Quarkonium production and polarisation

at Tevatron and LHC

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Lancaster University

New observables in quarkonium production
ECT* Trento, 29 February – 4 March 2016

Contents

These "highlights" are personal, apologies for any omissions and biases!

Talk includes: Overview of experimental results on quarkonium production in ppbar/pp collisions (cross section and polarisation) at the Tevatron and the LHC

Does NOT include: production of χ_c, χ_b, η_c etc

quarkonium production in pA or AA collisions

quarkonium production in association with another quarkonium

quarkonium production in association with vector bosons

Essentially, I was asked to exclude all the fun stuff -- "new observables'' -- and present the results on J/ψ, $\psi(2S)$ and Υ production and polarisation

Happy to do just that, since these are the baseline measurements for anything else

Still A LOT to cover, so let's get started…

J/ψ production: references

ALICE: J/ψ production at 7 TeV, 5.6/nb(ee, |y|< 0.9) + 15.6/nb(μμ, 2.5 <y<4)	PLB704(2011)442
ALICE: J/ψ production at 7 TeV, 5.6/nb(ee, |y|< 0.9)	JHEP11(2012) 065
ALICE: J/ψ production at 7 TeV, 1.35/pb (μμ, 2.5 <y<4)	EPJ C74 (2014) 2974
ALICE: J/ψ production at 8 TeV, 1.28/pb (μμ, 2.5 <y<4)	CERN-PH-EP-2015-267
ALICE: J/ψ production at 2.76 TeV, 1.1/nb(ee, |y|< 0.9) + 19.9/nb(μμ, 2.5 <y<4	PL B718 (2012) 295
ATLAS: J/ψ production at 7 TeV, 2.3/pb, |y| < 2.4	NP B 850 (2011) 387
ATLAS: J/ψ production at 7 TeV, 2.1/fb and 8 TeV, 11.4/fb	arXiv:1512.03657
CMS: J/ψ production at 7 TeV, 37/pb	JHEP02(2012)011
CMS: J/ψ production at 7 TeV, 314/pb, |y| < 2.4	EPJ C71 (2011) 1575
CMS: J/ψ production at 7 TeV, 4.9/fb, |y| < 1.2	PRL 114 (2015) 191802
LHCb: J/ψ production at 13 TeV, 3/pb, pT < 14 GeV, 2 < y < 4.5	JHEP10(2015)172
LHCb: J/ψ production at 8 TeV, 18/pb, 2 < y < 4.5	JHEP06(2013)064
LHCb: J/ψ production at 7 TeV, 5.2/pb, 2 < y < 4.5	CERN-PH-EP-2011-018
CDF: J/ψ production at 1.96 TeV, 39.7/pb |y|< 0.6	PRD71 (2005) 032001
D0: J/ψ production, 1.8 TeV |η|<0.6	PLB 370(1996) 239
D0: J/ψ production , 1.8 TeV, 9.8/pb, 2.5<|η|<3.7	PRL 82(1999) 35

Prompt J/ψ production: Tevatron

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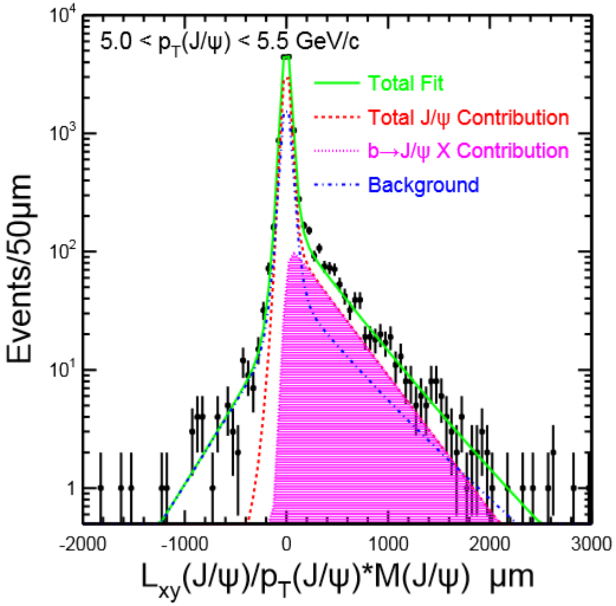

