

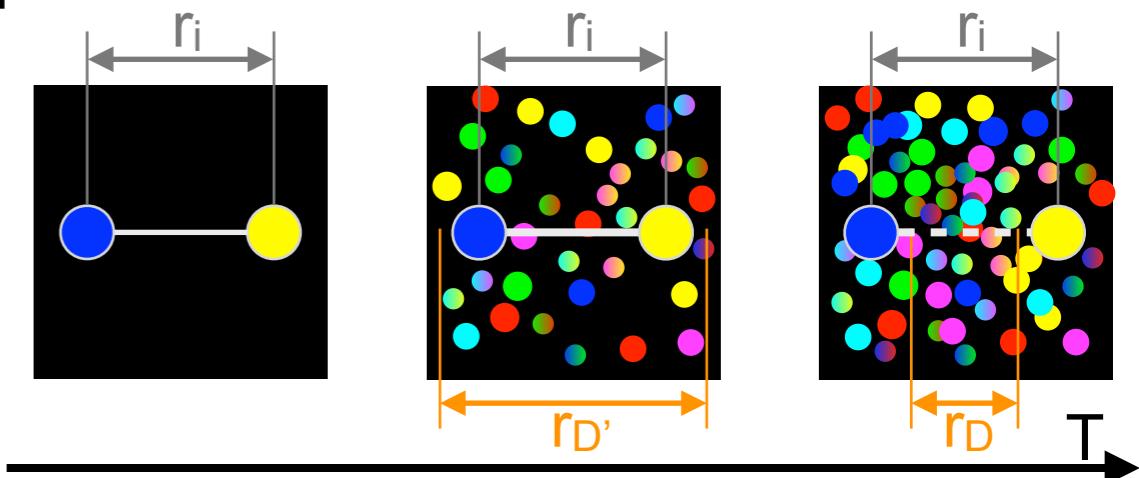
Hidden Heavy Flavor

Javier Castillo Castellanos
CEA Saclay

Quarkonium suppression

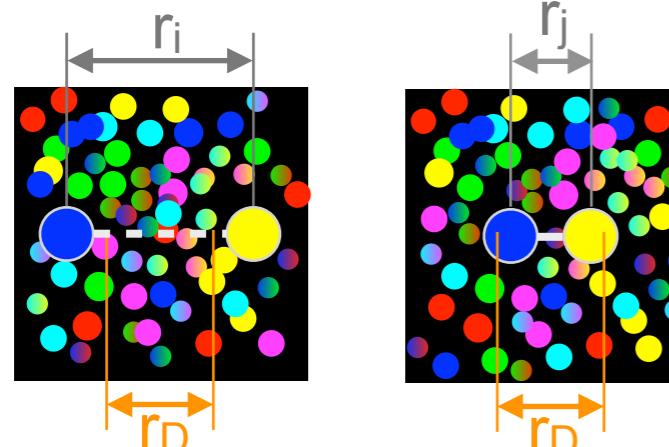
- Quarkonium suppression

- In a QGP, a Q-Qbar pair could be colour-screened by the surrounding coloured quarks and gluons [PLB 178 (1986) 416]
- Quarkonia should be suppressed by the QGP
- The suppression increases with the QGP temperature



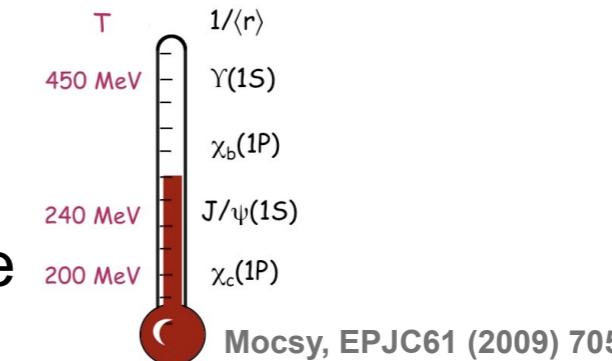
- Sequential suppression

- The survival probability of the quarkonium state depends on its binding energy (or radius) [ZPhysC 51 (1991) 209]
- Different quarkonium states have different survival probabilities



- Could provide an estimate of the QGP temperature

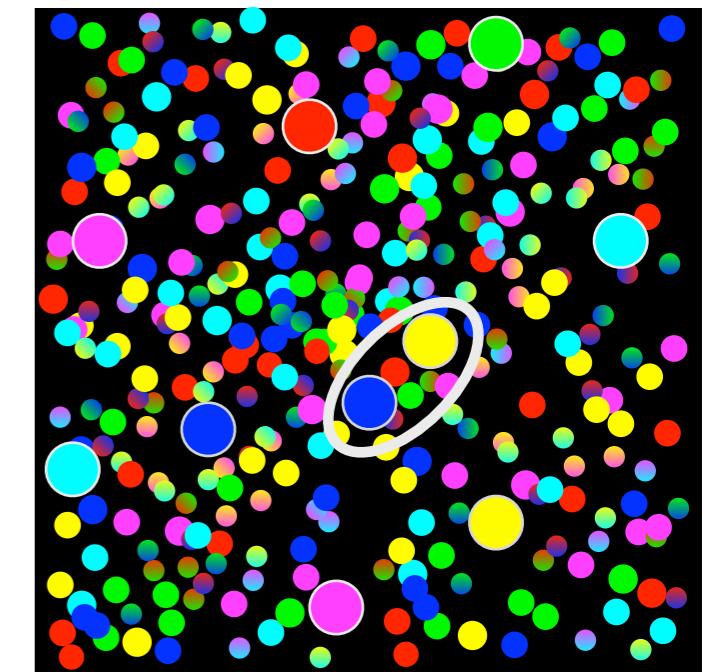
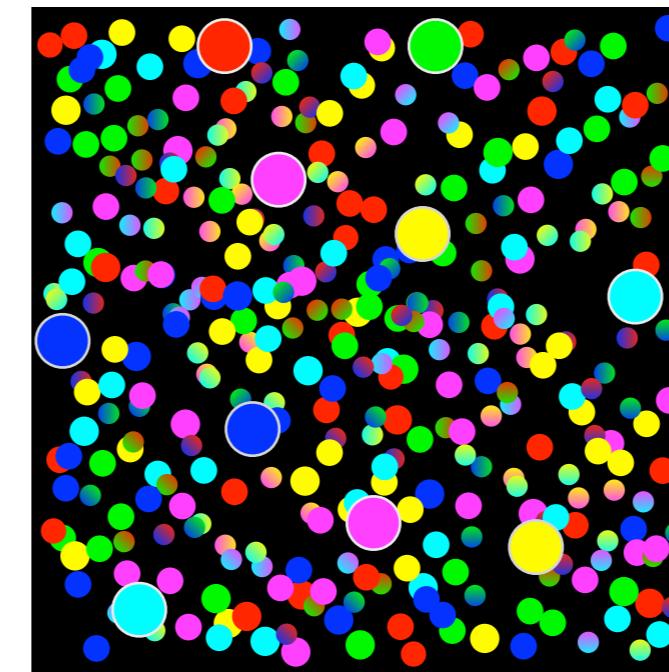
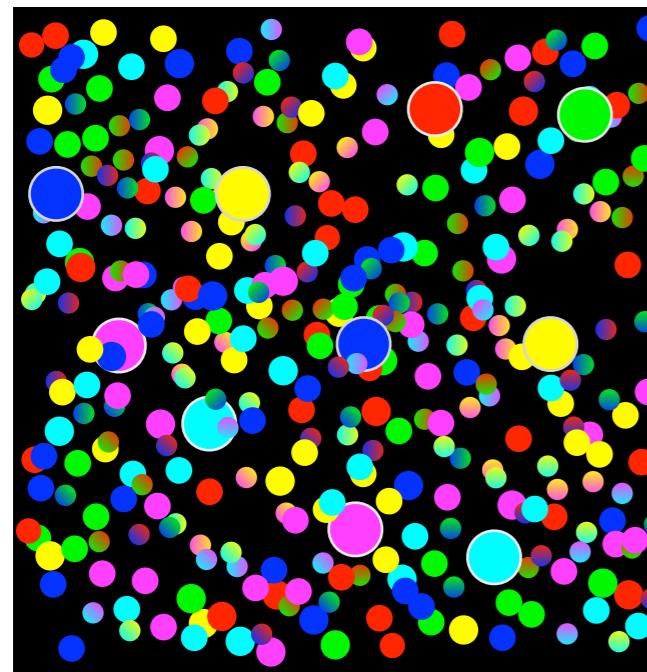
State	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	>4.0	1.76	1.60	1.19	1.17



Mocsy, EPJC61 (2009) 705

... or Quarkonium enhancement

- Quarkonium regeneration
 - If the initial number of Q-Qbar pairs is large
 - If heavy quarks thermalise in the QGP
 - Then quarkonia can form at the phase boundary by statistical hadronization [PLB 490 (2000) 196] or during the QGP evolution [PRC 63 (2001) 054905] by heavy quark recombination

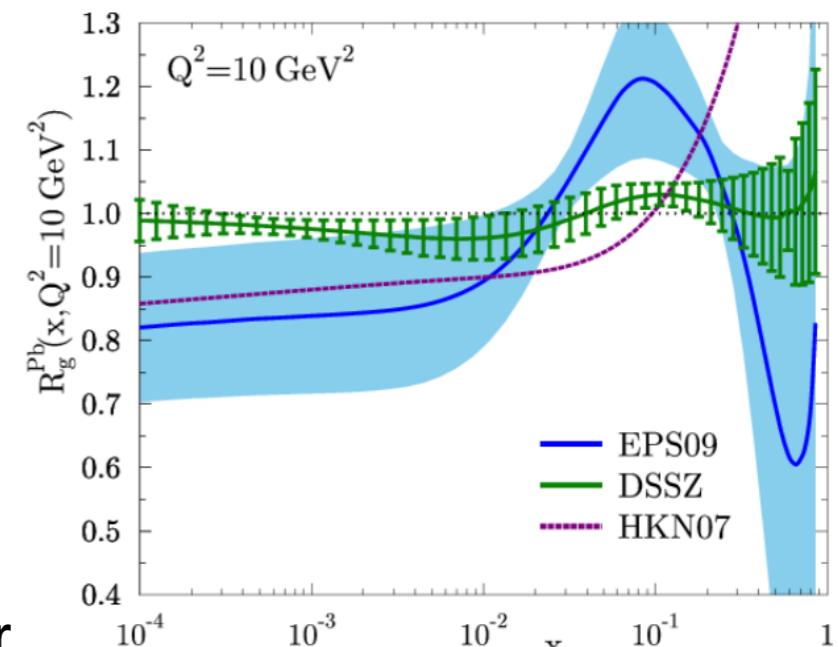


→ time

- Will compete with quarkonium suppression, possibly compensate or even exceed it
- Transport models implement a dynamical rate equation of quarkonium suppression and regenerations by gluon interaction
 - [PLB 678 (2009) 72] [NPA 859 (2011) 114]

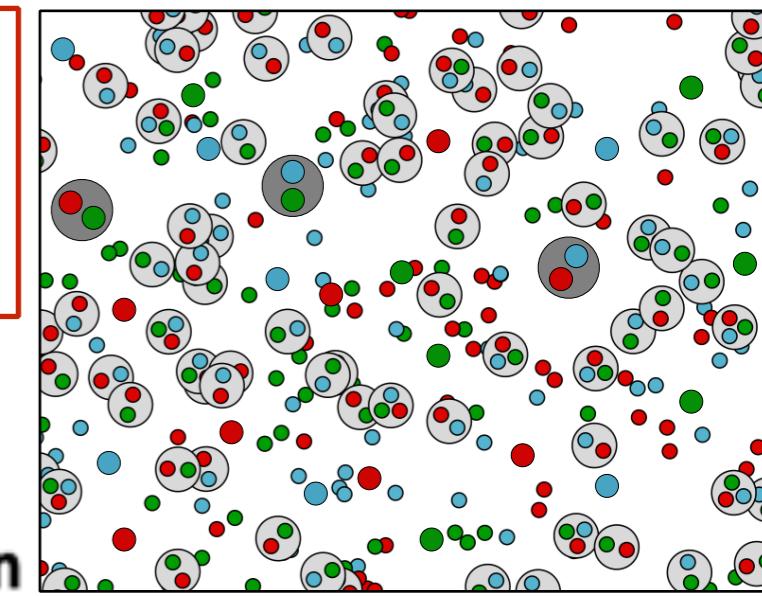
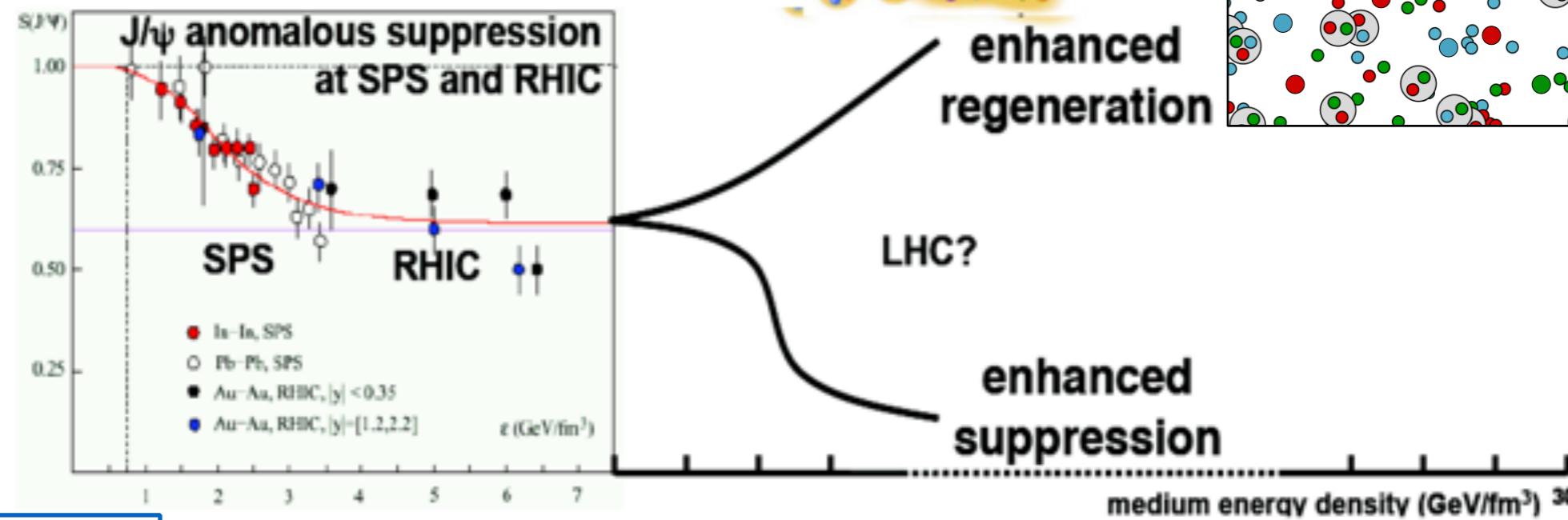
Cold Nuclear Matter (CNM) effects

- In Pb-Pb collisions quarkonium production is also affected by Cold Nuclear Matter (CNM) effects
 - Modification of the Parton Distribution Functions in the nuclei with respect to free nucleons
 - Has been parametrised over the past years
 - Significant uncertainties and spread between different approaches
 - Saturation via Colour Glass Condensate (CGC)
 - Energy loss of partons producing the heavy quark pair
 - Latest developments consider coherent parton energy loss
 - Nuclear absorption (heavy-quark pair break-up)
 - Expected to be negligible at LHC energies
- p-A collisions used to study CNM effects in the absence of a hot medium



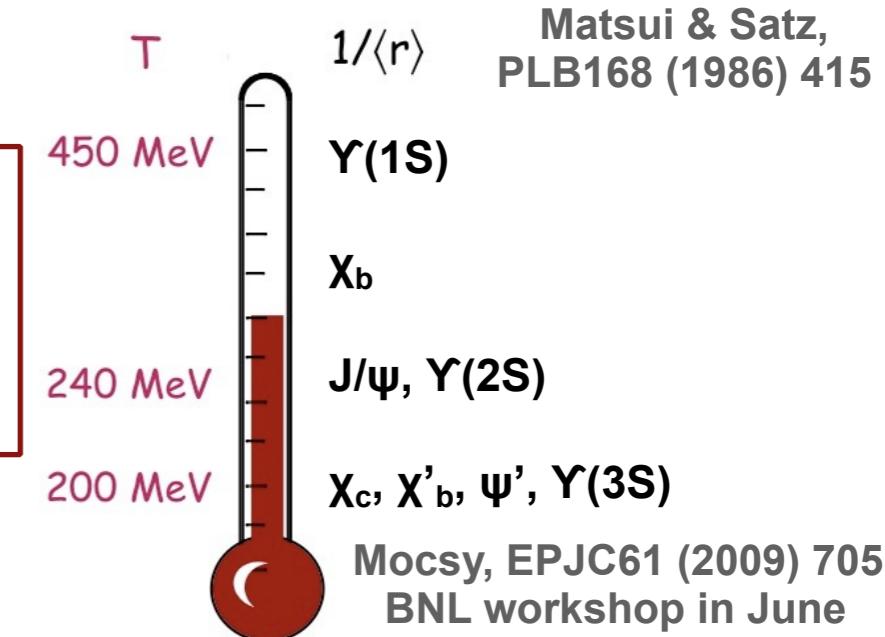
Quarkonia

If c-cbar pairs are abundantly produced and thermalize with the medium, recombination could compensate or exceed colour-screening suppression



“Cold Nuclear Matter” effects could alter the quarkonium yields: nuclear absorption, gluon shadowing, ...

Sequential quarkonium suppression by colour-screening could provide a measurement of the QGP initial temperature

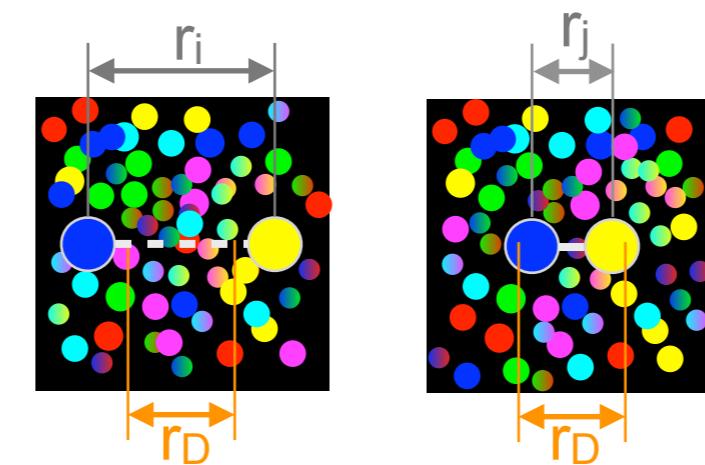


Outline

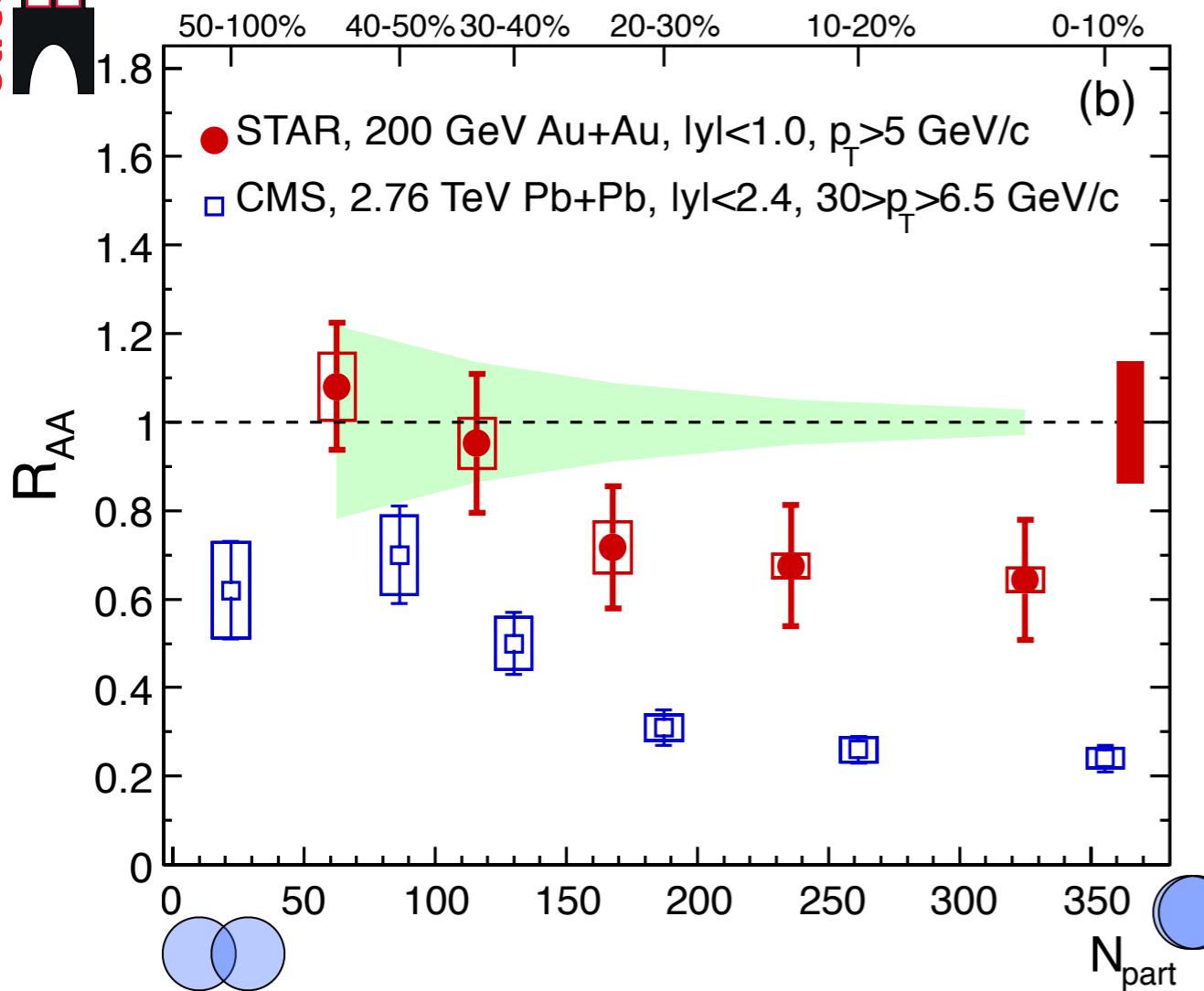
- Introduction
- Quarkonium suppression by the QGP
- Quarkonium regeneration in the QGP
- CNM effects on quarkonium production
- Summary



ABOUT QUARKONIUM SUPPRESSION

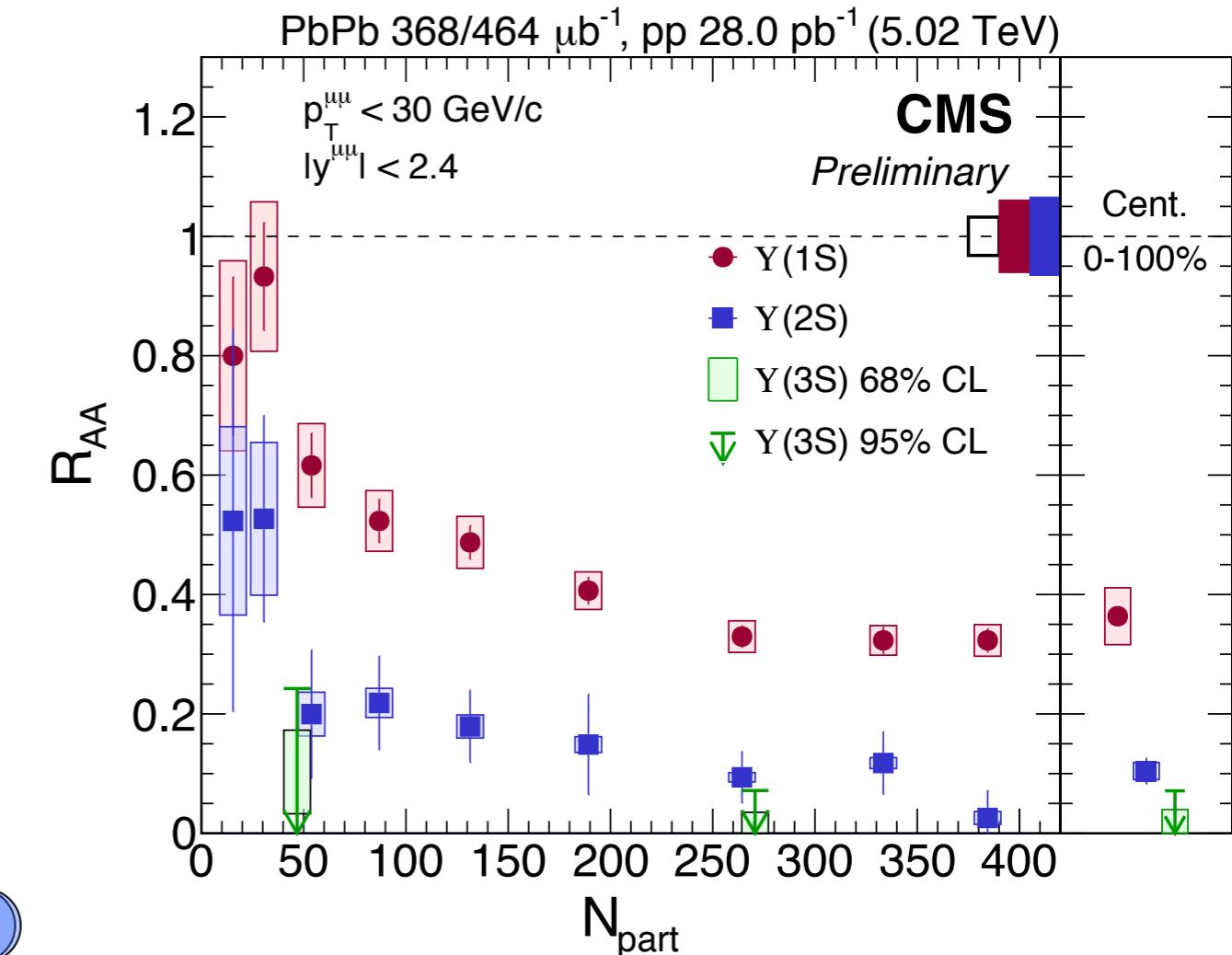


Suppression: figure of merit



- J/ψ at high p_T
 - Stronger suppression at LHC than at RHIC
 - Stronger suppression with higher energy density (or Temperature)

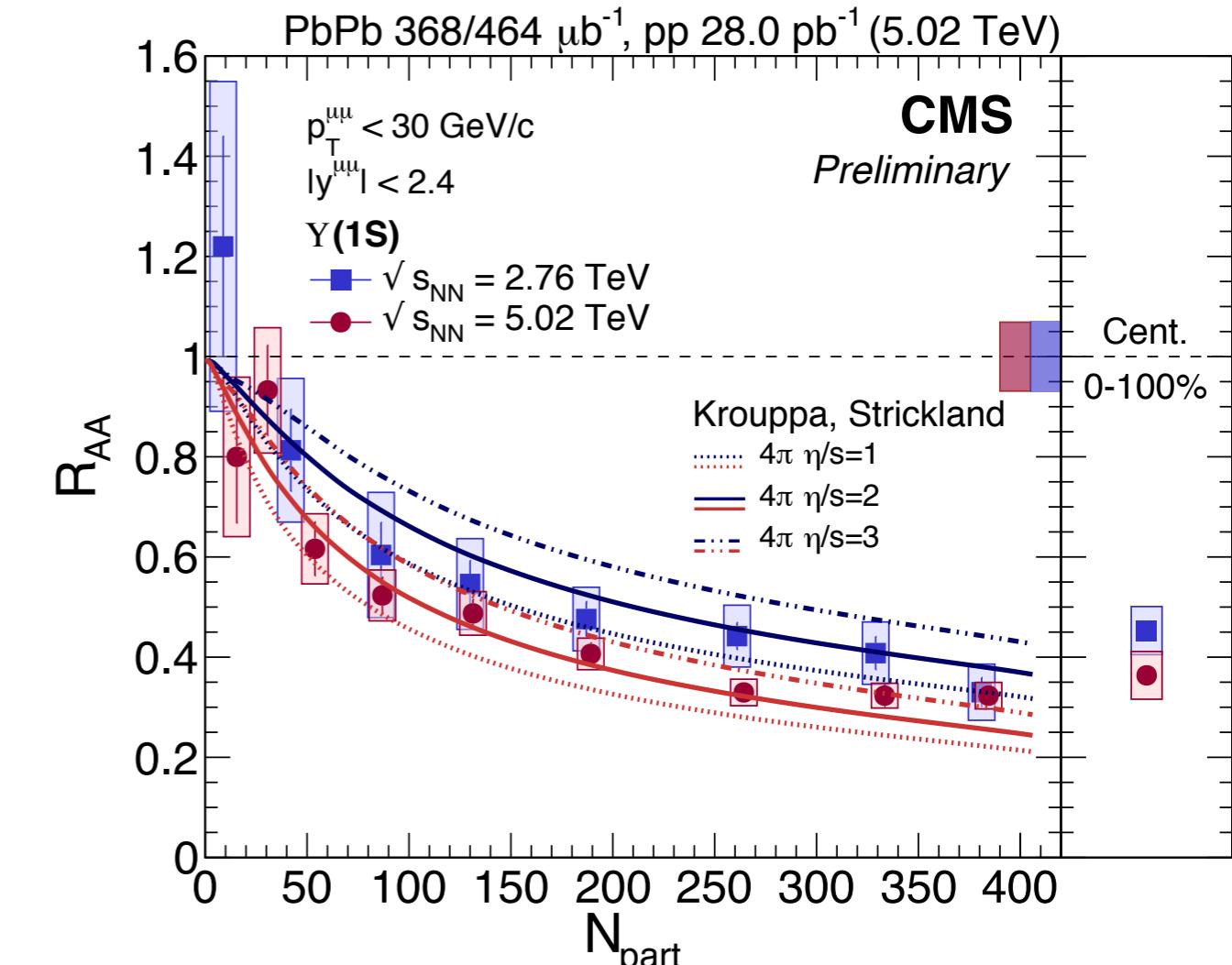
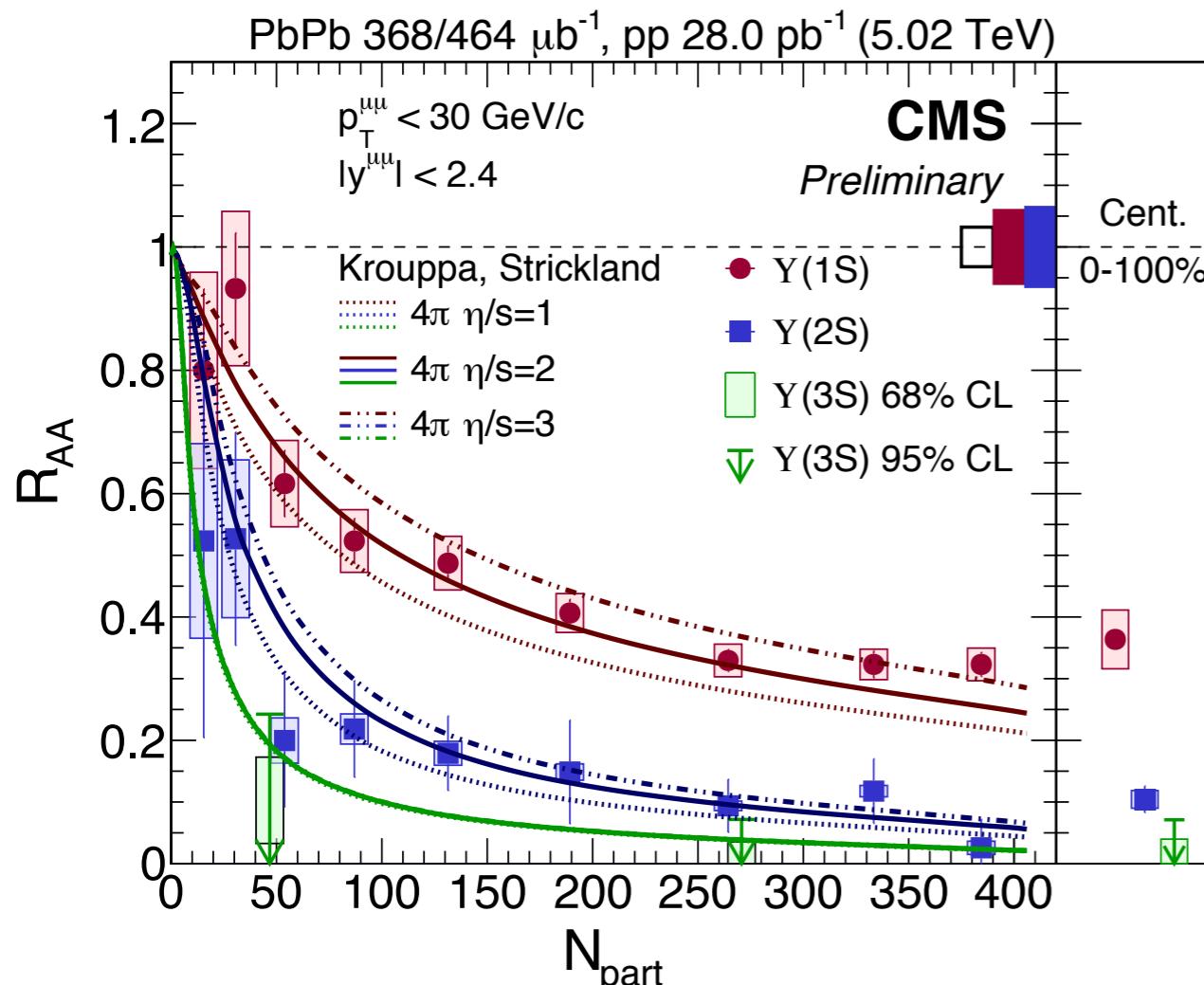
(High- p_T) Quarkonium suppression increases with increasing T
Weakly bound quarkonium states are more suppressed



