

# J/ $\psi$ Production in Pb-Pb Collisions at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$ measured at forward rapidity with ALICE at the LHC



ALICE

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Benjamin Audurier  
Subatech Laboratory, Nantes, France



## Outline

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### II. The ALICE Detector

### III. Analysis Steps

1. Event and Track selection
2. Signal Extraction
3. The Acceptance x Efficiency
4. The Normalisation Factor

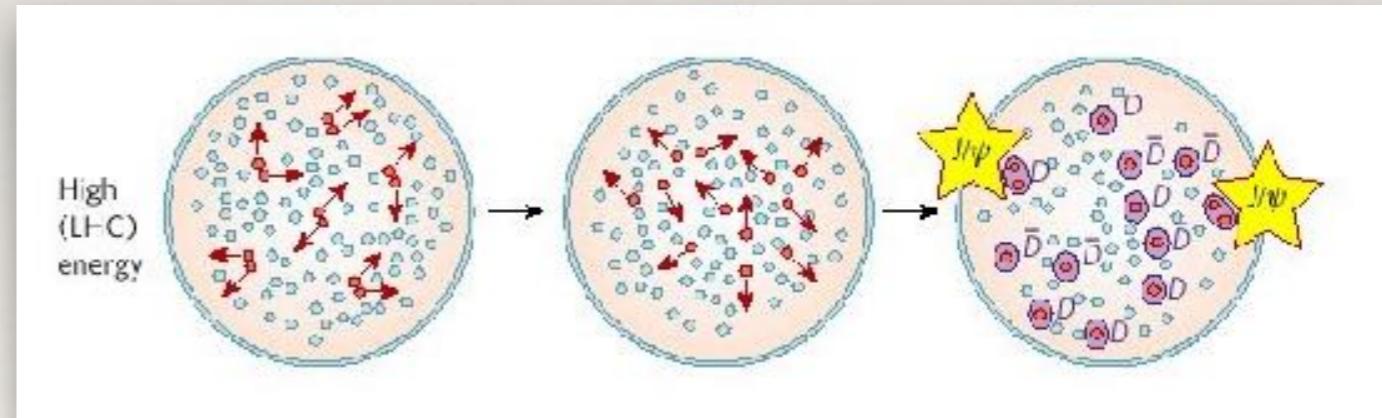
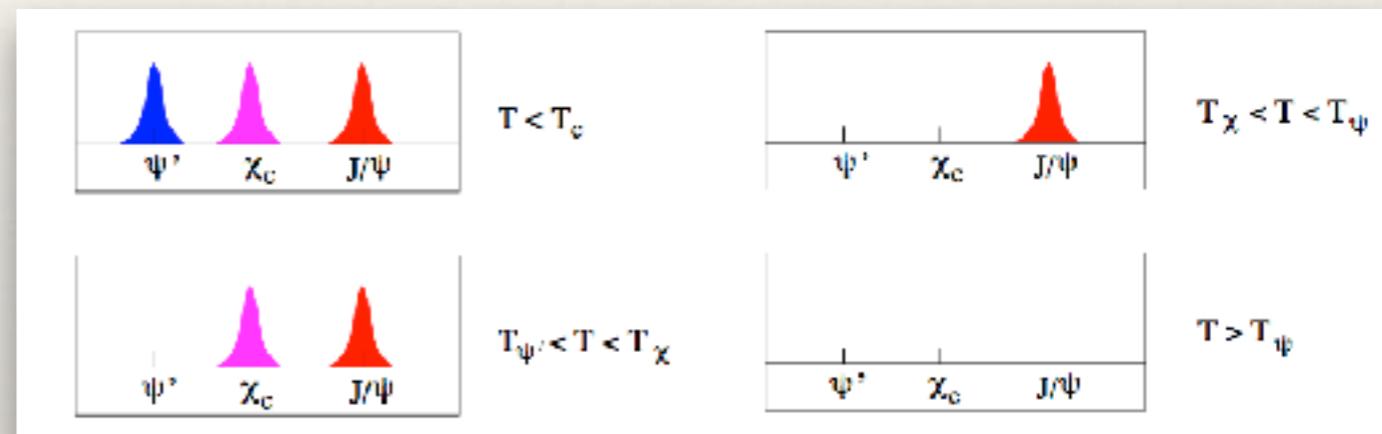
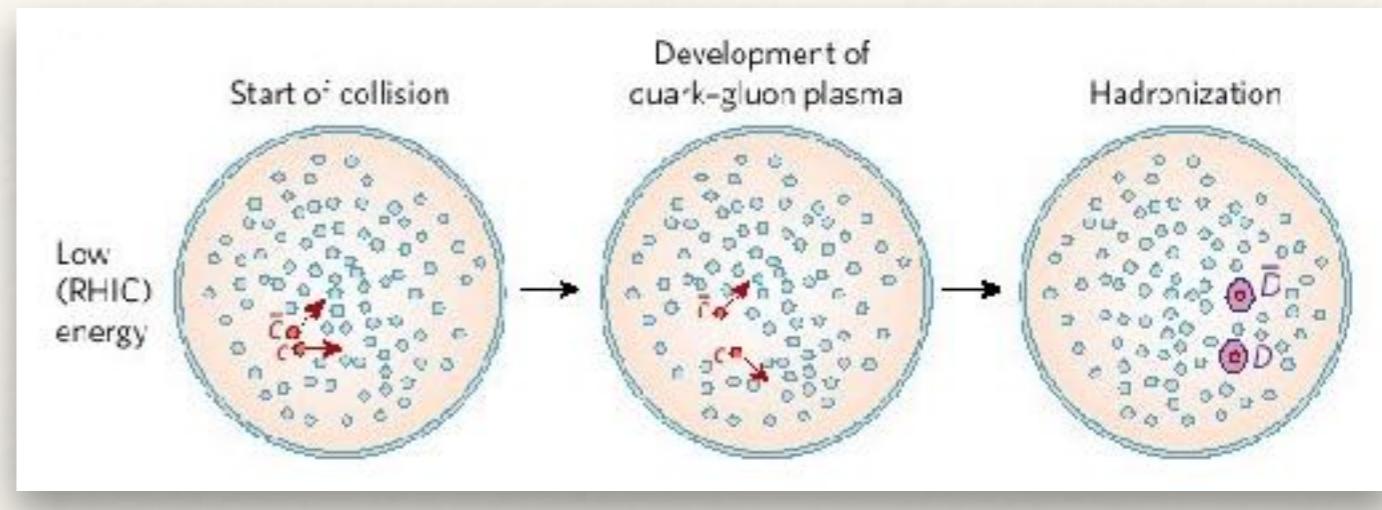
### IV. Results at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$

1. Inclusive J/ $\psi$   $R_{\text{AA}}$
2. Comparison with  $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$  results
3. Comparison with theoretical models

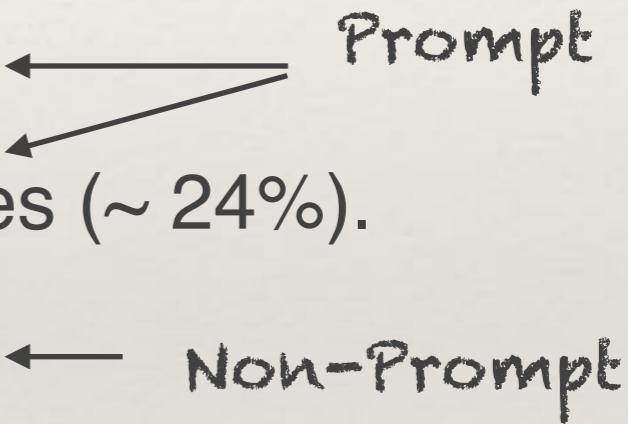
new !

# Physics Motivations

- ❖ Charmonium is produced at the earliest stage of the collision.
- ❖ In 1986 Matsui & Satz<sup>1</sup> predicted  $J/\psi$  suppression by the QGP through Debye like color screening mechanism.
- ❖ Color screening suppression depends on charmonium binding energy and medium temperature  
→ Sequential suppression
- ❖  $c\bar{c}$  cross-section increases at LHC energies → regeneration<sup>2,3)</sup>.
- ❖ charmonium states = good probes of deconfined state of QCD phase diagram.



- 1) Matsui & Satz,  $J/\psi$  suppression by quark-gluon plasma formation, Physics Letters B vol.178 n.4
- 2) P. Braun-Munzinger et al. PLB 490 (2000) 196
- 3) R. Thews et al: Phys. Rev. C63 054905 (2001)

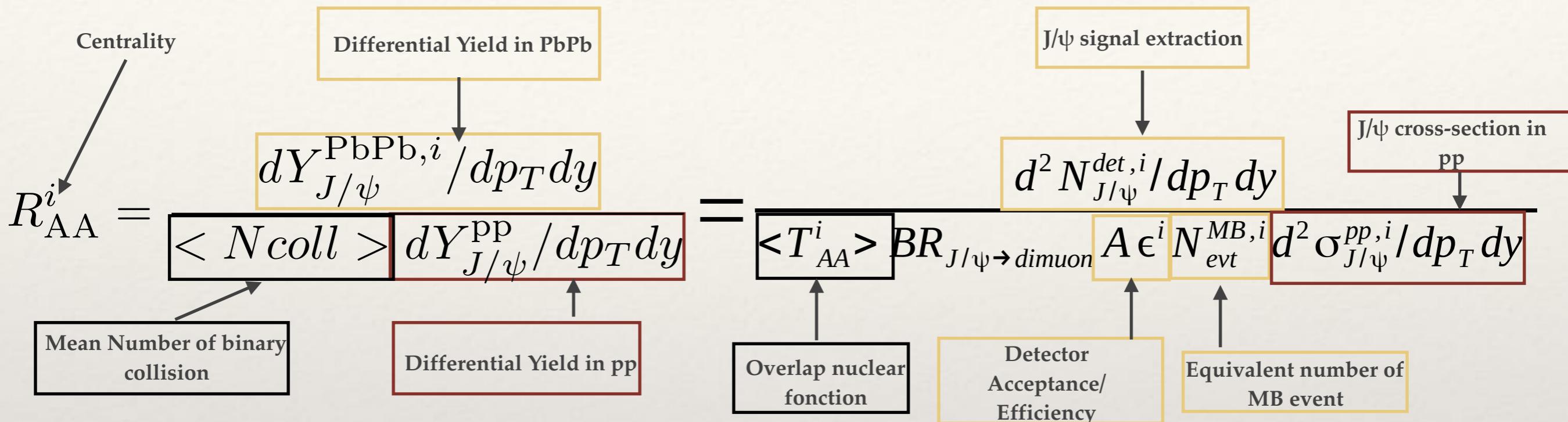
- ❖ Charmonium also sensitive to cold nuclear matter effects (energy loss, shadowing ...) → **Studied in p-Pb collisions.**
- ❖ A reference is needed to disentangle cold/hot nuclear matter effects from standard production → **Studied in p-p collisions.**
- ❖ Different sources of charmonium production :
  - ❖ Direct production.
  - ❖ Decay from higher mass charmonium states ( $\sim 24\%$ ).
  - ❖ Decay from B-hadrons ( $\sim 10\%$ ). 

Inclusive

The results presented here refer to the inclusive  $J/\psi$  production.

