Quarkonium production at forward rapidity in Pb-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV with the ALICE detector

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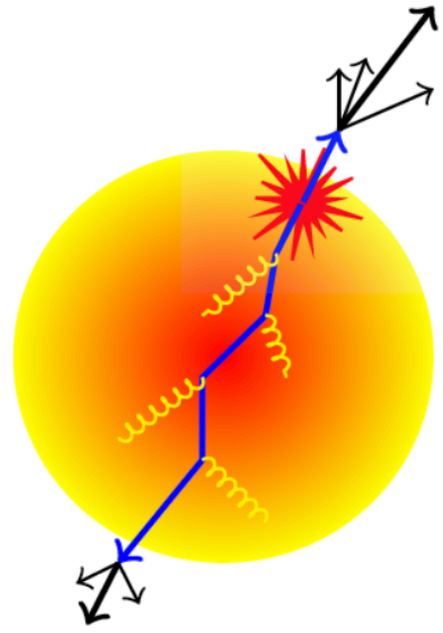
for the **ALICE Collaboration**

Subatech, France

Utrecht 2017

Motivations for quarkonium studies

- **Heavy quarks in Pb-Pb collisions at the LHC**
  - early production (c ~ 0.08 fm/c, b ~ 0.02 fm/c vs. QGP ~ 0.3 fm/c)
    → experience the full system evolution
    Nucl.Phys. A757 (2005) 184-283
  - interact with the QGP : sensitive to the medium properties
  - same number produced in Pb-Pb and in pp (no thermal production)
    Phys.Lett. B758 (2016) 434-439

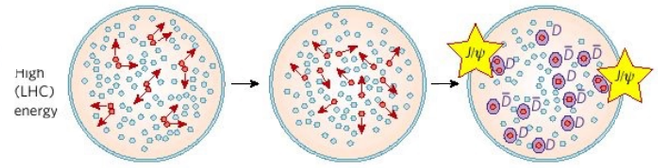


- **Quarkonium in Pb-Pb collisions : hard probes of the QGP**

Quarkonium suppression :

- Initially : J/ψ suppression predicted by Matsui and Satz in 1986 by Debye screening mechanism
  Phys.Lett. B178 (1986) 416-422
- Different quarkonium binding energy : sequential suppression with increasing medium temperature
  Phys. Rev. D 64 (2001) 094015

(Re)combination :



- Increased charm quark density →enhanced quarkonia production
- Less relevant for bottomonium than charmonium

Phys. Rev. C 63 (2001) 054905
Phys. Lett. B 490 (2000) 196–202
J. Phys. Conf. Ser. 509 (2014) 012019

Quarkonium studies

Nuclear modification factor R_{AA}

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

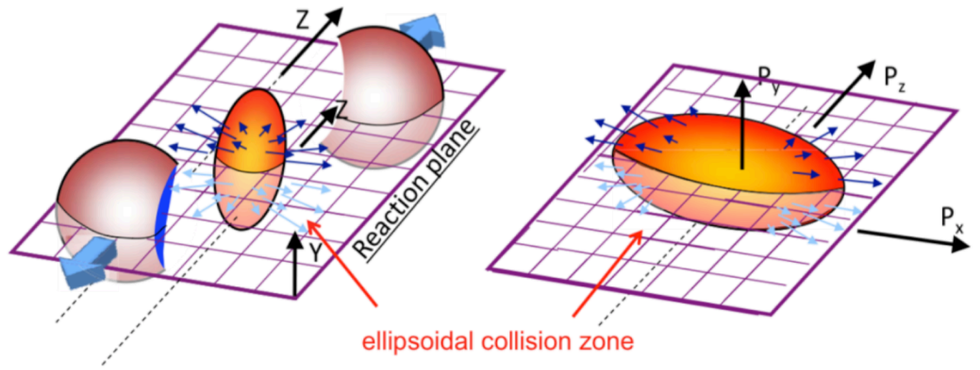
Quarkonium yield in AA compared to the pp one, scaled by the overlap factor T_{AA} (from Glauber model)

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

Latest results in pp and p-Pb in Astrid Morreale's talk

Elliptic flow v_2

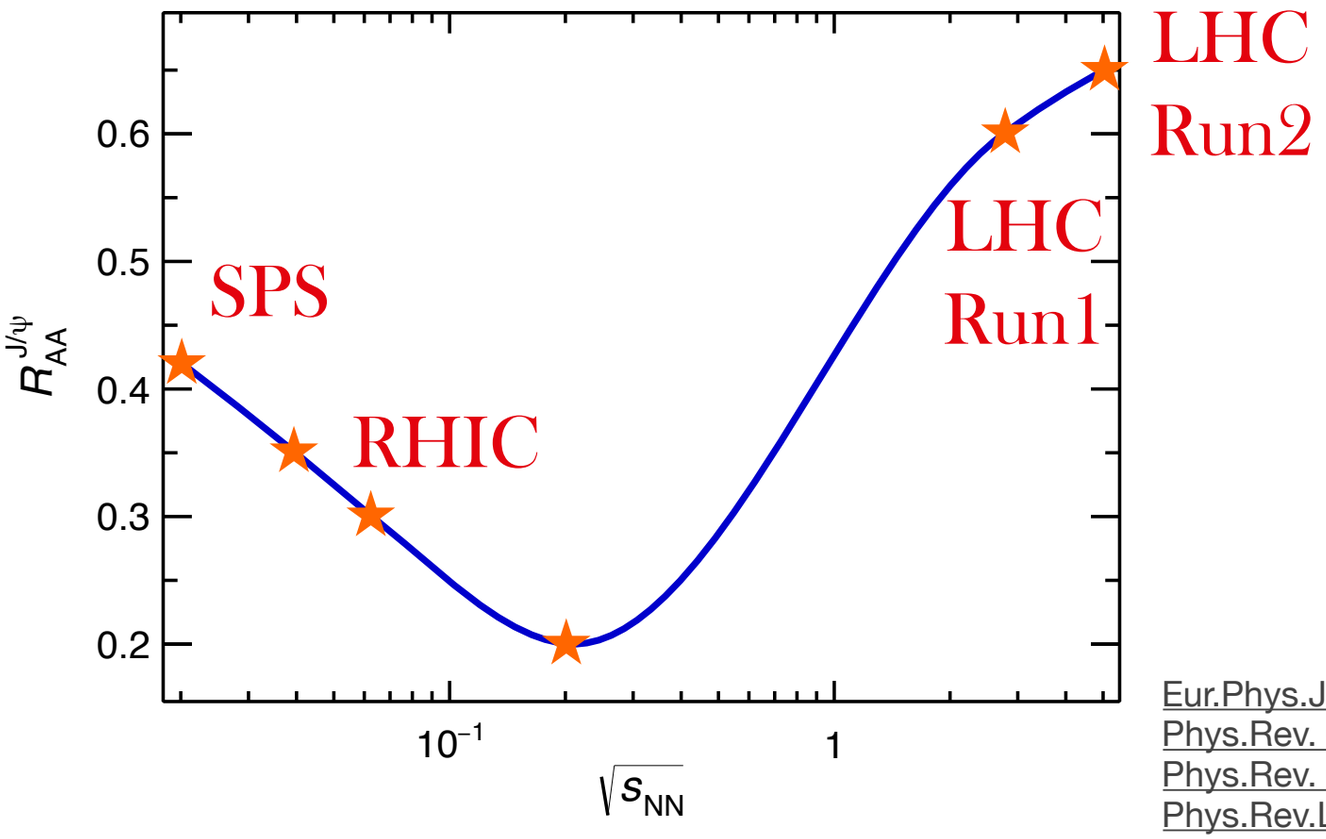
- heavy quarks participate to the collective expansion dynamics

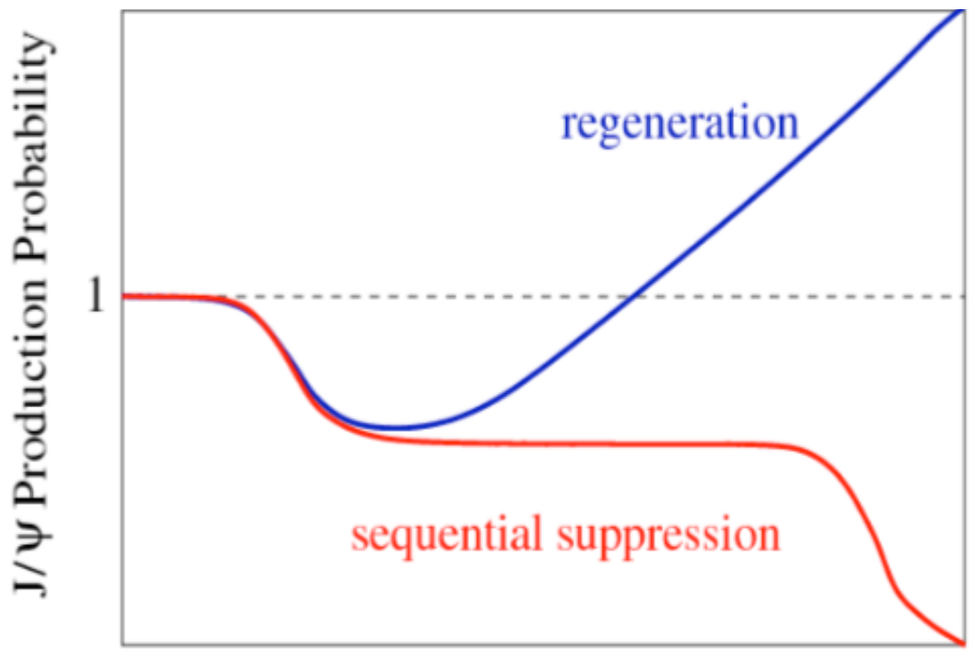


$$v_2 = \langle cos[2(\varphi - \Psi_{2,R})] \rangle$$

- If thermalization, recombined states should inherit their flow
- relevant observable for quarkonium (re)generation study

Previous results in AA systems

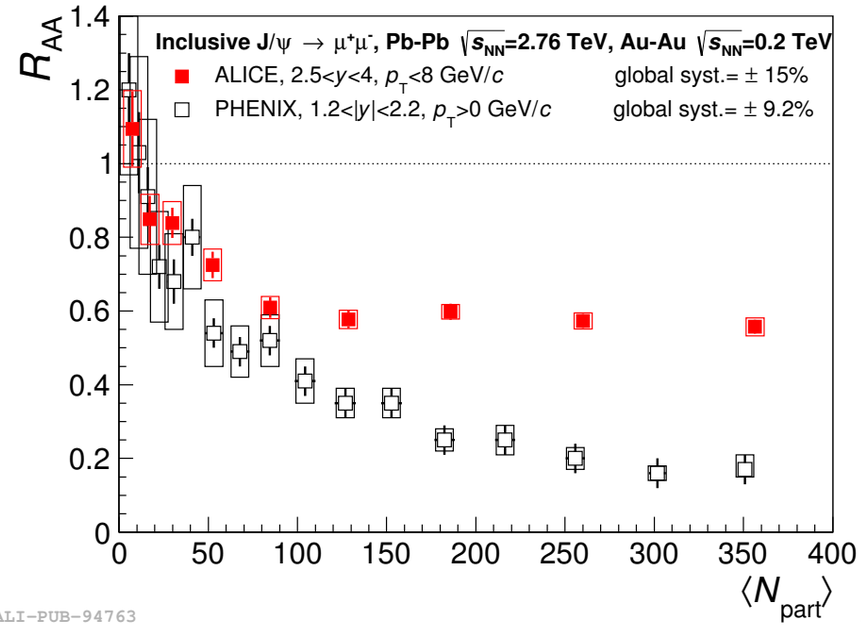




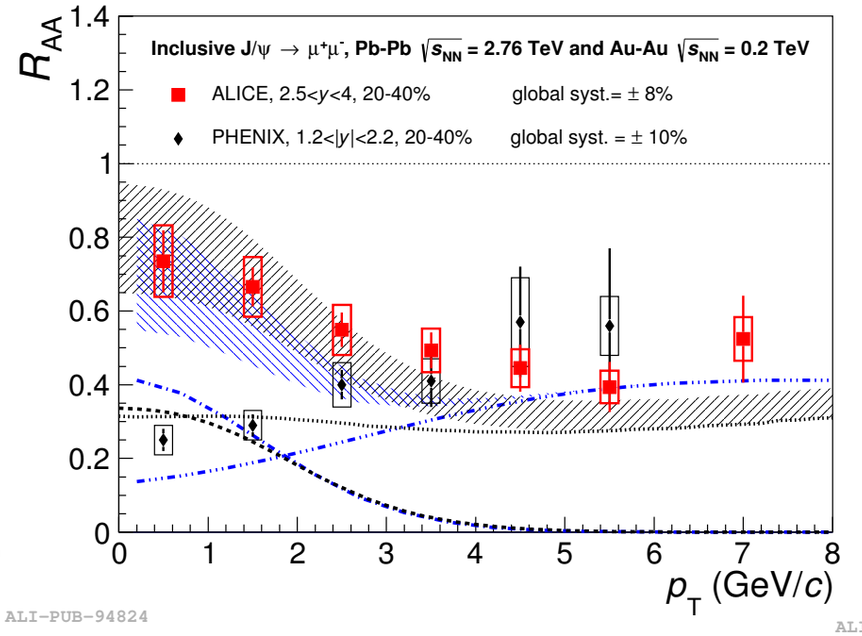
Eur.Phys.J. C39 (2005) 335-345
Phys.Rev. C84 (2011) 054912
Phys.Rev. C86 (2012) 064901
Phys.Rev.Lett. 109 (2012) 072301
Phys. Lett. B 766 (2017) 212-224

- (Re)combination of quarks allows theoretical models to describe experimental results
- Many unknowns : large uncertainties
  - Feed-down from higher quarkonium resonances and b decays
  - Precise determination of open charm cross-section
  - CNM effects on quarkonium production

Selection of previous results in AA systems



ALI-PUB-94763



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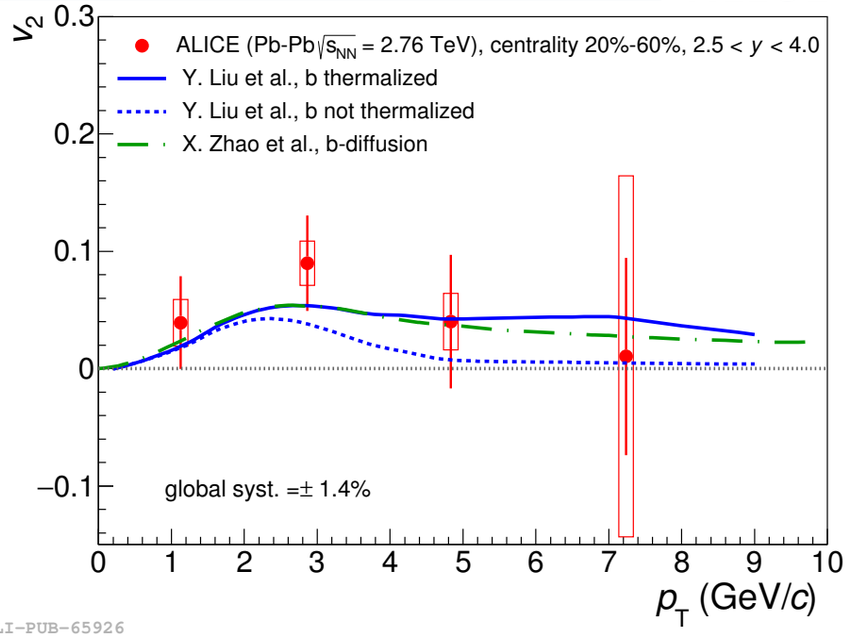

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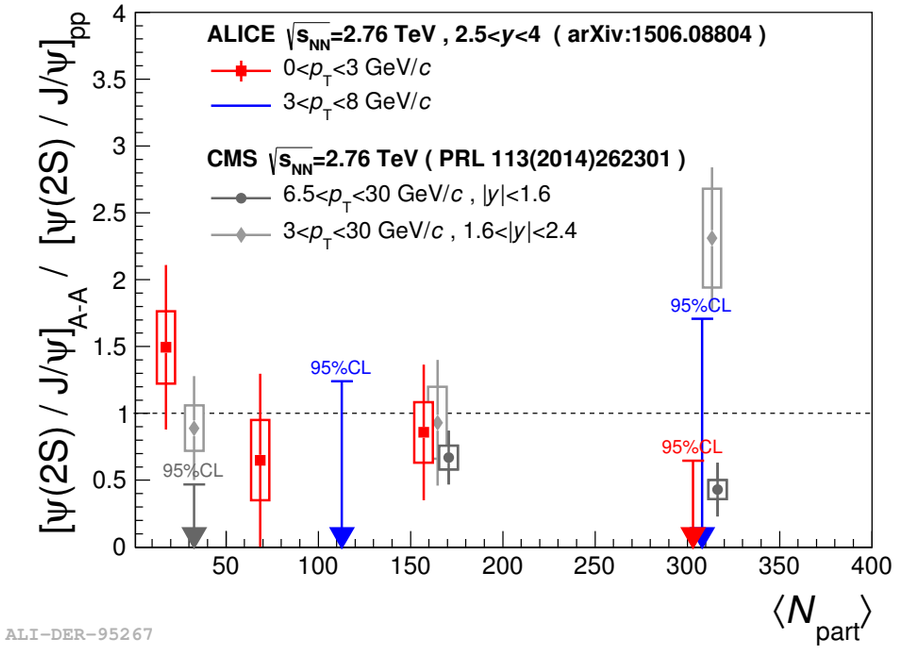
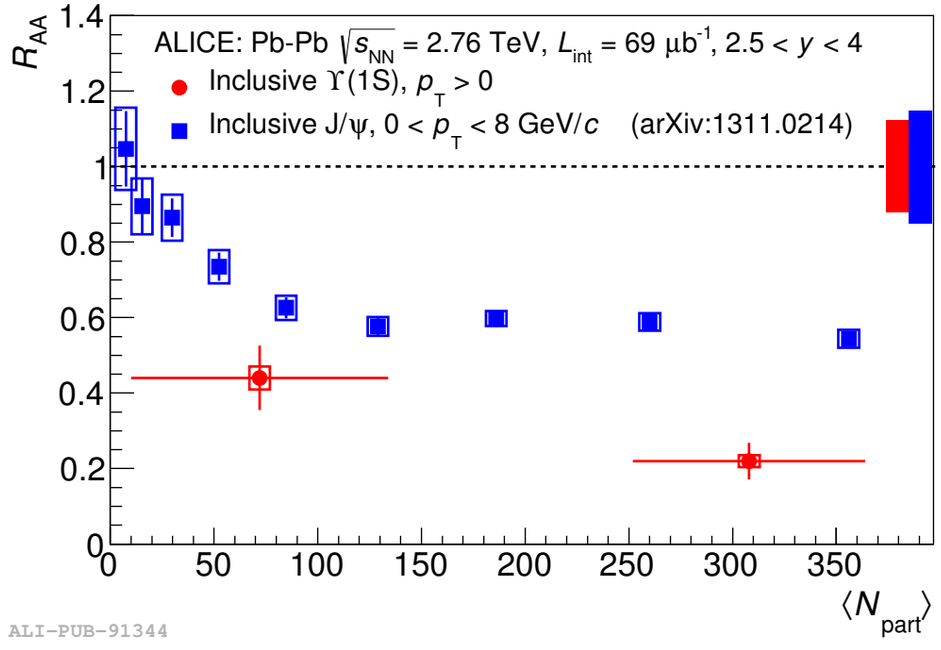


