Measurement of quarkonium polarization in pp collisions at $\sqrt{s} = 7\,\text{TeV}$ with the CMS experiment

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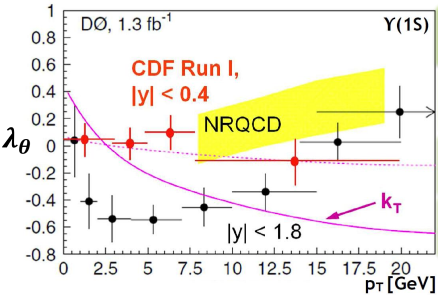
on behalf of
the CMS collaboration

- Despite many attempts made in recent years, quarkonium production is not yet well understood
- Various models can describe cross sections well, but quarkonium polarization is sensitive to the production mechanism and still puzzling
- New measurements needed, especially for the Υ family and at high p_{T}

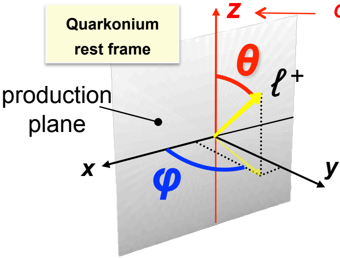


NRQCD factorization
Braaten & Lee, Phys. Rev. D63, 071501(R) (2001)

DØ
DØ Collaboration, Phys. Rev. Lett. 101, 182004 (2008)

CDF Run I
CDF Collaboration, Phys. Rev. Lett. 88, 161802 (2002)

k_T factorization
Baranov & Zotov, JETP Lett. 86, 435 (2007)

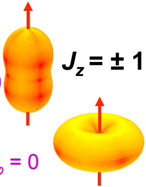


Quantization axis z

Most general observable
angular decay distribution:

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

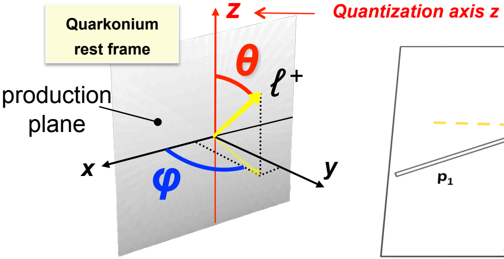
$\lambda_\theta = +1$
$\lambda_\varphi = \lambda_{\theta\varphi} = 0$

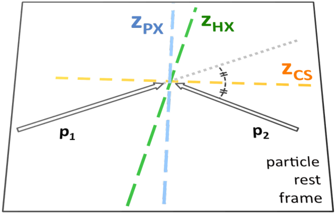


$J_z = \pm 1 \rightarrow$ $\lambda_\theta = +1$: **"transverse"** polarization

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

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





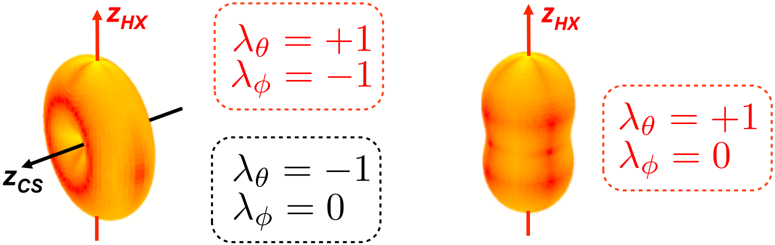
Helicity axis (HX): direction of quarkonium momentum

Collins-Soper axis (CS): direction of relative velocity of colliding particles (p_1, p_2)

Perpendicular helicity axis (PX): perpendicular to CS

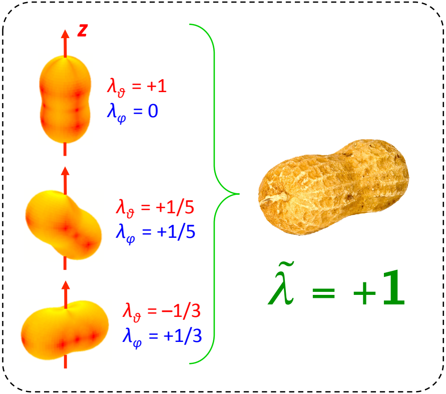
Need to measure full angular distribution

