Quarkonium production in p-Pb and Pb-Pb collisions with ALICE

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QWG 2019 - 13th International Workshop on Heavy Quarkonium
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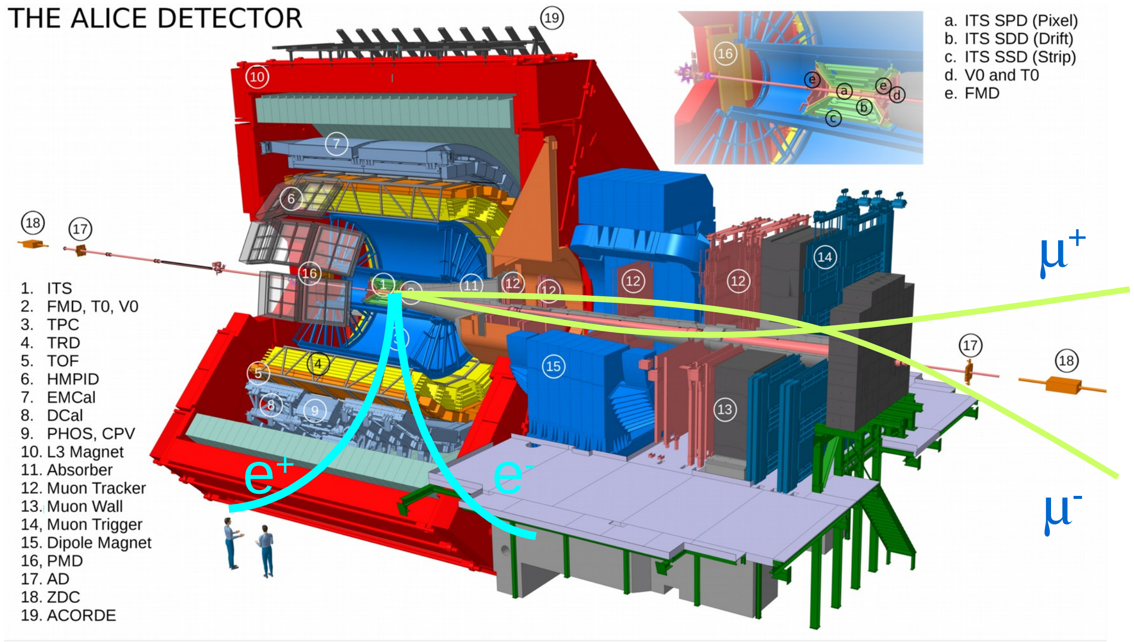
Outline

- ALICE detector
- p-Pb results at $\sqrt{s_{NN}}$ = 8.16 TeV
  - Rapidity, p_T and centrality dependence of quarkonium (J/ψ, ψ(2S) and Υ) (new J/ψ results at mid rapidity)
  - Multi-differential study of J/ψ
  - Azimuthal anisotropy of J/ψ
- Pb-Pb results at $\sqrt{s_{NN}}$ = 5.02 TeV
  - Multi-differential study of J/ψ
  - Azimuthal anisotropy of J/ψ
  - Centrality dependence of ψ(2S)
  - Rapidity, p_T and centrality dependence of Υ(1S)
  - Elliptic flow of Υ(1S) NEW!!
  - New results on the polarization of J/ψ will be presented by Luca in the next talk

A Large Ion Collider Experiment

→ Quarkonia in ALICE are measured in two rapidity ranges:



Central barrel:
$J/\psi \rightarrow e^+e^-$ ($|y| < 0.9$)

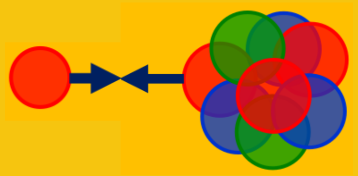
Electrons tracked using ITS and TPC
Particle identification: TPC (+TOF)

Forward muon arm:
$J/\psi \rightarrow \mu^+\mu^-$ ($2.5 < y < 4$)

Muons identified and tracked in the muon spectrometer

→ Acceptance coverage in both y regions is down to zero p_T
→ The ALICE results presented in this talk refer to inclusive J/ψ

p-Pb



cold nuclear matter effects:

shadowing/CGC, energy loss...

p-Pb collisions in ALICE

→ To understand Cold Nuclear Matter (CNM) effects such as nuclear parton shadowing/color glass condensate, energy loss and comovers absorption

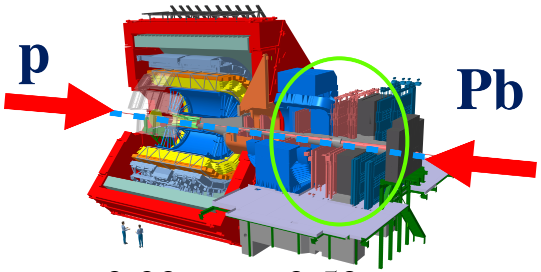
→ No Quark-Gluon Plasma (QGP) is expected in pA collisions.

→ The measurement of CNM effects in pA collisions is important to quantify the QGP effects in AA collisions

→ ALICE has collected p-Pb data at $\sqrt{s_{NN}}$ = 5.02 and 8.16 TeV

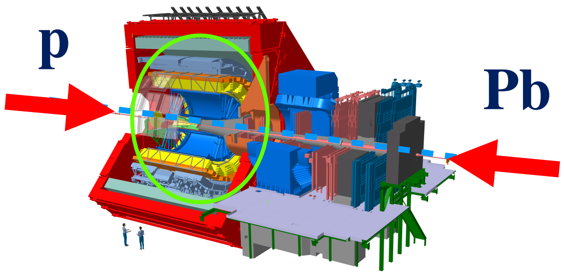
→ ALICE data are collected with two beam configurations: p-Pb and Pb-p, with Δy= +/- 0.465

Forward rapidity



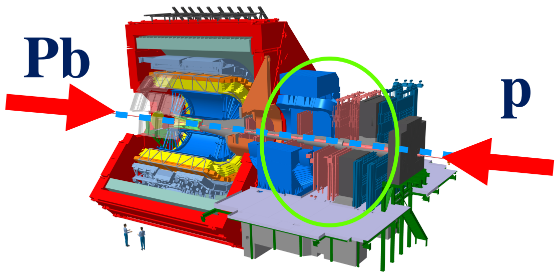
$2.03 < y_{cms} < 3.53$

Mid rapidity



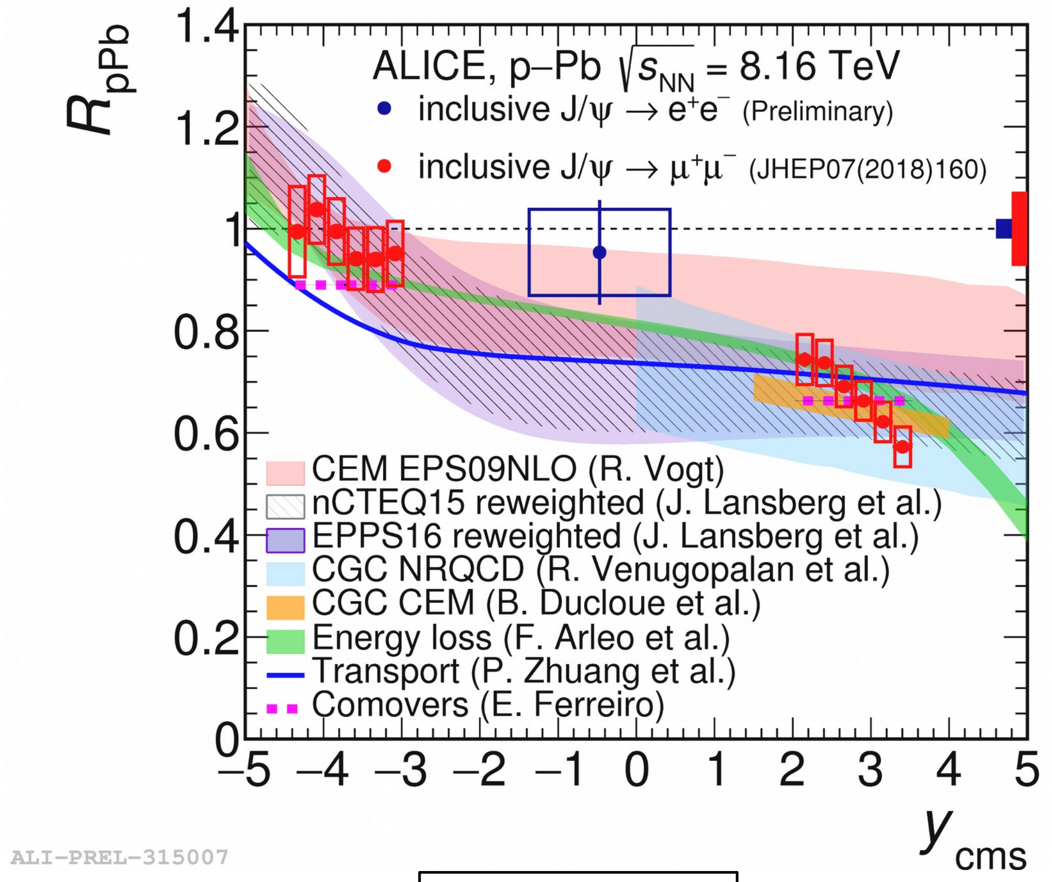
$-1.37 < y_{cms} < 0.43$

Backward rapidity



$-4.46 < y_{cms} < -2.96$

J/ψ R_{pPb} vs y_{cms} at $\sqrt{s_{NN}}$ = 8.16 TeV



JHEP 07 (2018) 160

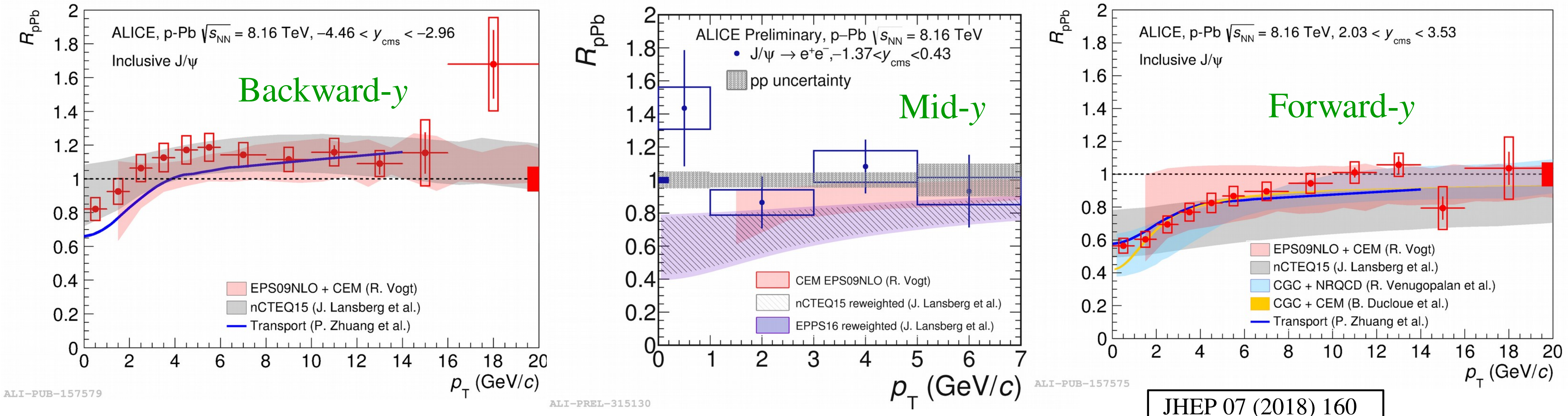
- Nuclear modification factor:

$$R_{pPb}^{J/\psi} = \frac{Y_{pPb}^{J/\psi}}{\langle T_{pPb} \rangle \, \sigma_{pp}^{J/\psi}}$$

- Stronger suppression is observed at forward rapidity, while R_{pPb} is compatible with unity both at mid and backward rapidity

- Models based on different shadowing implementations, CGC, energy loss, transport models and comovers fairly describe the data

