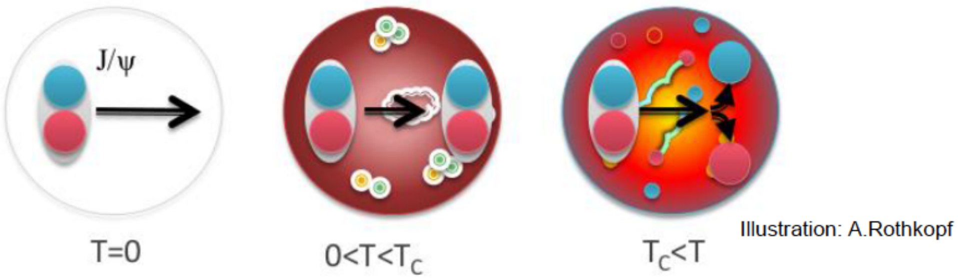
Quarkonium measurements via the di-muon decay channel in p+p and Au+Au collisions with the STAR experiment

Takahito Todoroki (BNL)
for the STAR Collaboration

Strangeness in Quark Matter 2016
From June 27th to July 1st 2016
UC Berkeley

Probe QGP with J/ψ

- **Color-screening** : J/ψ dissociates in the medium



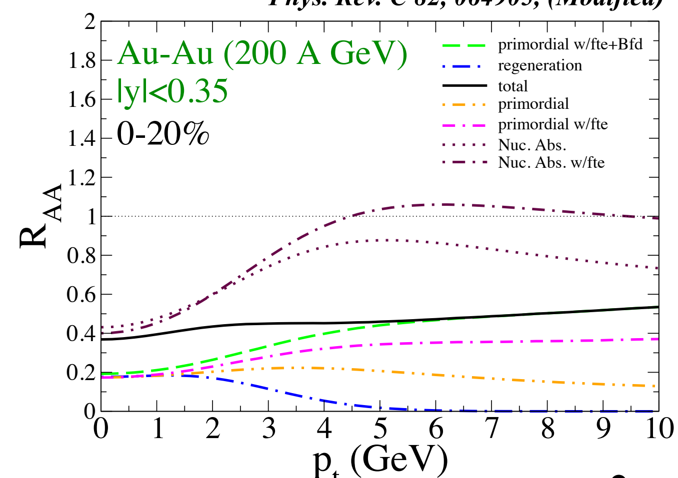
J/ψ suppression was proposed as a direct proof of deconfinement

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

HOWEVER

- **Various production mechanisms**
  - Prompt: direct production; decay of $\psi(2S)$ and χ_c (40%)
  - Non-prompt: B-meson decay (up to 20% at high p_T)
- **Different effects in play**
  - Hot nuclear matter effects
    - ***Dissociation***
    - Regeneration
    - Medium-induced energy loss
  - Cold nuclear matter effects

Phys. Rev. C 82, 064905, (Modified)



Υ : A cleaner but rarer probe

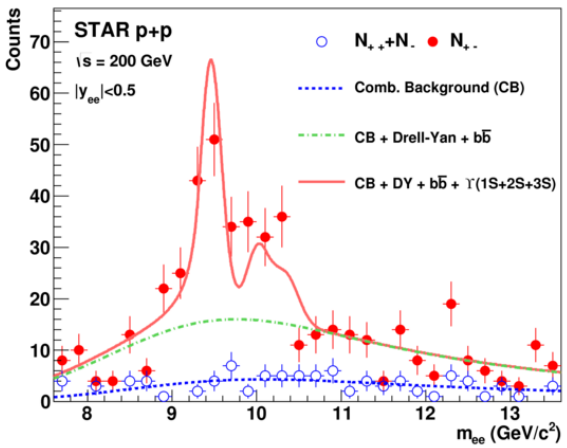
Advantage

- Much smaller effects from co-mover absorption and regeneration → ($\sigma_{cc} \sim 800\mu b$, $\sigma_{bb} \sim 2\mu b$)
- Sequential melting of different Υ states
- Low combinatorial background

Disadvantage

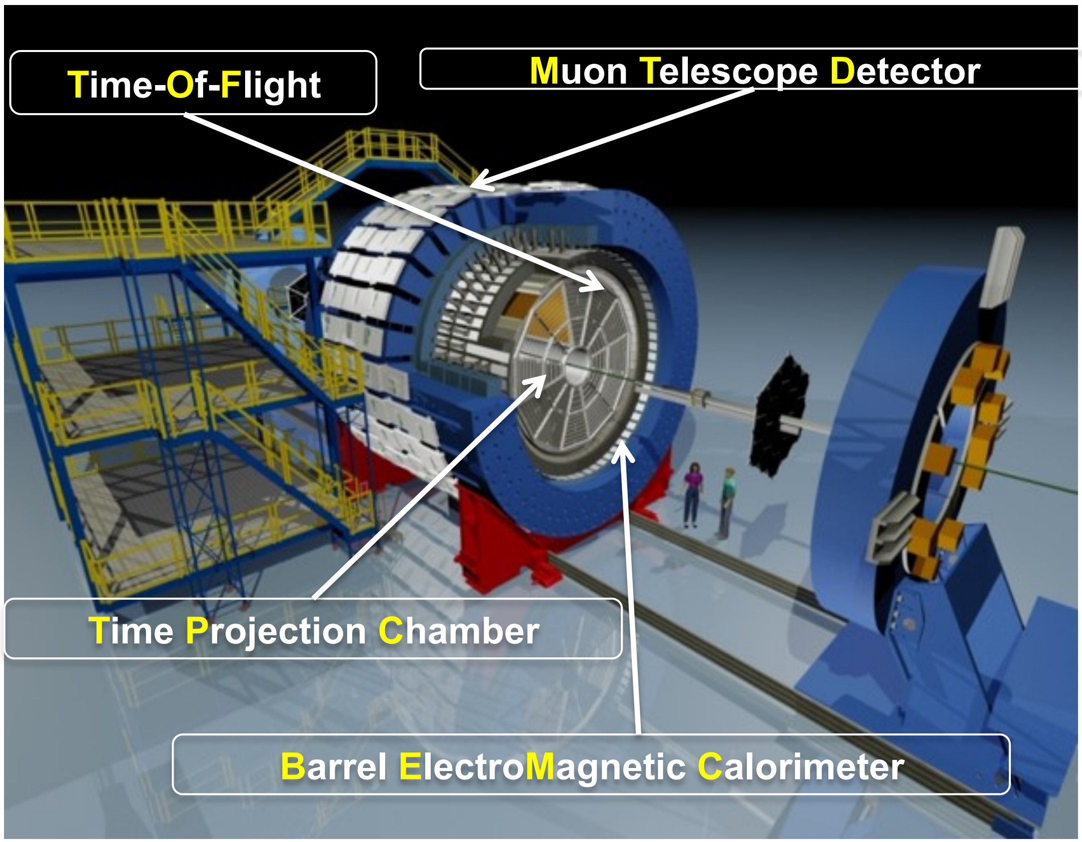
Phys. Lett. B 735 (2014) 127

- Much lower production rates ($m_b >> m_c$)
- Feed-down contribution to Υ(1S)
- Separation of different Υ states via the di-electron channel is challenging due to bremsstrahlung.



The Solenoid Tracker At RHIC (STAR)

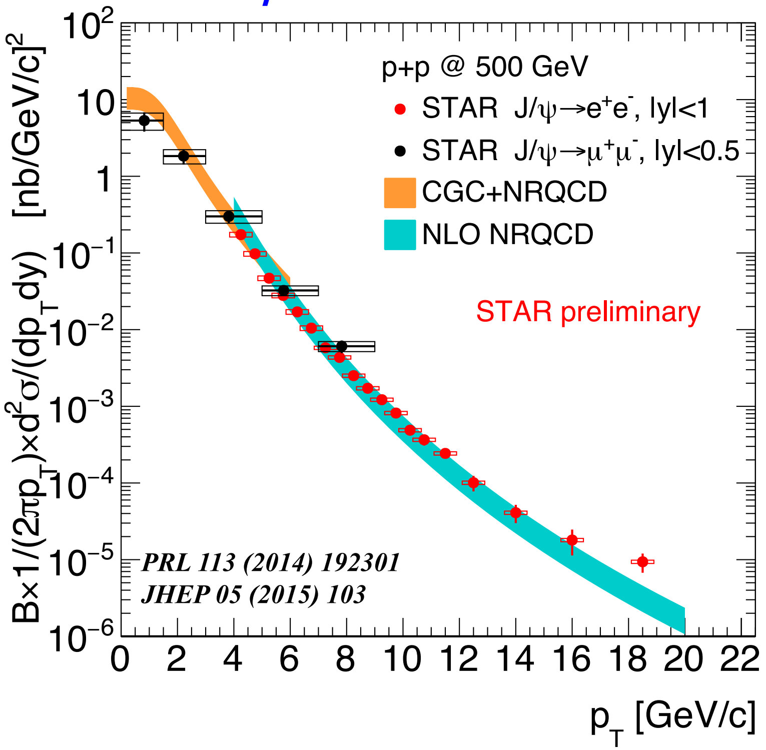
- Mid-rapidity detector: $|\eta| < 1$, $0 < \varphi < 2\pi$



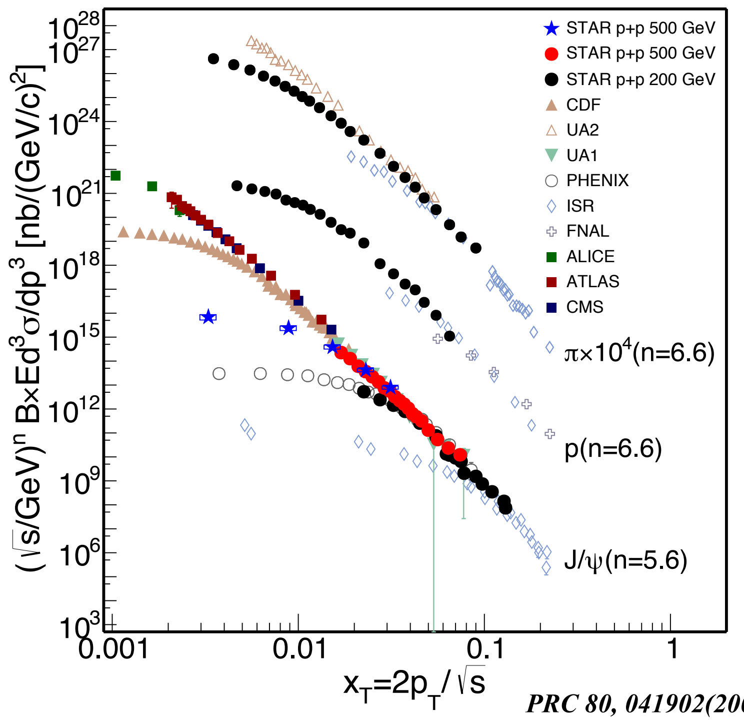
- **TPC**: precisely measure momentum and energy loss
- **TOF**: measure time-of-flight
- **BEMC**: trigger on and identify electrons
- **MTD ($|\eta|<0.5$)** : trigger on and identify muons
  - **Installed 63% in 2013 and 100% in 2014** behind magnet
  - ***Precise timing measurement (σ~100 ps)***
  - ***Dimuon trigger for quarkonia***

