New STAR Results
- A Peek into the RHIC Heavy Flavor Era

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for the STAR Collaboration

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Brookhaven National Lab
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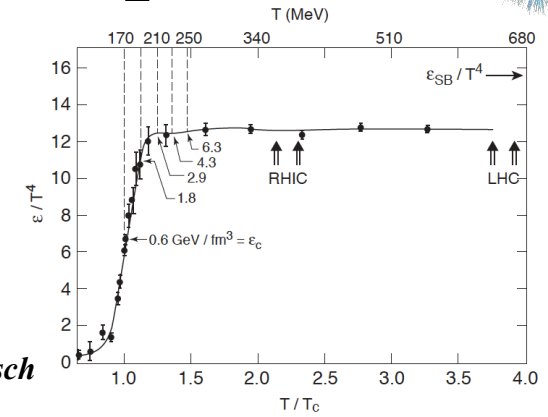
Outline

- Motivation
- STAR experiment
  - Heavy Flavor Tracker (HFT)
  - Muon Telescope Detector (MTD)
- Recent heavy flavor results
  - R_{AA} and v_2 measurements for D^0
  - R_{AA} and v_2 measurements for J/ψ
- Summary & Outlook

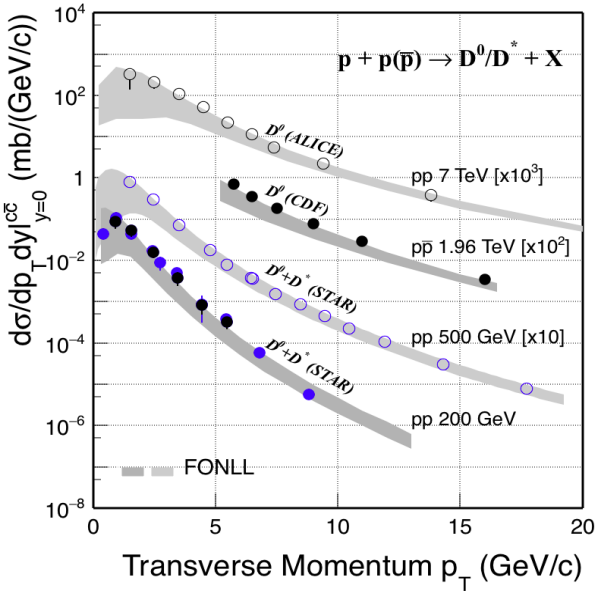
Probe QGP with charm quark

- pQCD predicts a phase transition from confined hadrons to Quark Gluon Plasma (QGP) in heavy-ion collisions where ***partons are the relevant degrees of freedom.***



Contemp.Phys. 42 (2001) 209, courtesy F. Karsch

- **Charm quark: $m_c >> T_{QGP}, \Lambda_{QCD}$**
  - Produced in the hard scatterings at the early stage of nuclear collisions → experience the entire evolution of medium
  - Charm cross section scales with N_{coll} in Au+Au collisions → important input for models to calculate regeneration contribution to charmonium
    - Currently, 16% uncertainty in 0-10% Au+Au events*
  - Clean probe at RHIC as contributions from gluon splitting and bottom quark are small.
  - Its production rate is well described by pQCD in elementary collisions

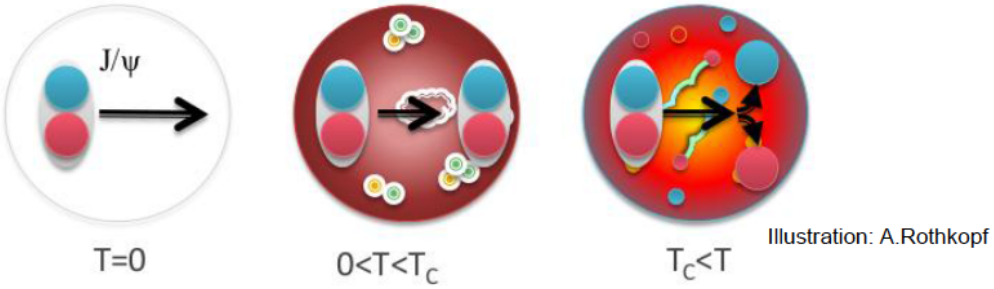


**PRL 113 (2014) 142301*

STAR: PRD 86 (2012) 072013, NPA 931 (2014) 520
CDF: PRL 91 (2003) 241804; ALICE: JHEP01 (2012) 128
FONLL: PRL 95 (2005) 122001

Probe QGP with quarkonium

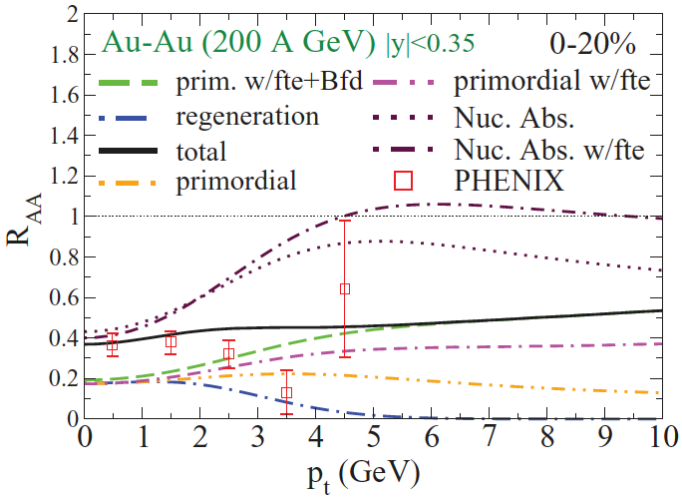
- **Color-screening**: quarkonium dissociates in the medium