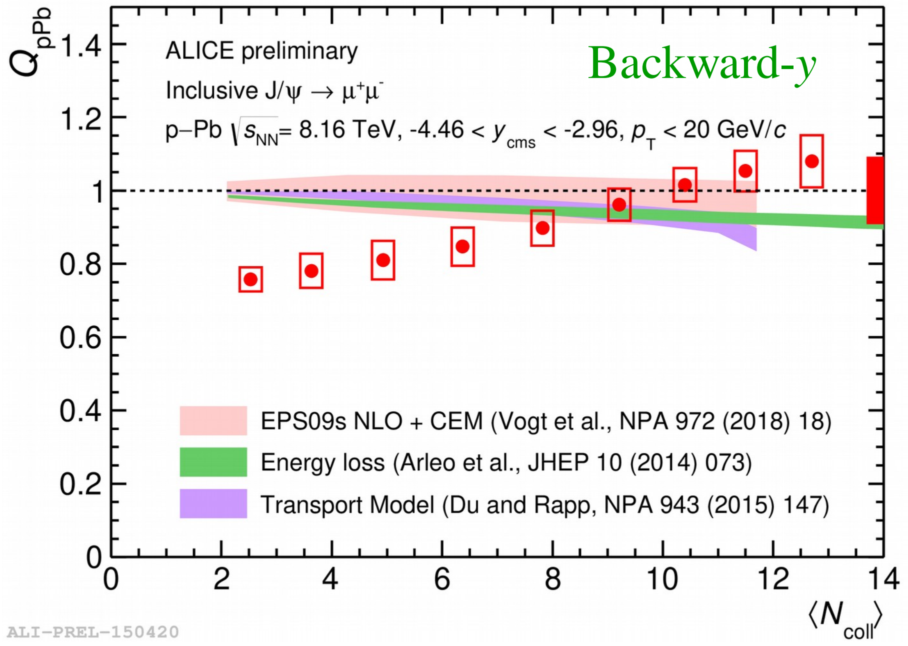
J/ψ R_{pPb} vs p_T at $\sqrt{s_{NN}}$ = 8.16 TeV

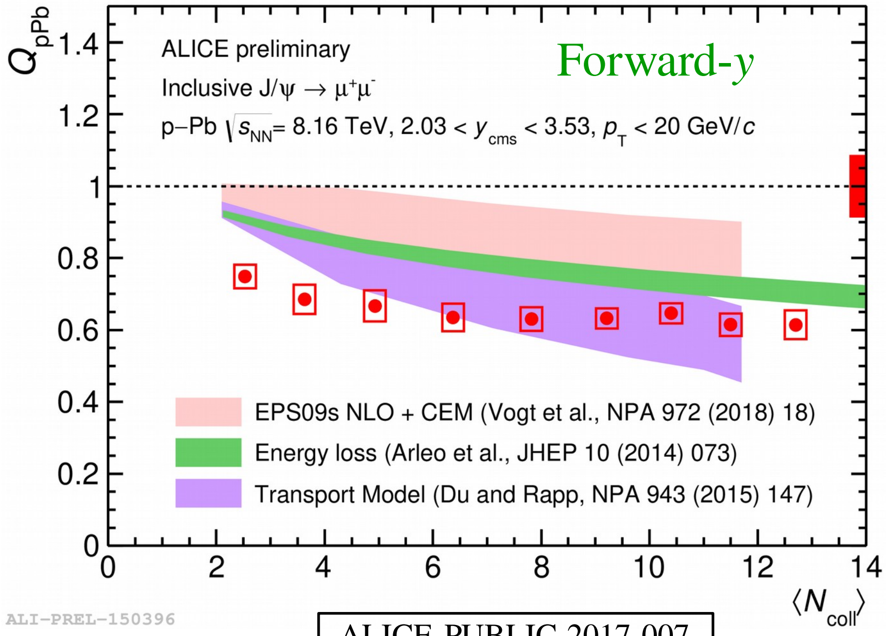


JHEP 07 (2018) 160

- R_{pPb} shows a p_T dependence, with an increase from low to high p_T at both forward and backward rapidity
- At mid rapidity R_{pPb} is compatible with unity with almost no p_T dependence
- Run2 results are more precise than the Run1 measurements at $\sqrt{s_{NN}}$ = 5.02 TeV [JHEP 06 (2015) 55]
- Uncertainties on the theoretical predictions are large compared to data

J/ψ Q_{pPb} at $\sqrt{s_{\mathrm{NN}}}$ = 8.16 TeV





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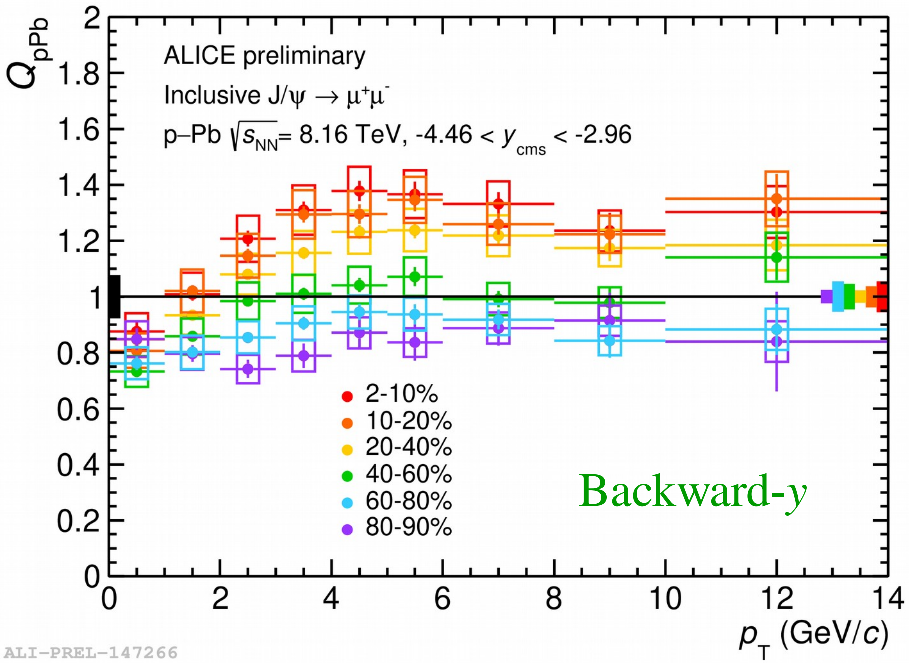
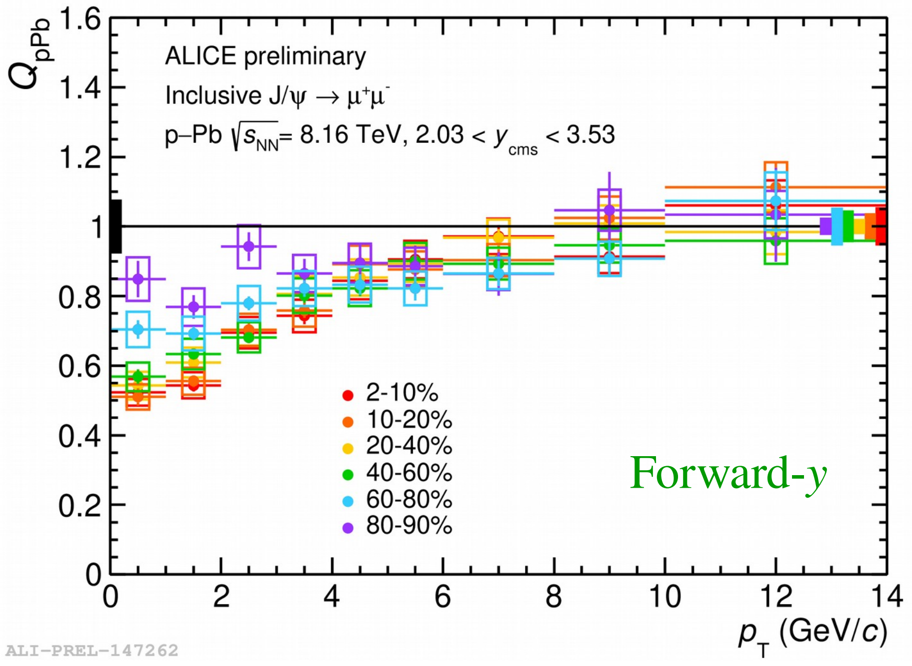
- We use the symbol Q_{pPb} instead of R_{pPb} for nuclear modification factor due to potential bias from the centrality estimator
- Two sets of Zero Degree Calorimeters (ZDC) have been used for the centrality estimation
- Q_{pPb} decreases slightly from peripheral to central collisions at forward rapidity, while trend is opposite at backward-y

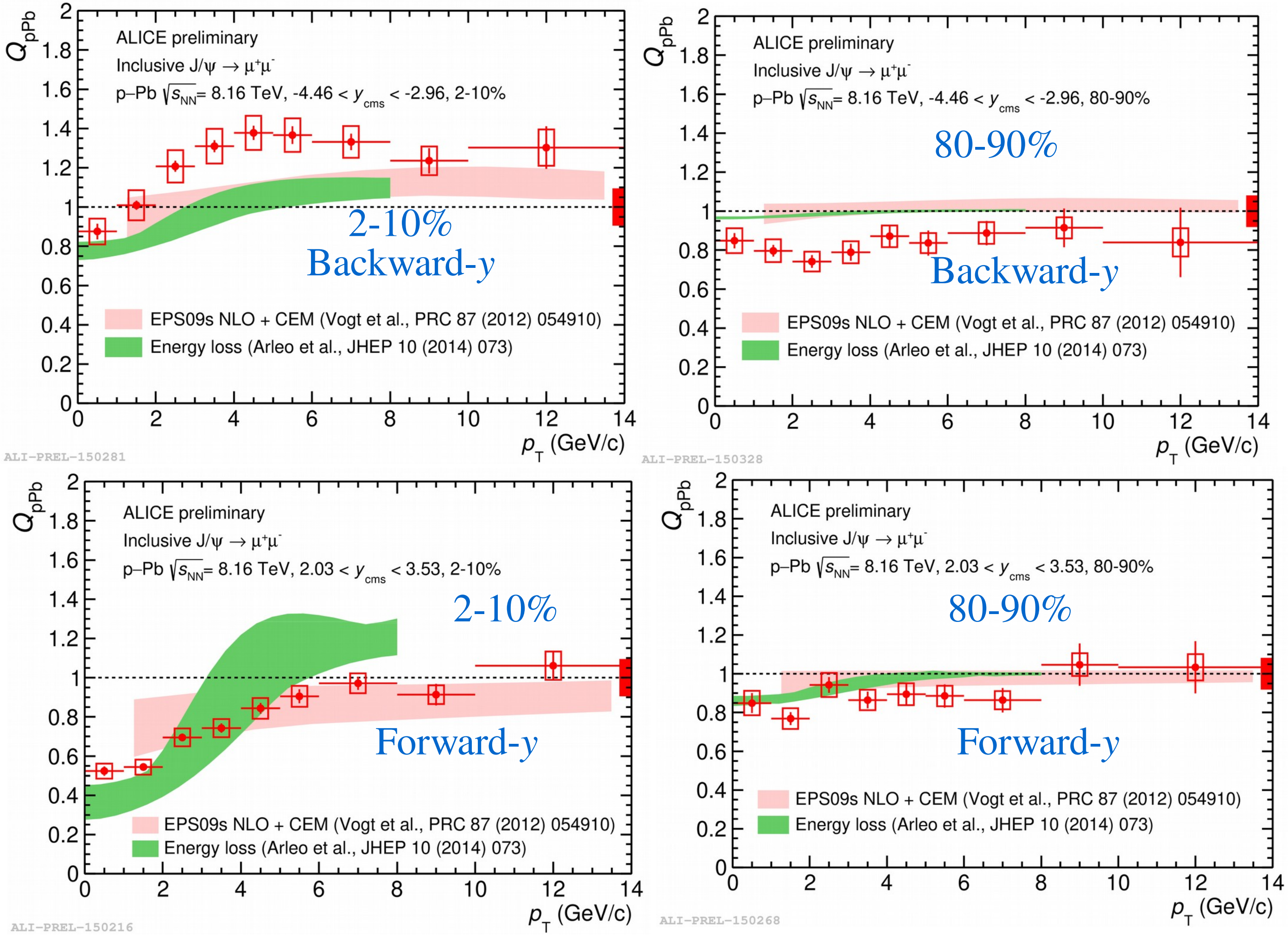
Multi-differential study of J/ψ Q_{pPb} at $\sqrt{s_{\mathrm{NN}}}$ = 8.16 TeV





