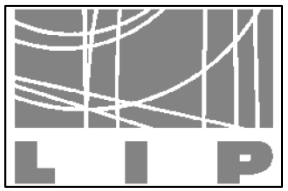
Quarkonium polarization at the LHC

Outline:

- Introductory remarks
- CMS measurements of the Y(1S), Y(2S) and Y(3S) polarizations
- CMS measurements of the prompt J/ψ and ψ(2S) polarizations
- LHCb measurement of the prompt J/ψ polarization

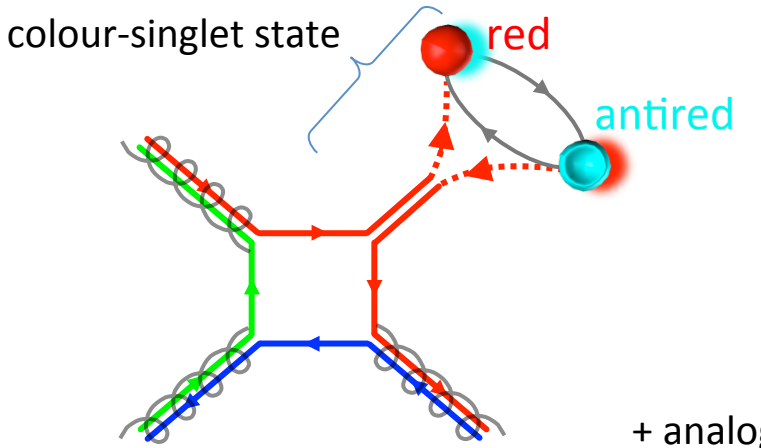


Pietro Faccioli (LIP Lisbon)
[presented by Luca Perrozzi (CERN)]
on behalf of the CMS and LHCb collaborations
QCD @ LHC 2013, 2–6 Sept., DESY, Hamburg

The quarkonium production dilemma: a matter of colour

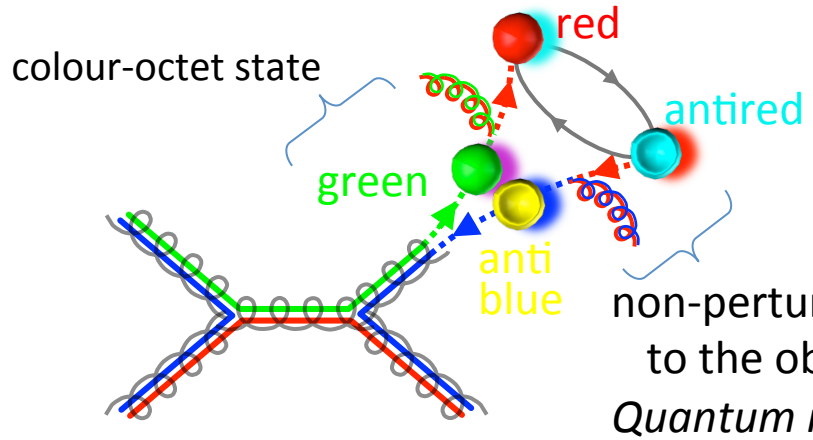
Studies of *heavy* quarkonia [J/ψ, χ_c, ψ', Υ, χ_b] should clarify how hadron properties are generated by QCD; how the observed *Q*-*Q*bar bound state acquires its quantum numbers

- **Colour Singlet Model**: quarkonia always produced directly as observable ***colour-neutral*** *Q*-*Q*bar pairs



+ analogous colour combinations

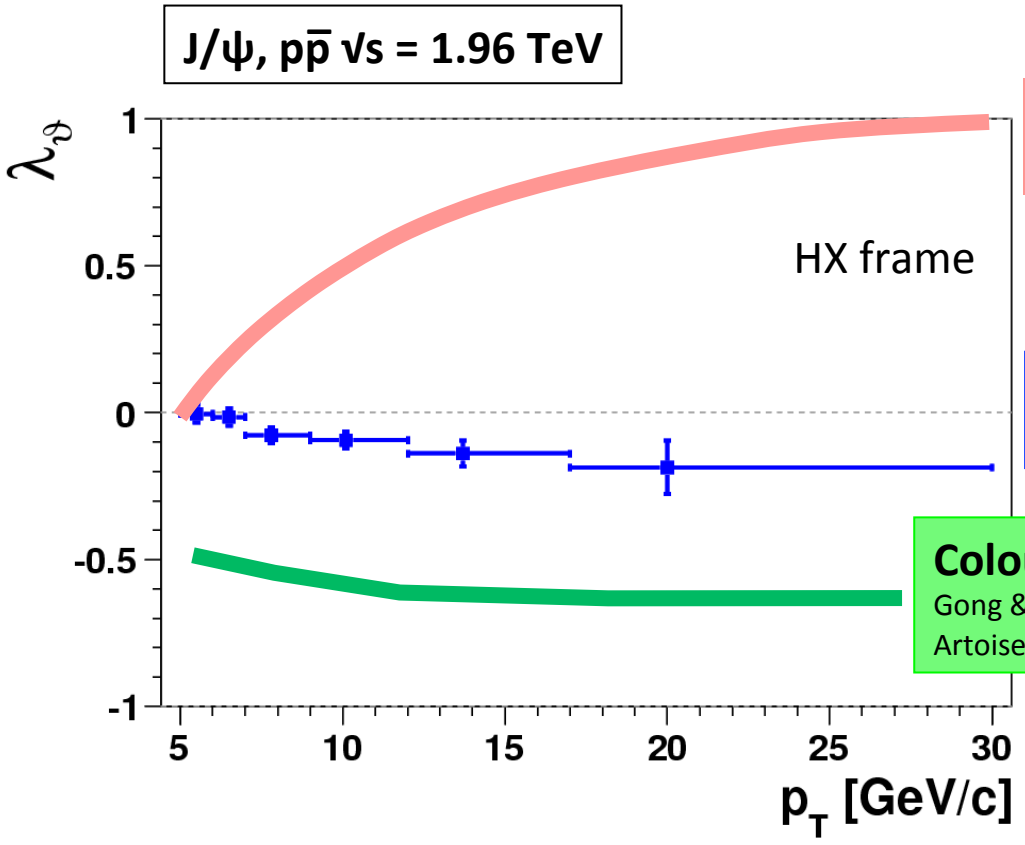
- **NRQCD factorization**: quarkonia are also produced through ***coloured*** *Q*-*Q*bar pairs *of any possible quantum numbers*



non-perturbative transition to the observable state. *Quantum numbers change!*

Polarization measurements should provide the most definitive answers

Polarization measurements at the Tevatron



NRQCD factorization
Braaten, Kniehl & Lee, PRD62, 094005 (2000)

direct J/ψ

CDF Run II
CDF Coll., PRL 99, 132001 (2007)

direct J/ψ
+ J/ψ *from* χ_c *decays*

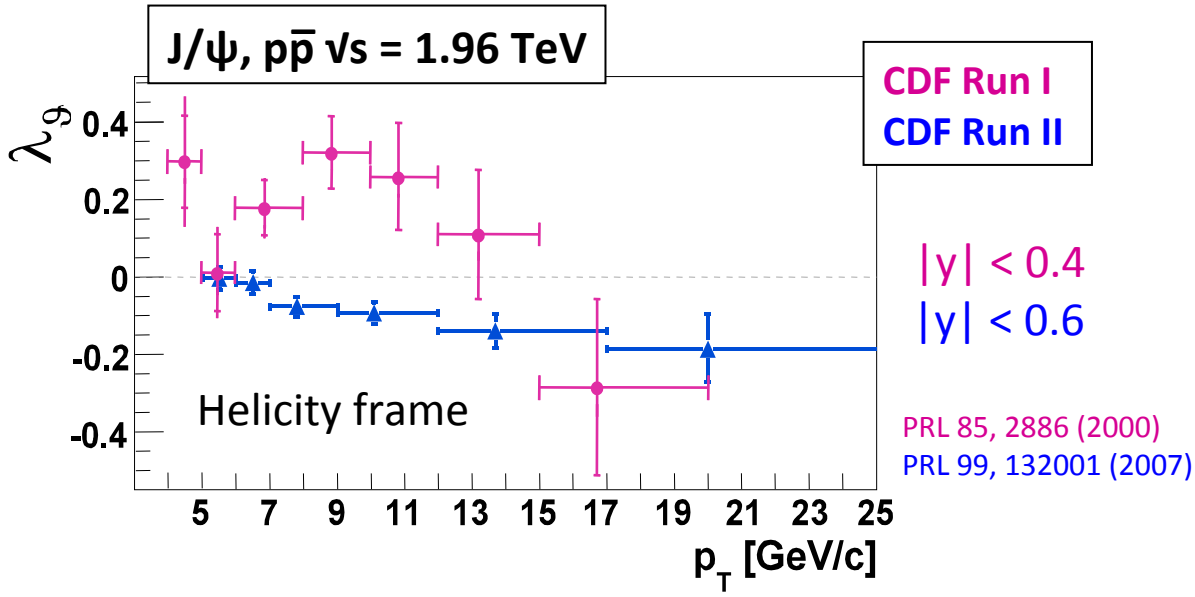
Colour Singlet Model
Gong & Wang, PRL 100, 232001 (2008)
Artoisenet et al., PRL 101, 152001 (2008)

direct J/ψ

⇒ Data and theory
in clear disagreement

The "J/ψ polarization puzzle"