J/ψ suppression was proposed as a direct proof of QGP formation

T. Matsui and H. Satz PLB 178 (1986) 416

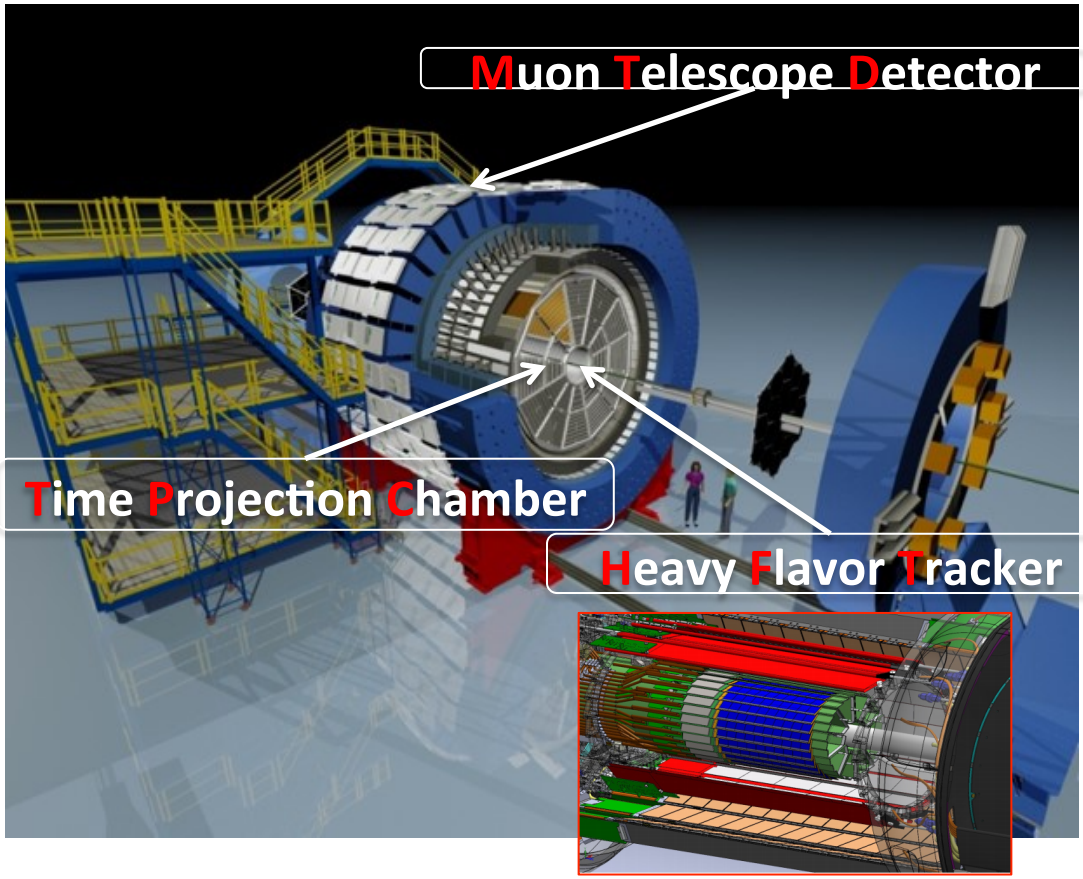
- However, interpreting J/ψ suppression is no easy job!
  - *Hot nuclear matter effects*
    - Dissociation
    - Regeneration from uncorrelated quarks
    - Medium-induced energy loss
    - Formation time effects
  - *Cold nuclear matter effects*
  - *Feed-down of excited charmonium states and B-hadrons*



Phys. Rev. C 82, 064905

The Solenoid Tracker At RHIC

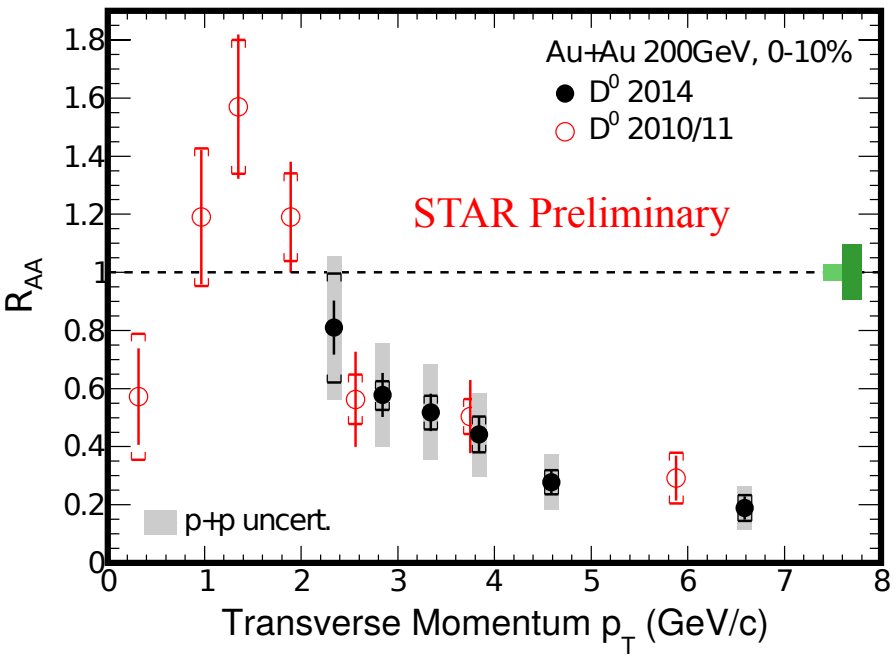
- Mid-rapidity detector: $|\eta| < 1$, $0 < \varphi < 2\pi$



- **TPC**: precise momentum and energy loss
- **HFT**: topological reconstruction of D meson
  - $\sigma_{DCA} < 50$ μm for kaon at 750 MeV/c
  - 1st layer of PXL <0.4%X_0
  - Take data: 2014-2016
- **MTD**: trigger on and identify muons
  - Precise timing measurement (σ~100 ps)
  - Fully installed in 2014

