Overview of recent heavy-flavor results from STAR

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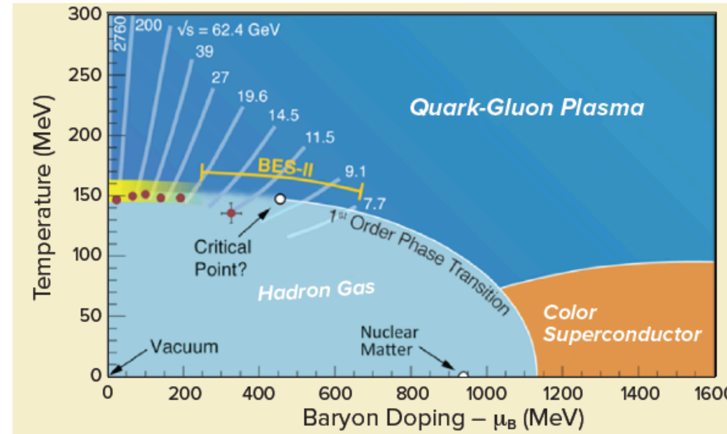
for the STAR Collaboration

Rencontres de Moriond
QCD and High Energy Interactions

LA THUILE, MARCH 25 - APRIL 1, 2017

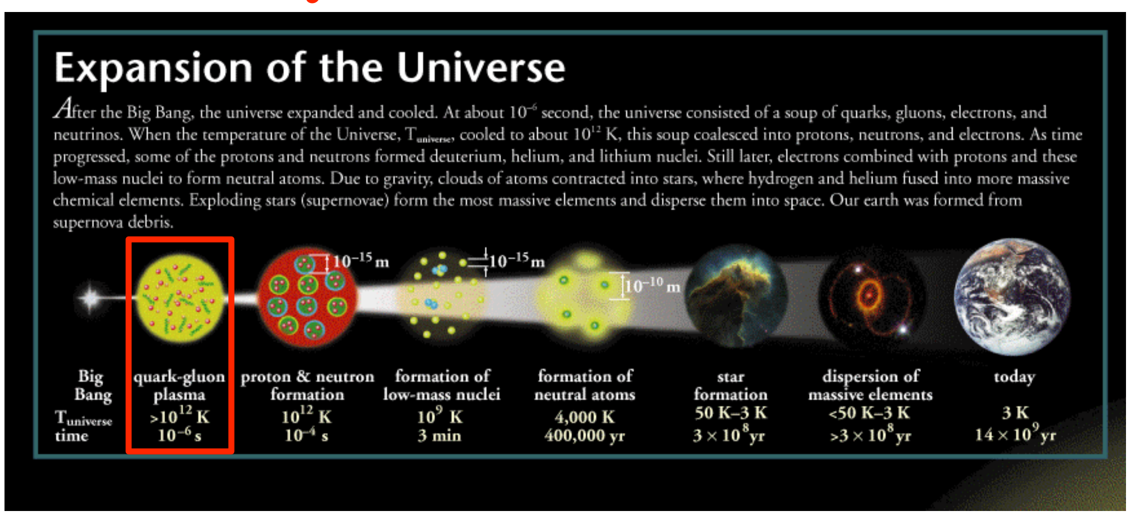
Quark-Gluon Plasma (QGP)

2015 Long Range Plan



- Lattice-QCD predicts a phase transition from confined hadrons to the Quark Gluon Plasma (QGP) where **quarks and gluons are deconfined.**
  - $\varepsilon_c \sim 0.6$ GeV/fm^3; $T_c \sim 150$ MeV

- **Have existed in early universe: $t \sim 10^{-6}$s**



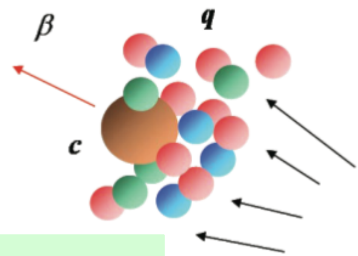
Probe QGP with Heavy Flavor

- **HEAVY: $m_{c,b} >> T_{QGP}, \Lambda_{QCD}$**
  - Produced in high-Q^2 scatterings → calculable in pQCD; scales with binary nucleon-nucleon collisions in heavy-ion collisions
  - Produced at early stage → imprint the entire evolution history of QGP

- **Open heavy flavor (Qq, Qqq)**
  - Radiative+collisional energy loss → *transport coefficient* $(\hat{q}, \hat{e})$

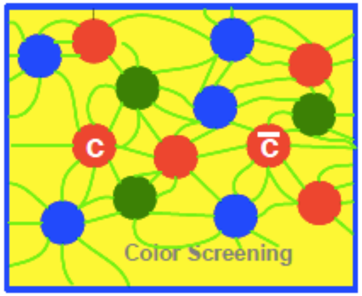
$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$

  - Collective behavior → *spatial diffusion coefficient*
  - Hadronization mechanism, e.g. coalescence