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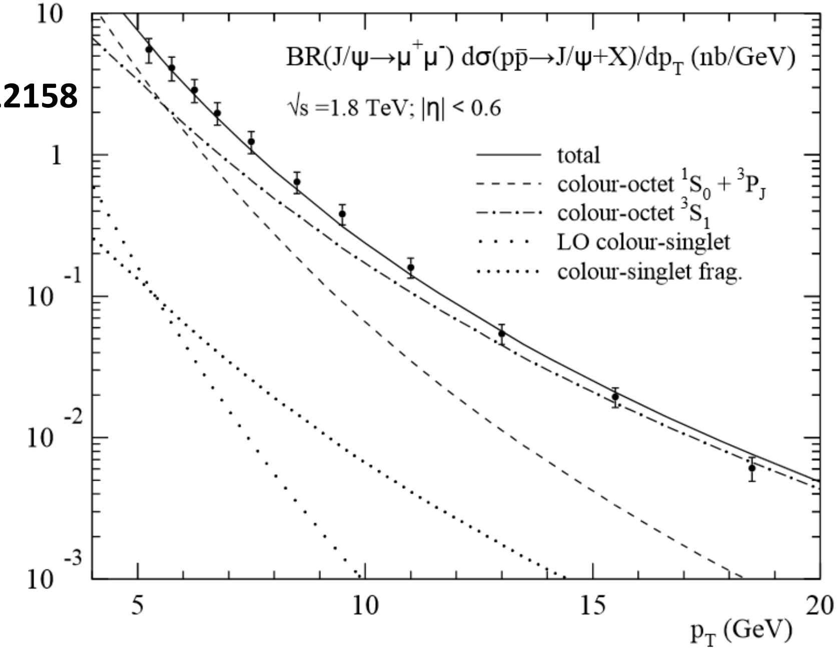
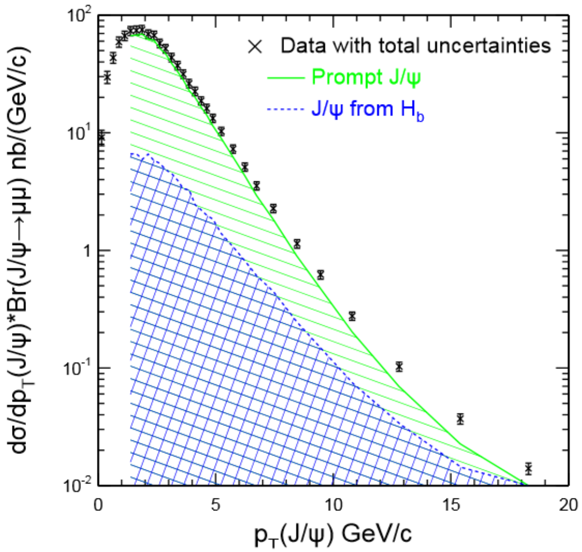
hep-ph 0412158



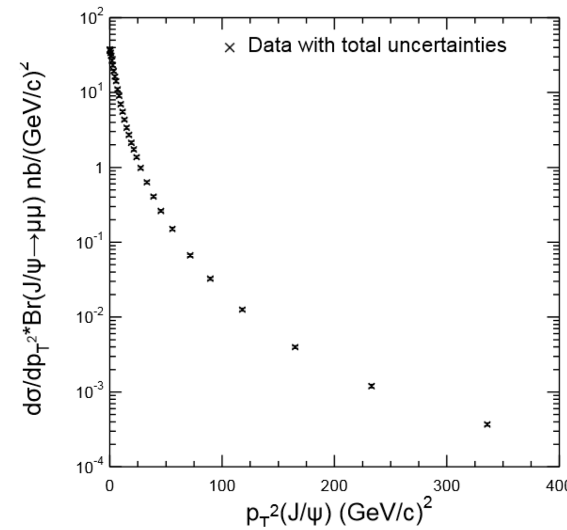


Separate prompt from non-prompt using effective lifetime info

Try to extract LDMEs from p_T spectra of inclusive prompt J/ψ

Maybe too many contributions?

