RHIC & AGS
Annual Users' Meeting
Hosted By Brookhaven National Laboratory

# 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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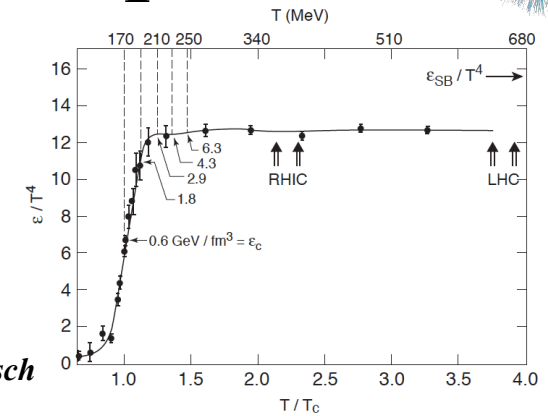
# Outline

- 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 $J/\psi$
- Summary & Outlook

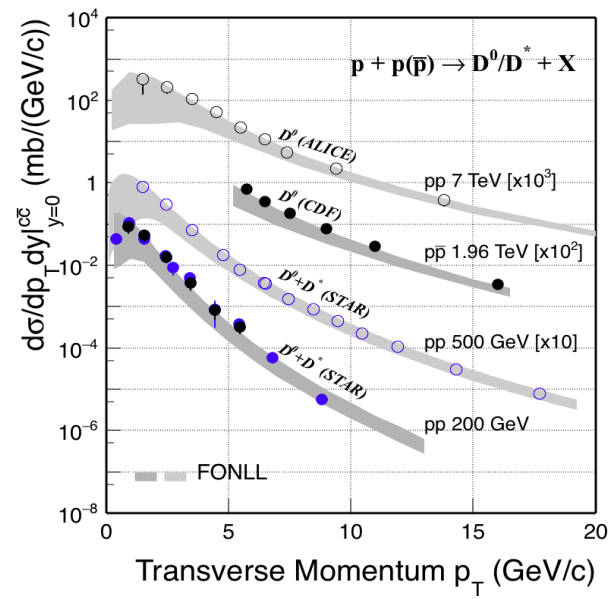
# Probe QGP with charm quark

- 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

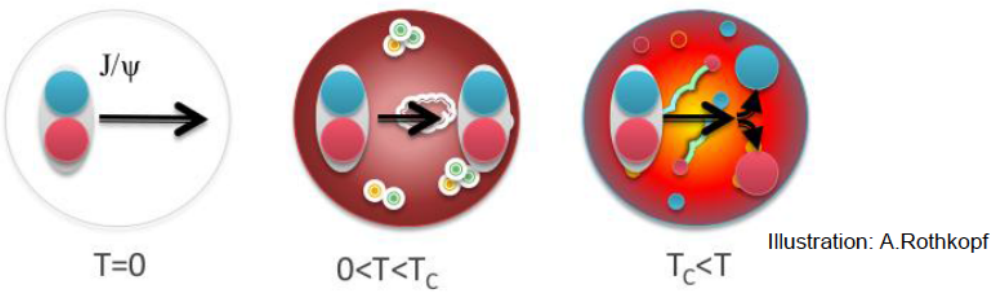



*STAR: PRD 86 (2012) 072013, NPA 931 (2014) 520*
*CDF: PRL 91 (2003) 241804; ALICE: JHEP01 (2012) 128*
*FONLL: PRL 95 (2005) 122001*

**PRL 113 (2014) 142301*

# Probe QGP with quarkonium

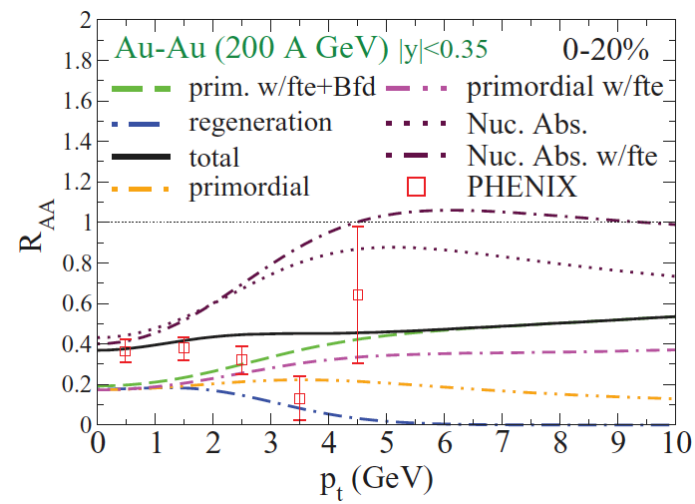
- **Color-screening**: quarkonium dissociates in the medium




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

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

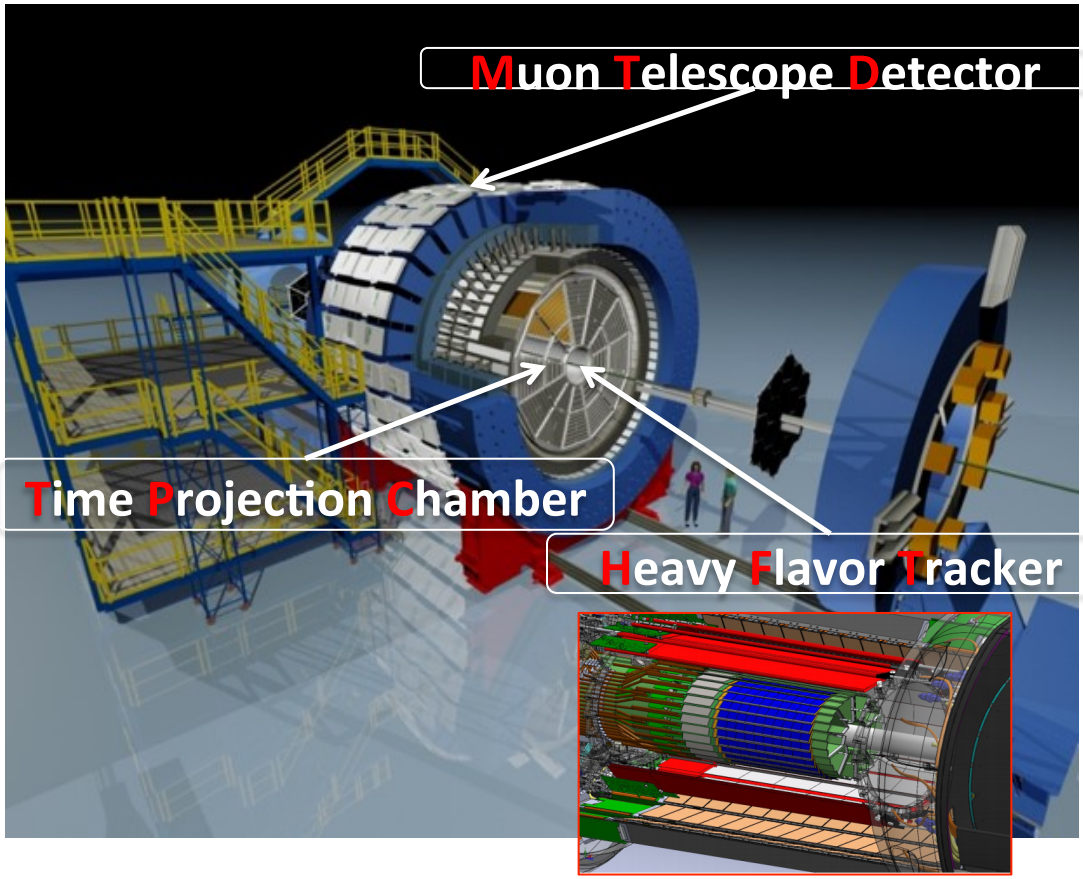
- However, interpreting J/ψ suppression is no easy job!
  - *Hot nuclear matter effects*
    - Dissociation
    - Regeneration from uncorrelated quarks
    - Medium-induced energy loss
    - Formation time effects
  - *Cold nuclear matter effects*
  - *Feed-down of excited charmonium states and B-hadrons*