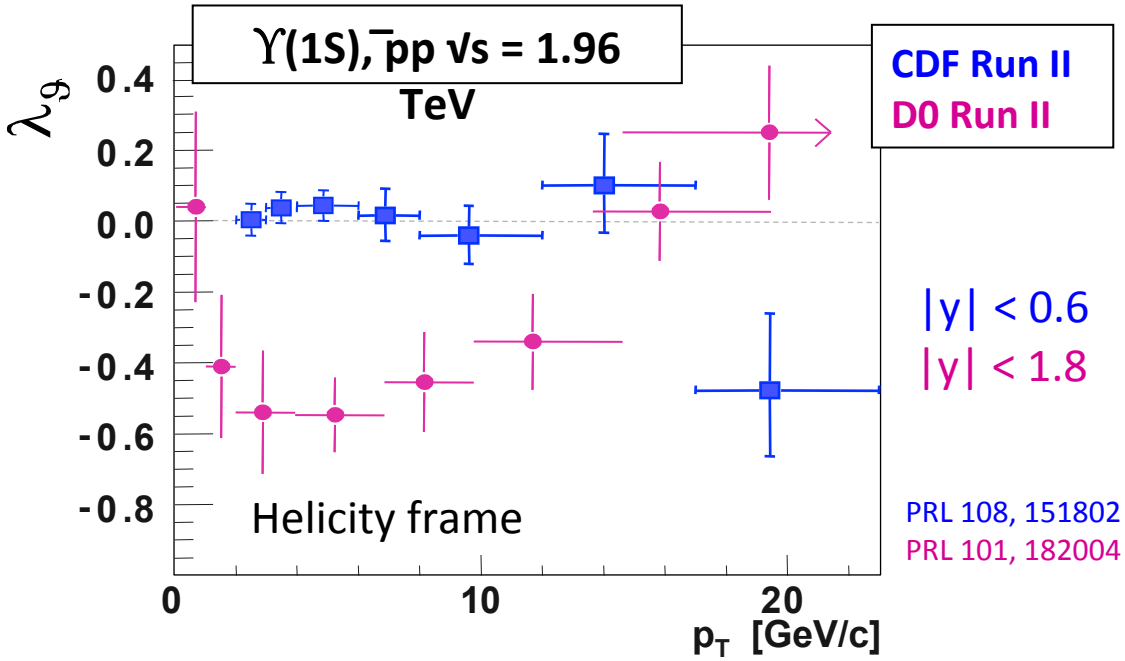
Polarization measurements at the Tevatron



|y| < 0.4
|y| < 0.6

PRL 85, 2886 (2000)
PRL 99, 132001 (2007)

- CDF II vs CDF I



|y| < 0.6
|y| < 1.8

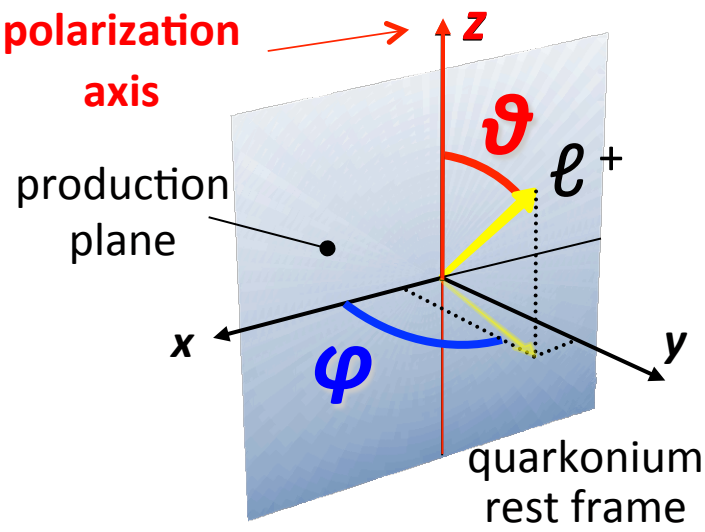
PRL 108, 151802 (2012)
PRL 101, 182004 (2008)

- CDF vs D0

⇒ Data and data also in clear disagreement

Improved results needed !

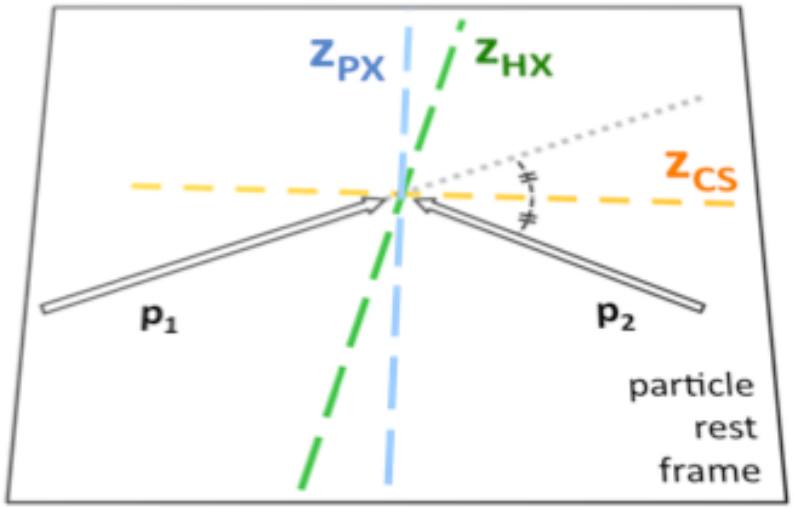
Back to basics: angles and frames



Most general angular-decay distribution for a dilepton decay of an S-wave quarkonium :

$$\frac{dN}{d\Omega} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_\varphi \sin^2\theta \cos 2\varphi + \lambda_{\theta\varphi} \sin 2\theta \cos\varphi$$

average polar anisotropy



Helicity (HX): z = direction of quarkonium momentum

Collins-Soper (CS): z = average of the two beam directions

Perpendicular helicity (PX): z = perpendicular to CS

“Transverse” and “longitudinal”: not so simple

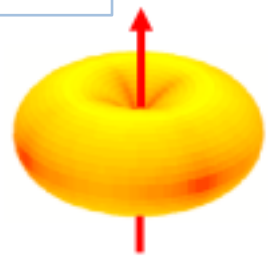
$\frac{dN}{d\Omega} \propto 1 + \cos^2\vartheta$

$\lambda_\vartheta = +1$
$\lambda_\varphi = 0$
$\lambda_{\vartheta\varphi} = 0$

“Transverse” polarization ($J_z = \pm 1$)

$\frac{dN}{d\Omega} \propto 1 - \cos^2\vartheta$

$\lambda_\vartheta = -1$
$\lambda_\varphi = 0$
$\lambda_{\vartheta\varphi} = 0$

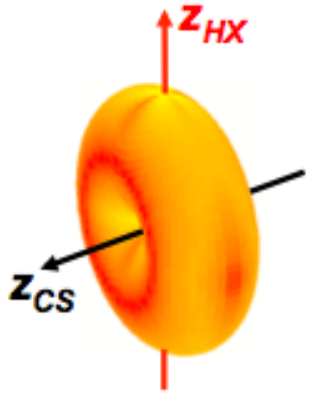


“Longitudinal” polarization ($J_z = 0$)

The value of λ_ϑ changes from -1 to +1 between the CS and HX frames

Two opposite physical cases are indistinguishable if we do not measure the full distribution

$\tilde{\lambda} = -1$



$\lambda_\vartheta = +1$
$\lambda_\varphi = -1$

$\lambda_\vartheta = -1$
$\lambda_\varphi = 0$

$\lambda_\vartheta = +1$
$\lambda_\varphi = 0$

$\tilde{\lambda} = +1$

The shape of the distribution is invariant and can be characterized by the frame invariant parameter

$$\tilde{\lambda} = (\lambda_\vartheta + 3\lambda_\varphi)/(1 - \lambda_\varphi)$$

