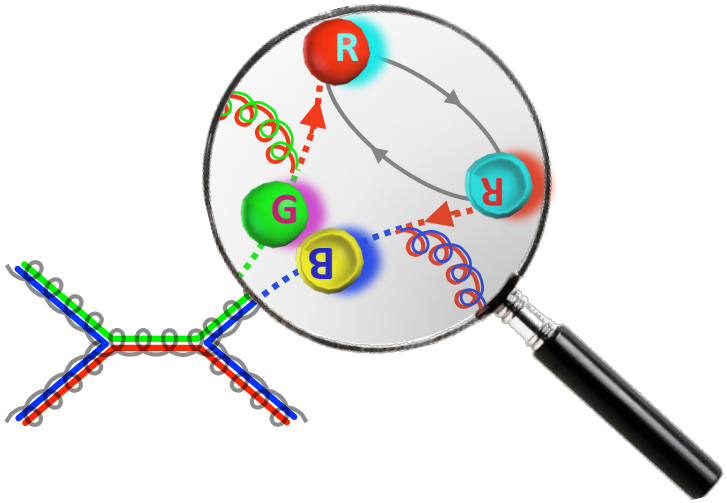
Critical review of quarkonium production results at hadron colliders

The LHC is a heavy quarkonium factory !



ATLAS, CMS, LHCb and ALICE reported
many studies of (prompt) quarkonium production

How do those measurements compare to each other?
Are there inconsistencies among the experimental results?

Executive summary

- Many measurements made at 7 TeV (2010+2011 data) and a few at 8 TeV (2012)
  - S-wave and P-wave cross sections and/or cross section ratios
  - χ_c and χ_b feed-down fractions to S-wave states
  - Polarizations of five S-wave states (charmonia and bottomonia)
- Much still to come
  - Many analyses of 2011 and 2012 data still ongoing or not even started…
  - Run II (13 TeV) will provide many more measurements
  - Availability of results limited by manpower, not by “statistics”
- In general, good agreement between measurements made by several experiments

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G. Aad et al. Measurement of the $\Upsilon(1S)$ production cross section in pp collisions at $\sqrt{s} = 7$ TeV in ATLAS. *Phys.Lett.*, B705:9–27, 2011.

G. Aad et al. Measurement of Υ production in 7 TeV pp collisions at ATLAS. *Phys.Rev.*, D87(5):052004, 2013.

G. Aad et al. Measurement of χ_{c1} and χ_{c2} production with $\sqrt{s} = 7$ TeV pp collisions at ATLAS. *JHEP*, 1407:154, 2014.

G. Aad et al. Measurement of the production cross section of $\psi(2S) \to J/\psi(\to \mu^+\mu^-)\pi^+\pi^-$ in pp collisions at $\sqrt{s} = 7$ TeV at ATLAS. *JHEP*, 1409:79, 2014.

R. Aaij et al. Measurement of J/ψ production in pp collisions at $\sqrt{s} = 7$ TeV. *Eur.Phys.J.*, C71:1645, 2011.

R Aaij et al. Measurement of ψ' meson production in pp collisions at $\sqrt{s} = 7$ TeV. *Eur.Phys.J.*, C72:2100, 2012.

R Aaij et al. Measurement of the cross-section ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ for prompt χ_c production at $\sqrt{s} = 7$ TeV. *Phys.Lett.*, B714:215–223, 2012.

R Aaij et al. Measurement of the ratio of prompt χ_c to J/ψ production in pp collisions at $\sqrt{s} = 7$ TeV. *Phys.Lett.*, B718:431–440, 2012.

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R Aaij et al. Measurement of J/ψ polarization in pp collisions at $\sqrt{s} = 7$ TeV. *Eur.Phys.J.*, C73:2631, 2013.

R Aaij et al. Measurement of J/ψ production in pp collisions at $\sqrt{s} = 2.76$ TeV. *JHEP*, 1302:041, 2013.

R. Aaij et al. Measurement of the relative rate of prompt χ_{c0}, χ_{c1} and χ_{c2} production at $\sqrt{s} = 7$TeV. *JHEP*, 1310:115, 2013.

R Aaij et al. Production of J/ψ and Υ mesons in pp collisions at $\sqrt{s} = 8$ TeV. *JHEP*, 1306:064, 2013.

R. Aaij et al. Measurement of ψ' polarisation in pp collisions at $\sqrt{s} = 7$ TeV. *Eur.Phys.J.*, C74:2872, 2014.

R. Aaij et al. Measurement of the $\chi_b(3P)$ mass and of the relative rate of $\chi_{b1}(1P)$ and $\chi_{b2}(1P)$ production. *JHEP*, 1411:031, 2014.

R. Aaij et al. Measurement of the $\eta_c(1S)$ production cross-section in pp collisions via the decay $\eta_c(2S) \to p\bar{p}$. *pp*. 2014.

R. Aaij et al. Measurement of Υ production in pp collisions at $\sqrt{s} = 2.76$ TeV. *Eur.Phys.J.*, C74:2835, 2014.

R. Aaij et al. Study of χ_b meson production in pp collisions at $\sqrt{s} = 7$ and observation of the decay $\chi_b(3P) \to \Upsilon(2S)\gamma$. *Eur.Phys.J.*, C74(10):3092, 2014.

T. Aaltonen et al. Production of ψ' Mesons in $p\bar{p}$ Collisions at 1.96 TeV. *Phys.Rev.*, D80:031103, 2009.

K. Aamodt et al. Rapidity and transverse momentum dependence of inclusive J/ψ production in pp collisions at $\sqrt{s} = 7$ TeV. *Phys.Lett.*, B704:442–455, 2011.

Many papers contributed to the preparation of this talk, from LHC and Tevatron experiments

F. Abe et al. Production of J/ψ mesons from χ_c meson decays in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. *Phys.Rev.Lett.*, 79:578–583, 1997.

B. Abelev et al. Inclusive J/ψ production in pp collisions at $\sqrt{s} = 2.76$ TeV. *Phys.Lett.*, B718:295–306, 2012.

B. Abelev et al. Measurement of prompt J/ψ and beauty hadron production cross sections at mid-rapidity in pp collisions at $\sqrt{s} = 7$ TeV. *JHEP*, 1211:065, 2012.

B. Abelev et al. J/ψ polarization in pp collisions at $\sqrt{s} = 7$ TeV. *Phys.Rev.Lett.*, 108:082001, 2012.

B. Abelev et al. Measurement of quarkonium production at forward rapidity in pp collisions at $\sqrt{s}$= 7 TeV. *Eur.Phys.J.*, C74:2974, 2014.

A. Abulencia et al. Measurement of $\sigma_{\chi_{c2}}\mathcal{B}(\chi_{c2} \to J/\psi\gamma)/\sigma_{\chi_{c1}}\mathcal{B}(\chi_{c1} \to J/\psi\gamma)$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. *Phys.Rev.Lett.*, 98:232001, 2007.

D. Acosta et al. Measurement of the J/ψ meson and b-hadron production cross sections in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. *Phys.Rev.*, D71:032001, 2005.

S. Chatrchyan et al. J/ψ and ψ' prompt double-differential cross sections in pp collisions at sqrt(s) = 7 TeV.

S. Chatrchyan et al. $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ cross section measurements in pp collisions at $\sqrt{s} = 7$ TeV.

S. Chatrchyan et al. J/ψ and ψ' production in pp collisions at $\sqrt{s} = 7$ TeV. *JHEP*, 1202:011, 2012.

S. Chatrchyan et al. Measurement of the relative prompt production rate of χ_{c2} and χ_{c1} in pp collisions at $\sqrt{s} = 7$ TeV. *Eur.Phys.J.*, C72:2251, 2012.

S. Chatrchyan et al. Measurement of the prompt J/ψ and ψ' polarizations in pp collisions at $\sqrt{s} = 7$ TeV. *Phys.Lett.*, B727:381–402, 2013.

S. Chatrchyan et al. Measurement of the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ cross sections in pp collisions at $\sqrt{s} = 7$ TeV. *Phys.Lett.*, B727:101–125, 2013.

S. Chatrchyan et al. Measurement of the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ polarizations in pp collisions at $\sqrt{s} = 7$ TeV. *Phys.Rev.Lett.*, 110:081802, 2013.

S. Chatrchyan et al. Measurement of the X(3872) production cross section via decays to J/$\psi\pi\pi$ in pp collisions at $\sqrt{s} = 7$ TeV. *JHEP*, 1304:154, 2013.

V. Khachatryan et al. Measurement of the inclusive upsilon production cross section in pp collisions at $\sqrt{s} = 7$ TeV. *Phys.Rev.*, D83:112004, 2011.

V. Khachatryan et al. Prompt and non-prompt J/ψ production in pp collisions at $\sqrt{s} = 7$ TeV. *Eur.Phys.J.*, C71:1575, 2011.

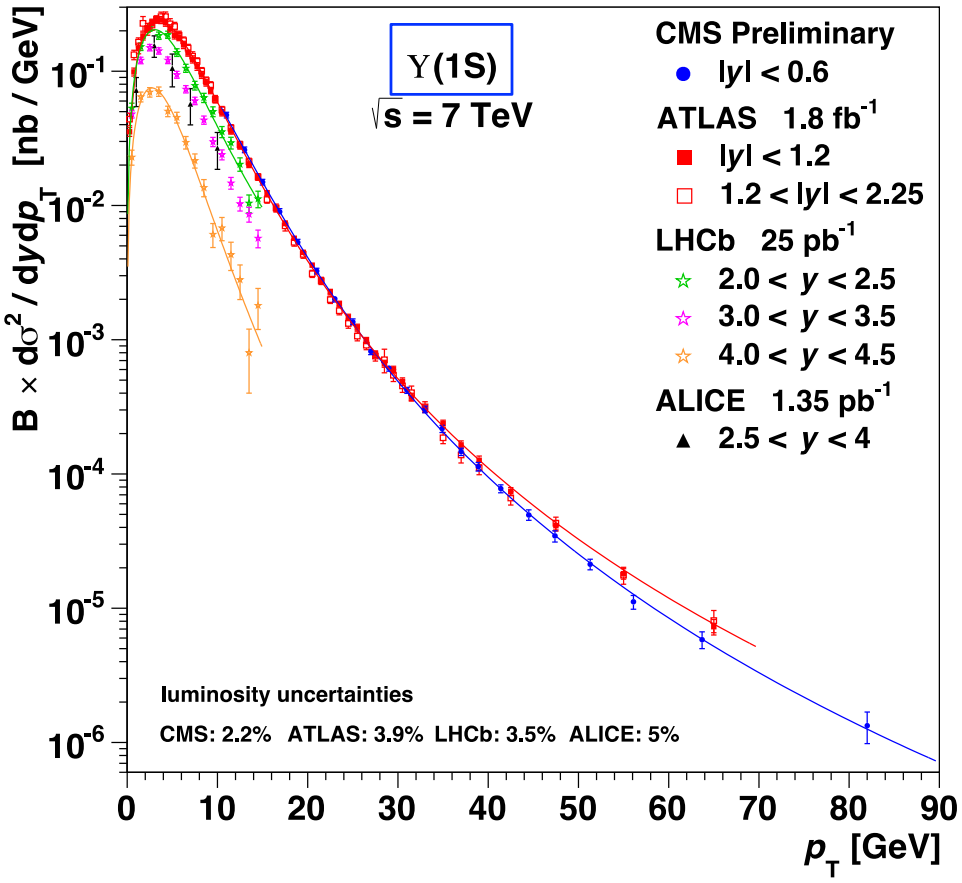
V. Khachatryan et al. Measurement of the production cross section ratio $\sigma(\chi_{2b}(1P))/\sigma(\chi_{1b}(1P))$ in pp collisions at $\sqrt{s} = 8$ TeV. 2014.

