Υ suppression in PbPb collisions at the LHC

– Torsten Dahms –
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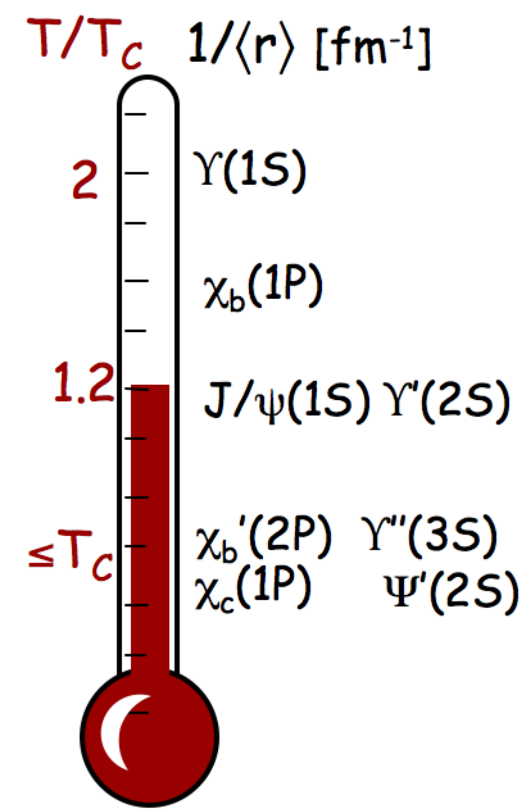
(on behalf of CMS)

14th Int. Conference on B-Physics at Hadron Machines,
Bologna, Italy
April 9th, 2013

ERC grant “QuarkGluonPlasmaCMS”

Quarkonia as a Thermometer

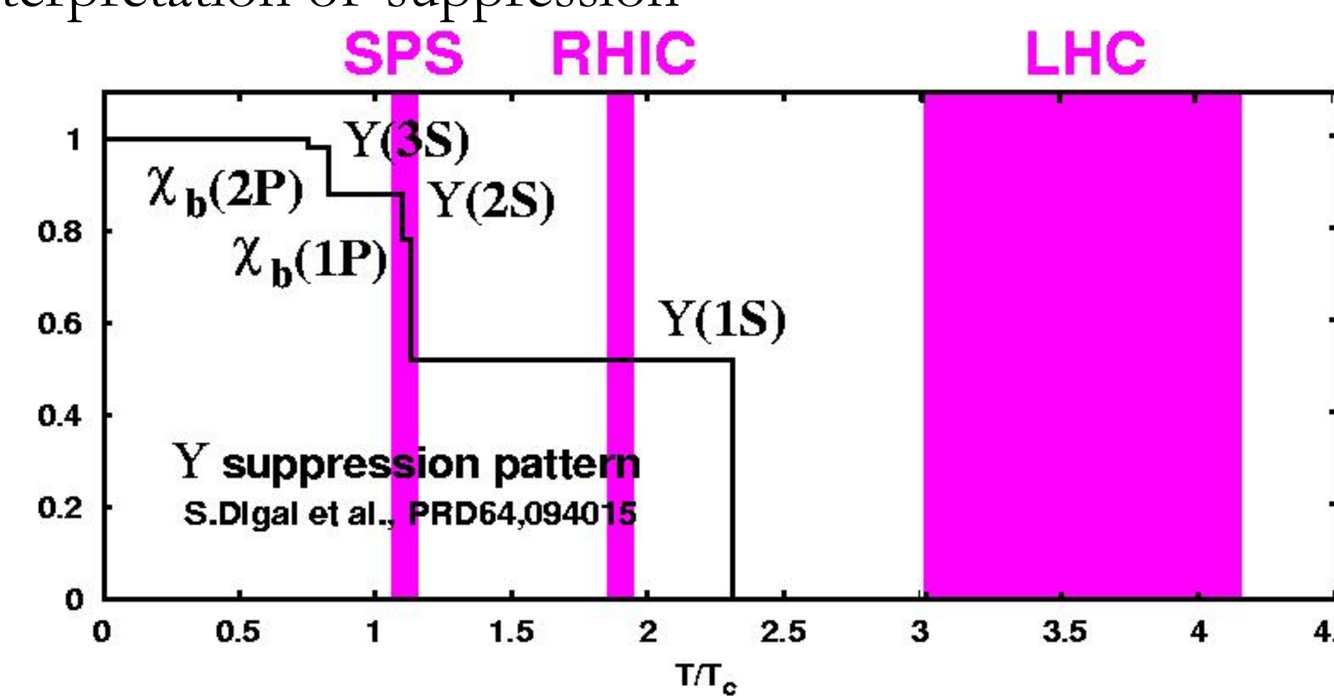
- Heavy quarks
  - Produced in the initial hard-scattering process
  - Debye screening in QGP leads to melting of quarkonia
- Different binding energies (radii) of bound states lead to sequential melting of the states with increasing temperature
- Advantages of bottomonium over charmonium
  - No B-hadron feed down
  - Three states with different T_d but similar BR×σ
  - Larger feed down fraction from excited states to Υ(1S)
  - Sensitive to larger temperature range above T_c
  - Expect much less regeneration: cleaner interpretation of suppression



Mocsy, EPJ C 61 (2009) 705

State	J/ψ (1S)	χ_c (1P)	ψ' (2S)
m (GeV/c^2)	3.10	3.53	3.68
r_0 (fm)	0.50	0.72	0.90

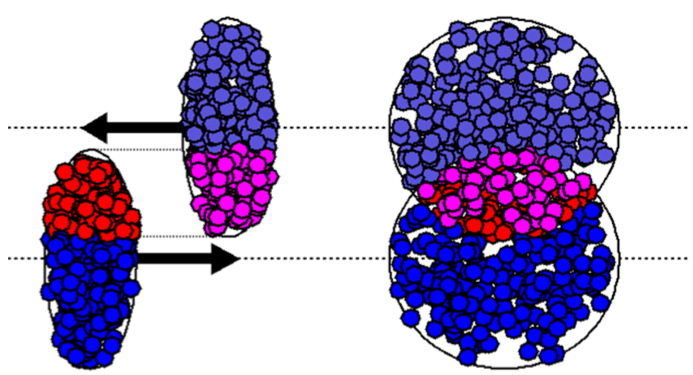
Υ (1S)	χ_b (1P)	Υ' (2S)	χ'_b (2P)	Υ'' (3S)
9.46	9.99	10.02	10.26	10.36
0.28	0.44	0.56	0.68	0.78



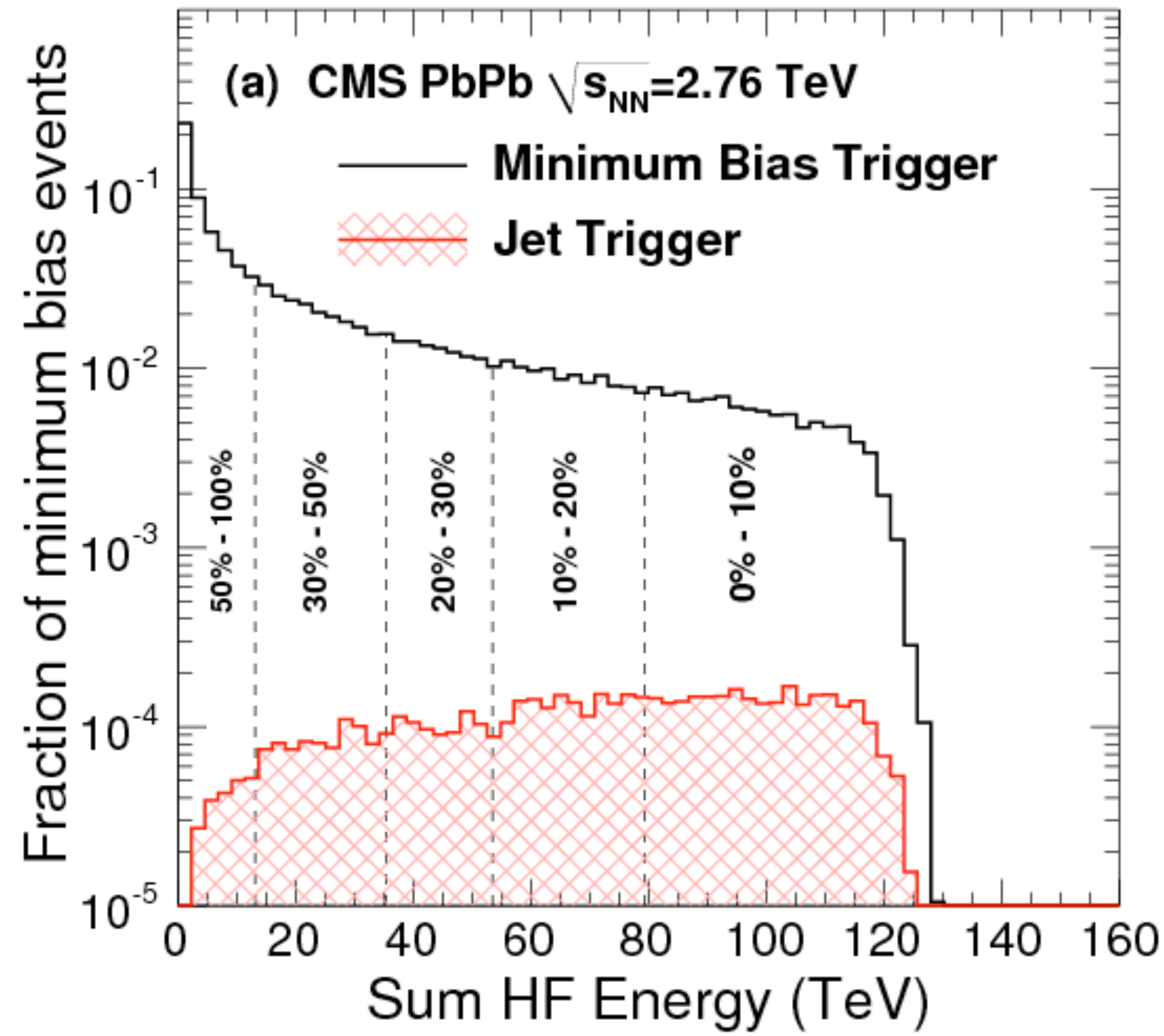
Heavy-Ion Collisions: Defining Centrality

- Collision centrality (overlap of the nuclei) related to the energy deposit in forward calorimeters

- Then: relate to geometrical quantities with a Glauber MC model
  - N_{part} = number of participating nucleons



  - N_{coll} = number of binary collisions
  - Yield of hard probes is expected to scale with N_{coll} in absence of medium effect: R_{AA} = 1

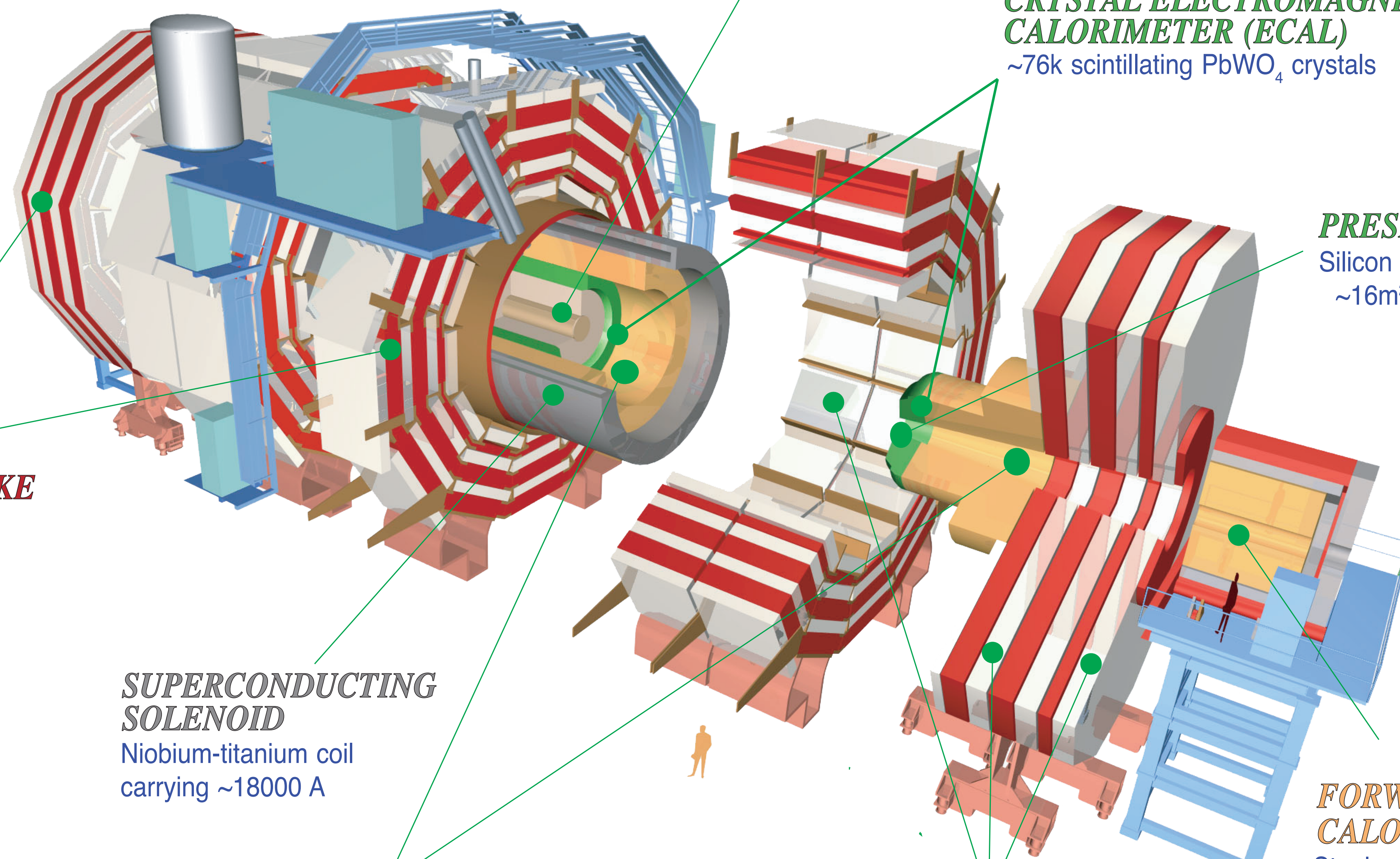


$$R_{AA} = \frac{N_{\mathrm{PbPb}}}{N_{\mathrm{coll}} \cdot N_{pp}}$$

The Compact Muon Solenoid

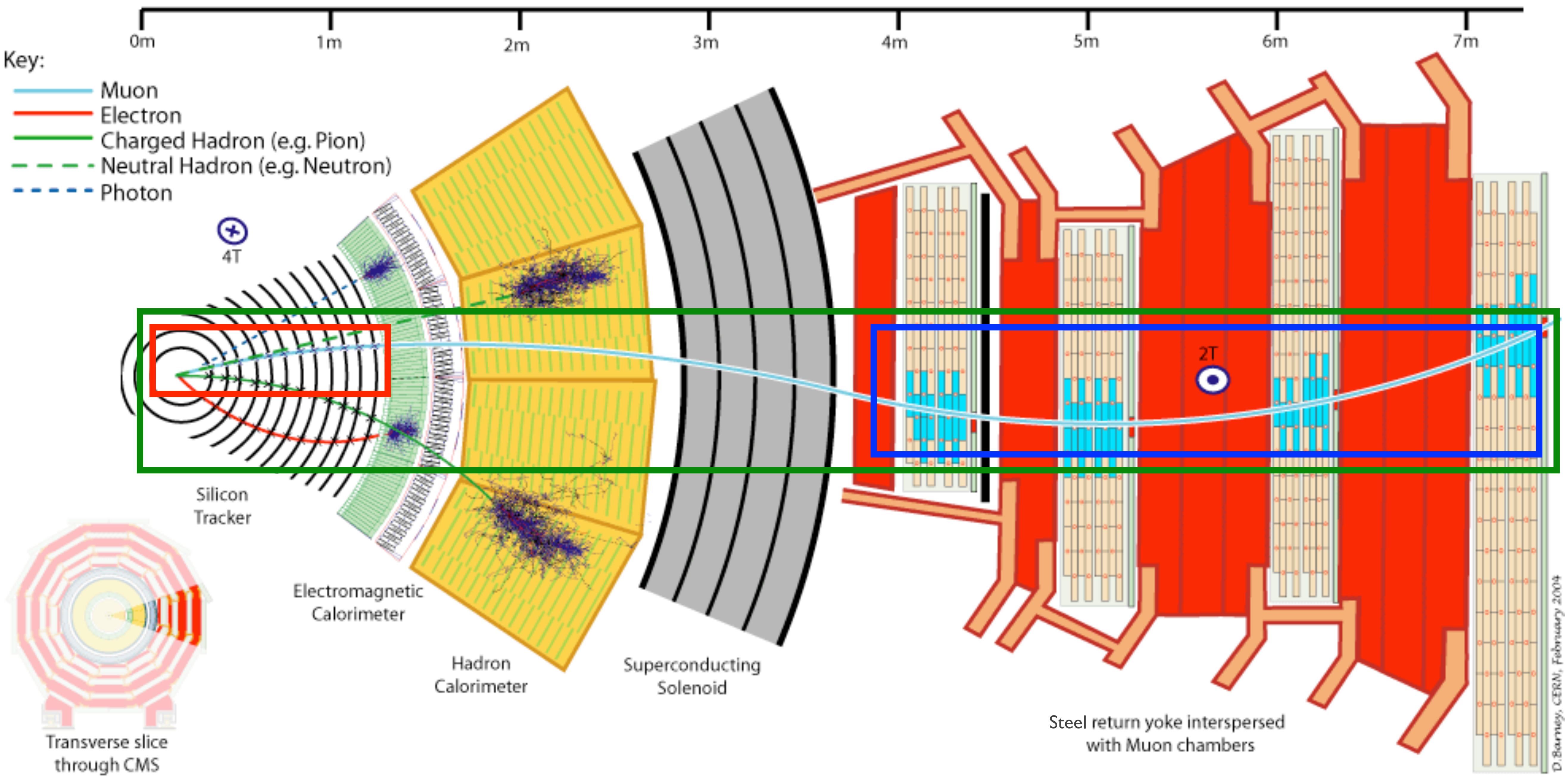
CMS Detector

Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons



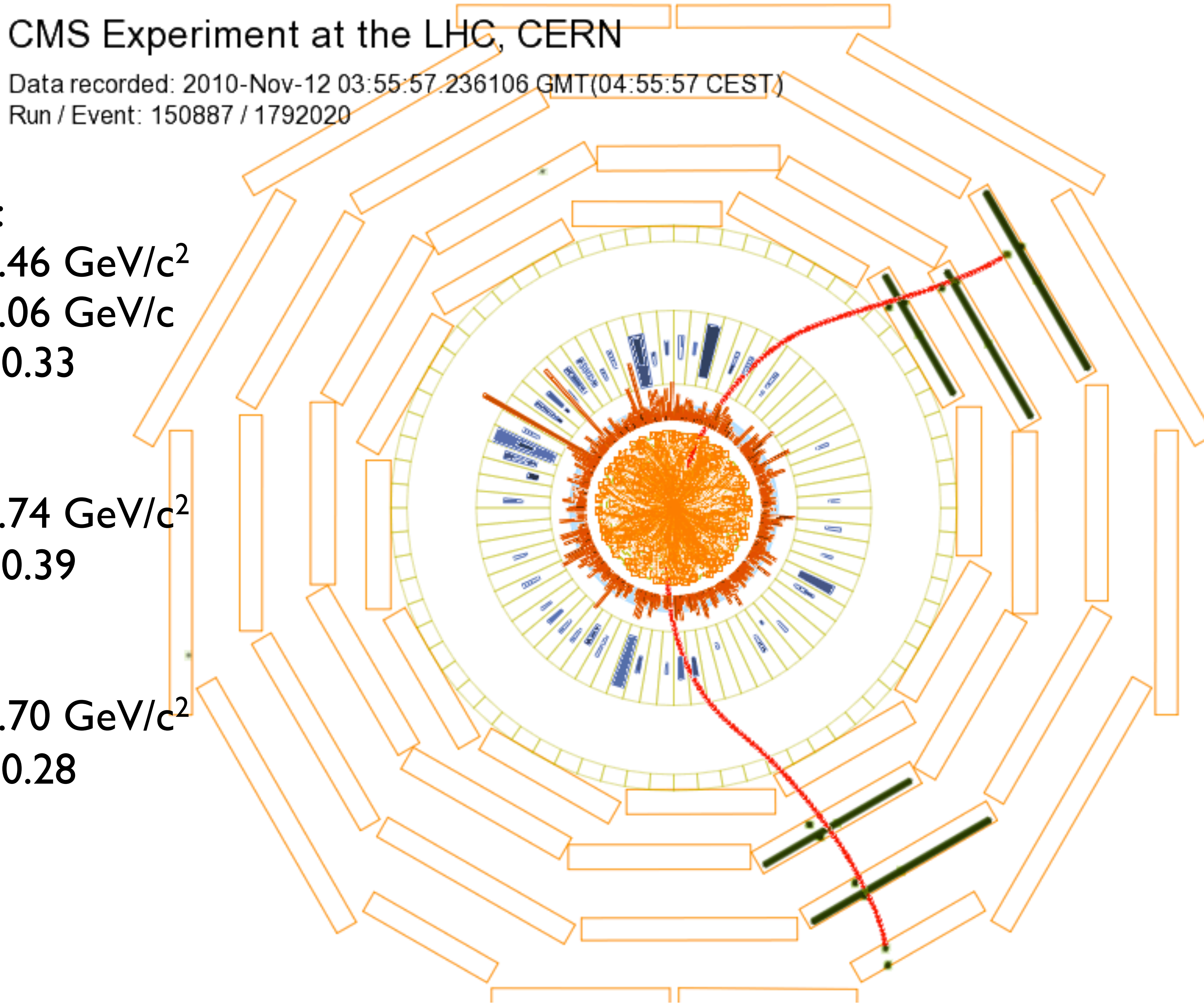
Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

Muon reconstruction in CMS



- Global muons reconstructed with information from inner tracker and muon stations
- Further muon ID based on track quality (χ^2, # hits…)
- Global muons need p ≳ 3 GeV/c to reach the muon station, but lose 2–3 GeV energy in the absorber → a minimum of ≈ 5 GeV/c total momentum required

