Measurement of Quarkonium polarization with the CMS detector

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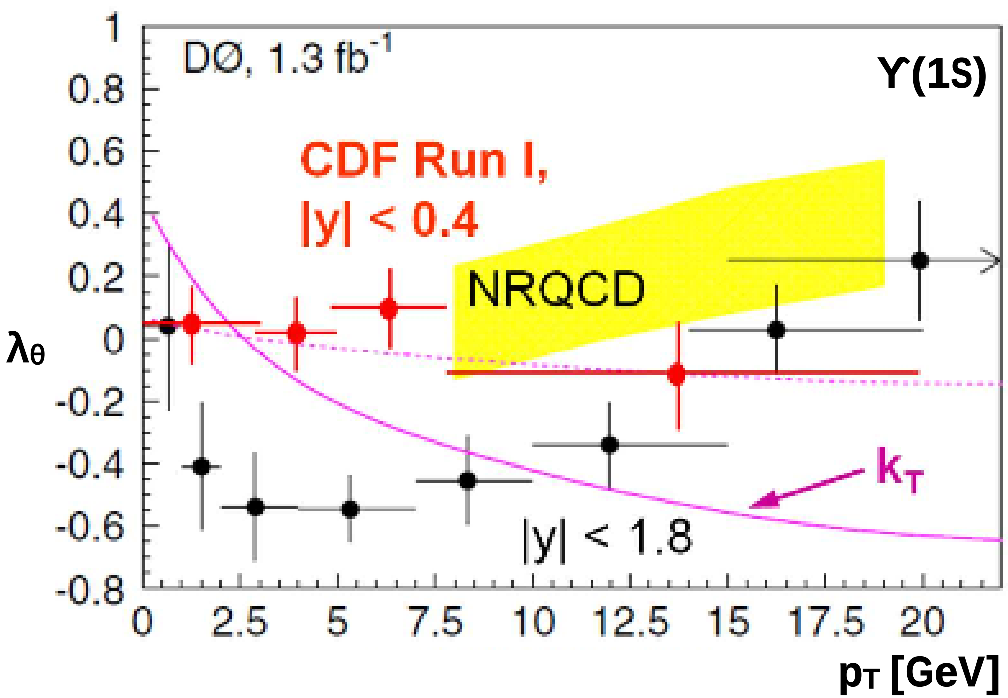
Motivation

- Despite decades of theoretical and experimental research, quarkonium production is still not well understood
- Quarkonium polarization is sensitive to the production mechanism and therefore important to unveil the characteristics of the production process.
- Up to now no theoretical model seems to work properly…



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

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

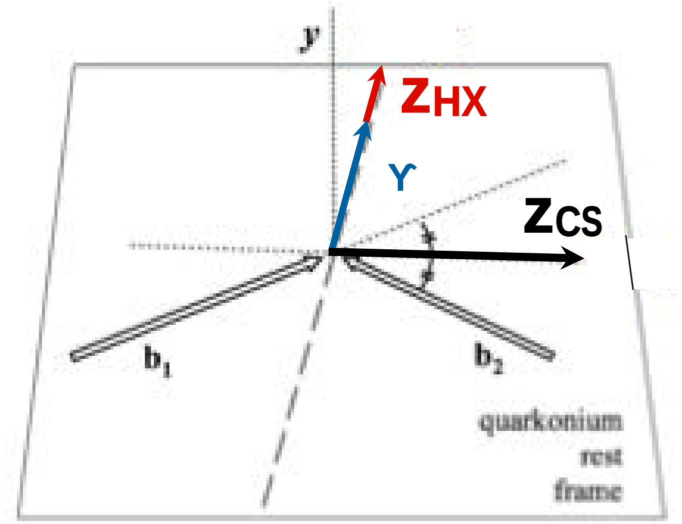
CDF Run I
CDF Collaboration, Phys. Rev. Lett. 88, 161802 (2002)

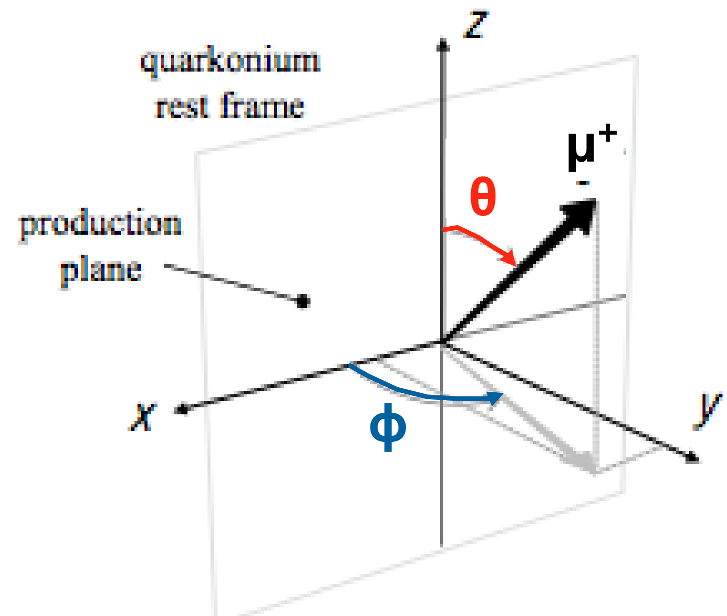
k_T factorization
Baranov & Zotov, JETP Lett. 86, 435 (2007)

See also tomorrow's talk by Andrew York

Quantization Axis Definition

- Using dimuon decay channel
  $\Upsilon(nS) \to \mu^+\mu^-$
- Angular decay distribution measured with respect to a chosen quantization axis in quarkonium rest frame:
  - 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 ($z_{PX} \perp z_{CS}$)
- Relation between polarization frames is kinematics dependent





Quarkonium Polarization

- Polarization is measured through the average angular decay distribution. Most general distribution for quarkonium:

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

where λ_θ, λ_Φ, $\lambda_{\theta\Phi}$ are the polarization parameters

- Two extreme angular decay distributions:

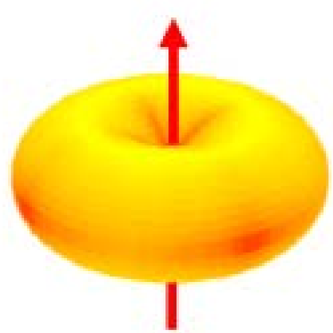
Longitudinal polarization

$J_z = 0$

$\lambda_\theta = -1$

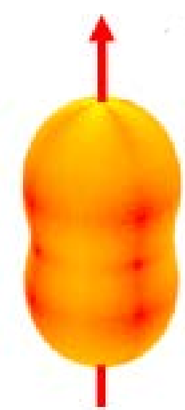
$\lambda_\phi = 0$

$\lambda_{\theta\phi} = 0$



Transverse polarization

$J_z = \pm 1$



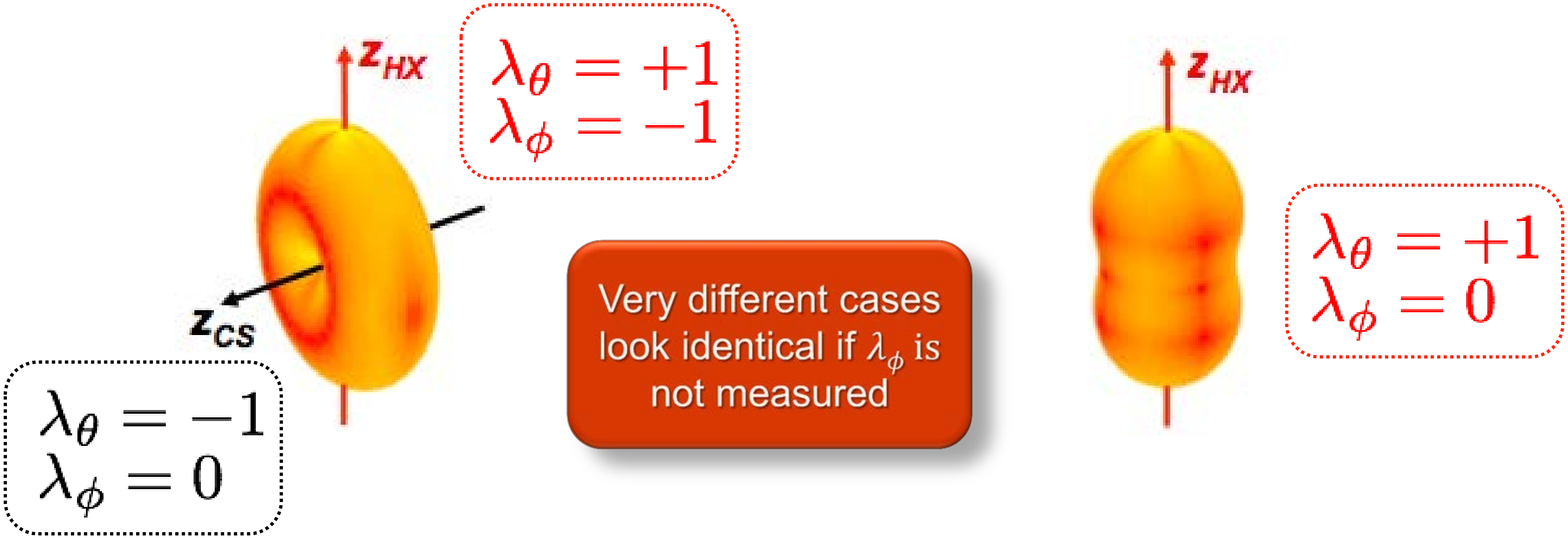
$\lambda_\theta = +1$

$\lambda_\phi = 0$

$\lambda_{\theta\phi} = 0$

Need to Measure Full Angular Distribution

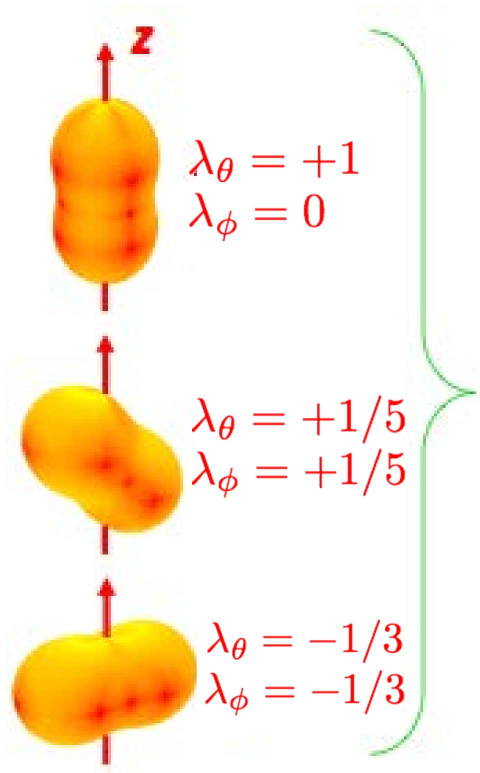
- Traditionally λ_θ was measured in one reference frame only
- Instead, the full angular decay distribution (three polarization parameters) must be measured: very different physical cases are indistinguishable if only λ_θ is measured.
- Observed polarization depends on the frame

