Measurements of Quarkonium Production and Polarization at CMS

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CMS Collaboration

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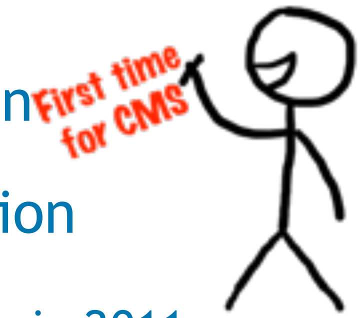
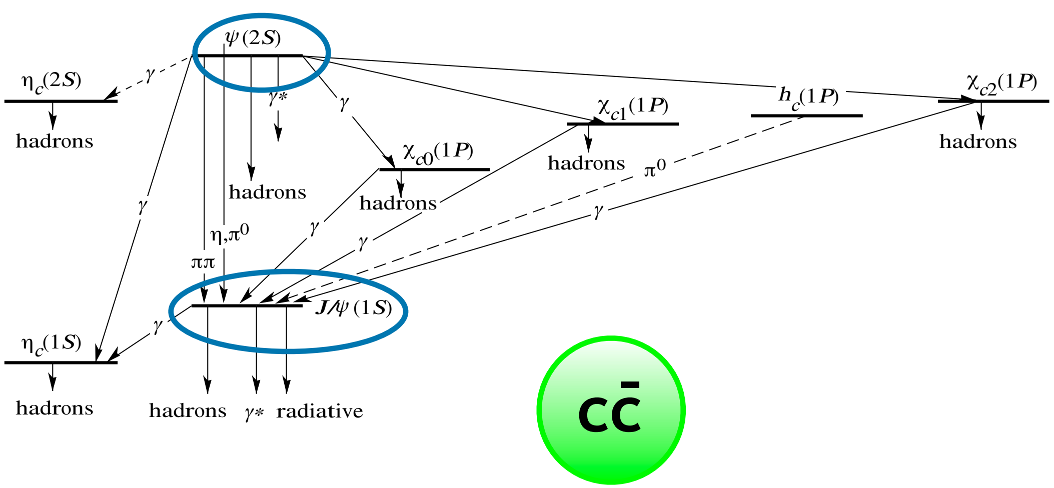
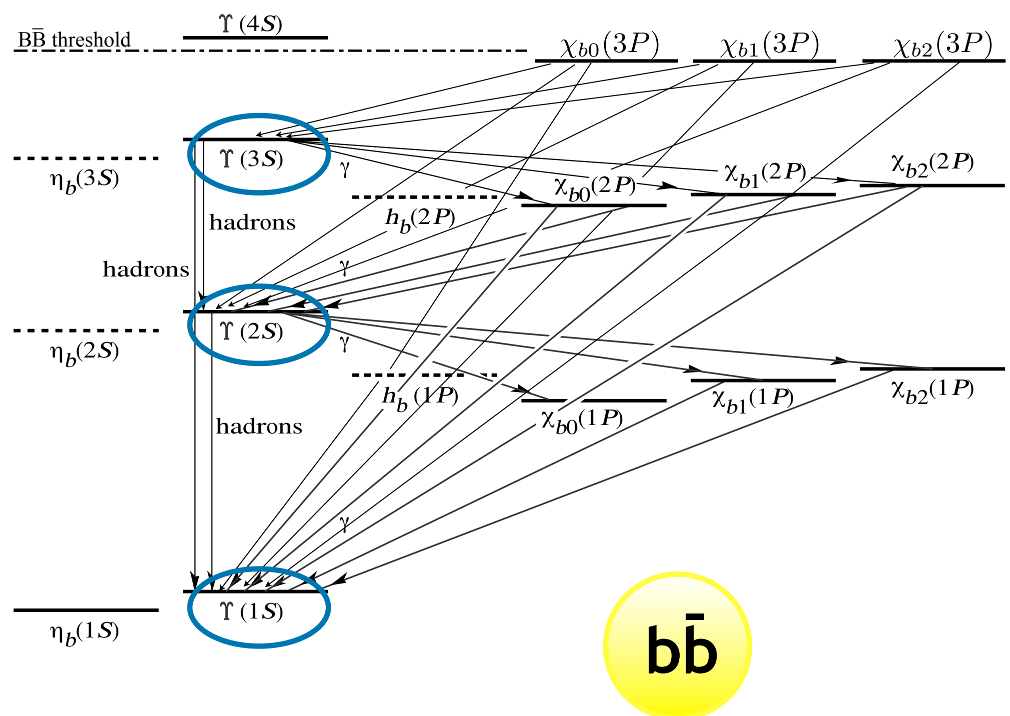
Outline

- Υ(nS) cross section
- Υ(nS) polarization
- Prompt J/ψ polarization
- Prompt ψ(2S) polarization



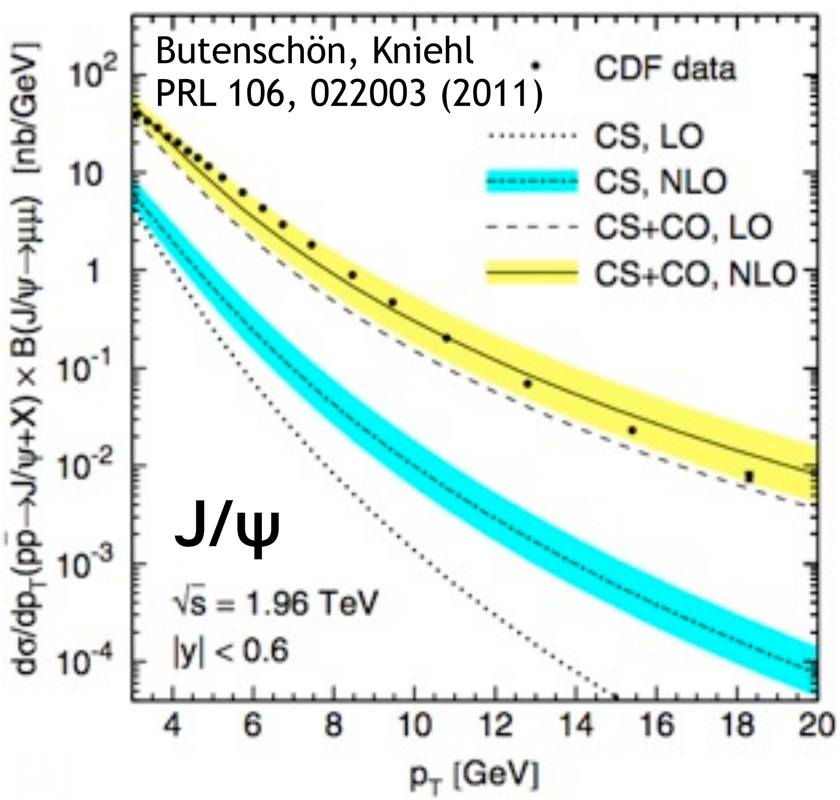
All results are based on a dimuon sample collected in pp collisions in 2011 at $\sqrt{s}$ = 7 TeV, corresponding to a total integrated luminosity of 4.9 fb^{-1}

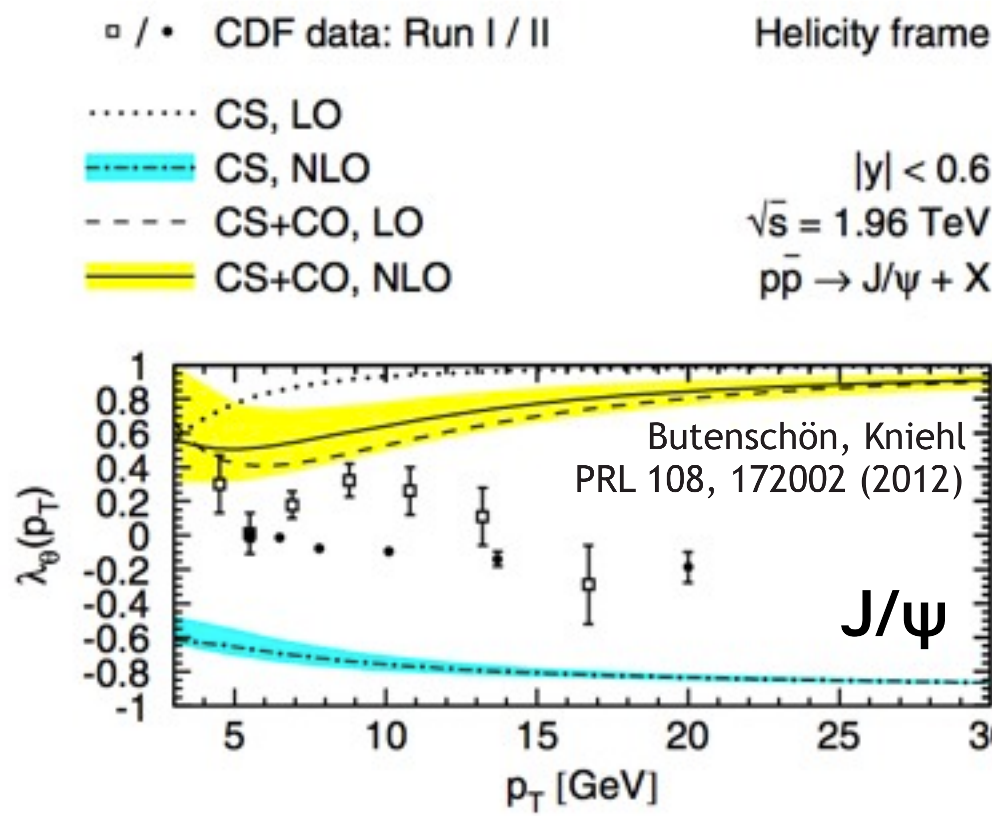




Motivation

- No theory has simultaneously explained experimental measurements of both quarkonium production and polarization
- Most previous polarization measurements only determined one out of three polarization parameters
- CMS has a higher reach in transverse momentum, p_T

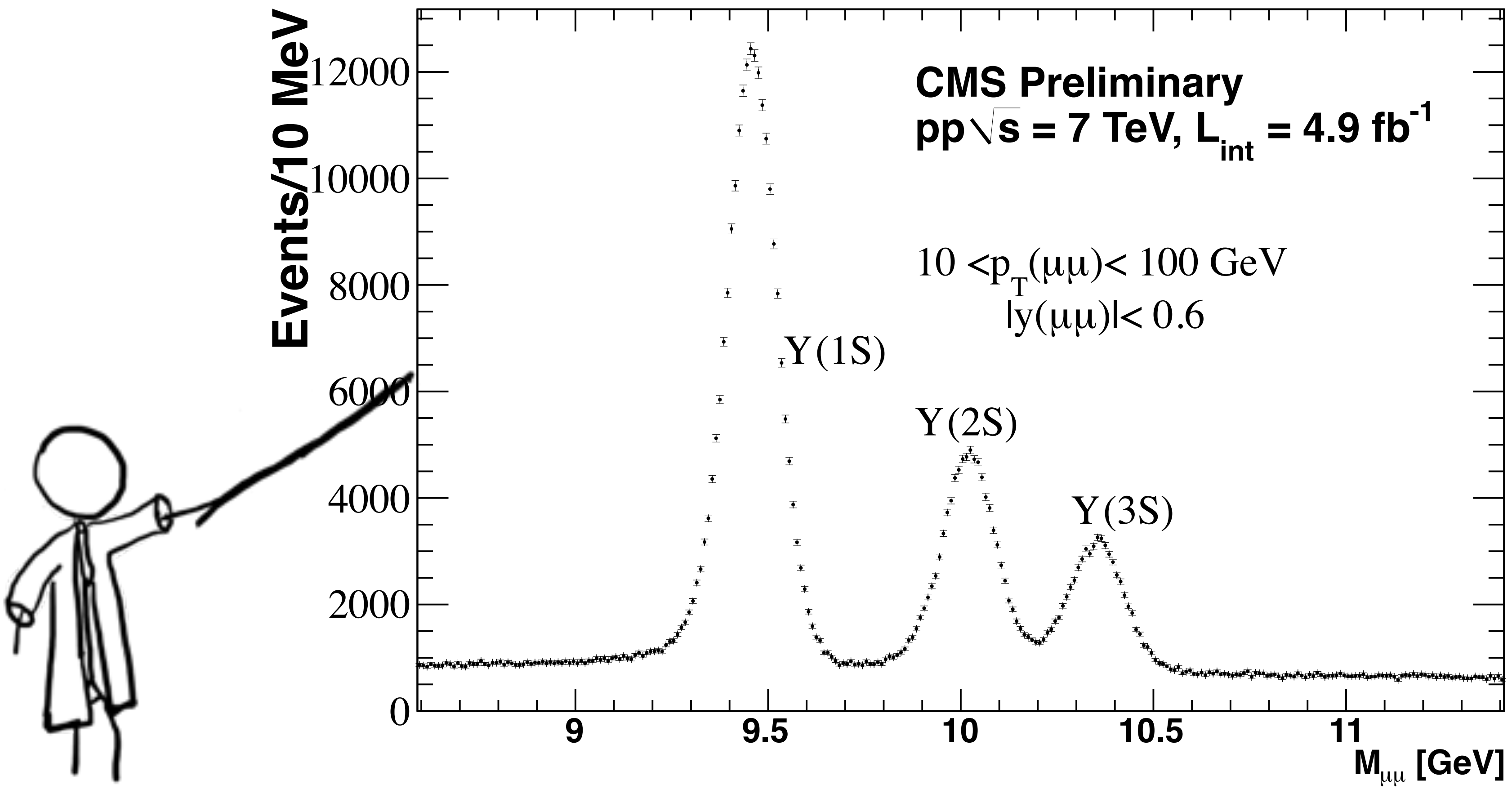




Υ(nS) Cross Section Analysis

- Uses results from CMS Υ(nS) polarization measurement for the calculation of the acceptance
- Kinematic range of measurement: $10 < p_T < 100$ GeV, $|y| < 0.6$

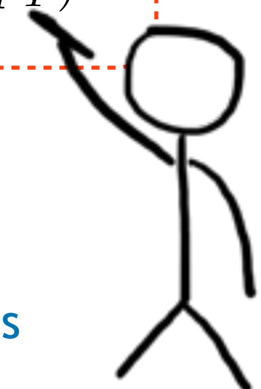
Details in CMS-PAS-BPH-12-006



Υ(nS) Differential Cross Section

- Υ(nS) differential cross section $\frac{d\sigma}{dp_T}$ times dimuon branching ratio $\mathcal{B}$ integrated over |y| < 0.6 in a given p_T bin of width Δp_T

