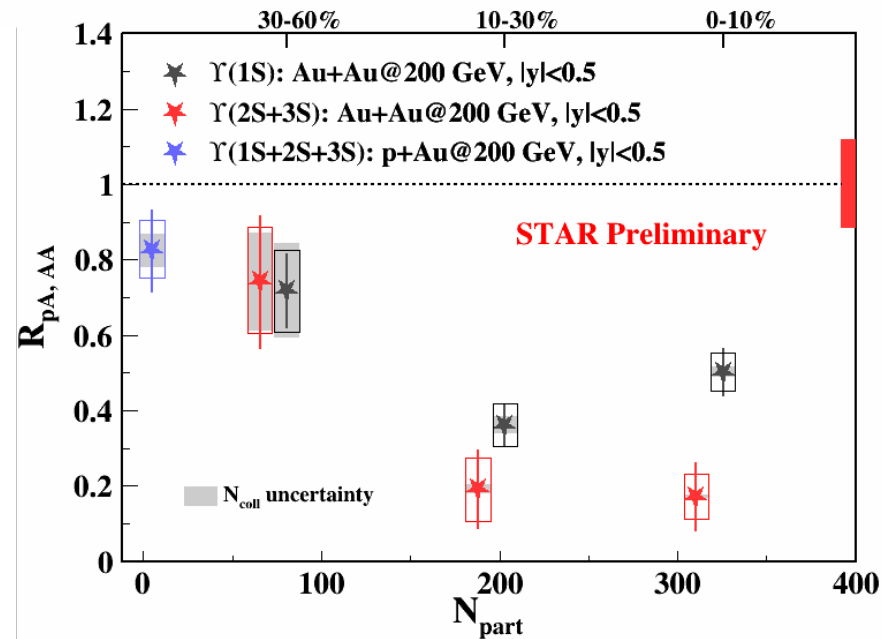
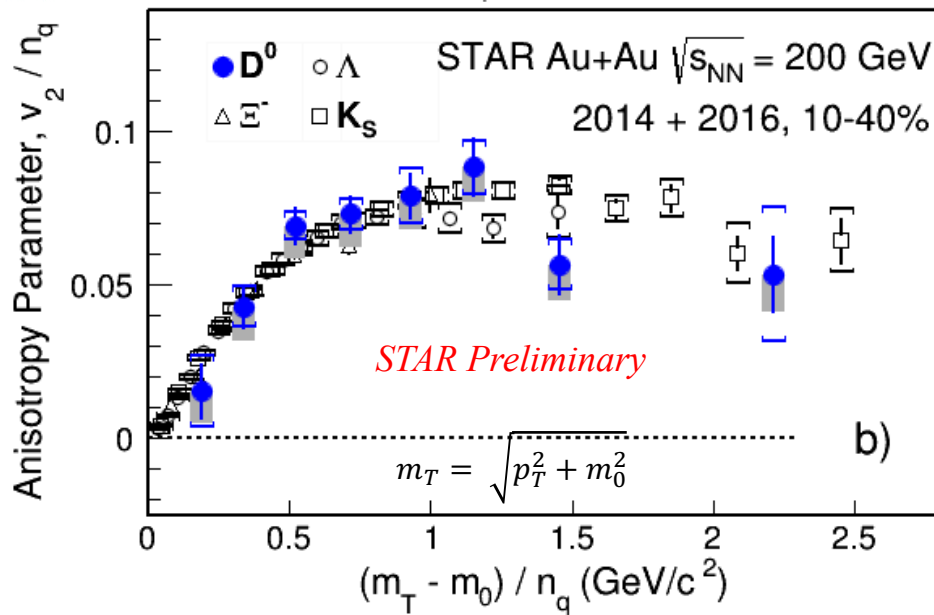
- Both models consistently describe RHIC and LHC excited Υ states suppression in semi-central and central collisions
 - KSU model is lower than data in 30-60% centrality

