The fate of quarkonia in heavy-ion collisions at LHC energies: a unified description of the sequential suppression patterns

1) The quarkonium production cross sections and polarizations measured in pp collisions by ATLAS and CMS show remarkably simple scaling patterns vs. mass and momentum

2) A simple extension of those pp observations, with only one free parameter, reproduces well the suppression patterns seen in Pb-Pb collisions for all quarkonia, providing crystal-clear evidence of the sequential suppression mechanism

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“Hot problems of Strong Interactions”
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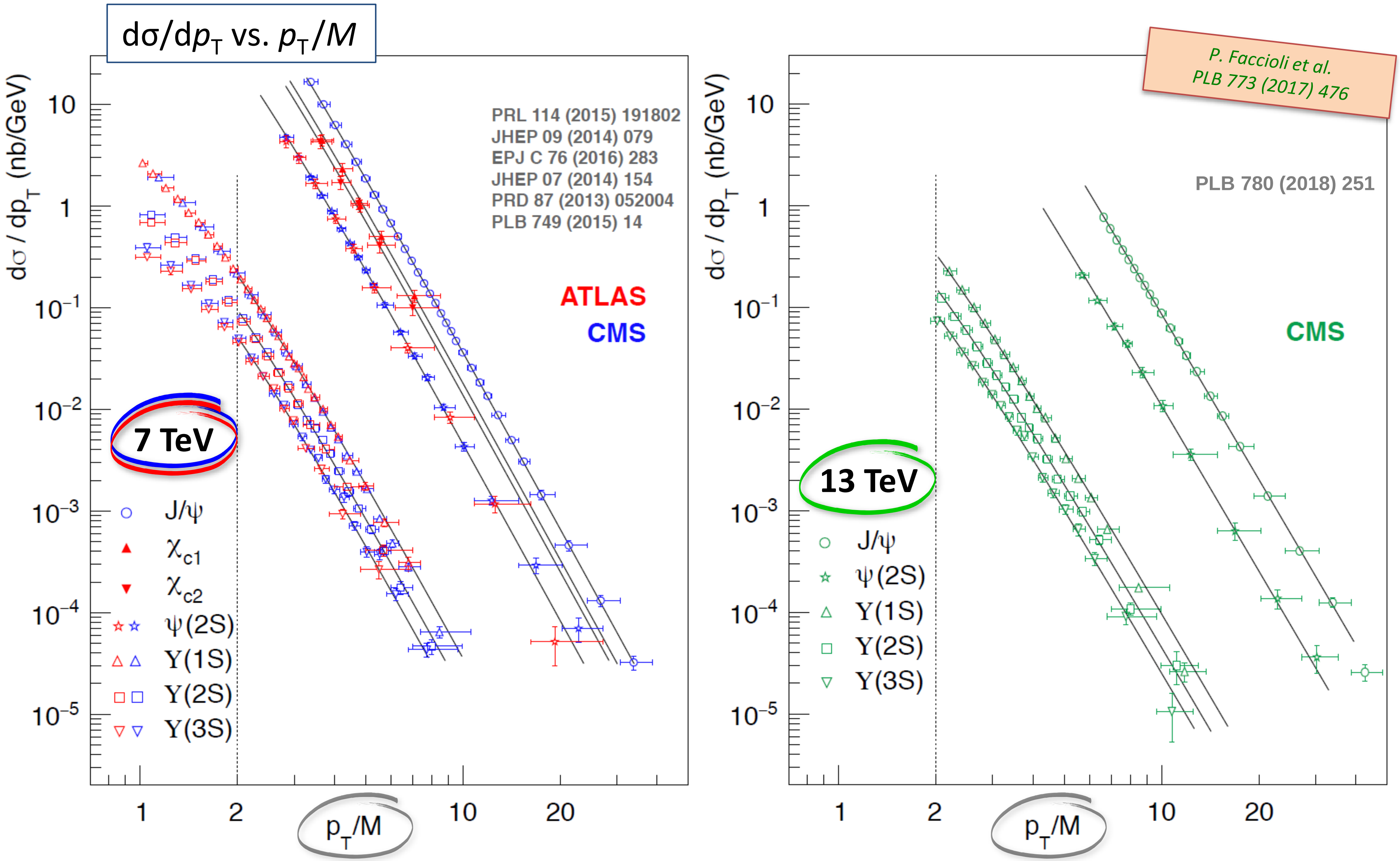
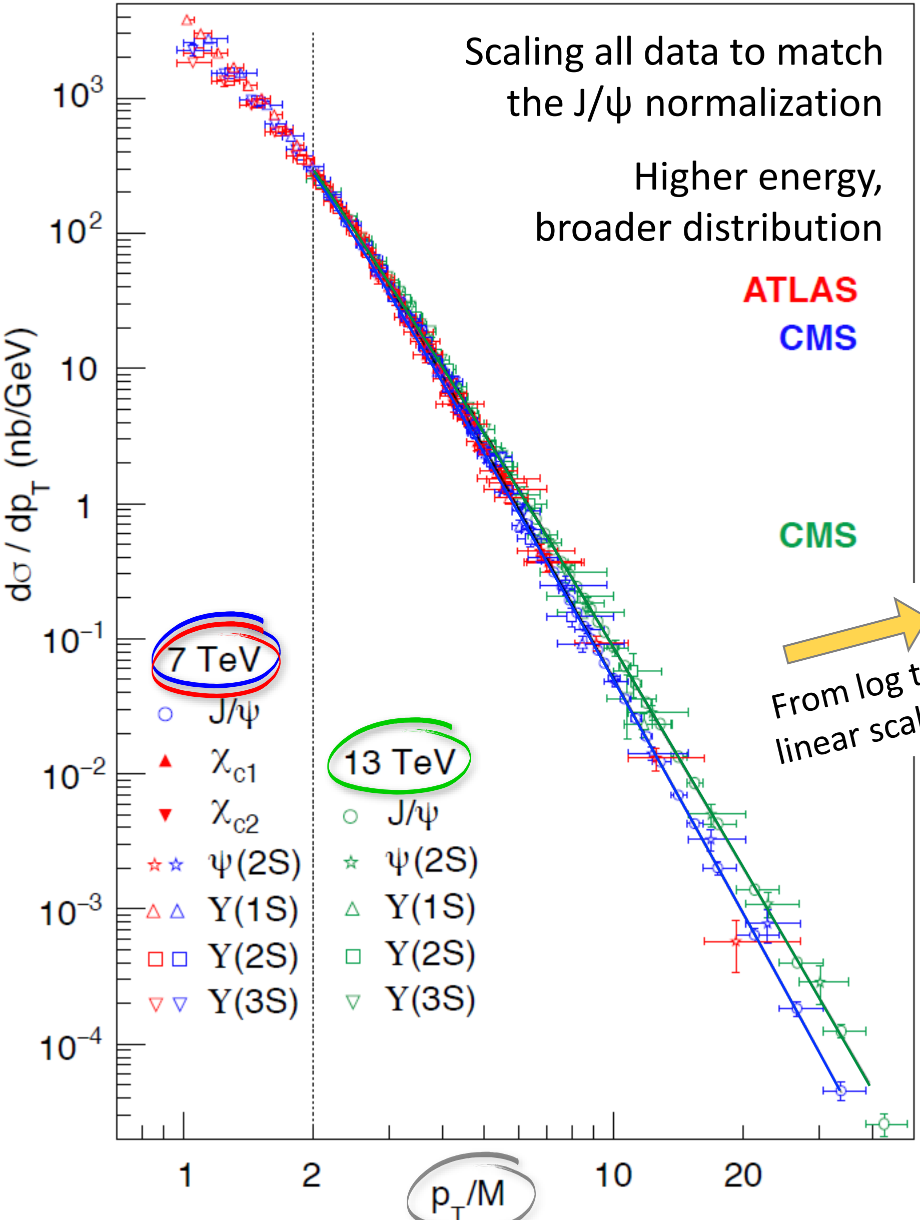
(and Carlos Lourenço)

The p_T distributions in pp collisions

The quarkonium cross sections measured at mid-rapidity by ATLAS and CMS show identical p_T/M-differential patterns, for $p_T/M > 2$, independently of mass and quantum numbers

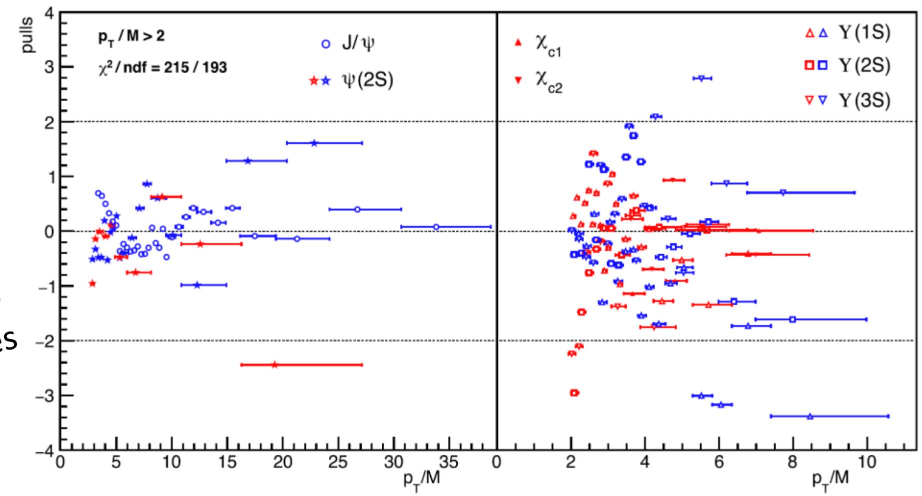


Unexpectedly simple data patterns



No hint of mass-dependence in mid-rapidity p_T distributions **from J/ψ to ϒ(3S)** after dimensional scaling, $p_T \to$ $\boldsymbol{p_T/M}$, at least for $p_T/M > 2$

