Measurements of heavy flavor properties at ATLAS and CMS

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on behalf of the CMS and ATLAS collaborations

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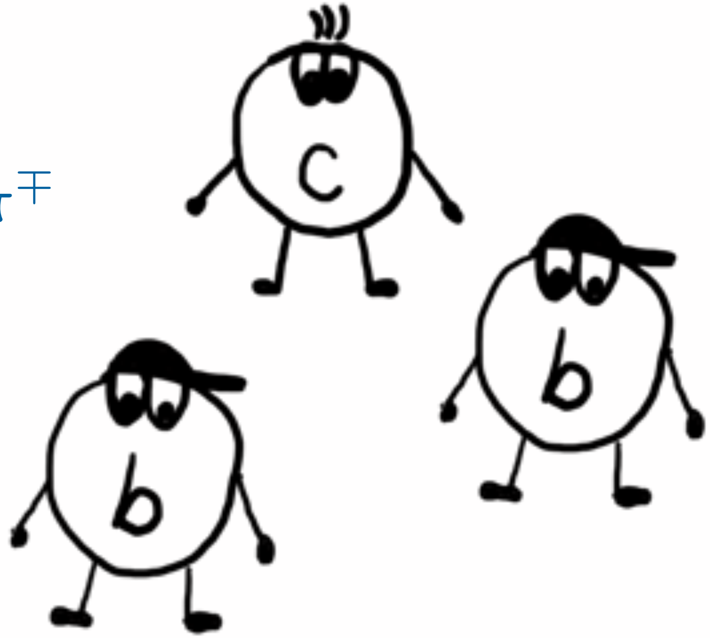
Outline

- ATLAS and CMS have a rich program in heavy flavor physics
- Heavy flavor production was already covered in Konstantin Toms' talk
- I will concentrate on a few recent topics:
  - Measurement of α_{b} in $\Lambda_{\mathrm{b}}^{0} \rightarrow \mathrm{J}/\psi\Lambda_{0}$
  - $\mathrm{B}_{\mathrm{c}}^{\pm} \rightarrow \mathrm{J}/\psi\pi^{\pm}$ and $\mathrm{B}_{\mathrm{c}}^{\pm} \rightarrow \mathrm{J}/\psi\pi^{\pm}\pi^{\pm}\pi^{\mp}$
  - Quarkonium polarization



α_b in $\Lambda_b^0 \to J/\psi \Lambda_0$

- Parity violation in the hadronic sector depends on the constituents of the hadron because of the presence of strongly bound spectator quarks

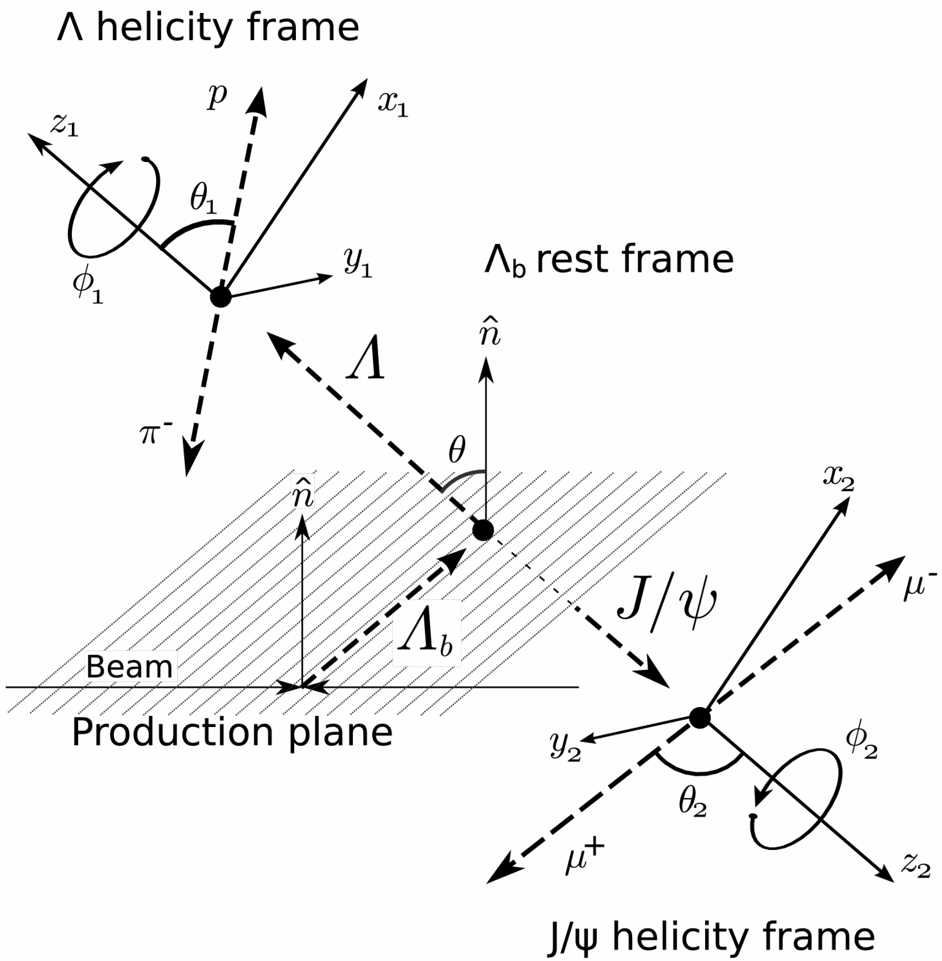
- Measurement of the parity-violating asymmetry parameter α_b provides a test for several theoretical models:
  - Perturbative quantum chromodynamics (pQCD): α_b = -0.17 to -0.14 (PRD 65, 074030 (2002))
  - Heavy quark effective theory (HQET): α_b = 0.78 (PLB 614, 165 (2005))

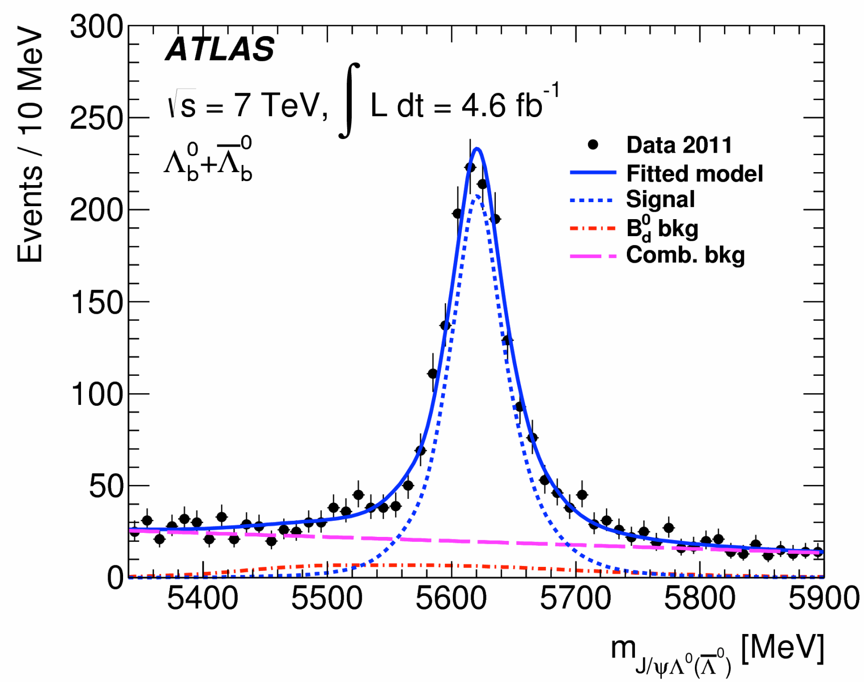
- LHCb result compatible with pQCD calculation:
  α_b= 0.05 ± 0.17 (stat.) ± 0.07 (syst.)
  (PLB 724 (2013), 27)

- ATLAS recently performed an independent measurement

$\Lambda_b^0 \to J/\psi \Lambda_0$

- Decay angles
  $\Omega = \{\theta, \phi, \theta_1, \phi_1, \theta_2, \phi_2\}$





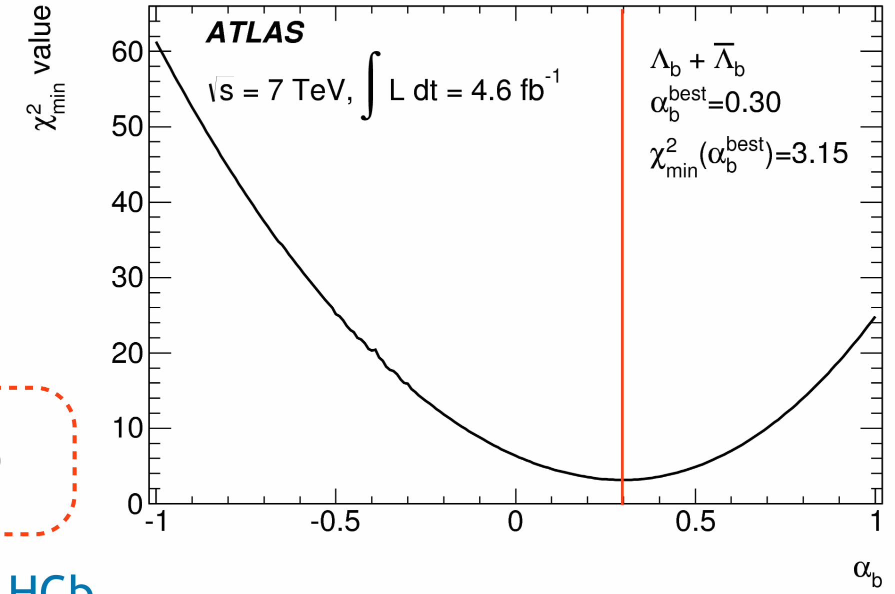
- Assume CP conservation

➡ Combination of Λ^0_b and $\bar{\Lambda}^0_b$ baryons

Details in arXiv:1404.1071

Measurement of α_b in $\Lambda_\mathrm{b}^0 \to J/\psi\Lambda_0$

- Parameters extracted in a least-squares fit to the distributions of decay angles



- Parity-violating asymmetry parameter

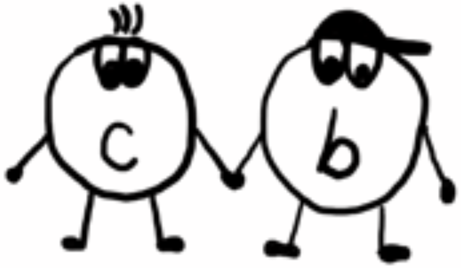
$$\alpha_\mathrm{b} = 0.30 \pm 0.16(\mathrm{stat.}) \pm 0.06(\mathrm{syst.})$$

  - ➡ Consistent with measurements from LHCb
  - ➡ Inconsistent with pQCD and HQET at a level of 2.6 and 2.8 standard deviations

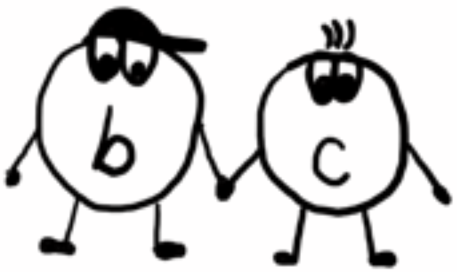
- Helicity amplitudes $A(\lambda_\Lambda, \lambda_{J/\psi})$

$$A(1/2,0) \equiv |a_+| = 0.17^{+0.12}_{-0.17}(\mathrm{stat.}) \pm 0.09(\mathrm{syst.})$$
$$A(-1/2,0) \equiv |a_-| = 0.59^{+0.06}_{-0.07}(\mathrm{stat.}) \pm 0.03(\mathrm{syst.})$$
$$A(-1/2,-1) \equiv |b_+| = 0.79^{+0.04}_{-0.05}(\mathrm{stat.}) \pm 0.02(\mathrm{syst.})$$
$$A(1/2,1) \equiv |b_-| = 0.08^{+0.13}_{-0.08}(\mathrm{stat.}) \pm 0.06(\mathrm{syst.})$$