- *70% (HFT) and 30% (MTD) of Run14 data were used for results shown here.*

D^0 R_{AA} in central Au+Au collisions

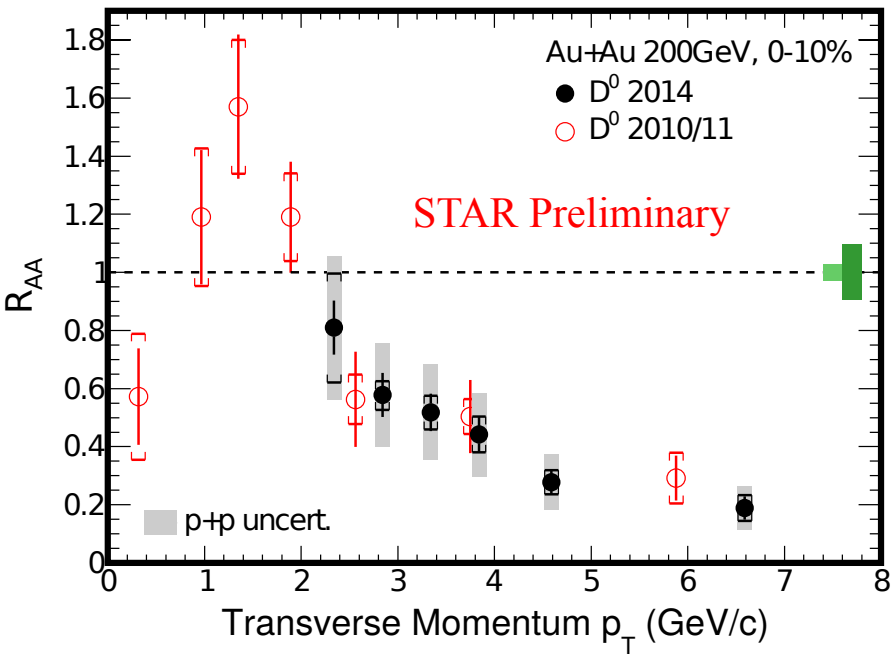


STAR: PRL 113 (2014) 142301

✓ $R_{AA} > 1$ for $p_T \sim 1.5$ GeV/c

Charm coalescence with the flowing medium

D^0 R_{AA} in central Au+Au collisions



STAR: PRL 113 (2014) 142301

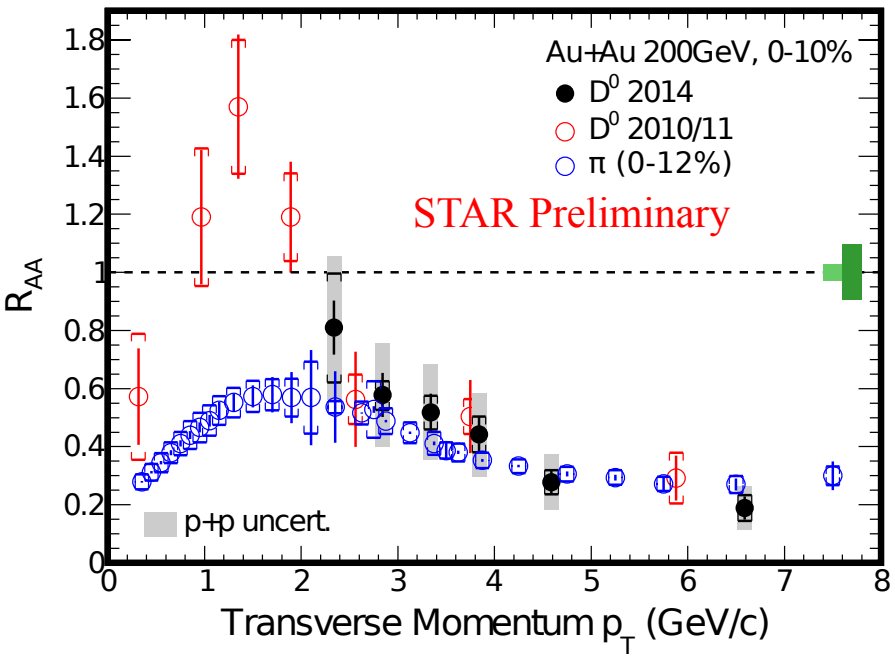
✓ $R_{AA} > 1$ for $p_T \sim 1.5$ GeV/c

Charm coalescence with the flowing medium

✓ $R_{AA} << 1$ for $p_T > 2.5$ GeV/c

Strong charm-medium interaction leading to sizable energy loss

D^0 R_{AA} in central Au+Au collisions



STAR: PRL 113 (2014) 142301

✓ $R_{AA} > 1$ for $p_T \sim 1.5$ GeV/c

Charm coalescence with the flowing medium

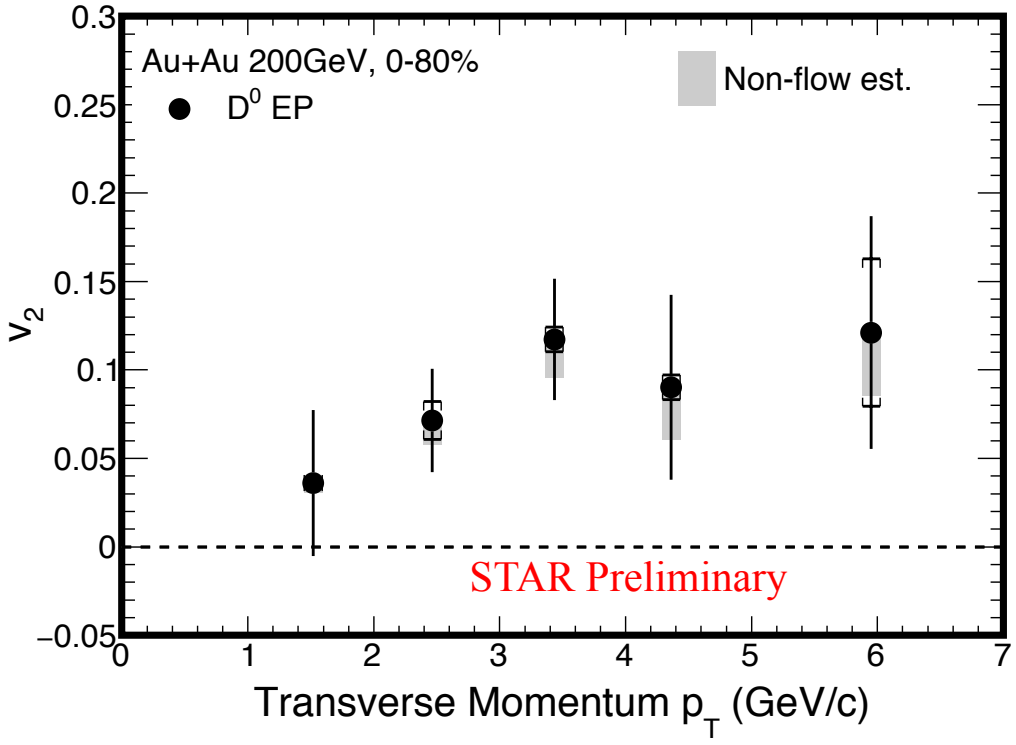
✓ $R_{AA} << 1$ for $p_T > 2.5$ GeV/c

Strong charm-medium interaction leading to sizable energy loss

✓ Similar suppression as pions at high p_T

- Collisional energy loss is important
- Shapes of parton spectrum & fragmentation function need to be taken into account.