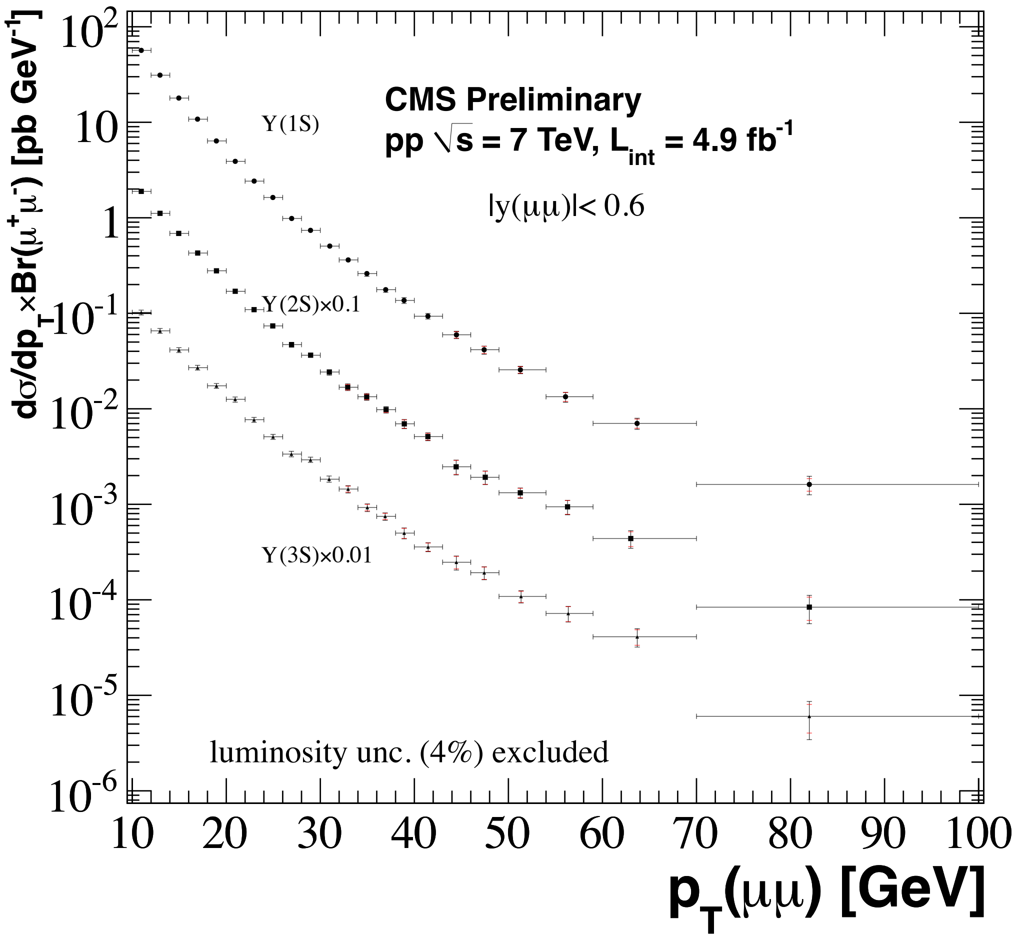
$$\left.\frac{d\sigma(pp \to \Upsilon(nS))}{dp_T}\right|_{y<0.6} \times \mathcal{B}(\Upsilon(nS) \to \mu^+\mu^-) = \frac{N^{fit}_{\Upsilon(nS)}(p_T)}{L_{int} \cdot \Delta p_T \cdot \varepsilon(p_T) \cdot \mathcal{A}(p_T)}$$

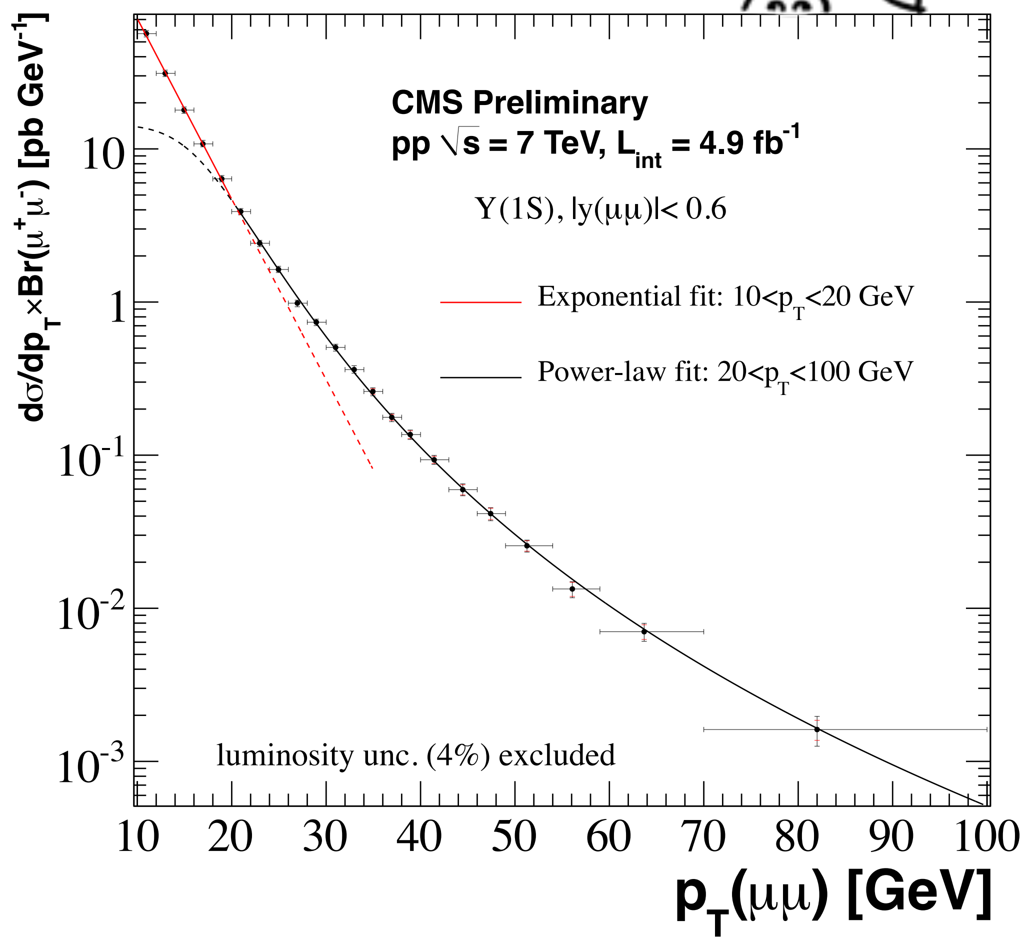


$N^{fit}_{\Upsilon(nS)}(p_T)$	number of Υ(nS) events in a p_T bin of width Δp_T
L_{int}	integrated luminosity (4.9 fb^{-1})
$\varepsilon(p_T)$	efficiency of trigger, reconstruction and analysis selections
$\mathcal{A}(p_T)$	acceptance calculated from Monte Carlo

- Acceptance is the polarization-weighted fraction of Υ decays where the muons satisfy the kinematic requirements to the total of weighted events in a given p_T, y bin

Υ(nS) Differential Cross Section





- Similar behaviour for all three Υ states
- Change of slope for p_T > 20 GeV suggests a change in the nature of the production process

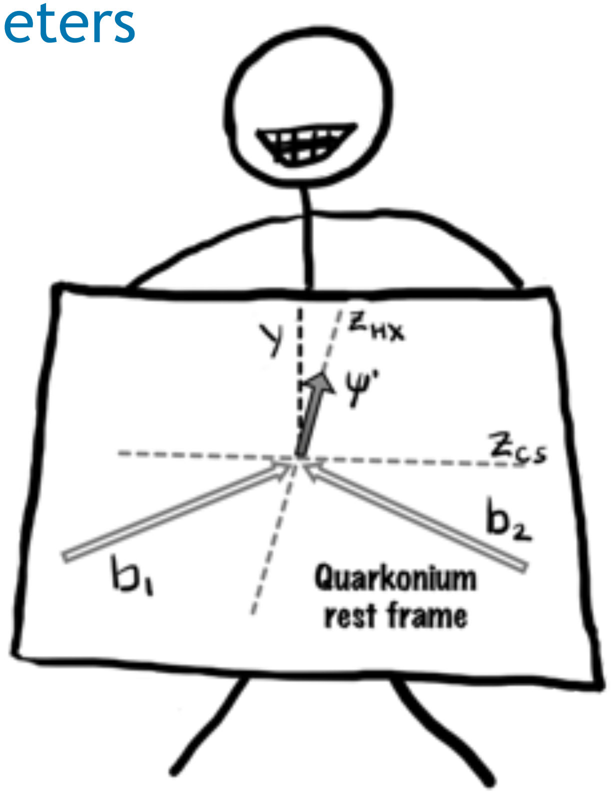
Quarkonium Polarization

- 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

- Angular decay distribution is measured with respect to a certain reference 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 ($z_{PX} \perp z_{CS}$)

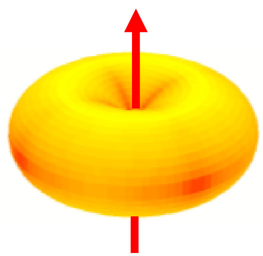


Need to Measure the Full Angular Distribution

- Two extreme angular decay distributions

Longitudinal polarization
$J_z = 0$

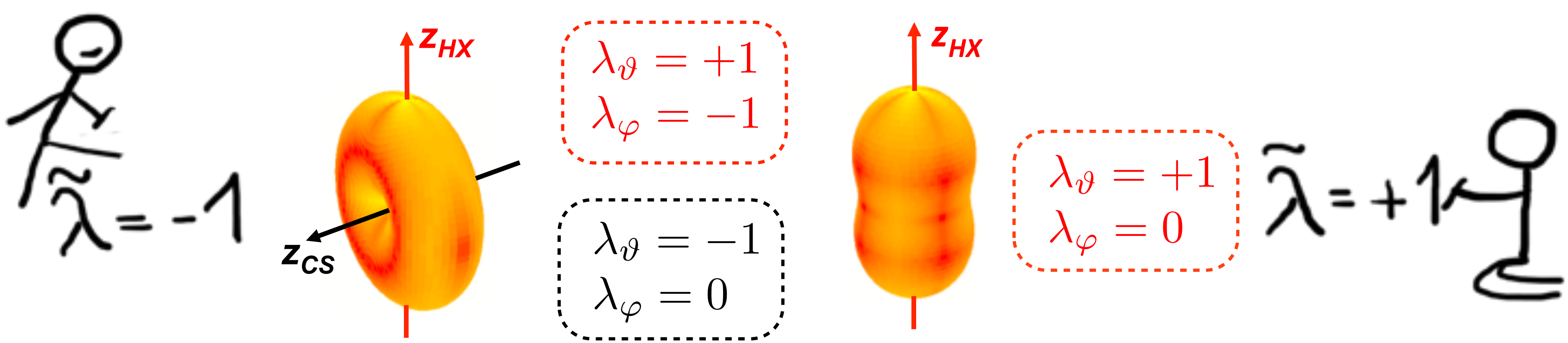
$\lambda_\vartheta = -1$
$\lambda_\varphi = 0$
$\lambda_{\vartheta\varphi} = 0$



Transverse polarization
$J_z = \pm 1$

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

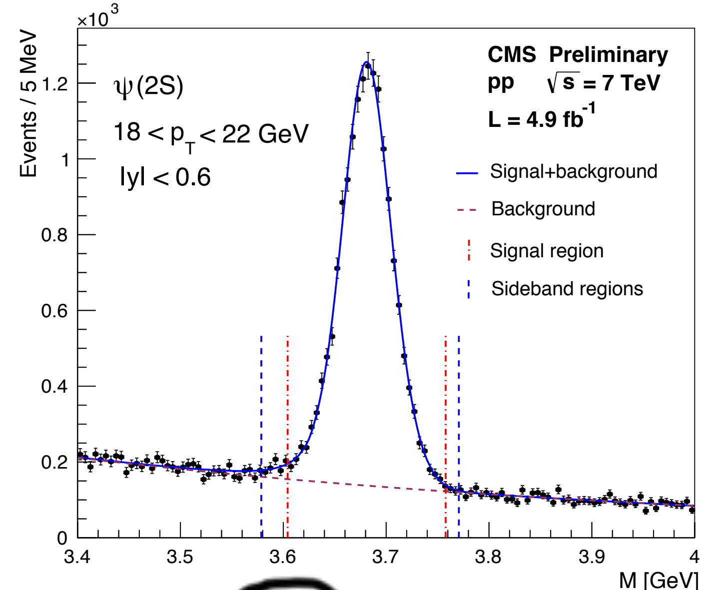
- The full angular distribution has to be measured. Otherwise two very different physical cases cannot be distinguished.
- The shape of the distribution is invariant and can be characterized by the frame invariant parameter $\tilde{\lambda} = (\lambda_\vartheta + 3\lambda_\varphi)/(1 - \lambda_\varphi)$

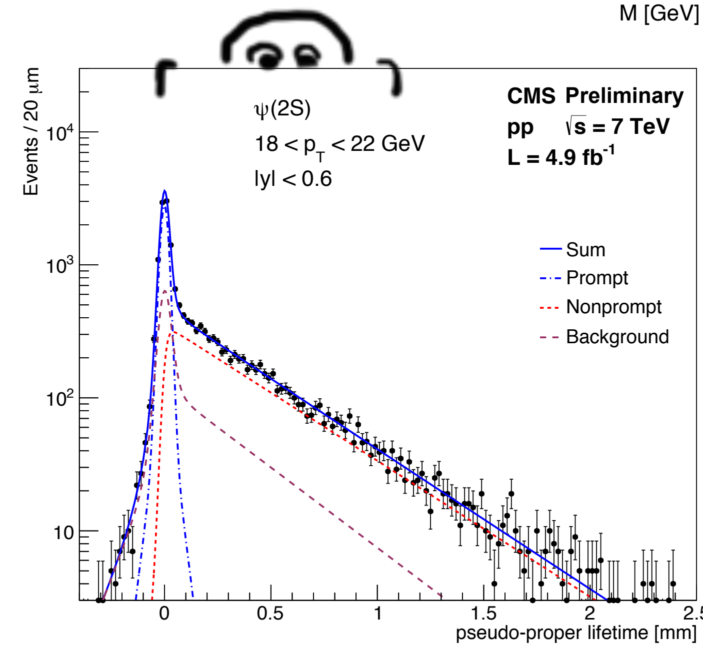


Quarkonium Polarization Measurements

- λ_ϑ, λ_φ, $\lambda_{\vartheta\varphi}$ and $\tilde{\lambda}$ are measured in three different reference frames (HX, CS, PX) for J/ψ, ψ(2S), ϒ(1S), ϒ(2S) and ϒ(3S) mesons
- As a function of transverse momentum p_T
  - J/ψ: $14 < p_T < 70$ GeV (10 bins)
  - ψ(2S): $14 < p_T < 50$ GeV (4 bins)
  - ϒ(nS): $10 < p_T < 50$ GeV (5 bins)
- And dimuon rapidity, |y|
  - J/ψ, ϒ(nS): |y| < 1.2 (2 bins)
  - ψ(2S): |y| < 1.5 (3 bins)
- An additional non prompt component has to be taken into account for ψ(nS) states

