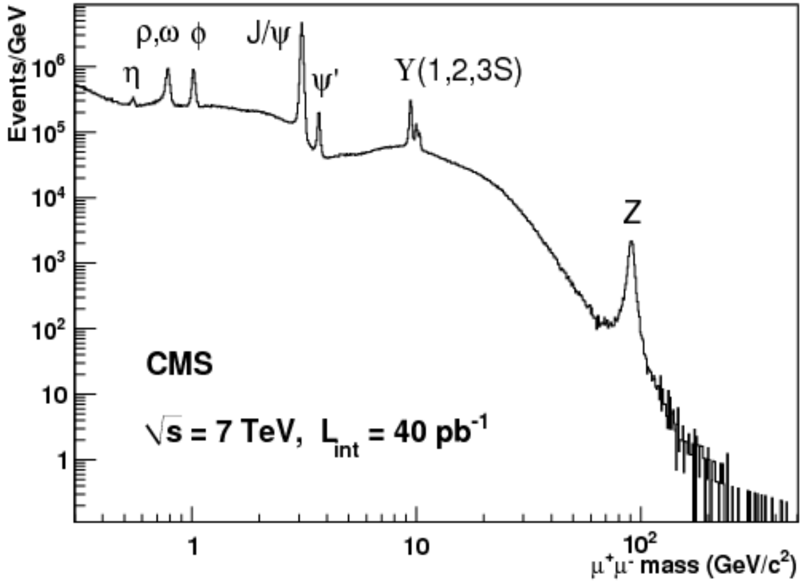
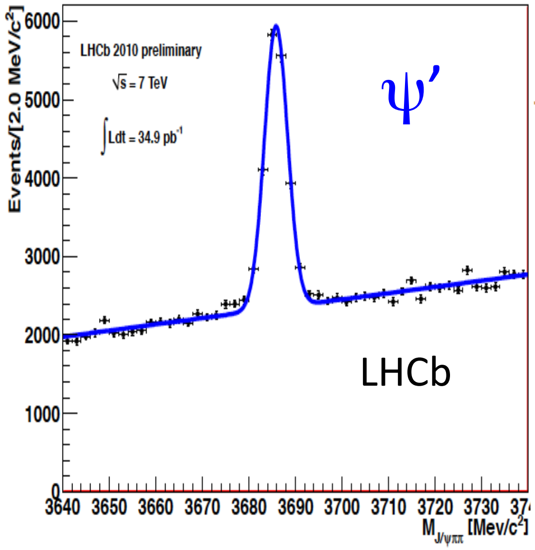
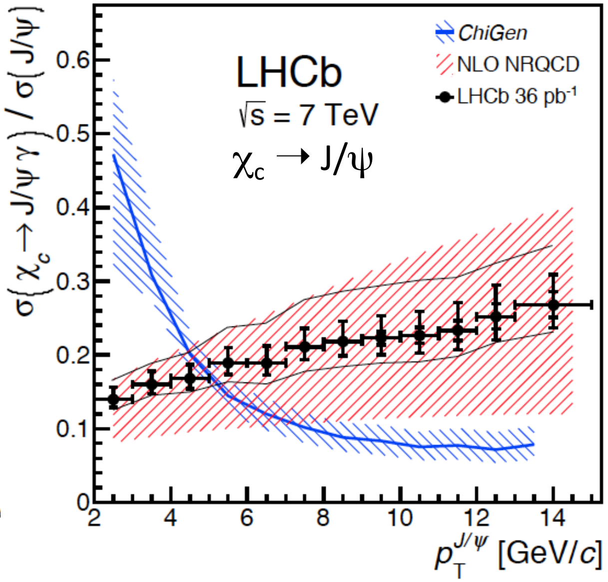
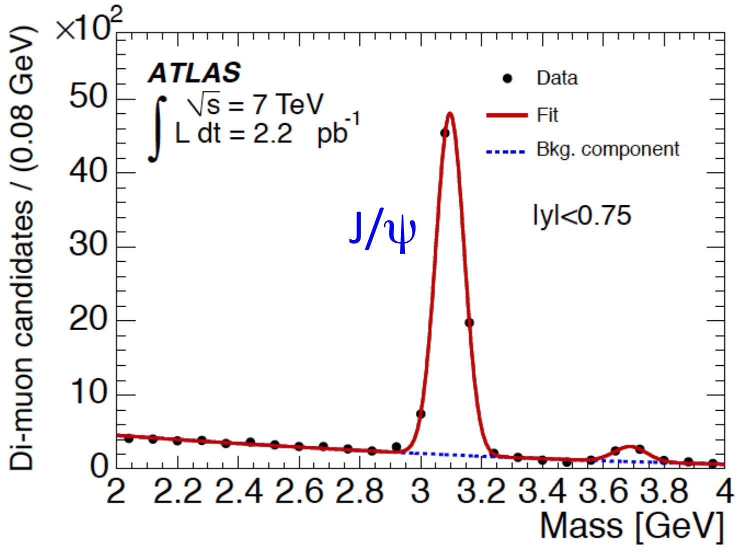
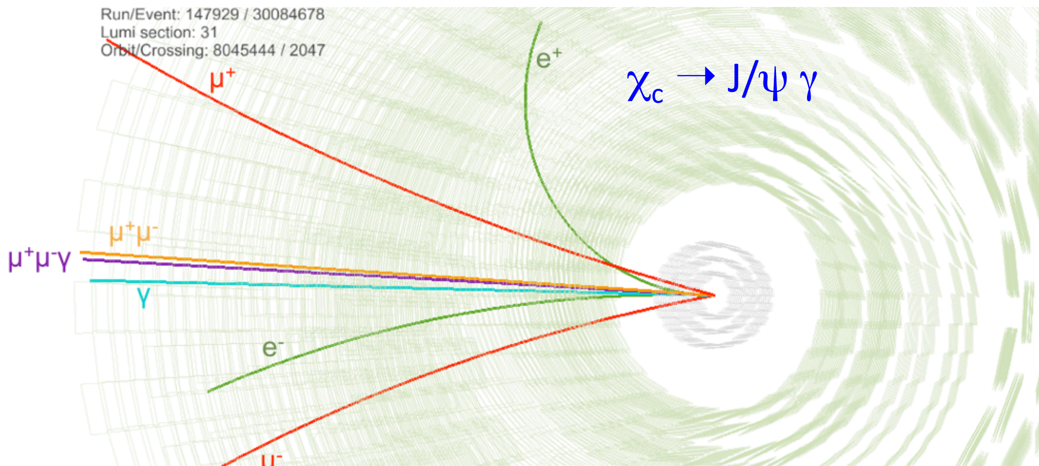
Highlights from quarkonium production at the LHC











Hermine K. Wöhri, CERN

Workshop on charmonium production and decays
LAL, Orsay, 6–8 March 2013

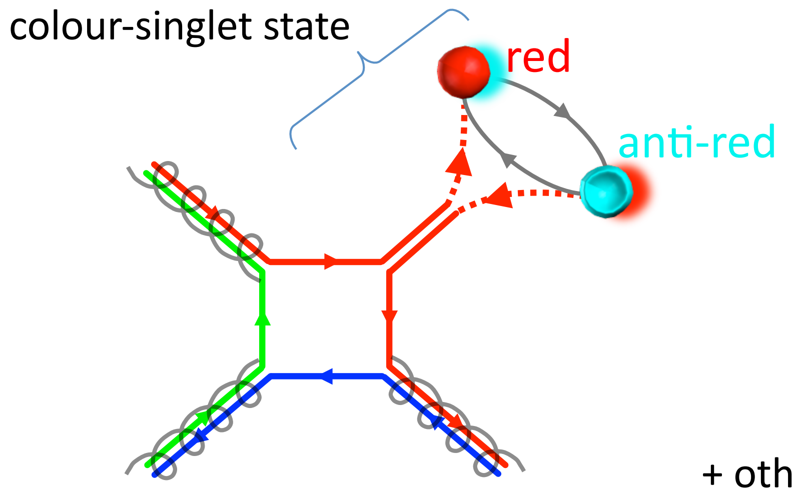
In collaboration with Pietro Faccioli,
Carlos Lourenço and Ramona Vogt

Quarkonium studies: a one-slide motivation

the illustrated edition

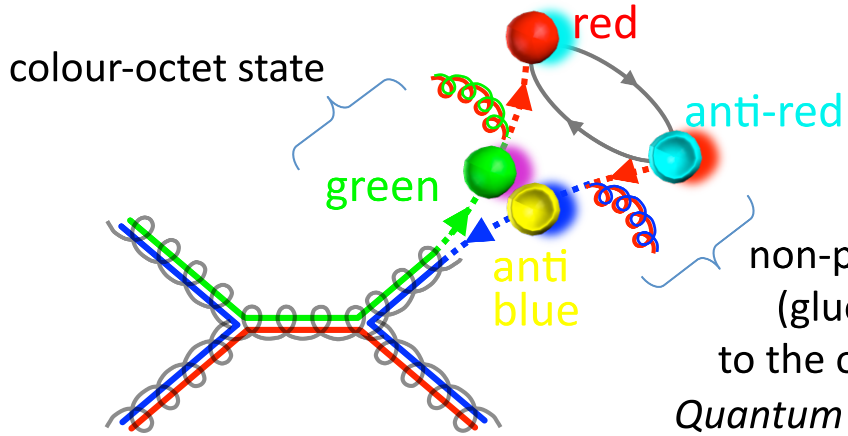
- Quarkonia: ideal probes of hadron formation (QCD); but production is not yet understood
- How/when do the observed *Q*-*Q*bar bound states acquire their quantum numbers?

- **Colour Singlet Model**: quarkonia always produced directly as observable ***colour-neutral*** *Q*-*Q*bar pairs



+ other colour combinations

- **NRQCD factorization**: quarkonia also produced as ***coloured*** *Q*-*Q*bar pairs *of any possible quantum numbers*



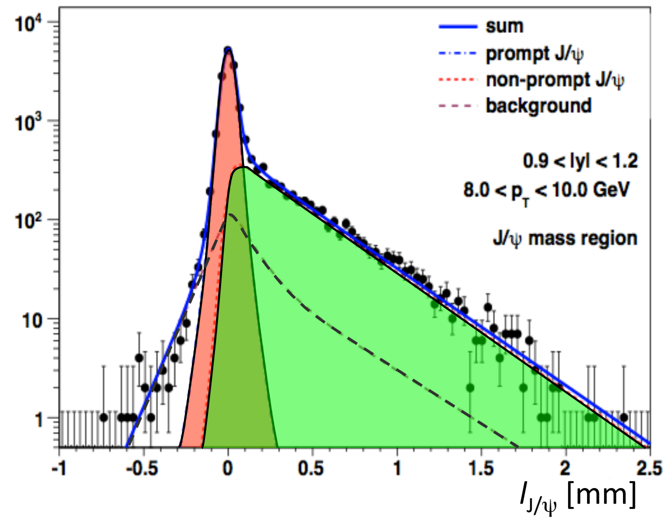
non-pert. transition (gluon emission) to the observable state *Quantum numbers change !*

- Two options leading to strong polarizations (longitudinal and transverse, resp.) for the directly-produced S-states → polarization measurements are fundamental

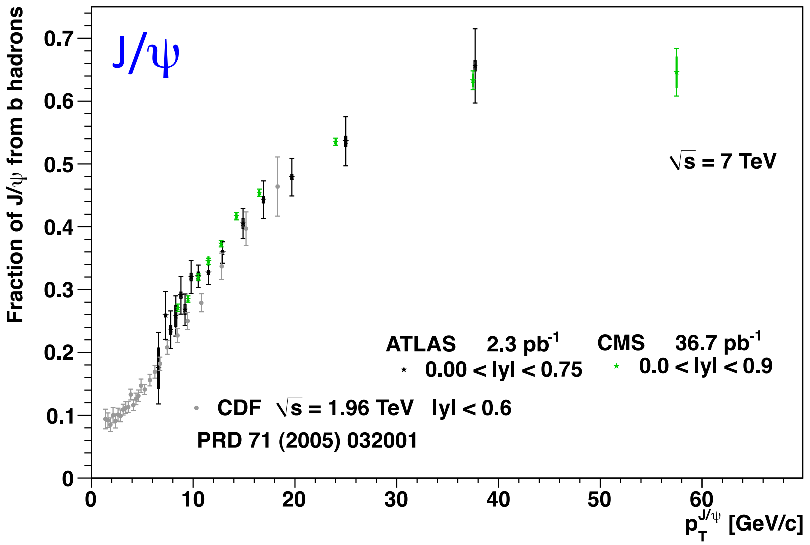
Figures by Pietro Faccioli

B feed-down to J/ψ and ψ'

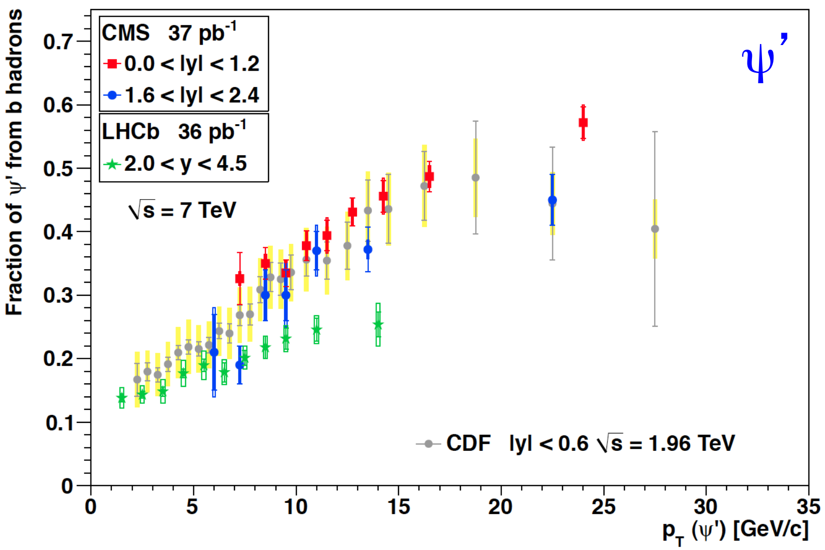
- Large B ($B \to \psi X$) : *background* for quarkonium studies
- For p_T > 20 GeV/c more than 50% of all ψ's come from B decays!
- Weak dependence on beam energy, from √s = 1.96 to 7 or 8 TeV

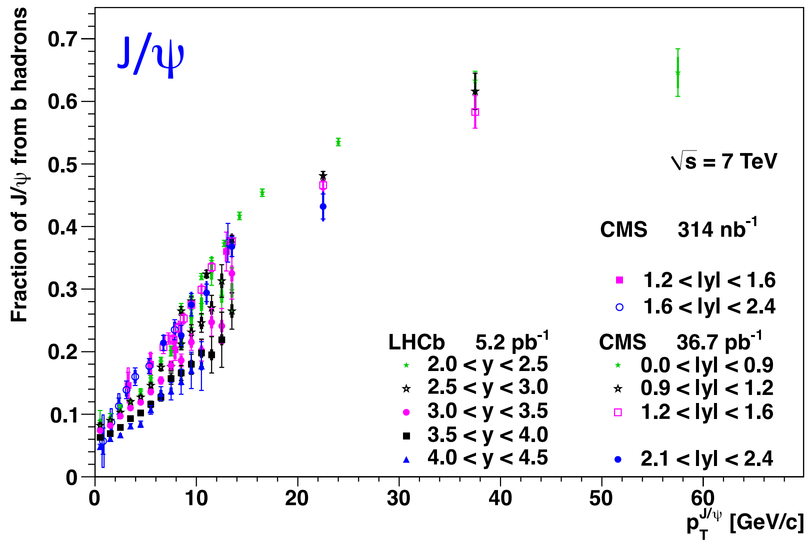


pseudo-proper decay length $$l_{J/\psi} = L_{xy} \cdot \frac{m_{J/\psi}}{p_T}$$



Forward data → smaller B fraction
low p_T and forward J/ψ's are mostly prompt
(relevant for ALICE dimuon results)

