Quarkonium production at LHC energies: understanding hadron formation by the strong force

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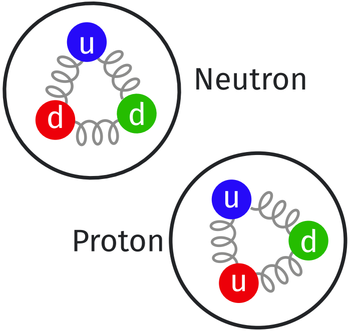
Introduction

Strong interactions

- The strong force binds quarks into nucleons and nucleons into atomic nuclei, determining the innermost structure of matter
- The interactions between quarks and gluons are described by quantum chromodynamics (QCD)
- Hadron formation involves non-perturbative processes and is not yet fully understood



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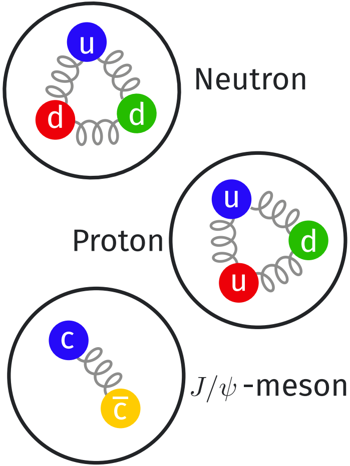
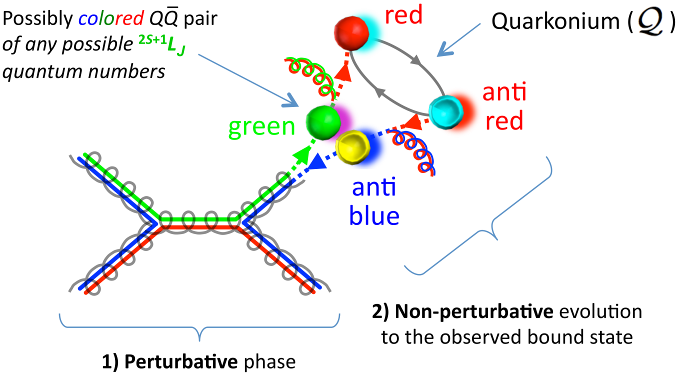
- Quarkonia:
  - $\rightarrow$ bound states of heavy quark-antiquark pairs
  - $\rightarrow$ ideal probes to study hadron formation



NRQCD - Non-Relativistic Quantum Chromodynamics

NRQCD is an effective field theory factorizing quarkonium production in two steps:

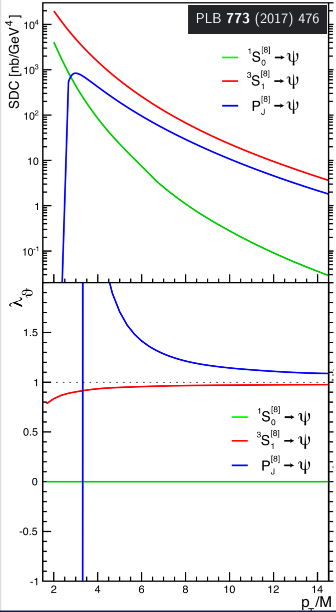
1. Creation of the initial quark-antiquark pair (perturbative QCD)
2. Hadronization of the pair into a bound Quarkonium state $\mathcal{Q}$ (non-perturbative QCD)



$$\sigma(\mathcal{Q}) = \sum_{\{n\}} \mathcal{S}[Q\bar{Q}(\{n\})] \cdot \mathcal{O}^{\mathcal{Q}}(\{n\})$$

- $\mathcal{S}$ Partonic processes via expansion in α_S (SDCs: theory)
- $\mathcal{O}$ (Assumed) universal constants, probabilities of the transitions $Q\bar{Q}$ pair $\rightarrow$ $\mathcal{Q}$ bound state (LDMEs: experiment)

