Charmonium production in Pb-Pb and p-Pb collisions at forward rapidity measured with ALICE

Mohamad Tarhini, IPN-Orsay
For the ALICE collaboration

Outline

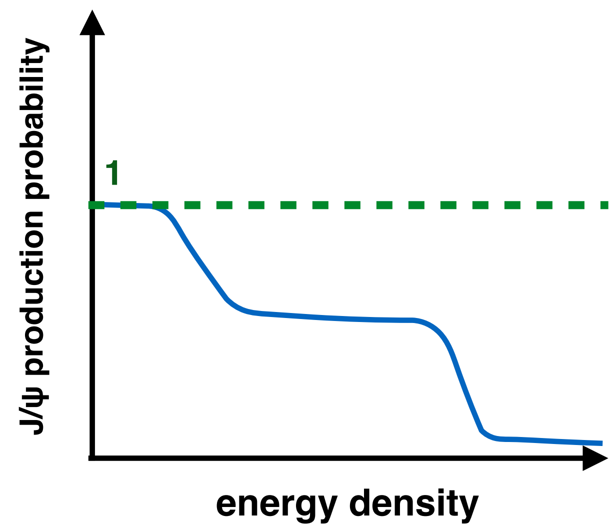
- Introduction and ALICE detector
- Results in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV
- Results in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV
- Summary

Introduction and motivation

[1] Phys. Lett. B178 (1986) 416
[2] Phys. Lett. B490 (2000) 196–202
[3] Phys. Rev. C63 (2001) 054905

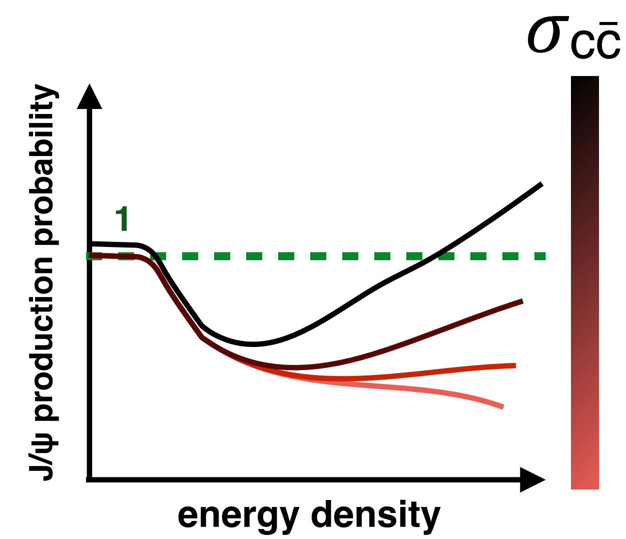
Original proposal:

- Measurement of charmonium production in heavy-ion collisions is a probe for the de-confinement aspect of the QGP [1]
  - Sequential dissociation of different charmonium states can serve as a QGP thermometer



But:

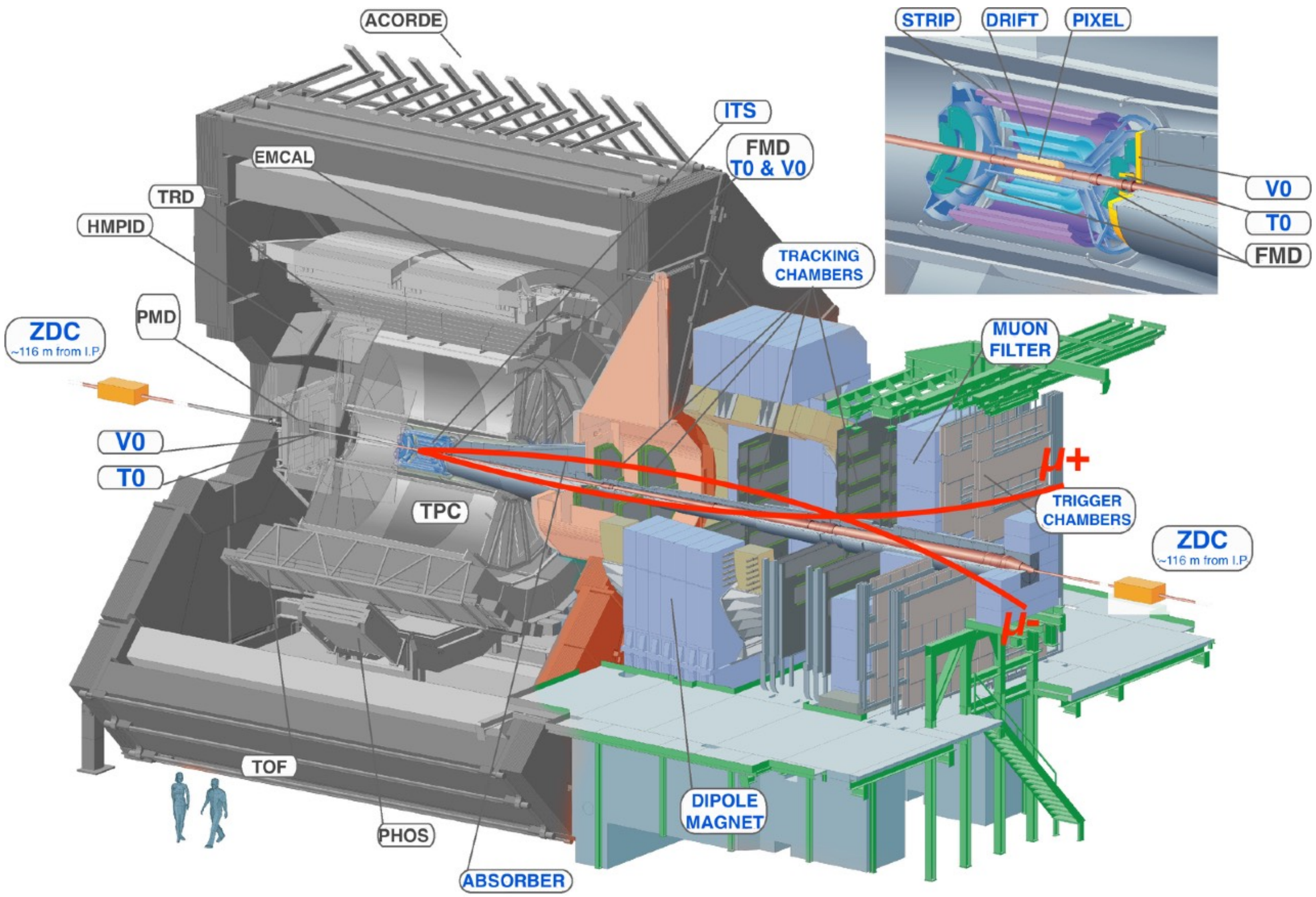
- If there are enough $c\bar{c}$ pairs, charmonium can be (re)generated [2,3]
  - (re)generation is treated in different ways in different models
    - How to distinguish between models ?
      - R_{AA}, J/ψ elliptic flow (v_2), J/ψ $\langle p_T \rangle$, ψ(2s)/J/ψ
  - $c\bar{c}$ cross section is a key ingredient



Other ingredients:

- Effects of cold nuclear matter (CNM) on the charmonium production and $c\bar{c}$ cross section
  ➡ Need for (p-A)-like data
- Different sources of charmonium production (inclusive = prompt + non-prompt)

ALICE detector and datasets



muon spectrometer

$-4 < \eta < -2.5$

Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

$\mathcal{L}_{int} \sim 225\ \mu b^{-1}$

[Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV: $\mathcal{L}_{int} \sim 70\ \mu b^{-1}$]

p-Pb at $\sqrt{s_{NN}}$ = 8.16 TeV

$\mathcal{L}_{int} \sim 8.7\ nb^{-1}$

[p-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV: $\mathcal{L}_{int} \sim 5\ nb^{-1}$]

Pb-p at $\sqrt{s_{NN}}$ = 8.16 TeV

$\mathcal{L}_{int} \sim 12.9\ nb^{-1}$

[Pb-p at $\sqrt{s_{NN}}$ = 5.02 TeV: $\mathcal{L}_{int} \sim 5.8\ nb^{-1}$]

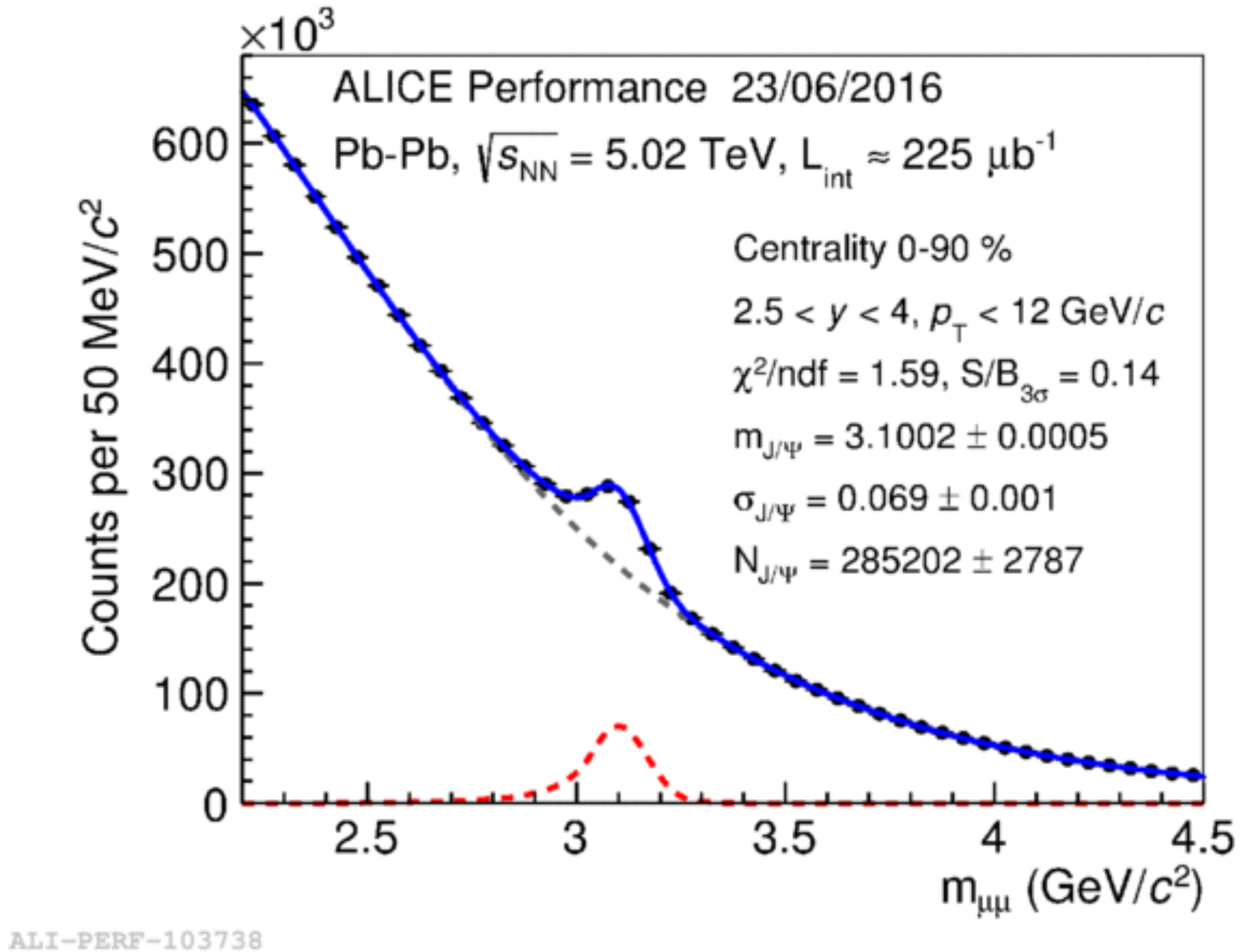
- Inclusive charmonia are reconstructed via their dimuon decay down to zero p_T

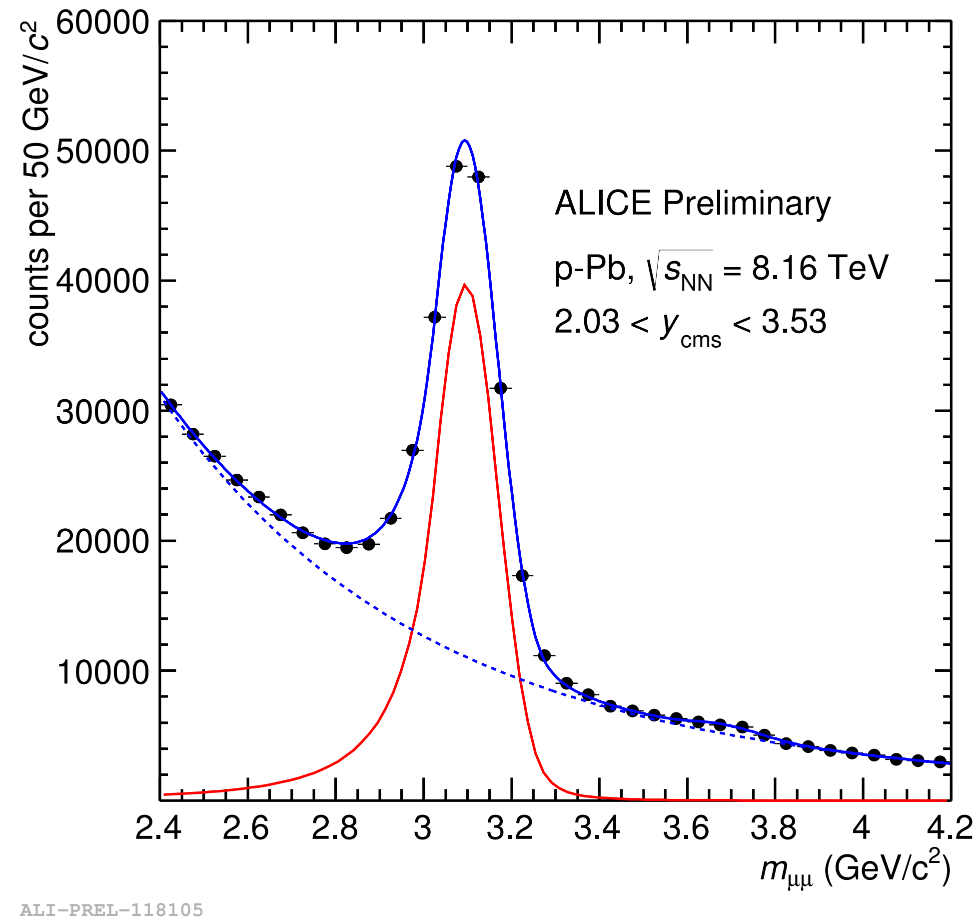
See the talk by Tonatiuh Bustamante (today, parallel session 1.3) on the ($J/\psi \rightarrow e^+e^-$) results at mid-rapidity

- In the v_2 analysis, the event plane is determined using V0 or SPD
- In Pb-Pb collisions, the centrality is estimated by a MC Glauber [1] fit of the V0 amplitude

Charmonium reconstruction

- Main single muon selections:
  - $-4 < \eta_\mu < -2.5$
  - Matching between trigger and tracker
- Muon pair selections:
  - $2.5 < y < 4$
  - Opposite sign charges