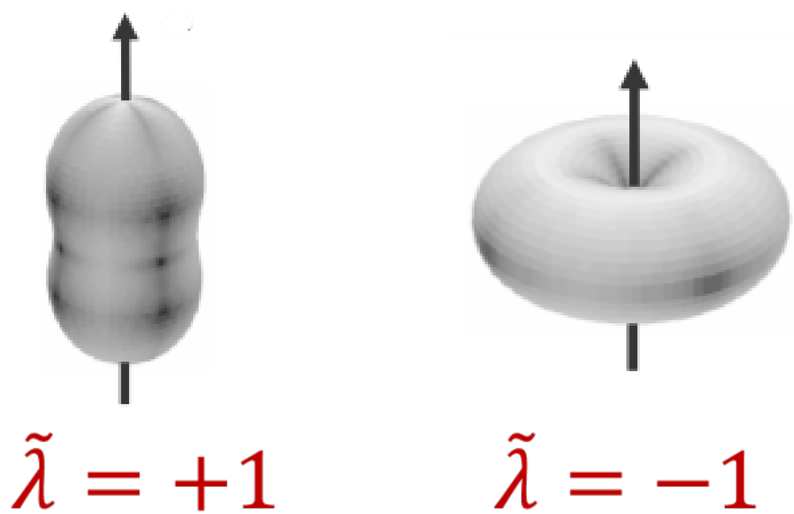


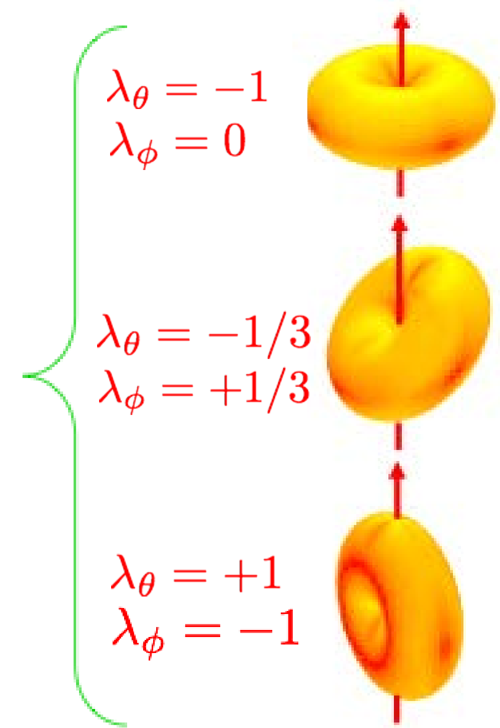
Frame Independent Parameter

- Define frame invariant parameters such as $\tilde{\lambda}$ from the angular decay distribution of a given frame

$$\tilde{\lambda} = \frac{\lambda_\theta + 3\lambda_\phi}{1 - \lambda_\phi}$$

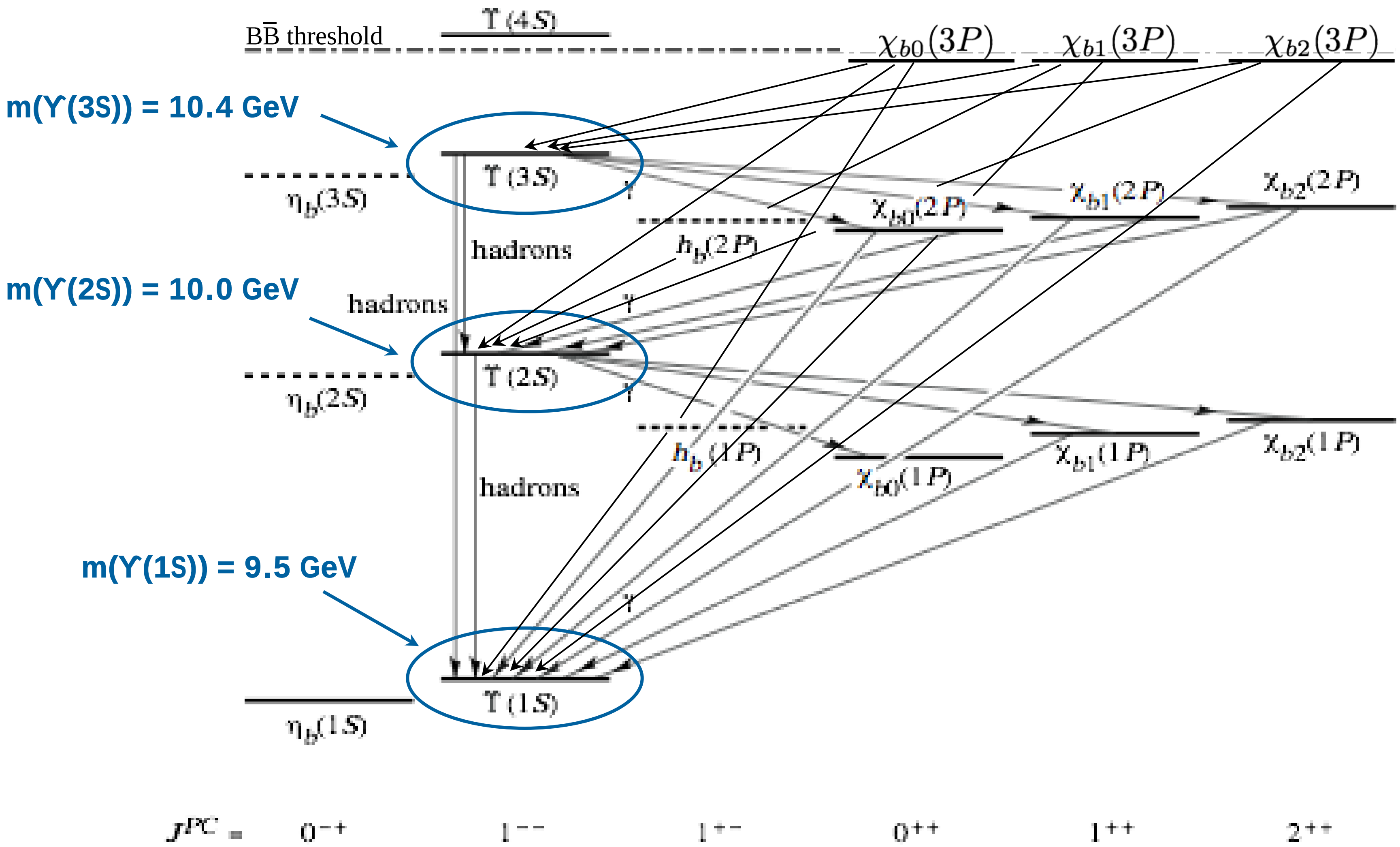






Eur. Phys. J. C 69 (2010) 657

Υ(nS) feed-down contributions



CDF Run II Υ(nS) Polarization Analysis

- Previous results only measured λ_θ in the HX frame
- In this analysis, λ_θ, λ_ϕ and $\lambda_{\theta\phi}$ are determined simultaneously in two different reference frames (CS, HX) for Υ(1S), Υ(2S) and Υ(3S) mesons – self-consistency of the results is tested with $\tilde{\lambda}$
- A dimuon sample collected in $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV, corresponding to a total integrated luminosity of 6.7 fb^{-1}, is used
- Estimated number of signal events in the kinematic phase space under consideration (p_T < 40 GeV, $|y|$ < 0.6):

Υ(1S)	Υ(2S)	Υ(3S)
550k	150k	76k

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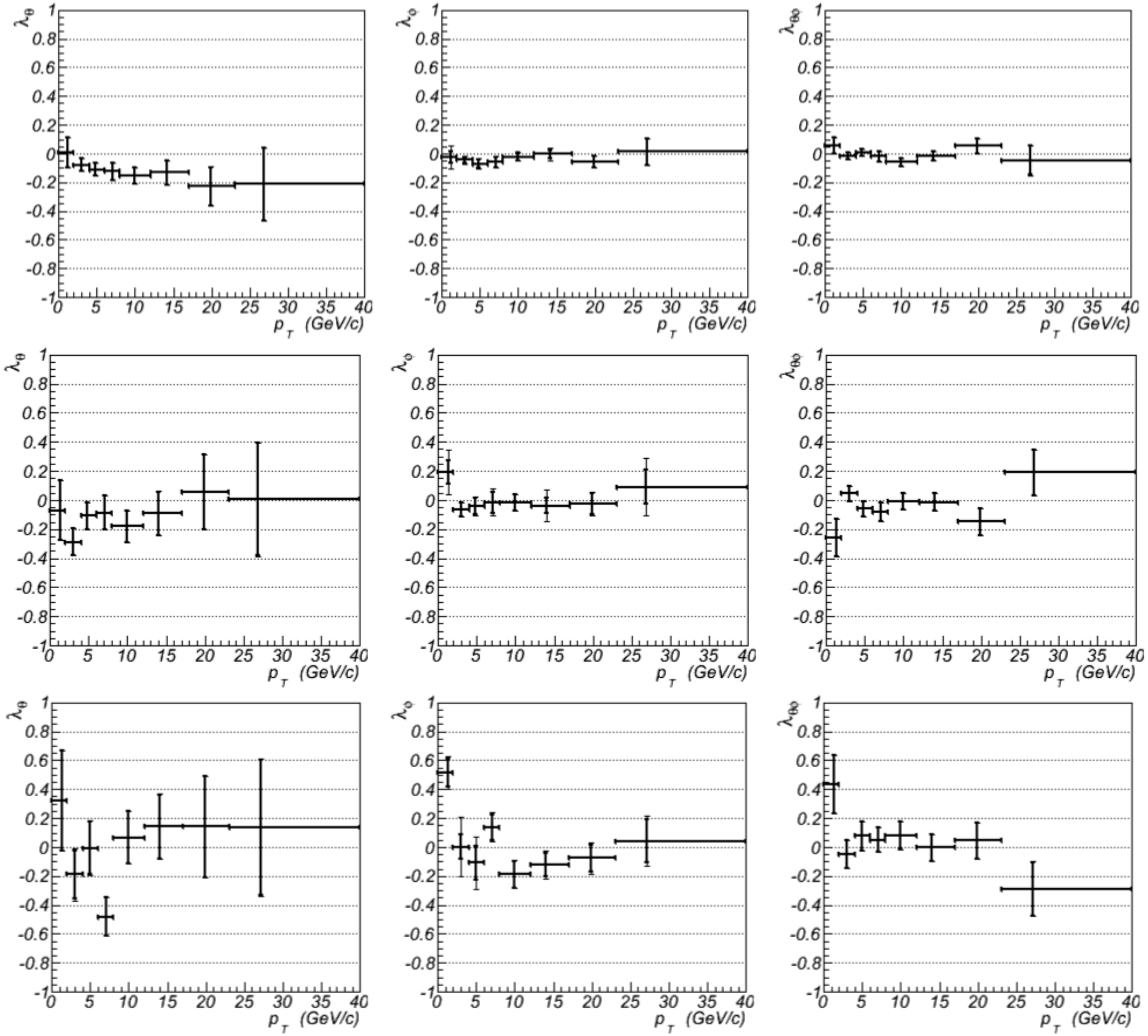
ϒ(nS) Polarization in the HX Frame, |y| < 0.6