$B_c^{\pm}$ meson

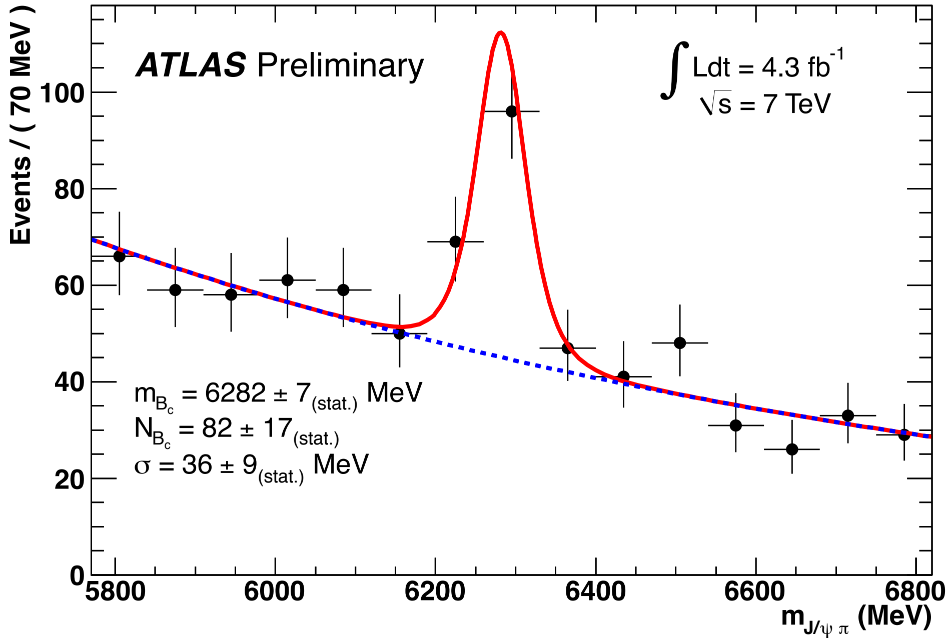


- First seen at CDF through the semileptonic decay $B_c^{\pm} \rightarrow J/\psi l^{+} \nu$
- Ground state of the $\bar{b}c$ ($b\bar{c}$) system
- Unique in that any of its quarks can decay weakly, leaving the other as a spectator
- Offers possibility to study the heavy quark dynamics that is inaccessible through the investigations on the $b\bar{b}$ and $c\bar{c}$ quarkonia



$B_c^\pm \to J/\psi\pi^\pm$

- ATLAS observed $B_c^\pm$ mesons through their decay to $J/\psi\pi^\pm$ for p_T > 15 GeV
- The yield is extracted using an unbinned maximum likelihood fit to the mass distribution



$$\text{yield} = 82 \pm 17(\text{stat.})\text{events}$$
$$\text{m}(B_c^\pm) = 6282 \pm 7(\text{stat.})\text{MeV}$$

- Consistent with PDG average: $\text{m}(B_c^\pm)$ = 6277 ± 6 MeV

Details in ATLAS-CONF-2012-028

$B_c^\pm \to J/\psi\pi^\pm$ and $B_c^\pm \to J/\psi\pi^\pm\pi^\pm\pi^\mp$

- CMS studied the $B_c^\pm \to J/\psi\pi^\pm$ and $J/\psi\pi^\pm\pi^\pm\pi^\mp$ decay modes for p_T > 15 GeV and |y| < 1.6

$$\frac{\sigma(B_c^\pm)\times Br(B_c^\pm \to J/\psi\pi^\pm)}{\sigma(B^\pm)\times Br(B^\pm \to J/\psi K^\pm)} =$$

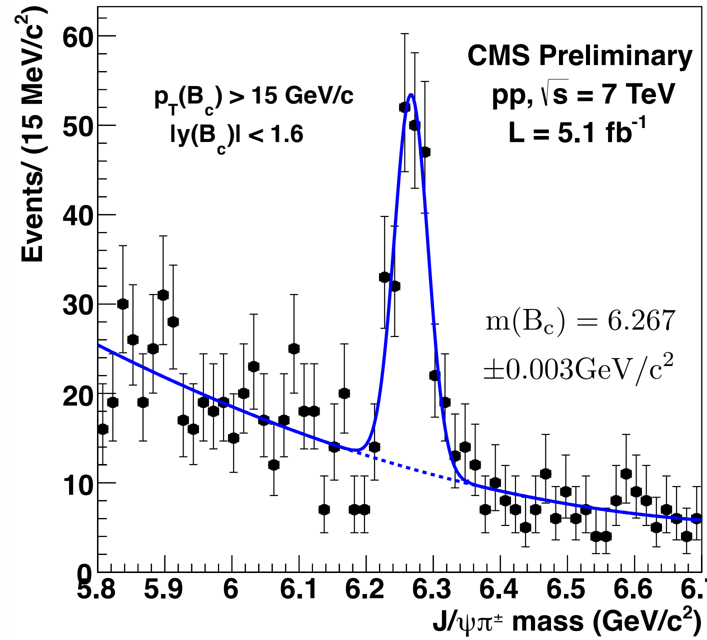
$$(0.48 \pm 0.05\ (\text{stat.})\ \pm 0.04\ (\text{syst.})\ {}^{+0.05}_{-0.03}(\tau_{B_c})) \times 10^{-2}$$

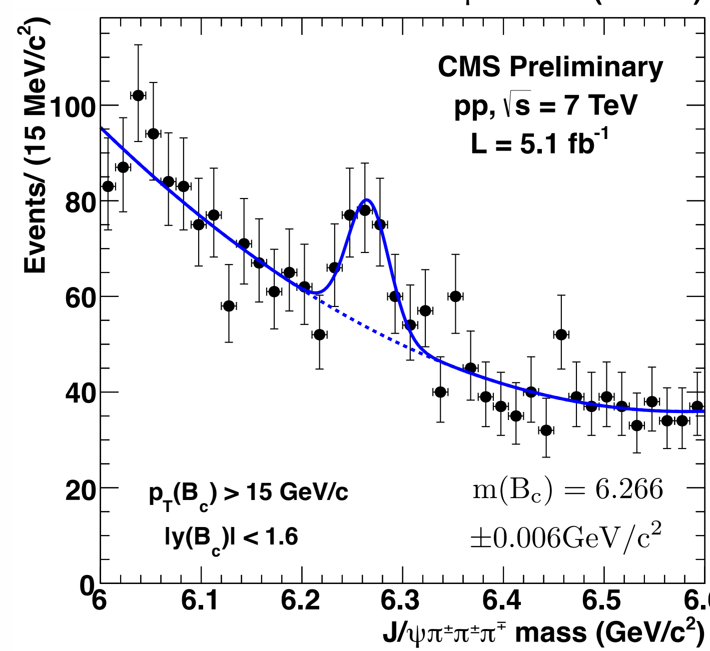
$$\frac{Br(B_c^\pm \to J/\psi\pi^\pm\pi^\pm\pi^\mp)}{Br(B_c^\pm \to J/\psi\pi^\pm)} =$$

$$2.43 \pm 0.76(\text{stat.})^{+0.46}_{-0.44}(\text{syst.})$$

- Branching fraction ratio in good agreement with LHCb result: 2.41 ± 0.30 (stat.) ± 0.33 (syst.) (PRL 109 (2012), 232001)

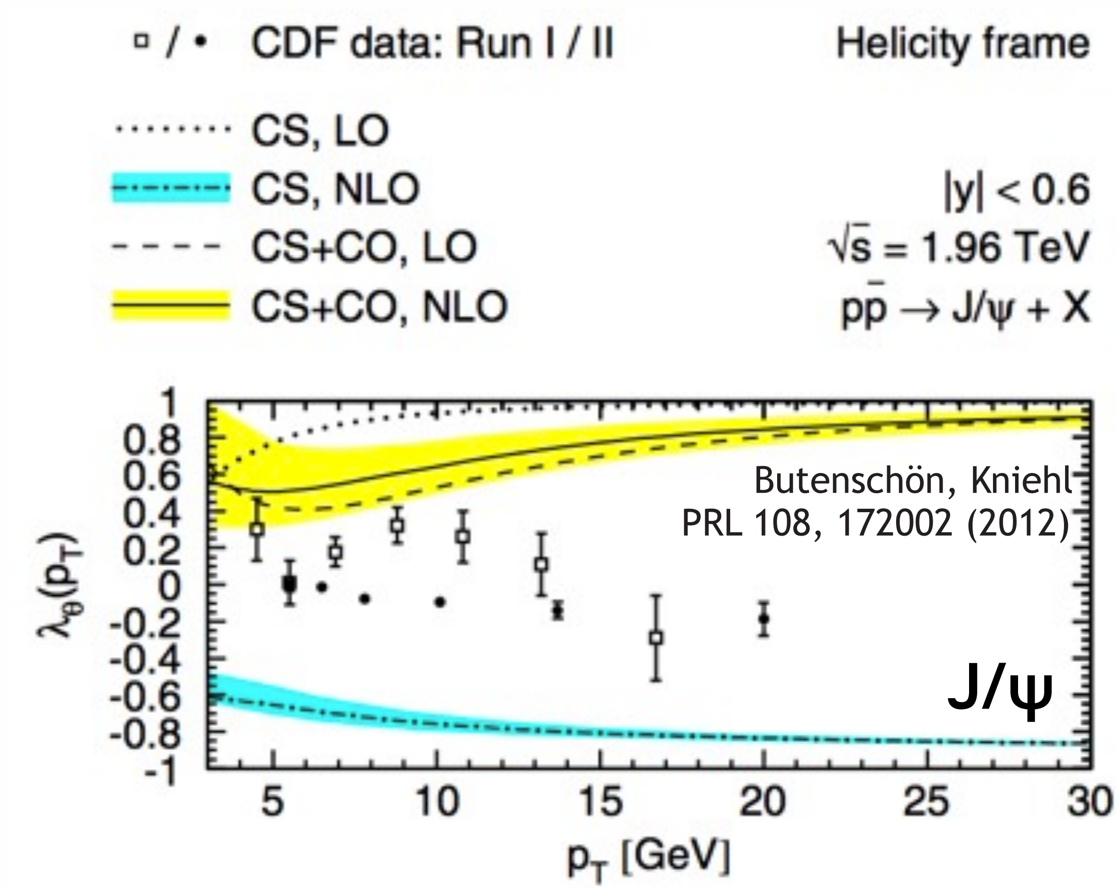
Details in CMS-PAS-BPH-12-011





Quarkonium polarization

- Long standing puzzle: No theoretical model has explained experimental measurements of quarkonium polarization
- Pre-LHC measurements showed inconsistencies in the determination of the polarization



CS … color singlet
CO … color octet

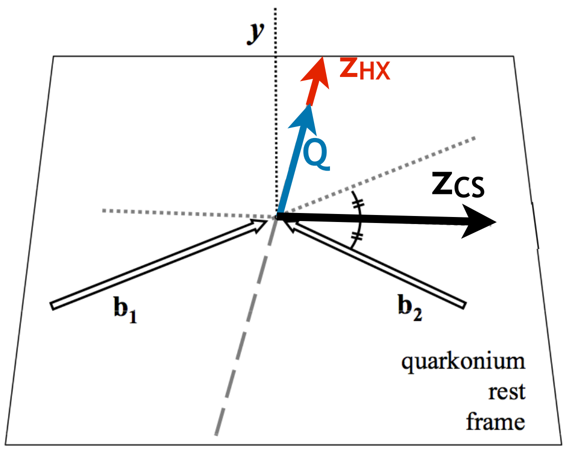
Quarkonium polarization

- Polarization is measured through the average angular decay distribution – for vector particles most generally written as

$$W(\cos\vartheta, \varphi|\vec{\lambda}) = \frac{3/(4\pi)}{(3+\lambda_\vartheta)}(1 + \lambda_\vartheta \cos^2\vartheta + \lambda_\varphi \sin^2\vartheta \cos 2\varphi + \lambda_{\vartheta\varphi} \sin 2\vartheta \cos\varphi)$$

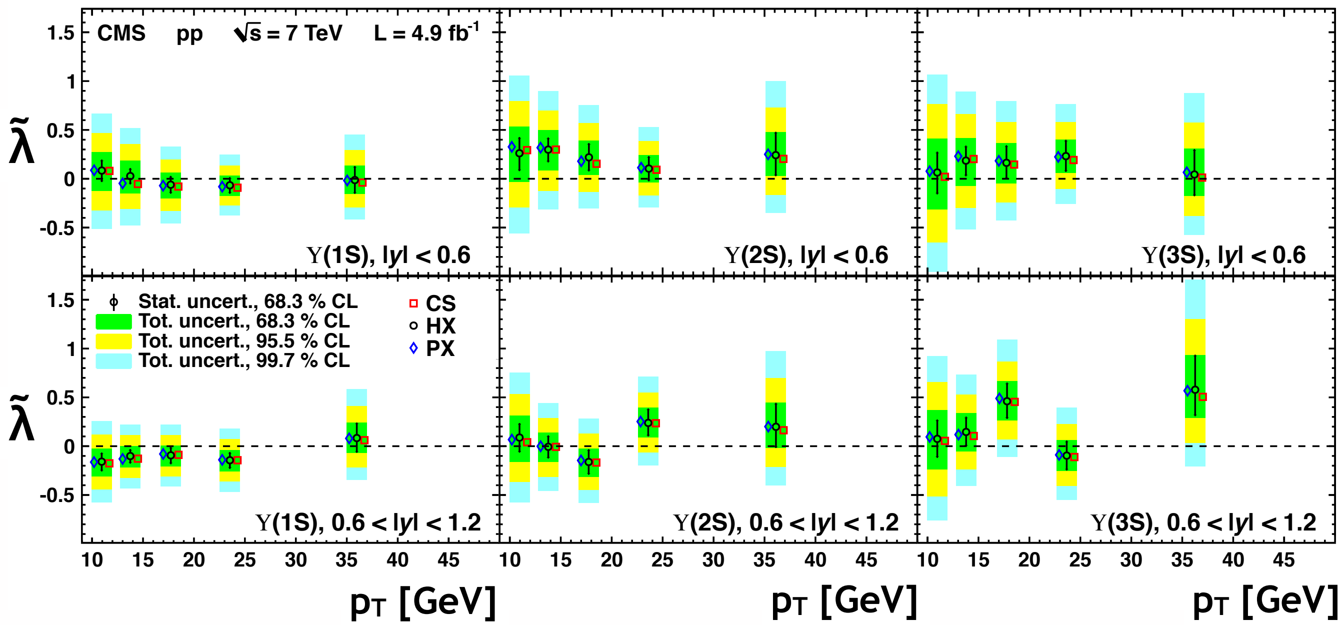
where λ_ϑ, λ_φ, $\lambda_{\vartheta\varphi}$ are the polarization parameters

