# Quarkonium polarization in pp collisions with CMS

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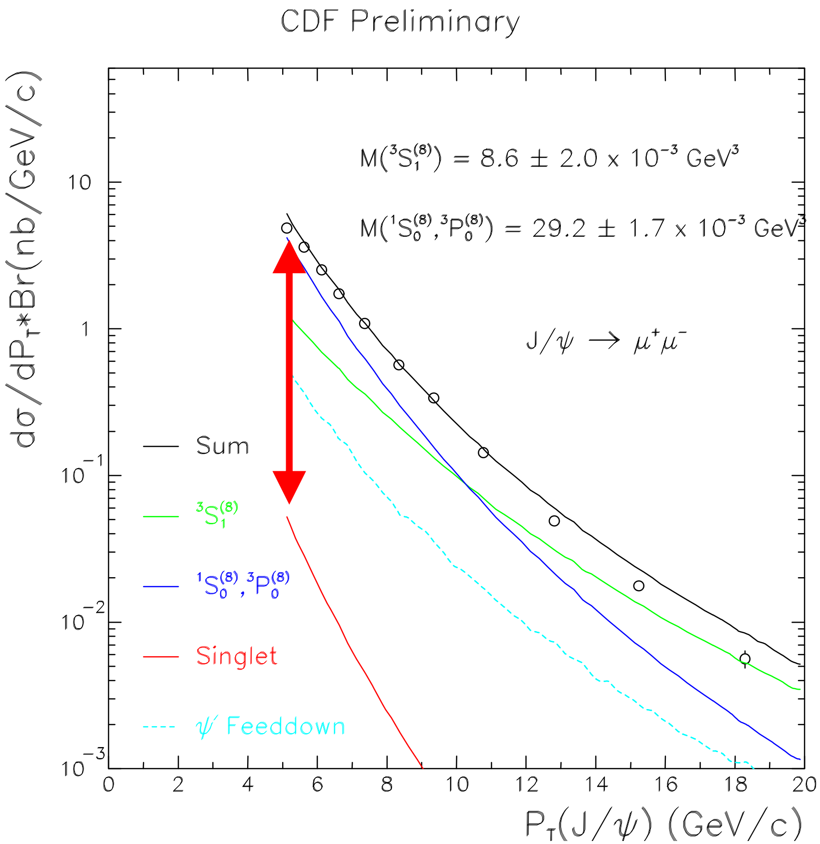
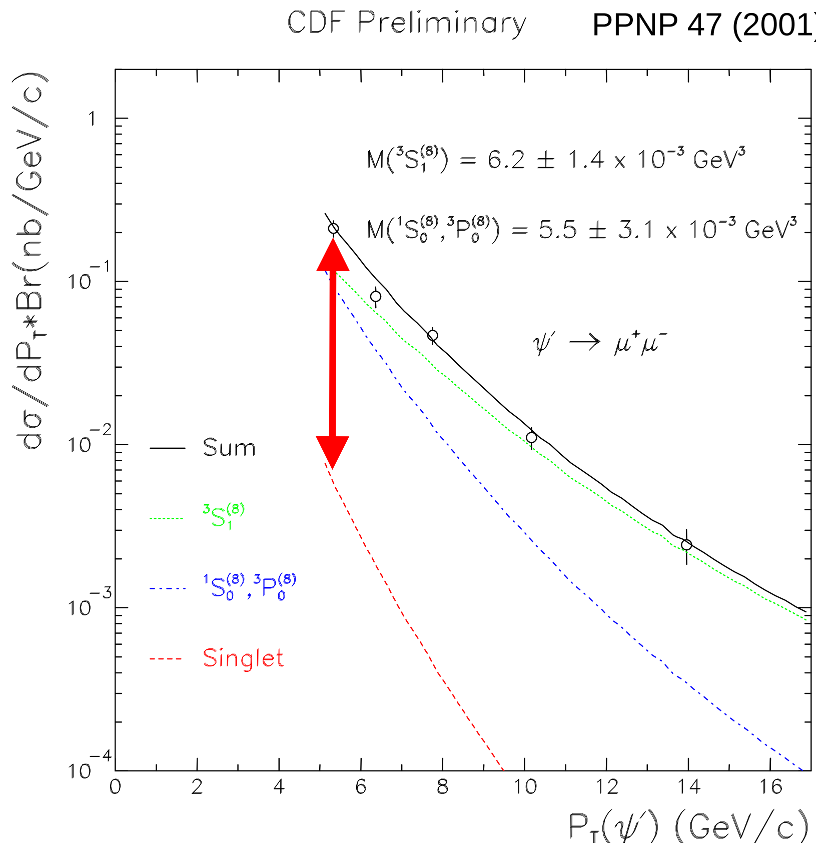
# Summary

- A bound state catastrophe
- Basic assumptions and predictions: factorization and NRQCD
- Quarkonium polarization basics
- CMS results on quarkonium polarization: kinematical dependence
- CMS results on quarkonium polarization: multiplicity dependence
- Conclusions

# A bound state catastrophe




PPNP 47 (2001)141

$J/\psi$'s not from $\chi$'s or B's

$\psi(2S)$'s not from B's

The measurement disagrees with the theory by a factor ~50

# Basic assumptions and predictions: factorization and NRQCD

One assumes that the production of **quark-antiquark states** can be described using **perturbative QCD**, as long as we "**factor out**" long-distance bound-state effects: there are **color singlet** and **color octet contributions**

Therefore in NRQCD the factorization hypothesis implies that the cross-section for the inclusive production of a meson H in a A+B collision is

$$\sigma(A+B\rightarrow H+X)=\sum_{S,L,C}\mathcal{S}(A+B\rightarrow Q\bar{Q}\left[{}^{2S+1}L_J^C\right]+X)\times\mathcal{L}(\,Q\bar{Q}\left[{}^{2S+1}L_J^C\right]\rightarrow H)$$

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SDC ← **Perturbative QCD**

LDME ← **Data + NRQCD scaling rules**

# Basic assumptions and predictions: factorization and NRQCD

The LDME's are supposed to be universal and proportional to the square of relative quark velocity $v^2$ (which is ~small)

This allows for an expansion in powers of velocity for the different angular momentum contributing states. Cut the expansion at $\mathcal{O}(v^4)$

S-wave quarkonia: $J^{PC}=1^{--}$

| $^{2S+1}L_J$ | $^1S_0$ | $^3S_1$ | $^1P_1$ | $^3P_J$ | $^3D_J$ | $^1D_2$ | … |
|---|---|---|---|---|---|---|---|
| Color singlet | | 1 | | | | | |
| Color octet | $v^4$ | $v^4$ | $v^8$ | $v^4$ | $v^8$ | $v^{12}$ | … |

P-wave quarkonia: $J^{PC}=J^{++}$

| $^{2S+1}L_J$ | $^1S_0$ | $^3S_1$ | $^1P_1$ | $^3P_J$ | $^3D_J$ | $^1D_2$ | … |
|---|---|---|---|---|---|---|---|
| Color singlet | | | | $v^2$ | | | |
| Color octet | $v^6$ | $v^2$ | $v^6$ | $v^6$ | $v^6$ | $v^{10}$ | … |

