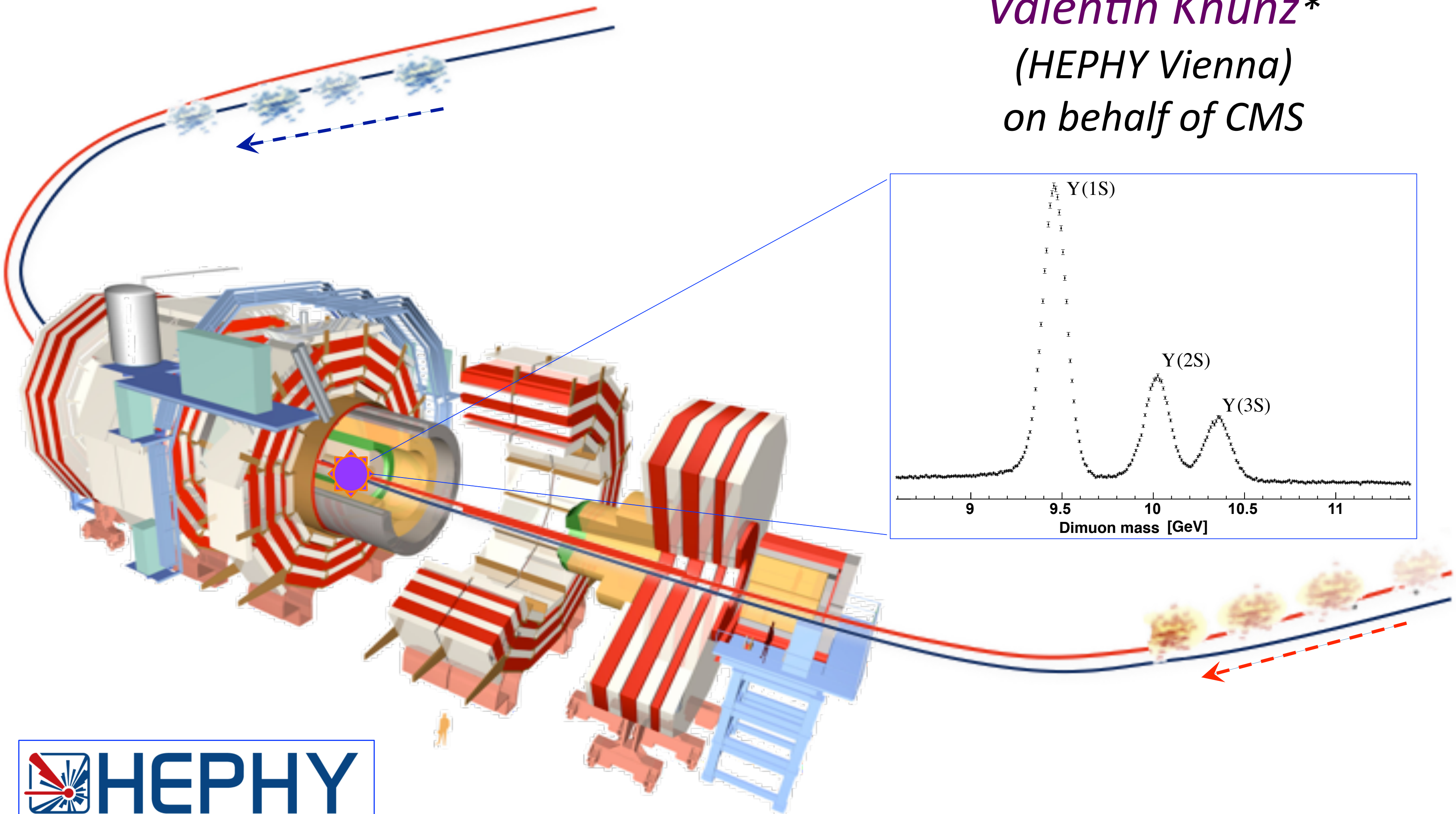
Quarkonium production and polarization in pp collisions with CMS

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



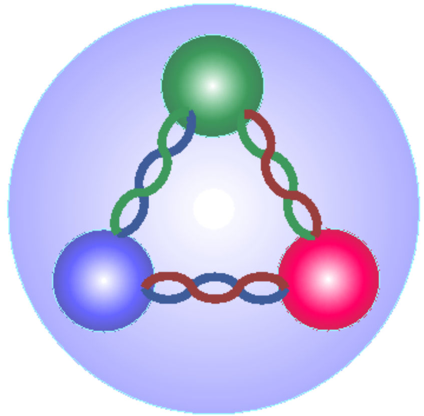
HEPHY
Institute of High Energy Physics

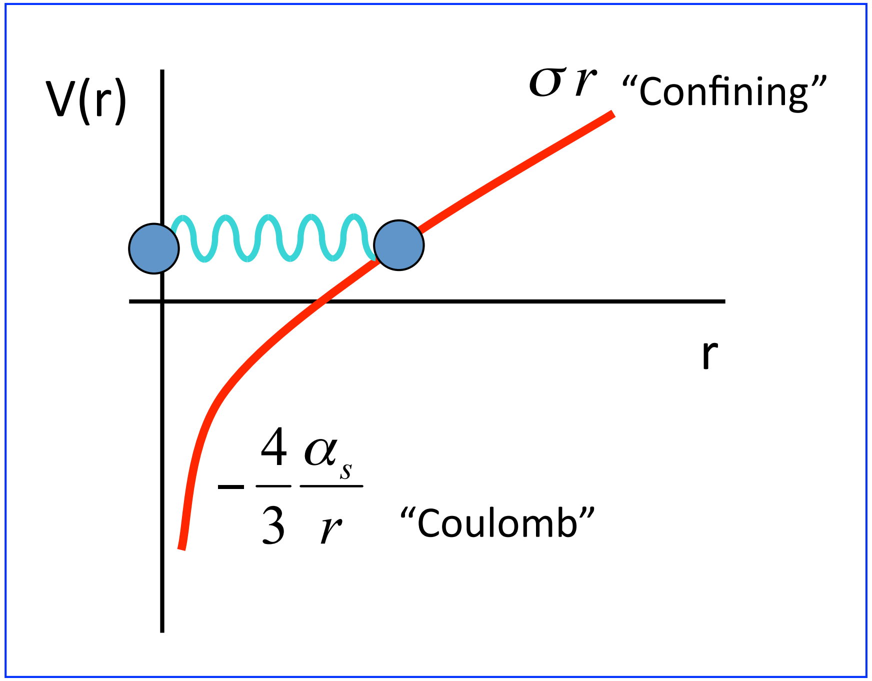
*Supported by FWF grant P 24167-N16

Hard Probes 2013
Stellenbosch, South Africa

The big picture in a nutshell

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





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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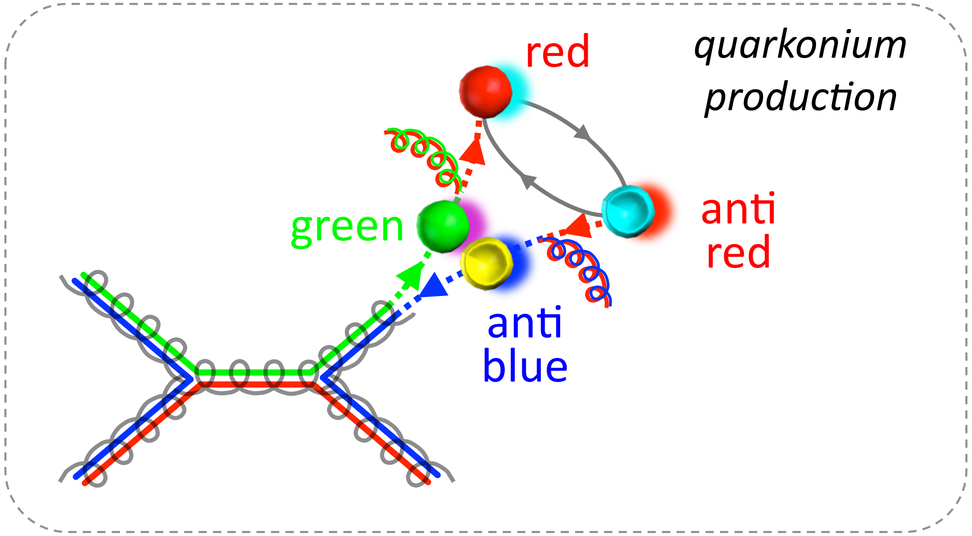
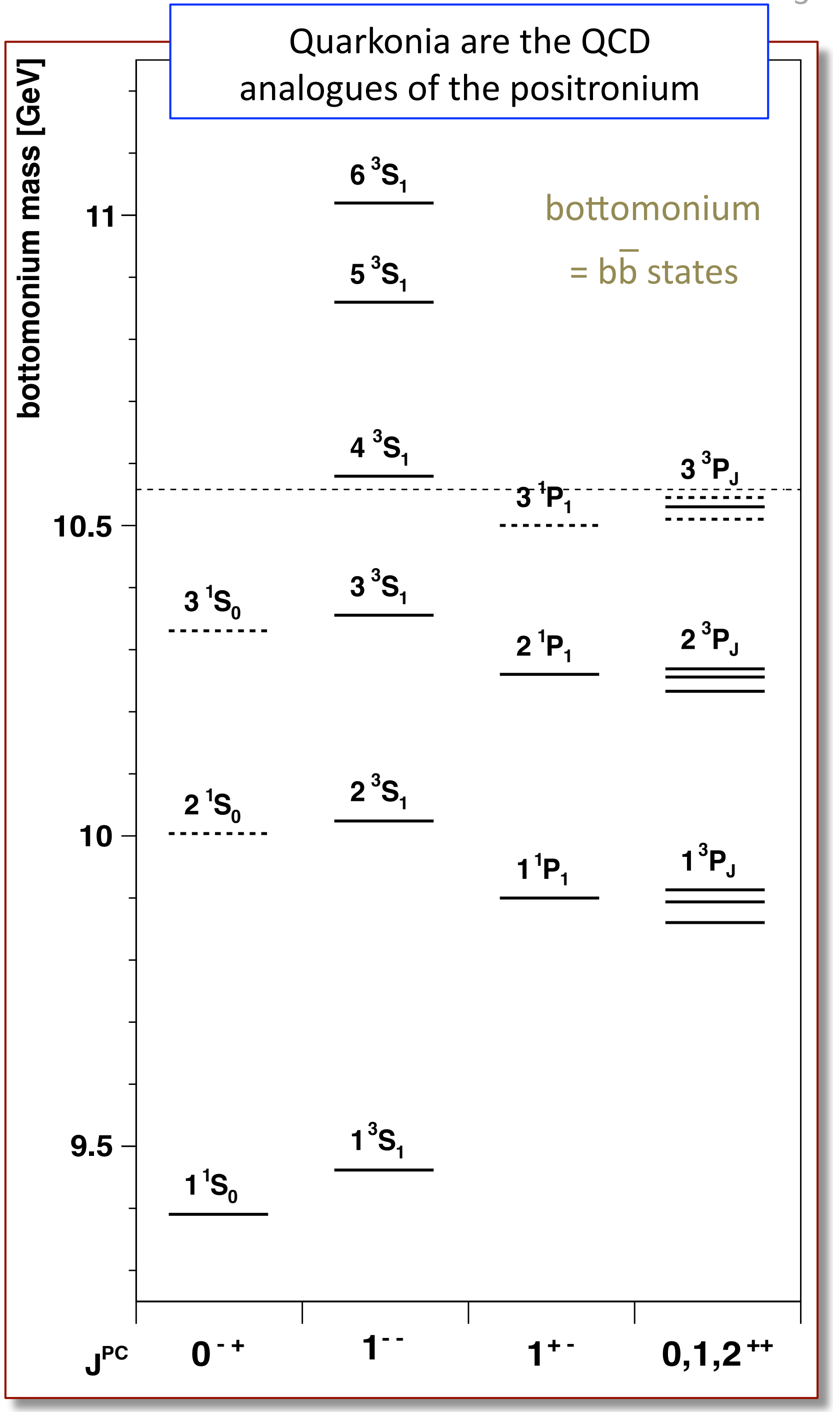
Quarkonium production…
is an ideal probe to study hadron formation





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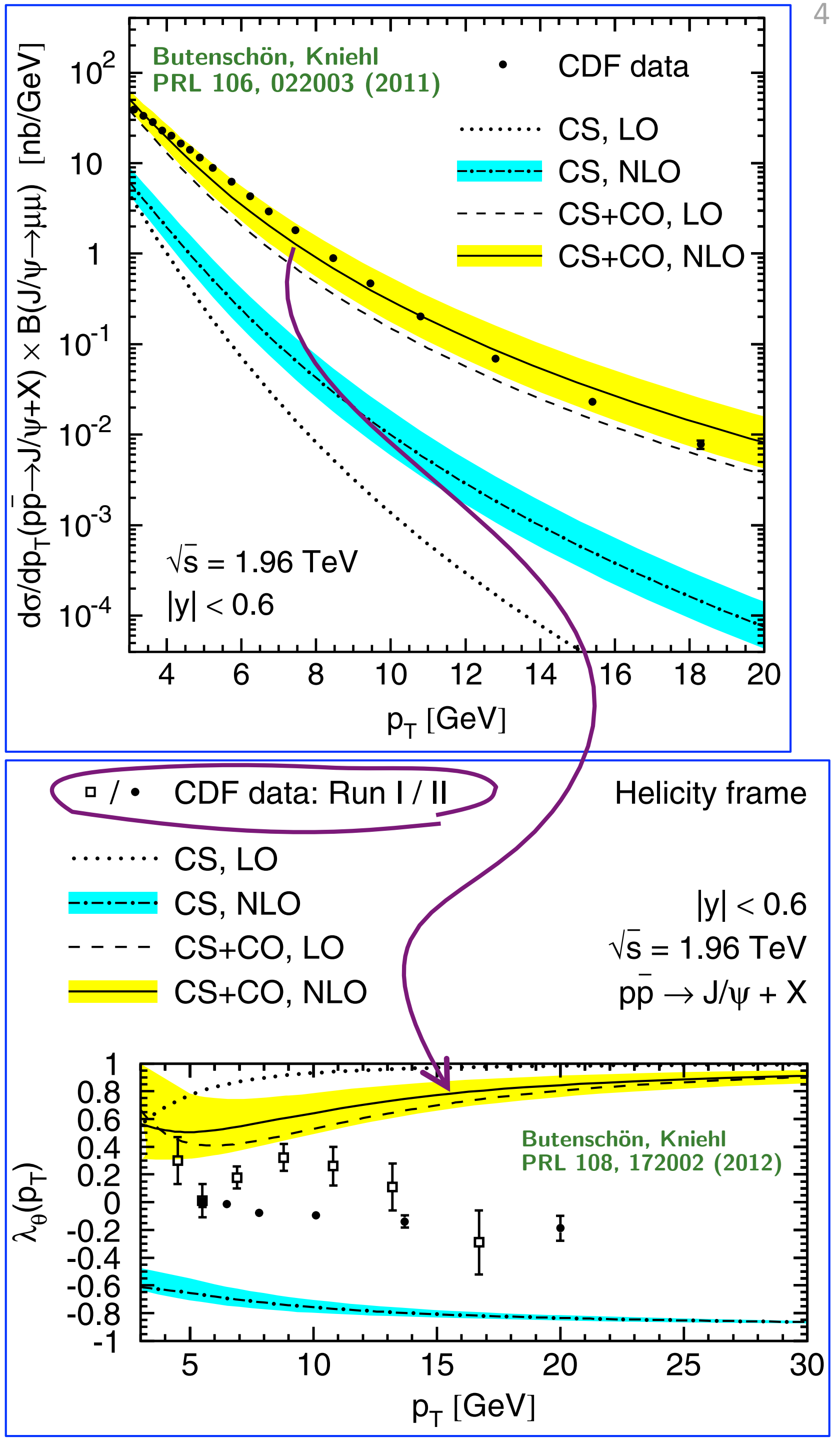
As will be explained in detail later in this talk, NRQCD calculations fit p_T-differential cross sections to extract long-distance matrix elements (LDMEs) and then predict the quarkonium polarization