CDF Run II, 6.7 fb^{-1}

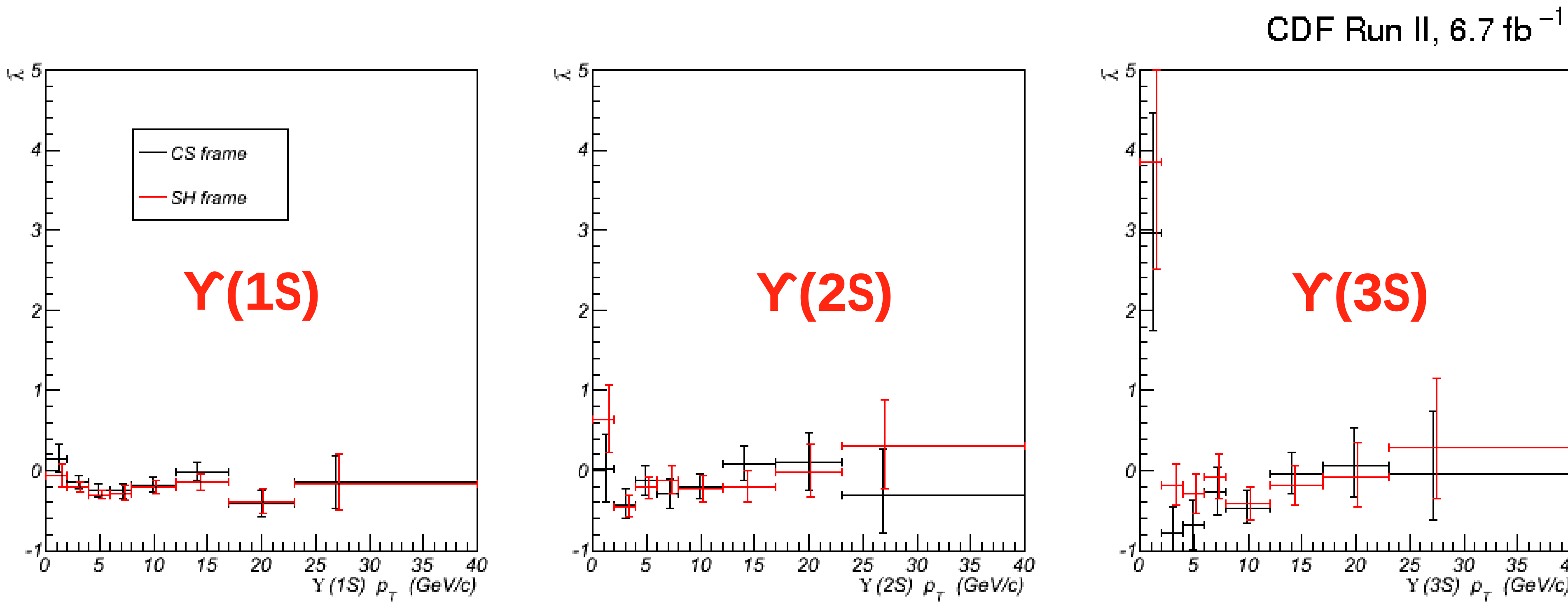
ϒ(1S)

ϒ(2S)

ϒ(3S)



Frame Invariant Parameter $\tilde{\lambda}$

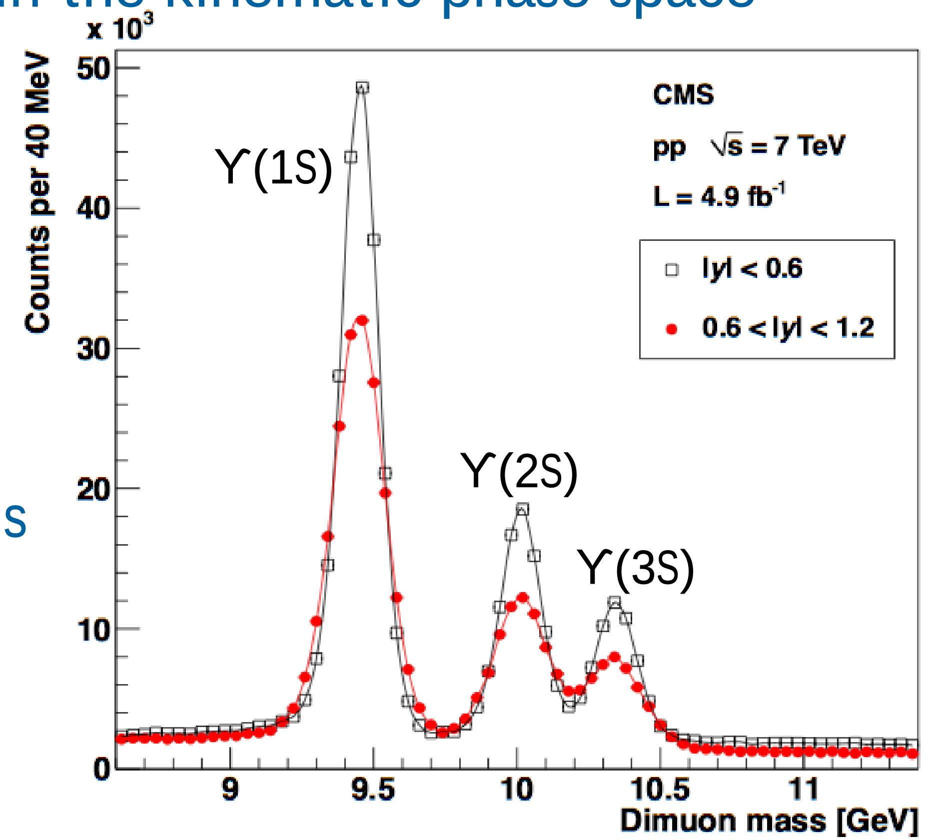


- Results in the two reference frames are consistent
- No evidence of strong polarization in the considered p_T range

CMS ϒ(nS) Polarization Analysis

- λ_θ, λ_ϕ, $\lambda_{\theta\phi}$ and $\tilde{\lambda}$ are measured in three different reference frames (PX, CS, HX) for ϒ(1S), ϒ(2S) and ϒ(3S) mesons
- Analysis based on dimuon sample collected in pp collisions in 2011 at $\sqrt{s}$ = 7 TeV, corresponding to a total integrated luminosity of 4.9 fb^{-1}
- Estimated number of signal events in the kinematic phase space under consideration (p_T > 10 GeV, |y| < 1.2):

ϒ(1S)	ϒ(2S)	ϒ(3S)
252k	94k	58k



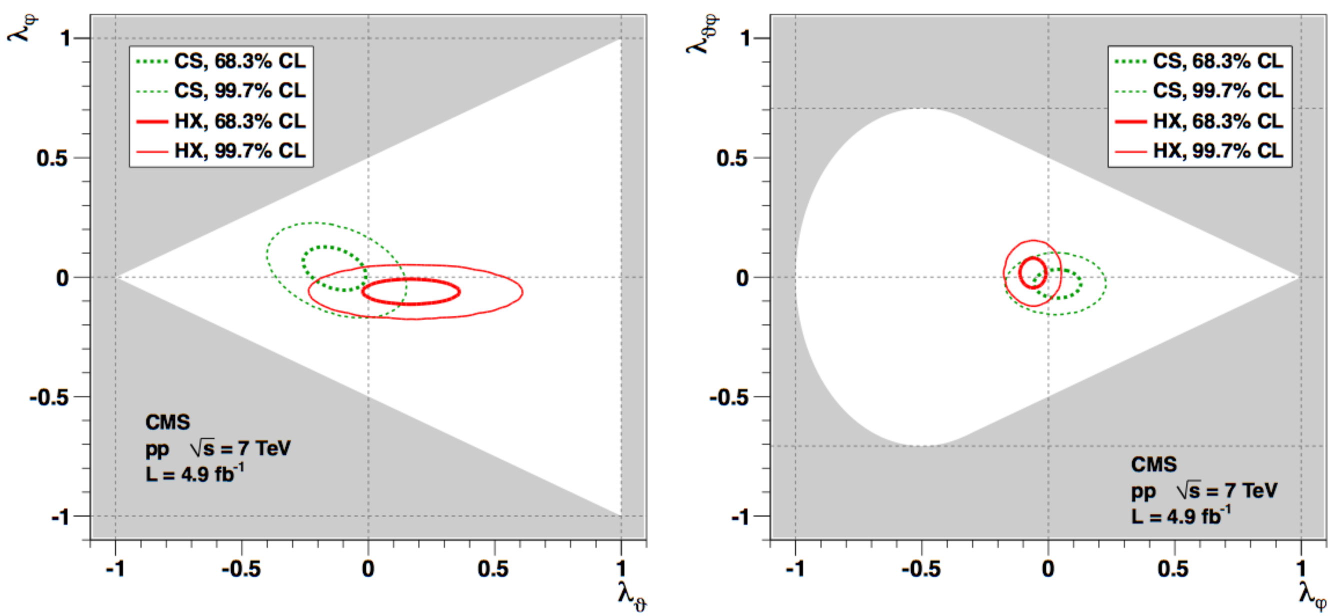
- Analysis performed independently in five transverse momentum p_T bins for two dimuon rapidity |y| cells

