

Measurement of bottomonium production in PbPb collisions at 2.76TeV with the CMS detector

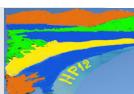
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for the CMS Collaboration



Outline

● Introduction

- bottomonia and heavy-ion collisions
- CMS bottomonium measurements in HI collisions

● Measurement

- muon reconstruction
- $\Upsilon(nS)$ yields extraction

● Results

- production of $\Upsilon(nS)$ states in PbPb and pp, with respect to the ground state
 - ▶ $[\Upsilon(nS)/\Upsilon(1S)]_{AA,pp}$
- production of $\Upsilon(nS)$ states in PbPb compared to pp
 - ▶ $R_{AA}^{\Upsilon(1S)}$ and $R_{AA}^{\Upsilon(2S)}$

● Summary

Bottomonium in HI collisions

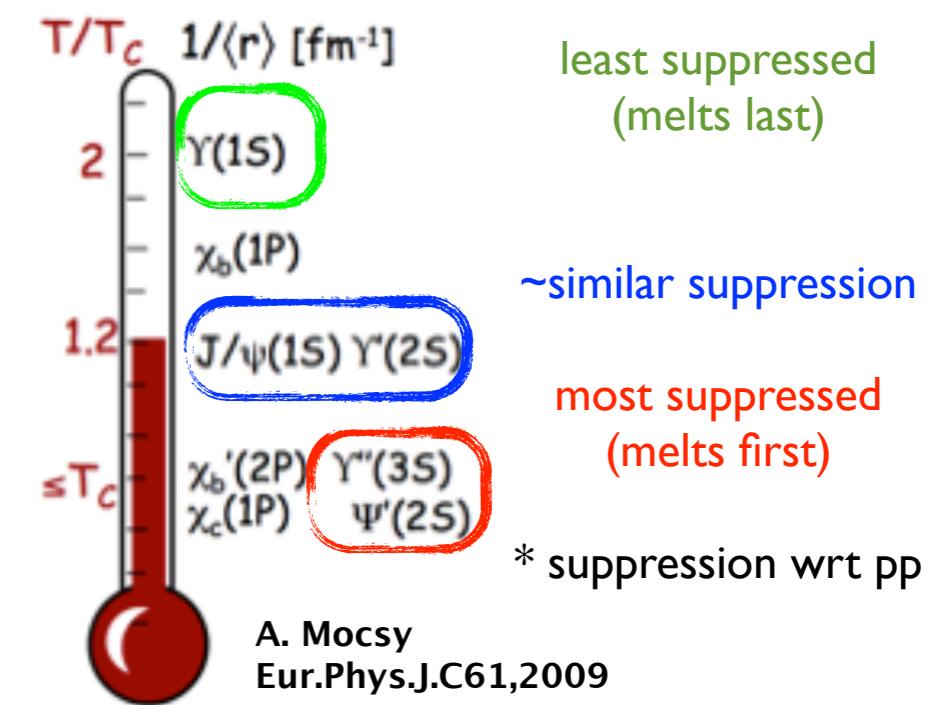
- Under better theoretical control than charm

- mass of the quark higher
- no B-hadron feed-down
- nPDF effects smaller ($Q^2 > 100 \text{ GeV}$)

- 3 similar states: close in mass, with relatively close cross-section x branching ratios
- The relative yields analysis of the 3 states

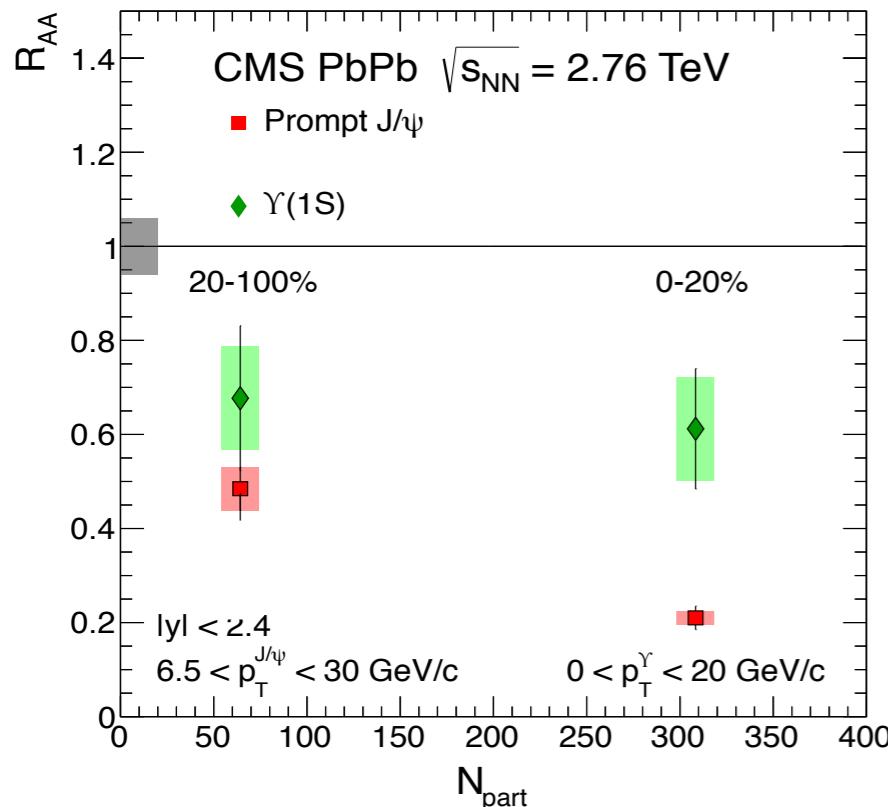
- cancels cold nuclear matter effects
 - ▶ nPDFs (shadowing, etc)
 - ▶ initial parton energy loss
 - ▶ final state nuclear absorption (if negligible at LHC energies)
- carries only effects related to final (hot) medium
 - ▶ *different binding energies* → color screening occurs at different temperatures → sequential melting → **thermometer of the final state medium**

state	$Y(1S)$	$Y(2S)$	$Y(3S)$
Mass(GeV)	9.46	10.0	10.36
ΔE (GeV)	1.10	0.54	0.20



Bottomonium in HI collisions with CMS

JHEP 1205 (2012) 063



- 2010: $\text{PbPb}@2.76\text{TeV}$
 - $7.28 \mu\text{b}^{-1}$
 - $86 \pm 12 \Upsilon(1S)$