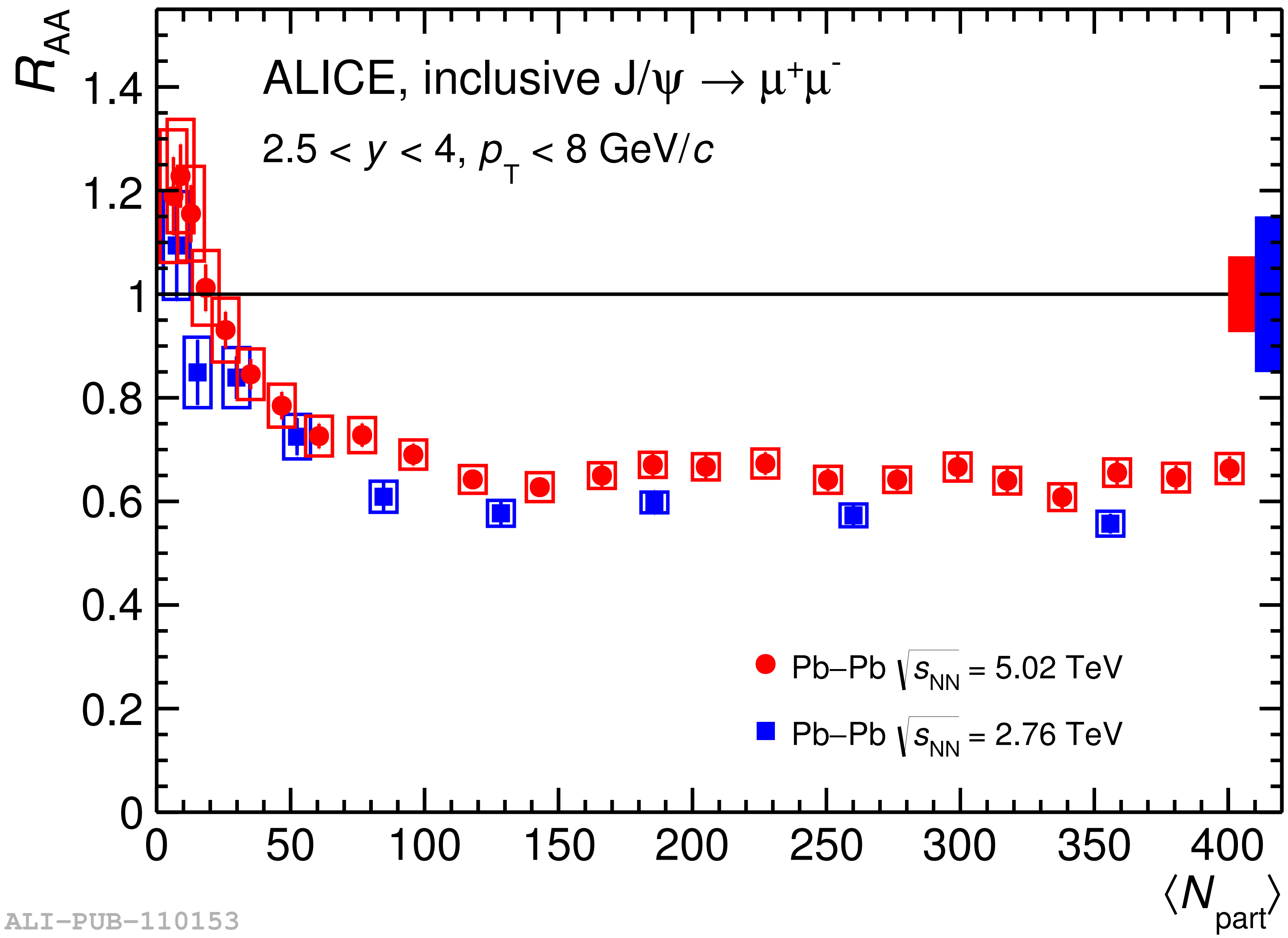
- The signal is extracted by fitting the dimuon invariant mass distribution with (background+signal) functions
  - Different signal and background shapes are considered
  - Event mixing is also used in Pb-Pb collisions to subtract the combinatorial background
- Number of charmonium candidates are further corrected by the detector acceptance times efficiency obtained via MC simulations

J/ψ R_{AA} vs Centrality

[1] arXiv:1606.08197
[2] PLB 734 (2014) 314-327

Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV: R_{AA} 0-90%(0<p_T<8 GeV/c) = 0.66 ± 0.01(stat.) ± 0.05 (syst.) [1]

Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV: R_{AA} 0-90%(0<p_T<8 GeV/c) = 0.58 ± 0.01(stat.) ± 0.09 (syst.) [2]



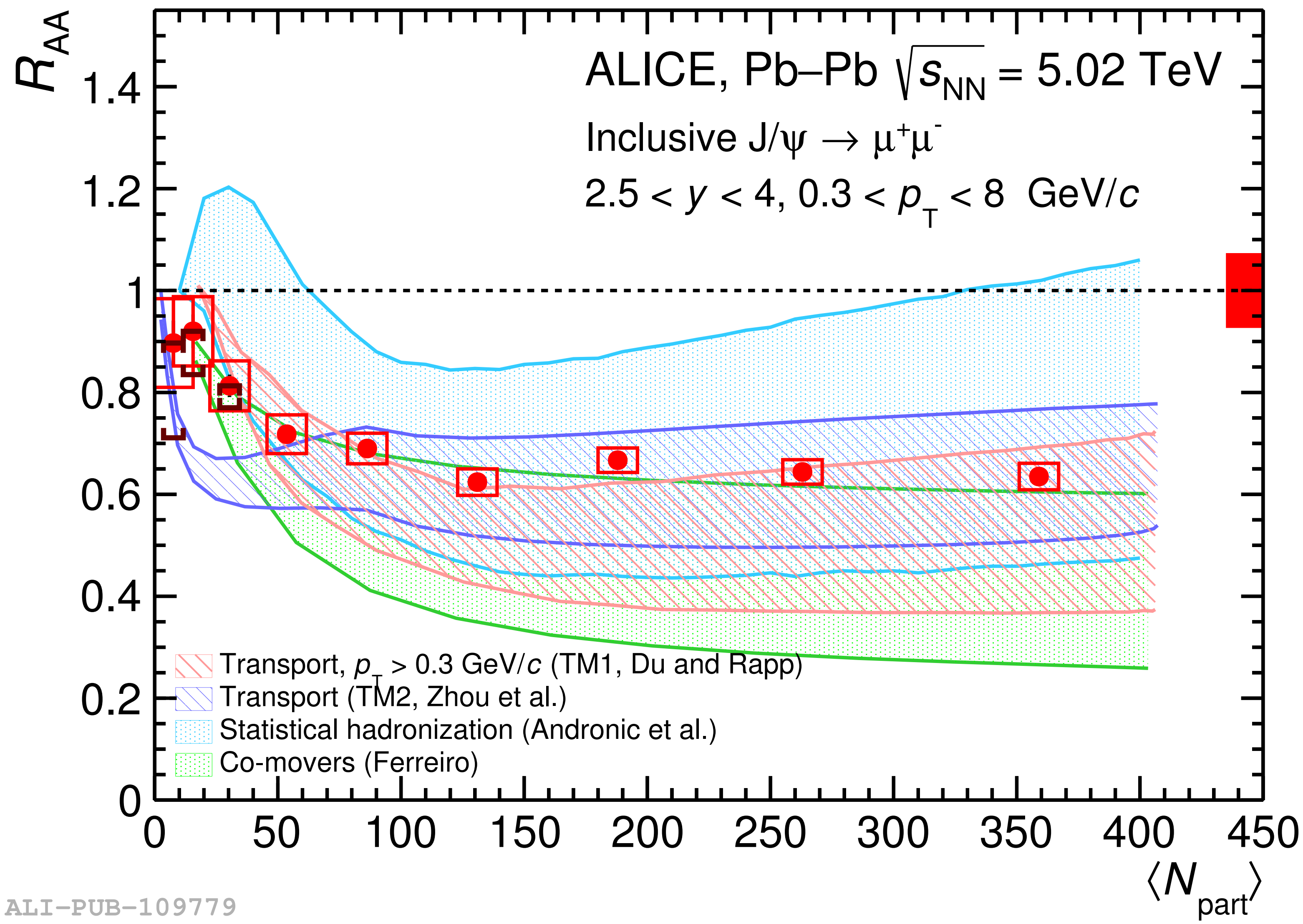
- A measured pp cross section is used in the R_{AA} calculation

See poster (C01) by Benjamin Audurier for more details

- Clear J/ψ suppression and almost no centrality dependence for N_{part} > 100 (centrality < 50 %)
- The precision of the measurement is improved with respect to $\sqrt{s_{NN}}$ = 2.76 TeV data
- A systematic difference of ~15% between the R_{AA} at two energies
  - The increase is within the uncertainties

J/ψ R_{AA} vs centrality (comparison with models)

[1] Nucl. Phys. A 859 (2011) 114–125
[2] Phys. Rev. C 89 no. 5, 459 (2014) 054911
[3] Nucl. Phys. A 904-905 (2013) 535c
[4] Phys. LeX. B 731 (2014) 57–63
[5] ALICE Coll. PRL116 (2016) 222301

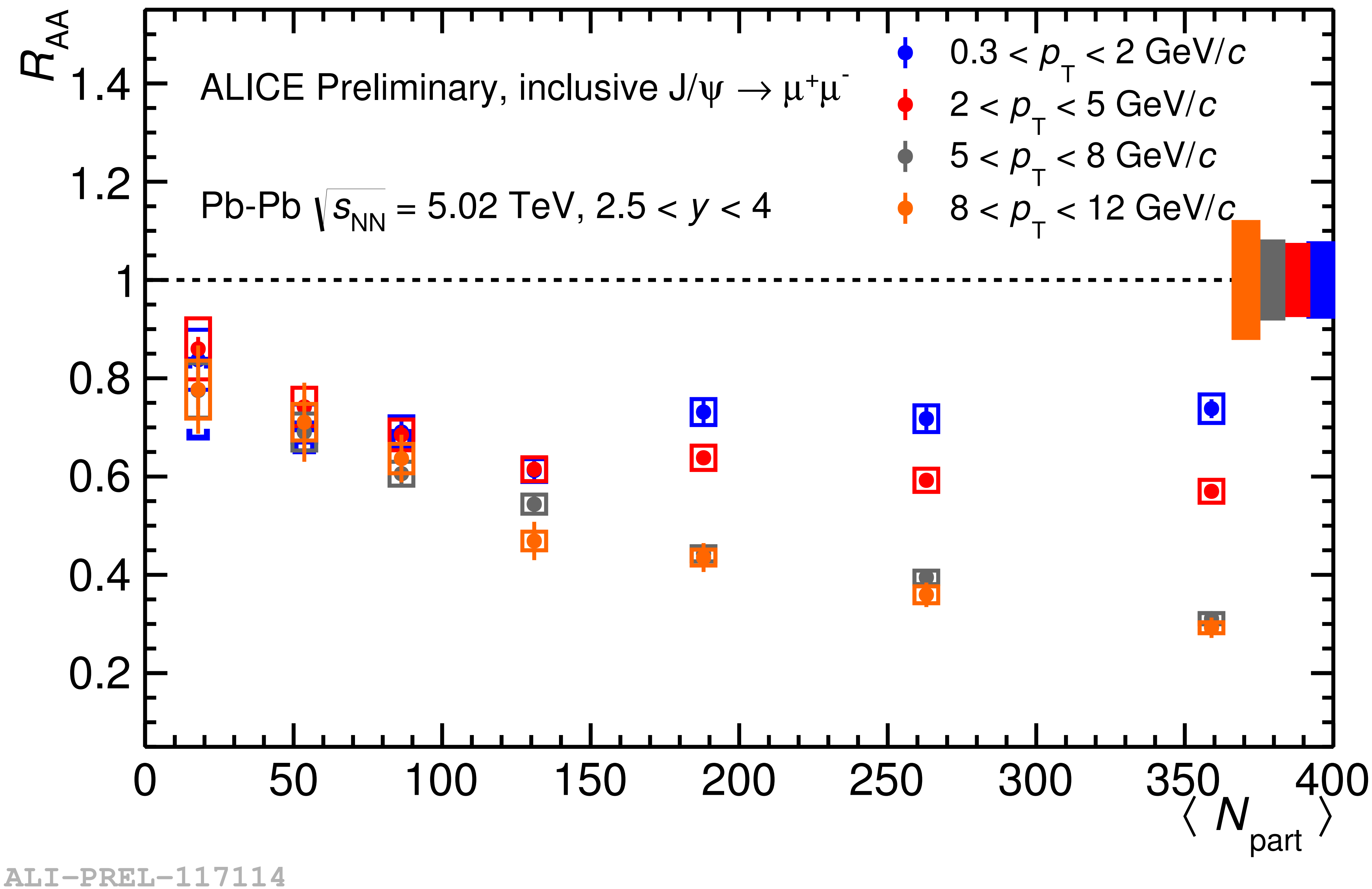


- p_T > 0.3 GeV/c to remove possible J/ψ photo-production contribution [5]
- Brackets represent maximum remaining contribution

- Results are compared with calculations based on different models:
  - Two transport models (TM1 [1] and TM2 [2]): continuous interplay between dissociation and (re)generation
  - **Statistical hadronisation model [3]:** all J/ψ are dissociated in the plasma. (Re)generation occurs at the phase boundary
  - **Comover model (CIM) [4]:** J/ψ are suppressed via interaction with a parton co-moving medium. (Re)generation added as a gain term
- **Measurement is precise enough to constrain the models**

New J/ψ R_{AA} vs centrality (in p_T ranges)

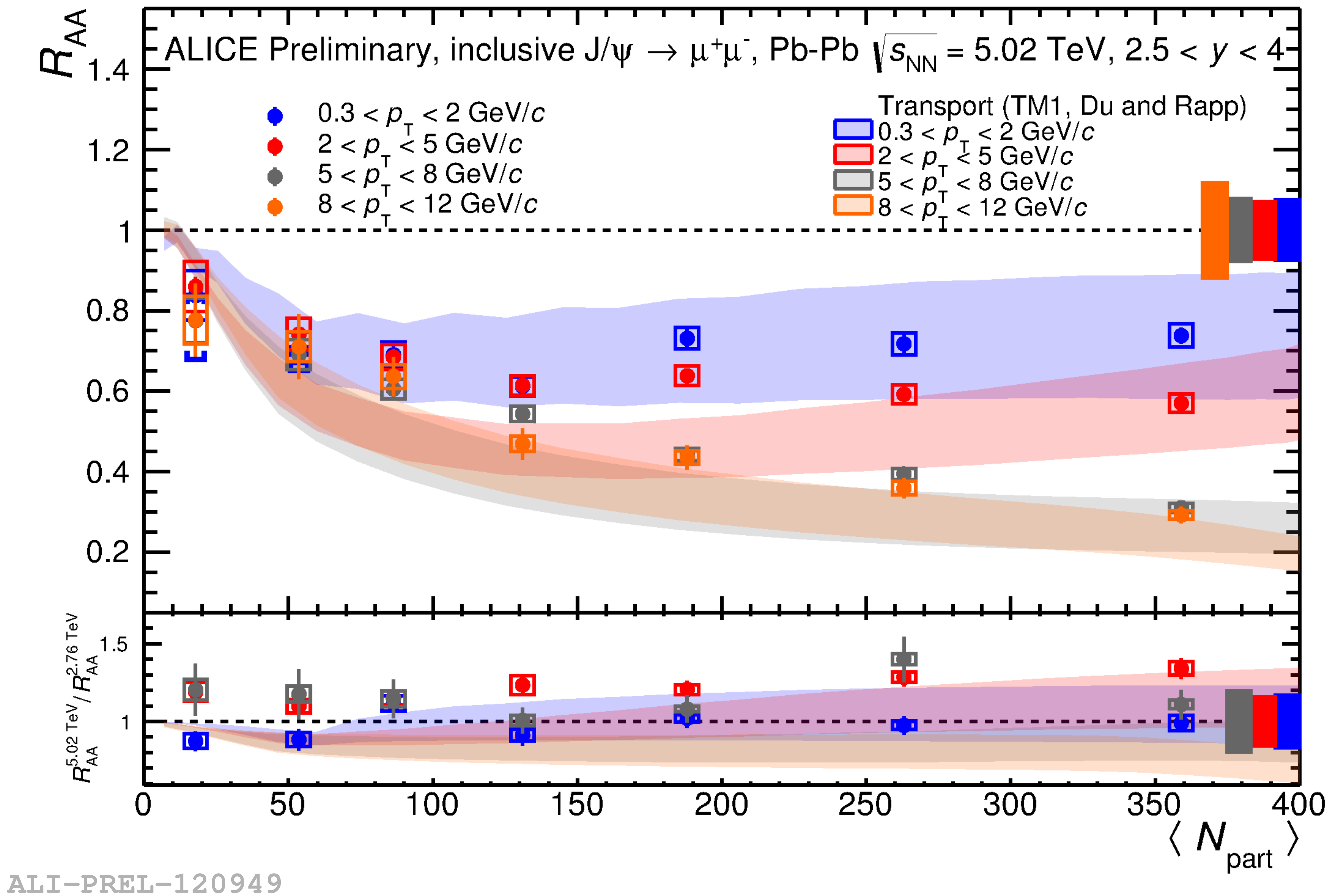
- For central events, the suppression is smaller at lower p_T
- R_{AA} shows a stronger centrality dependence at high p_T



J/ψ R_{AA} vs Centrality (in p_T ranges)

