Quarkonia Production and Polarization at the Hadron Colliders

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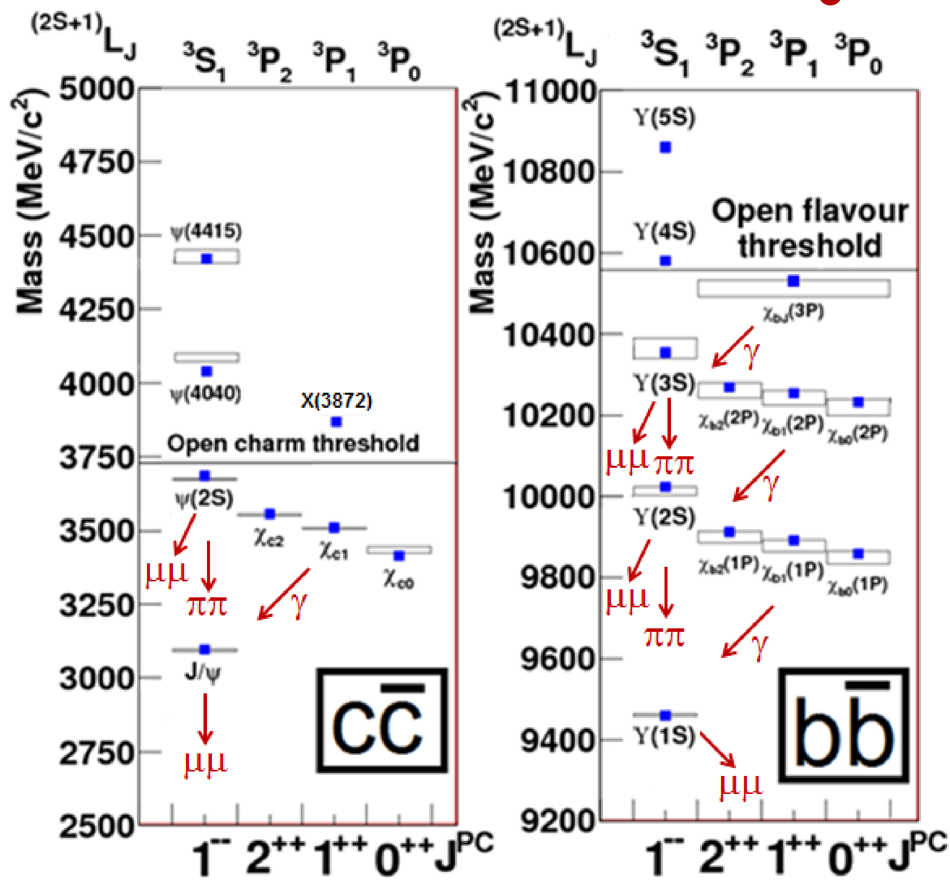
Quarkonium Introduction

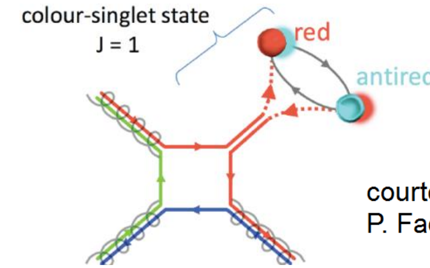
- Heavy quark $c\bar{c}$/$b\bar{b}$ bound state
- Generally well-understood system
- Motivations for study:
  - Important tests of QCD
  - Background to CPV/rare decays
  - Several emerging conflicts between theory and experiment
- Reconstruct decays to muons and radiative transitions



- Recent LHC results covered today:
  - Cross sections (J/ψ,ψ(2S),Υ(mS))
  - Production ratios (χ_{c2}/χ_{c1},χ_{b2}/χ_{b1})
  - Spin-alignment (polarization) measurements (J/ψ, ψ(2S), Υ(mS))
  - Other production channels (X(3872), J/ψ+J/ψ, W+J/ψ)

Color Singlet Model (CSM)

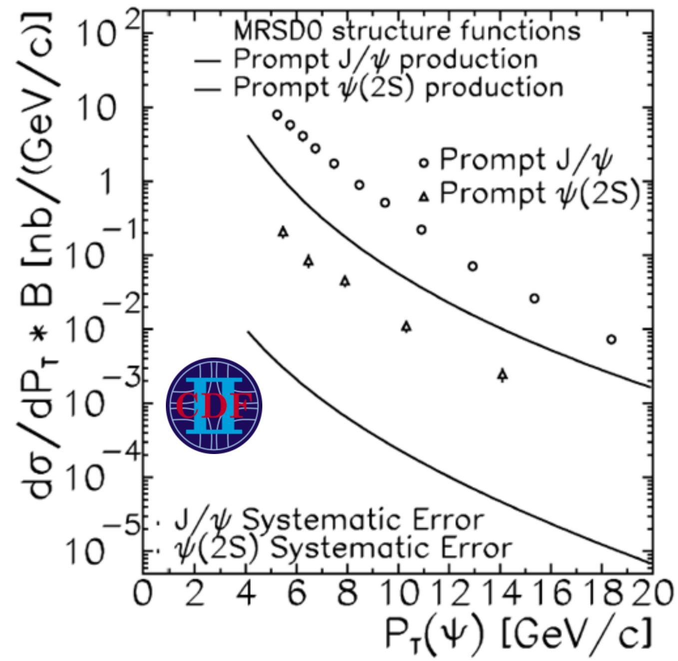
- Early model (~1970ies) for quarkonium production
- Heavy quark pair produced in a color singlet state evolves into the final state quarkonium with same quantum numbers (spin, color state)

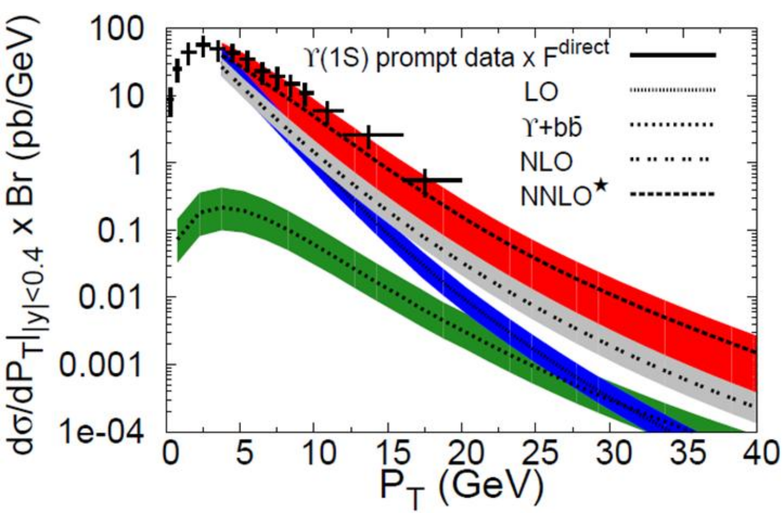


courtesy
P. Faccioli

- Initially successful until early CDF data
- Large disagreement with increasing p_T

CDF: PRL 79, 572 (1997)



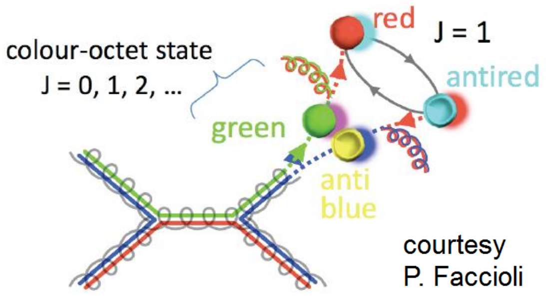


- Recent vast improvements with higher order (NLO, NNLO*) calculations

Artoisenet et al.: PRL 101, 152001 (2008)

Color Octet Model

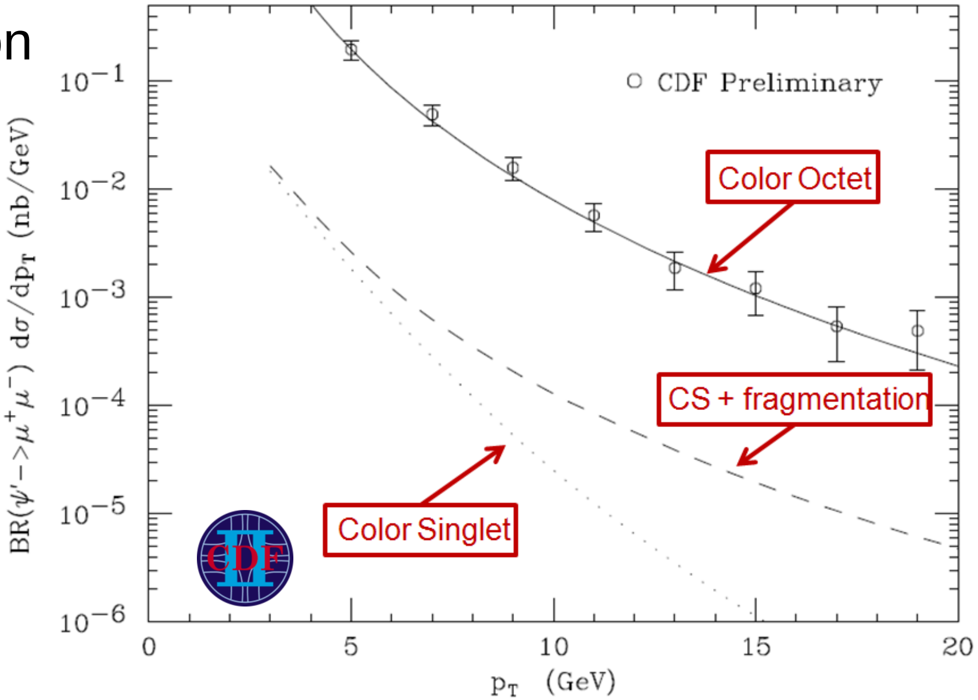
- Can also produce heavy quark pair in color octet state
- Evolves to singlet final state via soft gluon emission
- Calculations factorizable into perturbative part and Non-Relativistic QCD matrix elements fit to data