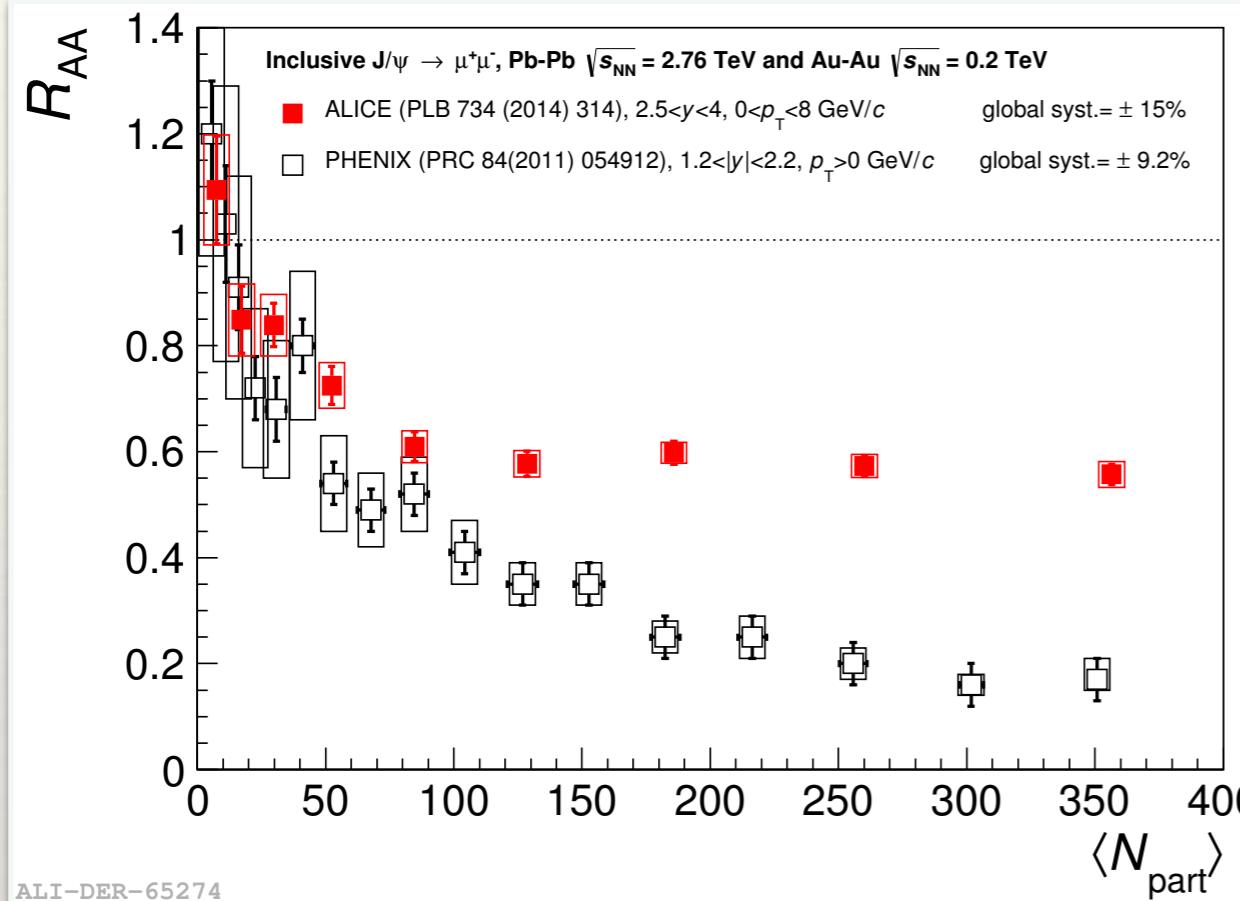
- 1) The LHCb Coll., *Measurement of the ratio of prompt  $x_c$  to  $J/\psi$  production in pp collisions at  $\sqrt{s} = 7$  TeV*, arXiv:1204.1462v2
- 2) The LHCb Coll., *Measurement of  $\psi(2S)$  meson production in pp collisions at  $\sqrt{s} = 7$  TeV*, arXiv:1204.1258
- 3) The LHCb Coll., *Measurement of  $J/\psi$  production in pp collisions at  $\sqrt{s} = 7$  TeV*, arXiv:1103.0423v2

❖ Assumption :  $\odot_{Pb \rightarrow \leftarrow} \odot_{Pb} = \langle N_{coll} \rangle \bullet_{p \rightarrow \leftarrow} \bullet_p$

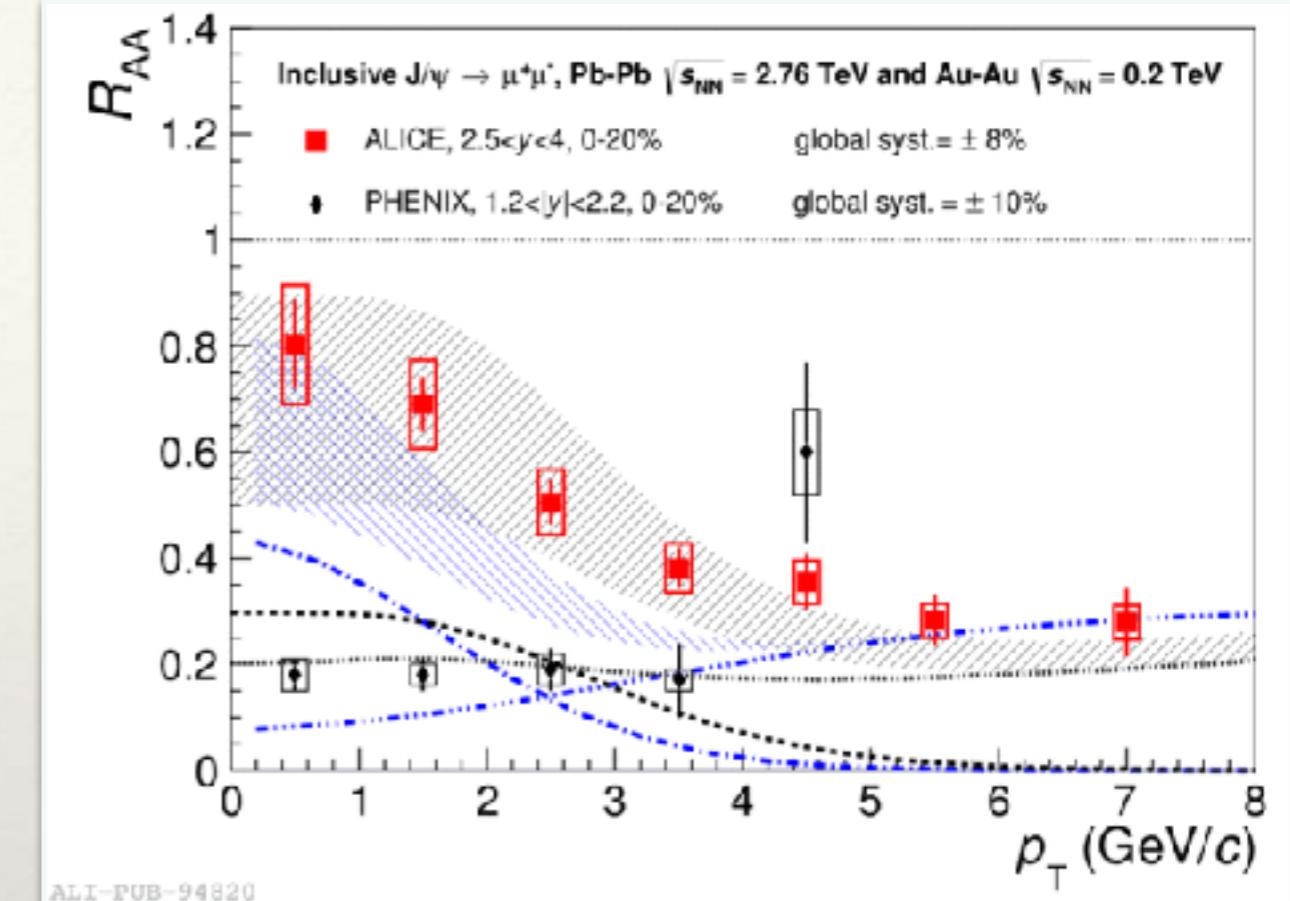


- ❖ If  $R_{AA} > 1 \rightarrow \underline{\text{More}}$  charmonium produced than expected from pp results.
- ❖ If  $R_{AA} = 1 \rightarrow \underline{\text{Same}}$  as compared to a superposition of pp.
- ❖ If  $R_{AA} < 1 \rightarrow \underline{\text{Less}}$  charmonium than expected from pp results.

ALICE Coll. PLB 734 (2014) 314



ALI-DER-65274



ALI-PUB-94820

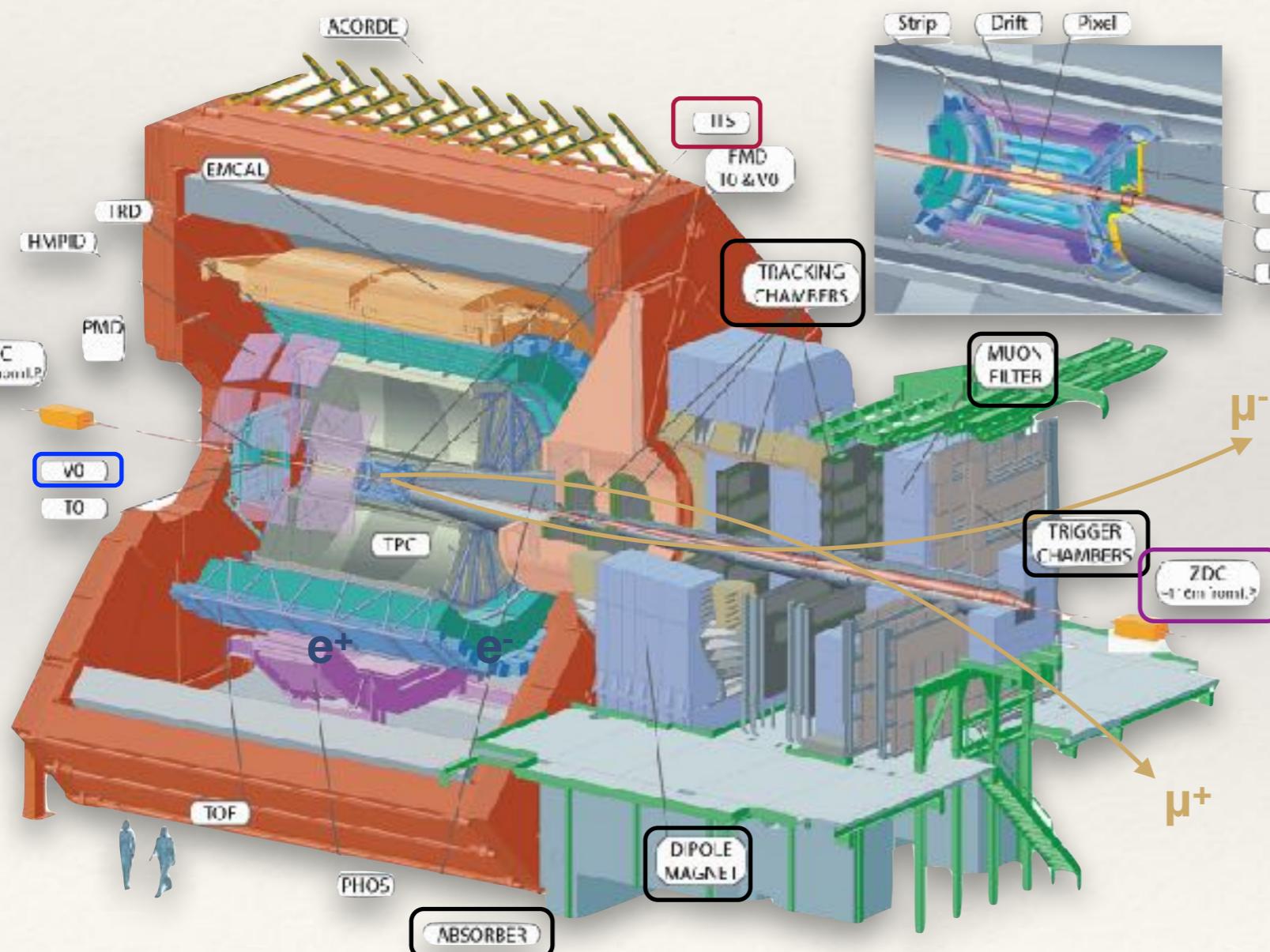
- ❖ Clear J/ $\psi$  suppression both at ALICE and PHENIX (Au-Au at  $\sqrt{s_{NN}} = 200 \text{ GeV}$ ) versus  $p_T$  and centrality.
- ❖ Weaker centrality dependence and smaller suppression for central events in ALICE compared to PHENIX.
- ❖ Less suppression at low than high  $p_T$ .
- ❖ **Everything indicates a suppression regeneration compensation scenario.**

What would happen if we double up the colliding energy ?

