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
- 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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## 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



## Same production dynamics for S- and P-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,  $J/\psi$  and  $\Upsilon(1S)$ , correcting for feed-down (#)

$$\frac{d\sigma/dp_{T}(\Upsilon(1S))}{d\sigma/dp_{T}(J/\psi)} = \left(\frac{m_{b}}{m_{c}}\right)^{-\alpha}$$
$$\longrightarrow \alpha = \begin{cases} 6.6 \pm 0.1 & 7 \text{ TeV} \\ 6.5 \pm 0.1 & 13 \text{ TeV} \end{cases}$$

(\*) Without model-dependent extrapolations to low  $p_T$ (#) Assumption for  $\Upsilon(1S)$  :  $f_{dir} = 50 \pm 10 \%$ 

## Comparison to a simple reference: Drell-Yan



quarkonium: 
$$m_Q^{-6}$$
  $\longrightarrow$  DY:  $M^{-3}$ 

The only difference seems to be the bound-state wave function, of dimension  $m_0^3$ 

## 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 dimensionality of the bound-state wave function  $\beta = 0.63 \pm 0.03$  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  $Q\overline{Q}$  creation × bound-state formation

## Implications of the observed scaling patterns

Inclusive quarkonium production cross section from pure dimensional analysis:

$$\frac{d\sigma}{dp_{\rm T}} = \sum_{\rm i} m_{\rm Q}^{-3} \times \frac{\mathcal{L}_{\rm i} (m_{\rm Q}, M, p_{\rm T}/M, y, \sqrt{s/M})}{m_{\rm Q}^{3}} \times \mathcal{F}_{\rm i} (m_{\rm Q}, M, p_{\rm T}/M, y, \sqrt{s/M}) \times \left(\frac{\sqrt{s}}{M}\right)^{\beta}$$

ATLAS and CMS data at  $|y| \ge 2$  and  $p_T/M \ge 2$  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 :

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

$$\frac{d\sigma}{dp_{\rm T}} = \sum_{\rm i} m_{\rm Q}^{-6} \times \left(\frac{\sqrt{s}}{M}\right)^{\beta} \times \mathcal{L}_{\rm i} (M/m_{\rm Q}) \times \mathcal{F}_{\rm i} (p_{\rm T}/M, y, \sqrt{s/M})$$

# Mass scaling of S-wave cross sections

Refined determination of the mass scaling, using all S states and adopting the short × long-distance "factorized" perspective: "short distance"  $m_Q^{-6} \times \left(\frac{\sqrt{s}}{M}\right)^p$ two sections of *same* curve dơ(ψ)/dp<sub>T</sub> at p<sub>T</sub>/M=7[nb/GeV] .0 .5 م 0.5 ق 7 TeV 0.5  $\frac{d\sigma/dp_{T}(M \rightarrow 2m_{b})}{d\sigma/dp_{T}(M \rightarrow 2m_{c})} = \left(\frac{m_{b}}{m_{c}}\right)^{-(6.63 \pm 0.08)}$  $d\sigma/dp_T (M \rightarrow 2m_c)$ ,=M\\_,q  $d\sigma/dp_{T}(M \rightarrow 2m_{h})$ J/ψ  $\mathcal{L}_{i} (M/m_{Q})$ at Y(1S) "long distance" d σ(Y)/dp<sub>T</sub> 0.1 Y(2S)  $\frac{d\sigma/dp_{T}(M = M_{\psi|\Upsilon})}{d\sigma/dp_{T}(M \rightarrow 2m_{c1b})} = \left(\frac{M_{\psi|\Upsilon}}{2m_{c1b}}\right)^{-(9.7 \pm 0.3)}$ Y(3S) ψ(2S) one common slope parameter < fits well both the  $\psi$  and  $\Upsilon$  states 3 5 10 M [GeV] initial assumption (iteratively improved):  $f_{\rm dir} = (50|60|70 \pm 10)\%$  for Y(1|2|3S) Using: inspired by data including LHCb's forward-rapidity  $\chi_{h}$  [EPJ C 74, 3092]  $2m_Q = M_{\eta_c(1S)} | M_{\eta_b(1S)}$ 

