Quarkonia measurements by CMS in Pb-Pb collisions

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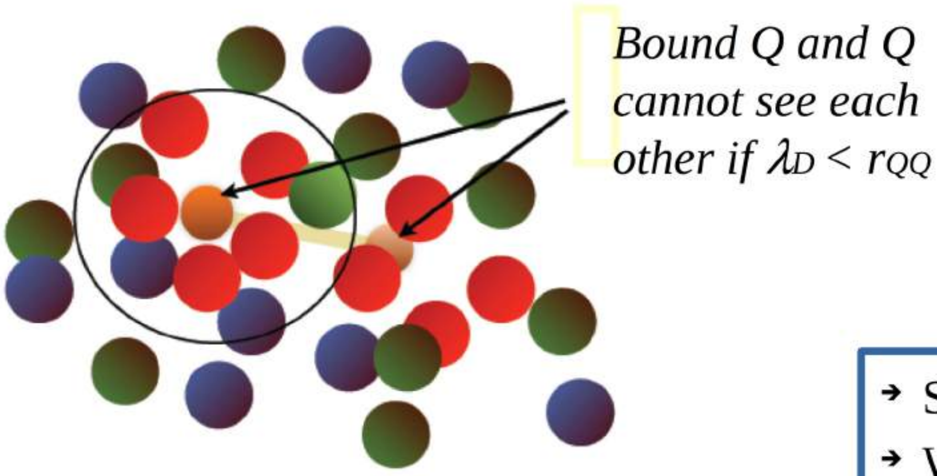
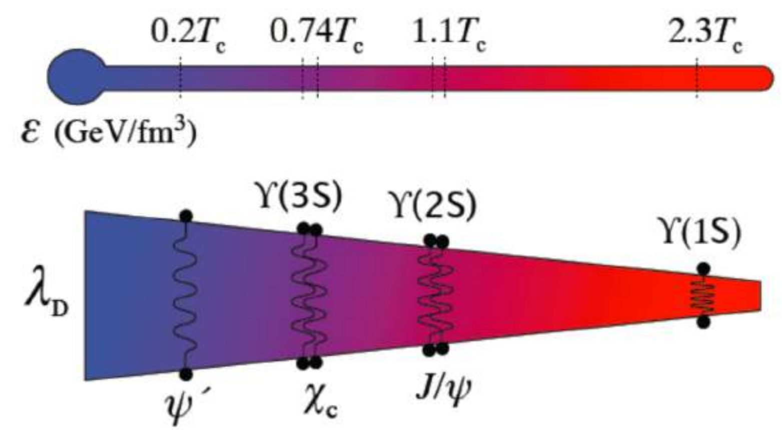
- Quarkonia: Massive states,
  - Produced in the early stages of collisions

Color screening





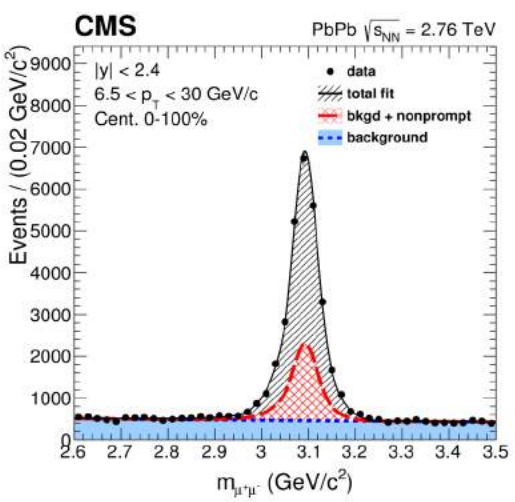
- Screening is different at different temperature T
- Weakly bound states dissociated at lower T
- Sequential melting scenario

- Cold nuclear matter effect: nPDF, shadowing, nuclear absorption, energy loss
- Regeneration of quarkonia: from uncorrelated quarks and anti-quarks produced in bulk.
  - Expected to be small for Υ states as compared to J/ψ.

Quarkonia measurements

1) Charmonia measurements in PbPb at **2.76 TeV**

- ✓ Nuclear modification, v2, ratio of yields, etc



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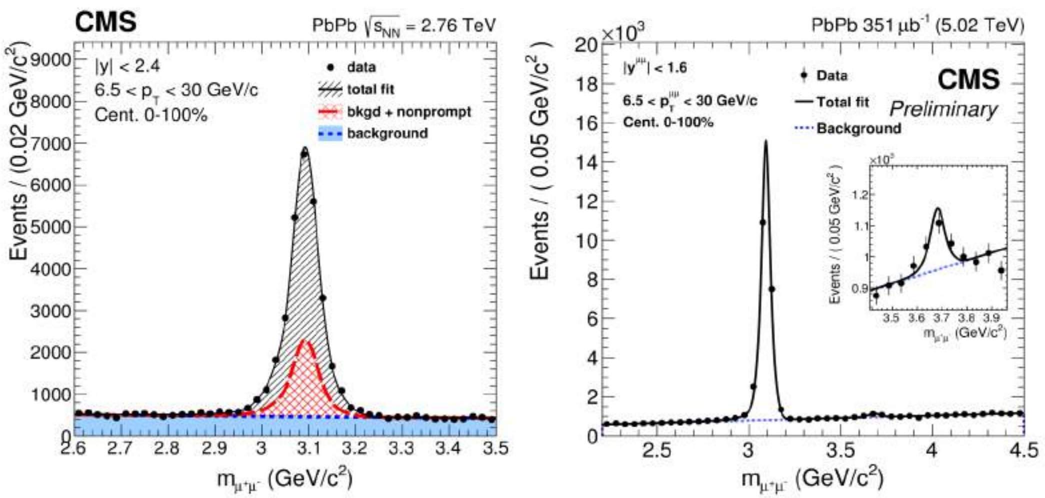
2) Charmonia measurements in PbPb at **5 TeV**

- ✓ Double ratio



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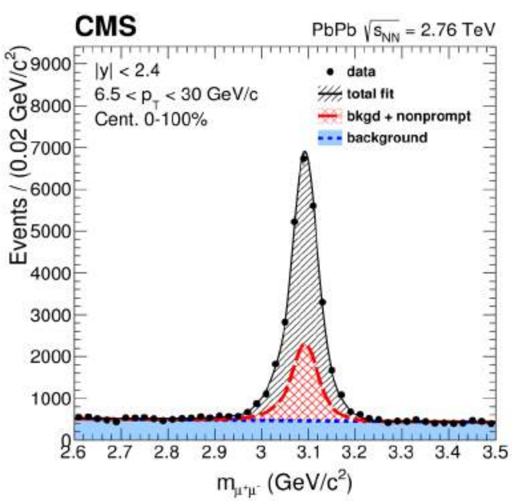

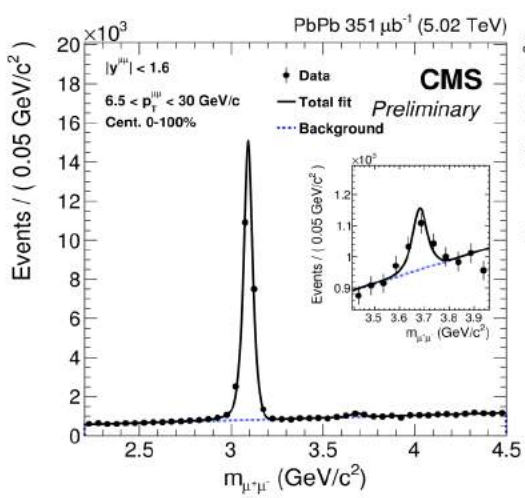

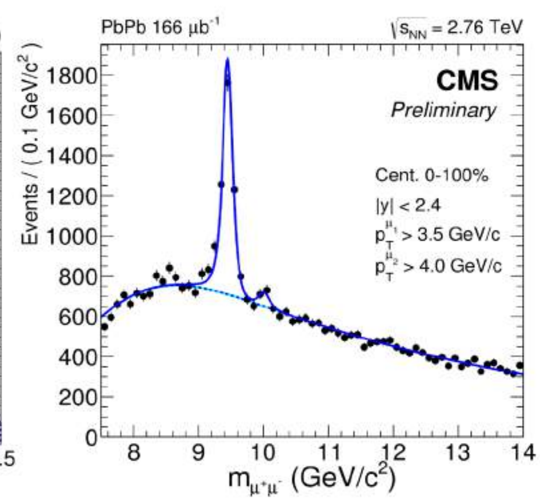

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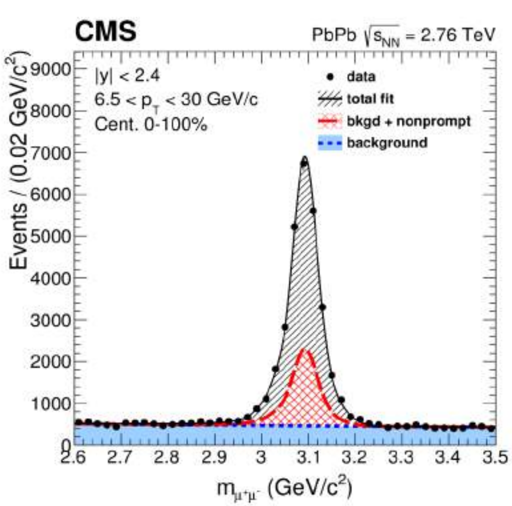

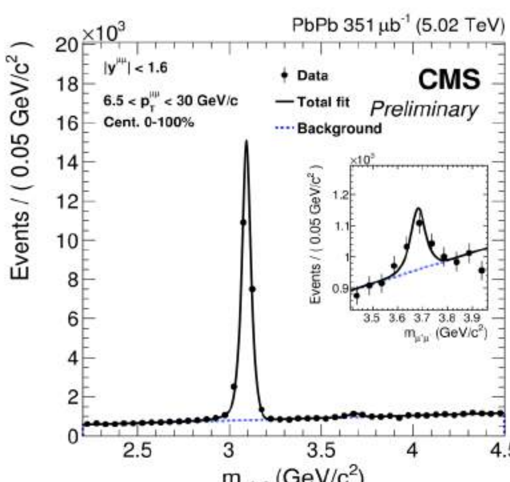

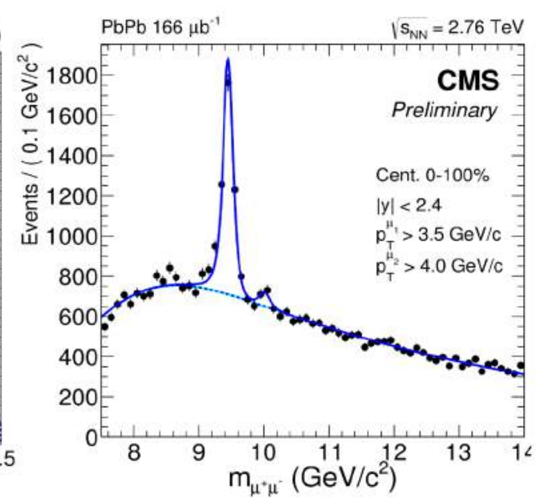

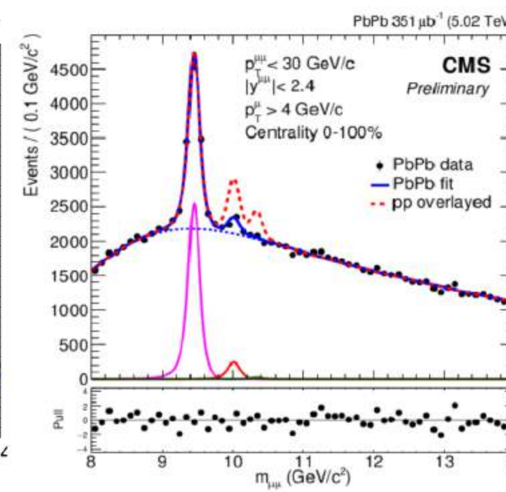

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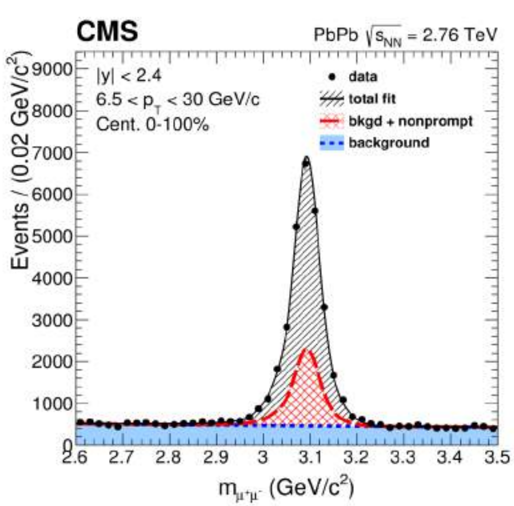
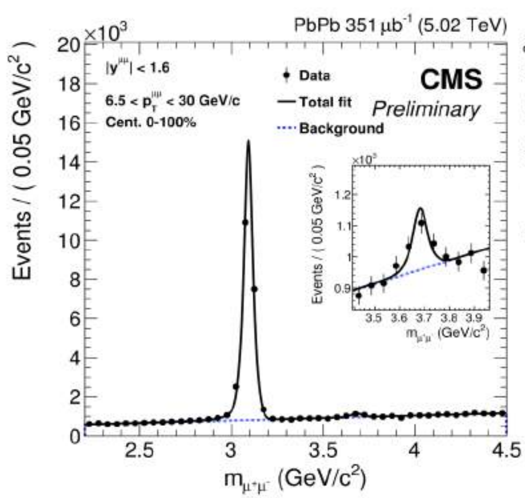
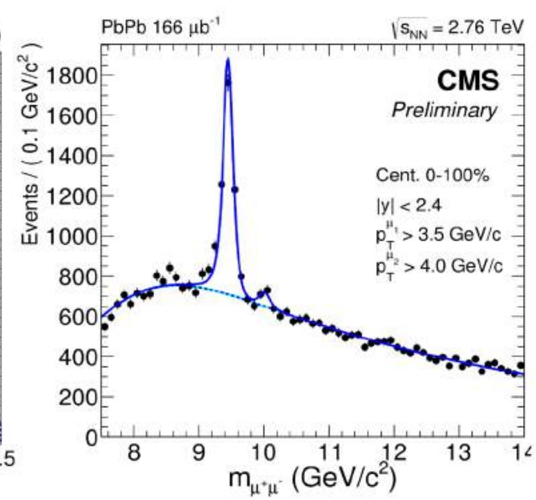
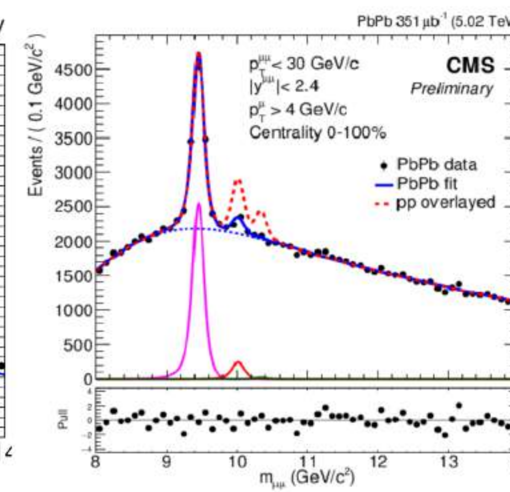
- Want to measure modification of the yields in Heavy-ion collisions
- Want to see the sequential suppression









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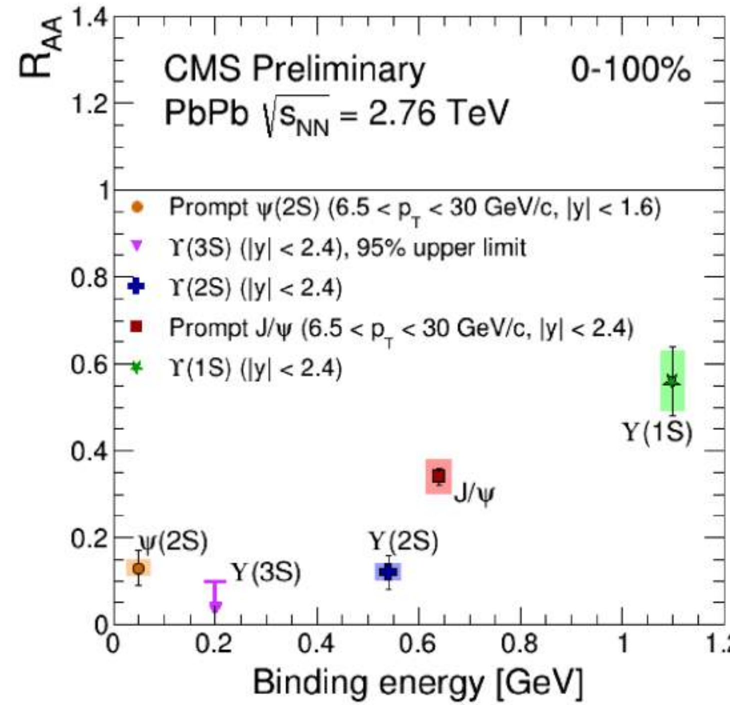
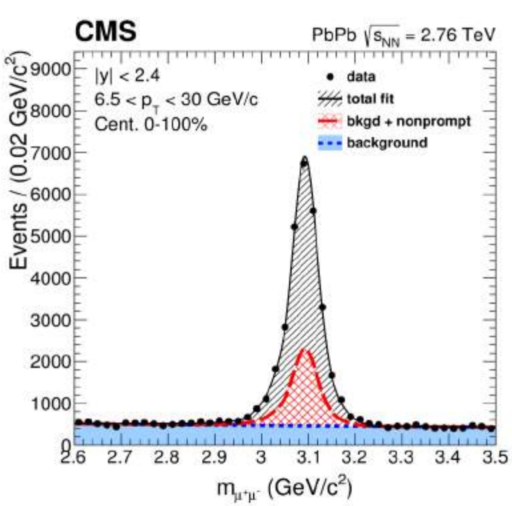
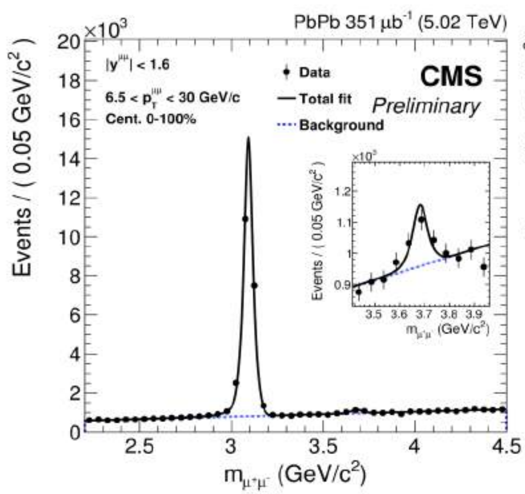
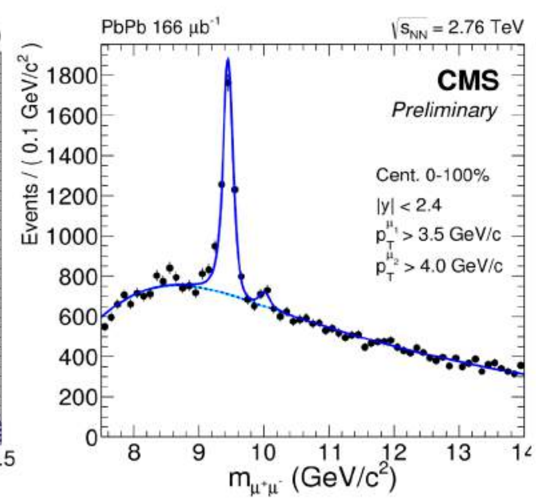
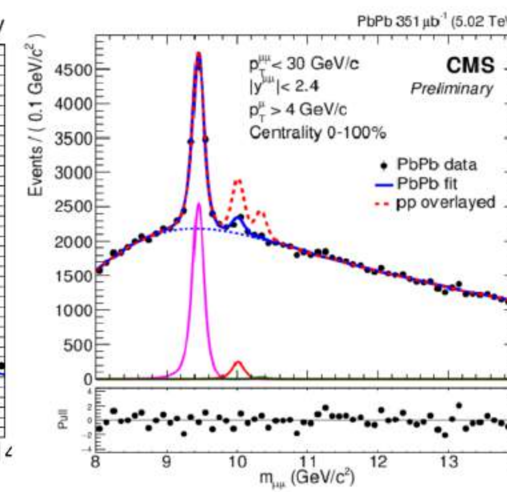










Observables

1) Nuclear modification factor R_{AA}

$$R_{AA} = \frac{\mathcal{L}_{pp}}{T_{AA} N_{MB}} \cdot \frac{N^{\Upsilon}_{PbPb}}{N^{\Upsilon}_{pp}} \cdot \frac{\varepsilon_{pp}}{\varepsilon_{PbPb}}$$

