Quarkonium production in pp, p-Pb, Pb-Pb collisions with ALICE at LHC

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QCD@Work - 7th International Workshop on QCD – Theory and Experiment

Outline

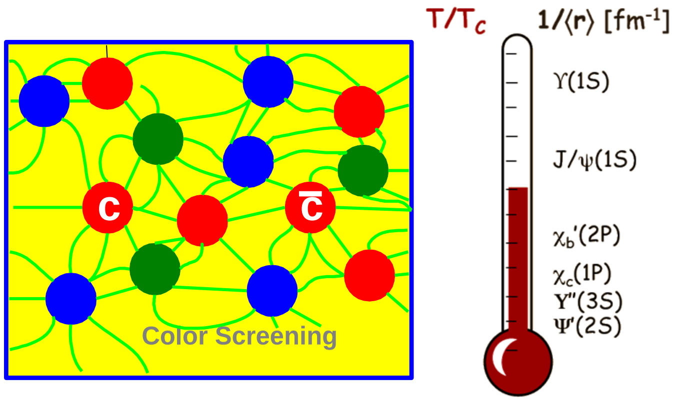
- Physics motivation
- ALICE setup
- ALICE results
  - Quarkonium in pp collisions at $\sqrt{s}$=2.76 TeV
  - Pb-Pb measurements at $\sqrt{s_{NN}}$ = 2.76 TeV
    - nuclear modification factor
  - p-Pb measurements at $\sqrt{s_{NN}}$ = 5.02 TeV
    - cold nuclear matter effects
- Conclusion and outlook

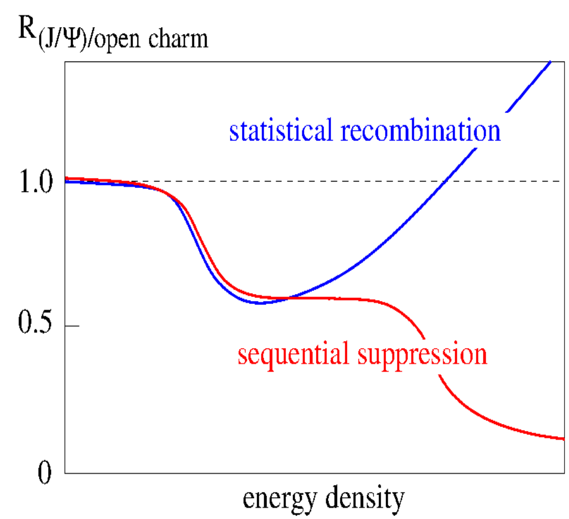
Probing the QGP : Quarkonium suppression and enhancement

- Quarkonium (J/ψ) suppression [Matsui,Satz; PLB 178 (1986) 416]
  - Color screening of strong interactions in QGP
  - Higher states are more easily dissociated, sequential suppression of resonances
- J/ψ enhancement [Braun-Munzinger, Stachel; PLB 490(2000) 196]
  - The $c\bar{c}$ production increases strongly with energy

In most central collisions [0-10%]	RHIC 200 GeV	LHC 2.76 TeV
N_{ccbar}/event	13	115
N_{bbbar}/event	0.1	3

  - A (re)combination of $c\bar{c}$ pairs to produce quarkonia may take place during the QGP stage or at the phase boundary





Digal, Satz,Vogt; PRC 85, (2012) 034906

Different sources of medium effects

- Nuclear modification factor R_{AA}:
  Ratio of the quarkonium yield in AA (Y_{AA}) with respect to the pp one, scaled by the overlap factor T_{AA} (from Glauber model)

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

If yield scales with the number of binary collisions

→ $R_{AA} = 1$

and if,

→ $R_{AA} \neq 1$

there are medium effects

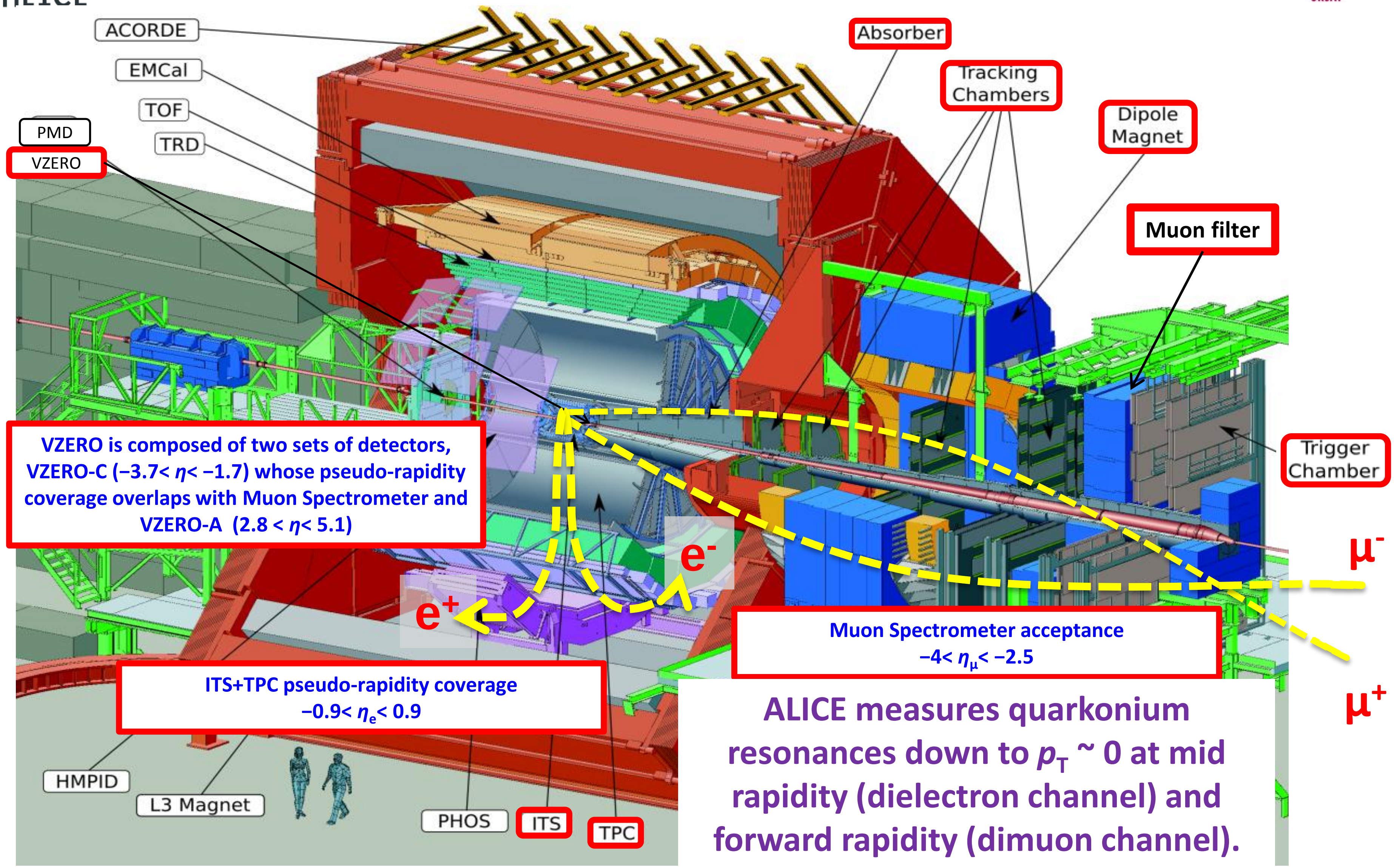
Hot Medium effects:

- Quarkonium suppression
- Enhancement due to recombination

Cold Nuclear Matter effects (CNM):

- Nuclear parton shadowing/gluon saturation
- Parton energy loss
- $c\bar{c}$ in medium break-up