## 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

 $\frac{\sigma_{\chi}}{\sigma_{Q\bar{Q}}} \propto E_{\rm binding}^{\rm 0.01}$ 

tot

Y2S

 $0.63 \pm 0.02$ 

45.0 + - 5.7

**Assuming** that the "universal" E<sub>binding</sub> dependence hypothesis can be extended to the P-wave states

 $\chi_c$  data constrain the  $\chi_b$  (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 (%):       Y1S       tot       59.0 +- 4.9       from chib1_2P       19.0 +- 3.8         Prom chib2_1P       1.22 +- 0.29       from chib0_3P       0.15 +- 0.12         Prom chib1_P       21.7 +- 3.6       from chib0_3P       0.15 +- 0.12         Prom chib1_P       1.22 +- 0.29       from chib0_3P       0.15 +- 0.12         Prom chib1_P       1.7 +- 3.6       from chib0_3P       0.15 +- 0.12         Prom chic1       15.61 +- 0.99       from chib1_P       1.3 +- 1.6       from chib2_3P       3.0 +- 0.79         from thic1       7.63 +- 0.53       from chib1_P       1.51 +- 0.28       from chib1_P       tot       3.09 +- 0.79         from trist       (5.57 +- 0.68)       from chib1_P       1.51 +- 0.28       from trist       5.9 +- 1.7         from y2s       (2.2 +- 2.2) E-5       from chib1_P       1.3 +- 1.6       from y3s       6.5 +- 1.6         from y2s       (2.1 +- 0.33)       from trist       from y2s       1.3 +- 1.0       from trist         from y1s       (4.4 + 0.48) E-5       from y2s       6.8 +- 1.7       from trist       from y2s         from y2s       2.61 +- 0.33       from y2s       0.033 +- 0.020       from trist       from trist       from y2s         fro		quarkon	ium producen		oc runy pre			from chib0 2P	1.42 + - 0.43	
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Feed-down fractions in pp (%):       from chib0_1p       1.22 + 0.29       from chi0.3P       5.7 + 1.2         'psi       tot       31.9 + 1.6       from chib2_1P       21.7 + 3.6       from chib1_3P       5.9 + 1.7         'psi       tot       31.9 + 1.6       from chib2_2P       0.167 + 0.082       from chib2_3P       3.7 + 1.3         'psi       tot       31.9 + 1.6       from chib2_2P       0.167 + 0.082       from chib2_3P       3.09 + 0.79         from chic1       15.61 + 0.99       from chib1_2P       3.19 + 0.74       from chib2_3P       3.09 + 0.79         from chib2       7.67 + 0.88       from chib2_3P       0.018 + 0.016       from Y3S       3.09 + 0.79         from y1S       (5.57 + - 0.69) E-5       from chib2_3P       1.35 + - 0.52       from Y3S       6.5 + 1.6         from y2S       2.09 + 0.26       from Y3S       0.09 + - 0.028       from Y3S       6.8 + 1.7         from y2S       2.61 + 0.33       from Y3S       0.033 + - 0.028       from chib2_3P       1.3 + - 1.0         from y2S       2.61 + - 0.33       from Y3S       0.033 + - 0.020       from chib2_3P       7.8 + 2.4         from Y2S       2.81 + - 0.35       from Y3S       0.372 + - 0.099       from chib2_3P       7.8 + 2.4 <t< th=""><th></th><th></th><th></th><th>• Y15</th><th>tot</th><th>59 0 +- 4 9</th><th></th><th>from chib2_2P</th><th>9.2 +- 2.1</th><th></th></t<>				• Y15	tot	59 0 +- 4 9		from chib2_2P	9.2 +- 2.1	
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chic0       tot       2.09 + - 0.26       from y25       2.09 + - 0.26       from y25       2.58 + - 0.61         from y15       (3.4 + - 3.4) E-5       from y25       (1.5 + - 1.5) E-5       (hib)1P       tot       4.8 + - 1.0       y35       tot       25.9 + - 5.5       (hib)1P       tot       y35       tot       y36       y36       y37       y37       y36       y37       y37		from Y2S	(2.2 + - 2.2) = -5	1	from chib2_3P	1.35 +- 0.52	· chih2 20	tot	68 - 17	
<pre>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 +- 0.89) E-5 from y2S (2.10 +- 0.89) E-5 from y2S (2.10 +- 0.85) E-5 from y2S (2.10 +- 0.35) E-5 from y1S (7.1 +- 2.) E-5 from y1S (7.1 +- 2.) E-5 from y1S (1.01 +- 0.22) E-4 from y2S (0.35 +- 0.35) E-4</pre>							CITID2_2P	from V26	0.0 + 1.7	
from psi2s       2.09 + 0.26       from Y2S       2.58 + - 0.61       Y3S       tot       25.9 + - 5.5         from Y1S       (3.4 + - 3.4) E-5       from Y3S       0.099 + - 0.028       Y3S       tot       25.9 + - 5.5         from Y2S       (1.5 + - 1.5) E-5       ifrom Y3S       0.099 + - 0.028       Y3S       tot       25.9 + - 5.5         chic1       tot       2.61 + - 0.33       from Y2S       4.7 + - 1.0       from chib1_3P       17.0 + - 4.5         chic1       tot       2.61 + - 0.33       from Y3S       0.033 + - 0.020       from chib2_3P       7.8 + - 2.4         chic2       tot       2.81 + - 0.35       from Y2S       5.0 + - 1.1       from Y3S       0.372 + - 0.099         chic2       tot       2.81 + - 0.35       from Y3S       0.372 + - 0.099       item Y3S       item Y3S       item Y3S       item Y3S         psi2s       tot       (1.36 + - 0.43) E-4       item Y3S         psi2s       tot       (1.36 + - 0.43) E-4       item Y3S         psi2s       tot	· chic0	tot	2 09 + - 0 26	· Chib0_1P	tot	2.67 +- 0.62		11011 135	0.0 +- 1.7	