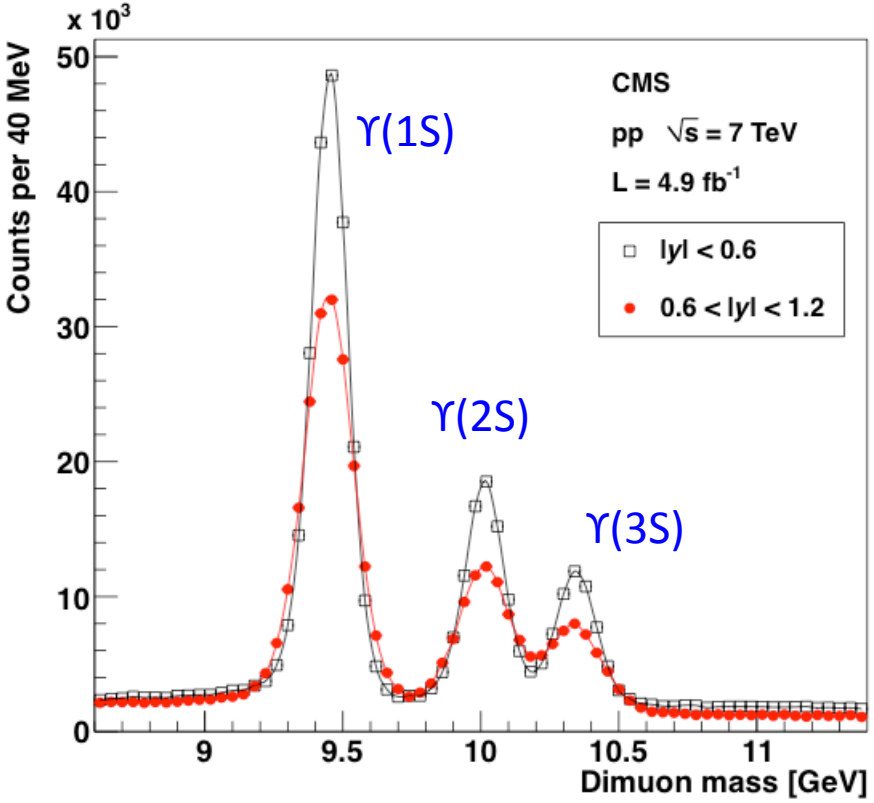
CMS measurements: phase space coverage

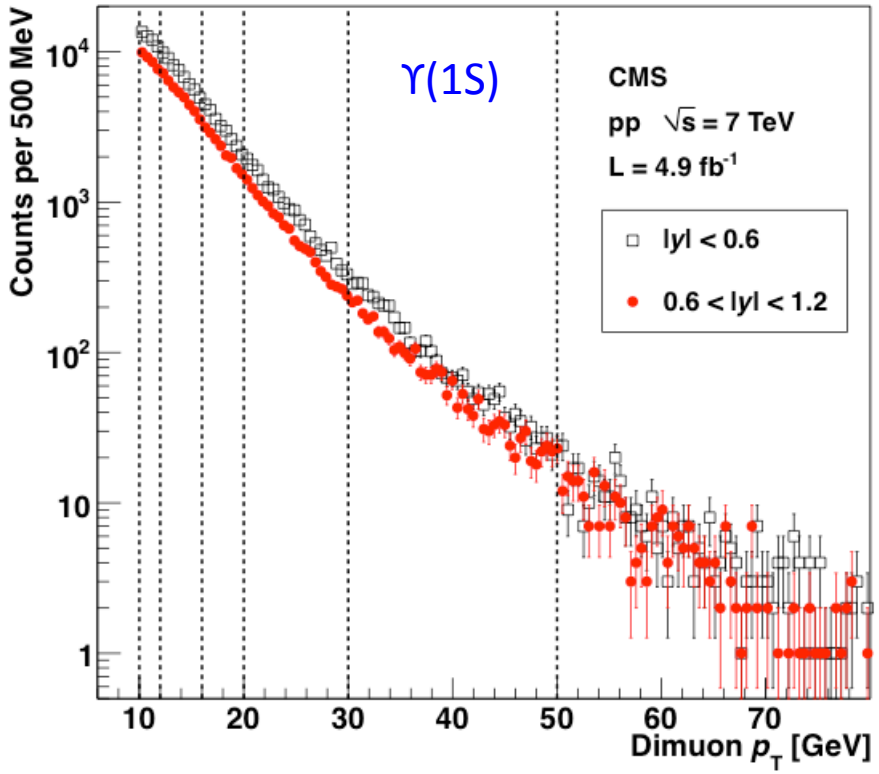
CMS measured the λ_ϑ, λ_ϕ, $\lambda_{\vartheta\phi}$ and $\tilde{\lambda}$ parameters of the J/ψ, ψ(2S), ϒ(1S), ϒ(2S) and ϒ(3S) mesons promptly produced in pp collisions at 7 TeV, in the HX, CS and PX frames

The measurements are made in 2 [or 3 for the ψ(2S)] |y| bins and in several p_T bins: ϒ(nS): 10–50 GeV; J/ψ: 14–70 GeV; ψ(2S): 14–50 GeV

Data collected in 2011, using a dedicated dimuon trigger (integrated luminosity = 4.9 fb^{-1})

Details on the analysis and results: PRL 110, 081802 (2013) and arXiv:1307.6070 [hep-ex]



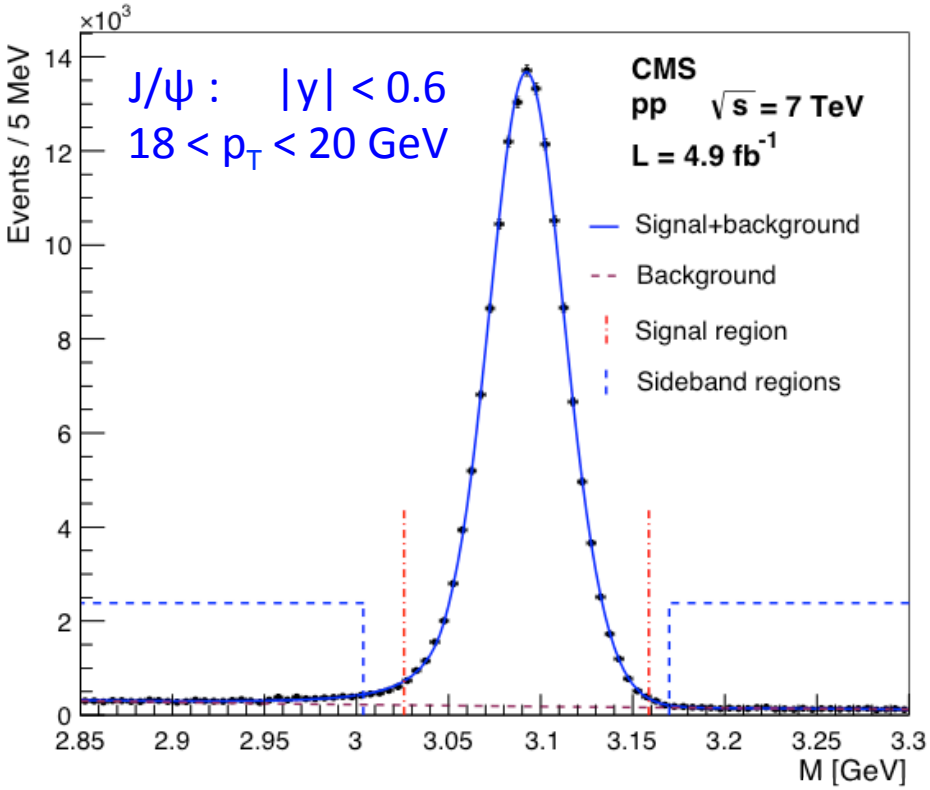


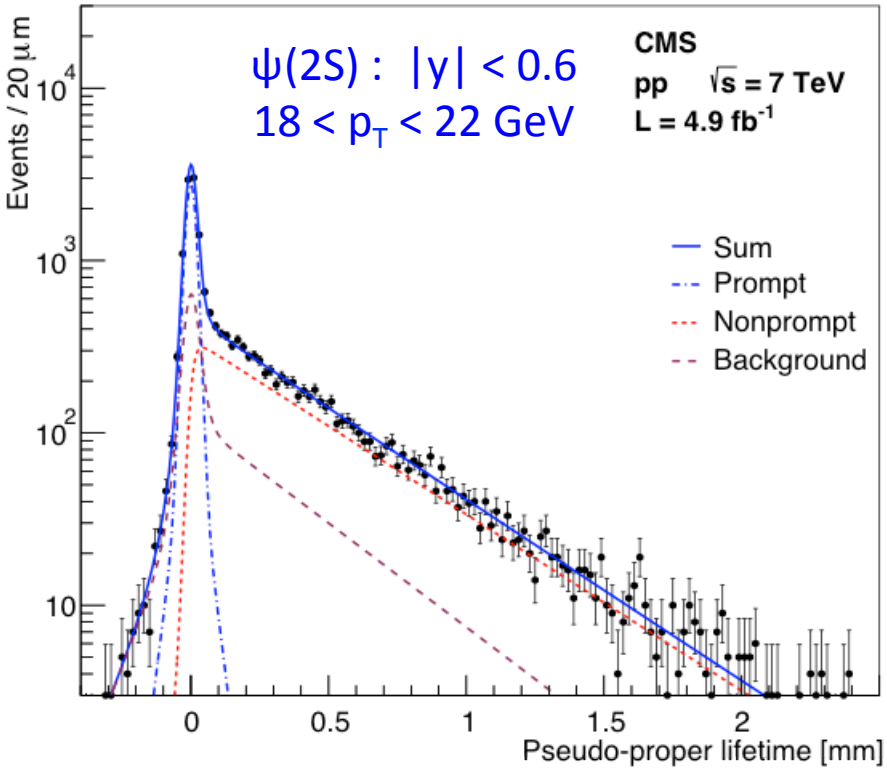
CMS measurements: signal and backgrounds

