Studies of P-wave and S-wave Quarkonium Production with the CMS detector

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Overview

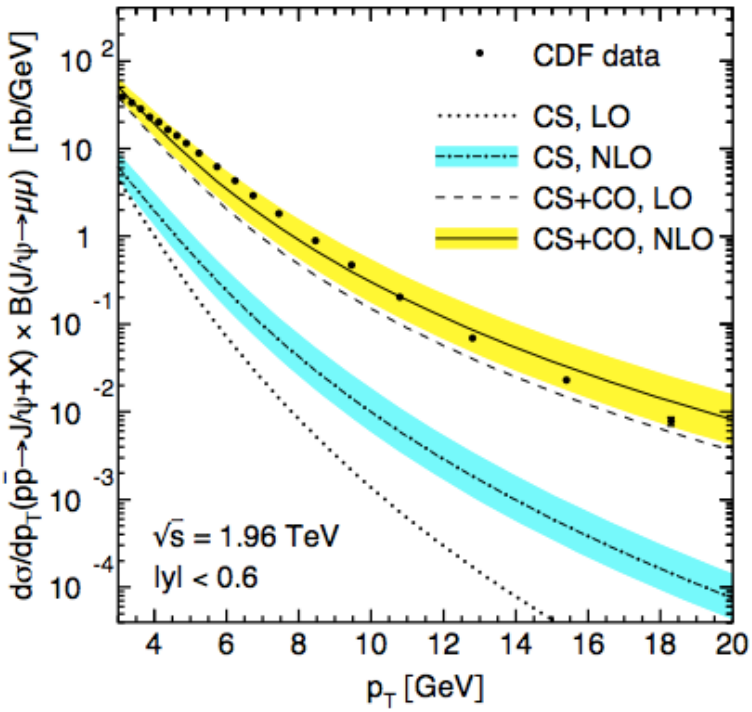
- Motivation--the quarkonium production puzzle
- Recent CMS measurements:
  - Studies of S-wave quarkonia production: Υ(1S,2S,3S)
  - studies of P-wave quarkonia production: χ_c, χ_b
  - J/Ψ and Ψ' polarization and Υ(1S,2S,3S) polarization
- Conclusions

Motivation

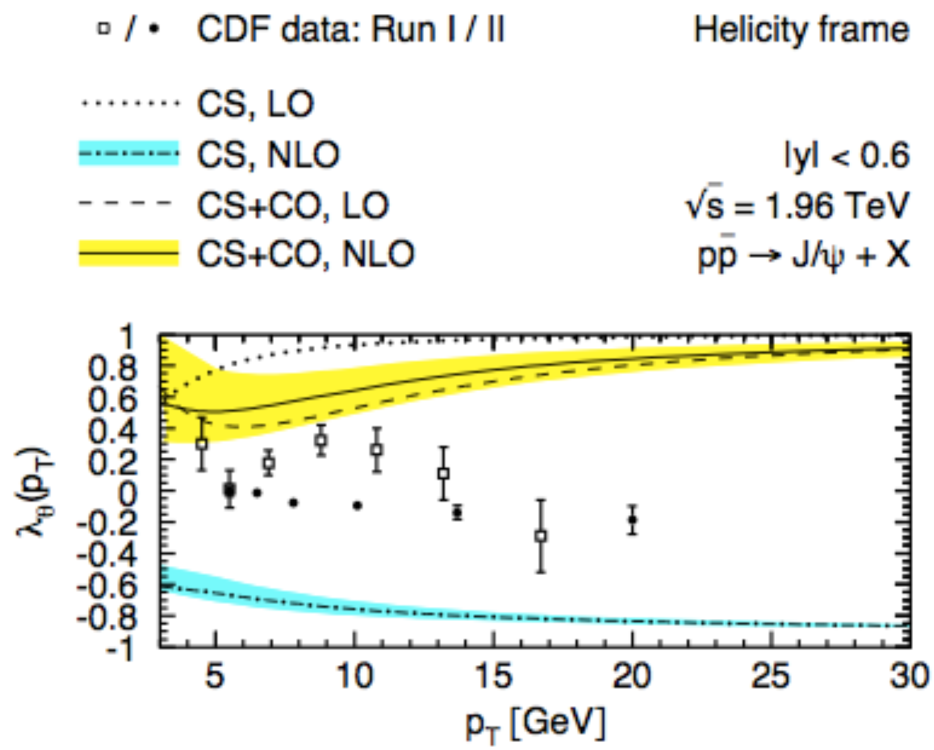
- Quarkonium production is an ideal probe to study hadron formation, part of the non-perturbative QCD sector
- Properties of QCD can be probed through several quarkonium production measurements: cross sections and polarizations
- The J/Ψ production cross section was found to be higher by a factor ~30 compared to predictions at CDF. The important color octet (CO) contributions!
- NRQCD was born. It is found to describe differential cross sections well. It needs some experimental input.
- It also predicts that S-wave quarkonia should be transversely polarized at high p_T.

Tevatron legacy

Butenschoen, Kniehl
PRL 106, 022003 (2011)



Butenschoen, Kniehl
PRL 108, 172002 (2012)



Decent agreement of differential cross sections reached, but not for polarization

Theoretical framework: NRQCD

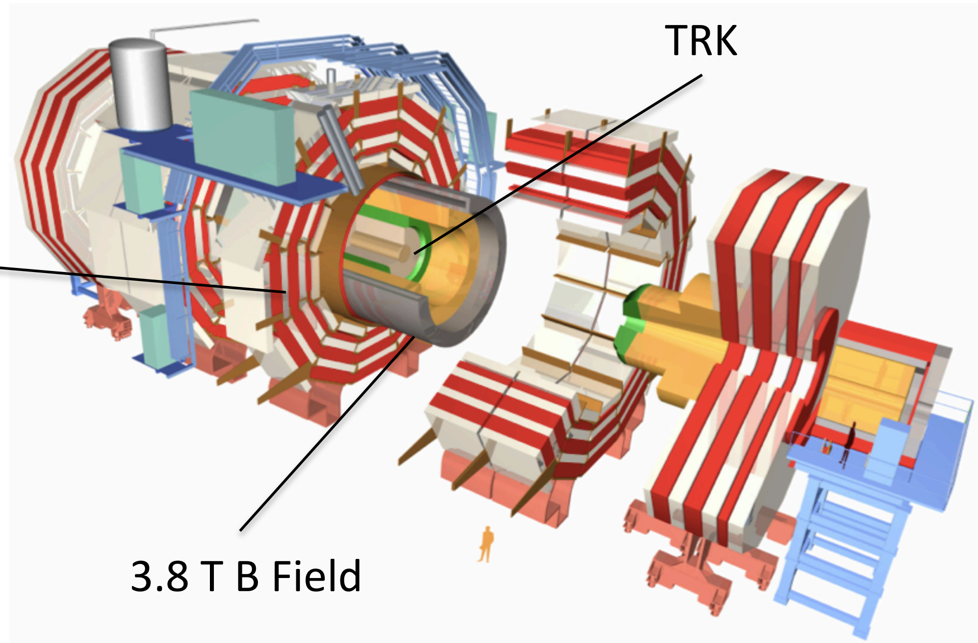
- Effective field theory featuring the factorization of perturbative short-distance processes and long-distance effects

$$d\sigma(H+X) = \sum_n d\hat{\sigma}(Q\bar{Q}[n]+X)\,\langle \mathcal{O}^H[n] \rangle$$

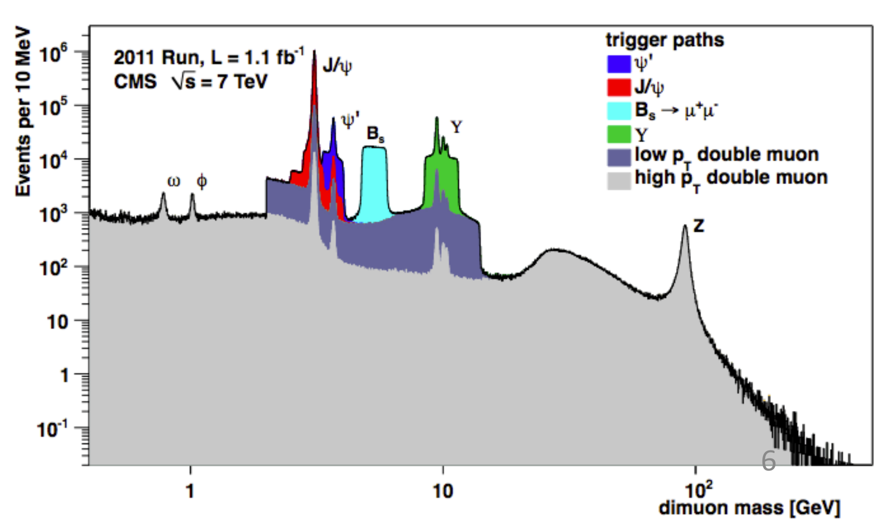
Short-distance perturbative term
and Parton Distribution Functions

Long-distance matrix elements (LDMEs)
Process independent.
Non-perturbative, extracted phenomenologically
or from lattice calculations,
with the help of scaling rules

Potential of CMS in quarkonium studies



- The Muon system, the Silicon Tracker and the Magnetic Field system allow accurate measurement of muon pairs over a wide range of η and p_T.
- Low-energy photons can be measured accurately using conversions
- A flexible trigger system accommodates Higgs physics, SUSY searches, and also quarkonium



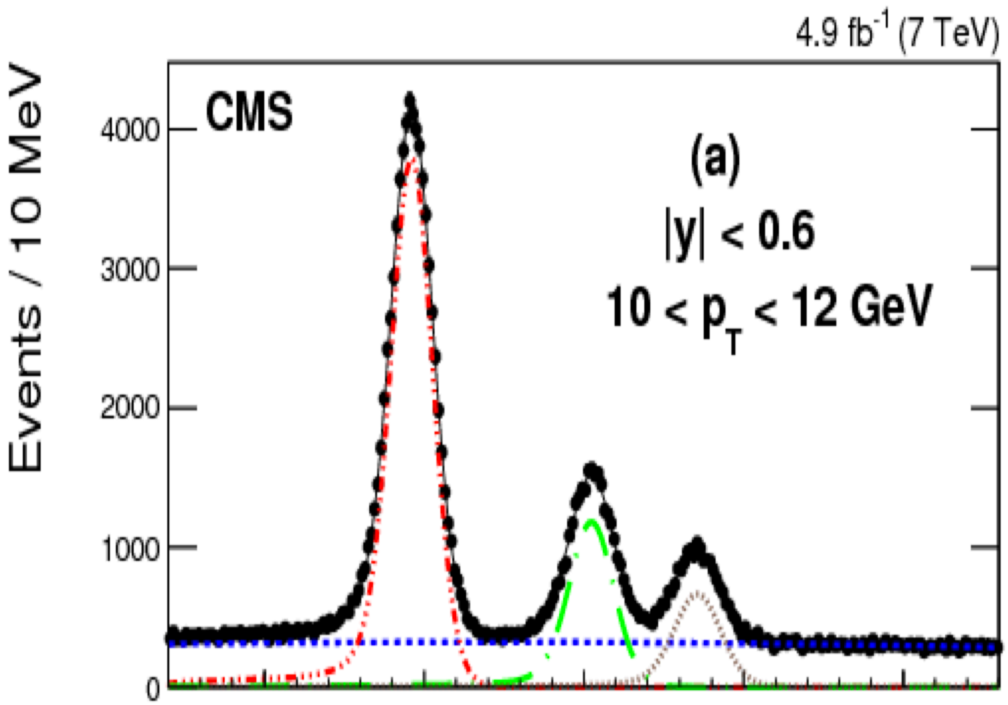
Y production

CMS-PAS-BPH-12-006, **arXiv:1501.07750 [hep-ex]**

- First measurements published on 2010 data PRD 83,112004 (2011)
- The new result (2011 data) extends the p_T coverage up to 100 GeV
- Technique: measure yields and apply event-by-event efficiency corrections

