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# $\psi(2S)$ production in Pb-Pb collisions in ALICE

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# Outline

## I. Introduction

- I. Physics motivation
- II. The ALICE detector

## II. Other results

- I.  $\psi(2S)$  in Pb-Pb at  $\sqrt{s_{NN}} = 2.76$  TeV
- II. CMS results
- III.  $J/\psi$  at  $\sqrt{s_{NN}} = 5.02$  TeV

## III. $\psi(2S)$ in Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV results

## IV. Conclusion



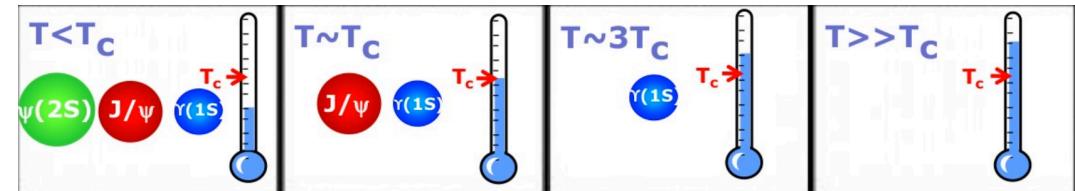
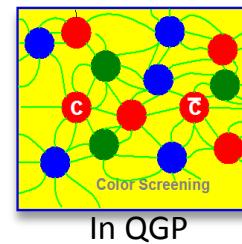
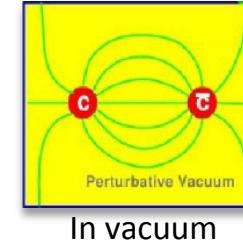
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# Introduction – Charmonia

- Charmonia ( $J/\psi$ ,  $\psi(2S)$ ) are bound states of a c-cbar pair

- Theory predicts that charmonia are dissociated in a QGP because of the colour screening  
(Phys. Lett. B 178 (1986) 416)

- Difference between binding energies leads to a sequential melting of charmonia as function of temperature



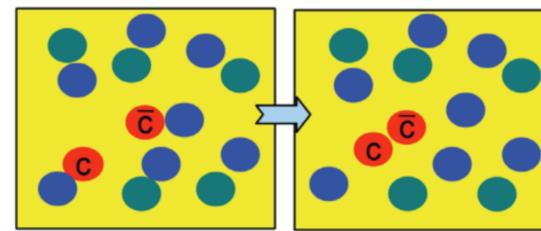
→  $\psi(2S)$  and  $J/\psi$  have different melting temperatures

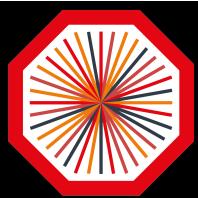


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# Introduction – Charmonia

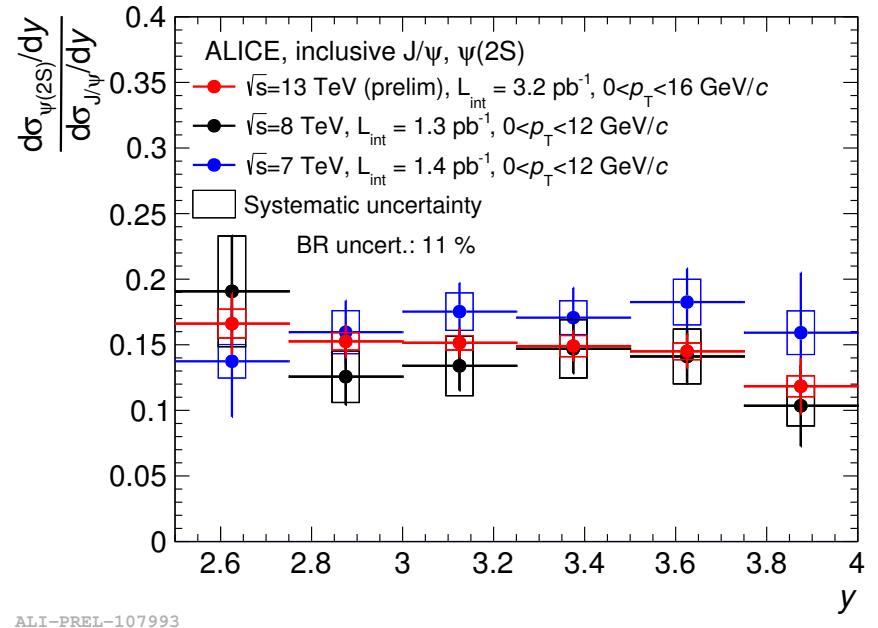
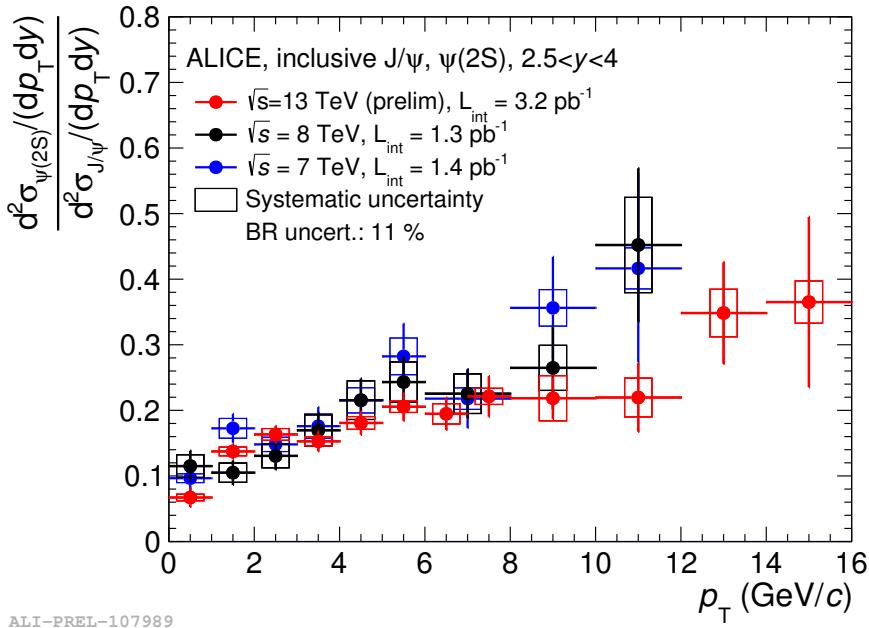
- If there are enough charm-anticharm pairs, and if thermalized in QGP :  
→ quarkonia regeneration  
(Phys. Lett. B 490 (2000) 196)
- Models including recombination processes might have different predictions for  $\psi(2S)$   
→ It might provide a way to separate between models





