Review on ALICE J/ψ results in Pb-Pb collisions

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for the ALICE collaboration

GDR PH-QCD meeting

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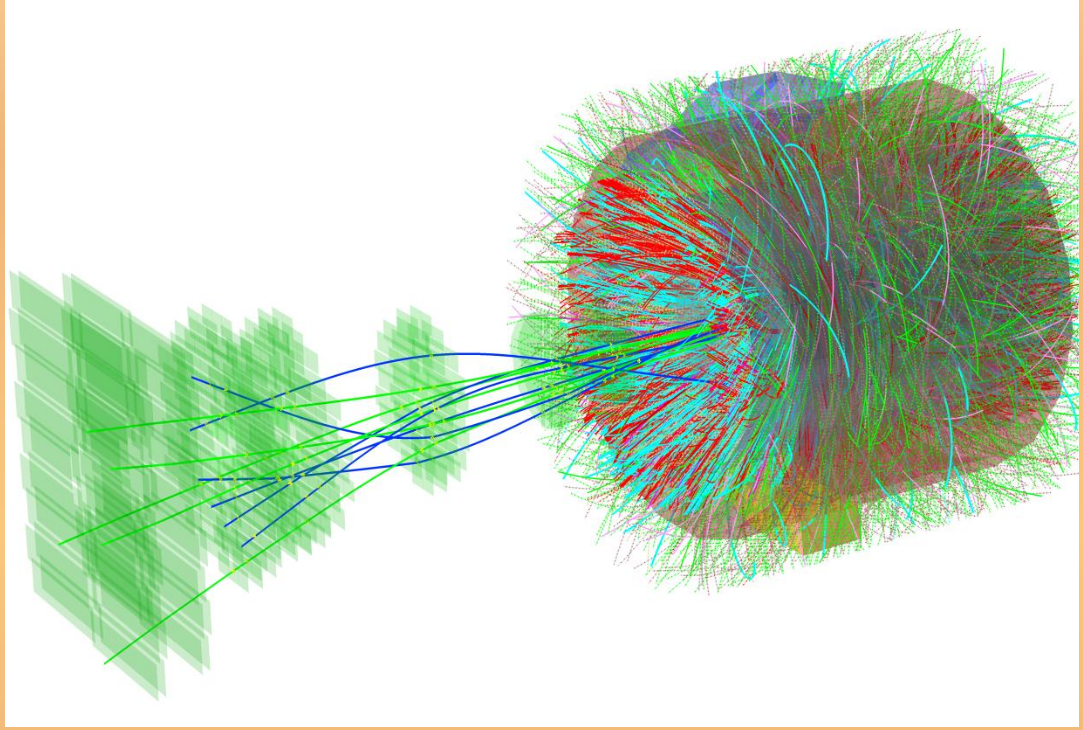
Outline

- Physics motivations.
- The ALICE detector.
- Analysis:
  - J/ψ → ee ($|y| < 0.9$).
  - J/ψ → μμ ($2.5 < y < 4.0$).
- Results:
  - J/ψ R_{AA} vs N_{part}, y and p_T.
  - J/ψ $< p_T >$.
- ψ(2S) → μμ.
- J/ψ photoproduction.
- Conclusions.



Quarkonium hadroproduction in A-A

- Ultrarelativistic heavy-ion collisions → high energy densities.
- Quark Gluon Plasma: deconfined state of quarks and gluons.

Quarkonium as a probe of deconfinement:

✓ Created in the early stages of the collision.
✓ Suppressed by Debye screening.
✓ Different radii & binding energies → sequential suppression.

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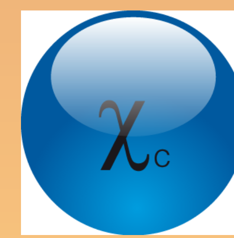

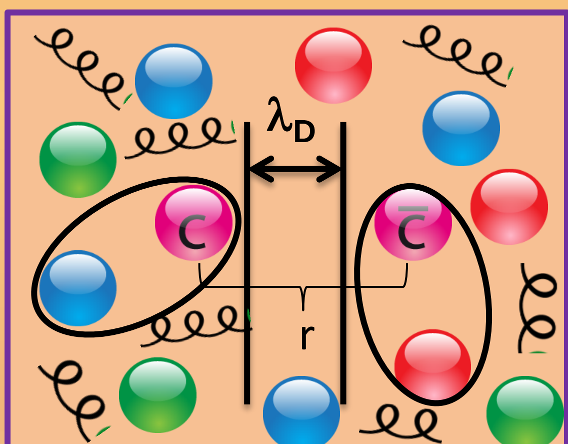

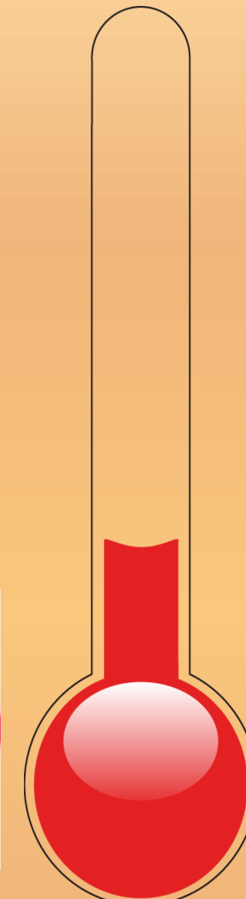

$T < T_c$

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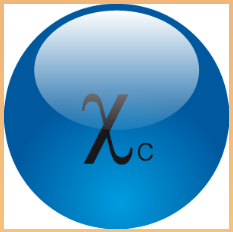

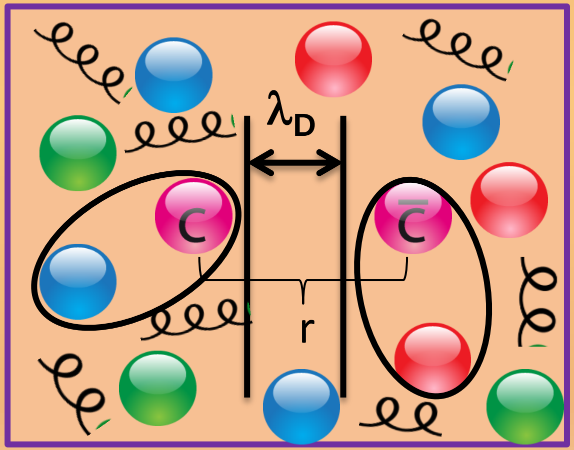

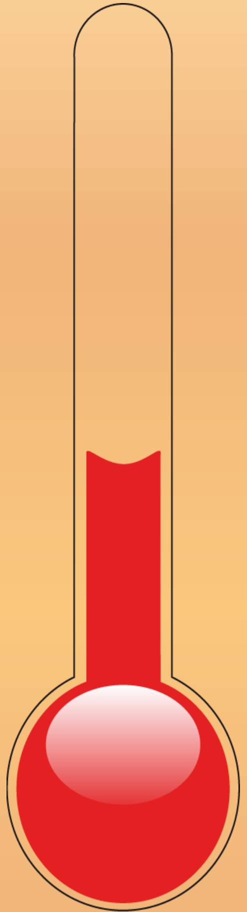

$T \approx T_c$

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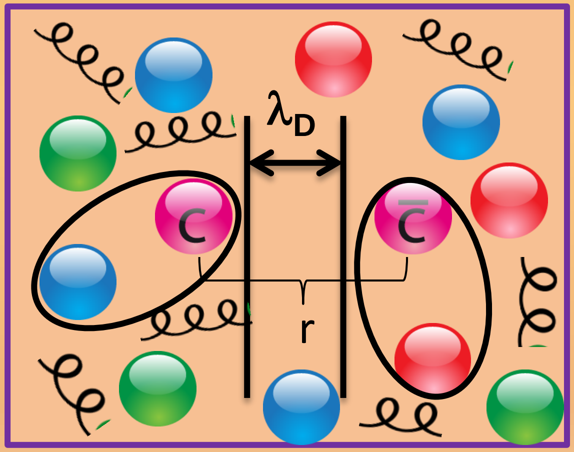

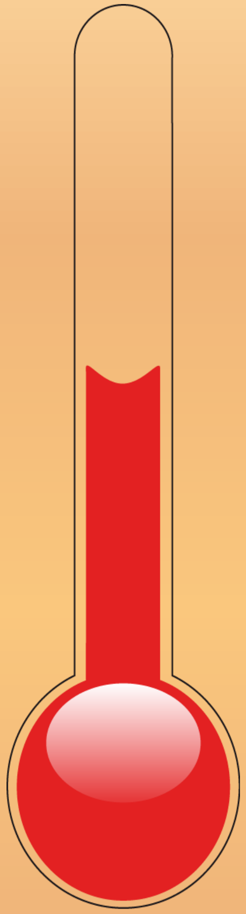

$T \approx 1.1\ T_c$

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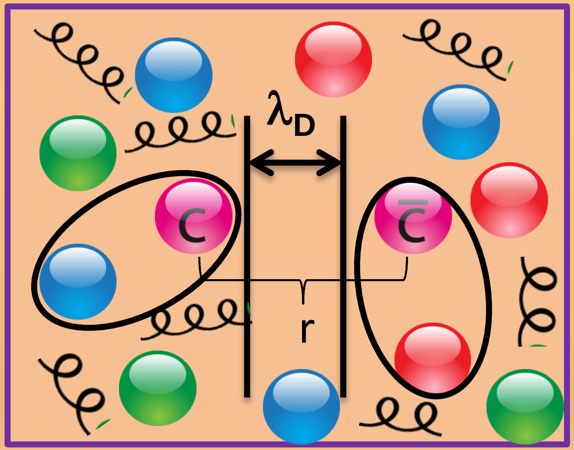
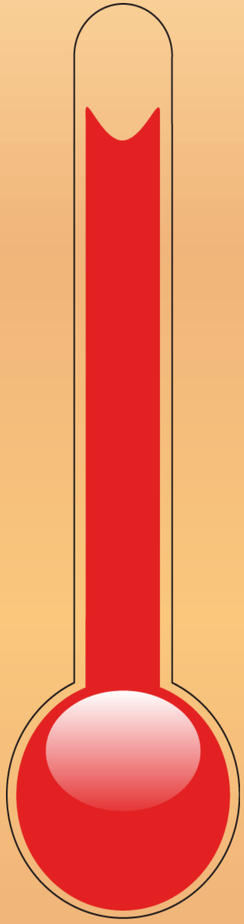


Quarkonium family can be used as a thermometer for the QGP!



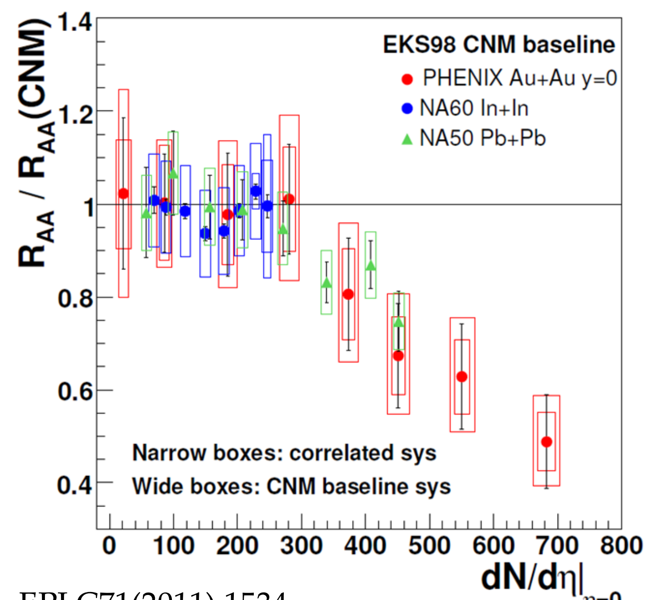
T ≈ 2.1 T_c

Quarkonium hadroproduction in A-A

Quarkonium production in A-A previously studied by different experiments:

$$R_{\mathrm{AA}} = \frac{Y^{J/\psi}_{\mathrm{A-A}}}{< N_{Coll} > Y^{J/\psi}_{pp}}$$

- ❑ Significant J/ψ suppression beyond the Cold Nuclear Matter effects.
- ❑ Suppression is practically $\sqrt{s}$ - independent.



EPJ C71(2011) 1534

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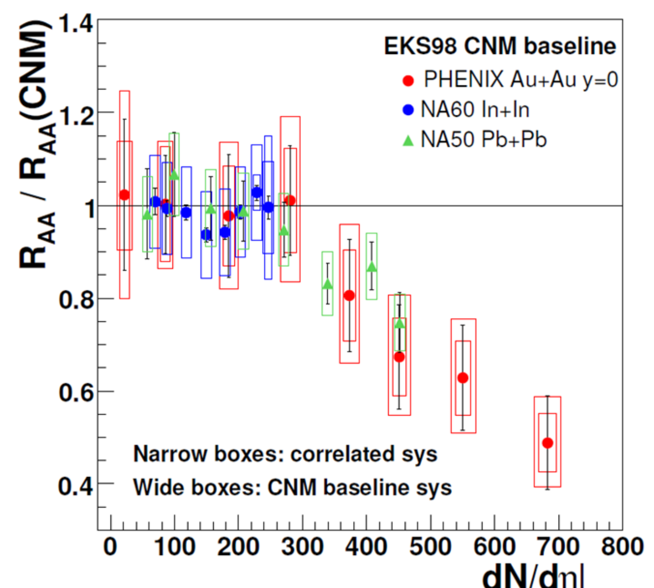

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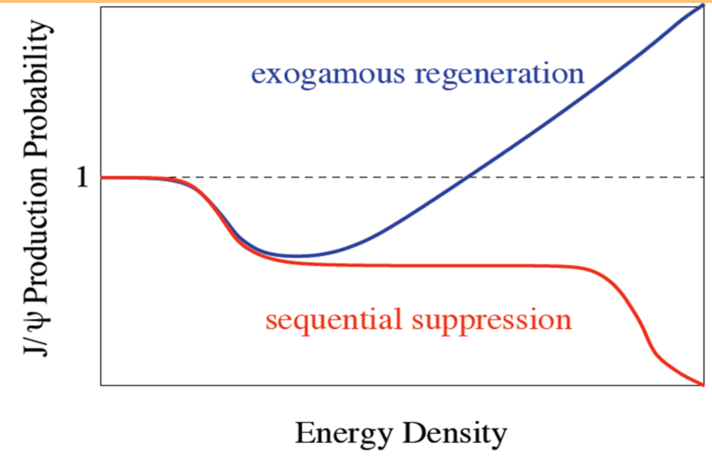


What can we expect at the LHC?