*Phys. Rev. C 82, 064905*

# The Solenoid Tracker At RHIC

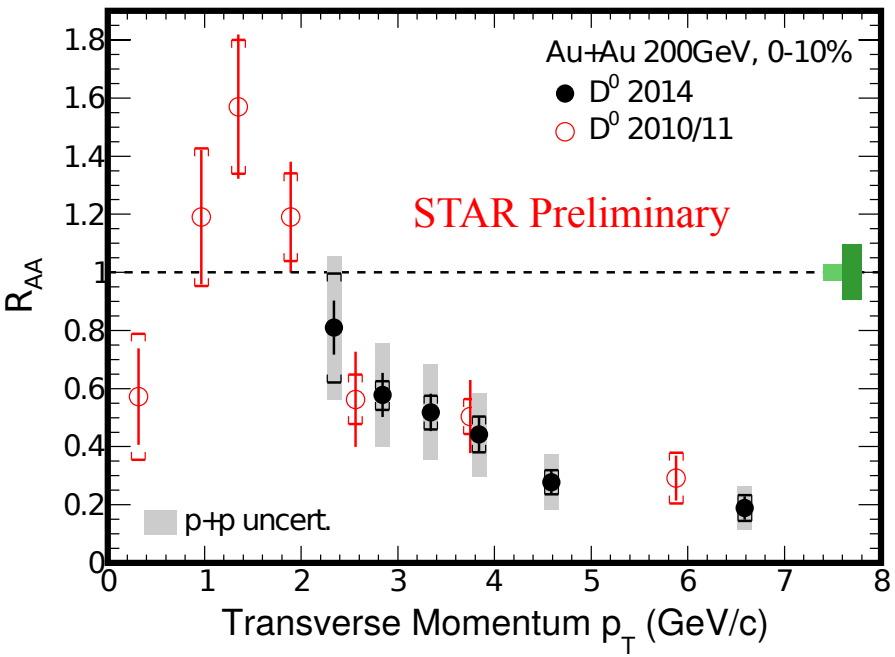
- Mid-rapidity detector: $|\eta| < 1$, $0 < \varphi < 2\pi$




- **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 ($\sigma$~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