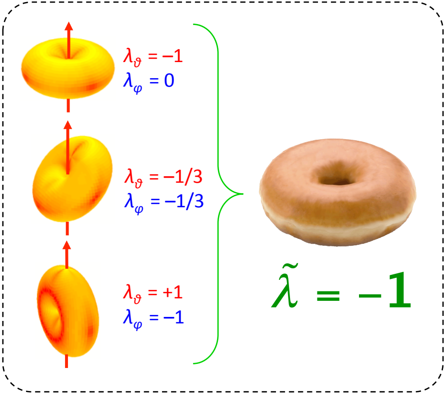
- In the past, only λ_ϑ was measured in one reference frame
- Two very different physical cases are with same λ_ϑ (shown below), so the full angular distribution (three polarization parameters) must be measured
- Observed polarization depends on the frame



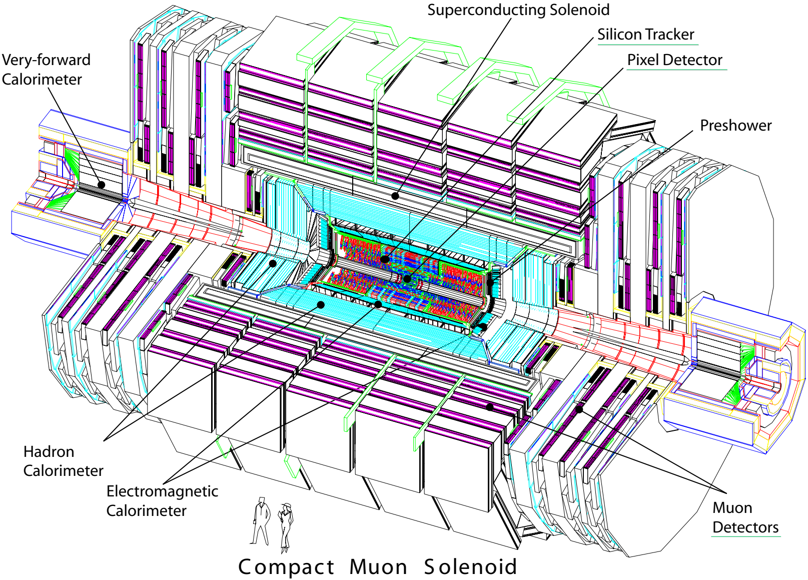
- The shape of the angular distribution is obviously frame-invariant (= invariant by rotation)
- It can be characterized by a frame-independent parameter, e.g.

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

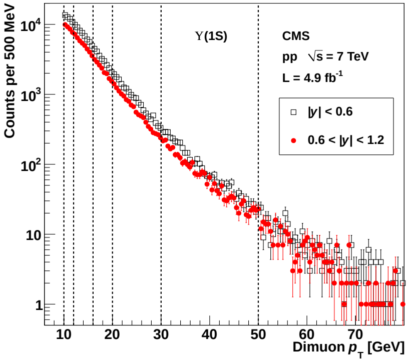




The CMS detector



- We measure λ_ϑ, λ_φ, $\lambda_{\vartheta\varphi}$ and $\tilde{\lambda}$ in three frames (HX, CS, PX)
- Data collected in 2011 with $L_{\rm int} = 4.9\,\text{fb}^{-1}$
- Upsilon dimuon trigger:
  - dimuon mass: 8.5–11.5 GeV
  - dimuon rapidity: $|y| < 1.25$
  - dimuon $p_{\rm T} > 5$, 7, 9 GeV
- Independent in five $p_{\rm T}$ bins: 10 – 50 GeV and two rapidity ranges: $|y| < 0.6$ and $0.6 < |y| < 1.2$