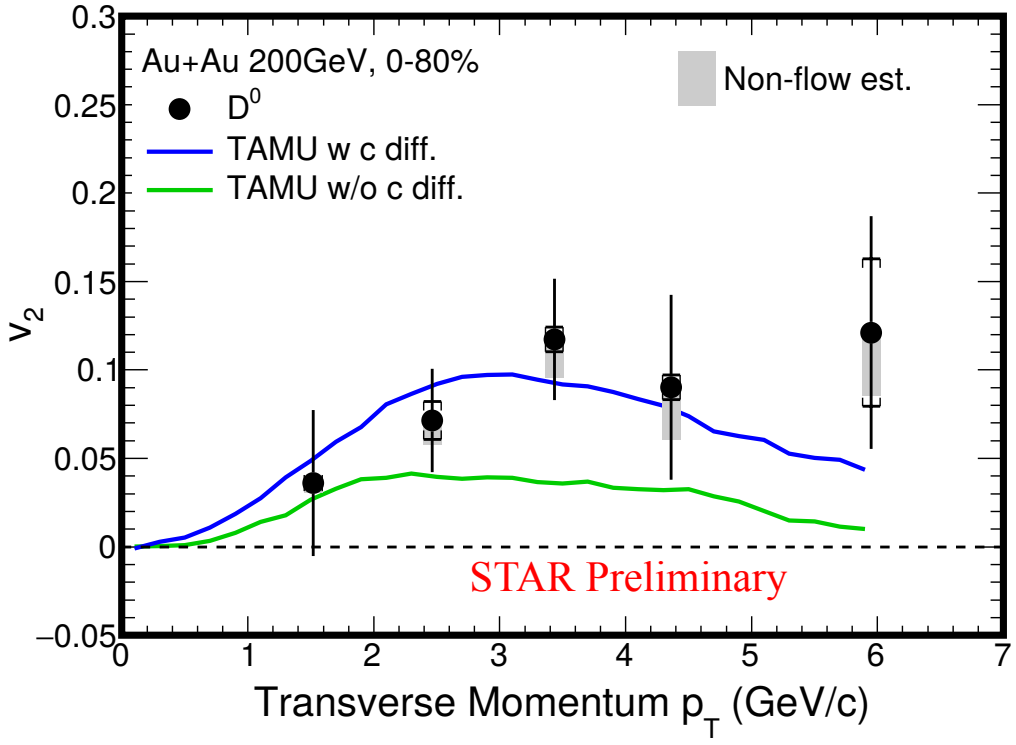
First D^0 v_2 measurement at RHIC



✓ Finite D^0 v_2 observed above 2 GeV/c

D^0 v_2: data vs model

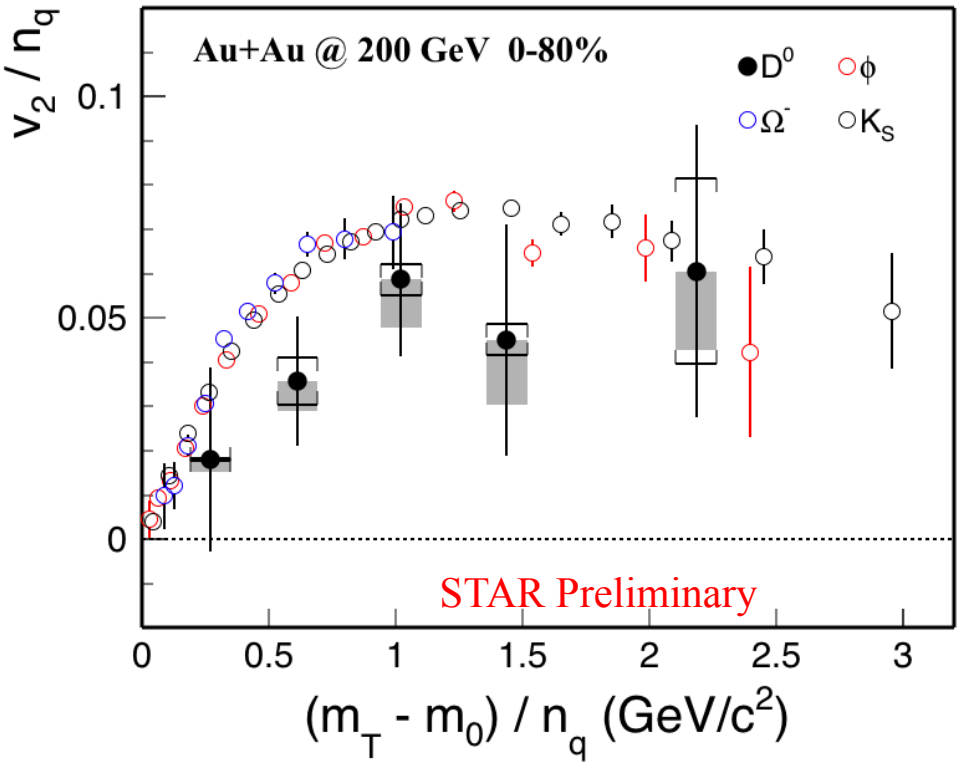
Theory: arXiv:1506.03981
private comm.



✓ Data favor a model with charm diffusion

→ Charm quark flows in the medium

v_2: D^0 vs light hadrons



STAR: PRL 116 (2016) 062301

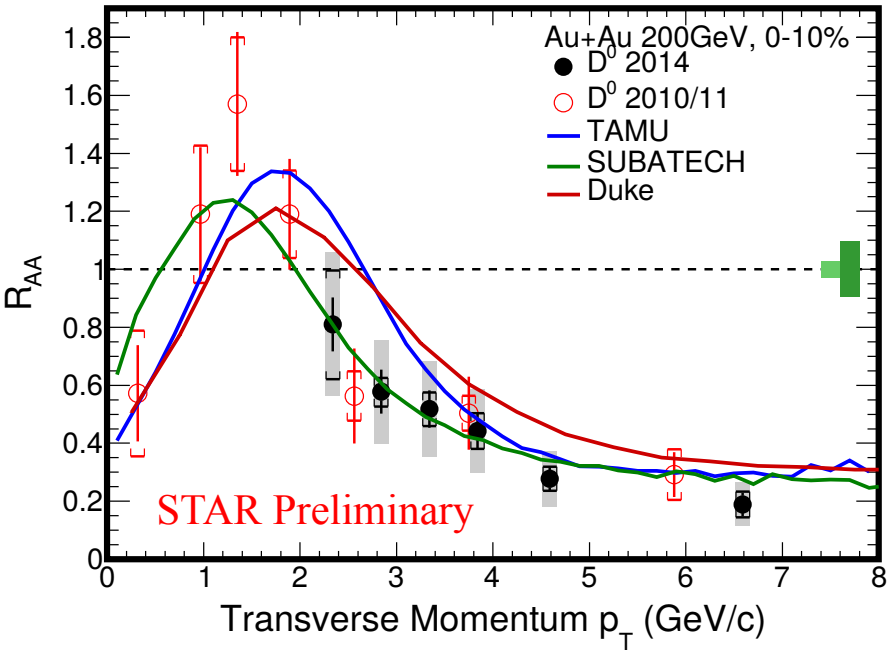
✓ v_2 for D^0 is systematically lower than those of light hadrons

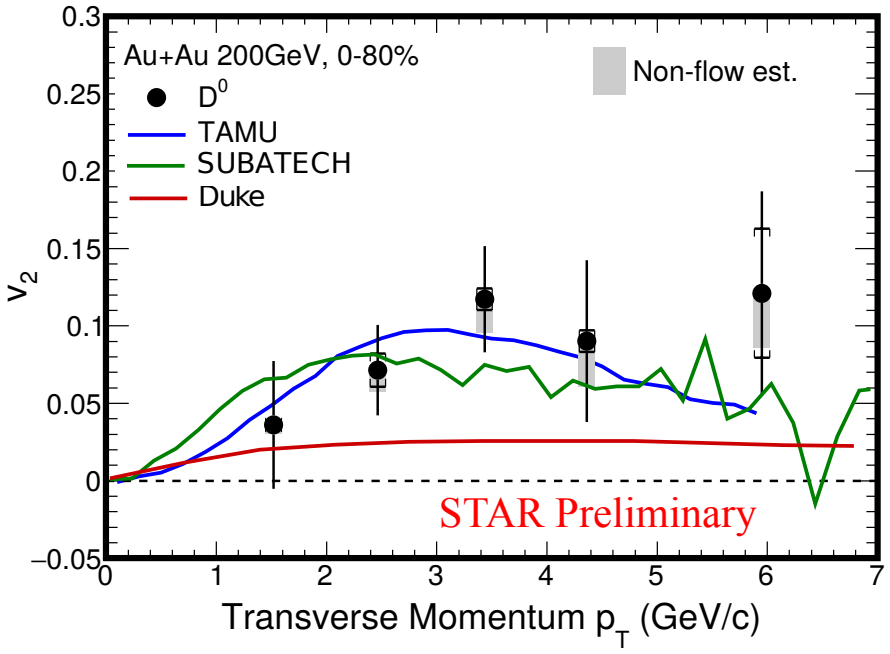
→ Hints that charm quarks might not be fully thermalized with medium

Can theory describe R_{AA} & v_2?