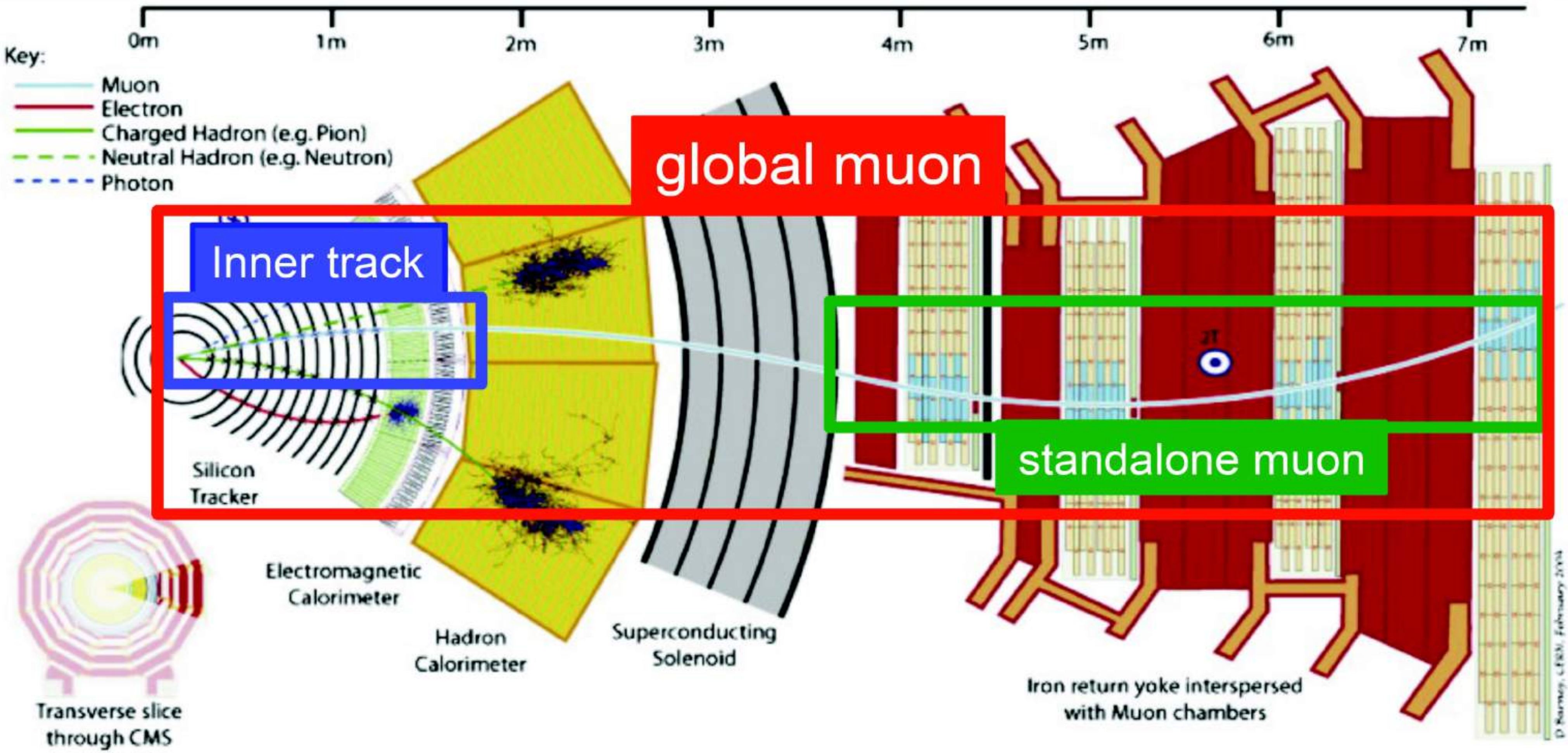
2) Double ratio (DR)

$$DR = \frac{\left[\frac{\left[\chi(nS)\right]}{\left[\chi(1S)\right]}\right]_{PbPb}}{\left[\frac{\left[\chi(nS)\right]}{\left[\chi(1S)\right]}\right]_{pp}} = \frac{R_{AA}\left[\chi(nS)\right]}{R_{AA}\left[\chi(1S)\right]}$$

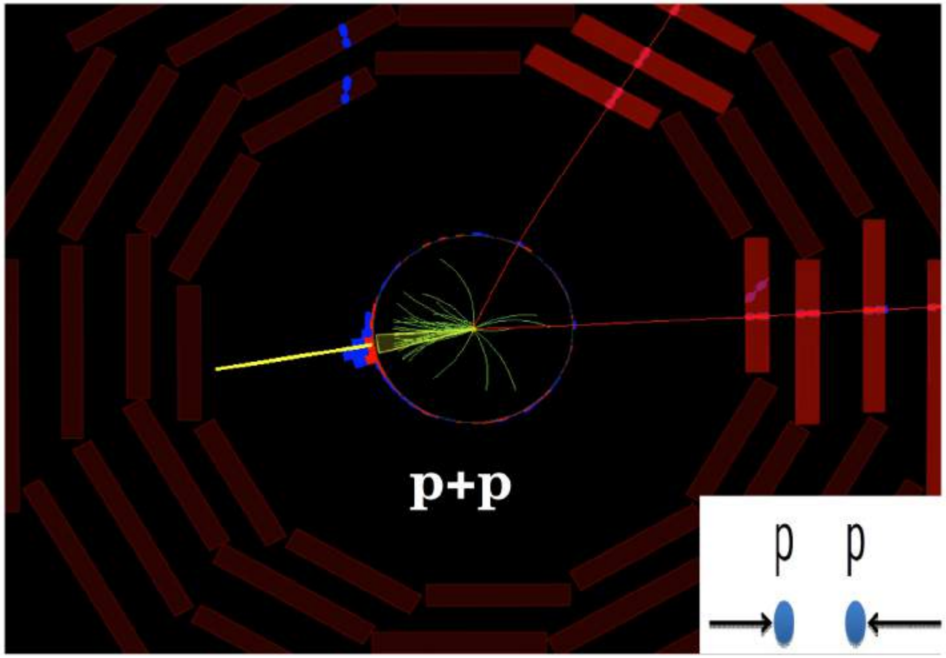
$X = \psi, \Upsilon$

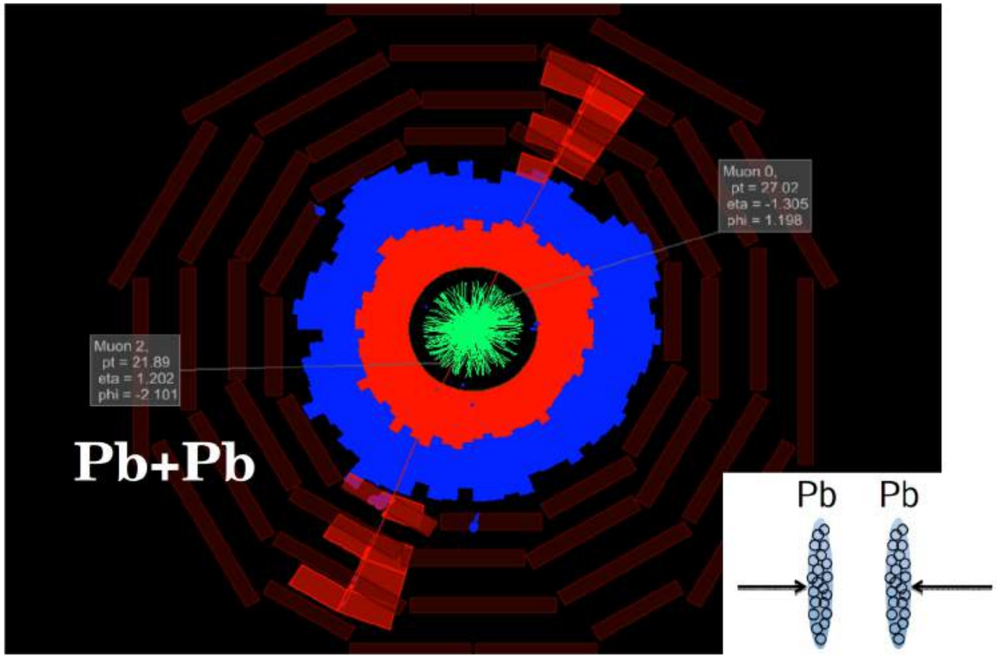
3) Elliptic flow, v2

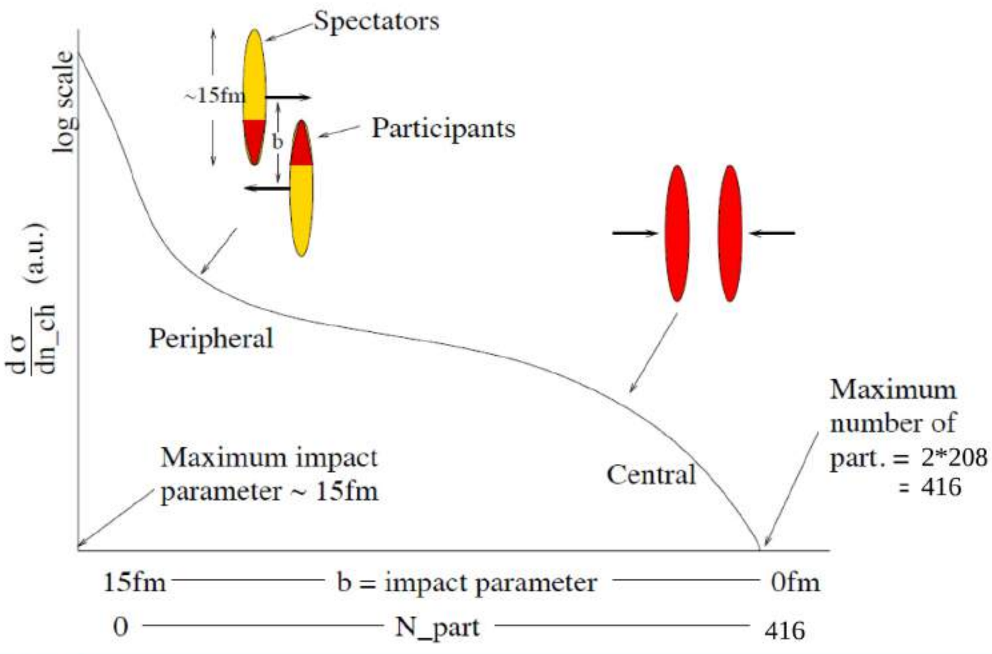
$$dN/d\Phi \propto 1 + 2v_2 \cos[2(\Phi - \Psi_{PP})]$$

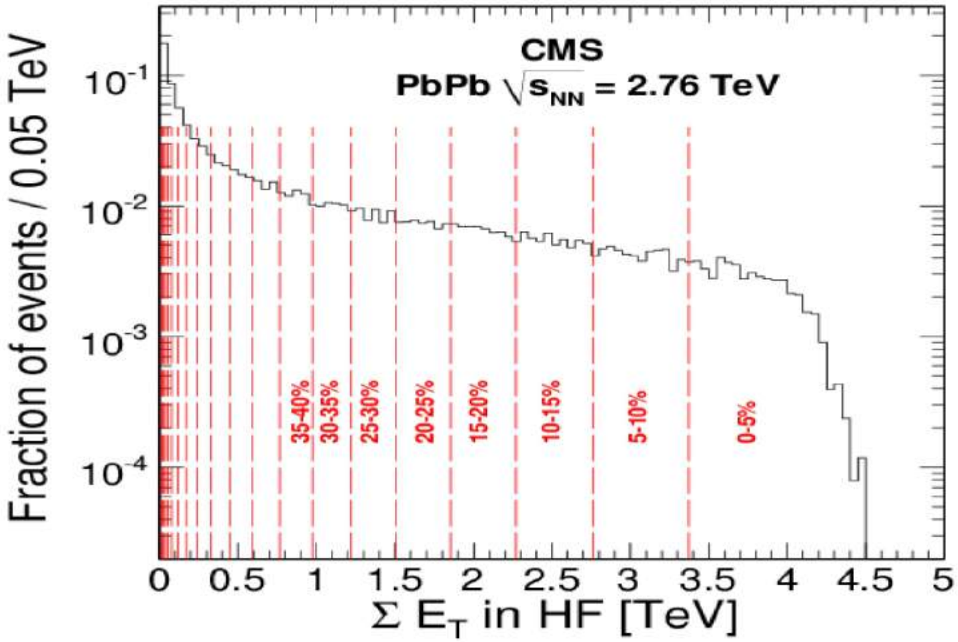


- Global Muons reconstructed with information from inner tracker and muon stations.
- StandAloneMuons in Muon chambers only.


p+p
p p


Muon 0,
pt = 27.02
eta = -1.305
phi = 1.198
Muon 2,
pt = 21.89
eta = 1.202
phi = -2.101
Pb+Pb
Pb Pb


Spectators
~15fm
b
Participants
log scale
$\frac{d\sigma}{dn\_ch}$ (a.u.)
Peripheral
Central
Maximum impact parameter ~ 15fm
Maximum number of part. = 2*208 = 416
15fm b = impact parameter 0fm
0 N_part 416


CMS
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
Fraction of events / 0.05 TeV
10^{-1}
10^{-2}
10^{-3}
10^{-4}
35-40%
30-35%
25-30%
20-25%
15-20%
10-15%
5-10%
0-5%
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5
ΣE_T in HF [TeV]

J/ψ measurement with 2011 *Pb+Pb* at 2.76 TeV (p+p 2013)

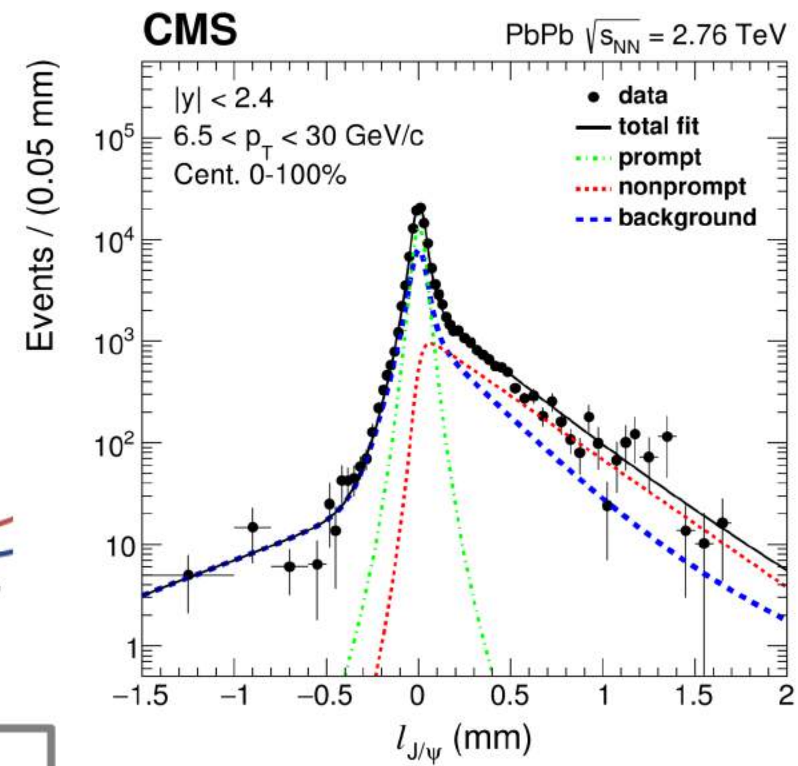
Detailed Measurement of charmonia, **arXiv:1610.00613**

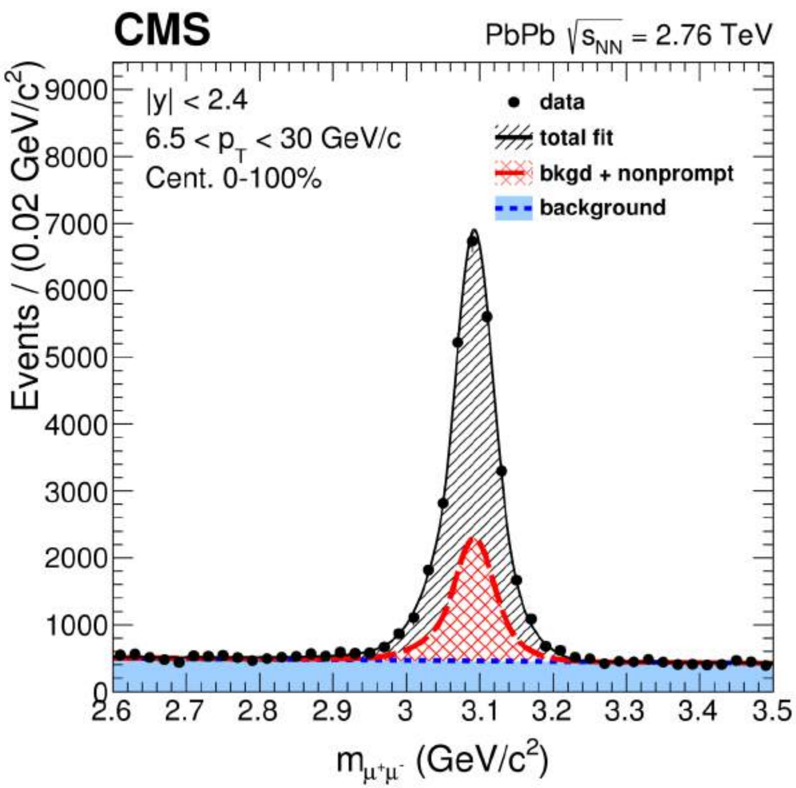
Signal extraction

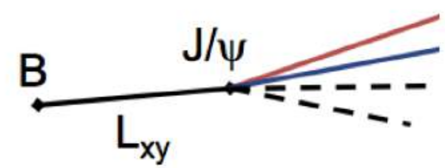
arXiv:1610.00613

Inclusive J/ψ

- Prompt J/ψ
  - Direct J/ψ
  - Feed-down: ψ(2S), χ_c
- Non-Prompt J/ψ from B-decays





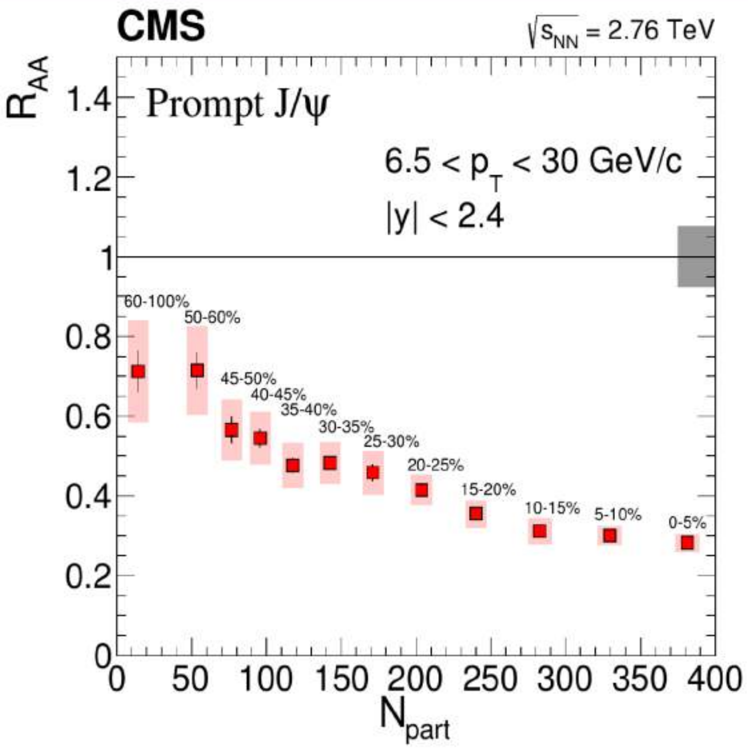


$$\ell_{J/\psi} = L_{xy}\frac{m_{J/\psi}}{p_T}$$

- 2D fit of dimuon mass and pseudo-proper decay length

J/ψ in PbPb at 2.76TeV: R_{AA} vs N_{part}, |y|, pT

arXiv:1610.00613



- Strong centrality dependence (stronger suppression in central events)
  - → R_{AA} < 1 in the most peripheral bin (60-100%)
- No significant rapidity or pT dependence

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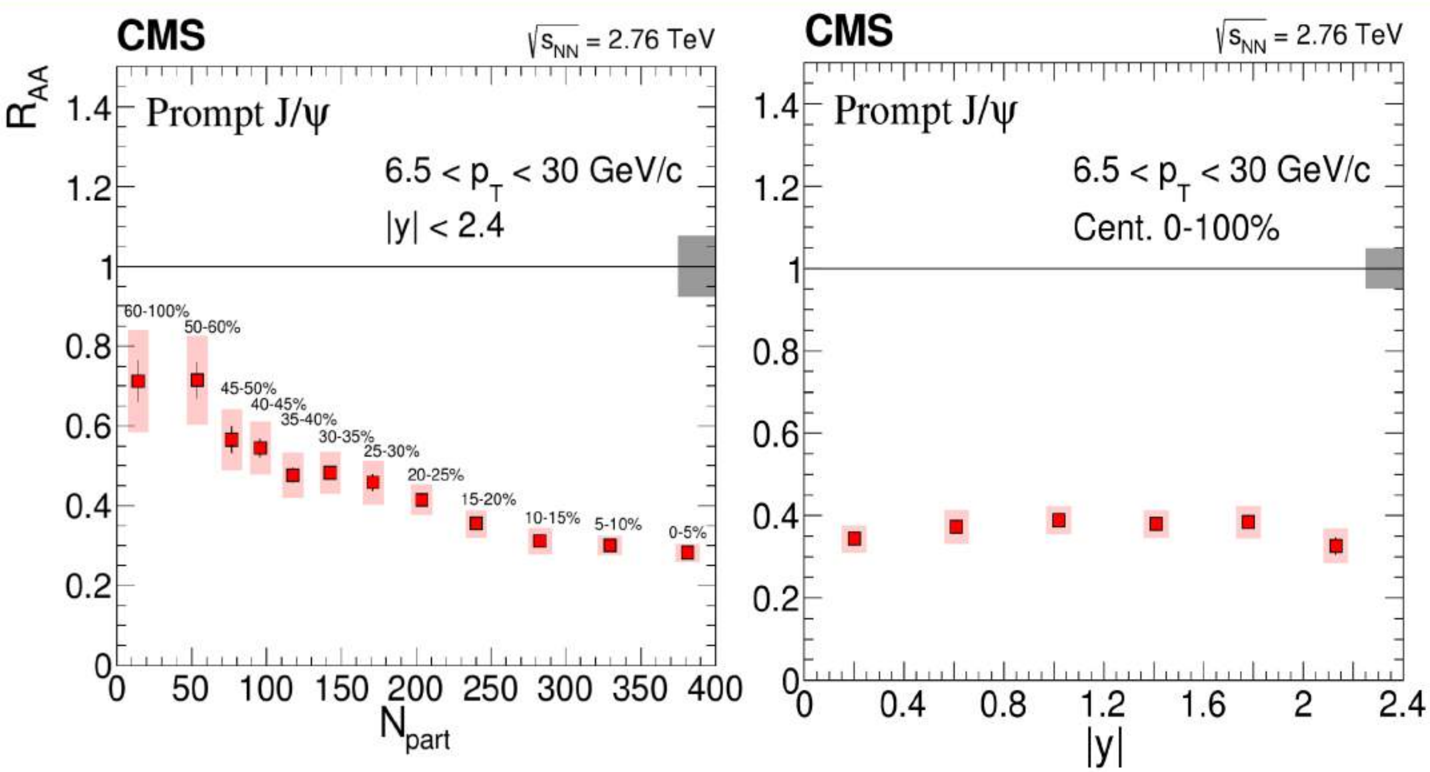