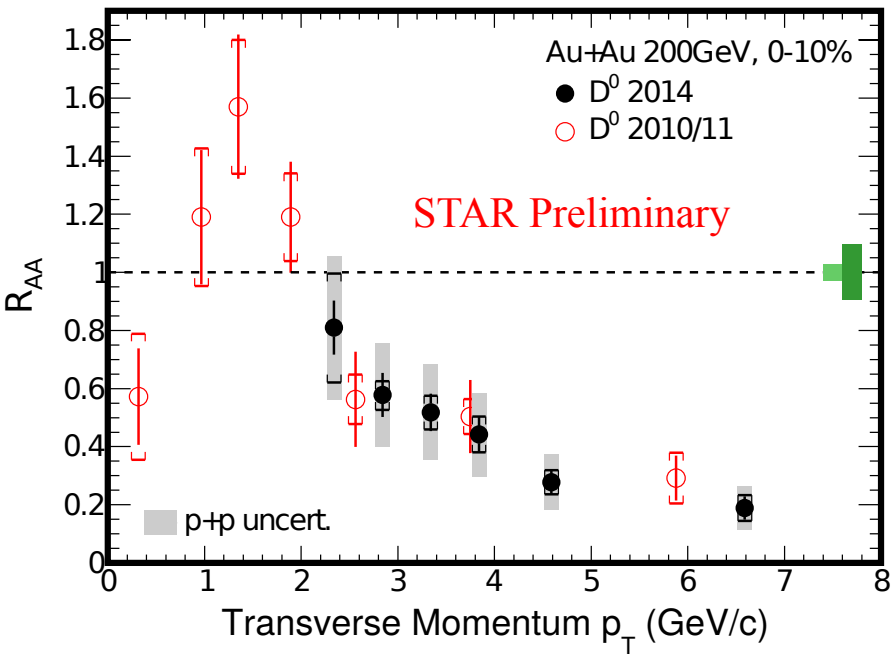



*STAR: PRL 113 (2014) 142301*

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

Charm coalescence with the flowing medium

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

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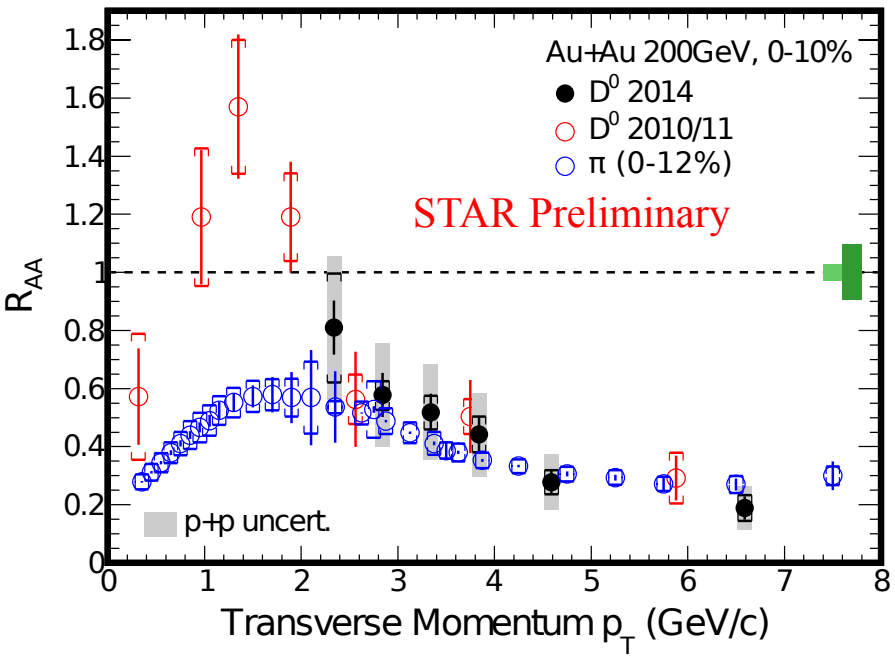
✓ $R_{AA} > 1$ for $p_T \sim 1.5$ GeV/c

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

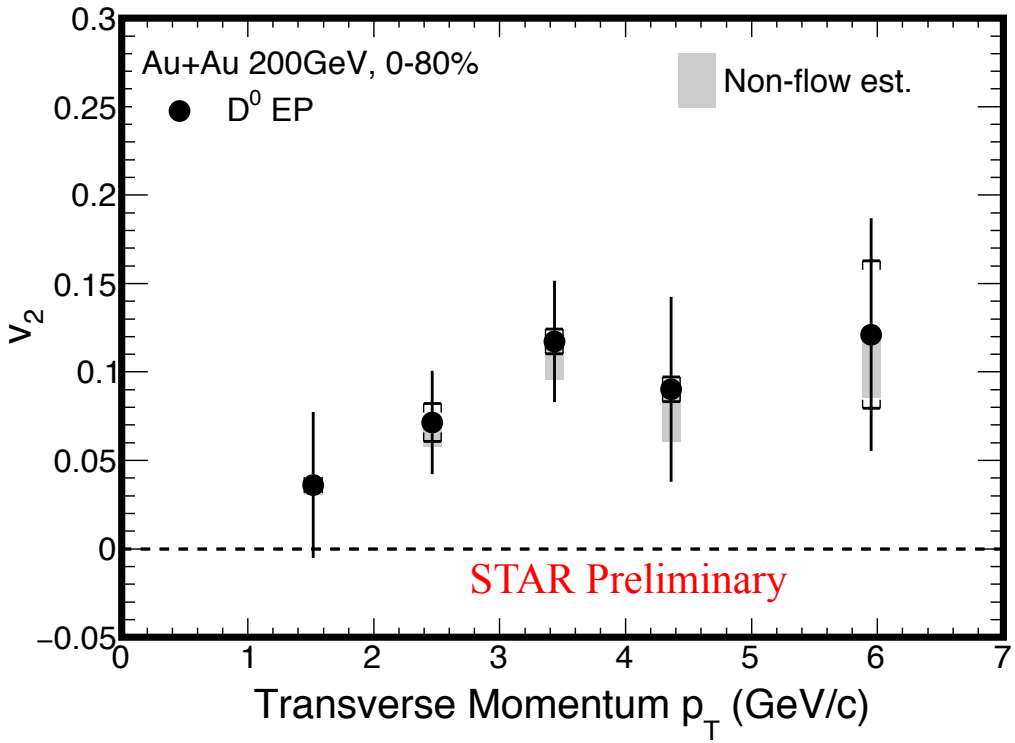
✓ $R_{AA} << 1$ for $p_T > 2.5$ GeV/c

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.