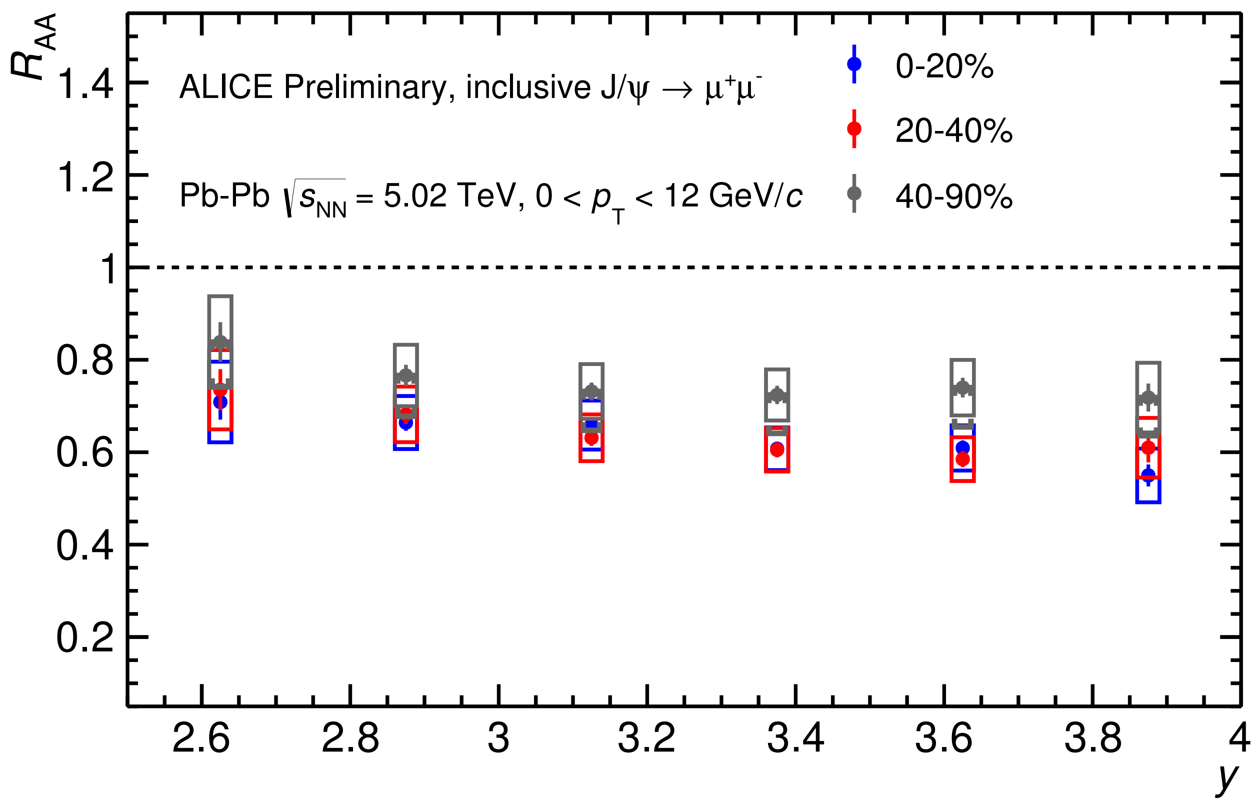
[1] Nucl. Phys. A 859 (2011) 114–125

- For central events, the suppression is smaller at lower p_T
  - This behaviour is reproduced by models that include J/ψ (re)generation (for instance TM1 [1])
- R_{AA} shows a stronger centrality dependence at high p_T



New J/ψ R_{AA} vs Rapidity

- Rapidity dependence of the R_{AA} is studied in three centrality ranges



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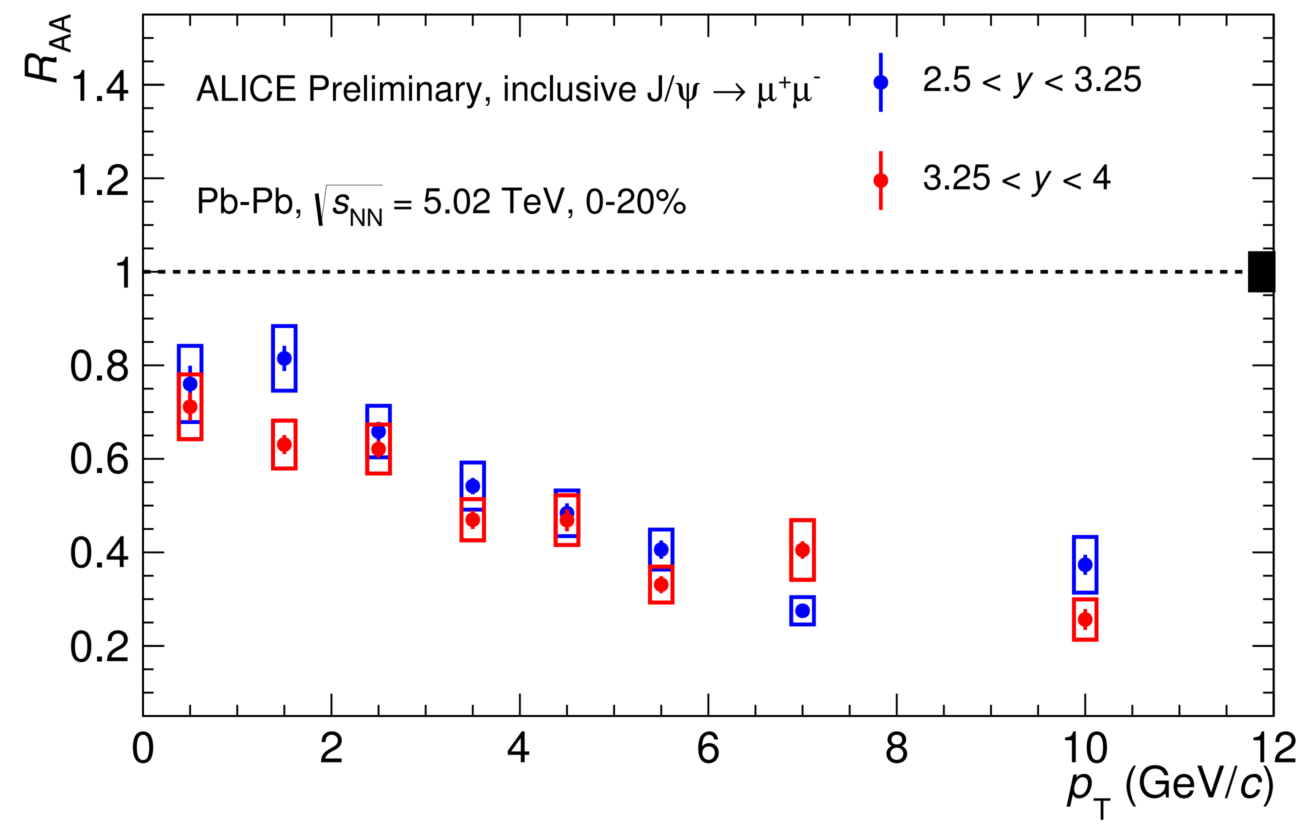

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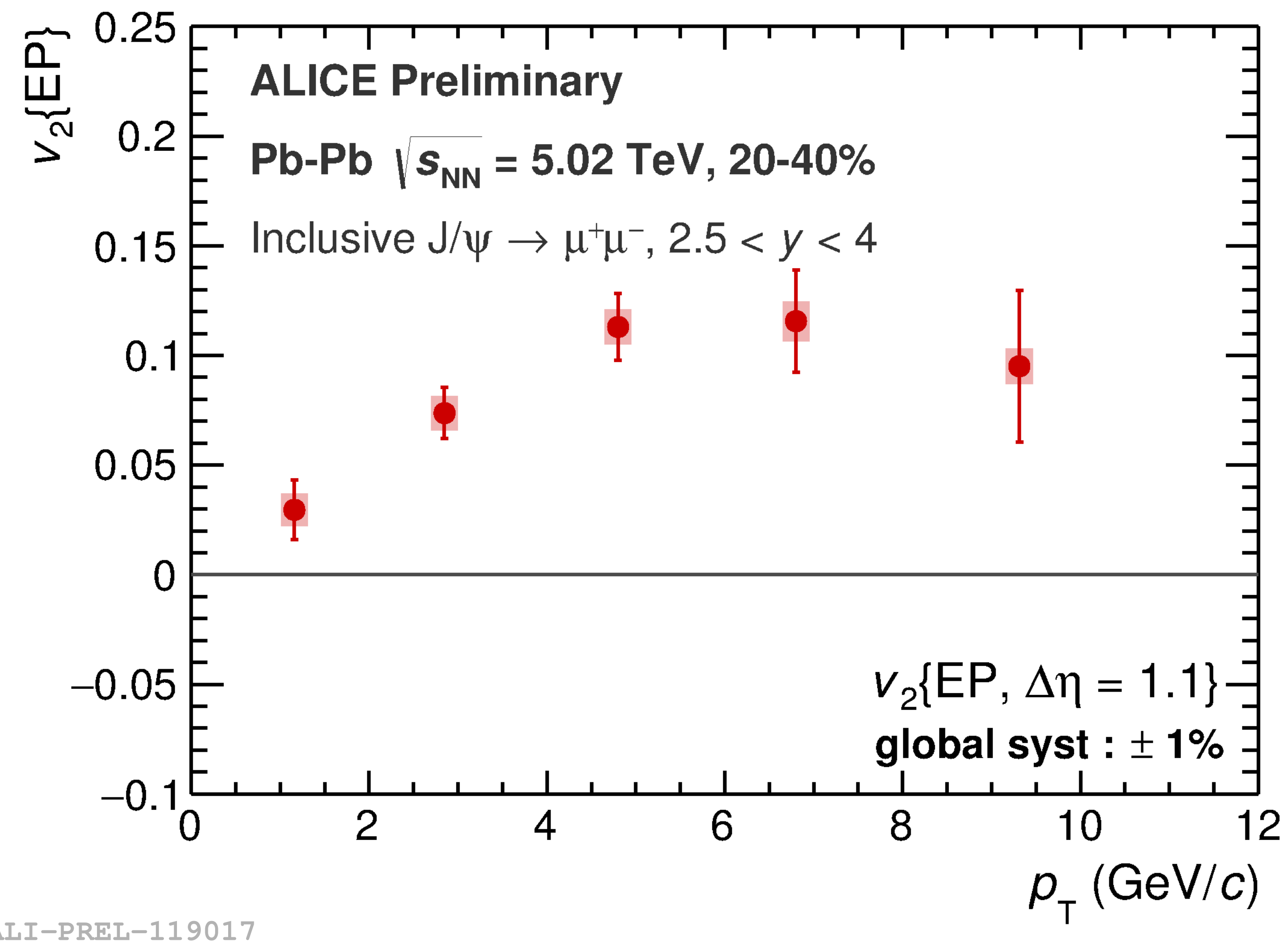
- A negligible rapidity dependence of the R_{AA} in different centrality and p_T ranges
- Would be interesting to have comparison with model calculations !

New J/ψ elliptic flow (v_2)

- Charm quarks, if thermalised in the QGP, should exhibit the elliptic flow generated in this phase
  - ➡ Non zero v_2 for re-generated J/ψ



- A non zero J/ψ v_2 seen in semi-central collisions (20-40%) [7.6 σ significance in 4< p_T < 6 GeV/c]

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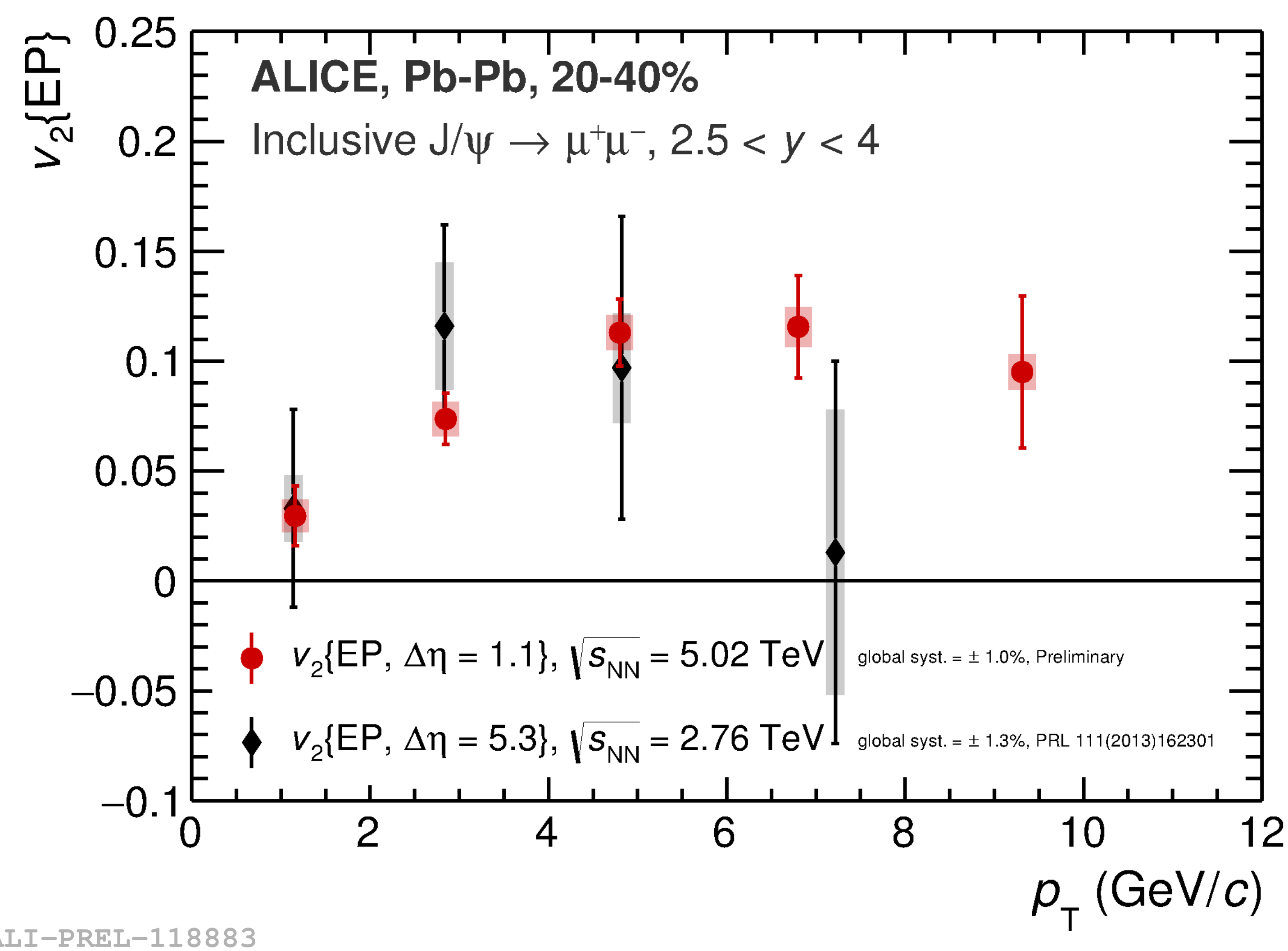