- Υ suppression at the LHC
 - $R_{AA}(\Upsilon(1S)) > R_{AA}(\Upsilon(2S)) > R_{AA}(\Upsilon(3S))$
 - Observation of sequential suppression of Υ states at mid- y in Pb-Pb collisions at $\sqrt{s}_{NN} = 5.02 \text{ TeV}$

γR_{AA} @ LHC vs. models

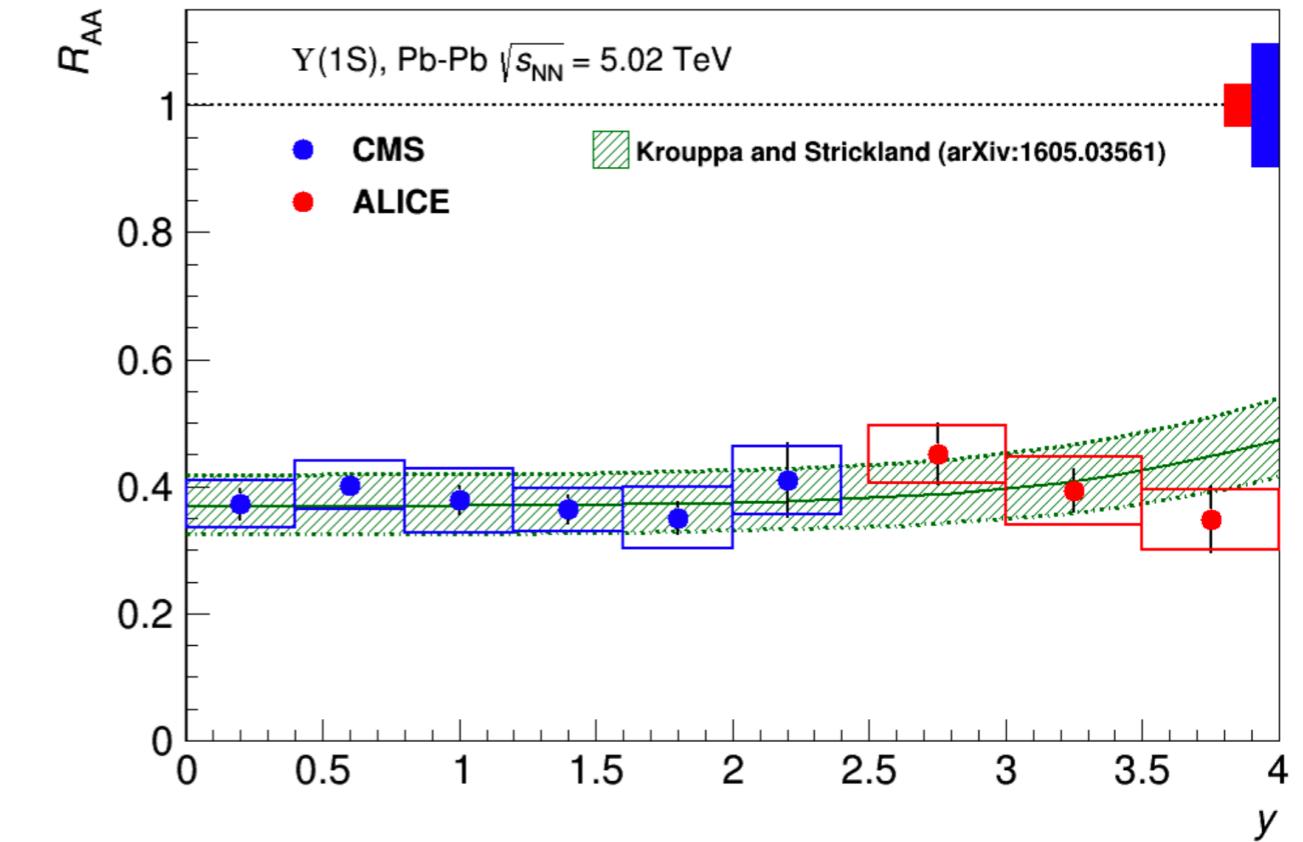
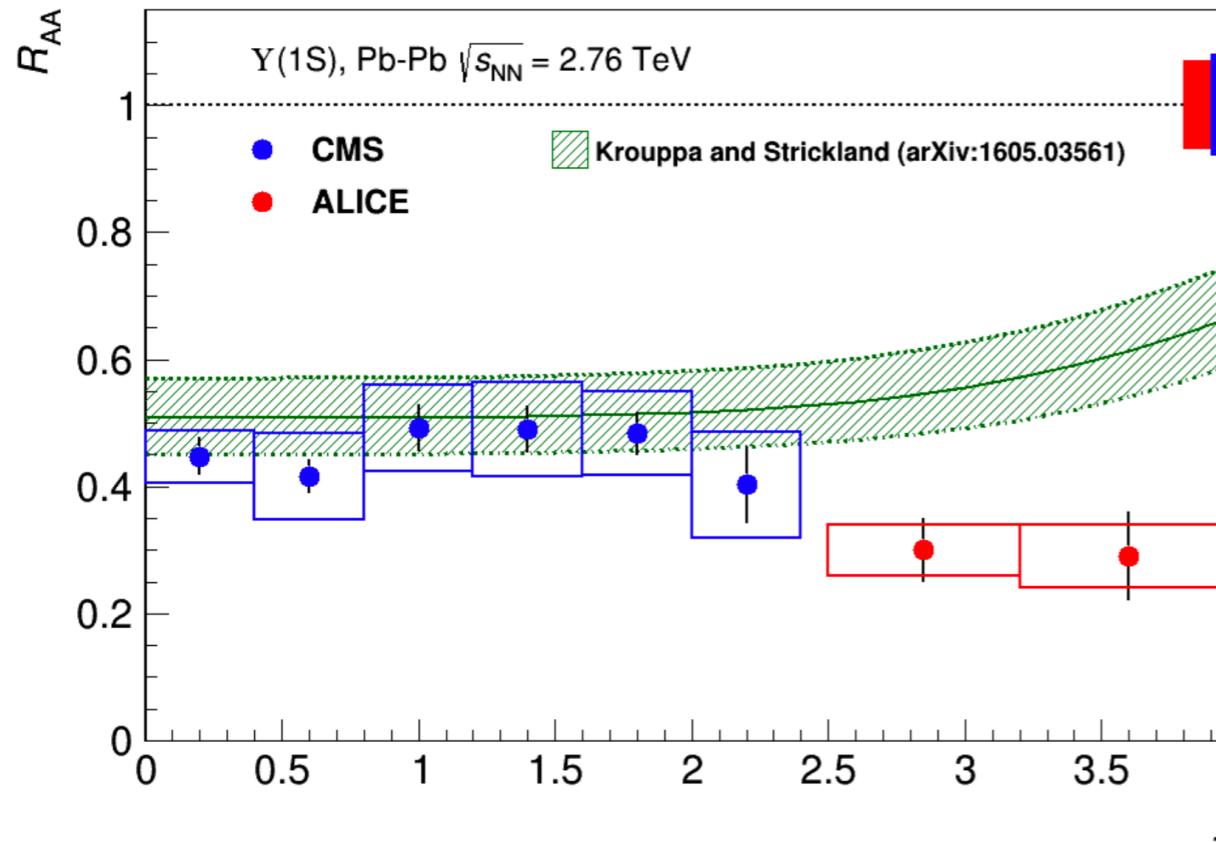
- Sequential suppression of $\Upsilon(3S)$, $\Upsilon(2S)$ and $\Upsilon(1S)$
 - (Also at forward- y)
- Hint of increasing suppression of $\Upsilon(1S)$ from 2.76 to 5.02 TeV



- Correctly described by Krouppa, Strickland, Universe 2 (2016) no.3, 16
 - Thermal quarkonium suppression
 - Anisotropic hydro medium

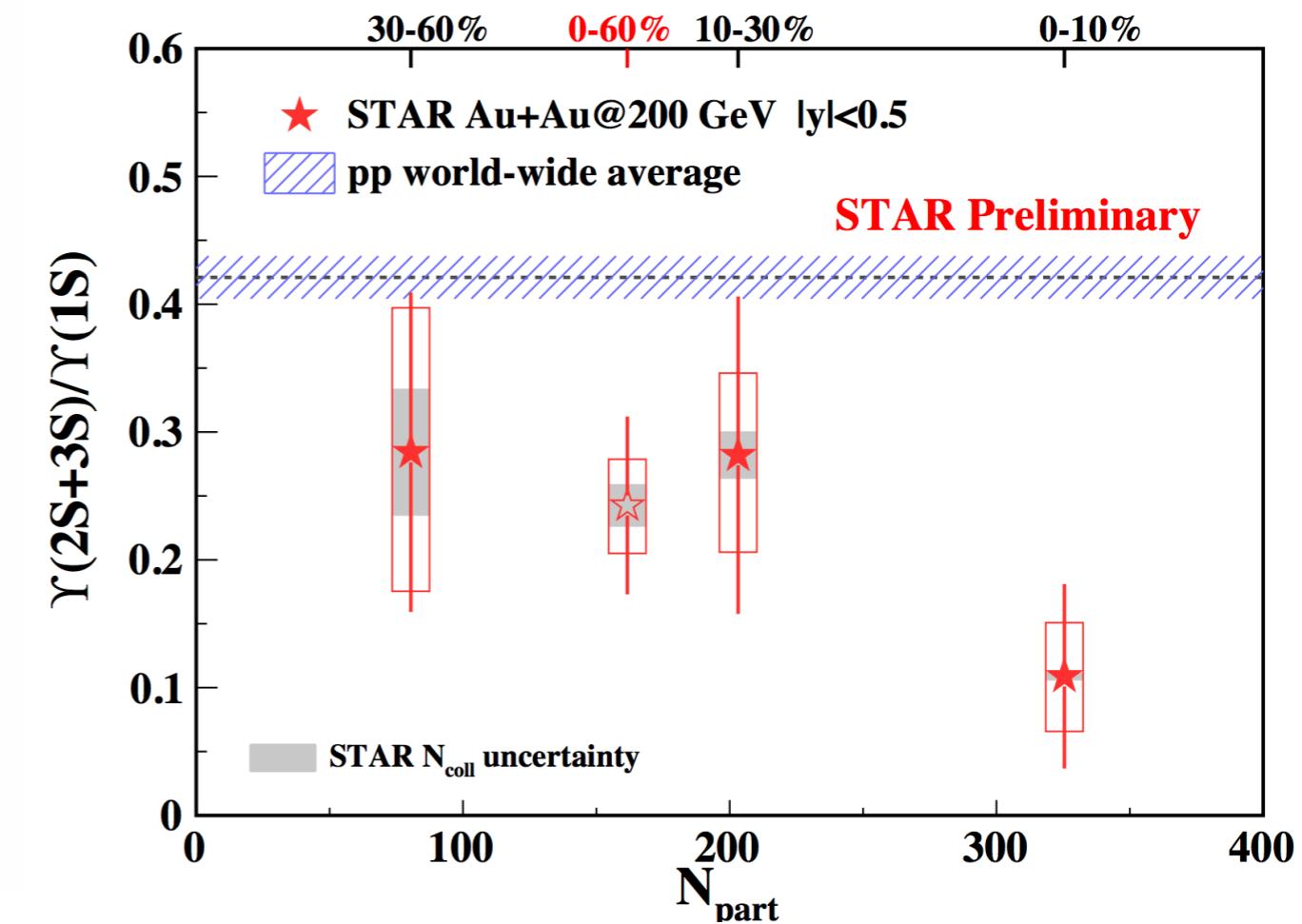
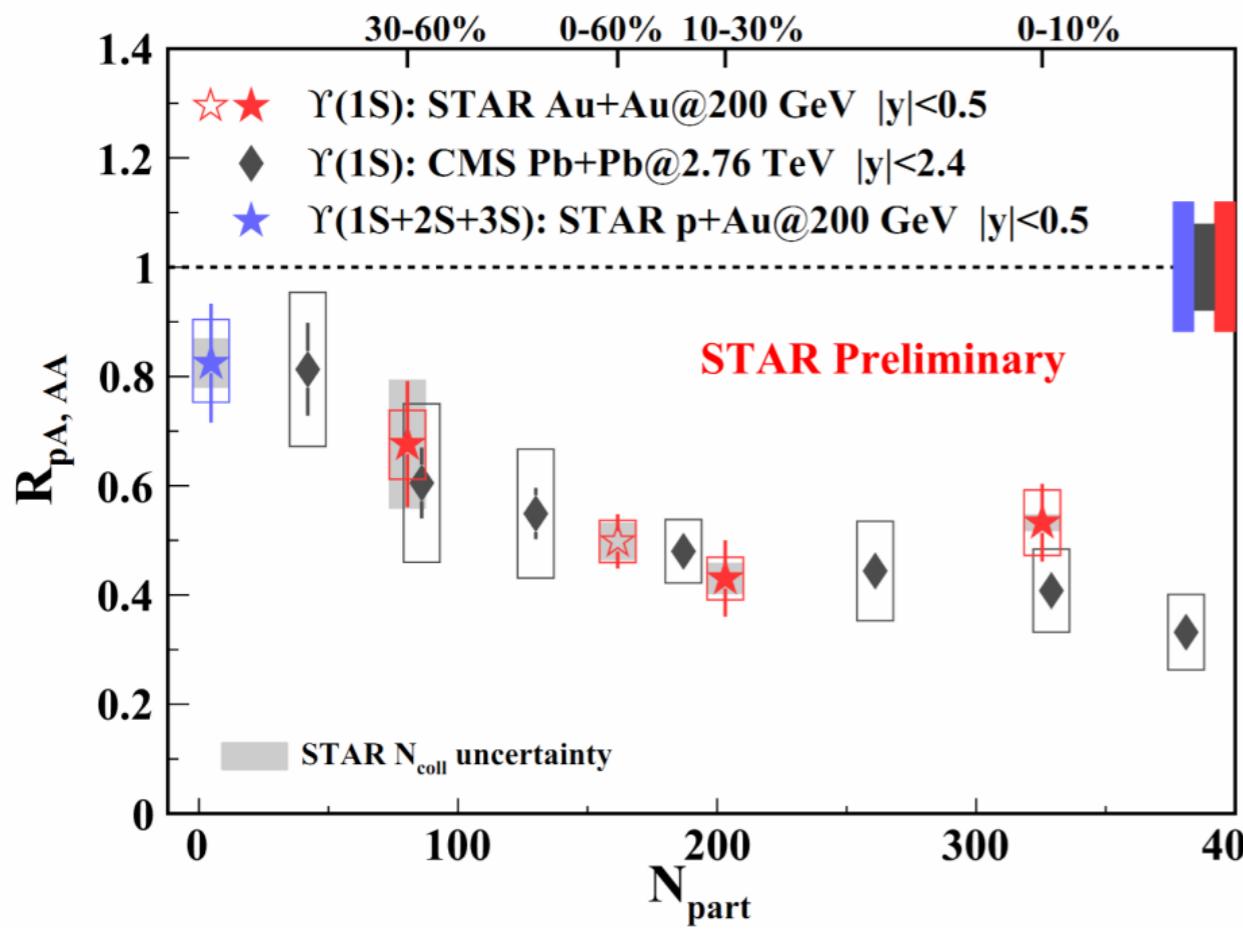
γR_{AA} @ LHC vs. rapidity

- Possibly flatter rapidity dependence at 5.02 than at 2.76 TeV



- Tension between model and data, specially at 2.76 TeV
 - No CNM included
- Is direct Y(1S) suppressed?
 - Feed down could account for about 30% (LHCb)
 - What about CNM effects?

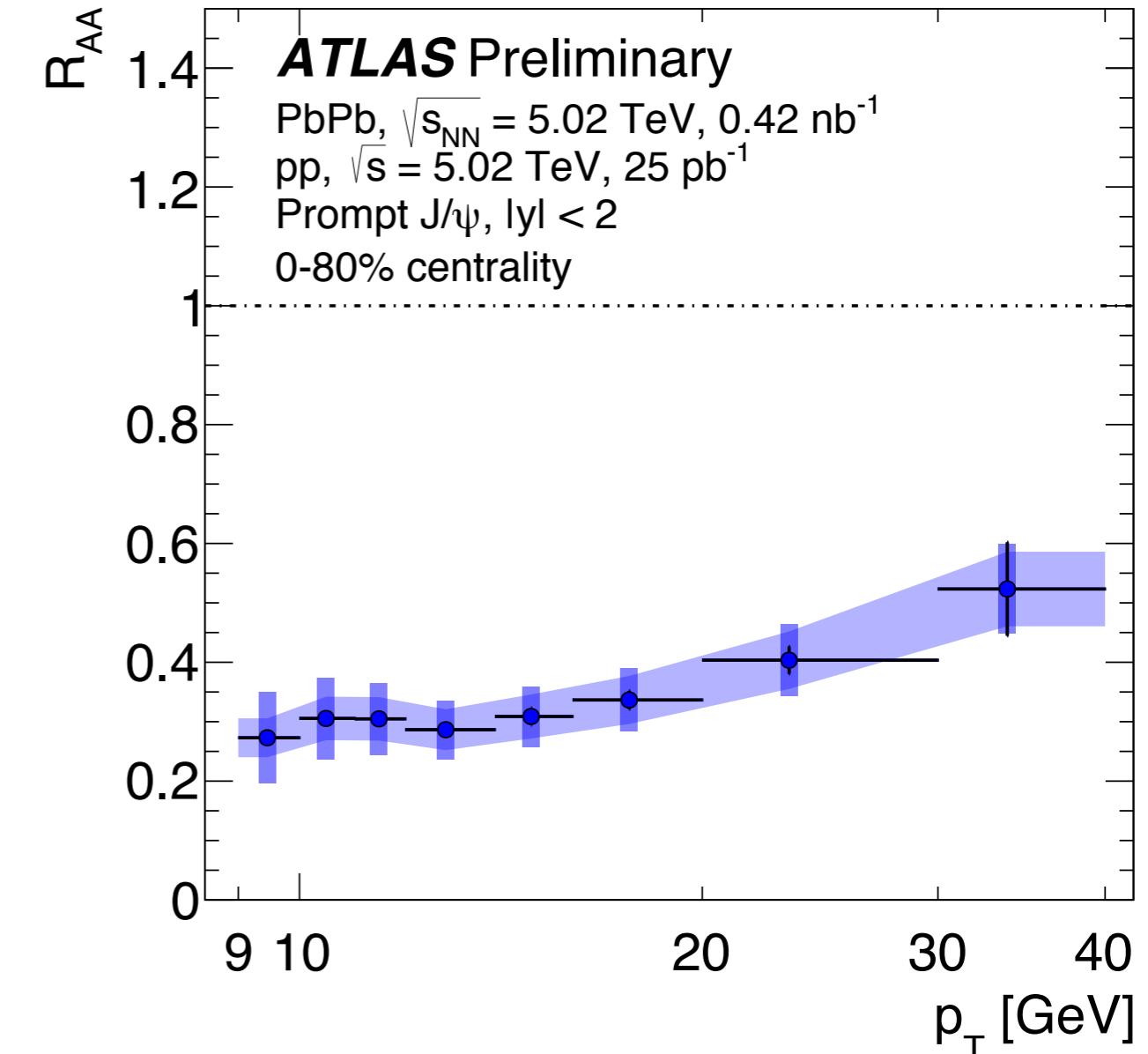
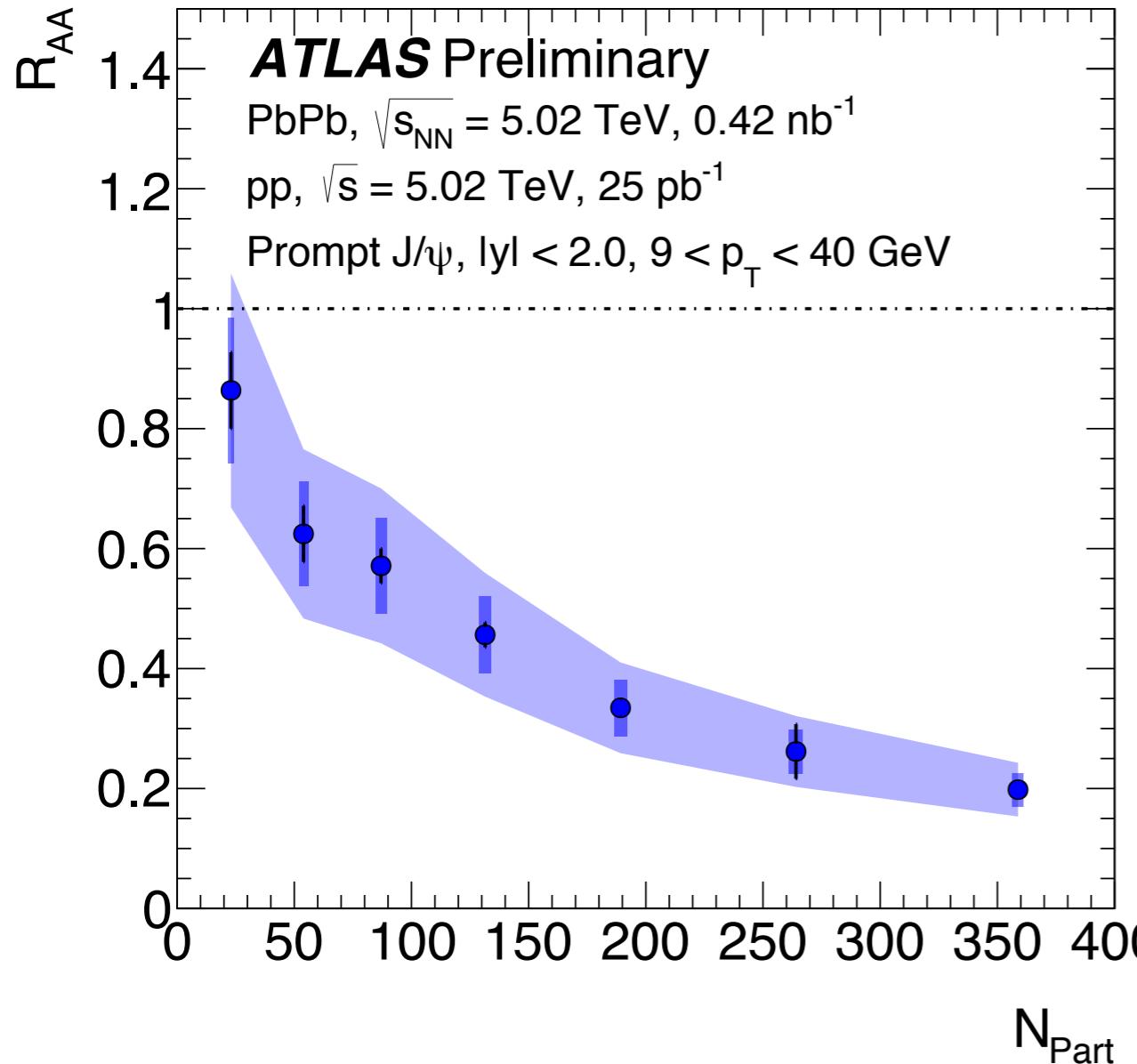
- $\Upsilon(1S)$ also strongly suppressed at RHIC energies
 - Suppression seems to increase with increasing centrality
- $\Upsilon(2S+3S)$ is more suppressed than $\Upsilon(1S)$ in most central collisions



- Same $\Upsilon(1S)$ suppression at 200 GeV than at 2.76 TeV ?

J/ ψ suppression at high p_T

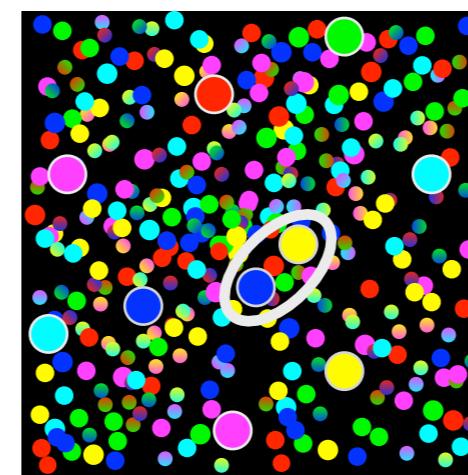
- Clear increasing suppression of high-p_T J/ ψ with increasing centrality in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV



- Decreasing suppression towards very high p_T
 - c-cbar dissociation or parton energy loss effect?

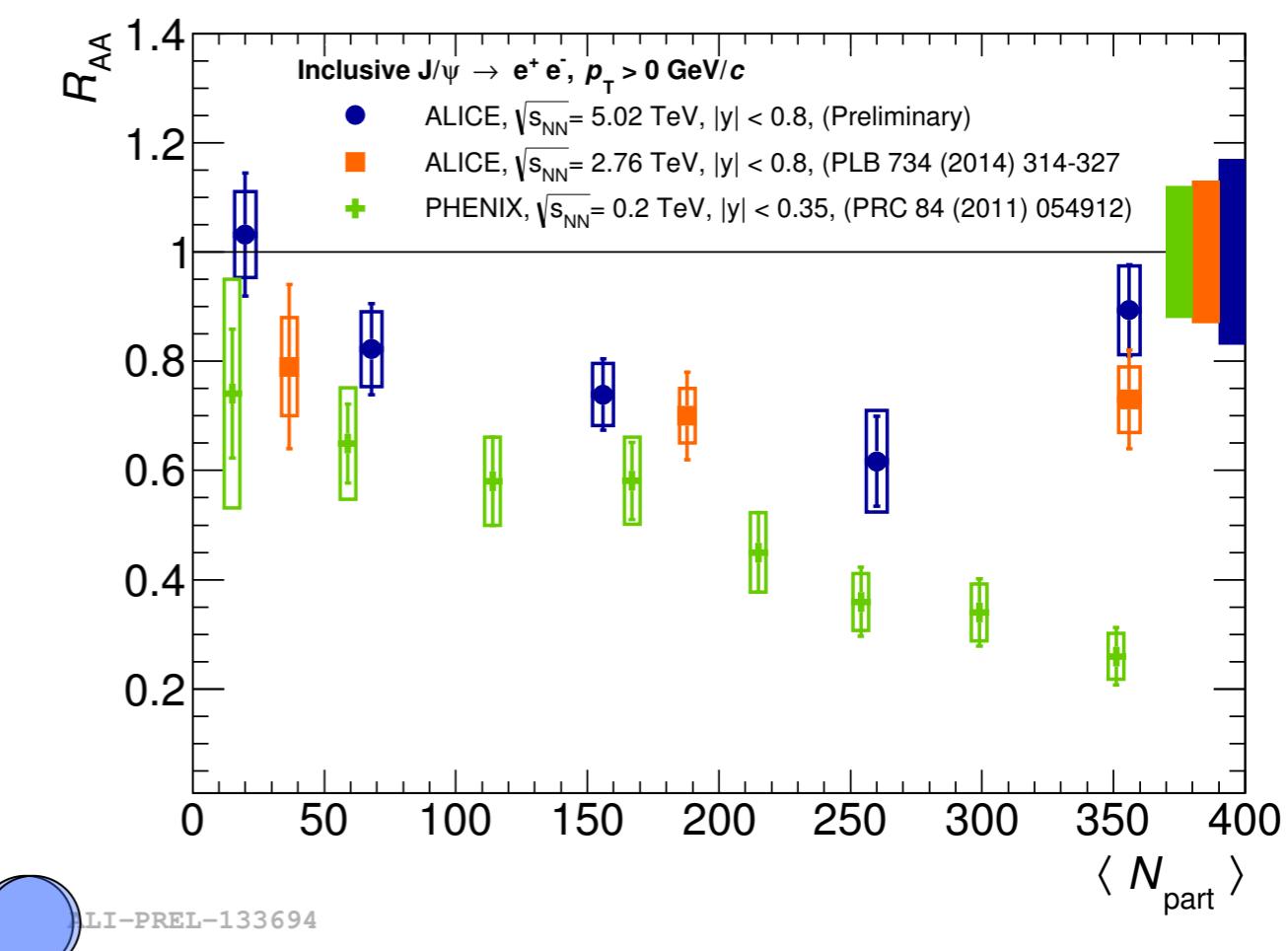
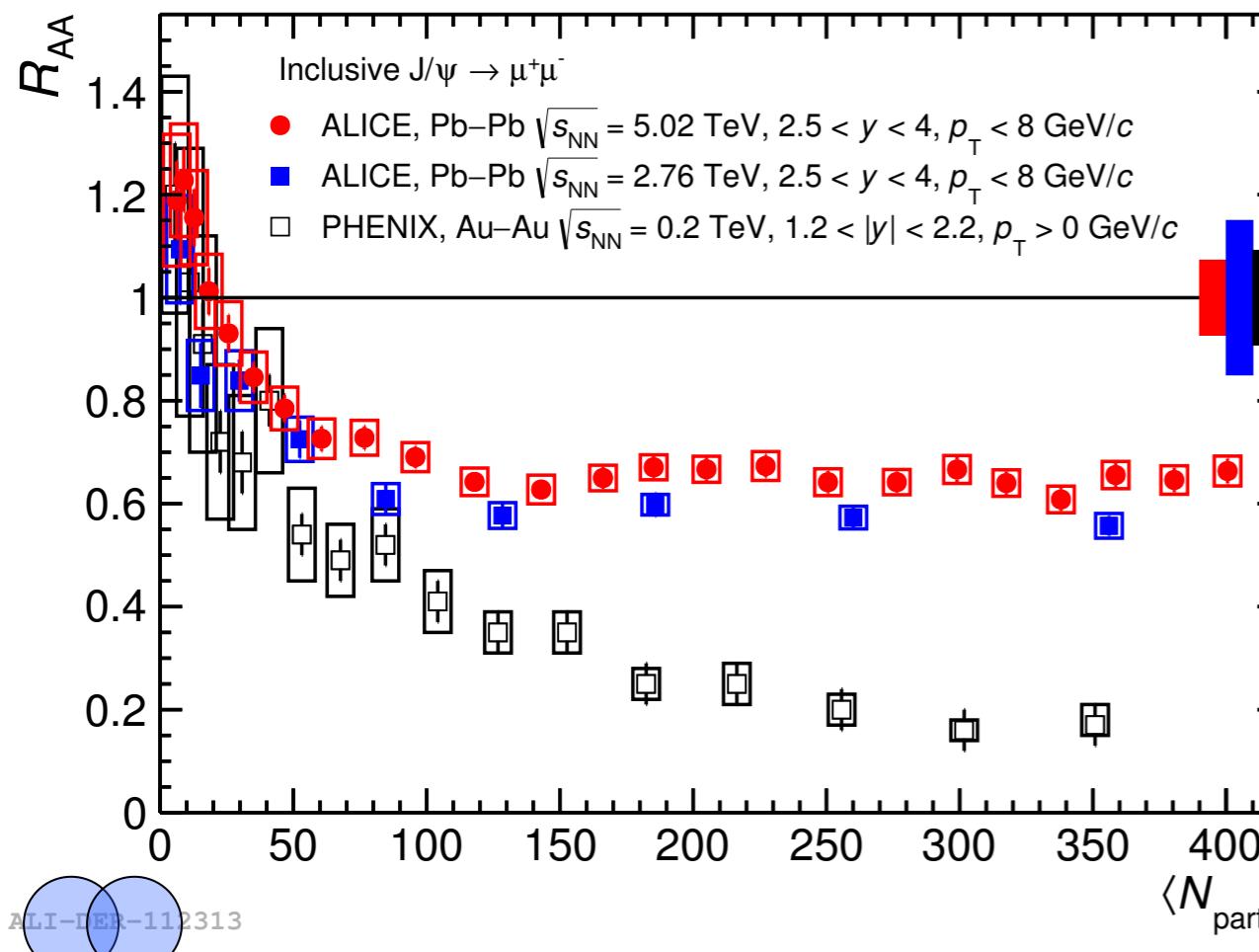


ABOUT REGENERATION



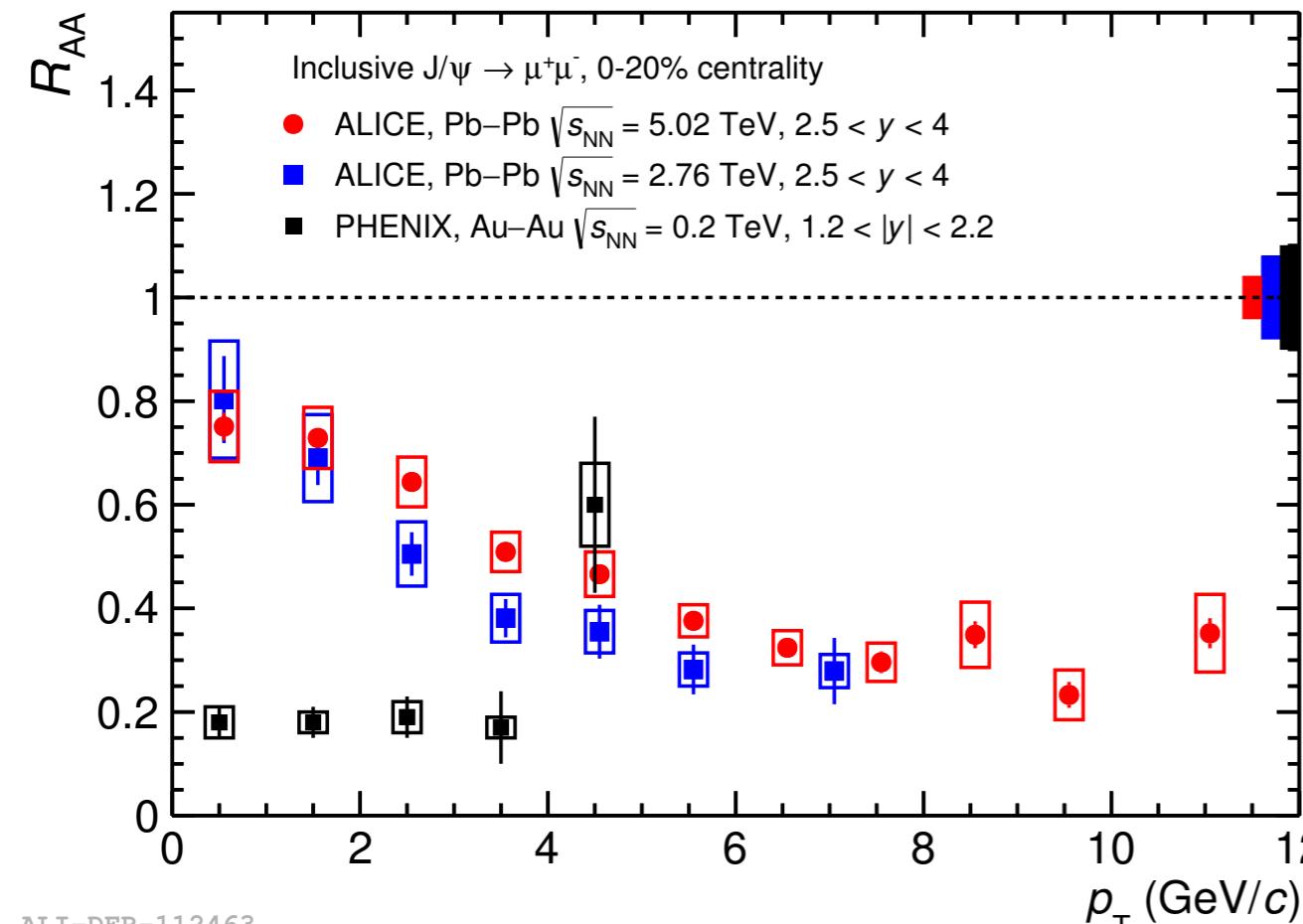
Regeneration: figure of merit

- J/ ψ at low p_T
 - Smaller suppression at LHC than at RHIC!
 - Larger regeneration at
 - higher c-cbar pair density
 - higher energy density
 - At LHC, no centrality dependence of R_{AA} for $N_{part} > 70$ (increase at mid-y ?)