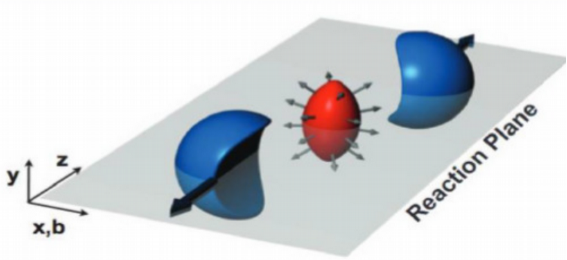
- Clear evolution of Q_{pPb} vs p_{T} in different centrality classes
- At backward rapidity, enhancement in most central collisions for $p_{\mathrm{T}} > 3$ GeV/c
- At forward rapidity, stronger suppression at low p_{T} in most central collisions and Q_{pPb} is compatible with unity for $p_{\mathrm{T}} > 7$ GeV/c within uncertainties for all centrality intervals

Multi-differential J/ψ Q_{pPb} compared to theoretical models



- In central collisions:
  - shadowing predicts a weaker p_{T} dependence w.r.t. the one observed in data
  - energy loss predicts an increase of Q_{pPb} with a different steepness than the measured one
- In peripheral collisions:
  both theory models show no p_{T} dependence, consistent with the Q_{pPb} measurement, within uncertainties
- The models can not describe simultaneously all aspects of J/ψ suppression (rapidity, p_{T} and centrality)

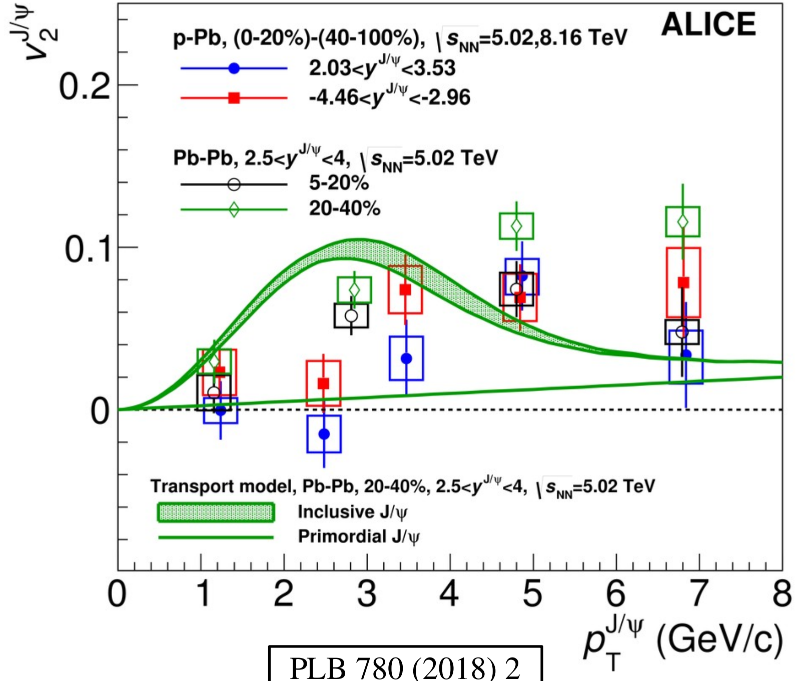
Azimuthal anisotropy (v_2) of J/ψ



- In a strongly-interacting medium, pressure gradients convert any initial spatial anisotropy into a momentum anisotropy
- Anisotropy is quantified by the 2nd order coefficient v_2 of the Fourier expansion of the particle azimuthal distribution

$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1+\sum_{n=1}^{\infty} 2v_n \cos\left(n\left(\varphi-\Psi_n\right)\right)\right)$$

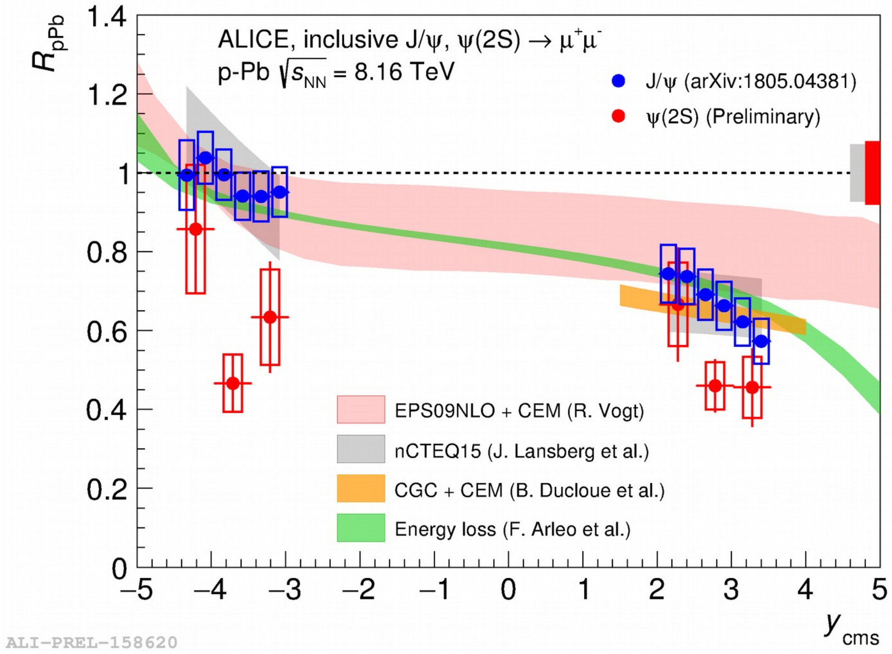
$$v_n = \langle \cos\left(n(\varphi-\Psi_n)\right)\rangle$$

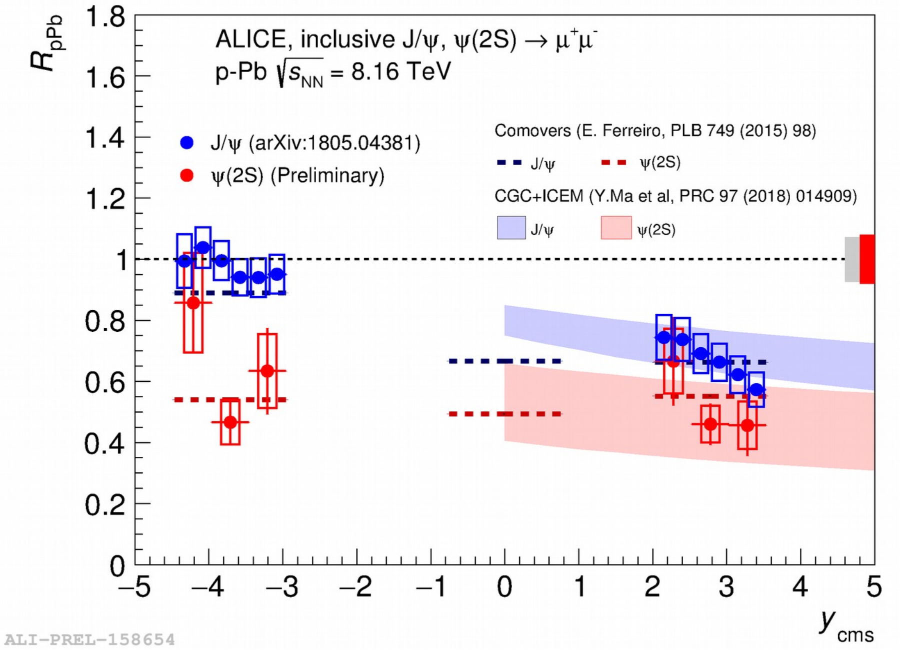


PLB 780 (2018) 2

- Observation of non-zero v_2 in p-Pb for p_T > 3 GeV/c!
- Total significance (forward + backward, 5.02+8.16 TeV, 3 < p_T < 6 GeV/c) ~ 5σ
- Values are similar to the ones obtained in Pb-Pb for p_T > 3 GeV/c
- In Pb-Pb collisions, non-zero J/ψ v_2 suggests charm quark participation to the collective expansion of the system
- Common mechanism in p-Pb and Pb-Pb?

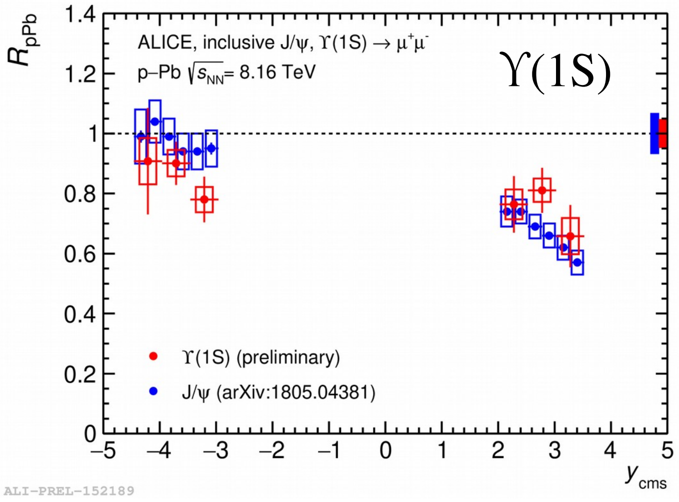
$\psi(2S)$ R_{pPb} vs y_{cms} at $\sqrt{s_{NN}}$ = 8.16 TeV

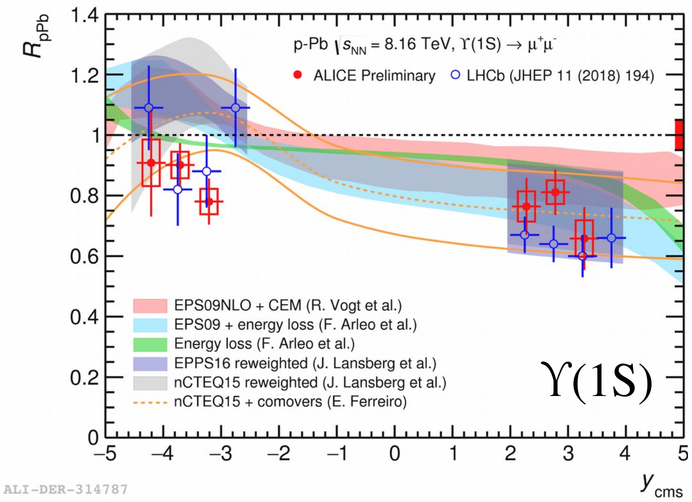


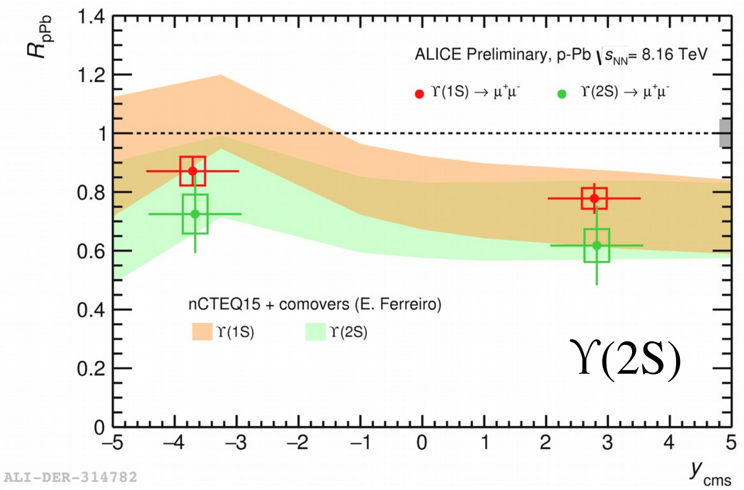


- $\psi(2S)$ suppression is stronger than the J/ψ one, especially at backward rapidity
- Theoretical predictions based on shadowing and energy loss can not describe the stronger $\psi(2S)$ suppression
- Models including final-state effects reproduce $\psi(2S)$ behaviour at both forward and backward rapidity

