

Quarkonium in AA collisions with the ALICE experiment

Audrey FRANCISCO
Subatech, France
for the ALICE Collaboration



34th Winter Workshop on Nuclear Dynamics
March 25-31th 2018 • Guadeloupe



Motivations for quarkonium studies

- Heavy quarks in Pb-Pb collisions at the LHC

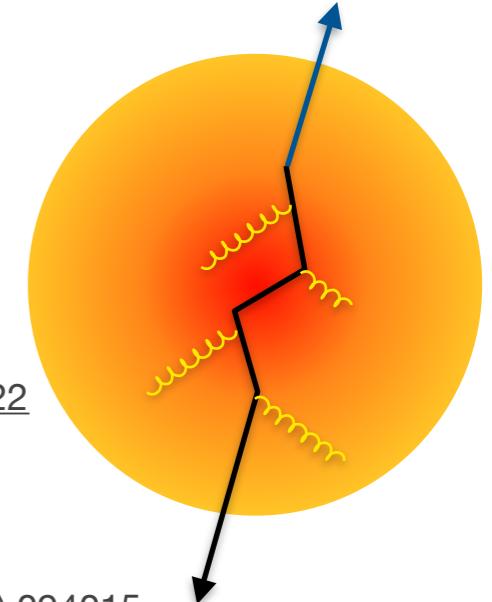
- early production ($c \sim 0.08 \text{ fm}/c$, $b \sim 0.02 \text{ fm}/c$ vs. QGP $\sim 0.3 \text{ fm}/c$)
 → experience the full system evolution

[PHENIX, Nucl.Phys. A757 \(2005\) 184-283](#)

- interact with the QGP: sensitive to the medium properties

[Matsui & Satz, Phys.Lett. B178 \(1986\) 416-422](#)

- same number per binary collision produced in Pb-Pb and in pp



- Quarkonium in Pb-Pb collisions : hard probes of the QGP

[Satz et al., Phys. Rev. D 64 \(2001\) 094015](#)

[Zhou et al., Phys.Lett. B758 \(2016\) 434-439](#)

Quarkonium suppression:

Debye screening (1986)

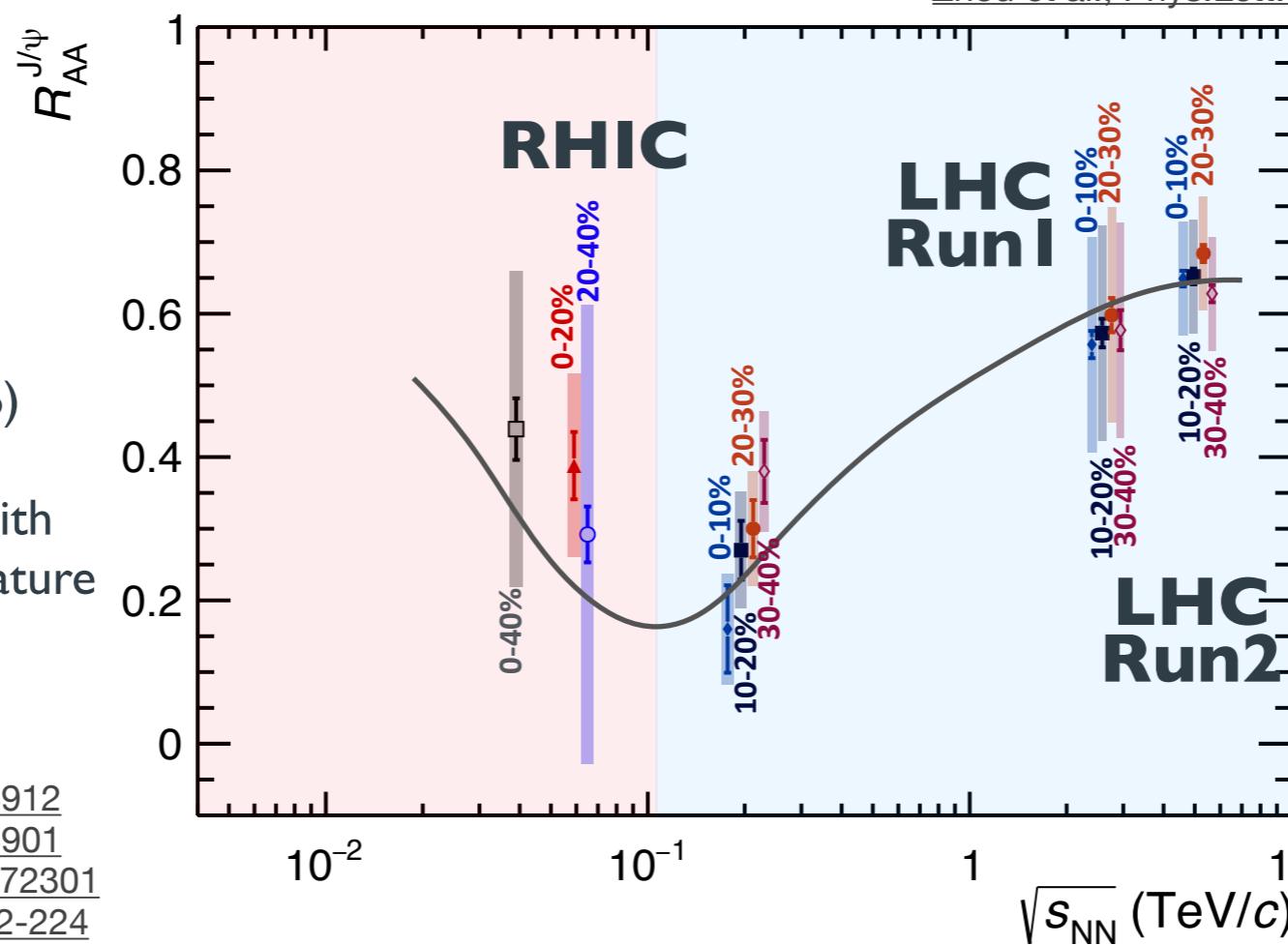
sequential suppression with increasing medium temperature

[PHENIX, Phys.Rev. C84 \(2011\) 054912](#)

[PHENIX, Phys.Rev. C86 \(2012\) 064901](#)

[ALICE, Phys.Rev.Lett. 109 \(2012\) 072301](#)

[ALICE, Phys. Lett. B 766 \(2017\) 212-224](#)



(Re)combination:

Increased charm quark density

Less relevant for bottomonium than charmonium

Quarkonium studies

Nuclear modification factor

R_{AA}

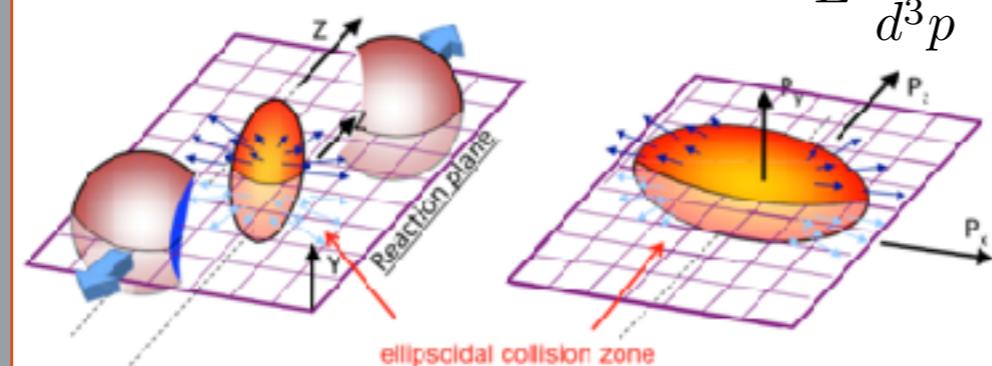
Quarkonium yield in AA compared to the pp one,
scaled by the overlap factor T_{AA} (from Glauber model)

$$R_{AA} = \frac{Y_{AA}}{\langle T_{AA} \rangle \sigma_{pp}}$$

- No medium effect: $R_{AA} = 1$
- $R_{AA} \neq 1$: cold nuclear matter and/or hot medium effects

Elliptic flow
 v_2

Anisotropic matter distribution around the collision



$$E \frac{d^3 N}{d^3 p} = \frac{1}{N} \frac{d^2 N}{p_T dp_T dy} \left\{ 1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \Psi_{RP})) \right\}$$

Flow coefficients :

$$v_n = \langle \cos\{n(\Phi_i - \Psi_{RP})\} \rangle$$

directed flow (v_1), elliptic flow (v_2), ...

INCLUSIVE J/ ψ

Prompt J/ ψ

Direct J/ ψ

Feed-down from
excited states

Non-prompt J/ ψ

B-hadron decays

Quarkonium measurements with ALICE in Pb-Pb

Performed both at mid- and forward rapidity

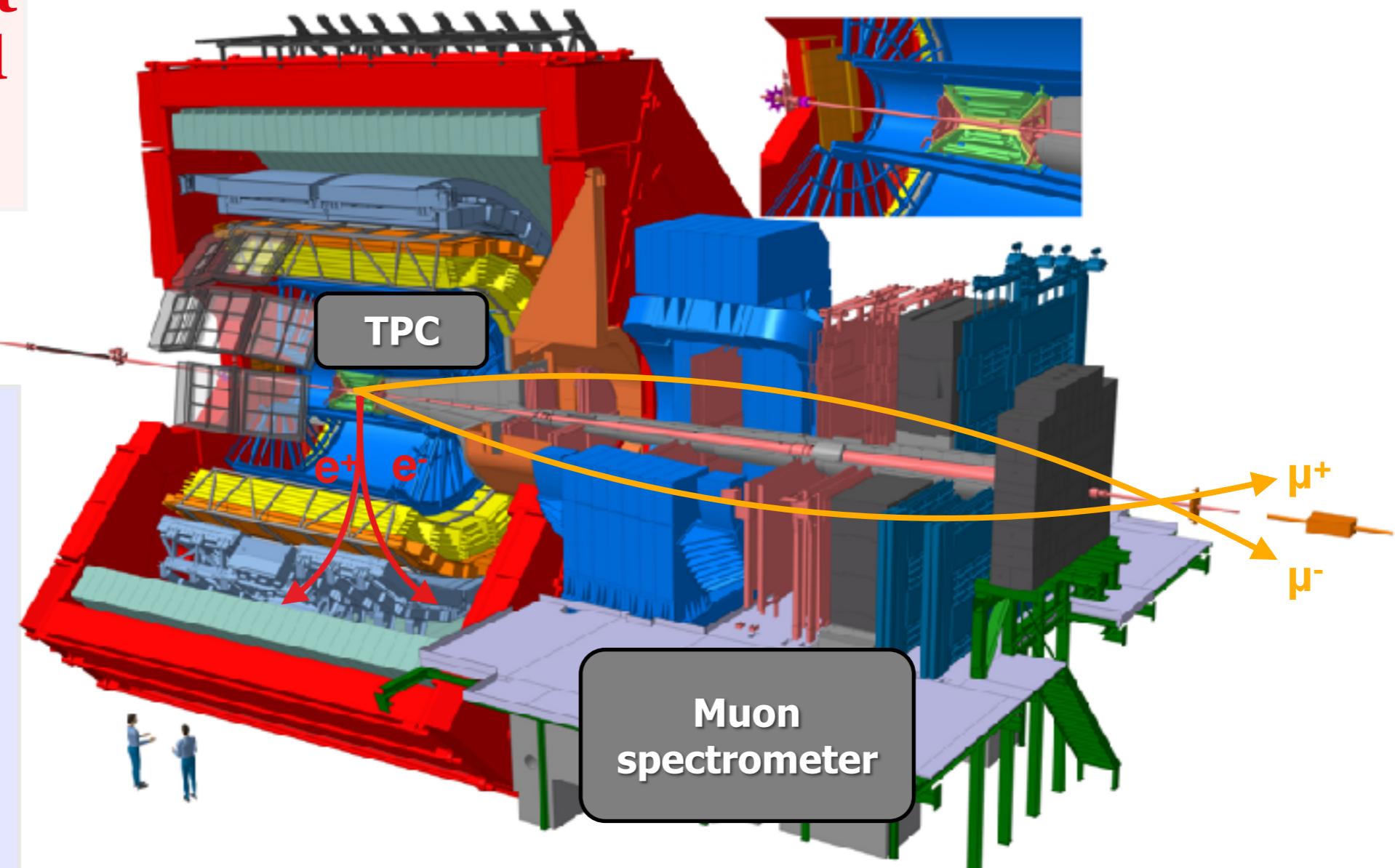
Quarkonium $\rightarrow e^+e^-$:

- $|y| < 0.9$
- down to $p_T = 0$
- $\mathcal{L} = 13 \mu b^{-1}$

Quarkonium $\rightarrow \mu^+\mu^-$:

- $2.5 < y < 4$
- down to $p_T = 0$
- $\mathcal{L} = 225 \mu b^{-1}$

Run 2 (2015-2016) Pb-Pb at $\sqrt{s_{NN}}=5.02$ TeV



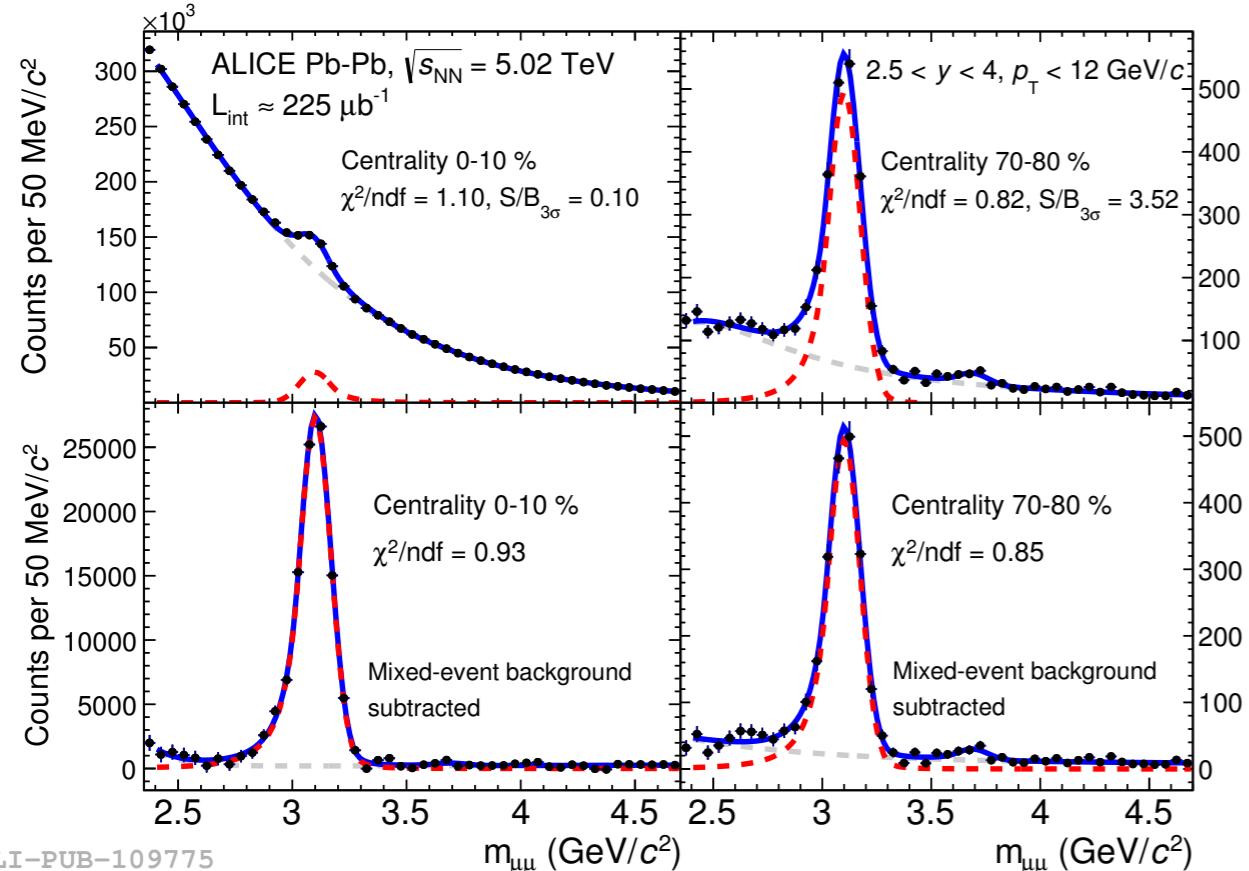
V0: Event plane (EP) + centrality

ITS (SPD): vertex + EP

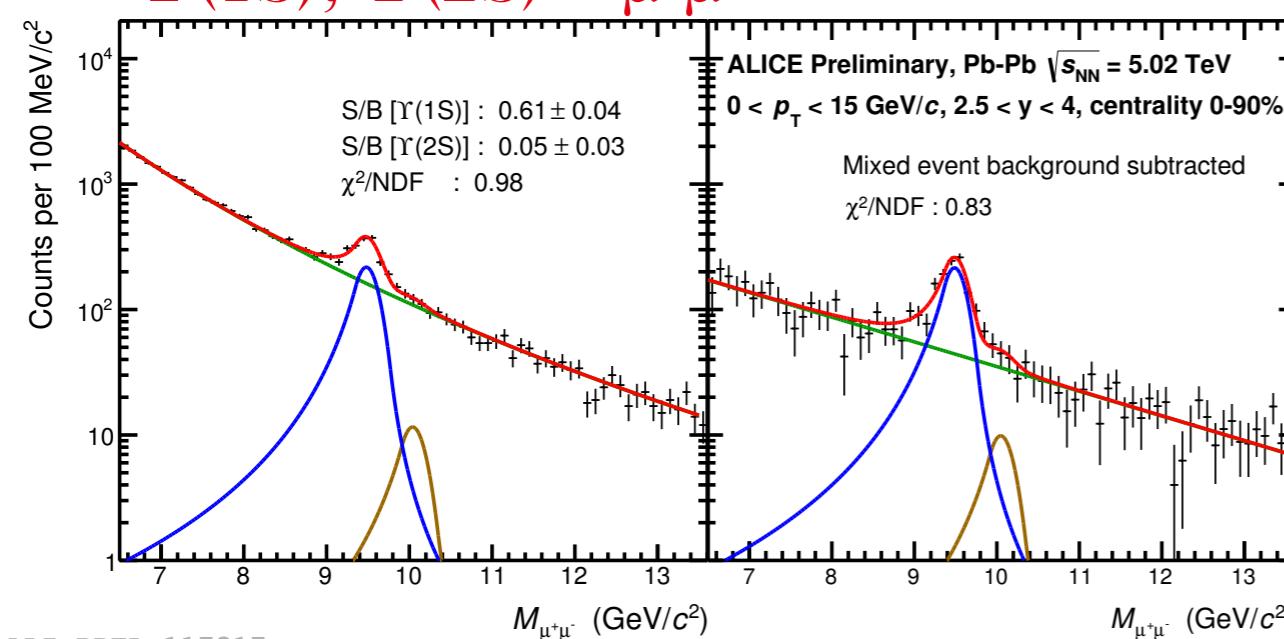
T0: luminosity

Signal extraction

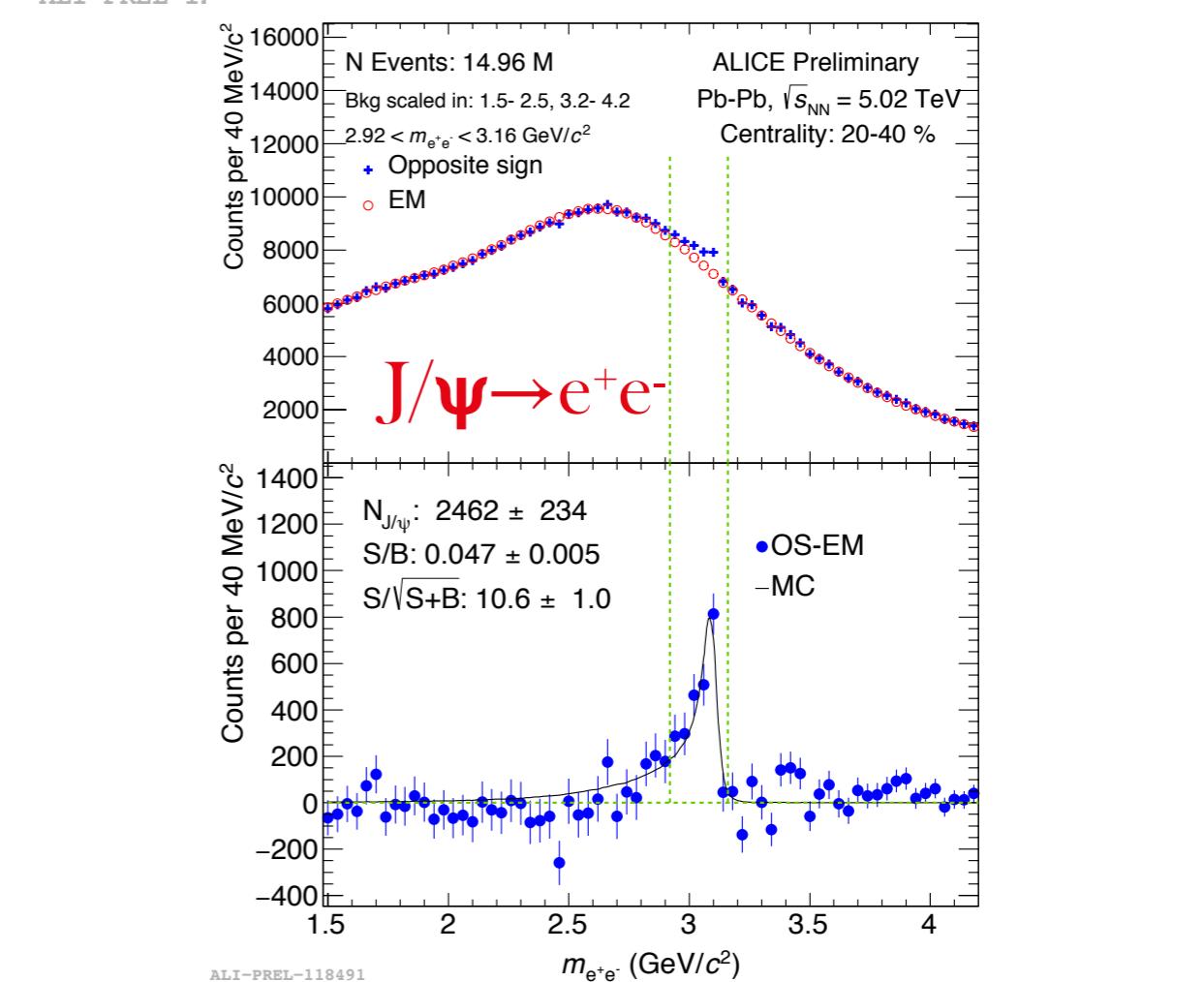
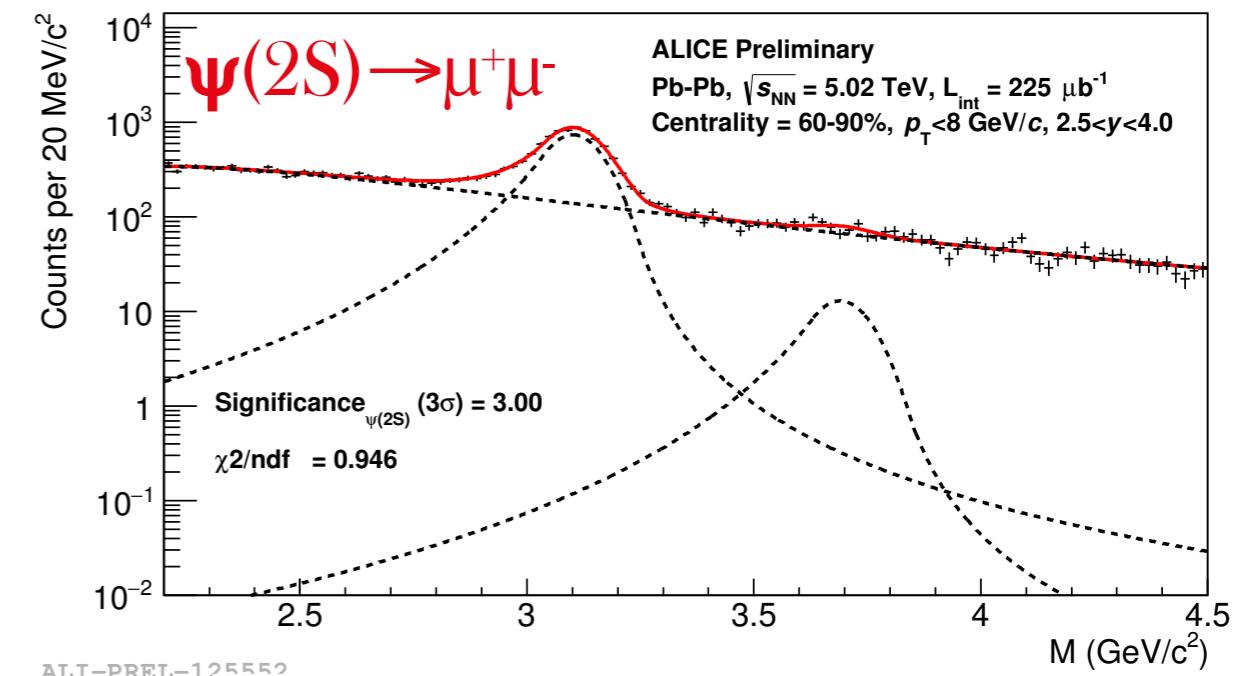
$J/\psi \rightarrow \mu^+ \mu^-$



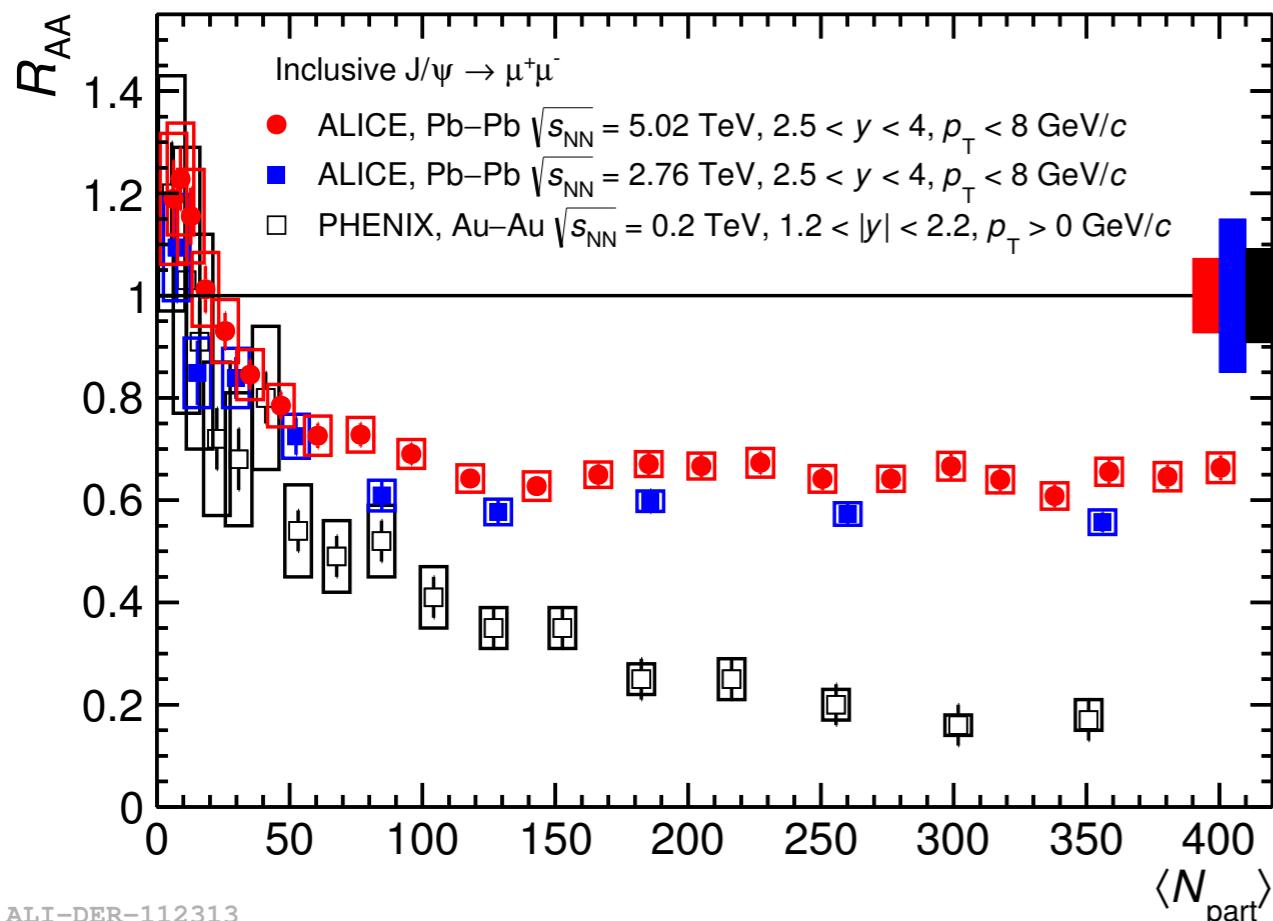
$\Upsilon(1S), \Upsilon(2S) \rightarrow \mu^+ \mu^-$



