ψ(2S) production in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV with ALICE

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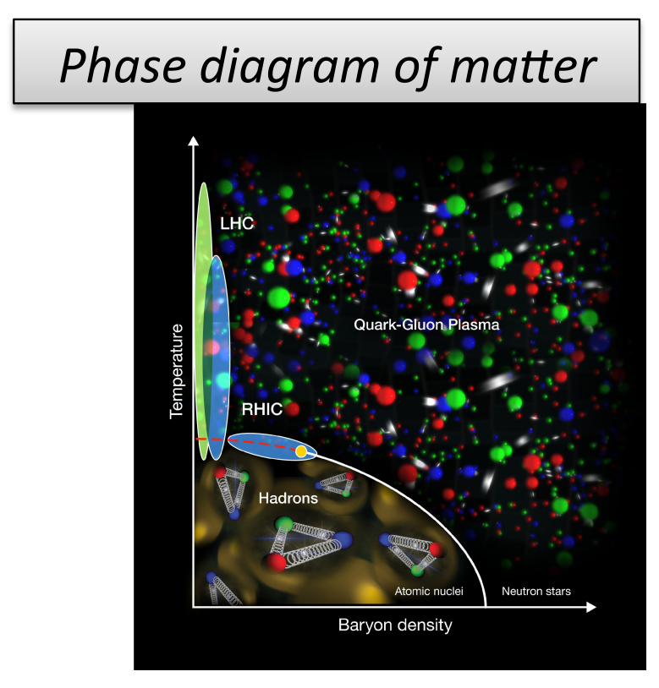
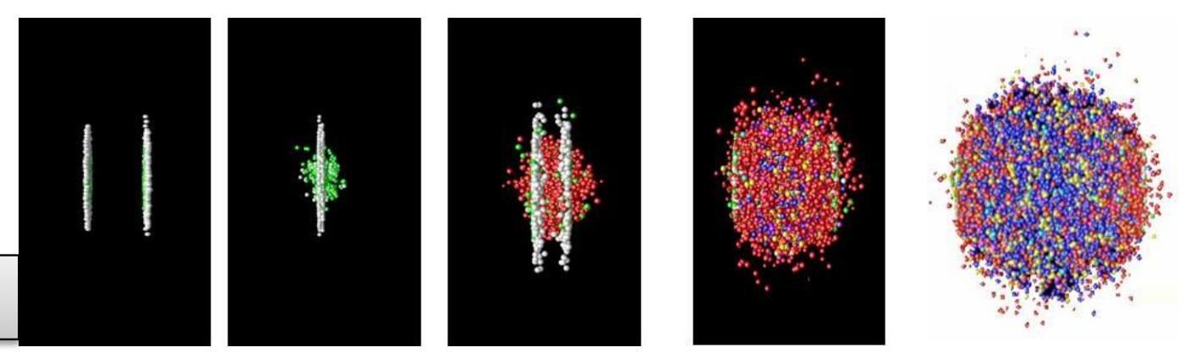
Physics Motivation:

Phase diagram of matter



The Quark-Gluon Plasma (QGP) is a state of matter predicted by QCD where quark and gluons are deconfined

It is possible to recreate the QGP with ultra-relativistic heavy-ion collisions, but only during a short period of time (≈10 fm/*c* at LHC) and in a very small volume (≈ 10^4 fm^3 at LHC)



Nuclei collision dynamics

Charmonia (J/ψ, ψ(2S)), bound states of $c-\overline{c}$ pairs, are good probes for the QGP. They are formed at the early stages of the collision.

