Scaling patterns
in ATLAS & CMS quarkonium production data

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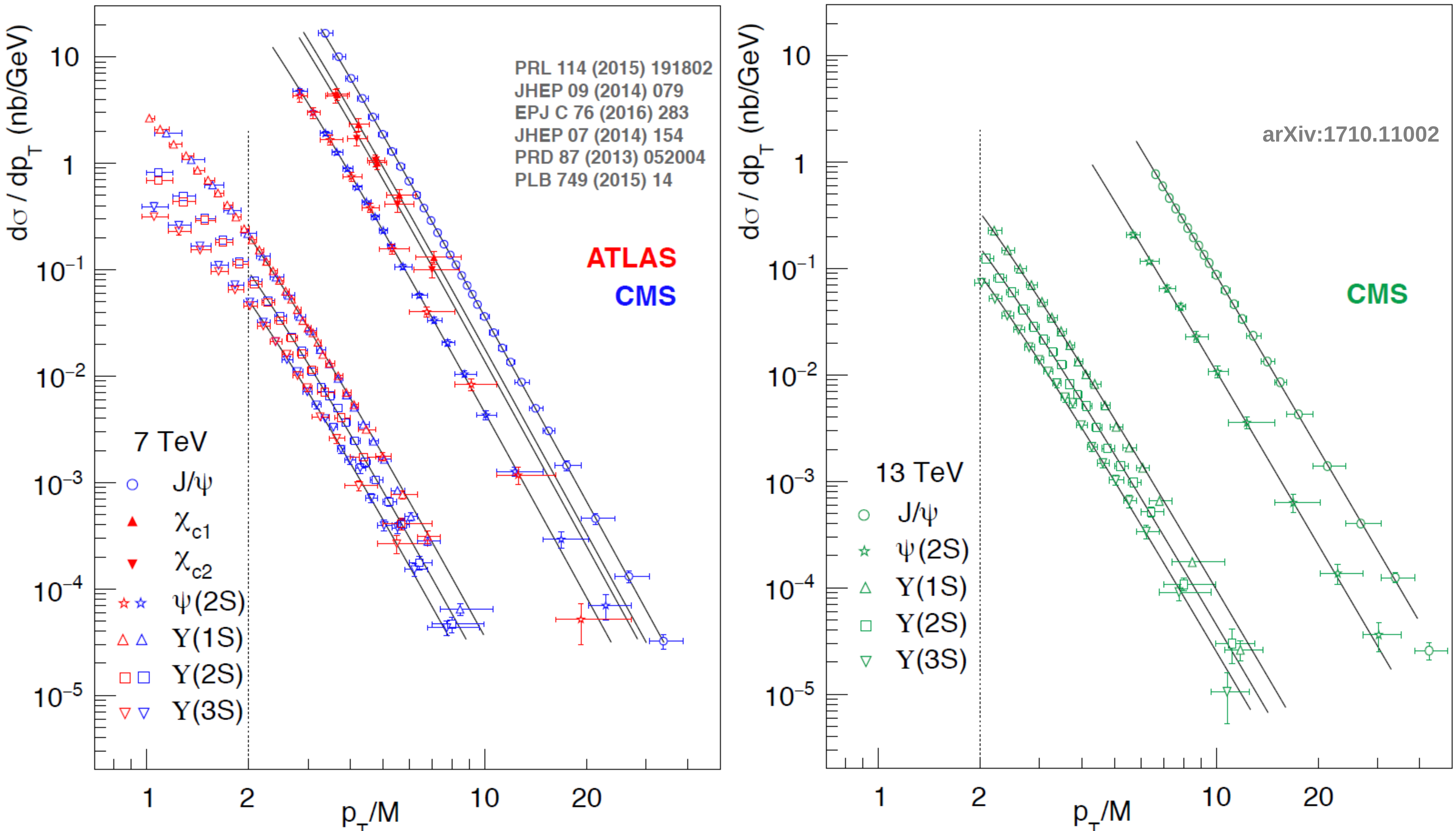
Quarkonium Working Group, November 8th 2017

1. **shapes of the p_T distributions in pp collisions**
2. **pp cross-section scaling with mass**
3. **centrality dependence in Pb-Pb collisions**

p_T distributions in pp collisions

Mid-rapidity cross section measurements show a *common shape pattern* for $p_T/M \gtrsim 2$

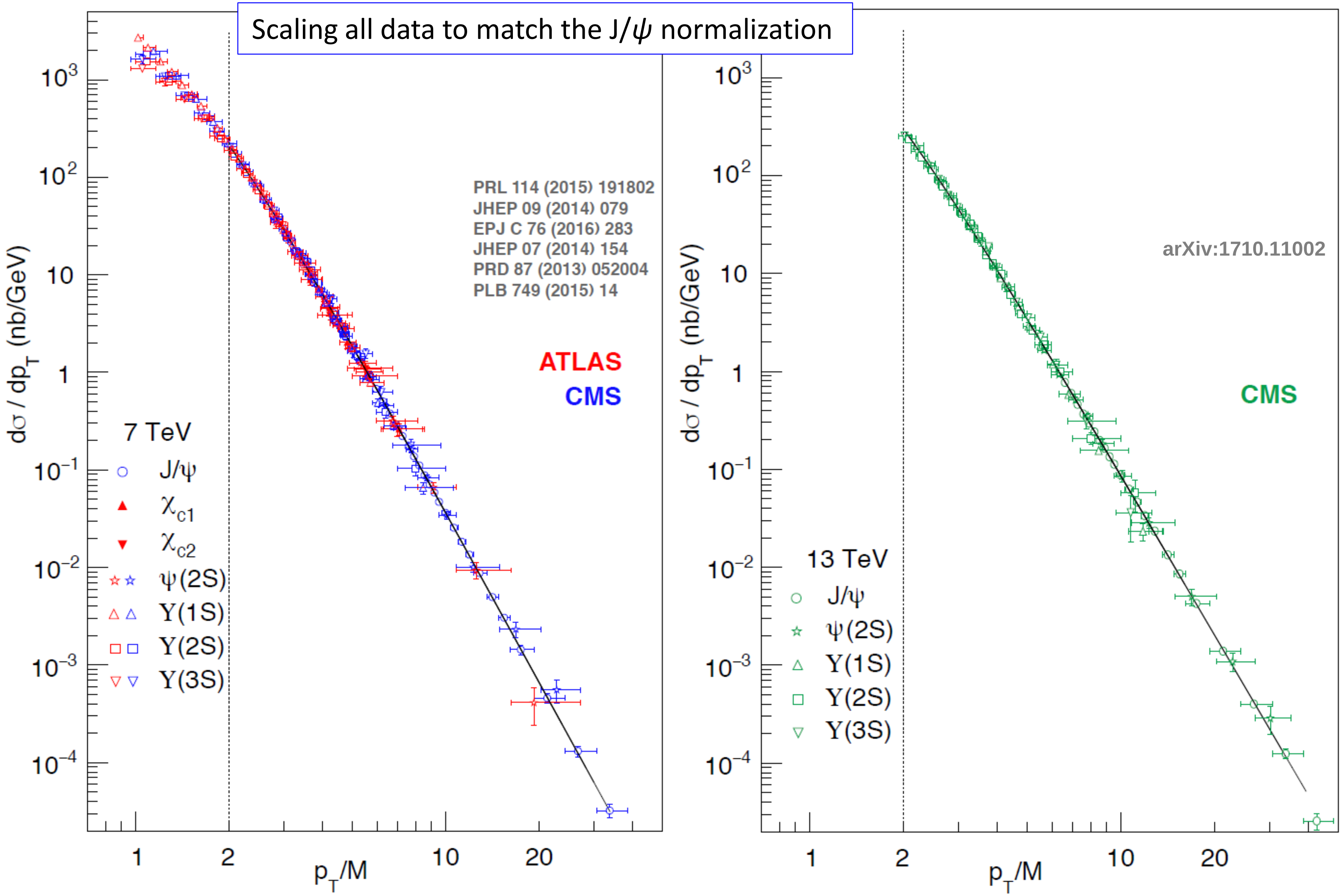
$d\sigma/dp_T$ vs p_T/M



[PF et al. PLB 773, 476 (2017)]