- 2011: $\text{pp}@2.76\text{TeV}$
 - 231 nb^{-1}
 - $101 \pm 12 \Upsilon(1S)$

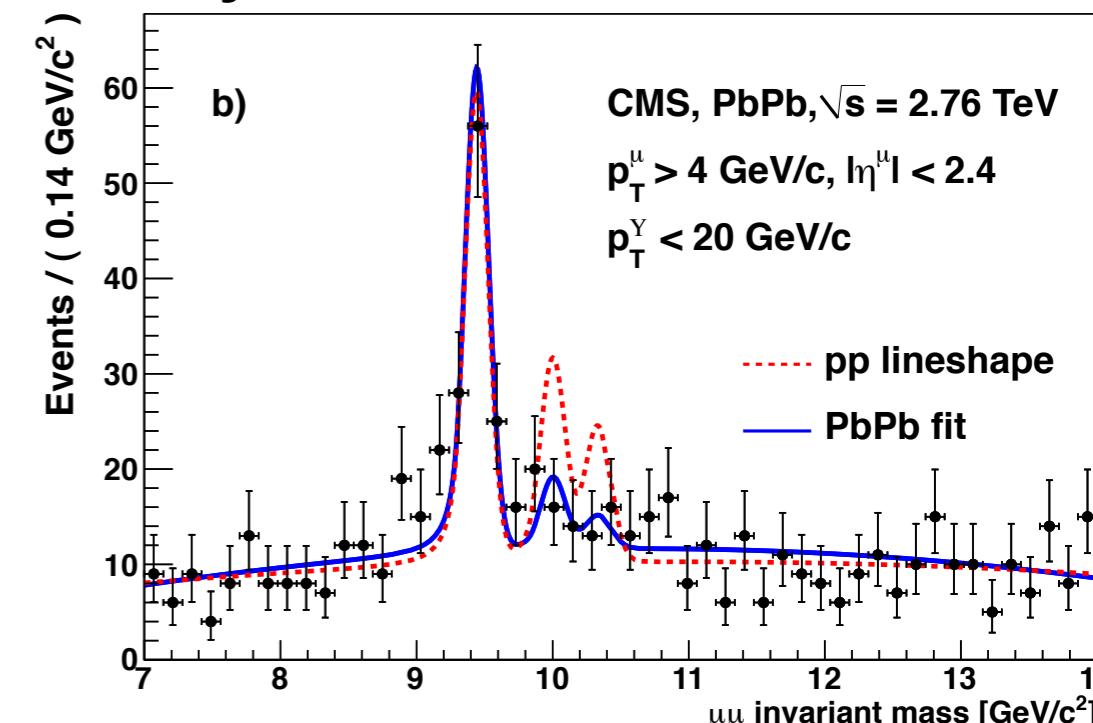
● $\Upsilon(1S)$ -- ground state

→ 20-100 %: $R_{AA} = 0.62 \pm 0.11 \pm 0.10$

→ 0-20% : $R_{AA} = 0.60 \pm 0.12 \pm 0.10$

→ less suppressed than J/ψ

Phys.Rev.Lett.107, 2011

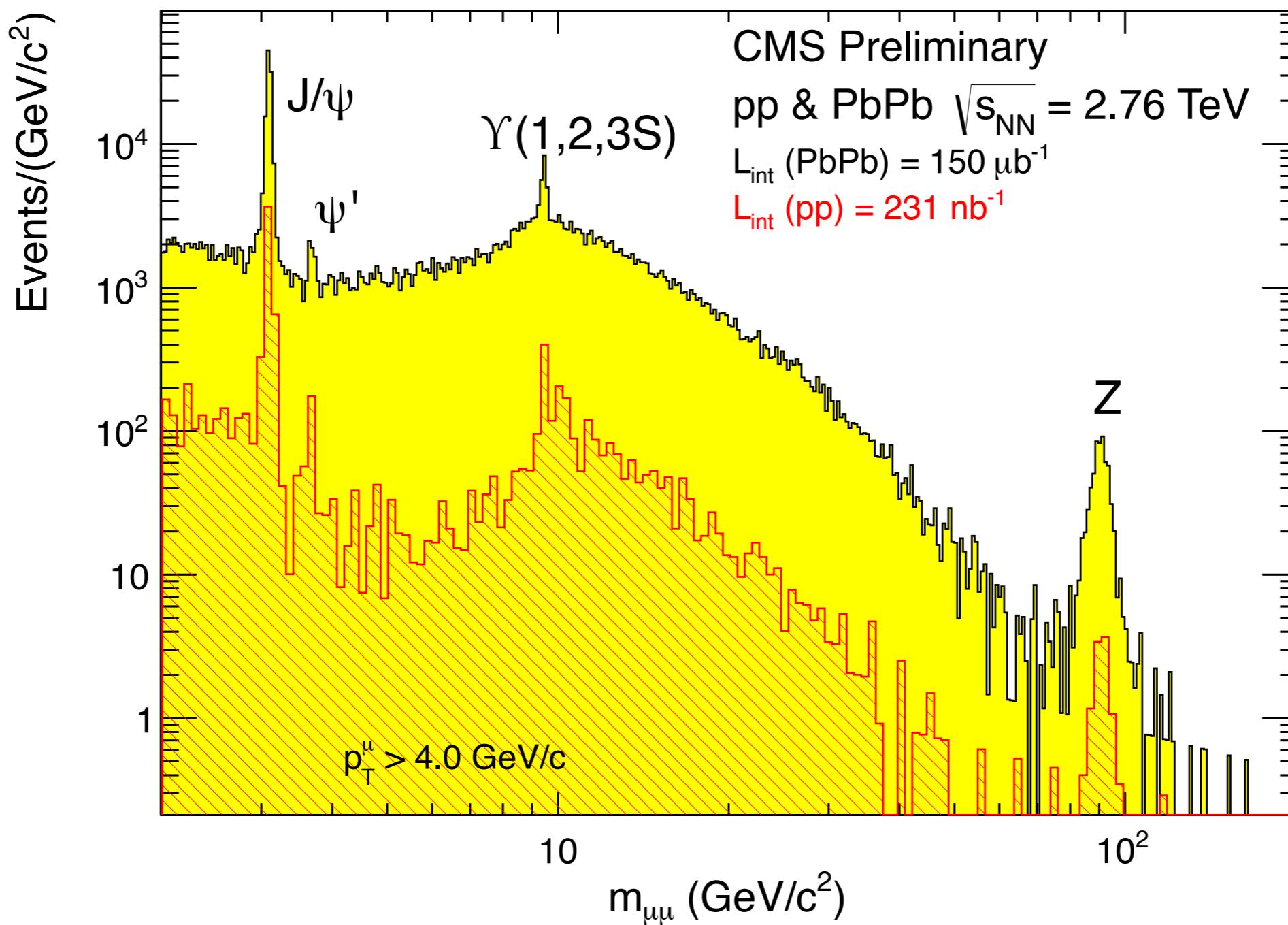


● $\Upsilon(2S+3S)$ -- excited states

$$\chi_{23} = \frac{\Upsilon(2S+3S)/\Upsilon(1S)|_{\text{PbPb}}}{\Upsilon(2S+3S)/\Upsilon(1S)|_{\text{pp}}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