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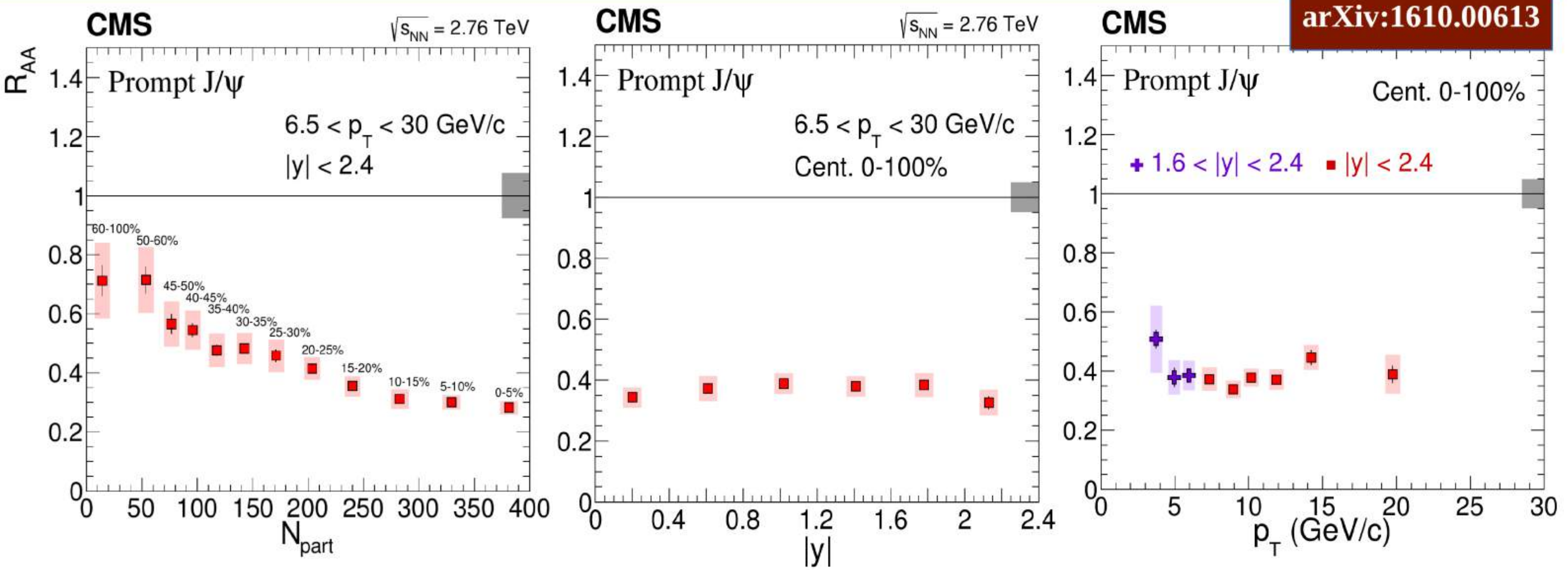

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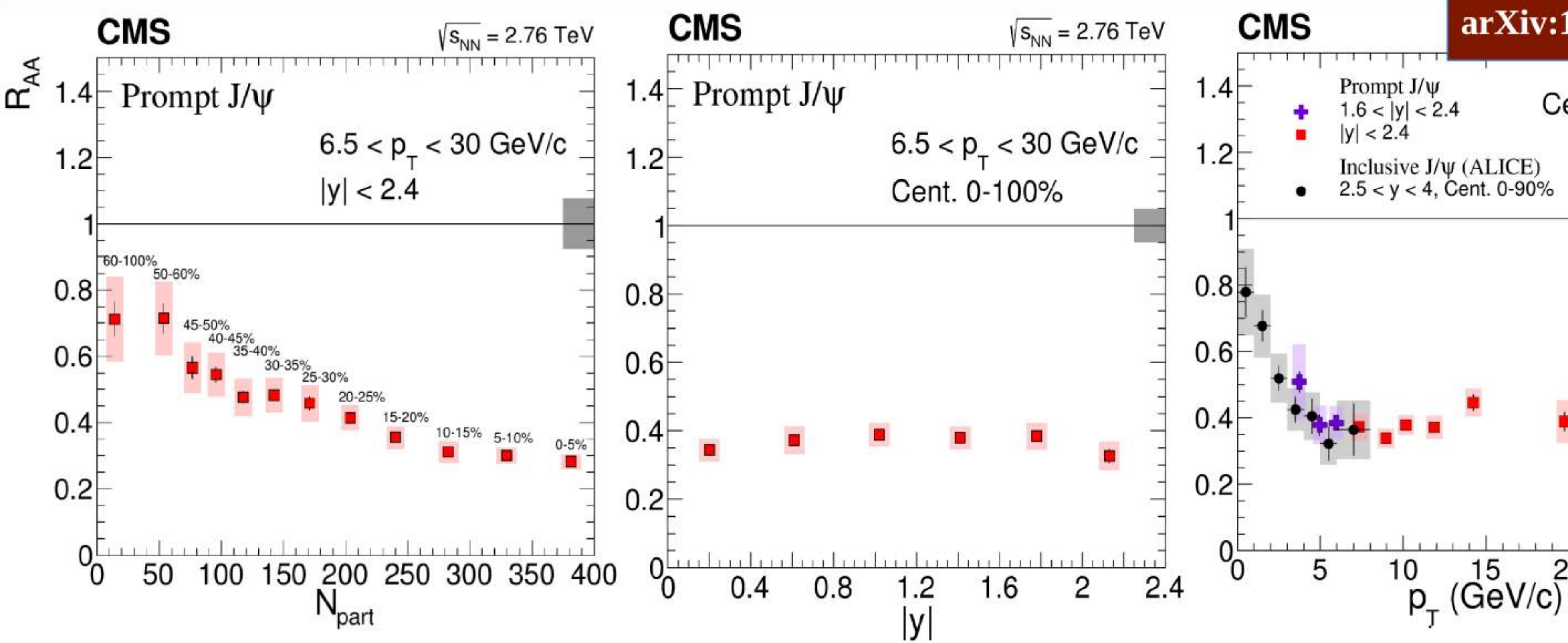

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J/ψ in PbPb at 2.76TeV: v_2

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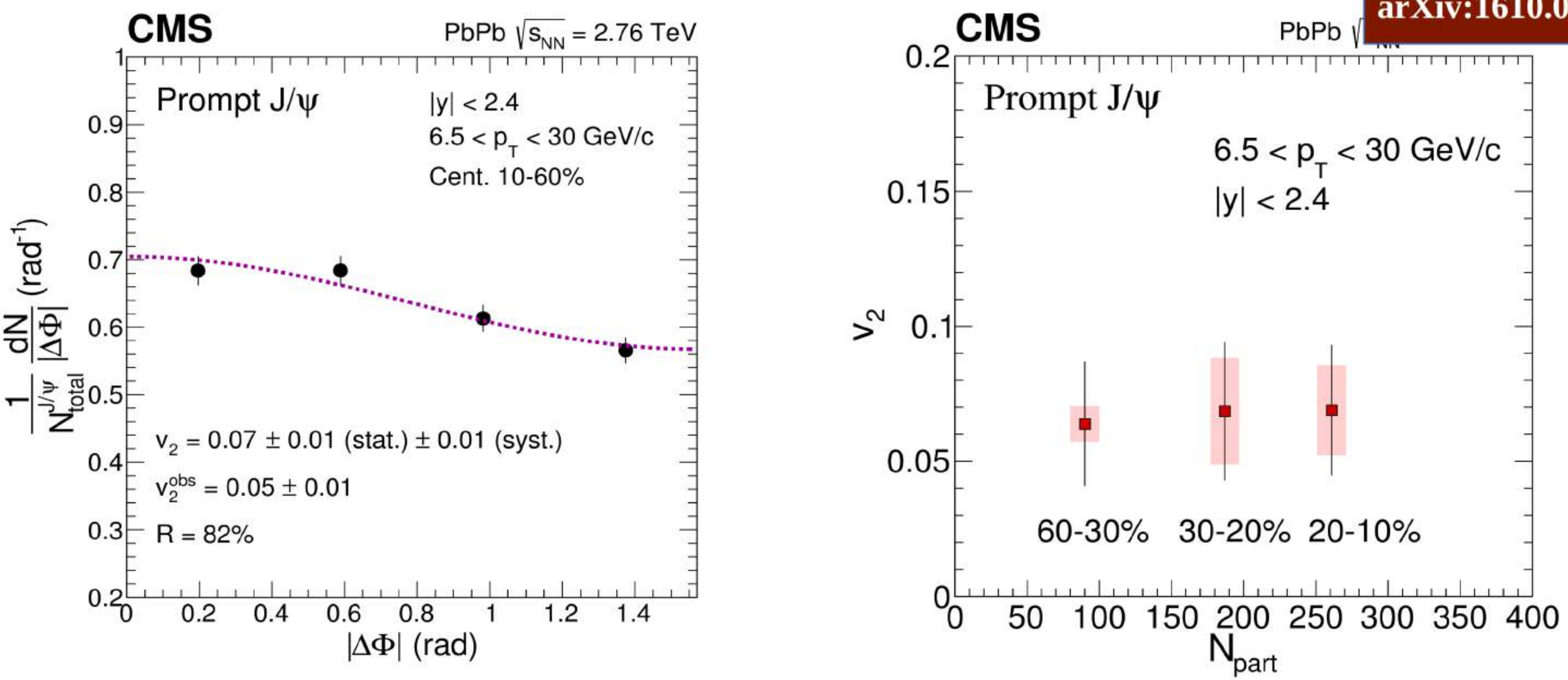

- |y| < 2.4, 6.5 < pT < 30 GeV/c, 10-60% centrality:
  - → V_2 = 0.066 ± 0.014(stat) ± 0.014(syst) ± 0.002(global)
- Significant non-zero v_2
- Charm quark in the collective expansion of the medium ?

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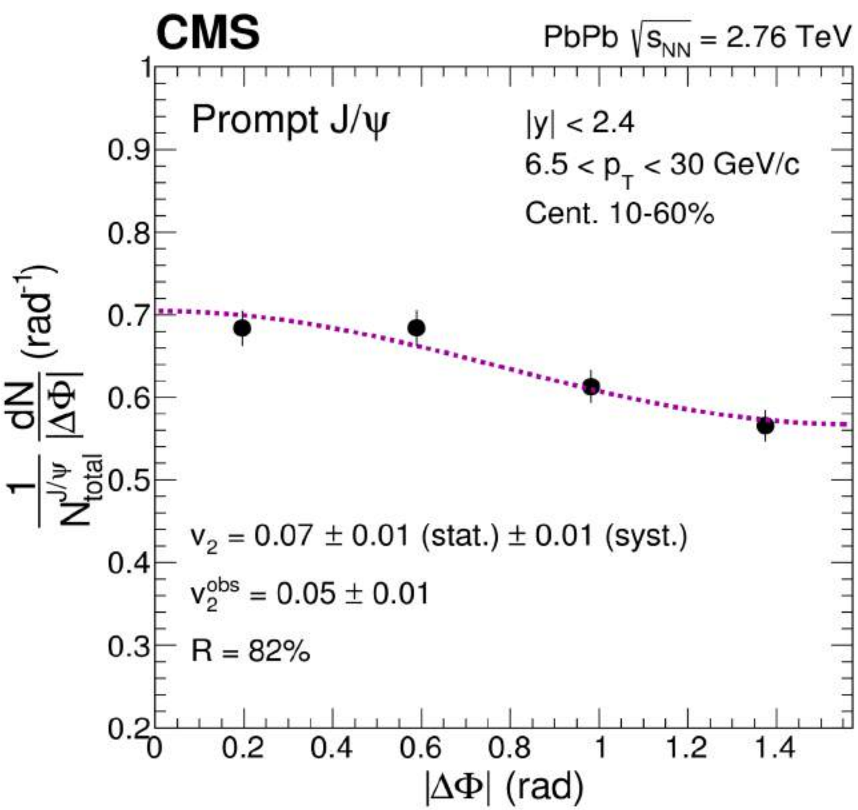

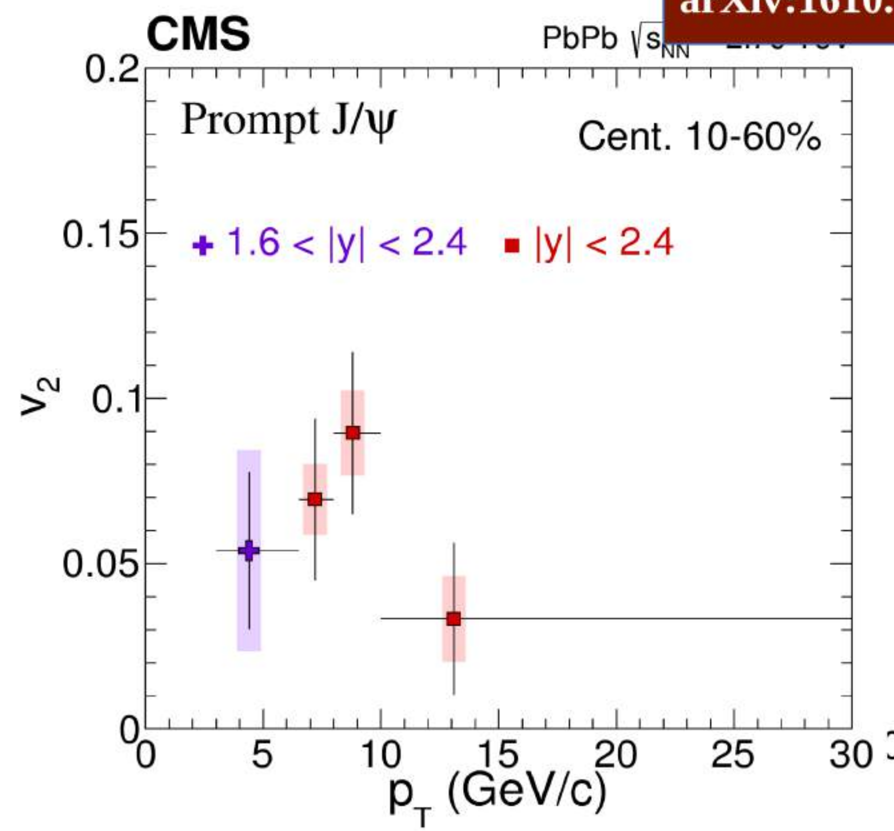

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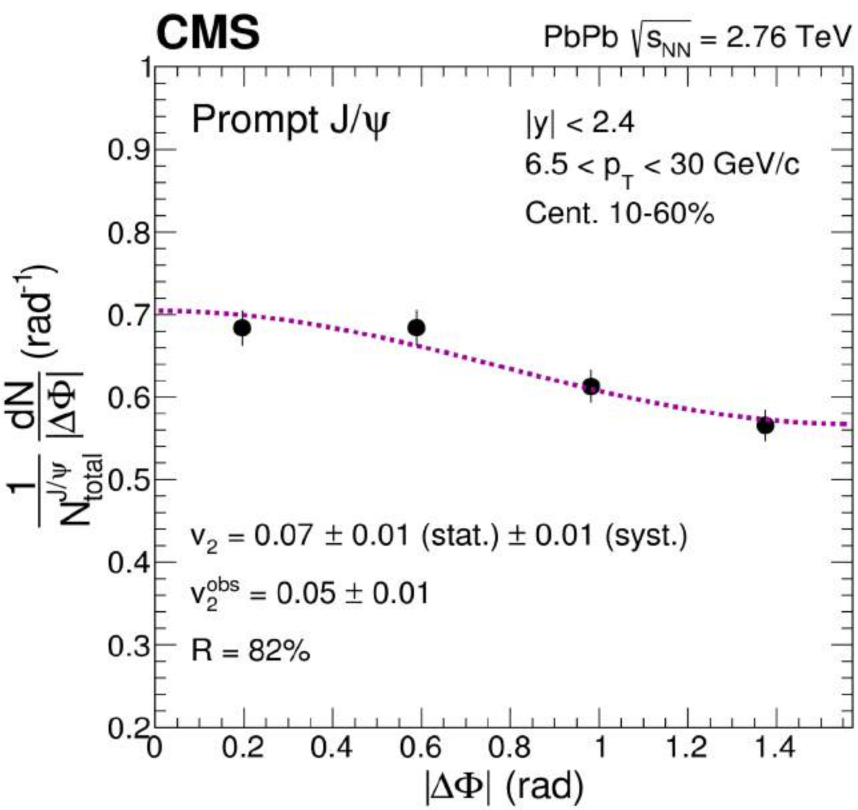

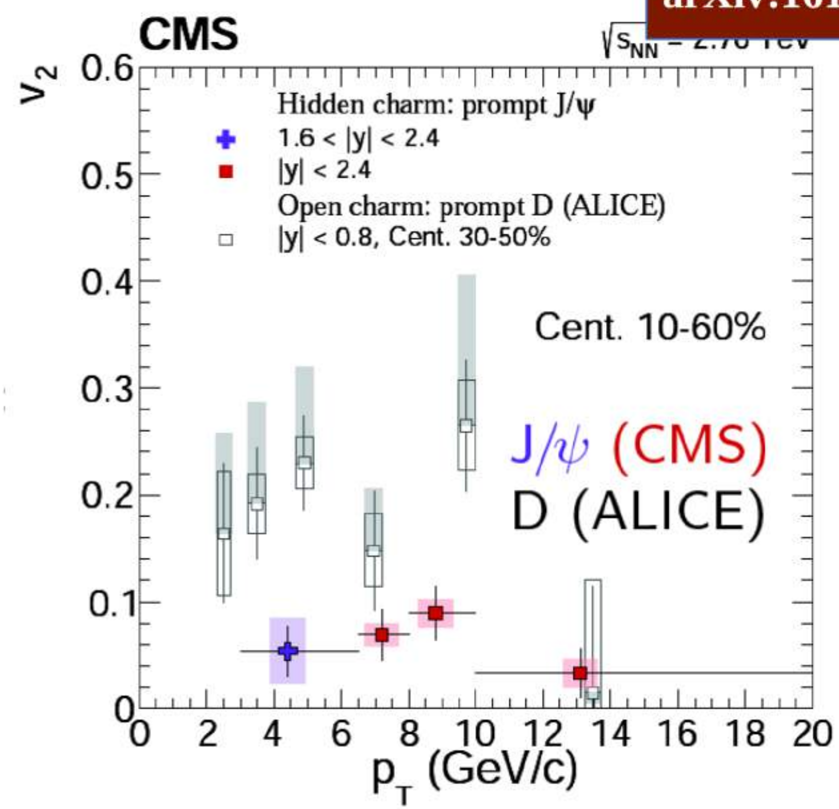

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ψ(2S)/ψ(1S) measurement with 2015 *Pb+Pb* at 5.02 TeV

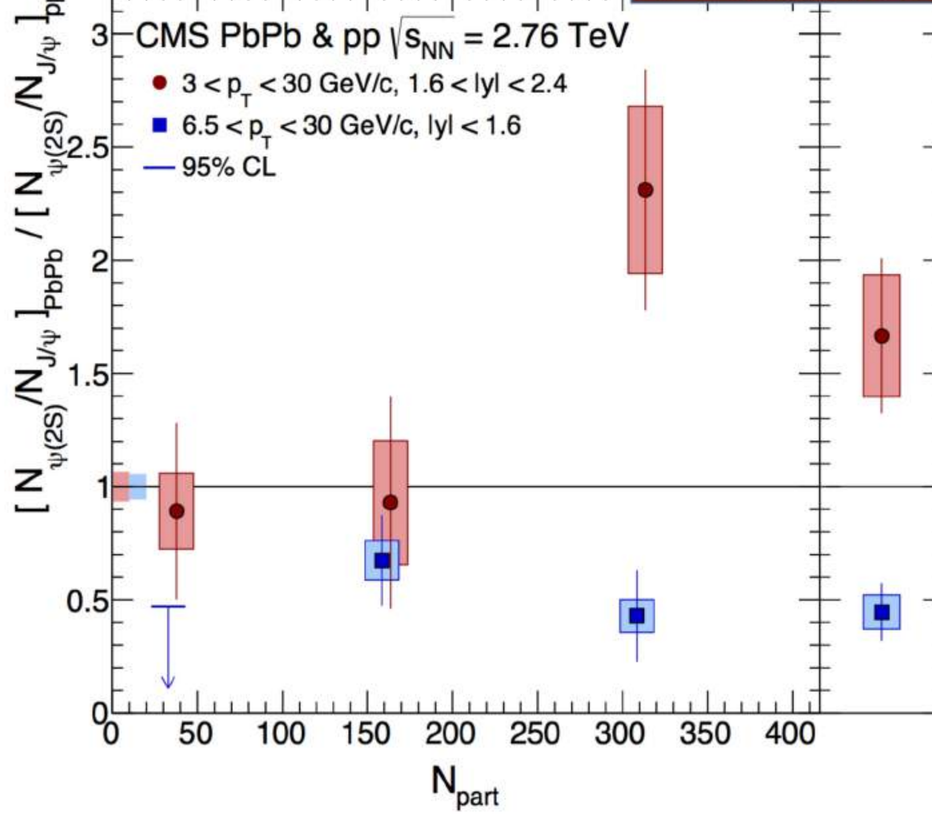
ψ(2S)/ψ(1S) Double ratio in PbPb at 2.76TeV

- Double ratio in PbPb at 2.76 TeV

$$\frac{\frac{[\psi(2S)]}{[\psi(1S)]}_{PbPb}}{\frac{[\psi(2S)]}{[\psi(1S)]}_{pp}} = \frac{R_{AA}[\psi(2S)]}{R_{AA}[\psi(1S)]}$$

- Many theoretical and experimental quantities uncertainties cancel in this ratio