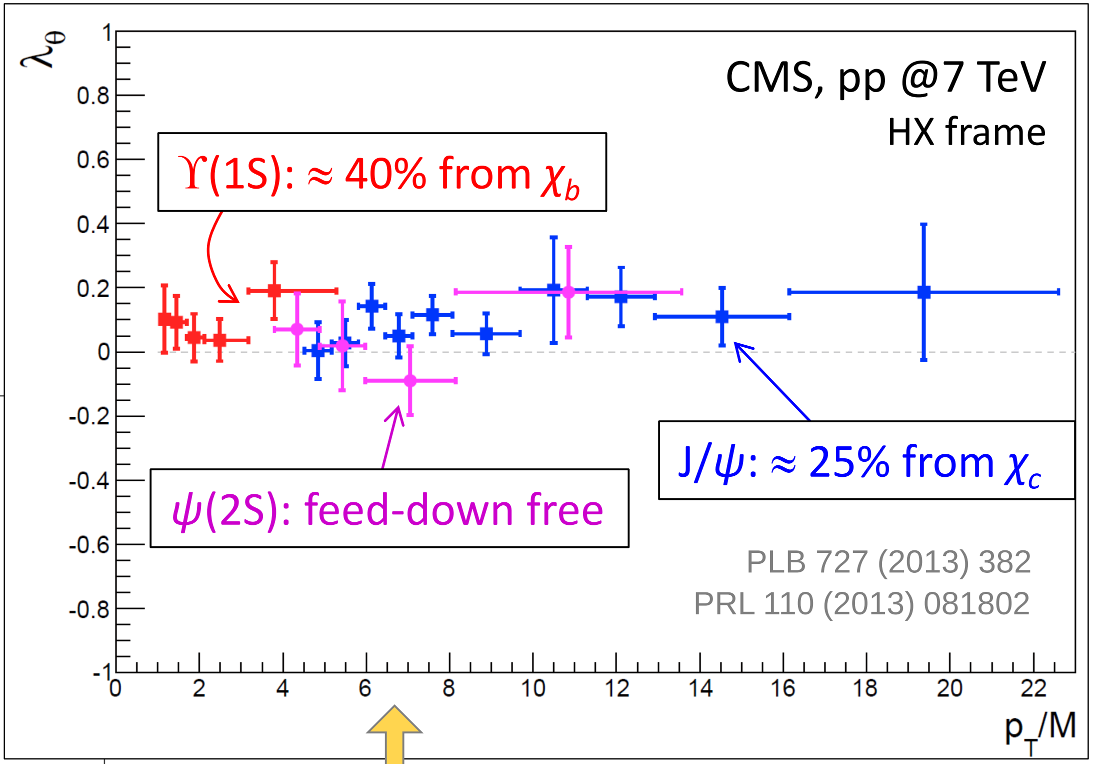
From log to linear scales



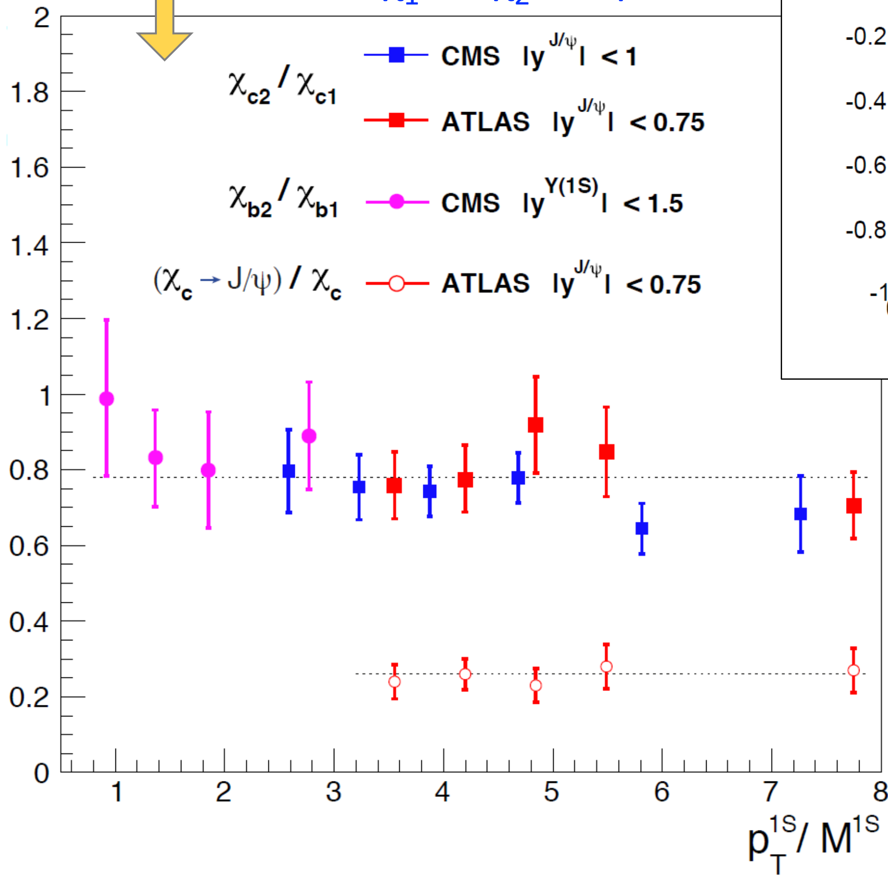
All data points are very well aligned on a single universal pattern, with only a small number of points deviating by more than 2σ

Same production dynamics for S- and P-wave states

Pure *kinematic* scaling
$\Rightarrow$ no sign of dependence of the production *dynamics* on the quantum numbers !

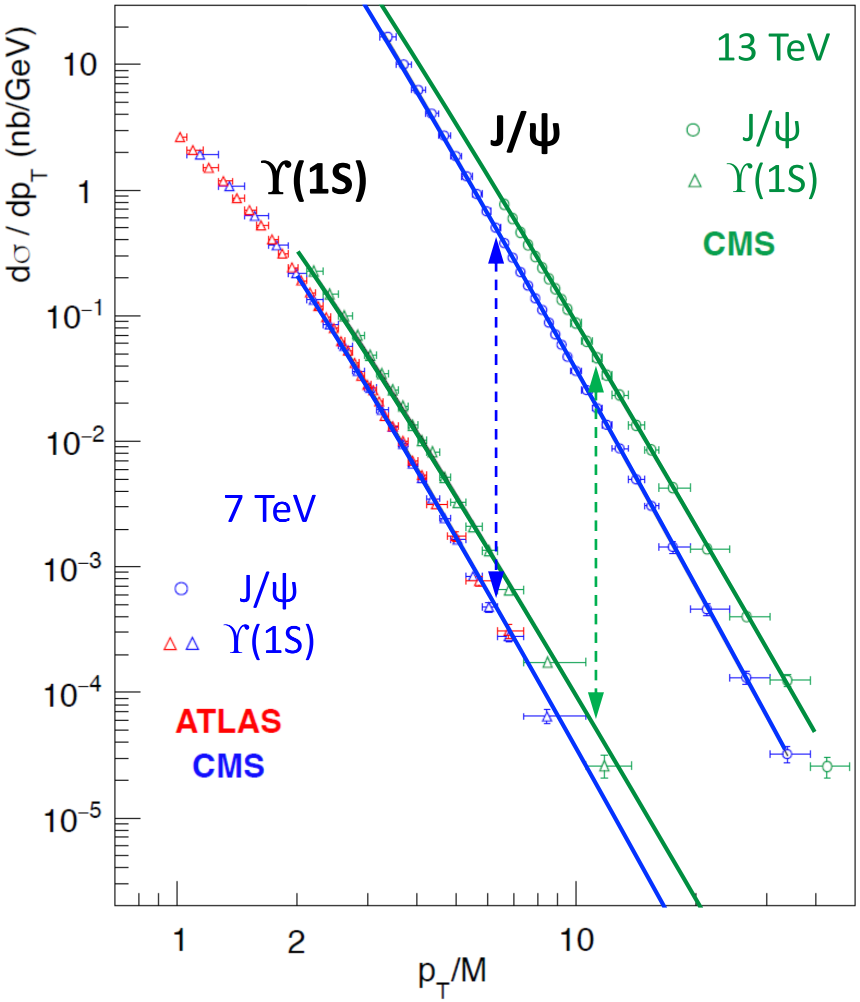


"Zoom": χ_1 vs. χ_2 vs. ψ/Υ



Negligible polar decay anisotropies,
with no p_T dependences,
for all S-wave states

Mass scaling from charm to beauty



Exploiting p_T/M scaling, we can determine the mass scaling of the cross section through the ratio of the fitted p_T/M distributions at one (arbitrary) p_T/M point (*)

How do the production cross sections scale from charmonium (m_c) to bottomonium (m_b) ?