Experimental observables

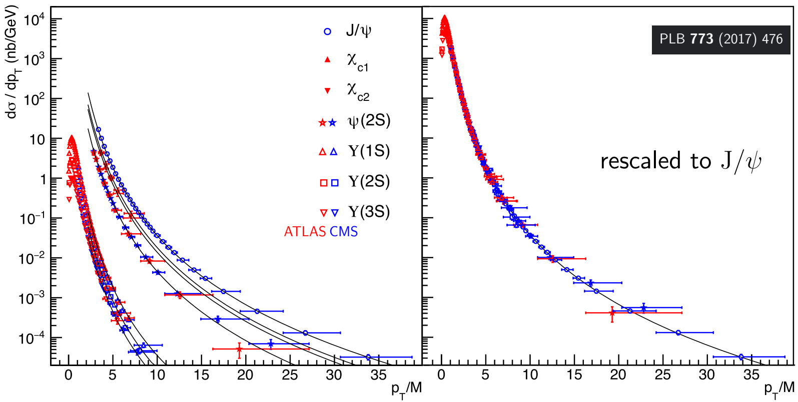


- Cross sections cannot easily distinguish between different subprocesses, given the similarity of the SDC(p_{T}) shapes
- Quarkonium states can be observed in different eigenstates of the angular momentum component J_z; observing states in a preferred eigenstate is referred to as polarization
- The polarization is reflected in the two-dimensional decay angular distribution of the quarkonium states

$$W(\cos\vartheta, \varphi|\vec{\lambda}) \propto \frac{1}{3+\lambda_\vartheta}\Big(1 + \lambda_\vartheta \cos^2\vartheta + \lambda_\varphi \sin^2\vartheta \cos 2\varphi + \lambda_{\vartheta\varphi} \sin 2\vartheta \cos\varphi\Big)$$

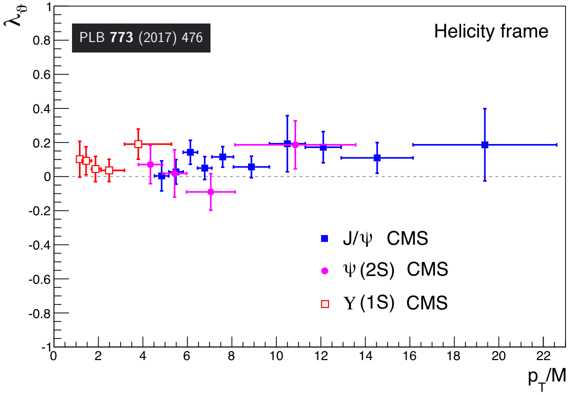
- The three main NRQCD subprocesses for S-wave production have very different polarizations

Experimental status - cross sections in pp collisions



- Cross section measurements for seven states reported, at mid-rapidity, by ATLAS and CMS
- Universal pattern of the shapes as a function of p_T/M
- In stark contrast with the intrinsic diversity of the NRQCD SDCs

Experimental status - polarizations in pp collisions



- Measurements of prompt *S*-wave states exclude strong polarizations
- Very similar trends, despite vastly different feed-down contributions

The vector S-wave quarkonia: J/ψ, $\psi(2S)$, $\Upsilon(nS)$

- Vector particles are generally produced with maximal polarization; even if for a given p_T in a given frame the polarization can become zero, there is always a kinematical domain and an "optimal" frame where it approaches maximal values
- Only a "fortunate" mixture of subprocesses or randomization effects can lead to unobservable polarization
- This "fine-tuning" cancellation is not a natural or expected explanation
- NRQCD foresees that vector quarkonium states come from three competing octet terms of similar magnitude: ${}^1S_0^{[8]}$, ${}^3S_1^{[8]}$ and ${}^3P_J^{[8]}$
- The mesons from ${}^1S_0^{[8]}$ (intrinsically polarized along the unobservable ${}^1S_0^{[8]}$-state direction) "look" unpolarized because of rotational smearing, but those from ${}^3S_1^{[8]}$ and ${}^3P_J^{[8]}$ are strongly, and not oppositely, polarized, according to NLO calculations