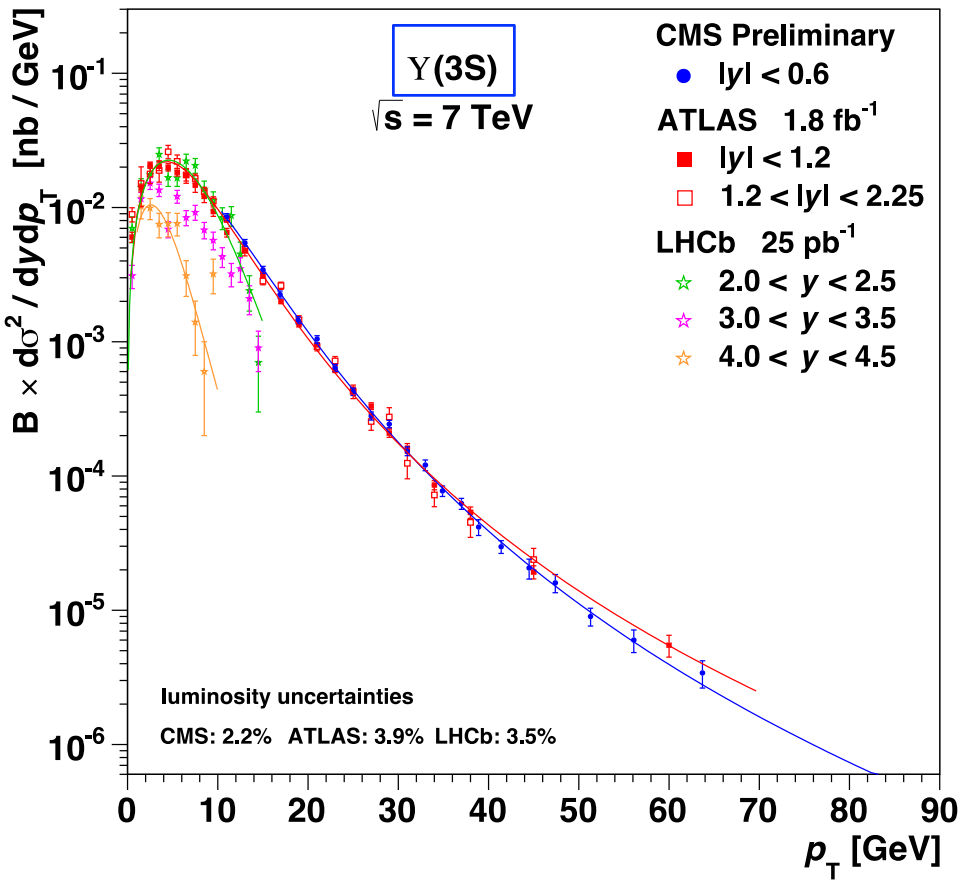
Many papers contributed to the preparation of this talk, from LHC and Tevatron experiments

Υ(nS) cross sections

- Measured in the p_T range from 0 to 100 GeV
- No hint of significant discrepancies between measurements

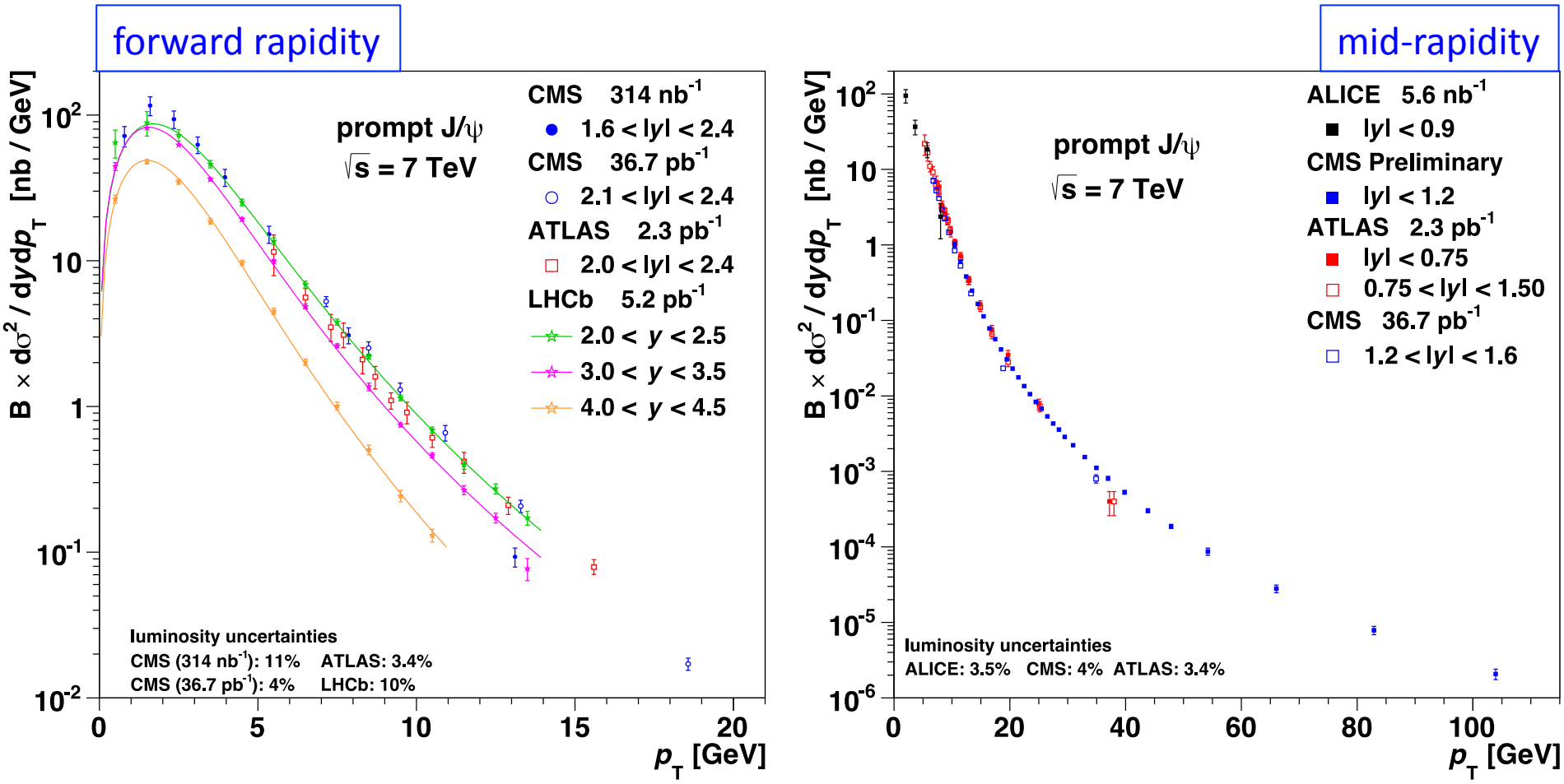
- The curves represent fits to the function $N \cdot p_T \cdot \left[1 + \frac{1}{\beta-2} \cdot \frac{p_T^2}{\gamma}\right]^{-\beta}$





Prompt J/ψ cross sections

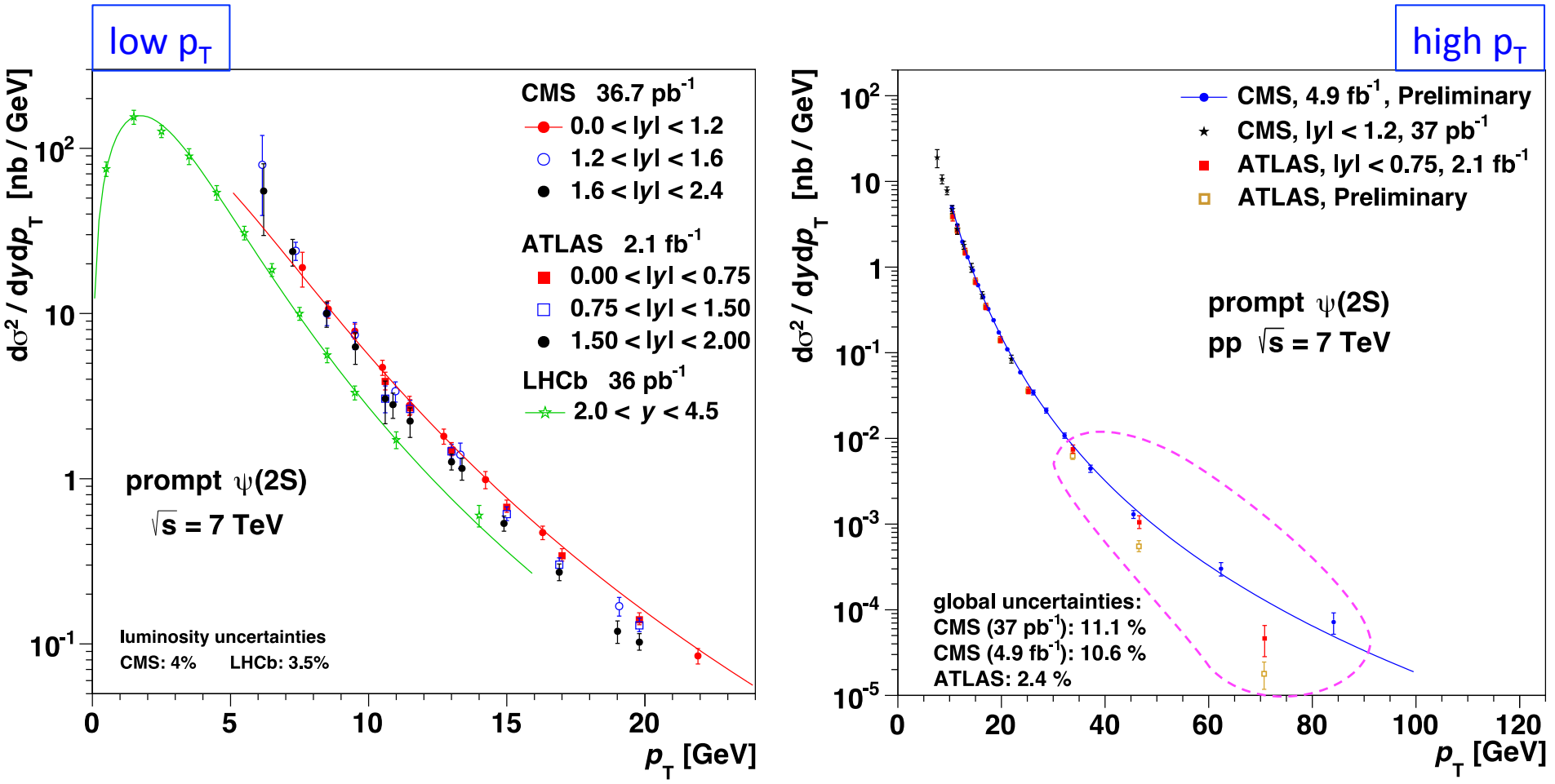
- Measured in the p_T range from 0 to 120 GeV
- No hint of significant discrepancies between measurements