PRL113, 262301



PRL113, 262301

- Double ratio in PbPb at 2.76 TeV

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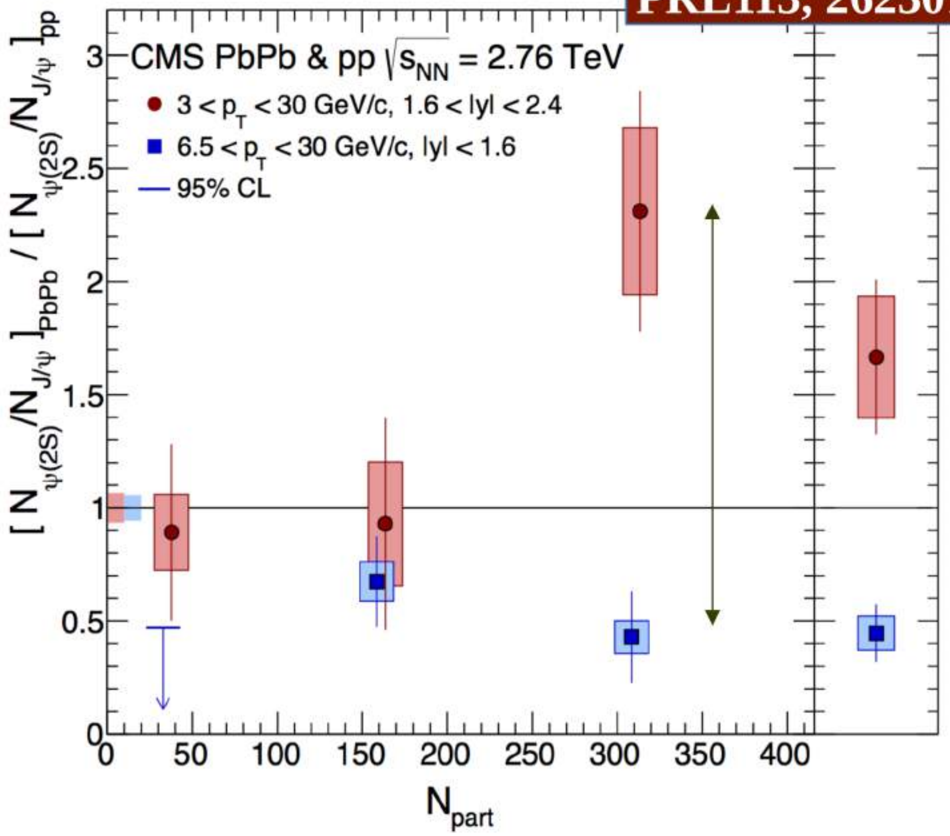
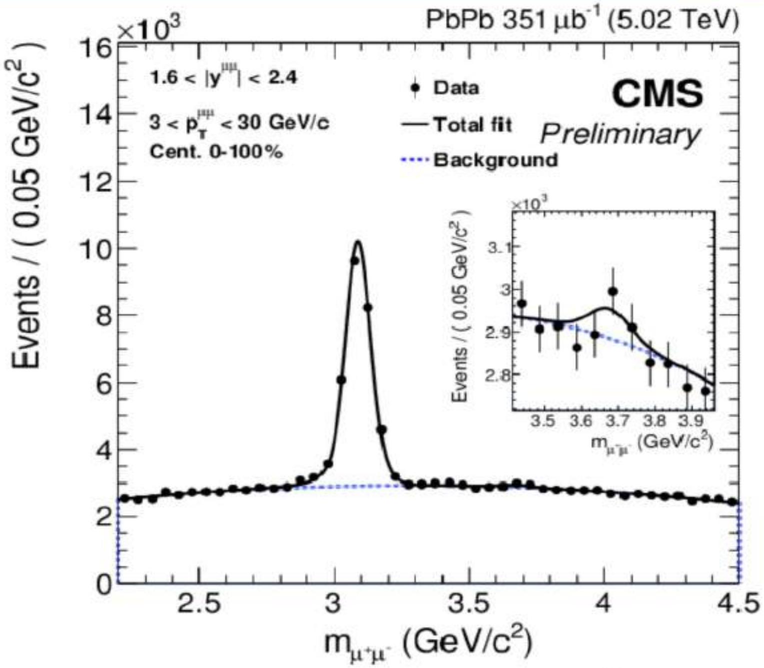
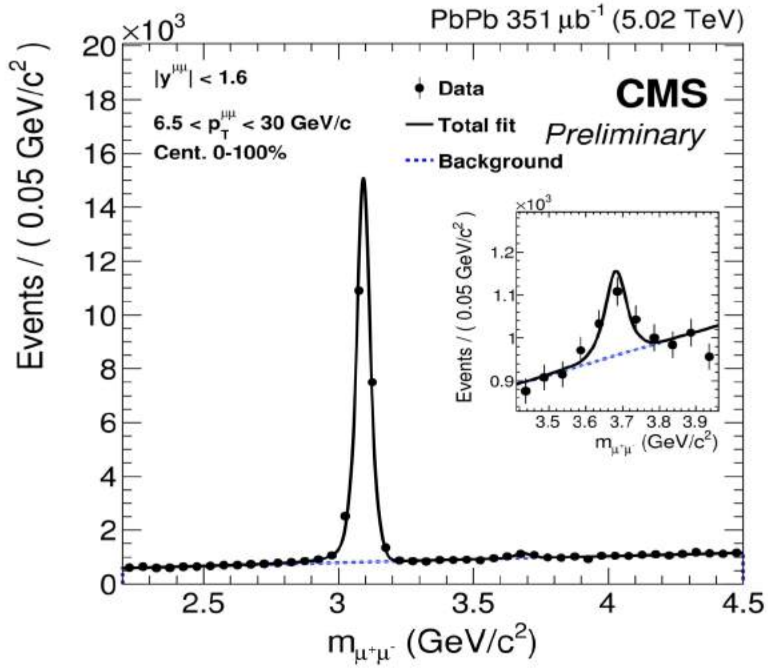


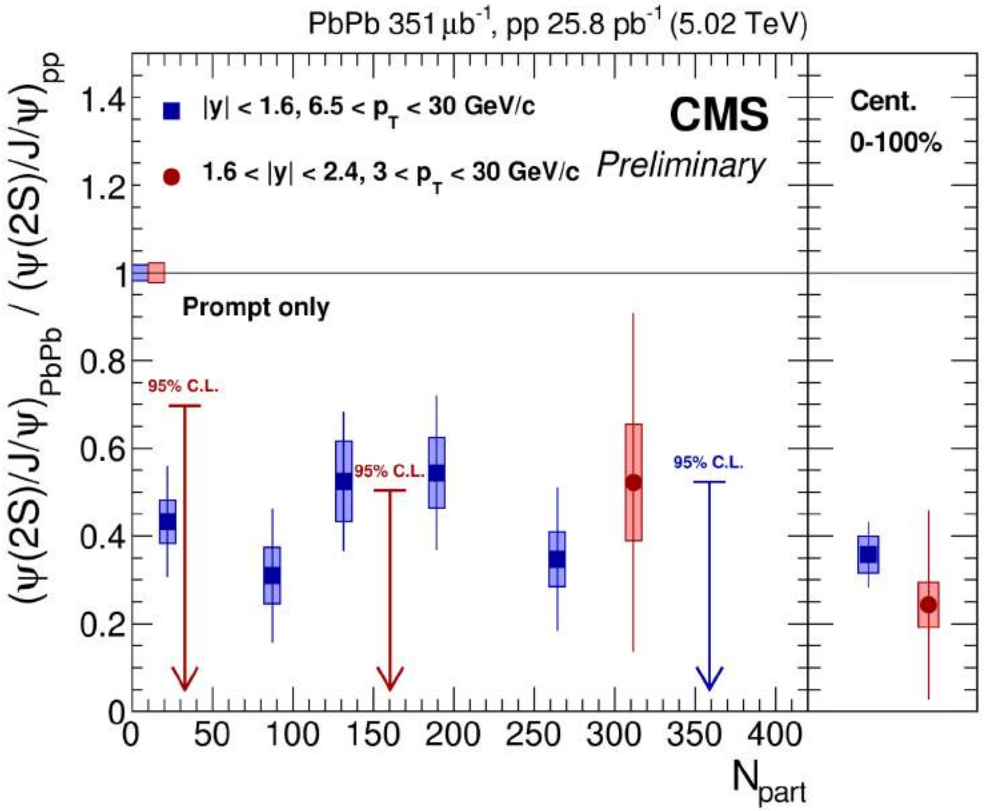
- In PbPb at 2.76 TeV, an interesting and surprising observation
  - ➔ ψ(2S) is suppressed in the range |y|< 1.6 and 6.5 < pT < 30 GeV (=> sequential melting)
  - ➔ While it is enhanced in the range 1.6 < |y|< 2.4 and 3.0 < pT < 30 GeV.
  - ➔ Need to investigate kinematic pT and rapidity dependence

- ✓ At higher energy 5.02 TeV
- ✓ With larger pp samples
- ✓ With larger PbPb samples (2.3x)
- ✓ Non-prompt contamination removed





arXiv:1611.01438



- Centrality binning:
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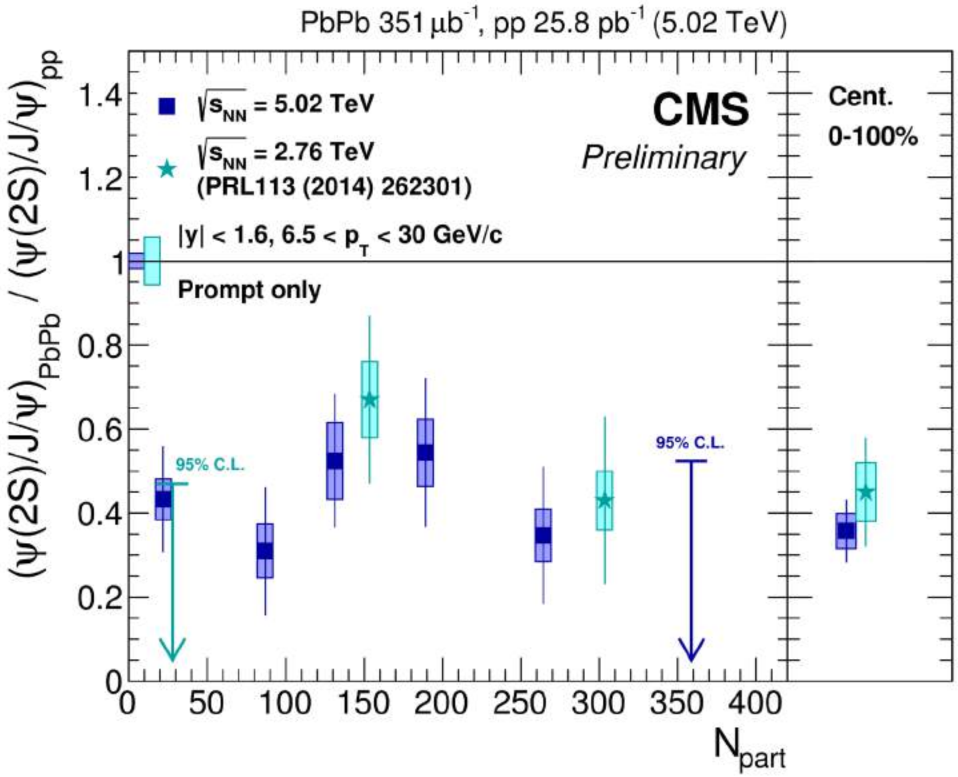

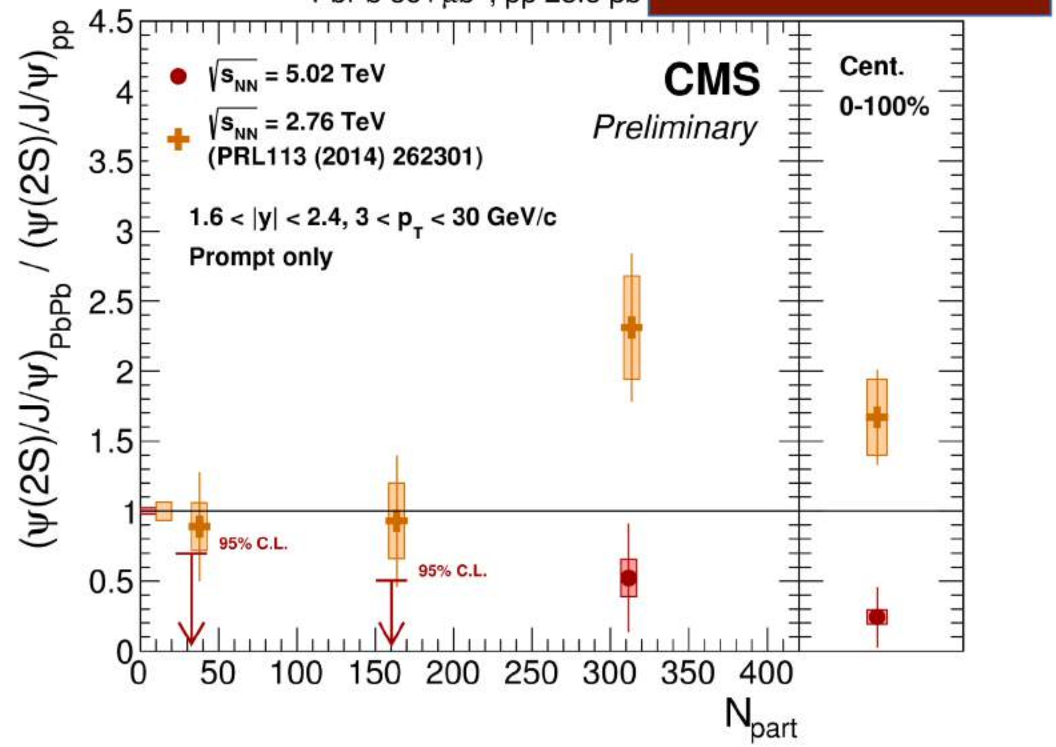

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ψ(2S)/ψ(1S) DR at 5.02 TeV: Centrality

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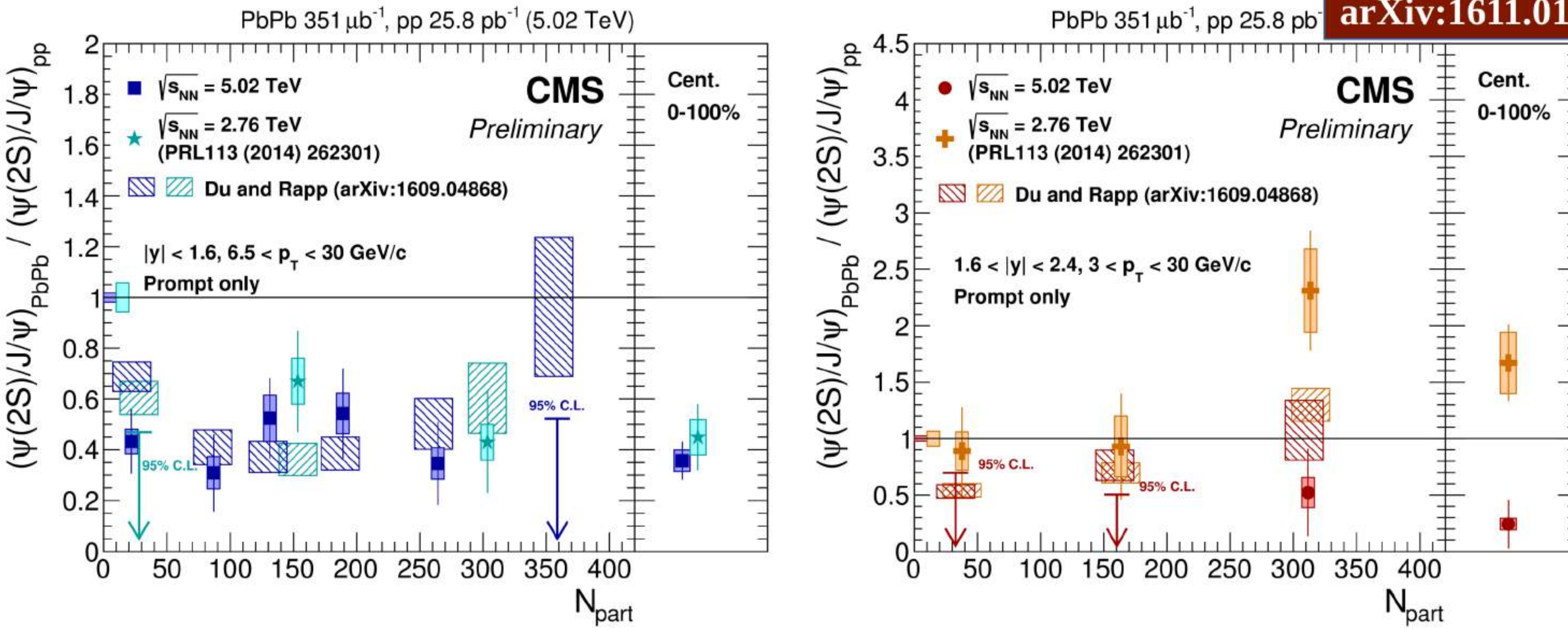

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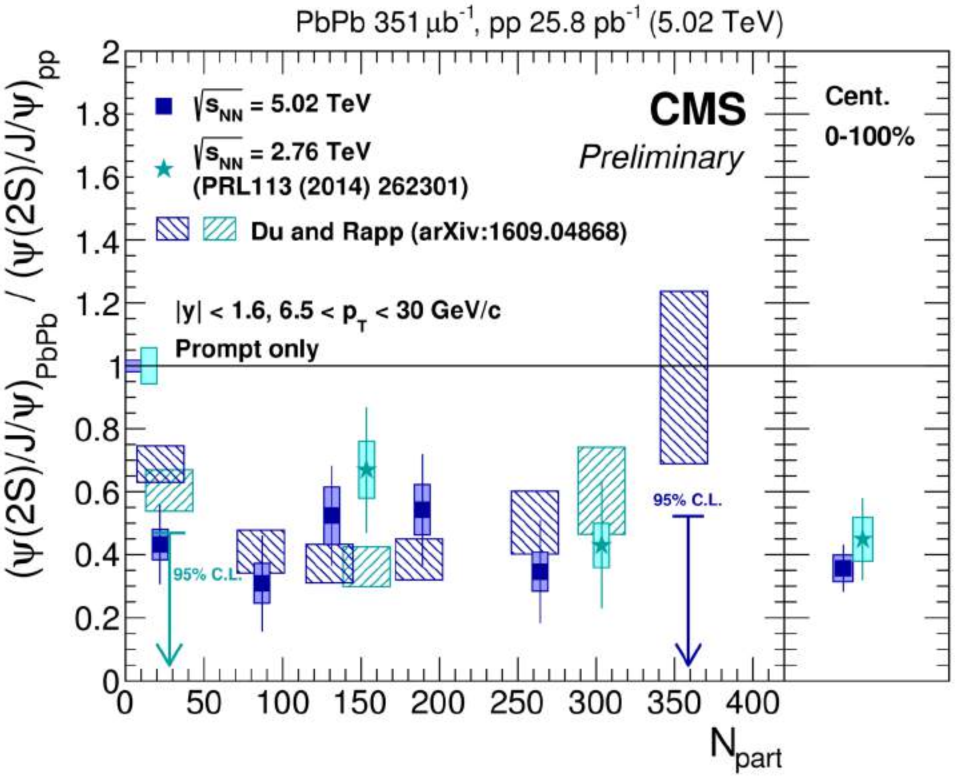
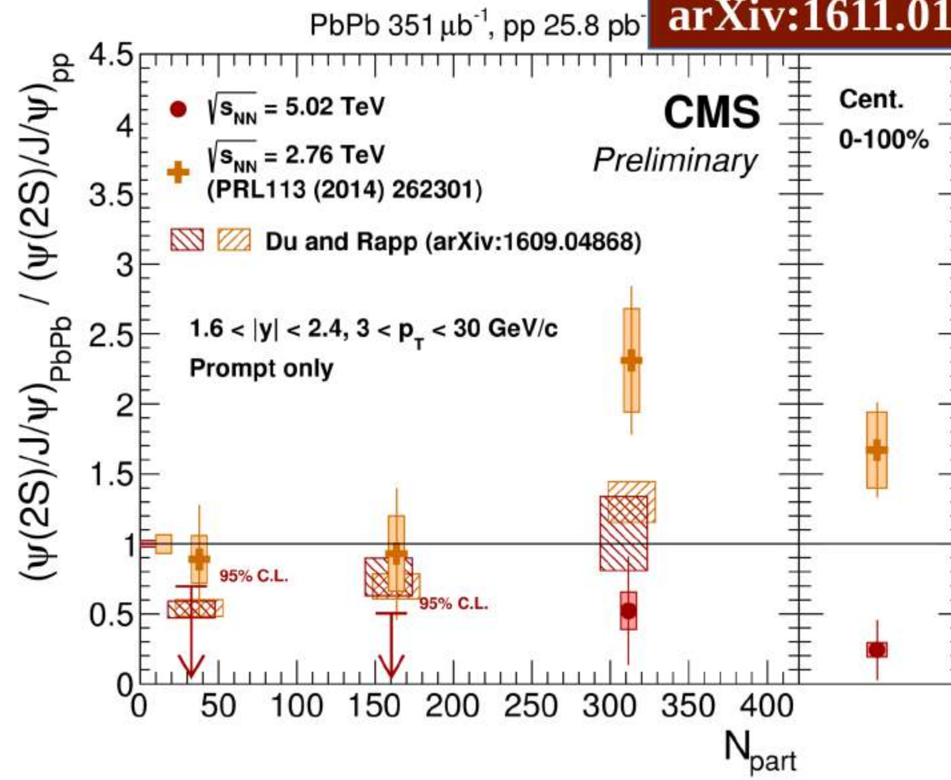
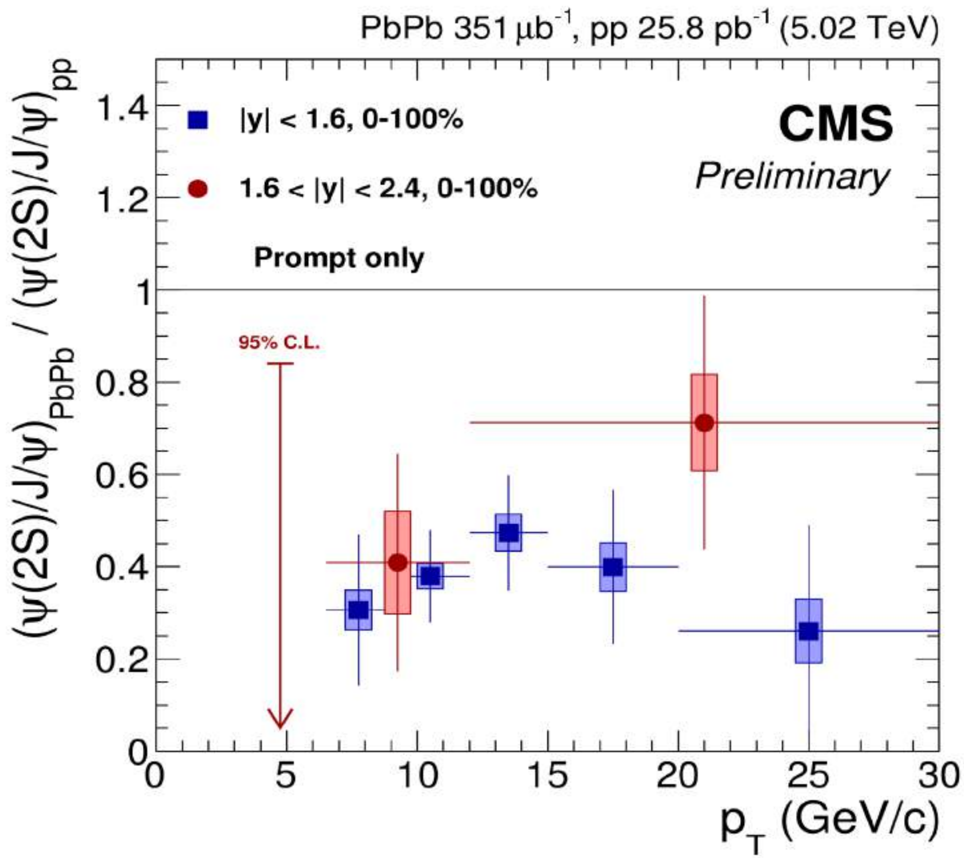




Transport Model

- Quasi-free dissociation for the break up of charmonia
- ψ(2S) regenerated later than J/ψ in the fireball evolution
- Sequential regeneration mechanism

arXiv:1611.01438



- Two rapidity bins: |y| < 1.6, 1.6 < |y| < 2.4
- Double ratio < 1 in all bins: ψ(2S) more suppressed than J/ψ
  - ✓ 95% C.L. upper limits when no significant ψ(2S) in PbPb
- No significant pT dependence
- Interplay of J/ψ and ψ(2S) regeneration in transverse momenta.