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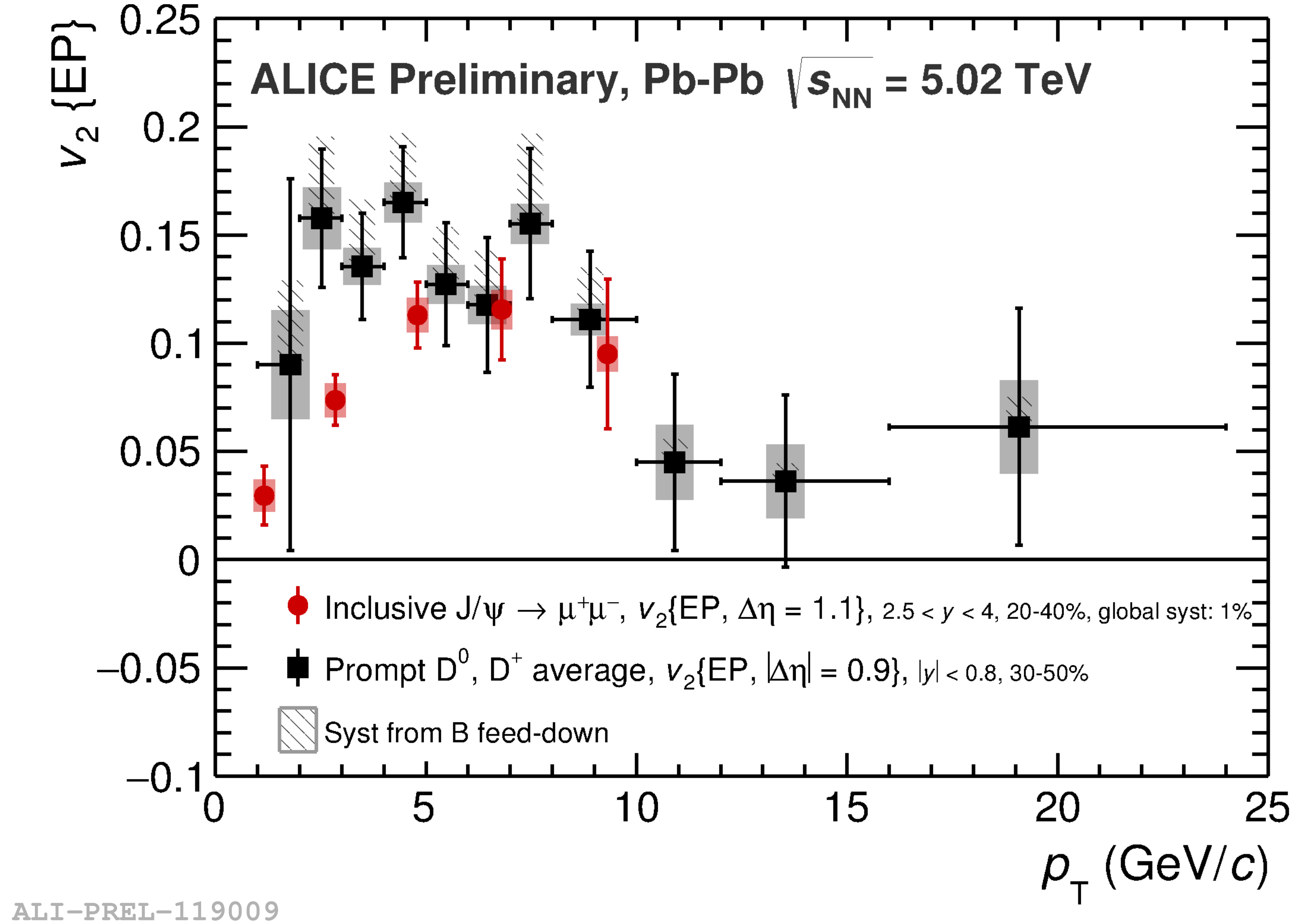
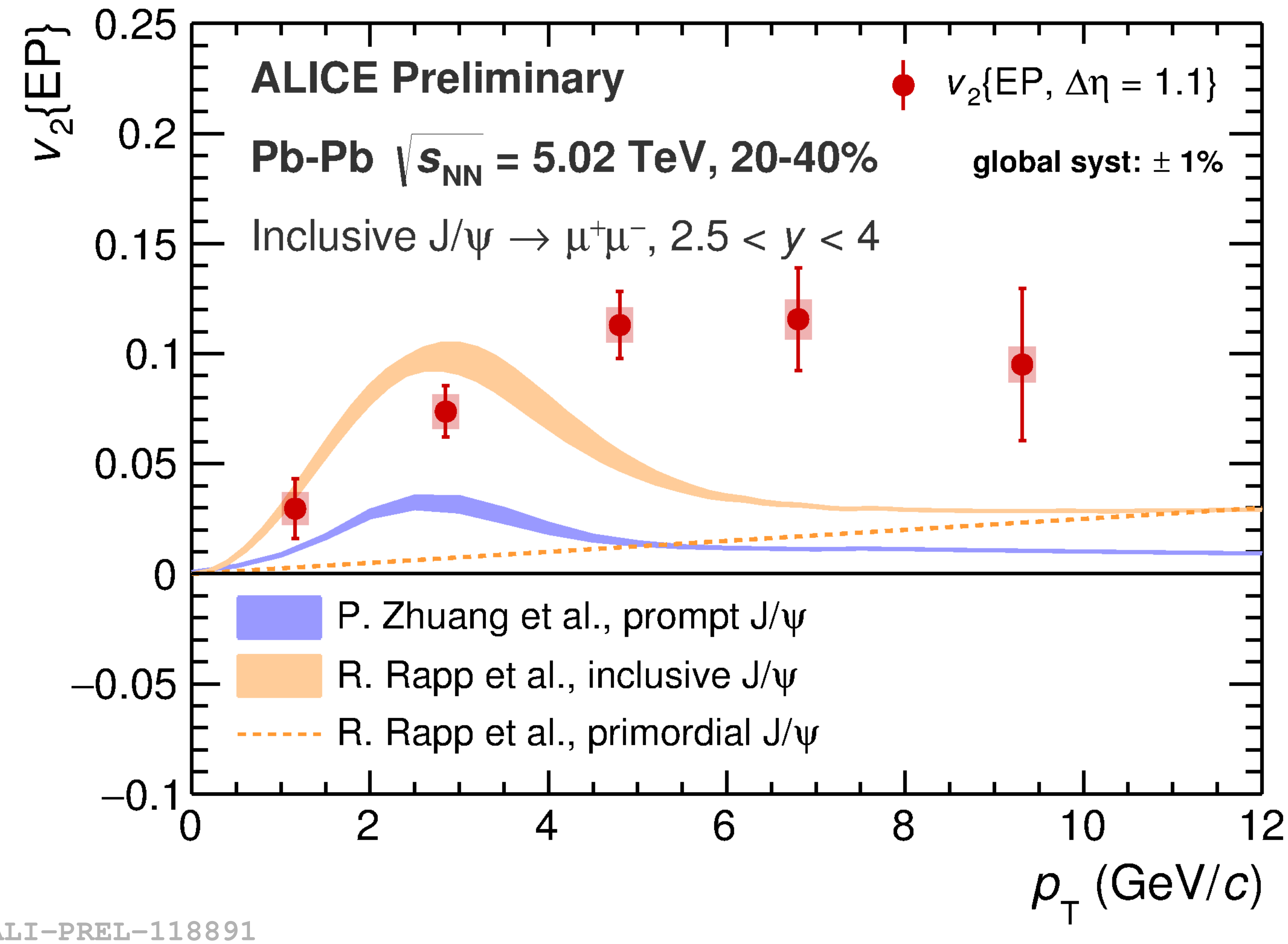


J/Ψ at $\sqrt{s_{NN}}$ = 5.02 TeV
centrality 20-40%
2.5 < y < 4
Open charm at
$\sqrt{s_{NN}}$ = 5.02 TeV
centrality 30-50%
-0.8 < y < 0.8

- A non zero J/ψ v_2 seen in semi-central collisions (20-40%) [7.6 σ significance in 4< p_T < 6 GeV/c]
- Precision is significantly increased in run-2 measurement with respect to run-1
- Similar measured v_2 values for hidden and open charm (see Anastasia Barbano talk at 16:50)

J/ψ elliptic flow (v_2)

- Charm quarks, if thermalised in the QGP, should exhibit the elliptic flow generated in this phase
  - ➡ Non zero v_2 for re-generated J/Ψ

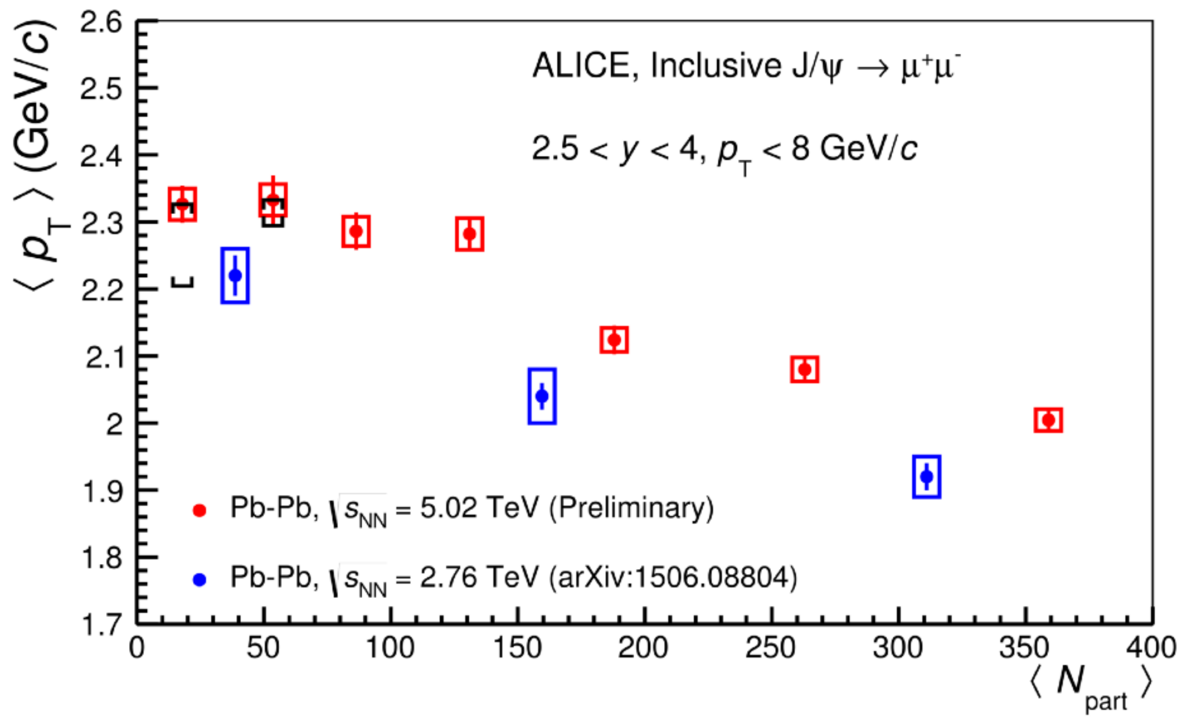


- A non zero J/ψ v_2 seen in semi-central collisions (20-40%) [7.6 σ significance in 4< p_T < 6 GeV/c]
- Precision is significantly increased in run-2 measurement with respect to run-1
- Similar measured v_2 values for hidden and open charm
- Models have difficulties to reproduce the measured J/ψ v_2 in the measured p_T interval

New J/ψ average p_T ($<p_T>$)

[1] JHEP 05 (2016) 179
[2] Nucl. Phys. A 859 (2011) 114–125

- The J/ψ $<p_T>$ and the r_{AA} are complementary observables to the R_{AA} and the v_2



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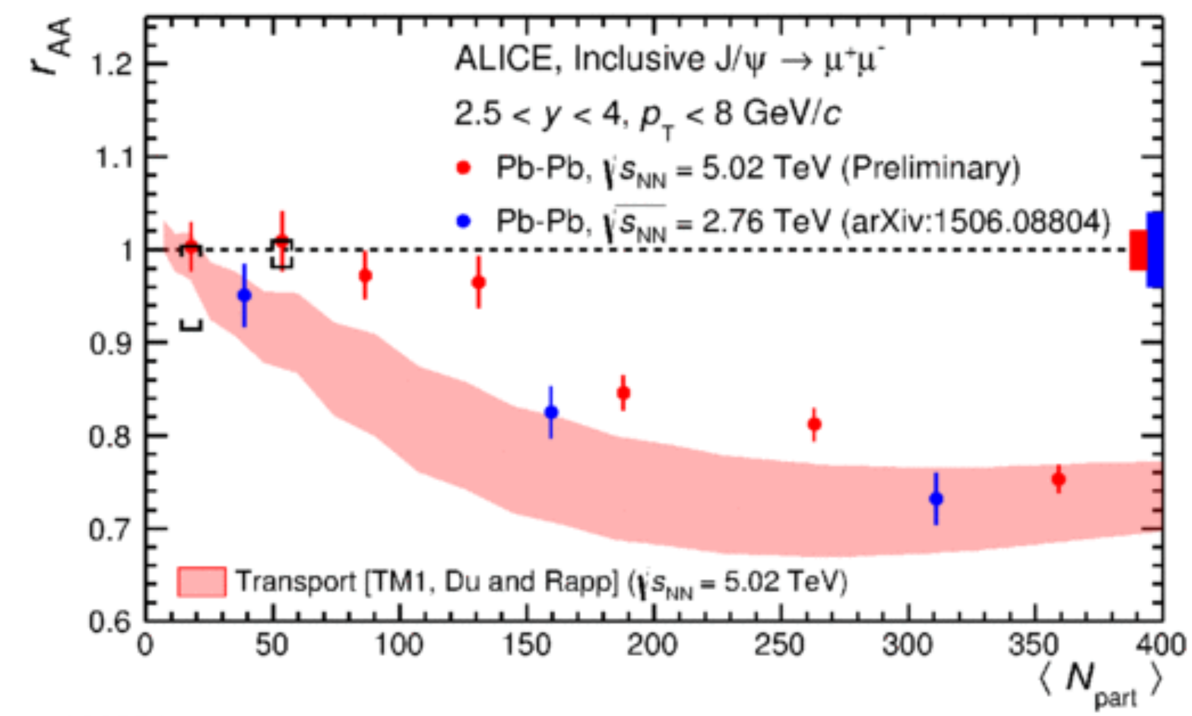

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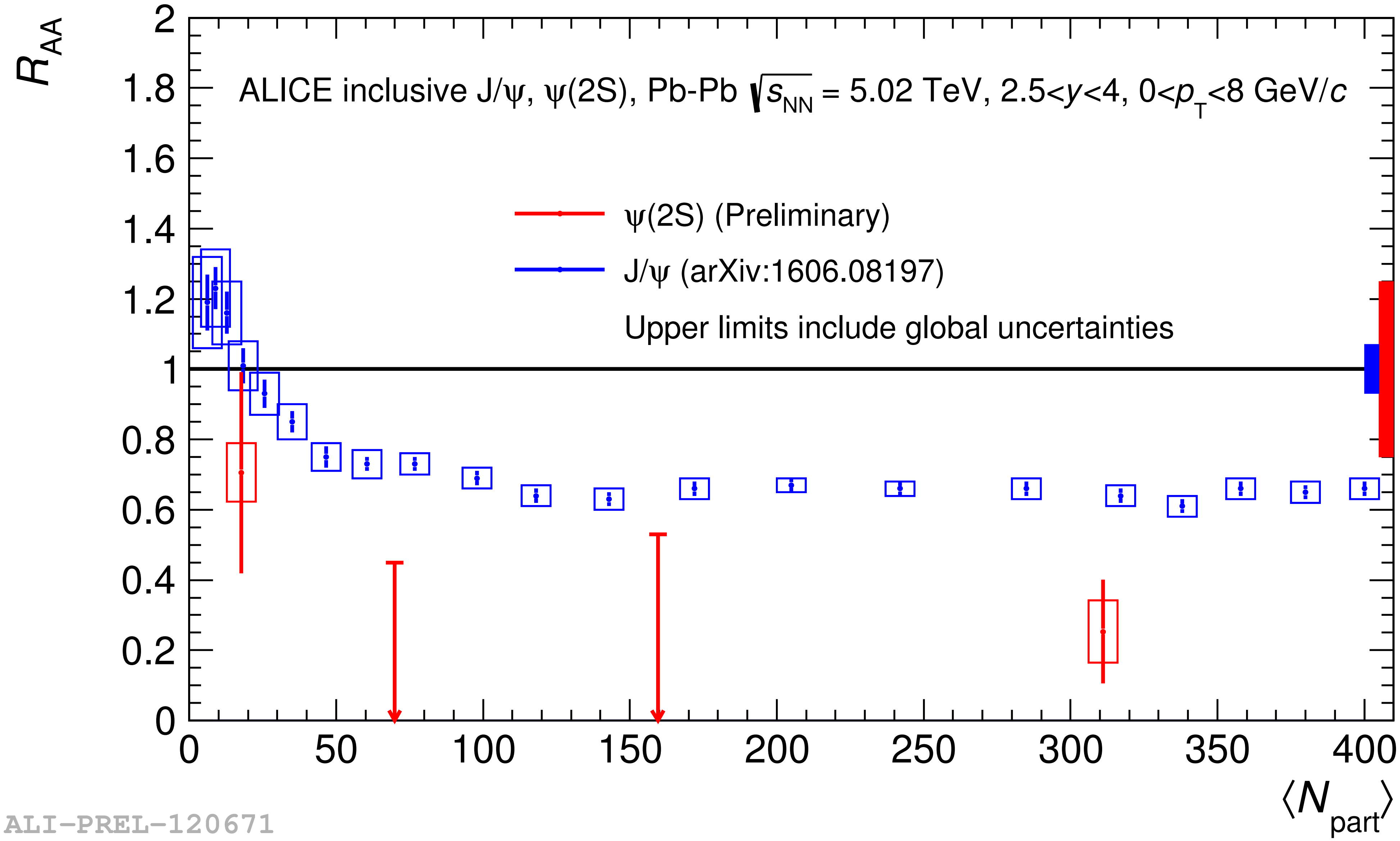
$$r_{AA} = \frac{\langle p_T^2 \rangle_{AA}}{\langle p_T^2 \rangle_{pp}}$$

- The J/ψ $<p_T>$ is smaller in central events than in peripheral ones→ (re)generation
- The results of r_{AA} at $\sqrt{s_{NN}} = 5.02$ TeV and $\sqrt{s_{NN}} = 2.76$ TeV [1] are compatible within uncertainties
- Discrepancies are seen in some centralities (e.g > 3 σ for 30-40 %) between the measurements and calculations based on TM1 [2] model

New $\psi(2S)$ R_{AA}

- The ratios between different charmonium states are essential to discriminate between different models



- For the bins with too small $\psi(2S)$ significance, an upper limit with 95% CL is calculated
- **The $\psi(2S)$ is more suppressed than the J/ψ in semi-central and central collisions**