$$\left.\frac{d\sigma(pp \to Y(nS))}{dp_T}\right|_{|y|<0.6} \times \mathcal{B} = \frac{N^{Y(nS)}(p_T)}{L\ \Delta p_T\ \varepsilon_{\mu\mu}(p_T)\ \mathcal{A}(p_T)}$$

luminosity efficiency acceptance

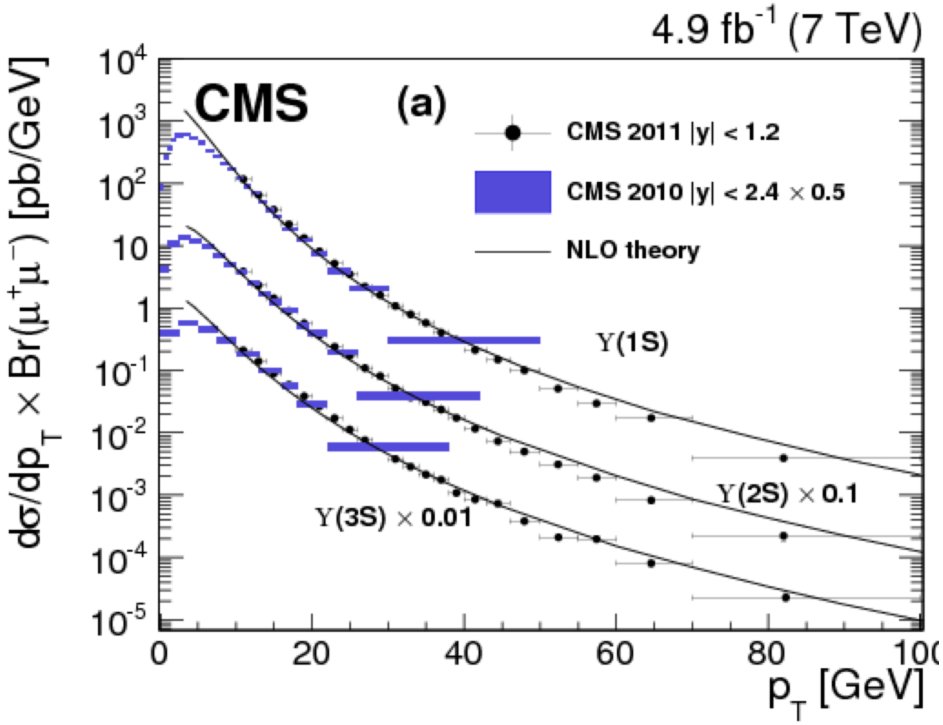


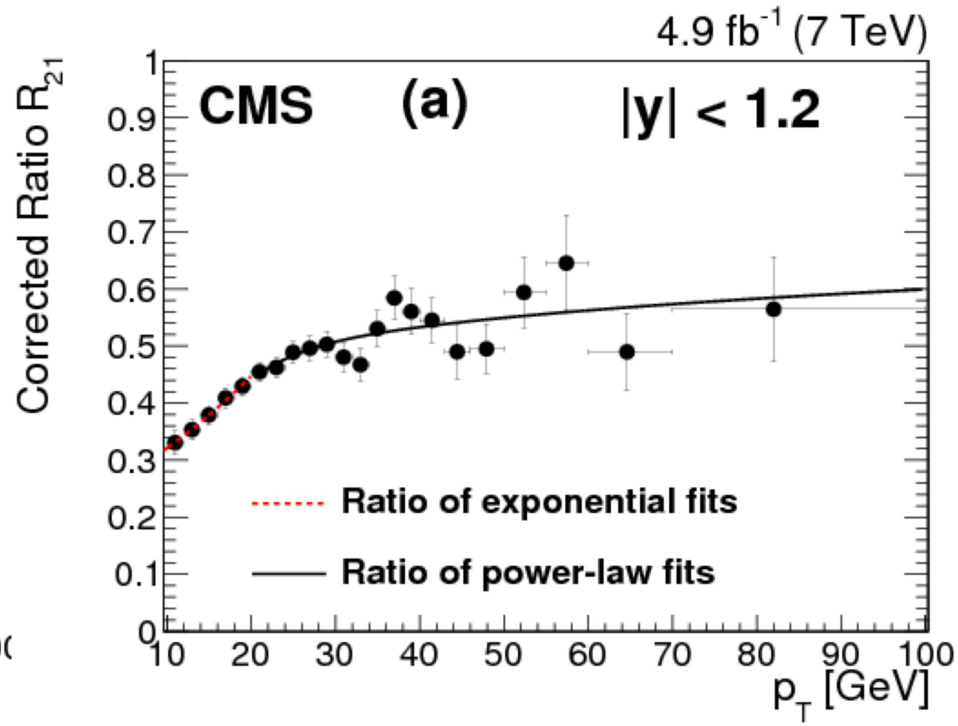
N^Y : yield from fit

acceptance calculated taking into account the results on Y polarization

For Ψ(nS), see:
arXiv:1502.04155 [hep-ex]

Y(1S), Y(2S) and Y(3S) production



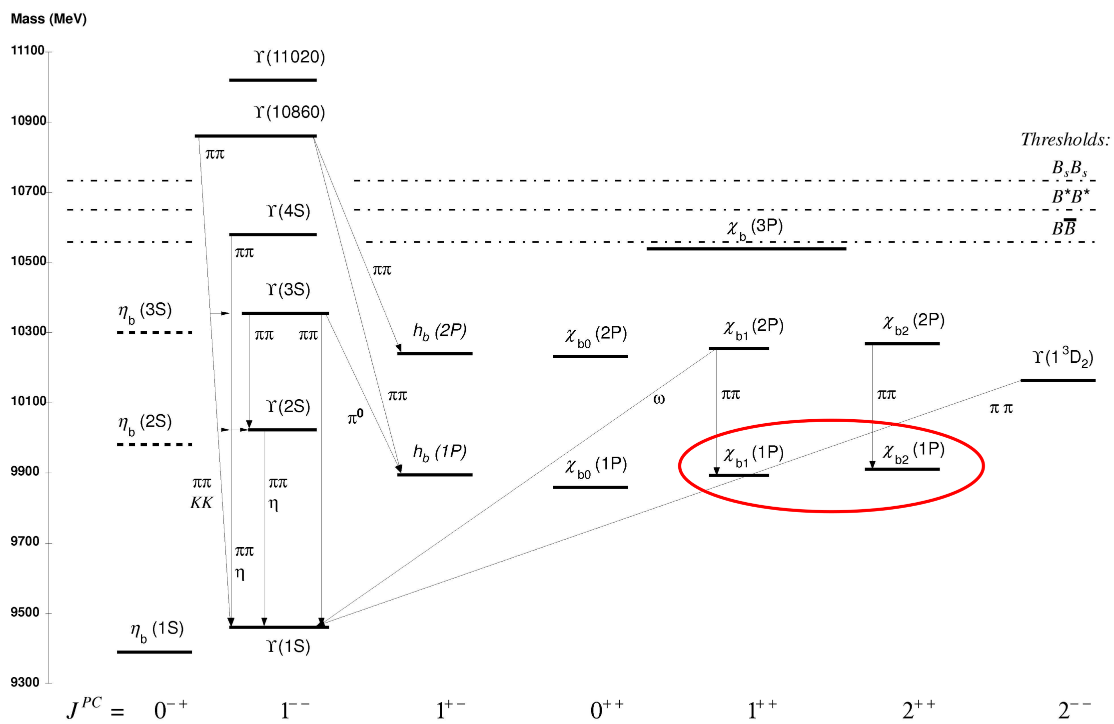


CMS-PAS-BPH-12-006, [arXiv:1501.07750 [hep-ex]]

Extended p_T coverage. Low-p_T measurement agrees well with previous CMS measurement

P-wave quarkonia

- P-Wave states are an essential piece to the quarkonium puzzle
- Feed-down from P-wave states must be taken into account when studying S-wave states.
- Relative production cross section ratios of P-waves are by themselves interesting tests of (NR)QCD. Naïve expectations are challenged (example: suppression of $^3P_1$).



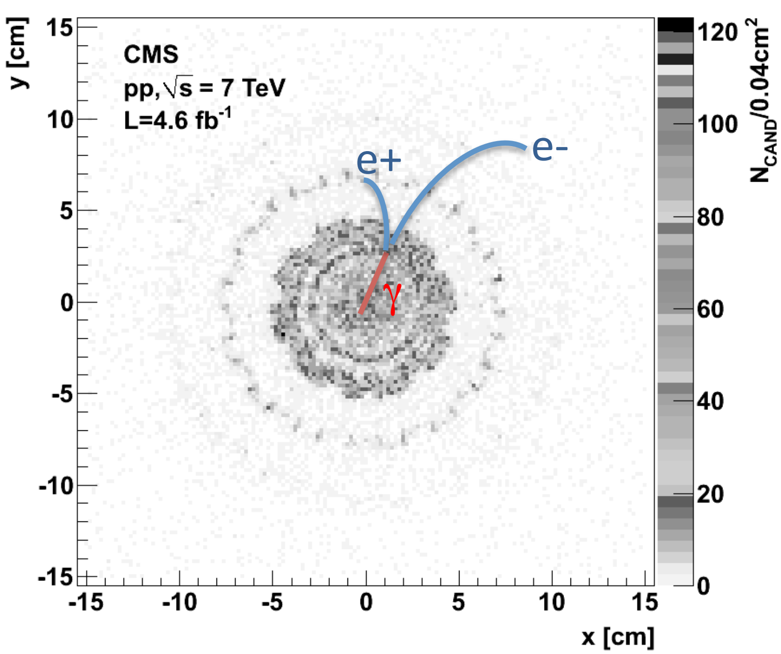
P-Wave quarkonia in CMS

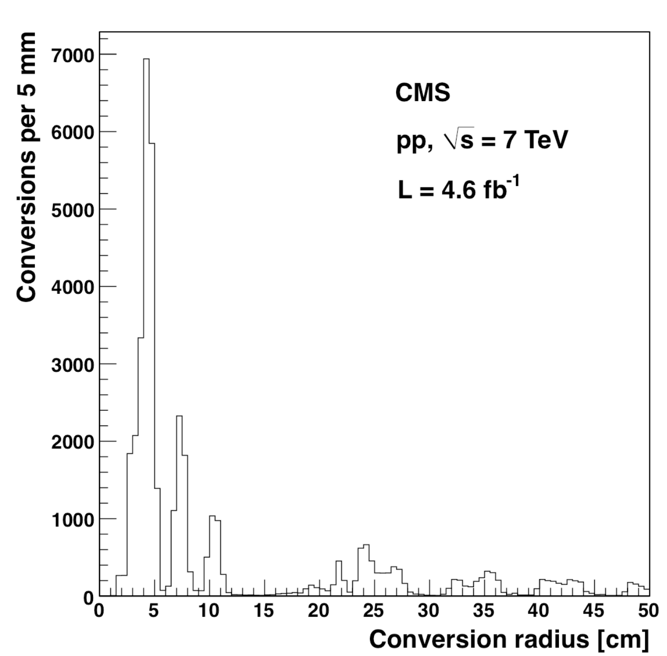
P-Wave quarkonium states can be detected via their radiative decays:

$$\chi_{c1,2} \rightarrow J/\psi + \gamma$$

$$\chi_{b1,2}(nP) \rightarrow \Upsilon(nS) + \gamma$$

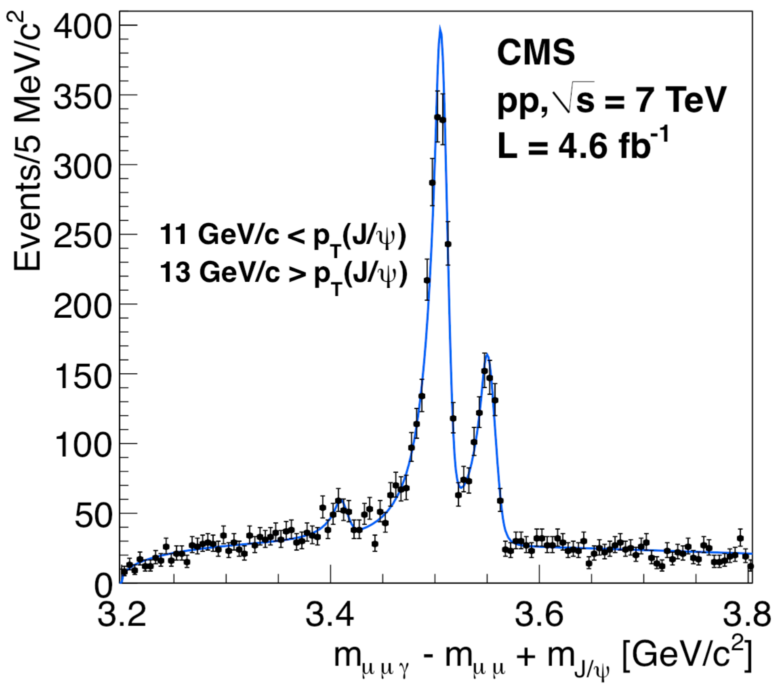
However, a calorimetric measurement of the photon would not feature sufficient invariant mass resolution to separate the two states (E_γ = 0.5-2 GeV).
The use of photon conversions in the silicon tracker gives good photon energy and χ mass resolution .





χ_{c2} / χ_{c1} cross section ratio

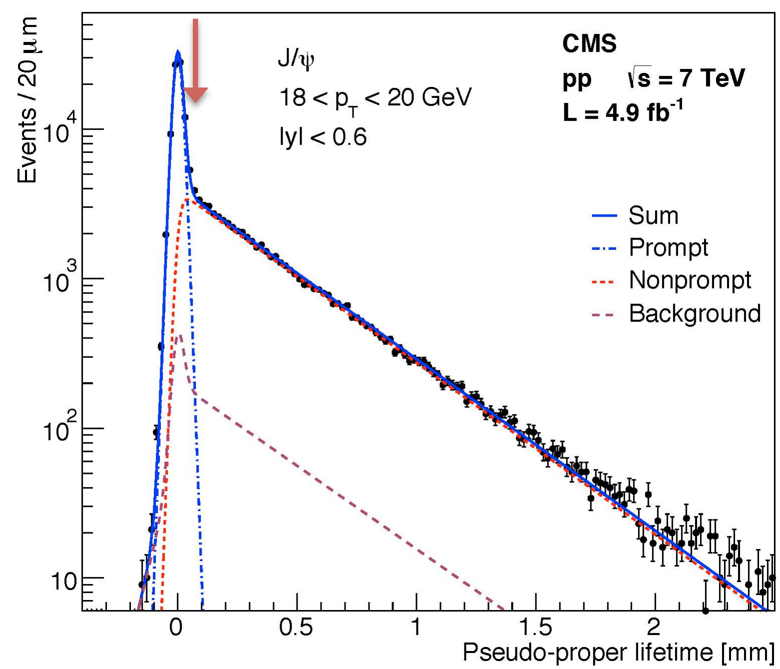
EPJC 72 (2012) 2251



$$\frac{\sigma(pp \to \chi_{c2} + X)}{\sigma(pp \to \chi_{c1} + X)} \times \frac{BR(\chi_{c2} \to J/\psi + \gamma)}{BR(\chi_{c1} \to J/\psi + \gamma)}$$

$$\chi_c \to J/\psi + \gamma$$

$J/\psi \to \mu^+\mu^-$, $\gamma \to e^+e^-$



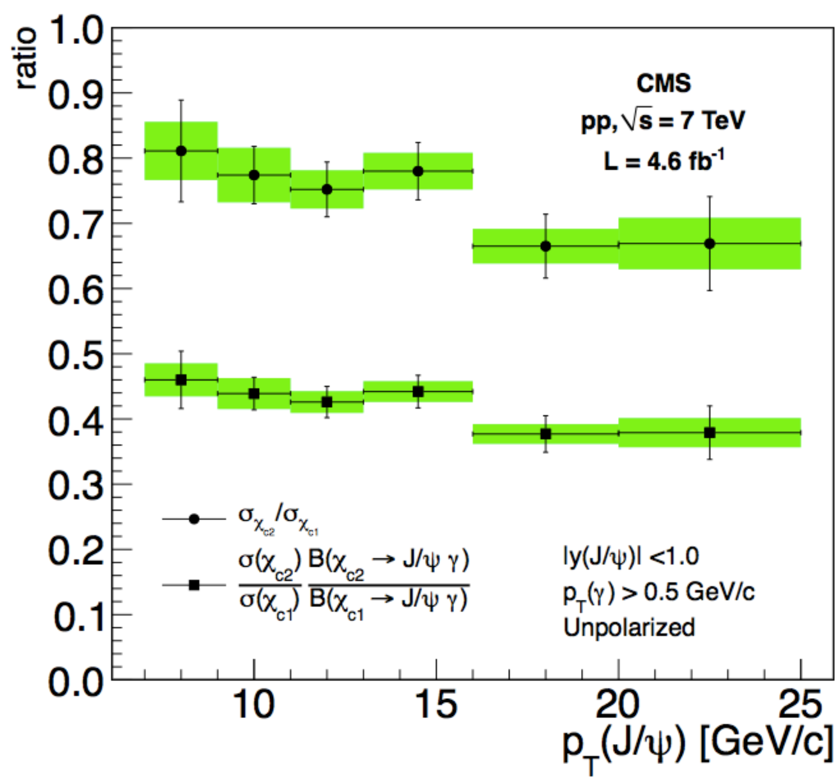
Contamination from non-prompt < 0.7%

- Use of the mass difference to cancel out muon resolution
- Prompt J/ψ trigger
- Loose μ selection, $3.0 < m_{\mu\mu} < 3.2$ GeV, prob(v) > 0.01
- R_{conv}> 1.5 cm
- Prompt component selection: $l_{J/\psi}$< 30 μm
- $|y(J/\psi)| < 1.0$, $p_T(\gamma) > 500$ MeV

χ_{c2} / χ_{c1} cross section ratio

EPJC 72 (2012) 2251

$$R_p \equiv \frac{\sigma(pp \to \chi_{c2} + X)\mathcal{B}(\chi_{c2} \to J/\psi + \gamma)}{\sigma(pp \to \chi_{c1} + X)\mathcal{B}(\chi_{c1} \to J/\psi + \gamma)} = \frac{N_{\chi_{c2}}}{N_{\chi_{c1}}} \cdot \frac{\varepsilon_1}{\varepsilon_2}$$



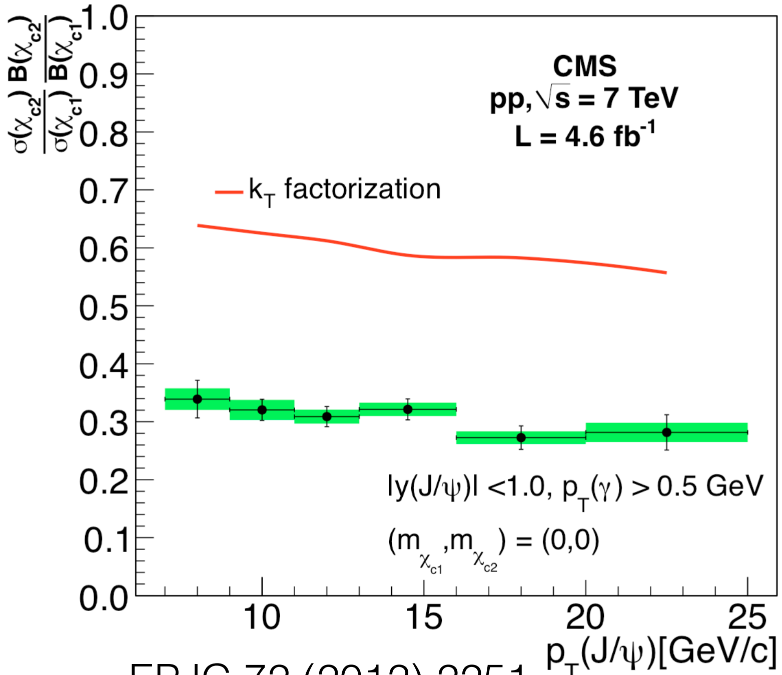
Green bands show systematic errors only
5.6% uncertainty on BR not shown

- $\chi_{c2,1}$ counting using unbinned log-likelihood minimization. Signal shape (detector response) determined from simulation.
- $\varepsilon_1/\varepsilon_2$ determined from simulation.
- Ratio of BR from recent PDG updates, 5.6% uncertainty

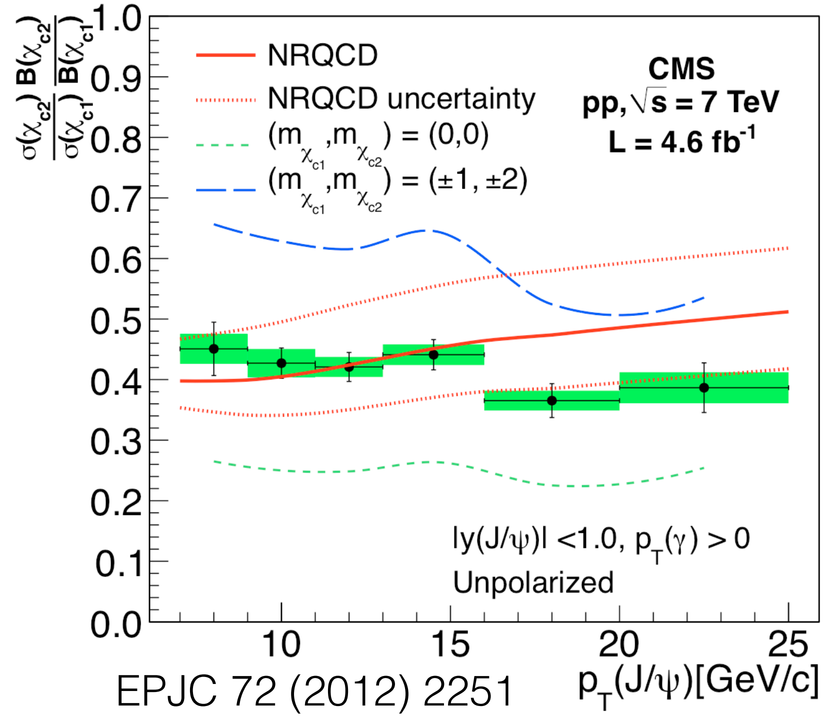
Systematic uncertainties:

- Signal parameterization
- Ratio of Efficiencies
- (BR)

P-wave charmonium ratios



EPJC 72 (2012) 2251
Baranov et al., PRD 83 (2011) 034085



EPJC 72 (2012) 2251
Ma et al., PRD 83 (2011) 111503

Comparison of CMS result with two theoretical predictions.