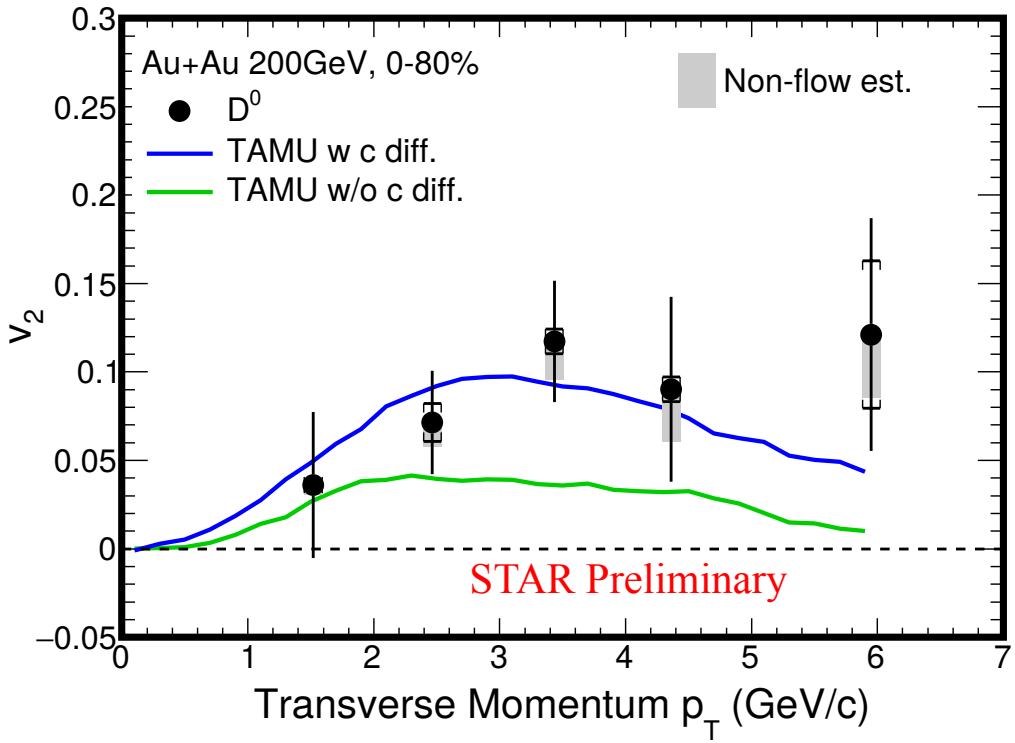
# First $D^0$ $v_2$ measurement at RHIC




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

# $D^0$ $v_2$: data vs model

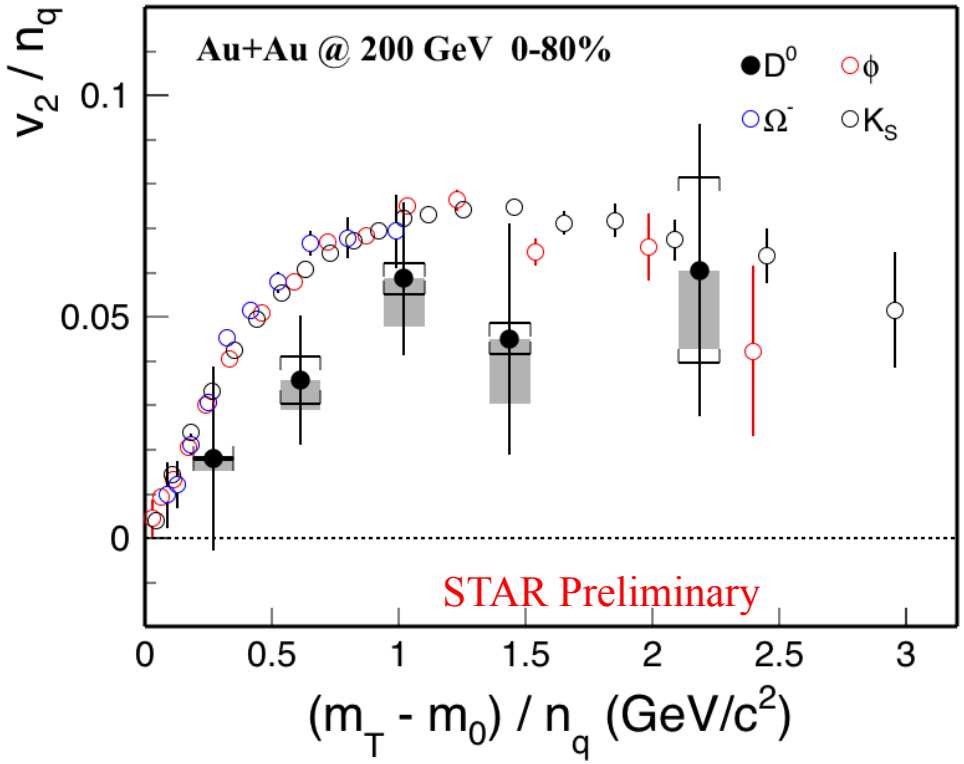
*Theory: arXiv:1506.03981*
*private comm.*




✓ 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*

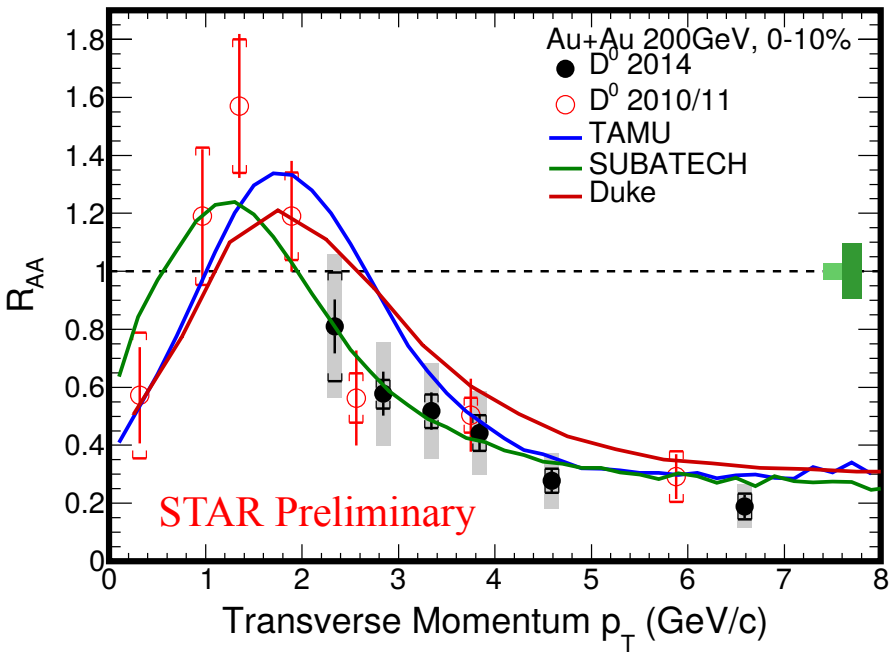
✓ $v_2$ for $D^0$ is systematically lower than those of light hadrons

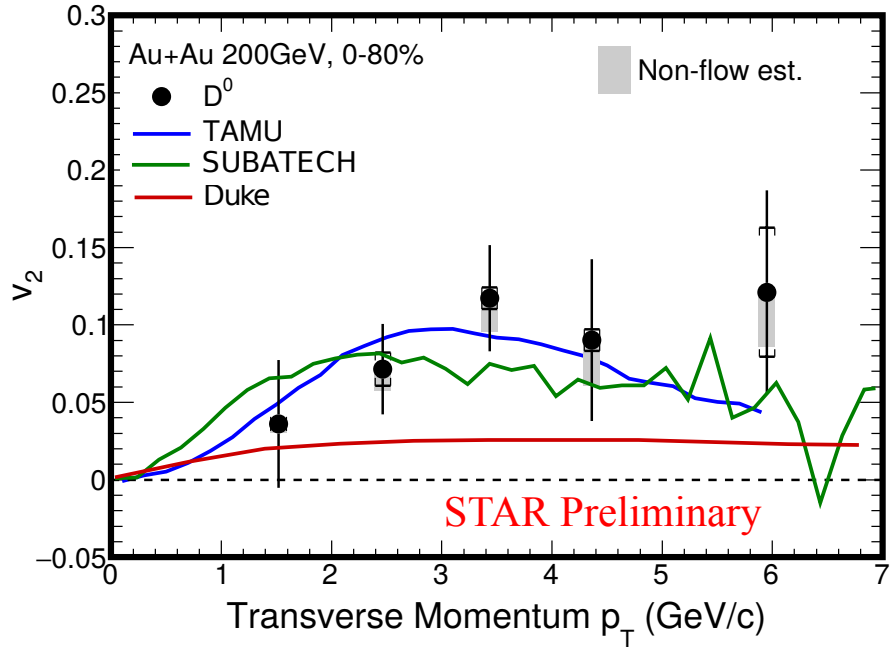
→ Hints that charm quarks might not be fully thermalized with medium