In each (p_T, y) cell, the dimuon mass and lifetime (for the charmonia) distributions are used to measure the respective resolutions, then used to define signal / prompt regions, as well as “mass sidebands” (MSB) and “non-prompt regions” (NPR)

The MSB and NPR are used to define the background model, in (cosϑ, ϕ), for the mass continuum Bg and for the non-prompt charmonia, respectively

Events in the signal region distributed as the Bg model are removed, until reaching the total Bg fraction extracted from the mass and lifetime fits





CMS measurements: the PPD of the λ parameters

The remaining (signal-like) events are used to build the posterior probability density (PPD) of the polarization parameters

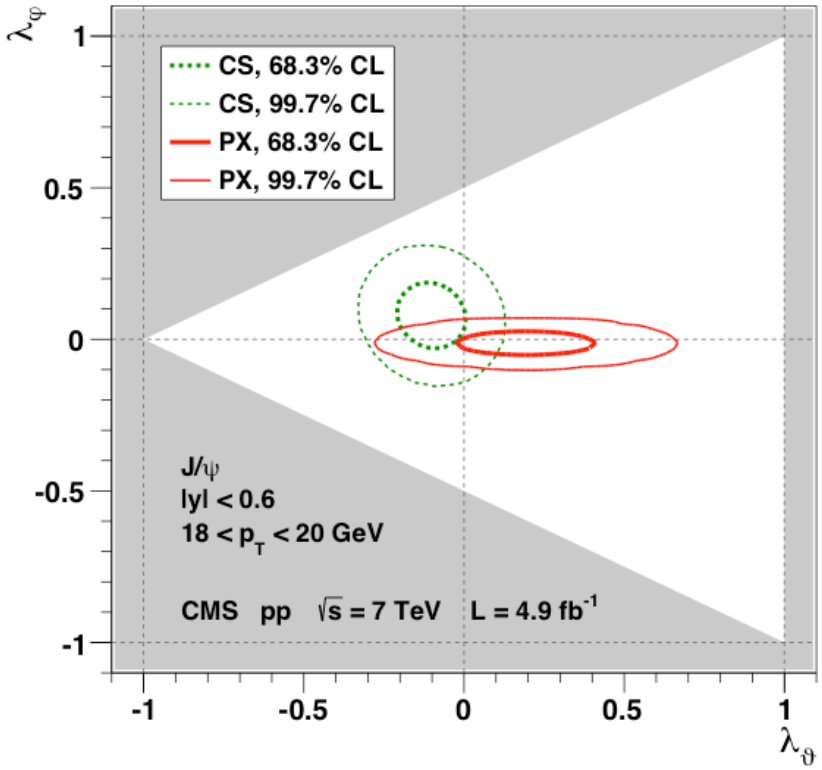
Numerical results and graphical representations are obtained from 1D and 2D projections

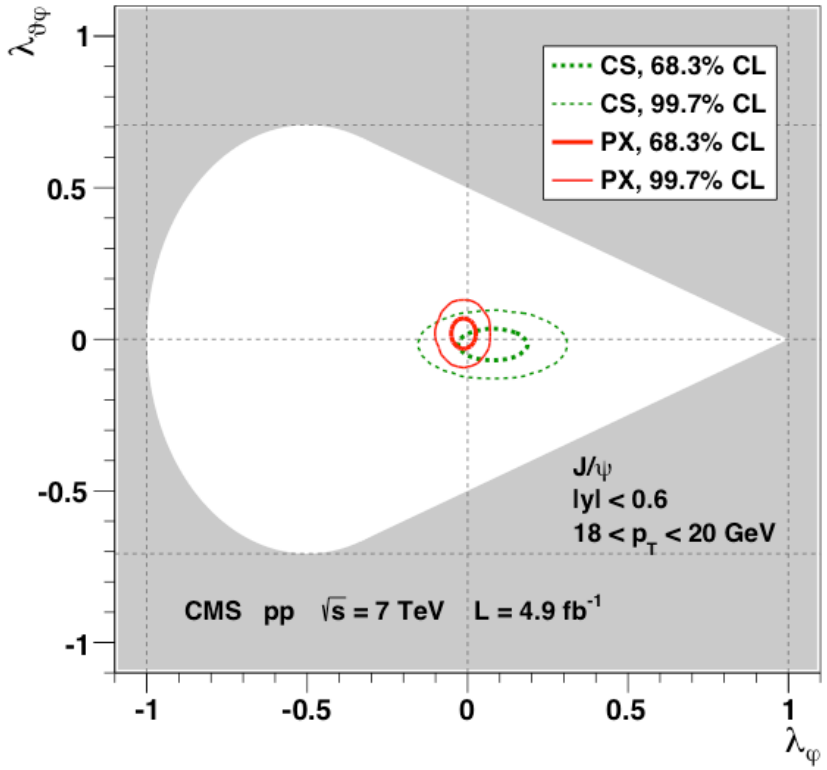
Systematic uncertainties are propagated to the PPD; dominant uncertainties at low p_T:

→ Bg model for the Υ(2S) and Υ(3S)

→ muon and dimuon efficiencies for the J/ψ and ψ(2S)

J/ψ : $|y| < 0.6$
$18 < p_T < 20$ GeV



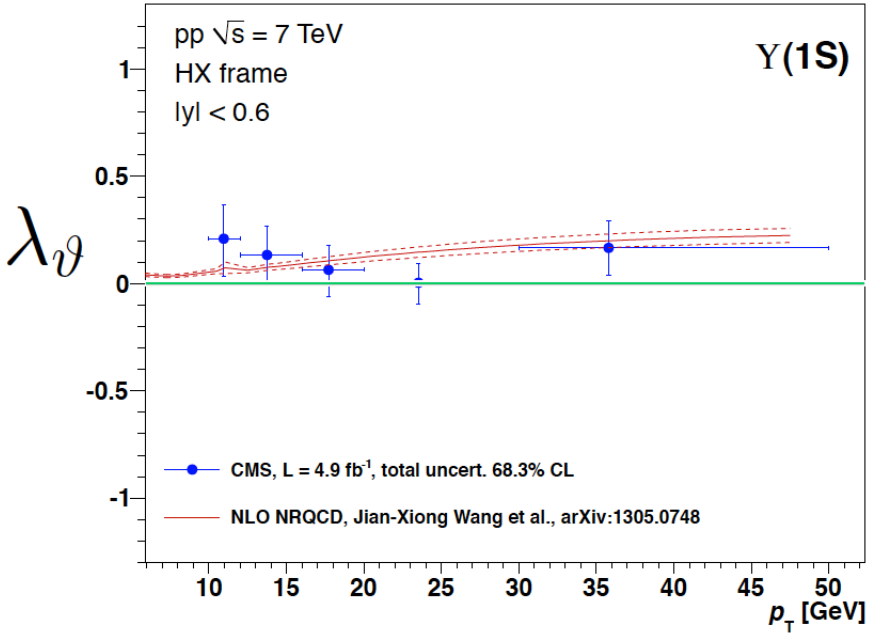


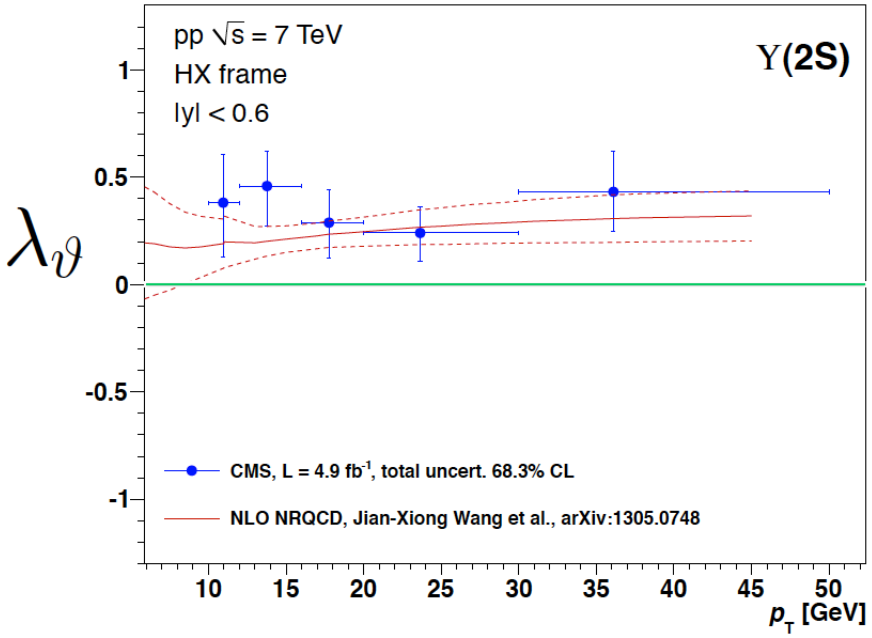
Υ(nS) polarizations: CMS data vs. NLO NRQCD