- k_T predicts polarization states $m\chi_1 = m\chi_2 = 0$
- The NRQCD prediction does not give a particular polarization. Different polarization scenarios can change the picture quite dramatically.
- New LHCb result : arXiv:1307.4285

χ_{b2} / χ_{b1} cross section ratio

CMS-PAS-BPH-13-005

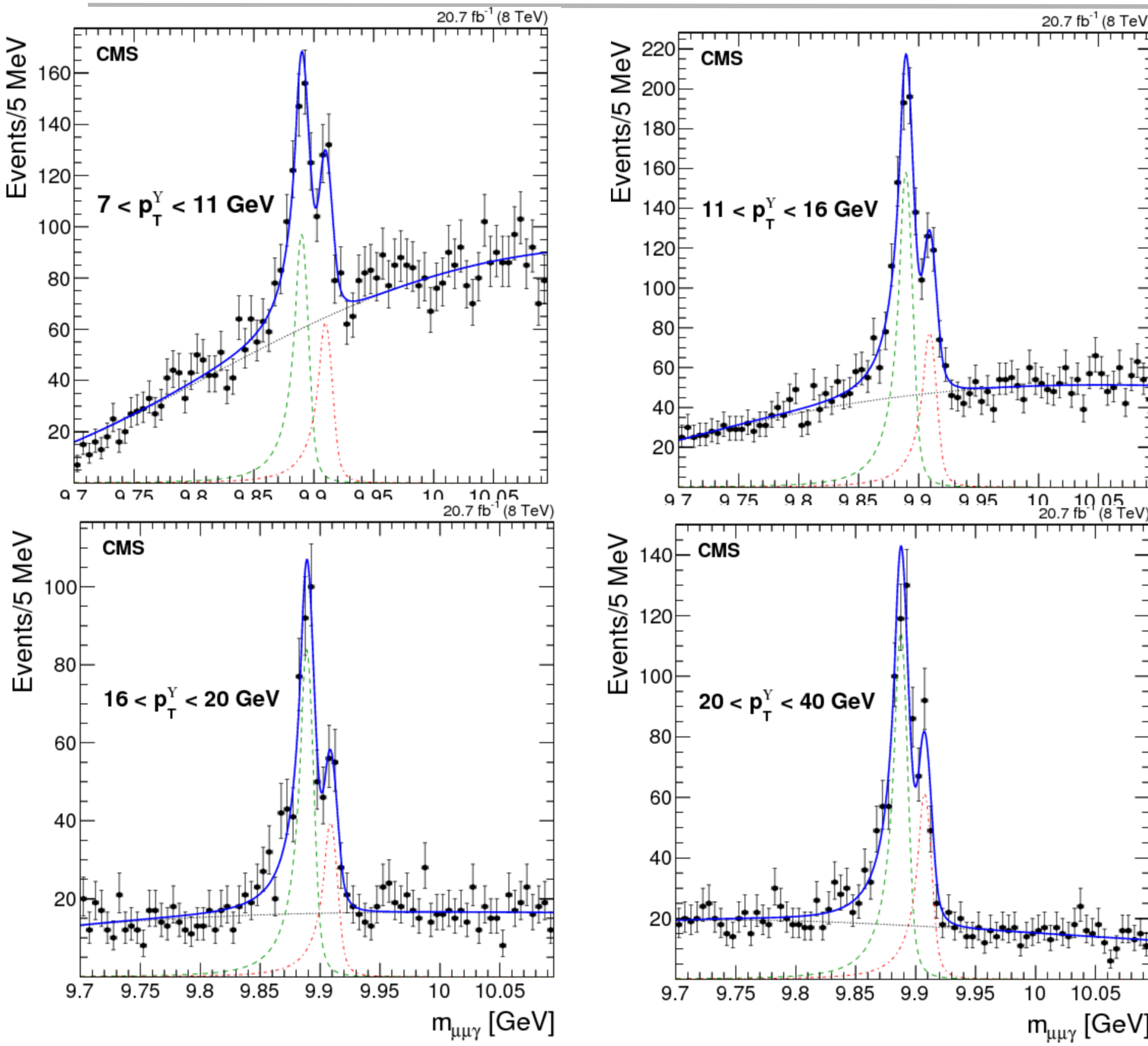
Particle	Mass [MeV]	$BR(\chi_b \to \Upsilon(1S) + \gamma)$	$\Delta m(\chi_b, \Upsilon)$ [MeV]
$\chi_{b0}(1P)$	$9859.44 \pm 0.42 \pm 0.31$	1.76 ± 0.35 %	399.1
$\chi_{b1}(1P)$	$9892.78 \pm 0.26 \pm 0.31$	33.9 ± 2.2 %	432.5
$\chi_{b2}(1P)$	$9912.21 \pm 0.26 \pm 0.31$	19.1 ± 1.2 %	451.9

- The ratio measurement has been repeated in the bottomonium sector with 2012 data (~20 fb^{-1}), in four bins of $p_T(Y)$.
- This is the first time this measurement is performed.
- Extremely challenging due to the small mass separation (~19 MeV), low energy of the photon and lower statistics.
- Cuts optimized for best photon energy resolution.
- Use of kinematic fit to reconstruct $m_{\mu\mu\gamma}$