Details in PRL 110, 081802 (2013) and CMS-PAS-BPH-13-003

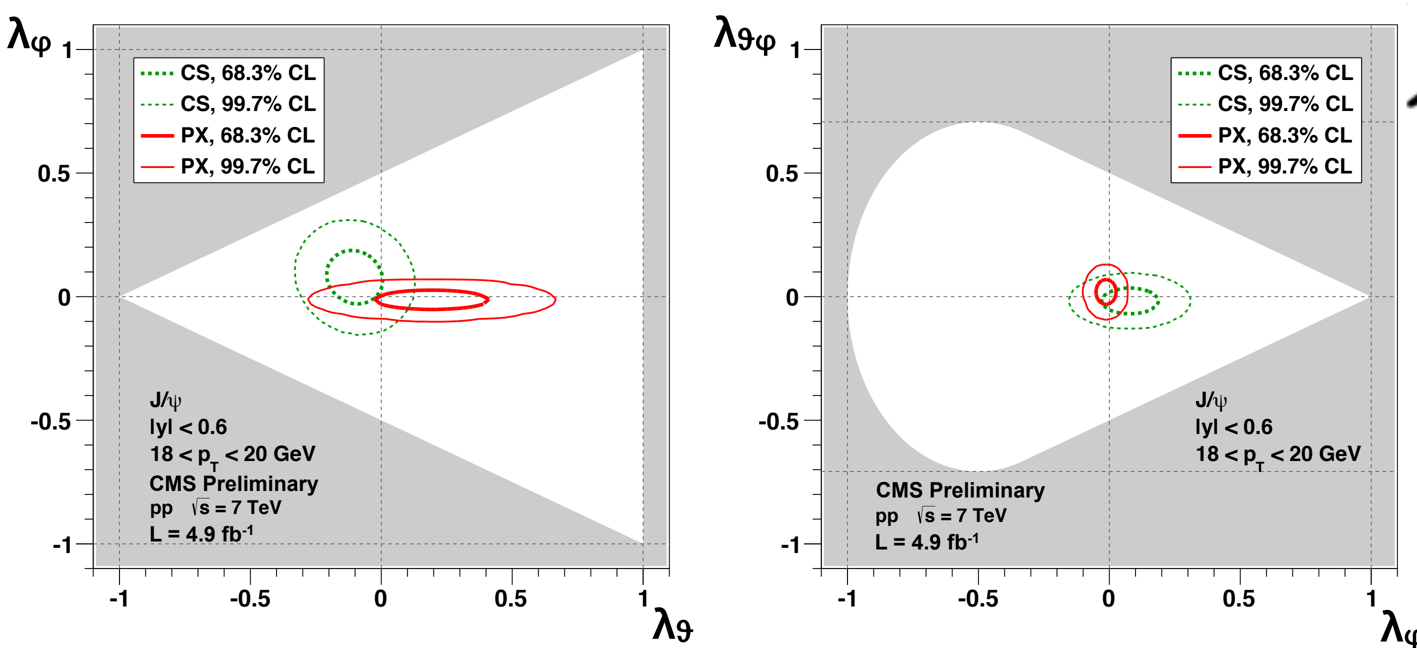


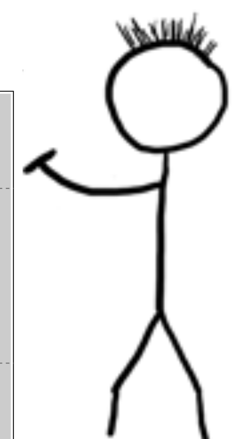


Obtaining Polarization Parameters

- Full and direct calculation of the Posterior Probability Distribution (PPD) of the polarization parameters λ_ϑ, λ_φ, $\lambda_{\vartheta\varphi}$

  1. Events distributed as in the background model are subtracted from the data sample until the previously determined background fraction is reached
  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

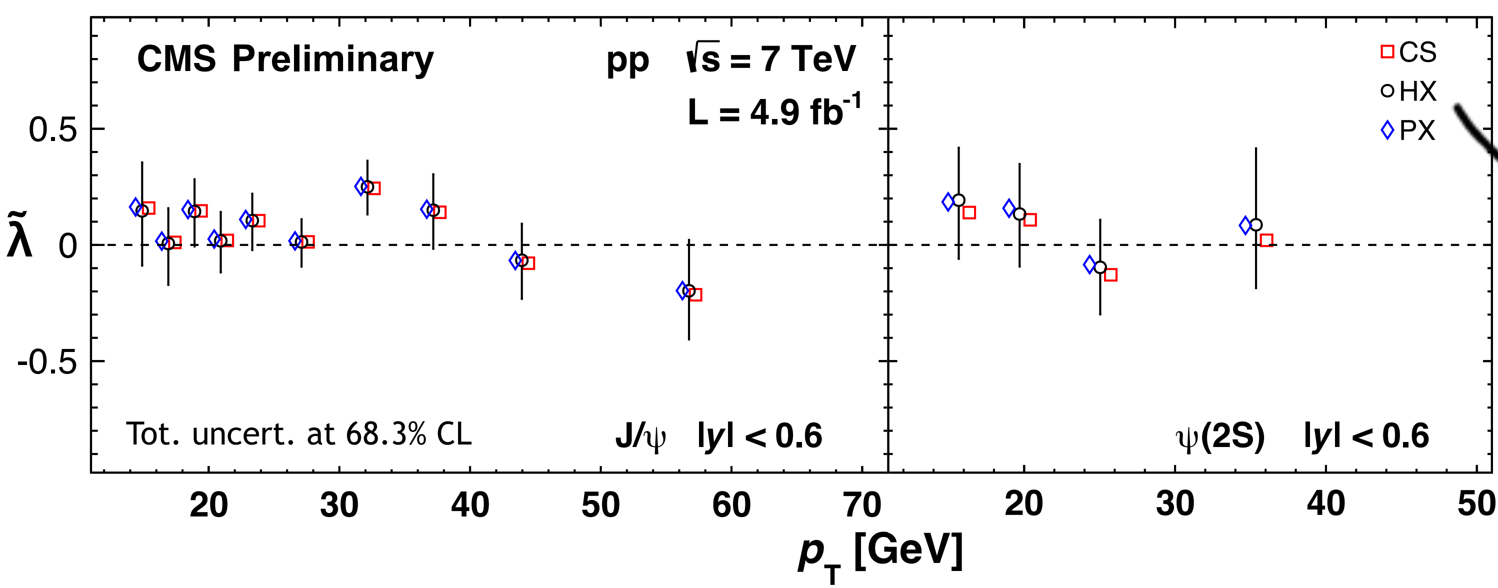


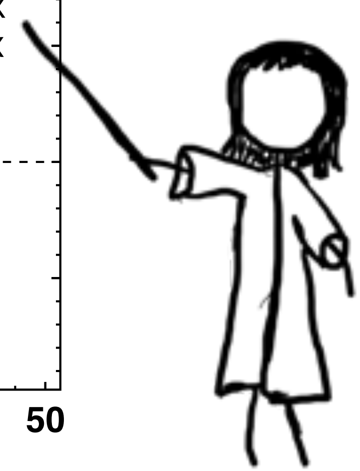


J/ψ
$|y| < 0.6$
$18 < p_T < 20$ GeV

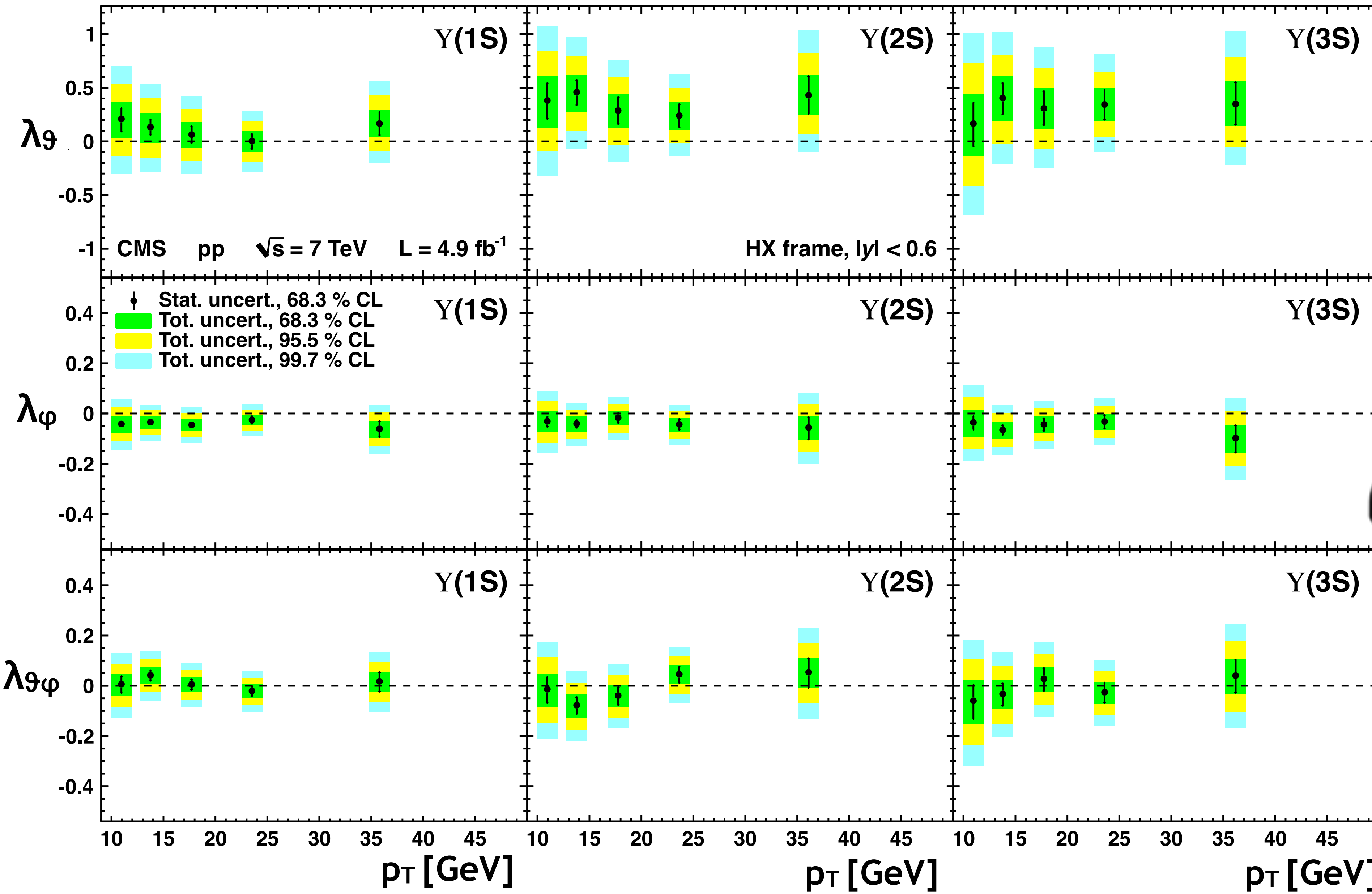
Systematic Effects

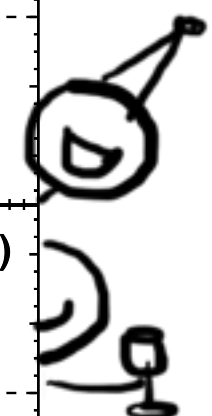
- Sources of systematic effects:
  - Extraction of polarization parameters
  - Background model
  - Muon efficiencies
- Systematic uncertainties are propagated to the PPD
- Good agreement between the $\tilde{\lambda}$ parameters in the three reference frames shows no indication of unaccounted systematic uncertainties



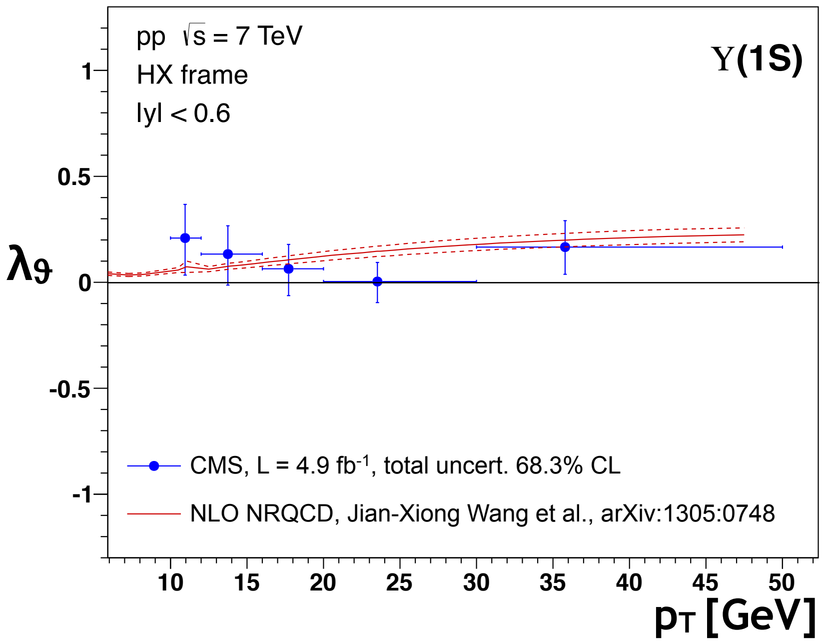


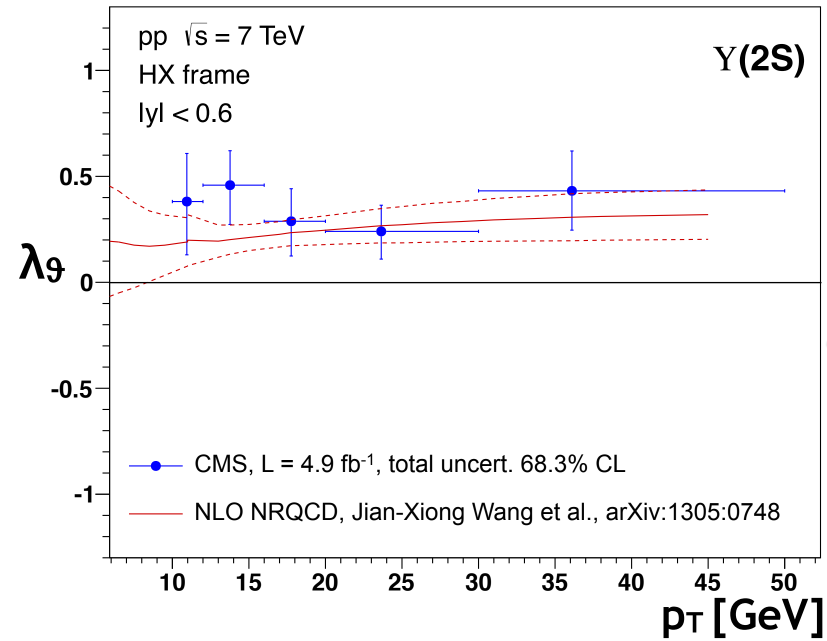
Υ(nS) Polarization in the HX Frame, |y| < 0.6