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



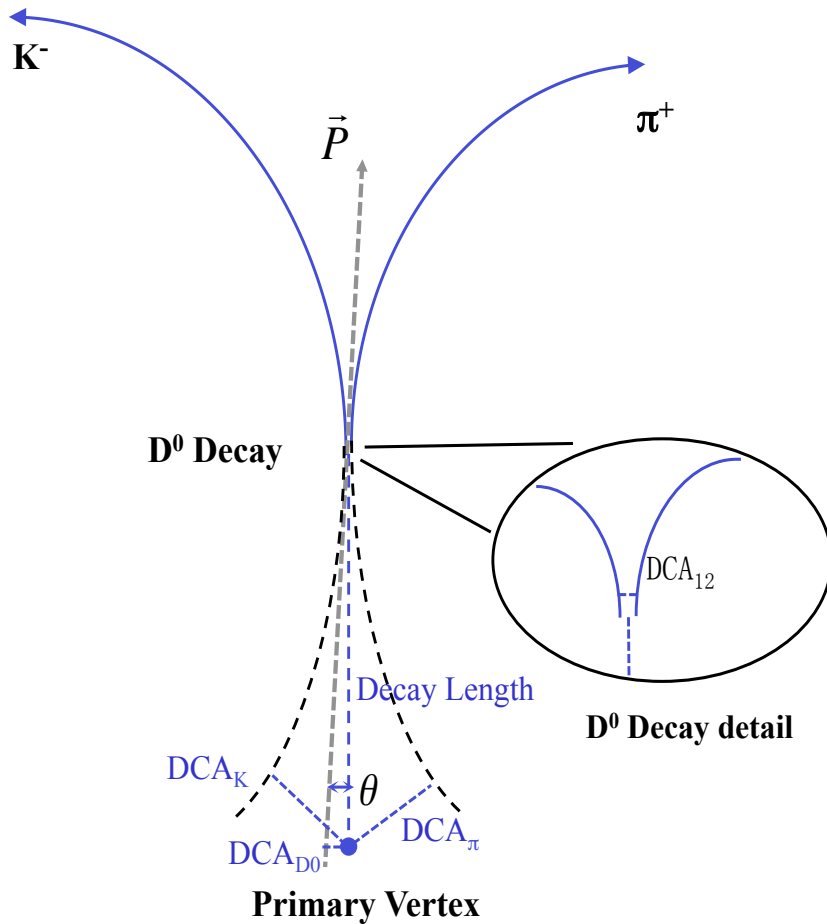
- Open heavy flavor
 - Significant collective behavior for charm \rightarrow charm quark diffusion in medium
 - Hint of $R_{AA}(b \rightarrow e) > R_{AA}(c \rightarrow e) \rightarrow$ mass hierarchy
 - D_s/D^0 and Λ_c^+/D^0 enhancement \rightarrow coalescence hadronization
- Quarkonium
 - Strong suppression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



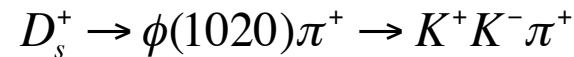
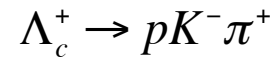
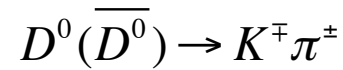
Back up