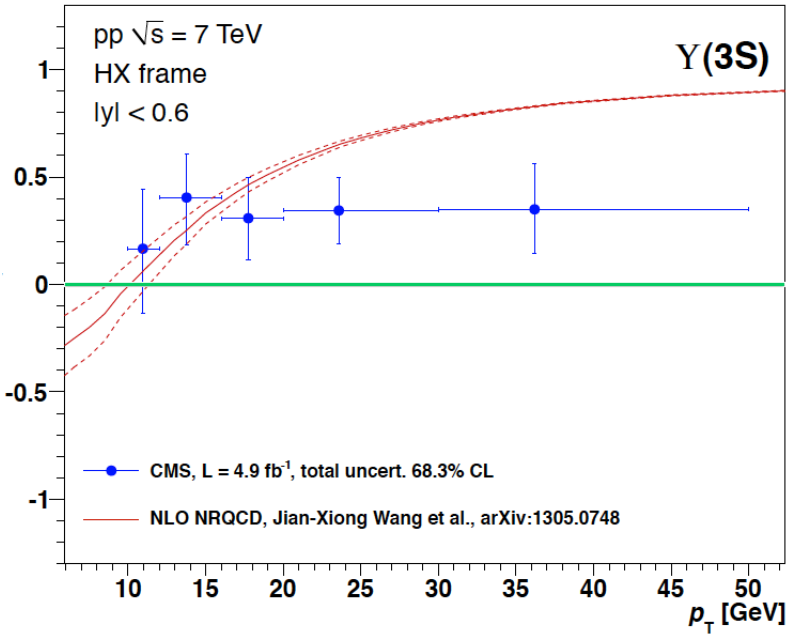
Theory curves are fitted to hadro-production data, including the CMS Υ(nS) polarizations

The (unknown) feed-down from the χ_b states provides freedom to adjust the LDMEs

No such flexibility exists for the 3S, where the fit quality is much worse
(3P not included in the model)







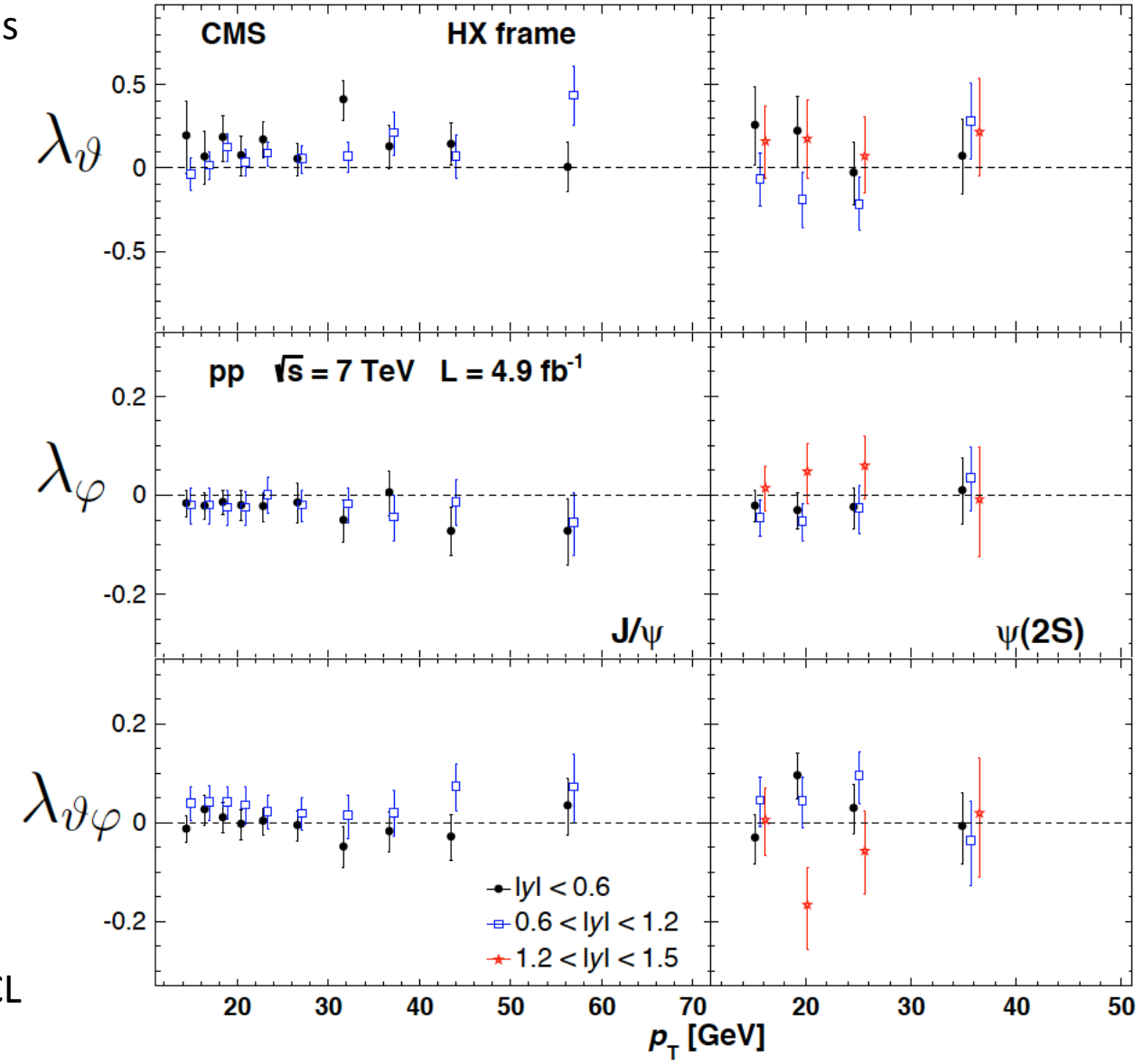
CMS measurements: J/ψ and ψ(2S) polarizations