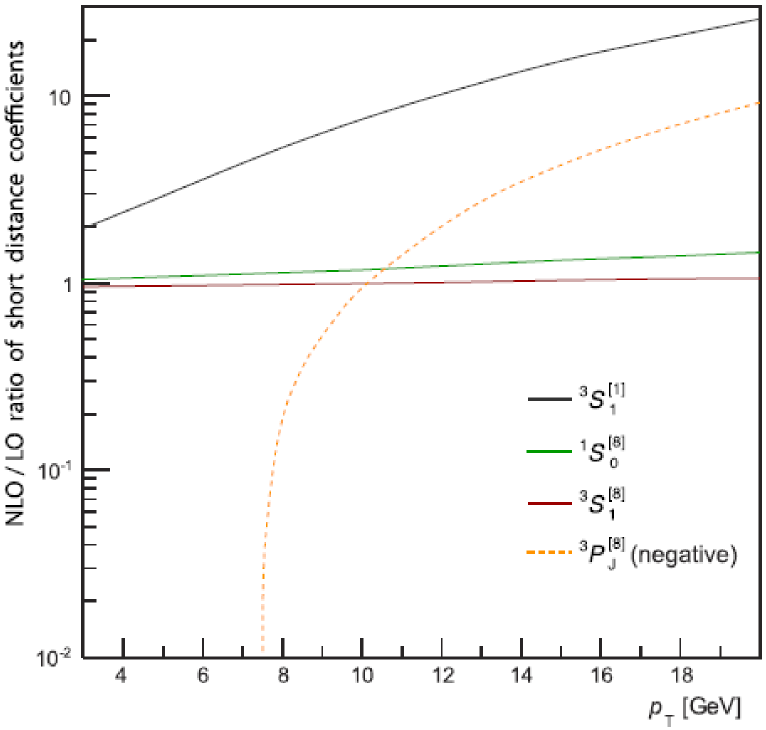
# Basic assumptions and predictions: factorization and NRQCD

Quantum Mechanics provides the angular distribution for the decay of these states into dileptons once a quantization axis is chosen:

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

**Notice:** the coefficient $\lambda_\theta = \frac{\mathcal{S}_T + \mathcal{S}_L}{\mathcal{S}_T - \mathcal{S}_L}$

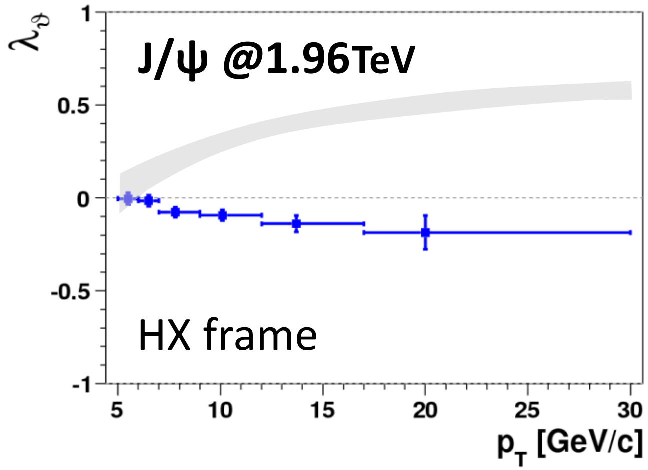
See P. Faccioli's talk



# Basic assumptions and predictions: factorization and NRQCD

A seemingly inescapable prediction of NRQCD approach is that "high" $p_T$ quarkonia come from fragmenting gluons and are fully tranversely polarized

The first polarization data were not encouraging...



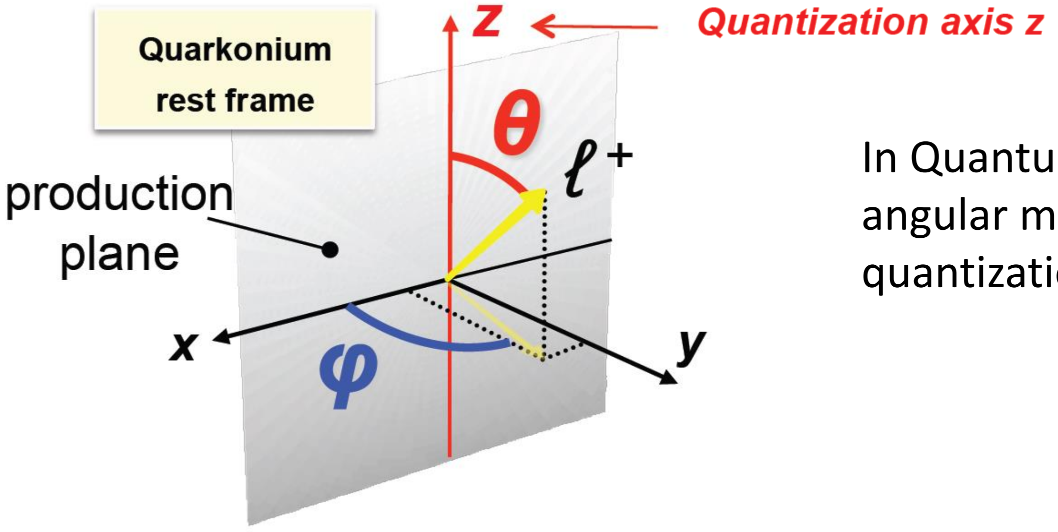

**NRQCD factorization**
Braaten, Kniehl & Lee, PRD62, 094005 (2000)

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

But:

- The experimental situation was contradictory and incomplete, as it was emphasized in Eur. Phys. J. C69, 657 (2010)
  → improve drastically the quality of the experimental information
- maybe the theory is only valid at asymptotically high $p_T$
  → extend measurements to $p_T >> M$
- contributions of intermediate *P*-wave states have not been fully calculated yet and are still unknown experimentally
  → measure polarizations of *directly* produced states, $\psi'$ and $\Upsilon$(3S)
  → measure polarizations of *P*-wave states, $\chi_c$ and $\chi_b$, and their feeddown to *S* states

# Quarkonium polarization basics

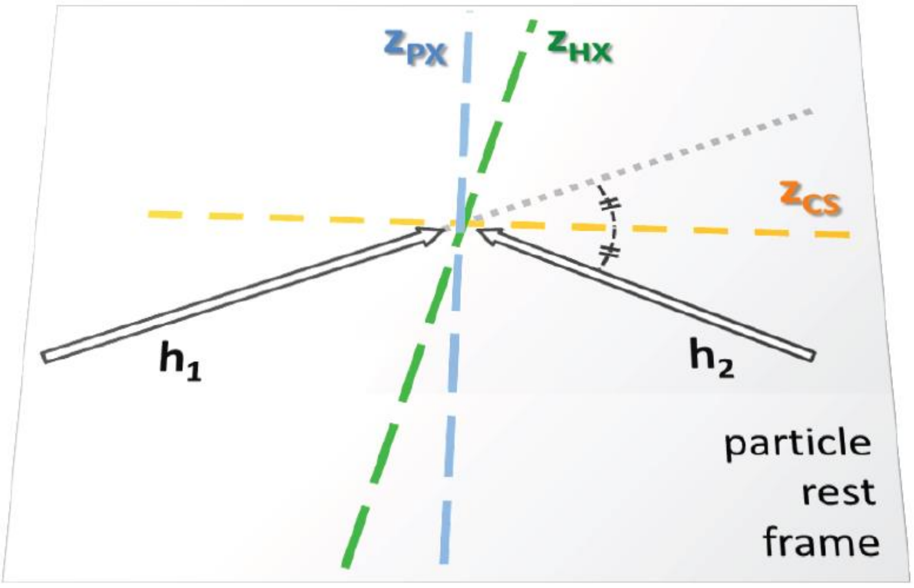



In Quantum Mechanics the study of angular momentum requires a quantization axis (aka *"z-axis"*)

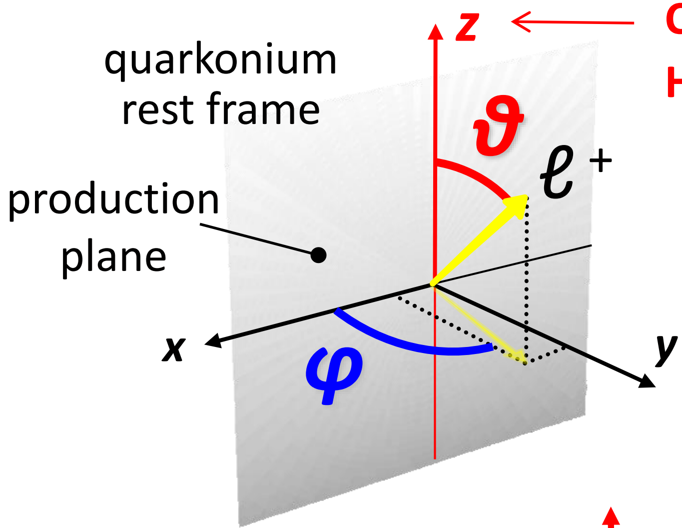
Many possible (known) choices:

- Gottfried-Jackson (GJ)
- Collins-Soper (CS)
- Helicity (HX)
- Perpendicular Helicity (PX)

All frames related by a rotation around the y axis



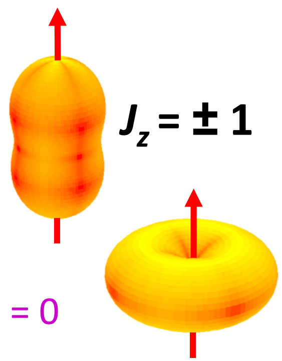
# Quarkonium polarization basics




**Collins-Soper axis (CS):** ≈ dir. of colliding partons

**Helicity axis (HX):** dir. of quarkonium momentum

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



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

$J_z = \pm 1$ → $\lambda_\vartheta = +1$ : **"transverse"** (= photon-like) pol.