# Can theory describe $R_{AA}$ & $v_2$?

*Theory: arXiv:1506.03981*
*arXiv:1505.01413*
*private comm.*

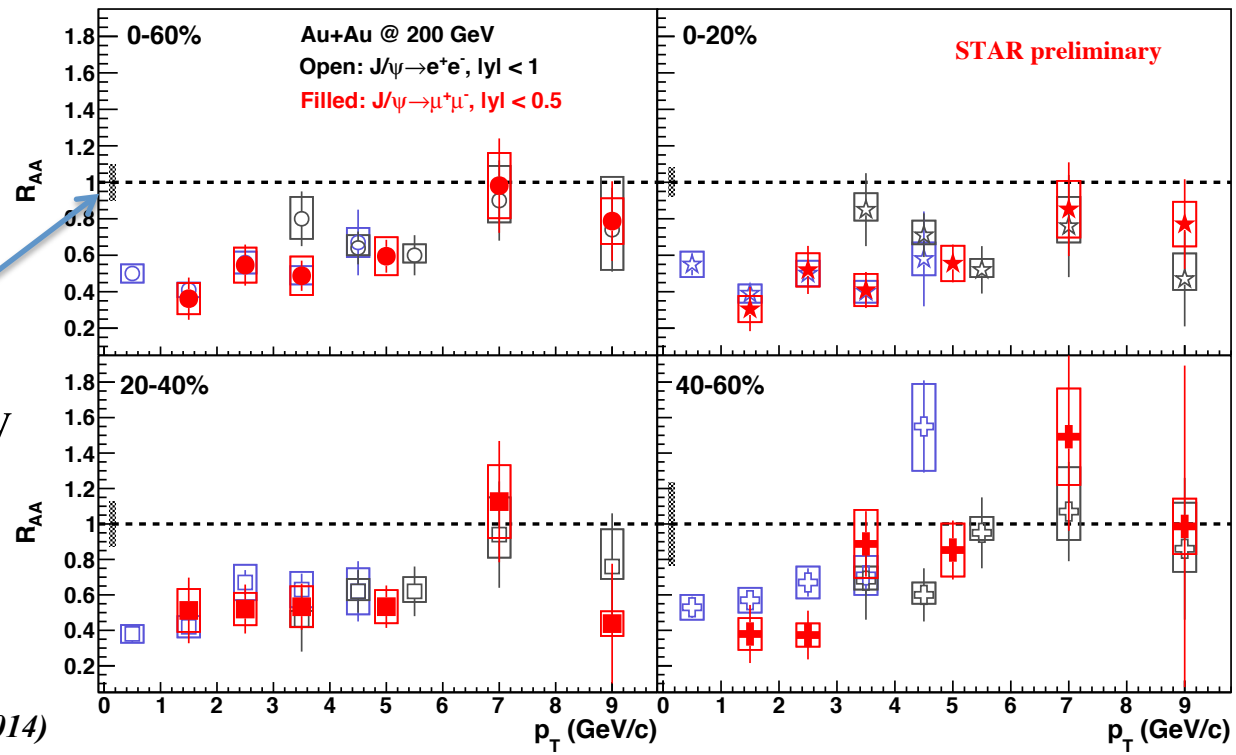
*STAR: PRL 113 (2014) 142301*




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

# J/$\psi$ suppression in Au+Au collisions

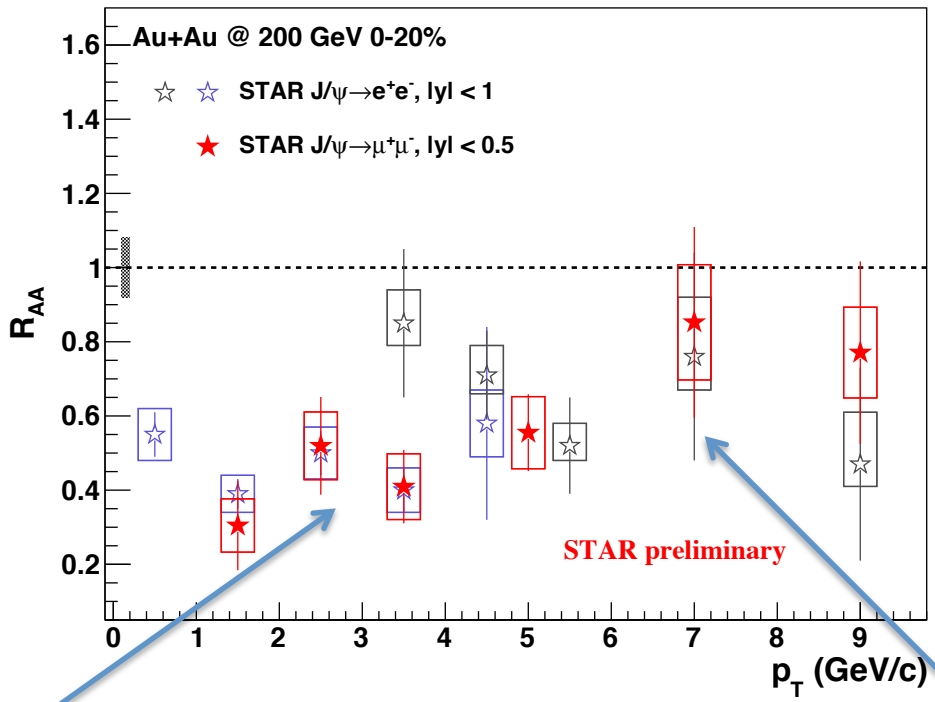



Scale uncertainty for $\sigma_{inel}$ and $N_{coll}$

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

- **Distinct** rising $R_{AA}$ with $p_T$ for J/$\psi$ 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)*