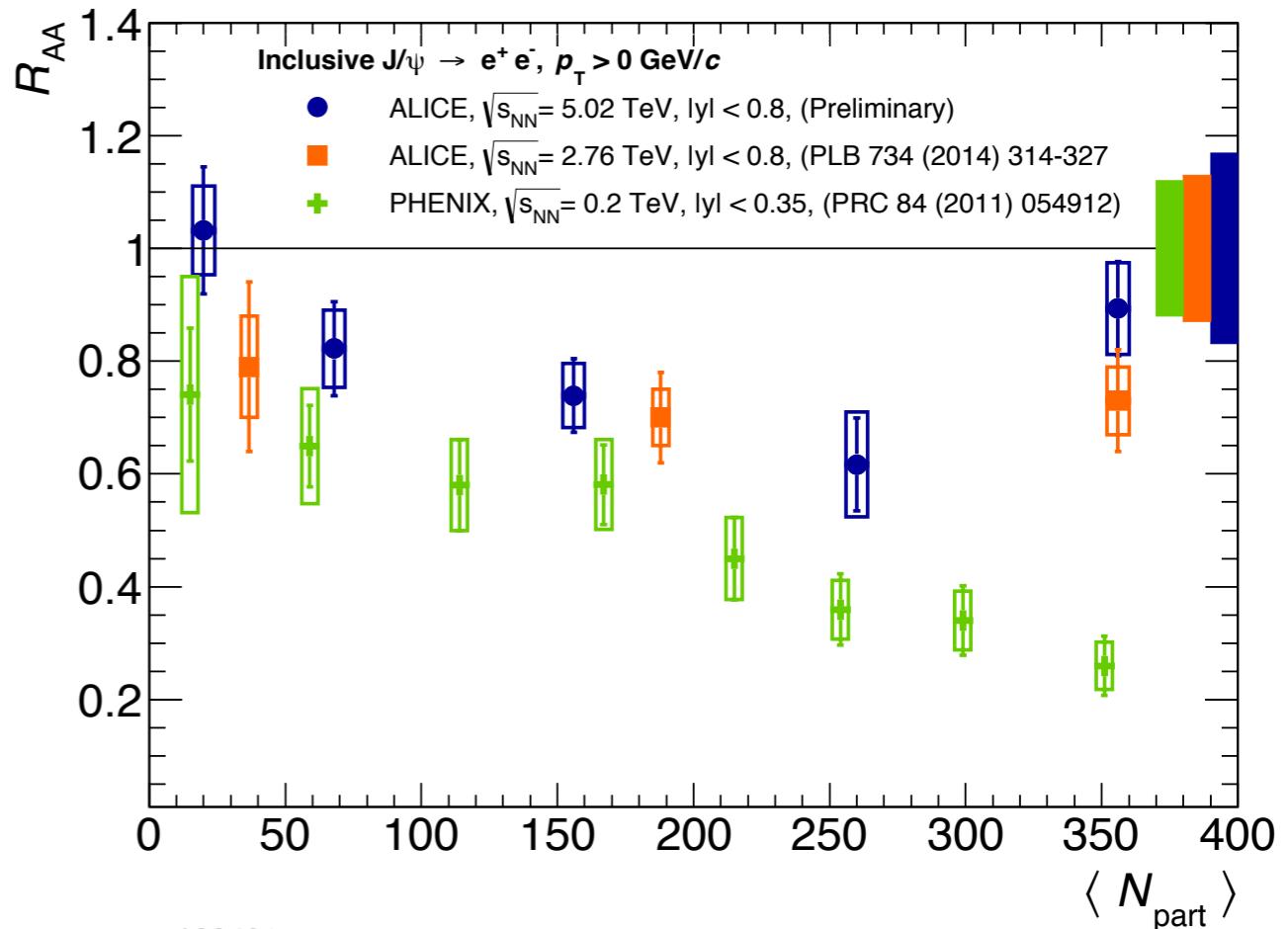
ALI-PREL-117317



$J/\psi R_{AA}$ measurements with ALICE



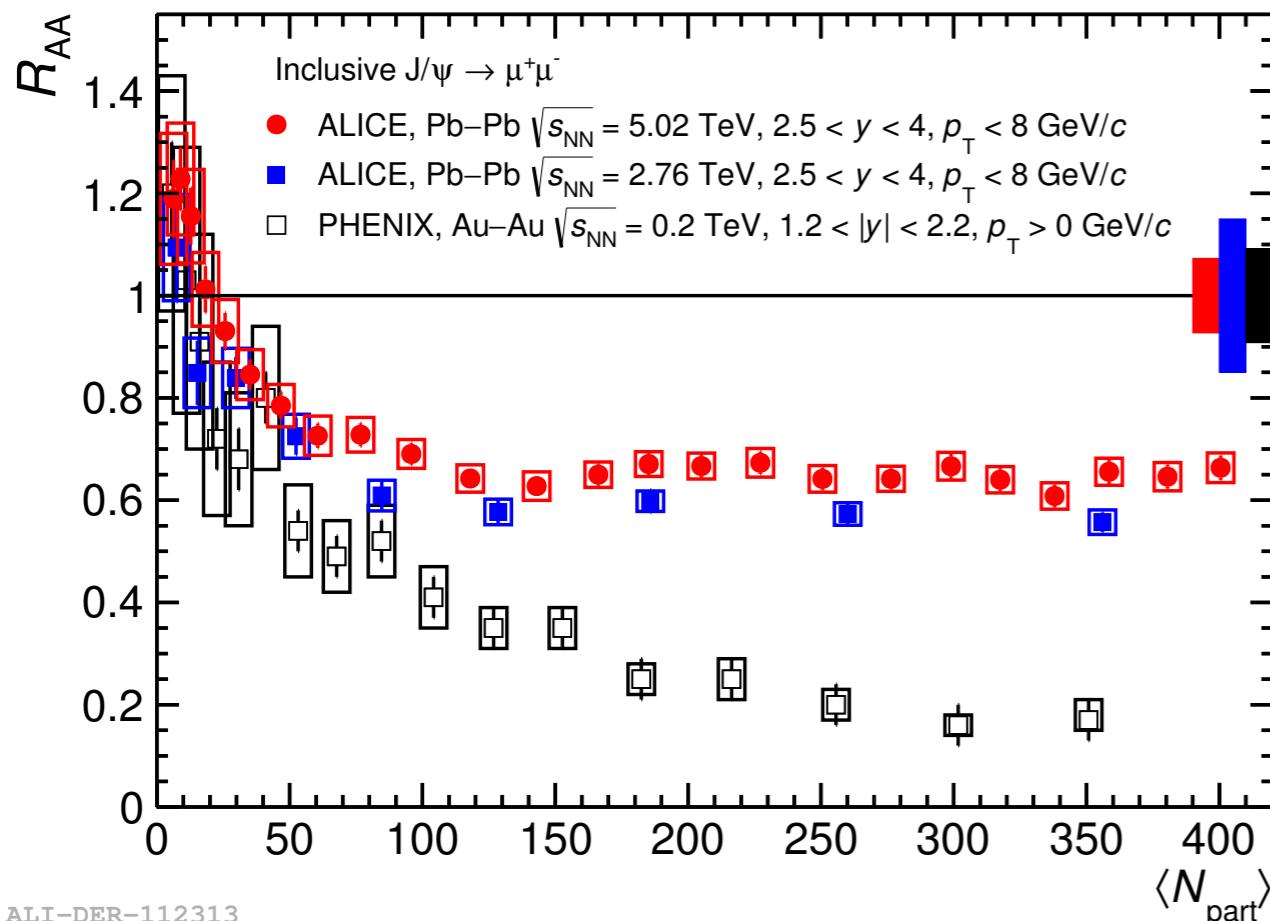
ALI-DER-112313



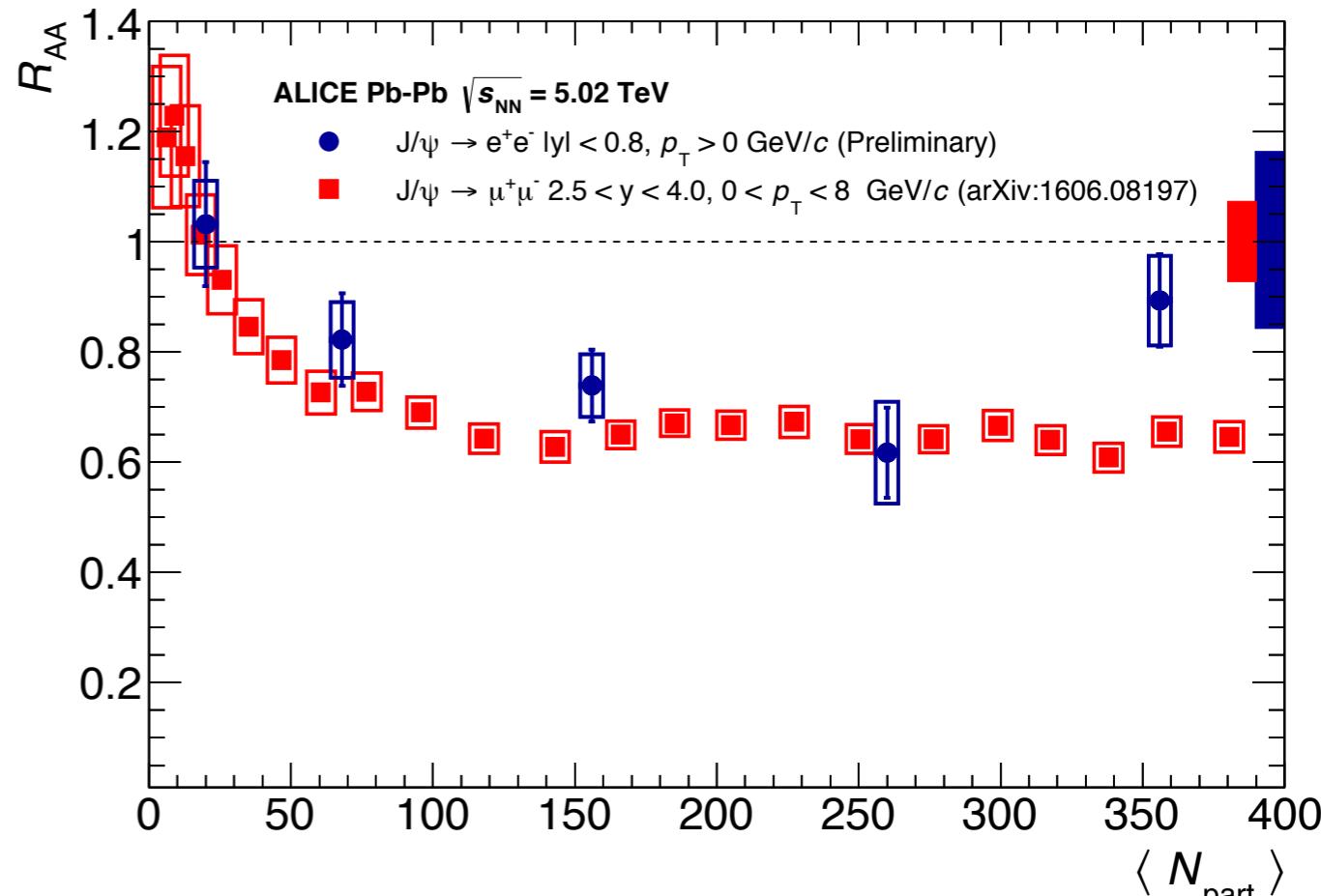
ALI-PREL-133694

- From $\langle N_{\text{part}} \rangle > 50$: no significant centrality dependence at LHC significantly different from RHIC observations
- J/ψ suppression at $\sqrt{s_{NN}}=5.02$ TeV confirms observations at $\sqrt{s_{NN}}=2.76$ TeV with an increased precision
- Good agreement between both rapidity measurements with hint of a production increase for the most central collisions at mid- y

$J/\psi R_{AA}$ measurements with ALICE



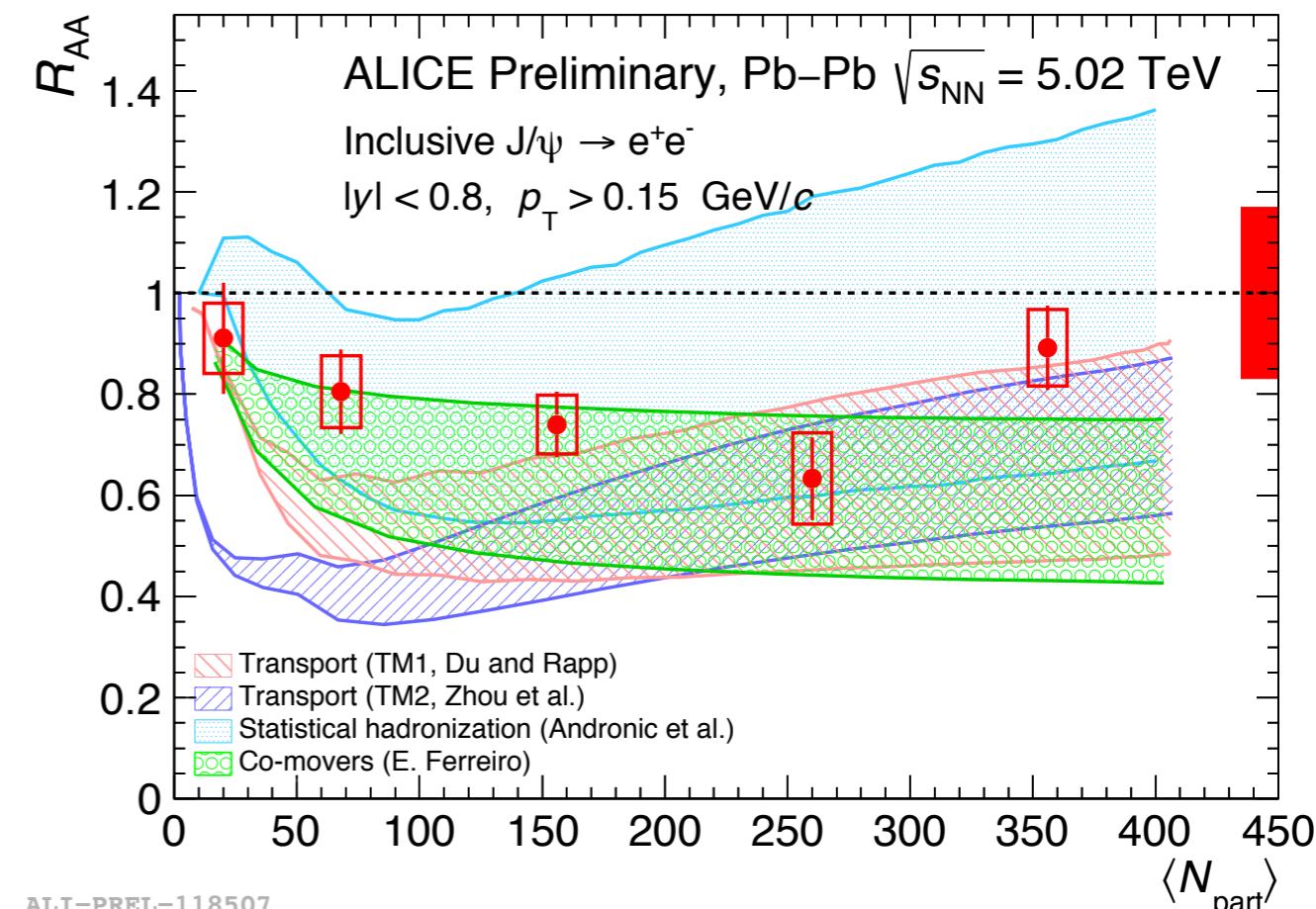
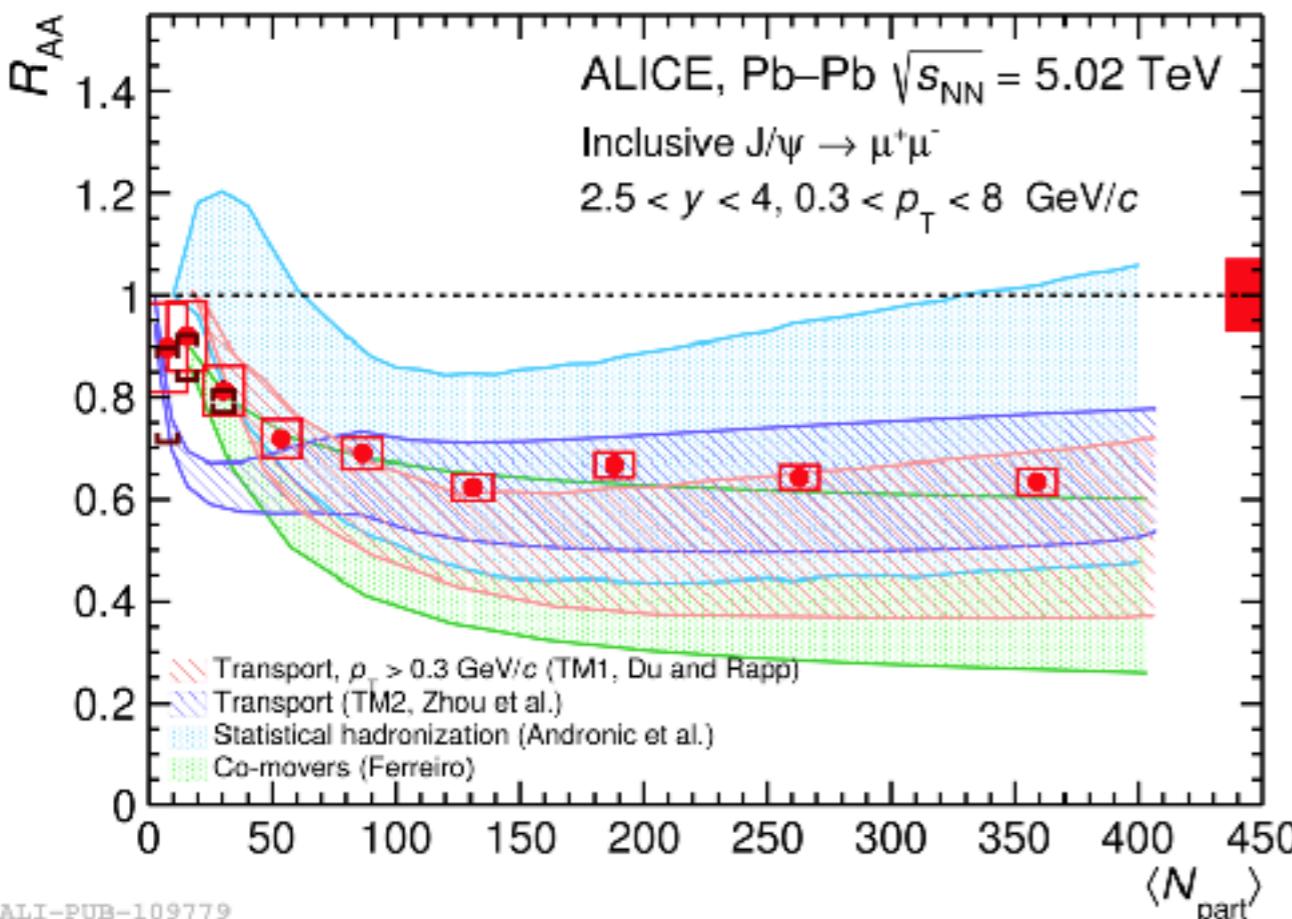
ALI-DER-112313



ALI-PREL-118519

- From $\langle N_{\text{part}} \rangle > 50$: no significant centrality dependence at LHC significantly different from RHIC observations
- J/ψ suppression at $\sqrt{s_{\text{NN}}}=5.02 \text{ TeV}$ confirms observations at $\sqrt{s_{\text{NN}}}=2.76 \text{ TeV}$ with an increased precision
- Good agreement between both rapidity measurements with hint of a production increase for the most central collisions at mid- y

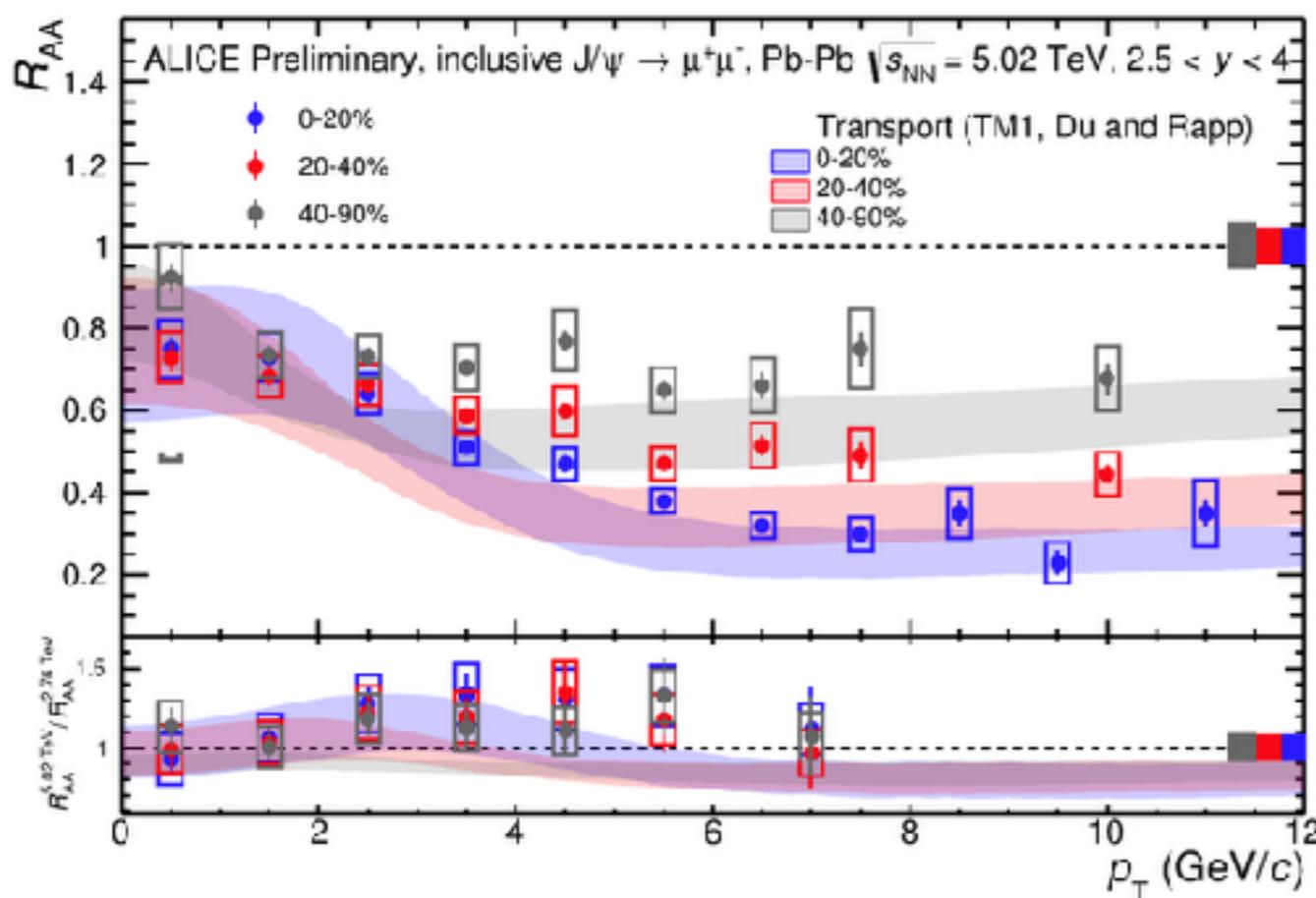
$\text{J}/\psi R_{AA}$ vs model calculations



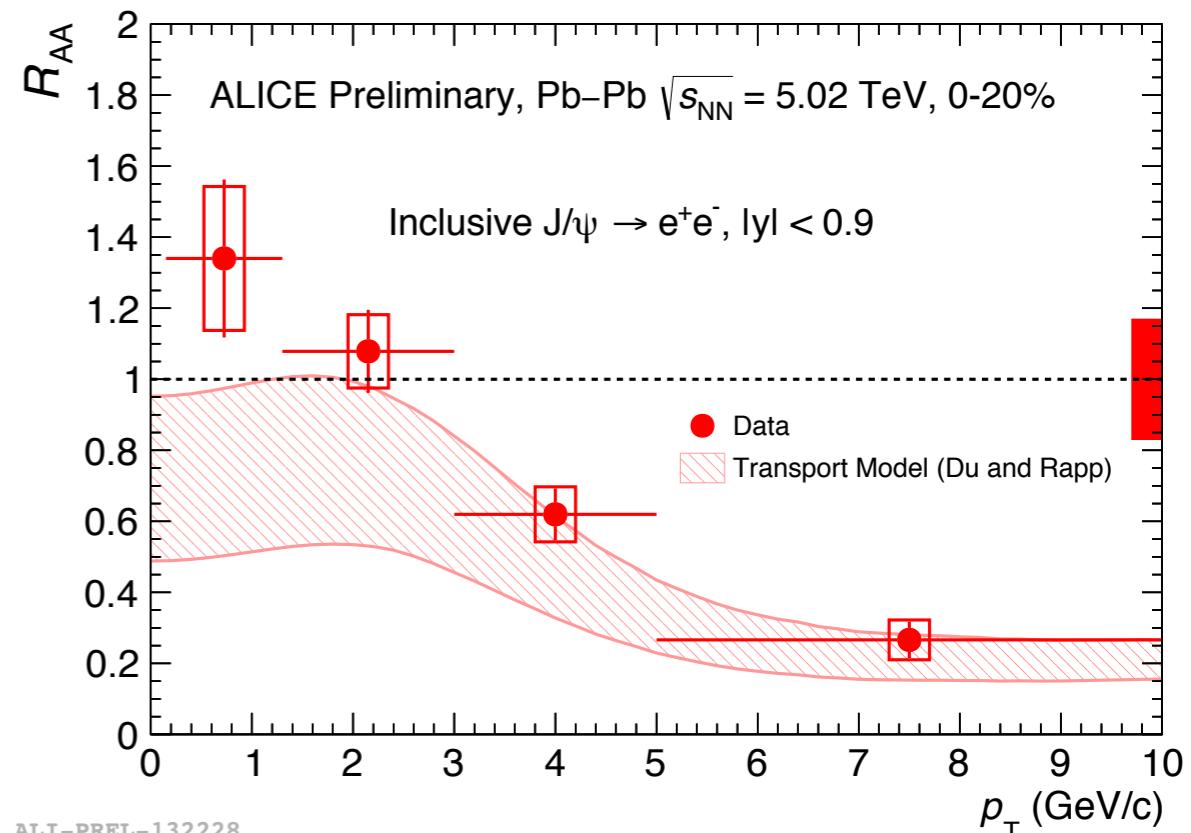
- Exp. observations interpreted as suppression + (re)combination
- All models reproduce data
- Main sources of uncertainties
 - Precise determination of $c\bar{c}$ cross-section
 - CNM effects on quarkonium production

Transport models: TM1 and TM2
[Zhao et al., NPA859, 114](#), [Zhou et al., PRC89, 054911](#)
Statistical hadronization
[Andronic et al., NPA 904-5, 535c](#)
Co-movers interaction model
[Ferreiro et al., PLB731, 57](#)