ALI-DER-95267



ALI-PUB-91344

➡ Next : results at $\sqrt{s_{NN}}$=5.02 TeV

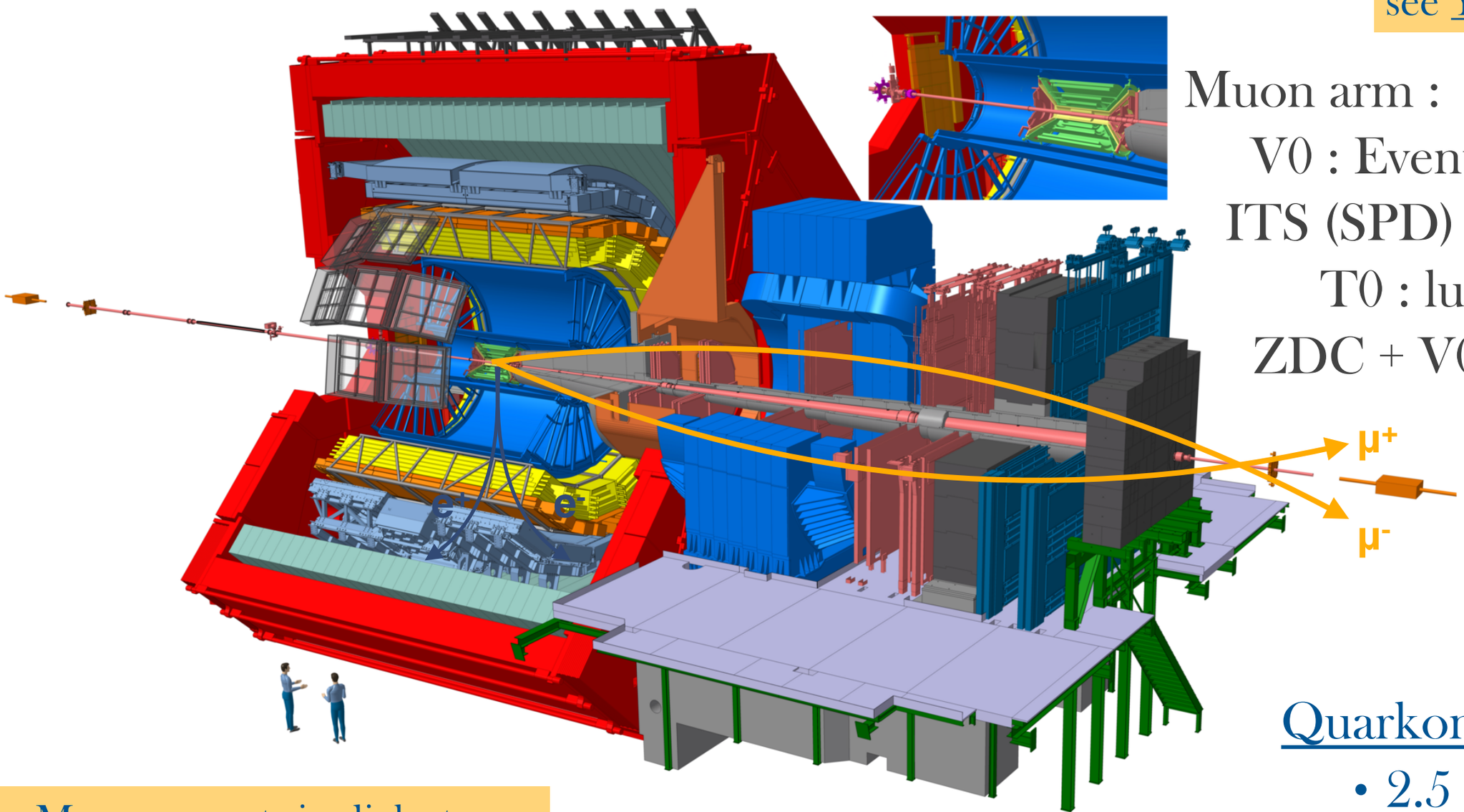
The ALICE detector

Run 2 (2015-2016)
Pb-Pb at $\sqrt{s_{NN}}$=5.02 TeV
$\mathcal{L}$ = 225μb^{-1}

ALICE detector upgrades :
see Gines Martinez-Garcia's talk

Future prospectives at forward y :
see Andry Rakotozafindrabe's talk

ITS upgrade :
see Yoo In-Kwon's talk



Muon arm : trigger/tracking
V0 : Event plane (EP)
ITS (SPD) : vertex + EP
T0 : luminosity
ZDC + V0 : centrality

Quarkonium → $\mu^+\mu^-$:
- 2.5 < y < 4
- down to p_T = 0

Measurements in dielectron channel : see Dennis F. Weiser

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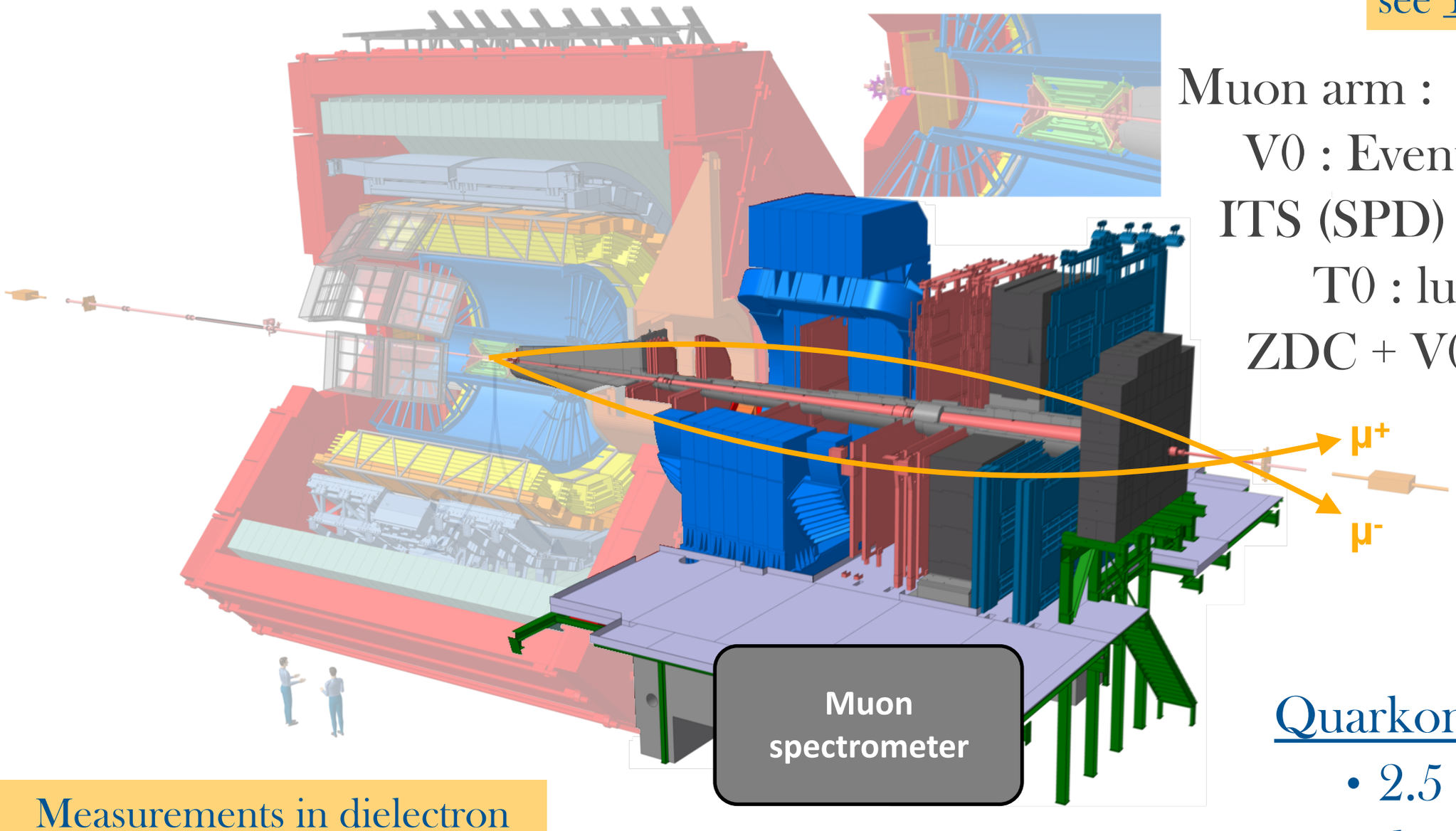

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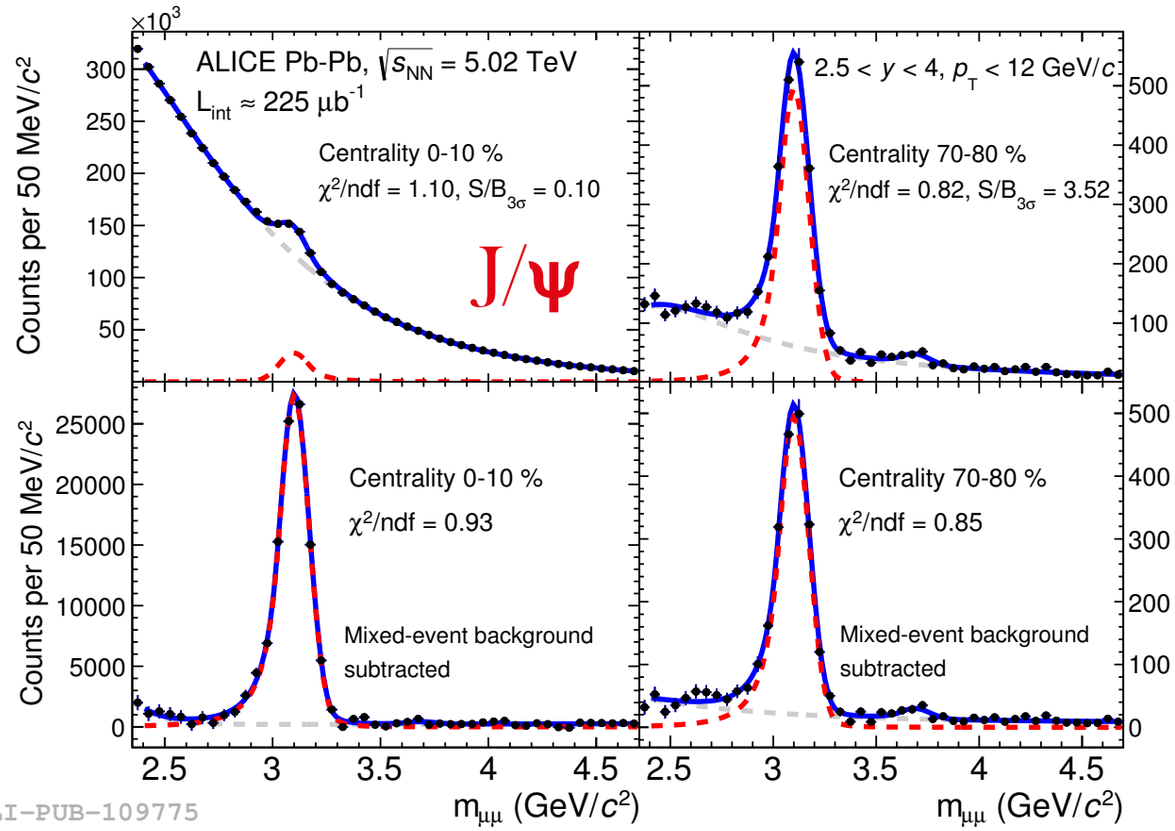
Quarkonium reconstruction at forward-y



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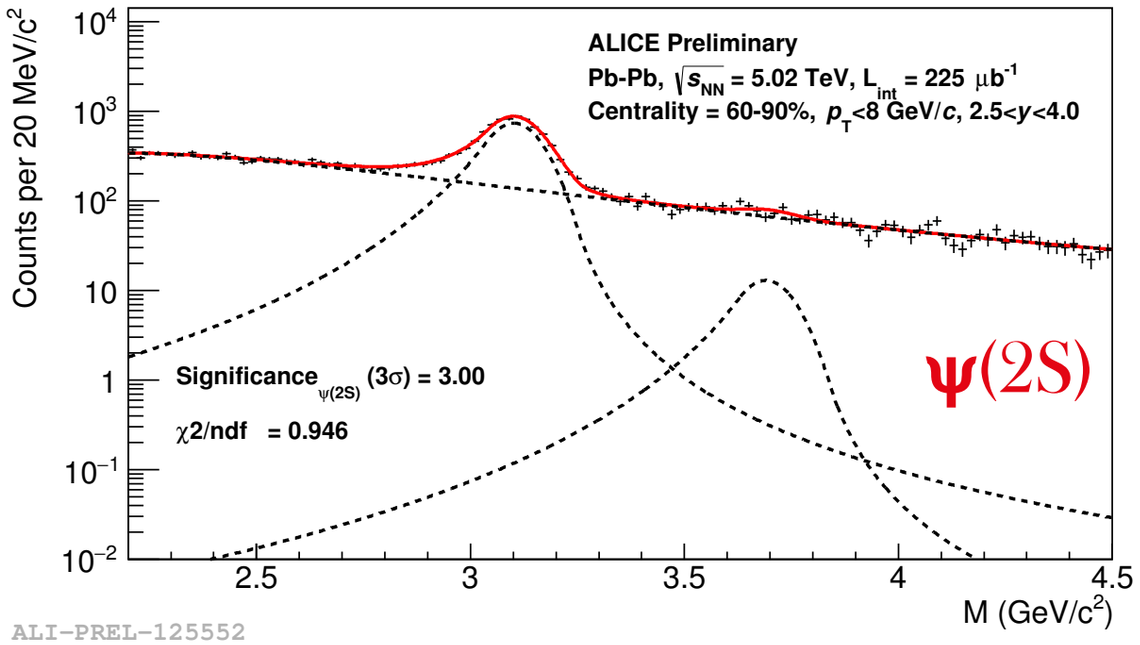
Yield extraction :

Fit of the dimuon invariant mass distribution with several signal + background shapes

ϒ(1S), ϒ(2S)



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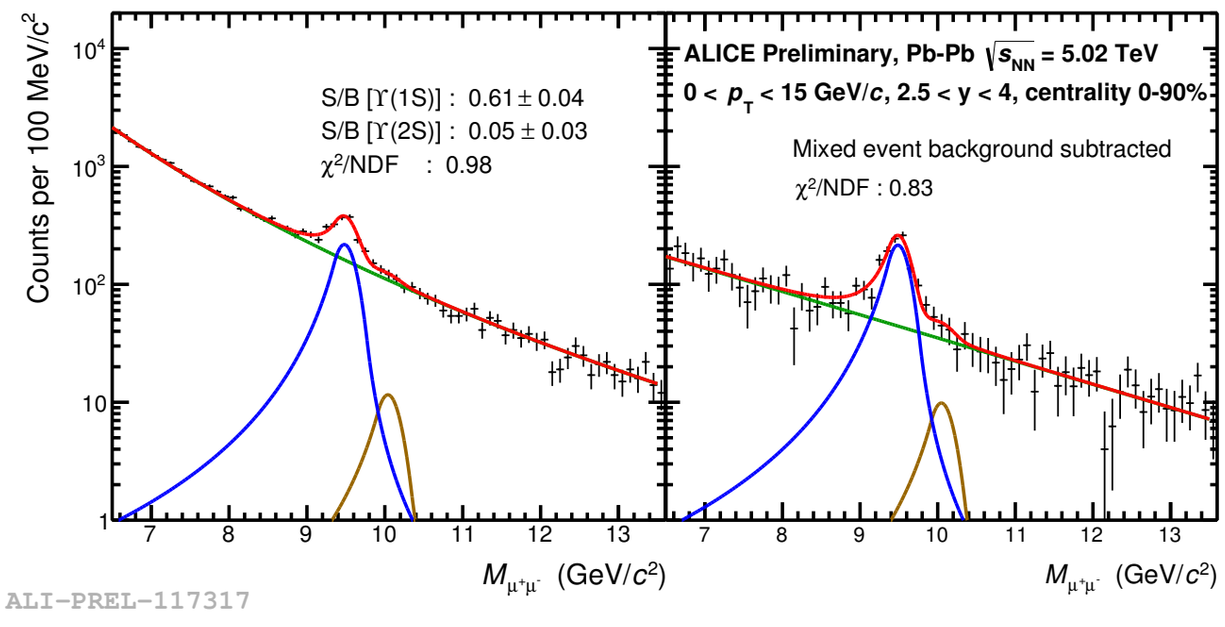

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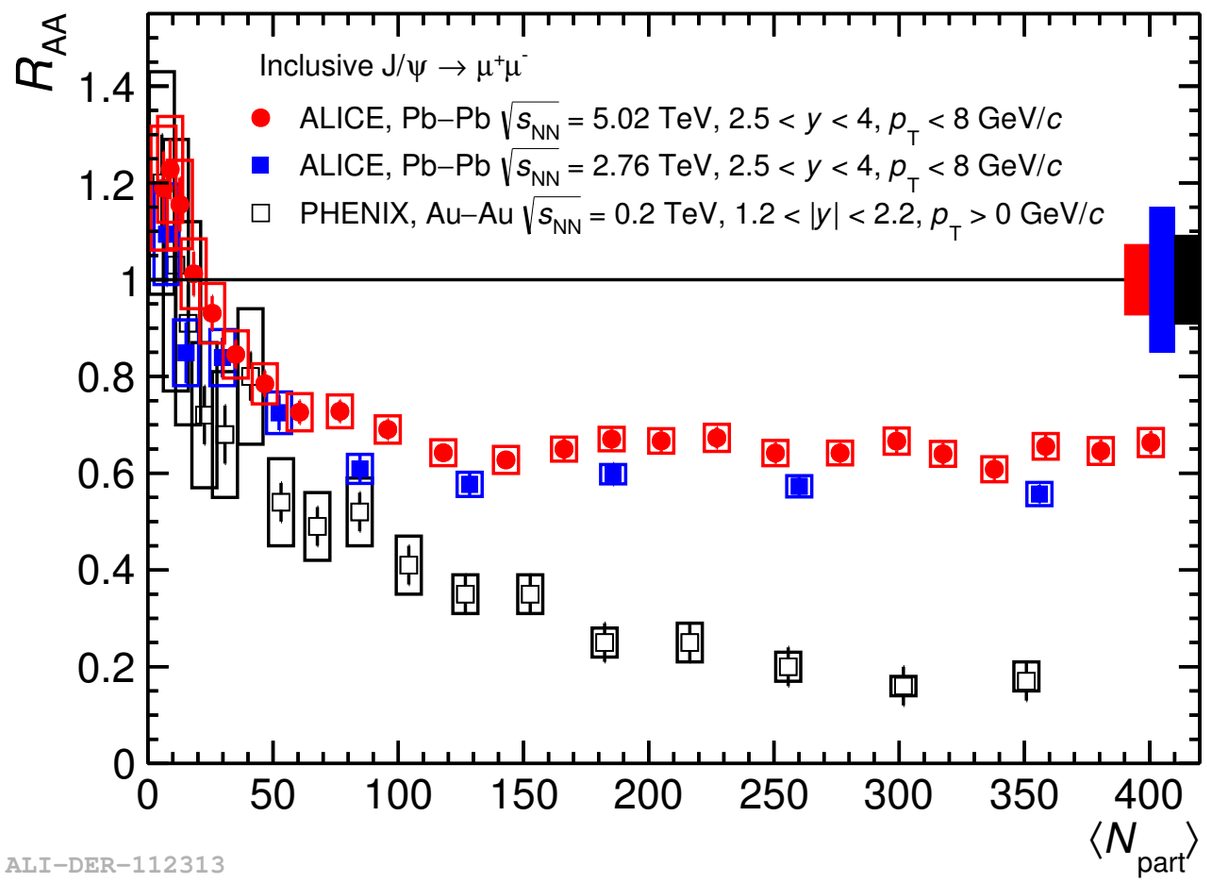
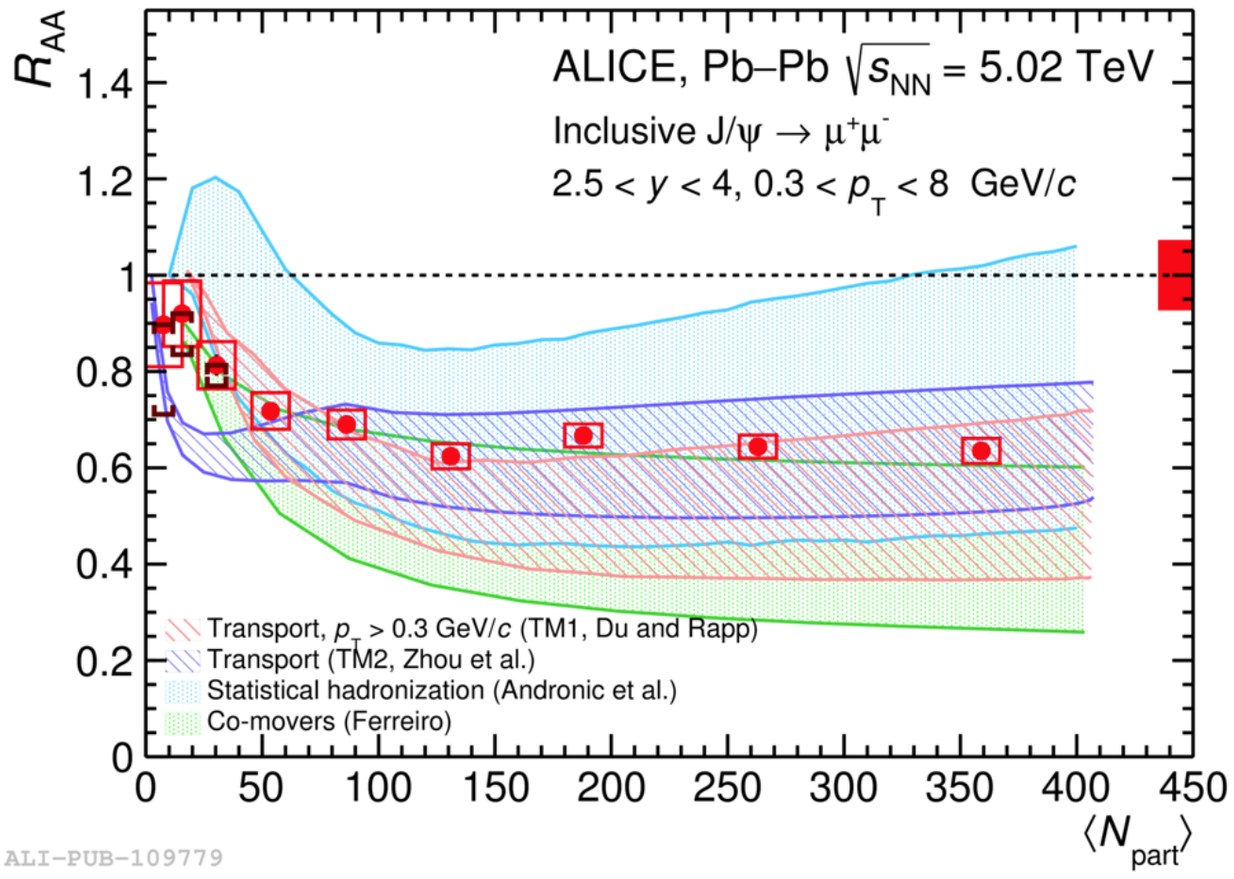
J/ψ Nuclear Modification Factor vs centrality