- CMS measured λ_ϑ, λ_φ, $\lambda_{\vartheta\varphi}$ and the frame invariant parameter $\tilde{\lambda} = (\lambda_\vartheta + 3\lambda_\varphi)/(1-\lambda_\varphi)$ for J/ψ, ψ(2S), Υ(1S), Υ(2S) and Υ(3S) mesons decaying to $\mu^+\mu^-$ three different reference frames:
  - center-of-mass helicity HX (polar axis z_{HX} ≈ direction of quarkonium momentum)
  - Collins-Soper CS (z_{CS} ≈ direction of relative velocity of colliding particles)
  - perpendicular helicity PX ($z_{PX} \perp z_{CS}$)

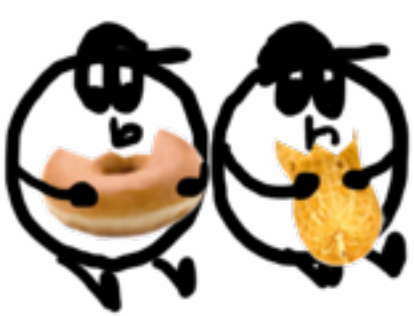


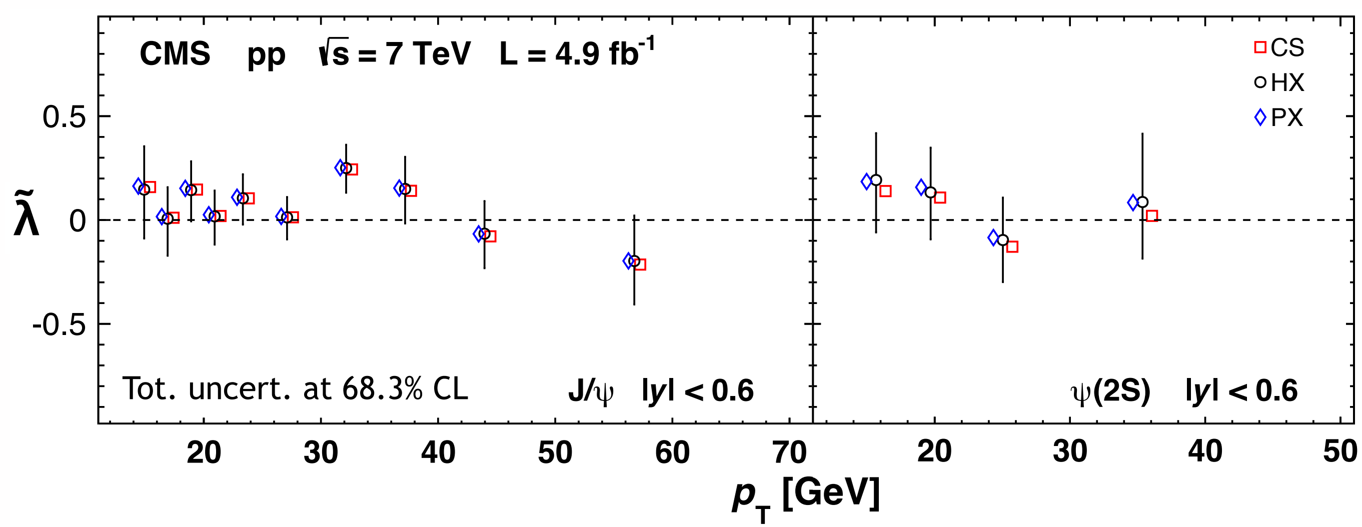
Details in PRL 110 (2013), 081802 and PLB 727 (2013), 381

Frame Invariant Parameter $\tilde{\lambda}$

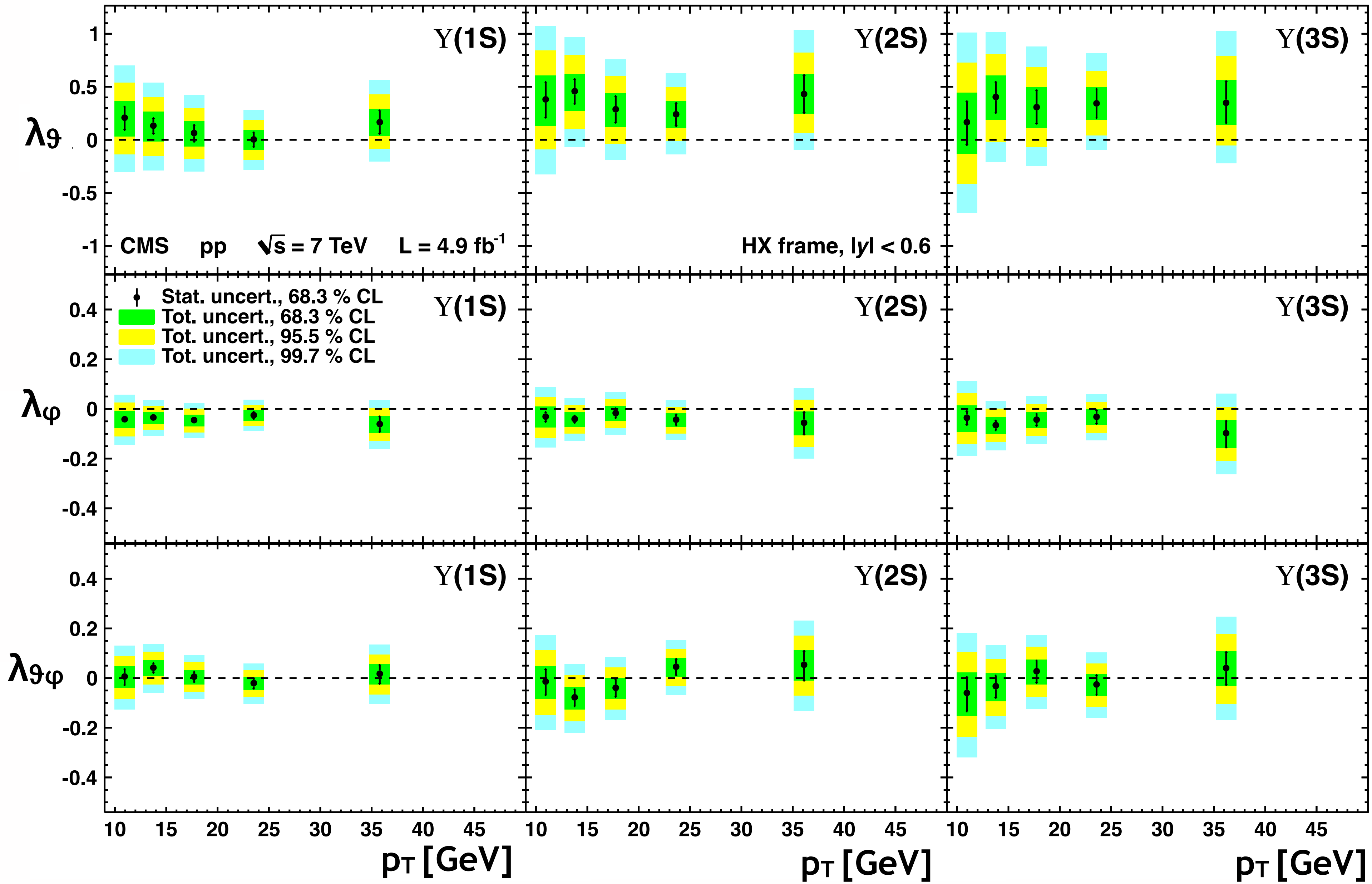


Good agreement between the $\tilde{\lambda}$ parameters in the three reference frames shows that the results are consistent

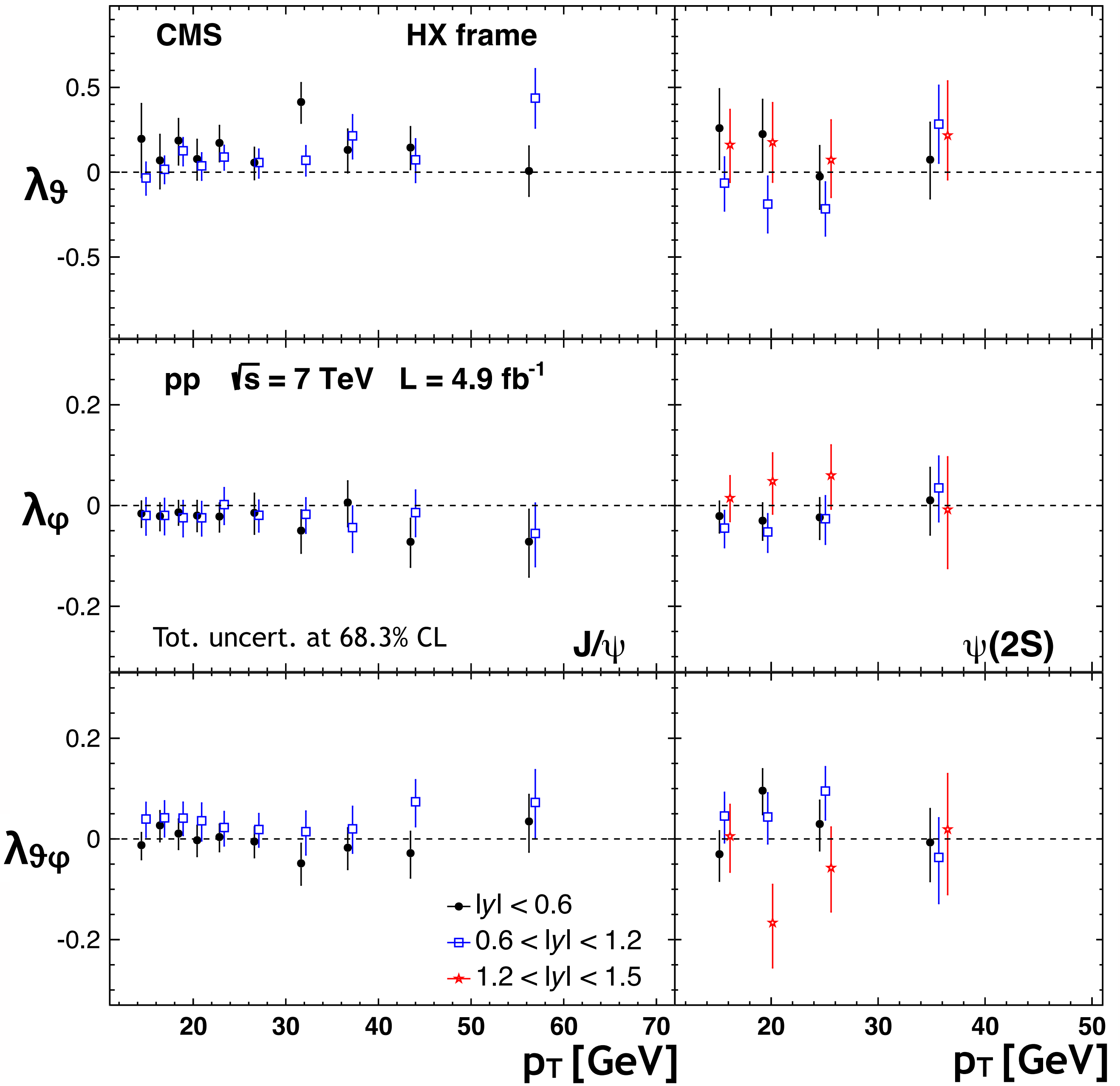




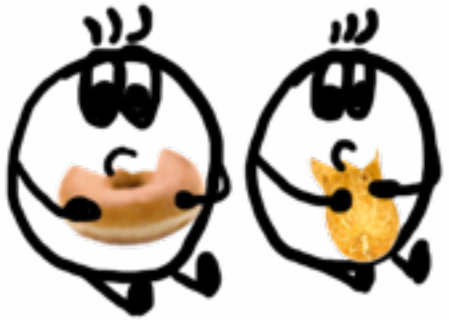
ϒ(nS) Polarization in the HX Frame, |y|< 0.6