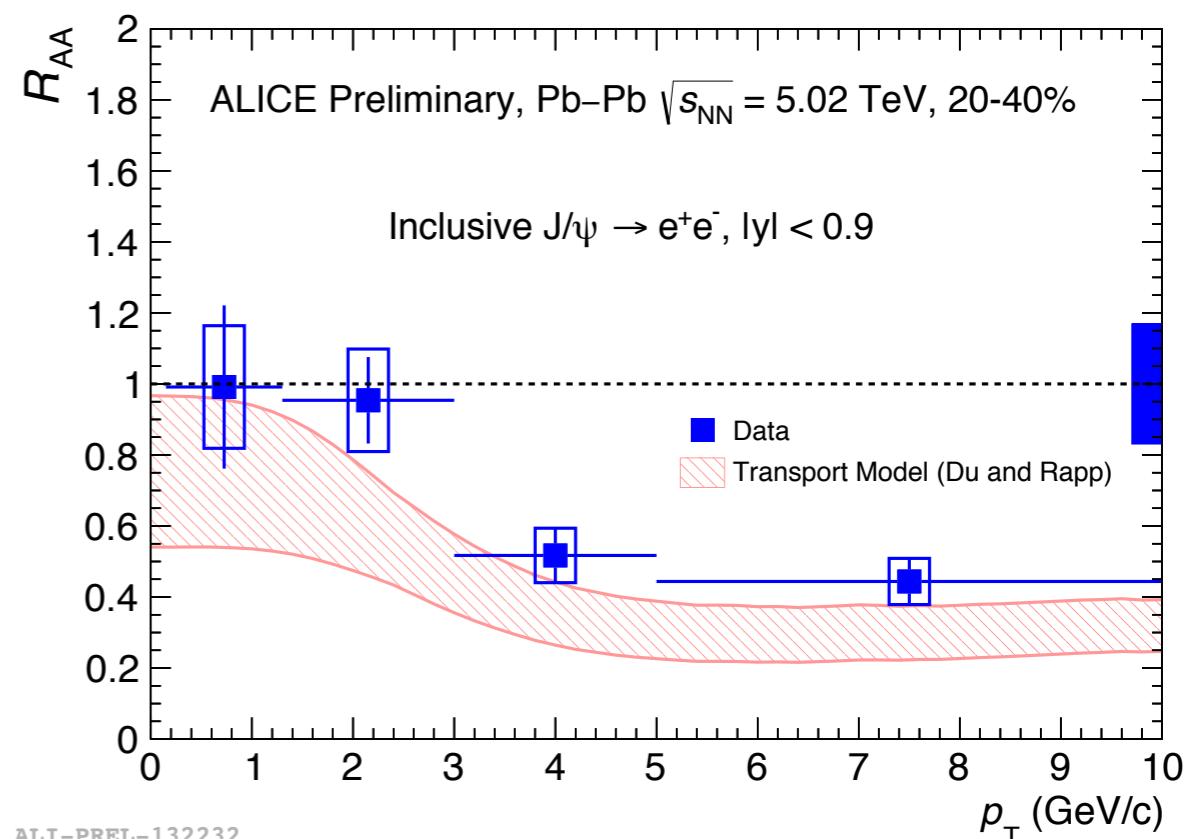
$\text{J}/\psi R_{\text{AA}}$ VS p_{T}



ALI-PREL-126572

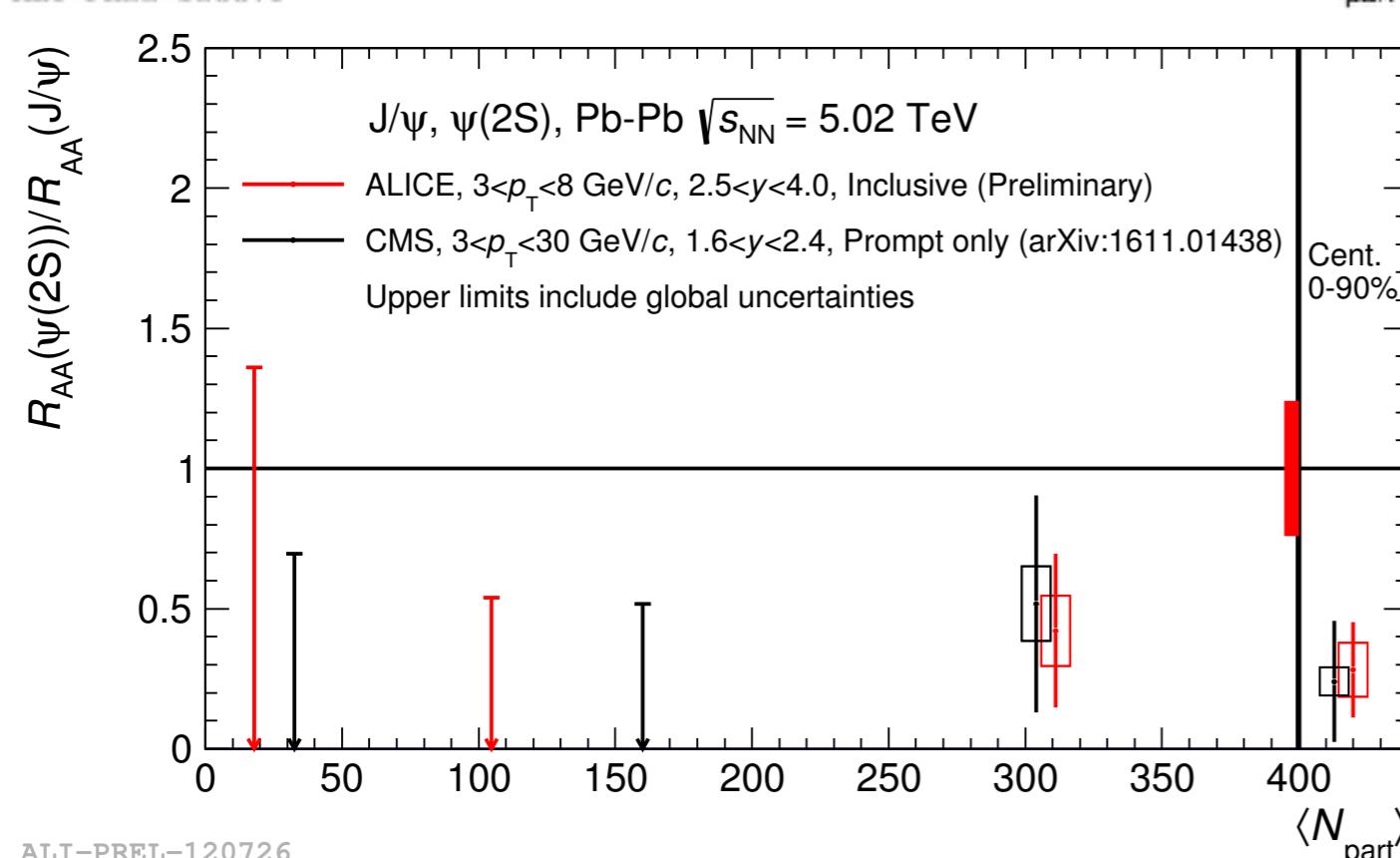
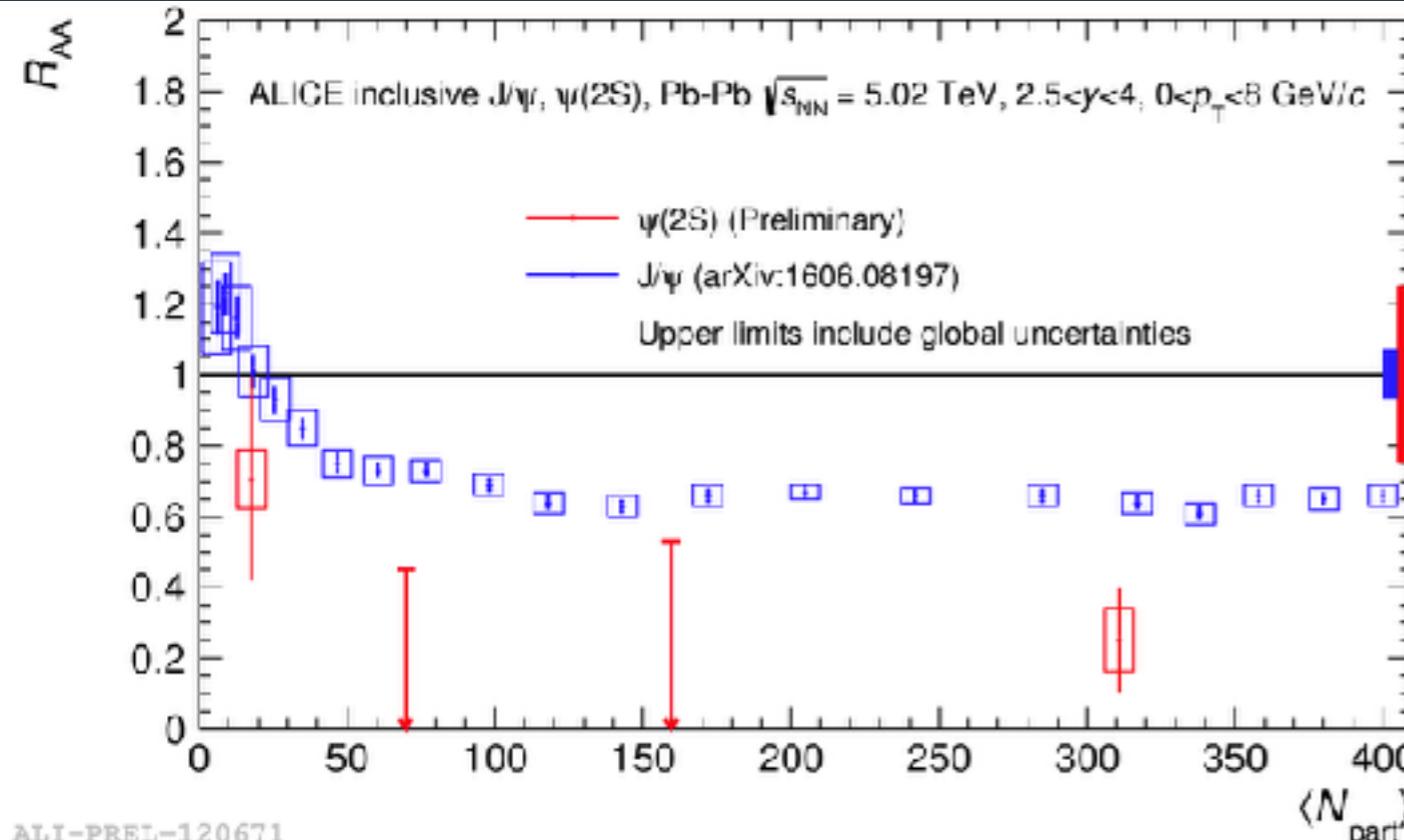


ALI-PREL-132228



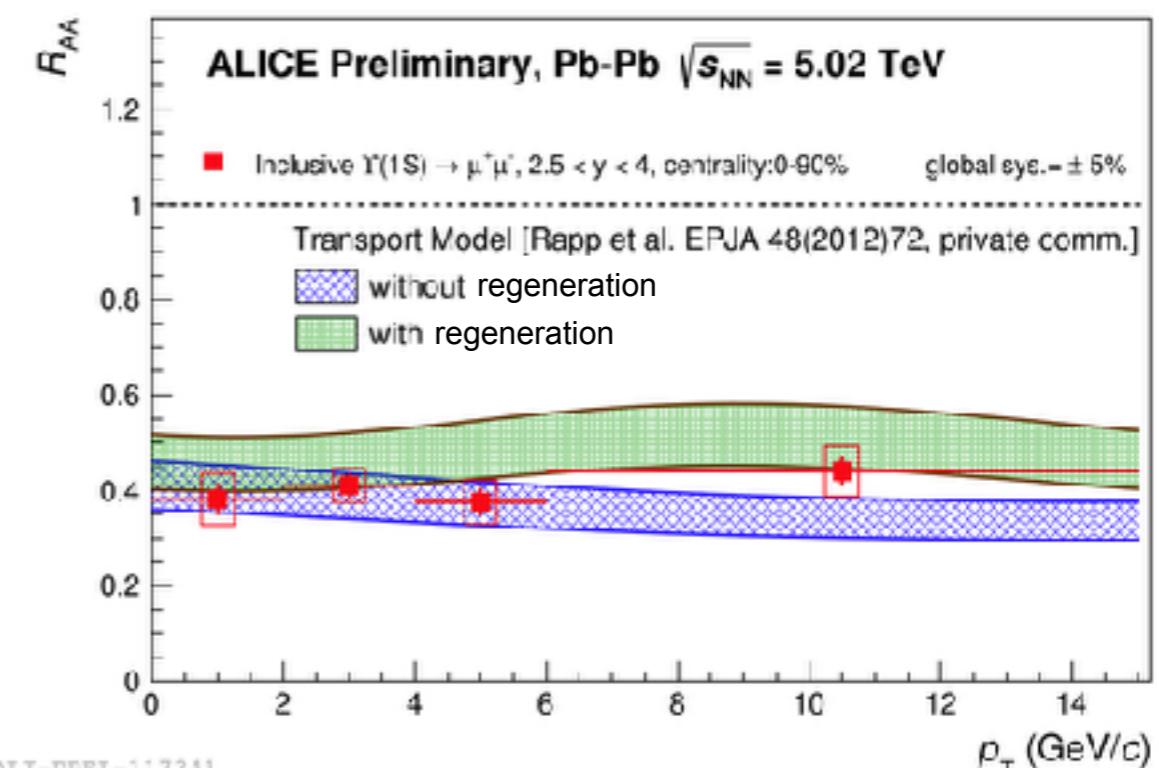
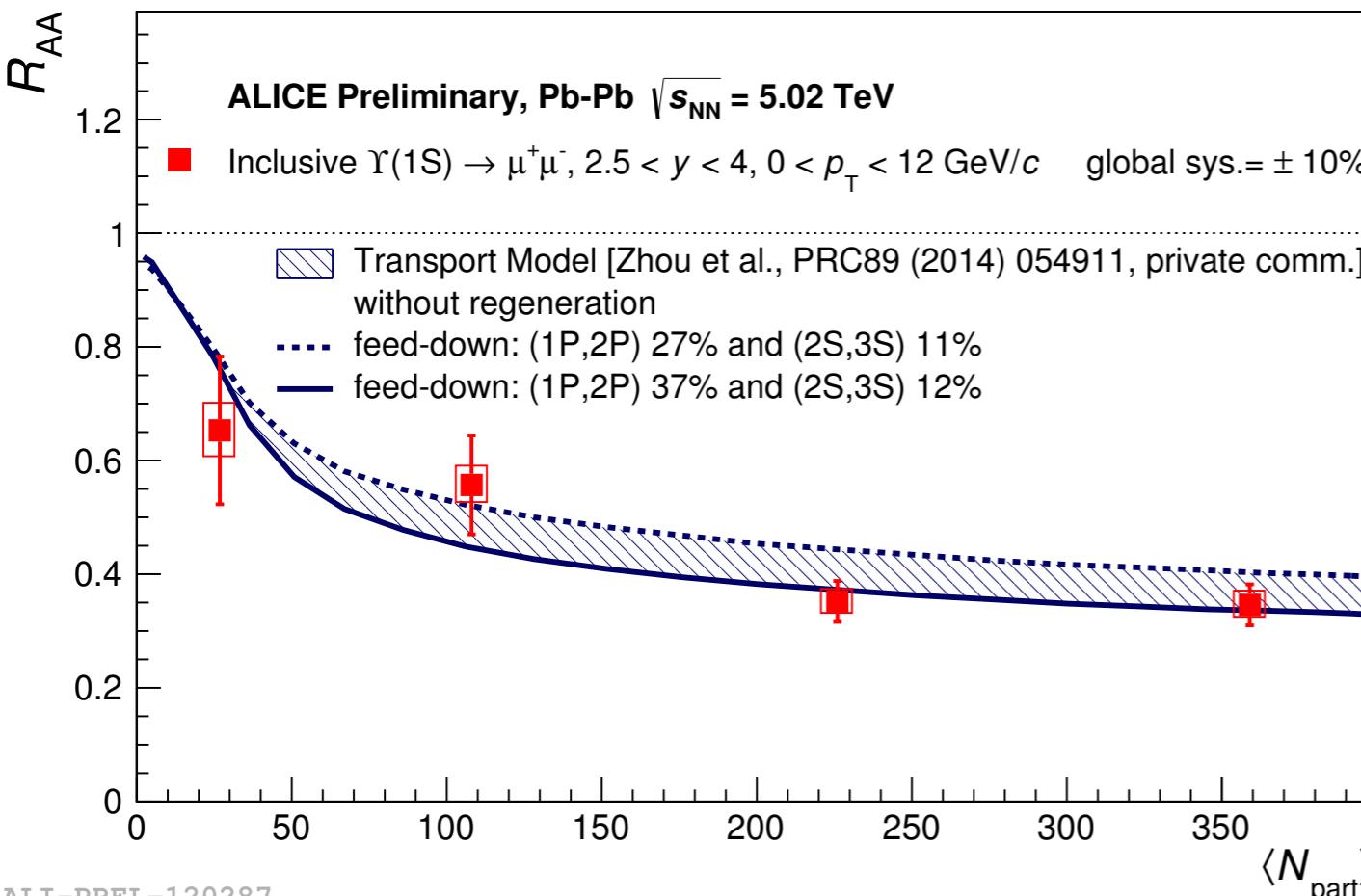
ALI-PREL-132232

$\psi(2S)$ R_{AA} and ratio of 2S/1S



- $\psi(2S)$ is expected to be more easily dissociated than J/ψ
- $\psi(2S)/\psi(1S)$ should greatly help model discrimination
- Data show a stronger suppression in semi-central and central collisions
- For low significance : upper limit at 95% CL
- More statistics are needed → upgrades for LHC run 3

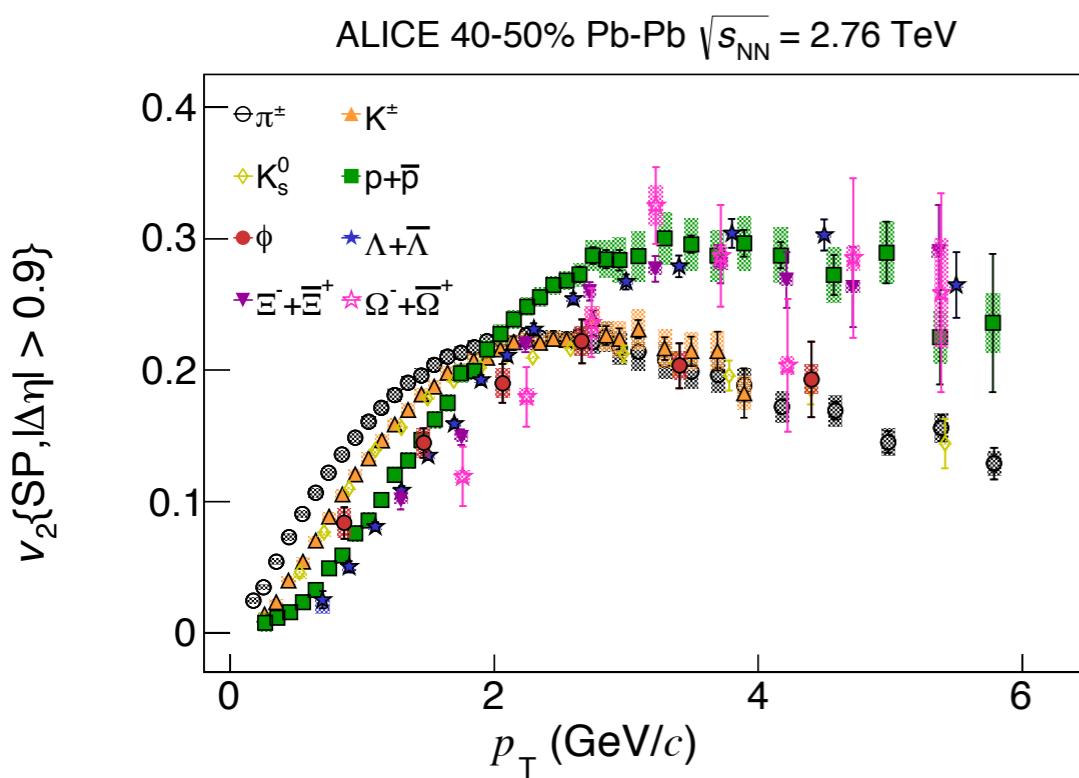
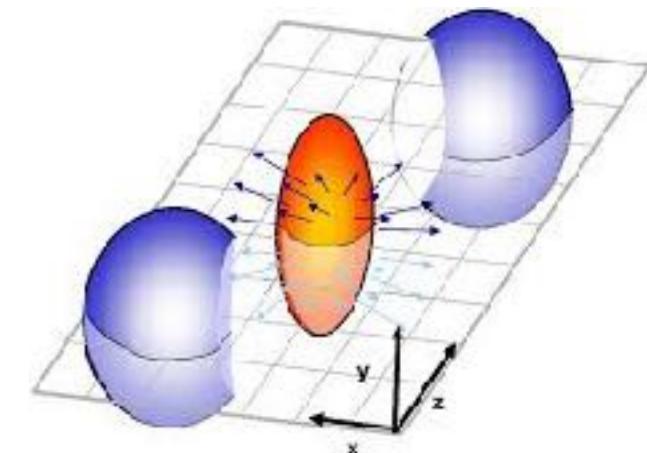
$\Upsilon(1S)$ RAA



- Strong $\Upsilon(1S)$ suppression vs centrality (similar to $\sqrt{s_{NN}} = 2.76$ TeV)
 - Direct $\Upsilon(1S)$ production suppressed ?
 - Need precise feed-down measurement for P-wave states (from pp) at low p_T
 - Compatible with transport models w/wo (re)generation
 - No p_T dependence within uncertainties

Heavy quark flow

- Recombined states should inherit the flow of heavy quarks
- Relevant observable for quarkonium (re)generation and path length study
- Further constrain to theoretical models describing quarkonium production



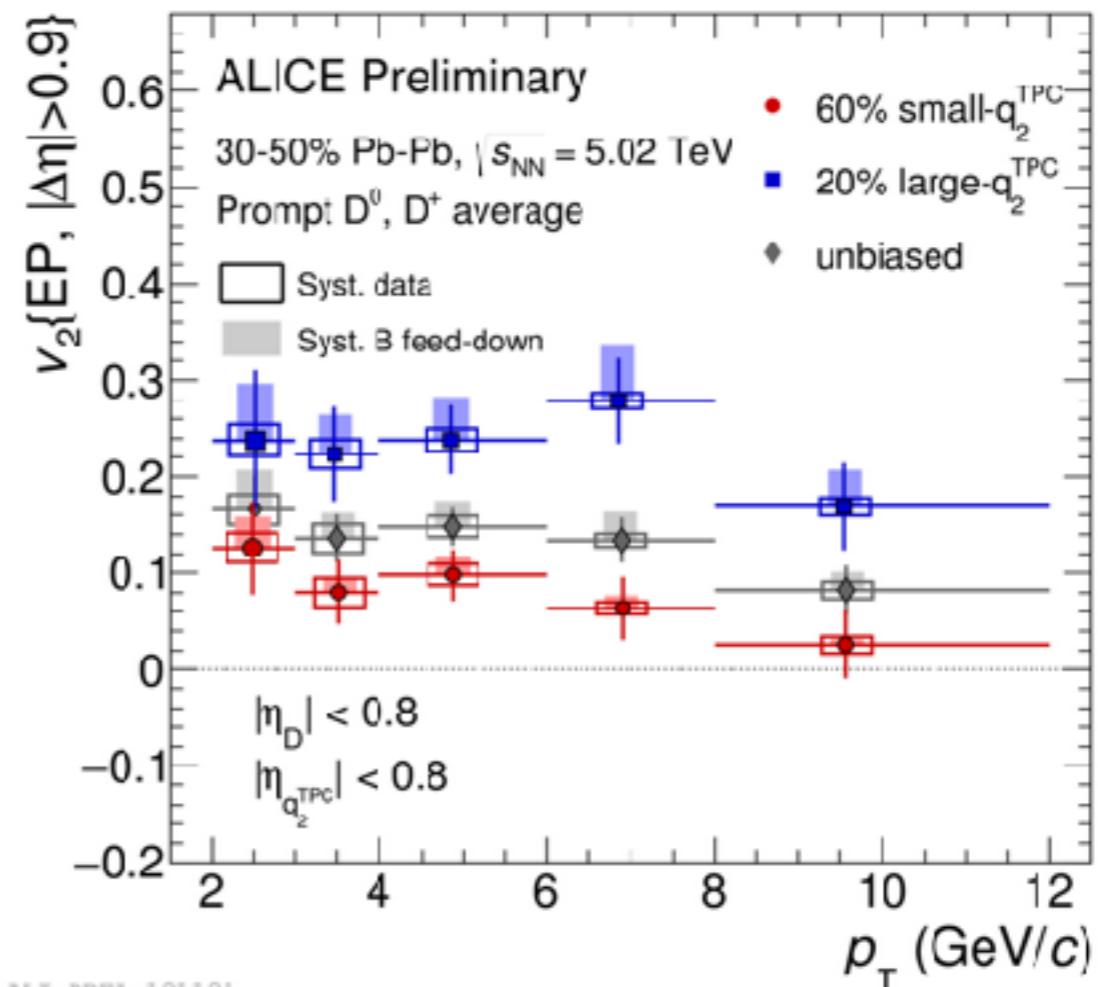
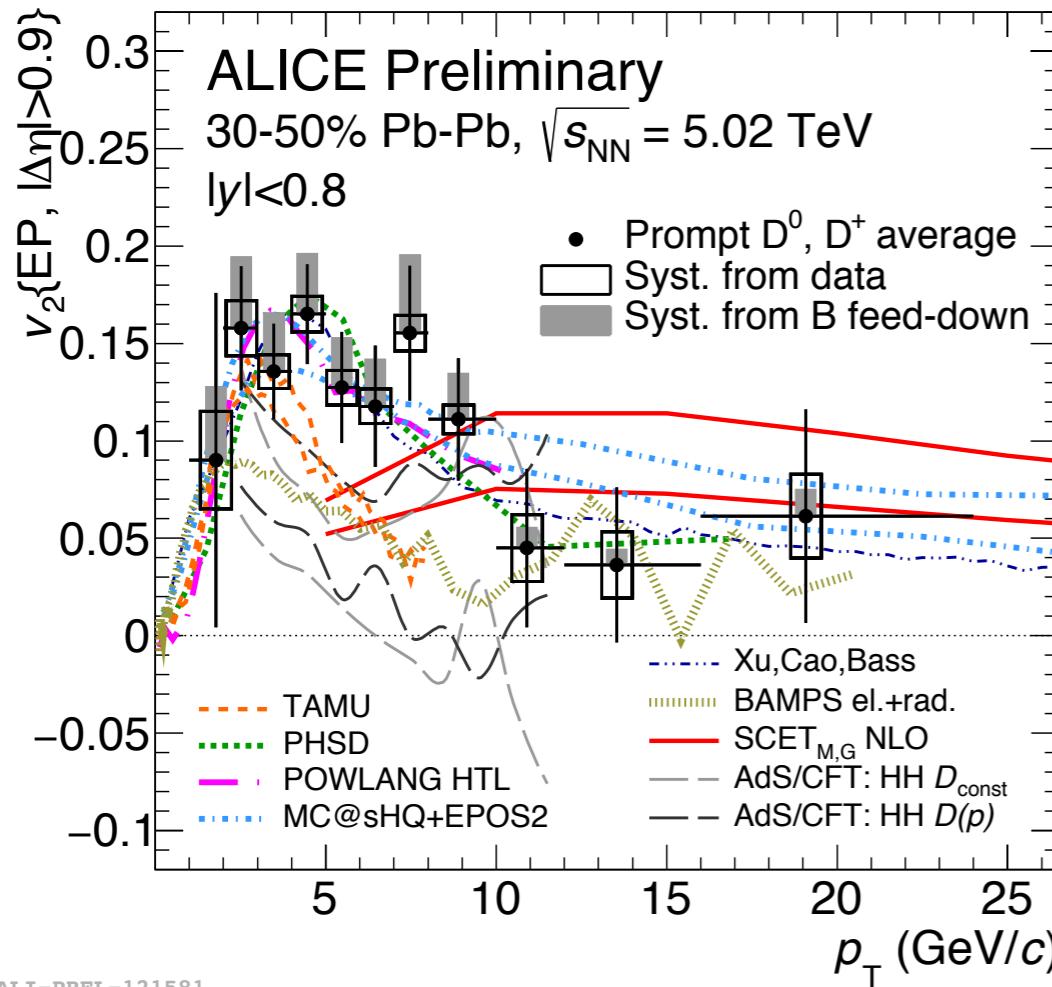
Open questions :

- Do charm quarks thermalize?
- Do they follow collective dynamics of bulk?
- If yes, how do their flow scale with lighter quarks ?

ALI-PUB-82660

[ALICE, JHEP 06 \(2015\) 190](#)

The elliptic flow of D mesons



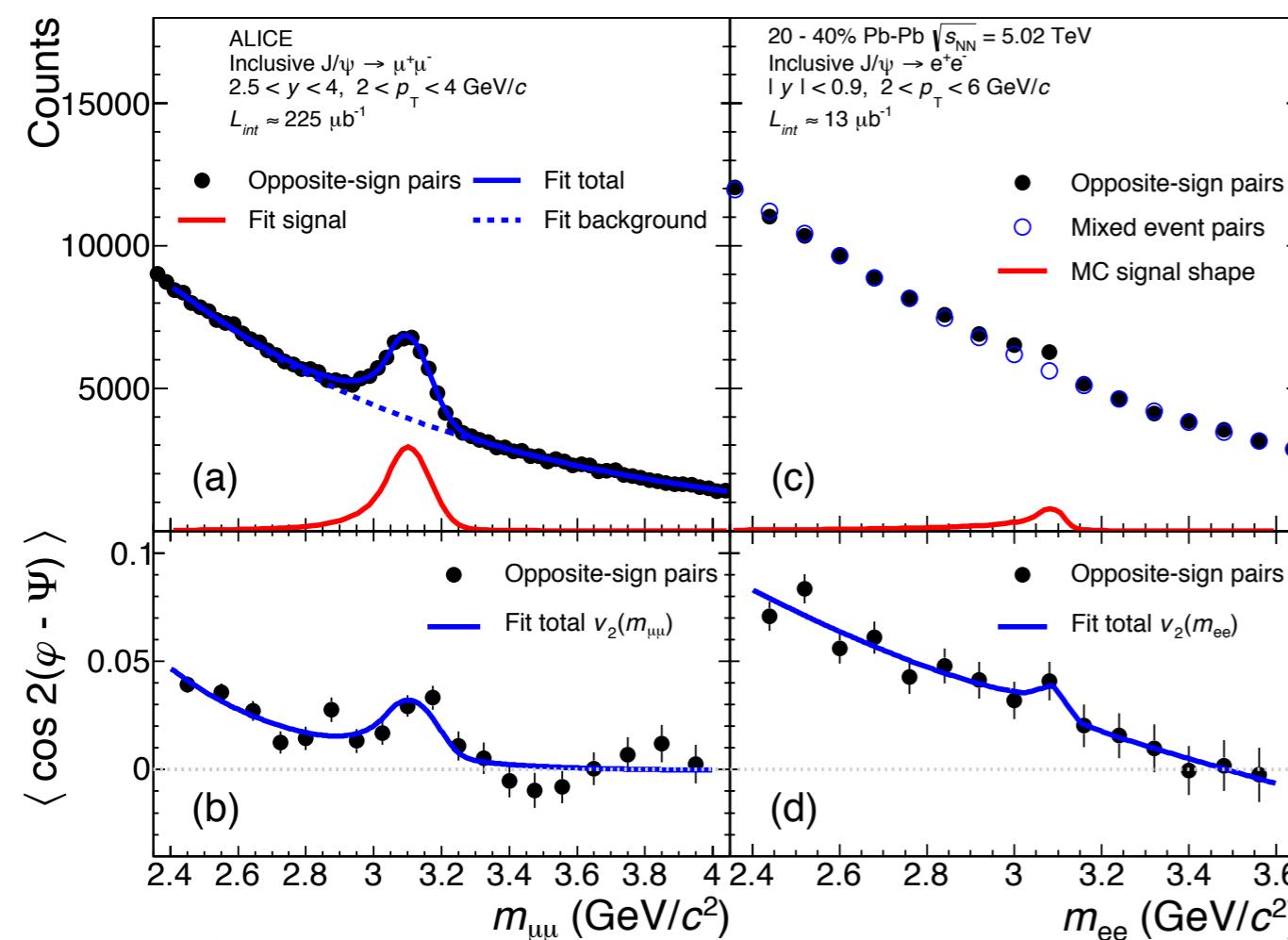
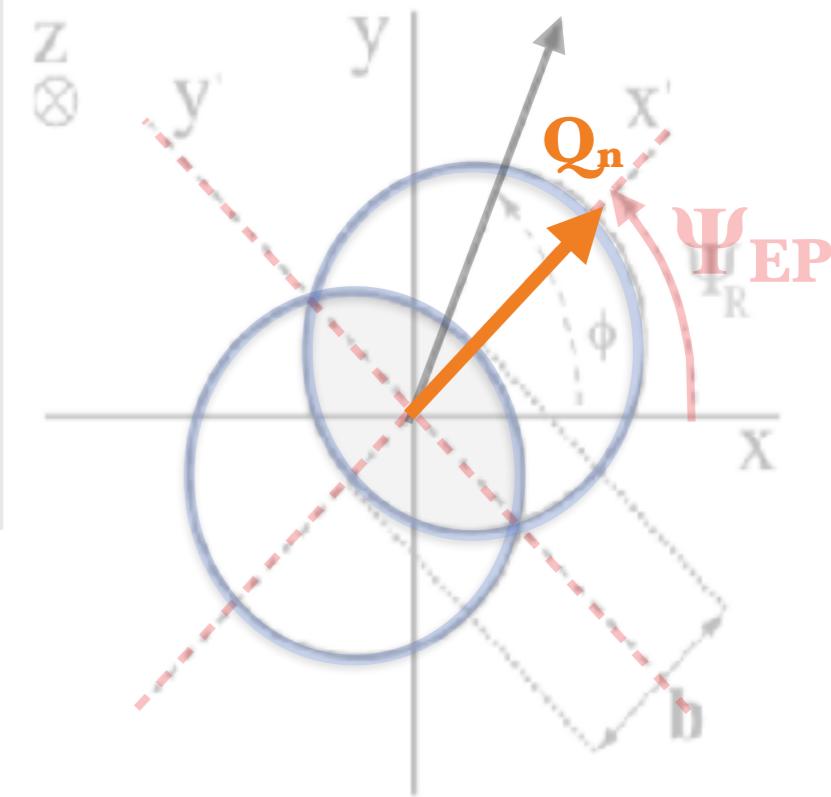
- A significant elliptic flow was measurement for D mesons
- Event shape engineering technique: study the coupling of c quark to the bulk of light quarks in the underlying medium
- Heavy quarks participate to the collective expansion dynamics

J/ ψ elliptic flow: how to measure it ?