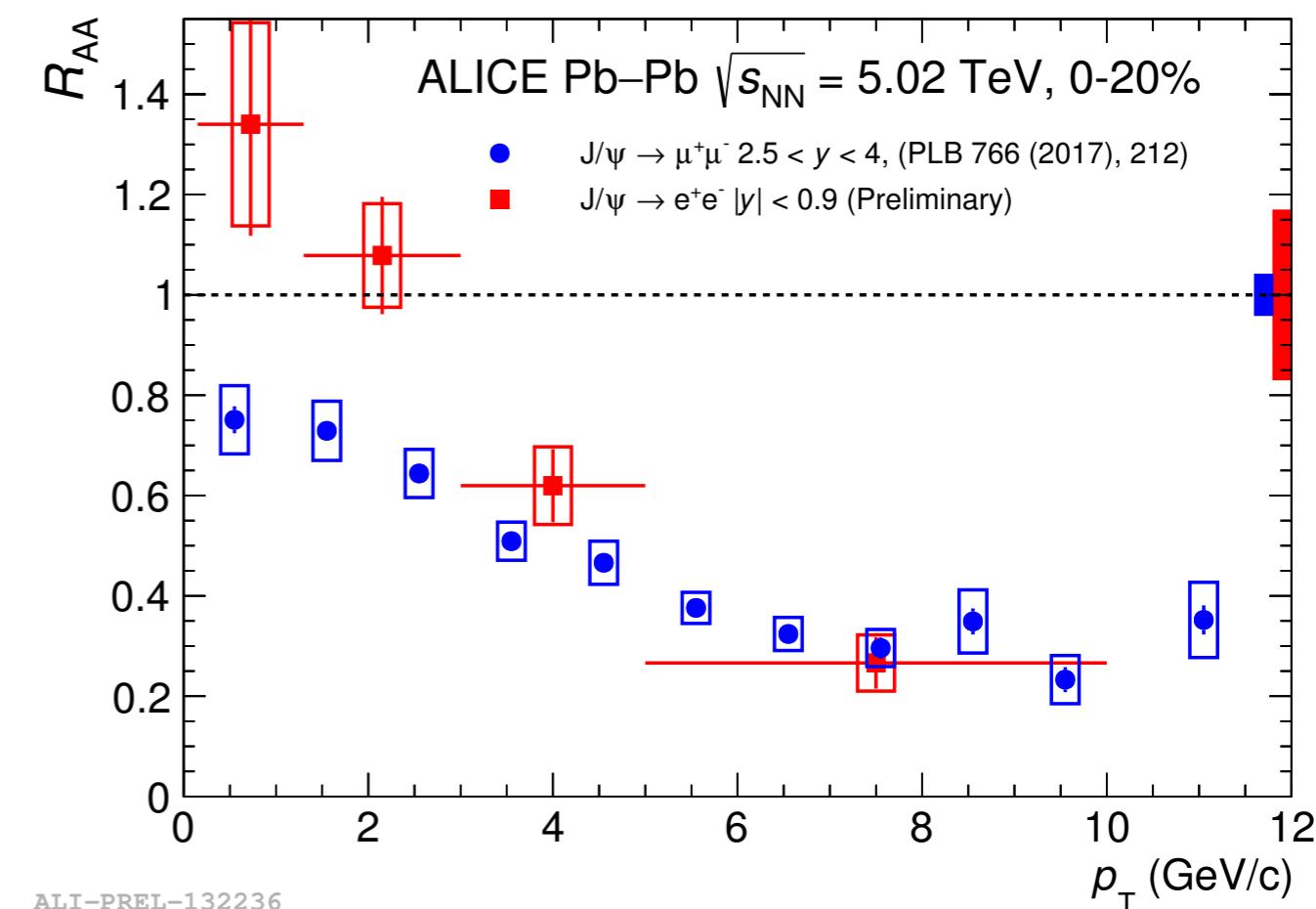


J/ ψ R_{AA} vs. p_T in central collisions

- Regeneration component is expected to contribute mainly at low transverse momentum



ALI-DER-112463

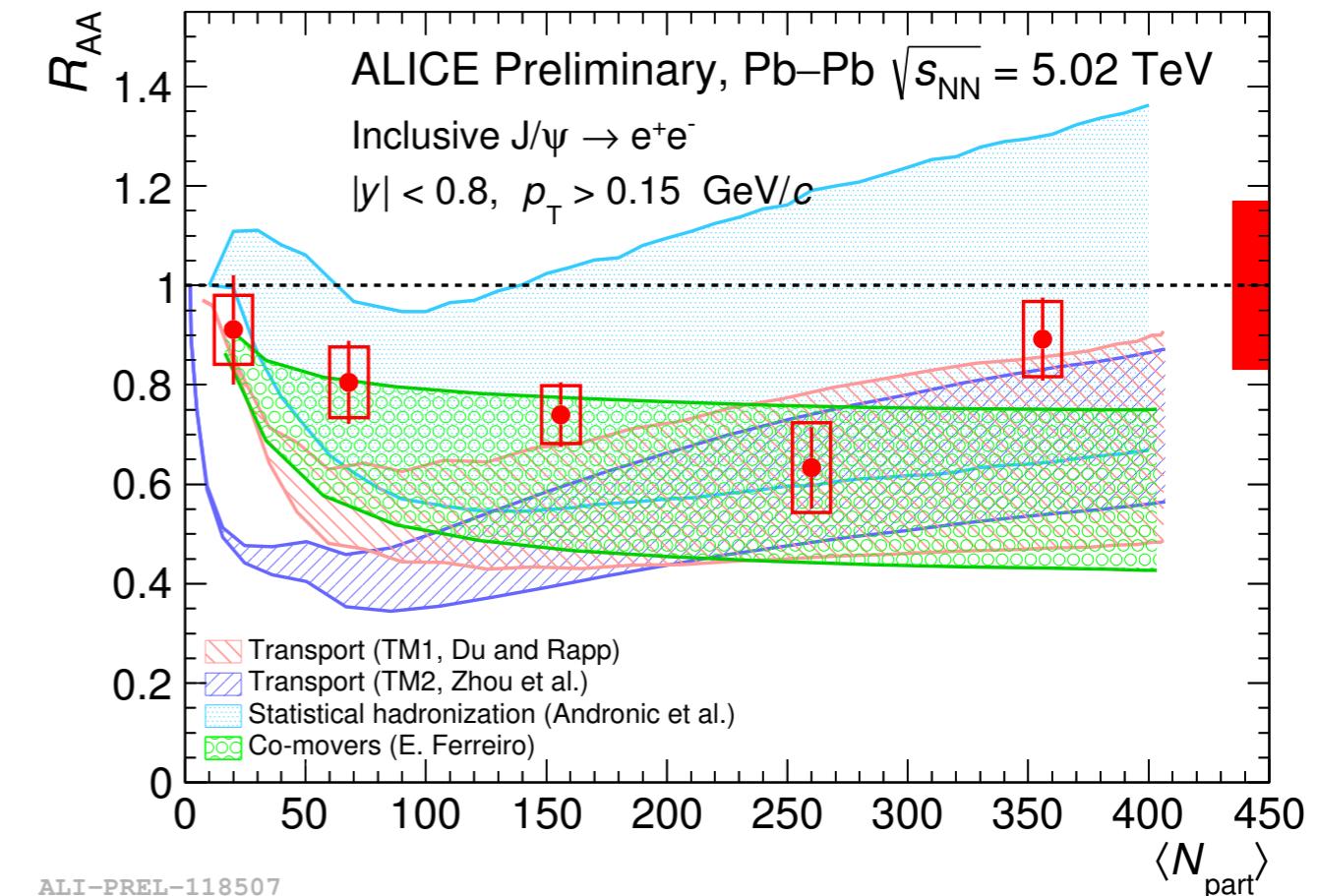
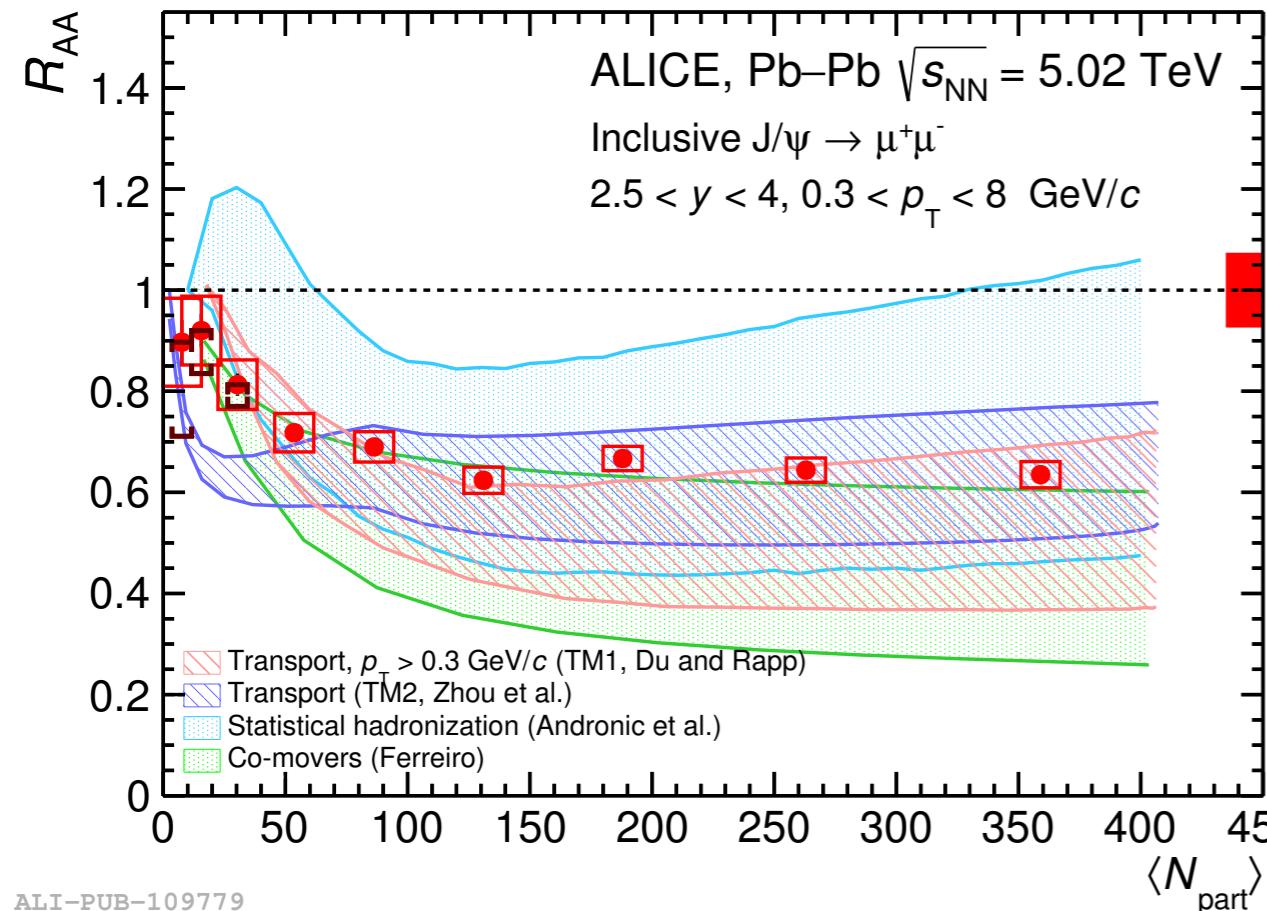


ALI-PREL-132236

- Strikingly different p_T dependence at RHIC and LHC
 - At high p_T the J/ ψ suppression is similar at RHIC and LHC
 - At the LHC the suppression decreases towards low p_T
 - Similar trend at 2.76 and 5.02 TeV
- At the LHC, the suppression decreases from forward to mid-rapidity
 - R_{AA} larger than unity at low p_T at mid-y in central Pb-Pb collisions at 5.02 TeV?

J/ ψ R_{AA} vs. centrality

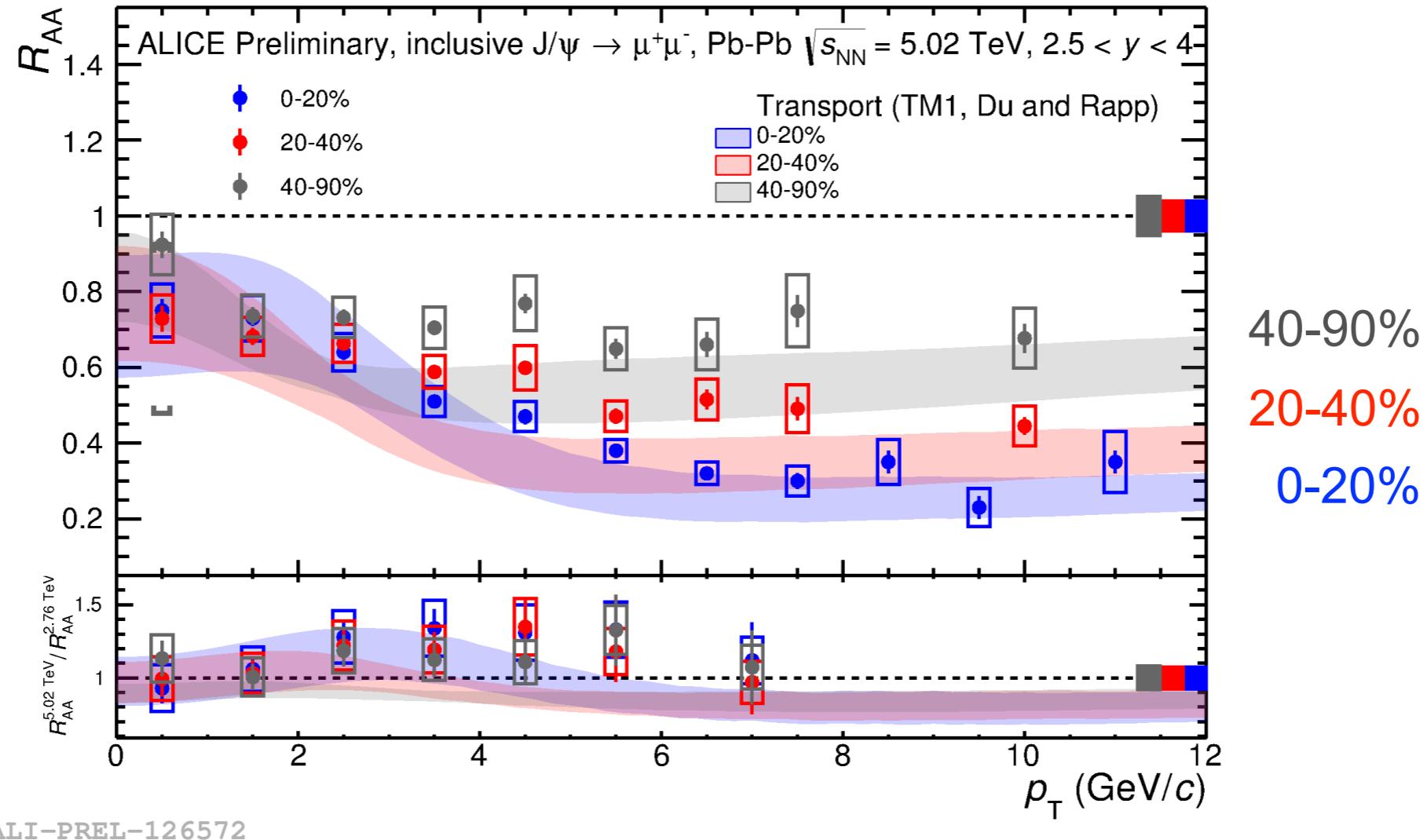
- Inclusive J/ ψ with p_T > 0 GeV/c
 - For both, forward and mid-rapidity smaller suppression at LHC than at RHIC
 - Reasonable description by models including a significant regeneration component



- Statistical Hadronization Model [Braun-Munzinger et al., PLB 490 (2000) 196]
 - Screening by the QGP of all prompt J/ ψ
 - Charmonium production at phase boundary by statistical combination of deconfined charm quarks
 - CNM (shadowing) on open charm
- Transport models [Liu et al., PLB 678 (2009) 72] [Zhao et al., NPA 859 (2011) 114]
 - prompt J/ ψ dissociation in QGP
 - J/ ψ regeneration by charm quark pair recombination
 - Shadowing effect
 - Feed-down contributions from B
- Comover Interaction Model [Ferreiro, PLB 731 (2014) 57]
 - Interaction with a co-moving partonic medium causing J/ ψ dissociation ($\sigma_{co} = 0.65$ mb)
 - Recombination effects prop. to σ_{co}, n_{ccbar}
 - Shadowing similar to EKS98/nDSg

J/ ψ R_{AA} vs. p_T in centrality classes

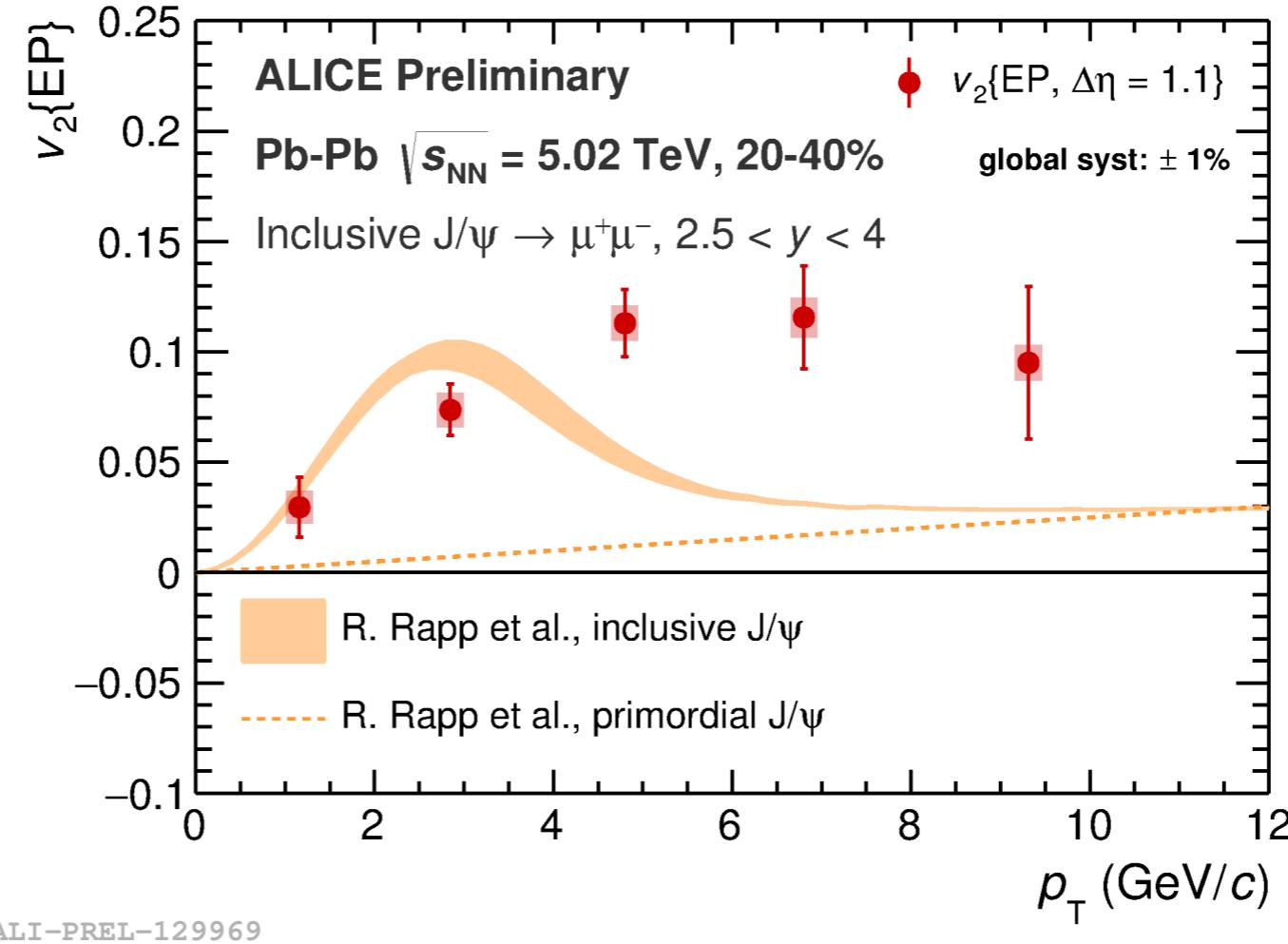
- Regeneration component is expected to contribute mainly at low transverse momentum



- From 2.76 to 5.02 TeV, increase of R_{AA} at intermediate p_T (2-6 GeV/c)
- Transport models (fairly) reproduce the observed trend as a function of transverse momentum and centrality

J/ ψ elliptic flow – 5 TeV

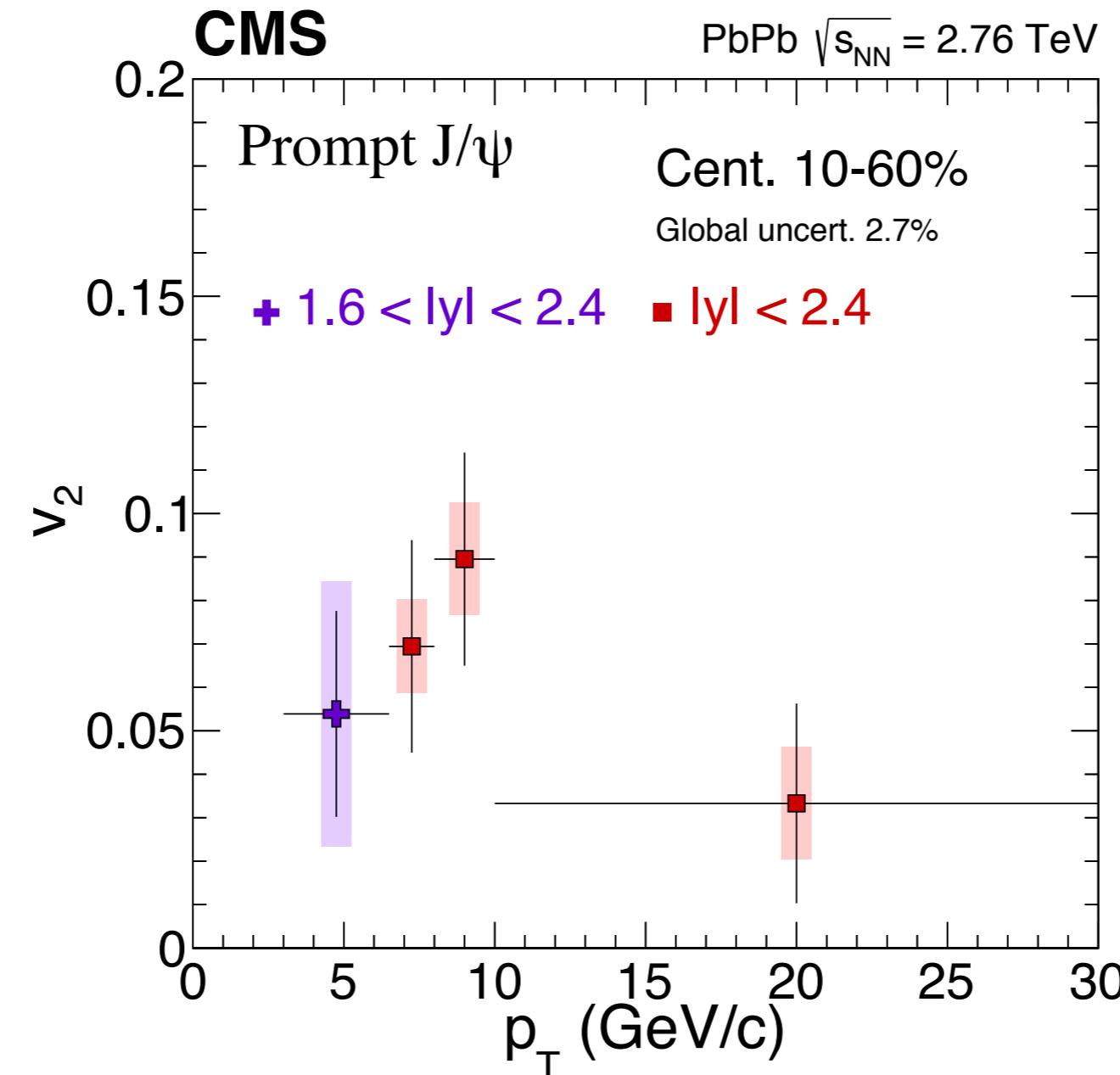
- Unambiguous observation of non-zero J/ ψ v_2 in semi-central (20-40%) Pb-Pb collisions at 5 TeV for J/ ψ with $0 < p_T < 12$ GeV/c
- J/ ψ $v_2(p_T)$ increases with p_T up to about 0.11 at $4 < p_T < 6$ GeV/c and saturates or decreases thereafter



- In the framework of transport models, the large v_2 values measured can only be achieved by including a strong J/ ψ (re)generation component from (re)combination of thermalized charm quarks in the QGP
 - Dominant at low p_T (< 4 GeV/c), dying out at high p_T
- The large values of the J/ ψ v_2 at high p_T are a challenge to models ...

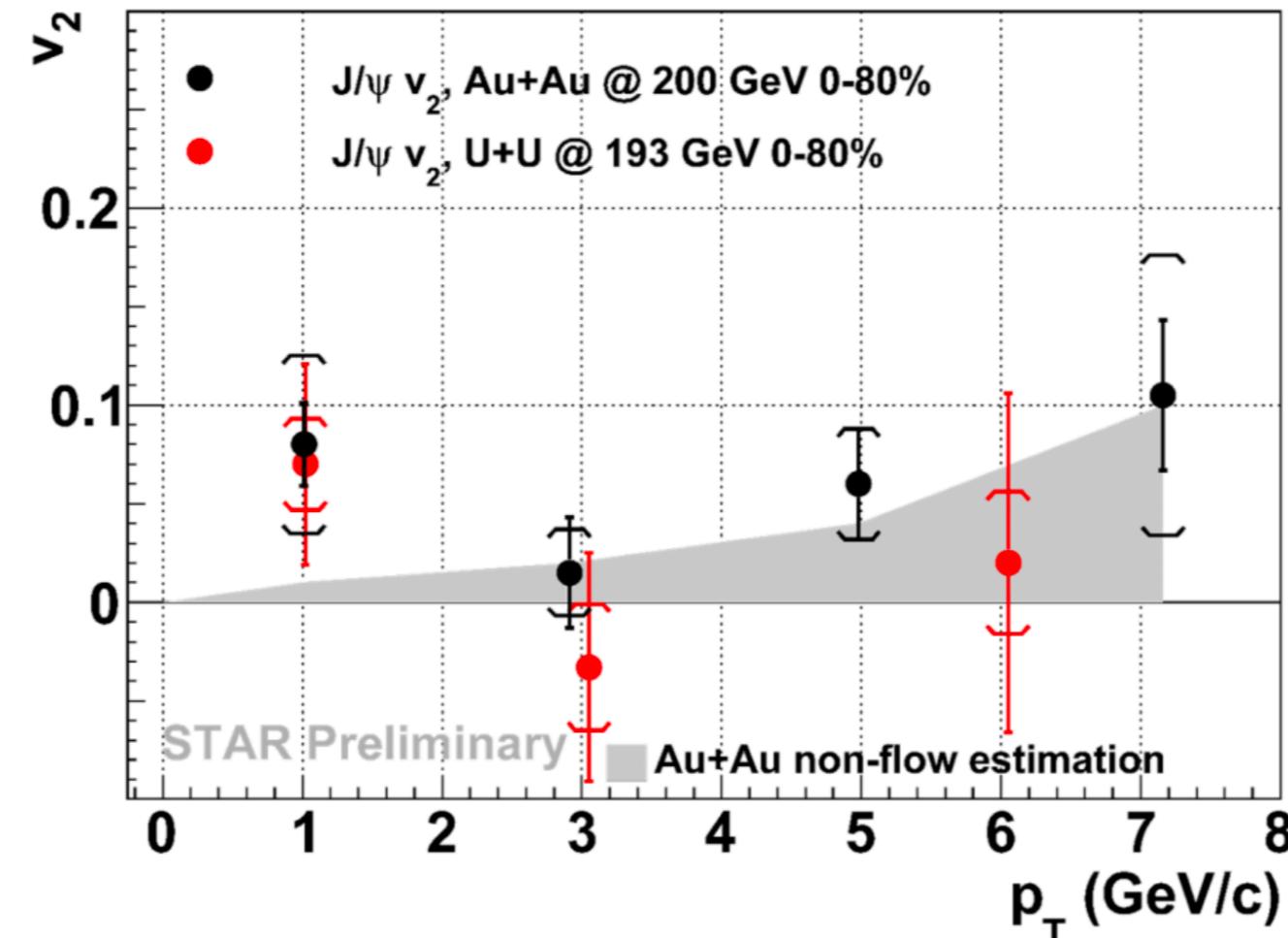
Prompt-J/ ψ v_2 at high p_T

- Prompt J/ ψ also exhibit large v_2 at high transverse momentum



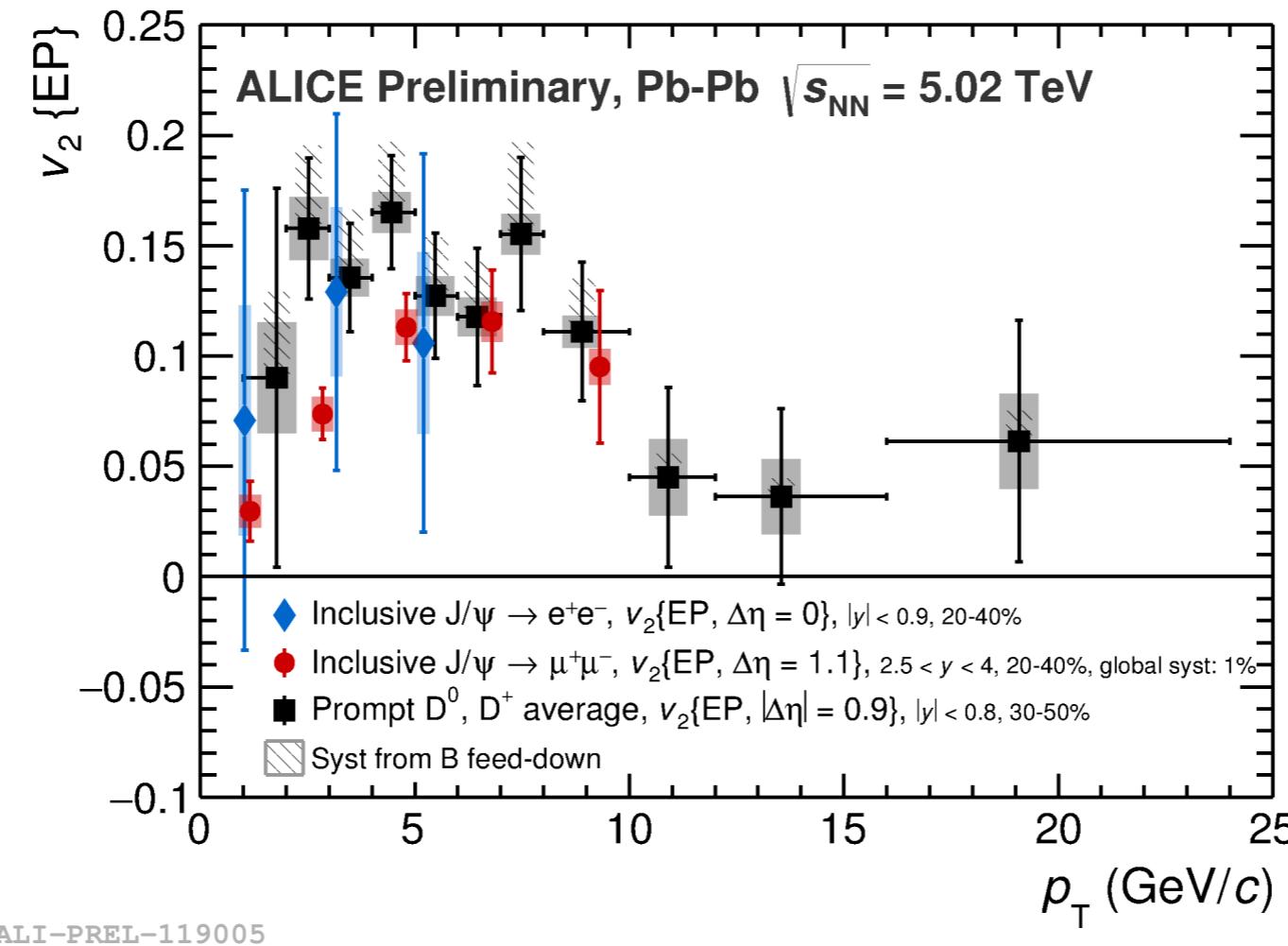
J/ ψ (No)azimuthal anisotropy at RHIC

- J/ ψ v_2 compatible with zero in both Au+Au and U+U collisions at RHIC energies