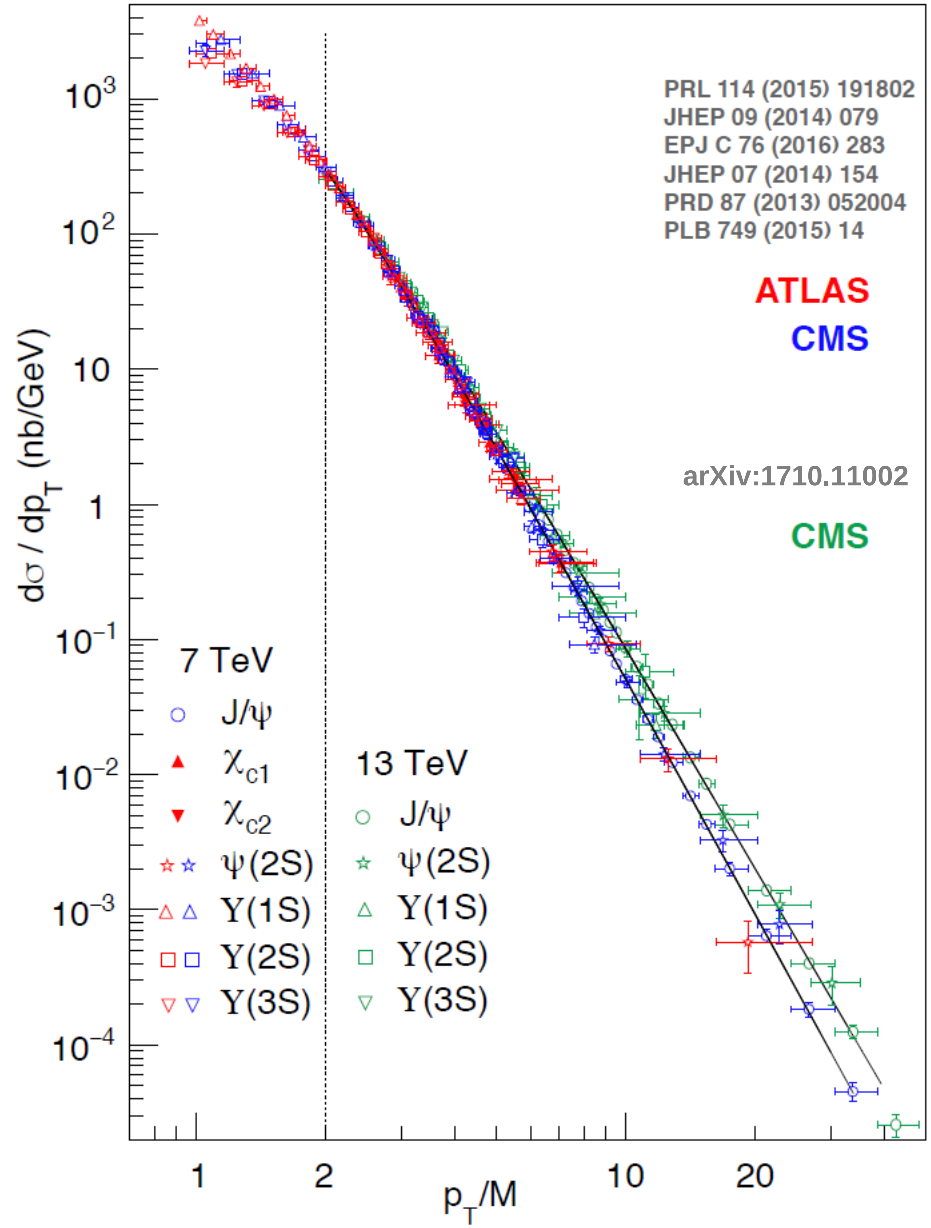
p_T distributions in pp collisions

Scaling all data to match the J/ψ normalization



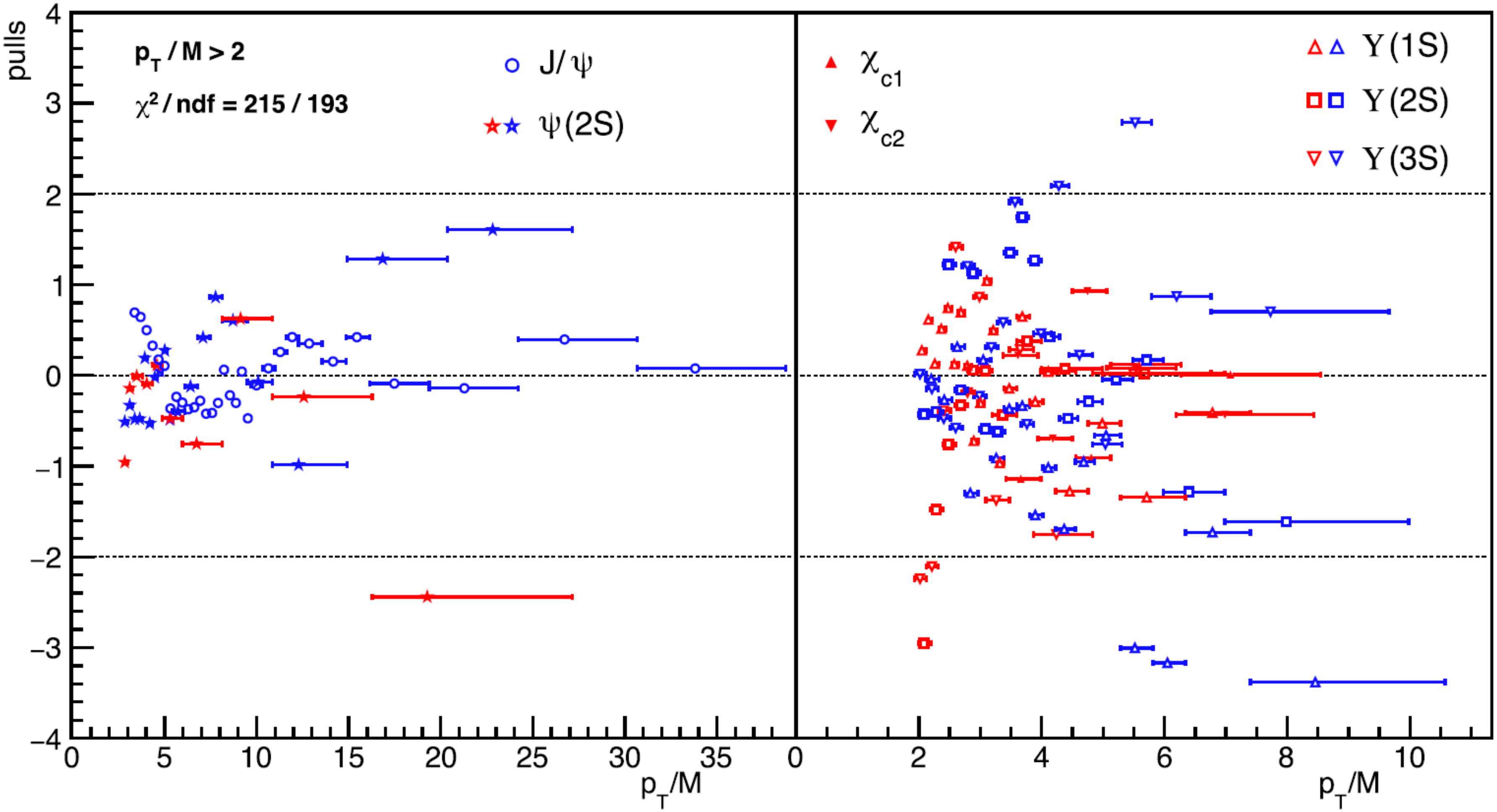
p_T distributions in pp collisions

Higher energy, broader distribution

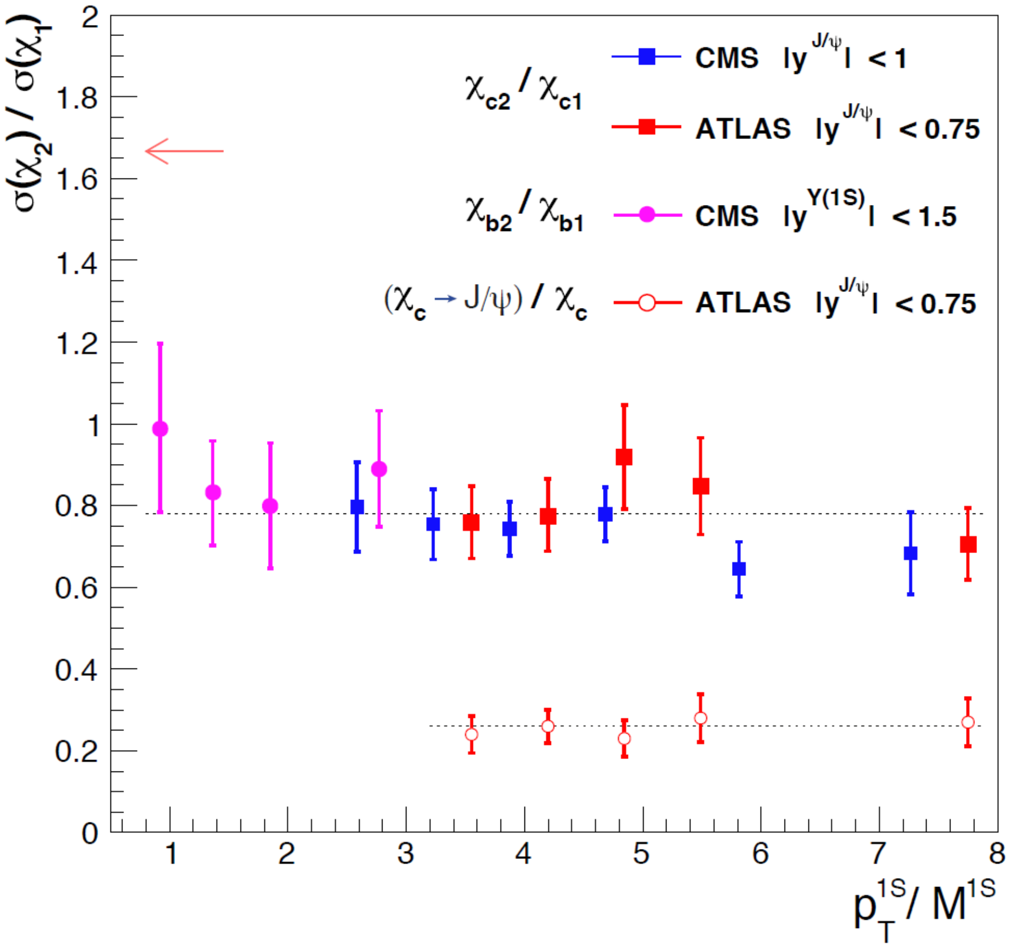


Goodness of the global p_T/M fit

Distribution of pulls (7 TeV fit)