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:
more reliable analysis methods and higher p_T reach



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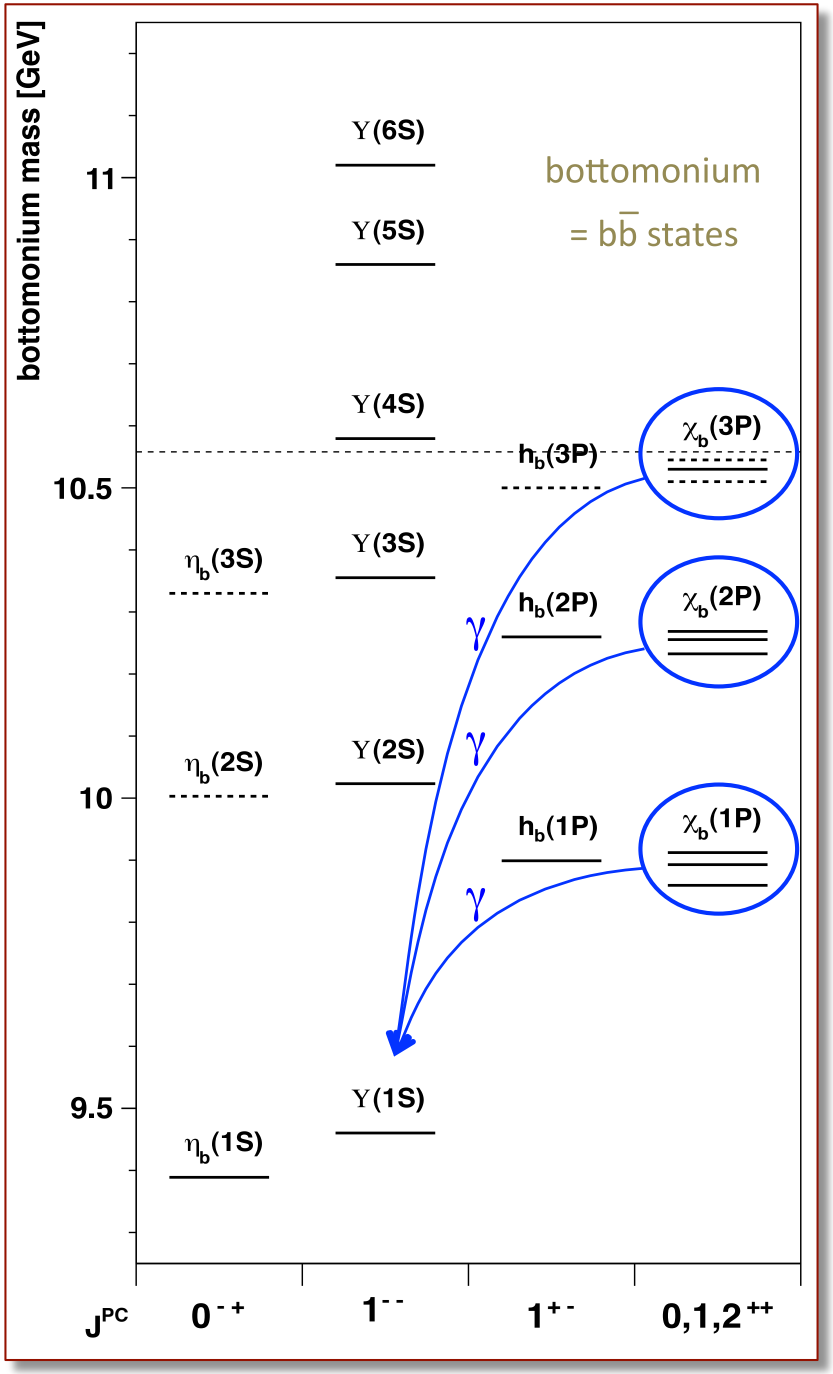
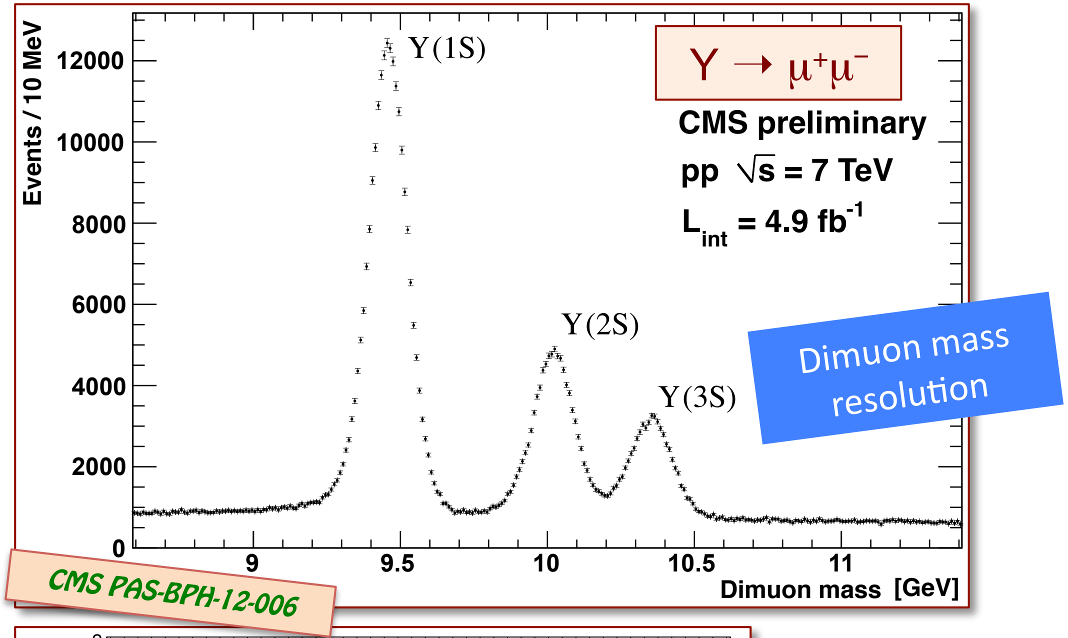
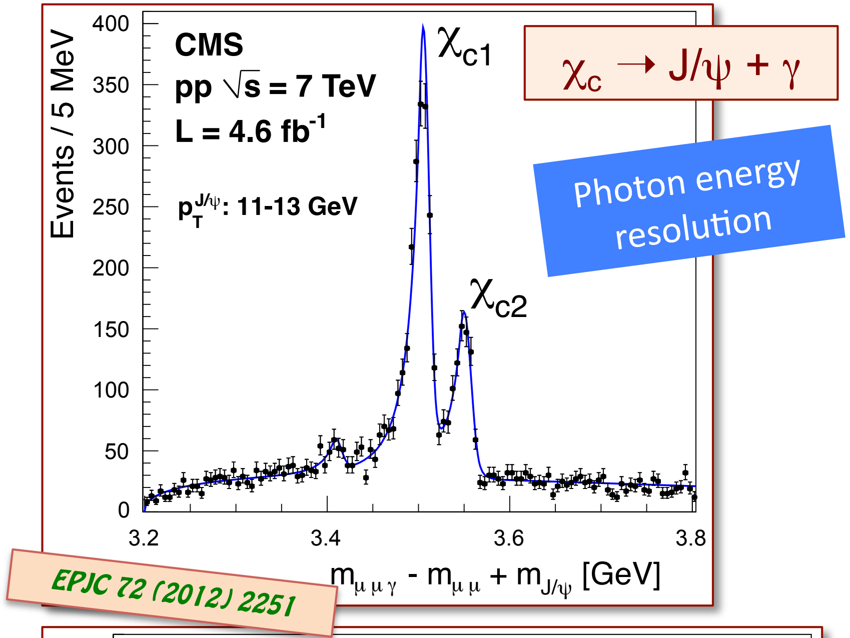
The present results are limited to S-wave states, affected by feed-down from P-wave decays…

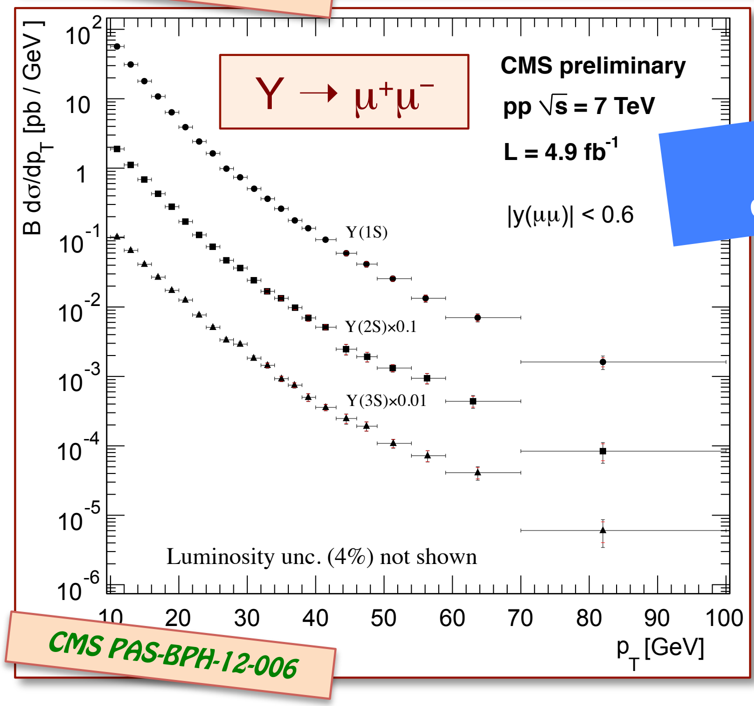
Next measurements: cross sections, feed-down fractions and polarizations of P-wave quarkonia