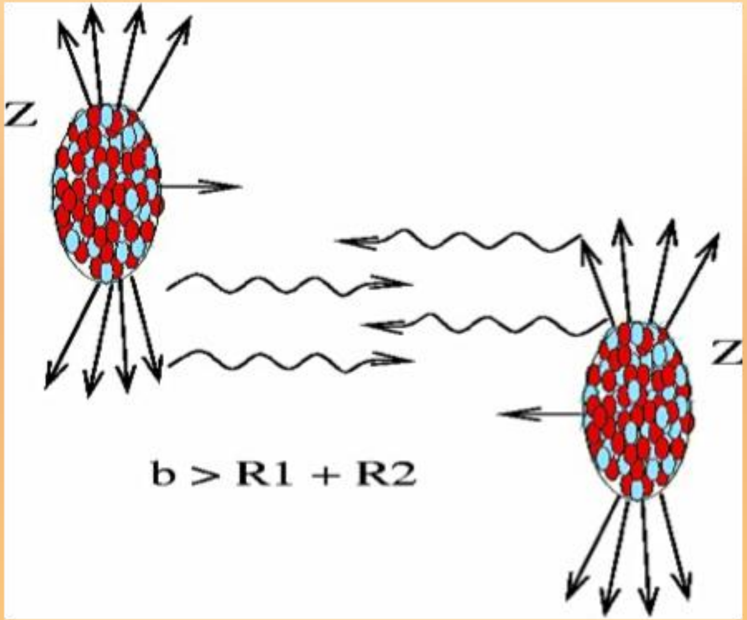
1. New collision energy regime
   ➔ larger suppression?
2. $N_{c\bar{c}}$/central collision ≈ 10 × RHIC
   ➔ measurable effects from regeneration?

Quarkonium photoproduction in A-A

- Electromagnetic (hadronic) interactions are dominant (suppressed) in HI collisions when $b > R_1 + R_2$.

- High flux in the number of photons (scales as Z^2).

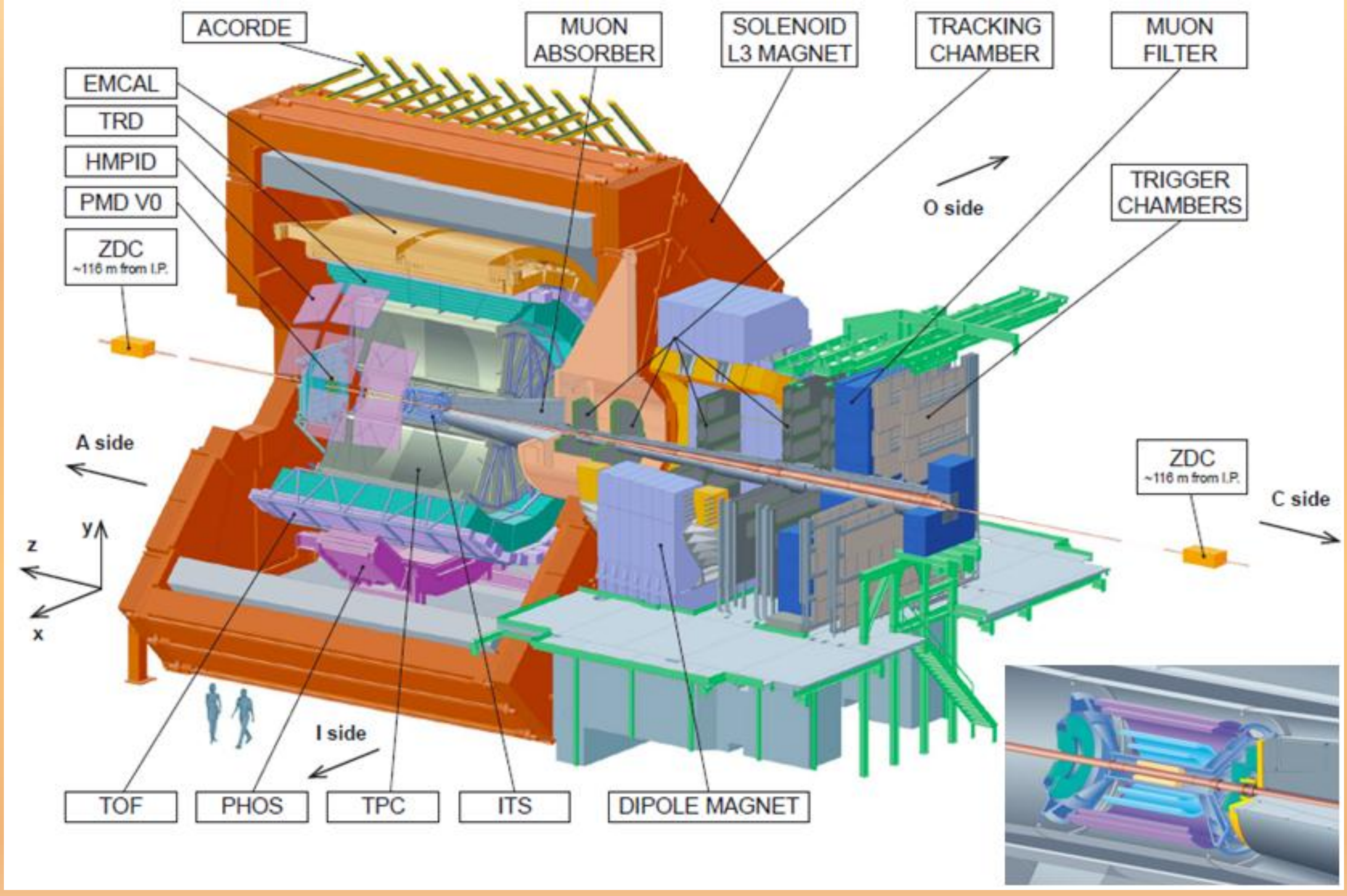
- Powerful tool to study gluon distribution of the nuclei (low Bjorken-x poorly known).



- Coherent production:
  - Photon couples to all nucleons.
  - J/ψ $\langle p_T \rangle \approx 60$ MeV/c.
  - Nucleus normally does not break up.

- Incoherent production:
  - Photon couples to a single nucleon.
  - J/ψ $\langle p_T \rangle \approx 500$ MeV/c.
  - Nucleus normally breaks up.

The ALICE detector



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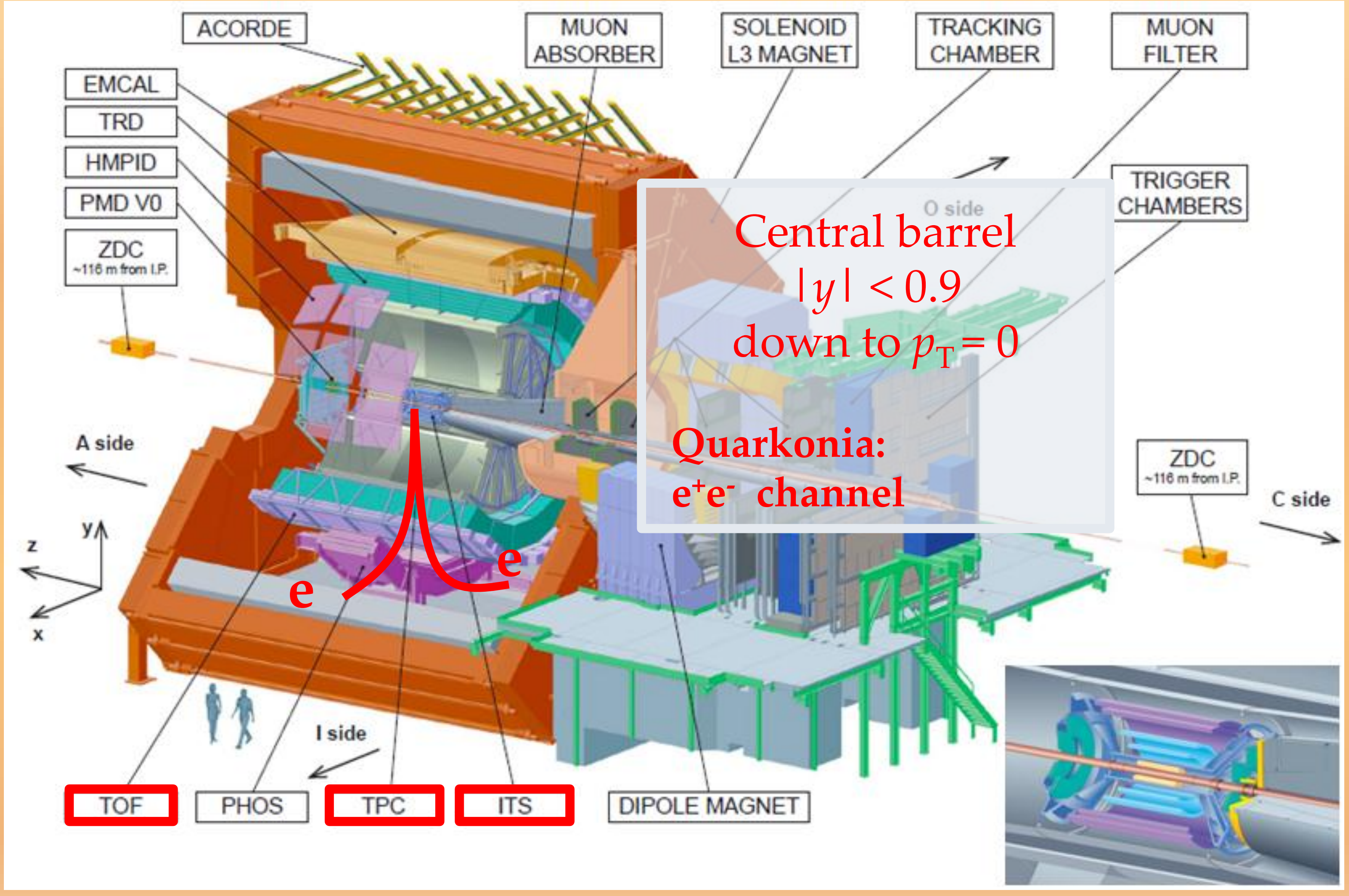

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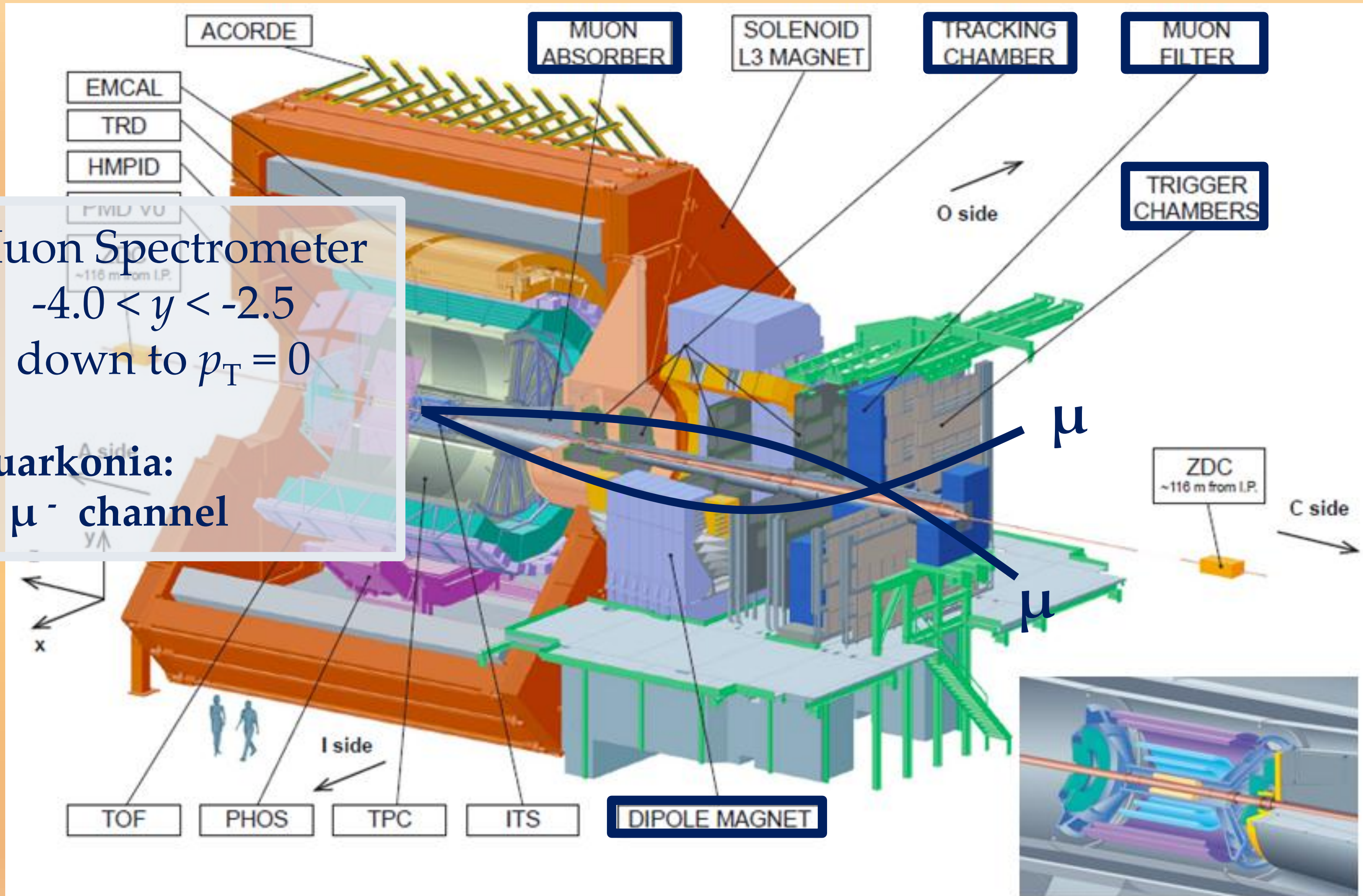


Muon Spectrometer
$-4.0 < y < -2.5$
down to $p_{\mathrm{T}} = 0$

Quarkonia:
$\mu^{+}\mu^{-}$ channel

Trigger and centrality

- $J/\psi \to ee$:

2010 + 2011 data set: Minimum Bias (MB) and centrality triggered events ➔ $L_{int} \approx 15\ \mu b^{-1}$.