The vector S-wave quarkonia: J/ψ, $\psi(2S)$, $\Upsilon(nS)$

- Are we seeing an *accidental* cancellation of the ${}^3S_1^{[8]}$ and ${}^3P_J^{[8]}$ polarizations in a specific kinematic domain?
- OR is such cancellation actually an exact degeneracy (to be found in not yet available higher order calculations), indicating that the NRQCD expansion is not the most natural one?
- OR are we seeing that the ${}^1S_0^{[8]}$ term dominates, violating the NRQCD hierarchy expectations?

Open questions

We find that vector quarkonium production has a number of surprising behaviors, raising two main questions:

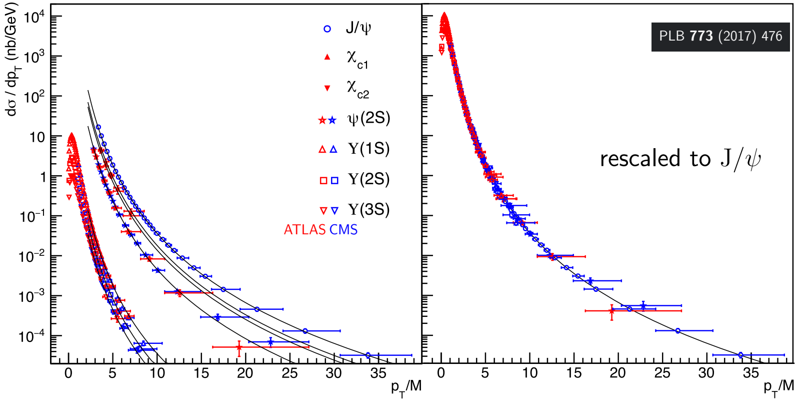
1) Are vector quarkonia really produced universally?
2) Why don't they show the strong polarization of other vector particles?

My thesis addresses these questions, through phenomenological studies and the analysis of CMS data, structured in two main steps:

1) Probe the universal scaling previously observed in the ATLAS and CMS mid-rapidity data with a more stringent test, expanding the global-fit analysis to include LHCb forward-rapidity data and more pp collision energies (7, 8 and 13 TeV data)
2) Probe the absence of strong S-wave polarizations with much better precision, by using Run 2 CMS data and improved analysis methods

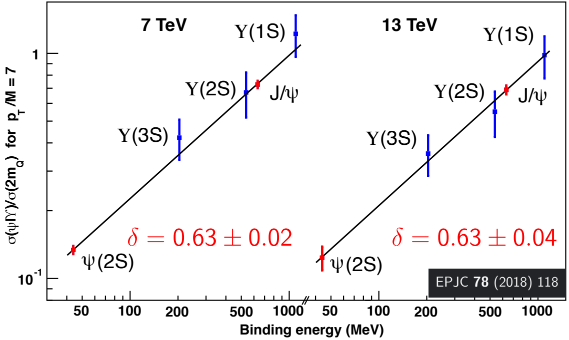
Phenomenology

Short-distance scaling patterns



- All quarkonia have identical p_T/M-differential cross section shapes, for $p_T/M > 2$, at mid-rapidity, independently of mass and quantum numbers

Long-distance scaling patterns



$$\frac{\sigma_{\psi|\Upsilon}}{\sigma_{Q\overline{Q}}} \propto E^{\delta}_{\text{binding}}$$

The $Q\overline{Q} \rightarrow$ bound-state "transition probabilities" show a clear correlation with binding energy

