Quarkonium production measurement in Pb-Pb collisions with the ALICE experiment at the LHC

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for the ALICE collaboration

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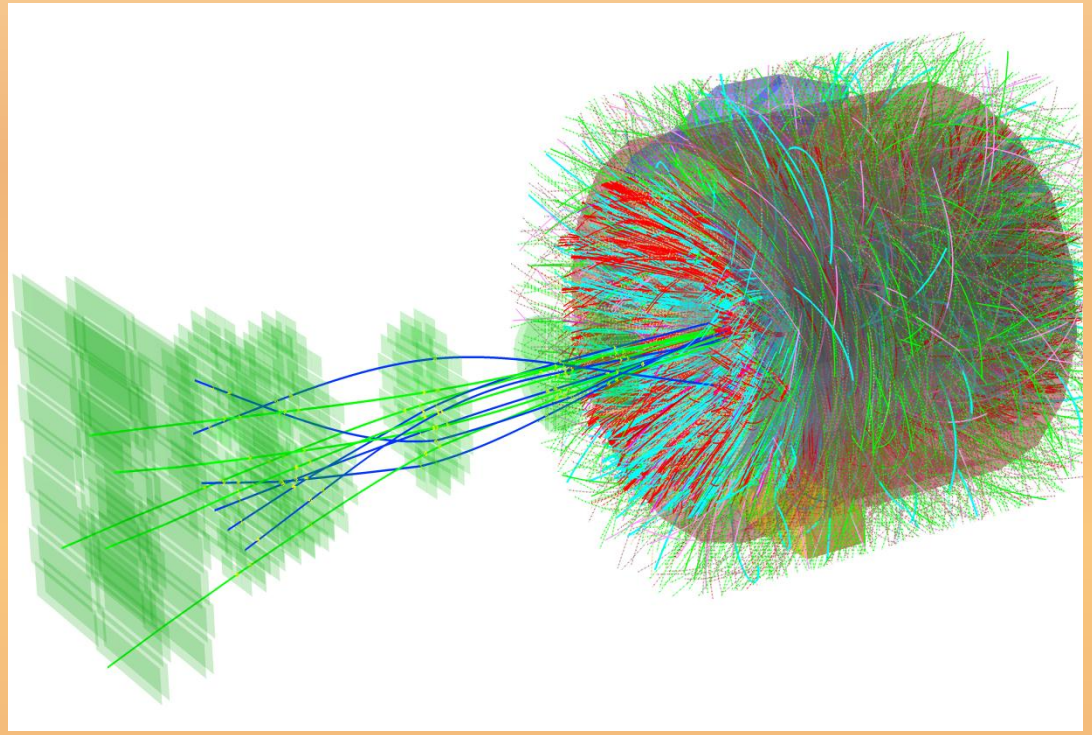
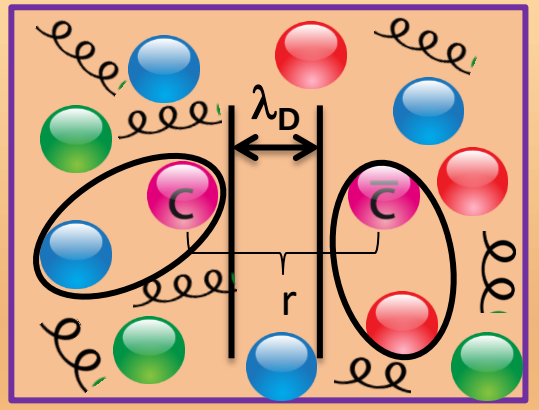
Outline

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



Quarkonium 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 & bounding energies → sequential suppression.

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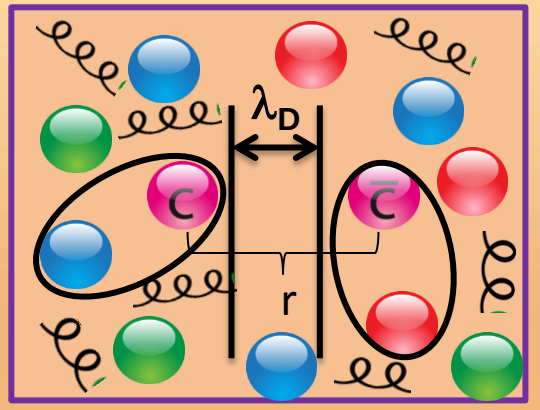

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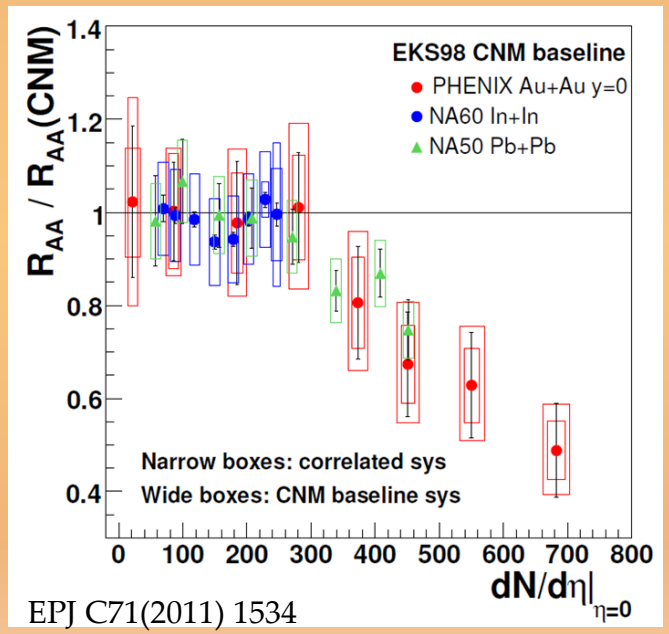
Quarkonium production in A-A previously studied by different experiments:

- ❑ Significant J/ψ suppression beyond the Cold Nuclear Matter effects.
- ❑ Suppression is practically $\sqrt{s}$ - independent.
- ❑ Is quarkonium regeneration playing a role?

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



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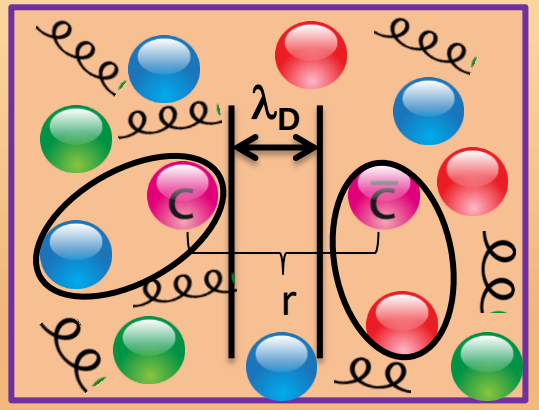
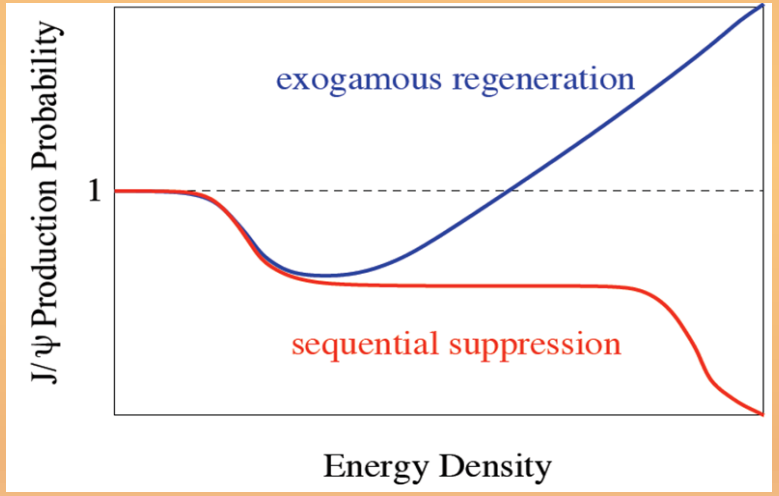


Quarkonium as a probe of deconfinement:

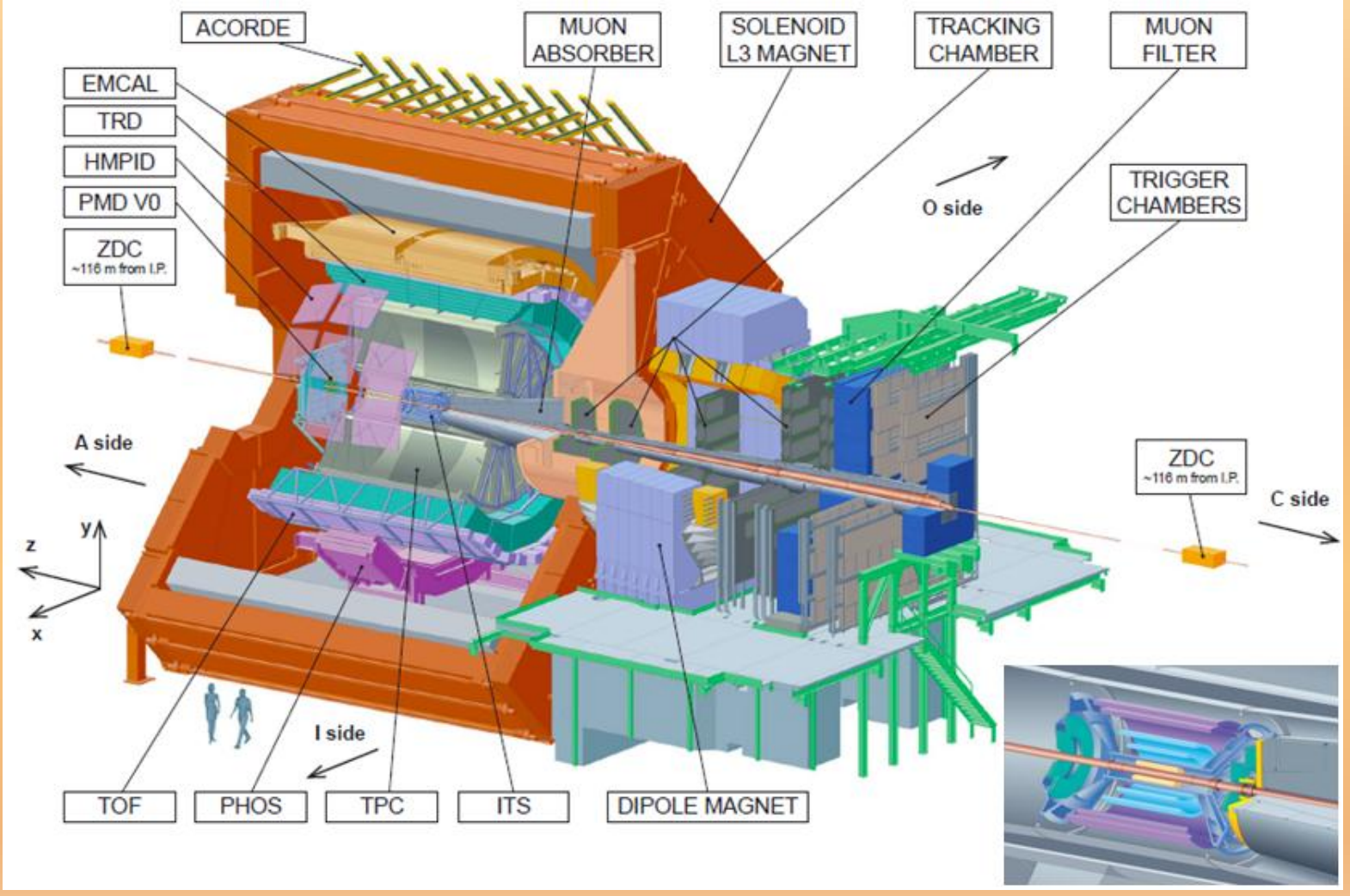
✓ Created in the early stages of the collision.
✓ Suppressed by Debye screening.
✓ Different radii & bounding energies → sequential suppression.

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?