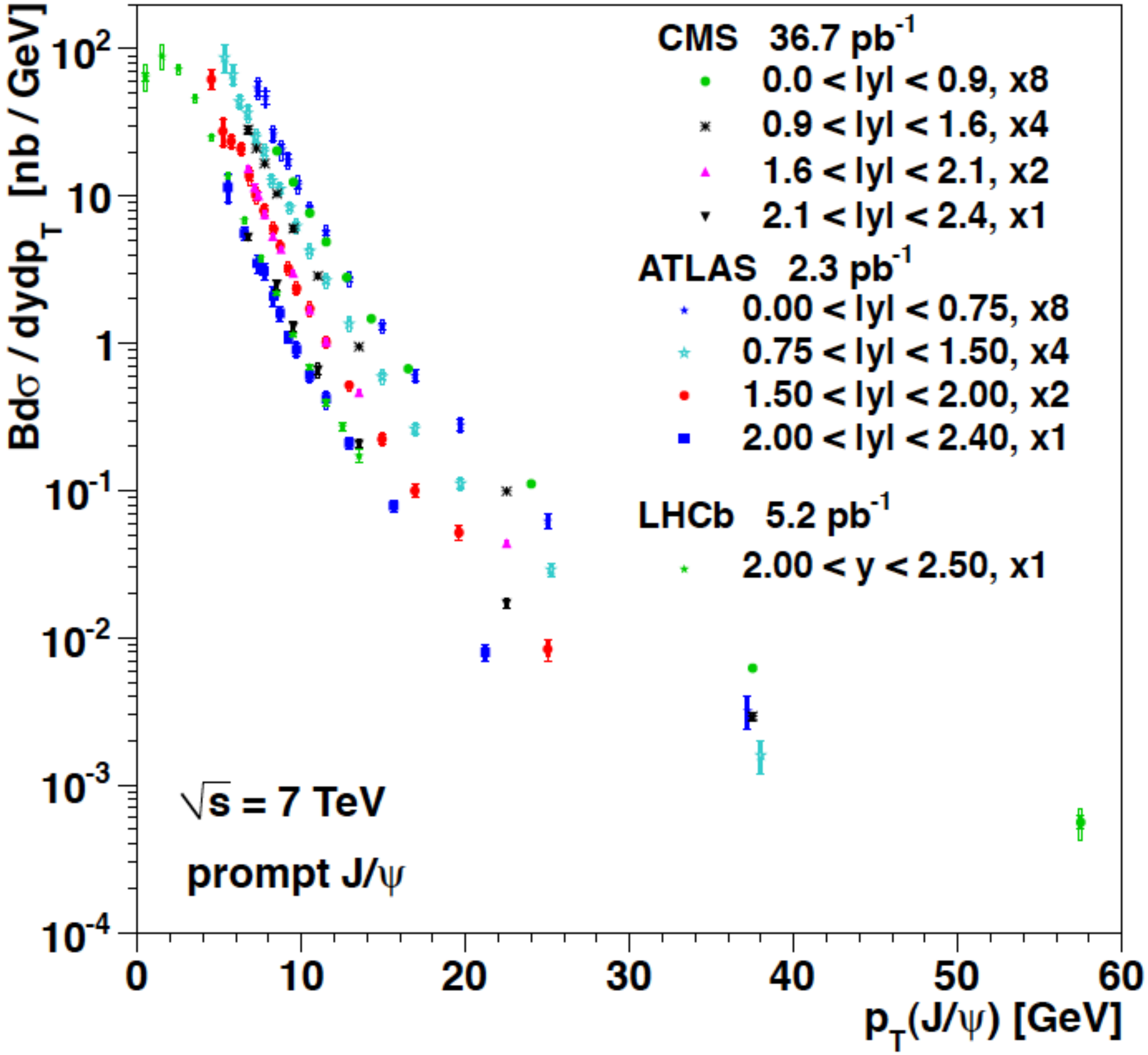




ATLAS: NPB 850 (2012) 387
CMS: JHEP 02 (2012) 011
CDF: PRD 71 (2005) 032001
CDF: PRD 80 (2009) 031103
LHCb: EPJC 71 (2011) 1645
LHCb: EPJC 72 (2012) 2100

Prompt J/ψ differential cross sections

- Prompt J/ψ p_T spectra extend from 0 up to 70 GeV/c, spanning 6 orders of magnitude



ATLAS: NPB 850 (2012) 387
CMS: JHEP 02 (2012) 011
LHCb: EPJC 71 (2011) 1645

Prompt J/ψ differential cross sections

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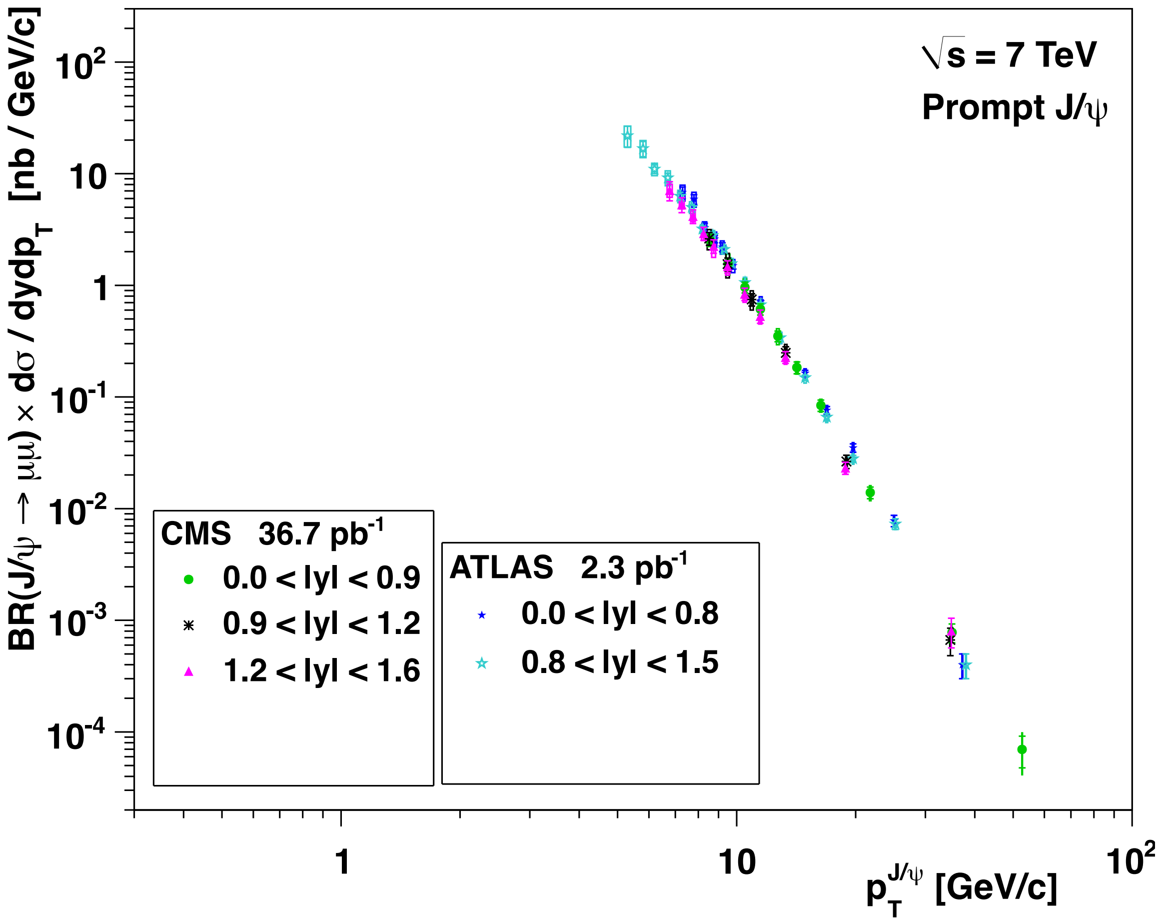
- The ATLAS and CMS data agree over the full p_T range



mid-rapidity
|y| < 1.6

ATLAS: NPB 850 (2012) 387
CMS: JHEP 02 (2012) 011

Prompt J/ψ differential cross sections

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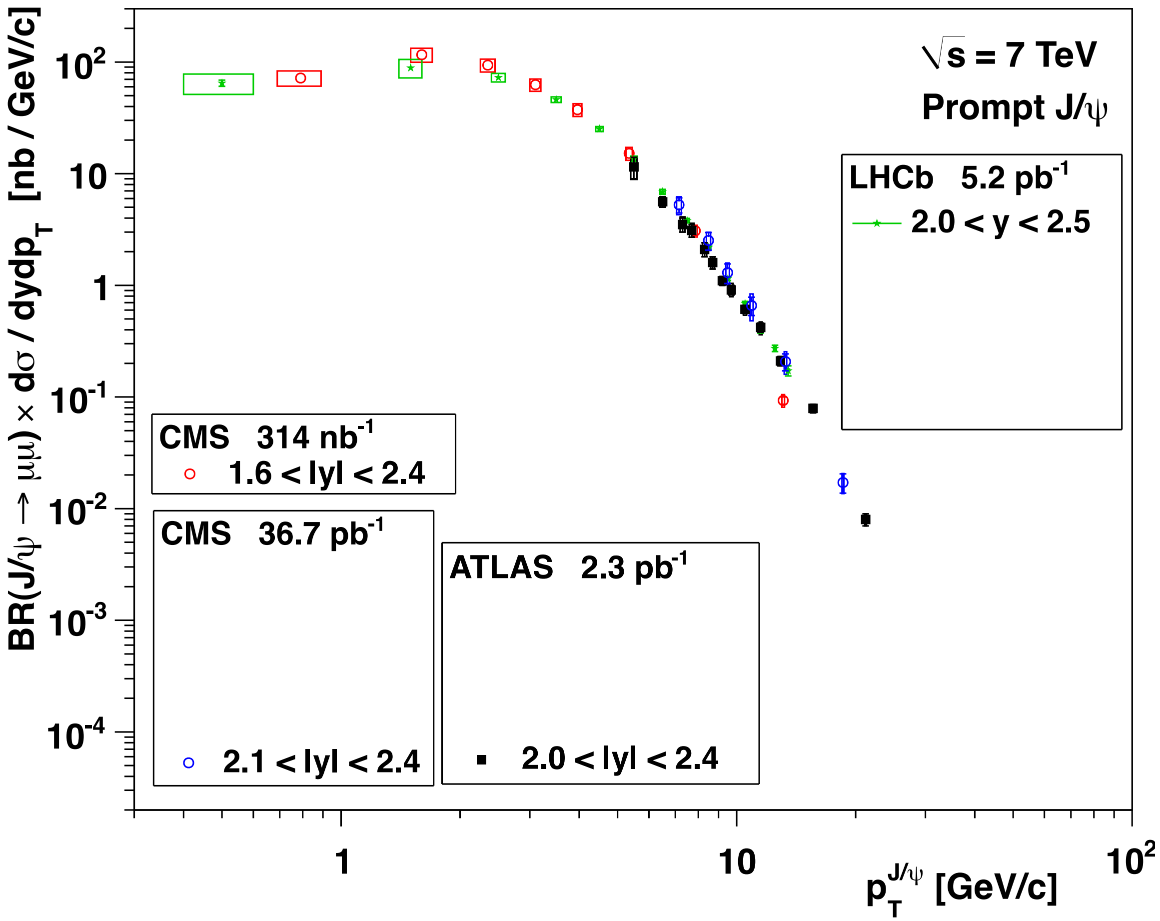
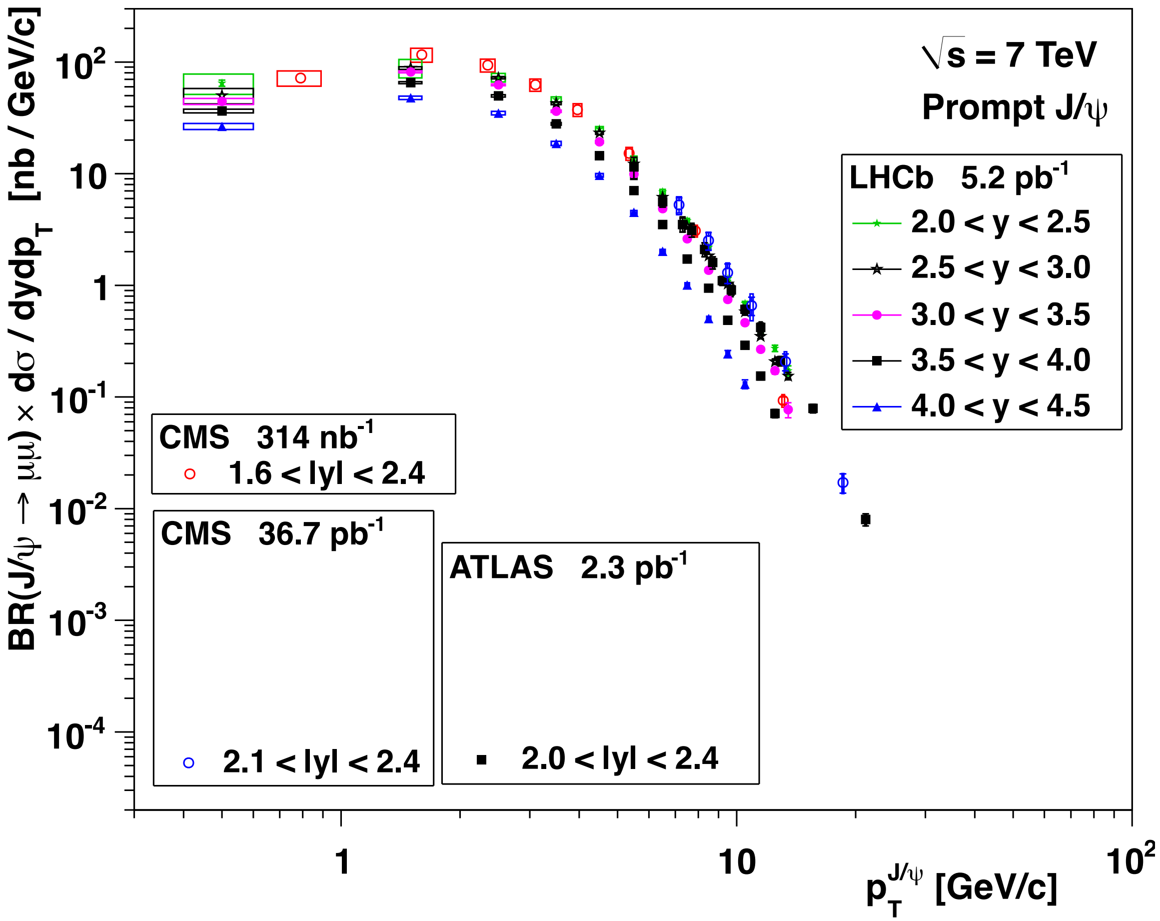


intermediate rapidity
1.6 < |y| < 2.4

ATLAS: NPB 850 (2012) 387
CMS: JHEP 02 (2012) 011
LHCb: EPJC 71 (2011) 1645

Prompt J/ψ differential cross sections

- Prompt J/ψ p_T spectra extend from 0 up to 70 GeV/c, spanning 6 orders of magnitude
- The ATLAS and CMS data agree over the full p_T range
- Also the forward LHCb data fits into the global picture



