Measurement of $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ polarizations in pp collisions at $\sqrt{s} = 7\,\text{TeV}$ with the CMS experiment

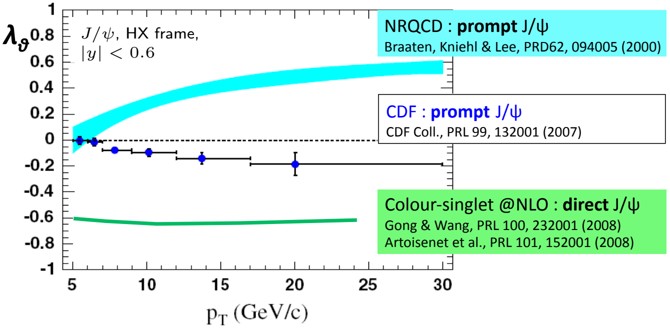
Valentin Knünz*
(HEPHY Vienna)

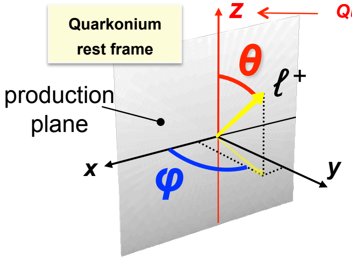
on behalf of
the CMS Collaboration

ICHEP, Melbourne, July 7^{th} 2012

*Supported by the Austrian Science Fund (FWF): P 24167-N16

- Quarkonium production is not yet understood, despite recent progress
- Differential cross sections are well described by various models, but quarkonium polarization remains very puzzling
- New measurements needed, especially for the Υ family and at high p_T





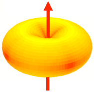
Most general observable angular decay distribution:

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

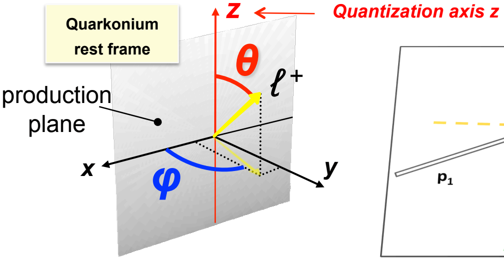
$\lambda_\theta = +1$
$\lambda_\varphi = \lambda_{\theta\varphi} = 0$

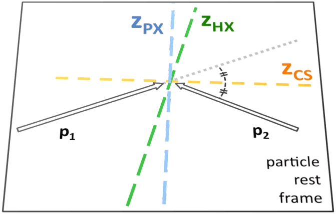
$J_z = \pm 1$ $\rightarrow$ λ_θ **= +1** : **"transverse"** polarization

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



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





Helicity axis (HX): quarkonium momentum direction

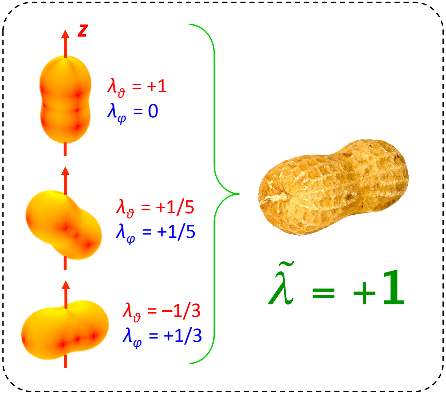
Collins-Soper axis (CS): average of the two beam directions

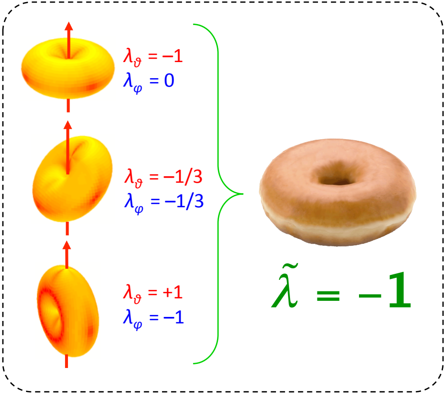
Perpendicular helicity axis (PX): perpendicular to CS