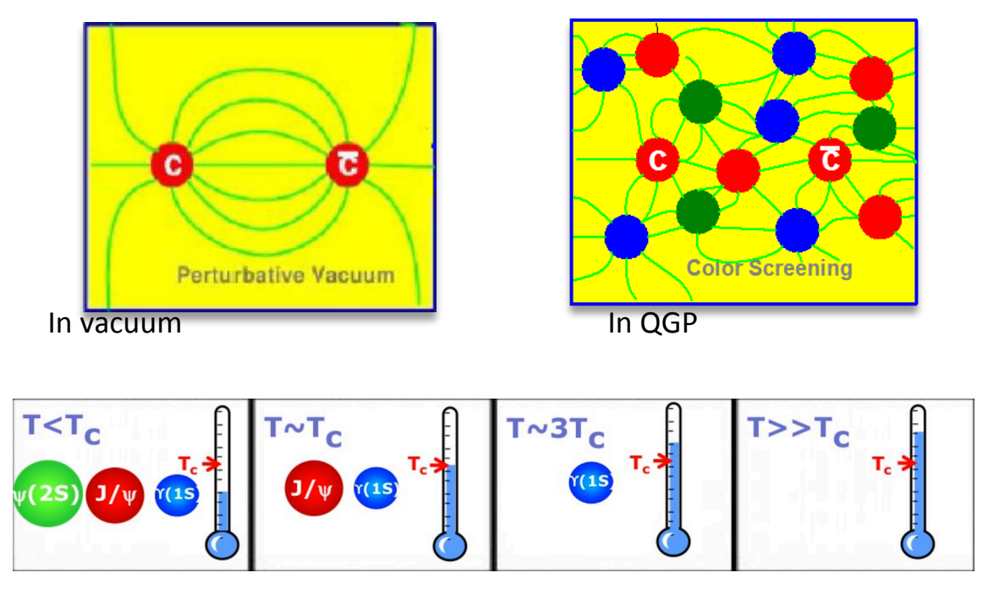


Illustration of the color screening mechanism

Theory predicts that charmonia are dissociated in a QGP because of color screening [1].
ψ(2S) and J/ψ are characterized by different binding energies, leading to different melting temperatures.
The ψ(2S) is expected to be more suppressed than the J/ψ.

(Re)combination of charm quarks may occur during or at the end of the partonic phase, with different probabilities to form J/ψ and ψ(2S) [2].
➔ ψ(2S) might provide a way to rule out some of the models

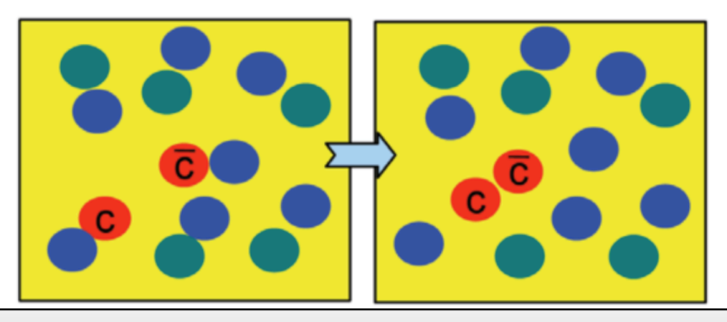


Illustration of the recombination mechanism

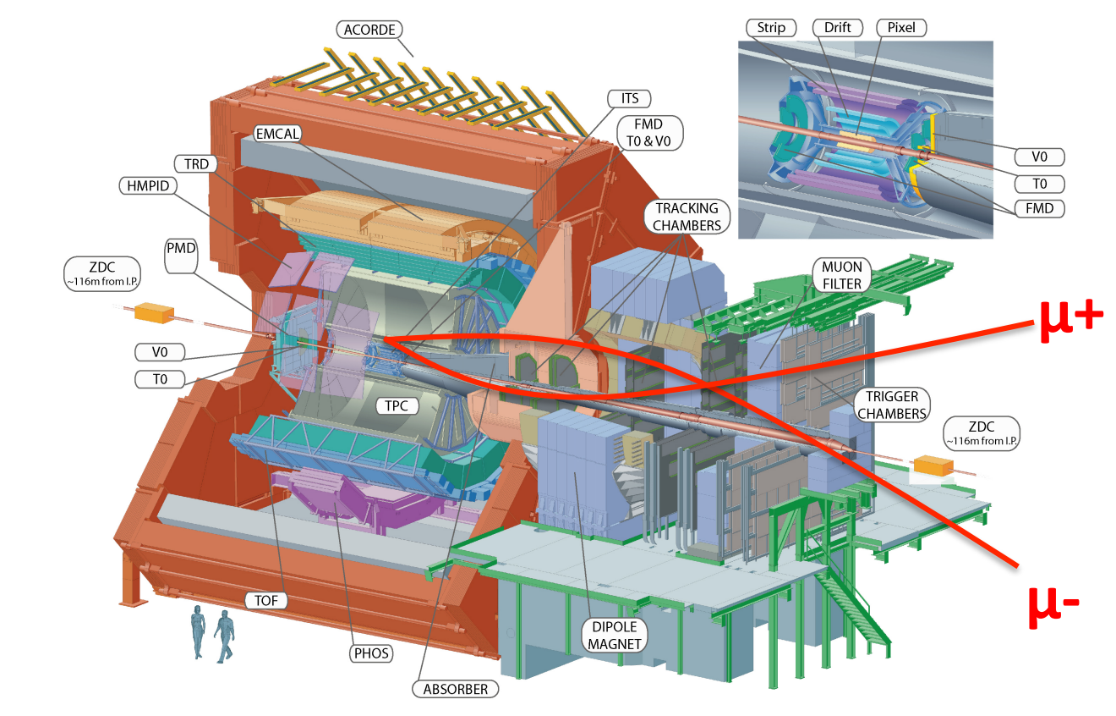
Challenging measurement :

