Quarkonium polarization in pp collisions at $\sqrt{s} = 7$ TeV with the CMS experiment

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on behalf of the CMS collaboration

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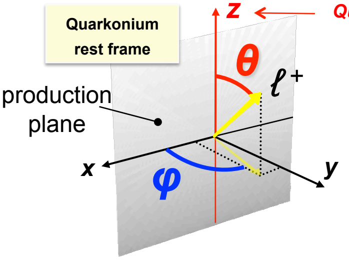
Quarkonium polarization: testing non-perturbative QCD

- Quarkonium production allows us to study hadron formation; important to understand 99% of the visible mass in the Universe
- The Standard Model for hadron formation is (non-perturbative) QCD; NRQCD = effective theory devoted to high-p_T quarkonium production

- Υ polarization measurements: probe NRQCD for heavy quarkonia and high p_T
- J/ψ and $\psi(2S)$ measurements: probe NRQCD at very high p_T/m ratios
- $\psi(2S)$: the only S-wave quarkonium not affected by feed-downs from P states

- This talk presents the polarizations of the $\Upsilon(nS)$ and $\psi(2S)$ states, measured by CMS in pp collisions at $\sqrt{s} = 7$ TeV
- The $\psi(2S)$ results are *new*

Quarkonium polarization: variables and frames



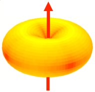
Most general observable angular decay distribution:

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

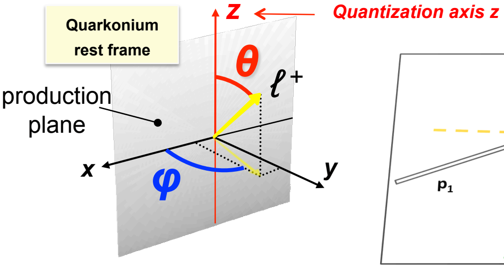
$\lambda_\theta = +1$
$\lambda_\varphi = \lambda_{\theta\varphi} = 0$

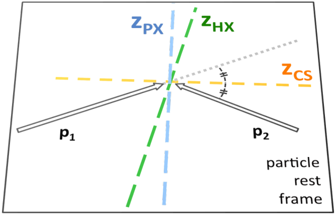
$J_z = \pm 1$ → $\lambda_\theta = +1$: **"transverse"** polarization

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



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



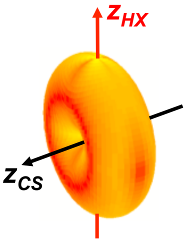


Helicity (HX): direction of quarkonium momentum
Collins-Soper (CS): direction of relative velocity of colliding particles (p_1, p_2)
Perpendicular helicity (PX): perpendicular to CS

Importance of measuring the full angular distribution

- Most experiments only measured the polar anisotropy, λ_ϑ, and only in one frame; this is insufficient to characterize the polarization of a particle
- The full angular distribution (three λ parameters) must be provided; ideally in more than one frame
- The shape of the angular distribution is invariant by rotation and can be characterized by the frame-independent parameter $\tilde{\lambda}$

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



$$\lambda_\theta = +1 \quad \lambda_\phi = -1$$

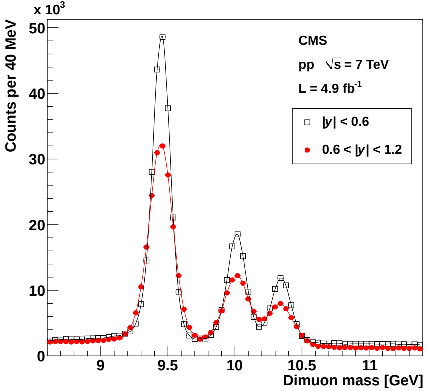
$$\lambda_\theta = -1 \quad \lambda_\phi = 0$$