$|y(Y)| < 1.5$
$|\eta(\gamma)| < 1.0$
$7 < p_T(Y) < 40$ GeV

χ_{b2} / χ_{b1} cross section ratio

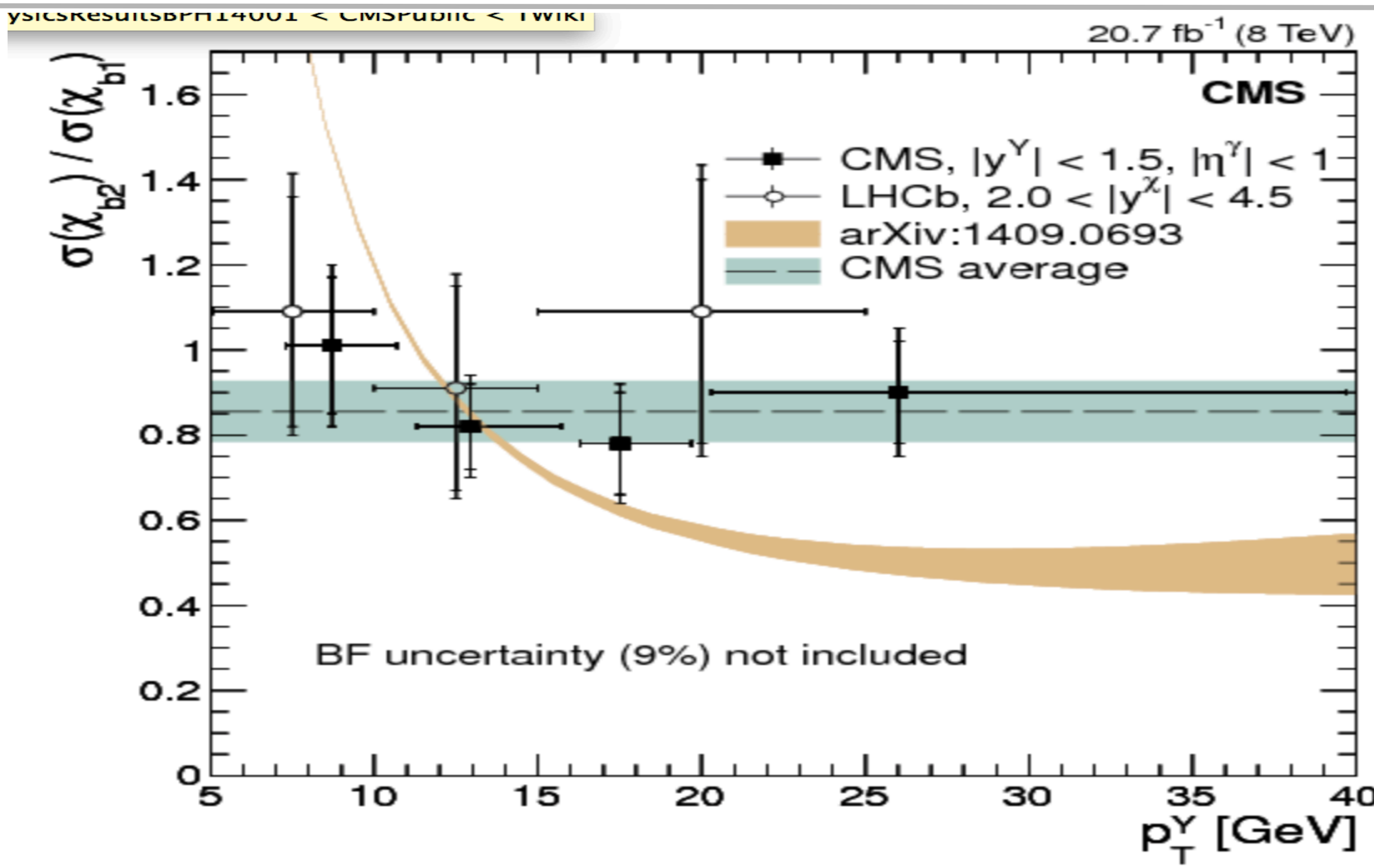
PLB 743 (2015) 383-402



mass resolution:
~ 5 MeV

χ_{b2} / χ_{b1} cross section ratio

PLB 743 (2015) 383-402

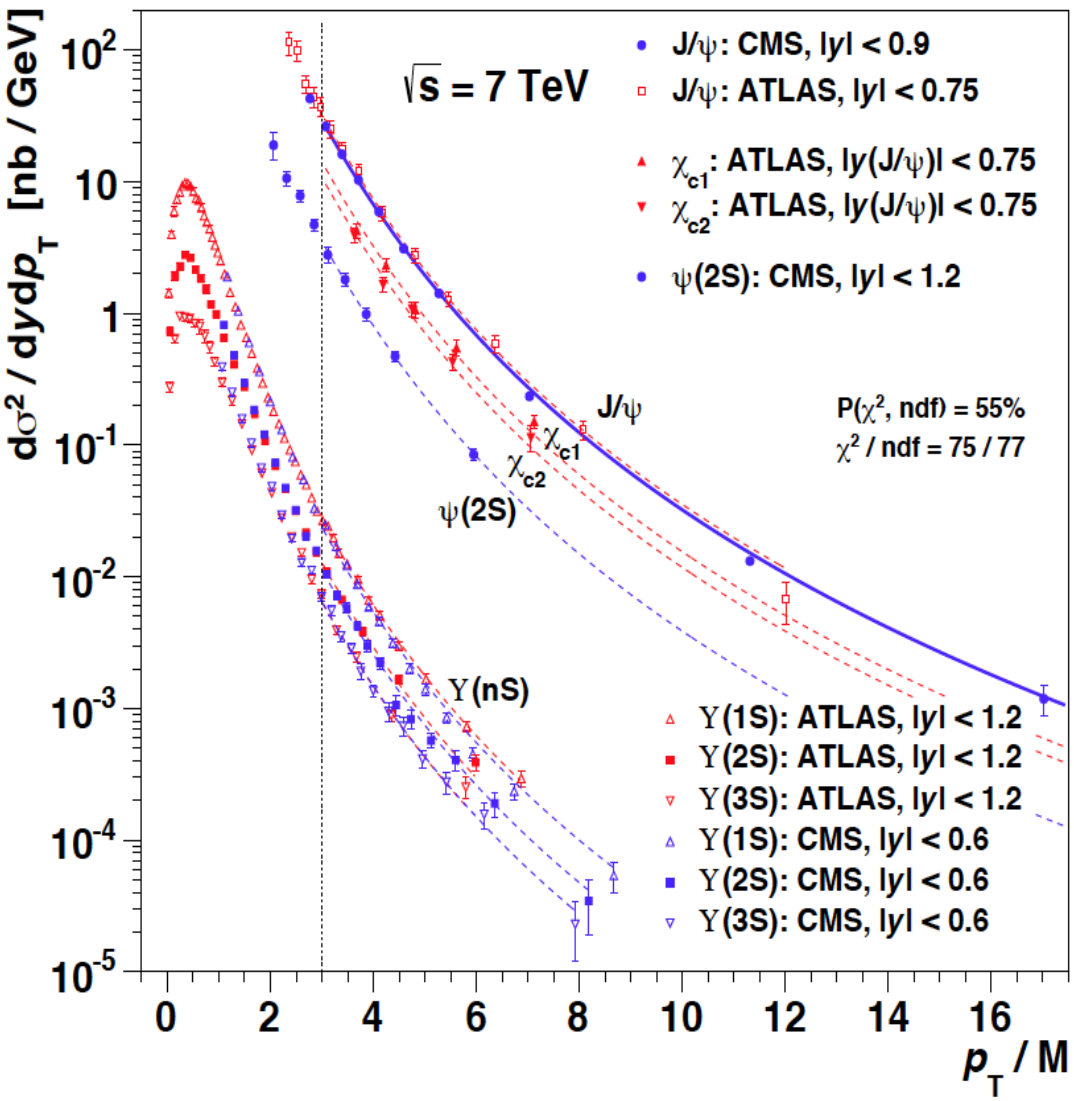


Blue bands show total uncertainty

The most recent theoretical work PRD 86 (2012) 074027, using also the CMS χ_c result, predicts an increase of the ratio at low p_T . This increase is not observed in this analysis

LHC data for quarkonium production

By P.Faccioli *et al.*, arXiv:1403.3970 (2014)



The double differential cross section as a function of p_T/m over the 7 states.

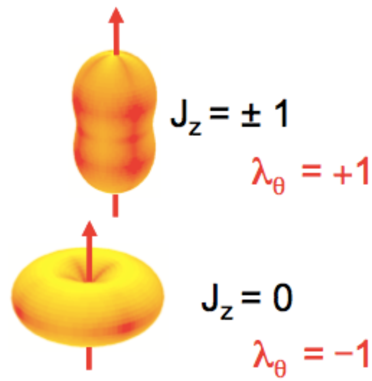
Shapes are well described by a single empirical power-law for $p_T/m>3$. Suggests a simple composition of processes dominated by one single mechanism—CO (CS negligible)

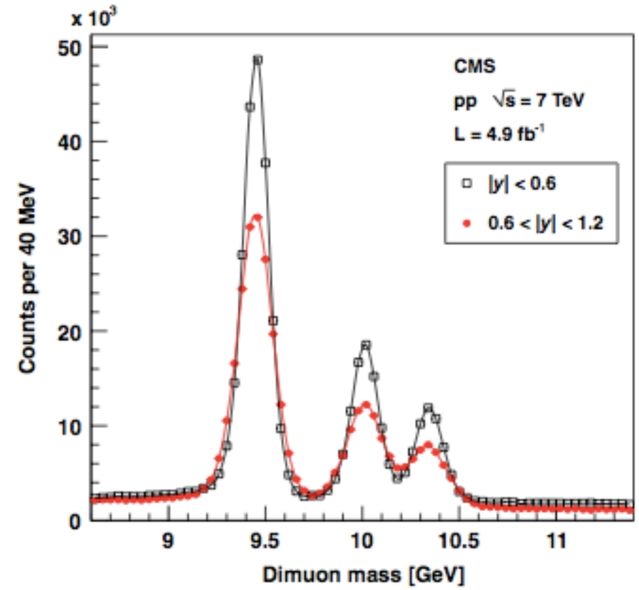
Needs confirmation from:
--more accurate data up to high p_T.
--polarization data

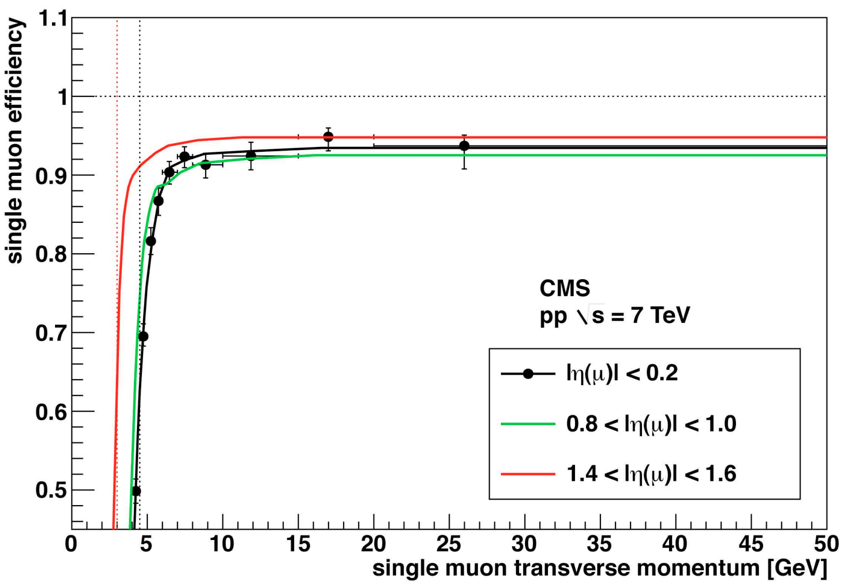
Polarization

Quarkonia polarizations are measured from angular distributions of μμ decays.

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







Experimental challenge:
Precise mapping of efficiencies in p_T and η (Tag&Probe method)

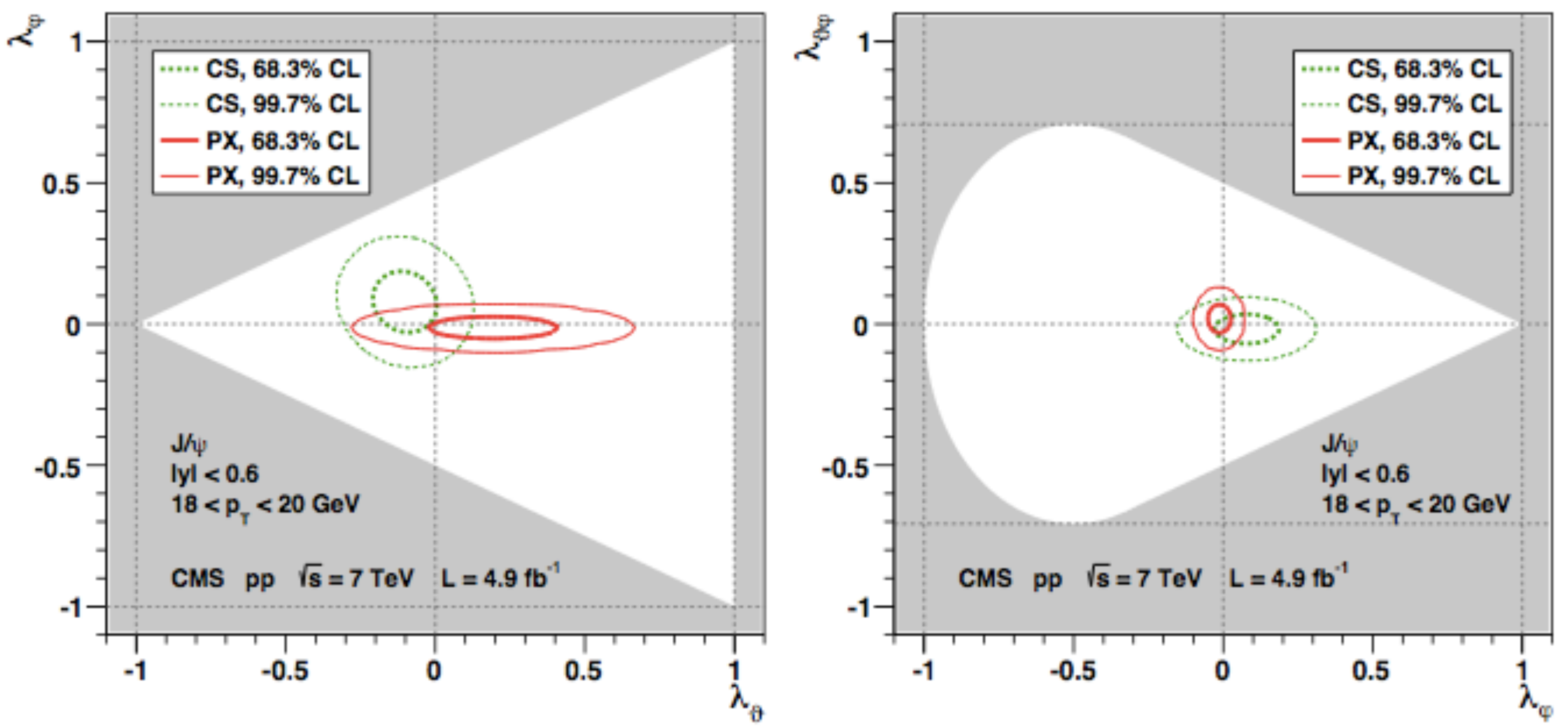
CMS measured the λ_θ, λ_ϕ and $\lambda_{\theta\phi}$ parameters (in 3 frames) for five charmonium and bottomonium S states vs. p_T and in several |y| ranges

J/ψ polarization results

Phys. Lett. B 727 (2013) 381

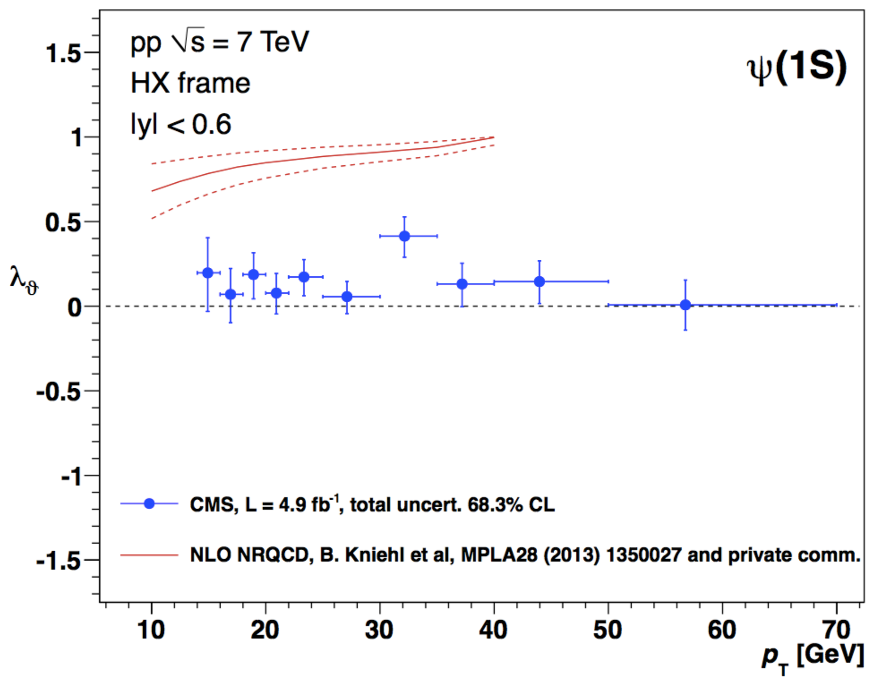
- Results are given in terms of posterior probability densities.
- Systematic uncertainties are studied with data and pseudo-experiments.
- No large anisotropies observed.