CMS: excellent performance in quarkonium reconstruction







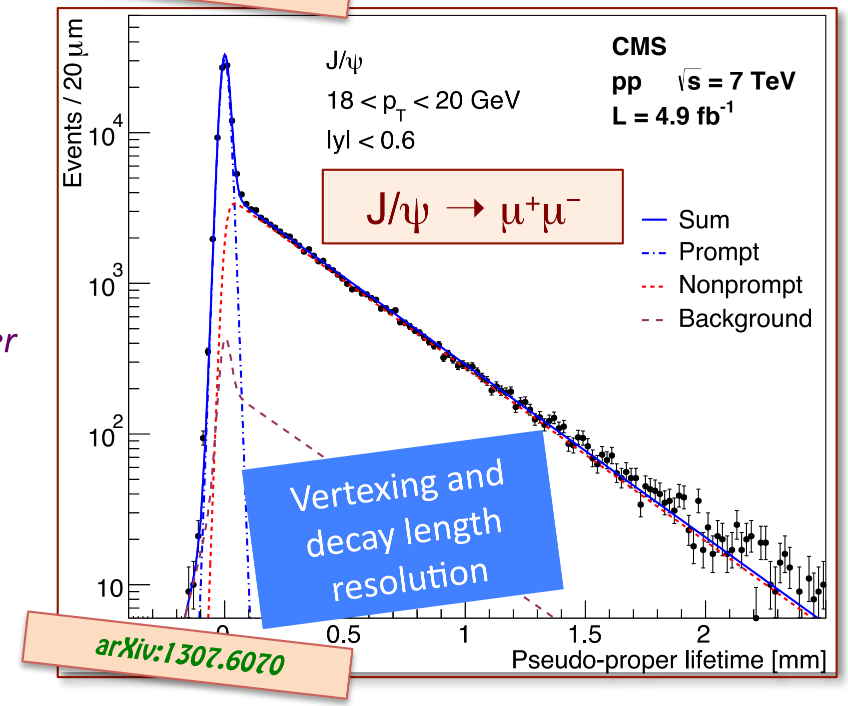
Huge silicon tracker

Very strong field

Broad acceptance

Flexible trigger

Powerful DAQ

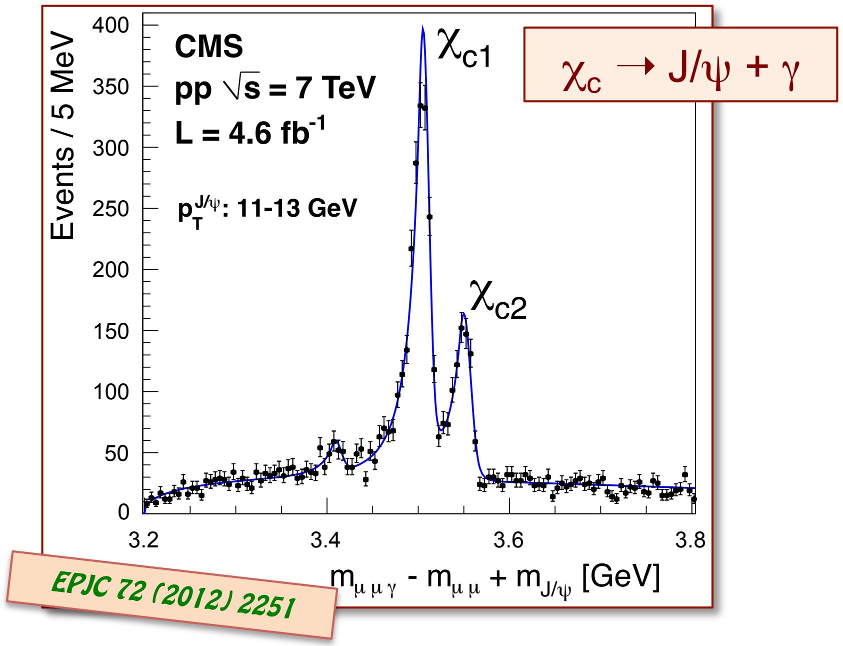


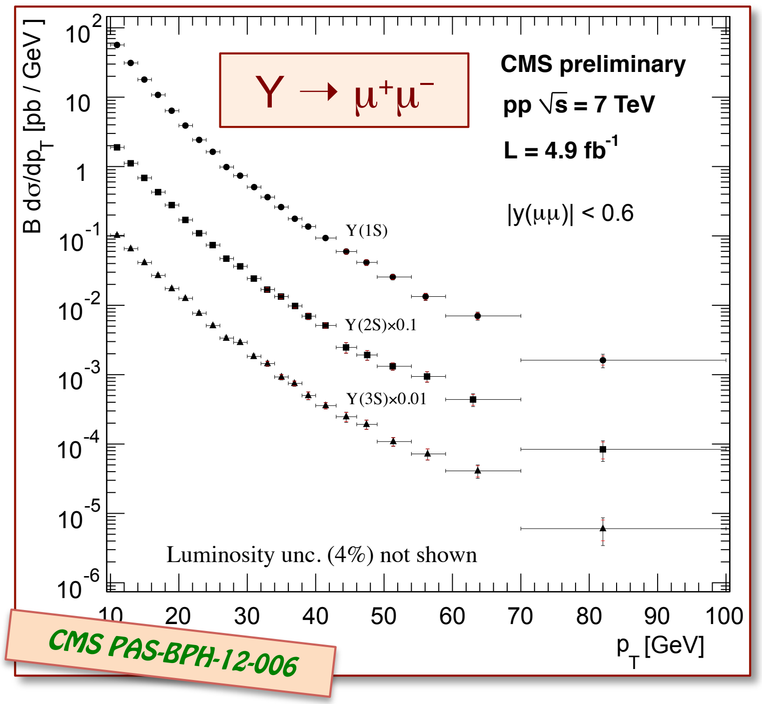
S-wave cross sections and P-wave ratios

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





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

Efficiencies cancel almost completely in the χ_{c2} / χ_{c1} cross-section ratio

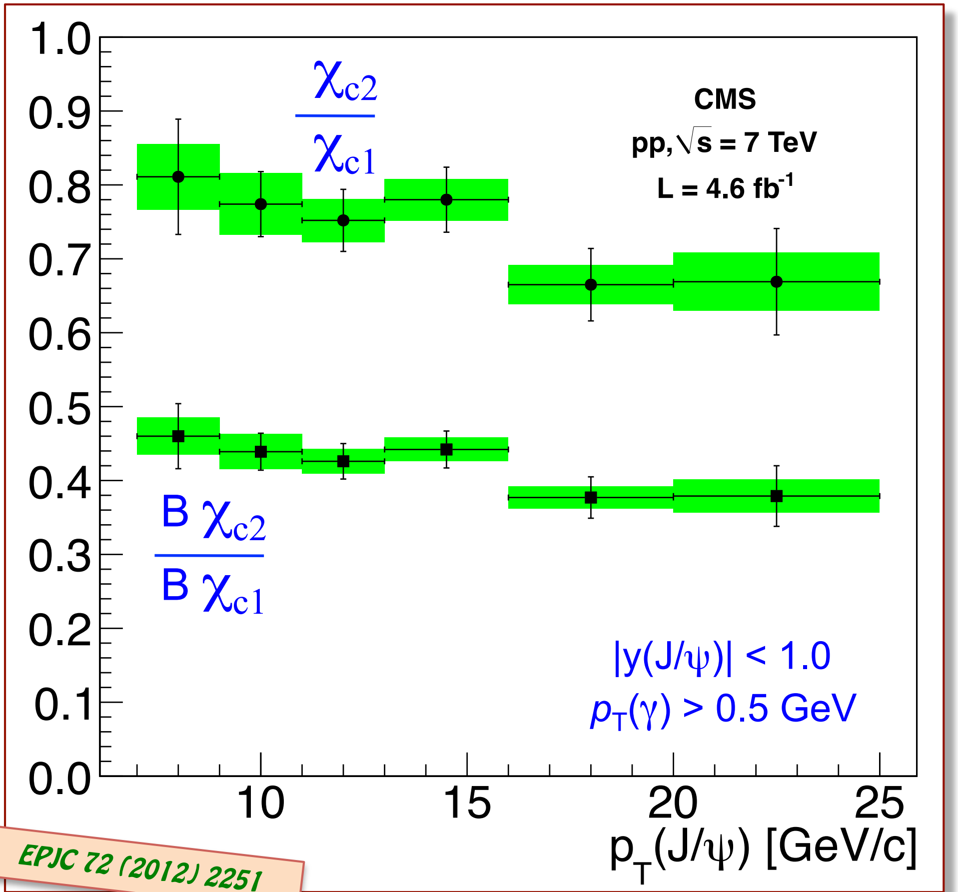
Results on P-wave charmonia

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

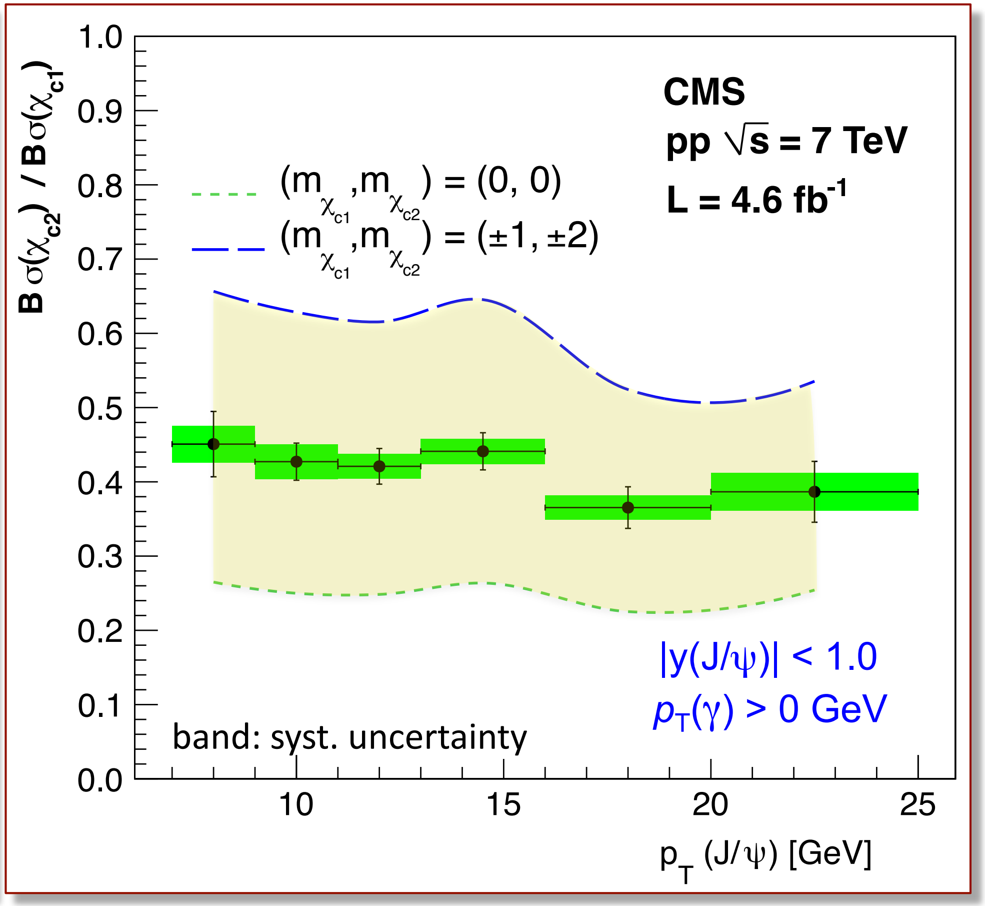
Systematic uncertainties are dominated by fit to mass distribution

To compare with theory calculations:

- the photon p_T distribution was extrapolated down to 0 GeV
- care is needed regarding assumed polarizations, that can significantly change the result



EPJC 72 (2012) 2251

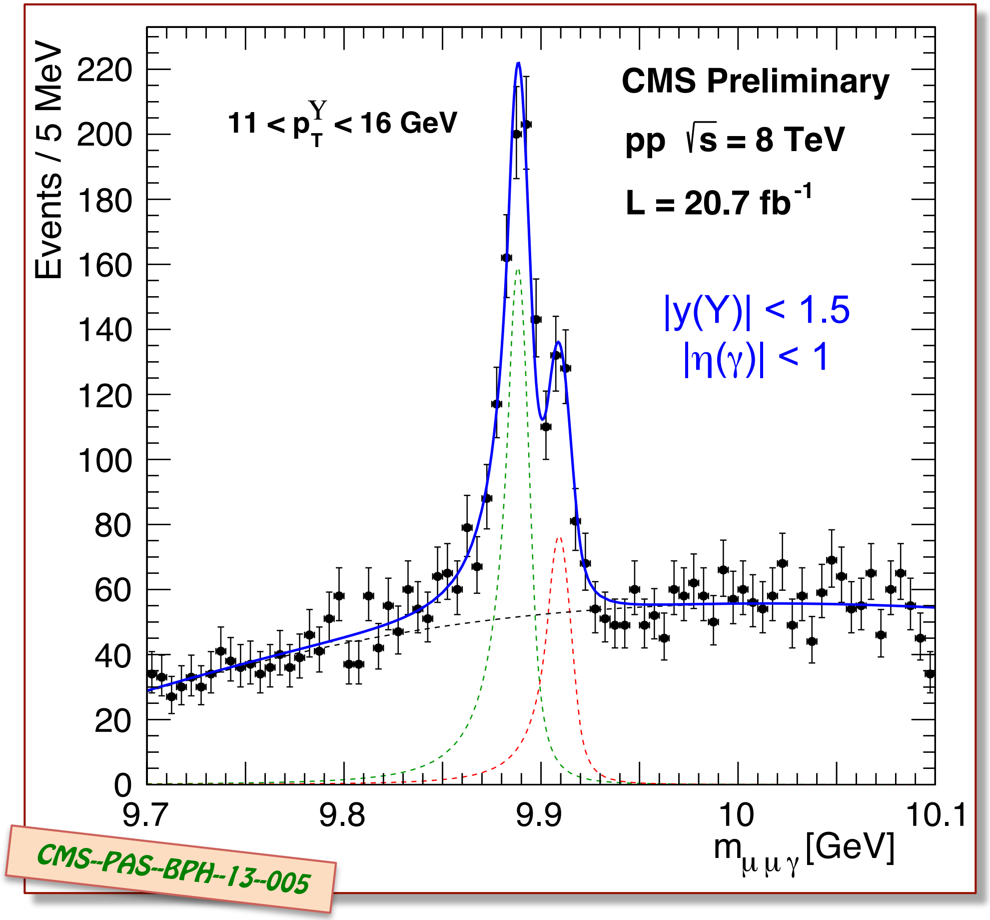


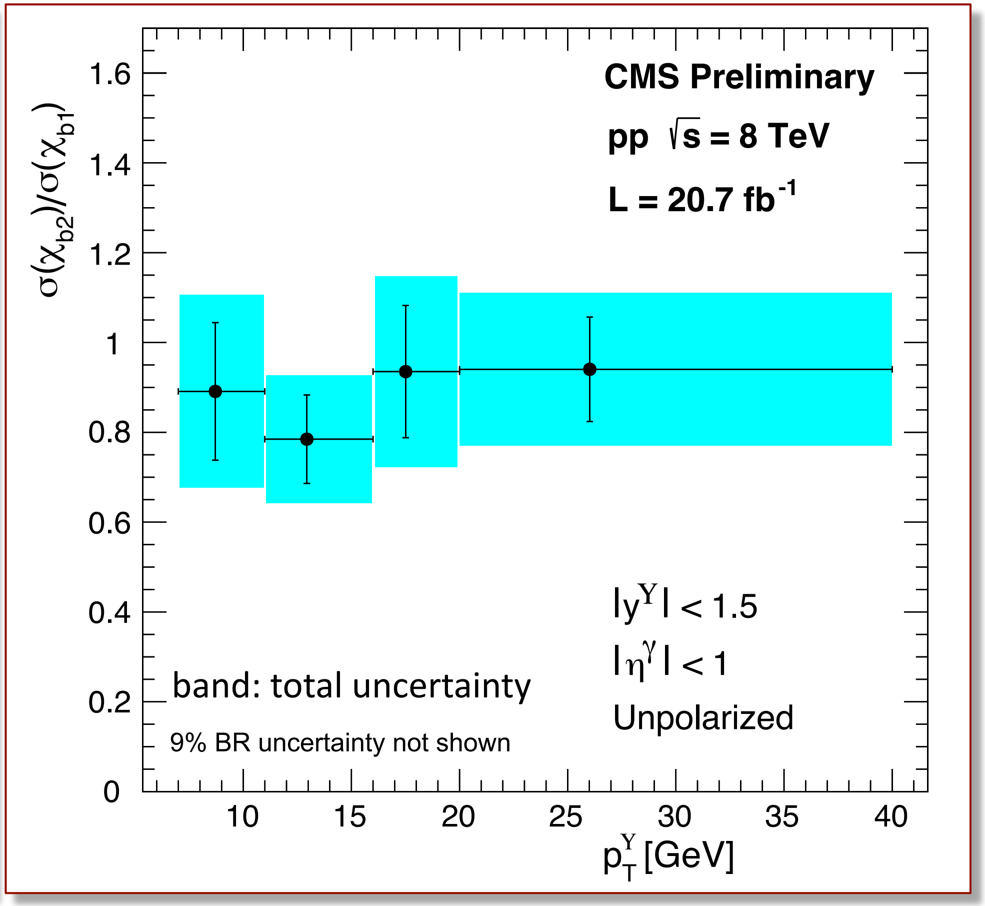
Results on P-wave bottomonia

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

NEW

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



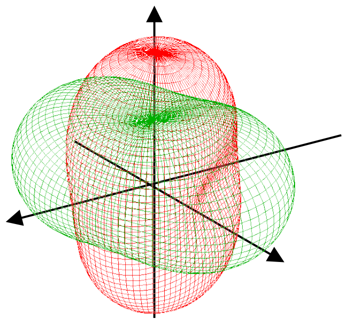


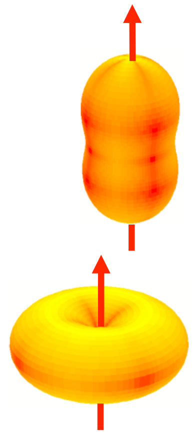
Quarkonium polarization analyses

Quarkonia 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)