We consider the two lightest mesons, J/ψ and ϒ(1S), correcting for feed-down (#)

$$\frac{d\sigma/dp_T\,(\Upsilon(1S))}{d\sigma/dp_T\,(J/\psi)} = \left(\frac{m_b}{m_c}\right)^{-\alpha}$$

$$\alpha = \begin{cases} 6.6 \pm 0.1 & 7\text{ TeV} \\ 6.5 \pm 0.1 & 13\text{ TeV} \end{cases}$$

(*) Without model-dependent extrapolations to low p_T

(#) Assumption for ϒ(1S) : $f_{dir} = 50 \pm 10$ %

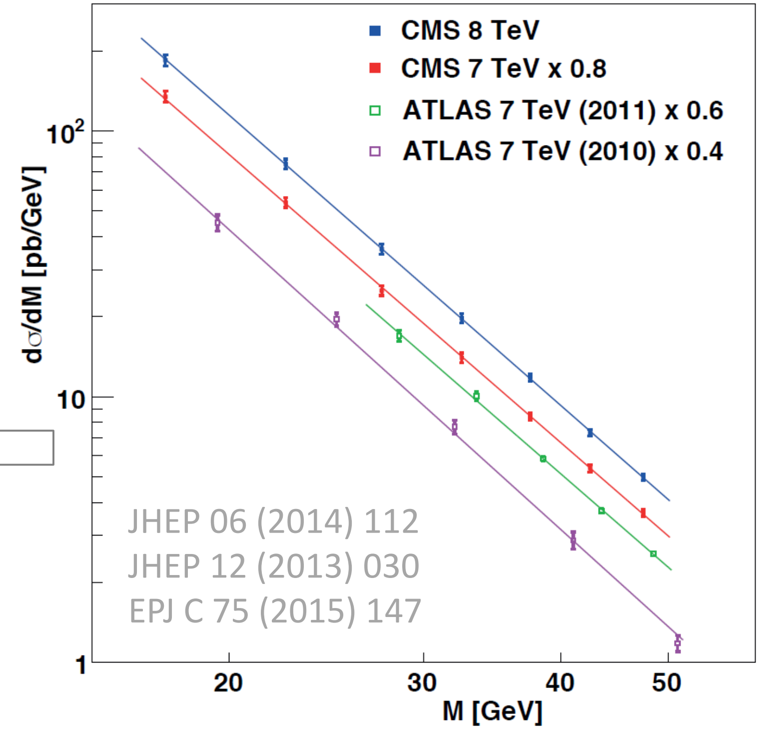
Comparison to a simple reference: Drell-Yan

quarkonium, 7 TeV:

$$\frac{d\sigma/dp_T\,(\Upsilon(1S))}{d\sigma/dp_T\,(J/\psi)} = \left(\frac{m_b}{m_c}\right)^{-(6.6\,\pm\,0.1)}$$

Drell-Yan at 7|8 TeV for M < M_Z:

$$\frac{d\sigma/dM\,(M_2)}{d\sigma/dM\,(M_1)} = \left(\frac{M_2}{M_1}\right)^{-(3.63\,\pm\,0.03)}$$



From dimensional analysis:

at partonic level

$$\frac{d\sigma^{\,DY}}{dM} \propto M^{-(3\,+\,\beta)}$$

parton-luminosity factor
$\approx (\sqrt{s}\,/\,M)^{\beta}$
common to all processes

$\Rightarrow \beta = 3.63 - 3 = 0.63\ (\pm\,0.03)$

$\Rightarrow$ the "PDF-undressed" quarkonium cross section goes like $m_Q^{-(6.6\,-\,0.63)}$

quarkonium: m_Q^{-6} ⟺ DY: M^{-3}

The only difference seems to be the bound-state wave function, of dimension m_Q^{3}

Implications of the observed scaling patterns

Inclusive quarkonium production cross section from pure dimensional analysis:

$$\frac{d\sigma}{dp_T} = \sum_i m_Q^{-3} \times \frac{\mathcal{L}_i\,(m_Q, M, p_T/M, y, \sqrt{s}/M)}{m_Q^3} \times \mathcal{F}_i\,(m_Q, M, p_T/M, y, \sqrt{s}/M) \times \left(\frac{\sqrt{s}}{M}\right)^{\beta}$$

global dimensionality

$\mathcal{L}$ = purely formal "LDME" terms, defined to have the same $[m_Q^3]$ dimensionality of the bound-state wave function

generic dimensionless factors

parton luminosity

$\beta = 0.63 \pm 0.03$ for $\sqrt{s}$ = 7-8 TeV

$\mathcal{L}_i$ and $\mathcal{F}_i$ are here *a priori generic* (and redundant) functions of the relevant variables.
No assumption about possible factorization into $Q\bar{Q}$ creation $\times$ bound-state formation

Implications of the observed scaling patterns

Inclusive quarkonium production cross section from pure dimensional analysis:

$$\frac{d\sigma}{dp_T} = \sum_i m_Q^{-3} \times \frac{\mathcal{L}_i\,(m_Q, M, p_T/M, y, \sqrt{s}/M)}{m_Q^{3}} \times \mathcal{F}_i\,(m_Q, M, p_T/M, y, \sqrt{s}/M) \times \left(\frac{\sqrt{s}}{M}\right)^{\beta}$$

ATLAS and CMS data at $|y| \lesssim 2$ and $p_T/M \gtrsim 2$ tell us that :

1) the p_T/M dependence is identical for all states, independently of m_Q and M
   $\Rightarrow$ experimental evidence that short- and long-distance effects "factorize"
   $\Rightarrow$ $\mathcal{L}$ does not depend on p_T/M and $\mathcal{F}$ does not depend on mass :

$$\mathcal{L}\,(m_Q, M, \sqrt{s}/M) \times \mathcal{F}\,(p_T/M, y, \sqrt{s}/M)$$

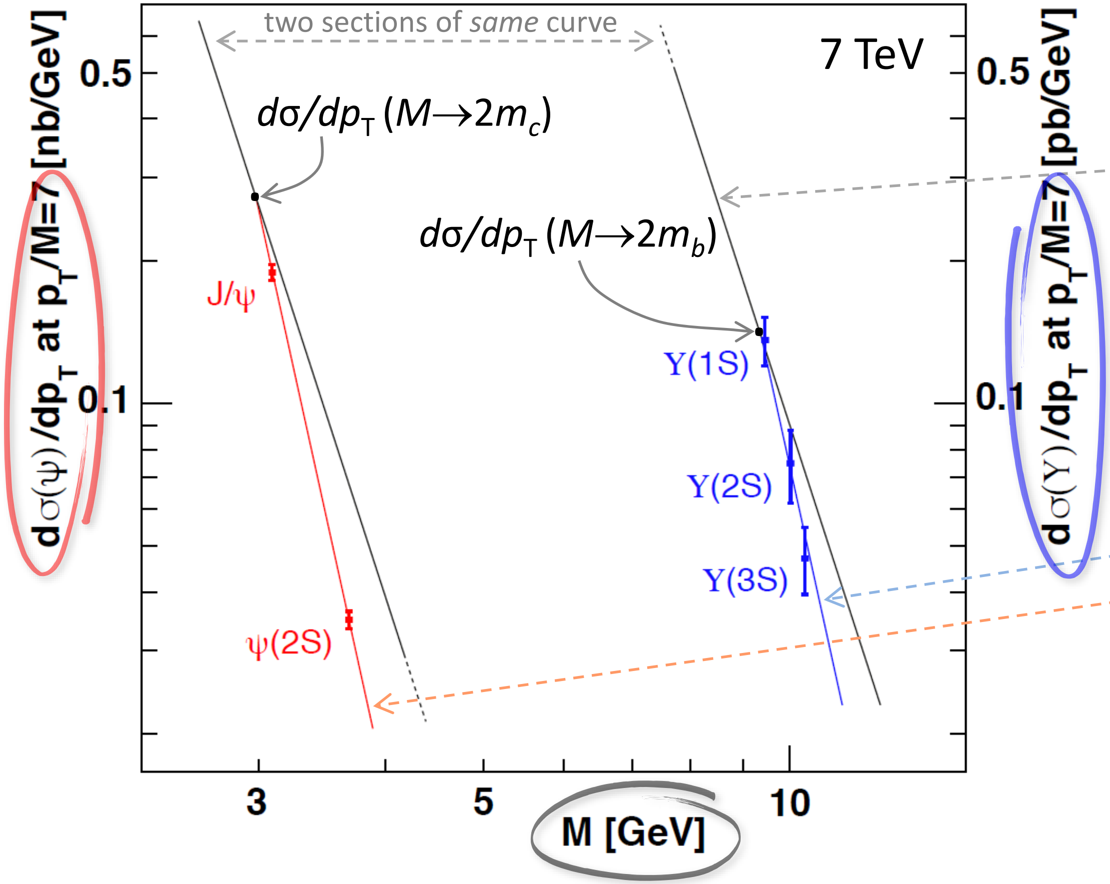
2) from charmonia to bottomonia the partonic-level cross section scales like m_Q^{-6}, with no $\sqrt{s}$ *dependence*
   $\Rightarrow$ $\mathcal{L}$ must not have further m_Q dependences, besides the factor $m_Q^{-3} \times 1/m_Q^{3}$
   $\Rightarrow$ $\mathcal{L}$ does not depend on $\sqrt{s}$
   $\Rightarrow$ further simplification of the "LDME" ; only a function of the M/m_Q ratio :

$$\mathcal{L} = \mathcal{L}(M/m_Q)$$

$$\boxed{\frac{d\sigma}{dp_T} = \sum_i m_Q^{-6} \times \left(\frac{\sqrt{s}}{M}\right)^{\beta} \times \mathcal{L}_i\,(M/m_Q) \times \mathcal{F}_i\,(p_T/M, y, \sqrt{s}/M)}$$