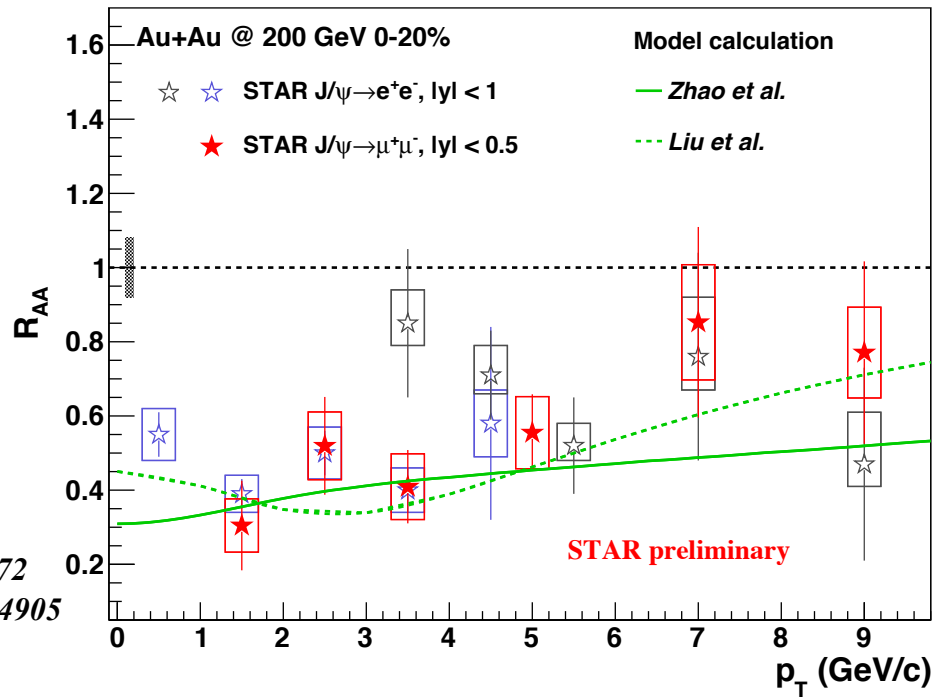
**Strong suppression at low $p_T$**

- Dissociation
- Cold nuclear matter effect
- Regeneration

**Less suppression at high $p_T$**

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

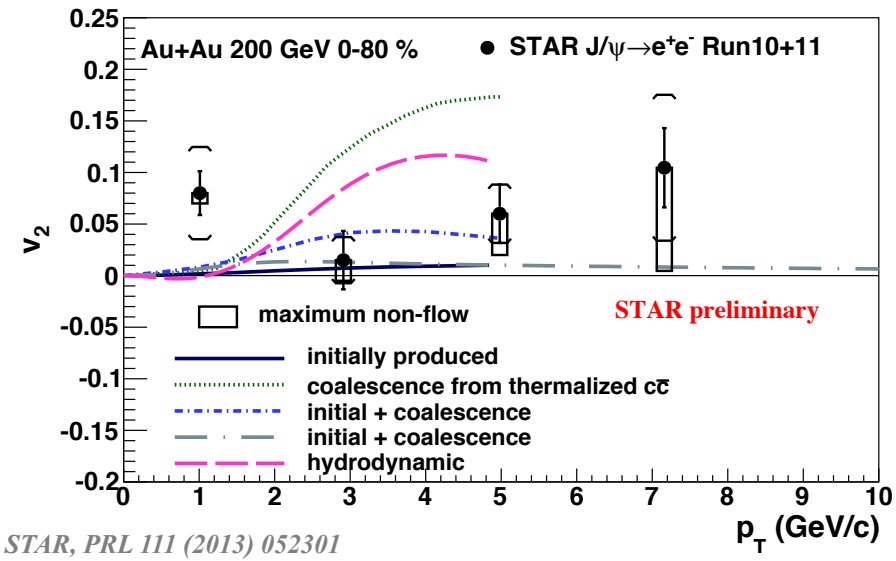
# Compare with model calculations



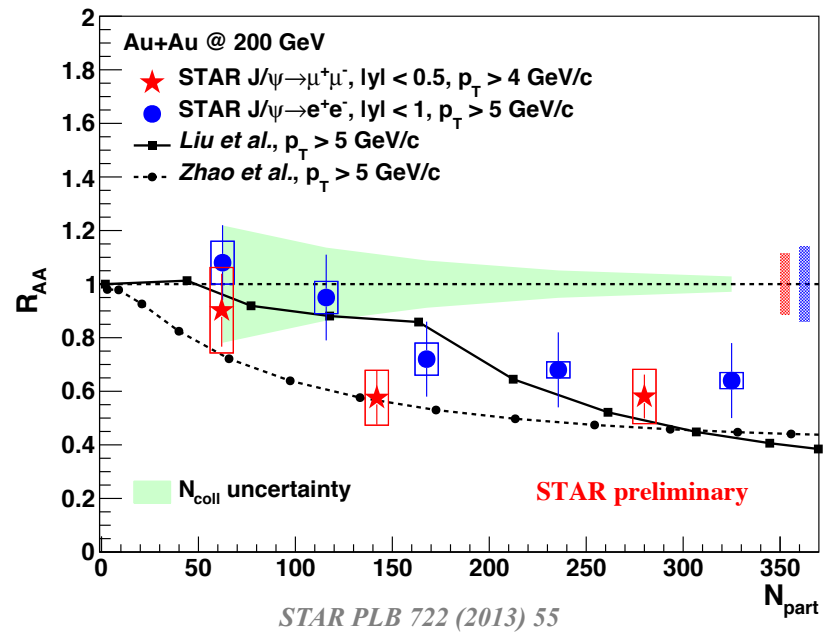

*STAR PLB 722 (2013) 55*
*STAR PRC 90, 024906 (2014)*
*Y.-p. Liu, et al. PLB 678 (2009) 72*
*X. Zhao et al. PRC 82 (2010) 064905*