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





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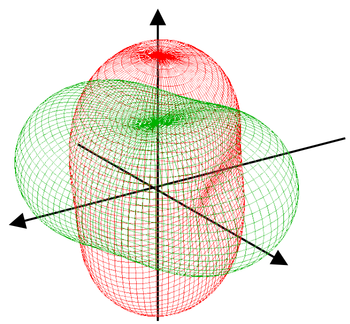

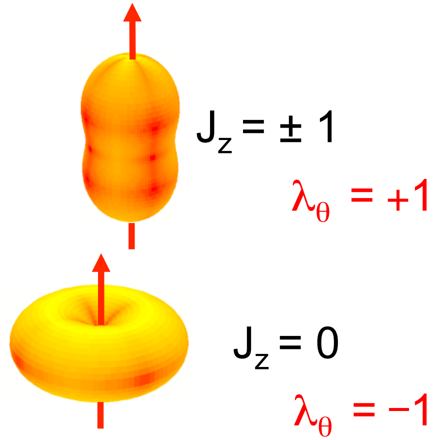

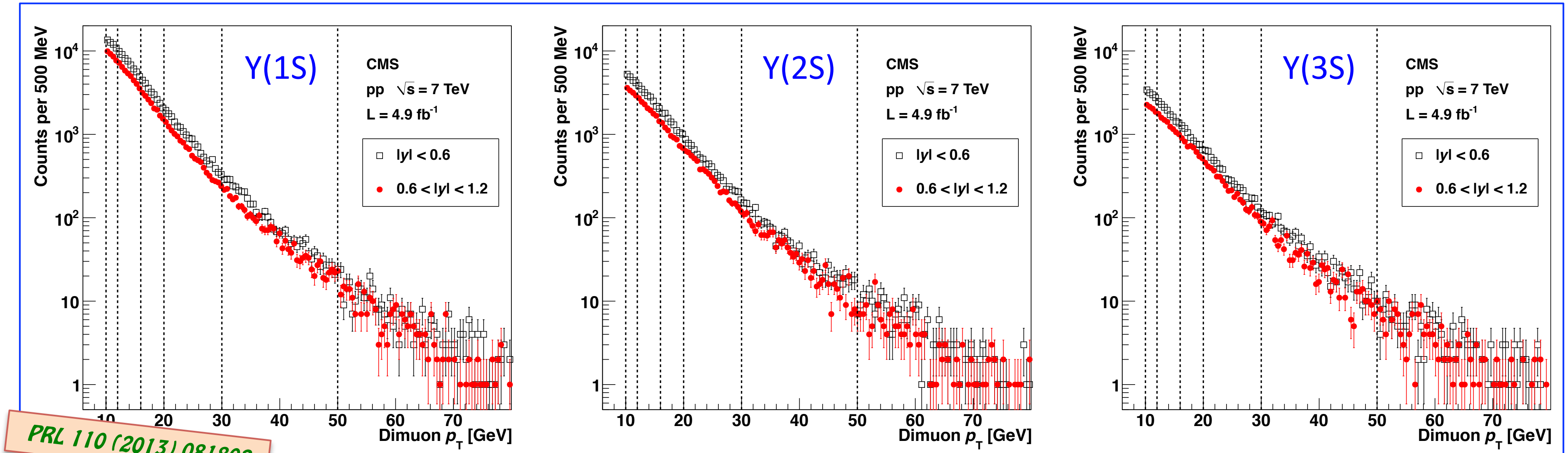

PRL 110 (2013) 081802

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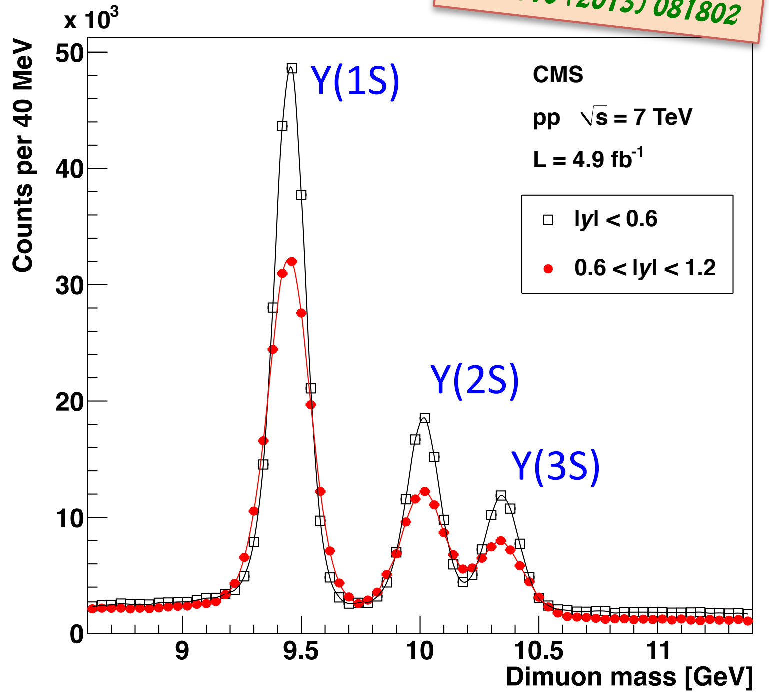
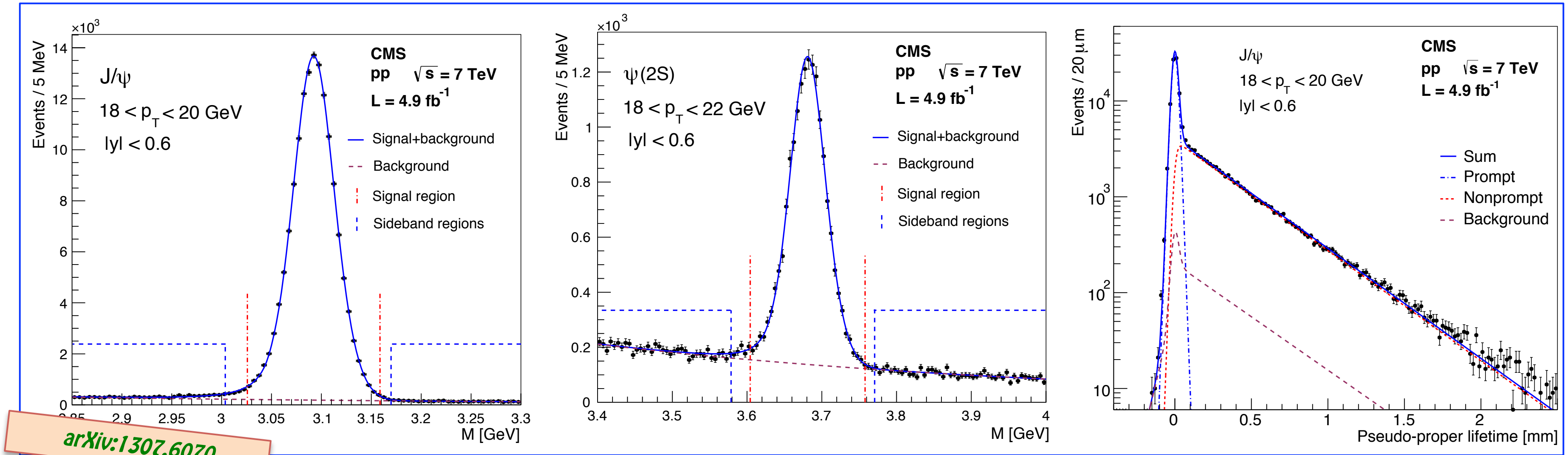
The underlying continuum background is removed using invariant mass distribution;
and the non-prompt charmonia using the decay length

PRL 110 (2013) 081802





arXiv:1307.6070

Quarkonium polarization analyses

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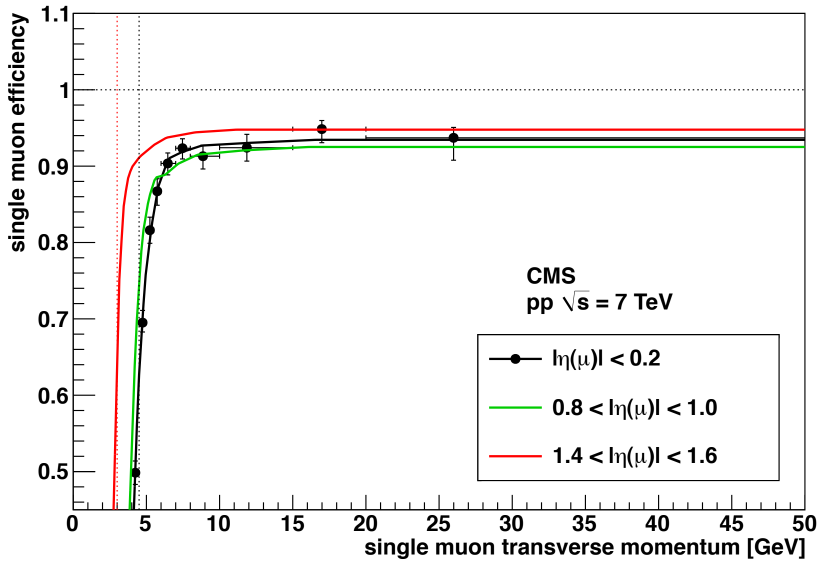
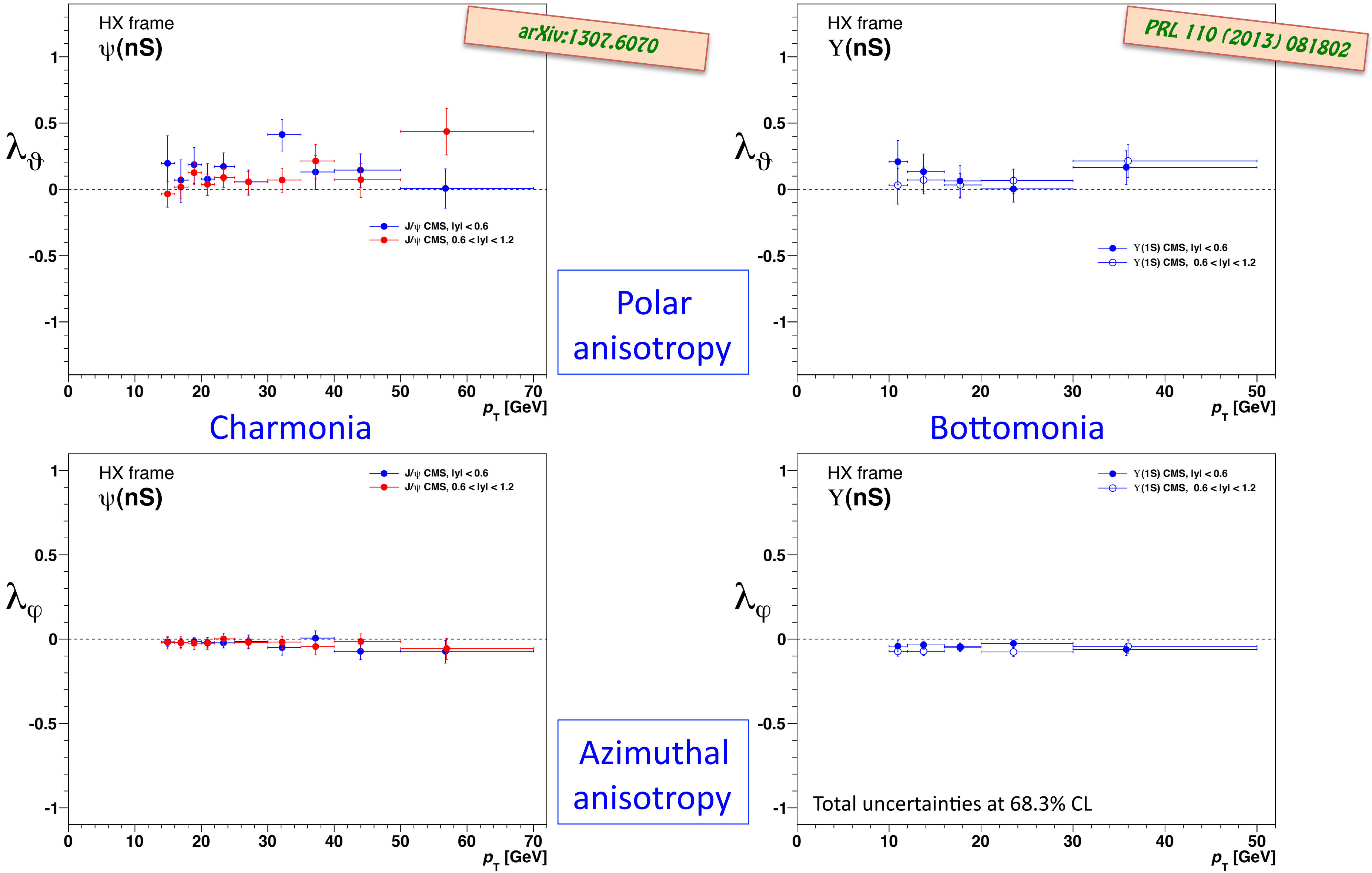
Main experimental challenges:
✧ precise mapping of (di)muon efficiencies (T&P)
✧ reliable background modeling (sidebands)