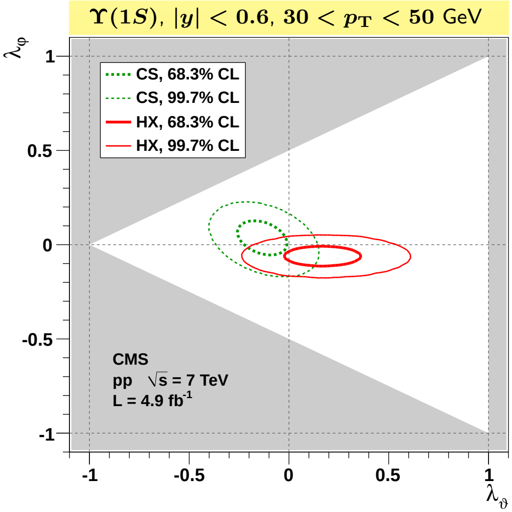


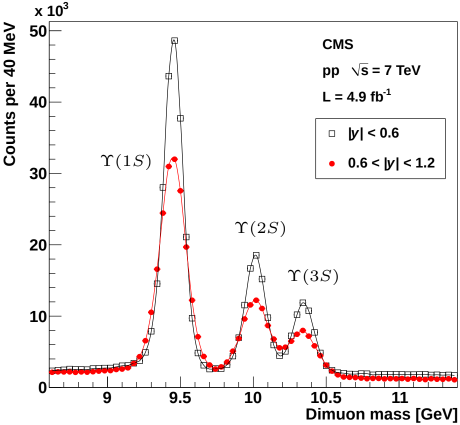
- Estimated signal yields in the probed kinematic phase space:

$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
222 k	82 k	51 k

The Posterior Probability Distribution (PPD) of the polarization parameters $\vec{\lambda} = (\lambda_\vartheta, \lambda_\varphi, \lambda_{\vartheta\varphi})$, is directly calculated

1. Events distributed in the background model are subtracted from the data sample
2. Define the PPD from the remaining signal-like events
3. Numerical results and uncertainties are obtained from the 1D projections of the PPD

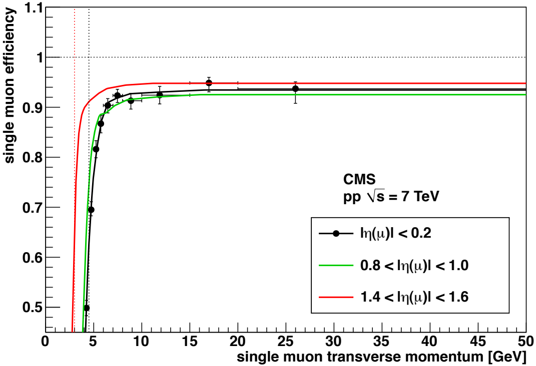




- Signal regions defined as $\pm 1\sigma$ around mass peaks
- Background fractions in these regions are determined by fits to the dimuon mass distributions
- Angular distribution and dimuon kinematics (p_{T}, M, $|y|$) of background events modeled as weighted sums of the distributions in the mass sidebands, left of the $\Upsilon(1S)$ and right of the $\Upsilon(3S)$

- Event-by-event background subtraction of *background-like* events using a likelihood-ratio criterion