Topological Reconstruction



- Direct topological reconstruction through hadronic channels

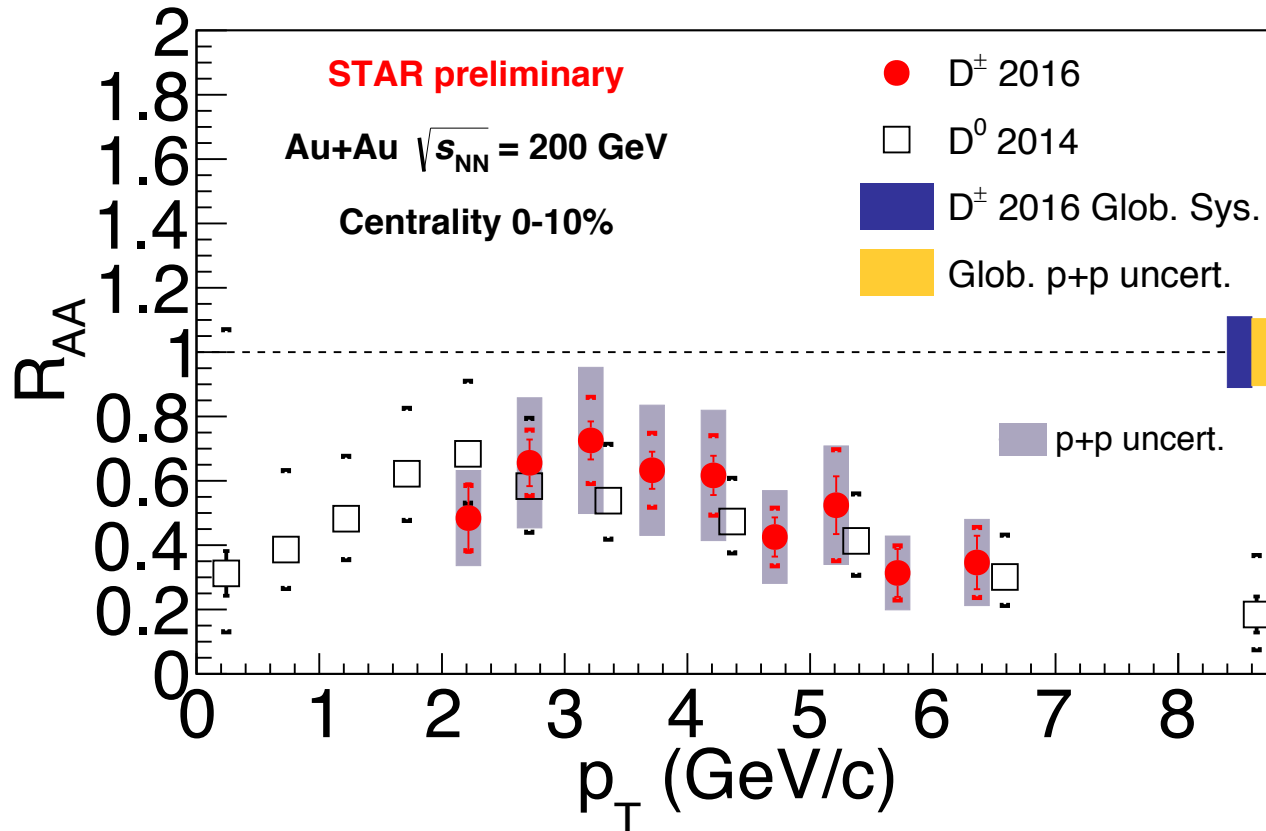


- With HFT: greatly reduced combinatorial background
- Topological cuts optimized by TMVA (Toolkit for Multi Variate Analysis)



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

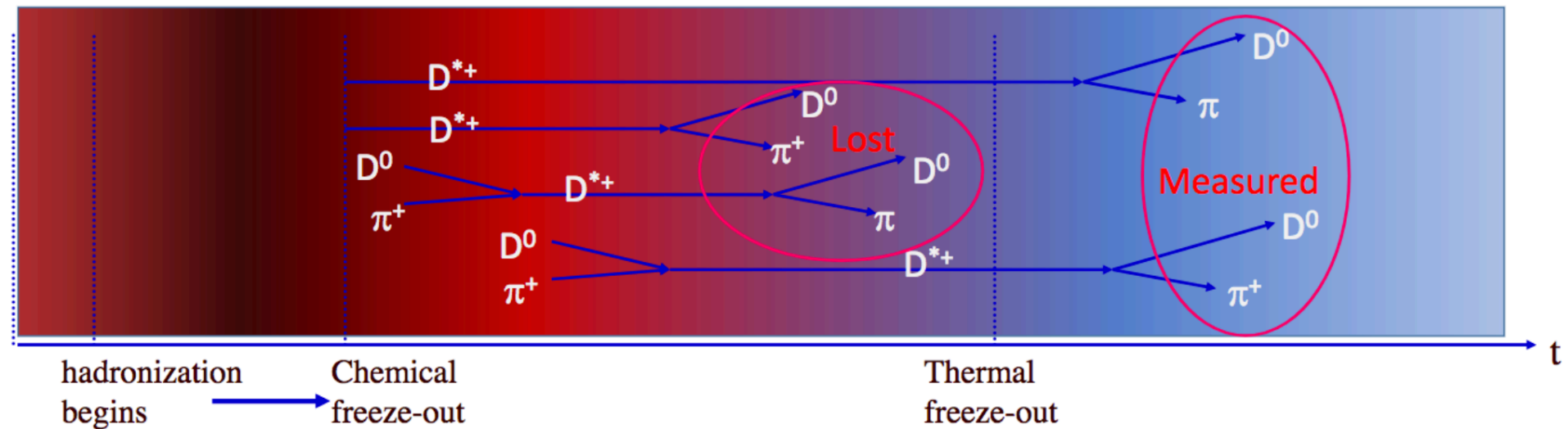
- Similar suppression for D^0 and $D^{+/-}$
- Spectra measurement is important for the total charm cross-section