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# Introduction – Charmonia



- The ratio between cross section in pp collisions is around 15%

- Difference between Branching ratios :

$$BR_{J/\psi \rightarrow \mu^+ \mu^-} = 5.96\%$$

$$BR_{\psi(2S) \rightarrow \mu^+ \mu^-} = 0.79\%$$

- Signal for  $\psi(2S)$  is expected to be 2% of the  $J/\psi$  signal

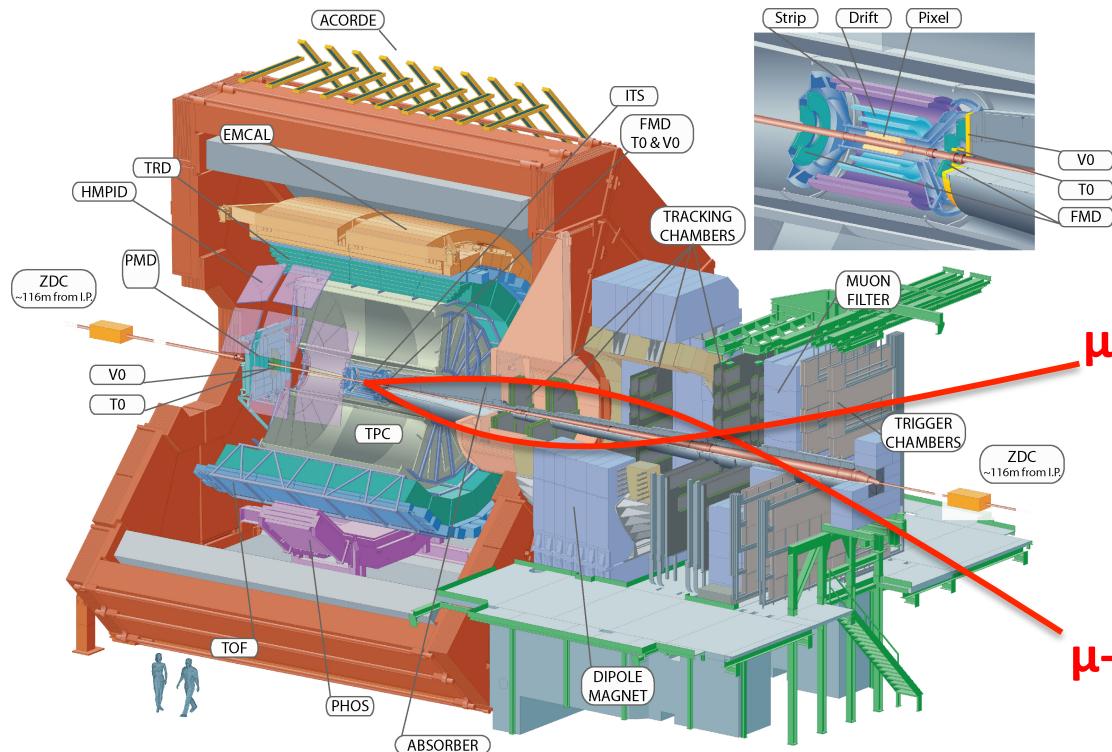
→ Challenging measure



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# Introduction - ALICE

- ALICE : 41 countries, 159 institutes, 1665 members



- Muon Arm :  $J/\psi \rightarrow \mu^+ \mu^-$
- Acceptance :  $2.5 < y < 4.0$
- Down to  $p_T = 0$
- 5 stations of tracking chambers
- 2 stations of trigger chambers
- Dipole Magnet
- Absorbers

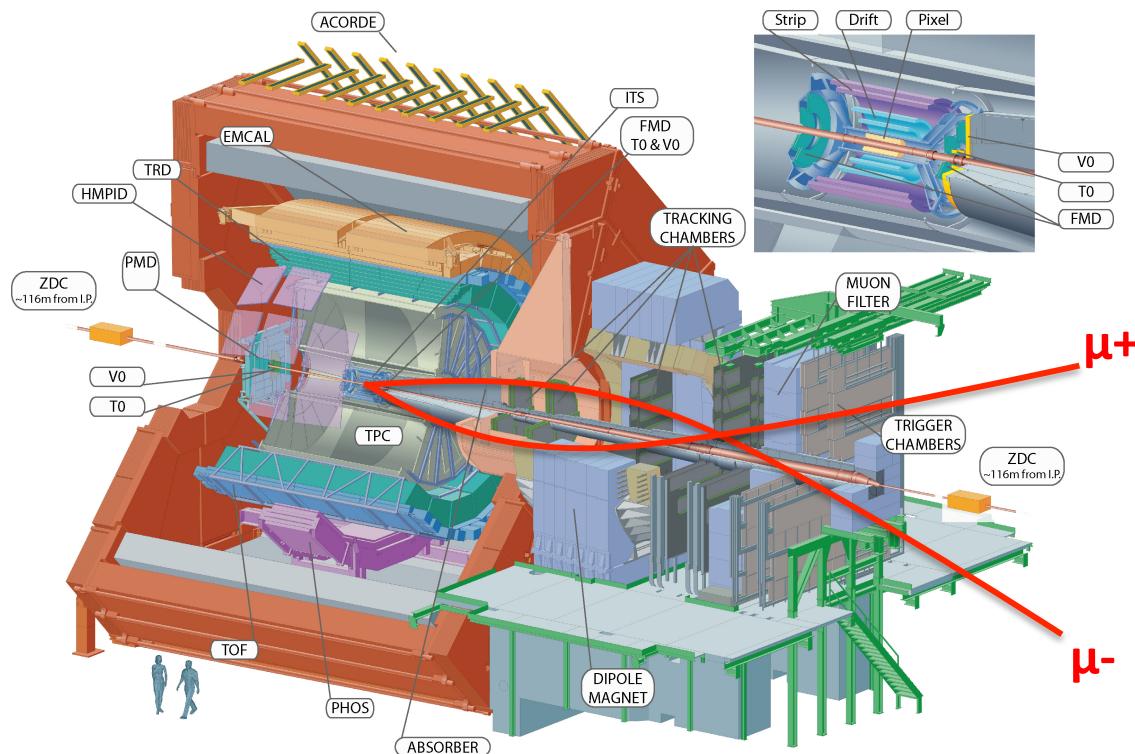
With the Muon spectrometer, we only measure inclusive charmonia (prompt and non-prompt)