Phys.Lett. B766 (2017) 212-224





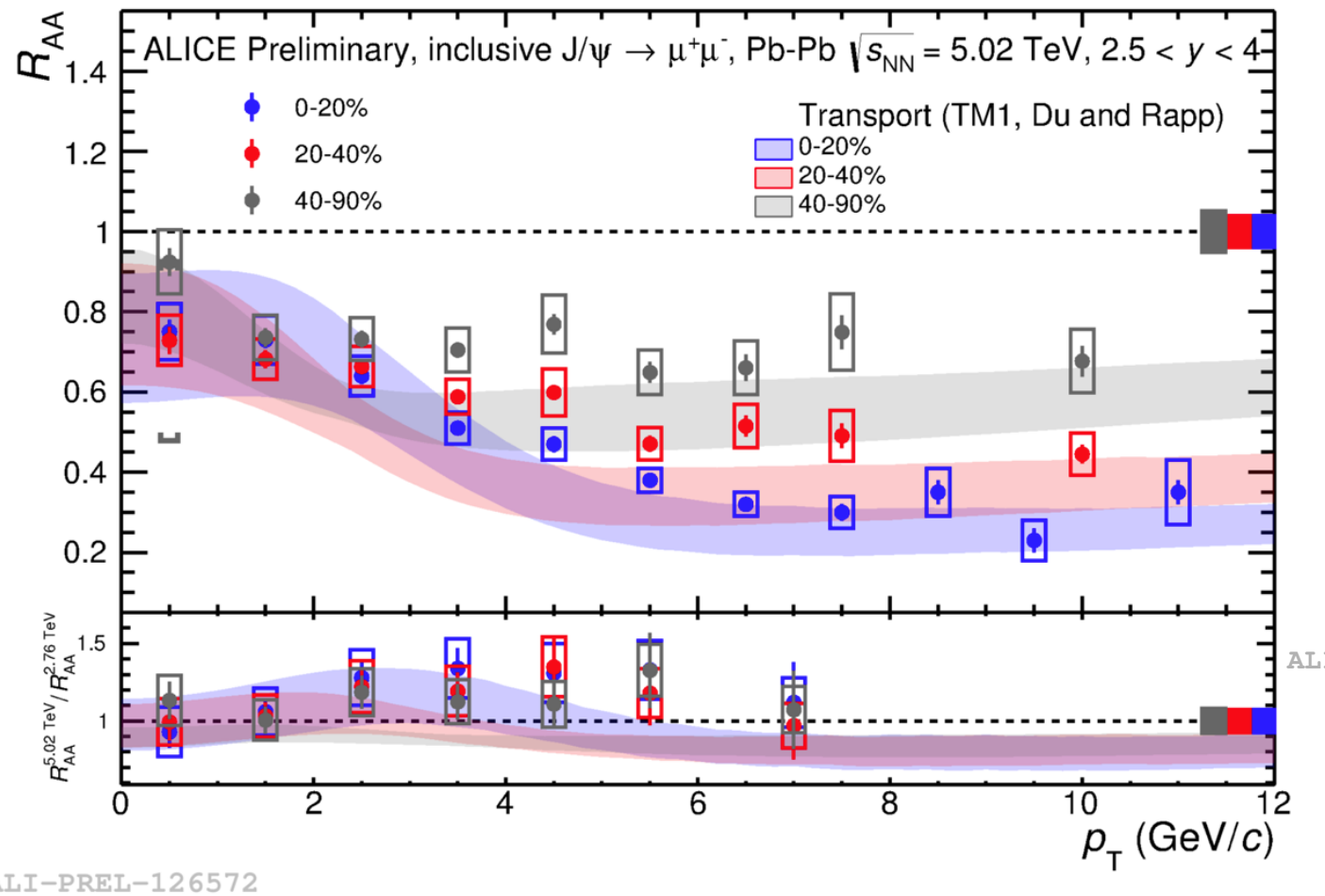
- From $\langle N_{part} \rangle$ > 50 : no significant centrality dependence
- J/ψ suppression at $\sqrt{s_{NN}}$=5.02 TeV confirms observations at $\sqrt{s_{NN}}$=2.76 TeV with an increased precision
- p_T > 0.3 GeV/c to remove most of photo-production (brackets for the remaining contribution)

Transport models: TM1 and TM2
NPA 859 (2011) 114, PRC 89 no.5, 459 (2014) 054911

Statistical hadronization
NPA 904-5 (2013) 535c

Co-movers interaction model
PLB 731 (2014) 57

J/ψ Nuclear Modification factor vs p_T, $\langle p_T \rangle$, r_{AA}



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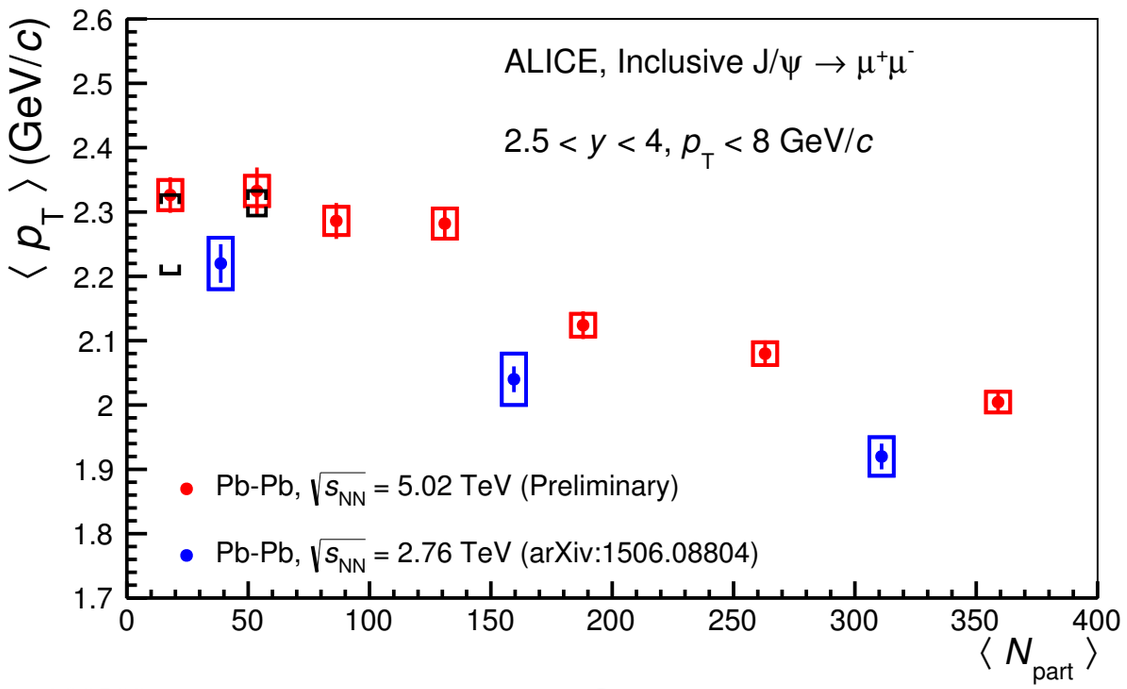
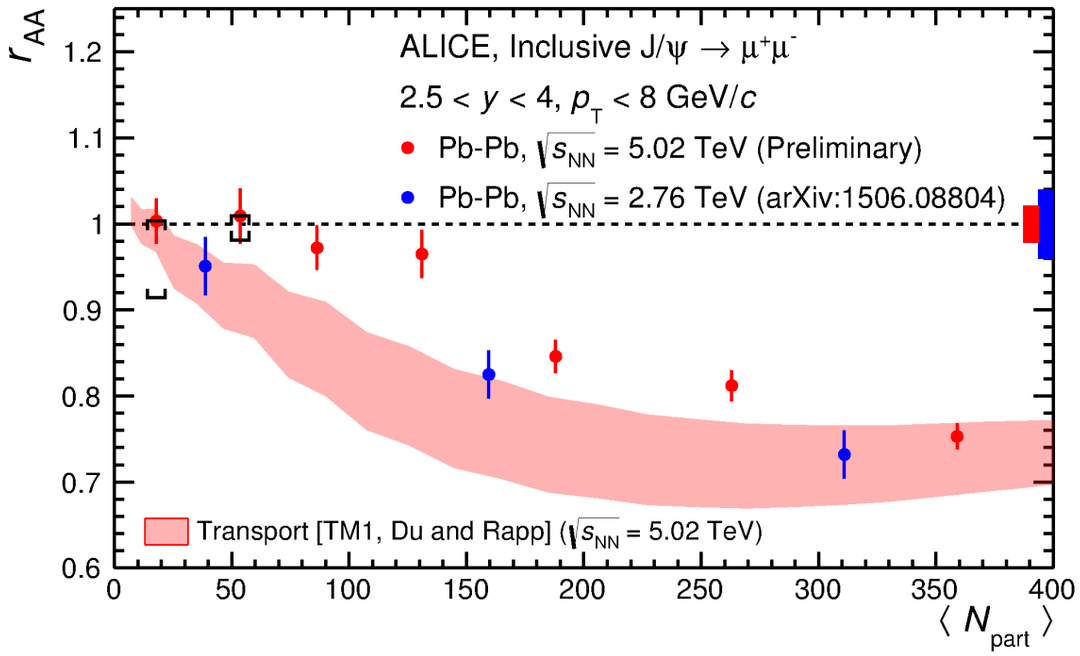


ALI-PREL-120593

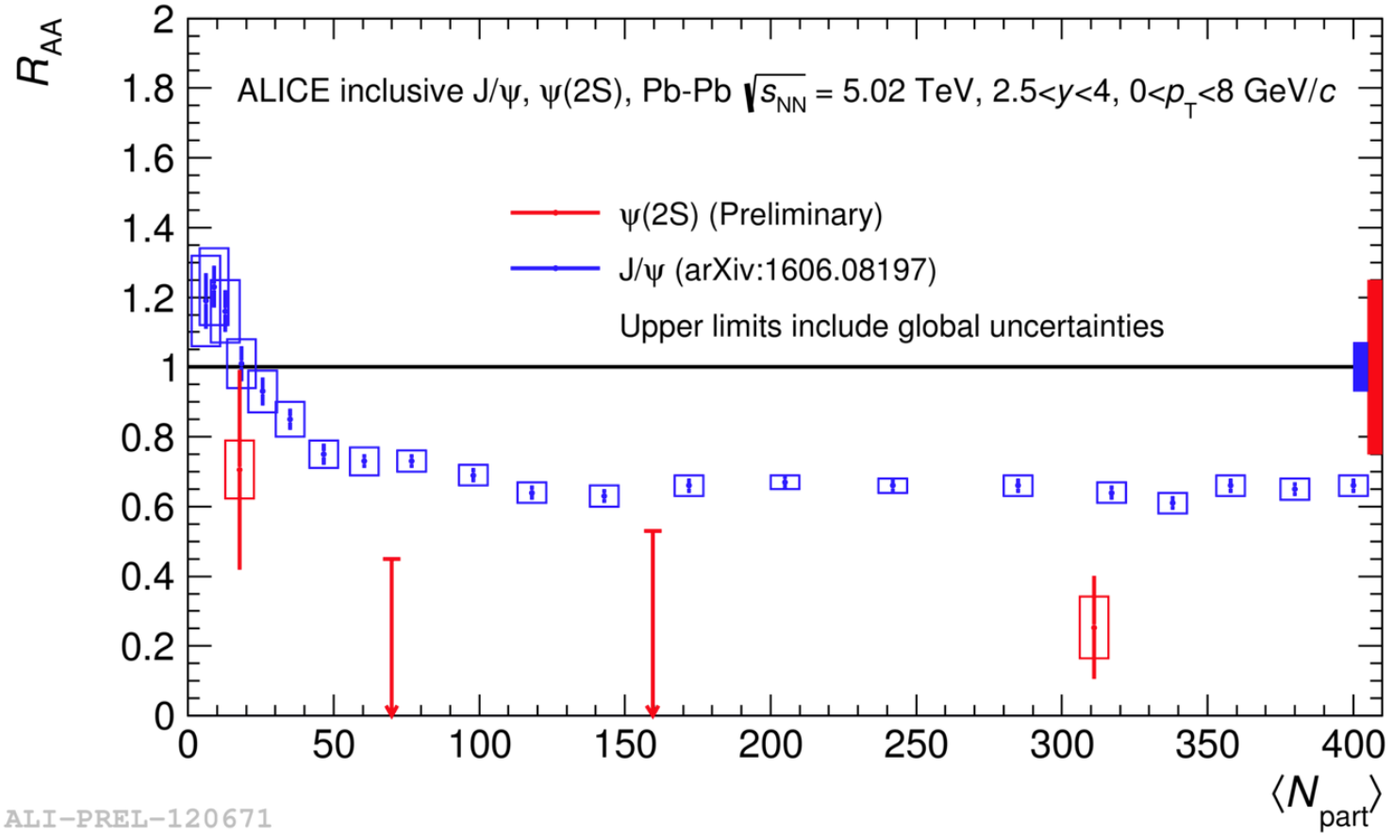
$$r_{AA} = \frac{\langle p_T^2 \rangle_{AA}}{\langle p_T^2 \rangle_{pp}}$$

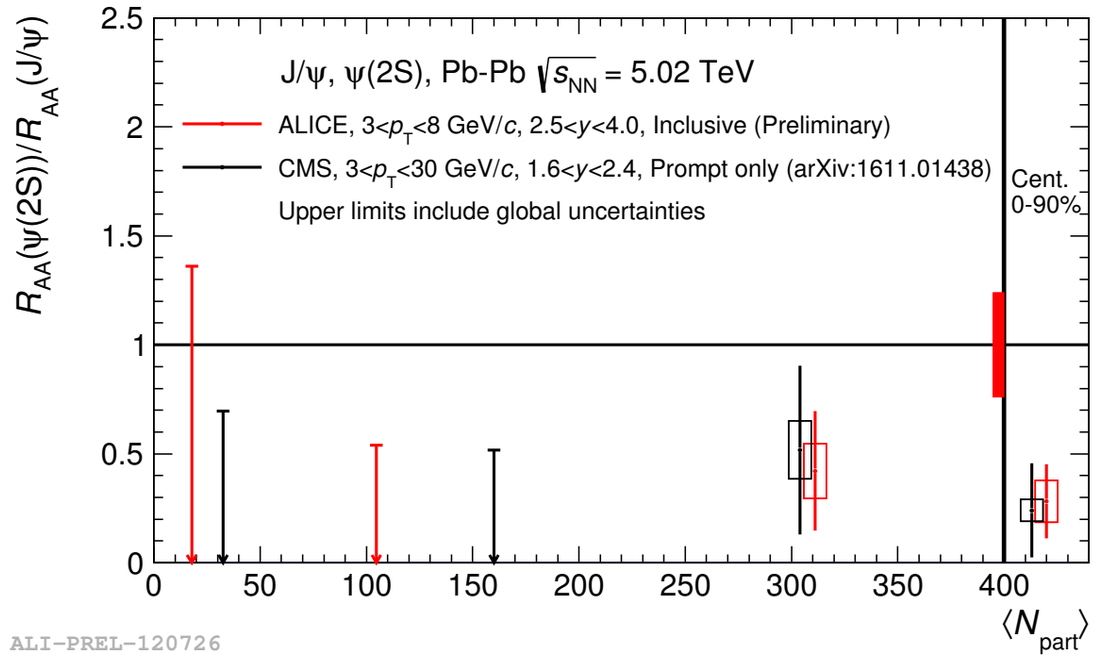
- J/ψ suppression is stronger at high p_T and in central collisions
- Transport model predicts similar trend
- Brackets give limits for possible contamination from J/ψ photo-production



