Quarkonium production and polarization in pp collisions with the CMS detector

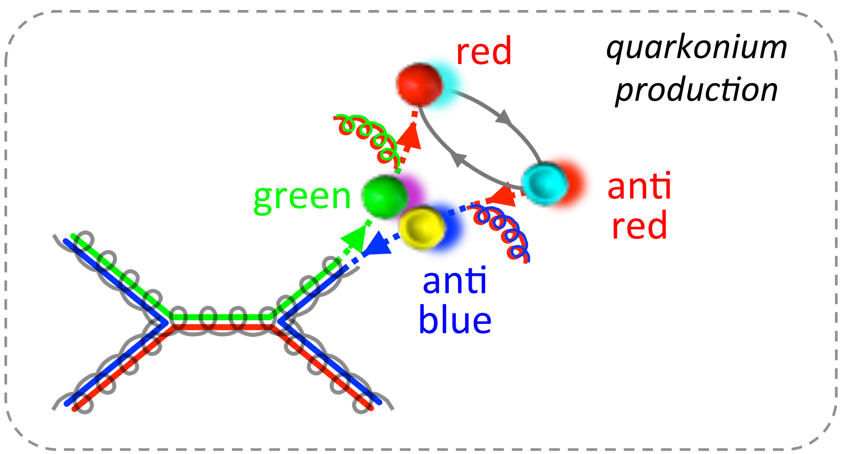
Ilse Krätschmer* (HEPHY Vienna)

on behalf of the CMS Collaboration

* supported by Austrian Science Fund (FWF): P24167

Motivation

- Quarkonia are bound states of a heavy quark and its antiquark ($c\bar{c}$, $b\bar{b}$)
- Quarkonium production is an ideal probe to study hadron formation, part of the non-perturbative QCD sector
- Fundamental question: How do quarks combine into a bound state?
- Properties of QCD can be probed through several quarkonium production measurements, including production cross sections and polarizations



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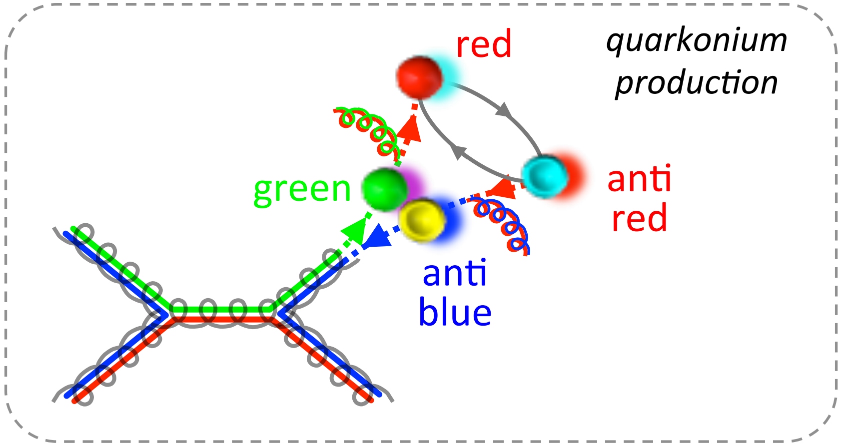

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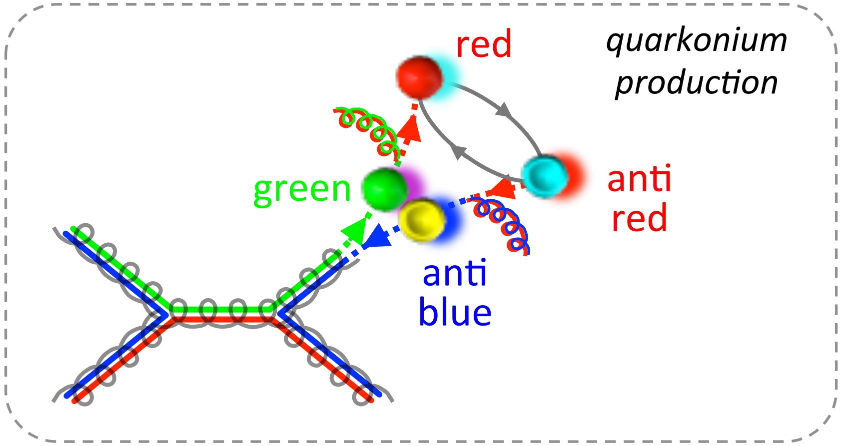
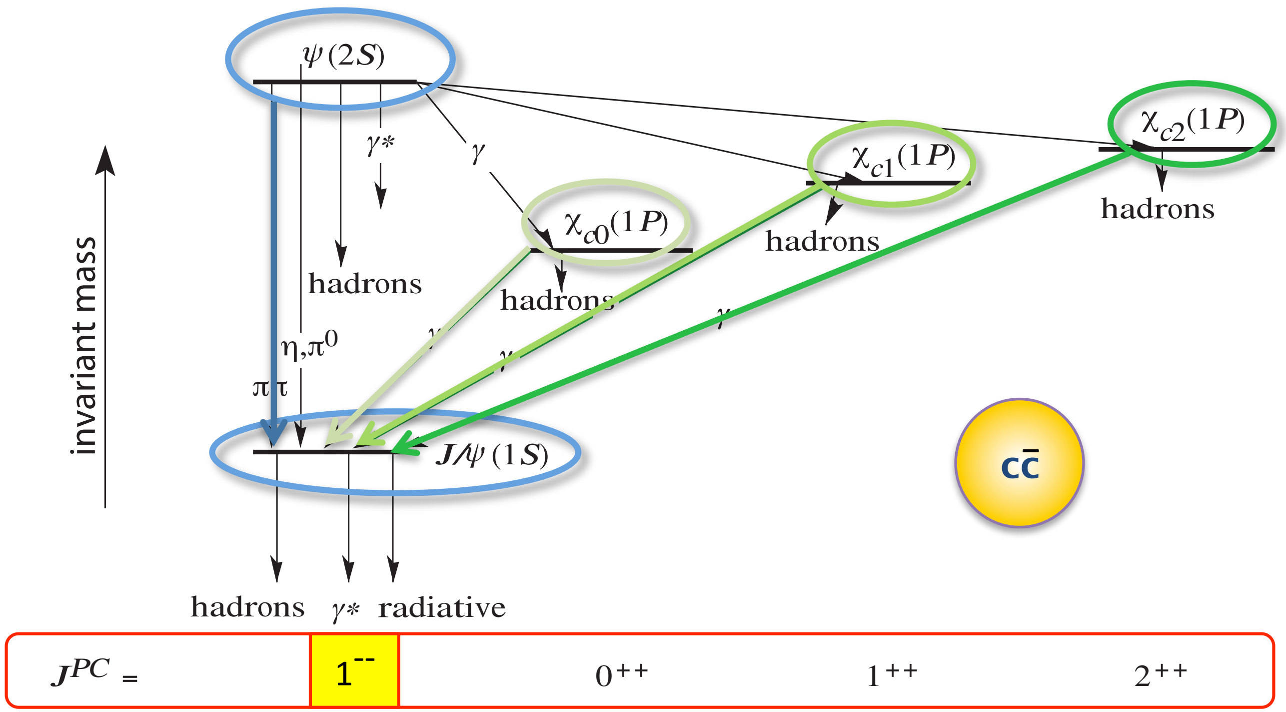
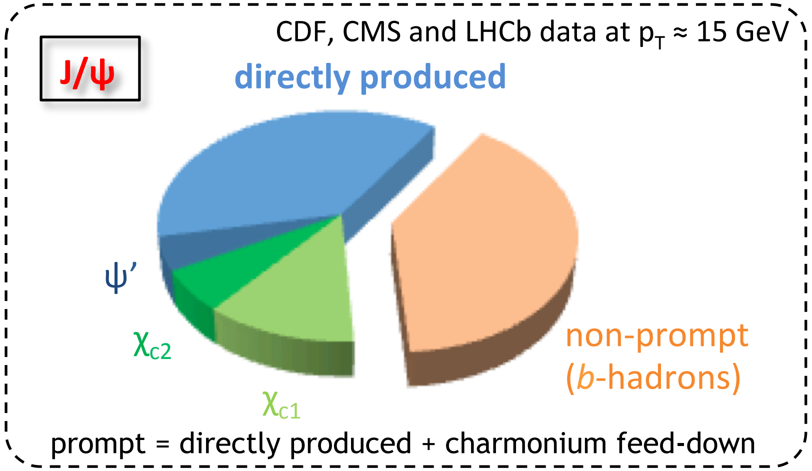


A bound state created through a strong interaction

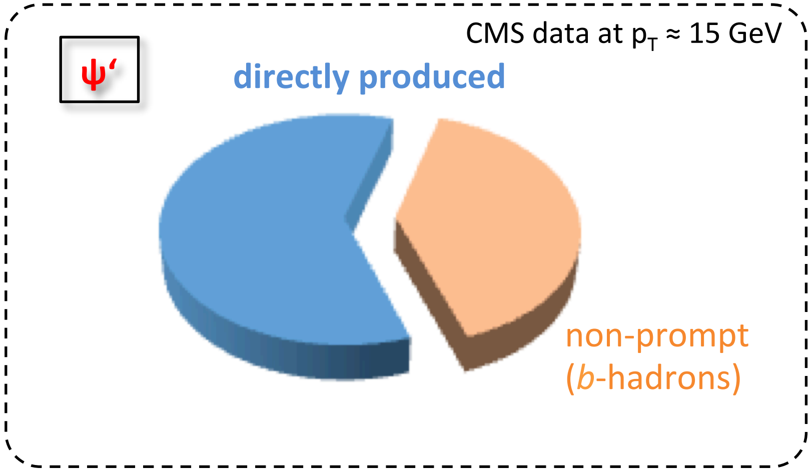
Charmonium



ψ(2S)
γ*
γ
χc2(1P)
χc1(1P)
χc0(1P)
hadrons
hadrons
hadrons
hadrons
η,π0
ππ
γ
γ
γ
J/ψ(1S)
invariant mass
hadrons γ* radiative
JPC =
1--
0++
1++
2++
cc̄



CDF, CMS and LHCb data at pT ≈ 15 GeV
J/ψ
directly produced
ψ'
χc2
χc1
non-prompt
(b-hadrons)
prompt = directly produced + charmonium feed-down



CMS data at pT ≈ 15 GeV
ψ'
directly produced
non-prompt
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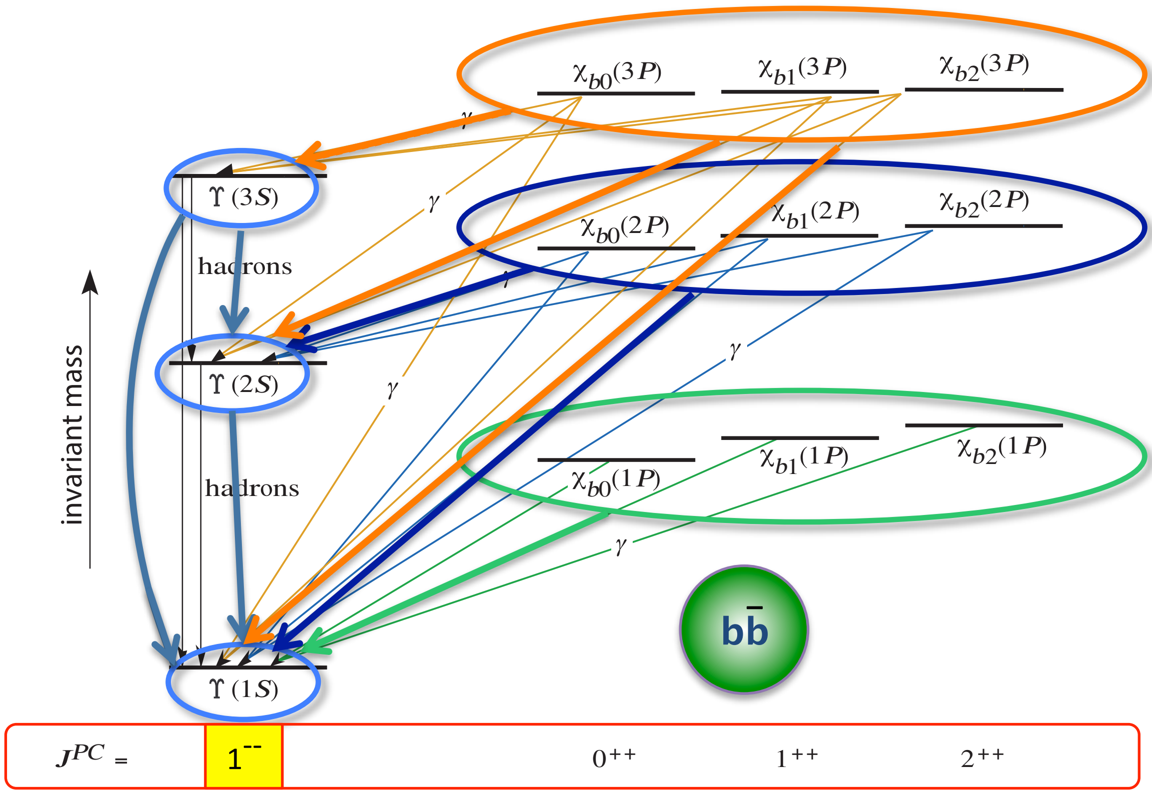
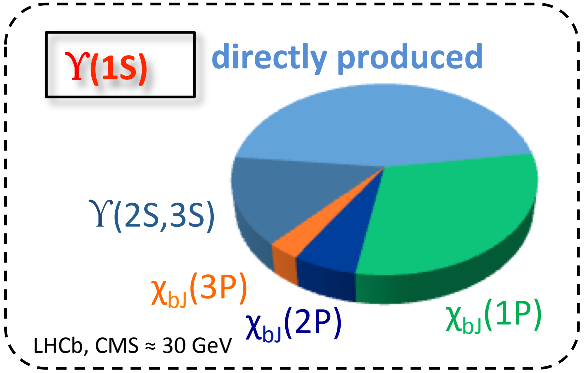
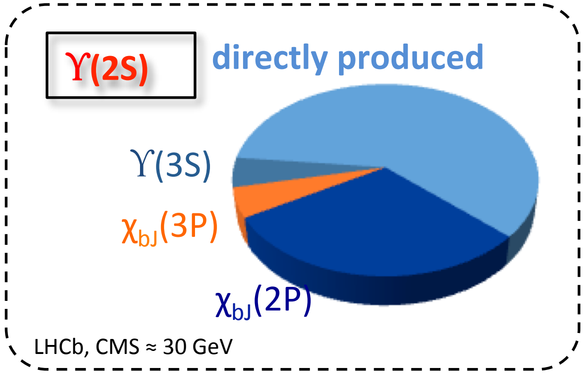
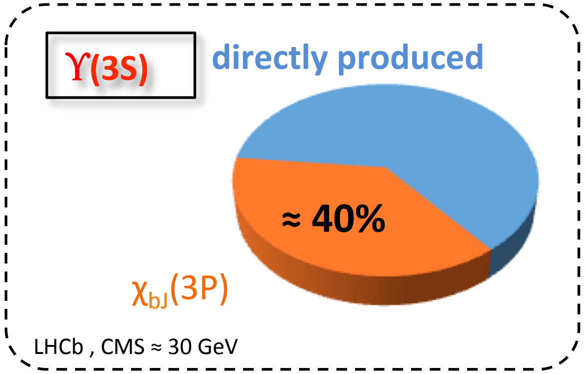
Bottomonium



$\chi_{bj}(3P)$ triplet structure not yet established







LHCb: EPJC 74 (2014) 3094

NRQCD factorization approach

Non Relativistic Quantum ChromoDynamics (NRQCD) is an effective theory that factorizes quarkonium production into 2 steps

1. Production of the initial quark-antiquark pair (perturbative QCD)
2. Hadronization of the initial pair into a bound state (non-perturbative QCD)

$$\sigma(\mathcal{Q}) = \sum_n \mathcal{S}[Q\bar{Q}(n)] \left\langle \mathcal{O}^{\mathcal{Q}}(n) \right\rangle$$

$n = {}^{2S+1}L_J^{[C]}$ Quantum number of the heavy quark pair (C = 1,8)
S, L, J = spin, orbital and total angular momentum

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long distance matrix elements (LDMEs)