J/ψ cross section and x_T scaling in p+p collisions

J/ψ cross section



x_T scaling

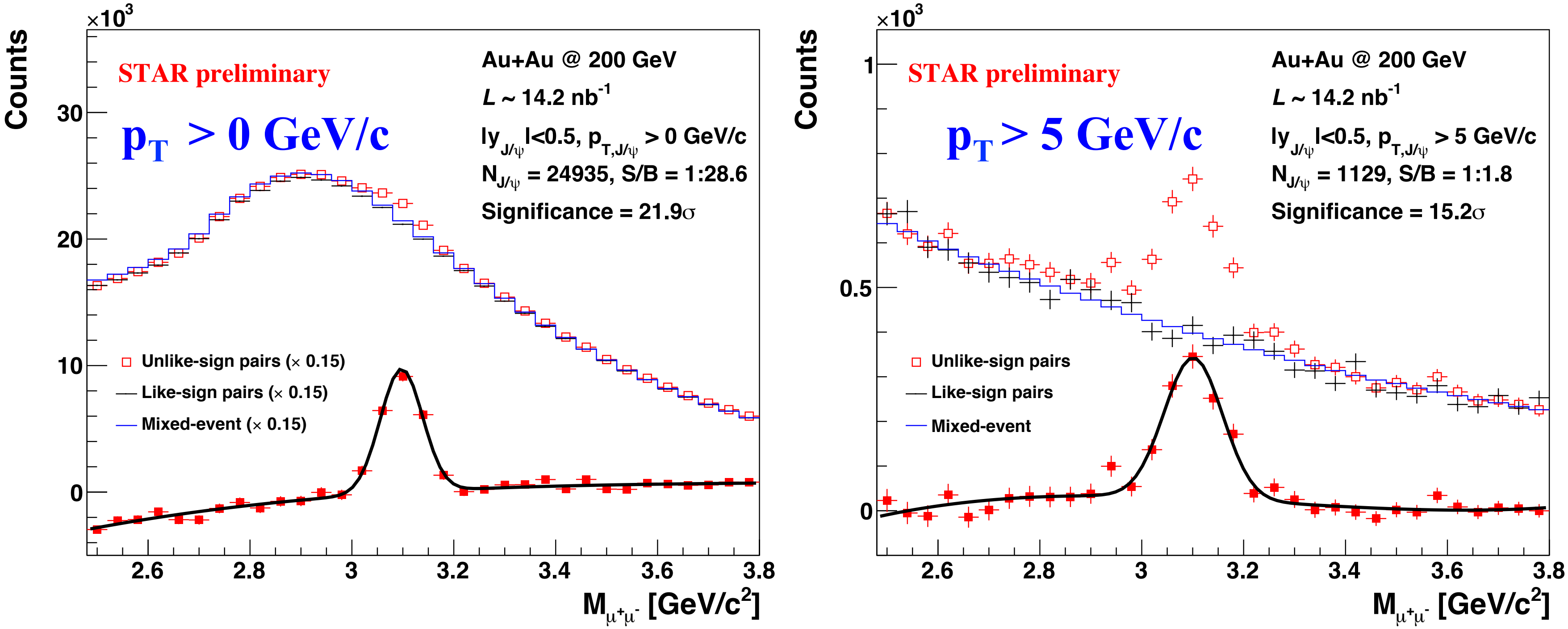


PRC 80, 041902(2009)

- Inclusive J/ψ cross section measured in **$0 < p_T < 20$ GeV/c**
  - **CGC+NRQCD and NLO NRQCD agree with data**
- x_T scaling of high-p_T J/ψ observed for 500 GeV p+p collisions
  - Breaking of x_T scaling : affected by soft process

J/ψ yield extraction

Full statistics from 2014 Au+Au 200 GeV run

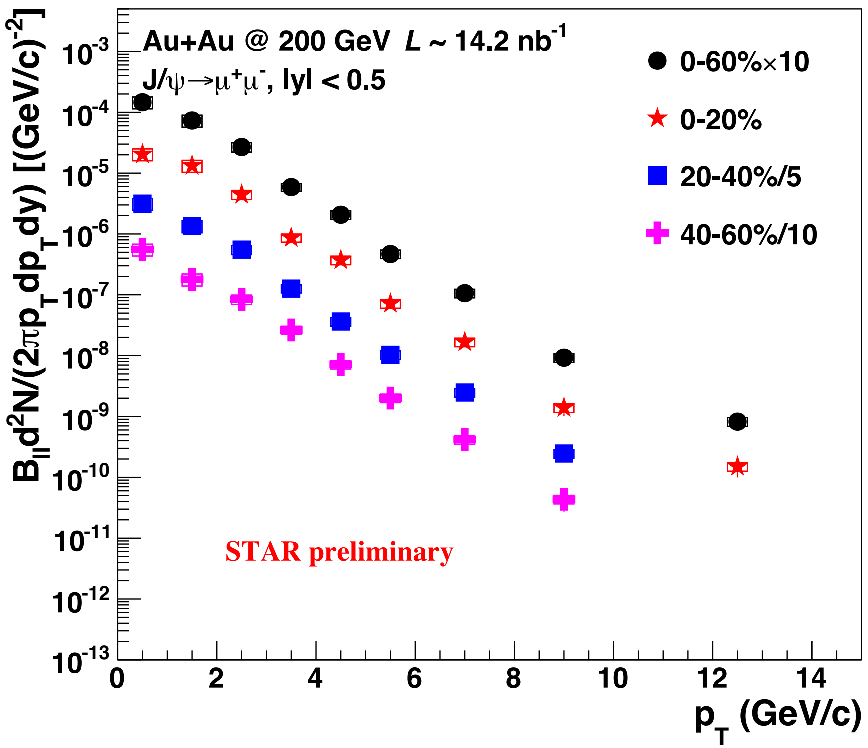


Signal extraction

- Mixed-event → combinatorial background.
- Fit background-subtracted unlike-sign with Gaussian+pol3
- Signal = (counting in[2.9,3.3] GeV/c²) – (residual background)

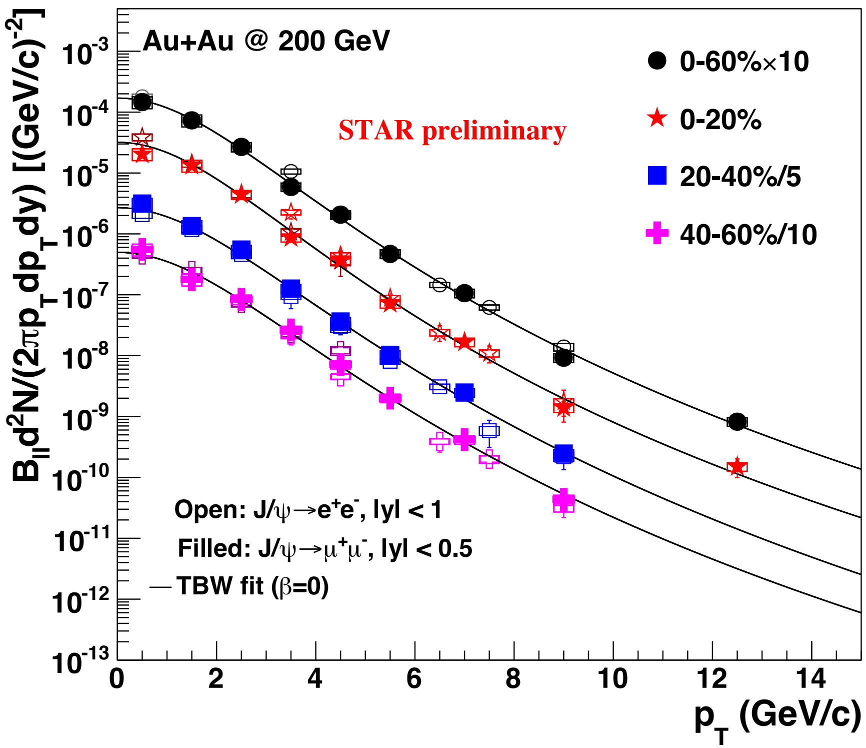
No bremsstrahlung tail
N ~ 25000
S/B ratio & Significance
S/B = 1:29, ~ 22σ @ p_T > 0 GeV/c
S/B = 1:1.8, ~ 15σ @ p_T > 5 GeV/c

Invariant yield of J/ψ



- **First mid-rapidity measurement of J/ψ yield in Au+Au collisions via the di-muon channel for $0 < p_T < 15$ GeV/c**

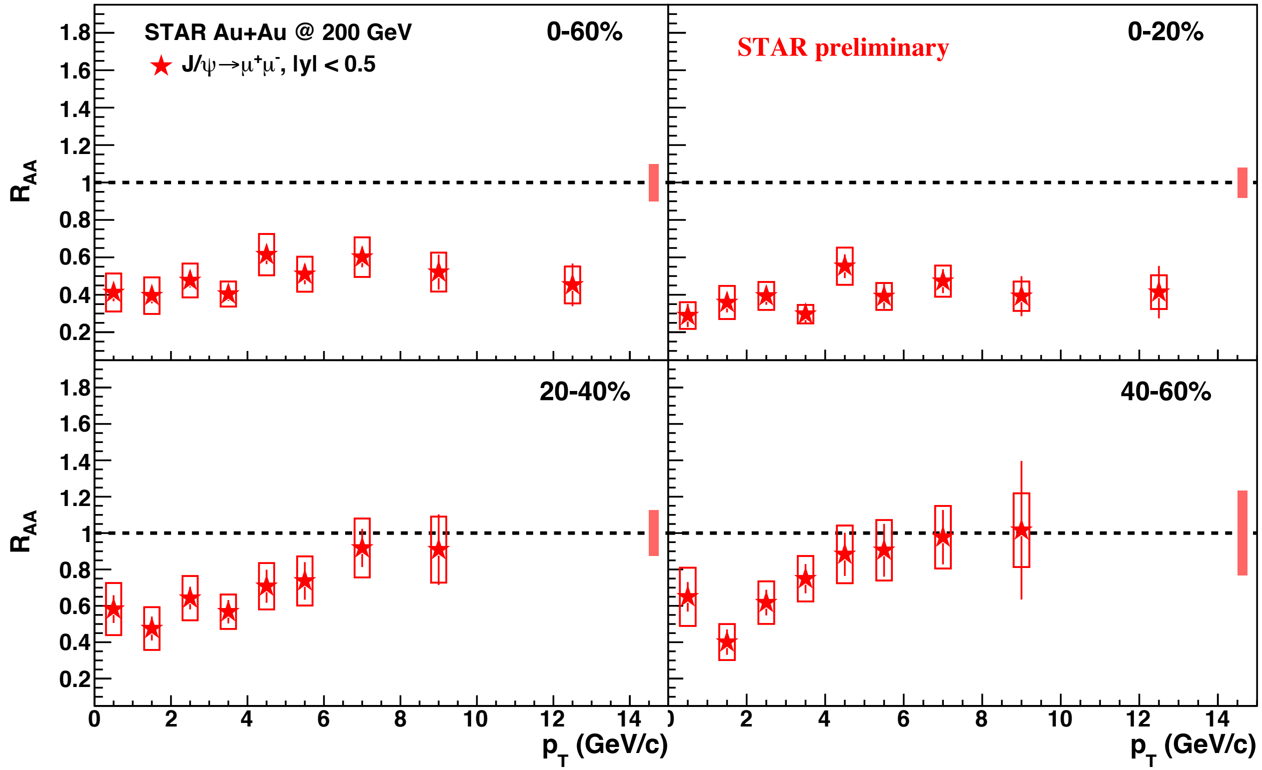
Invariant yield of J/ψ



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

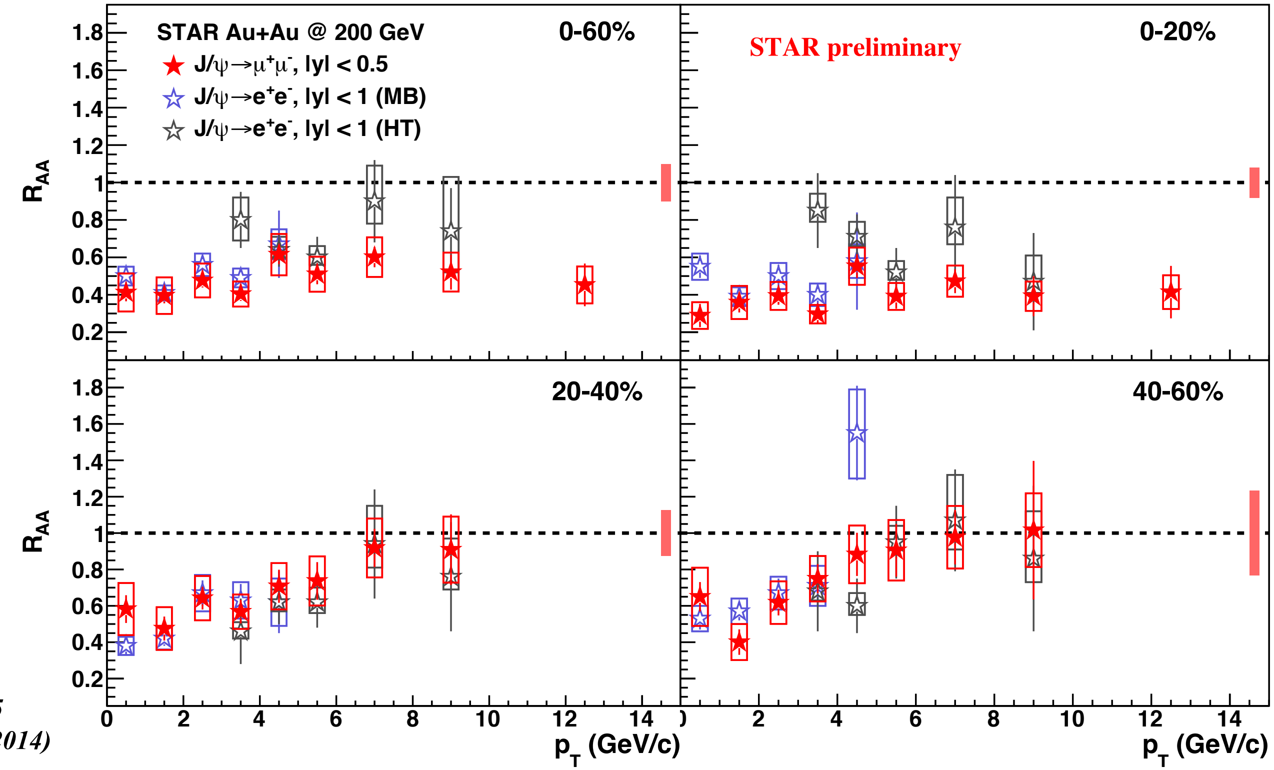
- **First mid-rapidity measurement of J/ψ yield in Au+Au collisions via the di-muon channel for $0 < p_T < 15$ GeV/c**
- Consistent with the published di-electron results using Run10 data over the entire kinematic range.