Prompt ψ(2S) cross sections

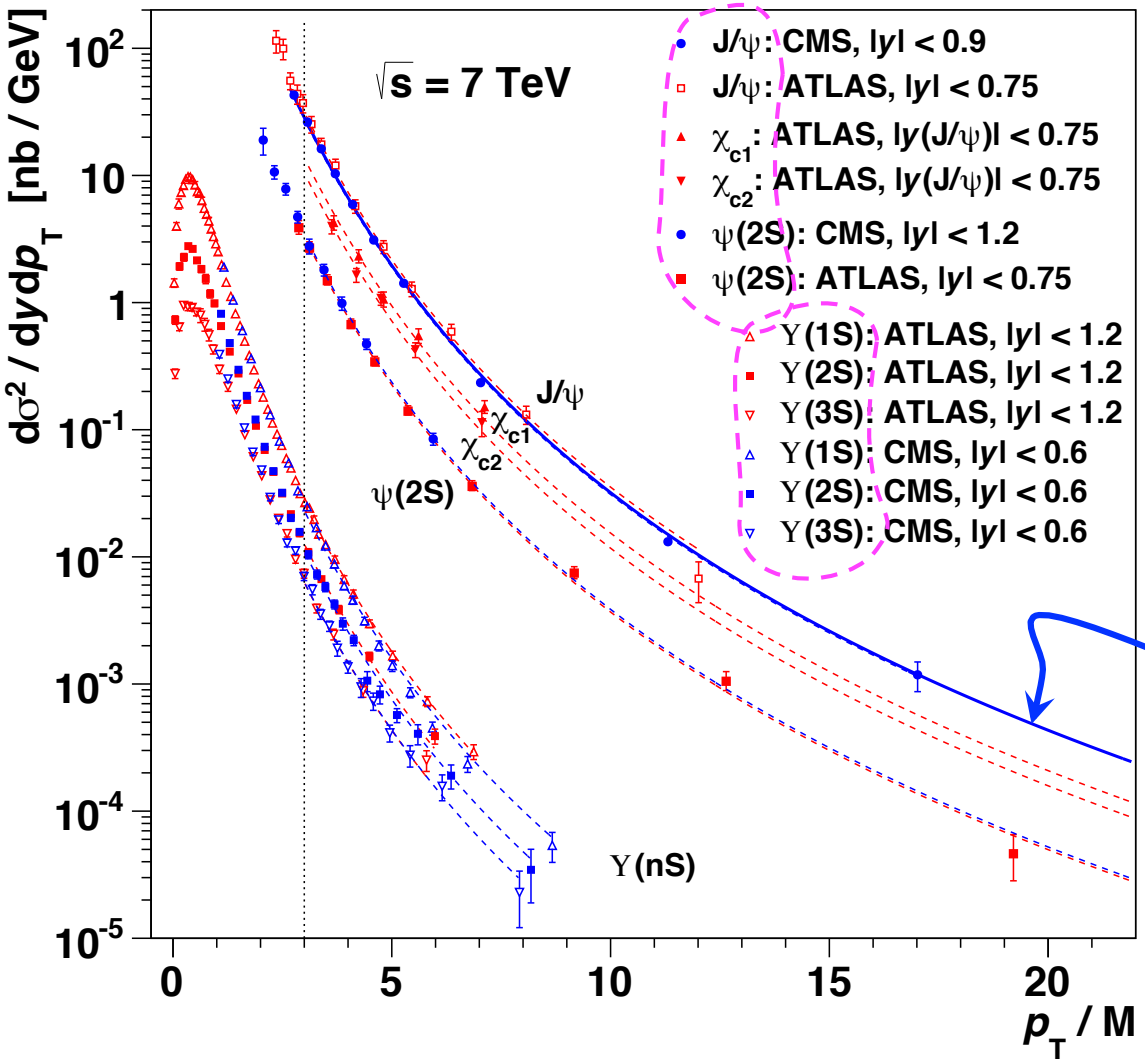
- Measured in the p_T range from 0 to 100 GeV

- Comparing CMS and ATLAS *preliminary* results showed a problem at high-p_T
  The ATLAS points were corrected in the final publication
  ⟶ Shows that these comparisons are *very* useful ☺



All together now: 7 different quarkonia

- Mid-rapidity cross sections for seven quarkonia have identical p_T/M shapes, for $p_T/M > 3$
- Interesting empirical observation



ATLAS and CMS will soon have J/ψ and ψ(2S) differential cross sections up to p_T/M ~ 30 !

All 12 (!) curves have identical shapes

Fitted to the CMS J/ψ data for $p_T/M > 3$

Global χ^2/ndf = 91/85 ; P = 30%

Disclaimer

For some measurements, the several experiments use a different binning in p_T or y; small corrections (intra/extrapolations) were applied to improve the comparisons

To make the ratio of two distributions measured with different p_T bins, we first fit each distribution and then show the ratio of the functions

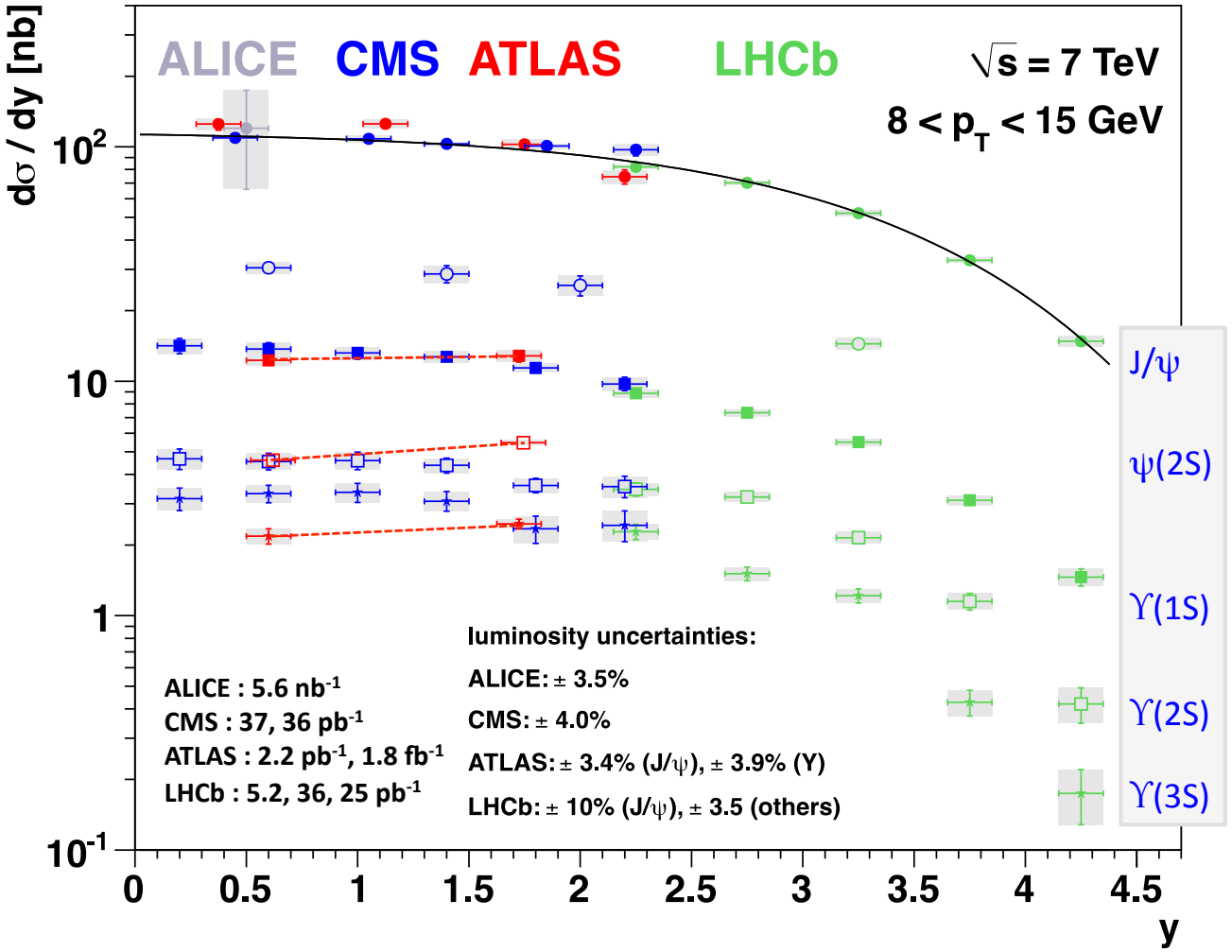
→ Such “harmless manipulations” are identified by the “sticker” Derived

The same label identifies figures showing “derived variables”…

The LHC collaborations are not responsible for these “derivations” ☺

S-wave quarkonium cross sections vs. rapidity

- All experiments measured cross sections in the bin $8 < p_T < 15$ GeV (or very similar)
  → Allows us to see how the cross sections change with rapidity and state
- At first sight, reasonable overlap between ATLAS, CMS and LHCb…
  but looking more closely we see significant differences (given the tiny uncertainties)



ATLAS ϒ(nS) :
cross sections seem to *increase* with rapidity

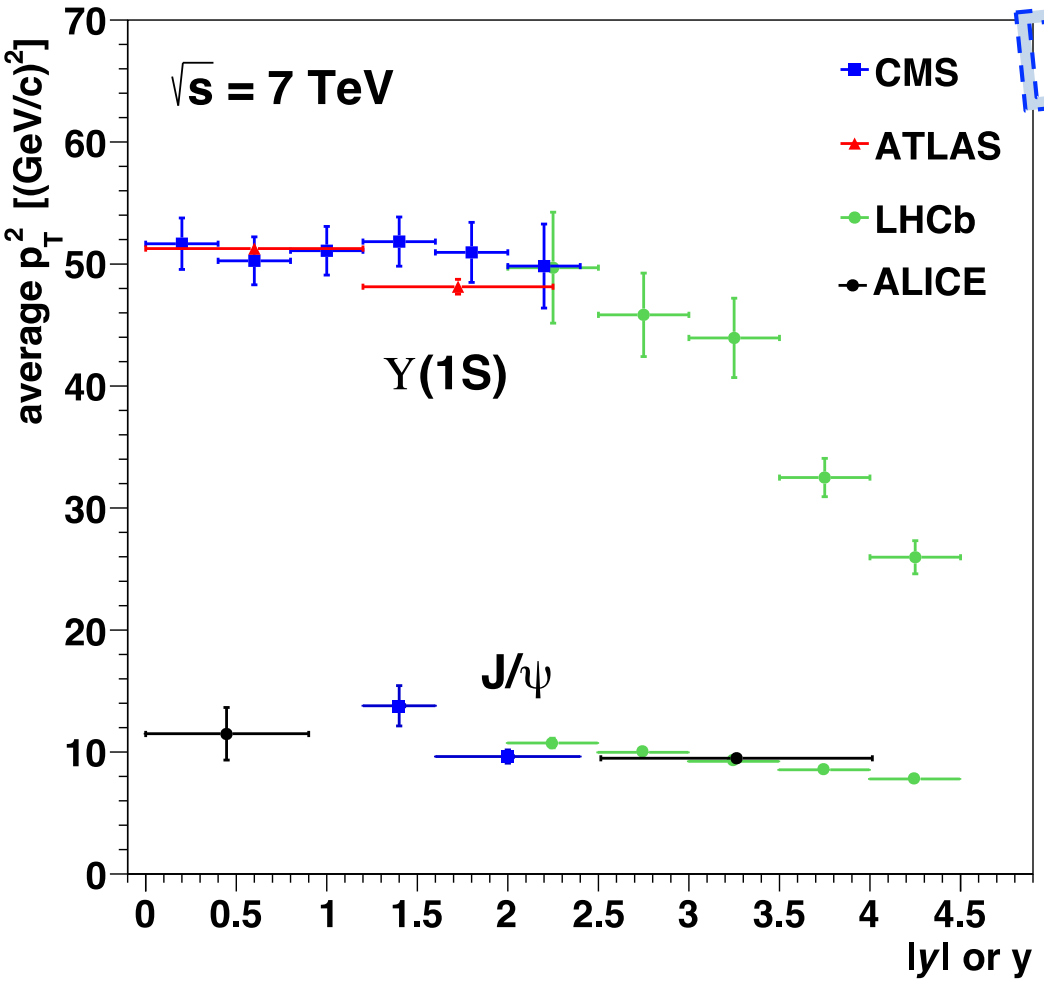
Other states and experiments show a decrease

Derived

Slightly different p_T bins implied interpolations

Changes of p_T with rapidity

- The shape of the p_T distributions changes with rapidity
  - ➞ Interesting to see the average p_T^2 versus rapidity
    Sensitive to the low-p_T reach of the data…