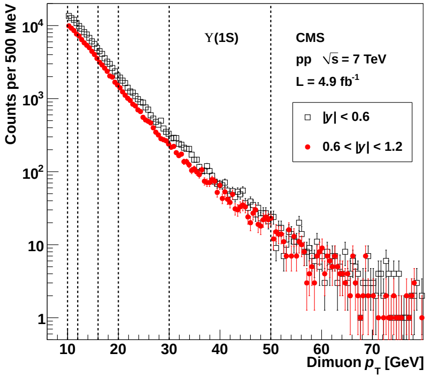
$$\tilde{\lambda} = -1$$

$$\lambda_\theta = +1 \quad \lambda_\phi = 0$$

$$\tilde{\lambda} = +1$$

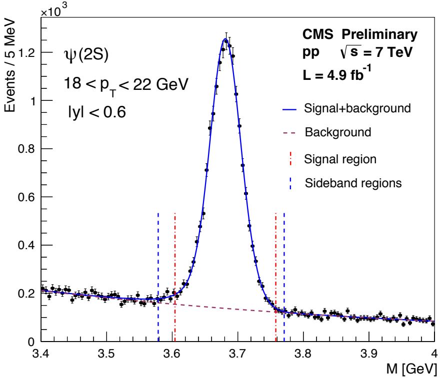
- $\Upsilon(nS)$ dimuon trigger: $M = 8.5$–11.5 GeV; $p_{\rm T} > 9$ GeV; $|y| < 1.25$
- Analysis in 5 $p_{\rm T}$ bins (10–50 GeV) and 2 $|y|$ bins: 0–0.6; 0.6–1.2
- Total signal yields: 222 k (1S); 82 k (2S); 51 k (3S)

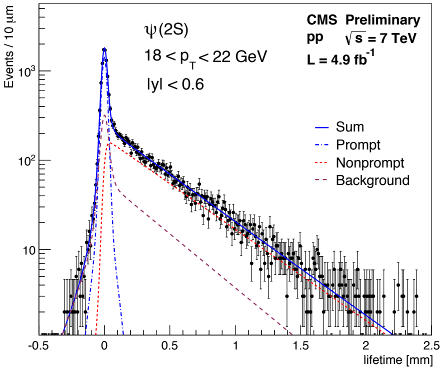




The $\psi(2S)$ 7 TeV data; 2011; $L_{\text{int}} = 4.9\,\text{fb}^{-1}$

- $\psi(2S)$ dimuon trigger: $M = 3.35$–4.05 GeV; $p_T > 7$ GeV
- Analysis in 4 p_T bins (14–50 GeV) and 2 $|y|$ bins: 0–0.6; 0.6–1.2
- Total signal yields: 262 k (prompt plus non-prompt)

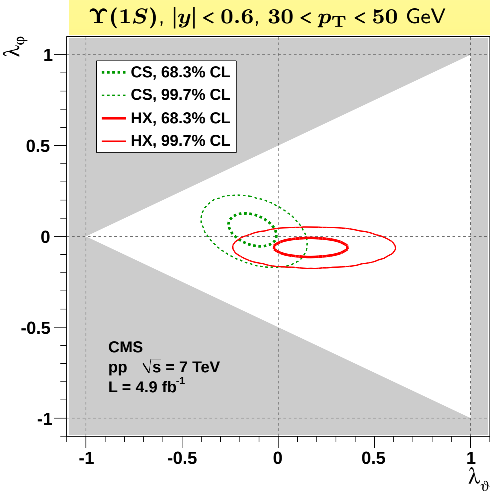




The analysis framework

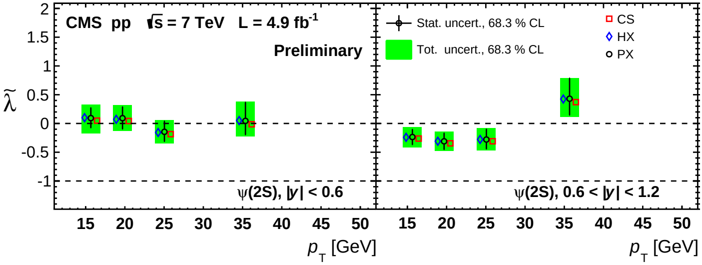
- We measure the Posterior Probability Distributions of the λ_ϑ, λ_φ, $\lambda_{\vartheta\varphi}$ and $\tilde{\lambda}$ polarization parameters in three frames (HX, CS, PX)

1. Events distributed as in the background model (built from the sidebands) are subtracted from the data sample (using a likelihood-ratio criterion)
2. The PPD is determined from the remaining signal-like events
3. Results and uncertainties are obtained from 1D projections of the PPDs