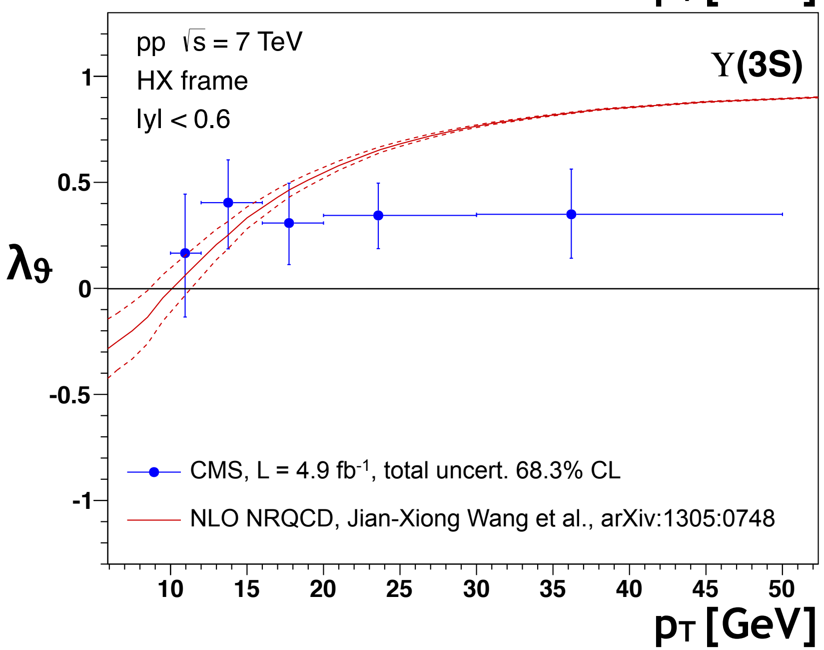




Υ(nS): Comparison to NLO NRQCD

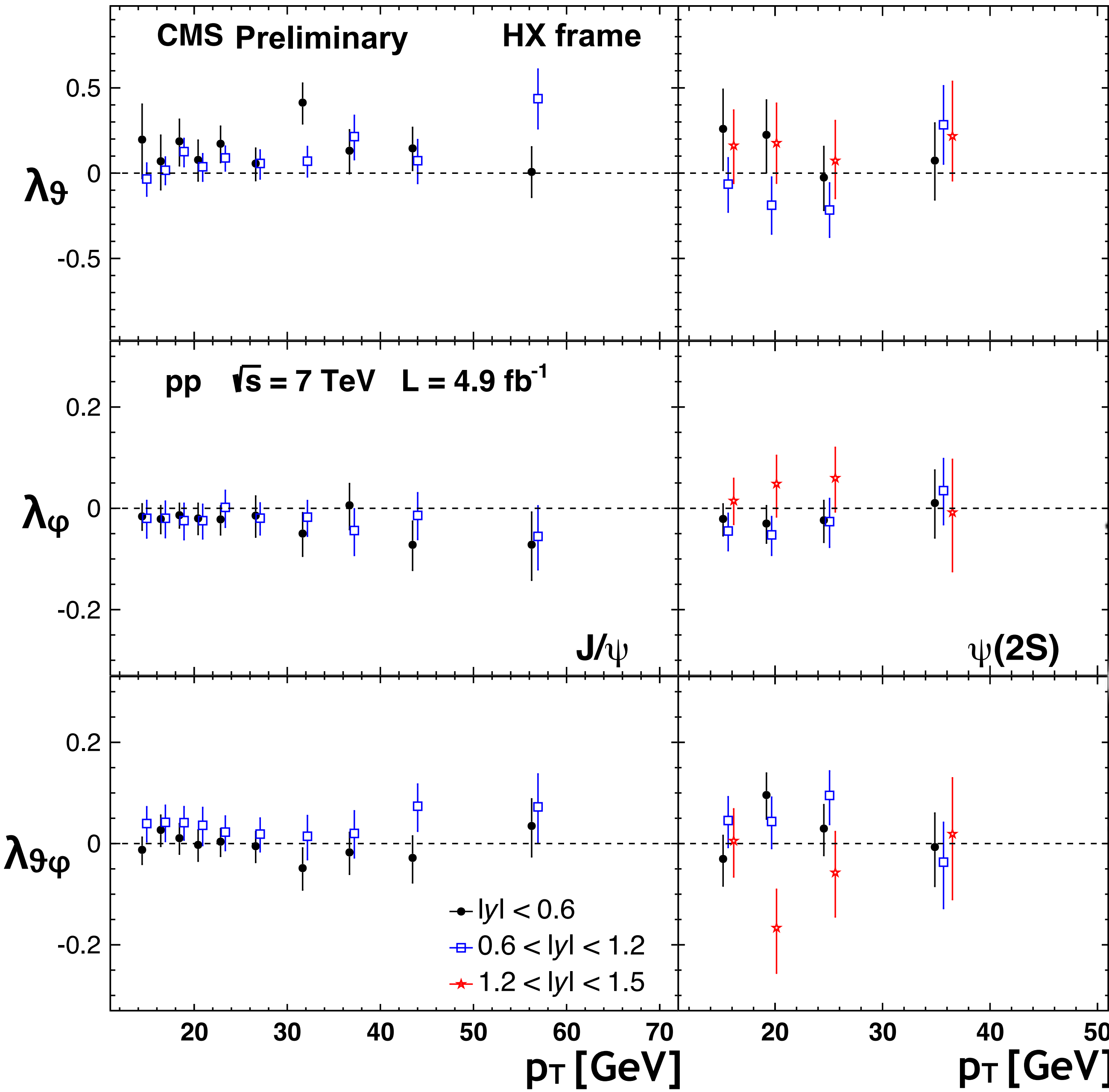




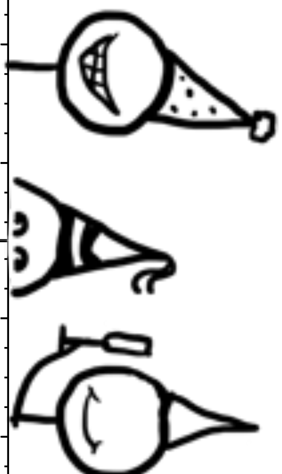


- Theory calculation accounts for feed-down contributions to Υ(1S) and Υ(2S) states
- Prediction for Υ(3S) may change when including feed-down from χ_b (3P) states
- Color octet matrix elements are fit to hadroproduction data only

Prompt ψ(nS) Polarization in the HX Frame



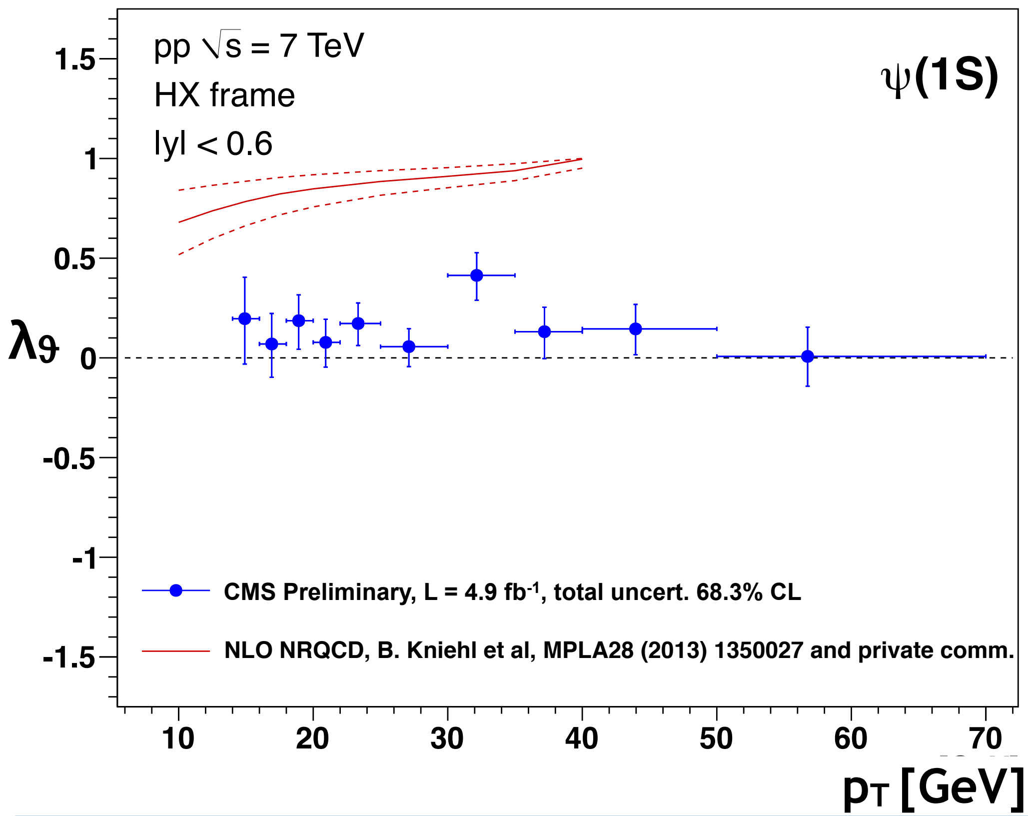
- No sign of strong polarization
- ψ(2S) is not affected by feed-down decays from higher states

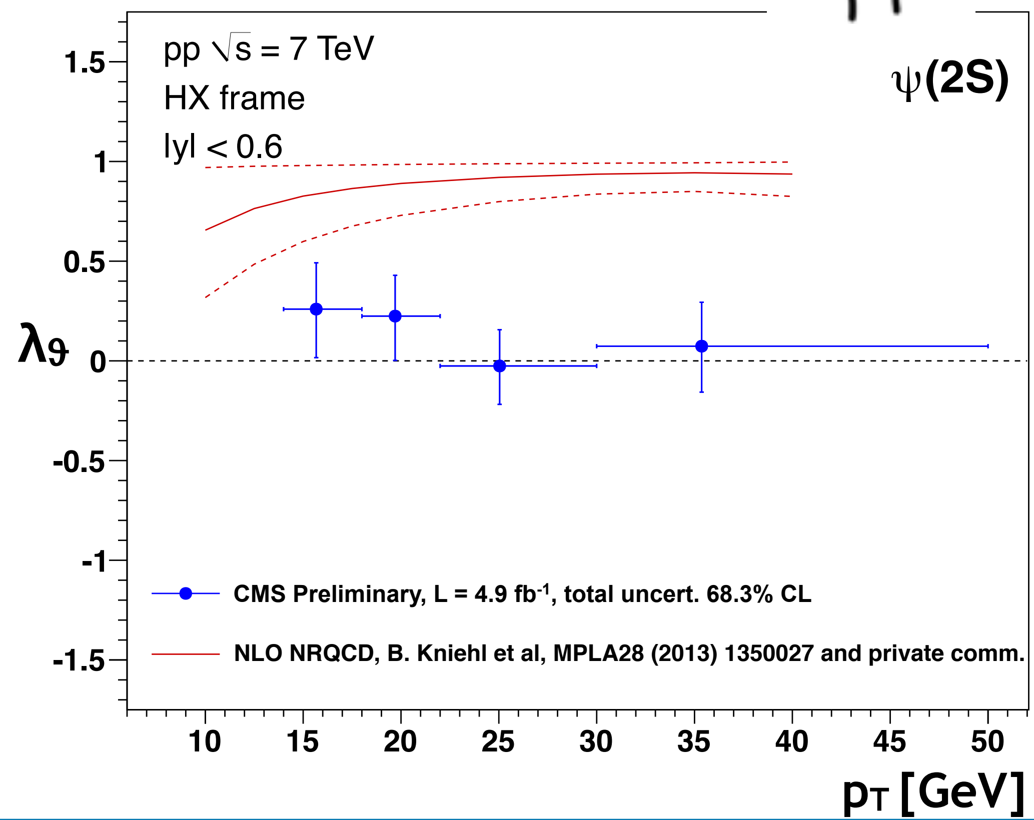


Error bars show total uncertainties at 68.3% CL

ψ(nS): Comparison to NLO NRQCD

- CMS results disagree with the NLO NRQCD calculations
- Calculations use a global fit of color octet matrix elements to photo- as well as hadroproduction data
- Theory predicts polarization only for directly produced J/ψ's





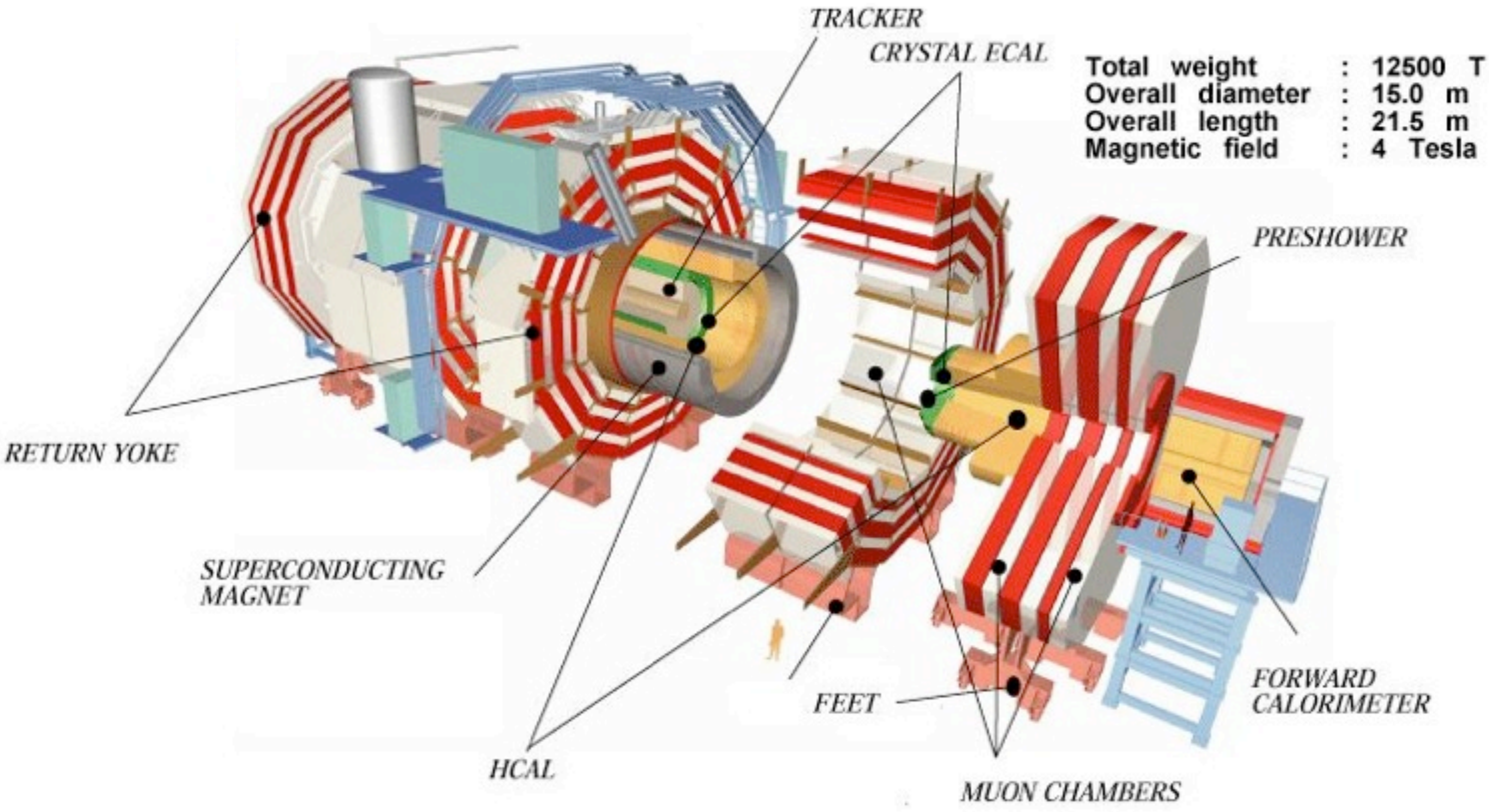
Summary and Conclusions

- $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ differential cross sections for $10 < p_T < 100$ GeV are measured using CMS polarization results
- A change in the slope of the differential cross sections from an exponential to power-law is observed