Υ candidate in PbPb at $\sqrt{s_{NN}} = 2.76$ TeV



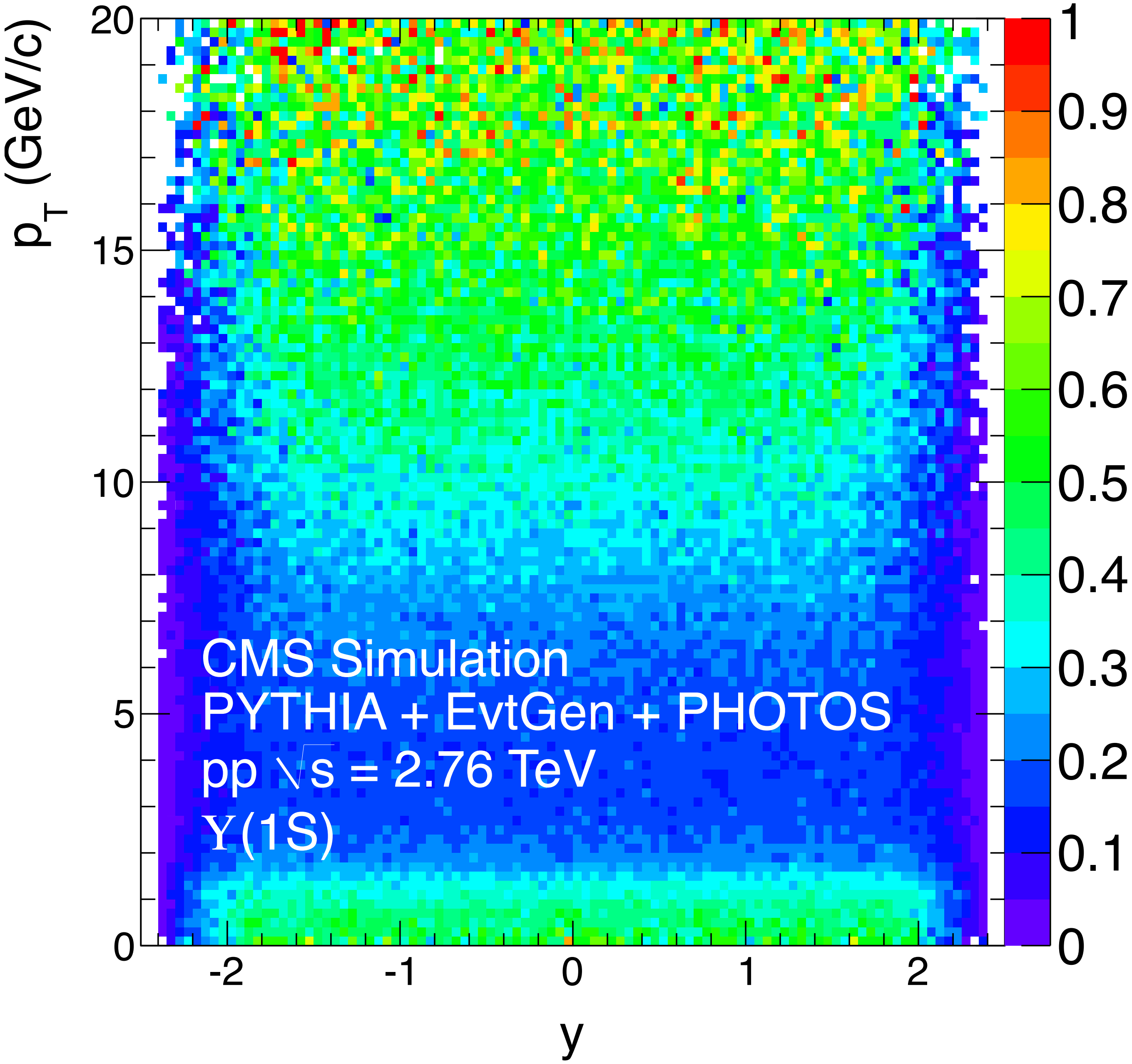
$\mu^+\mu^-$ pair:
mass: 9.46 GeV/c^2
p_T: 0.06 GeV/c
rapidity: −0.33

μ^+:
p_T = 4.74 GeV/c^2
η = −0.39

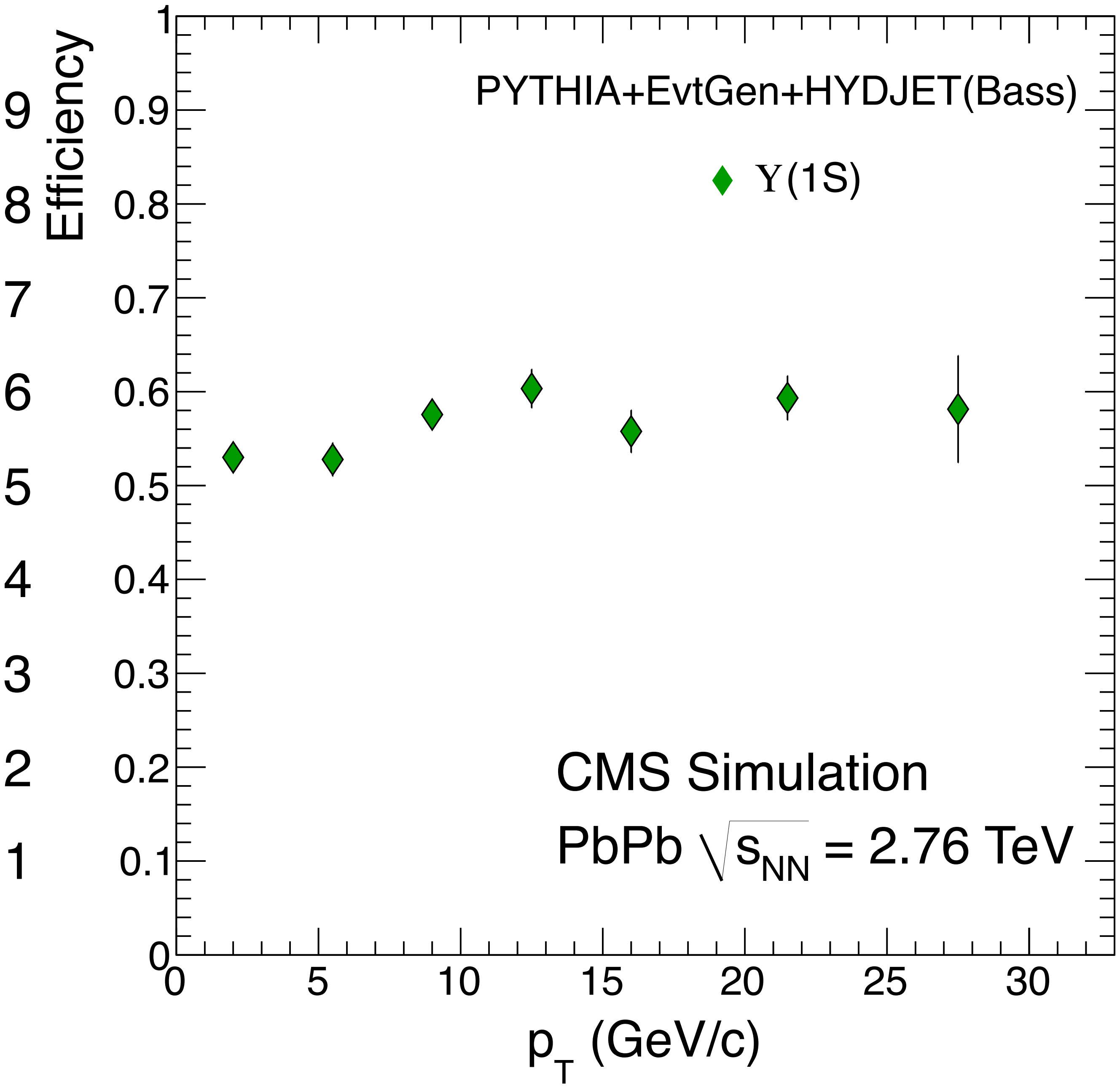
μ^-:
p_T = 4.70 GeV/c^2
η = −0.28

Υ(1S) Acceptance and Efficiency

Acceptance

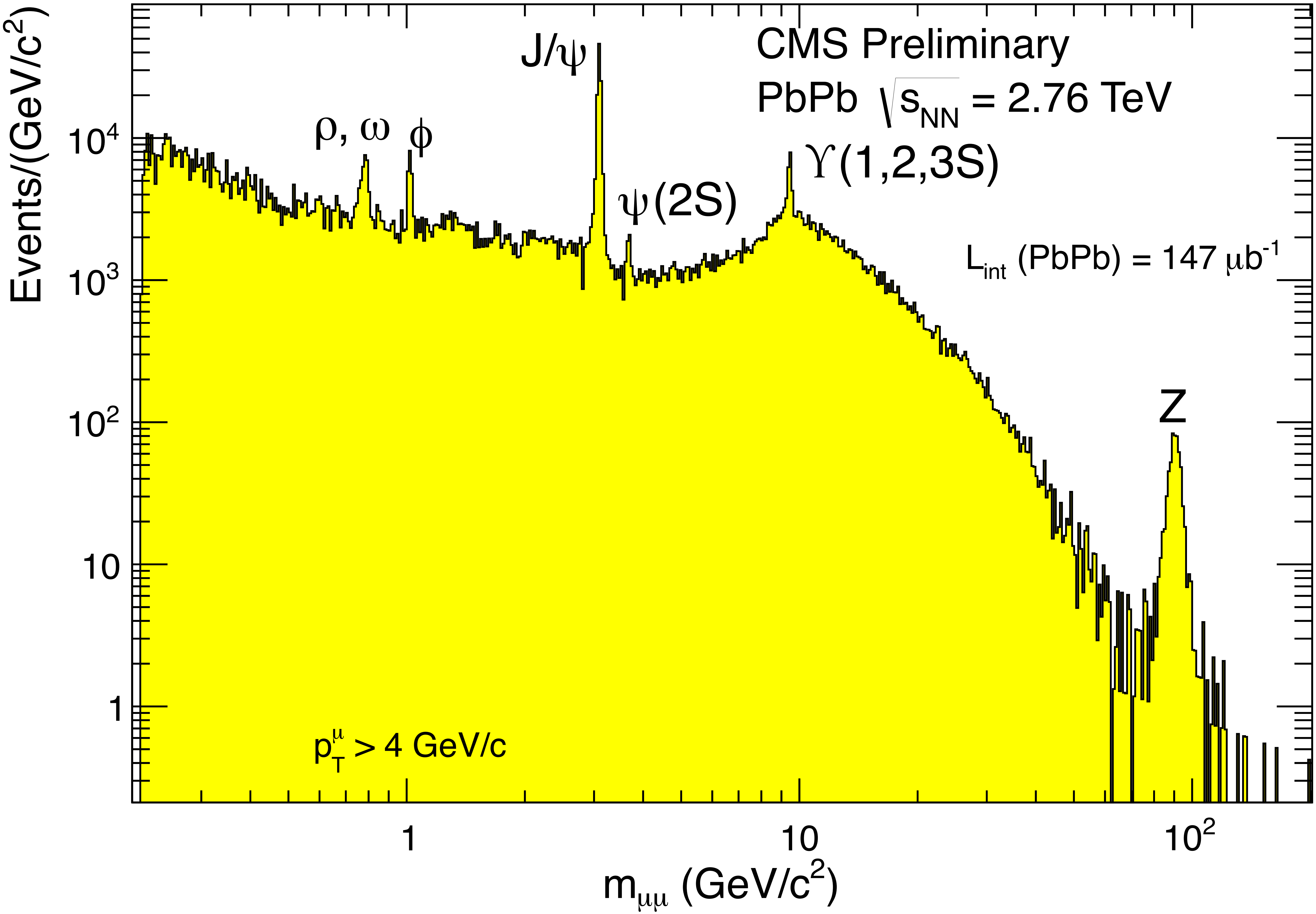


Efficiency



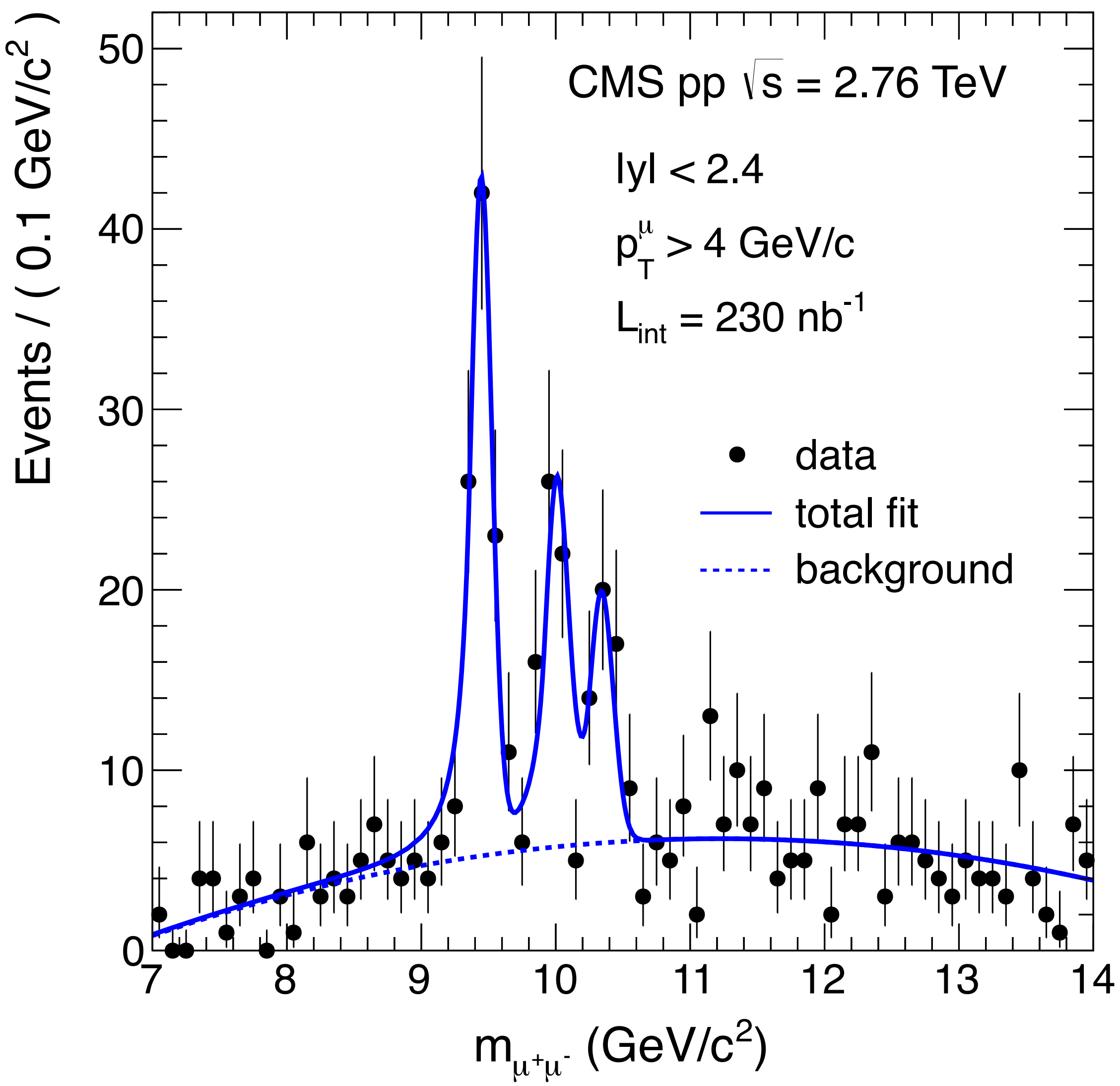
- Efficiencies from Monte Carlo
  - Validated with data driven method (Tag & Probe)
- Acceptance to $p_T = 0$ GeV/c

Muon Pairs in PbPb at $\sqrt{s_{NN}}$ = 2.76 TeV

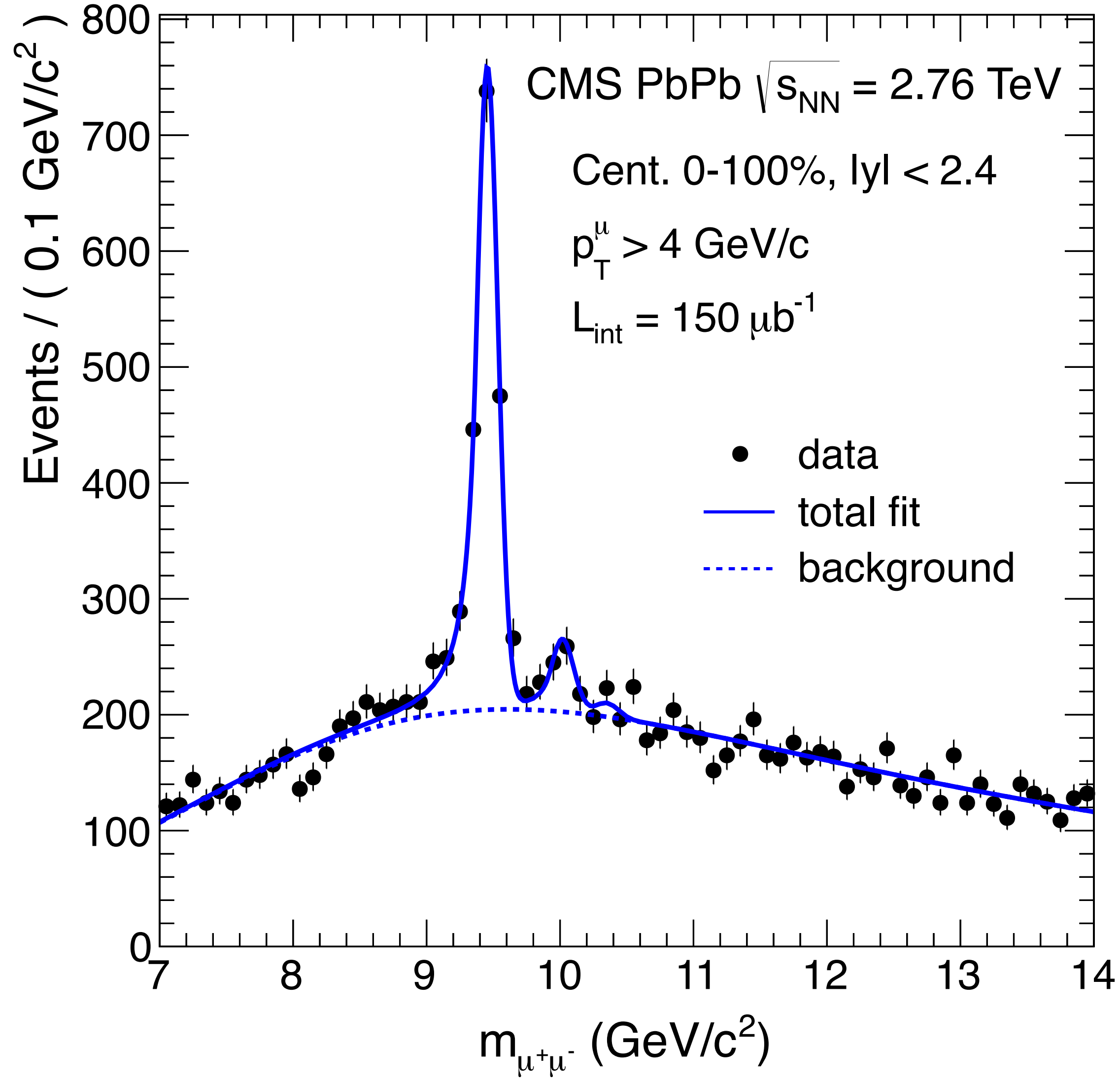


ϒ(nS)/ϒ(1S) Single Ratios

pp



PbPb



$$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{pp} = 0.56 \pm 0.13 \pm 0.02$$
$$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{pp} = 0.41 \pm 0.11 \pm 0.04$$

$$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{PbPb} = 0.12 \pm 0.03 \pm 0.02$$
$$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{PbPb} < 0.07$$

Limited by pp statistics!

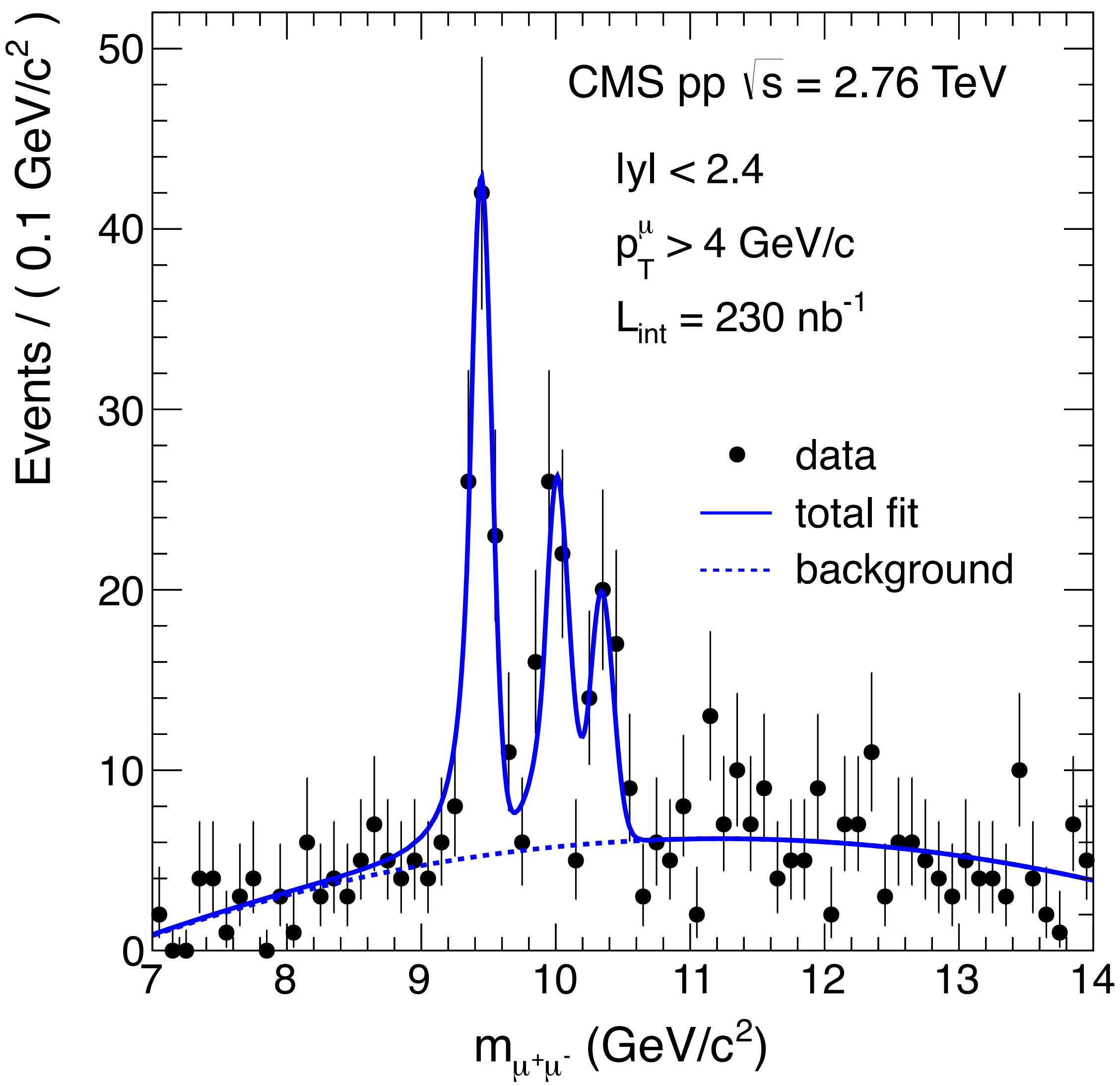
	pp	PbPb
ϒ(1S)	88 ± 11	1317 ± 73
ϒ(2S)	49 ± 10	156 ± 38