ALI-PREL-120574

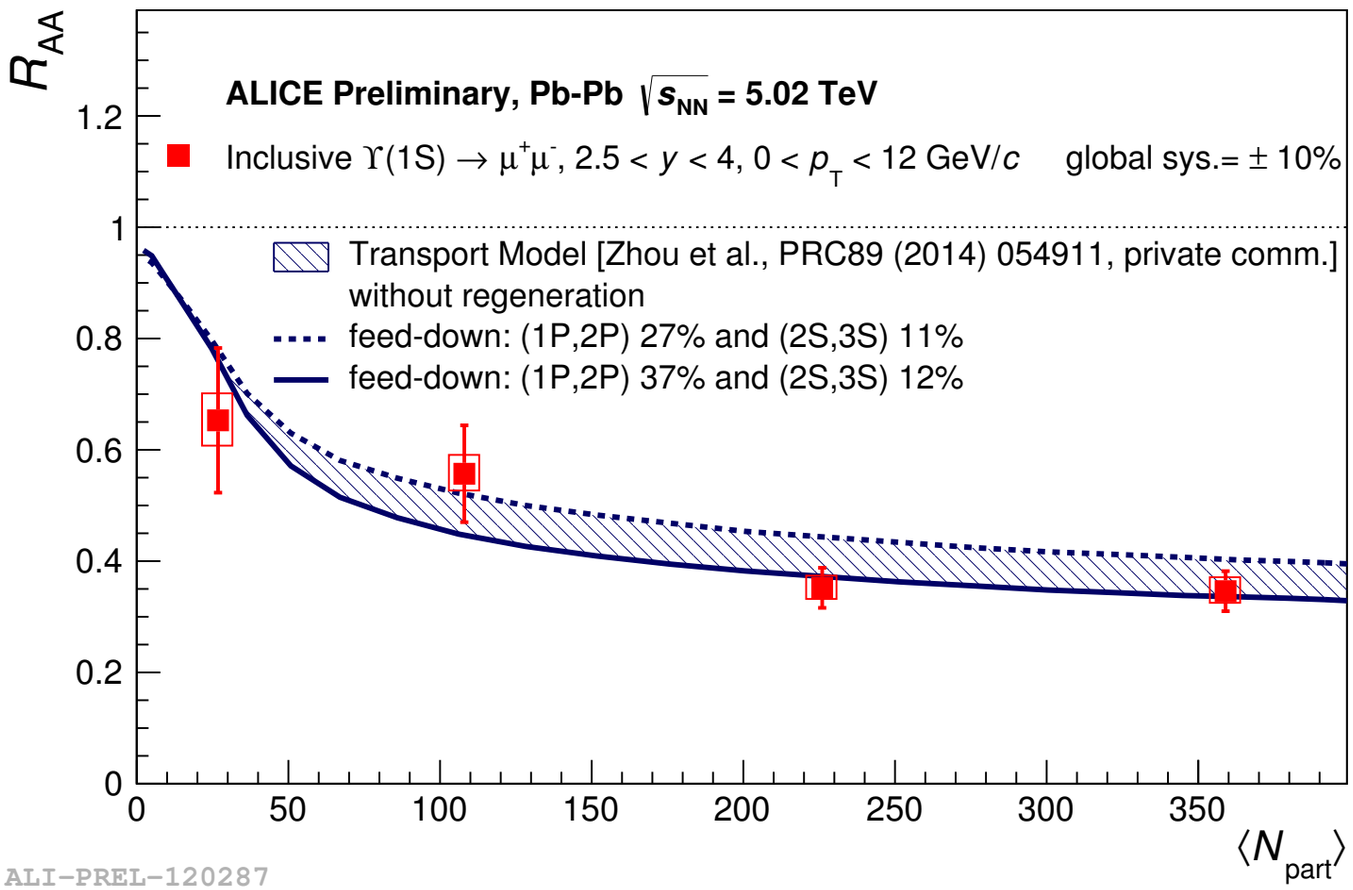
ψ(2S) Nuclear Modification factor and ratio of 2S/1S

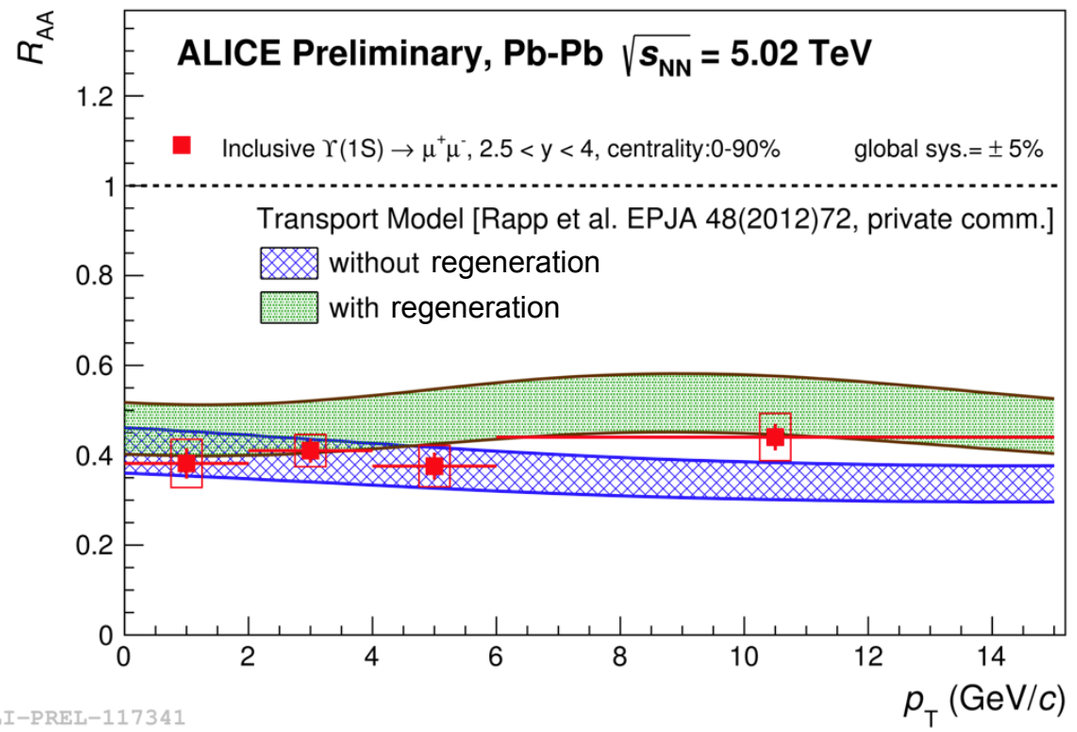




- **ψ**(2S) is expected to be more easily dissociated than J/**ψ** (lower binding energy)
- Data shows a stronger suppression in semi-central and central collisions
- For low significance : upper limit at 95% CL
- More statistics are needed → upgrades for LHC run 3

Υ(1S) Nuclear Modification factor

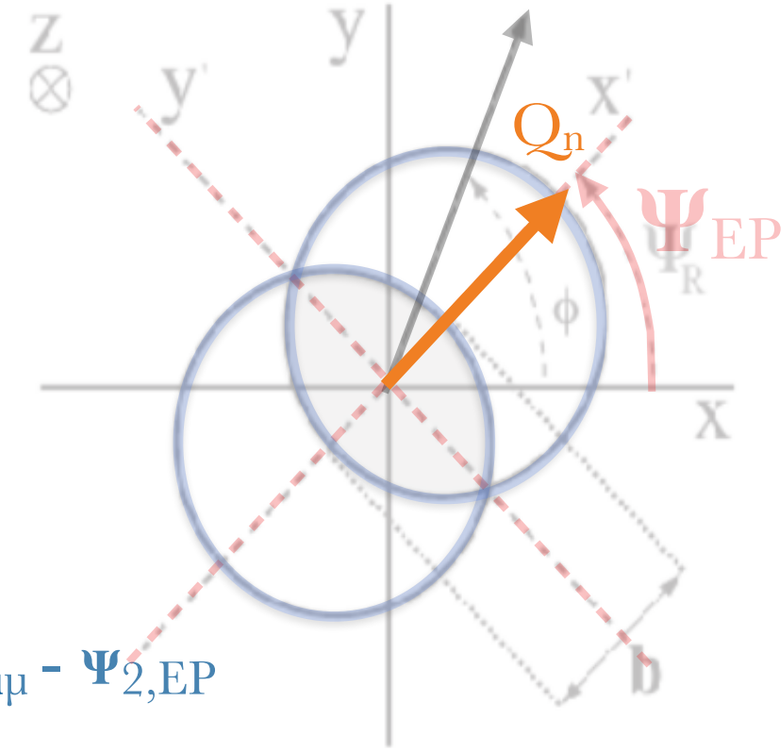




- Strong Υ(1S) suppression vs centrality (similar to $\sqrt{s_{NN}}$ =2.76 TeV)
- Compatible with transport models w/wo (re)generation
- No significant variation with p_T
- Need precise feed-down measurement for 2S and 3S (from pp)

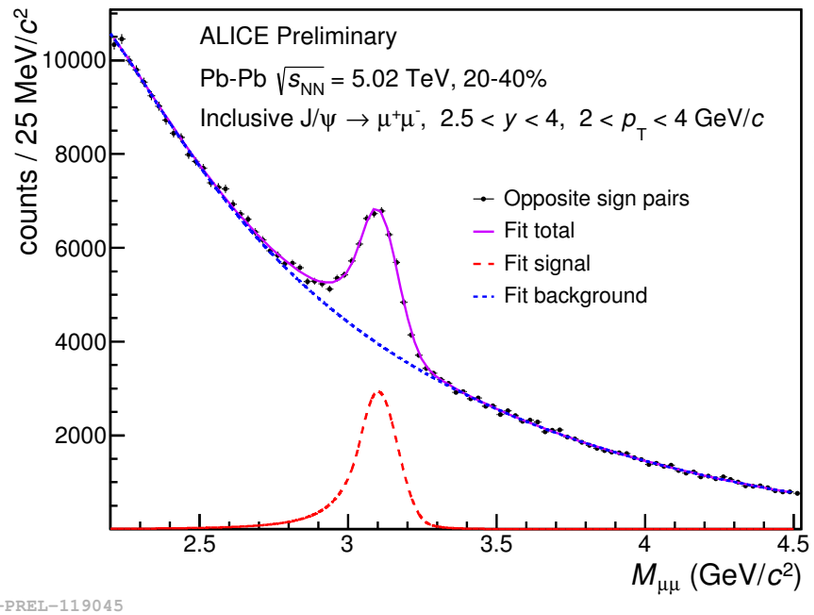
J/ψ elliptic flow: how to measure it ?

- Methods based on event plane determination
  From detector multiplicities : $\Psi_n = \frac{1}{n} \arctan(Q_{n,x}, Q_{n,y})$
  - Correct for detector resolution : using 3 sub-event method
  - Deal with non-uniform acceptance



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

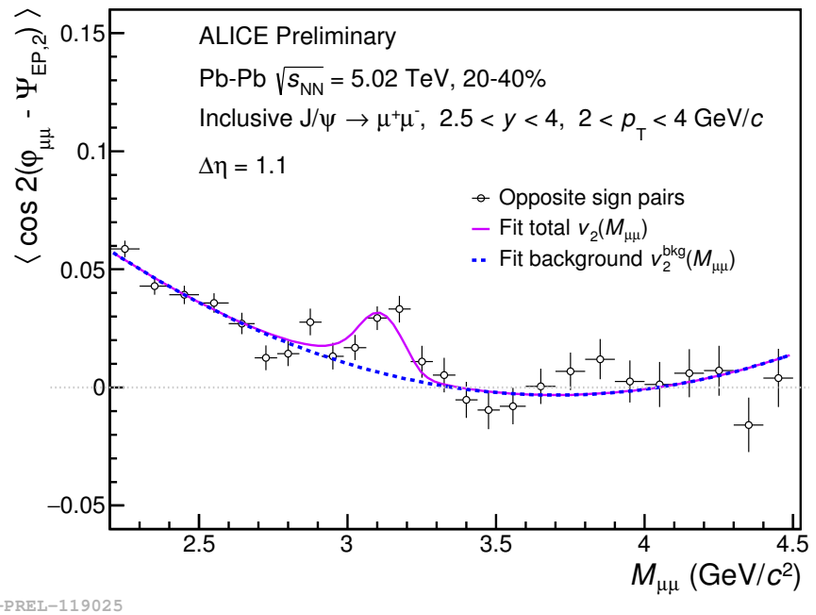
- Model total flow as $v_2(m_{\mu\mu}) = v_2^{sig}\alpha(m_{\mu\mu}) + v_2^{bck}(1-\alpha(m_{\mu\mu}))$