ALICE setup

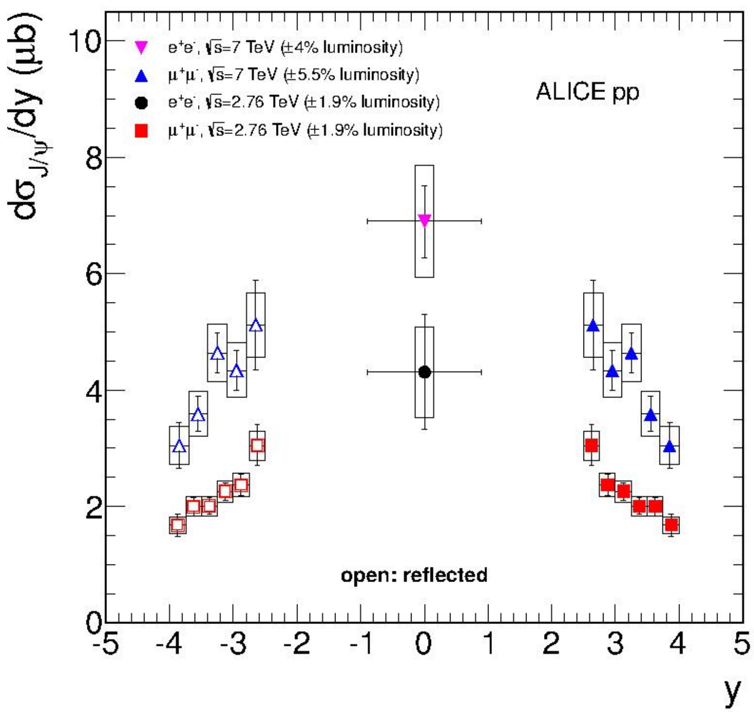


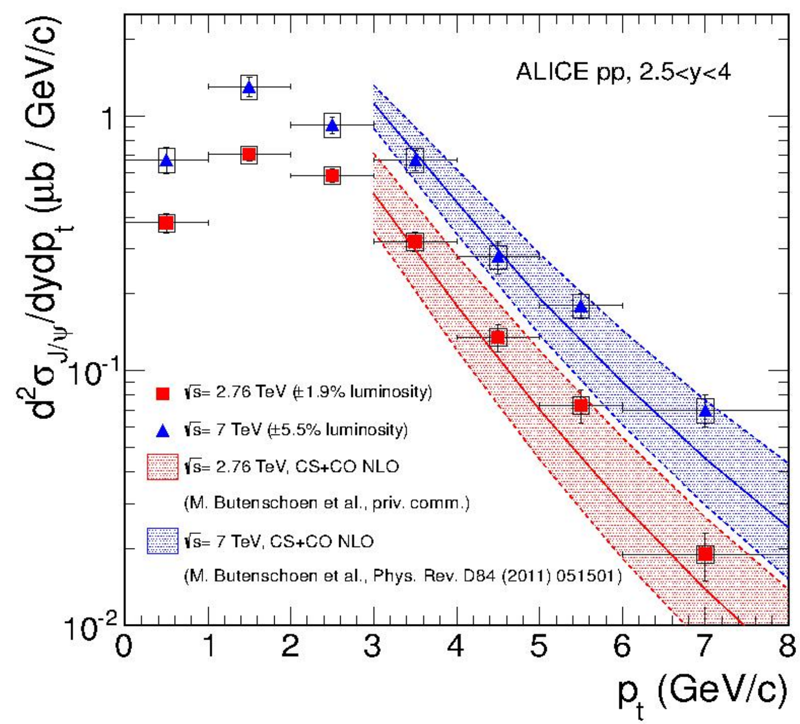
ALICE measures quarkonium resonances down to $p_T \sim 0$ at mid rapidity (dielectron channel) and forward rapidity (dimuon channel).

ALICE Results : Reference set pp collisions

Data taking at √s=2.76 TeV essential to build the R_{AA} reference, result based on L_{int}^{e}=1.1 nb^{-1} and L_{int}^{μ}=19.9 nb^{-1}

$$\sigma_{J/\psi}(|y|<0.9) = 7.75 \pm 1.78(\text{stat.}) \pm 1.39(\text{syst.}) + 1.16(\lambda_{HE}=1) - 1.63(\lambda_{HE}=-1)\,\mu\text{b and}$$
$$\sigma_{J/\psi}(2.5<y<4) = 3.34 \pm 0.13(\text{stat.}) \pm 0.27(\text{syst.}) + 0.53(\lambda_{CS}=1) - 1.07(\lambda_{CS}=-1)\,\mu\text{b.}$$





ALICE Coll., PLB 718 (2012) 295

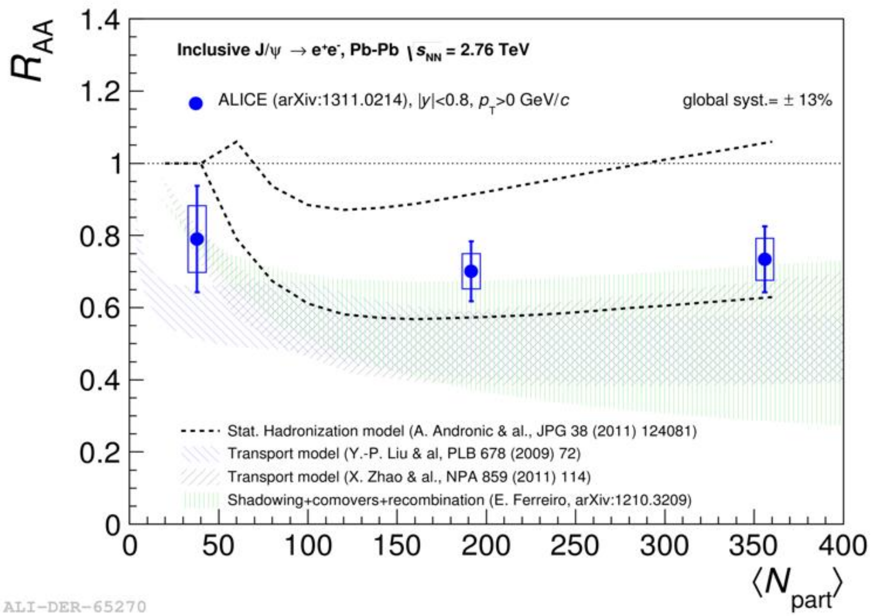
(Note the updated high precision results of pp at √s=7 TeV is available at arXiv:1403.3648)

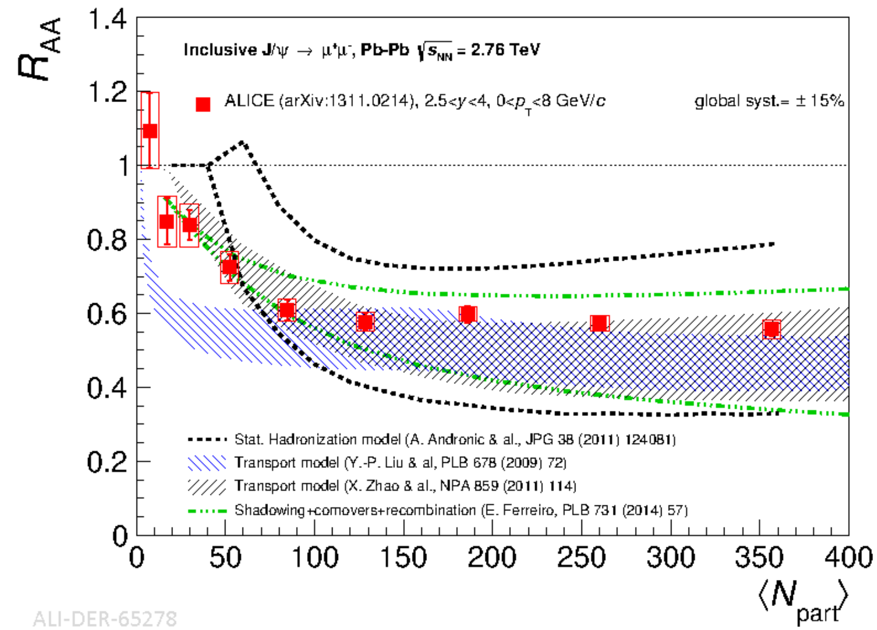
Results in agreement with NLO NRQCD calculations

J/ψ R_{AA} in Pb-Pb

A reduction of the J/ψ yield wrt to pp collisions is observed at SPS (√s=17GeV), RHIC (√s=200GeV) and finally LHC (√s=2.76TeV)! [ALICE central and forward rapidity luminosities are $23\mu b^{-1}$ and $70\mu b^{-1}$, respectively]