Υ(1S) and Υ(2S) R_{pPb} vs y_{cms} at $\sqrt{s_{NN}}$ = 8.16 TeV







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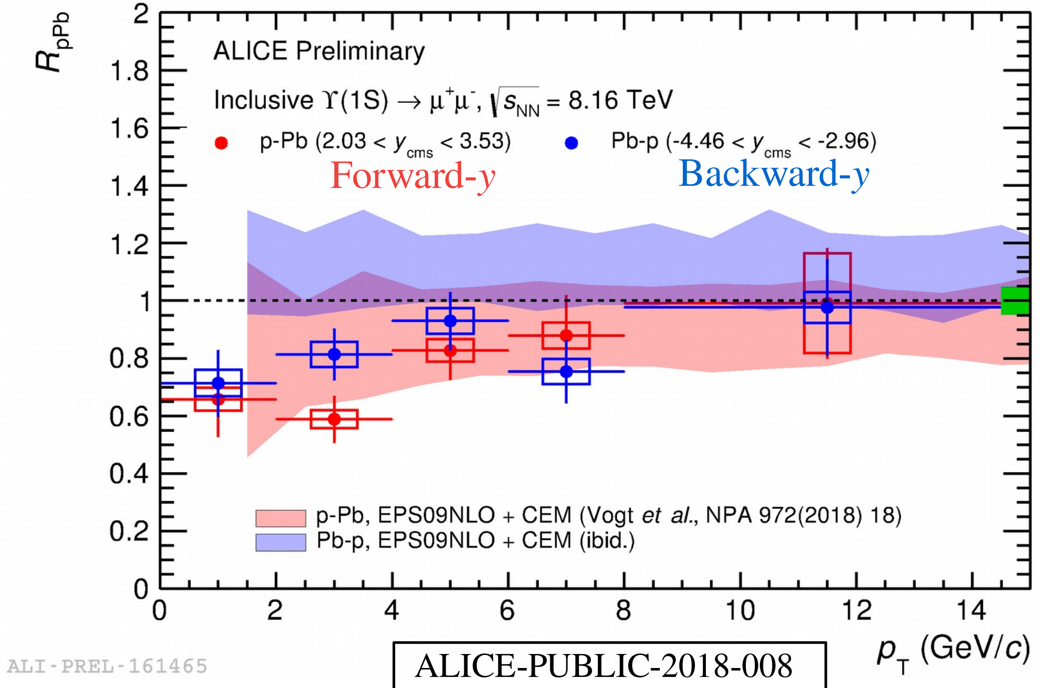
- Similar Υ(1S) suppression at forward and backward rapidity
- Υ(1S) and J/ψ R_{pPb} agree within ~ 1σ both at forward and backward rapidity
- Theoretical predictions based on shadowing and energy loss describe the forward rapidity results but slightly overestimate the backward rapidity results
- Υ(2S) suppression is consistent with Υ(1S) but a small hint of being more suppressed (as also observed by CMS and ATLAS at mid-*y*, and by LHCb at forward-*y*)

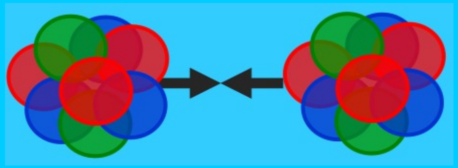
$\Upsilon(1S)$ R_{pPb} vs p_T at $\sqrt{s_{NN}}$ = 8.16 TeV



ALICE-PUBLIC-2018-008

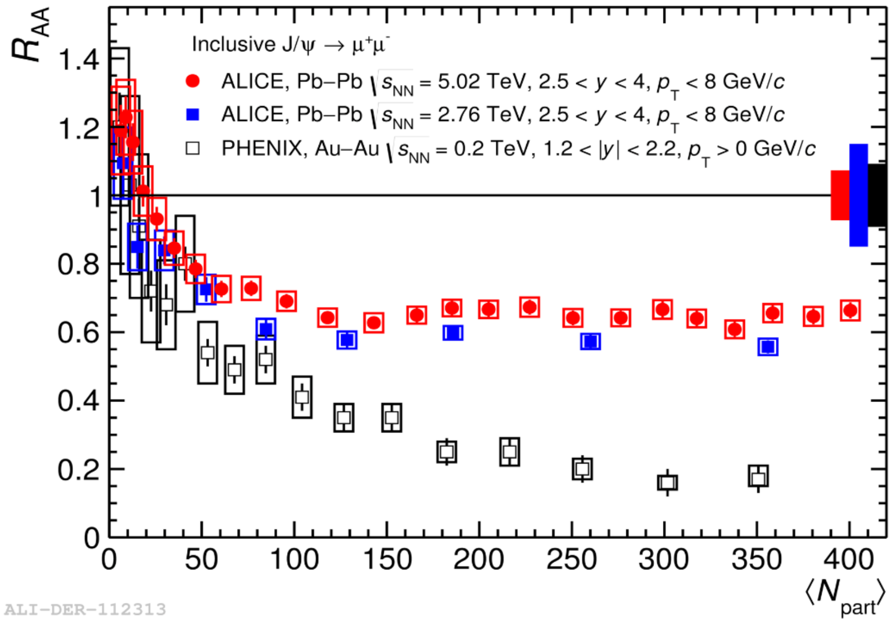
- Similar behaviour at both forward and backward rapidity with a hint of a stronger suppression at low p_T
- Theoretical predictions based on shadowing describe the forward rapidity results but slightly overestimate the backward rapidity results

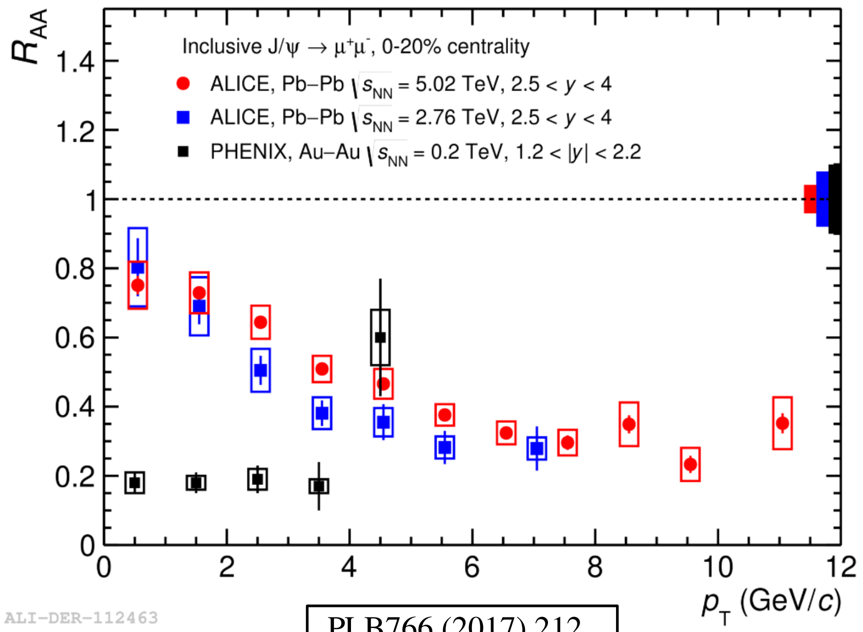
Pb-Pb



hot matter effects:
suppression vs regeneration

J/ψ R_{AA} in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV



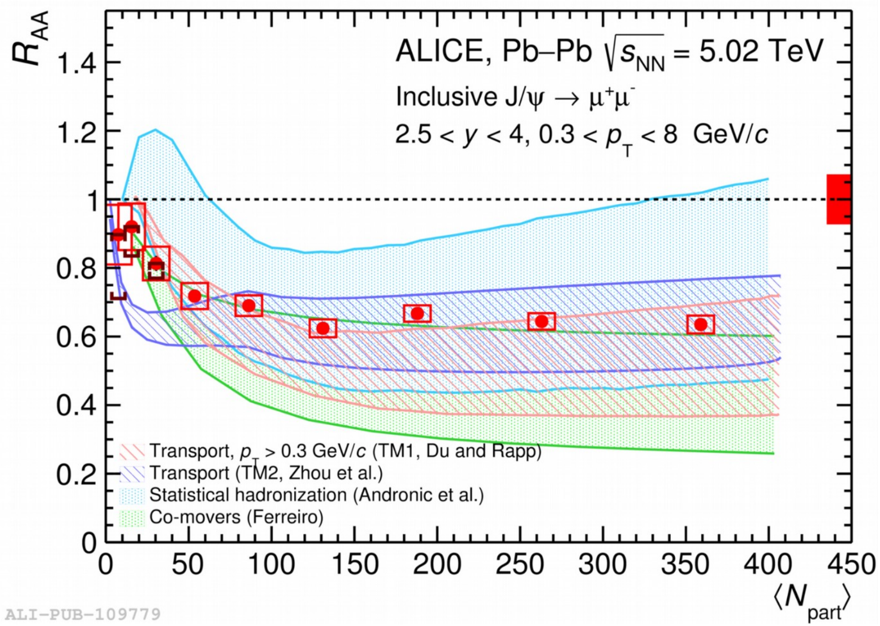


PLB766 (2017) 212

$$R_{AA}^{J/\psi} = \frac{Y_{AA}^{J/\psi}}{\langle T_{AA}\rangle\, \sigma_{pp}^{J/\psi}}$$

- Forward-y J/ψ suppression measured precisely in fine bins of centrality
- Clear J/ψ suppression with almost no centrality dependence for $N_{part} > 100$
- Weaker low-p_T suppression measured by ALICE compared to PHENIX
- Different behaviour in RHIC and LHC R_{AA} is related to the interplay of suppression and regeneration mechanisms

Comparison with theoretical models



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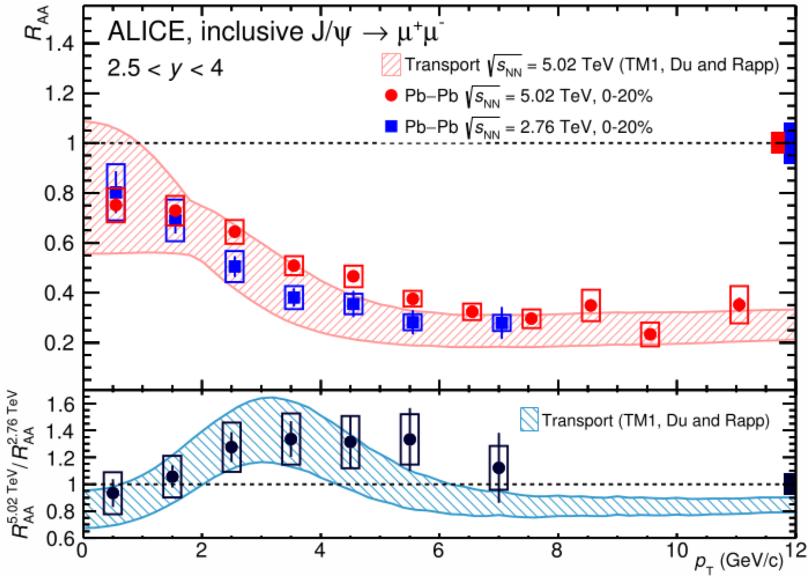
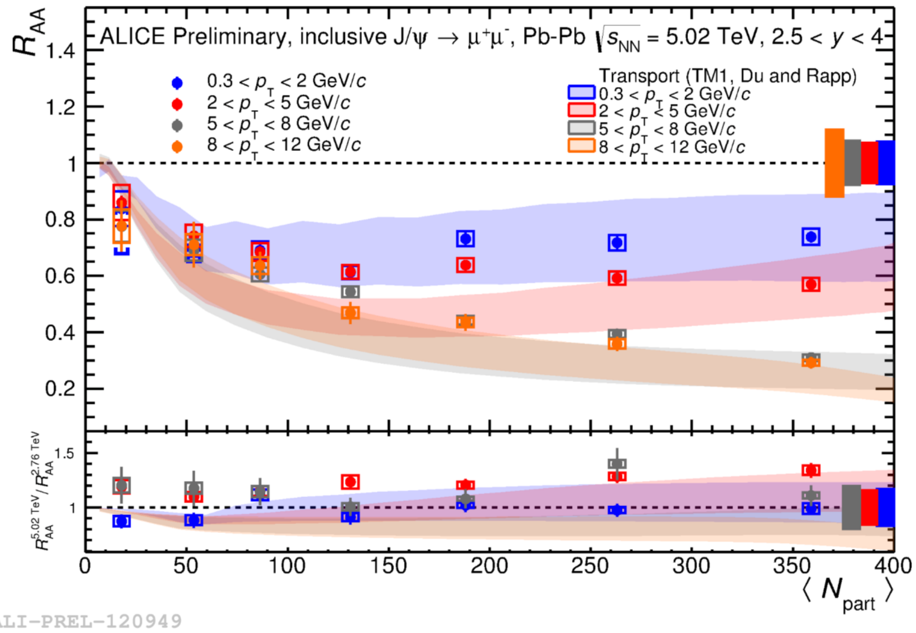
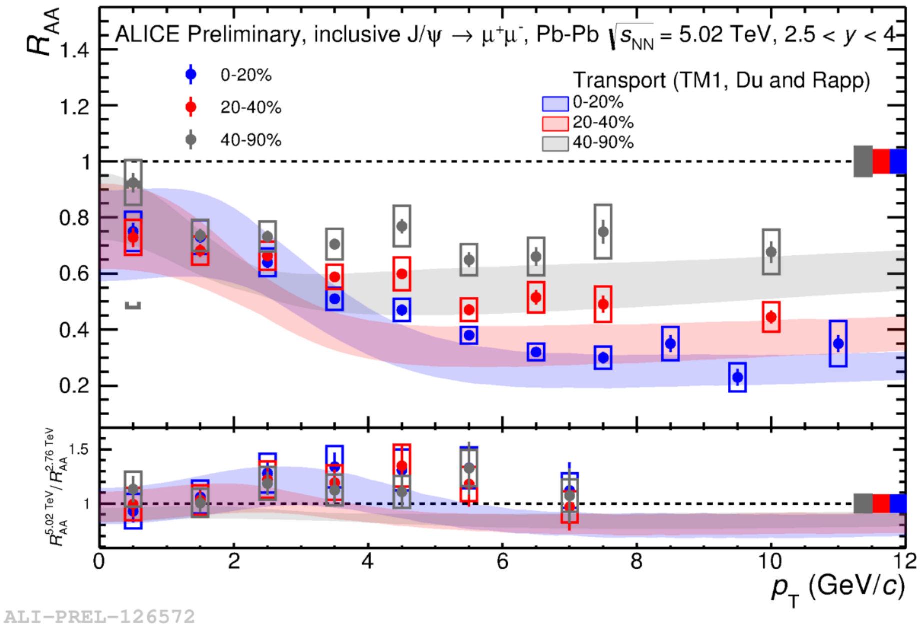