- Methods based on **event plane** determination
From detector multiplicities:

$$\Psi_n = \frac{1}{n} \arctan(Q_{n,x}, Q_{n,y})$$

- Fit of $\langle \cos(2 \Delta\phi) \rangle$ distribution vs inv. mass
with $\Delta\phi = \Phi_{\mu\mu} - \Psi_{2,\text{EP}}$



ALI-PUB-138829

Model total flow as:

$$v_2(m_\ell) = v_2^{\text{sig}} \alpha(m_\ell) + v_2^{\text{bck}} (1 - \alpha(m_\ell))$$

signal shape extracted
from M_{inv} fit

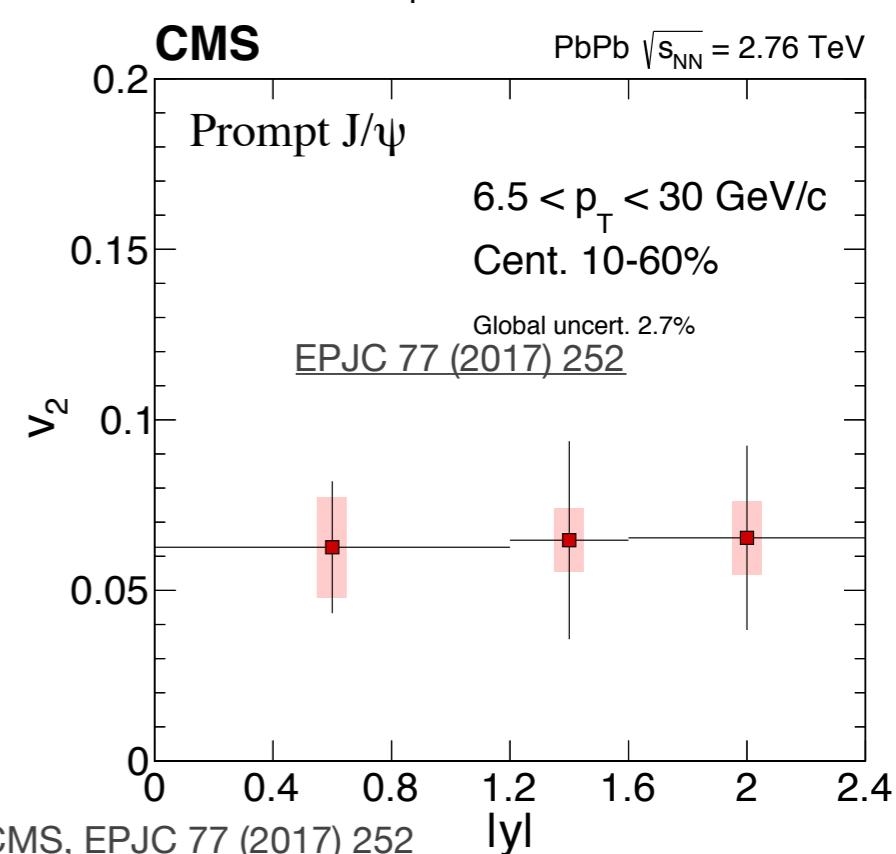
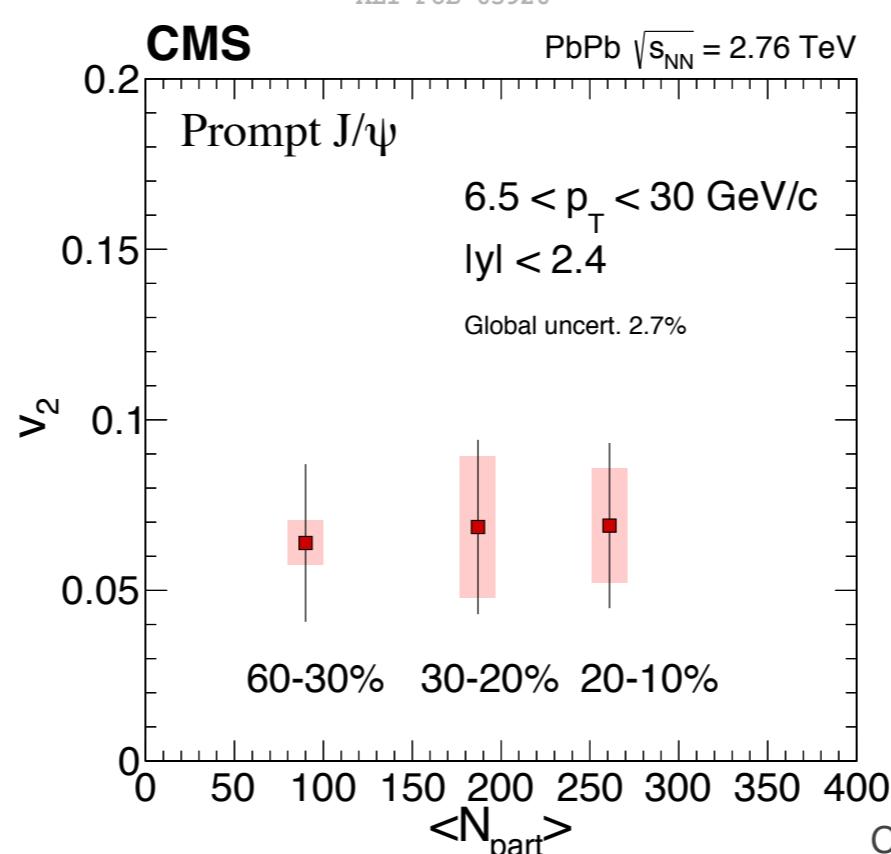
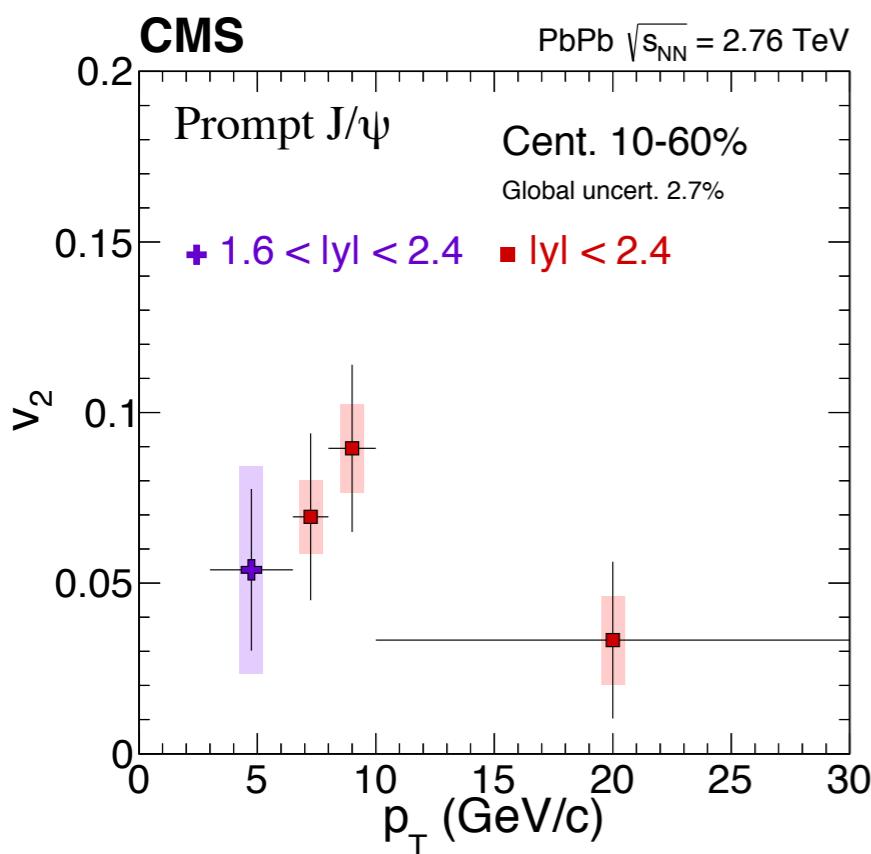
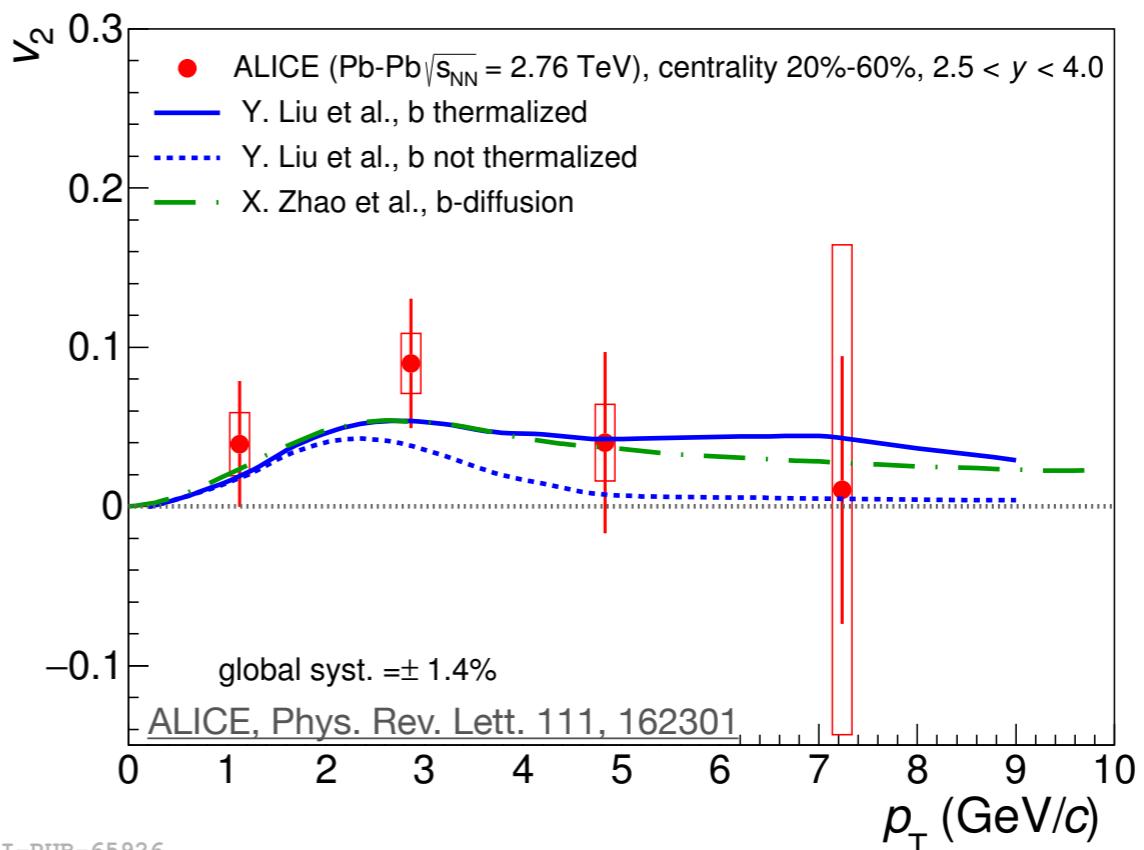
background : e.g.
polynomial function

$\text{J}/\psi v_2$ at $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$

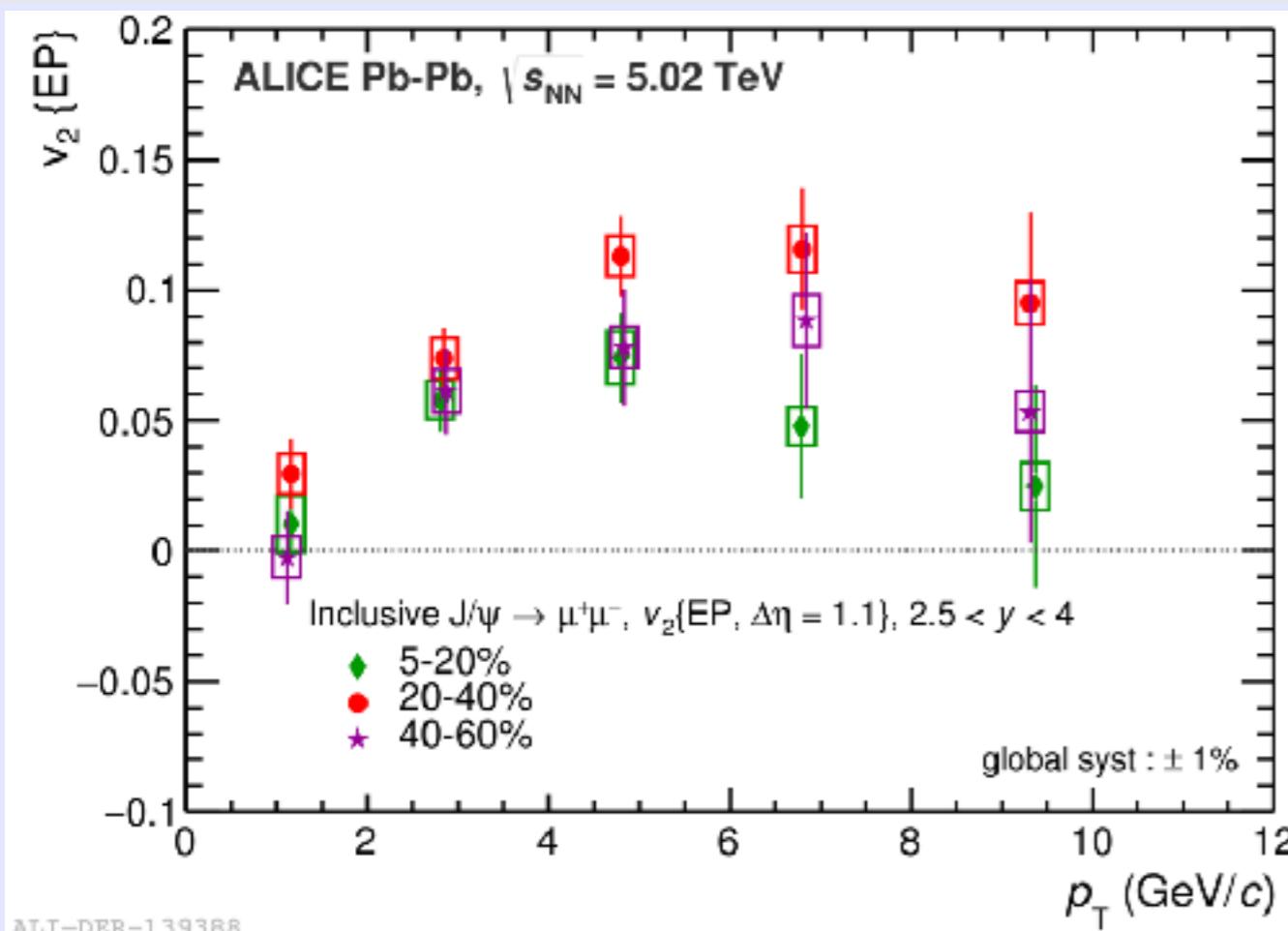
First hint of $\text{J}/\psi v_2$

measured by both
CMS and **ALICE**

→ different kinematic regions !

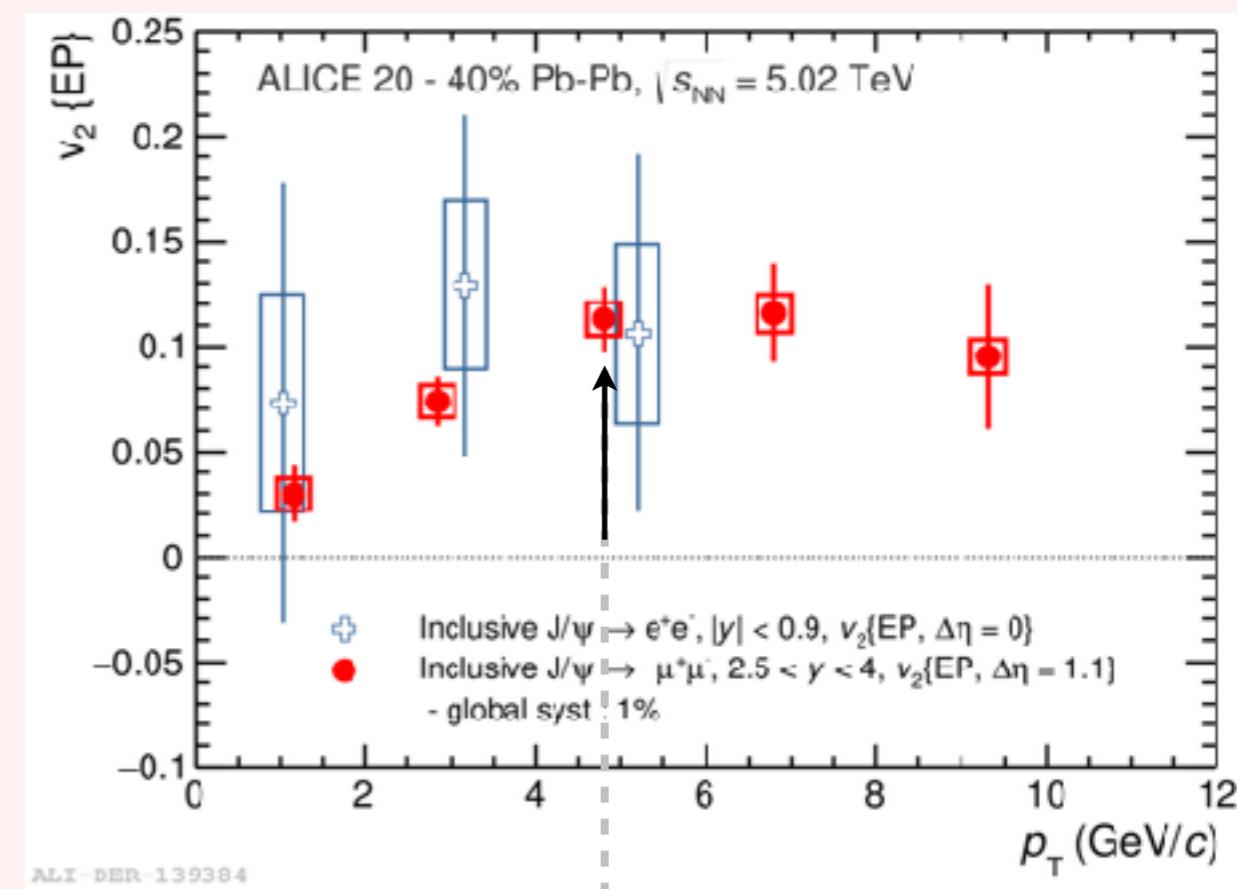


Results at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$



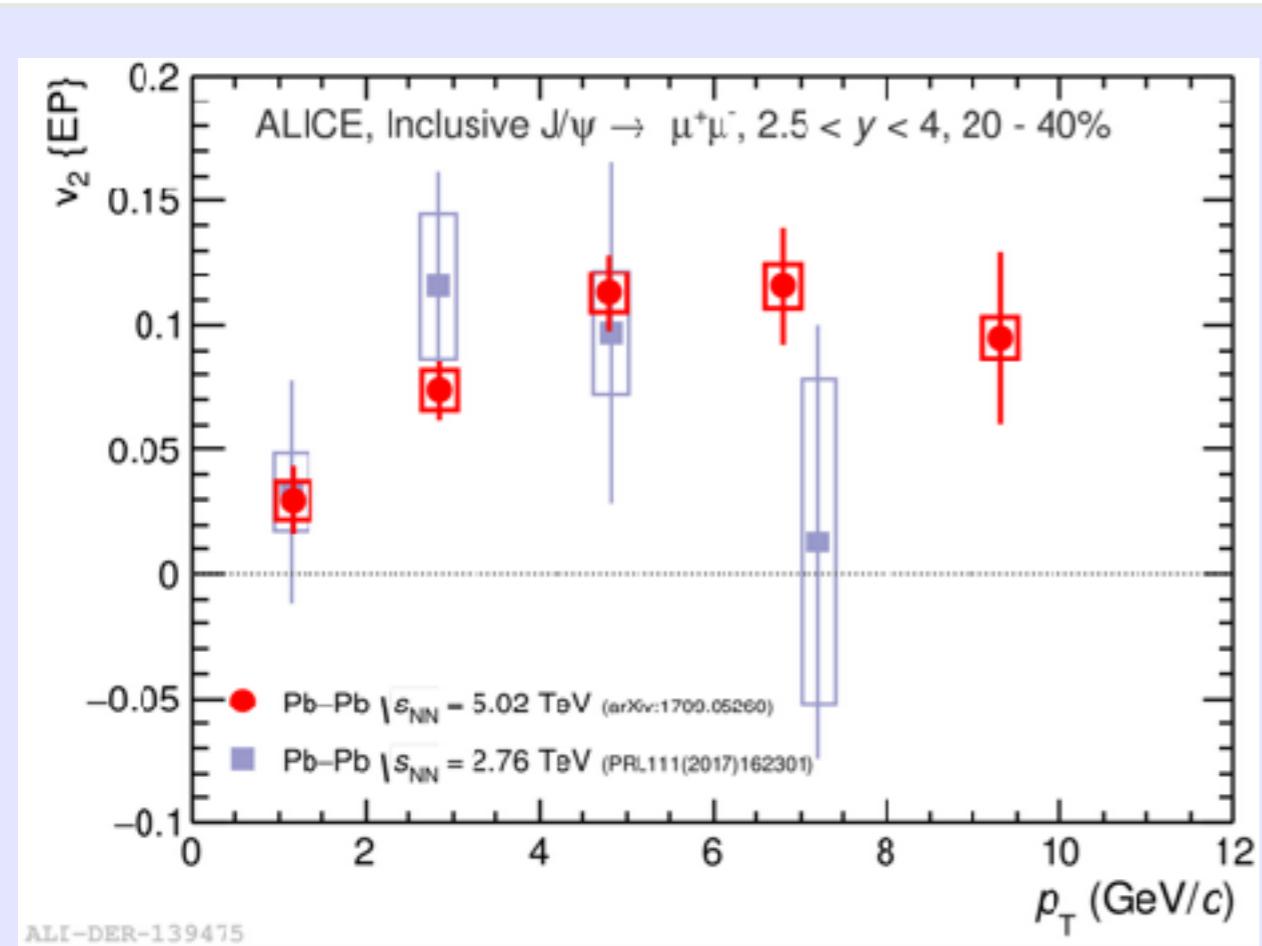
A significant v_2 is observed for various centrality and p_T bins

Compatible results between both rapidity measurements



Highest significance: 6.6σ for 20-40% and $4 < p_T < 6 \text{ GeV}/c$
 $v_2 = 0.113 \pm 0.015(\text{stat}) \pm 0.008(\text{syst})$

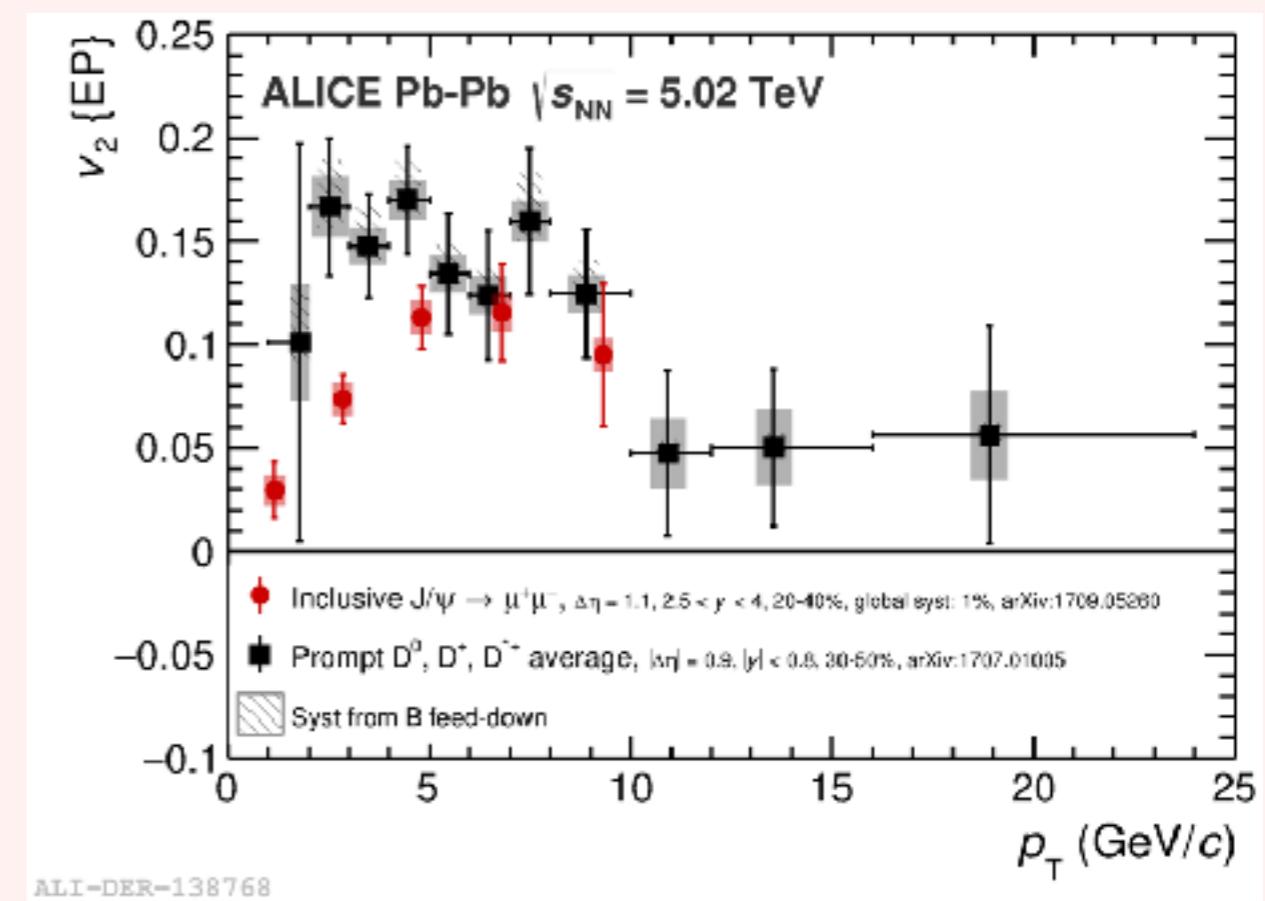
$\text{J}/\psi v_2$ measurement comparisons



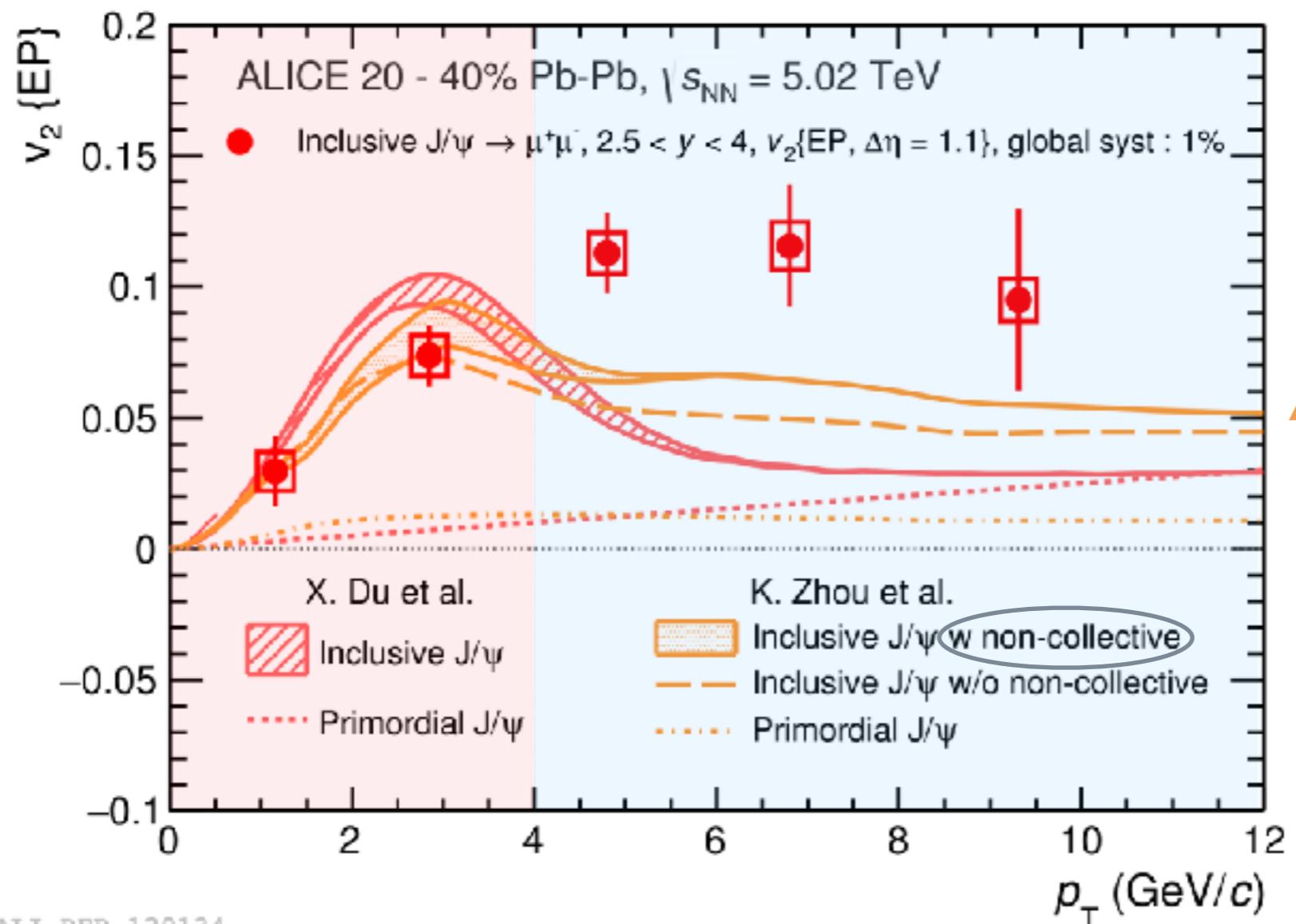
Compatible with results at $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$ with a higher precision (prompt J/ψ from CMS also indicate a non-zero v_2)

CMS, EPJC 77 (2017) 252

Comparison to open charm
 \rightarrow indication of:
charm recombination and
thermalization in the medium



Comparison with theory



Magnitude at low p_T is reproduced by including a strong J/ψ (re)generation component

At high p_T the v_2 is underestimated

Additionnal component from initial magnetic field could help better describe high p_T anisotropy

Summary

Quarkonia are suppressed in Pb-Pb collisions at the LHC

- Charmonium

- less suppression at the LHC than at RHIC
- Consistent with strong (re)generation component for J/ψ at LHC
- Evidence of positive $J/\psi v_2$ suggests **charm thermalisation** in the medium
 - At high $p_T v_2$ amplitude is not understood
- More statistics are needed to better study $\psi(2S)$

- Bottomonium

- $\Upsilon(1S)$ suppression plays dominant role with negligible (re)generation
- Strong R_{AA} centrality dependence

Thank you for your attention !