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

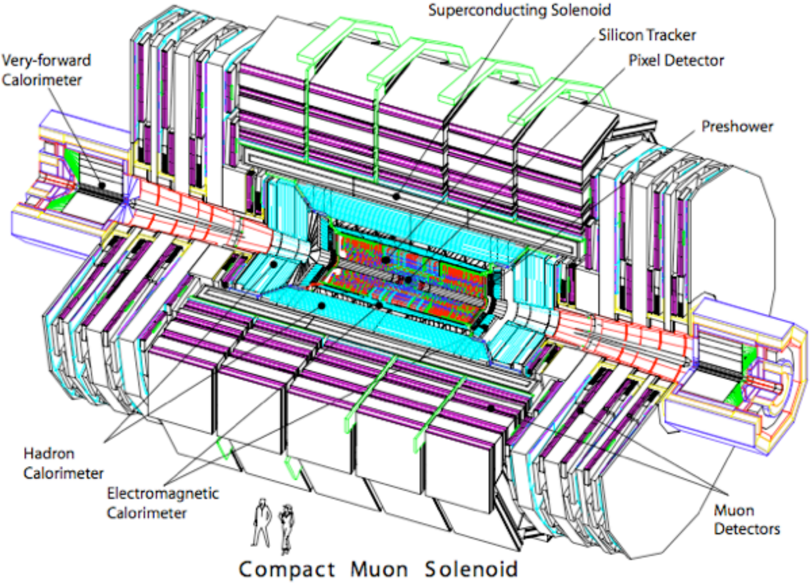
$$\tilde{\lambda} = \frac{\lambda_\vartheta + 3\lambda_\varphi}{1 - \lambda_\varphi}$$

Eur. Phys. J. C 69 (2010) 657

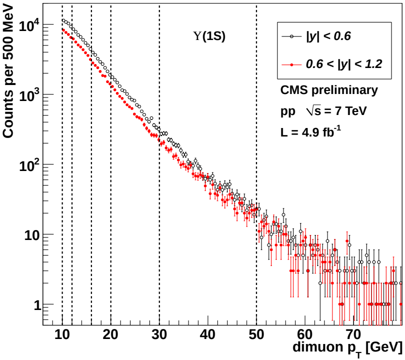




The CMS detector



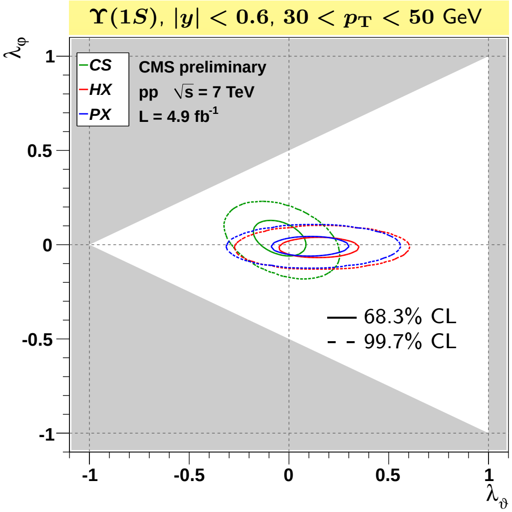
- We measure λ_ϑ, λ_φ, $\lambda_{\vartheta\varphi}$ and $\tilde{\lambda}$ in three frames (HX, CS, PX)
- In five p_T bins: 10–50 GeV and two rapidity ranges: $|y| < 0.6$ and $0.6 < |y| < 1.2$
- Using 2011 data: $L_{\text{int}} = 4.9\,\text{fb}^{-1}$
- Using an "Upsilon dimuon trigger":
  - dimuon mass: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