PRL 110, 081802 (2013)

Obtaining Polarization Parameters

Full and direct calculation of the Posterior Probability Distribution (PPD) of the polarization parameters λ_θ, λ_Φ, $\lambda_{\theta\Phi}$

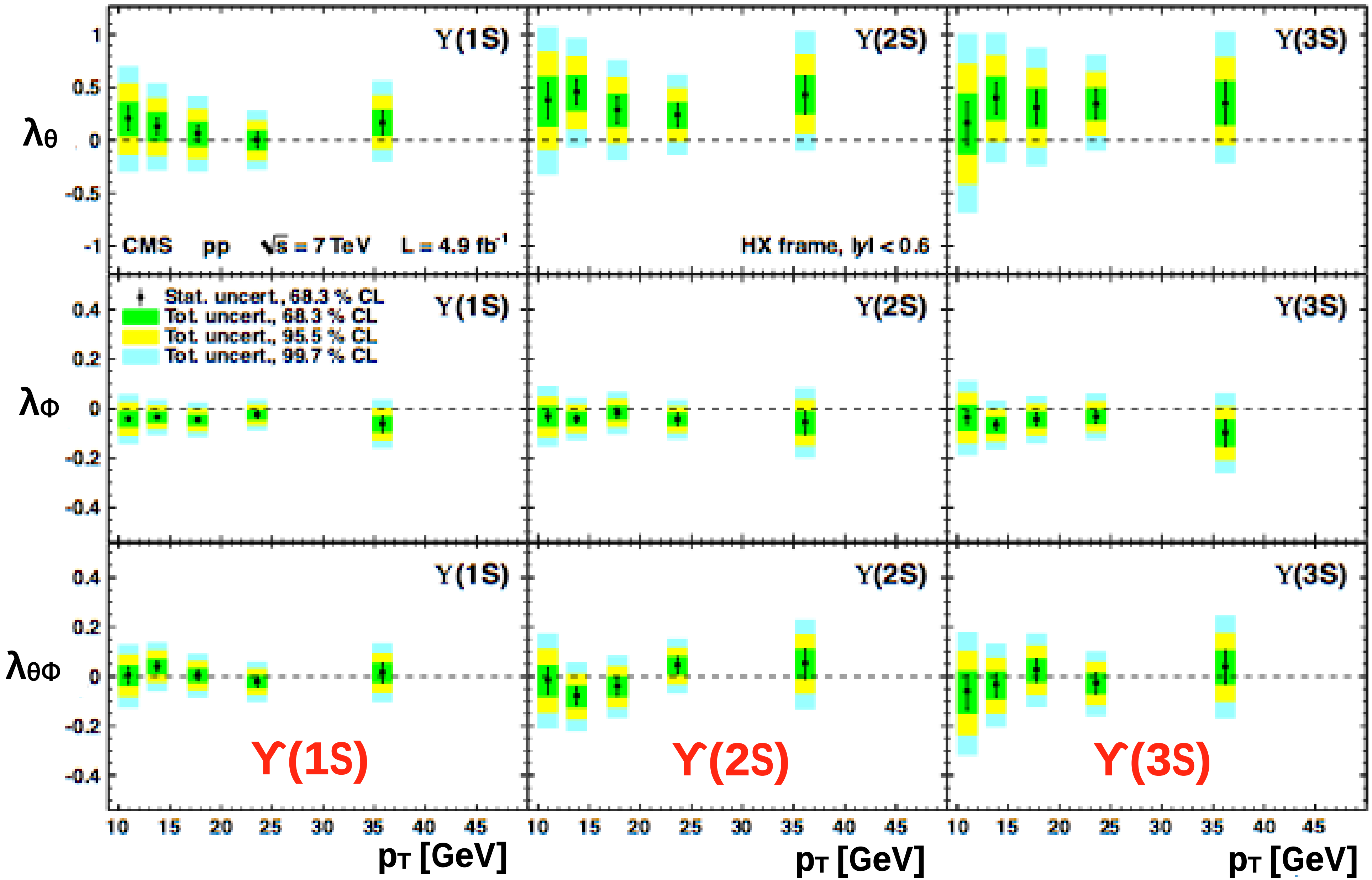
1. Events distributed as in the background model are subtracted from the data sample
2. Definition of the PPD from the remaining signal-like events
3. Numerical results and graphical representations are determined from 1D and 2D projections of the PPD



