Quarkonium production and polarization
in pp collisions with CMS

Introduction to quarkonium physics

Quarkonium measurements with CMS

A data-driven interpretation of the results

*Valentin Knünz**
(HEPHY Vienna)
on behalf of the CMS collaboration

* Supported by FWF grant P 24167-N16

The big picture in a nutshell

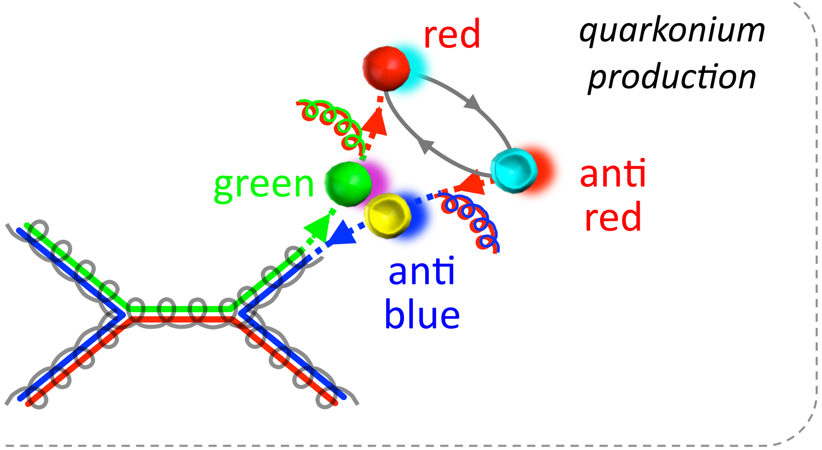
Hadron formation… a mystery within the SM;
“QCD is full of surprises and challenges” (J. Lykken)

Quarkonium production is an ideal probe to study hadron formation, part of the non-perturbative QCD sector → how do quarks combine into a bound state?

Quarkonia are bound states of a heavy quark and a it‘s antiquark ($c\bar{c}$, $b\bar{b}$) and exist in “families” of several states (colorless, neutral mesons)

Properties of QCD can be probed through several quarkonium prouction measurements, including
→ Production cross sections
→ Polarizations

ALMOST ALL THE VISIBLE MATTER IN THE UNIVERSE IS MADE OF HADRONS; THE HIGGS MECHANISM DEALS WITH ONLY 0.1% OF THE TOTAL MASS…



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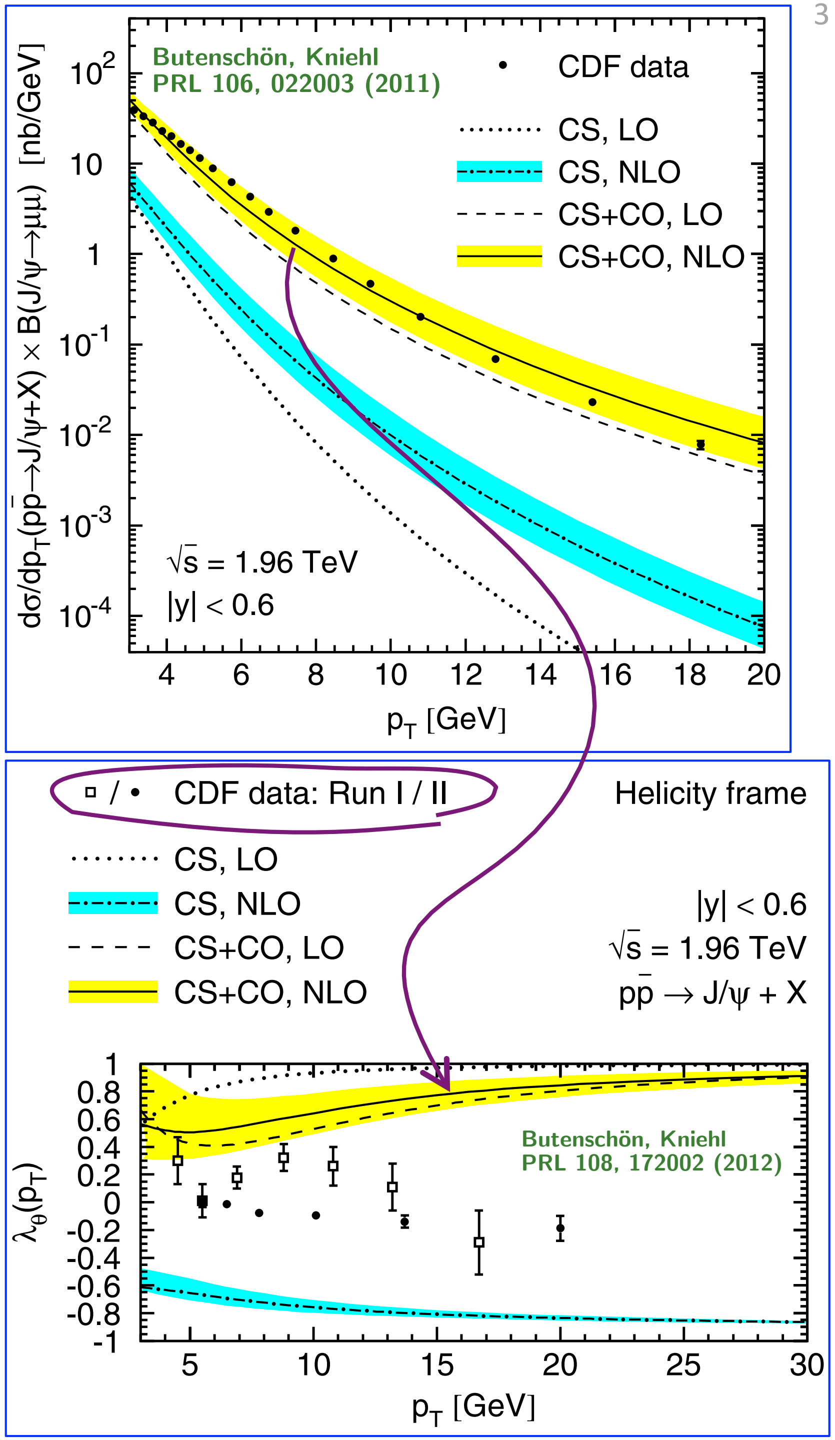
→ Polarizations

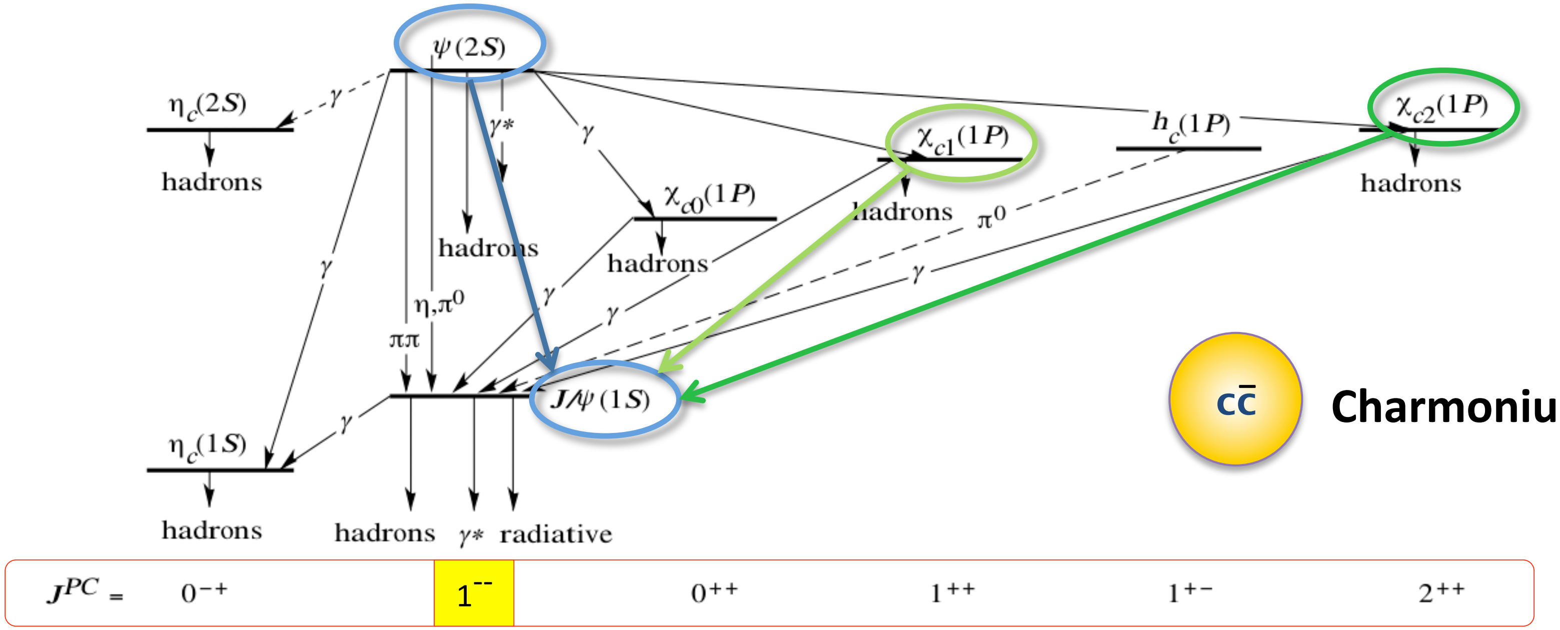
NRQCD calculations fit p_T-differential cross sections to extract long-distance matrix elements (LDMEs) and then predict the quarkonium polarization
→ “Quarkonium polarization puzzle”

The pre-LHC polarization measurements - affected by some inconsistencies - were left out of the LDME fits

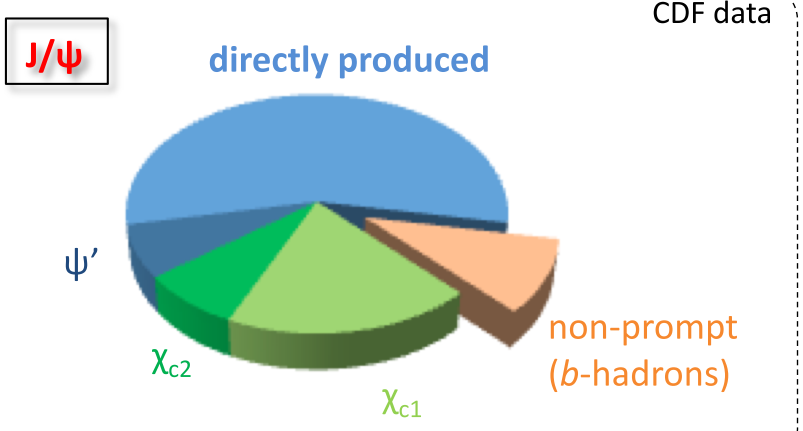
LHC cross sections and polarizations can provide significant improvements, due to more reliable analysis methods and higher p_T reach