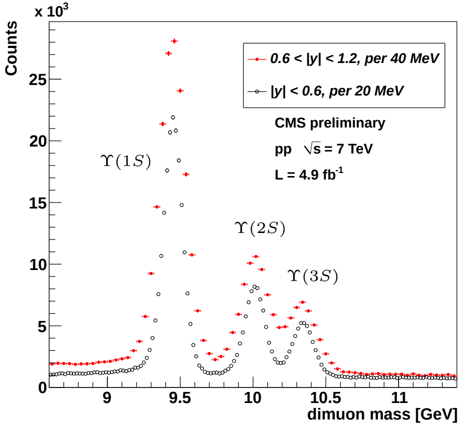


- Signal yields in the probed phase space: $\sim$222 k $\Upsilon(1S)$; $\sim$82 k $\Upsilon(2S)$; $\sim$51 k $\Upsilon(3S)$
- The analysis is independent of MC simulations, except to validate the absence of muon-pair correlations in the efficiencies

Instead of doing a fit, we *calculate directly* the posterior probability distribution (PPD) of the polarization parameters $\vec{\lambda} = (\lambda_\vartheta, \lambda_\varphi, \lambda_{\vartheta\varphi})$

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

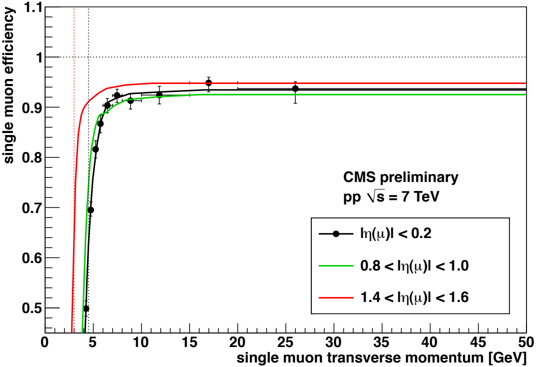




- Signal regions defined as $\pm 1\sigma$ around mass peaks
- Background fractions in these regions are determined by fits to the dimuon mass distributions
- Angular distribution and dimuon kinematics (p_{T}, M, $|y|$) of background events modeled as weighted sums of the distributions in the mass sidebands,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

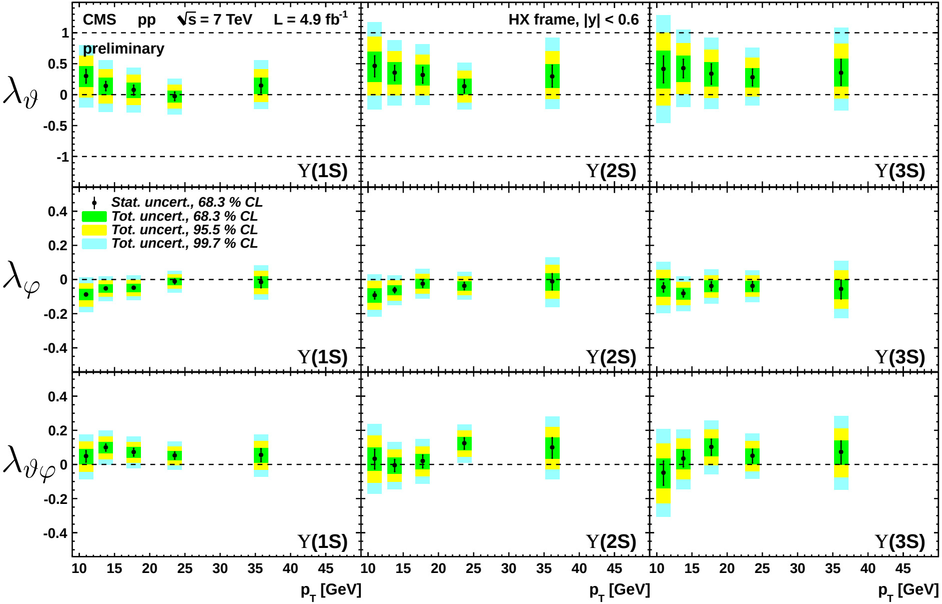
- Event-by-event background subtraction of *background-like* events (using a likelihood-ratio criterion)