The ALICE experiment



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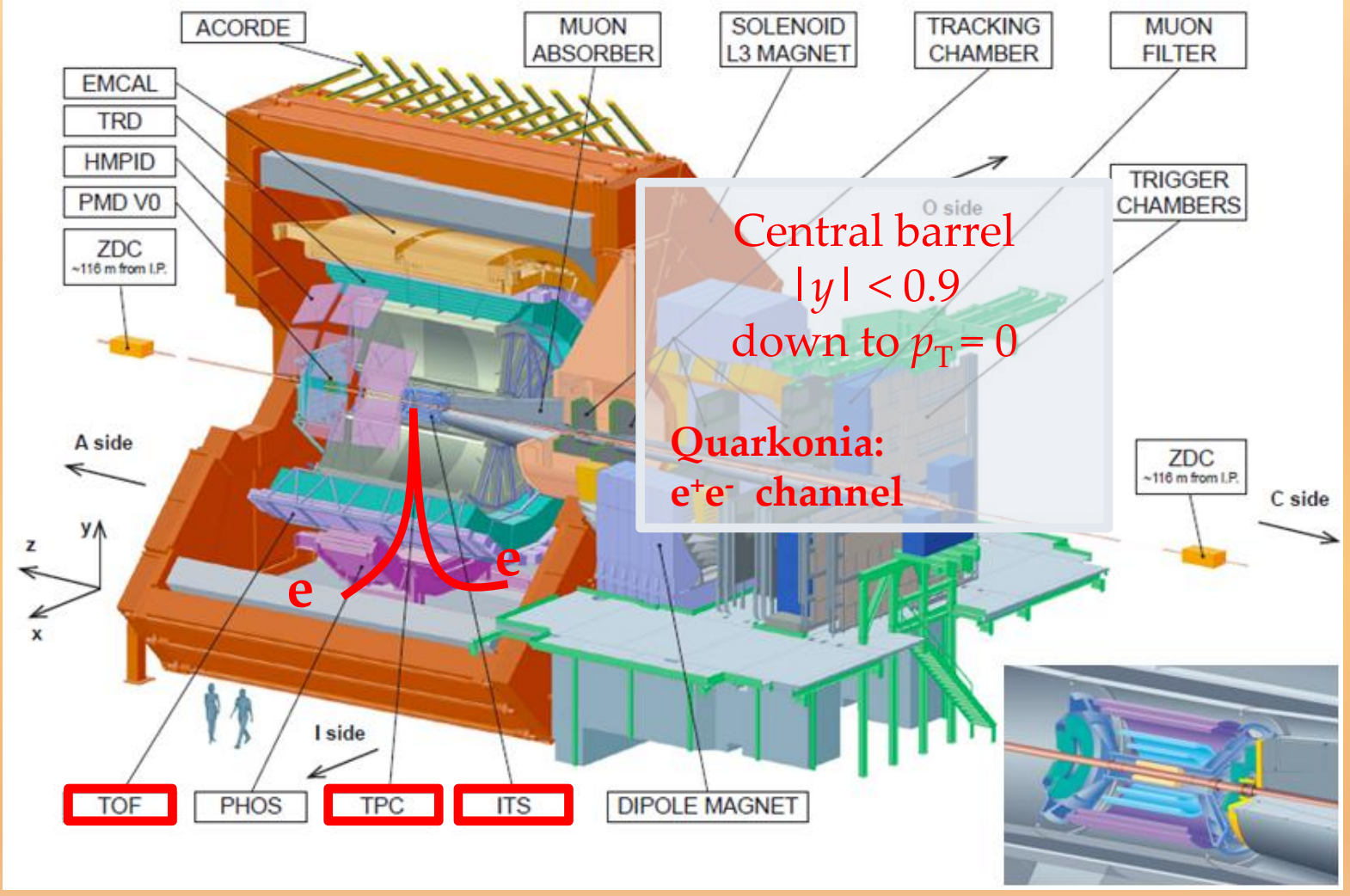

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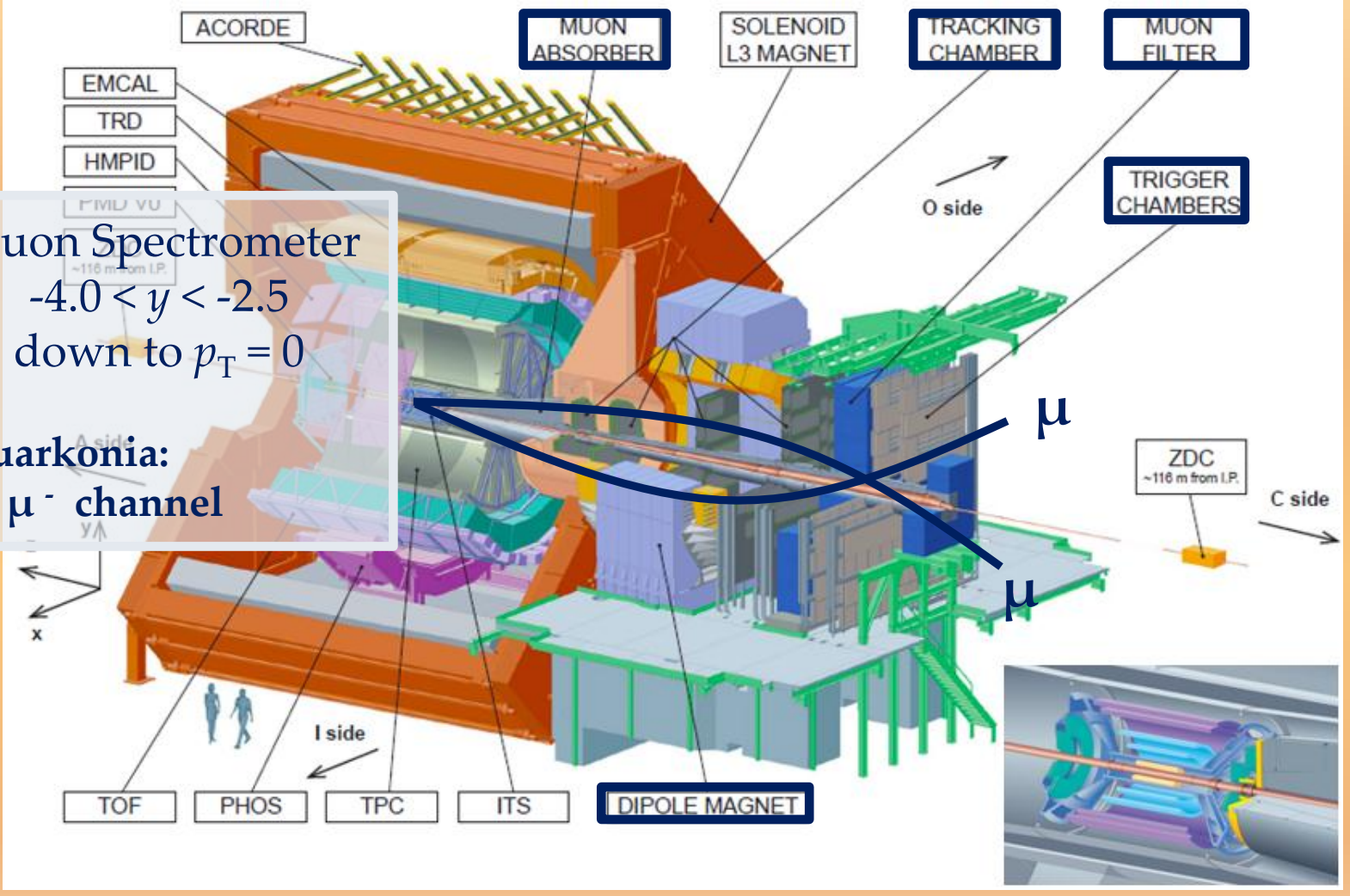


Muon Spectrometer
$-4.0 < y < -2.5$
down to $p_T = 0$

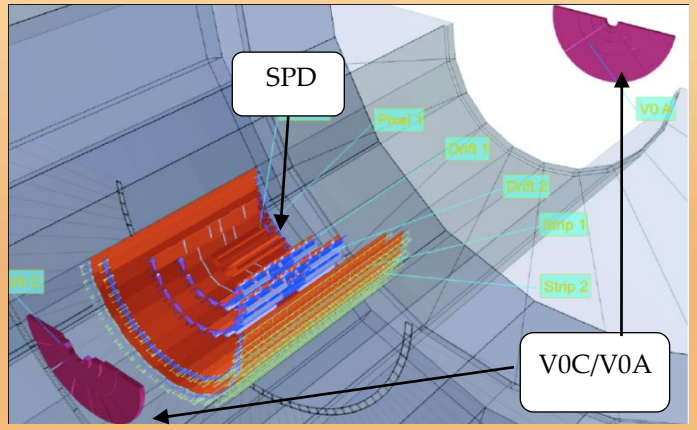
Quarkonia:
$\mu^+ \mu^-$ channel

Trigger, event selection and centrality

- $J/\psi \rightarrow ee$:

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

2010 MB trigger: signal in two hodoscope scintillators (V0A and V0C) and in the outer layer of a pixel detector (SPD) ➔ $L_{int} \approx 2\ \mu b^{-1}$.

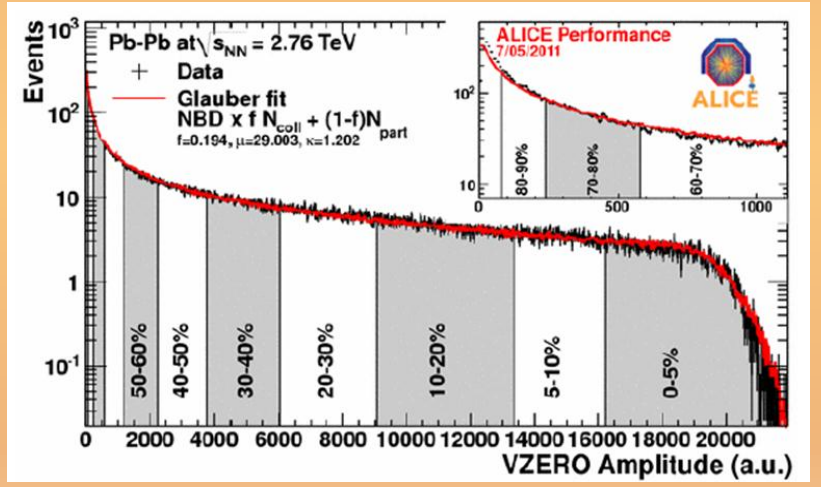


2011 Centrality triggered events ➔ $L_{int} \approx 15\ \mu b^{-1}$.

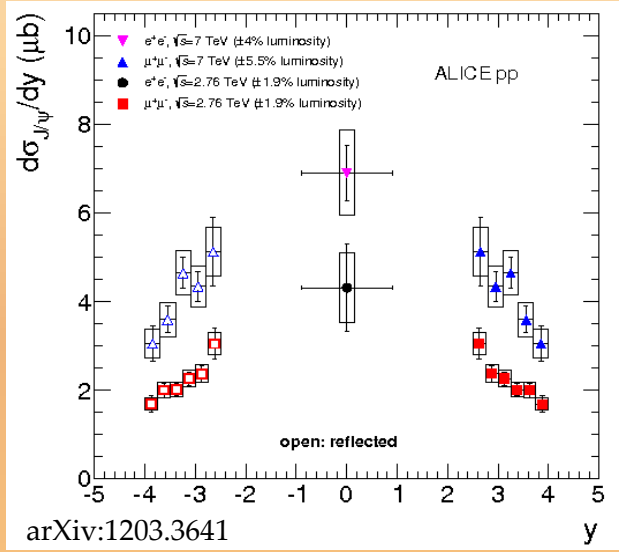
- $J/\psi, \psi(2S) \rightarrow \mu\mu$:

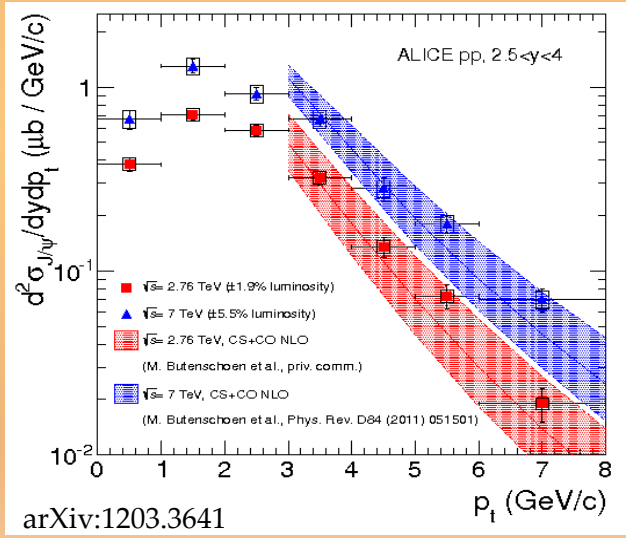
2011 data set: dimuon events from the muon trigger, $L_{int} \approx 70\ \mu b^{-1}$.

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



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





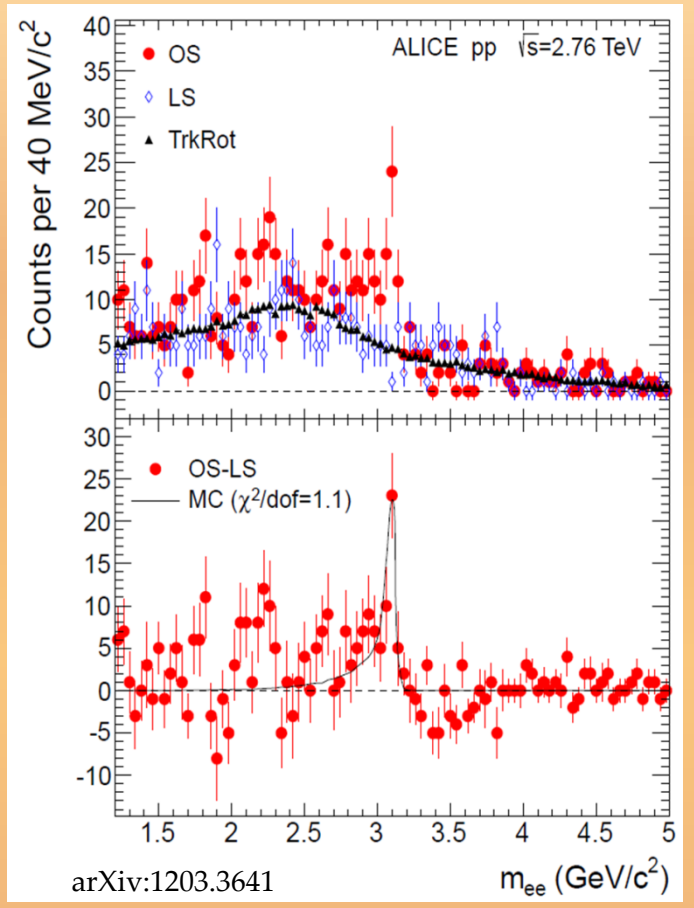
Reference from pp collisions is needed!