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

- D^{*+} feeds down to D⁰ 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

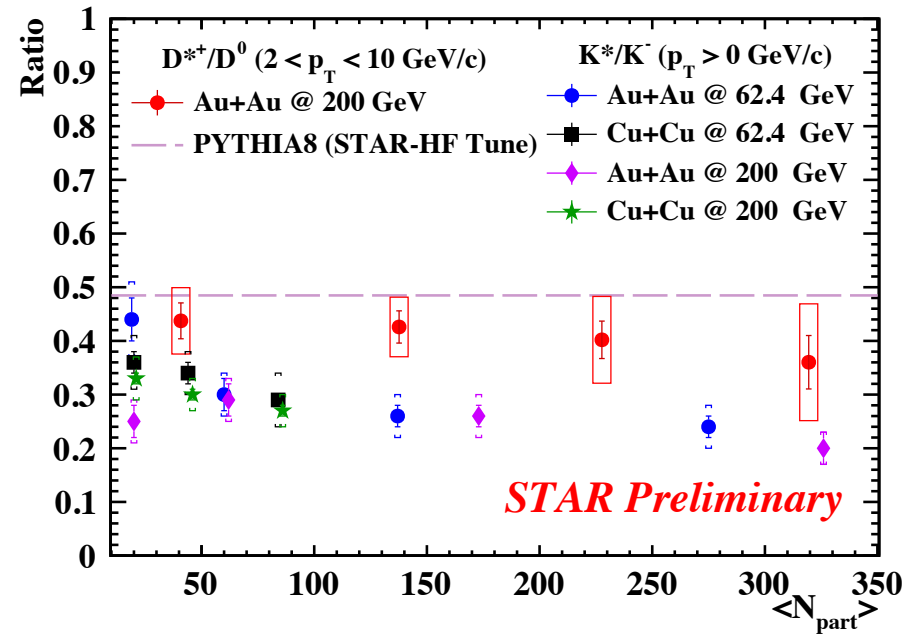
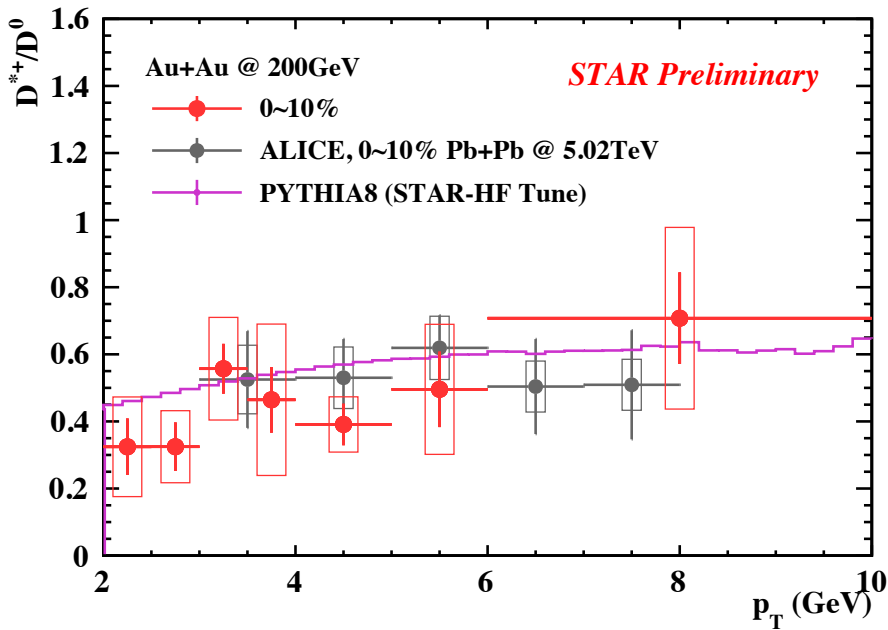