- Frame dependent polarization parameters λ_ϑ, λ_φ, $\lambda_{\vartheta\varphi}$ and the frame invariant parameter $\tilde{\lambda}$ are measured in three different frames (CS, HX, PX) for the $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ and prompt J/ψ and $\psi(2S)$ mesons
- J/ψ results are shown for the first time
- No evidence of strong longitudinal or transverse polarizations has been observed
- J/ψ and $\psi(2S)$ measurements are in disagreement with current theoretical predictions

BACKUP

CMS Detector

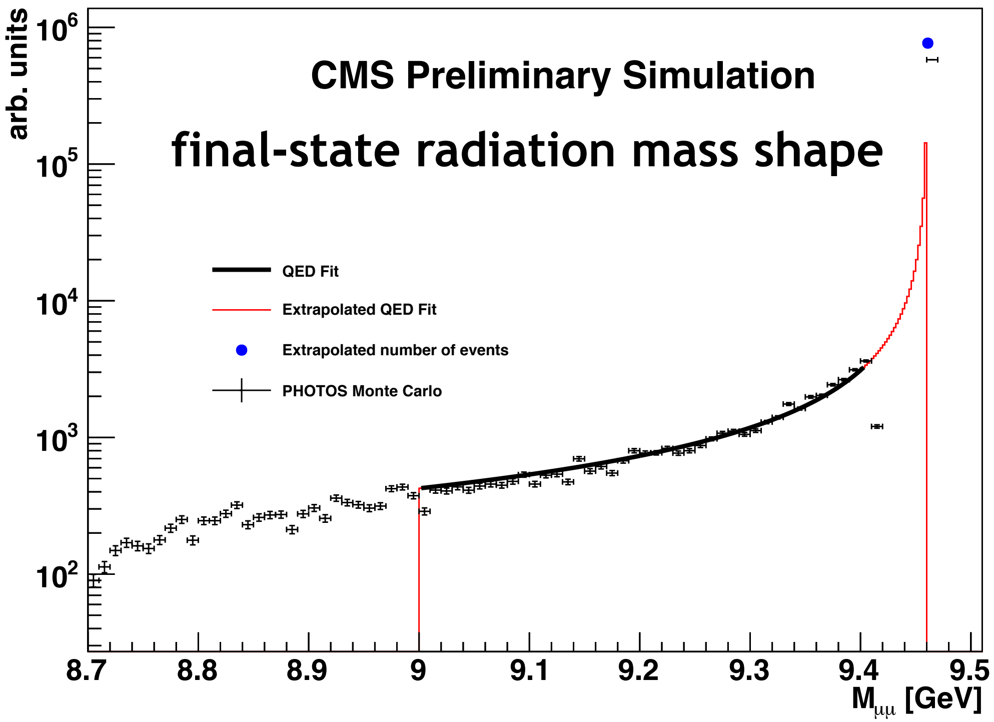


Quarkonium Production

Line Shape Determination

- Mass PDF was defined with the help of radiative line shape determined from Monte Carlo and the mass resolution

$$\mathcal{F}(M_{\mu\mu}; c_w, \delta m) = \frac{1}{N}\sum_{i=1}^{N} \frac{1}{\sqrt{2\pi} c_w \zeta_i} e^{-(M_{\mu\mu}-m_i-\delta m)^2/2c_w^2\zeta_i^2}$$



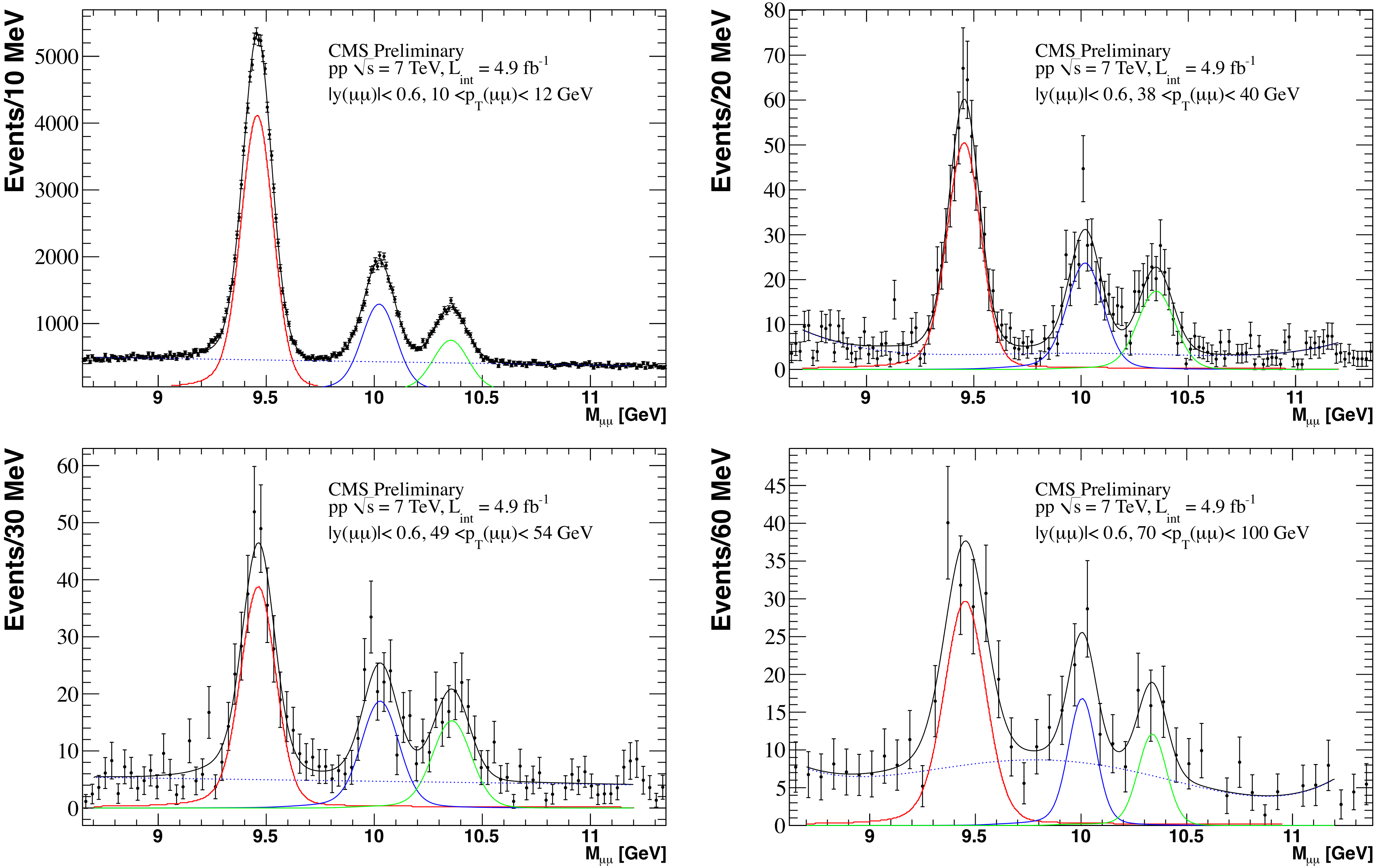
c_w width scale factor

δm mass shift scale factor

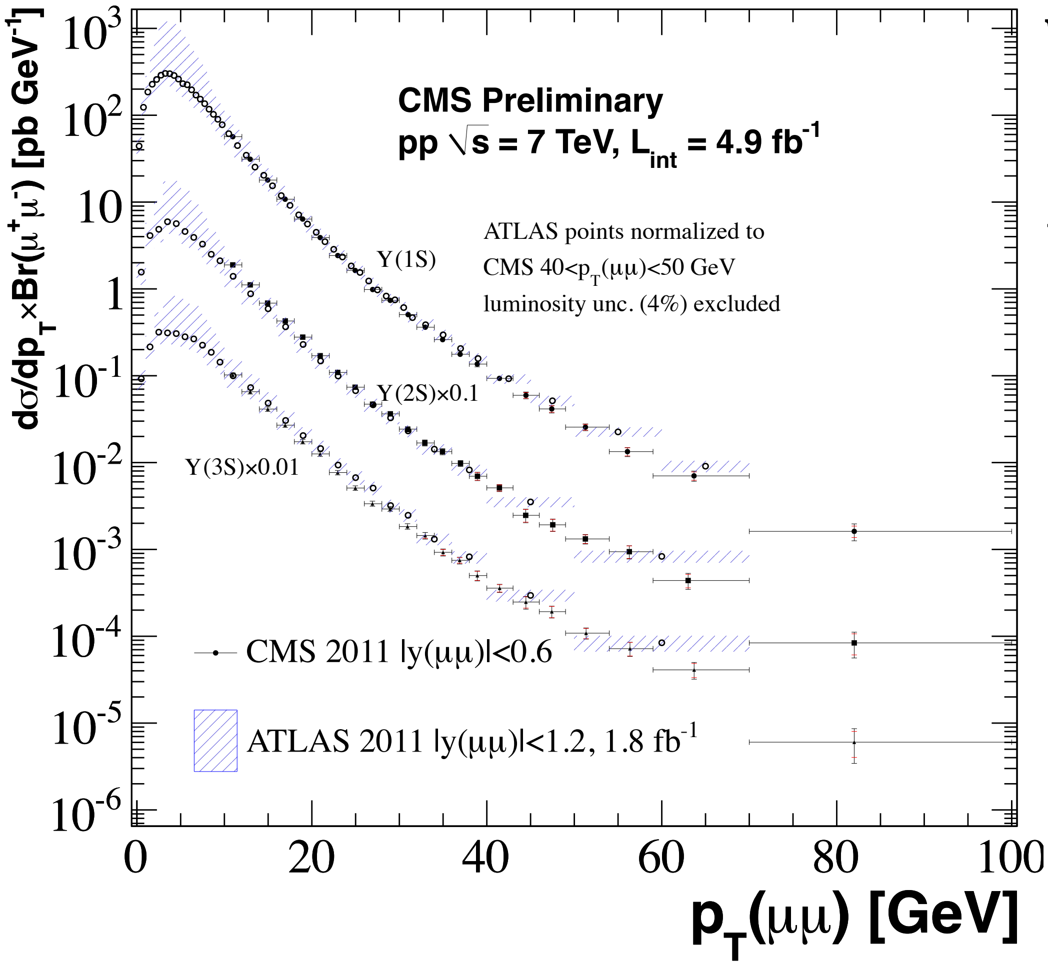
m_i was sampled from the final-state radiation mass shape

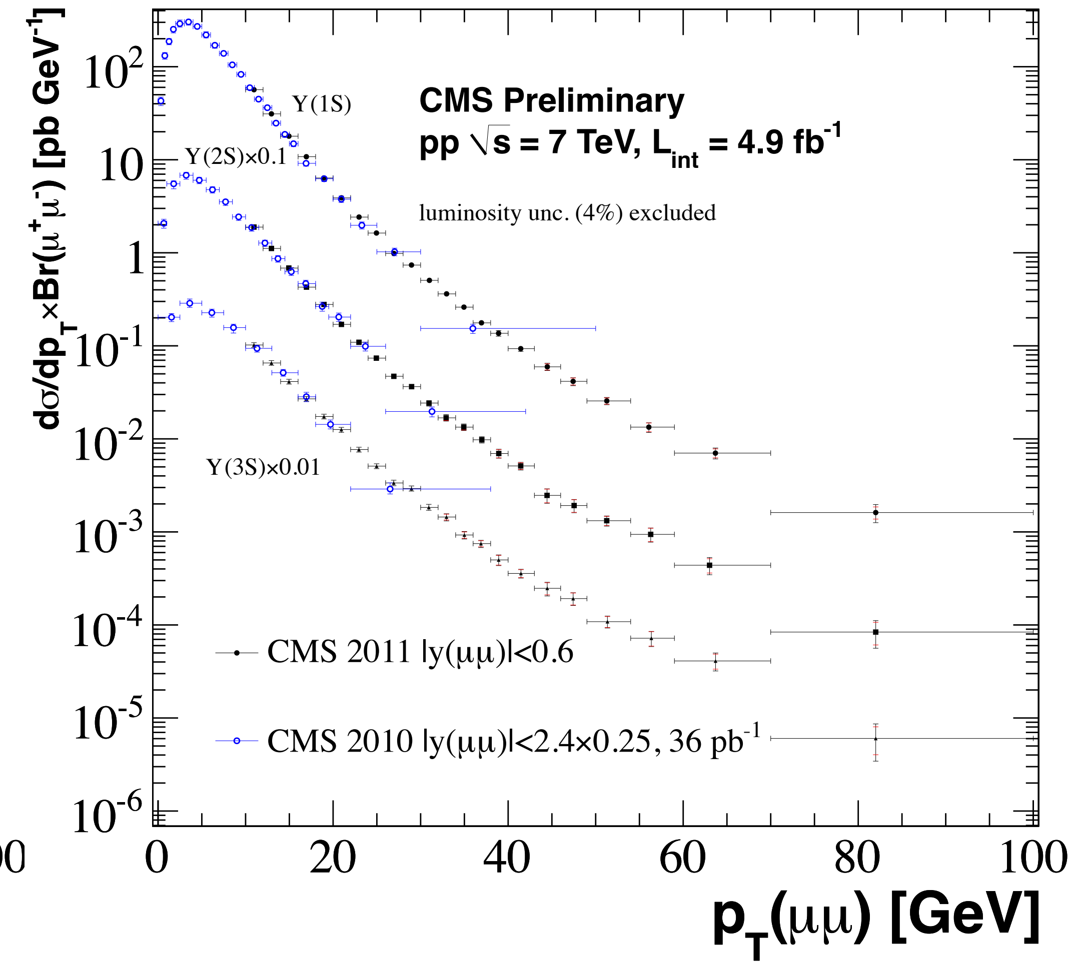
ζ approximates the detector effects on the mass error