Hidden versus Open charm v_2

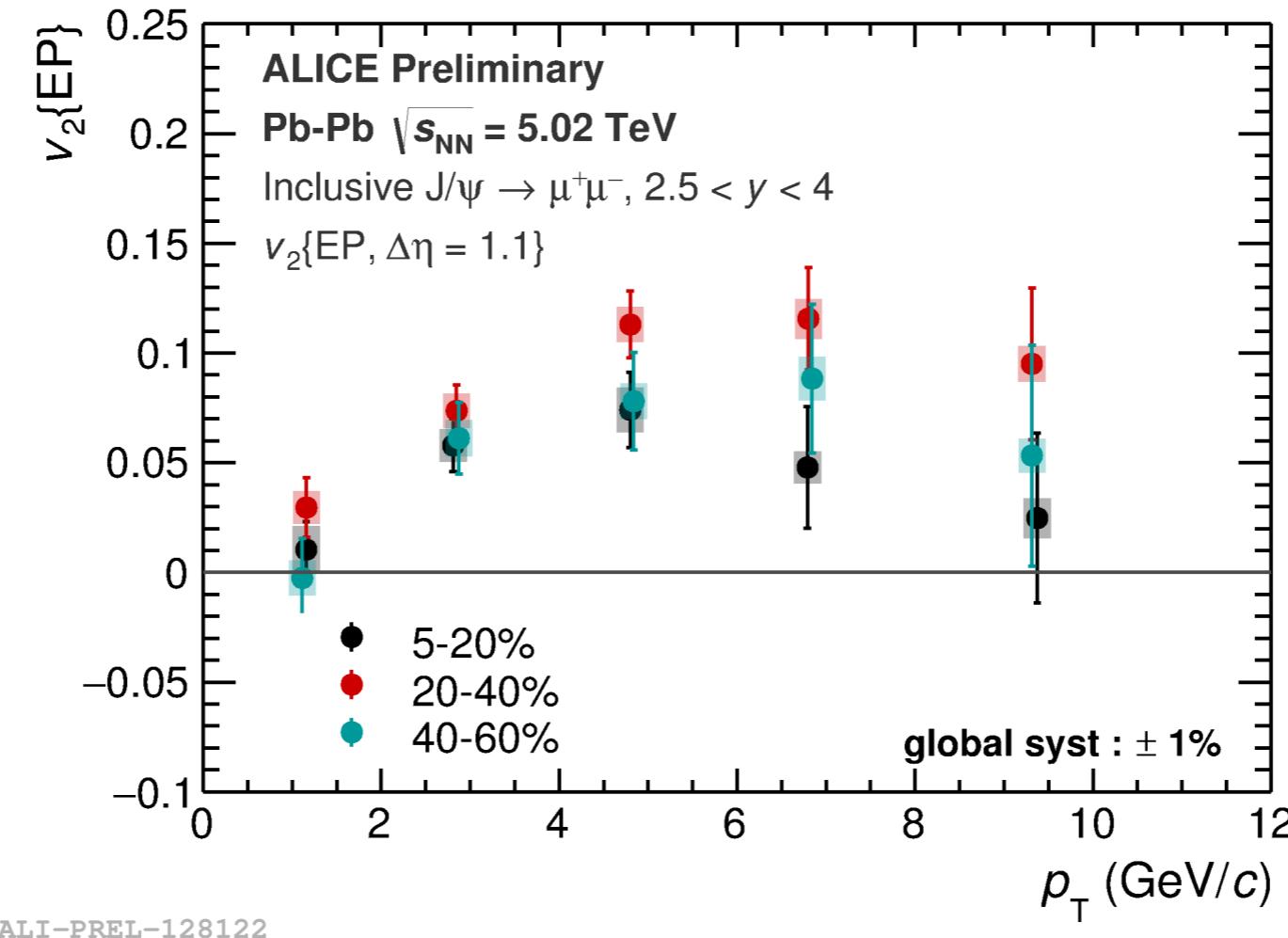
- J/ ψ v_2 at mid- y compatible (within large uncertainties) with the measurement at forward- y



- Comparison v_2 open vs hidden charm
 - Similar magnitude (but different centrality and rapidity)
 - Quantitative comparison pending
 - Consistently suggesting that charm quark flows!

Centrality dependence

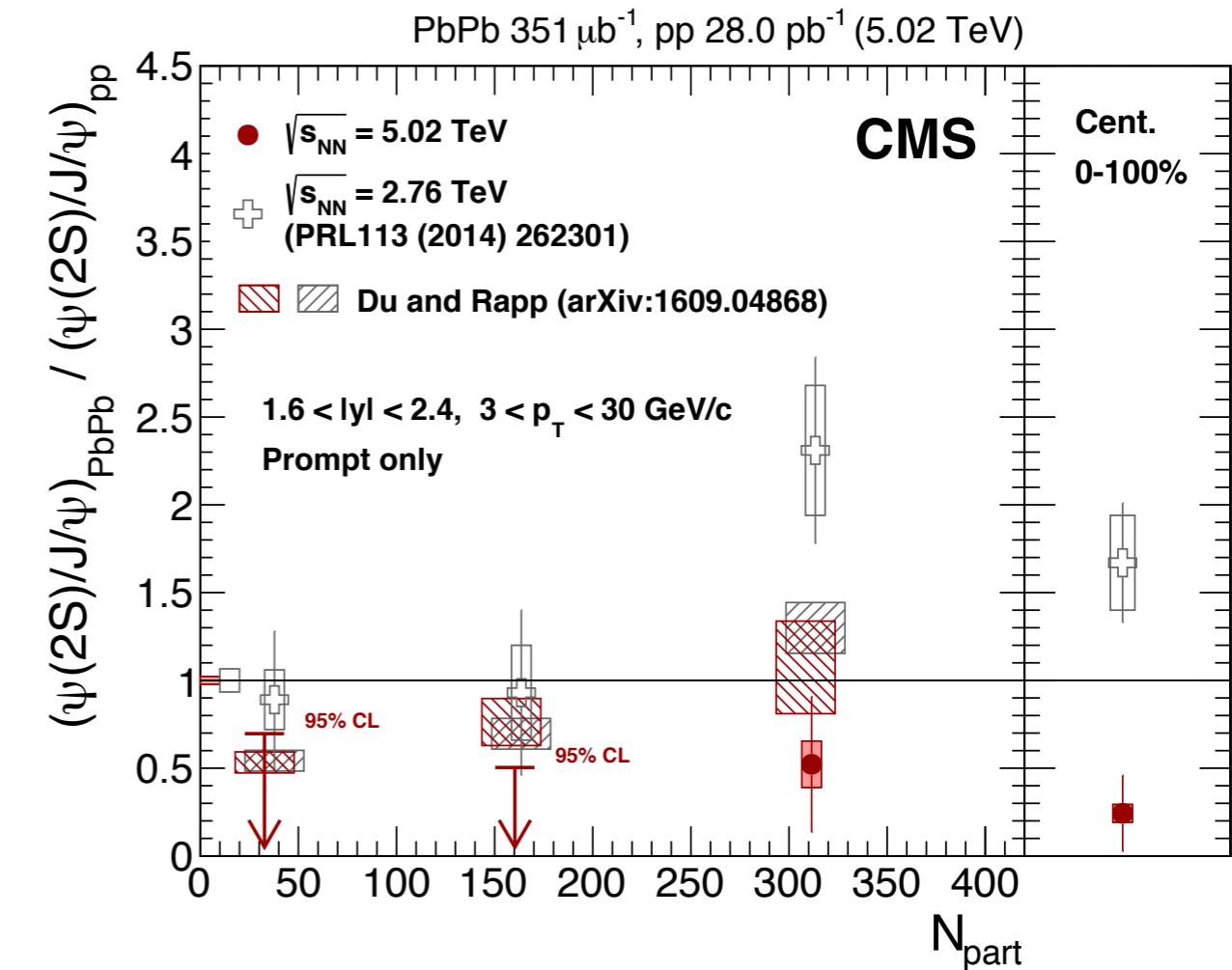
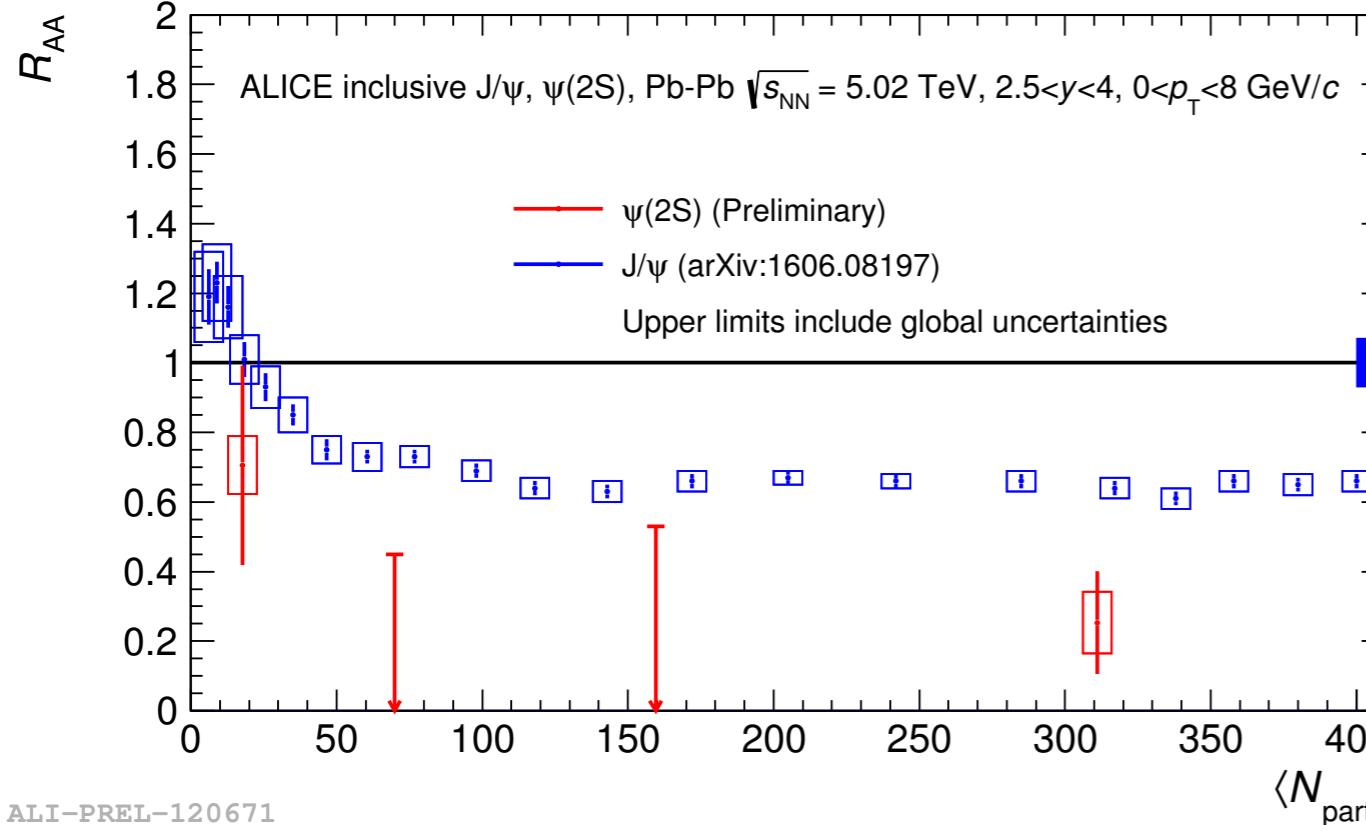
- Large v_2 values observed also in 5-20% and 40-60% for J/ψ with $2 < p_T < 8 \text{ GeV}/c$
- Similar trend in the three centralities



- $J/\psi v_2(p_T)$ is maximum for 20-40%
 - Apparently different than for light hadrons ...

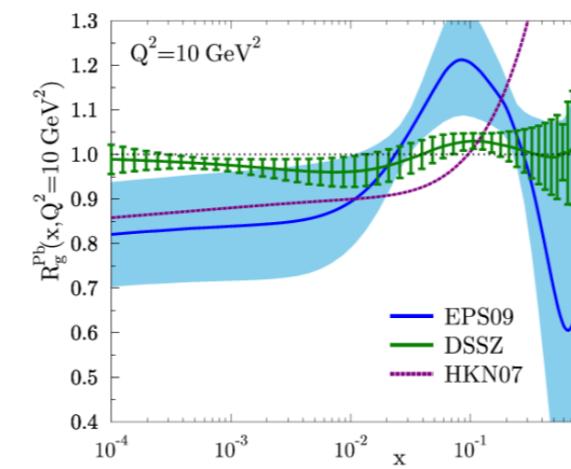
$\Psi(2S)$ suppression

- At low p_T (but also at high p_T), $\Psi(2S)$ is more suppressed than J/ψ

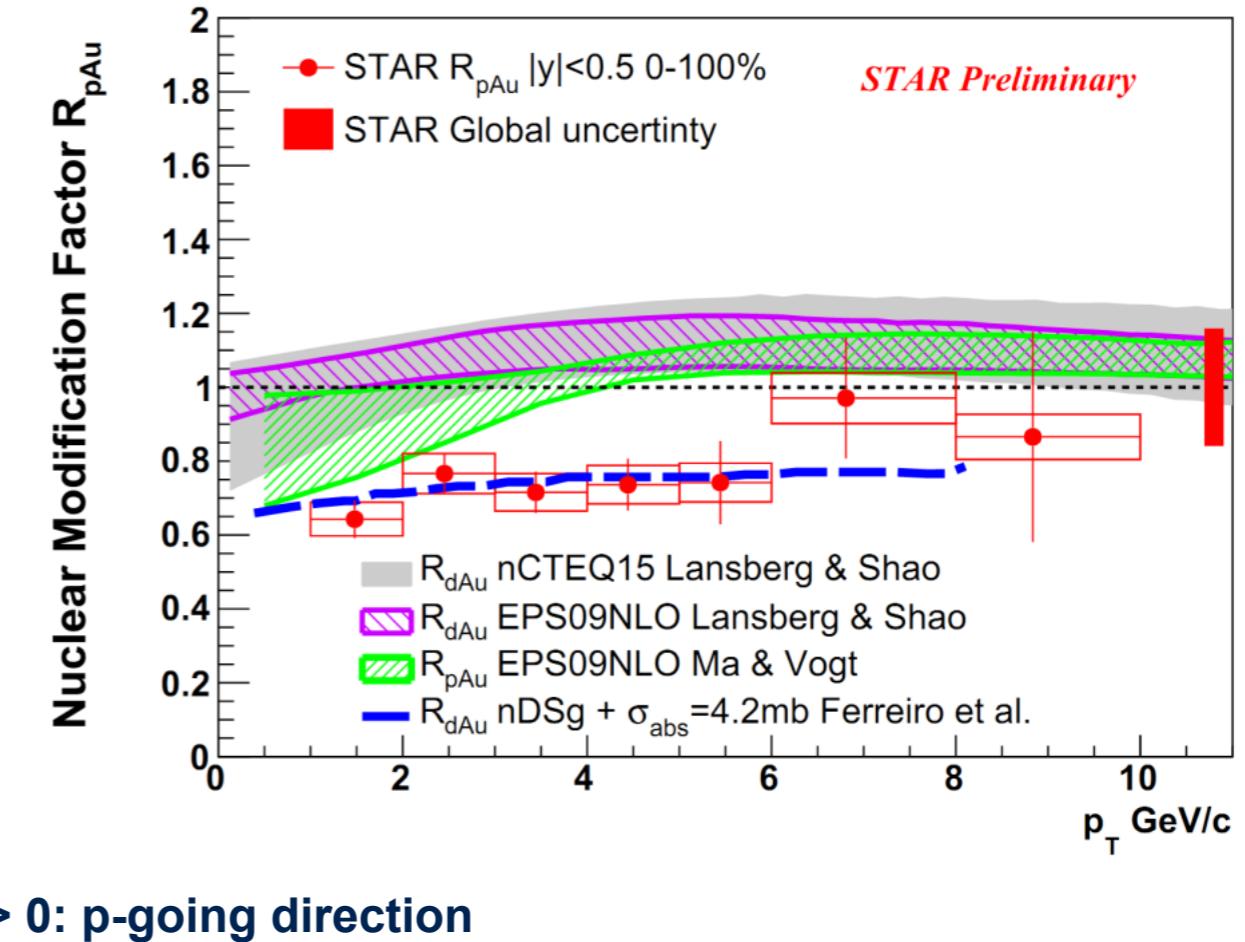
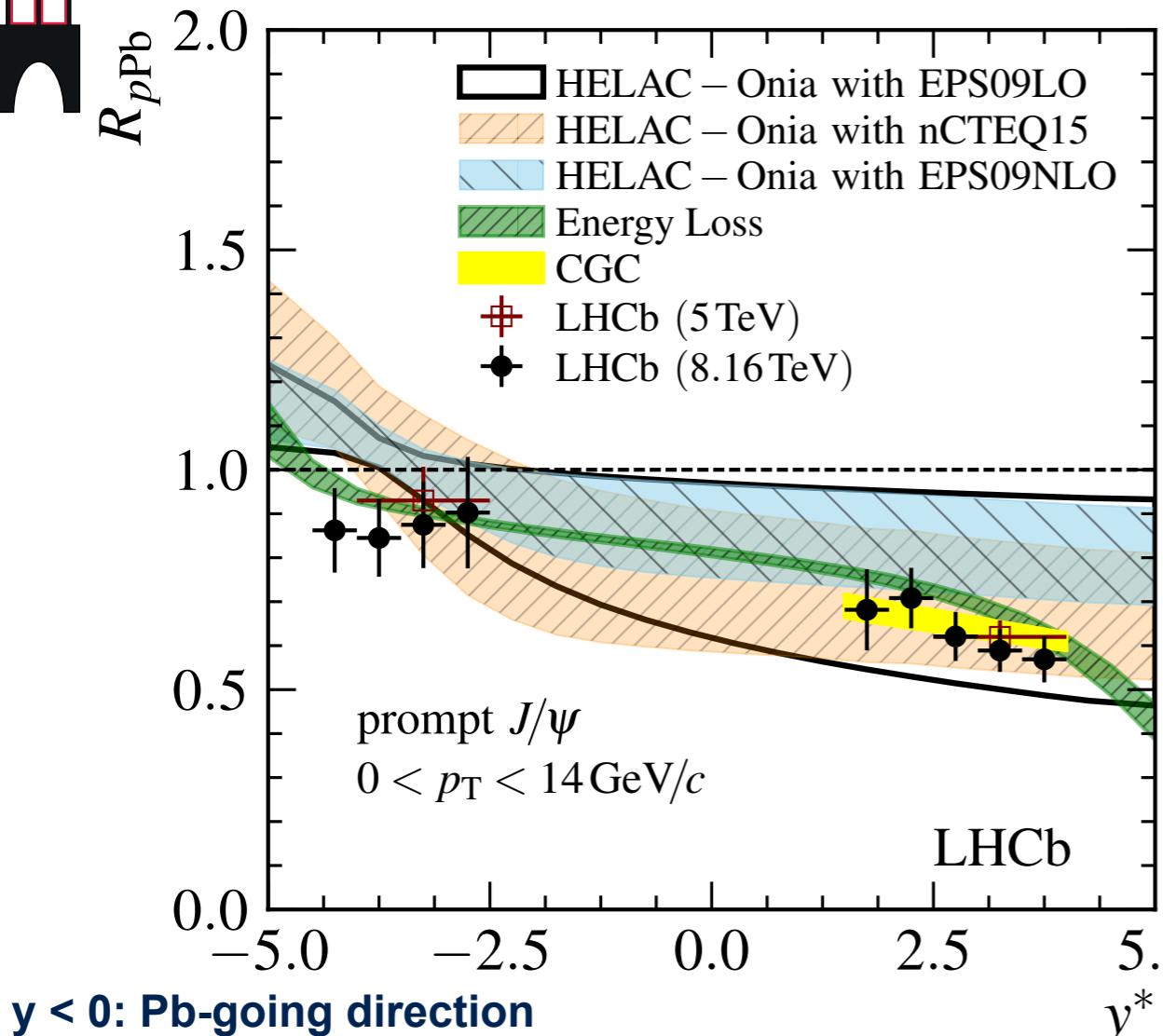


- Stronger relative suppression of $\Psi(2S)$ than J/ψ at 5.02 than 2.76 TeV?
- Still need higher precision data to challenge models (e.g. SHM vs transport)

ABOUT COLD NUCLEAR MATTER EFFECTS



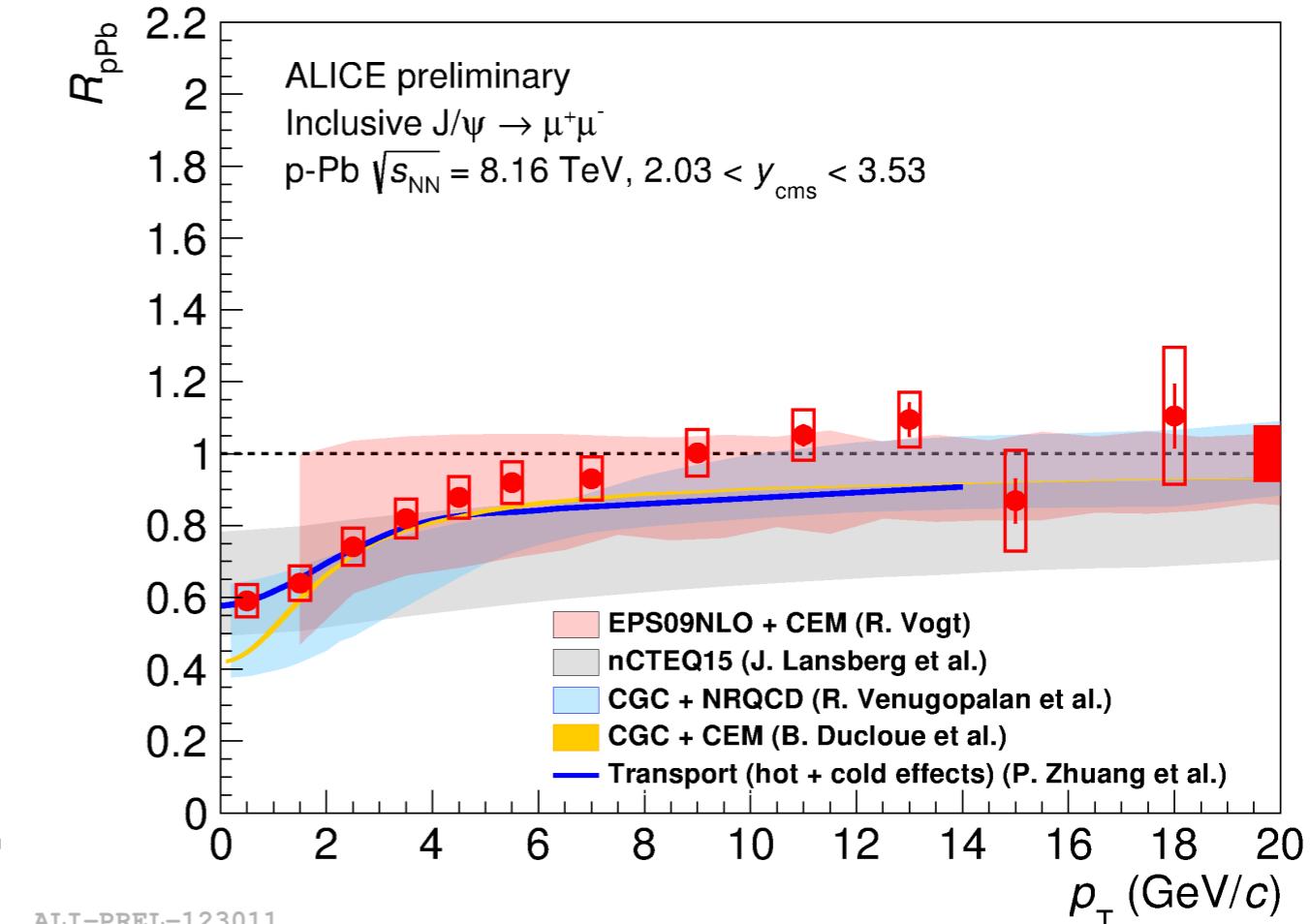
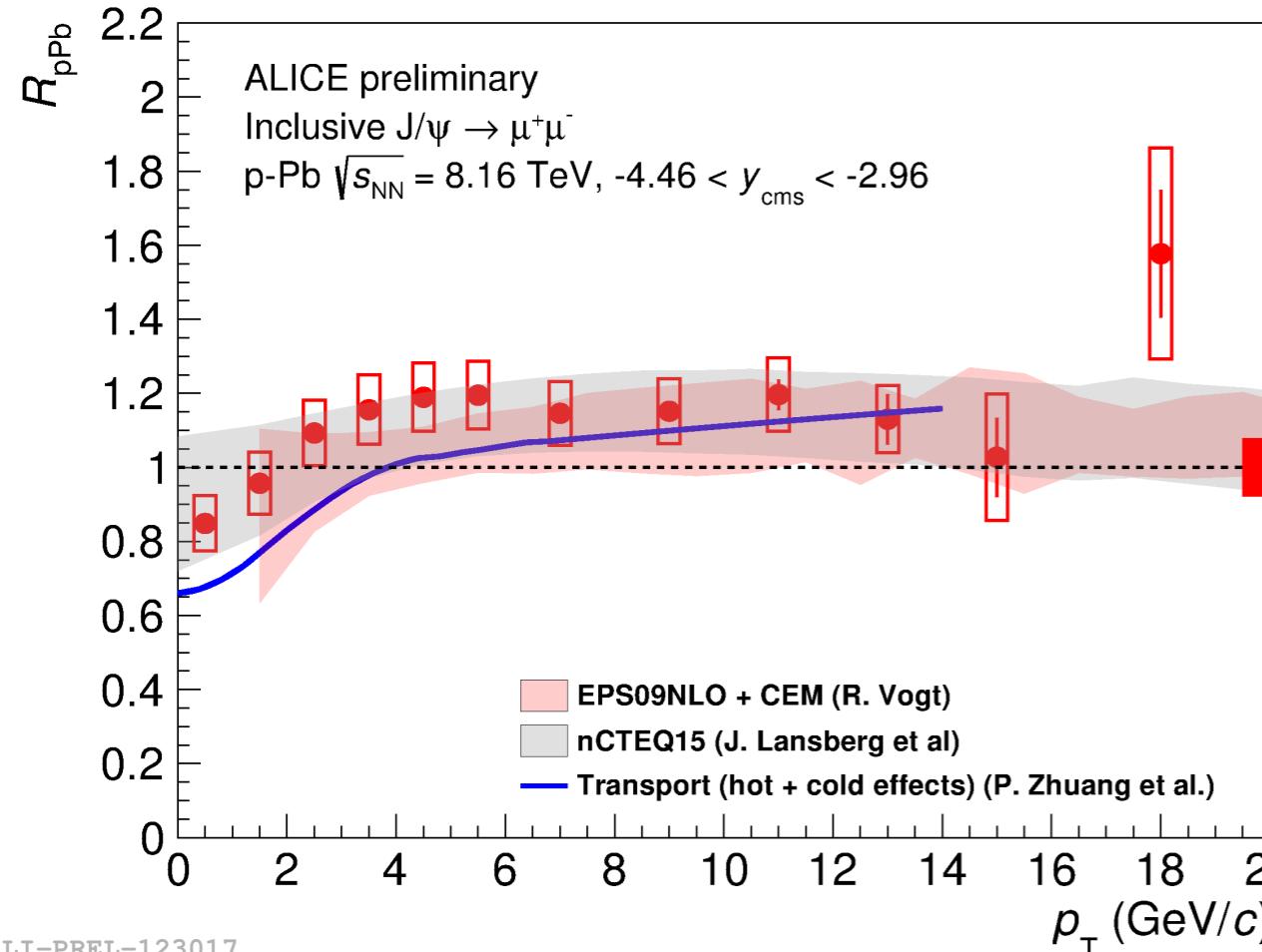
CNM: figure of merit



- High precision J/ψ measurements in p-A collisions at the LHC and RHIC
- At the LHC
 - Strong suppression at forward rapidity; Close to unity at backward rapidity
 - Fair description by shadowing, E-Loss or CGC (forward) models
- At RHIC
 - Significant suppression at mid-y
 - Significant nuclear absorption favored

J/ ψ R_{pPb} vs p_T

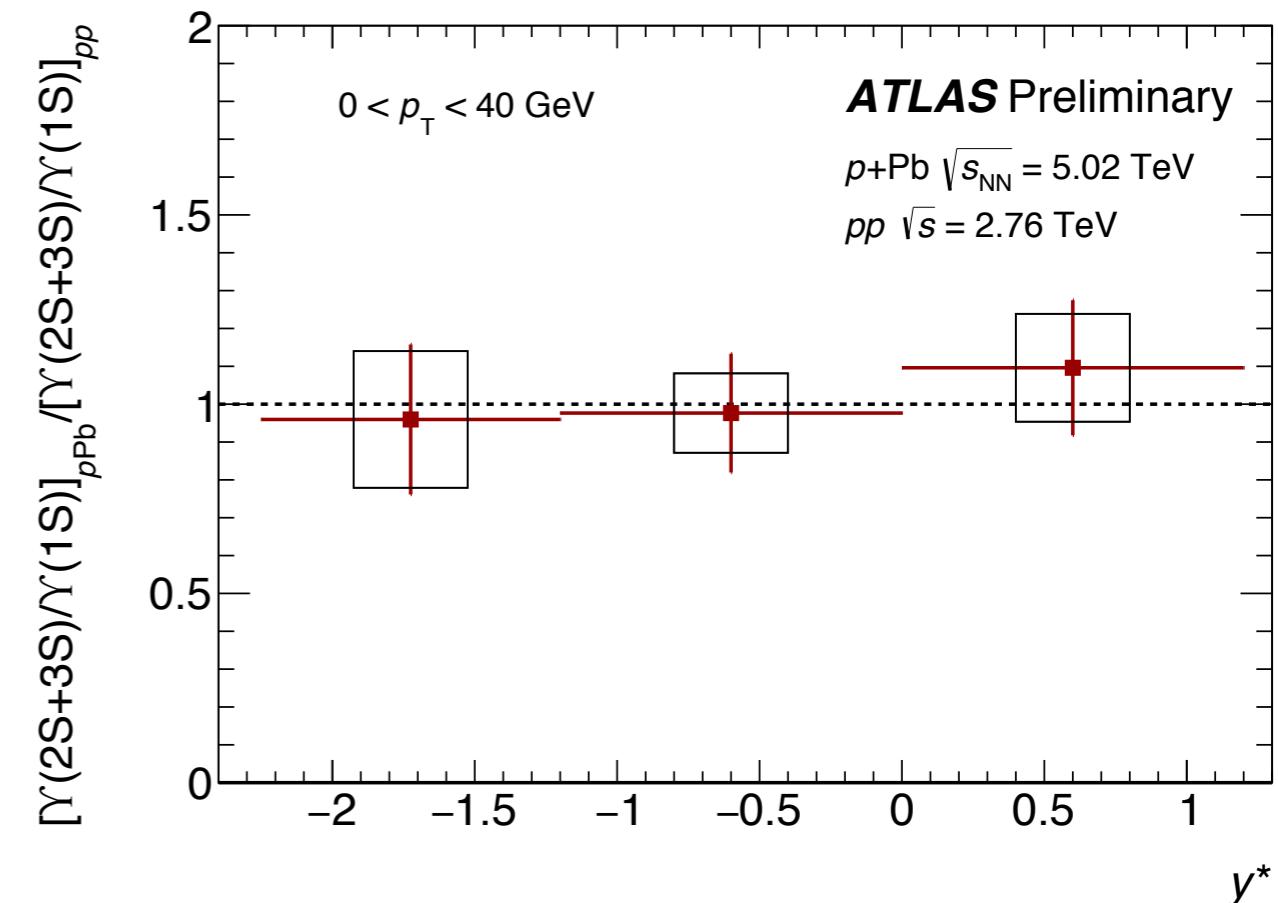
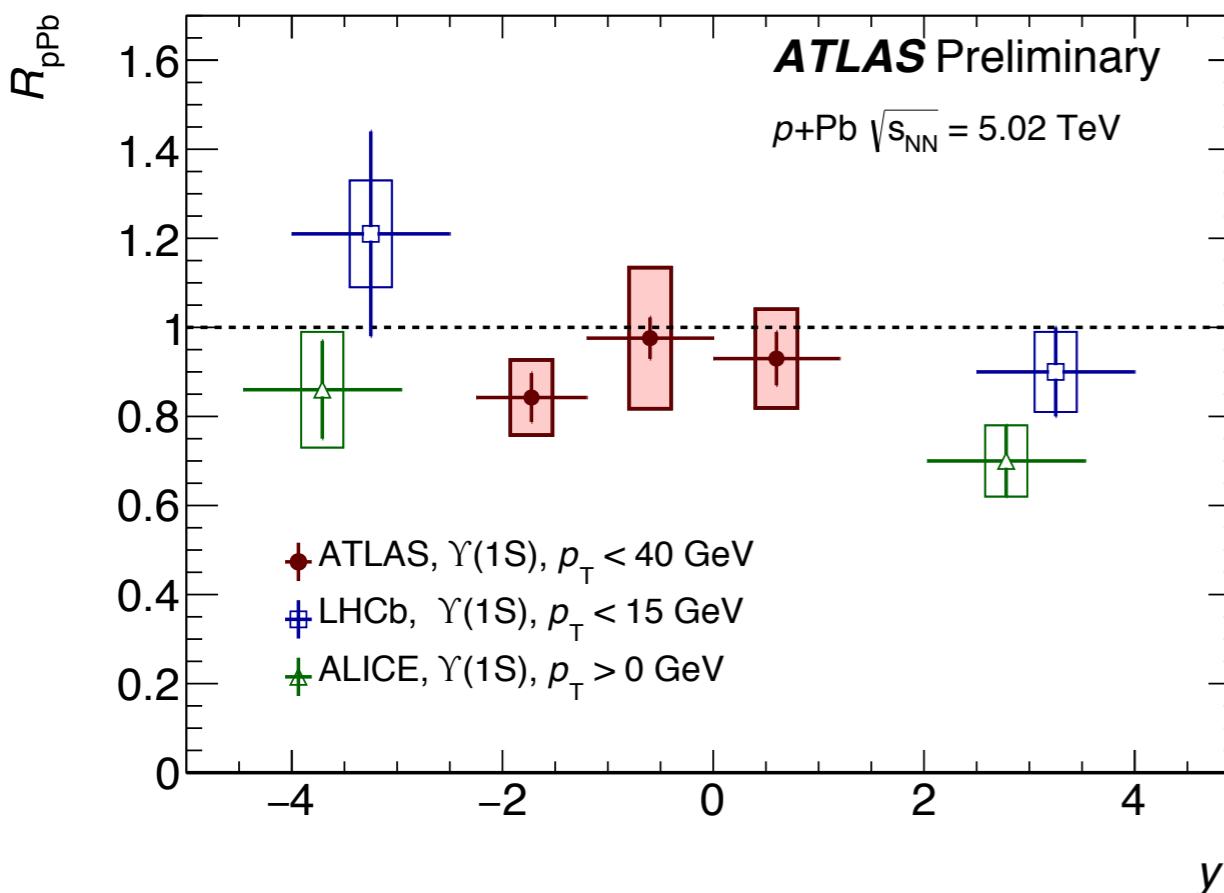
- Inclusive J/ ψ R_{pPb} at 8.16 TeV up to p_T = 20 GeV/c



- Backward-y
 - Weak p_T dependence; Hint for R_{pPb} > 1 for p_T > 4 GeV/c (due to non-prompt)
 - Fairly well described by models (shadowing, ...)
- Forward-y
 - Stronger p_T dependence; Saturates at 1 for p_T > 8 GeV/c
 - Fairly well described by models (shadowing, CGC, ...)