J/ψ suppression: $R_{AA} = \frac{\sigma_{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA} / dy dp_T}{d^2 \sigma_{pp} / dy dp_T}$



- **Suppression at Low-p_T**
  - Dissociation
  - Regeneration
  - Cold nuclear matter effect
- **At high p_T, strong suppression in 0-20% and a rising trend in 20-60% central collisions**
  - Dissociation
  - Formation time effect; B feed down

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



Di-electron:
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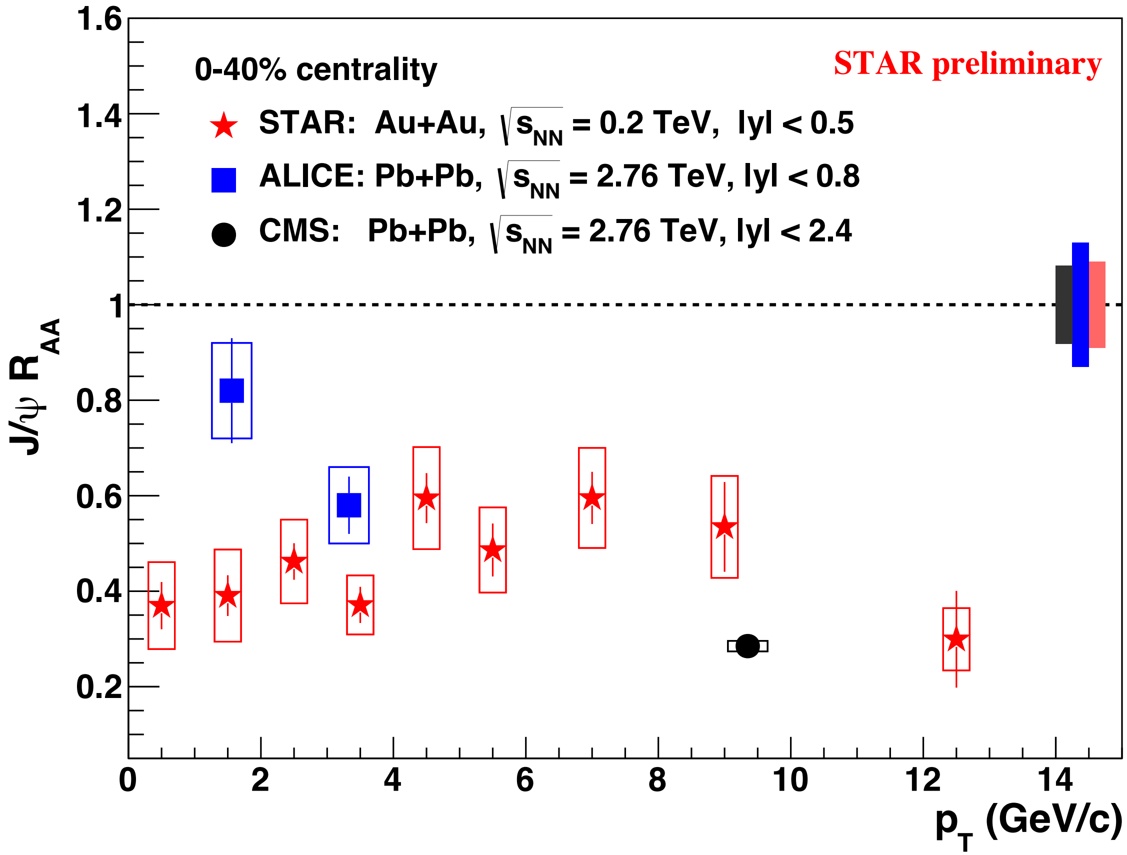
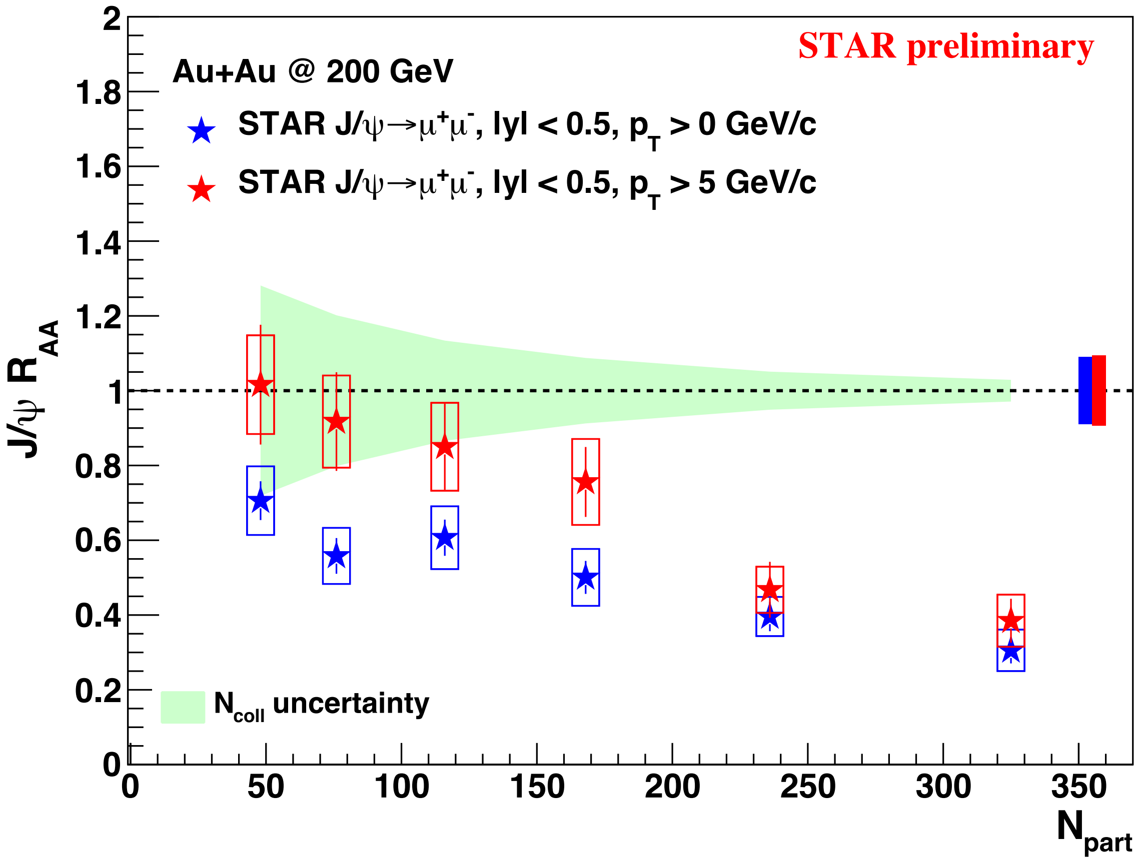
- **Consistent with di-electron channel results for the entire p_T range within uncertainties in all centralities**

J/ψ R_{AA} vs p_T : RHIC vs LHC



- Less suppressed at LHC in low-p_T → **larger regeneration contribution due to higher charm cross-section**
- More suppressed at LHC in high-p_T → **larger dissociation rate due to higher temperature**

R_{AA} vs. centrality

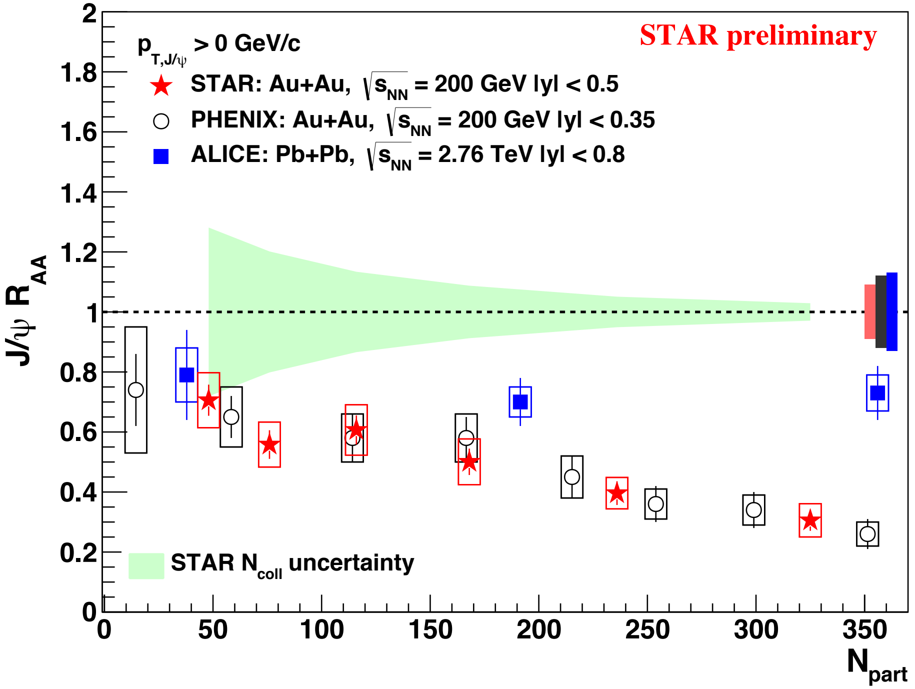


- Central collisions : **significant suppression is observed for $p_T > 0$ GeV/c and $p_T > 5$ GeV/c** → interplay of different effects
- Peripheral collisions : R_{AA} of J/ψ for $p_T > 0$ GeV/c is smaller than that for $p_T > 5$ GeV/c probably due to cold nuclear matter effects

Centrality dependence : RHIC vs LHC

p_T > 0 GeV/c

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



- STAR data are consistent with PHENIX with better statistical precision for p_T > 0 GeV/c

Centrality dependence : RHIC vs LHC

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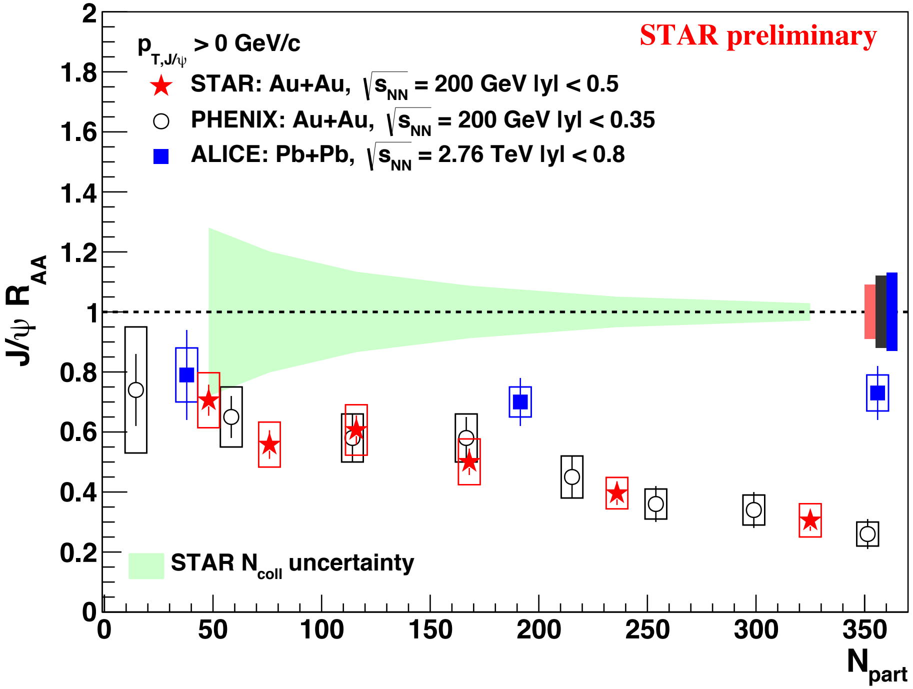