- common to both charmonium and bottomonium
- identical at 7 and 13 TeV

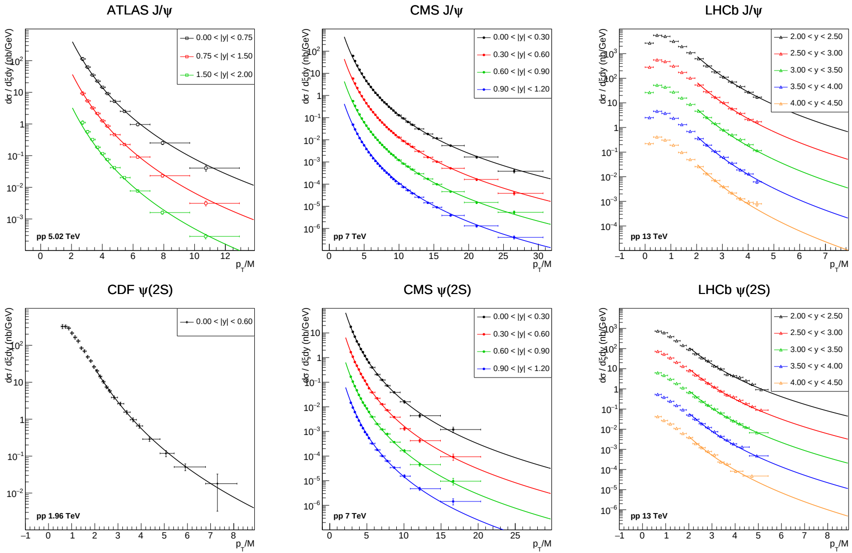
The picture so far

- So far, the work has been focused on mid-rapidity production with CMS and ATLAS measurements
- Looking at the short-distance scaling, it was found that the universal p_T/M-differential cross section shape can be parametrized as

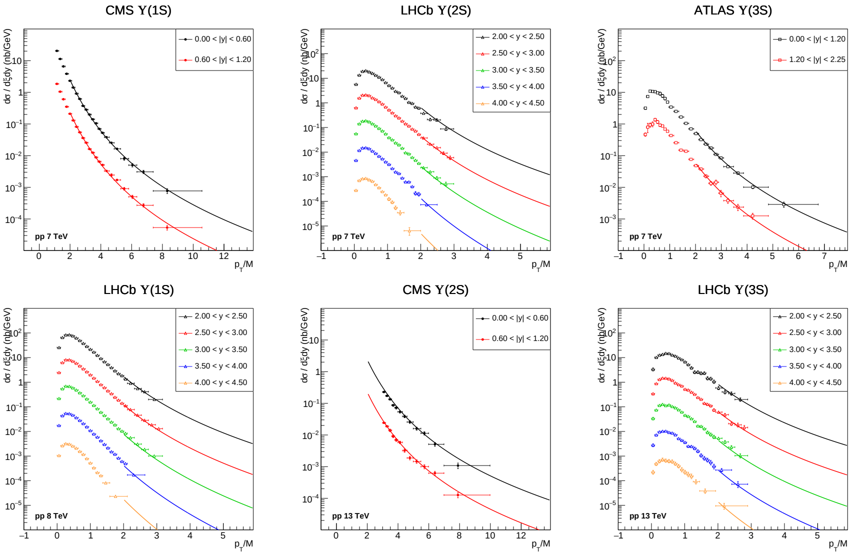
$$\frac{d\sigma}{dp_T/M} \propto p_T/M \left(1 + \frac{1}{\beta - 2}\frac{(p_T/M)^2}{\gamma}\right)^{-\beta}$$

  with single universal γ and β for each value of $\sqrt{s}$
- In order to further probe the observed universality, we want to extend our analysis in two dimensions not yet considered: rapidity and $\sqrt{s}$