Ratios not corrected for acceptance and efficiency

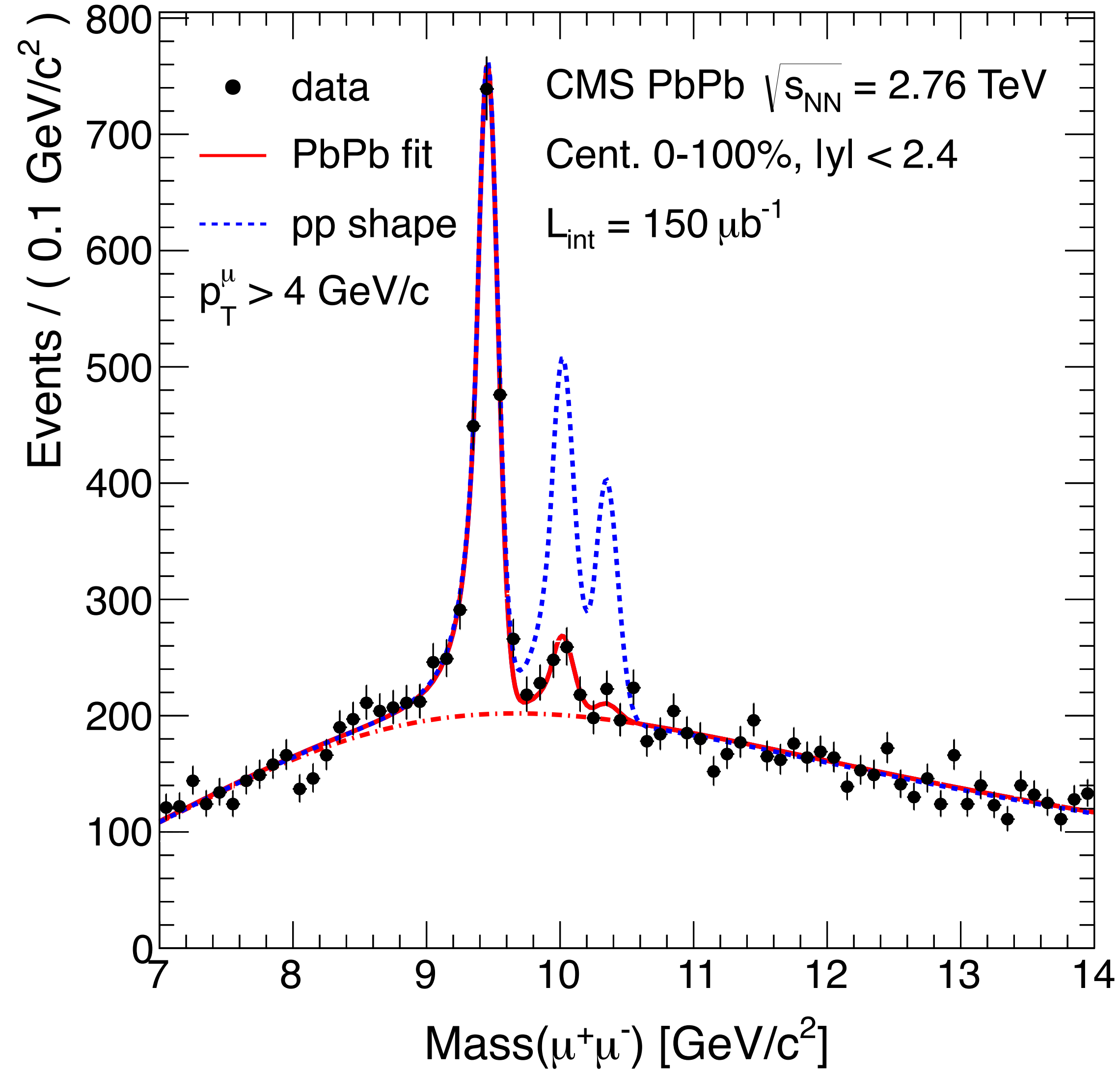
CMS HIN-11-011
PRL 109 (2012) 222301

Υ(nS)/Υ(1S) Single Ratios

pp



PbPb



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CMS HIN-11-011
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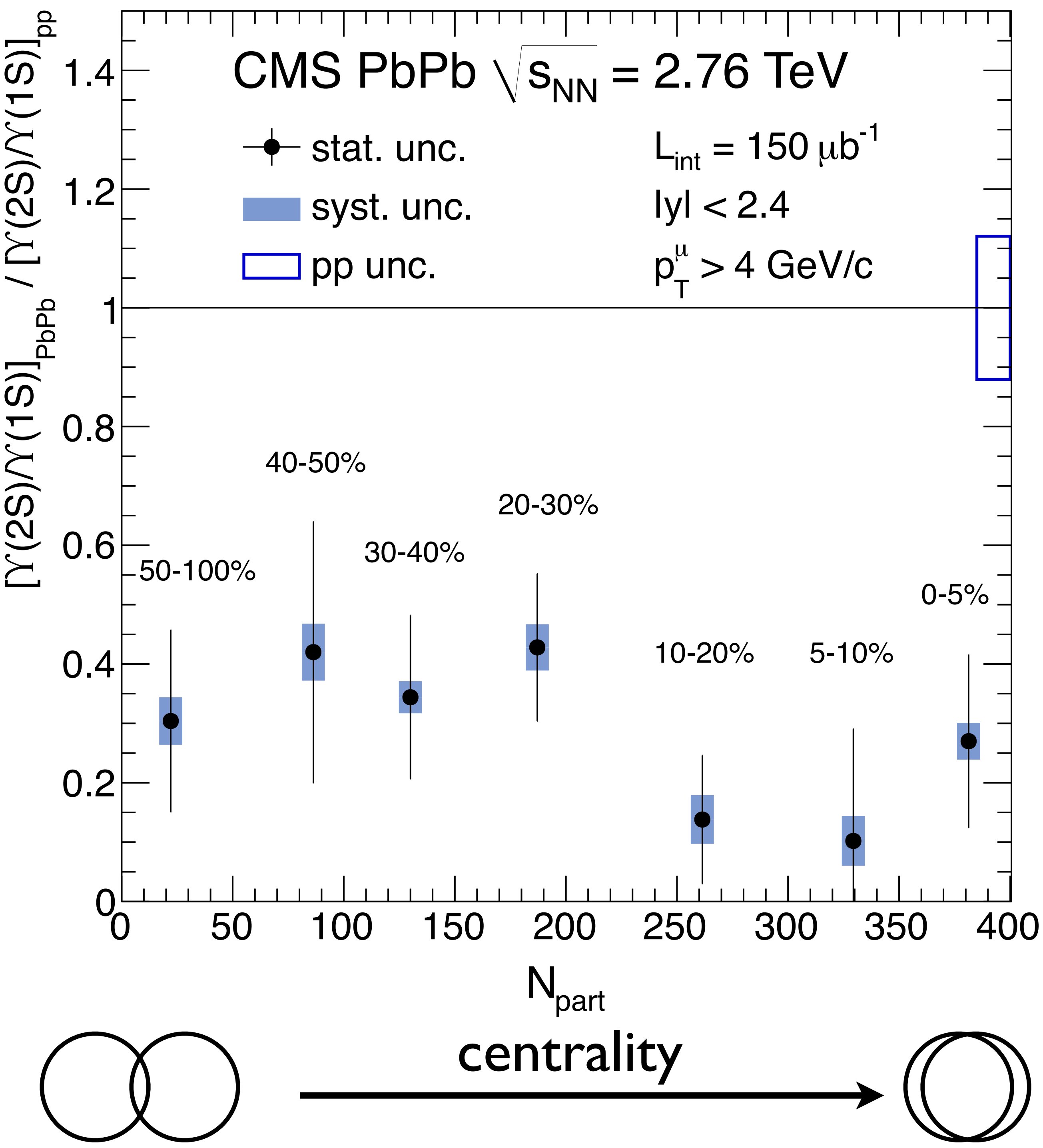
Υ(nS)/Υ(1S) Double Ratio



- Separated Υ(2S) and Υ(3S)
- Measured Υ(2S)/Υ(1S) double ratio vs. centrality
  - Centrality integrated

$$\frac{N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{\text{PbPb}}}{N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{\text{pp}}} = 0.21 \pm 0.07 \pm 0.02$$

  - No strong centrality dependence
- Upper limit on Υ(3S)
  - Centrality integrated:

$$\frac{N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{\text{PbPb}}}{N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{\text{pp}}} < 0.17 \ (95\% \text{ C.L.})$$

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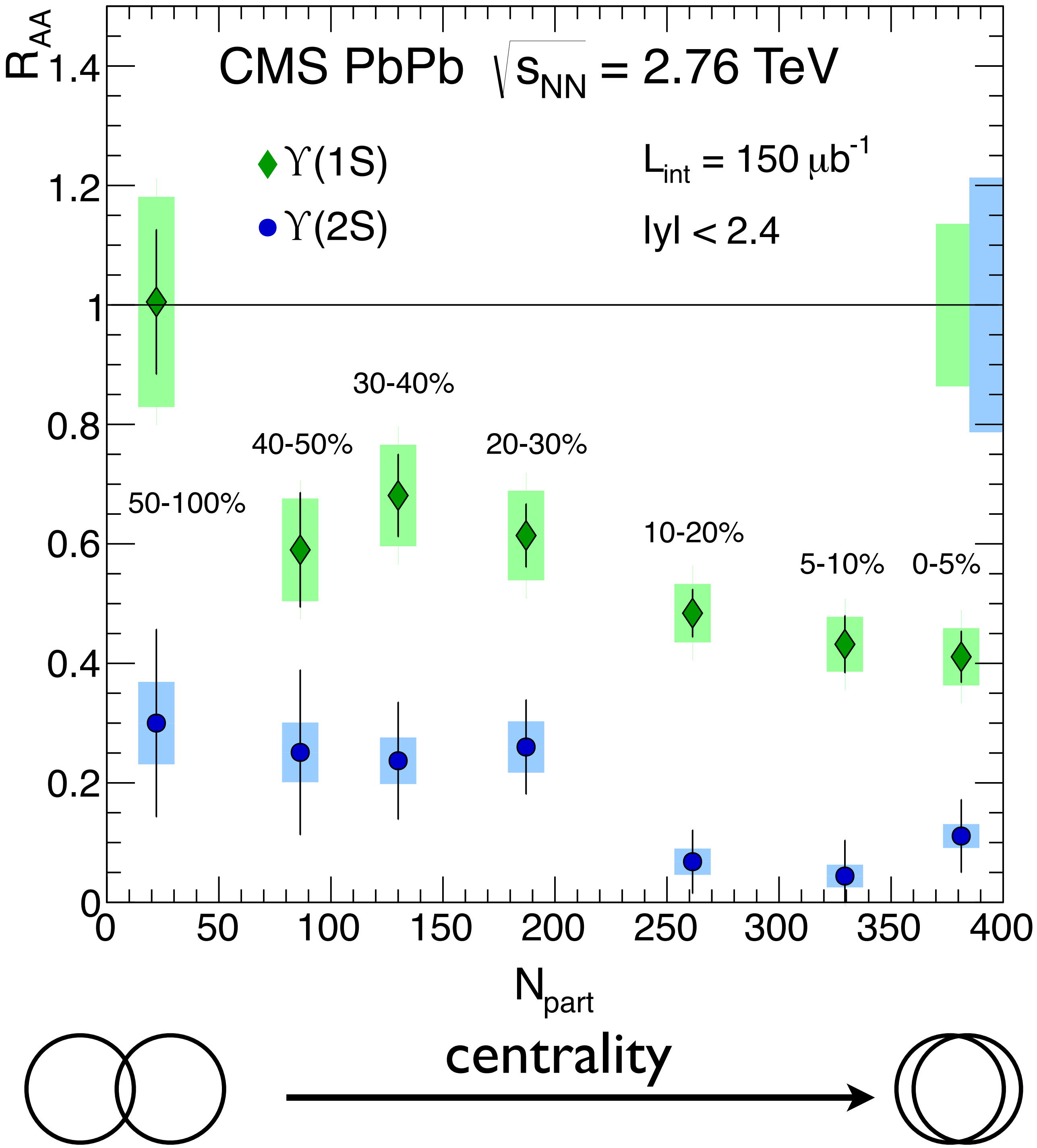
PRL 109 (2012) 222301

Υ(nS) R_{AA} vs. Centrality

$$R_{AA} = \frac{N_{\mathrm{PbPb}}}{N_{\mathrm{coll}} \cdot N_{pp}}$$



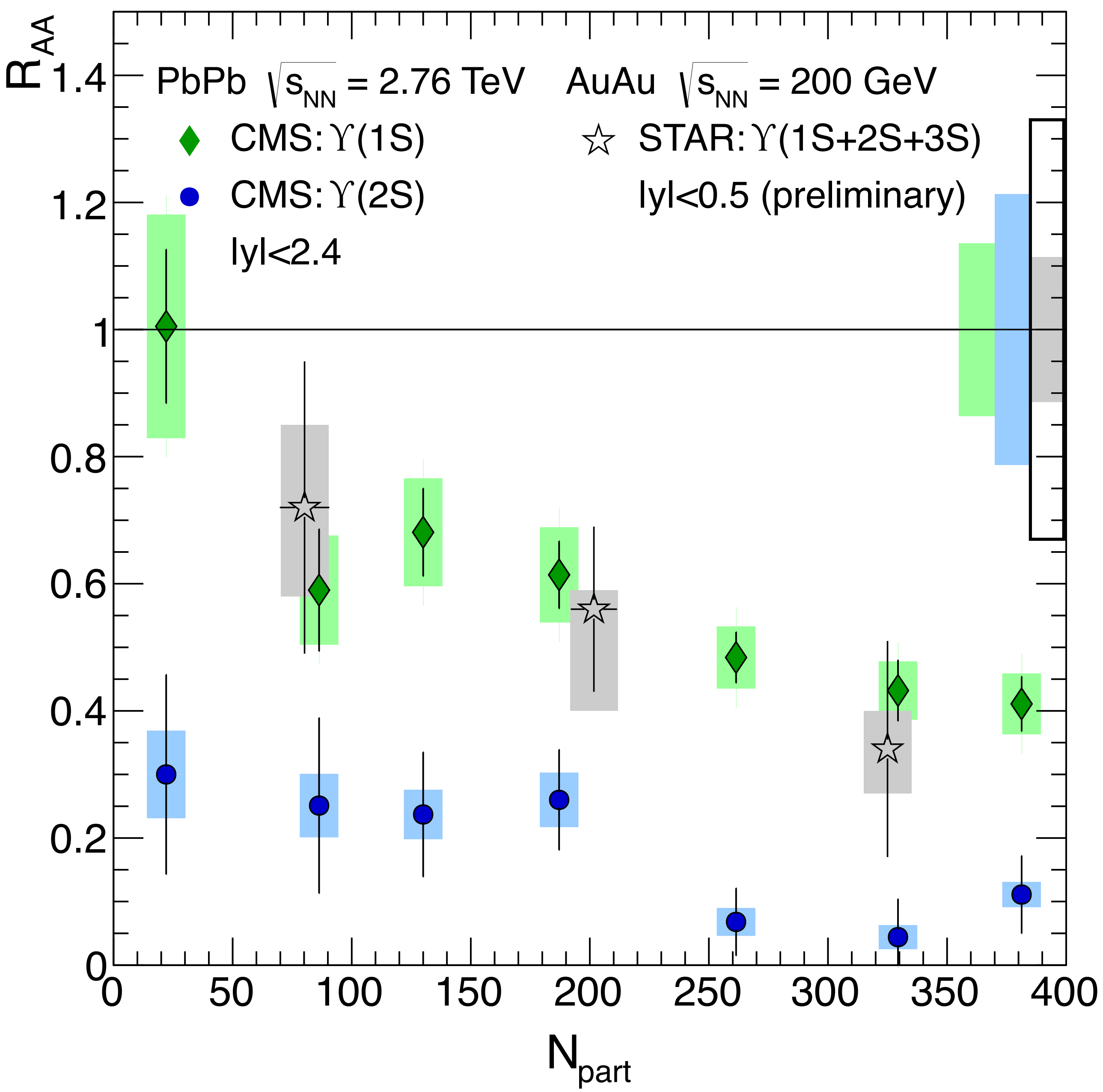
- Υ(1S) R_{AA} in 7 centrality bins
- Clear suppression of Υ(2S)
- Υ(1S) suppression consistent with excited state suppression (~50% feed down)
- Centrality integrated:

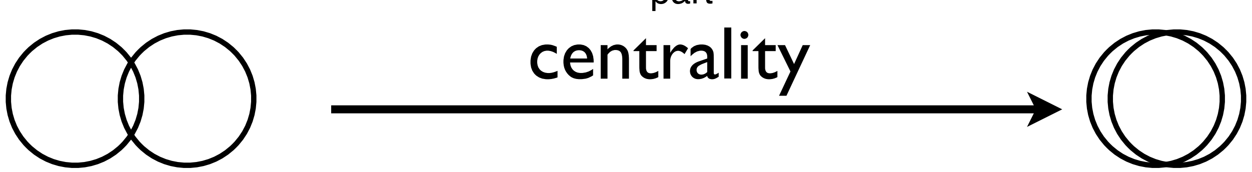
$$R_{AA}(\Upsilon(1S)) = 0.56 \pm 0.08\,(\mathrm{stat.}) \pm 0.07\,(\mathrm{syst.})$$
$$R_{AA}(\Upsilon(2S)) = 0.12 \pm 0.04\,(\mathrm{stat.}) \pm 0.02\,(\mathrm{syst.})$$
$$R_{AA}(\Upsilon(3S)) < 0.1 \;\; (\mathrm{at}\ 95\%\ \mathrm{C.L.})$$

- Sequential suppression of the three states in order of their binding energy

CMS HIN-11-011
PRL 109 (2012) 222301

Υ(nS) R_{AA}: comparison to RHIC (STAR)





- STAR measured R_{AA} of Υ(1S+2S+3S) combined (arXiv:1109.3891)
  - Centrality integrated:

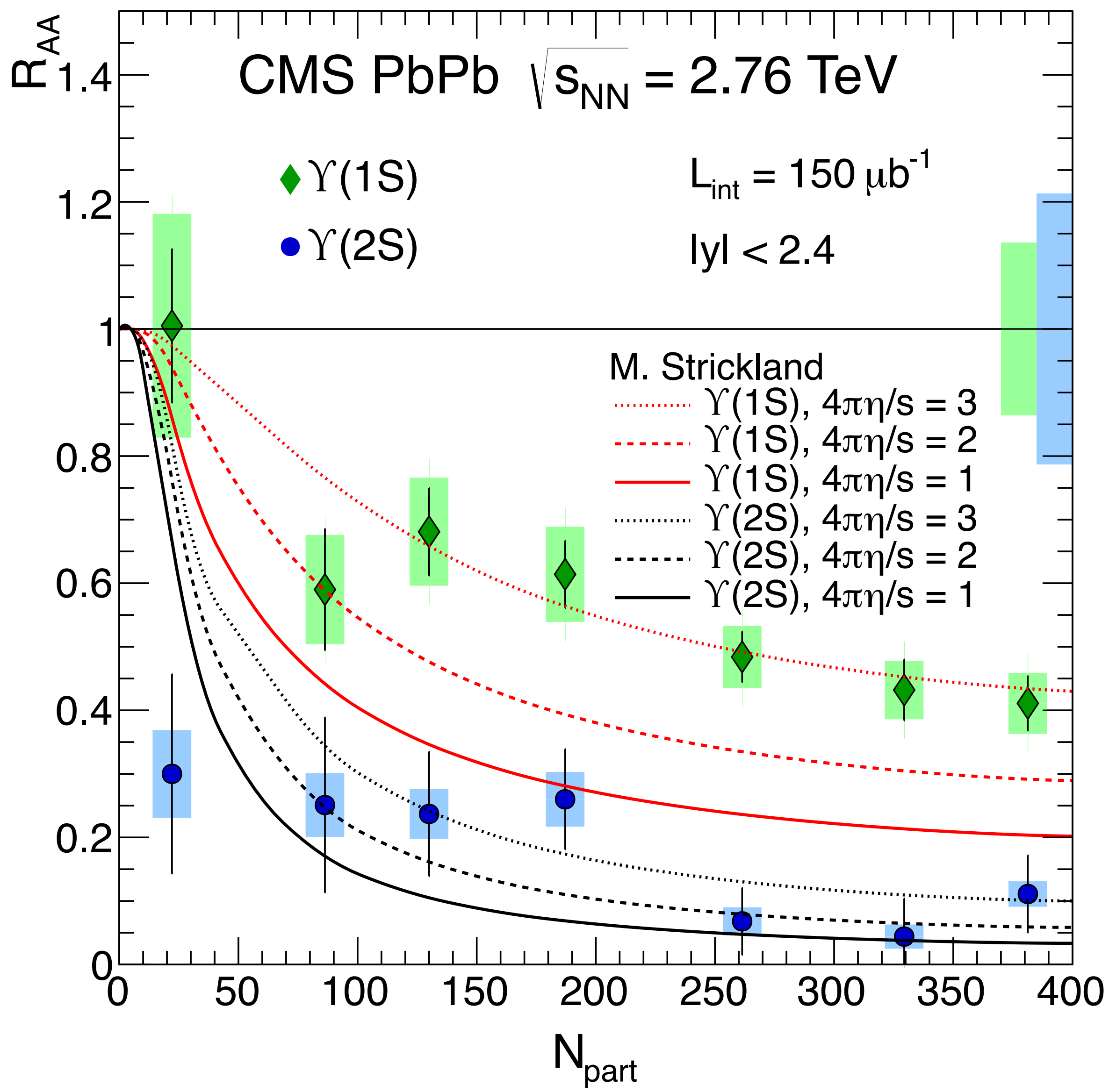
$$R_{AA}(\Upsilon(1S+2S+3S)) = 0.56 \pm 0.21^{+0.08}_{-0.16}$$

- CMS: separate R_{AA} for Υ(1S), Υ(2S), Υ(3S)
  - Can calculate centrality integrated R_{AA} of Υ(1S+2S+3S):

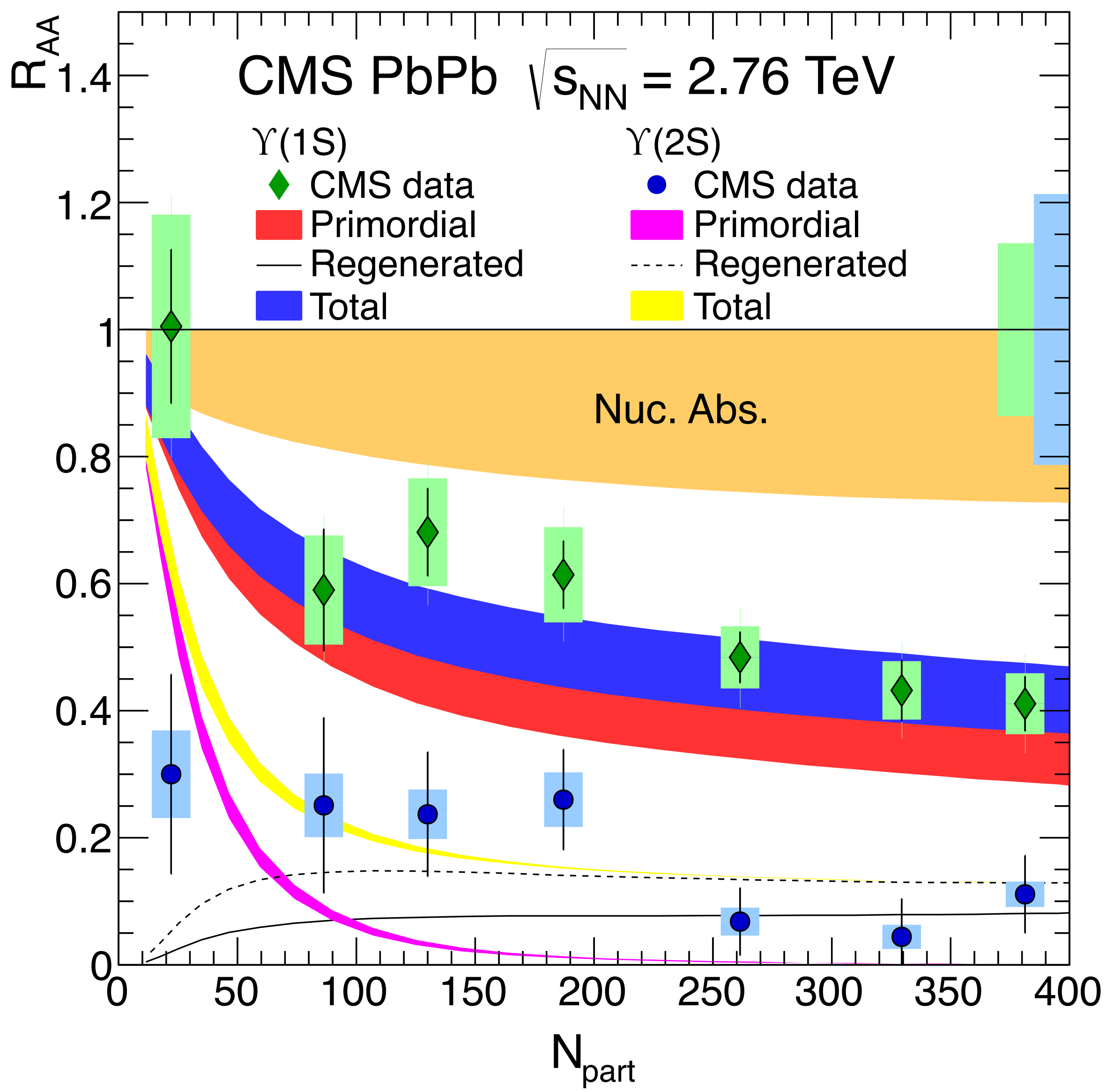
$$R_{AA}(\Upsilon(1S+2S+3S))$$
$$= R_{AA}(\Upsilon(1S)) \times \frac{1+\Upsilon(2S+3S)/\Upsilon(1S)|_{\mathrm{PbPb}}}{1+\Upsilon(2S+3S)/\Upsilon(1S)|_{\mathrm{pp}}}$$
$$= 0.56 \times \frac{1+0.14}{1+0.97} \approx 0.32$$