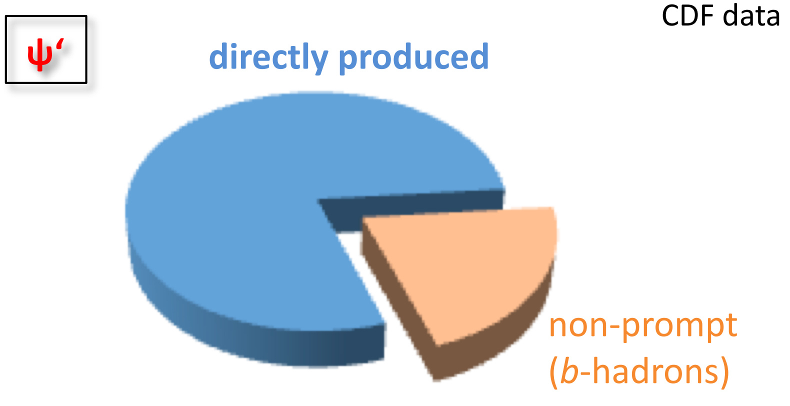


Quarkonium spectra & Feed-down considerations



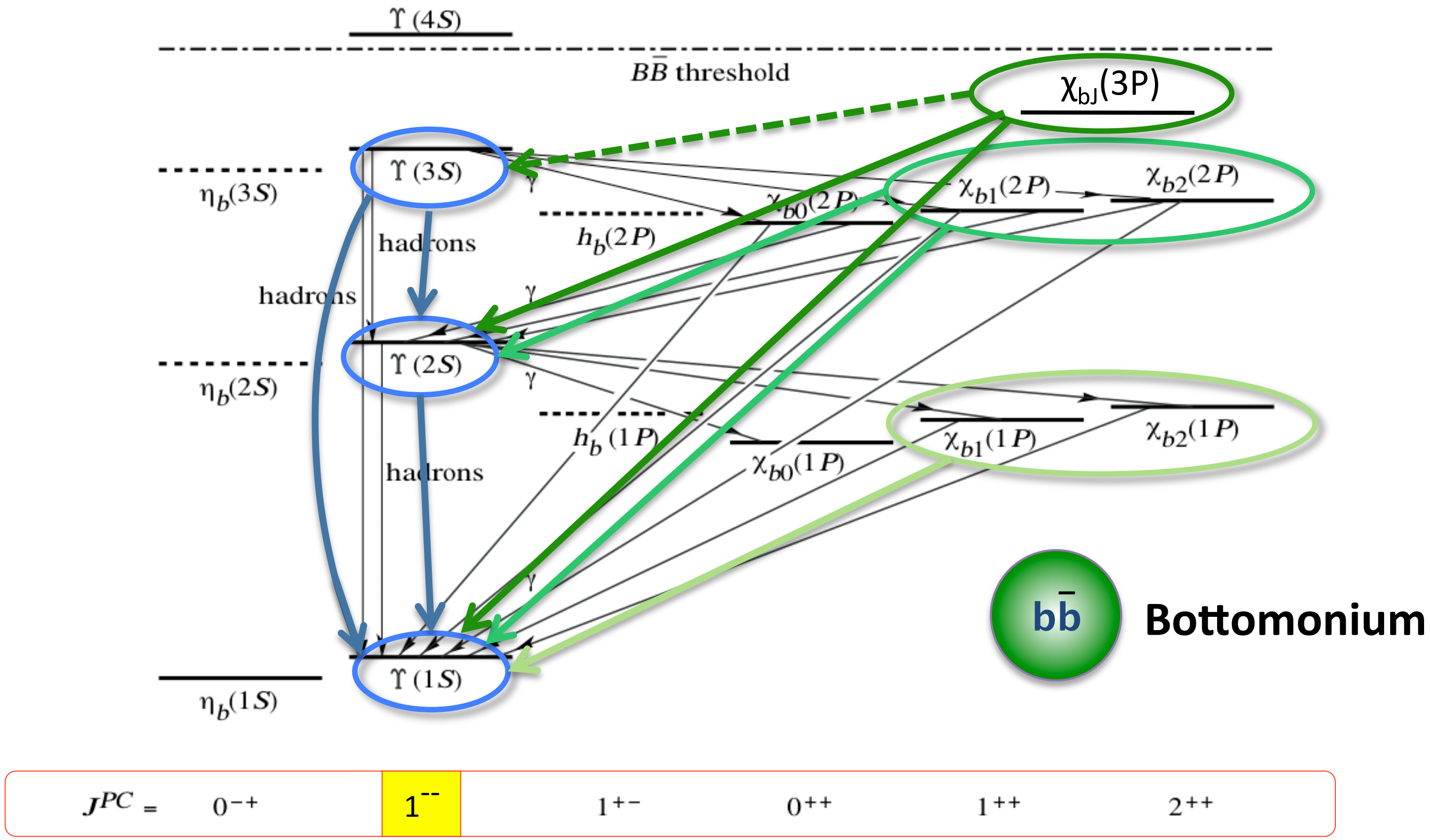
$c\bar{c}$ **Charmonium**

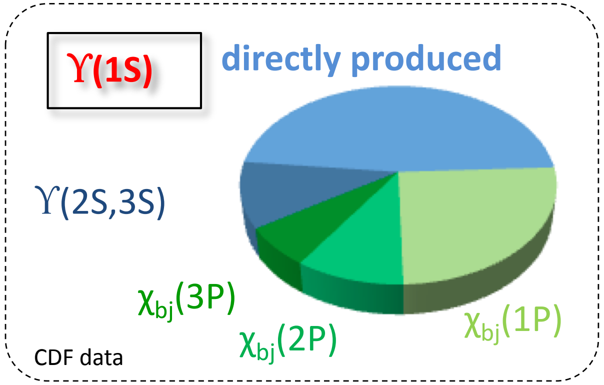




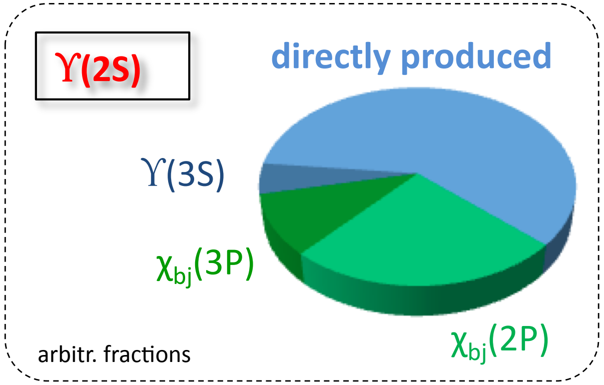
Prompt contribution = Direct production + charmonium feed-down

Quarkonium spectra & Feed-down considerations

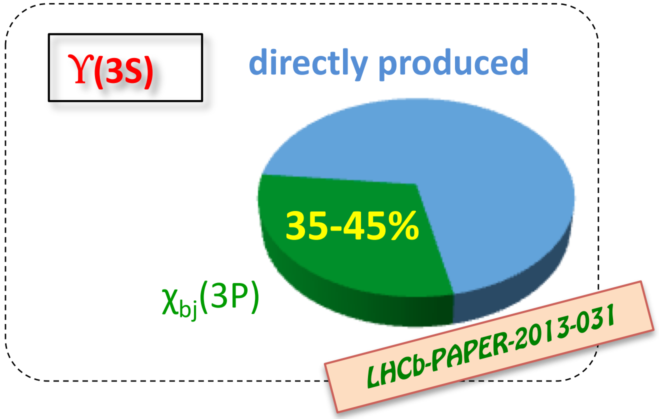




CDF data

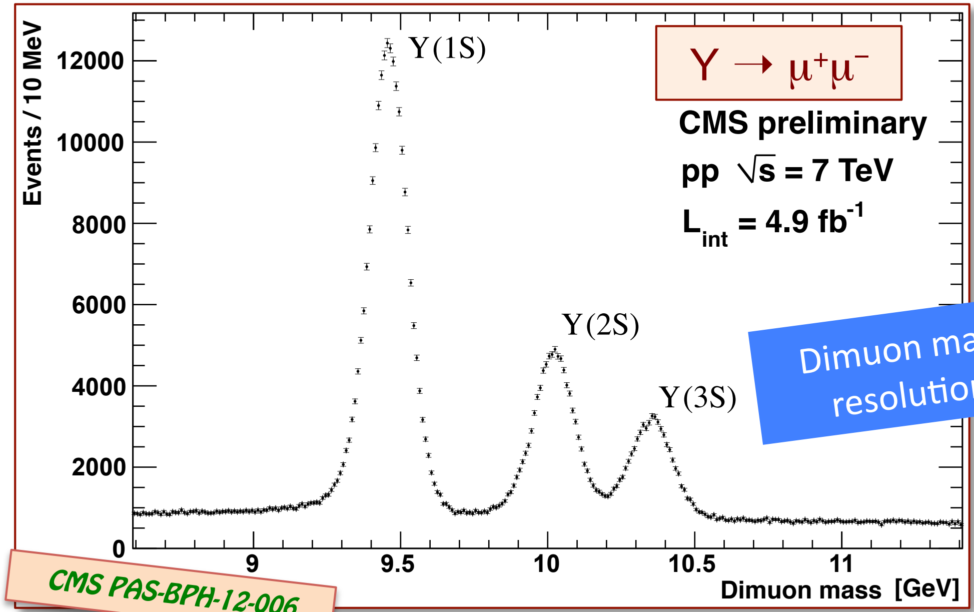


arbitr. fractions



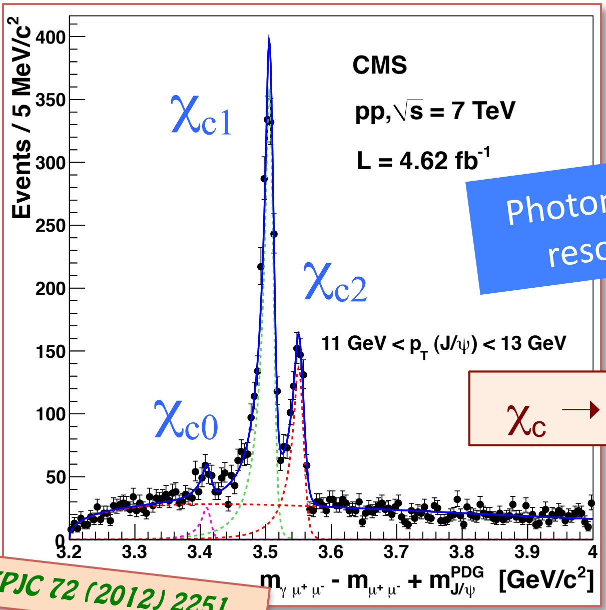
LHCb-PAPER-2013-031

CMS: excellent performance in quarkonium reconstruction



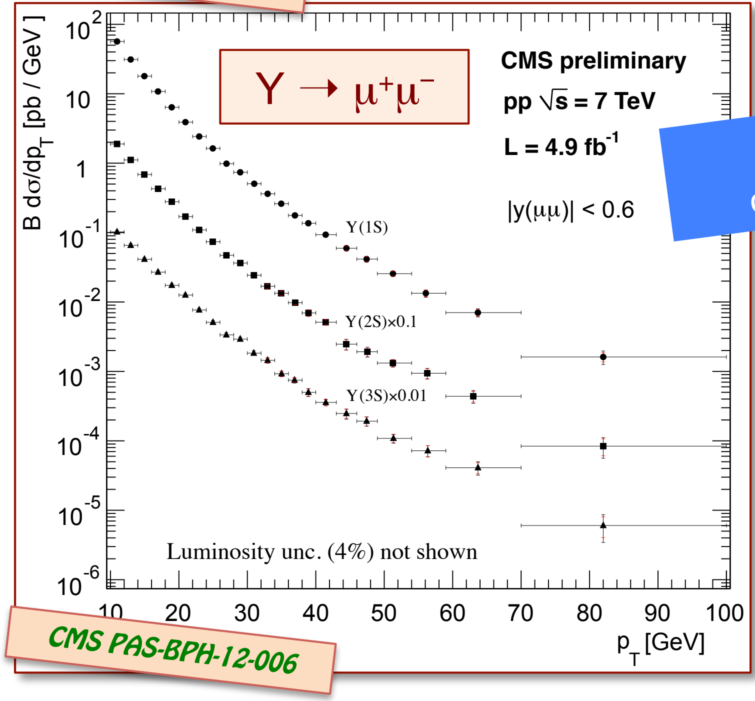
Dimuon mass resolution

CMS PAS-BPH-12-006



Photon energy resolution

EPJC 72 (2012) 2251



High-p_T coverage

CMS PAS-BPH-12-006

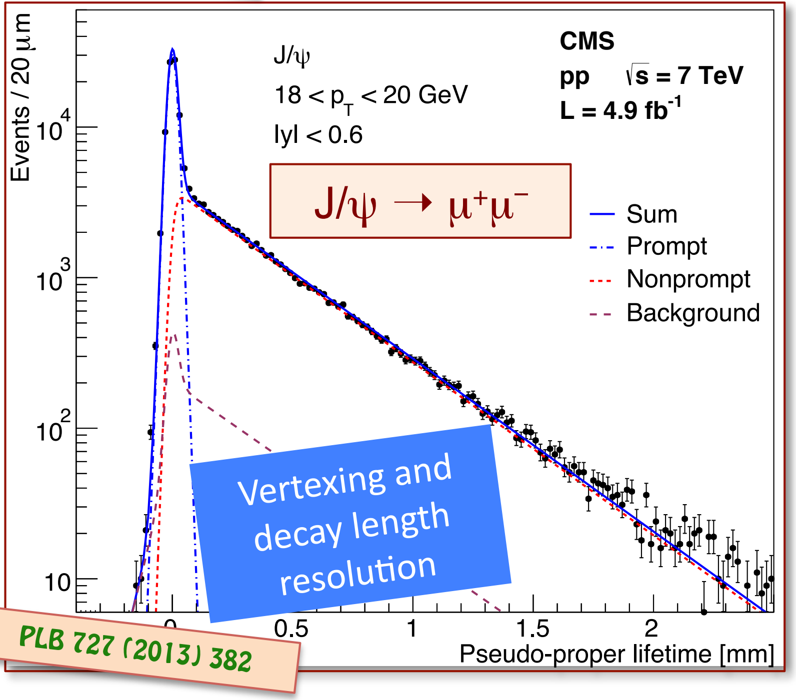
Huge silicon tracker

Very strong field

Broad acceptance

Flexible trigger

Powerful DAQ



Vertexing and decay length resolution

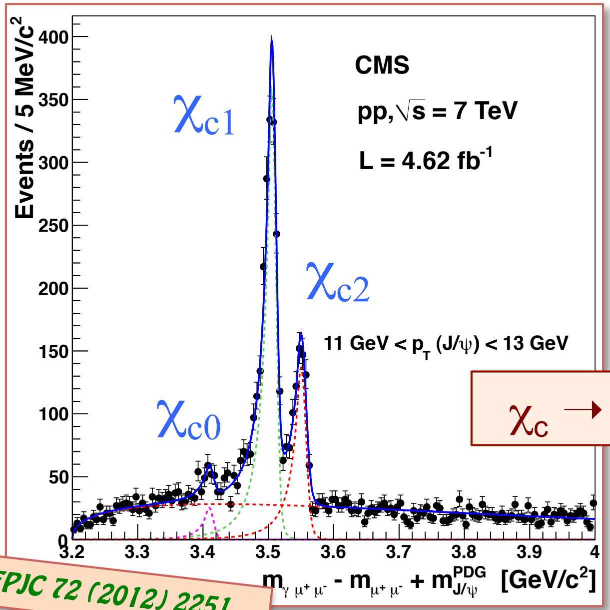
PLB 727 (2013) 382

CMS: S-wave cross sections and P-wave ratios

The Υ(nS) differential cross sections were measured in the p_T range 10–100 GeV for $|y| < 0.6$