forward rapidity
2.0 < |y| < 4.5

ATLAS: NPB 850 (2012) 387
CMS: JHEP 02 (2012) 011
LHCb: EPJC 71 (2011) 1645

Prompt J/ψ differential cross sections

- Prompt J/ψ p_T spectra extend from 0 up to 70 GeV/c, spanning 6 orders of magnitude
- The ATLAS and CMS data agree over the full p_T range
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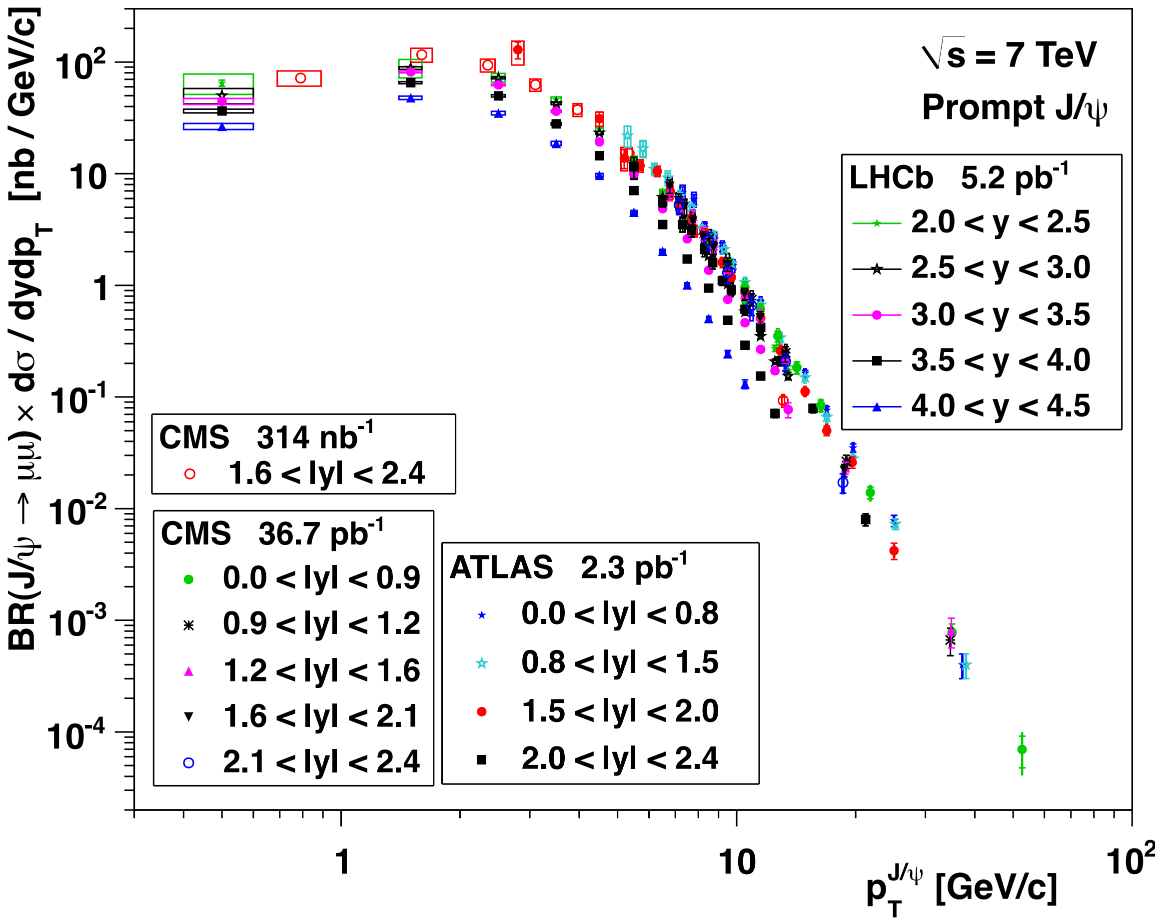
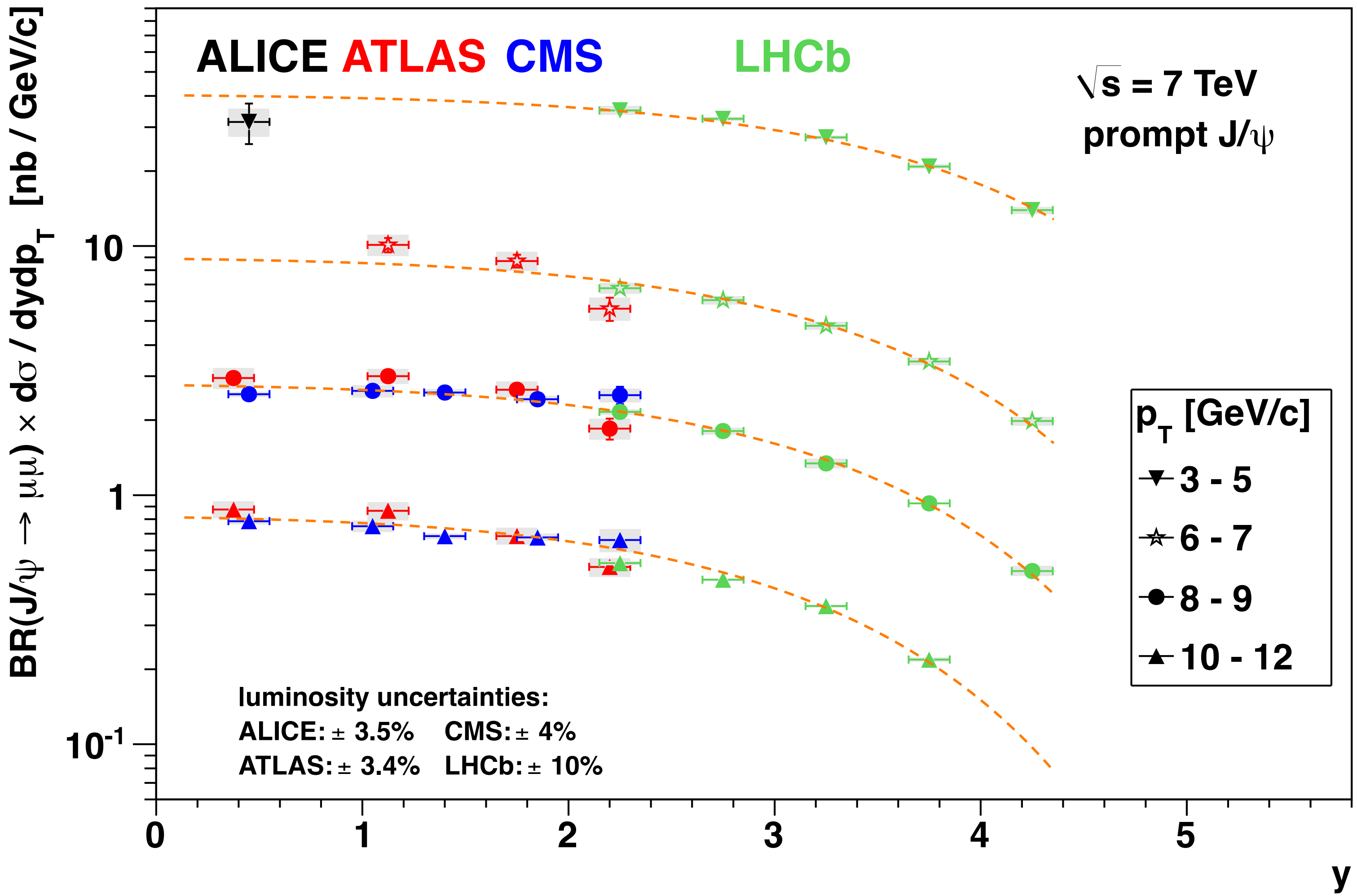


all together now

ATLAS: NPB 850 (2012) 387
CMS: JHEP 02 (2012) 011
LHCb: EPJC 71 (2011) 1645

Prompt J/ψ differential cross sections

- A closer look reveals slight differences between experiments: CMS tends to see flatter rapidity dependences than ATLAS…

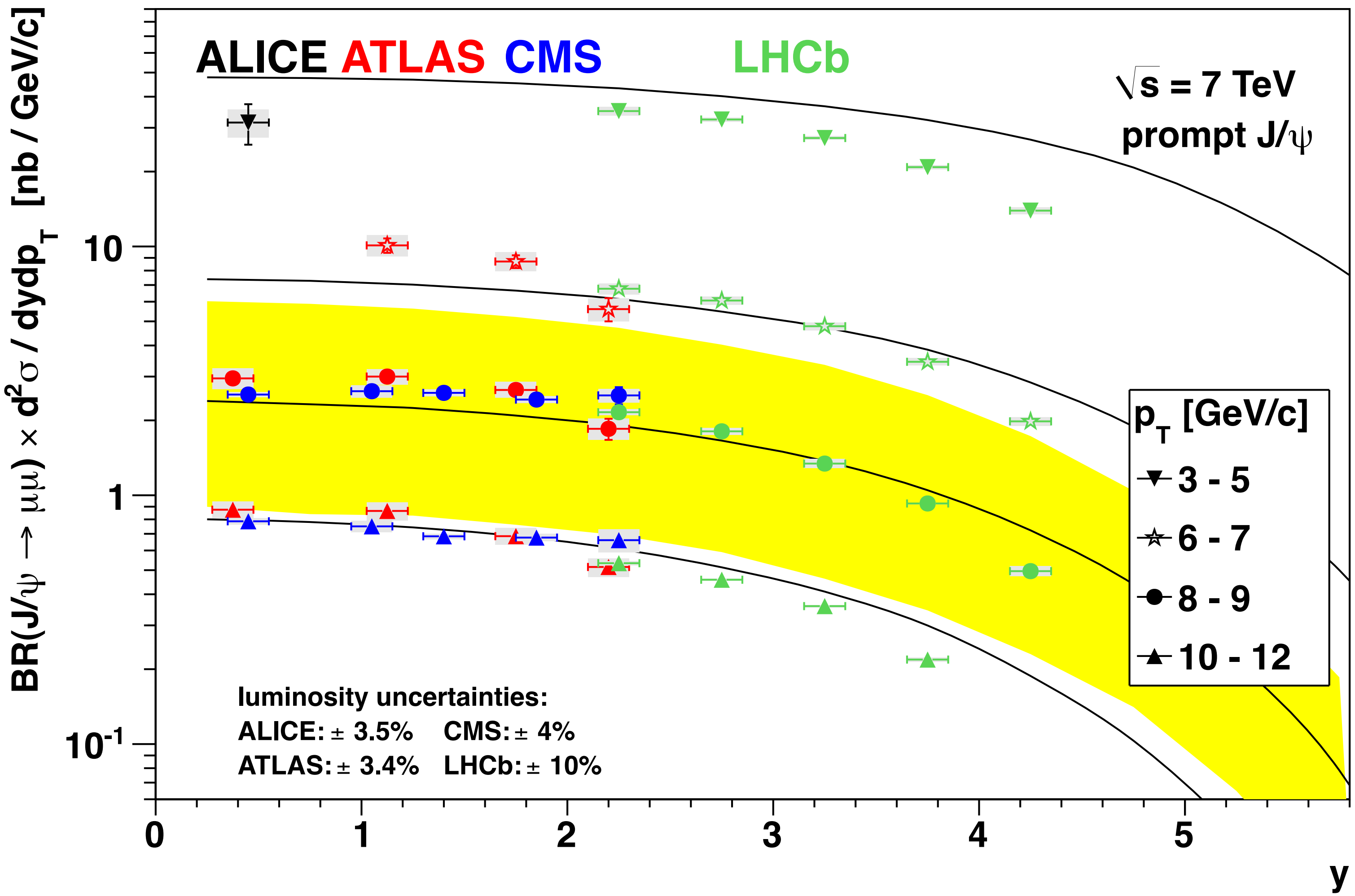


Note: the lines do not represent any theoretical model; they are added to help guiding the eye through the points

ALICE: JHEP11 (2012) 065
ATLAS: NPB850 (2011) 387
CMS: JHEP02 (2012) 011
LHCb: EPJC 71 (2011) 1645

Prompt J/ψ differential cross sections

- A closer look reveals slight differences between experiments:
  CMS tends to see flatter rapidity dependences than ATLAS…
- The Color Evaporation Model calculations help comparing LHCb with ATLAS/CMS

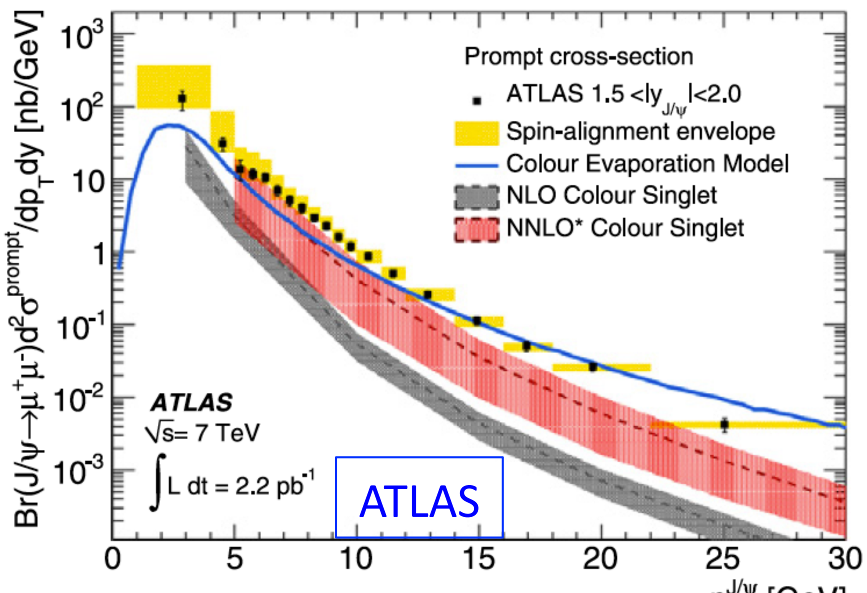


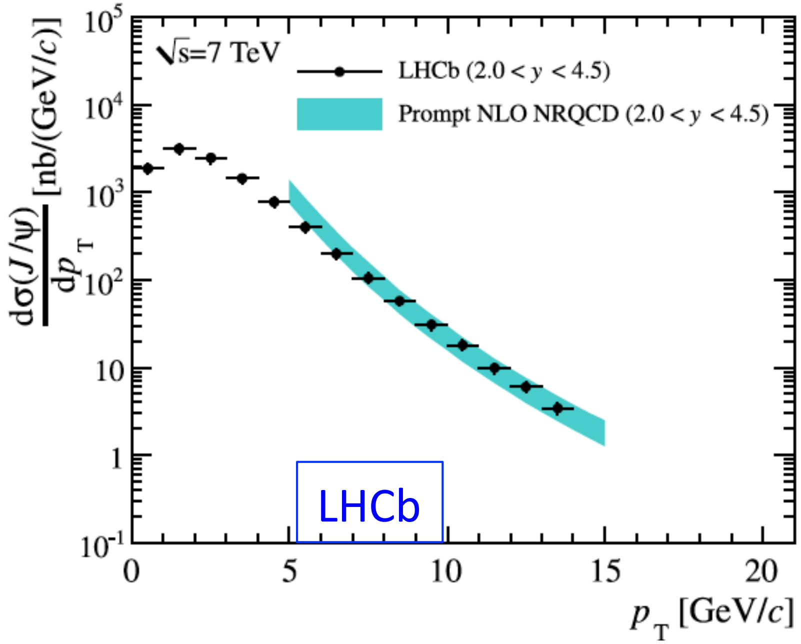
Note: the lines represent CEM calculations made by Ramona Vogt;
they are added to help guiding the eye through the points

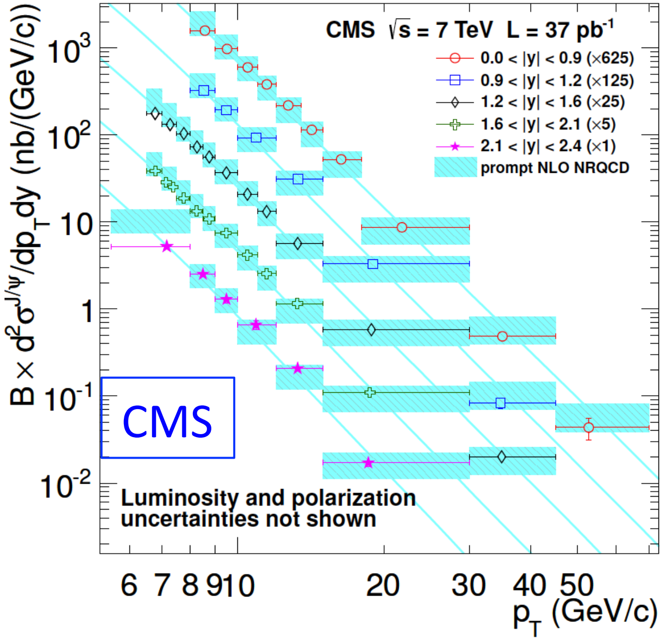
ALICE: JHEP11 (2012) 065
ATLAS: NPB850 (2011) 387
CMS: JHEP02 (2012) 011
LHCb: EPJC 71 (2011) 1645

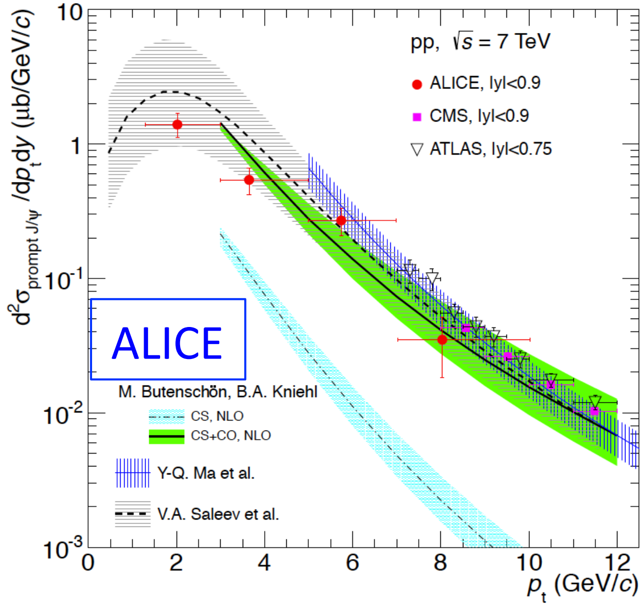
Prompt J/ψ differential cross sections: data vs. theory

- High-p_T J/ψ data well described by NLO NRQCD; note that the χ_c feed-down has not been subtracted…