Prompt ψ(nS) Polarization in the HX Frame

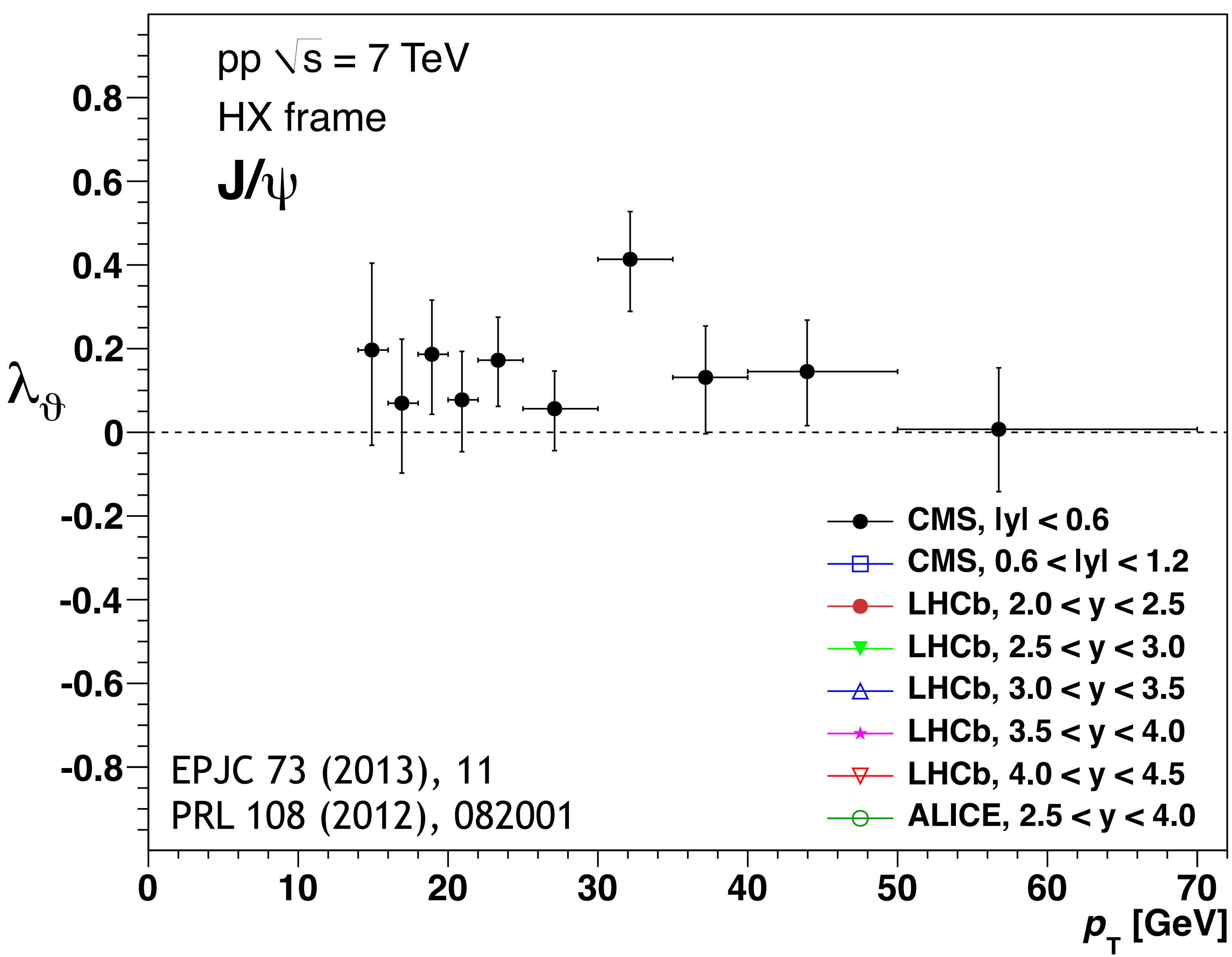


- ψ(2S) is not affected by feed-down decays from higher states
- No sign of strong polarization



Comparison to Other LHC Experiments: J/ψ

All LHC results are compatible with each other.



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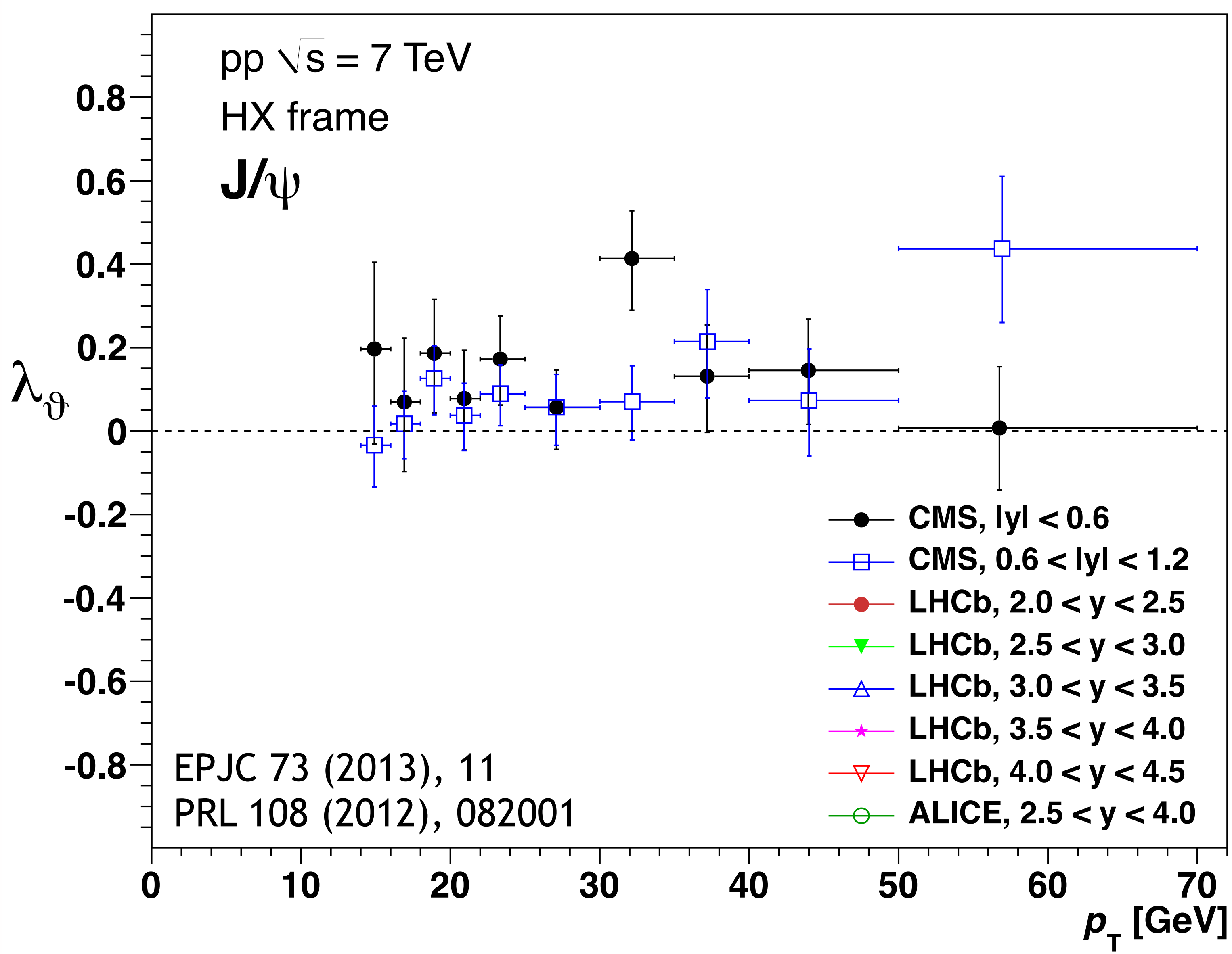

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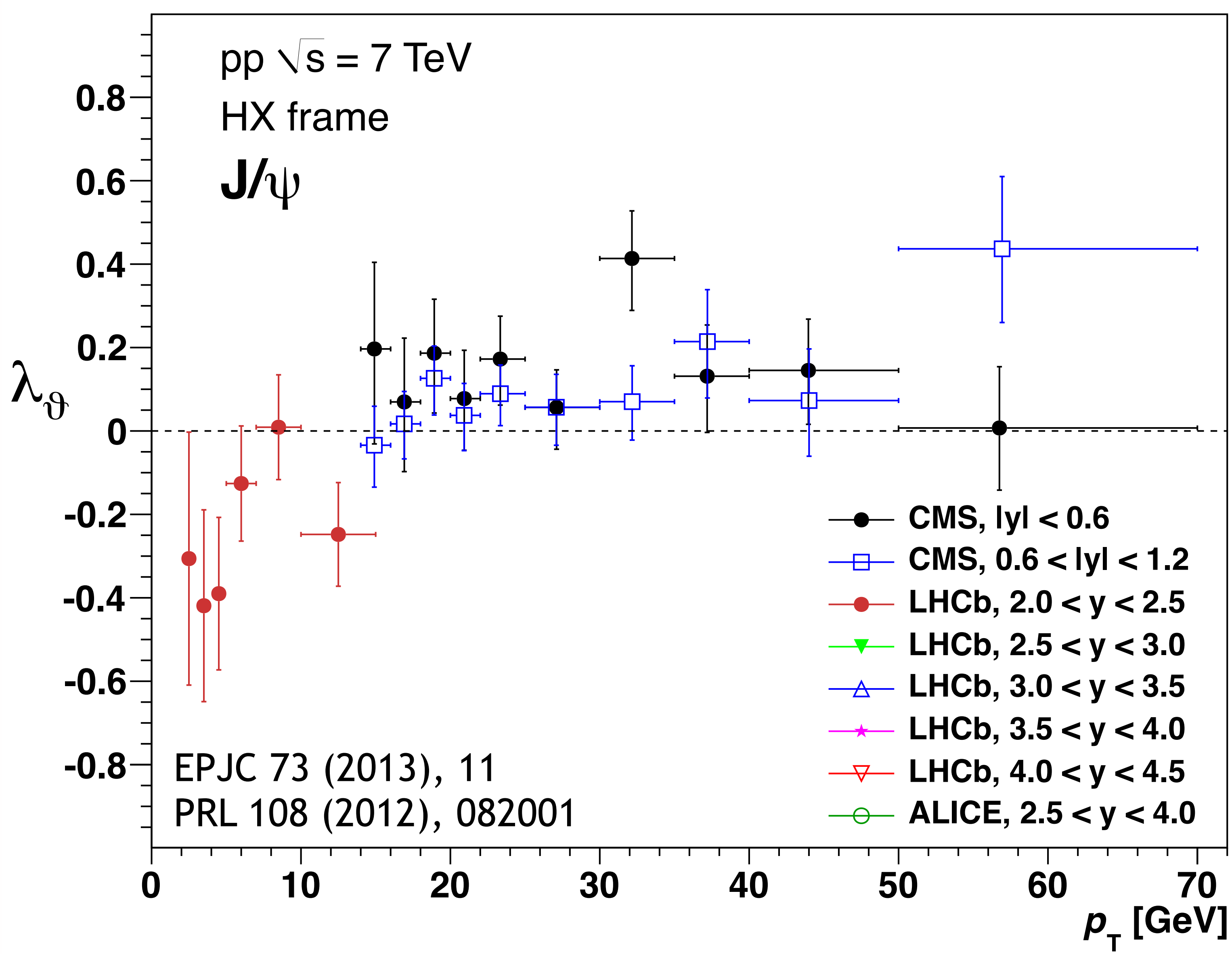