Derived p_T distributions fitted

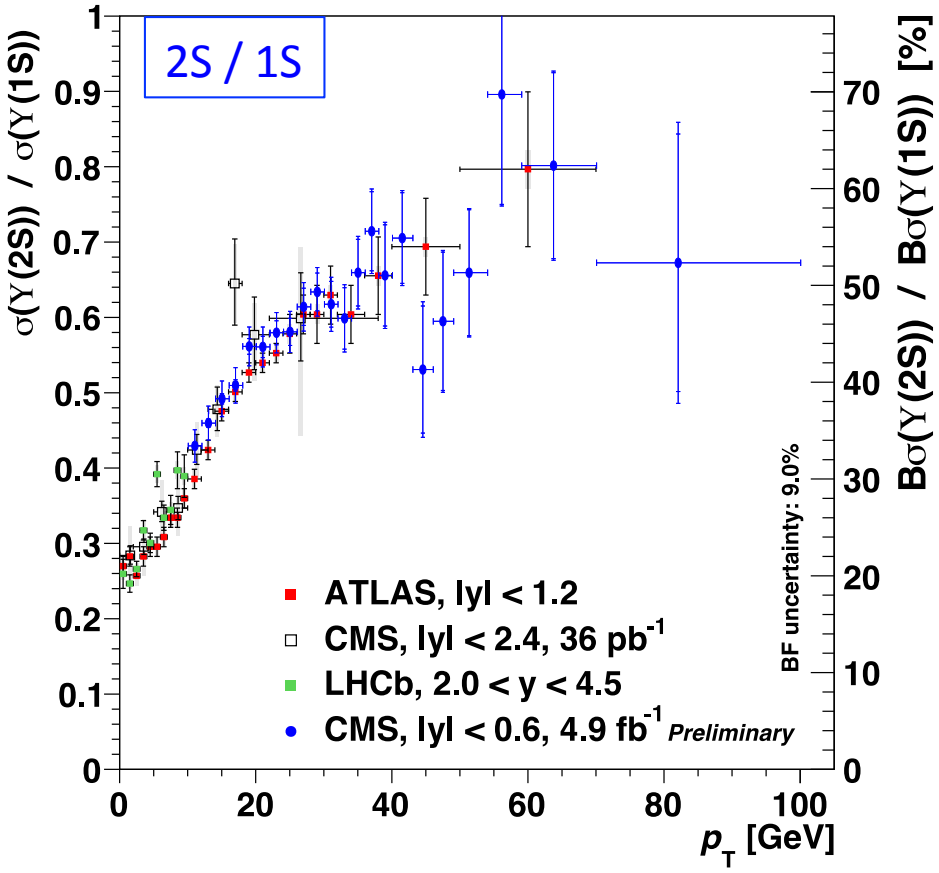
Υ(nS):
ATLAS, CMS and LHCb compatible;
striking drop at forward-rapidity

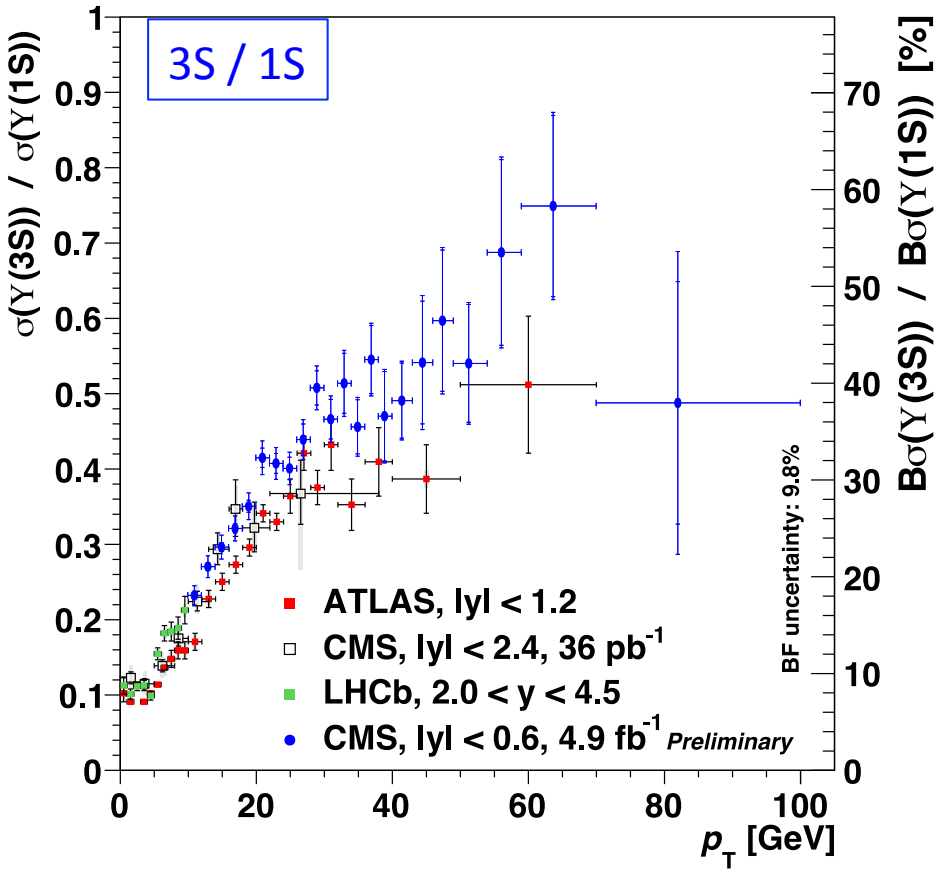
J/ψ:
ALICE forward y is inclusive
others are prompt;
flatter trend vs. y than Upsilons

Cross section ratios: bottomonium

- The nS/1S cross section ratios increase steeply with p_T up to around 40 GeV
  - ➞ At higher p_T the increase seems to slow down and the trend might flatten out…
  - ➞ More high-p_T data needed to clarify the observations

- The ATLAS 3S/1S ratio is systematically lower than the LHCb and CMS trends…

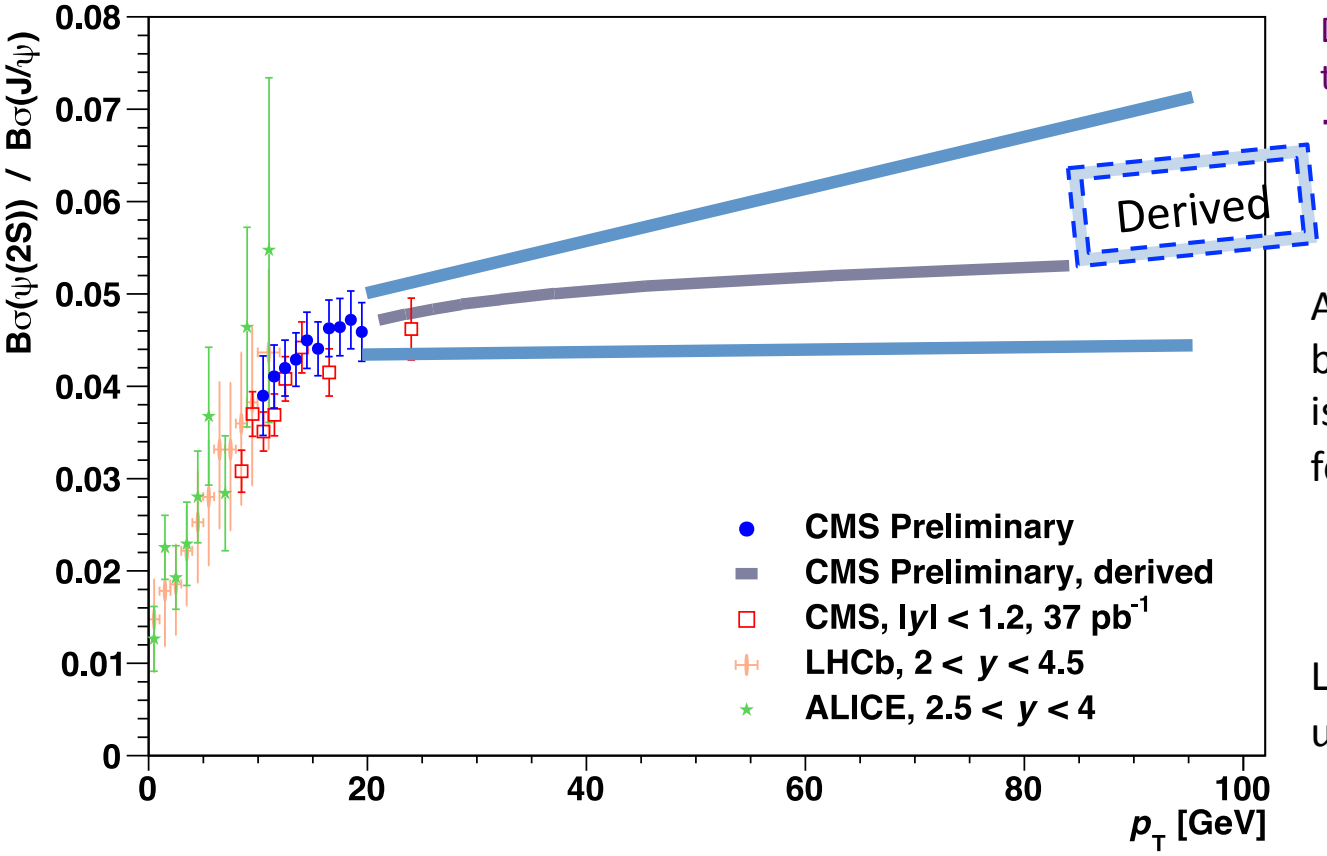




Cross section ratios: charmonium

- The 2S/1S cross section ratio increases steeply with p_T up to around 20 GeV
  - ➞ At higher p_T we see some tendency for saturation… but the errors are very large
  - ➞ More measurements needed to clarify the high-p_T trend

- ATLAS and CMS are working on improved measurements; should be available “soon”



Different p_T bins for the 1S and 2S states
➞ ratio of fitted functions

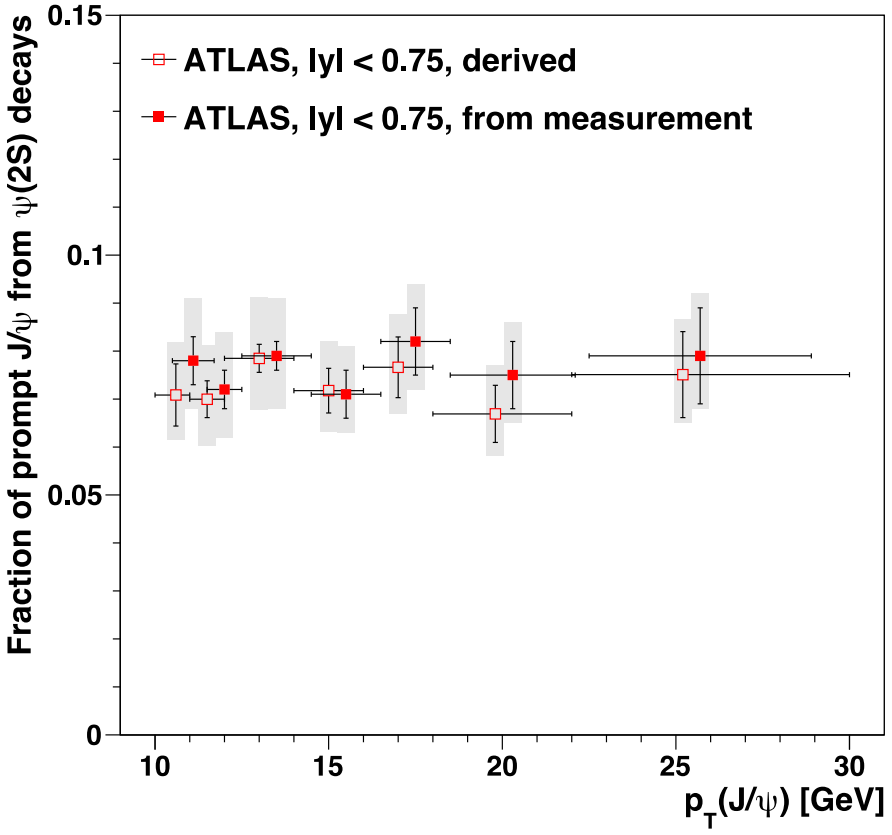
ALICE measures *inclusive* ratio… but the low-p_T b-hadron fraction is small and identical for the 1S and 2S states

LHCb values include global uncertainties on each point…

From cross section ratios to feed-down fractions (1)

- We have *derived* the "1S from nS feed-down fractions" from the cross section ratios
  - correcting for the ratios of branching fractions
  - scaling the nS p_T by the mass ratio M(1S) / M(nS)