CMS HIN-11-011
PRL 109 (2012) 222301

Bottomonia: Theory meets Experiment



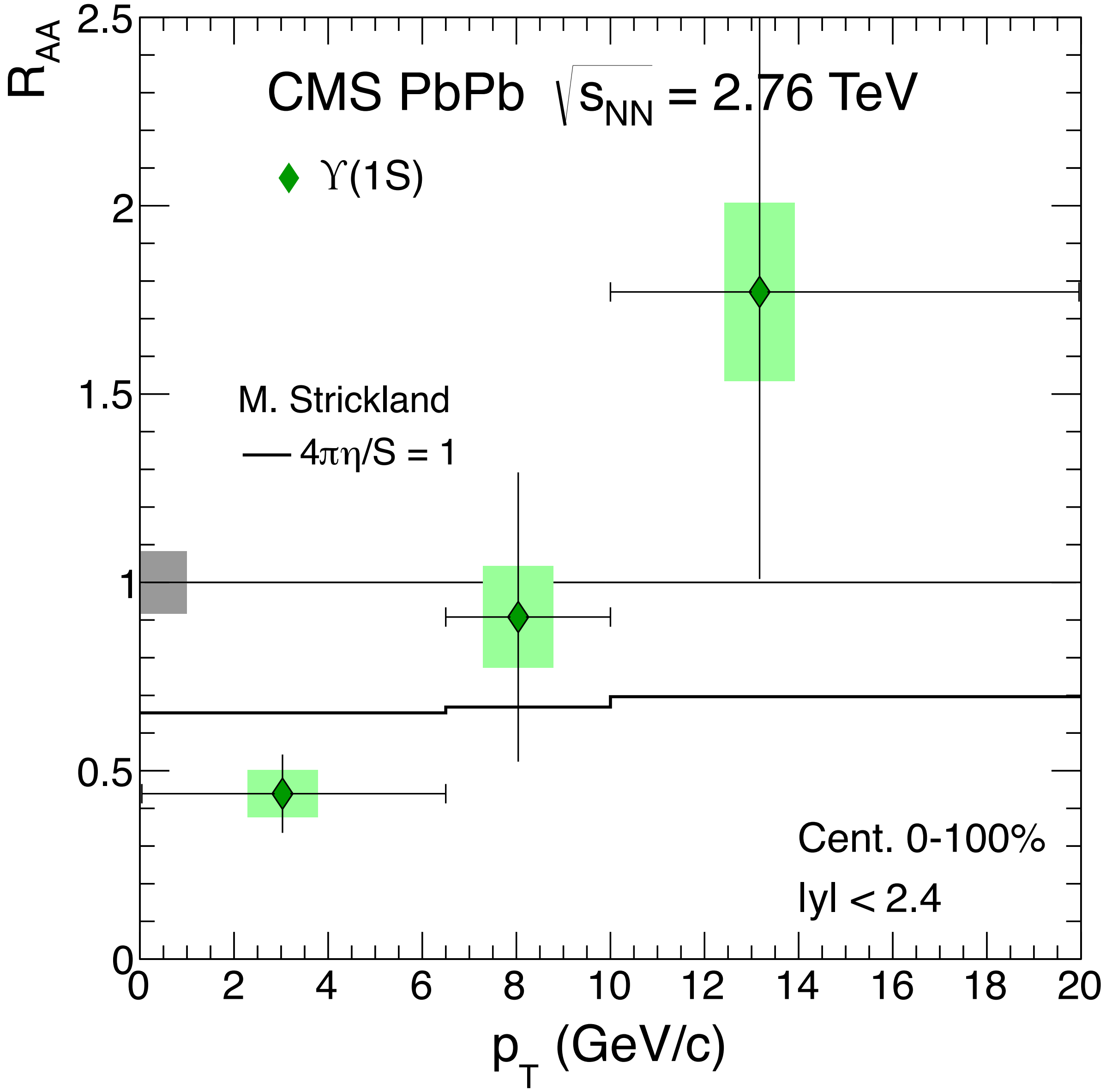
Strickland arXiv:1207.5327

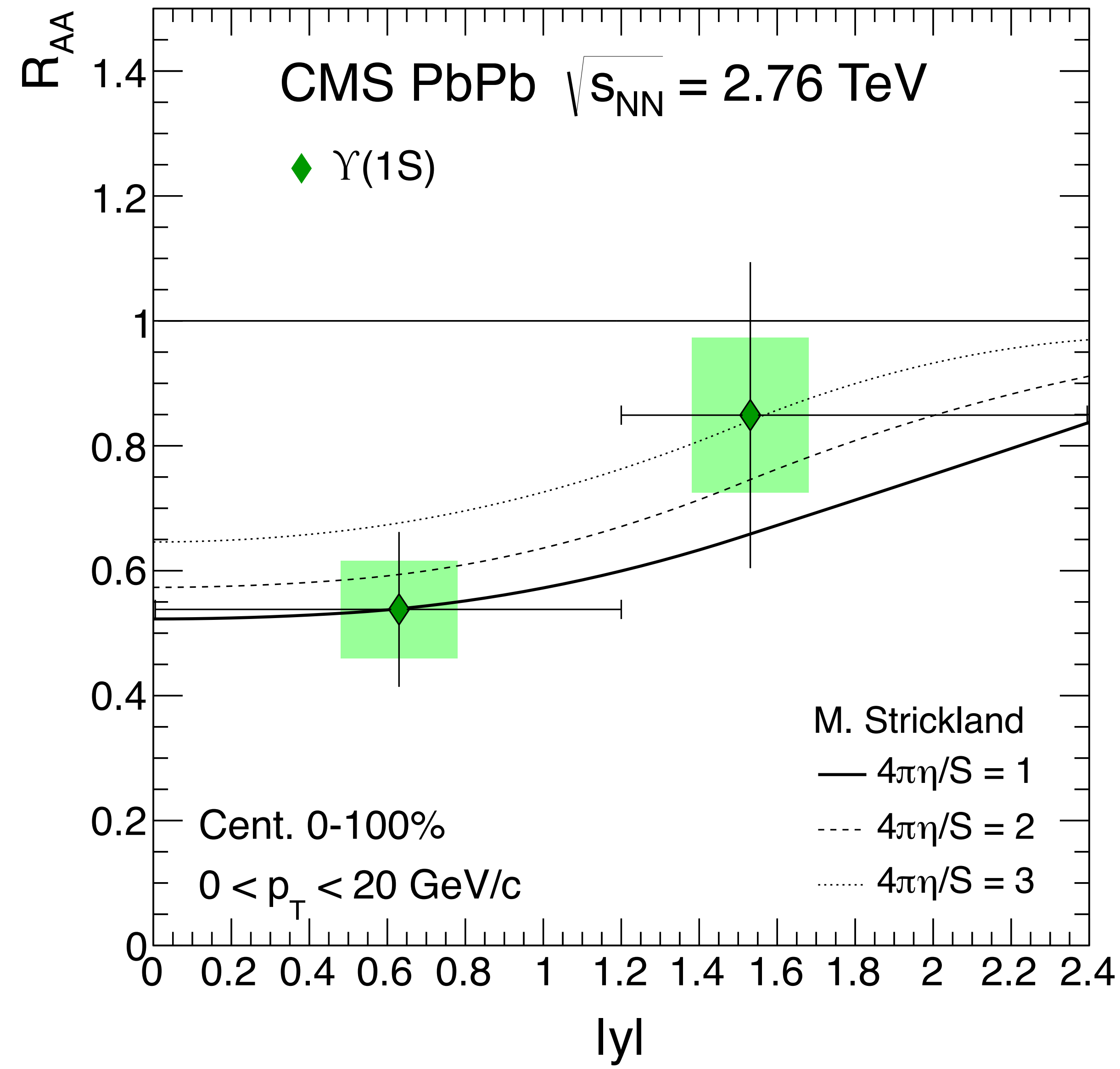


Rapp et al. EPJ A48 (2012) 72

- Strickland: some tension to describe Υ(1S) and Υ(2S) simultaneously with the same η/S value
- Rapp: regeneration and nuclear absorption could be significant also for bottomonia

Υ(1S) R_{AA}: rapidity and p_T dependence



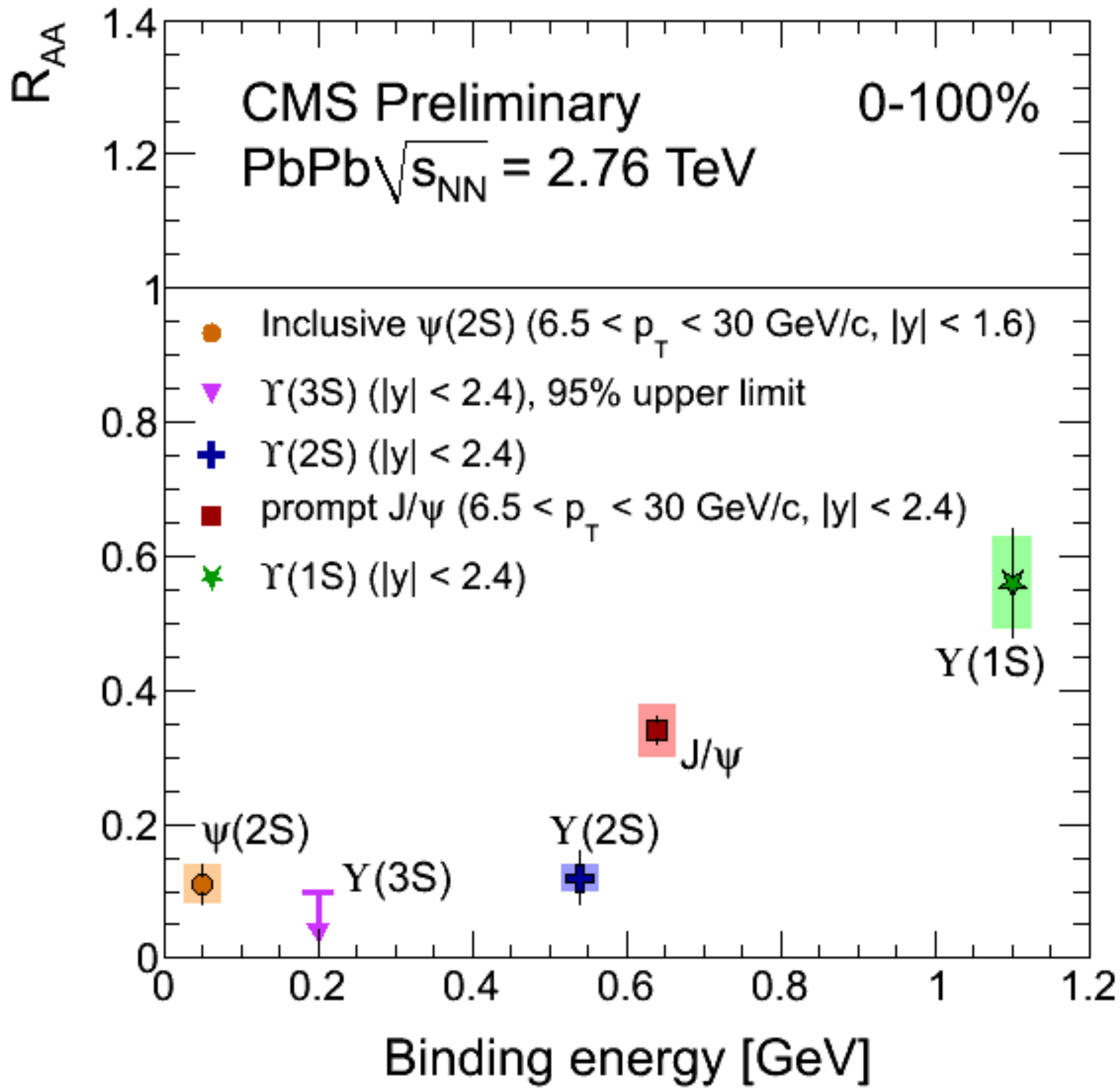


- Υ(1S) suppressed at low p_T, no clear rapidity dependence
  - Based on 2010 PbPb data (L_{int} = 7.28 μb^{-1}) and 2011 pp data (230 nb^{-1})
- In 2011 PbPb sample was increased by a factor 20 (150 μb^{-1}):
  - p_T and y dependence limited by pp statistics
  - Recorded ~5.4 pb^{-1} of pp collision in 2013: will improve measurement of R_{AA} vs. p_T and y

Strickland
PRL 107 (2011) 132301

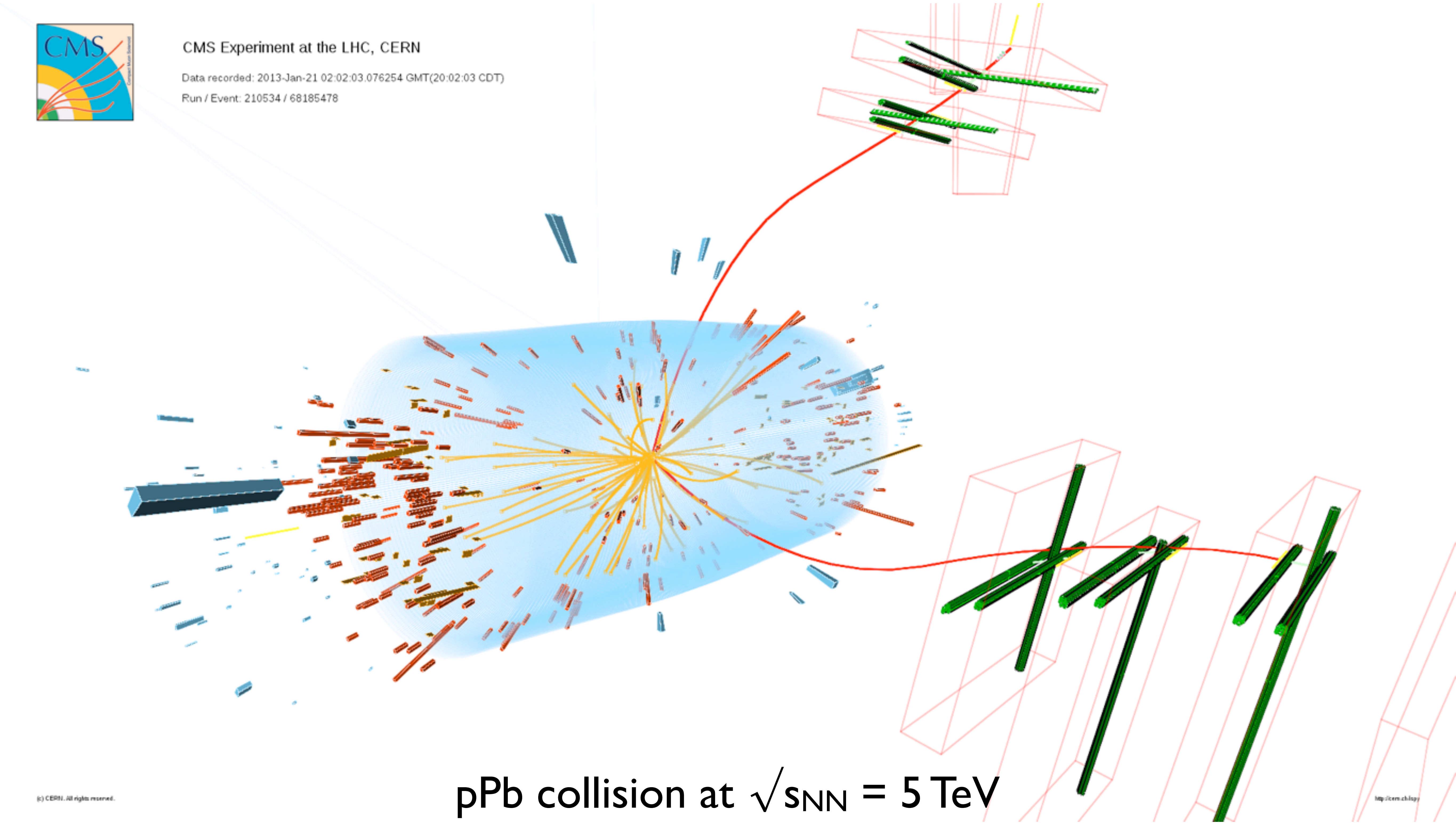
CMS HIN-10-006
JHEP 05 (2012) 063

Summary



- Clear ordering of the suppression of the three ϒ states with their binding energy
  - As expected from sequential melting
  - Charmonium states at high p_T follow the same trend
- R_{AA} vs. rapidity and p_T?
  - Recent high statistics pp run (5.4 pb^{-1}) will provide crucial baseline
- Cold nuclear matter effects?
  - Recent pPb run will help to quantify them
- ALICE:
  - Expecting results on ϒ suppression in 2.5<y<4 soon

Υ(1S) candidate in pPb at $\sqrt{s_{NN}}$ = 5 TeV

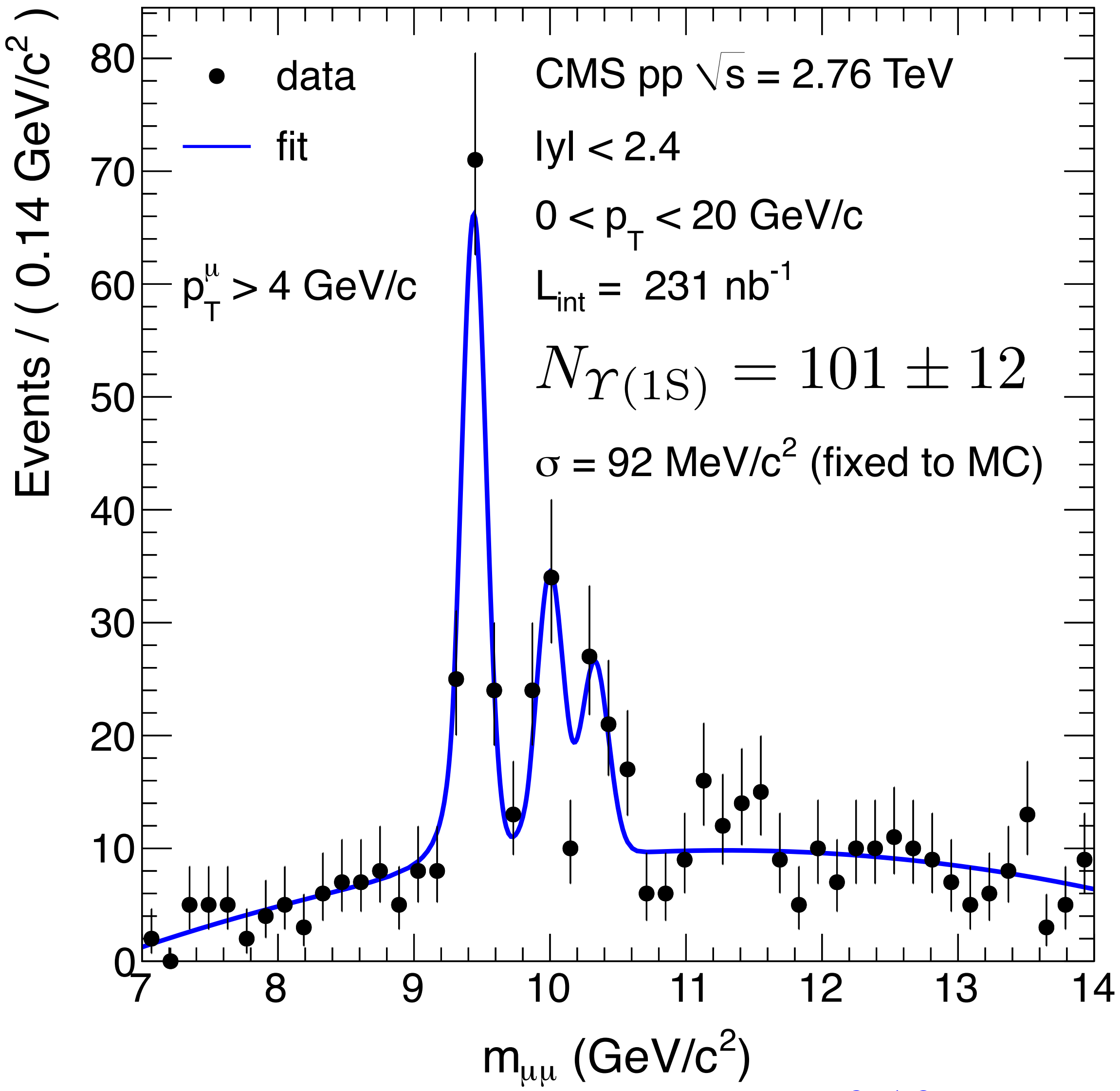


CMS DP-2013-001

Backup

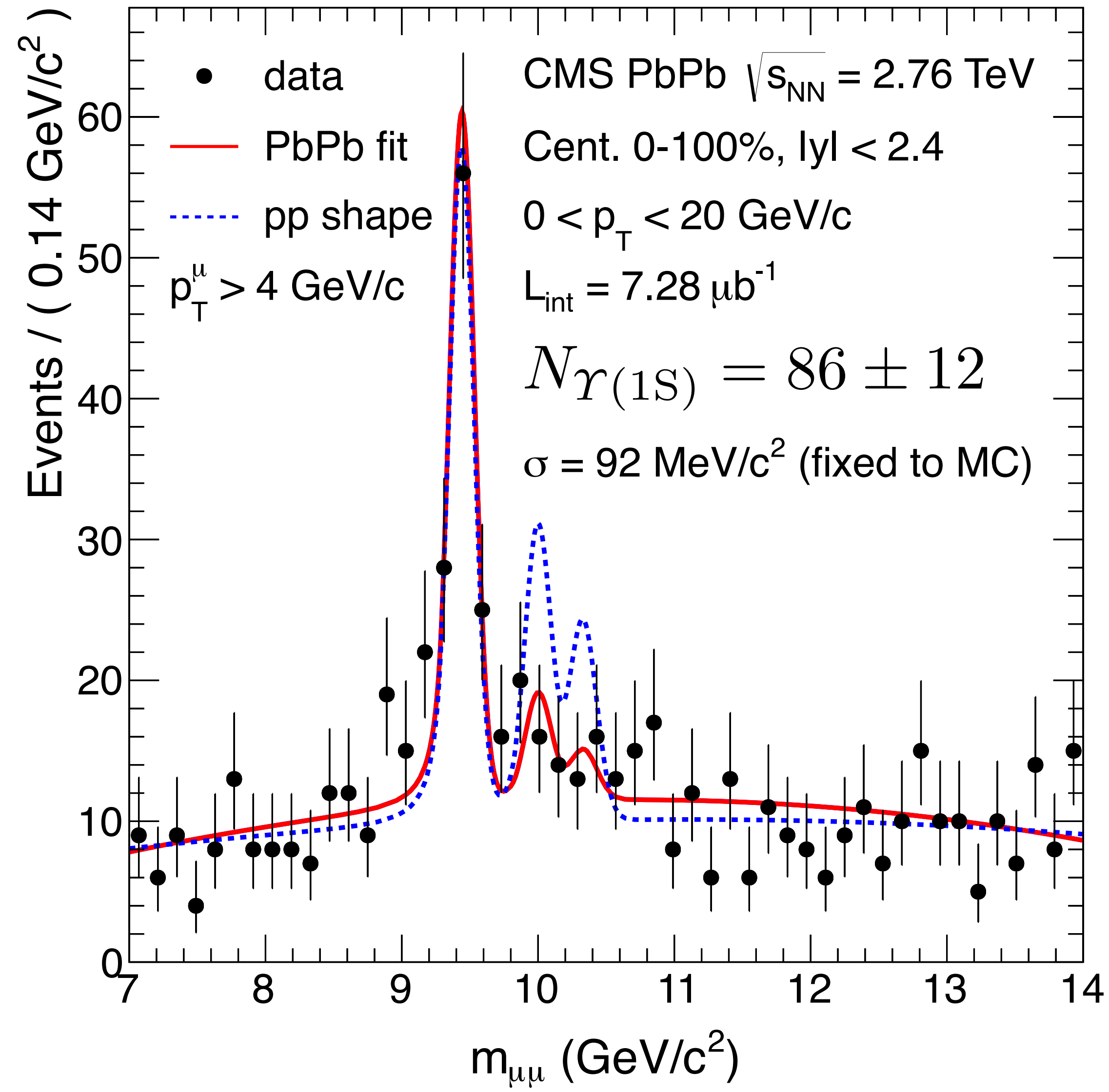
Bottomonia: with 2010 data

pp



$\Upsilon(2S+3S)/\Upsilon(1S)|_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02$