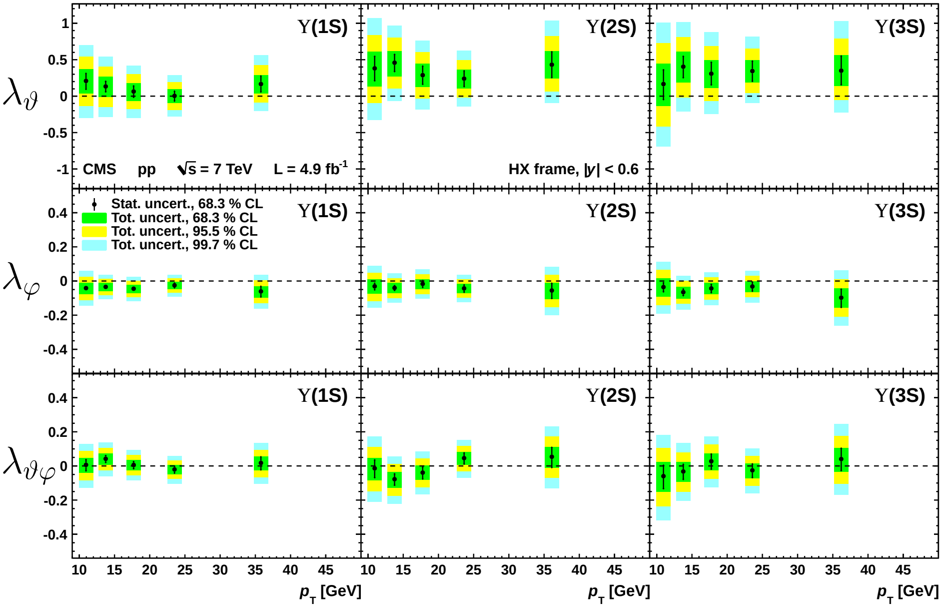
- Single-muon efficiencies measured with data-driven *Tag&Probe* method
- Carefully studied to avoid artificial spurious polarizations
- Muon-pair correlations are negligible in the probed phase space from detailed MC studies
- Efficiencies are accounted for on an event-by-event basis



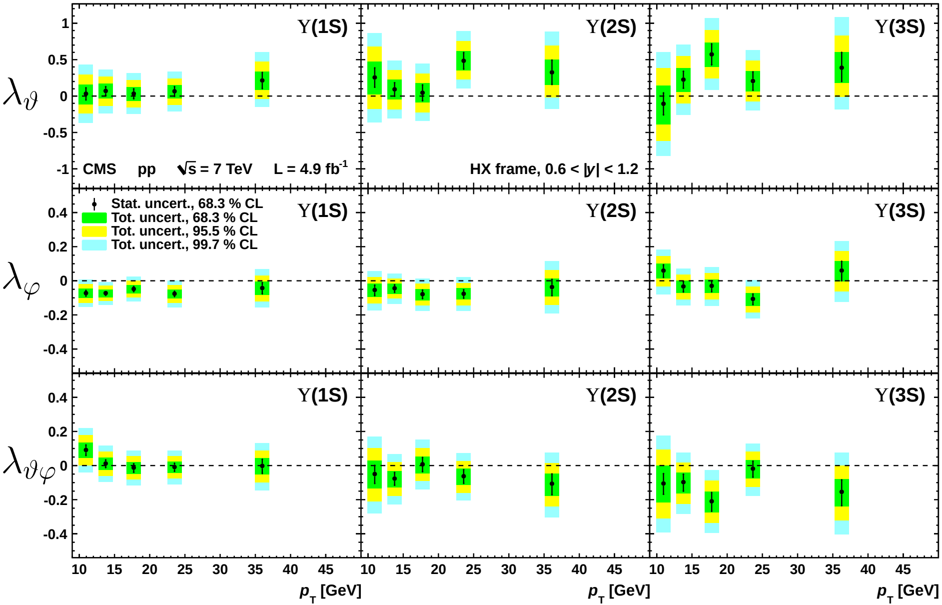
Systematic effects

- Systematic effects studied on data and with pseudo-experiments
- Individual sources of systematic uncertainty are related to:
  1. Analysis framework
  2. Background model
  3. Muon efficiencies
- Systematic uncertainties are propagated to the PPD
- Total uncertainties of the measurements are dominated by systematics at low p_{T} and statistics at high p_{T}
- $\Upsilon(2S)$ and $\Upsilon(3S)$ systematic uncertainties are dominated by the background model uncertainty, especially at low p_{T}