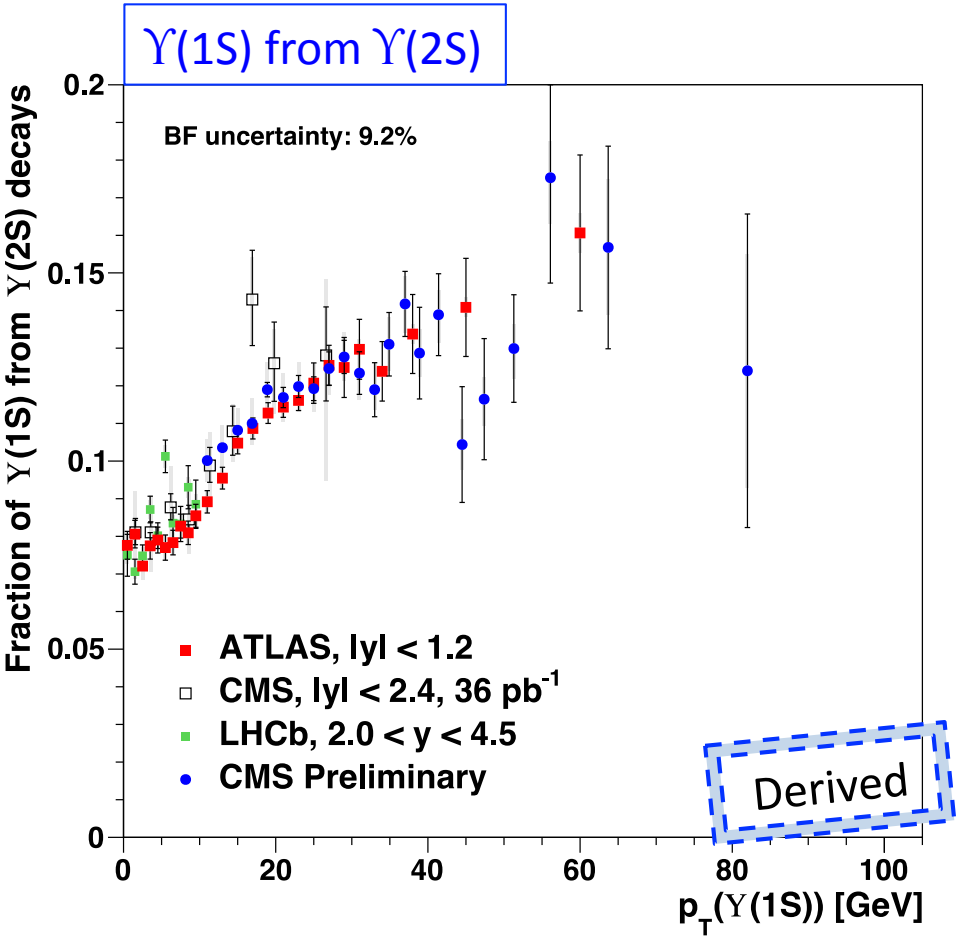
- Method validated using 2S → 1S π π results, available from ATLAS both vs. 1S *and* 2S p_T

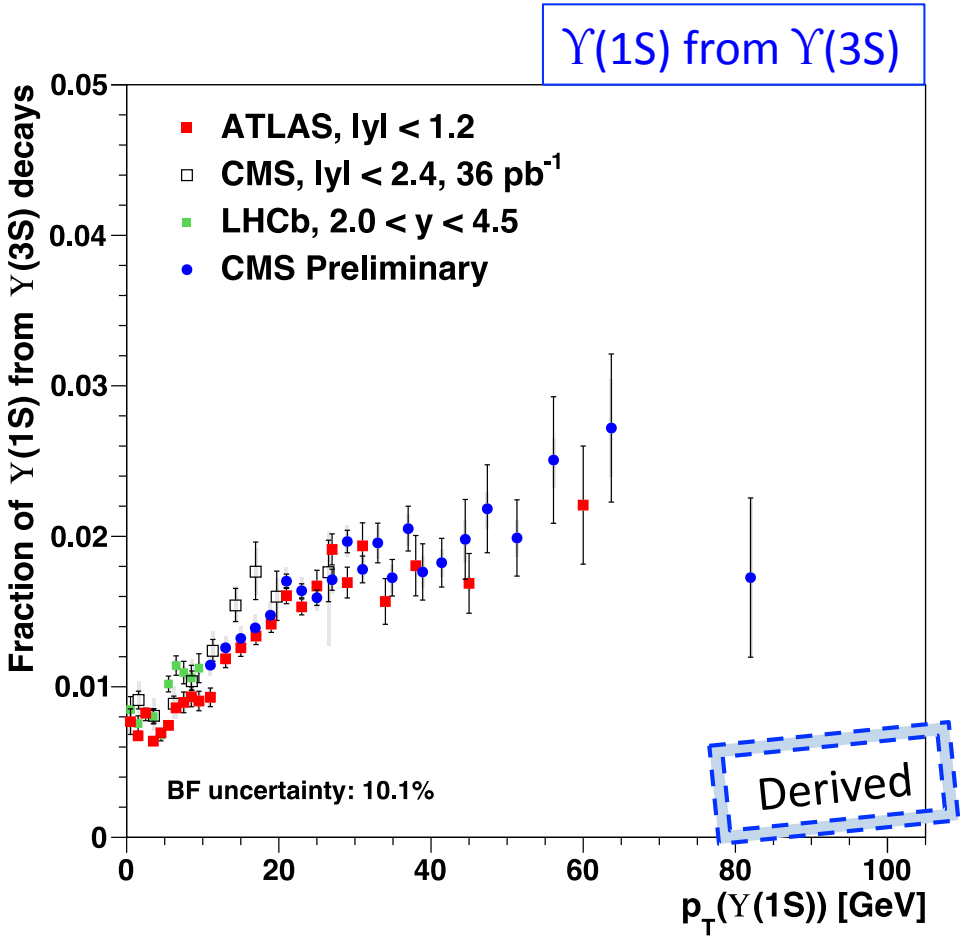


The derived results agree very well with those measured directly by ATLAS

From cross section ratios to feed-down fractions (2)

- Applying the method to the bottomonium family, we see that:
  - a fraction between 7% and 15% of the Υ(1S) is produced from Υ(2S) decays while the Υ(3S) feed-down contribution is less than 2.5%
  - the S-wave feed-down "contamination" increases with p_T

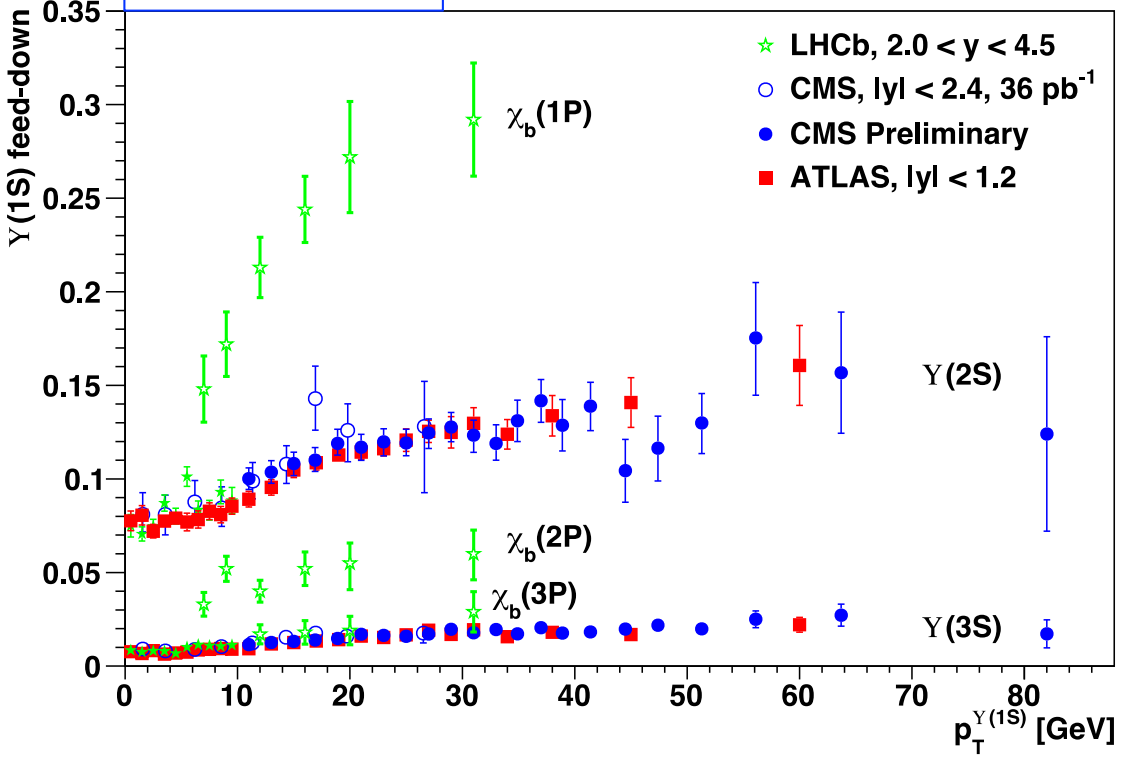




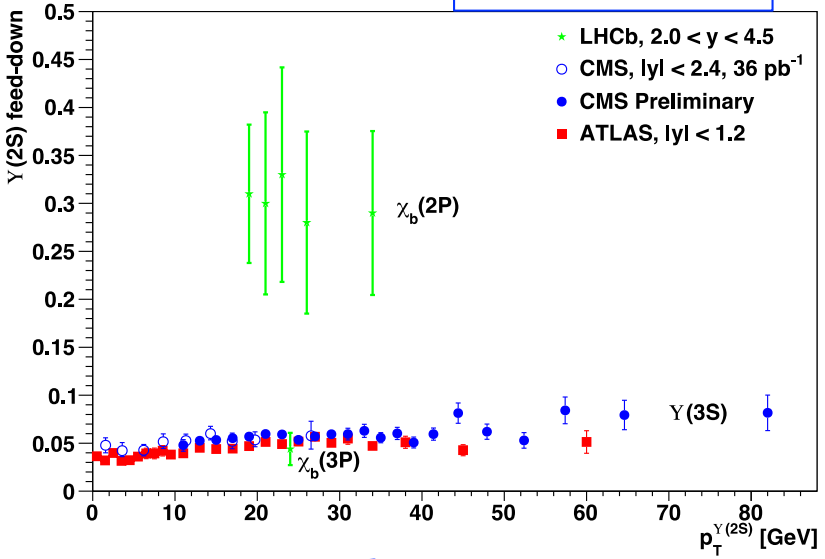
From cross section ratios to feed-down fractions (3)

- LHCb recently reported measurements of the nP → mS feed-down fractions:
  - the biggest Υ(1S) feed-down contribution comes from the χ_b(1P)
  - at around 30 GeV, more than half of the Υ(1S) mesons result from feed-down
  - the Υ(2S) gets contributions from Υ(3S), χ_b(2P) and χ_b(3P) decays
  - the Υ(3S) feed-down from χ_b(3P) decays is 37±7 % (in $25 < p_T < 40$ GeV)

Υ(1S) from all



Υ(2S) from all

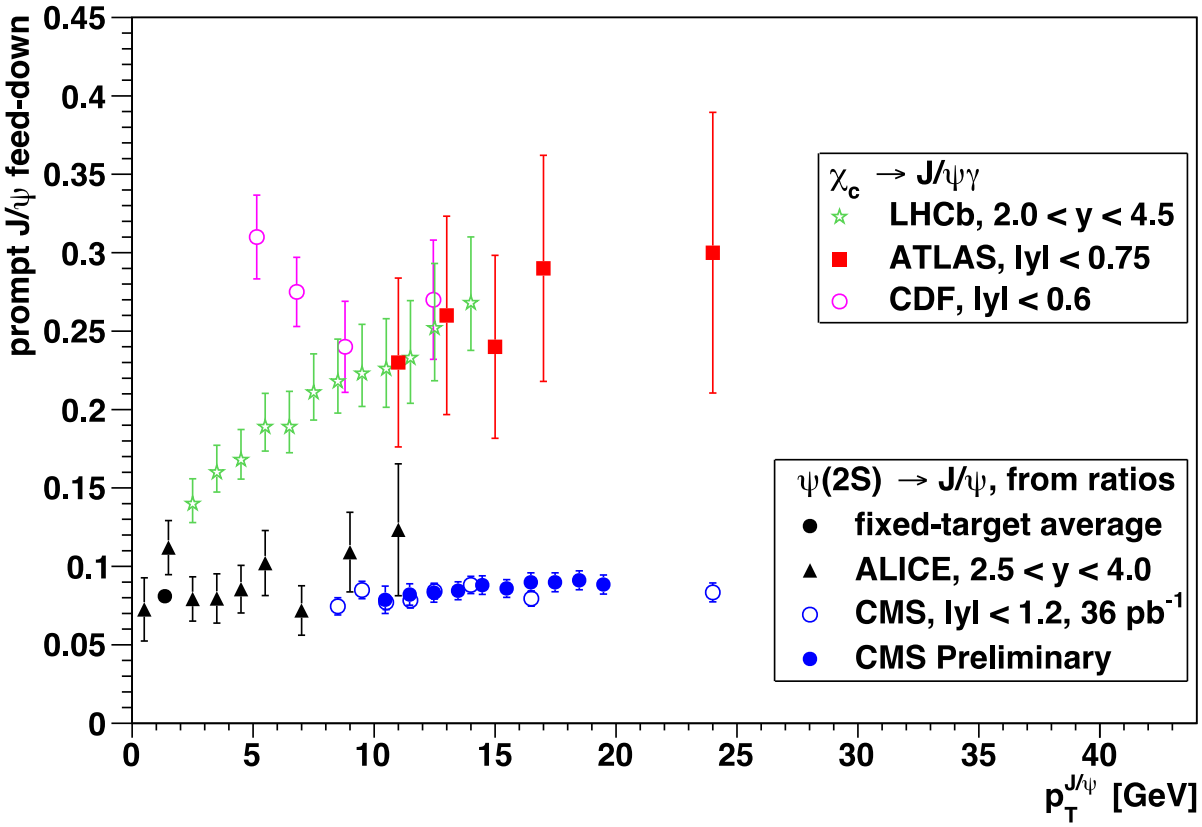


Derived

Important inputs to interpret the Υ(nS) suppression seen in p-Pb and Pb-Pb collisions