# The ALICE Detector

$J/\psi \rightarrow \mu^+ \mu^-$ :

- $2.5 < y < 4$
- down to  $p_T = 0$



### ❖ V0 detector :

- ❖ gives the Minimum Bias collision trigger
- ❖ evaluates the collision centrality

### ❖ ITS detector :

- ❖ gives the collision vertex

### ❖ ZDC detector :

- ❖ Rejects electromagnetic interaction contamination

### ❖ Muon Spectrometer :

- ❖ rapidity range  $-4 < \eta < -2,5$
- ❖ full  $\Phi$  coverage

# Analysis Steps

$$R_{AA}^i = \frac{d^2 N_{J/\psi}^{det,i} / dp_T dy}{\langle T_{AA}^i \rangle BR_{J/\psi \rightarrow dimuon} A \epsilon^i N_{evt}^{MB,i} d^2 \sigma_{J/\psi}^{pp,i} / dp_T dy}$$

The diagram illustrates the components of the analysis steps for  $R_{AA}^i$ . The formula is shown as:

$$R_{AA}^i = \frac{d^2 N_{J/\psi}^{det,i} / dp_T dy}{\langle T_{AA}^i \rangle BR_{J/\psi \rightarrow dimuon} A \epsilon^i N_{evt}^{MB,i} d^2 \sigma_{J/\psi}^{pp,i} / dp_T dy}$$

The terms in the numerator are highlighted with yellow boxes:

- $d^2 N_{J/\psi}^{det,i} / dp_T dy$
- $A \epsilon^i N_{evt}^{MB,i}$

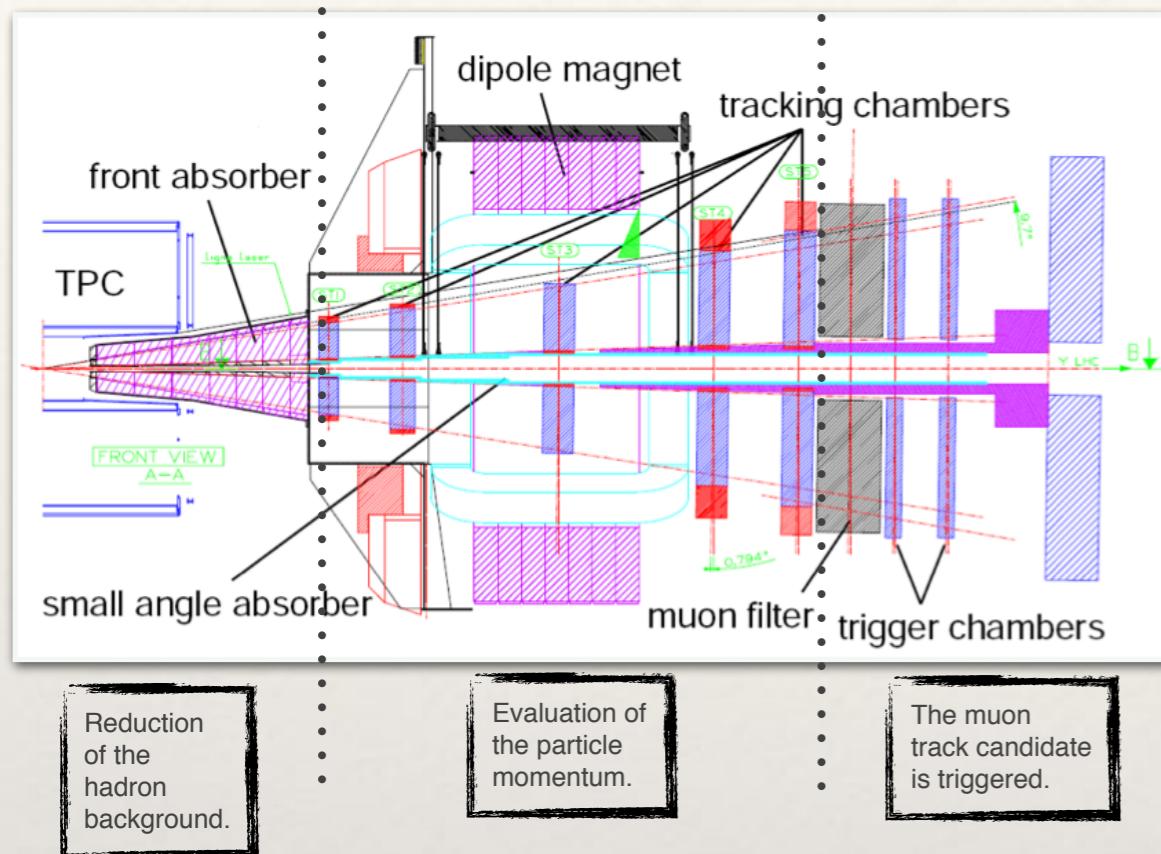
The term in the denominator is highlighted with a red box:

- $d^2 \sigma_{J/\psi}^{pp,i} / dp_T dy$

Arrows from external boxes point to these highlighted terms:

- A yellow box labeled "J/ $\psi$  signal extraction" points to  $d^2 N_{J/\psi}^{det,i} / dp_T dy$ .
- A yellow box labeled "Detector Acceptance/Efficiency" points to  $A \epsilon^i N_{evt}^{MB,i}$ .
- A yellow box labeled "Equivalent number of MB event" points to  $N_{evt}^{MB,i}$ .
- A red box labeled "See Jana's Talk!" points to  $d^2 \sigma_{J/\psi}^{pp,i} / dp_T dy$ .

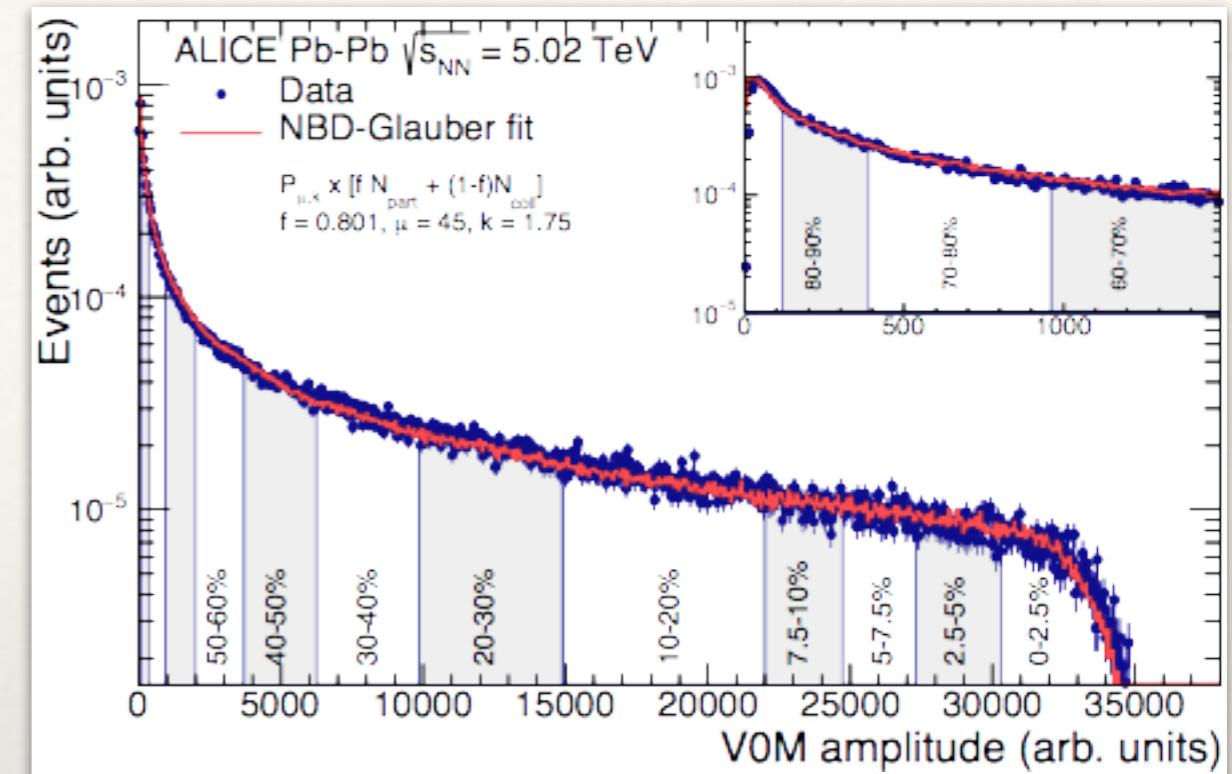
PRL. 116, 222302 (2016)

Muon Track selection :

- ❖ Trigger matching
- ❖  $-4 < \eta_\mu < -2.5$
- ❖  $17.6 < R_{\text{abs}} < 89.5 \text{ cm}$

Reconstructed pairs cut :

- ❖  $2.5 < y_{\mu\mu} < 4$
- ❖ opposite sign tracks

❖ Event selection :