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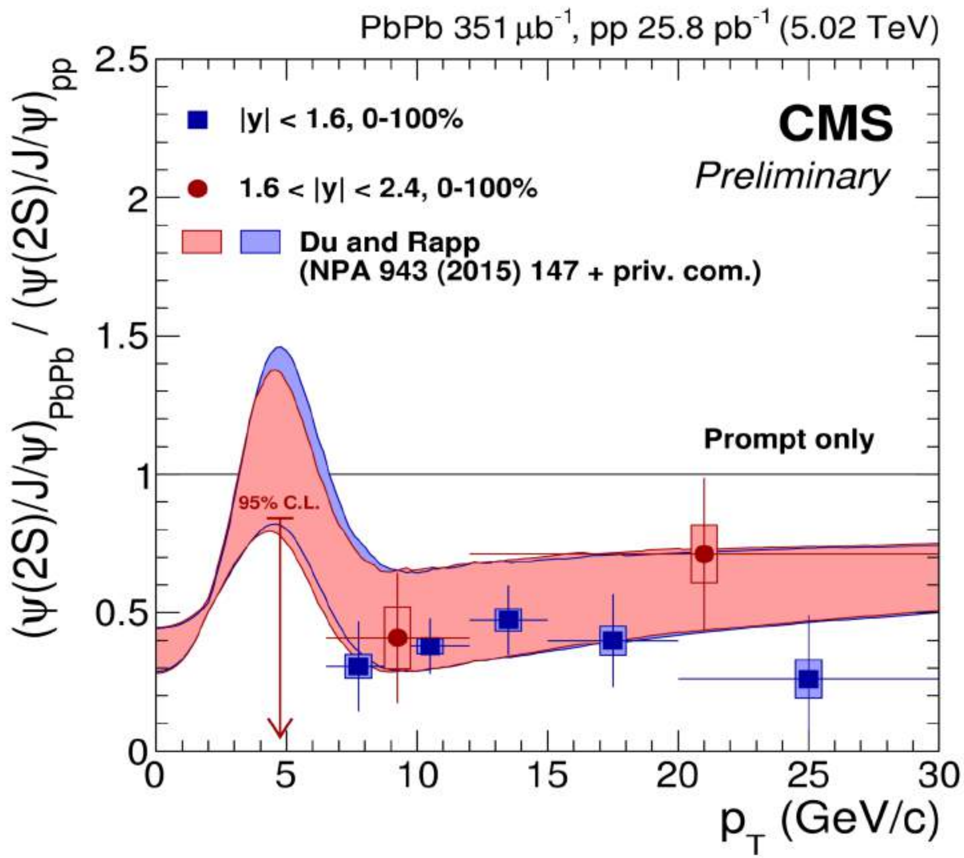
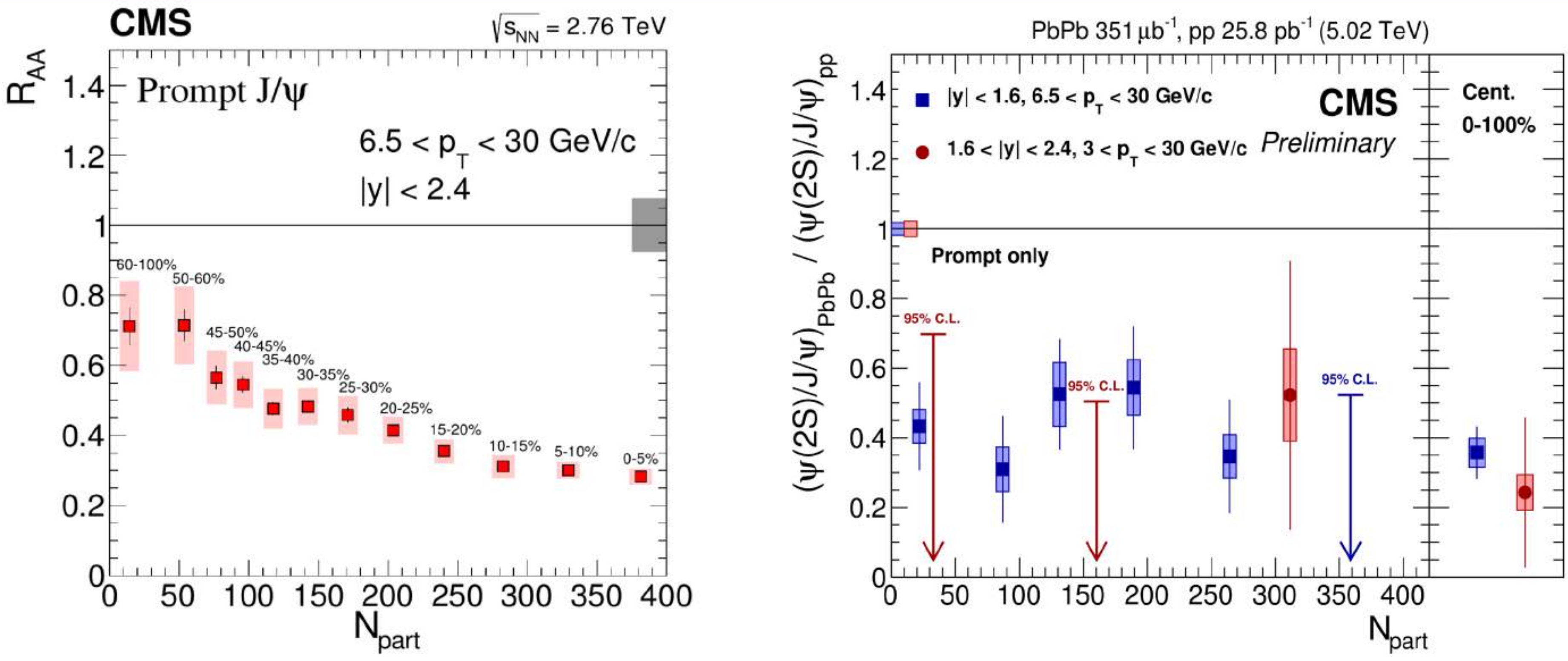


- Two rapidity bins: |y| < 1.6, 1.6 < |y| < 2.4
- Double ratio < 1 in all bins: ψ(2S) more suppressed than J/ψ
  - ✓ 95% C.L. upper limits when no significant ψ(2S) in PbPb
- No significant pT dependence
- Interplay of J/ψ and ψ(2S) regeneration in transverse momenta.

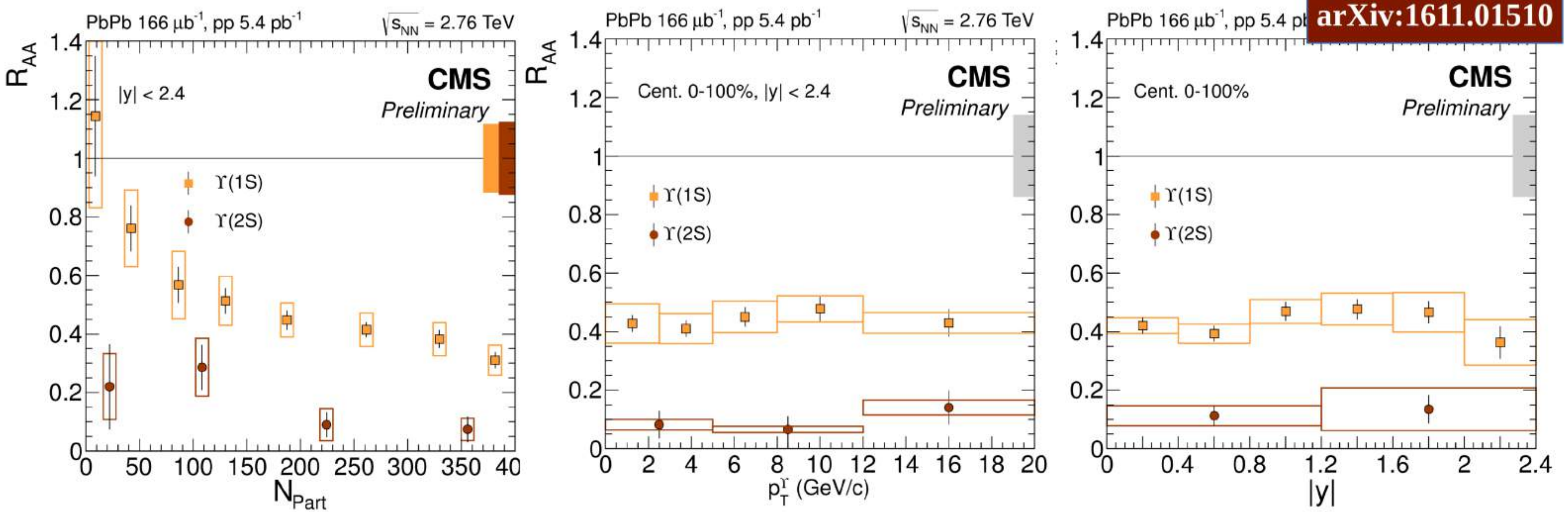


- J/psi: Shows strong centrality dependence, more suppressed in central events
- DR: psi(2S) is more suppressed than J/psi => sequential meting
- DR: No strong centrality dependence at 5.02 TeV

Υ(nS) measurement with 2011 *Pb+Pb* at 2.76 TeV (p+p 2013)

R_{AA} at 2.76 TeV

arXiv:1611.01510



- Υ(1S) shows gradual centrality dependence
- Υ(2S) largely suppressed at all centralities

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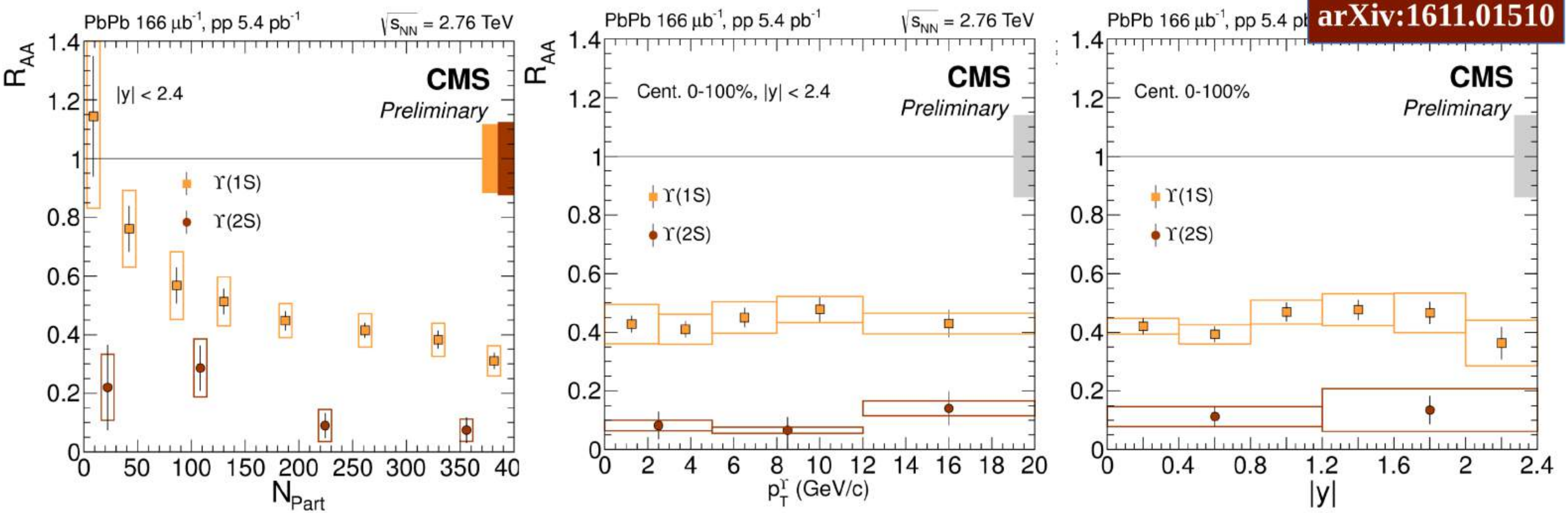
arXiv:1611.01510



- ϒ(1S) shows gradual centrality dependence
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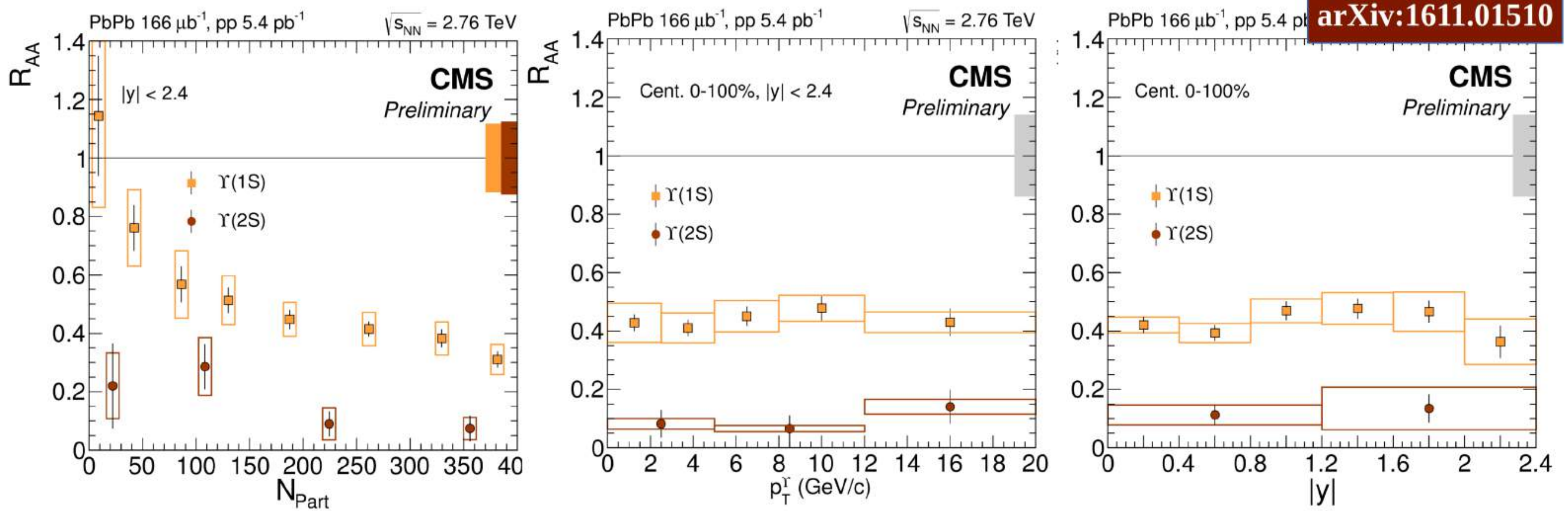
R_{AA} at 2.76 TeV

arXiv:1611.01510



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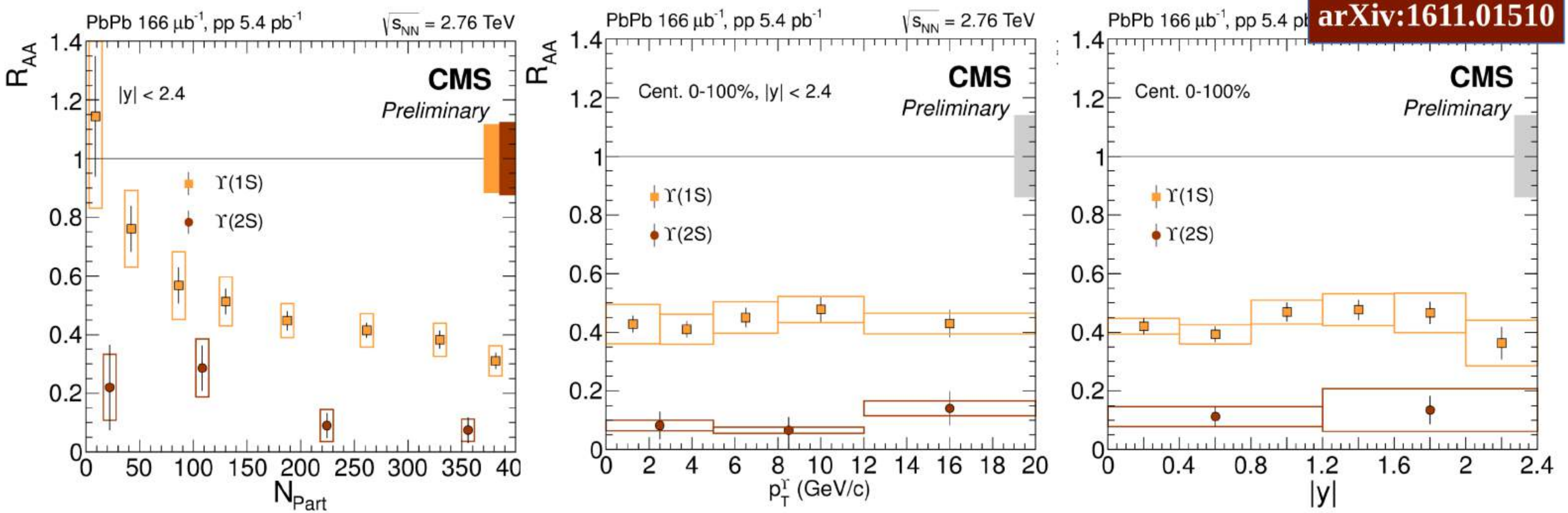
R_{AA} at 2.76 TeV

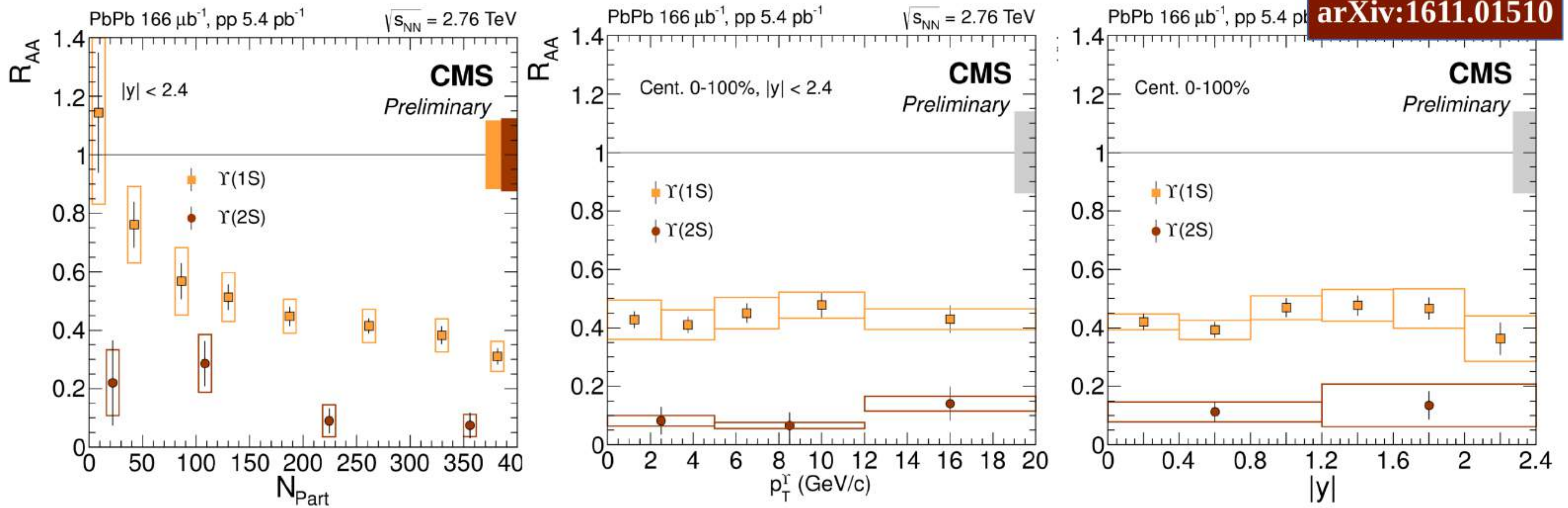
arXiv:1611.01510



- Υ(1S) shows gradual centrality dependence
- Υ(2S) largely suppressed at all centralities
- Both R_{AA} are flat over |y| < 2.4 and pT < 20GeV/c