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

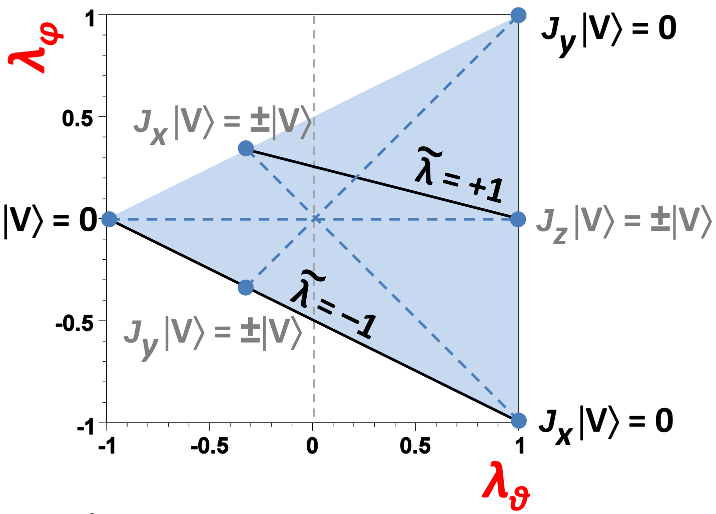
$J_z = 0$ → $\lambda_\vartheta = -1$ : **"longitudinal"** pol.

The ***shape*** of the distribution is obviously frame-invariant.
→ it can be characterized by a frame-independent parameter, e.g.

$$\tilde{\lambda} = \frac{\lambda_\vartheta + 3\lambda_\varphi}{1 - \lambda_\varphi}$$

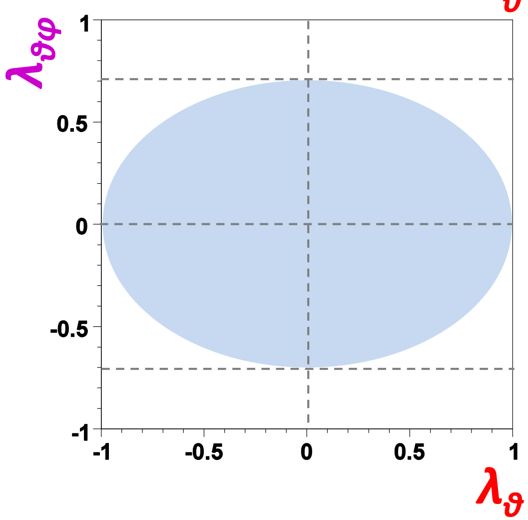
# Quarkonium polarization basics

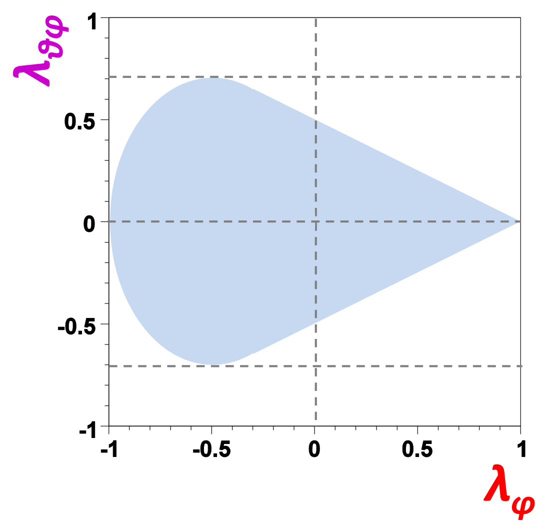
- General and frame-independent constraints on the anisotropy parameters of vector particle decays




$$|\lambda_\varphi| \leq \frac{1}{2}(1+\lambda_\vartheta)\,, \quad \lambda_\vartheta^2 + 2\lambda_{\vartheta\varphi}^2 \leq 1\,,$$
$$|\lambda_{\vartheta\varphi}| \leq \frac{1}{2}(1-\lambda_\varphi)\,,$$
$$(1+2\lambda_\varphi)^2 + 2\lambda_{\vartheta\varphi}^2 \leq 1 \quad \text{for} \quad \lambda_\varphi < -1/3$$

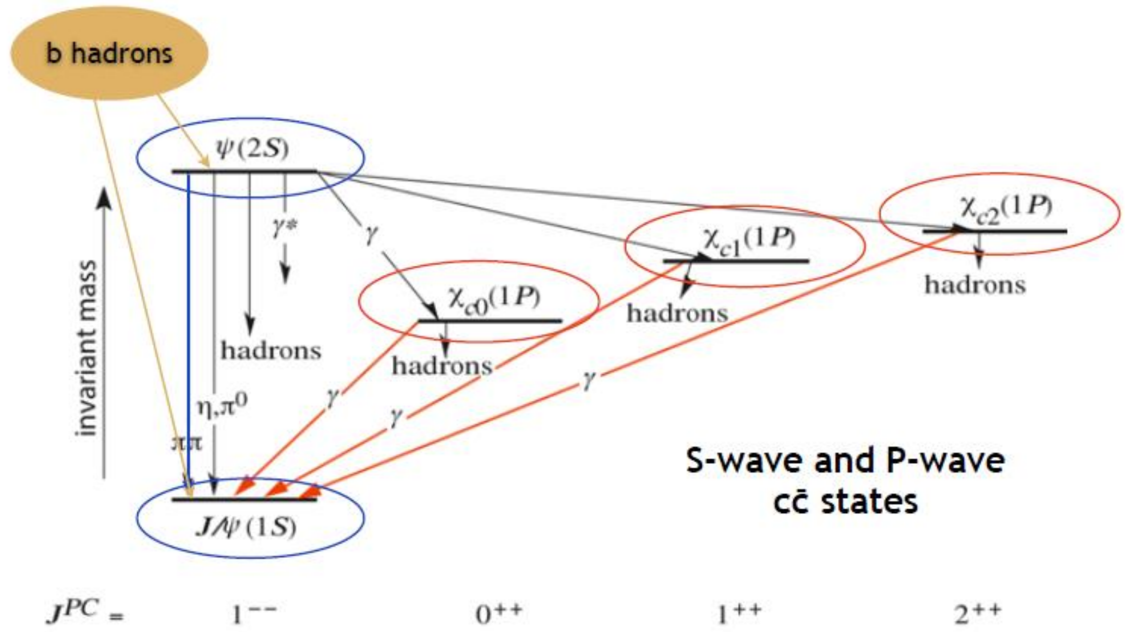
P. F., C.L., J.S., Phys. Rev. D 83, 056008 (2011)