Υ in p-Pb collisions at LHC

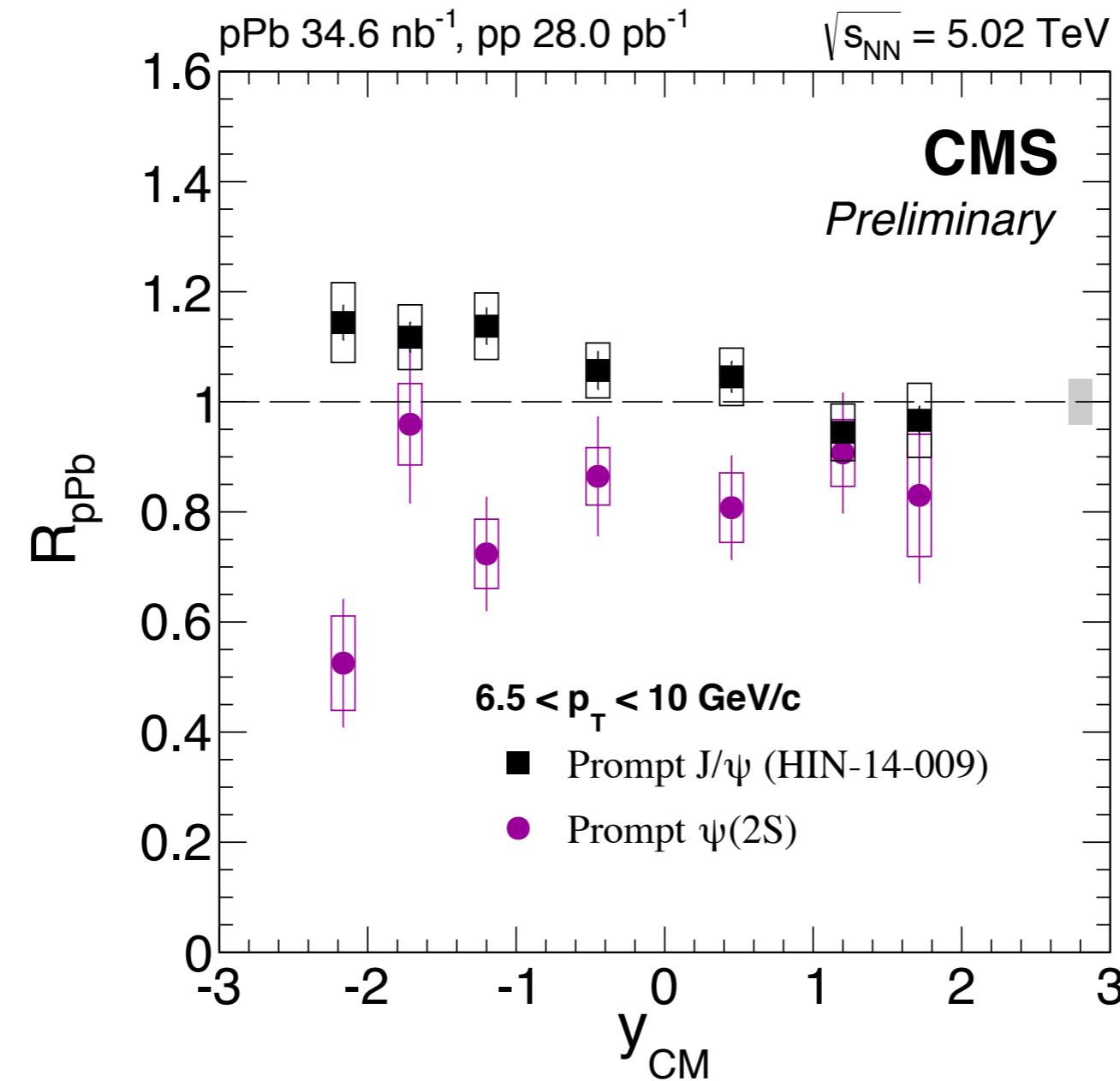
- $\Upsilon R_{p\text{Pb}}$ measured over a wide rapidity range by ALICE, LHCb and ATLAS
 - No strong suppression observed at backward nor mid-y
 - Signs of suppression at forward y



- Note: Different amount of CNM effects on the excited state $\Upsilon(2S)$ than on the ground state $\Upsilon(1S)$ is also seen (CMS [PRL 109 (2012) 222301])
 - Double ratio $[\Upsilon(2S)/\Upsilon(1S)]_{p\text{Pb}}/[\Upsilon(2S)/\Upsilon(1S)]_{pp} = 0.83 \pm 0.05(\text{stat.}) \pm 0.05(\text{syst.})$
 - Not confirmed (yet) by ALICE nor ATLAS

$\psi(2S)$ in p-Pb collisions at LHC

- $\psi(2S)$ is more suppressed than J/ψ in p-Pb collisions at the LHC
 - Stronger effect towards backward rapidity

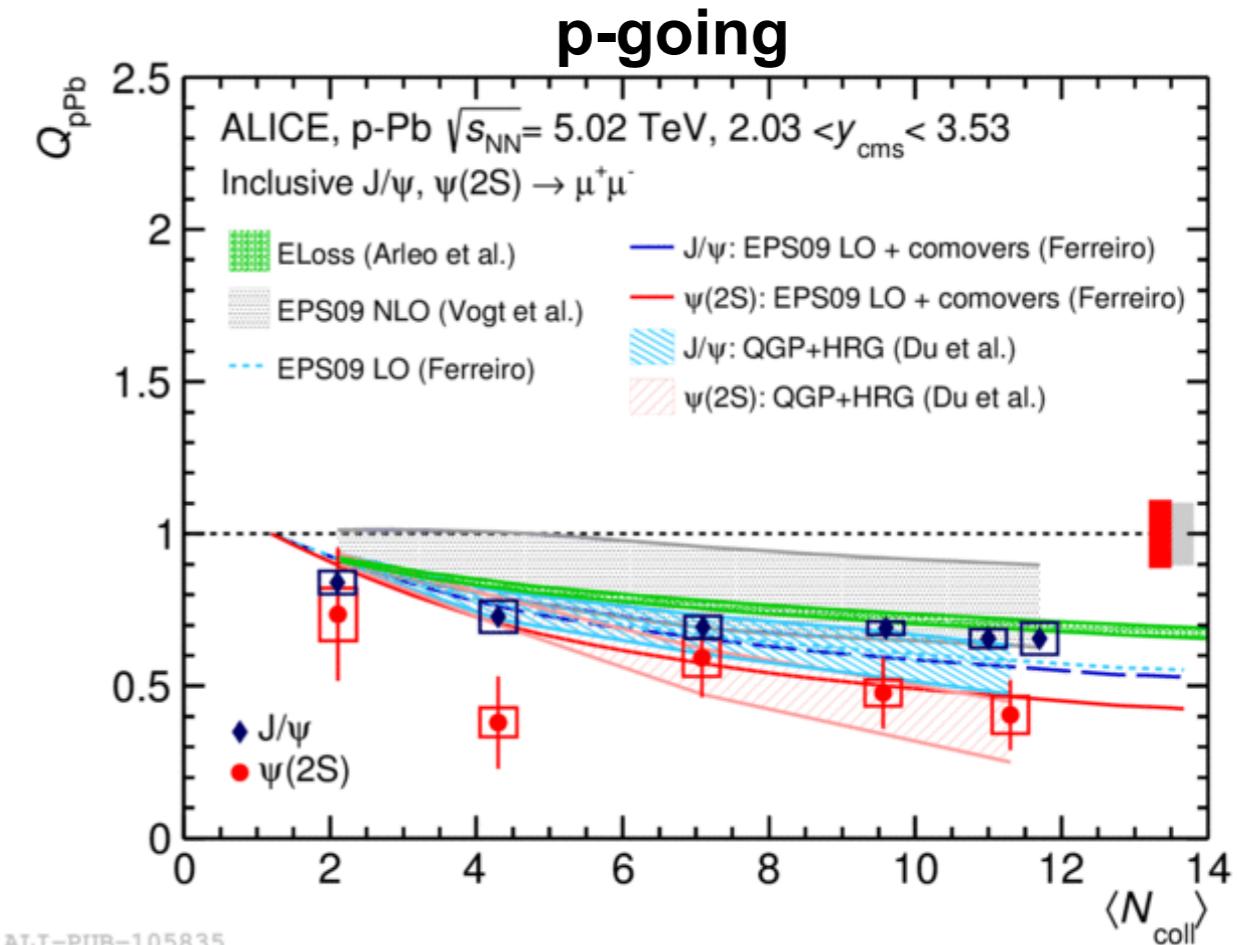
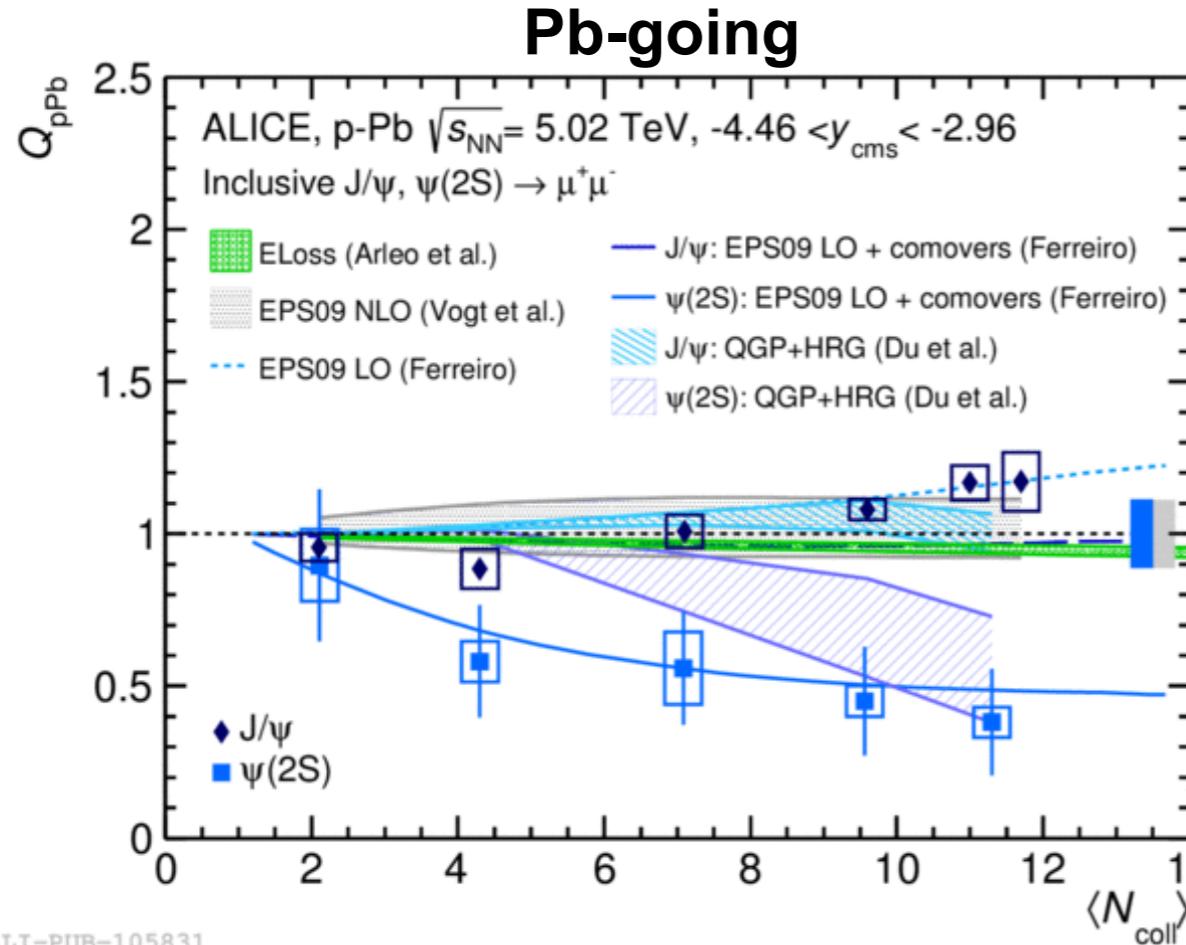


- Not expected in shadowing or E-loss models

J/ ψ and $\psi(2S)$ in p-Pb collisions at 5.02 TeV

JHEP 1606 (2016) 050

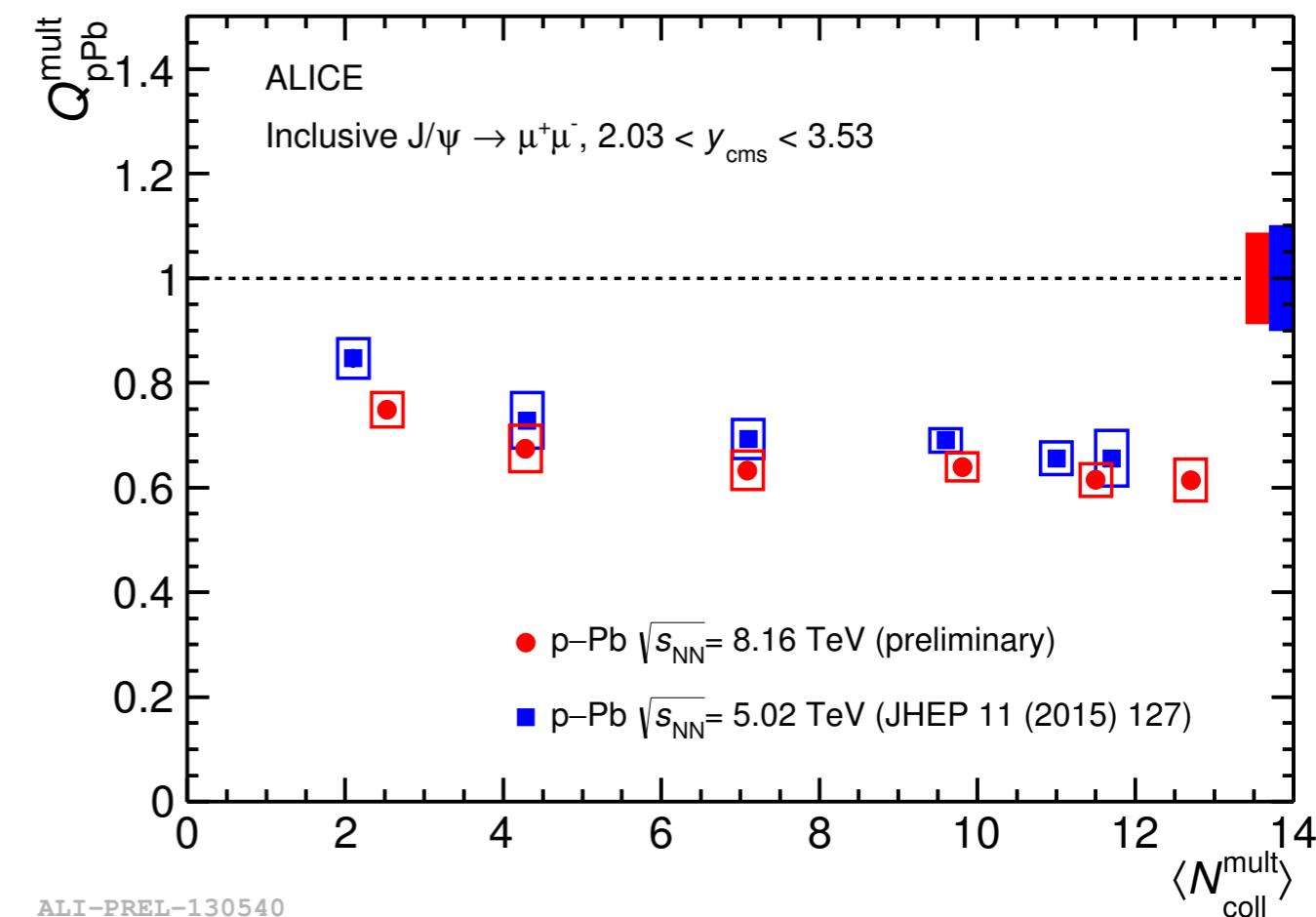
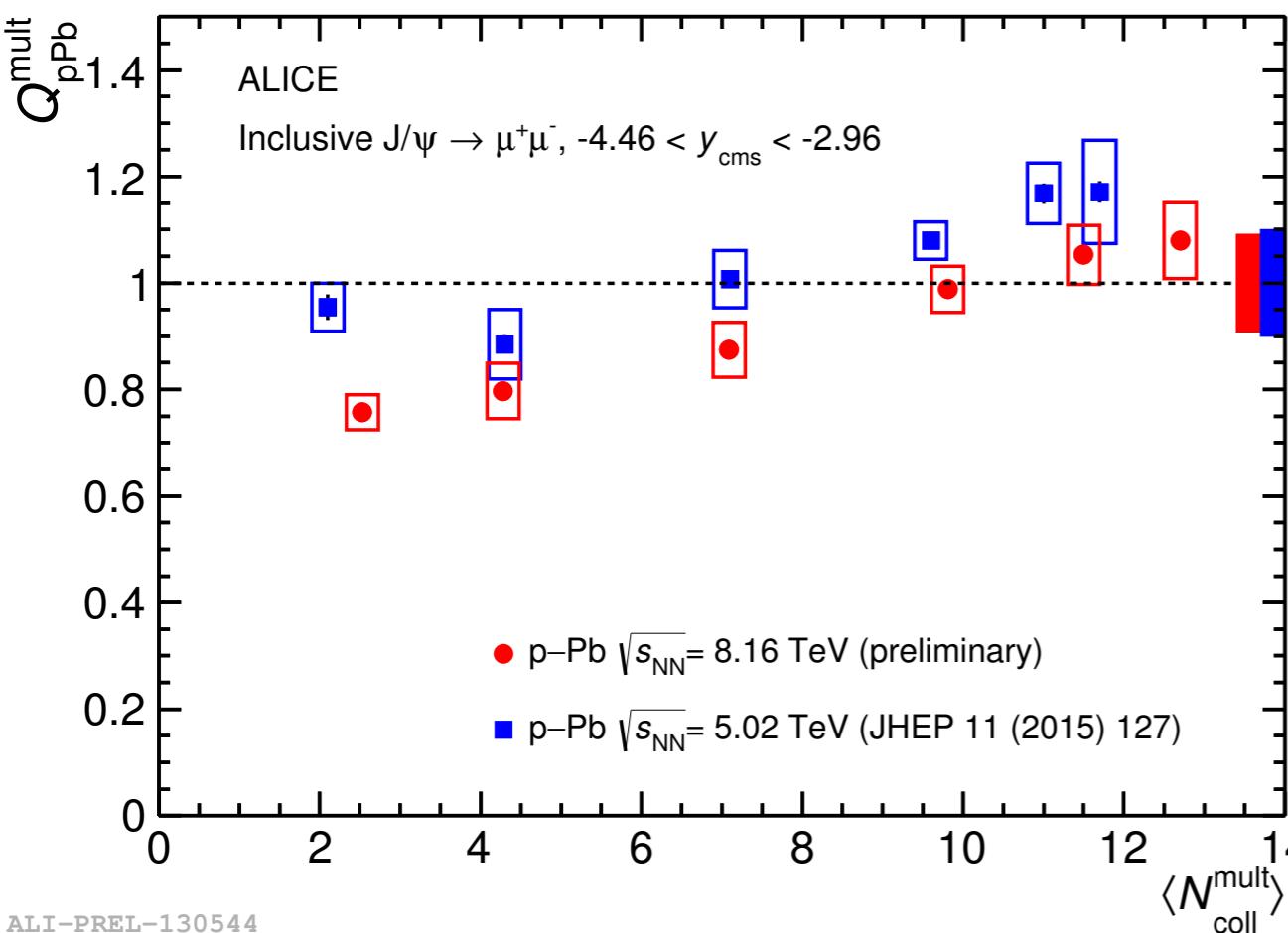
- Centrality dependence of J/ ψ and $\psi(2S)$ in p-Pb collisions at 5.02 TeV



- J/ ψ is suppressed in the p-going direction
 - Models including shadowing or energy loss mechanisms can describe the observed centrality dependence
- $\psi(2S)$ is more suppressed than J/ ψ
 - Stronger effect in the Pb-going than in the p-going direction
 - Effect increases with increasing centrality
 - Only models including some final-state interaction with co-moving medium reproduce the results

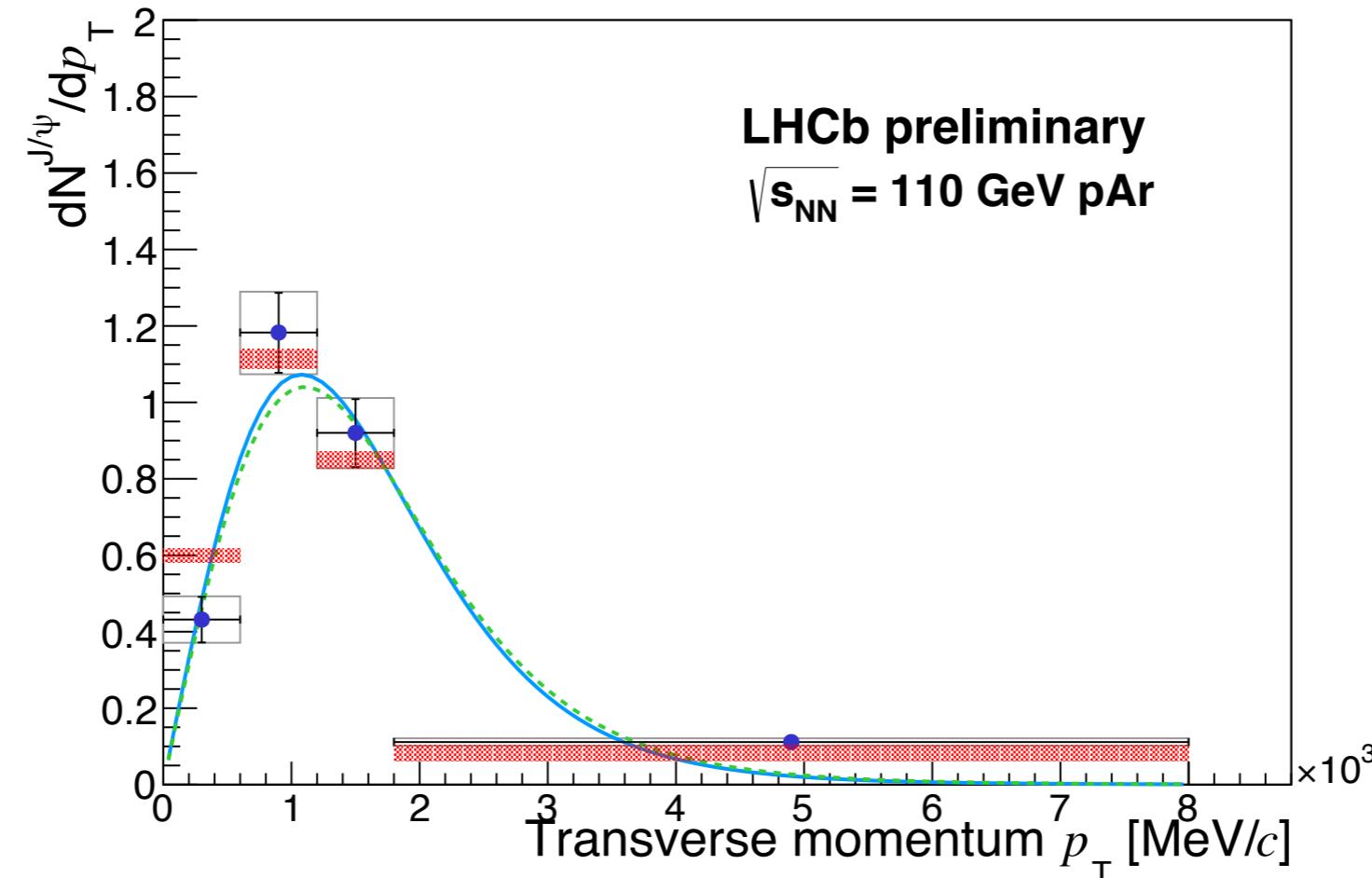
Inclusive J/ ψ Q_{pPb} versus N_{coll} at 8 TeV

- Similar patterns at 8 TeV than at 5 TeV
 - Improved uncertainties
 - Q_{pPb} decreases with N_{coll} at forward rapidity while the opposite trend is observed in backward rapidity
 - Slightly lower values at 8 TeV



Fixed target at LHC

- p-Ar collisions at 110 GeV
 - CM Frame at Rapidity 4.77
 - $2 < y_{\text{lab}} < 4.9$ and $-2.77 < y < 0.13$



- J/ψ is suppressed at low p_T
 - Compared to PYTHIA 8 (red shaded boxes)
 - Well described by E-loss calculation [JHEP 05 (2013) 155]
- First steps towards a systematic mapping of CNM effects

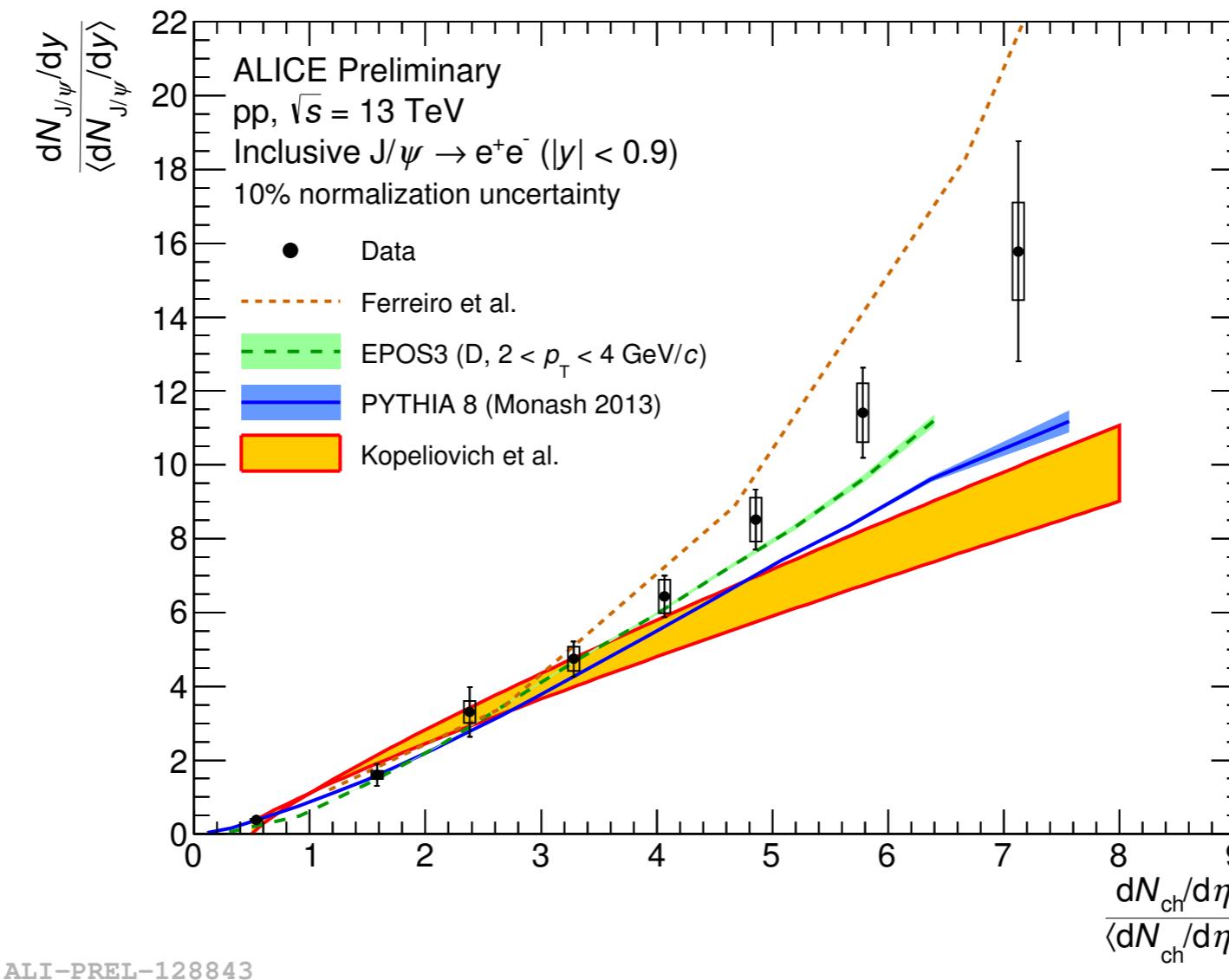
Summary

- Sequential suppression of quarkonium resonances is observed
 - Upsilon family
 - High transverse momentum charmonia
- The regeneration mechanism do play an important role in charmonium production
 - $J/\psi R_{AA}$ at low transverse momentum is higher at LHC than at RHIC
 - Centrality, p_T and y dependence of $J/\psi R_{AA}$
 - Non-zero $J/\psi v_2$
- “Cold Nuclear Matter effects” are important and complicate the picture, but are being nailed-down
 - Qualitatively well understood, not yet quantitatively
 - The extrapolation from $p\text{-}A$ to $A\text{-}A$ is still a challenge
- High precision data is becoming available at both RHIC and LHC
 - It is time for a quantitative (not only qualitative) description of all quarkonium results