From cross section ratios to feed-down fractions (4)

- The same method can be applied to the charmonium family:
  - the biggest J/ψ feed-down fraction is from χ_c decays
  - the LHCb and ATLAS points are very well aligned…
  - while the low p_T CDF points seem to be outliers…



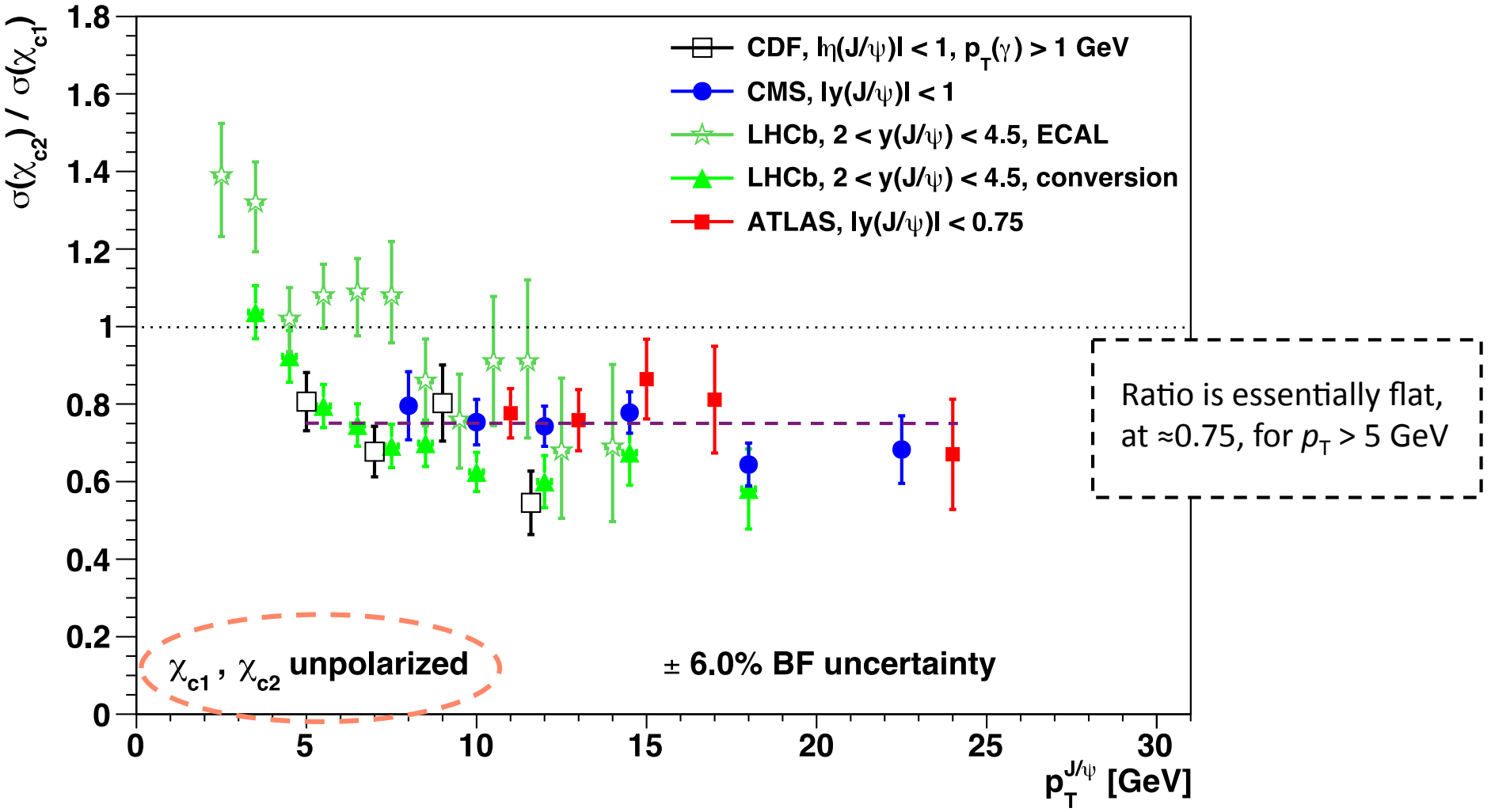
ALICE points from *inclusive* ratio

Derived

χ_{c2} / χ_{c1} cross section ratios

- Measurements using photon conversions are well aligned with each other

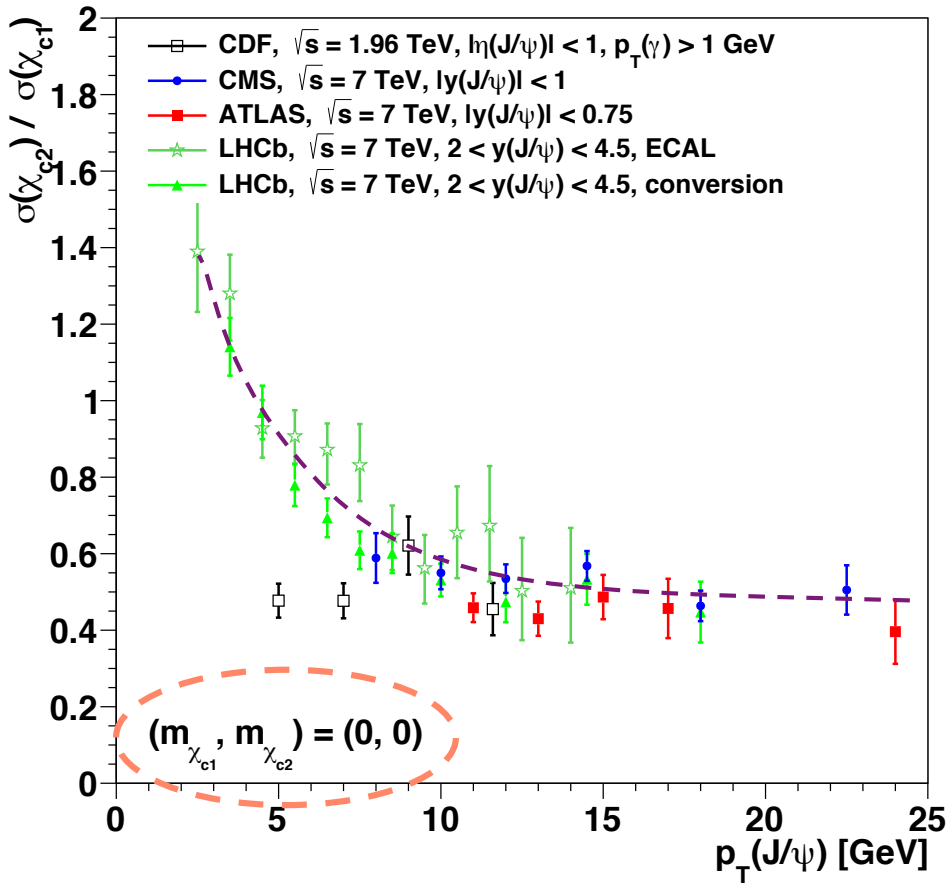
- LHCb results with ECAL and conversions *are quite different*, for $p_T < 8$ GeV
  → Is there an experimental problem? Or is this a physics (phase space) effect?

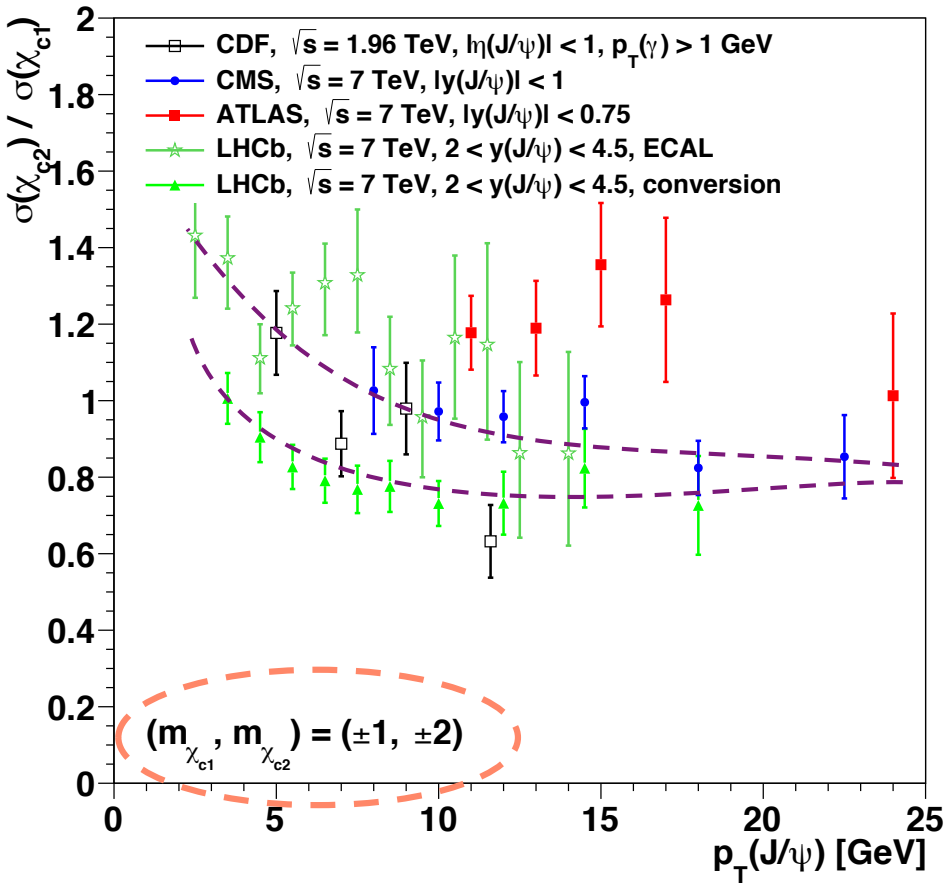


χ_{c2} / χ_{c1} cross section ratios

- Results depend on the polarizations assumed for the two states (acceptance correction)
  - If both states have helicity = 0, the LHCb results with ECAL and conversions *agree well*
  - If they have extreme polarizations (±1, ±2), the spread of the measurements increases