p_T^2 spectra could be useful near zero: exact shape depends on mechanism

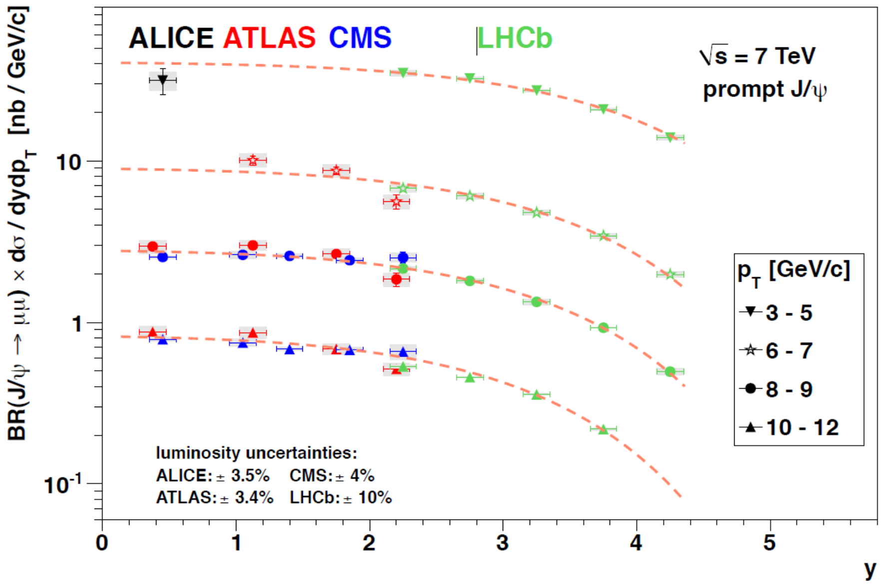


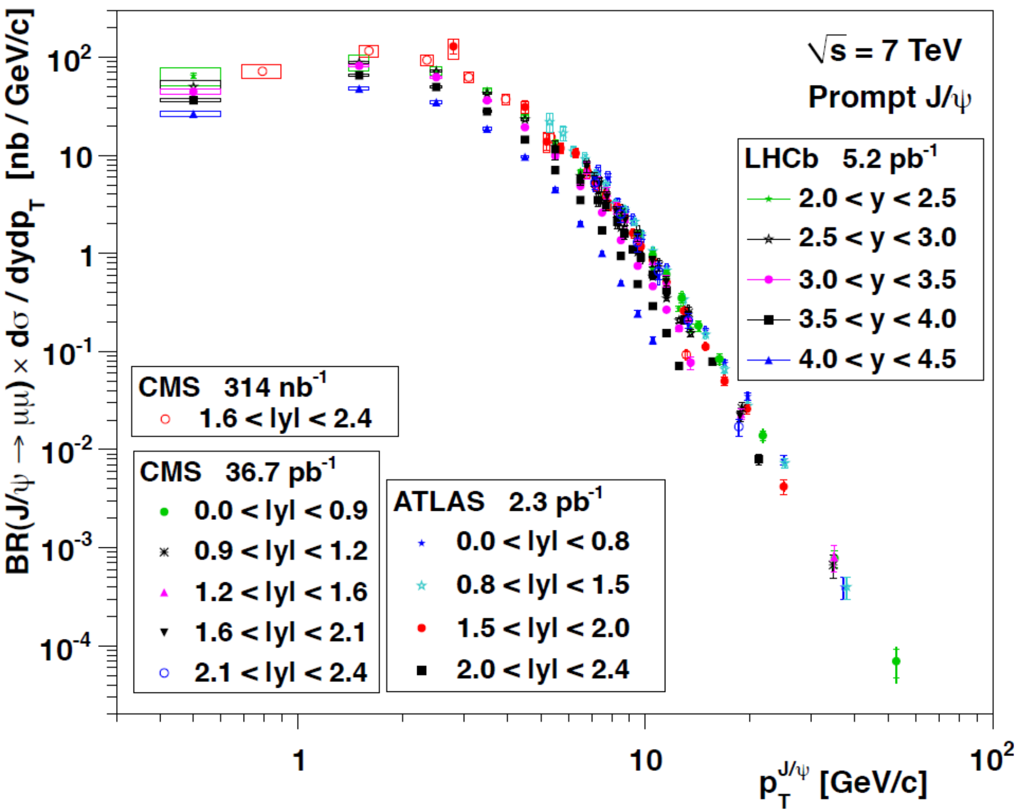
Prompt J/ψ production: LHC

Compilations by Hermine K. Woehri

(a couple of years old by now)

Nice synergy between the LHC experiments



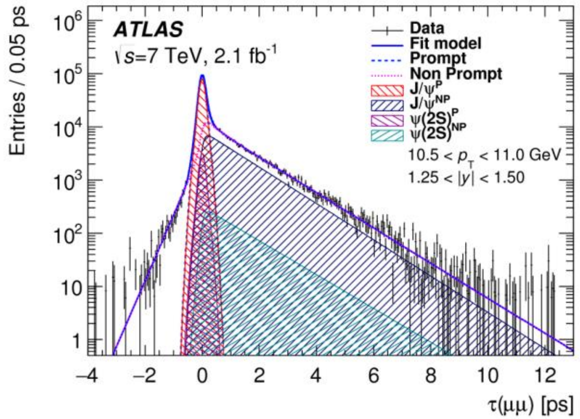