Shuai Y. F. Liu and Ralf Rapp. *Phys. Rev. C* 97 (2018) 034918.



D^{*+}/D⁰ Ratio in Au+Au Collisions

- D^{*+}/D⁰ 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



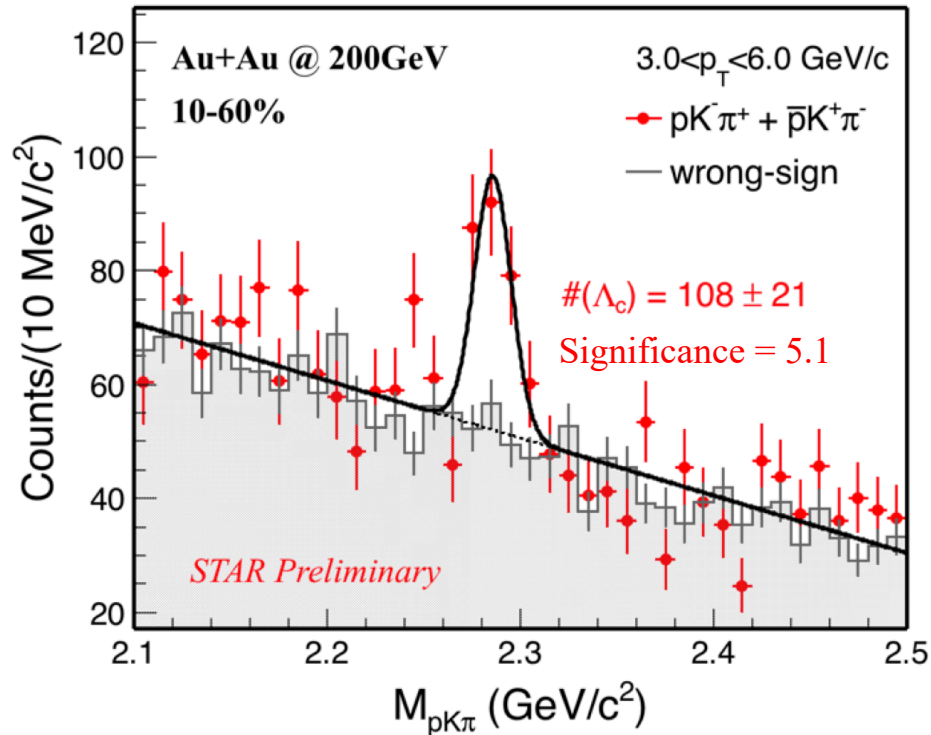
K^{*}/K, *Phys. Rev. C* (2011) 84. 034909.
ALICE Collaboration, *arXiv:1804.09083*.