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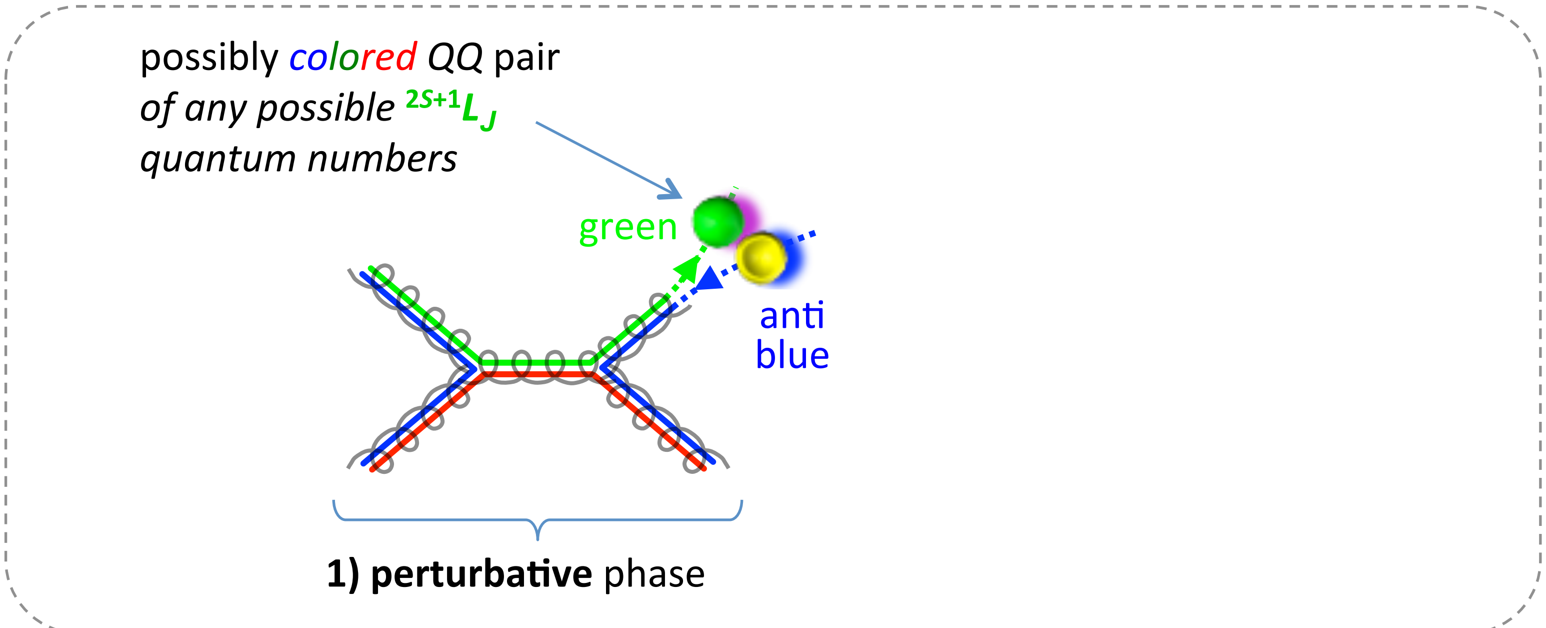

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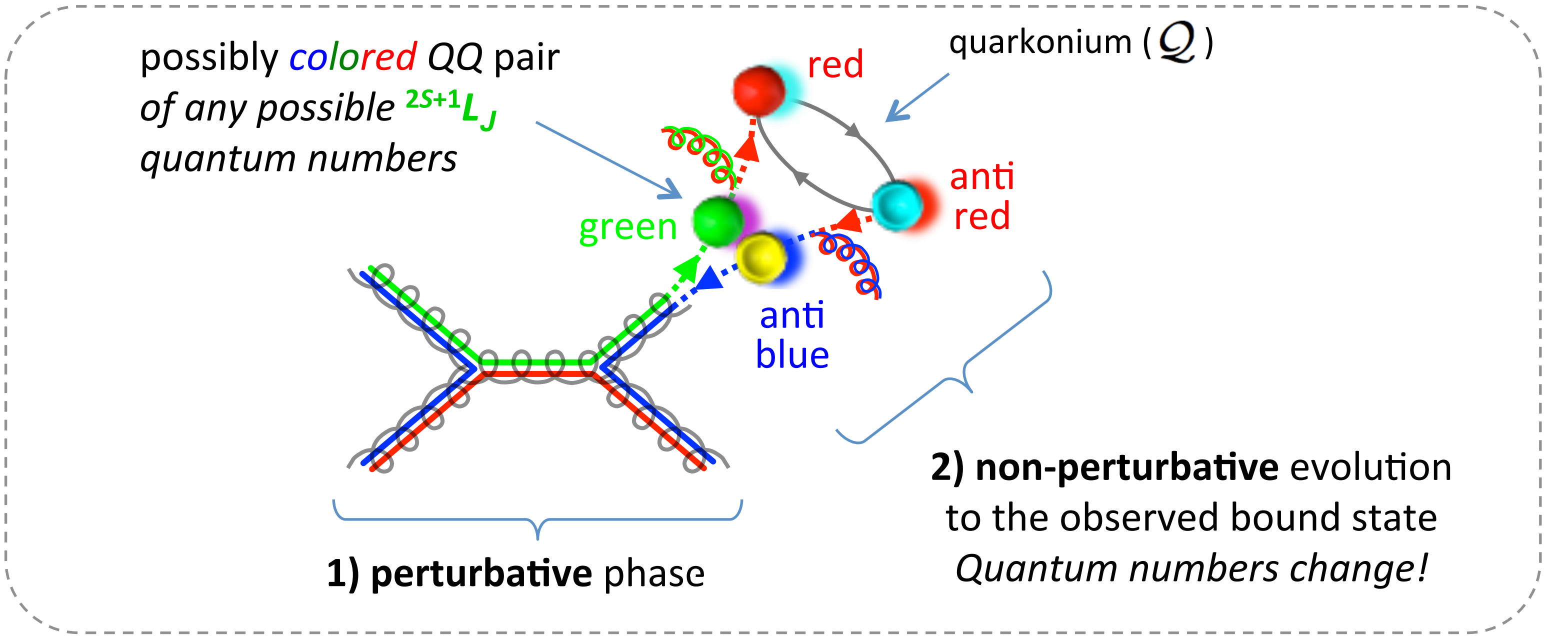
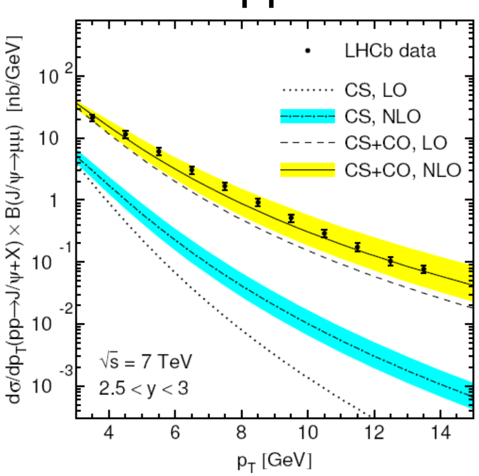


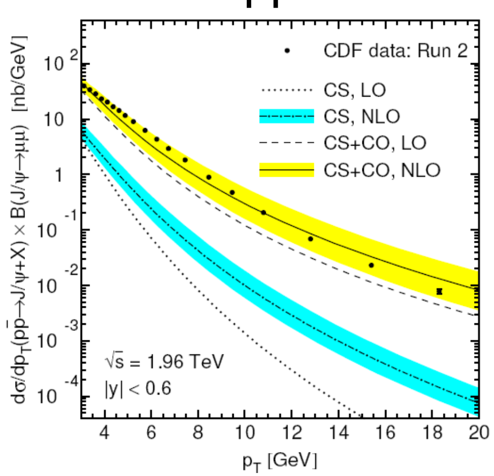
NRQCD factorization approach

- SDCs are calculated using perturbative QCD
- LDMEs are conjectured to be constant (independent of the quarkonium momentum) and universal (process independent)
- LDMEs cannot be calculated and have to be determined from fits to experimental data
- Cross section and polarization measurements constrain the LDMEs

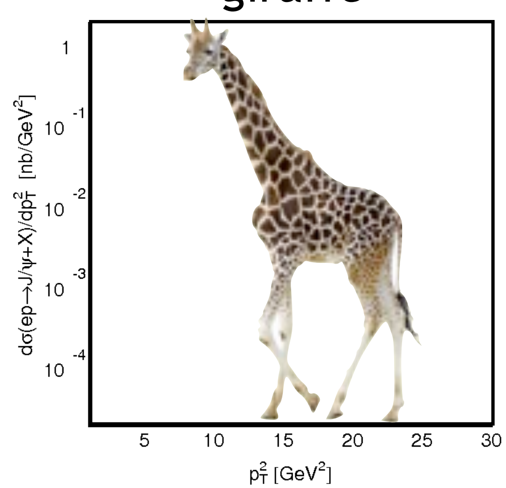
pp



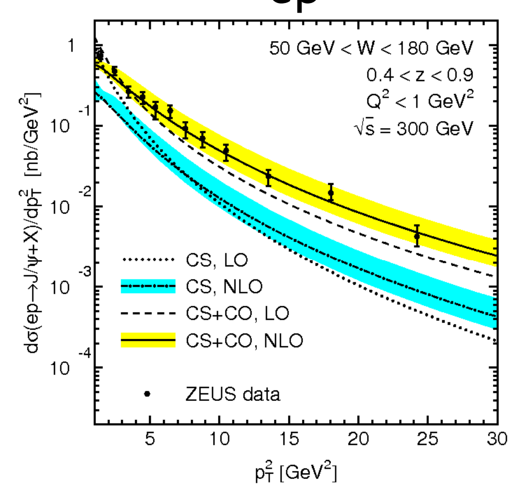
p$\bar{p}$



giraffe



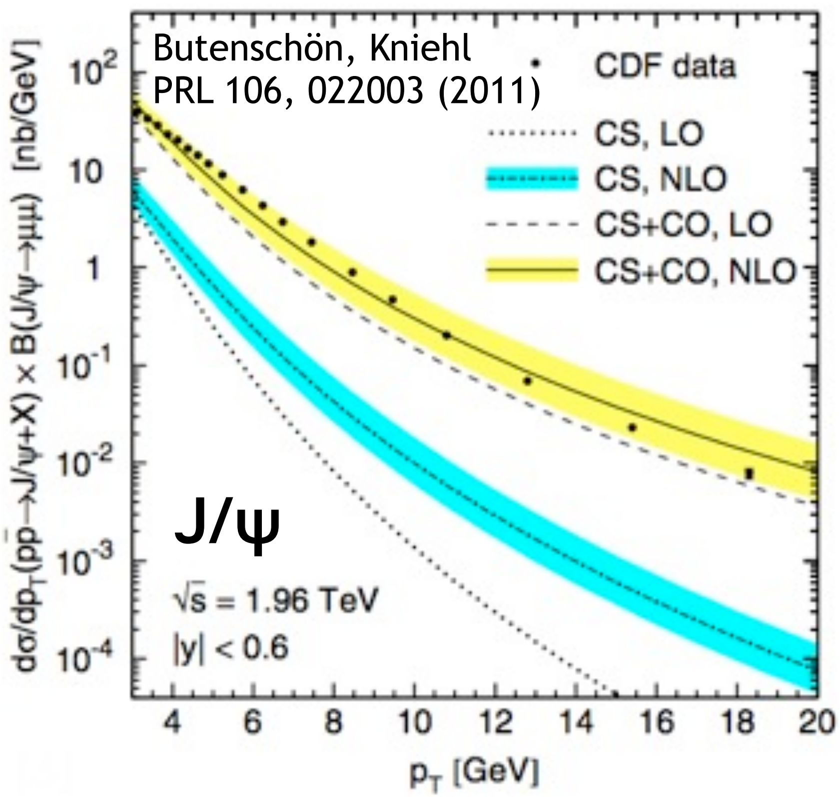
ep

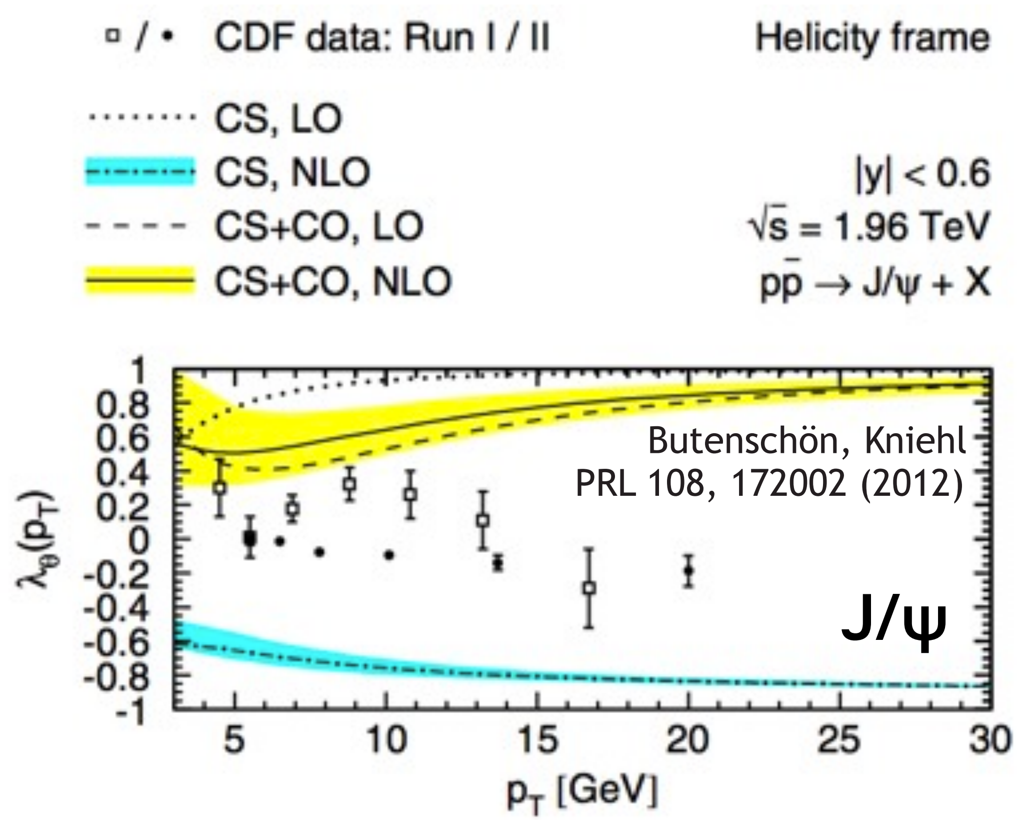


Pre-LHC era

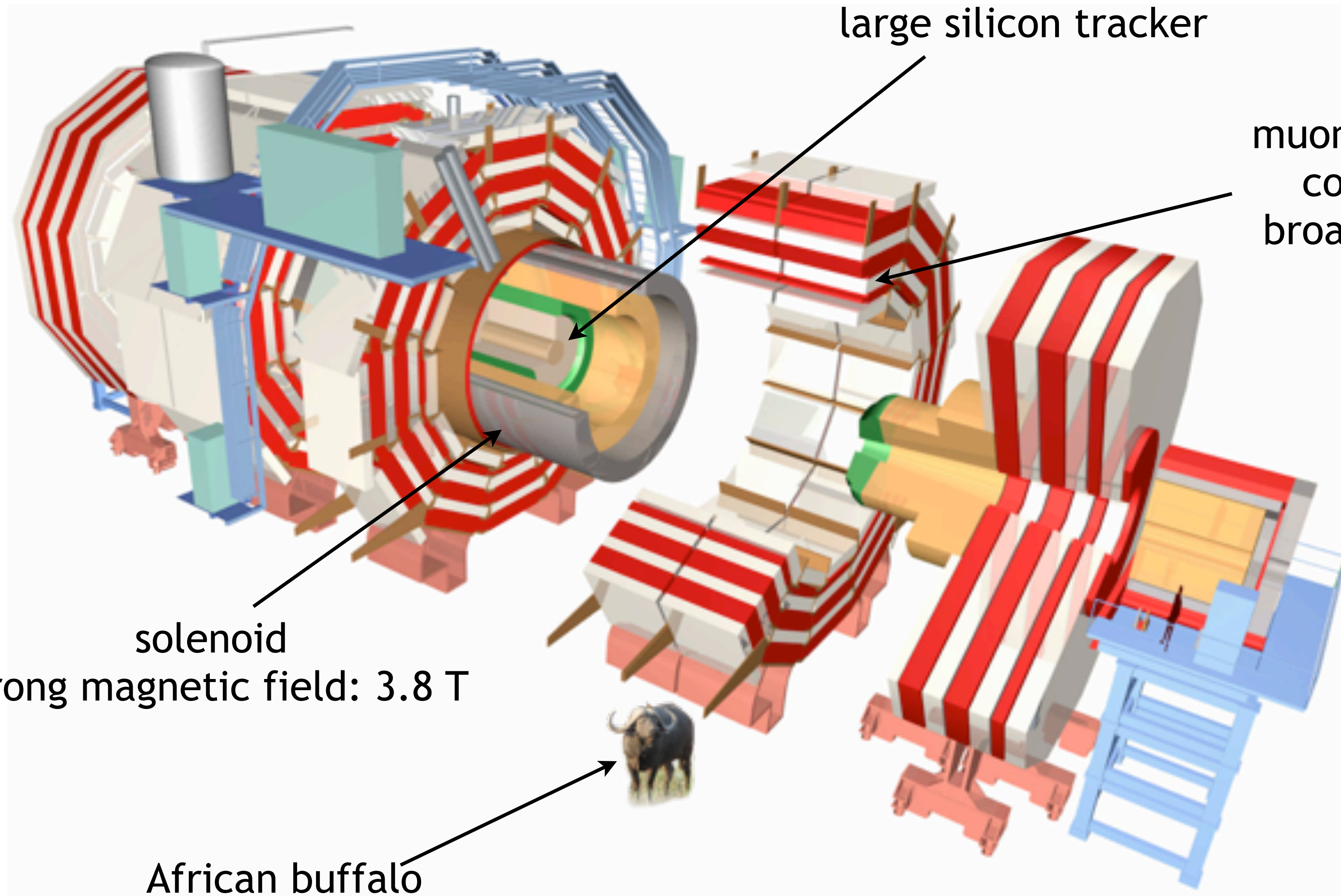
- Theory calculations cannot simultaneously describe the production cross sections and polarizations measured at the Tevatron
- Determination of the polarization parameters was inconsistent