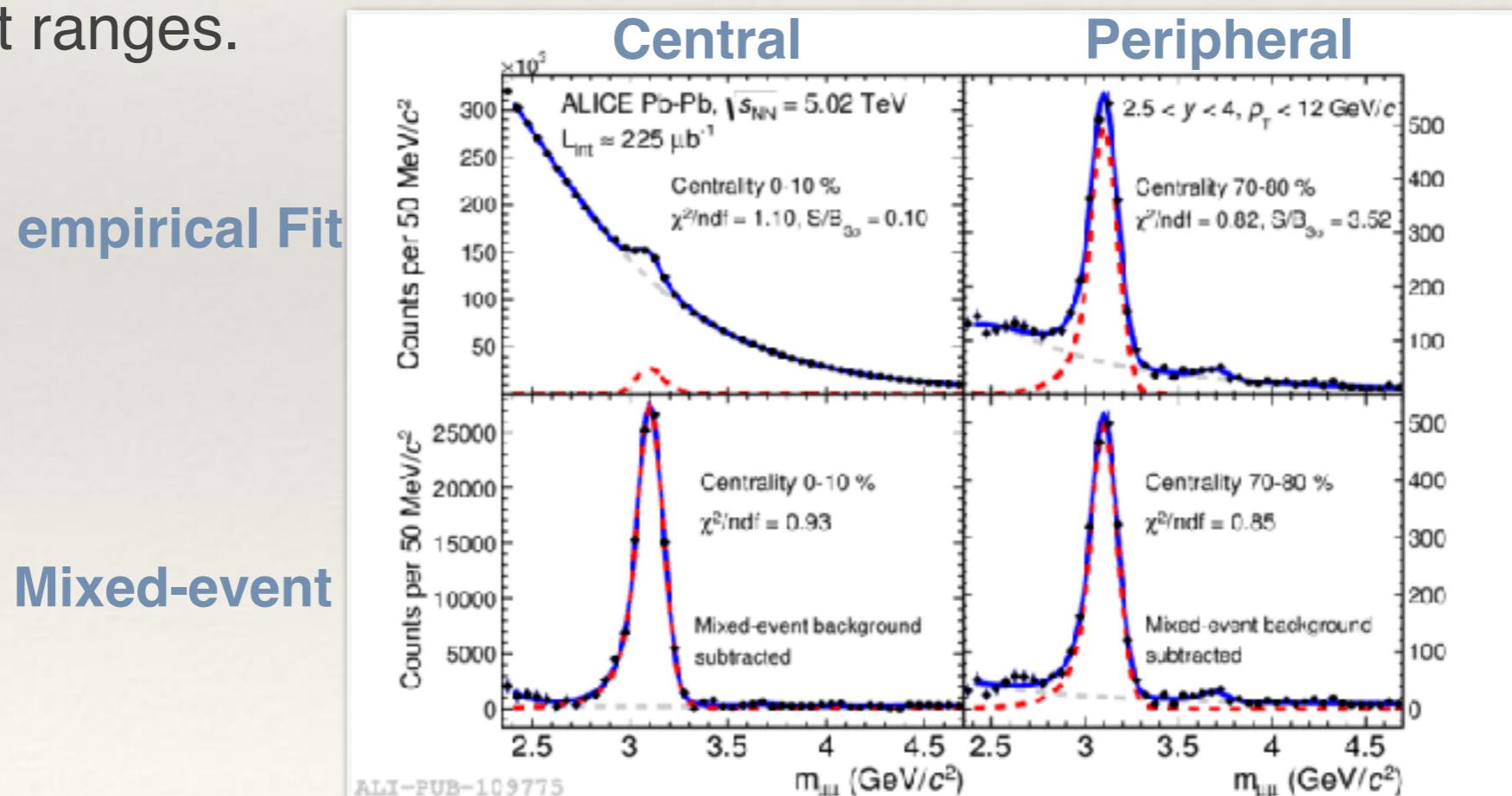
- ❖ Minimum bias collision + muons of opposite sign firing the trigger.
- ❖ Beam-gas interaction rejected with V0 and ZDC.
- ❖ Centrality estimation based on a Glauber model fit of the V0 amplitude.

Total Luminosity  $\sim 225 \mu\text{b}^{-1}$

- ❖ ~7 times more statistics compared to Run-1.

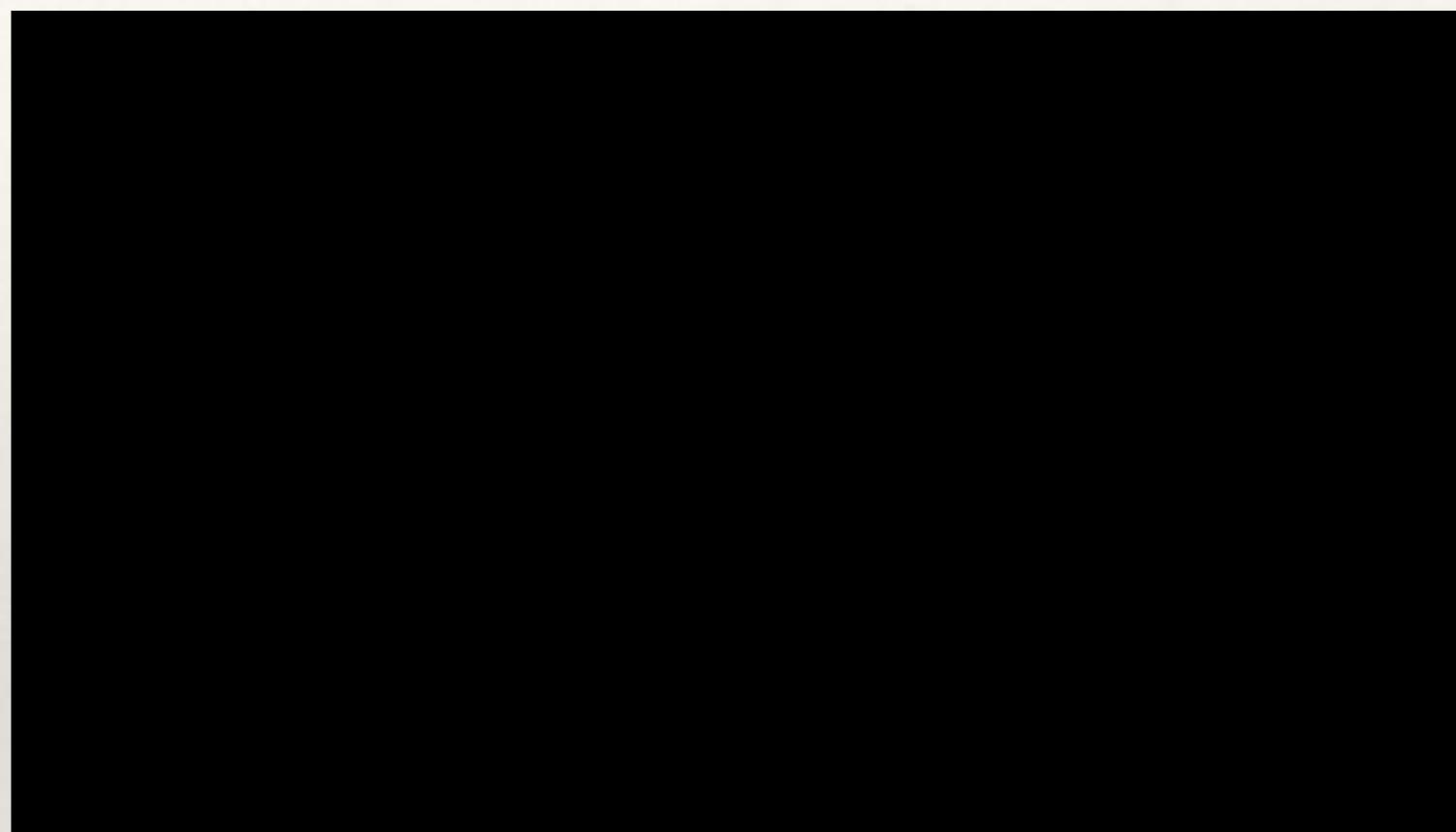
$$R_{AA}^i = \frac{d^2 N_{J/\psi}^{det,i} / dp_T dy}{\langle T_{AA}^i \rangle BR_{J/\psi \rightarrow dimuon} A \epsilon^i N_{evt}^{MB,i} d^2 \sigma_{J/\psi}^{pp,i} / dp_T dy}$$

- ❖ J/ $\psi$  yield extracted by fitting the opposite sign dimuon invariant mass spectrum.
- ❖  $\langle J/\psi \rangle$  and the syst. uncertainties are evaluated from the combination of :
  - ❖ Two fit functions for the signal peak.
  - ❖ Two methods to deal with the background (empirical fit or mixed-event background subtraction).
  - ❖ Two fit ranges.



- ❖ Strategy : make realistic simulations of an embedded pur J/ $\psi$  signal into a realistic Monte Carlo event.
- ❖ AccxEff =  $N_{J/\psi}^{\text{rec.}} / N_{J/\psi}^{\text{Gen.}}$
- ❖ The quality of the simulations is controlled at different levels :
  - The tracking efficiency.
  - The trigger efficiency.
  - The pairing between the trigger and the tracker.
  - The input shapes.

$$R_{AA}^i = \frac{d^2 N_{J/\psi}^{\text{det},i} / dp_T dy}{\langle T_{AA}^i \rangle BR_{J/\psi \rightarrow \text{dimuon}} A \epsilon^i N_{\text{evt}}^{\text{MB},i} d^2 \sigma_{J/\psi}^{pp,i} / dp_T dy}$$



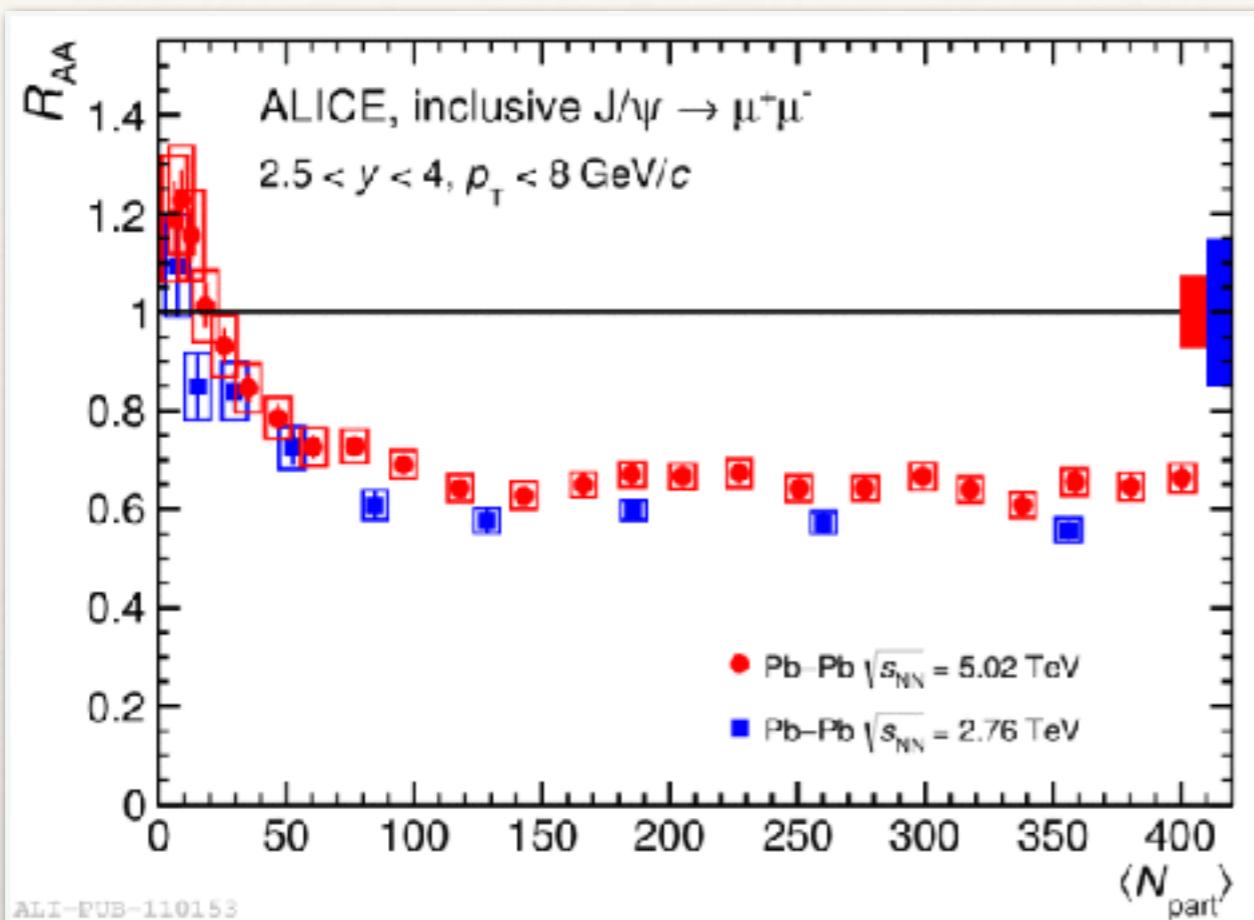
# The Normalisation Factor

$$R_{AA}^i = \frac{d^2 N_{J/\psi}^{det,i} / dp_T dy}{\langle T_{AA}^i \rangle BR_{J/\psi \rightarrow dimuon} A \epsilon^i N_{evt}^{MB,i} d^2 \sigma_{J/\psi}^{pp,i} / dp_T dy}$$