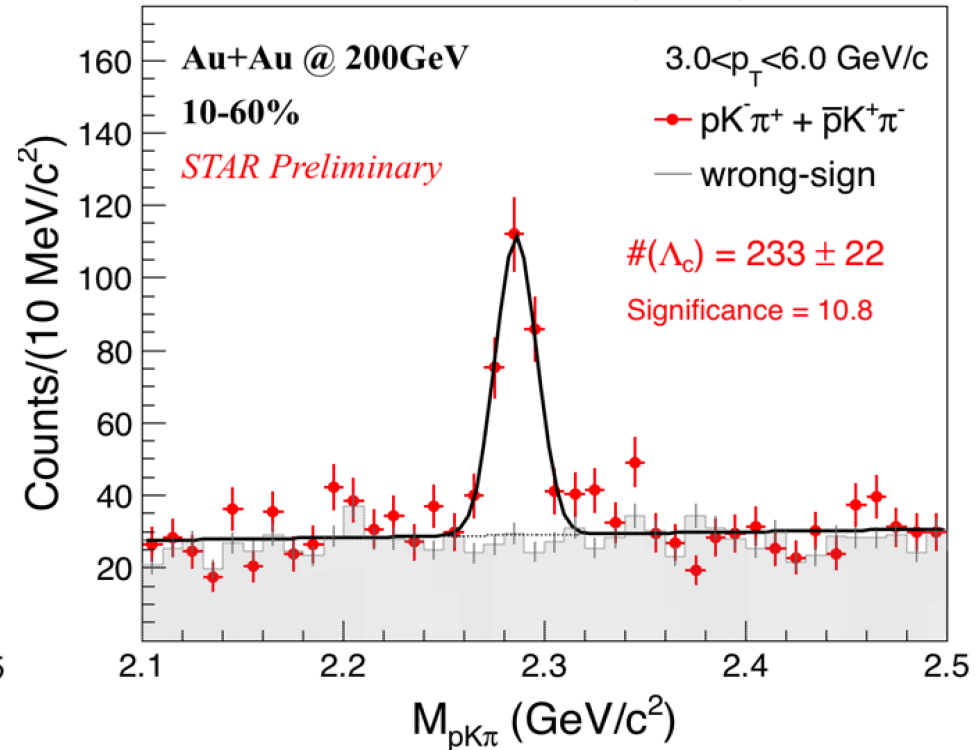
Λ_c Reconstruction

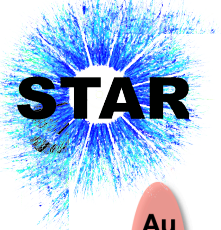
- More than 50% improvement in signal significance with TMVA BDT
- Also new data from 2016
- Effectively **4x** more data

2014 (Rectangular) QM17

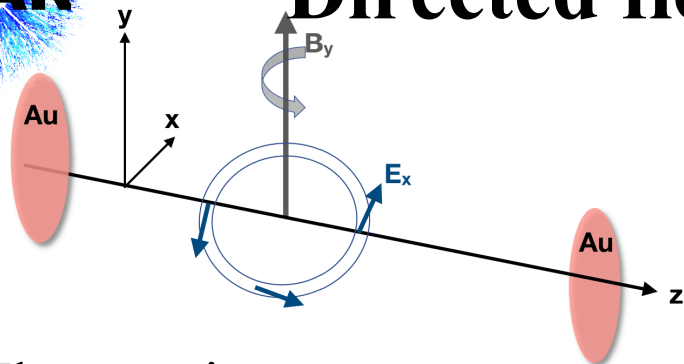


2014+2016 (BDT)