Julian Book, QM (2014)

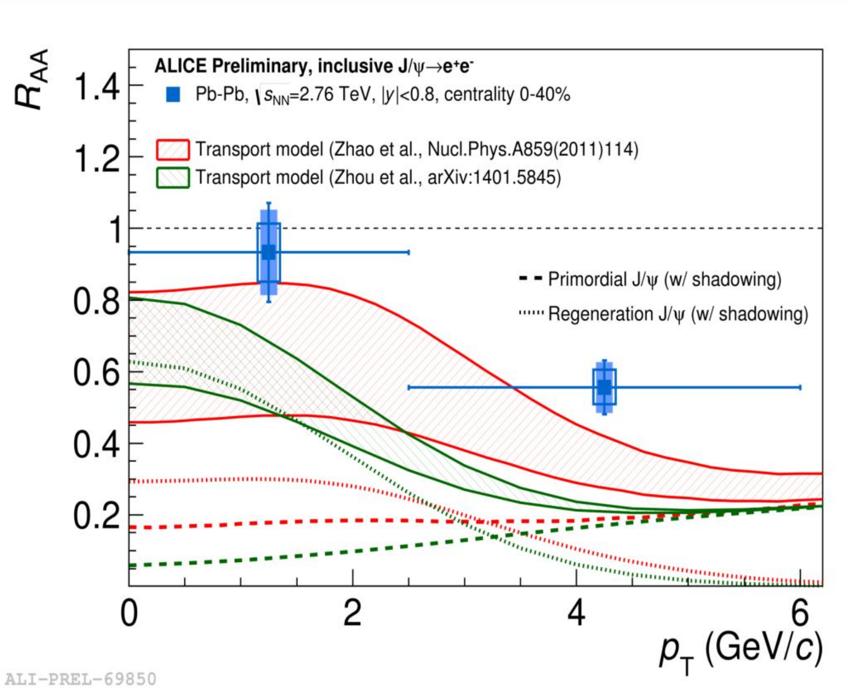




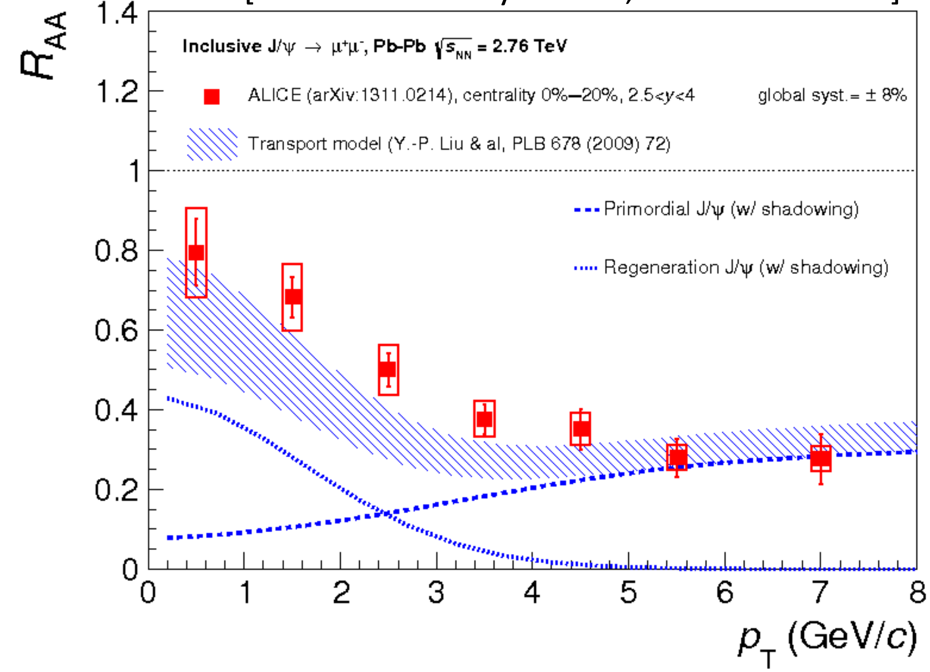
Statistical hadronization and transport models which respectively feature a full and a partial J/ψ suppression of charm quarks at hadronization or in the QGP phase can describe the data. Note that both models take into account the recombination of $c\bar{c}$ pair to J/ψ during the QGP stage or at the phase boundary.

J/ψ R_{AA} in Pb-Pb

Another signature of recombination is visible when the R_{AA} is plotted as function of p_T . For central events, the model prediction of ~50% low-p_T J/ψ production via recombination and no recombination at high-p_T well reproduces the data in left plot for mid-rapidity and right plot for forward rapidity.

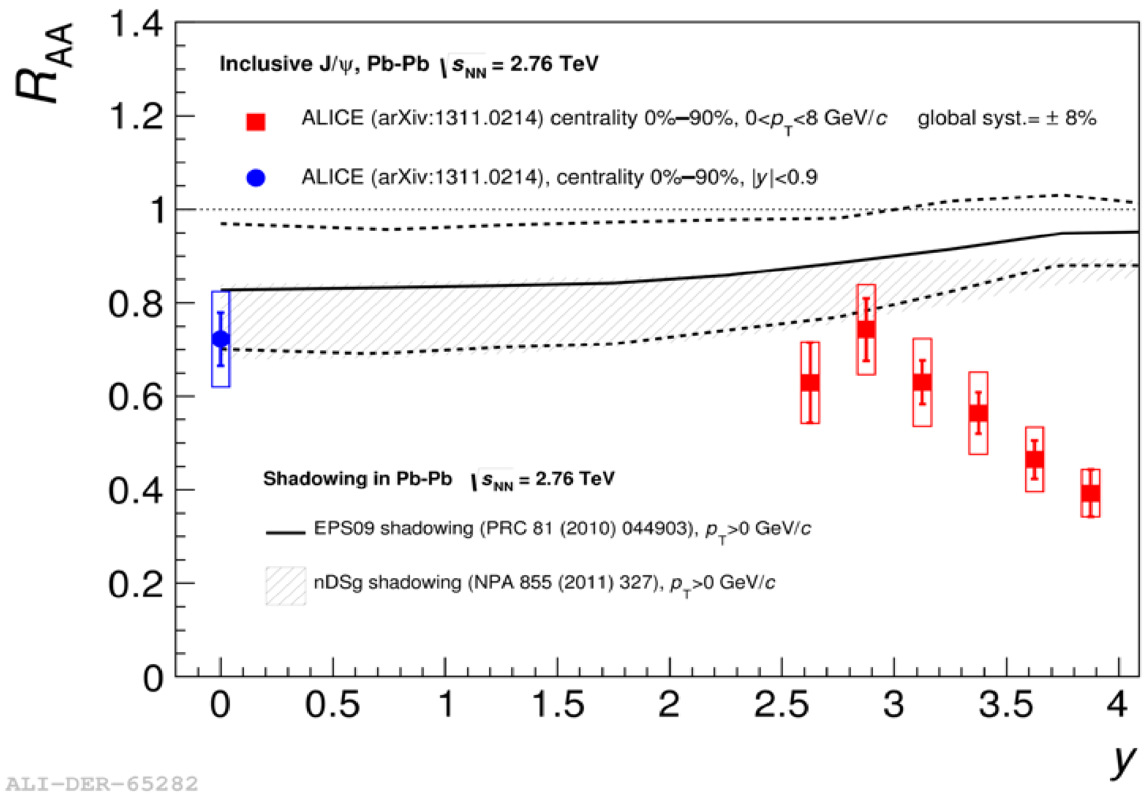


[submitted to Phys.Lett.B, arXiv:1311.0214]



J/ψ R_{AA} in Pb-Pb

Inclusive J/ψ measured also as a function of rapidity: R_{AA} decreases by 40% from *y*=2.5 to *y*=4