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



Quarkonium polarization results

No strong anisotropies seen in any of the measurements



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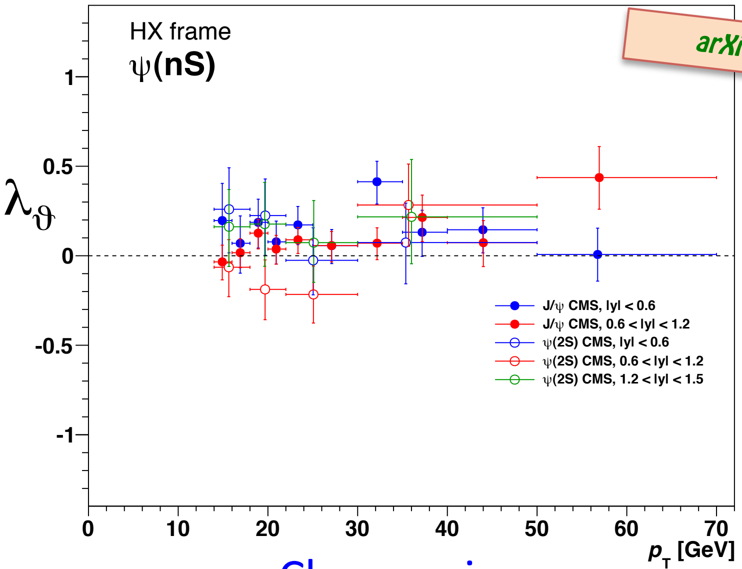
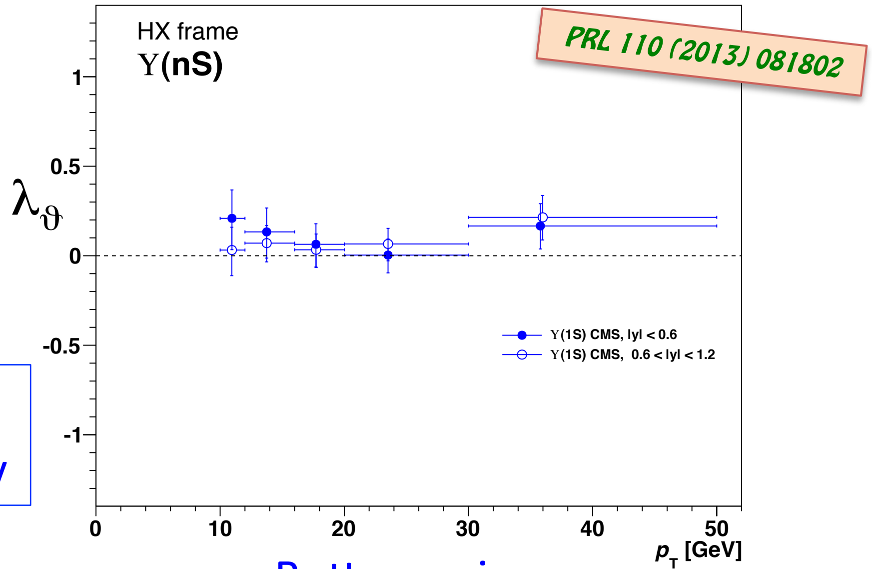
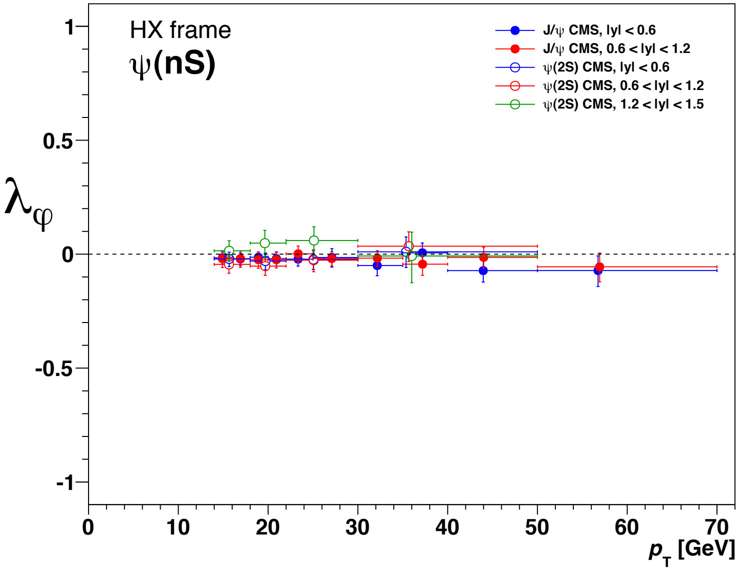


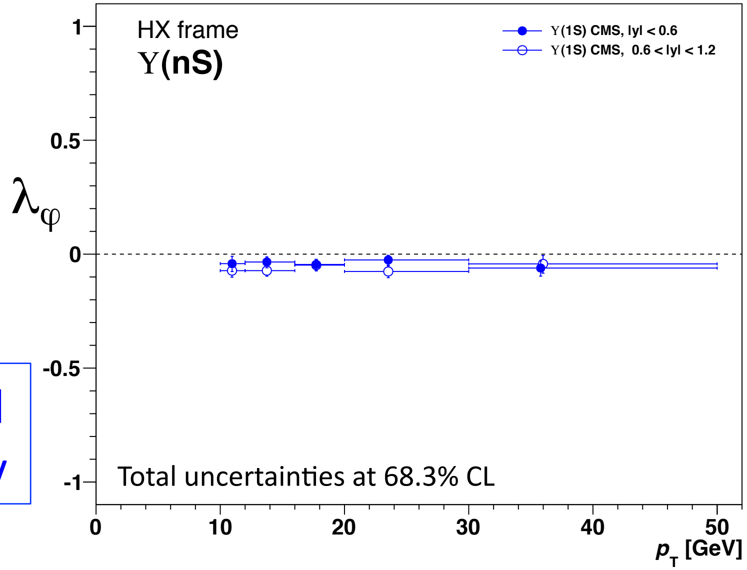


Polar anisotropy

Charmonia

Bottomonia





Azimuthal anisotropy

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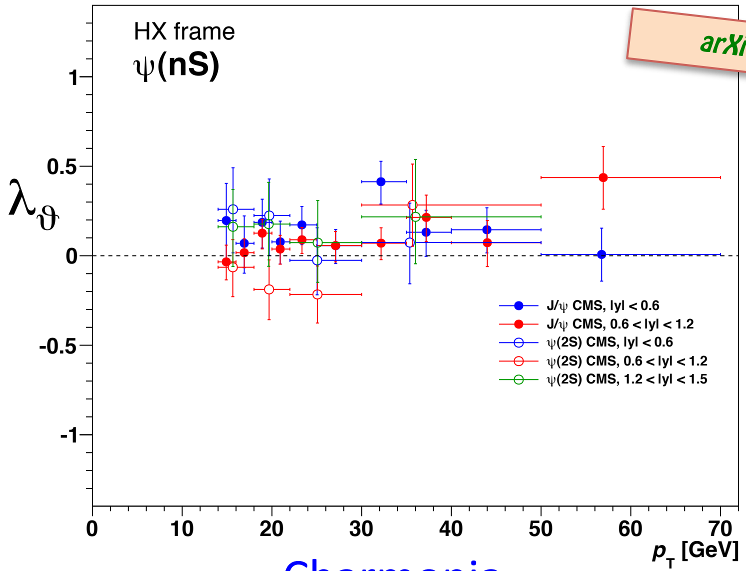

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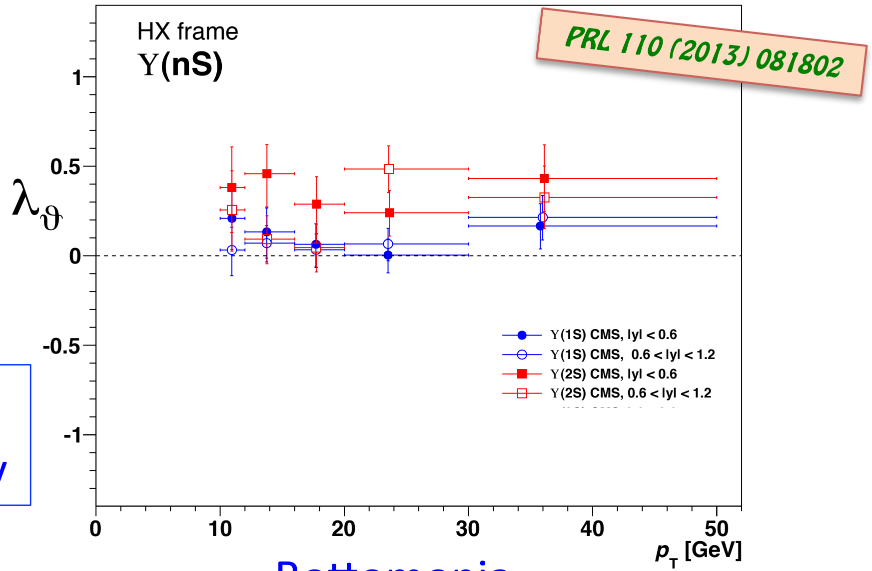

Bottomonia

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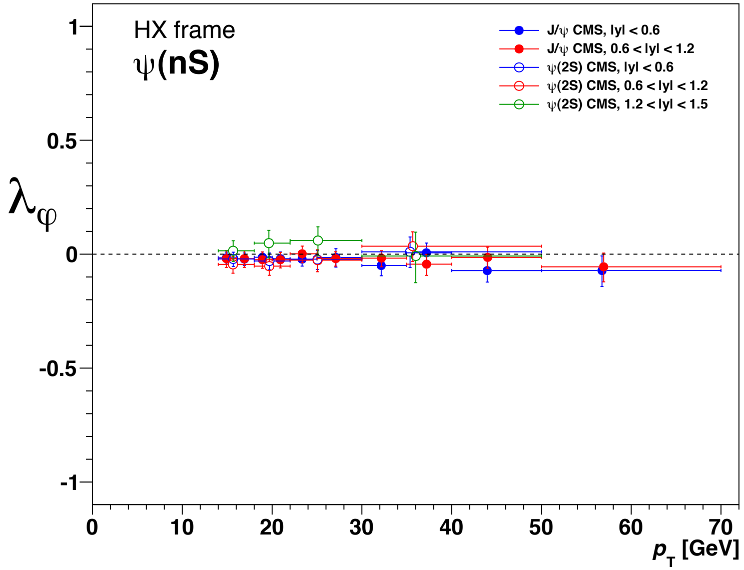

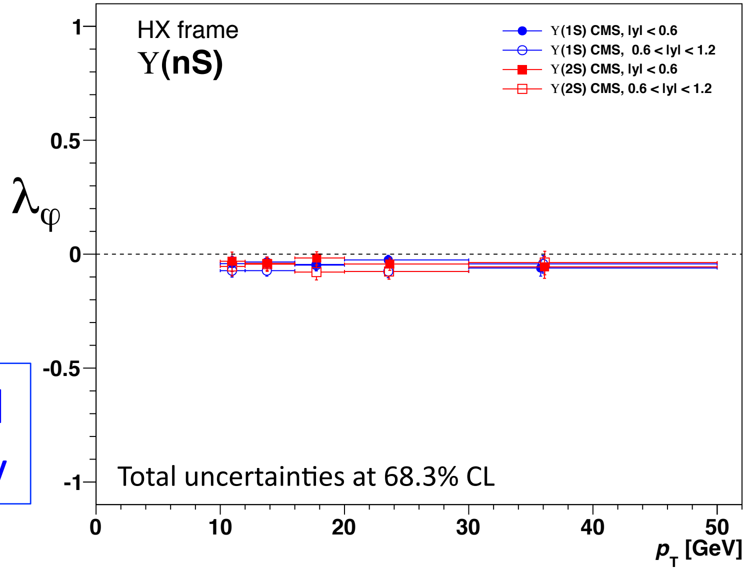

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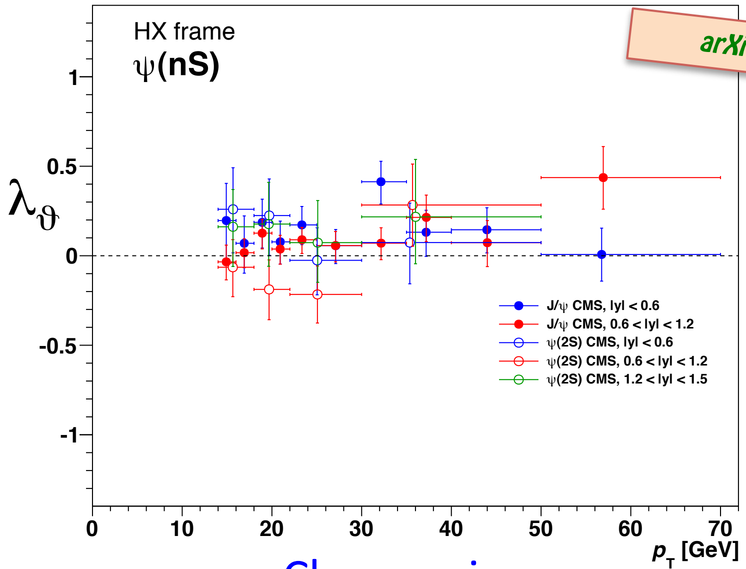