Extend analysis to rapidity and $\sqrt{s}$ dimensions



Extend analysis to rapidity and $\sqrt{s}$ dimensions

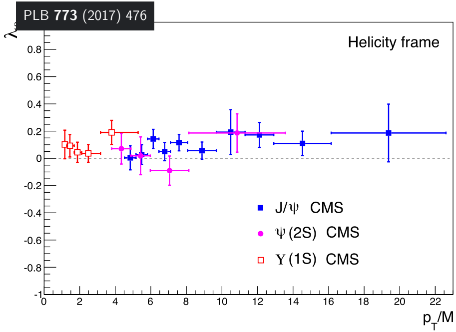


Extend analysis to rapidity and $\sqrt{s}$ dimensions

- We upgraded our empirical parametrization to reflect first principles:
  - Previously, we parametrized the pp cross section $pp \to \mathcal{Q} + X$
  - Now, we use the partonic cross section $gg \to \mathcal{Q} + X$ as universal function, coupled with state-of-the-art proton PDFs
- We use a similarly simple parametrization, which has a dominant universal component and a (state-dependent) corrective component that increases monotonically from $\sim 4\%$ to $\sim 30\%$ with state mass
- The model reproduces reasonably well the $\psi(nS)$, χ_c, $\Upsilon(nS)$ data from CDF, CMS, ATLAS and LHCb, at several $\sqrt{s}$, from 1.96 to 13 TeV, for absolute rapidity from 0 to 4.5, for a total of 922 data points

CMS data analysis

Main goal

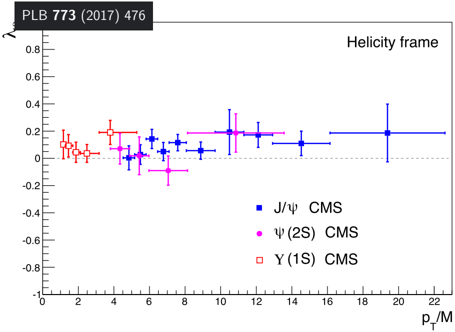


The existing LHC measurements of the J/ψ, $\psi(2S)$ and $\Upsilon(nS)$ polarizations show that these particles are not produced with strong polarizations (unlike what happens for other vector states) but are not sufficiently precise to clarify two crucial questions:

1) Are the polarizations independent of p_T, over a very broad p_T range?

   If yes, then we can exclude a coincidental cancellation between two different processes and, instead, conclude that those processes are related to each other (by a deeper symmetry than assumed in NRQCD)

Main goal



The existing LHC measurements of the J/ψ, $\psi(2S)$ and $\Upsilon(nS)$ polarizations show that these particles are not produced with strong polarizations (unlike what happens for other vector states) but are not sufficiently precise to clarify two crucial questions:

2) Are the polarizations compatible with zero to within a small uncertainty?

If yes, then we must conclude that we are seeing a smoking-gun signal of an extremely peculiar and unexpected symmetry of Nature, not at all "natural" in the NRQCD framework

Polarization measurement procedure

- The polarization of a quarkonium state can be determined experimentally through the state's decay angular distribution

$$W(\cos\theta, \phi|\vec{\lambda}) \propto \frac{1}{3+\lambda_\theta}\left(1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos\phi\right)$$

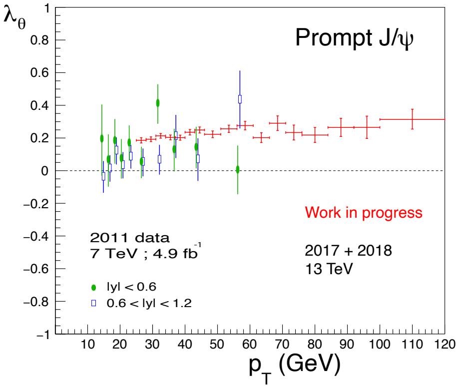
- The λ parameters can be determined by fitting W to the measured angular distribution
- Shaping effects due to the acceptance and efficiency of the detector will affect the measured distribution and must be accounted for in any polarization measurement
- The ratio between data and (unpolarized) Monte Carlo (MC) allows us to cancel out shaping effects and obtain the corrected data distribution, from which the polarization parameters can be determined