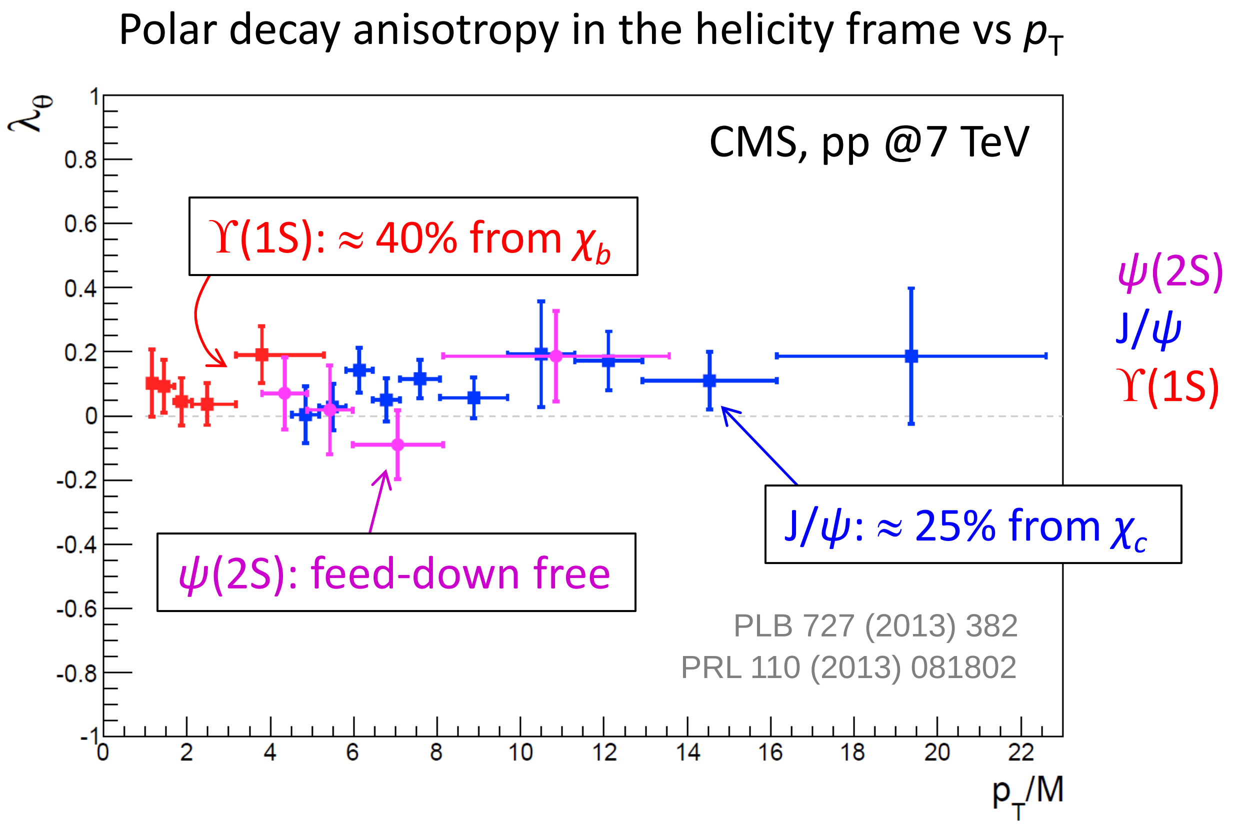


"Zoom": χ_1 vs χ_2 vs ψ



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

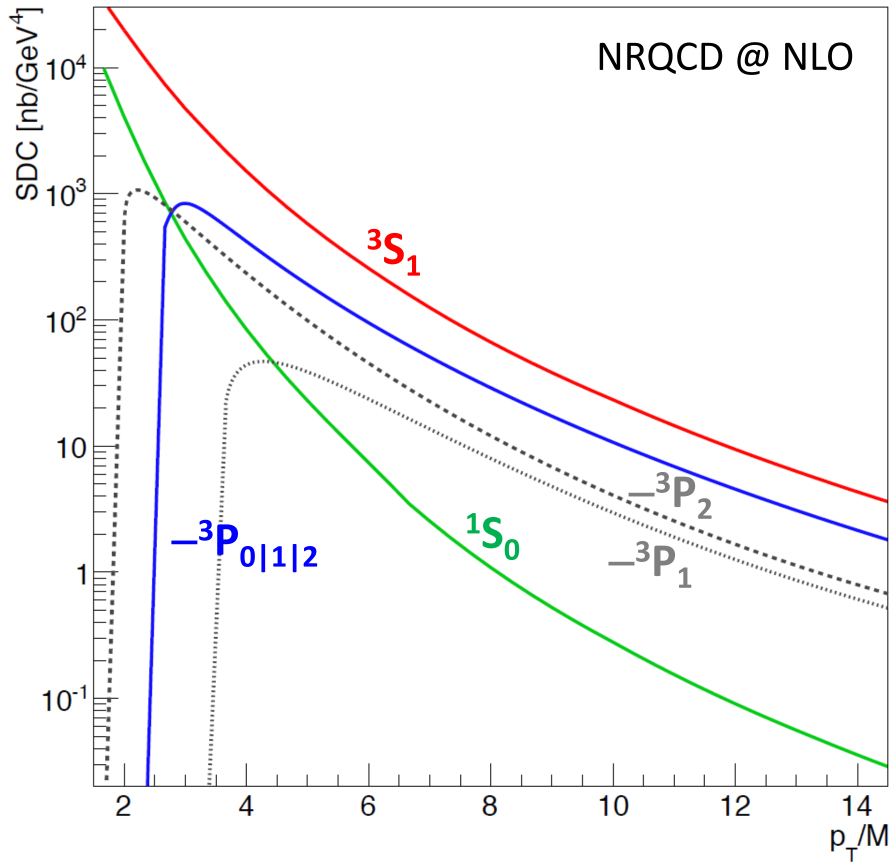
Polarization



- S-wave quarkonia: small decay anisotropies with no significant p_T dependences
- No indications of differences between states,
  despite very different feed-down contributions from P-wave states

NRQCD vs simple data pattern

Considering e.g. cross-section SDC contributions (polarizations are as much diversified):



${}^1S_0$ ${}^3S_1$ ${}^3P_{0|1|2}$ $\Rightarrow$ J/ψ, $\psi(2S)$, $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$

${}^3P_1$ ${}^3S_1$ $\Rightarrow$ χ_{c1} , χ_{b1}

${}^3P_2$ ${}^3S_1$ $\Rightarrow$ χ_{c2} , χ_{b2}

- Negative P-wave contributions require exact **cancellation** for every p_T/M to recover physical result
- Different final states come from different pre-resonance mixtures, with rather **diversified** kinematic behaviours

- The variety of kinematic behaviours in NRQCD seems **redundant** with respect to the observed “universal” p_T/M scaling and lack of polarization

$\Rightarrow$ Conspiring SDC×LDME combinations needed to reproduce data

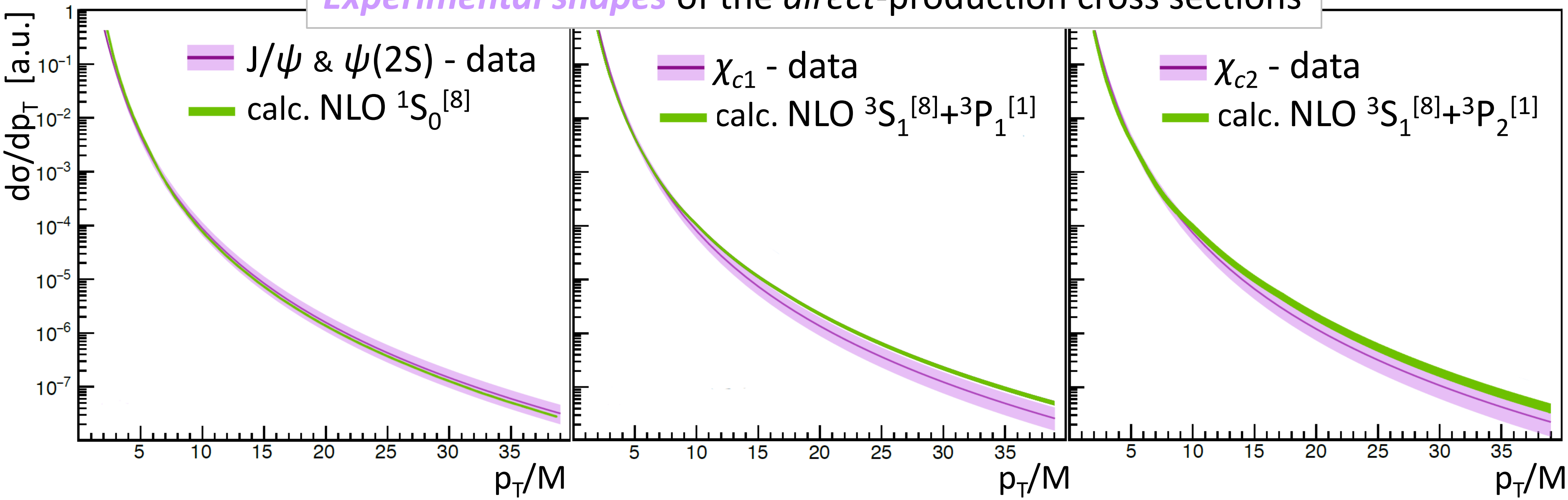
Curves from H.-S. Shao et. al., PRL 108, 242004; PRL 112, 182003; Comput. Phys. Commun. 198, 238

A “surprising” agreement

- Conspiracies actually happen: NRQCD is able to reproduce the simple data patterns

New method of theory-data comparison [PF et al., PLB 773, 476 (2017)], unbiased by specific theoretical calculations of partonic cross sections: **calculated NLO SDC combinations** are in good agreement with the **results of a fully data-driven fit** of charmonium data, taking into account feed-down and constrained by polarization results