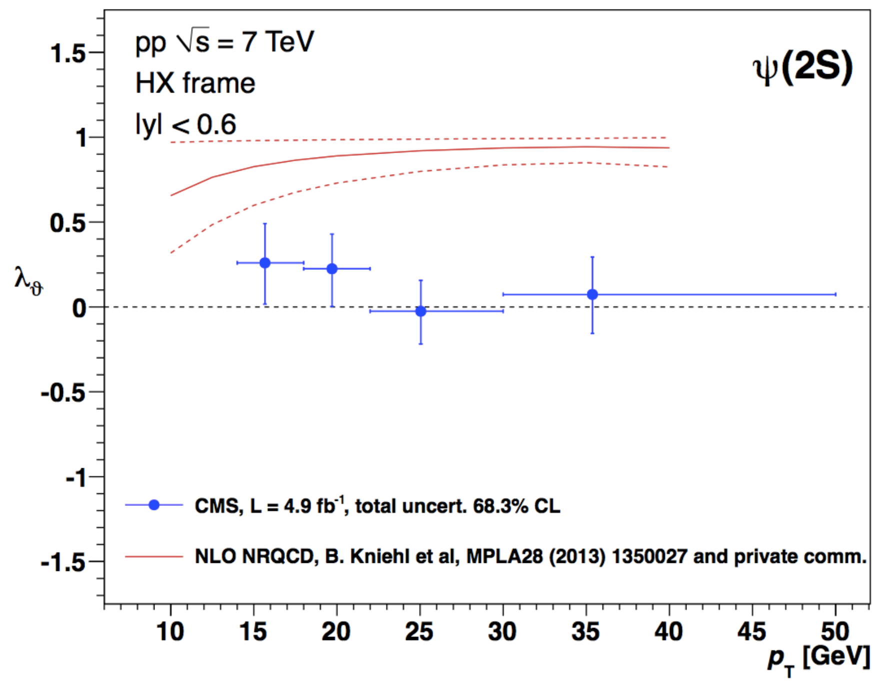
CS--Collins–Soper frame, PX--perpendicular helicity frame



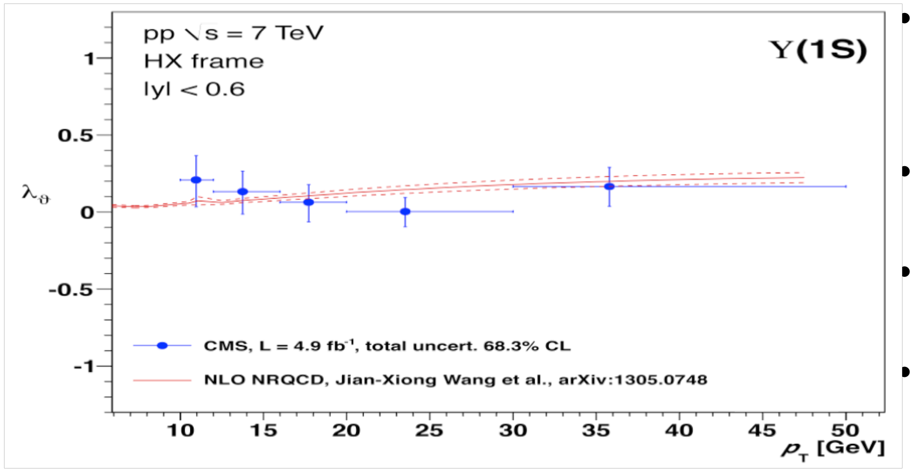
J/ψ, ψ(2S) polarization, CMS vs NLO NRQCD

- Butenschoen and Kniehl [PRL 108 (2012) 172002] use hadro and photoproduction data, excluding polarization results, to fit the CO LDMEs;
- feed-down decays from P-wave states are not accounted for;
- the predicted transverse polarization is not observed.

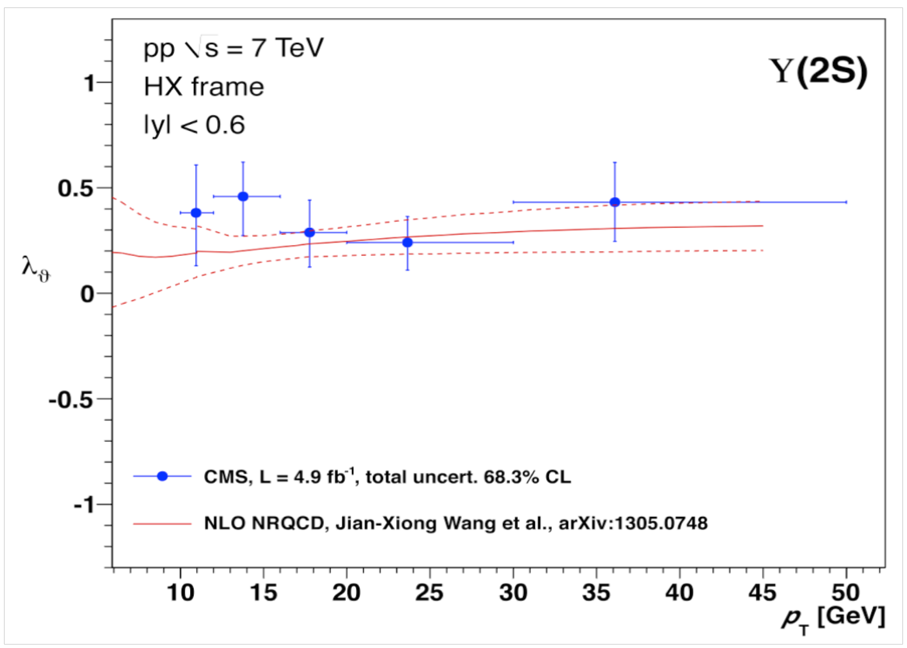


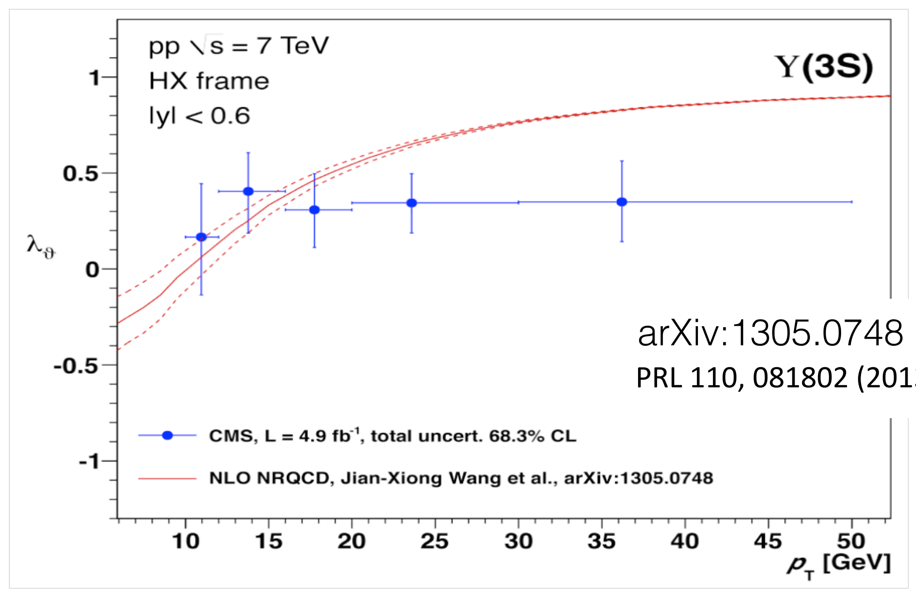


Υ(nS) polarization, CMS vs NLO NRQCD



- Gong et al. (arXiv:1305.0748) use hadroproduction data, including the CMS Υ(nS) polarization results, to fit the CO LDMEs
- The Υ(1S) and Υ(2S) predictions include the feed-down from P waves
- The Υ(3S) is assumed to be 100% directly produced
- Absence of data on the feed-down fractions and polarizations of the P states gives the model the freedom to fit the 1S and 2S polarizations





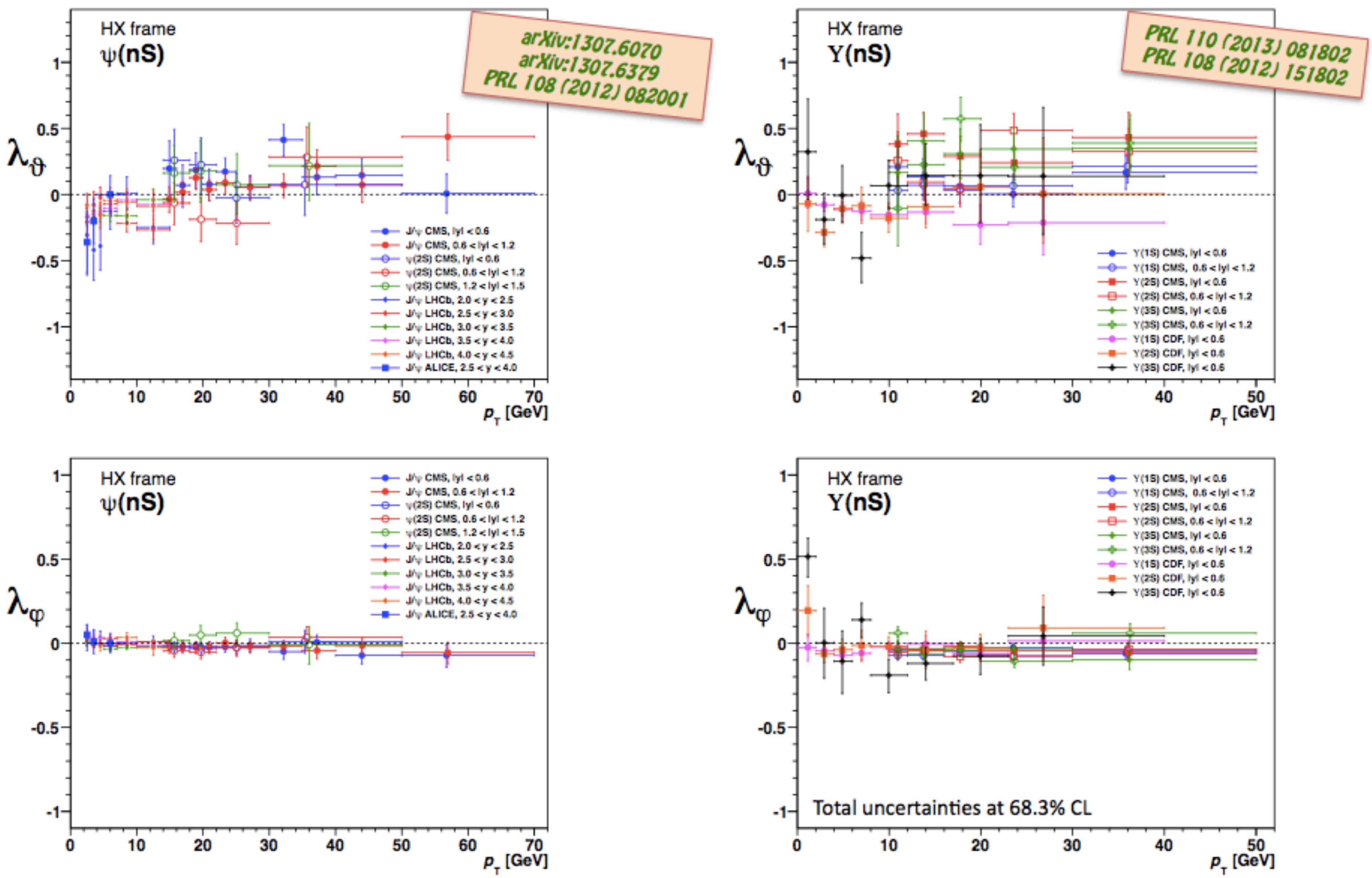
arXiv:1305.0748
PRL 110, 081802 (2013)

Conclusions

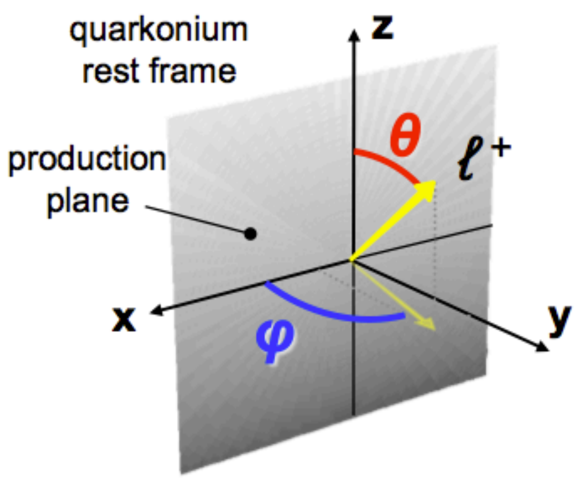
- CMS has produced several new results in the field of quarkonium production and polarization.
- Present NRQCD calculations cannot describe the observed cross sections and polarization at the same time. Especially none of the measured states show polarization.
- The new results should help in the solution to the quarkonium puzzle
- P-wave quarkonia are an essential piece in this puzzle and further measurements are needed (i.e. feed-down fractions and polarizations)
- New CMS measurements planned with Run I&II data, stay tuned!