from Y15       (3.4 + - 3.4) E-5         from Y25       (1.5 + - 1.5) E-5         from y25       (1.5 + - 1.5) E-5         chic1       tot         2.61 + - 0.33         from Y15       (4.26 + - 0.89) E-5         from Y25       (2.10 + - 0.55) E-5         chib2_1P       tot         from Y25       (2.10 + - 0.55) E-5         from Y15       (7.1 + - 2.) E-5         from Y15       (1.36 + - 0.43) E-4         from Y15       (1.36 + - 0.43) E-4         from Y25       (2.48 + - 0.92) E-5         from Y15       (1.01 + - 0.22) E-4         from Y25       (0.35 + - 0.35) E-4		from nsi2s	2 09 + 0 26	1	from Y2S	2.58 +- 0.61	• V2C	+ + +	25.0 . 5.5	
from Y1S       (0.4 + 0.37) E-3         from Y2S       (1.5 + - 1.5) E-5         chib1_1P       tot       4.8 + - 1.0         from psi2S       2.61 + - 0.33         from Y1S       (4.26 + - 0.89) E-5         from Y2S       (2.10 + - 0.55) E-5         from Y2S       (2.10 + - 0.55) E-5         from y1S       (2.10 + - 0.55) E-5         from y1S       (7.1 + - 2.) E-5         from Y1S       (1.36 + - 0.43) E-4         psi2S       tot         from Y1S       (1.01 + - 0.22) E-4         from Y2S       (0.35 + - 0.35) E-4		from V1S	(3.4 + 3.4) = 5	-8	trom Y3S	0.099 + - 0.028	155		25.9 +- 5.5	
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 from y2S (2.10 +- 0.55) E-5 from y1S (7.1 +- 2.) E-5 from Y1S (7.1 +- 2.) E-5 from Y1S (1.01 +- 0.22) E-4 from Y2S (0.35 +- 0.35) E-4		from V2S	(15 + 15) = 5	- 8			13	from Chib0_3P	1.02 +- 0.61	
<pre>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 Y1S (7.1 +- 2.) E-5 from Y1S (1.01 +- 0.22) E-4 from Y1S (1.01 +- 0.22) E-4 from Y2S (0.35 +- 0.35) E-4</pre>		11011123	(1.) +- 1.) L-J	<pre>chib1_1P</pre>	tot	4.8 +- 1.0	1	from chib1_3P	17.0 +- 4.5	1
from psi2s       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         from psi2s       2.81 +- 0.35         from y1s       (7.1 +- 2.) E-5         from Y1s       (7.1 +- 2.) E-5         from Y1s       (1.36 +- 0.43) E-4         psi2s       tot         from Y1s       (1.01 +- 0.22) E-4         from Y2s       (0.35 +- 0.35) E-4	· chic1	tot	2 61 . 0 33	-	from Y2S	4.7 +- 1.0		from chib2_3P	7.8 +- 2.4	
from y1s       2.61 += 0.33         from Y1s       (4.26 += 0.89) E=5         from y2s       (2.10 += 0.55) E=5         from y2s       (2.10 += 0.55) E=5         from y2s       (2.10 += 0.35) E=5         from y1s       (7.1 += 2.) E=5         from y2s       (2.48 += 0.92) E=5         psi2s       tot         (1.36 += 0.43) E=4         from Y2s       (0.35 += 0.35) E=4	·	from nci26	2.01 + 0.33	•	from Y3S	0.033 + - 0.020	1			
From Y1S       (4.26 +- 0.89) E-5         from Y2S       (2.10 +- 0.55) E-5         from y2S       (2.10 +- 0.55) E-5         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 Y2S       (0.35 +- 0.35) E-4		from pS125	2.01 + 0.35	•			-			
rrom Y2S       (2.10 +- 0.35) E-3         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 Y2S       (0.35 +- 0.35) E-4		from YIS	(4.26 + -0.89) = -5	<pre>chib2_1P</pre>	tot	5.3 +- 1.1	•			
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         from Y1s       (1.01 +- 0.22) E-4         from Y2s       (0.35 +- 0.35) E-4		Trom Y2S	(2.10 +- 0.55) E-5	-	from Y2S	5.0 +- 1.1	•			•
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         from Y1s       (1.36 +- 0.43) E-4         from Y2s       (0.35 +- 0.35) E-4			2 01 0 25		from Y3S	0.372 + - 0.099	•			•
from ps12s       2.81 +- 0.35         from Y1s       (7.1 +- 2.) E-5         from Y2s       (2.48 +- 0.92) E-5         psi2s       tot         from Y1s       (1.36 +- 0.43) E-4         from Y1s       (1.01 +- 0.22) E-4         from Y2s       (0.35 +- 0.35) E-4	· Ch1C2	tot	2.81 +- 0.35	-2			-1			•
from Y1S $(7.1 + - 2.) E-5$ from Y2S $(2.48 + - 0.92) E-5$ psi2S       tot         from Y1S $(1.36 + - 0.43) E-4$ from Y1S $(1.01 + - 0.22) E-4$ from Y2S $(0.35 + - 0.35) E-4$		from psi2S	2.81 +- 0.35	-			•			•
from Y2S       (2.48 +- 0.92) E-5         psi2S       tot         from Y1S       (1.01 +- 0.22) E-4         from Y2S       (0.35 +- 0.35) E-4	•	from Y1S	(7.1 + 2.) = 5							
<pre>psi2s tot (1.36 +- 0.43) E-4 from Y1s (1.01 +- 0.22) E-4 from Y2s (0.35 +- 0.35) E-4</pre>	1	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	1									
from Y1s         (1.01 +- 0.22) E-4           from Y2s         (0.35 +- 0.35) E-4	· psi2S	tot	(1.36 +- 0.43) E-4	12/1						
from Y2S (0.35 +- 0.35) E-4	•	from Y1S	(1.01 +- 0.22) E-4							
	1	from Y2S	(0.35 +- 0.35) E-4	12.						
	•			•						