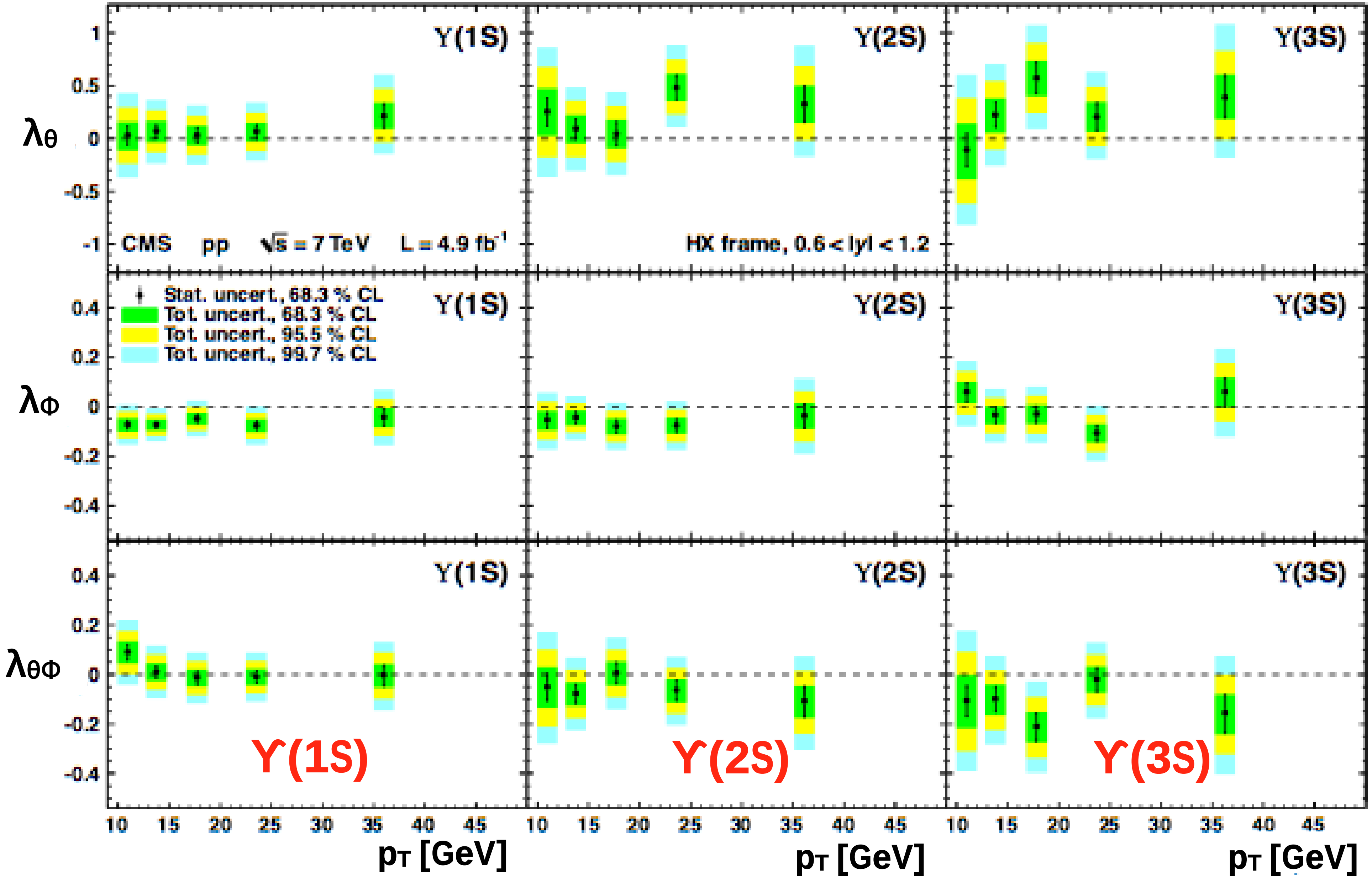
Unphysical parameter region

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

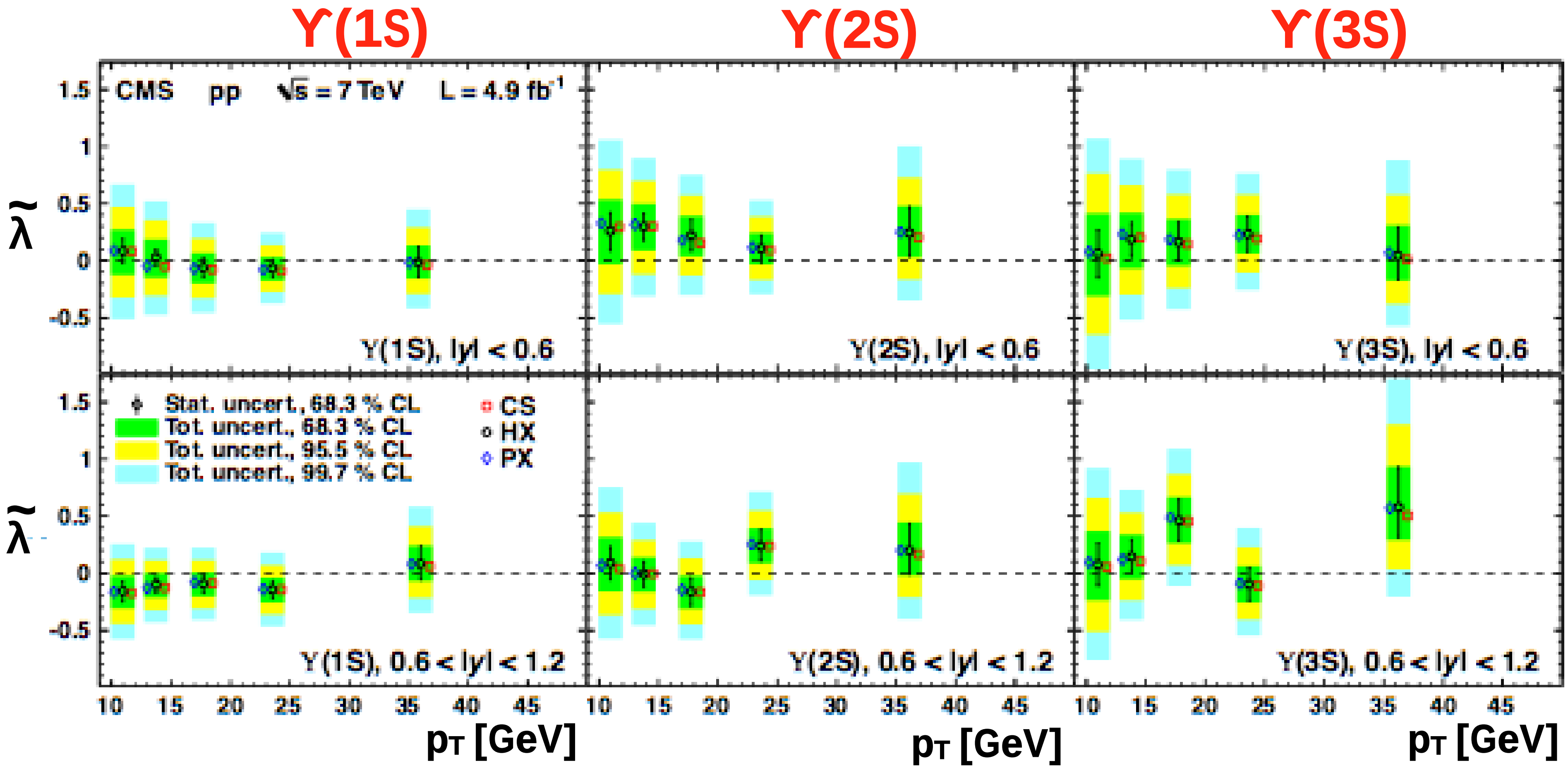
Υ(nS) Polarization in the HX Frame, |y| < 0.6



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

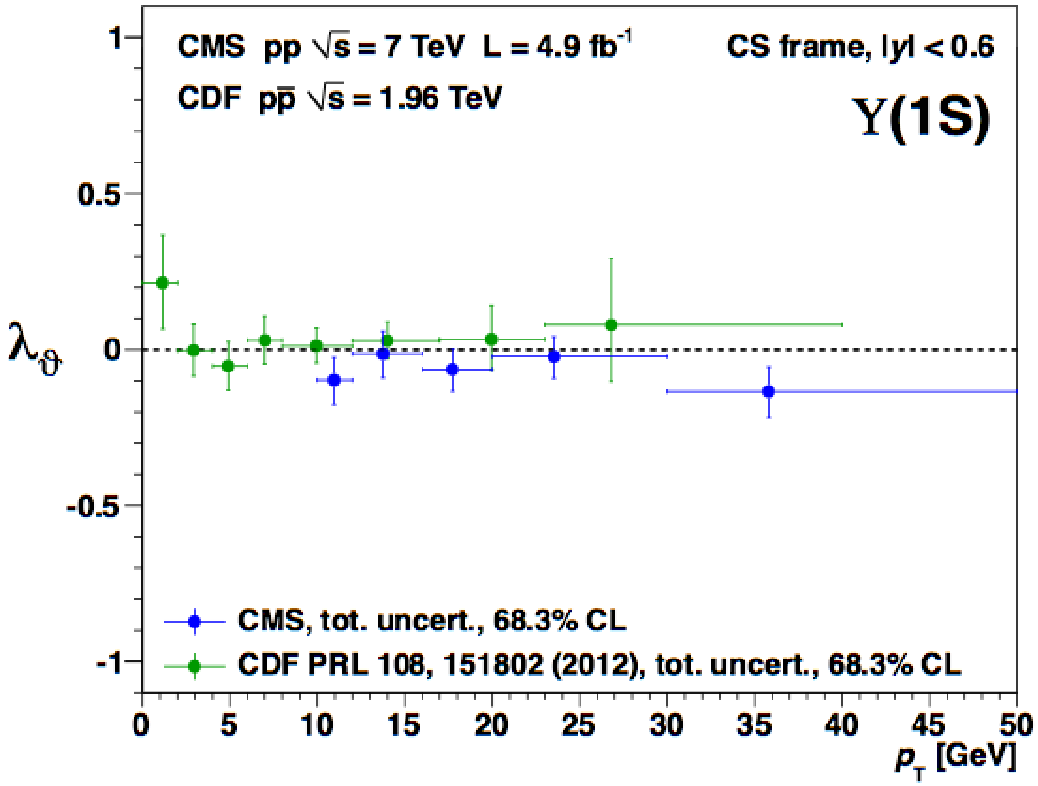


Frame Invariant Parameter $\tilde{\lambda}$



- Results in all three reference frames are consistent
- No evidence of unaccounted systematic uncertainties

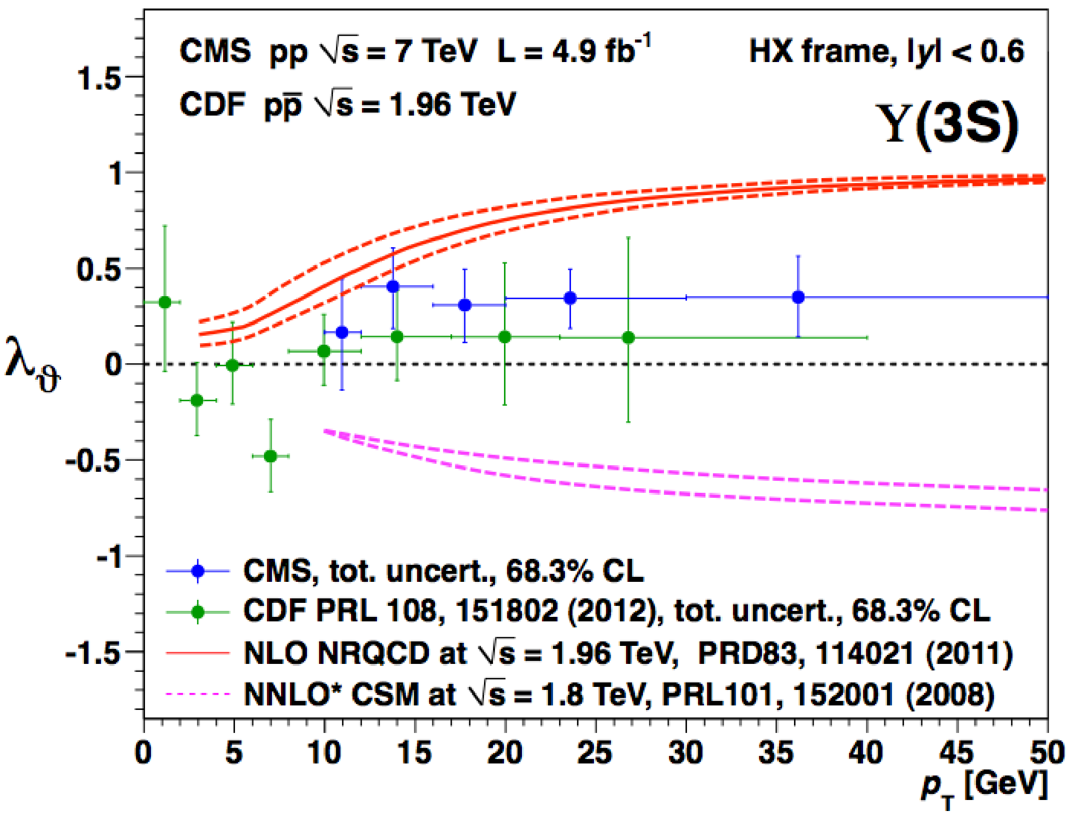
CDF vs CMS



- Results from CDF and CMS are consistent
- CMS extends the measurements beyond the p_T and rapidity ranges probed by CDF
  CDF: $p_T < 40$ GeV, $|y| < 0.6$
  CMS: $10 < p_T < 50$ GeV, $|y| < 1.2$
- No evidence of strong polarization

Comparison to Theory

- $\Upsilon(1S)$ suffers from large χ_b feed-down contribution, with unknown polarization
- $\Upsilon(3S)$ is the less affected by feed-down and thus predictions should be more reliable
- Theory predictions do not, however, agree with experimental results