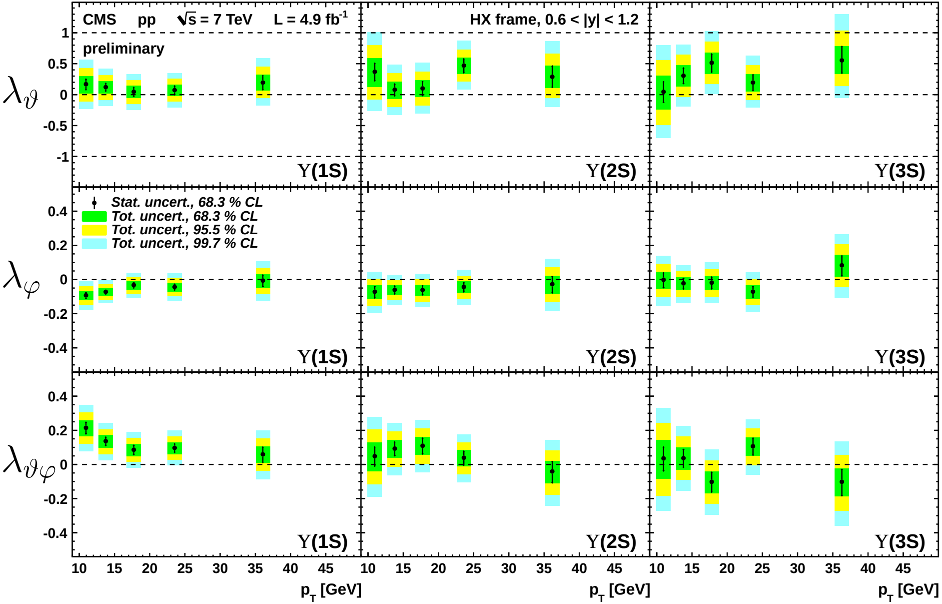
- Single-muon efficiencies measured with *Tag&Probe* using J/ψ dimuons
- Studied carefully: biased efficiencies $\rightarrow$ *spurious polarizations*
- Muon-pair correlations negligible in analysis phase space ($p_{\mathrm{T}} = 10$–50 GeV) (studied with detailed MC simulations)
- Efficiencies are accounted for on an event-by-event basis: $\varepsilon(p_{\mathrm{T}}^{\mu}, \eta^{\mu})$



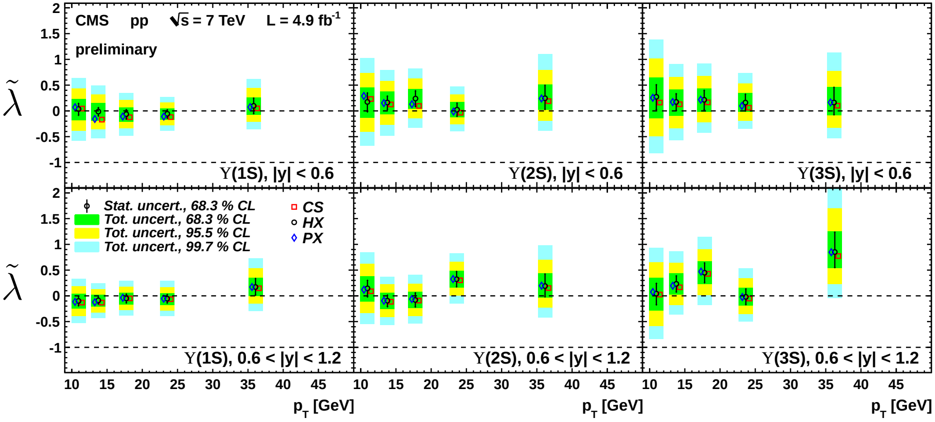
- Systematic effects studied on data and with pseudo-experiments
- The individual sources of systematic uncertainty are related to:
  1. Analysis framework
  2. Background model
  3. Muon efficiencies
- The systematic uncertainties are propagated to the PPD
- The total uncertainties of the measurements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