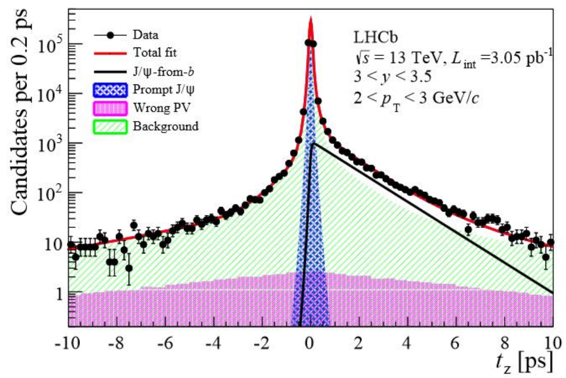
Between the experiments, a huge kinematic range is covered: $|y| < 4.5$, $0<p_T<100$ GeV

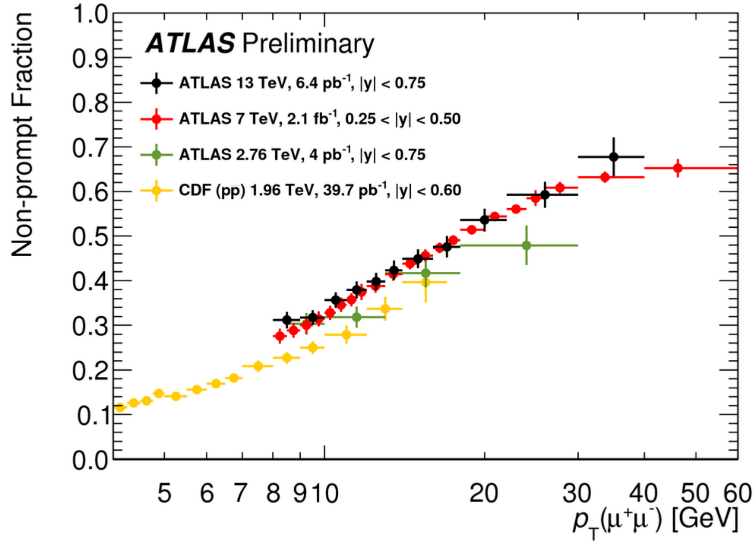
Over 6 orders of magnitude in p_T

Given the diversity of experiments and conditions, consistency of measurements is really remarkable