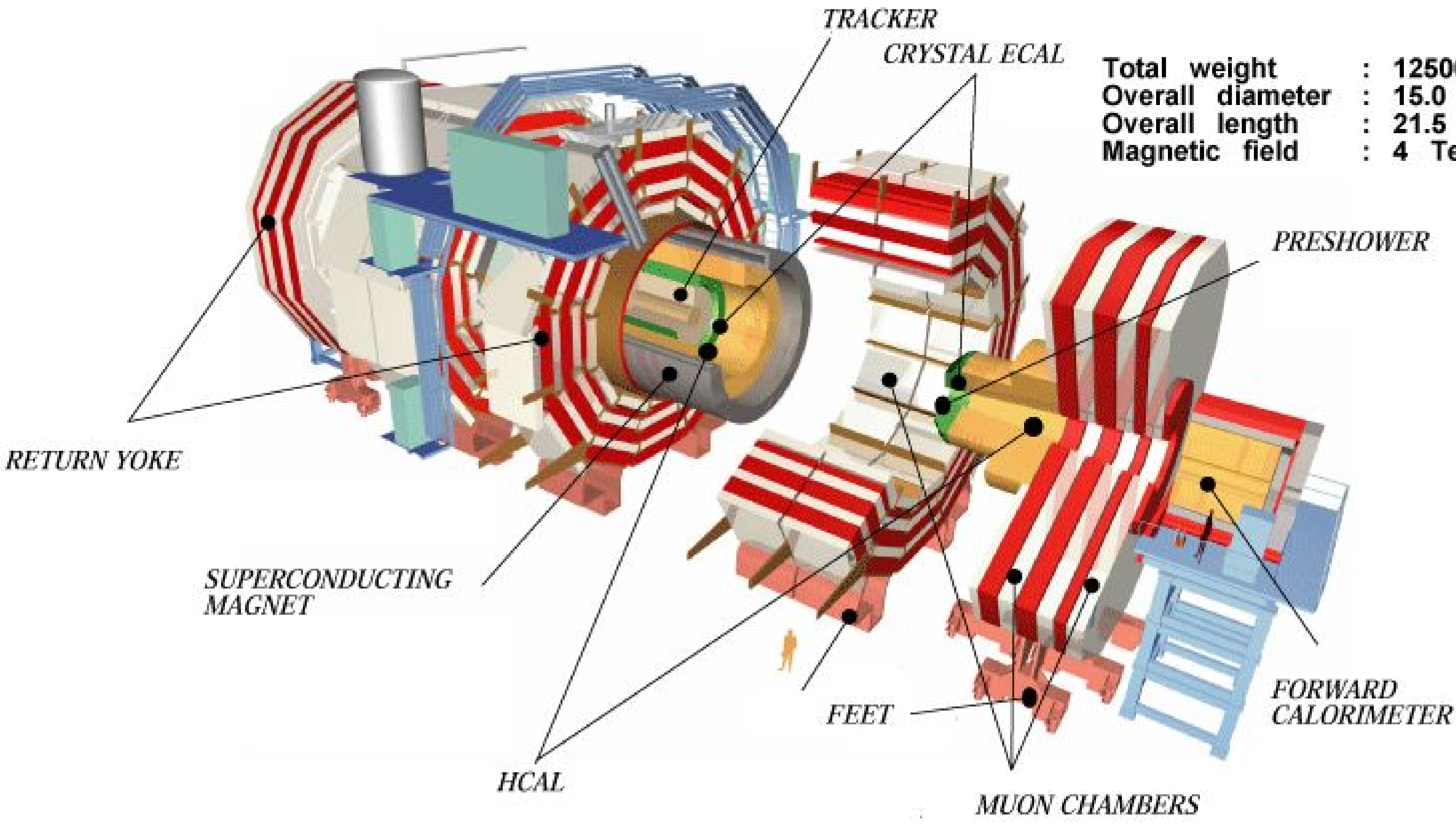


Summary and Conclusions

- CMS has measured the polarization of $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ mesons
- Three frame dependent anisotropy parameters λ_θ, λ_ϕ, $\lambda_{\theta\phi}$ and the frame invariant parameter $\tilde{\lambda}$ have been measured in CMS:
  - Measurement in 3 different frames (CS, HX, PX)
  - ($10 < p_T < 50$ GeV, $|y| < 1.2$) extend the measurement beyond the p_T and rapidity ranges probed by CDF ($p_T < 40$ GeV, $|y| < 0.6$)
  - No evidence of strong polarization has been observed
- Zero polarization is in itself a *totally unexpected* result

BACKUP

CMS Detector



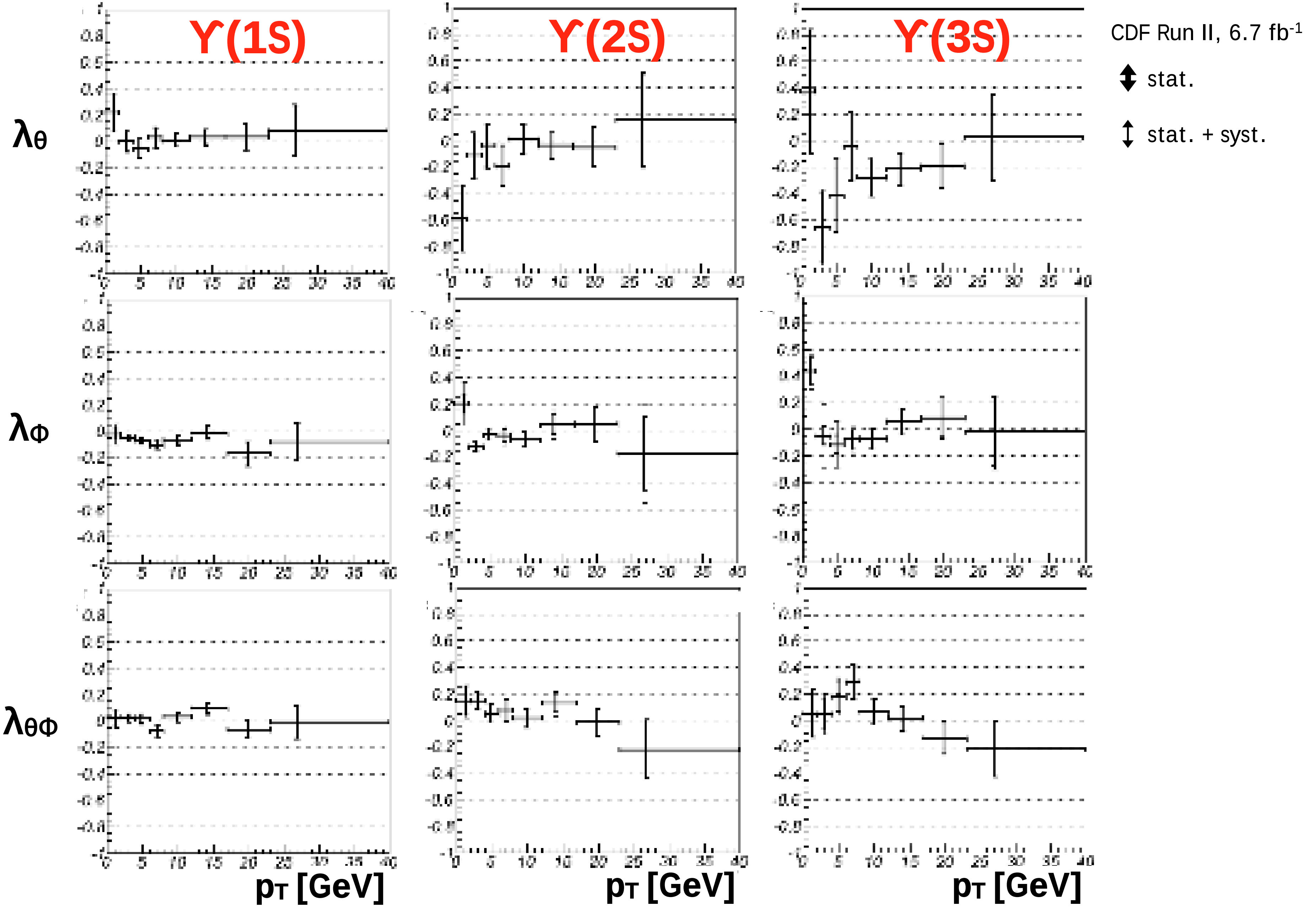
Total weight	:	12500 T
Overall diameter	:	15.0 m
Overall length	:	21.5 m
Magnetic field	:	4 Tesla

Definition of the PPD

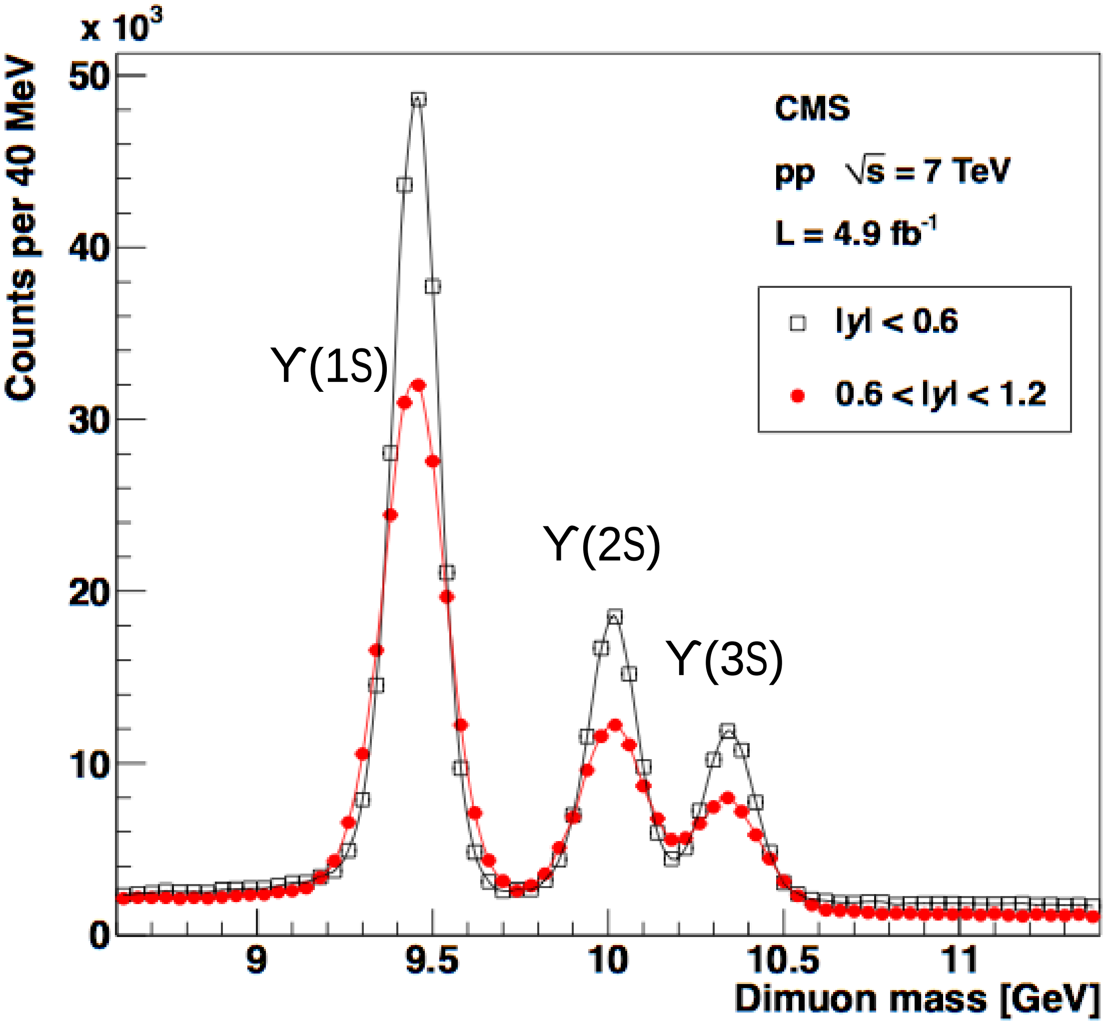
$$\mathcal{P}(\vec{\lambda}) \propto \prod_i \frac{1}{\mathcal{N}(\vec{\lambda})} W(\cos\theta^{(i)}, \phi^{(i)} \mid \vec{\lambda}) \quad \varepsilon(\vec{p_1^{(i)}}\vec{p_2^{(i)}})$$