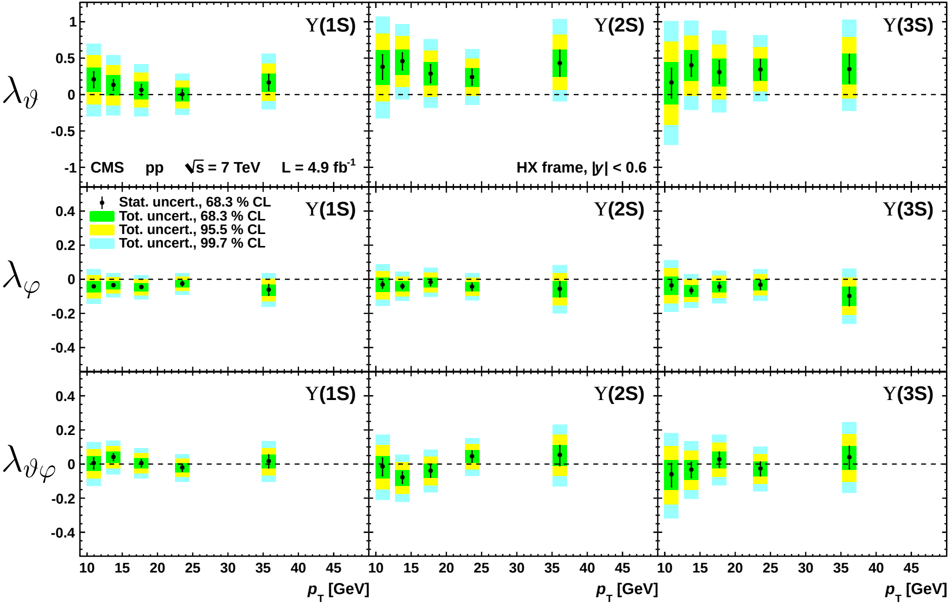


Systematic uncertainties

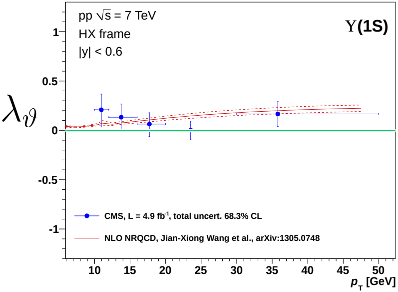
- Systematic effects are studied on data and with pseudo-experiments
- Main sources: framework; background model; and (di)muon efficiencies
- These uncertainties are propagated to the PPD
- Total uncertainties are dominated by systematics at low p_{T} and statistics at high p_{T}
- Very good agreement between the $\tilde{\lambda}$ parameters measured in the three frames: no indication for unaccounted systematic effects

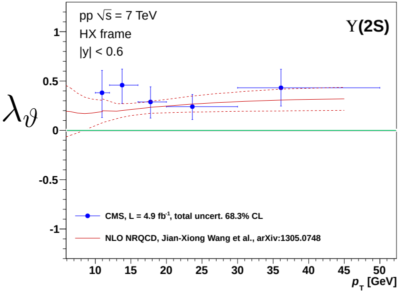


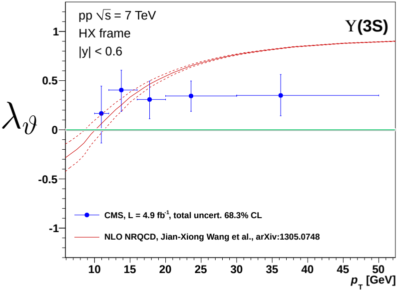
$\Upsilon(nS)$ polarizations in the HX frame, $|y| < 0.6$