➡ LHC is a quarkonium factory (high energy and luminosity)





CMS detector



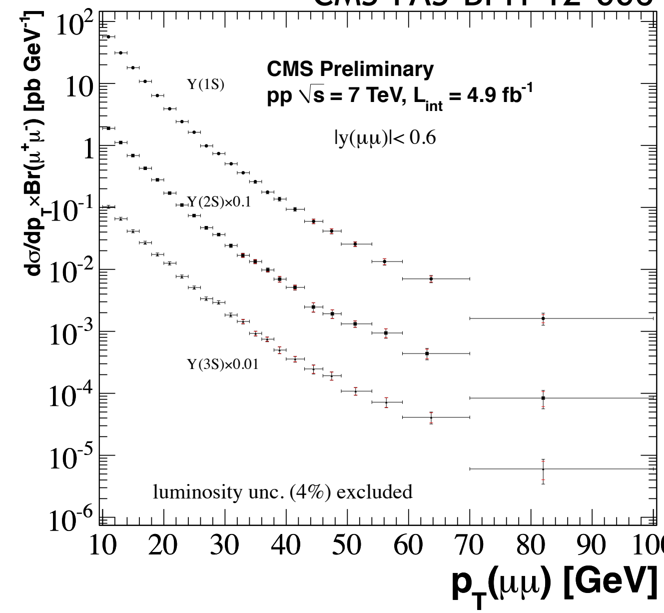
flexible trigger

CMS detector performance

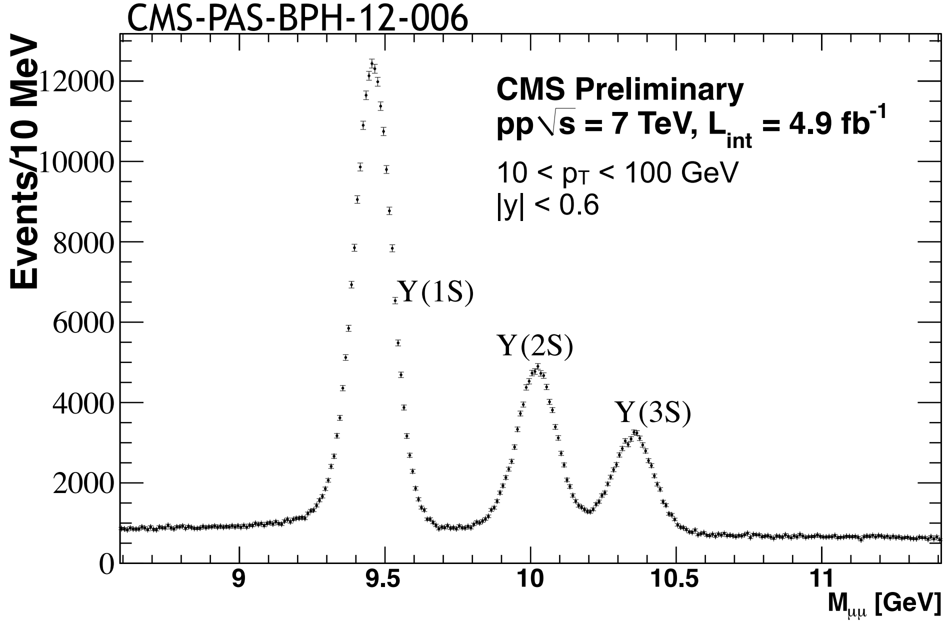
CMS is ideal for the study of quarkonia:

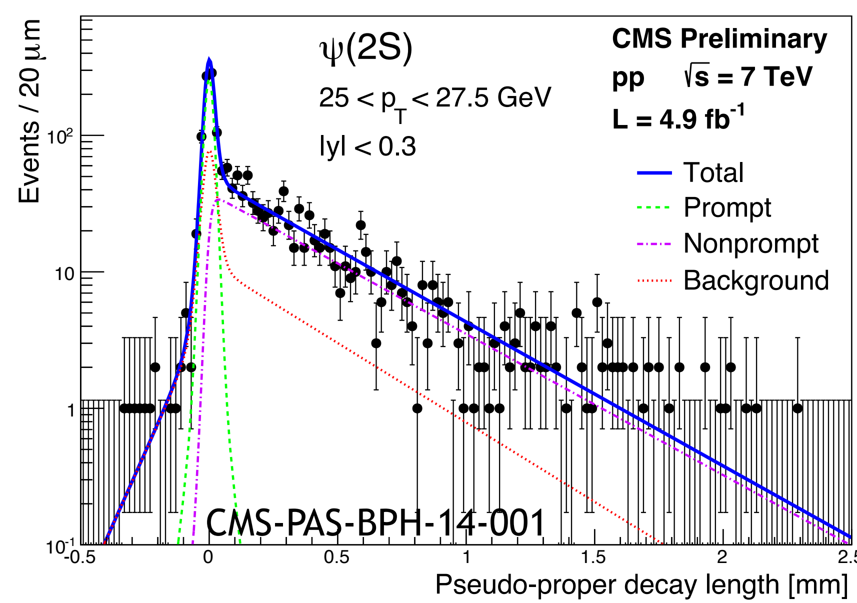
- high p_T coverage
- excellent dimuon mass resolution
- excellent decay length resolution

CMS-PAS-BPH-12-006



CMS-PAS-BPH-12-006





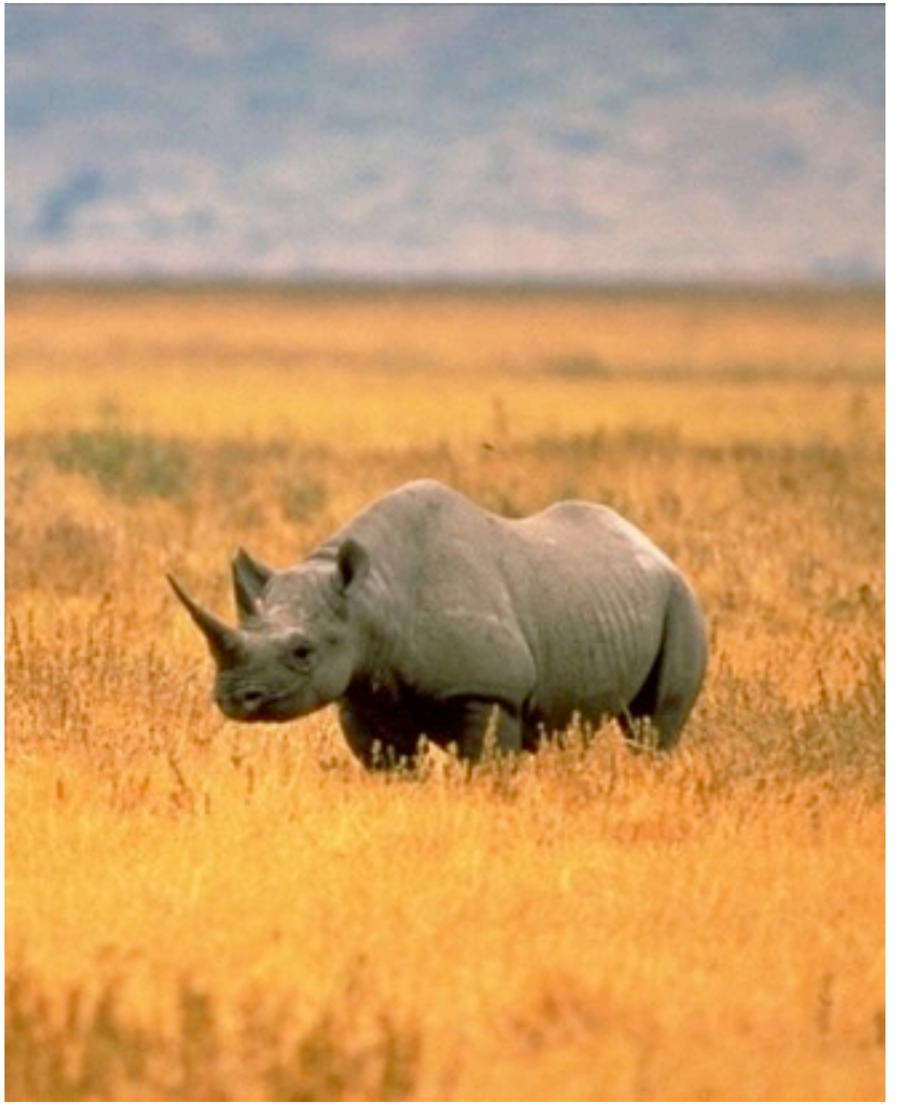
CMS-PAS-BPH-14-001

Quarkonium studies at CMS

Data

- collected with dimuon triggers in 3 mass windows:
  - J/ψ: $2.8 < m < 3.4$ GeV
  - $\psi(2S)$: $3.4 < m < 4$ GeV
  - $\Upsilon(nS)$: $8.5 < m < 11.5$ GeV
- at $\sqrt{s}$ = 7 TeV (2011) and $\sqrt{s}$ = 8 TeV (2012)
- corresponding to an integrated luminosity of 4.9 fb^{-1} (2011) and 20.7 fb^{-1} (2012)

Studies shown here use 7 TeV data unless specifically stated



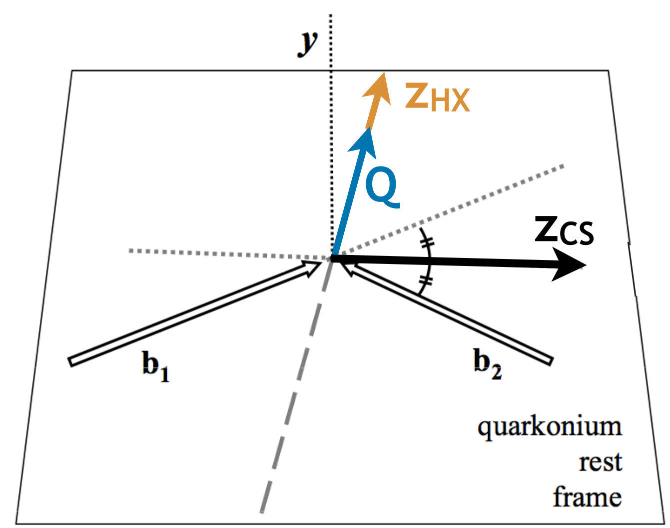
Quarkonium polarization

- Polarization is measured through the angular decay distribution of the quarkonium decaying into two muons

$$W(\cos\vartheta, \varphi|\vec{\lambda}) = \frac{3/(4\pi)}{(3+\lambda_\vartheta)}(1 + \lambda_\vartheta \cos^2\vartheta + \lambda_\varphi \sin^2\vartheta \cos 2\varphi + \lambda_{\vartheta\varphi} \sin 2\vartheta \cos\varphi)$$

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 ($z_{PX} \perp z_{CS}$)

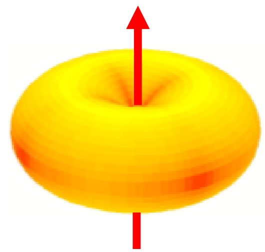


Full angular decay distribution

- Two extreme angular decay distributions

Longitudinal polarization
$J_z = 0$

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

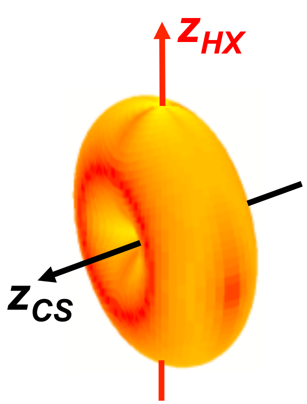


Transverse polarization
$J_z = \pm 1$

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

- Unless the full angular distribution is measured, two very different physical cases are indistinguishable.

$\tilde{\lambda} = -1$



$\lambda_\vartheta = +1$
$\lambda_\varphi = -1$

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

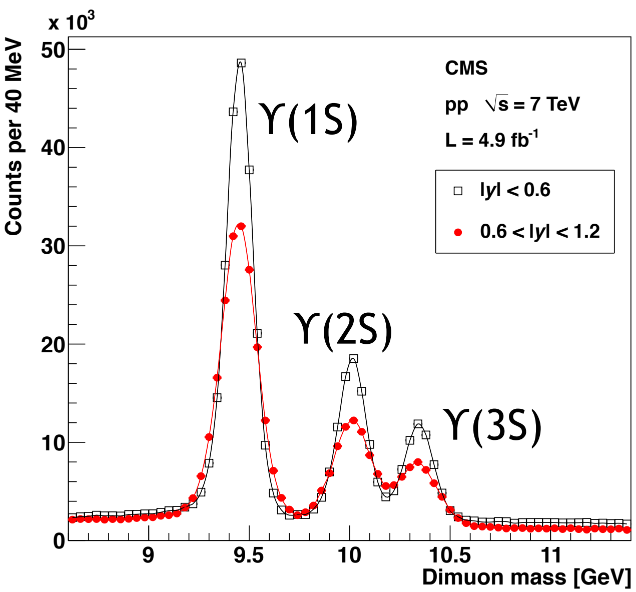
$\lambda_\vartheta = +1$
$\lambda_\varphi = 0$

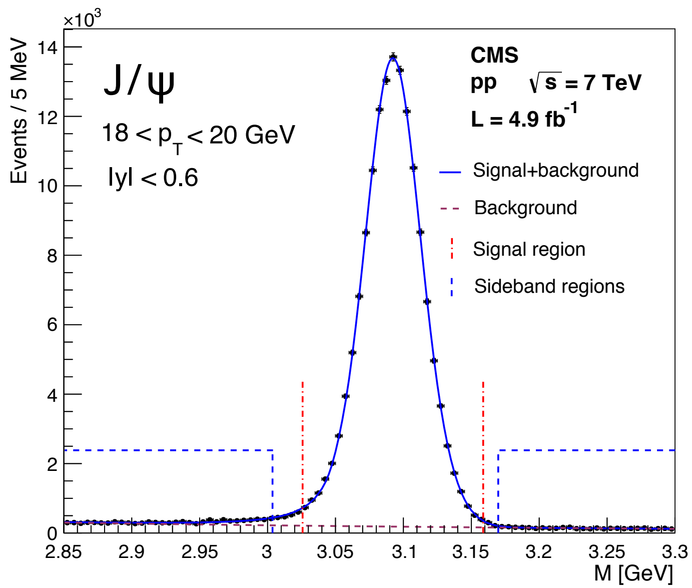
$\tilde{\lambda} = +1$

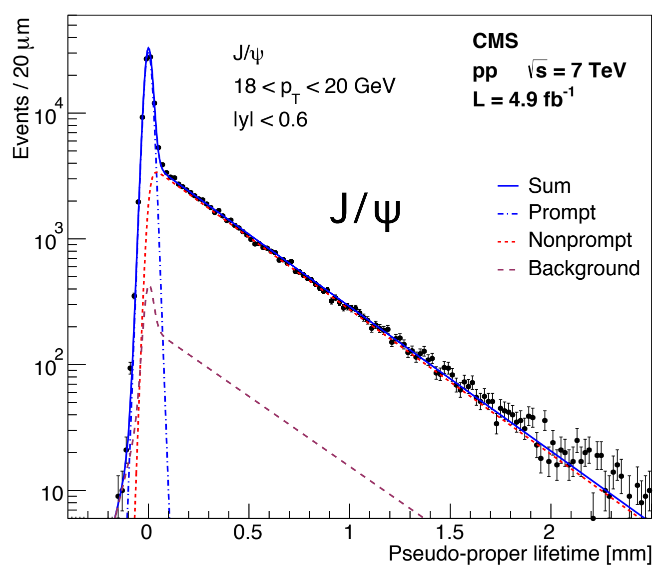
- The shape of the distribution is invariant and can be characterized by the frame invariant parameter $\tilde{\lambda} = (\lambda_\vartheta + 3\lambda_\varphi)/(1 - \lambda_\varphi)$

Quarkonium polarization measurements

- CMS measured λ_ϑ, λ_φ, $\lambda_{\vartheta\varphi}$ and $\tilde{\lambda}$ in three different reference frames (HX, CS, PX) for the J/ψ, ψ(2S), ϒ(1S), ϒ(2S) and ϒ(3S) mesons
- As a function of transverse momentum, p_T, and dimuon rapidity, |y|
- The non-prompt term (B decays) is subtracted in the ψ(nS) cases