R_{AA} at 2.76 TeV

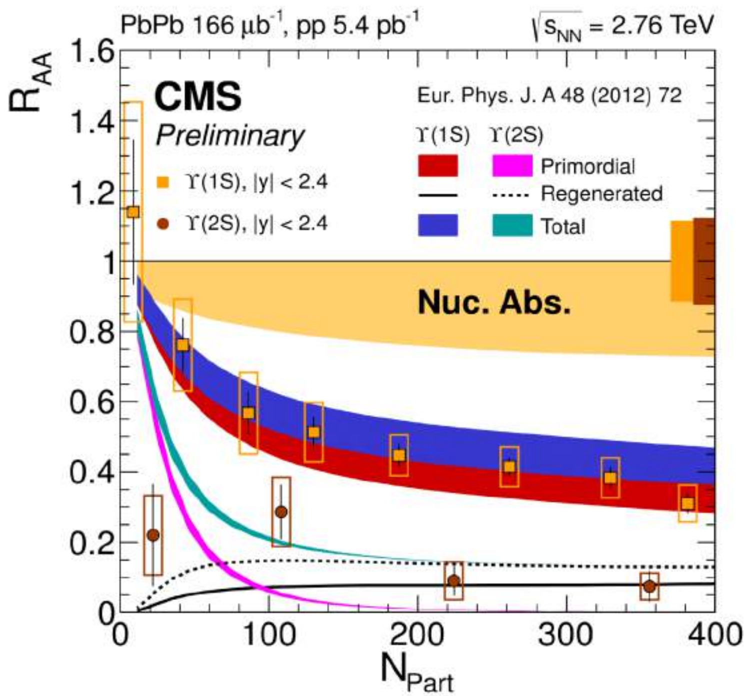
arXiv:1611.01510



- Υ(1S) shows gradual centrality dependence
- Υ(2S) largely suppressed at all centralities
- Both R_{AA} are flat over $|y| < 2.4$ and $pT < 20$GeV/c
- Υ(3S) not observed $R_{AA}(3S) < 0.14$ at 95% confidence level

R_{AA} : Comparison with models

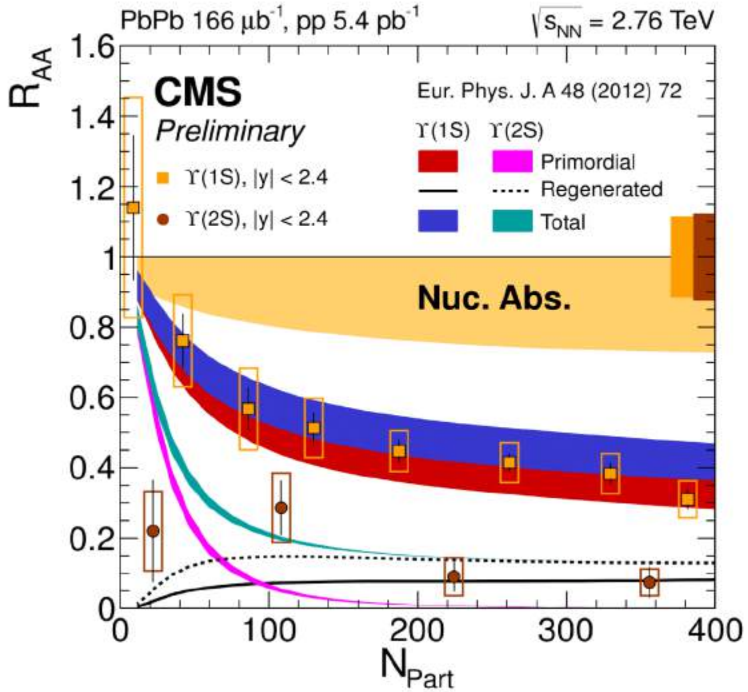
R_{AA}: Comparison with models



Kinetic Theory Model

- Strong and weak-binding scenarios
- ϒ(1S) not affected by color screening at LHC
- Significant regeneration contributions

R_{AA}: Comparison with models



Kinetic Theory Model

- Strong and weak-binding scenarios
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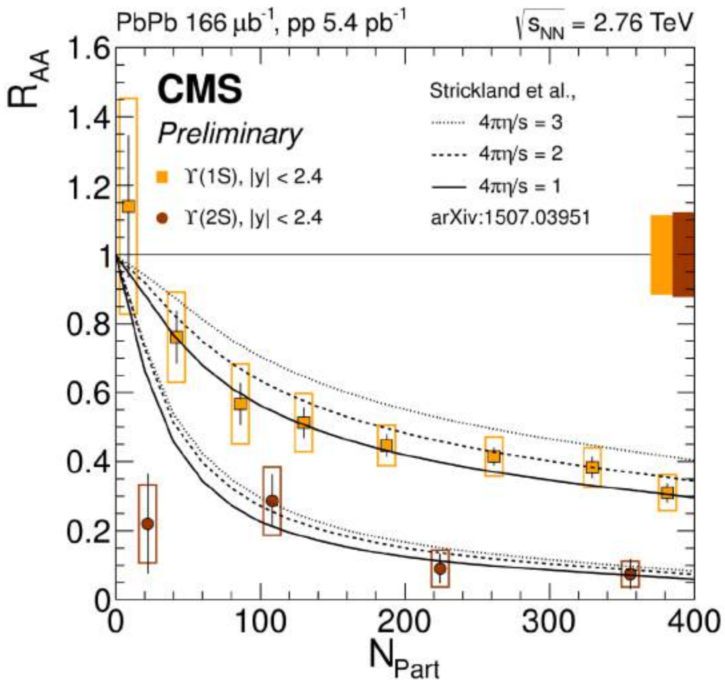
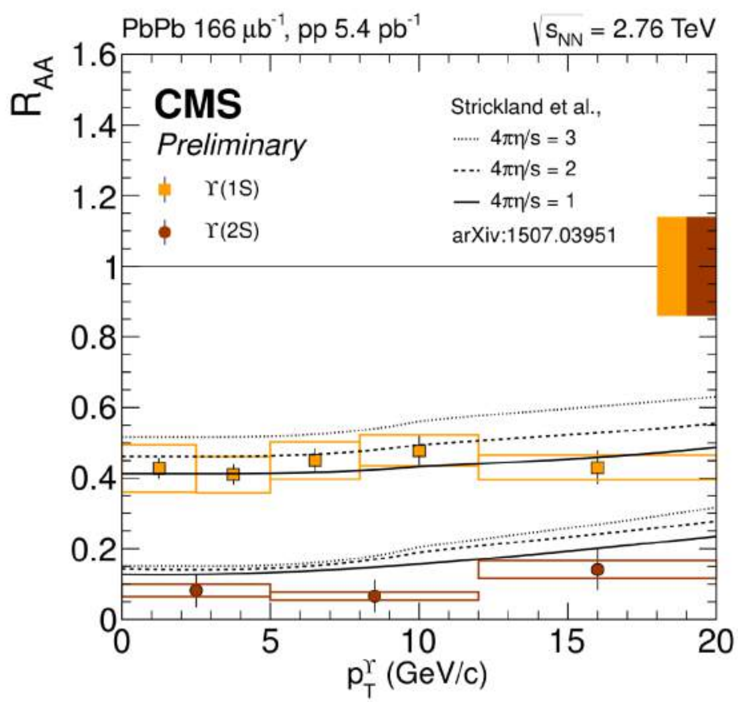
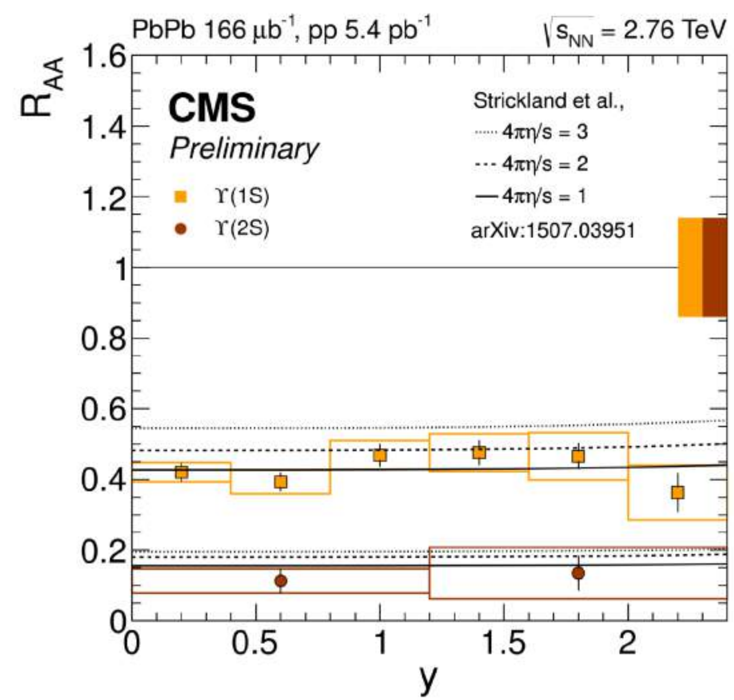


Hydrodynamics model

- Thermal parameters are constrained by data
- Good agreement with CMS data
- Data preferring small shear viscosities in the range $1 < 4\pi\eta/s < 2$





Hydrodynamics model

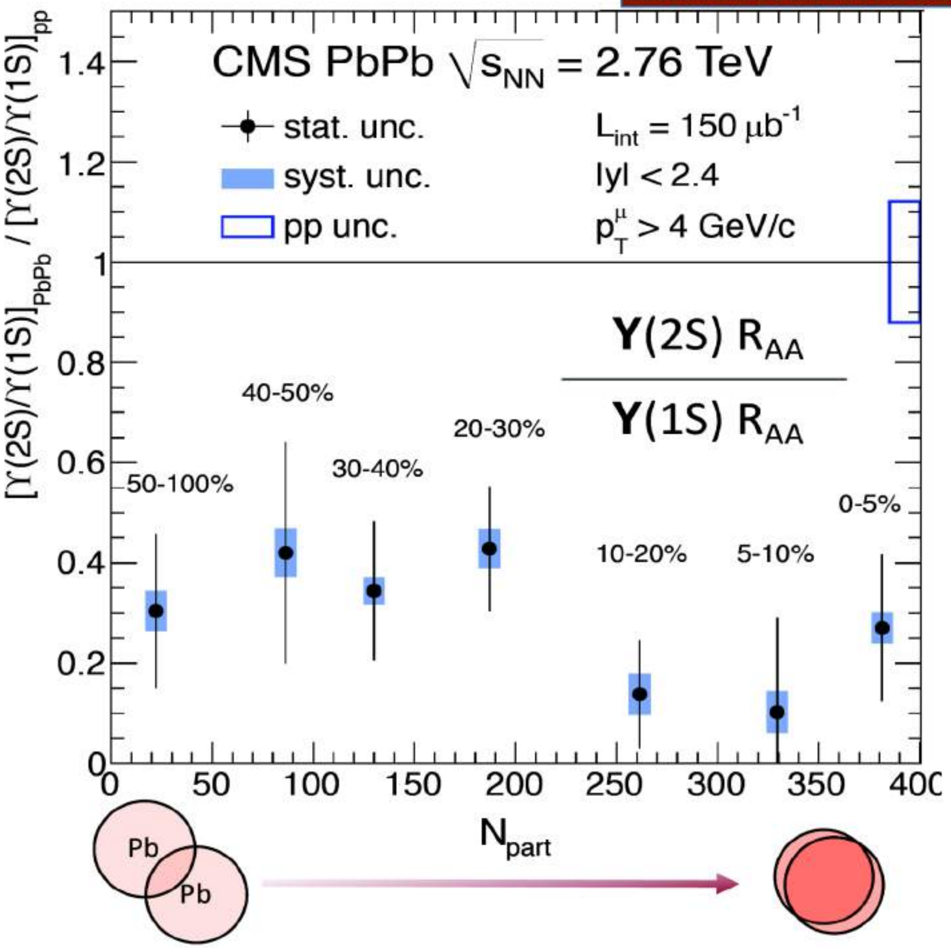
- As a function of rapidity and pT, model reproducing the trends seen in the data
- As a function of pT, bottomonia spectra are unaffected due to the lack of thermalization
- Preferring low shear viscosity to entropy density ratio => QGP created in HIC behaves like a nearly perfect fluids ?

Υ(nS)/Υ(1S) measurement with 2015 *Pb+Pb* at 5.02 TeV

Double ratio from 2.76 TeV PbPb

PRL.109.222301

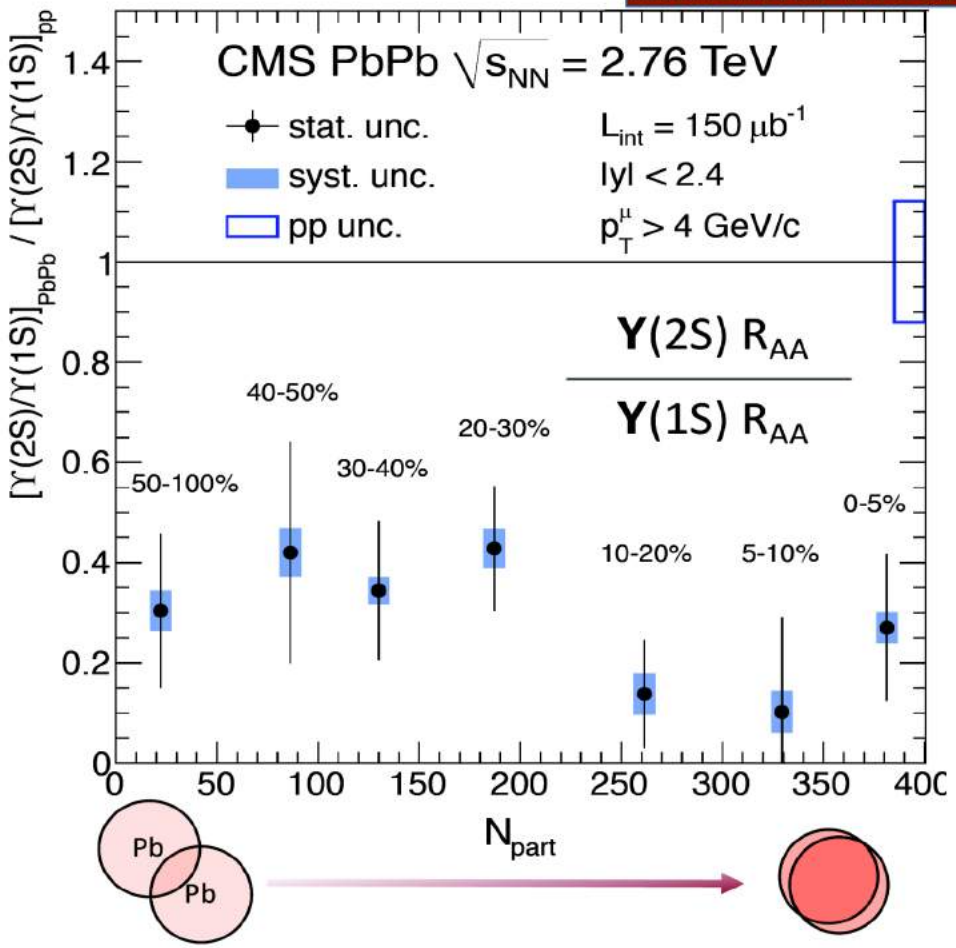
- At 2.76TeV, ϒ(2S) is more suppressed than ϒ(1S) at all centralities



PRL.109.222301

- At 2.76TeV, $\Upsilon(2S)$ is more suppressed than $\Upsilon(1S)$ at all centralities

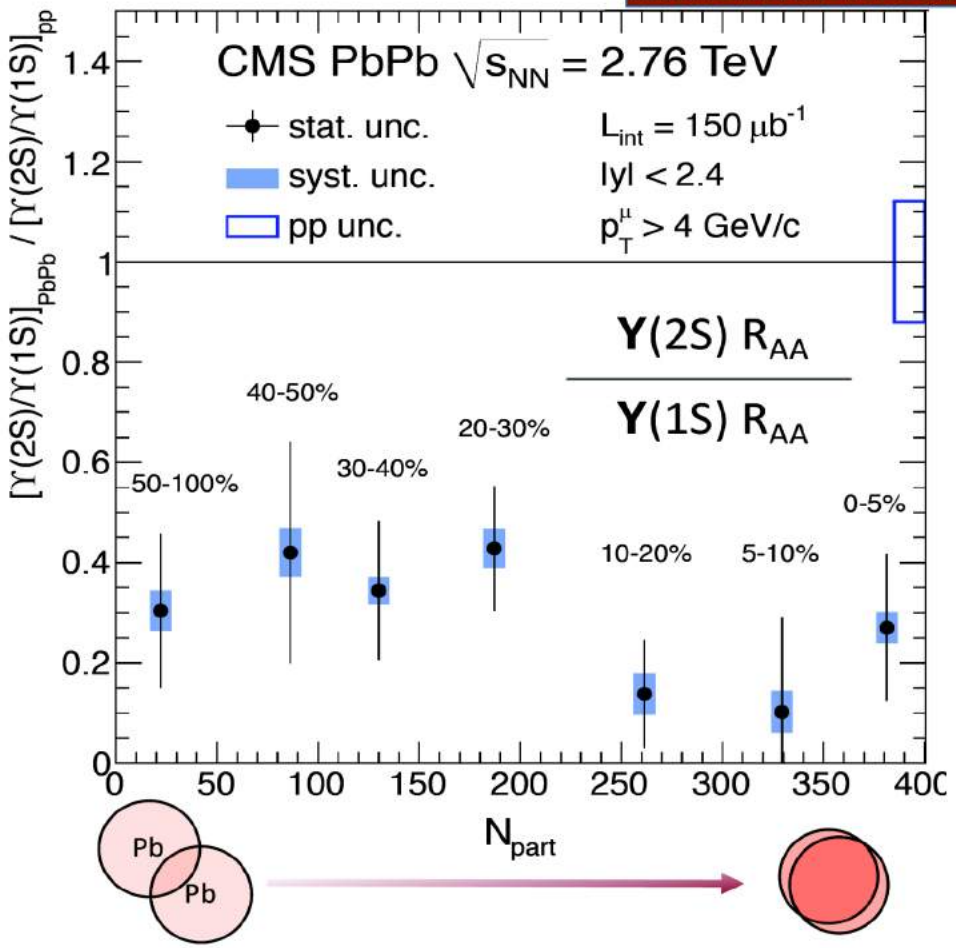
- Is there any centrality dependence?



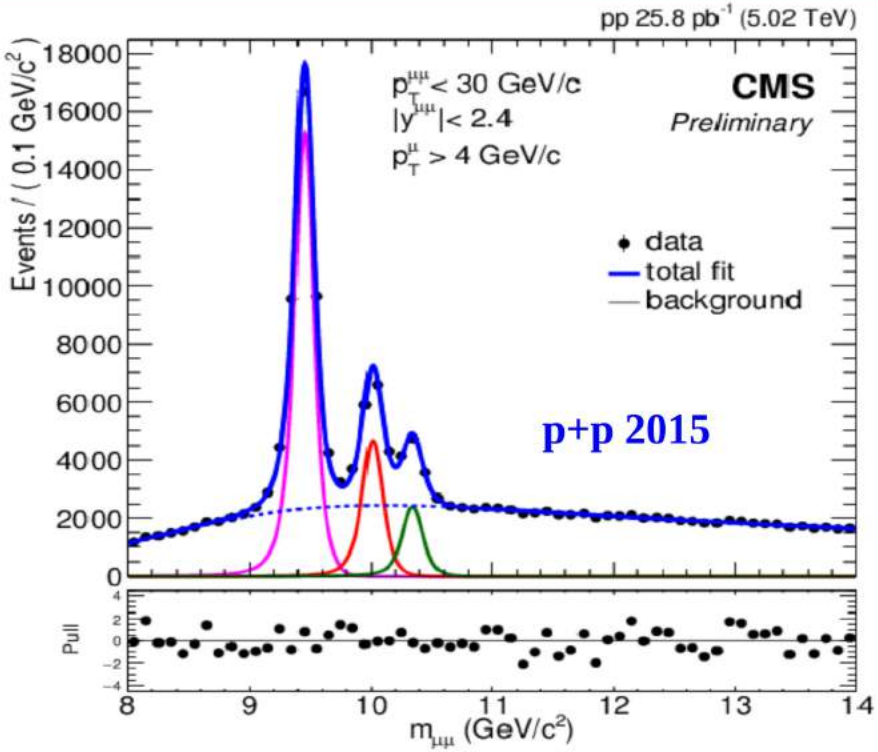
Double ratio from 2.76 TeV PbPb

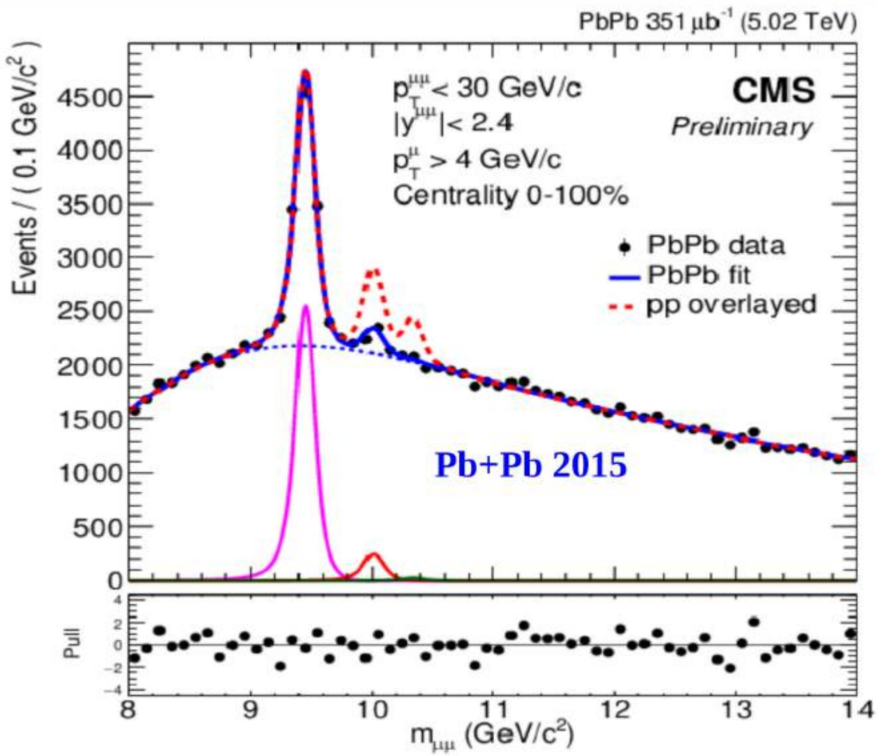
PRL.109.222301

- At 2.76TeV, ϒ(2S) is more suppressed than ϒ(1S) at all centralities
- Is there any centrality dependence?
- Can the new data at 5.02 TeV give any answer ?