TM1: Nucl. Phys. A859 (2011) 114–125
TM2: Phys. Rev. C89 no. 5, 459 (2014) 054911
Stat. hadronization: NPA 904-905 (2013) 535c
Co-movers: Phys. Lett. B731 (2014) 57–63

- All models fairly describe the data but large uncertainties associated to charm cross section and shadowing
- Precise charm cross section measurement and more differential analyses needed

Multi-differential J/ψ R_{AA} in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV



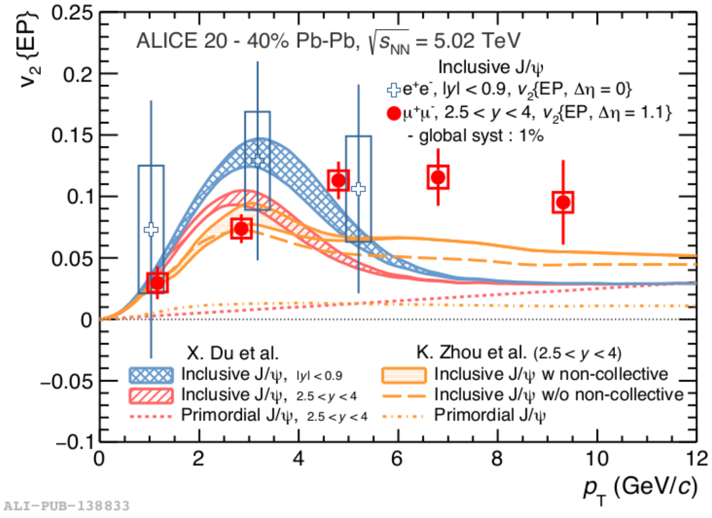


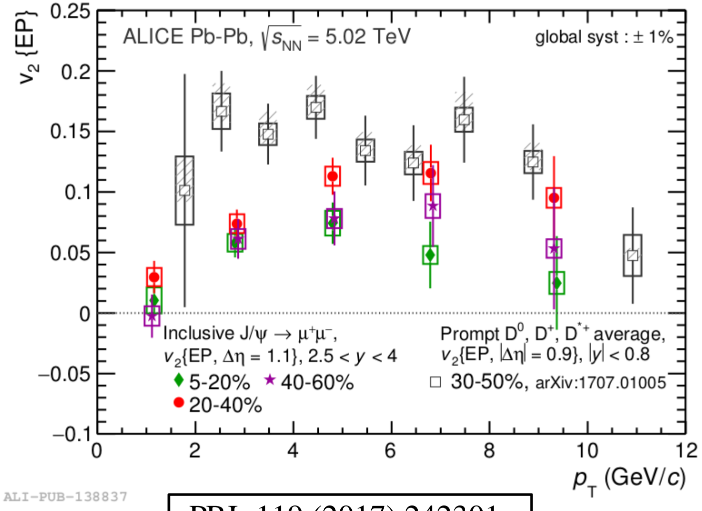
- Constraints to the theoretical models can be imposed by more differential R_{AA} studies

- The suppression is stronger at high p_T and for central collisions
- R_{AA} decreases by 60-80% at large p_T and for most central collisions

- TM1 prediction agrees with data within uncertainties

Elliptic (v_2) and triangular (v_3) flow of J/ψ in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV





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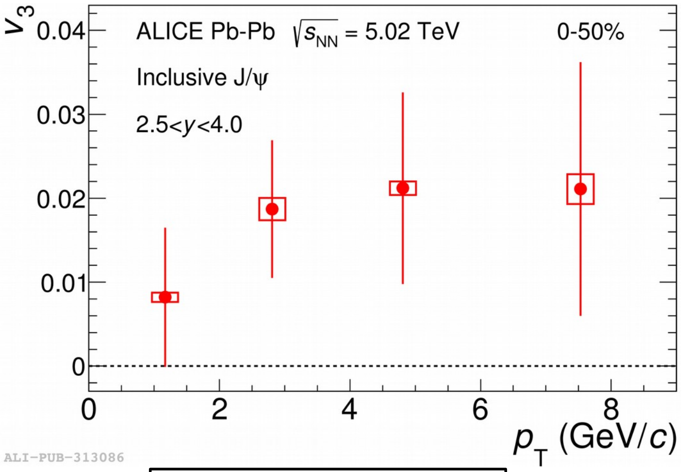
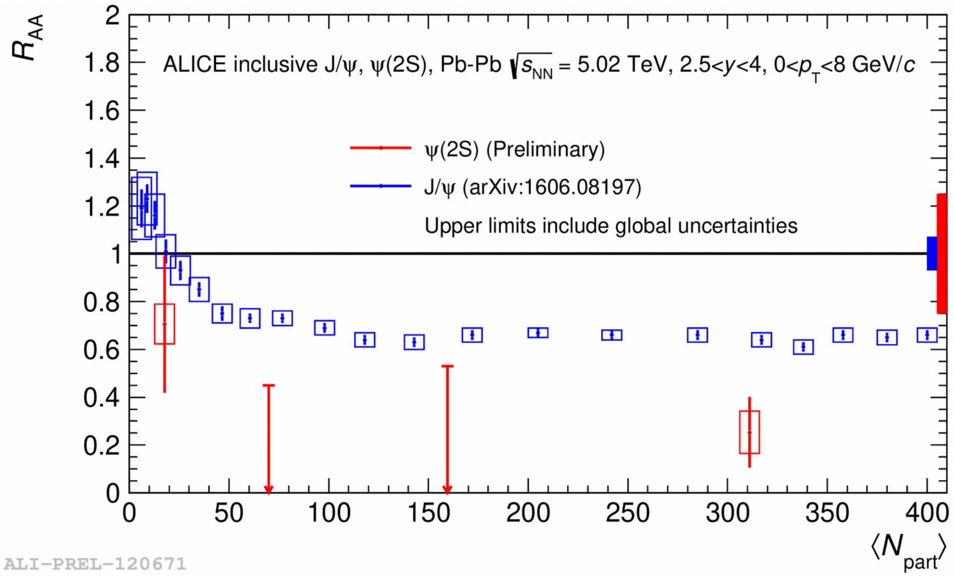


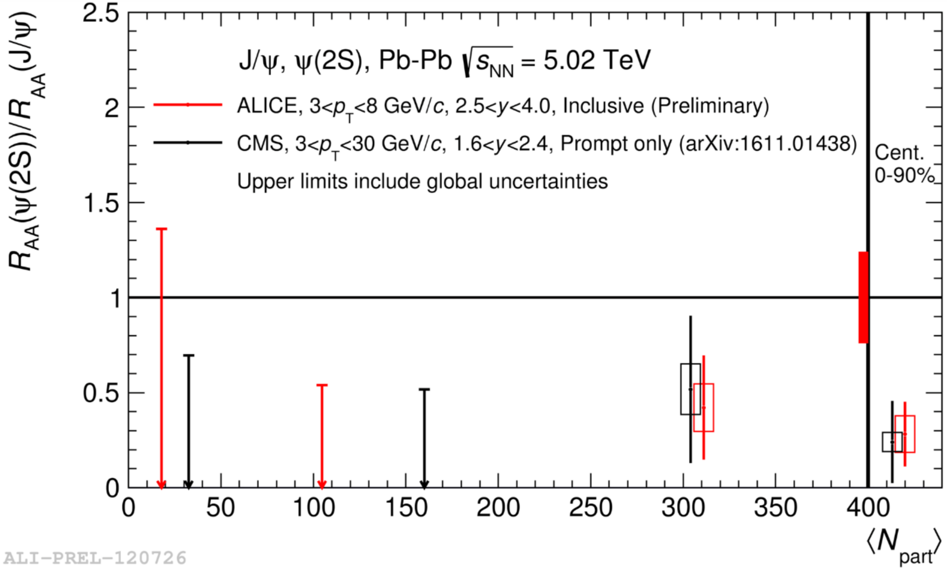
JHEP 1902 (2019) 012

- J/ψ v_2 at mid-y shows agreement with forward-y result within uncertainties
- Non-zero J/ψ v_2 is consistent with that of open-charm mesons
- The transport model predictions are not able to describe the data in higher p_T region
- A significant fraction of the observed J/ψ comes from charm quarks thermalized in the QGP

- First observation of positive J/ψ v_3 in Pb-Pb collisions (3.7 σ significance)
- v_3 is sensitive to fluctuations of initial nucleon distributions in the overlap region

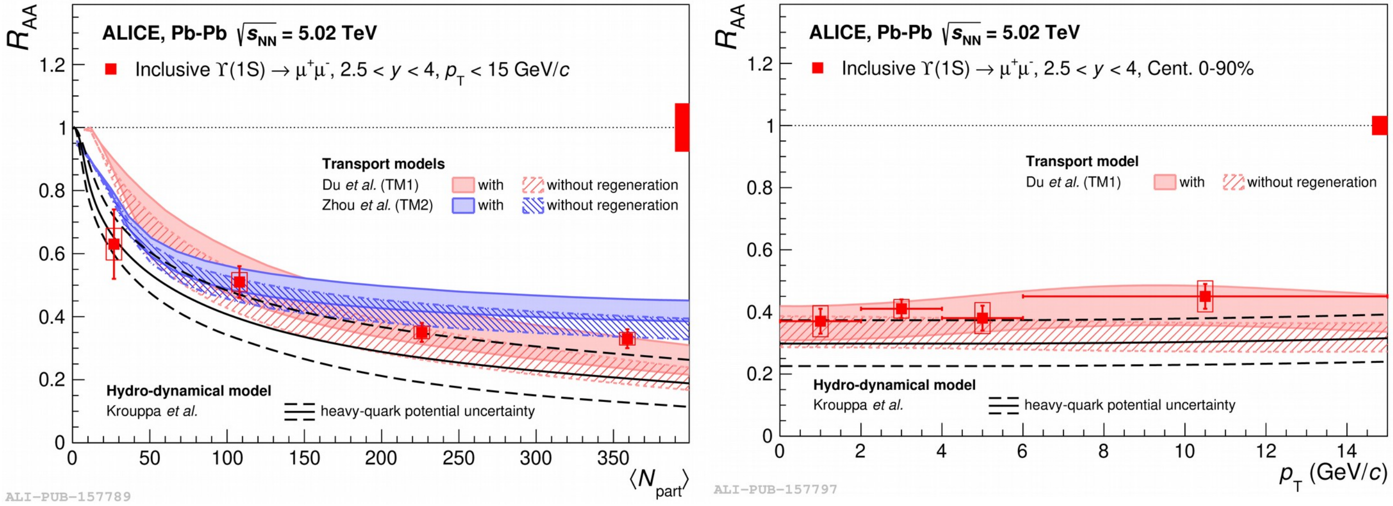
ψ(2S) R_{AA} in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV





- ψ(2S) shows a stronger suppression, in semi-central and central collisions, than the J/ψ one
- However, the low significance limits the precision of the measurements
  [95% CL is provided for bins with too low significance]
- Results are compatible with CMS
- The 2018 data sample with ~ 3 times increase in statistics will give more precise measurement, stay tuned!