Non-prompt J/ψ fraction: LHC recent



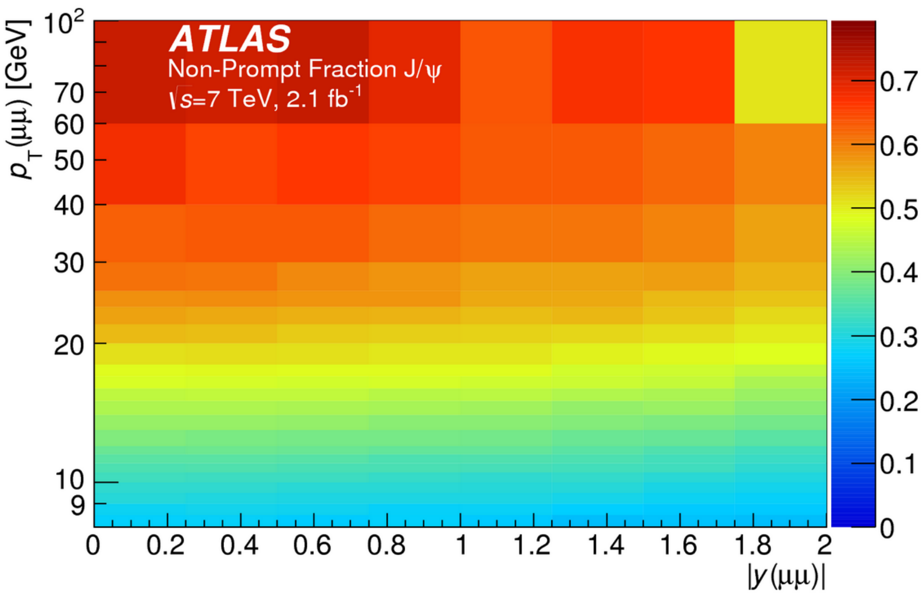


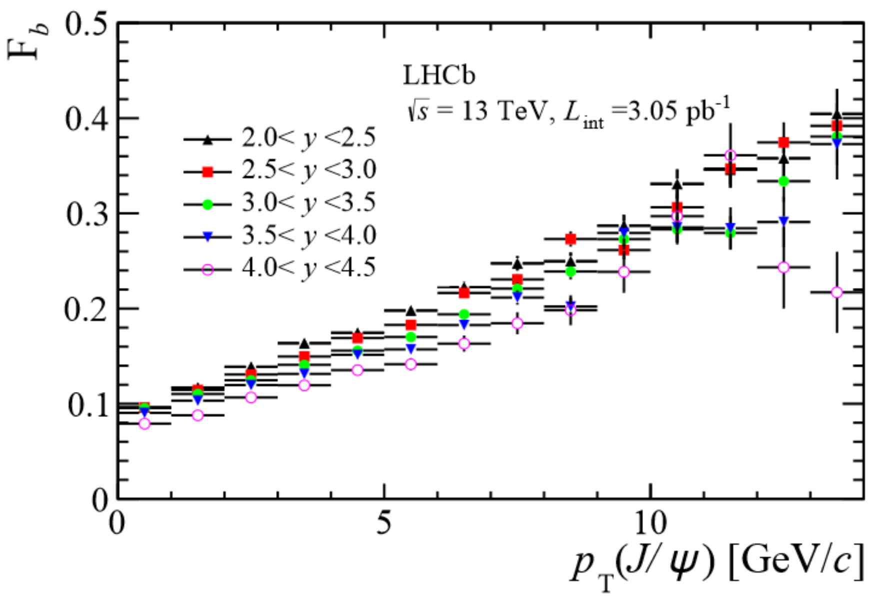


Strong pT dependence

No dramatic evolution with energy

Some dependence on rapidity forward