- 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

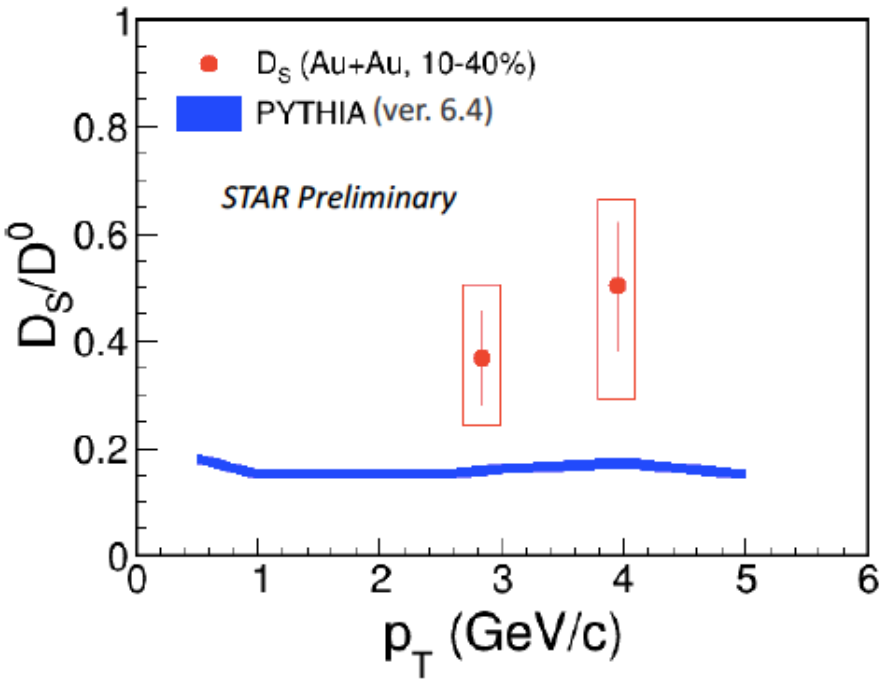
- Heavy-flavor results using part of Run14 data taken with newly upgraded MTD and HFT detectors are shown.
- **D meson by HFT**
  - Charm quarks interact strongly with the medium
  - Charm quarks also flow with the medium, even though they do not seem to be fully thermalized.
- **J/$\psi$ by MTD**
  - 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/$\psi$ mesons; measurements of even rare probes, e.g. $\Lambda_c$, $\Upsilon$, etc
  - Run15 pp/pA data: important reference measurements & cold nuclear matter effects