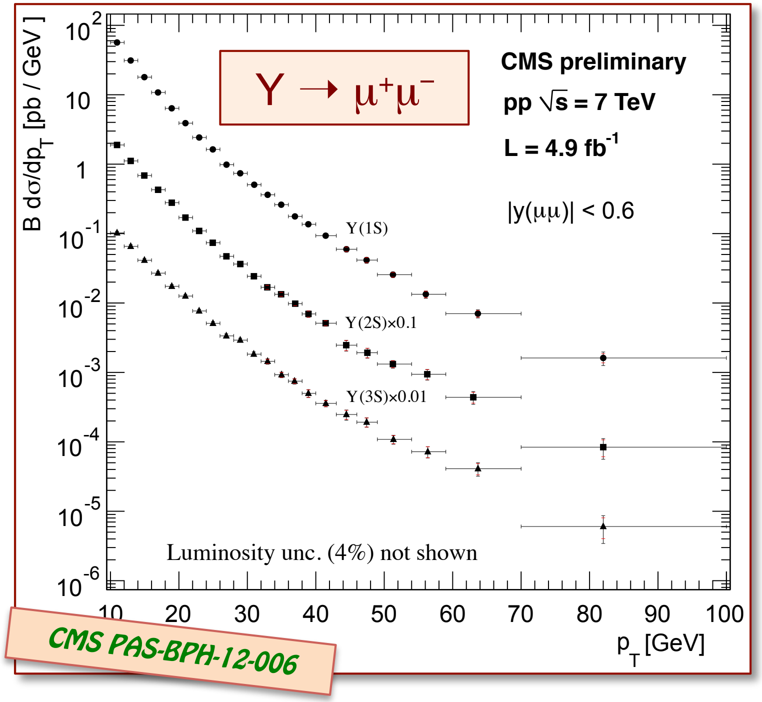
Acceptance corrections depend on polarization; using the measured polarizations reduced the biggest uncertainty of previous measurements

The three S states show similar patterns; P-wave feed-down contribution does not seem to significantly affect the p_T trends



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

EPJC 72 (2012) 2251



$\Upsilon \rightarrow \mu^+\mu^-$

CMS PAS-BPH-12-006

The photons emitted in χ decays have ~1% probability to convert and be reconstructed in the silicon tracker

The e^+e^- tracking provides ≈5 MeV mass resolution, crucial to resolve the two states

Current CMS results limited to measurements of the cross-section ratio of the χ_{c2} / χ_{c1} and χ_{b2}(1P) / χ_{b1}(1P) systems

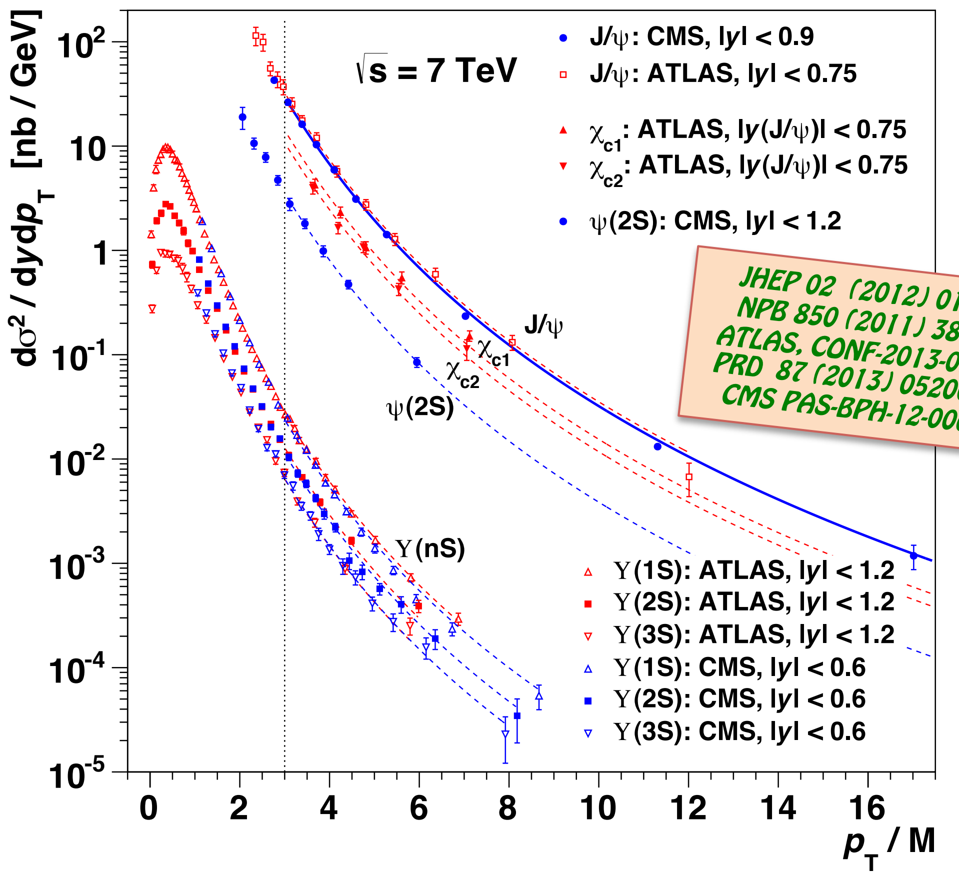
Efficiencies cancel almost completely in the χ_2 / χ_1 cross-section ratios

LHC: Quarkonium cross sections

Differential cross sections at mid-rapidity, for 7 different quarkonium states, measured by CMS and ATLAS, as function of $p_T/M^{(*)}$

Shapes are well described by a single empirical power-law (for pT/M>3), common to all considered results (5 S-wave and 2 P-wave states, with highly varying feed-down characteristics)

This strongly suggests quarkonium production is dominated by 1 single production mechanism, common to all S and P-wave quarkonia



JHEP 02 (2012) 011
NPB 850 (2011) 387
ATLAS, CONF-2013-095
PRD 87 (2013) 052004
CMS PAS-BPH-12-006

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

solid: fit to CMS J/ψ data
dashed: replicas with adjusted normalizations

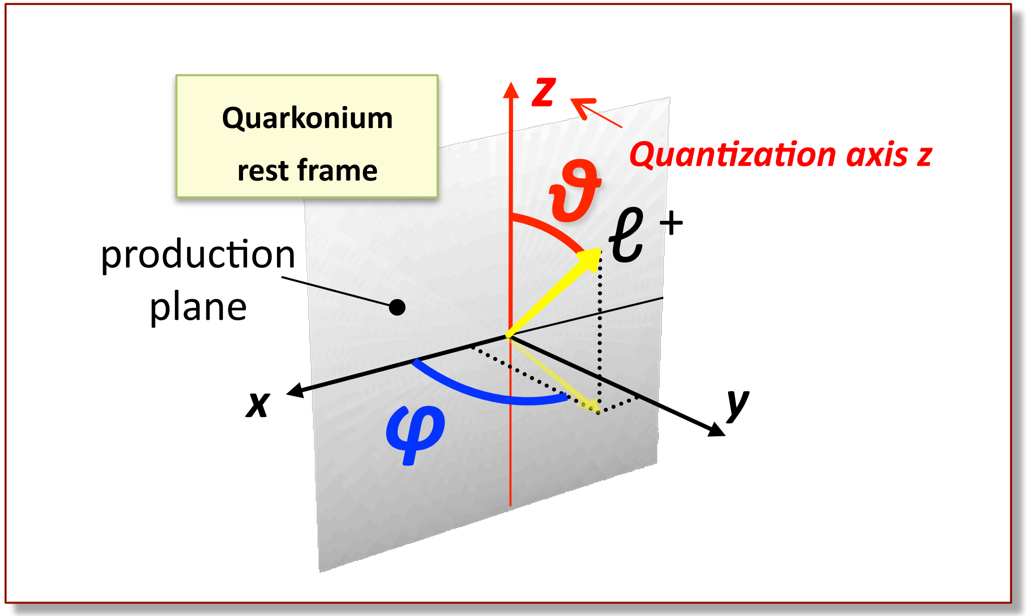
$^{(*)}p_T$ is mass-rescaled to equalize the kinematic effects of different average parton momenta and phase spaces

CMS: Quarkonium polarization analyses

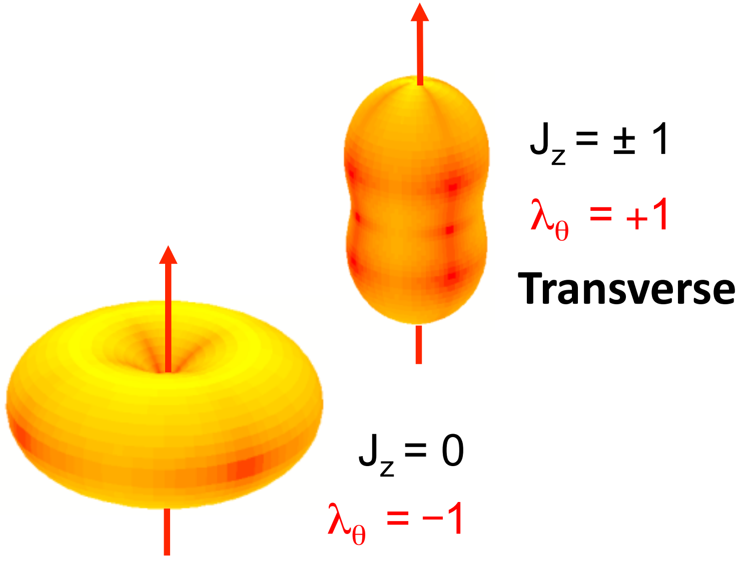
EPJC C69 (2010) 657

Quarkonium polarizations are measured from the angular decay distributions in dimuon decays

We measure the full angular distribution and report the λ_θ, λ_ϕ and $\lambda_{\theta\phi}$ polarization parameters (in 3 frames) for five S states, vs. p_T and in several $|y|$ ranges.
We further measure the frame-invariant parameter $\tilde{\lambda}$



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



$J_z = \pm 1$

$\lambda_\theta = +1$

Transverse

$J_z = 0$

$\lambda_\theta = -1$

Longitudinal

Frame-invariant:

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

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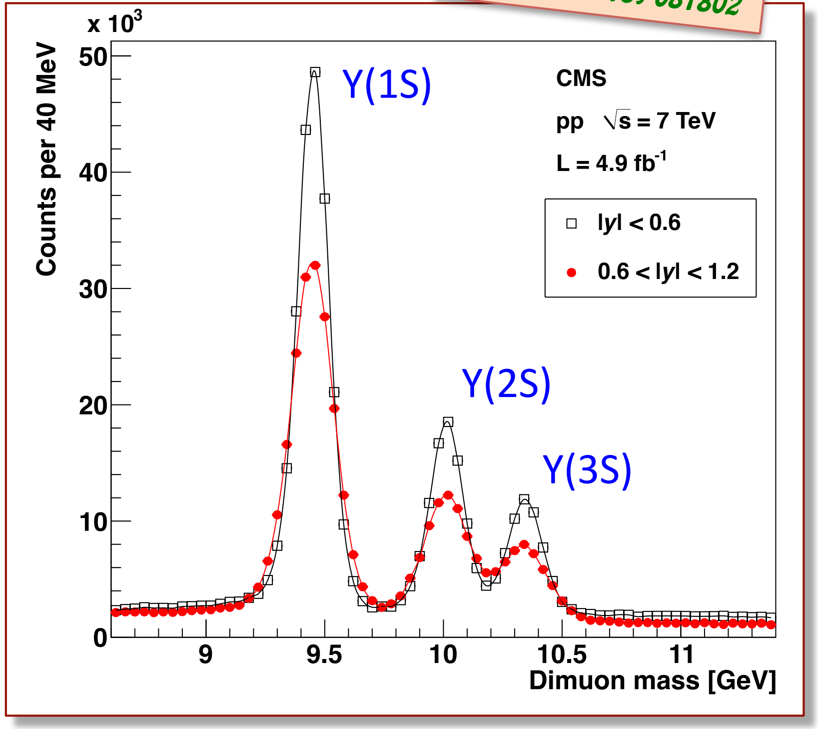
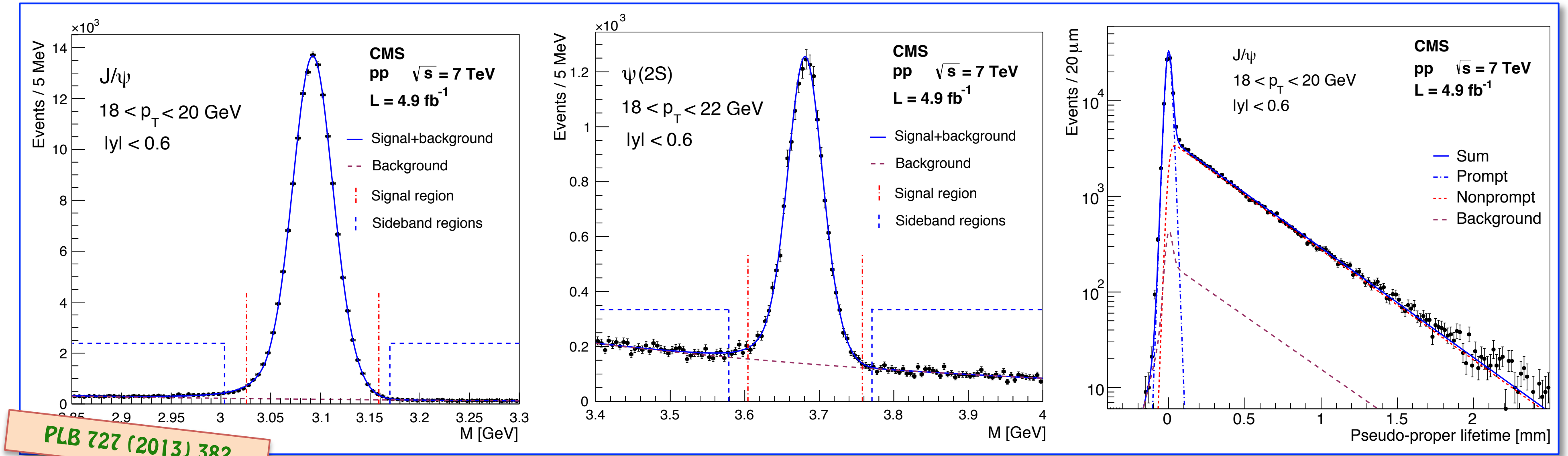
The underlying continuum background is removed using the invariant mass distribution;
and the non-prompt charmonia using the decay length

PRL 110 (2013) 081802





PLB 727 (2013) 382

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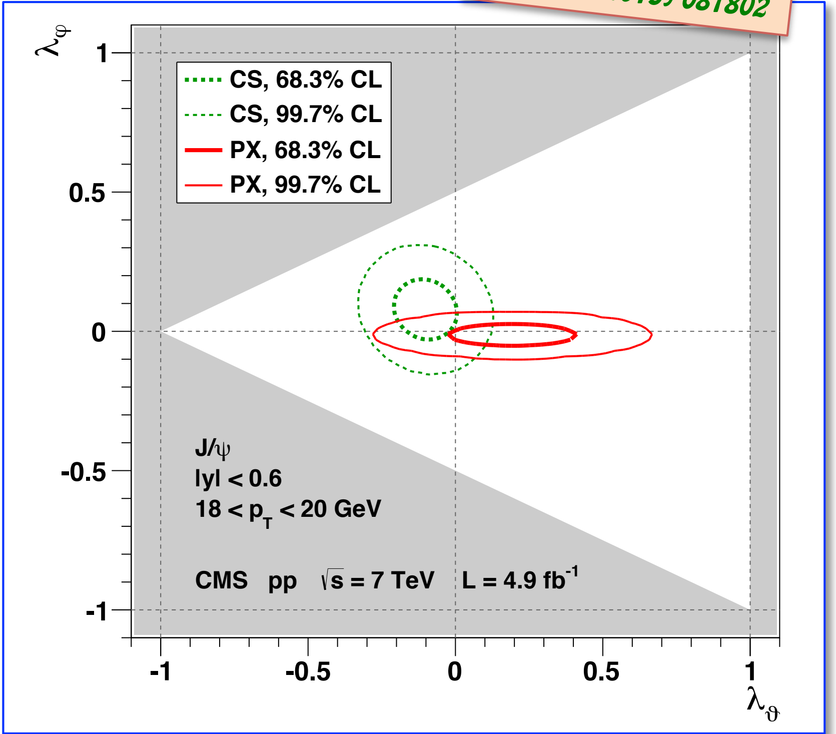
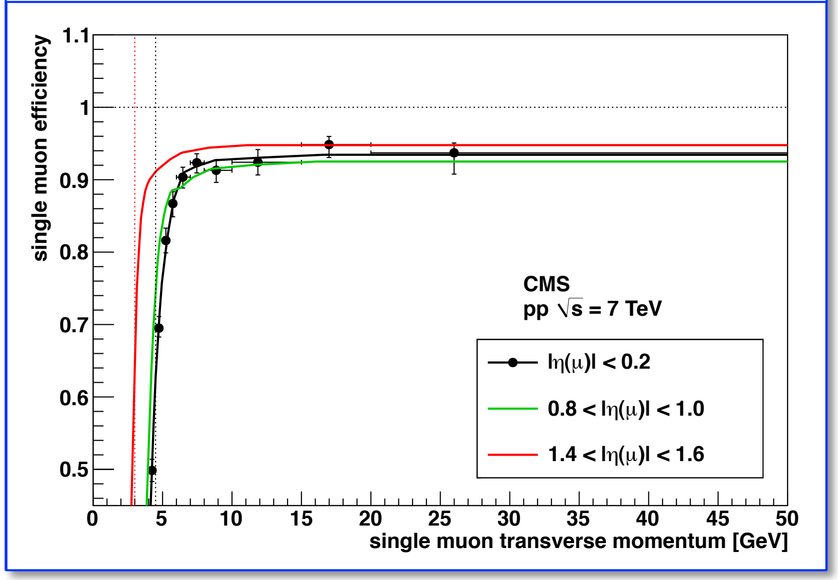
We calculate the multi-dimensional posterior probability density as result of the analysis

Main experimental challenges:
✧ reliable background modeling (sidebands)
✧ precise mapping of (di)muon efficiencies (T&P)

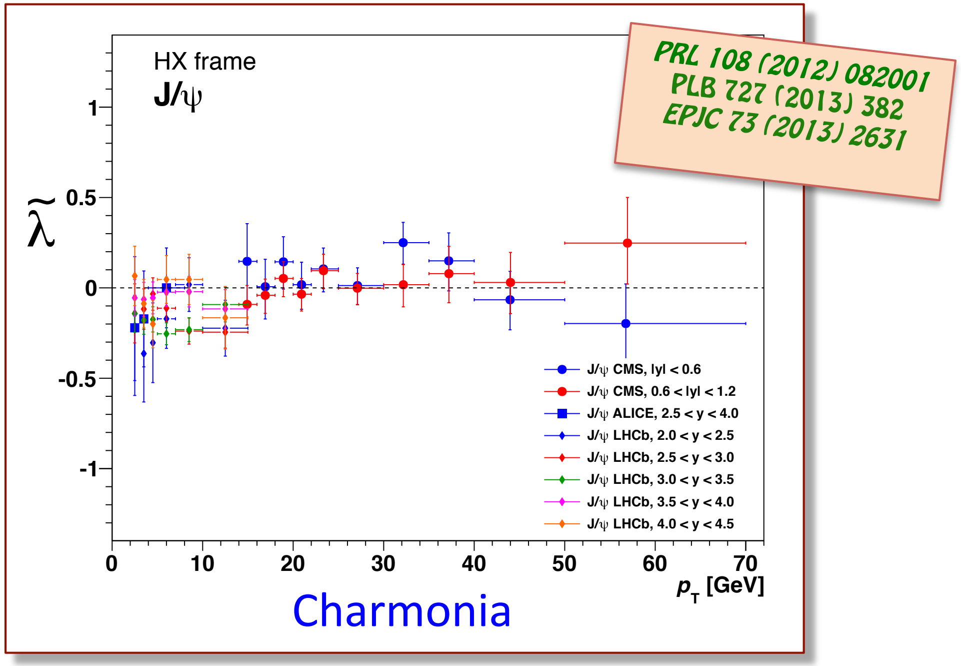
Uncertainties are dominated by systematics at low p_T and by statistics at high p_T

PRL 110 (2013) 081802





LHC: Quarkonium polarization results



PRL 108 (2012) 082001
PLB 727 (2013) 382
EPJC 73 (2013) 2631

Good consistency between CMS, LHCb, ALICE and CDF. Previous experimental inconsistencies overcome due to novel and more robust analysis techniques (*EPJC C69 (2010) 657*).

No strong polarizations seen in any of the measurements

→ no dependencies on p_T or rapidity
→ no strong changes between S-states with very different P-wave feed-down characteristics
→ no evident differences between charmonium and bottomonium states

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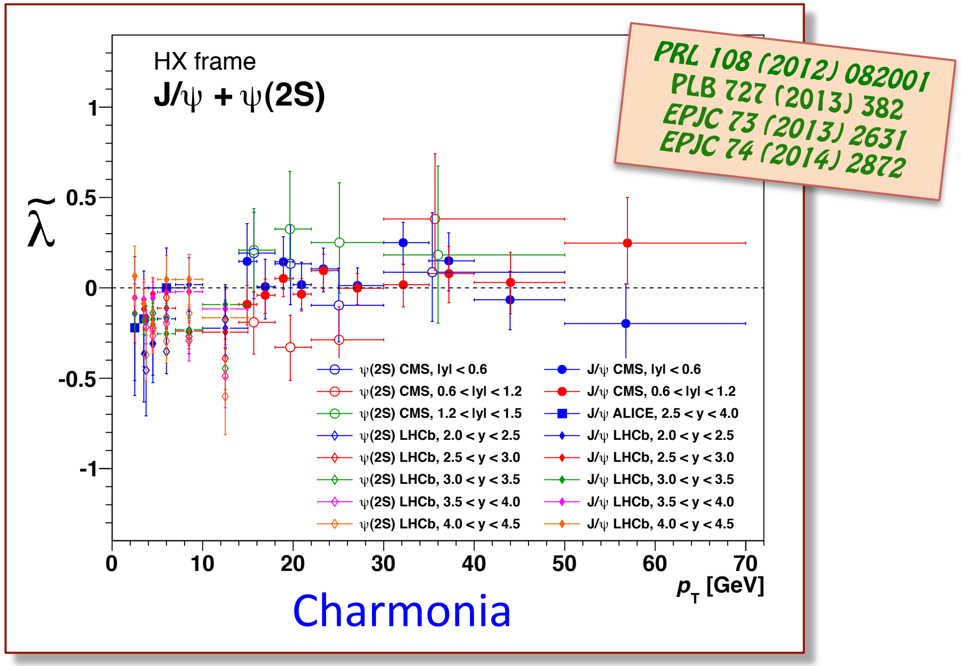

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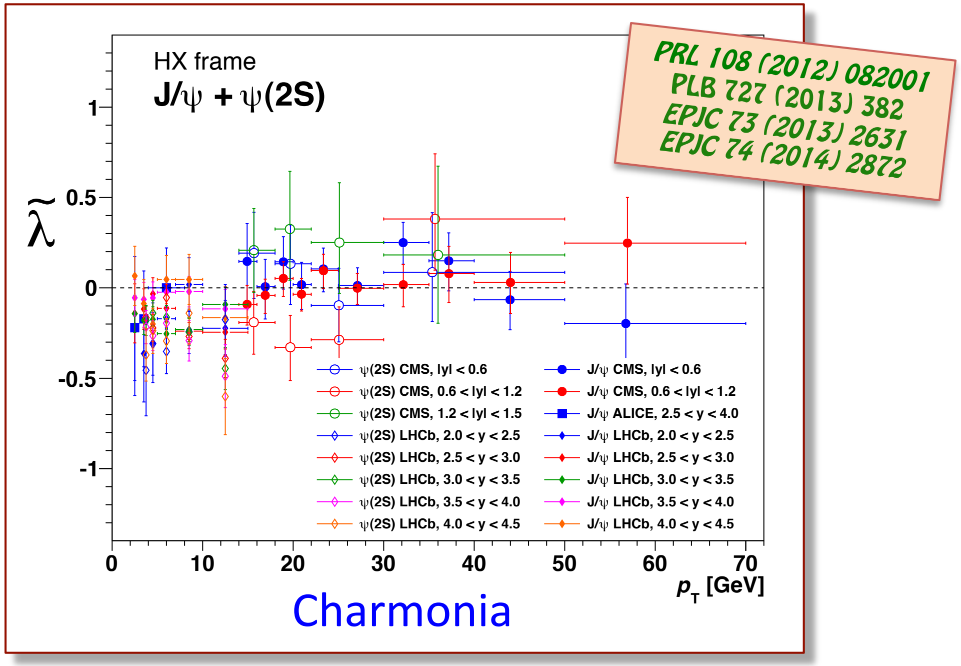