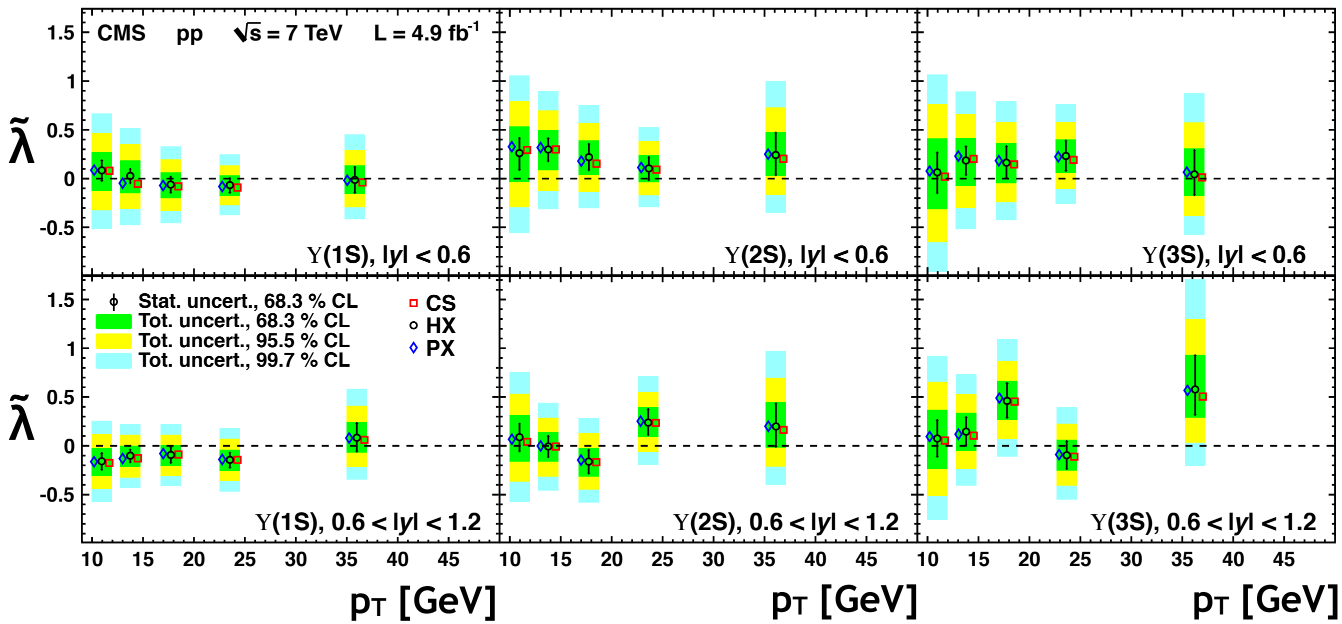


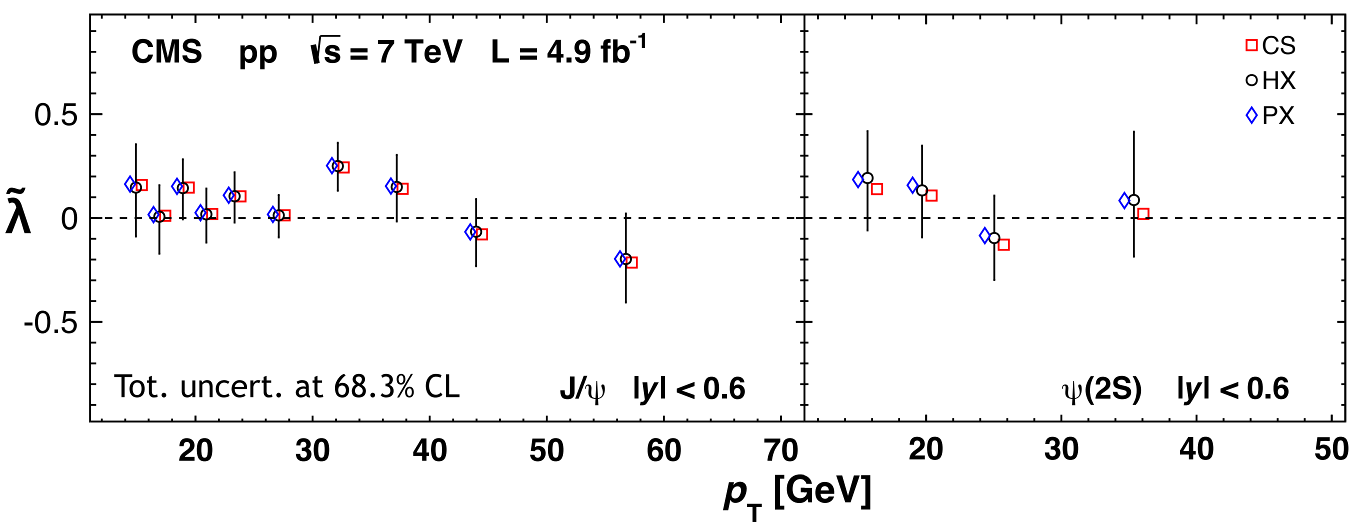




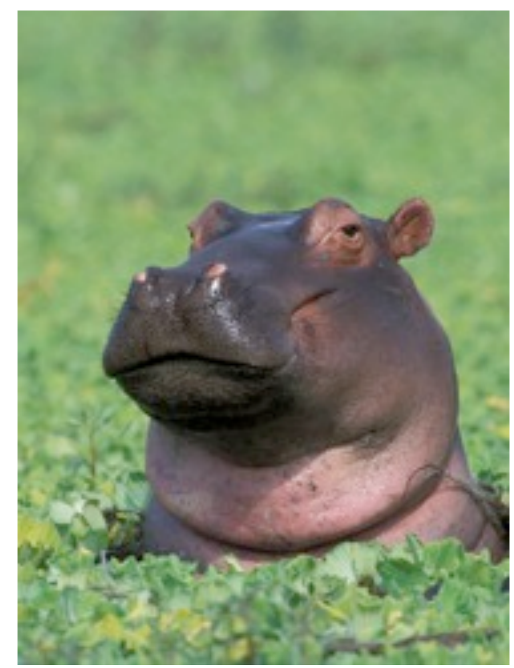
Details in PRL 110, 081802 (2013) and PLB 727, 381 (2013)

Frame invariant parameter $\tilde{\lambda}$

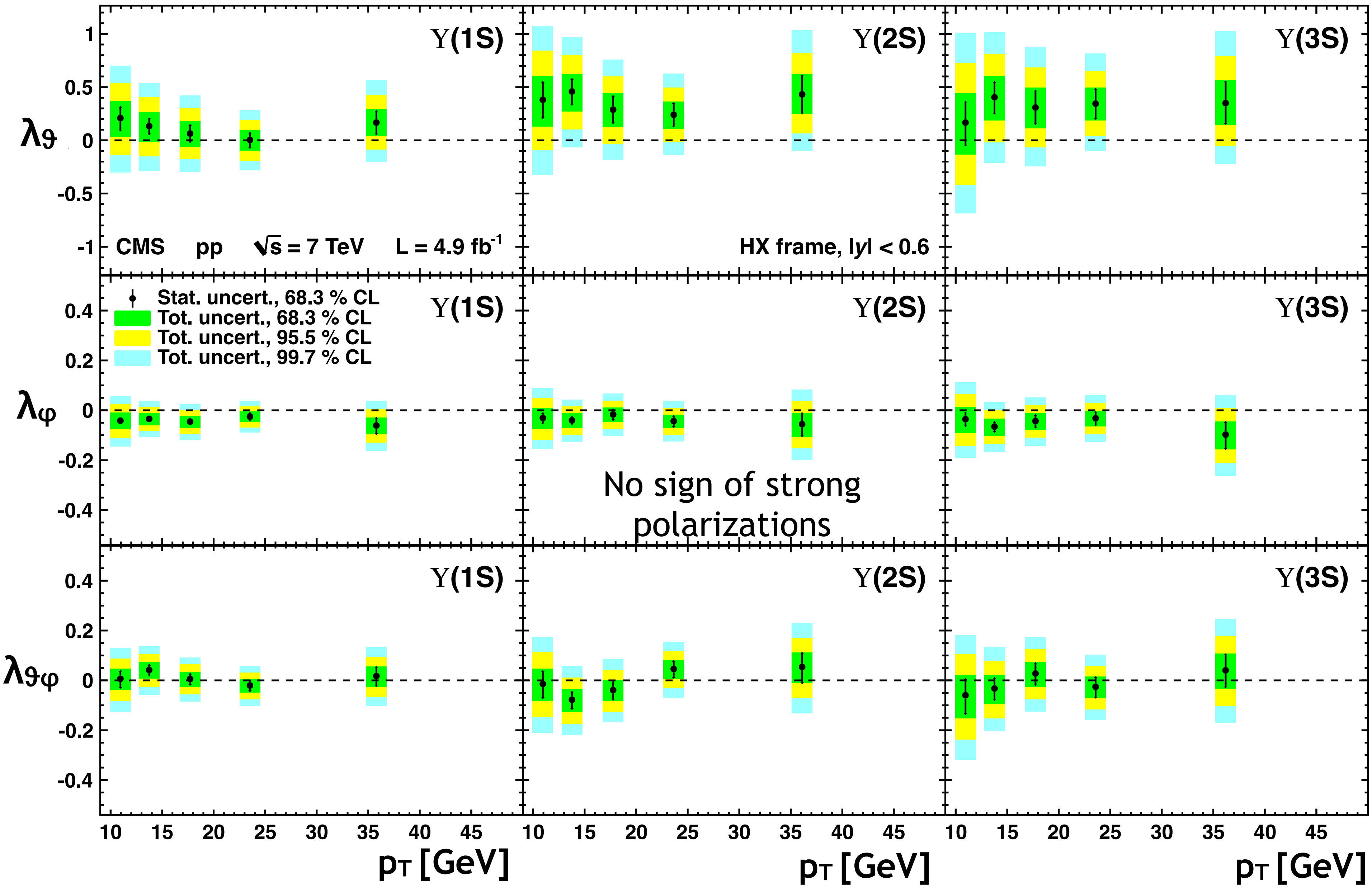




Good agreement between the $\tilde{\lambda}$ parameters in the three reference frames shows that the results are reliable

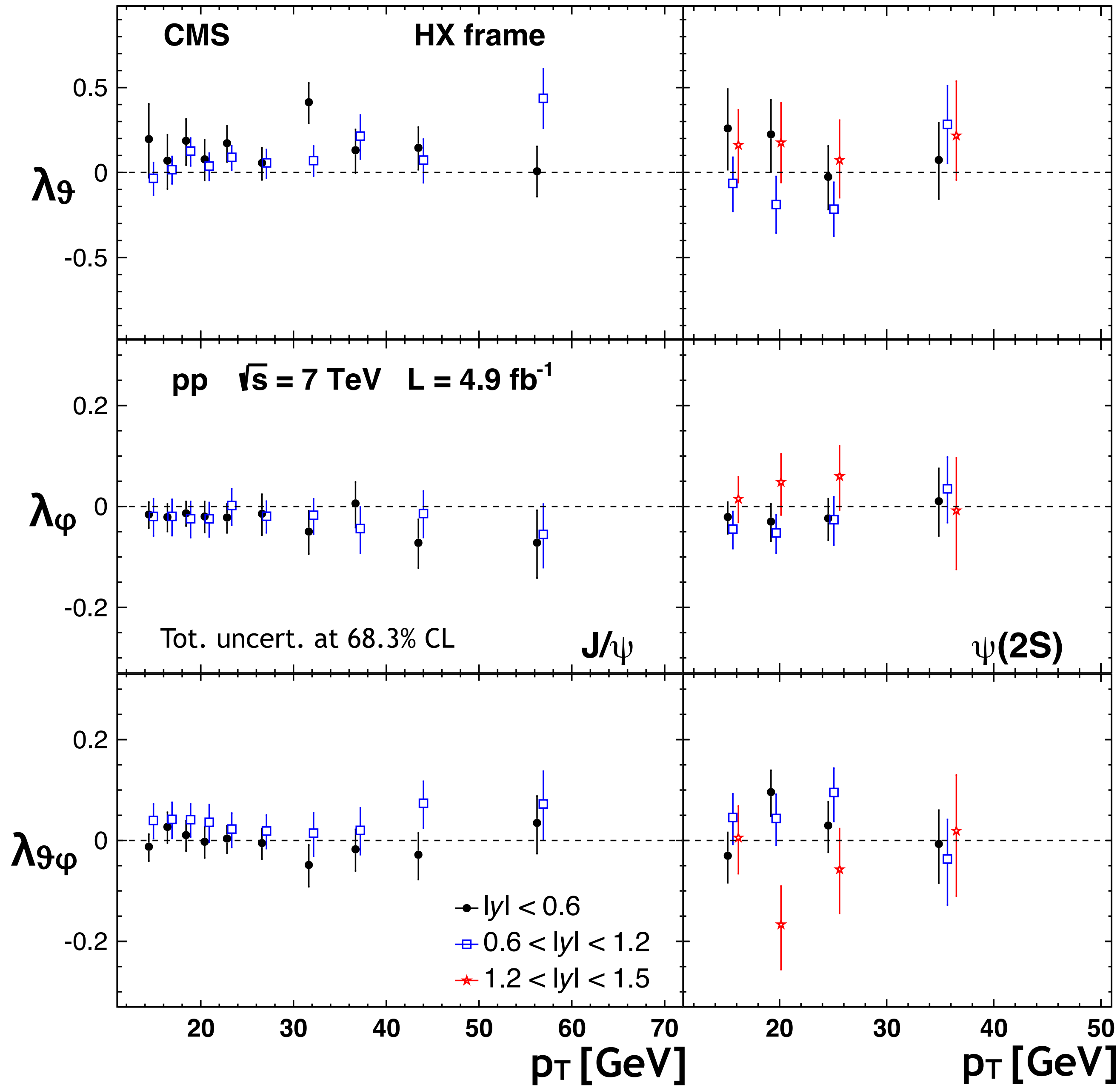


Υ(nS) polarization in the HX frame, |y| < 0.6



No sign of strong polarizations

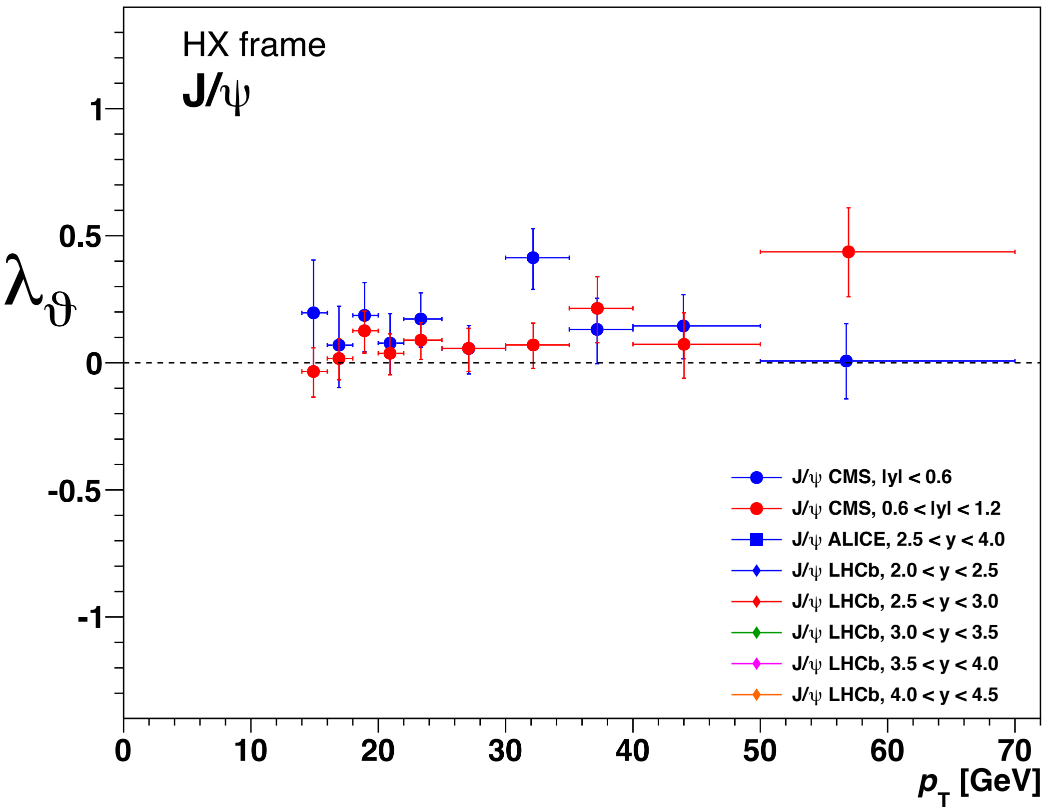
Prompt ψ(nS) polarization in the HX frame