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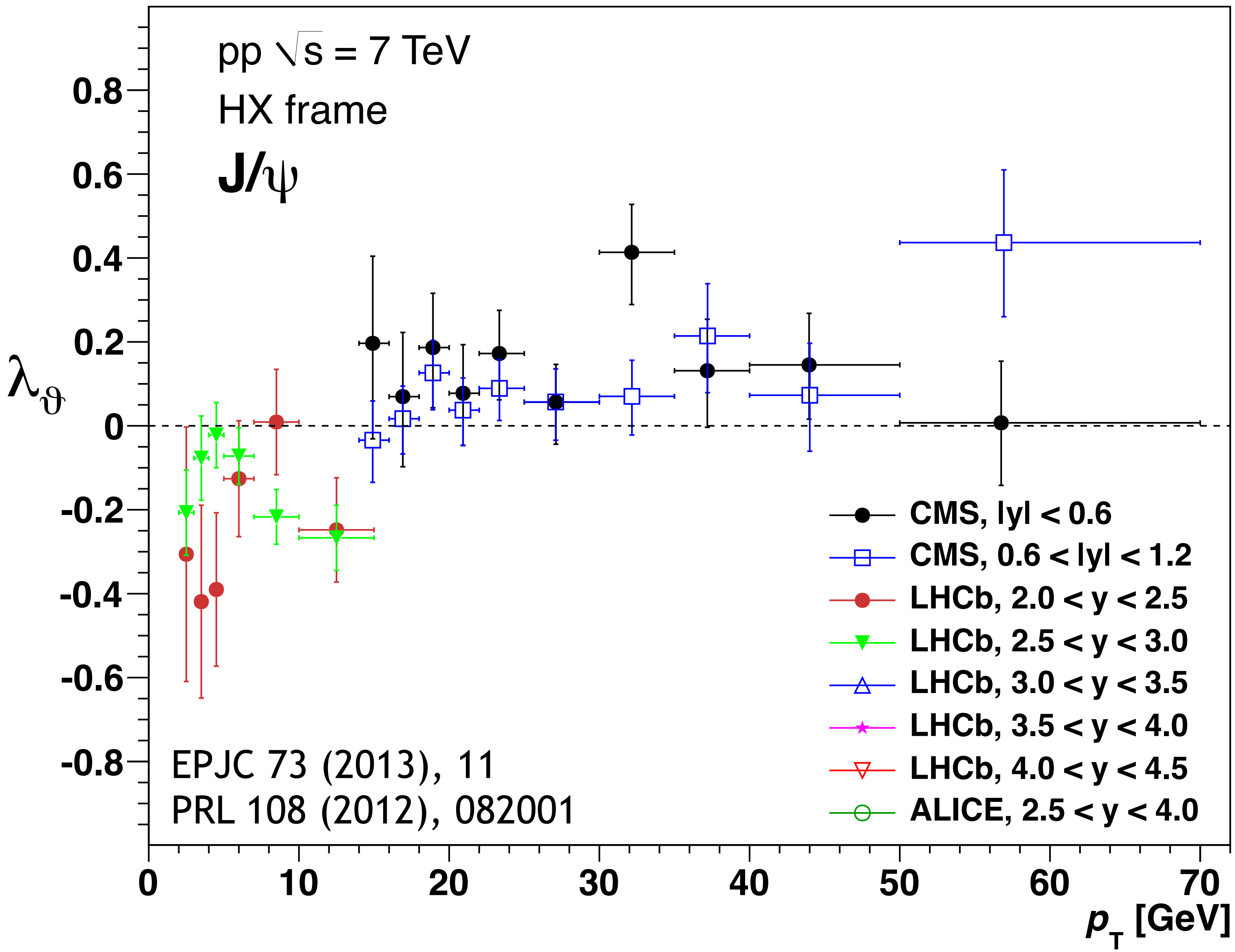

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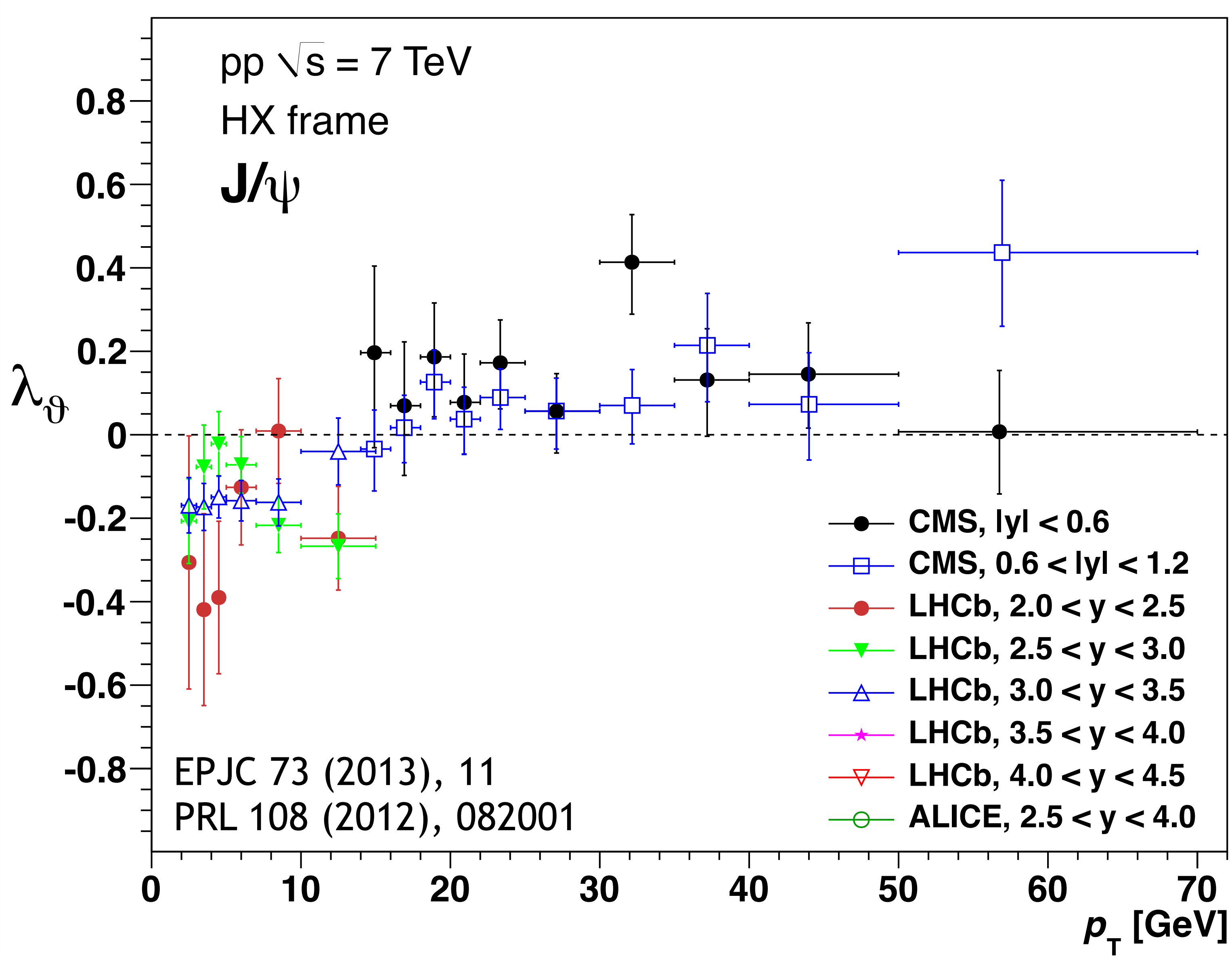

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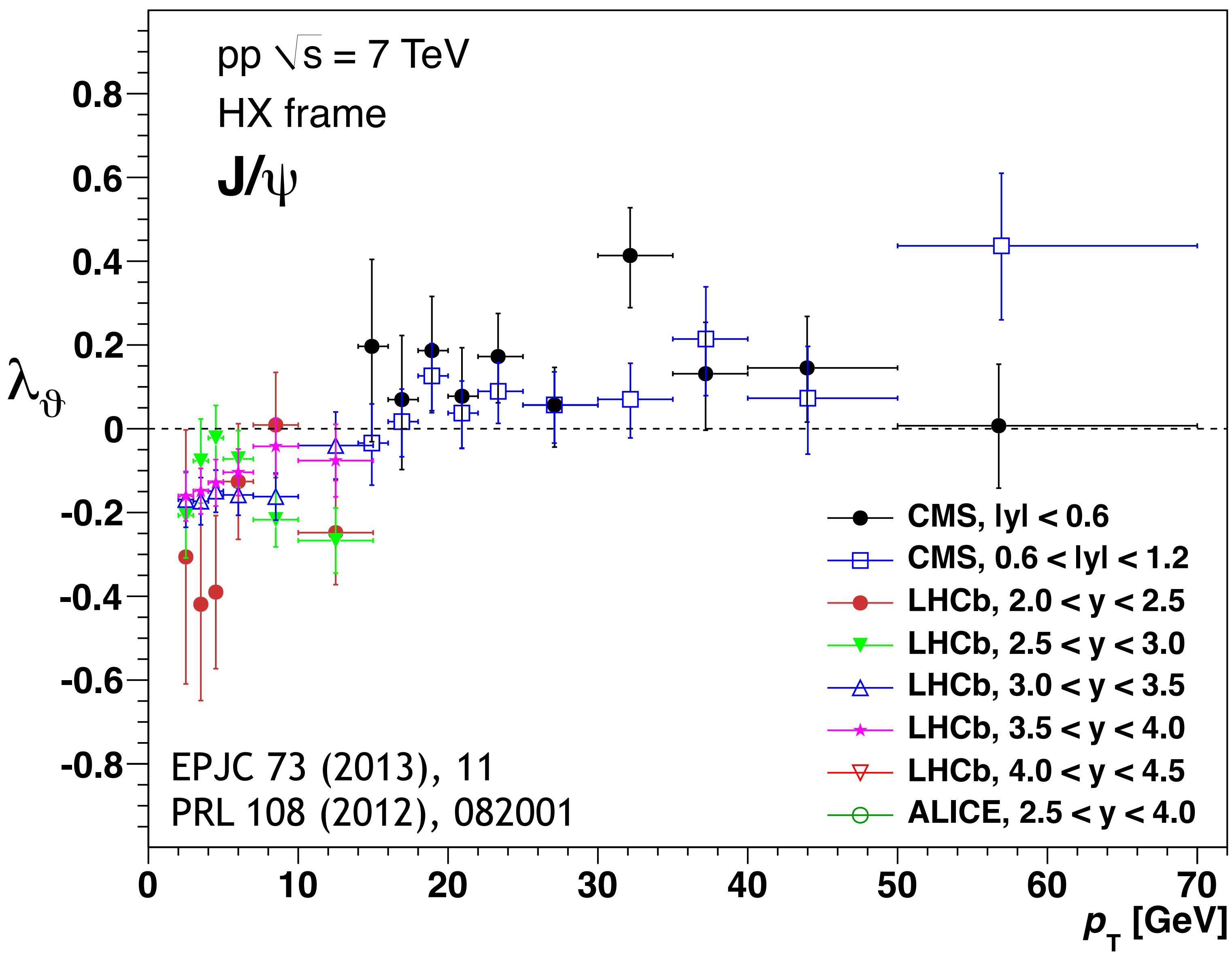

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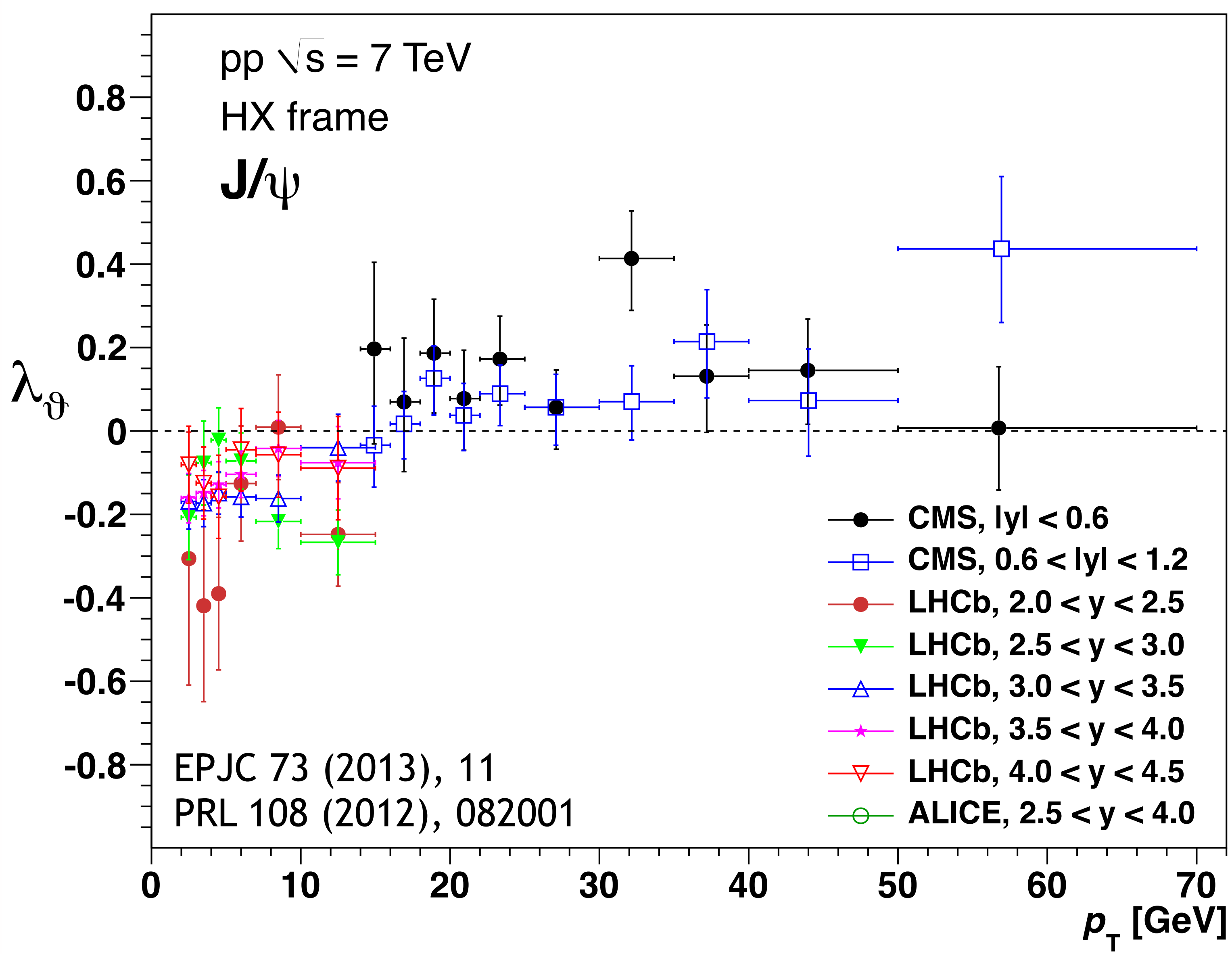