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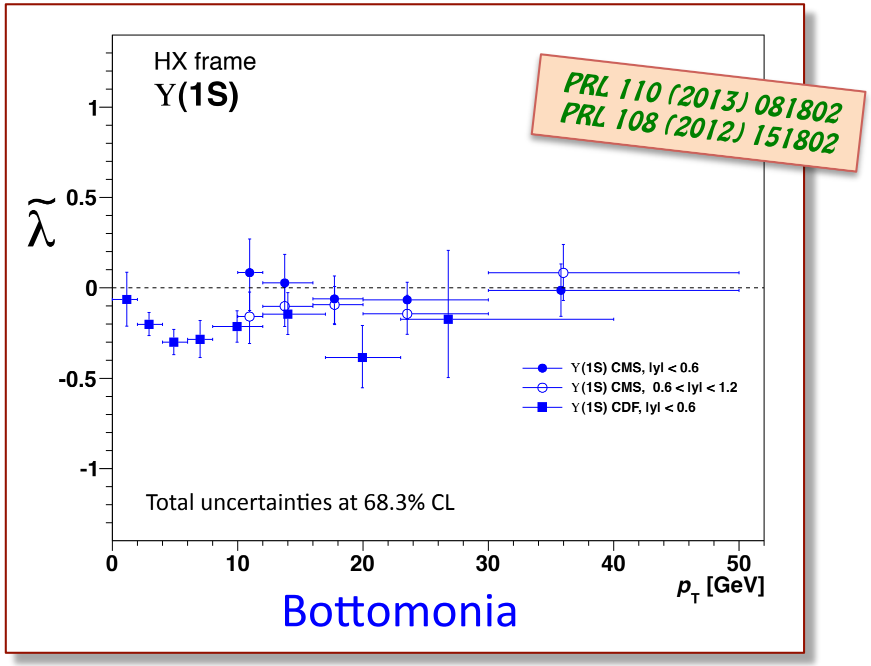

PRL 110 (2013) 081802
PRL 108 (2012) 151802

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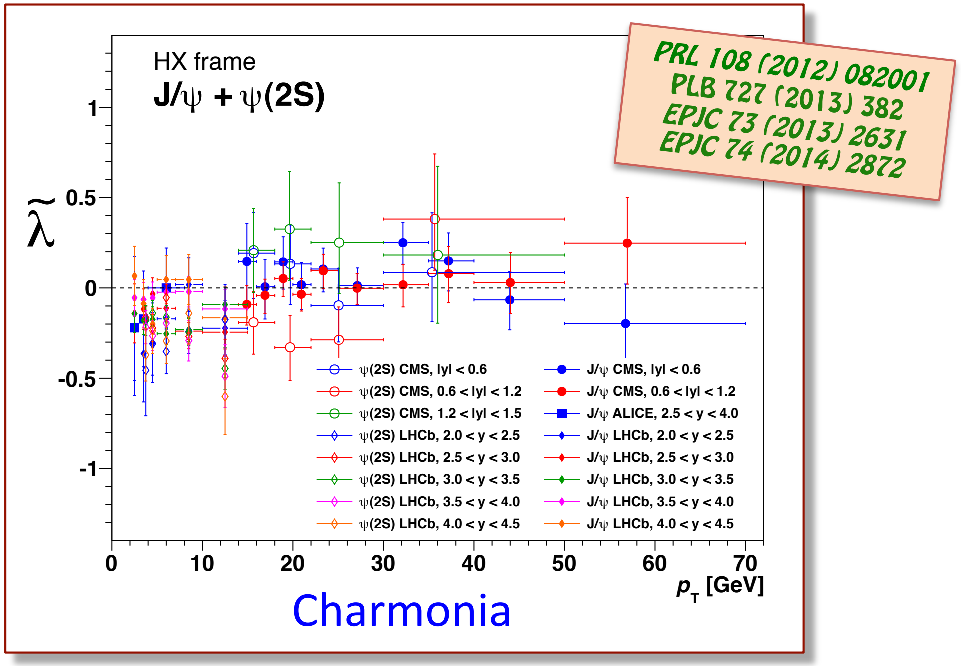

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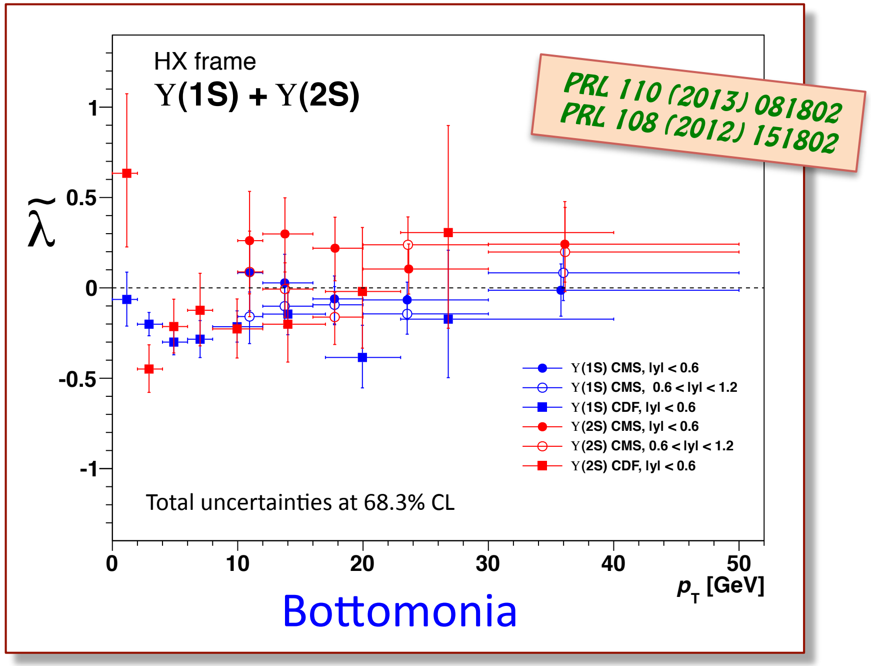

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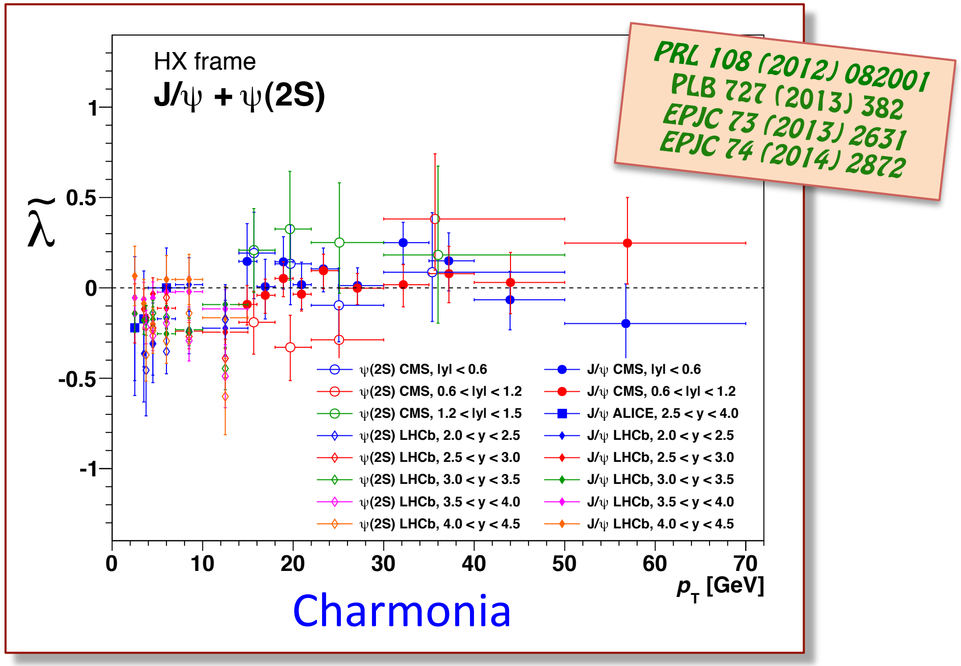

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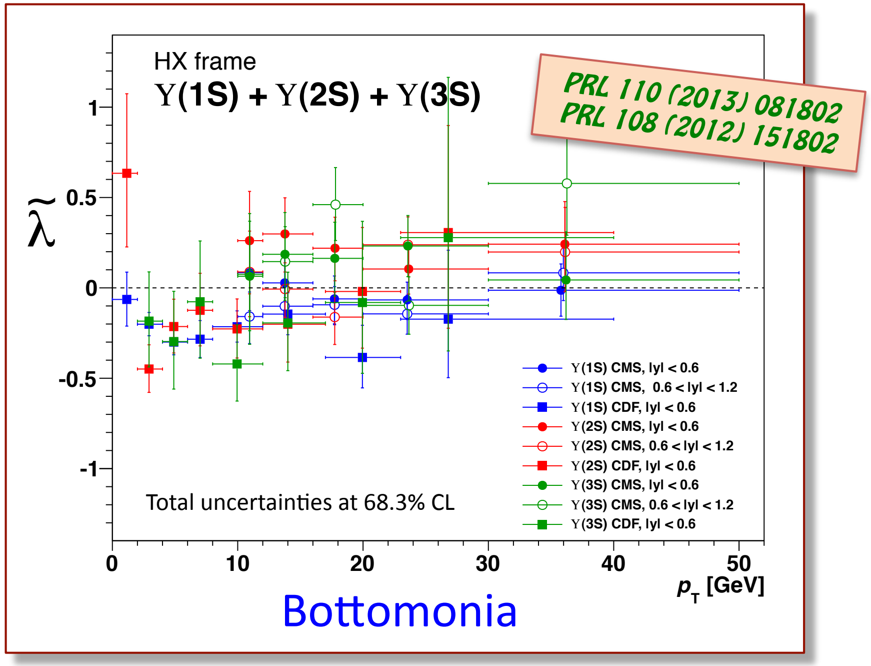

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The NRQCD factorization approach

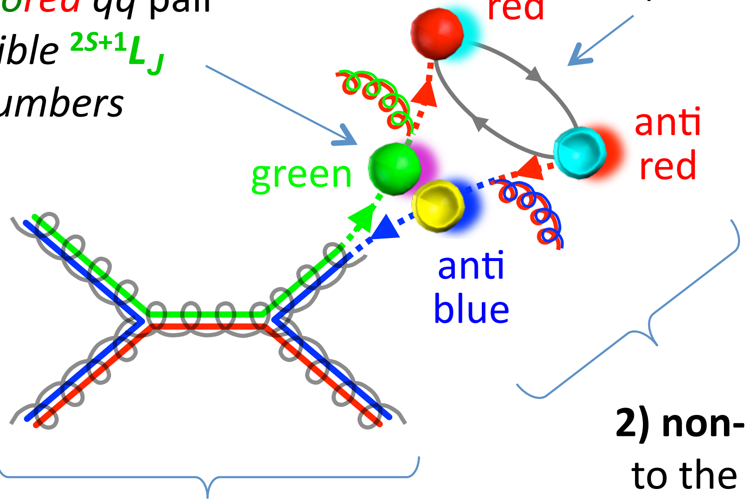
NRQCD is an effective field theory that factorizes quarkonium production in two steps:

1) production of the initial quark-antiquark pair (perturbative QCD)
2) hadronization of the quark pair into a bound quarkonium state (non-perturbative QCD)

$$\sigma(\mathcal{Q}) = \sum_n \sigma[q\bar{q}(n)]\,\langle \mathcal{O}^{\mathcal{Q}}(n)\rangle$$

$n = {}^{2S+1}L_J^{[C]}$, C = 1,8

Quantum numbers of the heavy quark pair
S, L, J = spin, orbital and total ang. momentum



possibly *colored* $q\bar{q}$ pair
of any possible $^{2S+1}L_J$
quantum numbers

quarkonium ($\mathcal{Q}$)

1) perturbative phase

2) non-perturbative evolution
to the observed bound state
Quantum numbers change!