→ more suppressed than $\Upsilon(1S)$

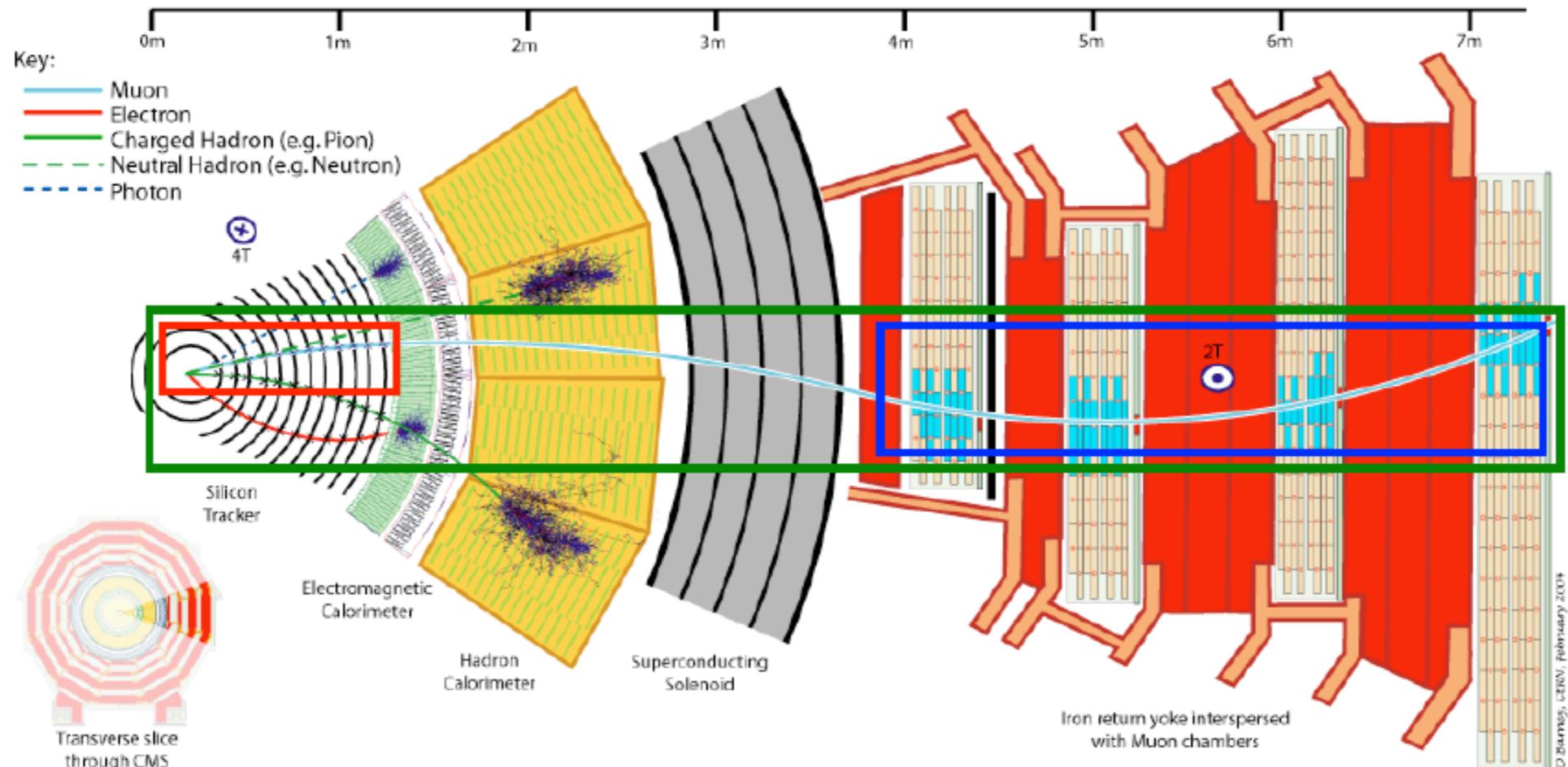
PbPb 2011: $150 \mu\text{b}^{-1}$



● 2011 results:

- PbPb: $150 \mu\text{b}^{-1}$ (20 times more data than 2010)
- pp : 231 nb^{-1} (same as for 2010 results)

Muon reconstruction

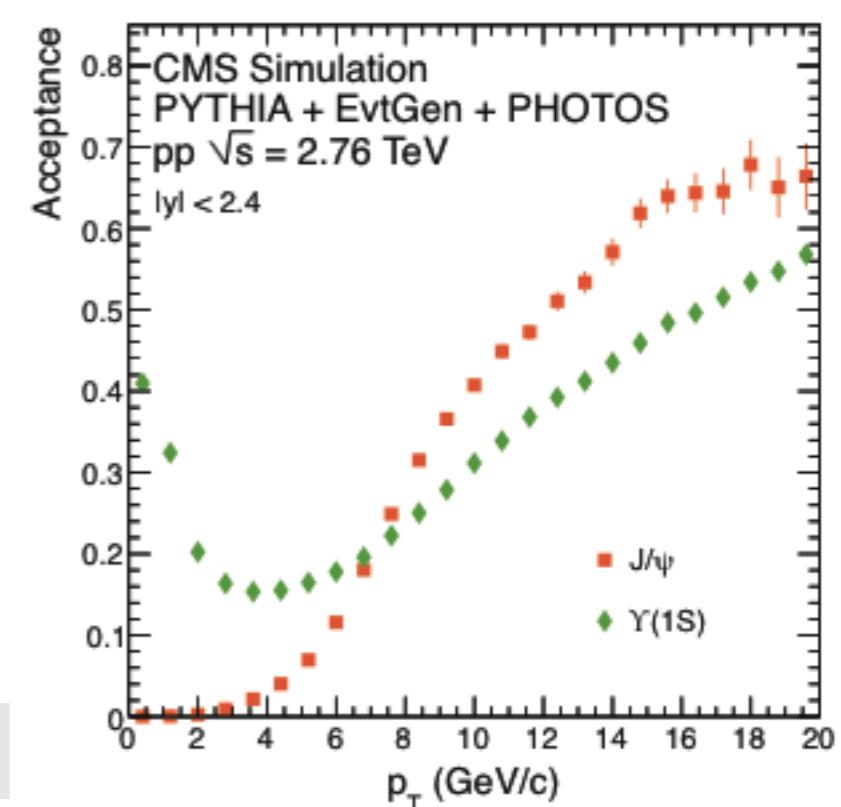


- Global muons = **tracker + muon stations**

- ID cuts at analysis level:
 - reconstructed both inside-out and outside-in
 - min #hits in the tracker (10), χ^2 , DCA, etc.

- For upsilon analysis: $p_T^\mu > 4 \text{ GeV}/c$, $|\eta^\mu| < 2.4$

- acceptance down to $p_T^\gamma = 0 \text{ GeV}/c$ for $|\gamma^\gamma| < 2.4$



$\Upsilon(nS)$ yield extraction: pp

- Unbinned max likelihood fit

- Signal

→ 3 Crystal-ball: Gaussian core & power law tail

$$f_{CB}(m) = \begin{cases} \frac{N}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(m-m_0)^2}{2\sigma^2}\right), & \text{for } \frac{m-m_0}{\sigma} > -\alpha; \\ \frac{N}{\sqrt{2\pi}\sigma} \left(\frac{n}{|\alpha|}\right)^n \exp\left(-\frac{|\alpha|^2}{2}\right) \left(\frac{n}{|\alpha|} - |\alpha| - \frac{m-m_0}{\sigma}\right)^{-n}, & \text{for } \frac{m-m_0}{\sigma} \leq -\alpha. \end{cases}$$

→ Free parameters:

- ▶ yield, resolution and mass for $\Upsilon(1S)$
- ▶ yield ratios: $\Upsilon(2S+3S)/\Upsilon(1S)$, $\Upsilon(2S)/\Upsilon(1S)$
- ▶ tail parameter, α (transition Gaussian→power-law)