Experimental shapes of the *direct*-production cross sections

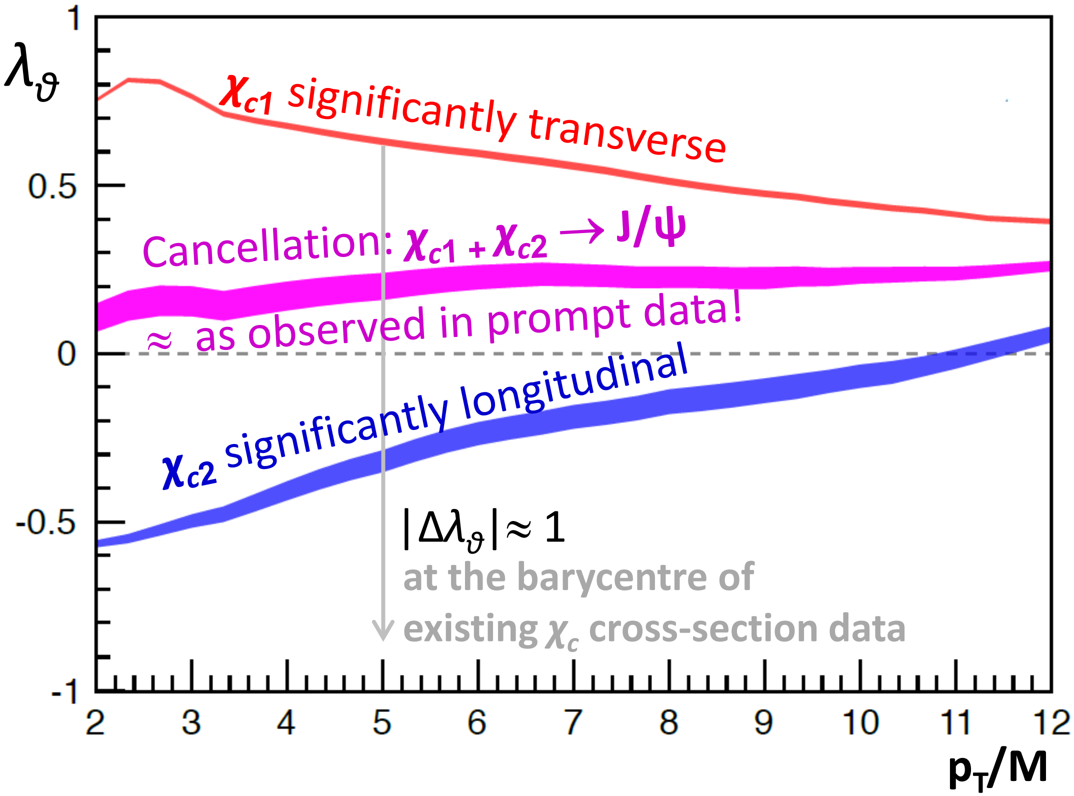


The three *measured shapes* are almost identical to one another

Calculated shapes are within ≈ 0 | 1.5 | 1 sigma from data

Ultimate conspiracy or need for a better NRQCD?

Coincidentally, this seeming success of NRQCD brings along a strong prediction:
the unmeasured χ_{c1} and χ_{c2} polarizations must be very different from one another



This prediction
(PF et al., arXiv:1702.04207)
is dramatically different from that of
H.-S. Shao et al., PRL 112, 182003,
because the huge
acceptance-polarization
correlations in the χ_c-ratio data
are properly considered

A potentially striking exception
to the uniform picture
of mid-rapidity quarkonium
production!

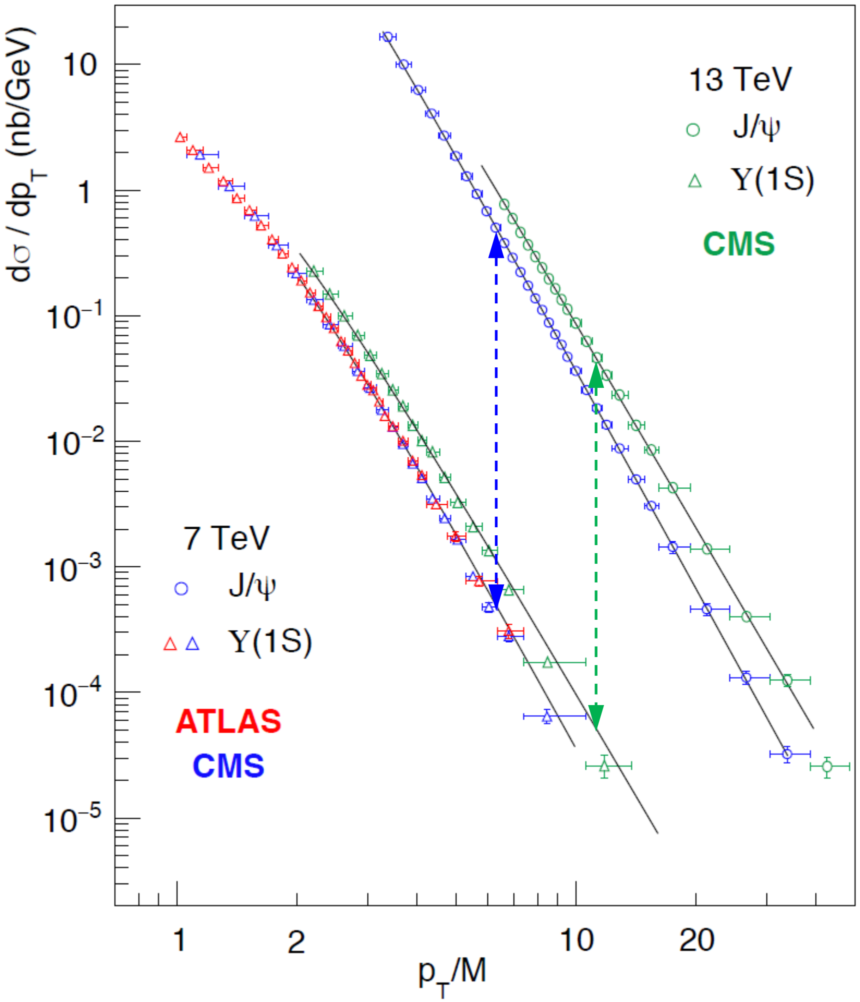
Will experiments find...

... a large $\chi_{c2} - \chi_{c1}$ polarization difference? $\Rightarrow$ smoking gun!

... weak χ_{c1} and χ_{c2} polarizations as for S-wave states?

$\Rightarrow$ need of improved (simpler?) NRQCD hierarchies
or better perturbative calculations

Mass scaling from charm to beauty



Exploiting p_T/M scaling we can determine the mass scaling of the cross section without model-dependent extrapolations to low p_T: it is sufficient to measure the ratio of the fitted p_T/M distributions at one (arbitrary!) p_T/M point

How does the production cross section scales from charmonium (m_c) to bottomonium (m_b)? We consider the two mesons closer to ground state, J/ψ and ϒ(1S), correcting for feed-down. Assumption for ϒ(1S): $f_{\mathrm{DIR}} = (50 \pm 10)\%$

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

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

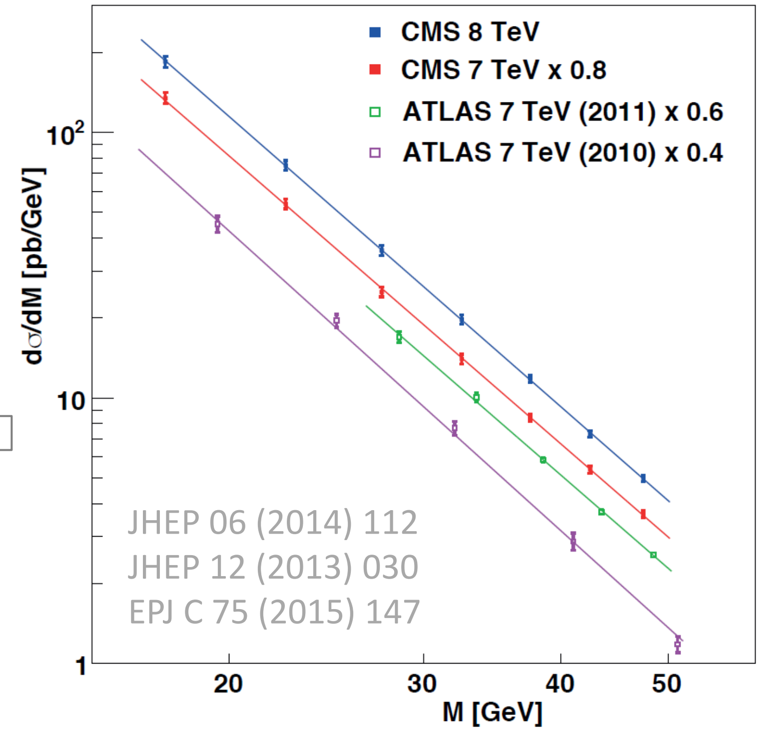
Comparison to a simple reference: Drell-Yan

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:

$$\frac{d\sigma^{DY}}{dM} \propto M^{-3}$$ at partonic level

$$\frac{d\sigma^{DY}}{dM} \propto M^{-(3+\beta)}$$ including parton-luminosity factor $\approx(\sqrt{s}/M)^{\beta}$, common to all processes

$\Rightarrow$ **β = 0.63 ± 0.03**

$\Rightarrow$ the "PDF-undressed" quarkonium cross section goes like $m_Q^{-(6.0 \pm 0.1)}$

Note: the power-3 difference of quarkonium wrt DY is just what is needed to accommodate the $[m_Q^3]$-dimensional bound-state wave function

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

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

1) the p_T/M dependence is the same irrespectively of m_Q and M
2) from charmonium to bottomonium the partonic-level (PDF-undressed) cross section scales like m_Q^{-6}, with no observed dependence on $\sqrt{s}$

1) ⇒ p_T/M and $\{m_Q, M\}$ do not mix: $\mathcal{L} \times \mathcal{F}$ writeable as

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

y dependence to be studied (→LHCb data)

⇒ an experimental evidence that short- and long-distance effects "factorize"(*)

2) ⇒ further specification of the "LDME": $\mathcal{L} = \mathcal{L}(M/m_Q)$, independent of m_Q and $\sqrt{s}$ (*)

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Inclusive quarkonium production cross section from pure dimensional analysis:

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

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AT ... 2 and $p_T/M \gtrsim$ 2 tell us that:
1) ... m_Q and M
2 ...

(*) Disclaimer. The $\mathcal{L}$ functions are not the same as the LDMEs of NRQCD.
They do not involve unobservable energy scales
$\Rightarrow$ they obey simple dimensional-analysis considerations leading to $\mathcal{L} = \mathcal{L}(M/m_Q)$
$\Rightarrow$ they are experimentally definable (see next slide)

1) $\Rightarrow$ p_T/M and $\{m_Q, M\}$ do not mix: $\mathcal{L} \times \mathcal{F}$ writea...