ALI-PREL-119045

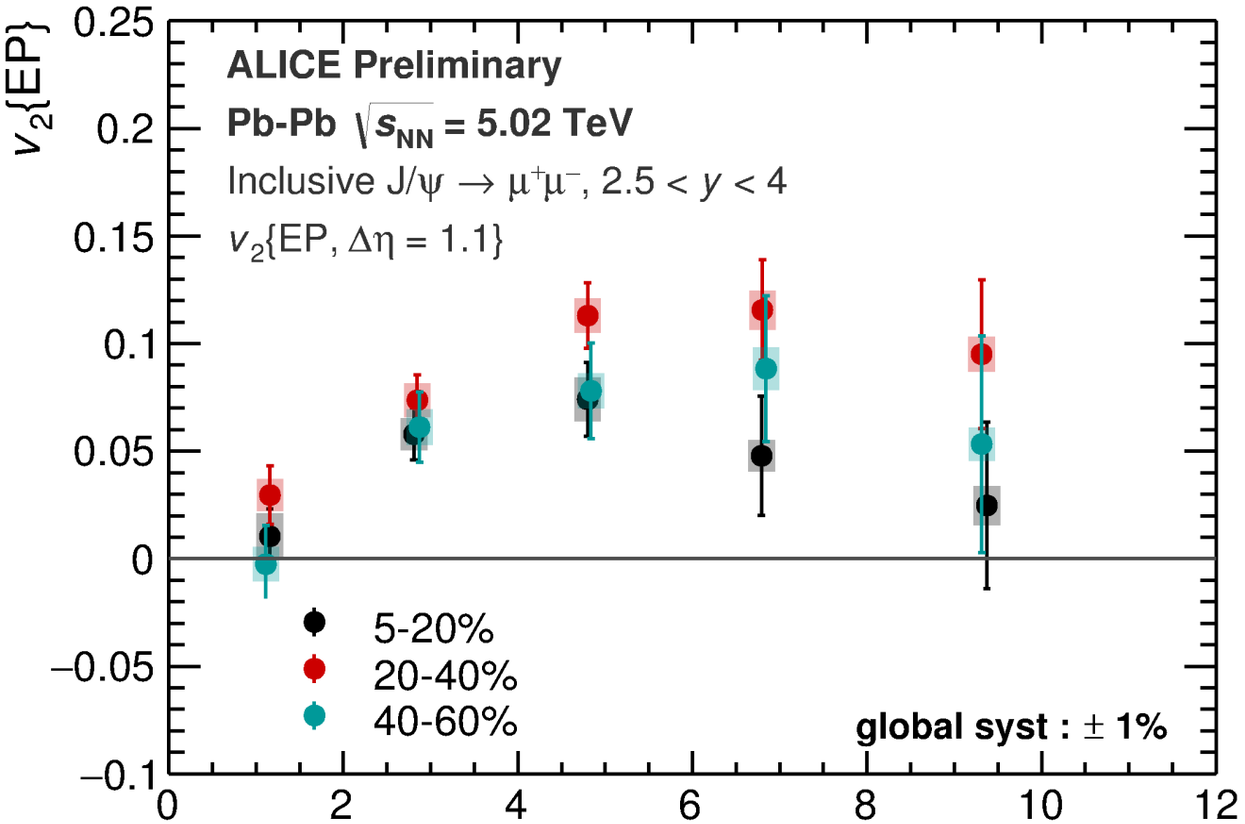
signal shape extracted from M_{inv} fit

background : e.g. polynomial function

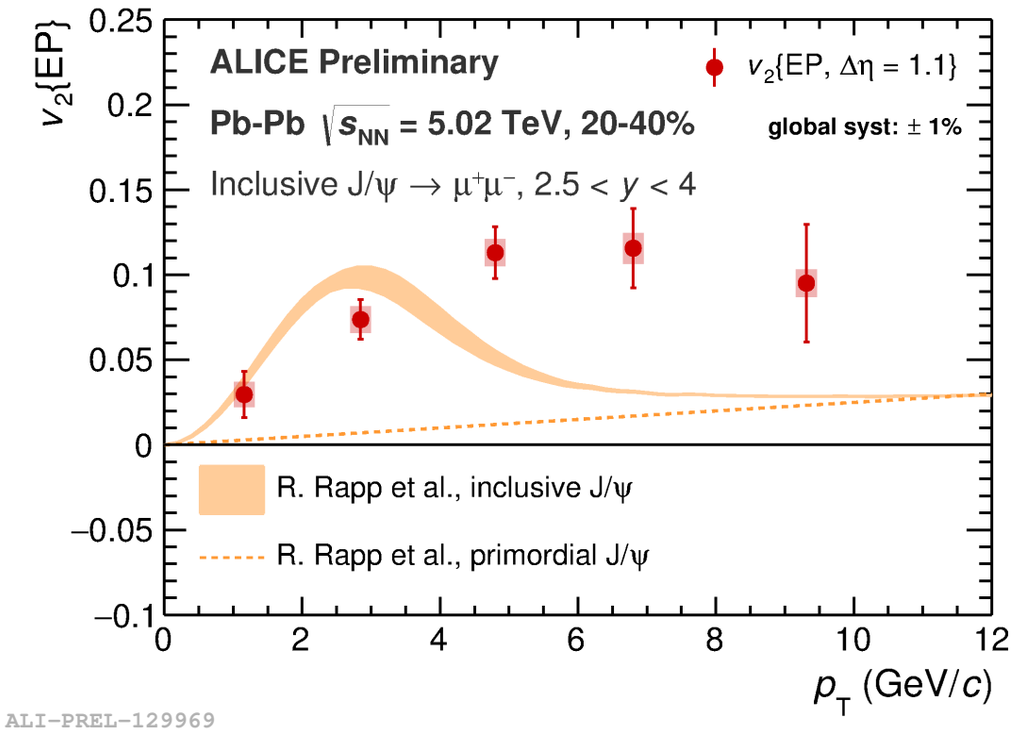


ALI-PREL-119025

J/ψ v_2 results vs p_T and theory comparison

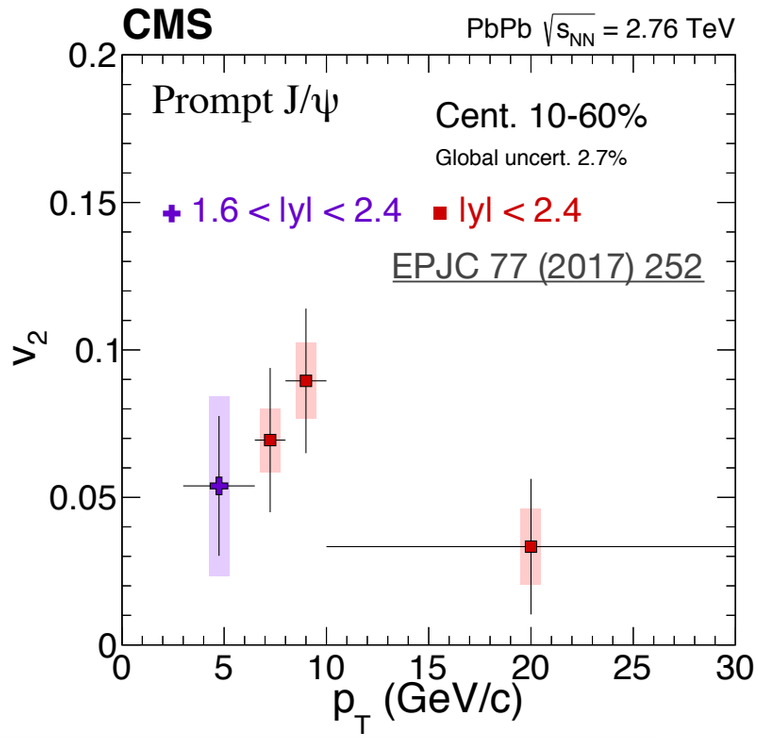


ALI-PREL-128122

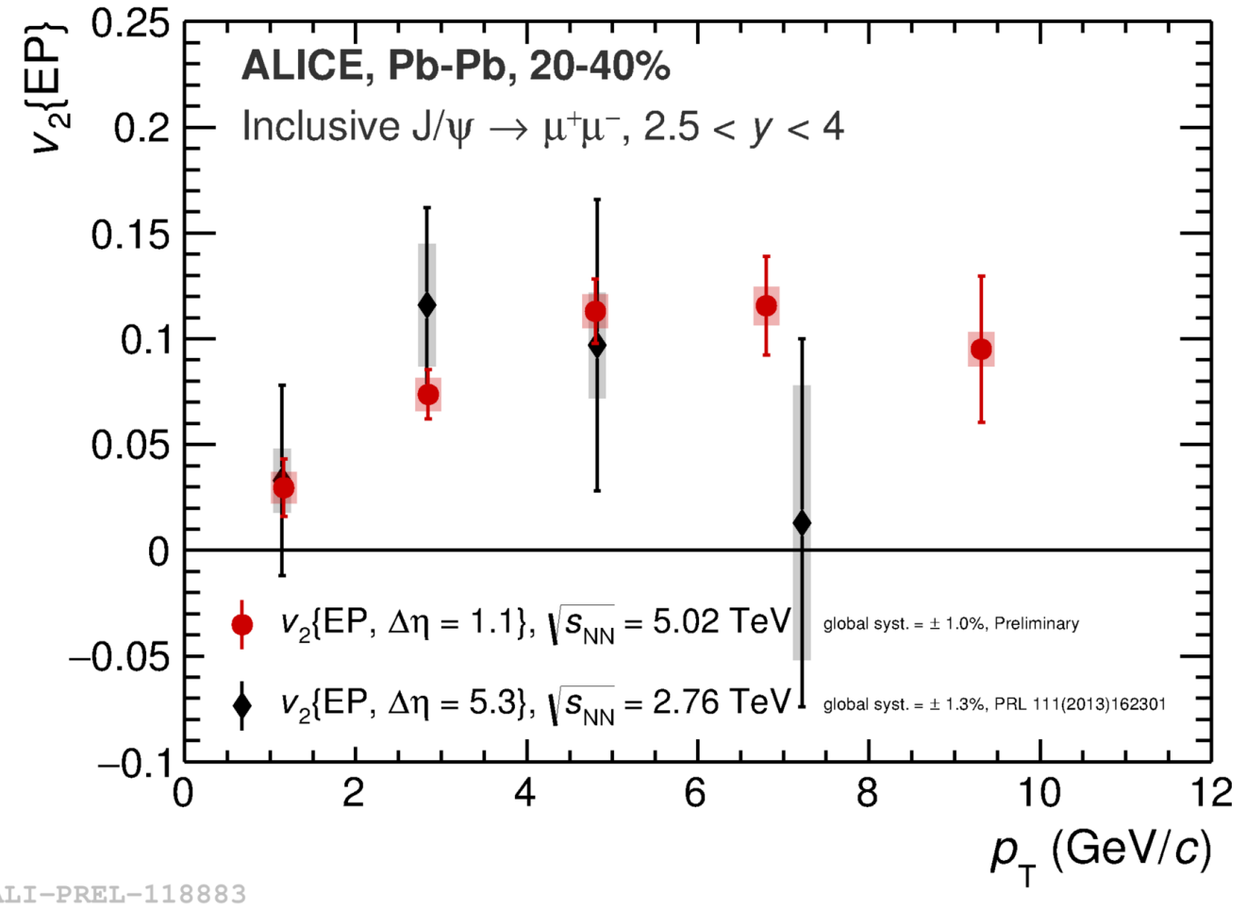


ALI-PREL-129969

- A clear v_2 signal is observed in various centrality and p_T bins
- Comparison with transport model :
  - 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 (prompt J/ψ from CMS also indicate a non-zero v_2)



J/ψ v_2 comparison with $\sqrt{s_{NN}}$ =2.76 TeV and D mesons



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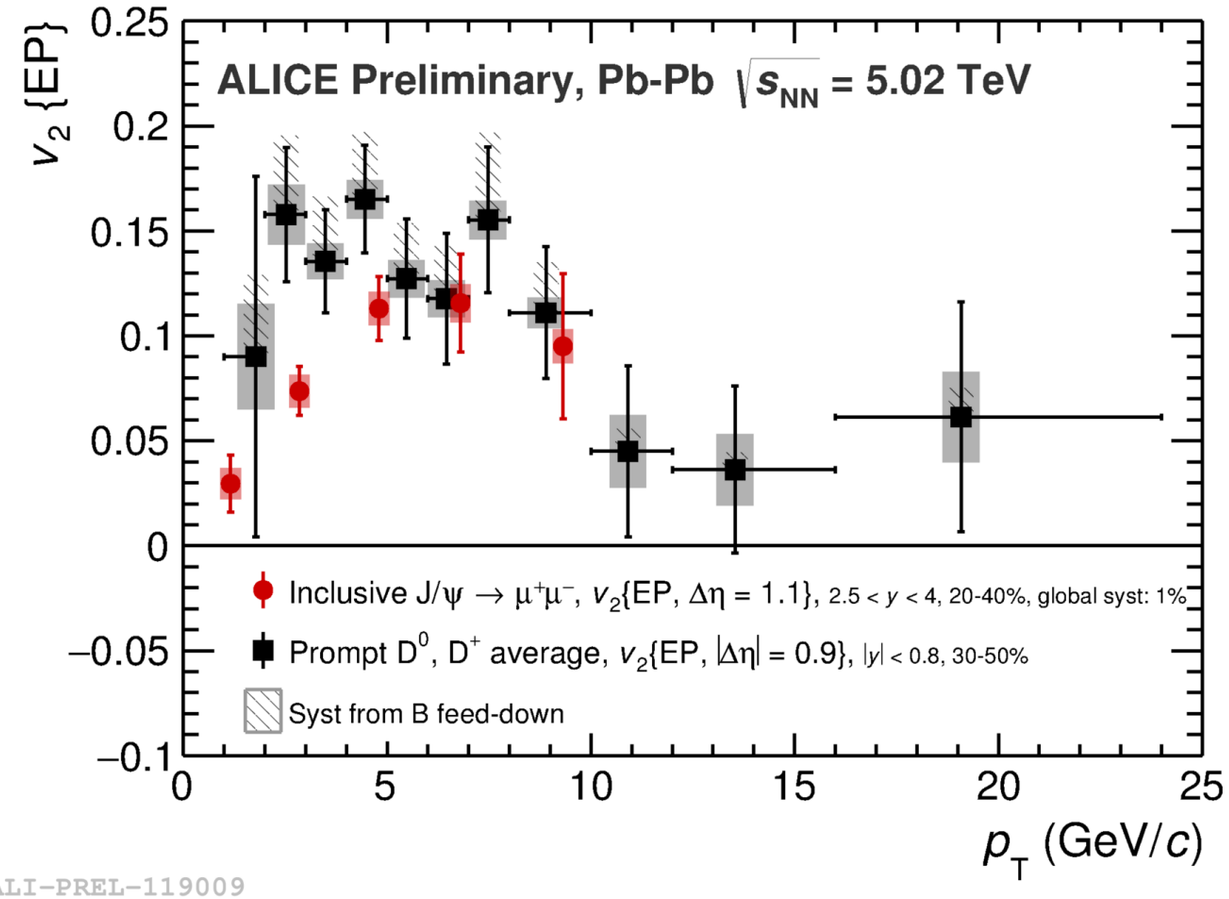

ALI-PREL-119009

- Compatible with results at $\sqrt{s_{NN}}$ = 2.76TeV with a higher precision
- Comparison to open charm
  → indication of : charm recombination and thermalization in the medium

Summary

- Charmonium
  - Interplay of suppression and (re)generation mechanisms
  - Compatible results with $\sqrt{s_{NN}}$ = 2.76 TeV but precision is increased
  - Confirmation of J/ψ elliptic flow
  - Stronger ψ(2S) suppression
- Bottomonium
  - Suppression plays dominant role with negligible (re)generation
  - Stronger R_{AA} centrality dependence

Thank you for
your attention !

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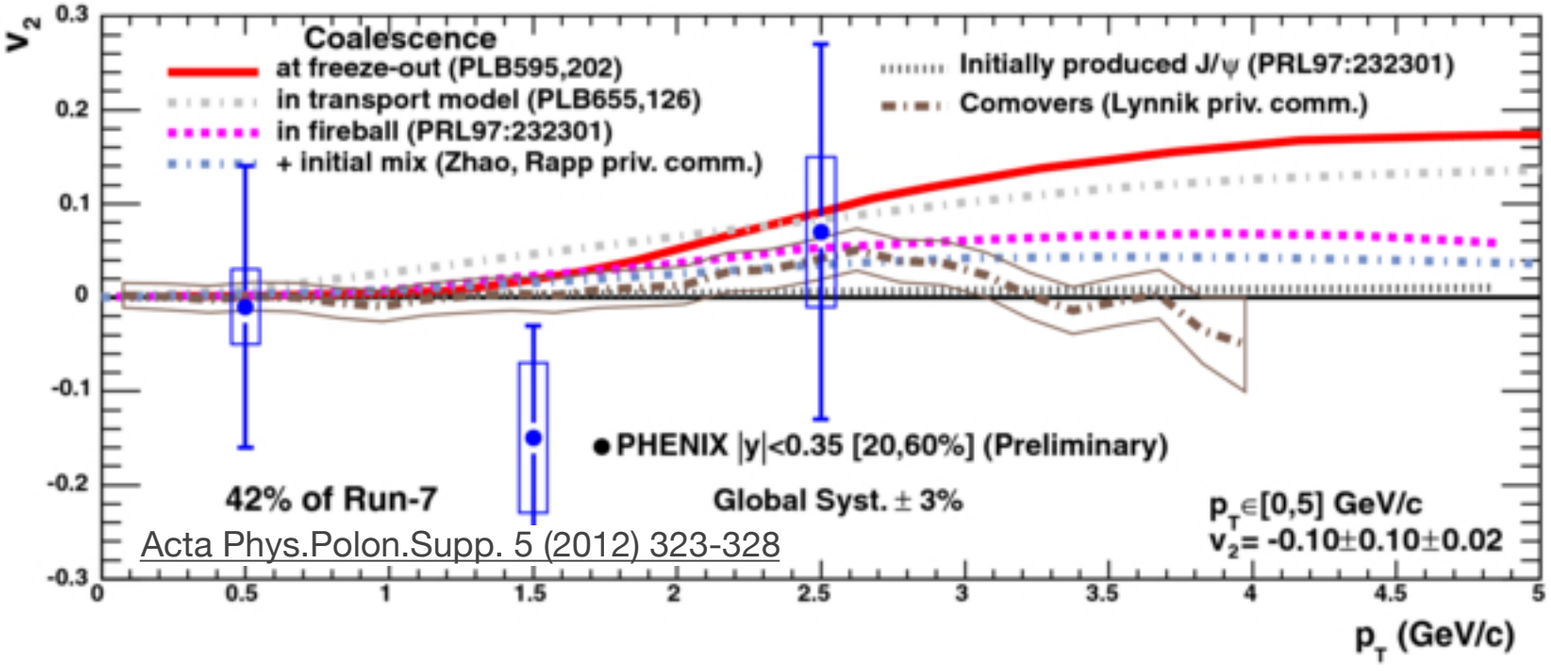
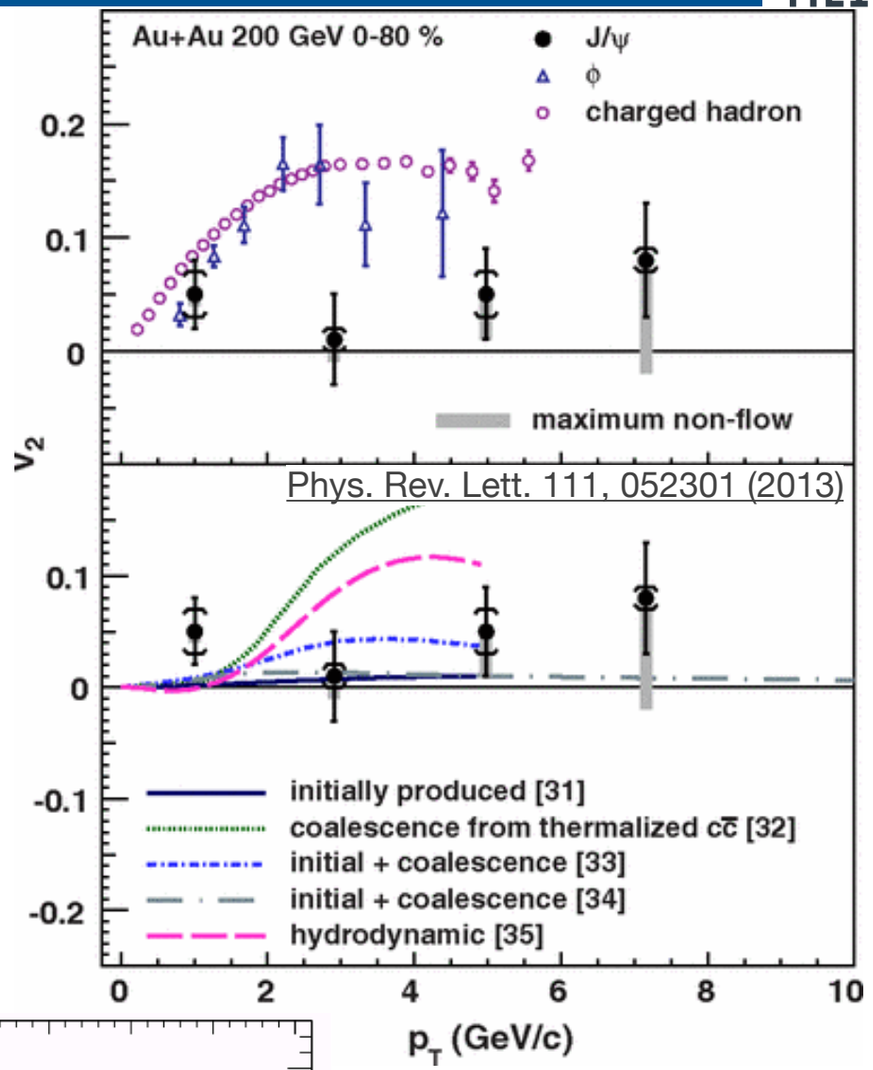
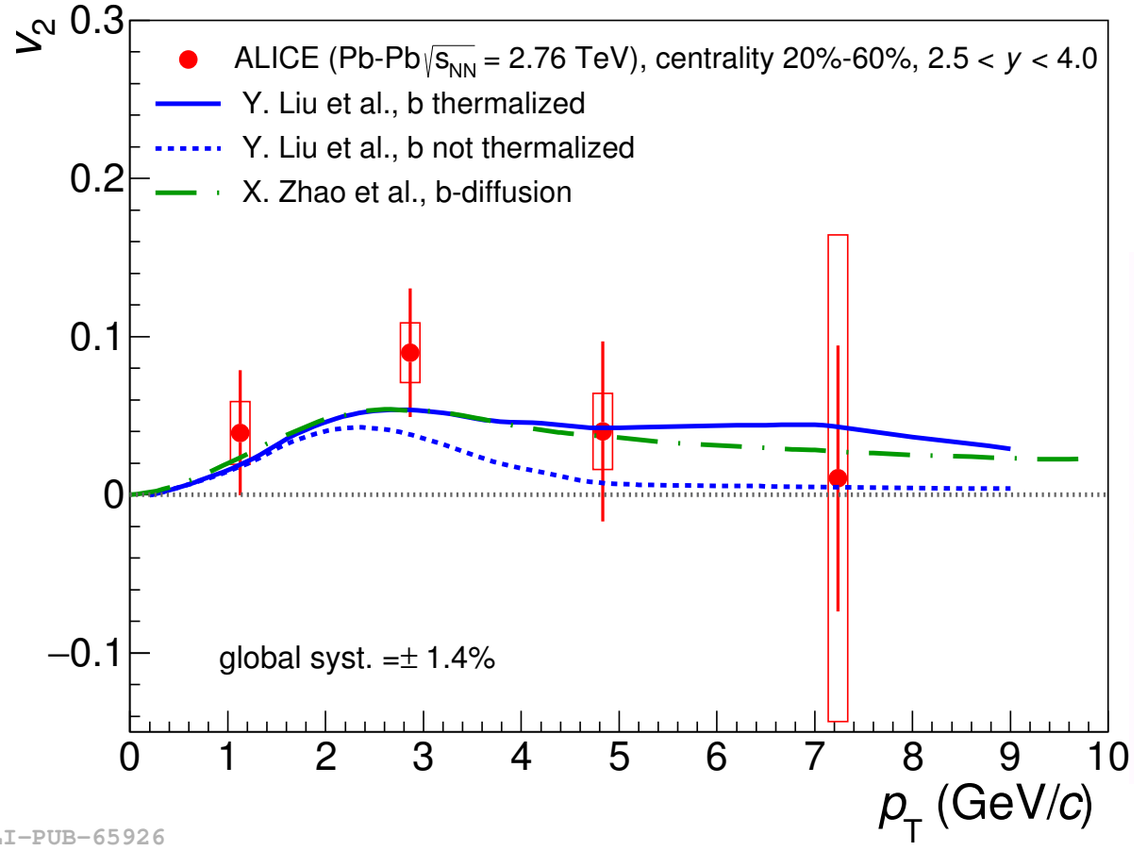
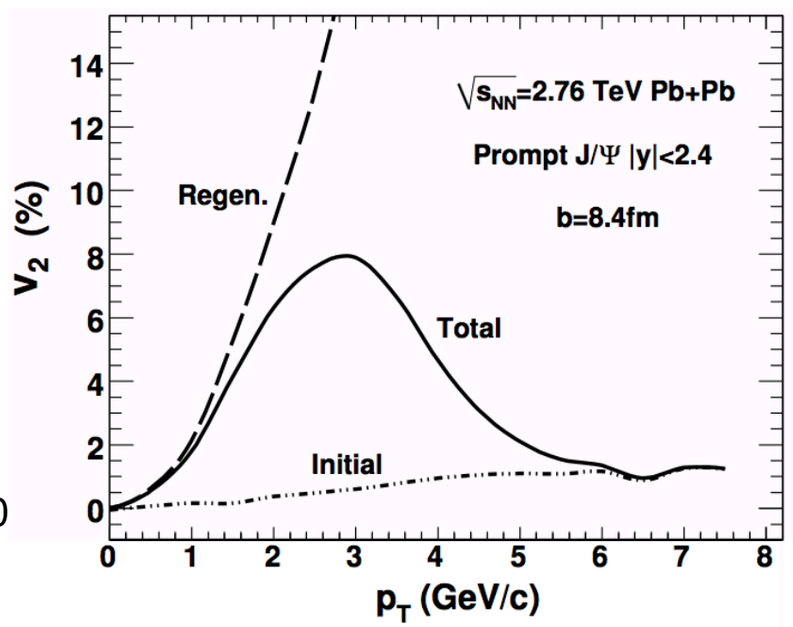
Previous measurements of J/ψ elliptic flow (v_2)