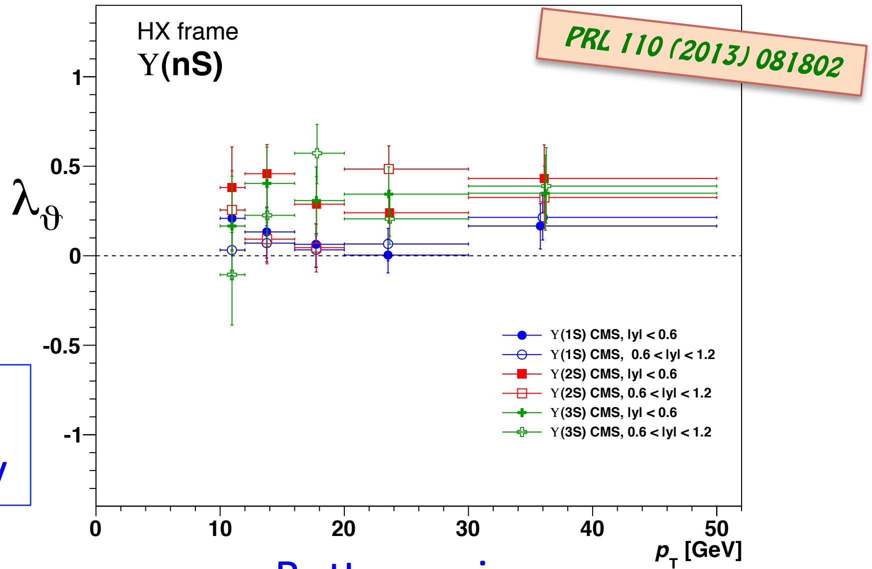

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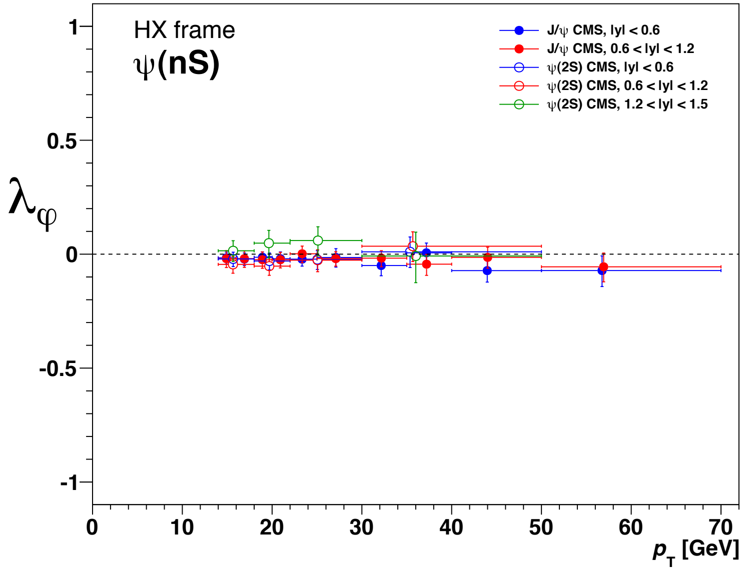

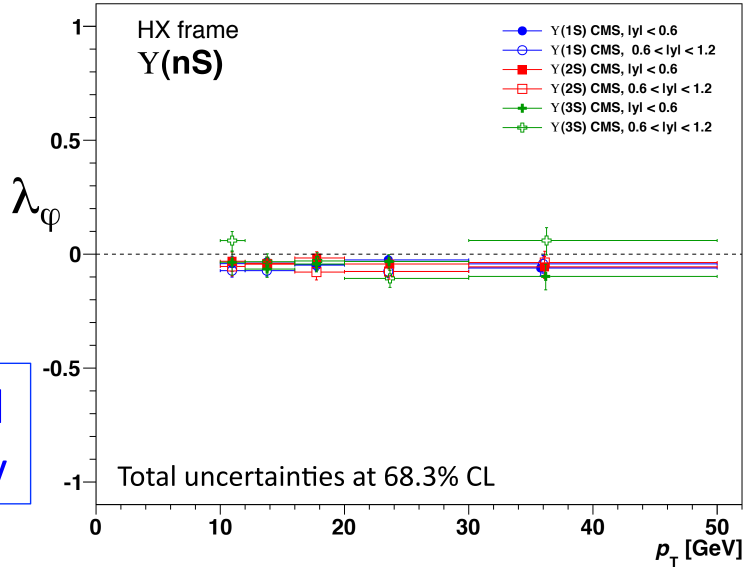

Azimuthal anisotropy

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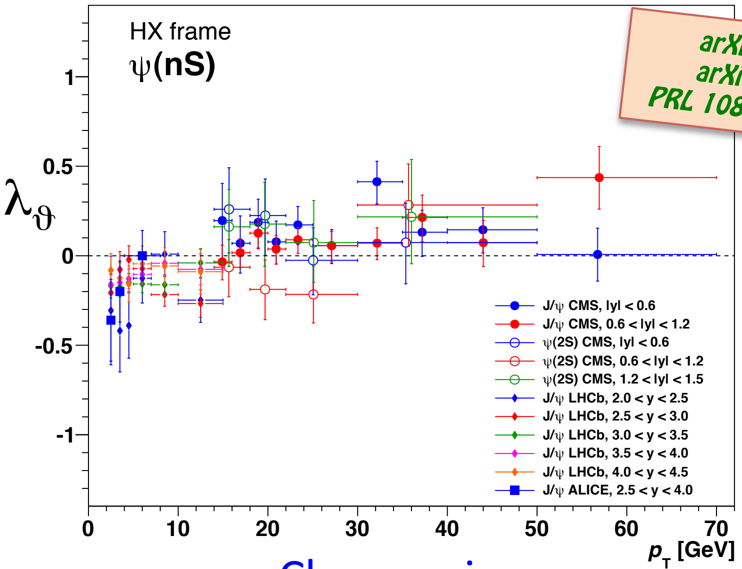
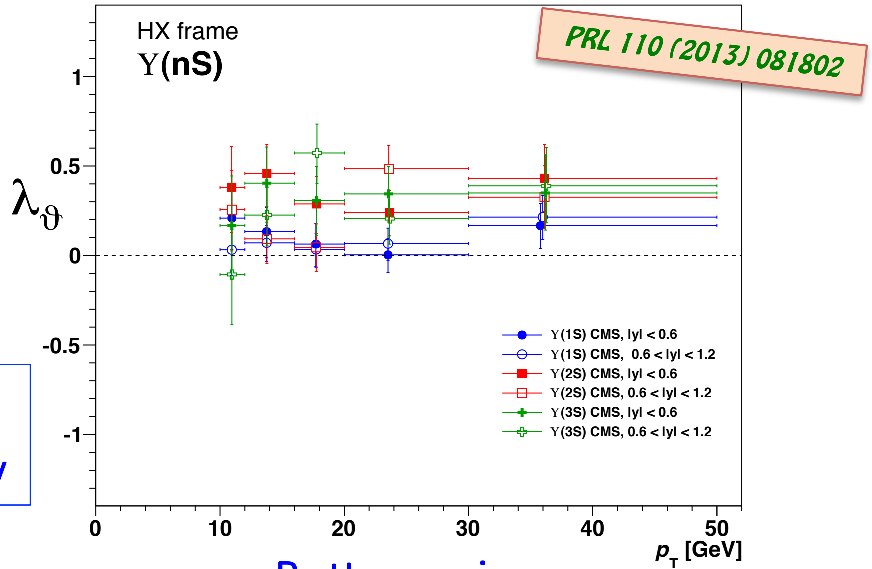
Good consistency between CMS, LHCb, ALICE





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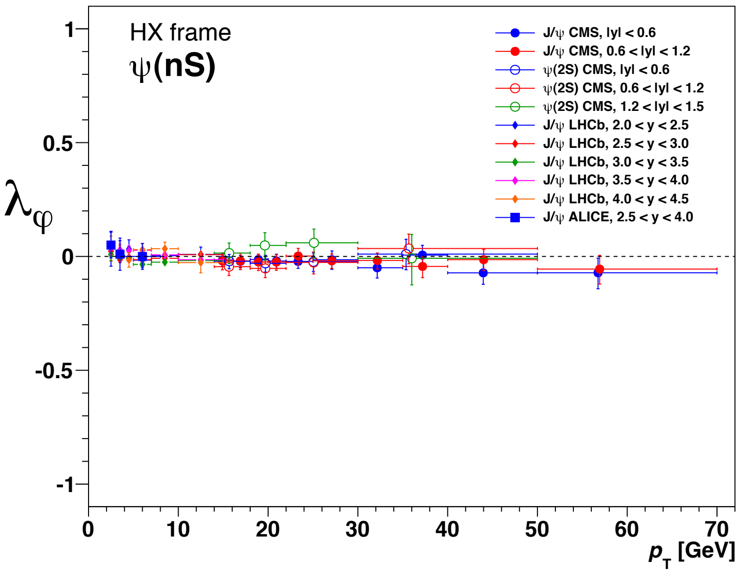

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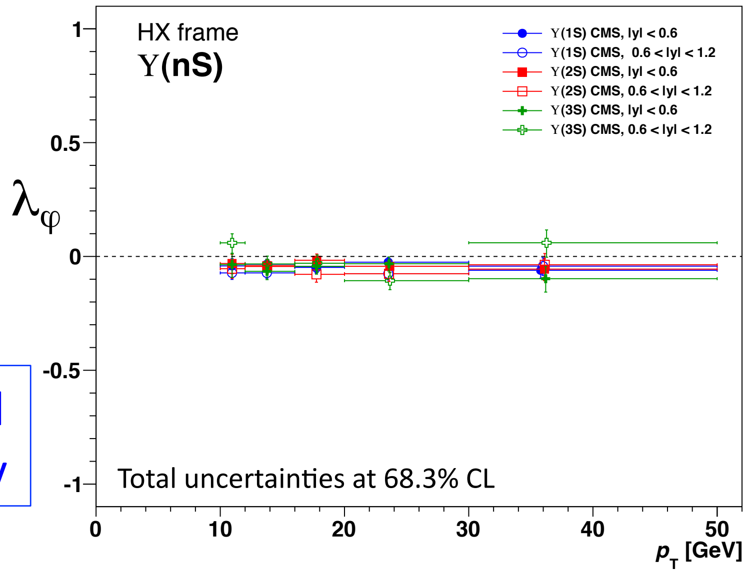
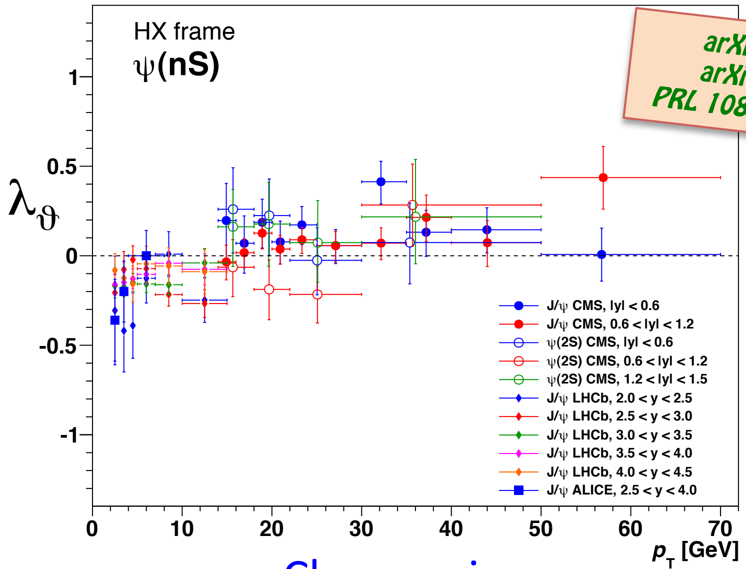
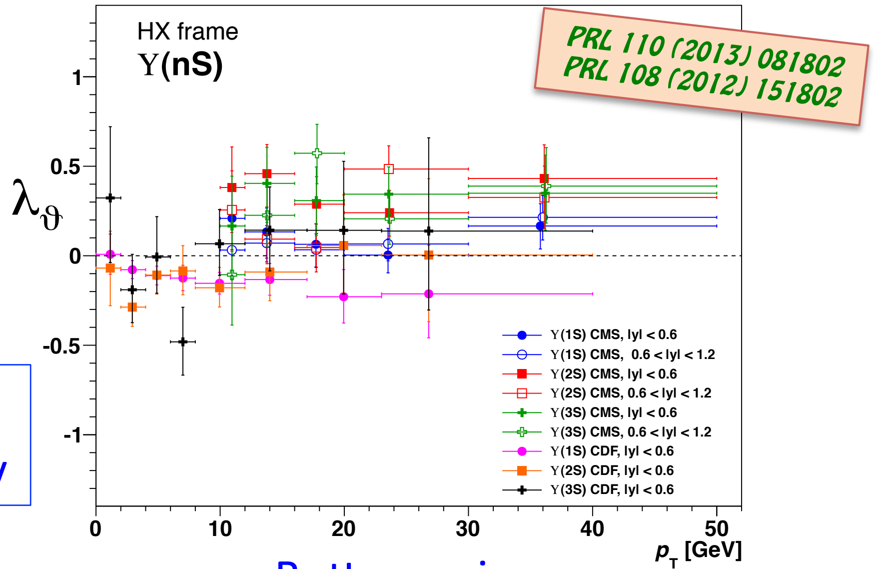


Quarkonium polarization results

No strong anisotropies seen in any of the measurements
Good consistency between CMS, LHCb, ALICE and CDF





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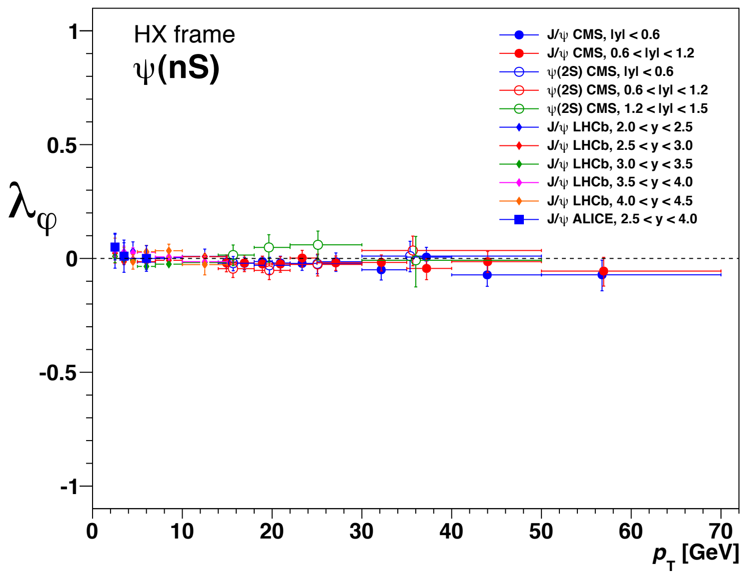
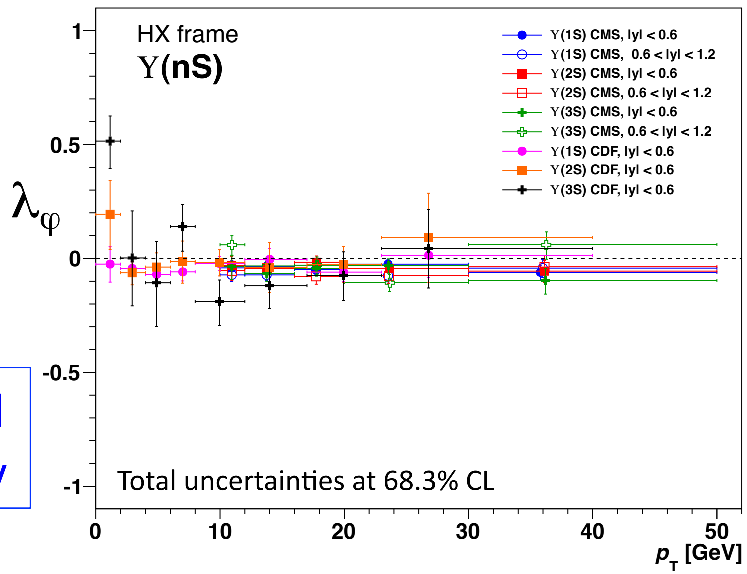