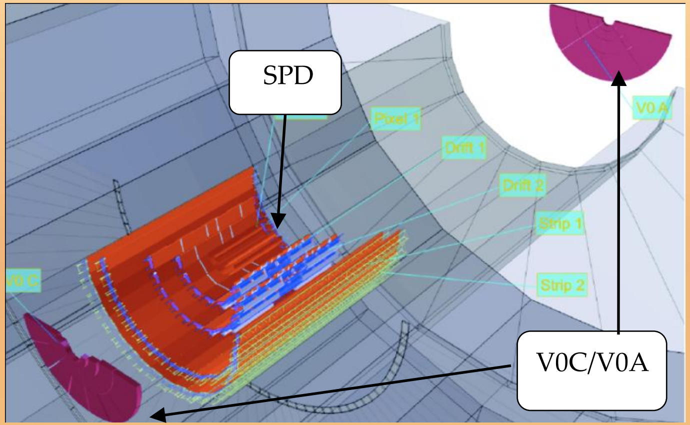
- $J/\psi, \psi(2S) \to \mu\mu$:

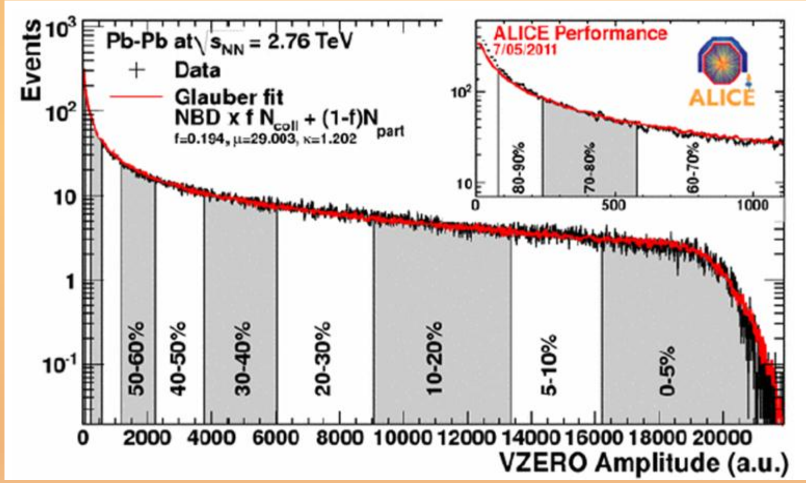
2011 data set: dimuon events from the muon trigger ➔ $L_{int} \approx 70\ \mu b^{-1}$.

- $J/\psi \to \mu\mu$ in UPC:

2011 data set: UPC trigger ➔ $L_{int} \approx 55\ \mu b^{-1}$.

Centrality estimation is based on a Glauber model fit of the V0 amplitude.



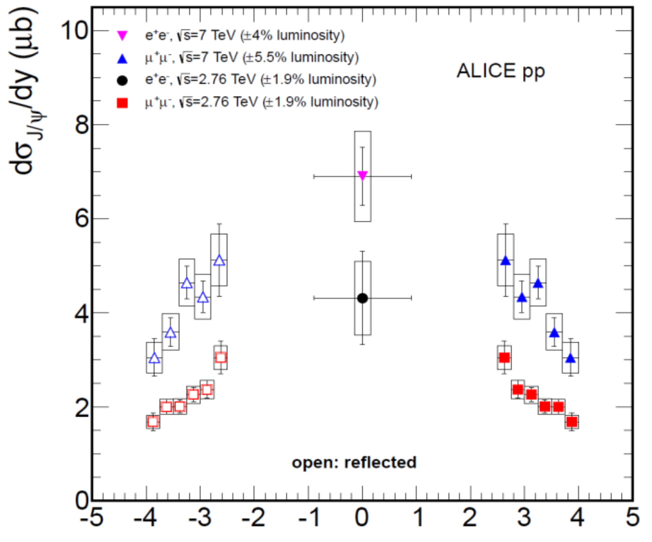


pp measurement at $\sqrt{s} = 2.76$ TeV

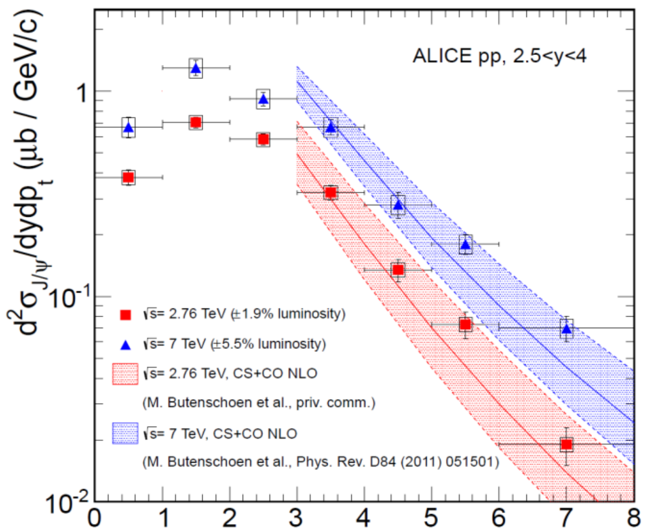
In order to extract the R_{AA}, a reference from pp collisions is needed!

In this case, both at forward ($J/\psi \rightarrow \mu\mu$) and midrapity ($J/\psi \rightarrow ee$).

$2.5 < y < 4.0$: NRQCD calculations describe the measured $d^2\sigma/dydp_T$ at 7 and 2.76 TeV.



arXiv:1203.3641v2



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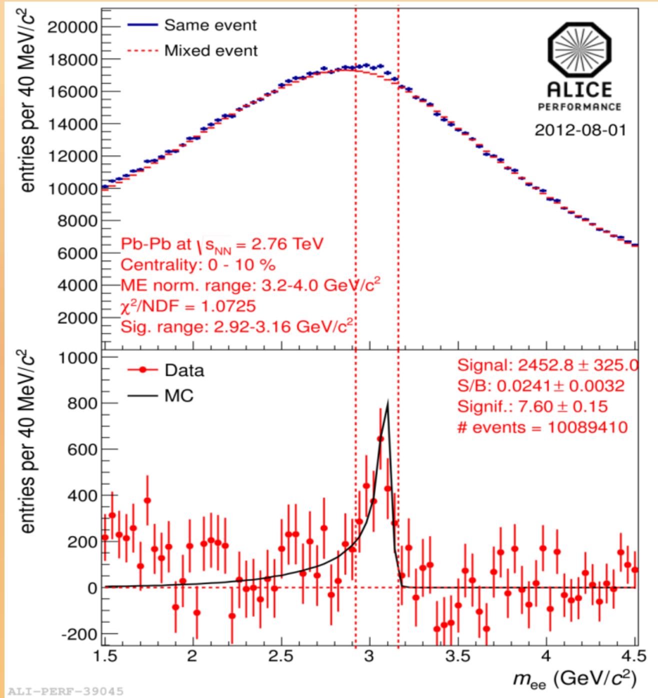
pp reference is the main source of systematics in the Nuclear Modification Factors:

- 9% for $J/\psi \rightarrow \mu\mu$.
- 26% for $J/\psi \rightarrow ee$.

J/ψ → ee in Pb-Pb: Analysis



- ✓ J/ψ yield obtained by subtracting the background from the opposite sign dielectron invariant mass spectrum using the mixed event technique.
- ✓ The MC signal includes the bremsstrahlung of the electrons in the detector material.
- ✓ Signal extracted in three centrality bins: 0-10%, 10-40% and 40-80%.

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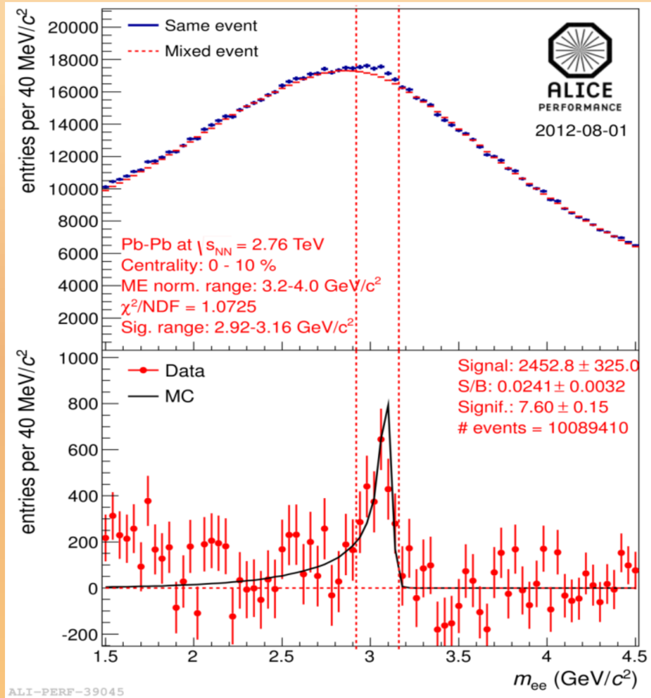

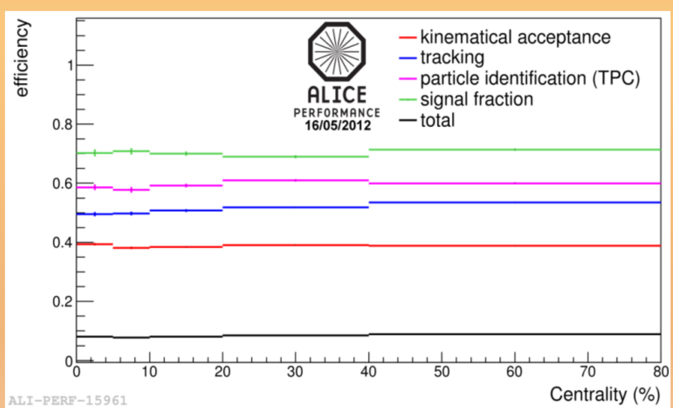

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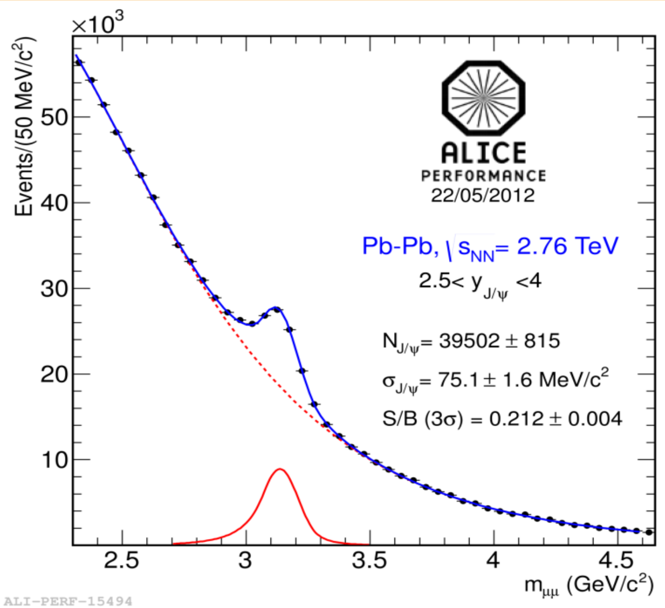
- ✓ Signal extracted in three centrality bins: 0-10%, 10-40% and 40-80%.
- ✓ Efficiency computed using a MC HI generator (HIJING) enriched with J/ψ.
- ✓ Little dependence on the centrality.

J/ψ → μμ in Pb-Pb: analysis



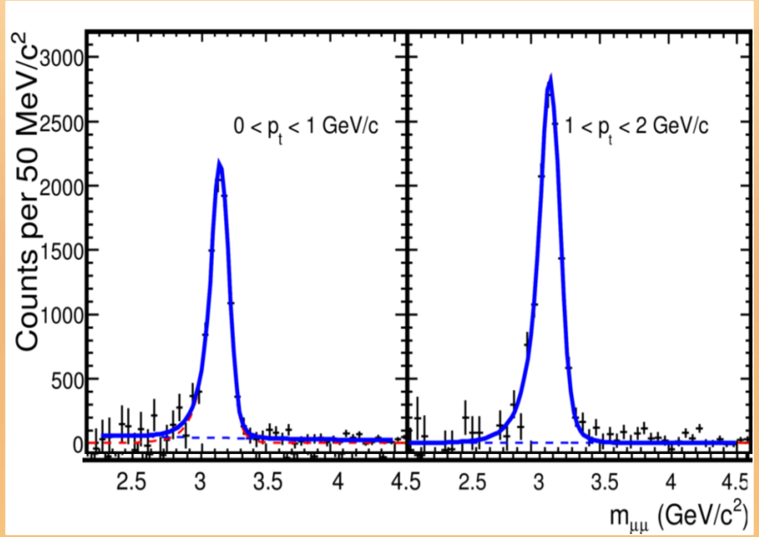
2011 statistics allows the extraction of J/ψ yields in narrow y, p_T and centrality bins.

Yield extracted by fitting the unlike sign invariant dimuon mass spectrum:

- ✓ Signal: modified Crystal Ball.
- ✓ Background: different functions. Also subtracted using the event mixing technique.

Results are then combined to obtain a mean weighted $N_{J/\psi}$ and to extract systematic uncertainties on signal extraction.

J/ψ → μμ in Pb-Pb: analysis



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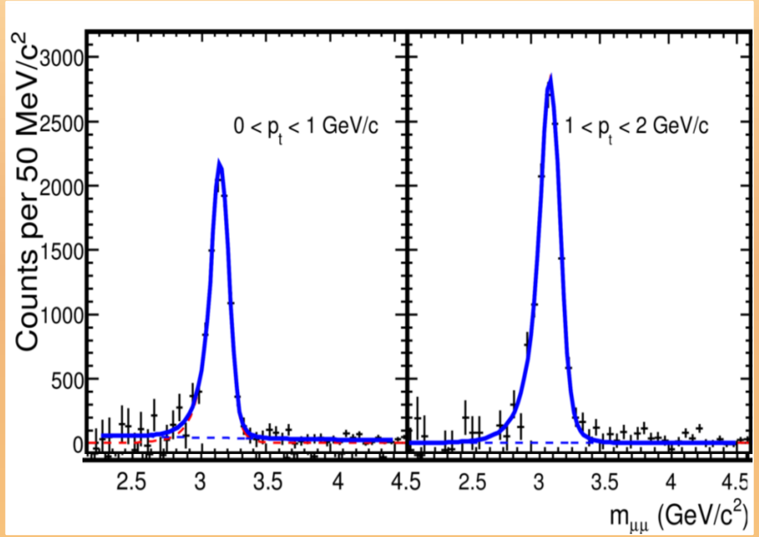

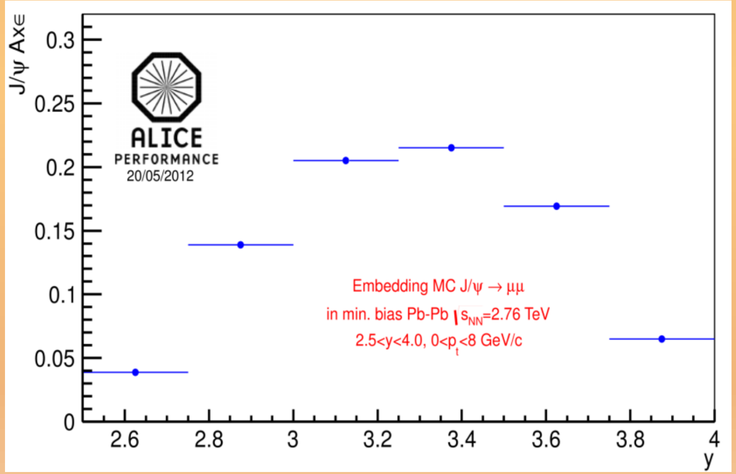

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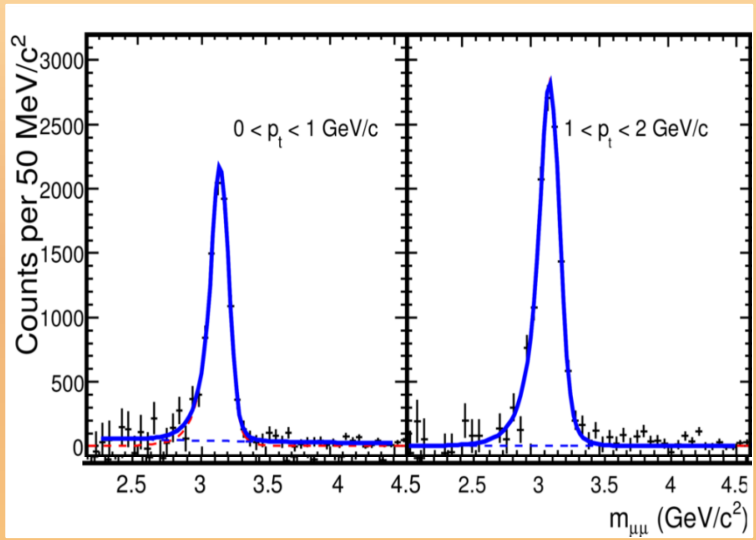
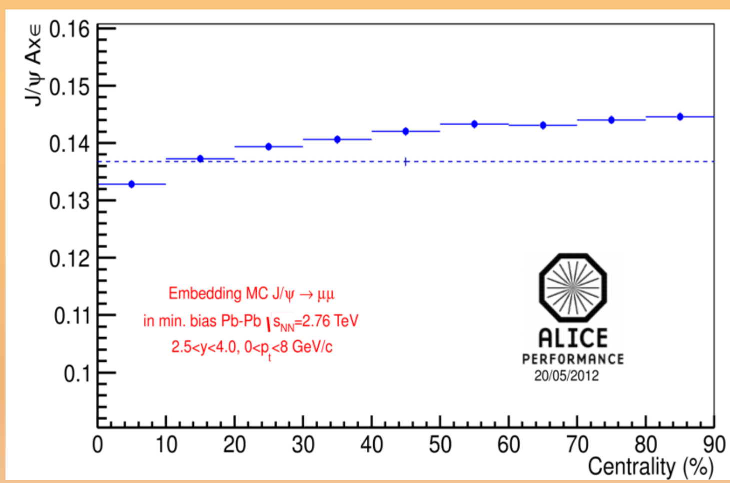
Acceptance x efficiency values are obtained by embedding MC J/ψ into real events.