Comparison with NLO NRQCD: $\Upsilon(nS)$

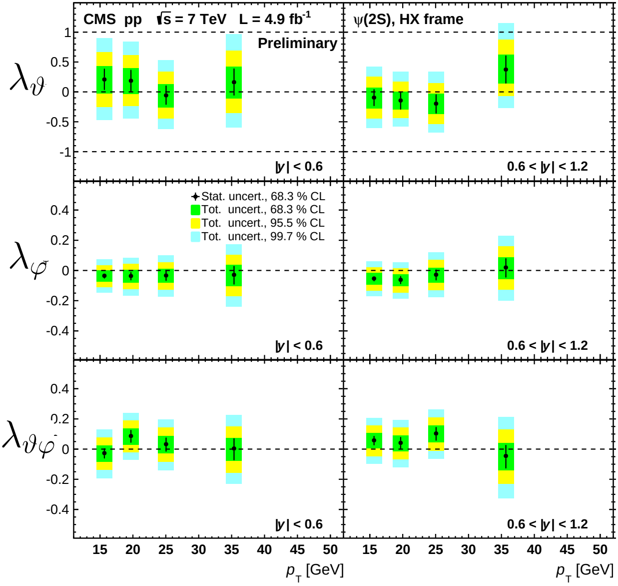






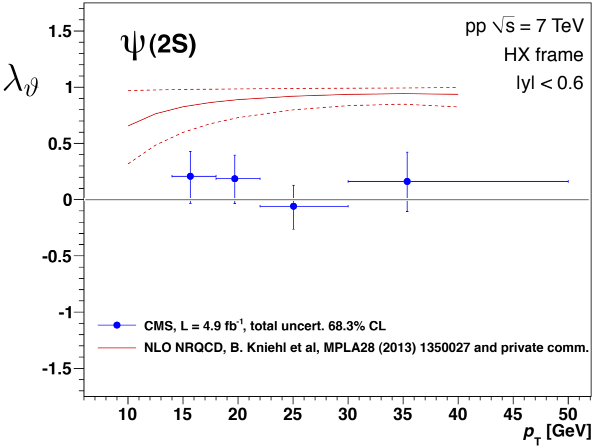
- $\Upsilon(1S)$: large χ_b feed-down contribution, but the χ_b octet MEs are unconstrained (lack of data on χ_b yields and polarizations)
- $\Upsilon(3S)$: practically always produced directly and depends only on (constrained) $\Upsilon(nS)$ octet MEs $\rightarrow$ the data-theory comparison is more stringent
- In fact, the $\Upsilon(3S)$ case is where the data and theory disagree the most...
- NLO NRQCD calculations by J.-X. Wang et al., arXiv:1305.0748 [hep-ph]

$\psi(2S)$ polarizations in the HX frame, $|y| < 0.6$ and $0.6 < |y| < 1.2$



- The $\psi(2S)$ shows no signs of strong polarizations
- The $\psi(2S)$ is not affected by feed-down from heavier quarkonia → easier comparison to theory. . .

Comparison with NLO NRQCD: $\psi(2S)$



- The CMS results disagree with existing NLO NRQCD theoretical calculations
- Calculations by Mathias Butenschoen and Bernd Kniehl; arXiv:1212.2037 [hep-ph]

Summary of the CMS measurements

- The $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ and $\psi(2S)$ polarizations were measured in pp collisions at $\sqrt{s} = 7$ TeV, with dimuon data collected by CMS, corresponding to an integrated luminosity of 4.9 fb^{-1}

- The three anisotropy parameters λ_ϑ, λ_φ, $\lambda_{\vartheta\varphi}$ and the frame-invariant $\tilde{\lambda}$ were measured in three frames: HX, CS and PX

- Results were obtained in several p_T bins and two rapidity ranges, covering the ranges $10 < p_\mathrm{T} < 50$ GeV and $|y| < 1.2$

- No evidence of strong polarizations, transverse or longitudinal

- For more details on the concepts, analysis and results:
  CMS Coll., PRL 110, 081802 (2013)
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH11023
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH13003
  P. Faccioli et al., Eur. Phys. J. C69 (2010) 657 and references therein

- We sincerely thank Bernd Kniehl and Jian-Xiong Wang for providing us with their NLO NRQCD calculations

Conclusion: NRQCD is far from explaining quarkonium hadroproduction

- The measured $\Upsilon(3S)$ and $\psi(2S)$ polarizations, at high p_{T} and high p_{T}/m, do not show strong transverse polarizations, contrary to predictions for directly produced S-wave quarkonia

- This observation might reveal that:

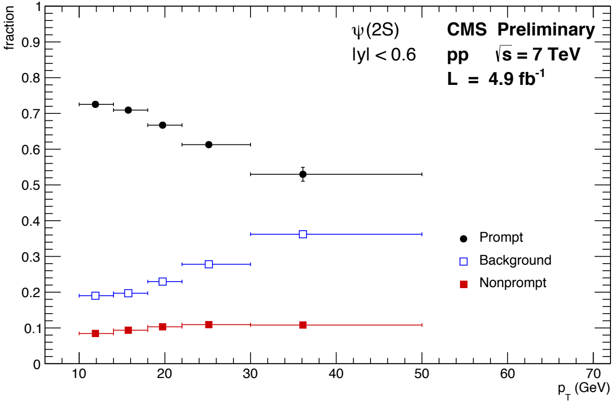
  1. the colour-octet transition LDMEs are incorrectly fitted
  2. NRQCD is not a good approximation of QCD:
     are short- and long-distance processes factorizable?
     are the velocity scaling rules correct?
  3. (non-perturbative) QCD is unable to describe quarkonium production
     $\rightarrow$ physics beyond the standard model ? ☺

- The J/ψ polarization at 7 TeV is also being measured, up to $p_{\mathrm{T}} \sim 70$ GeV
- The 2012 data (8 TeV, $L_{\mathrm{int}} \sim 20$ fb^{-1}) will allow more precise measurements of the $\Upsilon(nS)$ and $\psi(nS)$ polarizations
- We will also attempt the very challenging measurement of the polarizations of the χ_c and χ_b states, using the radiative decays $\chi \to V + \gamma$, with the γ reconstructed from conversions to e^+e^-