Azimuthal anisotropy

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

Short-distance coefficients (SDC)
Cross section of partonic processes to form $q\bar{q}$ in state $n \otimes$ PDF

Long-distance matrix elements (LDME)
Probability of $q\bar{q}$ in state n to form quarkonium state $\mathcal{Q}$

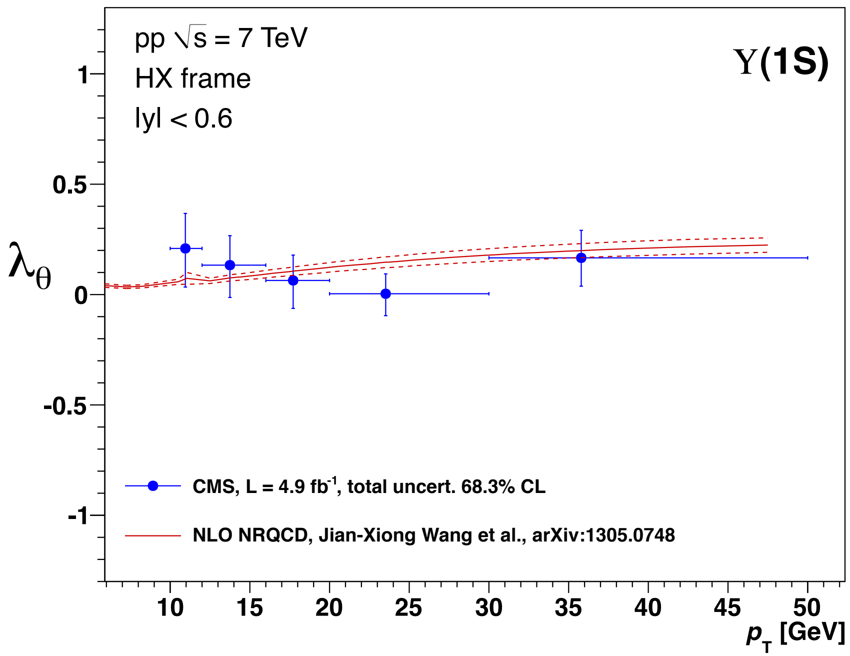
The SDCs can be calculated perturbatively while the LDMEs are determined from fitting data.

The LDMEs are (assumed to be) universal constants and should follow a hierarchy in powers of *v*, the relative velocity of the quark pair in the quarkonium system

For S-state production, the ${}^1S_0$, ${}^3S_1$ and ${}^3P_J$ octet terms “scale” with v^4; the other LDMEs are suppressed

CMS data vs. NLO NRQCD: Υ(nS)

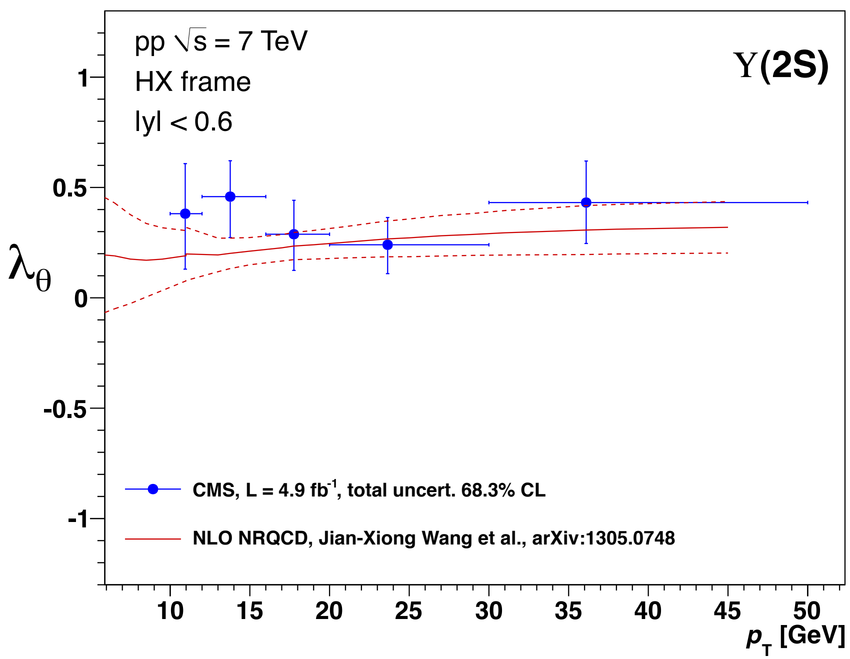
arXiv:1305.0748

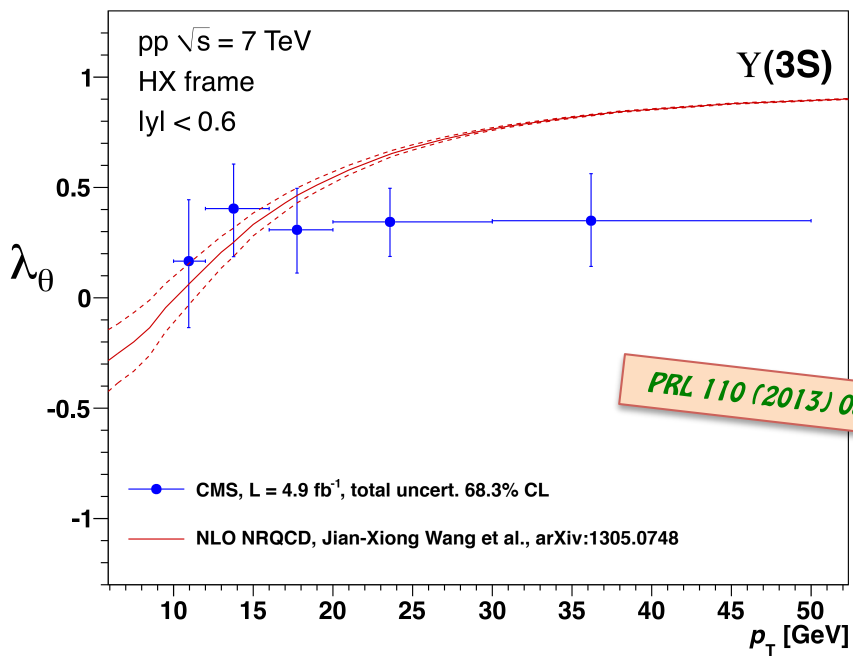


Gong et al. use hadroproduction data, including the CMS Υ(nS) polarization results, to fit the CO LDMEs

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

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

$O(^3S_1^{[1]}) = 1.32\ \text{GeV}^3$

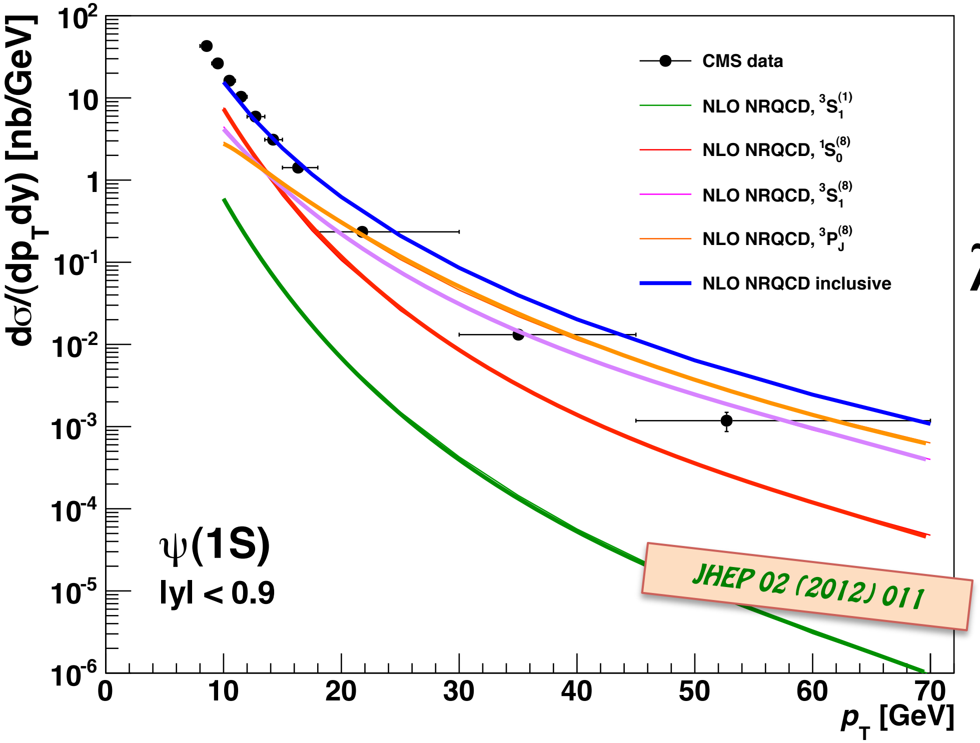
$O(^1S_0^{[8]}) = 0.0497\ \text{GeV}^3$

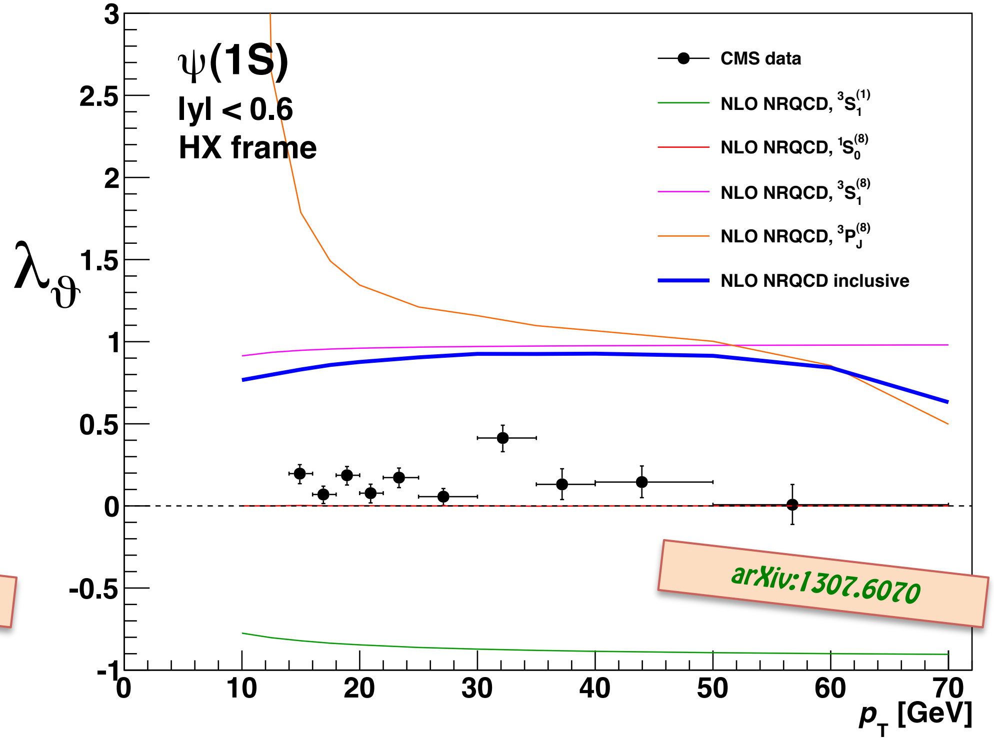
$O(^3S_1^{[8]}) = 0.00224\ \text{GeV}^3$

$O(^3P_J^{[8]}) = -0.0161\ \text{GeV}^5$

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





Many thanks to Mathias Butenschön and Bernd Kniehl for sending us their calculations and explaining them in detail

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

$O(^3S_1^{[1]}) = 0.76\ \mathrm{GeV}^3$

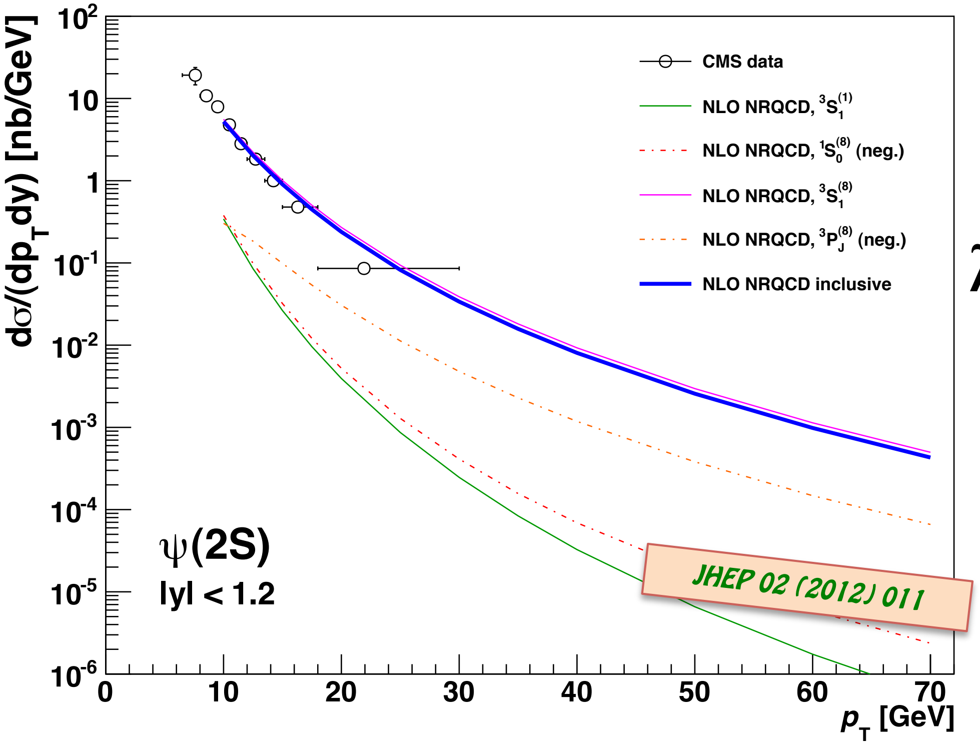
$O(^1S_0^{[8]}) = -0.00247\ \mathrm{GeV}^3$