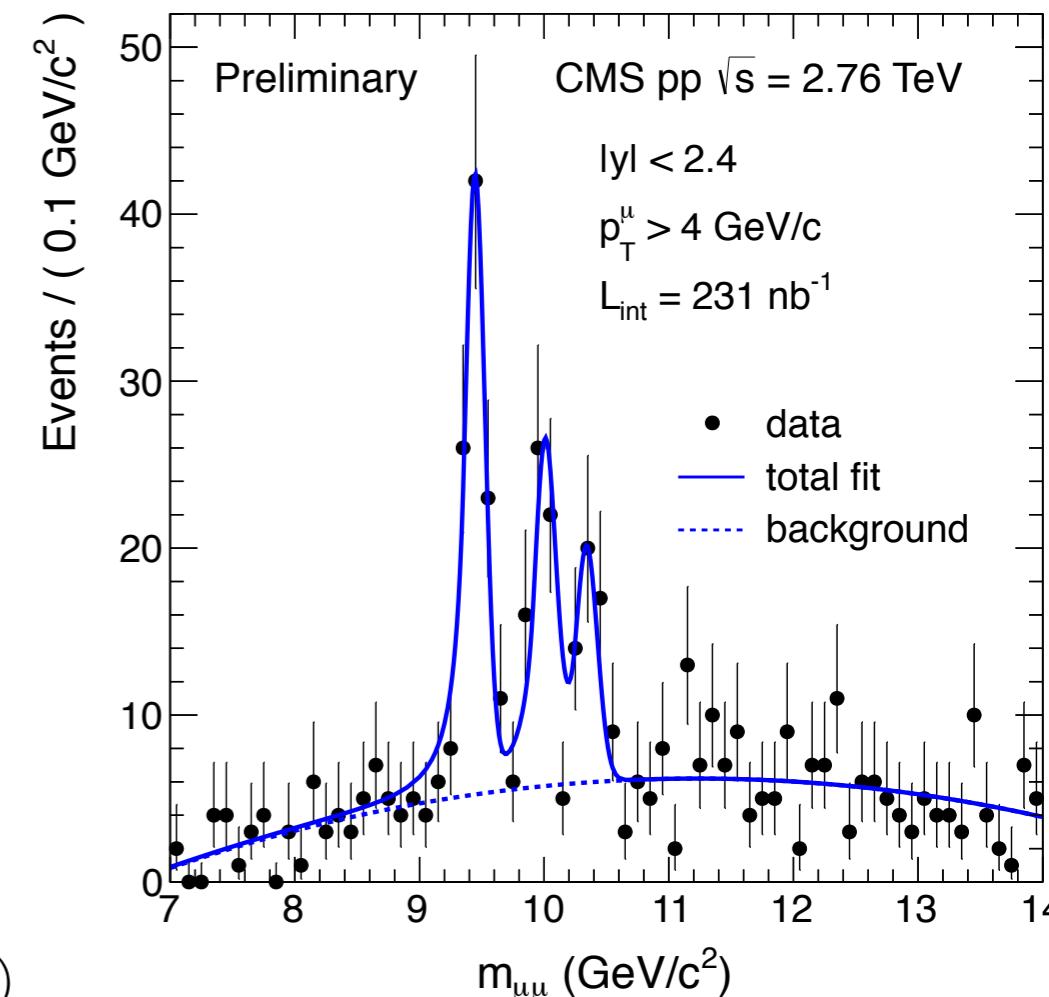
→ Fixed parameters:

- ▶ n (MC), exponent for tail description
- ▶ resolution forced to scale with PDG mass ratios

- Background

→ 2nd order polynomial

- ▶ Free parameters: all



Raw ratios

(no acceptance or efficiency corrected)

$$\frac{\Upsilon(2S)}{\Upsilon(1S)}|_{pp} = 0.56 \pm 0.13 \pm 0.01$$

$$\frac{\Upsilon(3S)}{\Upsilon(1S)}|_{pp} = 0.41 \pm 0.11 \pm 0.02$$

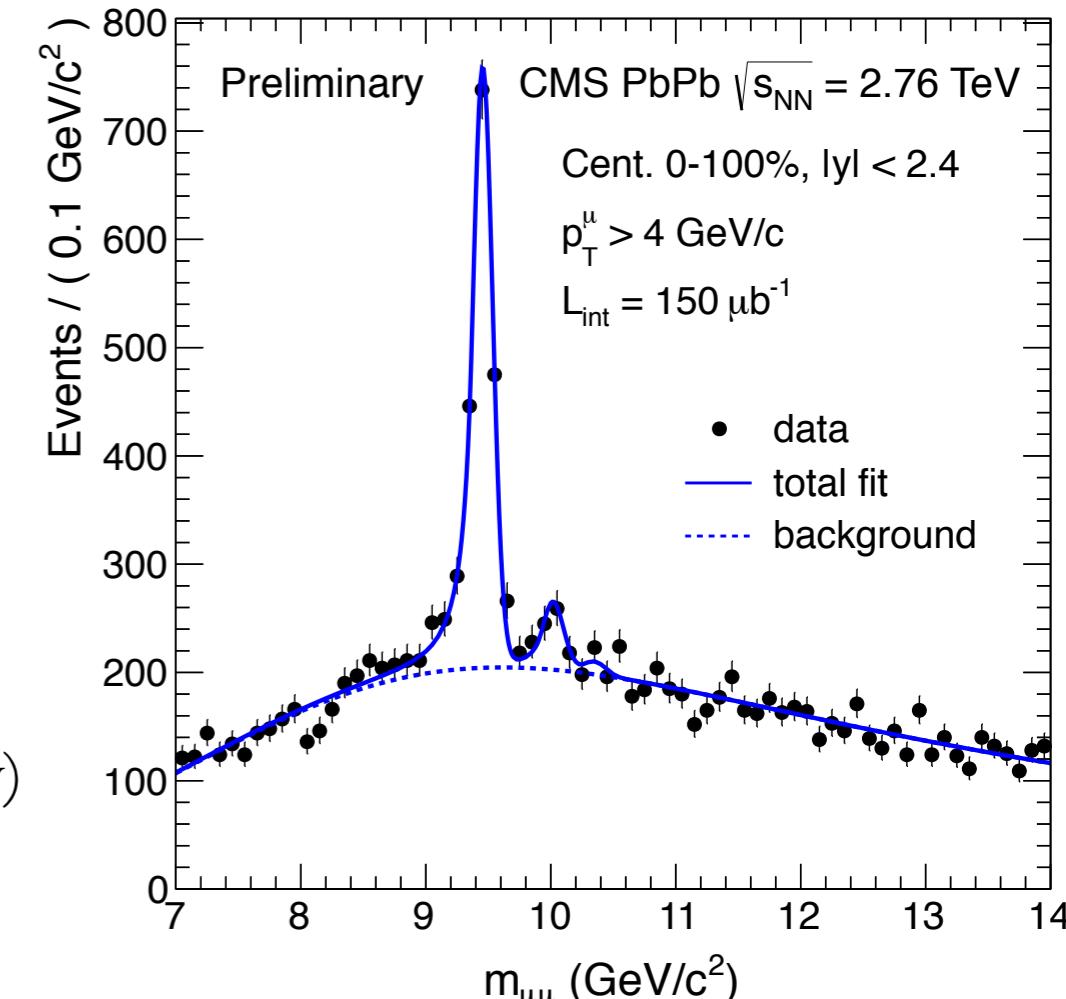
$\Upsilon(nS)$ yield extraction: PbPb

- Unbinned max likelihood fit
- Signal (same as for pp)
 - 3 Crystal-ball: Gaussian core & power law tail
 - Free parameters:
 - ▶ yield, resolution and mass for $\Upsilon(1S)$
 - ▶ yield ratios: $\Upsilon(2S+3S)/\Upsilon(1S)$, $\Upsilon(2S)/\Upsilon(1S)$
 - ▶ tail parameter, α (transition Gaussian \rightarrow power-law)
 - Fixed parameters:
 - ▶ n (MC), exponent for tail description
 - ▶ resolution forced to scale with PDG mass ratios

● Background ('shoulder'-like structure)

- exponential x error function
- Free parameters: all
 - ▶ exponential decay constant
 - ▶ error fct shoulder mean and width

$$\text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt$$



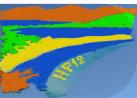
Raw ratios (0-100%)
(no acceptance or efficiency corrected)

$\frac{\Upsilon(2S)}{\Upsilon(1S)}|_{PbPb} = 0.12 \pm 0.03 \pm 0.01$

$\frac{\Upsilon(3S)}{\Upsilon(1S)}|_{PbPb} < 0.07$ (95% C.L.)