Rapidity bins: detector acceptance.

$J/\psi \rightarrow \mu\mu$ in Pb-Pb: analysis





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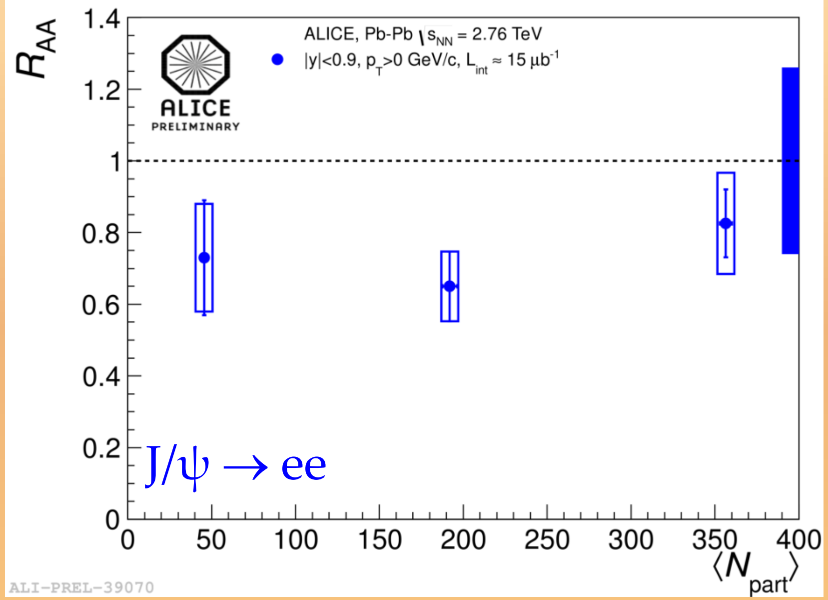
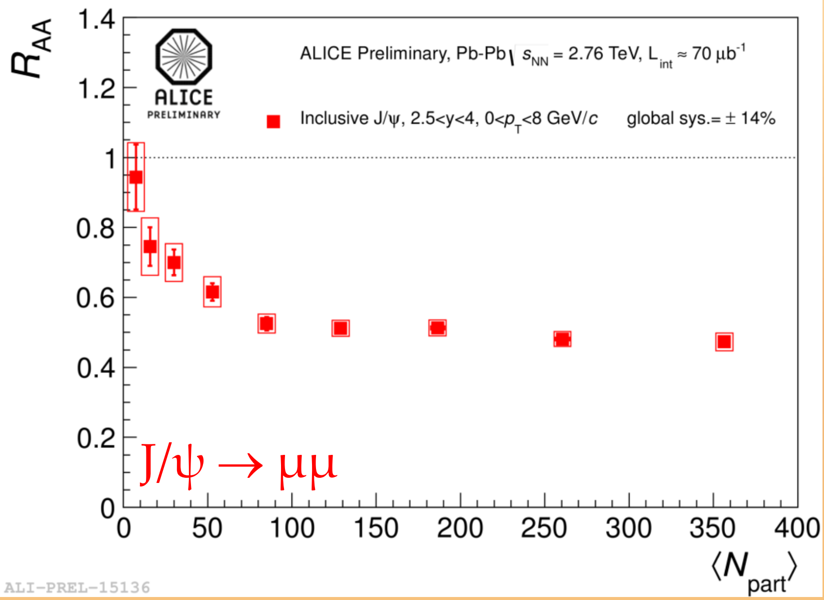
Weak centrality dependence.

Results: J/ψ R_{AA} vs centrality





- No significant centrality dependence within errors.
- No significant centrality dependence for N_{part} > 100.

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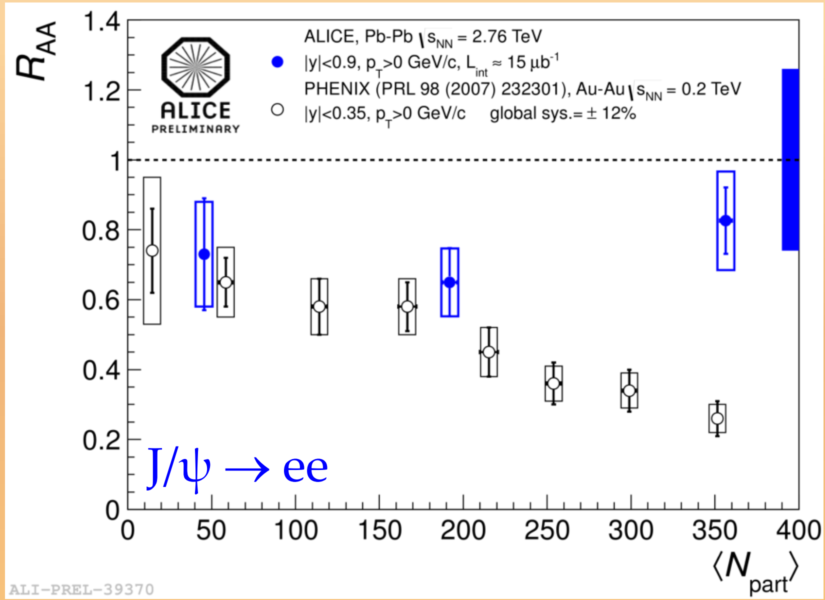
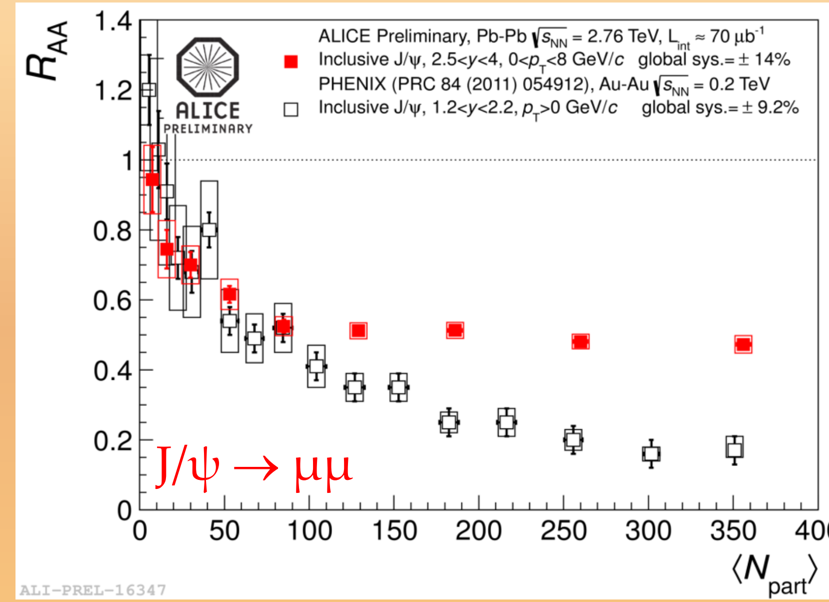
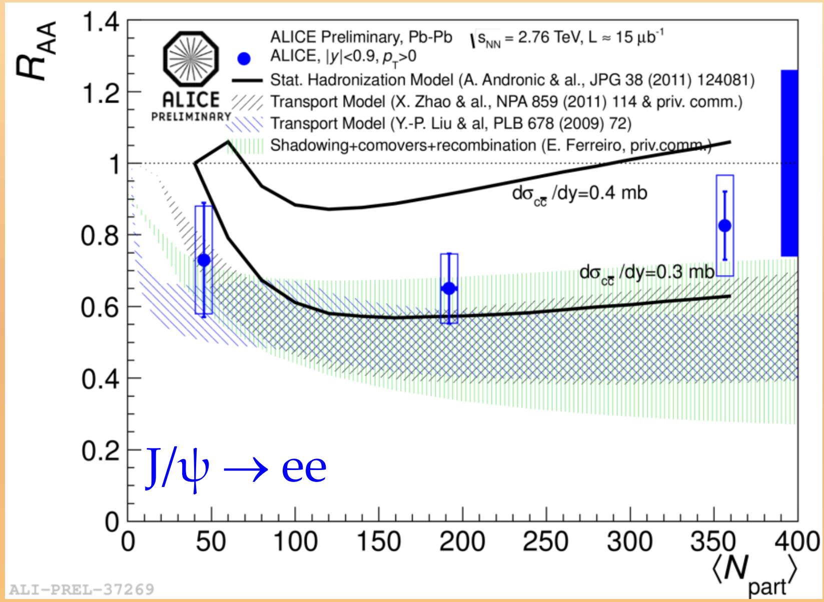
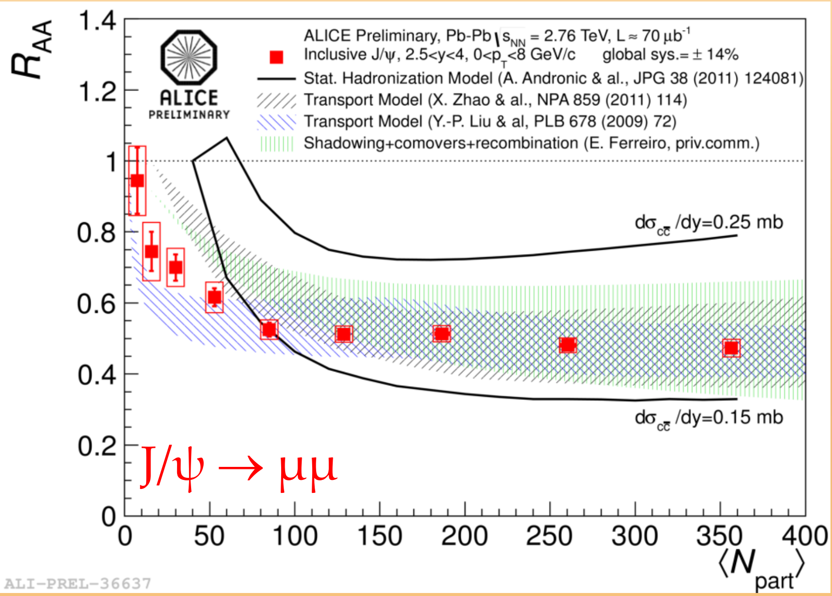




- No significant centrality dependence within errors.
- No significant centrality dependence for $N_{part} > 100$.
- R_{AA} in the most central collision from ALICE is ~3 times larger than at PHENIX.
- $R_{AA}^{ALICE} \sim 3 \text{ x } R_{AA}^{PHENIX}$ for $N_{part} > 200$.

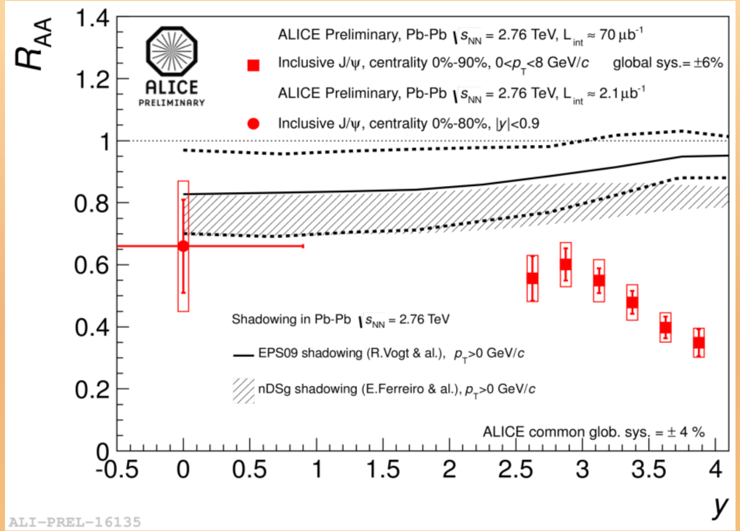
Results: J/ψ R_{AA} vs centrality

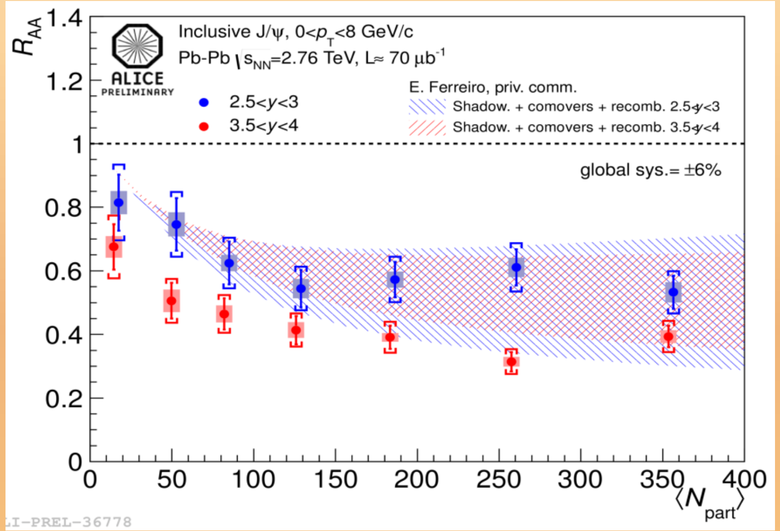




- Statistical Hadronisation Model: prediction for two $d\sigma_{c\bar{c}}/dy$.
- Transport Models: different rate equations of J/ψ dissociation and regeneration in QGP, in both cases more than 50% of measured yield in the most central collisions due to J/ψ regeneration, the rest is from initial production.
- Green band: includes shadowing, comovers and recombination.
- Need to measure Cold Nuclear Matter effects.