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

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



Background Subtraction

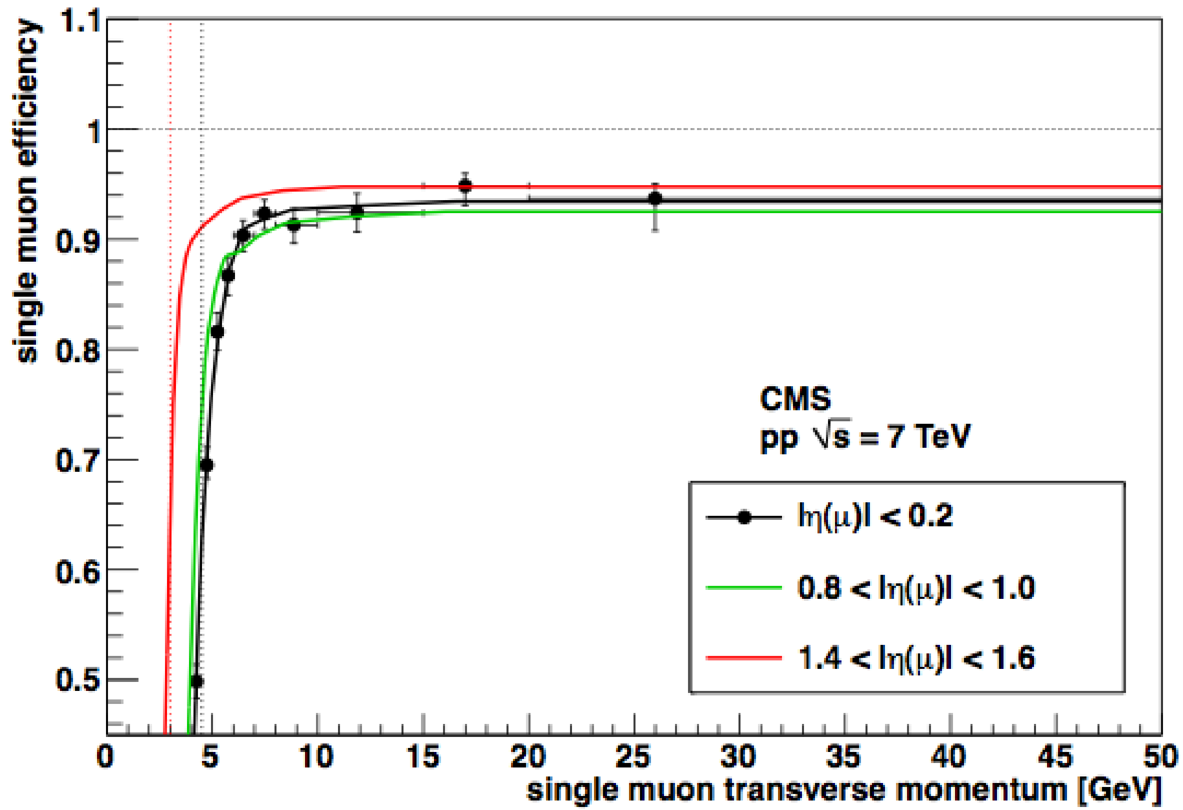


- Signal region is defined as ±1σ around mass peak
- Background fraction is determined by fits to the dimuon mass distribution
- Angular distribution of the background events are modeled as weighted sums of the distributions in the sidebands, left of ϒ(1S) and right of ϒ(3S) peak

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

Efficiencies

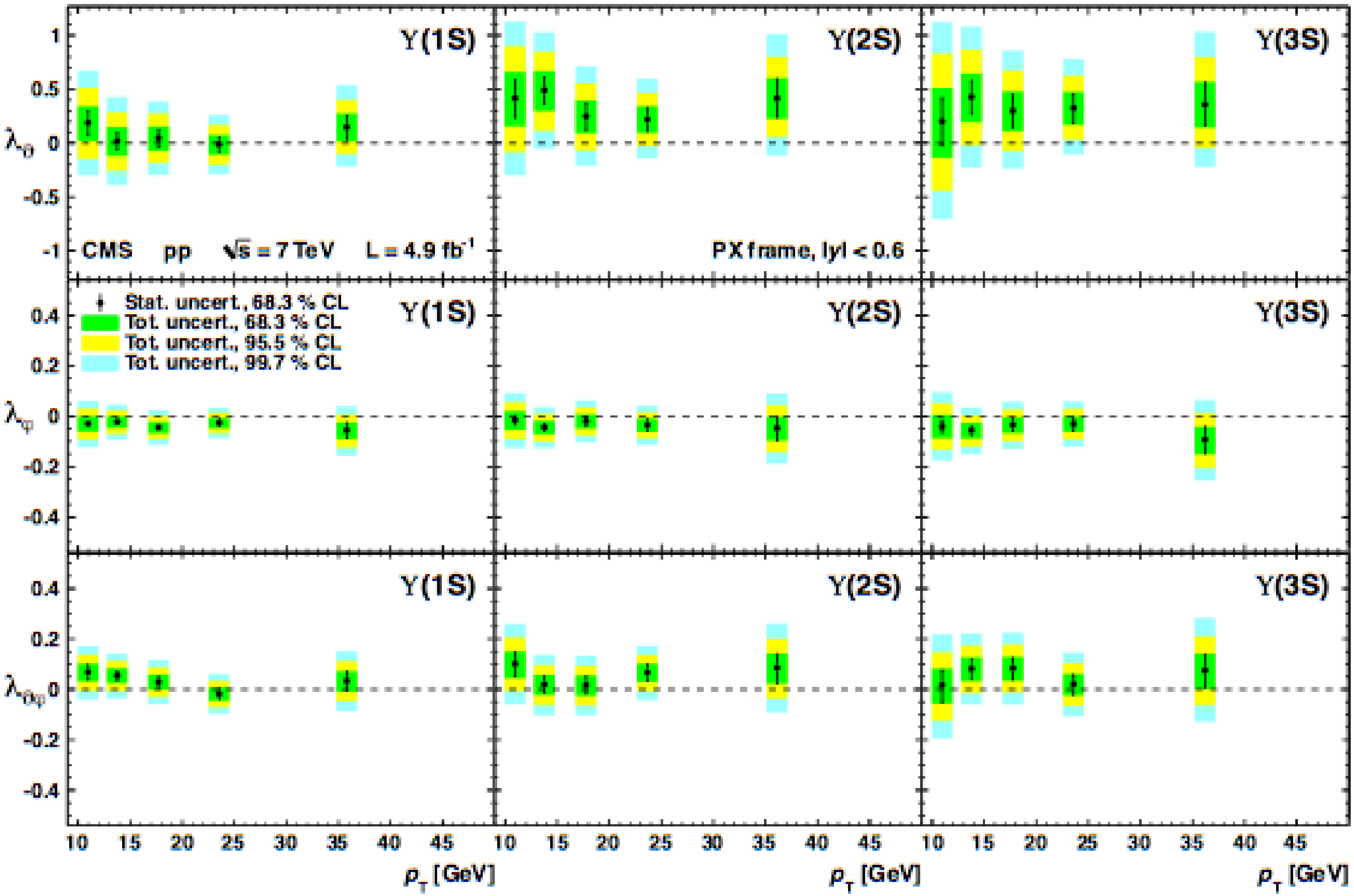
- Data-driven single muon efficiencies measured with the *Tag&Probe* method
- Precise knowledge of efficiencies needed to avoid introducing artificial polarization
- Dimuon efficiencies are calculated as the product of single muon efficiencies
- Correlations between muons are negligible as seen in detailed MC studies
- Efficiencies are accounted for on an event-by-event basis