Mass scaling of S-wave cross sections

Refined determination of the mass scaling, using all S states and adopting the short $\times$ long-distance "factorized" perspective:



$$m_Q^{-6} \times \left(\frac{\sqrt{s}}{M}\right)^{\beta}$$

"short distance"

$$\frac{d\sigma/dp_T\,(M\to 2m_b)}{d\sigma/dp_T\,(M\to 2m_c)} = \left(\frac{m_b}{m_c}\right)^{-(6.63 \pm 0.08)}$$

$$\mathcal{L}_i\,(M/m_Q)$$

"long distance"

$$\frac{d\sigma/dp_T\,(M = M_{\psi|\Upsilon})}{d\sigma/dp_T\,(M\to 2m_{c|b})} = \left(\frac{M_{\psi|\Upsilon}}{2m_{c|b}}\right)^{-(9.7 \pm 0.3)}$$

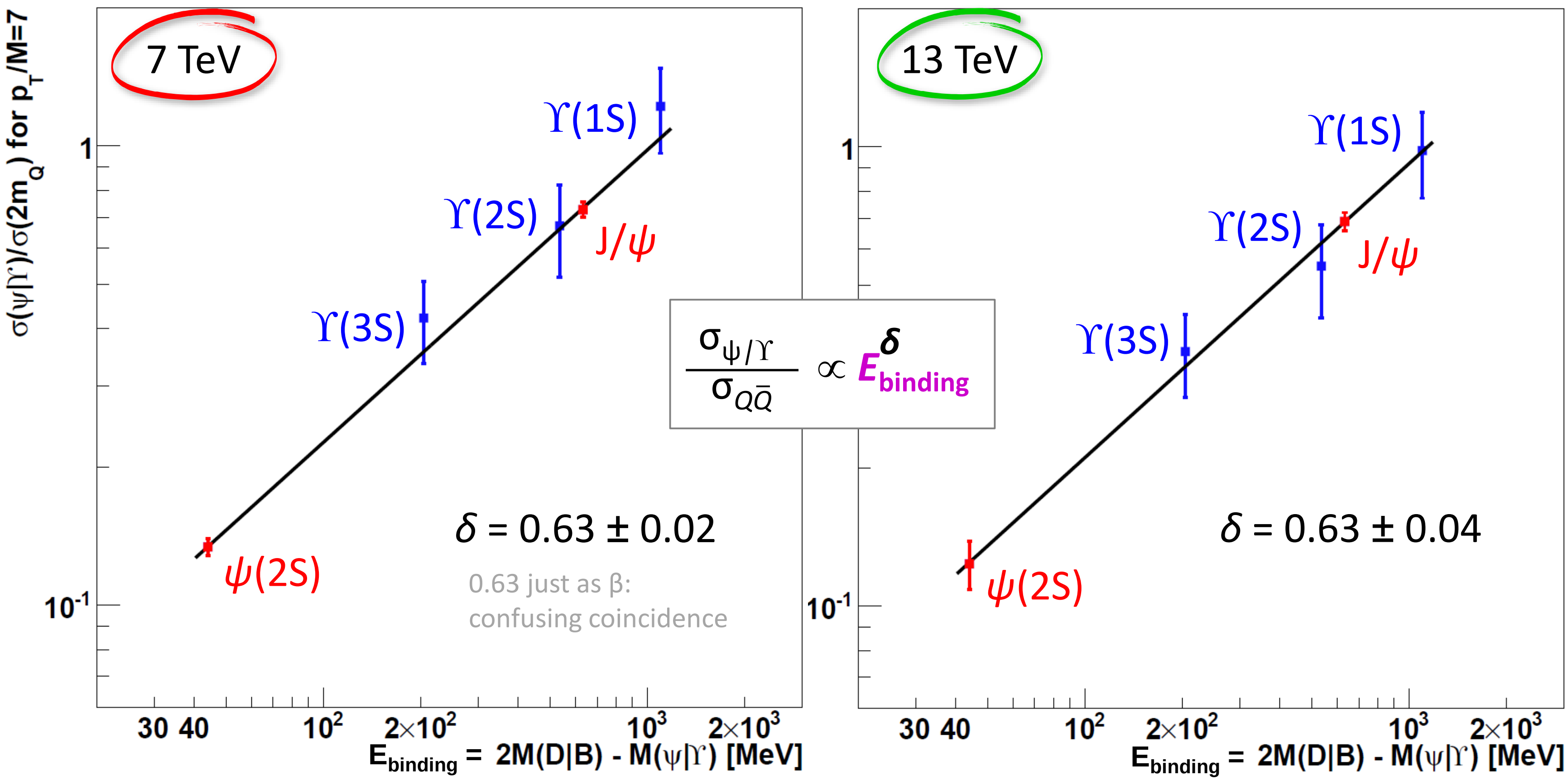
one common slope parameter fits well both the ψ and Υ states

Using:
$2m_Q = M_{\eta_c(1S)} | M_{\eta_b(1S)}$

initial assumption (iteratively improved):
f_{dir} = (50|60|70 ± 10)% for Υ(1|2|3S)
inspired by data including LHCb's forward-rapidity χ_b [EPJ C 74, 3092]

Long-distance scaling: a universal pattern?

The “LDMEs” show a clear power-law dependence on the **binding energy**
– common to charmonium and bottomonium
– identical at 7 and 13 TeV



⇒ further support to the assumption that the dependence on bound-state mass is a “*factorizable*” long-distance effect (= abstract from lab momentum dependence)

The "missing pieces" of quarkonium feed-down

Assuming that the "universal" E_{binding} dependence hypothesis can be extended to the P-wave states

$$\frac{\sigma_{\chi}}{\sigma_{Q\bar{Q}}} \propto E_{\text{binding}}^{0.63 \pm 0.02}$$