Results

<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN11011>



Double ratio: $[\Upsilon(nS)/\Upsilon(1S)]_{PbPb} / [\Upsilon(nS)/\Upsilon(1S)]_{pp}$

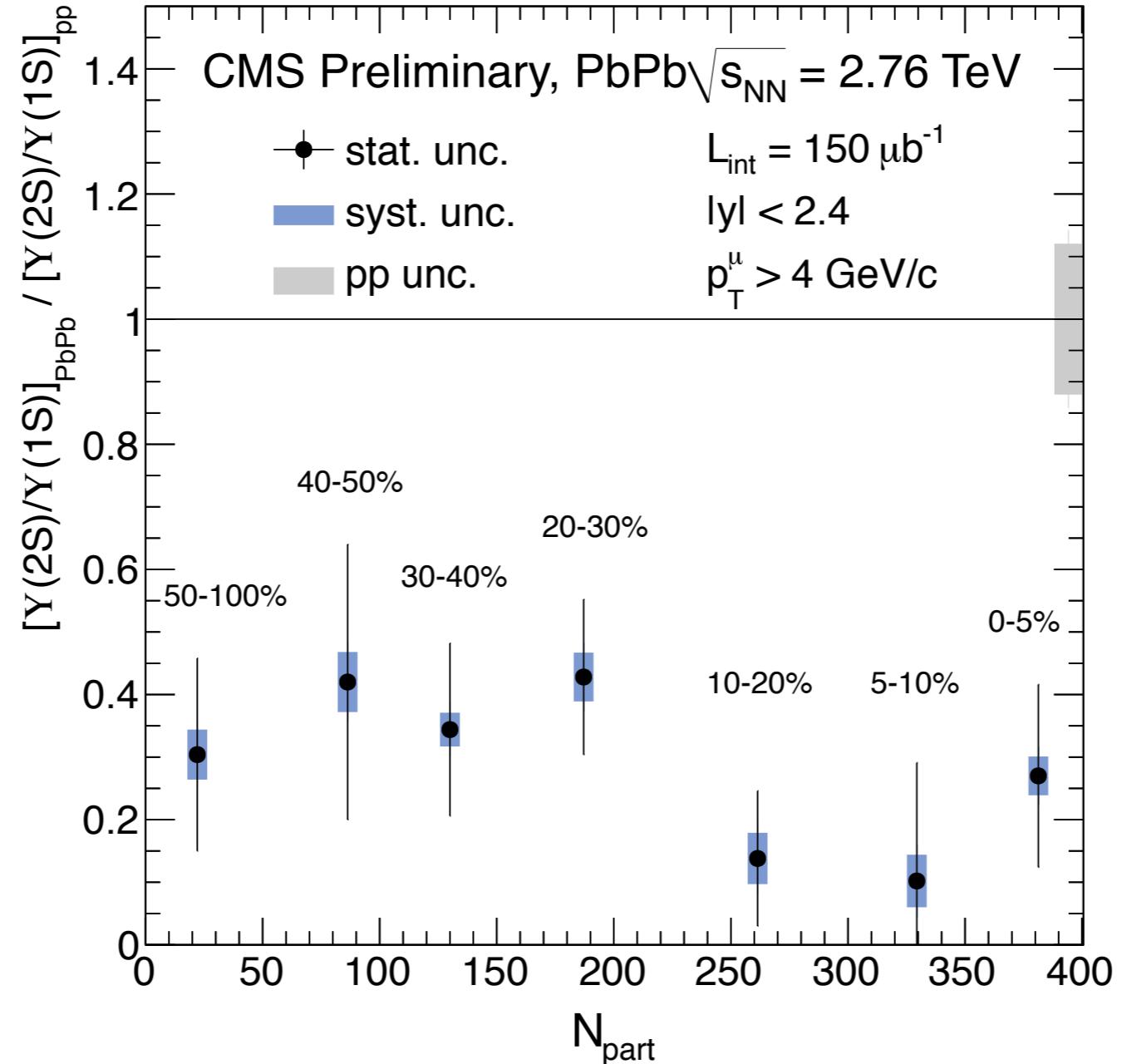
- Measure the relative suppression of the excited states relative to the ground state
- Simultaneous fit to pp and PbPb data
 - Signal: common shape and parameters to all 6 CB (same α , n , σ and $\Upsilon(1S)$ mean)
 - Background: left to float separately
- Uncertainties:
 - imperfect acceptance+efficiency cancelation: 1%
 - fitting (10%)
 - ▶ Final state radiation modeling: variations from fixing CB parameters to MC expectations
 - ▶ Background modeling: constraining parameters from like-sign and track-rotated dimuon spectra, then fitting the opposite-sign spectra
 - ▶ use largest variation for equivalent sources, and added in quadrature otherwise

$$\text{0-100%: } \frac{[\Upsilon(2S)/\Upsilon(1S)]|_{PbPb}}{[\Upsilon(2S)/\Upsilon(1S)]|_{pp}} = 0.21 \pm 0.07 \pm 0.02 \text{ (5.4}\sigma\text{ significance)}$$

$$\frac{[\Upsilon(3S)/\Upsilon(1S)]|_{PbPb}}{[\Upsilon(3S)/\Upsilon(1S)]|_{pp}} < 0.1 \text{ (95\% C.L.)}$$

Suppression pattern: $\Upsilon(3S) > \Upsilon(2S) > \Upsilon(1S)$

Double ratio: $[\Upsilon(2S)/\Upsilon(1S)]_{\text{PbPb}} / [\Upsilon(2S)/\Upsilon(1S)]_{\text{pp}}$