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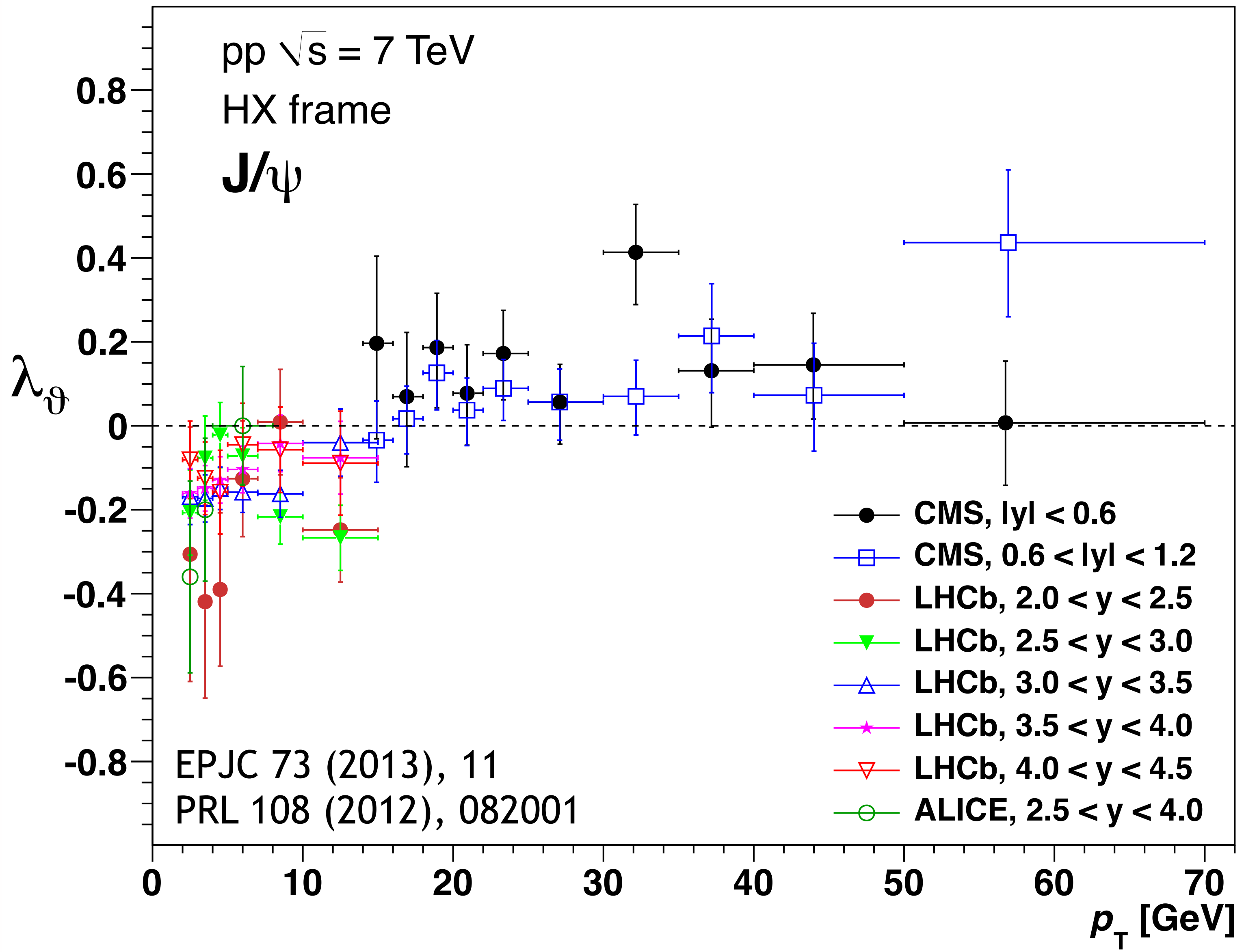
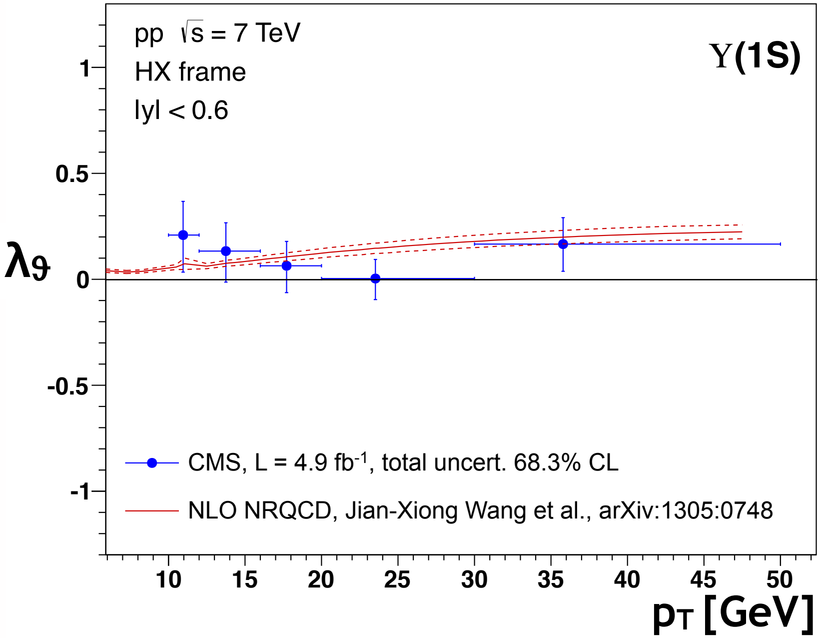
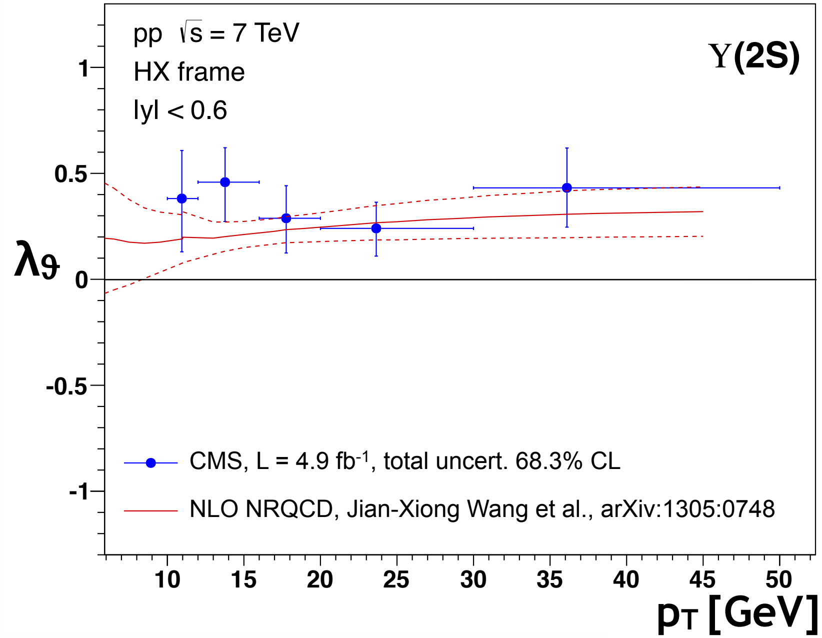
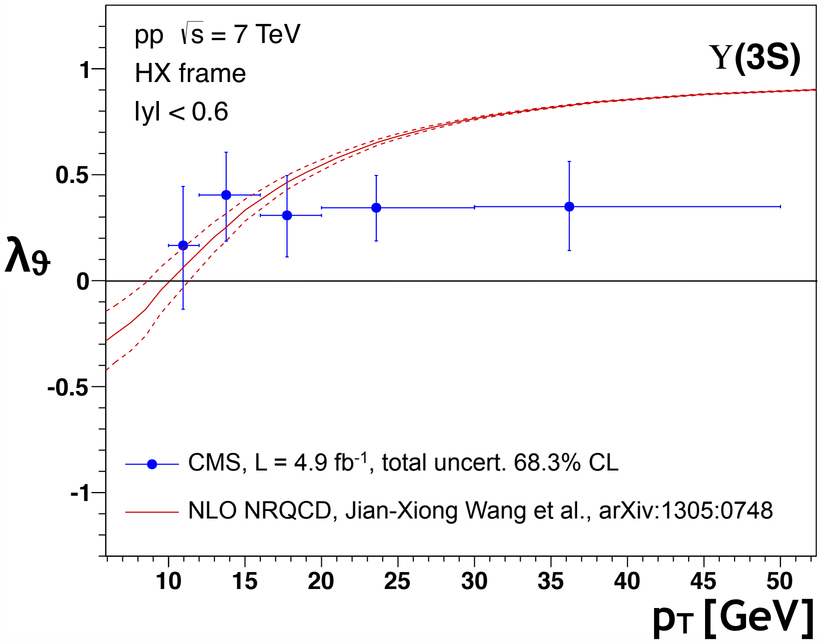


NLO NRQCD Comparison: Υ(nS)