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

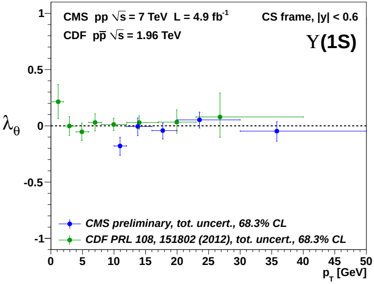


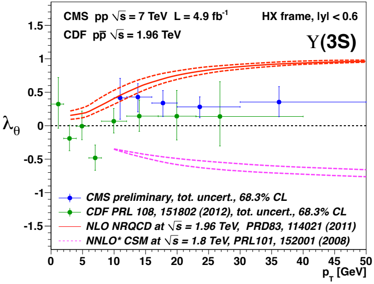

CMS pp √s = 7 TeV L = 4.9 fb-1
preliminary
HX frame, 0.6 < |y| < 1.2
λϑ
λφ
λϑφ
Stat. uncert., 68.3 % CL
Tot. uncert., 68.3 % CL
Tot. uncert., 95.5 % CL
Tot. uncert., 99.7 % CL
Υ(1S)
Υ(2S)
Υ(3S)
pT [GeV]

$\tilde{\lambda}$ results



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





- CMS extends the measurements beyond the p_{T} and rapidity ranges probed by CDF at the Tevatron
- With smaller uncertainties at high p_{T}, where the theory is more reliable
- 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

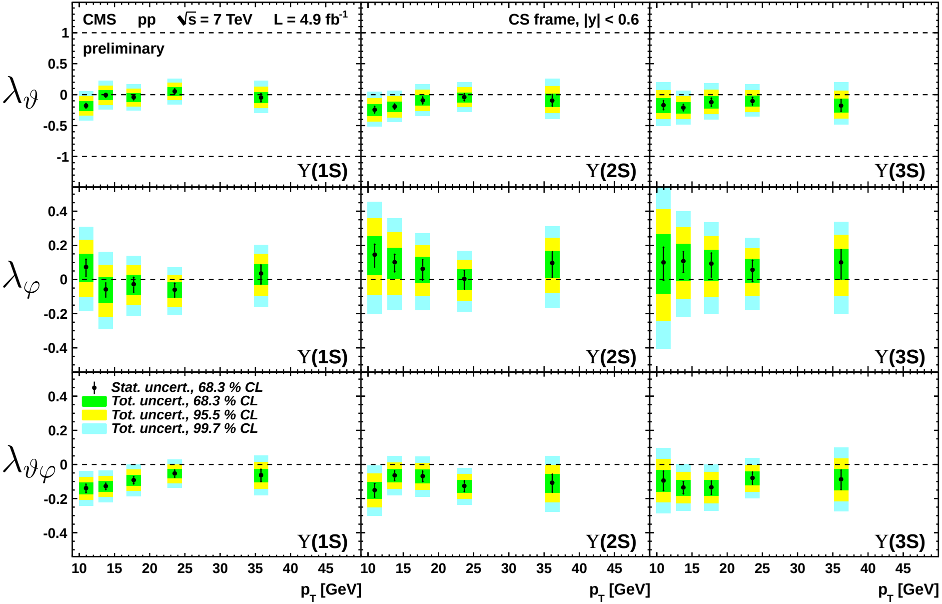
Summary

- CMS measured the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ polarizations in pp collisions at 7 TeV, using the 2011 dimuon data, corresponding to an integrated luminosity of 4.9 fb^{-1}
- The anisotropy parameters λ_ϑ, λ_φ and $\lambda_{\vartheta\varphi}$, as well as $\tilde{\lambda}$, were measured in three polarization frames: HX, CS and PX
- The results were obtained in five p_T bins and for two y ranges, covering the kinematic range $10 < p_\mathrm{T} < 50$ GeV and $|y| < 1.2$
- No strong polarizations, transverse or longitudinal, have been observed