Results: J/ψ R_{AA} vs centrality, *y* bins





J/ψ is less suppressed if shadowing calculations are considered.

Model underestimates the suppresssion in the most forward *y* region

Cold Nuclear Matter effects need to be quantified!

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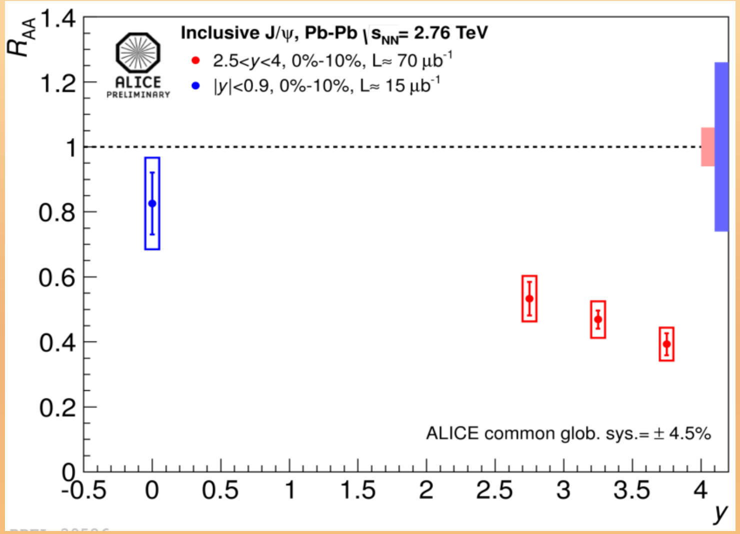

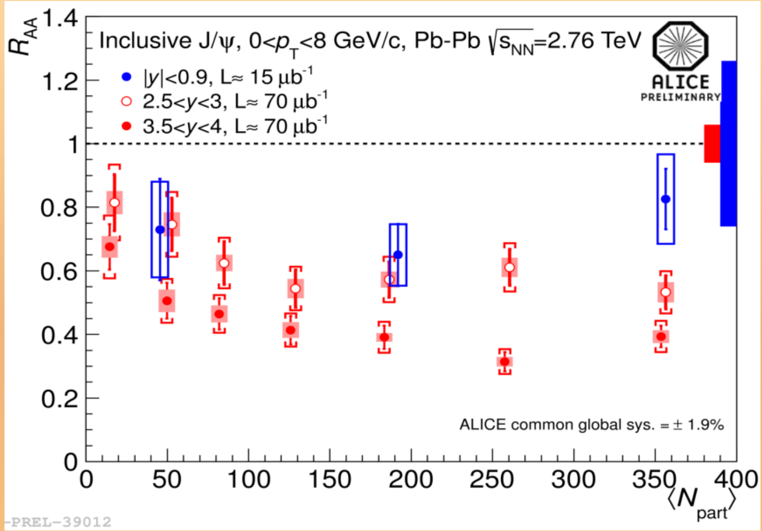

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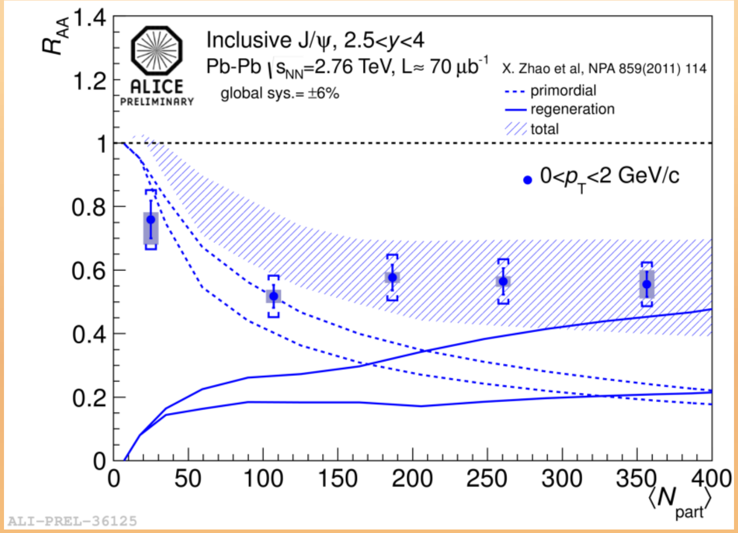
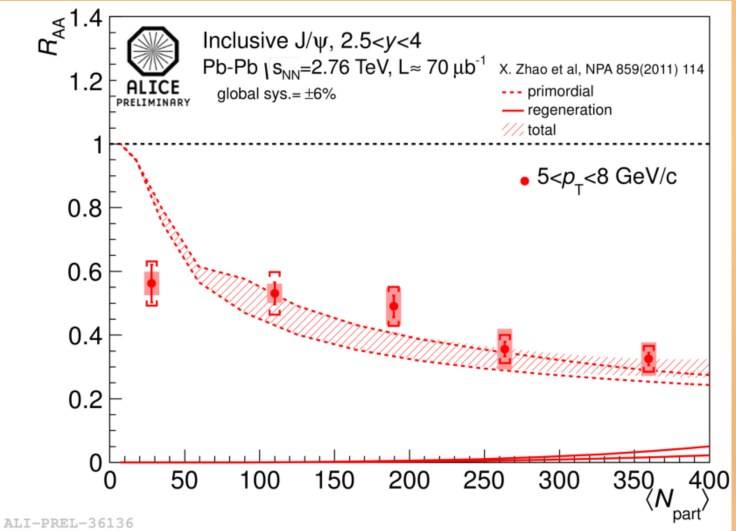
Cold Nuclear Matter effects need to be quantified!

Hint of smaller suppression at mid rapidity than at forward rapidity in the most central collisions.

Results: J/ψ R_{AA} vs centrality, p_T bins





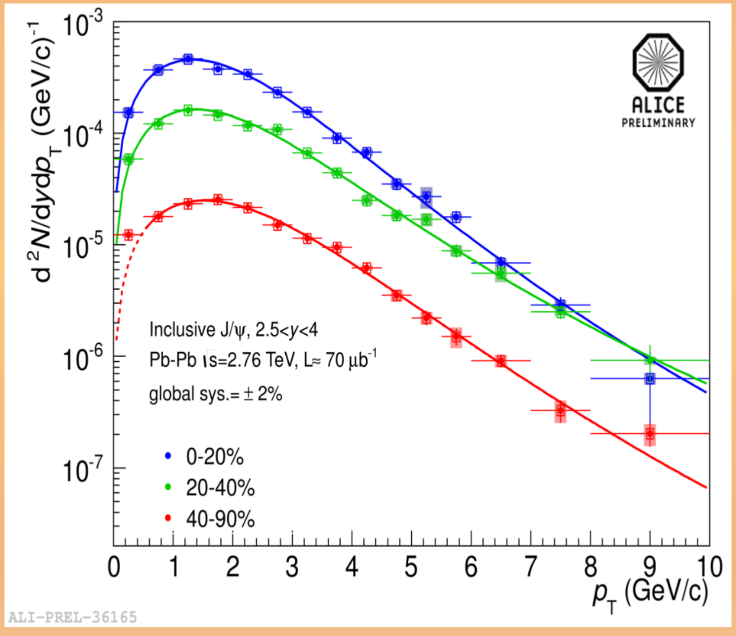
- Stronger suppression for high-p_T J/ψ.
- No centrality dependence for low-p_T J/ψ when $N_{part} > 100$.
- Consistent behavior with (re)combination.
- Good agreement between data and Transport Model.
- Around 50% of the low-p_T J/ψ are produced by (re)combination.
- For high-p_T J/ψ this contribution is very small.

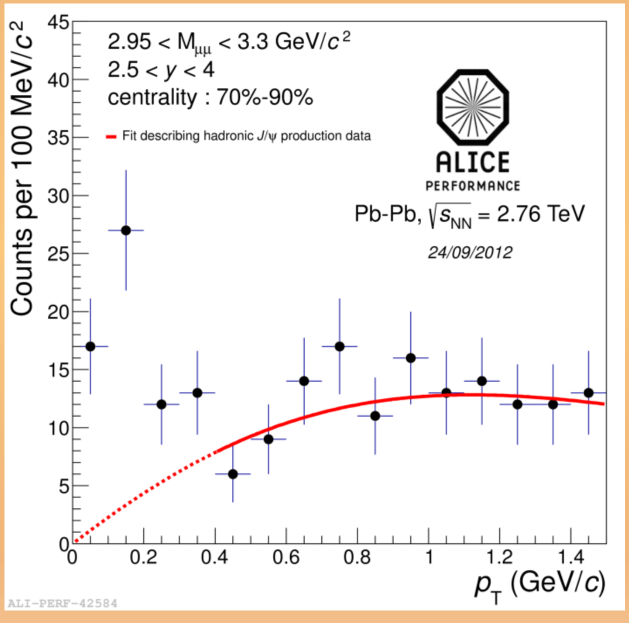
Results: J/ψ $< p_T >$

$< p_T >$ values were obtained by fitting $\frac{d^2N}{dy dp_T} \propto \frac{p_T}{\left[1+(p_T/p_0)^2\right]^n}$ in three different centrality bins.

There is a clear deviation, at low- p_T for the most peripheral collisions, to the expected J/ψ hadroproduction.

J/ψ photoproduction could be responsible of this excess.





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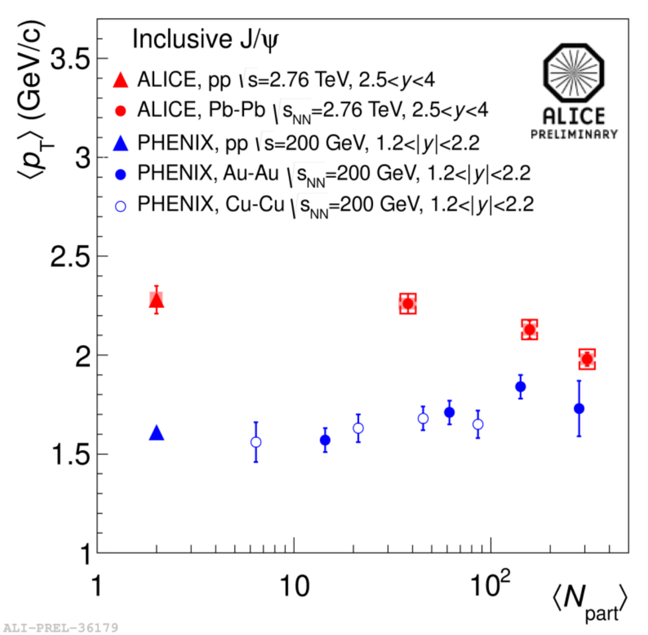


ALICE: clear decrease of $< p_T >$ with increasing N_{part}.

This confirms the observation that low-p_T J/ψ are less suppressed in central collisions.

Striking difference with respect to lower energy results!

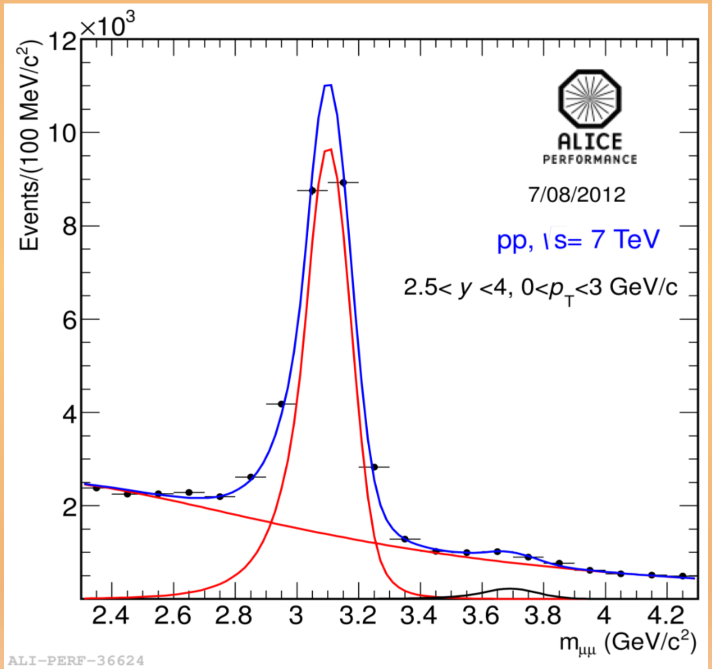
$\psi(2S) \to \mu\mu$

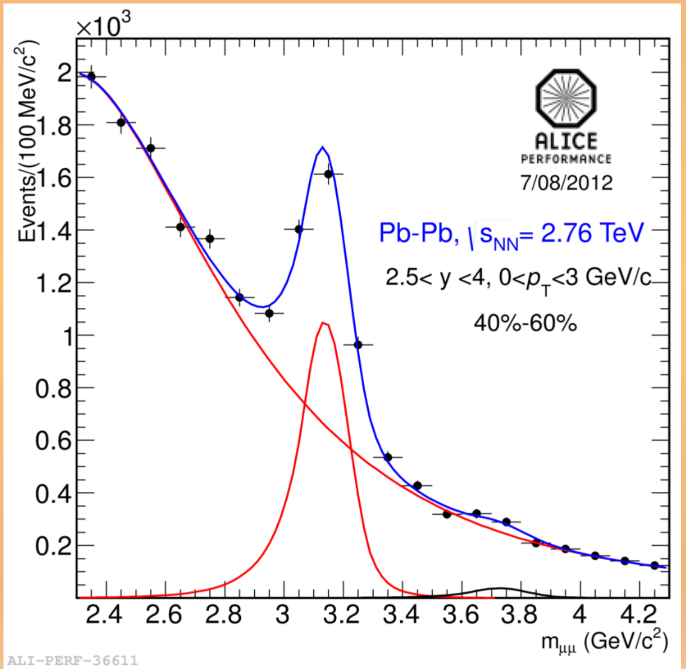
Low significance for $\psi(2S)$, both in pp and Pb-Pb.

Signal extraction only possible in 2 p_T bins:

- $0 < p_T < 3$ GeV/c: 20-40%, 40-60% and 60-90%.
- $3 < p_T < 8$ GeV/c : 0-20% and 20-60%.