PbPb



$\Upsilon(2S+3S)/\Upsilon(1S)|_{PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02$

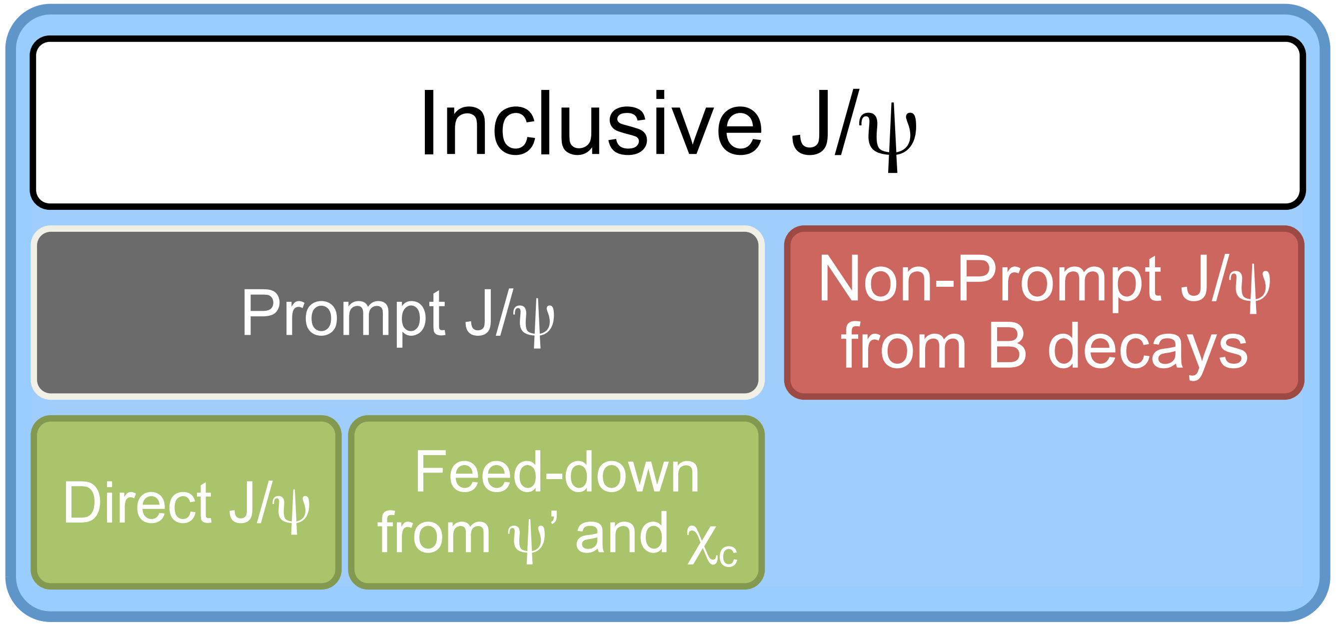
- Measure ϒ(2S+3S) production relative to ϒ(1S) production
- Simultaneous fit to pp and PbPb data at 2.76 TeV

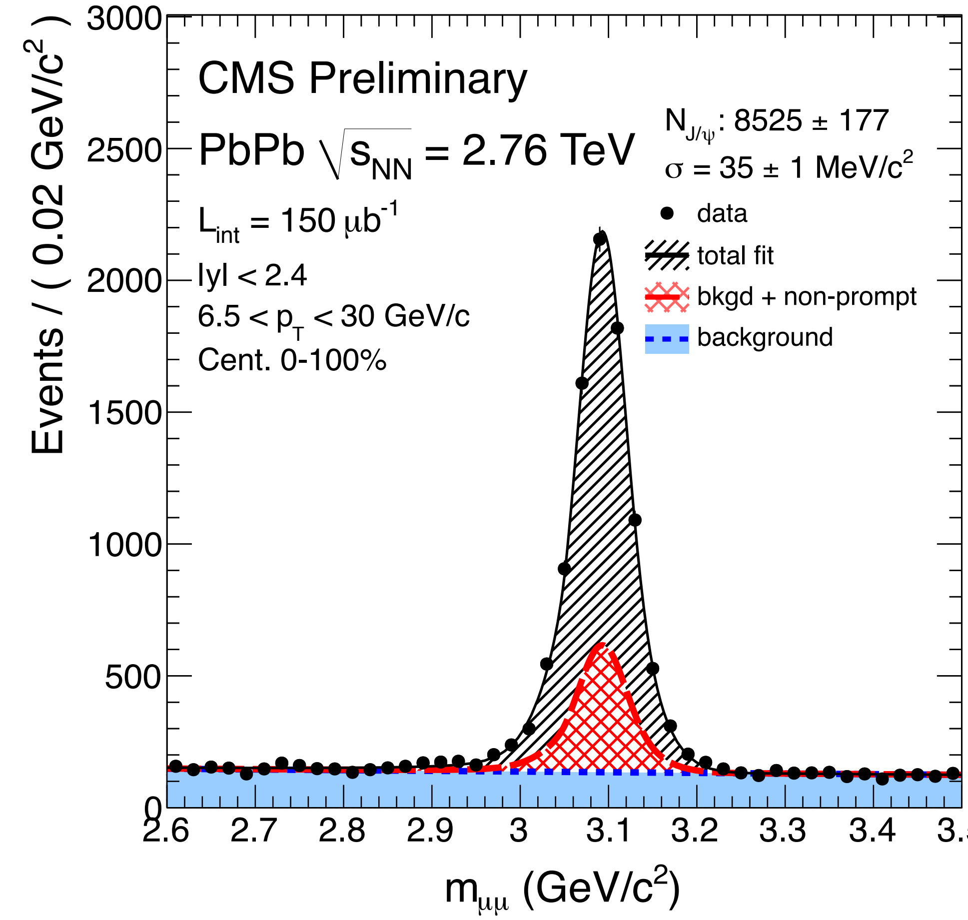
PRL 107 (2011) 052302

$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

- Probability to obtain measured value, or lower, if the real double ratio is unity, has been calculated to be less than 1%

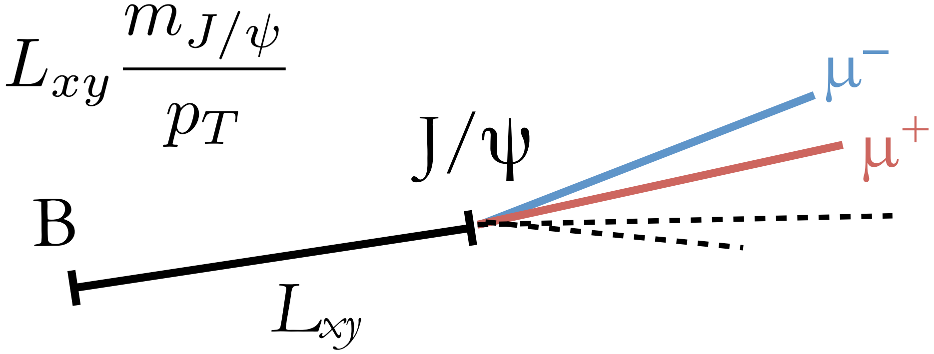
J/ψ in PbPb at $\sqrt{s_{NN}}$ = 2.76 TeV

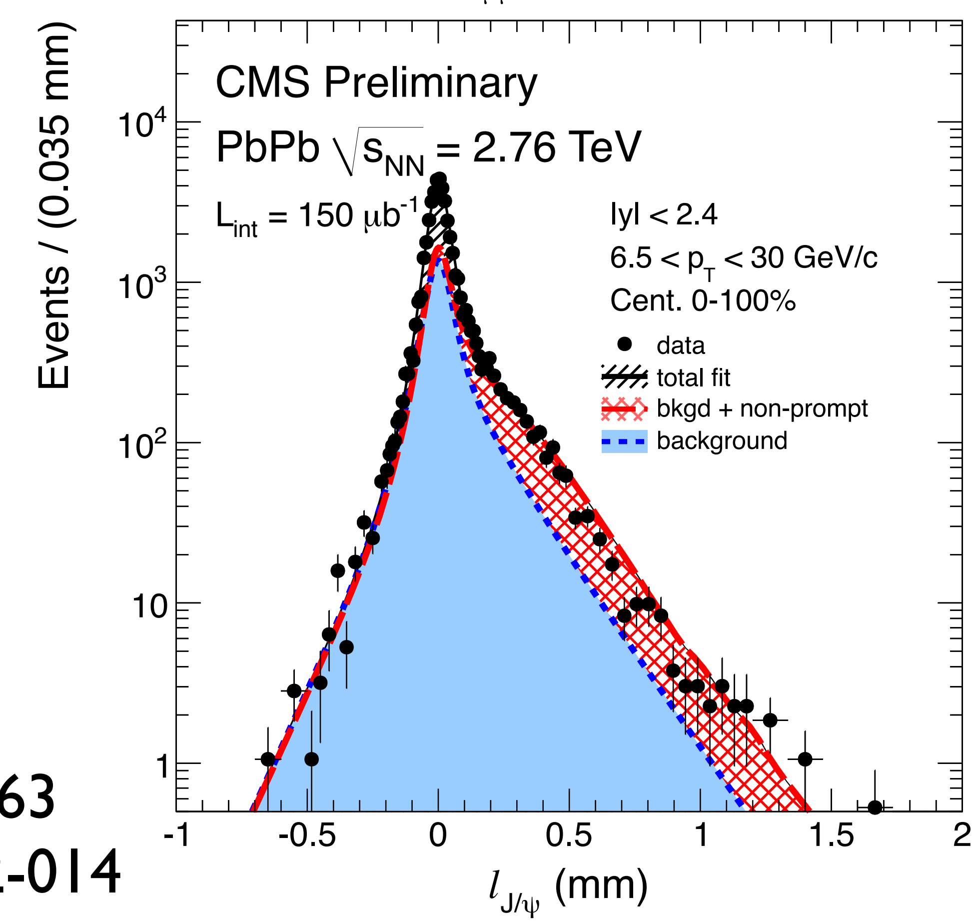




- Non-prompt J/ψ become significant towards higher p_T (20–30%)!
- Reconstruct $\mu^+\mu^-$ vertex
- Simultaneous fit of $\mu^+\mu^-$ mass and pseudo-proper decay length

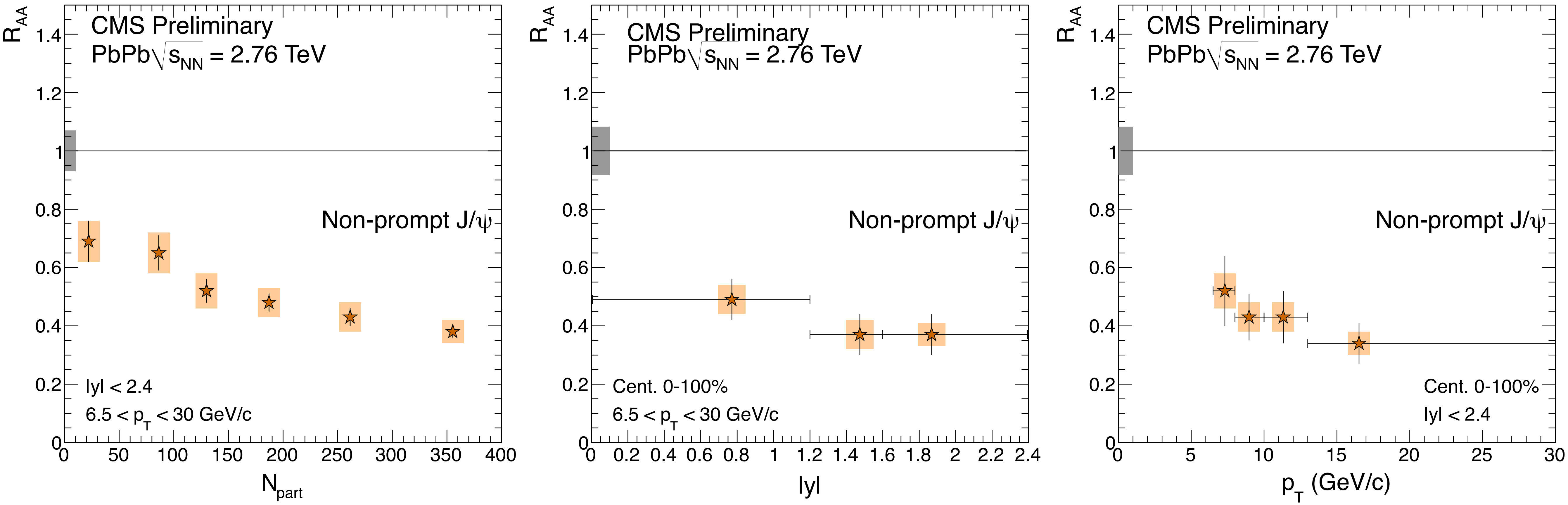
$$\ell_{J/\psi} = L_{xy}\frac{m_{J/\psi}}{p_T}$$





2010 data: JHEP 05 (2012) 063
2011 data: CMS PAS HIN-12-014

Open Bottom: Non-prompt J/ψ R_{AA}

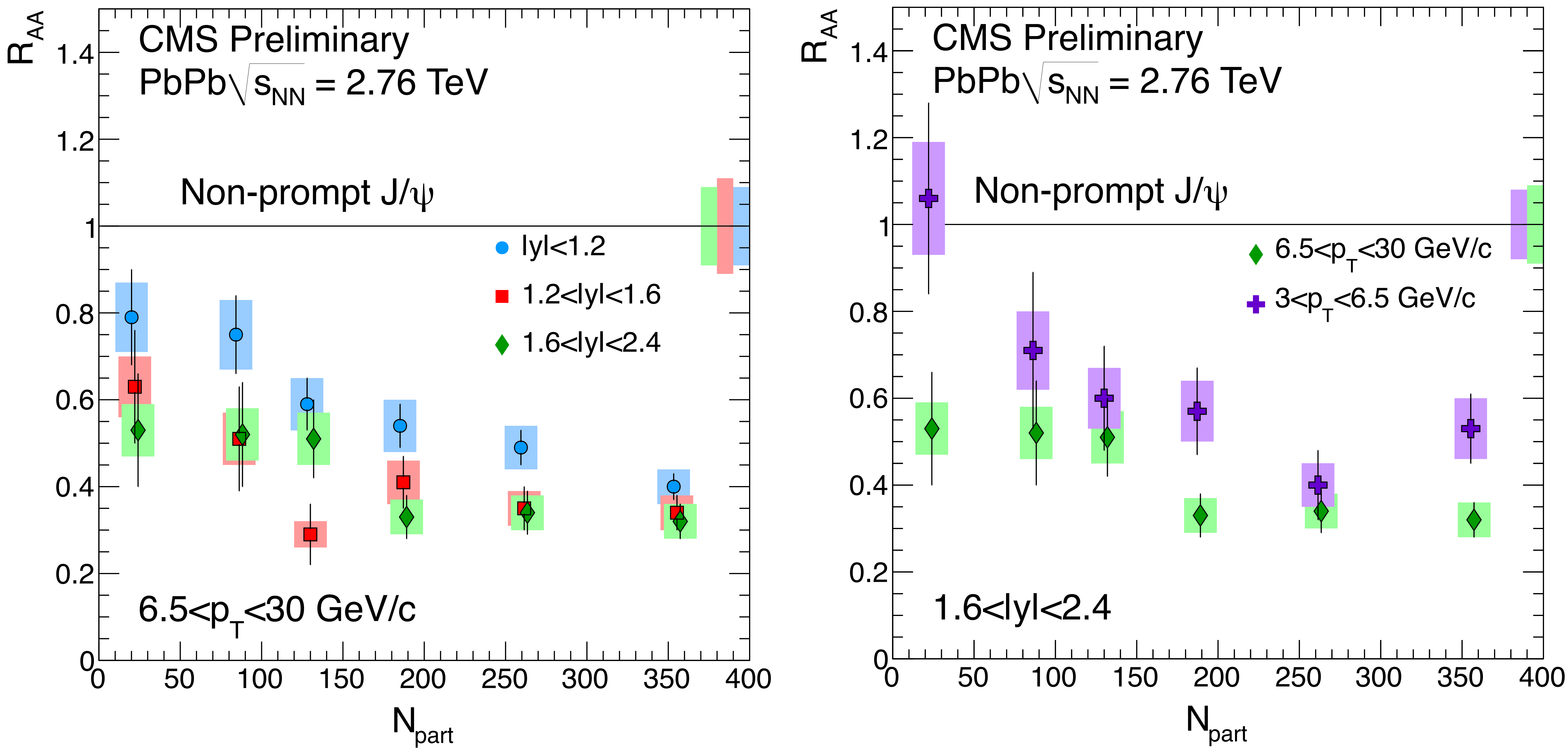


$$R_{AA} = \frac{\mathcal{L}_{pp}}{T_{AA} N_{\rm MB}} \frac{N_{\rm PbPb}}{N_{pp}} \frac{\varepsilon_{pp}}{\varepsilon_{\rm PbPb}}$$

- Non-prompt J/ψ from b-hadron decays: direct access to energy loss of b quarks
- Integrated over $p_T > 6.5$ GeV/c and $|y| < 2.4$
  - in 0–10% centrality: suppressed by a factor 2.5
  - in 50–100% centrality: suppressed by a factor ~1.4
- Integrated over centrality:
  - hint of increasing suppression with rapidity or p_T

CMS PAS HIN-12-014

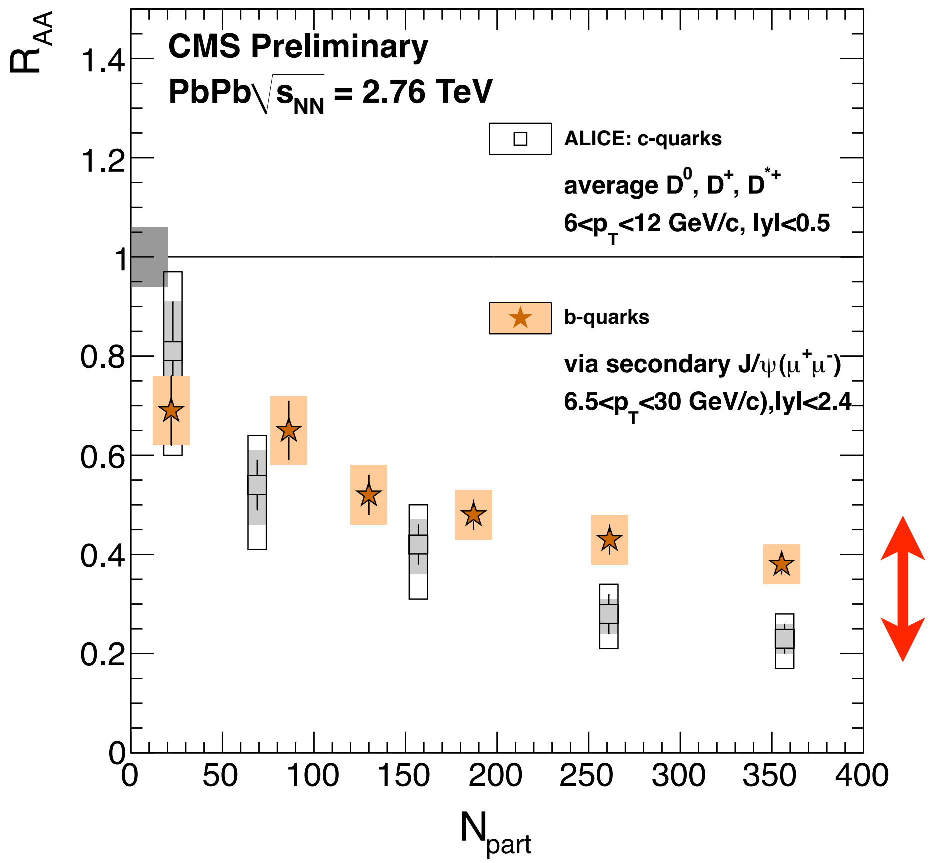
Non-prompt J/ψ R_{AA}: double differential



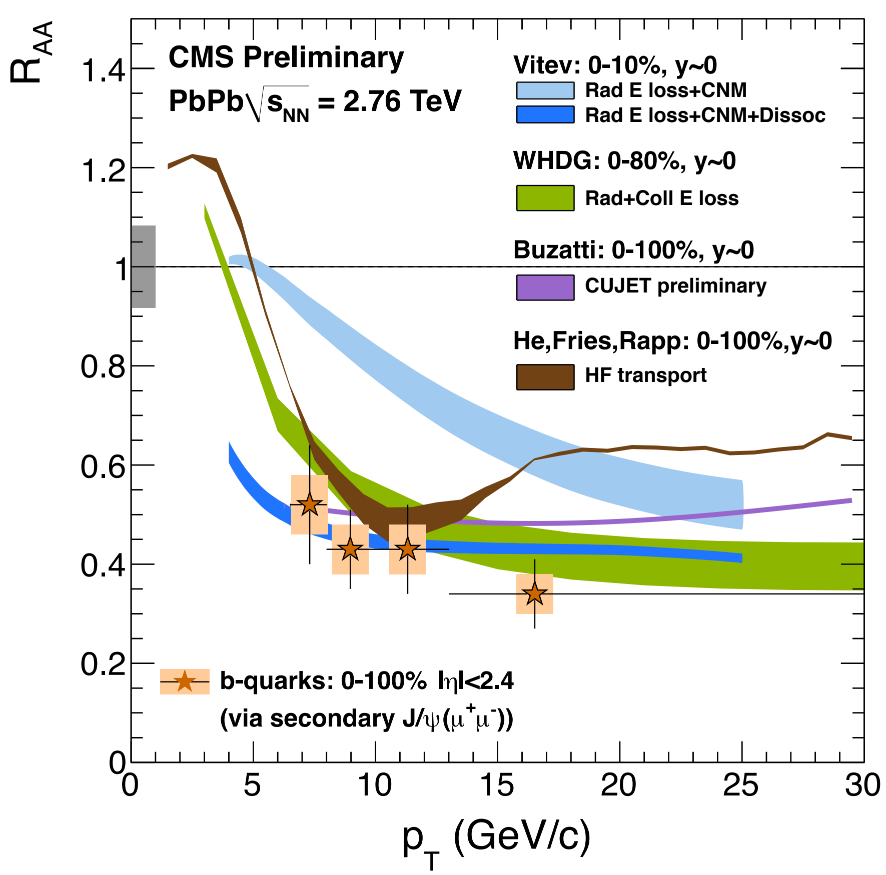
CMS PAS HIN-12-014

- Centrality dependence is independent of rapidity
- At forward rapidity: access to lower p_T ($3 < p_T < 6.5$ GeV/c)
  - slightly less suppression in most central collision at low p_T than at high p_T