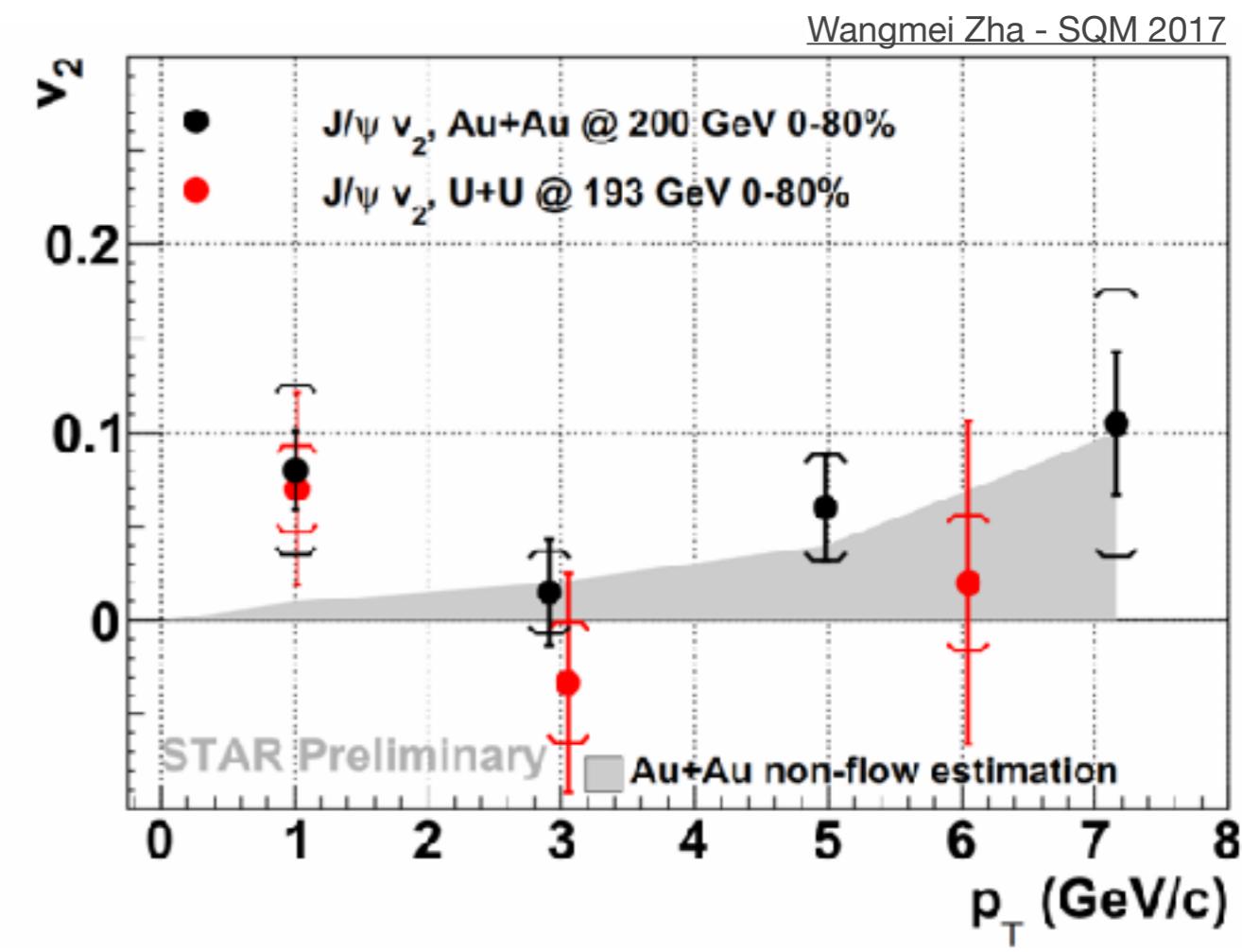
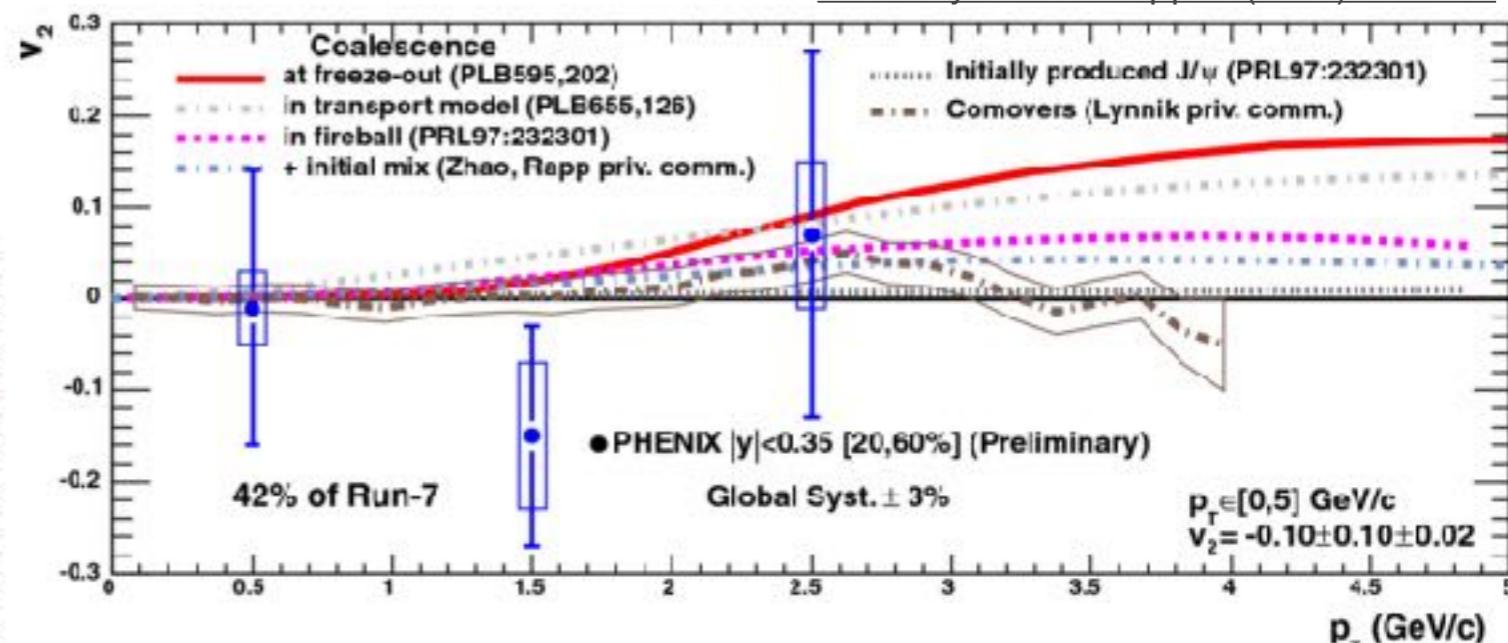
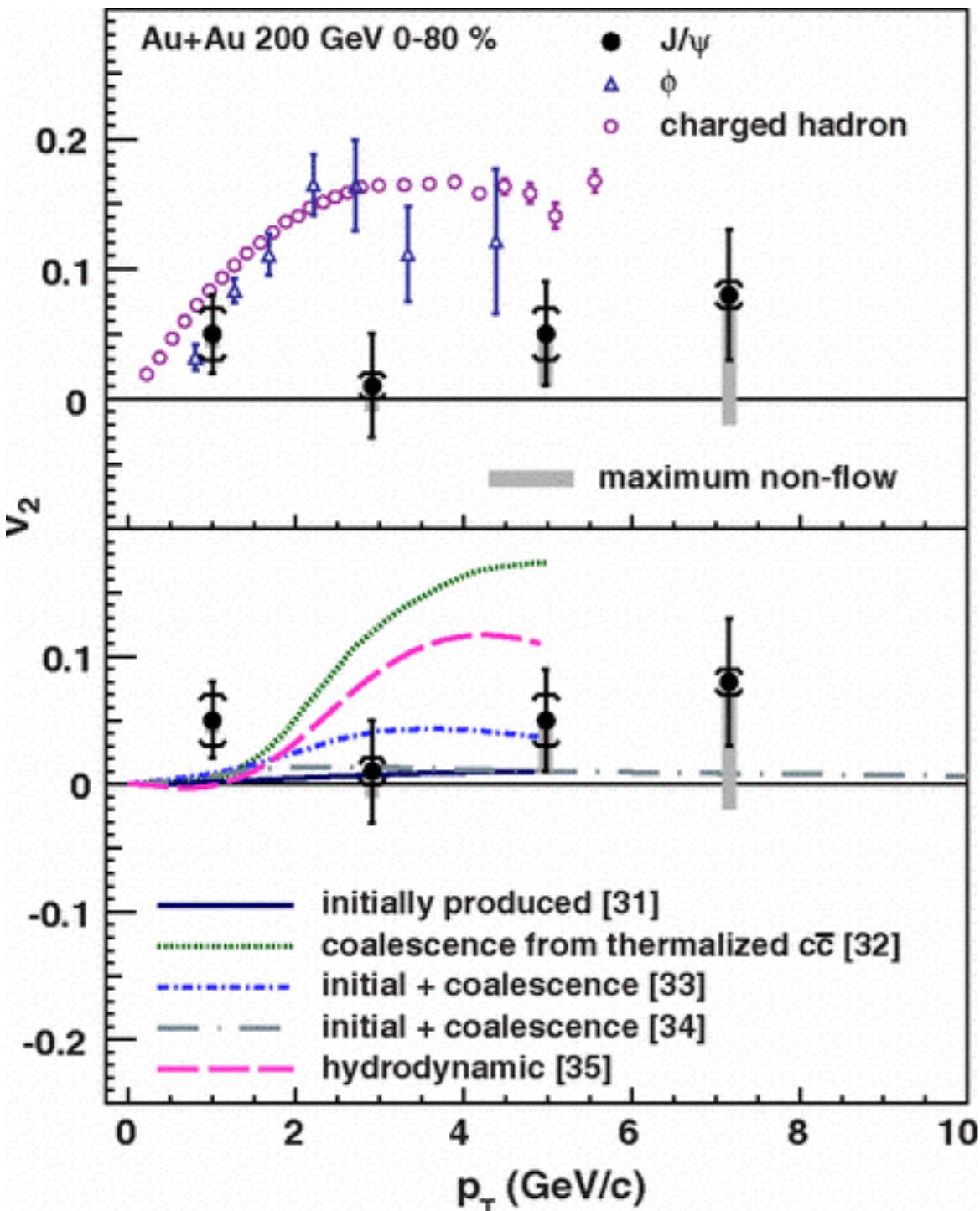
Back-up

$\text{J}/\psi v_2$ at RHIC energies

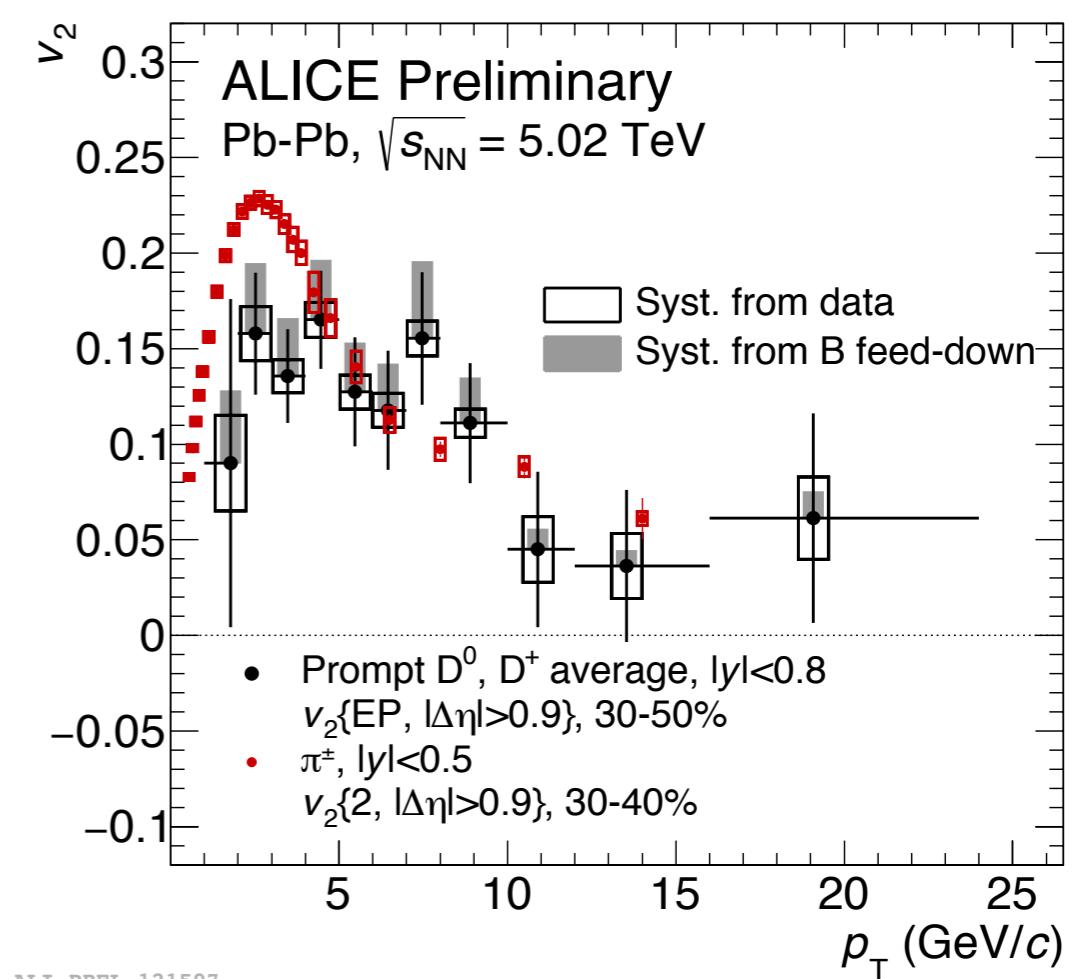
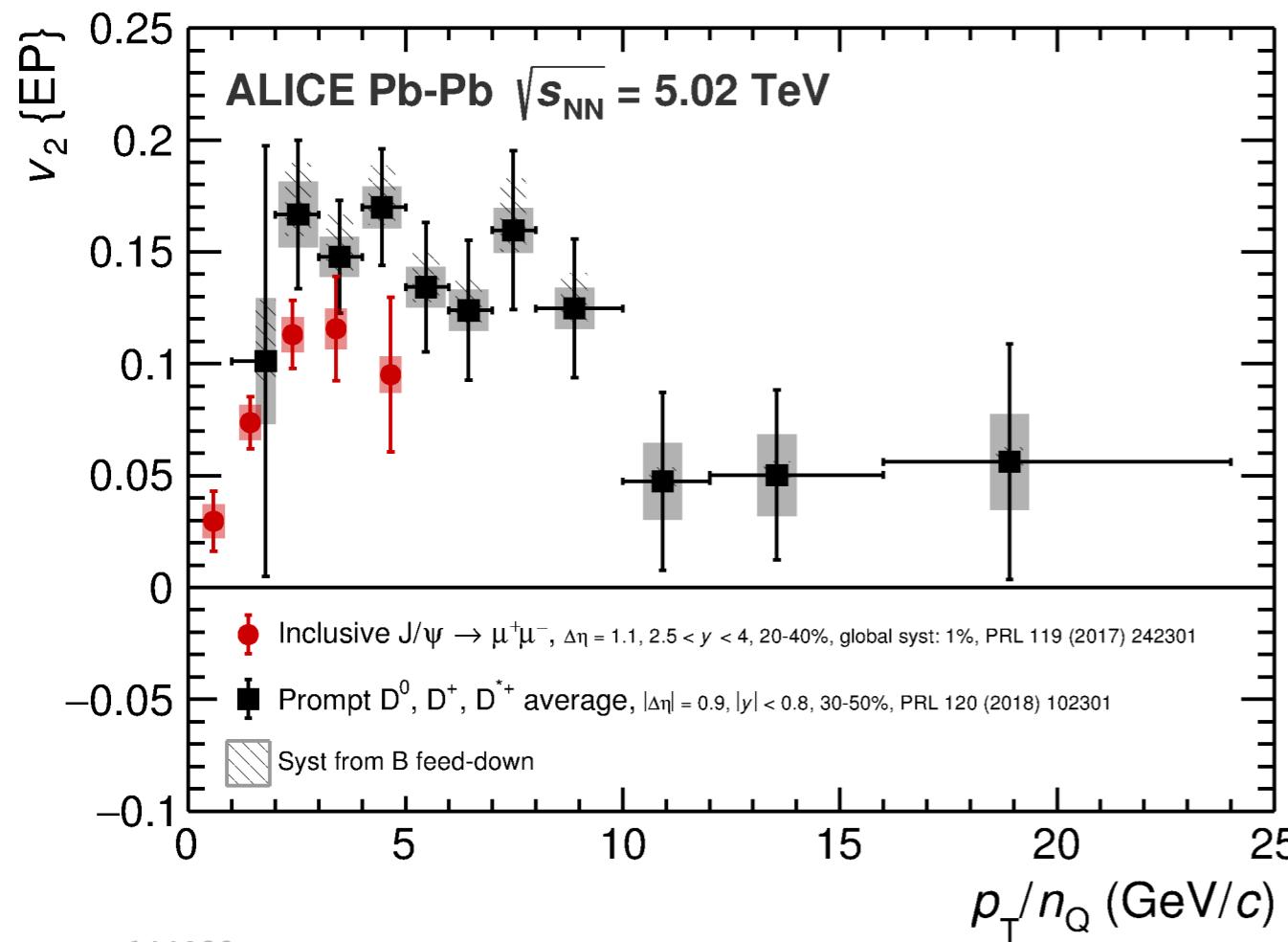
Acta Phys.Polon.Supp. 5 (2012) 323-328

$v_2 \sim 0$ at RHIC energies
 $v_2 < 0$ at low p_T ?

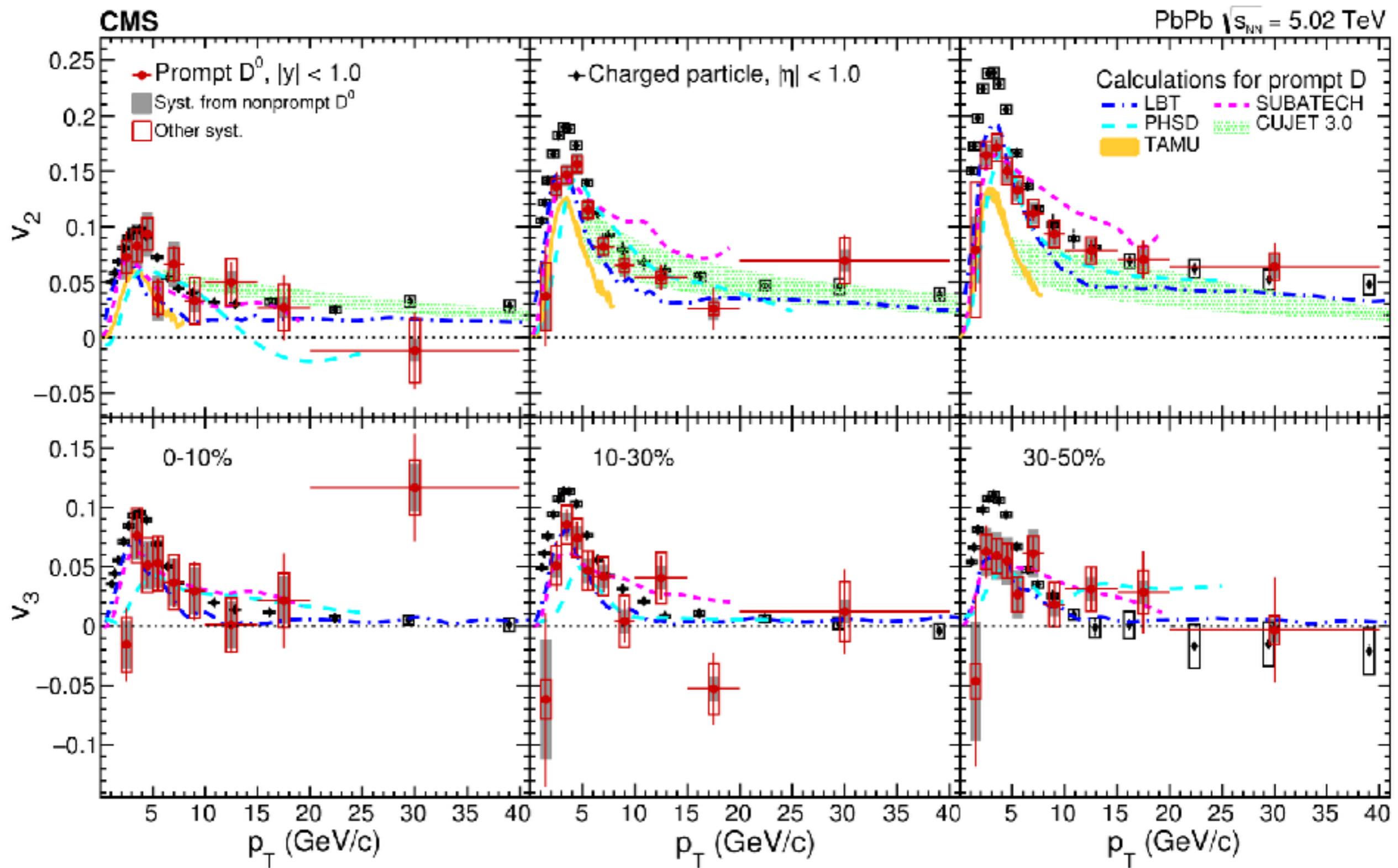
Phys. Rev. Lett. 111, 052301 (2013)



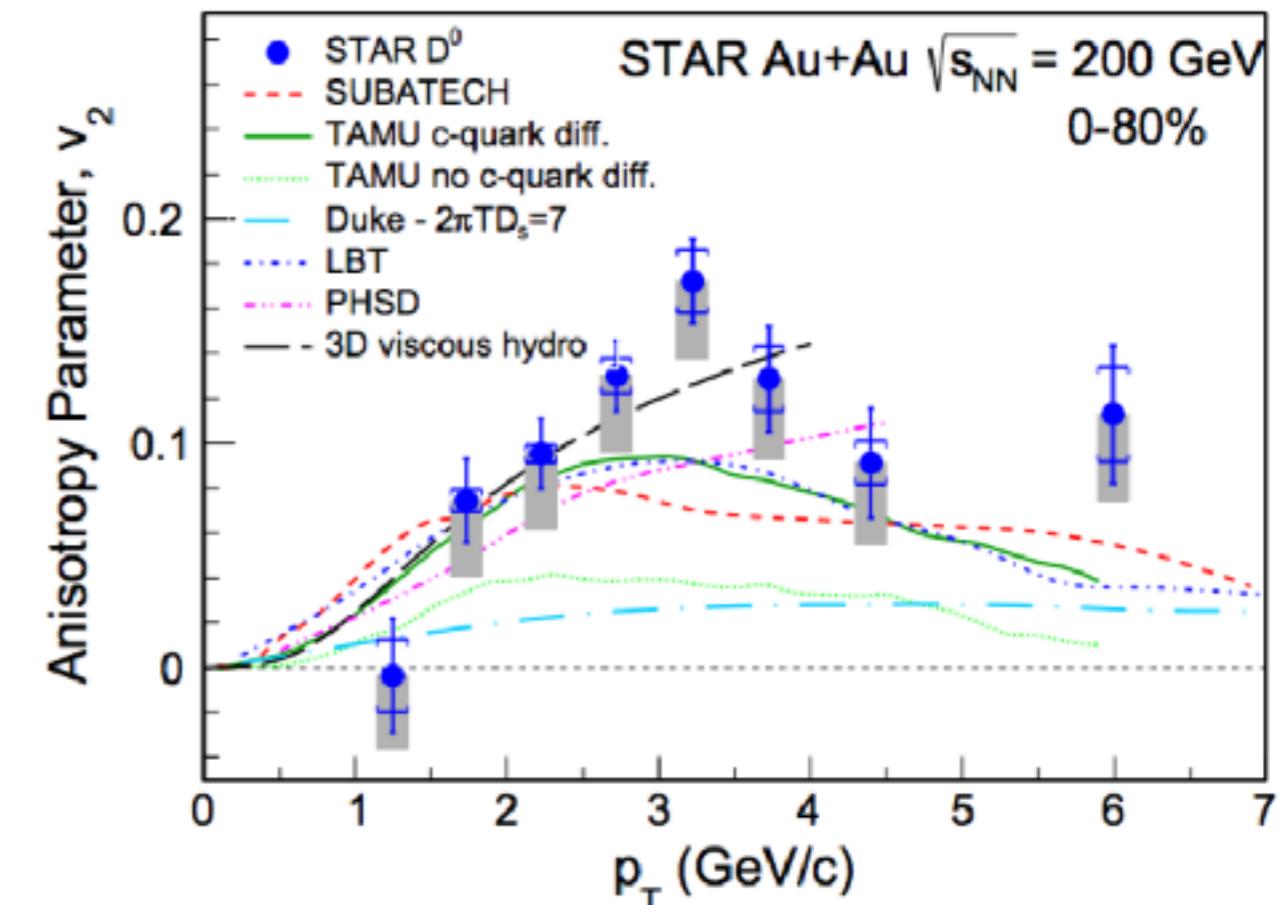
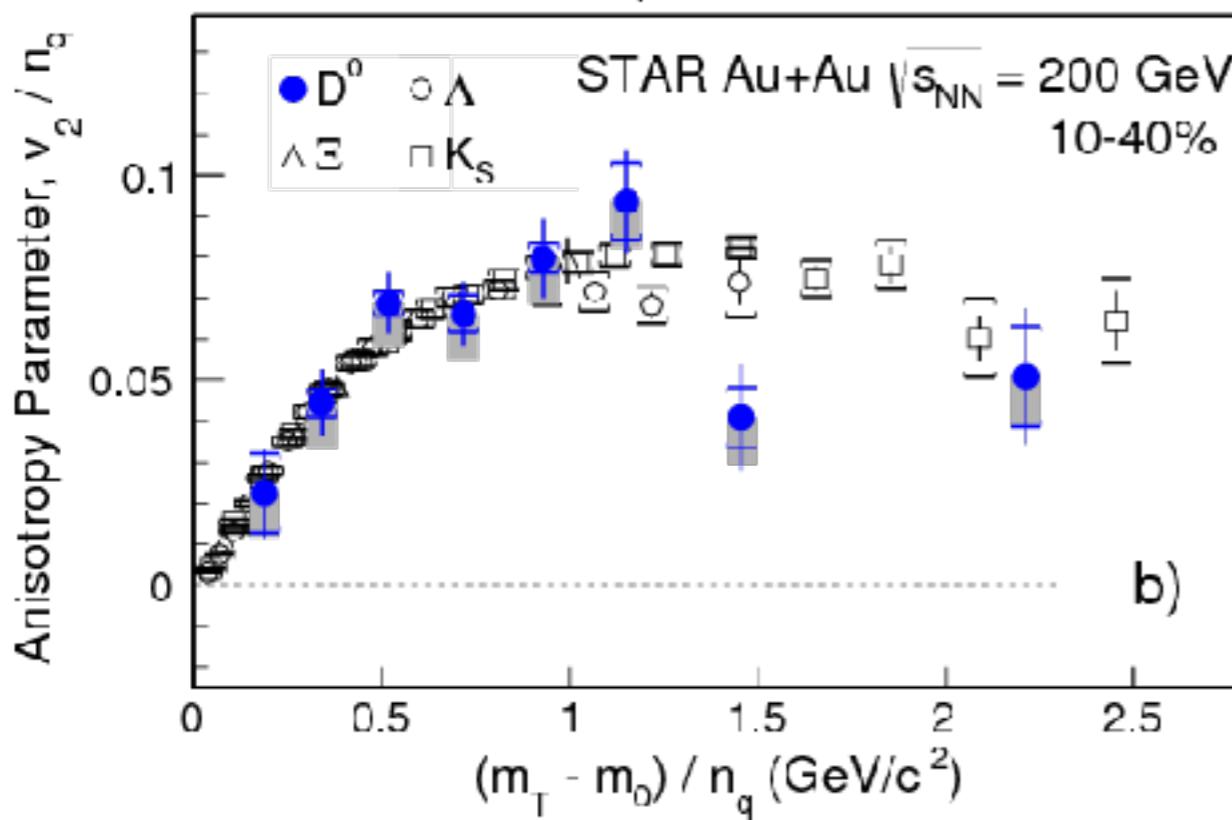
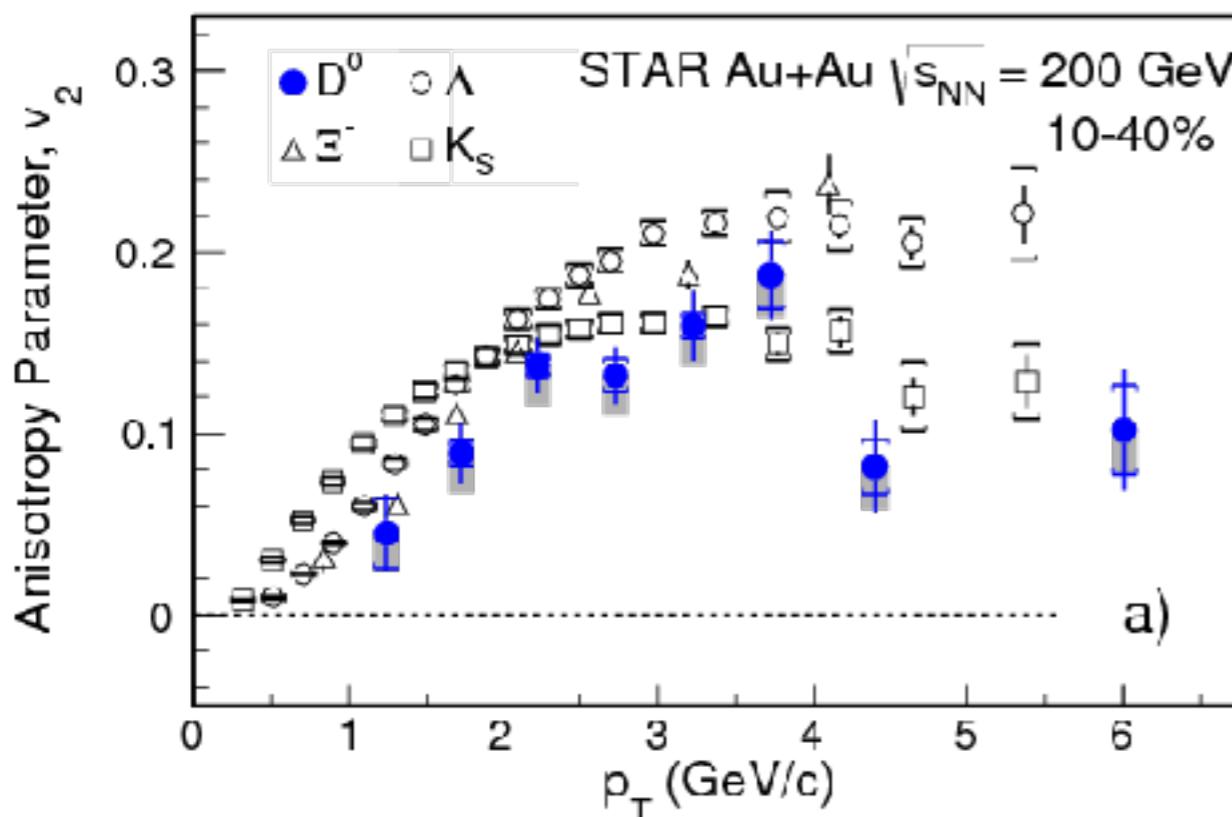
v_2 results comparison