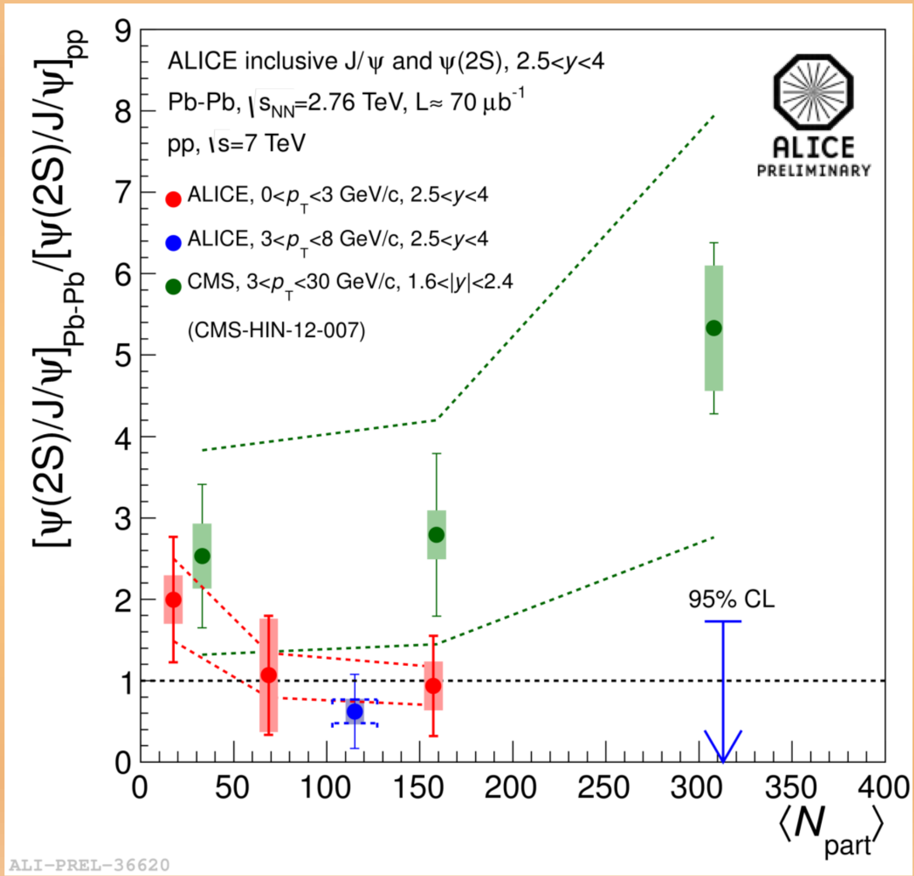
S/B in Pb-Pb: between 0.01 and 0.3 from 20-40% to 60-90% centrality.





$\psi(2S) \to \mu\mu$

ALICE used pp at $\sqrt{s} = 7$ TeV as reference: small $\sqrt{s}$ and y dependence from $[\psi(2S) / J/\psi]_{pp}$ results by CDF, LHCb and CMS taken into account in the systematic uncertainty (~ 15%).



Dashed lines show the error on the pp reference: CMS used pp at $\sqrt{s} = 2.76$ TeV.

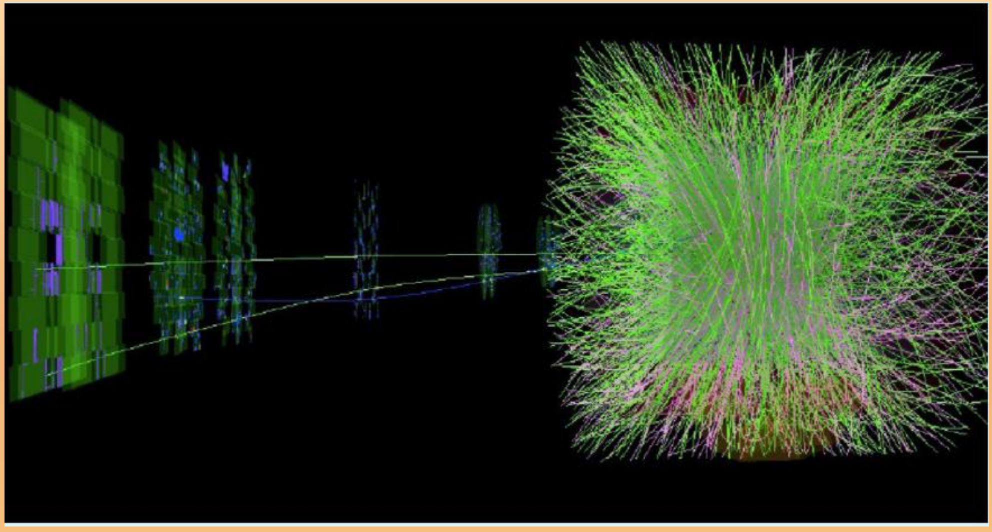
Signal extraction and MC inputs for Acceptance x Efficiency corrections are the main source of systematics (some others vanish in the double ratio).

No decisive conclusion on the $\psi(2S)$ enhancement/suppression vs N_{part} due to large statistical and systematic uncertainties.

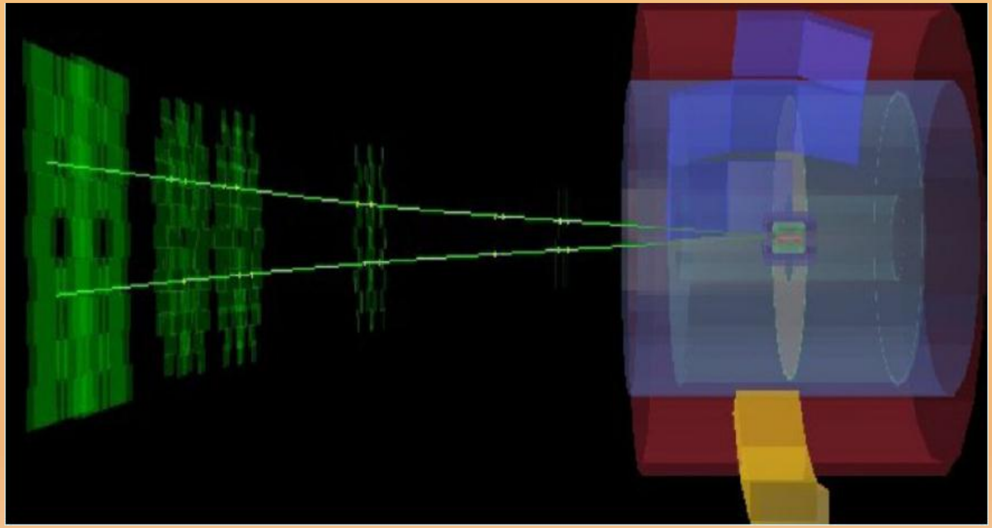
Excluded large enhancement in the most central collisions.

Coherent J/ψ photoproduction in UPC

Typical inclusive J/ψ candidate in a Pb-Pb collision.



UPC: two muon tracks from a J/ψ candidate in a very clean event.

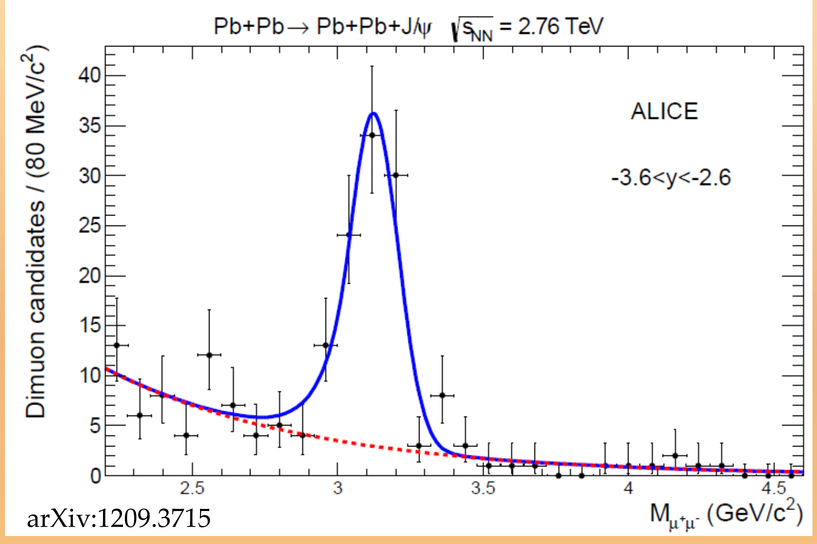


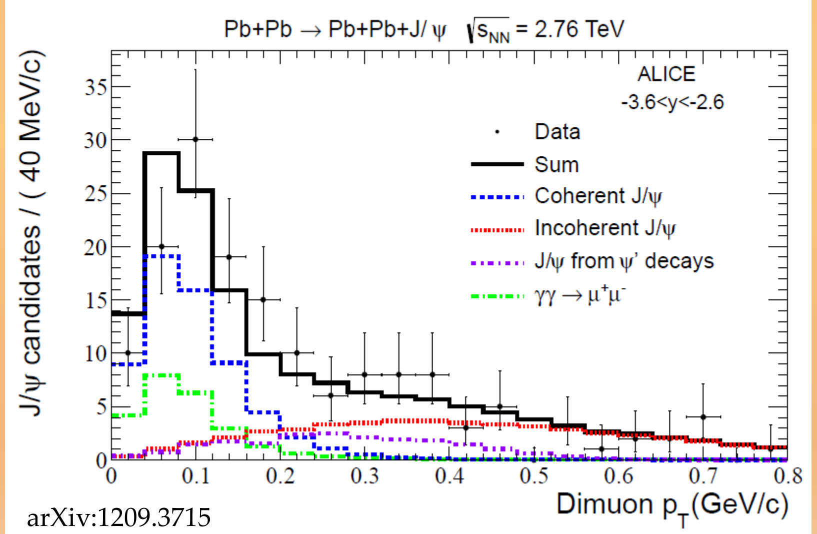
Coherent J/ψ photoproduction in UPC

- Fitting function: CB (signal) + exponential (background).
- Combinatorial background < 2% at 90% C.L. in $2.8 < M_{\mathrm{inv}} < 3.4$ GeV/c².
- Extracted J/ψ yield is 96 ± 12 ± 6.
- J/ψ from coherent production clearly dominate in the region $p_T < 0.3$ GeV/c.
- $$N^{coh}_{J/\psi} = \frac{N_{Yield}}{1 + f_I + f_D} = 78 \pm 10^{+7}_{-11}$$

  f_D fraction of J/ψ from ψ′.

  f_I is the incoherent/coherent events.



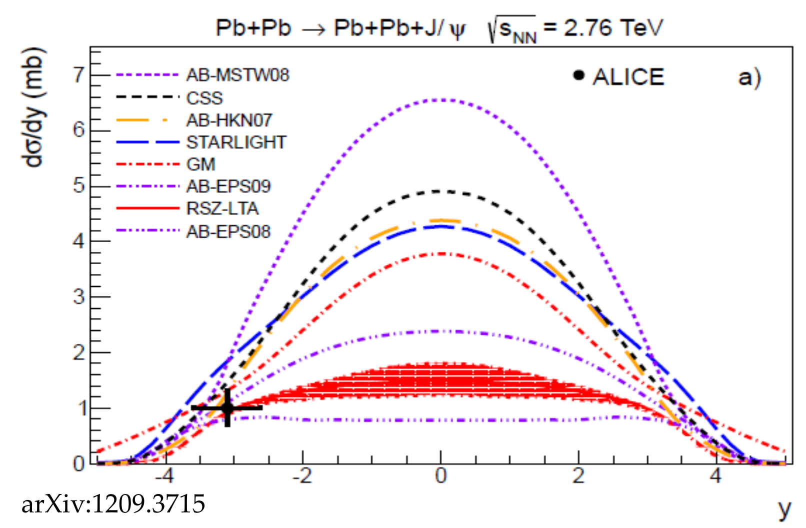


Coherent J/ψ photoproduction in UPC

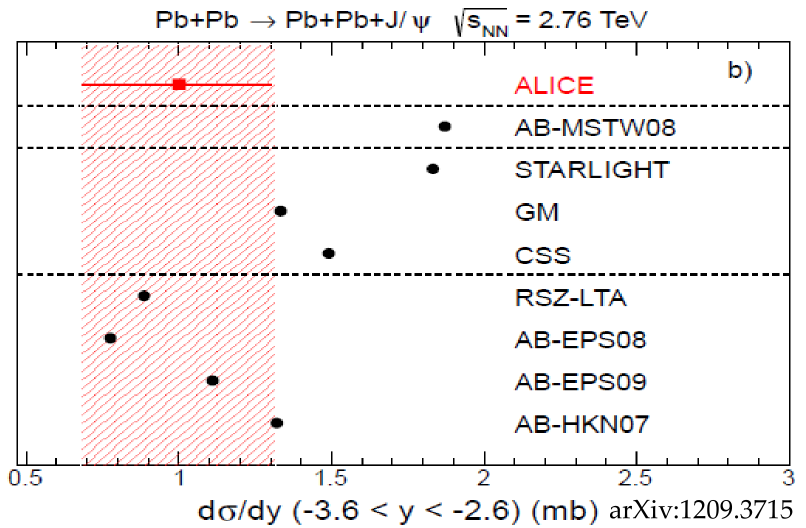
- To compute the differential cross-section of coherent J/ψ production, the $\gamma\gamma \rightarrow \mu^+\mu^-$ QED process is used:

$$\frac{d\sigma^{coh}_{J/\psi}}{dy} = \frac{1}{BR(J/\psi \rightarrow \mu^+\mu^-)} \cdot \frac{N^{coh}_{J/\psi}}{N\gamma\gamma} \cdot \frac{(Acc\times\varepsilon)_{\gamma\gamma}}{(Acc\times\varepsilon)_{J/\psi}} \cdot \frac{\sigma_{\gamma\gamma}}{\Delta y}$$

$$= 1.00 \pm 0.18^{+0.24}_{-0.26} \text{ mb}$$



- AB-MSTW08: All nucleons contribute to the scattering, scales as A^2 (no nuclear effect).
- STARLIGHT, CM and CSS: Glauber approach to calculate the number of nucleons contributing to the scattering.
- AB-EPS08, ABEPS09, AB-HKN07 and RSZ-LTA: cross-section proportional to the nuclear gluon distribution squared (partonic models).



Conclusions

- ALICE results vs N_{part} show a different behavior relative to RHIC energies:
  - Flat centrality dependence in all rapidities ($N_{part} > 100$ at forward y).
    - $R_{AA}^{ALICE} \sim 3 \text{ x } R_{AA}^{PHENIX}$ for the most central collisions.

- Hint of smaller suppression at mid rapidity than at forward rapidity in the most central collisions.

- Stronger suppression for high-p_T J/ψ relative to the low-p_T ones.

- $< p_T >$ decreases with increasing centrality collision, opposite behavior compared to lower energy results.

- Comparisons to models point to (re)generation.