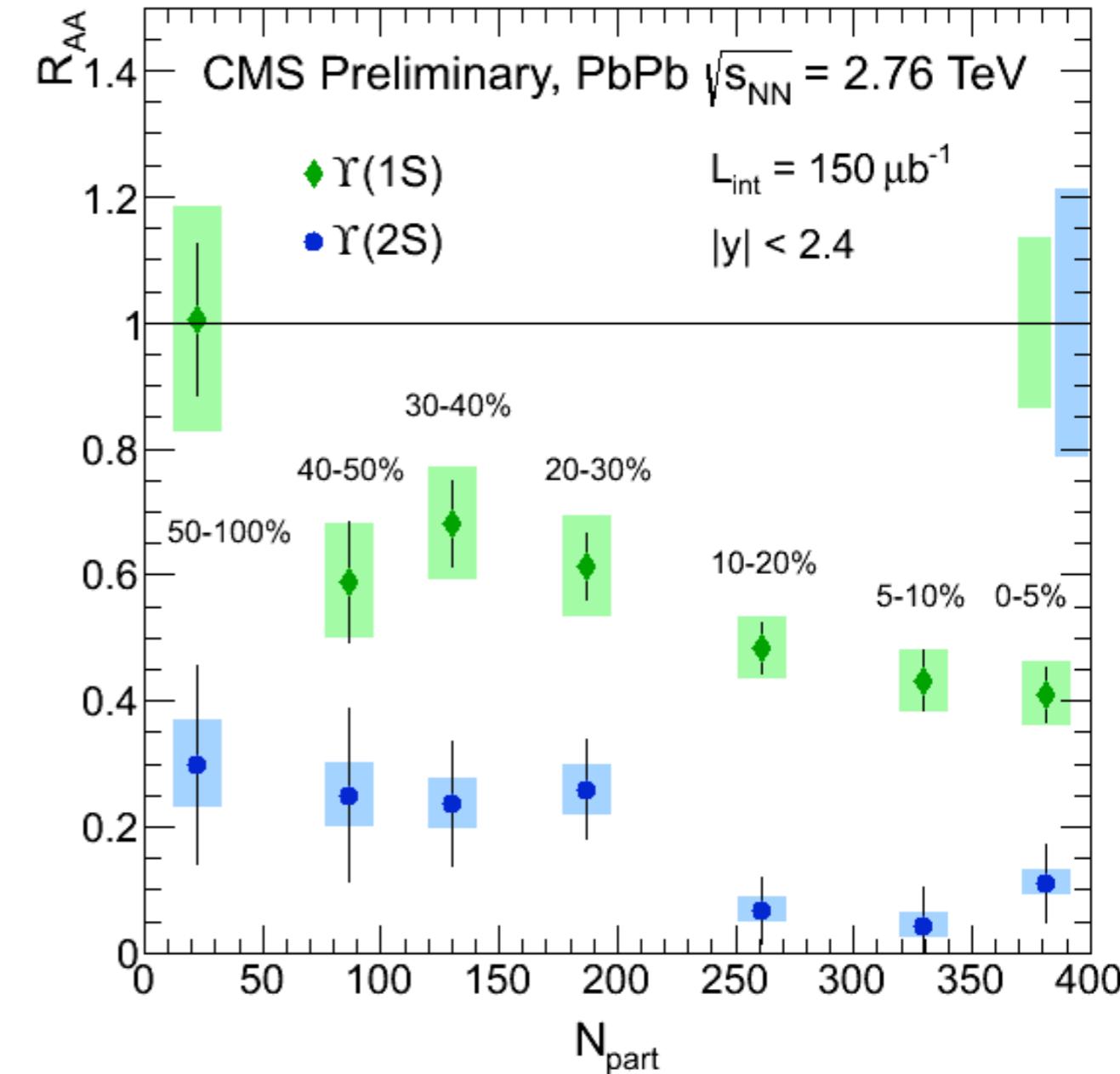


- In absence (by cancellation) of cold nuclear matter effects, $\Upsilon(1S)$ and $\Upsilon(2S)$
- show no obvious centrality dependence, within uncertainties, of the remaining hot nuclear matter induced effects

Nuclear modification factor: $R_{AA}(N_{\text{part}})$

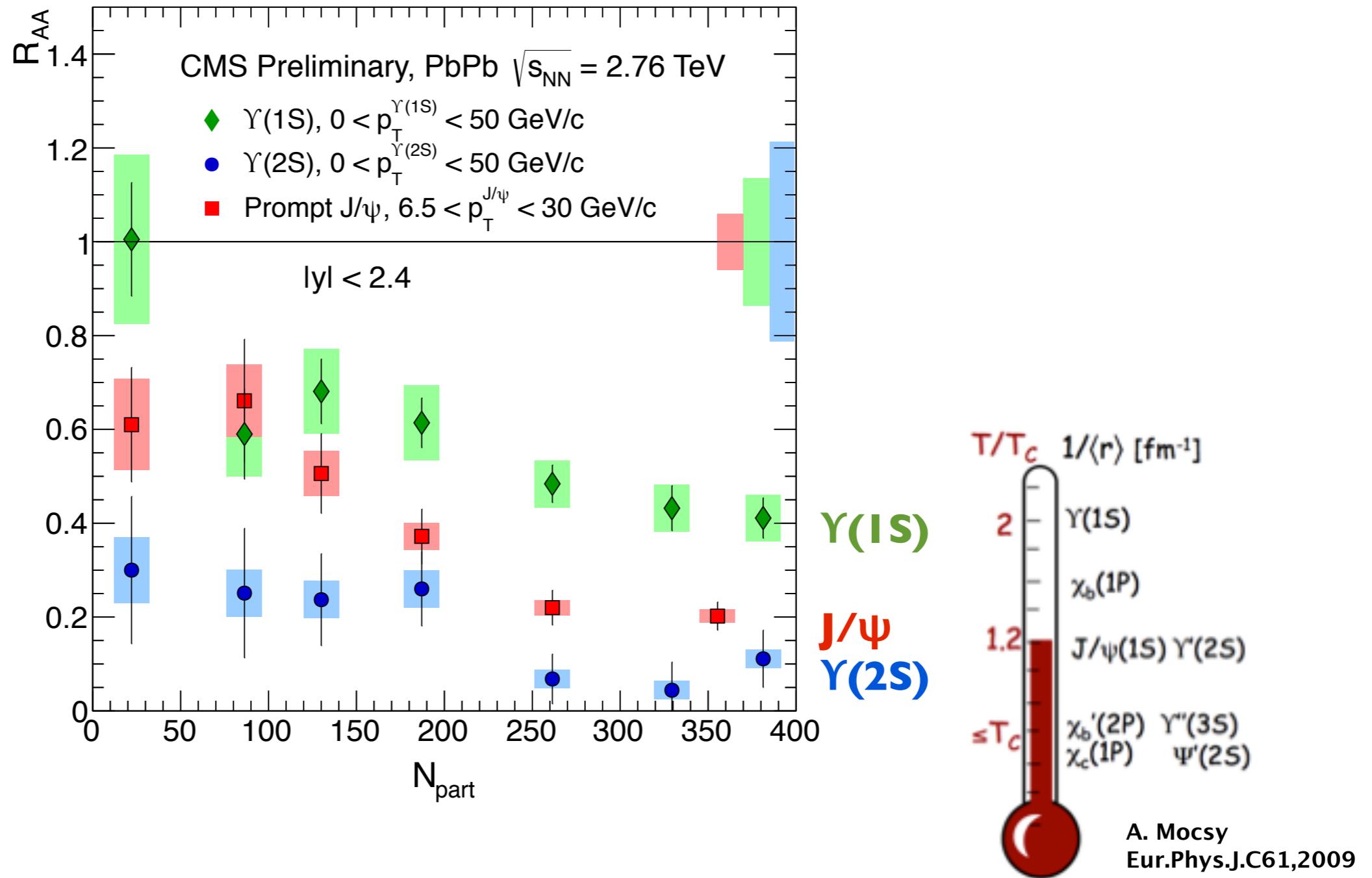
$$R_{AA} \equiv \frac{L_{\text{pp}}}{T_{AA} N_{\text{MB}}} \frac{\Upsilon(nS)|_{\text{PbPb}}}{\Upsilon(nS)|_{\text{pp}}} \frac{\epsilon_{\text{pp}}}{\epsilon_{\text{PbPb}}}$$

- $L_{\text{pp}} = 231 \text{ nb}^{-1}$ [6% uncertainty]
- $N_{\text{MB}} = 1.13 \text{ billion}$
- $T_{AA} = [4-15\% \text{ uncertainty}]$
- $\Upsilon(nS)$ yields
 - 4-9% systm. uncertainty for $\Upsilon(1S)$
 - 10-40% systm. uncertainty for $\Upsilon(2S)$
- $\epsilon_{\text{pp}}, \epsilon_{\text{PbPb}}$ efficiency corrections [$<7\%$]
- Global uncertainty: lumi & pp(stat+syst)
 - 14% for $\Upsilon(1S)$
 - 21% for $\Upsilon(2S)$