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

LHC polarization measurements

- CMS polarization measurements show no sign of strong polarizations
- No evident differences between charmonium and bottomonium states or directly produced states and those affected by feed-down



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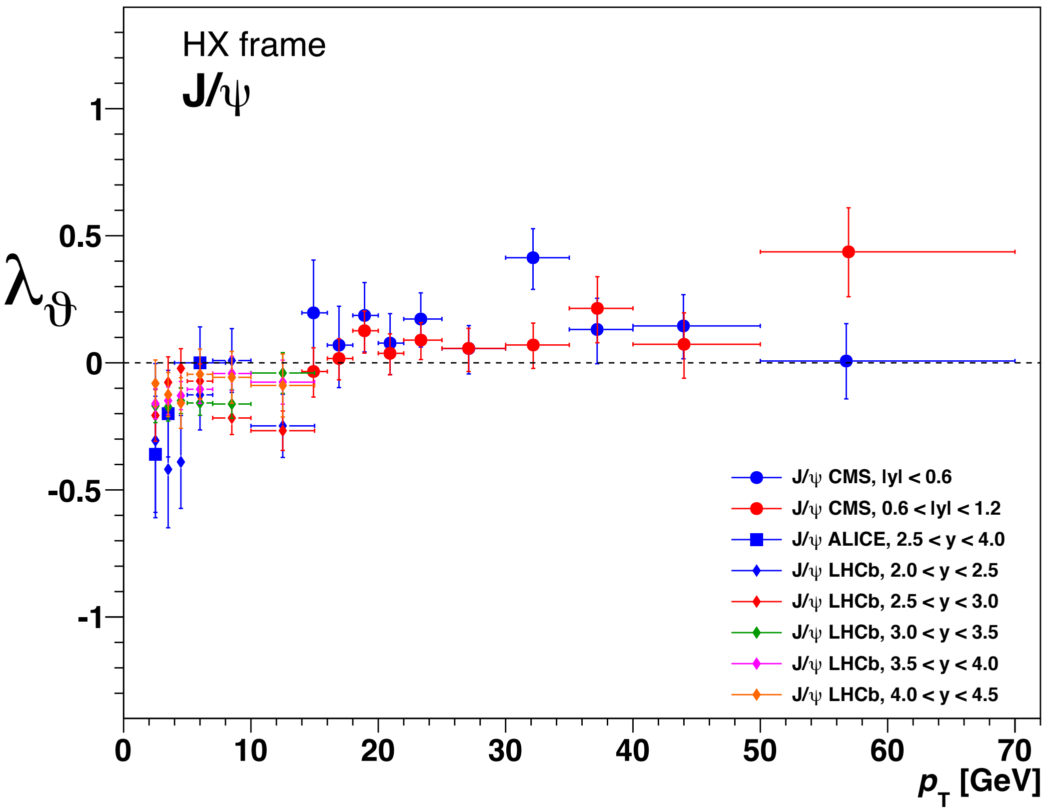

- Good consistency with other polarization measurements done by LHCb, ALICE and CDF

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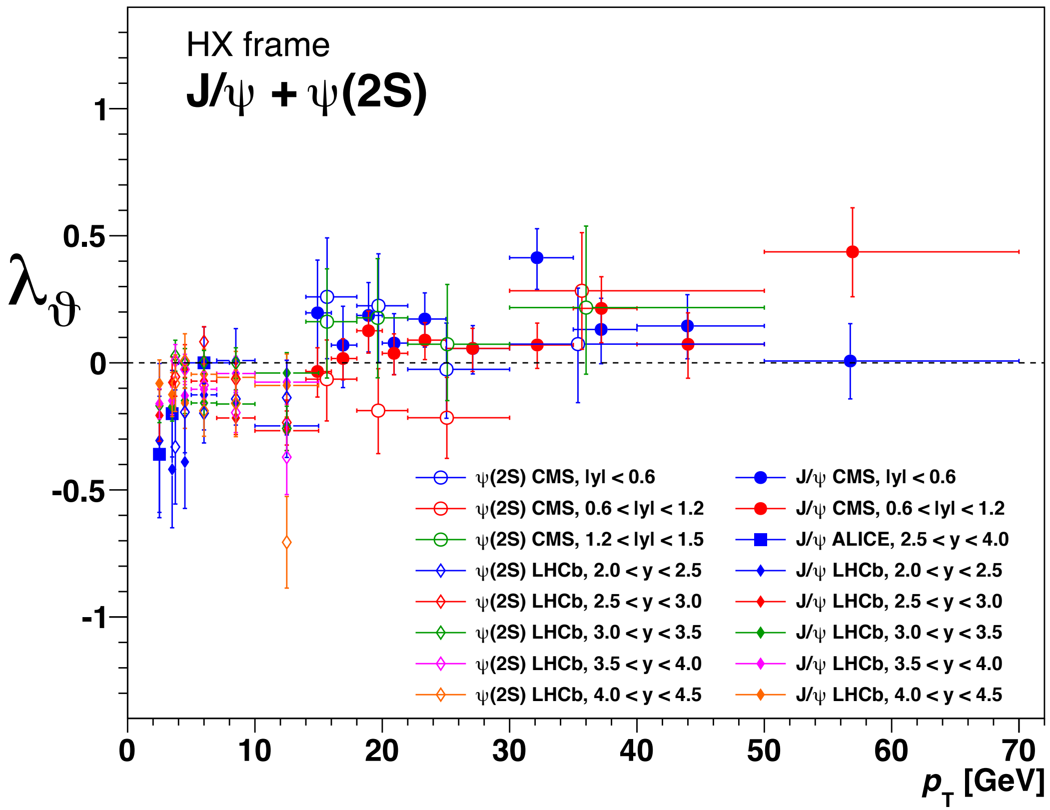
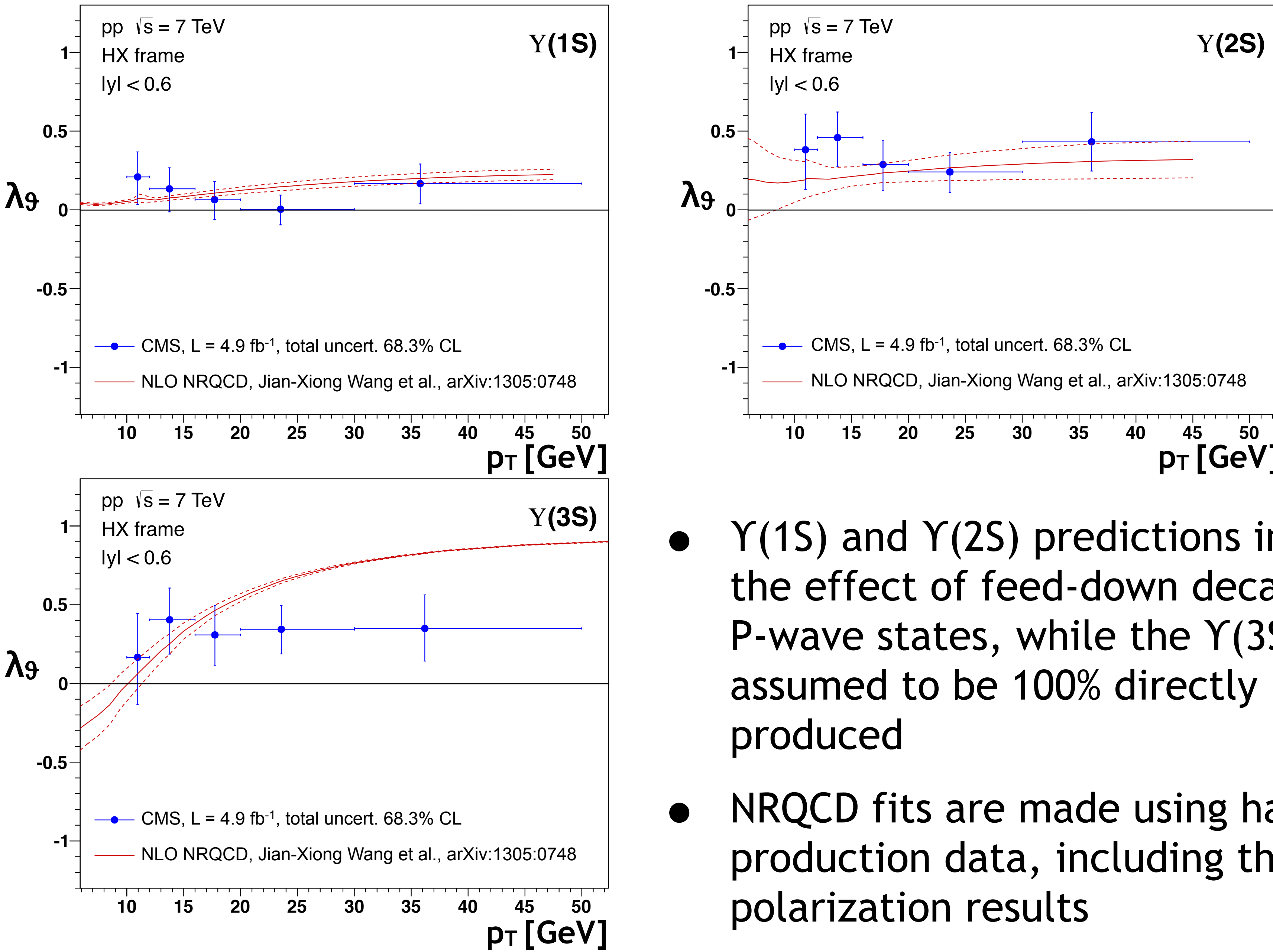


- Good consistency with other polarization measurements done by LHCb, ALICE and CDF
- Previous experimental inconsistencies are overcome by novel and more robust analysis techniques (EPJC 69, 657 (2010))

Υ(nS): CMS data vs NLO NRQCD (J.X. Wang et al.)



- Υ(1S) and Υ(2S) predictions include the effect of feed-down decays of P-wave states, while the Υ(3S) is assumed to be 100% directly produced
- NRQCD fits are made using hadro-production data, including the CMS polarization results

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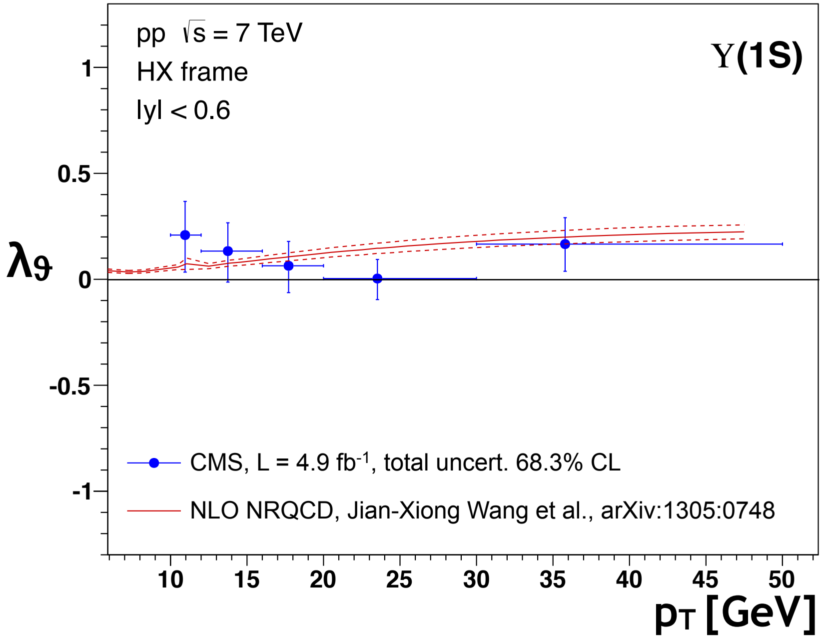
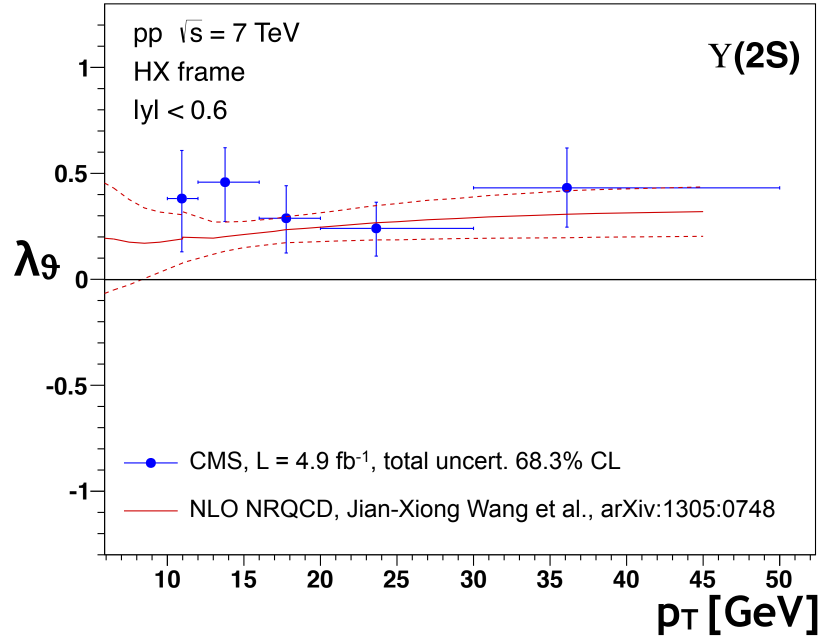
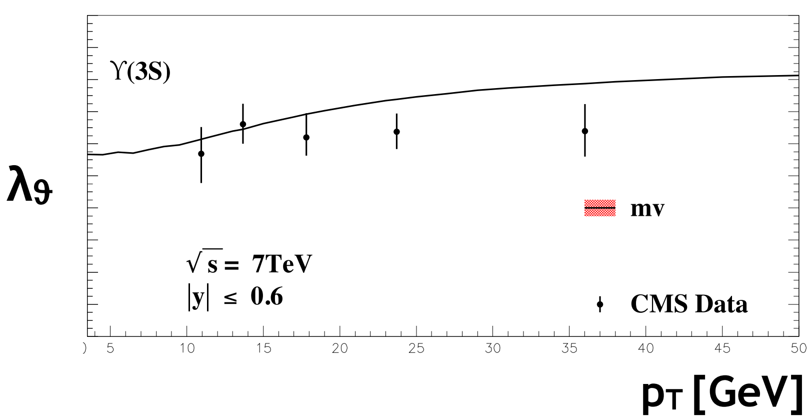




Updated fits including feed-down presented at QWG 2014



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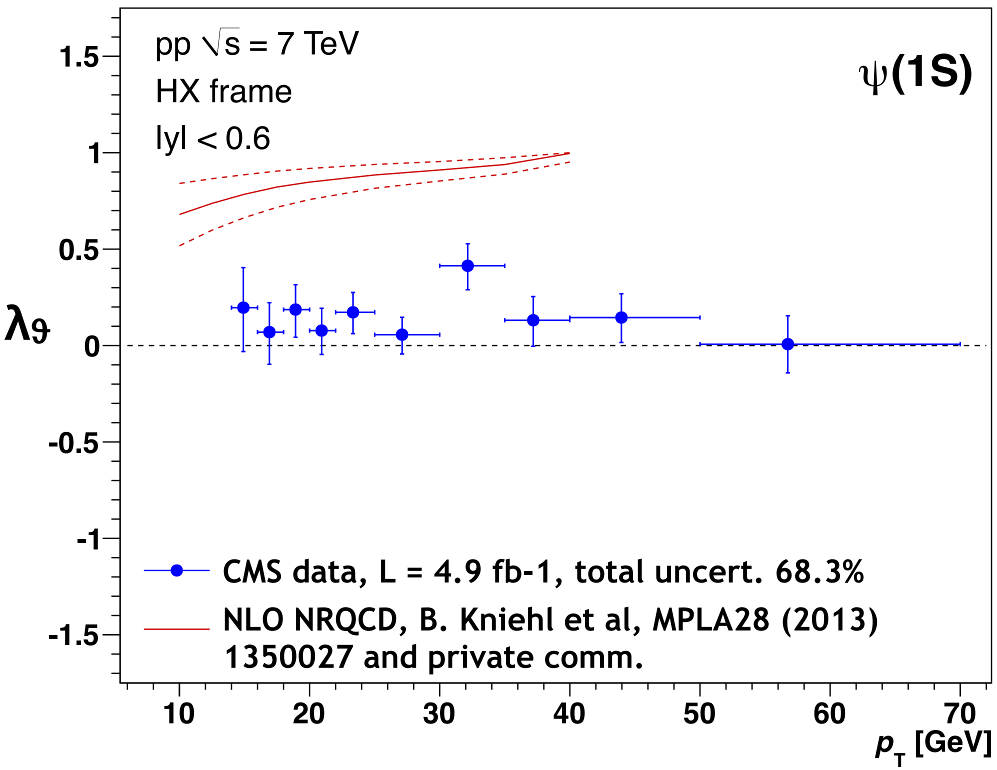
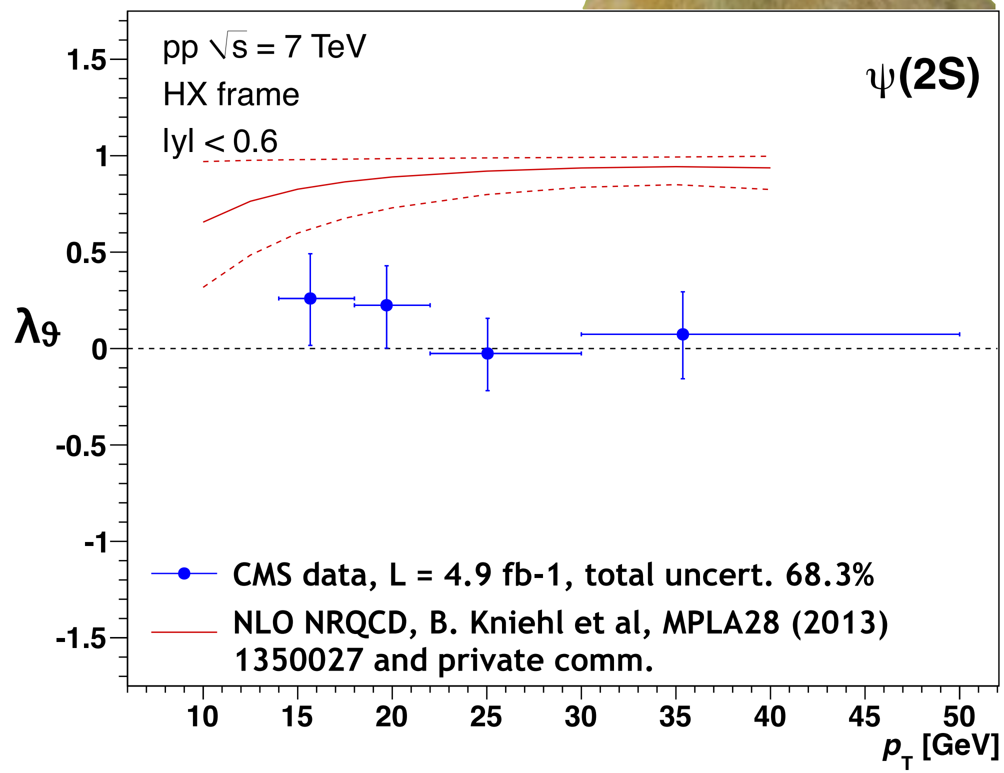
ψ(nS): CMS data vs NLO NRQCD (B. Kniehl et al.)