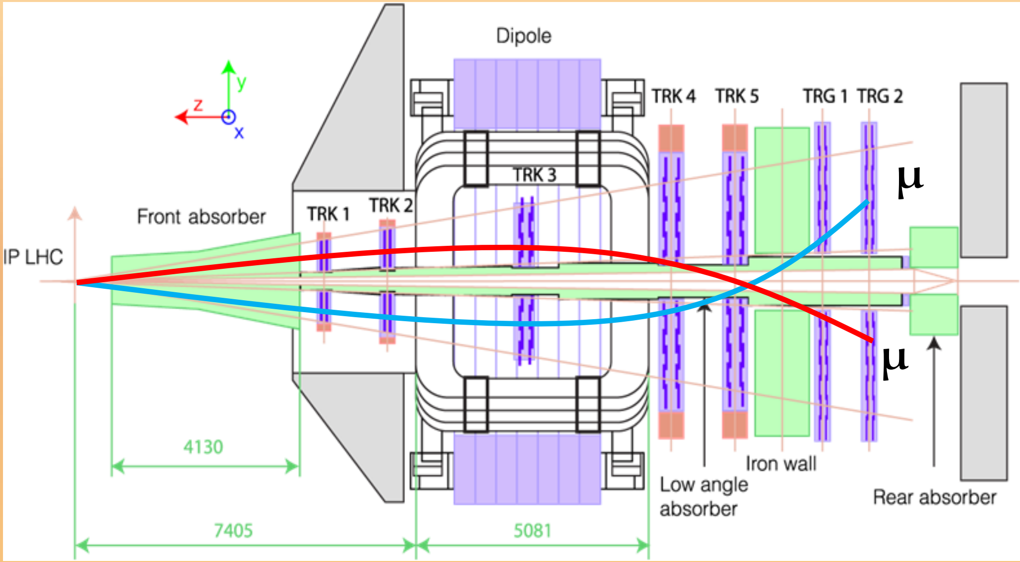
- ψ(2S): a strong enhancement in central Pb-Pb collisions seems unlikely.

- ALICE has performed the first measurement of J/ψ coherent photoproduction in Pb-Pb collisions at the LHC.

Backup

The ALICE Muon Spectrometer

Located in the forward rapidity region and with a full azimuthal coverage, it is composed by:



- Absorbers:

  a) Front absorber.- Absorbs hadrons, photons and electrons.

  b) Beam shield.- Protects from particles produced at large *y*.

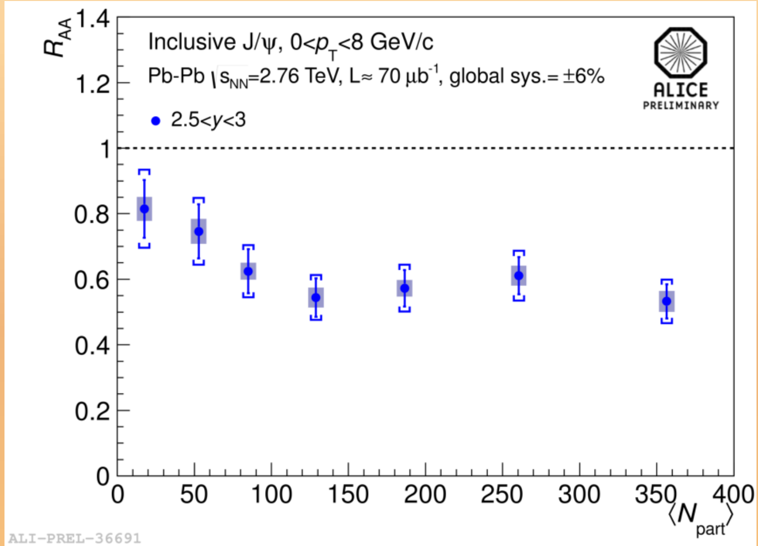
  c) Iron wall.- Absorbs hadrons that punch-through the frontal absorber.

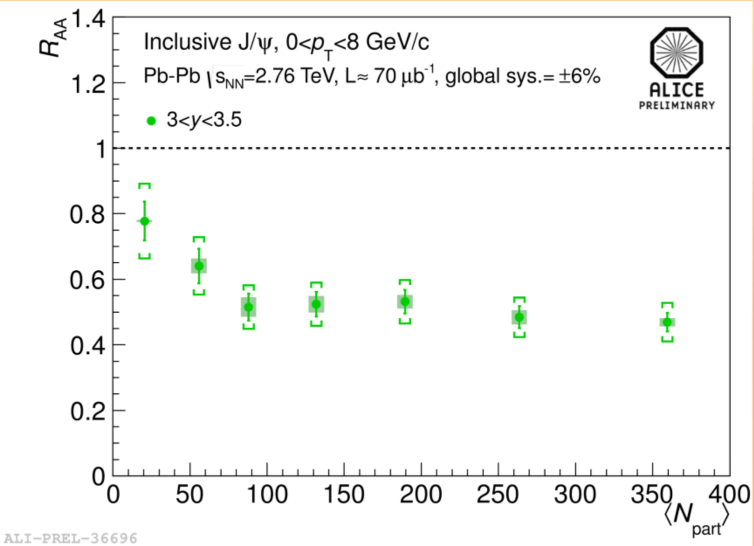
- Magnetic dipole.- 3 T·m integrated magnetic field, bends charged particles allowing to extract the sign of their electric charge and momentum.

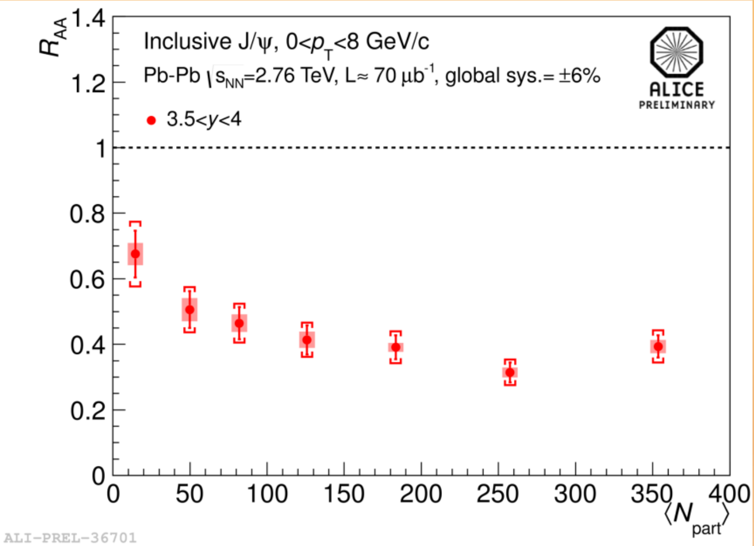
- Tracking chambers.- Spatial resolution, in bending coordinate, better than 100 μm in order to identify and disentangle the ϒ family (100 MeV resolution).

- Trigger chambers.- Timing resolution of 1-2 ns and latency of 700 ns (LØ trigger), can trigger likesign and unlikesign events.