Dimuon Mass Fits



Comparison to ATLAS and Previous CMS Measurements

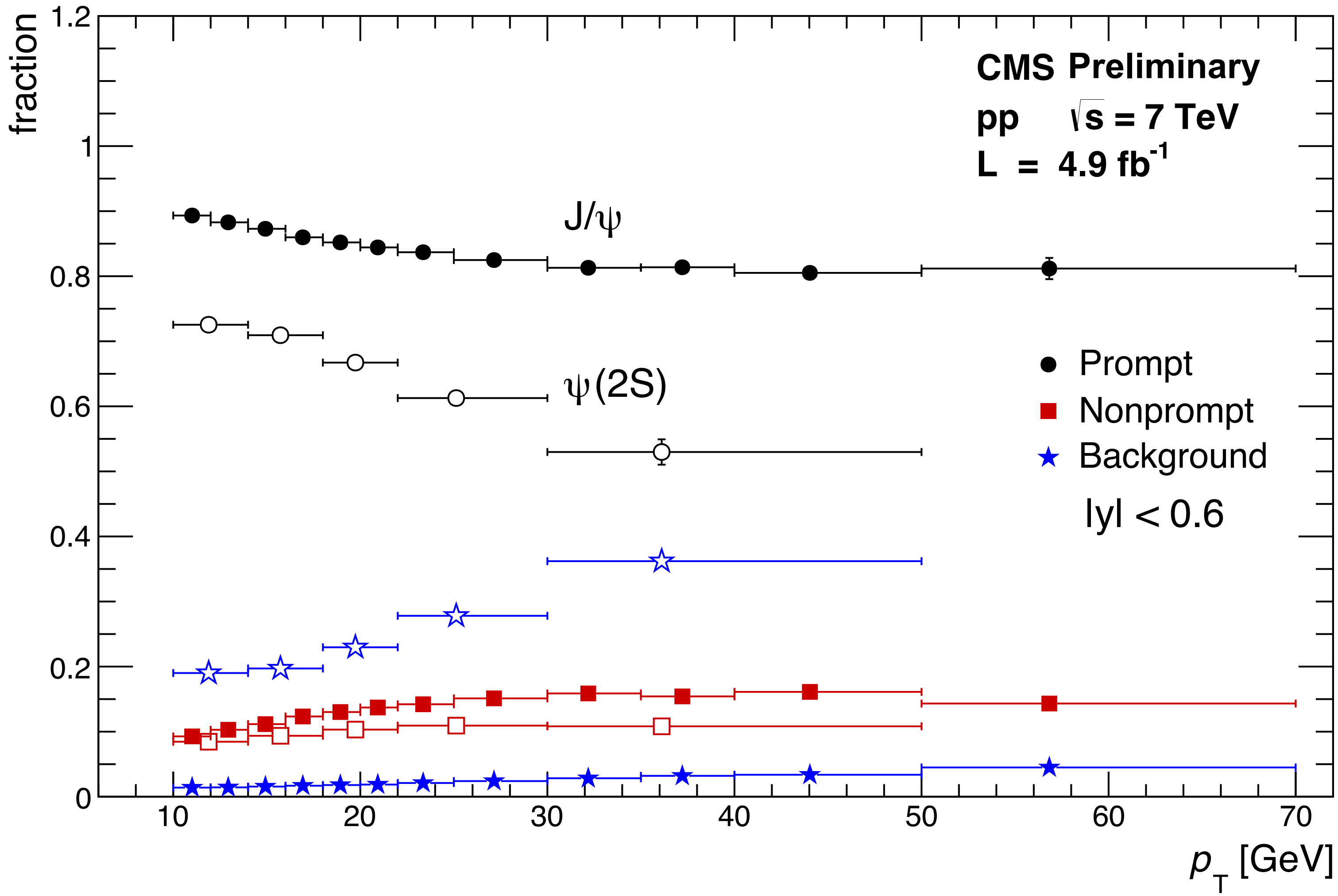




Quarkonium Polarization

Contributions to the ψ(nS) Prompt Signal Region

- The prompt-signal region is defined as a 2D window of ±3σ widths in dimuon mass and (pseudo-proper) lifetime



Definition of the PPD

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

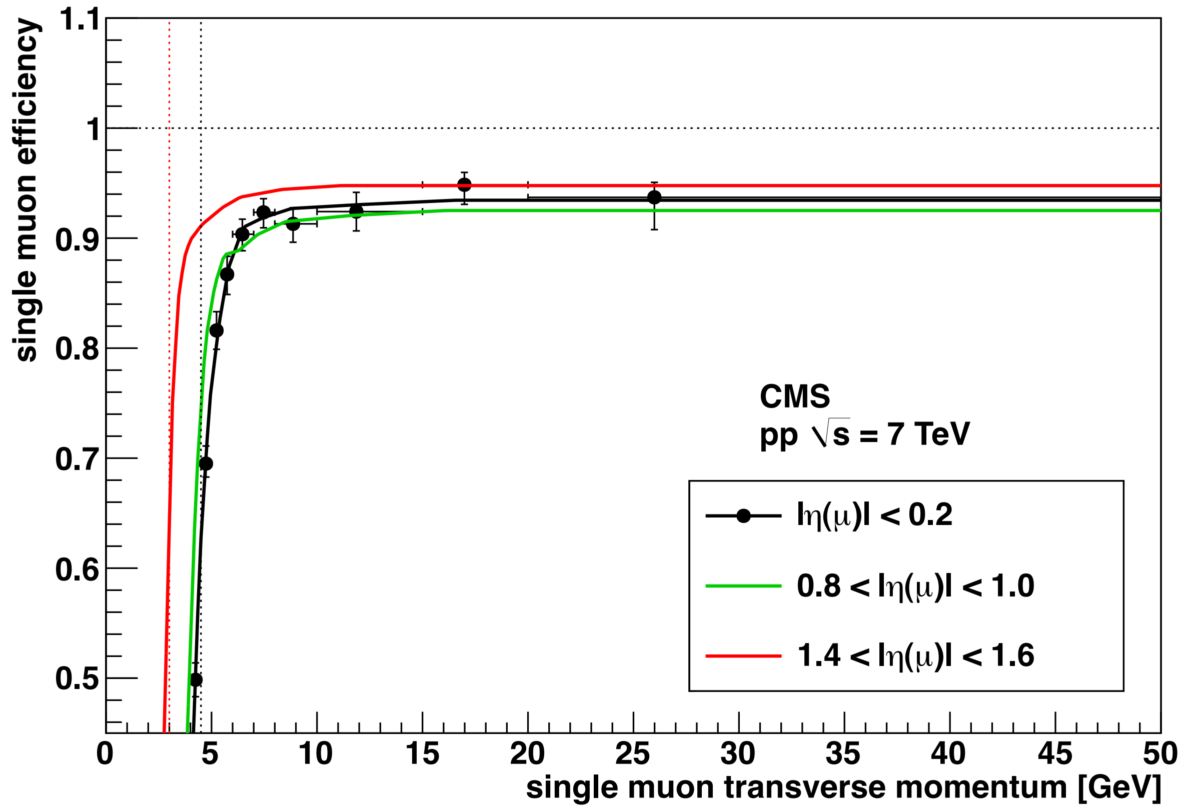
$\mathcal{N}$: normalization

W: general angular distribution

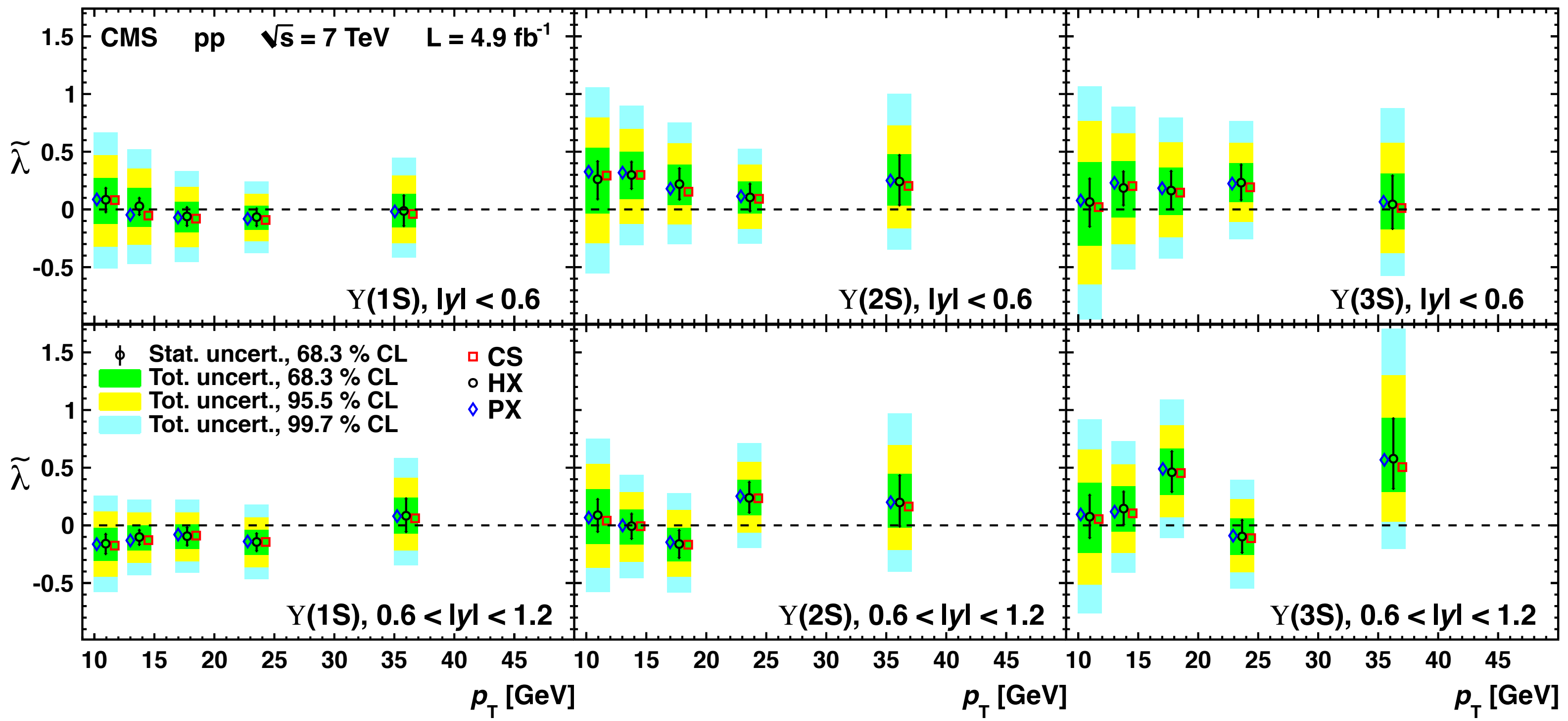
ε: dimuon efficiency as a function of the muon momenta