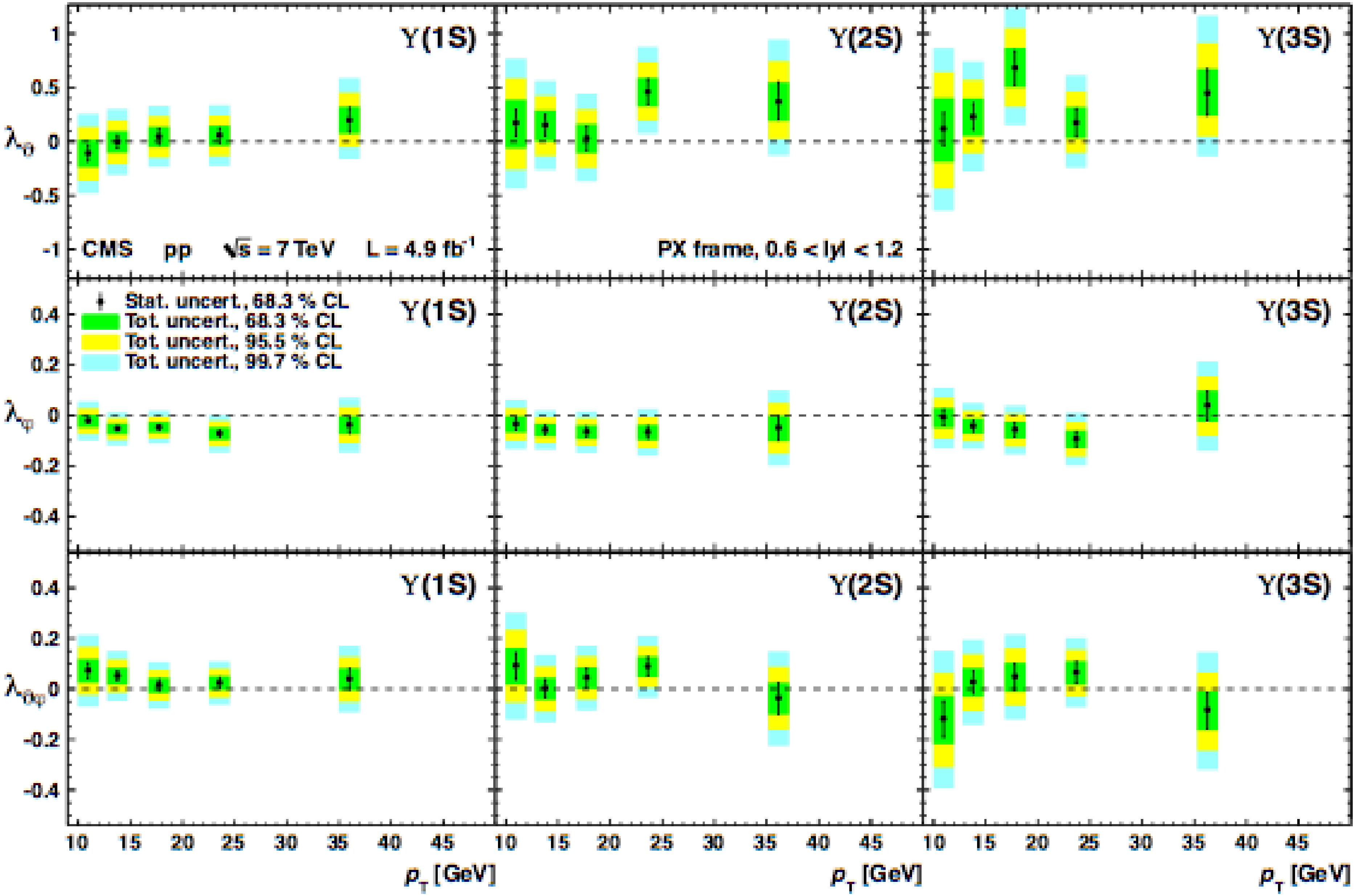
Systematic Effects

- Sources of systematic effects:
  - Analysis method
  - Background model
  - 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

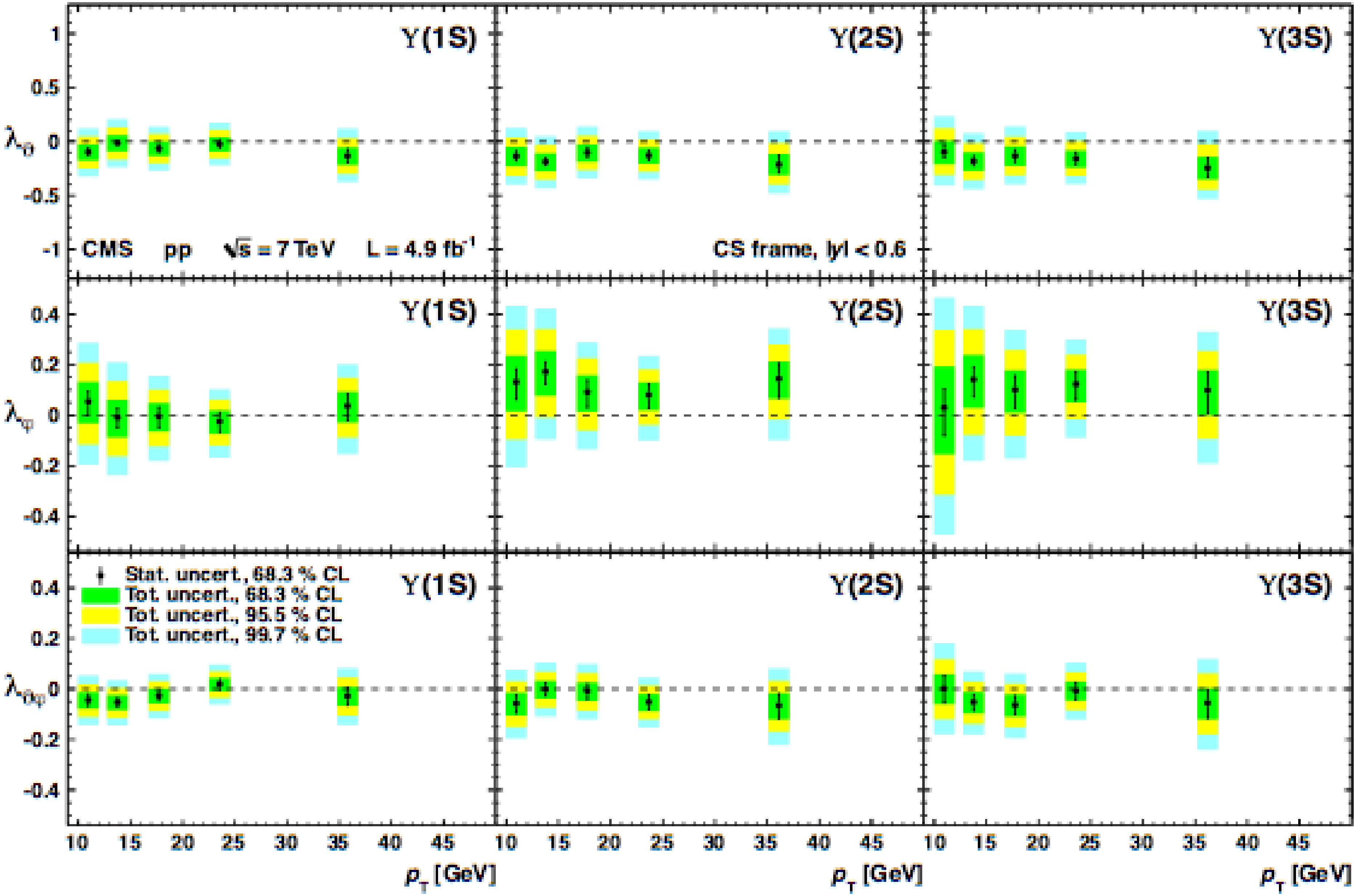
ϒ(nS) Polarization in the PX Frame, |y| < 0.6



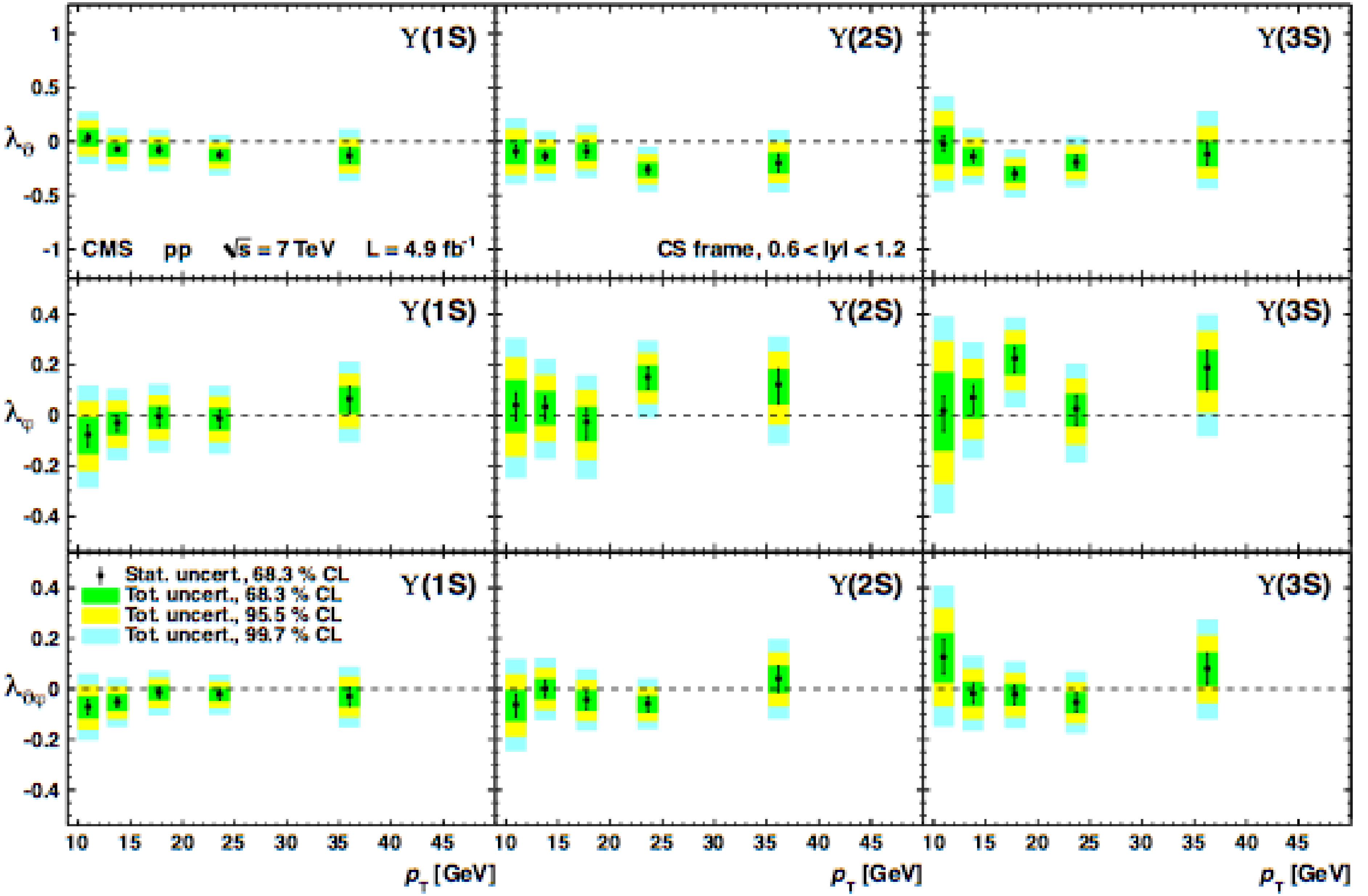
ϒ(nS) Polarization in the PX Frame, 0.6 < |y| < 1.2



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



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



Comparison to Previous CDF Result

- New CDF Run II result agrees with the previous CDF Run I result