No sign of strong polarizations even for p_T > 30 GeV

The ψ(2S) is not affected by feed-down decays from P-wave states

→ More direct comparison to the theory calculations

Error bars represent the total uncertainties at 68.3% CL

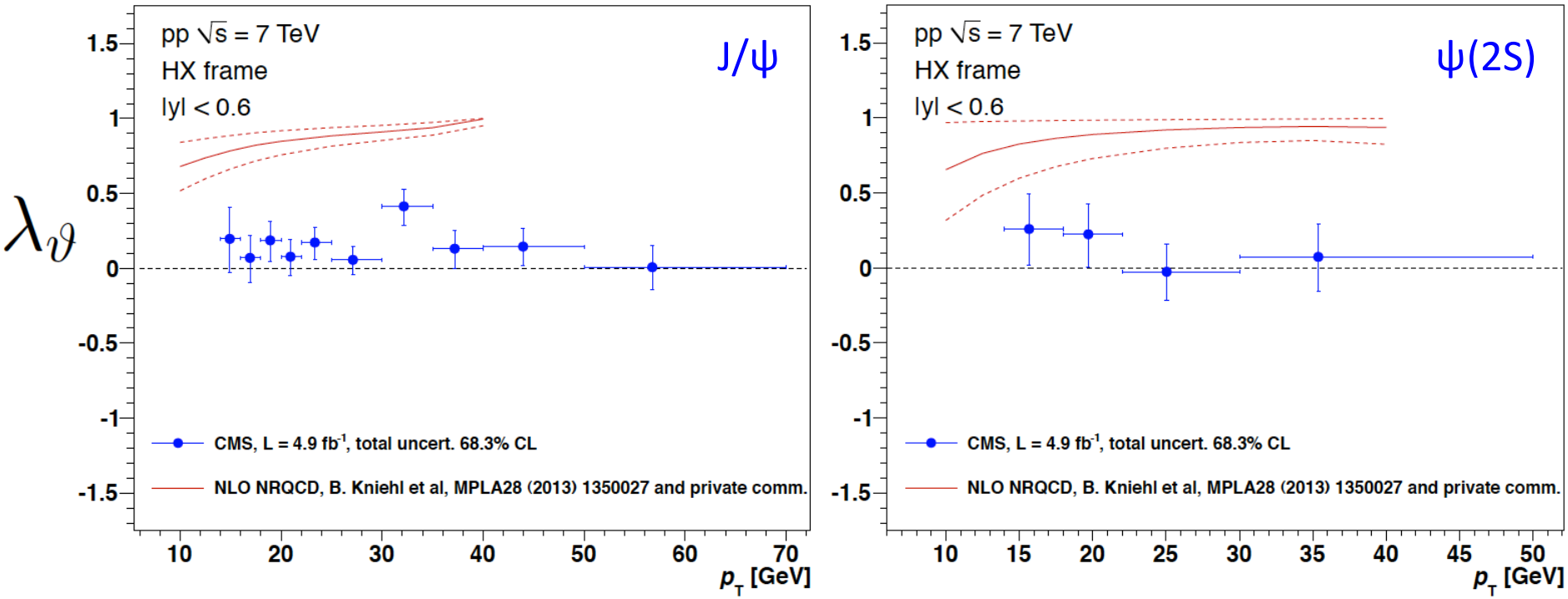


ψ(nS) polarizations: CMS data vs. NLO NRQCD

These theory curves are fitted to hadro-production and photo-production cross sections, excluding polarization measurements

The expected full transverse polarization at high p_T is not observed in the measurements, which extend to very high p_T / M ratios, where the theory should be applicable

Calculations are for the directly produced mesons; in the J/ψ case, this could justify the discrepancy between the theory and the data, depending on the polarization of the P states



LHCb measurements: J/ψ polarization at forward rapidity

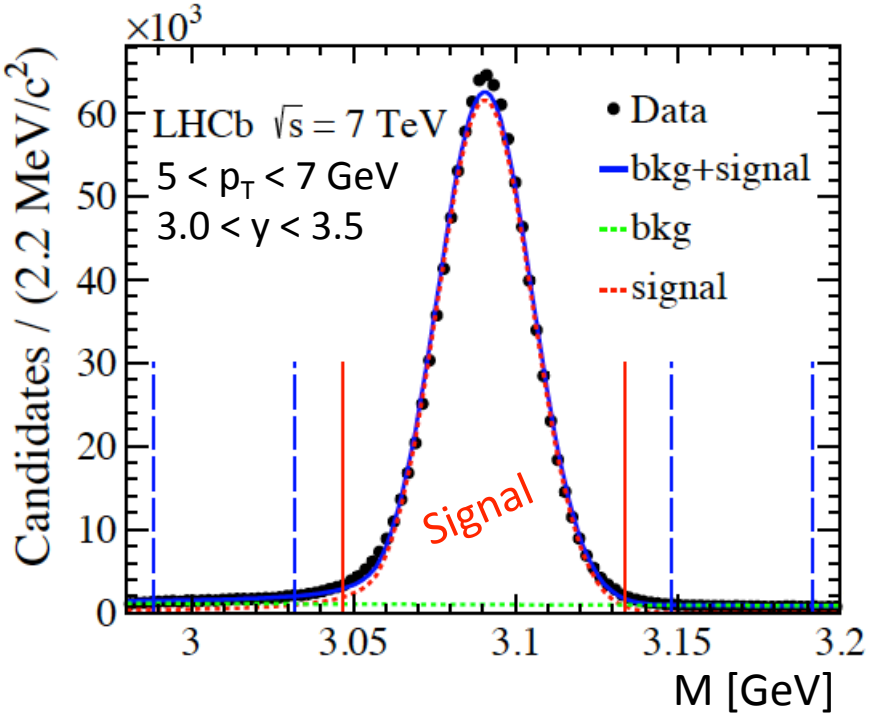
LHCb measured the λ_ϑ, λ_ϕ, $\lambda_{\vartheta\phi}$ and $\tilde{\lambda}$ parameters of the J/ψ mesons promptly produced in pp collisions at 7 TeV, in the HX and CS frames

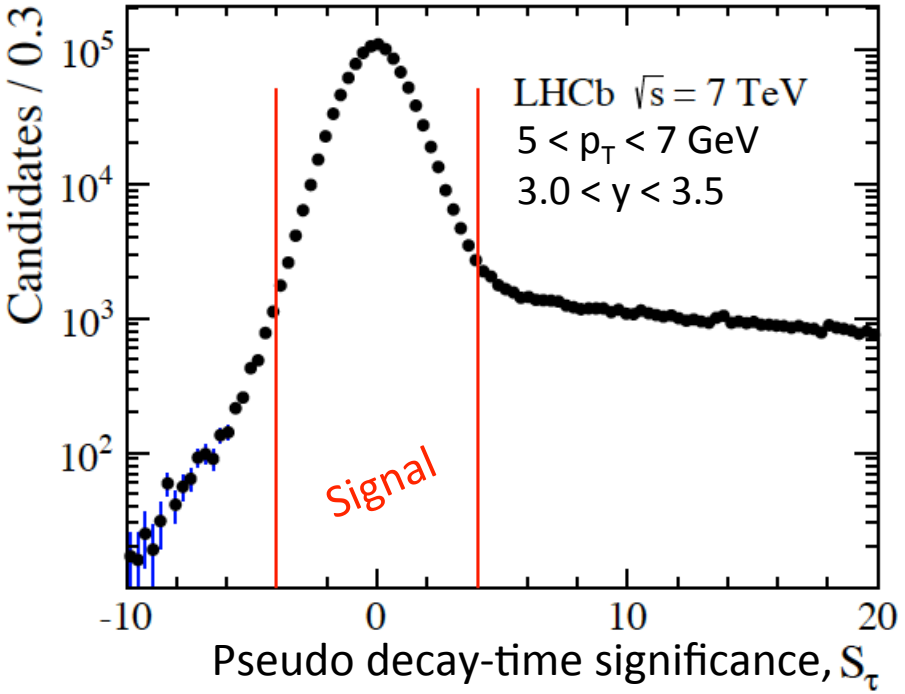
The measurements are made in the kinematic region $2 < p_T < 15$ GeV and $2.0 < y < 4.5$

Data collected in the first half of 2011 (integrated luminosity = 0.37 fb^{-1})

Details on the analysis and results: arXiv:1307.6379 [hep-ex]

With the requirement $|S_\tau| < 4$, only 3% of the kept J/ψ mesons are due to B decays



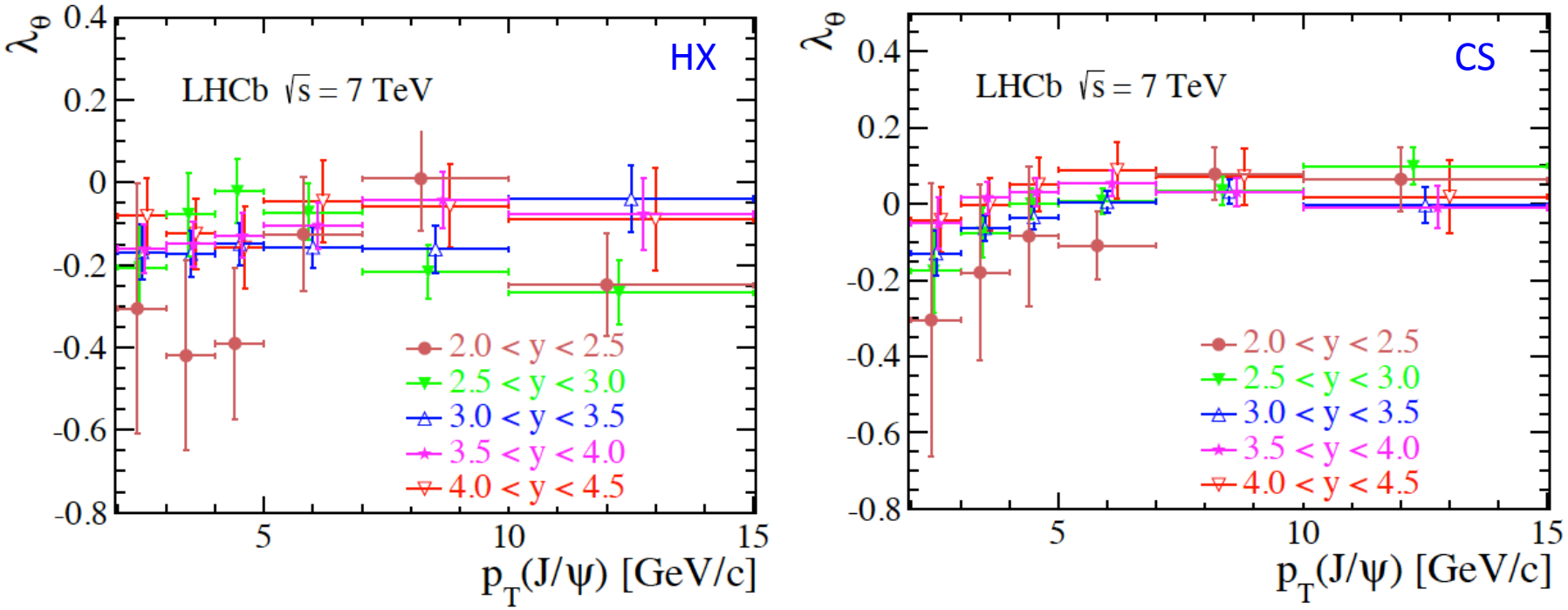


LHCb analysis and results

The background in the signal region is subtracted using the events in the mass sidebands, assuming that the 2D angular distribution of these two event classes are similar and that the mass distribution of the background is approximately linear

The polarization parameters are determined from a maximum likelihood fit to the ($\cos\vartheta$, ϕ) angular distribution of the decay muons, including the detection and trigger efficiencies, which are estimated from MC and corrected with a $B^+ \rightarrow J/\psi\, K^+$ data sample ($\rightarrow$ major source of systematic uncertainty). The signal selection is the result of a per-event probability assignment (sPlot weighting technique).