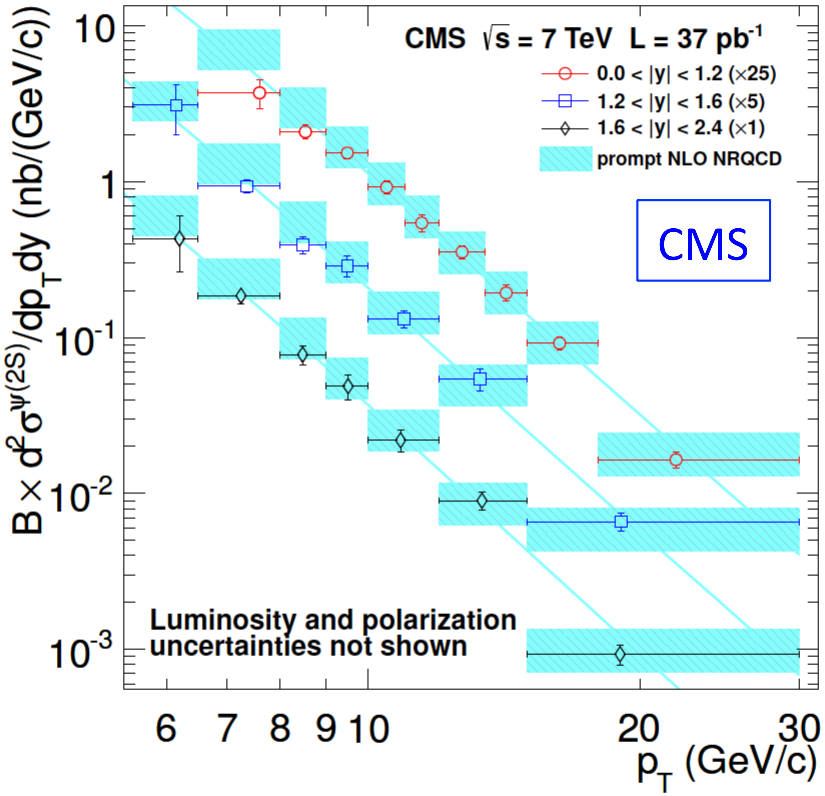


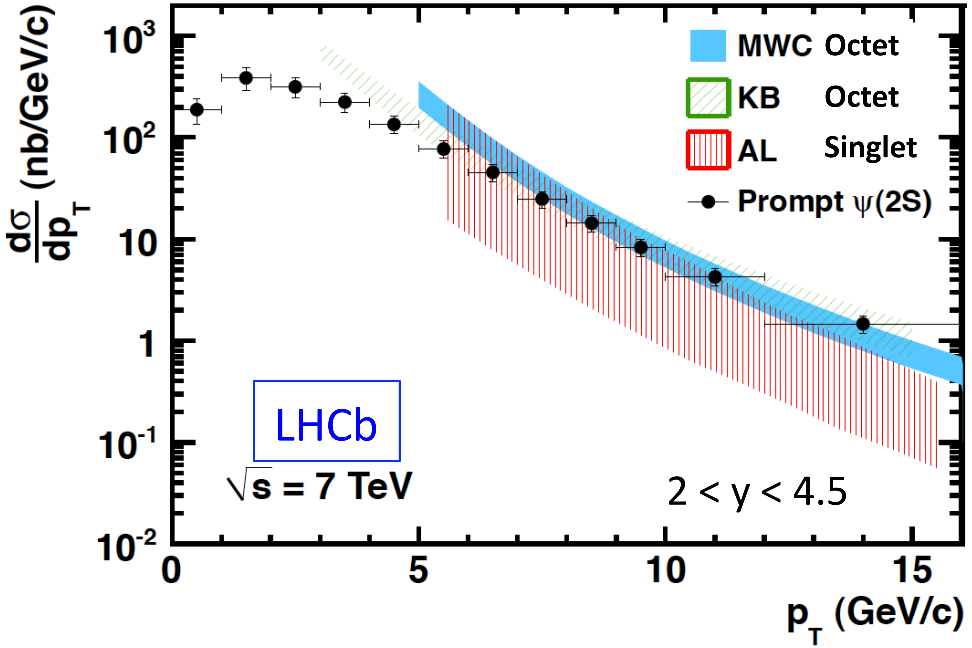


ALICE: JHEP11 (2012) 065
ATLAS: NPB850 (2011) 387
CMS: JHEP02 (2012) 011
LHCb: EPJC 71 (2011) 1645

Prompt ψ' differential cross sections: data vs. theory

- High-p_T ψ' data well described by NLO NRQCD (including singlet and octet production)
- ψ' production is not affected by χ_c feed-down → more robust comparison with theory

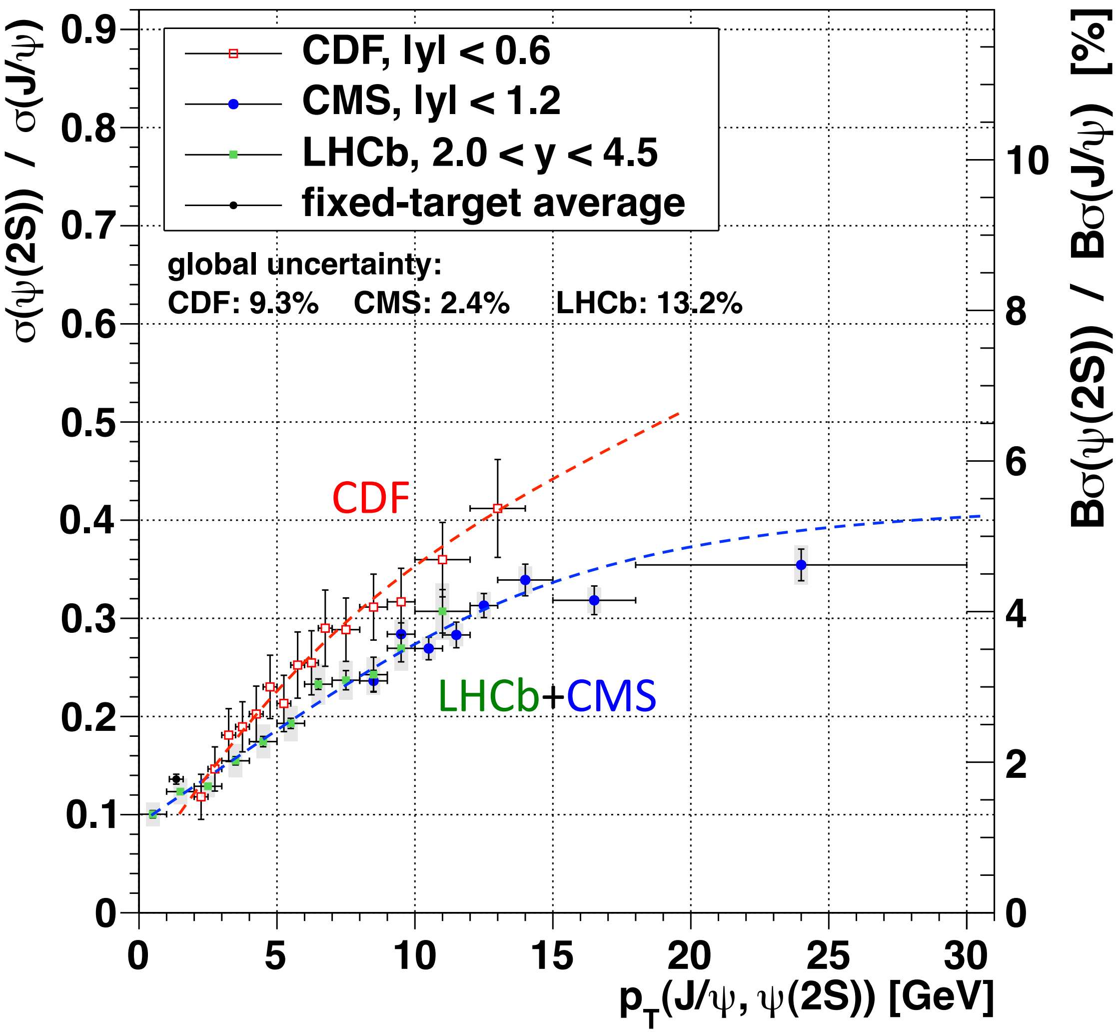




CMS: JHEP 02 (2012) 011
LHCb: EPJC 72 (2012) 2100

ψ’ over J/ψ prompt cross-section ratio

- Good overlap between mid-rapidity CMS data and forward LHCb data
- CDF results show *stronger* p_T dependence…



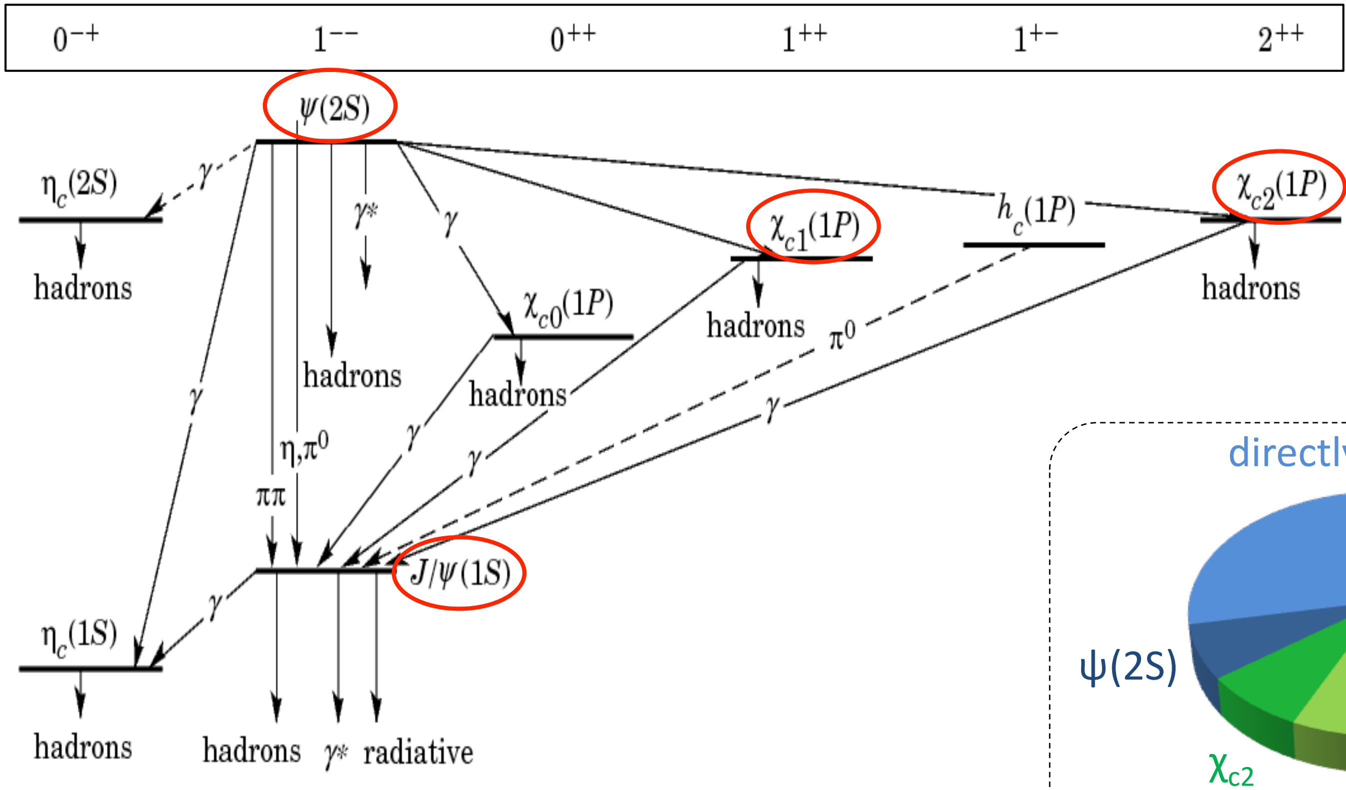
In the $\mu^+\mu^-$ decay channel, the ψ’ yield is only 1–6 % of the J/ψ yield

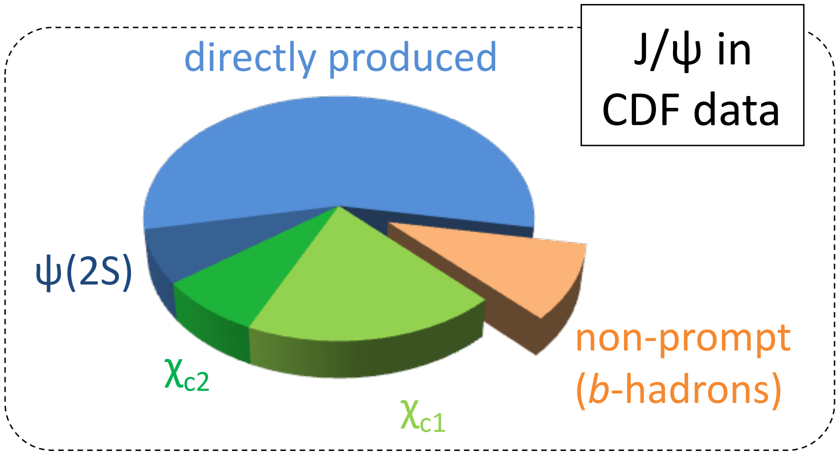
Note: the lines do not represent any theoretical model; they are added to help guiding the eye through the points

fixed-target: JHEP10 (2008) 004
CDF: PRD80 (2009) 031103 (R)
CMS: JHEP 02 (2012) 011
LHCb: EPJC 71 (2011) 1645
LHCb: EPJC 72 (2012) 2100

Feed-down contributions to the J/ψ

- Observed quarkonia: directly produced plus those resulting from feed-down decays

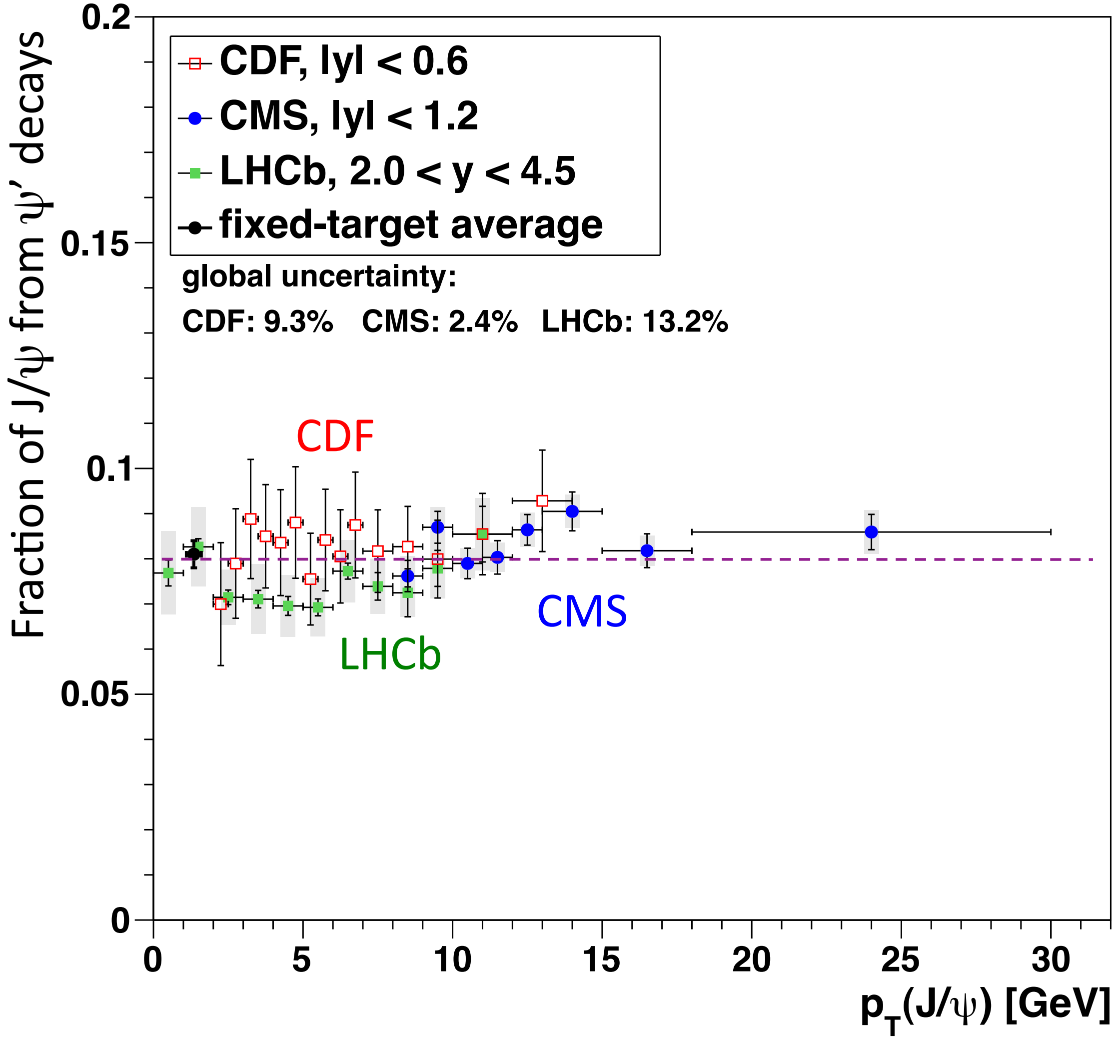




- The fraction of the inclusive J/ψ yield due to b-hadron decays increases strongly with J/ψ p_T
- What about the fractions from ψ' and χ_c feed-down?