Backup

Consistency LHC and CDF results



Quarkonium Polarization: Framework



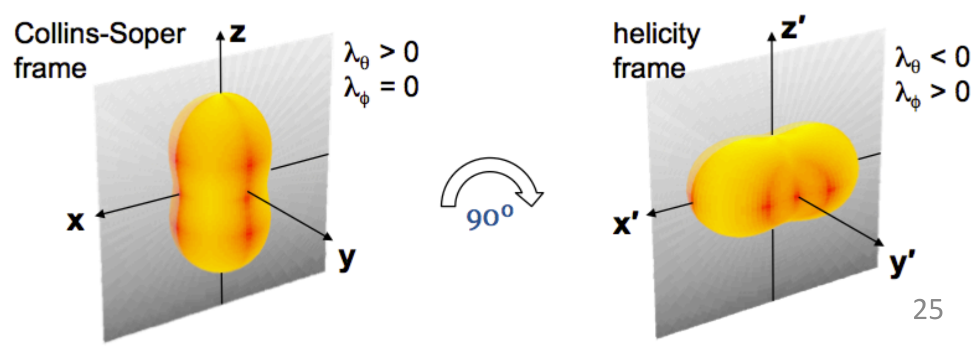
$$\frac{dN}{d(\cos\theta)\,d\varphi} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_{\theta\varphi} \sin 2\theta \cos\varphi + \lambda_\varphi \sin^2\theta \cos 2\varphi$$

Polarization is frame dependent:

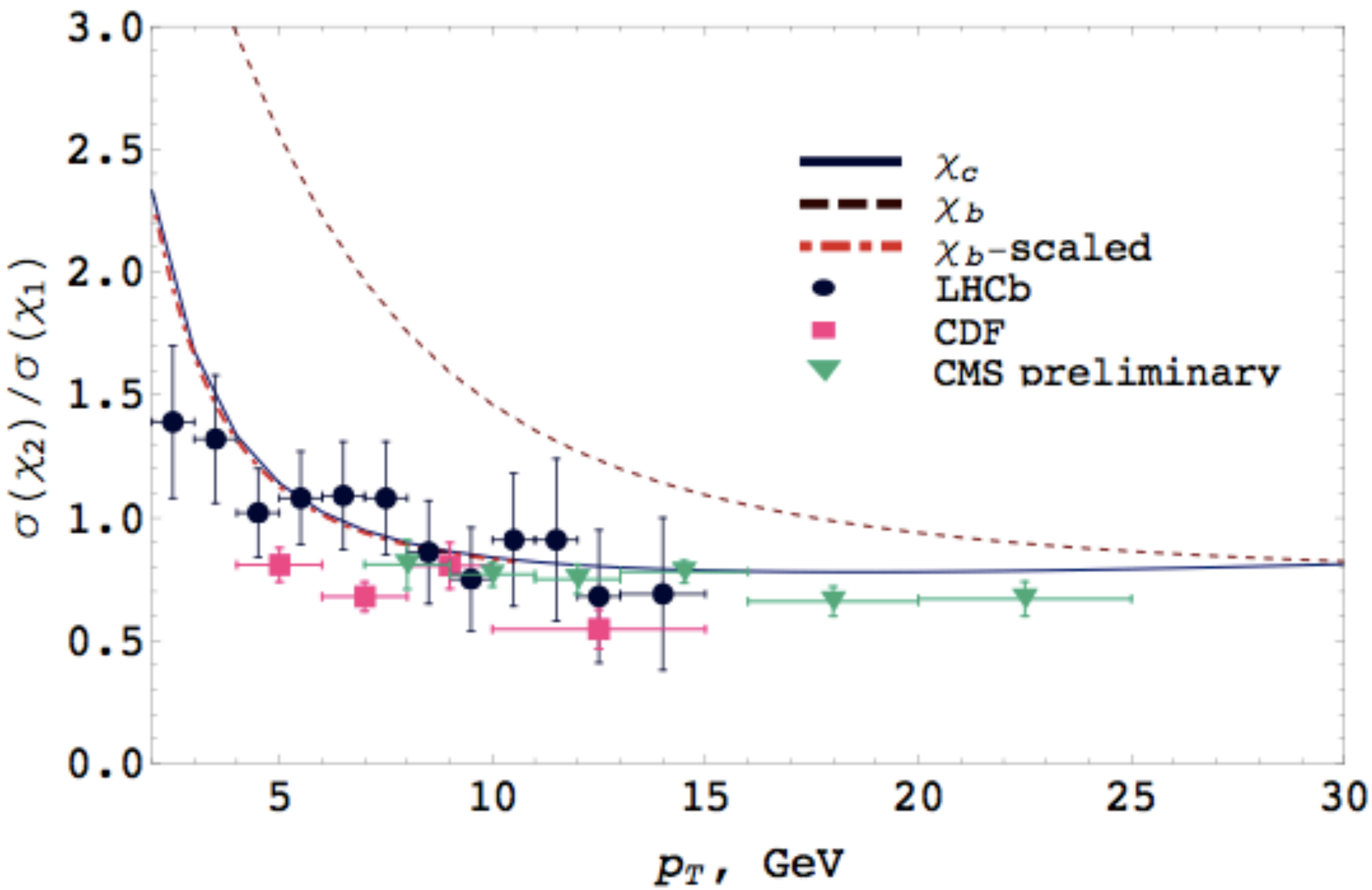
CS : z axis bisector of beam momenta in particle rest frame

HX: z axis // particle momentum in lab

PX: z axis ⊥ to CS

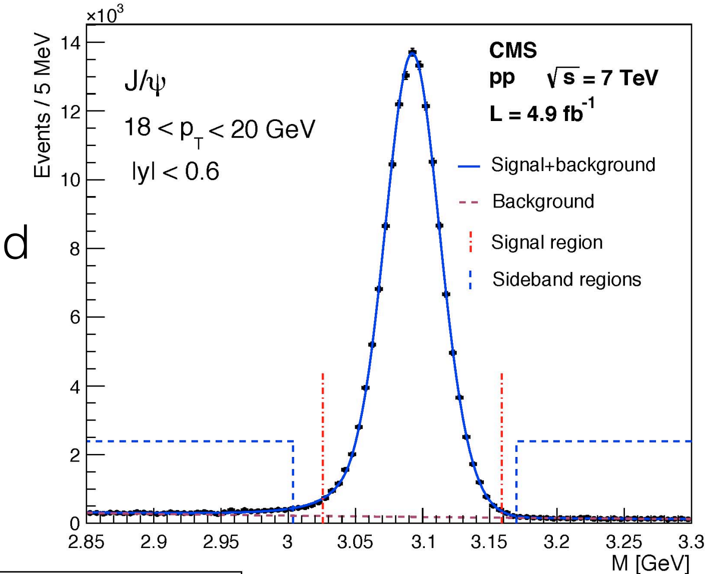


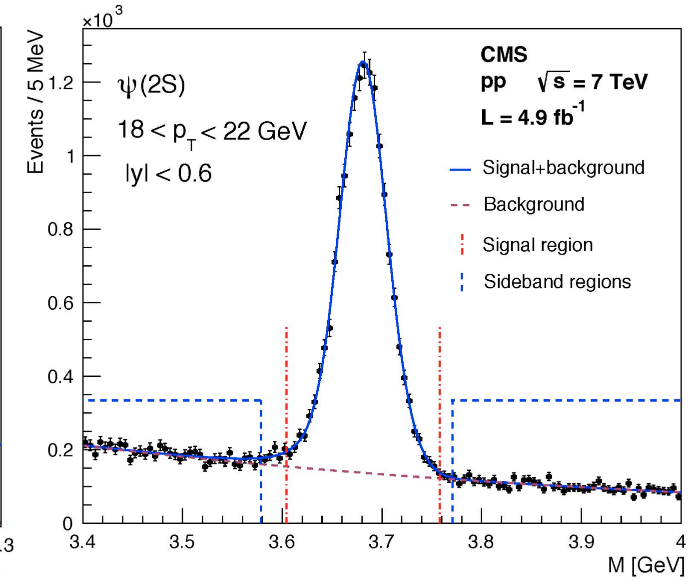
χ_{b2} / χ_{b1} prediction *PRD* **86** (2012) 074027