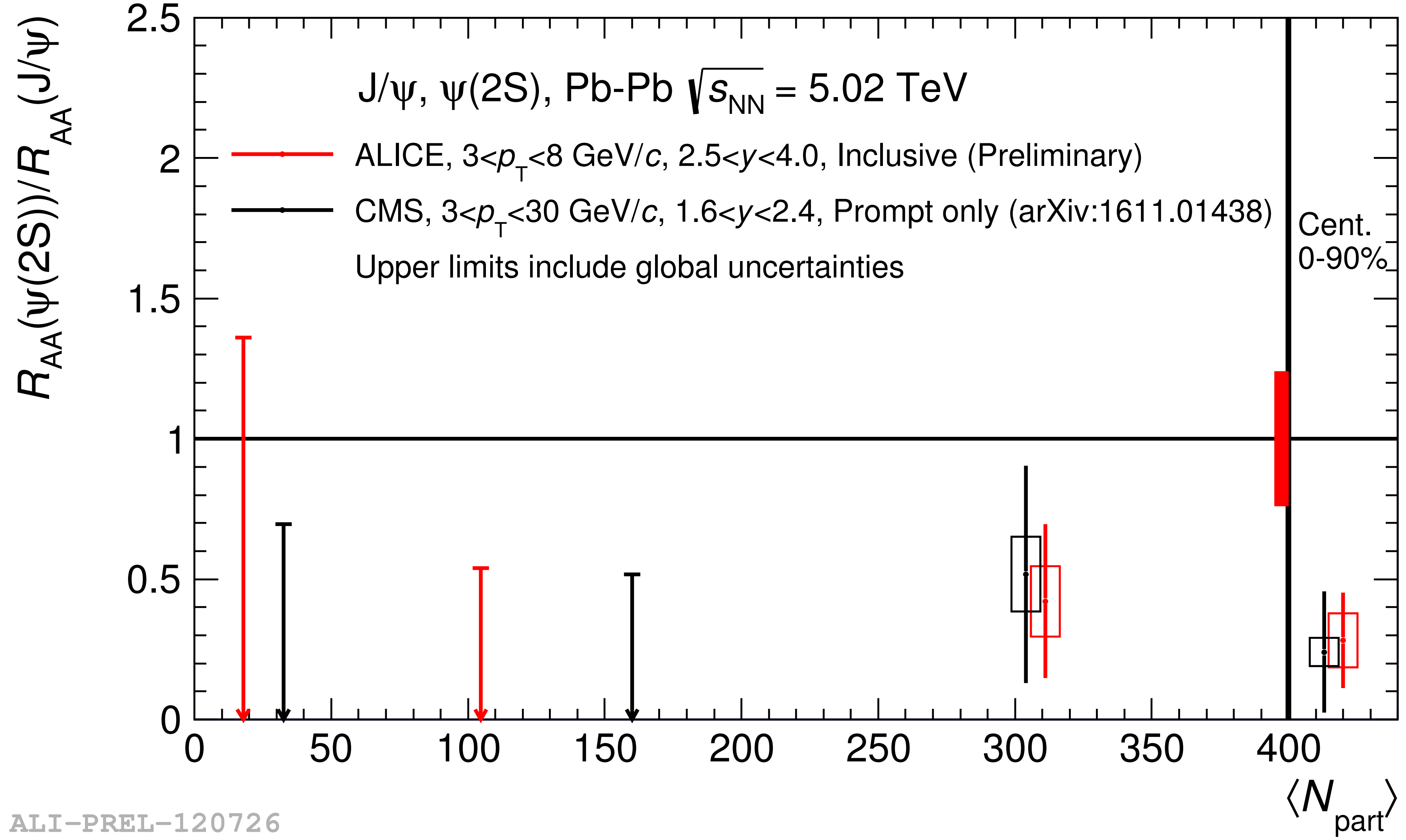
New ψ(2S)/J/ψ

[1] arXiv:1611.01438

- The ratios between different charmonium states are essential to discriminate between different models

ALICE:
Inclusive
$3 < p_T < 8$ GeV/c
$2.5 < y < 4$

CMS:
Prompt
$3 < p_T < 30$ GeV/c
$1.6 < y < 2.4$

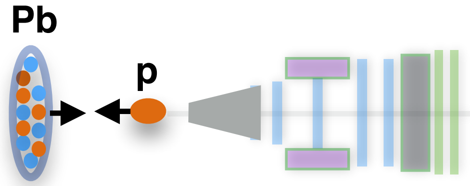


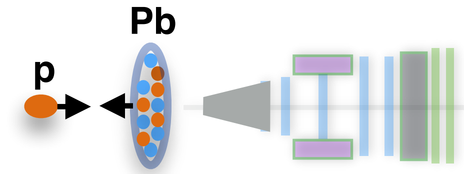
- The results of the double ratio at $\sqrt{s_{NN}} = 5.02$ TeV are compatible within uncertainties with the ones from CMS [1]

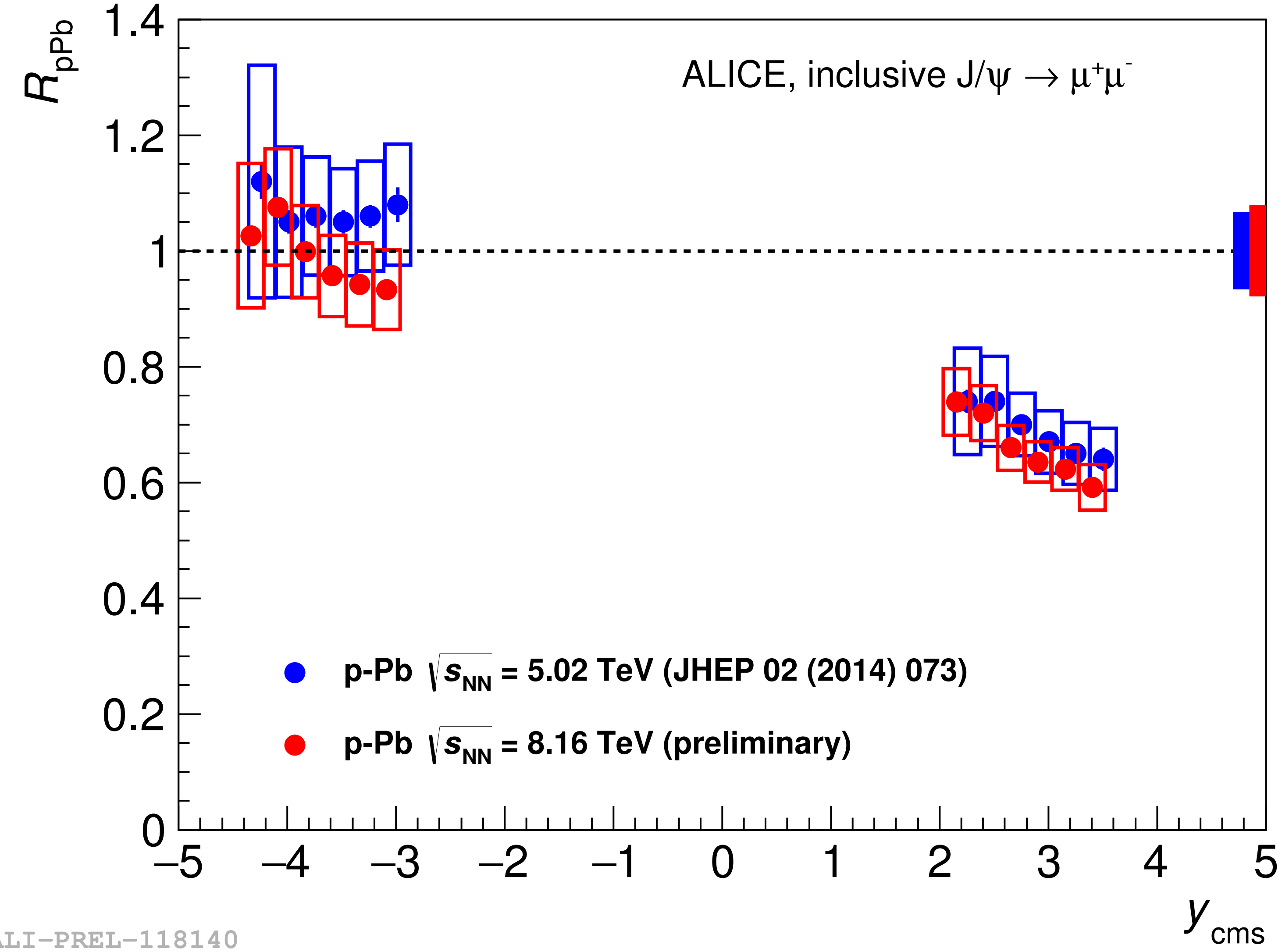
New J/ψ in p-Pb collisions at $\sqrt{s_{NN}}$ = 8.16 TeV

[1] Eur.Phys.J. C76 (2016) no.4, 184
[2] JHEP06(2013)064
[3] JHEP 1402 (2014) 073

- The inclusive J/ψ R_{pPb} has been measured in p-Pb and Pb-p collisions at the new energy of $\sqrt{s_{NN}} = 8.16$ TeV
- ALICE [1] and LHCb [2] pp data at $\sqrt{s_{NN}} = 8$ TeV are used as a reference to calculate the R_{pPb}







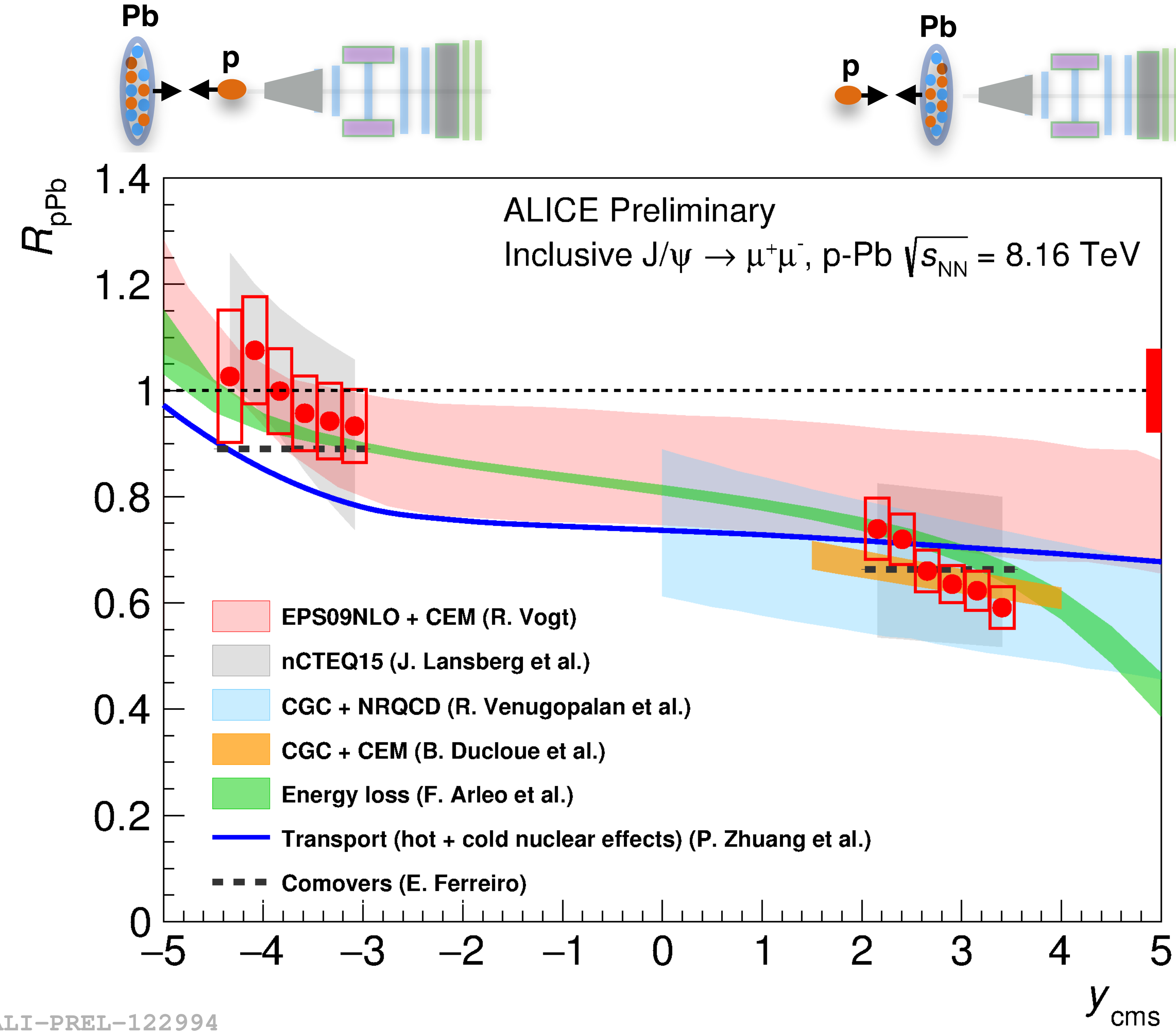
ALICE-PUBLIC-2017-001

- Clear suppression at positive rapidities, and compatible with unity at negative rapidity
- The R_{pPb} measured at $\sqrt{s_{NN}} = 8.16$ TeV is similar to the one measured at $\sqrt{s_{NN}} = 5.02$ TeV[3]

J/ψ in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV

[1] Eur.Phys.J. C76 (2016) no.4, 184
[2] JHEP06(2013)064

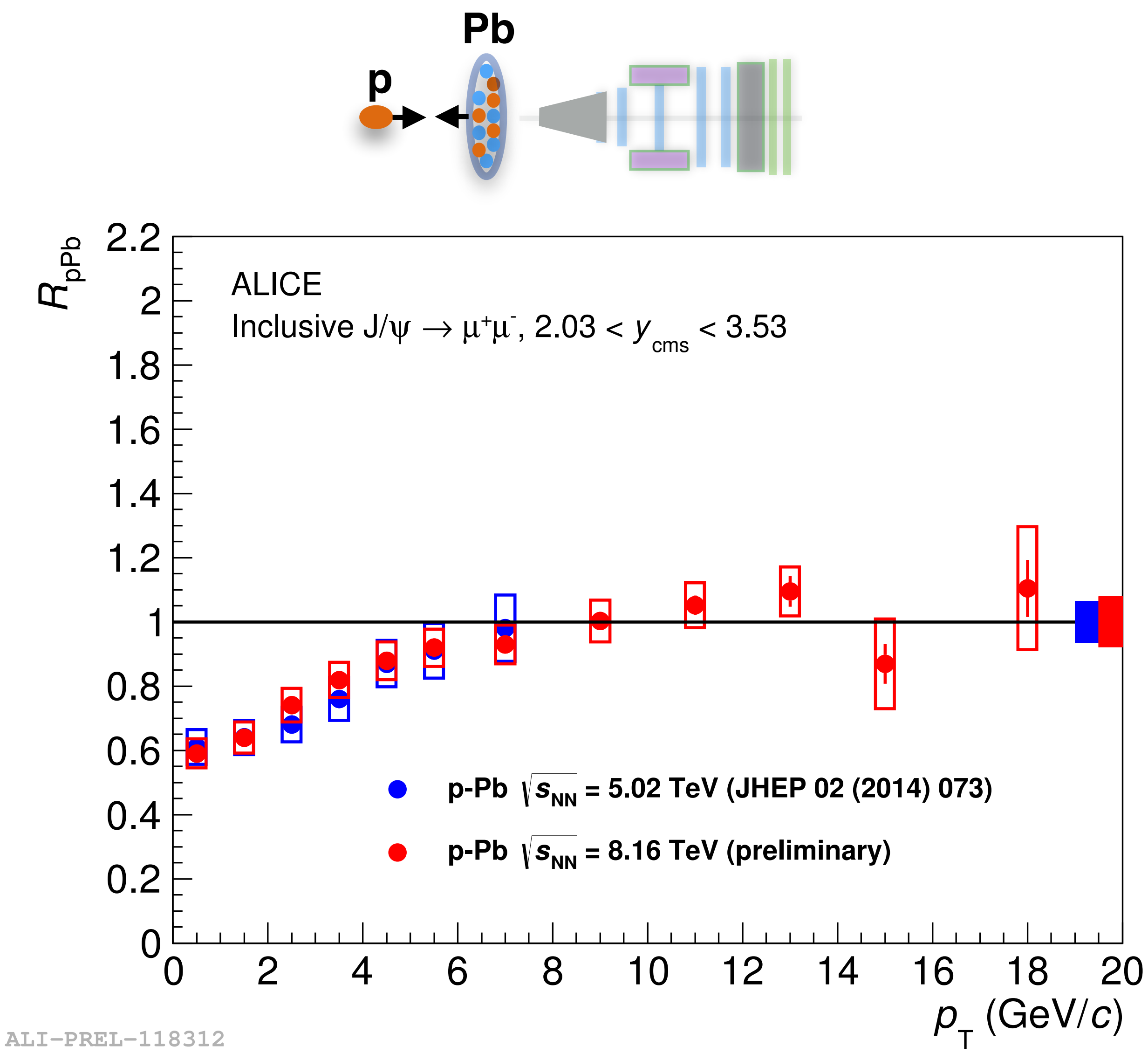
- The inclusive J/ψ R_{pPb} has been measured in p-Pb and Pb-p collisions at the new energy of $\sqrt{s_{NN}} = 8.16$ TeV
- ALICE [1] and LHCb [2] pp data at $\sqrt{s_{NN}} = 8$ TeV are used as a reference to calculate the R_{pPb}