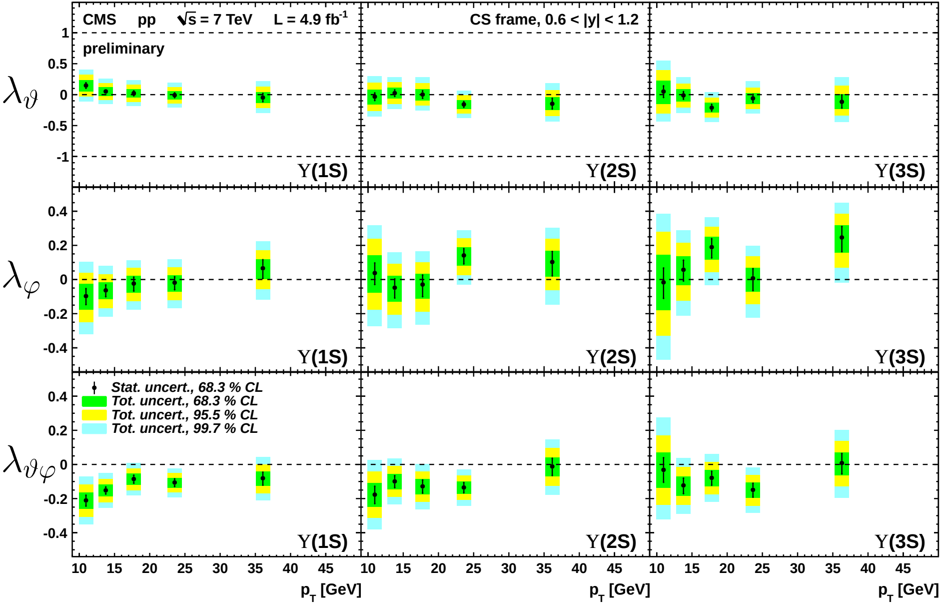
Other CMS B-Physics contributions at ICHEP:
Keith Ulmer - Heavy Flavour Results from CMS
Kai Yi - Quarkonium production with the CMS experiment

Backup slides

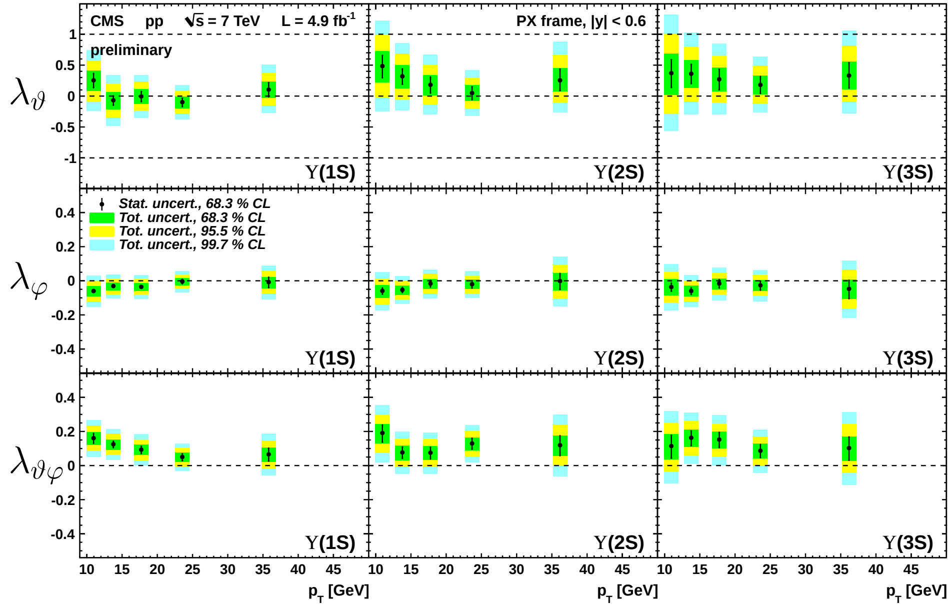
$\Upsilon(nS)$ polarization in the CS frame, $|y| < 0.6$