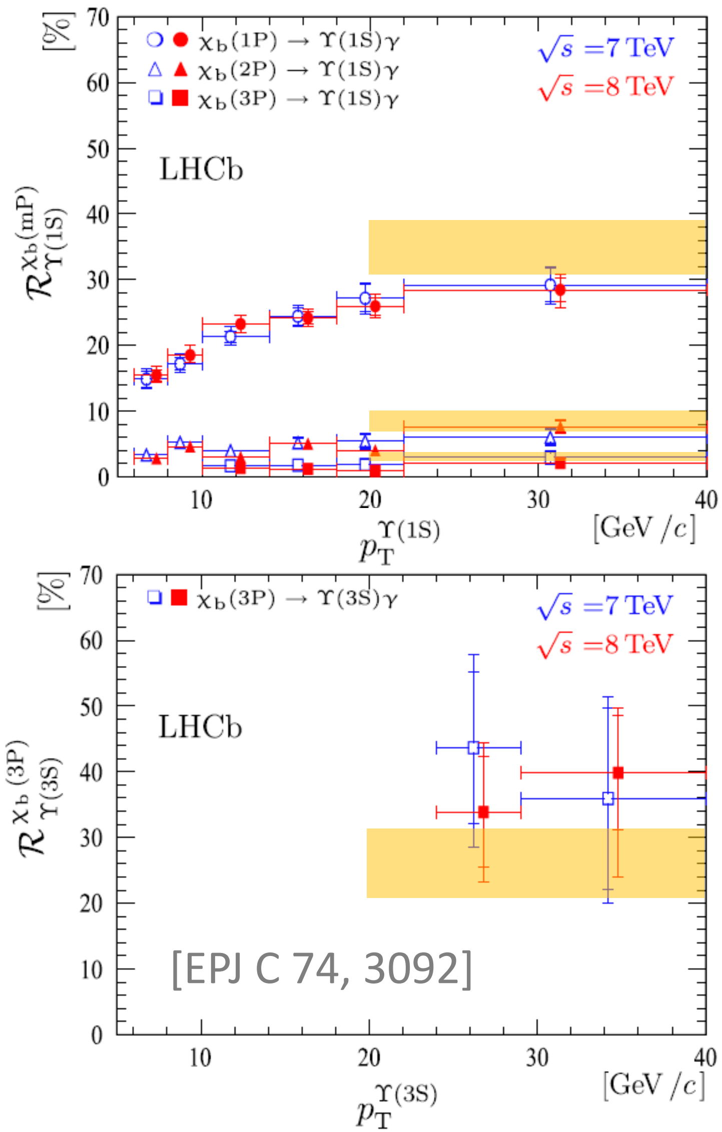
χ_c data constrain the χ_b(1-2-3P) cross sections and, using BRs from PDG, the feed-down structure of quarkonium production can be fully predicted

```
Feed-down fractions in pp (%):
------------------------------
Jpsi      tot            31.9 +- 1.6
          from chic0     0.762 +- 0.059
          from chic1     15.61 +- 0.99
          from chic2     7.83 +- 0.53
          from psi2S     7.67 +- 0.88
          from Y1S       (5.57 +- 0.69) E-5
          from Y2S       (2.2  +- 2.2) E-5

chic0     tot            2.09 +- 0.26
          from psi2S     2.09 +- 0.26
          from Y1S       (3.4 +- 3.4) E-5
          from Y2S       (1.5 +- 1.5) E-5

chic1     tot            2.61 +- 0.33
          from psi2S     2.61 +- 0.33
          from Y1S       (4.26 +- 0.89) E-5
          from Y2S       (2.10 +- 0.55) E-5

chic2     tot            2.81 +- 0.35
          from psi2S     2.81 +- 0.35
          from Y1S       (7.1 +- 2.) E-5
          from Y2S       (2.48 +- 0.92) E-5

psi2S     tot            (1.36 +- 0.43) E-4
          from Y1S       (1.01 +- 0.22) E-4
          from Y2S       (0.35 +- 0.35) E-4
```

```
Y1S       tot            59.0 +- 4.9
          from chib0_1P  1.22 +- 0.29
          from chib1_1P  21.7 +- 3.6
          from chib2_1P  11.5 +- 2.1
          from Y2S       11.3 +- 1.6
          from chib0_2P  0.167 +- 0.082
          from chib1_2P  5.1 +- 1.1
          from chib2_2P  3.40 +- 0.74
          from Y3S       1.51 +- 0.28
          from chib0_3P  0.018 +- 0.016
          from chib1_3P  1.59 +- 0.52
          from chib2_3P  1.35 +- 0.52

chib0_1P  tot            2.67 +- 0.62
          from Y2S       2.58 +- 0.61
          from Y3S       0.099 +- 0.028

chib1_1P  tot            4.8 +- 1.0
          from Y2S       4.7 +- 1.0
          from Y3S       0.033 +- 0.020

chib2_1P  tot            5.3 +- 1.1
          from Y2S       5.0 +- 1.1
          from Y3S       0.372 +- 0.099
```

```
Y2S       tot            45.0 +- 5.7
          from chib0_2P  1.42 +- 0.43
          from chib1_2P  19.0 +- 3.8
          from chib2_2P  9.2 +- 2.1
          from Y3S       5.7 +- 1.2
          from chib0_3P  0.15 +- 0.12
          from chib1_3P  5.9 +- 1.7
          from chib2_3P  3.7 +- 1.3

chib0_2P  tot            3.09 +- 0.79
          from Y3S       3.09 +- 0.79

chib1_2P  tot            6.5 +- 1.6
          from Y3S       6.5 +- 1.6

chib2_2P  tot            6.8 +- 1.7
          from Y3S       6.8 +- 1.7

Y3S       tot            25.9 +- 5.5
          from chib0_3P  1.02 +- 0.61
          from chib1_3P  17.0 +- 4.5
          from chib2_3P  7.8 +- 2.4
```

Comparison with existing data



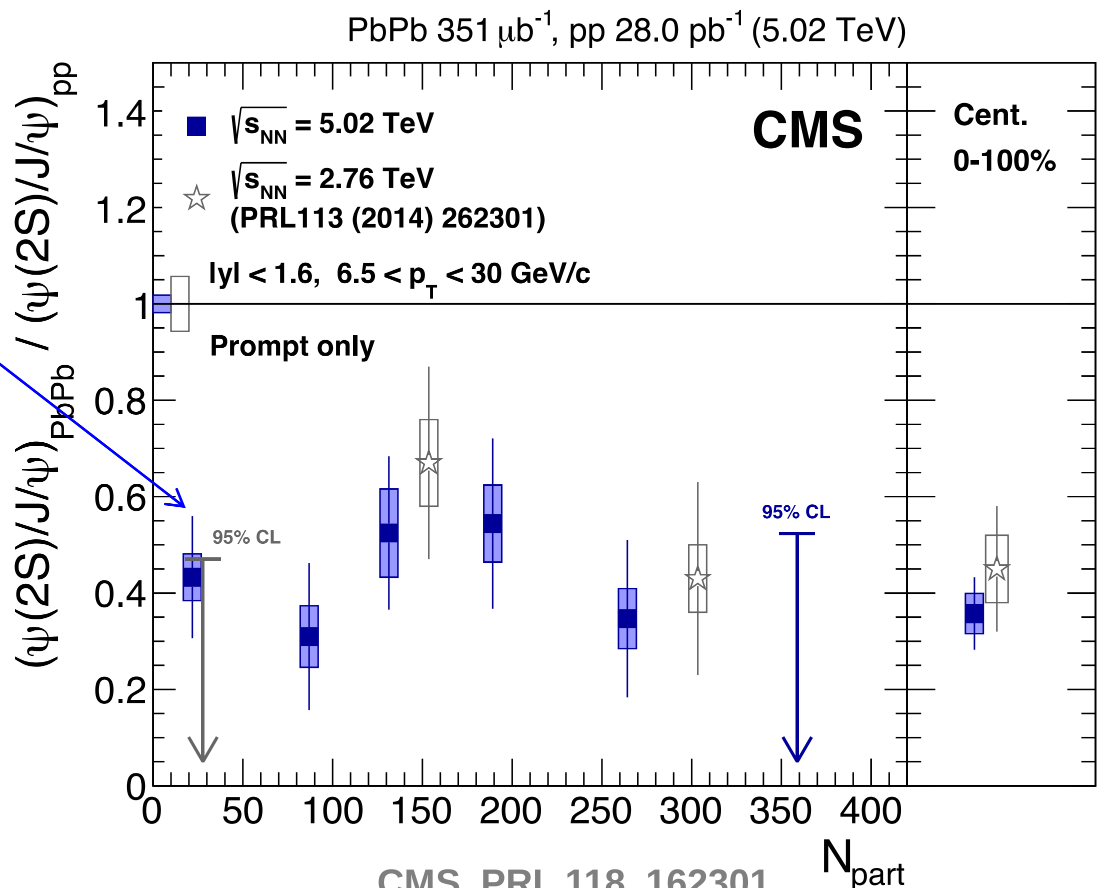
The predicted $\chi_b \to \Upsilon$ feed-downs are in reasonable agreement with forward-rapidity LHCb data (considered for $p_T/M > 2$)

Nuclear modifications in Pb-Pb

How is the universal E_{binding}-scaling modified in Pb-Pb?
Can we describe Pb-Pb data assuming a minimal modification of the simple parametrization found for pp data?

Hint from data: the double charmonium ratio $R_{AA}(2S)/R_{AA}(1S)$ is well below 1 already in peripheral events

ψ(2S) has a *very* small binding energy
⇒ a *threshold effect* in binding energy?