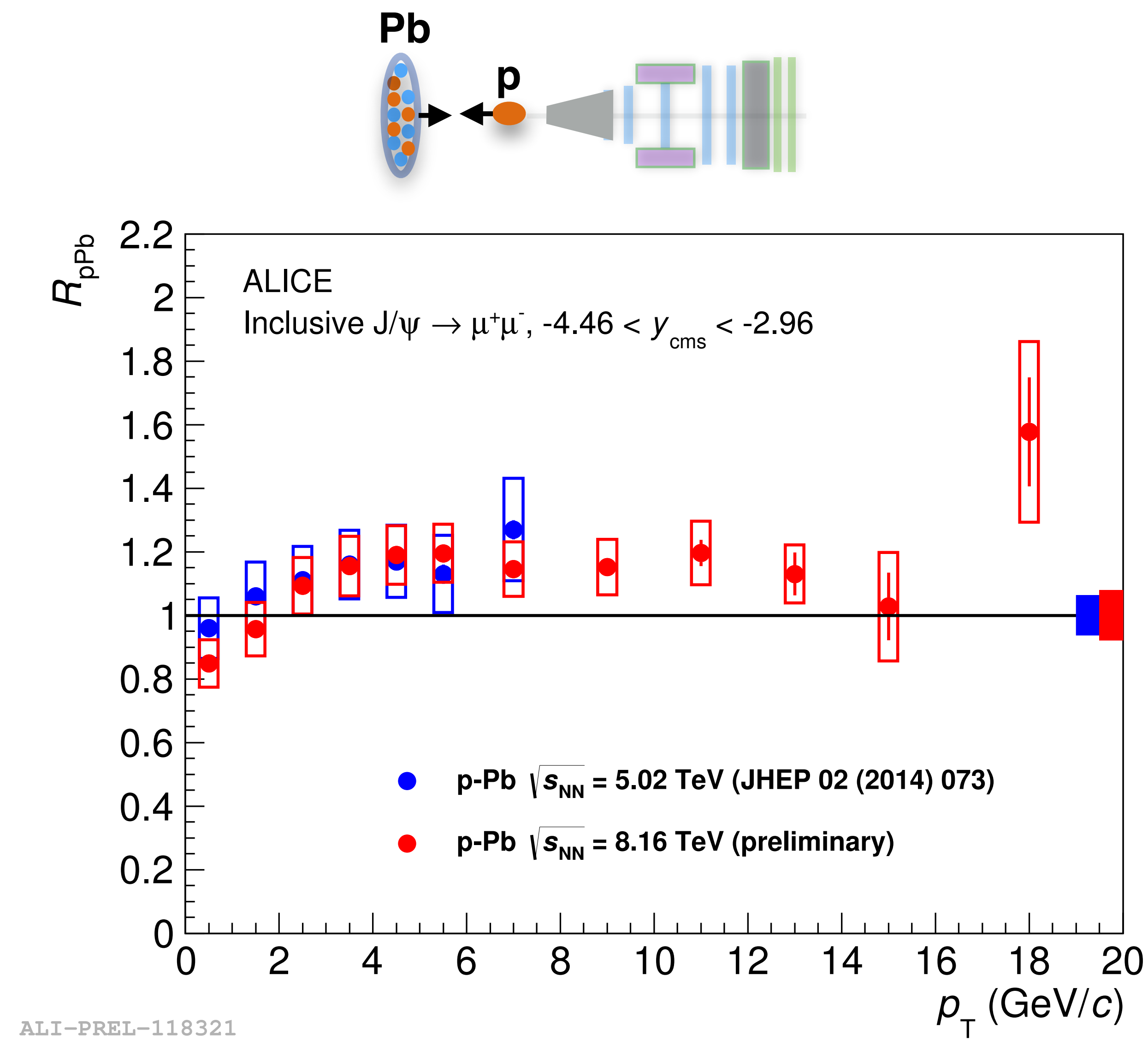


ALICE-PUBLIC-2017-001

- Clear suppression at positive rapidities, and compatible with unity at negative rapidity
- Different models (shadowing, energy loss, CGC) can describe well the data

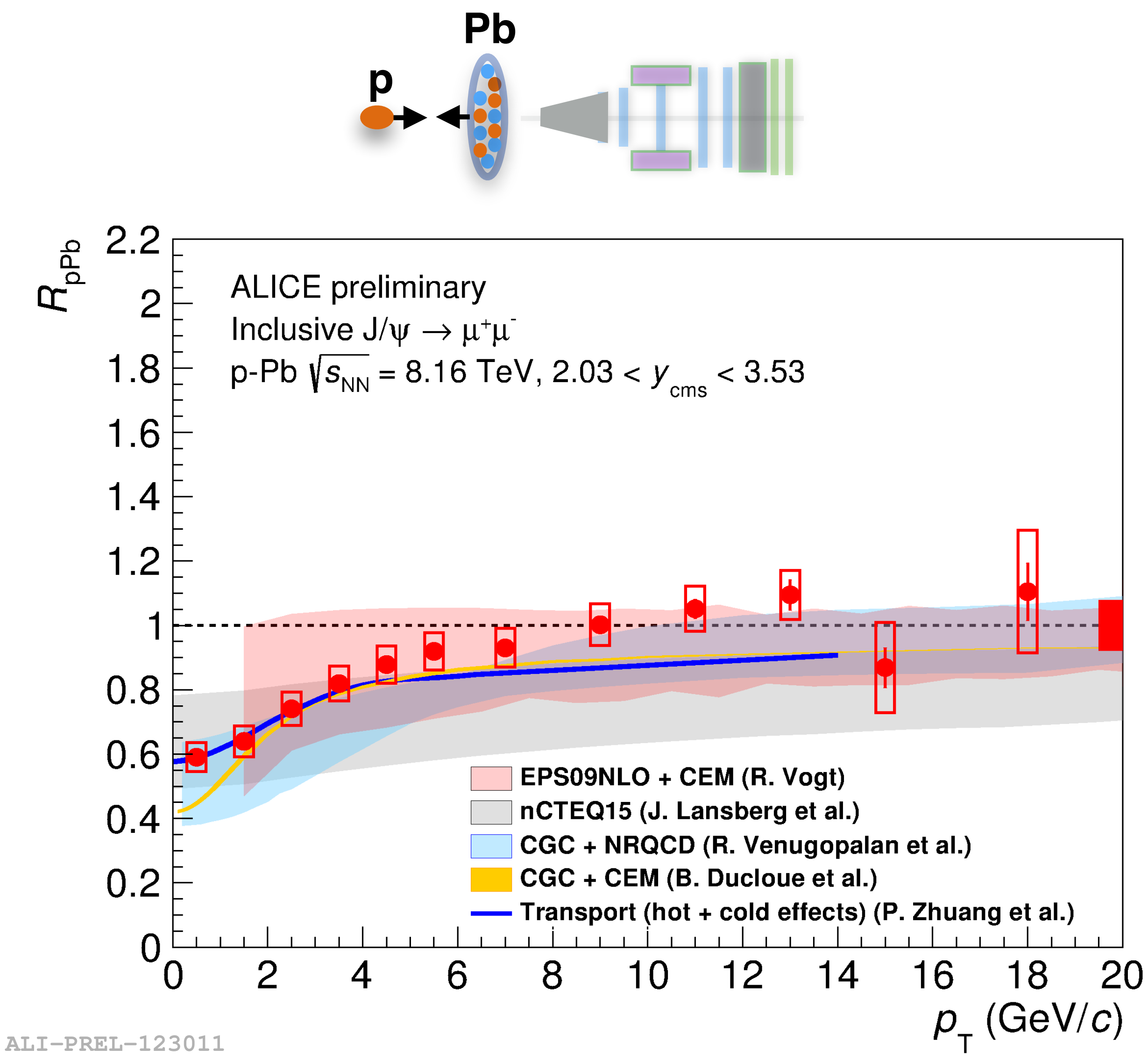
J/ψ in p-Pb collisions at $\sqrt{s_{NN}}$ = 8.16 TeV

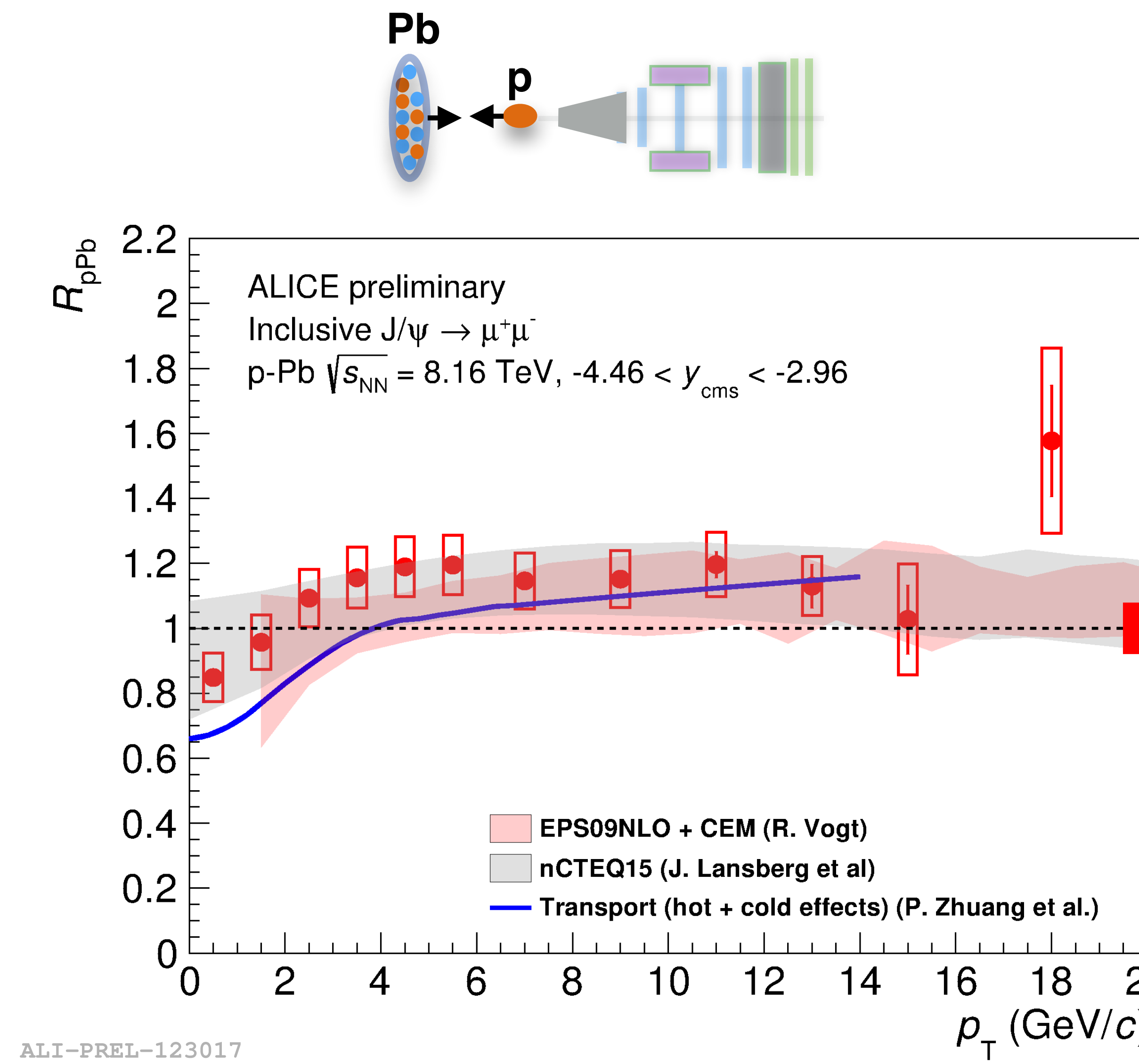




- The p_T reach of the R_{pPb} has been extended to 20 GeV/c
- The suppression is higher at low p_T for the positive rapidity range

J/ψ in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV





- The p_T reach of the R_{pPb} has been extended to 20 GeV/c
- The suppression is higher at low p_T for the positive rapidity range
- Different models (shadowing, energy loss, CGC) can describe well the data in the two rapidity ranges

Summary

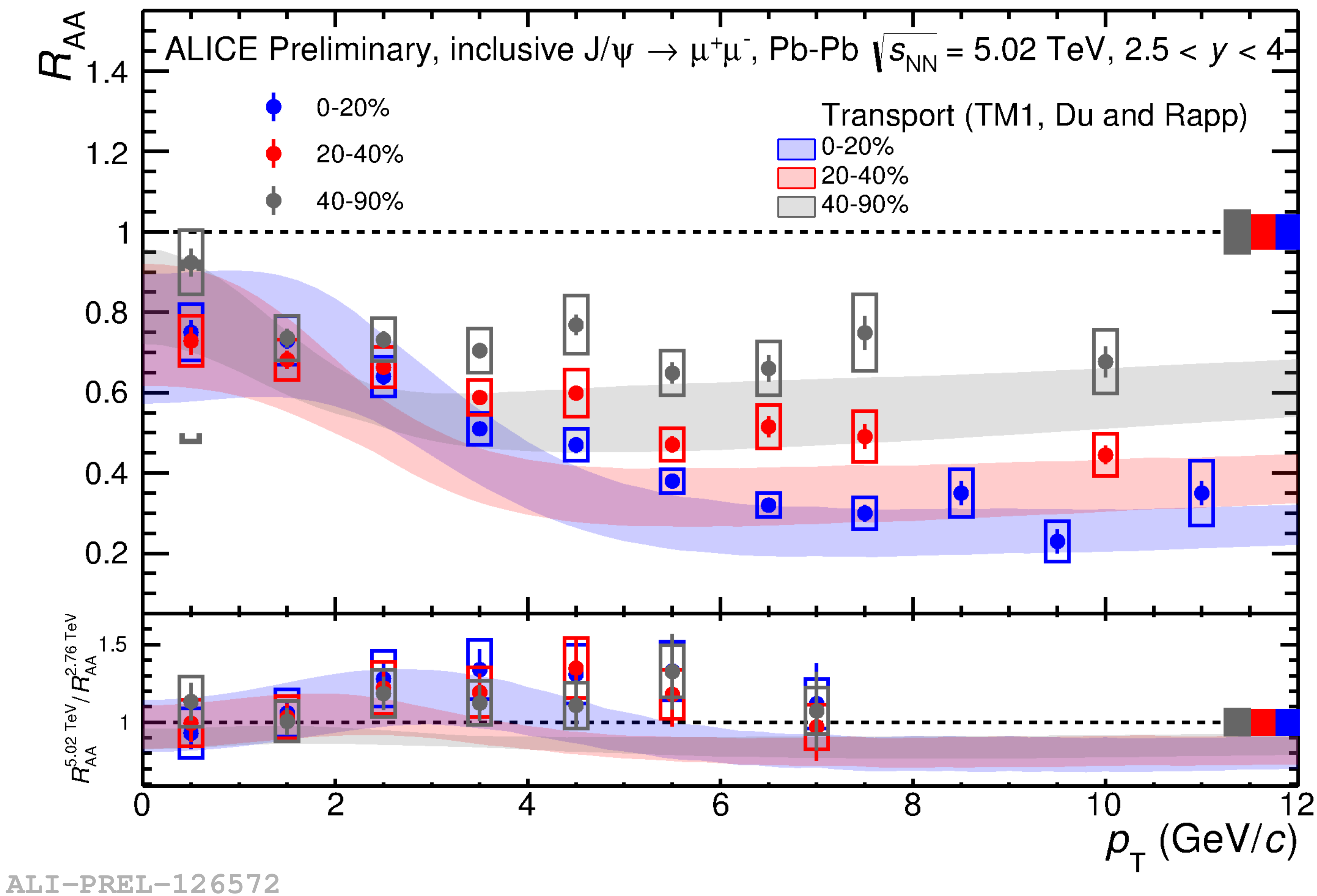
- **J/ψ results in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV**
  - R_{AA} as a function of centrality, rapidity and transverse momentum
  - Elliptic flow
  - Average p_T
- Results compared to models calculations and to results at $\sqrt{s_{NN}} = 2.76$ TeV
- High precision measurement can constrain the models

- The ψ(2s) is more suppressed than the J/ψ in central and semi-central collisions at $\sqrt{s_{NN}} = 5.02$ TeV

- The J/ψ $R_{p\text{-}Pb}$ at $\sqrt{s_{NN}} = 8.16$ TeV has been measured as a function of rapidity and transverse momentum
  - Clear suppression at positive rapidity and low p_T
  - $R_{p\text{-}Pb}$ can be described by different CNM effects