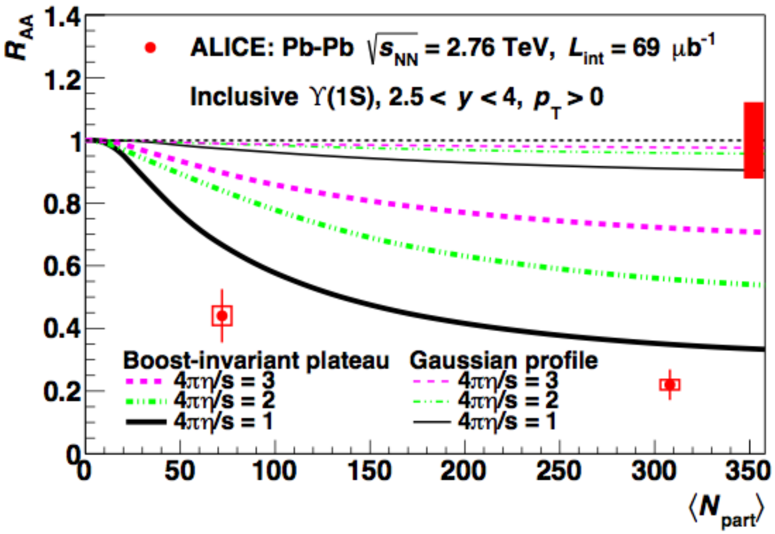


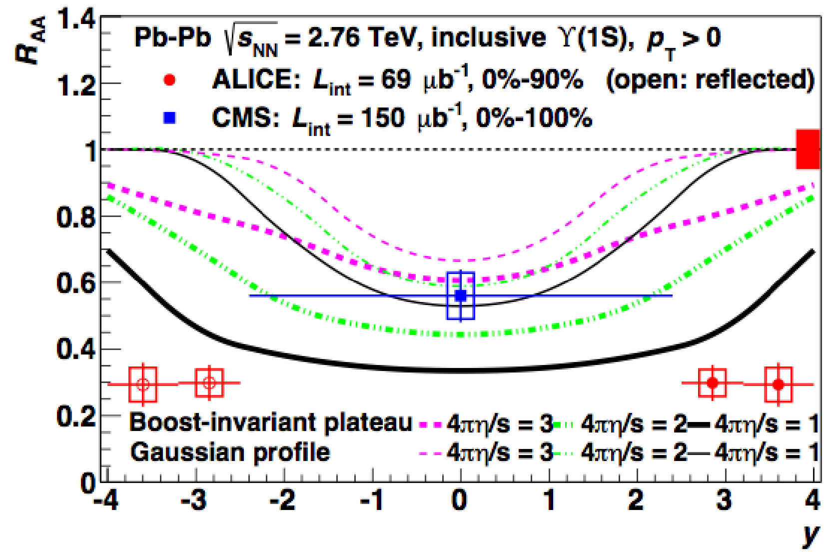
[submitted to Phys.Lett.B, arXiv:1311.0214]

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

A strong suppression have been observed in the inclusive measurement of $\Upsilon(1S)$ state in heavy-ion collision at forward rapidity (2.5<y<4.0)

arXiv:1405.4493





CMS: PRL109 (2012) 222301

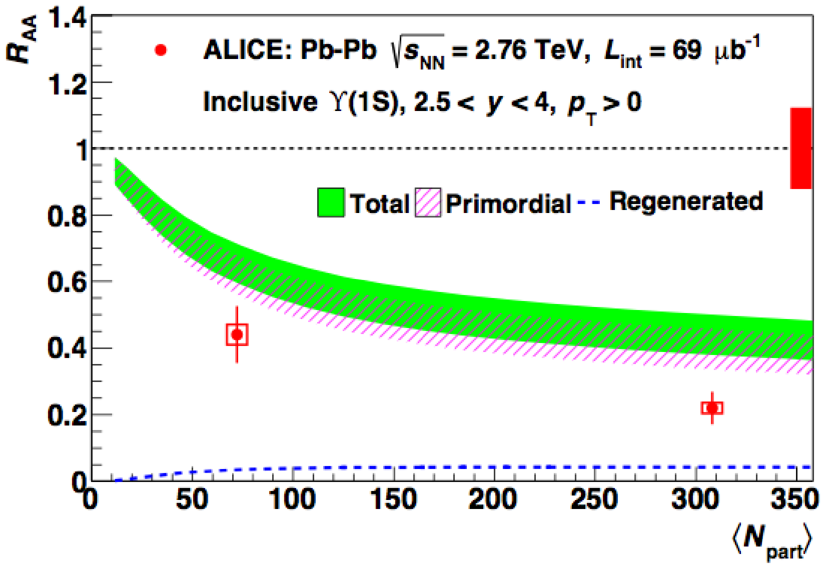
M. Strickland, [arXiv:1207.5327]

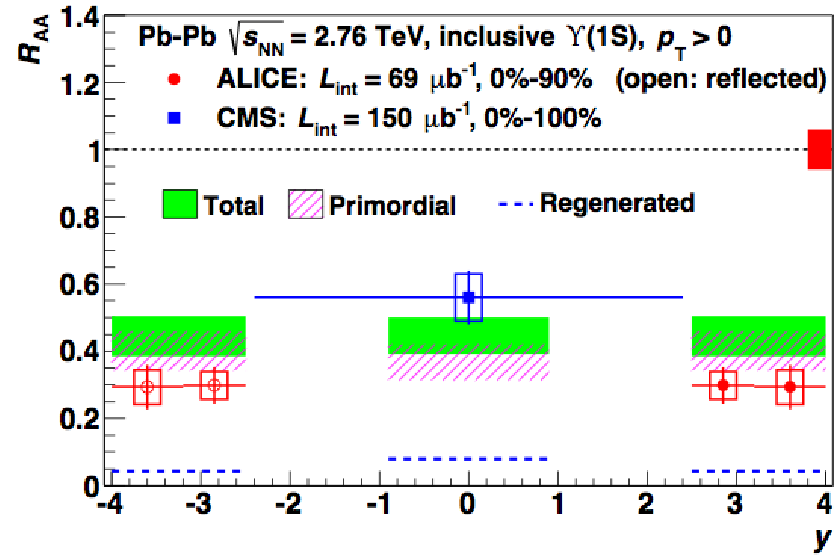
- Thermal suppression of bottomonium states
- Anisotropic hydro model
- Two temperature rapidity profiles: Boost invariant or Gaussian
- Three shear viscosities
- Feed down from higher mass states included
- No CNM included
- No regeneration included

In all cases the model underestimates the measured Y(1S) suppression at forward rapidity

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

arXiv:1405.4493





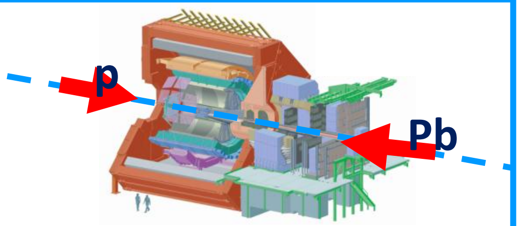
CMS: PRL109 (2012) 222301

A. Emerick et al., [EPJ A48 (2012) 72]

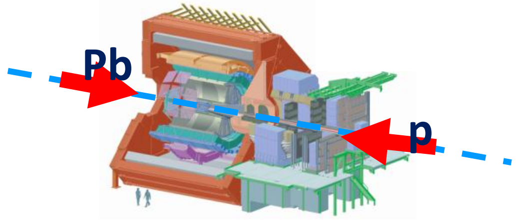
- Transport model
- Suppression of $\Upsilon(1S)$ resonances by the QGP
  - Mainly of the higher mass states
- Small regeneration component included
- Feed down from higher mass states included
- CNM included via an "effective" σ_{ABS} = 0–2 mb

Model does not reproduce the strong rapidity dependence of the R_{AA} and underestimates the $\Upsilon(1S)$ suppression at forward rapidity

R_{pA} in p-Pb



$2.03<y_{CMS}<3.53$ L~5.03 nb^{-1}



$-4.46<y_{CMS}<-2.96$ L~5.81 nb^{-1}

ALICE collected p-Pb/Pb-p data at $\sqrt{s_{NN}}$=5.02TeV at the beginning of 2013

$\Delta y = 0.465$ towards the direction of p-beam

Nuclear modification factor R_{pA}:

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

The full coverage of the ALICE muon spectrometer $2.5<y_{LAB}<4$ can be exploited

Modification factor Q_{pA}:

$$Q_{pA} = \frac{Y_{pA}}{< T_{pA}^{mult} > \cdot \sigma_{pp}}$$

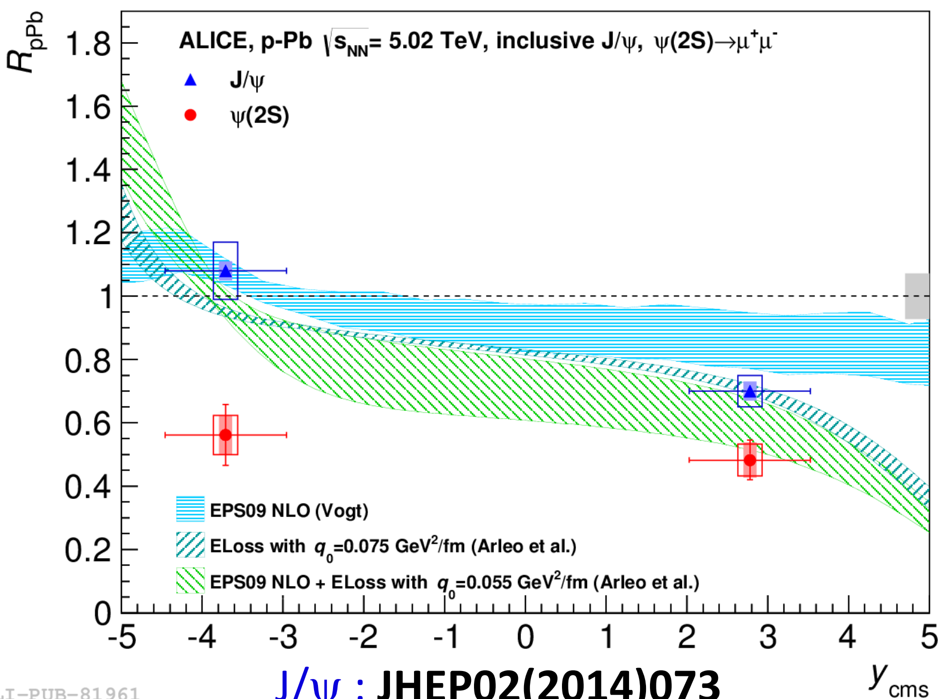
For centrality dependent studies Q_{pA} instead of R_{pA}

[Phys Lett B 727 (2013) 371–380]

In LHC there were no data for pp collision at $\sqrt{s}$=5.02TeV, therefore the reference cross section σ_{pp} is obtained by means of an interpolation procedure based on ALICE data at $\sqrt{s_{NN}}$=7 and 2.76 TeV

J/ψ and ψ(2S) R_{pA} vs y

Theoretical models including initial state effects as shadowing and parton energy loss predict the same suppression (within <5%) for J/ψ and ψ (2S). However, while they are qualitatively in agreement with the J/ψ results they cannot reproduce the ψ (2S) suppression.



J/ψ : **JHEP02(2014)073**

ψ(2S) : **arXiv : 1405.3796**

possible if formation time (τ_f ~0.05-0.15fm/c) < crossing time (τ_c)

forward-*y*:
τ_c~10^{-4} fm/c
backward-*y*:
τ_c~$7\cdot10^{-2}$ fm/c

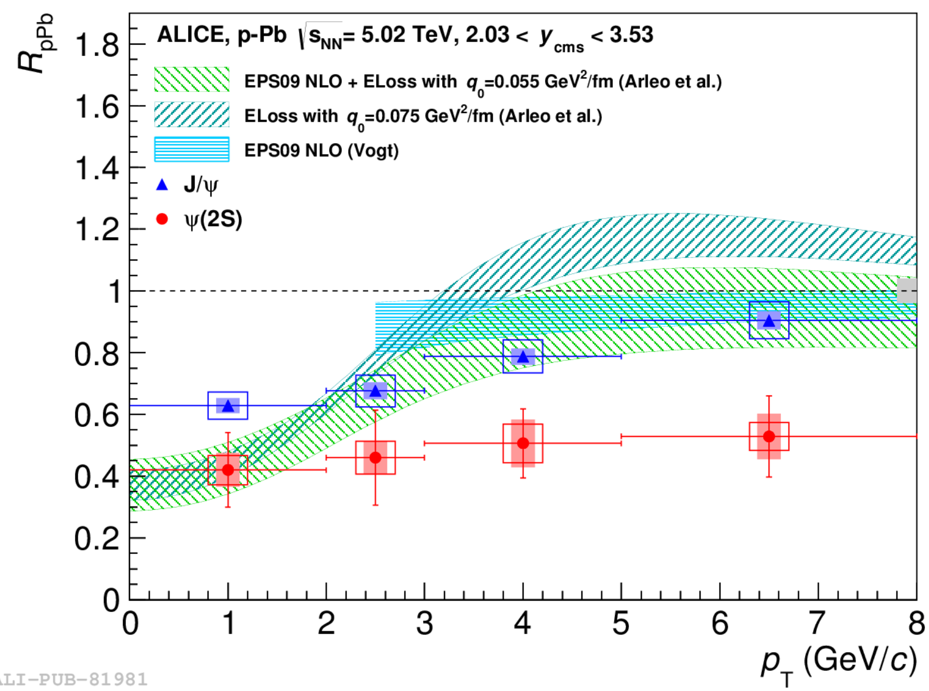
$$\tau_c = \frac{\langle L \rangle}{(\beta_z \gamma)}$$

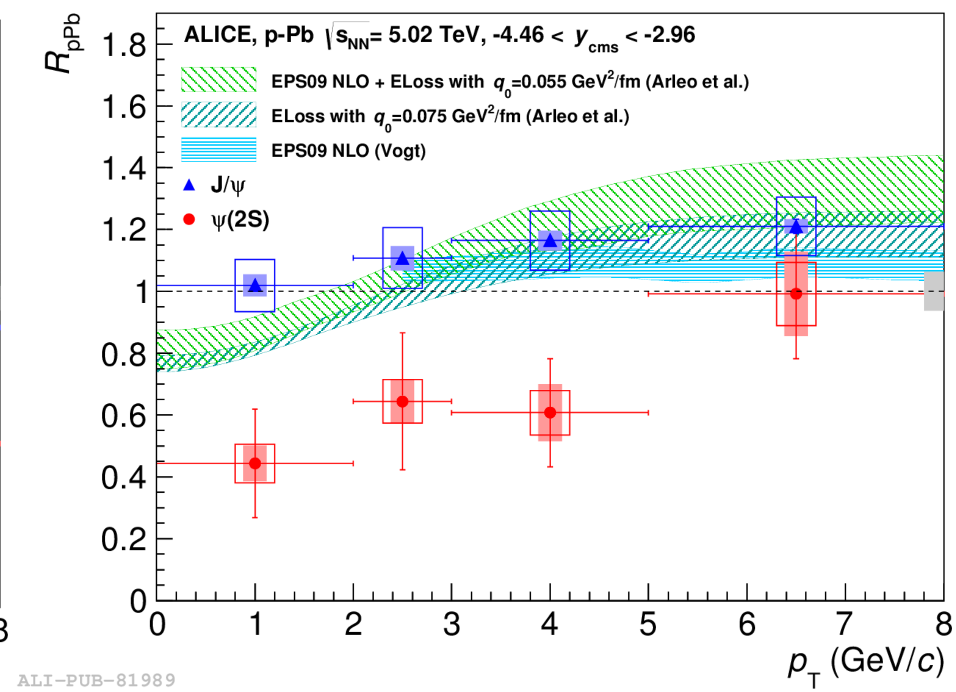
D. McGlinchey, A. Frawley and R.Vogt, PRC 87,054910 (2013)

- break-up effects excluded at forward-*y*
- at backward-*y*, since τ_f ~ τ_c, break-up in CNM can hardly explain the very strong difference between J/ψ and ψ(2S) suppressions

May be the final state effects can explain the observed difference.