CMS measurement of prompt $D^0 v_2$ at 5.02 TeV

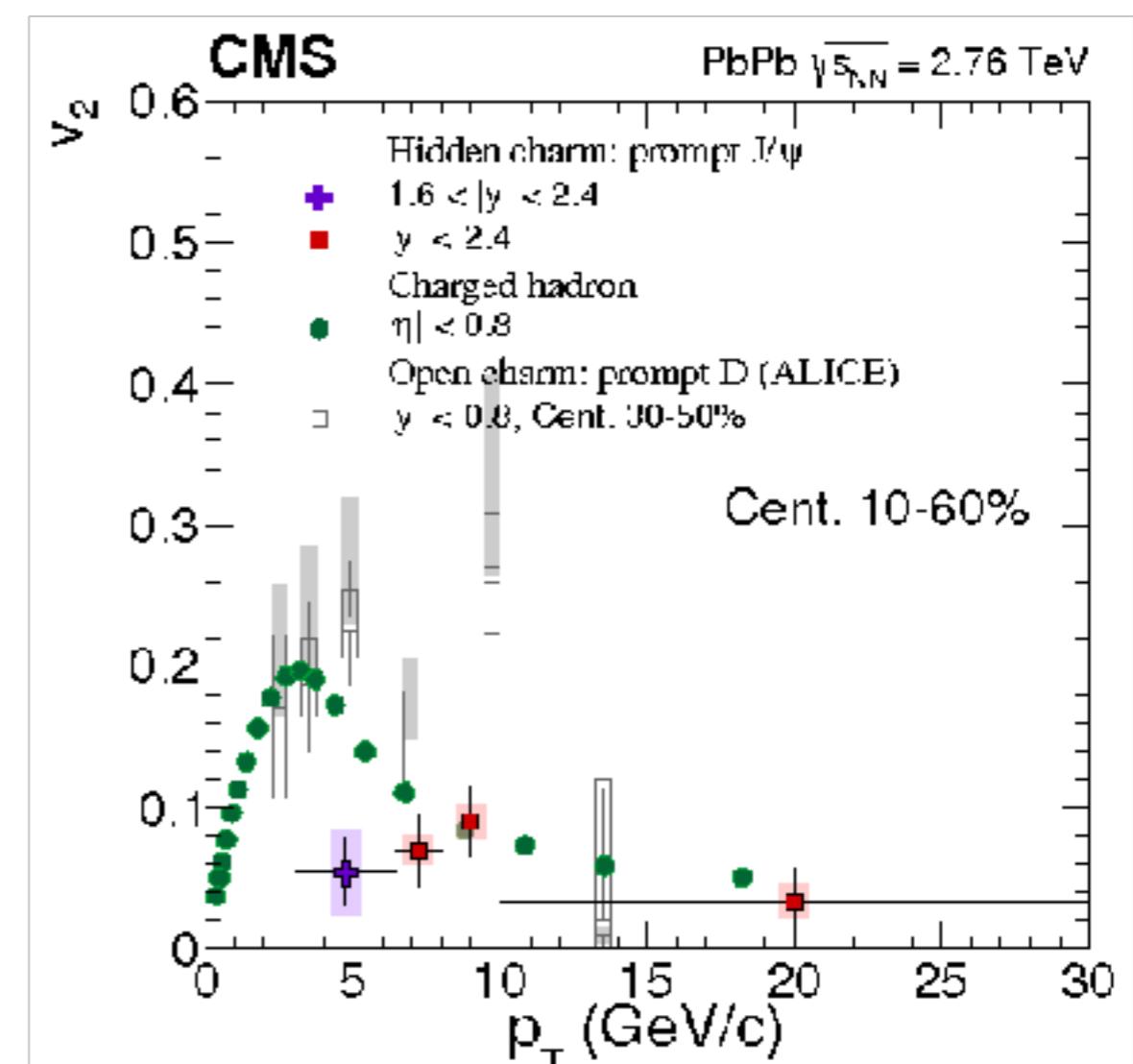
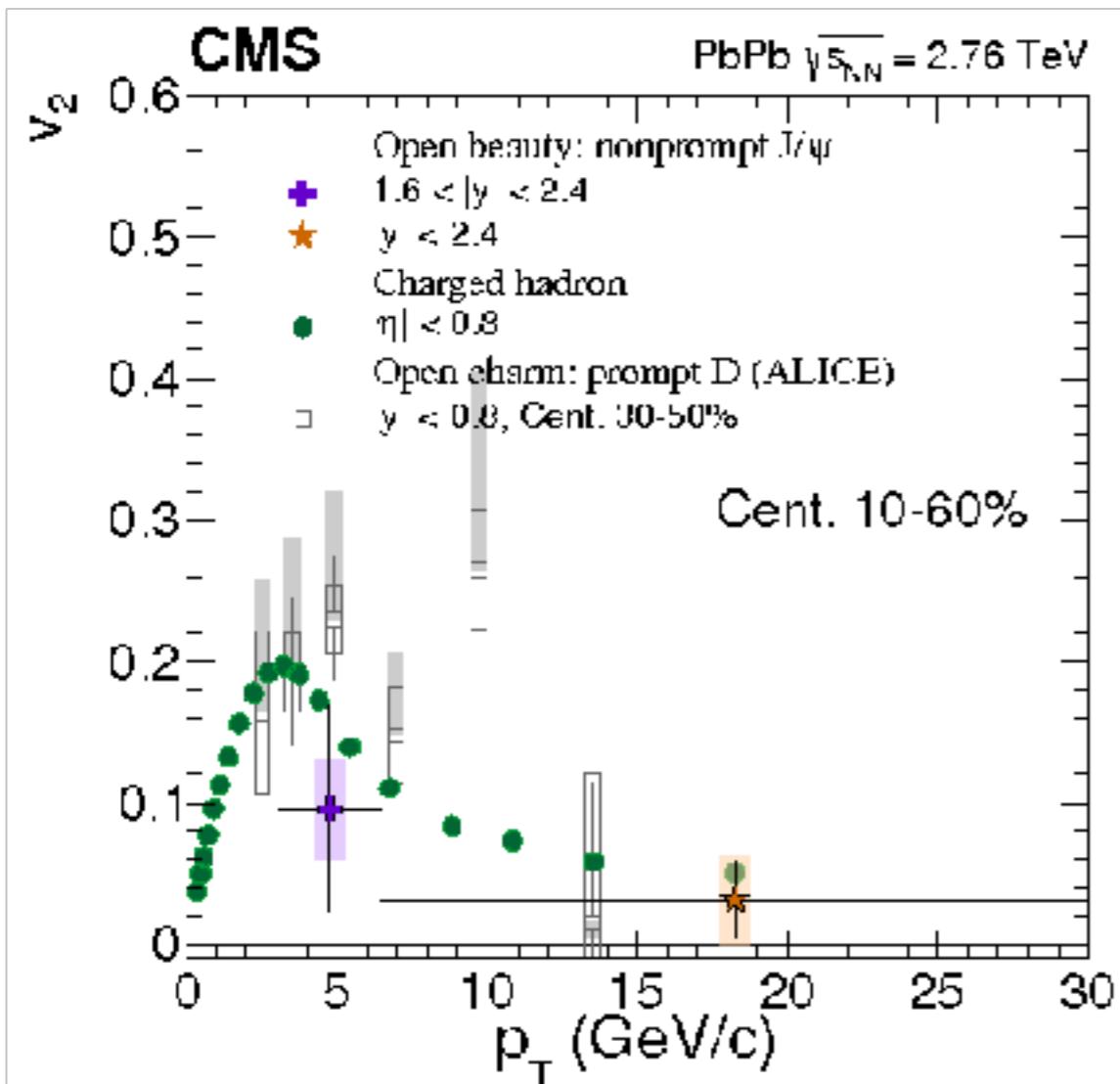


D⁰ meson v_2 with STAR at 200GeV/c

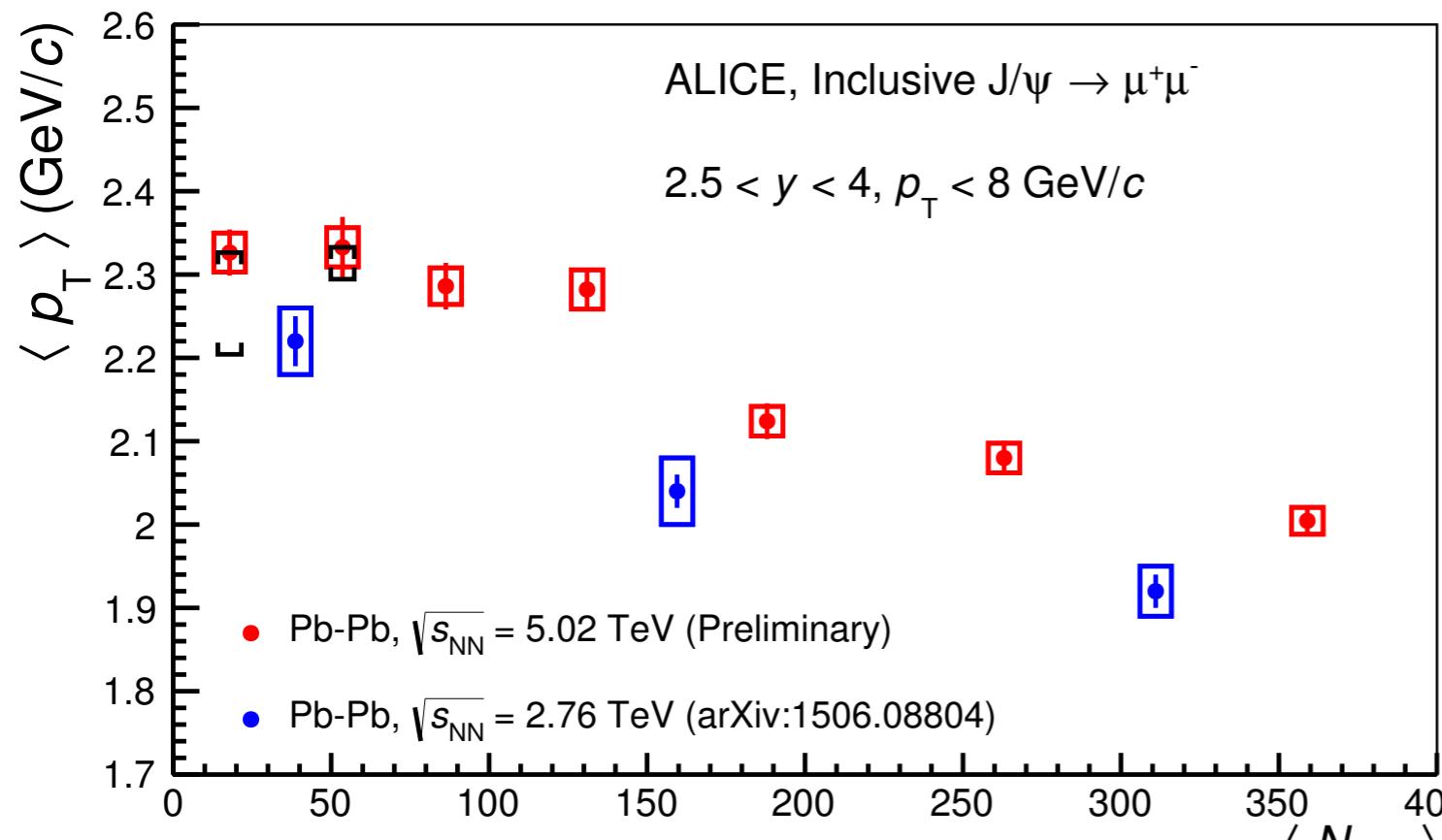


v_2 consistent with light mesons
suggestion of local thermal equilibrium for charm quarks

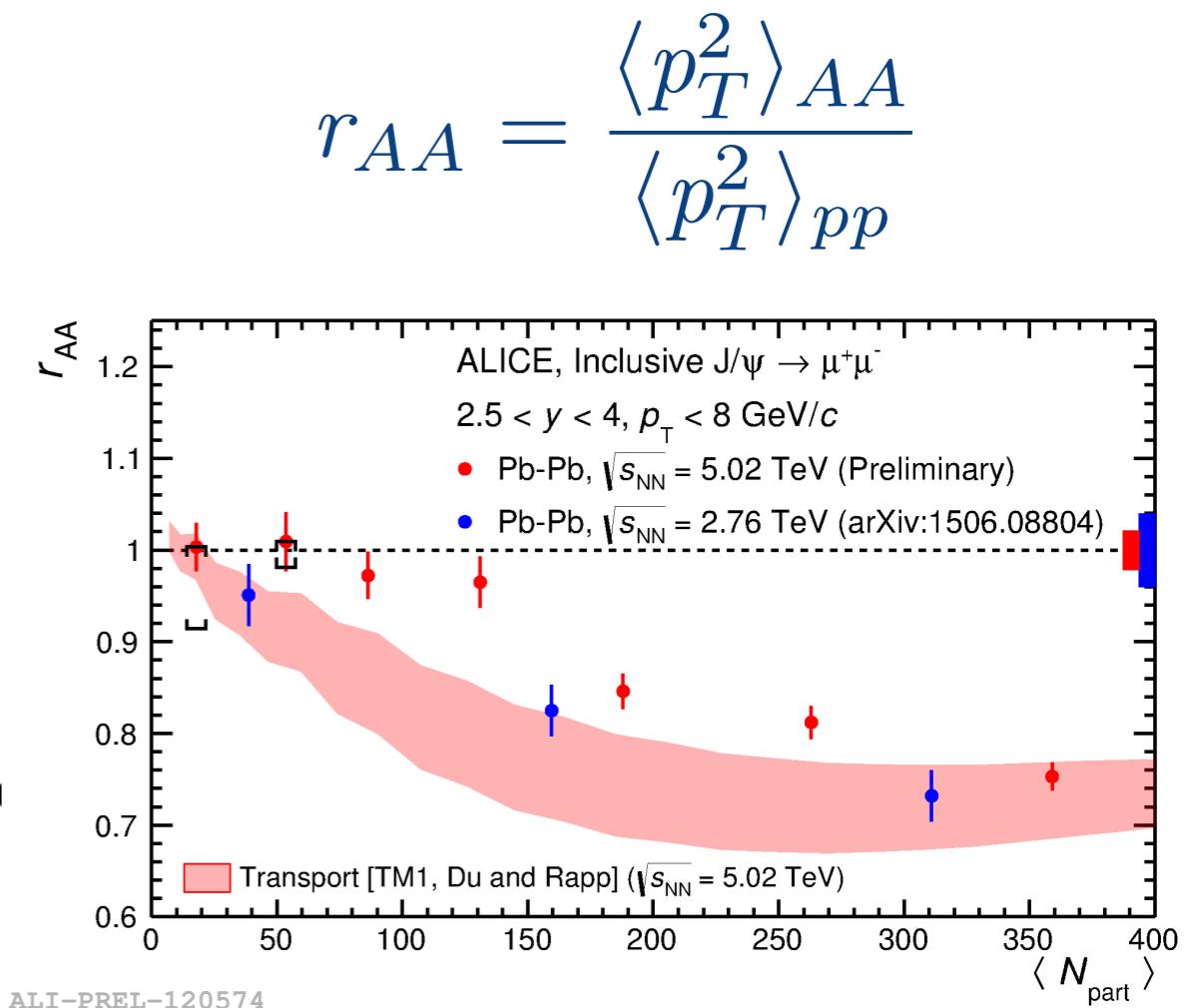
Non-prompt J/ ψ v_2 with CMS



J/ ψ $\langle p_T \rangle$ and r_{AA}



ALI-PREL-120593



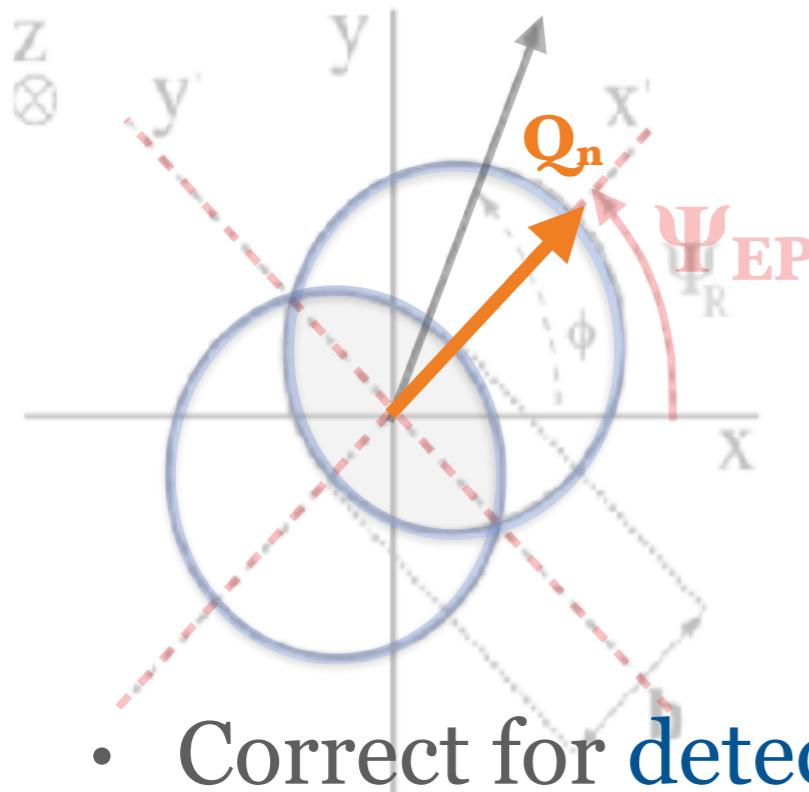
ALI-PREL-120574

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

Detector equalization and resolution

- Focus on methods **based on event plane determination**

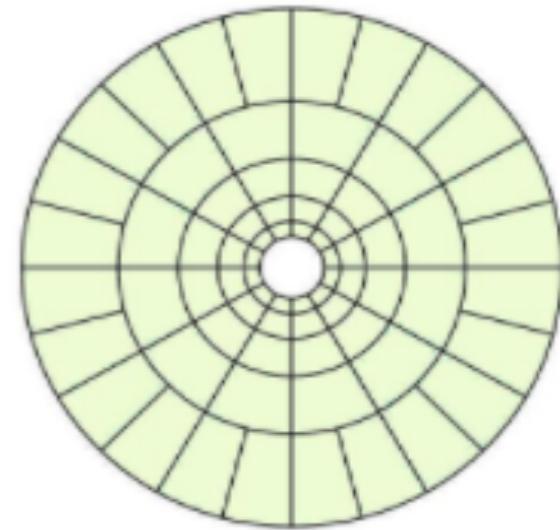
- From **detector multiplicities** :



$$Q_n = \sum_{i=0}^{\infty} e^{in\Phi_i} = Q_{n,x} + i Q_{n,y}$$

$$Q_{n,x} = \frac{\sum_{scint.} s_i \cos(n\Phi_i)}{\sum_{scint.} s_i} = |Q_n| \cos(n\Psi_n)$$

$$Q_{n,y} = \frac{\sum_{scint.} s_i \sin(n\Phi_i)}{\sum_{scint.} s_i} = |Q_n| \sin(n\Psi_n)$$



$$\Psi_n = \frac{1}{n} \arctan(Q_{n,x}, Q_{n,y})$$

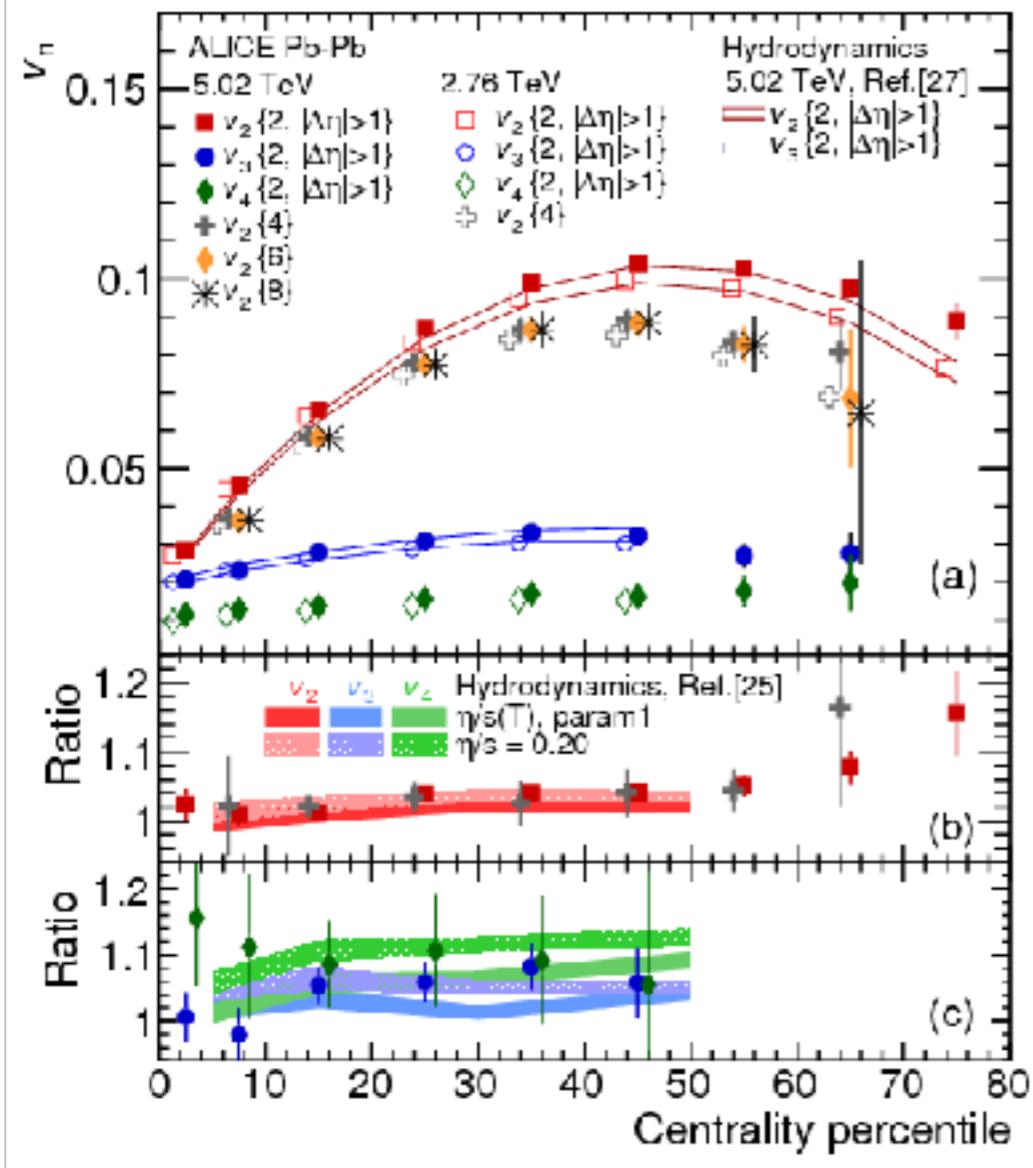
- Correct for **detector resolution** : using 3 sub-event method

$$\langle \cos \{n(\Psi_2^a - \Psi_R)\} \rangle = \sqrt{\frac{\langle \cos \{n(\Psi_2^a - \Psi_2^b)\} \rangle \langle \cos \{n(\Psi_2^a - \Psi_2^c)\} \rangle}{\langle \cos \{n(\Psi_2^b - \Psi_2^c)\} \rangle}}$$

A. M. Poskanzer and S. A. Voloshin, Phys Rev. C58, 1671

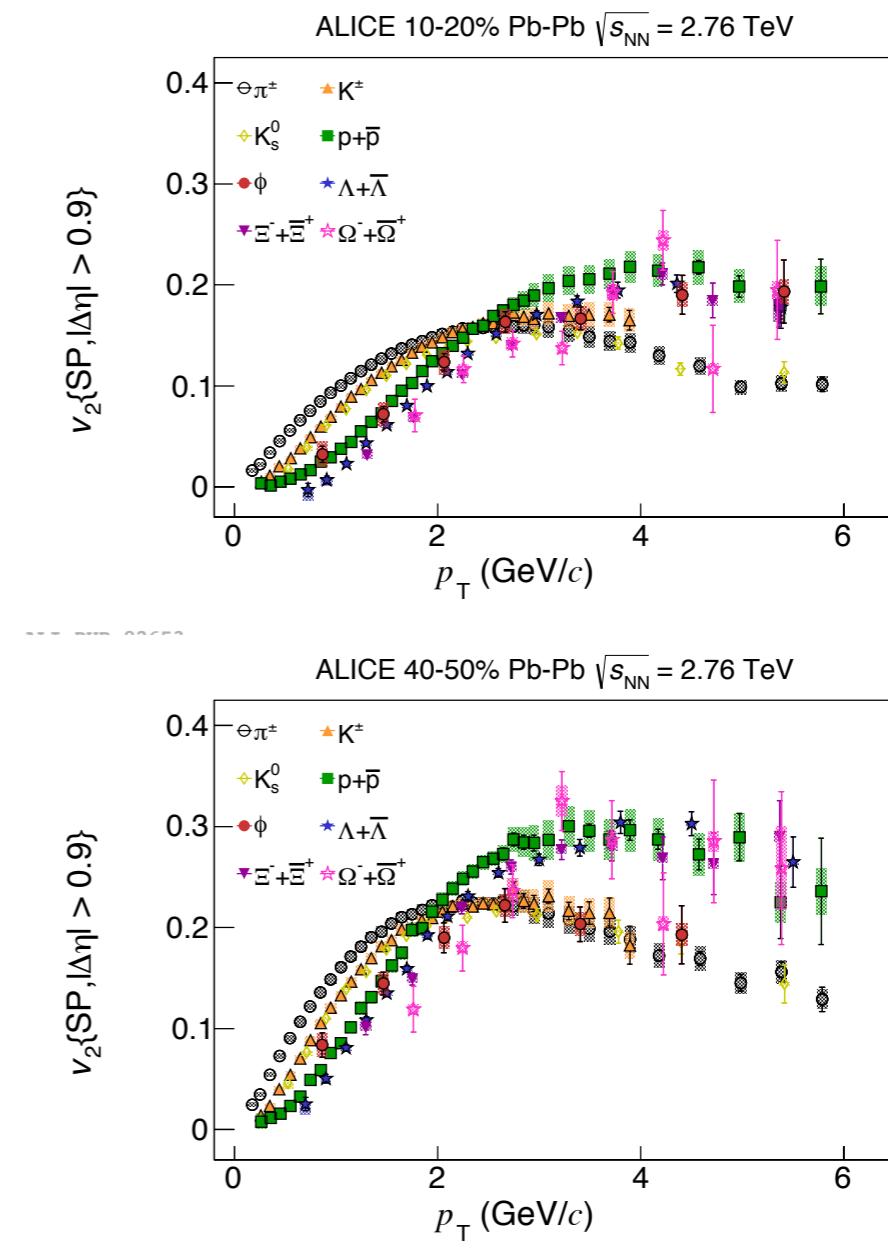
- Detector equalization to deal with **non-uniform acceptance**

Hydrodynamics : charged hadrons with ALICE

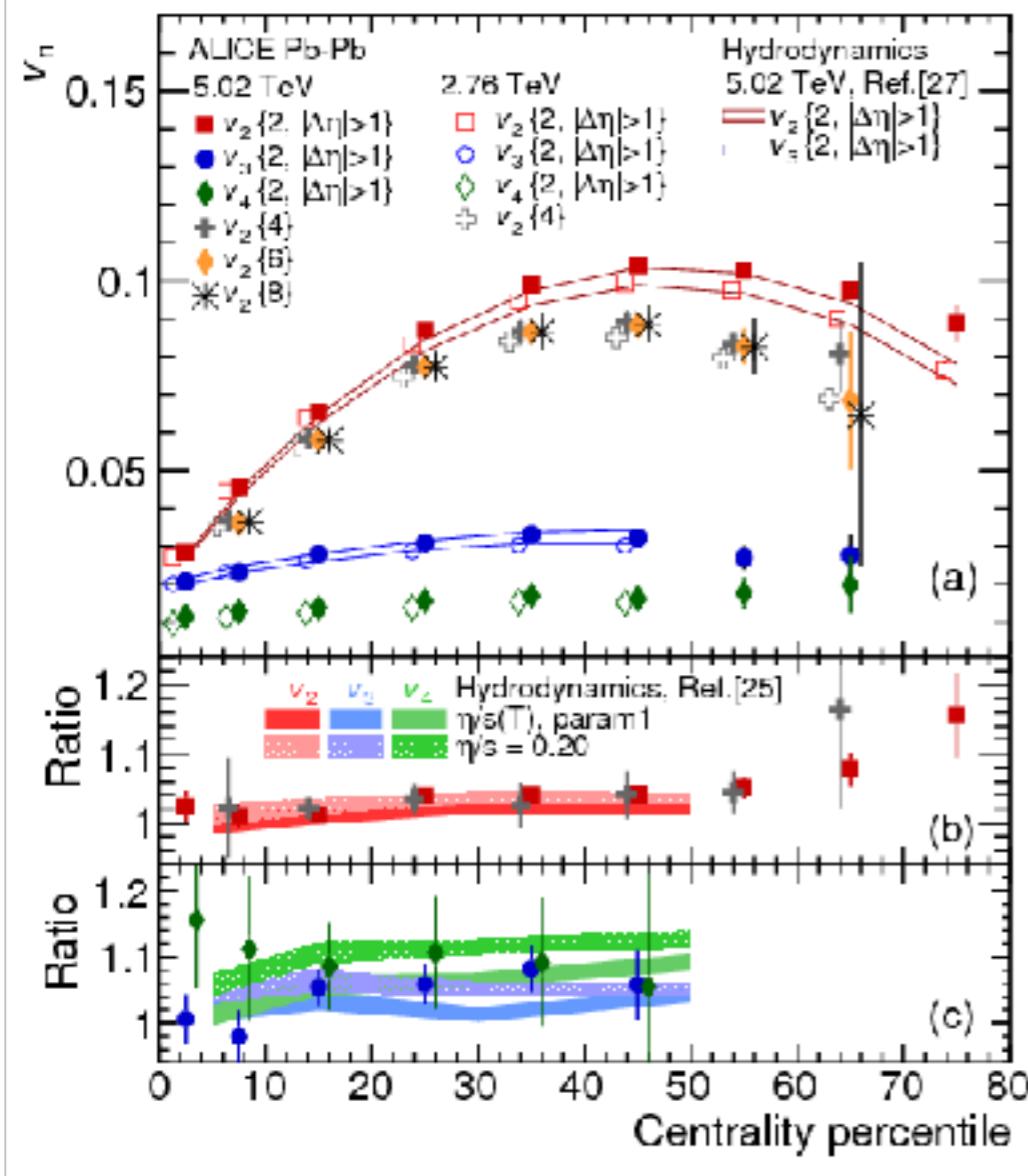


Comparison to hydro at low p_T :

- v_2 origin: early, partonic stages of the system
- v_2 governed by the QGP evolution