Invariant Mass from 5.02 TeV

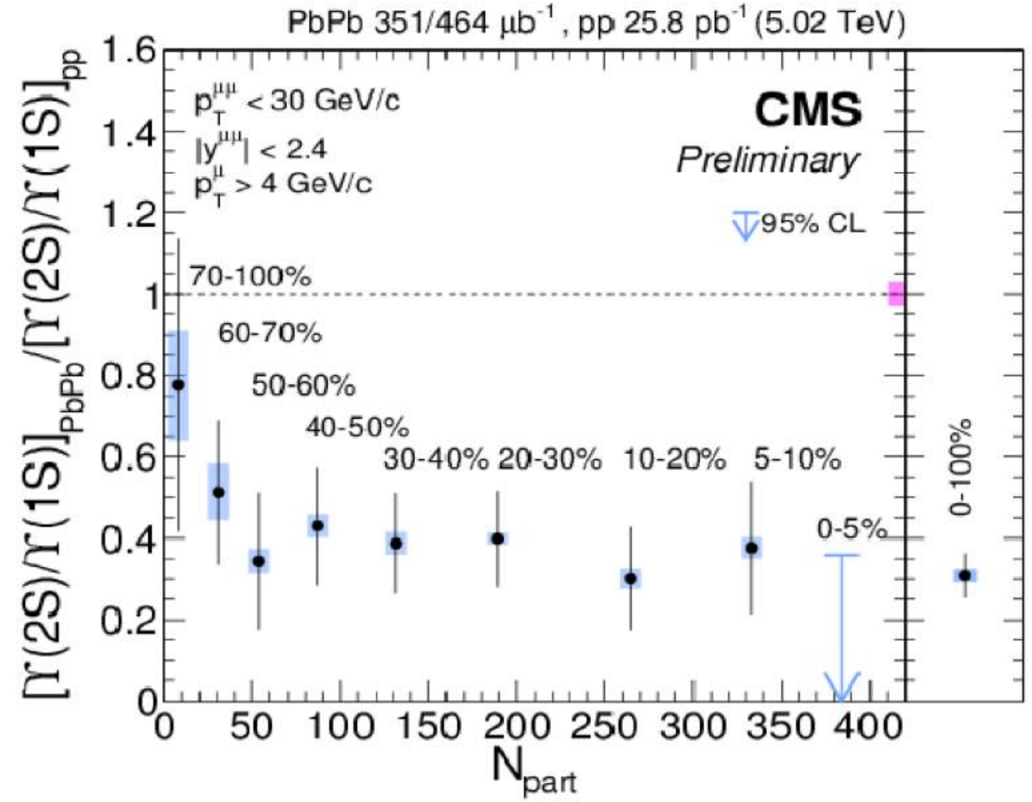




- ➔ ϒ(1S) in pp collisions (red dashed line) normalized to PbPb ϒ(1S)
- ➔ ϒ(3S) in PbPb consistent with zero!

Υ(2S)/Υ(1S) double ratio with Pb+Pb

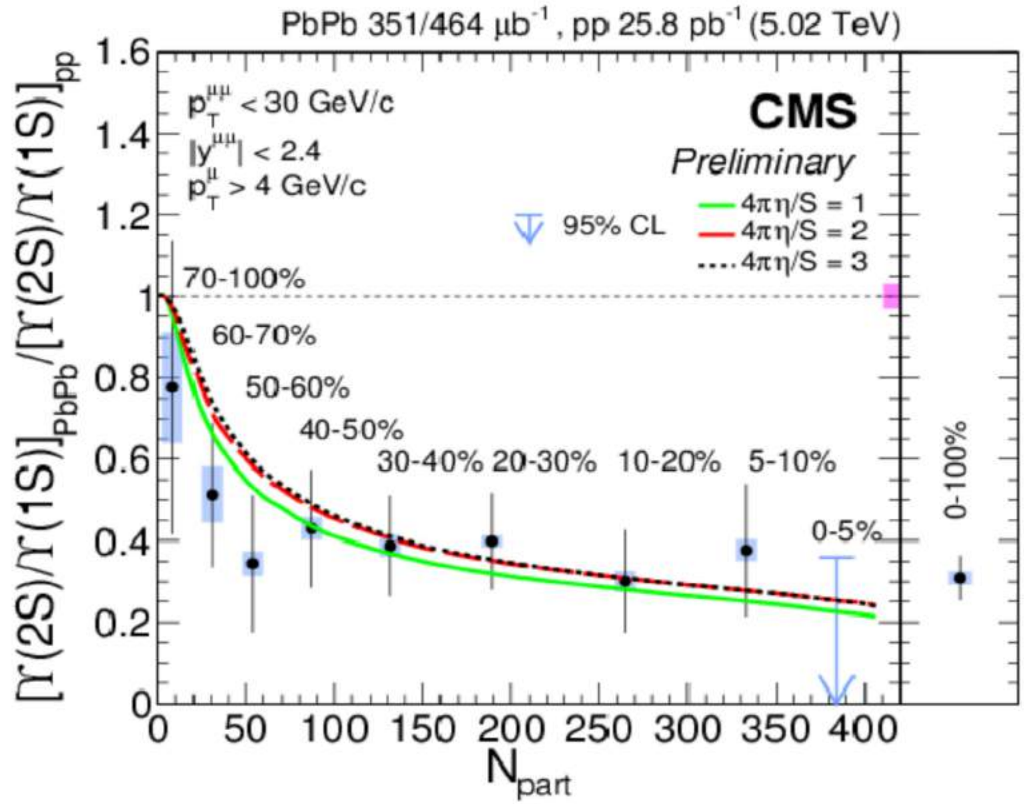
- *DR* is the ratio of R_{AA} of Υ(2S) and Υ(1S)
- In 0-5% bin, Υ(2S) signal is consistent with zero < 0.36 at 95% CL
- DR_{21} is compatible with unity in the most peripheral bins (70-100%),



$$\frac{\Upsilon(2S)\ R_{AA}^{(0\text{-}100\%)}}{\Upsilon(1S)\ R_{AA}} \text{ is } 0.308 \pm 0.055(\text{stat}) \pm 0.017(\text{syst})$$

ϒ(2S)/ϒ(1S) double ratio with Pb+Pb

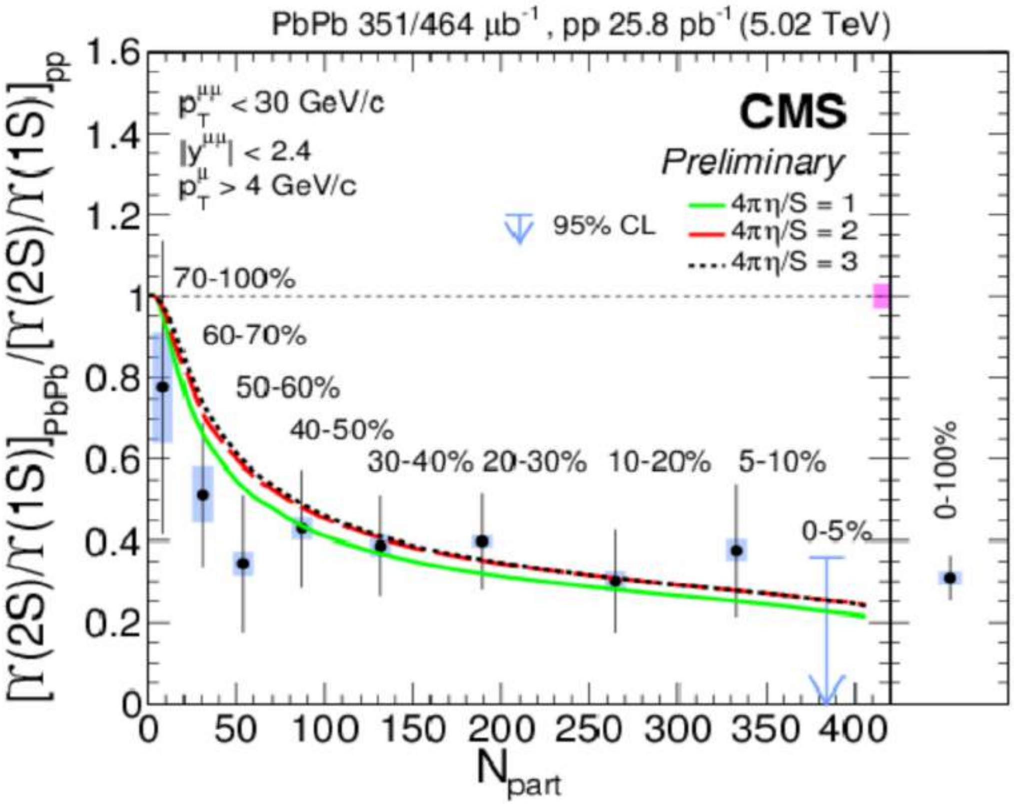
- *DR* is the ratio of R_{AA} of ϒ(2S) and ϒ(1S)
- In 0-5% bin, ϒ(2S) signal is consistent with zero < 0.36 at 95% CL
- DR_{21} is compatible with unity in the most peripheral bins (70-100%),
- Theory curves use hydrodynamics and lattice-based potential
  - → Obtained from the ratio of R_{AA} predictions of ϒ(1S) and ϒ(2S)



$$\frac{\Upsilon(2S)\ R_{AA}^{(0\text{-}100\%)}}{\Upsilon(1S)\ R_{AA}}$$ is 0.308 ± 0.055(stat) ± 0.017(syst)

$\Upsilon(2S)/\Upsilon(1S)$ double ratio with Pb+Pb

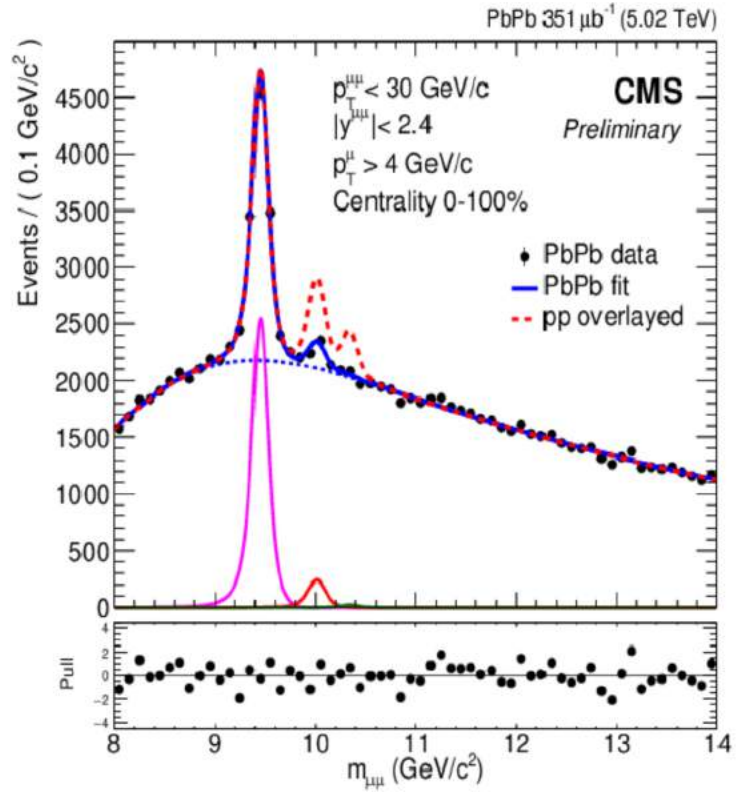
- *DR* is the ratio of R_{AA} of $\Upsilon(2S)$ and $\Upsilon(1S)$
- In 0-5% bin, $\Upsilon(2S)$ signal is consistent with zero < 0.36 at 95% CL
- DR_{21} is compatible with unity in the most peripheral bins (70-100%),
- Theory curves use hydrodynamics and lattice-based potential
  - Obtained from the ratio of R_{AA} predictions of $\Upsilon(1S)$ and $\Upsilon(2S)$
- What about $\Upsilon(3S)$?



$$\frac{\Upsilon(2S)\ R_{AA}^{(0\text{-}100\%)}}{\Upsilon(1S)\ R_{AA}}$$ is $0.308 \pm 0.055(\text{stat}) \pm 0.017(\text{syst})$

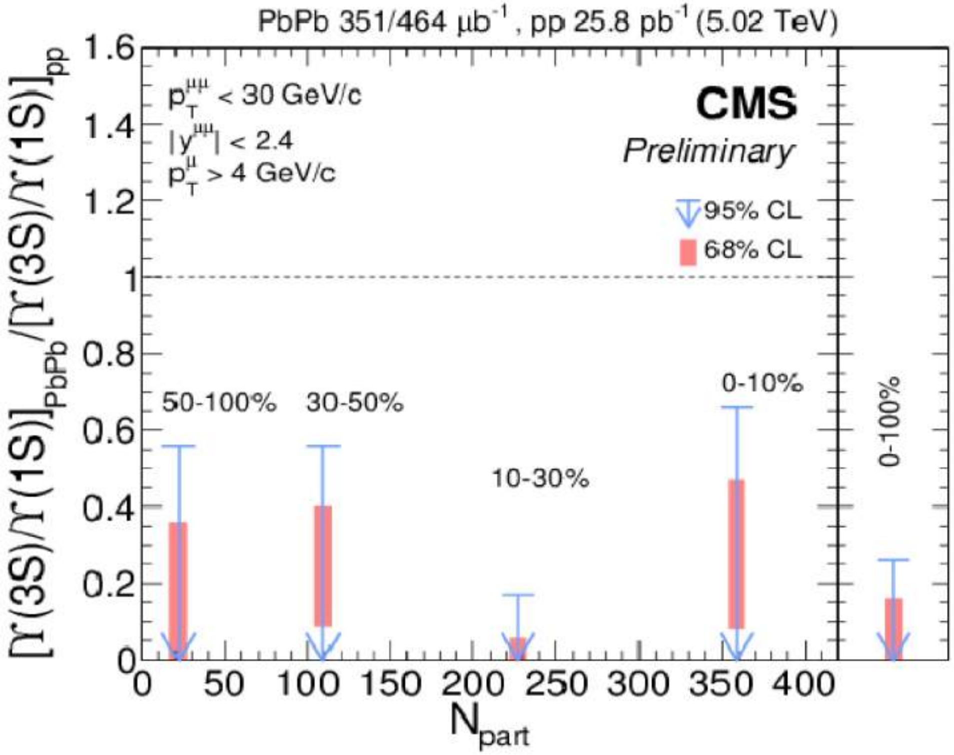
ϒ(3S)/ϒ(1S) double ratio vs centrality

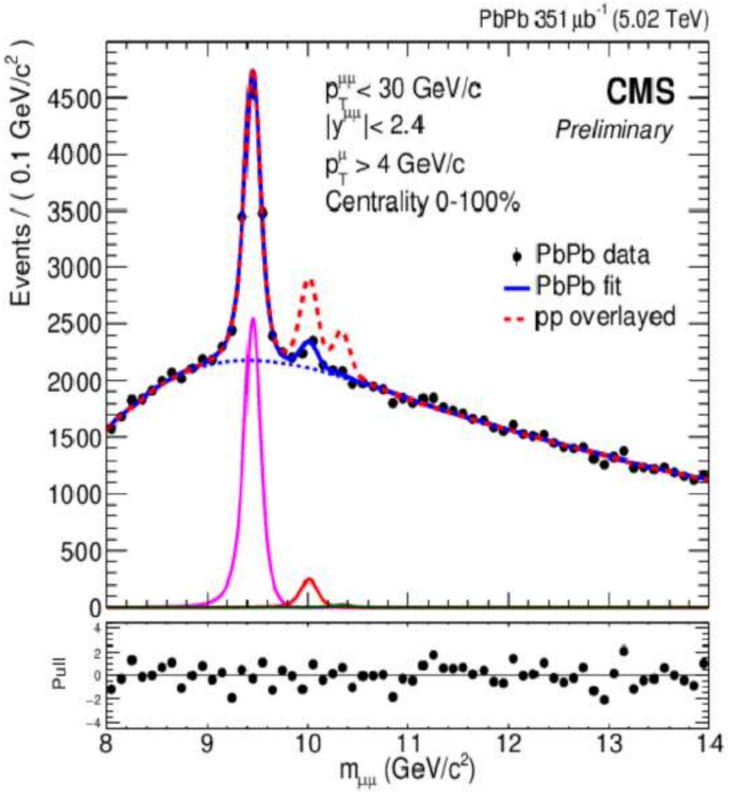
- The ϒ(3S) double ratio is lower than unity in all centrality bins



Υ(3S)/Υ(1S) double ratio vs centrality

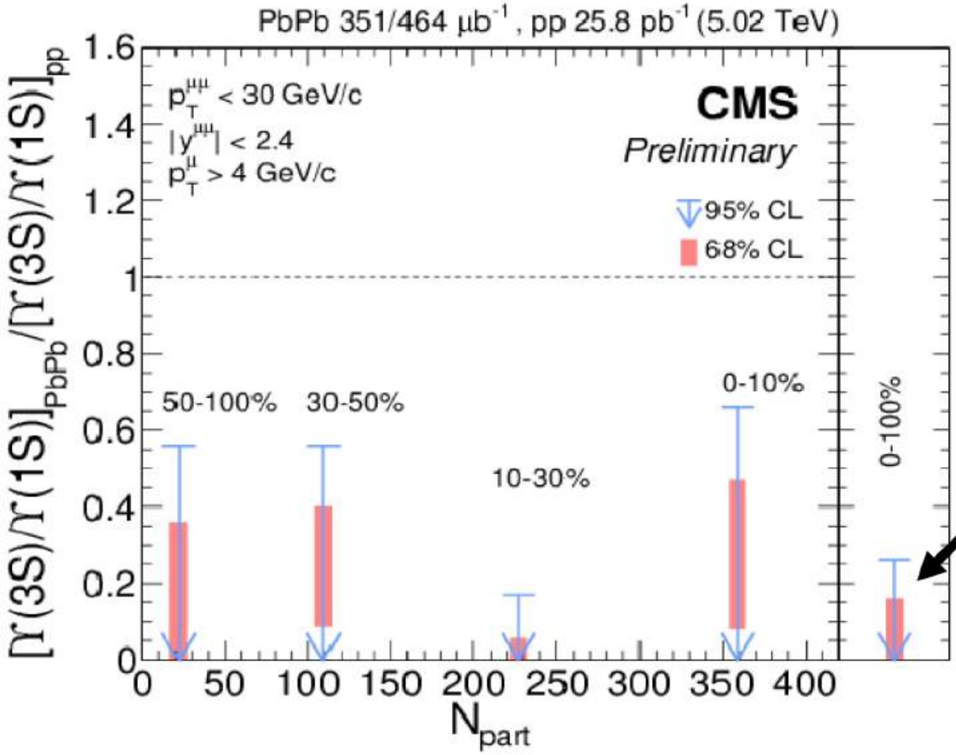
- The Υ(3S) double ratio is lower than unity in all centrality bins
  - → no indication that the suppression is weaker in the most peripheral events