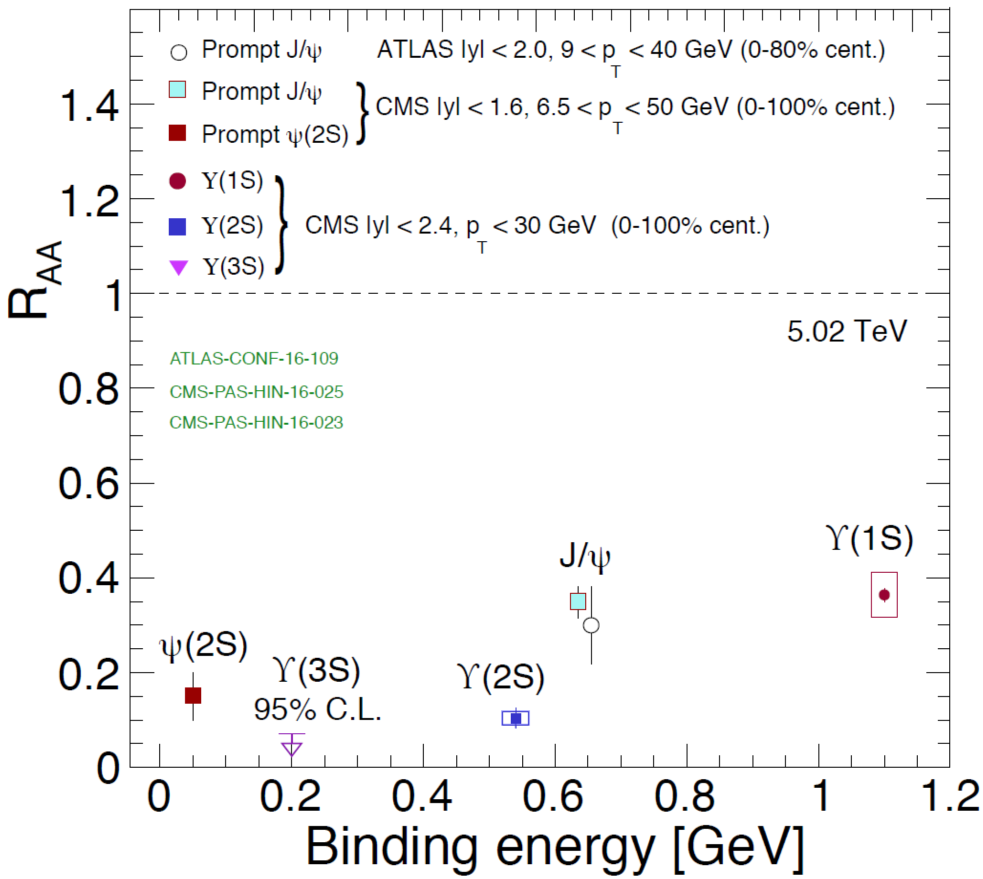


CMS, PRL 118, 162301

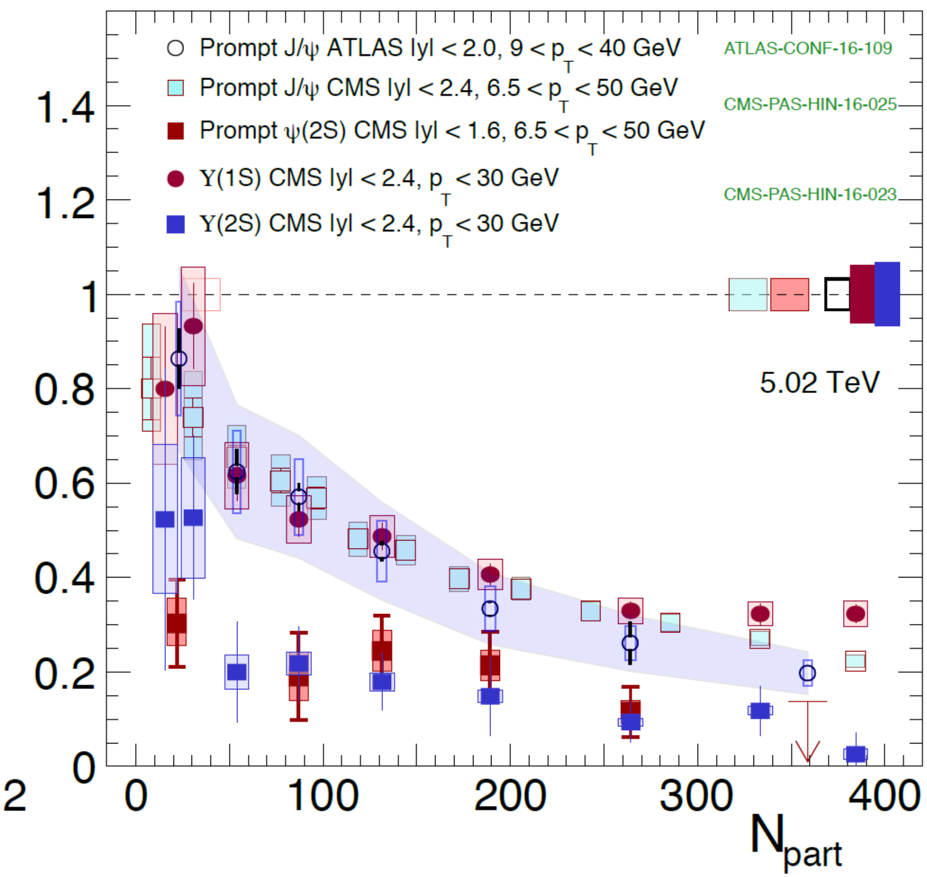
Nuclear modifications in Pb-Pb

We want to study the measured AA-to-pp production ratio R_{AA} as a function of

binding energy



centrality



One hypothesis, different interpretations

Base assumption:
nuclear effects modify the "universal bound-state formation pattern" as follows:

$$\boxed{\frac{\sigma_{\mathcal{Q}}}{\sigma_{Q\bar{Q}}} \propto \boldsymbol{E}_{\textbf{binding}}^{\boldsymbol{\delta}}}_{\text{pp}} \Longrightarrow \boxed{\frac{\sigma_{\mathcal{Q}}}{\sigma_{Q\bar{Q}}} \propto (\boldsymbol{E}_{\textbf{binding}} - \boldsymbol{\Delta E})^{\boldsymbol{\delta}}}_{\text{AA}} \qquad \mathcal{Q} = \psi \;/\; \chi_{c/b} \;/\; \Upsilon$$

$$E_{\text{binding}}(\text{J}/\psi) = 2M(D^0) - M(\text{J}/\psi)$$

With increasing ΔE it becomes less and less probable to *form* the bound state.
For $\Delta E > E_{\text{binding}}$ the $Q\bar{Q}$ never transforms into quarkonium

An *empirical* parametrization with different interpretations and possibly including different physics effects, e.g.:

$$E_{\text{binding}}(\text{J}/\psi) - \boldsymbol{\Delta E} = \begin{cases} [2\boldsymbol{M(D^0)} - \boldsymbol{\Delta E}] - M(\text{J}/\psi) \;\; ? \Rightarrow \text{screening effectively reduces di-meson threshold?} \\ 2M(D^0) - [\boldsymbol{M(\text{J}/\psi)} + \boldsymbol{\Delta E}] \;\; ? \Rightarrow \text{multiple scattering effectively increases } Q\bar{Q} \text{ relative momentum and invariant mass?} \end{cases}$$

→ J. Qiu et al., PRL 88 (2002) 232301

Parameters and ingredients

$$\left.\boxed{\frac{\sigma_{\mathcal{Q}}}{\sigma_{Q\bar{Q}}} \propto \boldsymbol{E_{\text{binding}}^{\delta}}}\right._{\text{pp}} \Longrightarrow \left.\boxed{\frac{\sigma_{\mathcal{Q}}}{\sigma_{Q\bar{Q}}} \propto (\boldsymbol{E_{\text{binding}}} - \boldsymbol{\Delta E})^{\boldsymbol{\delta}}}\right._{\text{AA}} \qquad \mathcal{Q} = \psi \;/\; \chi_{c/b} \;/\; \Upsilon$$

ΔE is determined from data in each condition (centrality, energy);
in this study, however, we will be assuming that it is *always the same for all states,* which is the simplest possible scenario.

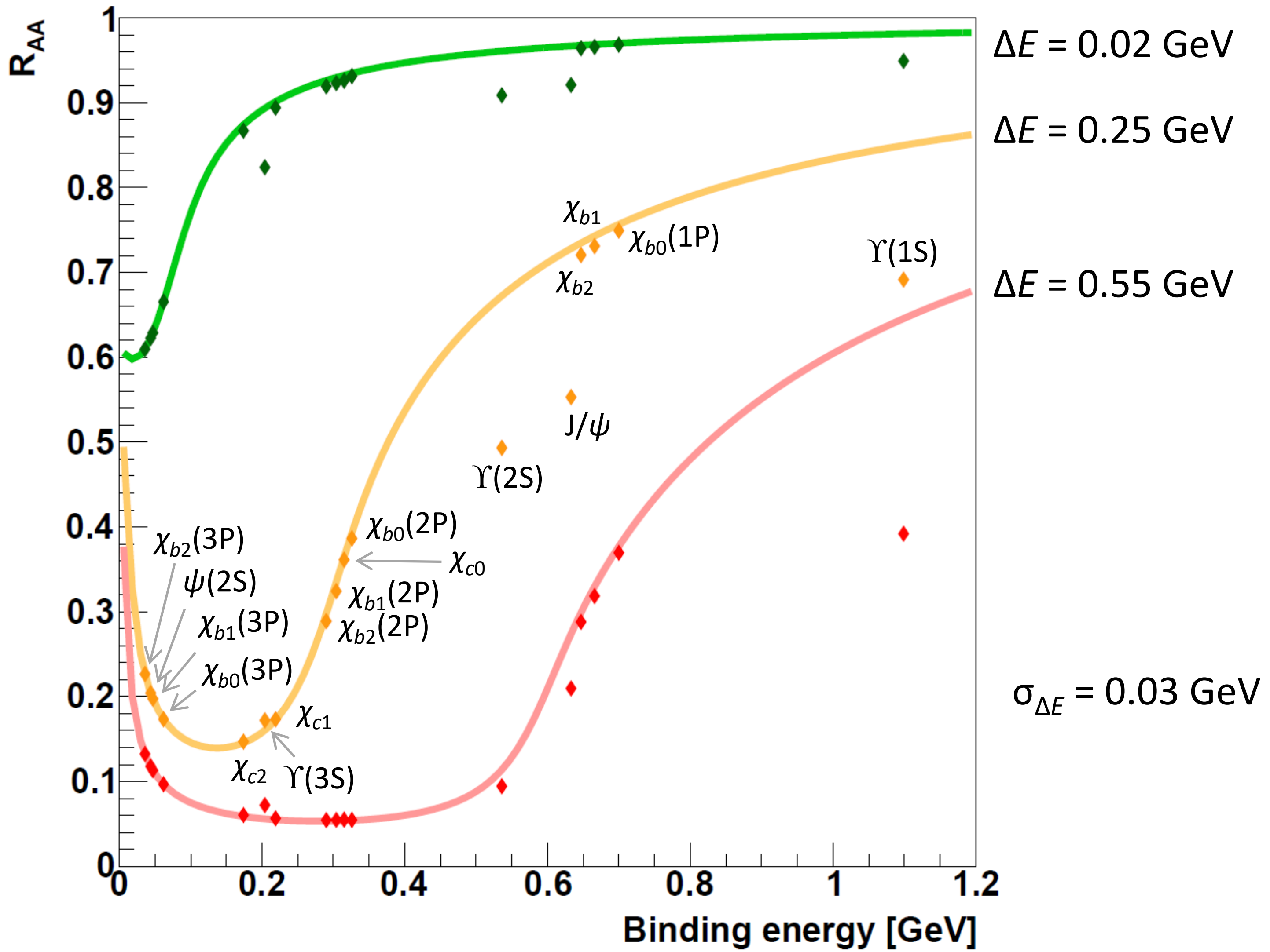
Additional parameter:
the width of the ΔE distribution, $\sigma_{\Delta E}$, is kept centrality-independent, for simplicity