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# Introduction - ALICE

- ALICE : 41 countries, 159 institutes, 1665 members



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



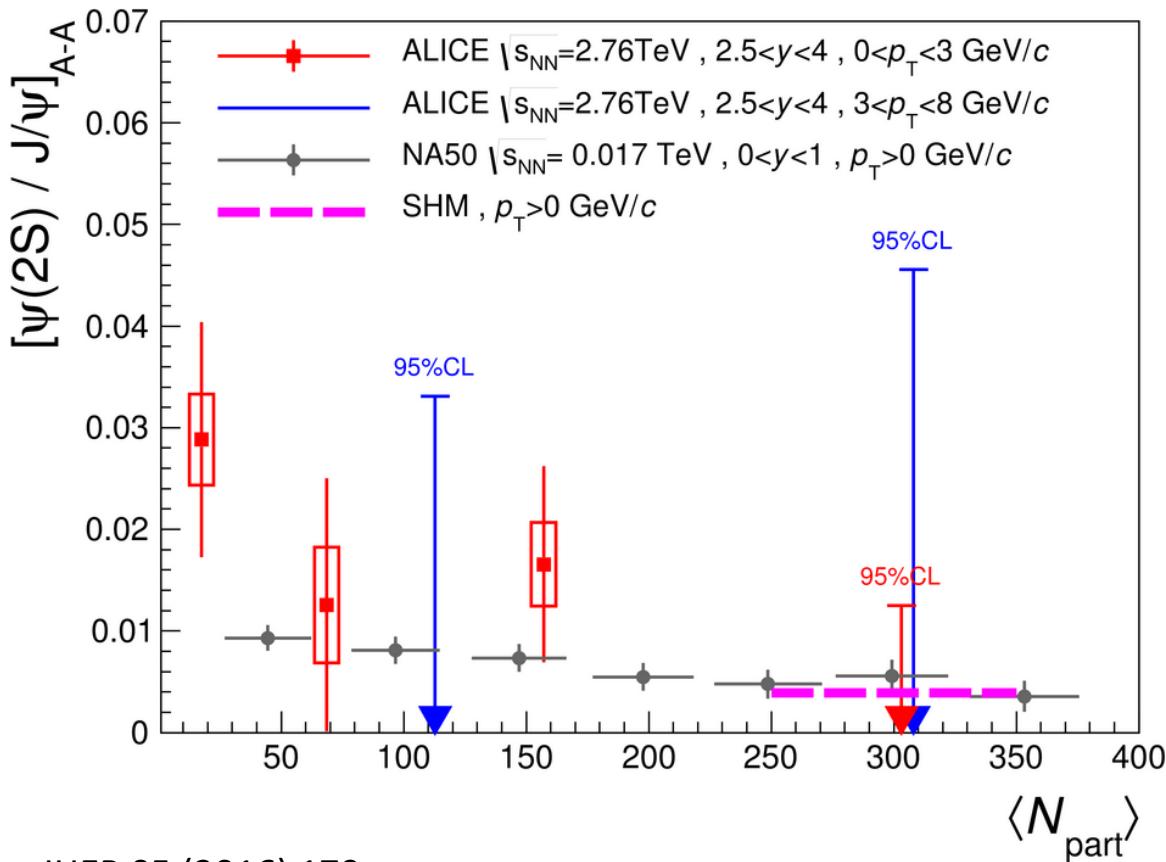
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# PREVIOUS RESULTS FOR $\Psi(2S)$ AND NEW RESULTS FOR $J/\psi$



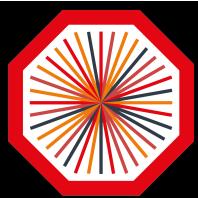
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# $\psi(2S)/\text{J}/\psi$ production ratio



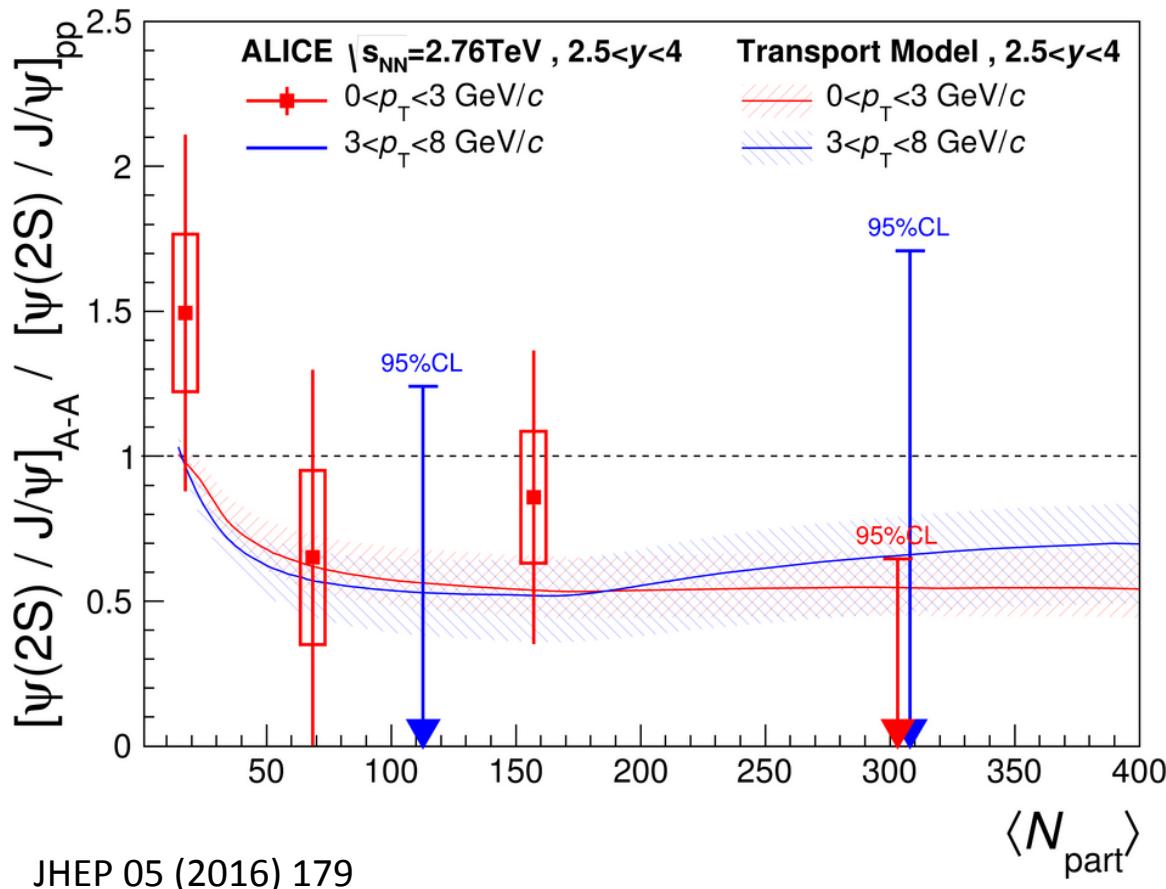
JHEP 05 (2016) 179

- At 2.76 TeV, the  $\psi(2S)$  could only be extracted in a few centrality and  $p_T$  bins, for others the 95% confidence level was calculated
- No clear energy dependence or rapidity dependance within large uncertainties



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# $\Psi(2S)/\text{J}/\psi$ double ratio