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

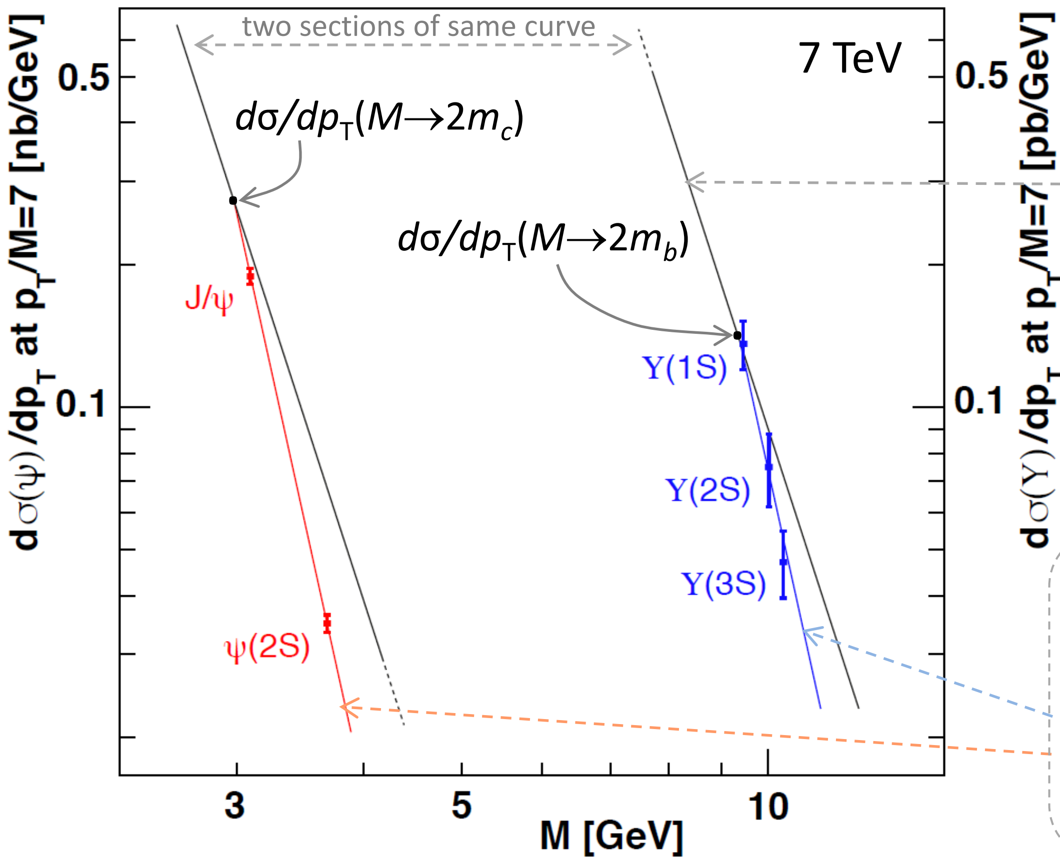
$\Rightarrow$ an experimental evidence that short- and long-distance effects "factorize"(*)

2) $\Rightarrow$ further specification of the "LDME": $\mathcal{L} = \mathcal{L}(M/m_Q)$, independent of m_Q and $\sqrt{s}$ (*)

Mass scaling of S-wave cross sections

Refined determination of the mass scaling, using all S states and adopting the short × long-distance "factorized" point of view:

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]



"short distance"
(dependence on m_Q):

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

"long distance"
(M/m_Q)-dependent "LDME":

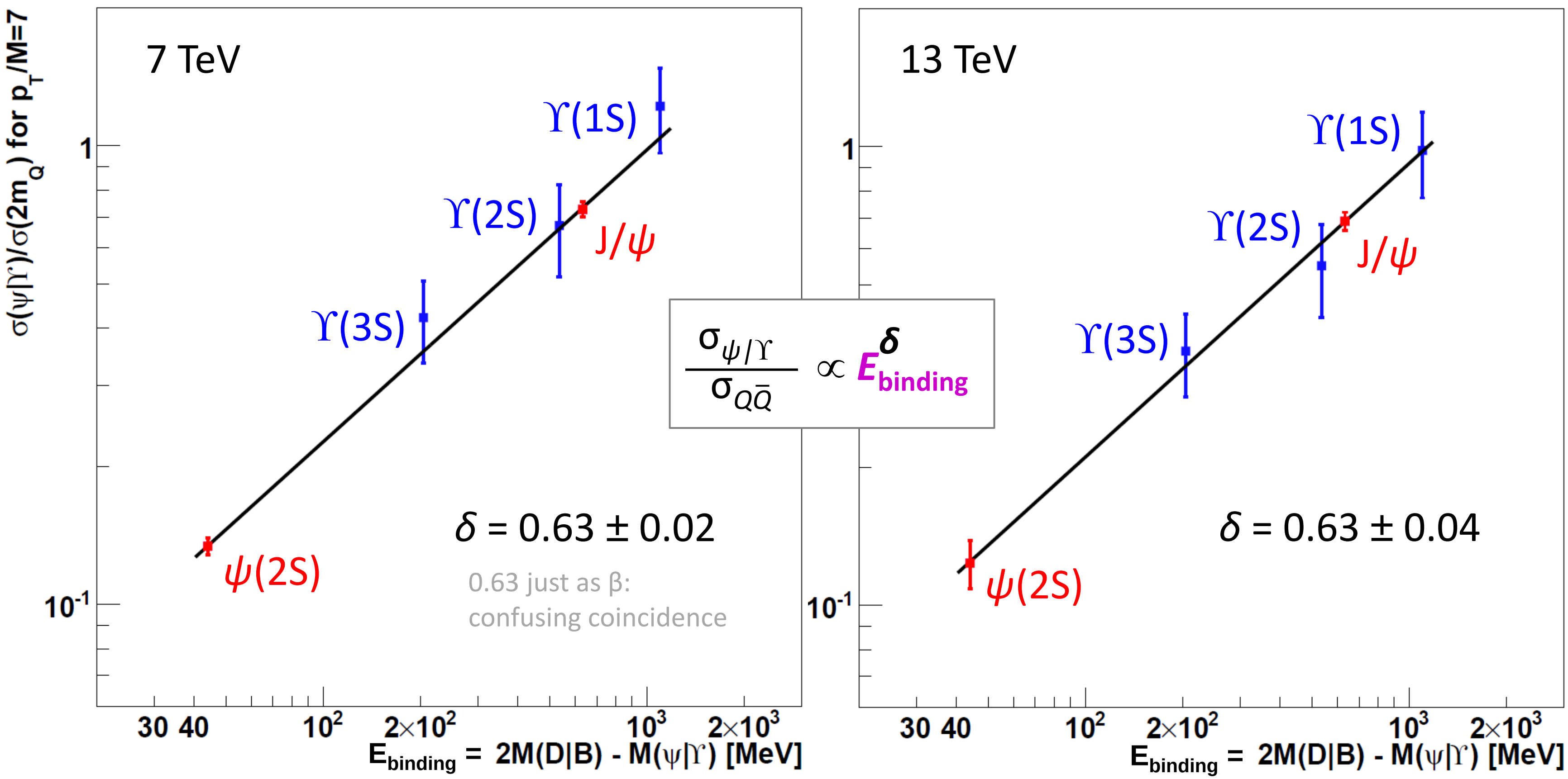
$$\frac{d\sigma/dp_T(M = M_{\psi|\Upsilon})}{d\sigma/dp_T(M \to 2m_{c|b})} = \left(\frac{M_{\psi|\Upsilon}}{2m_{c|b}}\right)^{-(9.7 \pm 0.3)}$$

one common slope parameter fits well ψ and Υ states

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

Long-distance scaling: a universal pattern?

The "LDMEs" show a clear correlation with **binding energy**,
– common to charmonium and bottomonium
– identical at 7 and 13 TeV



$$\frac{\sigma_{\psi/\Upsilon}}{\sigma_{Q\bar{Q}}} \propto E_{\text{binding}}^{\delta}$$

⇒ 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,

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

χ_c data come to 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

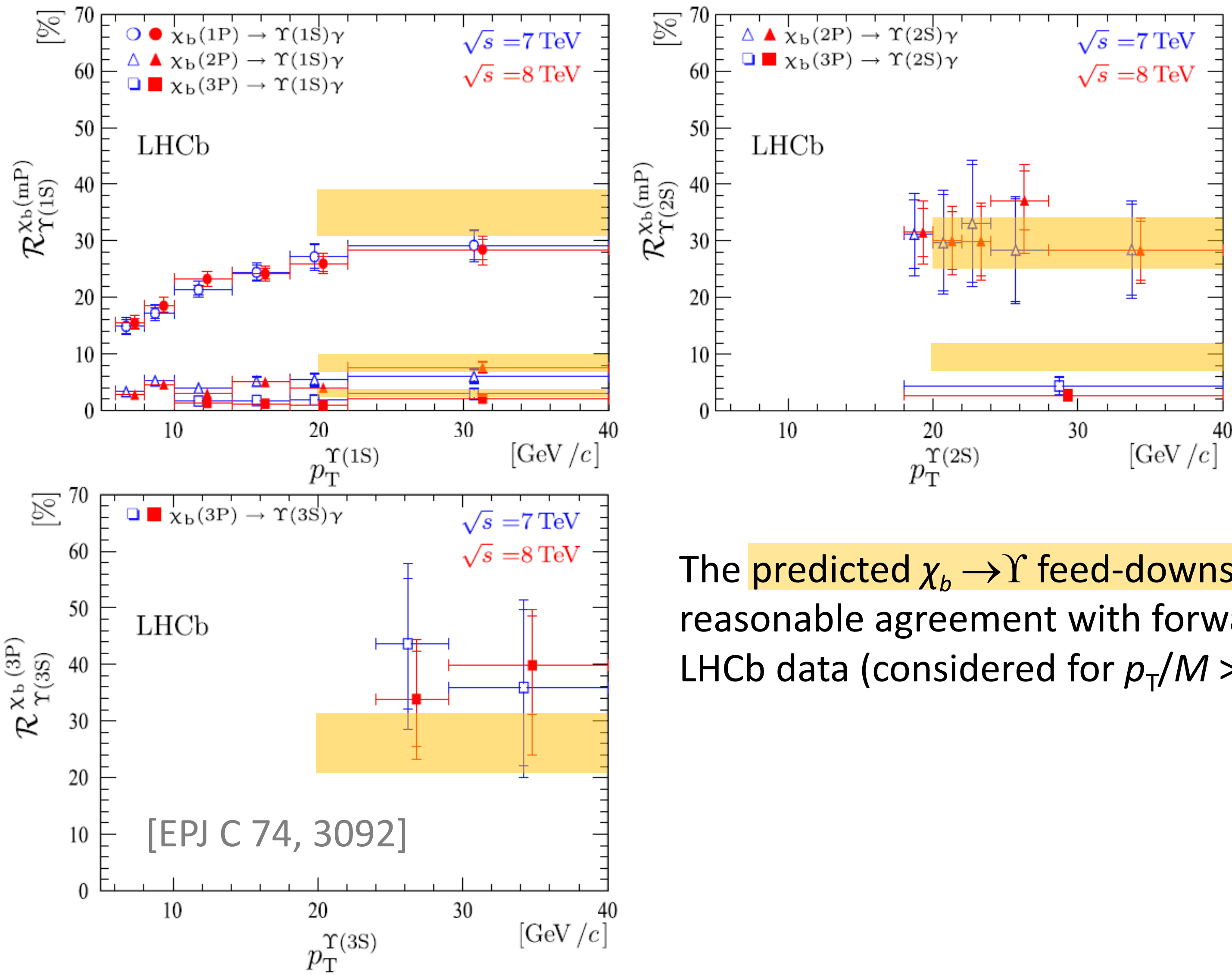
Feed-down fractions in pp (%):