Cartoon by P. Faccioli

NRQCD predicts the existence of intermediate color-octet (CO) states in nature, that subsequently evolve into physical color-singlet (CS) quarkonia by non-perturbative emission of soft gluons.

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Quantum numbers of the heavy quark pair
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Short-distance coefficients (SDCs)

- Cross section of partonic processes to form $Q\bar{Q}$ in state $n \otimes$ PDF
- Process-dependent functions of kinematics
- Can be calculated perturbatively (expansion in α_s)

Long-distance matrix elements (LDMEs)

- Probability of $Q\bar{Q}$ in state n to form quarkonium state $\mathcal{Q}$
- Universal constants (independent of kinematics)
- Determined from fits to experimental data

The LDMEs should follow a hierarchy in powers of *v*, the relative velocity of the quark pair in the quarkonium system → Non-relativistic approximation (v^2~0.3 for the ψ and ~0.1 for the ϒ):

→ Truncation of v-expansion for S-wave states

→ NRQCD includes 4 terms (intermediate states):

CS term ${}^3S_1^{[1]}$ (same n as $\mathcal{Q}$)

CO terms: ${}^1S_0^{[8]}$, ${}^3S_1^{[8]}$ and ${}^3P_J^{[8]}$

Every term has a specific polarization:

${}^3S_1^{[1]} \rightarrow \lambda_\theta \approx -0.9$ (longitudinal)

${}^1S_0^{[8]} \rightarrow \lambda_\theta = 0$ (isotropic)

${}^3S_1^{[8]} \rightarrow \lambda_\theta \approx +1$ (transverse)

${}^3P_J^{[8]} \rightarrow \lambda_\theta >> +1$ (“hyper-transverse“)

@NLO, approximations,
HX frame

CMS data vs. NLO NRQCD: J/ψ

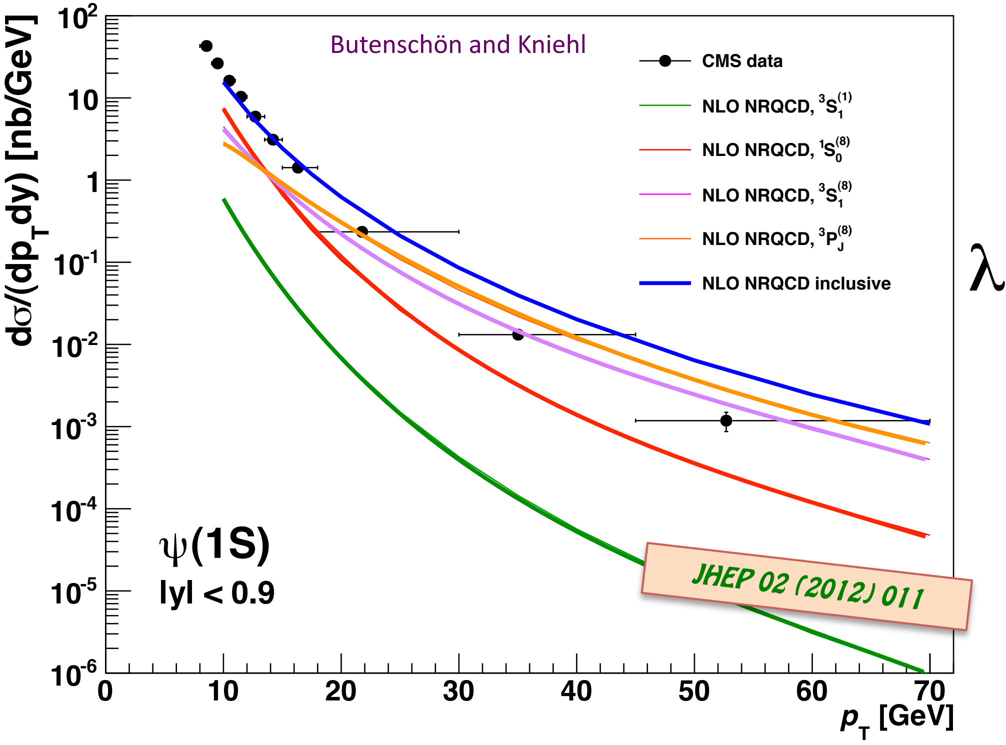
PRL 108 (2012) 172002
+ private communication

Butenschön and Kniehl use hadro- and photo-production data, excluding polarization results, to fit the color octet LDMEs; feed-down decays are not accounted for

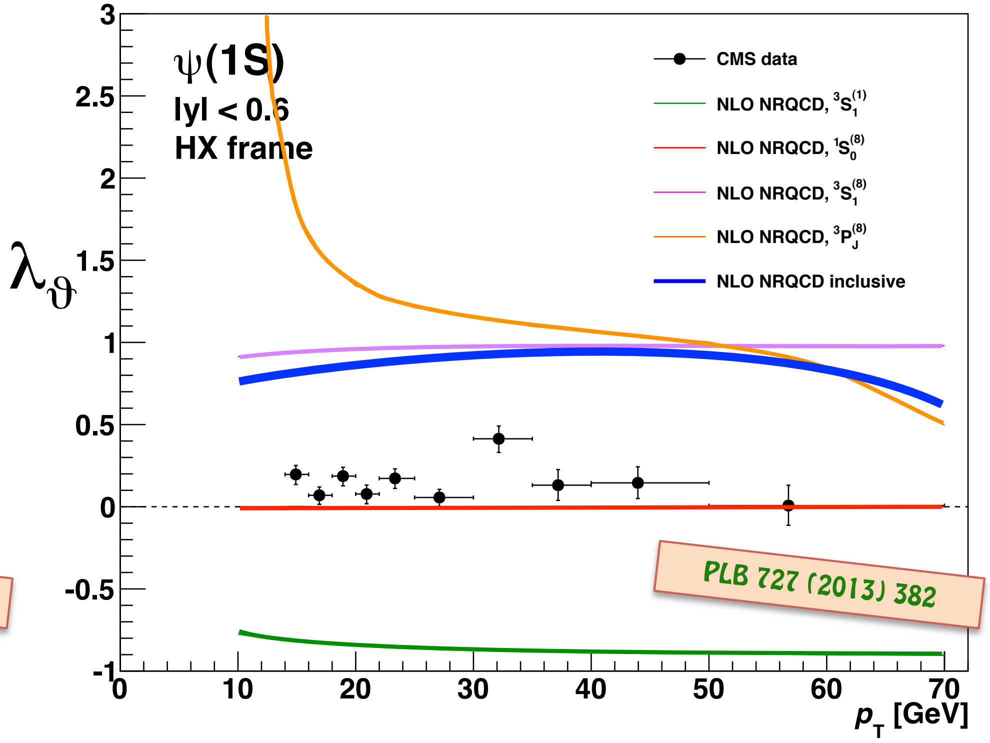
$O(^3S_1^{[1]}) = 1.32$ GeV^3
$O(^1S_0^{[8]}) = 0.0497$ GeV^3
$O(^3S_1^{[8]}) = 0.00224$ GeV^3
$O(^3P_J^{[8]}) = -0.0161$ GeV^5

The $^3S_1$ and ^3P_J octet terms dominate $d\sigma/dp_T$ at high p_T
→ transverse polarization is predicted

This prediction fails to describe the CMS measurements



JHEP 02 (2012) 011



PLB 727 (2013) 382

CMS data vs. NLO NRQCD: ψ(2S)

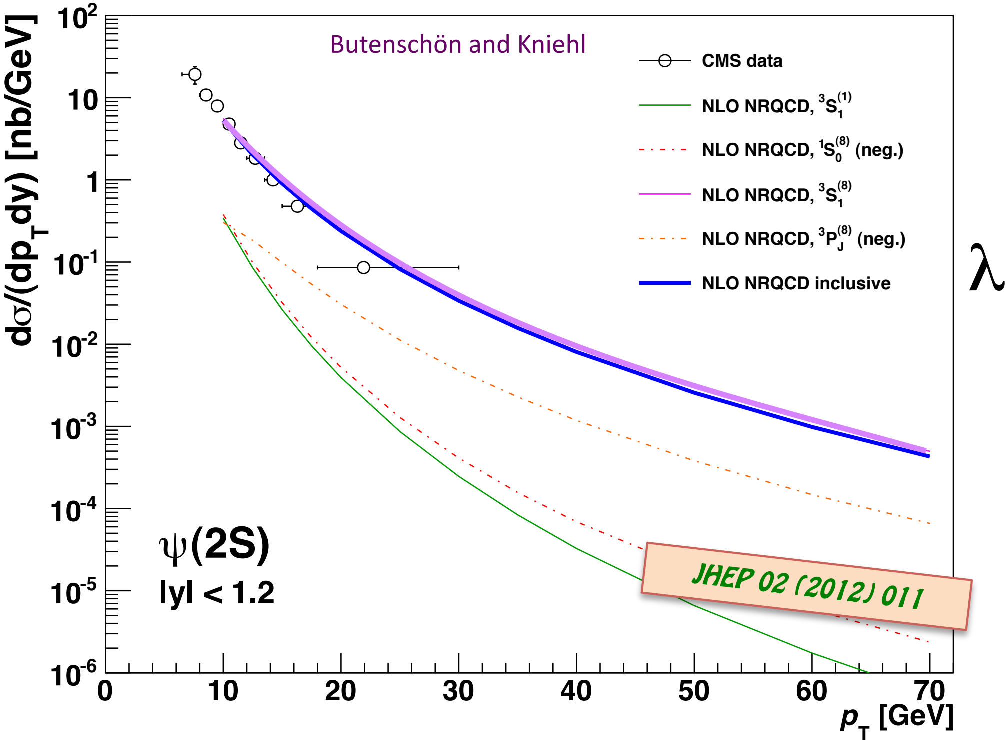
PRL 108 (2012) 172002
+ private communication

Butenschön and Kniehl use hadro- and photo-production data, excluding polarization results, to fit the color octet LDMEs;
ψ(2S) is the only S-wave quarkonium unaffected by feed-down decays

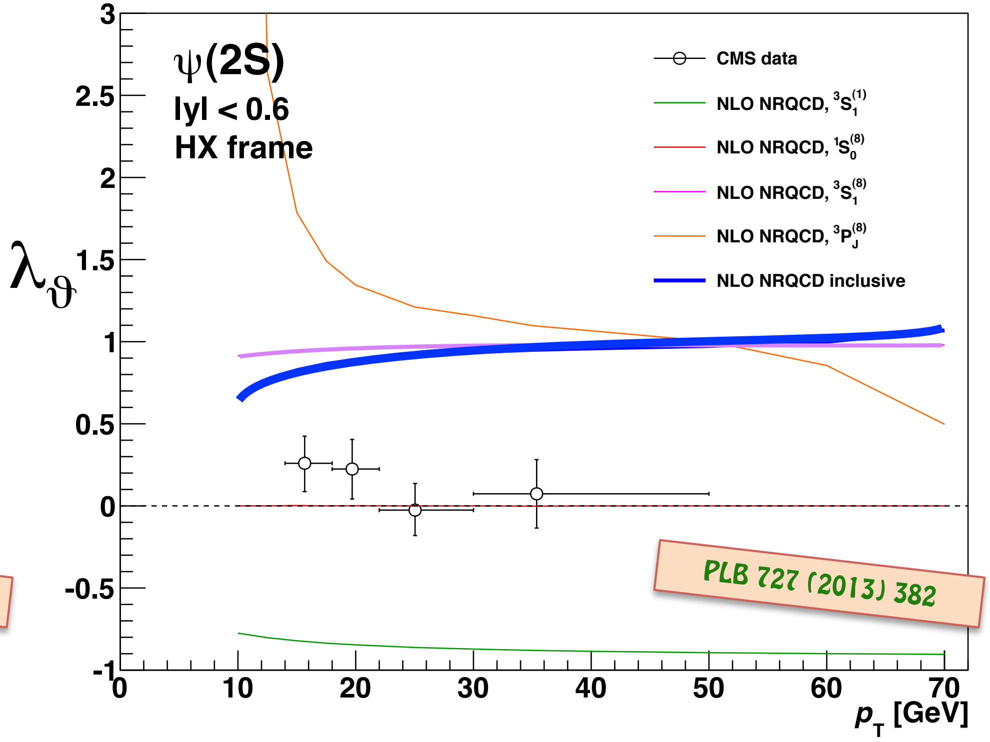
$O(^3S_1^{[1]}) = 0.76\ \mathrm{GeV}^3$
$O(^1S_0^{[8]}) = -0.00247\ \mathrm{GeV}^3$
$O(^3S_1^{[8]}) = 0.00280\ \mathrm{GeV}^3$
$O(^3P_J^{[8]}) = 0.00168\ \mathrm{GeV}^5$