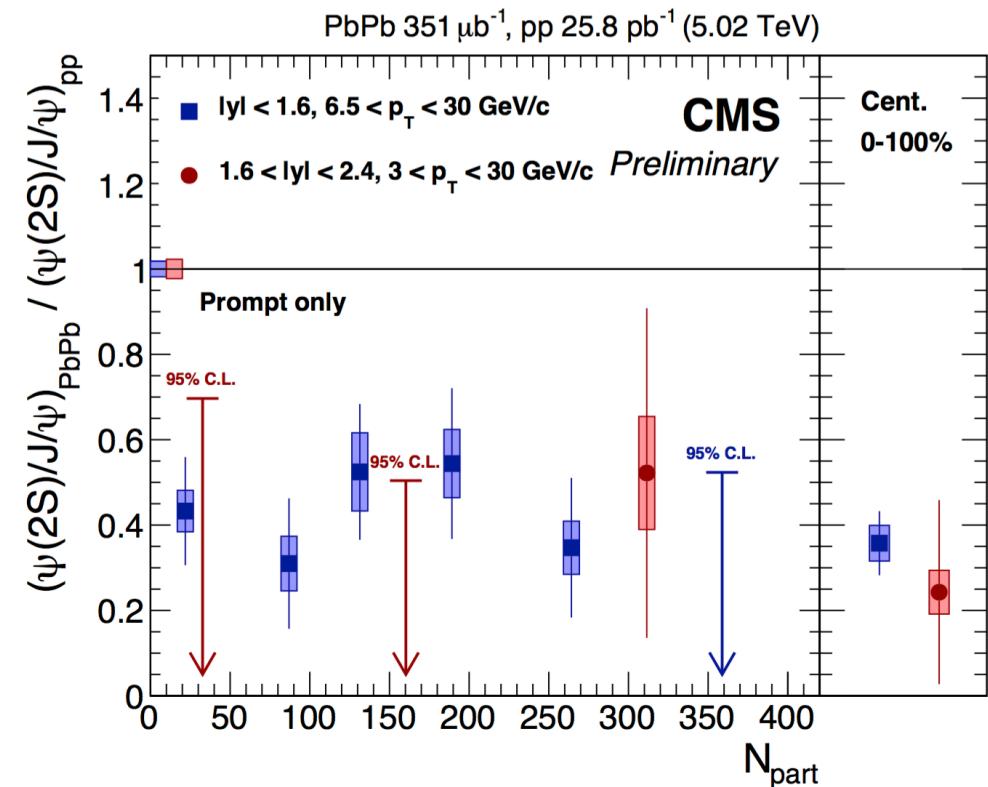
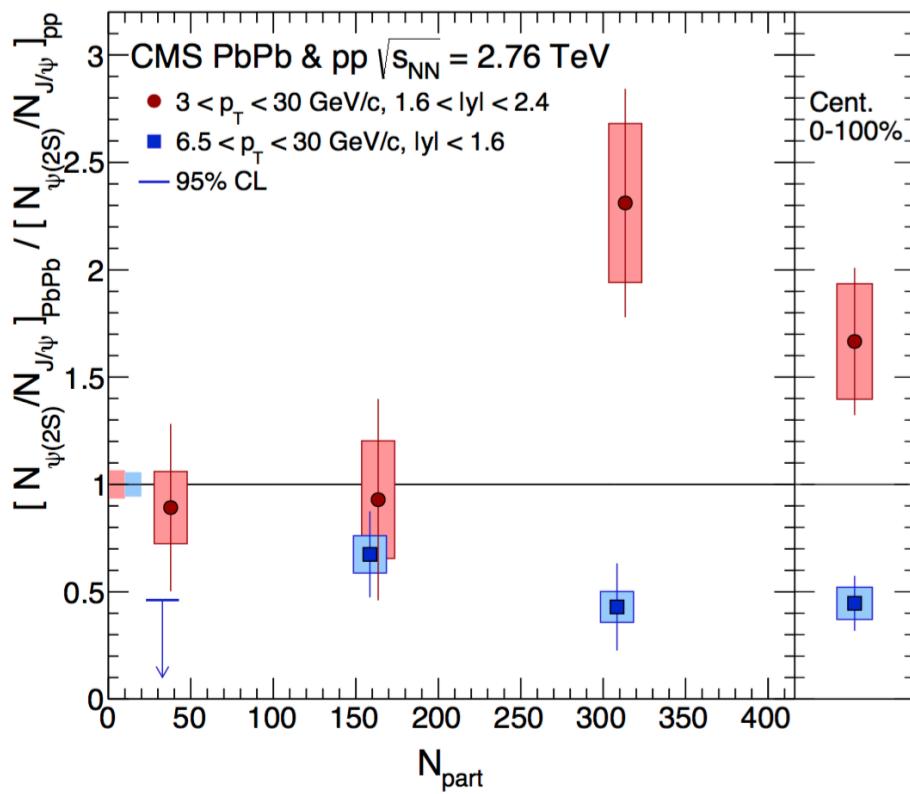


- No firm conclusion can be drawn because of the large uncertainties
- The 0-20% centrality bin at low  $p_T$  points towards stronger  $\Psi(2S)$  suppression in that region



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# CMS Results



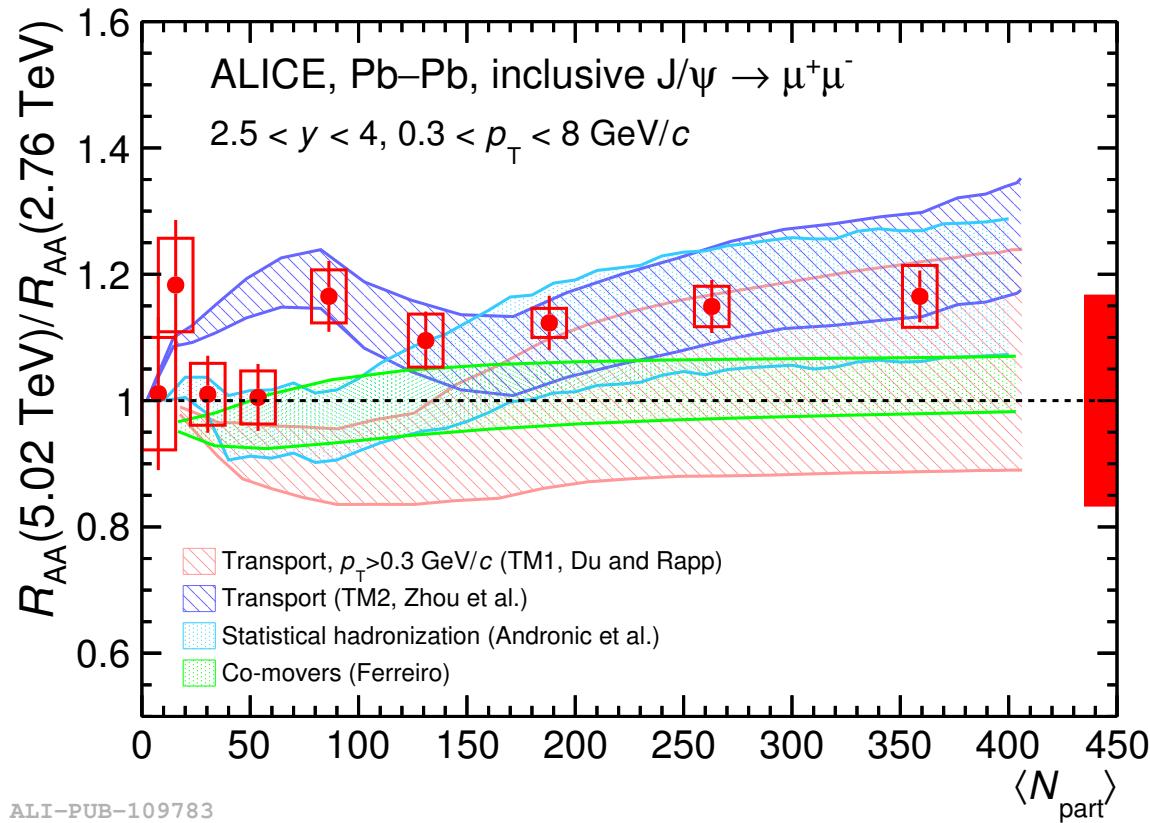
- 2.76 TeV CMS results compatible with the Confidence Levels Calculated
- 5.02 TeV CMS results show a stronger suppression of the  $\psi(2S)$
- Caution : CMS shows prompt charmonium, whereas ALICE show inclusive charmonium