Theory: arXiv:1506.03981
arXiv:1505.01413
private comm.

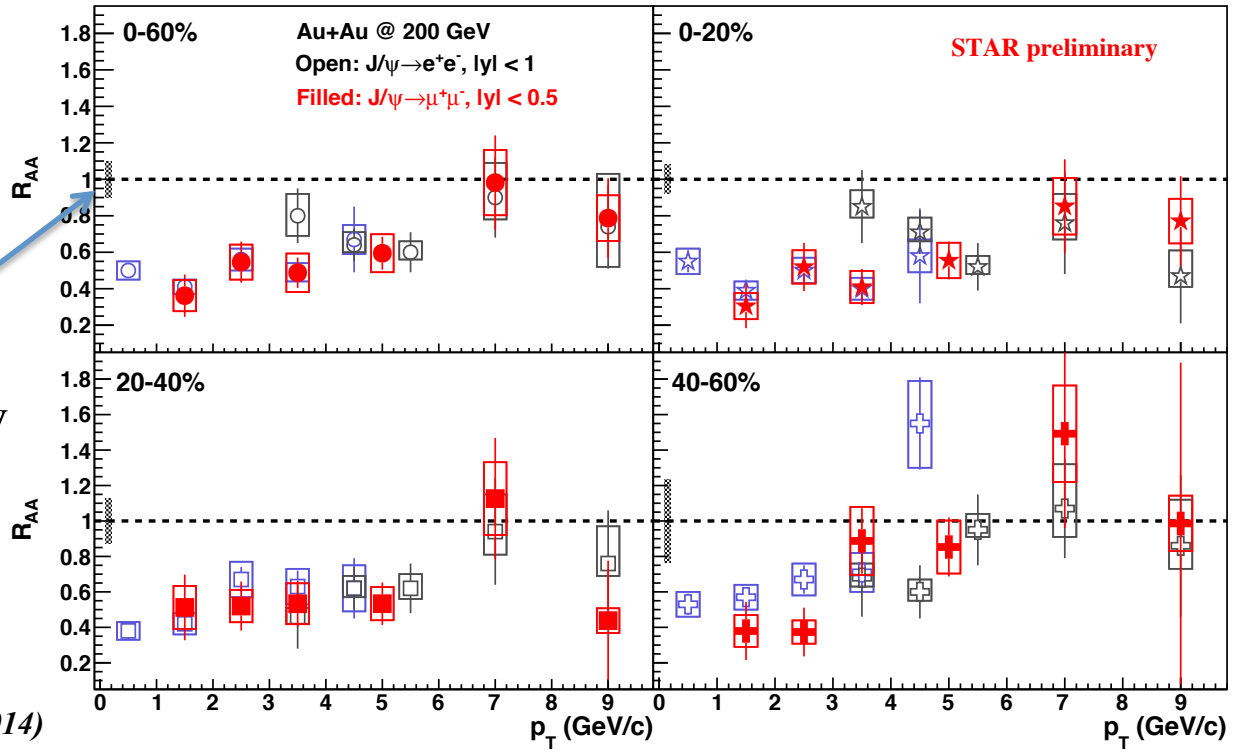
STAR: PRL 113 (2014) 142301





- *Favors model with charm diffusion coefficient between 2-11.*
- Measurements with better precision are needed to discriminate between different models.

J/ψ suppression in Au+Au collisions

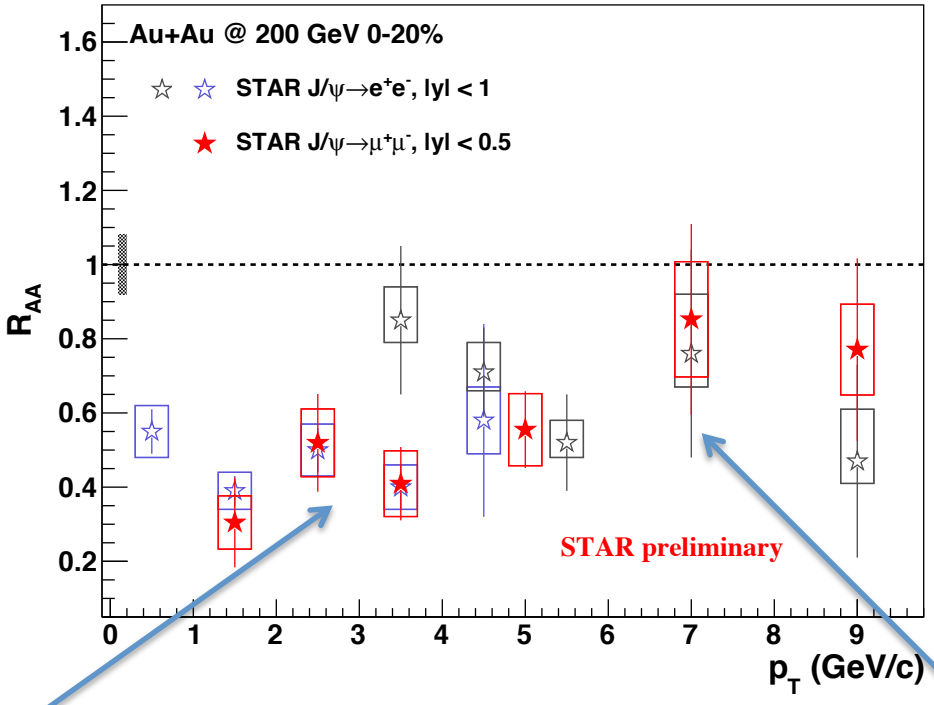


Scale uncertainty for σ_{inel} and N_{coll}

Di-electron:
STAR PLB 722 (2013) 55
STAR PRC 90, 024906 (2014)

- **Distinct** rising R_{AA} with p_T for J/ψ in all centrality bins as seen in the di-electron channel

Closer look at the central collisions



Di-electron:
STAR PLB 722 (2013) 55
STAR PRC 90, 024906 (2014)