Bodwin, Braaten & Lepage: PRD 51, 1125 (1995)

- Very good agreement with production cross section data (by design)

Braaten & Fleming: PRL 74, 3327 (1995)



- Other models include:
  - Color Evaporation Model

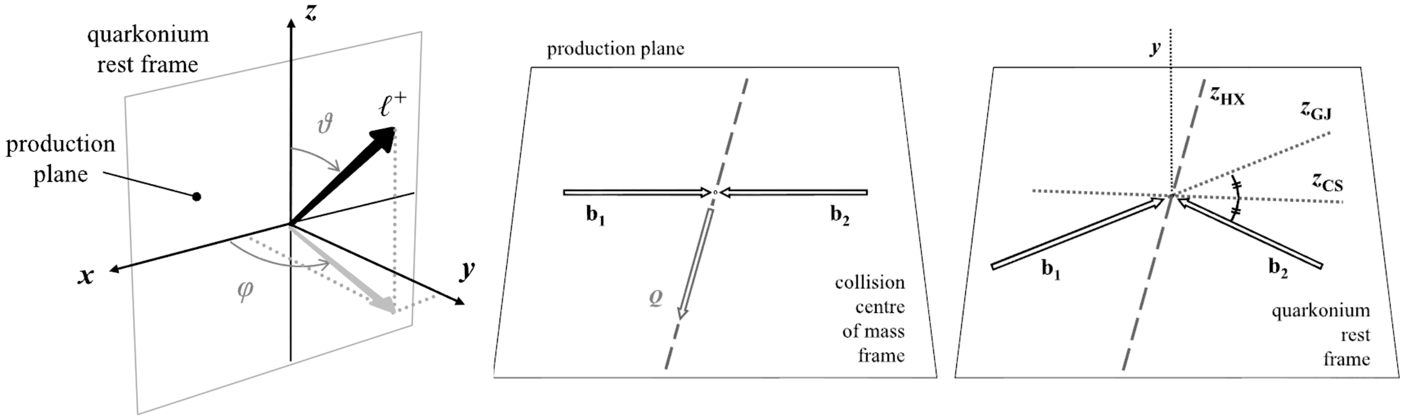
    Amundson et al.: PLB 390, 323 (1997)
  - k_T Factorization

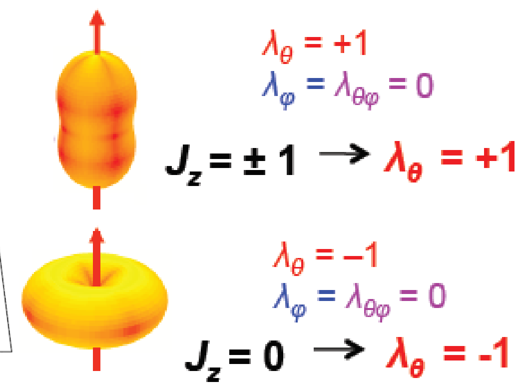
    Baranov: PRD 66, 114003 (2002)
  - (Not covered in detail here)

Spin Alignment (Polarization)

- Spin alignment quantified by the relative importance of spin-1 eigenstates in production by measuring the angular distribution of the leptonic pair decay

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



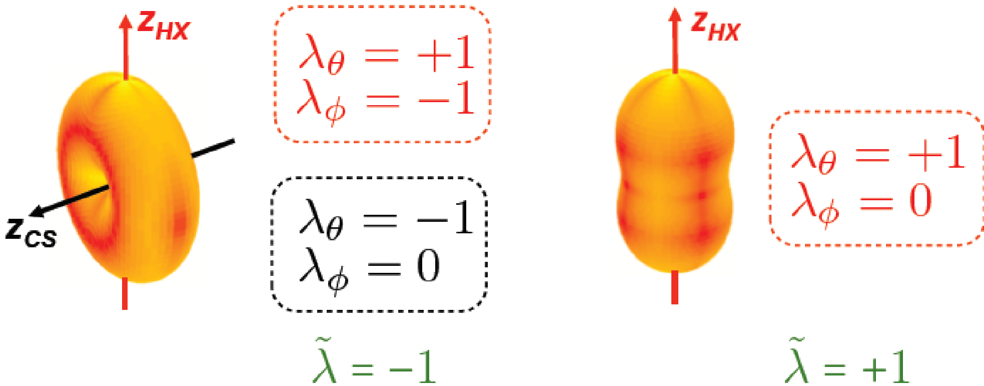


Faccioli et al.: EPJC 69, 657 (2010)

- Quantization axis "z" analysis-dependent, defining the reference frame:
  - Helicity (HX): quarkonium flight direction in the c.m. of the beams
  - Gottfried-Jackson (GJ): momentum direction of one of the beams
  - Collins-Soper (CS): average of the two beam directions

Spin Alignment (Polarization)

- Spin alignment results depend on choice of quantization axis, and cannot be determined by measuring a single parameter (e.g. λ_θ)



Faccioli et al.: EPJC 69, 657 (2010)

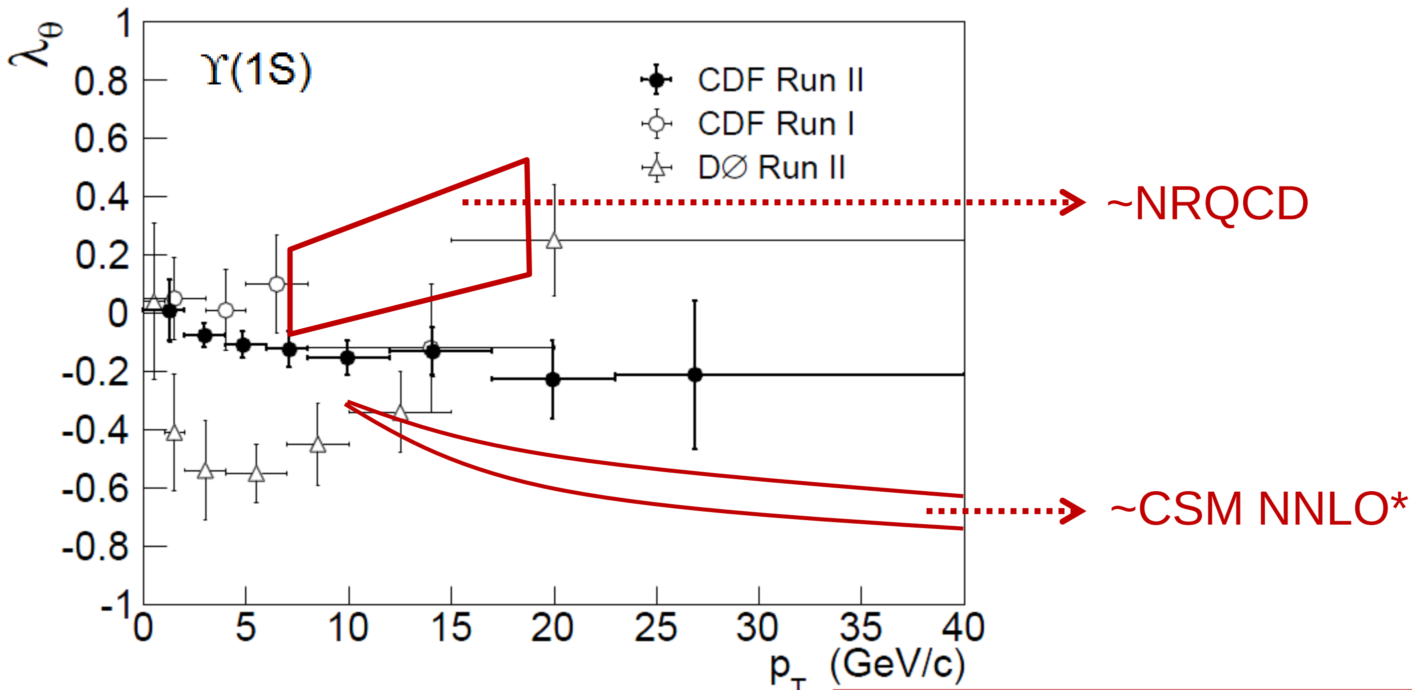
- Key measurables
  - All three polarization parameters (λ)
  - Multiple reference frames for cross-check
  - Verify with use of frame-invariant quantity

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

- Theoretical predictions (HX frame)
  - CO: “transverse” polarization (λ_θ = +1, $\lambda_\phi = \lambda_{\theta\phi}$ = 0)
  - CS: “longitudinal” polarization (λ_θ = -1, $\lambda_\phi = \lambda_{\theta\phi}$ = 0)
  - Differences make this measurement an ideal discriminator

Tevatron Spin Alignment Results

- Most recent result (CDF): Υ(1,2,3S) spin alignment

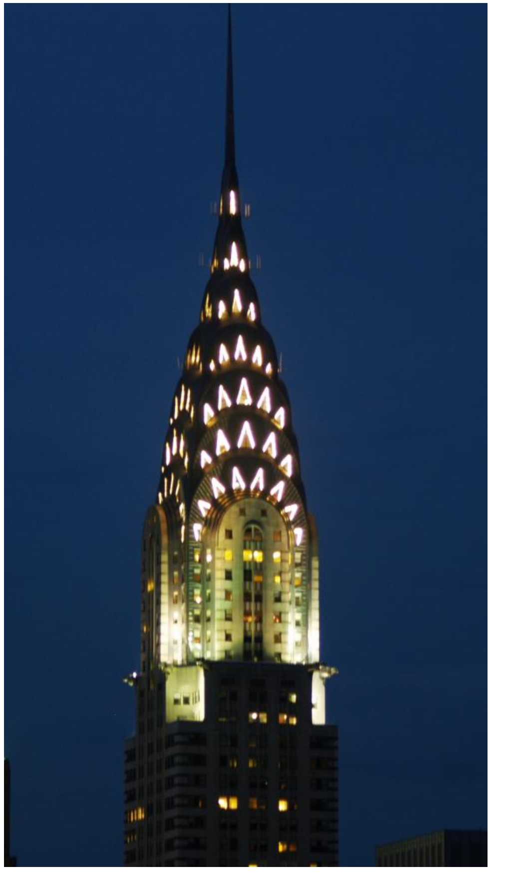


CDF: PRL 108, 151802 (2012)