- ❖ A normalisation factor is needed to extract an equivalent number of MB events given the number of dimuon event (MUL).
- ❖ We use three approaches :
  - ❖ One step offline
  - ❖ Two steps offline
  - ❖ The scalers from OCDB
- ❖  $F_{Norm}^{Off1} = P.U \times N_{CINT7} / N_{CINT7 \& 0MUL}$
- ❖  $F_{Norm}^{Off2} = P.U \times N_{CMSL} / N_{CMSL \& 0MUL} \times N_{CINT7} / N_{CINT7 \& 0MSL}$
- ❖  $F_{Norm}^{Scl} = (F_{MUL}^{MB purity} * L0b_{MB}) / (L0b_{MUL} * F_{purity}^{MB}) \times F_{pileup}^{MB}$

- ❖ Systematic uncert. taken as the difference between the three approaches.
- ❖ **Mean Fnorm = 11.842 +/- 0.001 (stat. 0.008%) +/- 0.059 (syst. 0.5%).**

# Results in Pb-Pb@5.02 TeV



arXiv:1606.08197

$R_{AA}^{0-90\%}(0 < p_T < 8 \text{ GeV}/c)$ :  $0.66 \pm 0.01 \text{ (stat.)} \pm 0.05 \text{ (syst.)}$

2011  $R_{AA}^{0-90\%}(0 < p_T < 8 \text{ GeV}/c)$ :  $0.58 \pm 0.01 \text{ (stat)} \pm 0.09 \text{ (syst.)}$

- ❖ Higher statistics leads to **finer bins in centrality**.
- ❖ Better control of the syst. uncert.
- ❖ **Clear  $J/\psi$  suppression** with no centrality dependence in the most central collisions.
- ❖ Effect of the non-prompt component on the inclusive  $R_{AA}$ :

$$R_{AA(\text{non-prompt})} = 0$$

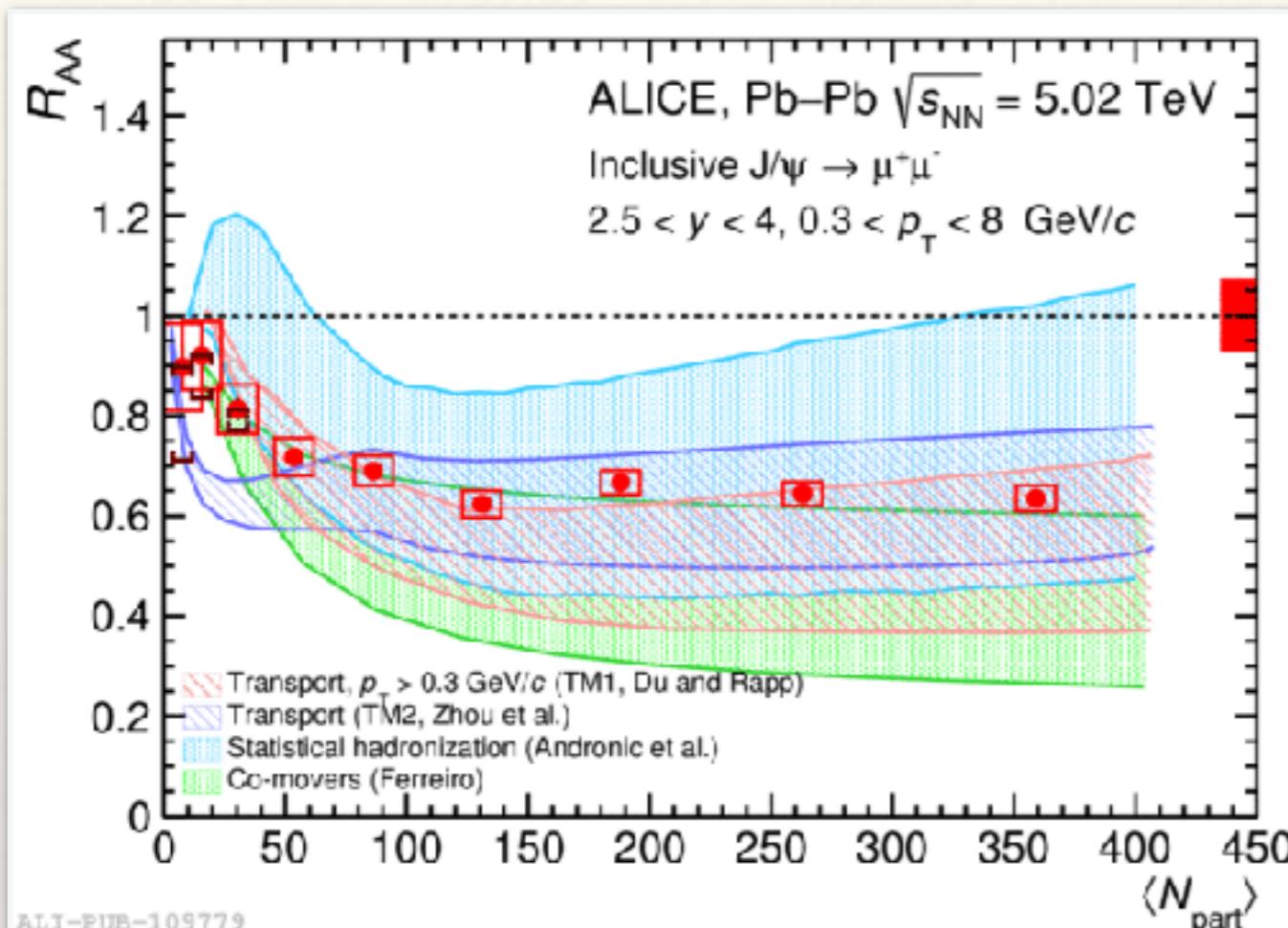
- All non-prompt  $J/\psi$  are suppressed
- $R_{AA(\text{prompt})}$  10% higher



$$R_{AA(\text{non-prompt})} = 1$$

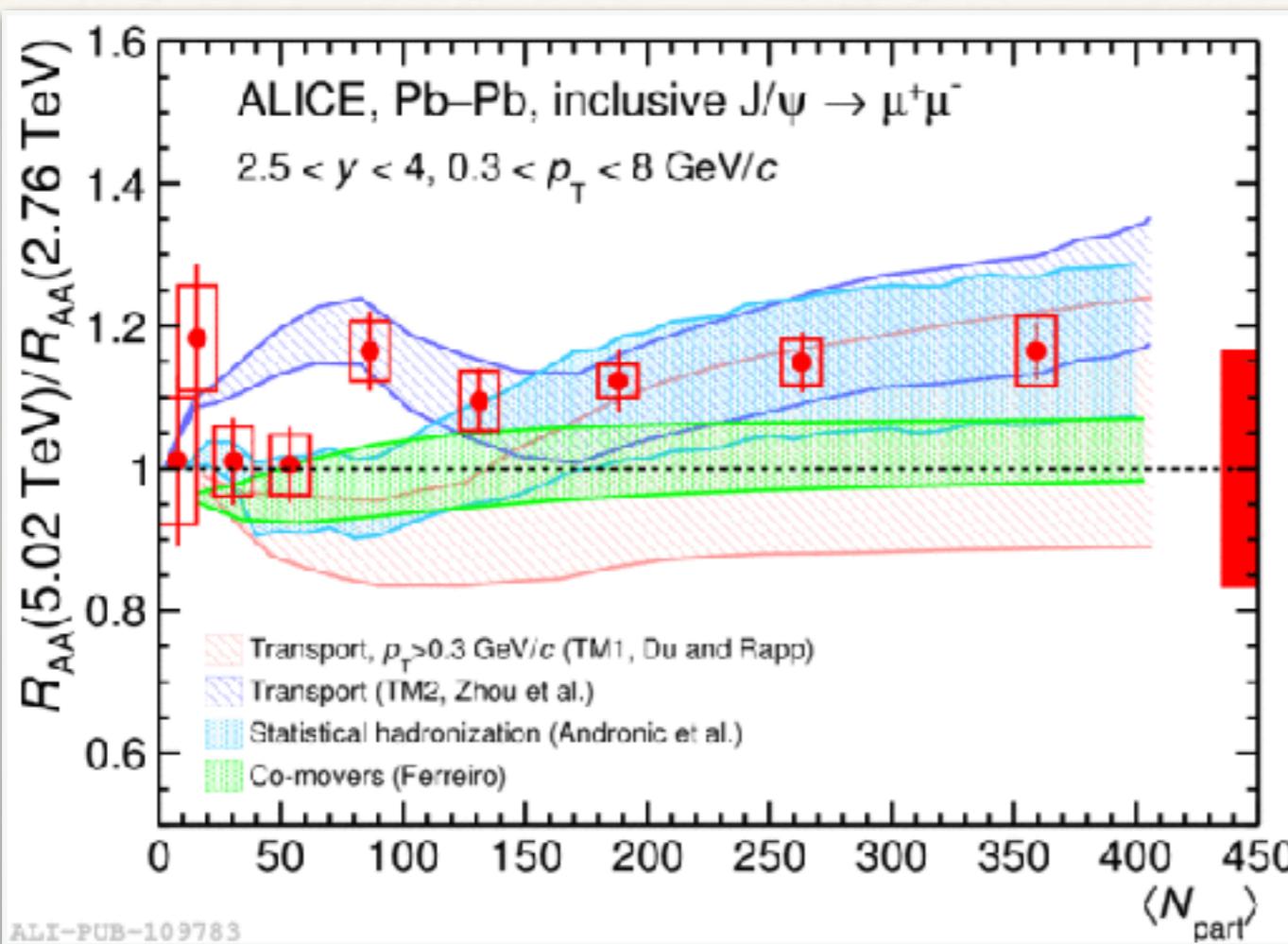
- All non-prompt  $J/\psi$  survive
- $R_{AA(\text{prompt})}$  5% to 1% lower

Results between  $\sqrt{s}_{NN} = 2.76$  and  $5.02 \text{ TeV}$   
 data are compatible within uncertainties



TM1: Nucl. Phys. A859 (2011) 114–125  
 TM2: Phys. Rev. C89 no. 5, 459 (2014) 054911  
 Stat. hadronization: NPA 904-905 (2013) 535c  
 Co-movers: Phys. Lett. B731 (2014) 57–63

- ❖ The  $p_T > 0.3$  GeV/c cut removes ~80% of the photoproduced J/ $\psi$ .
- ❖ Large uncertainties on the theoretical calculations due mainly to the choice of  $\sigma_{c\bar{c}}$ .
- ❖ **All models include a large amount of regeneration**
- ❖ A better agreement is found for some transport (Du and Rapp) and co-movers (Ferreiro) models when we consider their upper limit.
- ❖ In transport models this corresponds to **the absence of nuclear shadowing -> extreme assumption.**