Both at forward and midrapity.

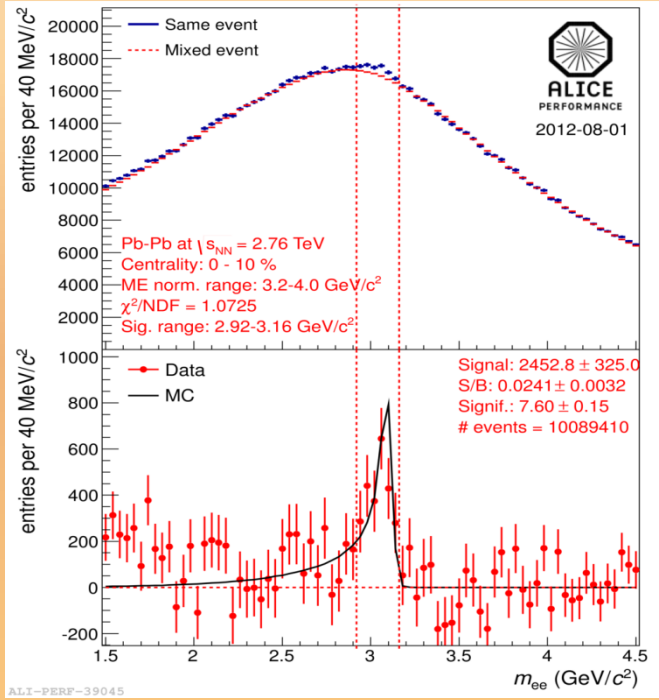
$2.5 < y < 4.0$: NRQCD calculations describe the measured $d^2\sigma/dy dp_T$ at 7 and 2.76 TeV.

pp reference is the main source of systematics in the R_{AA}:

- 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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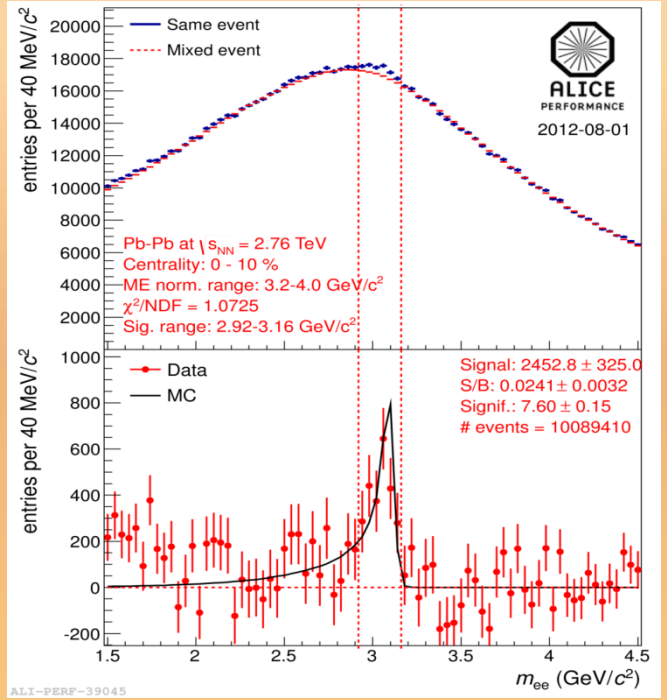

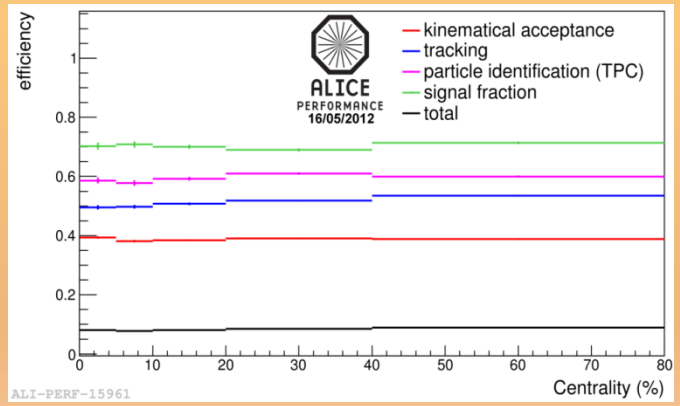

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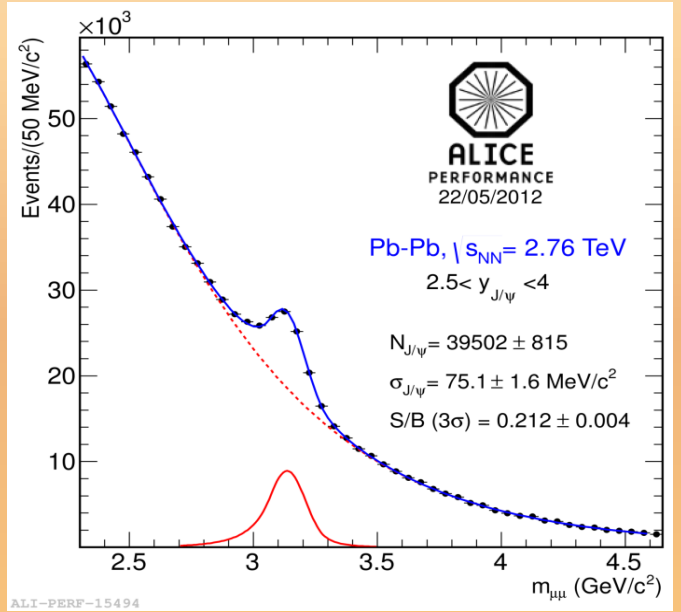
- ✓ Signal extracted in three centrality bins: 0-10%, 10-40% and 40-80%.
- ✓ Efficiency computed using HIJING enriched with J/ψ.
- ✓ Little dependence on the centrality.

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.

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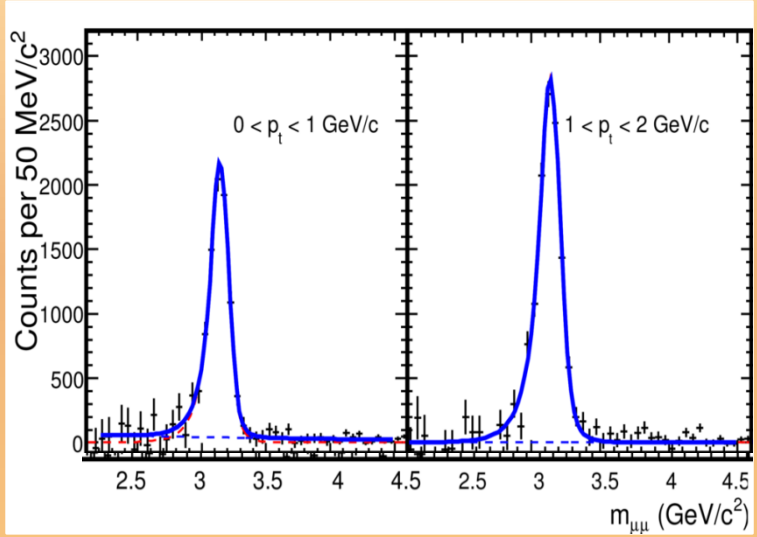

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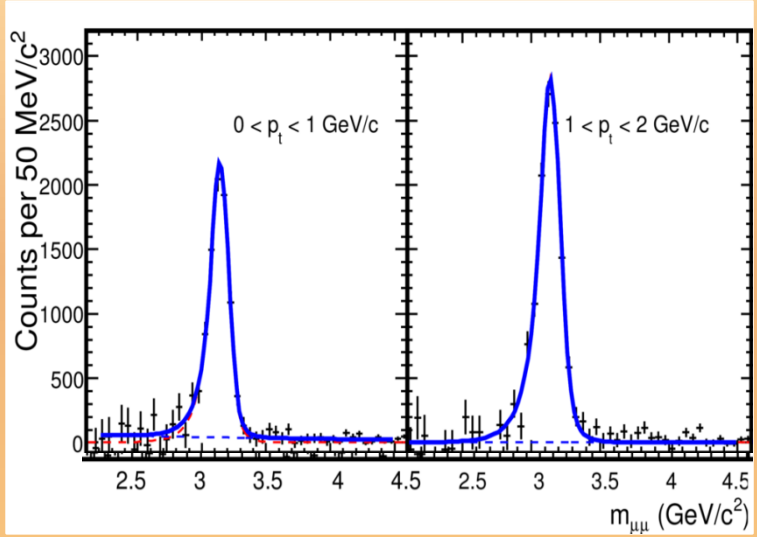

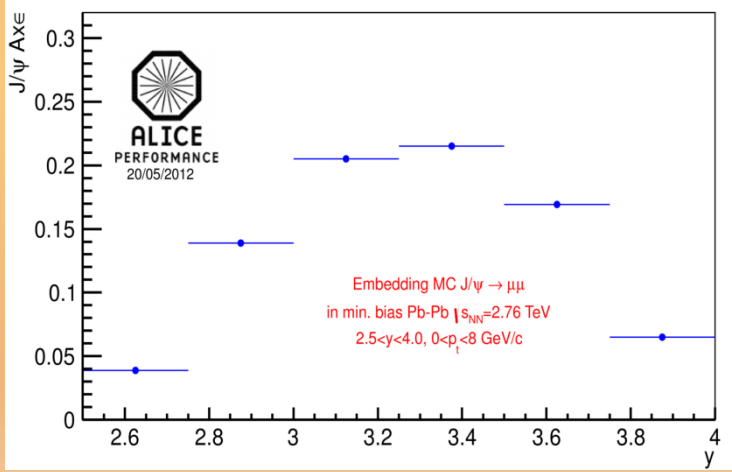

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Acceptance x efficiency values are obtained by embedding MC J/ψ into real events.

Rapidity bins: detector acceptance.

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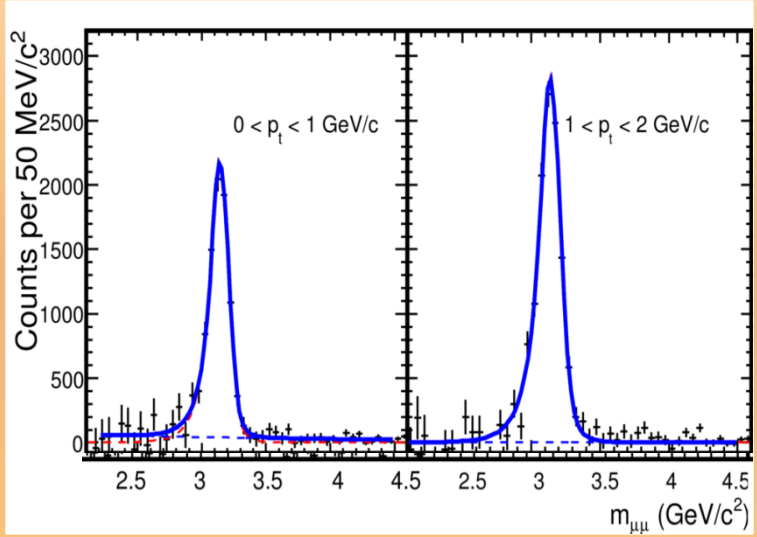