- Consistent with previous CDF, inconsistent with DØ
- Inconsistent with both CSM and NRQCD predictions
- No clear evidence for polarization in Υ(1,2,3S)
- Turn to LHC to for further understanding

Introductory Summary

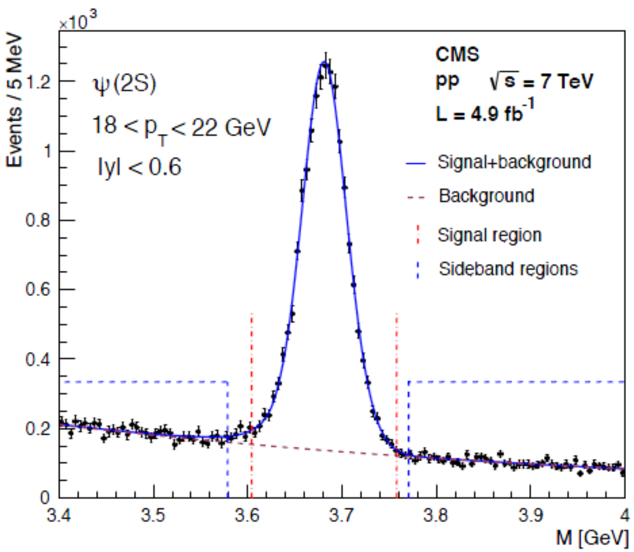
- Two leading contenders to describe quarkonia production
  - Color singlet: improved agreement with higher orders
  - Color octet: good agreement; tuned to data

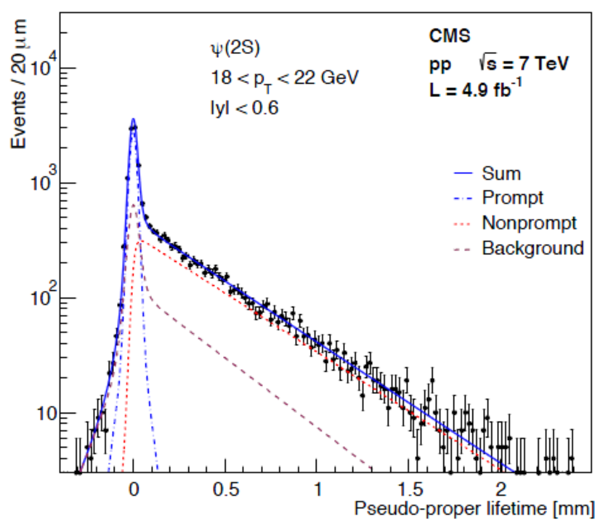


- Spin alignment ("polarization") has widely divergent theoretical predictions and can be a good discriminator
  - Ambiguous results from the Tevatron
- Next: LHC results offer new possibilities…
  - Higher luminosity and energy
  - Increased p_T and $|y|$ ranges

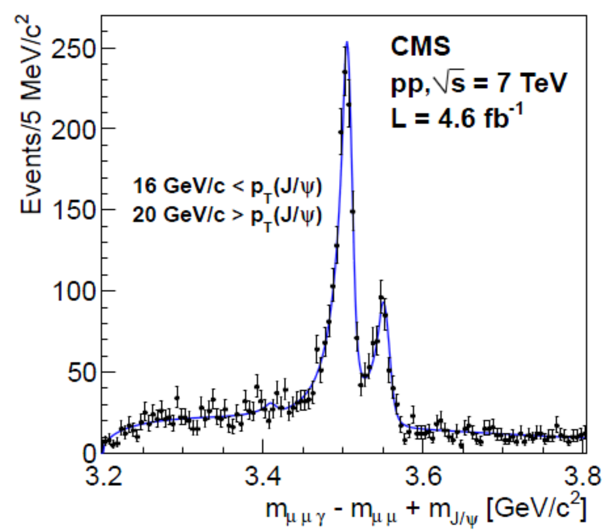
General Experimental Technique

- LHC measurements have higher luminosity, greater p_T reach
- Typically reconstruct J/ψ, $\psi(2S)$, $\Upsilon(1,2,3S)$ decays to $\mu^+\mu^-$
  - Understanding detector (muon) acceptance is crucial
  - Use sidebands to determine background
- Non-prompt $B \to c\bar{c}\,X$ decays defined by vertex-related variables
- For $\chi \to \gamma\psi$ use converted photons to separate J=1,2 states
- Fit $m_{\ell\ell}$ yield in bins of e.g.: p_T, $|y|$, $\cos\theta$, ϕ





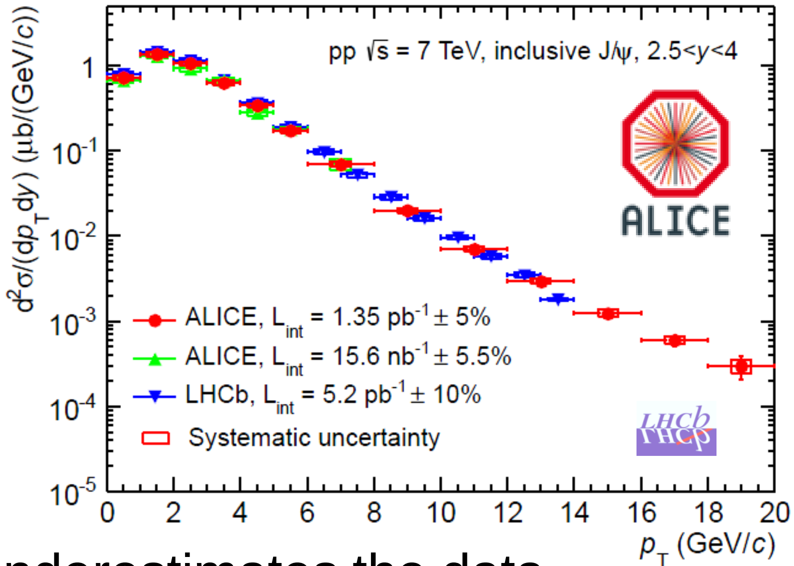
CMS: PLB 727, 381 (2013)

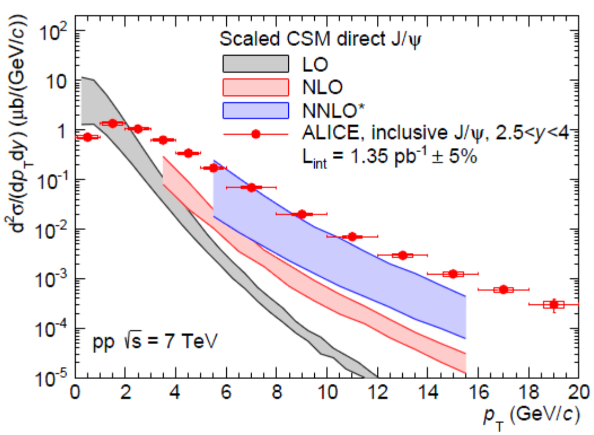


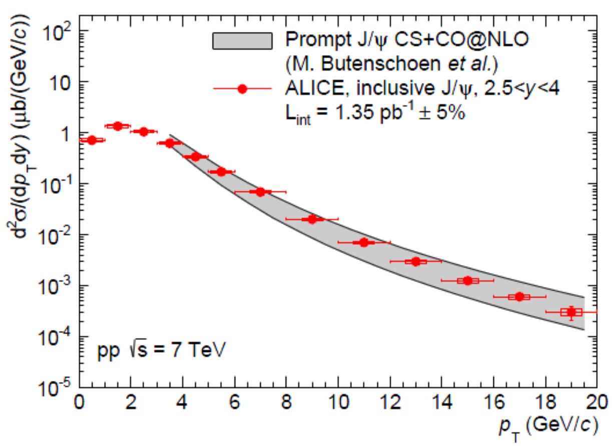
CMS: EPJC 72, 2251 (2012)

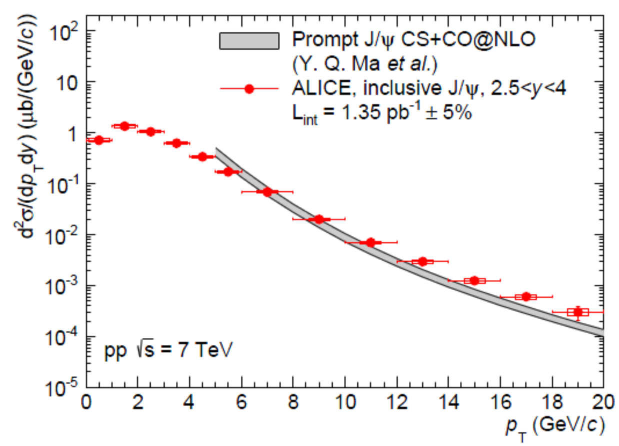
J/ψ Production Cross Section

- Highlighted result:
  ALICE: arXiv:1403.3648 (2014)
- Good agreement with LHCb
  - See also LHCb: EPJC 73, 2631 (2013) for higher statistics ($0.37 fb^{-1}$) result
  - (No ATLAS/CMS update since 2011)
- Theoretical comparison:
  - CSM NNLO* improves agreement but underestimates the data
  - Two NRQCD calculations show better agreement