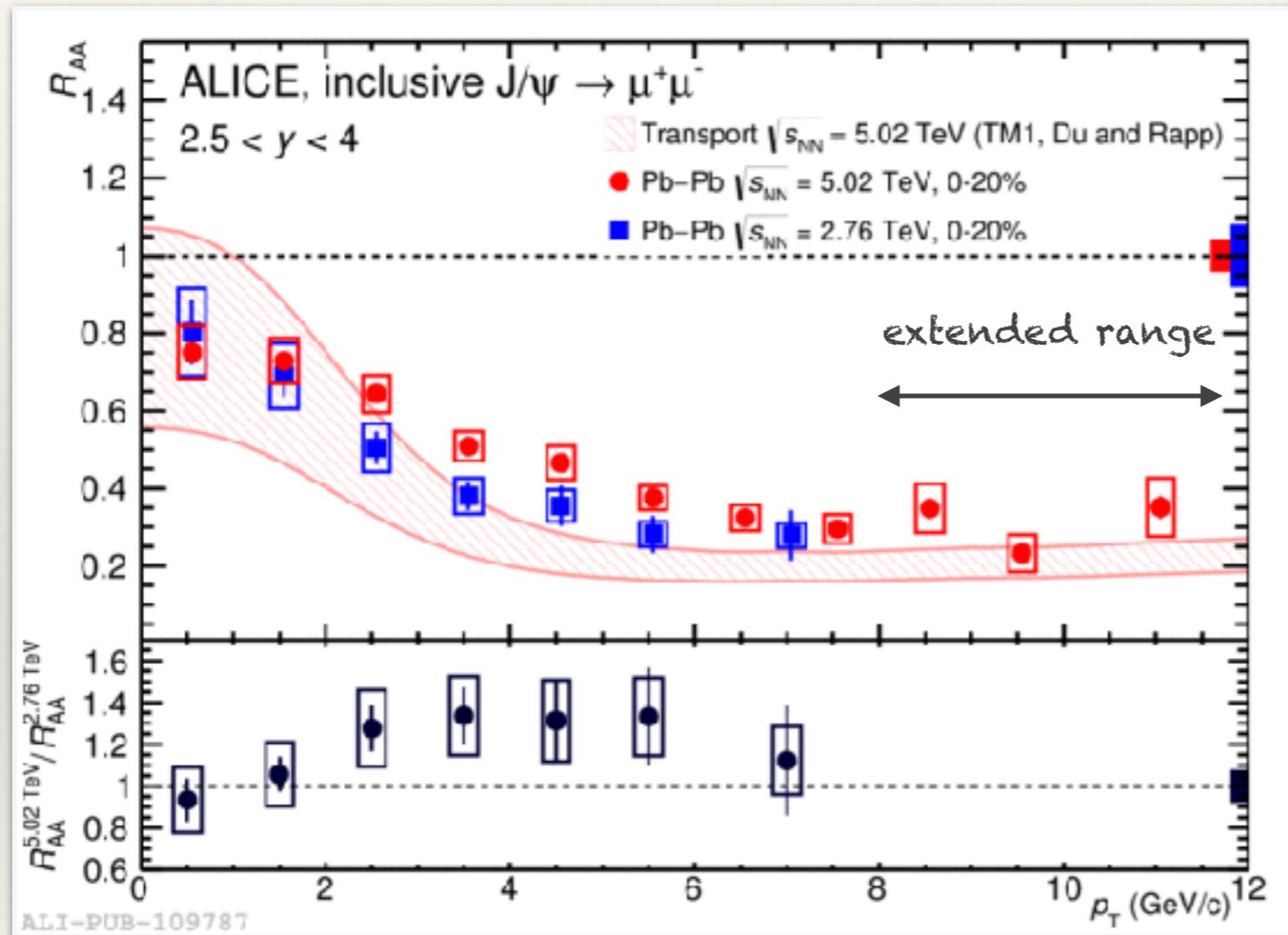


- ❖  $R_{AA}$  ratio allows some uncertainties on the models to cancel out
- ❖  $T_{AA}$  uncert. also cancels out for the experimental results
- ❖ Error bands on models correspond to a 5% variation of  $\sigma_{c\bar{c}}$

- ❖ 2% variation of the ratio when considering the non-prompt contribution
- ❖ Ratio value for the most central events :  $1.17 \pm 0.04$  (stat.)  $\pm 0.20$  (syst.)

Models are compatible with data within uncertainties showing no clear centrality dependance of the ratio.

arXiv:1606.08197



- ❖ Less suppression at low  $p_T$  w.r.t high  $p_T$ .
- ❖ Assuming **beauty fully suppressed** :
  - ❖  $R_{AA(\text{prompt})}$  expected to be **7% larger** for  $p_T < 1 \text{ GeV}/c$ .
  - ❖  $R_{AA(\text{prompt})}$  expected to be **30% larger** for  $10 < p_T < 12 \text{ GeV}/c$ .
- ❖ Assuming **beauty binary scaling** :
  - ❖  $R_{AA(\text{prompt})}$  expected to be **2% smaller** for  $p_T < 1 \text{ GeV}/c$ .
  - ❖  $R_{AA(\text{prompt})}$  expected to be **55% smaller** for  $10 < p_T < 12 \text{ GeV}/c$ .

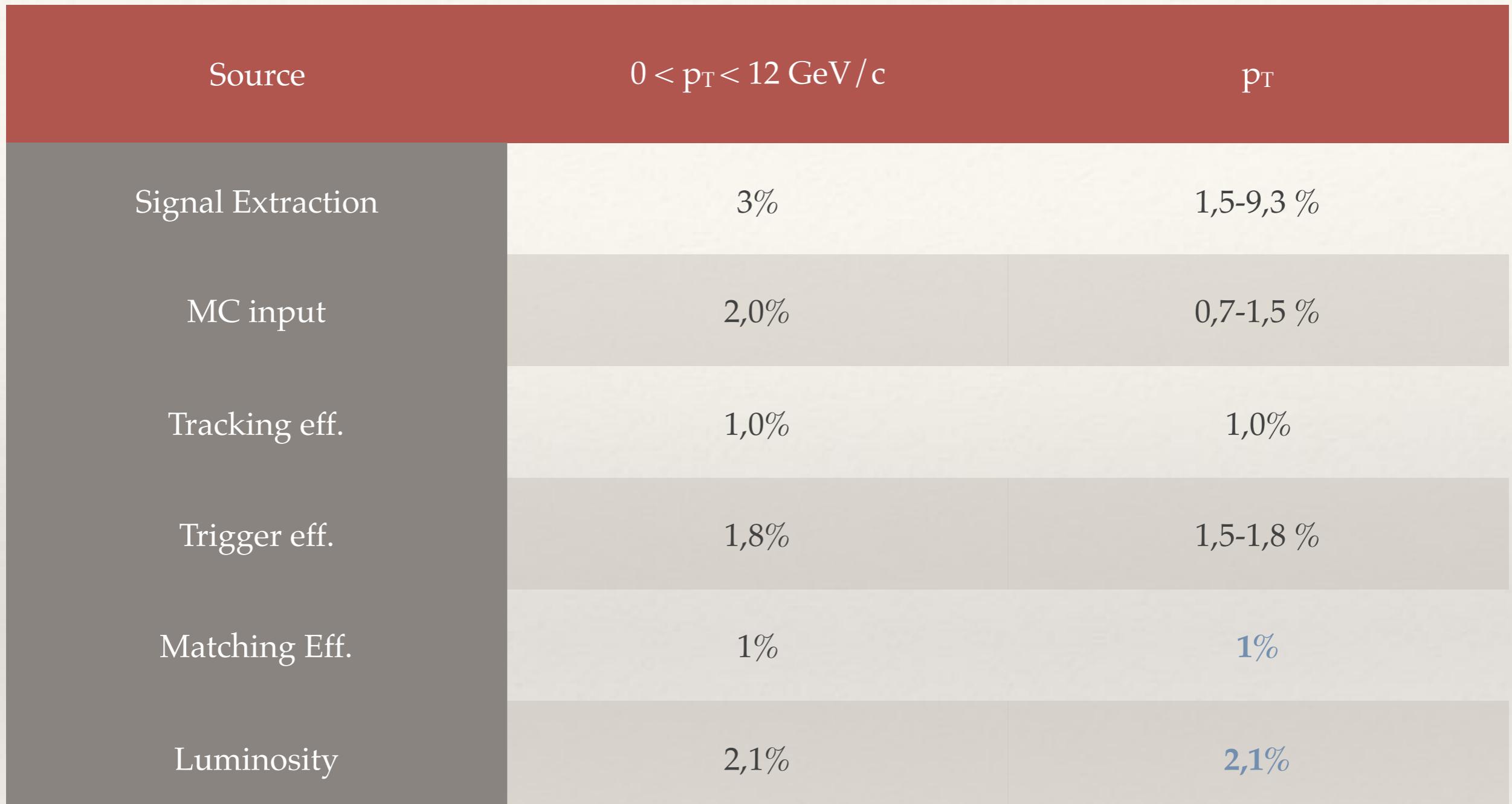
- ❖ The inclusive J/ $\psi$  nuclear modification factor in PbPb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV at forward rapidity has been measured down to  $p_T = 0$  GeV/c.
- ❖ The  $p_T$  range of the  $R_{AA}$  has been extended up to 12 GeV/c.
- ❖ The study of the centrality and  $p_T$  dependence of  $R_{AA}$  shows :
  - ❖ an increase of the J/ $\psi$  suppression with centrality up to  $N_{part} \sim 100$  followed by a saturation as for previous results in PbPb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV.
  - ❖ less suppression at low  $p_T$  with respect to high  $p_T$ .
- ❖ The comparison between  $\sqrt{s_{NN}} = 2.76$  and 5.02 TeV results through  $R_{AA}$  ratio shows that results show no significant energy dependence within uncertainties in the full centrality range and versus  $p_T$ .
- ❖ **Data and theoretical models are compatible within uncertainties and support a picture of competing J/ $\psi$  suppression and regeneration in the QGP.**
- ❖ **Outlook :**
  - ❖ Start the multi-differential study.

Thank you !