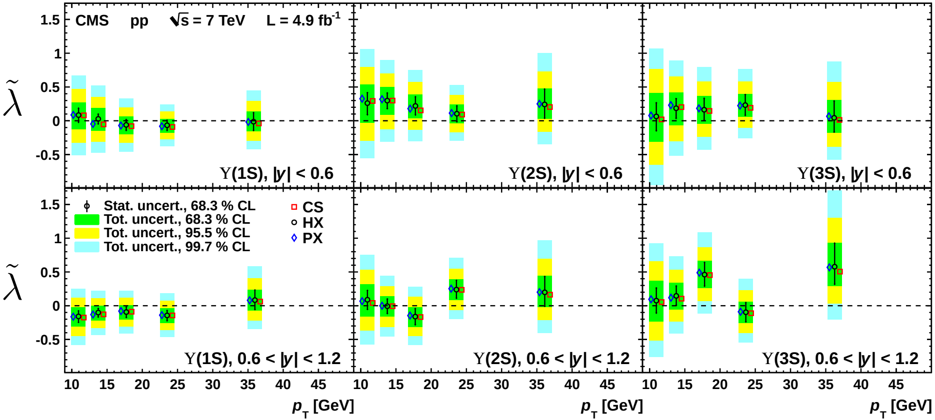
$\Upsilon(nS)$ polarization in the HX frame, $|y| < 0.6$



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

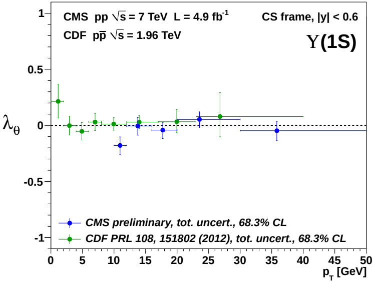


$\tilde{\lambda}$ results

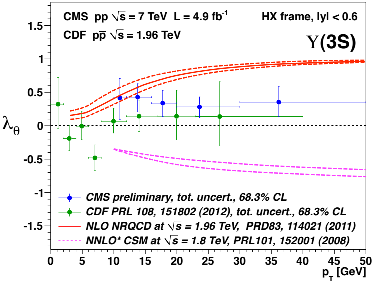


- Consistent frame-invariant parameters in the three reference frames
- No evidence for unaccounted systematic uncertainties

Comparison with CDF and theory



- CMS extends the measurements beyond the p_{T} and rapidity ranges probed by CDF at the Tevatron
- CMS has smaller uncertainties at high p_{T}, where the theory is more reliable
- Both measurements do not show strong polarizations: puzzling !



- $\Upsilon(1S)$ suffers from large χ_b feed-down contribution, with unknown polarization
- $\Upsilon(3S)$ polarization calculated more reliably
- Theory predictions needed for λ_φ and $\lambda_{\vartheta\varphi}$, and in the CS and PX frames