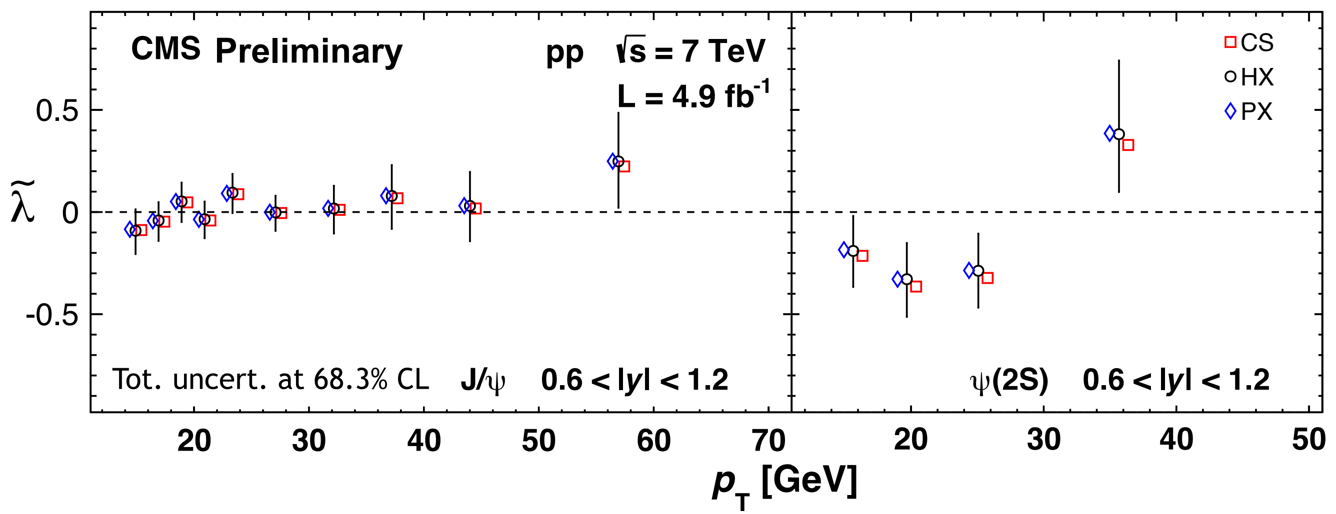
Efficiencies

- 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

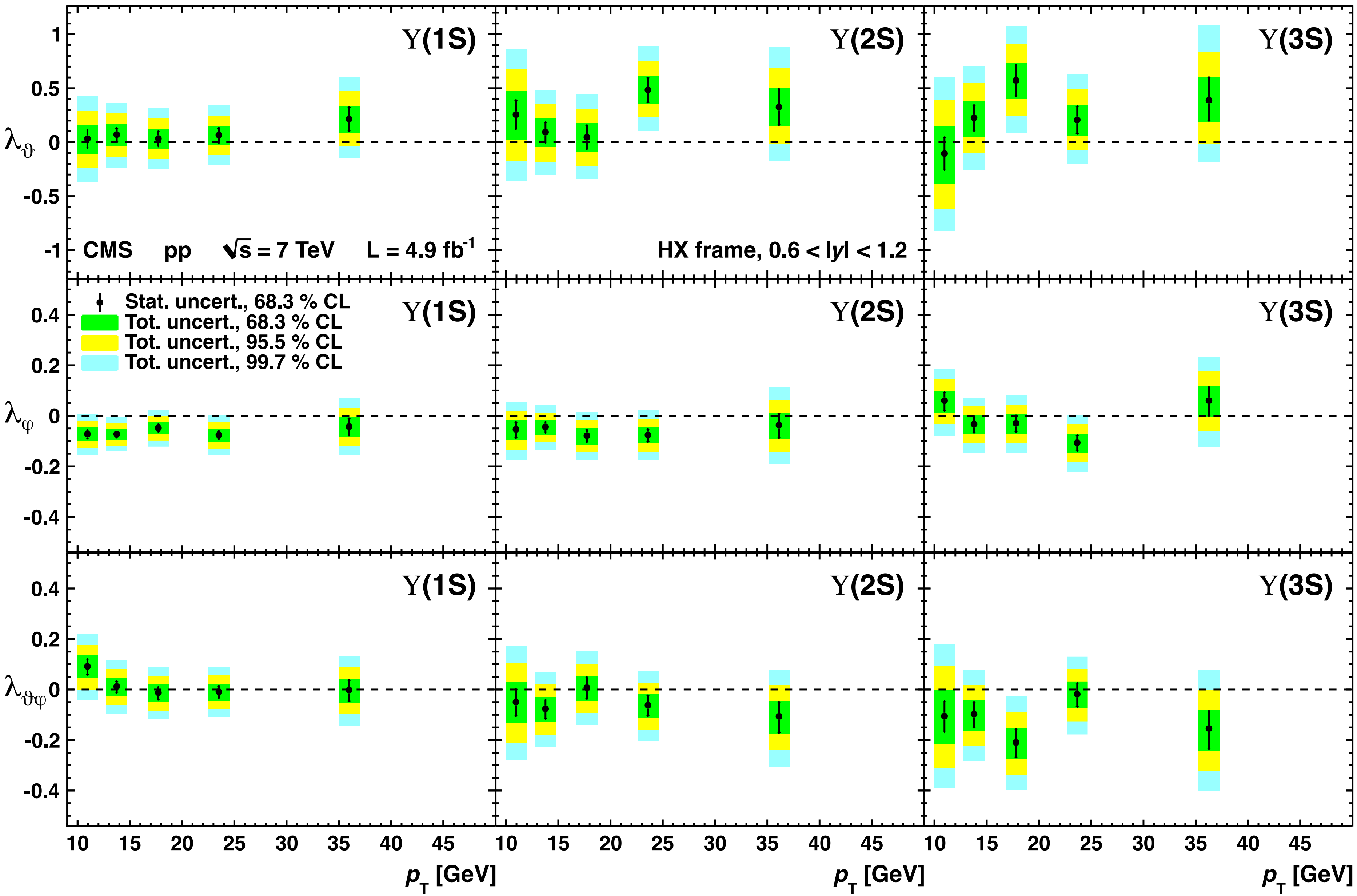


Frame Invariant Parameter $\tilde{\lambda}$

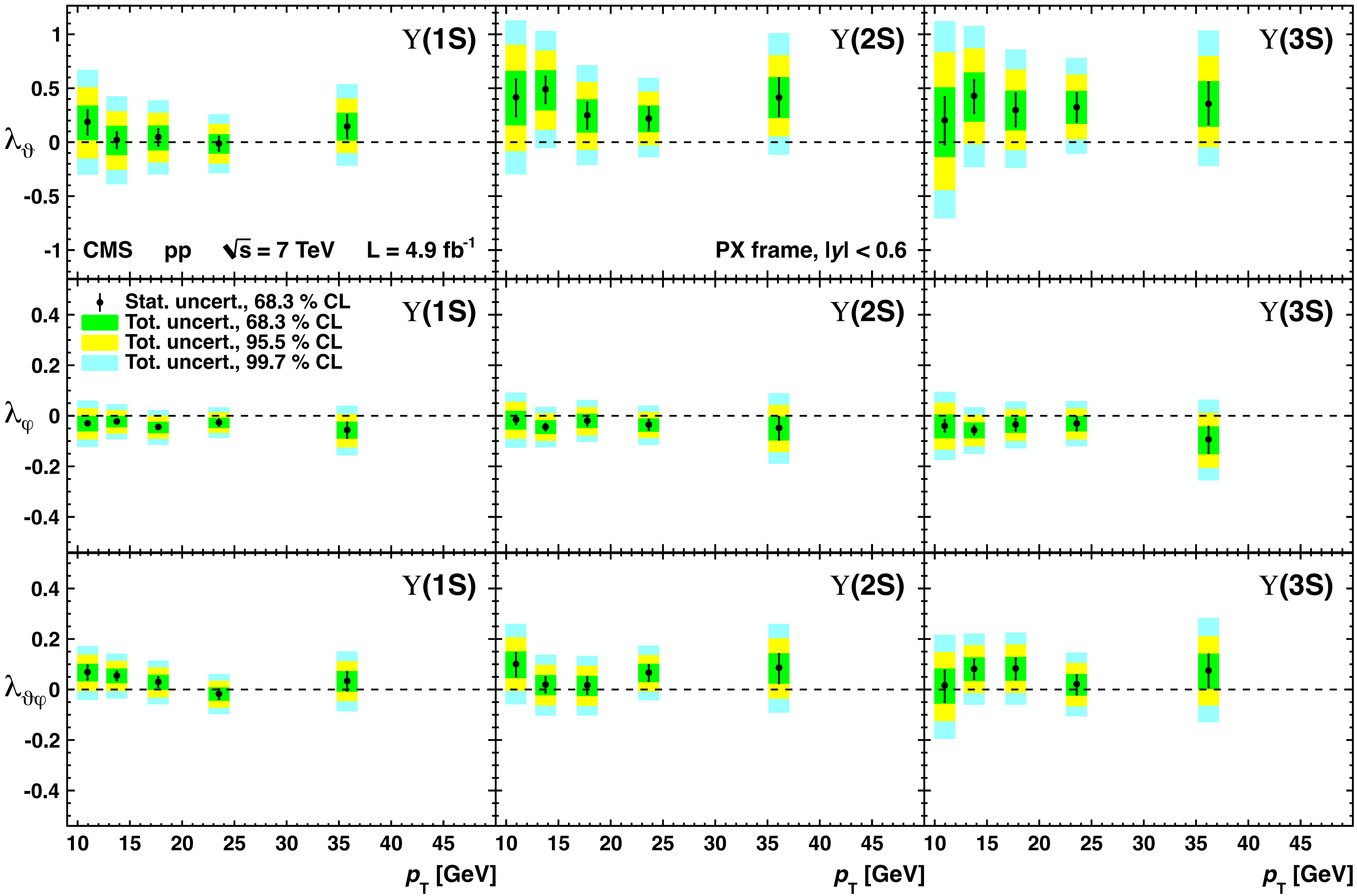




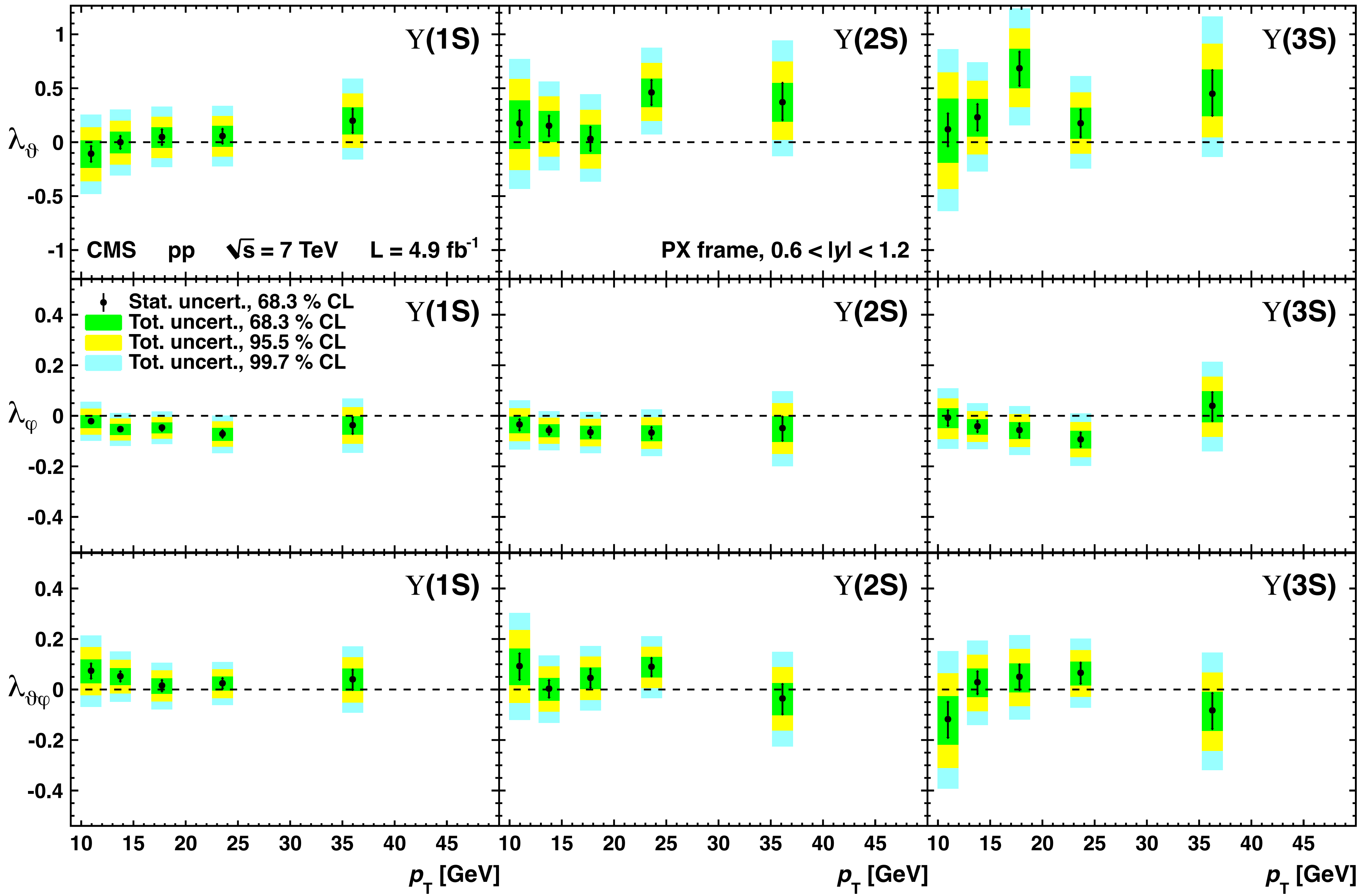
Υ(nS) Polarization in the HX Frame, 0.6 < |y| < 1.2



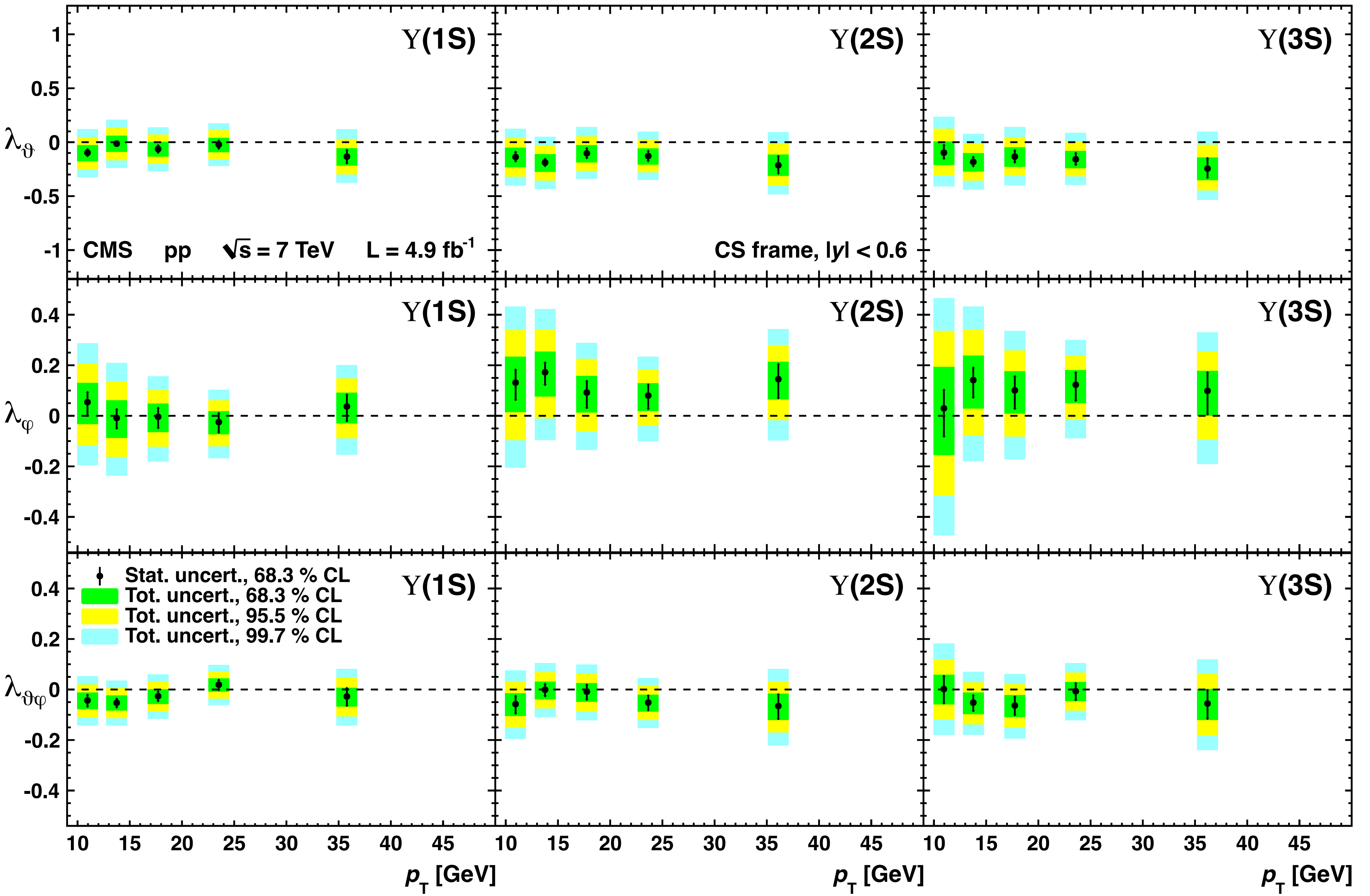
Υ(nS) Polarization in the PX Frame, |y|< 0.6