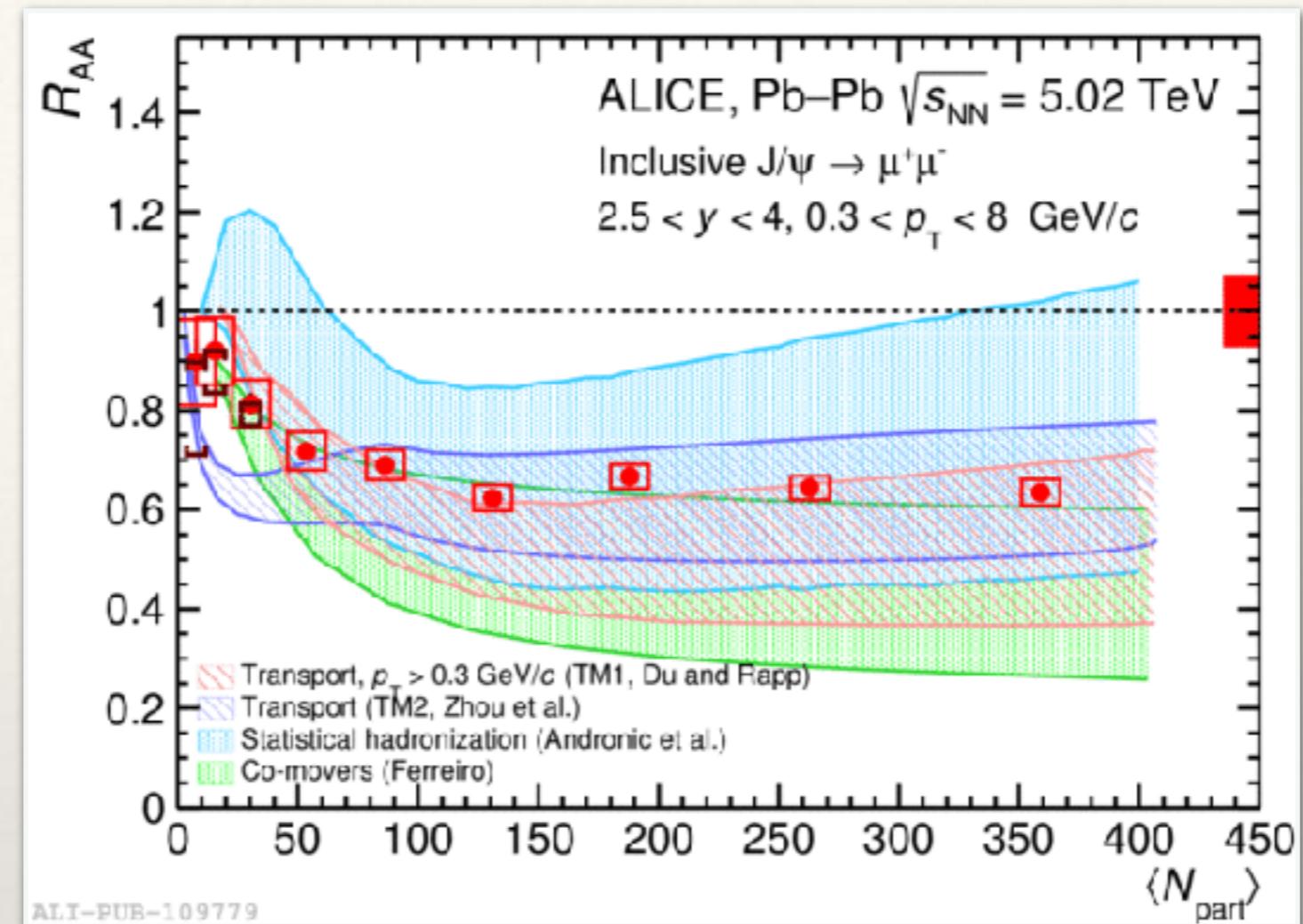
# Back-up

Source	0-90% $p_T < 12 \text{ GeV}/c$	$p_T$ (0-20%)	centrality
Signal Extraction	1,8%	1.2-3.1 %	1.6-2.8 %
MC input	2,0%	2,0%	<b>2%</b>
Tracking eff.	3,0%	3,0%	<b>3%</b>
Trigger eff.	3,6%	1.5-4.8	<b>3,6%</b>
Matching Eff.	1%	1%	<b>1%</b>
$F_{\text{Norm}}$	0,5%	0,5%	<b>0,5%</b>
$\langle T_{\text{AA}} \rangle$	3,2%	<b>3,2%</b>	3,1-7,6 %
Centrality limits	0%	<b>0,1%</b>	0-6,6 %
$\sigma^{\text{pp}} J/\psi$ (data)	5,0%	3-10% + 2.1%	<b>4,9%</b>

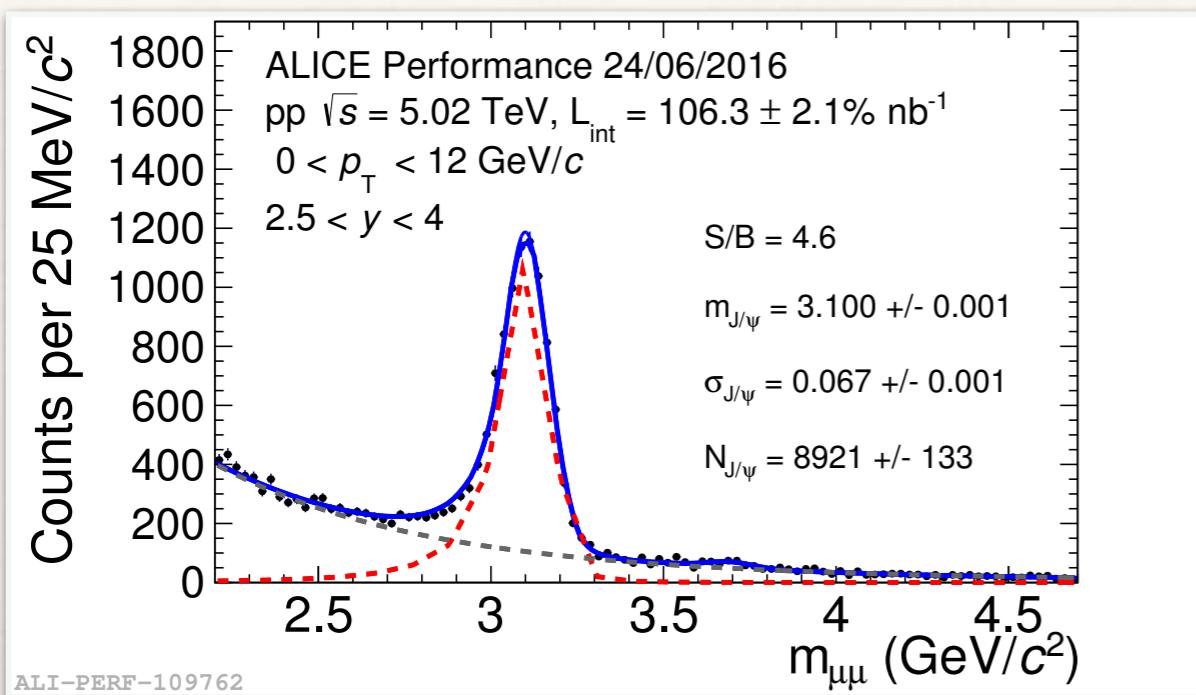
Uncorrelated uncertainties  
**Correlated uncertainties**



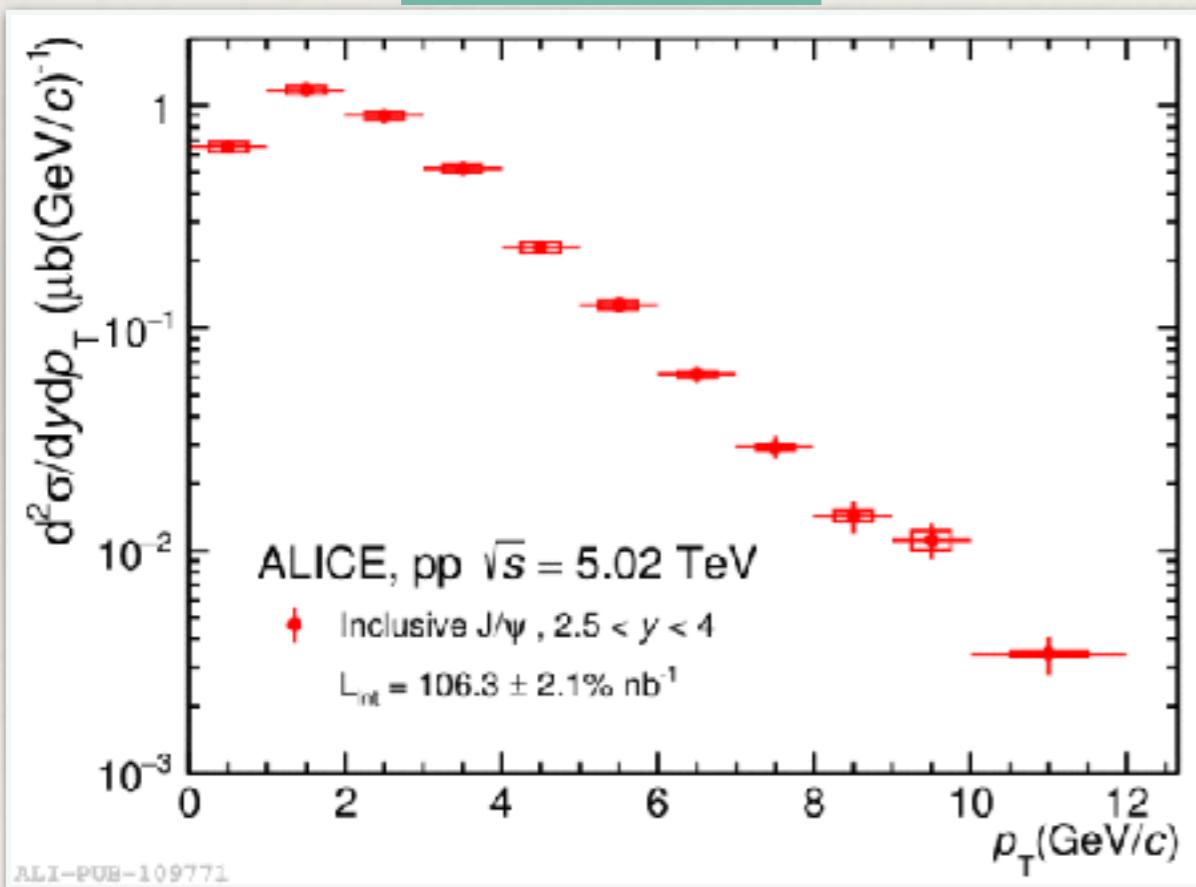
Uncorrelated uncertainties  
Correlated uncertainties



model	$\sigma_{c\bar{c}}$ (mb)	N-N $\sigma_{c\bar{c}}$ ( $\mu$ b)	comover $\sigma_{J/\psi}$	Shadowing
Transport	0.57	3.14	-	EPS09
Transport	0.82	3.5	-	EPS09
Stat.	0.45	-	-	EPS09
Comovers	[0.45,0.7]	3.53	0.65	Glauber-Gribov theory



arXiv:1606.08197



$$R_{AA}^i = \frac{d^2 N_{J/\psi}^{\text{det},i} / dp_T dy}{\langle T_{AA}^i \rangle BR_{J/\psi \rightarrow \text{dimuon}} A \epsilon^i N_{\text{evt}}^{\text{MB},i} d^2 \sigma_{J/\psi}^{\text{pp},i} / dp_T dy}$$