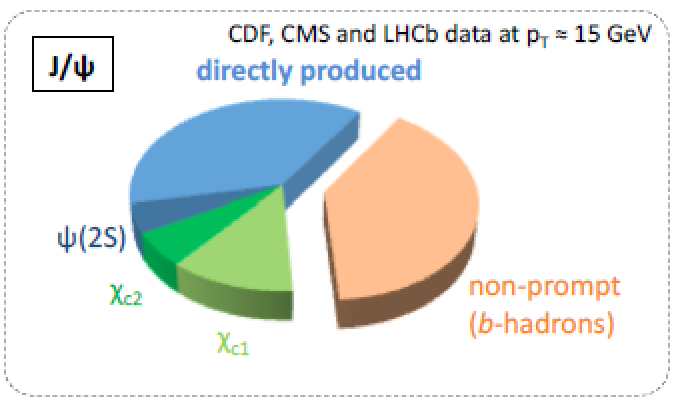

physical domain

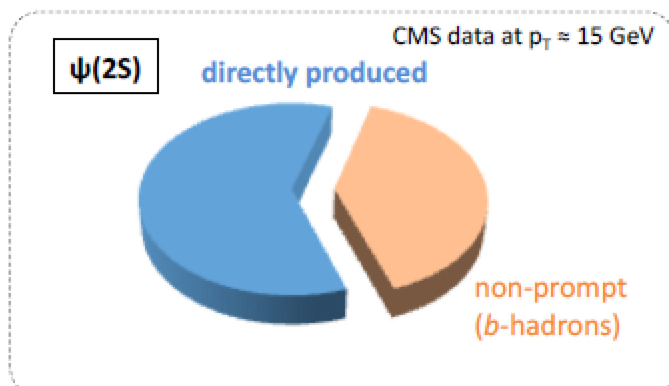
# Quarkonium polarization basics



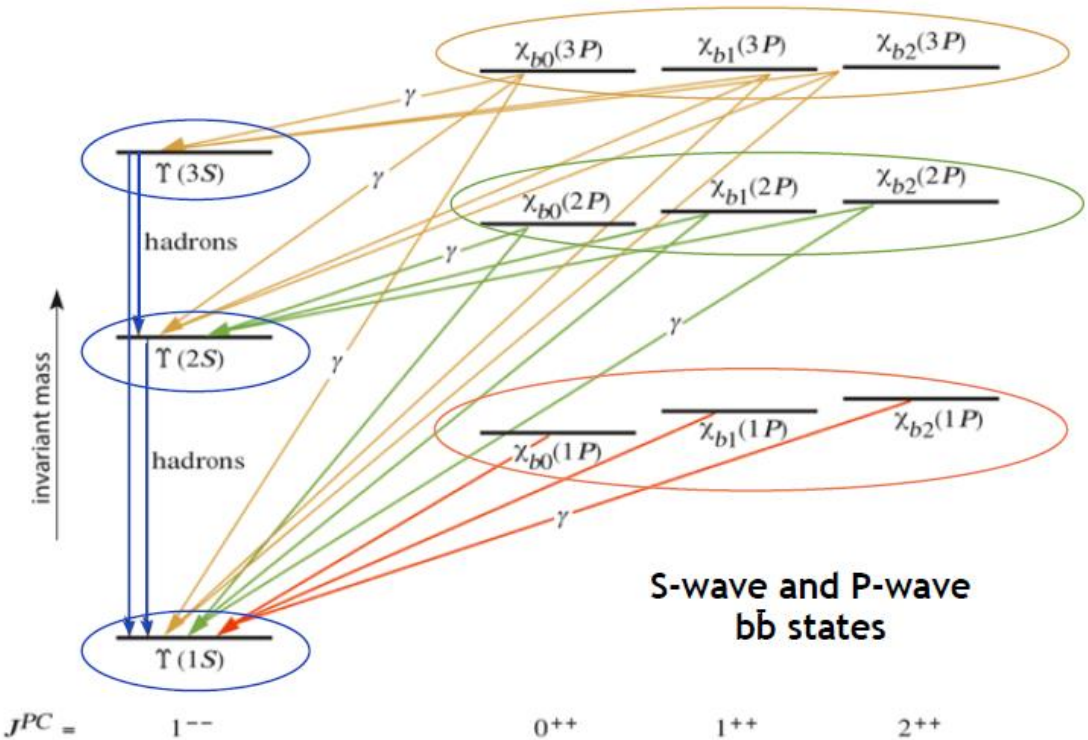

## Charmonium family

- Non-prompt feed-down contribution from B hadrons separated experimentally
- Prompt J/$\psi$ contains directly produced + feed-down from $\chi_c$ and $\psi$(2S)
- No feed-down contribution to $\psi$(2S)