- Clear centrality dependence, with $\Upsilon(2S)$ more suppressed than $\Upsilon(1S)$
 - $\Upsilon(1S)$: $0.41 \pm 0.05 \pm 0.04$ (0-5%) → $1.01 \pm 0.18 \pm 0.12$ (50-100%)
 - $\Upsilon(2S)$: $0.11 \pm 0.02 \pm 0.06$ (0-5%) → $0.30 \pm 0.07 \pm 0.16$ (50-100%)
- Relative suppression, for both states: ~ 2.5 from 0-5% → 50-100%

Nuclear modification factor: $R_{AA}(N_{\text{part}})$



- Suppression pattern in most central collisions, as expected from sequential melting

Summary (1)

- First separate measurement, in HI collisions, of the relative suppression of $\Upsilon(2S)$ and $\Upsilon(3S)$ excited states wrt to the ground state

- Suppression pattern as expected in the sequential melting scenario

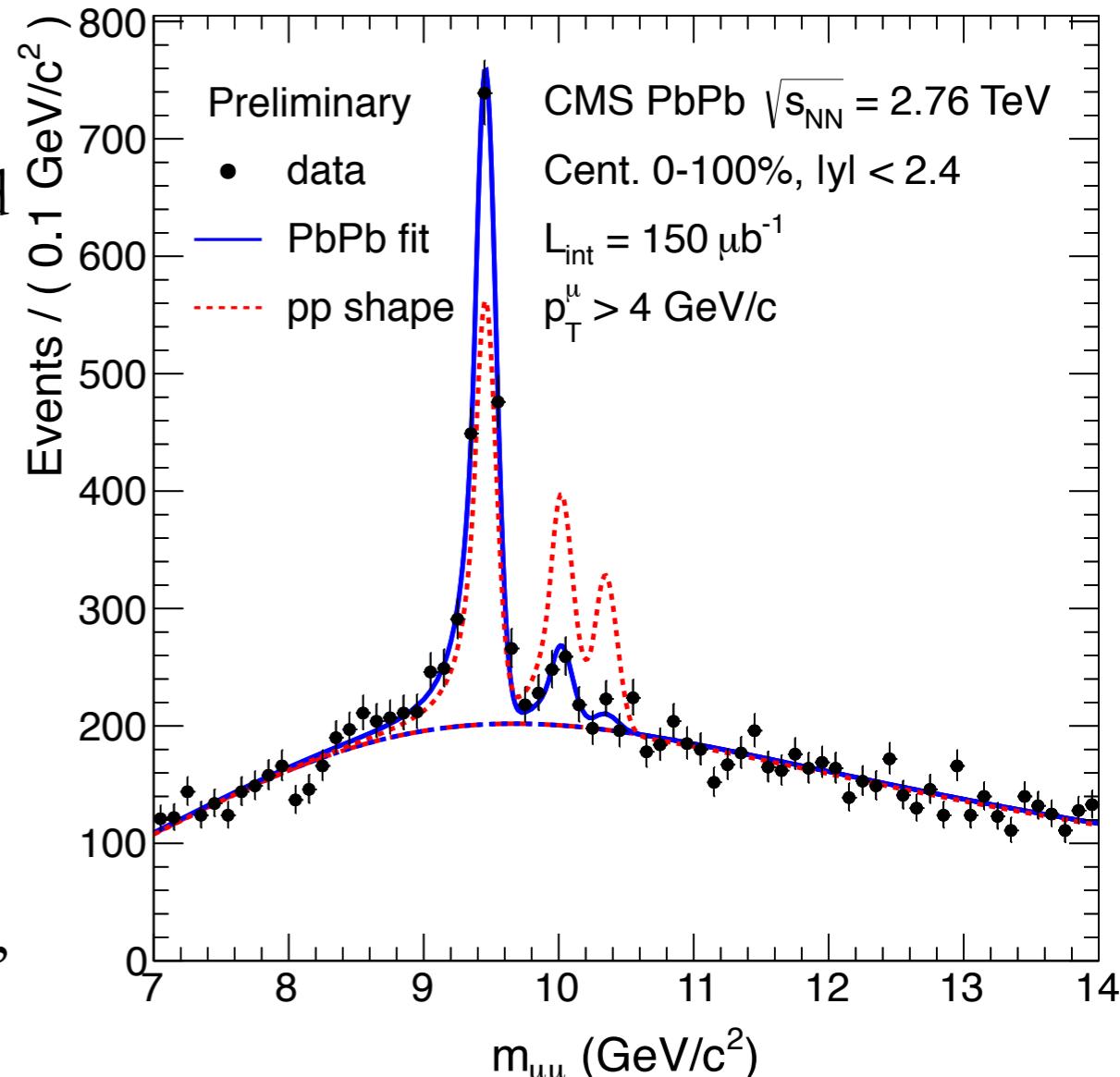
$$\Upsilon(3S) > \Upsilon(2S) > \Upsilon(1S)$$

- No centrality dependence, within uncertainties, of the $[\Upsilon(2S)/\Upsilon(1S)]_{PbPb} / [\Upsilon(2S)/\Upsilon(1S)]_{pp}$

0-100%:

$$\frac{[\Upsilon(2S)/\Upsilon(1S)]|_{PbPb}}{[\Upsilon(2S)/\Upsilon(1S)]|_{pp}} = 0.21 \pm 0.07 \pm 0.02 \text{ (5.4}\sigma\text{ significance)}$$

$$\frac{[\Upsilon(3S)/\Upsilon(1S)]|_{PbPb}}{[\Upsilon(3S)/\Upsilon(1S)]|_{pp}} < 0.1 \text{ (95\% C.L.)}$$