The λ_ϕ and $\lambda_{\vartheta\phi}$ measured in the HX frame are consistent with zero, within uncertainties



LHCb results on λ_ϑ

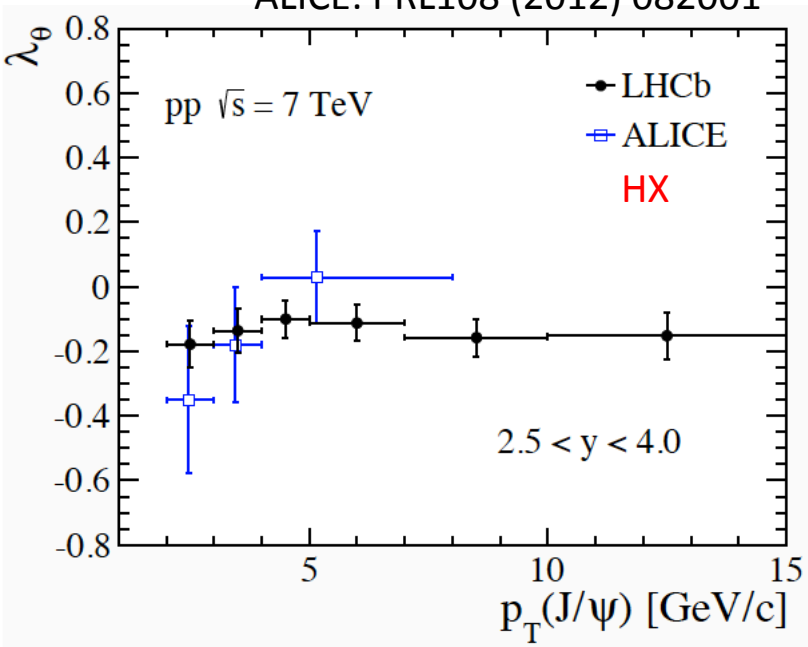
The λ_ϑ measured in the HX frame, integrating over p_T and y, is -0.145±0.027, adding the stat and syst errors in quadrature

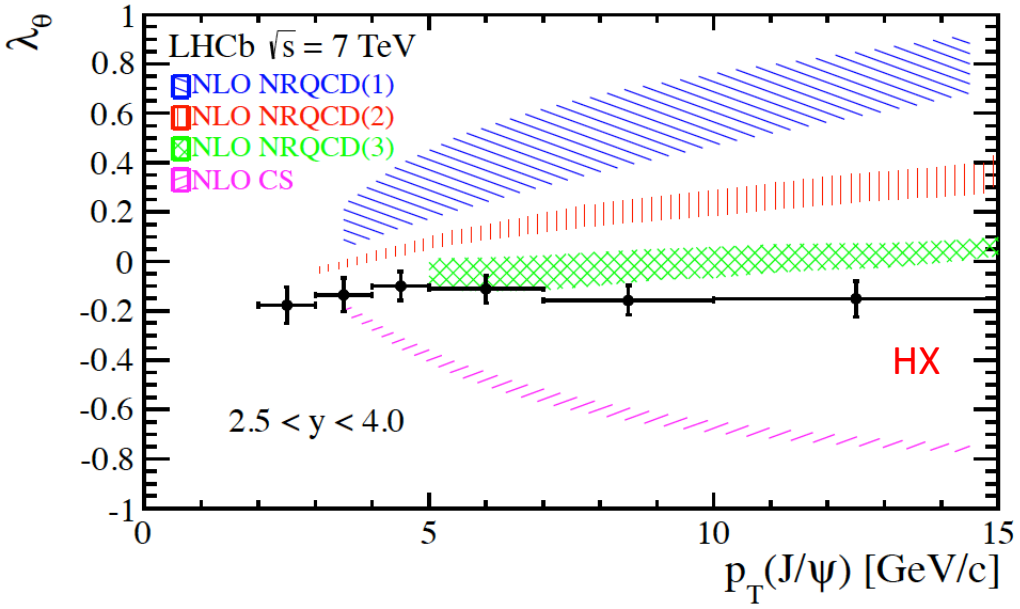
The LHCb and ALICE results agree well, within the large uncertainties of the ALICE data (which contain also the non-prompt component)

The LHCb results show that λ_ϑ is very close to zero, contrary to theory expectations

In conclusion, at forward rapidity and $p_T < 15$ GeV the prompt J/ψ mesons are produced with almost no polarization (as at central rapidity and high p_T)

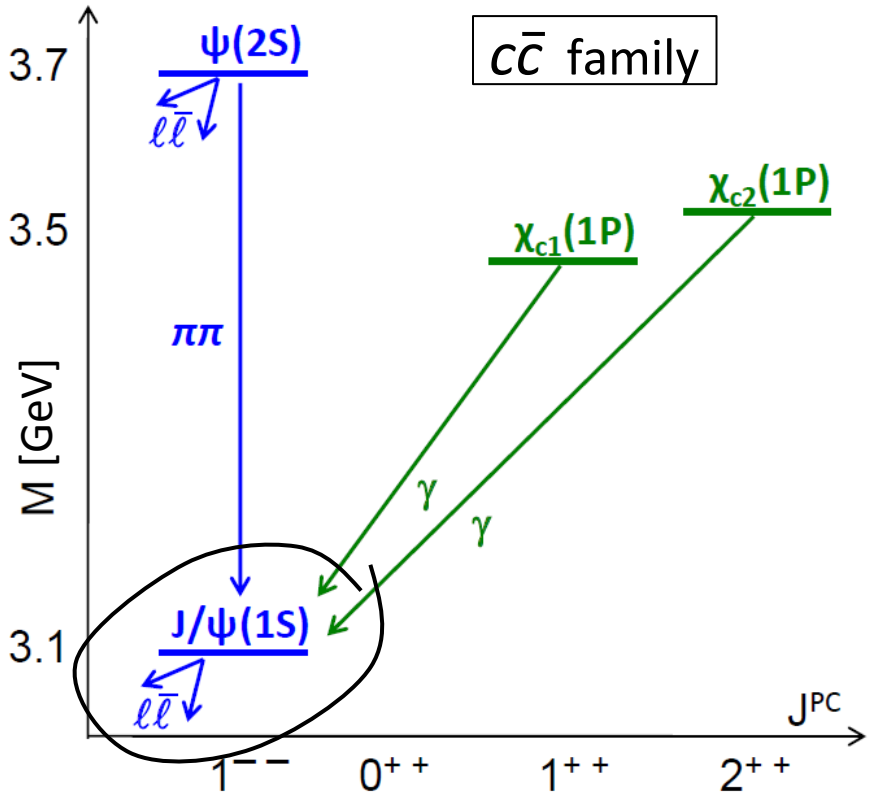
ALICE: PRL108 (2012) 082001

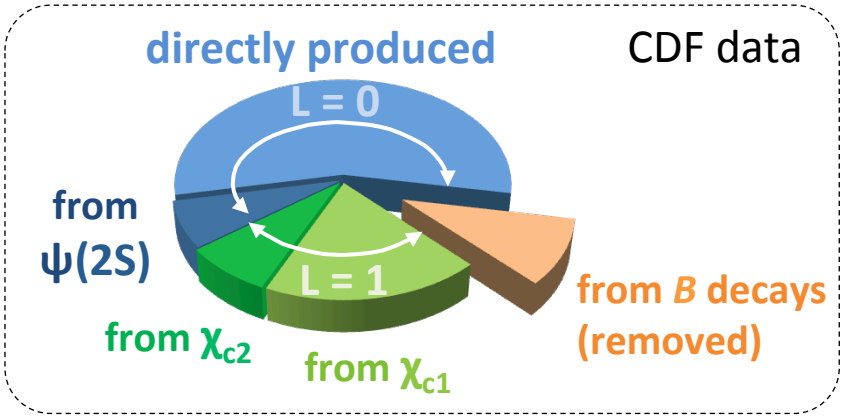




Can the S and P polarizations cancel each other?