J/ψ and ψ(2S) R_{pA} vs p_T

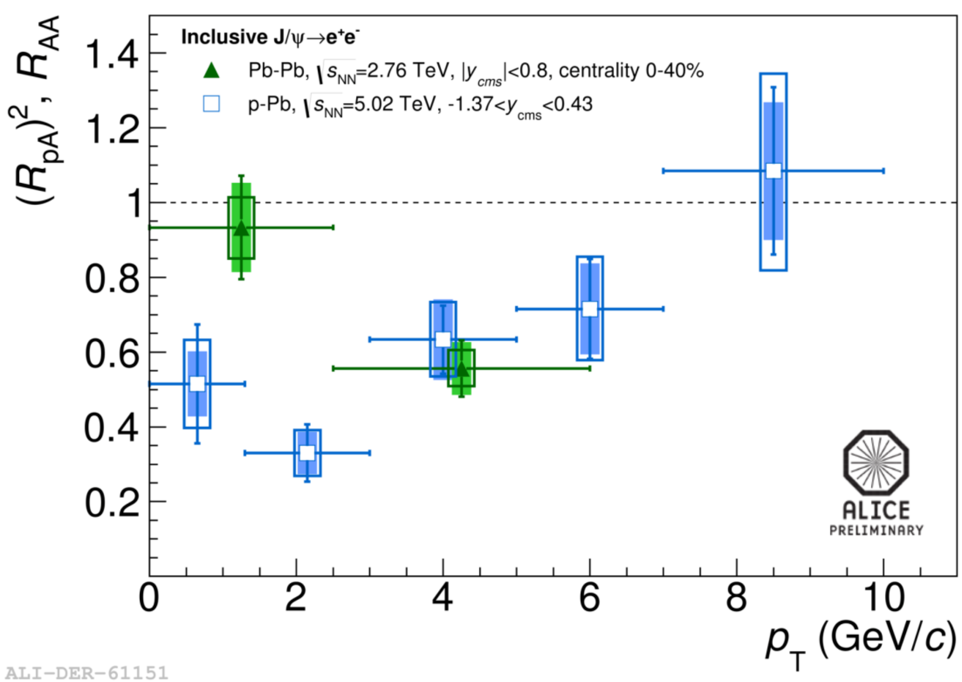


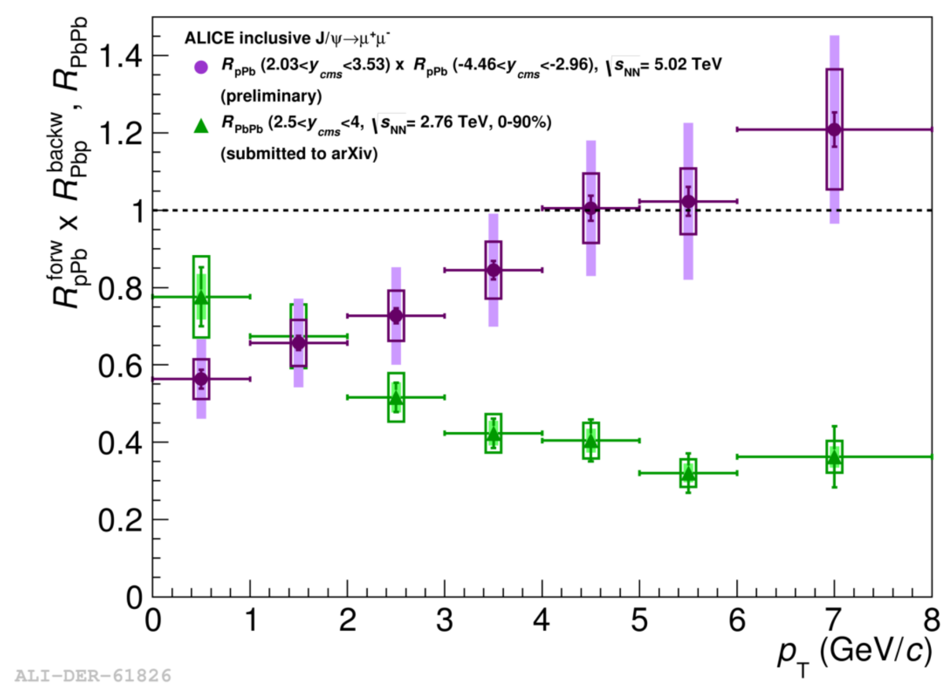


As already observed for the p_T-integrated results, ψ(2S) is more suppressed than the J/ψ

Theoretical models are in fair agreement with the J/ψ, but clearly overestimate the ψ(2S) results

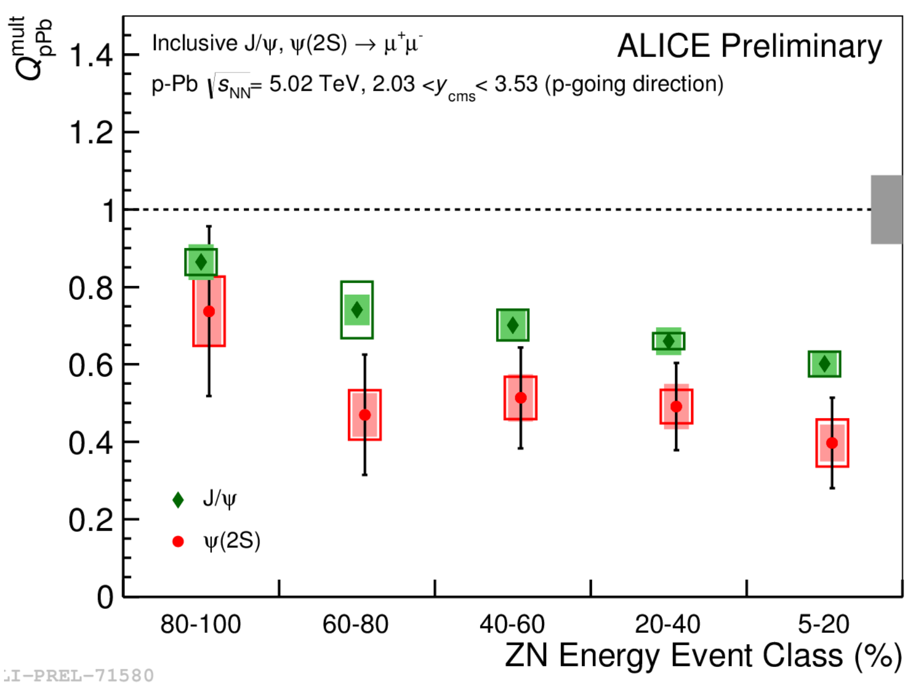
J/ψ R_{pA} and R_{AA} in mid and forward rapidity

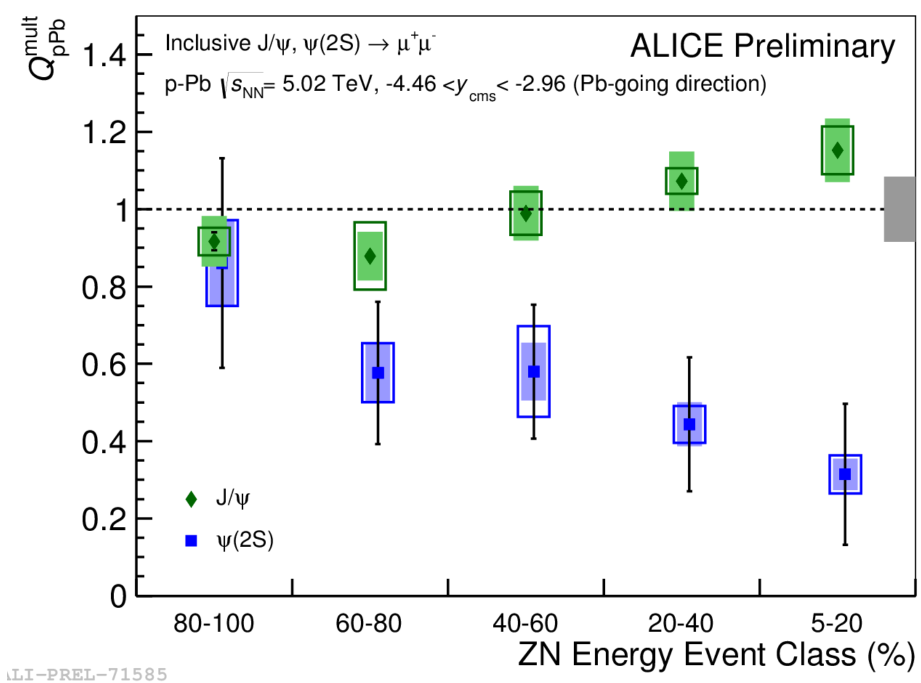




The CNM effects in AA is extrapolated using the pA results. The R_{AA} is compared to R_{pA} x R_{Ap} ($R_{pA}{}^2$ at midrapidity) one can see that CNM effects are not enough to describe the high p_T suppression in AA and that at low p_T there is an enhancement which may be a hint for recombination