- STAR data are consistent with PHENIX with better statistical precision for $p_T > 0$ GeV/c
- $p_T > 0$ GeV/c : more suppressed at RHIC in central collisions

Centrality dependence : RHIC vs LHC

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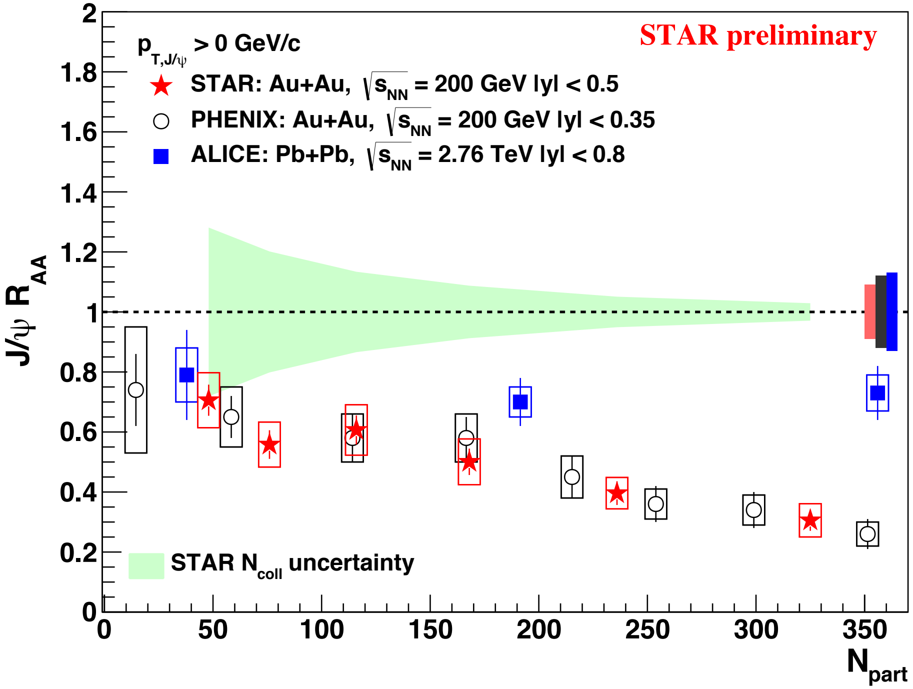
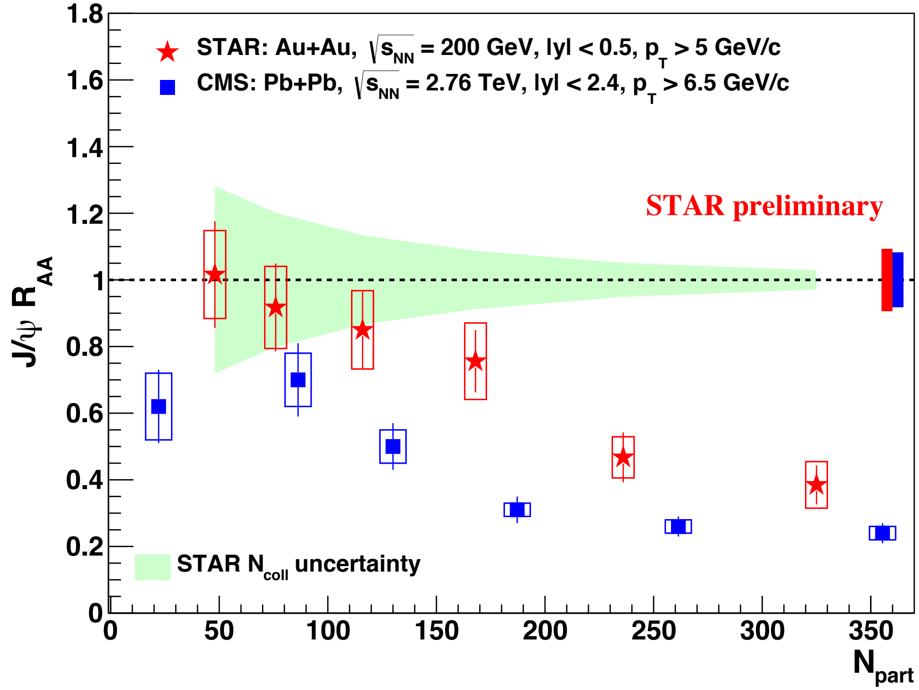


p_T > 5 GeV/c

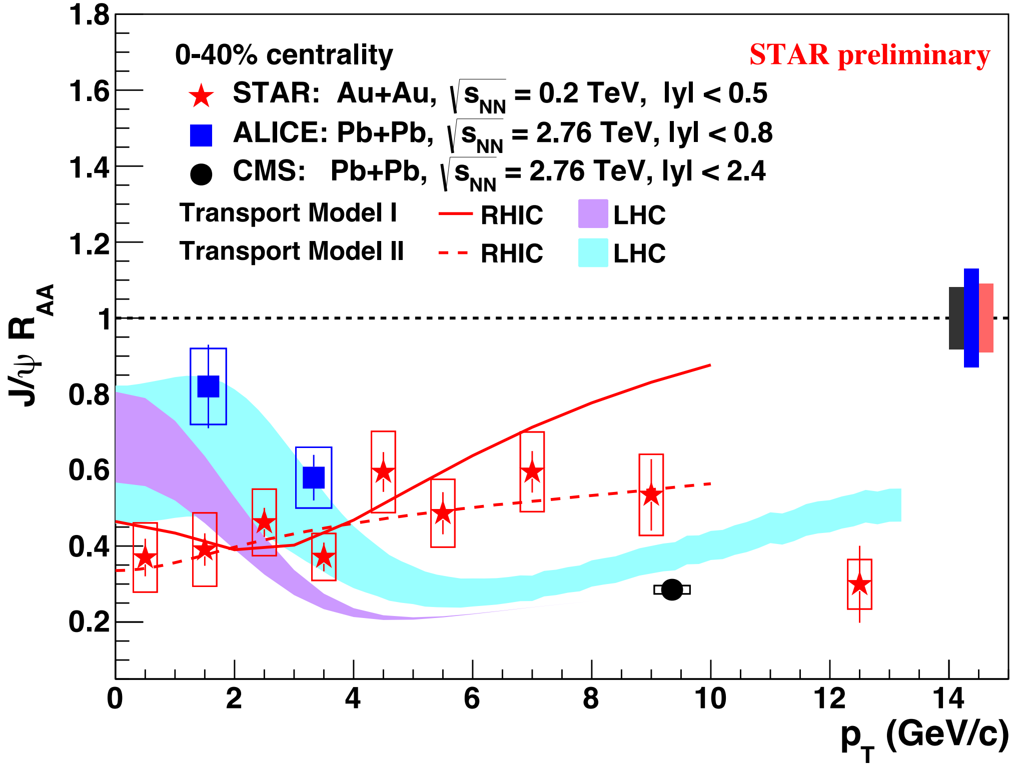
CMS: JHEP 05 (2012) 063



- STAR data are consistent with PHENIX with better statistical precision for p_T > 0 GeV/c
- p_T > 0 GeV/c : more suppressed at RHIC in central collisions
- High p_T : less suppressed at RHIC in all centralities

Transport Models

Transport model:
Model I at RHIC: PLB 678 (2009) 72
Model I at LHC: PRC 89 (2014) 054911
Model II at RHIC: PRC 82 (2010) 064905
Model II at LHC: NPA 859 (2011) 114



Model I :
Tsinghua Group
Model II :
TAMU Group

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

- Transport models including **dissociation and regeneration effects** qualitatively describe p_T dependence shape
- Model I : below data at low-p_T for LHC and shows different trend at high p_T for RHIC

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p_T > 0 GeV/c

ALICE : PLB 734 (2014) 314
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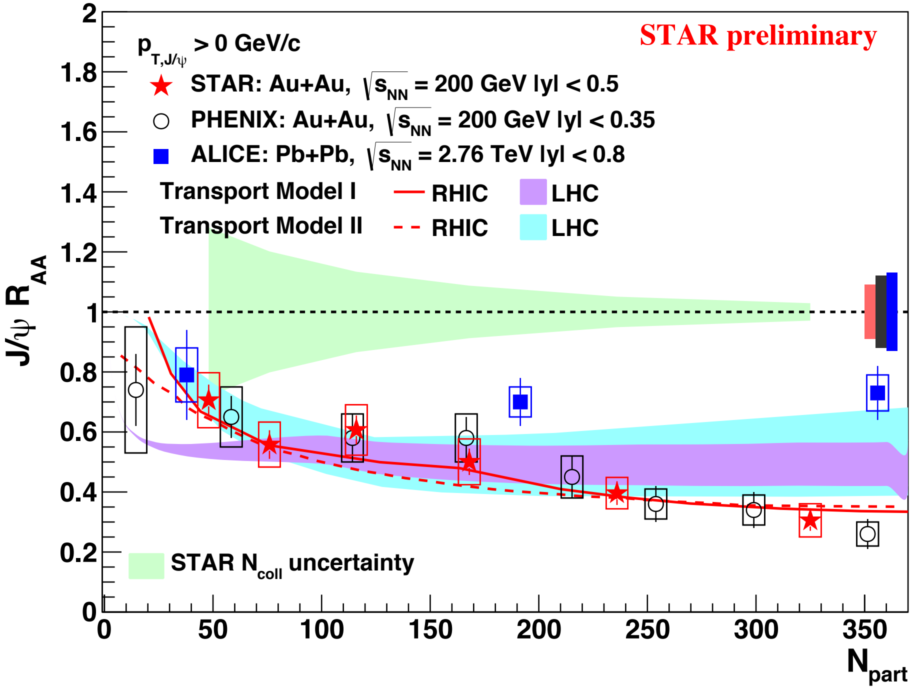

- p_T > 0 GeV/c : both models can describe centrality dependence at RHIC, but tends to overestimate suppression at LHC