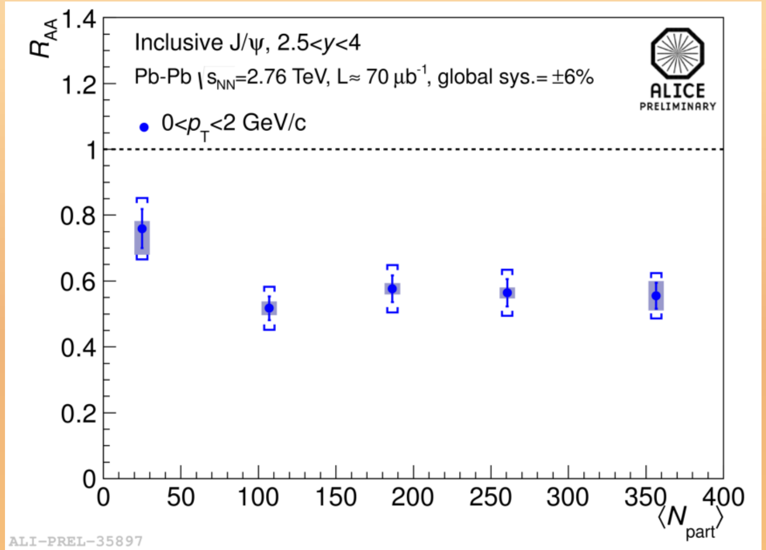
R_{AA} vs Centrality, y bins

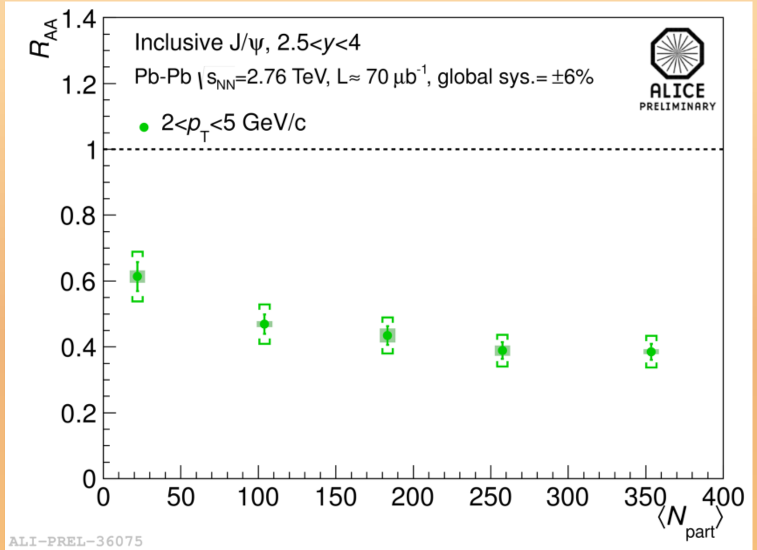


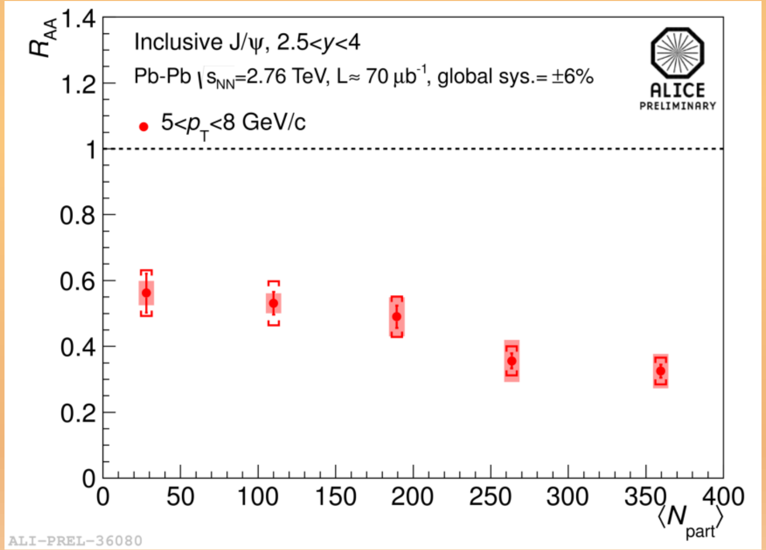




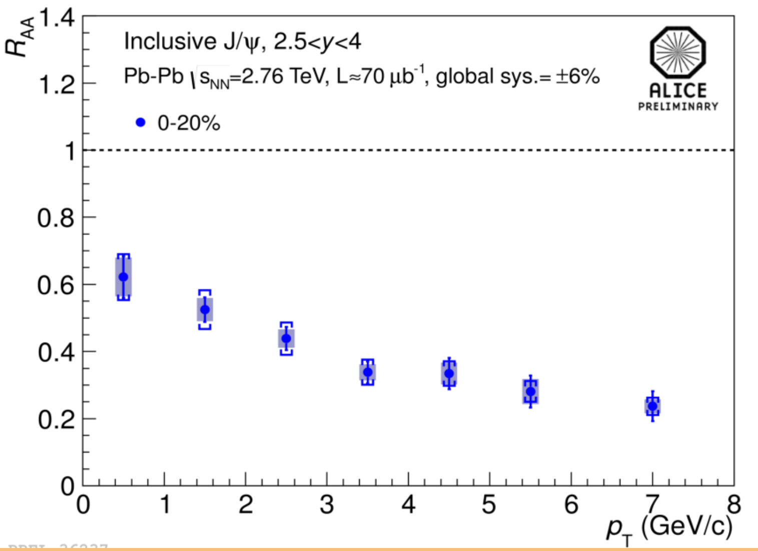
R_{AA} vs Centrality, p_T bins

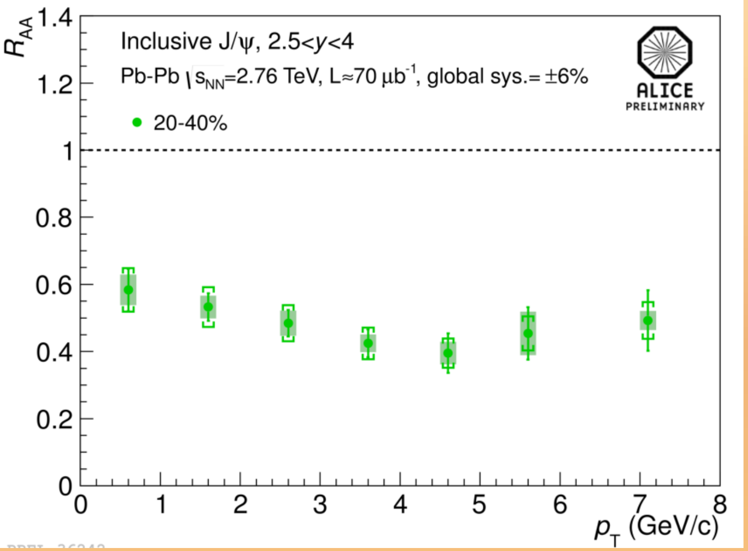


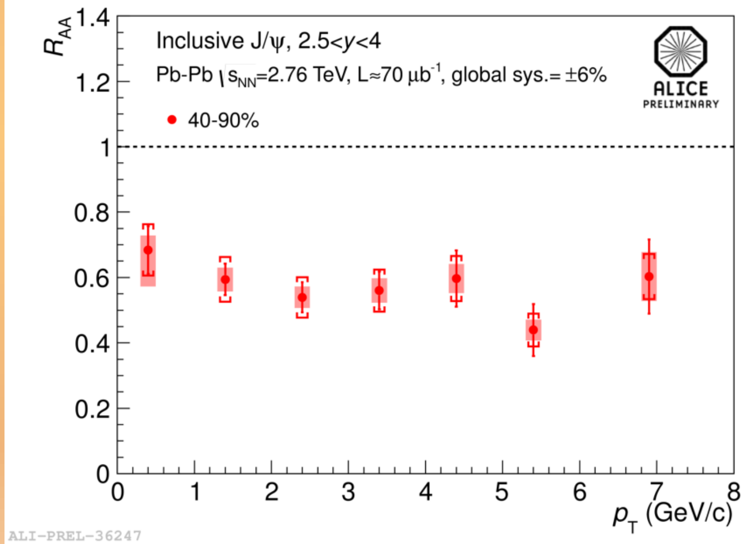




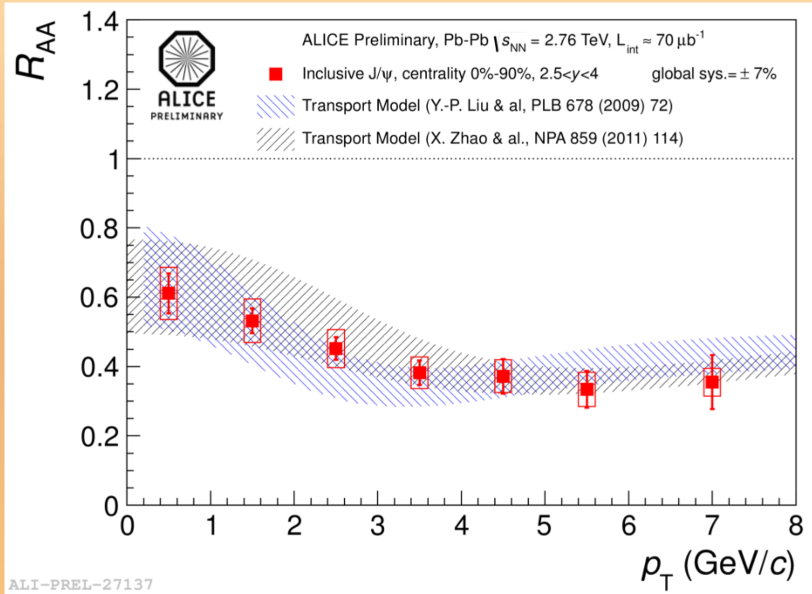
R_{AA} vs p_T, centrality bins

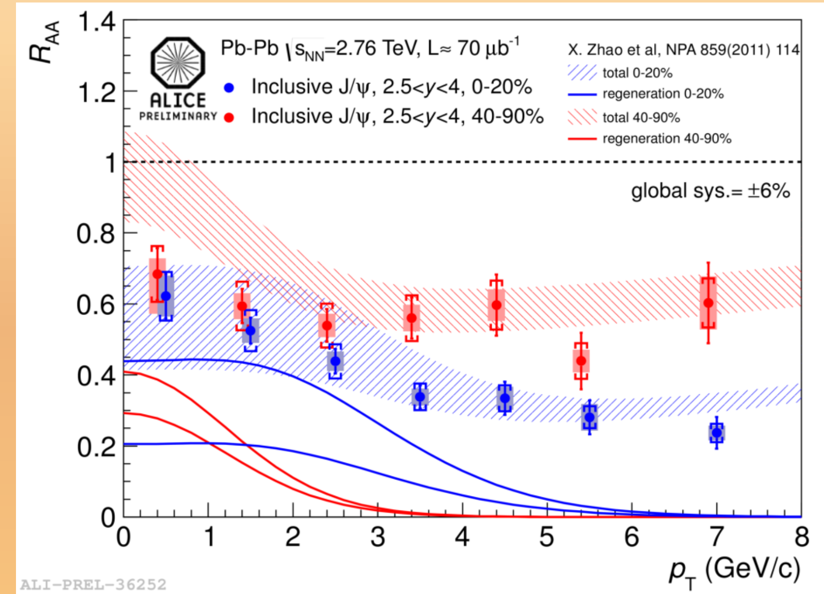






Results: J/ψ R_{AA} vs p_T, centrality bins





Stronger suppression for high-p_T J/ψ.

Stronger p_T dependence for central collisions.

Very good agreement with Transport Models.

Discrepancy between model and data at low-p_T in peripheral collisions.

Regeneration at work in the low-p_T regime.

Systematic uncertainties: Concepts & values

Concept	Value (%)
Luminosity pp	1.9
R factor pp	3.0
Normalization (MUL → MB)	2.1
Trigger	6.4
Tracking	6.0
Matching	2.0
MC input	5.0

Systematic uncertainties: Integrated R_{AA}

Corr. systematics: MC input + Matching + Tracking + Trigger + Normalization + J/ψ pp + pp Lumi.

Unc. systematics: n J/ψ + T_{AA} + Tracking + Trigger.

Statistics: n J/ψ.

vs centrality

Corr. systematics: Normalization + pp Lumi + T_{AA} + corr. J/ψ pp.

Unc. Systematics: n J/ψ + nMB + Tracking + Trigger + MC input + Matching + non corr. J/ψ pp.

Statistics: n J/ψ + J/ψ pp .

vs p_T/y

In the plots:
Statistics: vertical line at each point.
Unc. systematics: shaded area at each point.
Corr. Systematics: written at the top.

Systematic uncertainties: Multidimensional R_{AA}

Unc. systematics: n J/ψ.

P.C. systematics: MC input + Matching + Tracking + Trigger + TAA + unc. J/ψ pp.

vs centrality

Unc. systematics: n J/ψ + unc. J/ψ pp.

P.C. systematics: MC input + Matching + Tracking + Trigger + TAA.

vs p_T

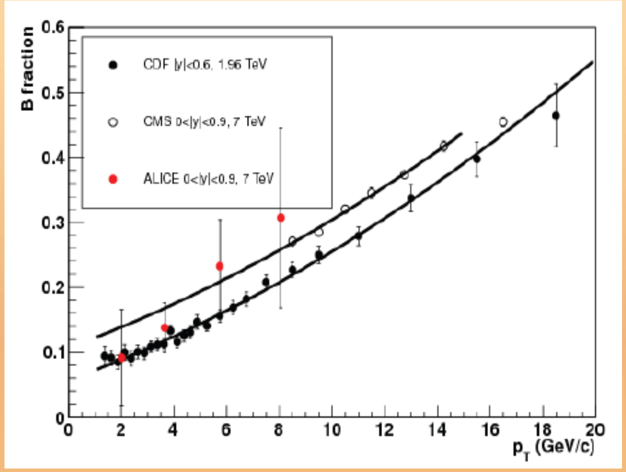
Corr. systematics: Normalization + corr. J/ψ pp.

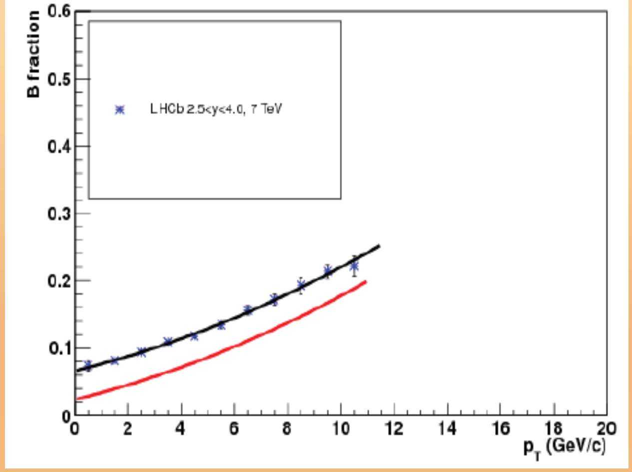
Statistics: n J/ψ + J/ψ pp .

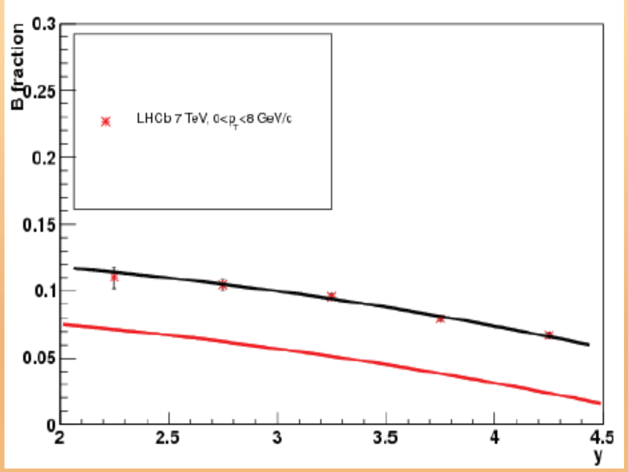
vs centrality/ p_T

In the plots:
Statistics: vertical line.
Unc. systematics: shaded area at each point.
P.C. systematics: boxes at each point,
Corr. Systematics: written at the top.

Effect of non-prompt J/ψ on ALICE R_{AA}







Non-prompt fraction of the inclusive J/ψ yield in pp at mid rapidity (f_B):
CDF vs CMS: increase of 5% and p_T independent.

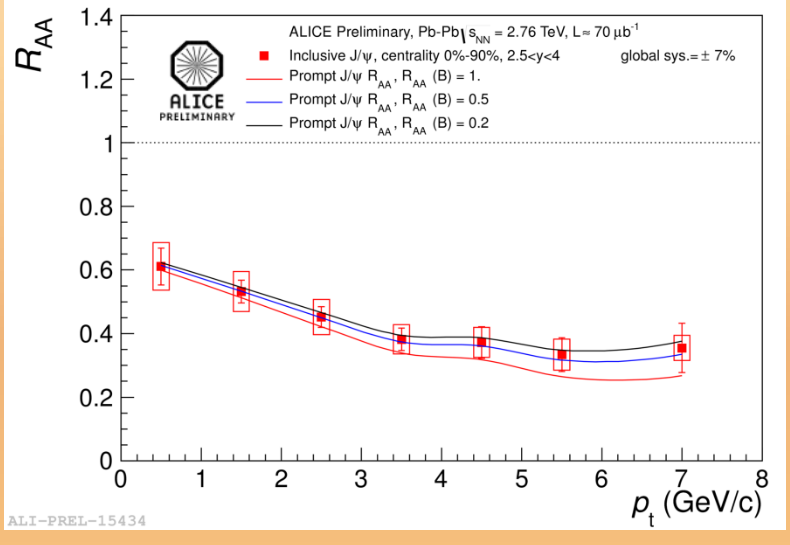
Assume:
1. Linear increase of $f_B(\sqrt{s})$.
2. It does not depend on the y region.

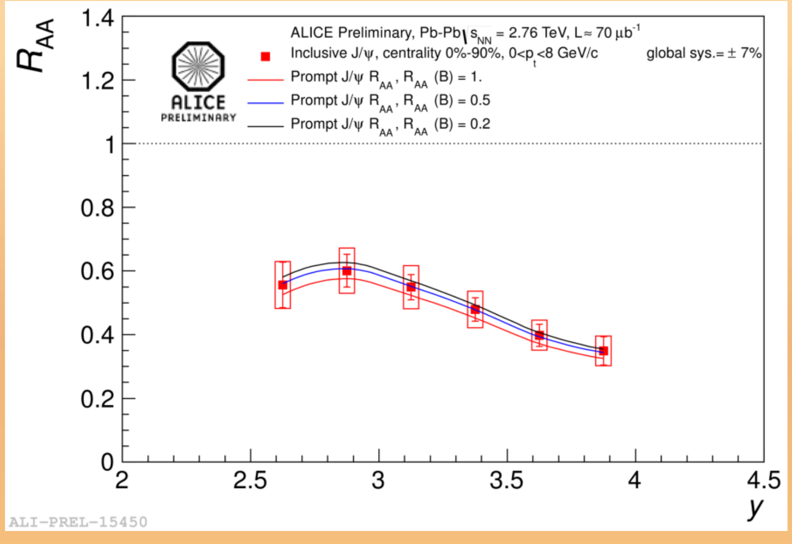
$f_B(p_T)$ for $\sqrt{s} = 2.76$ TeV

b-hadron suppression factor in Pb-Pb (q)? $R^D_{AA} \approx 0.3$ for $2 < p_T < 16$ GeV/c (JHEP09 (2012) 112) ➔ 'Dead cone effect': $R^B_{AA} > R^D_{AA}$.

$0.2 < q < 1$ is used

Effect of non-prompt J/ψ on ALICE R_{AA}





$$R_{AA}^{prompt}(p_T) = \frac{R_{AA}^{incl} - f_B q}{1 - f_B}$$ ➔ small effect on the inclusive J/ψ R_{AA} results.

Similar study can be carried out for R_{AA} vs y: LHCb shows $f_B(y)$ decreases with increasing rapidity.

➔ Difference between inclusive and prompt R_{AA} well within errors.

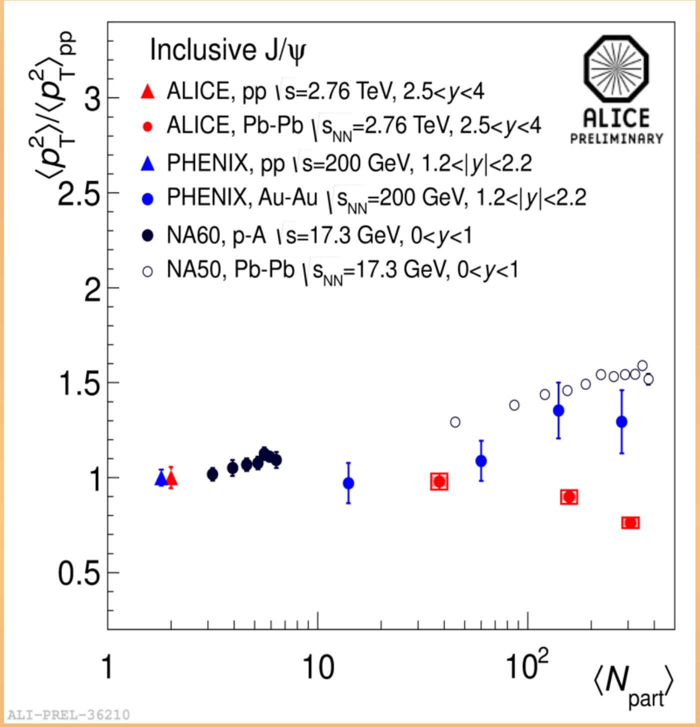
Theoretical models: inputs

Statistical hadronization
Thermal model with T=164 MeV, μ = 1 MeV (from particle ratio fits).
All charm produced in the initial hard-scatterings.
Charmonium production at phase boundary.

Transport Model by Rapp & Zhao
Boltzman transport equation for the J/ψ.
V_{FB} adjusted to measured $dN_{ch}/d\eta$.
$\sigma_{c\bar{c}}|_{y=3.25} \approx 0.5$ mb.
Shadowing: 30% suppression in the most central collisions.
No Croning effect and $\sigma_{Abs} = 0$.
10% of J/ψ ← B and no quenching.

Transport Model by Liu *et al.*
Boltzman transport equation for the J/ψ.
$\sigma_{c\bar{c}}|_{y=3.25} \approx 0.38$ mb.
EKS98 shadowing and $\sigma_{Abs} = 0$.
10% of J/ψ ← B and R_{AA} (b) = 0.4 for all p_T range.

J/ψ $< p_T^2 >$



Inclusive J/ψ
ALICE, pp √s=2.76 TeV, 2.5<y<4
ALICE, Pb-Pb √sNN=2.76 TeV, 2.5<y<4
PHENIX, pp √s=200 GeV, 1.2<|y|<2.2
PHENIX, Au-Au √sNN=200 GeV, 1.2<|y|<2.2
NA60, p-A √s=17.3 GeV, 0<y<1
NA50, Pb-Pb √sNN=17.3 GeV, 0<y<1
ALICE PRELIMINARY
⟨p²T⟩/⟨p²T⟩pp
⟨Npart⟩
0.5
1
1.5
2
2.5
3
1
10
10²
ALI-PREL-36210