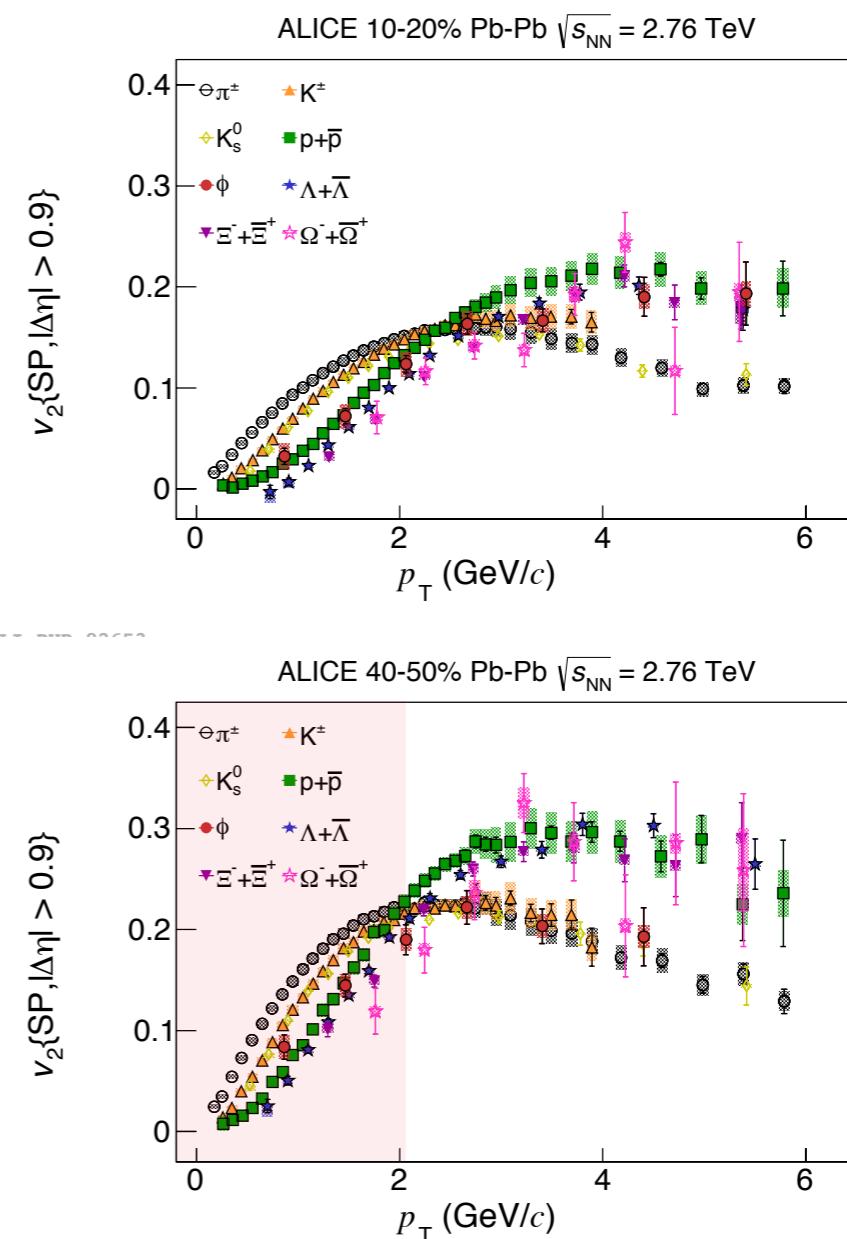
Hydrodynamics : charged hadrons with ALICE



Comparison to hydro **at low p_T** :

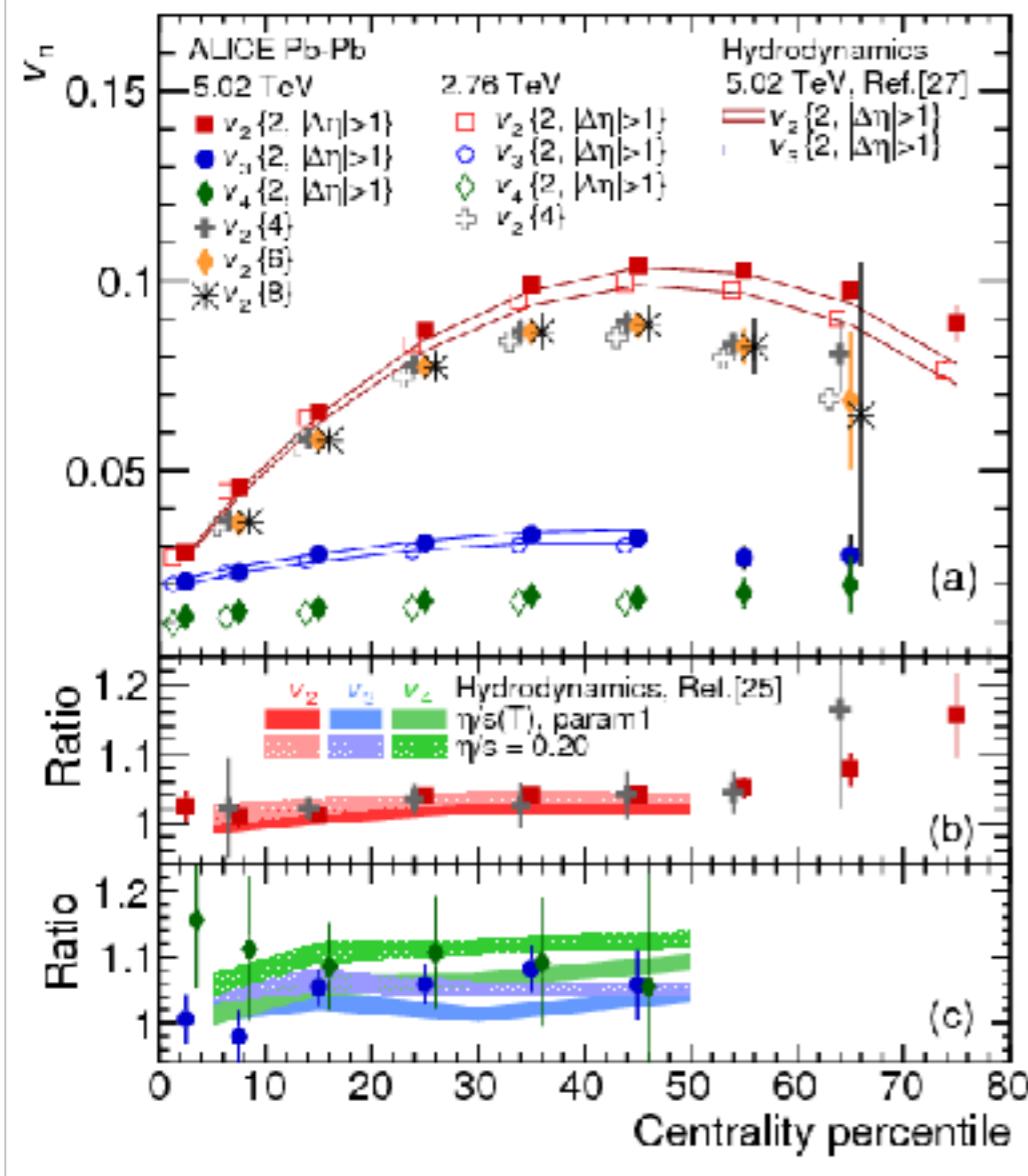
- v_2 origin: **early, partonic stages of the system**
- v_2 governed by the **QGP evolution**

At low p_T ($p_T < 2 \text{ GeV}/c$):
mass ordering



ALICE-PUB-82660

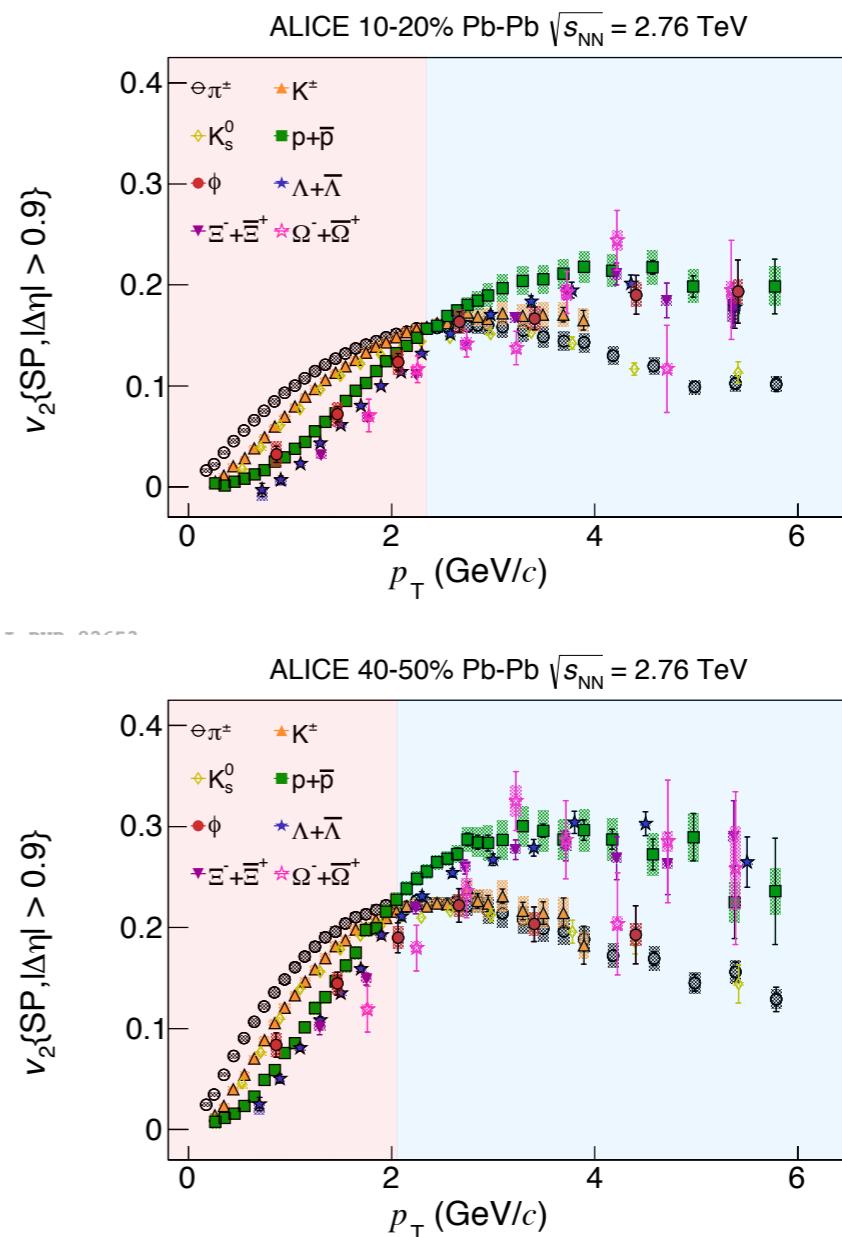
Hydrodynamics : charged hadrons with ALICE



Comparison to hydro **at low p_T** :

- v_2 origin: **early, partonic stages of the system**
- v_2 governed by the **QGP evolution**

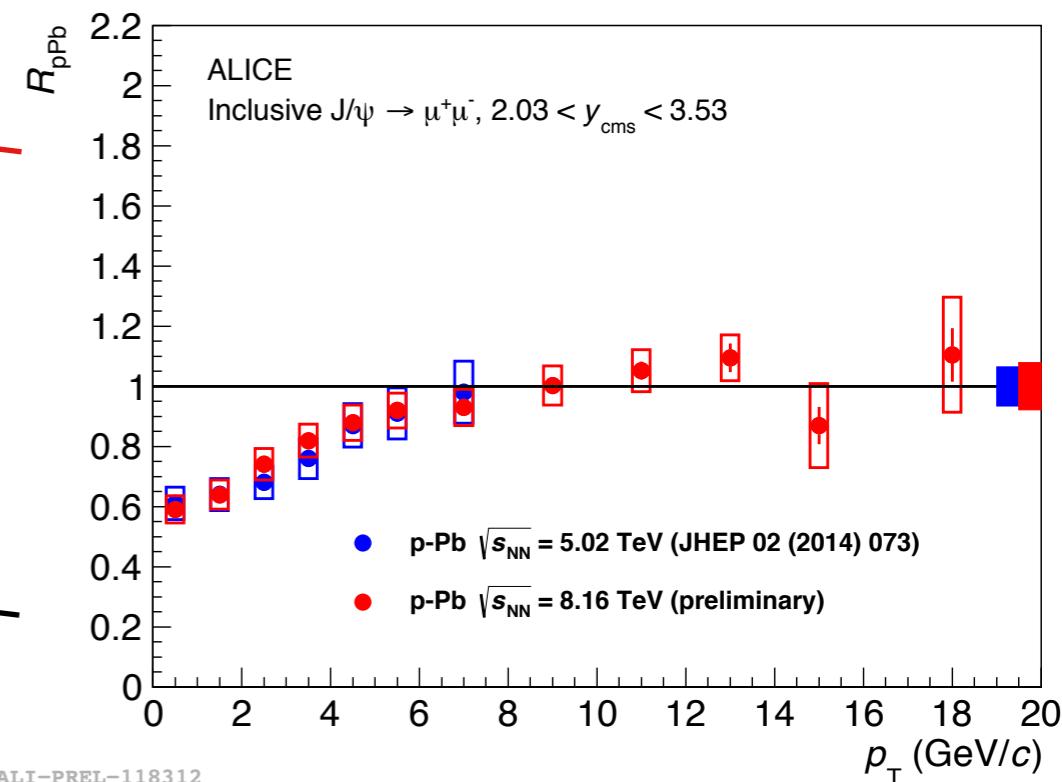
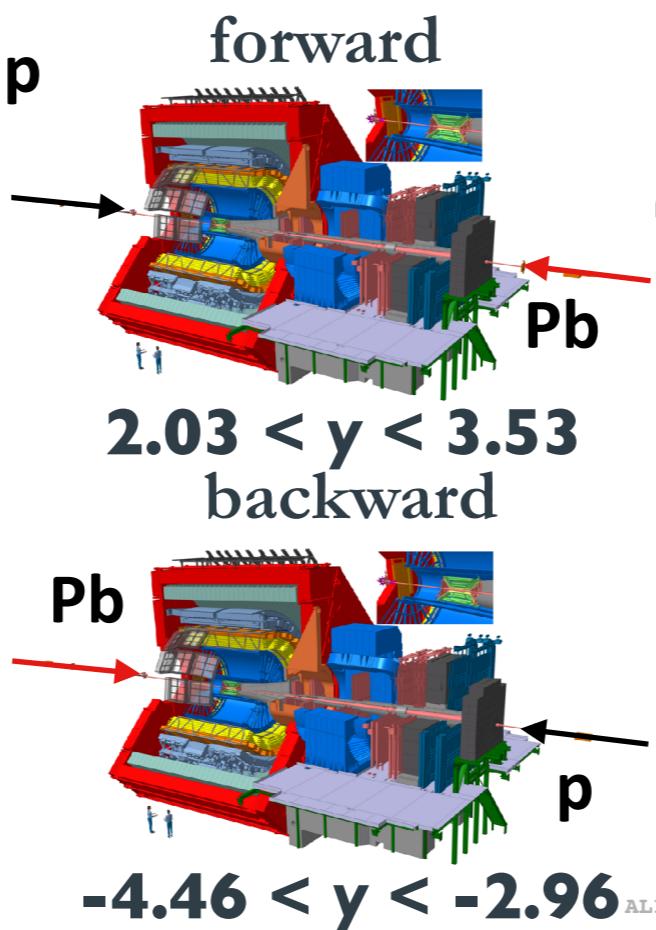
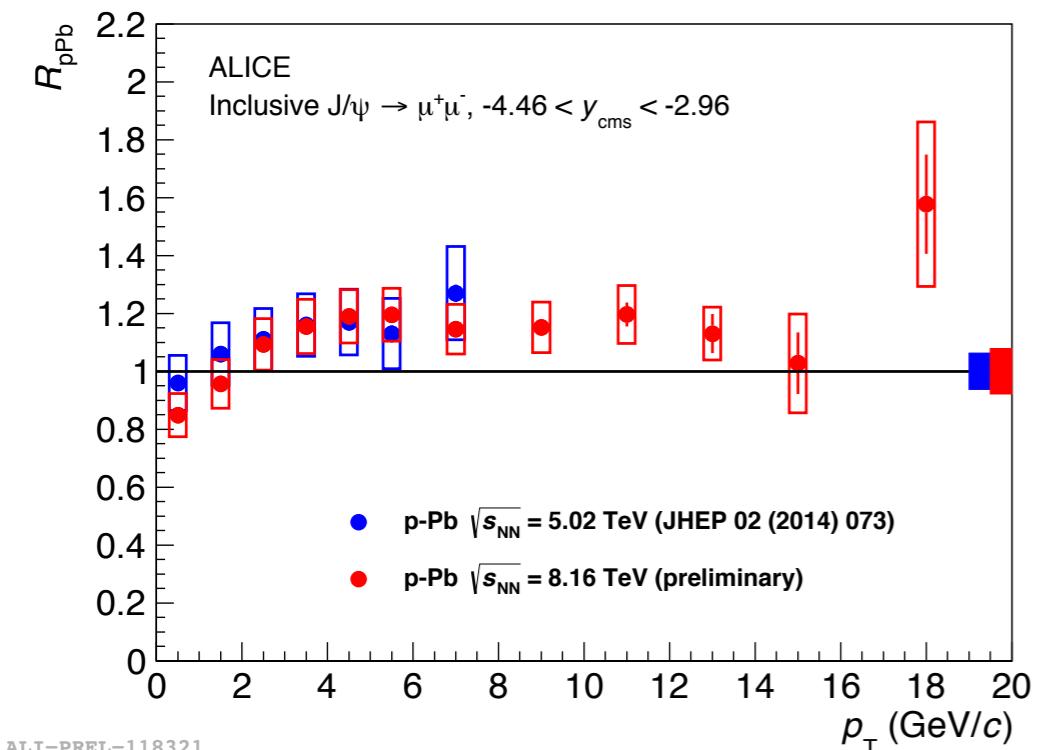
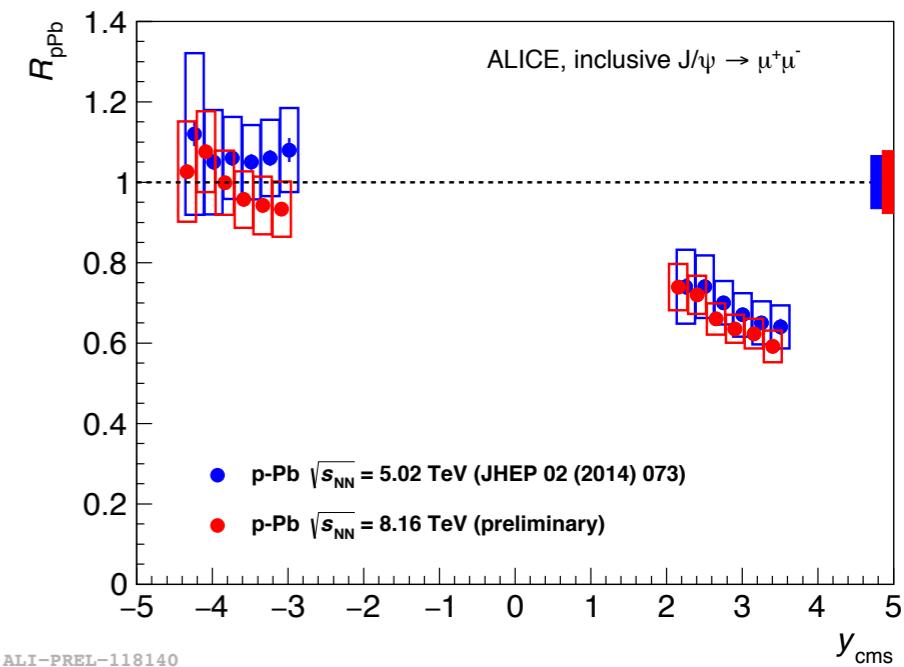
At low p_T ($p_T < 2 \text{ GeV}/c$):
mass ordering



For intermediate p_T :
 $v_2(\text{Baryons}) > v_2(\text{Mesons})$

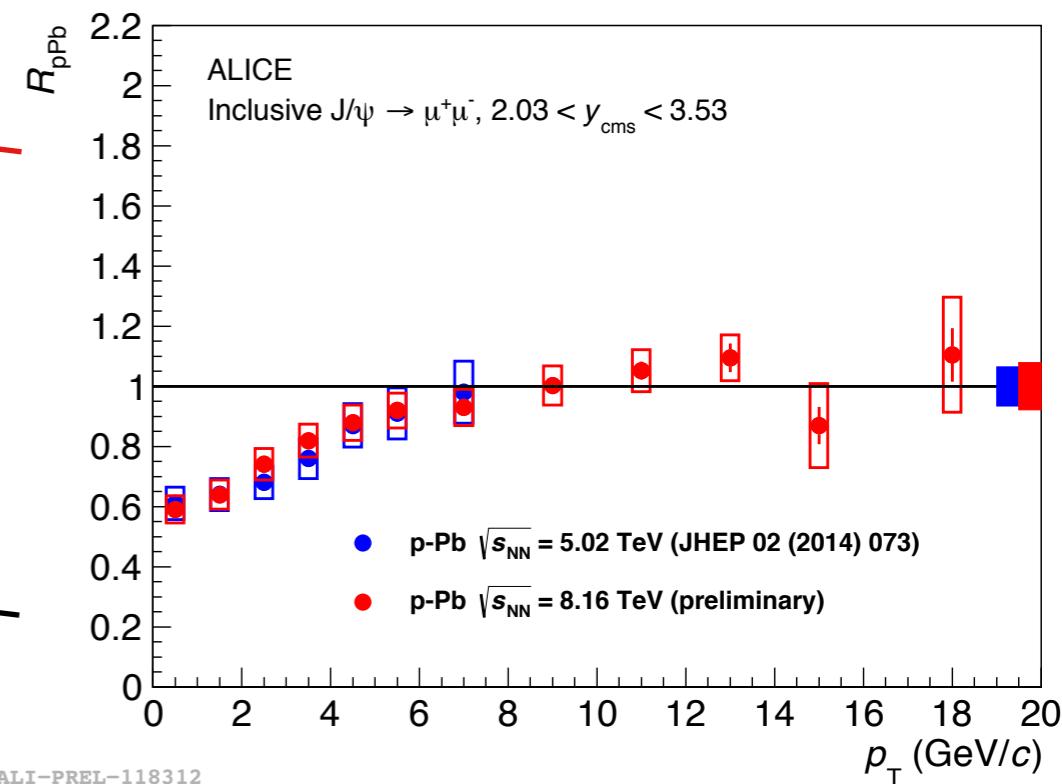
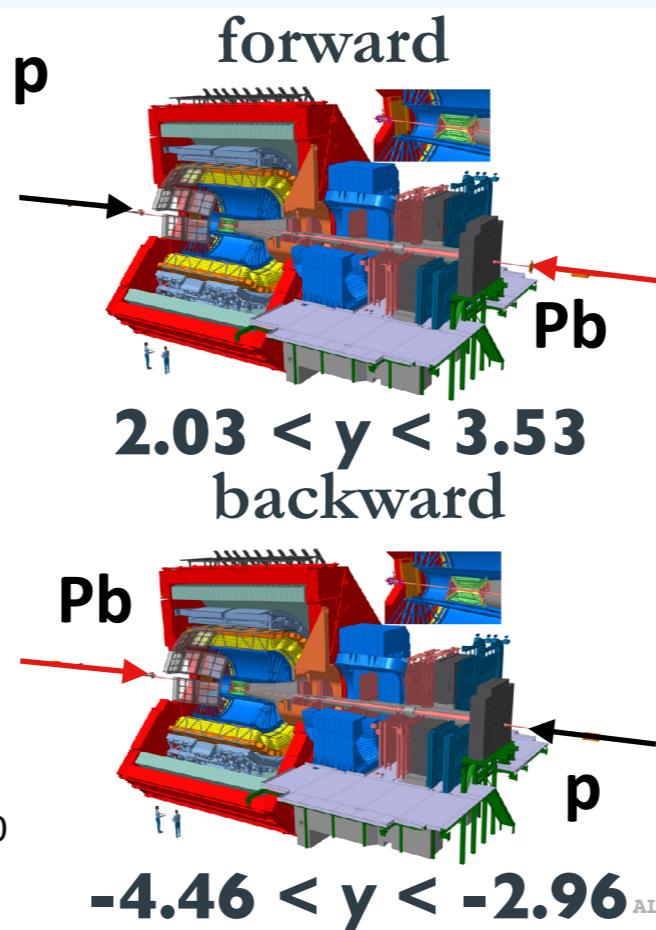
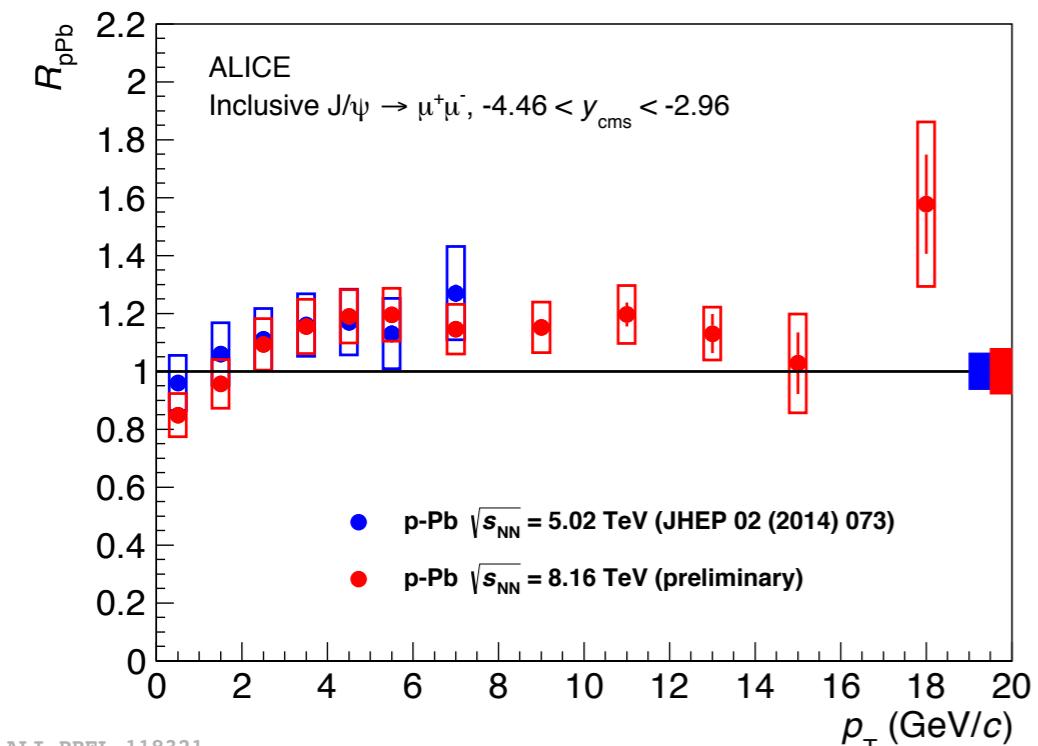
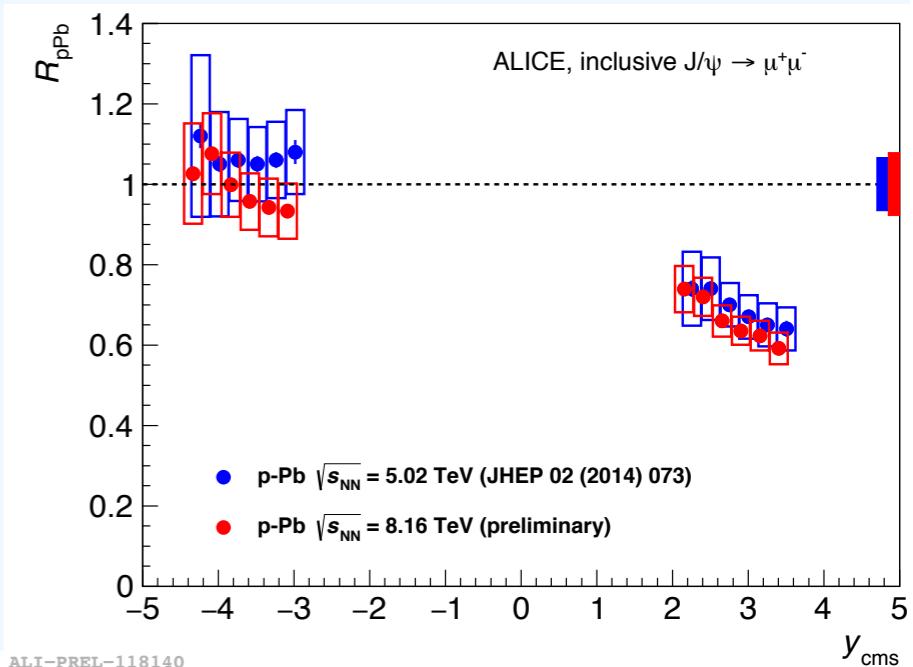
Cold nuclear matter effects

- Outside hot matter mechanisms, other effects might affect quarkonium production
 - Energy loss
 - Initial state: nuclear parton shadowing/CG condensate
 - Final state: nuclear absorption
- CNM investigated in p-A collisions