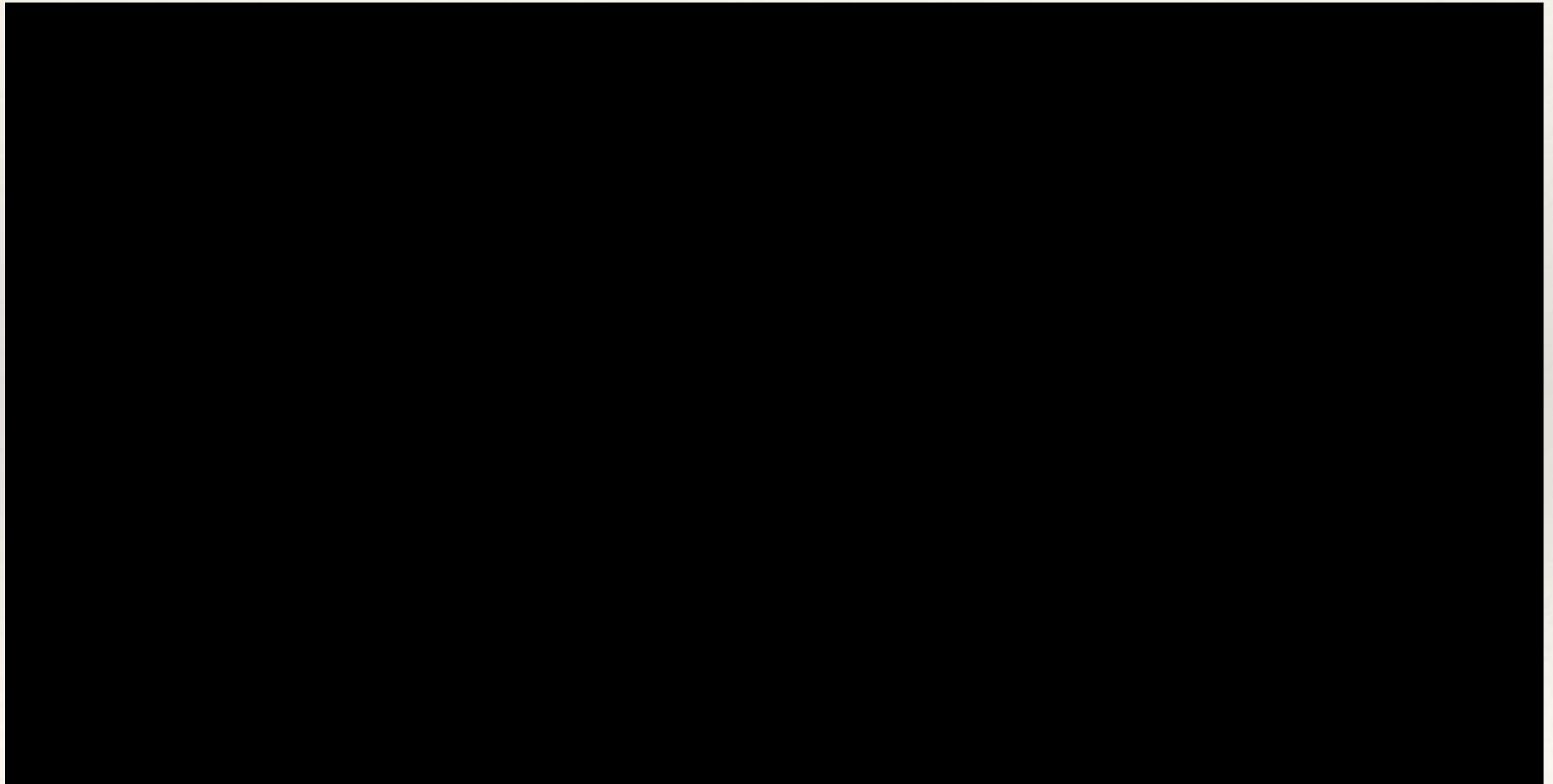
Similar ingredients as for Pb-Pb analysis

$$\frac{d^2 \sigma_{J/\psi}^{\text{pp}}}{dp_T dy} = \frac{d^2 N_{J/\psi}^{\text{det,pp}} / dp_T dy}{BR_{J/\psi \rightarrow \mu^+ \mu^-} A \epsilon} \times \frac{\sigma_{\text{MB}}^{\text{pp}}}{N_{\text{evt}}^{\text{MB}}}$$

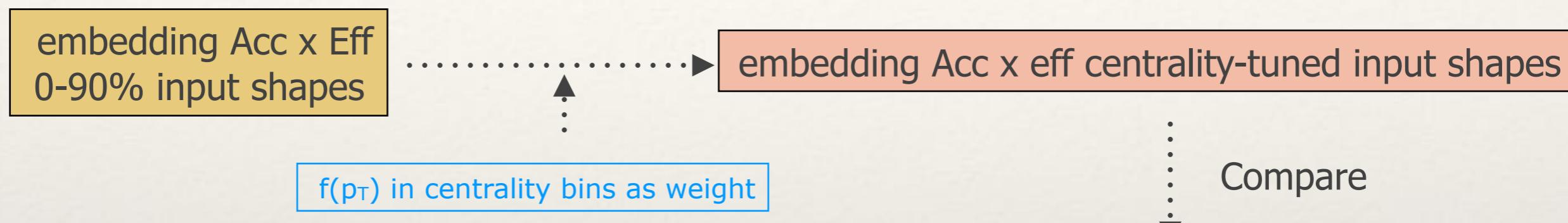
- ❖ Data collected during 4 days at  $\sqrt{s} = 5.02 \text{ TeV}$  for a total of  **$106.3 \pm 0.1(\text{stat.}) \pm 2.1 \text{ (syst.) nb}^{-1}$  integrated luminosity.**
- ❖ For details, see Jana's talk !

Integrated cross section ( $p_T < 12 \text{ GeV}/c$ ) :  
 **$5.61 \pm 0.08 \text{ (stat.)} \pm 0.28 \text{ (syst.) } \mu\text{b}$**

- ❖ Systematic evaluated as the RMS of the distribution of the J/ $\psi$  numbers.

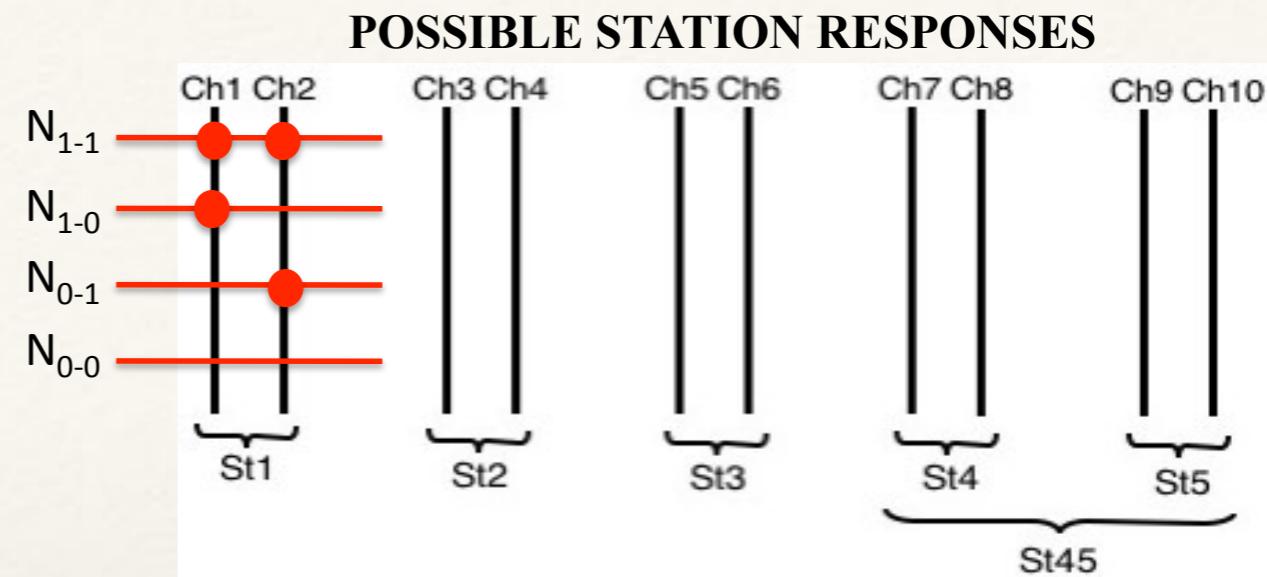


- ❖ Given the high 2015 statistics, a new procedure has been followed in order to compute the MC input shapes systematic uncertainties :



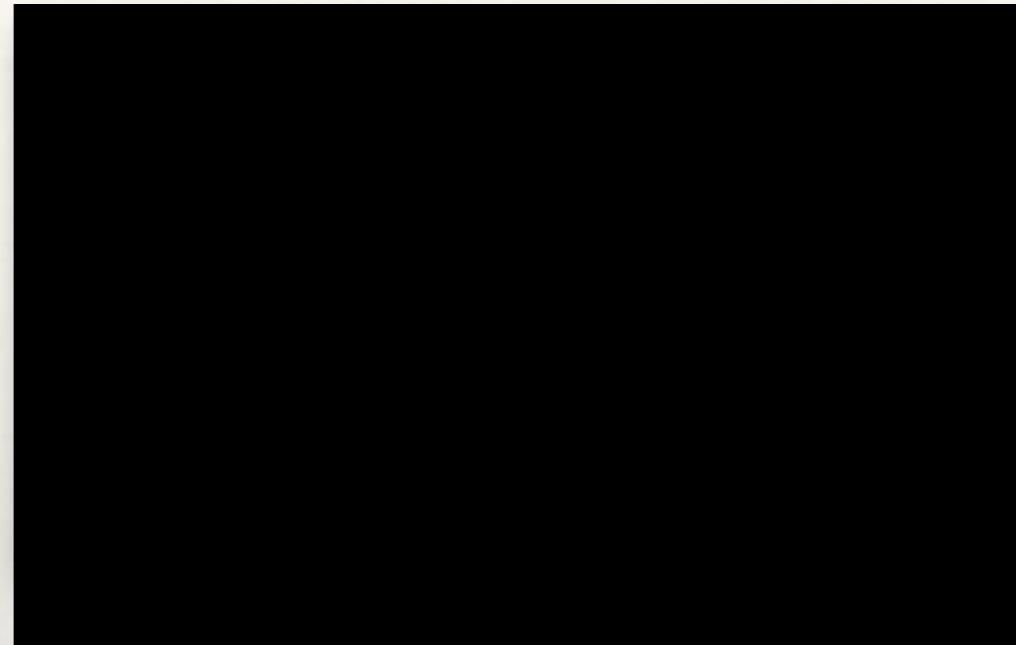
- ❖ Two sources of uncertainties :
  - ❖  $p_T$ - $y$  correlation  $\rightarrow 1.5\%$
  - ❖ data points displacement within the statistical uncertainties  $\rightarrow < 1\%$
- ❖ **Summing in quadrature the two contributions gives the Syst. unc. on MC input shapes at 1.6 %**

- ❖ To evaluated the Tracking Efficiency, we use the reconstructed tracks and the redundancy of the tracking chamber.
- ❖ Syst. uncert. evaluated from the comparison of data and MC.
- ❖ 1.5% at single muon level —> 3% for J/ $\psi$



$$\epsilon_{\text{Global}} = \epsilon_{\text{St1}} \epsilon_{\text{St2}} \epsilon_{\text{St3}} \epsilon_{\text{St45}}$$

- ❖ Two contributions to the trigger efficiency systematic uncertainties :
  - ❖ Difference in the shapes of the trigger response between Data and MC.
    - We compare the dimuons inv. mass spectrum in data and MC with weighted muons based on the Lpt cut.
  - ❖ Uncertainty on the trigger chamber efficiency.
    - We compare those weighted inv. mass spectrum for different sets of simulation with different efficiency.
- ❖ **3% for  $p_T$  and  $y$  integrated case.**
- ❖ **1.5-4.8% ( $\sim$ 2-6%) for  $p_T$  ( $y$ ).**



- ❖ The MC  $\text{J}/\psi$  signal is embed at the level of SDigits in a real data event (CINT7) and reconstruct the merged SDigits → 5 times more  $\text{J}/\psi$  in MC than in data, spread over the full run list.
- ❖  $\text{J}/\psi$  input shapes tuned on the acceptance corrected  $p_{\text{T}}$  and  $y$  distributions in 0-90% centrality (obtained via an iterative procedure).
- ❖ The AccxEff is corrected to take into account that we have kinematic input shapes tuned in each centrality bins.