Open heavy-flavour



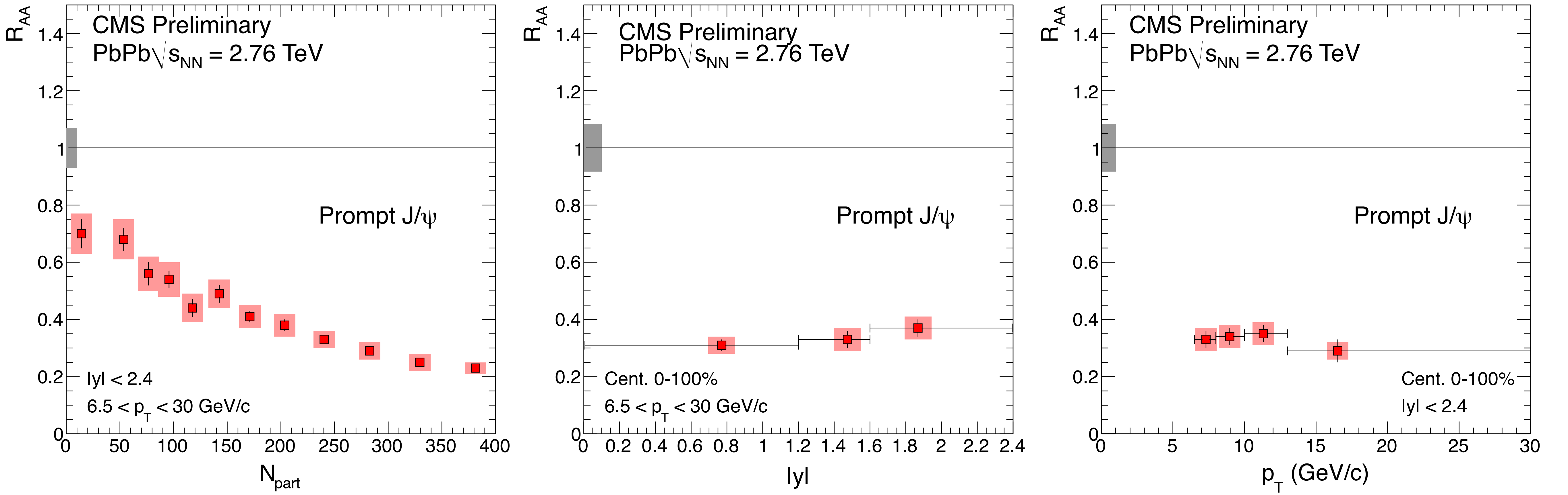
- ALICE measures R_{AA} of various D mesons
- CMS measures non-prompt J/ψ from b-hadron decays
- Expect ordering of suppression with quark mass
  - a.k.a. “dead-cone effect”
- There is order!



- Radiative energy loss alone is not enough to describe b-quark energy loss
- Models do not decay B, so are for B p_T
  - B p_T > J/ψ p_T (at high p_T)

CMS: PAS HIN-12-014
ALICE: JHEP 09 (2012) 112
Vitev: J. Phys.G35 (2008) 104011 + priv. comm.
Horowitz: arXiv:1108.5876 + priv. comm.
Buzzatti, Gyulassy: arXiv: 1207.6020 + priv. comm.
He, Fries, Rapp: PRC86(2012)014903 + priv. comm.

Prompt J/ψ R_{AA} at high p_T

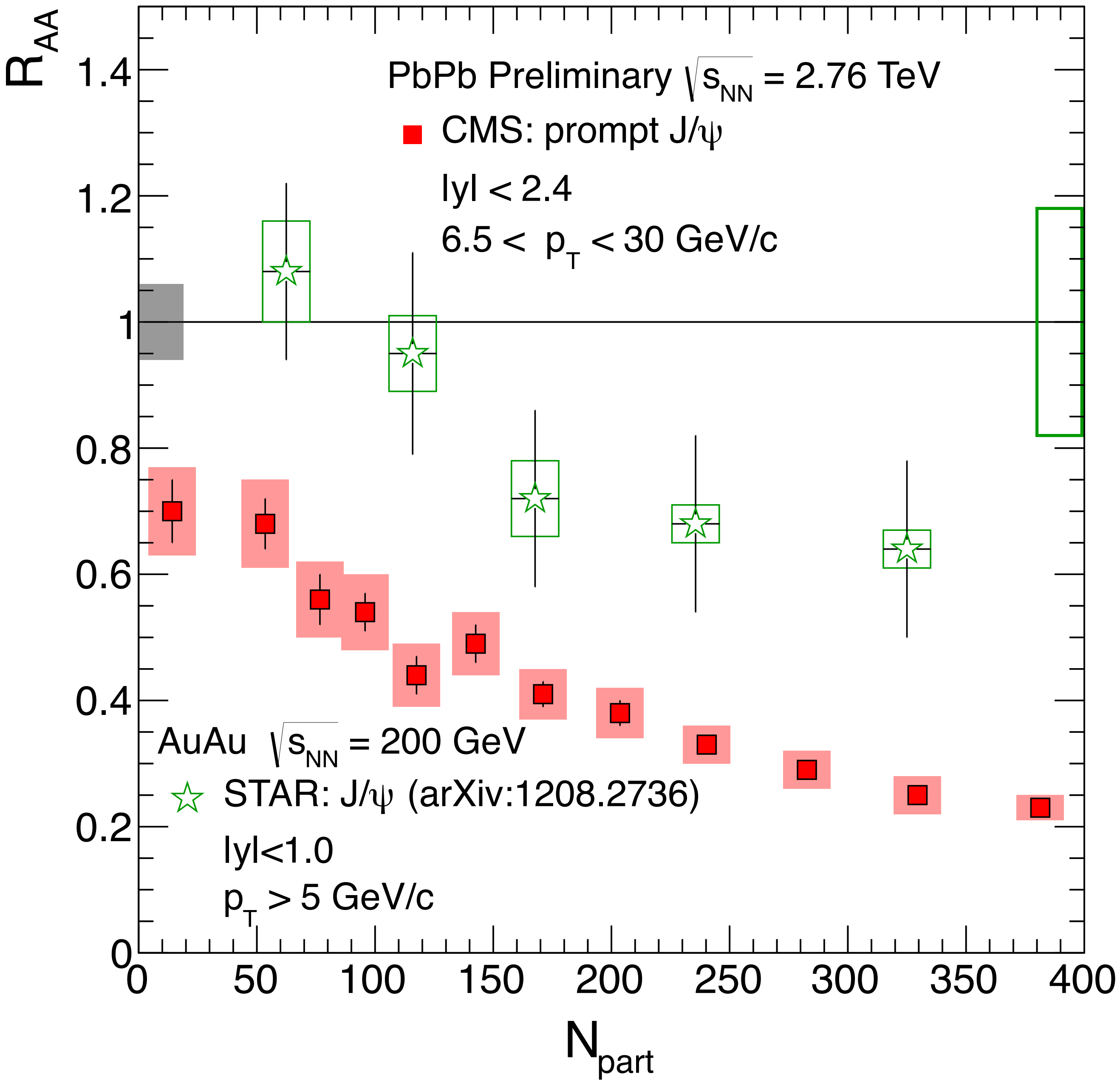


$$R_{AA} = \frac{\mathcal{L}_{pp}}{T_{AA} N_{\mathrm{MB}}} \frac{N_{\mathrm{PbPb}}}{N_{pp}} \frac{\varepsilon_{pp}}{\varepsilon_{\mathrm{PbPb}}}$$

- Calculated prompt J/ψ R_{AA} based on pp reference at $\sqrt{s}$ = 2.76 TeV ($\mathcal{L}_{pp}$ = 231 nb^{-1})
- Integrated over p_T > 6.5 GeV/c and |y| < 2.4
  - in 0–5% centrality: suppressed by a factor 5
  - in 60–100% centrality: suppressed by a factor ~1.4
- Integrated over centrality:
  - no significant dependence on rapidity or p_T

CMS PAS HIN-12-014

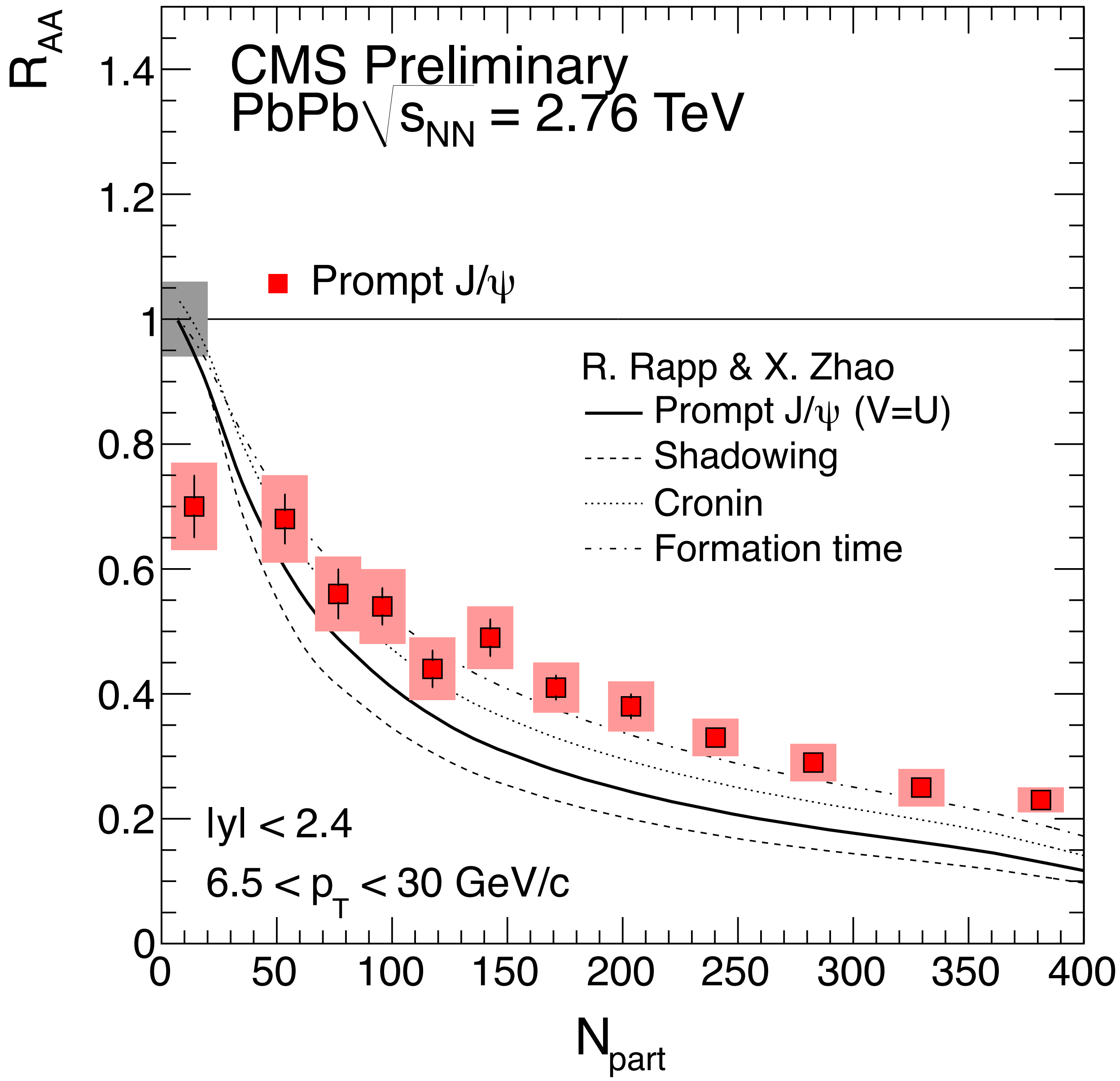
Prompt J/ψ at high p_T: RHIC - LHC



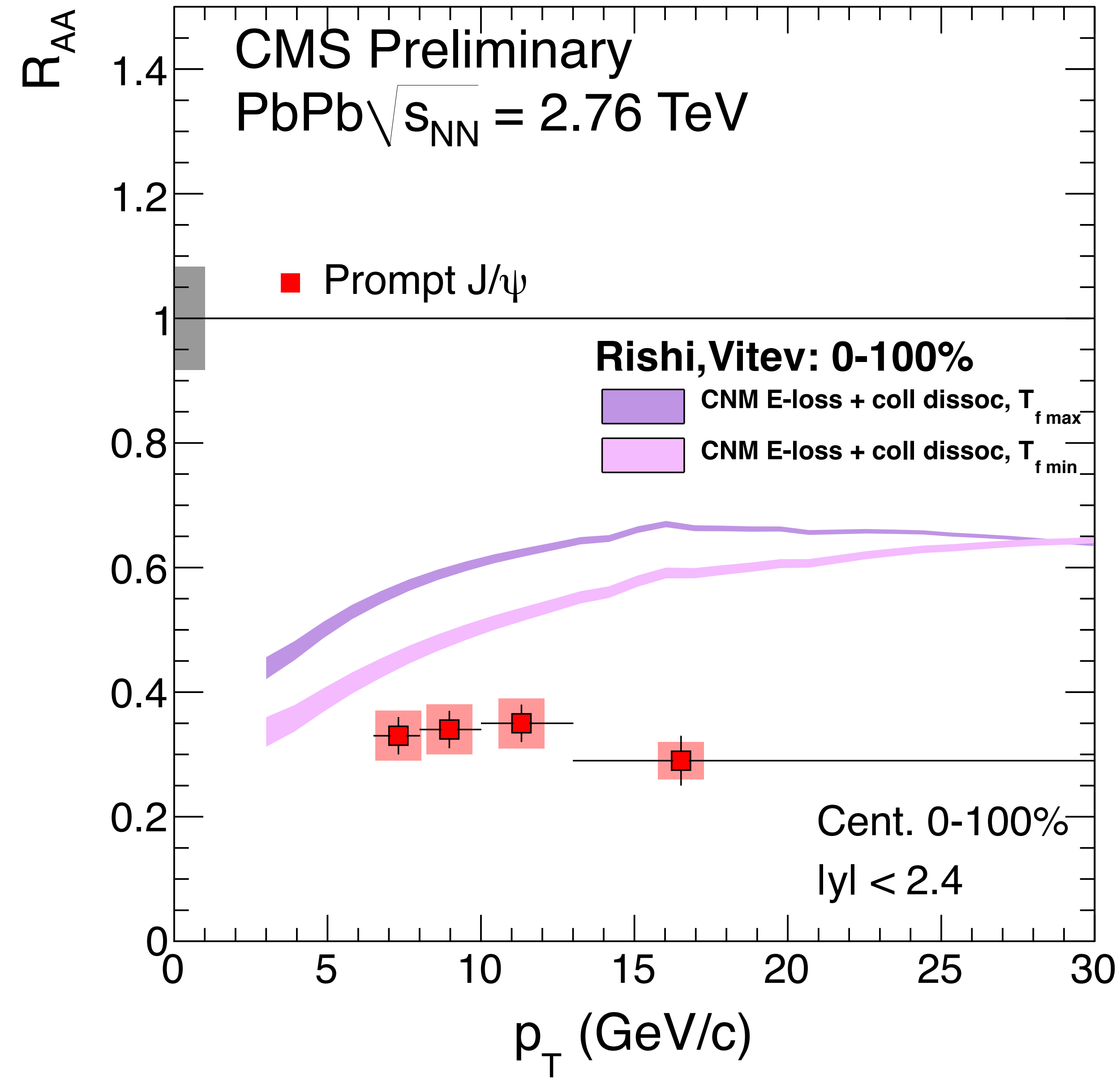
- CMS: Prompt J/ψ
  - p_T > 6.5 GeV/c & |y| < 2.4
  - in 0–5% centrality: suppressed by a factor 5
  - in 60–100% centrality: suppressed by a factor ~1.4
- STAR: inclusive J/ψ
  - p_T > 5 GeV/c & |y| < 1
  - less suppression at RHIC than at the LHC

CMS PAS HIN-12-014

Prompt J/ψ: Theory meets Experiment



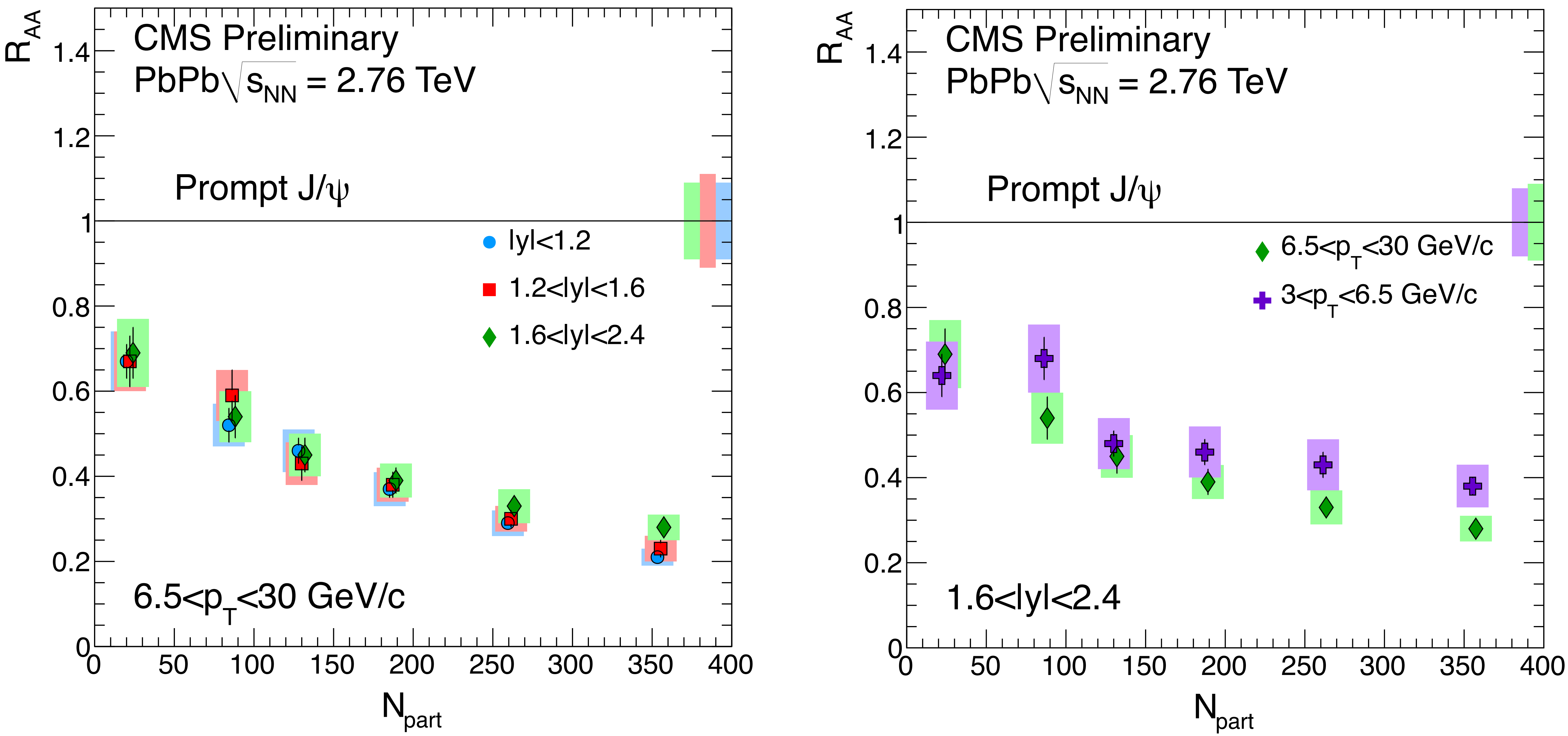
NPA 859 (2011) 114 + private communication



arXiv:1203.0329 + private communication

- Rapp: no need for recombination to describe data at high p_T (p_T > 6.5 GeV/c)
- Vitev: quarkonium suppression due to energy loss (similarly to open heavy-flavour) not supported by data

Prompt J/ψ R_{AA}: double differential



CMS PAS HIN-12-014

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  - slightly less suppression in most central collision at low p_T than at high p_T