The measured **prompt J/ψ** reflects production properties of all charmonia, in a global "average"



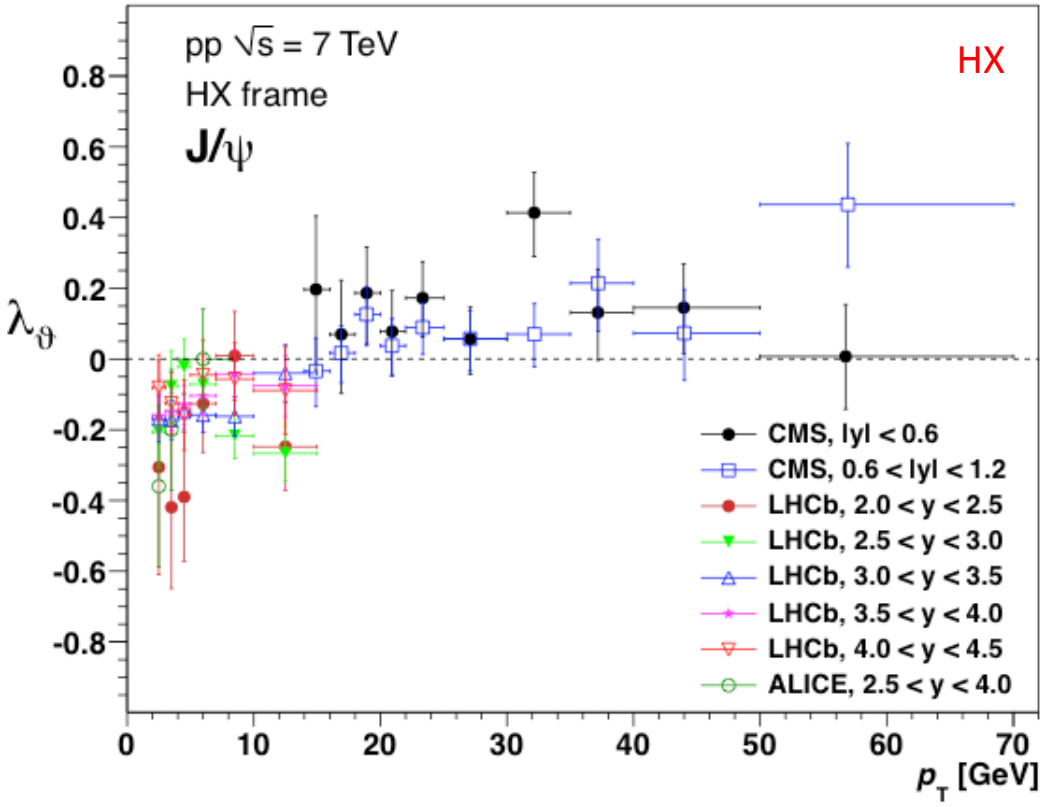


The polarizations of **direct J/ψ** and of **J/ψ from ψ(2S)** might be very different from those of **J/ψ from χ_c decays**

We need to measure the polarizations of the P-wave states, χ_c and χ_b, and their feed-down fractions to the S states

All together now…

It is interesting to compare the CMS, LHCb and ALICE λ_ϑ measurements (HX frame)

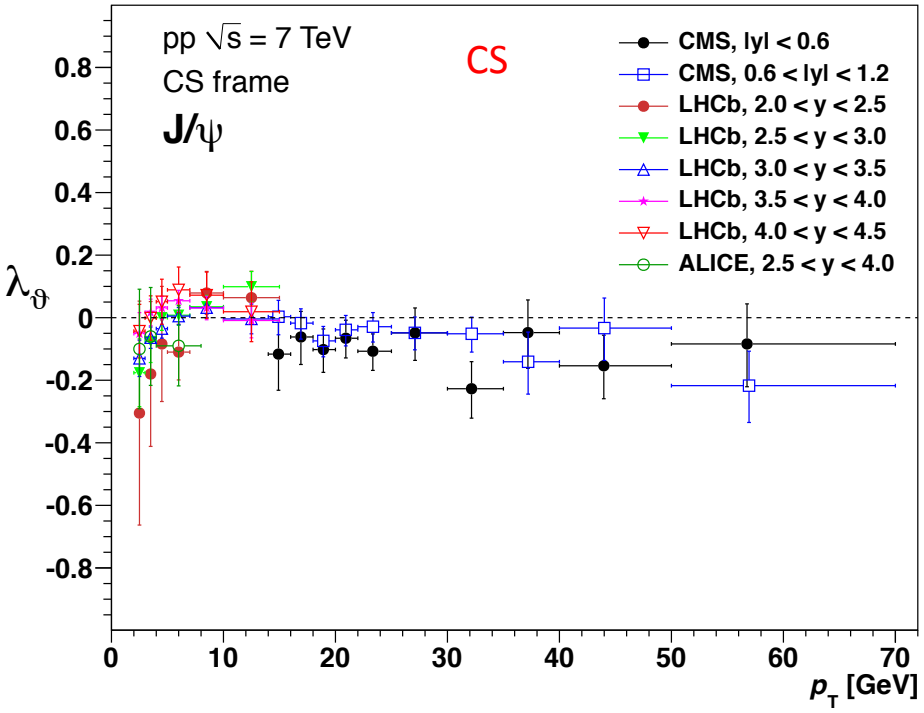


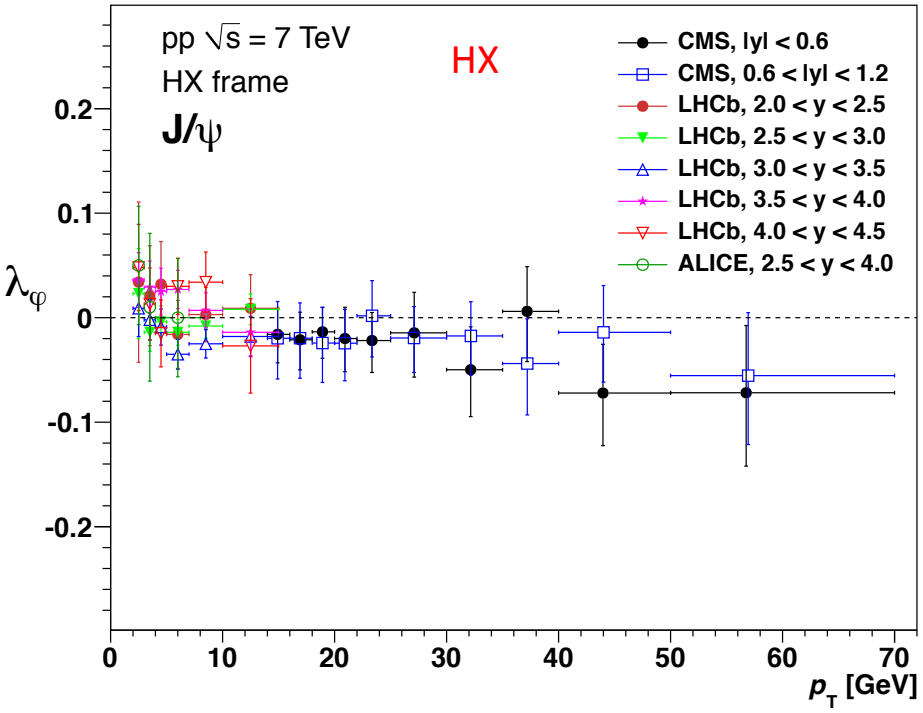
The LHC results seem to be internally consistent (unlike the Tevatron results)

There is no evidence for significant dependencies of the J/ψ polarization on rapidity

All together now…

Two other dimensions in the data comparison: λ_ϑ in the CS frame and λ_ϕ in the HX frame





Very reasonable continuity or overlap among the LHC experiments

Summary and outlook

Quarkonium polarization has been measured by the CMS and LHCb experiments

Measurements extend up to high p_T for all the five S-wave states

No evidence has been seen of the strong transverse polarizations predicted by NRQCD

Further experimental and theoretical efforts needed to understand quarkonium production

Next steps:

1) improve the accuracy of these measurements and extend them to even higher p_T

2) measure the polarizations of the P states

3) derive the polarizations of the *directly* produced S states

The data collected in 2012, at 8 TeV, should already allow us to reach some of these goals

Backup

In the CMS charmonia analysis, the prompt-signal region (PSR) is defined as a 2D window of ±3σ in dimuon mass and (pseudo-proper) lifetime, where σ are the resolutions, for each (p_T, y) cell

In the PSR, there are three kinds of events, dominated by prompt signal events