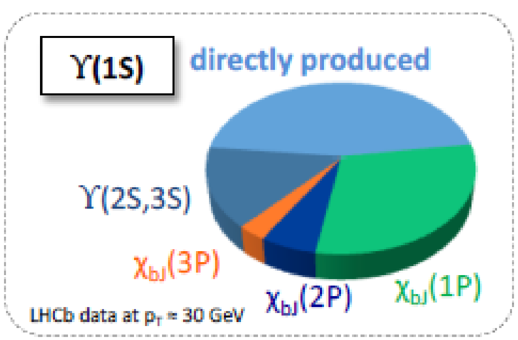



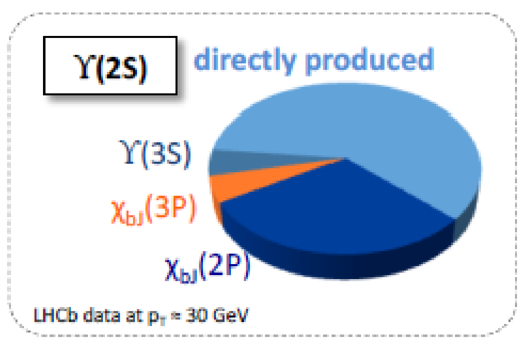
# Quarkonium polarization basics

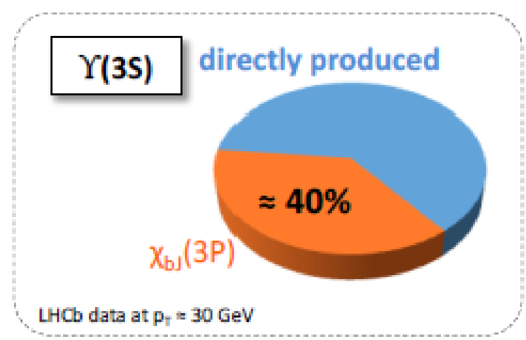



## Bottomonium family

- Feed-down affects all S-wave states
- No non-prompt decays

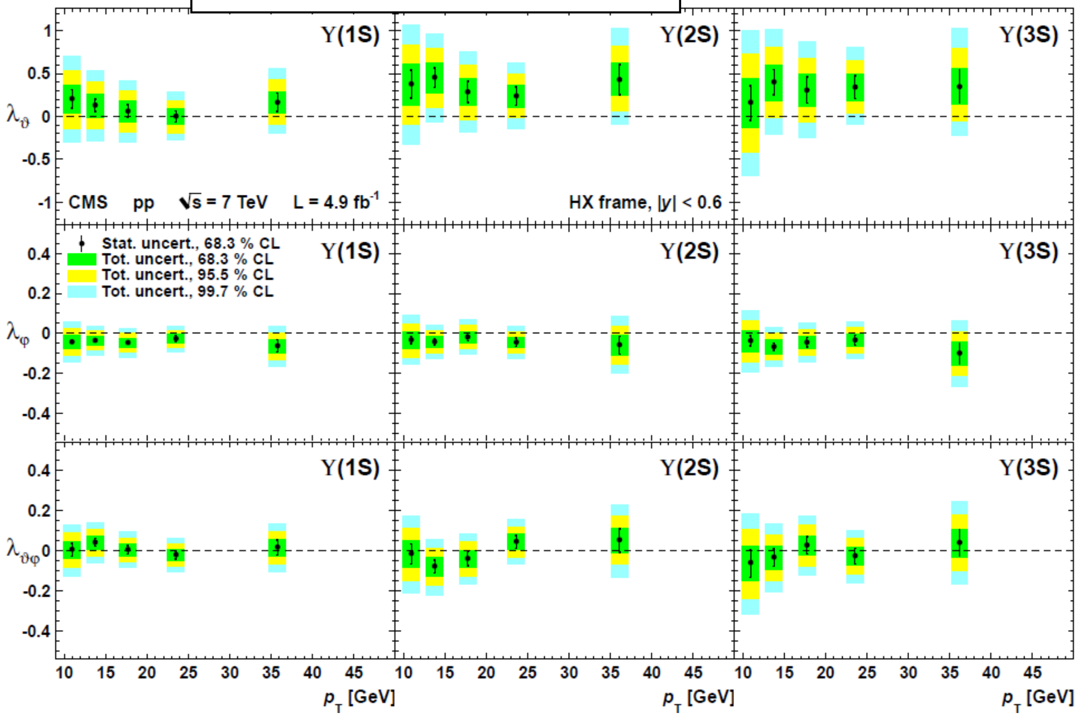


# CMS results on quarkonium polarization: kinematical dependence

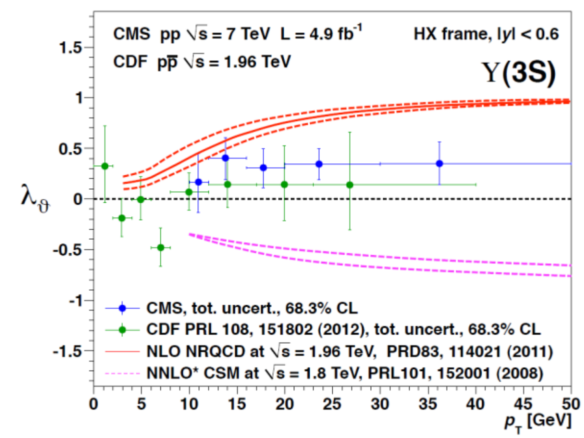
**ϒ(nS), pp √s = 7 TeV**




Phys.Rev.Lett. 110 (2013) 081802

- $\lambda_\theta$, $\lambda_\phi$ and $\lambda_{\theta\phi}$ measured
- Three frames used (**HX, CS, PX**)
- $\tilde{\lambda}$ checked
- Fully multidimensional

|y| < 0.6
0.6<|y| < 1.2
10 < $p_T$ < 40 GeV/c




Comparison with CDF results

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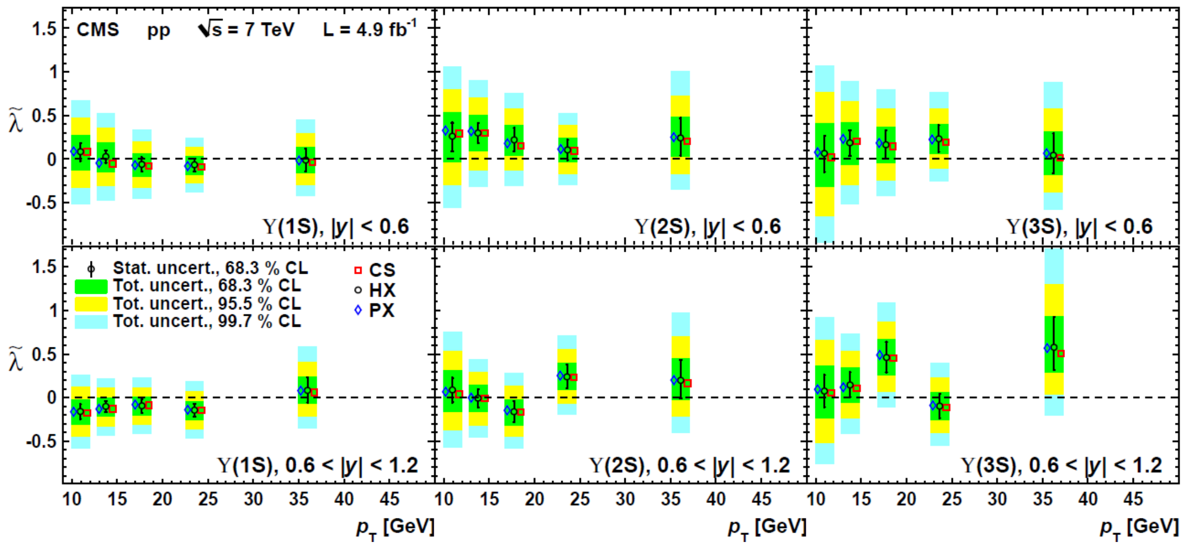


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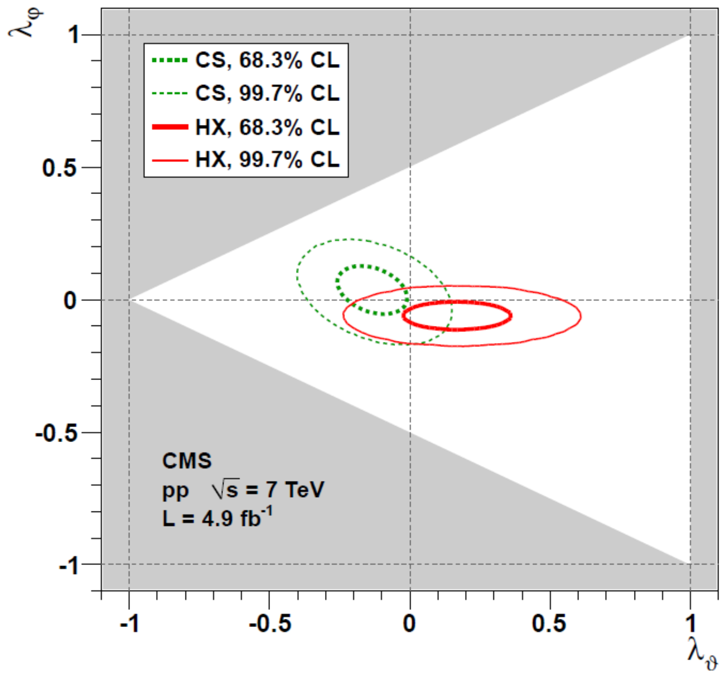
# CMS results on quarkonium polarization: kinematical dependence

**$\Upsilon(nS)$, pp $\sqrt{s}$ = 7 TeV**

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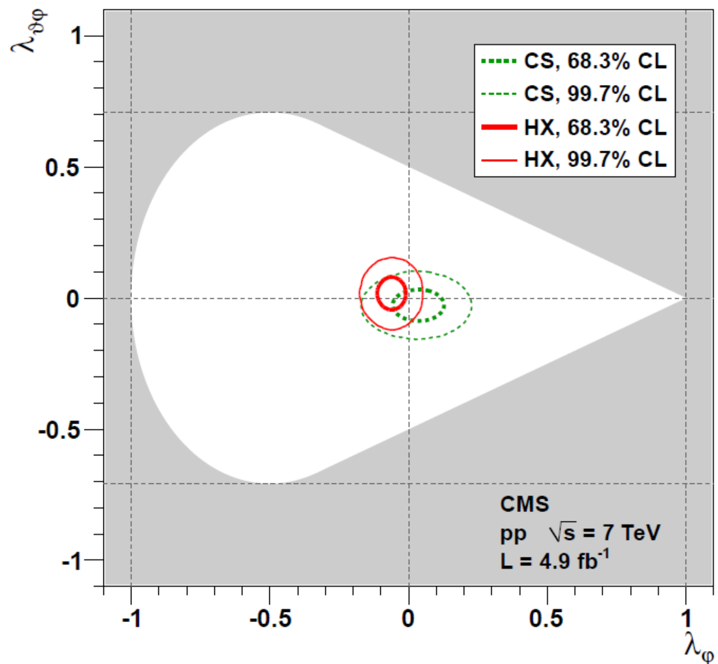