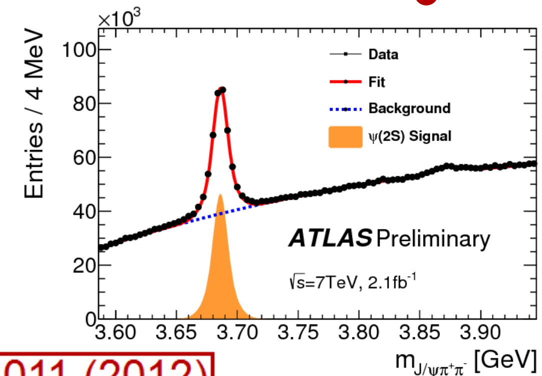




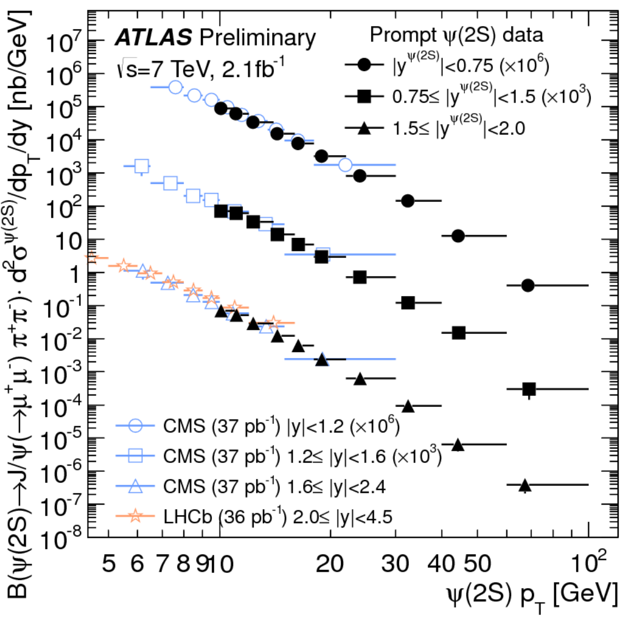


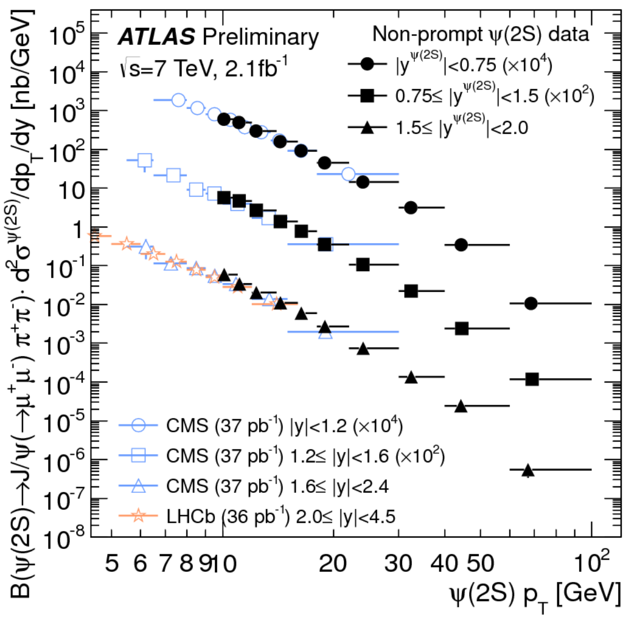
ψ(2S) Production Cross Section

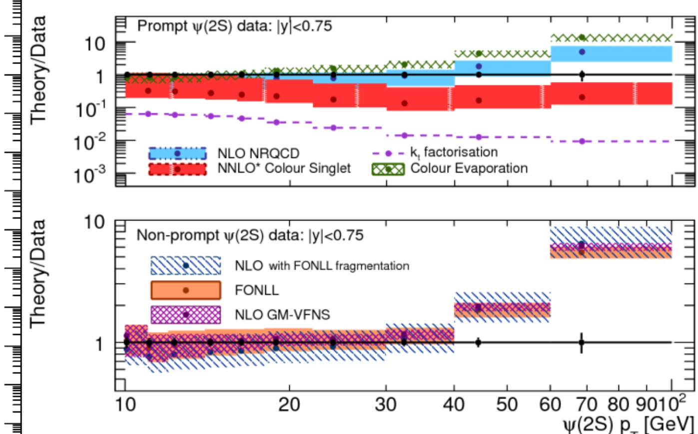
- Highlighted result: ATLAS: arXiv:this week! (2014)
  - Considers $\psi(2S)\to\pi^+\pi^- J/\psi$ rather than $\psi(2S)\to\mu^+\mu^-$
  - Non/prompt fractions by pseudo-proper lifetime
- Good agreement with previous measurements
  - Plot includes: LHCb: EPJC 72, 2100 (2012) CMS: JHEP 02, 011 (2012)
- Data agree with NRQCD up to highest p_T, CS undershoots
- Large non-prompt disagreement at high p_T