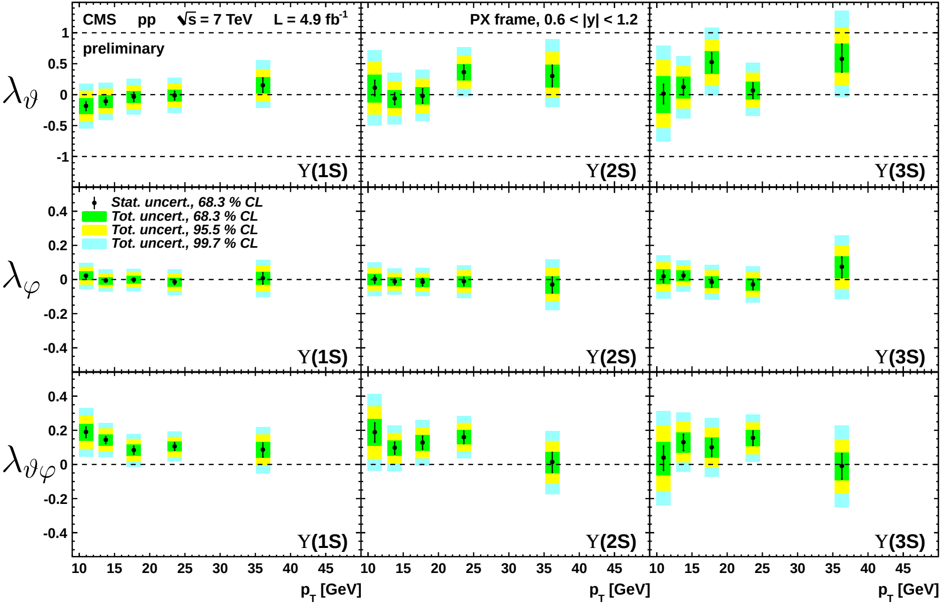
$\Upsilon(nS)$ polarization in the CS frame, $0.6 < |y| < 1.2$



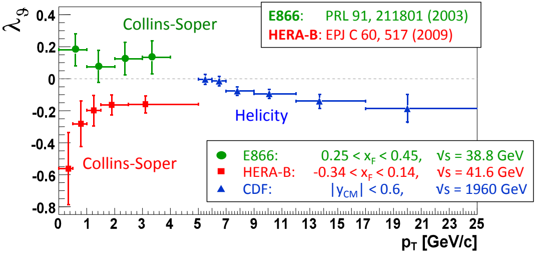
$\Upsilon(nS)$ polarization in the PX frame, $|y| < 0.6$