Extra Slides

J/Ψ R_{AA} Vs p_T

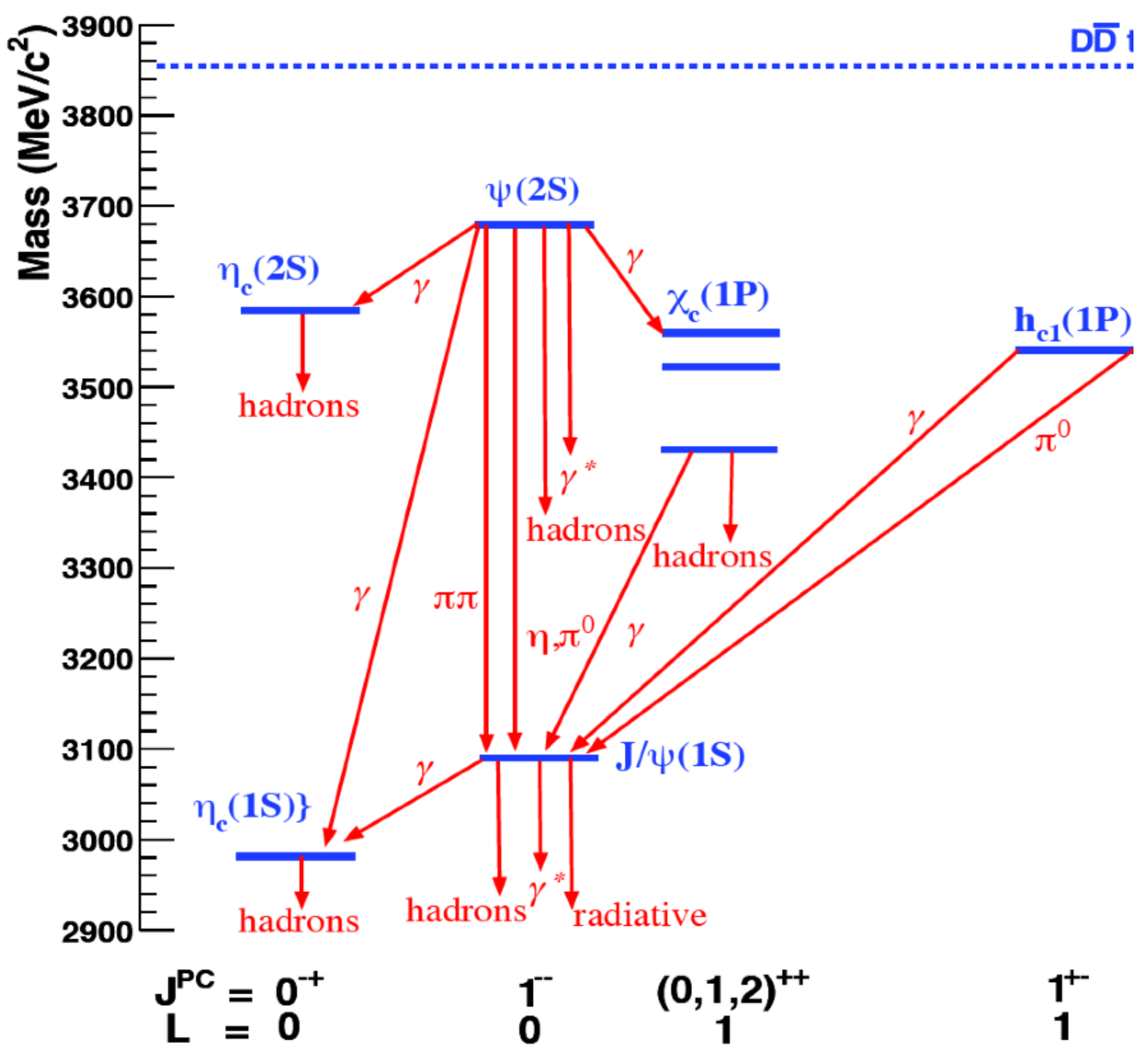


ALICE Preliminary, inclusive J/ψ → μ⁺μ⁻, Pb-Pb √s_NN = 5.02 TeV, 2.5 < y < 4
0-20%
20-40%
40-90%
Transport (TM1, Du and Rapp)
0-20%
20-40%
40-90%
R_AA
R_AA^5.02 TeV / R_AA^2.76 TeV
p_T (GeV/c)
ALI-PREL-126572

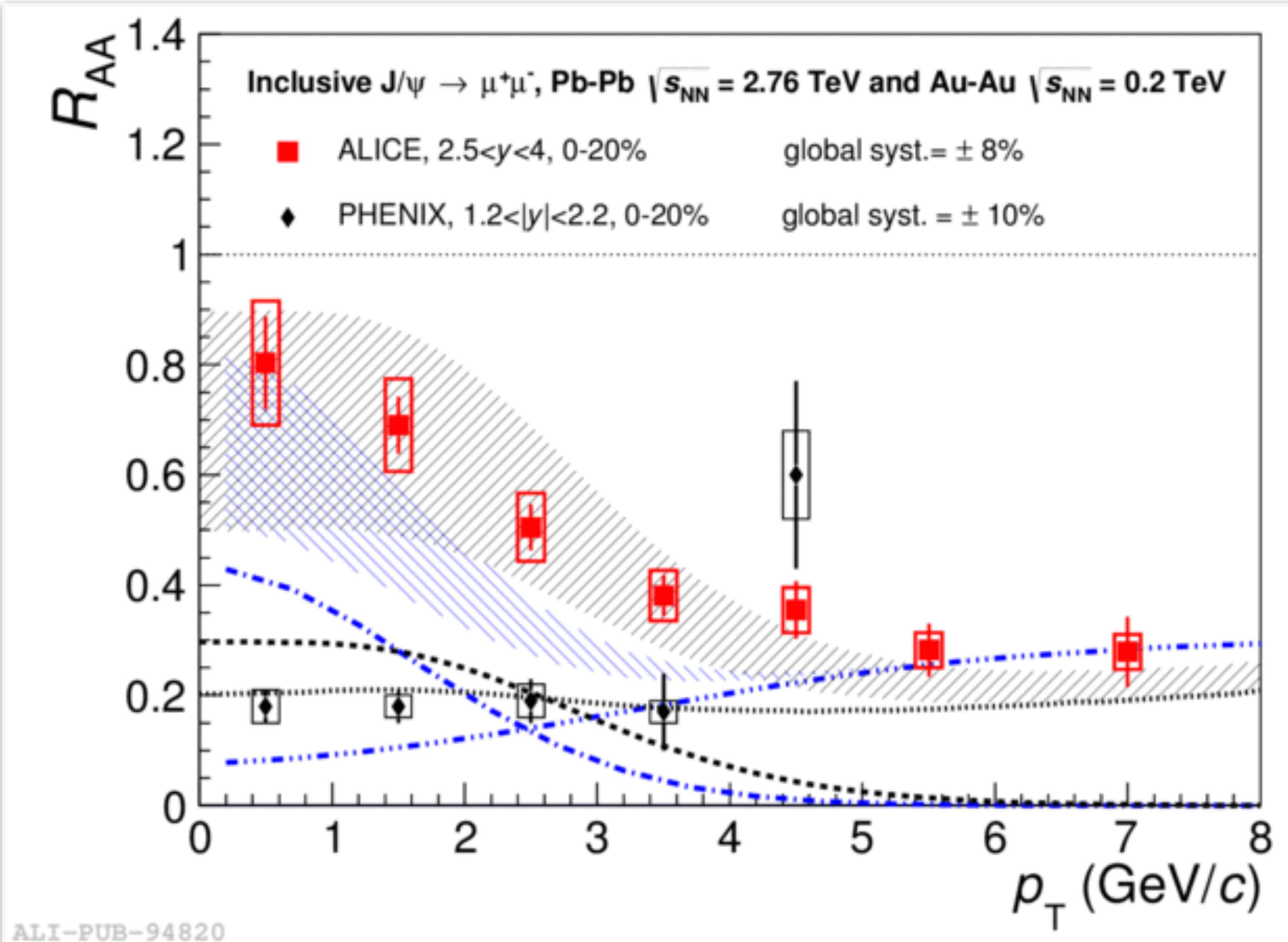
H. Satz, J. Phys. G32 (2006) R25

State	J/Ψ	χ_c	Ψ′	ϒ	χ_b	ϒ′	χ_b'	ϒ″
mass [GeV]	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
ΔE[GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
ΔM[GeV]	0.02	-0.03	0.03	0.06	-0.06	-0.06	-0.08	-0.07
radius [fm]	0.25	0.36	0.45	0.14	0.22	0.28	0.34	0.39

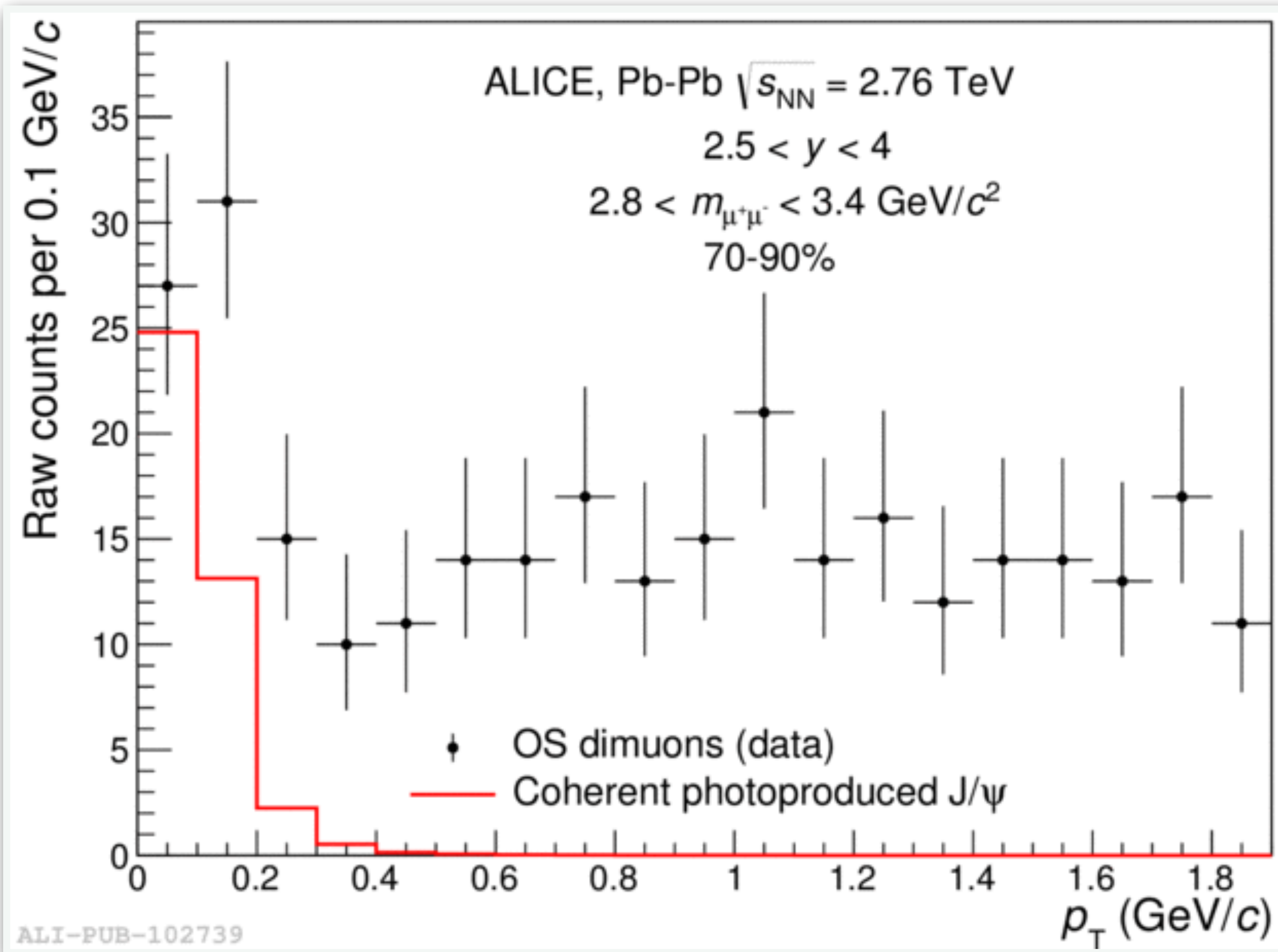
Charmonia decay schemes:



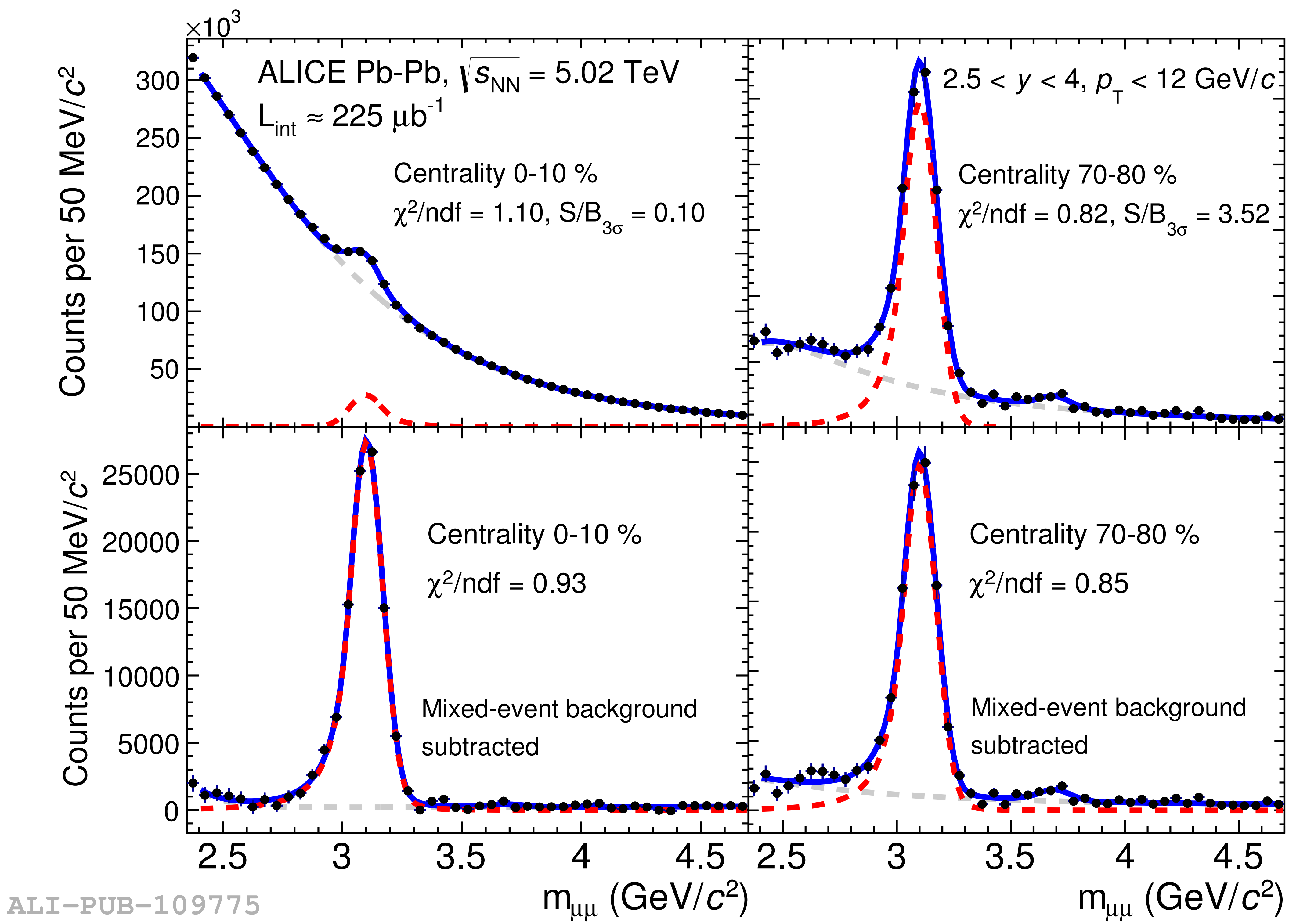
ALICE Vs PHENIX



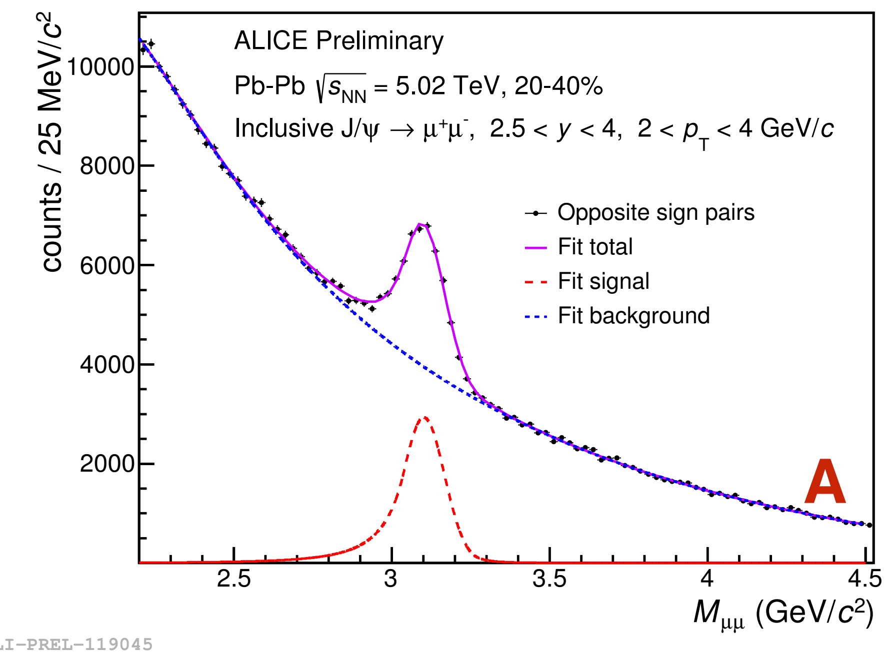
Excess at very low pT

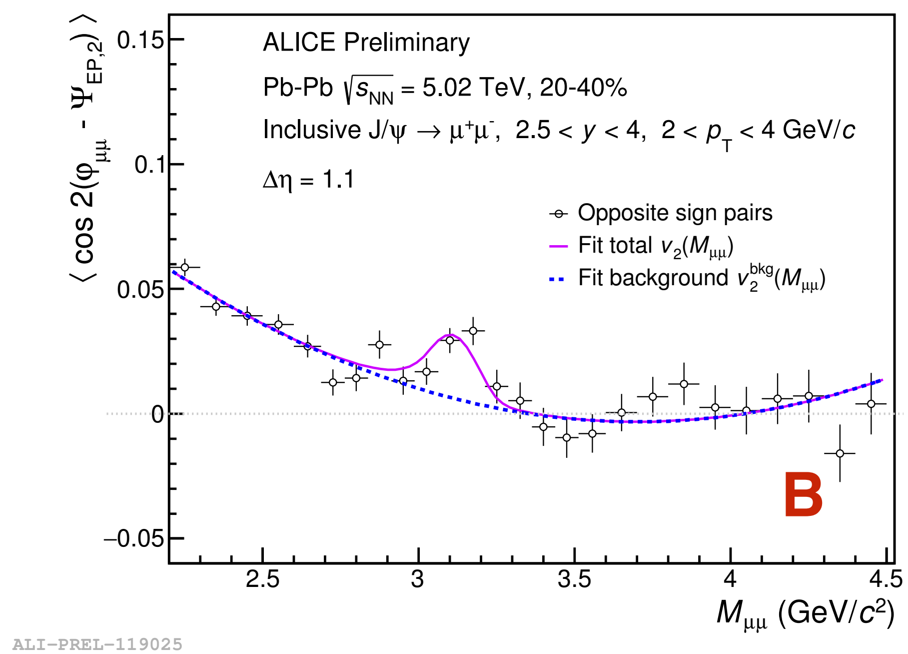


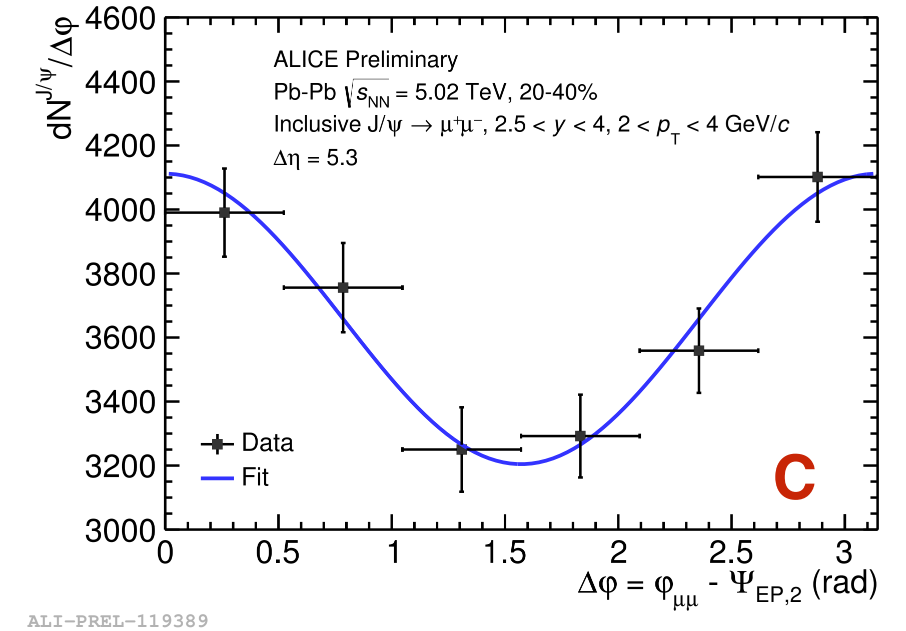
Signal extraction



J/Ψ elliptic flow (v_2) extraction







First method

- For each muons pair, calculate $\langle cos2(\Phi_{\mu\mu} - \Psi)\rangle$ in bins of invariant mass (**B**)
- Using S/B parameters from the J/Ψ signal extraction (**A**), fit the distribution with:

$$v_2(m_{\mu\mu}) = v_2^{J/\Psi}\alpha(m_{\mu\mu}) + v_2^{bkgd}(m_{\mu\mu})[1 - \alpha(m_{\mu\mu})]$$

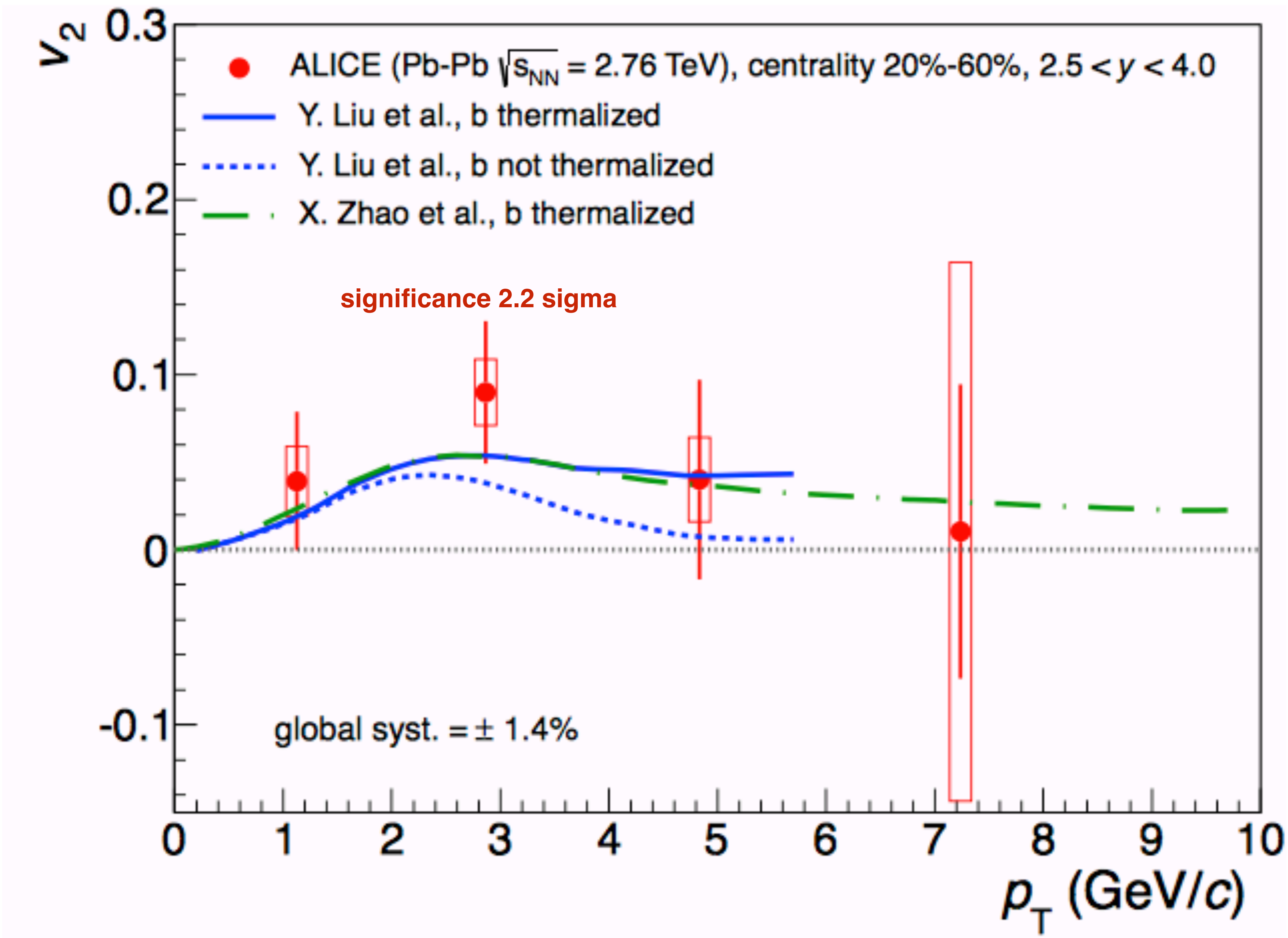
Second method

- Extract the J/psi signal in bins of $\Delta\varphi$ = **Ψ**-ϕ$_{\mu\mu}$ (**C**)
- Fit the distribution with:

  N_0[(1+2v_2)*cos(2 Δφ)]

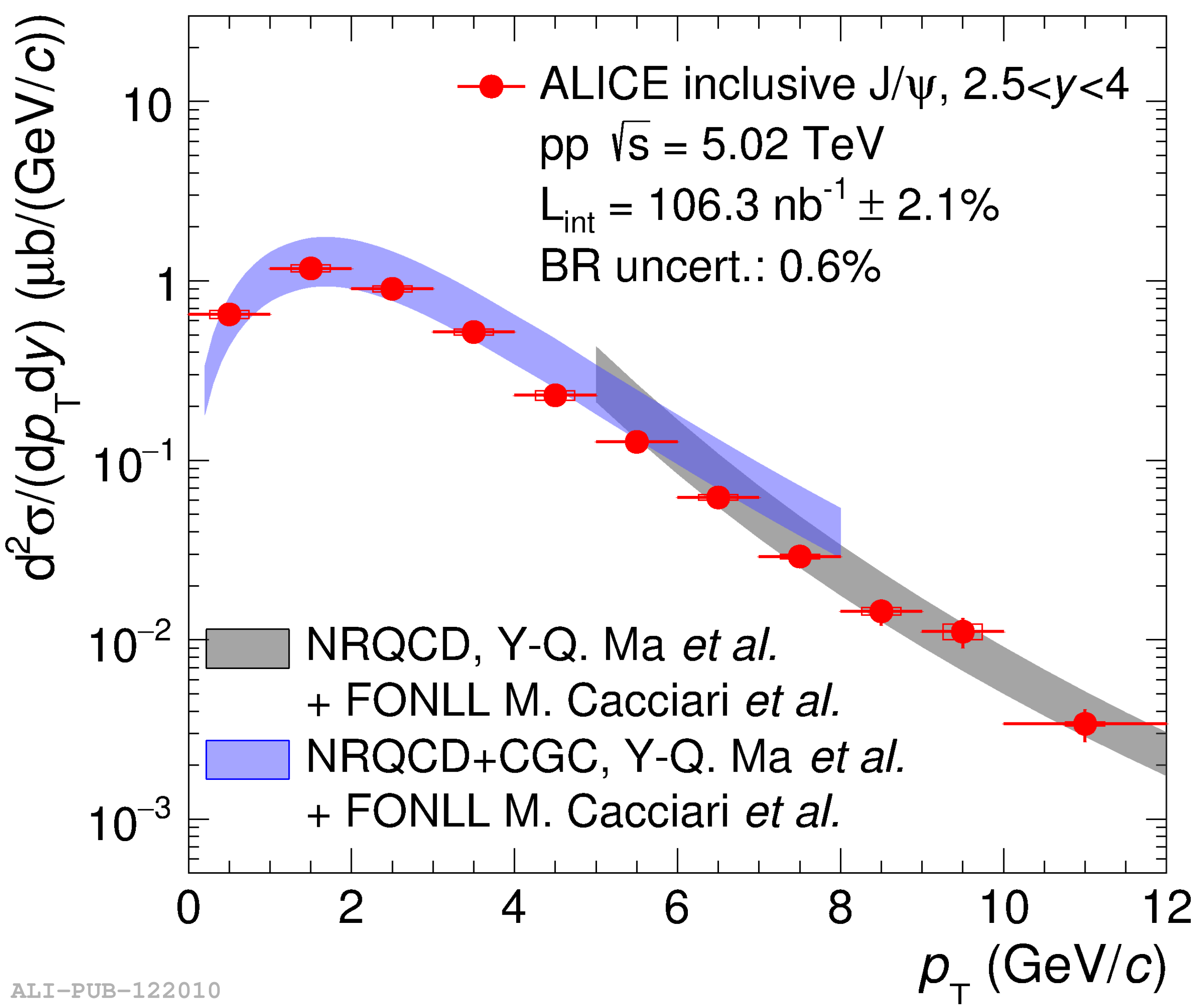
- **Ψ** and ϕ$_{\mu\mu}$ are the azimuthal angle of the event plane and the muon pairs
- **Ψ** is determined using two different detectors (V0A and SPD) that cover two different pseudo-rapidity ranges and do not overlap with the muon spectrometer acceptance

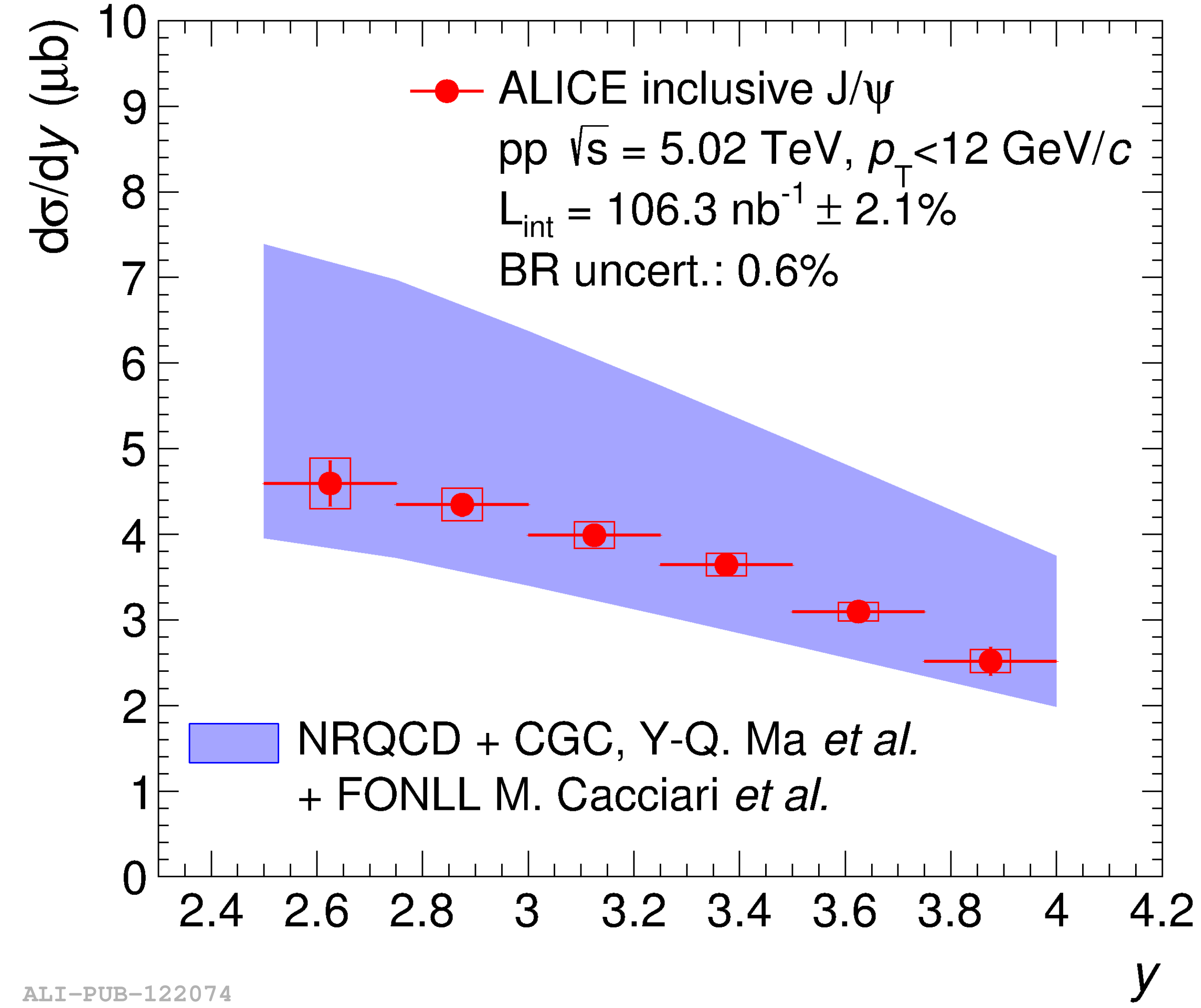
v2 @ 2.76 TeV



v_2
0.3
0.2
0.1
0
-0.1
ALICE (Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV), centrality 20%-60%, 2.5 < y < 4.0
Y. Liu et al., b thermalized
Y. Liu et al., b not thermalized
X. Zhao et al., b thermalized
significance 2.2 sigma
global syst. = ± 1.4%
0
1
2
3
4
5
6
7
8
9
10
p_T (GeV/c)

pp cross section at 5.02 TeV





rAA at 2.76 TeV