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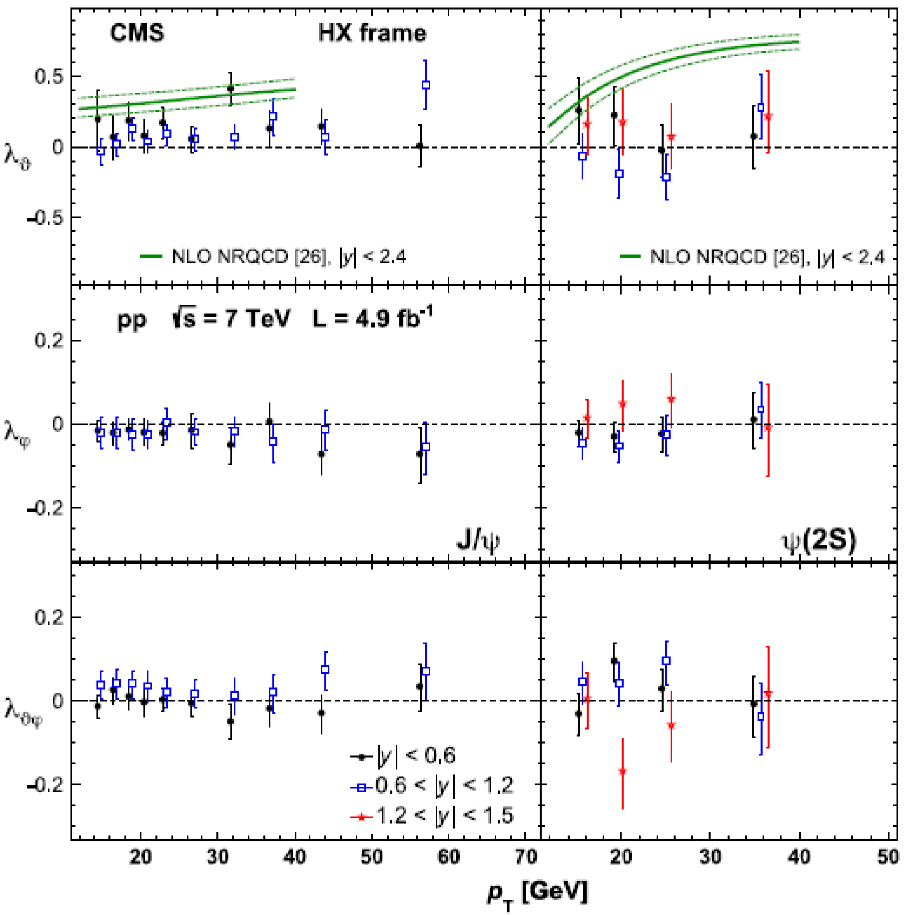
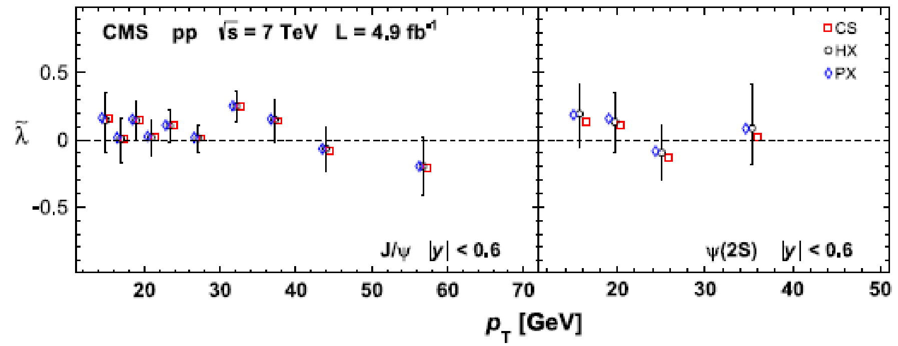
**$\psi$(nS), pp √s = 7 TeV**




|y| < 0.6

0.6<|y| < 1.2

1.2<|y| < 1.5 ($\psi$(2S))

14 <$p_T$< 70 GeV/c ($\psi$(1S))

14 <$p_T$< 50 GeV/c ($\psi$(2S))

PLB 727(2013) 381

NLO NRQCD.Gong,L.-P.Wan,J.-X.Wang,H.-F.Zhang, Phys.Rev.Lett.110 (2013) 042002

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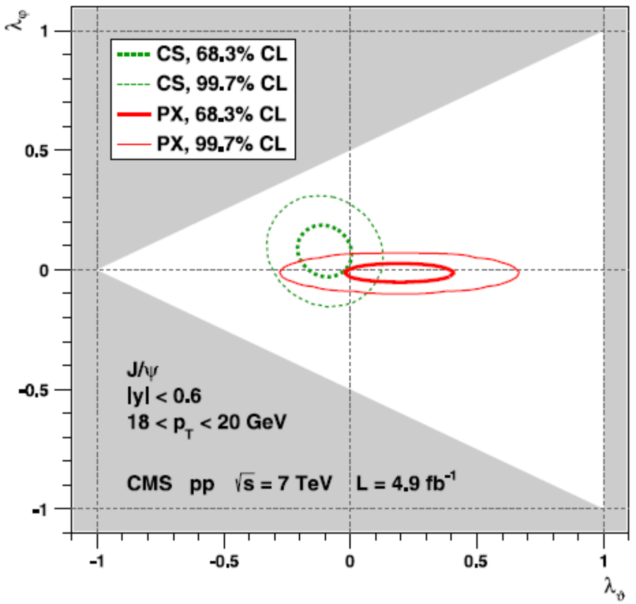
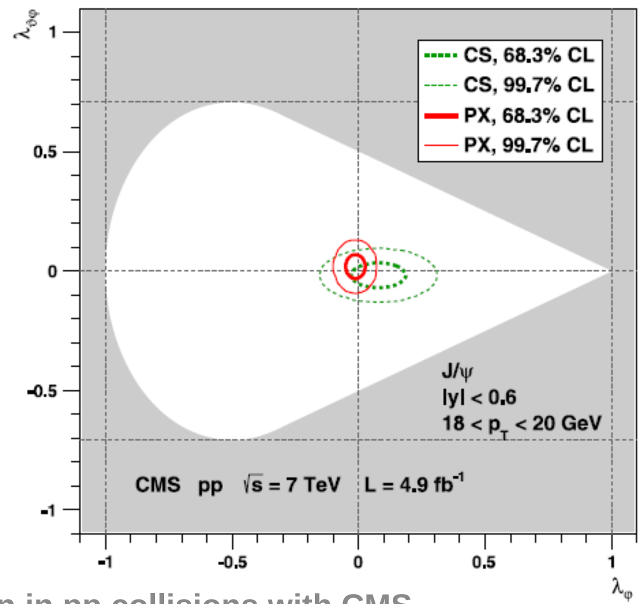
$\psi$(nS), pp √s = 7 TeV