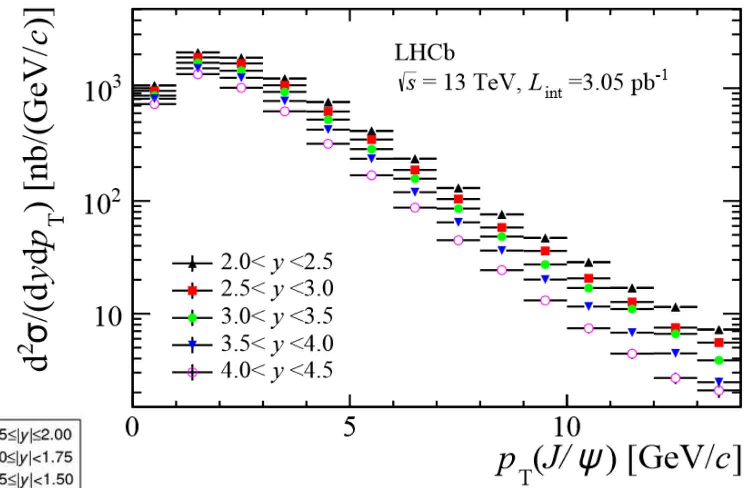


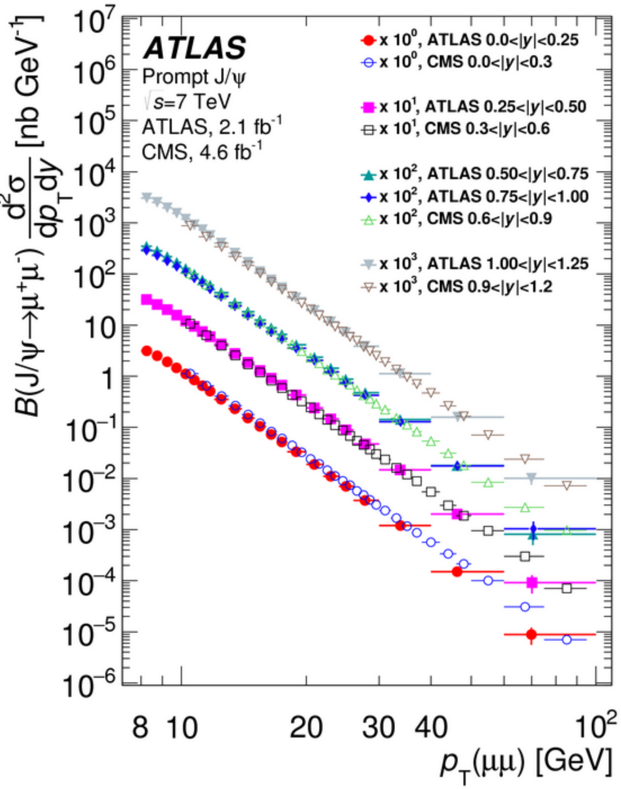
Prompt J/ψ production: LHC recent

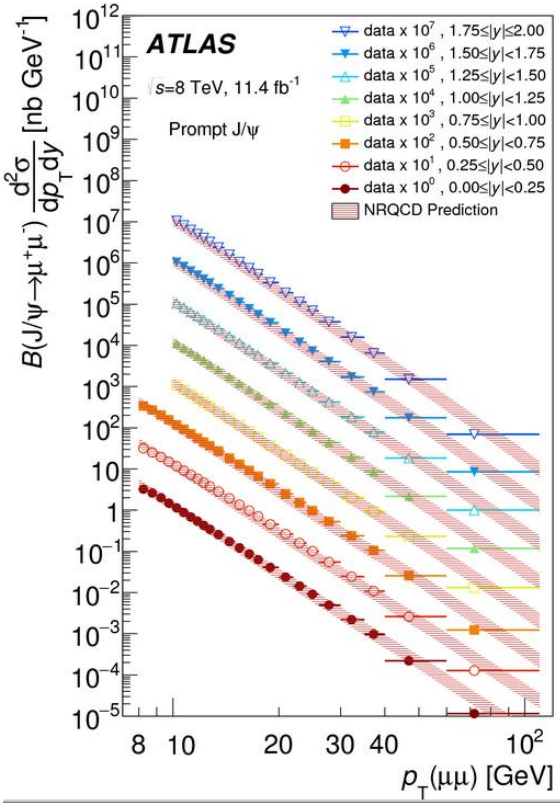
Detailed distributions in a number of bins in pT and rapidity