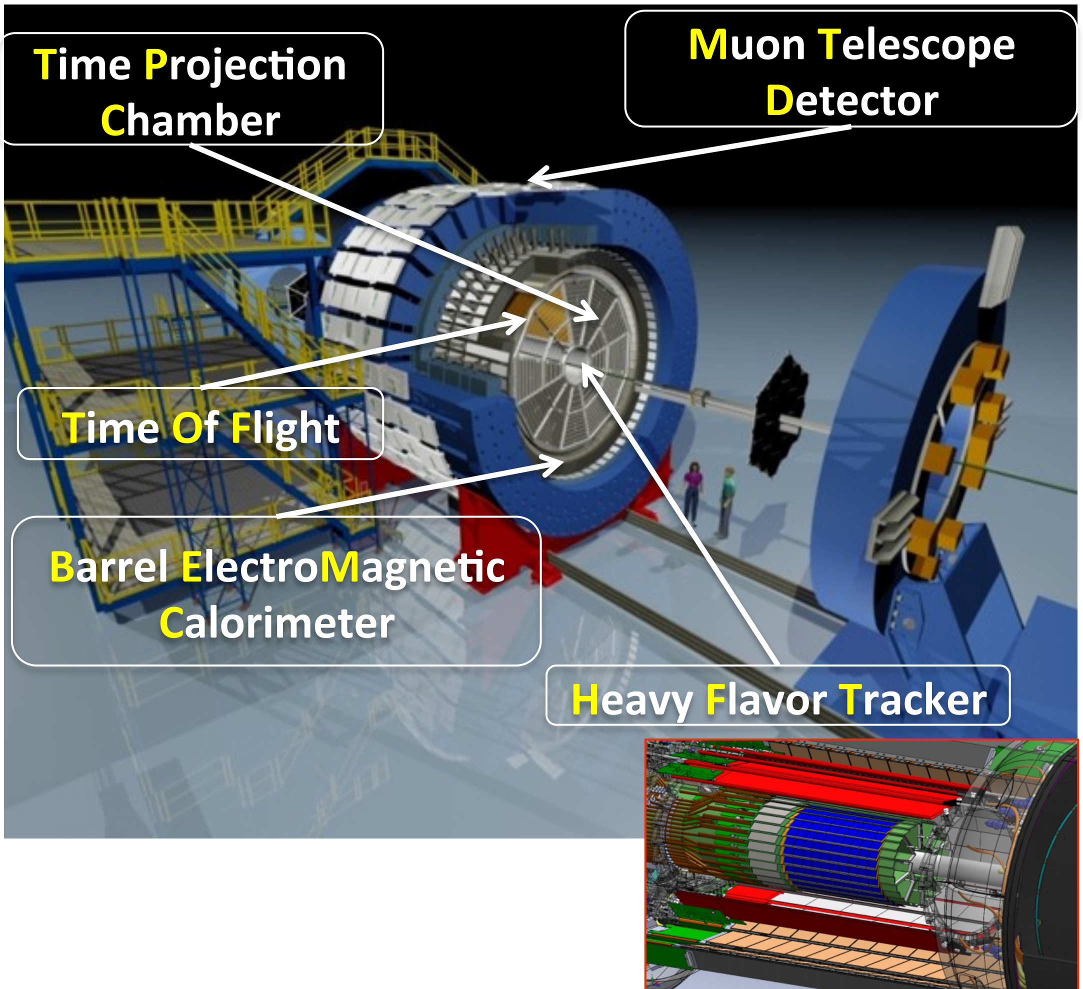
"Brownian" motion

- **Quarkonium ($Q\bar{Q}$)**
  - Dissociation: $Q\bar{Q}$ potential color-screened in the medium → *direct evidence of QGP formation*
    - However, deconfined quarks and anti-quarks can recombine
  - Sequential melting: different quarkonia dissociate at different temperatures → *constrain medium temperature*



The Solenoid Tracker At RHIC

- Large acceptance: $|\eta| < 1$, $0 < \varphi < 2\pi$



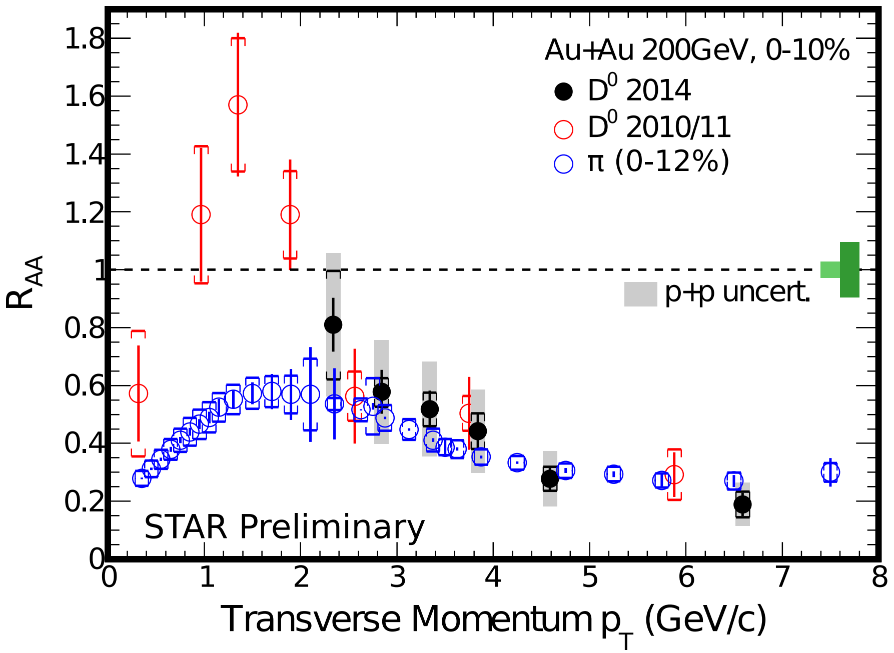
- **HFT (2014-2016)**: measure track points
  - Inner pixel layers (MAPS): high resolution; low material budget
- TPC: measure momentum and energy loss
- TOF: measure particles' flight time to enhance PID at low p_T
- BEMC: trigger on and identify high-p_T electrons
- **MTD (2013-present)**: trigger on and identify muons
  - $|\eta| < 0.5$, $\varphi \sim 45\%$
  - Less bremsstrahlung

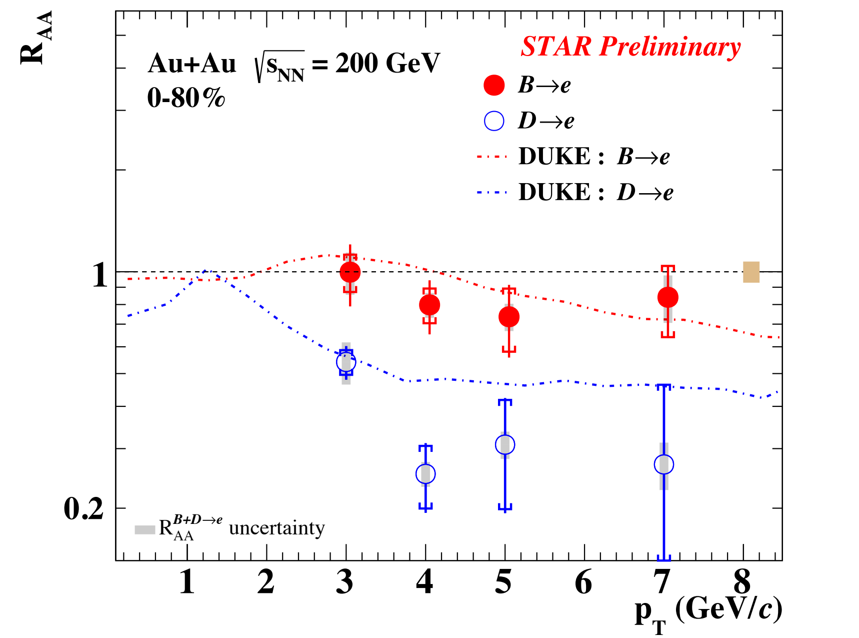
B/D Energy Loss

$$R_{AA} = \frac{\sigma_{inel}^{pp}}{\langle N_{coll} \rangle} \frac{d^2N_{AA}/dydp_T}{d^2\sigma_{pp}/dydp_T}$$

STAR: PRL 113 (2014) 142301
STAR: PLB 655 (2007) 2014

DUKE: PRC 92 (2015) 024907



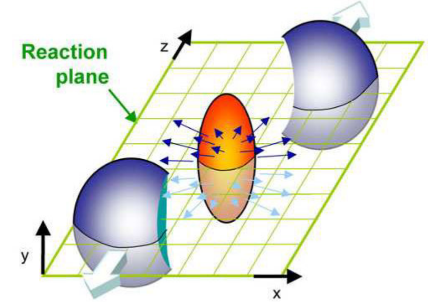


- Strong suppression of D^0 meson at high p_T → **substantial energy loss of charm quarks** due to strong interactions with the medium
- $R_{AA}(D^0) \sim R_{AA}(\pi)$ above 3 GeV/c: spectrum shape & fragmentation play an important role