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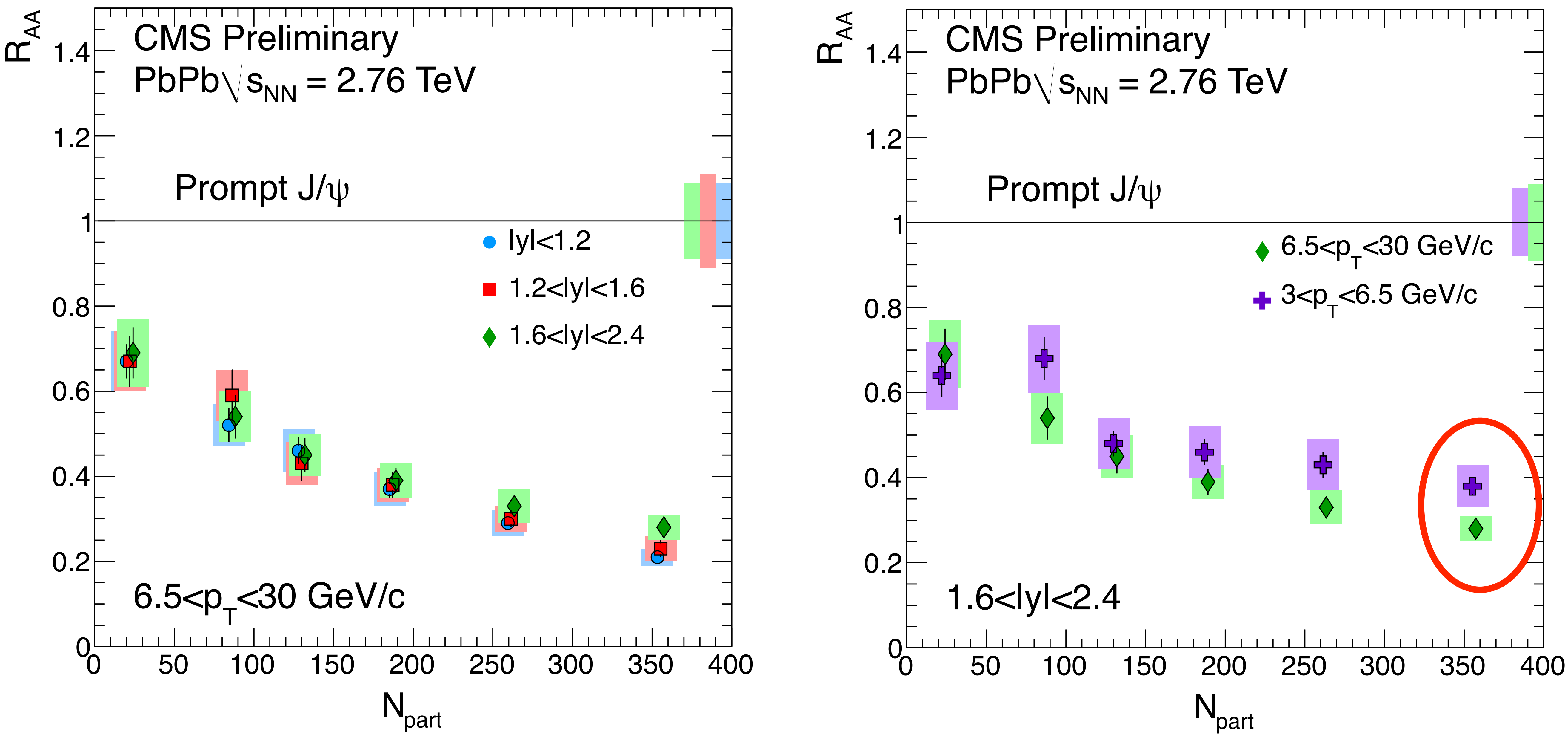
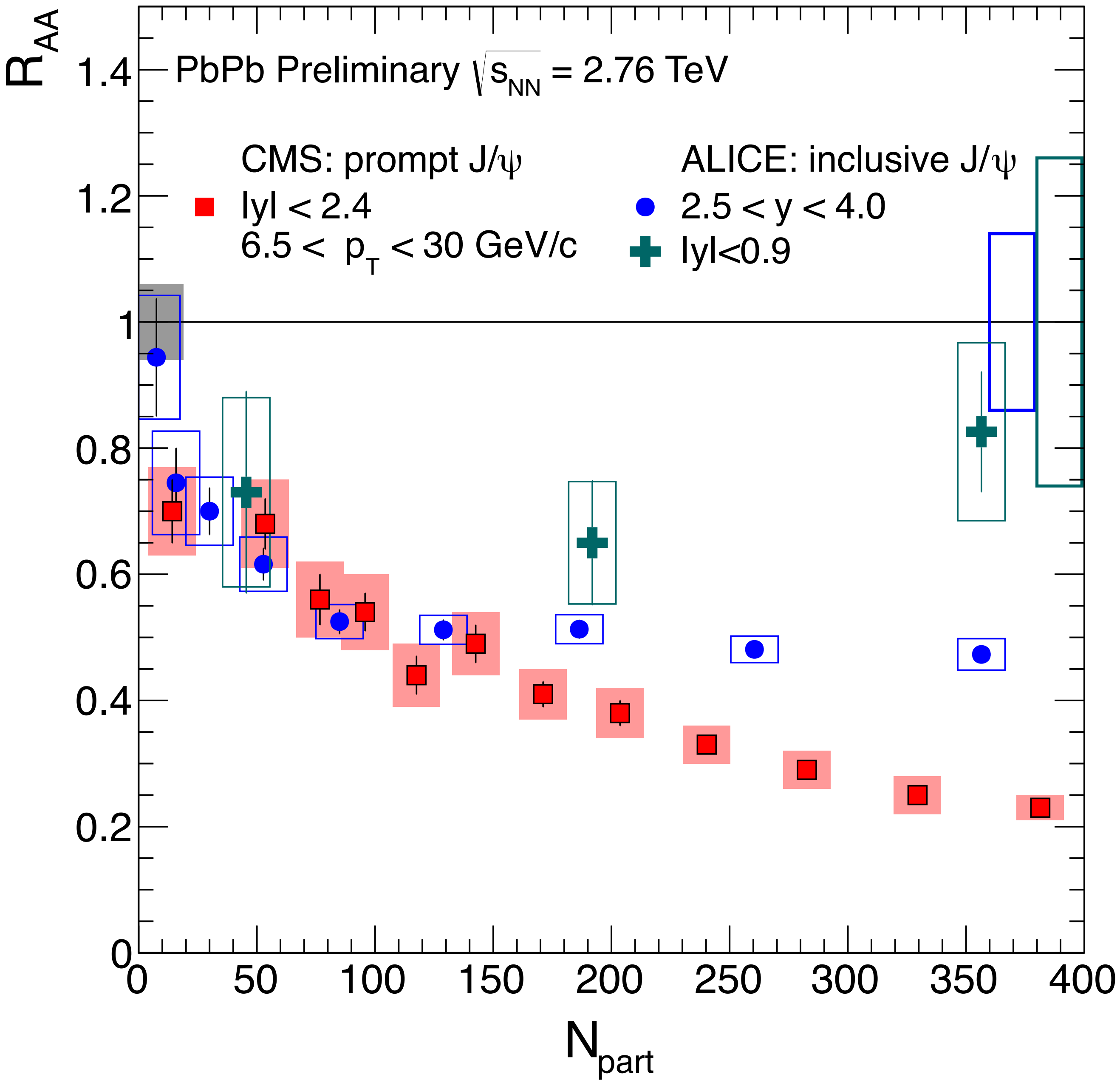


CMS PAS HIN-12-014

- Centrality dependence is independent of rapidity
- At forward rapidity: access to lower p_T ($3 < p_T < 6.5$ GeV/c)
  - slightly less suppression in most central collision at low p_T than at high p_T

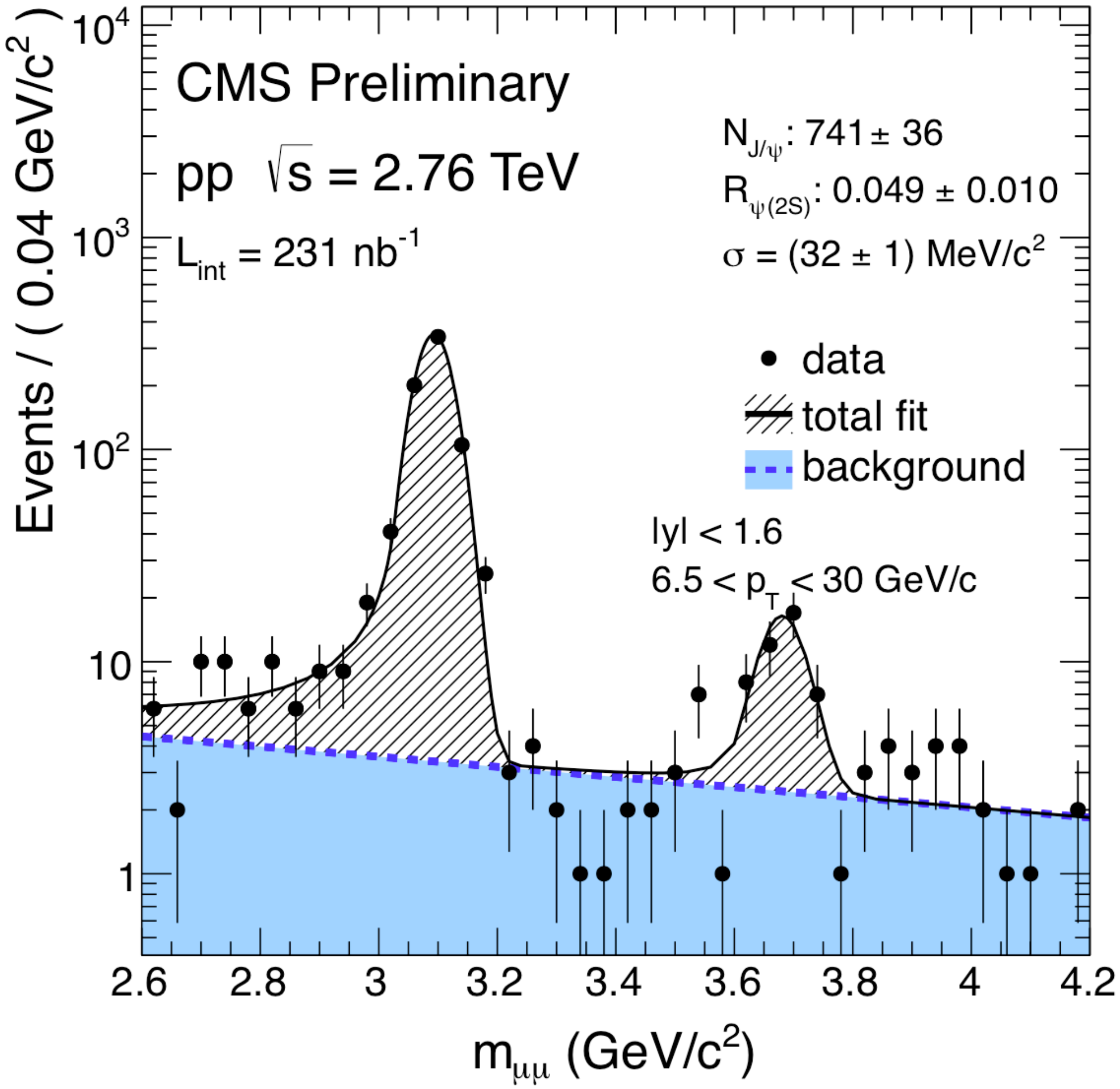
J/ψ at the LHC: CMS - ALICE

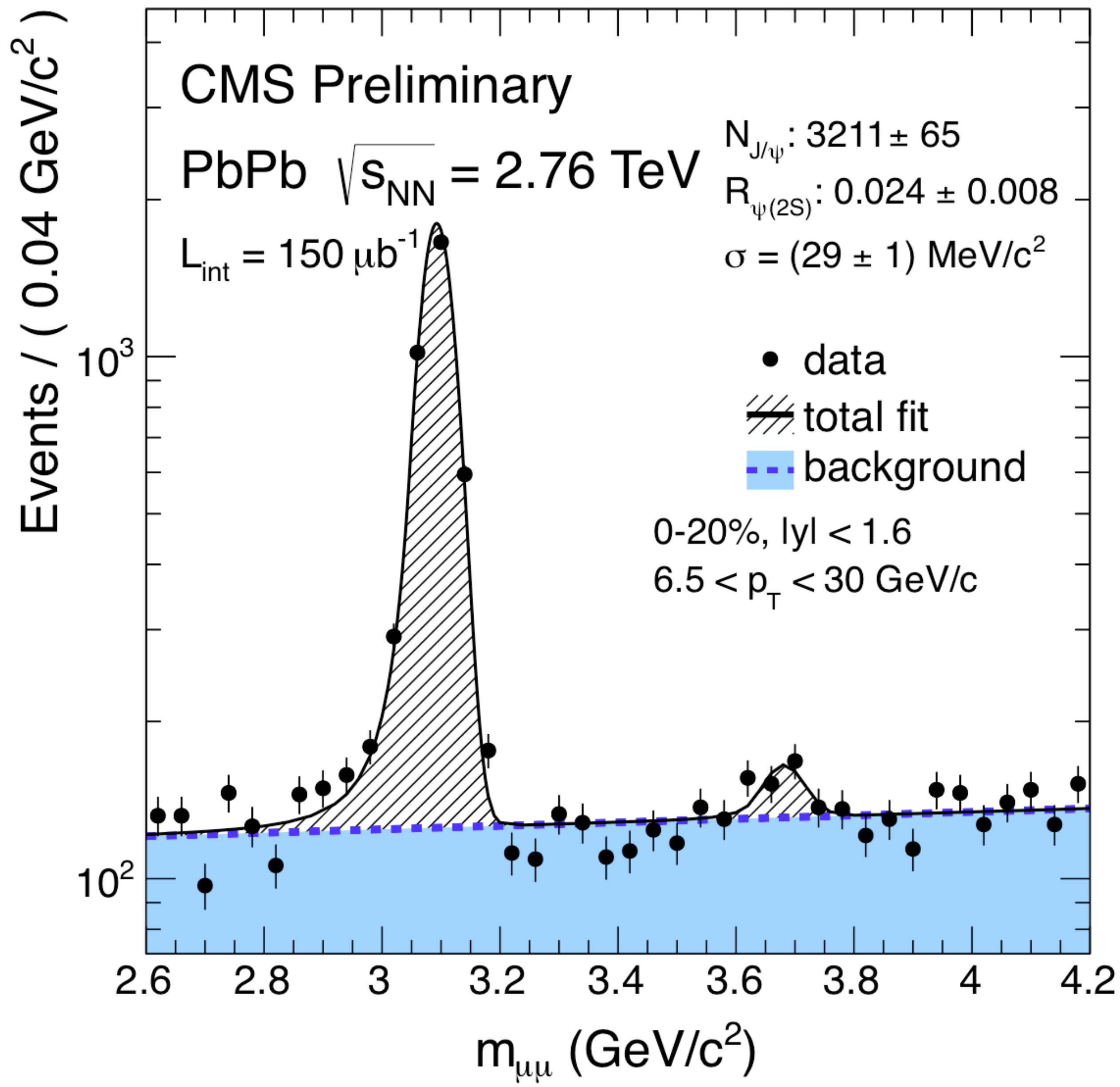


- CMS: Prompt J/ψ
  - p_T > 6.5 GeV/c & |y| < 2.4
  - in 0–5% centrality: suppressed by a factor 5
  - in 60–100% centrality: suppressed by a factor ~1.4
- ALICE: inclusive J/ψ (p_T > 0 GeV/c)
  - |y|<0.9 (Preliminary QM 2012)
  - 2.5 < y < 4 (Preliminary HP 2012)
  - less suppression at low p_T, both at mid- and forward rapidity
  - includes ~10% b-fraction: prompt R_{AA} could drop 11%

CMS PAS HIN-12-014

ψ(2S) in pp & PbPb at $\sqrt{s_{NN}}$ = 2.76 TeV





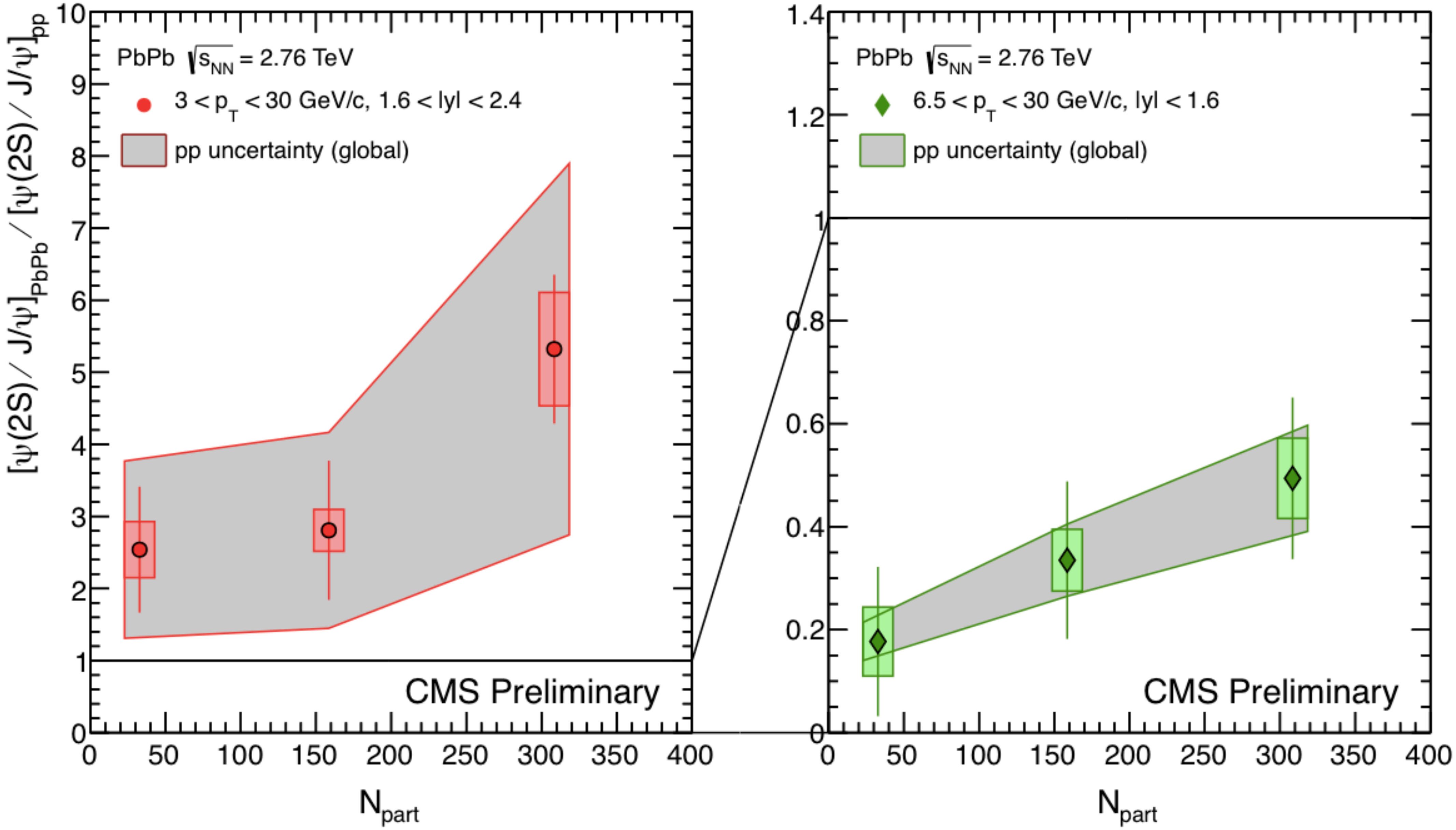
- Raw yield ratio of ψ(2S) / J/ψ: $R_{\psi(2S)}$
- For $p_T > 6.5$ GeV/c and $|y| < 1.6$:
  $R_{\psi(2S)}$ in 0–20% PbPb ~2× smaller than in pp

CMS PAS HIN-12-007

ψ(2S) / J/ψ Double Ratio

CMS PAS HIN-12-007

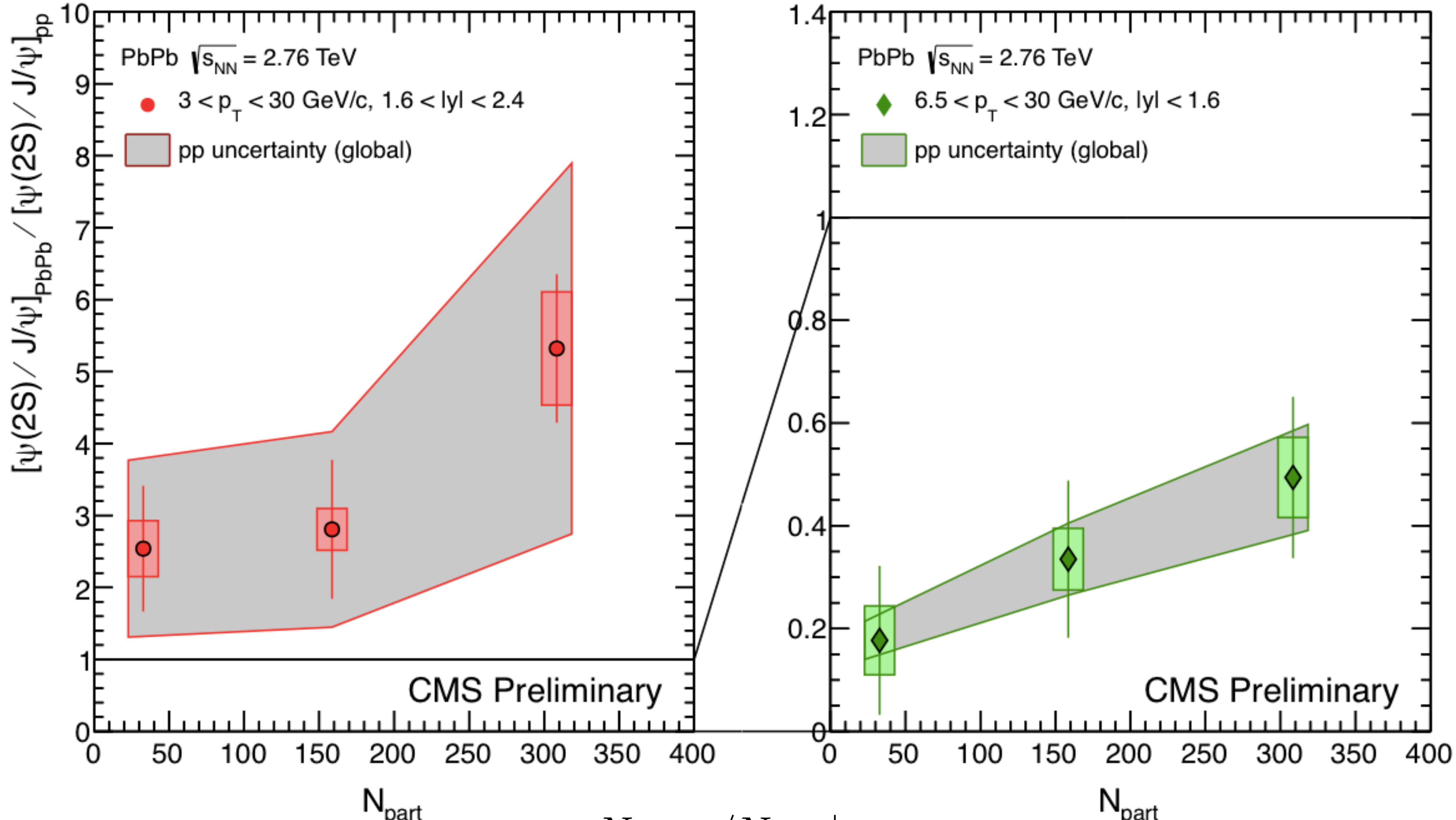
- Double ratio of $[\psi(2S) / J/\psi]_{PbPb}$ / $[\psi(2S) / J/\psi]_{pp}$



- For $p_T > 3$ GeV/c and $1.6 < |y| < 2.4$: large uncertainties on pp
  Indication of ψ(2S) being less suppressed than J/ψ, but need more statistics (in particular pp)!
- For $p_T > 6.5$ GeV/c and $|y| < 1.6$: ψ(2S) are more suppressed than J/ψ