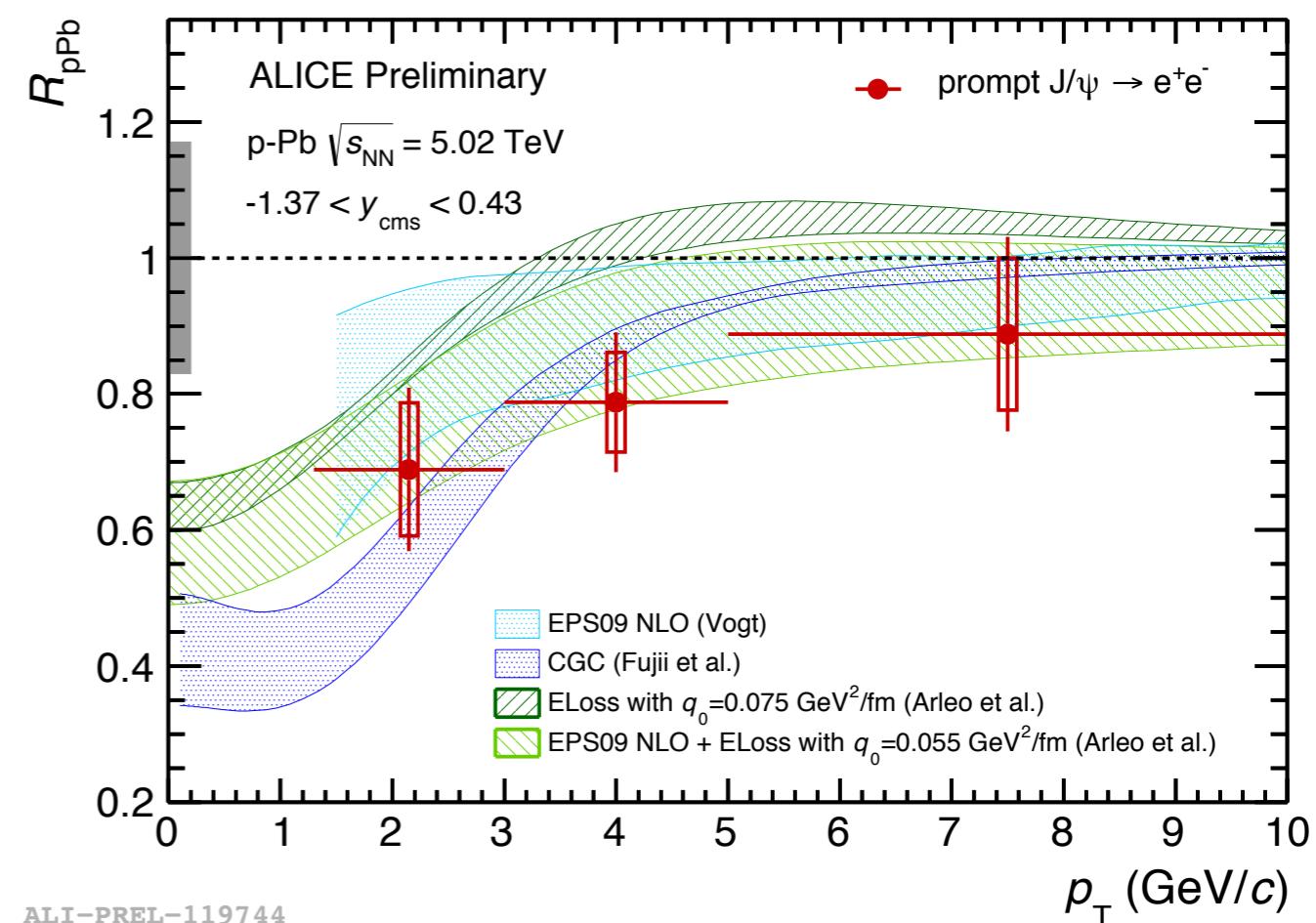
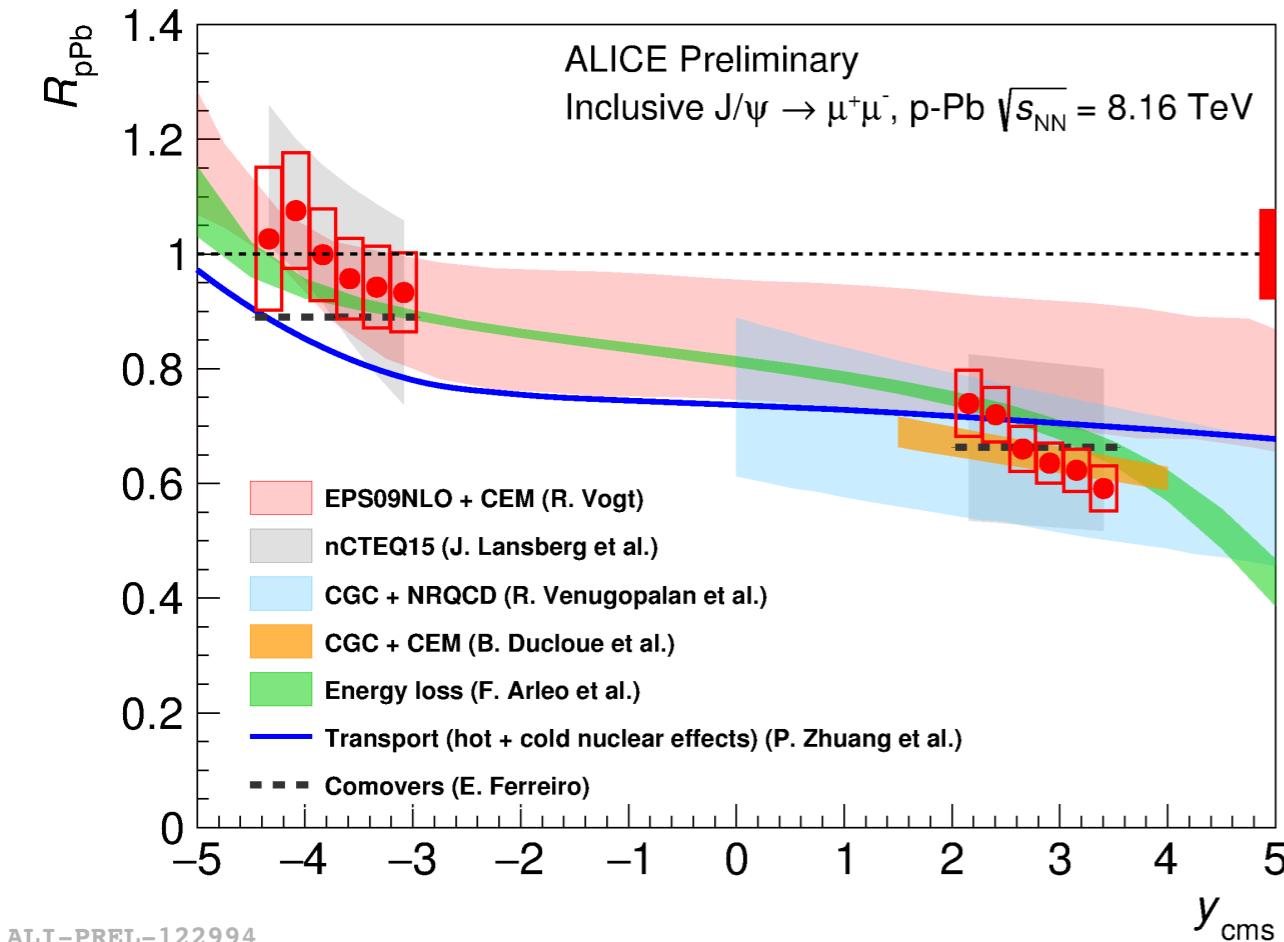


Cold nuclear matter effects

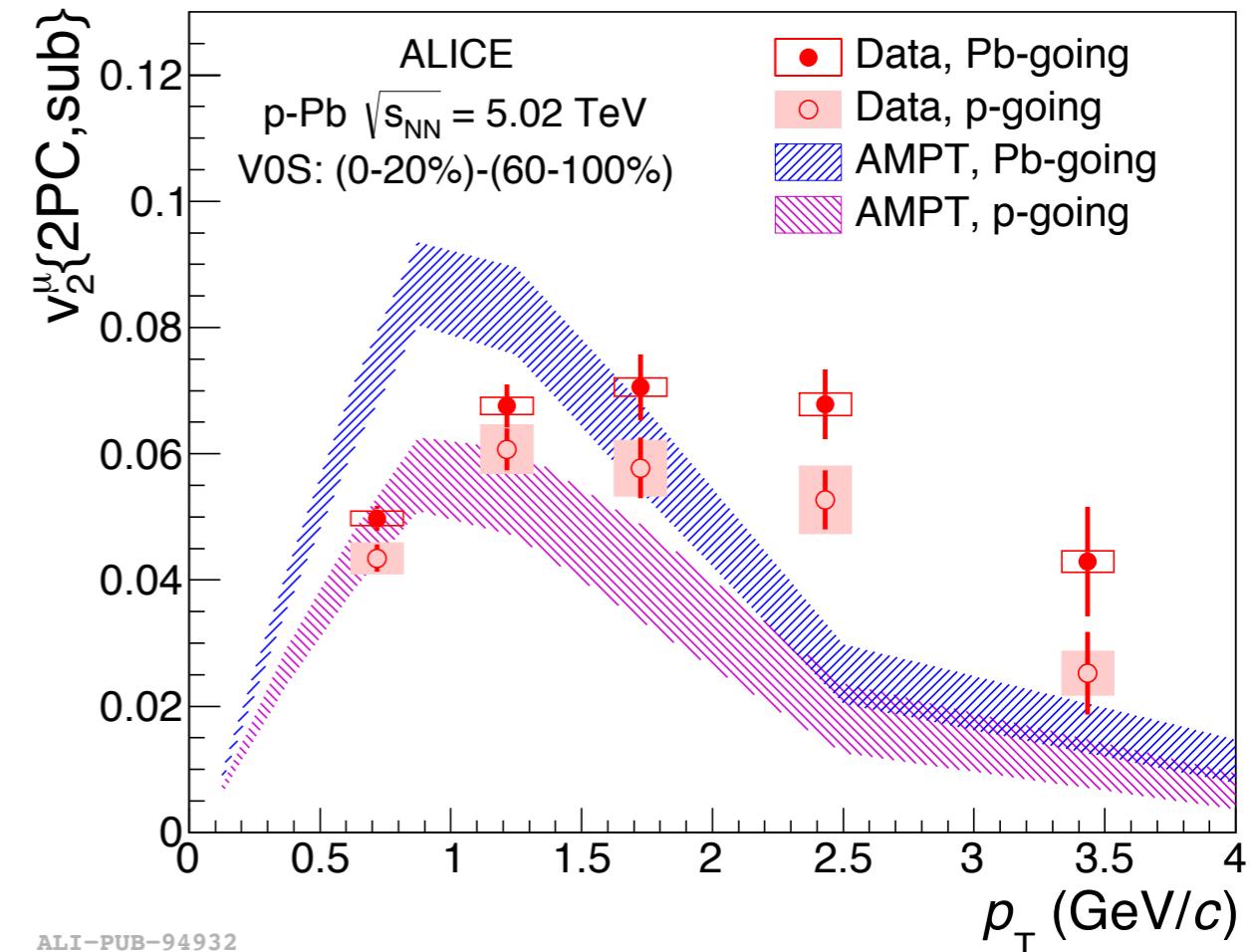
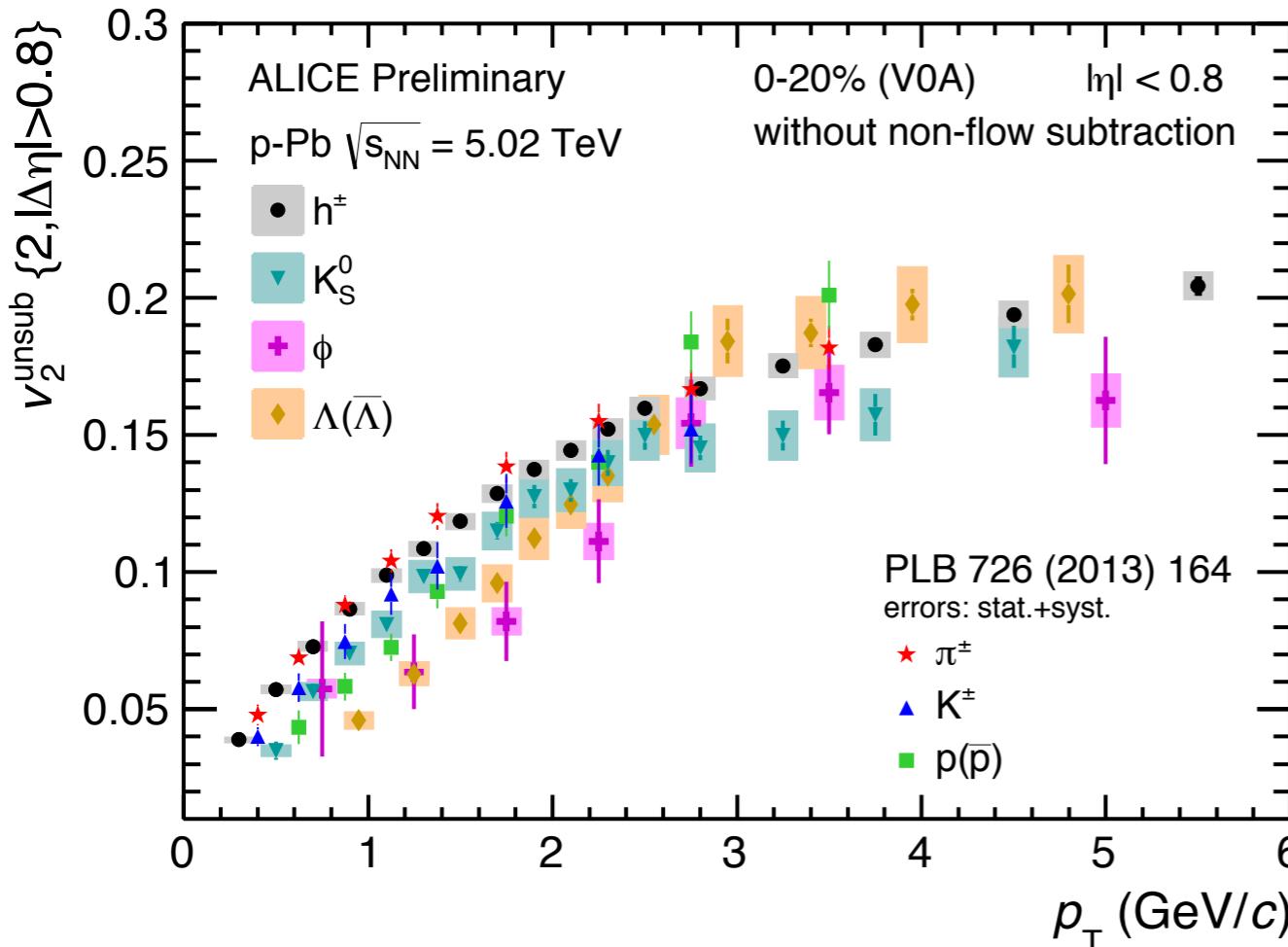
- Outside hot matter mechanisms, other effects might affect quarkonium production
 - Energy loss
 - Initial state: nuclear parton shadowing/CG condensate
 - Final state: nuclear absorption
- CNM investigated in p-A collisions



Charmonium production in p-Pb

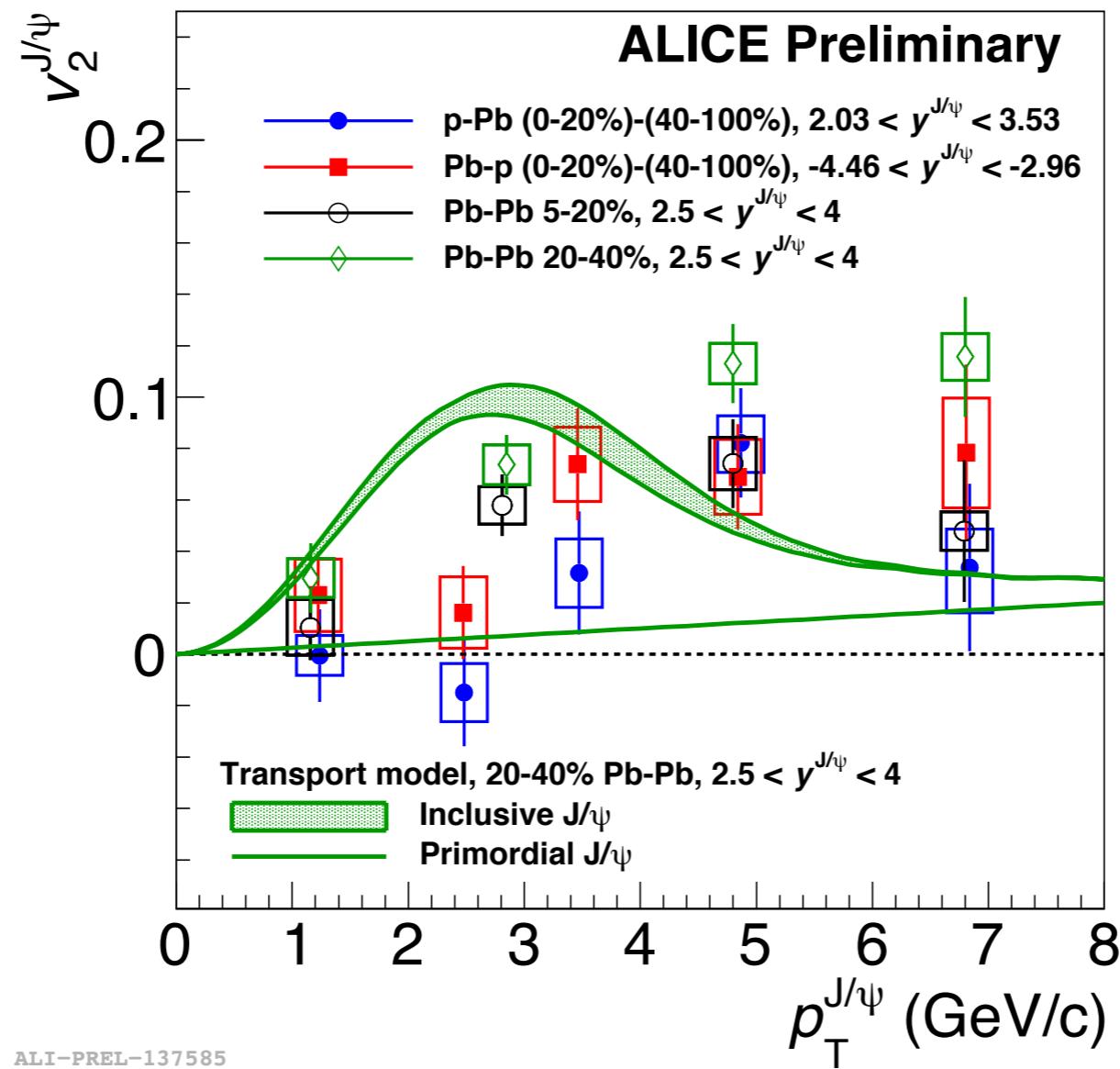


Collectivity in p-Pb collisions ?



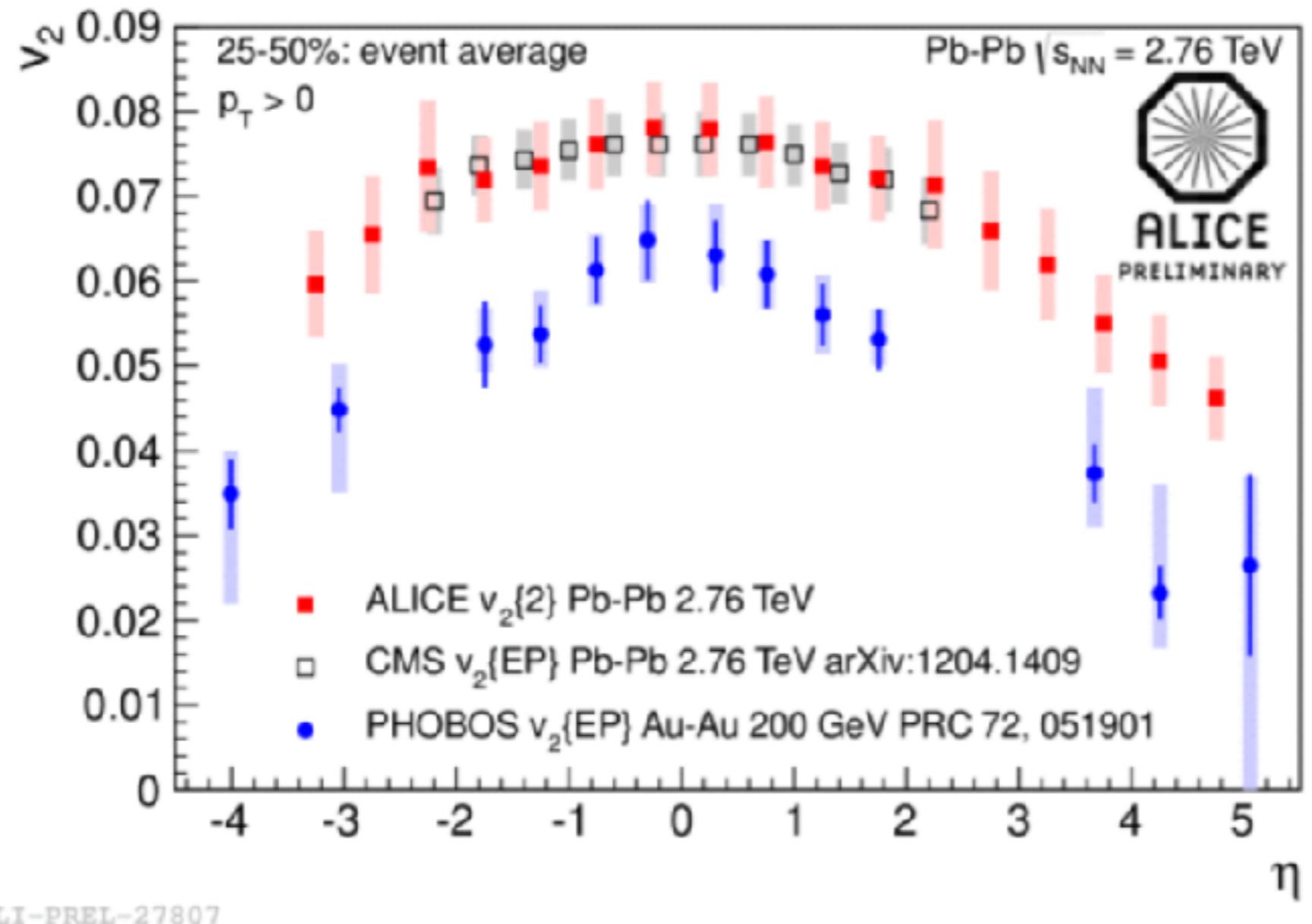
- Positive v_2 observation for charged particles
- Mass ordering for $p_T < 2.5 \text{ GeV}/c$
- At high p_T muons are dominated by HF decays

Collective effect for J/ ψ in p-Pb ?



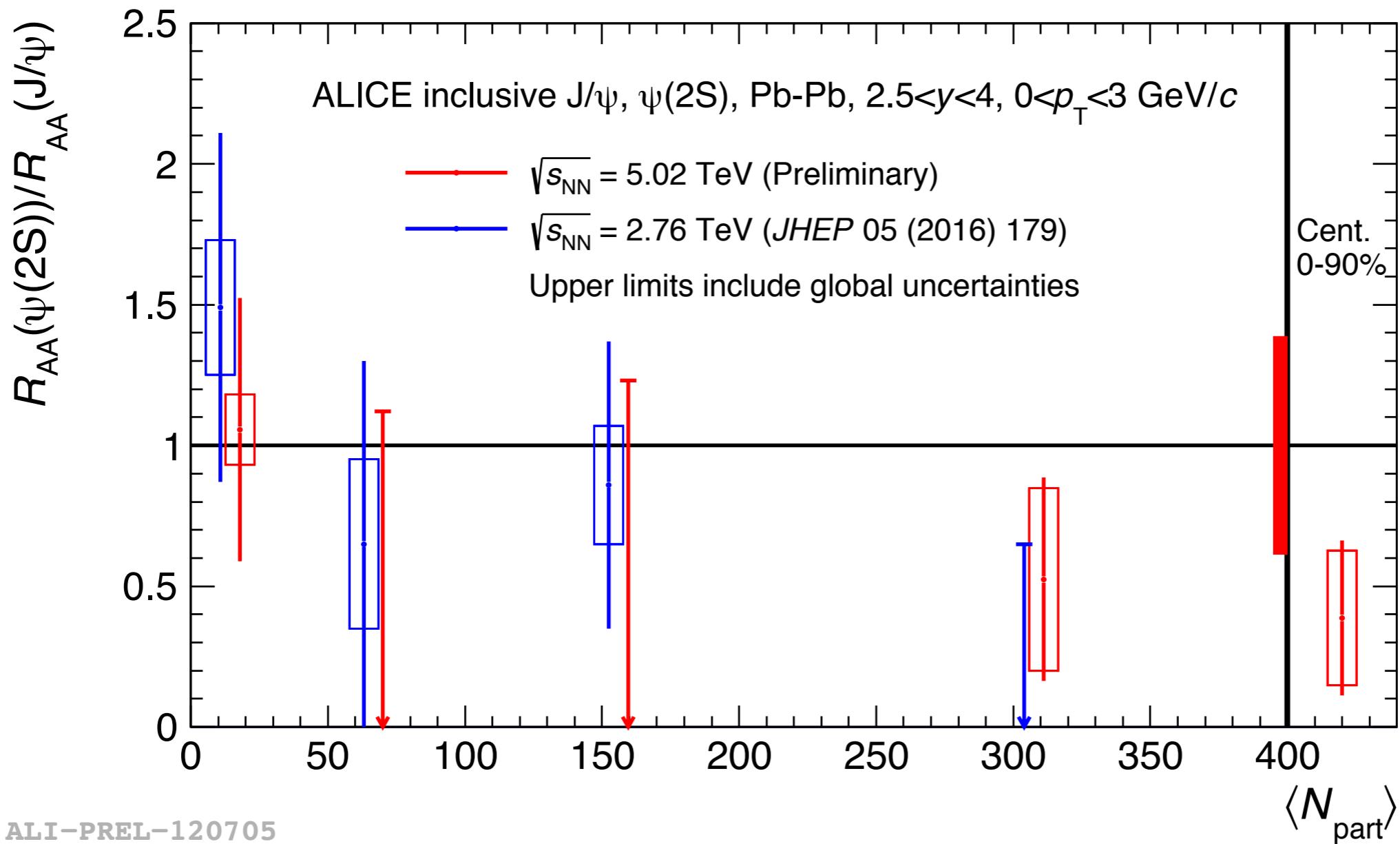
- Azimuthal correlations between J/ ψ (in the dimuon channel) and mid-rapidity charged particles
- Sizeable v_2 measured in p-Pb collisions at 5.02 and 8.16 TeV (compatible with Pb-Pb in 5-20%)
- No significant (re)generation contribution is expected and lesser path-length effect w.r.t Pb-Pb

Pseudo-rapidity dependency



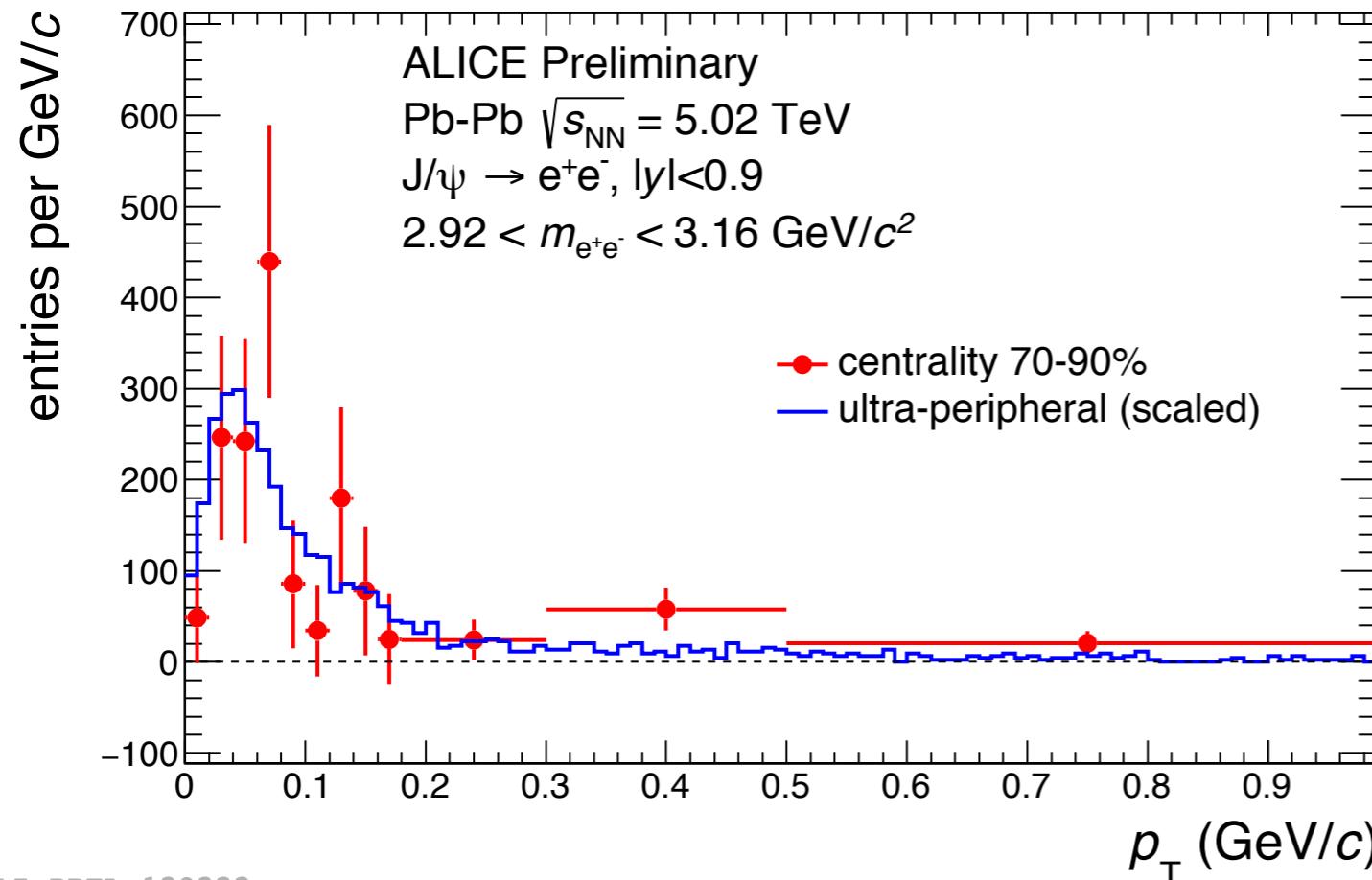
- depends on particle multiplicity

$R_{AA}(\psi(2S))/R_{AA}(J/\psi)$ ratio comparison

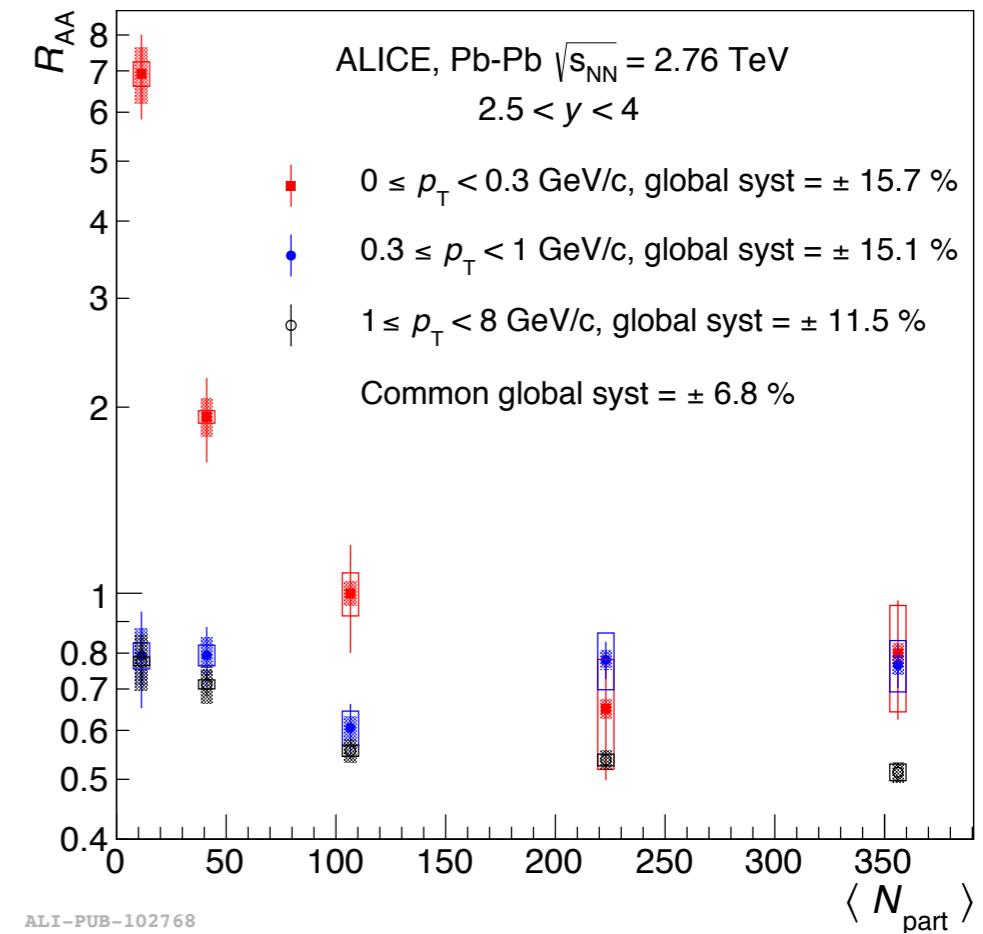


ALI-PREL-120705

Low- p_T J/ ψ excess



ALI-PREL-120222



ALI-PUB-102768

- Observation of **yield excess at very low p_T** ($0 < p_T < 0.3$ GeV/ c) in peripheral collisions
- Behaviour not reproduced by transport models
- p_T distribution matches expectation from **coherent photoproduction** of J/ ψ measured in ultra-peripheral collisions