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# J/ $\psi$ at 5.02 TeV

arXiv:1606.08197



- Double Ratio compatible with unity
- Data compatible with the models
- Difficult to rule out some of the models



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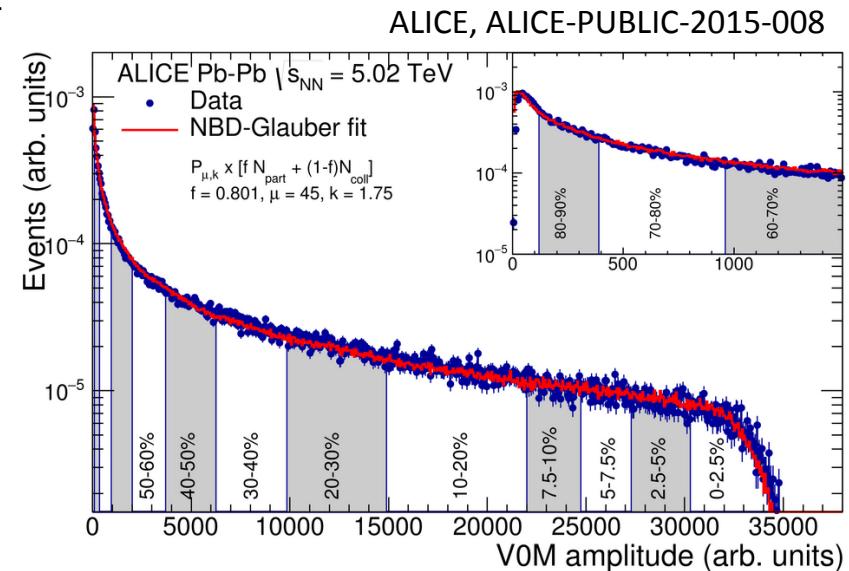
# **$\Psi(2S)$ AT $\sqrt{s_{NN}} = 5.02$ TeV : SIGNAL EXTRACTION**



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# Event and Track Selection

- Results from Run 2, december 2015
- Integrated Luminosity  $\approx 225 \mu\text{b}^{-1}$
- Muon pair selection :
  - Pseudo rapidity on each muon  $-4.0 < \eta < -2.5$
  - Radial transverse position at the end of the absorber  $17.6 < R_{\text{abs}} < 89.5 \text{ cm}$
  - Rapidity of the dimuon  $2.5 < y < 4.0$
  - Muons of opposite sign
  - Matching tracks between tracking chambers and trigger
- Event selection
  - Beam gas and electromagnetic interactions rejected using V0 and ZDC
  - SPD used for vertex determination
- Centrality estimated on a Glauber model fit of the V0 amplitude (PRL. 116 (2016) 222302)

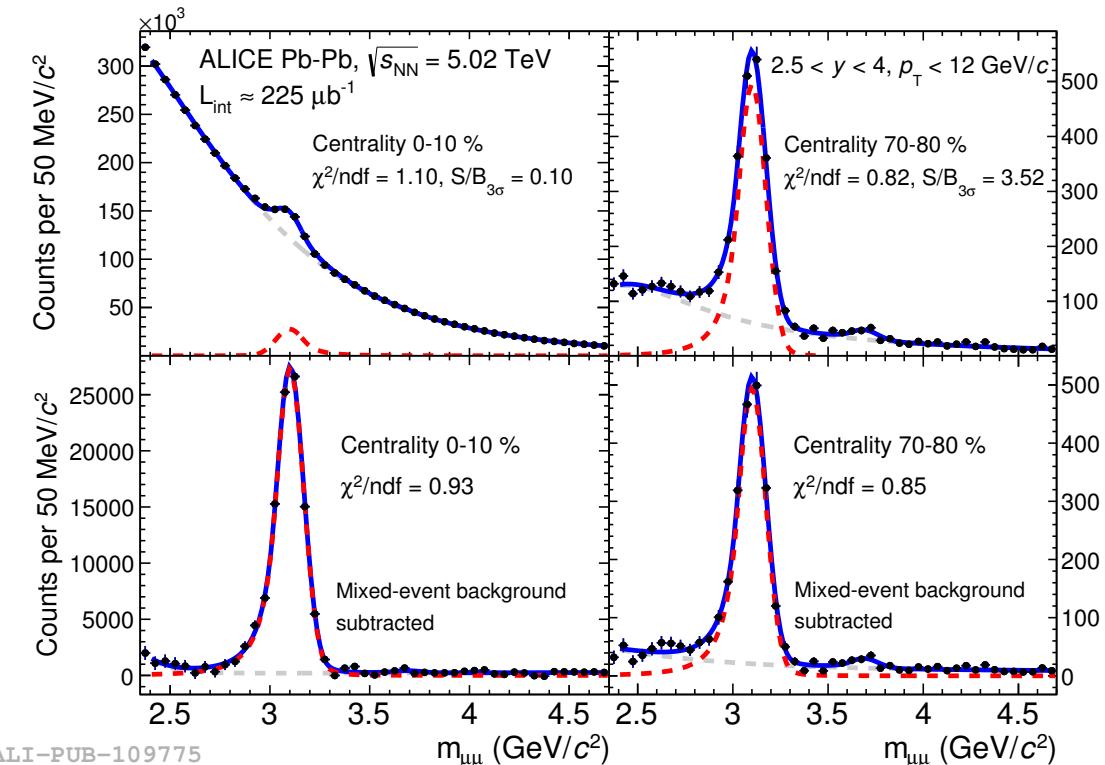




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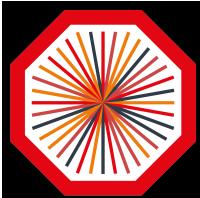
# Signal extraction

- $J/\psi$  and  $\psi(2S)$  yield extracted by fitting the opposite sign dimuon invariant mass spectrum
- The signal is extracted using :
  - 2 signal functions
  - 2 methods of dealing with the background : empirical fit or mixed-event background subtraction
  - Several fit ranges



arXiv:1606.08197

- $N_{J/\psi} \approx 277000$  (7 times larger than in Run 1)
- $N_{\psi(2S)} \approx 2000$  (estimation)



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# Signal extraction

- The signal extraction is challenging :