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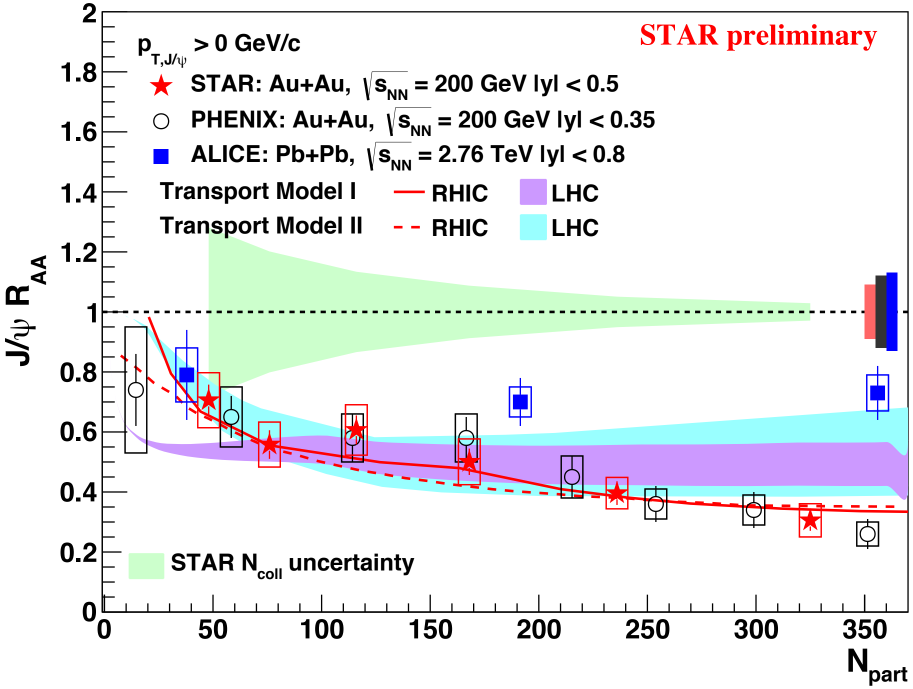
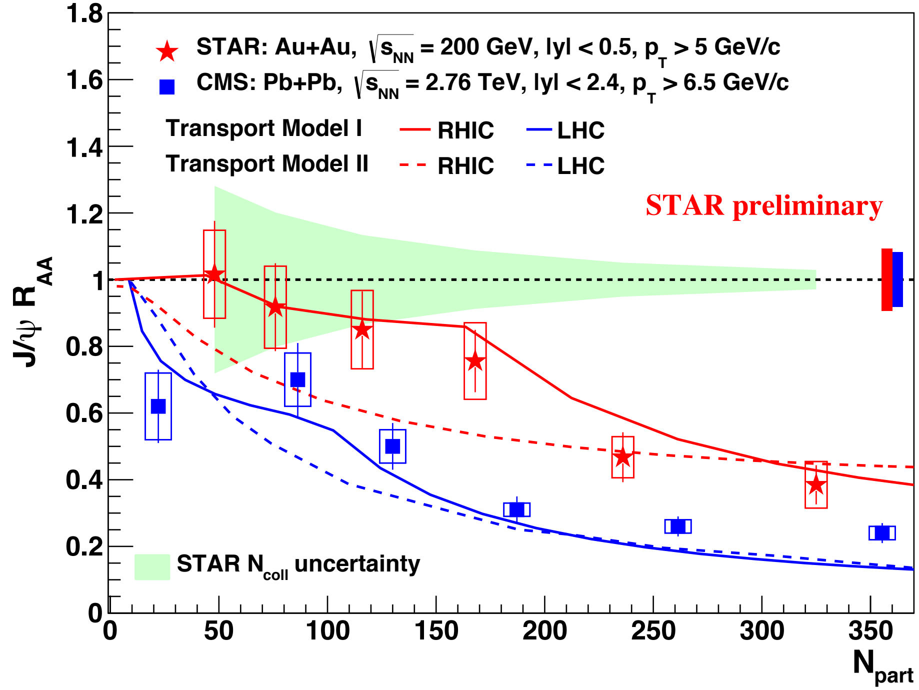


p_T > 5 GeV/c

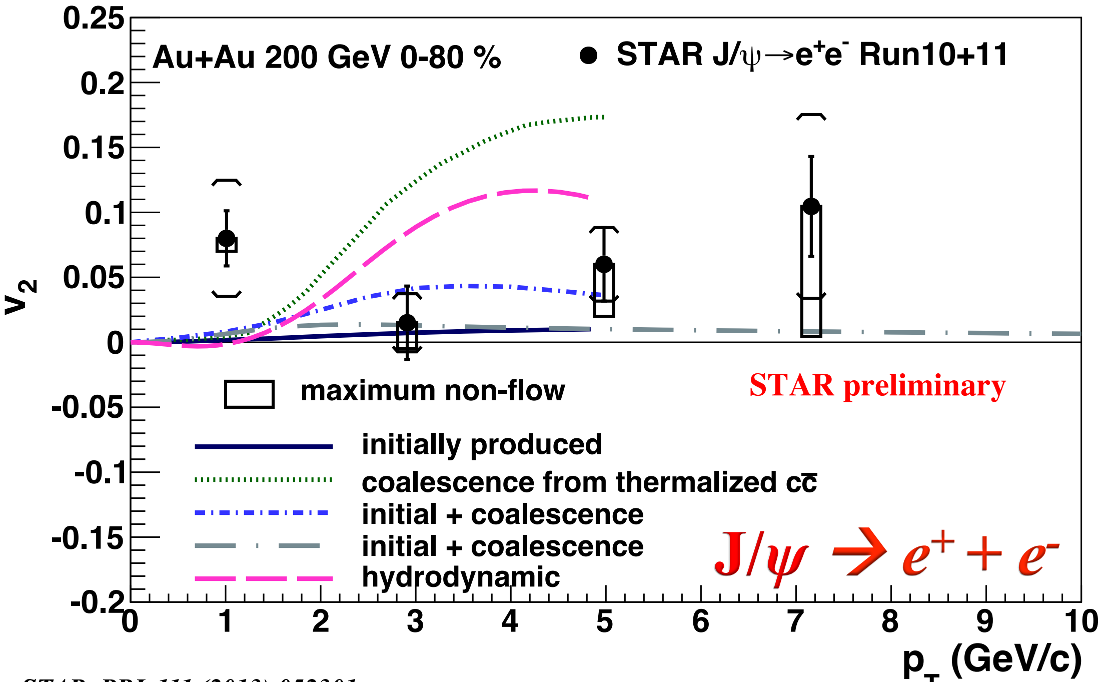
CMS: JHEP 05 (2012) 063



- p_T > 0 GeV/c : both models can describe centrality dependence at RHIC, but tends to overestimate suppression at LHC
- p_T > 5 GeV/c : there is tension among models and data

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



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)

- **For p_T above 2 GeV/c, v_2 is consistent with zero → *contribution of regenerated J/ψ is small***
  - Non-flow effects estimated using J/ψ-h correlation in pp collision can account for possible deviation of v_2 from zero at high p_T

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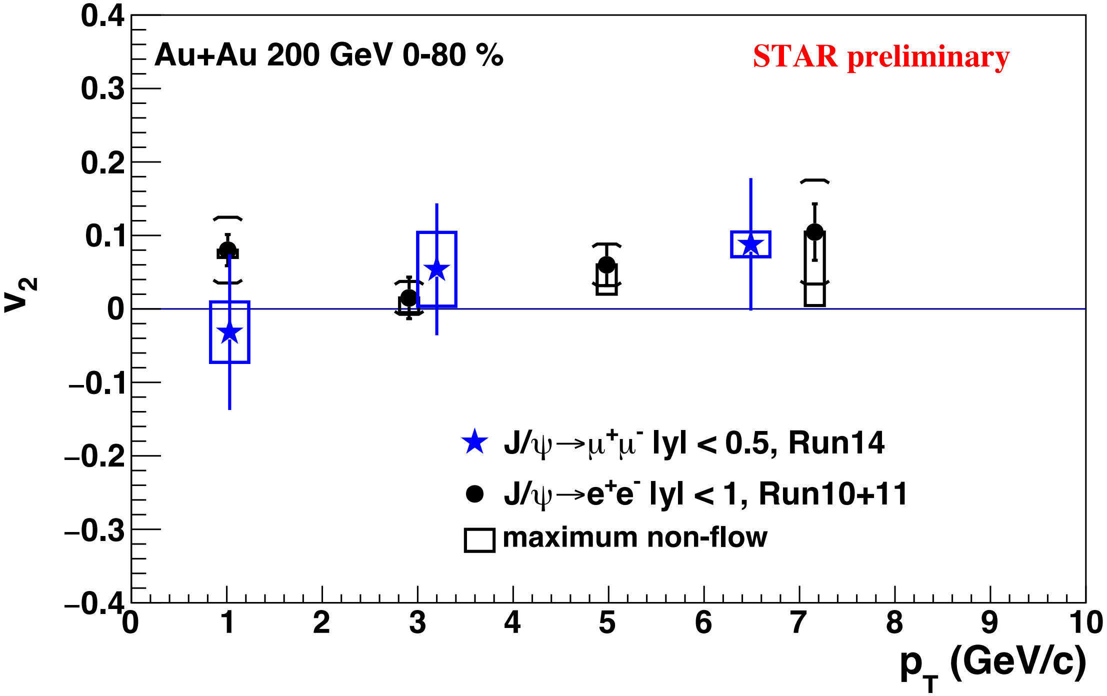
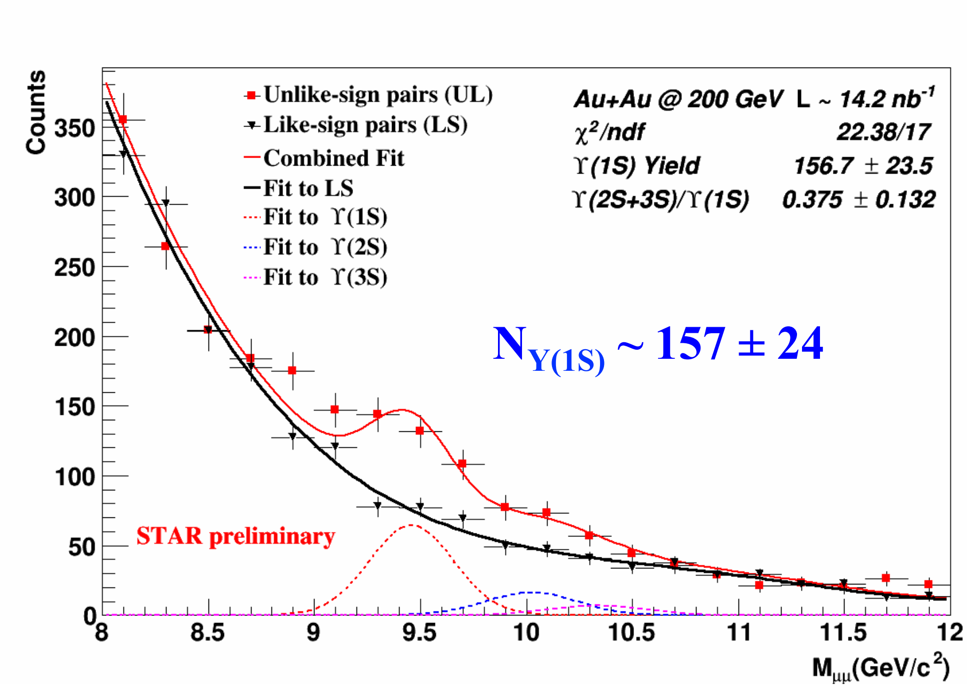
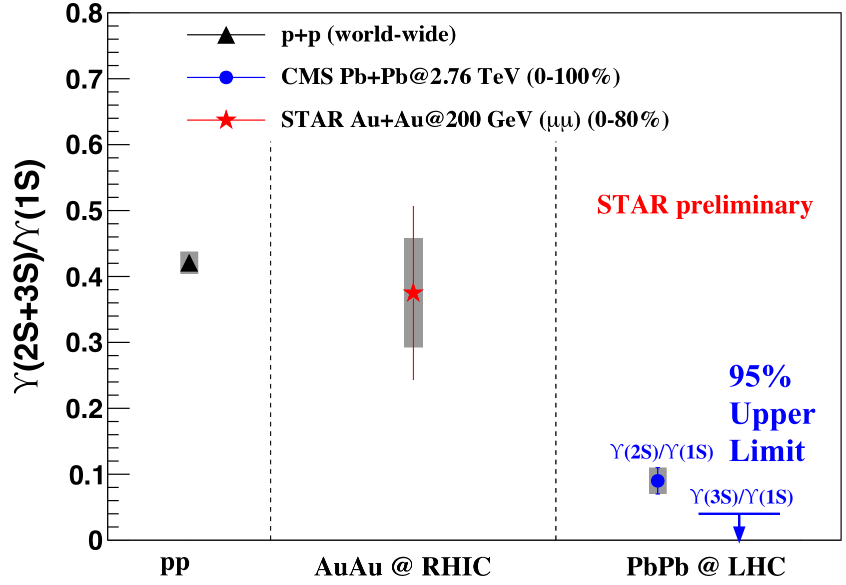


- **Consistent results from di-muon channel within large error bars**

Υ(2S+3S)/Υ(1S) ratio





World-wide PRC 88(2013) 067901
CMS : PRL 109(2012) 222301
CMS : JHEP 04 (2014) 103