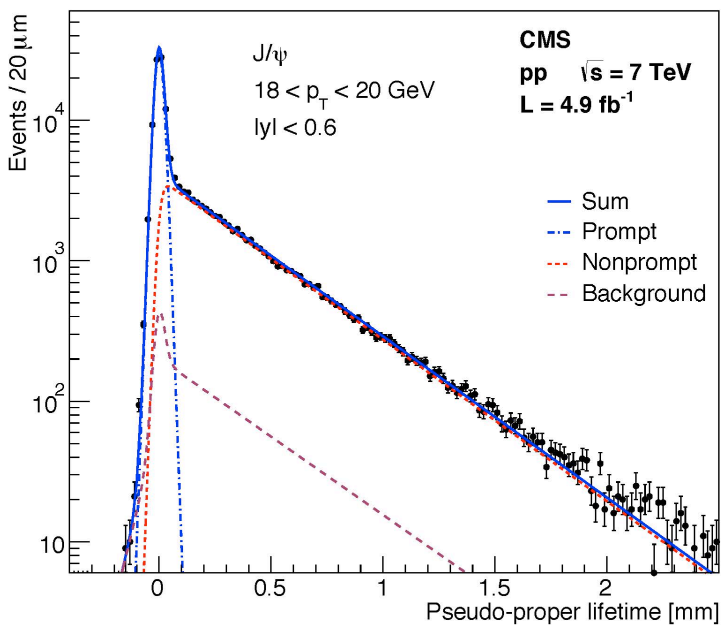


Polarization

Underlying continuum background subtracted using sidebands



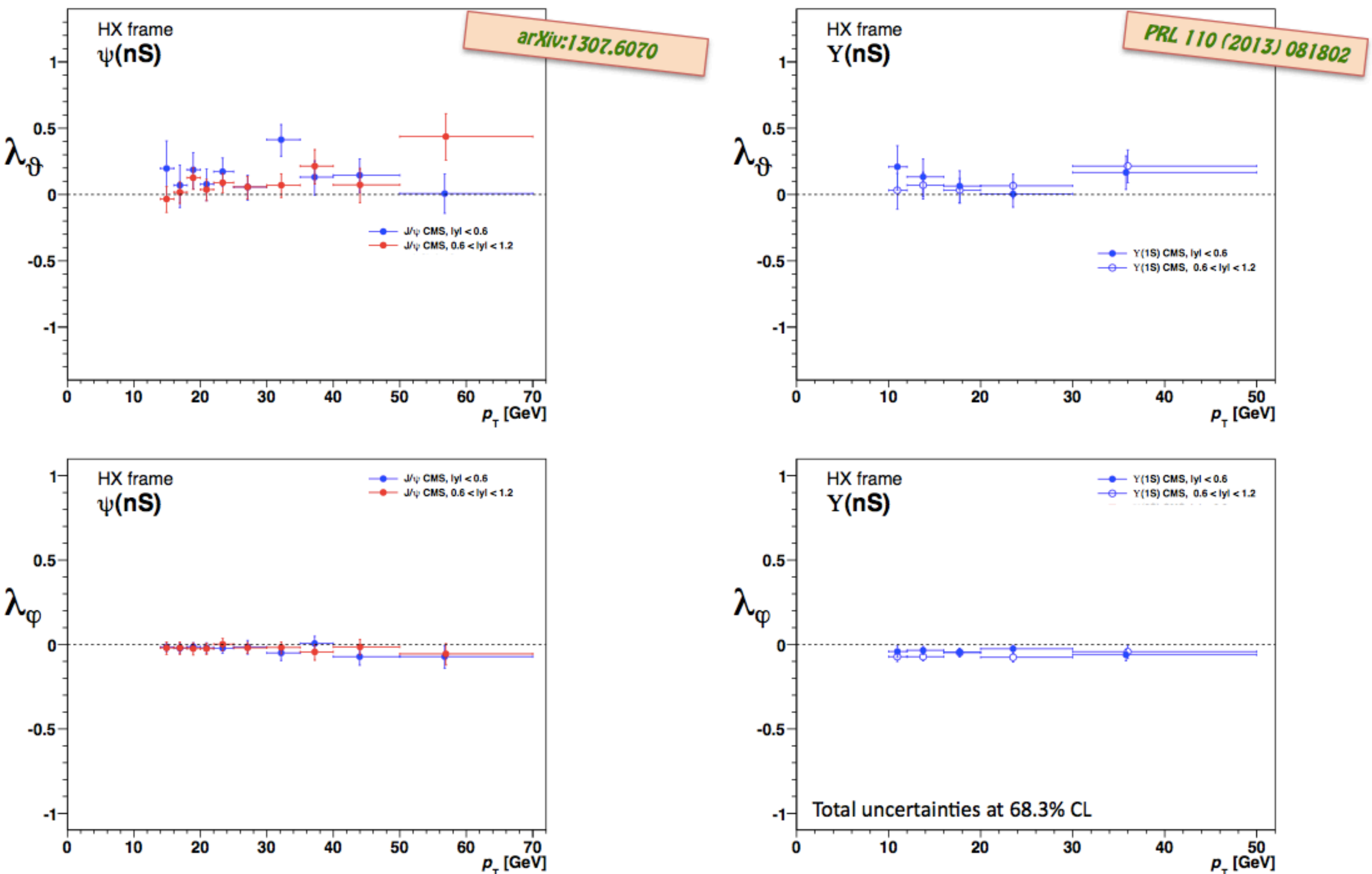




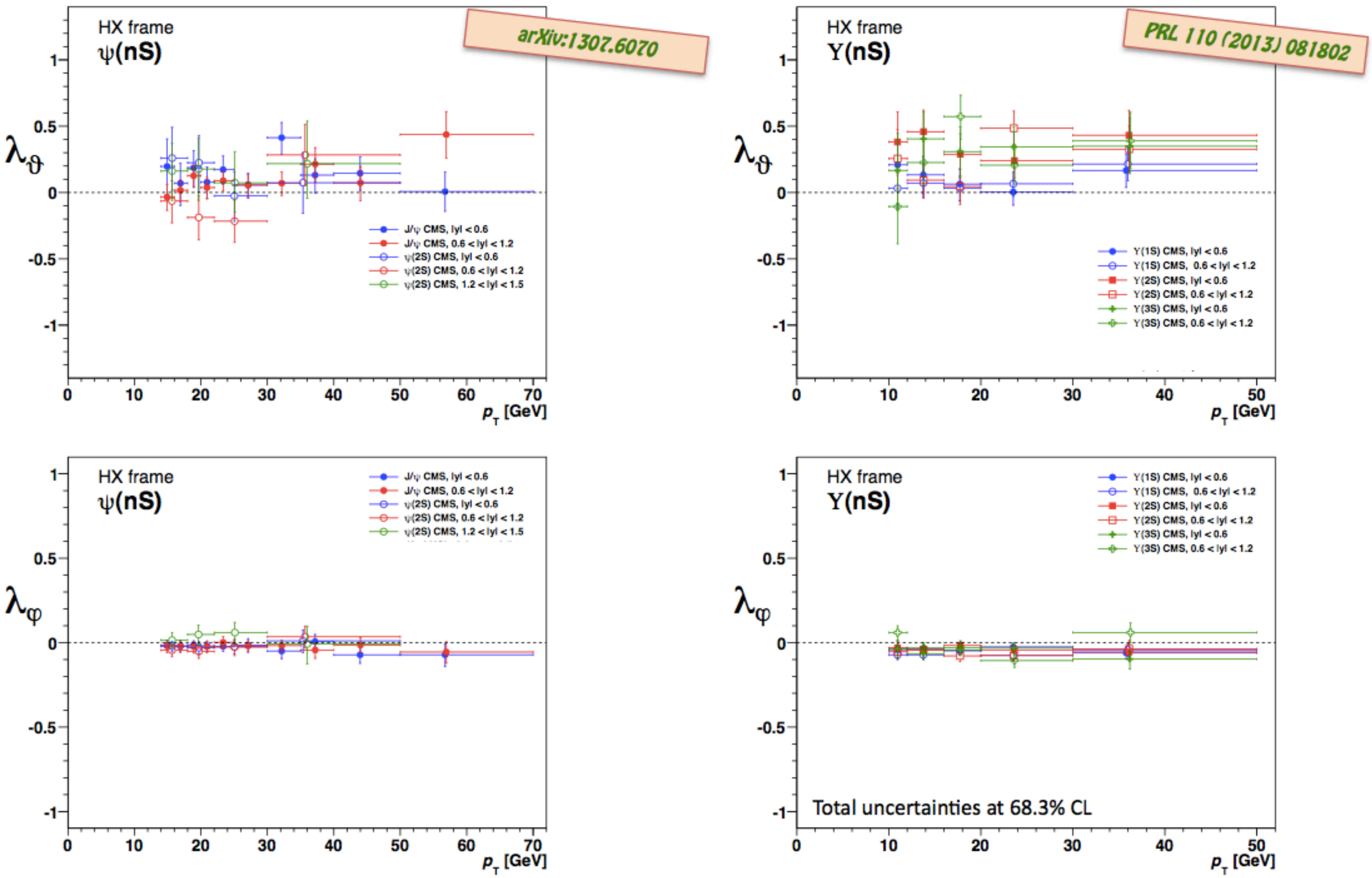
In charmonium, non-prompt component from B decays subtracted using the decay length

The (quasi) feed down free ψ(2S) and Υ(3S) are particularly valuable

J/ψ and Υ(1S) polarization results



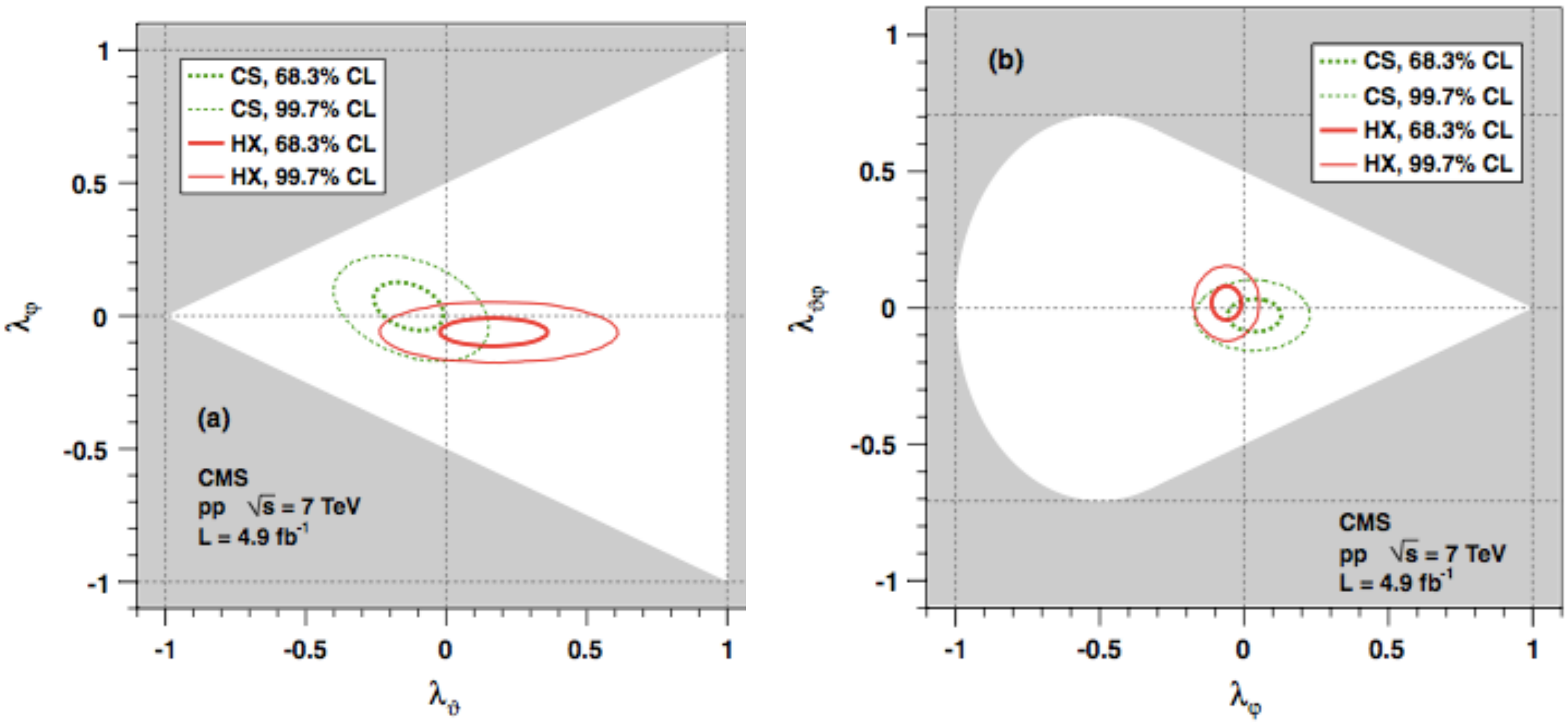
ψ(nS) and Υ(nS) polarization results



Y(1S) polarization results

Results are given in terms of posterior probability densities
Systematic Uncertainties are studied with data and pseudo-experiments.
Systematics dominate total uncertainties at low p_T

PRL 110 (2013) 081802



ψ(nS) production

JHEP 02 (2012) 011