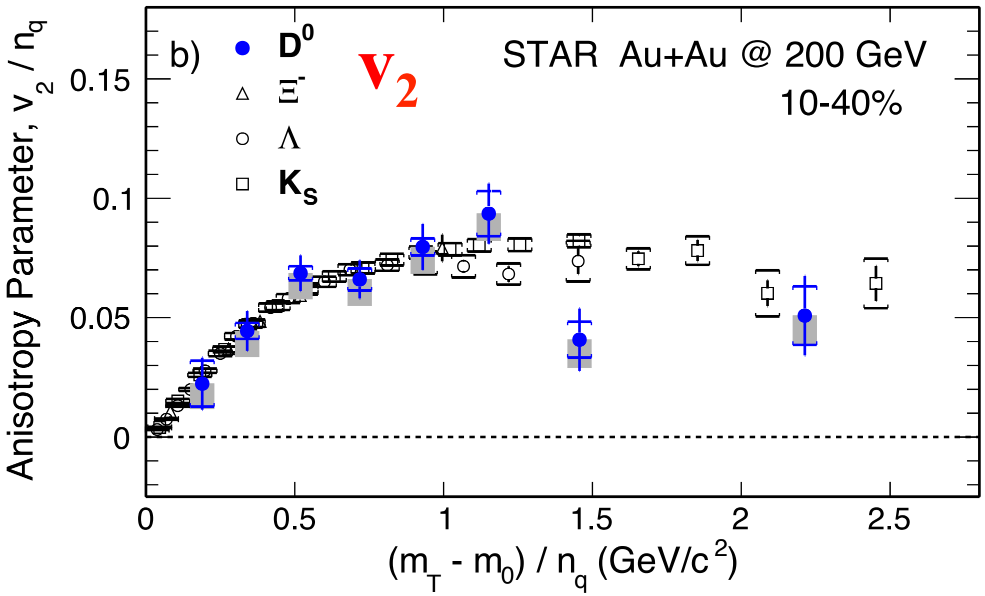
Djordjevic et al. PRC 90 (2014) 034910

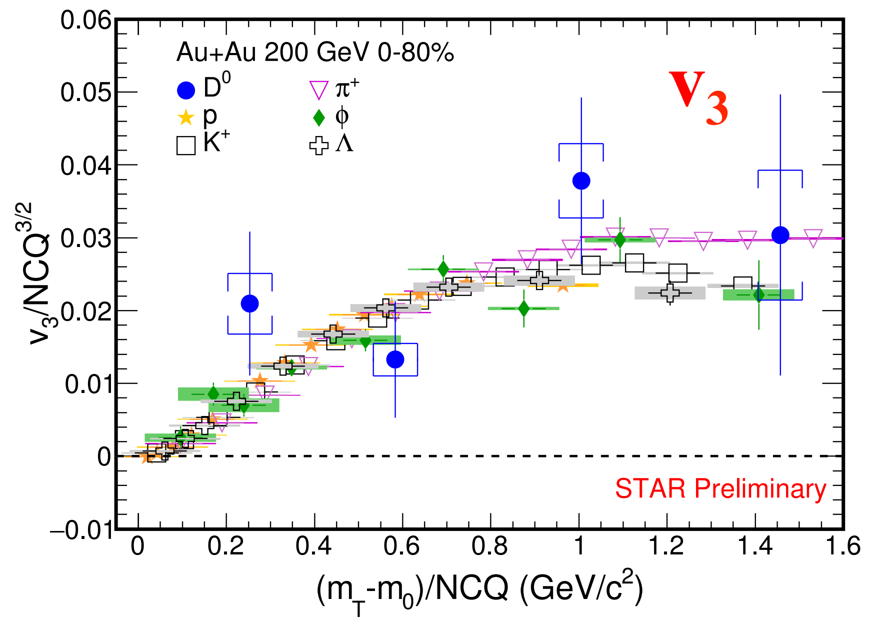
- $R_{AA}(B \rightarrow e) > R_{AA}(D \rightarrow e)$ → **consistent with mass hierarchy**

D^0 Anisotropic Flow



STAR: arXiv: 1701.06060

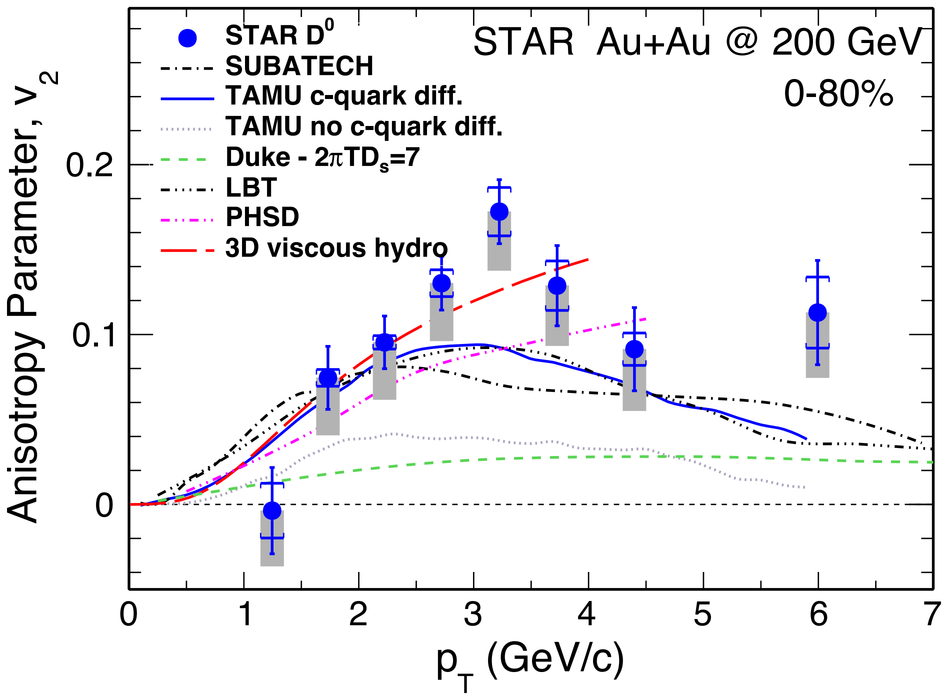




- Large non-zero D^0 v_2 and v_3 → **strong collective behavior**
- Both v_2 and v_3 follow the empirical m_T scaling as light hadrons → **charm quarks may have acquired similar flow as light quarks**