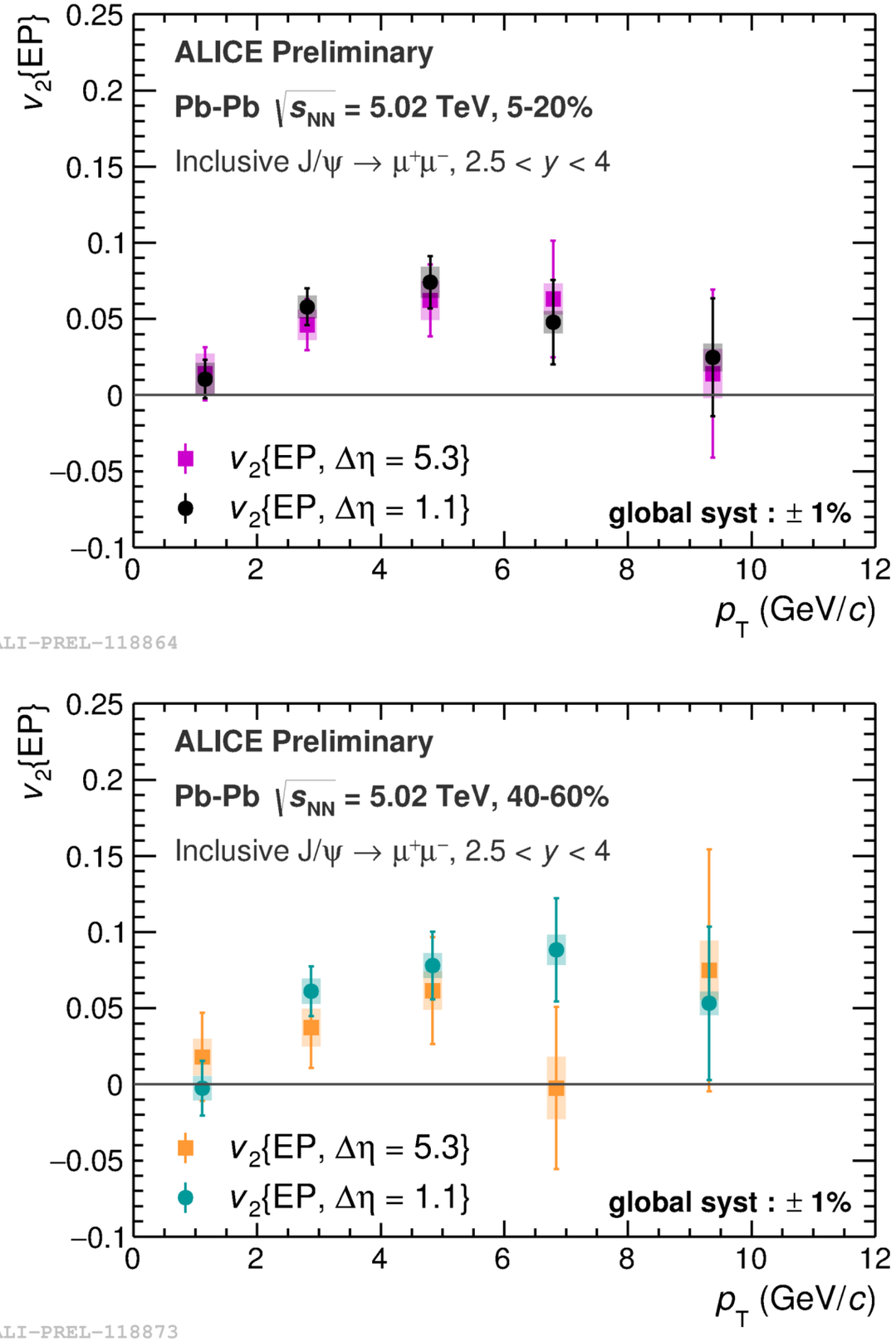




LHC at $\sqrt{s_{NN}}$ =2.76 TeV: First hint of non-zero J/ψ v_2

ALI-PUB-65926

J/ψ elliptic flow : non flow evaluation



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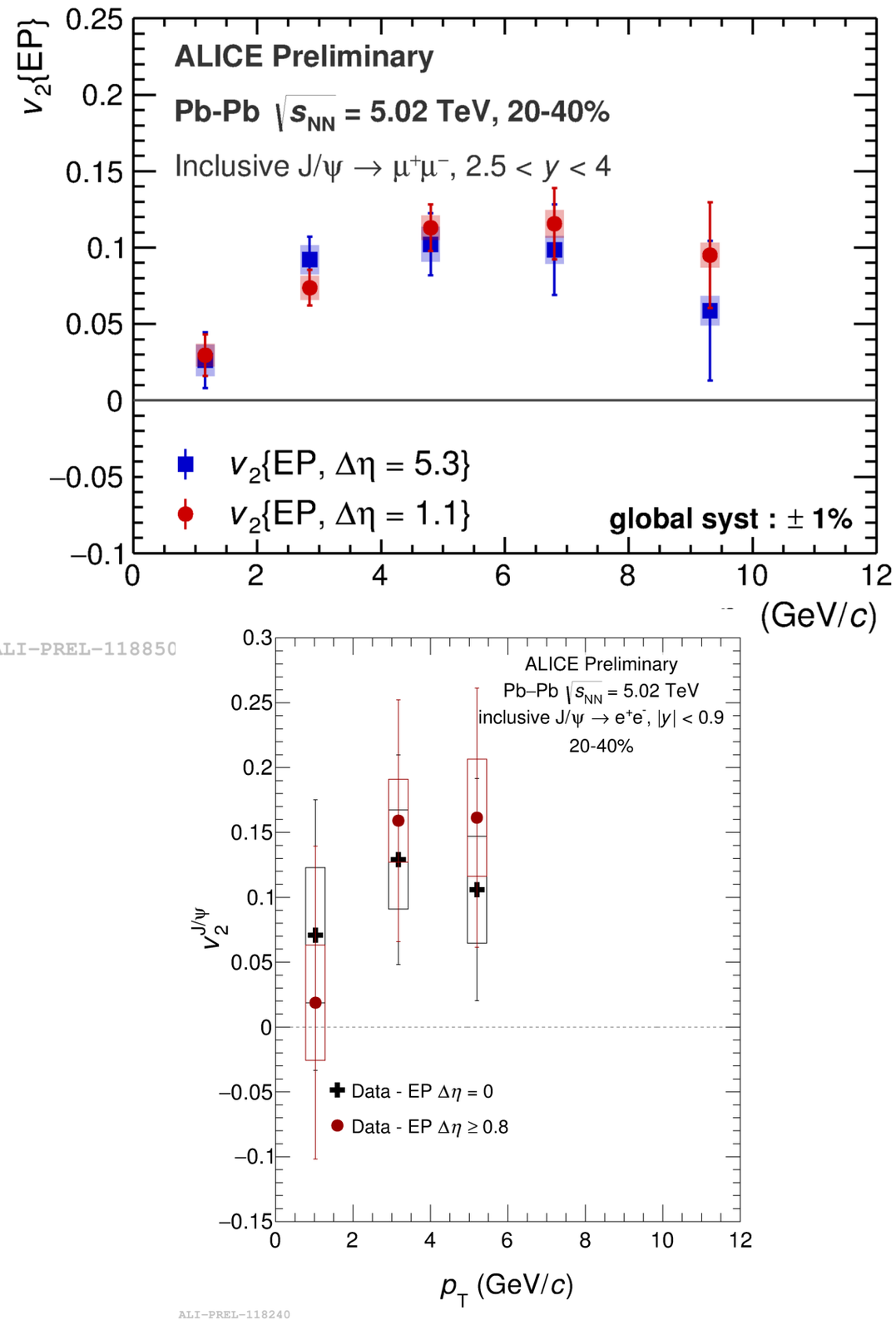

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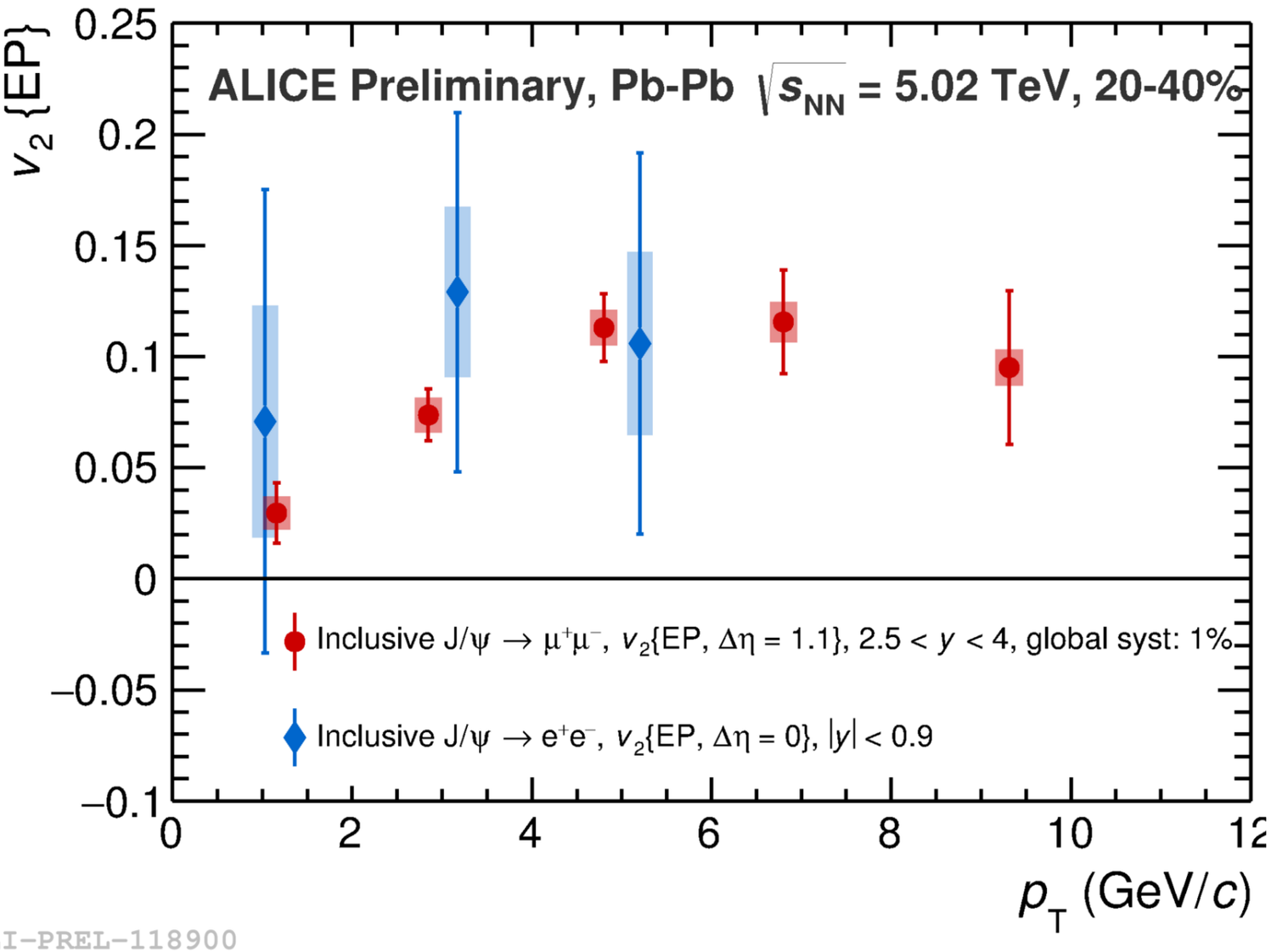
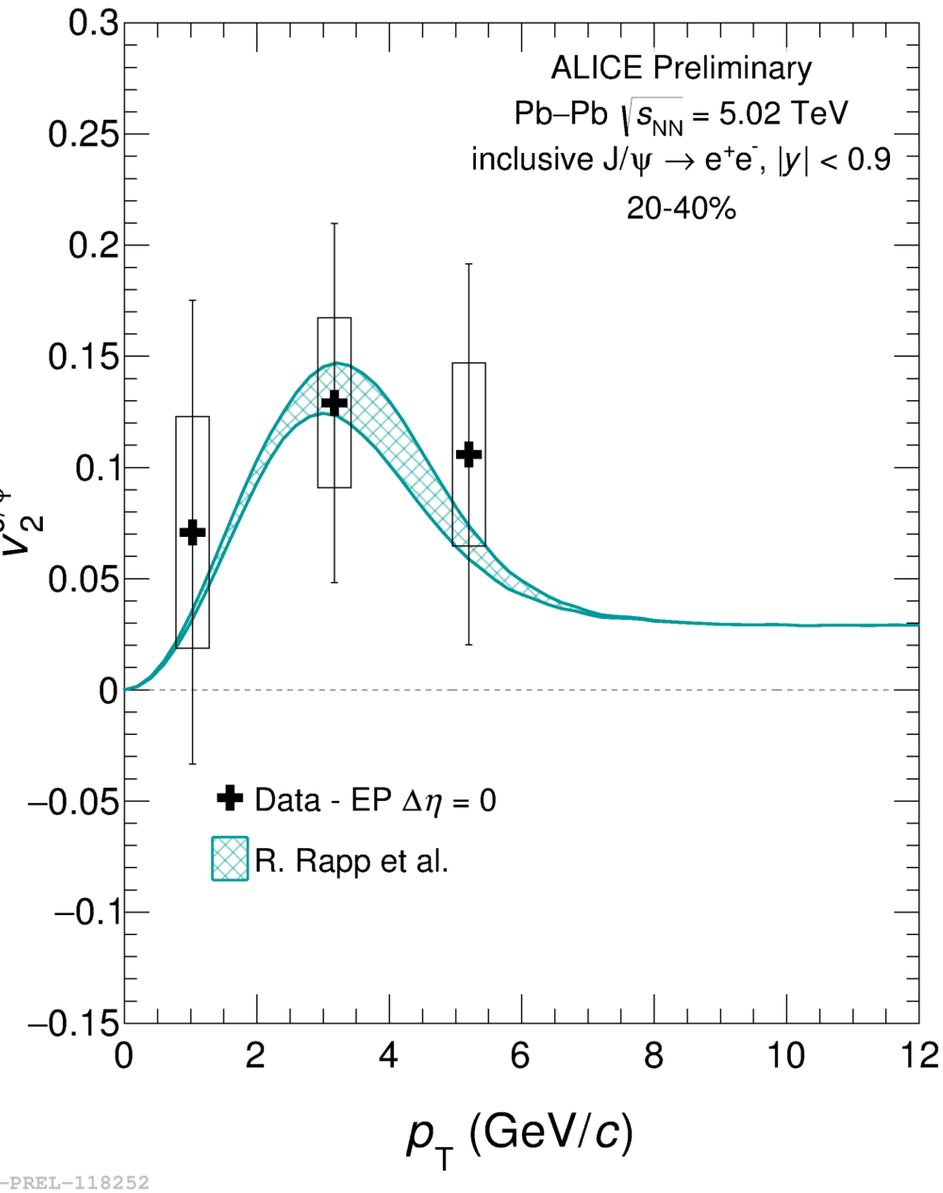
ALI-PREL-118873

ALI-PREL-118240

J/ψ elliptic flow : comparison to dielectron channel



ALI-PREL-118900



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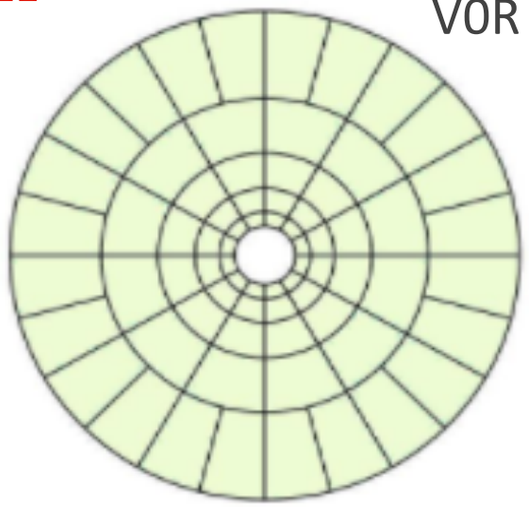
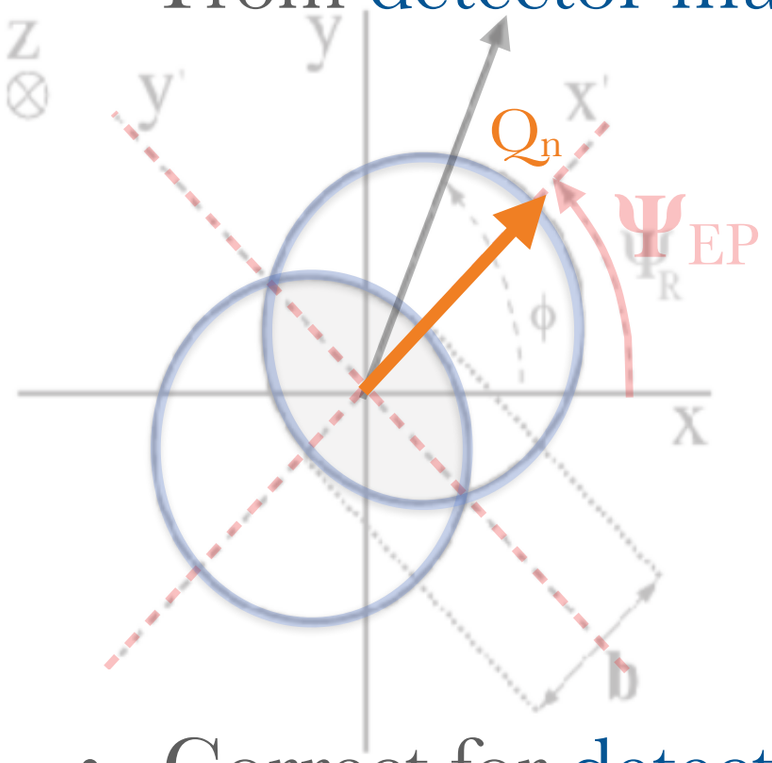
Detector equalization and resolution

- Focus on methods based on event plane determination



  - From detector multiplicities :



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

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

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

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

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

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

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

- Deal with non-uniform acceptance

Detector equalization and resolution

- Maximum residual oscillations after equalisation :
  SPD (20-30%): $v_2 \simeq 0.0012$; $v_4 \simeq 0.015$; $v_6 \simeq$ 2e-6

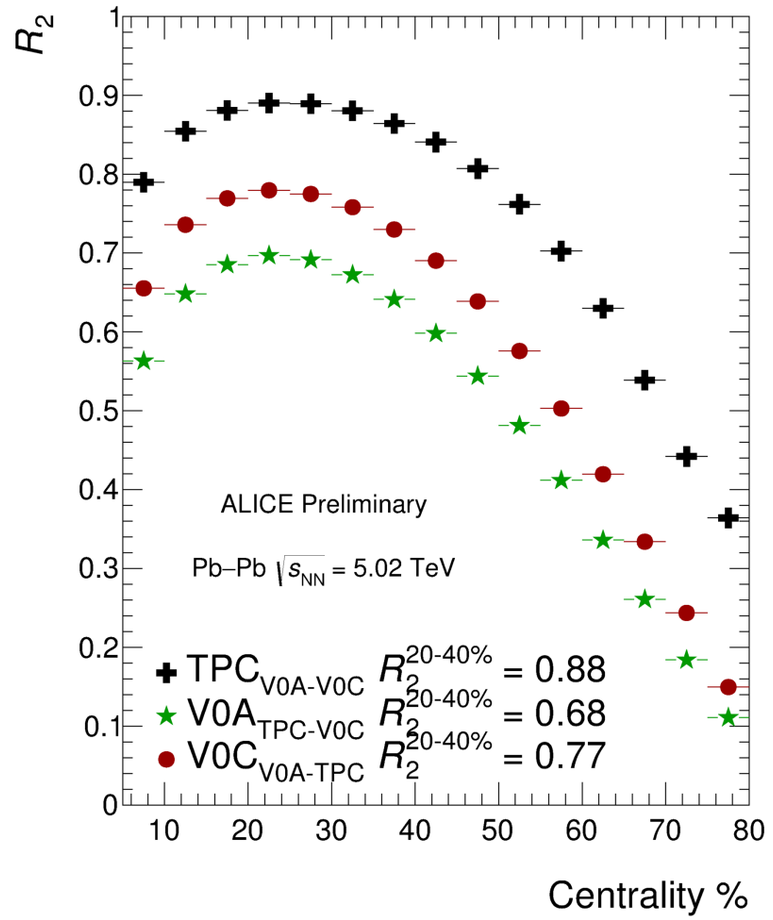
- ratio of cross-terms to same-terms as an estimation of the uncertainty on the EP determination : 1% systematic uncertainty correlated with centrality