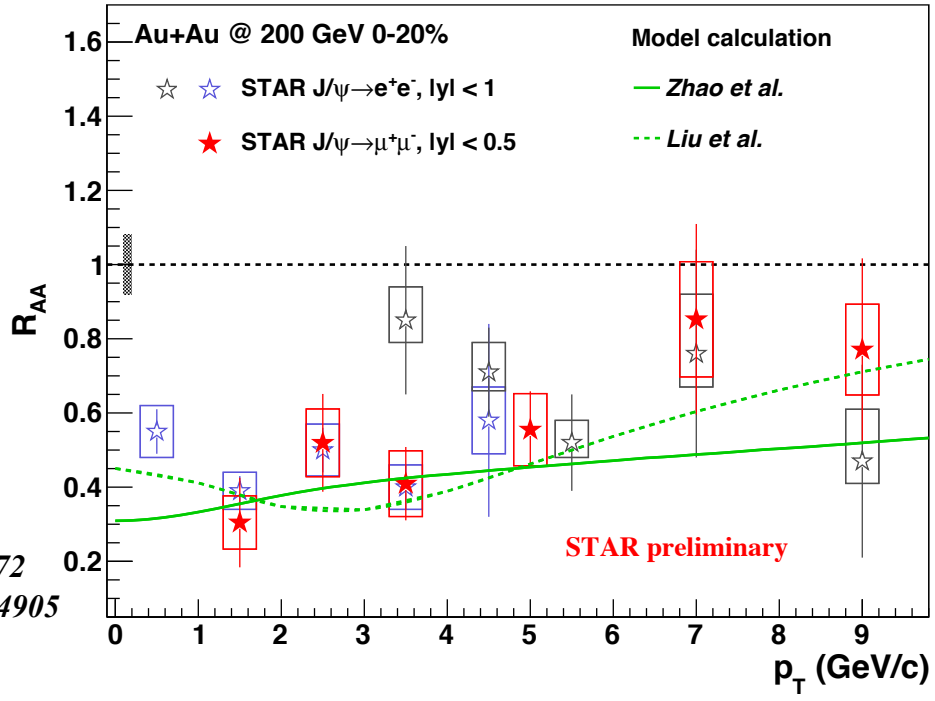
Strong suppression at low p_T

- Dissociation
- Cold nuclear matter effect
- Regeneration

Less suppression at high p_T

- Dissociation
- Formation time effect
- Feed-down from B-hadrons

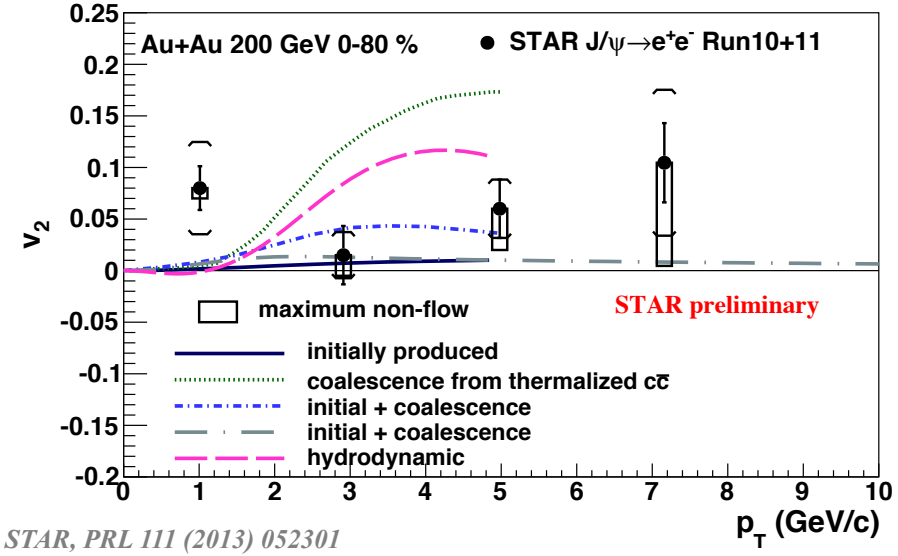
Compare with model calculations



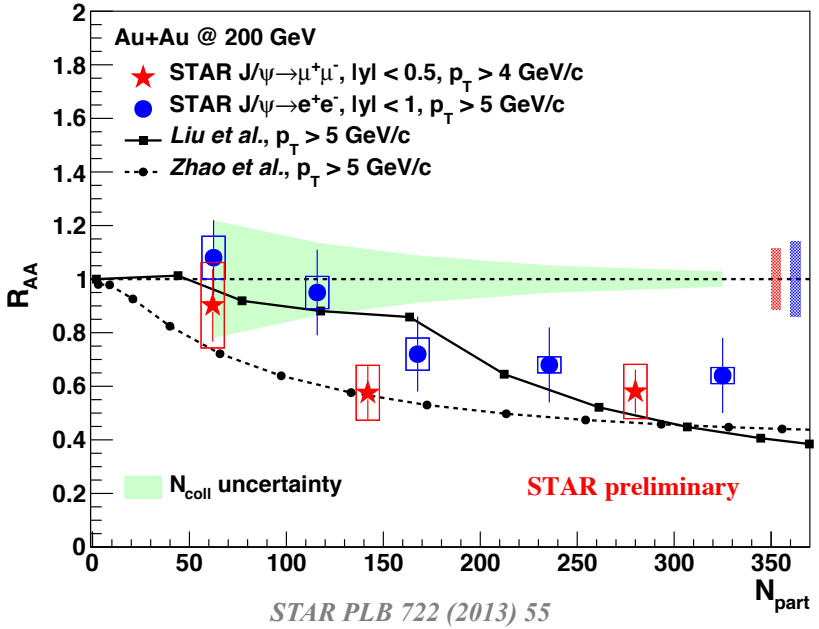
STAR PLB 722 (2013) 55
STAR PRC 90, 024906 (2014)
Y.-p. Liu, et al. PLB 678 (2009) 72
X. Zhao et al. PRC 82 (2010) 064905

- Both models include **dissociation of the prompt J/ψ and contribution of regenerated J/ψ** → qualitatively reproduce the rising trend seen in the data.

J/ψ dissociation at high p_T



STAR, PRL 111 (2013) 052301
L. Yan, P. Zhuang, and N. Xu, PRL 97 (2006) 232301
V. Greco, C.M. Ko, and R. Rapp, PLB 595 (2004) 202
X. Zhao and R. Rapp, arXiv: 0806.1239
Y. Liu, N. Xu and P. Zhuang, NPA 834 (2010) 317
U.W. Heinz and C. Shen, (private communication)



STAR PLB 722 (2013) 55
Y.-p. Liu, et al. PLB 678 (2009) 72
X. Zhao et al. PRC 82 (2010) 064905

- *J/ψ* v_2 is consistent with zero at high p_T → *regeneration contribution is small given finite v_2 of charm quarks.*
- Meanwhile, J/ψ is strongly suppressed at high p_T in central events → **dissociation**