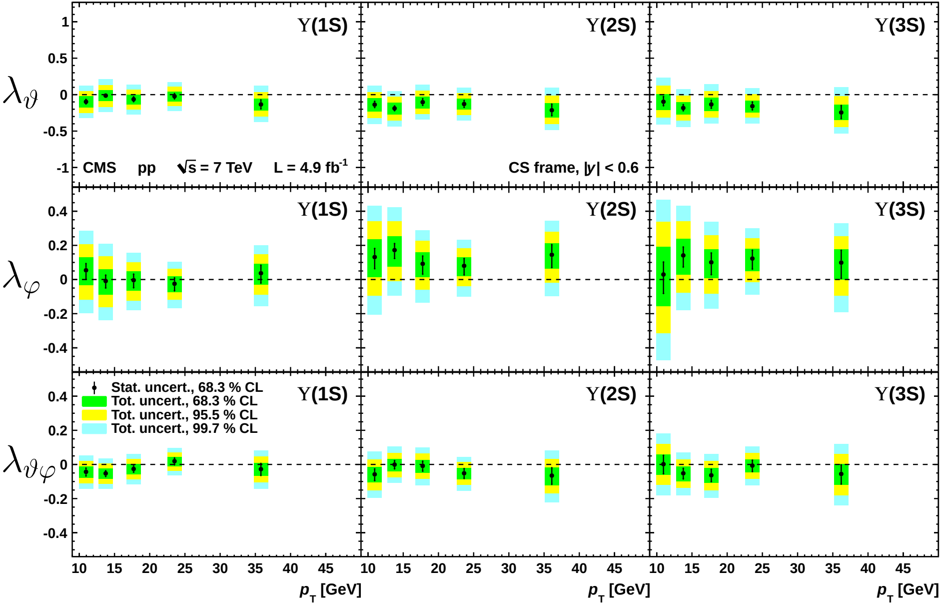
Summary

- $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ polarizations have been measured in pp collisions at $\sqrt{s} = 7$ TeV using the 2011 dimuon data collected by CMS, corresponding to an integrated luminosity of 4.9 fb^{-1}
- Three anisotropy parameters λ_{ϑ}, λ_{φ}, $\lambda_{\vartheta\varphi}$ and the frame invariant parameter $\tilde{\lambda}$ have been measured in three polarization frames: HX, CS and PX
- Results were obtained in five p_{T} bins and for two rapidity ranges, covering the kinematic region of $10 < p_{\mathrm{T}} < 50$ GeV and $|y| < 1.2$
- No evidence of strong polarizations, transverse or longitudinal, has been observed