Summary of the CMS analysis

We have applied this method to measure the J/ψ and $\psi(2S)$ polarizations with the Run 2 data (13 TeV) of CMS. This new measurement benefits from:

- A broad p_T coverage, from 25 to 120 GeV
- Large event samples, both for data and MC

These conditions allow us to probe both open questions with a good precision



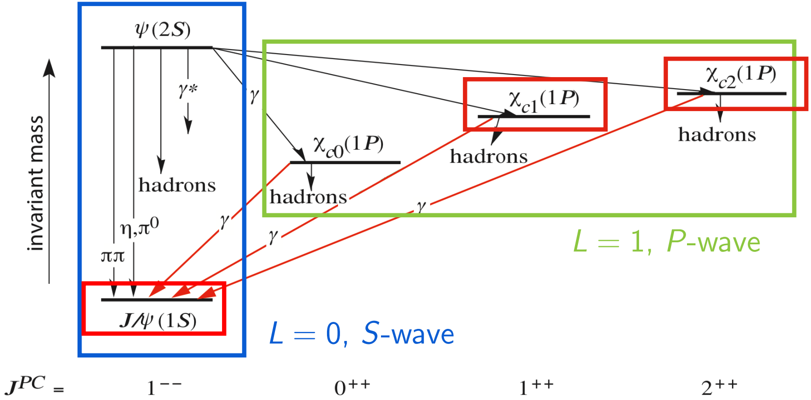
Summary

Summary

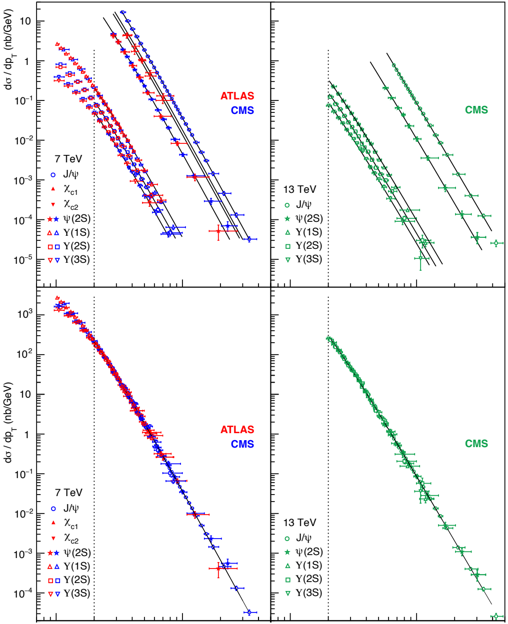
- In my PhD, I am submitting the apparent universality of quarkonium production and the absence of significant vector quarkonium polarizations, two observations not expected in the NRQCD theory approach, to more stringent tests
- On one hand, I am performing a phenomenological study, expanding previous global-fit analyses (only made at mid-rapidity and for one $\sqrt{s}$ value) to forward rapidity and several $\sqrt{s}$ values
  - → The fit model shows stable results, with good agreement across all dimensions probed, and is being subjected to final checks before submitting for publication
- On the other hand, I am doing an analysis of CMS data to obtain precise measurements of S-wave polarizations, up to higher p_T values than previously explored
  - → The analysis has been finalized, with polarization results in the form of $\lambda_\theta(p_T)$, and the documentation is being compiled for internal scrutiny