ψ(2S) / J/ψ Double Ratio → $R_{AA}(\psi(2S))$

CMS PAS HIN-12-007



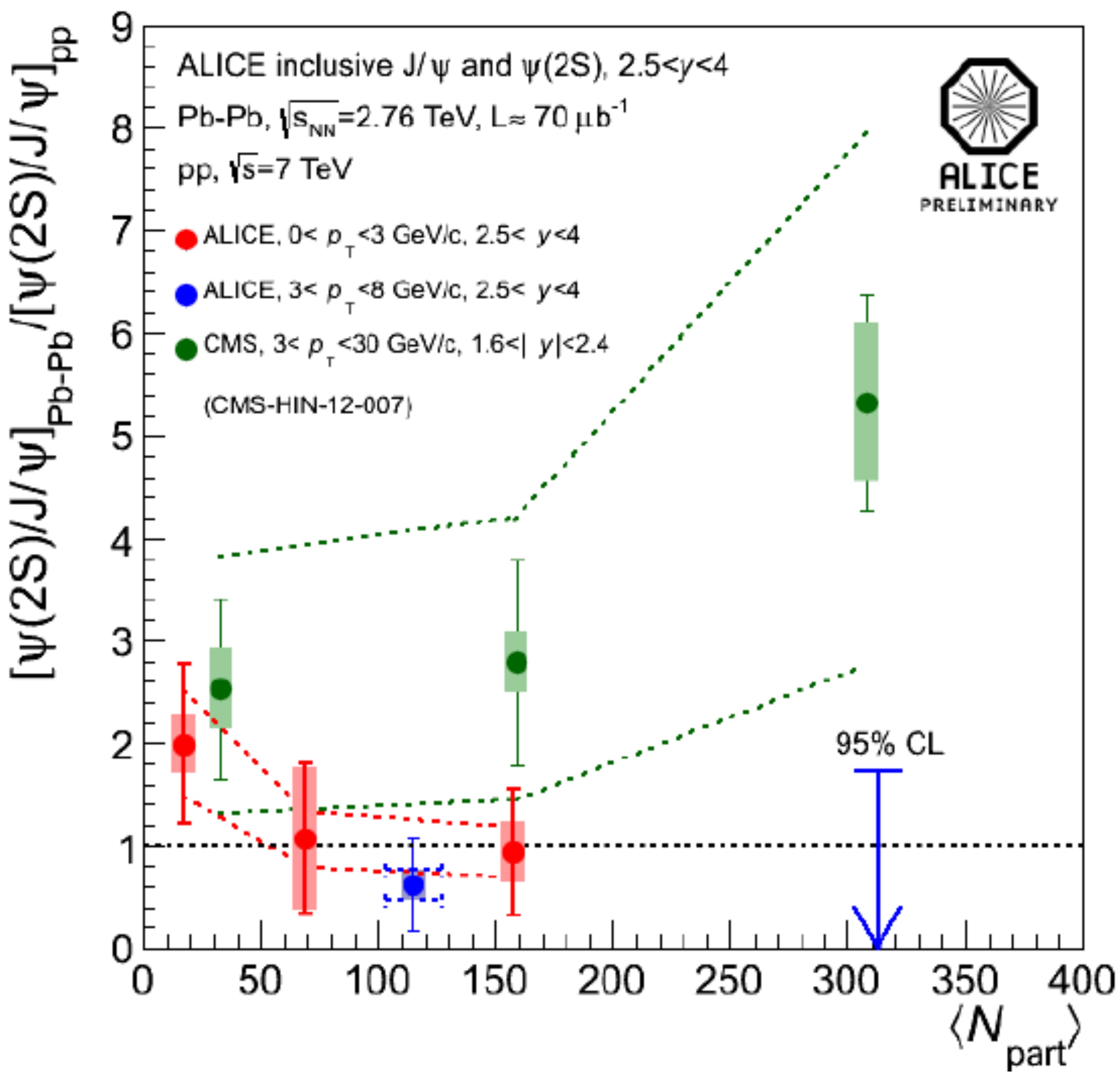
$$R_{AA}(\psi(2S)) = \frac{N_{\psi(2S)}/N_{J/\psi}|_{PbPb}}{N_{\psi(2S)}/N_{J/\psi}|_{pp}} \times R_{AA}(J/\psi)$$

take $R_{AA}(J/\psi)$ from JHEP 1205 (2012) 063

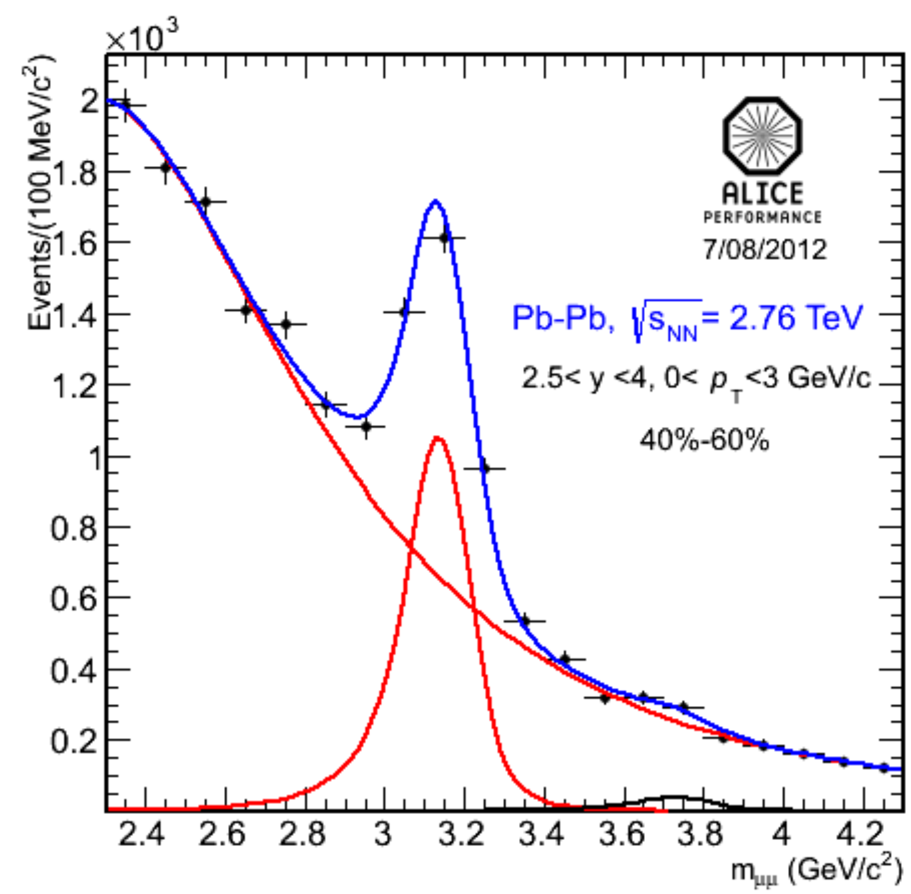
$$R_{AA}^{0-100\%}(\psi(2S)) = 1.54 \pm 0.32\,(\text{stat}) \pm 0.22\,(\text{syst}) \pm 0.76\,(\text{pp})$$

$$R_{AA}^{0-100\%}(\psi(2S)) = 0.11 \pm 0.03\,(\text{stat}) \pm 0.02\,(\text{syst}) \pm 0.02\,(\text{pp})$$

ψ(2S) / J/ψ Double Ratio: CMS vs. ALICE



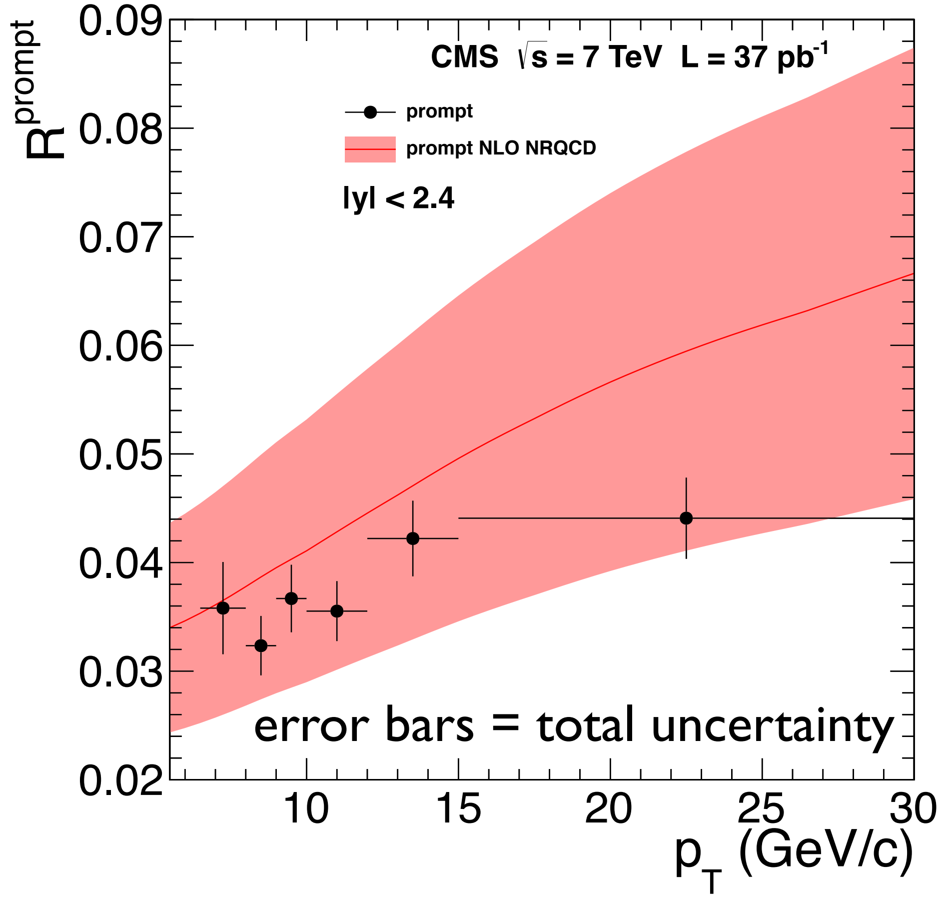
- CMS has a hint (less than 2σ!) of less suppression of the ψ(2S) w.r.t. the J/ψ at lower p_T
  - used pp at √s = 2.76 TeV
- ALICE looked and does not see it…
  - used pp at √s = 7 TeV
- However, given the large uncertainties:
  - No discrepancy!

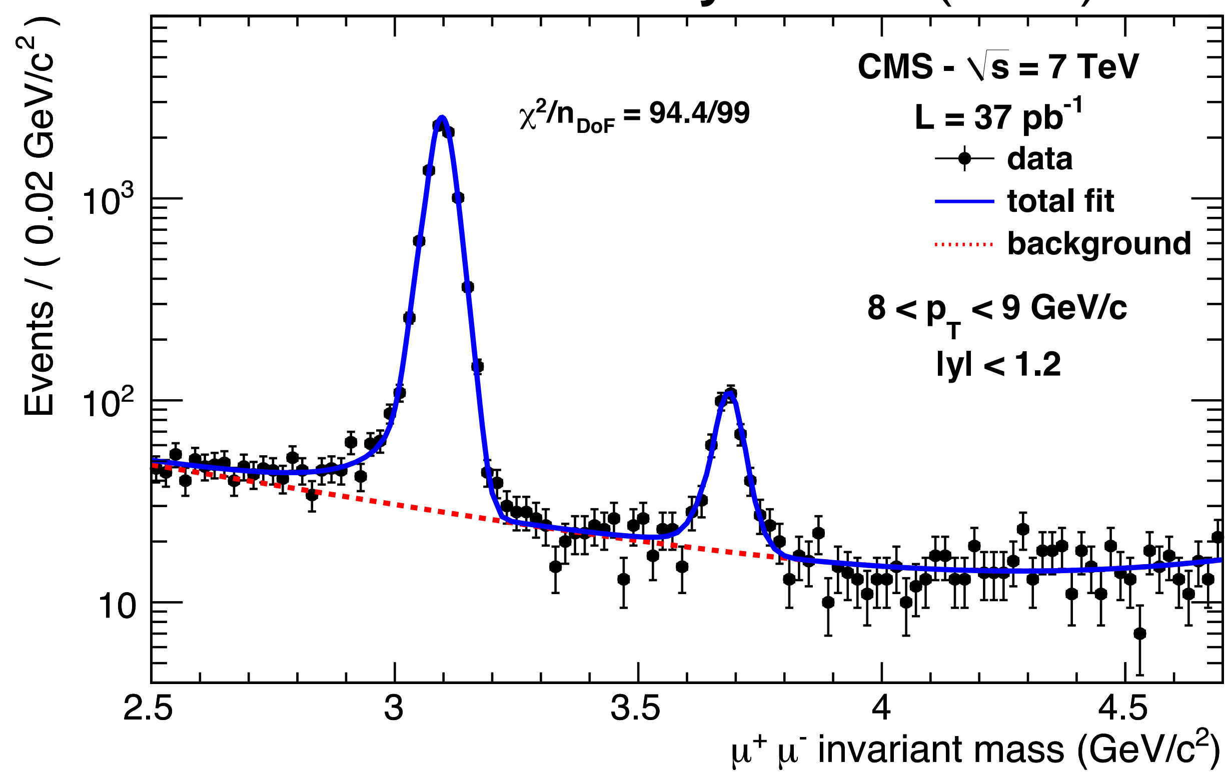


CMS: PAS HIN-12-007
ALICE: Scomparin, Arnaldi (QM 2012)

ψ(2S) in pp at √s = 7 TeV

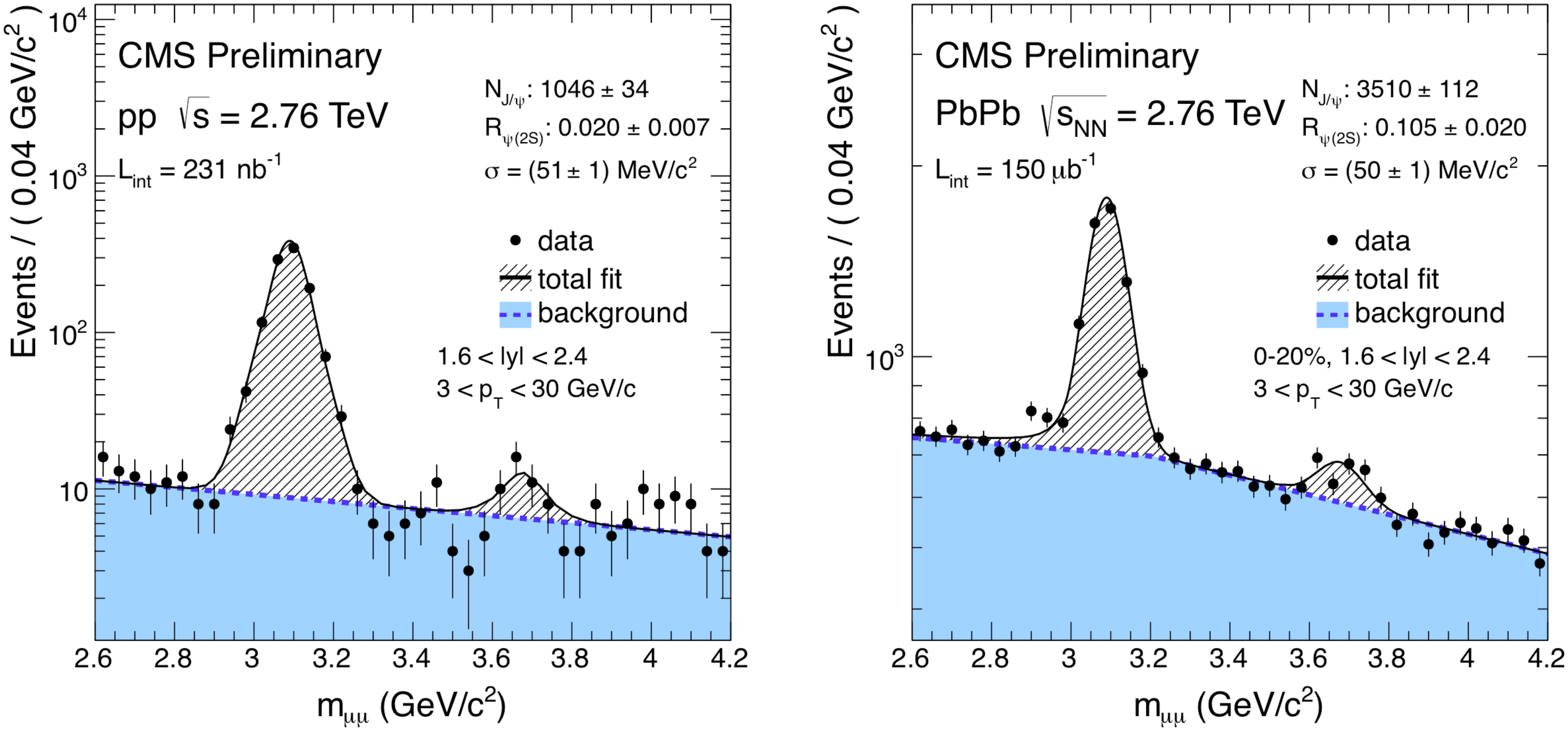
JHEP 02 (2012) 011





- CMS measured ψ(2S) cross section in pp at √s = 7 TeV
- ψ(2S) / J/ψ cross-section ratio ~0.035 for p_T > 6.5 GeV/c
- Uncertainties on theory larger than experimental uncertainties

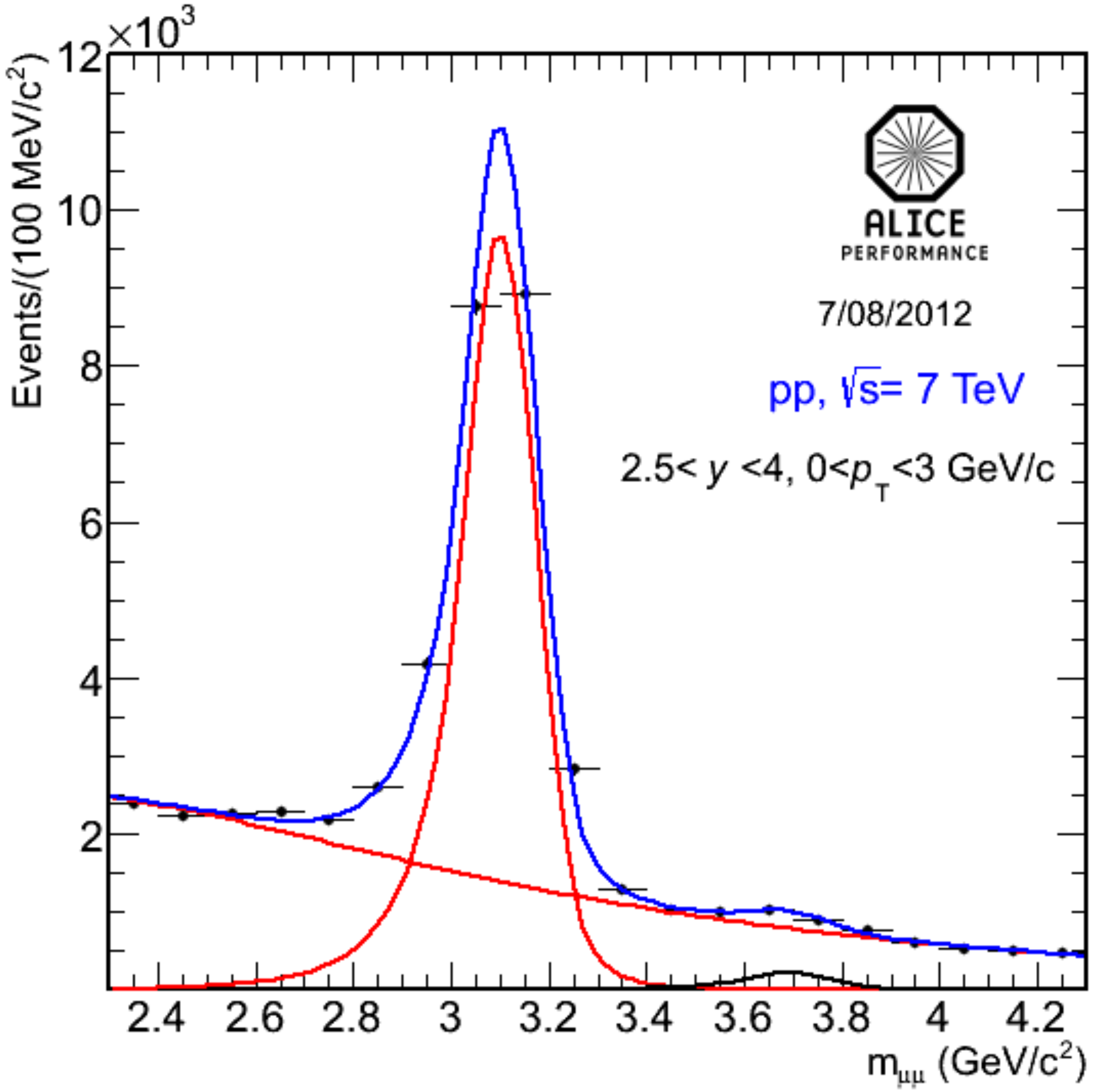
$\psi(2S)$ in pp & PbPb at $\sqrt{s_{NN}}$ = 2.76 TeV

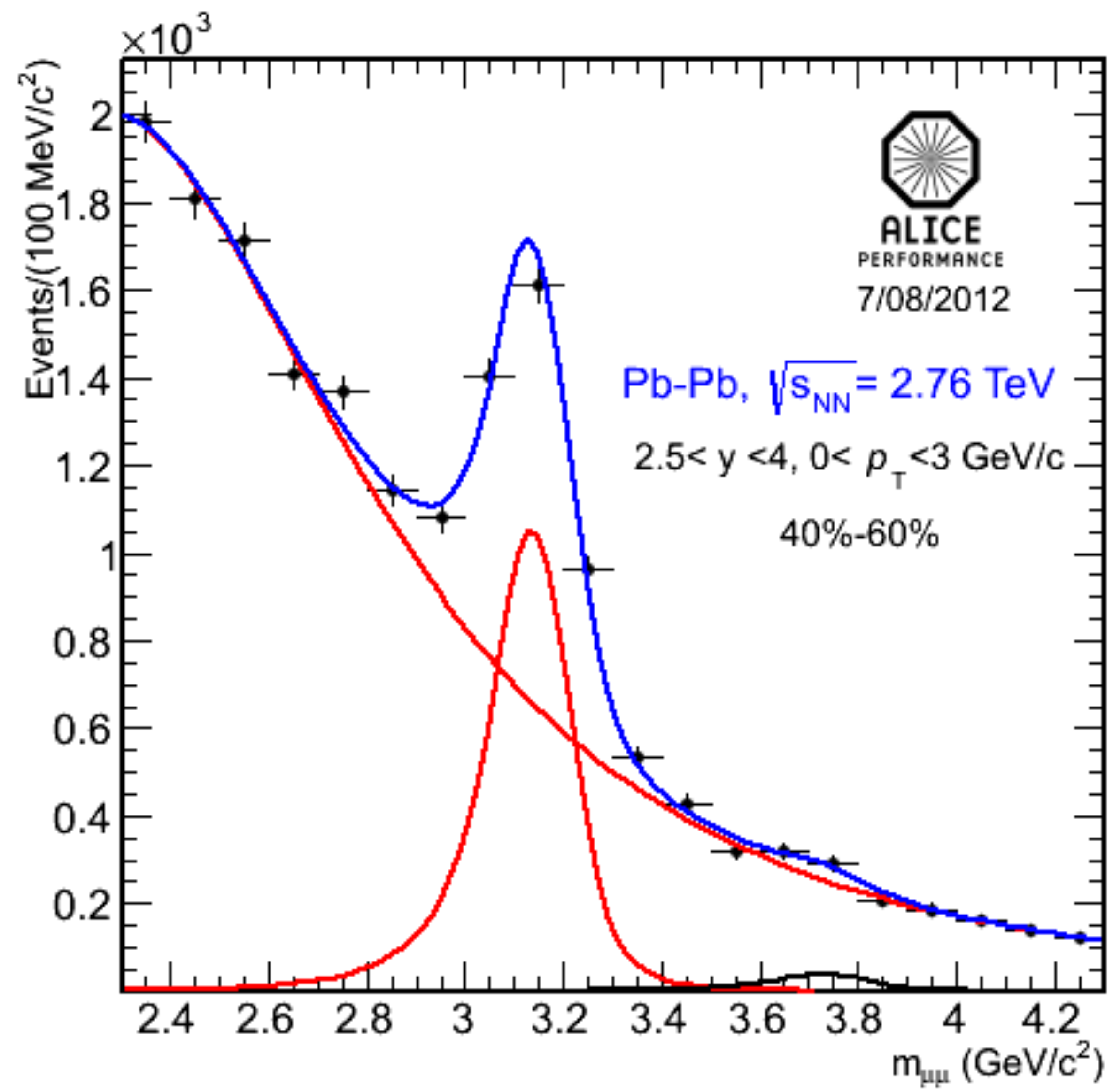


- Raw yield ratio of $\psi(2S)$ / J/ψ: $R_{\psi(2S)}$
- For $p_T > 3$ GeV/c and $1.6 < |y| < 2.4$:
  $R_{\psi(2S)}$ in 0–20% PbPb ~5× larger than in pp

CMS PAS HIN-12-007

ALICE: ψ(2S)





- PbPb: Signal/Background (at 3σ around the ψ(2S)) varies between 0.01 and 0.3 from central to peripheral collisions