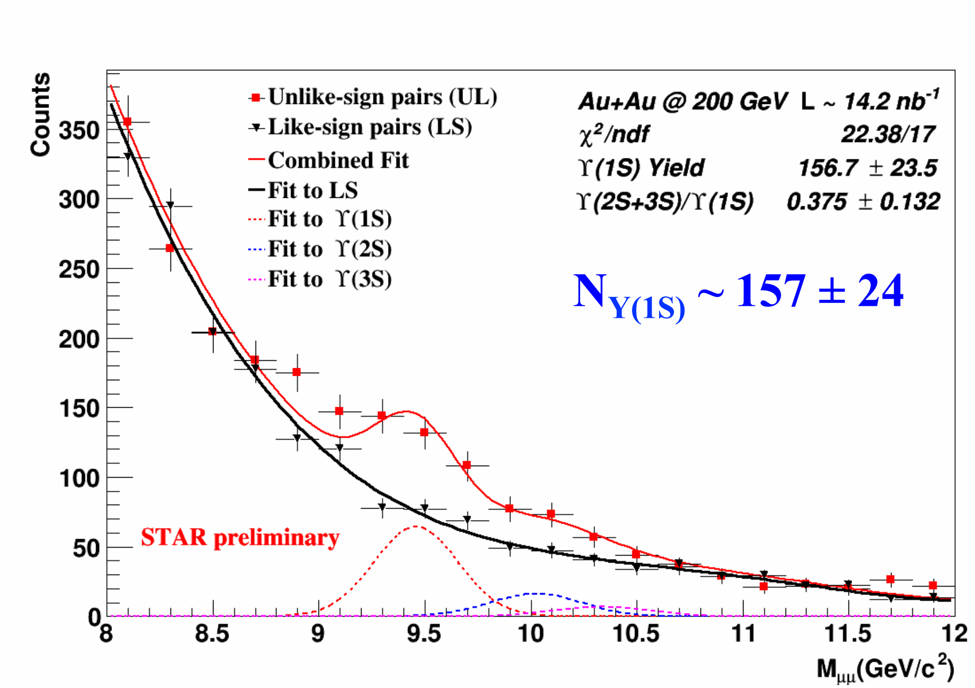
- **Signs of Υ(2S+3S) from the di-muon channel**
  - Challenging for di-electron channel due to Bremsstrahlung
- Hint of less melting of Υ(2S+3S) at RHIC than at LHC

Summary

- **First J/ψ and Υ measurements via di-muon channel at mid-rapidity at RHIC**
- **p+p collisions at $\sqrt{s}$ = 500 GeV**
  - Inclusive J/ψ cross section can be described by CGC+NRQCD & NLO NRQCD for $0<p_T<20$ GeV/c
- **Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV (Run 14 full statistics)**
  - Clear J/ψ suppression above 5 GeV/c in central collisions → Dissociation
  - J/ψ R_{AA} can be qualitatively described by transport models including dissociation and regeneration. However there is tension at high p_T
  - Updated J/ψ v_2 in di-electron channel using Run10+11 data → favors small contribution from regeneration above 2 GeV/c
  - Hint of less melting of Υ(2S+3S) at RHIC compared to that at LHC
- **Similar amount of data from Run16 on tape. Stay tuned!!**

Back Up

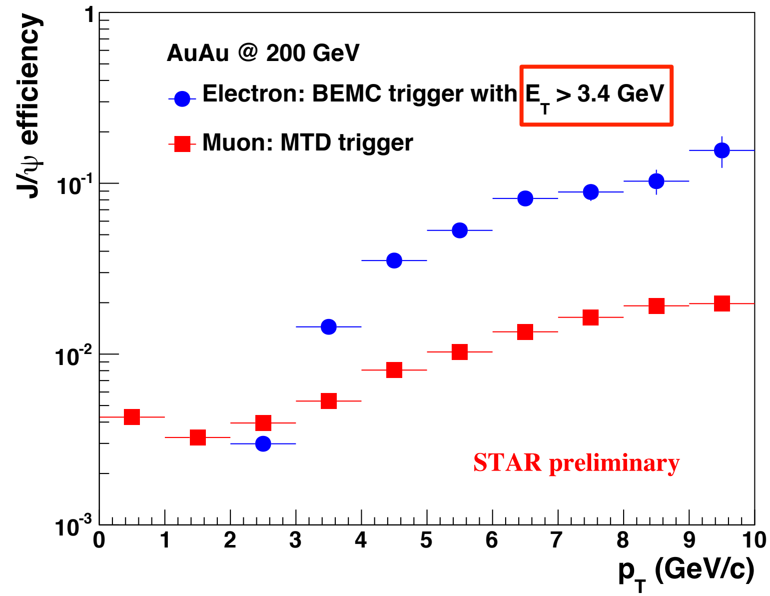
ϒ(2S+3S)/ϒ(1S) ratio



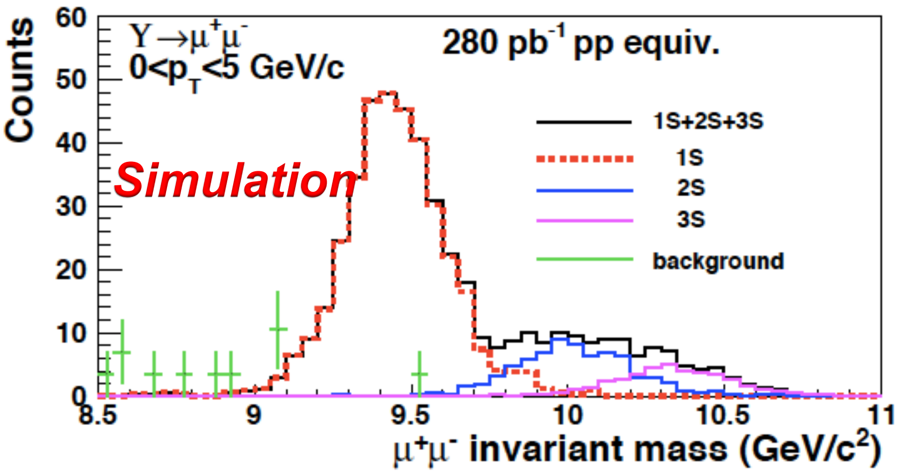
- **Fit the like-sign and unlike-sign simultaneously:**
  - Mean of ϒ is fixed to PDG value, while width is determined from simulation.
  - Ratio of ϒ(2S)/ϒ(3S) is fixed to pp value, and shape of bb and Drell-Yan background is estimated using PYTHIA

Muon Telescope Detector (MTD)

- **Relatively high efficiency for J/ψ at low p_T** → cover wide kinematic range



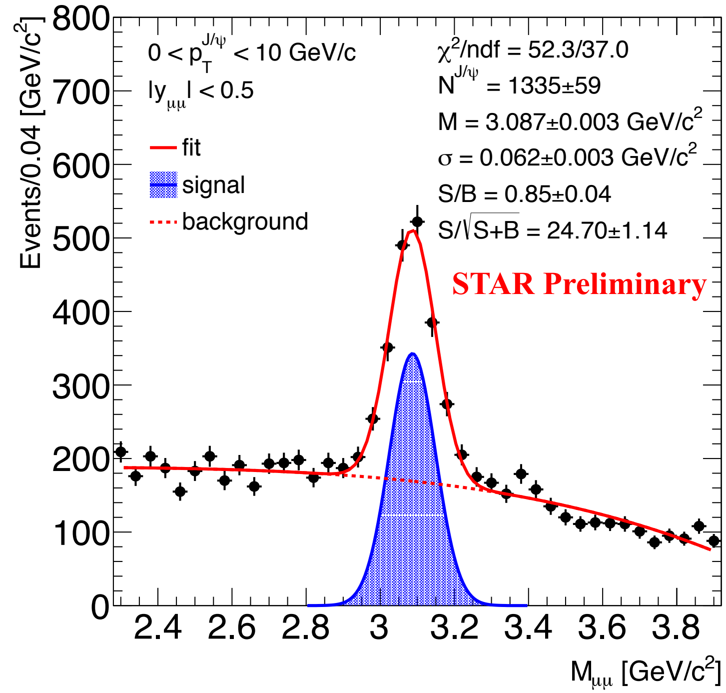
- **Separate Υ(2S+3S) from Υ(1S)**
- **Potential to separate Υ(2S) and Υ(3S)** states as muons suffer less from bremsstrahlung



Run13 p+p 500 GeV Analysis details

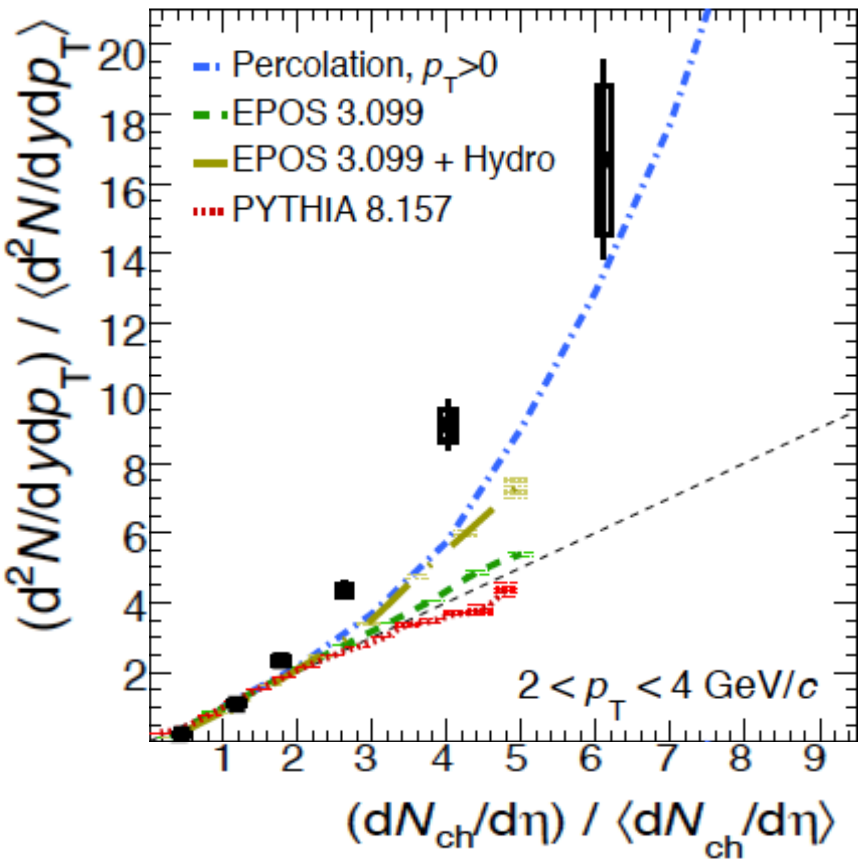
- Decay channel: J/ψ → $\mu^+ + \mu^-$
- Data set: p+p collisions at 500 GeV taken in 2013
- MTD dimuon trigger: two hits in MTD
  - *Sampled integrated luminosity* ~ 28.3 pb^{-1}
- **Muon identification**
  - Match TPC tracks to MTD
  - Require z residual below 20 cm
- Background: fitting Gaussian (signal) & pol3

➢ Signal extraction: Integral of Gaussian



A closer look: event multiplicity dependence

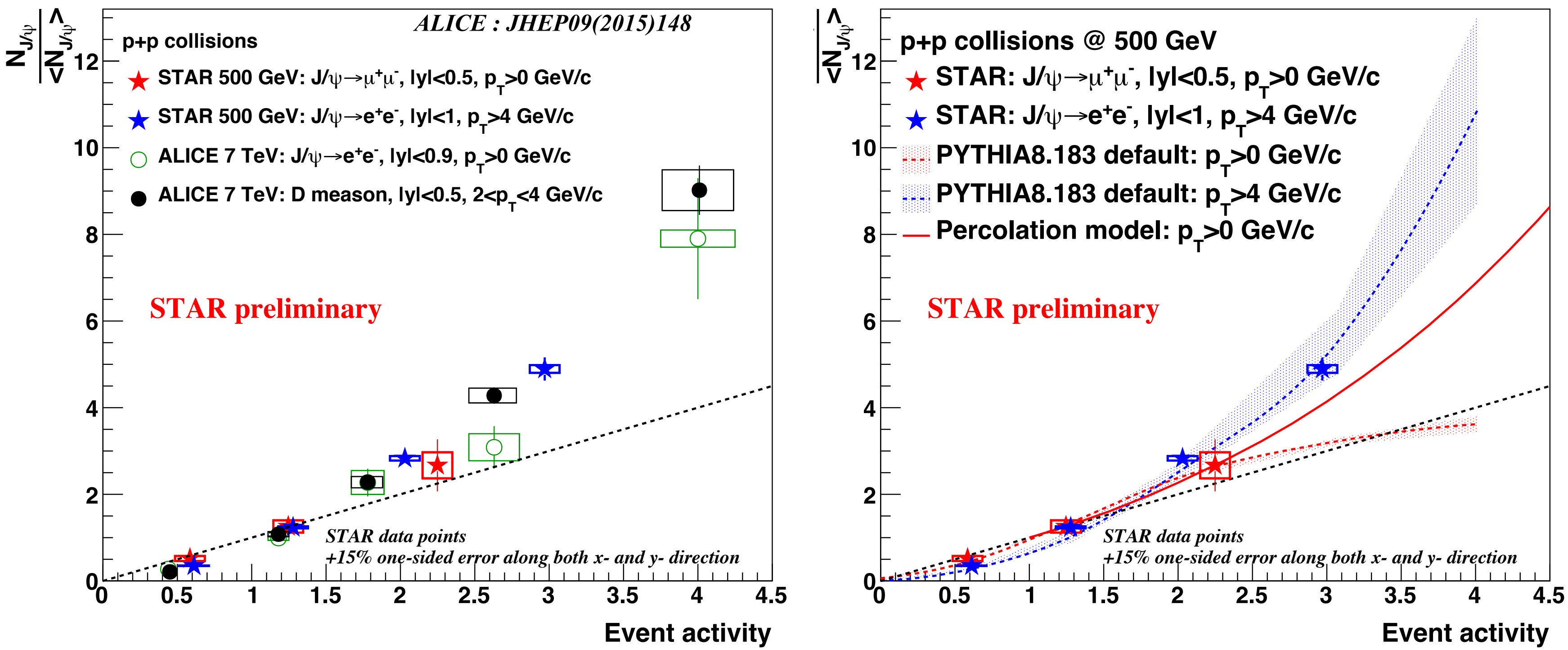
ALICE pp @ 7 TeV *arXiv:1505.00664*



- Stronger-than-linear rise of open charm production vs event activity.
- Similar behavior seen for inclusive J/ψ at both mid- and forward-rapidity.
- Several ideas on the market:
  - PYTHIA 8: c and b quarks produced in Multi-Parton-Interaction -> **underestimate yield at large multiplicity**
  - Percolation model: string screening -> **quadratic rise at high multiplicity**
  - Hard process is associated with larger gluon radiation