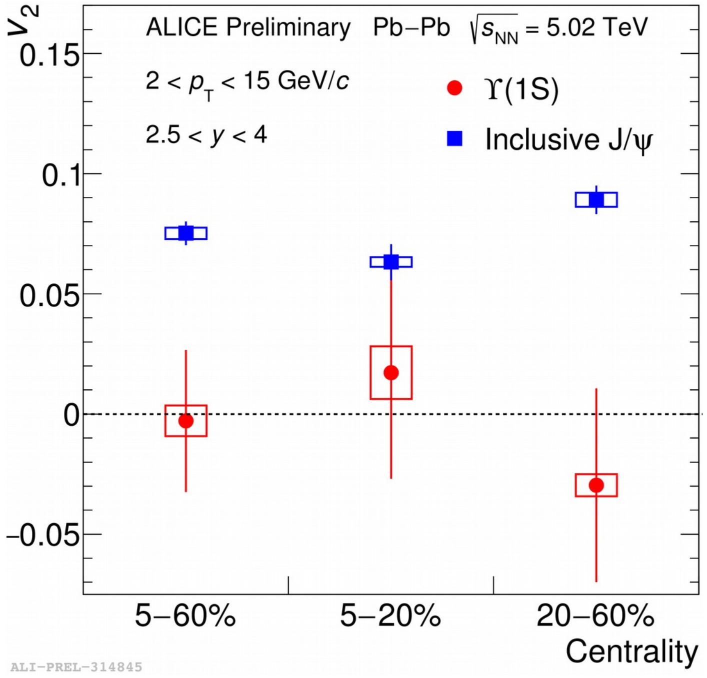
$\Upsilon(1S)$ R_{AA} in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

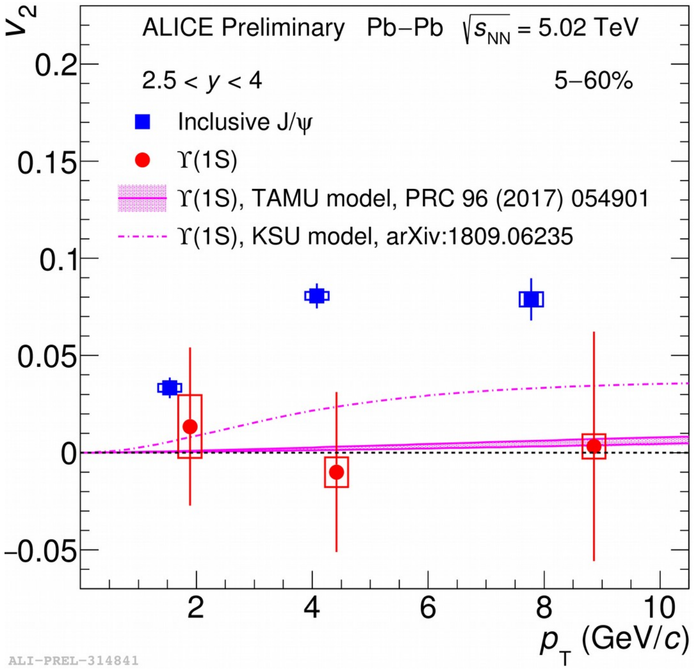


PLB790 (2019) 89

- The suppression is stronger in central collisions than in peripheral events
- R_{AA} does not show a significant dependence on p_T and y
- Amount of direct $\Upsilon(1S)$ suppression is an open question since feed-down fraction to $\Upsilon(1S)$ is not precisely known
- Transport models describe the results with and without a regeneration component within uncertainties
- Only upper edge of hydro-dynamical model agrees with data

NEW!! Elliptic flow (v_2) of Υ(1S) in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV





- The Kent State University (KSU) model calculations consider only the path-length dissociation of initially-created bottomonia inside the QGP medium
- The Texas A&M University (TAMU) model incorporates in addition a regeneration component originating from the recombination of thermalized bottom quarks

- Υ(1S) v_2 is compatible with zero and with the small values predicted by the available theoretical models within uncertainties
- Excluding low p_T, Υ(1S) v_2 is 2.6 σ lower with respect to that of inclusive J/ψ
- This Υ(1S) result includes both 2015 and 2018 Pb-Pb data sets. This is the first result coming out of this new data set

Conclusions

- → We have shown quarkonium production results measured in p-Pb and Pb-Pb collisions
- → Run2 results increased significantly the precision of the measurements
- → Models face difficulties in describing consistently all results

p-Pb:

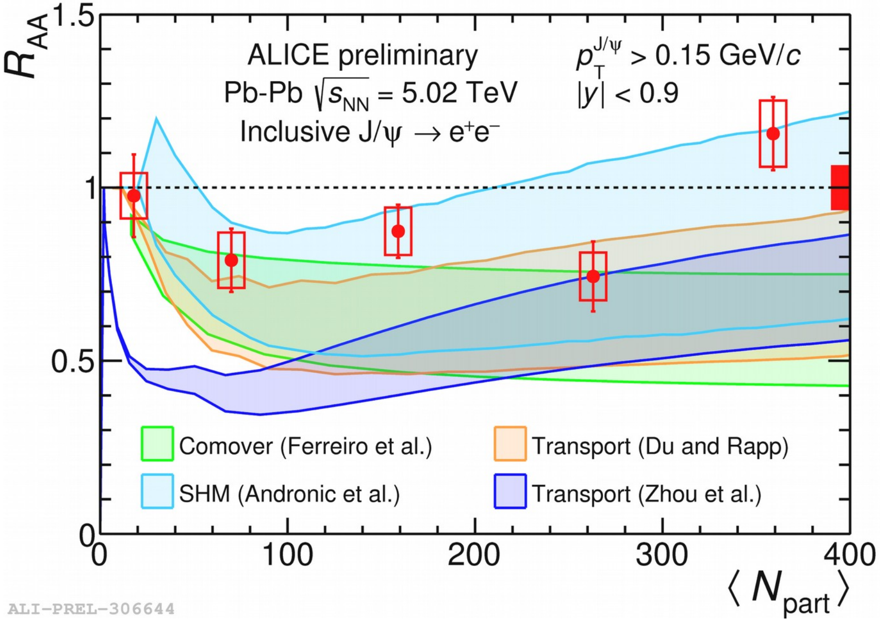
- → J/ψ shows a stronger suppression at forward-*y* than at backward-*y*, where R_{pPb} is compatible with unity
- → Theoretical models based on CNM effects qualitatively describe J/ψ results
- → ψ(2S) shows a stronger suppression than J/ψ, final-state effects needed to explain the ψ(2S) behaviour
- → Similar ϒ(1S) and ϒ(2S) suppression at backward and forward-*y*
- → Shadowing and energy loss models describe ϒ(1S) behaviour at forward-*y* results while they overestimate backward-*y* results

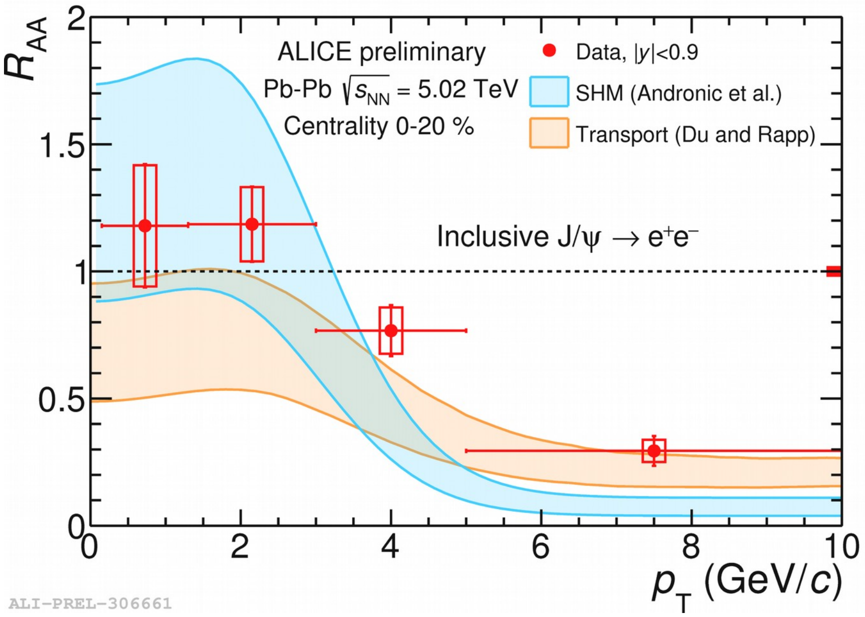
Pb-Pb:

- → J/ψ R_{AA} at LHC shows an interplay of suppression and (re)generation
- → Differential R_{AA} results put strong constraints on the models
- → Non zero J/ψ elliptic flow agrees with regeneration picture
- → Clear suppression of ϒ(1S) with no indication of a significant regeneration component
- → ϒ(1S) v_2 is compatible with zero and with the current model predictions within uncertainties