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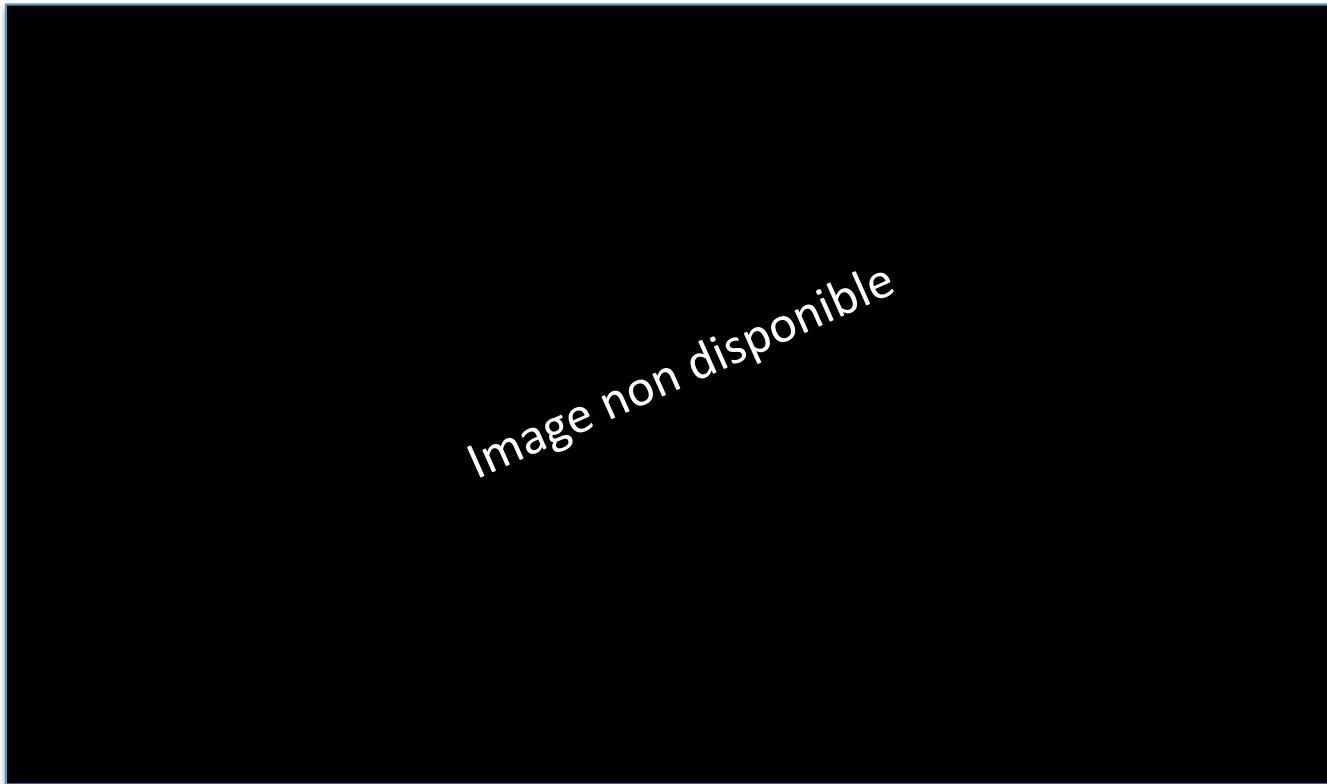
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# Signal extraction

- Reproducing the  $p_T$  and centrality bins from 2.76 TeV



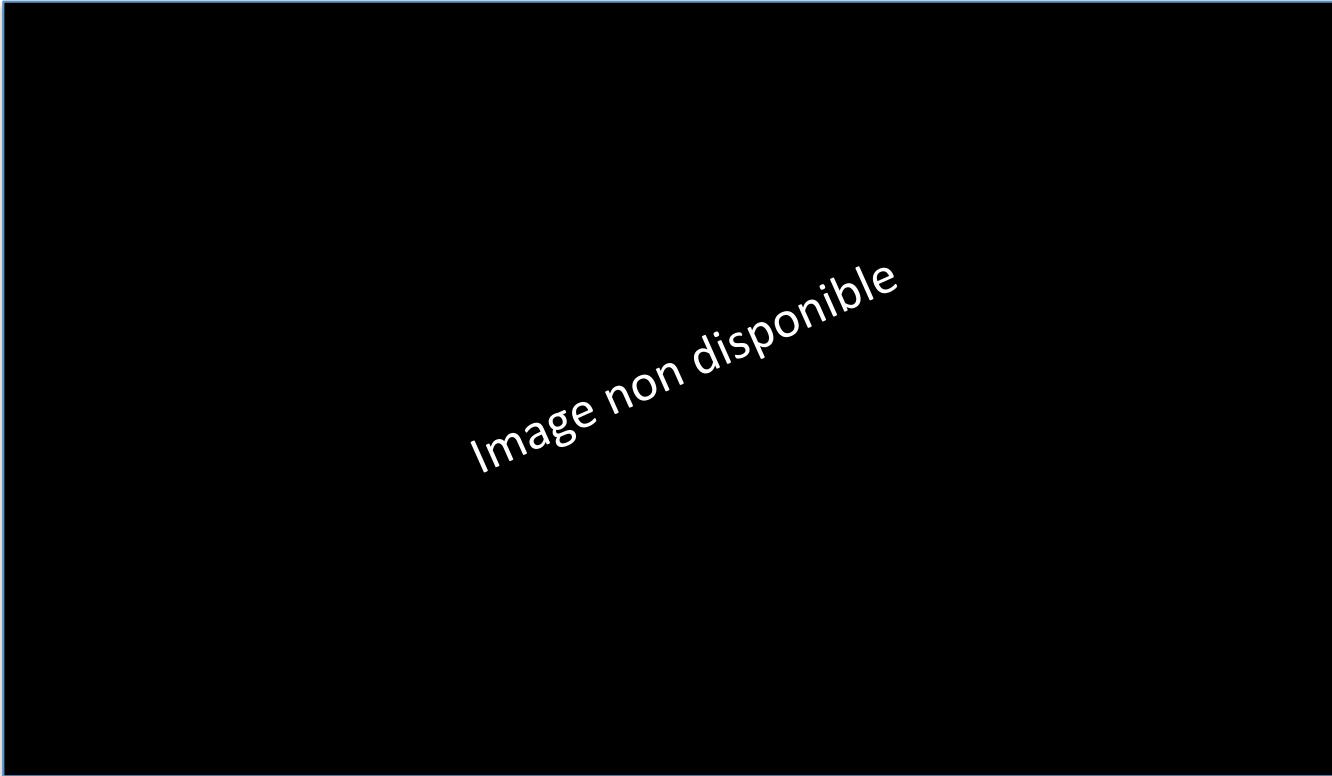
- Data compatible with zero in most of the bins
- Need use of confidence levels : the CLs method



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# Signal extraction

- Reproducing the  $p_T$  and centrality bins from 2.76 TeV



- Data compatible with zero in most of the bins
- Need use of confidence levels : the CLs method



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# Definition of Confidence Levels

- Hypothesis : known Background, unknown signal  
We define  $X$ , a statistical test of the known background and hypothetical signal which ranks experiments from least to most signal like
- The Confidence Level is calculated as

$$CL_{s+b} = P_{s+b}(X \leq X_{obs})$$

i.e., assuming the presence of signal and background at their hypothesized levels, it is the probability that the statistical test is less or equal to the one observed in the data  
This Probability is evaluated by making « experiments » satisfying the hypothesis  $s+b$ , that gives you a distribution for  $X$  that you can compare to  $X_{obs}$ .