Compare D^0 v_2 with Models

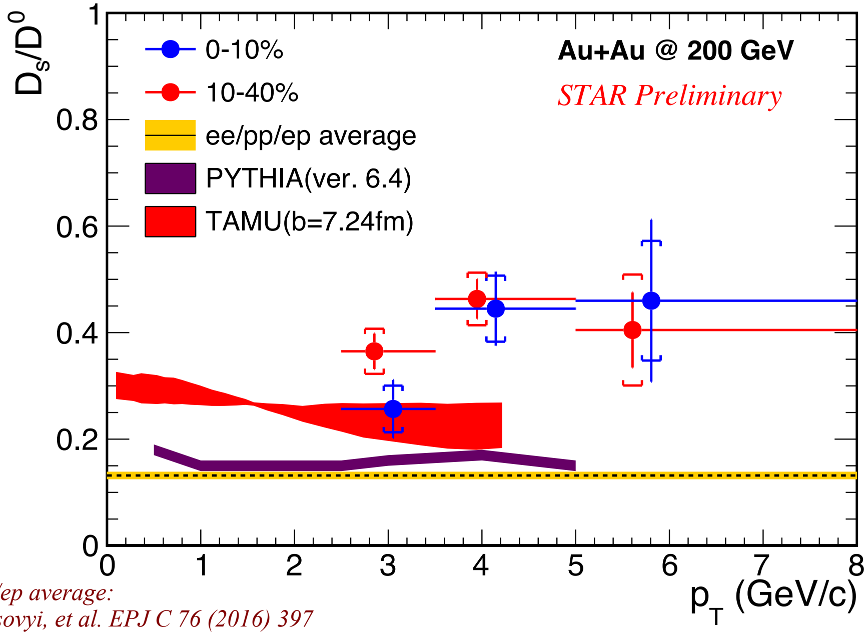
STAR: arXiv: 1701.06060



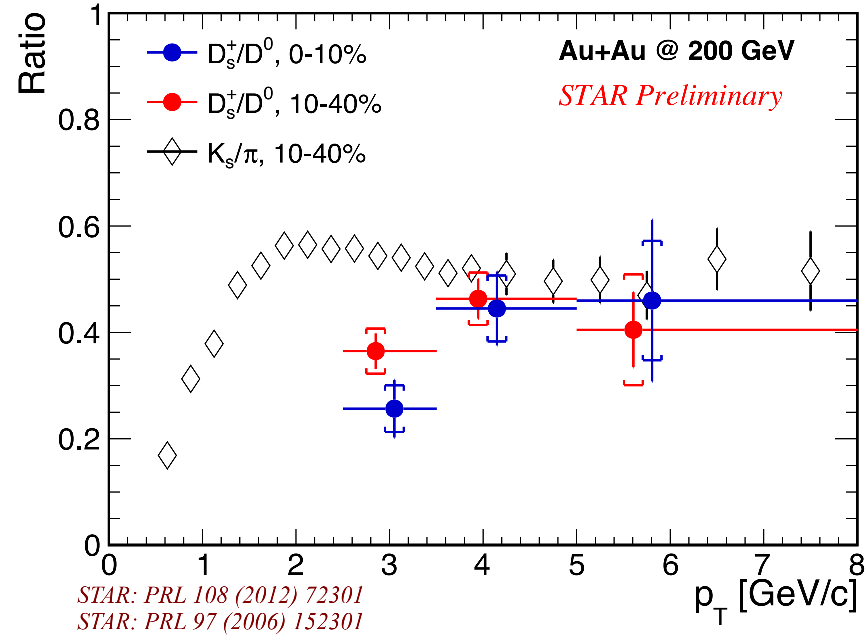
SUBATECH: pQCD + hard thermal loop
P. B. Gossiaux, J. Aichelin, T. Gousset, and V. Guiho, Strangeness in quark matter
TAMU: T-matrix, non-perturbative, internal energy potential
M. He, R. J. Fries, and R. Rapp, PRC86, 014903 (2012)
Duke: free constant Ds, fit to LHC high p_T R_{AA}
S. Cao, G.-Y. Qin, and S. A. Bass, PRC88, 044907 (2013)
hydro: A 3D viscous hydrodynamic model
L.-G. Pang, Y. Hatta, X.-N. Wang, and B.-W. Xiao,PRD91, 074027 (2015)
PHSD: Parton-Hadron-String Dynamics, a transport model
H. Berrehrah et al. PRC90 (2014) 051901
LBT: A Linearized Boltzmann Transport model
S. Cao, T. Luo, G.-Y. Qin, and X.-N. Wang, PRC94, 014909 (2016)

- 3D hydro model: agrees with data quite well → *fully thermalized*
- Dynamic models are also consistent with data
  - Charm quark diffusion is clearly needed
  - Diffusion coefficient: $D_s \times 2\pi T \sim 2\text{-}12$ within $T_c\text{-}2T_c$

Charm-strange Hadron Enhancement



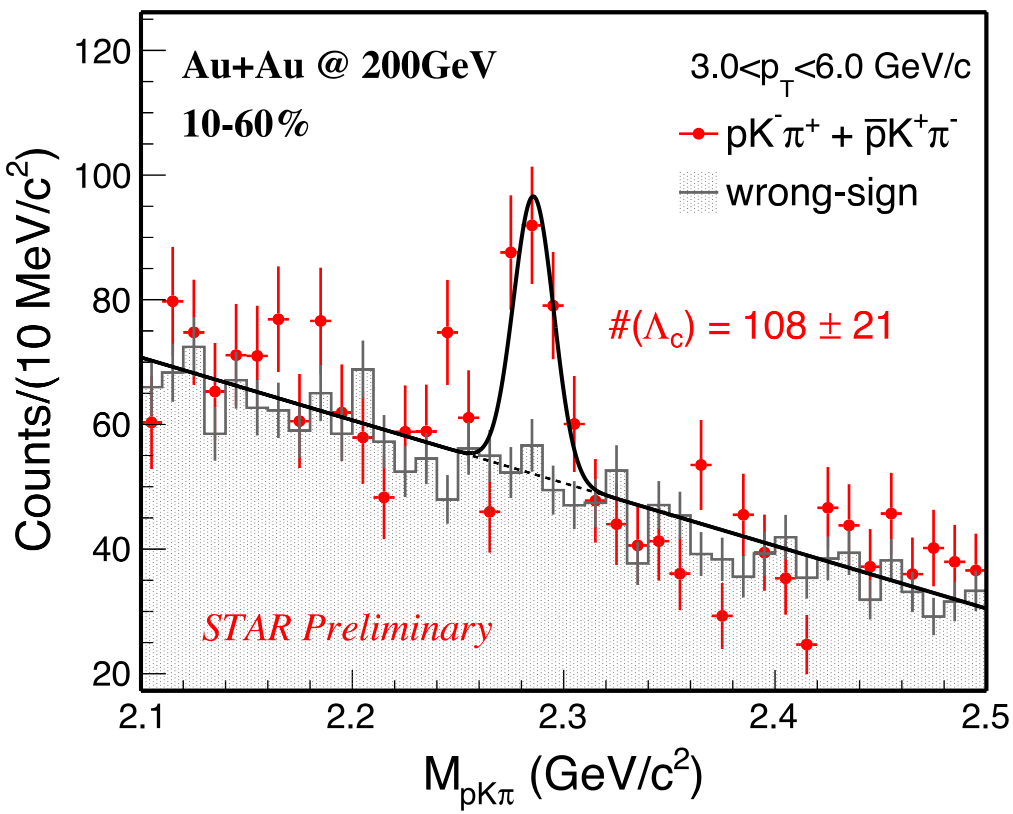
ee/pp/ep average:
M. Lisovyi, et al. EPJ C 76 (2016) 397
TAMU:
H. Min et al. PRL 110 (2013) 112301