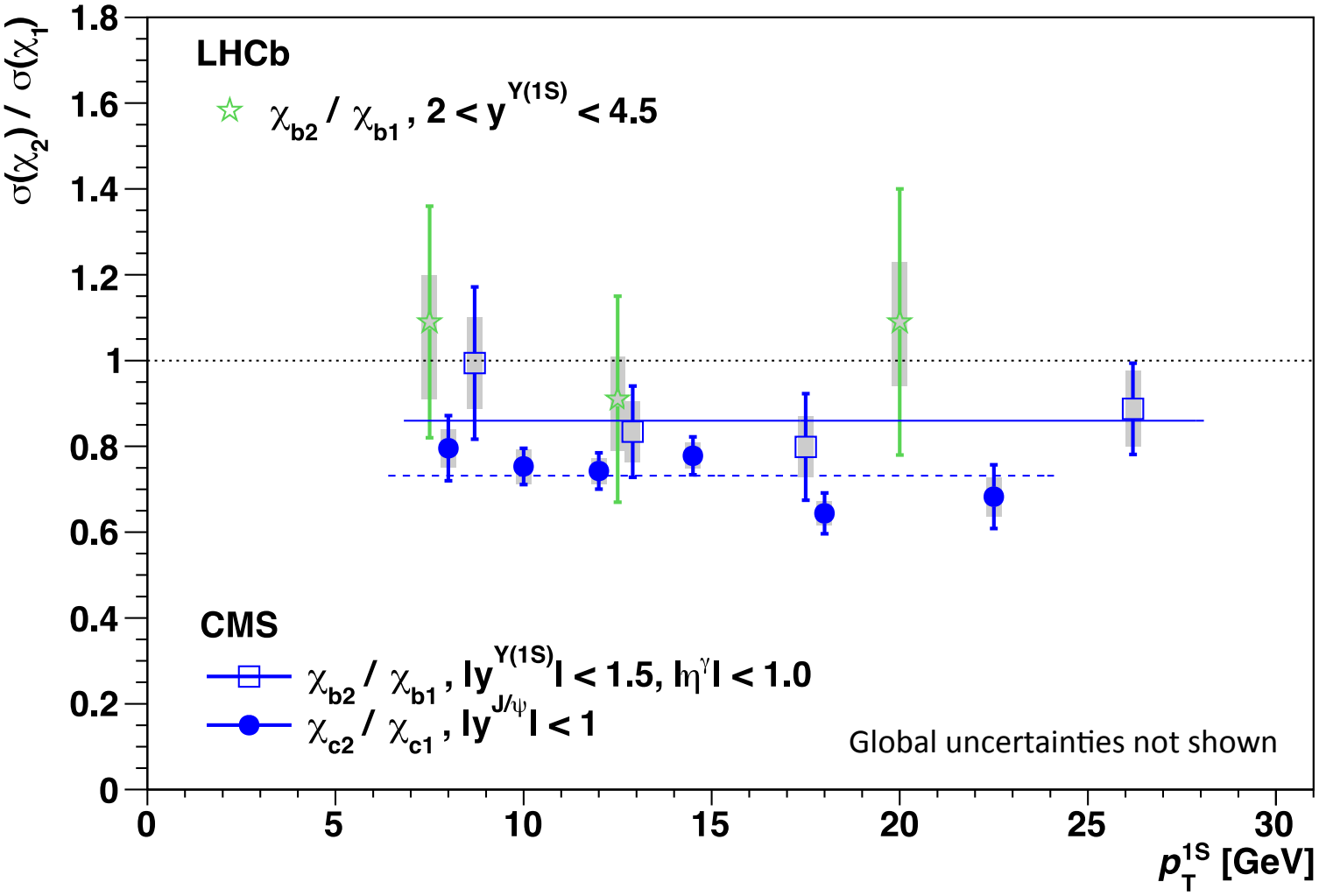
  ➞ Important to measure the polarizations of the χ_{c1} and χ_{c2} mesons





χ_{b2} / χ_{b1} cross section ratios

- The corresponding ratio in the bottomonium family is also seemingly flat
- LHCb and CMS results agree well, within the large uncertainties

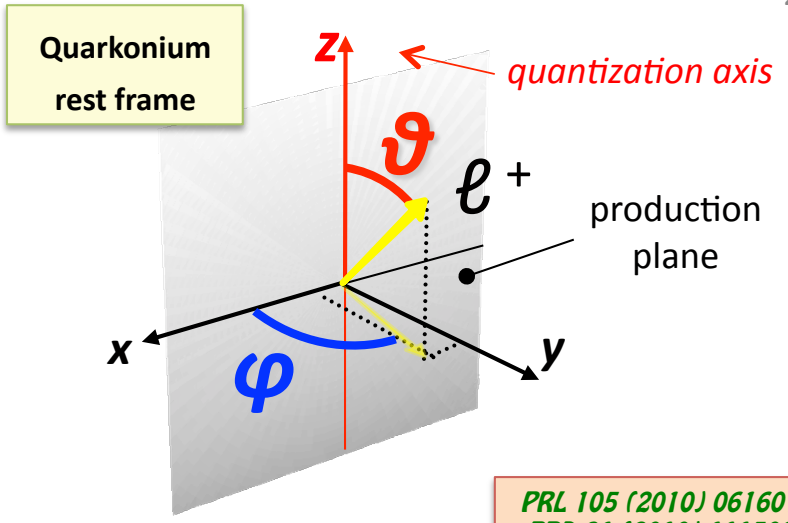


Quarkonium polarization

S-wave polarizations are measured from the dimuon angular decay distributions

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

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



PRL 105 (2010) 061601
PRD 81 (2010) 111502
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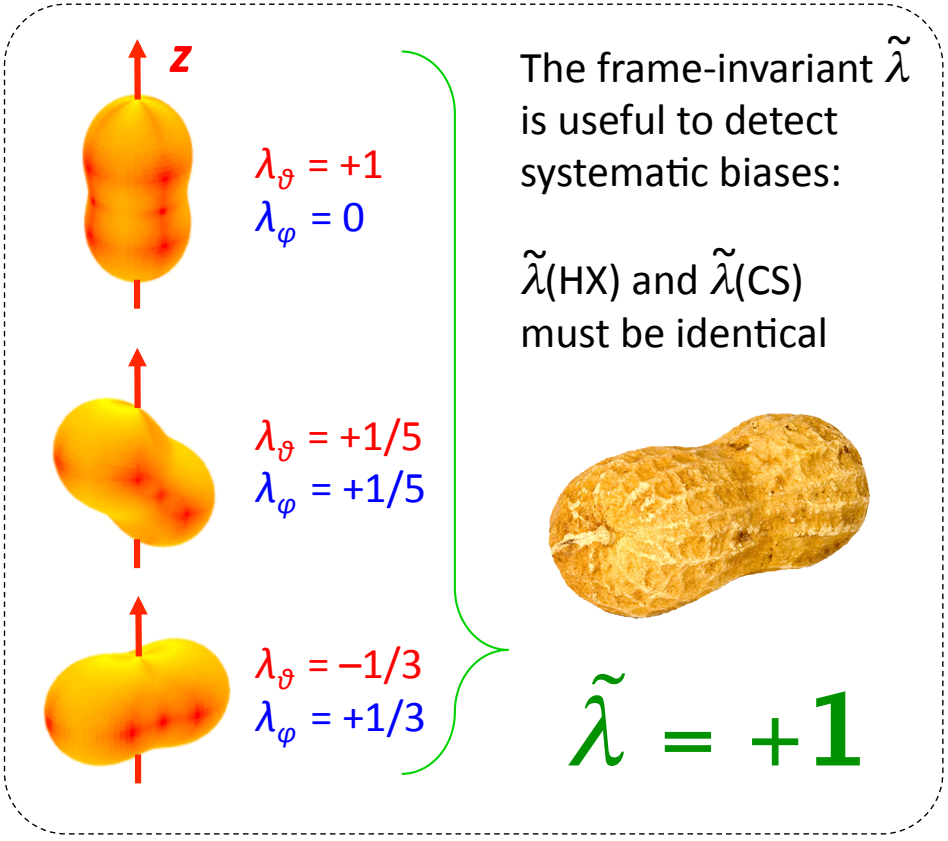
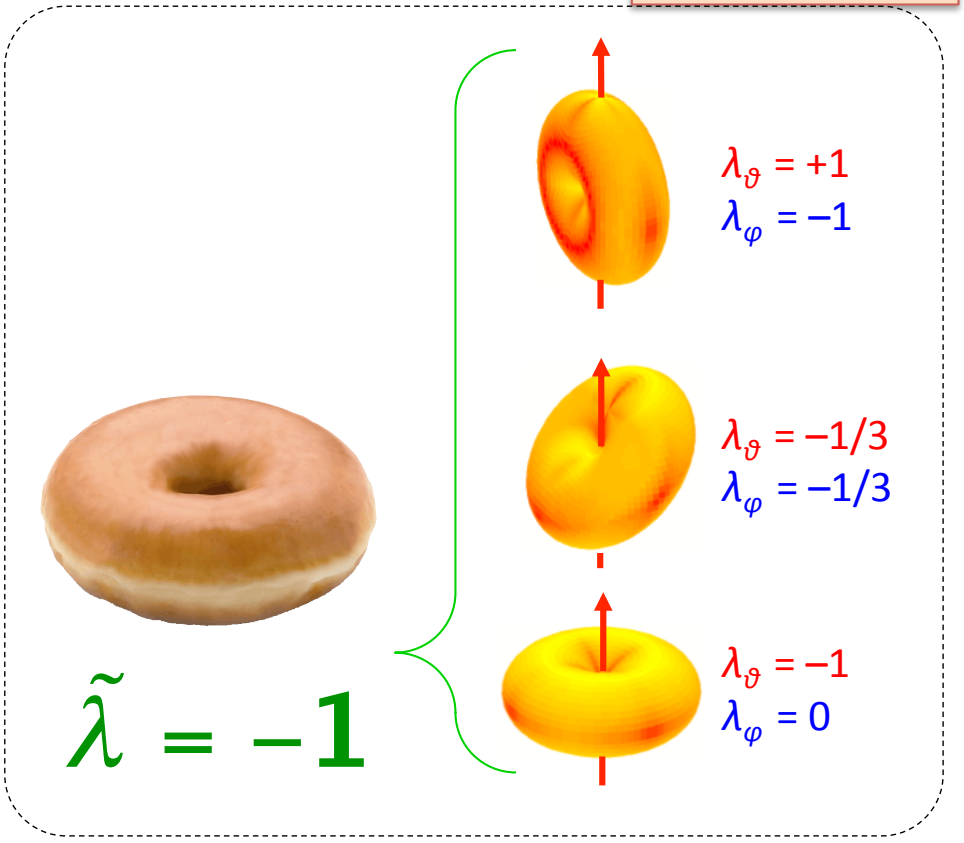
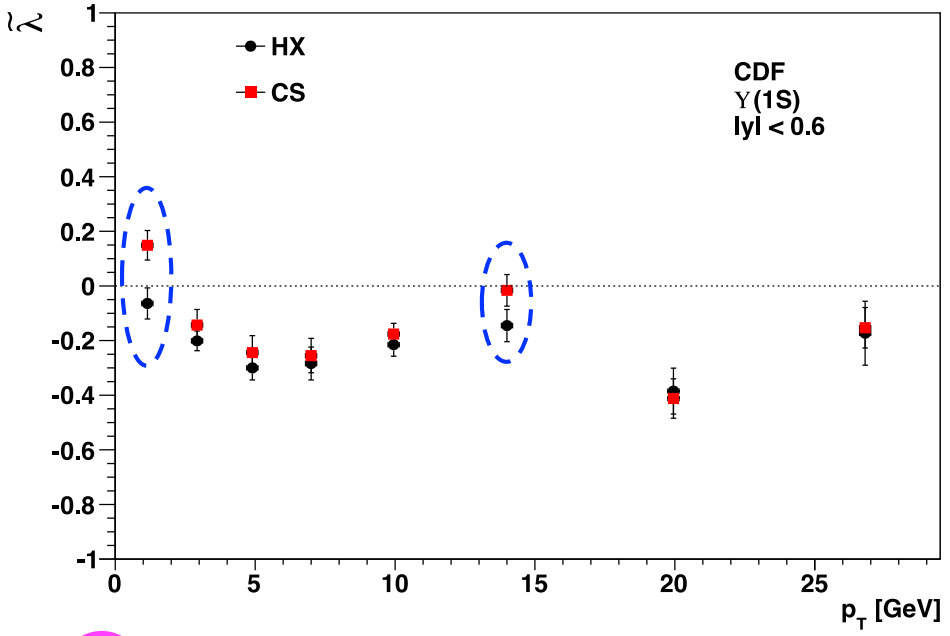
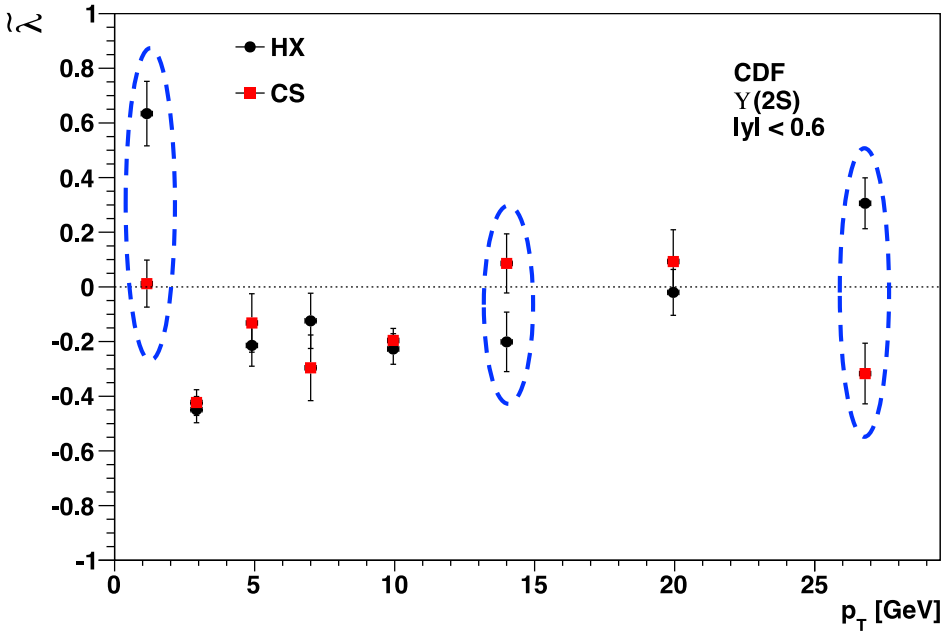