- Color octet matrix elements are fitted using photo- as well as hadro-production data, excluding polarization results
- Theory predictions do not account for feed-down decays from P-wave states

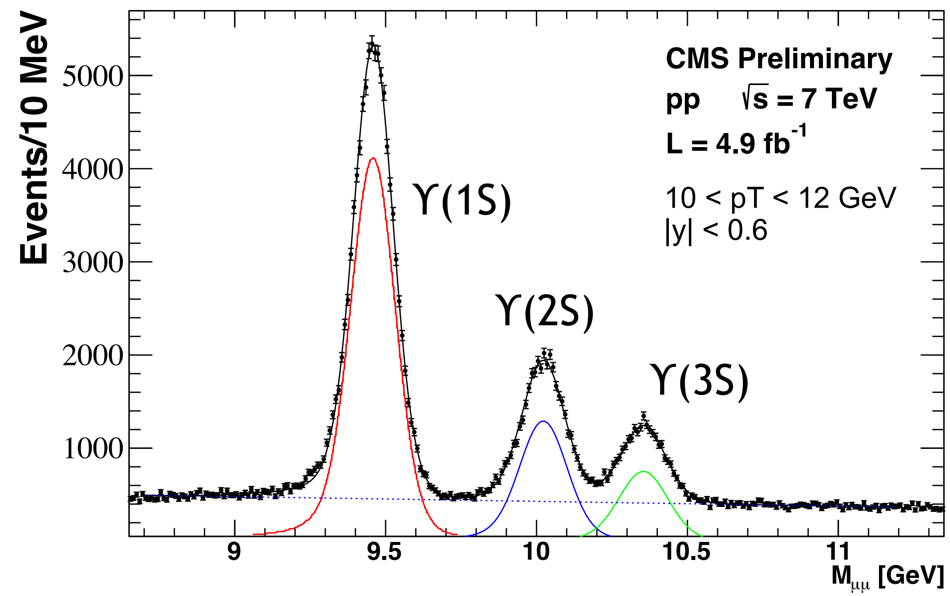


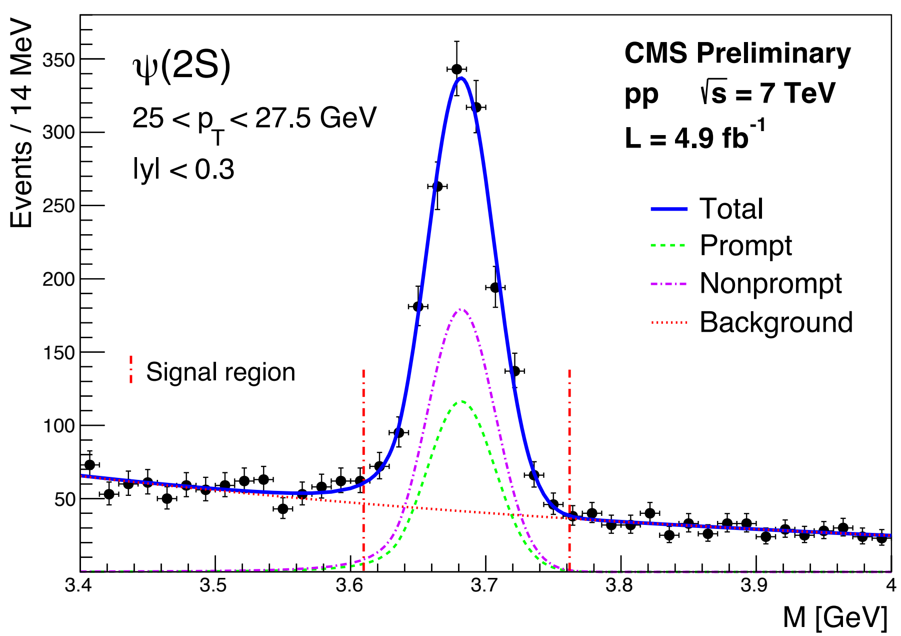


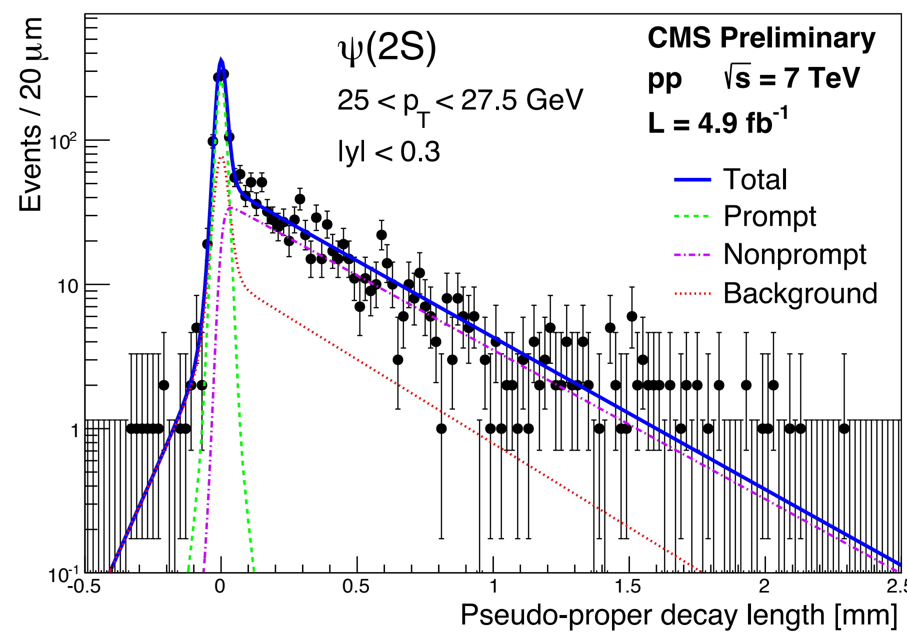
S-wave quarkonium production cross sections

- Extraction of yields through unbinned maximum likelihood fits to invariant mass and decay length

Details in CMS-PAS-BPH-14-001 and CMS-PAS-BPH-12-006

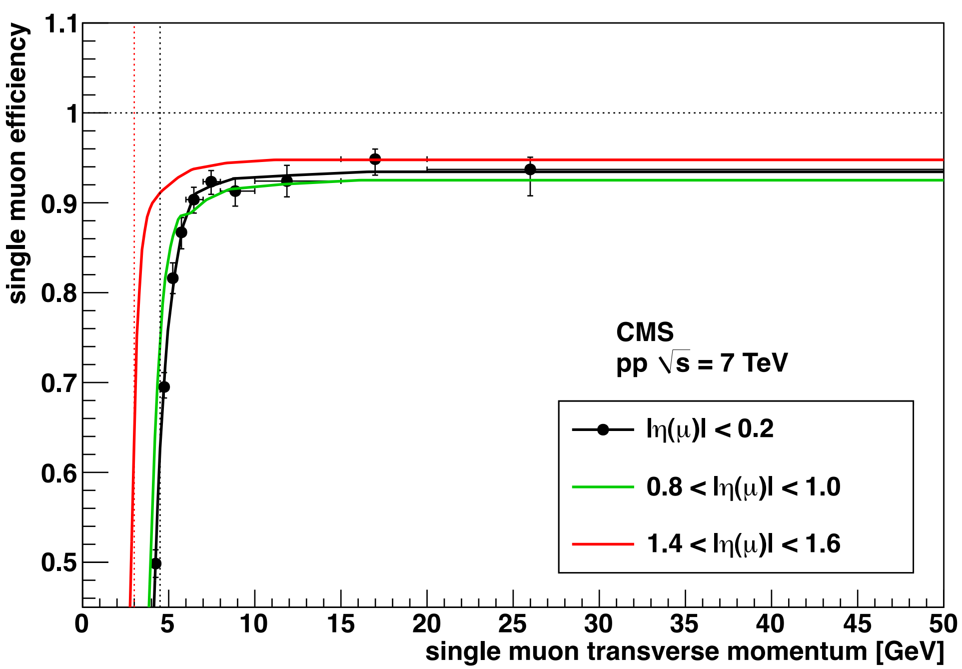


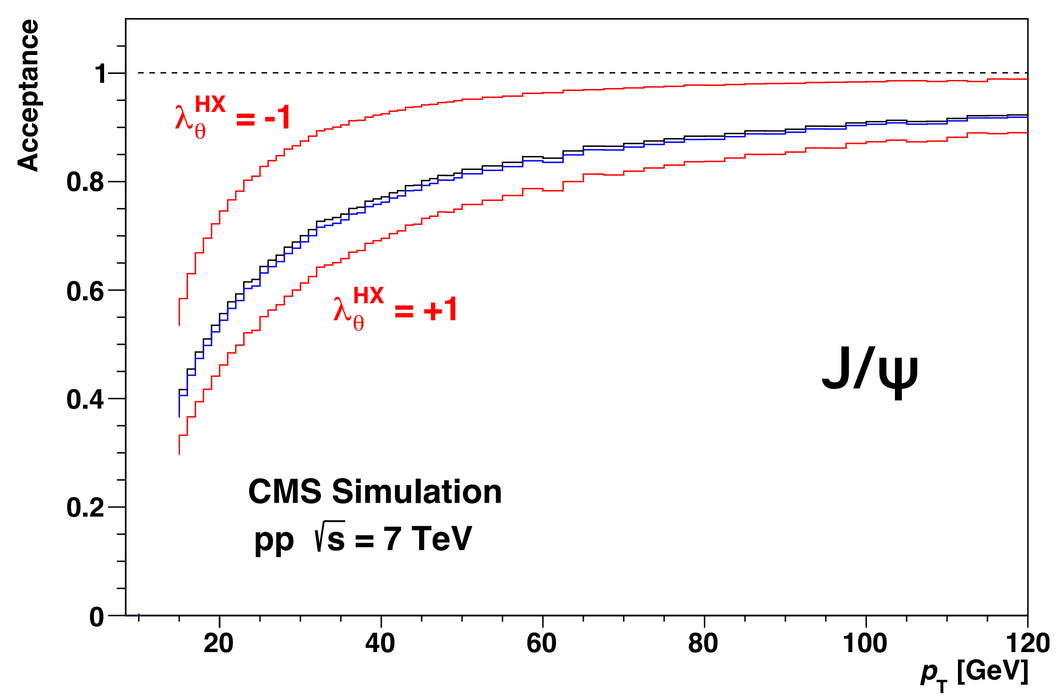




Yield corrections

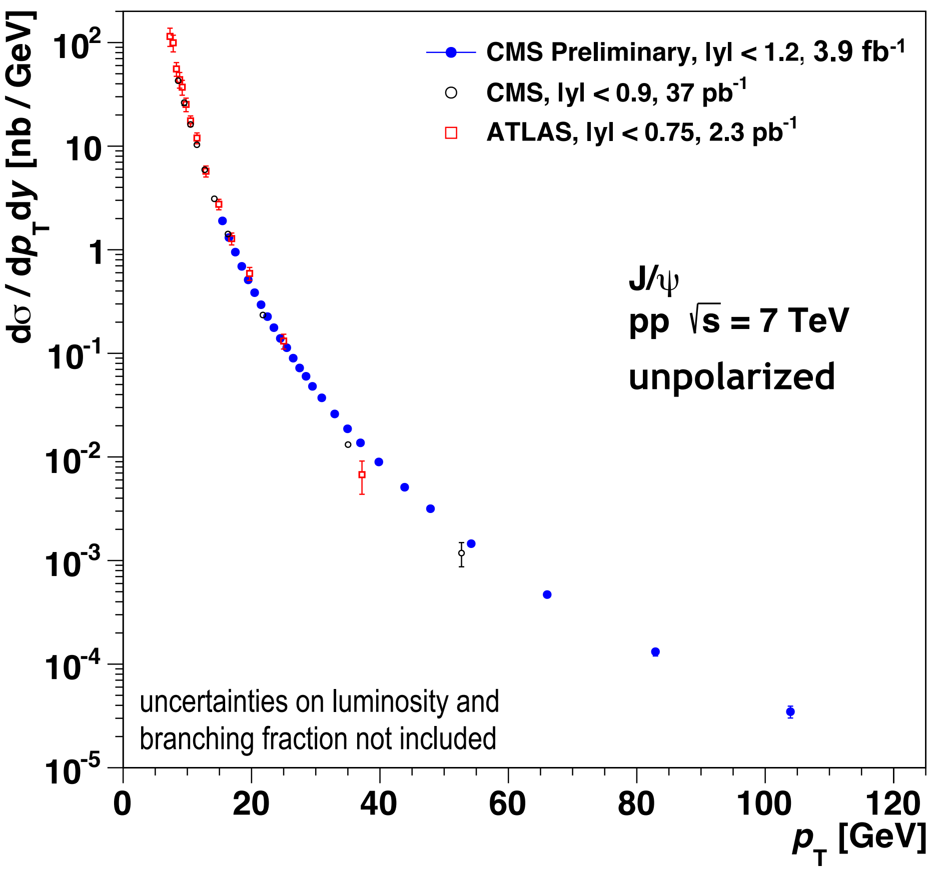
- Acceptance and single muon and dimuon efficiencies are corrected for on an event-by-event basis
- Acceptance depends on the assumed polarizations; Results given for several scenarios: measured, unpolarized, $\lambda_\vartheta^{HX} = \pm1$