STAR: PRL 108 (2012) 72301
STAR: PRL 97 (2006) 152301

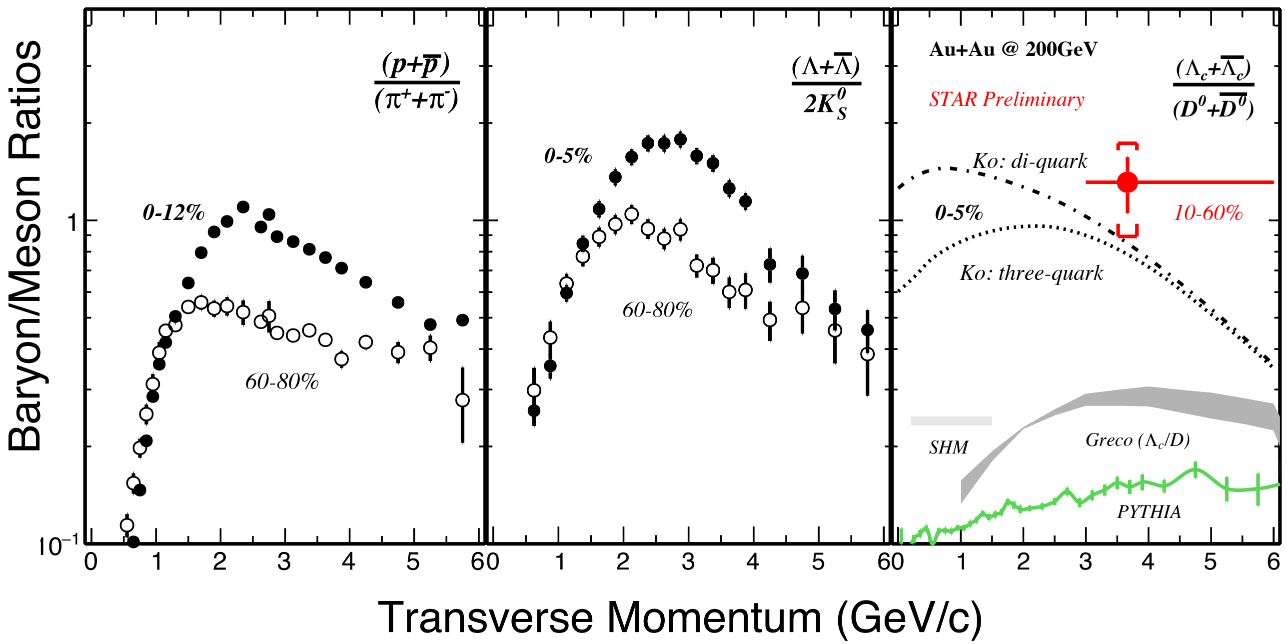
- D_s/D^0: larger than fragmentation baseline and PYTHIA → **coalescence**
- TAMU model (10-40%) under-predicts the enhancement around 3 GeV/c
  - *For TAMU model, even harder to get high-p_T enhancement with coalescence*
- Charm vs. light flavor: similar enhancement above 3.5 GeV/c, but smaller within 2.5-3.5 GeV/c

Λ_c in Heavy-ion Collisions



- First ever Λ_c signal reconstructed in heavy-ion collisions
- 5.4σ significance

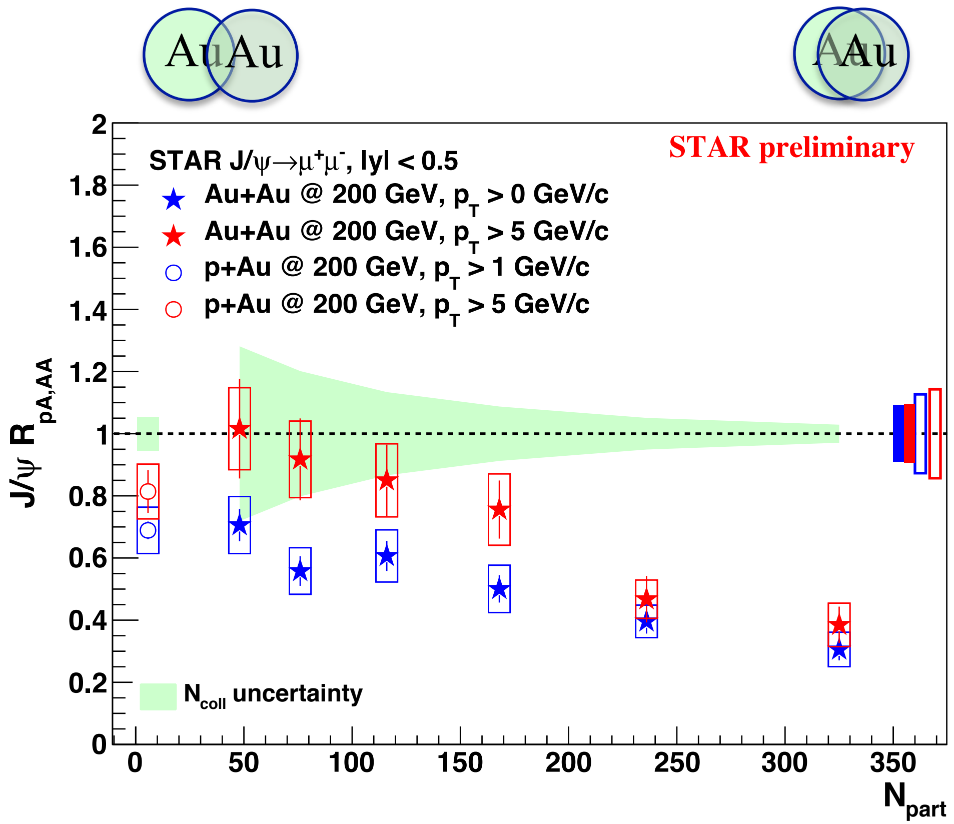
Λ_c Enhancement in Heavy-ion Collisions



Ko: Y. Oh, et al. PRC 79 (2009) 044905
Greco: S. Ghosh, et al. PRD 90 (2014) 054018
SHM:
Y. Oh, et al. PRC 79 (2009) 044905
I. Kuznetsova and J. Rafelski., EPJ C51 (2007) 113
A. Andronic., et al. PLB 659 (2008) 149

- **Enhancement of Λ_c/D^0 ratio relative to PYTHIA prediction**
  - STAR: 1.3 ± 0.3 (stat) ± 0.4 (sys); PYTHIA: 0.1-0.15
- Ko model (0-5%) including coalescence and thermalized charm quark is consistent with data
- Magnitude of the enhancement is similar to that for light hadrons

J/ψ R_{AA} vs. Centrality

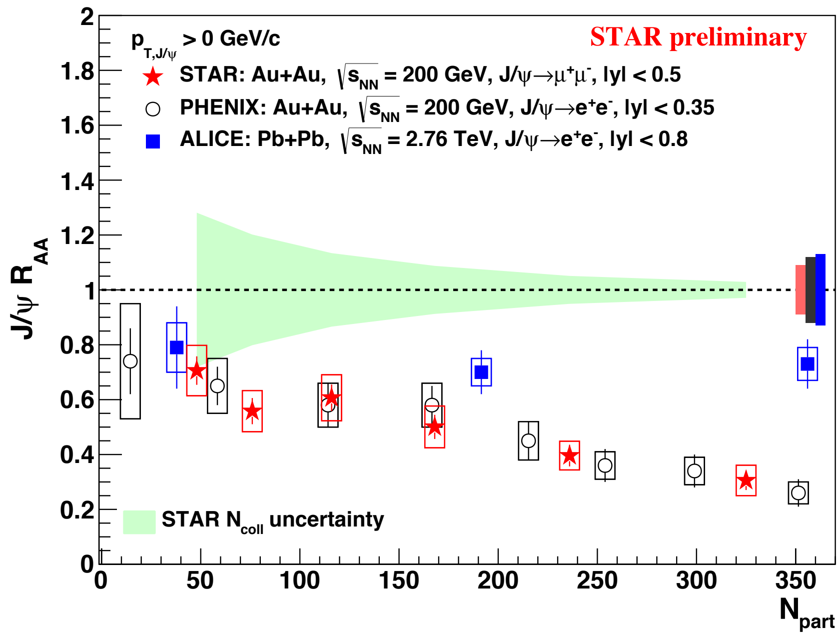


- Central collisions: **significant suppression for $p_T > 0$ GeV/c and $p_T > 5$ GeV/c** → interplay of dissociation, regeneration, formation time effect, etc.
- Peripheral collisions: R_{AA} of J/ψ for $p_T > 0$ GeV/c is less than 1→ consistent with cold nuclear matter (CNM) effects