See talk by D. Price Heavy Flavor 2

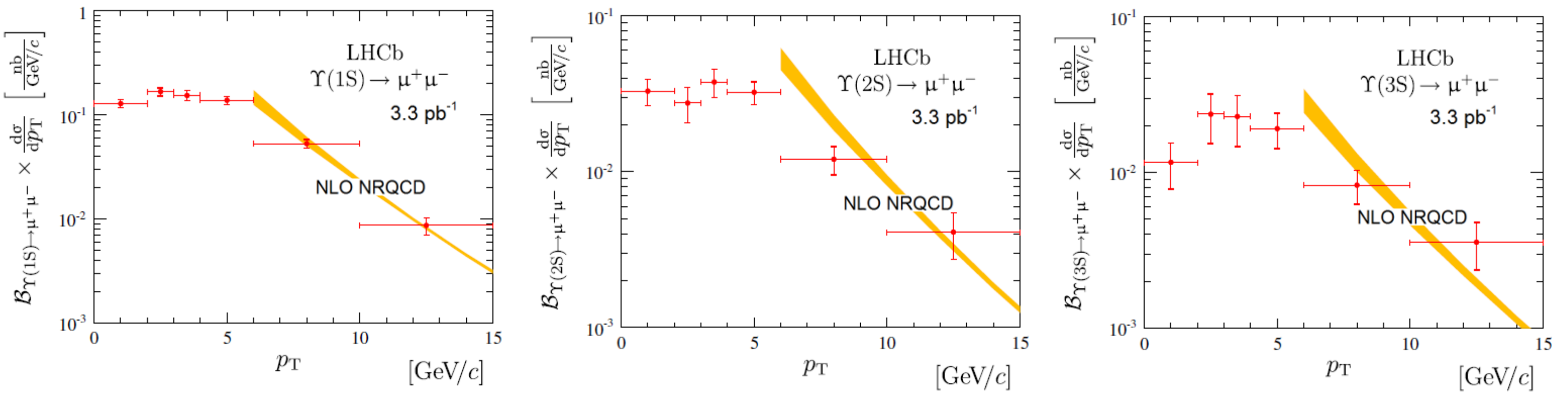




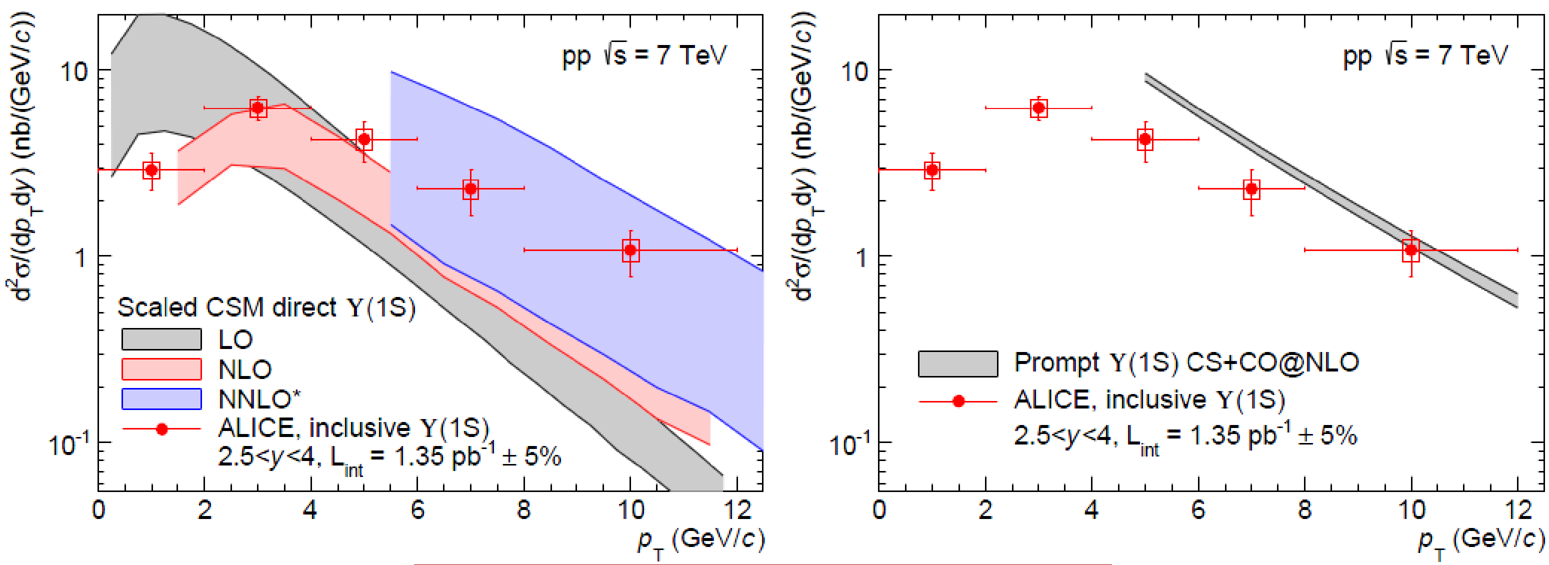


Low-p_T $\Upsilon(mS)$ Production Cross Section

- Recent experimental results agree; theory reach is limited



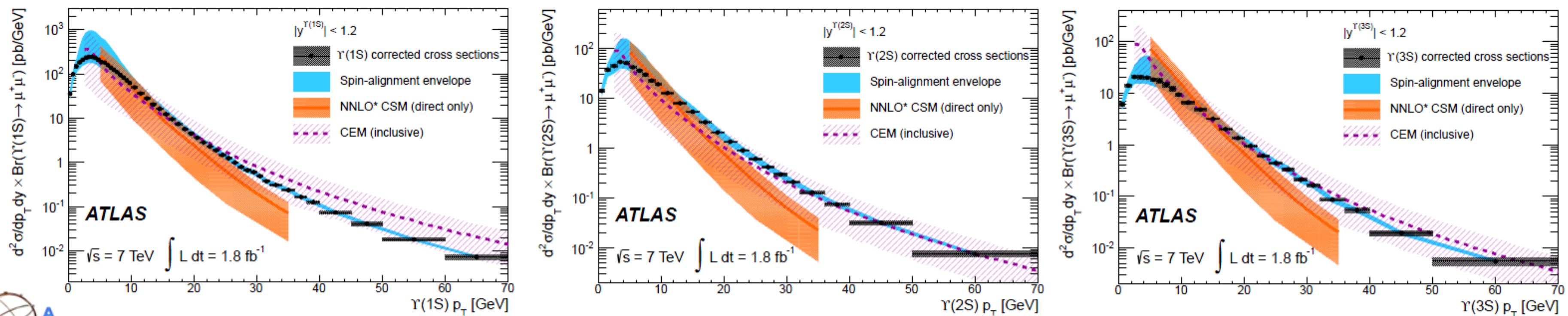
LHCb: EPJC 74, 2835 (2014)



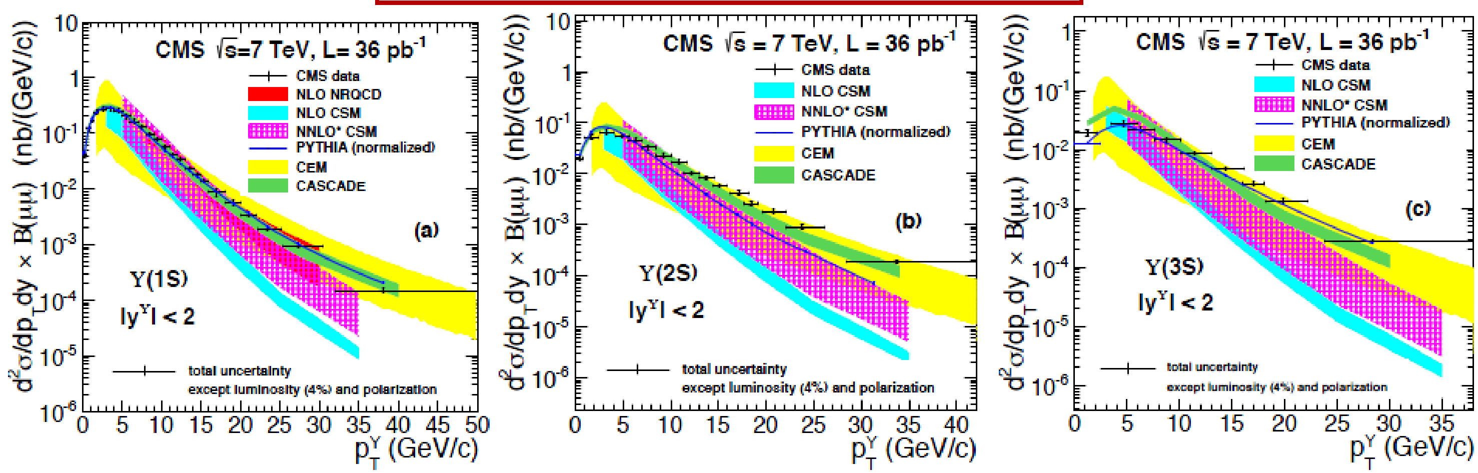
ALICE: arXiv:1403.3648 (2014)

High-p_T $\Upsilon(mS)$ Production Cross Section

- ATLAS and CMS results consistent with one another
- Reasonable agreement with theory (CSM and COM); worsens with p_T
- Departure may be due to feed-down contributions



ATLAS: PRD 87, 052004 (2013)

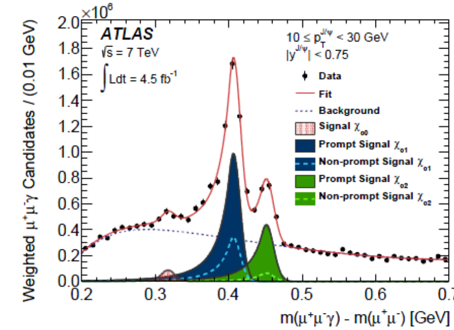


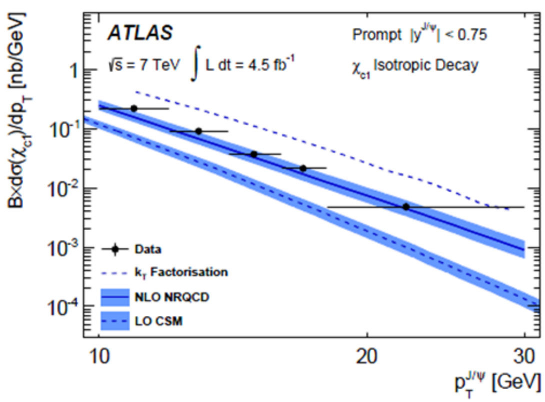
CMS: PLB 727, 101 (2013)

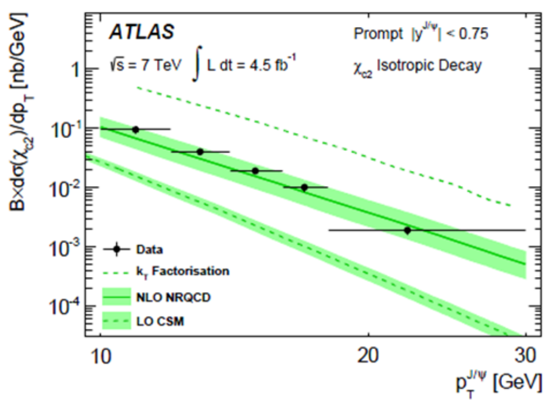
χ_{cJ}(1P) Production

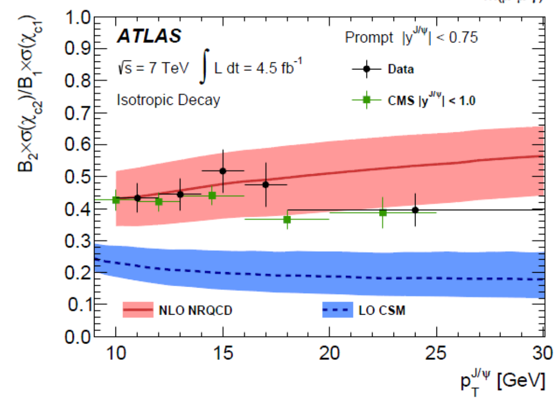
- Measurement of χ_{c2}/χ_{c1} production rates/ratio
  - Reconstruct $\chi_c \rightarrow \gamma J/\psi$ using converted photon
  - First measure of absolute χ_{cJ}(1P) rates
- Best agreement with NLO NRQCD predictions
  - (Plot includes CMS: EPJC 72, 2251 (2012))

ATLAS: arXiv:1404.7035 (2014)



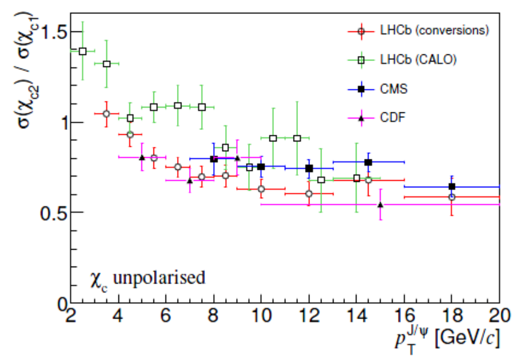


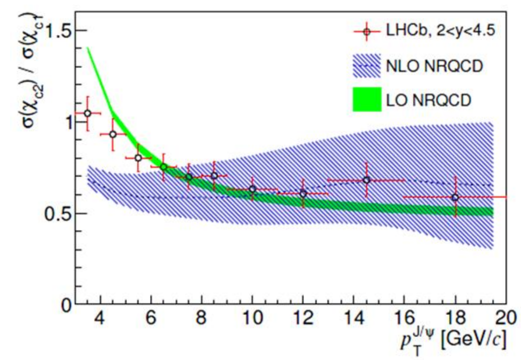




- Low-p_T, χ_{c2}/χ_{c0} probed by LHCb
- Consistent with previous results

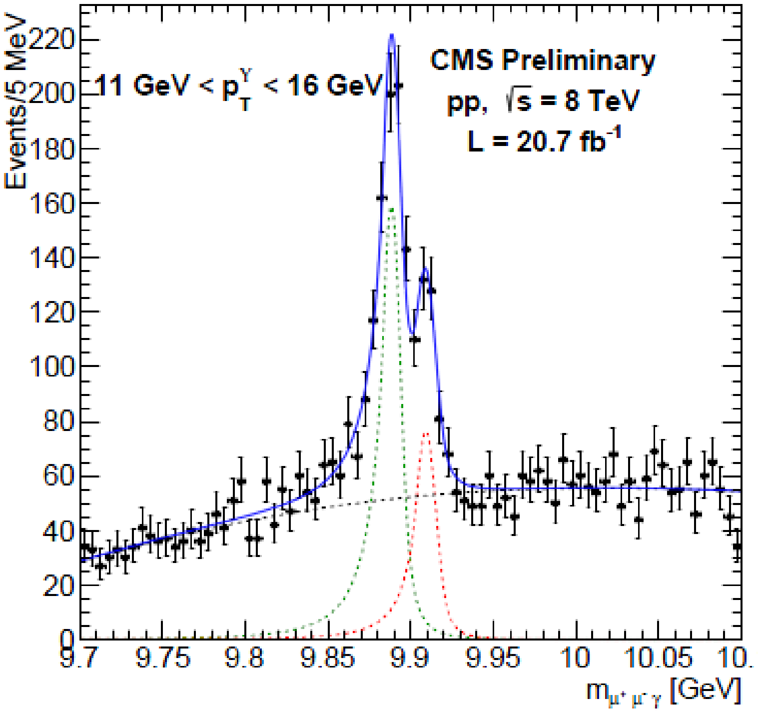
LHCb: JHEP 10, 115 (2013)