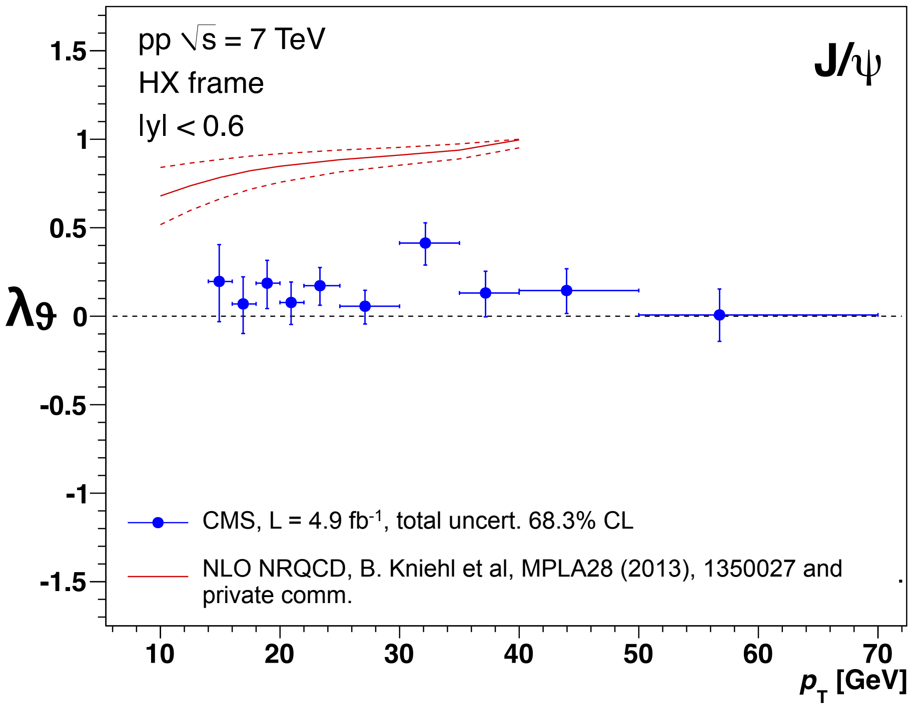


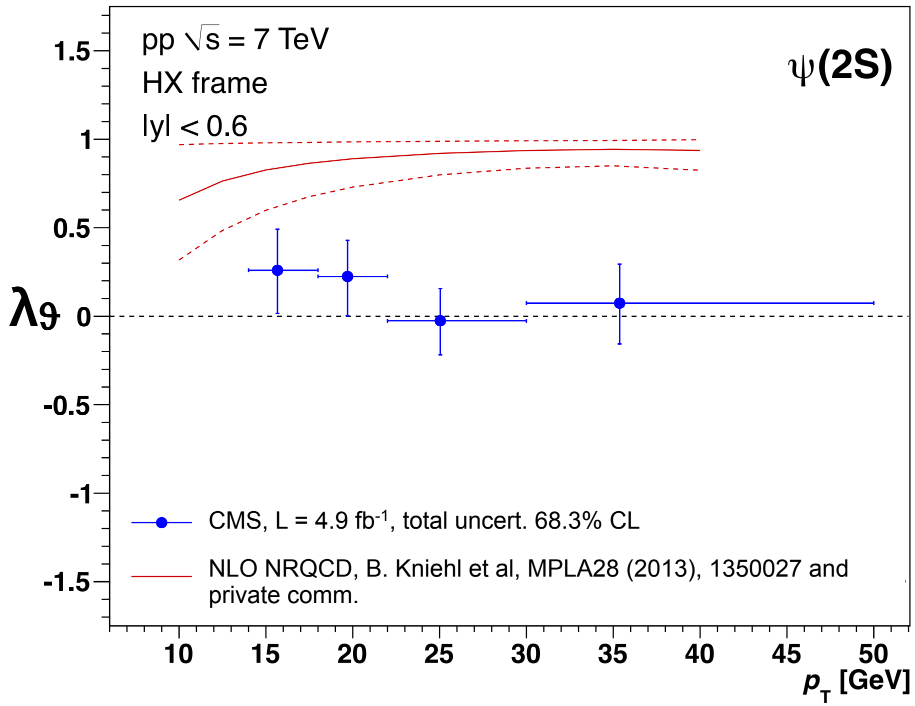


- Theory calculation accounts for feed-down contributions to Υ(1S) and Υ(2S) states
- Prediction for Υ(3S) may change when including feed-down from χ_b(3P) states
- Color octet matrix elements are fit to hadroproduction data only, including CMS Υ(nS) polarization results

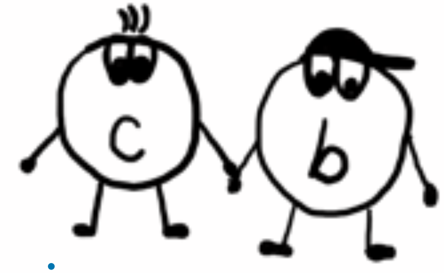
NLO NRQCD Comparison: ψ(nS)

- Calculations use a global fit of color octet matrix elements to photo- as well as hadroproduction data, excluding polarization results
- NLO NRQCD calculations fail to describe CMS results
- Theory predictions only consider directly produced J/ψ's
- ψ(2S) result can be directly compared to theory since it has no feed-down contribution





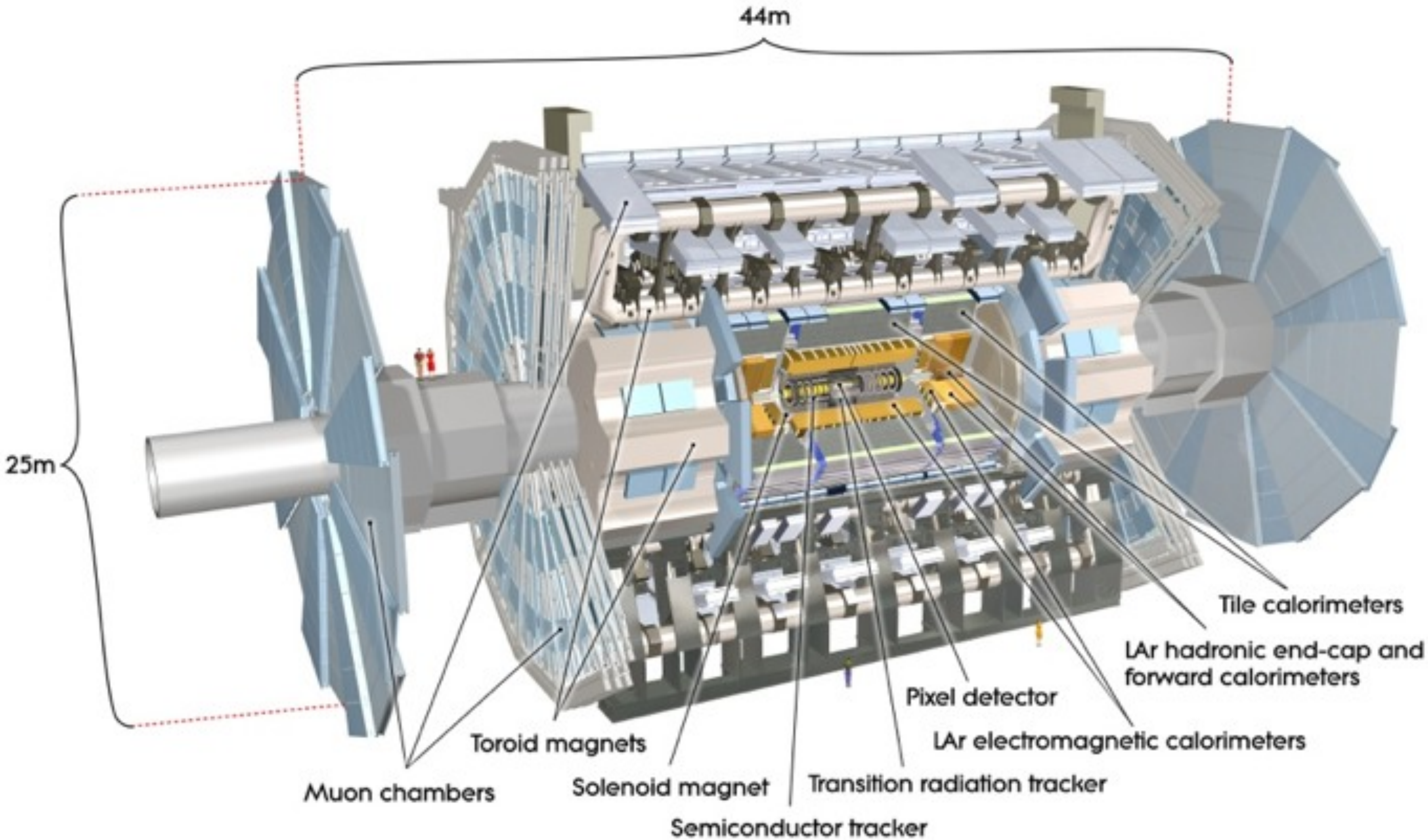
Summary



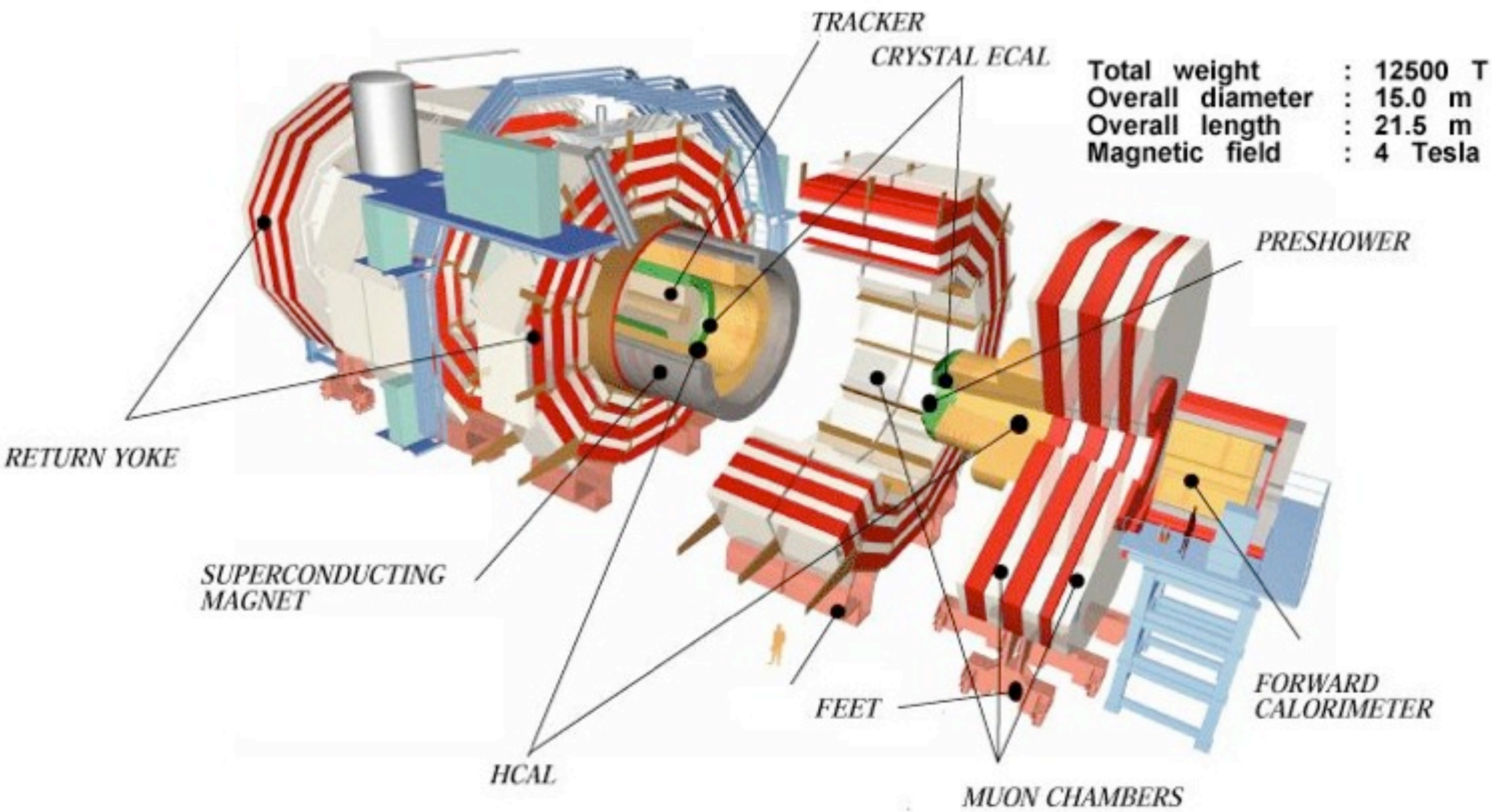
- ATLAS and CMS have a rich program in heavy flavor physics
- Topics shown today:
  - Measurement of α_{b} in $\Lambda_{\mathrm{b}}^{0} \rightarrow \mathrm{J}/\psi\Lambda_{0}$ inconsistent with pQCD and HQET at a level of 2.6 and 2.8 standard deviations
  - $\mathrm{B}_{\mathrm{c}}^{\pm} \rightarrow \mathrm{J}/\psi\pi^{\pm}$ and $\mathrm{B}_{\mathrm{c}}^{\pm} \rightarrow \mathrm{J}/\psi\pi^{\pm}\pi^{\pm}\pi^{\mp}$ modes observed
  - Quarkonium polarization measurements in disagreement with NLO NRQCD calculations
- More results are expected to come in the near future

BACKUP

ATLAS Detector



CMS Detector



α_{b} in $\Lambda_{\mathrm{b}}^0 \to \mathrm{J}/\psi\Lambda_0$

Full angular probability density function of the decay angles

$$w(\Omega, \vec{A}, P) = \frac{1}{(4\pi)^3} \sum_{i=0}^{19} f_{1i}(\vec{A}) f_{2i}(P, \alpha_\Lambda) F_i(\Omega)$$