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



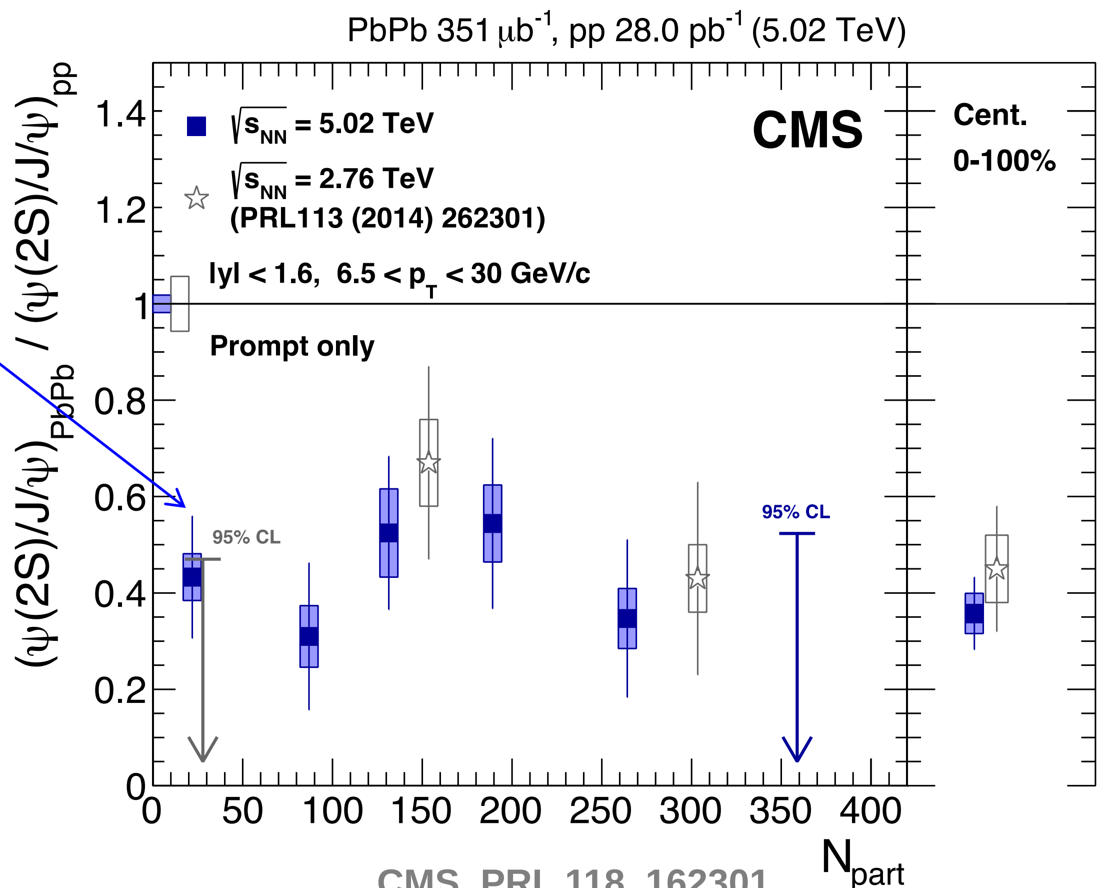
The predicted $\chi_b \to \Upsilon$ feed-downs are in reasonable agreement with forward-rapidity LHCb data (considered for $p_T/M > 2$)

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

$\psi(2S)$ has a *very* small binding energy $\Rightarrow$ a *threshold effect* in binding energy?

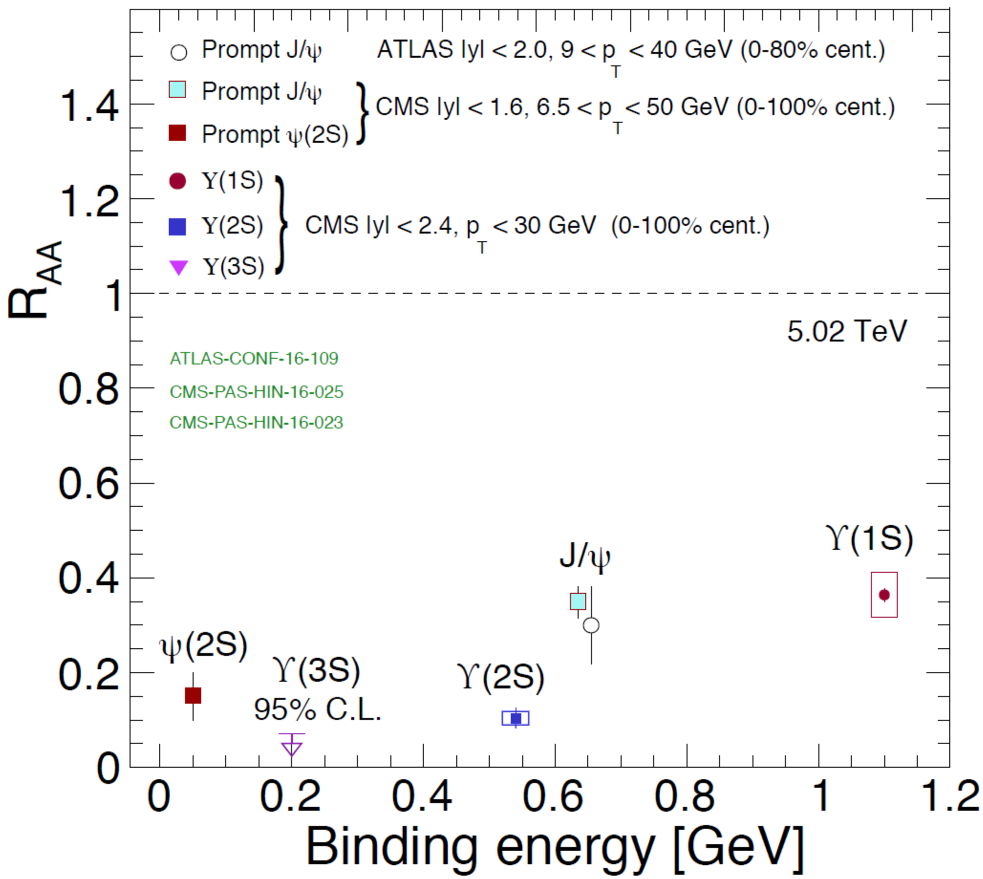


CMS, PRL 118, 162301

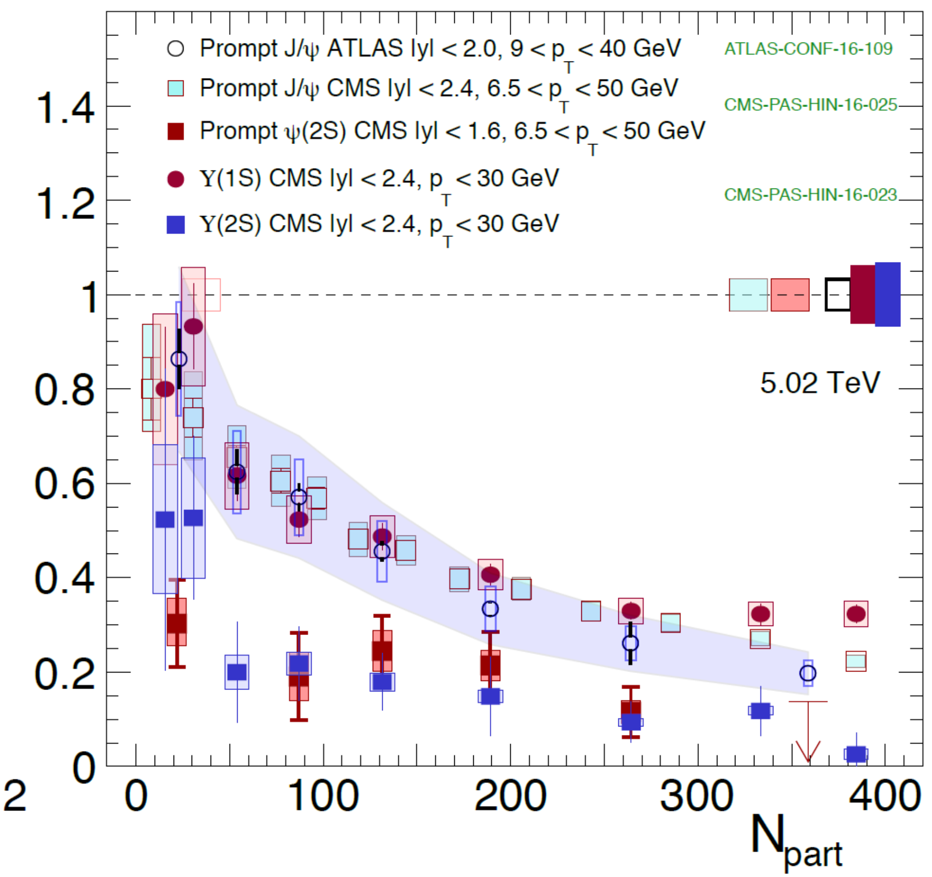
Nuclear modifications in Pb-Pb

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:

$$\left.\frac{\sigma_{\psi/\Upsilon}}{\sigma_{Q\bar{Q}}}\right|_{pp} \propto \boldsymbol{E}_{\mathbf{binding}}^{\boldsymbol{\delta}} \quad \Longrightarrow \quad \left.\frac{\sigma_{\psi/\Upsilon}}{\sigma_{Q\bar{Q}}}\right|_{AA} \propto (\boldsymbol{E}_{\mathbf{binding}} - \boldsymbol{\Delta E})^{\boldsymbol{\delta}}$$