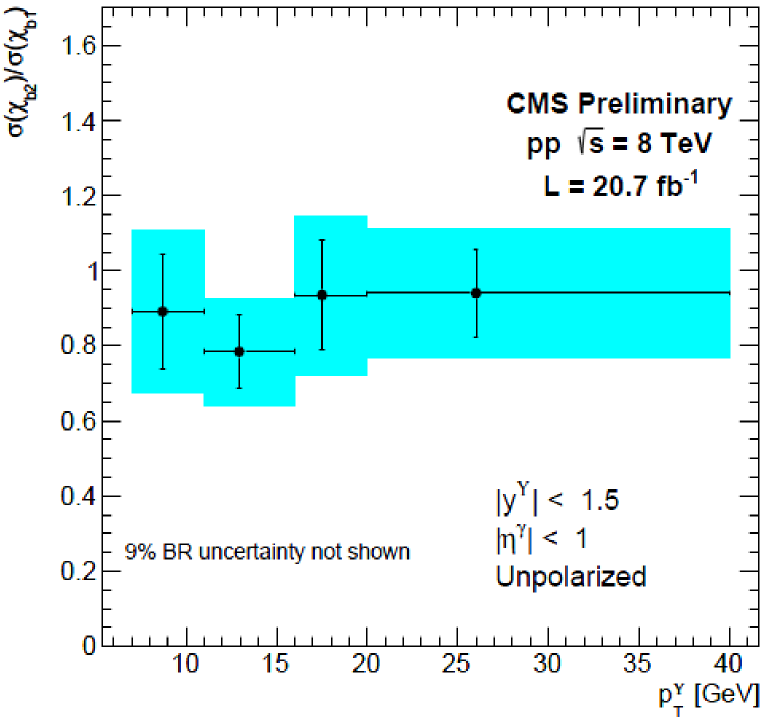




$\chi_{b1,2}$(1P) Production Ratios

- CMS preliminary CMS: CMS-PAS-BPH-13-005 (2013)
- Reconstruct $\chi_b \to \gamma\Upsilon(1S)$ using converted photon
- Difficult measurement due to small (~20MeV) χ_{b1}-χ_{b2} splitting
- First LHC experiment to resolve these as separate peaks



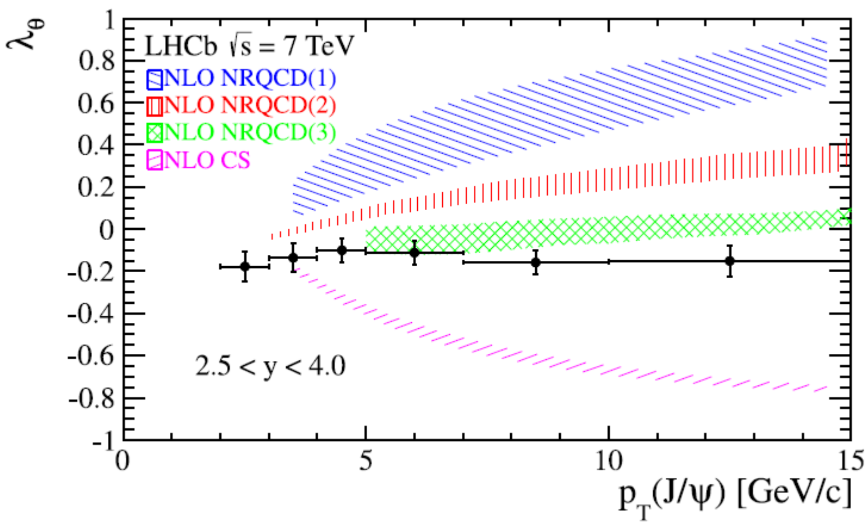


Production Cross Section Summary

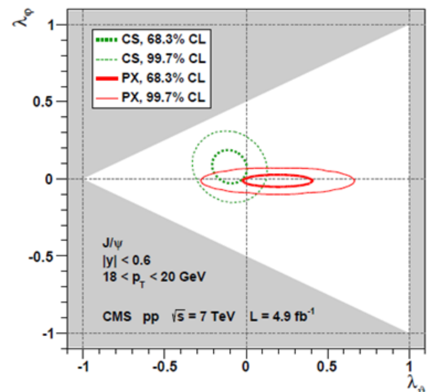
- LHC results span and are consistent across kinematic range
- Analysis of spin-1 (J/ψ, $\psi(2S)$, $\Upsilon(1,2,3S)$) states well-covered
  - Next step: analysis of χ_c, χ_b
- Production cross sections agree with theory up to high p_T
  - Color octet predictions generally best
- Next: Spin alignment…
  - Does the LHC resolve the issues seen in Tevatron data?

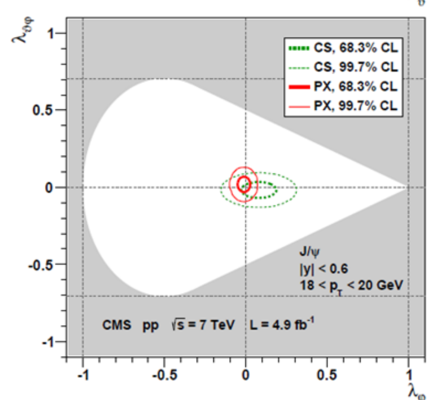
J/ψ Spin Alignment

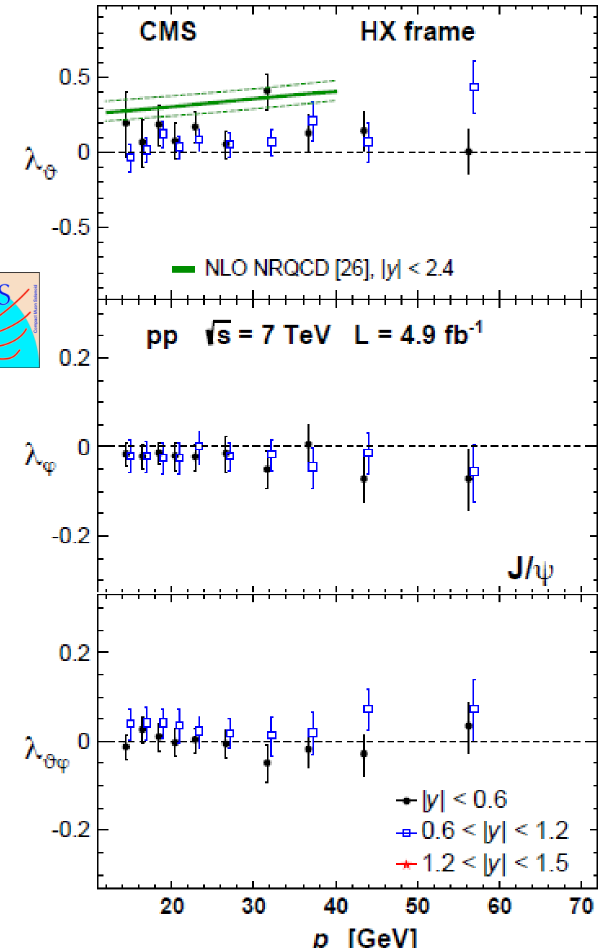
- Two LHC results complementary in p_T coverage
- Fit to all parameters and invariant as crosscheck
- Isotropic distributions: minimal polarization (if any)
- Disagreement with both CSM and COM
  - Due to $\chi_c(1P)/\psi(2S)$ feed-down effects?



LHCb: EPJC 73, 2631 (2013)