ψ' feed-down contribution to J/ψ production

- From the ψ' over J/ψ cross-section ratio, we can infer the ψ' to J/ψ feed-down fraction
- The measurements indicate a roughly constant ψ' to J/ψ feed-down fraction, of around 8%

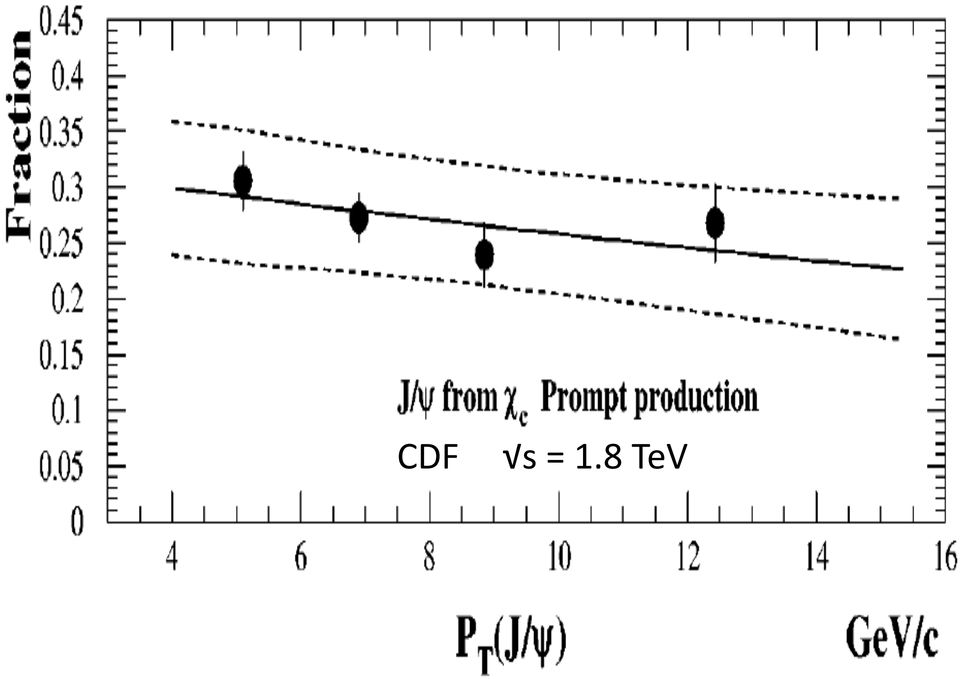


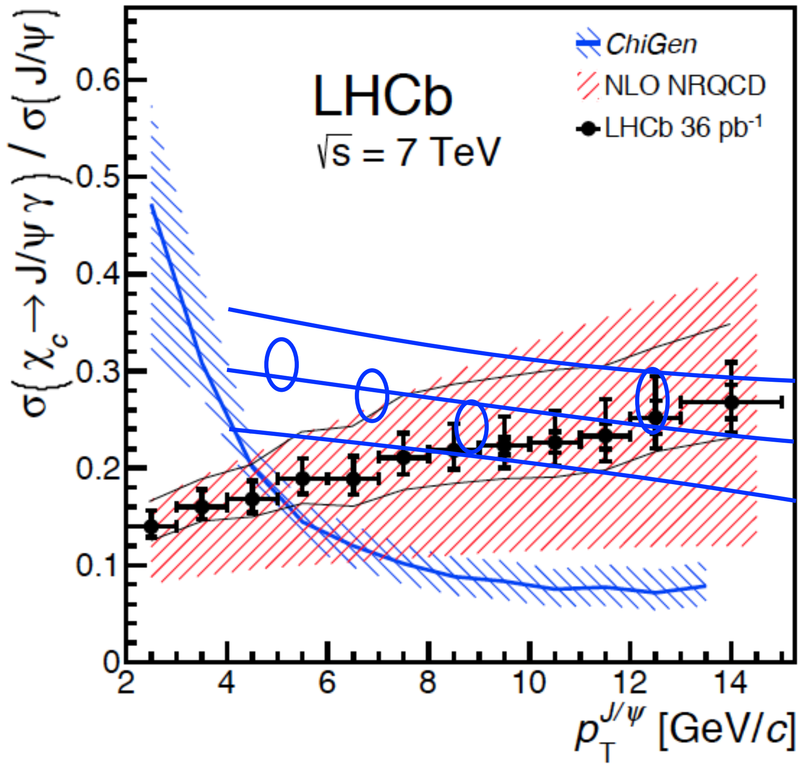
- We need to account for the shift from the ψ' p_T to the J/ψ p_T
- We assume $\langle p_T(\psi')\rangle / \langle p_T(J/\psi)\rangle = m(\psi') / m(J/\psi)$
- A toy MC simulation of the ψ' to J/ψ decay showed that this relation
  - does not depend significantly on the assumed polarizations
  - does not depend on the assumed $\pi^+\pi^-$ mass distribution shape

fixed-target: JHEP10 (2008) 004
CDF: PRD80 (2009) 031103 (R)
CMS: JHEP 02 (2012) 011
LHCb: EPJC 71 (2011) 1645
LHCb: EPJC 72 (2012) 2100

χ_c feed-down contribution to J/ψ production

- The χ_c represents the most important prompt feed-down source to J/ψ production
  - world average of fixed-target data : 25 ± 5 % [JHEP10 (2008) 004]
  - CDF [Run I] : around 25–30%
  - LHCb : from 14 to 27% between p_T = 2.5 and 14 GeV/c



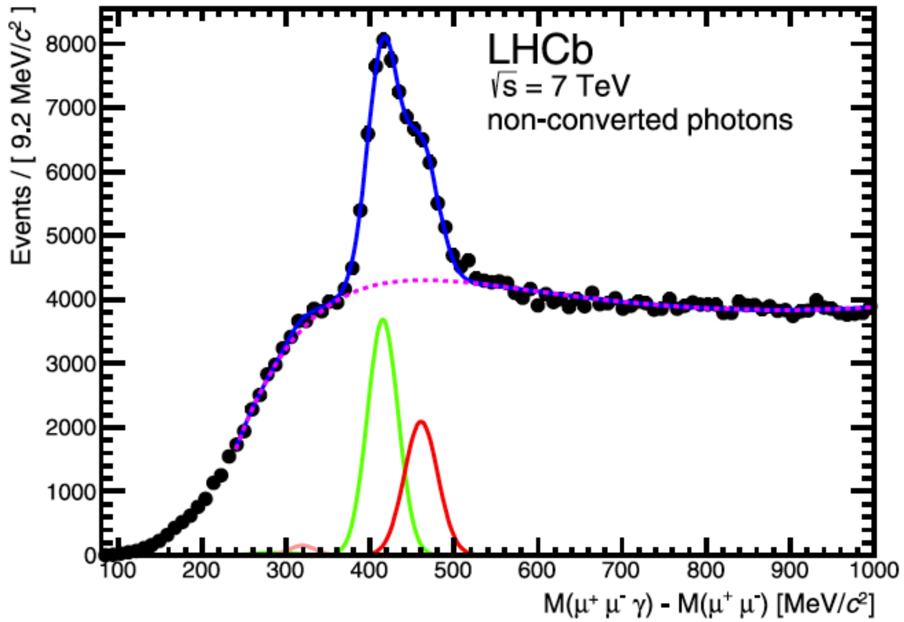


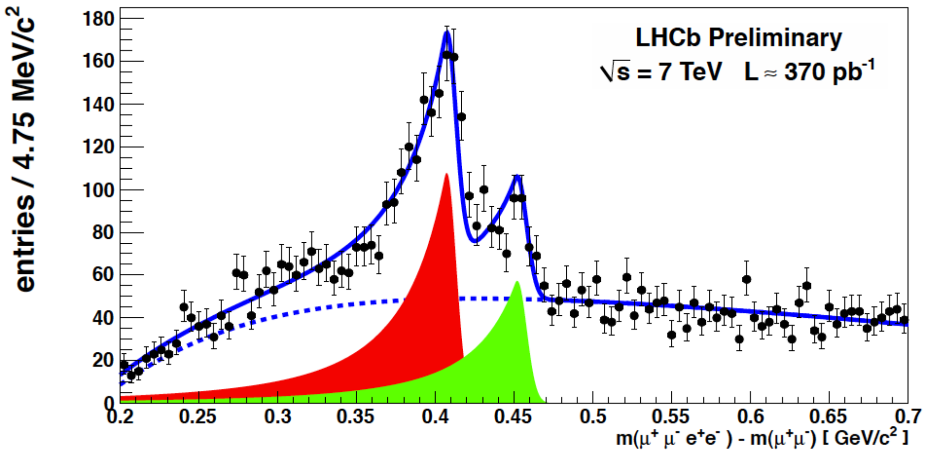
- It is not trivial to conciliate the CDF and LHCb observations…

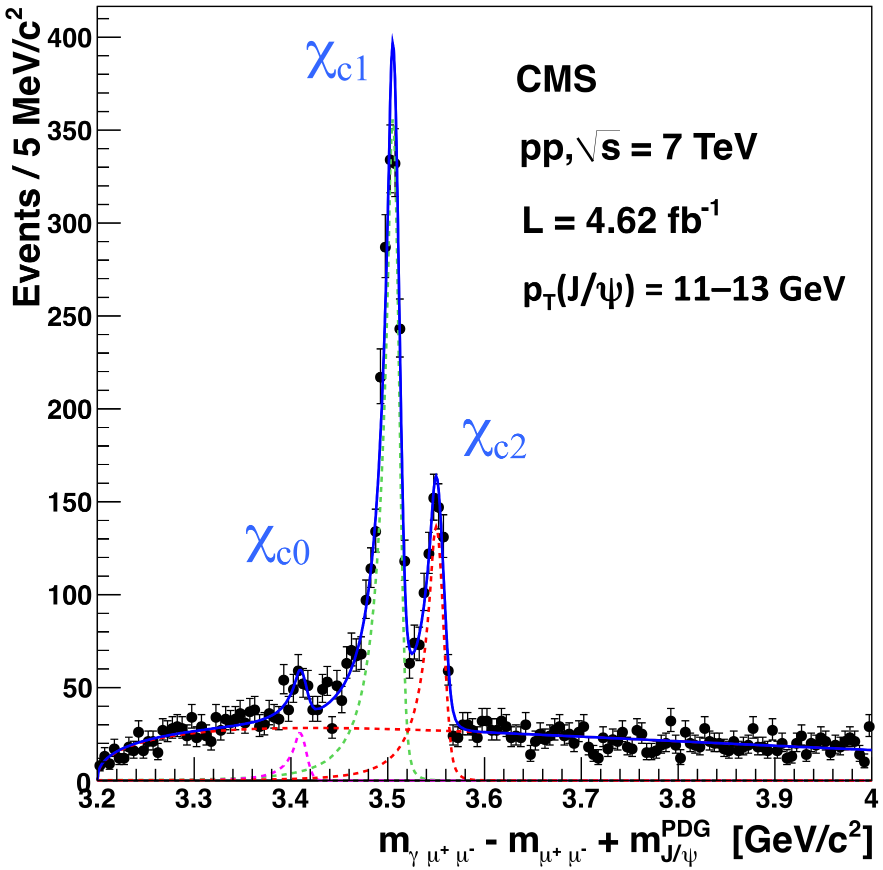
CDF: PRL79 (1997) 578
LHCb: PLB 718 (2012) 431

χ_c measurements at the LHC

- Detection of $\chi_c \to J/\psi + \gamma$ with ECAL photons or photon conversions, $\gamma \to e^+e^-$
  Photon conversions give much better resolution:
  the J = 1,2 states can be resolved (ΔM = 45 MeV)