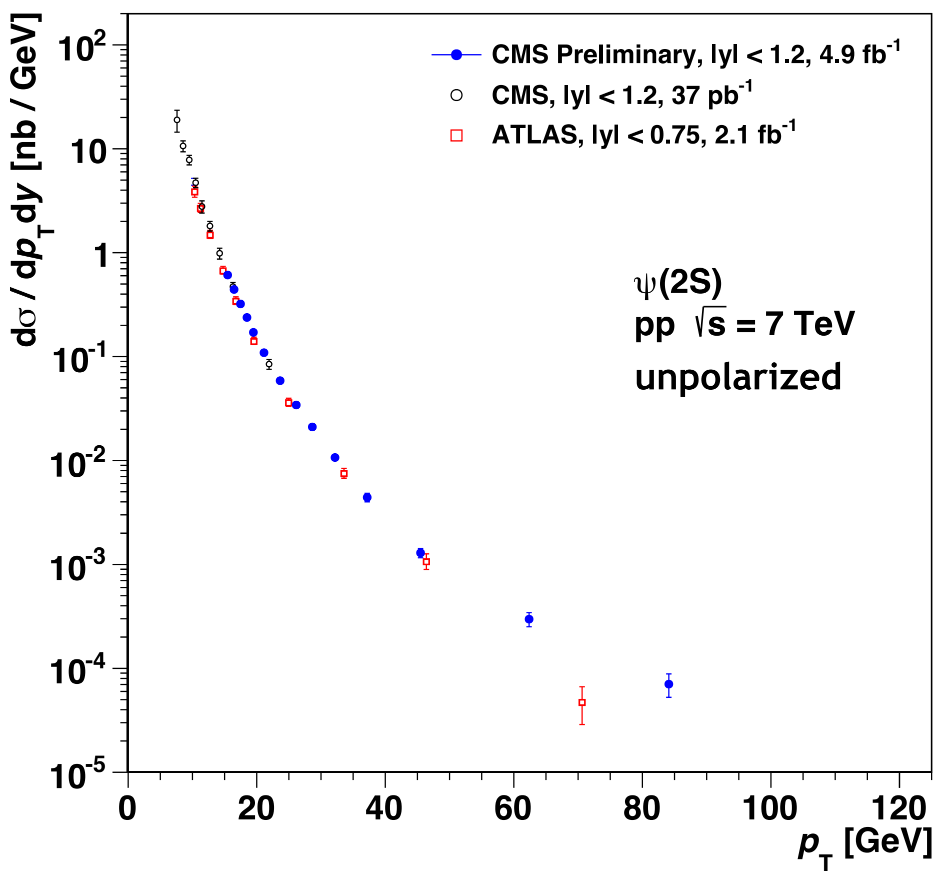




Prompt ψ(nS) production cross section

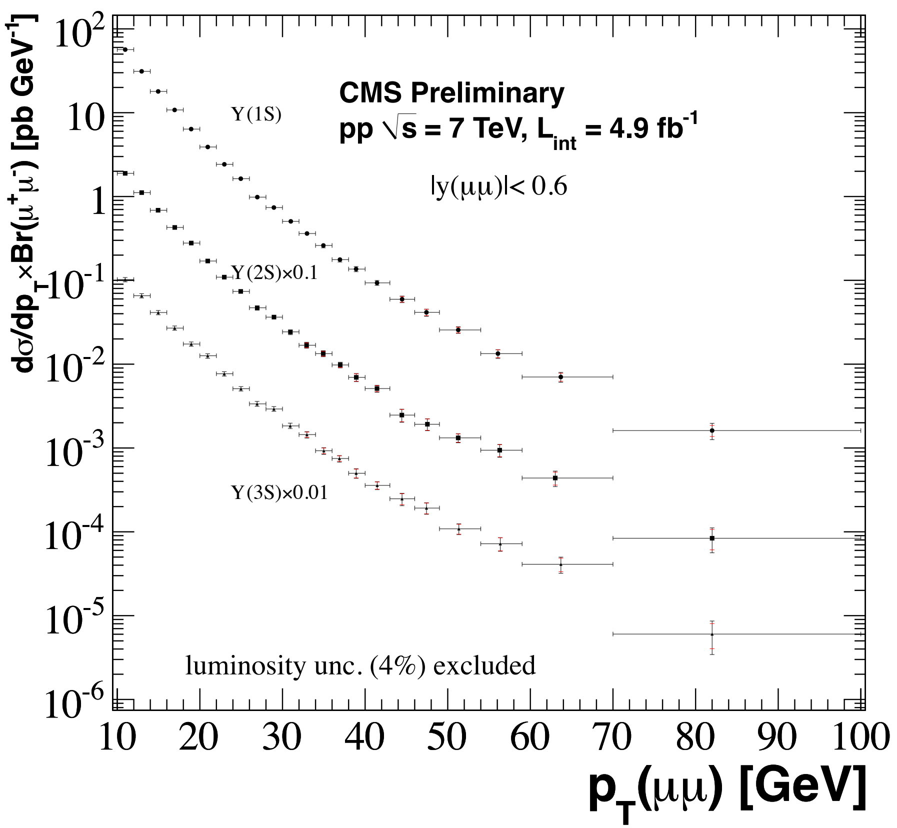
- Measurements were made as a function of p_T in four bins of dimuon rapidity as well as integrated in rapidity ($|y| < 1.2$)
- Prompt J/ψ and ψ(2S) cross sections up to p_T around 100 GeV

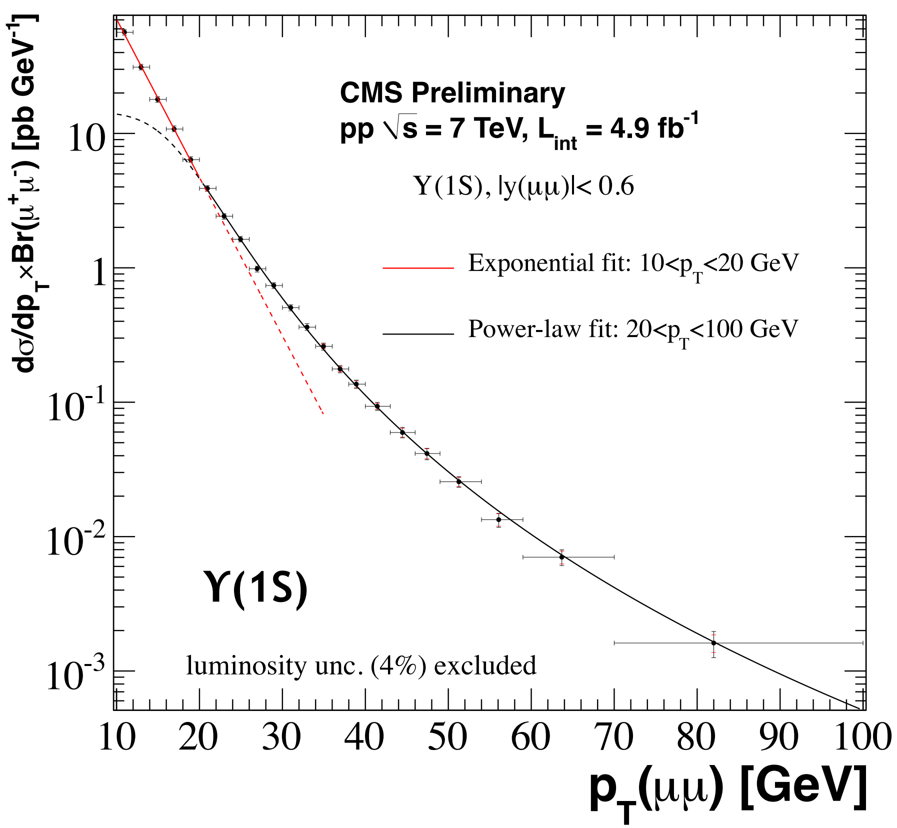




Υ(nS) production cross section

- Υ(nS) differential cross sections were measured in the p_T range 10–100 GeV
- All 3 states show similar trends
- Slope of cross section changes from exponential to power-law at p_T ~ 20 GeV





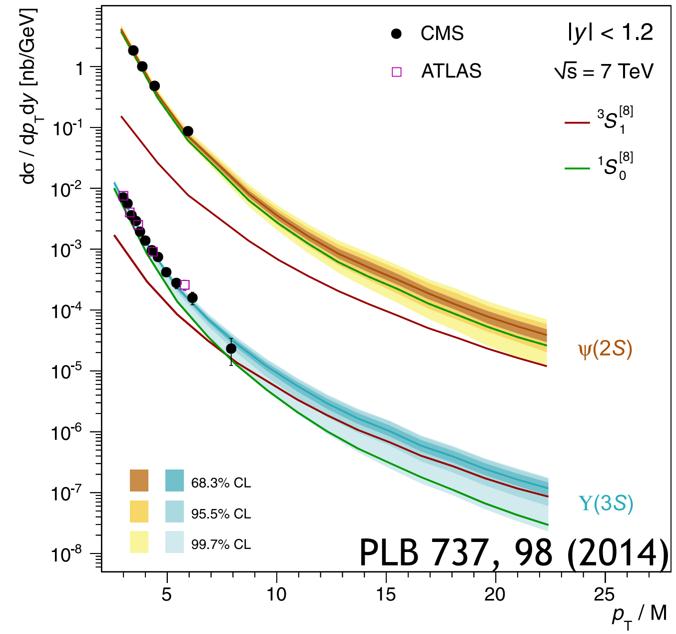
Recent developments to explain production

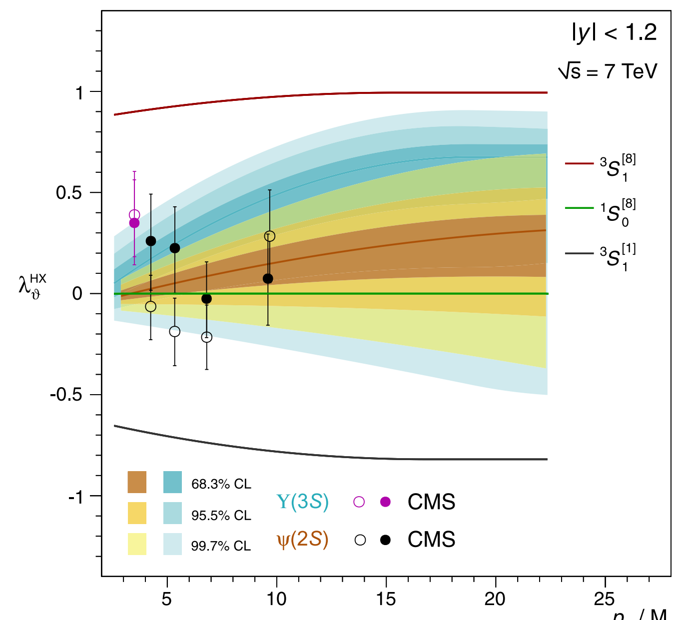
- Data-driven approach (PLB 737, 98 (2014)): Consistent treatment of the cross sections and polarizations
- Leading power fragmentation formalism (PRL 113, 022001 (2014))

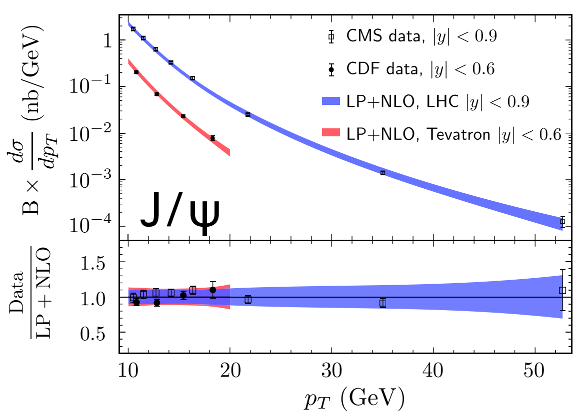
➡ Both approaches exclude data at low p_T

➡ Both get reasonable agreement with data

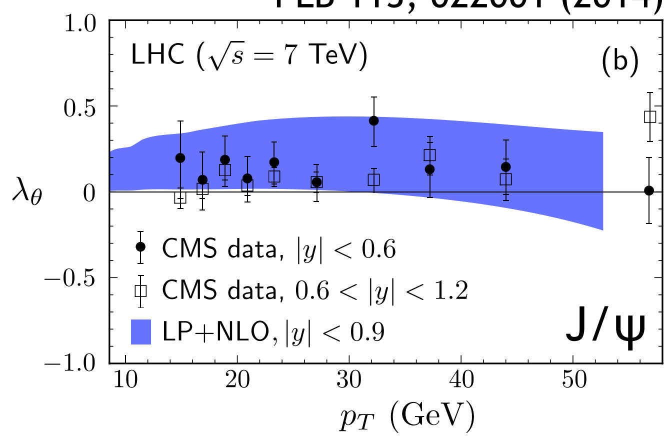
➡ Unpolarized CO contribution dominates the production





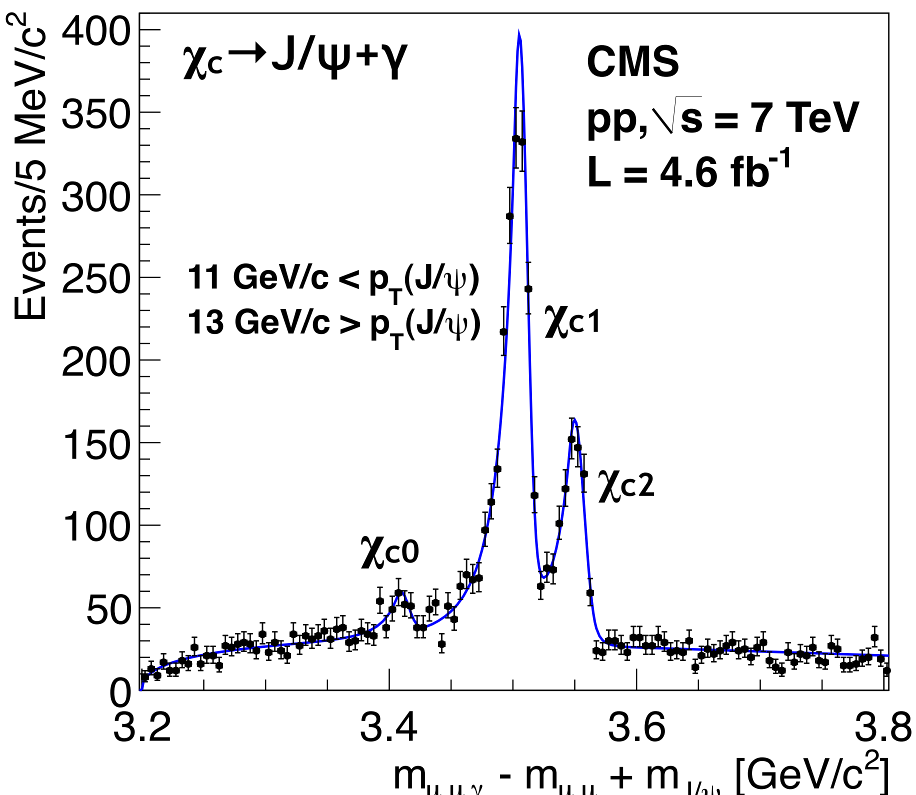


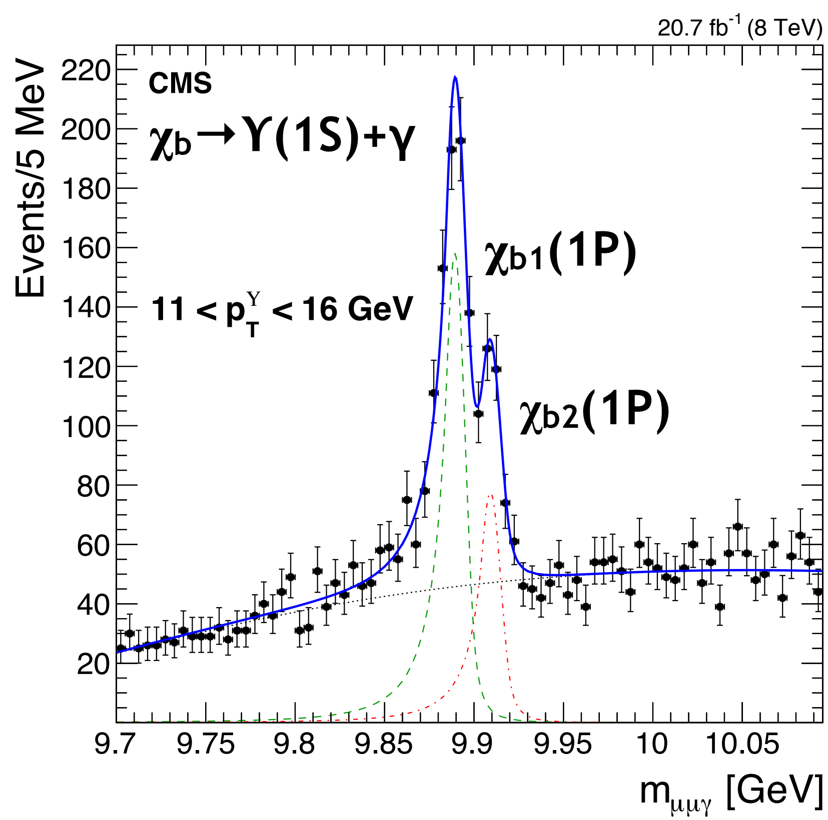
PLB 113, 022001 (2014)



P-wave quarkonium production

- χ states are measured through their radiative decays to S-wave quarkonia with the photon converting into an e^+e^- pair
- Excellent χ mass (≈6 MeV, $|y_{\mu\mu}|<1$ or $|\eta_\gamma|<1$) and conversion vertex resolutions
- Yield extraction through unbinned maximum likelihood fits