- ratio of cross-sections between J/ψ and ψ(2S) in pp collisions is about 15%
- difference in the branching ratios :

$$BR_{J/\psi\to\mu^+\mu^-}=5.96\% \qquad BR_{\psi(2S)\to\mu^+\mu^-}=0.79\%$$

➔When measured in the dimuon decay channel, the signal for ψ(2S) is expected to be 2% of the J/ψ signal

The ALICE Detector:



- Muon Arm: J/ψ (ψ(2S))➔μ$^+$μ$^-$
- Acceptance:
  - 2.5 < y < 4.0
  - Down to p_T = 0
- Muon spectrometer:
  - 5 stations od tracking chambers
  - 2 stations of trigger chambers
  - Dipole Magnet
  - Absorbers

- ITS used for vertex determination
- V0 hodoscopes used as trigger (in coincidence with Muon Trigger)
- V0 and ZDC used for background rejection
- T0 Cherenkov detectors used for luminosity calculations

Nuclear modification factor:

$$R^{i}_{AA}=\frac{N^{i}_{\psi(2S)}}{BR_{\psi(2S)\to\mu^+\mu^-}.N^{i}_{MB}.A\varepsilon^{i}.\left\langle T_{AA}\right\rangle^{i}.\sigma^{pp}_{\psi(2S)}}$$

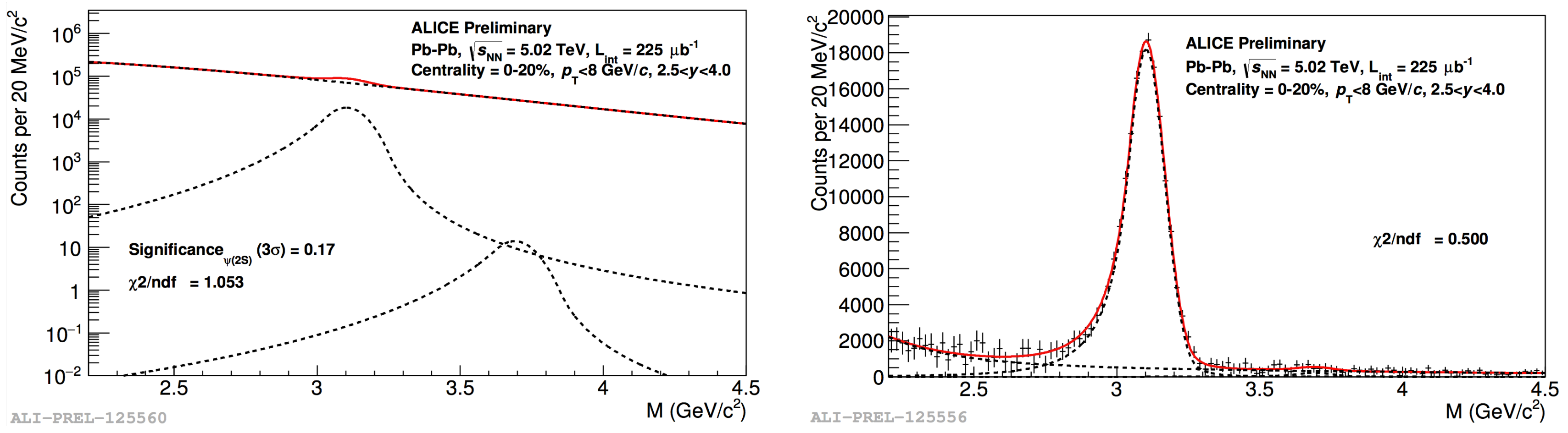
i : index of the centrality interval, which is related to the number of nucleons taking part in the collision <N_{part}>
$N_{\psi(2S)}$: number of ψ(2S) measured
$BR_{\psi(2S)\to\mu^+\mu^-}$: branching ratio
N_{MB} : number of minimum bias events
$\left\langle T_{AA}\right\rangle$: nuclear overlap function, calculated using a Glauber model
$A.\varepsilon$: acceptance×efficiency calculated with Monte-Carlo simulations and embedding technique
$\sigma^{pp}_{\psi(2S)}$: ψ(2S) cross-section in pp collisions at the same energy √*s* = 5.02 TeV