- Resolution calculated using the 3 sub-events method with V0A, V0C and SPD

- Centrality bins used for J/ψ v_2 analysis are large

- Non uniform distribution of the number of J/ψ

	5-20%	20-40%	40-60%	60-90%
SPD	0.87297±0.00019	0.91031±0.00014	0.83192±0.00022	0.55432±0.00333



Equalization steps

1. Gain equalization of individual detector channels

$$M_c' = M_c / \langle M_c \rangle$$

2. Recentering

$$\boldsymbol{q}_n' = \boldsymbol{q}_n - \langle \boldsymbol{q}_n \rangle$$

3. Width equalization

$$\boldsymbol{q}_n'' = \boldsymbol{q}_n' / \sigma_{\boldsymbol{q}_n}$$

4. Alignment

$$\boldsymbol{q}_n''' = \boldsymbol{q}_n'' + \boldsymbol{q}_{n,\phi}''$$

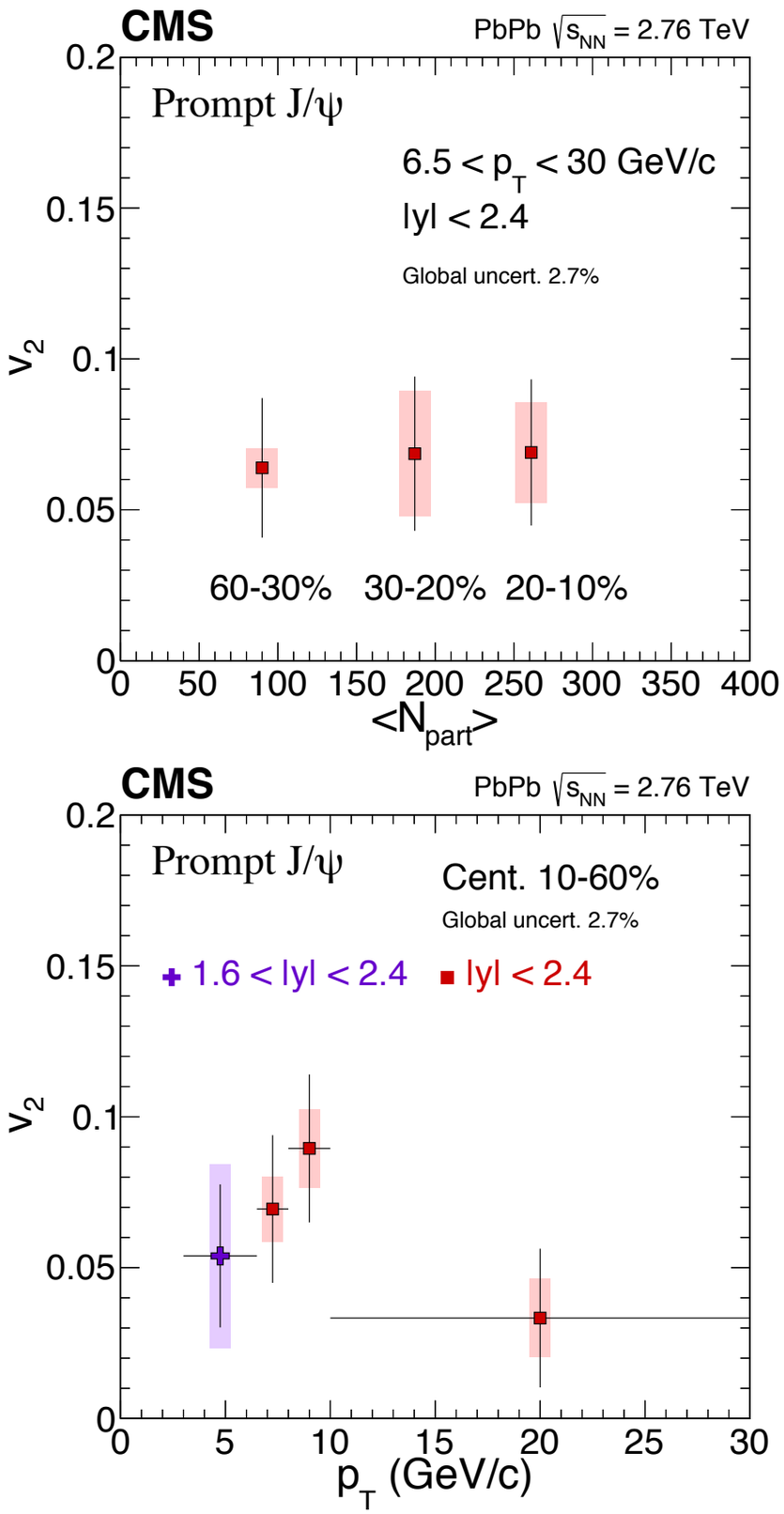
5. Twist

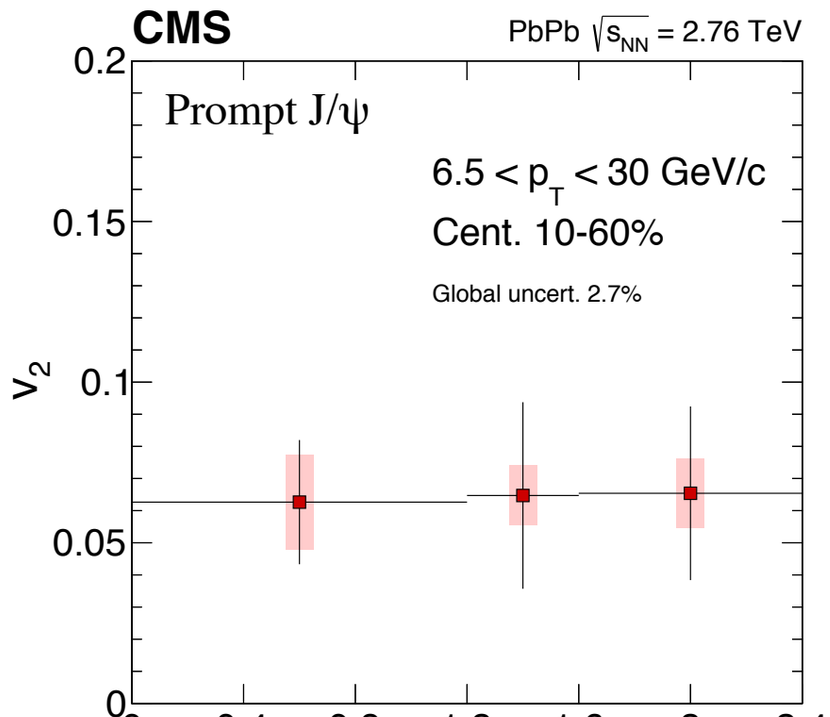
$$q_{n,(x,y)}'''' = (q_{n,(x,y)}''' - \Lambda_{2n}^{s(+,-)} q_{n,(y,x)}''')/(1 - \Lambda_{2n}^{s-}\Lambda_{2n}^{s+})$$

6. Rescaling

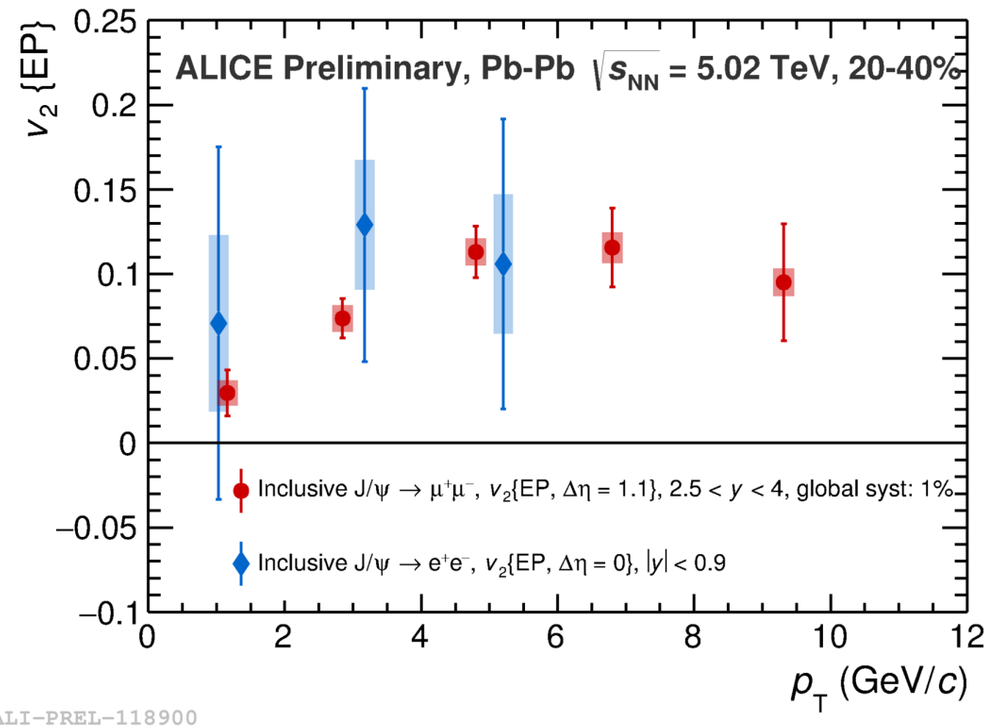
$$q_{n,(x,y)}''''' = q_{n,(x,y)}''''/A_{2n}^{(+,-)}$$

CMS results for J/ψ v_2





EPJC 77 (2017) 252

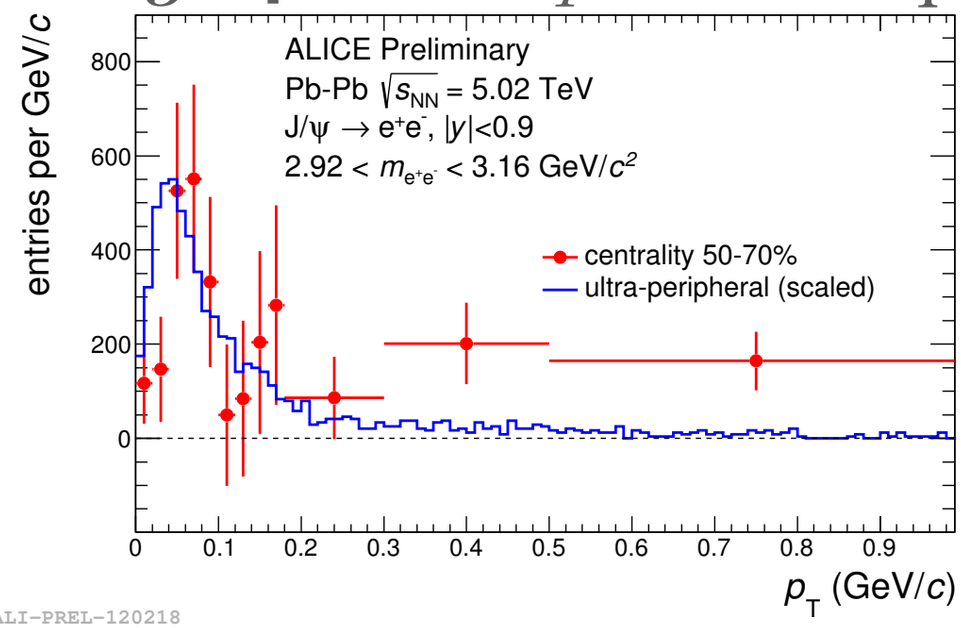


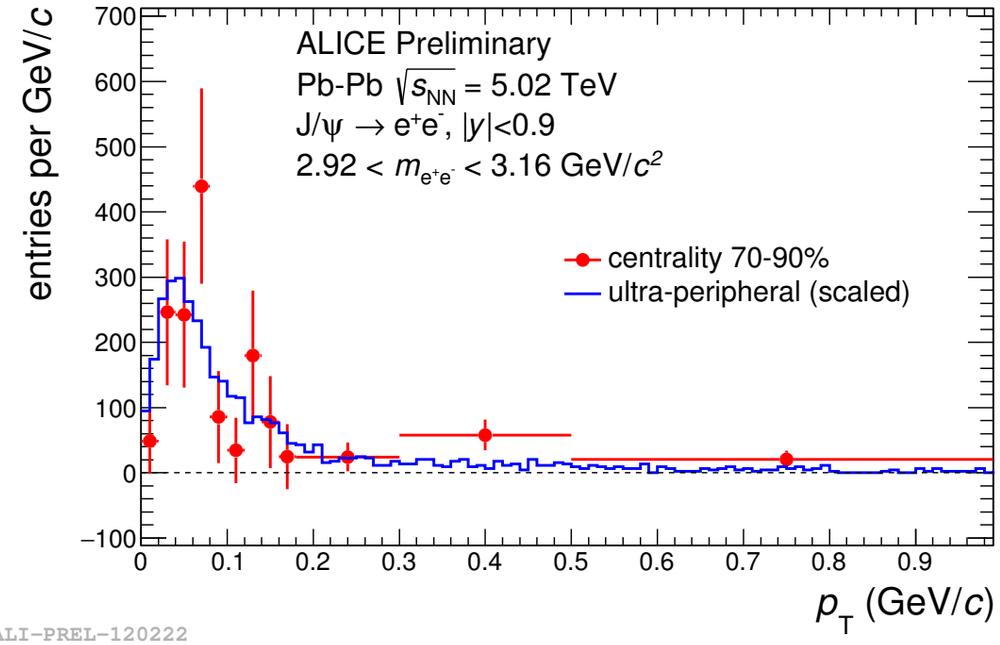
ALI-PREL-118900

Low-p_T excess

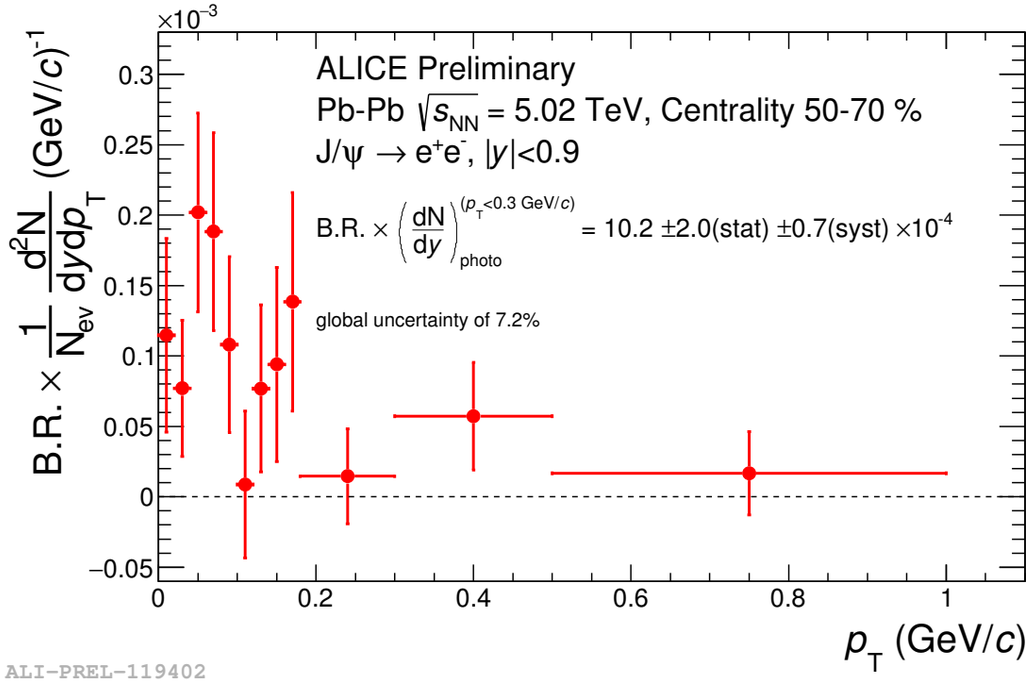
Compared to expected shape from J/ψ hadro-production :