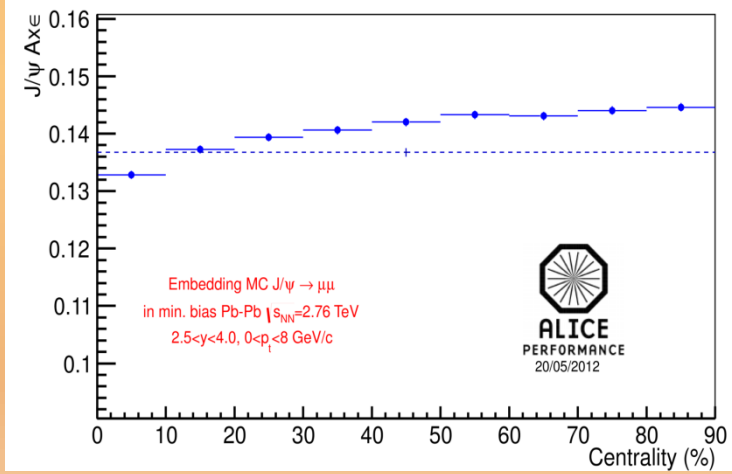

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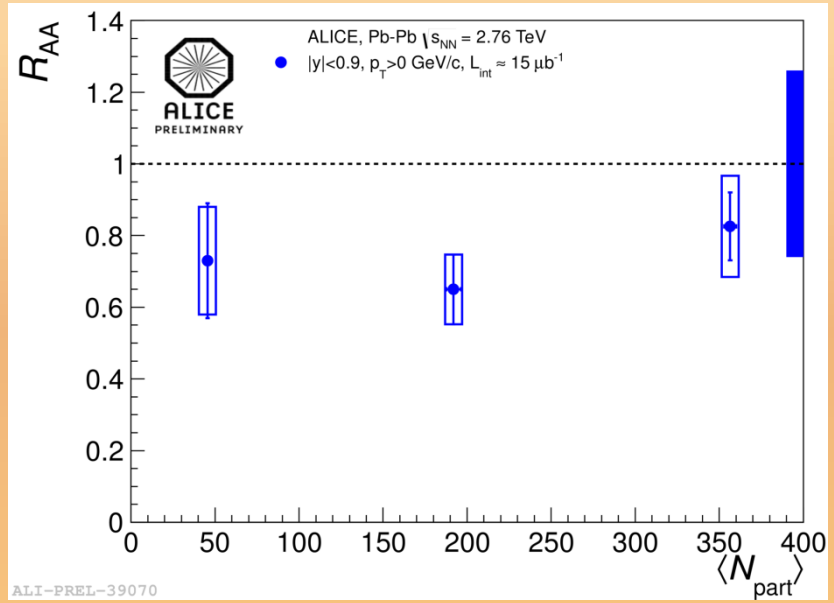
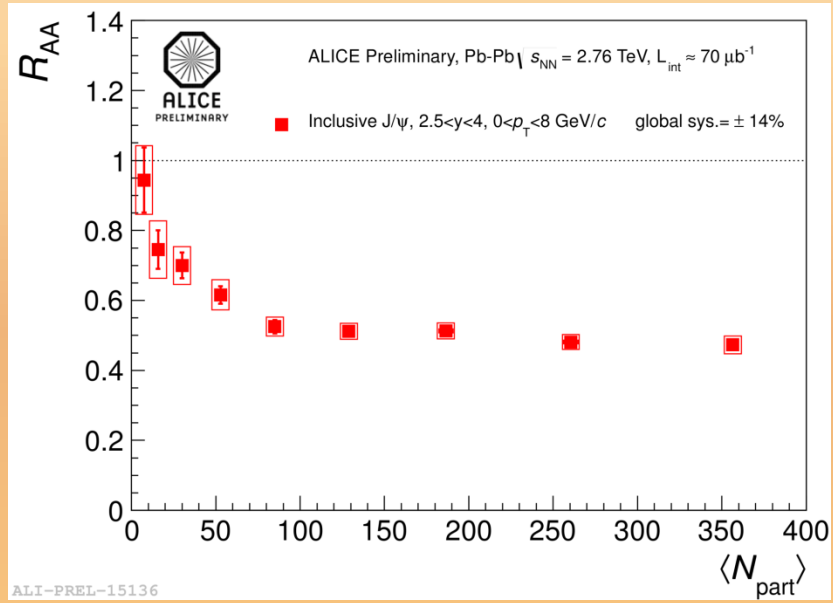
Weak centrality dependence.

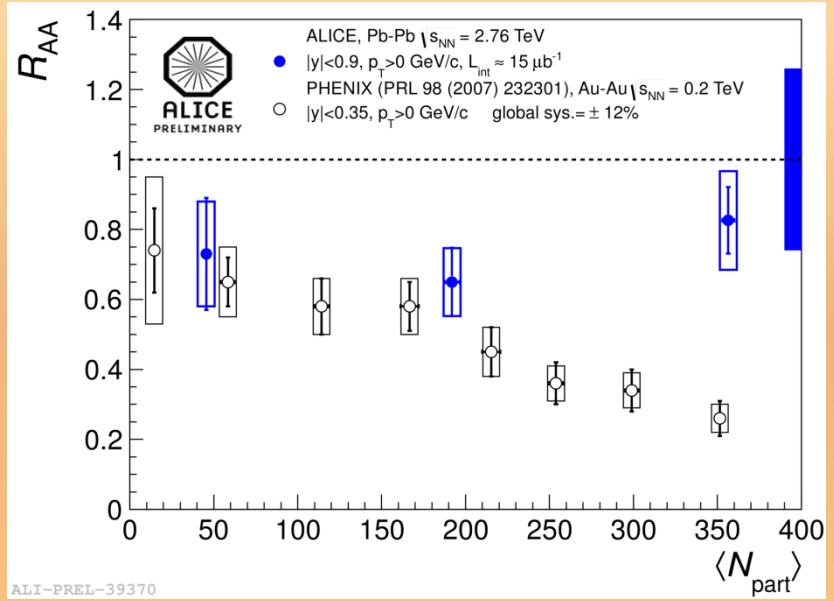
Results: J/ψ R_{AA} vs centrality

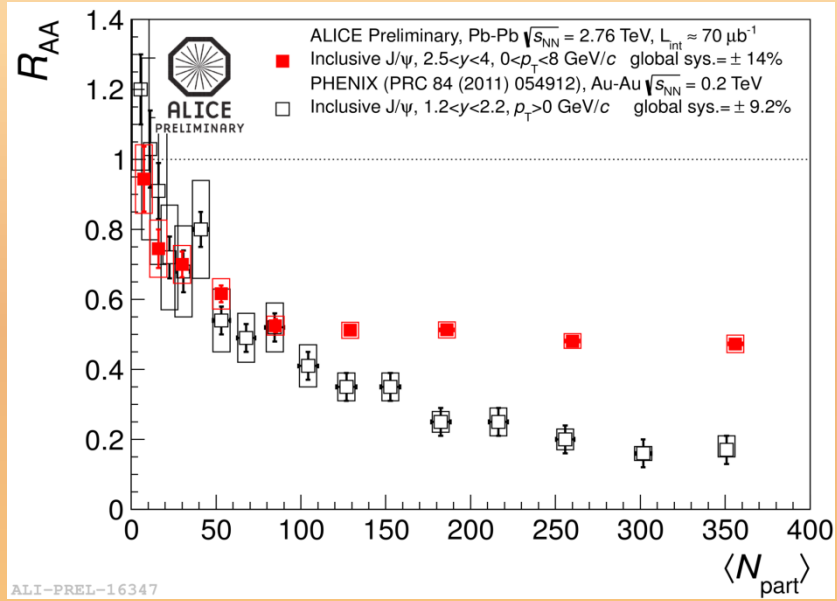




- No significant centrality dependence within errors.
- No significant centrality dependence for $N_{part} > 100$.

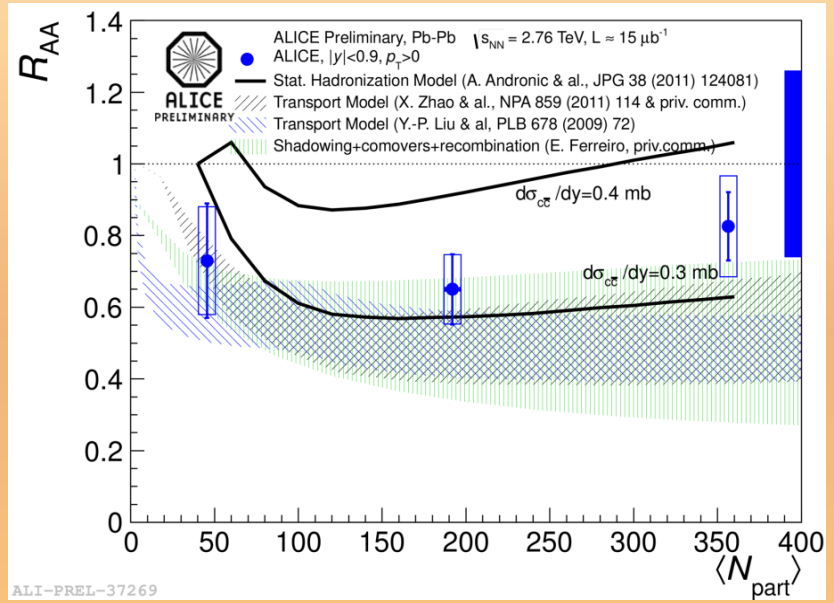
Results: J/ψ R_{AA} vs centrality

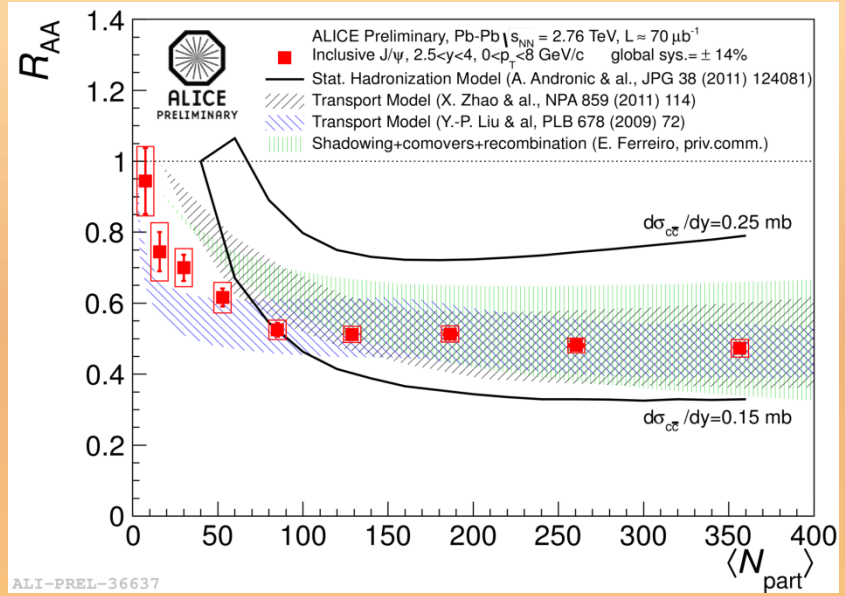




- No significant centrality dependence within errors.
- No significant centrality dependence for $N_{part} > 100$.
- R_{AA} in the most central collision from ALICE is ~3 times larger than at PHENIX.
- $R_{AA}^{ALICE} \sim 3 \times R_{AA}^{PHENIX}$ for $N_{part} > 200$.

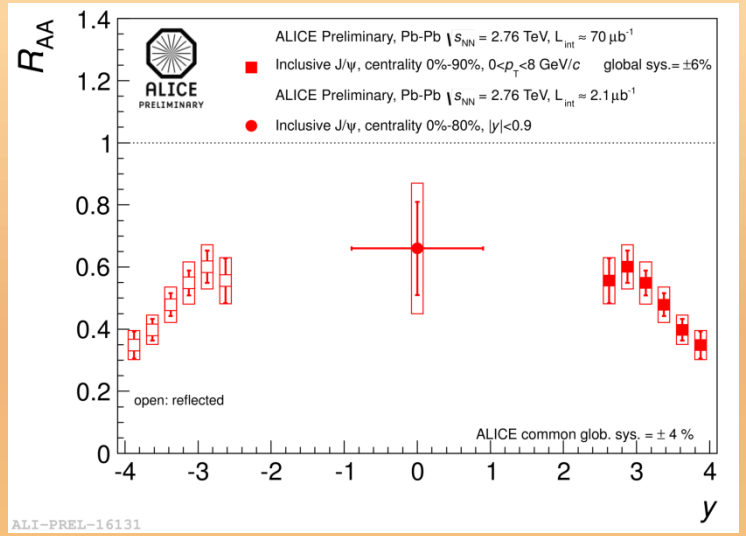
Results: J/ψ R_{AA} vs centrality

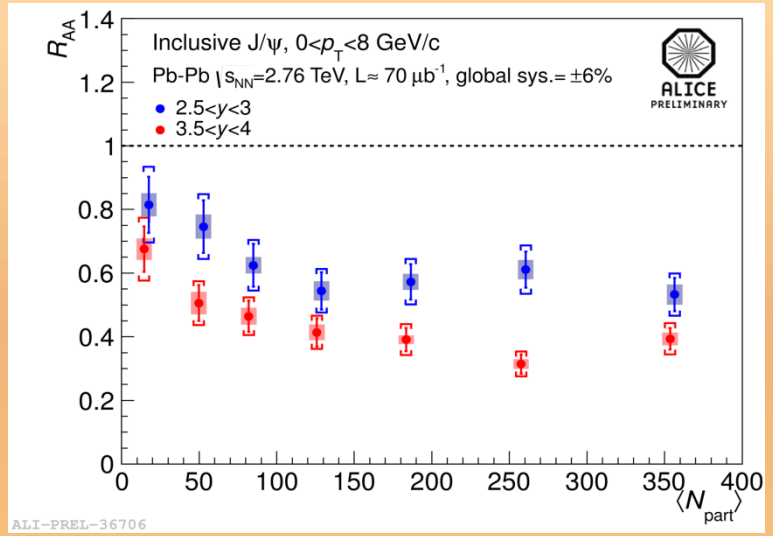




- Statistical Hadronisation Model: prediction for two $d\sigma_{c\bar{c}}/dy$.
- Transport Models: different rate equations of J/ψ dissociation and regeneration in QGP, in both cases more than 50% of measured yield in the most central collisions due to J/ψ regeneration, the rest is from initial production.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

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

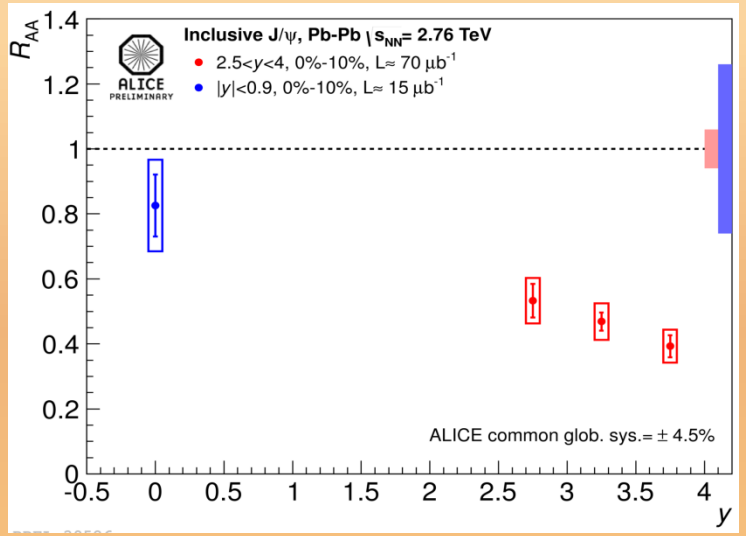


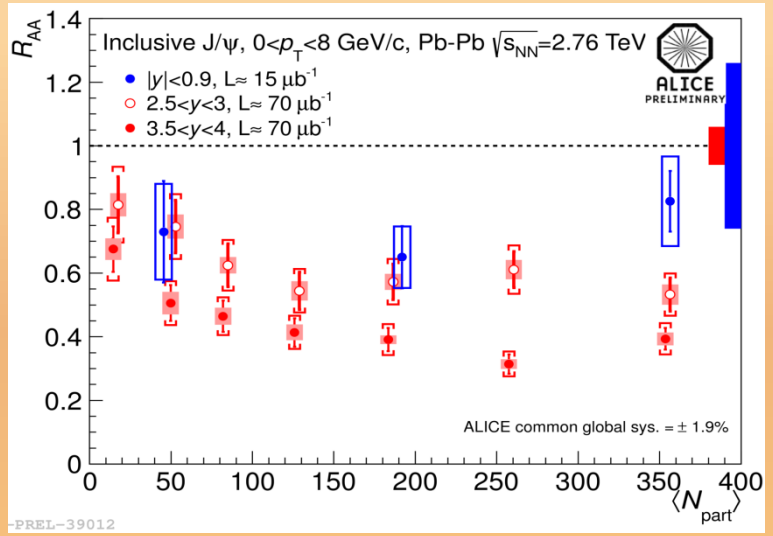


R_{AA} decreases by 40% from y = 2.5 to y = 4.