- We can also define the Confidence Level for the background alone :

$$CL_b = P_b(X \leq X_{obs})$$



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# Definition of Confidence Levels

- A classic computation is to normalize the signal+background hypothesis with respect to the background only hypothesis :

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

- The Modified Frequentist Confidence Level CLs allows to have conservative limits on the signal hypothesis.  
The signal hypothesis will be considered excluded at the confidence level  $\alpha$  when :

$$CL_s \leq 1 - \alpha$$



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# Likelihood ratio

- A common choice for the test statistic is the likelihood ratio :

$$X = \frac{P(n : s+b)}{P(n : b)}$$

Where  $P(n : s+b)$  is the probability to observe  $n$ , when  $s+b$  is the truth

- It ranks experiments based on the likelihood by which it is described by a given signal
- In the end we use :

$$\ln(X) = \sum_{i=1}^{n_{bins}} -s_i + n_i \ln\left(1 + \frac{s_i}{b_i}\right)$$

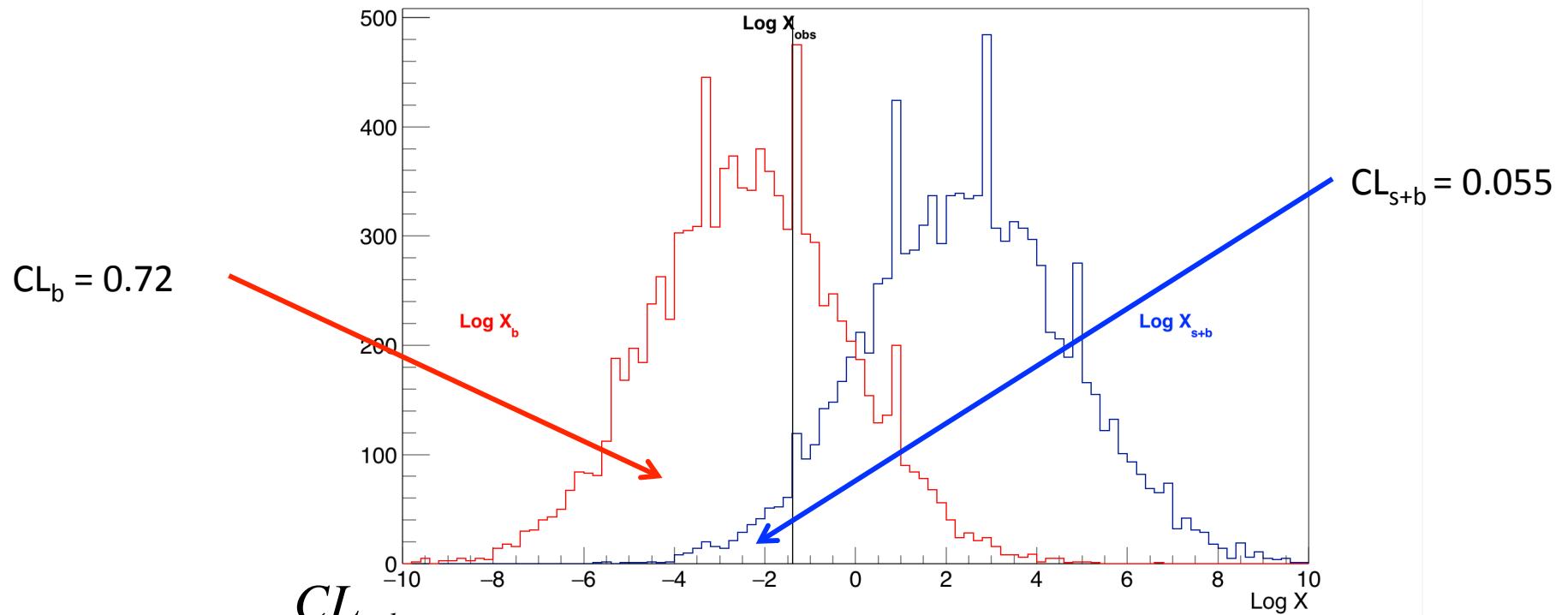


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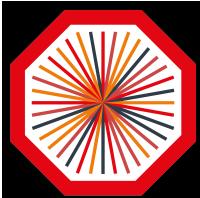
# Example for a Single Channel

- Known Background : 500 counts ; Hypothesized Signal : 50 counts ; Observed : 510 counts

$$\rightarrow \ln X_b = -50 + \text{Poisson}(500).\ln\left(1 + \frac{50}{500}\right) \quad \ln X_{s+b} = -50 + \text{Poisson}(550).\ln\left(1 + \frac{50}{500}\right)$$
$$\ln X_{obs} = -50 + 510.\ln\left(1 + \frac{50}{500}\right) = -1.39$$



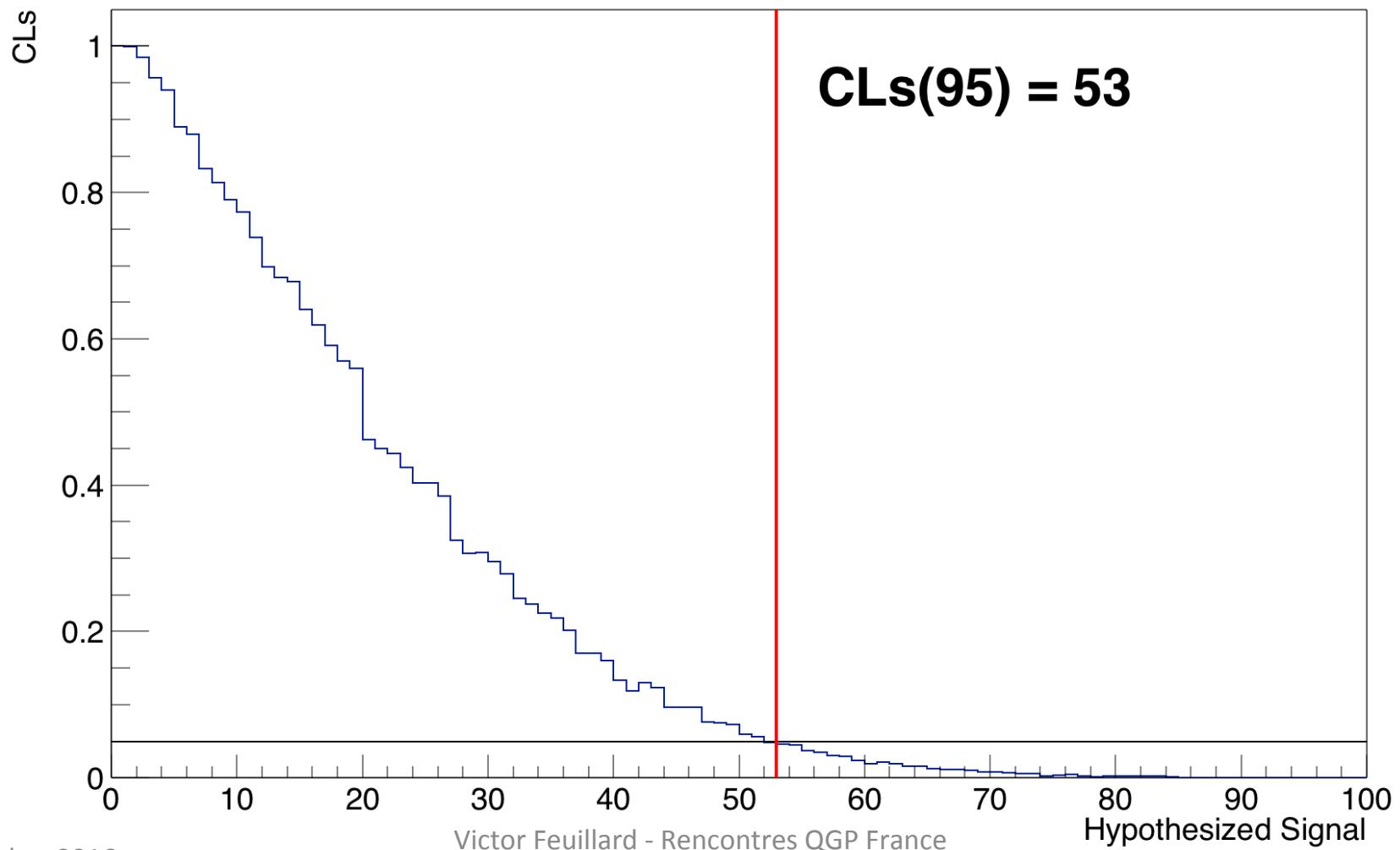
- We have  $CL_s = \frac{CL_{s+b}}{CL_b} = 0.072$