Thank you

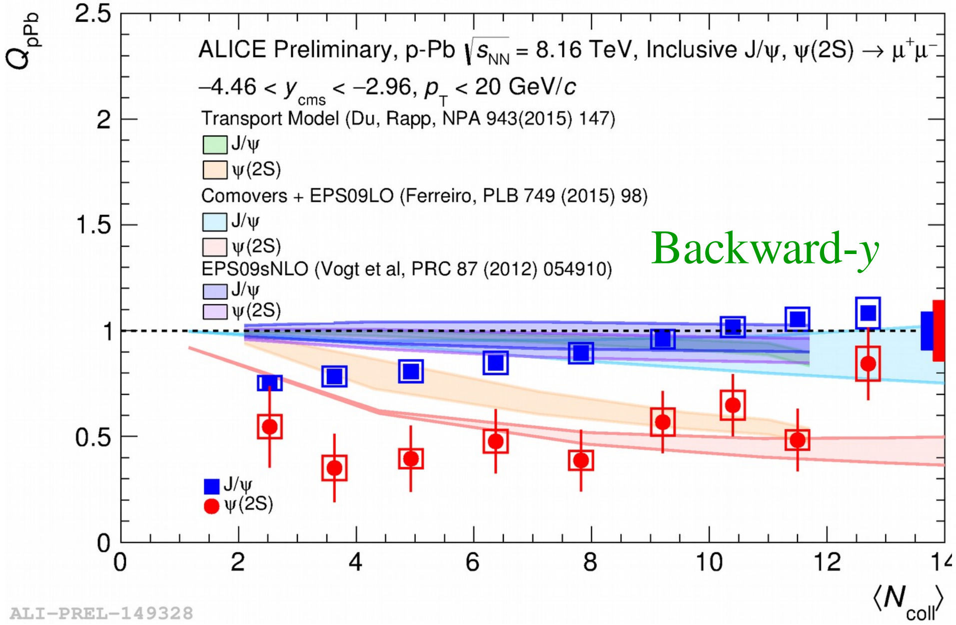
Comparison with theoretical models

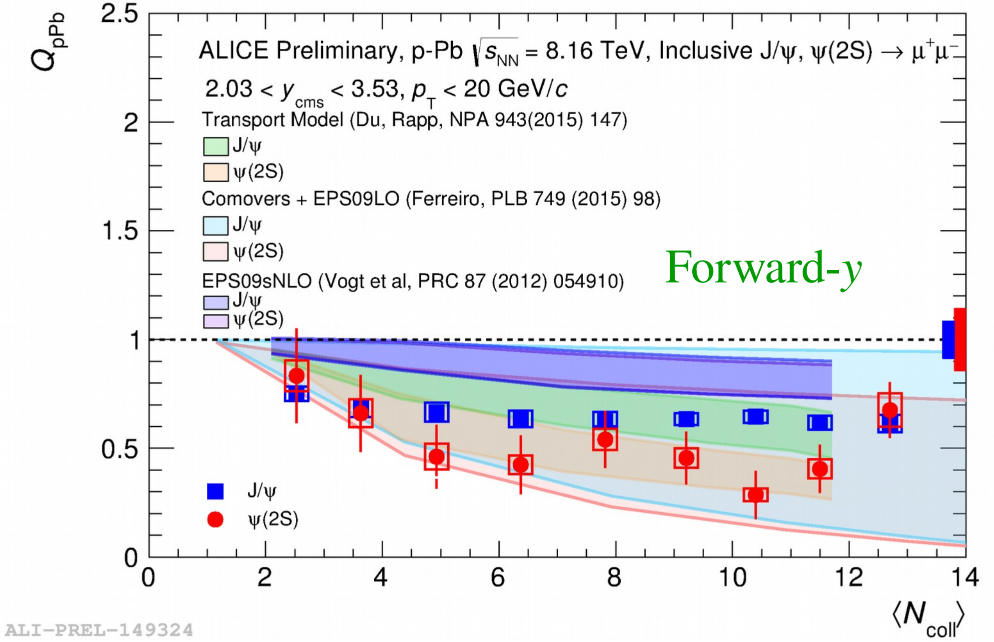




- All models fairly describe the data but large uncertainties associated to charm cross section and shadowing
- Precise charm cross section measurement and more differential analyses needed

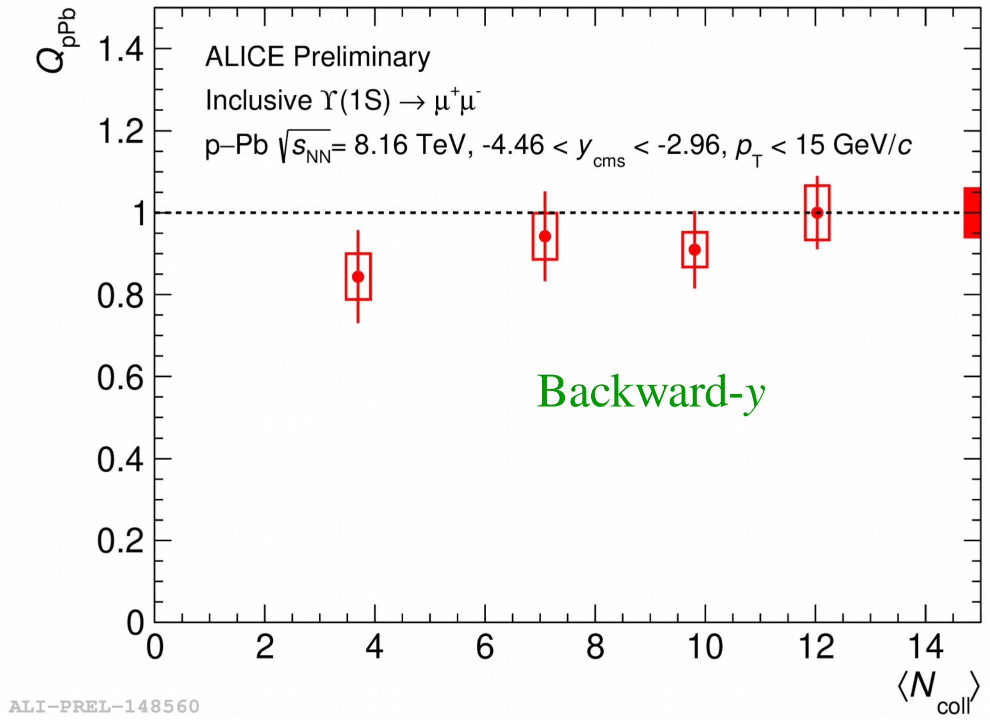
$\psi(2S)$ Q_{pPb} vs centrality at $\sqrt{s_{NN}} = 8.16$ TeV

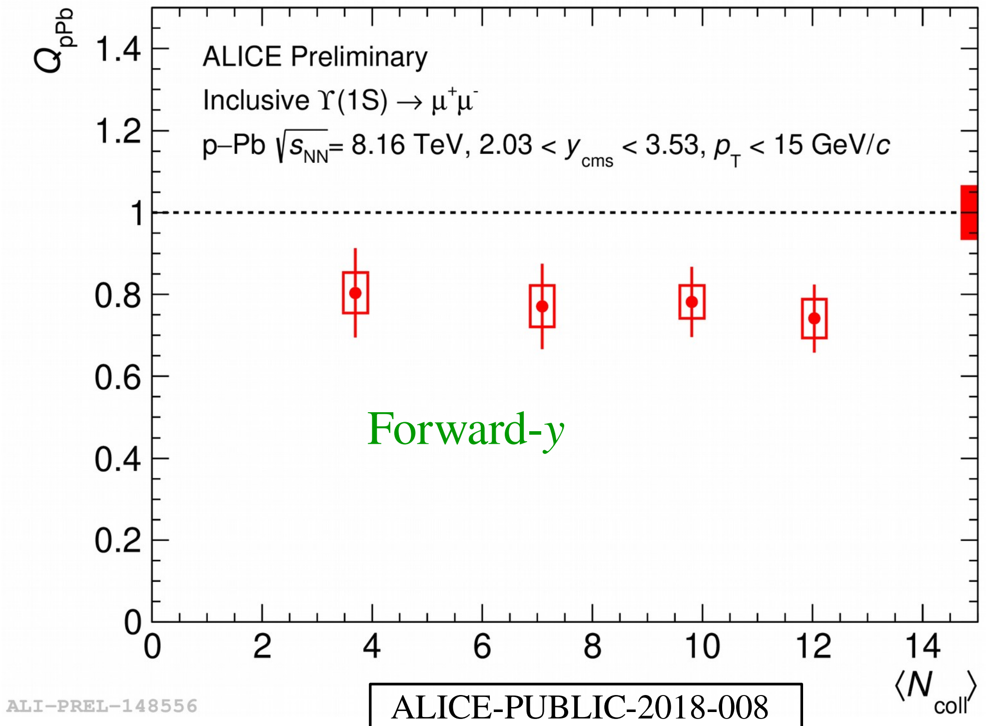




- The $\psi(2S)$ suppression is stronger than J/ψ one, especially at backward rapidity
- At forward rapidity the Q_{pPb} of $\psi(2S)$ follows the same trend as J/ψ while at backward rapidity trend is different
- At backward rapidity, final-state effects needed to explain the $\psi(2S)$ behaviour. Some discrepancies between the data and the model in the peripheral region

$\Upsilon(1S)$ Q_{pPb} vs centrality at $\sqrt{s_{NN}} = 8.16$ TeV

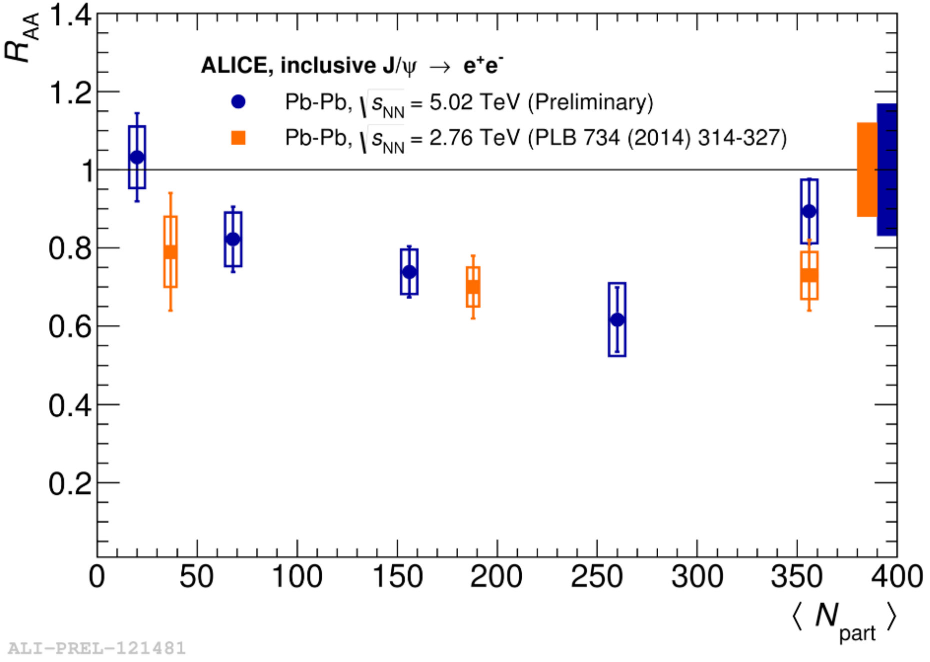


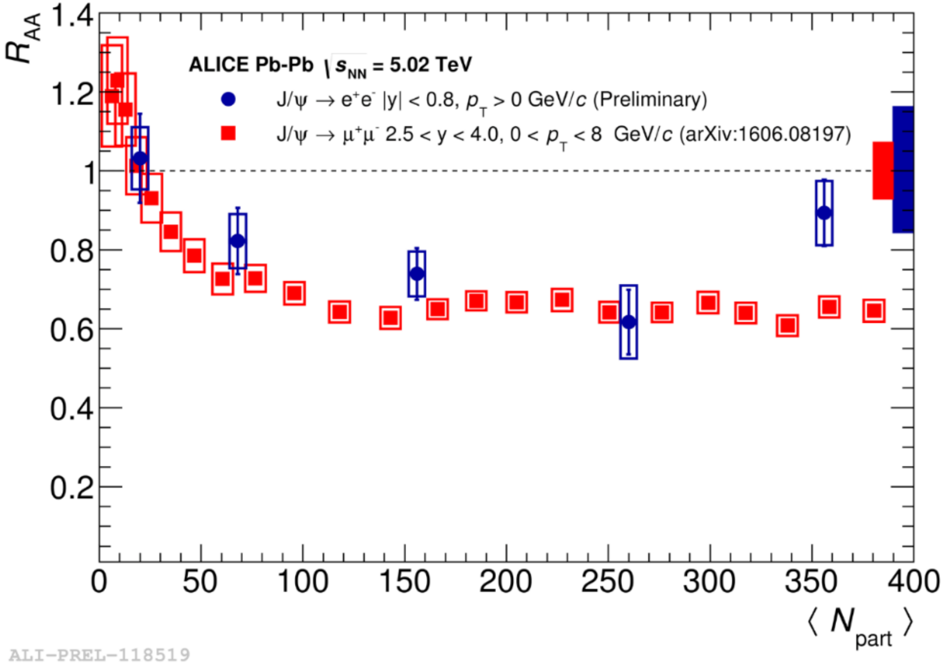


ALICE-PUBLIC-2018-008

- Almost no centrality dependence of Q_{pPb} both at forward and backward rapidity
- A hint for a stronger suppression at forward rapidity