Backup

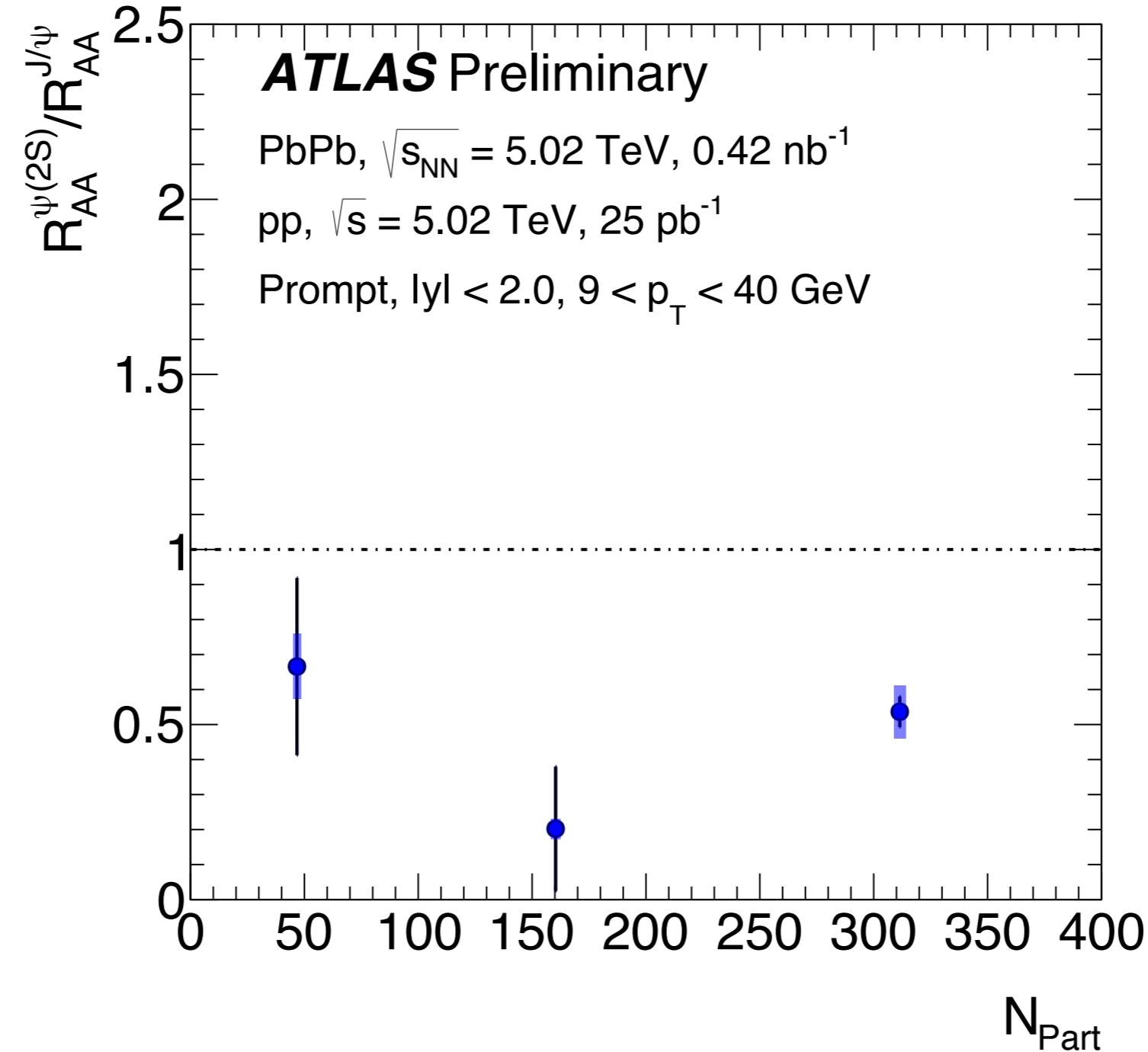
J/ ψ in high-multiplicity pp collisions

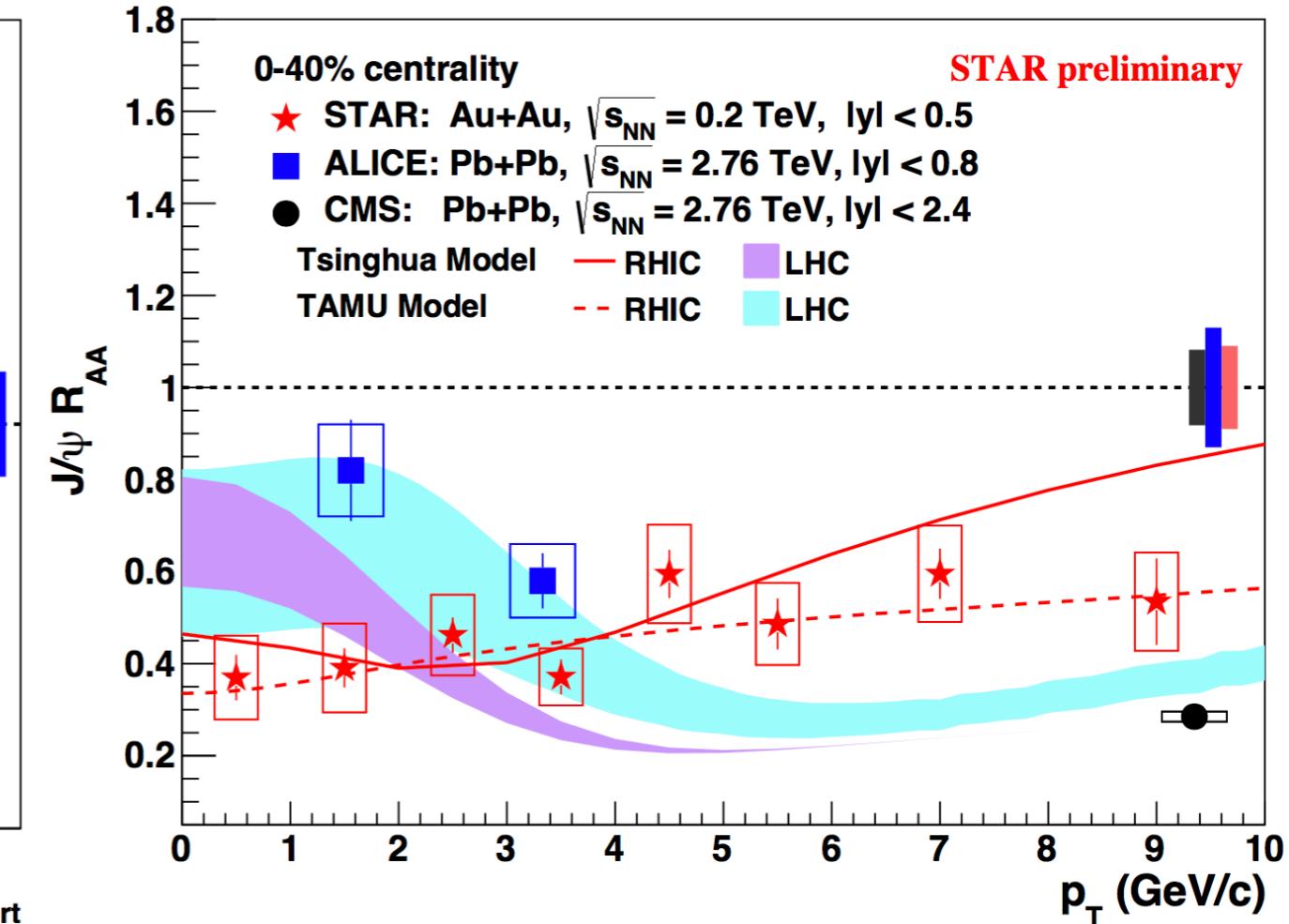
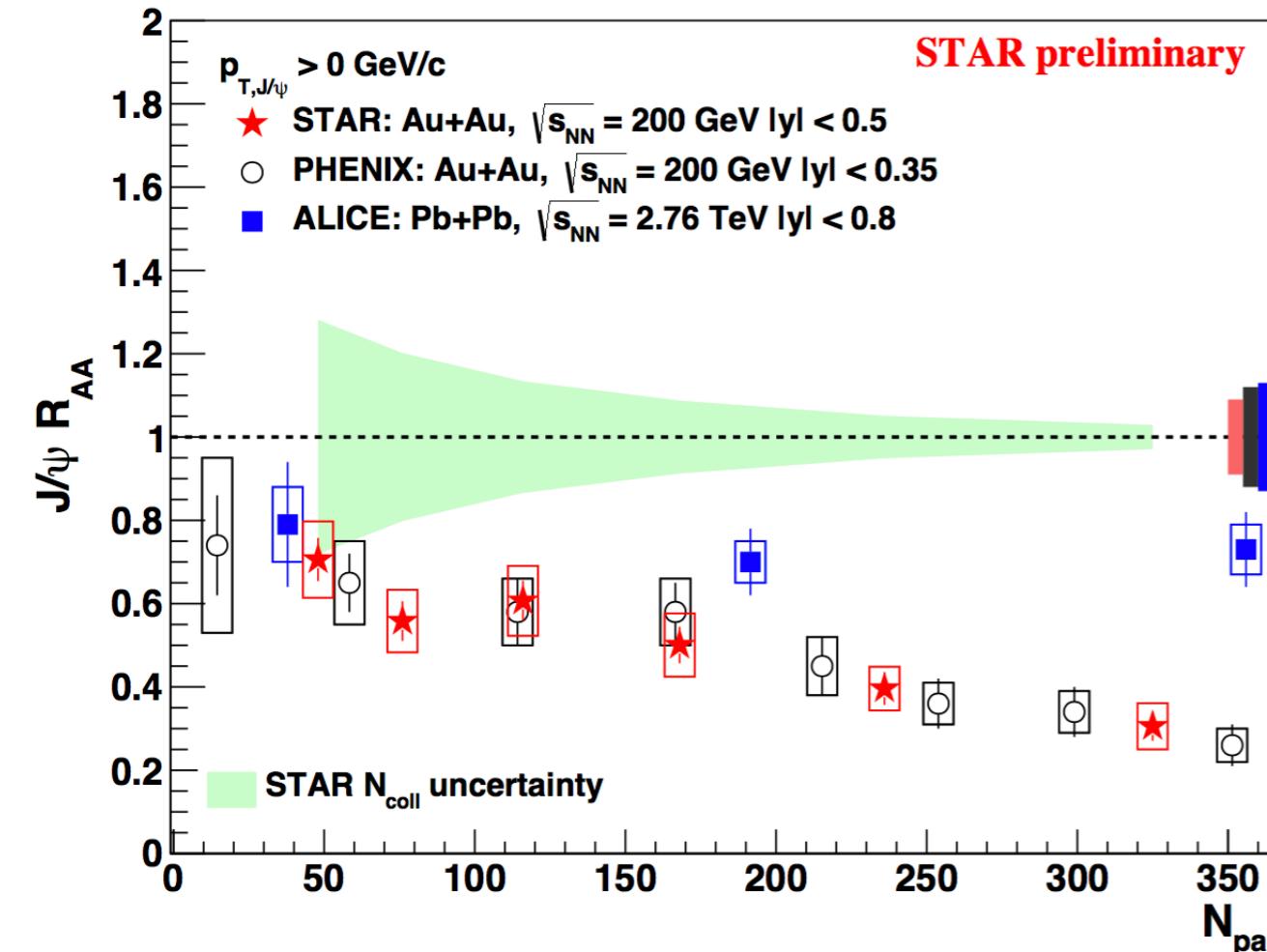
- Self-normalised yields vs relative charged-particle multiplicity at mid-rapidity in pp collisions at 13 TeV
- Faster than linear increase



High- p_T $\Psi(2S)$ suppression

- High- p_T $\Psi(2S)$ is more suppressed than high- p_T J/ψ

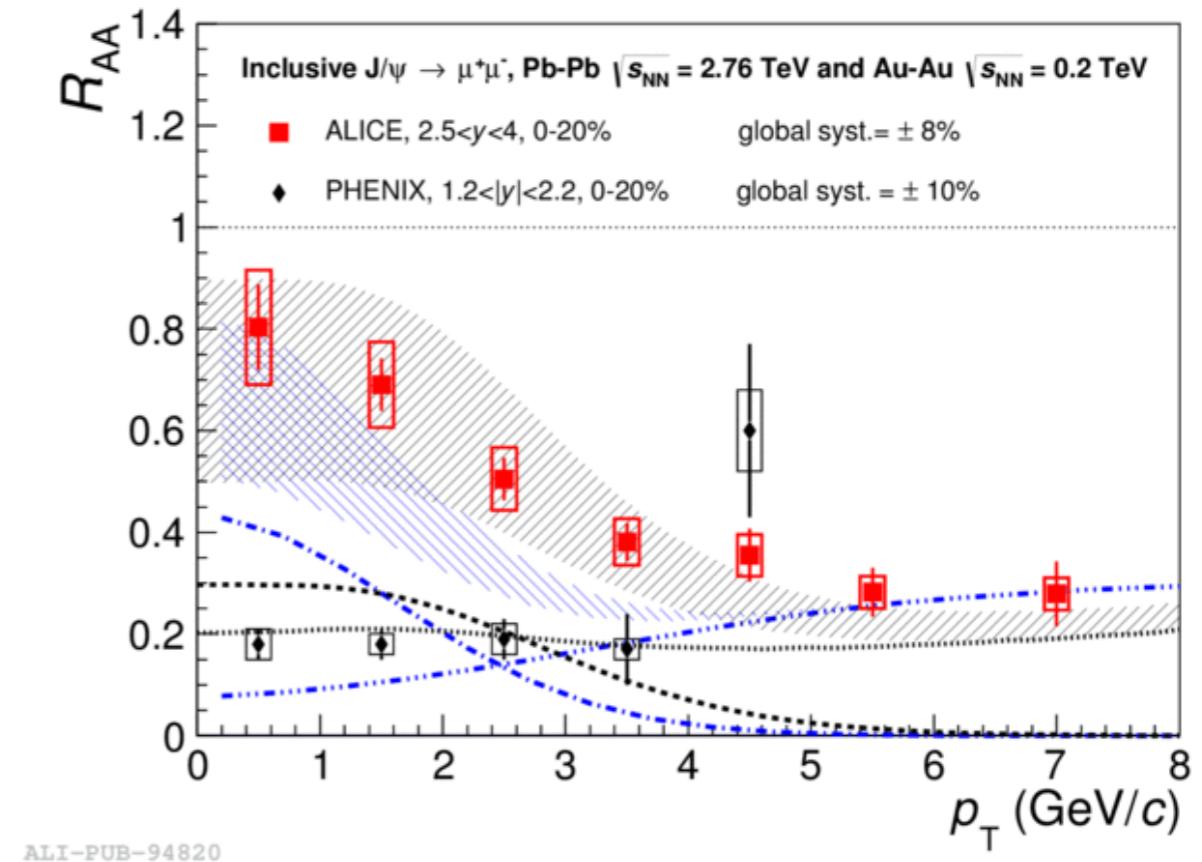
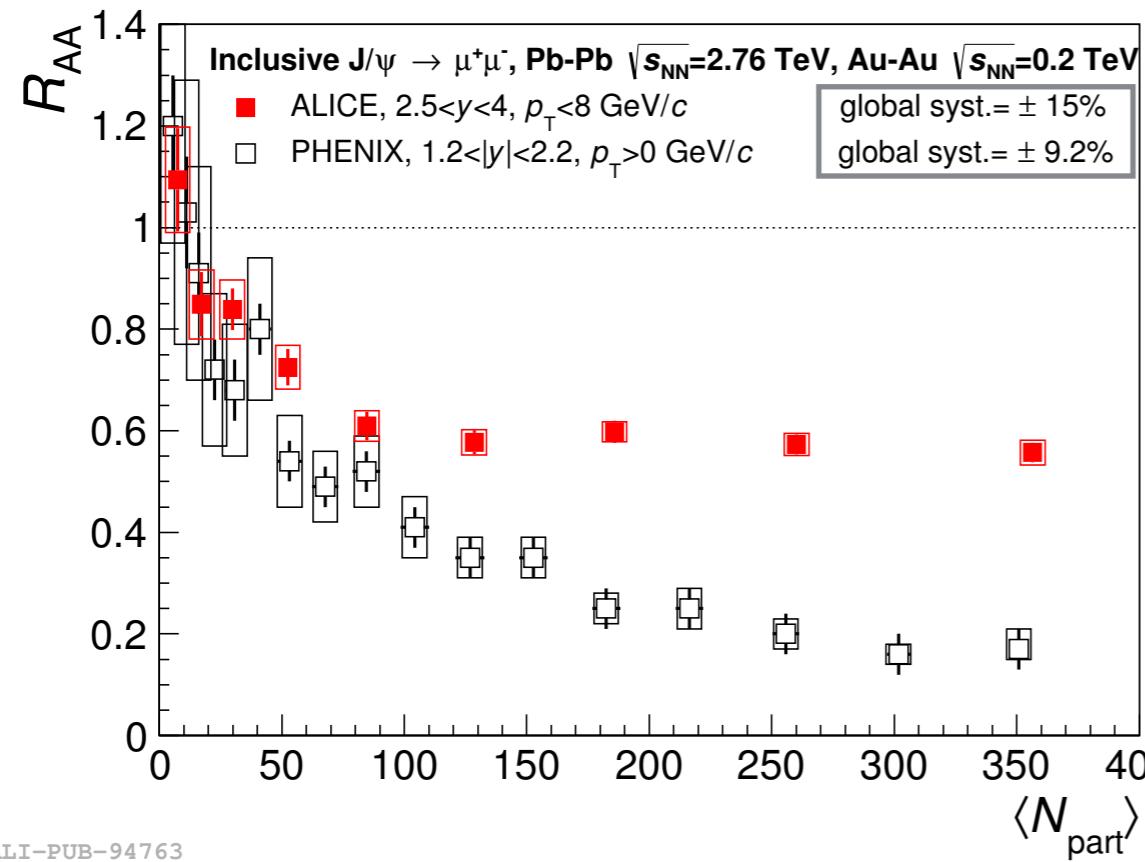




J/ ψ suppression in Pb-Pb collisions at 2.76 TeV

JHEP 1605 (2016) 179

- At 2.76 TeV
 - Flat J/ ψ R_{AA} for $N_{\text{part}} > 70$
 - Higher J/ ψ R_{AA} for central collisions at the LHC than at RHIC
 - J/ ψ R_{AA} increases with decreasing p_T

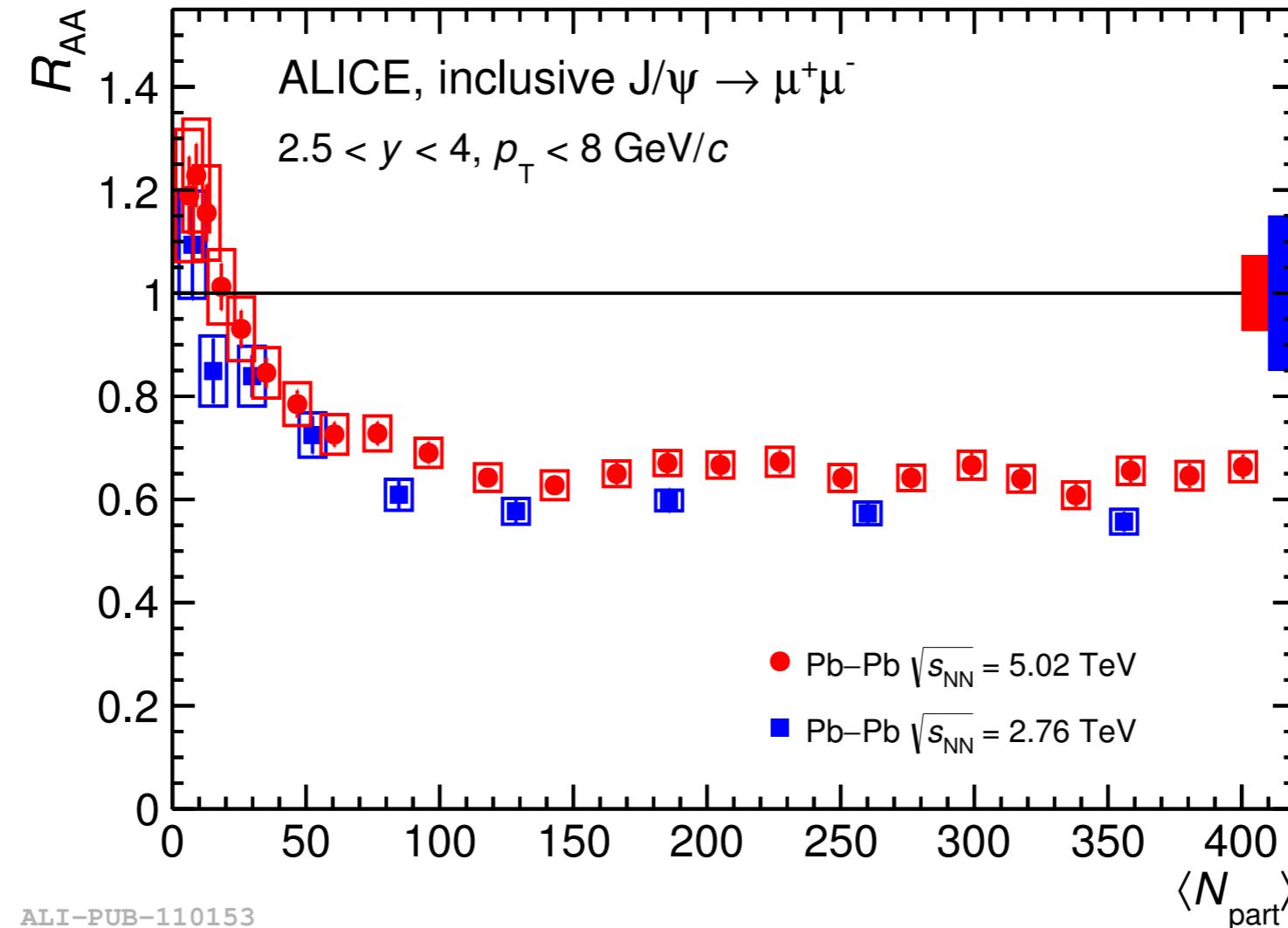


- Well described by models including partial or full regeneration of J/ ψ in the QGP or at hadronisation
- Confirmed at 5 TeV?

J/ ψ R_{AA} in Pb-Pb 5 TeV

CERN-EP-2016-162

- R_{AA} versus centrality
 - Similar trend at 5 TeV and at 2.76 TeV
 - Increased statistics and reduced uncertainties

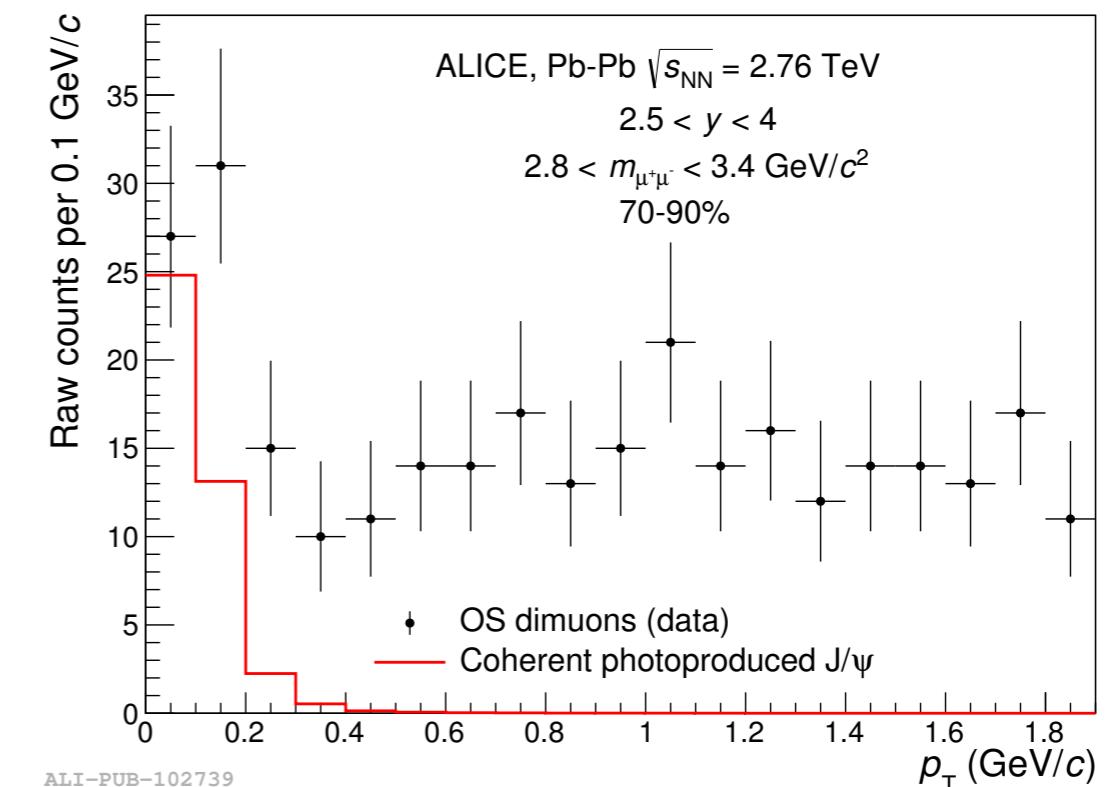
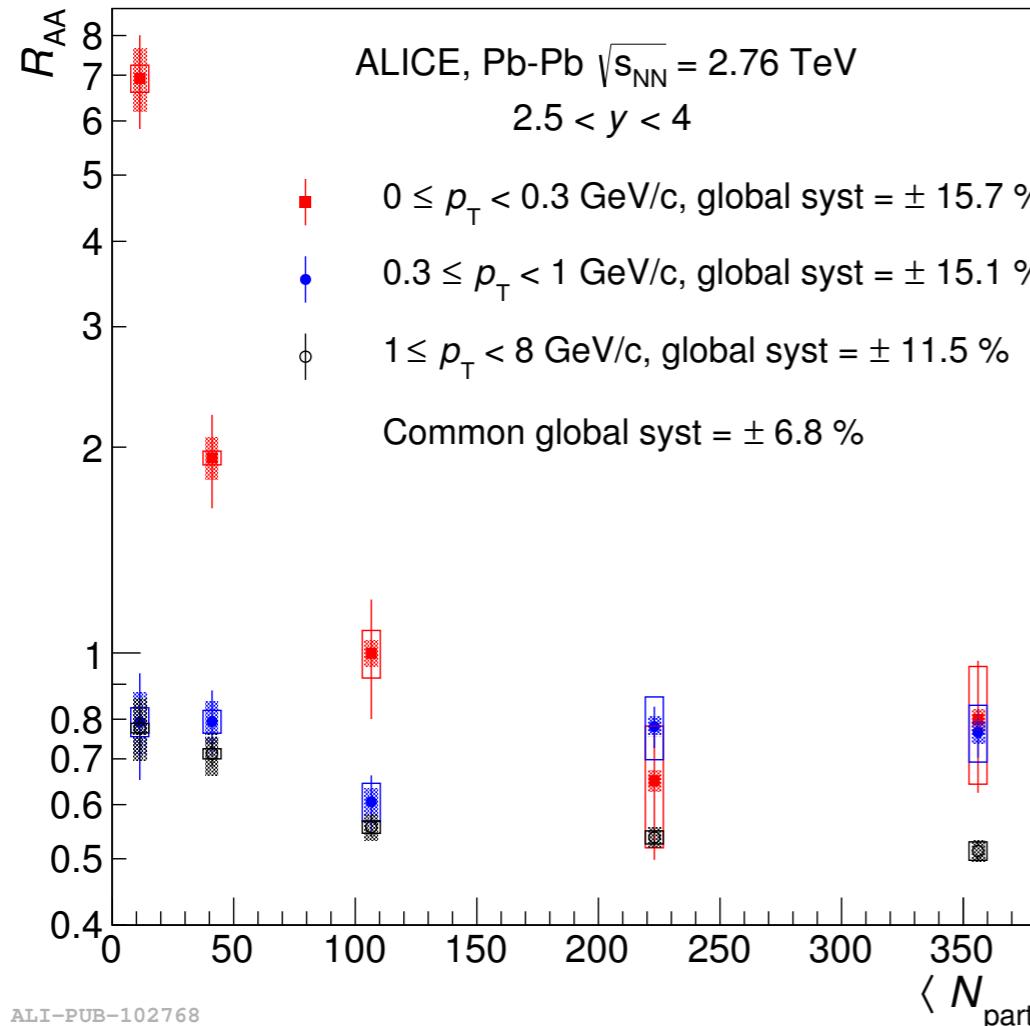


- $R_{AA}^{0-90\%}(5.02 \text{ TeV}, p_T < 8 \text{ GeV}/c) = 0.66 \pm 0.01(\text{stat}) \pm 0.05(\text{syst})$
- $R_{AA}^{0-90\%}(2.76 \text{ TeV}, p_T < 8 \text{ GeV}/c) = 0.58 \pm 0.01(\text{stat}) \pm 0.09(\text{syst})$
- $R_{AA}^{0-90\%}(5.02 \text{ TeV}) / R_{AA}^{0-90\%}(2.76 \text{ TeV}) = 1.13 \pm 0.02(\text{stat}) \pm 0.18(\text{syst})$

Excess of very-low- p_T J/ ψ

PRL 116 (2016) 222301

- Very-low- p_T J/ ψ excess
 - Seen in peripheral Pb-Pb collisions at 2.76 TeV
 - Presumably of EM origin

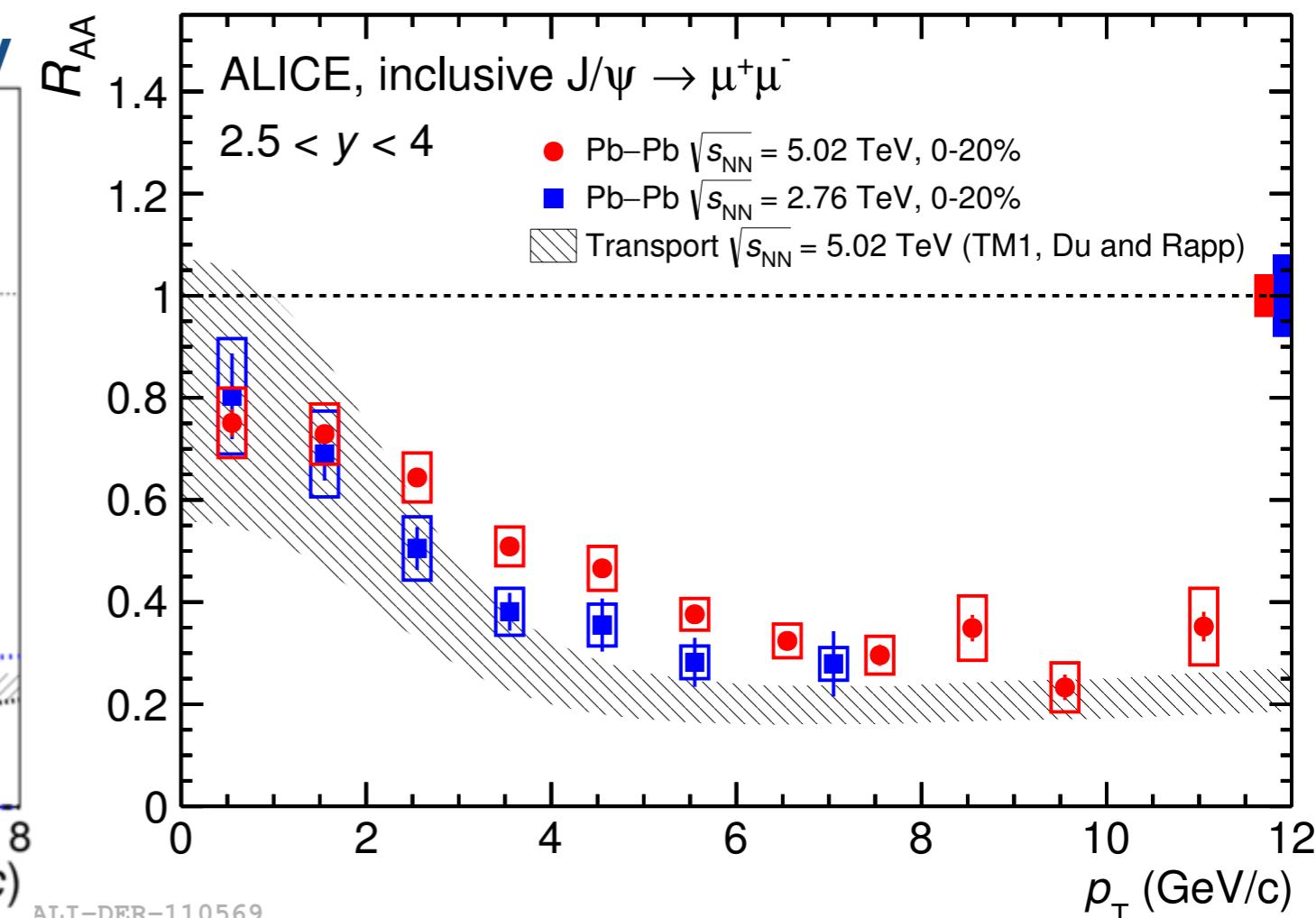
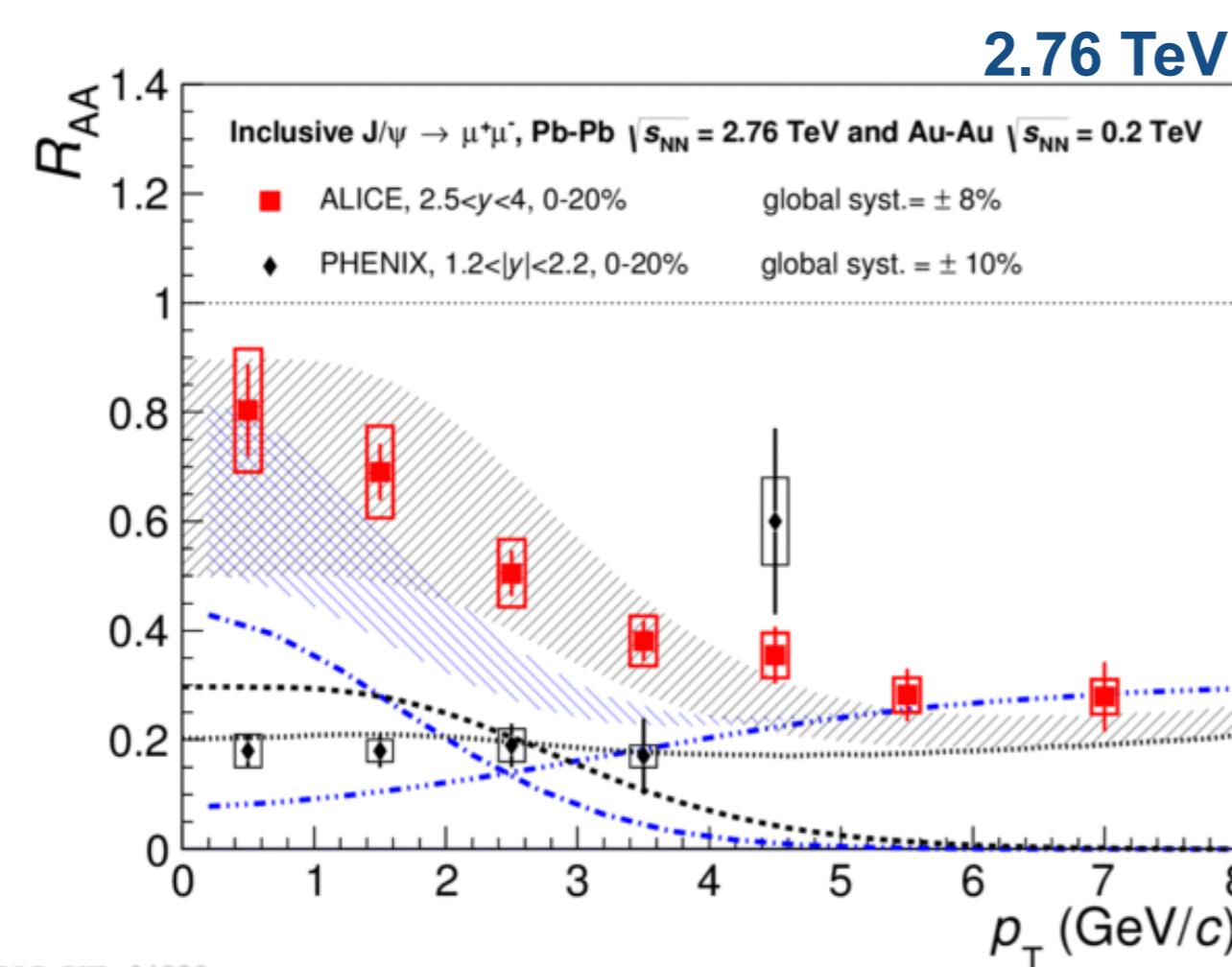