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# Example for a Single Channel

- For Hypothesized Signal from 0 to 100:





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# Application to the J/Ψ

- Background is known
- Shape of the signal known : Crystal Ball
- Hypothesis on the total number of signal counts
- We have :  $s_i = \text{SignalHypothesis} \times \text{CB2}(x_i)$   
 $b_i = \text{TotalBackground} \times \text{VWG}(x_i)$   
 $n_i^{obs} = \text{BinContent}(i)$
- And so

$$\ln(X_{s+b}) = \sum_{i=1}^{n_{bins}} -s_i + \text{Poisson}(s_i + b_i) \cdot \ln\left(1 + \frac{s_i}{b_i}\right) \quad \ln(X_{obs}) = \sum_{i=1}^{n_{bins}} -s_i + n_i^{obs} \ln\left(1 + \frac{s_i}{b_i}\right)$$

$$\ln(X_b) = \sum_{i=1}^{n_{bins}} -s_i + \text{Poisson}(b_i) \cdot \ln\left(1 + \frac{s_i}{b_i}\right)$$



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# Application to the J/ $\Psi$

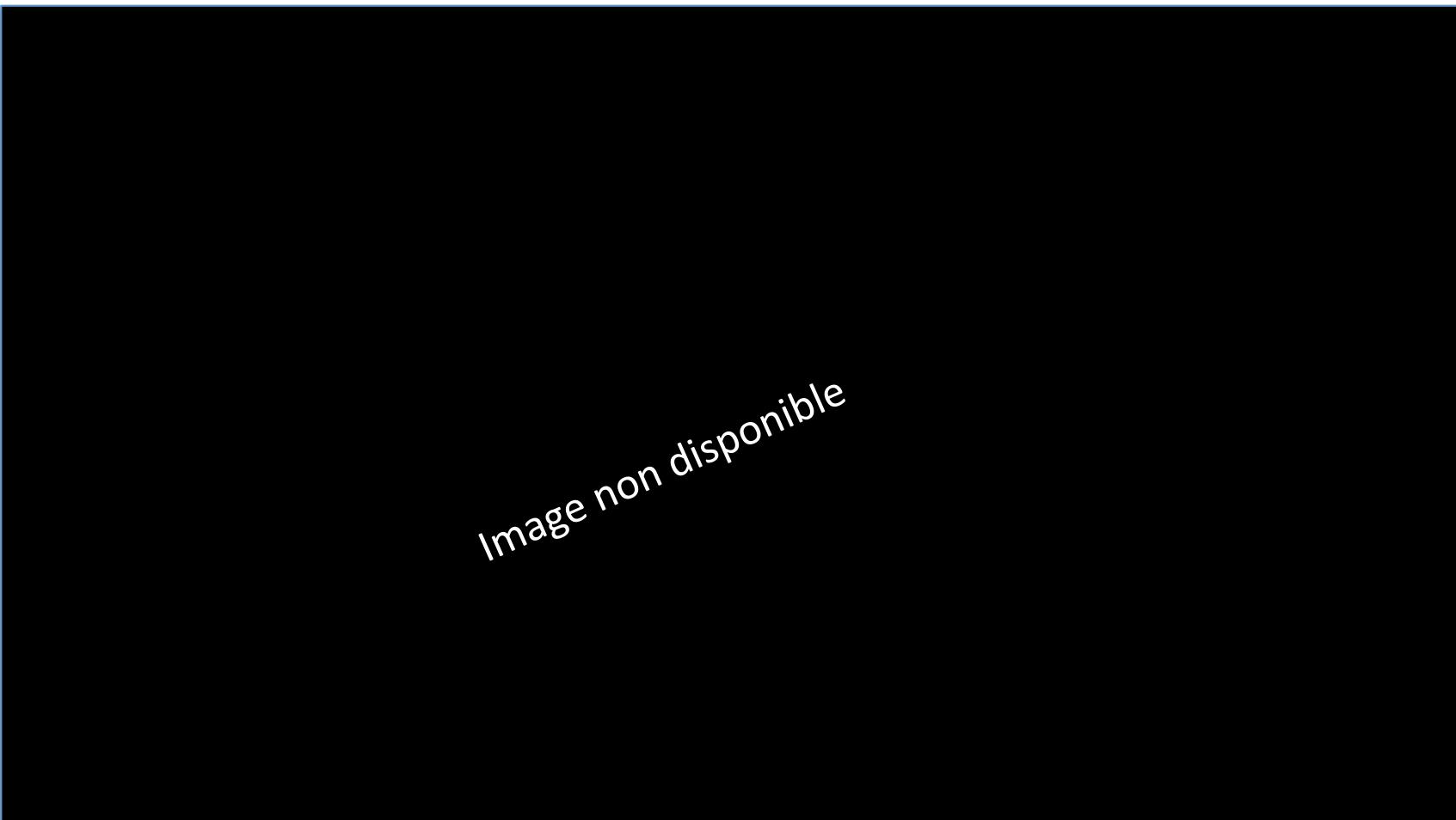
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# $\Psi(2S)$ Confidence Levels

- Results Vs Centrality





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# Conclusion

- The inclusive nuclear modification factor of the J/ $\psi$  in PbPb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV at forward rapidity has been measured down to  $p_T = 0$
- These results are compatible within uncertainties with theoretical models and support a picture of J/ $\psi$  suppression and regeneration competing in the QGP
- Measurement of the  $R_{AA}$  for the  $\Psi(2S)$  is ongoing  
→ This should help discriminate between models
- But, there is very low statistics, which is why we will use Confidence Levels for most of the centrality bins



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# To be done...

- Acc x eff corrections
  - Reference pp
  - How to handle systematics in the CLs calculation
  - Produce  $R_{AA}$
  - Double ratios
- To be presented at Quark Matter 2017

**THANK YOU FOR YOUR ATTENTION!**

**QUESTIONS?**