visible excess of J/ψ at low p_T in semi-peripheral and peripheral collisions





ALI-PREL-120218



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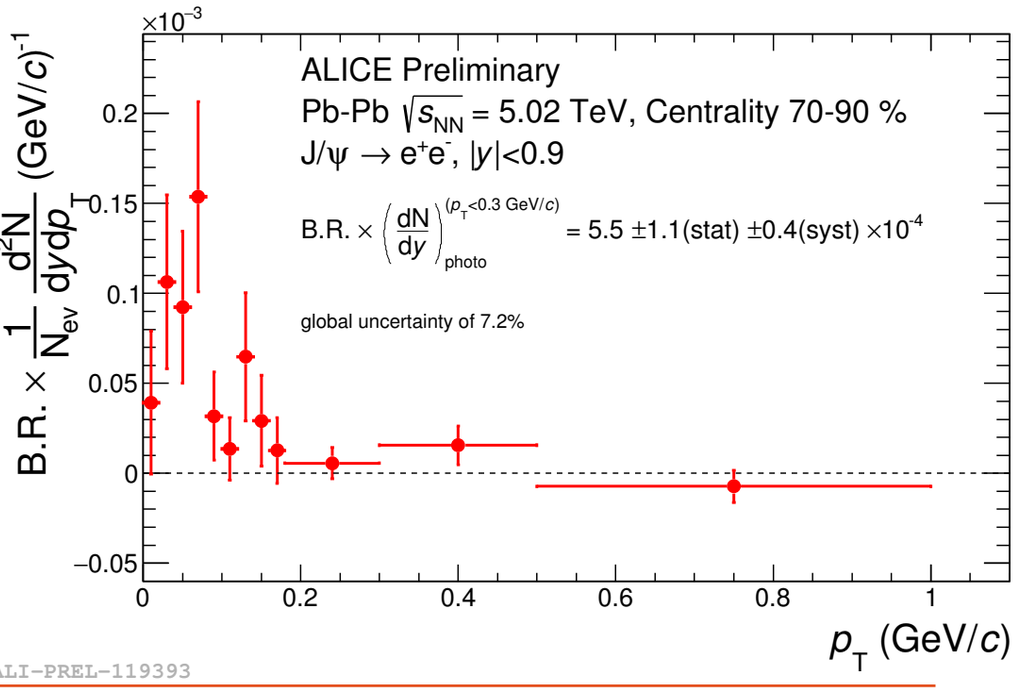
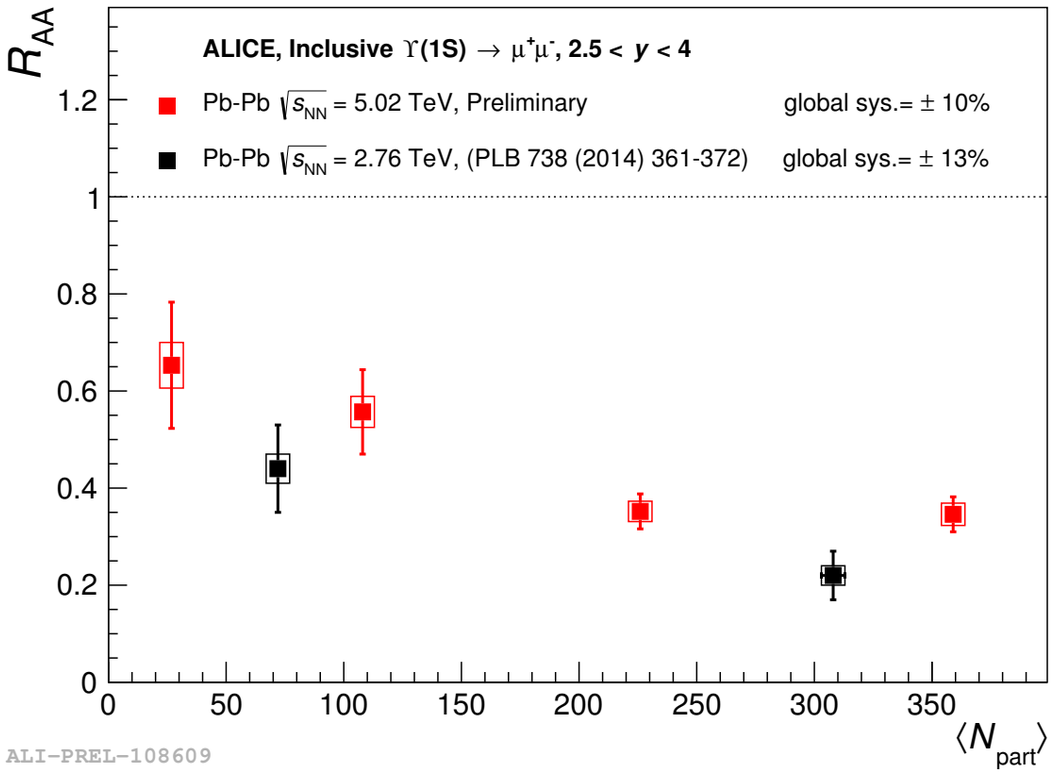
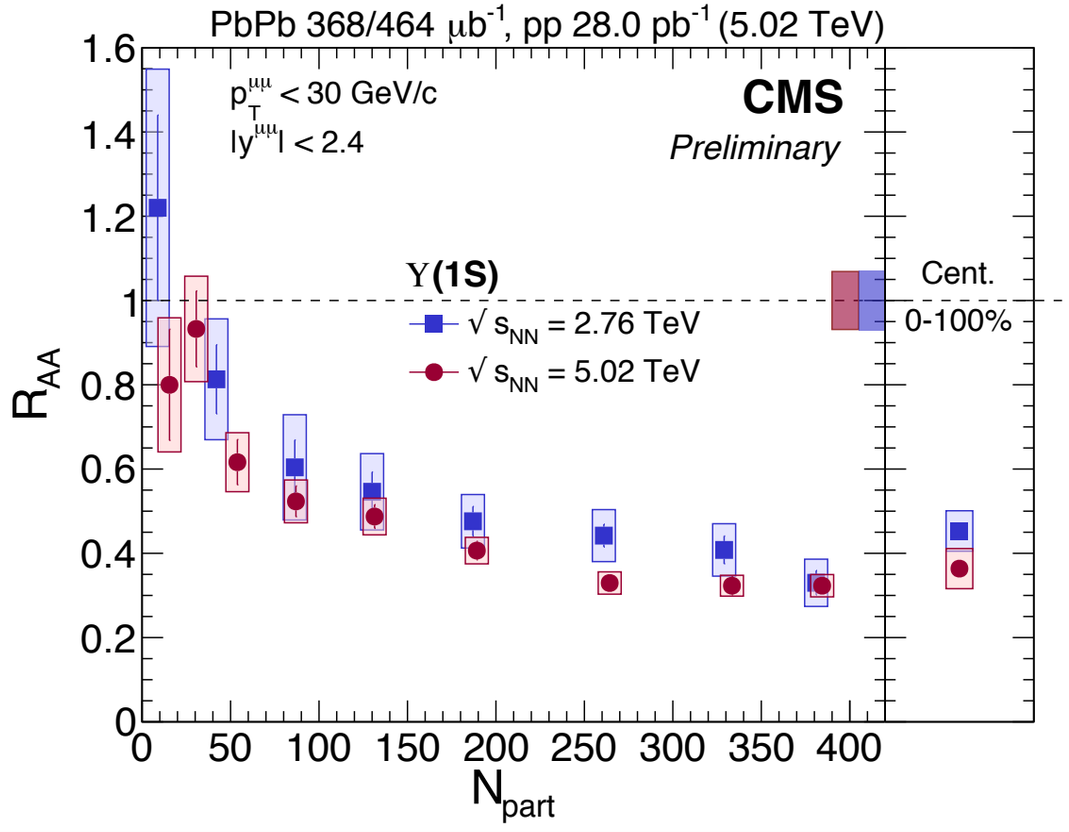
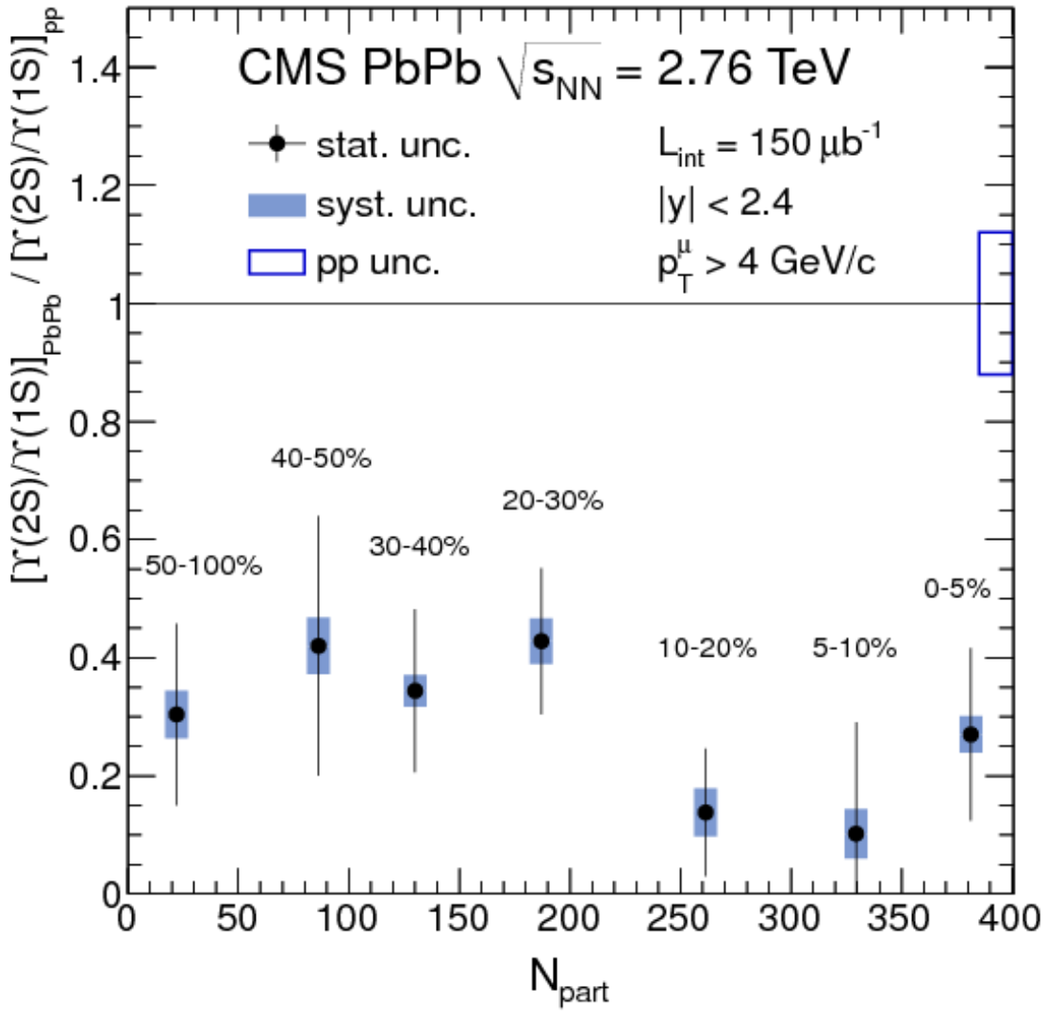


ALI-PREL-119393

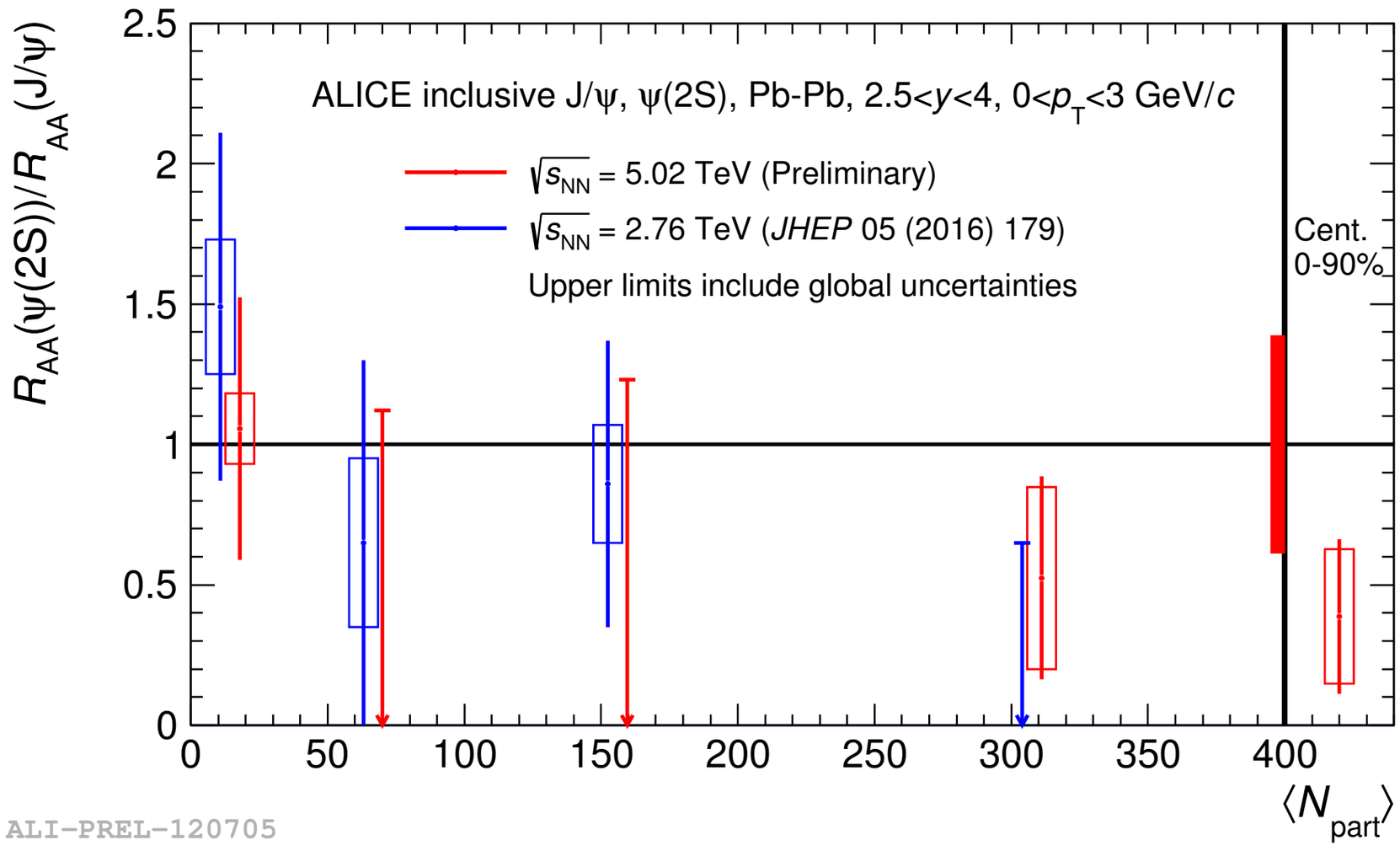
Υ(1S) suppression vs N_{part}







ψ(2S)/ψ(1S) R_{AA} ratio vs $\sqrt{s_{NN}}$ = 2.76 TeV



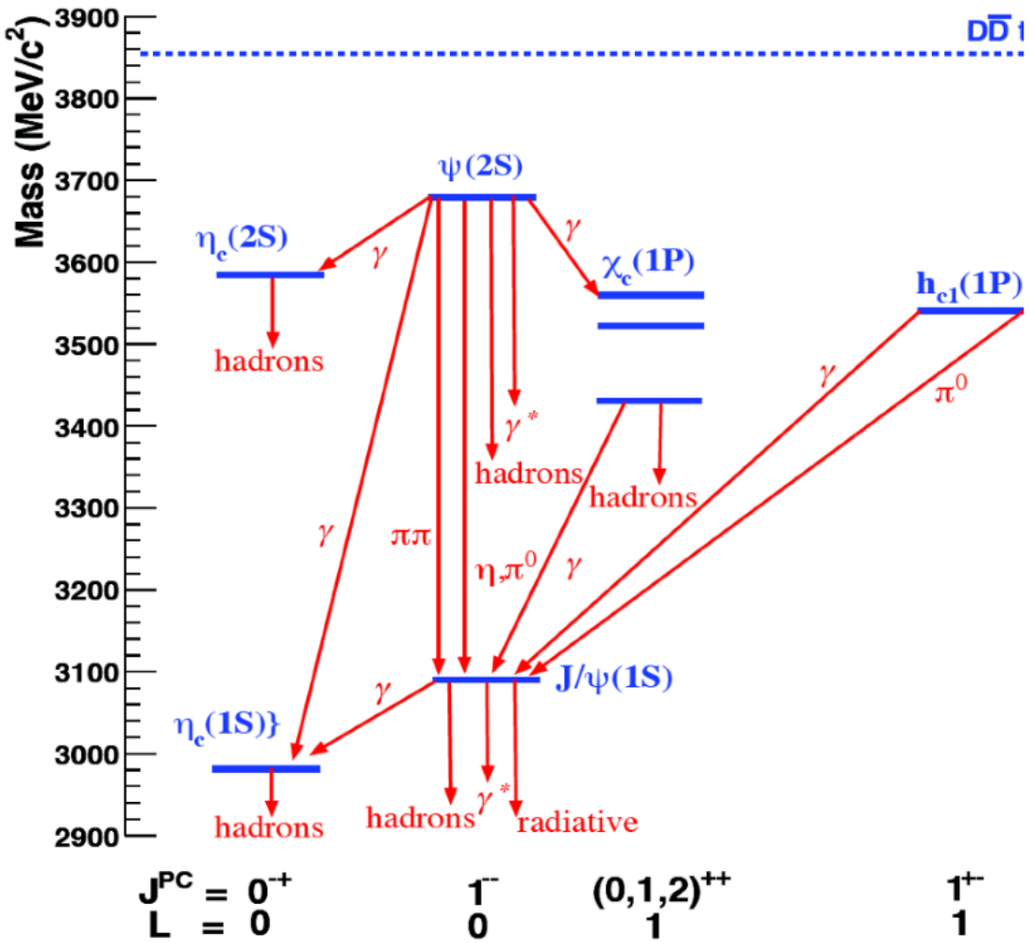
ALI-PREL-120705

Quarkonia particles

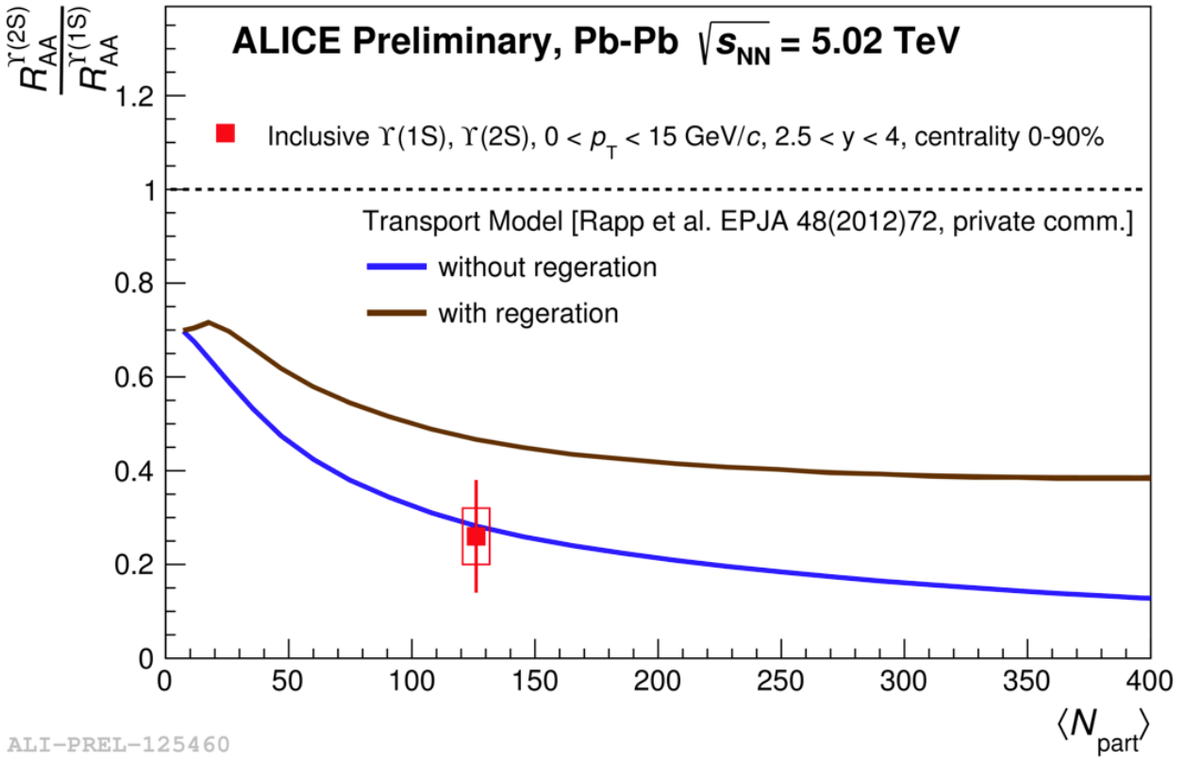
H. Satz, J. Phys. G32 (2006) R25

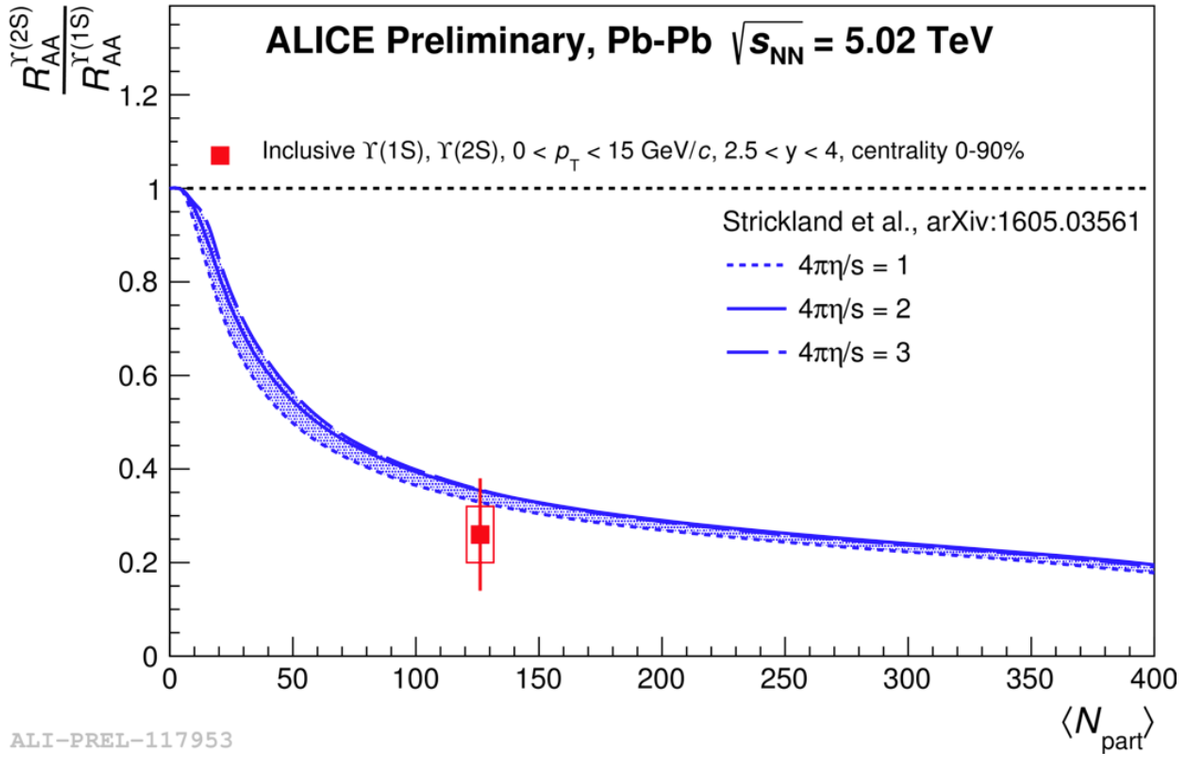
State	J/Ψ	χ_c	Ψ′	Υ	χ_b	Υ'	χ_b'	Υ''
mass [GeV]	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
ΔE[GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
ΔM[GeV]	0.02	-0.03	0.03	0.06	-0.06	-0.06	-0.08	-0.07
radius [fm]	0.25	0.36	0.45	0.14	0.22	0.28	0.34	0.39

Charmonia decay schemes:



Υ(2S) Nuclear Modification factor and 1S/2S ratio





- Stronger suppression of Υ(2S) with respect to Υ(1S)
- Compatible with anisotropic dynamics description and transport models without regeneration
- More statistics are needed → LHC run3