The rest is *fixed from pp data*:
– same parameter $\delta = 0.63 \pm 0.04$ used in AA as in pp

Cross sections of all states calculated in pp and AA for each condition;
all varying feed-down effects (from P- to S-waves, from S- to P-waves and in chains) included in the parametrization using PDG branching ratios and uncertainties

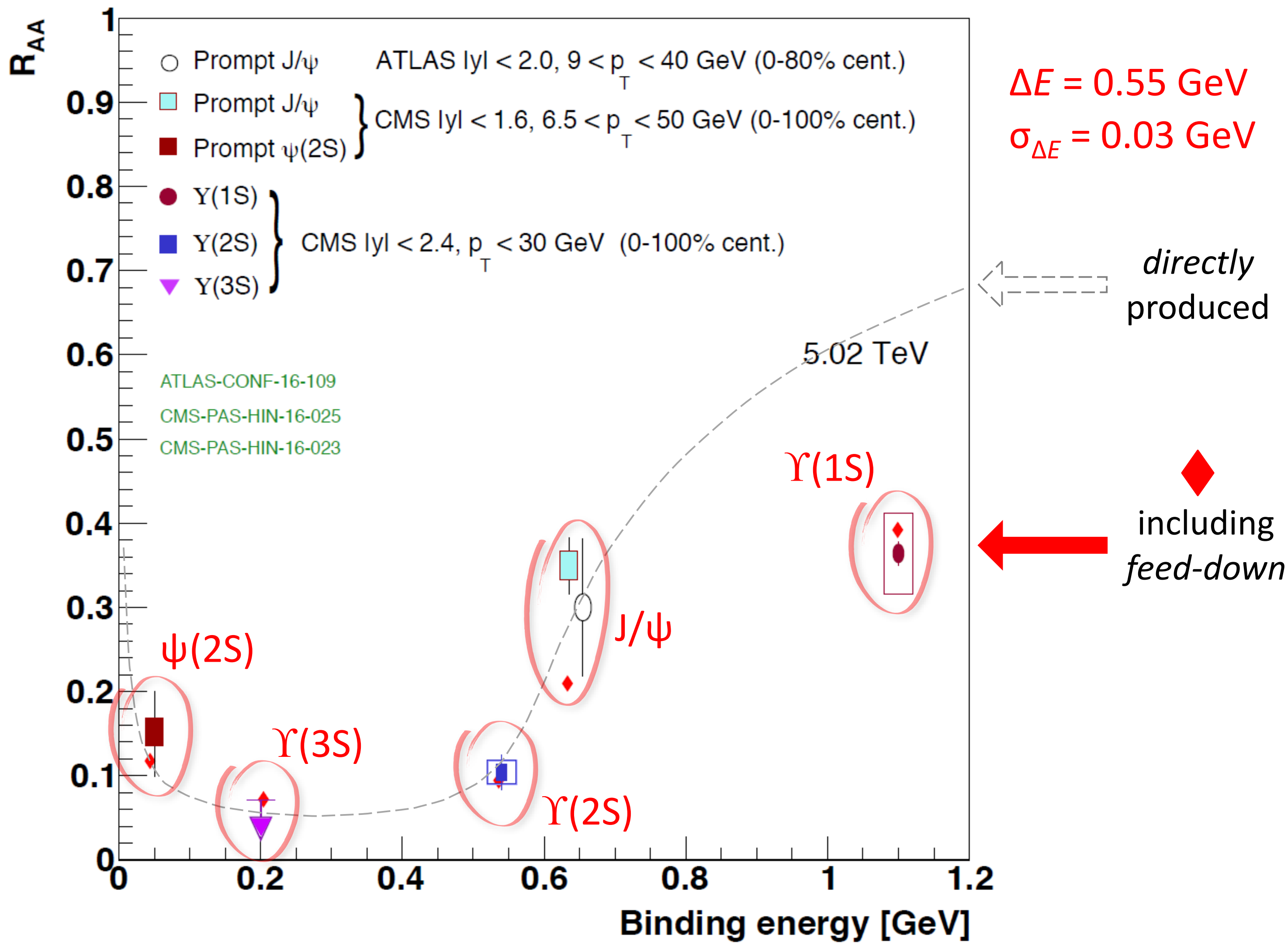
Examples

Curves: suppression of *directly* produced states
Points: including effect of feed-down specific to each state

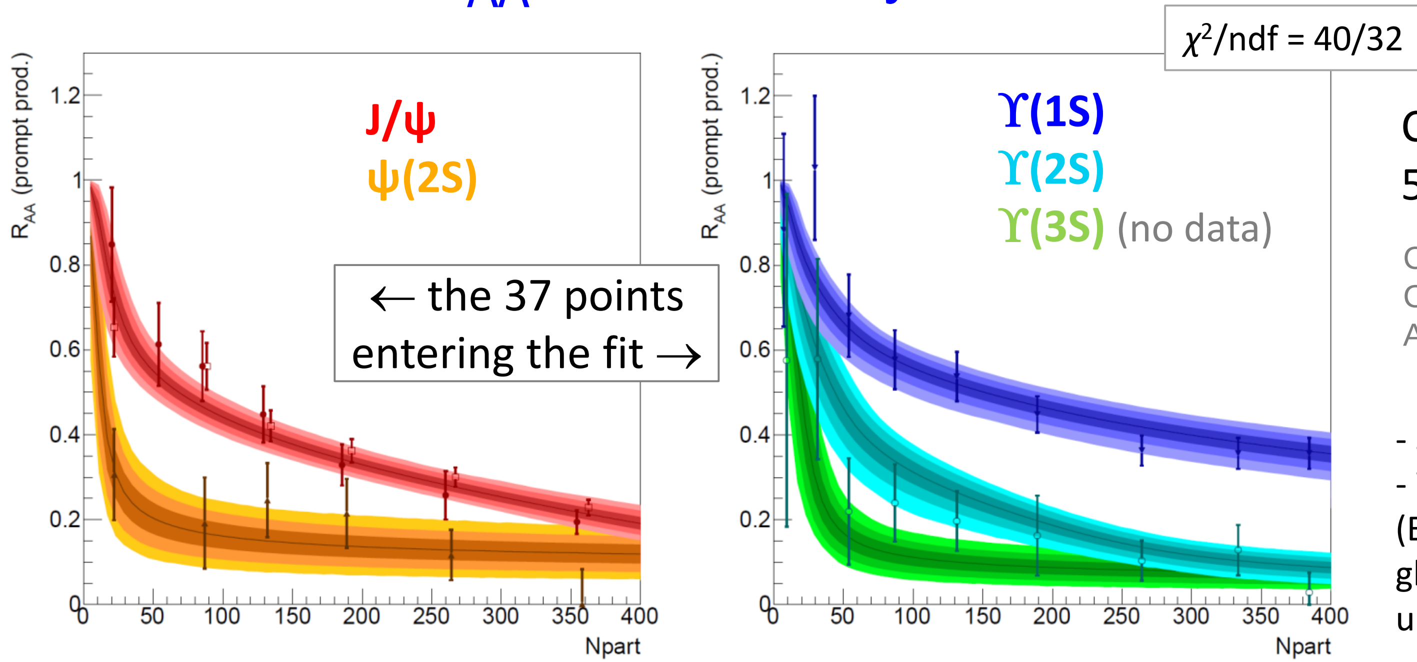


Examples

Dashed grey curve: suppression of *directly* produced states
Filled red markers: including effect of feed-down specific to each state