- Collective effects in high-multiplicity pp collisions?
- Do we see similar or different behavior at RHIC?

J/ψ yield vs event activity



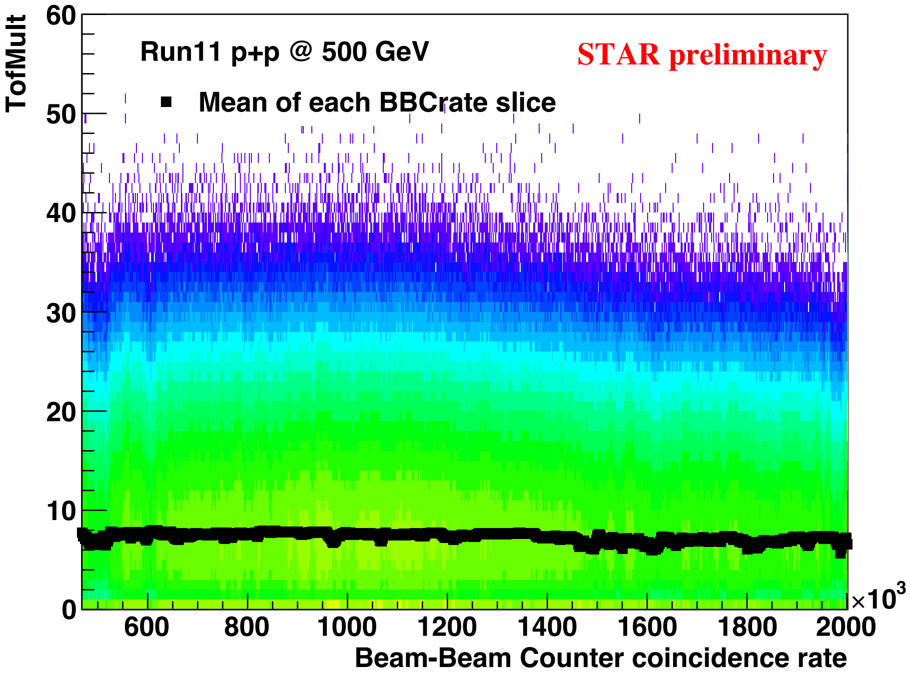
- **Stronger-than-linear** growth for relative J/ψ yield → **Soft and hard processes are correlated**
- Different trends for low and high p_T J/ψ
- **PYTHIA8** and **Percolation model** reproduce trends in data
- Measurements at high multiplicities can help distinguish different models

Characterize event activity

Multiplicity of TOF matched tracks

$|\eta| < 0.9$

→ $$\frac{\text{TofMult}}{<\text{TofMult}>}$$



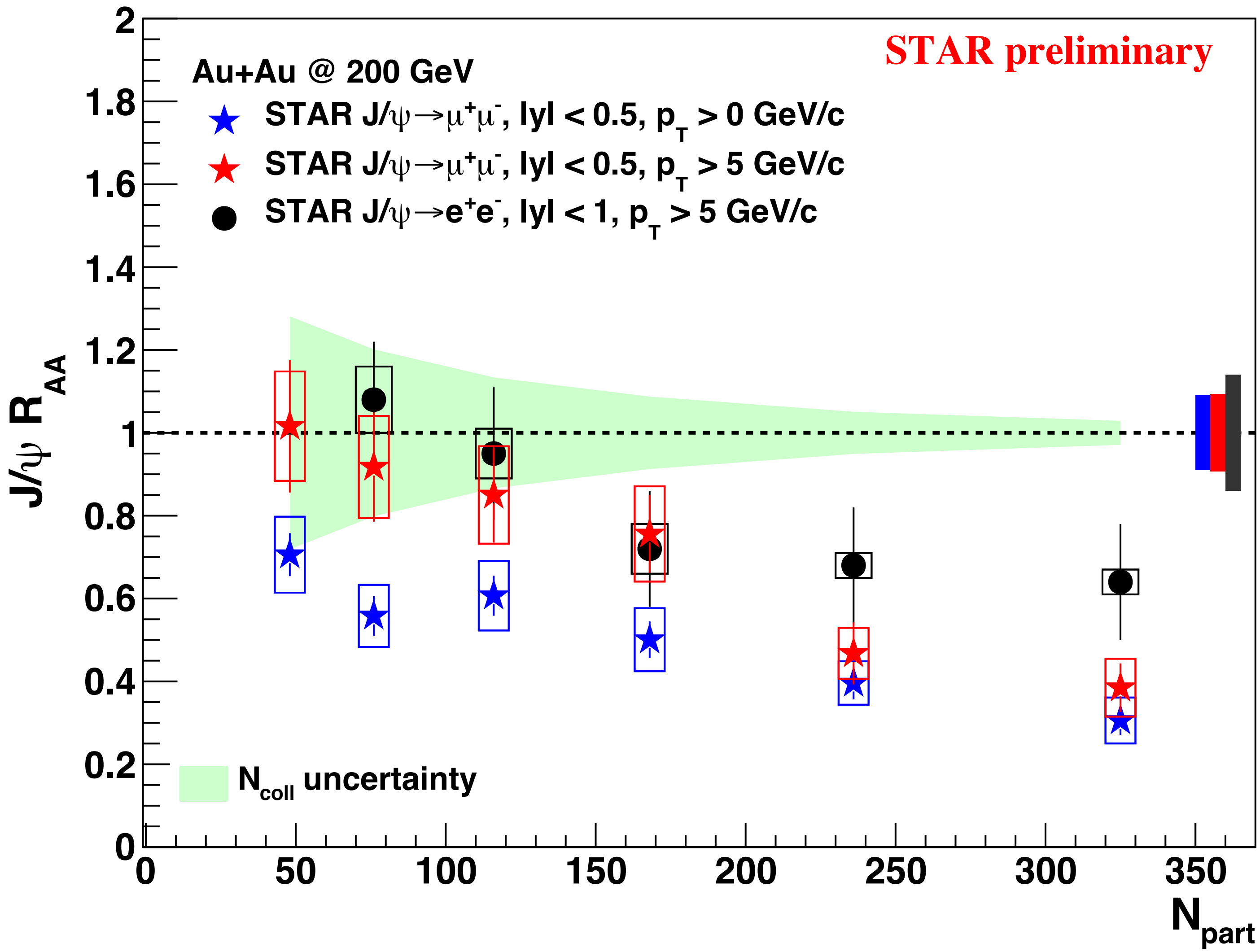
- **Insensitive to pile-up effects**

Run14 Au+Au 200 GeV Analysis details

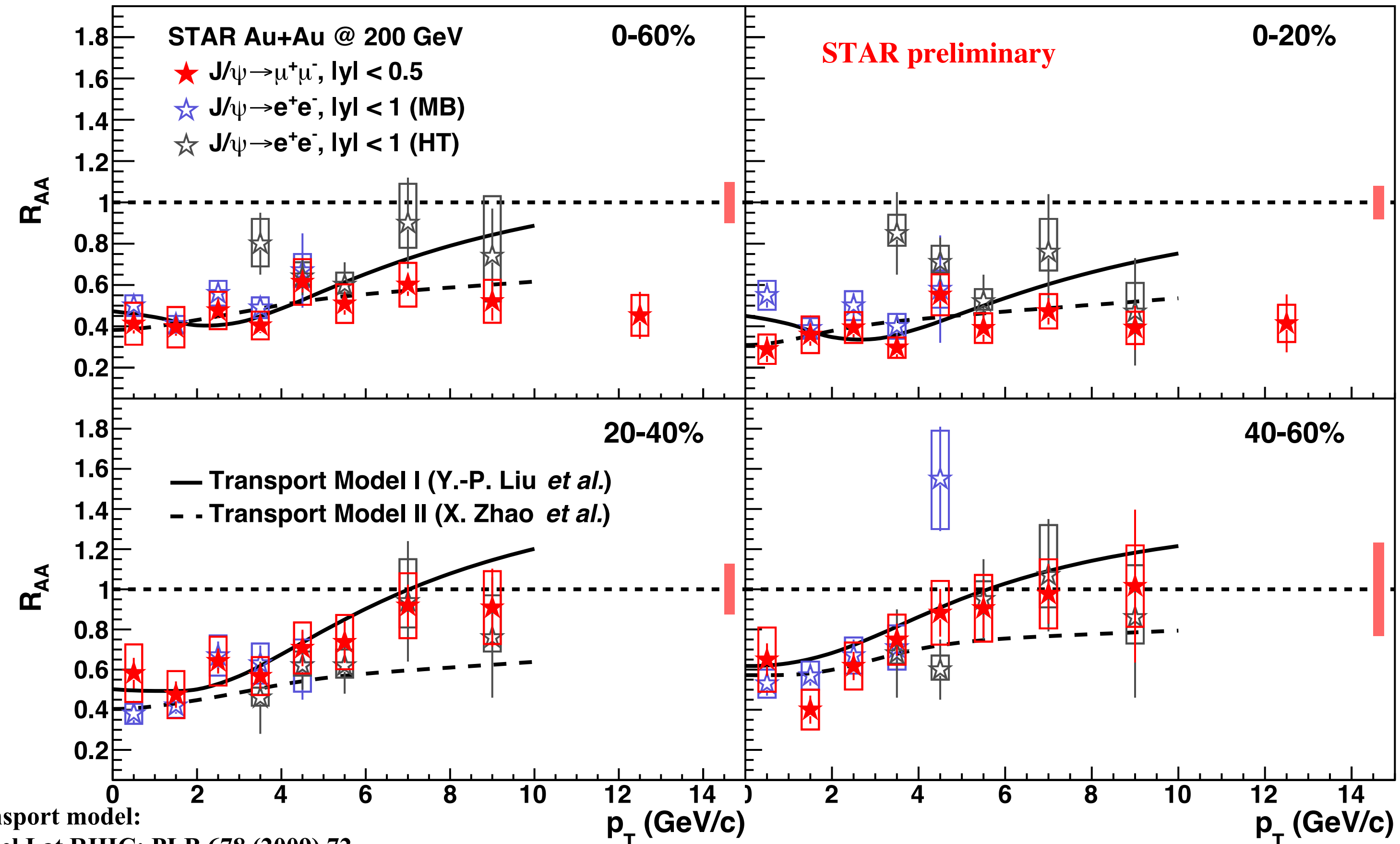
- Decay channel: J/ψ, Υ → $\mu^+ + \mu^-$
- **Dimuon trigger**: two hits in MTD
- Data set: Au+Au collisions at 200 GeV recorded in 2014
  - Integrated luminosity ~ 14.2 nb^{-1}
  - Equivalent or more data will be taken in 2016