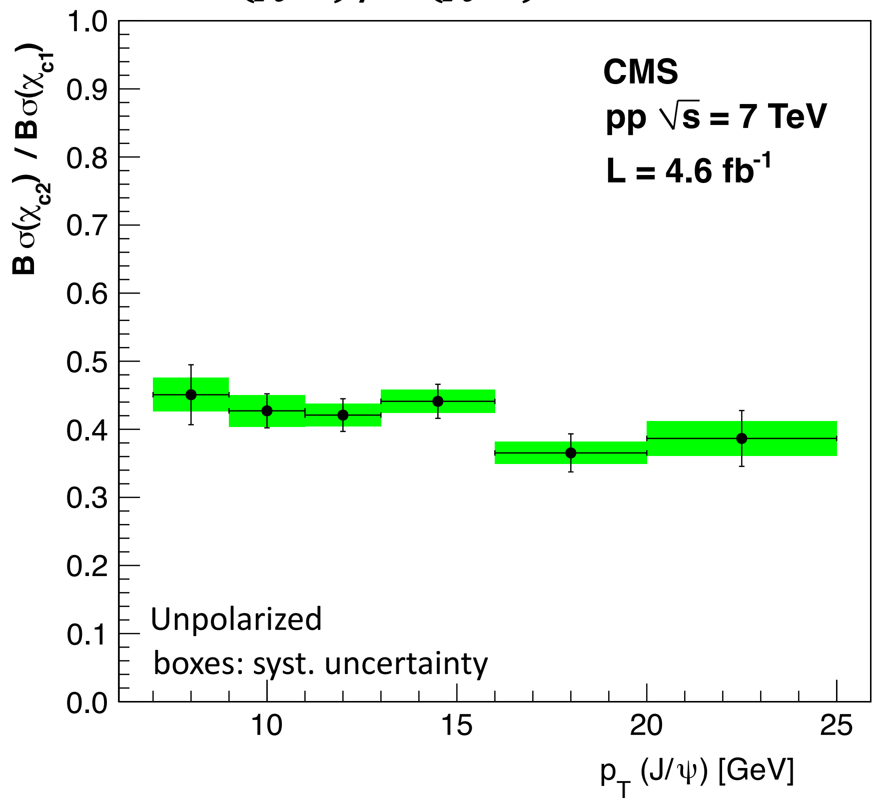


Details in EPJC 72, 2251 (2012) and arXiv:1409:5761

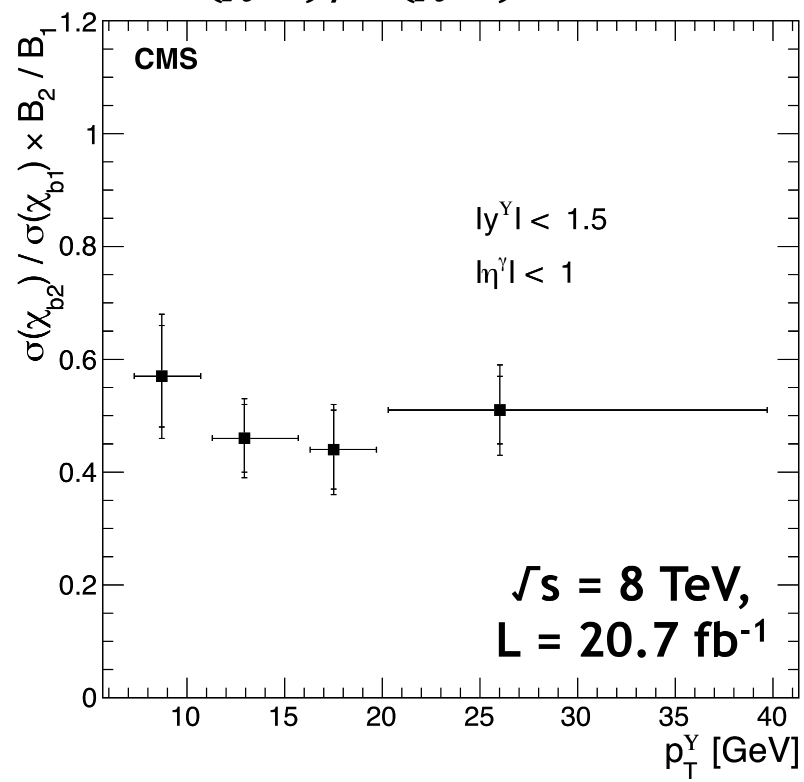
Relative production rate of P-wave states

- Prompt χ_{c2}/χ_{c1} and $\chi_{b2}(1P)/\chi_{b1}(1P)$ cross section ratios seem to be rather flat with p_T

$\sigma(\chi_{c2})/\sigma(\chi_{c1})$ x B_2/B_1



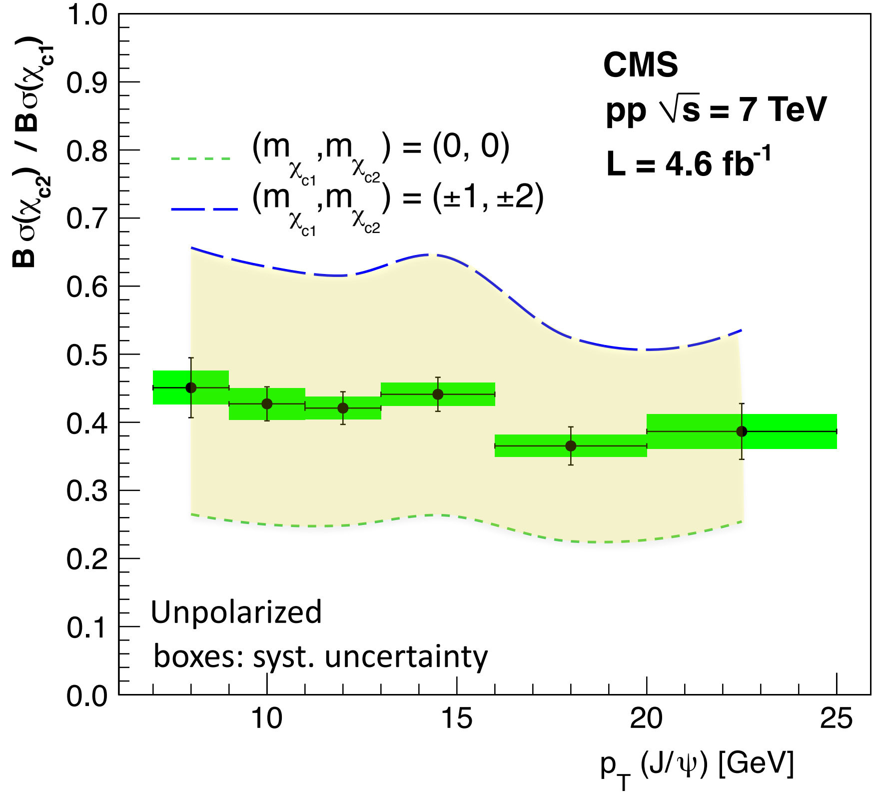
$\sigma(\chi_{b2})/\sigma(\chi_{b1})$ x B_2/B_1



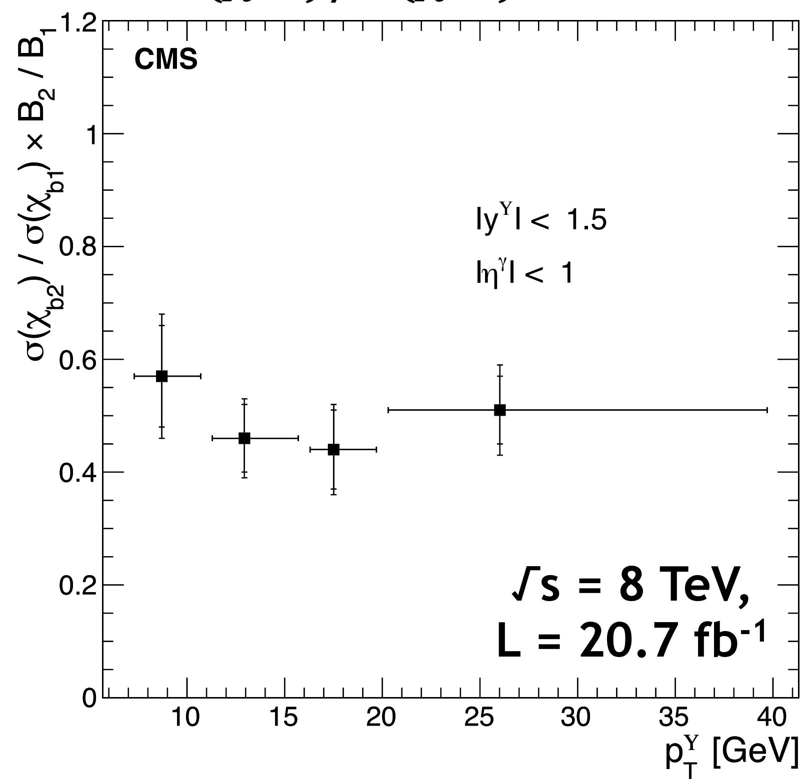
Relative production rate of P-wave states

- Prompt χ_{c2}/χ_{c1} and $\chi_{b2}(1P)/\chi_{b1}(1P)$ cross section ratios seem to be rather flat with p_T
- Prompt χ_{c2}/χ_{c1} ratio: Care is needed regarding the assumed polarizations; they can significantly change the result

$\sigma(\chi_{c2})/\sigma(\chi_{c1}) \times B_2/B_1$



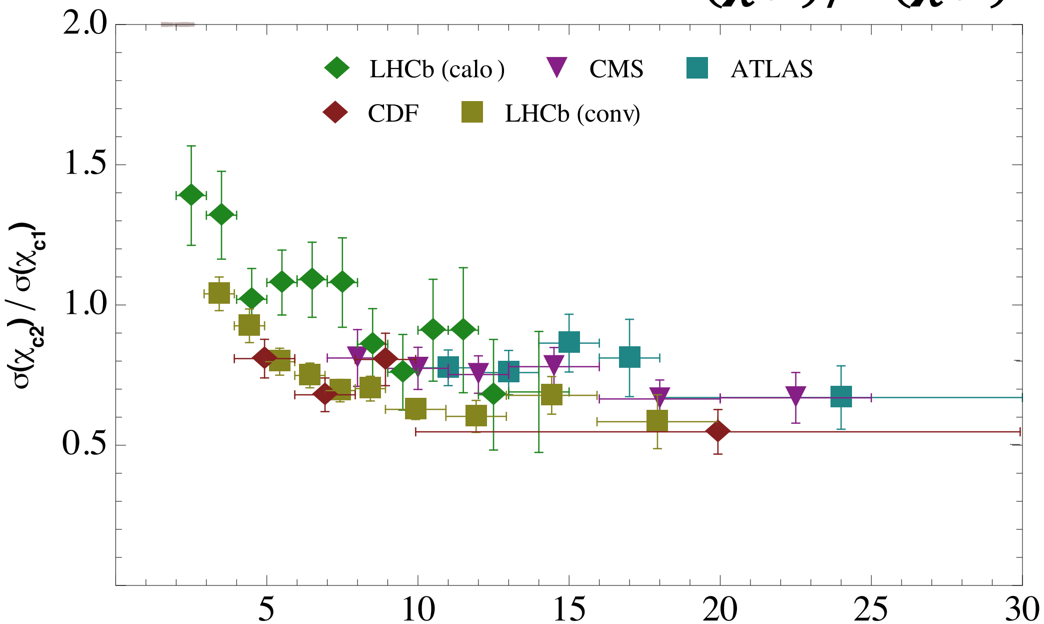
$\sigma(\chi_{b2})/\sigma(\chi_{b1}) \times B_2/B_1$



Relative production rate: data vs theory

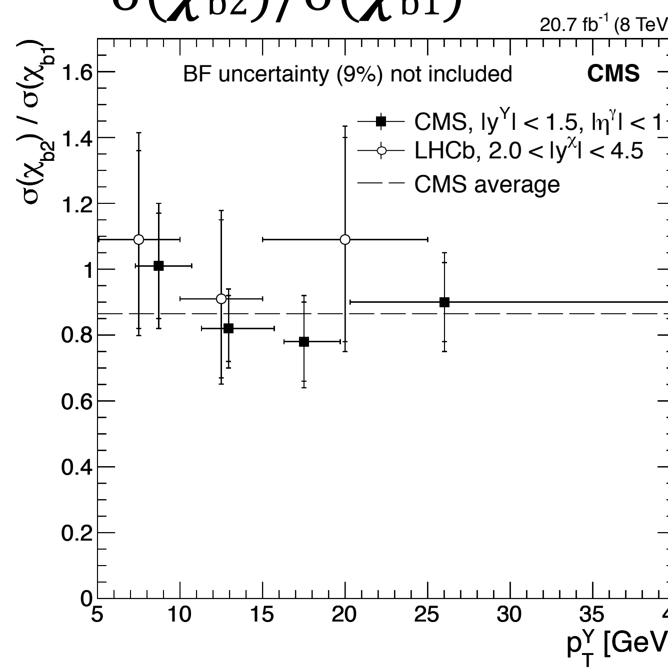
- Results compatible among experiments

$\sigma(\chi_{c2})/\sigma(\chi_{c1})$



Plot adapted from PRD 90 (2014) 074021

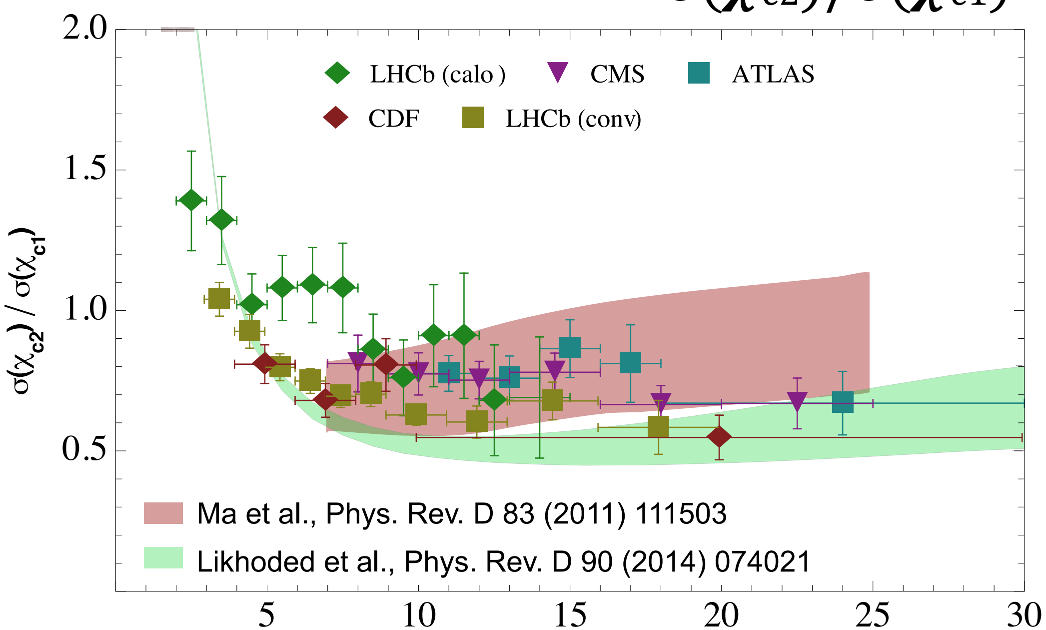
$\sigma(\chi_{b2})/\sigma(\chi_{b1})$



Relative production rate: data vs theory

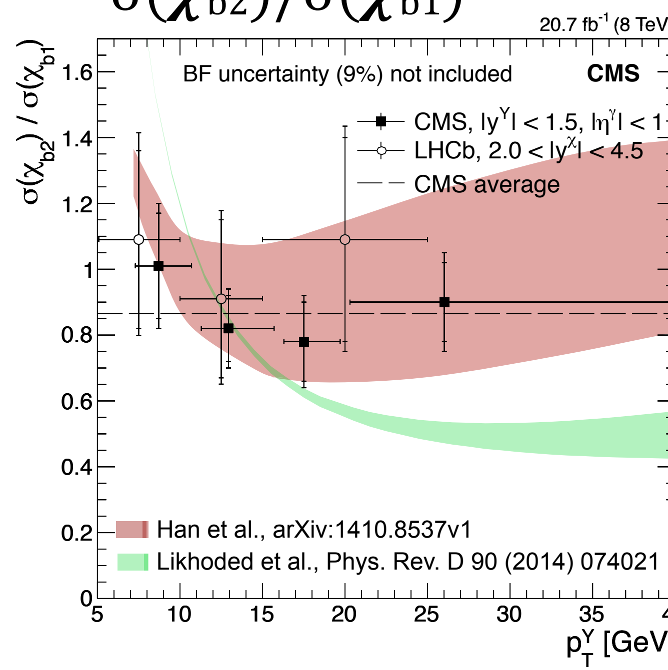
- Results compatible among experiments
- Measured χ_c ratio agrees with theory calculations
- χ_b ratio is well described by predictions from Han et al.

$\sigma(\chi_{c2})/\sigma(\chi_{c1})$



Plot adapted from PRD 90 (2014) 074021

$\sigma(\chi_{b2})/\sigma(\chi_{b1})$



Summary

- Cross sections and polarizations of five S-wave quarkonia were measured in pp collisions at $\sqrt{s}$ = 7 TeV
- None of the five S-wave states shows strong polarizations
- Relative production cross section ratios of prompt χ_{c2}/χ_{c1} and $\chi_{b2}(1P)/\chi_{b1}(1P)$ were measured

Many more quarkonium production analyses with 8 TeV data are still ongoing ...