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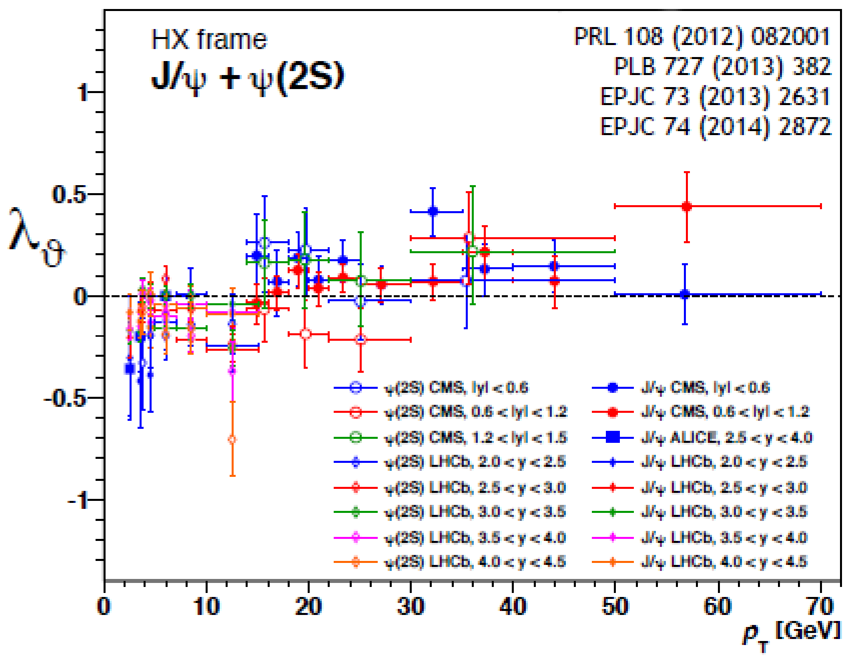
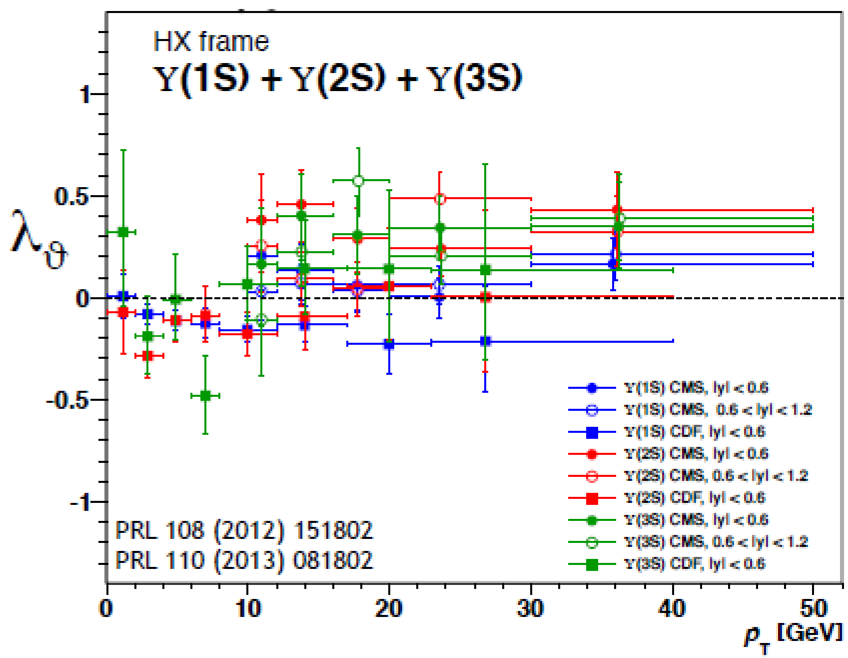
# CMS results on quarkonium polarization: kinematical dependence

- Good consistency between results from CMS, LHCb, ALICE and CDF
- No evidence for deviations from the unpolarized case



# CMS results on quarkonium polarization: multiplicity dependence

- Quarkonia are fundamental probes for the hot and dense matter produced in high energy heavy ion collisions.
- How sensitive is the produced $q\bar{q}$ pair to the surrounding medium? How are the LDME's affected by the complexity of the strongly interacting environment in which the $q\bar{q}$ pair is created?
- Polarization measurements, due to its sensitivity to the topology of the intervening processes, can provide evidence for changes in the bound state production mechanism associated to a change in nature of the surrounding medium.
- This program can be achieved by studying the polarization as a function of multiplicity in pp, pA and AA collisions
- As usual a base line is necessary  and thus a study in pp collisions is mandatory.

# CMS results on quarkonium polarization: multiplicity dependence

- Analysis performed in
  - 5 multiplicity bins: 0-10, 10-20, 20-30, 30-40, 40-60
  - 2 $p_T$ ranges: 10-15 and 15-35 GeV
  - Integrated in rapidity |y|<1.2

**ϒ(nS), pp √s = 7 TeV**

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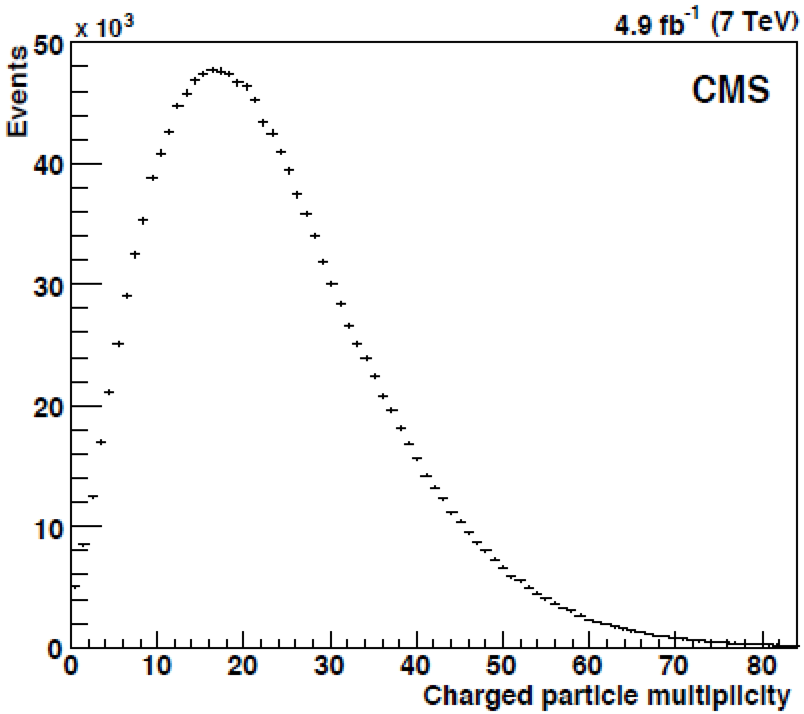