J/ψ and ψ(2S) Q_{pA} vs event activity





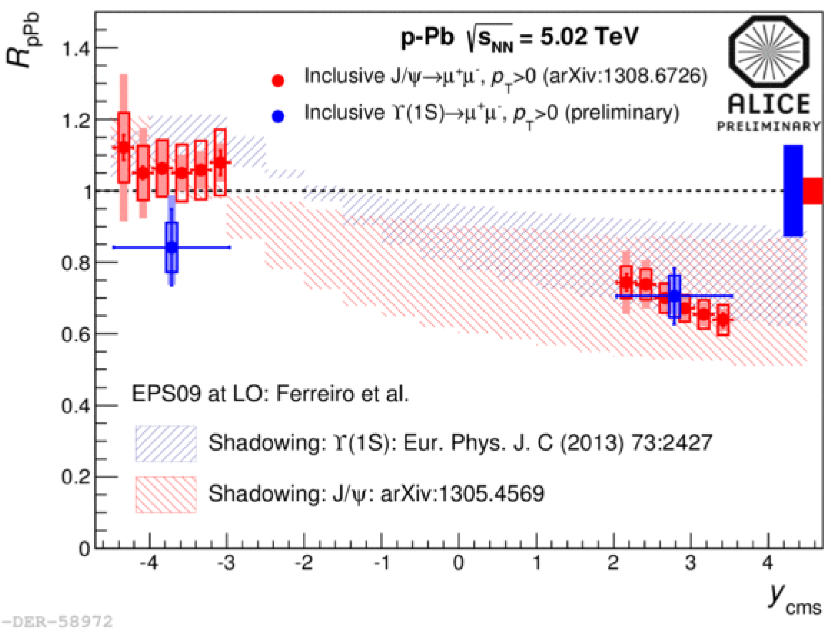
forward-*y:* J/ψ and ψ(2S) show a similar decreasing pattern vs event activity

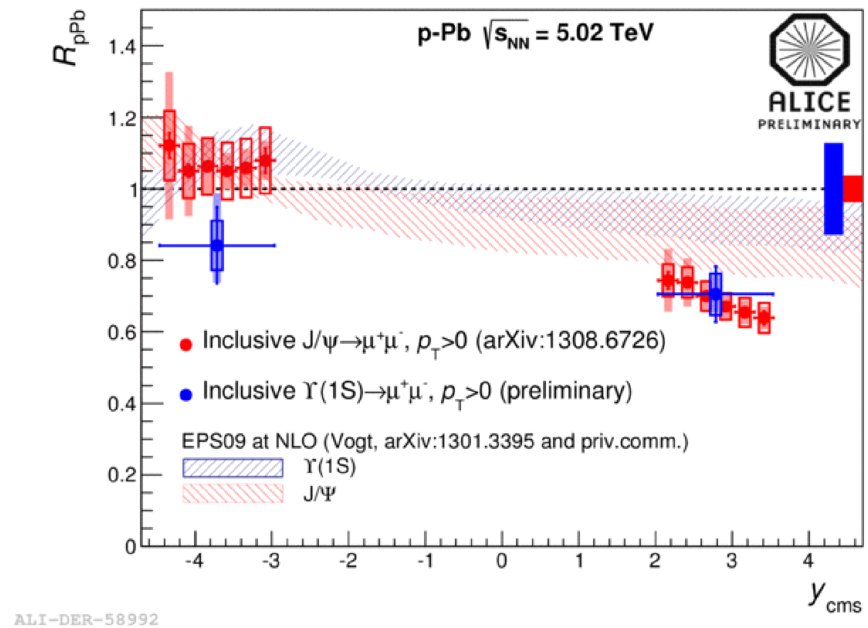
backward-*y:* the J/ψ and ψ(2S) behaviour is different, with the ψ(2S) significantly more suppressed for larger event activity classes

R_{pA} of $\Upsilon(1S)$

ALICE

- Comparison with ALICE J/ψ R_{pPb}
  - Forward: similar suppression
  - Backward: slightly lower R_{pPb} for $\Upsilon(1S)$, but compatible within uncertainties

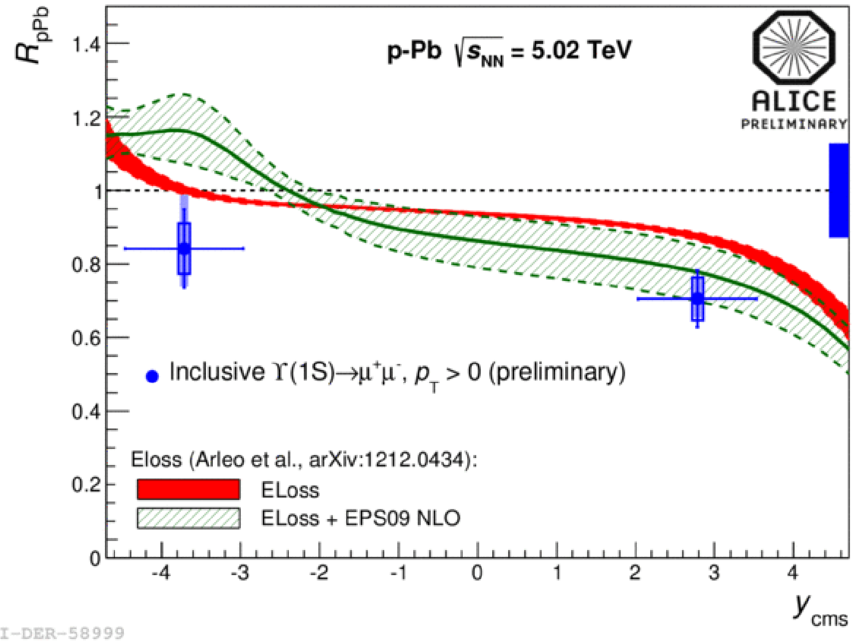




- Ferreiro et al. [EPJC 73 (2013) 2427]
  - 2→2 production model at LO
  - EPS09 shadowing parameterization at LO
  - Fair agreement with measured R_{pPb}
    - Although slightly overestimates it in the antishadowing region

- Vogt [arXiv:1301.3395]
  - CEM production model at NLO
  - EPS09 shadowing parameterization at NLO
  - Fair agreement with measured R_{pPb} within uncertainties
    - Although slightly overestimates it

R_{pA} of $\Upsilon(1S)$



- Arleo et al. [JHEP 1303 (2013) 122]
  - Model including a contribution from coherent parton energy loss
  - With or without shadowing (EPS09)
  - Forward: Better agreement with ELoss and shadowing
  - Backward: Better agreement with ELoss only