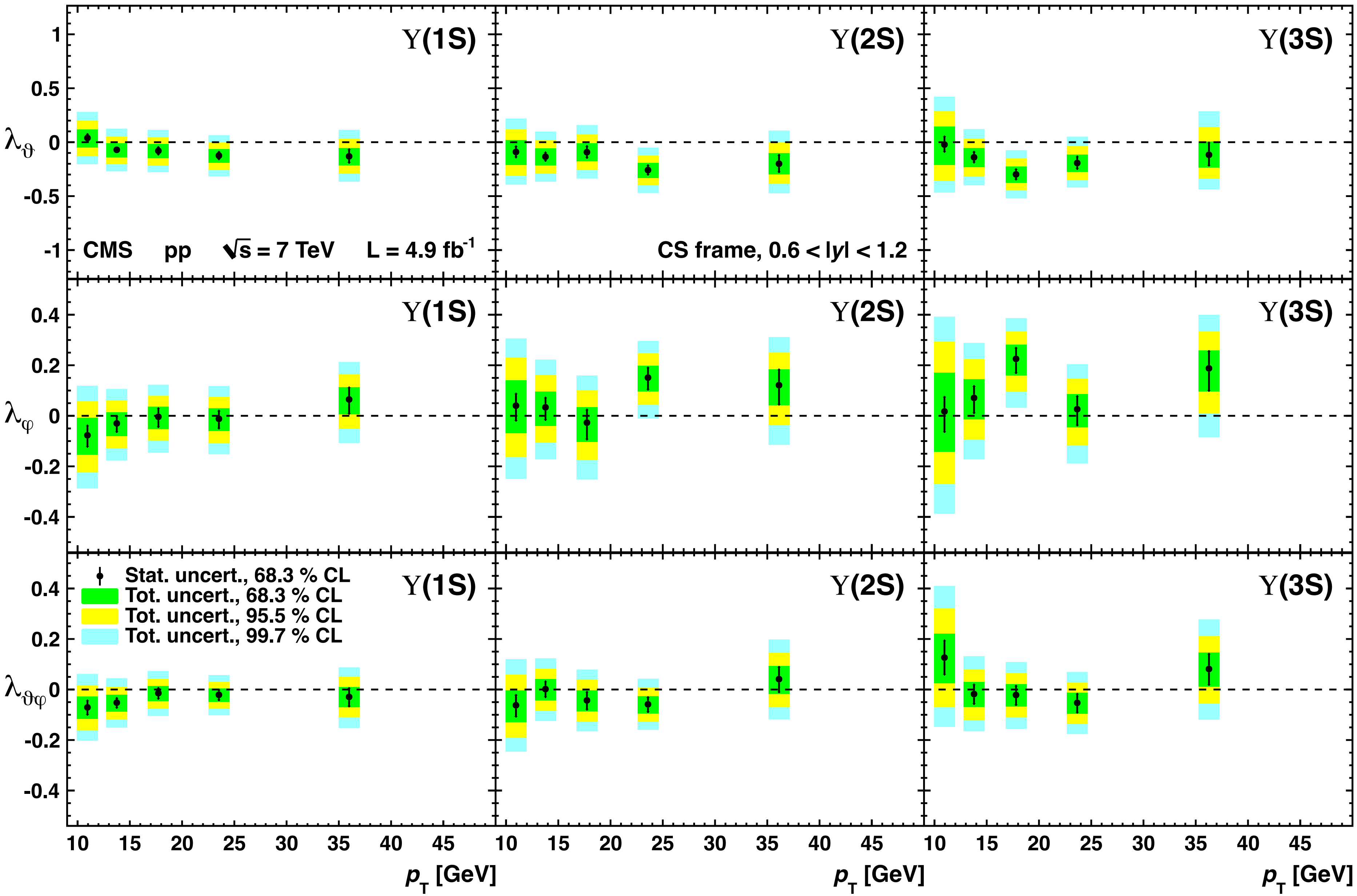
Υ(nS) Polarization in the PX Frame, 0.6 < |y| < 1.2



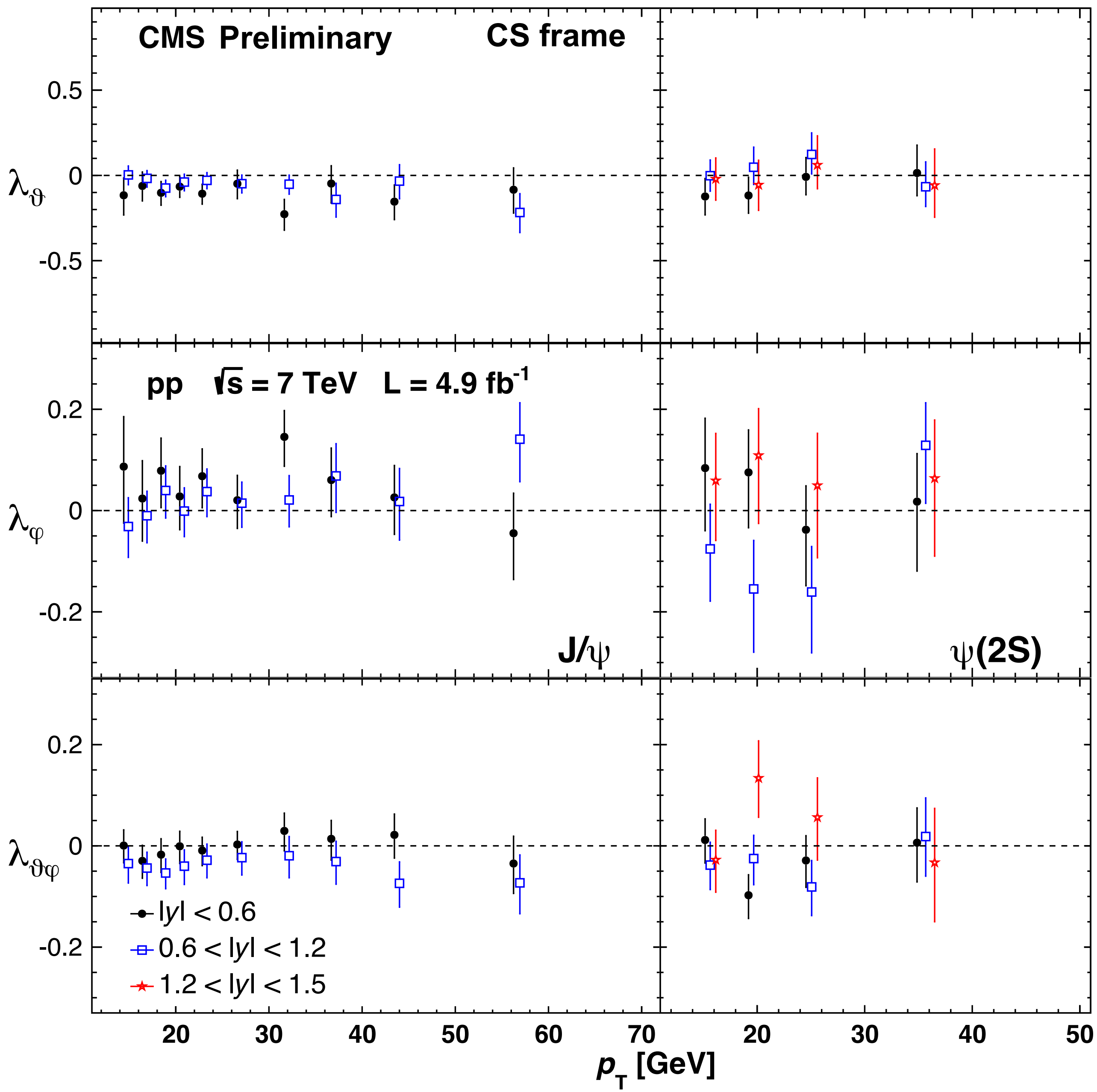
Υ(nS) Polarization in the CS Frame, |y| < 0.6



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

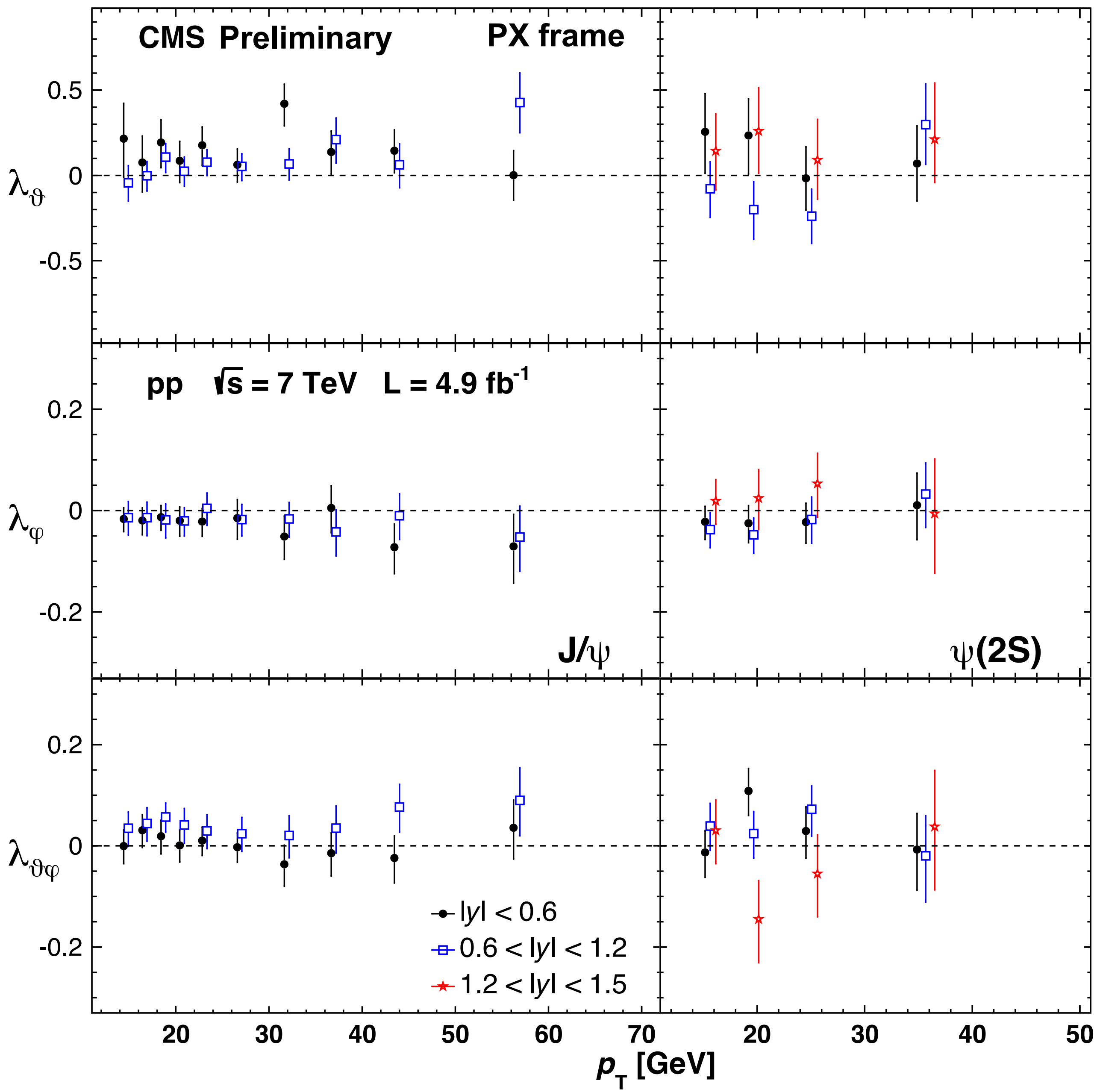


Prompt ψ(nS) Polarization in the CS frame



Error bars show total uncertainties at 68.3% CL

Prompt ψ(nS) Polarization in the PX frame



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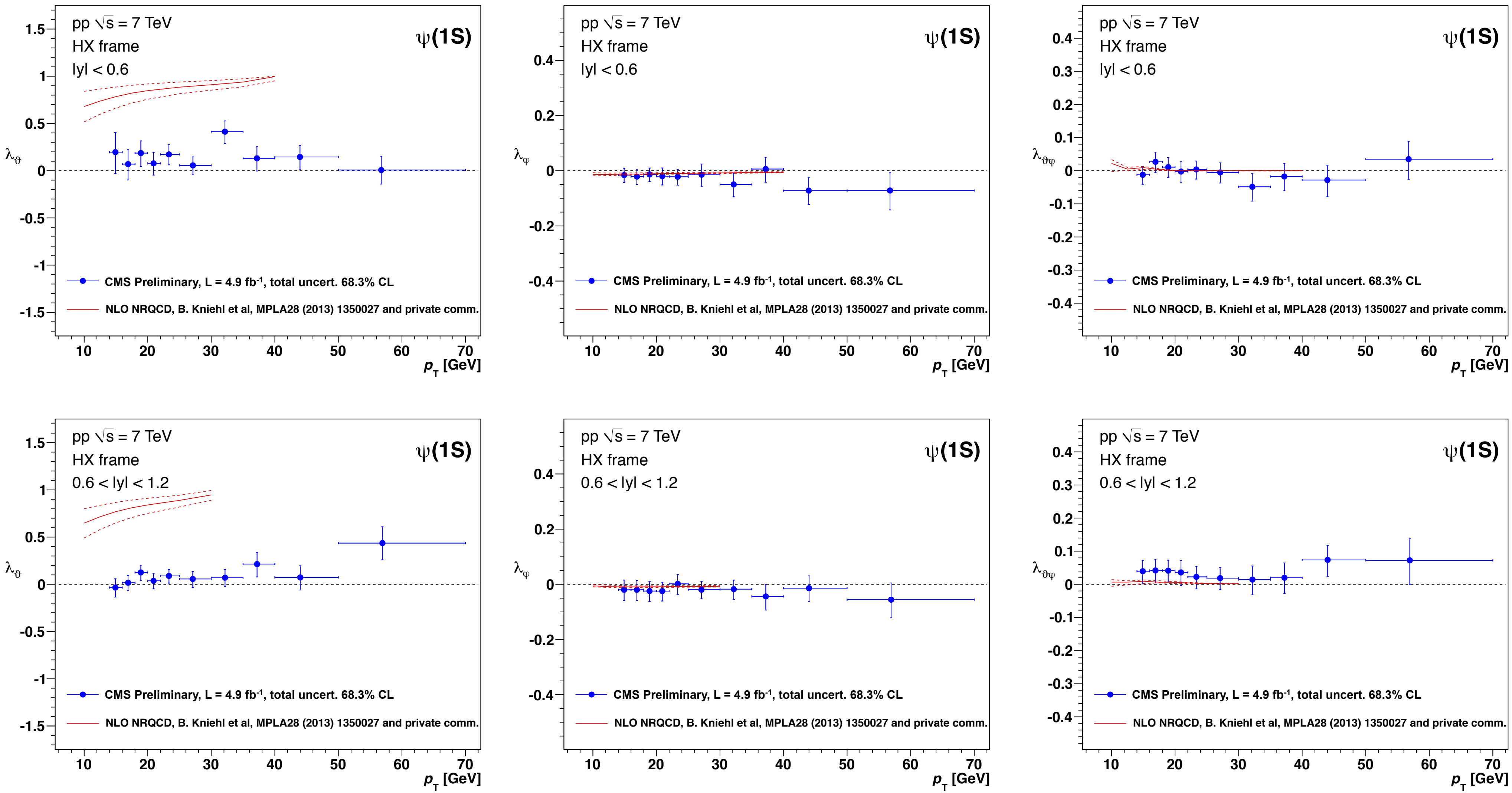
ψ(1S): Comparison to NLO NRQCD



ψ(2S): Comparison to NLO NRQCD