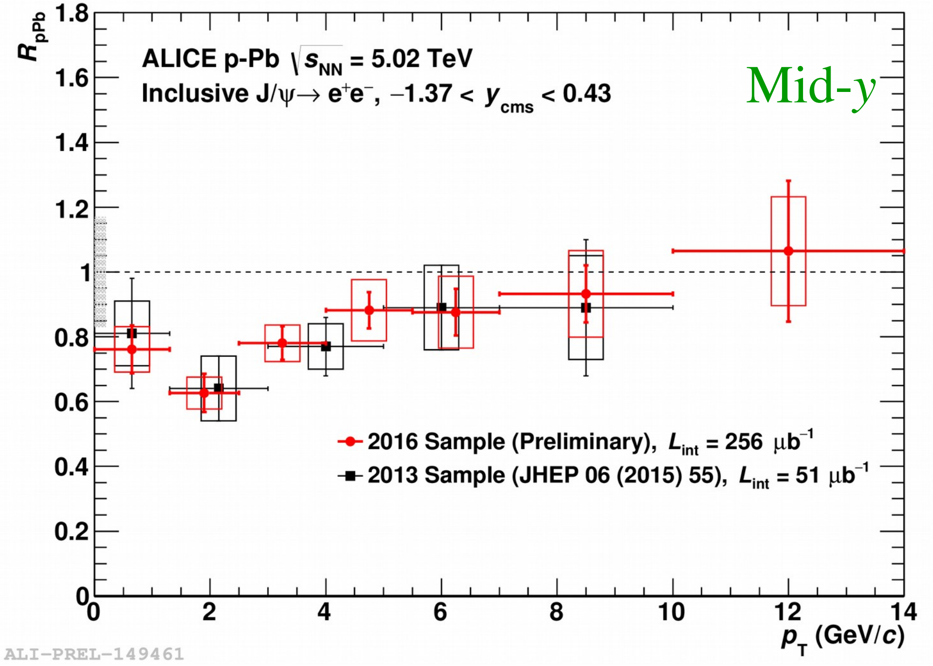
J/ψ R_{AA} in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV (Mid-y)

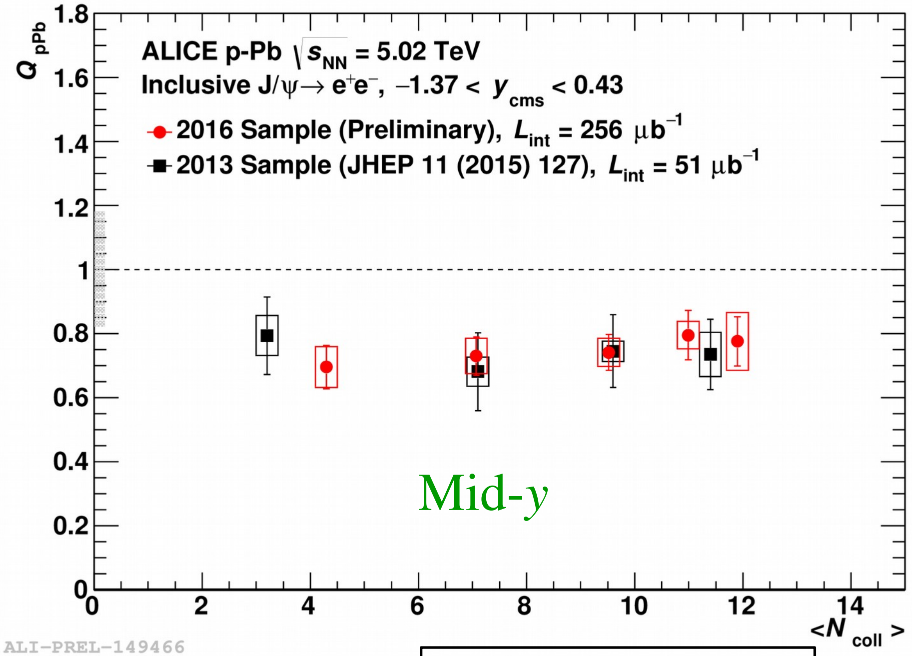




- No significant $\sqrt{s}$-dependence also at mid-rapidity, confirming observation at forward-y.
- Small R_{AA} increase in most central collisions, wrt forward-y, as expected in a (re)generation scenario (but fluctuations cannot be yet excluded).

J/ψ R_{pPb} and Q_{pPb} at $\sqrt{s_{NN}}$ = 5.02 TeV (mid-y)





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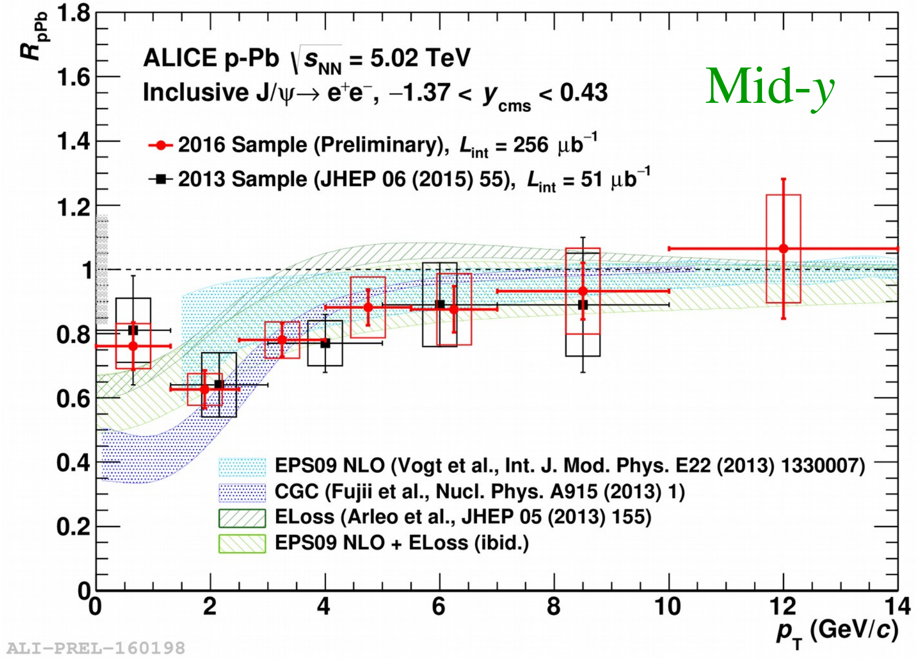
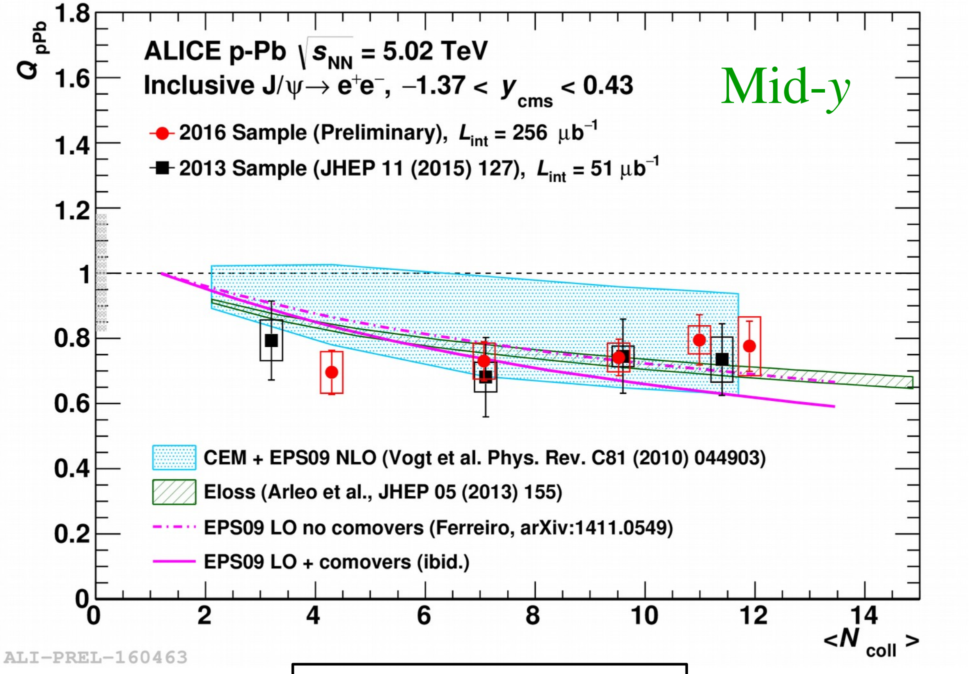
- Run2 analysis with increased luminosity (L_{int} (2016) = 256 μb^{-1}, L_{int} (2013) = 51 μb^{-1}) shows increased precision

- R_{pPb} increases with p_T
- No centrality dependence of Q_{pPb} is observed

J/ψ R_{pPb} and Q_{pPb} compared to theory at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV(mid-y)





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- Theoretical models based on shadowing and/or energy loss, CGC and comovers are in fair agreement with the data

Azimuthal anisotropy (v_2) of J/ψ in p-Pb collisions

Low multiplicity

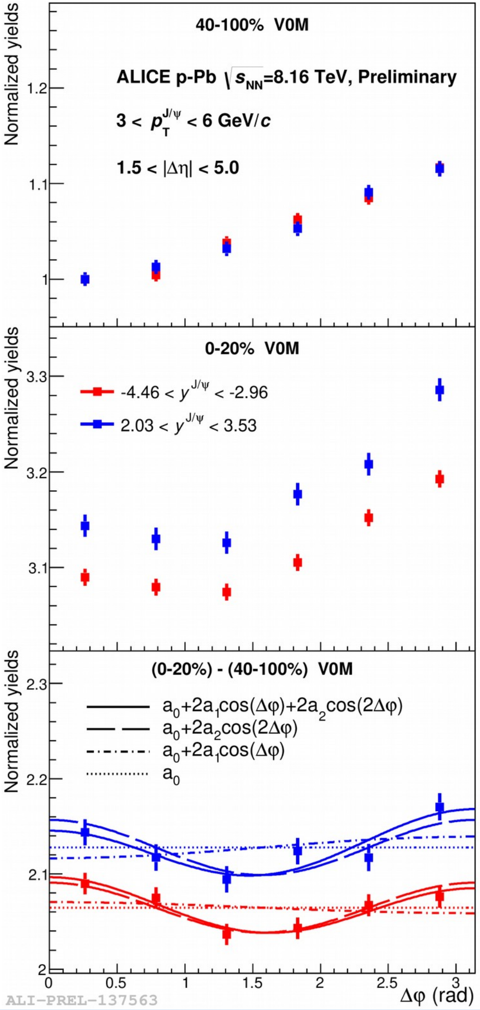
Clear away-side correlation presumably due to recoil jet

High multiplicity

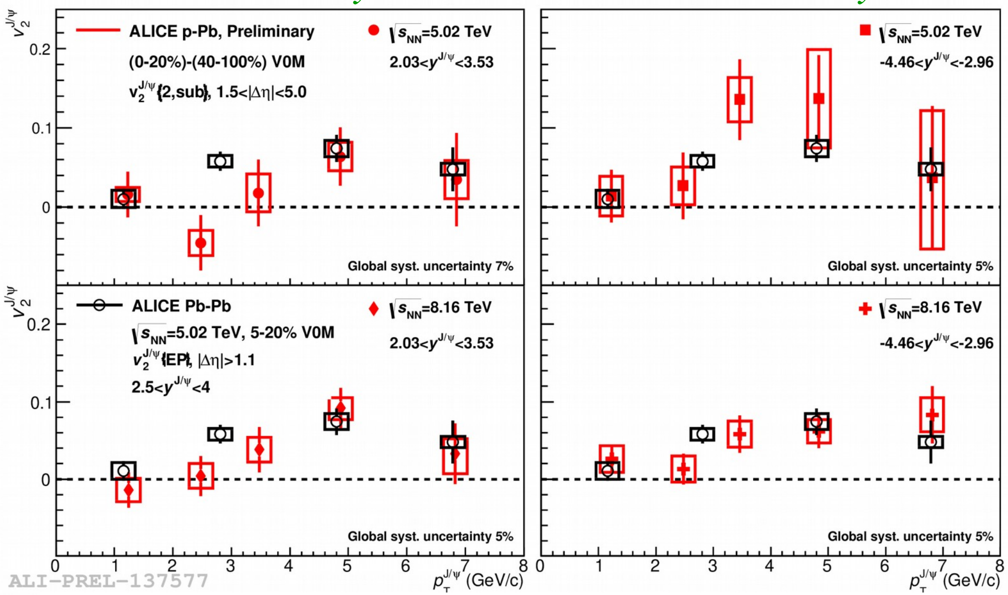
Additional enhancement at both near and away sides

Low multiplicity
–
High multiplicity

Jet correlations eliminated via subtraction



Forward-*y* | Backward-*y*



- p_T < 3 GeV/c → v_2 compatible with 0
  In line with expectation of no recombination
- 3 < p_T < 6 GeV/c → v_2 > 0
  Total (forward+backward,5.02+8.16 TeV) significance about 5σ
  Values comparable to the measurements in central Pb-Pb collisions