### Comparison with existing data



## Nuclear modifications in Pb-Pb

How is the universal *E*<sub>binding</sub>-scaling modified in Pb-Pb? Can we describe Pb-Pb data assuming a minimal modification of the simple parametrization found for pp data?



## 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:



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

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

$$E_{\text{binding}}(J/\psi) - \Delta E = \begin{cases} [2M(D^0) - \Delta E] - M(J/\psi) ? & \text{di-meson threshold?} \\ 2M(D^0) - [M(J/\psi) + \Delta E] ? & \text{multiple scattering effectively} \\ & \text{increases } Q\overline{Q} \text{ relative} \\ & \text{momentum and invariant mass?} \\ \rightarrow J. \text{ Qiu et al., PRL 88 (2002) 232301} \end{cases}$$

### Parameters and ingredients



 $\Delta E$  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  $\Delta E$  distribution,  $\sigma_{\Delta E}$  , is kept centrality-independent, for simplicity

The rest is *fixed from pp data*:

- same parameter  $\delta$  = 0.63 ± 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<sub>AA</sub> 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  $\Delta E$  is allowed to be different for charmonium and bottomonium

# Global data fit: R<sub>AA</sub> vs. E<sub>binding</sub>

CMS & ATLAS 5.02 TeV CMS-PAS HIN-16-023 CMS-PAS HIN-16-025 ATLAS-CONF-2016-109



## 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  $\rightarrow p_T/M$  (short distance)
- 2. pp cross-section scaling with mass  $\rightarrow E_{\text{binding}}$  (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  $\Delta E$  it becomes less and less probable to *form* the bound state).

This gives a third scaling variable :

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

### 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  $\Delta E$ ) should be the  $\chi_{c1}$ ,  $\chi_{c2}$ ,  $\chi_b$ (2P) and Y(3S) states; while the  $\chi_b$ (1P) and Y(1S) states should be the least suppressed ones

With respect to the 1S states, it should be easier to observe the  $\chi_b(1P)$  than the  $\chi_c$ states in (central) Pb-Pb collisions

The  $\chi_c/\psi$  ratio should drop to only 30% (!) while the  $\chi_b(1P)/Y(1S)$  ratio should almost not change from pp to Pb-Pb, nor from peripheral to central Pb-Pb collisions