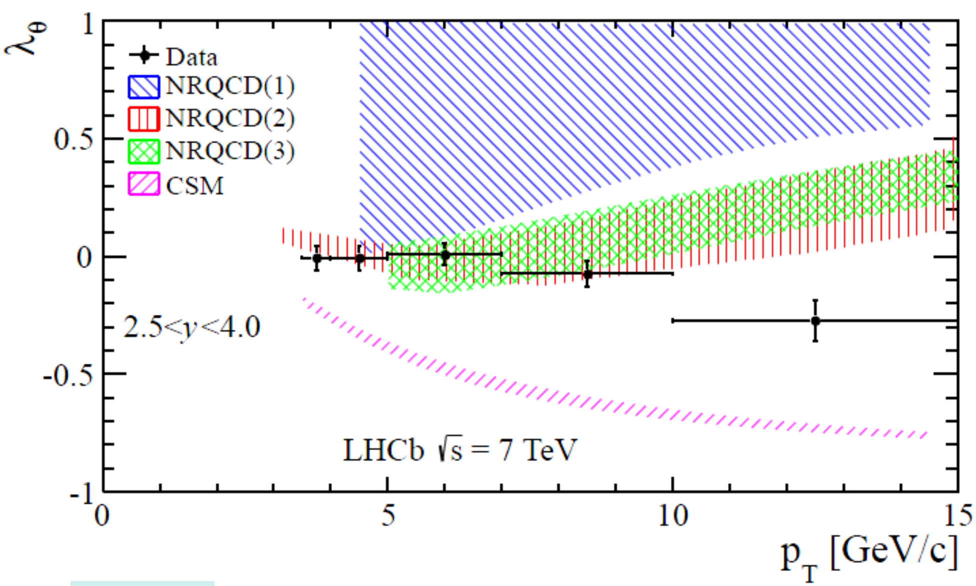


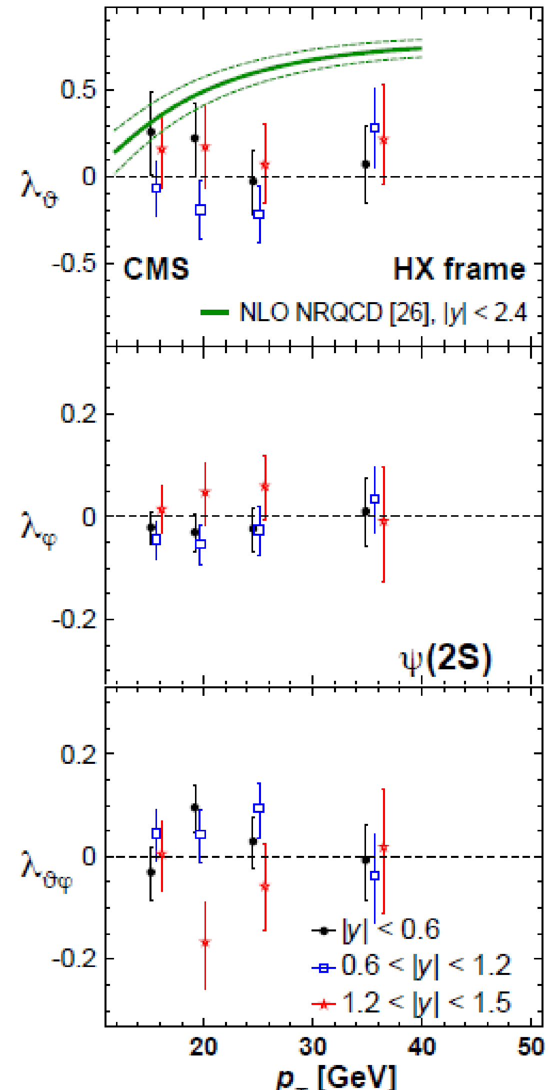
CMS: PLB 727, 381 (2013)

See talk by A. Pompili
Heavy Flavor 1

ψ(2S) Spin Alignment

- No feed-down effects, same result
- No evidence for polarization
- No agreement with CSM
- Some COM agreement at low p_T
- No agreement with theory at higher p_T



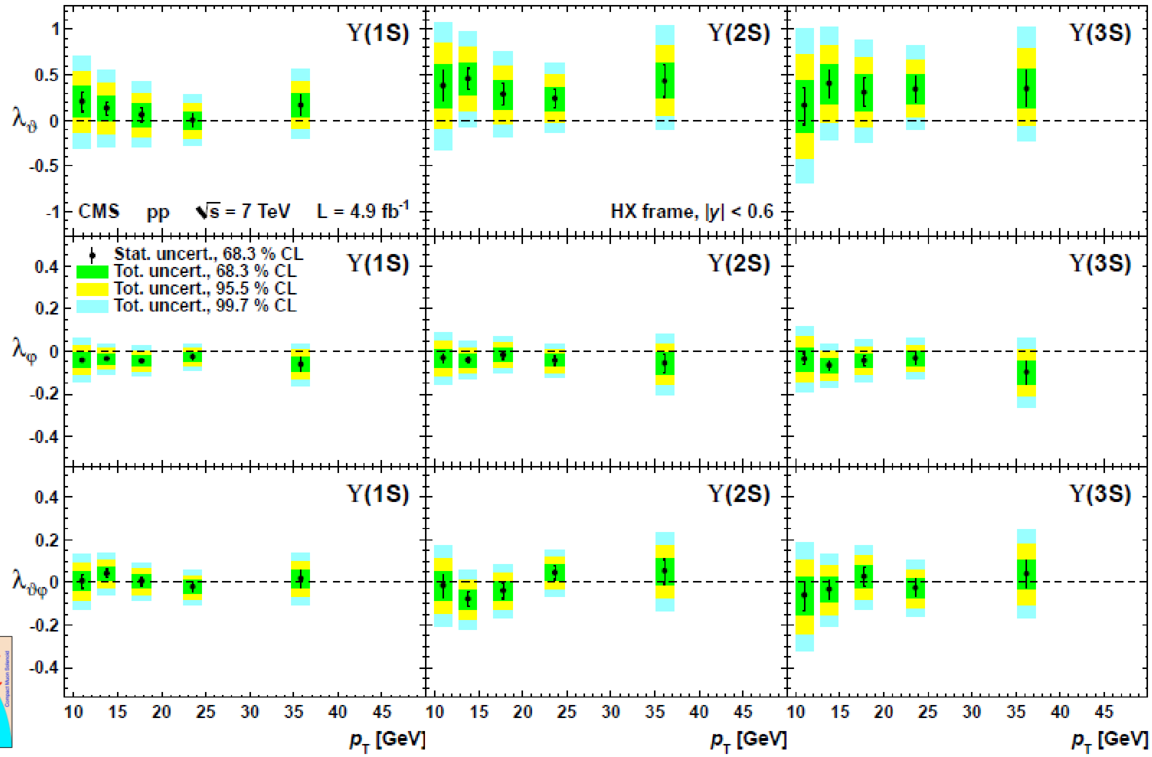


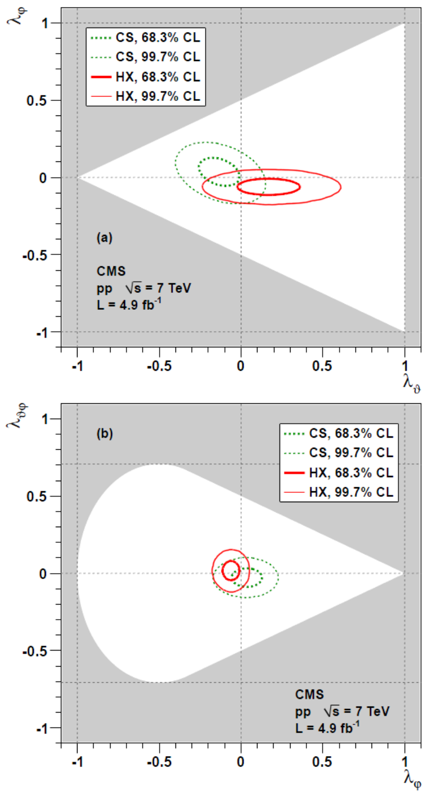
LHCb: arXiv:1403.1339 (2014)

CMS: PLB 727, 381 (2013)

ϒ(mS) Spin Alignment

- Expect better theory agreement with bottomonium and higher p_T
- CMS analysis results CMS: PRL 110, 081802 (2013)
  - Small/no polarization seen for any ϒ(mS) states
  - Could be effected by χ_b(nP) feed-down (even ϒ(3S))?





Spin Alignment Summary

- LHCb/CMS results span wide p_T and |y| kinematic range

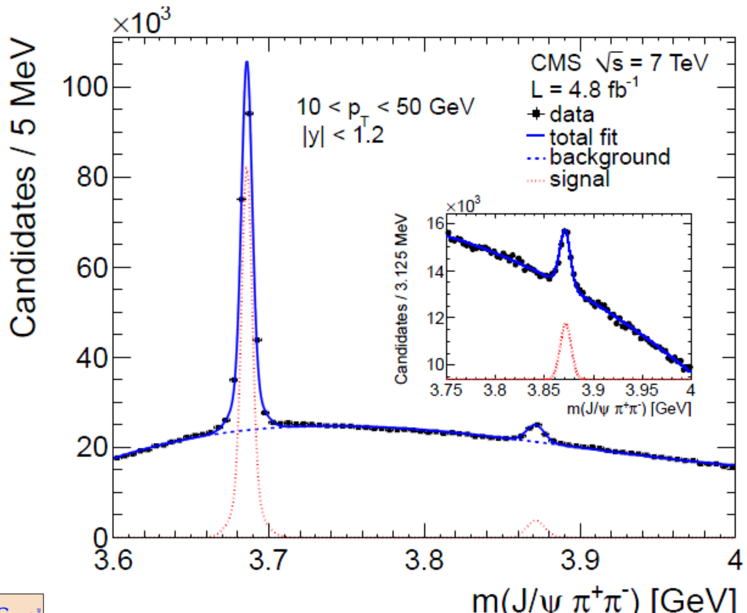
- No evidence for ANY polarization in ANY spin-1 production
  – Disagreement with both leading theory candidates
  – Feed-down effects not understood but cannot account for departure of results from theory (i.e.: ψ(2S))

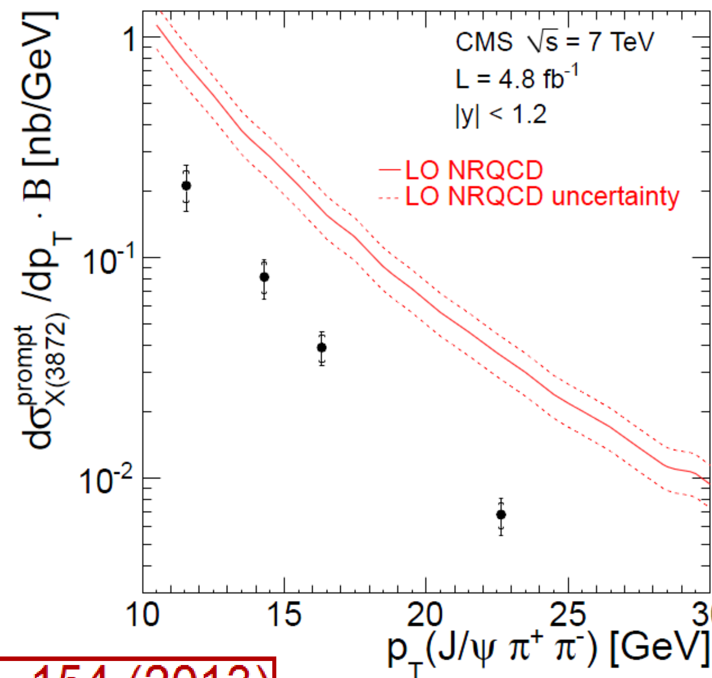
- Next: Other tests of production theory