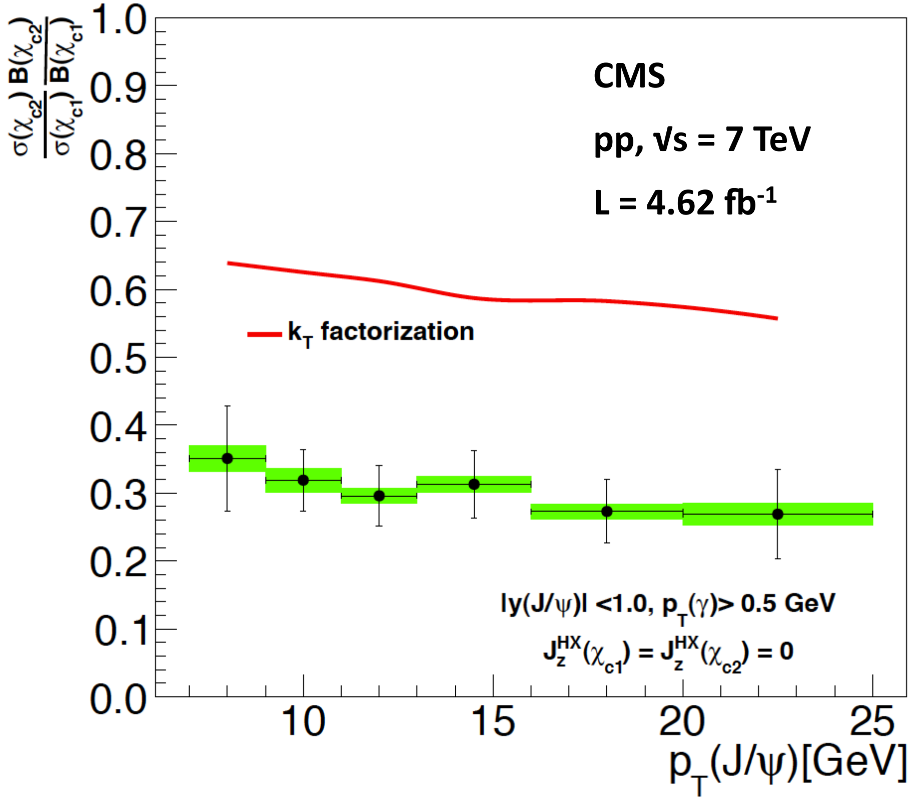


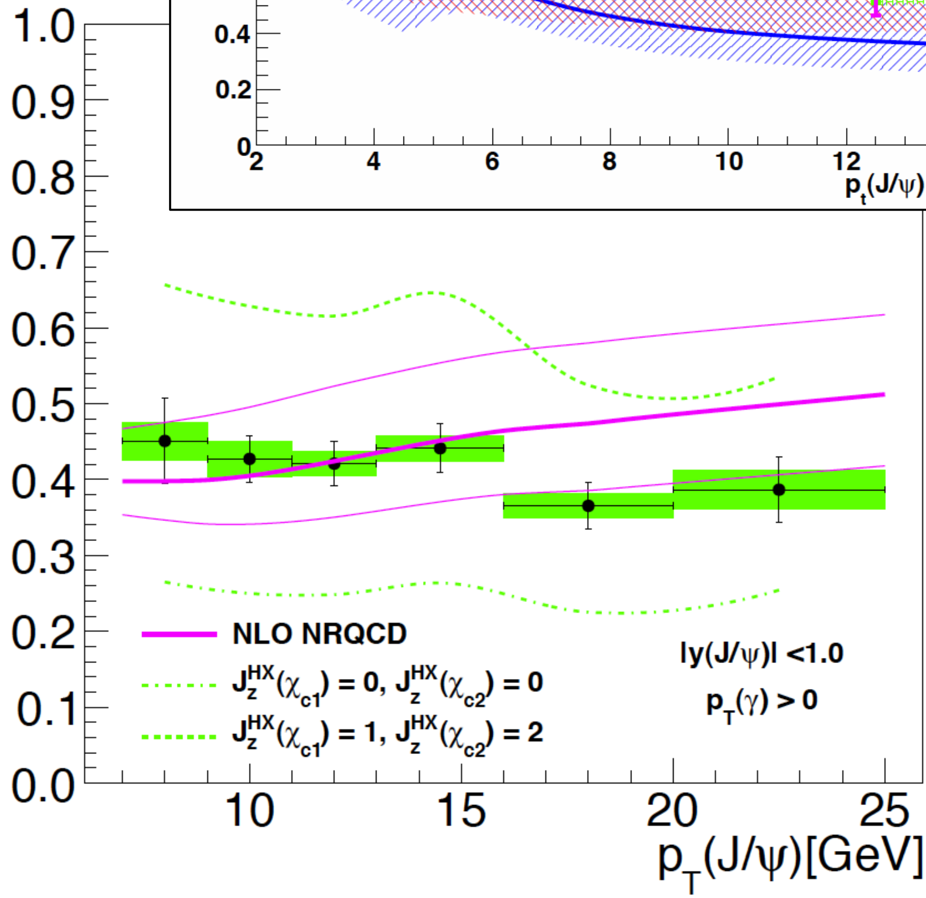


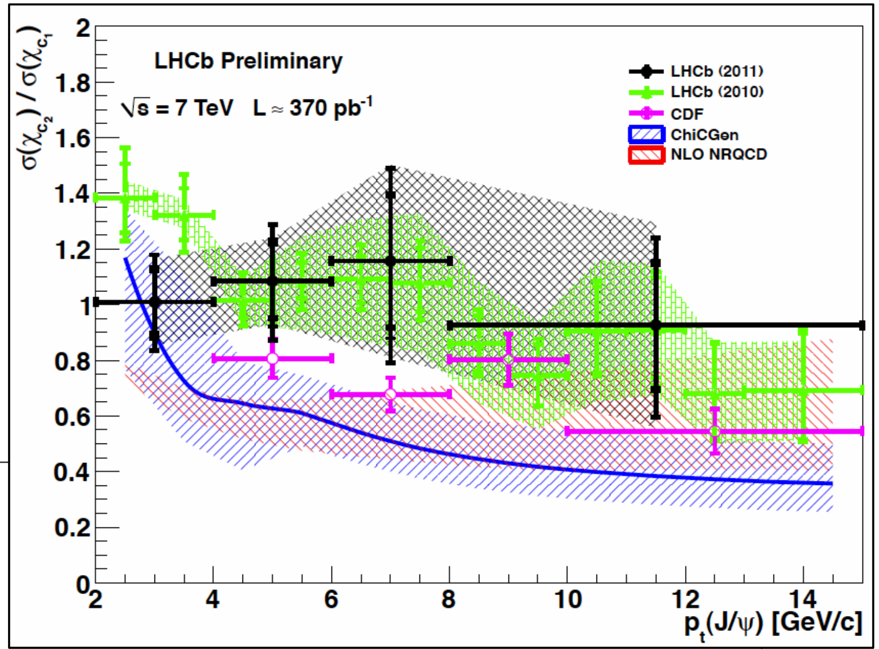
CMS: EPJC 72 (2012) 2251
LHCb: PLB 714 (2012) 215
LHCb: CONF-2011-062

χ_{c2} / χ_{c1} cross-section ratio: data vs. theory

- The k_T factorization model describes the p_T trend, but is a factor 2 higher than the data
- NRQCD NLO calculations do not include polarization
  → polarization scenarios induce large uncertainties
- The p_T < 8 GeV/c data is not described by NRQCD



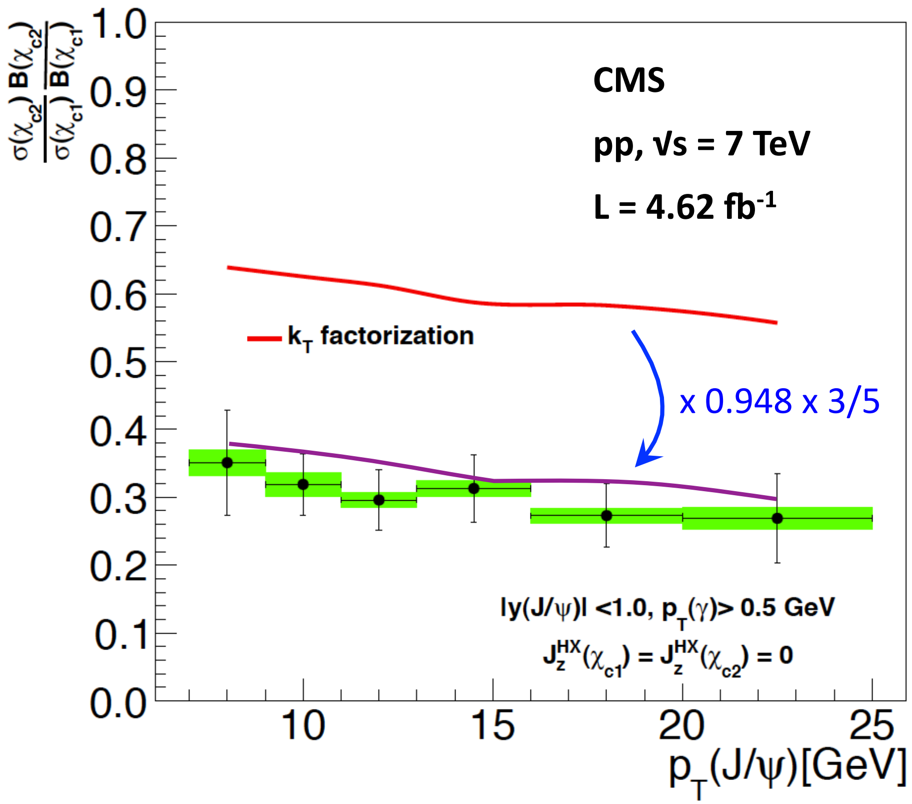




CMS: EPJC 72 (2012) 2251
LHCb: PLB 714 (2012) 215
LHCb: CONF-2011-062

χ_{c2} / χ_{c1} cross-section ratio: revisiting the k_T curve

- The k_T factorization curve assumes identical wave functions for the two states: $|R'_{\chi 2}(0)|^2 = |R'_{\chi 1}(0)|^2$
- But maybe the χ_{c1} has a narrower and higher wave function
- After all, BR($\psi' \to \chi_{c2} + \gamma$) / BR($\psi' \to \chi_{c1} + \gamma$) = 0.948 ± 0.055 [PDG] and not 5/3, as expected from spin counting, indicating that the two wave functions are different



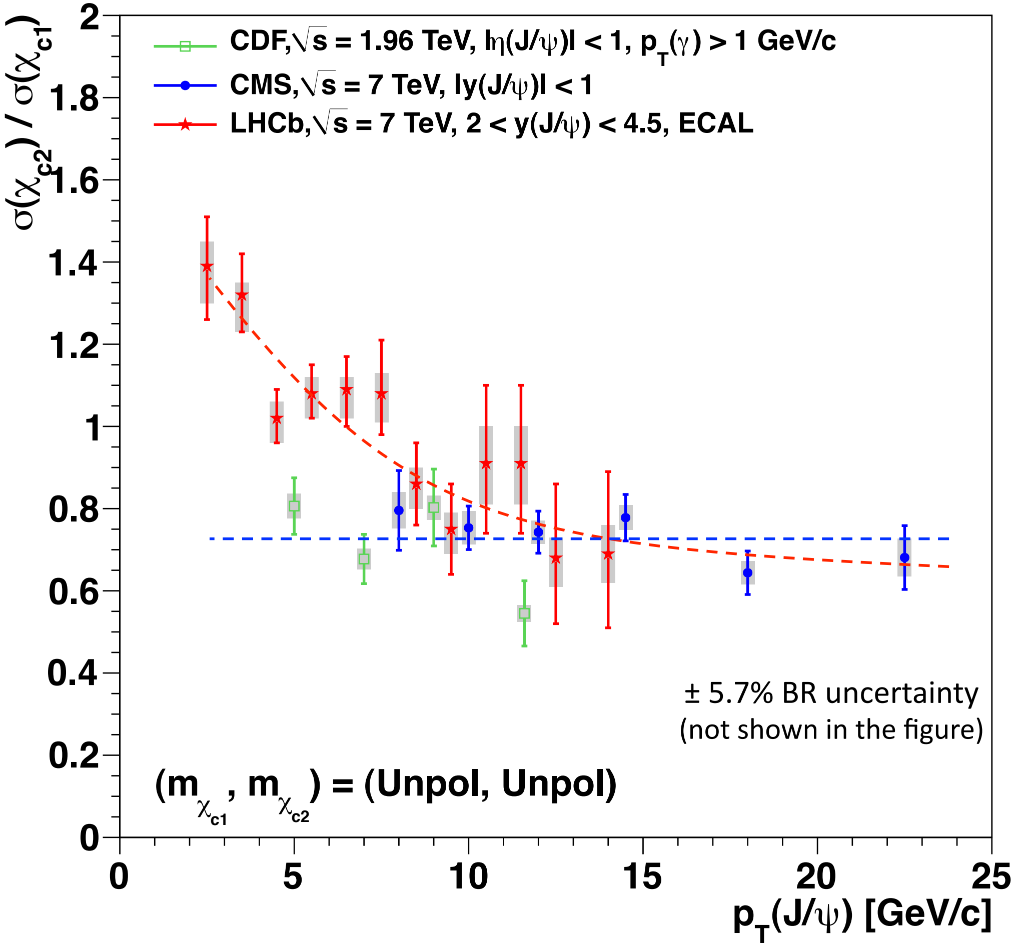
- The new normalization, suggested by the BR($\psi' \to \chi_{c2} + \gamma$) / BR($\psi' \to \chi_{c1} + \gamma$) ratio, gives a curve in good agreement with the CMS χ_{c2} / χ_{c1} cross-section ratio

- It seems that $|R'_{\chi 2}(0)|^2 / |R'_{\chi 1}(0)|^2 \sim 3/5$

CMS: EPJC 72 (2012) 2251
S. Baranov: PRD 83 (2011) 034035

χ_{c2} / χ_{c1} cross-section ratio: data vs. data

- At high p_T the χ_{c2} over χ_{c1} cross-section ratio is below 1: χ_{c2} are less copiously produced than χ_{c1} (contrary to naïve "spin counting": 5/3)
- Acceptance corrections assume that χ_{c1} and χ_{c2} are produced unpolarized



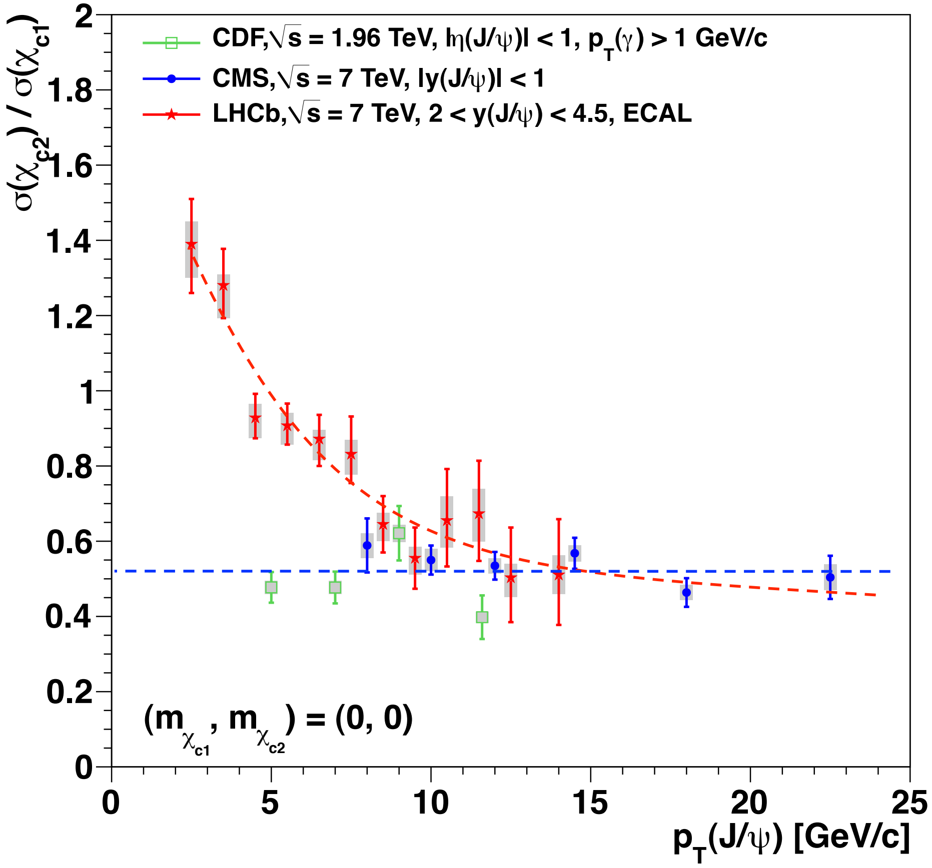
Note: the lines do not represent any theoretical model; they are added to help guiding the eye through the points

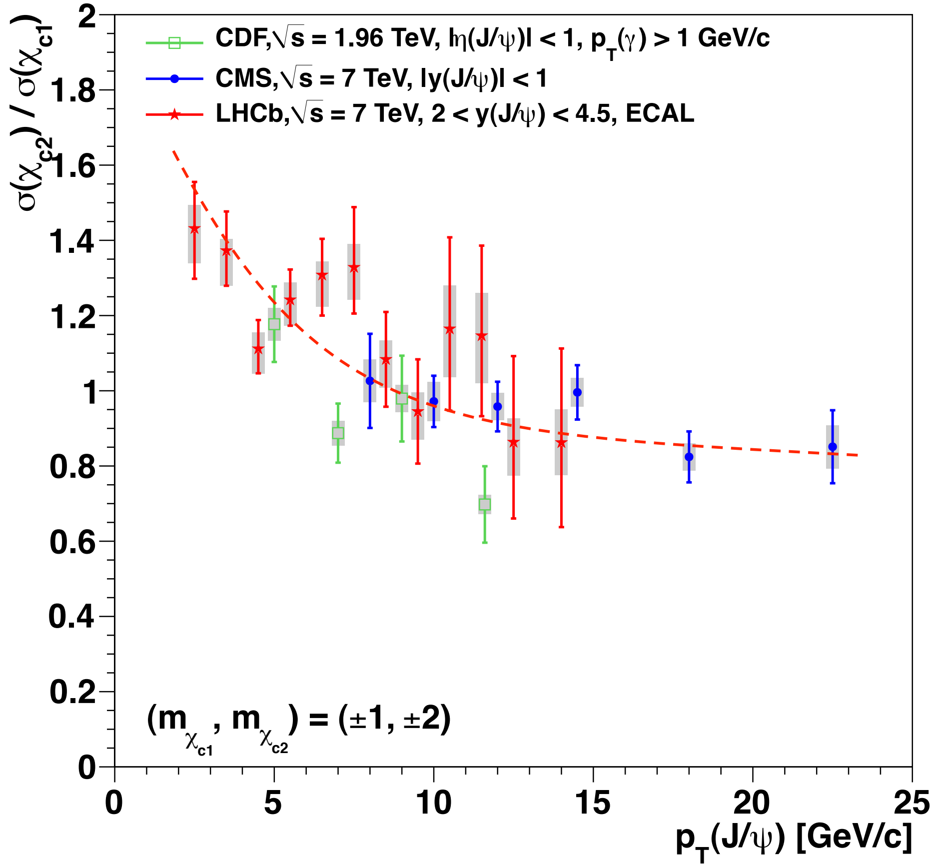
Red line: 7 TeV data (CMS + LHCb)
Blue line: mid-rapidity data (CMS + CDF)

CDF: PRL 98 (2007) 232001
CMS: EPJC 72 (2012) 2251
LHCb: PLB 714 (2012) 215
LHCb: CONF-2011-062

χ_{c2} / χ_{c1} cross-section ratio: data vs. polarization scenario

- The consistency between the CDF and LHCb points strongly depends on the assumed polarizations
- At p_T ~ 10 GeV, the χ_{c2} / χ_{c1} ratio varies by around a factor 2 depending on the polarization scenario





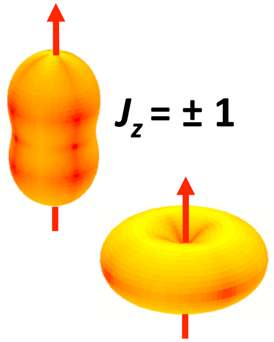
Note: the lines do not represent any theoretical model; they are added to help guiding the eye through the points

Red line: 7 TeV data (CMS + LHCb)
Blue line: mid-rapidity data (CMS + CDF)

Quarkonium polarization: angles and frames

Decay angular dist. of J = 1 particles:

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



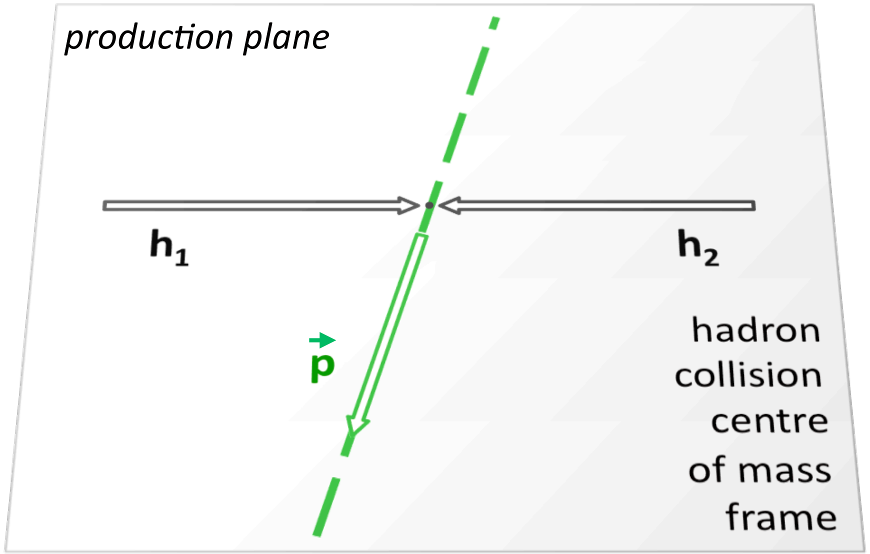
$J_z = \pm 1$ → $\lambda_\vartheta = +1$: transverse polarization

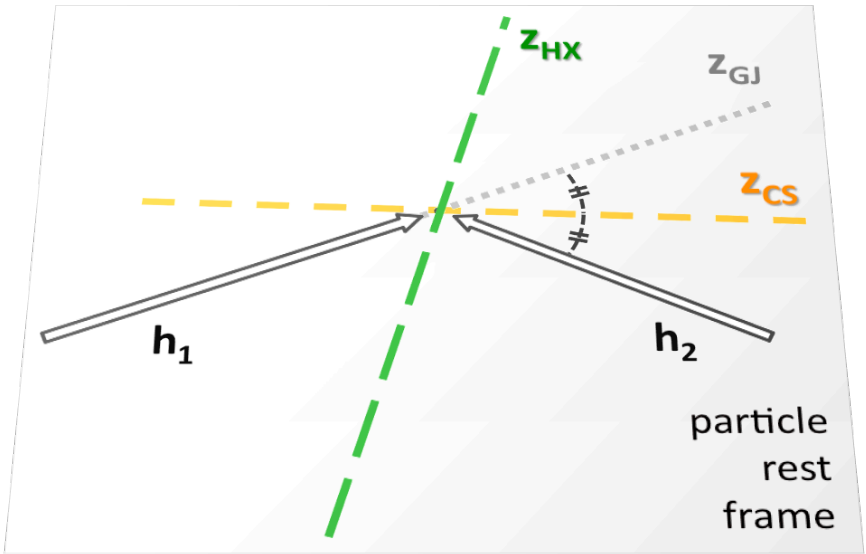
$J_z = 0$ → $\lambda_\vartheta = -1$: longitudinal pol.

Helicity axis (HX): quarkonium momentum direction

Gottfried-Jackson axis (GJ): direction of one or the other beam

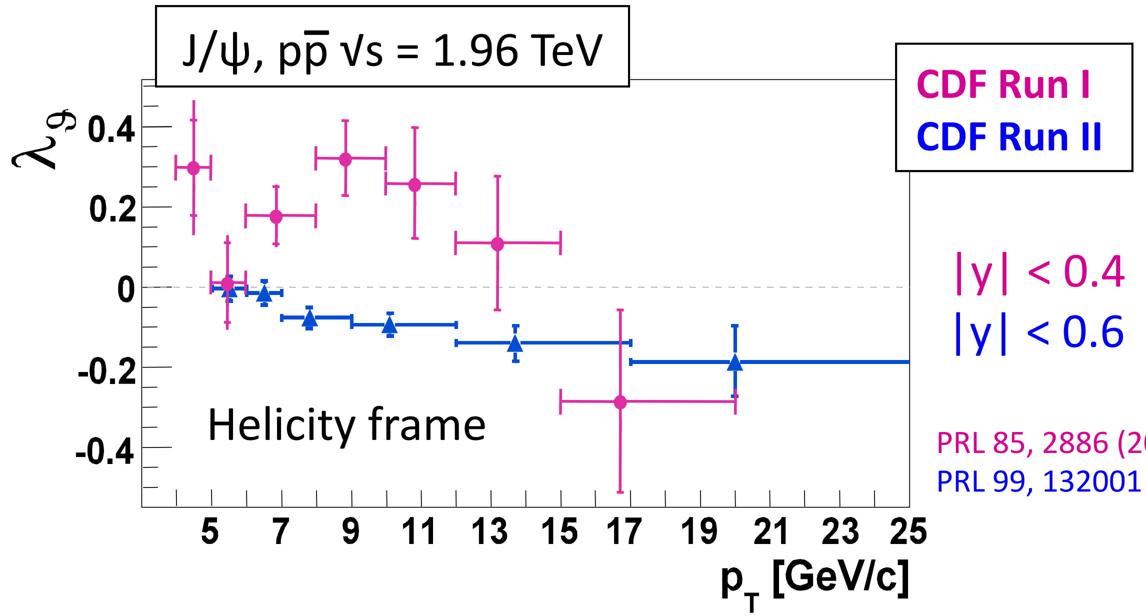
Collins-Soper axis (CS): average of the two beam directions





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

Quarkonium polarization: data vs. data puzzles



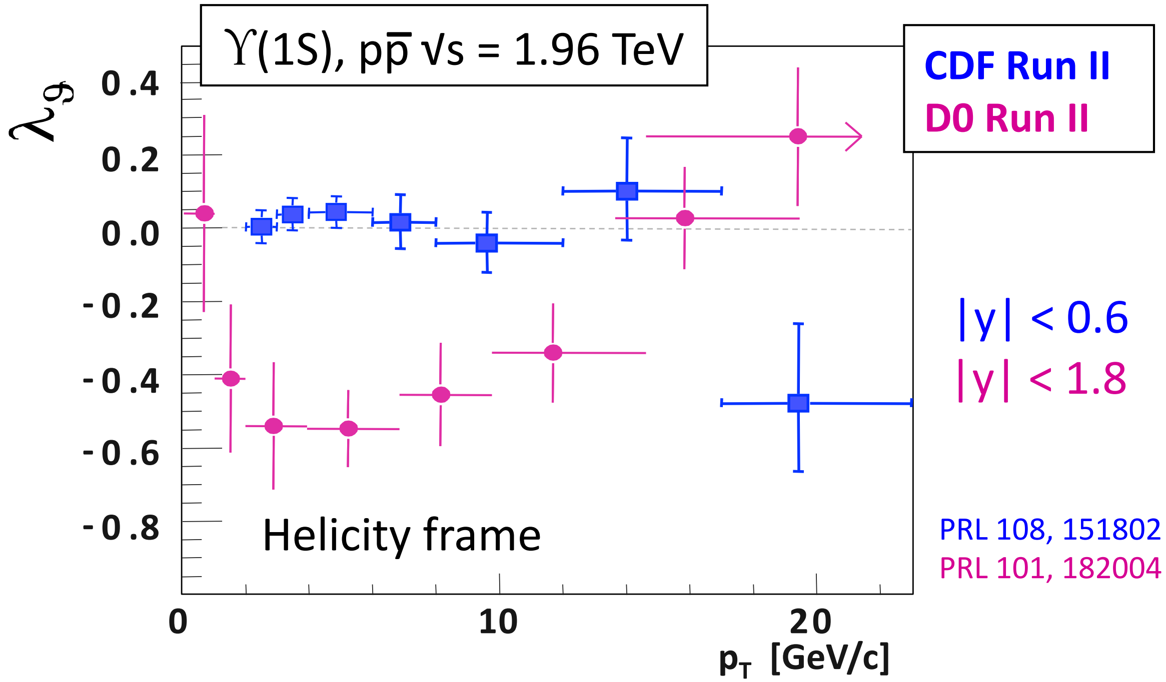
|y| < 0.4

|y| < 0.6

PRL 85, 2886 (2000)

PRL 99, 132001 (2007)

- **CDF II vs CDF I**
  → not known what caused the change



|y| < 0.6

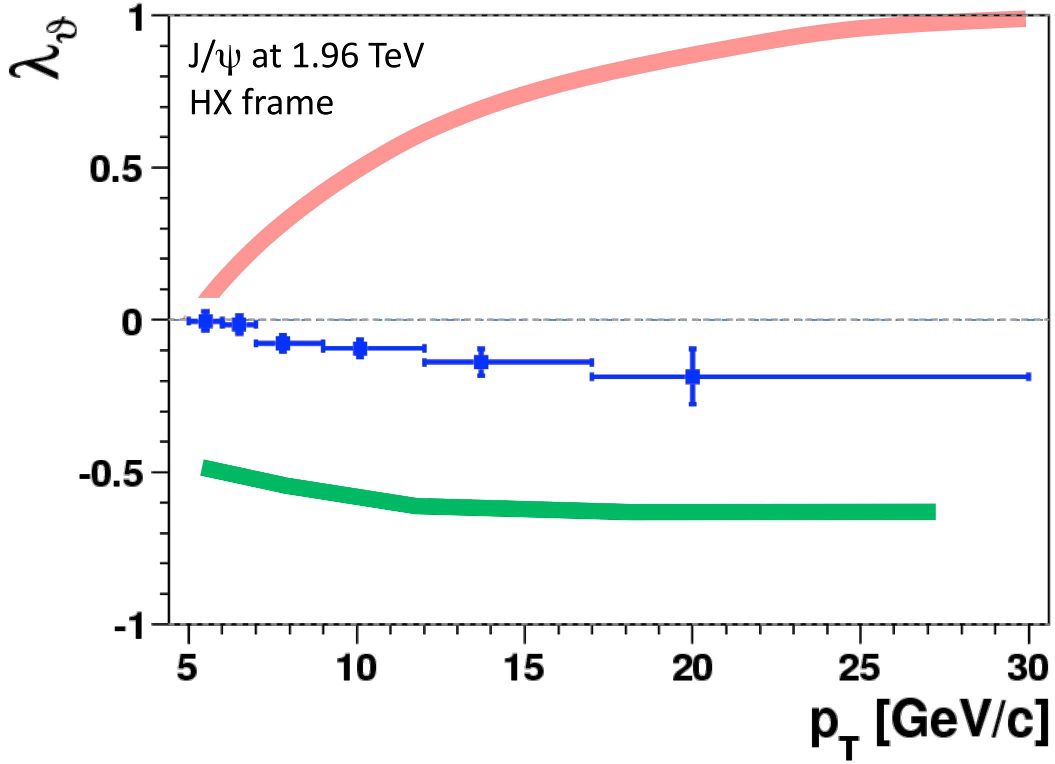
|y| < 1.8

PRL 108, 151802 (2012)

PRL 101, 182004 (2008)

- **CDF vs D0**
  → the different rapidity ranges should not justify the discrepancy...

Quarkonium polarization: data vs. theory puzzles



direct J/ψ

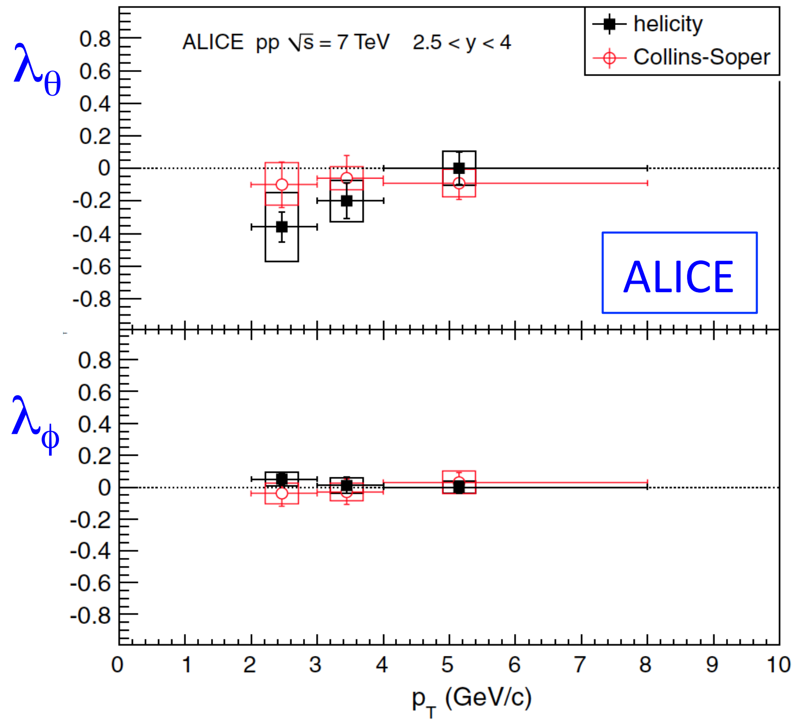
NRQCD factorization
Braaten, Kniehl & Lee, PRD62, 094005 (2000)

direct J/ψ
+ J/ψ *from χ decays*

CDF Run II
CDF Coll., PRL 99, 132001 (2007)

direct J/ψ

Colour Singlet Model
Gong & Wang, PRL 100, 232001 (2008)
Artoisenet et al., PRL 101, 152001 (2008)

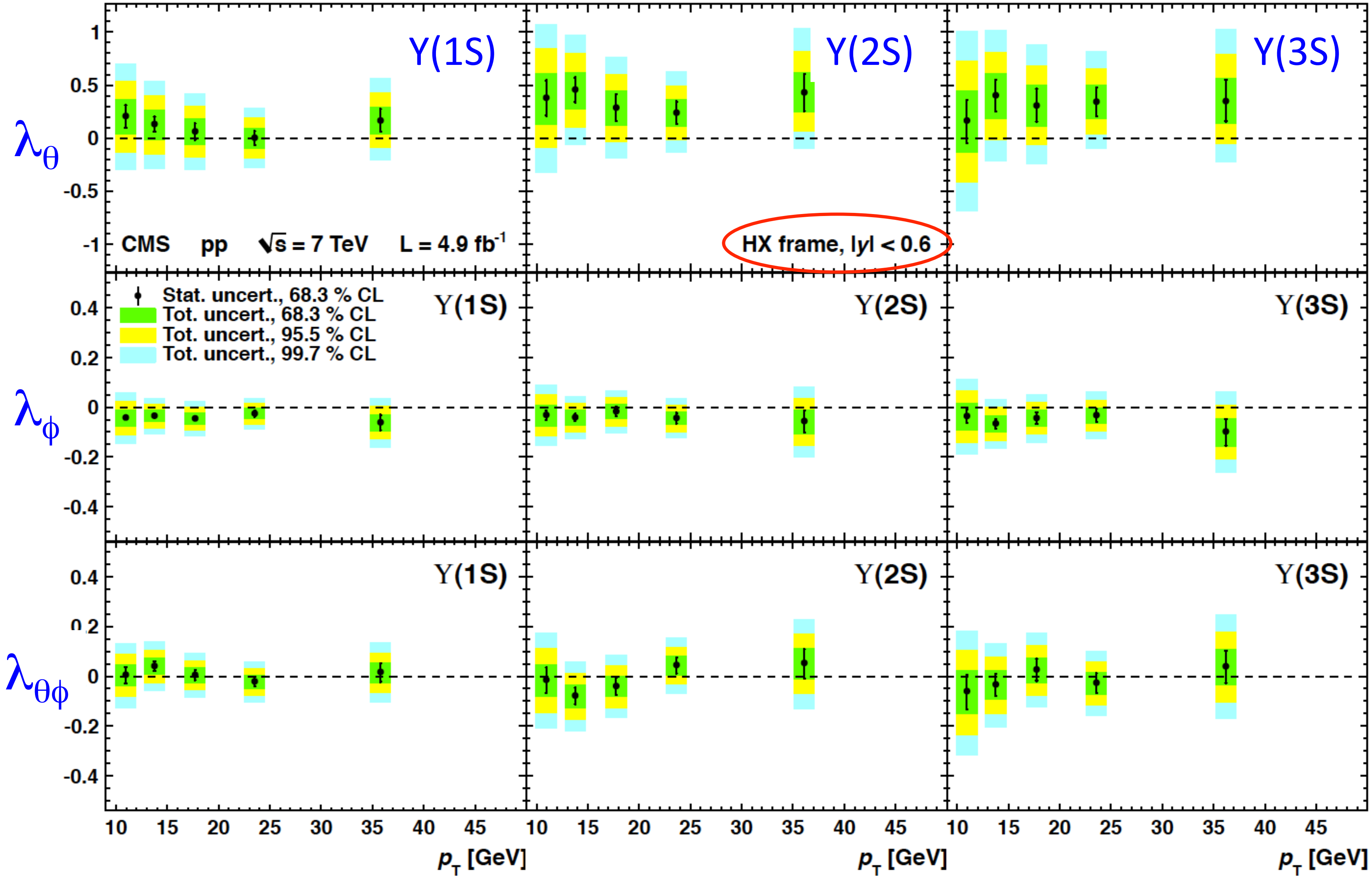


- ALICE has also not seen significant polarizations in inclusive low-p_T J/ψ mesons (p_T < ≈7 GeV/c)