Ω: decay angles

$\vec{A}$: helicity amplitudes

α_Λ: decay asymmetry parameter

P: polarization of Λ_b^0

α_{b} in $\Lambda_{\mathrm{b}}^0 \to \mathrm{J}/\psi\Lambda_0$

i	f_{1i}	f_{2i}	F_i
0	$a_+a_+^* + a_-a_-^* + b_+b_+^* + b_-b_-^*$	1	1
1	$a_+a_+^* - a_-a_-^* + b_+b_+^* - b_-b_-^*$	P	$\cos\theta$
2	$a_+a_+^* - a_-a_-^* - b_+b_+^* + b_-b_-^*$	α_Λ	$\cos\theta_1$
3	$a_+a_+^* + a_-a_-^* - b_+b_+^* - b_-b_-^*$	$P\alpha_\Lambda$	$\cos\theta\cos\theta_1$
4	$-a_+a_+^* - a_-a_-^* + \frac{1}{2}b_+b_+^* + \frac{1}{2}b_-b_-^*$	1	$\frac{1}{2}(3\cos^2\theta_2 - 1)$
5	$-a_+a_+^* + a_-a_-^* + \frac{1}{2}b_+b_+^* - \frac{1}{2}b_-b_-^*$	P	$\frac{1}{2}(3\cos^2\theta_2 - 1)\cos\theta$
6	$-a_+a_+^* + a_-a_-^* - \frac{1}{2}b_+b_+^* + \frac{1}{2}b_-b_-^*$	α_Λ	$\frac{1}{2}(3\cos^2\theta_2 - 1)\cos\theta_1$
7	$-a_+a_+^* - a_-a_-^* - \frac{1}{2}b_+b_+^* - \frac{1}{2}b_-b_-^*$	$P\alpha_\Lambda$	$\frac{1}{2}(3\cos^2\theta_2 - 1)\cos\theta\cos\theta_1$
8	$-3Re(a_+a_-^*)$	$P\alpha_\Lambda$	$\sin\theta\sin\theta_1\sin^2\theta_2\cos\varphi_1$
9	$3Im(a_+a_-^*)$	$P\alpha_\Lambda$	$\sin\theta\sin\theta_1\sin^2\theta_2\sin\varphi_1$
10	$-\frac{3}{2}Re(b_-b_+^*)$	$P\alpha_\Lambda$	$\sin\theta\sin\theta_1\sin^2\theta_2\cos(\varphi_1 + 2\varphi_2)$
11	$\frac{3}{2}Im(b_-b_+^*)$	$P\alpha_\Lambda$	$\sin\theta\sin\theta_1\sin^2\theta_2\sin(\varphi_1 + 2\varphi_2)$
12	$-\frac{3}{\sqrt{2}}Re(b_-a_+^* + a_-b_+^*)$	$P\alpha_\Lambda$	$\sin\theta\cos\theta_1\sin\theta_2\cos\theta_2\cos\varphi_2$
13	$\frac{3}{\sqrt{2}}Im(b_-a_+^* + a_-b_+^*)$	$P\alpha_\Lambda$	$\sin\theta\cos\theta_1\sin\theta_2\cos\theta_2\sin\varphi_2$
14	$-\frac{3}{\sqrt{2}}Re(b_-a_-^* + a_+b_+^*)$	$P\alpha_\Lambda$	$\cos\theta\sin\theta_1\sin\theta_2\cos\theta_2\cos(\varphi_1 + \varphi_2)$
15	$\frac{3}{\sqrt{2}}Im(b_-a_-^* + a_+b_+^*)$	$P\alpha_\Lambda$	$\cos\theta\sin\theta_1\sin\theta_2\cos\theta_2\sin(\varphi_1 + \varphi_2)$
16	$\frac{3}{\sqrt{2}}Re(a_-b_+^* - b_-a_+^*)$	P	$\sin\theta\sin\theta_2\cos\theta_2\cos\varphi_2$
17	$-\frac{3}{\sqrt{2}}Im(a_-b_+^* - b_-a_+^*)$	P	$\sin\theta\sin\theta_2\cos\theta_2\sin\varphi_2$
18	$\frac{3}{\sqrt{2}}Re(b_-a_-^* - a_+b_+^*)$	α_Λ	$\sin\theta_1\sin\theta_2\cos\theta_2\cos(\varphi_1 + \varphi_2)$
19	$-\frac{3}{\sqrt{2}}Im(b_-a_-^* - a_+b_+^*)$	α_Λ	$\sin\theta_1\sin\theta_2\cos\theta_2\sin(\varphi_1 + \varphi_2)$

α_{b} in $\Lambda_{\mathrm{b}}^0 \to \mathrm{J}/\psi\Lambda_0$

Fit model parametrization

$$\alpha_{\mathrm{b}} = |\mathrm{a}_+|^2 - |\mathrm{a}_-|^2 + |\mathrm{b}_+|^2 - |\mathrm{b}_-|^2$$

$$k_+ = \frac{|a_+|}{\sqrt{|a_+|^2 + |b_+|^2}}$$

$$k_- = \frac{|b_-|}{\sqrt{|a_-|^2 + |b_-|^2}}$$

$$\Delta_+ = \rho_+ - w_+$$

$$\Delta_- = \rho_- - w_-$$

a,b: helicity amplitudes

ρ, w: phases of helicity amplitudes

Quarkonium polarization

Definition of the PPD

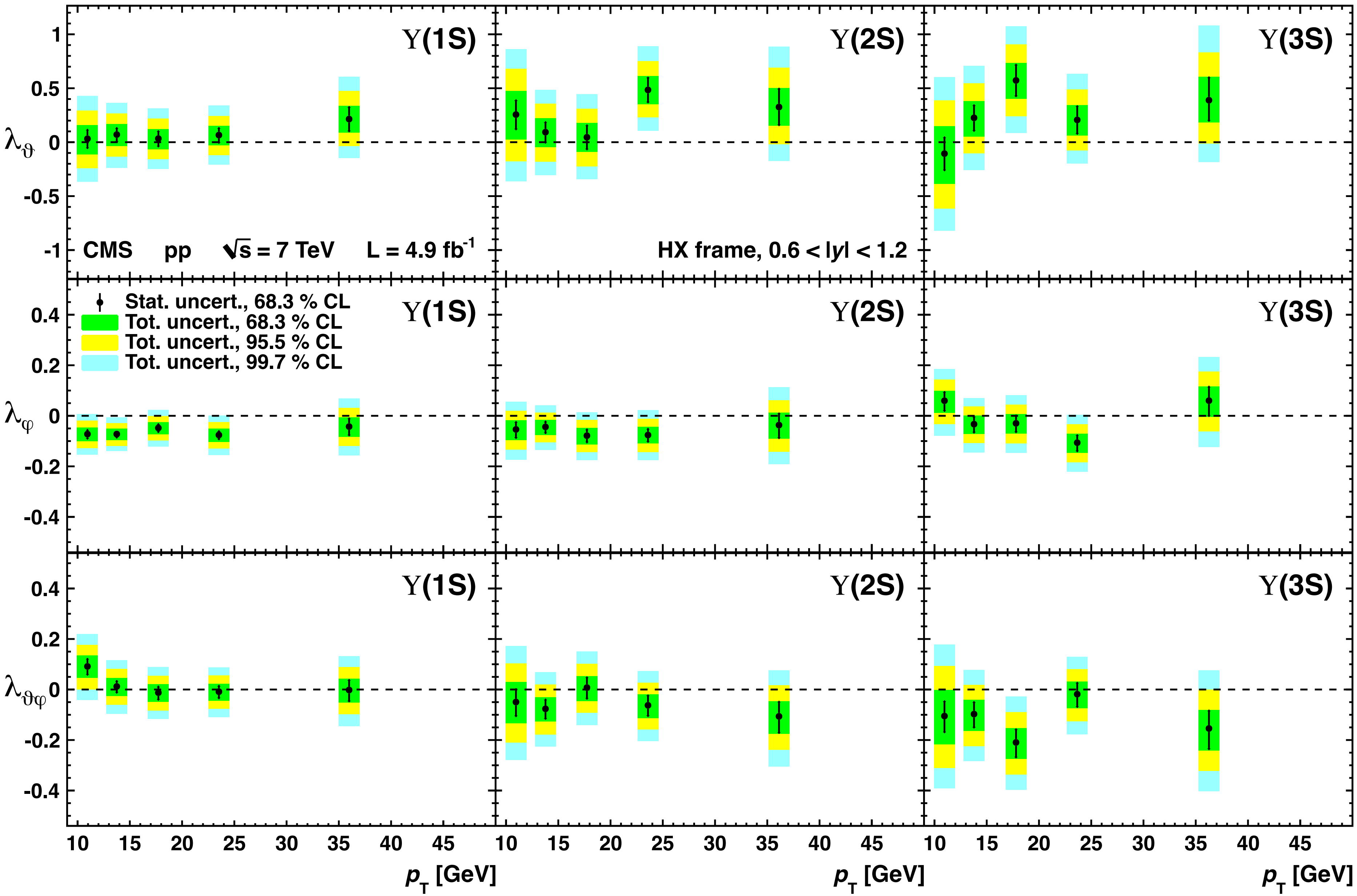
$$\mathcal{P}(\vec{\lambda}) \quad \propto \quad \prod_i \frac{1}{\mathcal{N}(\vec{\lambda})} \quad W(\cos\theta^{(i)}, \phi^{(i)} \mid \vec{\lambda}) \quad \varepsilon(\vec{p_1^{(i)}} \vec{p_2^{(i)}})$$

$\mathcal{N}$: normalization

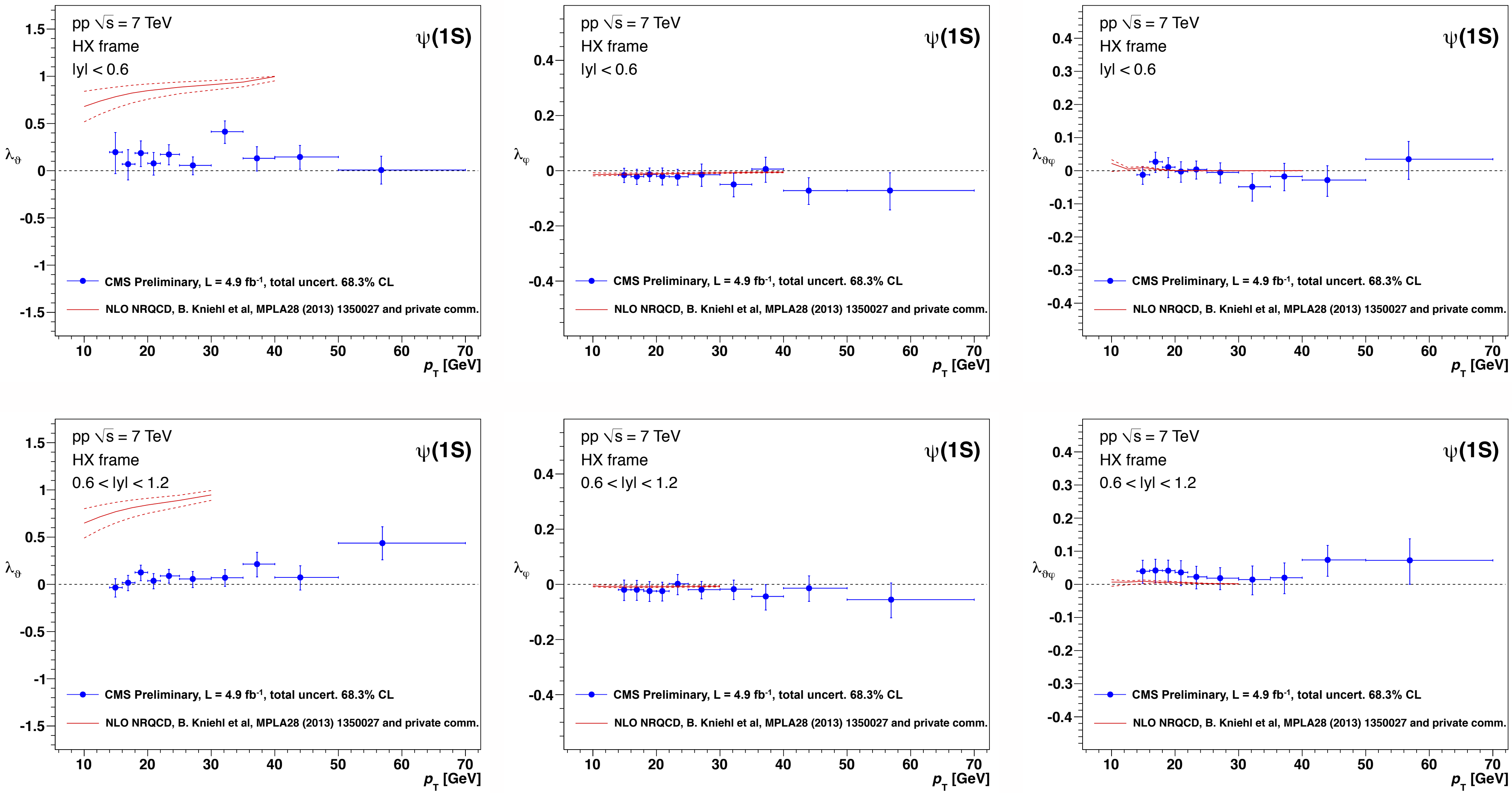
W: general angular distribution

ε: dimuon efficiency as a function of the muon momenta

Υ(nS) Polarization in the HX Frame, 0.6 < |y| < 1.2



ψ(1S): Comparison to NLO NRQCD



ψ(2S): Comparison to NLO NRQCD