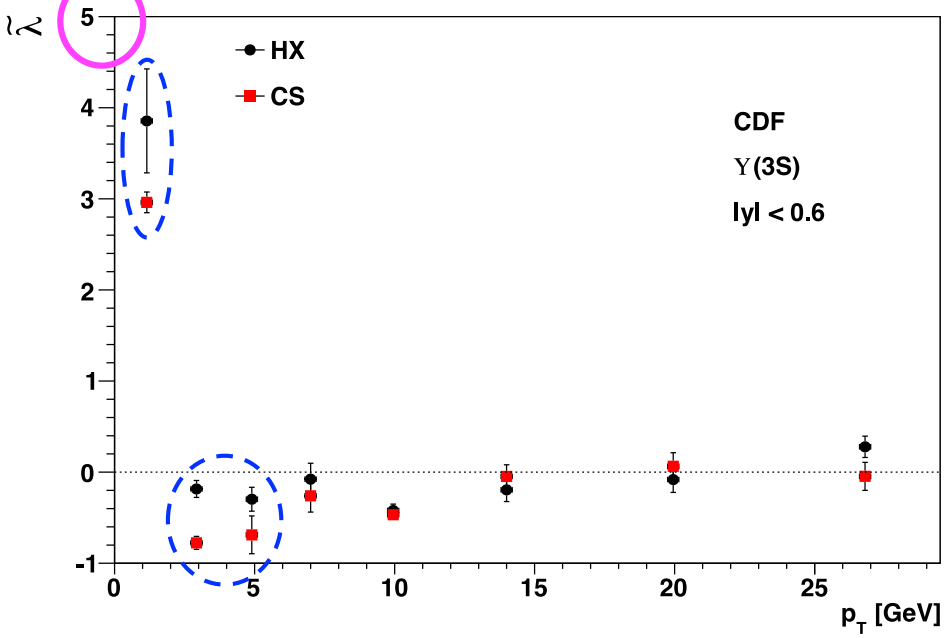


Quarkonium polarization: Υ(nS) from CDF run 2

- The $\tilde{\lambda}$ values reported by CDF for the Υ(nS) polarizations show systematic biases not covered by the uncertainties
- The lowest p_T Υ(3S) value is $\tilde{\lambda} >> 1$!
- Note: $\tilde{\lambda}$ is not frame invariant for background



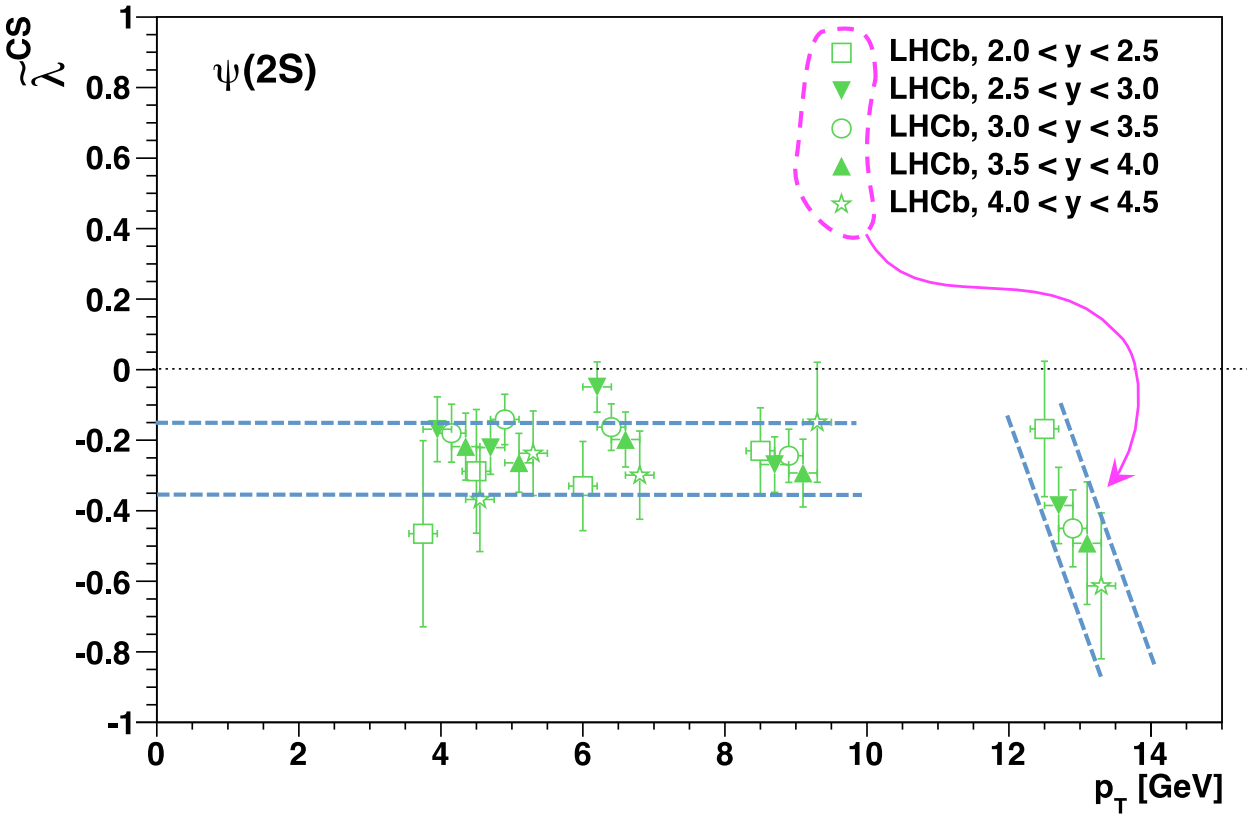




Quarkonium polarization: ψ(2S) in LHCb

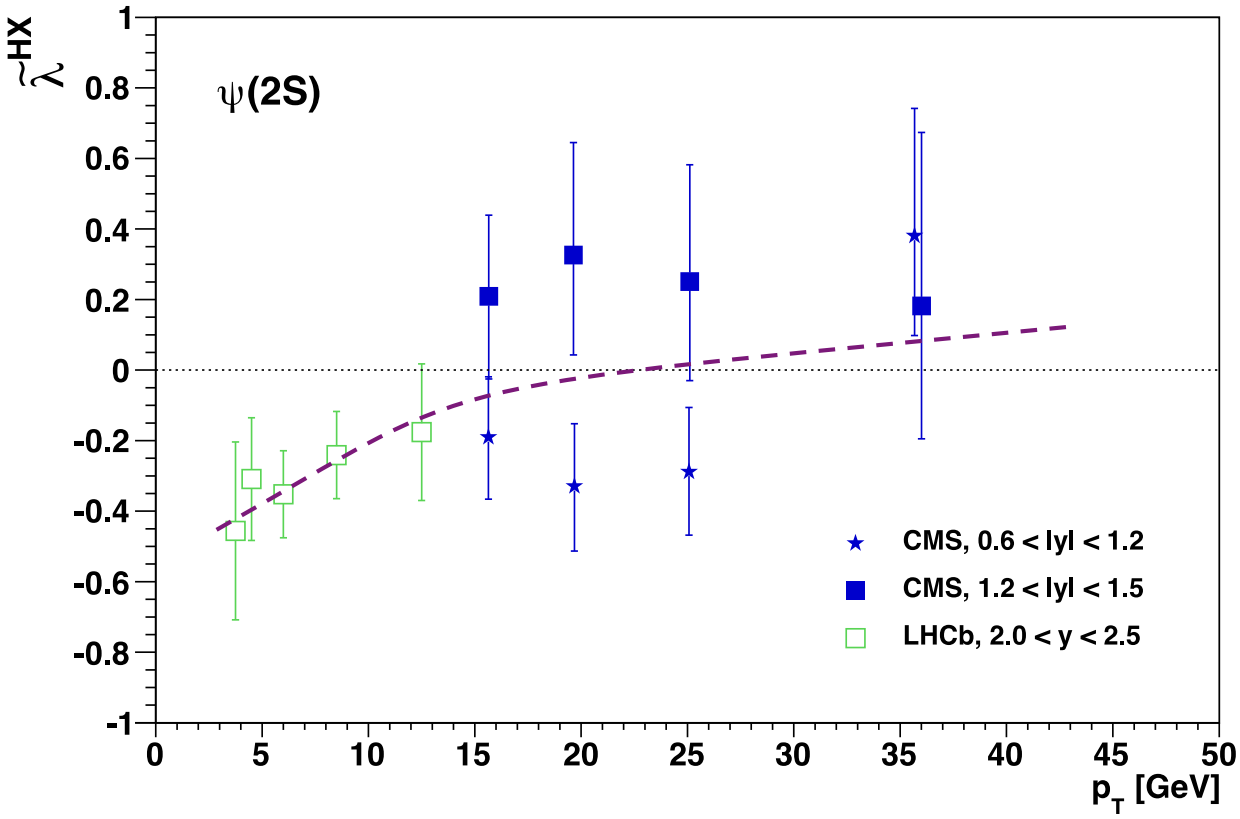
- The polarizations measured by LHCb for p_T < 10 GeV cluster at around $\tilde{\lambda}$ = - 0.25

- But the highest p_T bin shows values that systematically decrease with rapidity…
  An "edge effect" in the acceptance calculations? Or is this a physics (phase space) effect?



Quarkonium polarization: ψ(2S) in LHCb and CMS

- The polarizations measured by LHCb and CMS still suffer from large uncertainties…
  - We cannot say that there are significant discrepancies



Executive summary

- Many measurements made at 7 TeV (2010+2011 data) and a few at 8 TeV (2012)
  - S-wave and P-wave cross sections and/or cross section ratios
  - χ_c and χ_b feed-down fractions to S-wave states
  - Polarizations of five S-wave states (charmonia and bottomonia)
- Much still to come
  - Many analyses of 2011 and 2012 data still ongoing or not even started…
  - Run II (13 TeV) will provide many more measurements
  - Availability of results limited by manpower, not by "statistics"
- In general, good agreement between measurements made by several experiments

More results from quarkonium @ LHC can be found at:
ALICE: http://aliceinfo.cern.ch/ArtSubmission/publications
ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults
CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH
LHCb: http://lhcbproject.web.cern.ch/lhcbproject/CDS/cgi-bin/bq.php

χ_{c1} and χ_{c2} cross sections

So far, only ATLAS measured the χ_{c1} and χ_{c2} cross sections

A challenging result, given the very low photon conversion and reconstruction efficiencies