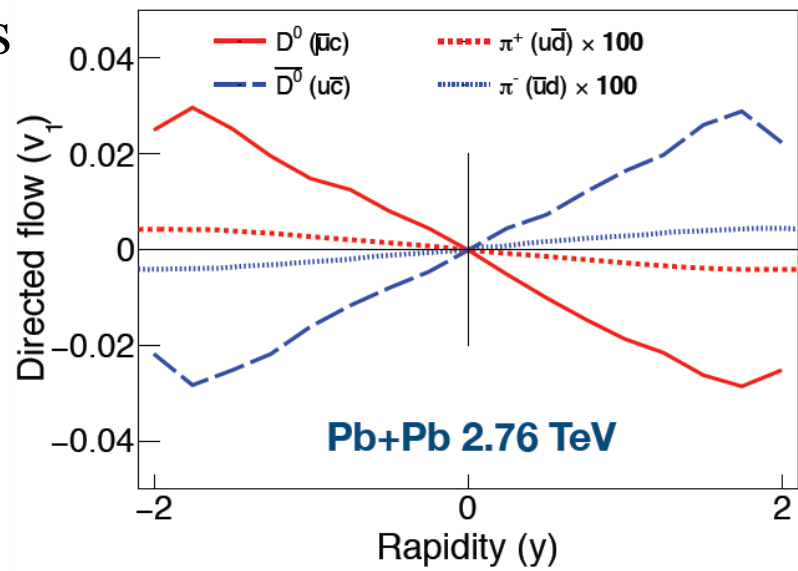
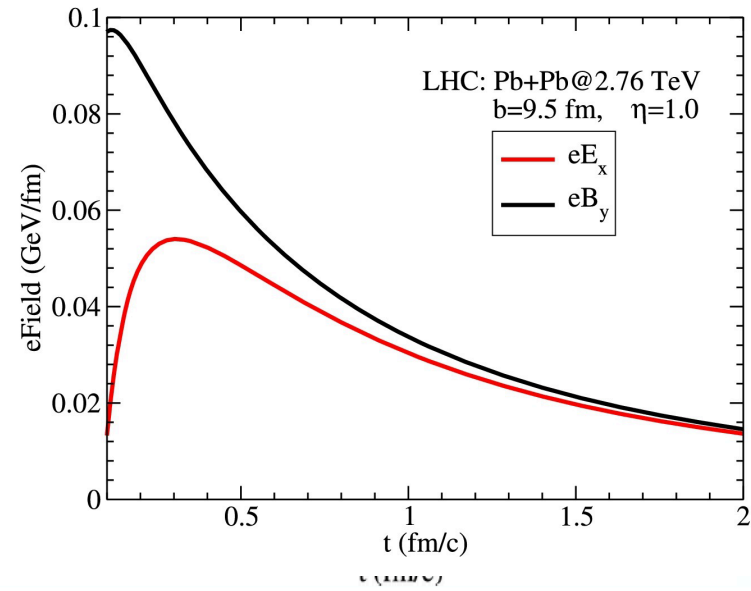




Directed flow (v_1) due to EM fields

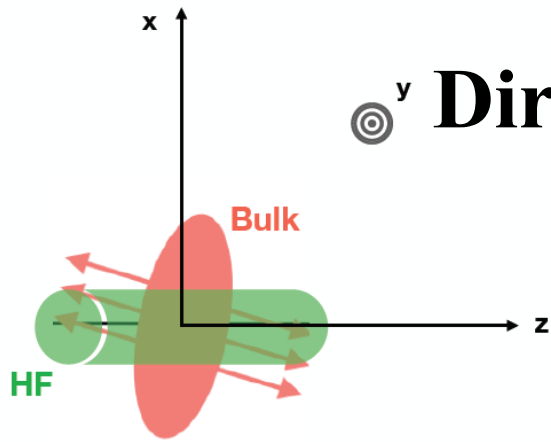


- The moving spectators can produce enormously large electromagnetic field ($eB \sim 10^{18}$ G at RHIC)
- Due to early production of heavy quarks ($\tau_{CQ} \sim 0.1$ fm/c) positive and negative charm quarks (CQs) can get deflected by the initial EM force
- D^0 and $D^0 v_1$ can offer insight into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