Same centrality behavior at forward y.

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





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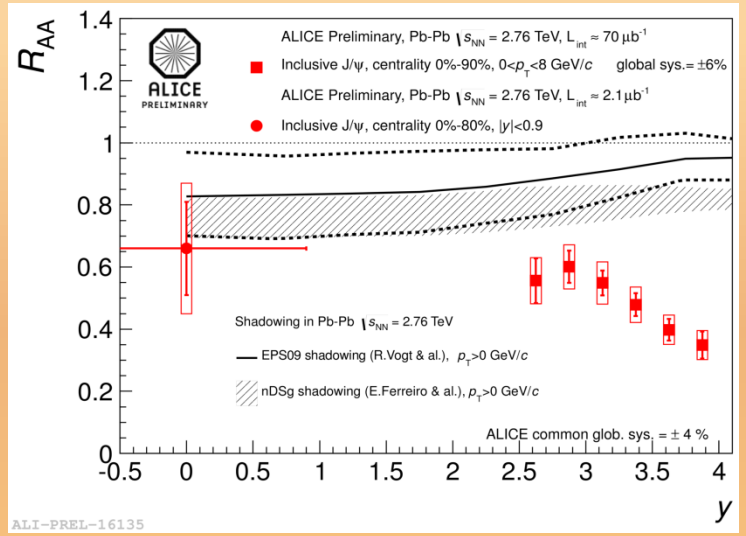

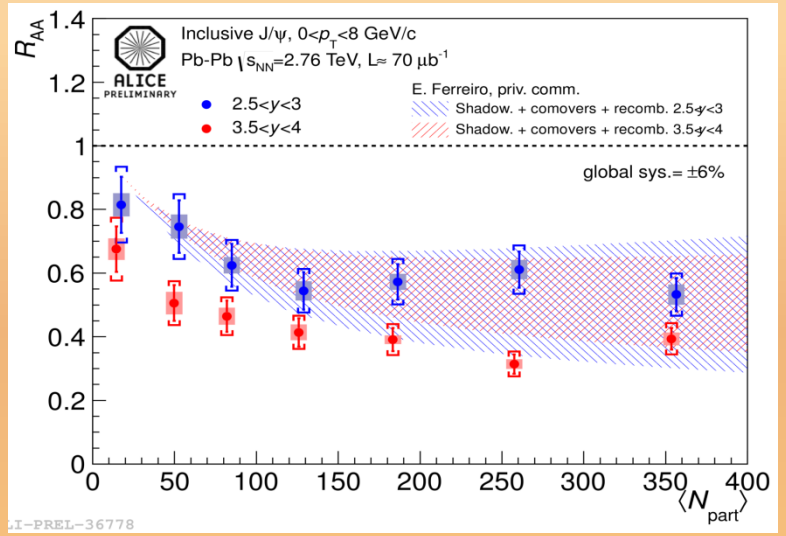

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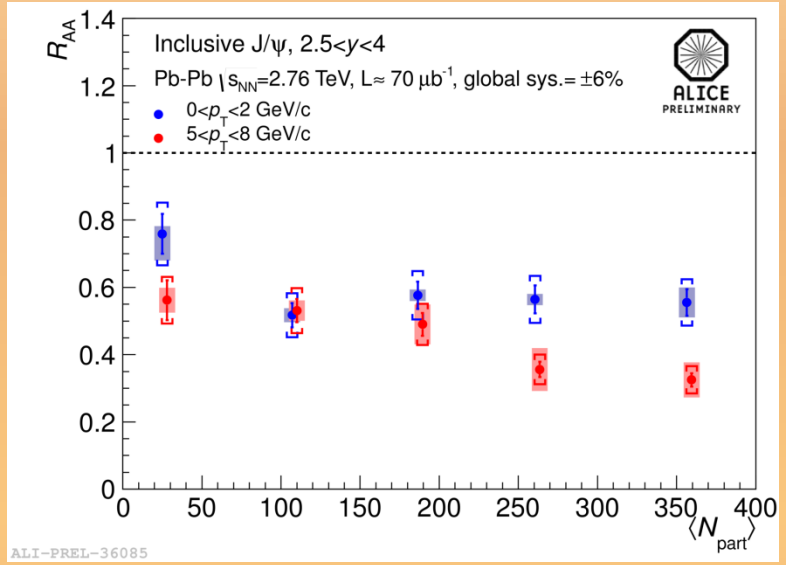
J/ψ less suppressed if shadowing calculations are considered.

Weaker y dependence predicted by shadow. + comovers + recombination.

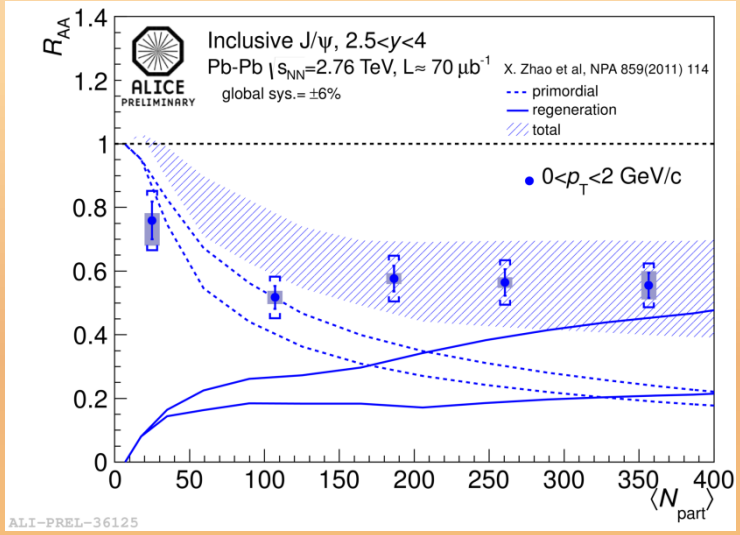
Cold Nuclear Matter effects need to be quantified!

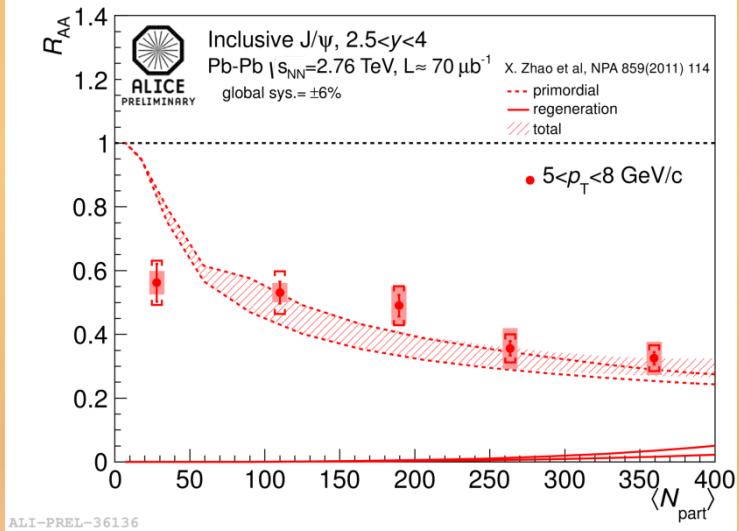
Results: J/ψ R_{AA} vs centrality, p_T bins



- Stronger suppression for high-p_T J/ψ.
- No centrality dependence for low-p_T J/ψ when $N_{part} > 100$.

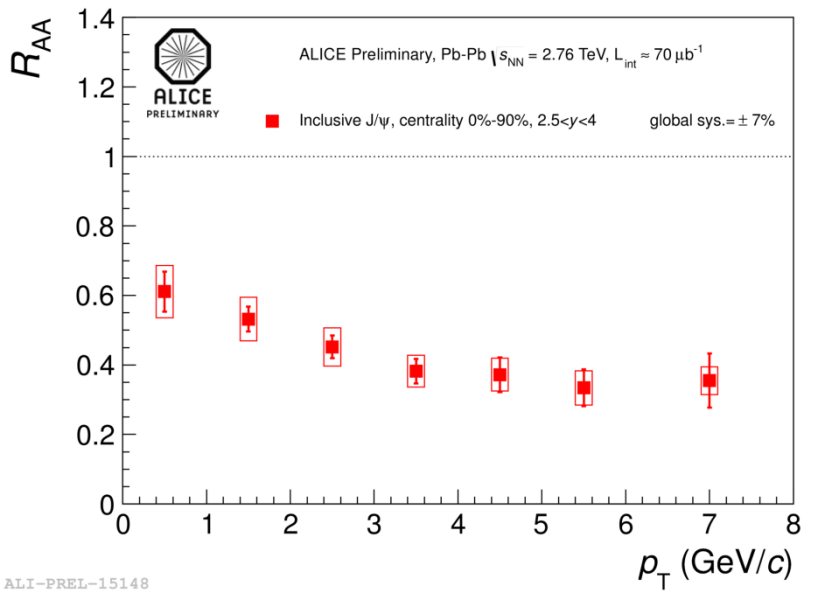
Results: J/ψ R_{AA} vs centrality, p_T bins





- 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 R_{AA} vs p_T, centrality bins



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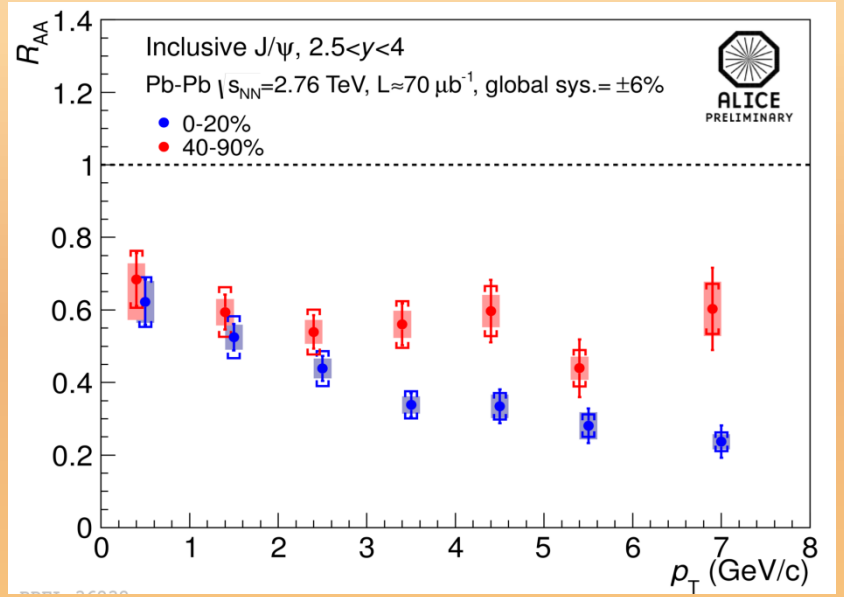
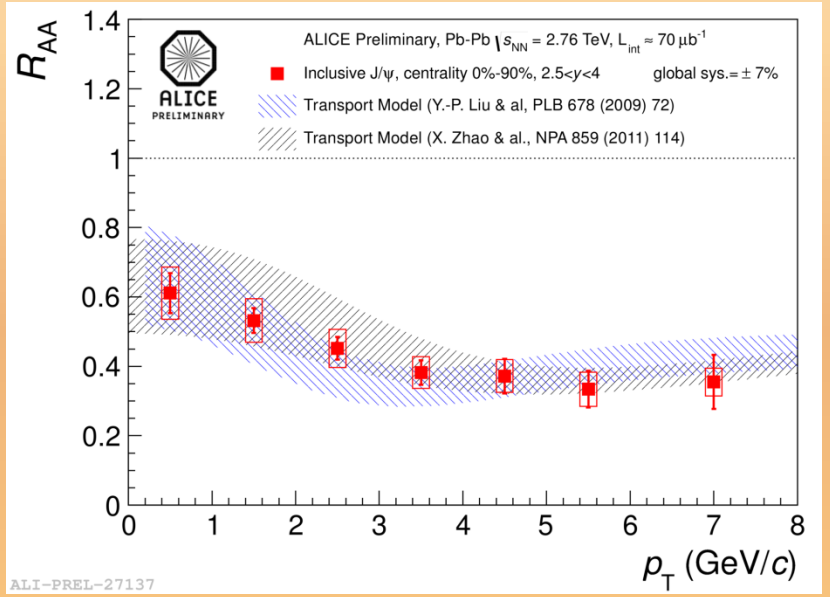
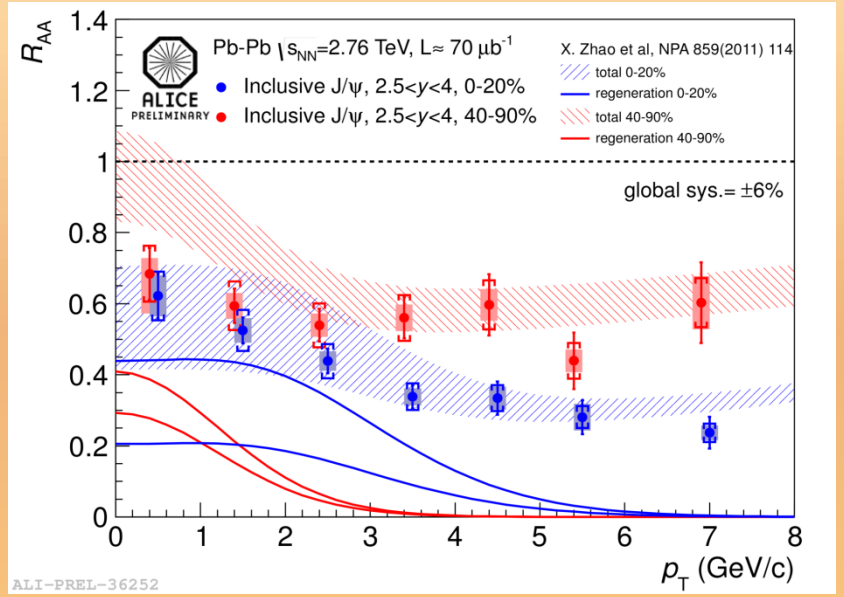


Stronger p_T dependence for central collisions.