If $R_{\text{AA}} \neq 1$, then there are nuclear effects

The ψ(2S) cross-section in pp collisions is evaluated using pp data at √*s* = 5 TeV.
We obtain **$\sigma_{pp}^{\psi(2S)}$ = 0.72 ± 0.16 (stat) ± 0.06 (syst) μb^{-1}** [3]

The number of ψ(2S) extracted is obtained from a fit to the dimuon invariant mass spectrum. The ψ(2S) mass and width are tied to the J/ψ ones, and the final value is the average of the combination of the following tests :

- 2 signal functions : extended Crystal Ball and gaussian function with a mass-dependent width
- 2 methods of dealing with the background : empirical fit or mixed-event background subtraction
- Several fit ranges
- 2 values for the ratio of the ψ(2S) width to the J/ψ one
- 2 different sets of tails for the signal function based either on pp data or Monte Carlo



Example of signal extraction with the direct fit method and the event-mixing background subtraction method

The systematic uncertainty on the signal extraction is the RMS of all the tests.

➔Due to the impossibility to extract the signal in some of the centrality bins (namely 20-40% and 40-60%), a 95% confidence limit must be calculated on the R_{AA} for those bins.

Upper limit calculation – the CL$_s$ method:

We implemented the CL$_s$ method, used for Higgs search [4] for instance.
For CL$_s$ calculations, we assume the background is known and make hypothesis on the signal.

We define the test statistic *X* and construct the *pdf* of *X* by « tossing » pseudo-observations.

The Confidence Limit on the *signal+background* hypothesis is defined as: $CL_{s+b}=P\left(X\le X_{obs}\mid s+b\right)=P_{s+b}\left(X\le X_{obs}\right)$
and calculated by « tossing » pseudo-observations under the *signal+background* hypothesis.

We also calculate: $CL_b=P\left(X\le X_{obs}\mid b\right)=P_b\left(X\le X_{obs}\right)$
by tossing pseudo-observations for the *background-only* hypothesis.

We then define: $CL_s=\dfrac{CL_{s+b}}{CL_b}$

One considers the signal is excluded at 95% Confidence Limit if $CL_s\le 0.05$

The test statistic used is the log likelihood ratio: $q=-2\ln\left(Q\right)=2\left(s-n\ln\left(1+\dfrac{s}{b}\right)\right)$

Systematics uncertainties have contributions from signal extraction, acc×eff corrections, <T_{AA}> and pp cross section.
They are taken into account in the CL$_s$ calculation using the Bayesian-frequentist method [5, 6].

Example:

- Known background = 500
- Observed events = 510
- Hypothesized signal = 50

$$CL_s=\frac{CL_{s+b}}{CL_b}=0.063$$

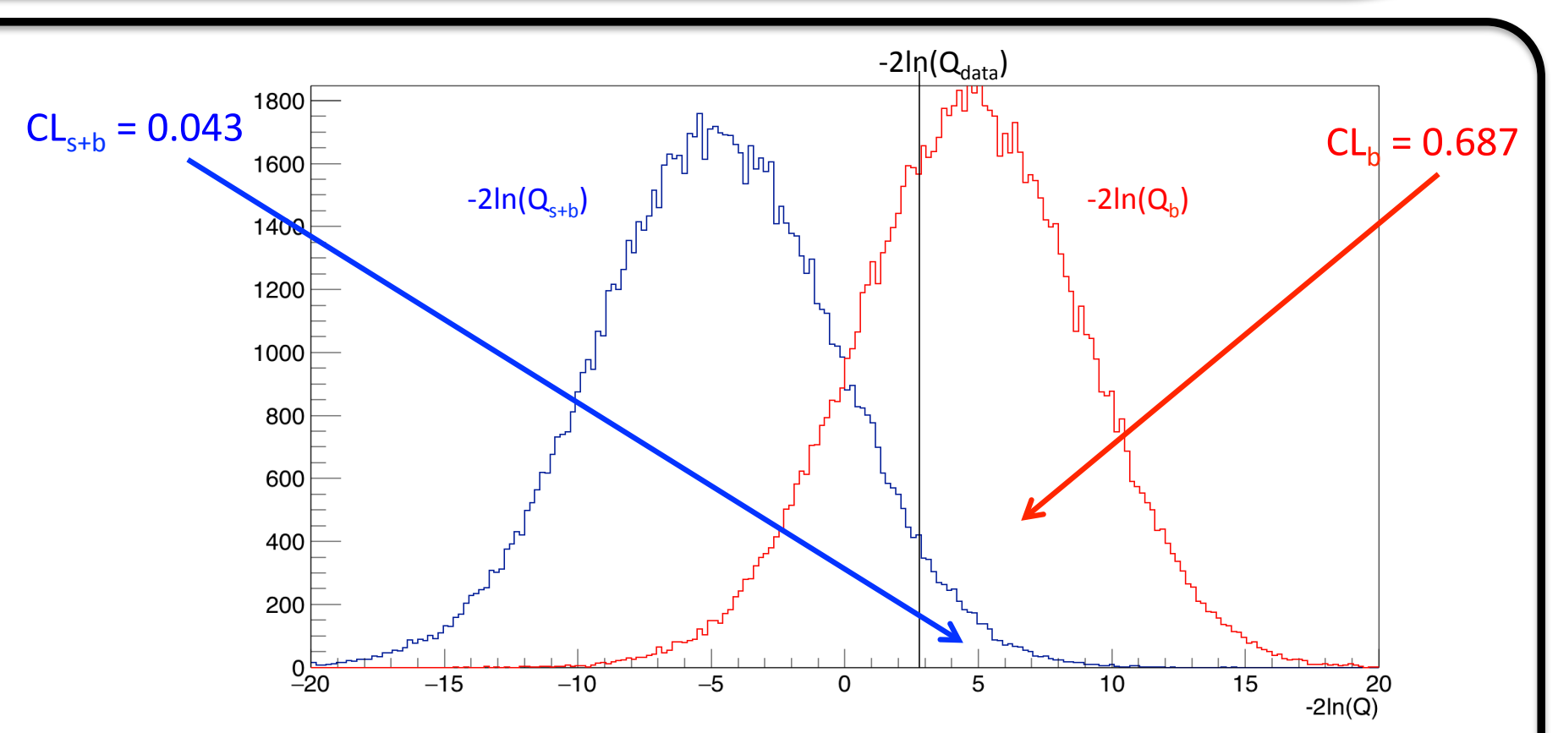
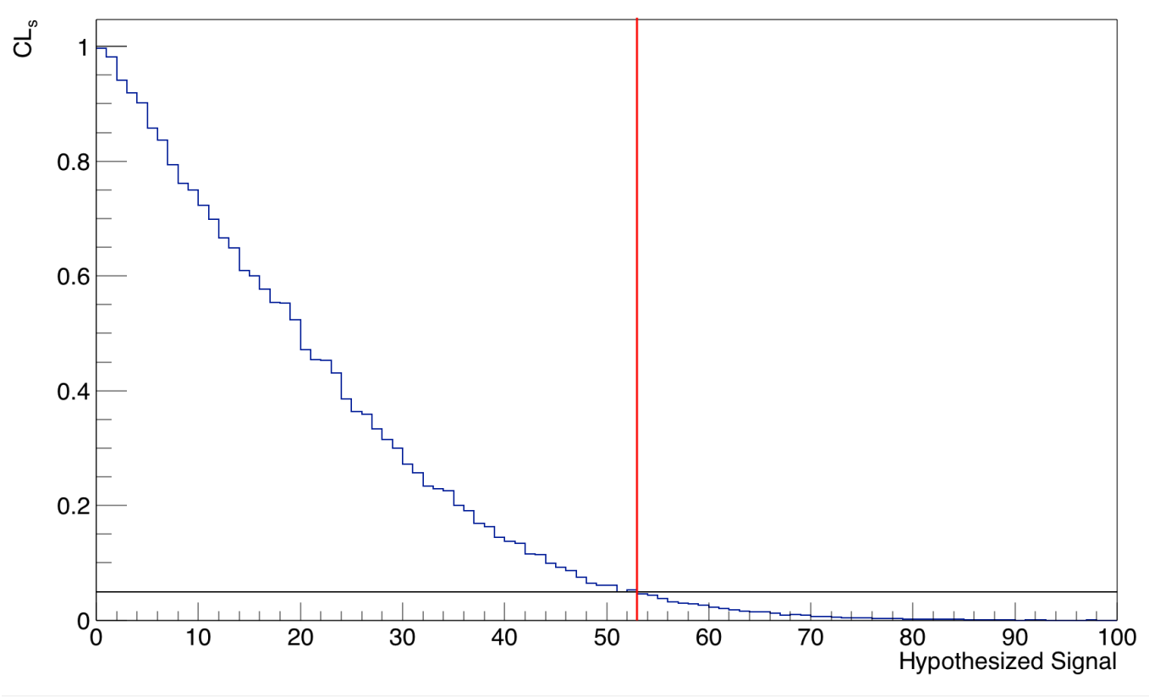