Backup

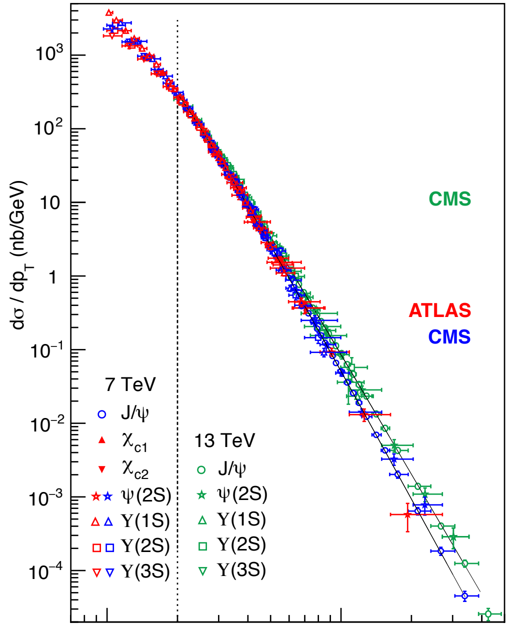
Charmonium spectrum



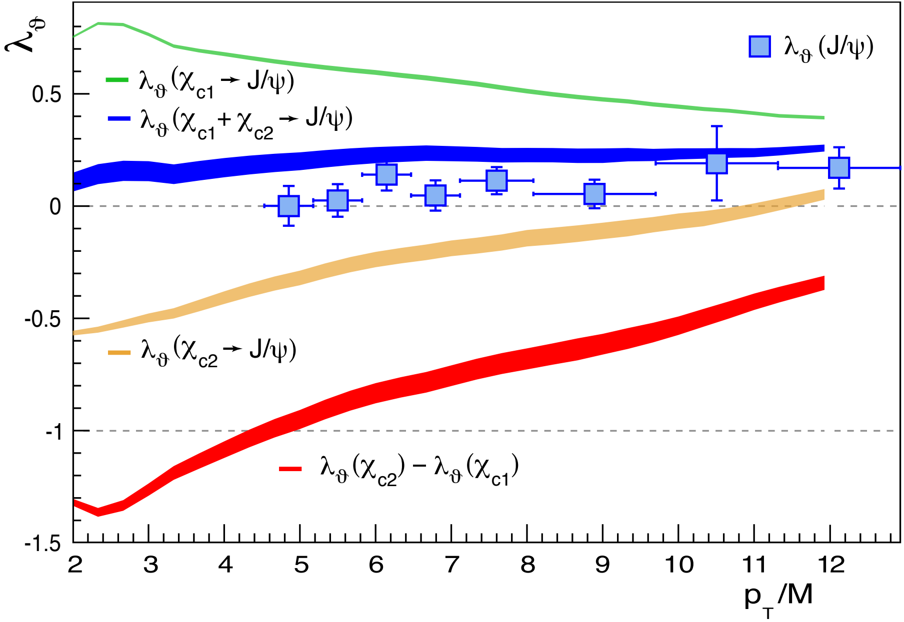
- All states, except the $\psi(2S)$, are affected by feed-down decays
  - All measurements refer to "prompt" (direct+feed-down) production
  - Around 30% of the promptly produced J/ψ mesons are from feed-down decays
  - Non-prompt (NP) contributions from b-hadron decays can be removed experimentally



dσ / dp_T (nb/GeV)
ATLAS
CMS
7 TeV
J/ψ
χc1
χc2
ψ(2S)
Υ(1S)
Υ(2S)
Υ(3S)
CMS
13 TeV
J/ψ
ψ(2S)
Υ(1S)
Υ(2S)
Υ(3S)



10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$d\sigma / dp_T$ (nb/GeV)
CMS
ATLAS
CMS
7 TeV
J/ψ
χ_{c1}
χ_{c2}
ψ(2S)
Υ(1S)
Υ(2S)
Υ(3S)
13 TeV
J/ψ
ψ(2S)
Υ(1S)
Υ(2S)
Υ(3S)



λ_ϑ
0.5
0
-0.5
-1
-1.5
2
3
4
5
6
7
8
9
10
11
12
p_T/M
$\lambda_\vartheta(\chi_{c1} \to J/\psi)$
$\lambda_\vartheta(\chi_{c1} + \chi_{c2} \to J/\psi)$
$\lambda_\vartheta(\chi_{c2} \to J/\psi)$
$\lambda_\vartheta(\chi_{c2}) - \lambda_\vartheta(\chi_{c1})$
$\lambda_\vartheta(J/\psi)$