The $^3S_1$ octet term dominates $d\sigma/dp_T$ at high p_T
→ transverse polarization is predicted

This prediction fails to describe the CMS measurements
The $^1S_0^{[8]}$ and $^3P_J^{[8]}$ terms have *negative* SDC x LDME



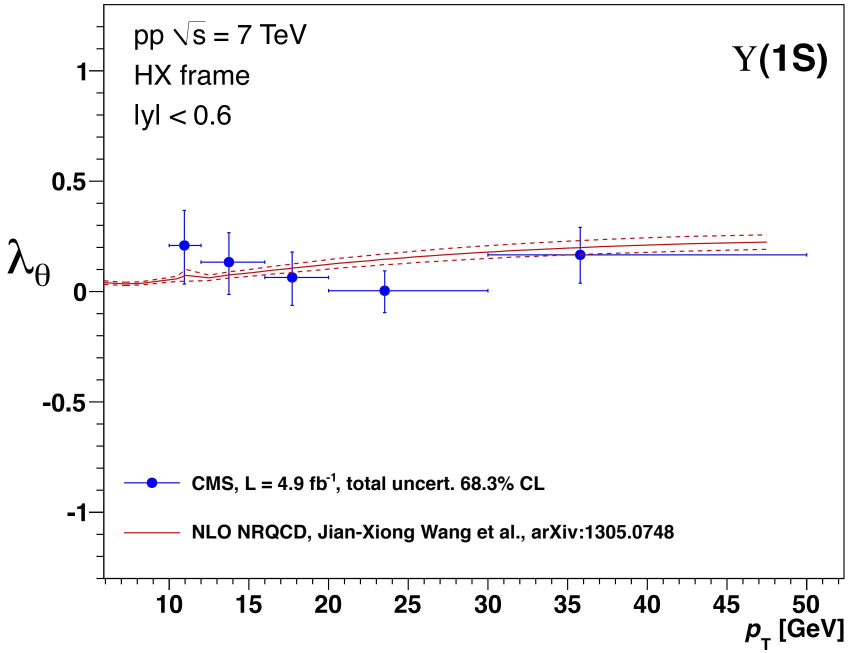
JHEP 02 (2012) 011



PLB 727 (2013) 382

CMS data vs. NLO NRQCD: Υ(nS)

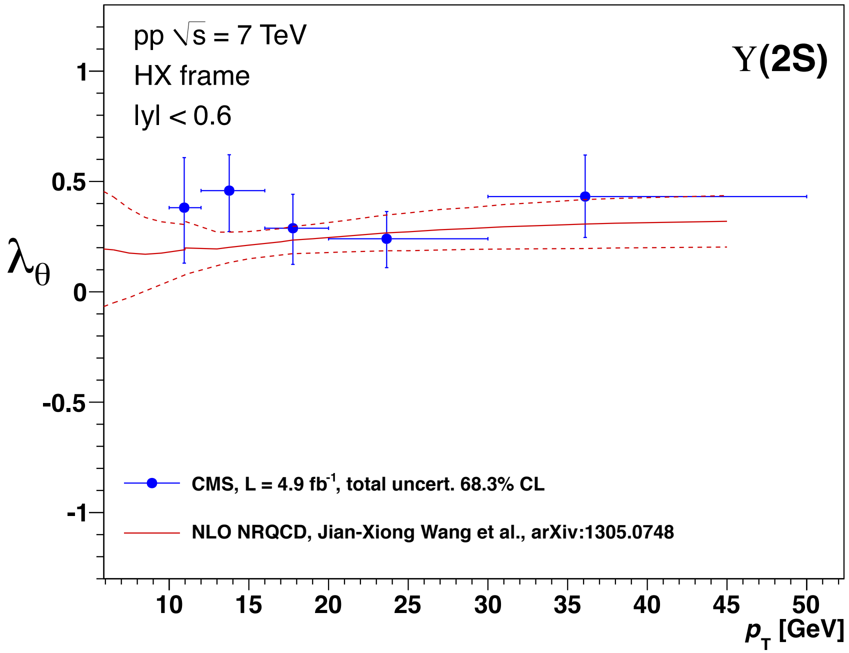
PRL 112 (2014) 032001

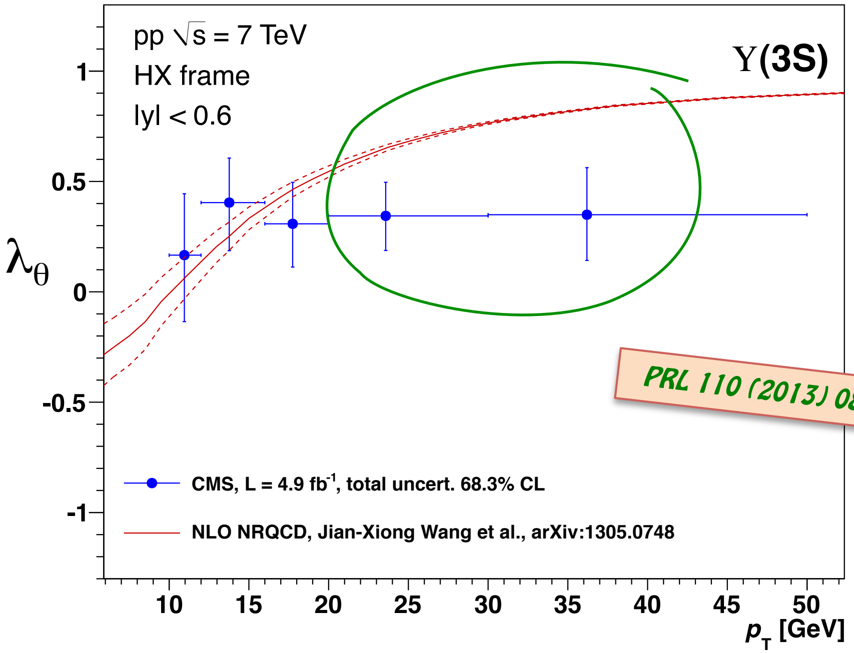


Gong et al. use hadroproduction data, including the CMS Υ(nS) polarization results, to fit the CO LDMEs

The 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

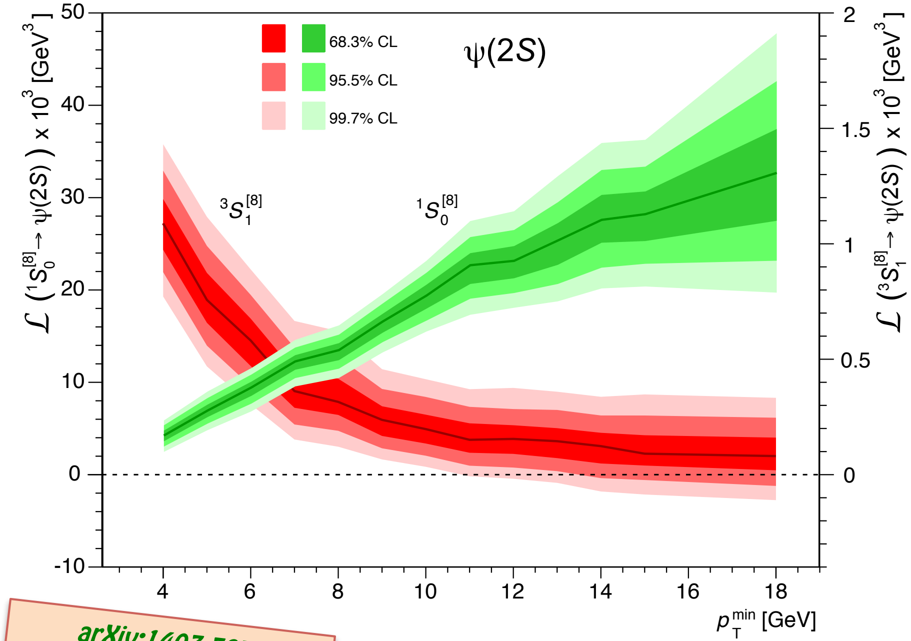
The *unknown* feed-down fractions and polarizations of the P states give the model the freedom needed to fit the Υ(1S) and Υ(2S) polarizations



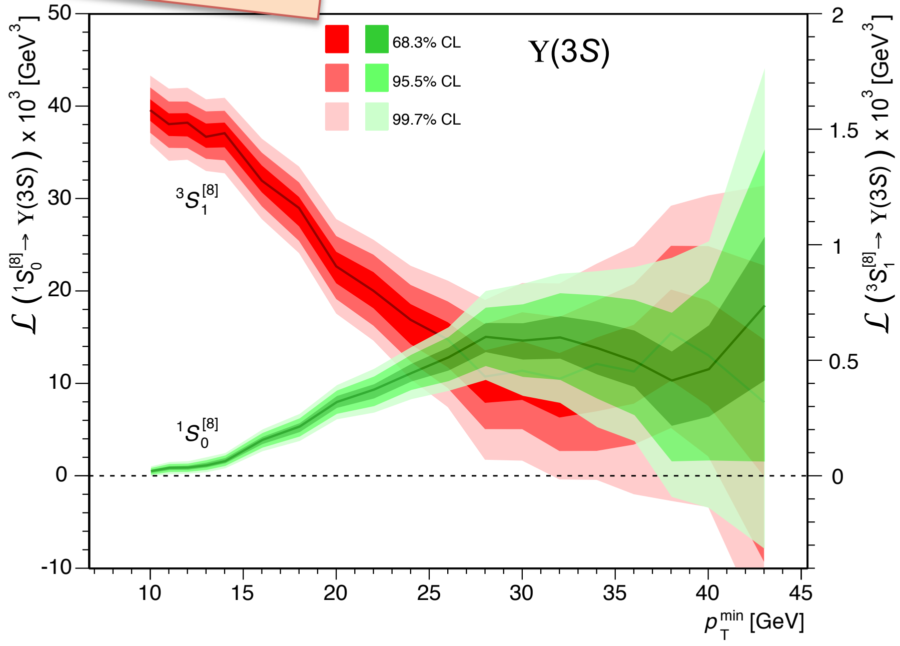


PRL 110 (2013) 081802

LHC data vs. NLO NRQCD: ψ(2S) + ϒ(3S)



arXiv:1403.3970



New analysis by P. Faccioli et al. takes a data-driven approach, moving polarization to the center of the study

Considers all LHC ψ(2S) and ϒ(3S) cross section and polarization results - assumed to be feed-down free (χ_b(3P) feed-down to ϒ(3S) is neglected)

$^3P_J^{[8]}$ CO component has negligible impact

Experimental and theoretical uncertainties taken into account within the fit procedure, which also recalculates acceptance corrections for each calculated polarization
→ First internally consistent NRQCD analysis

Kinematic scan, removing low p_T data reveals that NRQCD@NLO gives a very good description of all data, when restricting the fit to data with $p_T/M > 3$
→ Domain of validity of NLO NRQCD?