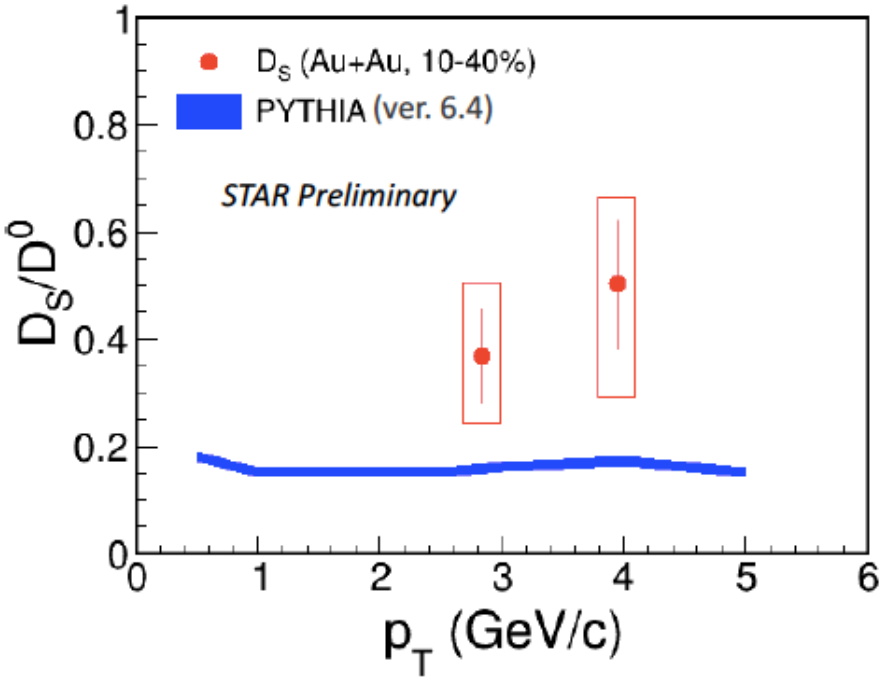
Summary & Outlook

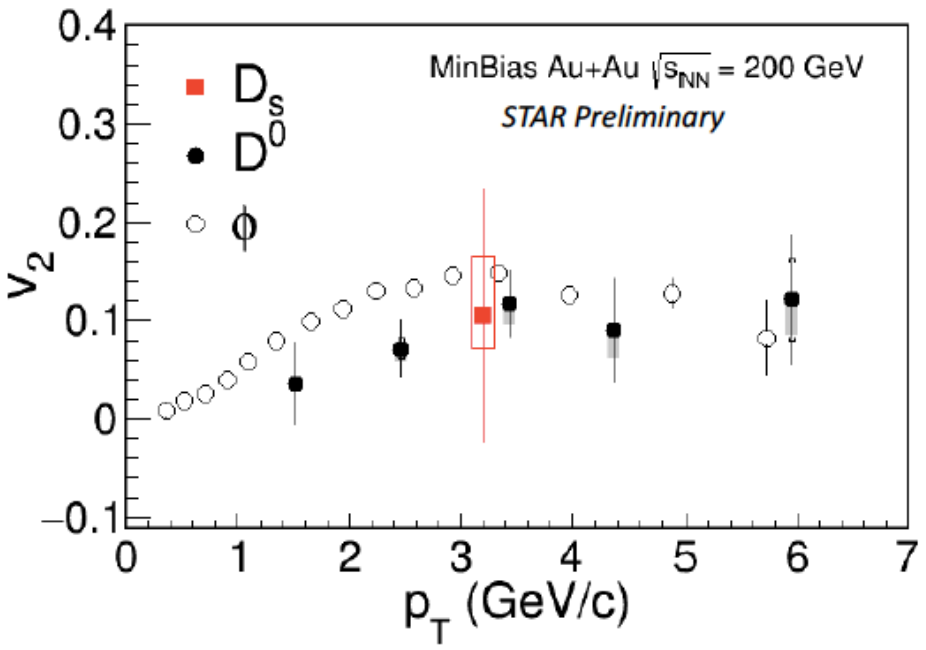
- Heavy-flavor results using part of Run14 data taken with newly upgraded MTD and HFT detectors are shown.
- **D meson by HFT**
  - Charm quarks interact strongly with the medium
  - Charm quarks also flow with the medium, even though they do not seem to be fully thermalized.
- **J/ψ by MTD**
  - Distinct rising R_{AA} with p_T
  - At high p_T, $R_{AA} < 1$ & $v_2 \sim 0$ → dissociation in effect
- **Outlook**
  - Run14&16 Au+Au data: improve precision of total charm cross-section; more differential measurements for D and J/ψ mesons; measurements of even rare probes, e.g. Λ_c, Υ, etc
  - Run15 pp/pA data: important reference measurements & cold nuclear matter effects

Backup

D_s: strange quark makes difference

- R_{AA} of D_s > D^0: strangeness enhancement in QGP
- v_2 of D_s < D^0: earlier freeze-out of D_s *PRL 110 (2013) 112301*



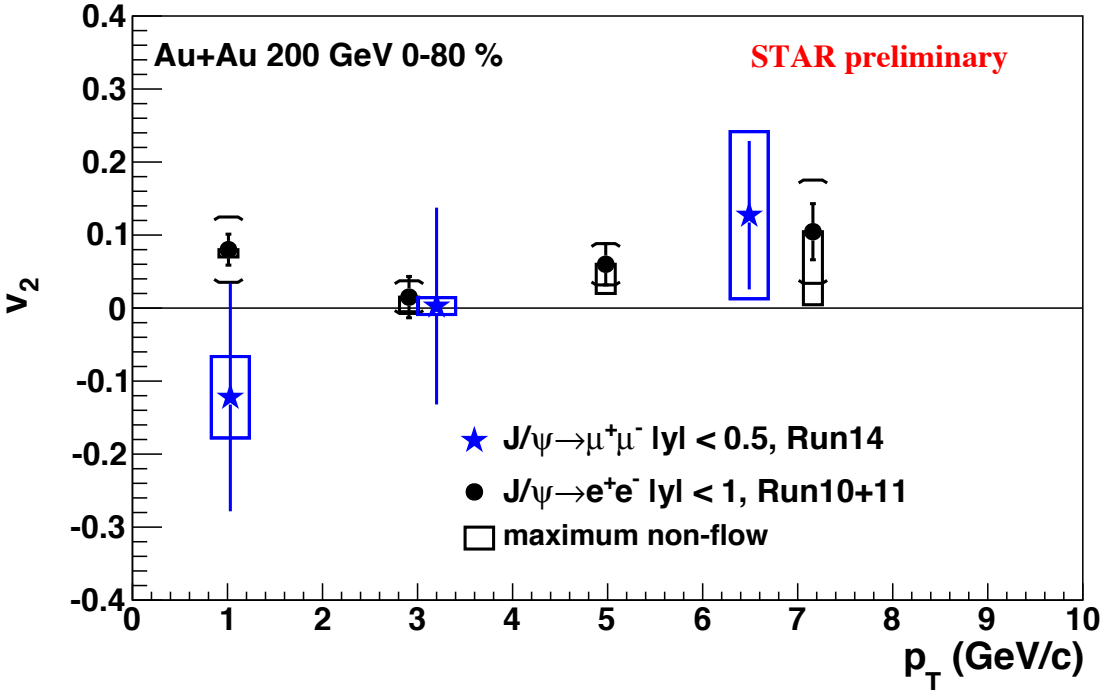


STAR: PRL 116 (2016) 062301

- Calls for more statistics to make conclusive comparison between expectations and measurements (Run14+16).