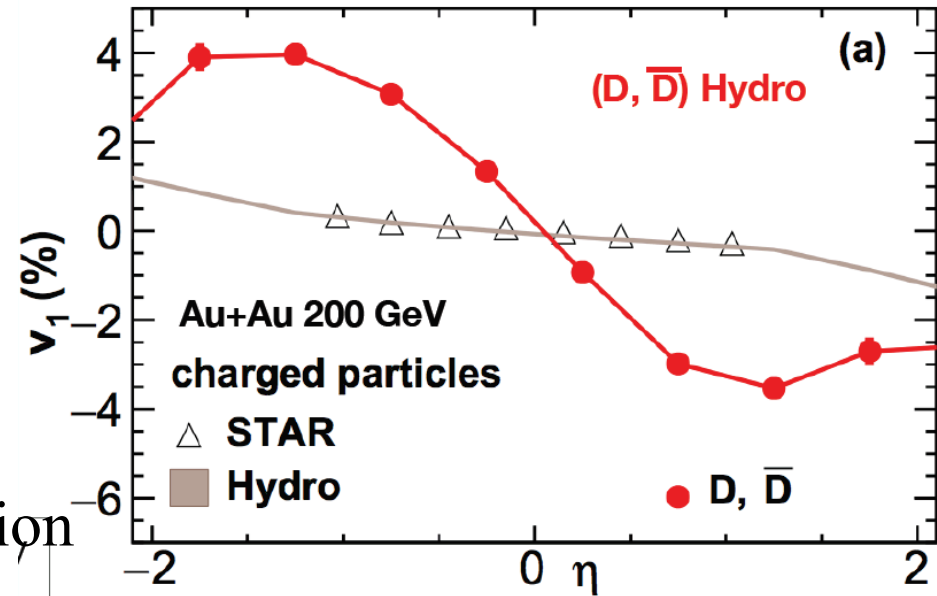


Das et. al., Phys Lett B 768, 260 (2017)

Directed flow (v_1) due to hydro



- Heavy quarks are produced according to N_{coll} 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



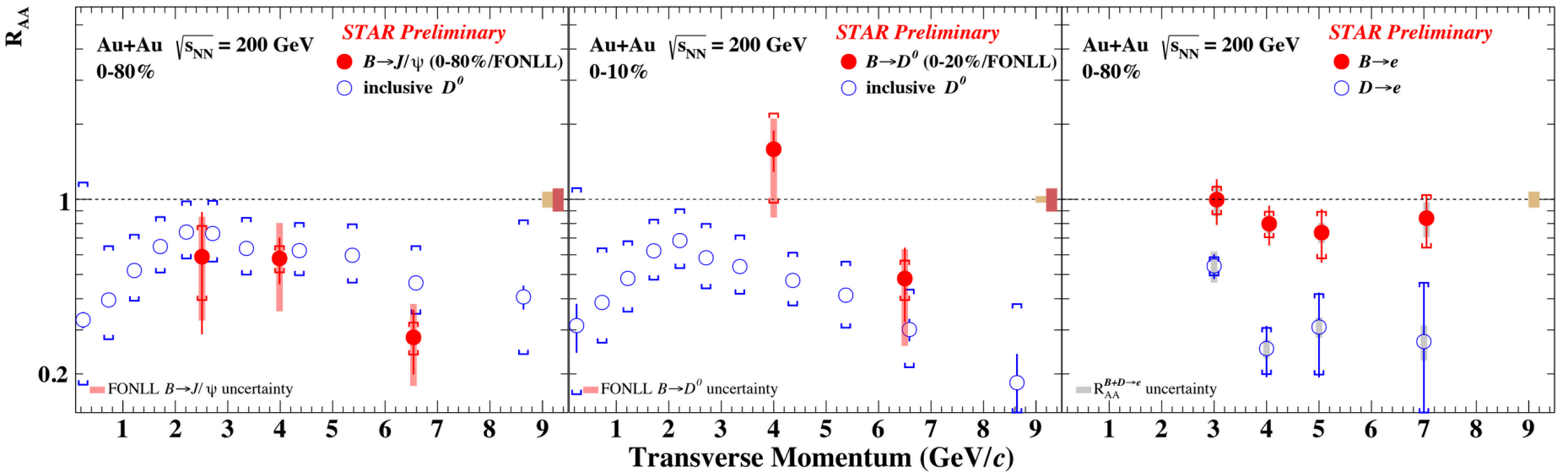
Chatterjee, Bozek:
Phys Rev Lett 120, 192301 (2018)

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



B Study from Non-prompt J/ψ & D⁰ & 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 $D \rightarrow e$ ($\sim 2 \sigma$): consistent with $\Delta E_c > \Delta E_b$. Measurements with improved precision on the way



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

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

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

Au+Au @ 200 GeV, Inclusive J/ψ

★ STAR: $J/\psi \rightarrow \mu^+\mu^-$, $|y| < 0.5$

□ Systematic uncertainty

⊕ PHENIX: $J/\psi \rightarrow e^+e^-$, $|y| < 0.35$

○ ● STAR: $J/\psi \rightarrow e^+e^-$, $|y| < 1$

Pb+Pb @ 2.76 TeV

□ ALICE: Inclusive J/ψ , 0-40%, $|y| < 0.8$

◇ CMS: Prompt J/ψ , 0-100%, $|y| < 2.4$