illustration of the calculation of CL$_s$

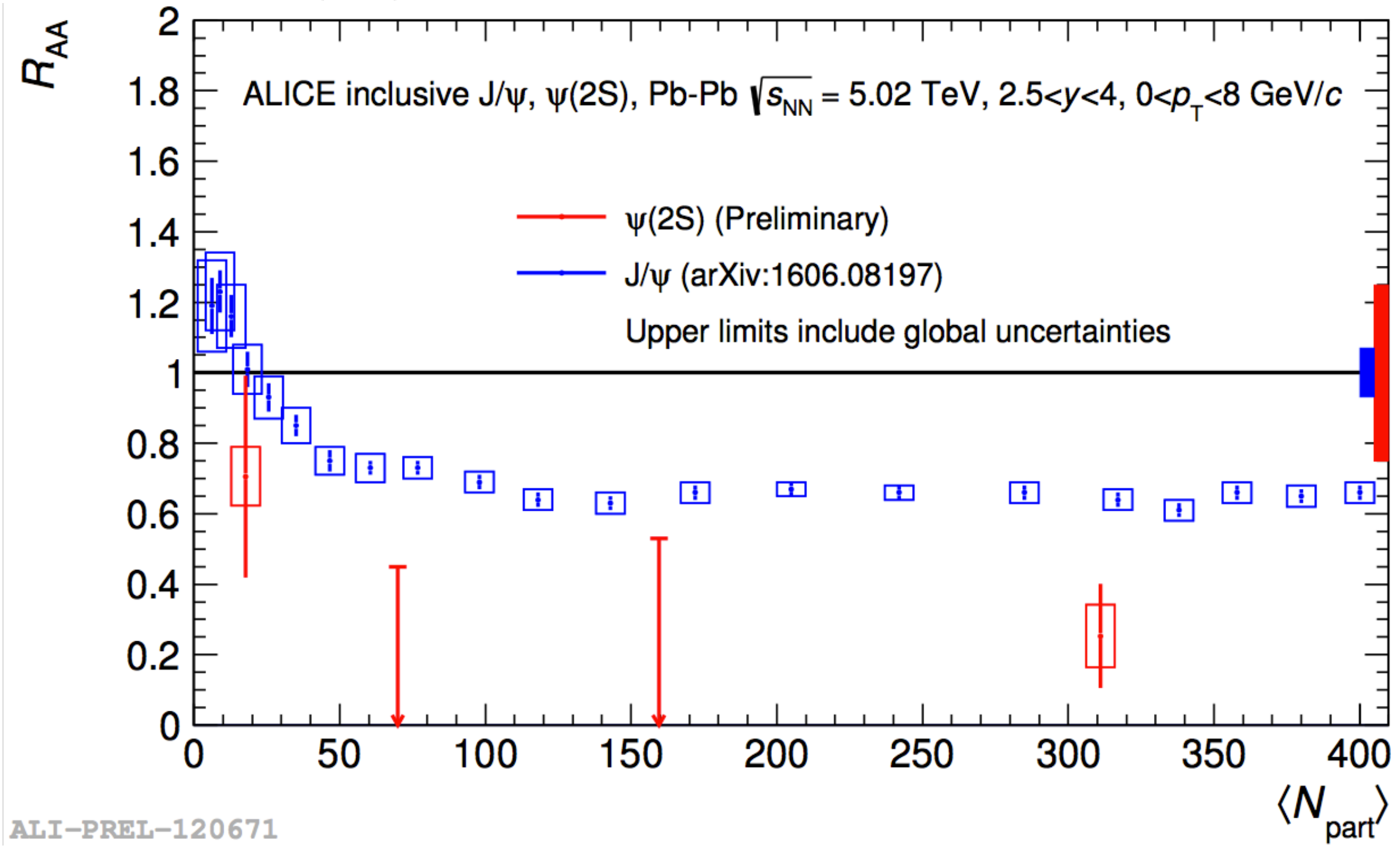
Search for the signal such as CL$_s$ = 0.05:

$$CL_s(95)=53$$



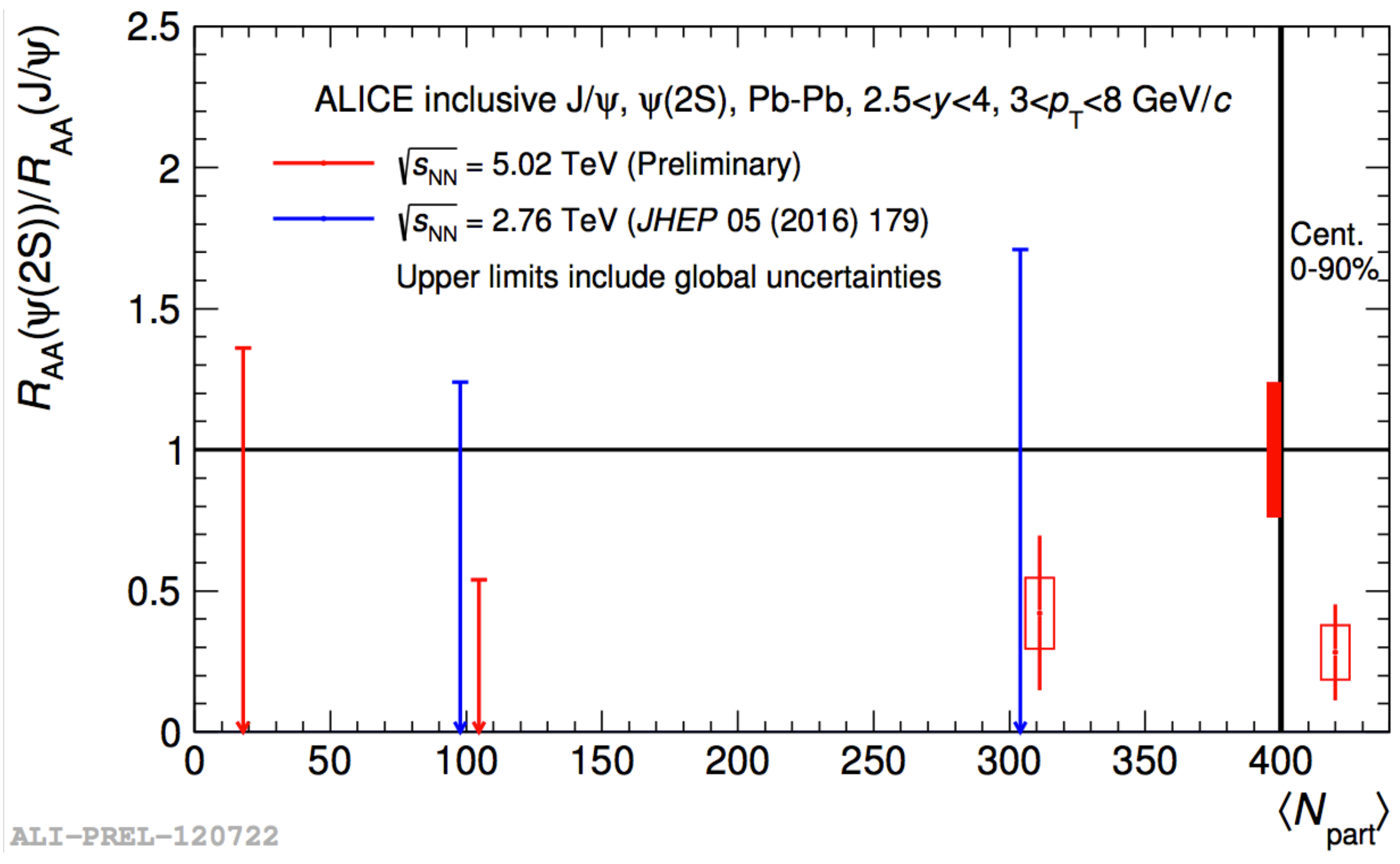
CL$_s$ as a function of the hypothesized signal

J/ψ and ψ(2S) nuclear modification factor:

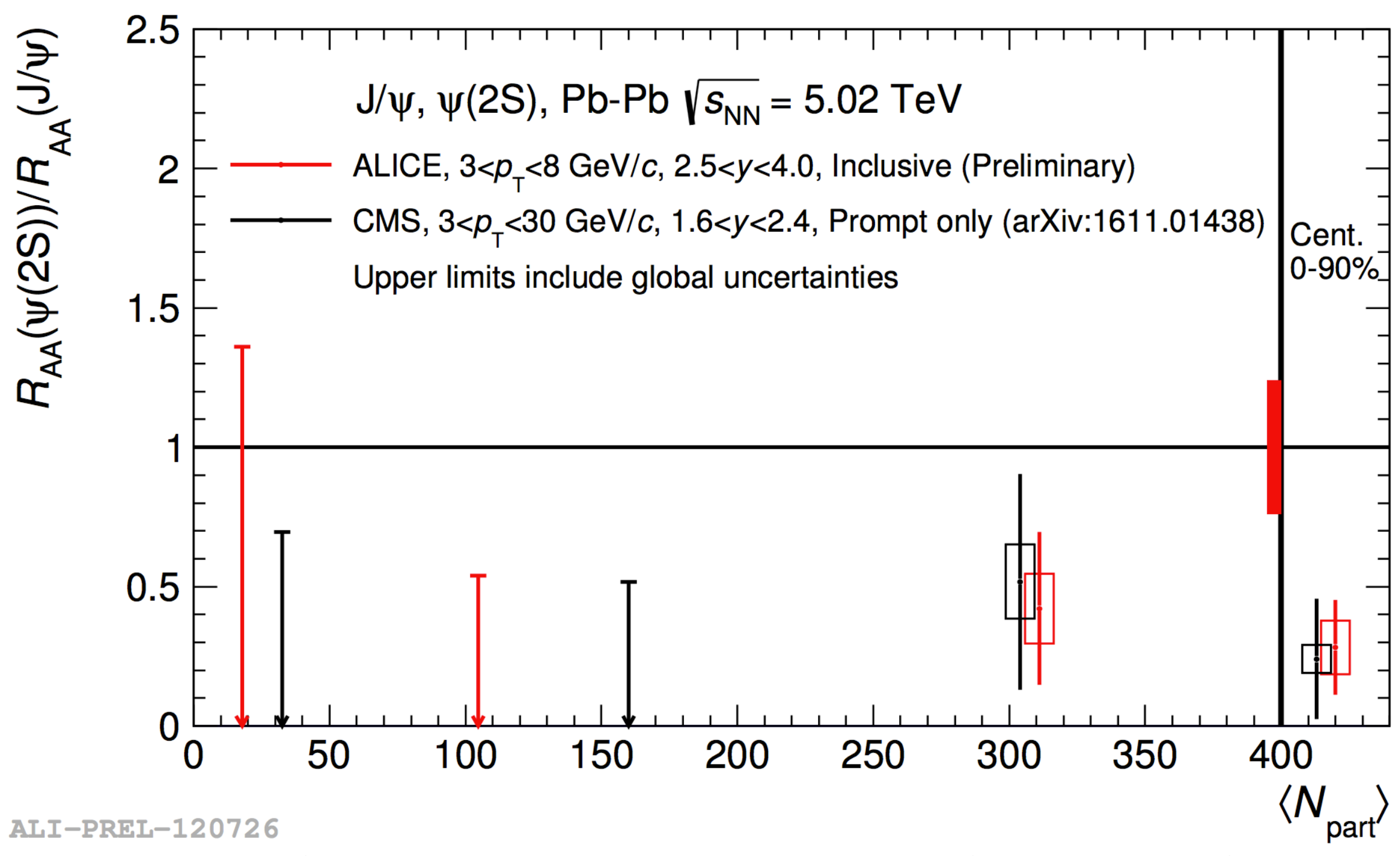


The R_{AA} shows that the ψ(2S) is more suppressed than the J/ψ at √s_{NN} = 5.02 TeV [7].

ψ(2S) and J/ψ nuclear modification factor ratio:



The results of the double ratio are comparable, within uncertainties, with those at √s_{NN} = 2.76 TeV [8].



Results are in good agreement with CMS results at √s_{NN} = 5.02 TeV for 1.5 < *y* < 2.4 [9].

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[8] ALICE, Differential studies of inclusive J/ψ and ψ(2S) production at forward rapidity in Pb-Pb collisions at √s_{NN} = 2.76 TeV. *JHEP*, 05:179, 2016
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