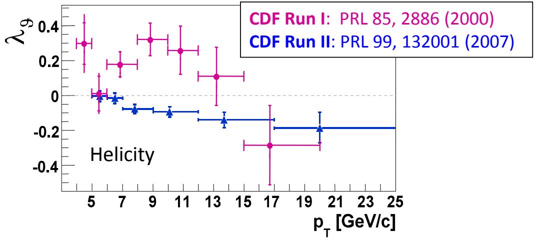


$\Upsilon(nS)$ polarization in the PX frame, $0.6 < |y| < 1.2$

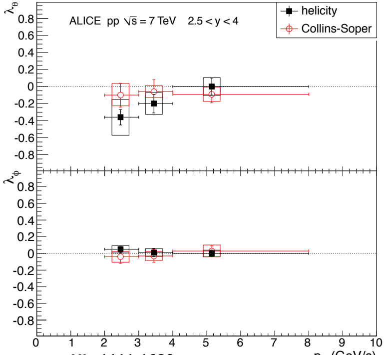


Experimental results on quarkonium polarization: J/ψ

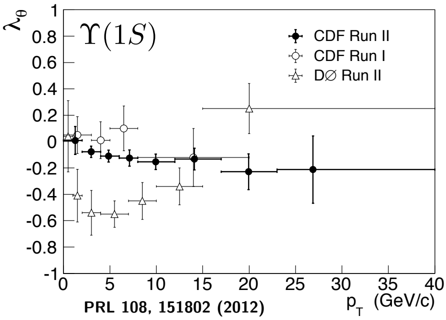


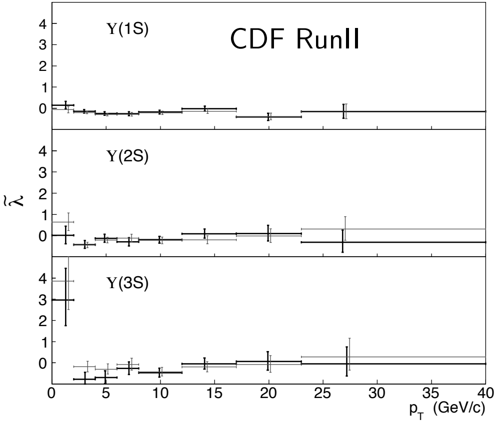


Apparent inconsistency of results between experiments and even within the same experiment.



arXiv:1111.1630





- First measurement of the polarization of the individual $\Upsilon(nS)$ states
- Measurement of λ_ϑ, λ_φ, $\lambda_{\vartheta\varphi}$ and $\tilde{\lambda}$ in two frames (CS, HX)

Definition of the PPD

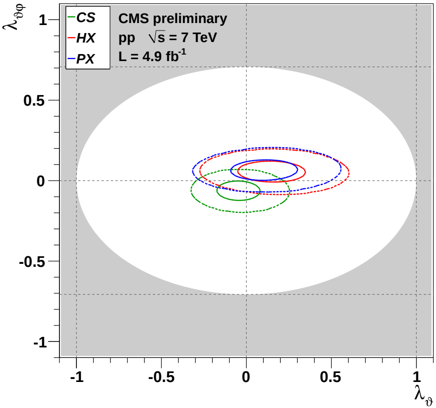
$$\mathcal{P}(\vec{\lambda}) \propto \prod_i \frac{1}{\mathcal{N}(\vec{\lambda})} K(p_{\mathrm{T}}^{(i)}, y^{(i)}, M^{(i)})\, W(\cos\vartheta^{(i)}, \varphi^{(i)} | \vec{\lambda})\, \epsilon(\vec{p}_1^{(i)}, \vec{p}_2^{(i)})$$

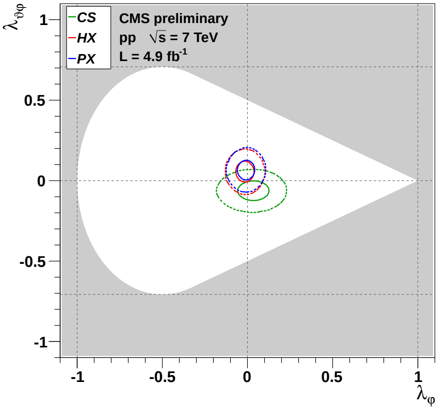
$\mathcal{N}$: normalization
K: event distribution in the bin, previously determined from the data
W: general angular distribution (see slide 3)
ϵ: dimuon efficiency as a function of the muon momenta

Background subtraction algorithm

- 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

$\Upsilon(1S)$, $|y| < 0.6$, $30 < p_T < 50$ GeV





$\Upsilon(nS)$ p_{T} distributions

$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$