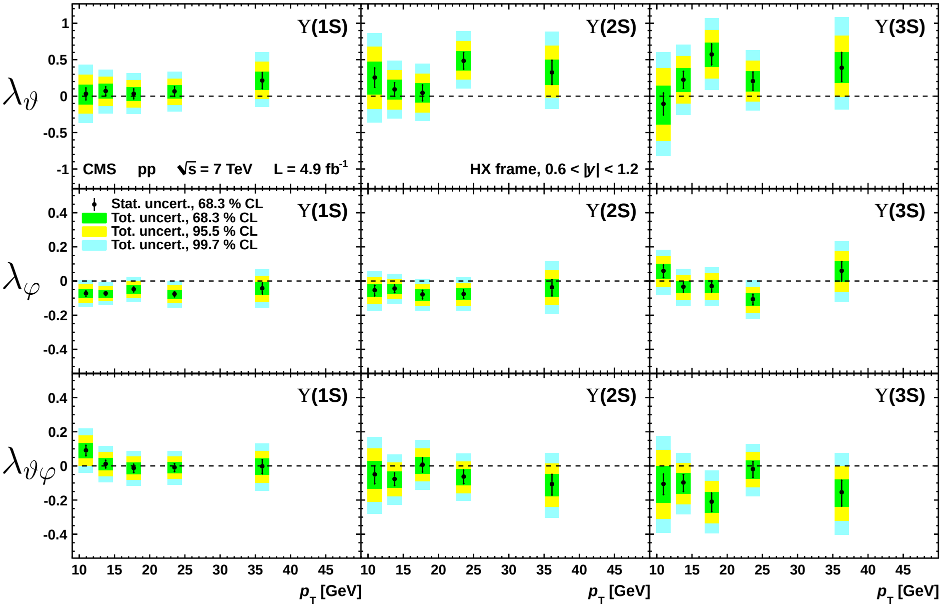
Backup slides

Contributions to the $\psi(2S)$ prompt signal region

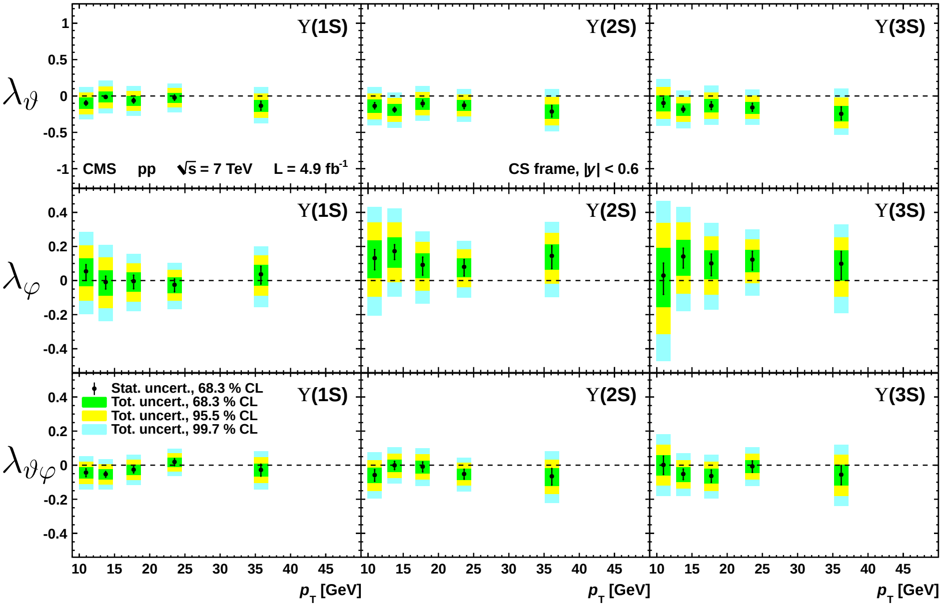
- Fractions of prompt (closed circles), continuum-background (open squares), and non-prompt (closed squares) $\psi(2S)$ events in the prompt-signal mass-lifetime region, as functions of p_{T}, for $|y| < 0.6$
- The prompt-signal region is defined as a 2D window of $\pm 3\sigma$ widths in dimuon mass and (pseudo-proper) lifetime, where the σ values are the respective resolutions, which depend on the dimuon p_{T} and $|y|$ bins



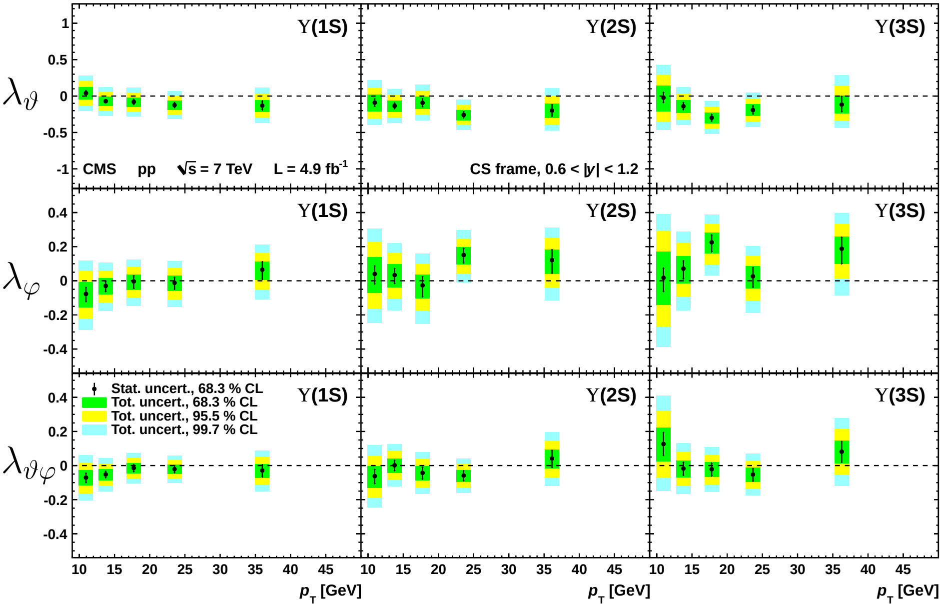
$\Upsilon(nS)$ polarization in the HX frame, $0.6 < |y| < 1.2$