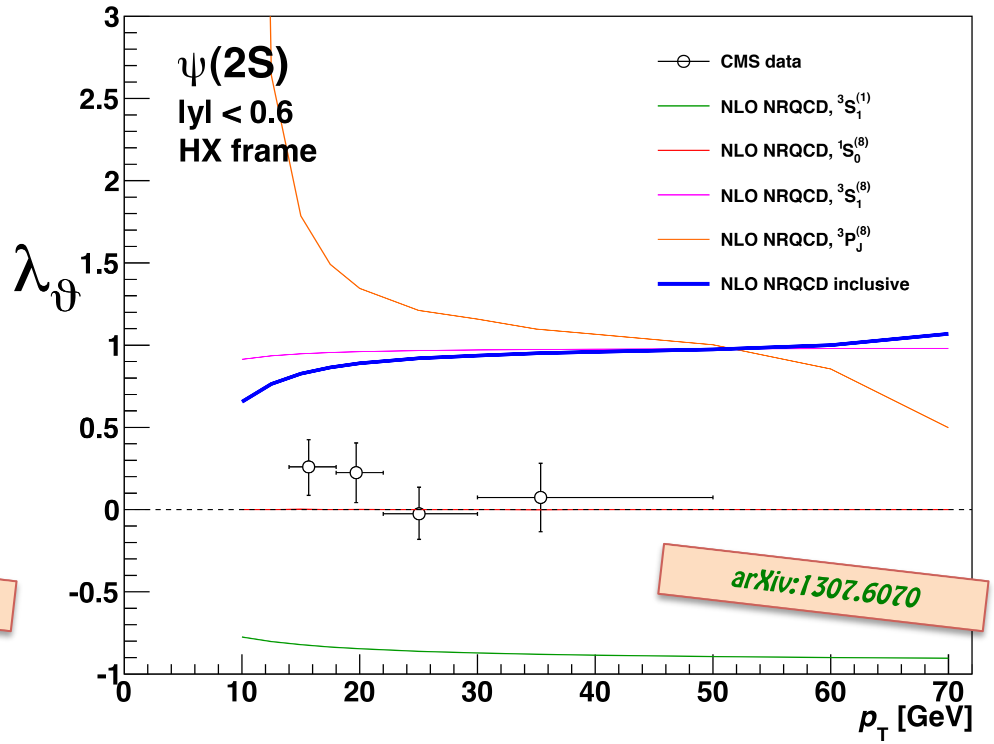
$O(^3S_1^{[8]}) = 0.00280\ \mathrm{GeV}^3$

$O(^3P_J^{[8]}) = 0.00168\ \mathrm{GeV}^5$

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





Many thanks to Mathias Butenschön and Bernd Kniehl for sending us their calculations and explaining them in detail

Summary

Cross sections and polarizations have been measured for five S-wave quarkonium states in pp collisions at $\sqrt{s}$ = 7 TeV

- ϒ(1S), ϒ(2S) and ϒ(3S)
  - both cross sections and polarizations measured with 4.9 fb^{-1} of data collected in 2011
- J/ψ and $\psi(2S)$
  - cross sections measured with only 37 pb^{-1} of data, collected in 2010 data
  - polarizations measured with 4.9 fb^{-1} of data collected in 2011

The χ_{c2} / χ_{c1} and $\chi_{b2}(1P) / \chi_{b1}(1P)$ cross-section ratios have also been measured, at 7 and 8 TeV, respectively

The menu will "soon" be complemented with more 8 TeV measurements:

- cross sections and feed-down fractions of P-wave states (χ_c and χ_b)
- polarizations of P-wave states (χ_{c1} ; χ_{c2} ; etc)
- J/ψ and $\psi(2S)$ cross sections up to very high p_T

all information in
twiki/bin/view/CMSPublic/PhysicsResultsBPH

Further reading

J/ψ and ψ(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]

Υ(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]

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

Relative production rate of χ_{b2}(1P) and χ_{b1}(1P)
CMS, CMS PAS-BPH-13-005 [20.7 fb^{-1}, 8 TeV] (to be made public soon)

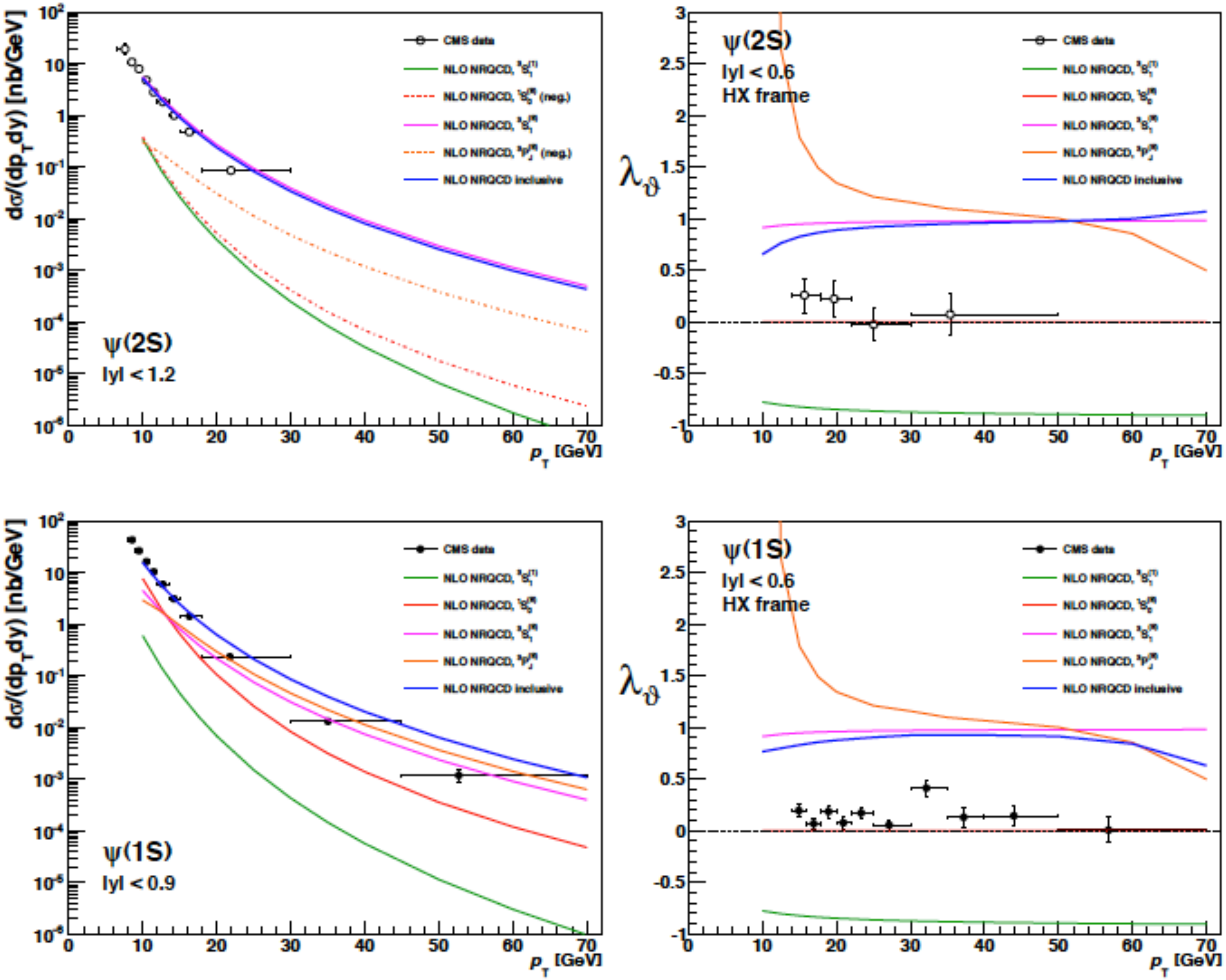
J/psi and ψ(2S) polarizations
ALICE: PRL 108 (2012) 082001 [100 nb^{-1}, 7 TeV]
CMS, arXiv:1307.6070 [4.9 fb^{-1}, 7 TeV]
LHCb: arXiv:1307.6379 [0.37 fb^{-1}, 7 TeV]

Υ(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]

NLO NRQCD studies of ψ(nS) and Υ(nS) cross sections and polarizations
M. Butenschön and B. Kniehl, PRL 108 (2012) 172002
B. Gong et al, arXiv:1305.0748

Backup

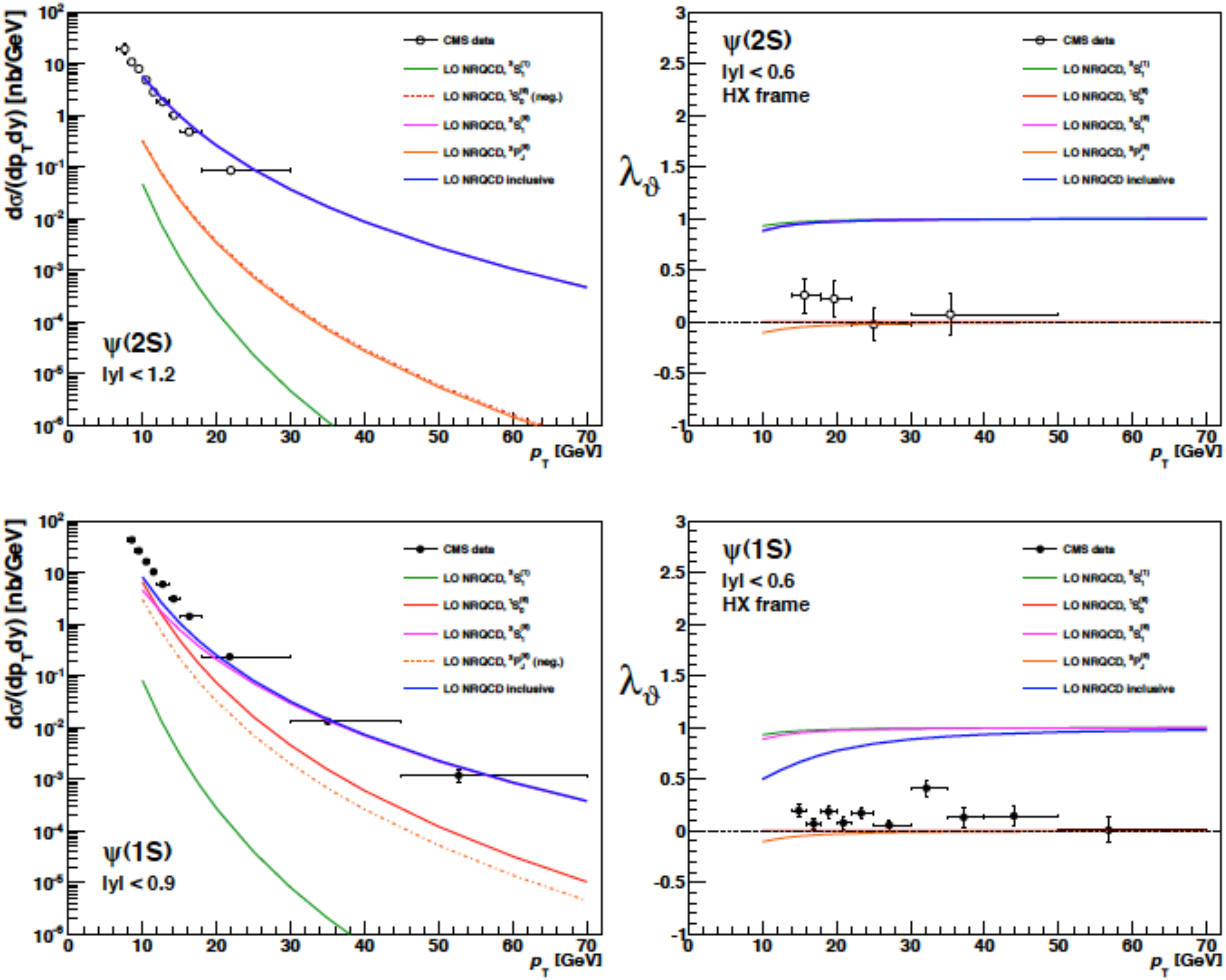
Singlet and octet terms in NRQCD at NLO



$\mathcal{O}^{^3S_1^{(1)}}_{\psi(2S)}$ =0.76 GeV^3,
$\mathcal{O}^{^1S_0^{(8)}}_{\psi(2S)}$ =-0.00247 GeV^3,
$\mathcal{O}^{^3S_1^{(8)}}_{\psi(2S)}$ =0.00280 GeV^3,
$\mathcal{O}^{^3P_J^{(8)}}_{\psi(2S)}$ =0.00168 GeV^5

$\mathcal{O}^{^3S_1^{(1)}}_{J/\psi}$ =1.32 GeV^3,
$\mathcal{O}^{^1S_0^{(8)}}_{J/\psi}$ =0.0497 GeV^3,
$\mathcal{O}^{^3S_1^{(8)}}_{J/\psi}$ =0.00224 GeV^3,
$\mathcal{O}^{^3P_J^{(8)}}_{J/\psi}$ =-0.0161 GeV^5

Singlet and octet terms in NRQCD at LO



$\mathcal{O}^{^3S_1^{(1)}}_{\psi(2S)}$ =0.76 GeV^3,
$\mathcal{O}^{^1S_0^{(8)}}_{\psi(2S)}$ =-0.00247 GeV^3,
$\mathcal{O}^{^3S_1^{(8)}}_{\psi(2S)}$ =0.00280 GeV^3,
$\mathcal{O}^{^3P_J^{(8)}}_{\psi(2S)}$ =0.00168 GeV^5

$\mathcal{O}^{^3S_1^{(1)}}_{J/\psi}$ =1.32 GeV^3,
$\mathcal{O}^{^1S_0^{(8)}}_{J/\psi}$ =0.0497 GeV^3,
$\mathcal{O}^{^3S_1^{(8)}}_{J/\psi}$ =0.00224 GeV^3,
$\mathcal{O}^{^3P_J^{(8)}}_{J/\psi}$ =-0.0161 GeV^5