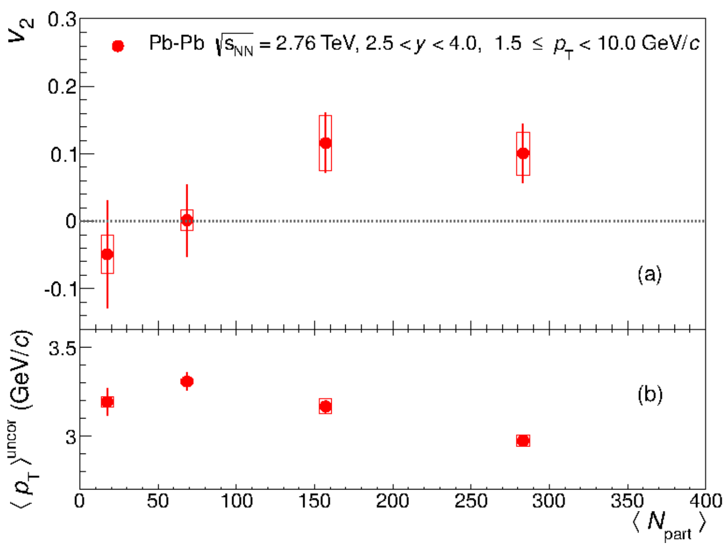
Summary

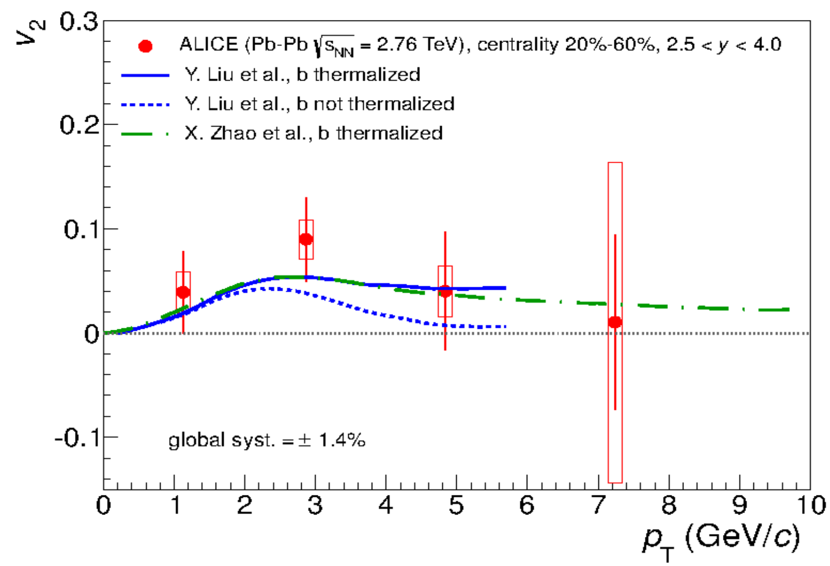
- ALICE findings in Pb-Pb collisions:
  - Two main mechanisms at play
    - Suppression by color screening or dissociation in QGP
    - Re-generation (for charmonium only!) at high $\sqrt{s}$ can qualitatively explain the main features of the results
  - R_{AA} exhibits a weak centrality dependence at all y for charmonium, however $\Upsilon(1S)$ shows centrality dependence.
  - Less suppression at low p_T with respect to high p_T , with stronger p_T dependence for central events
  - Stronger suppression when rapidity increases for J/ψ, whereas there is no rapidity dependence for $\Upsilon(1S)$.
- ALICE p-Pb results :
  - R_{pA} result shows an increasing suppression of the J/ψ and $\Upsilon(1S)$ yield towards forward *y*
  - pure nuclear shadowing and/or energy loss seem to reasonably describe the data, indicating that final state absorption for the J/ψ may indeed be negligible at LHC energies
  - ψ(2S) is significantly more suppressed than the J/ψ in both *y* regions
    - A similar p_T dependence of ψ(2S) suppression, with respect to the J/ψ, is observed within uncertainties at forward rapidity
    - at backward-*y*, ψ(2S) suppression shows an increase, with event activity, stronger than J/ψ
    - initial state nuclear effects (shadowing, energy loss) alone cannot account for the modification of the ψ(2S) yields
    - final state effects, as the resonance break-up with interactions with CNM, are unlikely, because of short cc pair crossing time. Other final states effects as the cc pair interaction with the hadronic medium created in p-Pb collisions should be considered

Thank You

J/ψ elliptic flow in Pb-Pb

ALICE coll, Phys. Rev. Lett. 111, 162301 (2013)

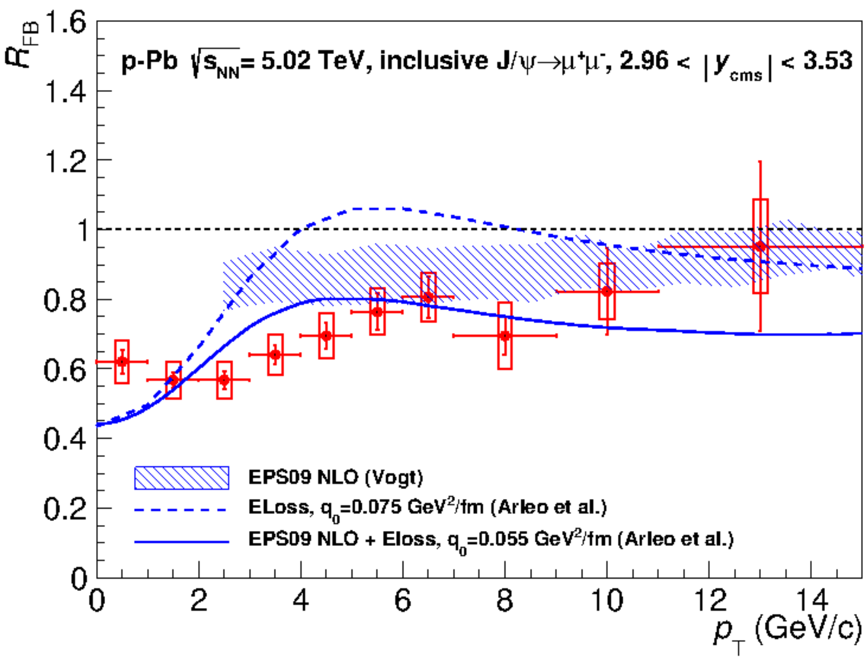


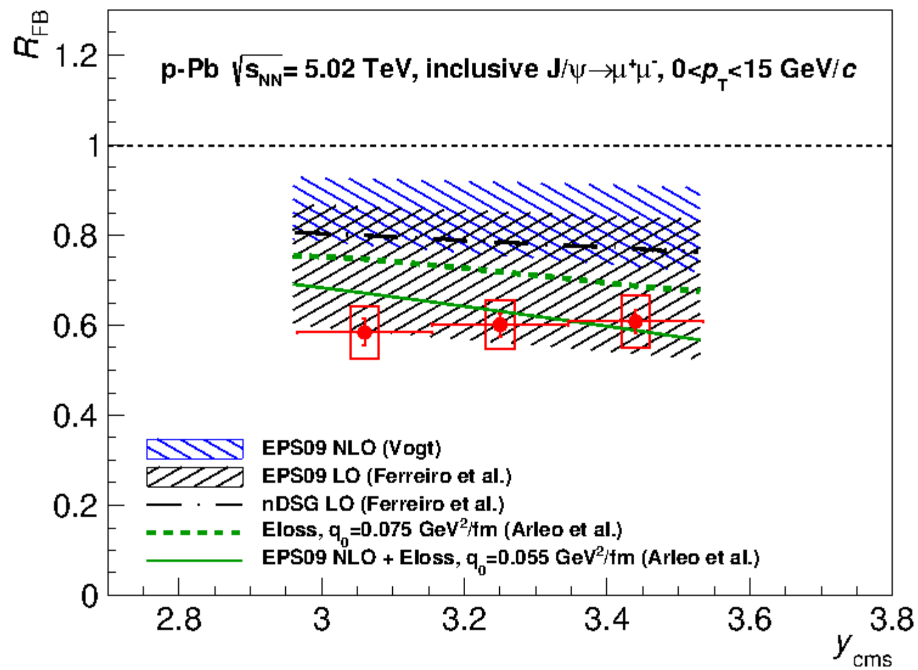


- Hint of non-zero v_2
- Complement R_{AA} results: a significant v_2 and less suppression with respect to RHIC, SPS are indications for an observation of (re)combination from charm quarks in the QGP phase
- In qualitative agreement with transport models with 50% regeneration

J/ψ R_{FB} in p-Pb

The R_{FB} rapidity dependence has also been investigated





ALICE Coll. JHEP02(2014)073

- Comparison with theoretical models confirms previous observations done on the *y*-integrated results
- Calculations including both shadowing and energy loss seem consistent with the data

J/ψ as function of multiplicity in p-Pb