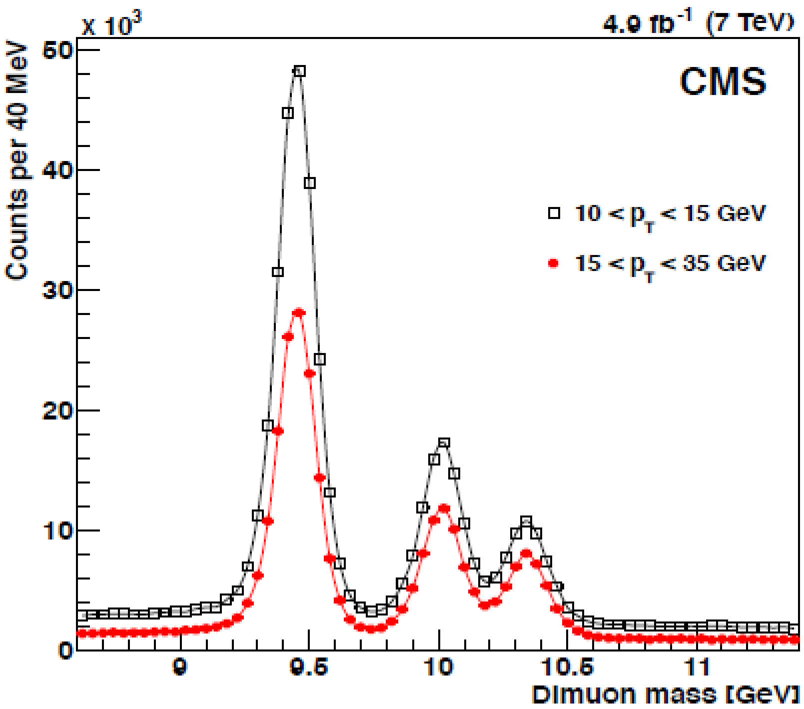

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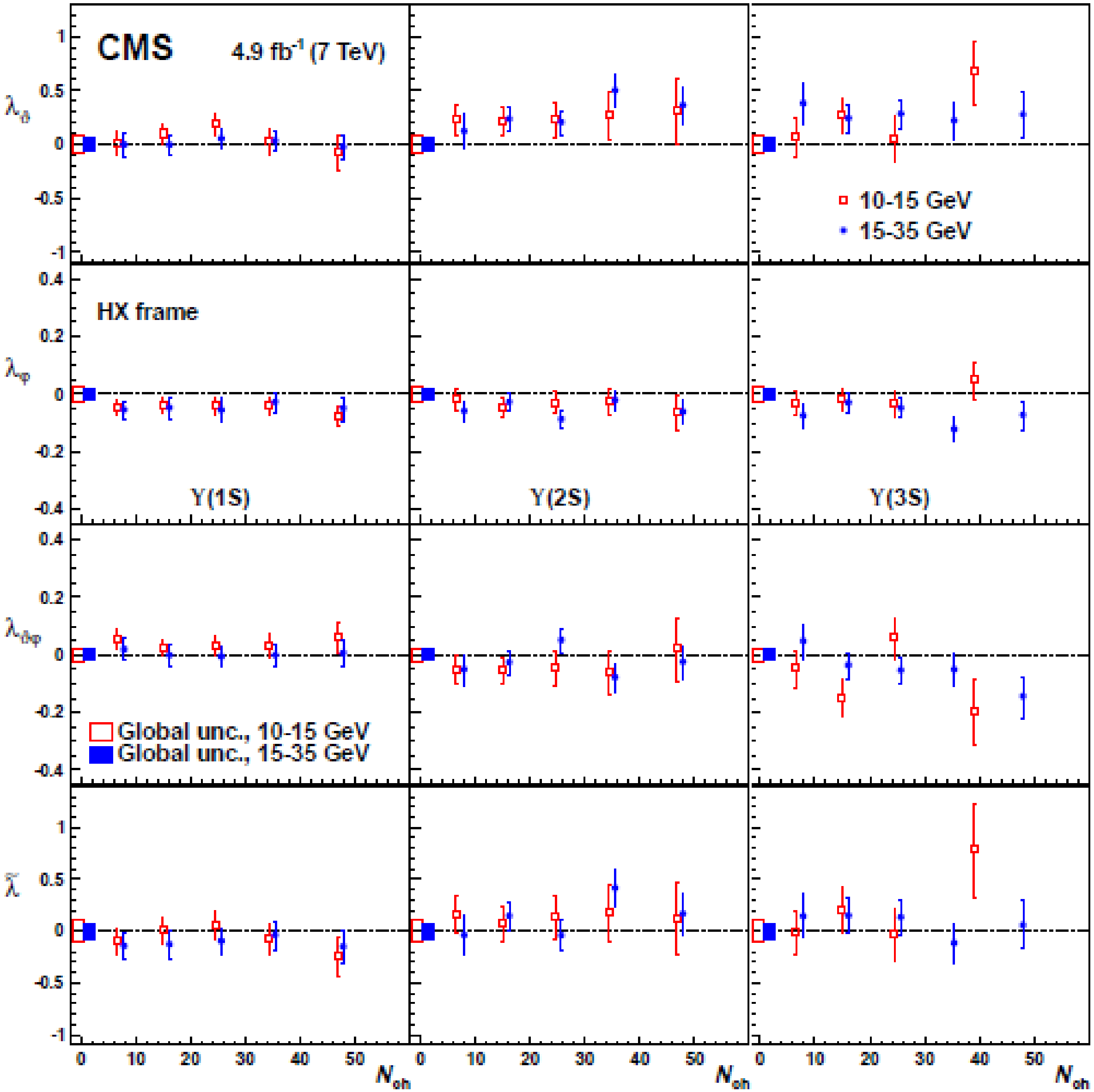


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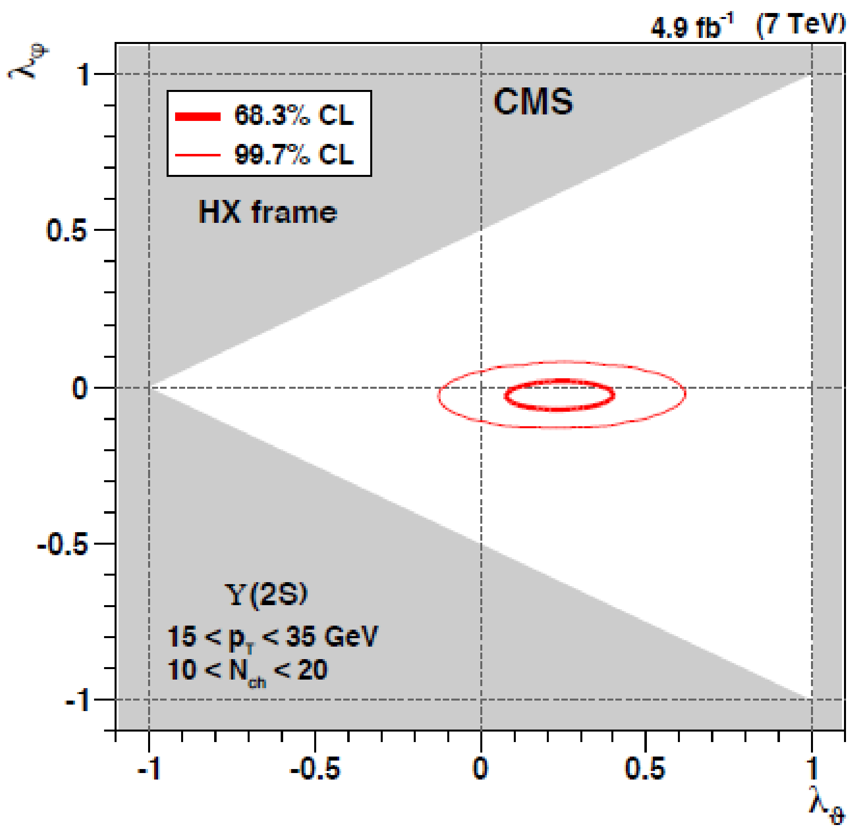


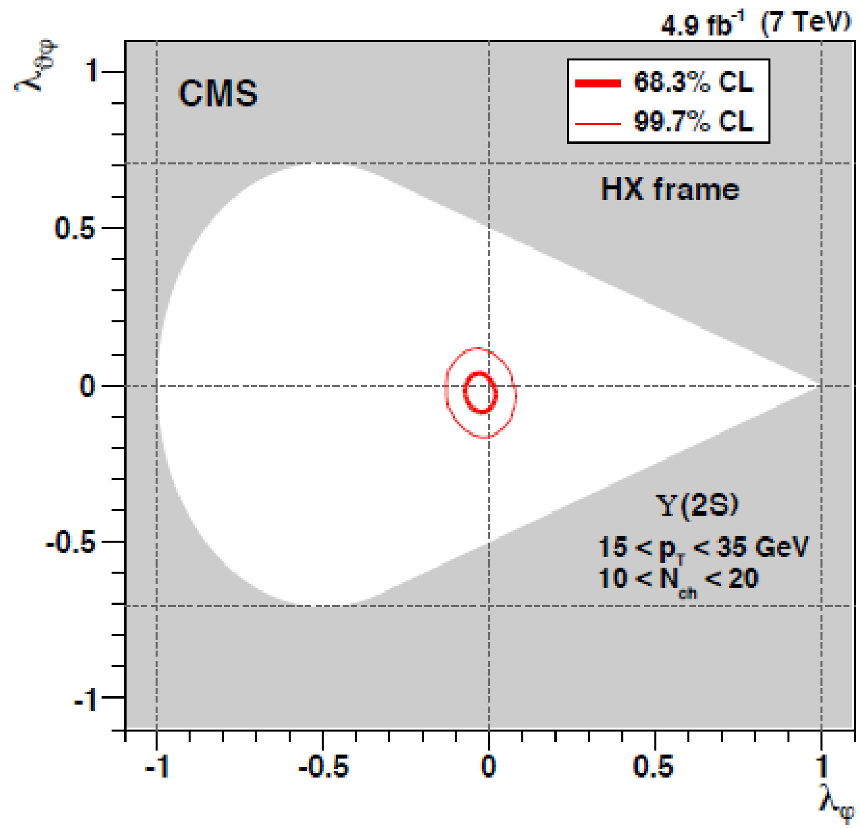


Phys. Lett B 761 (2016) 31

# Conclusions

- CMS has measured quarkonium polarization in pp collisions at $\sqrt{s}$ = 7 TeV with an integrated luminosity of 4.9 $fb^{-1}$ :
  - as a function of $p_T$ (integrated over charged particle multiplicity and in several rapidity ranges)
  - as a function of multiplicity (integrated over rapidity and in two $p_T$ ranges).
- All results are consistent with an unpolarized quarkonium production.
- No evidence is found for a change in polarization in pp collisions as a function of charged particle multiplicity, although the large uncertainties for the $\Upsilon$(2S) and $\Upsilon$(3S) preclude any definitive conclusion.