- Due to the very specific origin and kinematics, photo-produced J/ ψ could become an useful probe of the QGP
- In the mean time, it constitutes a “contamination” to the hadronic R_{AA}
 - Apply a cut $p_T > 0.3$ GeV to reduce photo-production contribution

J/ ψ R_{AA} – p_T dependence

CERN-EP-2016-162

- R_{AA} vs transverse momentum
 - Similar decreasing trend of R_{AA} with increasing p_T at both 2.76 and 5.02 TeV

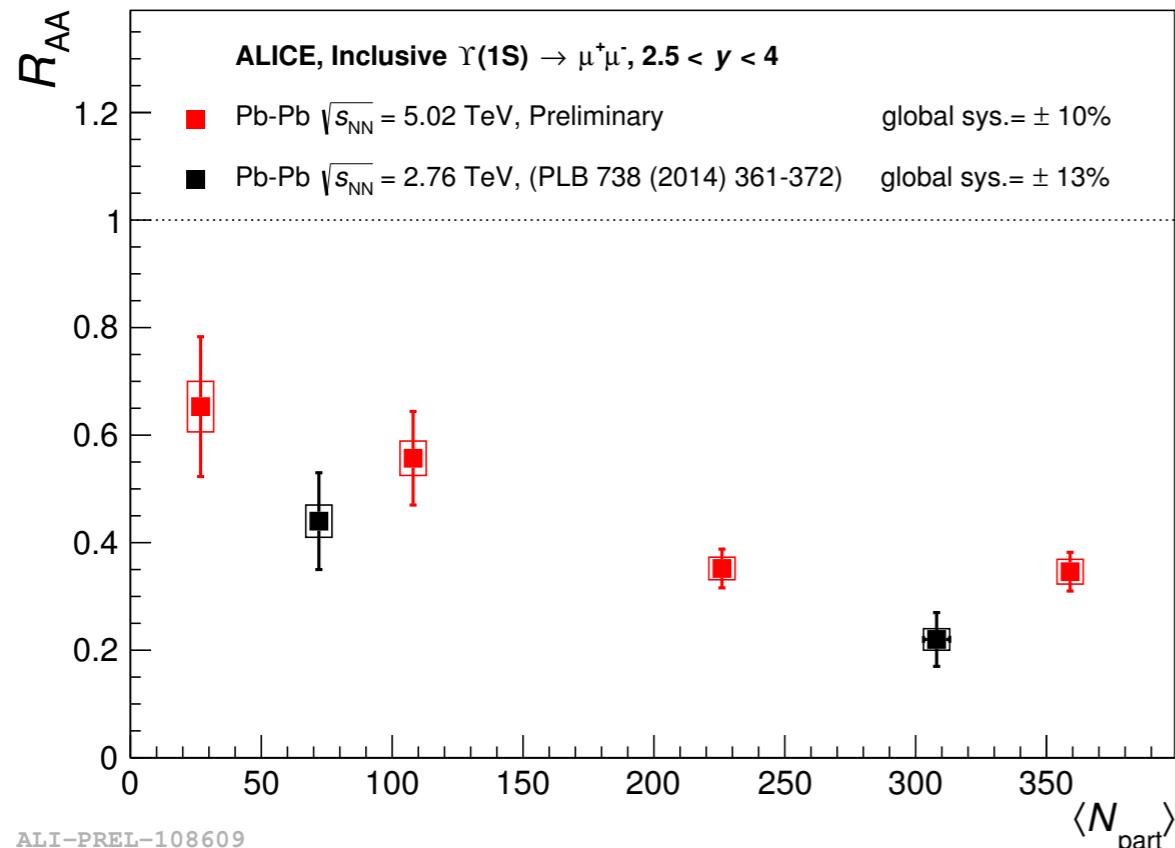


- Better model agreement at 2.76 TeV?

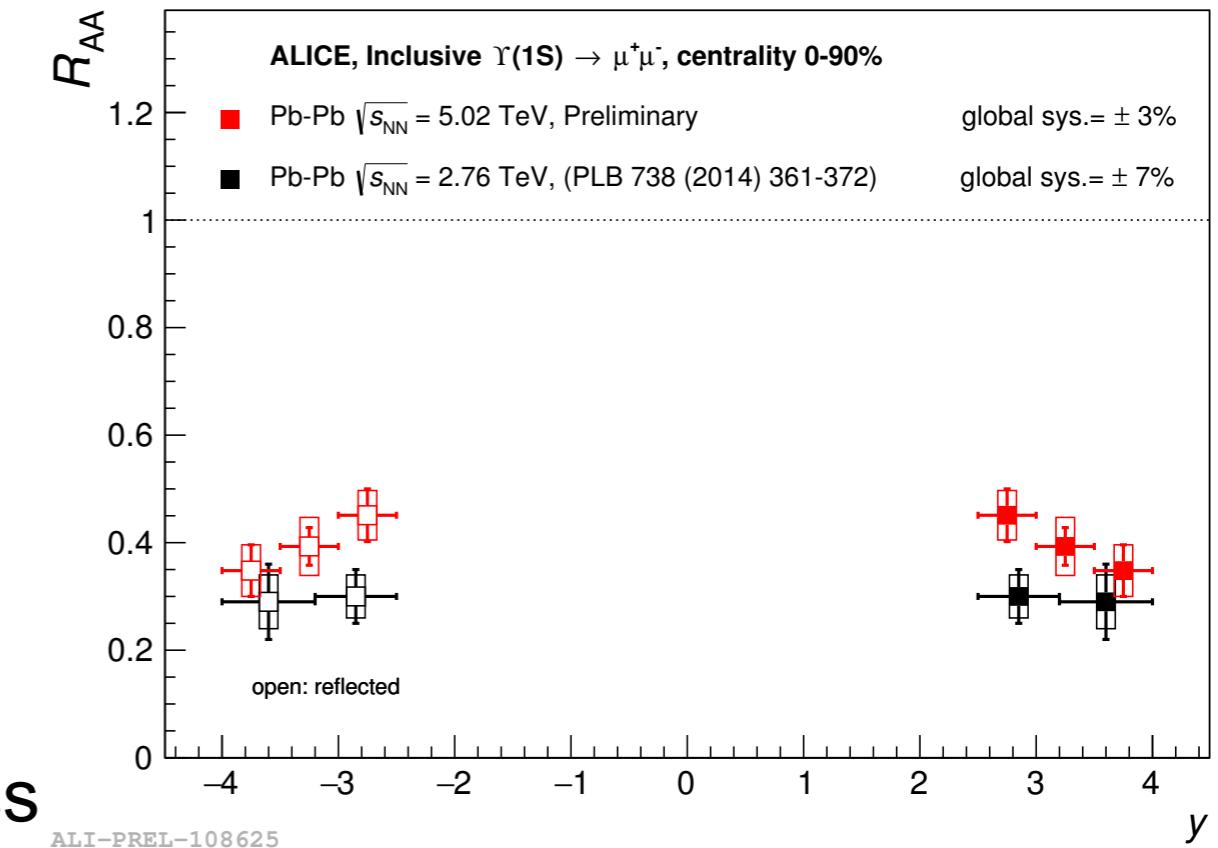
$\Upsilon(1S)$ R_{AA} in Pb-Pb at 5 TeV

- Integrated $\Upsilon(1S)$ R_{AA}

- $R_{AA}^{0-90\%}(5.02 \text{ TeV}) = 0.40 \pm 0.03(\text{stat}) \pm 0.04(\text{syst})$
- $R_{AA}^{0-90\%}(2.76 \text{ TeV}) = 0.30 \pm 0.05(\text{stat}) \pm 0.04(\text{syst})$
- $R_{AA}^{0-90\%}(5.02 \text{ TeV}) / R_{AA}^{0-90\%}(2.76 \text{ TeV}) = 1.3 \pm 0.2(\text{stat}) \pm 0.2(\text{syst})$



peripheral collisions

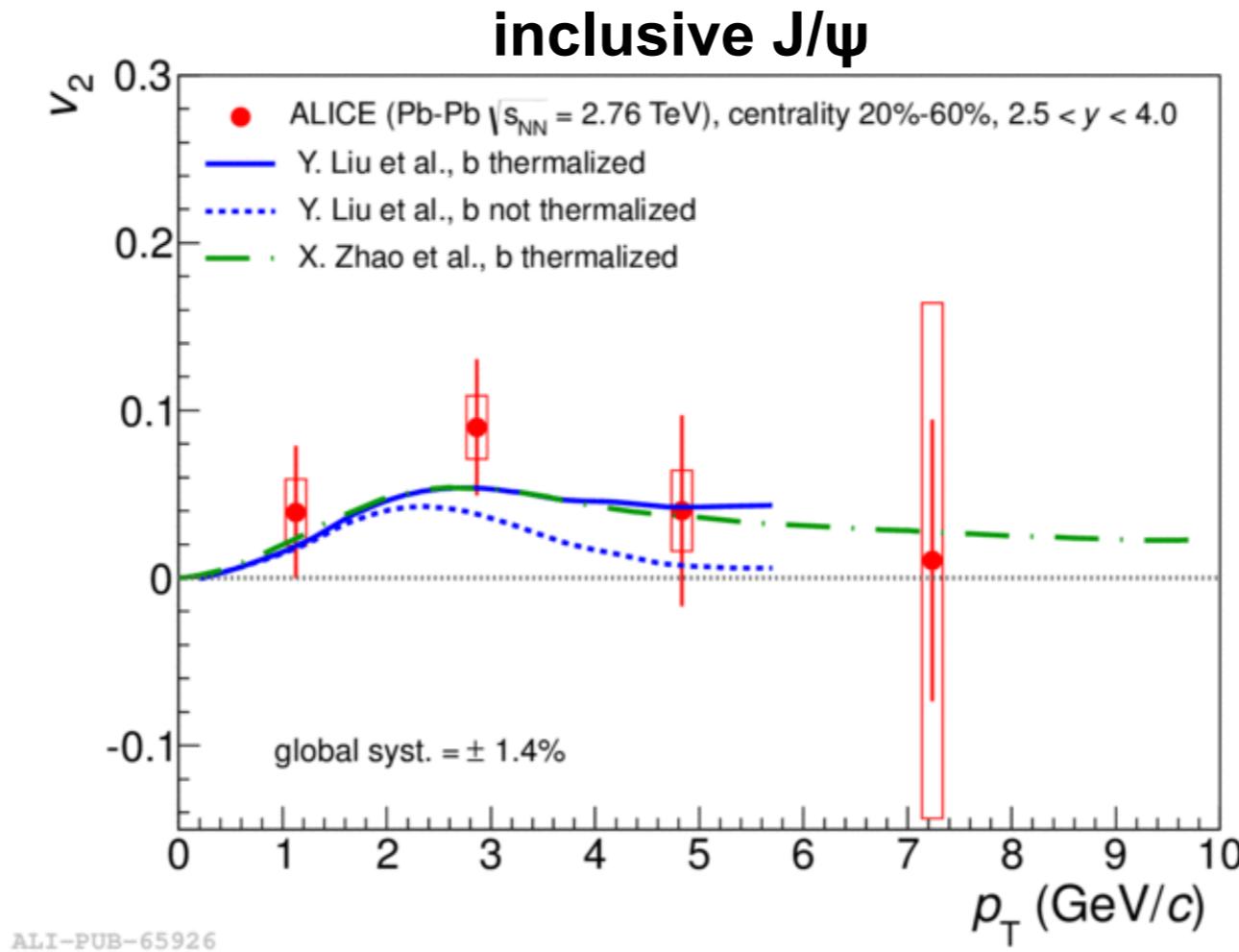


- No firm conclusion on the energy dependence possible with the current uncertainties

J/ψ elliptic flow

PRL 111 (2013) 162301

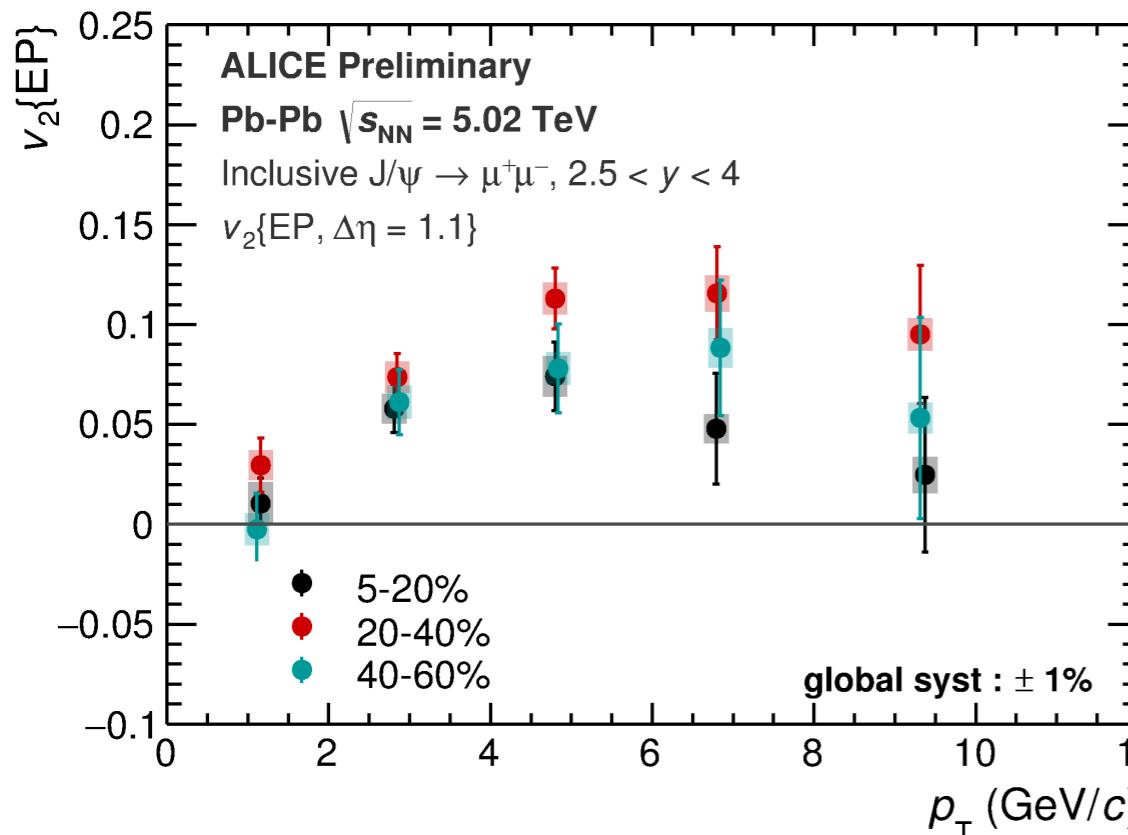
- If c quarks participate to the collective motion of the QGP, then they will acquire some elliptic flow
- Regenerated J/ψ will inherit the elliptic flow of the c quarks



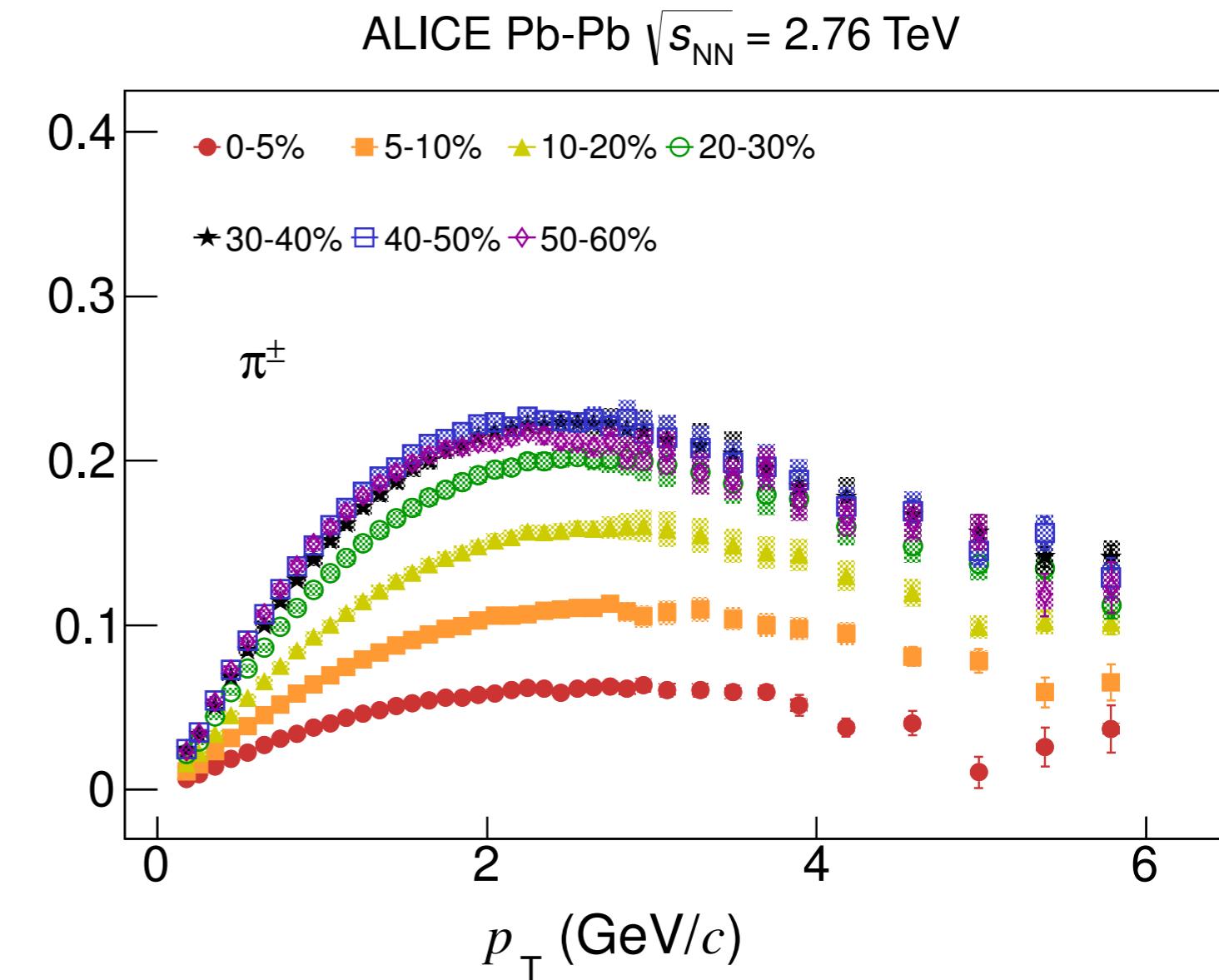
- Hint of non-zero J/ψ v_2 at intermediate p_T for semi-central collisions at the LHC
- Qualitatively described by models including regeneration
- Larger statistics of run 2 will help

Comparison to light particles

- Comparison to π^-
- Different centrality dependence
 - $J/\psi v_2(p_T)$:
 - $5\text{-}20\% < 20\text{-}40\% > 40\text{-}60\%$
 - $\pi^- v_2(p_T)$:
 - $40\text{-}60\% > 20\text{-}40\% > 5\text{-}20\%$



ALI-PREL-128122

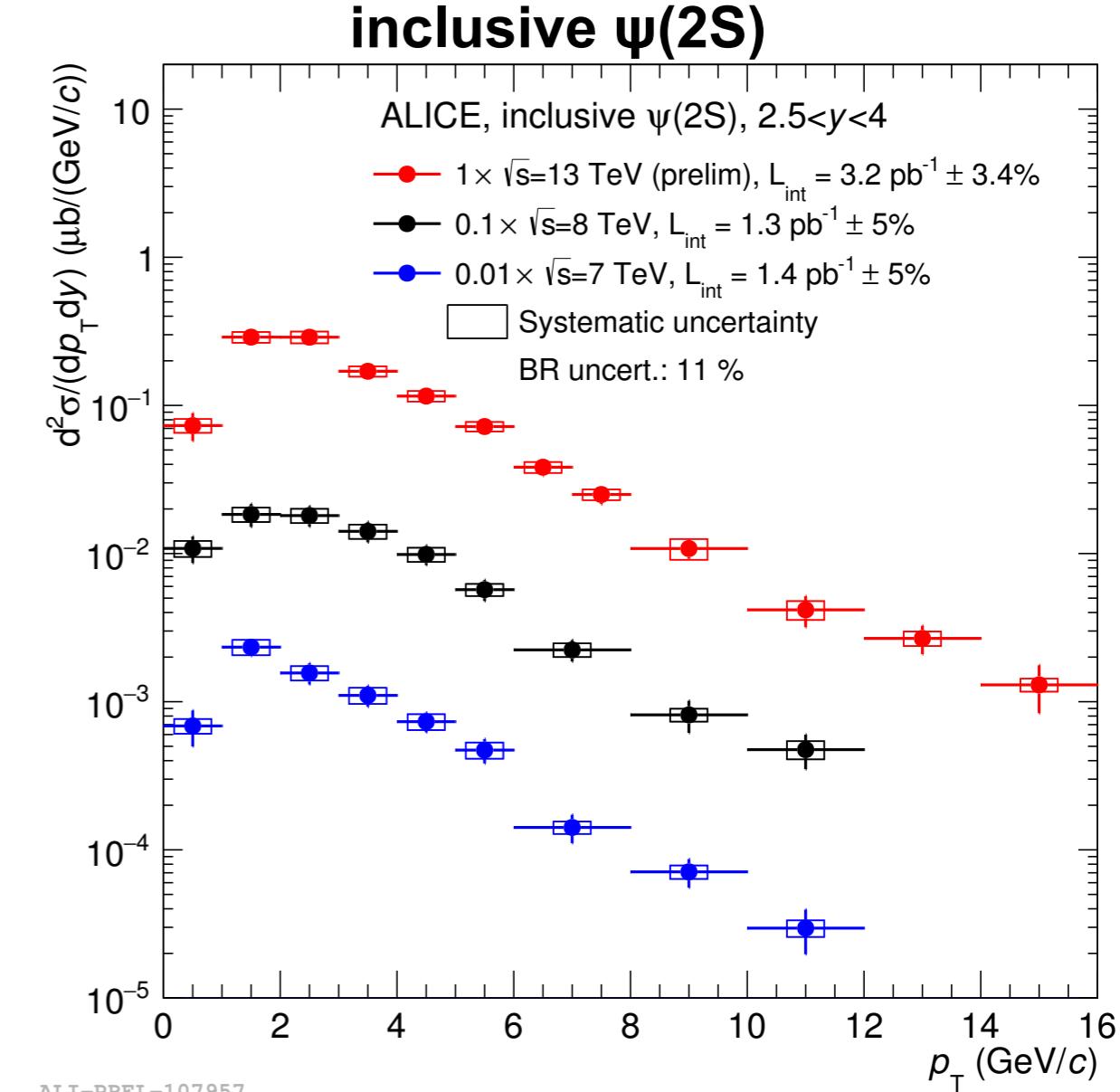
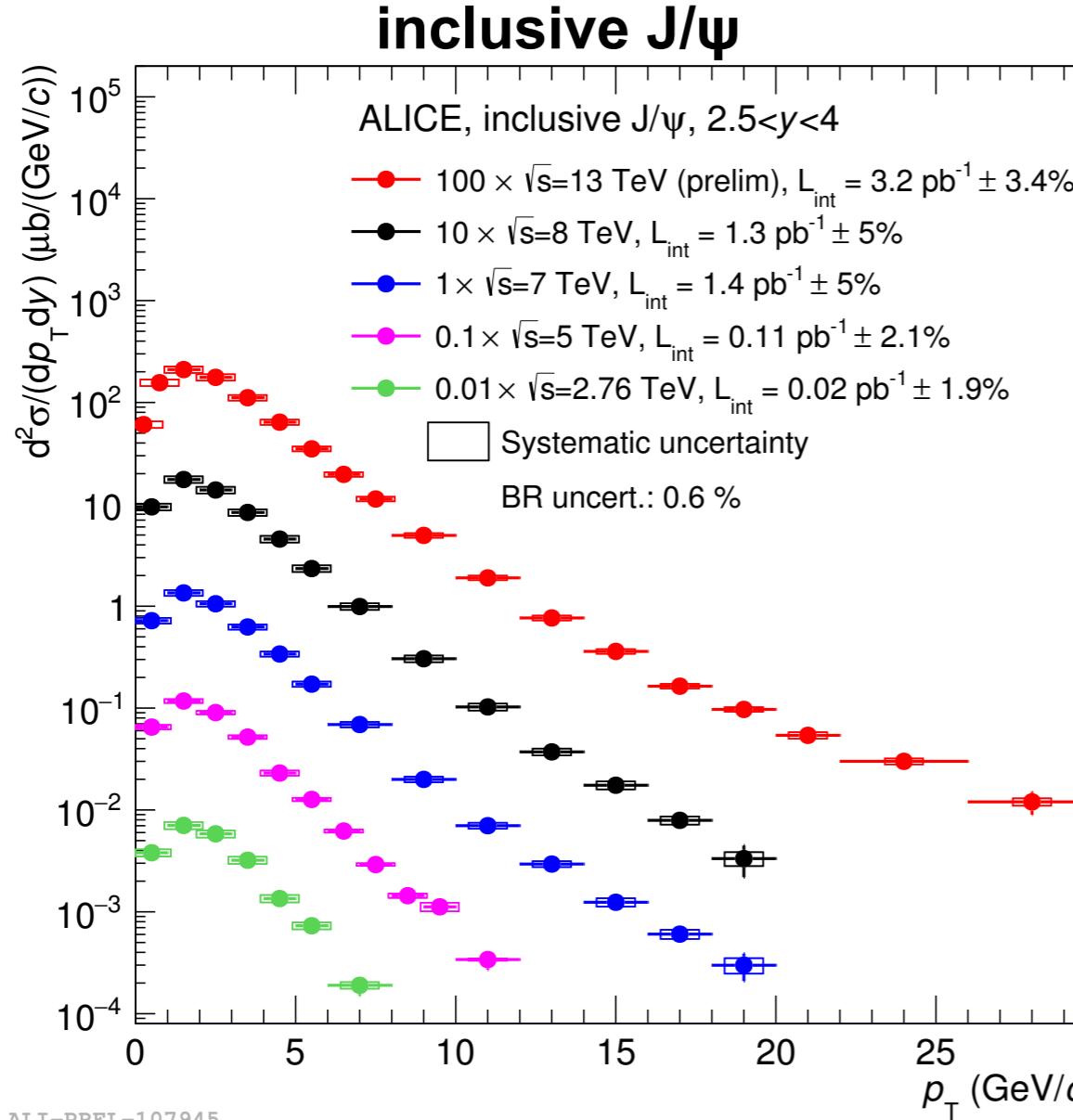


- In the context of thermal models it can be understood as a dropping contribution of J/ψ regeneration for more peripheral collisions
 - Seen in the R_{AA}

Charmonia in pp collisions

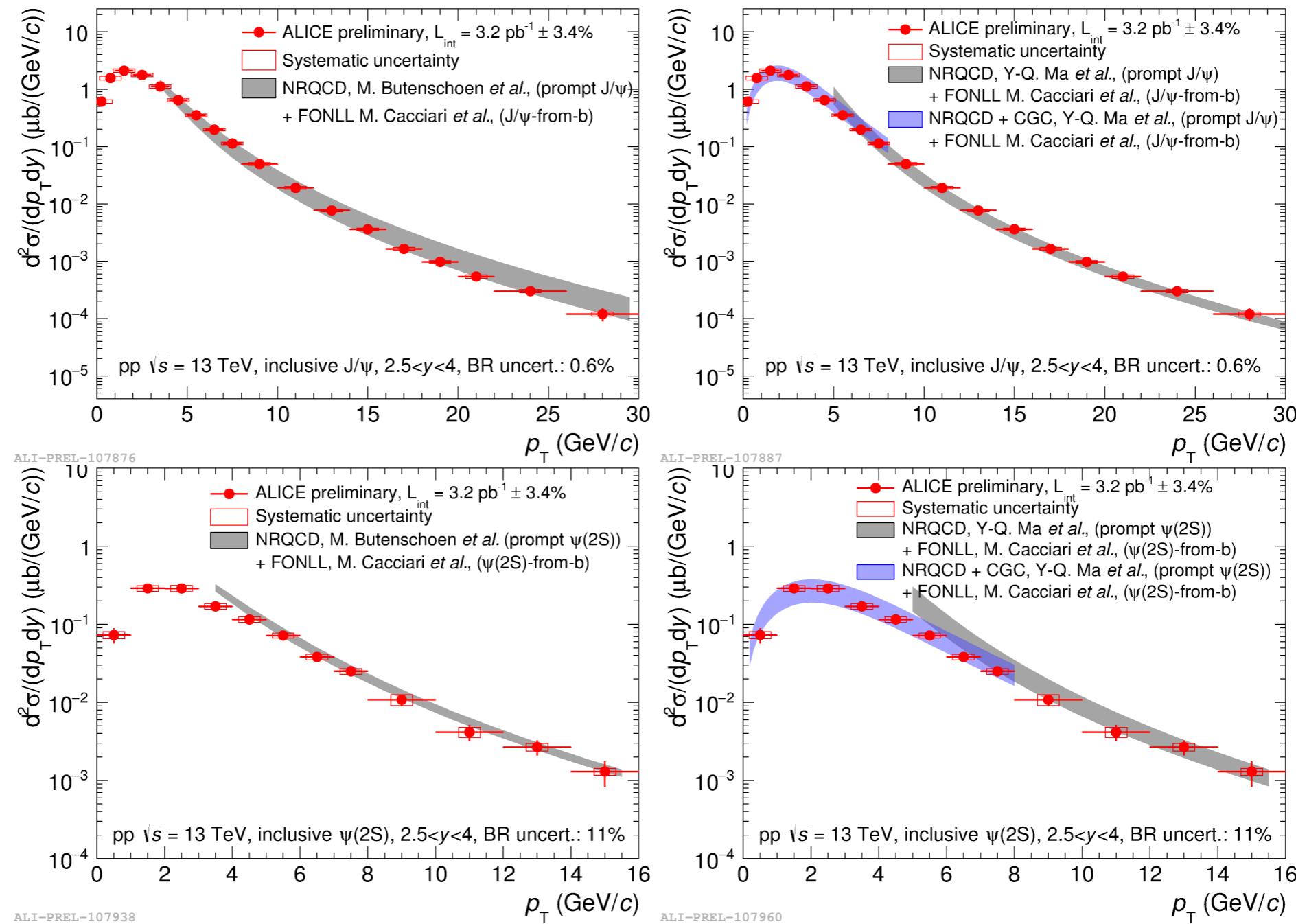
PLB 718 (2012) 2, CERN-EP-2016-162, EPJC 74 (2014) 29744, EPJC 76 (2016) 184

- New charmonium measurements in pp collisions at 5 and 13 TeV



- J/ψ and $\psi(2S)$ measured at five and three collision energies, respectively
 - Up to $p_T = 30 \text{ GeV}/c$ at 13 TeV
 - Only $\psi(2S)$ measurement at forward- y at 8 and 13 TeV