CDF: PRL 99 (2007) 132001
ALICE: PRL 108 (2012) 082001

Upsilon polarization at the LHC

- CMS measured the Υ(1S), Υ(2S) and Υ(3S) polarizations vs. p_T ($10 < p_T < 50$ GeV/c) in two |y| bins and three polarization frames: helicity (HX), Collins-Soper (CS) and perpendicular helicity (PX)



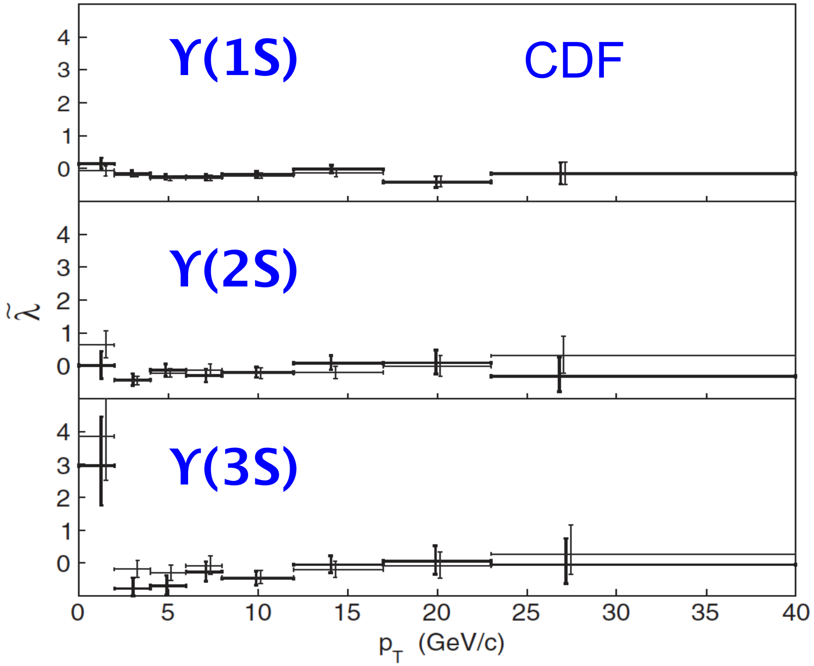
CMS: PRL 110 (2013) 081802

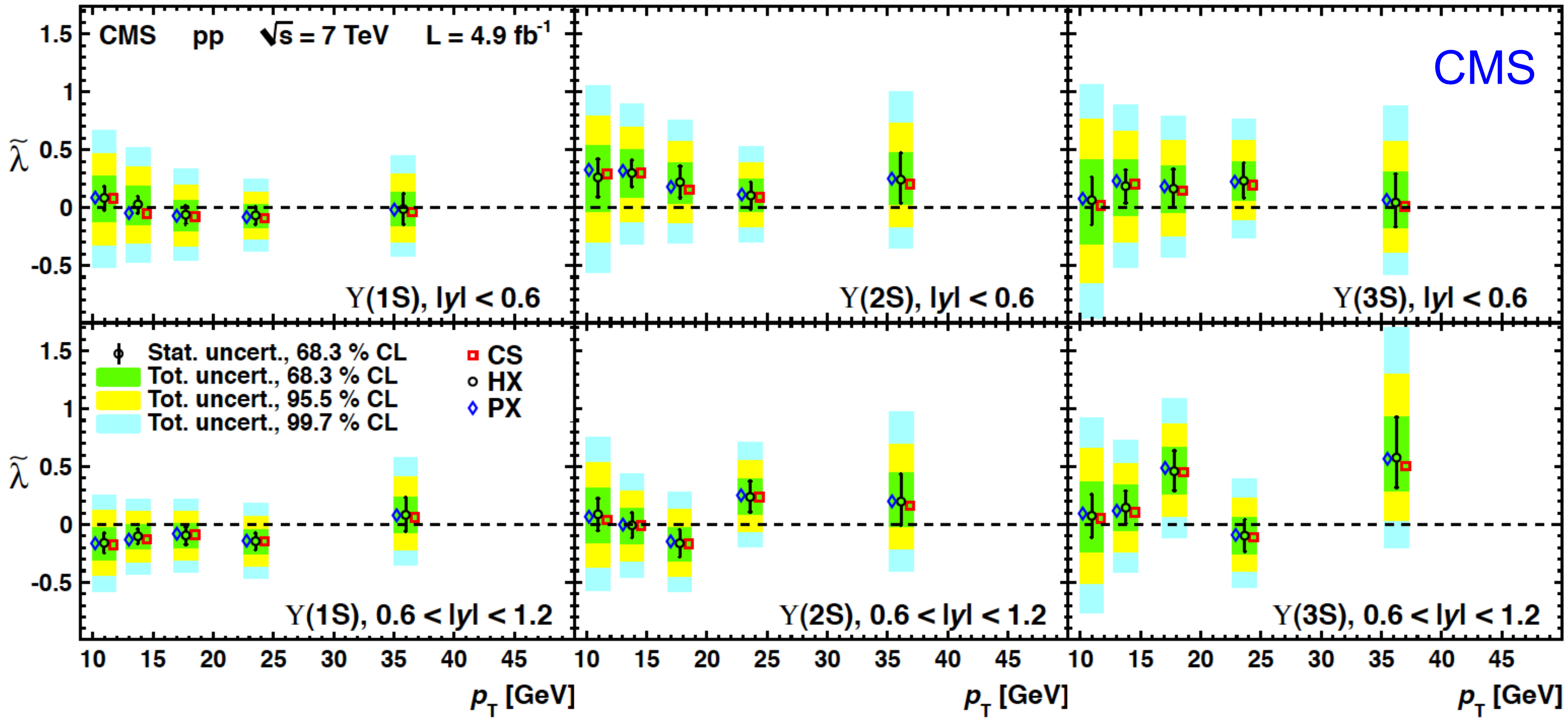
Frame-invariant polarizations

- The λ-tilde parameter provides a frame-invariant measure of quarkonium polarization:

$$\tilde{\lambda} = \frac{\lambda_\theta + 3\lambda_\phi}{1 - \lambda_\phi}$$

- Results of all reference frames are consistent
  → No evidence of unaccounted systematic uncertainties

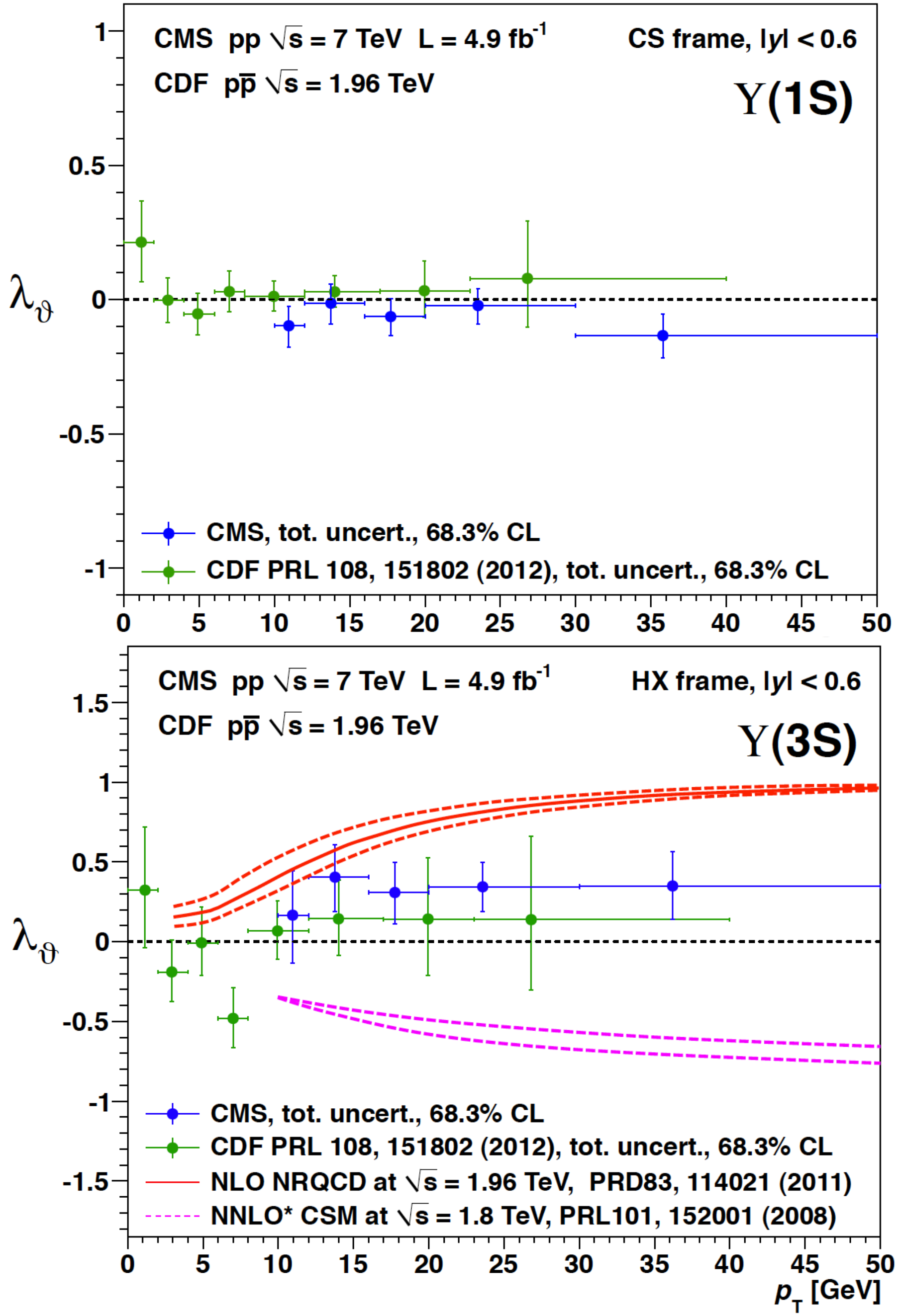




P. Faccioli et al.: PRL105 (2010) 061601
P. Faccioli et al.: PRD81 (2010) 111502(R)
CDF: PRL 108 (2012) 15180
CMS: PRL 110 (2013) 081802

Upsilon polarization: CMS vs. CDF and theory

- The LHC data extend the p_T and y coverage probed by previous experiments
- Theory is more reliable for $p_T >> m$
- Measured polarizations are much weaker than expected by the theory models
- Υ(1S) has a very large χ_b feed-down contribution, of unknown polarization
- Υ(3S) should be almost free from feed-down → more robust comparison to calculations
- Theory predictions for λ_ϕ and $\lambda_{\theta\phi}$ not available or restricted to the HX frame



CDF: PRL108 (2012) 151802
CMS: PRL 110 (2013) 081802

Summary (back to the future)

- Can QQbar production be described by pQCD, factorizing long-distance bound-state effects?
  How do the quarkonia acquire their final quantum numbers?
  Are they mainly produced as colour-neutral QQbar pairs (CSM)?
  Or also as coloured pairs, changing quantum numbers by non-pert. gluon emission (NRQCD)?
  These two options lead to strong polarizations (longitudinal and transverse, resp.)
  for the directly-produced S-states → polarization measurements are fundamental

→ both seem ruled out by existing data up to p_T ~ 35 GeV (CDF & CMS); higher-p_T data needed

- What is the role of P-wave states in the observed J/ψ and Υ polarizations?
  Do directly and indirectly produced states cancel their polarizations giving the observed, almost unpolarized, decay distributions?
  Or are quarkonia intrinsically produced almost unpolarized, an extremely peculiar scenario?

→ we must measure the polarizations of the ψ(2S) and Υ(3S), mostly directly produced
→ and evaluate the polarizations of the χ states

These open questions demand new (and accurate) quarkonium measurements
→ An important physics program, which the LHC experiments will continue addressing

Backup slides

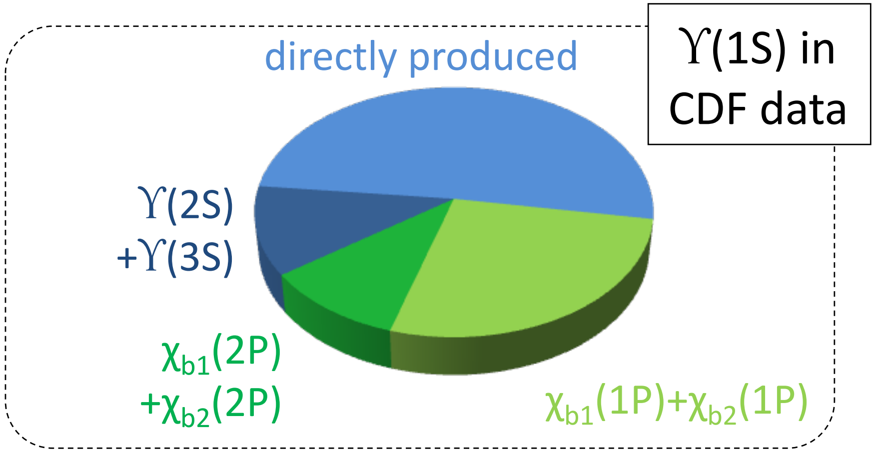
Feed-down contributions to the Υ(1S)

- CDF measured large feed-down fractions (F_X) into Υ(1S) at 1.8 TeV, |y| < 0.7, p_T > 8 GeV/c:

$$F_{\chi_b(1P)} = 27.1 \pm 6.9 \pm 4.4\%$$
$$F_{\chi_b(2P)} = 10.5 \pm 4.4 \pm 1.4\%$$

and estimated the direct Υ(1S) fraction:

$$50.9 \pm 8.2 \pm 9.0\ \%$$

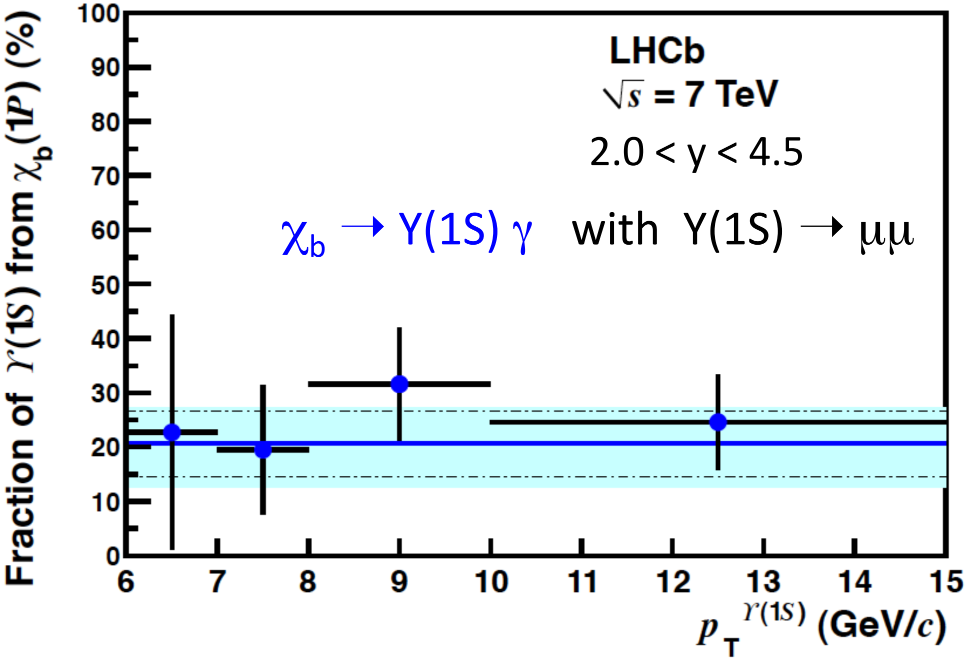


- LHCb recently measured F_X for 2.0 < y < 4.5, 6 < p_T < 15 GeV/c:

$$F_{\chi_b(1P)} = 20.7 \pm 5.7\ ^{+2.7}_{-5.4}\ \%$$

seemingly independent of p_T

$$F_X = \frac{\Upsilon(1S)\ \text{from X decays}}{\text{inclusive}\ \Upsilon(1S)}$$



CDF: PRL 84 (2000) 2094
LHCb: JHEP 1211 (2012) 031