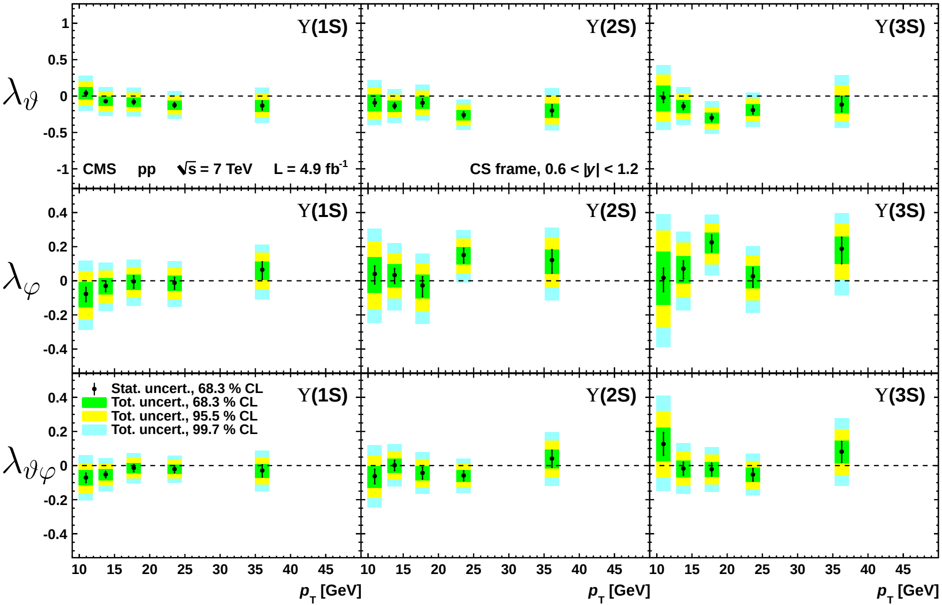
Thank you for your attention

Backup slides

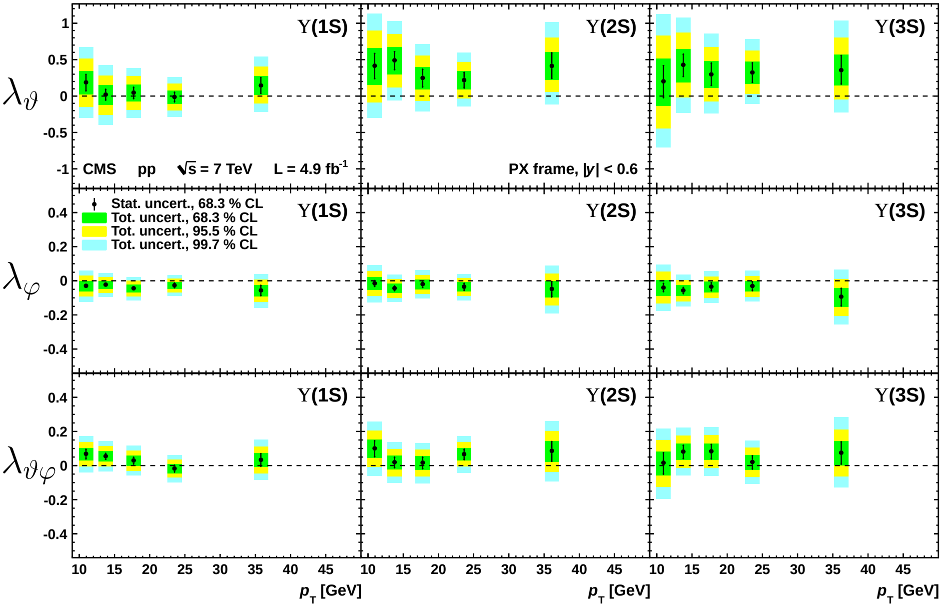
$\Upsilon(nS)$ polarization in the CS frame, $|y| < 0.6$



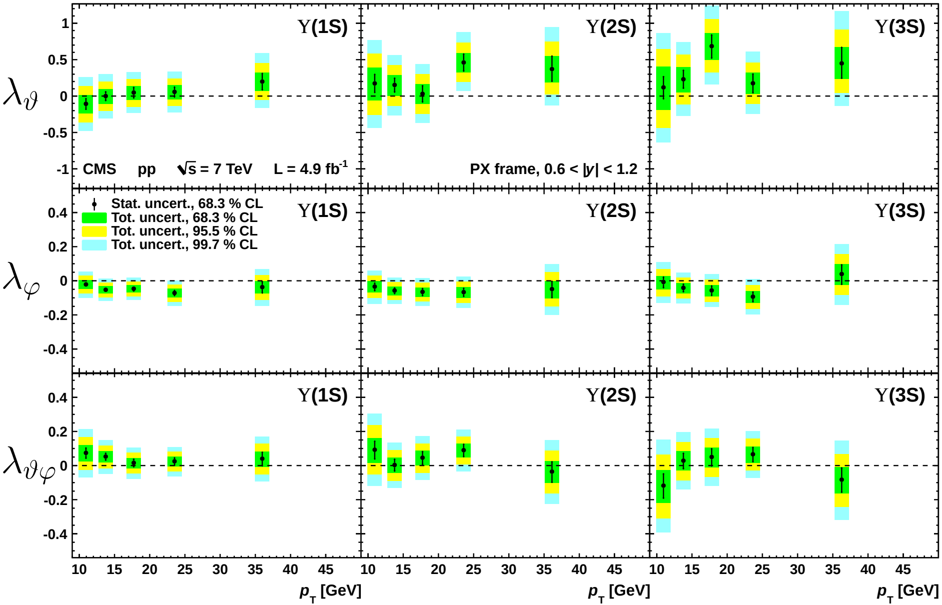
$\Upsilon(nS)$ polarization in the CS frame, $0.6 < |y| < 1.2$



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



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



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 a background model; in our case, we use an interpolation from the mass sidebands
- 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:
  - if $R > r$ the event is considered background
  - if $R < r$ the event is considered signal
- An event classified as background is removed from the sample