CMS: X(3872) Production Cross Section

- Charmonium-like X(3872) discovered in $\pi^+\pi^- J/\psi$ decay at the B-Factories
- Believed to be a tetraquark: charm meson ($D\bar{D}^*$) molecule or otherwise
- NRQCD production rate prediction exists based on Tevatron results

Artoisenet and Braaten: PRD 81, 114018 (2010)



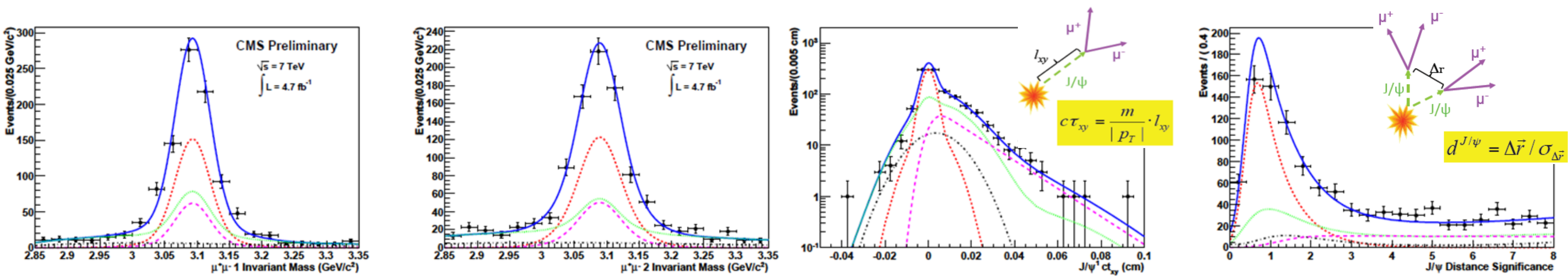


CMS: JHEP 04, 154 (2013)

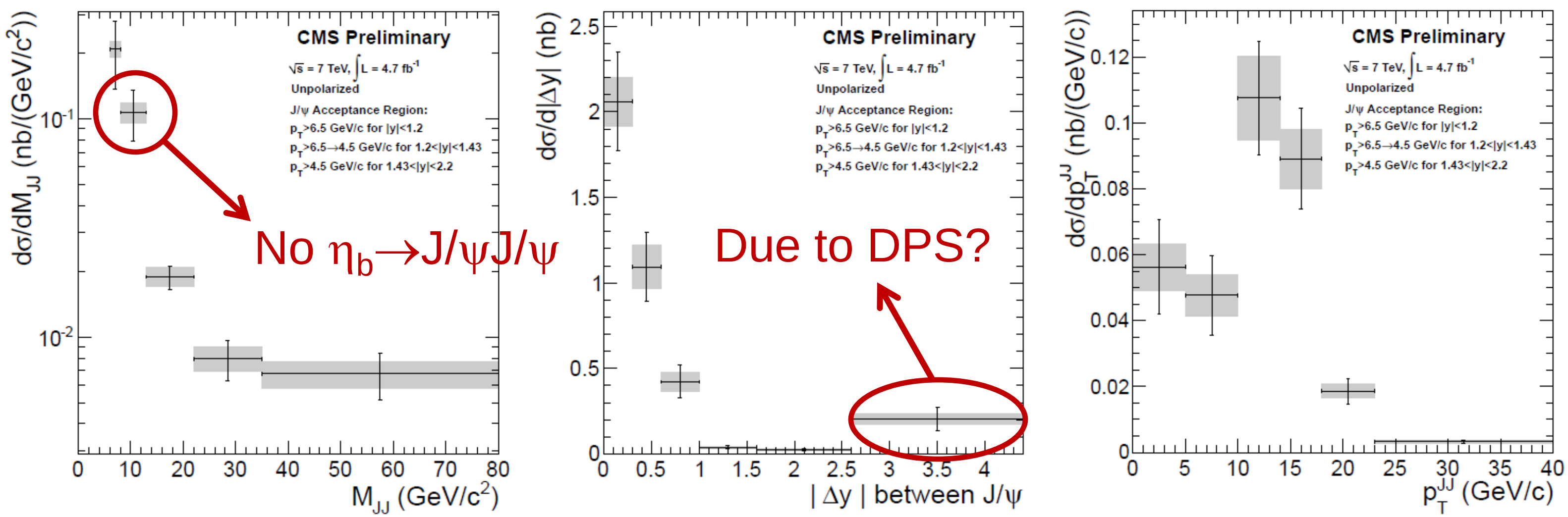
- Cross section has correct p_T dependence, but rate ~10x below prediction

CMS: Double J/ψ production

- Study production (single or double parton scattering) of double J/ψ
- Fit variables: $m_{J/\psi}$(high/low p_T), decay length, J/ψ distance significance



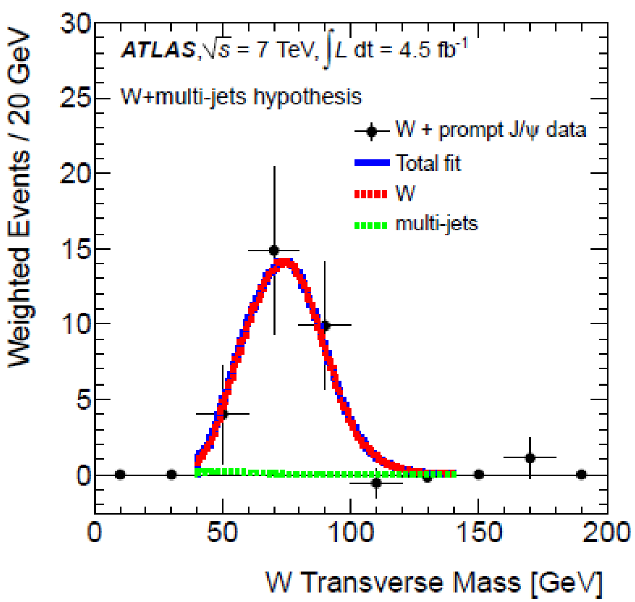
- Observe 446+/-23 prompt double J/ψ events from same vertex

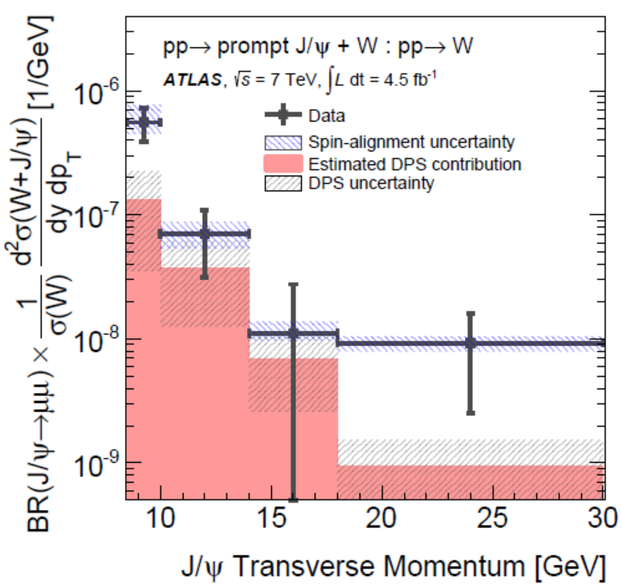


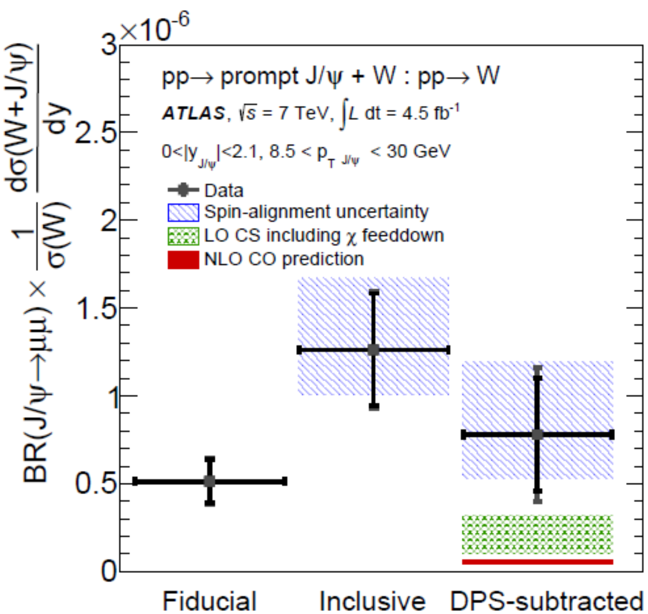
CMS: CMS-PAS-BPH-11-021 (2013)

ATLAS: W + Prompt J/ψ Production

- Theoretical prediction CS>>CO production contribution
- First observation: previous CDF search for J/ψ+W and J/ψ+Z had null results
- Reconstruct $J/\psi \to \mu^+\mu^-$ and $W \to \mu\nu$, fit to $m_{J/\psi}$ and pseudo-proper time
- Estimate and subtract DPS contribution; results >10x than prediction







ATLAS: JHEP 04, 172 (2014)

See talk by U. Blumenschein QCD 2 (Thursday PM)

Conclusions

- Summary
  - All LHC experiments provide results spanning |y| and p_T, providing new insights into quarkonium production
  - Color octet model calculations agree best with data
  - No polarization, disagreeing with leading theories
- Outlook
  - Experiments to exploit Run-II to increase statistics and p_T reach, to confirm results and explore χ_c & χ_b
  - Theoretical understanding of polarization: fit to new data to further understand color octet contributions

    Faccioli et al.: arXiv:1403.3970 (2014)
  - Study of more “quarkonium + X” channels

LHC is key to solving the puzzles of quarkonium hadroproduction

Thank you for your attention!