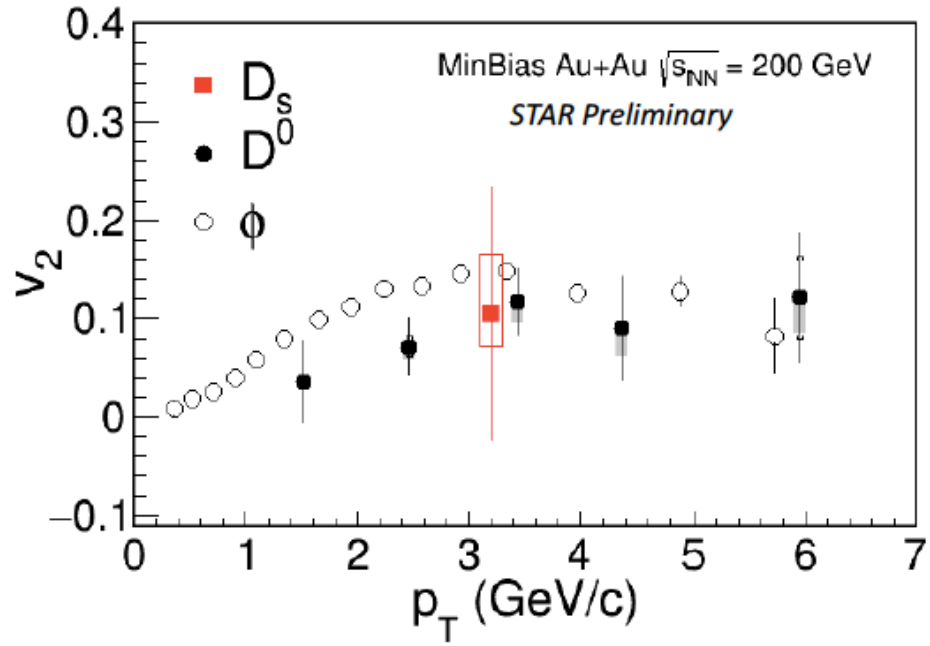
# Backup

# $D_s$: 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*



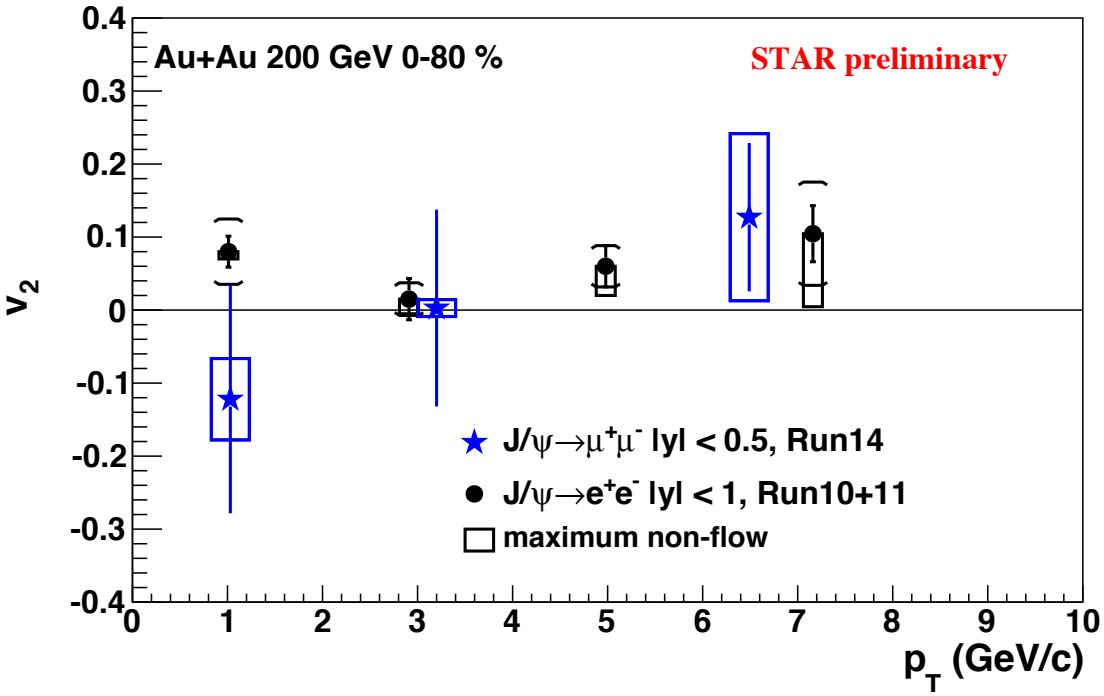




*STAR: PRL 116 (2016) 062301*

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

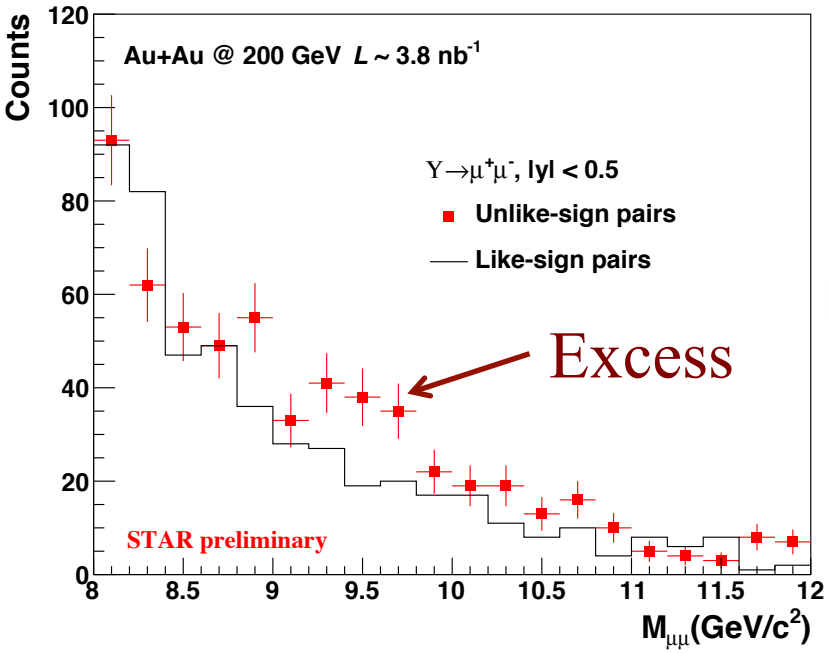
# Does J/$\psi$ flow?

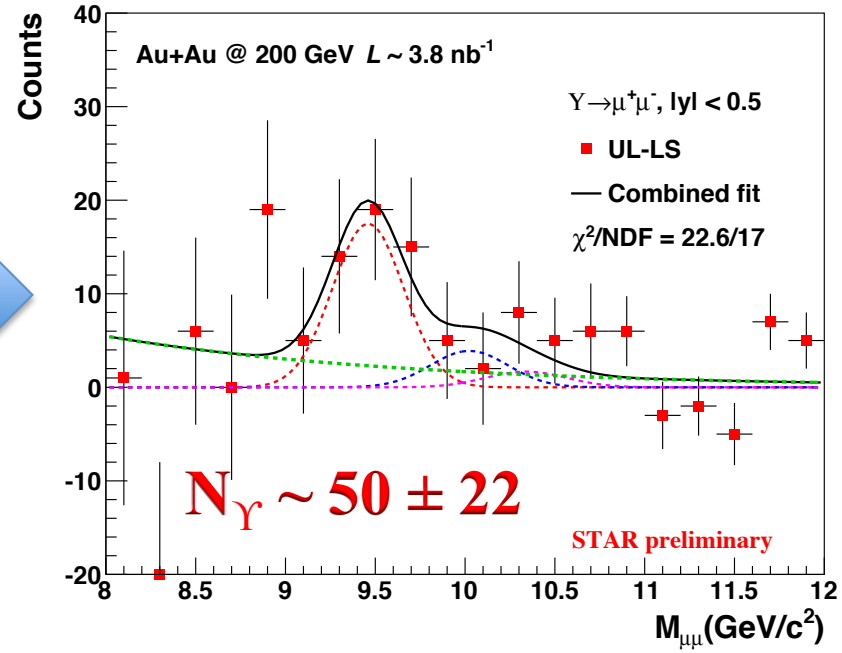
- Measure the second-order Fourier coefficient ($v_2$)
  - Primordial: little or zero $v_2$
  - Regenerated: inherit $v_2$ from the constituent charm quarks




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

# ϒ measurement

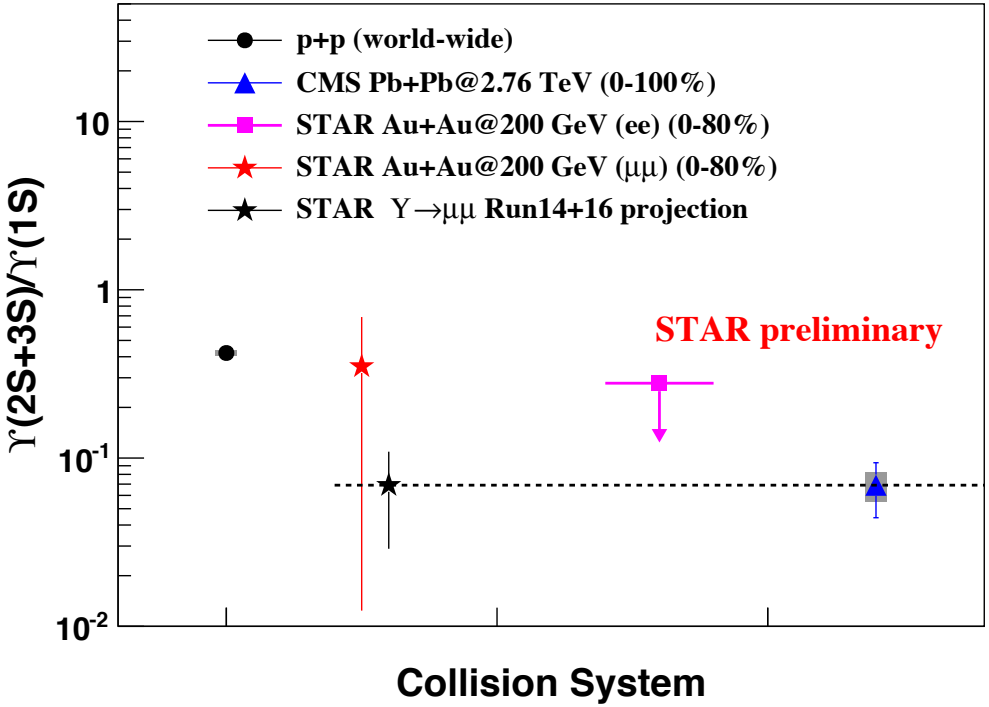



- Fit signal distribution after background subtraction:
  - Mean of ϒ is fixed to PDG value, while width is determined from simulation.
  - Ratio of ϒ(2S)/ϒ(3S) is fixed to pp value, and shape of bb and Drell-Yan background is estimated using PYTHIA

# 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 √2