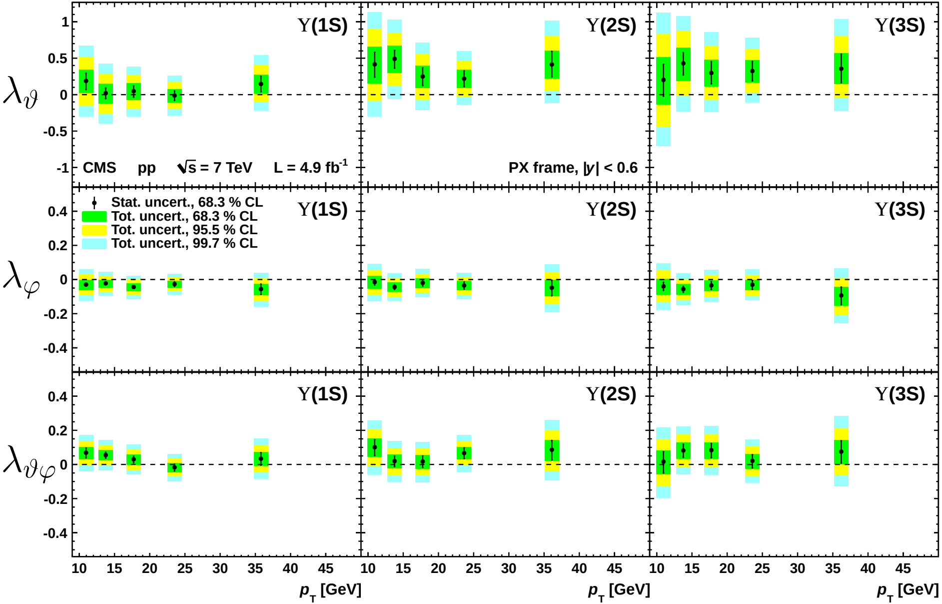
$\Upsilon(nS)$ polarization in the CS frame, $|y| < 0.6$



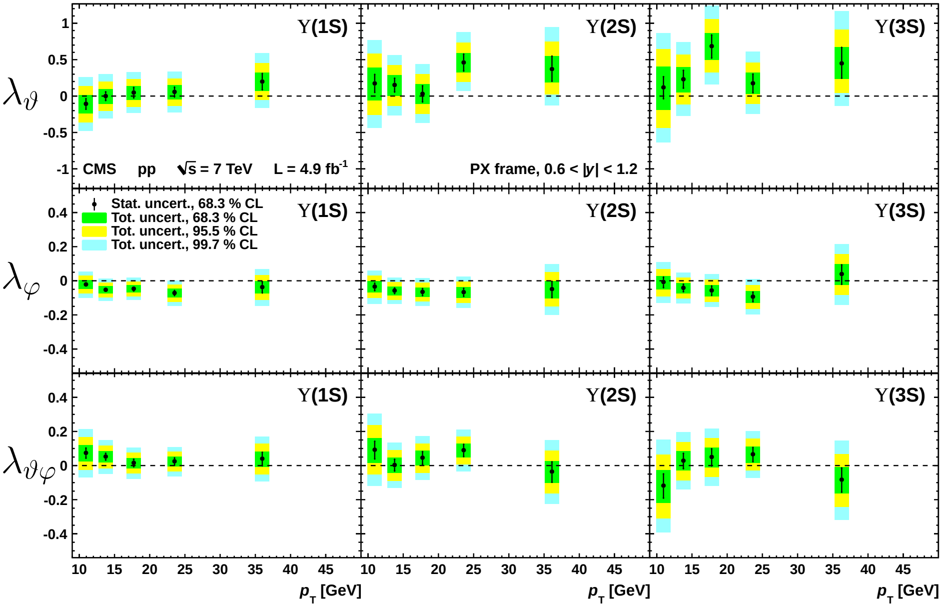
$\Upsilon(nS)$ polarization in the CS frame, $0.6 < |y| < 1.2$



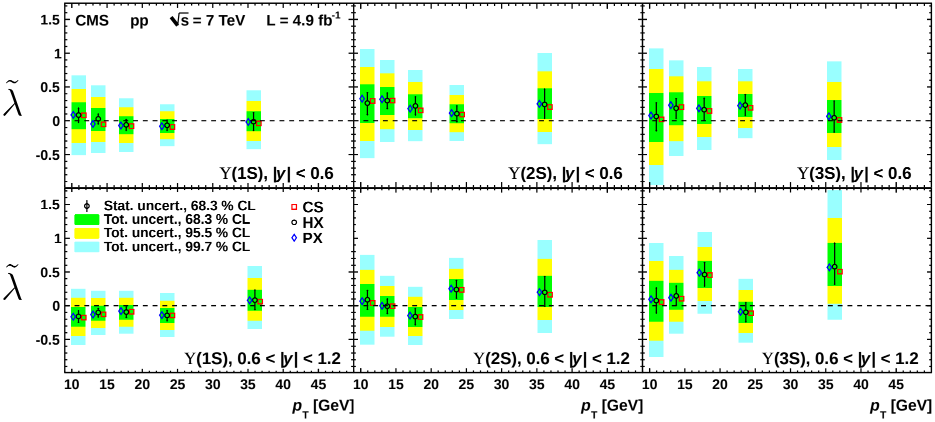
$\Upsilon(nS)$ polarization in the PX frame, $|y| < 0.6$