J/ψ R_{AA}: RHIC vs. LHC

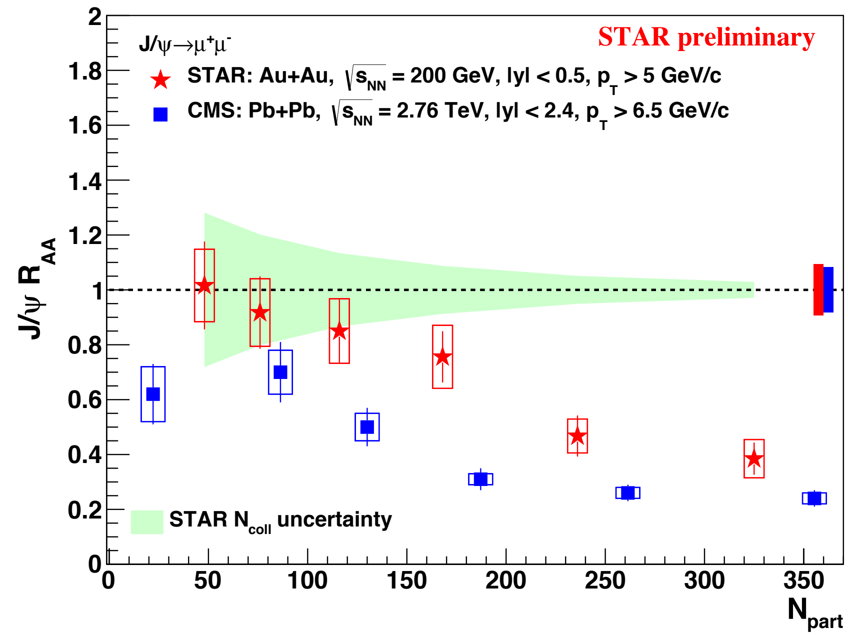
$p_T > 0$ GeV/c

ALICE : PLB 734 (2014) 314
PHENIX : PRL 98 (2007) 232301



$p_T > 5$ GeV/c

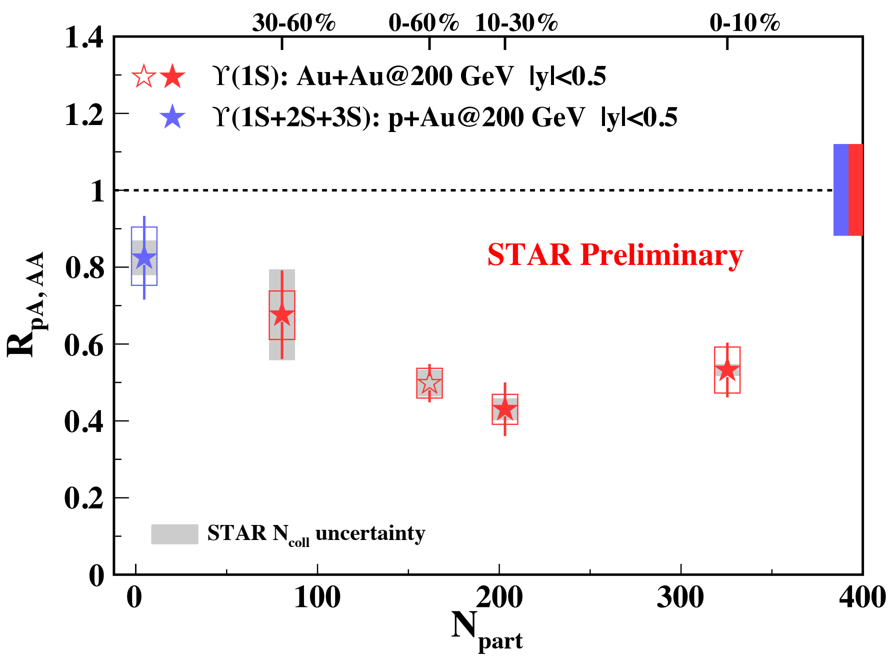
CMS: JHEP 05 (2012) 063



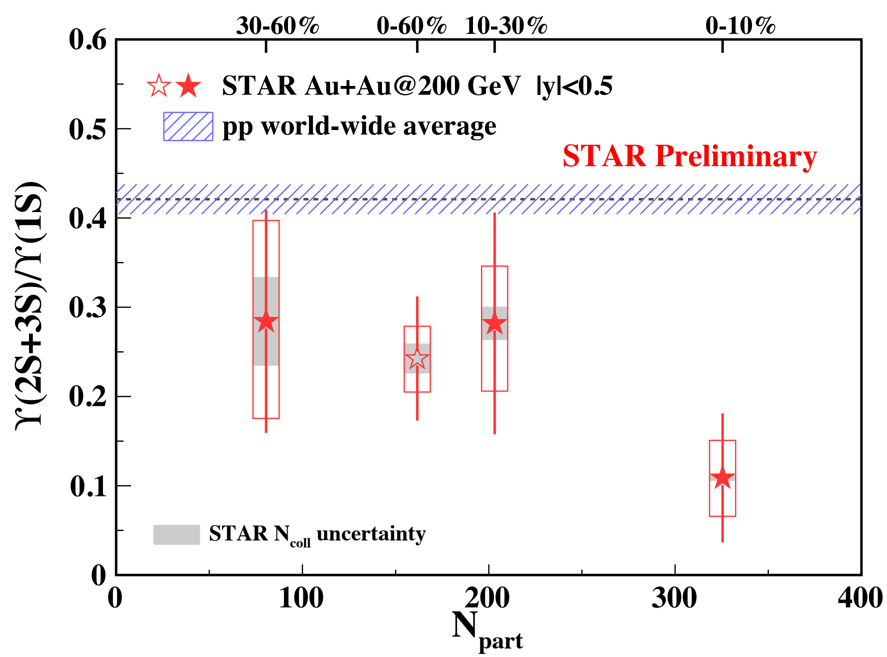
- $p_T > 0$ GeV/c: more suppressed at RHIC in central events → **smaller regeneration contribution due to lower charm cross-section**
- $p_T > 5$ GeV/c: less suppressed at RHIC → **smaller dissociation rate due to lower temperature**

Υ Suppression at RHIC

Υ(1S) R_{AA}



Υ(2S+3S)/Υ(1S)