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





Stronger suppression for high-p_T J/ψ.

Very good agreement with Transport Models.

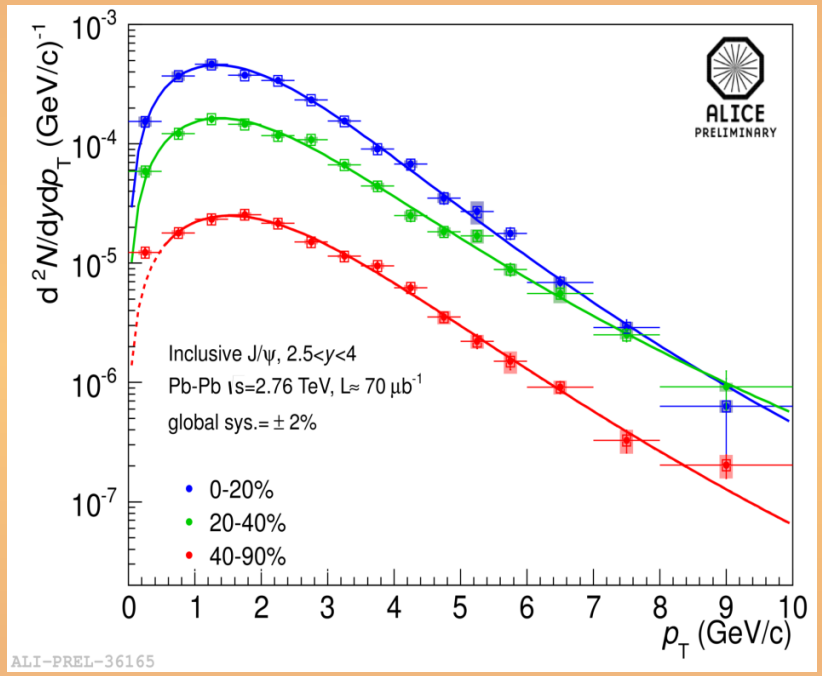
Stronger p_T dependence for central collisions.

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

Regeneration at work in the low-p_T regime.

Results: J/ψ < p_T >

$< p_T >$ values were obtained by fitting $\frac{d^2N}{dydp_T} \propto \frac{p_T}{\left[1+(p_T/p_0)^2\right]^n}$ in three different centrality bins. Low-p_T excess in the most peripheral bin due to non-hadronic production.



Results: J/ψ < p_T >

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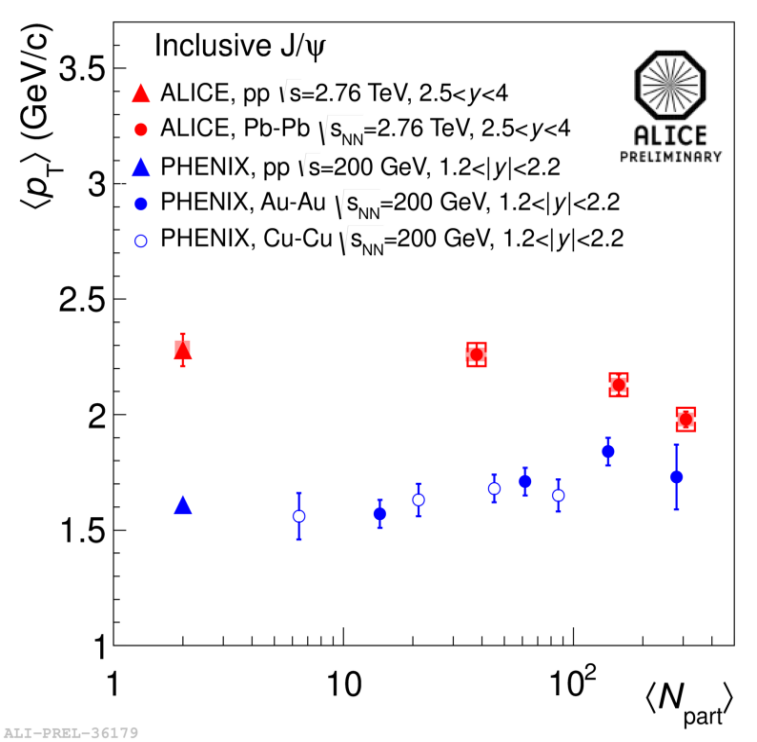


ALICE: clear decrease of < p_T > with increasing N_{part}.

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

Striking difference with respect to lower energy results!

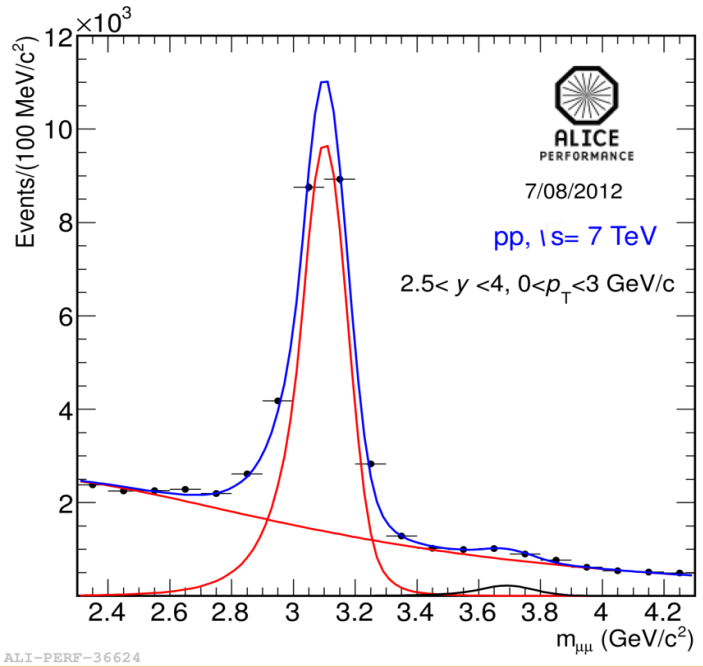
$\psi(2S) \rightarrow \mu\mu$

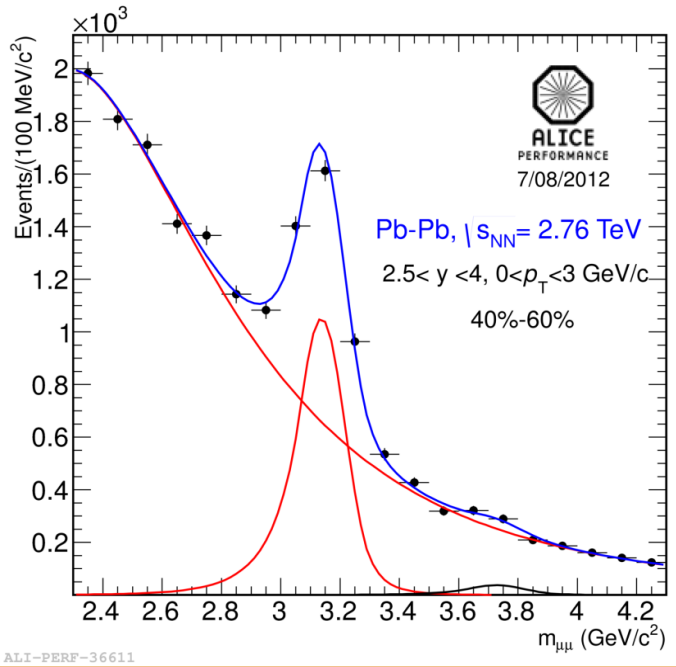
Low significance for $\psi(2S)$, both in pp and Pb-Pb.

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%.

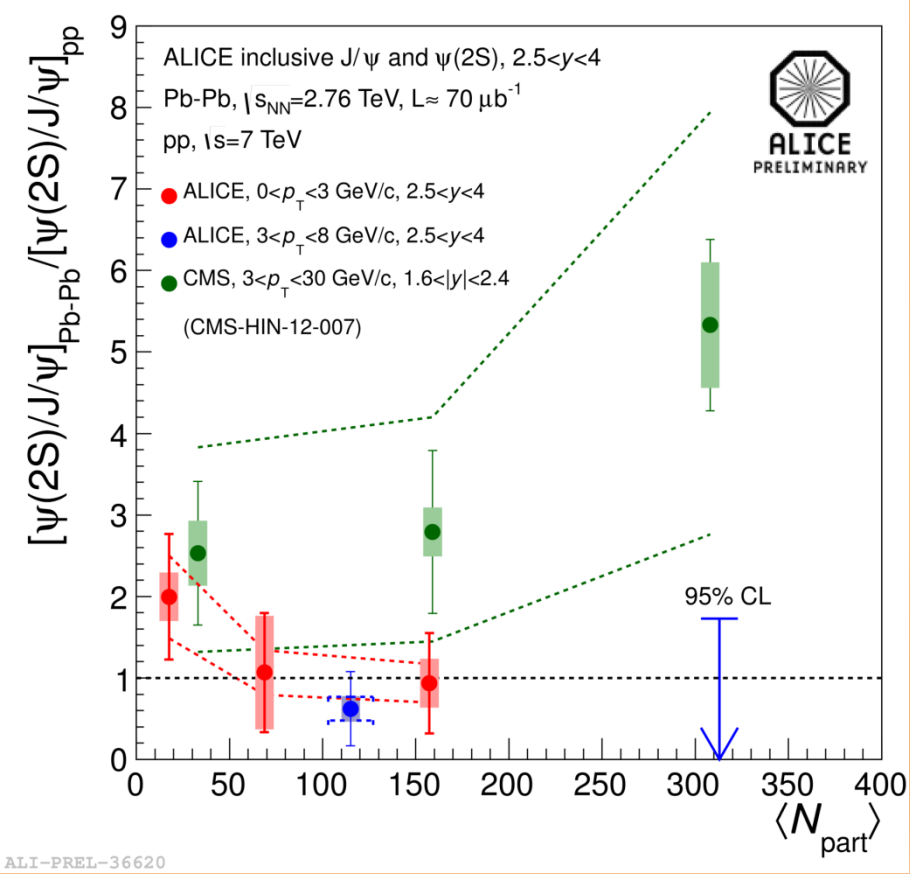
S/B in Pb-Pb: between 0.01 and 0.3 from 20-40% to 60-90% centrality.





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

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.

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).
  - $R_{AA}^{ALICE} \sim 3$ 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.

- Important to measure Cold Nuclear Matter effects.

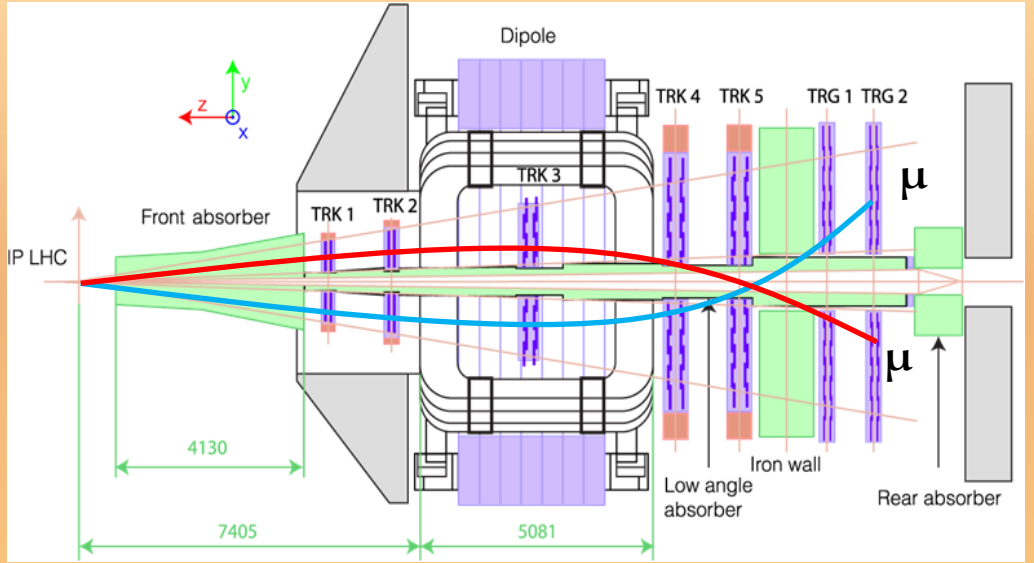
- ψ(2S): No firm conclusion on enhancement/suppression with respect to J/ψ, but a strong enhancement in central Pb-Pb collisions seems unlikely.