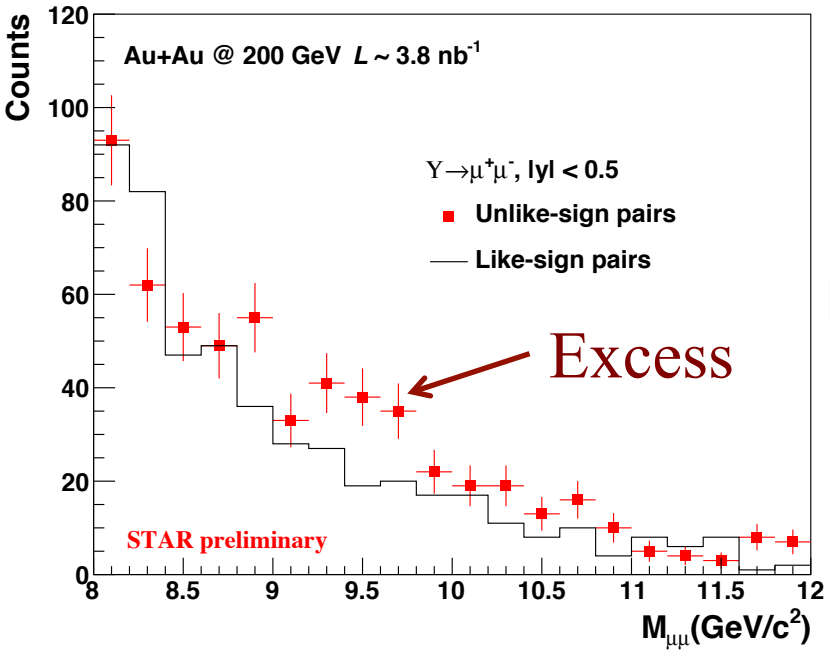
Does J/ψ flow?

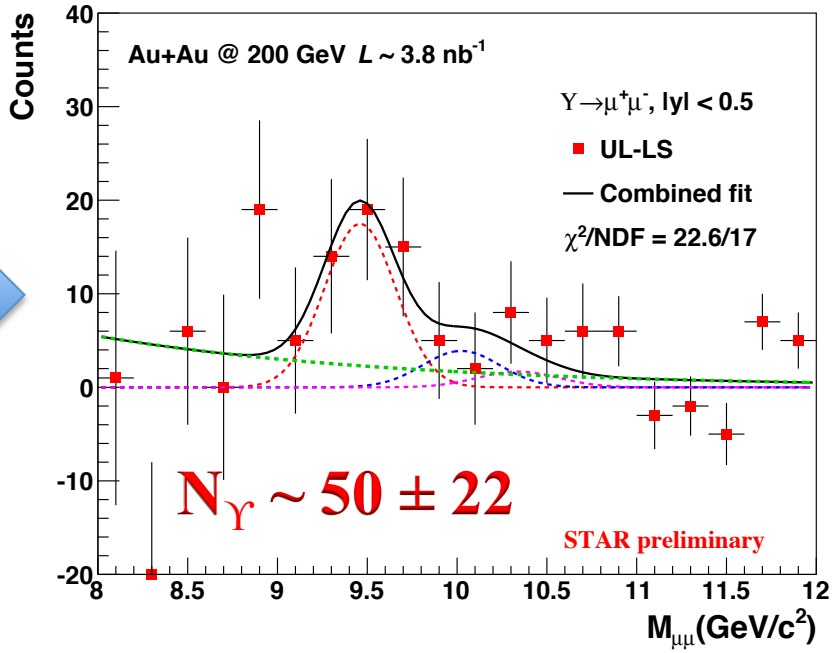
- Measure the second-order Fourier coefficient (v_2)
  - Primordial: little or zero v_2
  - Regenerated: inherit v_2 from the constituent charm quarks



- Consistent results from di-muon channel within large error bars

Υ measurement

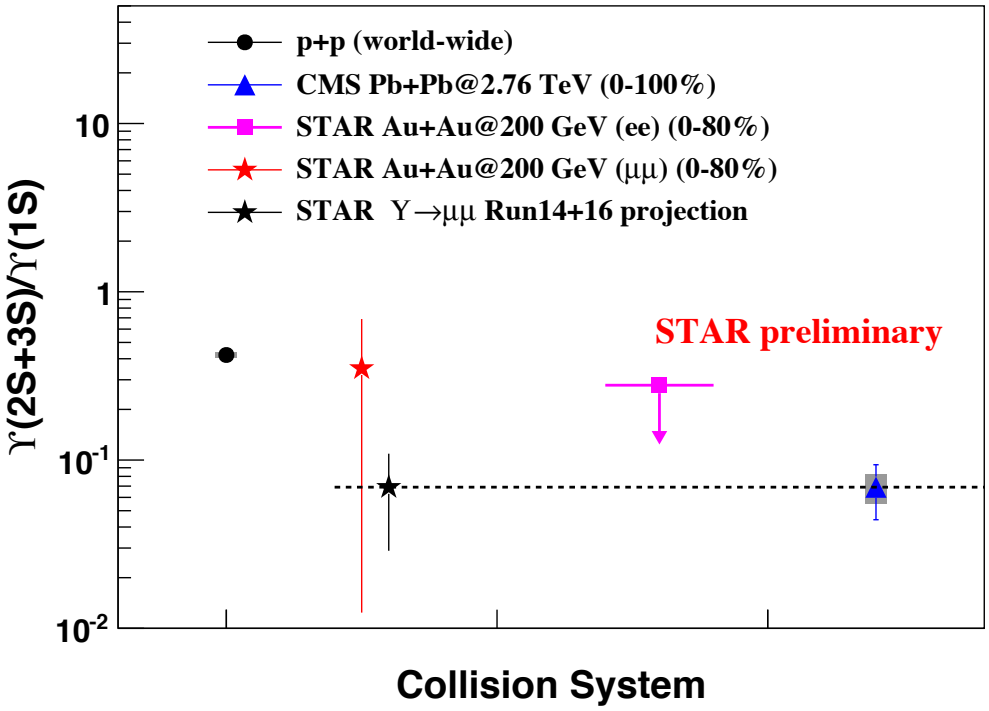




- Fit signal distribution after background subtraction:
  - Mean of Υ is fixed to PDG value, while width is determined from simulation.
  - Ratio of Υ(2S)/Υ(3S) is fixed to pp value, and shape of bb and Drell-Yan background is estimated using PYTHIA

Υ(2S+3S)/Υ(1S) ratio

PLB 735 (2014) 127
PRL 1029(2012) 222301



- Consistent with di-electron channel within large error bars

- The statistical error can be further reduced:
  - A factor of 7 more statistics with full Run14+16 data
  - Usage of mix-event can reduce statistical error by $\sqrt{2}$