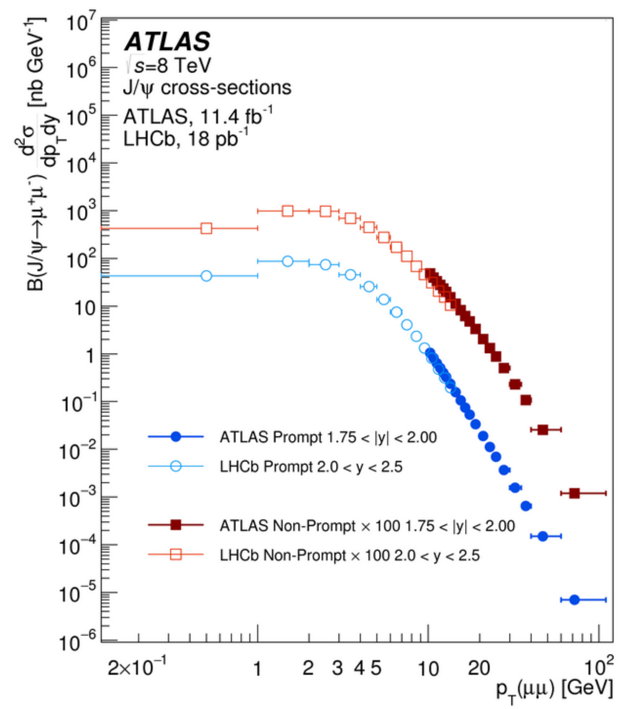
Low pT unaccessible for ATLAS, CMS at high energy / luminosity

Good consistency between ATLAS, CMS and LHCb where overlap









ψ(2S) production: references

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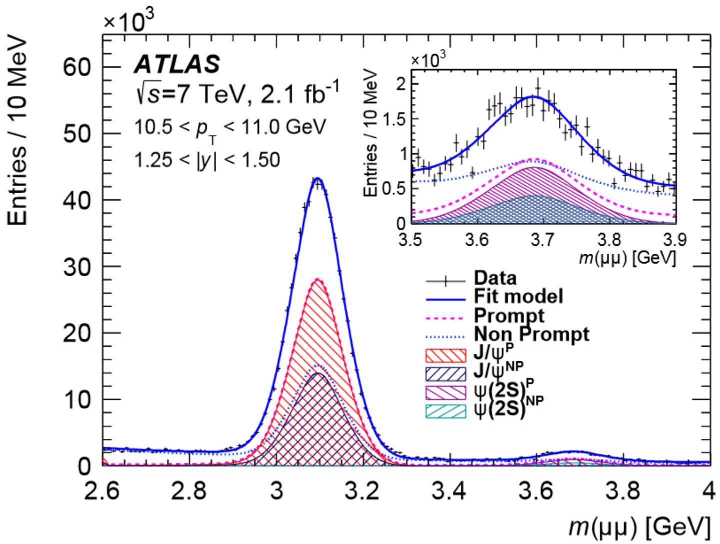
LHCb: ψ(2S) production at 7 TeV, 36/pb, pT<14 GeV, 2<y<4.5	EPJ C72 (2012) 2100
CMS: ψ(2s) production at 7 TeV, 37/pb	JHEP02(2012)011
CMS: ψ(2S) production at 7 TeV, 4.9/nb, |y| < 1.2	PRL114 (2015) 191802
ATLAS: ψ(2S) production at 7 TeV, 2.1/fb and 8 TeV, 11.4/fb	arXiv:1512.03657
ATLAS: ψ(2S) production (J/ψππ mode) at 7 TeV, 2.1/fb	JHEP09(2014)079
ALICE: ψ(2S) production at 7 TeV, 1.35/pb (μμ, 2.5 <y<4)	EPJ C74 (2014) 2974
ALICE: ψ(2S) production at 8 TeV, 1.28/pb (μμ, 2.5 <y<4)	CERN-PH-EP-2015-267
CDF: ψ(2S) production at 1.96 TeV, 1.1/fb |y|< 0.6	PRD 80 (2009) 031103