$\Upsilon(nS)$ polarization in the PX frame, $0.6 < |y| < 1.2$



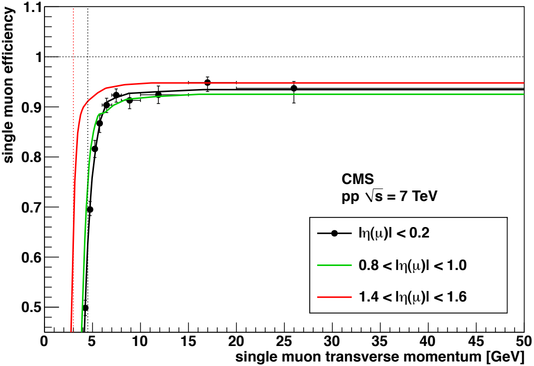
$\tilde{\lambda}$ results



- Consistent frame-invariant parameters in the three reference frames

- Single-muon efficiencies carefully measured with a *Tag&Probe* method and corrected for on an event-by-event basis

- Muon-pair correlations induced (at high p_{T}) by the dimuon trigger are negligible in the phase space of this analysis (from detailed MC studies, validated with data collected with single-muon triggers)

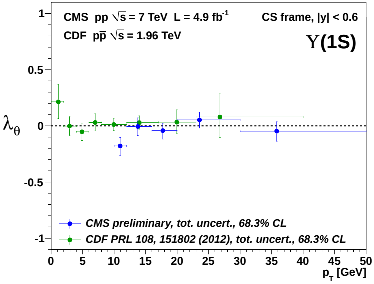


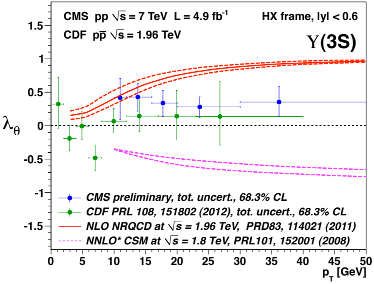
Definition of the PPD

$$\mathcal{P}(\vec{\lambda}) \propto \prod_i \frac{1}{\mathcal{N}(\vec{\lambda})} W(\cos\vartheta^{(i)}, \varphi^{(i)} | \vec{\lambda})\, \epsilon(\vec{p}_1^{\,(i)}, \vec{p}_2^{\,(i)})$$

$\mathcal{N}$: normalization
W: general angular distribution
ϵ: dimuon efficiency as a function of the muon momenta

- Construct the background model interpolating from the mass sidebands (and non-prompt region)
- Using the model, define the likelihood $\mathcal{L}_B$ for $(p_{\mathrm{T}}, y, M, \cos\vartheta, \varphi)$ to represent a background event
- Using the entire data sample in the considered p_{T}, y, M bin, define the likelihood $\mathcal{L}_{S+B}$ for $(p_{\mathrm{T}}, y, M, \cos\vartheta, \varphi)$ to represent an event in our analysis sample, irrespectively of being signal or background
- Normalize $\mathcal{L}_B$ to $\mathcal{L}_{S+B}$ so that the ratio of the integrals is the background fraction f_{BG}
- Take one event from the data sample and calculate $R = \mathcal{L}_B(p_{\mathrm{T}}, y, M, \cos\vartheta, \varphi) \,/\, \mathcal{L}_{S+B}(p_{\mathrm{T}}, y, M, \cos\vartheta, \varphi)$
- Generate a uniform deviate $r \in [0, 1]$
- Classify the event as background if $R > r$
- An event classified as background is removed from the sample





- Measurements of CMS extend beyond the p_{T} and $|y|$ ranges probed by CDF
- CMS has smaller uncertainties at high p_{T}, where the theory is more reliable
- Both measurements do not show strong polarizations