Backup

The ALICE Muon Spectrometer

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

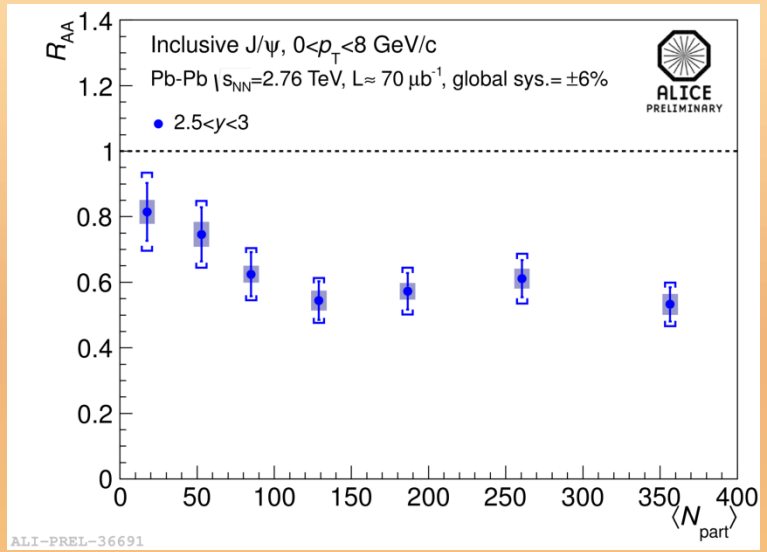
- Absorbers:
  a) Front absorber.- Absorbs hadrons, photons and electrons.
  b) Beam shield.- Protects from particles produced at large y.
  c) Iron wall.- Absorbs hadrons that punch-through the frontal absorber.
- Magnetic dipole.- 3 T·m integrated magnetic field, bends charged particles allowing to extract the sign of their electric charge and momentum.

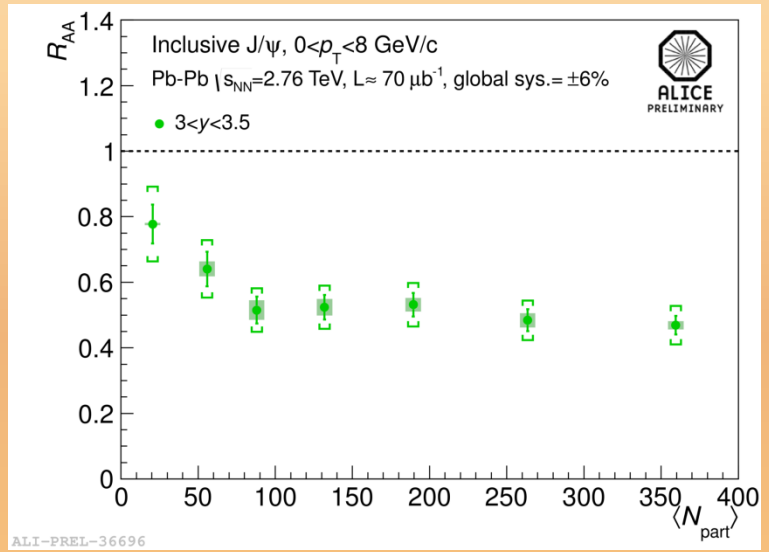


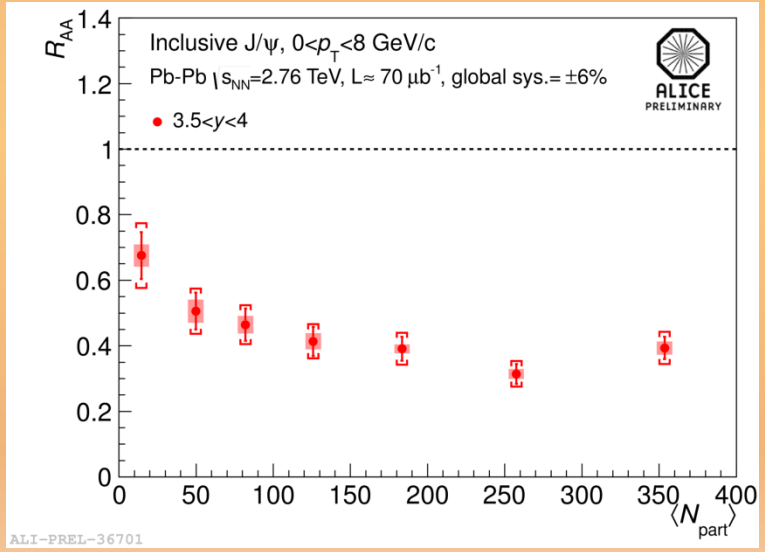
- Tracking chambers.- Spatial resolution, in bending coordinate, better than 100 μm in order to identify and disentangle the ϒ family (100 MeV resolution).

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

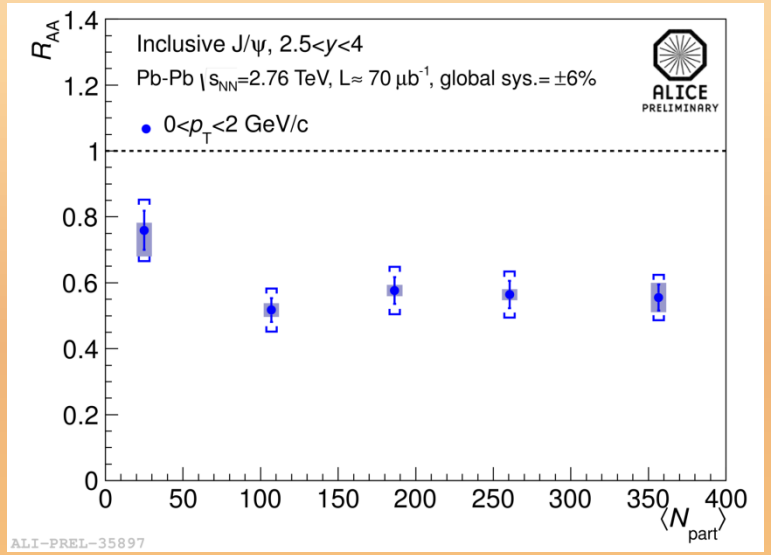
R_{AA} vs Centrality, y bins

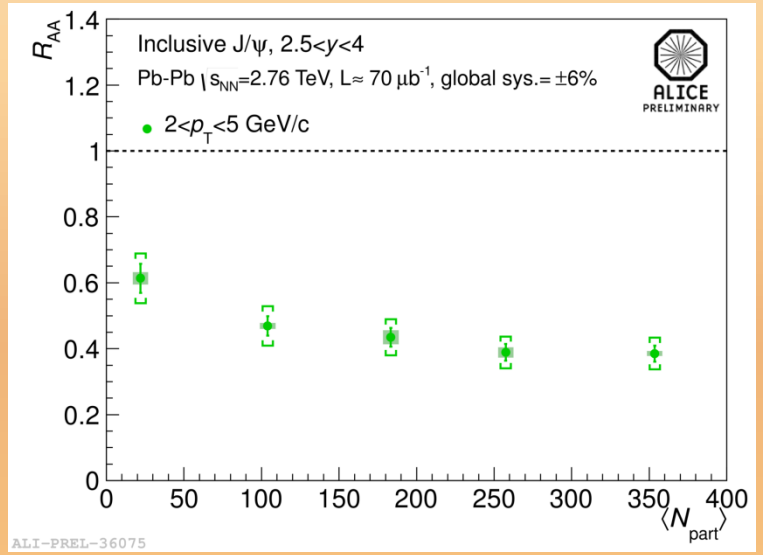


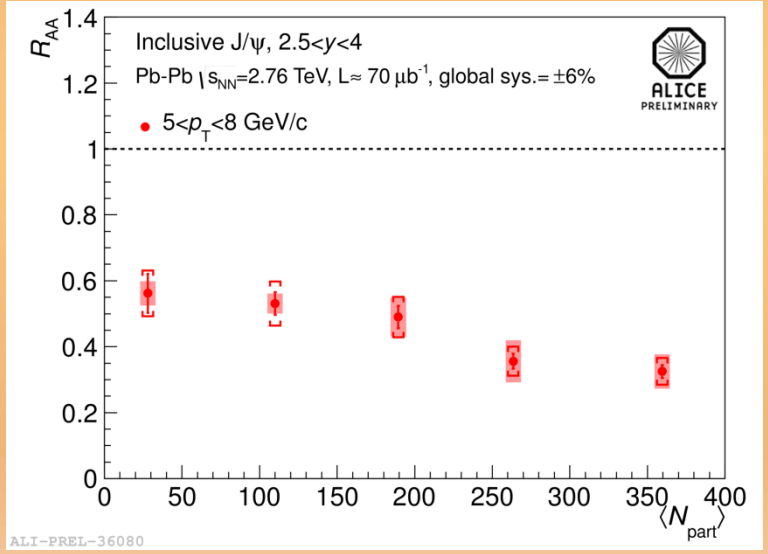




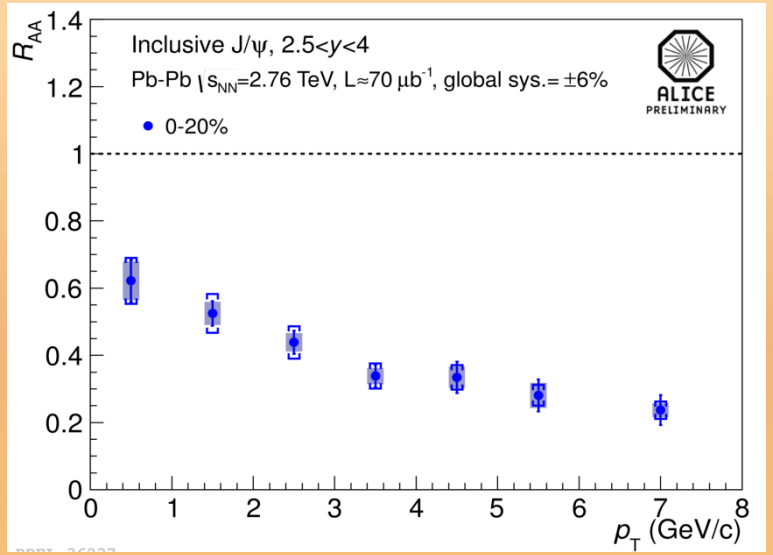
R_{AA} vs Centrality, p_T bins

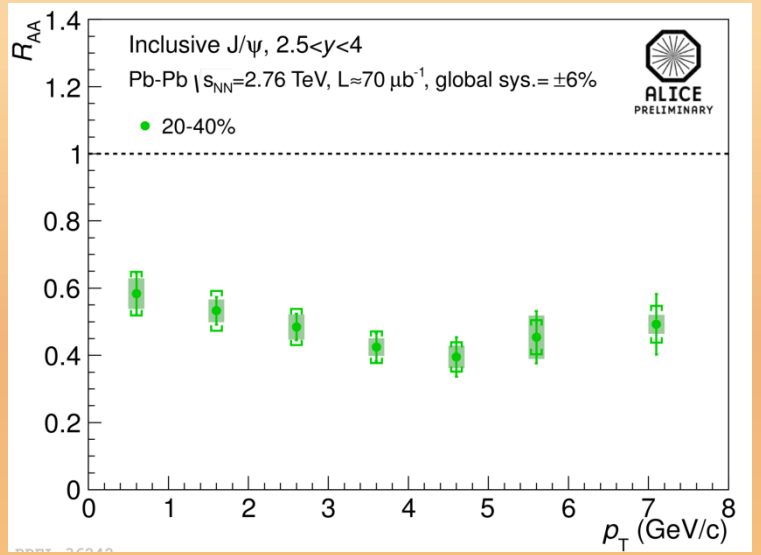


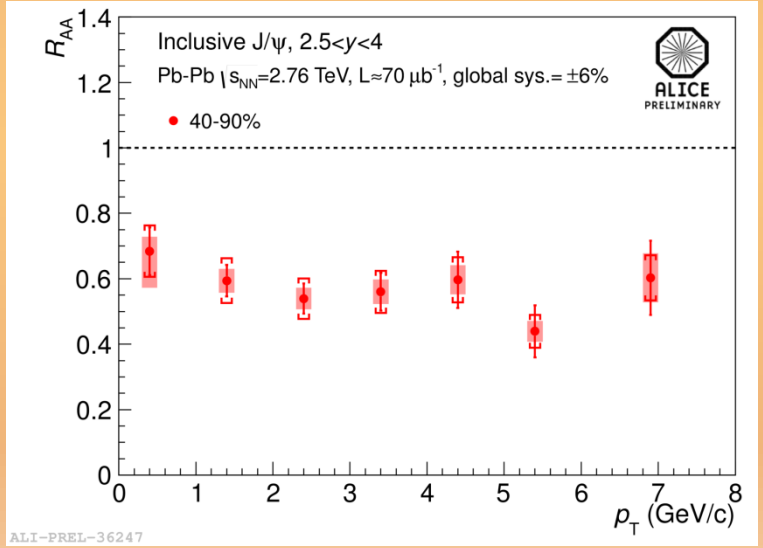




R_{AA} vs p_T, centrality bins







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

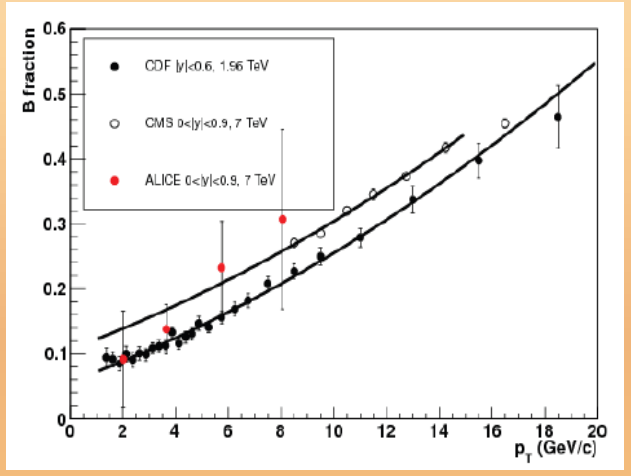
Corr. systematics: Normalization + corr. J/ψ pp.