- **Muon identification cuts**
  - Energy loss measurement by TPC
  - Match TPC tracks to MTD
    - Distance between MTD hits and projected TPC tracks along both z and φ directions
    - Time difference between MTD measured time and expected travel time of muons

Comparison to di-electron



J/ψ R_{AA} vs p_T : STAR vs Transport Models



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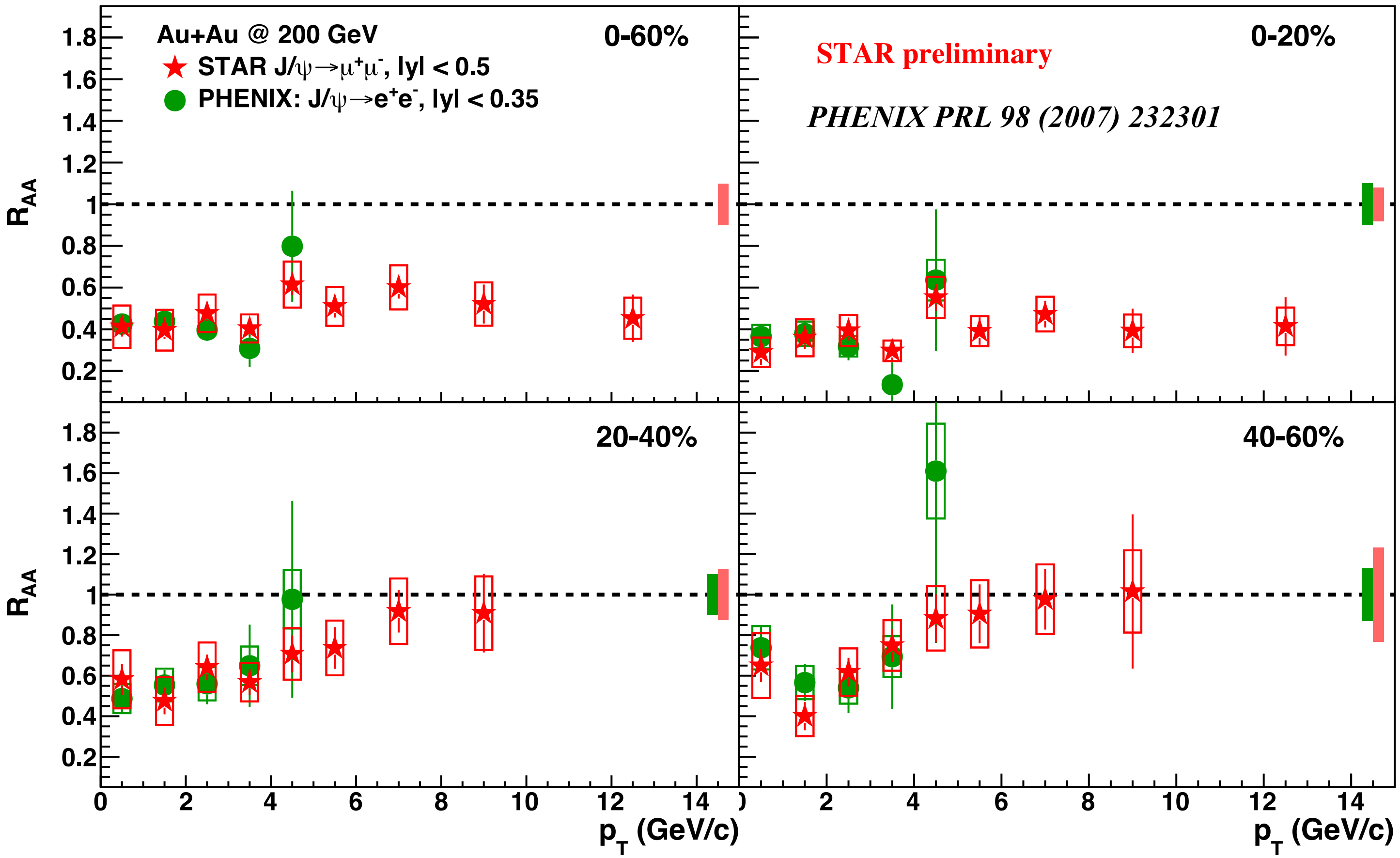
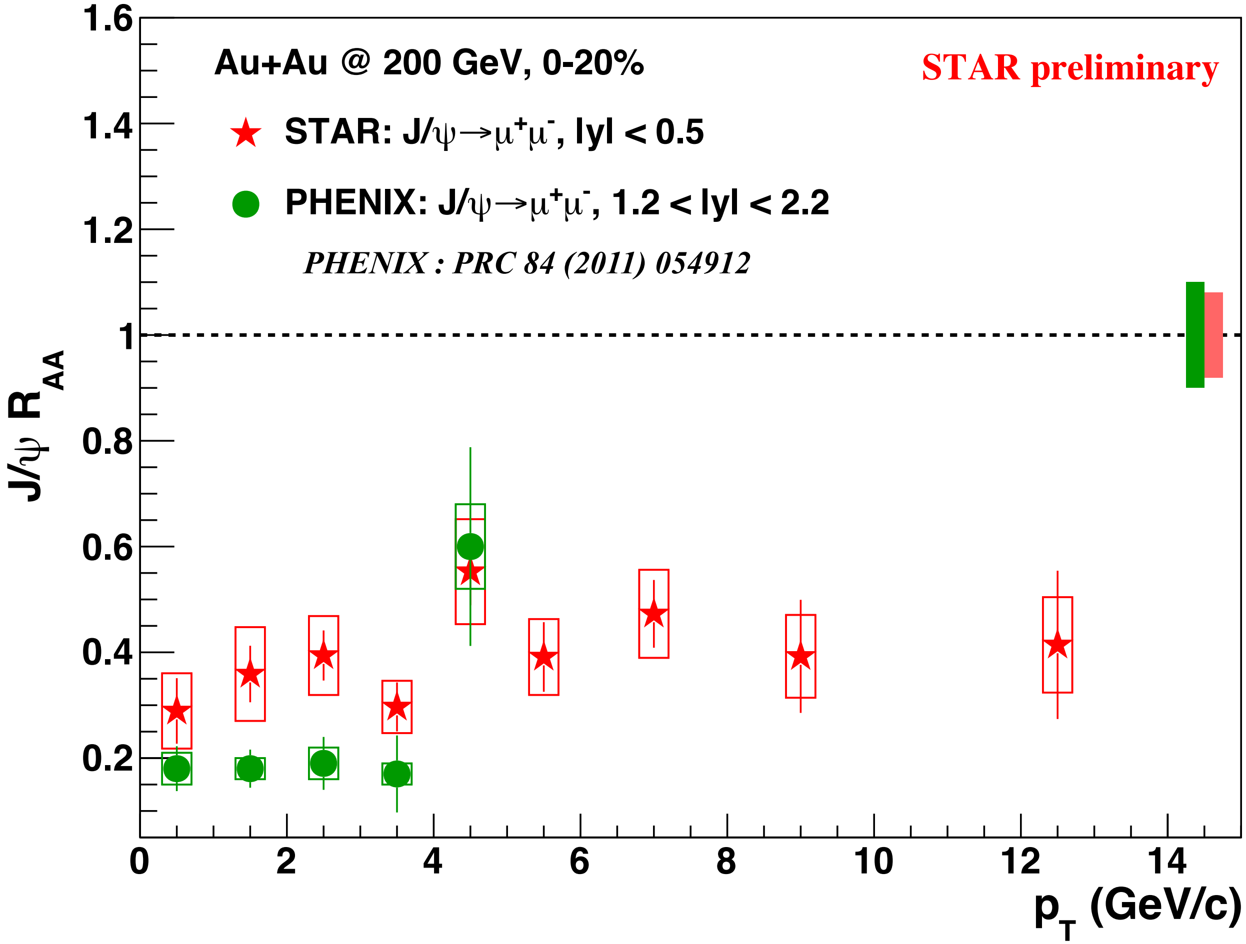
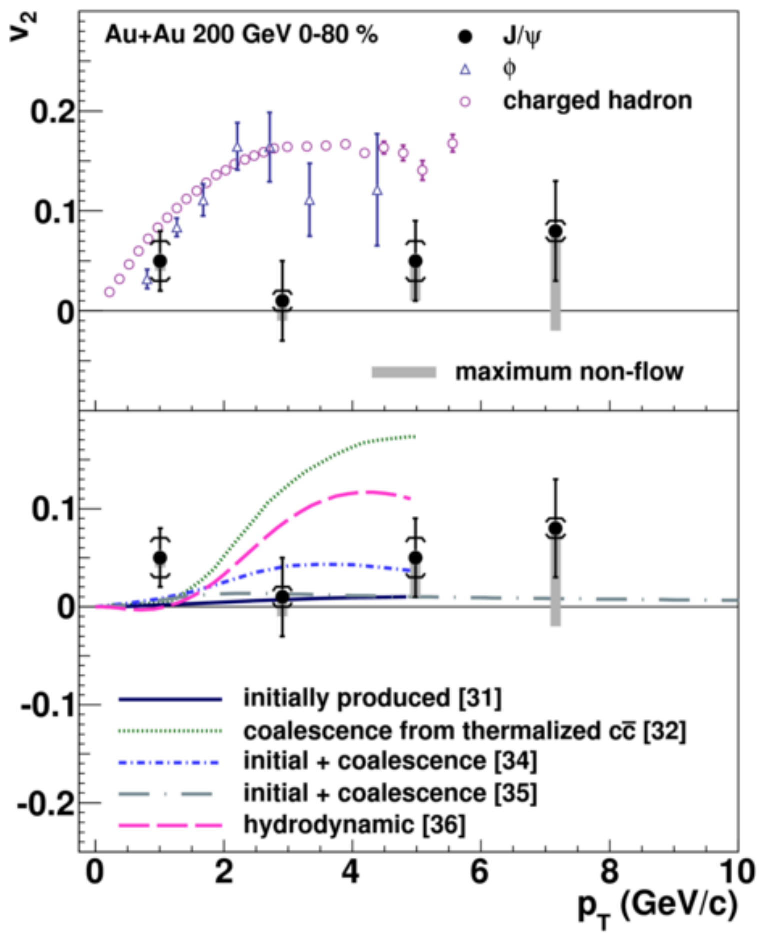
J/ψ R_{AA} vs p_T : STAR vs PHENIX



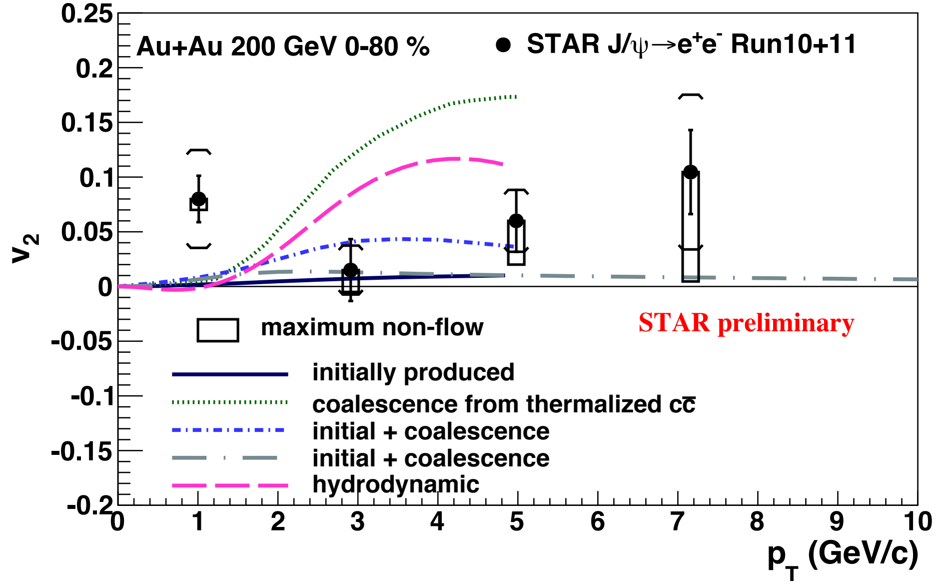
J/ψ R_{AA} vs p_T : Mid vs Forward rapidity



Compare J/ψ v_2



STAR, PRL 111 (2013) 052301



- By combining published results with Run11 analysis, the statistical error bar is reduced by a factor of $\sqrt{2}$.
- Additional systematic uncertainty is assigned due to J/ψ yield extraction.