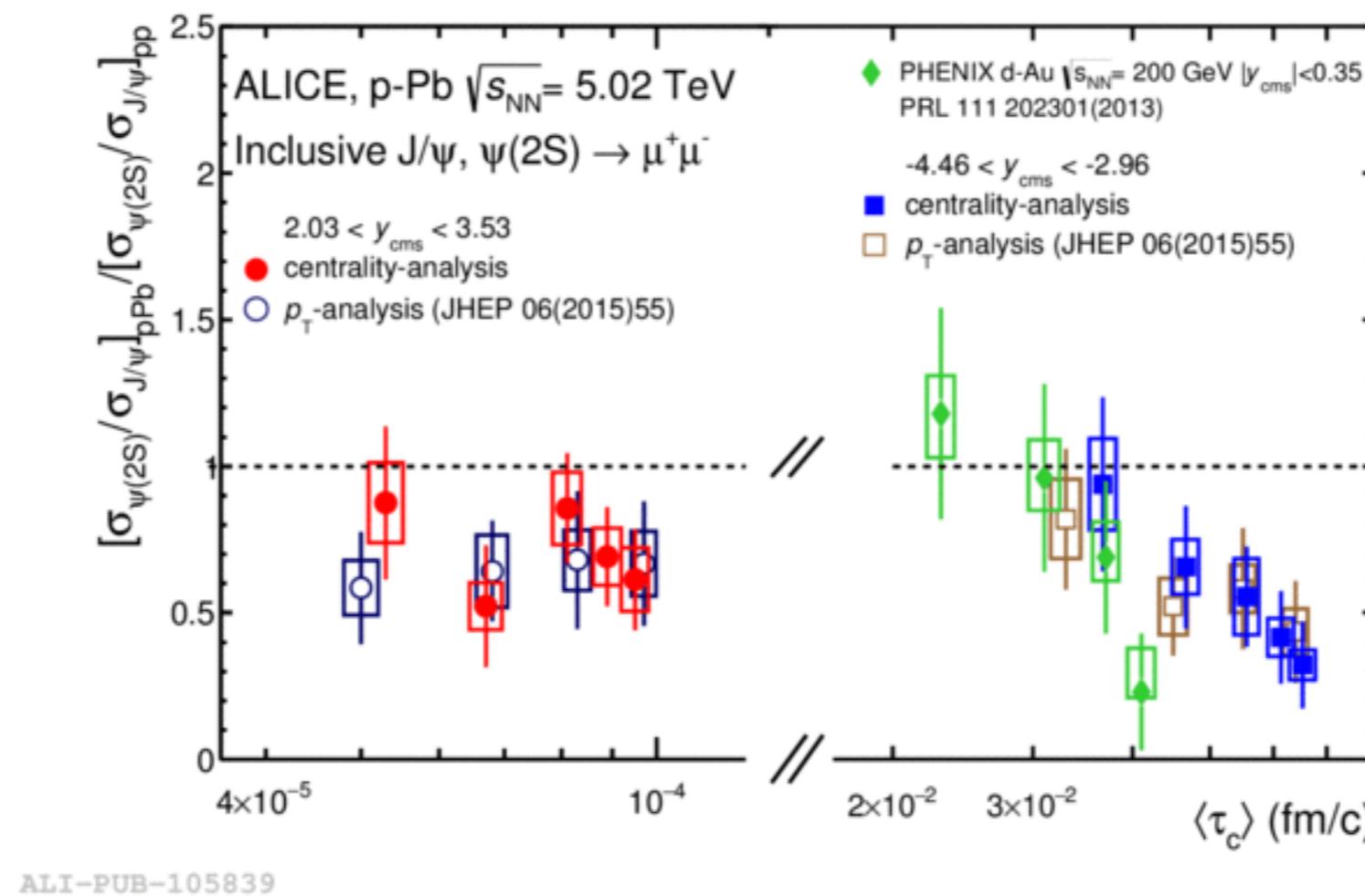
Charmonia in pp collisions at 13 TeV



- NRQCD calculations for prompt J/ψ ($\psi(2S)$) + FONLL calculations for non-prompt J/ψ ($\psi(2S)$) reproduce the p_T -differential cross section at high p_T
- NRQCD + CGC reproduces the low p_T region

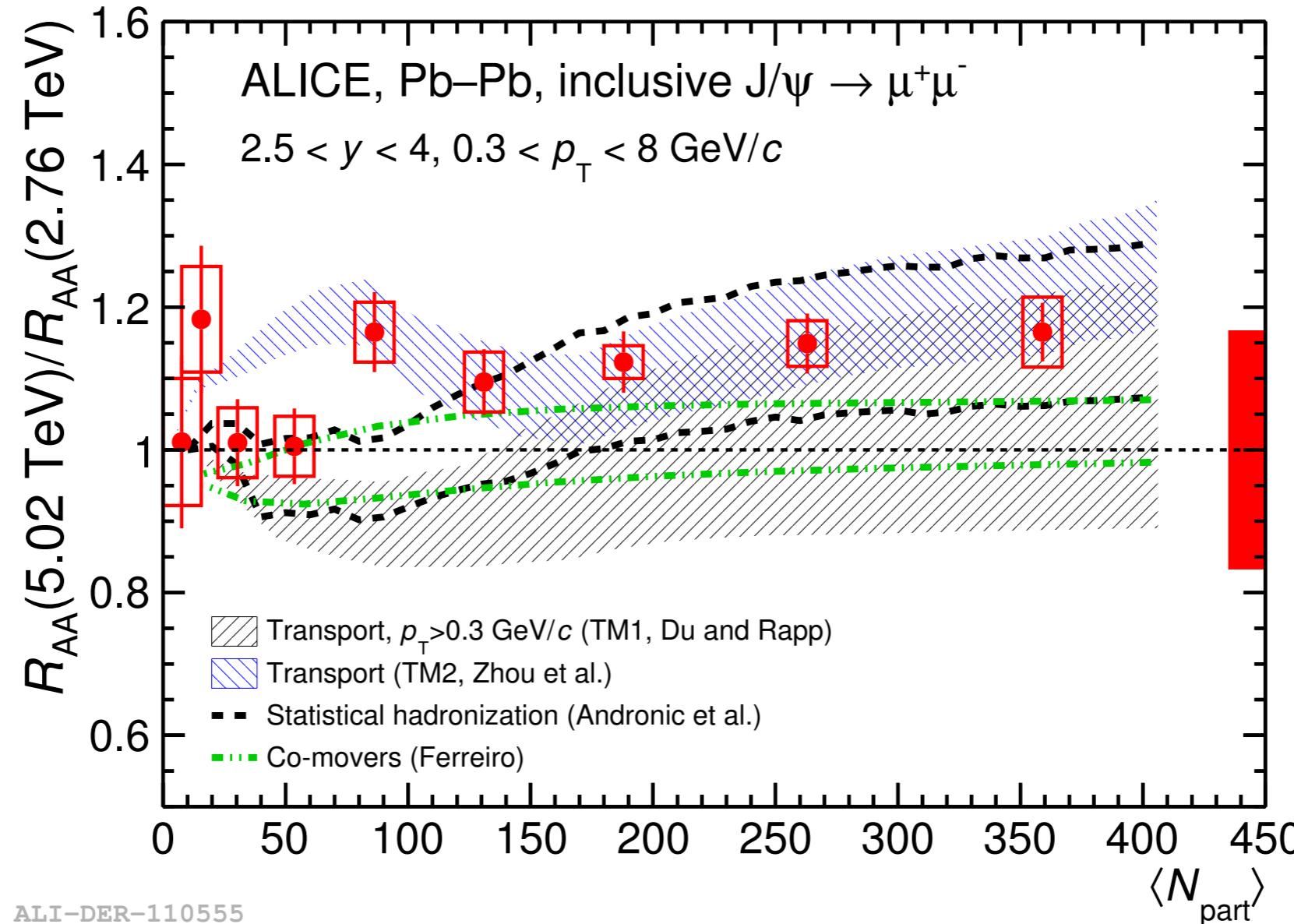
J/ ψ and $\psi(2S)$ in p-Pb 5.02 TeV

- Dependence with crossing-time
 - p-going direction: no time for in-nucleus dissociation
 - Pb-going direction: $\psi(2S)$ dissociation in the nucleus?



R_{AA}(5.02 TeV) / R_{AA}(2.76 TeV)

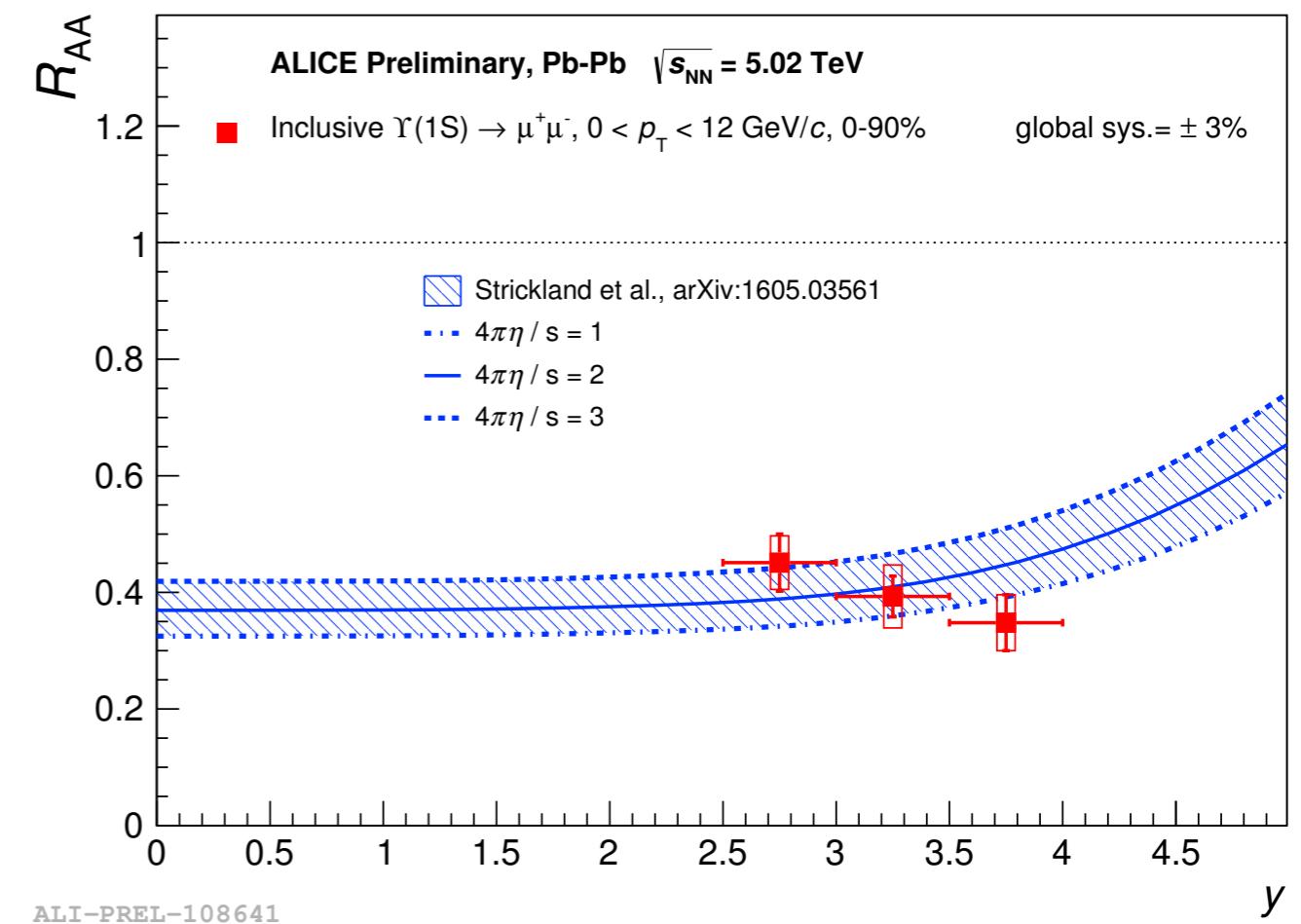
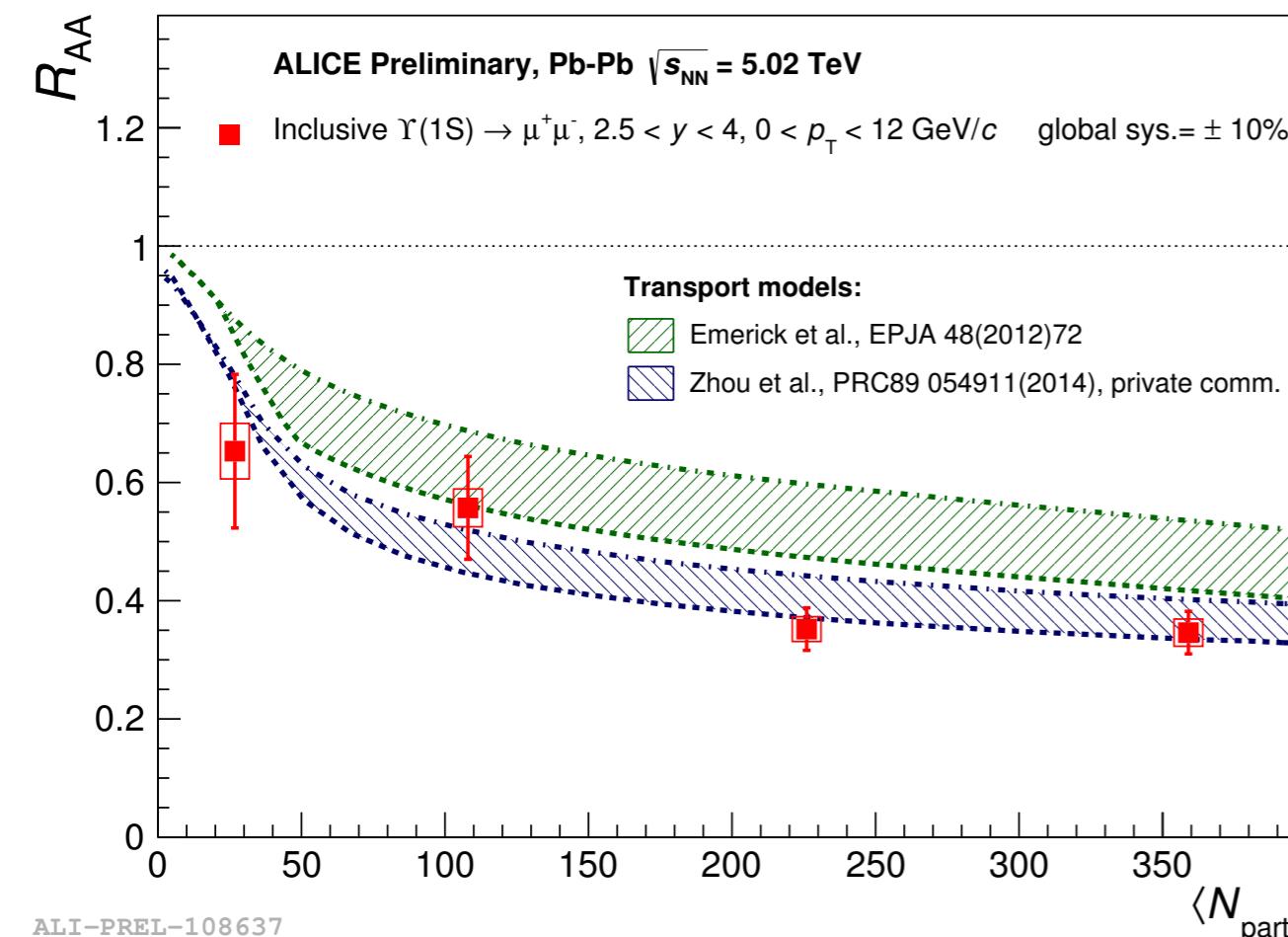
- R_{AA}(0-10%, 5.02 TeV) / R_{AA}(0-10%, 2.76 TeV) = $1.17 \pm 0.04 \pm 0.20$
- No clear trend with centrality



- Some model uncertainties (partially) cancel in the ratio
- Model bands express a 5% uncertainty on c-cbar cross section

$\Upsilon(1S)$ in Pb-Pb at 5 TeV – differential R_{AA}

- Differentially
 - versus centrality
 - versus rapidity

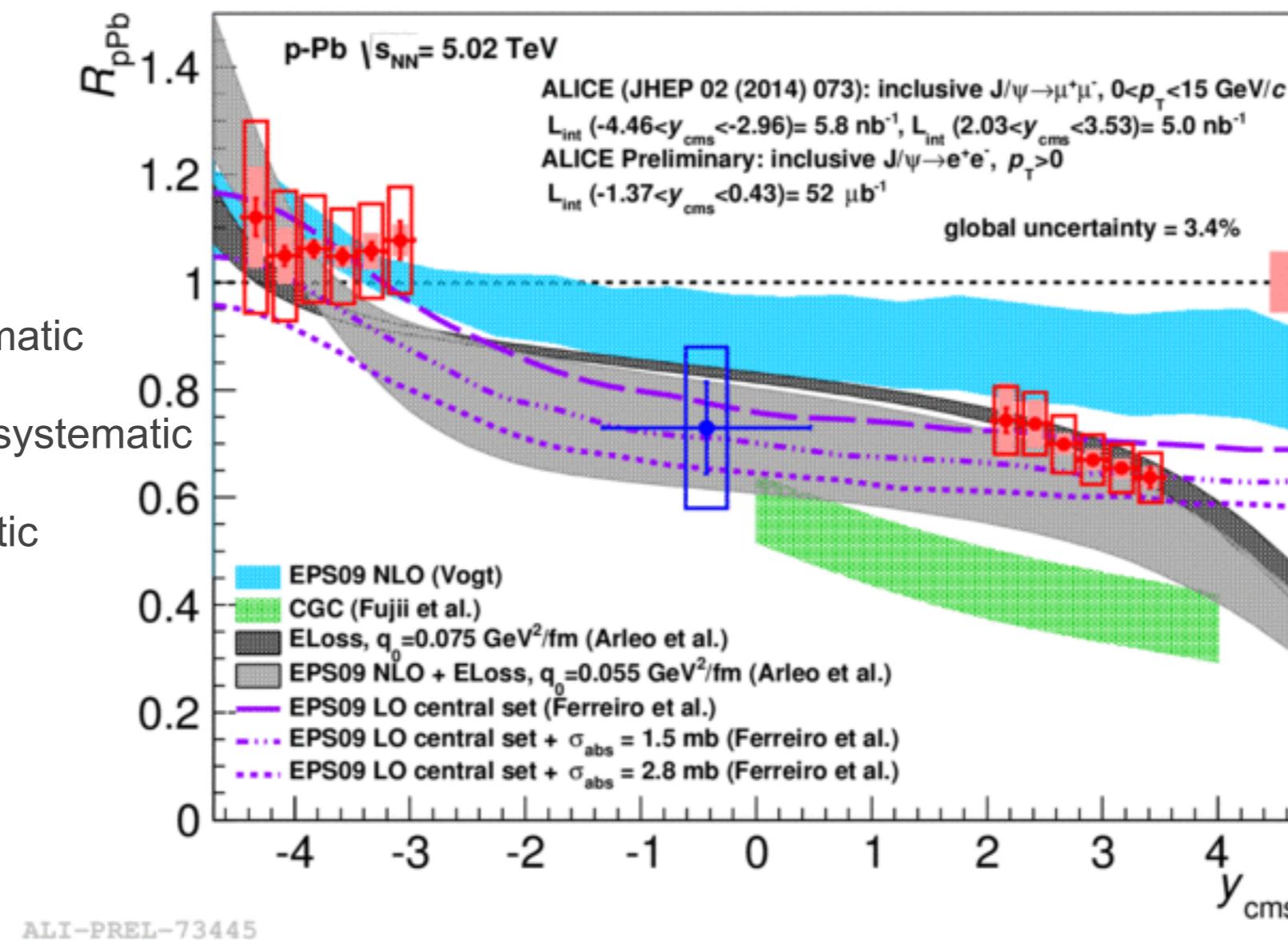


J/ ψ R_{pPb} vs y

JHEP 02 (2014) 073
e.g. arXiv:1404.1615

Uncertainties:

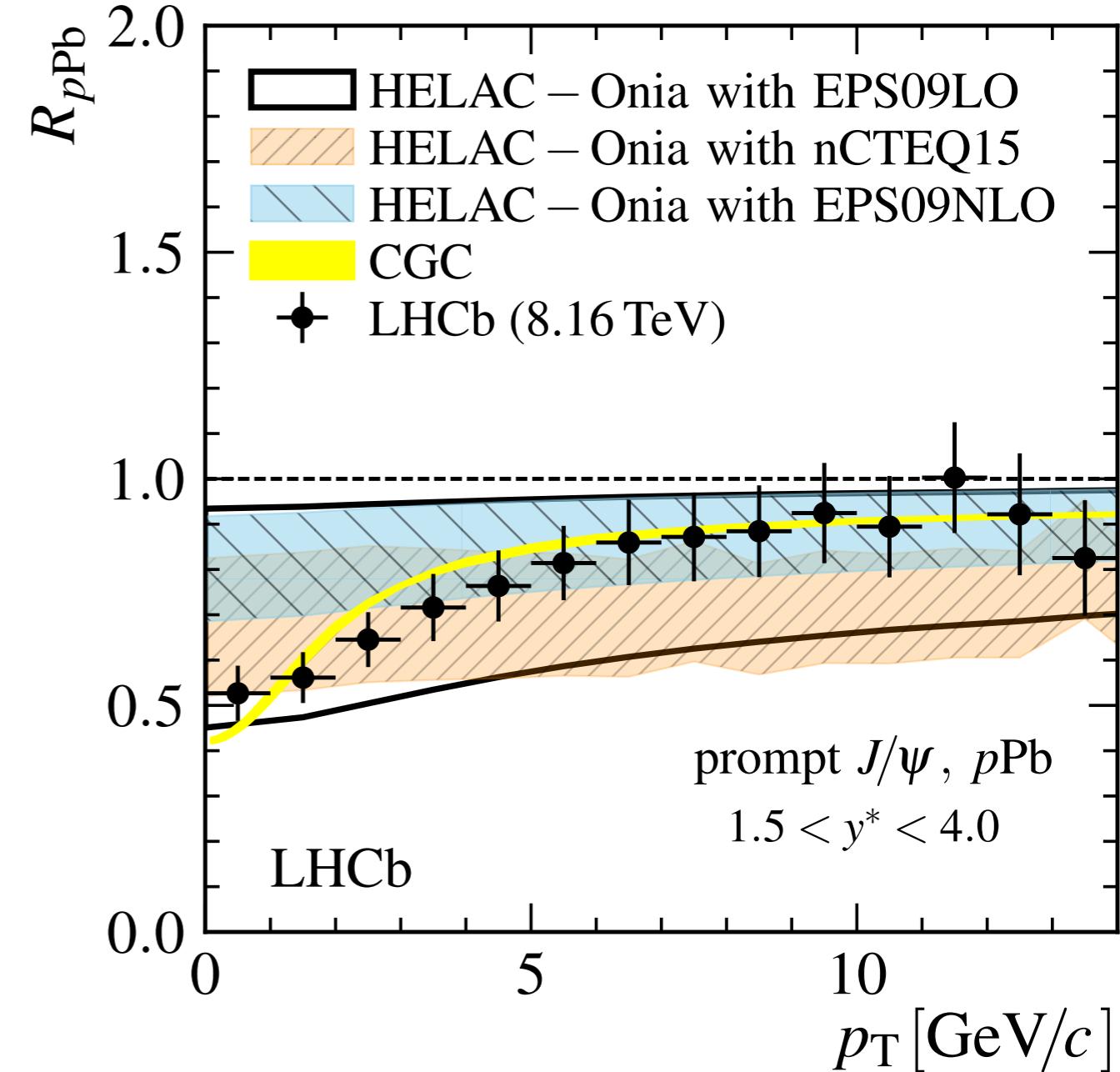
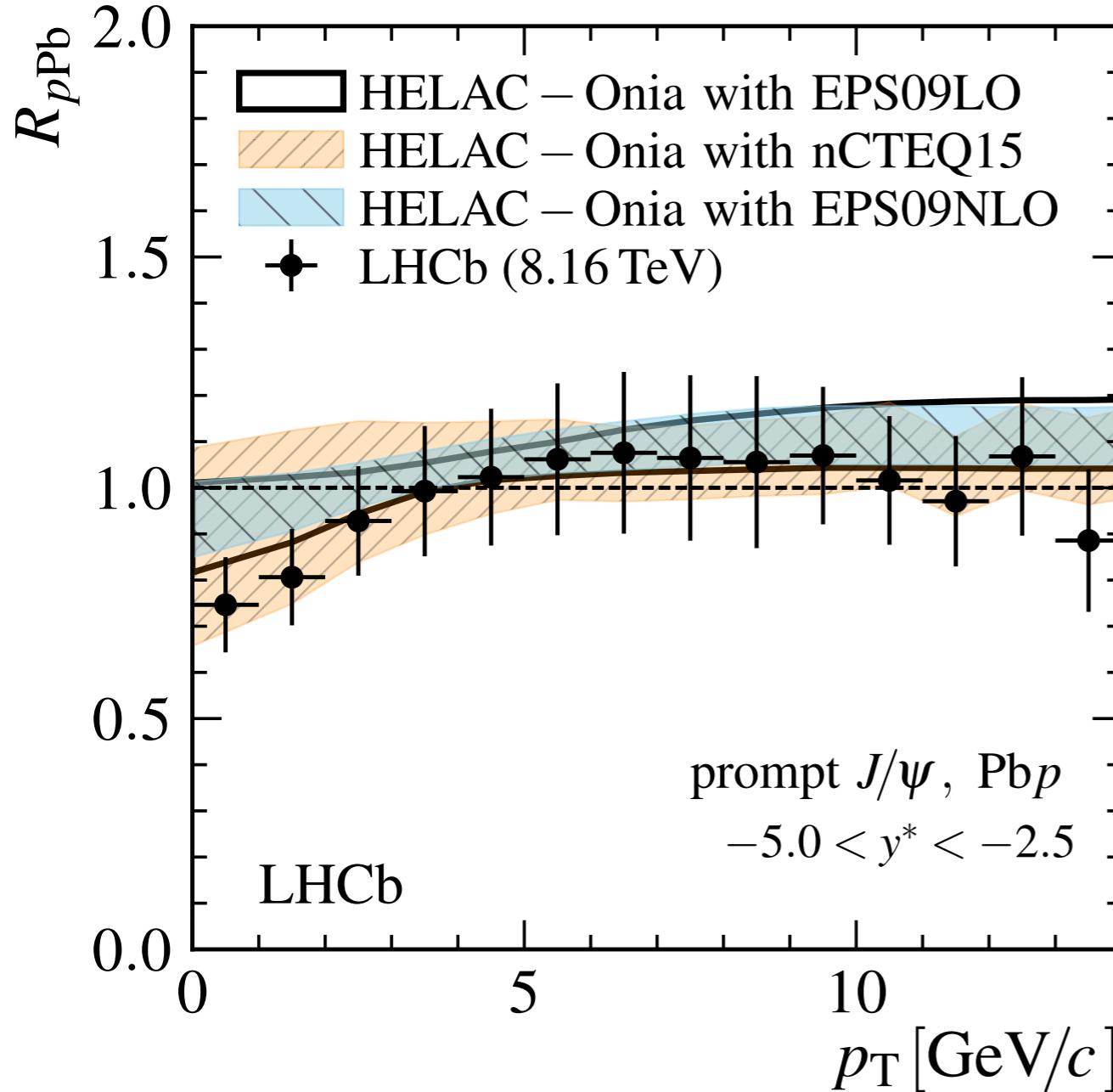
- Bars: Statistical
- Open boxes: Uncorrelated systematic
- Shaded boxes: Partially correlated systematic
- Full box: Correlated systematic



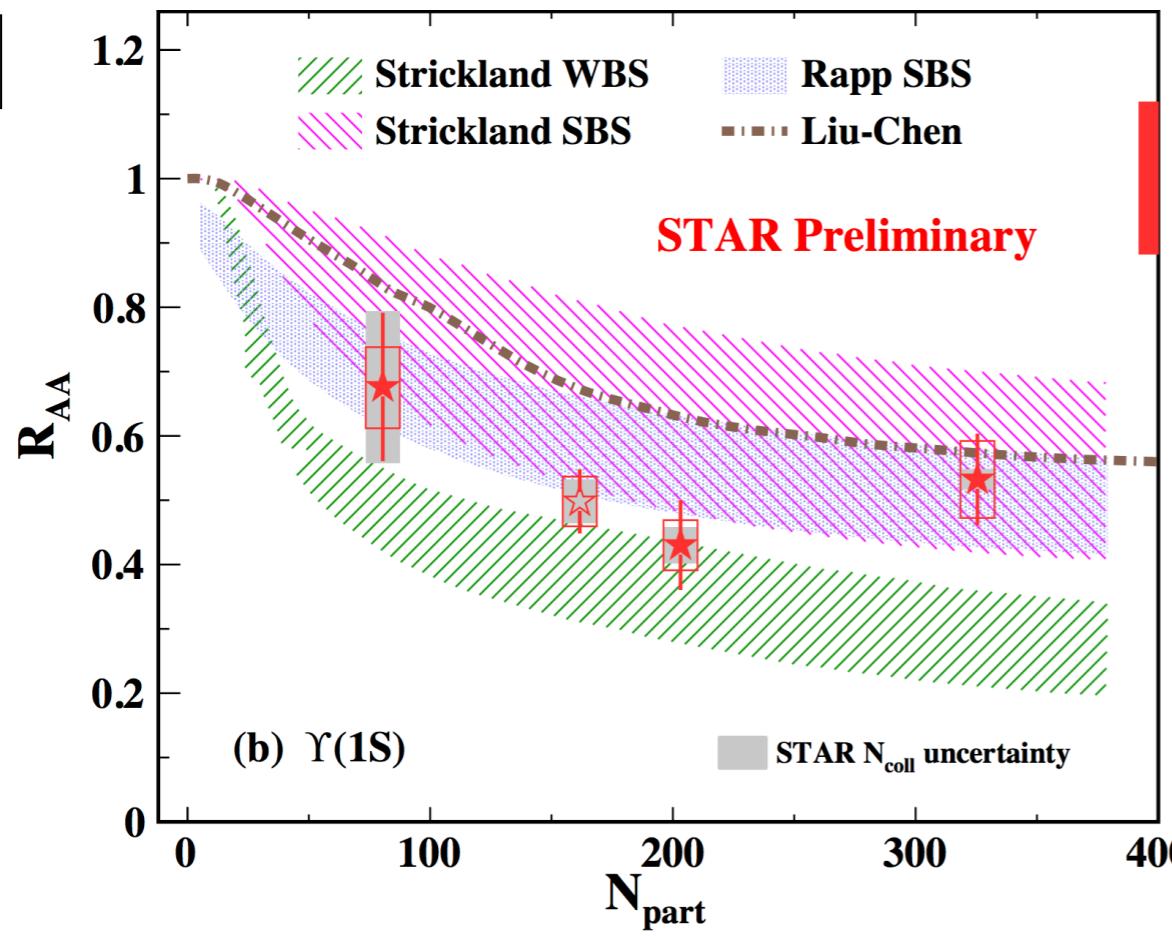
This CGC based [NPA 915 (2013) 1] calculation is clearly disfavoured

- Ferreiro et al. [PRC 88, (2013) 047901]
 - Generic 2→2 production model at LO
 - EPS09 shadowing parameterization at LO
 - Fair agreement with measured R_{pPb}
 - Here, effect of nuclear absorption highlighted, large σ_{abs} disfavoured (note: at RHIC $\sigma_{\text{abs}} = 4 \text{ mb}$ favoured)

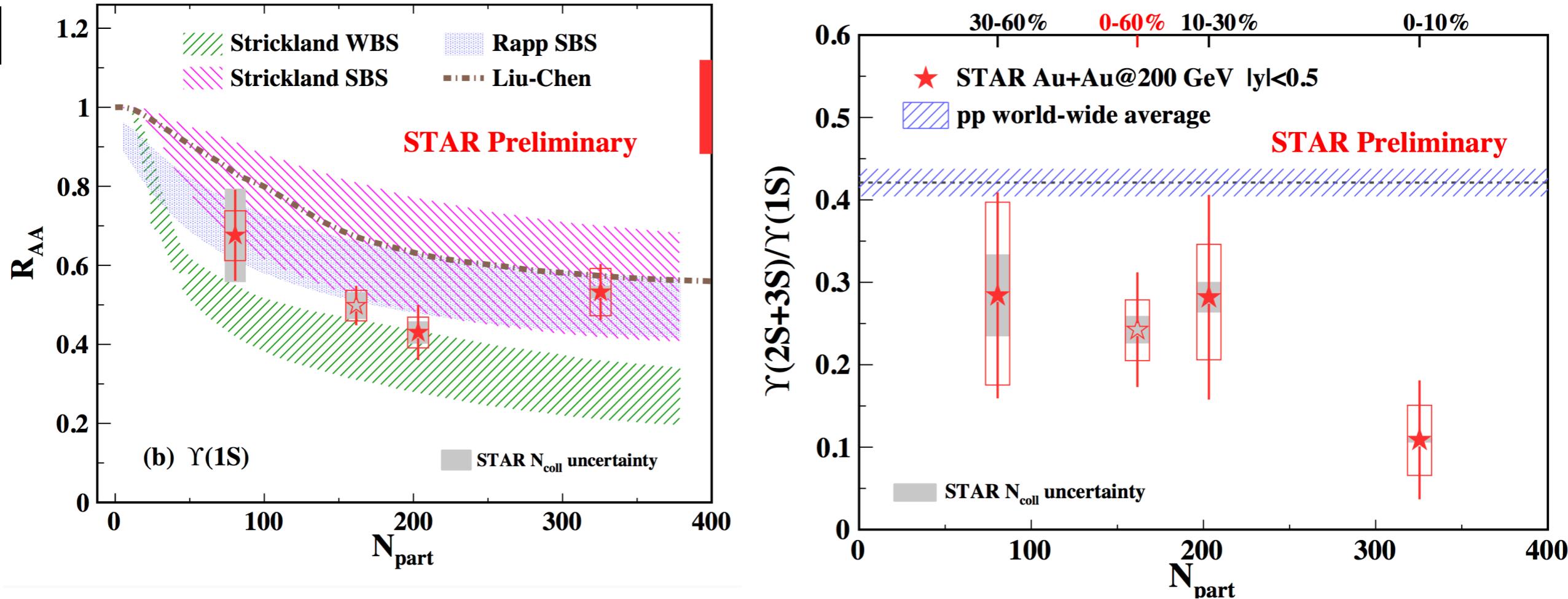
Prompt J/ ψ R_{pPb}



γR_{AA} @ RHIC vs. models



- M. Strickland, [arXiv:1207.5327]
 - Thermal suppression of bottomonium states
 - Anisotropic hydro model, best description with
 - Strongly Binding Scenario
 - Feed down from higher mass states included
 - **No CNM effects included**
 - No regeneration included



- A. Emerick et al., [EPJ A48 (2012) 72]
 - Transport model
 - Suppression of γ resonances by the QGP
 - Mainly of the higher mass states
 - $T_0 = 330$ MeV
 - Negligible regeneration component included
 - Feed down from higher mass states included
 - **CNM included via an “effective” $\sigma_{ABS} = 0-3$ mb**