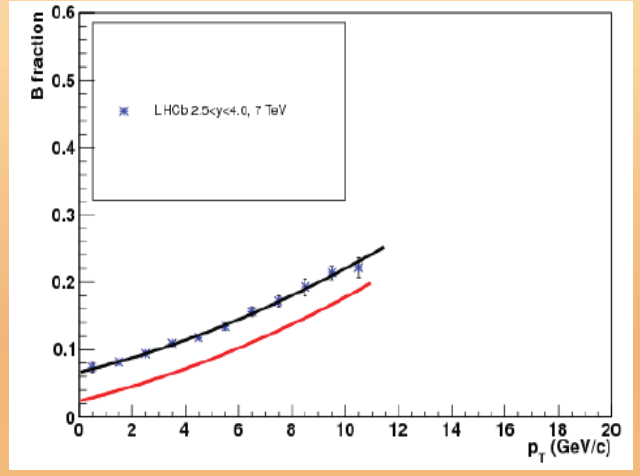
Statistics: n J/ψ + J/ψ pp .

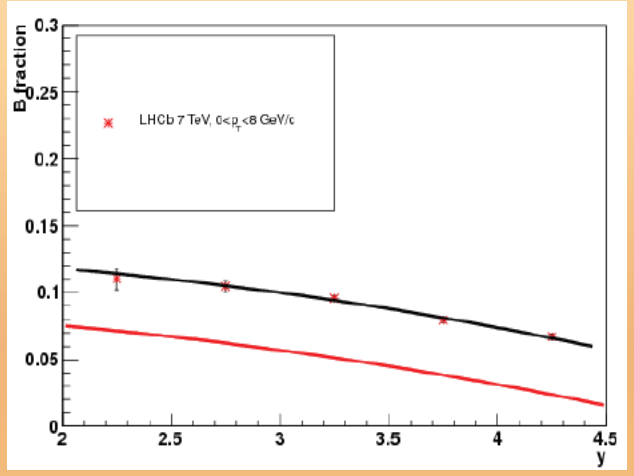
} vs centrality/ p_T

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.

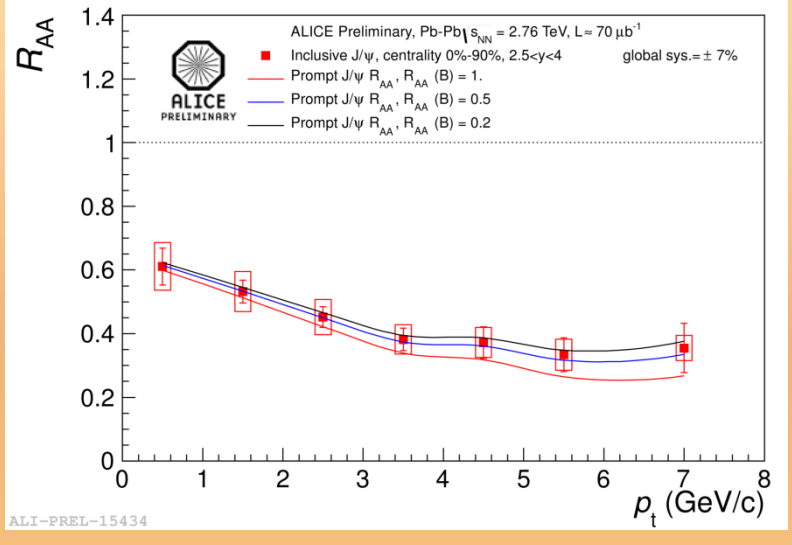
Assume:
1. Linear increase of $f_B(\sqrt{s})$.
2. It does not depend on the y region.

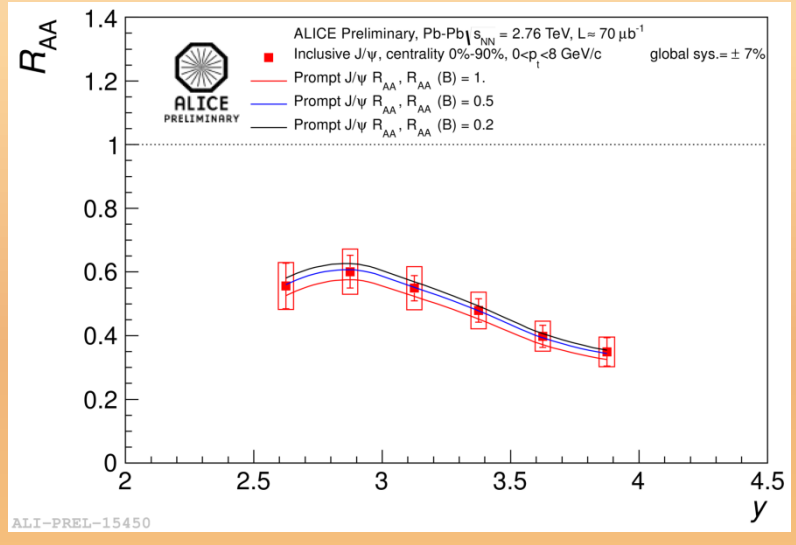
} $f_B(p_T)$ for $\sqrt{s}$ = 2.76 TeV

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

$0.2 < q < 1$ is used

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





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

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

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

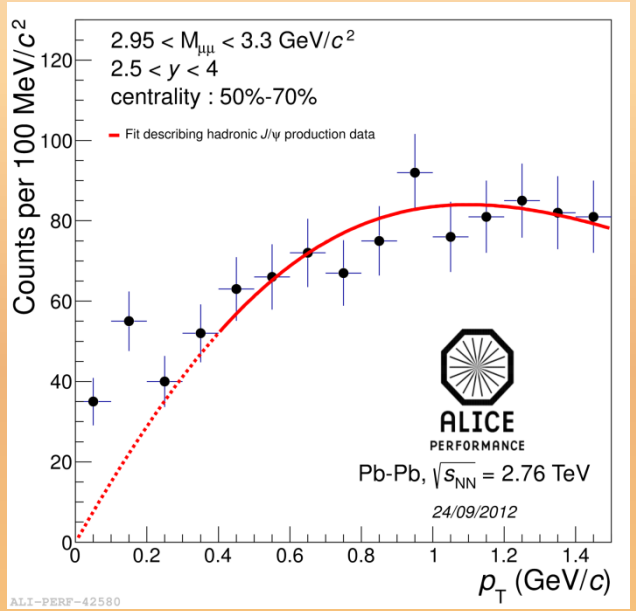
Theoretical models: inputs

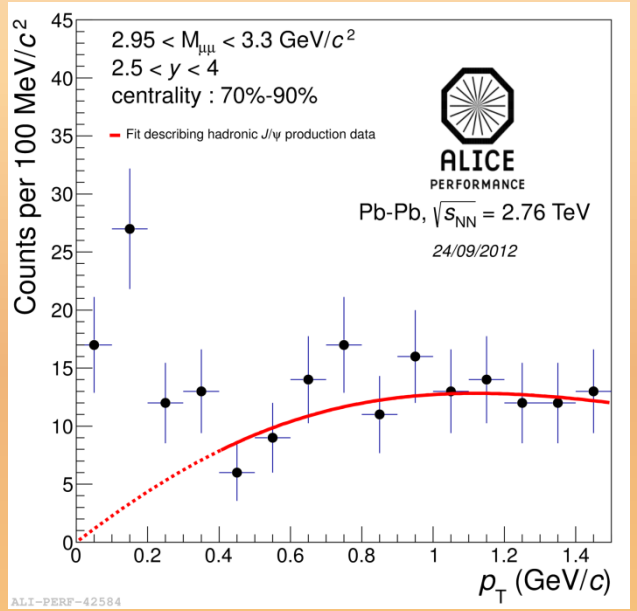
Statistical hadronization
Thermal model with T=164 MeV, μ = 1 MeV (from particle ratio fits).
All charm produced in the initial hard-scatterings.
Charmonium production at phase boundary.

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.

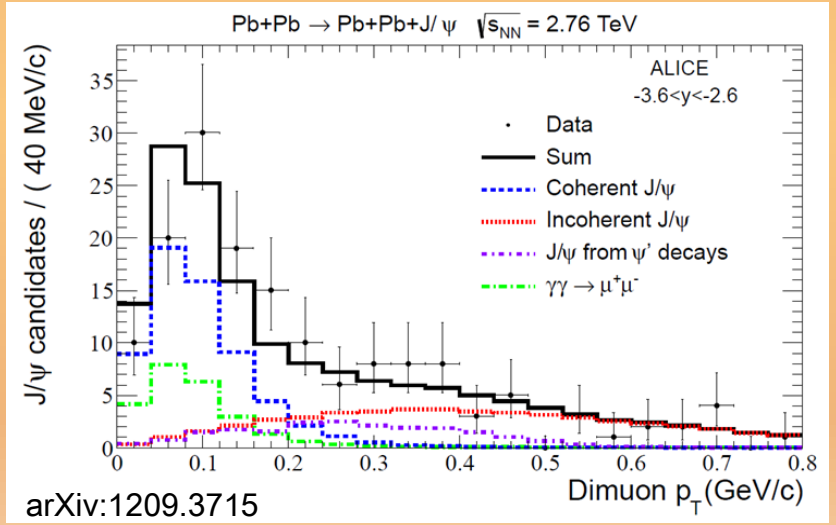
J/ψ photo-production





Clear deviation, at low-p_T for semi and peripheral collisions, to the expected J/ψ hadro-production.

J/ψ photo-production could be responsible of this excess.

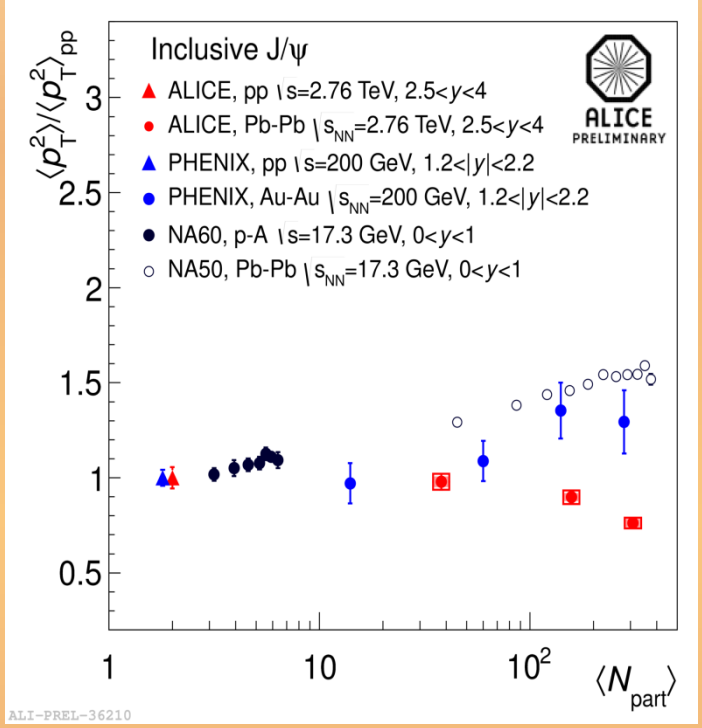


arXiv:1209.3715

More than 50% of the J/ψ from photo-production have a p_T in the 0-200 MeV/c range.

Only ~ 1% of the J/ψ from hadro-production have a p_T < 200 MeV.

$J/\psi < p_T^2 >$


Inclusive J/ψ
ALICE, pp √s=2.76 TeV, 2.5<y<4
ALICE, Pb-Pb √s_NN=2.76 TeV, 2.5<y<4
PHENIX, pp √s=200 GeV, 1.2<|y|<2.2
PHENIX, Au-Au √s_NN=200 GeV, 1.2<|y|<2.2
NA60, p-A √s=17.3 GeV, 0<y<1
NA50, Pb-Pb √s_NN=17.3 GeV, 0<y<1
ALICE
PRELIMINARY
⟨p_T^2⟩/⟨p_T^2⟩_pp
⟨N_part⟩
ALI-PREL-36210