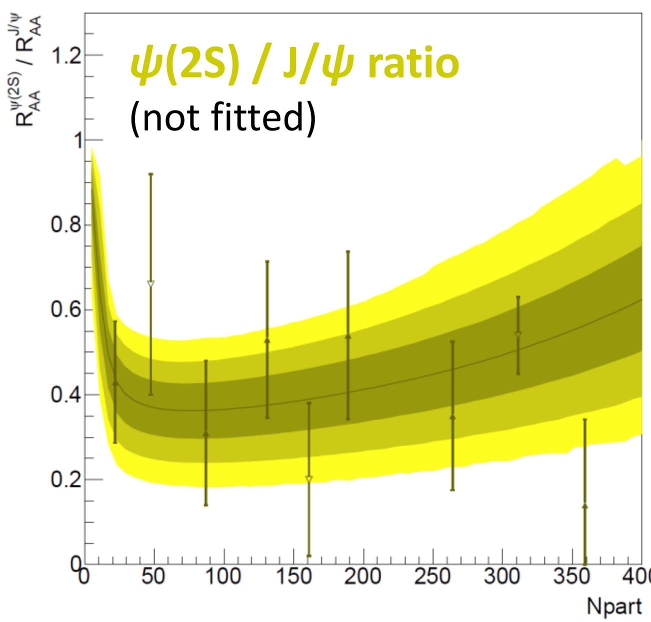
Global data fit: R_{AA} vs centrality

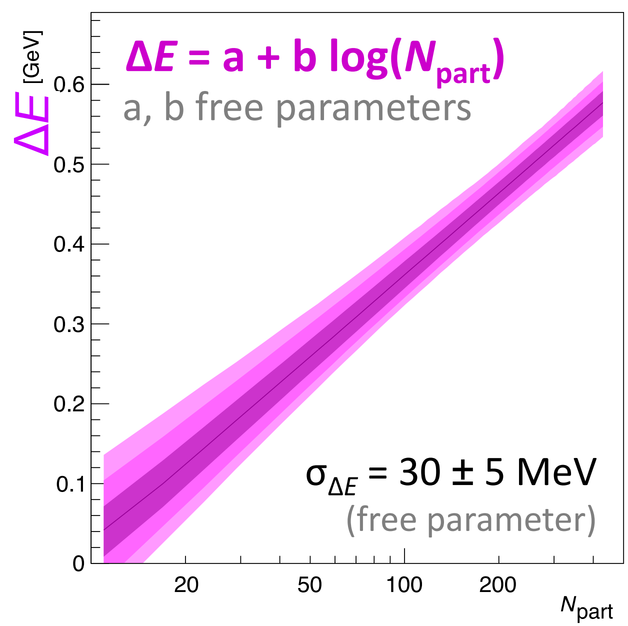


CMS & ATLAS
5.02 TeV

CMS-PAS HIN-16-023
CMS-PAS HIN-16-025
ATLAS-CONF-2016-109

- 3 free parameters
- 70 nuisance parameters (BRs, pp cross sections, global experimental uncertainties)





Good fit quality
$P(\chi^2)$ = 22%

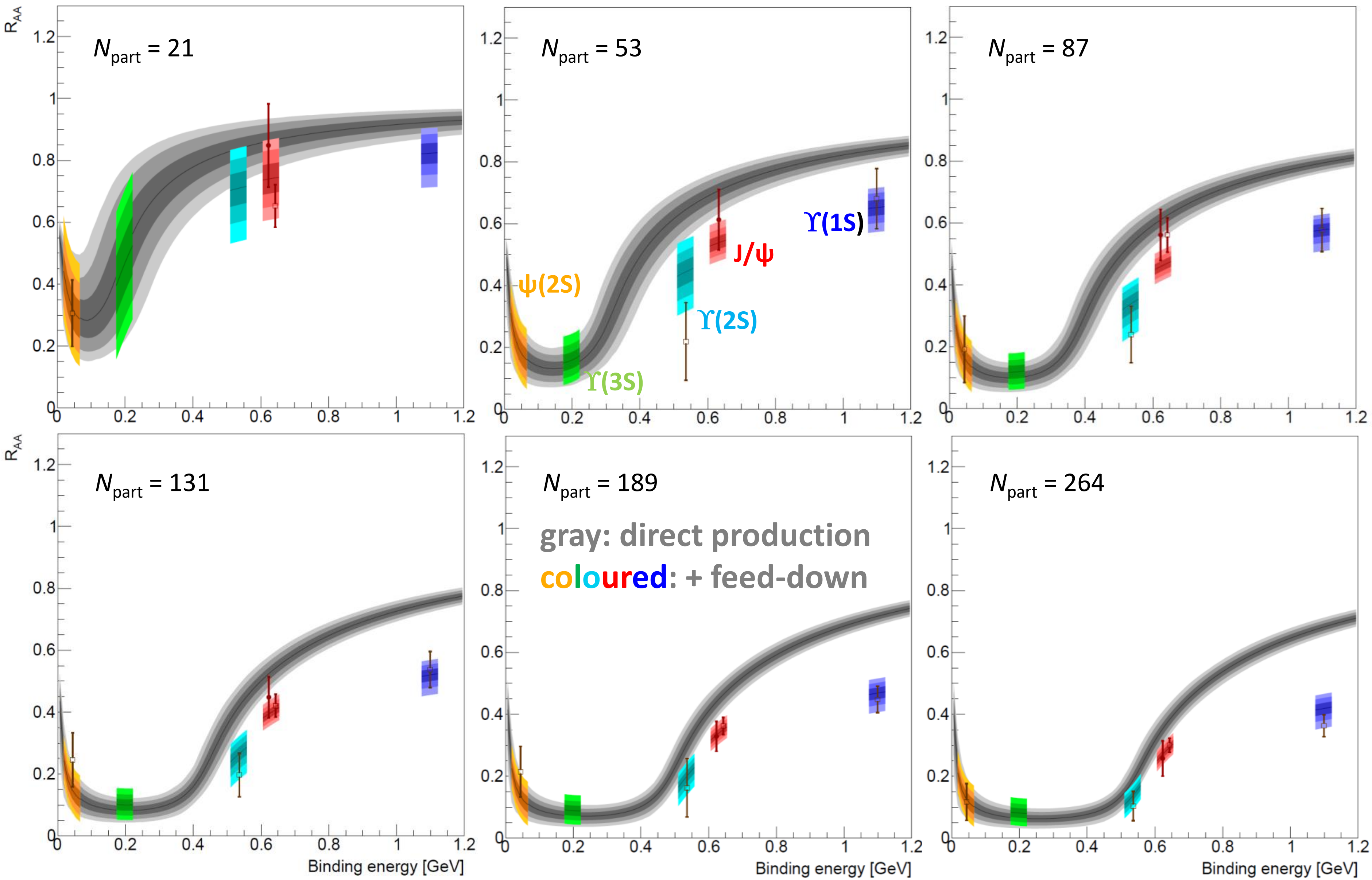
Improves if the absolute energy shift ΔE is allowed to be different for charmonium and bottomonium

Global data fit: R_{AA} vs. $E_{binding}$

CMS & ATLAS
5.02 TeV

CMS-PAS HIN-16-023
CMS-PAS HIN-16-025
ATLAS-CONF-2016-109

Examples of "projections" at some N_{part} values



Summary

Mid-rapidity LHC pp data for charmonium and bottomonium are well described by a **simple** parametrization reflecting a universal (=*state-independent*) **scaling** with two variables :

1. **shapes of the p_T distributions in pp collisions** $\rightarrow$ $\boldsymbol{p_T/M}$ (short distance)
2. **pp cross-section scaling with mass** $\rightarrow$ $\boldsymbol{E_{binding}}$ (long distance)

This parametrization mirrors well the general idea of factorization of NRQCD.

Also the Pb-Pb R_{AA} patterns can be described in a very simple way, assuming that the binding-energy is reduced by an amount (identical for all quarkonia) that increases from peripheral to central collisions

(with increasing ΔE it becomes less and less probable to *form* the bound state).

This gives a third scaling variable :

3. **centrality dependence in Pb-Pb collisions** $\rightarrow$ $\boldsymbol{E_{binding} - \Delta E}$

Outlook

Assuming that the binding energy is reduced in the hot nuclear medium reproduces well the measured nontrivial patterns and provides crystal clear evidence of the sequential suppression mechanism

Future data can probe the validity of the model: the most strongly suppressed states (in central collisions = large ΔE) should be the χ_{c1}, χ_{c2}, χ_b(2P) and Υ(3S) states; while the χ_b(1P) and Υ(1S) states should be the least suppressed ones

With respect to the 1S states, it should be easier to observe the χ_b(1P) than the χ_c states in (central) Pb-Pb collisions

The χ_c/ψ ratio should drop to only 30% (!) while the χ_b(1P)/Υ(1S) ratio should almost not change from pp to Pb-Pb, nor from peripheral to central Pb-Pb collisions