Unpolarized $^1S_0^{[8]}$ CO component dominates quarkonium production

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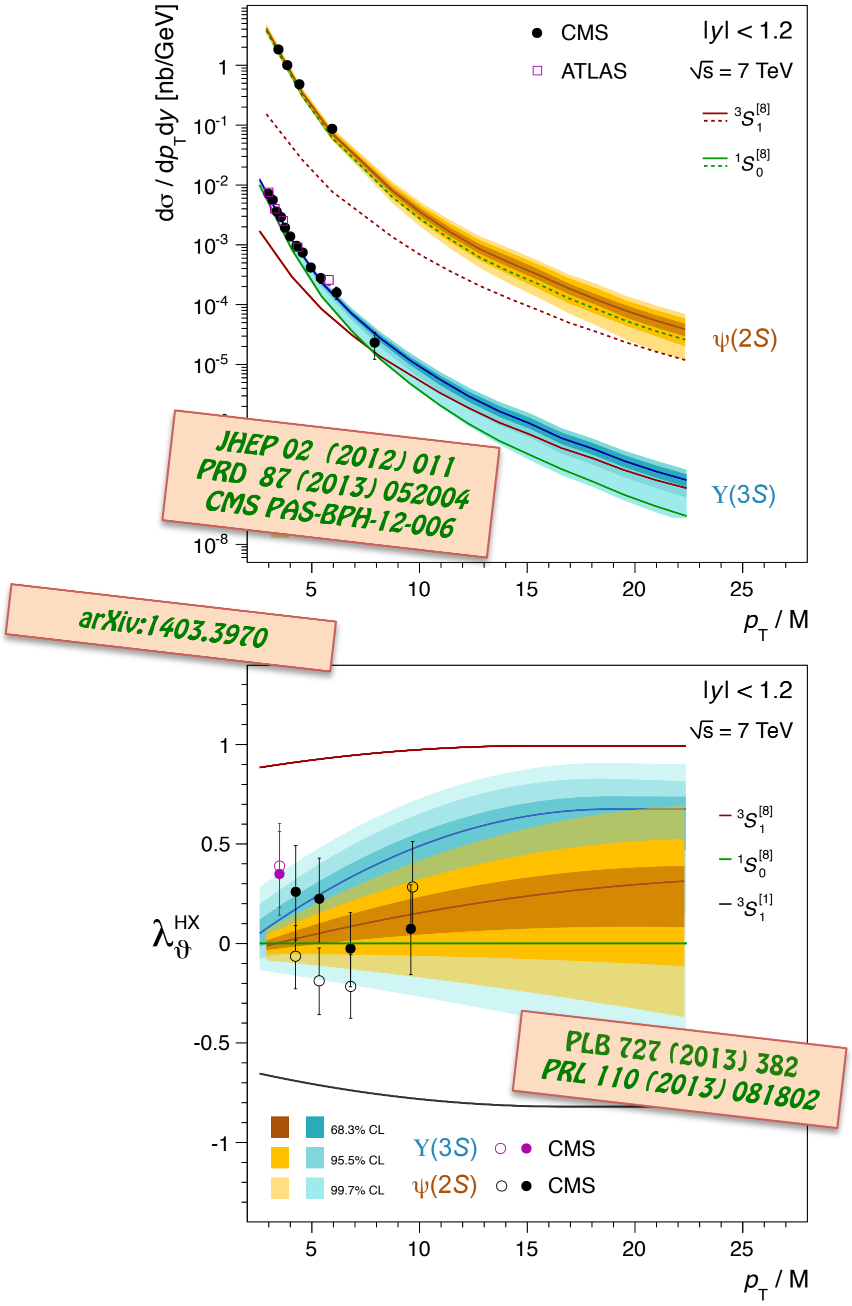

JHEP 02 (2012) 011
PRD 87 (2013) 052004
CMS PAS-BPH-12-006

arXiv:1403.3970

PLB 727 (2013) 382
PRL 110 (2013) 081802

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Summary and outlook

CMS measured cross sections and polarizations of five S-wave quarkonia in pp collisions at $\sqrt{s} = 7$ TeV

The χ_{c2} / χ_{c1} and $\chi_{b2}(1P) / \chi_{b1}(1P)$ cross-section ratios have also been measured

The quality of the (consistent) LHC measurements allows us to give priority to the polarization results:
= more reliable theory understanding than cross sections, and down to lower p_T values
= much better at resolving the several possible (singlet and octet) “pre-resonant states”

→ The absence of strong polarizations in *all* five S-wave states strongly suggests that
quarkonium production dominantly proceeds through the $^1S_0^{[8]}$ transition

Several more results will come from ongoing studies of 2012 data

The LHC run 2 will allow us to further extend the p_T reach of quarkonium measurements

Further reading

J/ψ and $\psi(2S)$ production cross sections
CMS, EPJC 71 (2011) 1575 [L = 314 nb^{-1}, 7 TeV]
CMS, JHEP 02 (2012) 011 [L = 37 pb^{-1}, 7 TeV]
ATLAS, NPB 850 (2011) 387 [2.3 pb^{-1}, 7 TeV]

χ_{c1} and χ_{c2} production cross sections
ATLAS, CONF-2013-095 [L = 4.5 fb^{-1}, 7 TeV]

$\Upsilon(nS)$ production cross section
CMS, PRD 83 (2011) 112004 [L = 3 pb^{-1}, 7 TeV]
CMS, CMS PAS-BPH-12-006 [4.9 fb^{-1}, 7 TeV]
ATLAS, PRD 87 (2013) 052004 [1.8 fb^{-1}, 7 TeV]

Relative production rate of χ_{c2} and χ_{c1}
CMS, EPJC 72 (2012) 2251 [4.6fb^{-1}, 7 TeV]

Relative production rate of $\chi_{b2}(1P)$ and $\chi_{b1}(1P)$
CMS, CMS PAS-BPH-13-005 [20.7 fb^{-1}, 8 TeV]

J/ψ and $\psi(2S)$ polarizations
ALICE: PRL 108 (2012) 082001 [100 nb^{-1}, 7 TeV]
CMS, PLB 727 (2013) 382 [4.9 fb^{-1}, 7 TeV]
LHCb: EPJC 73 (2013) 2631 [0.37 fb^{-1}, 7 TeV]
LHCb: EPJC 74 (2014) 2872 [1 fb^{-1}, 7 TeV]

$\Upsilon(nS)$ polarizations
CMS, PRL 110 (2013) 081802 [4.9 fb^{-1}, 7 TeV]
CDF, PRL 108 (2012) 151802 [6.7 fb^{-1}, 1.96 TeV]

Phenomenology studies of $\psi(nS)$ and $\Upsilon(nS)$ cross sections and polarizations
M. Butenschön and B. Kniehl, PRL 108 (2012) 172002
B. Gong et al., PRL 112 (2014) 032001
P. Faccioli et al., arXiv:1403.3970 (PLB, in Print)

all CMS public results in:
twiki/bin/view/CMSPublic/PhysicsResultsBPH

Backup

CMS: Results on P-wave charmonia

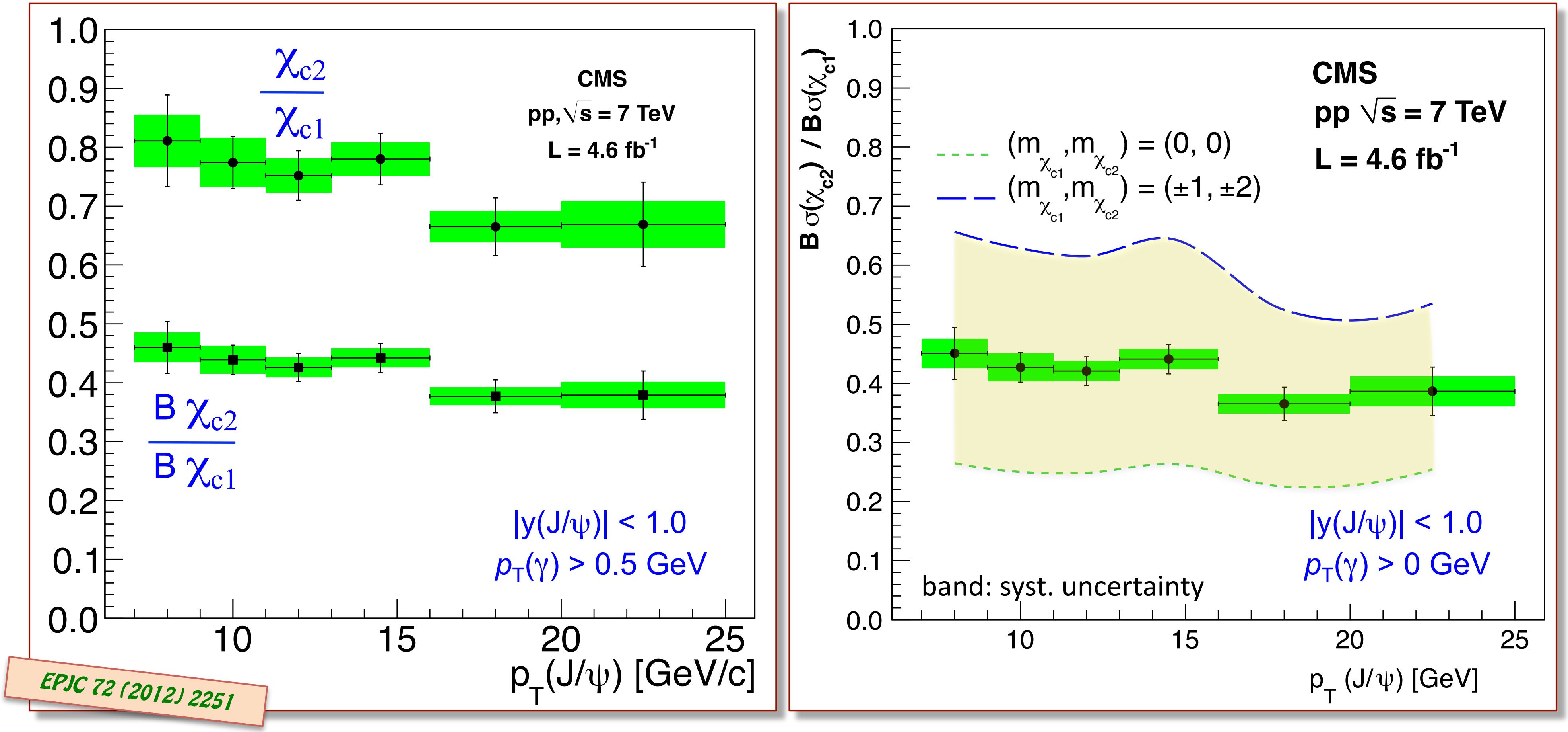
The χ_{c2} / χ_{c1} cross-section ratio has been measured vs. p_T, up to much higher p_T and with smaller uncertainties than previous measurements

Systematic uncertainties are dominated by fit to mass distribution

Cross-section ratio seems to be rather flat with p_T

To compare with theory calculations:

- care is needed regarding assumed polarizations, that can significantly change the result



EPJC 72 (2012) 2251

CMS: Results on P-wave bottomonia

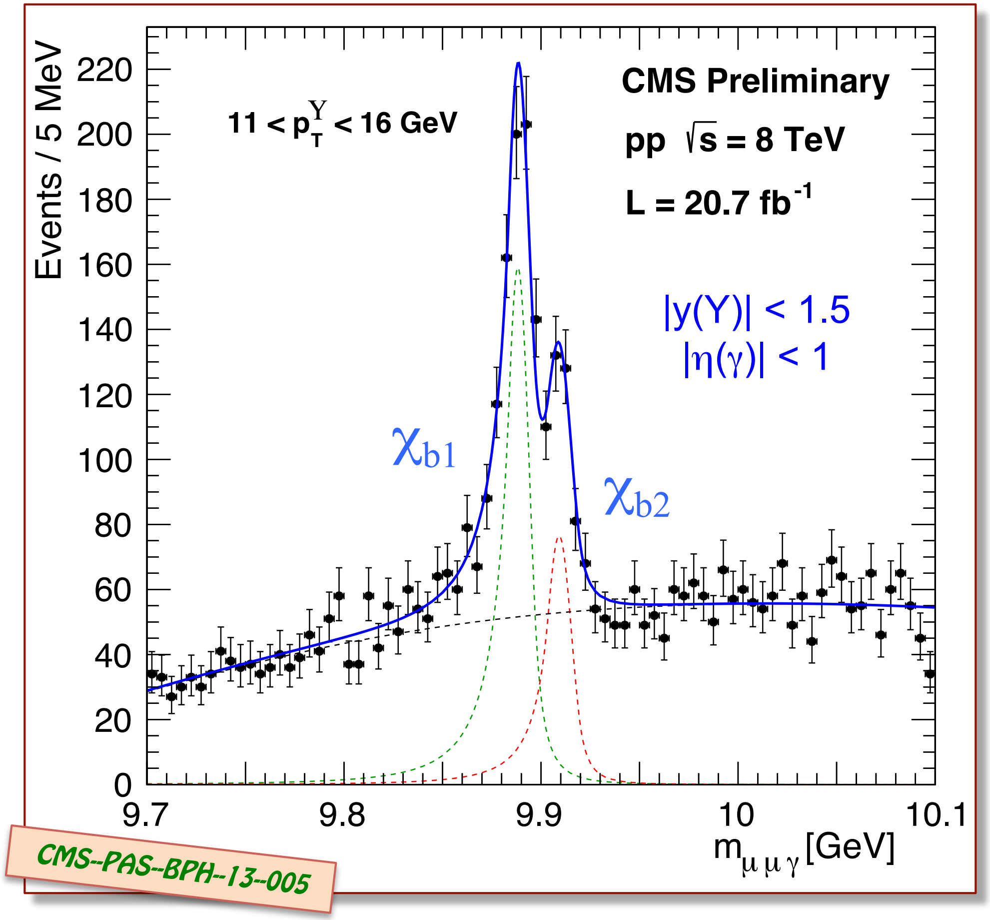
The $\chi_{b2}(1P)$ / $\chi_{b1}(1P)$ cross-section ratio has been measured vs. p_T, for the first time in a hadron collider

Systematic uncertainties are dominated by fit to mass distribution

Mass resolution of 5 MeV resolves the two peaks, separated by only 19 MeV

Cross-section ratio seems to be rather flat with p_T

No low-p_T increase, contrary to the theory prediction of Likhoded et al., PRD 86 (2012) 074027



CMS-PAS-BPH-13-005