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

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

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

$$E_{\text{binding}}(\mathrm{J}/\psi) - \boldsymbol{\Delta E} = \begin{cases} [2\boldsymbol{M(D^0)} - \boldsymbol{\Delta E}] - M(\mathrm{J}/\psi) \ \ ? \\ 2M(D^0) - [\boldsymbol{M(\mathrm{J}/\psi)} + \boldsymbol{\Delta E}] \ \ ? \end{cases}$$

screening effectively reduces di-meson threshold?

multiple scattering effectively increases Q–Qbar relative momentum and invariant mass?
→ J. Qiu et al., PRL 88 (2002) 232301

Parameters and ingredients

pp $\dfrac{\sigma_{\psi/\Upsilon}}{\sigma_{Q\bar{Q}}} \propto \boldsymbol{E}_{\mathbf{binding}}^{\boldsymbol{\delta}}$ $\Rightarrow$ AA $\dfrac{\sigma_{\psi/\Upsilon}}{\sigma_{Q\bar{Q}}} \propto (\boldsymbol{E}_{\mathbf{binding}} - \boldsymbol{\Delta E})^{\boldsymbol{\delta}}$

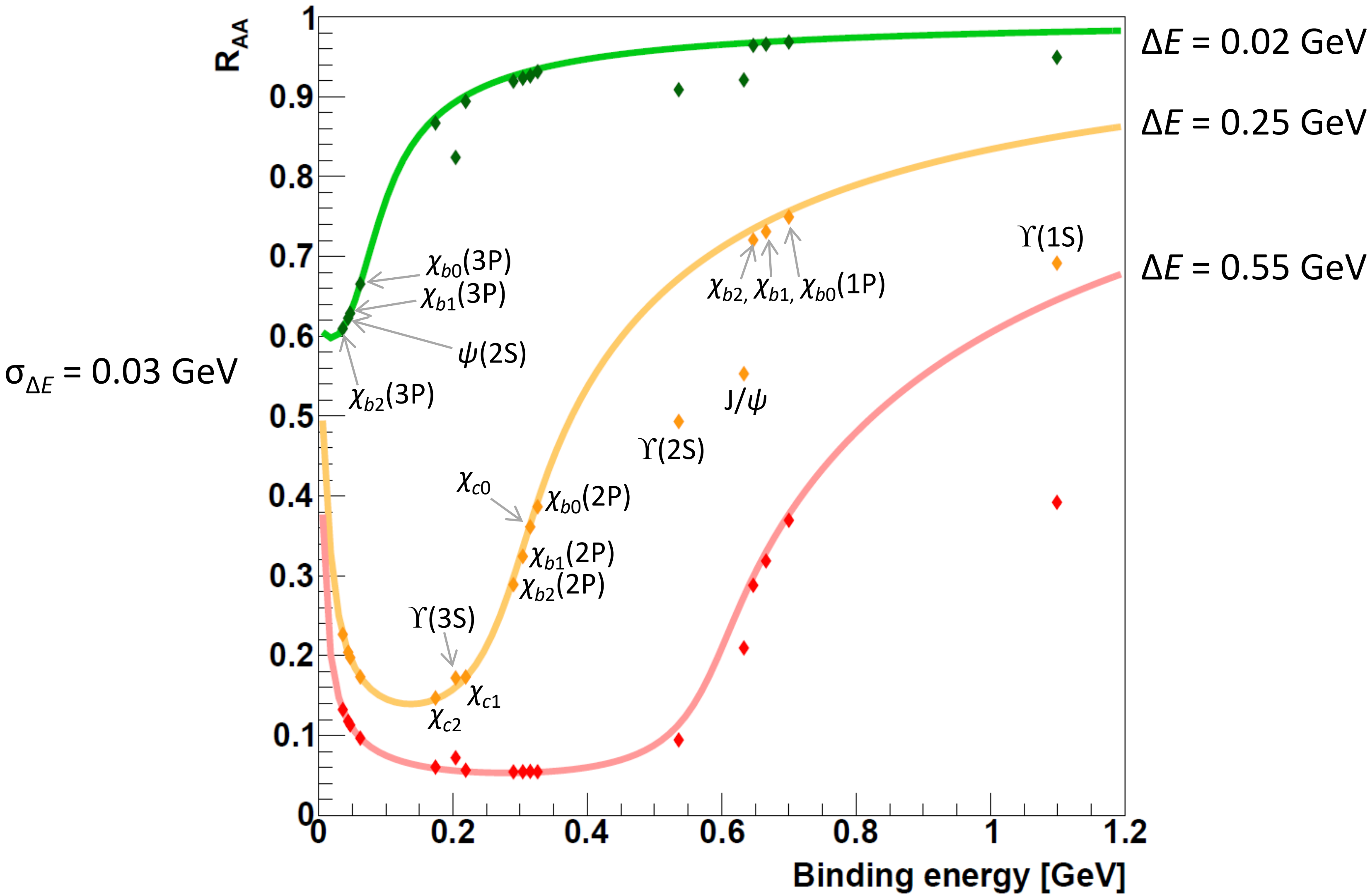
ΔE is determined from data in each condition (centrality, energy),
but we test the approximation that it is always *the same for all states*
Additional parameter:
the width of the ΔE distribution, $\sigma_{\Delta E}$, for simplicity centrality-independent

All the rest is *fixed* from pp data:

– same parameter $\delta = 0.63 \pm 0.04$ used in AA as in pp
– same short-distance cross-section dependence used in AA as in pp
– cross sections of all states calculated in pp and AA for each condition;
all varying feed-down effects included in the parametrization

Examples

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



Examples

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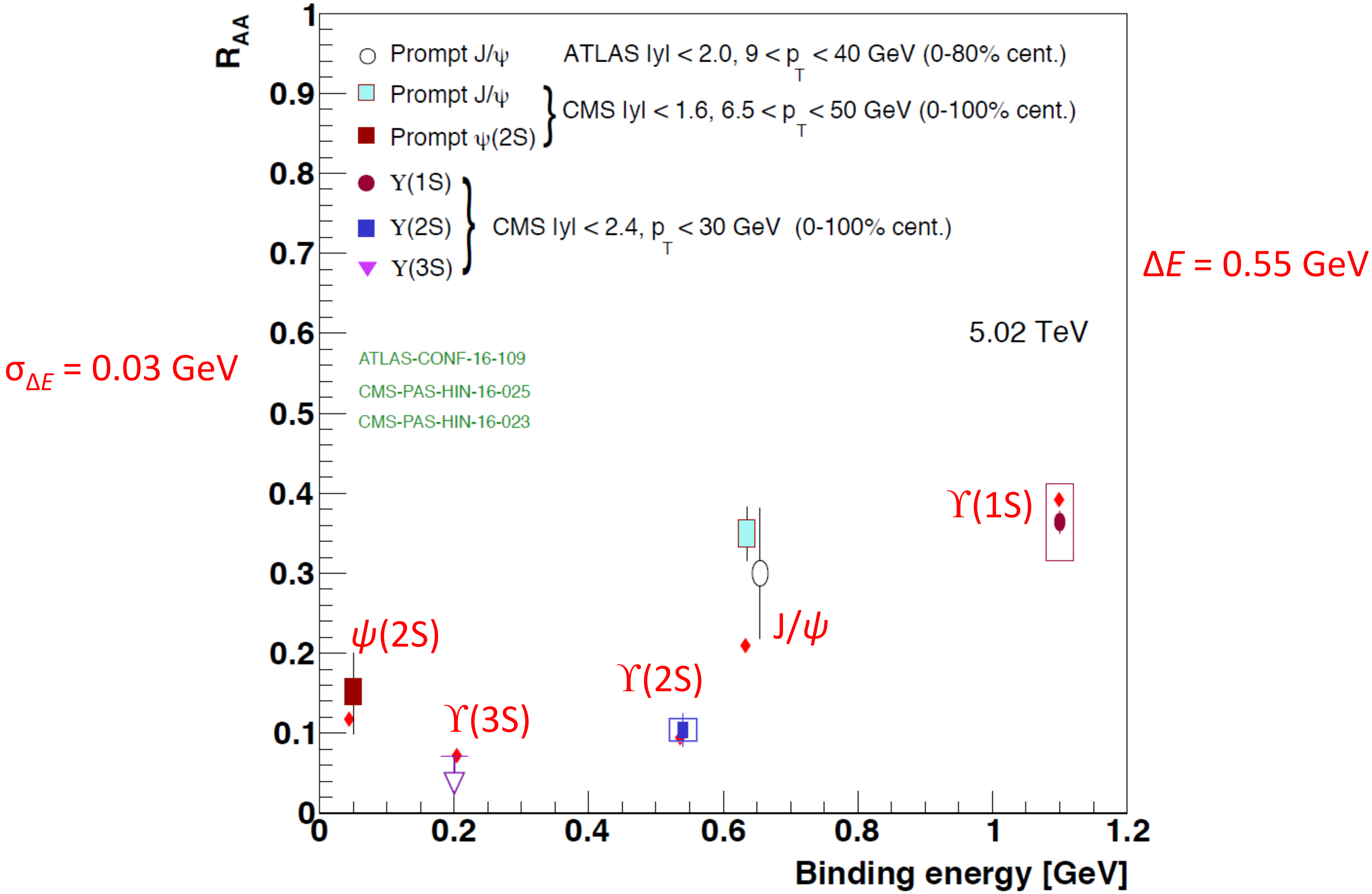
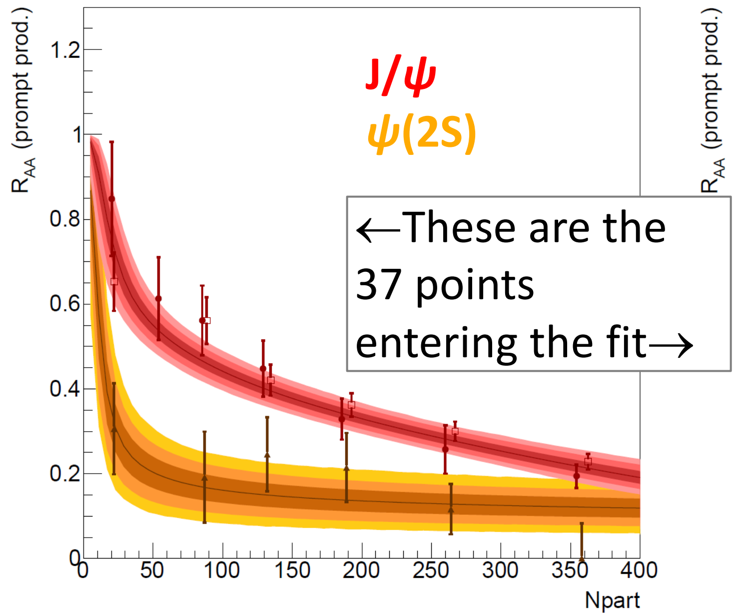
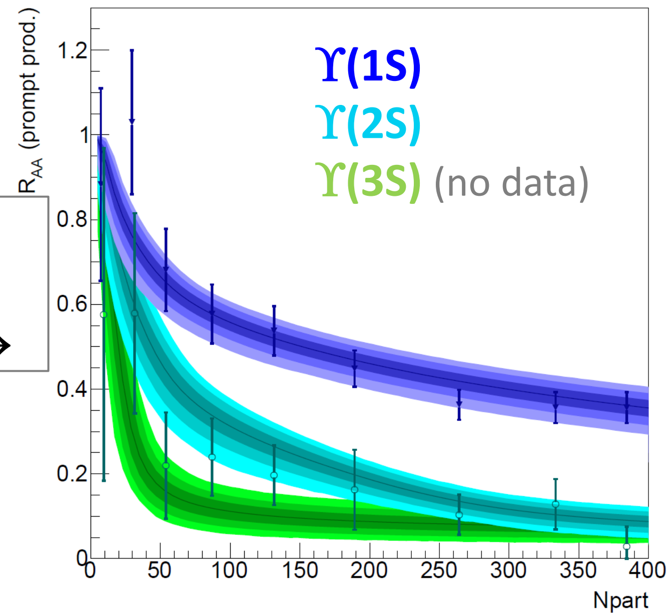