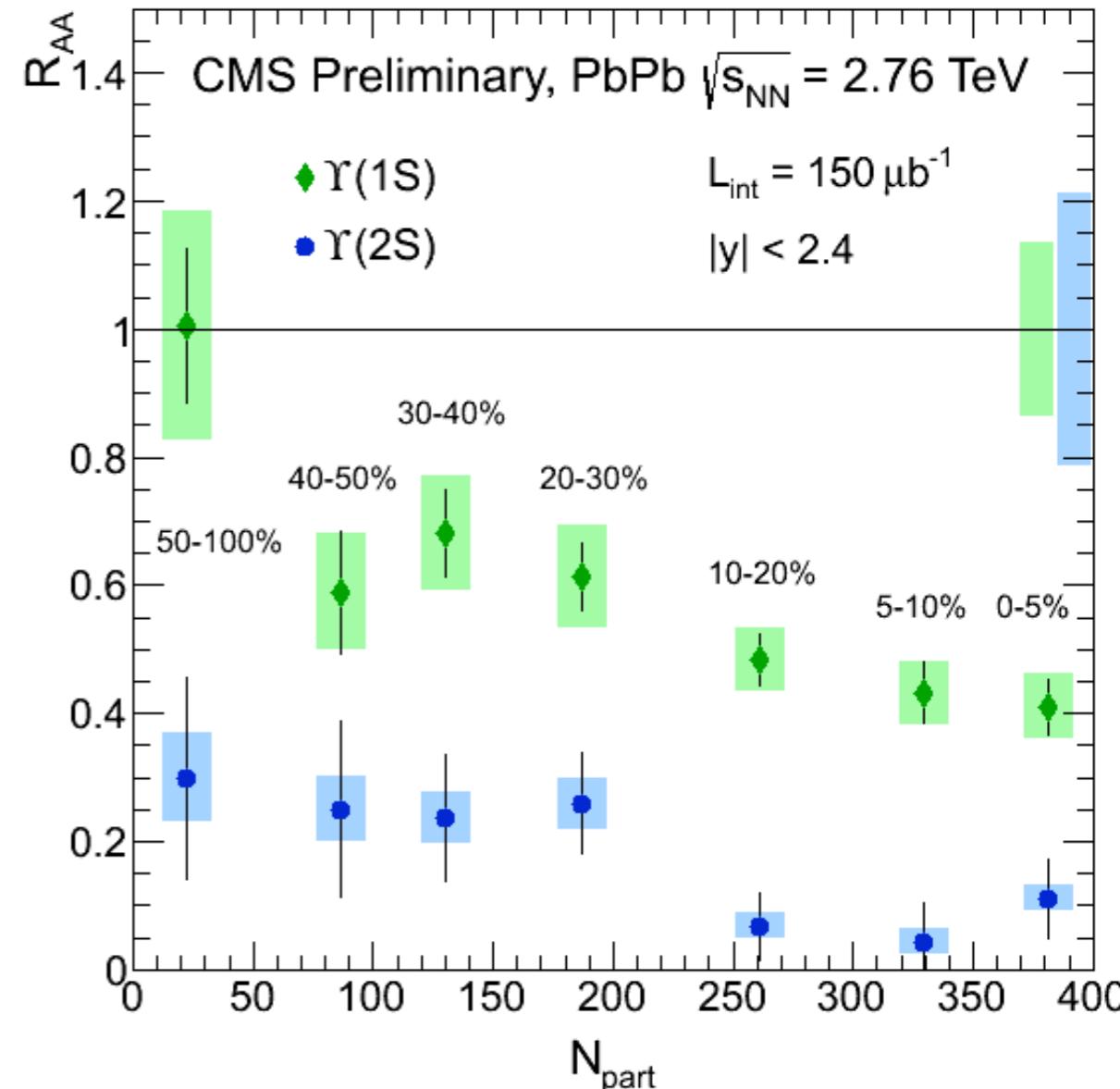
Summary (2)

● R_{AA} : $\Upsilon(1S)$

- detailed centrality study
- decrease of suppression from ~ 0.4 in 0-5% to ~ 1 in 50-100%

● R_{AA} : $\Upsilon(2S)$

- first time measured in HI collisions
- more suppressed than the ground state and still suppressed in 50-100% centrality bin



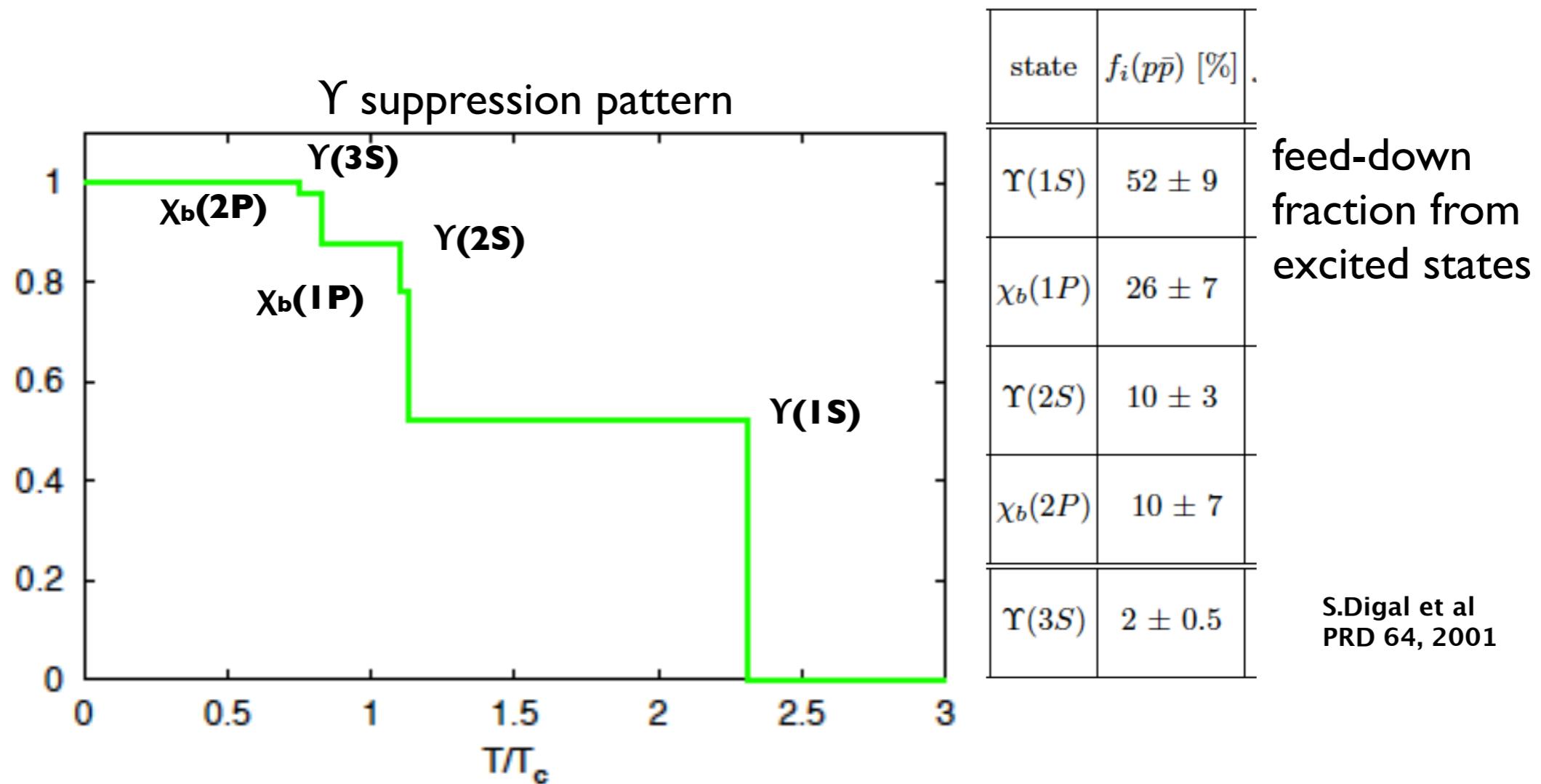
0-100%

$$R_{AA}|^{\Upsilon(1S)} = 0.53 \pm 0.07 \pm 0.07$$

$$R_{AA}|^{\Upsilon(2S)} = 0.13 \pm 0.04 \pm 0.02$$

Extra slides

Feed-down fraction from the excited states



Update of last year result

$$\frac{[\Upsilon(2S)/\Upsilon(1S)]|_{PbPb}}{[\Upsilon(2S)/\Upsilon(1S)]|_{pp}} = 0.21 \pm 0.07 \pm 0.02 \text{ (} 5.4\sigma \text{ significance)} \quad$$

$$\frac{[\Upsilon(3S)/\Upsilon(1S)]|_{PbPb}}{[\Upsilon(3S)/\Upsilon(1S)]|_{pp}} < 0.1 \text{ (} 95\% C.L. \text{)} \quad$$

$$\frac{[\Upsilon(2S + 3S)/\Upsilon(1S)]|_{PbPb}}{[\Upsilon(2S + 3S)/\Upsilon(1S)]|_{pp}} = 0.15 \pm 0.05 \pm 0.02 \quad$$