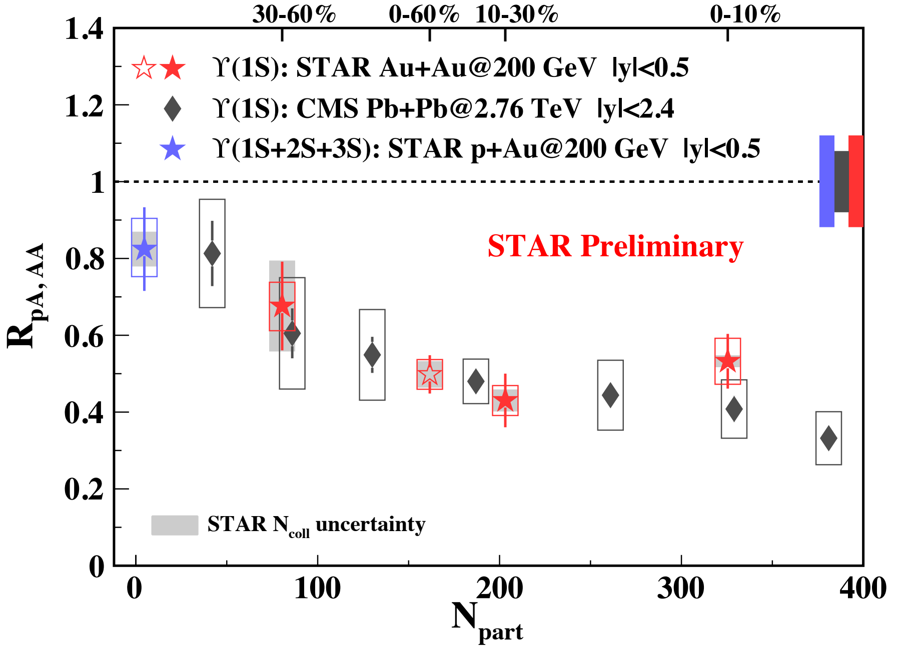


World-wide p+p: W. Zha, et. al, PRC 88 (2013) 067901

- **Υ(1S) is suppressed**
  - Indication of more suppression with increasing centrality
  - *Is direct Υ(1S) suppressed?*
- **Central: Υ(2S+3S) is more suppressed → sequential melting**

Υ(1S): RHIC vs. LHC

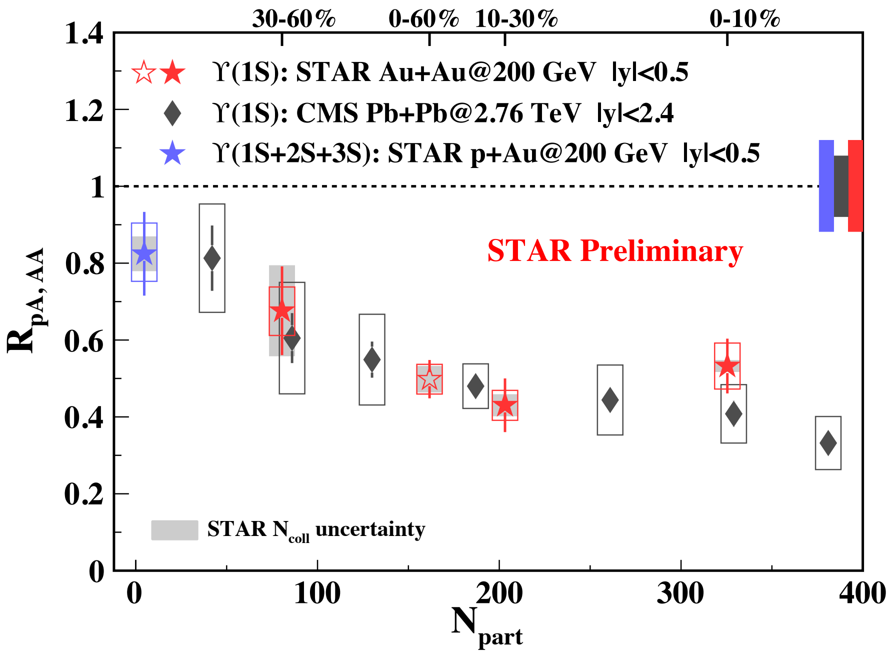
CMS: arXiv:1611.01510



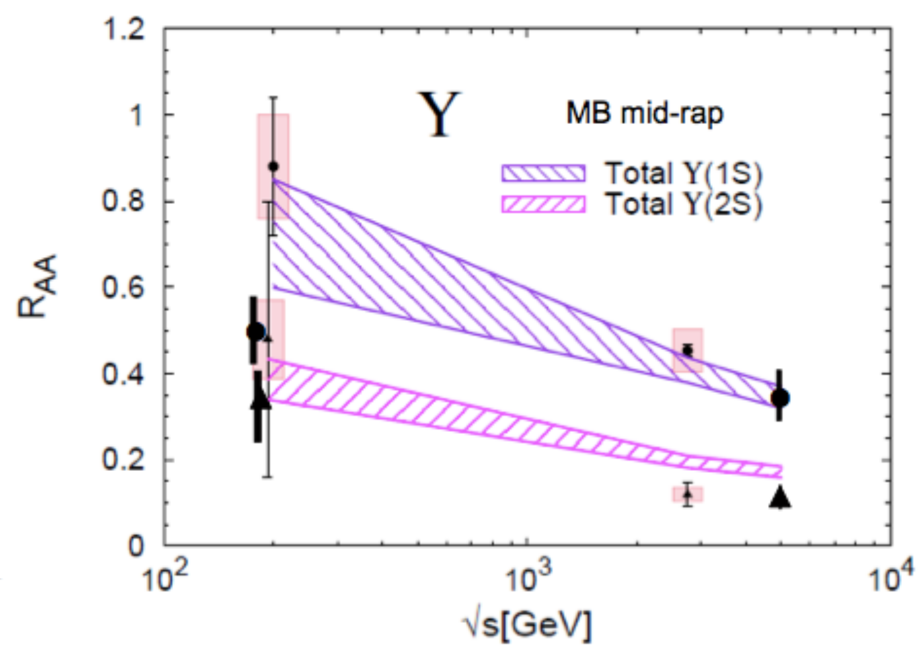
- Υ(1S) suppression: **similar at RHIC and LHC**

Υ(1S): RHIC vs. LHC

CMS: arXiv:1611.01510



R. Rapp (QM2017)

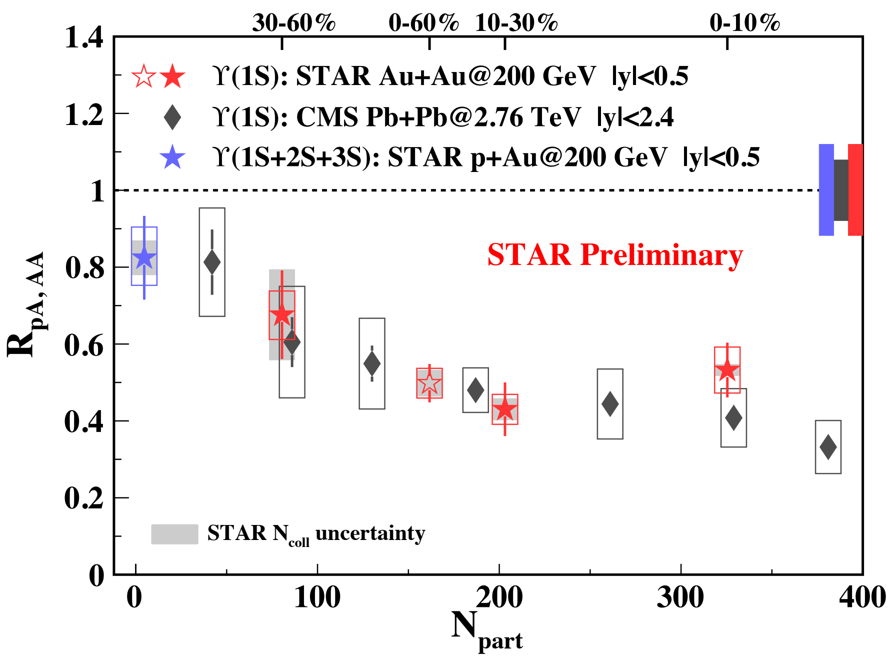


- Υ(1S) suppression: **similar at RHIC and LHC**
- Ralf model: seems consistent with Υ(1S) suppression by including CNM and regeneration
  - However, under-predicts the Υ(2S) suppression at the LHC