Global data fit: R_{AA} vs centrality

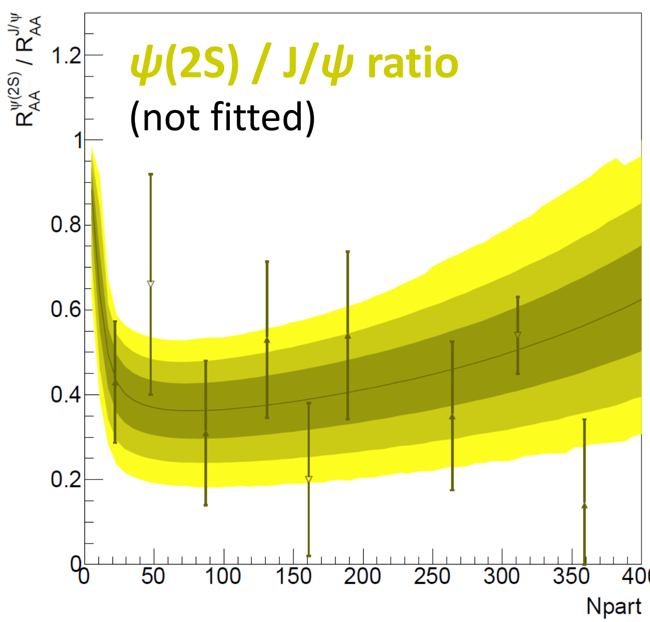


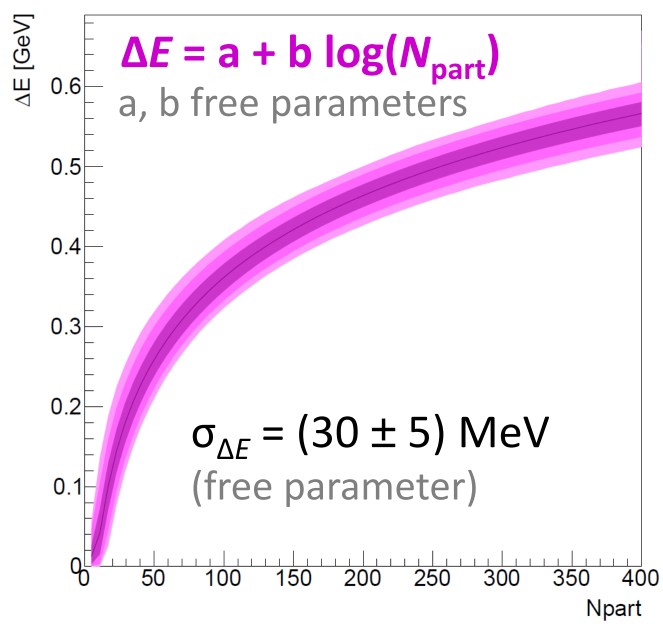


CMS & ATLAS
5.02 TeV

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%

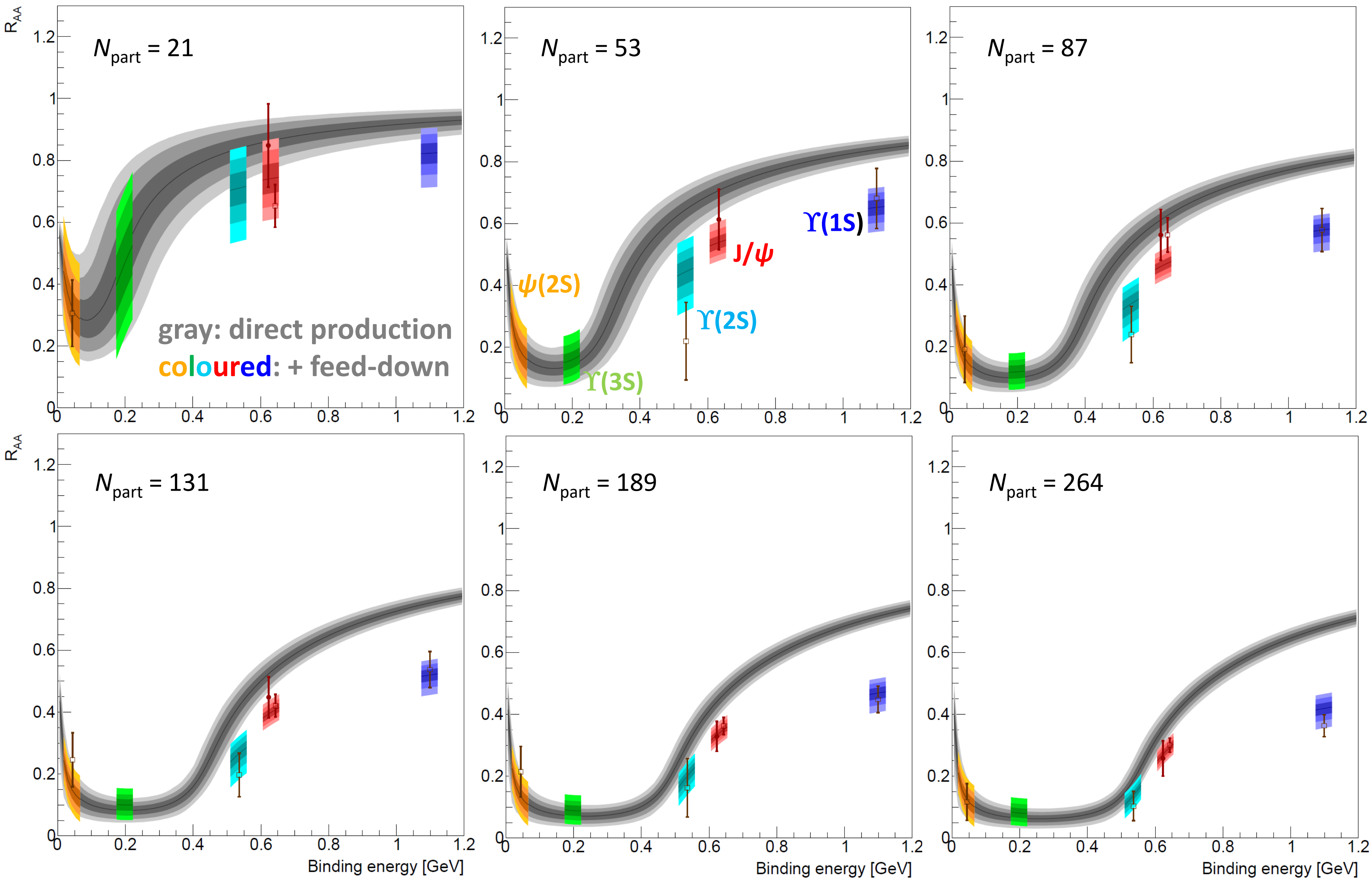
Improves if the absolute energy shift ΔE is allowed to be different for charmonium and bottomonium

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

Examples of “projections” at some N_{part} values

CMS & ATLAS
5.02 TeV

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



Summary

At the current level of experimental precision, 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** $\rightarrow$ **$E_{binding}$** long distance

This parametrization mirrors well the general idea of factorization of NRQCD.
While the observed simplicity is in seeming contradiction with the calculated SDCs, cancellations ultimately enable NRQCD to succeed.
Will the striking χ_{c1} and χ_{c2} polarization predictions bring us to a new theory-data clash?

Also PbPb data (for S-waves) show a surprisingly simple pattern:
R_{AA} can be parametrized assuming a (centrality/energy-dependent) shift of the binding-energy, equal in magnitude, at least in first approximation, for all c-cbar and b-bbar states

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