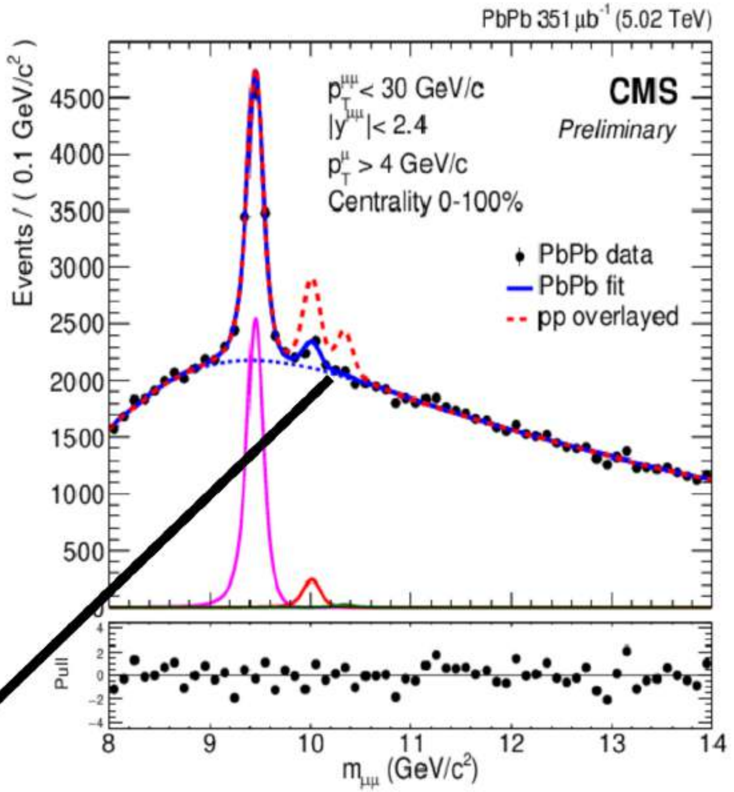




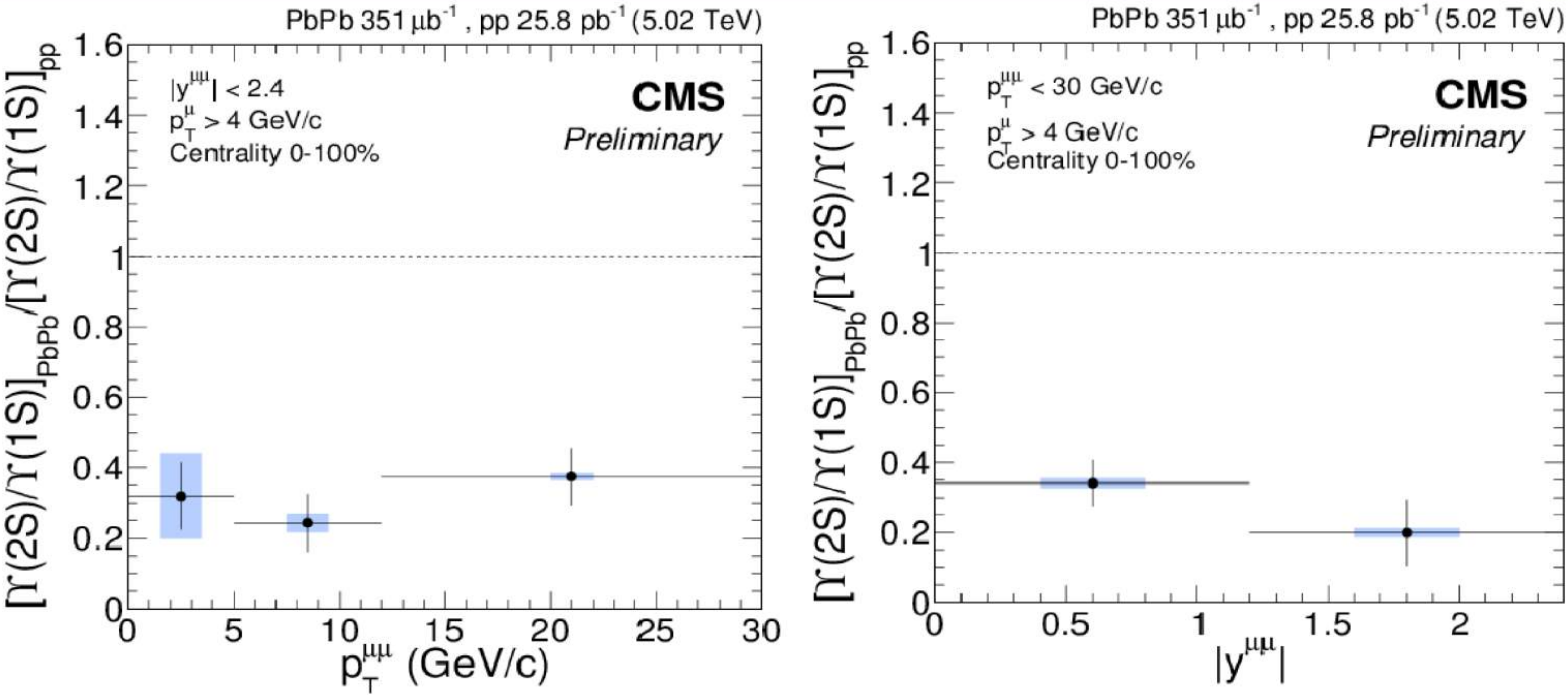
Υ(3S)/Υ(1S) double ratio vs centrality

- The Υ(3S) double ratio is lower than unity in all centrality bins
  - → no indication that the suppression is weaker in the most peripheral events
- $DR_{31} < 0.26$ at 95% CL
- Arrows are 95% CL and boxes are 68% CL

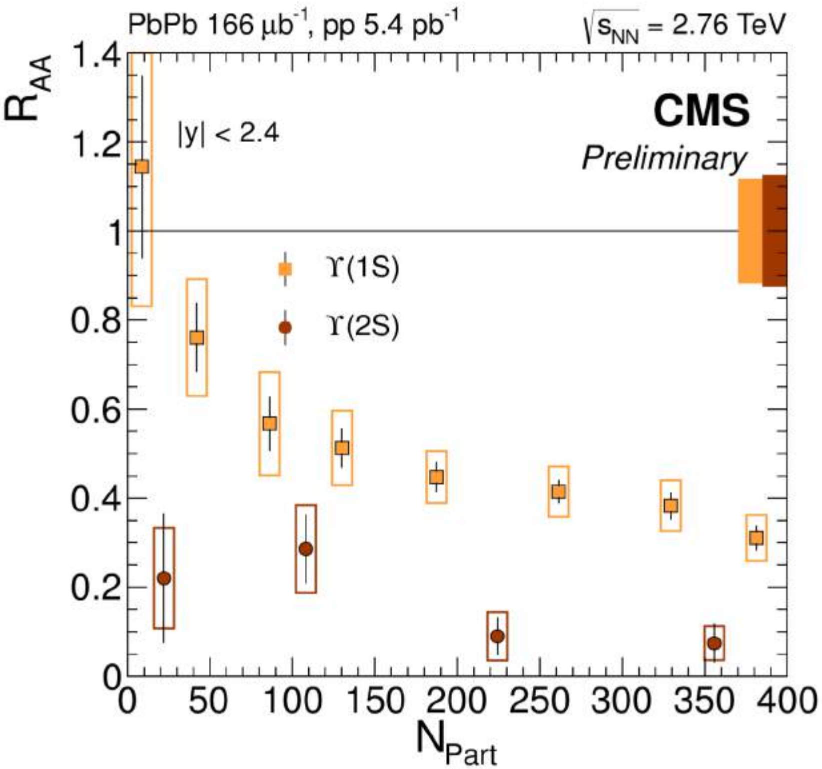




Double ratio of $\Upsilon(2S)$ in p_T and y bins

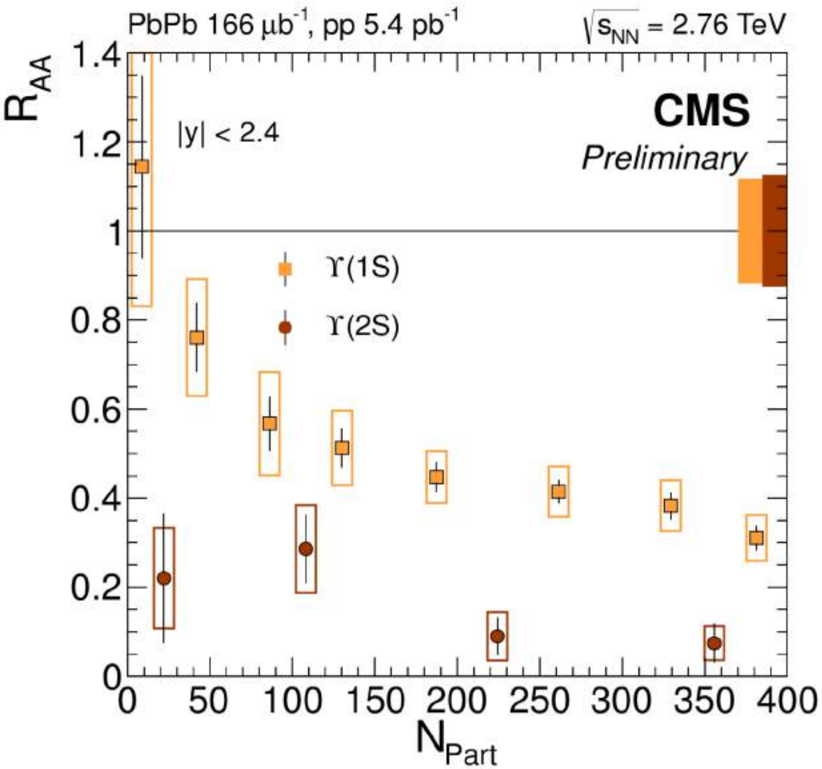


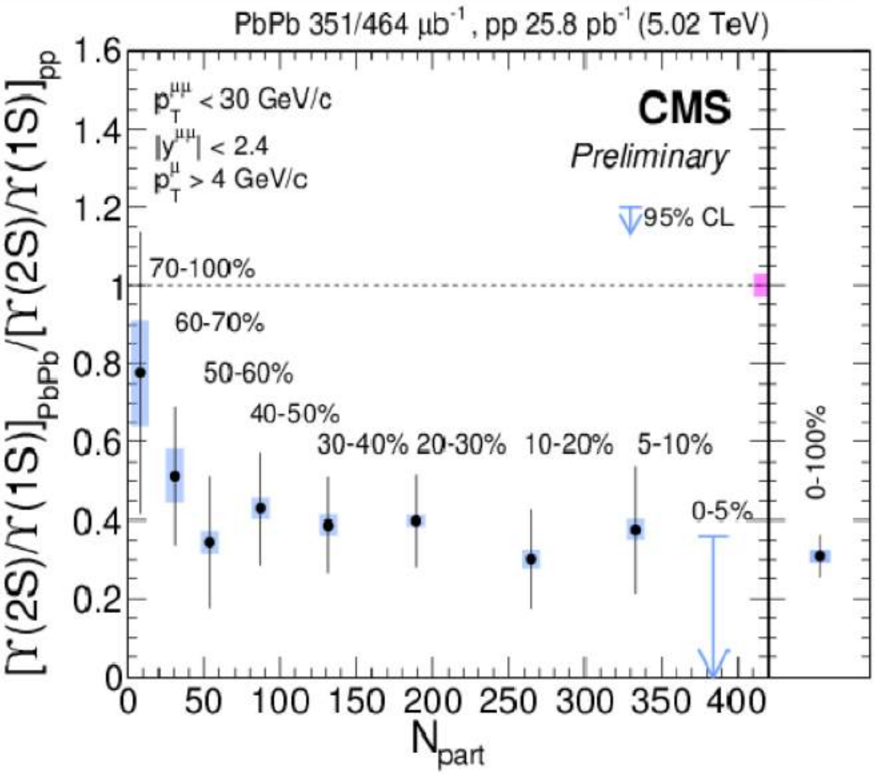
- DR has no clear dependence on pT or rapidity
- Similarly to 2.76TeV result



R_{AA}

- ϒ(1S) shows gradual centrality dependence
- ϒ(2S) largely suppressed at all centralities
- Sequential suppression of bottomonium states





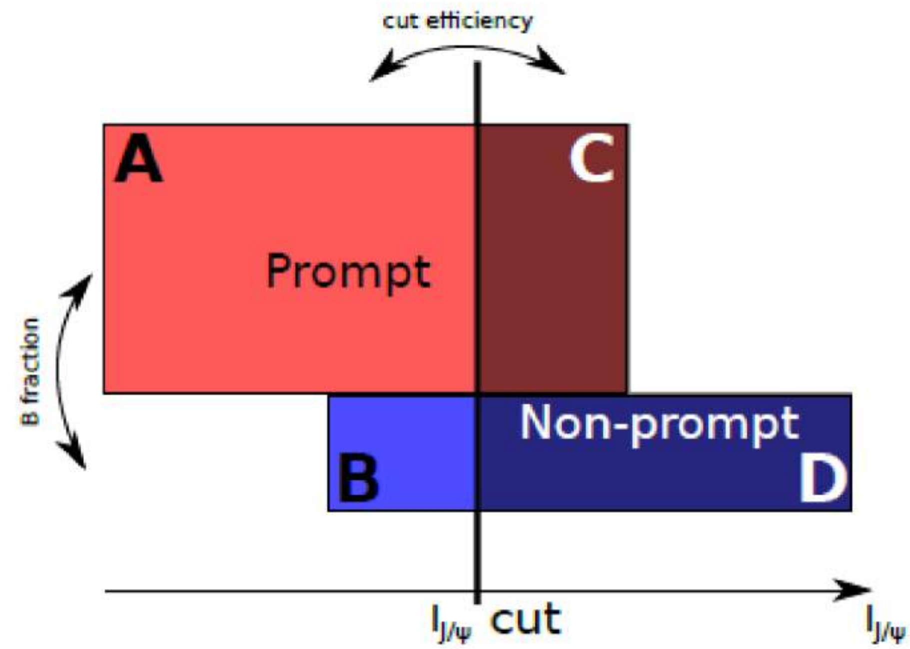
R_{AA}

- ϒ(1S) shows gradual centrality dependence
- ϒ(2S) largely suppressed at all centralities
- Sequential suppression of bottomonium states

DR

- ϒ(2S) strongly suppressed from mid-central collisions
- ϒ(2S) is less suppresses in the peripheral collisions ?
- ϒ(3S) is completely dissolved ?

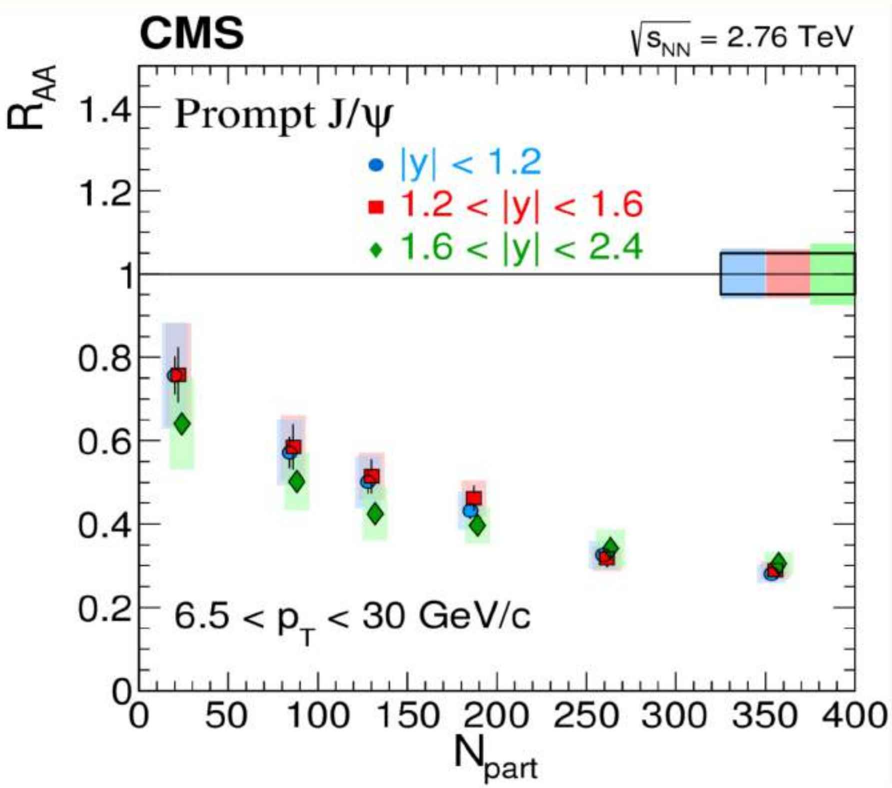
Extra Slides



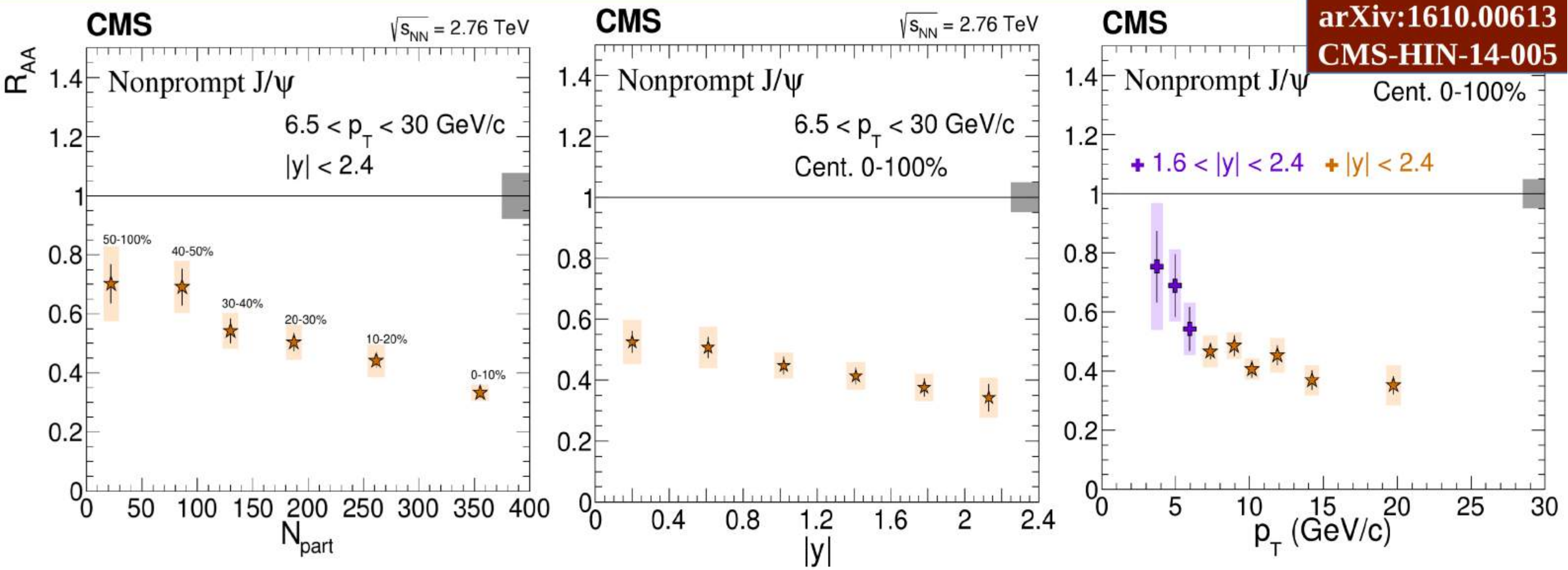
- 2D fits not possible for $\psi(2S)$ in PbPb at low p_T (too low S/B)
- Rejecting nonprompt using a $\ell^{3D}_{J/\psi}$ cut
- A nonprompt contamination is left but accounted for
- Estimated from data using a sideband in $\ell^{3D}_{J/\psi}$ (reverted $\ell^{3D}_{J/\psi}$ cut)
    - Also using the $\ell^{3D}_{J/\psi}$ cut efficiency from simulation

J/ψ in PbPb at 2.76TeV: R_{AA} vs N_{part}, |y|, pT

arXiv:1610.00613
CMS-HIN-14-005



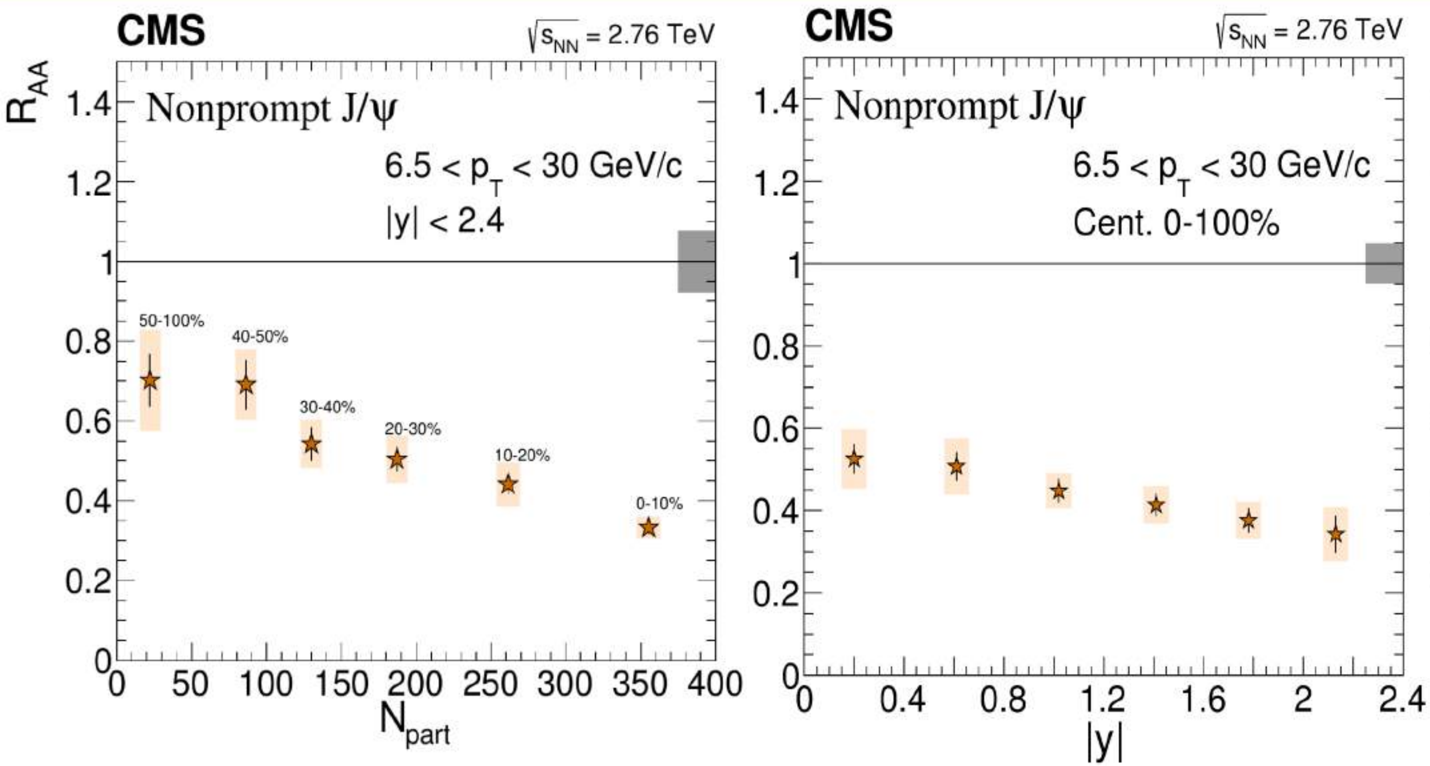
arXiv:1610.00613
CMS-HIN-14-005



- Strong centrality dependence
- No significantcant rapidity or pT dependence

Non-prompt J/ψ in PbPb at 2.76TeV: R_{AA} vs N_{part}, |y|, pT

arXiv:1610.00613
CMS-HIN-14-005



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Non-prompt J/ψ in PbPb at 2.76TeV: R_{AA} vs N_{part}, |y|, pT