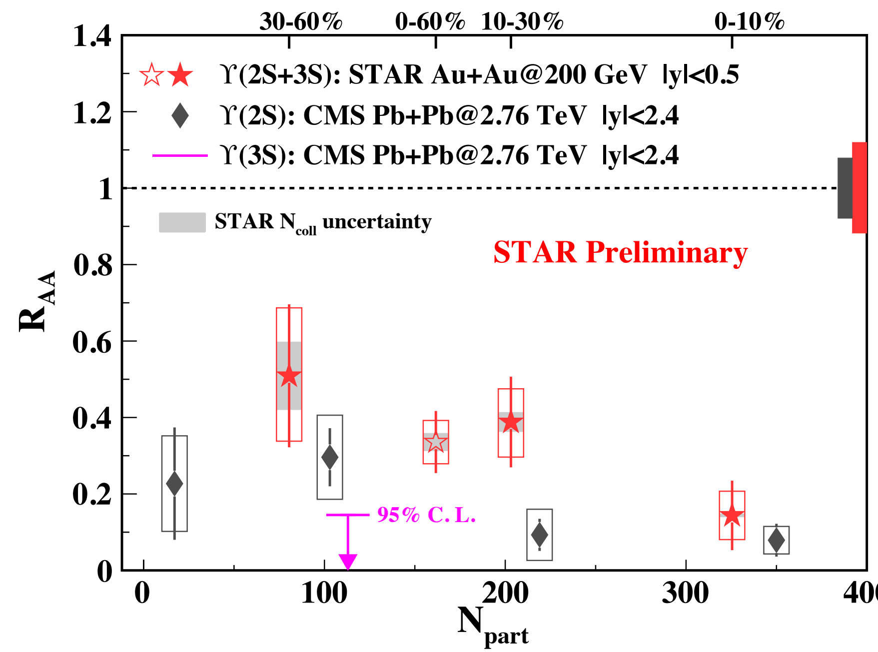
Υ: RHIC vs. LHC

CMS: arXiv:1611.01510

Υ(1S) R_{AA}



Υ(2S+3S) R_{AA}



- Υ(1S) suppression: **similar at RHIC and LHC**
- Υ(2S+3S): **hint of less suppression at RHIC than at the LHC**

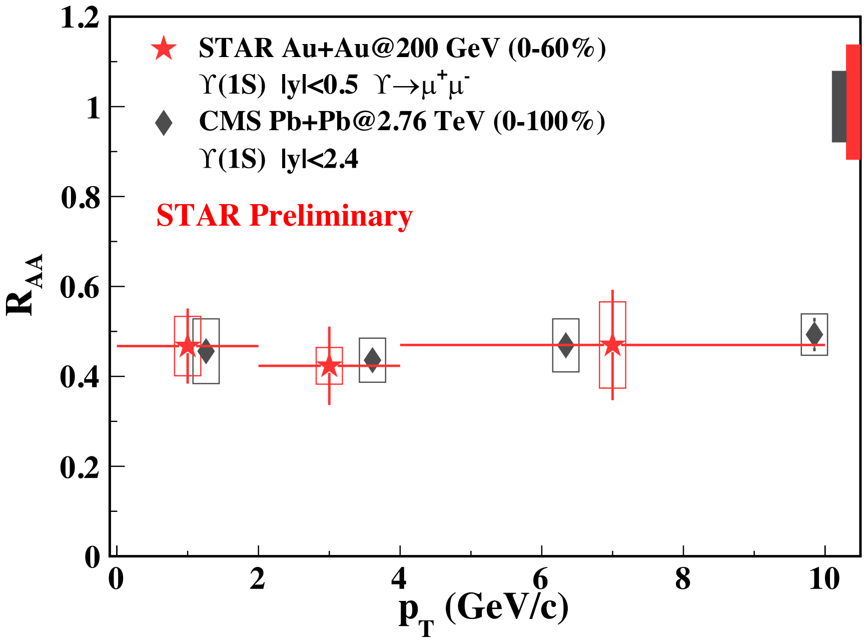
Summary & Outlook

- Upgrades of HFT and MTD greatly enhance STAR's capabilities of measuring both open and hidden heavy flavor production.
- Open heavy flavor
  - Mass hierarchy of energy loss → *strong interaction with medium*
  - Collective behavior of charm quarks → *suggests thermal equilibrium*
  - Charm quarks seem to also participate in coalescence hadronization
- Quarkonium
  - Strong suppression of J/ψ at high-p_T in central collisions → *dissociation*
  - Υ(2S+3S) is more suppressed than Υ(1S) in central collisions → *sequential melting*
  - *Υ(1S) R_{AA}: RHIC ≈ LHC. Model including CNM and regeneration seems consistent with data*
- Outlook: 2016 Au+Au data
  - A factor of 2 (minimum-bias) and 5 (high-p_T electrons) for HFT
  - Equivalent statistics for Υ measurement

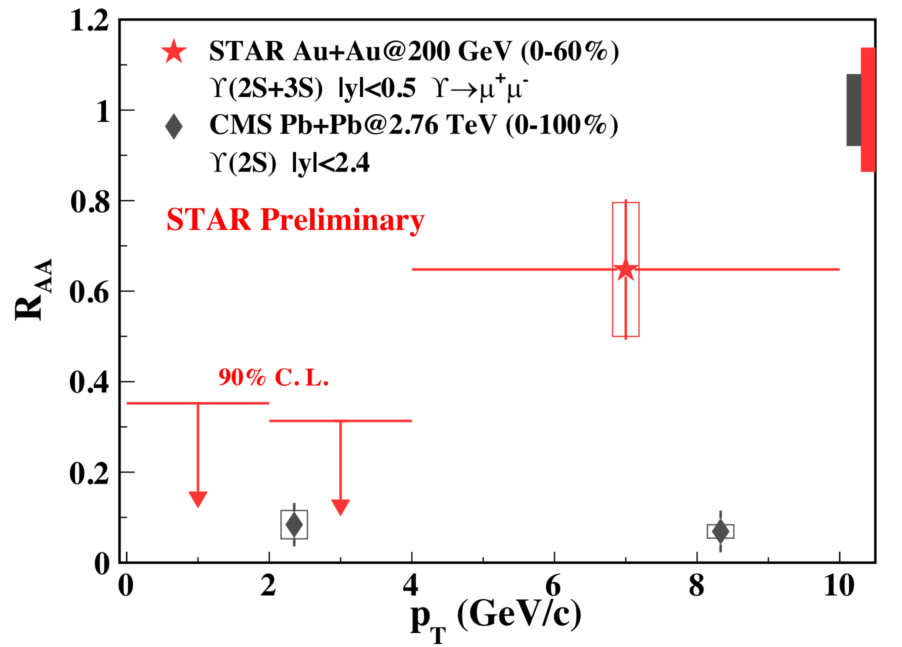
Backup

Υ R_{AA} vs. p_T

Υ(1S)



Υ(2S+3S)



- Υ(1S): no obvious dependence on p_T; similar to CMS
- Υ(2S+3S): hint of less suppression at high p_T