ψ(2S) production: general remarks



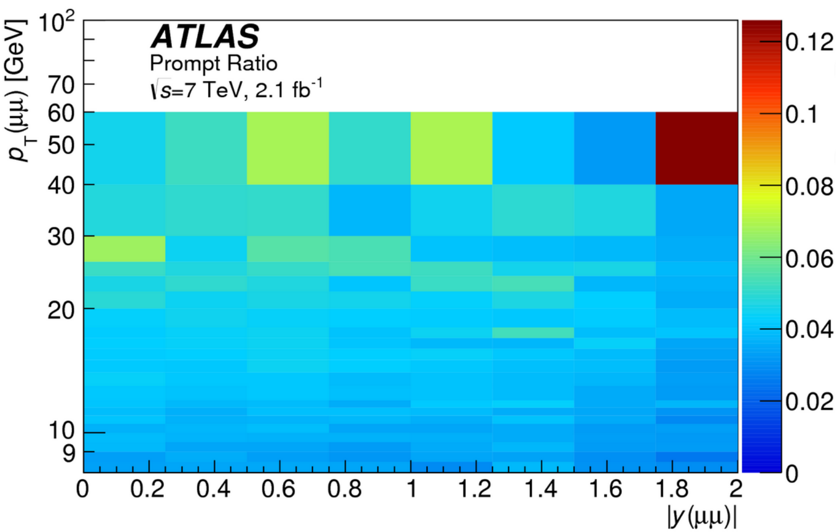
ψ(2S) more challenging: lower stats, higher background

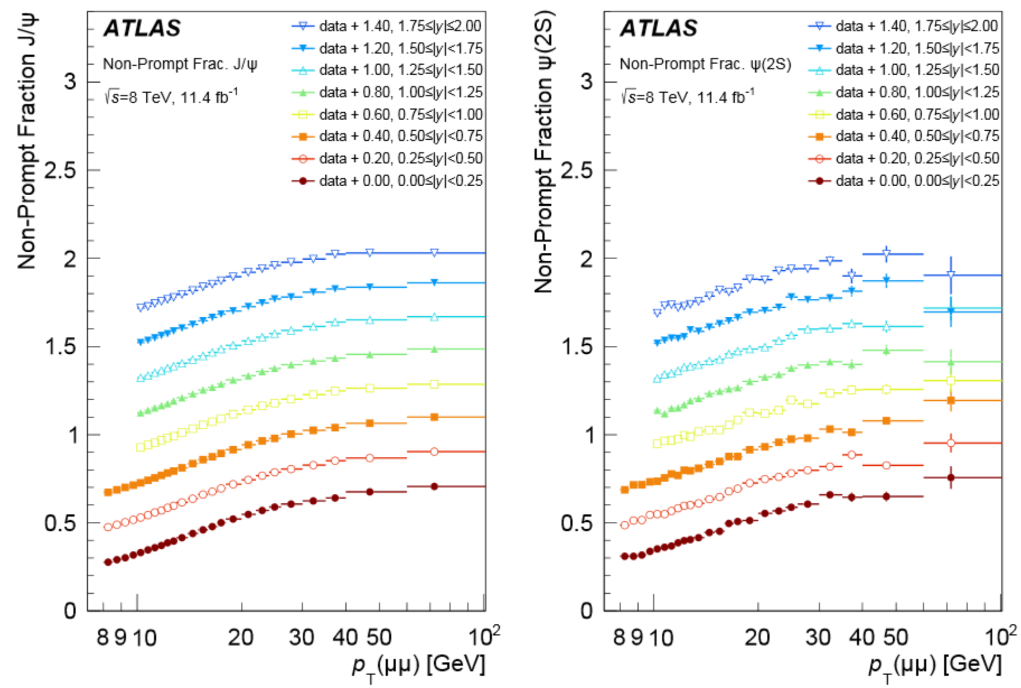
Production mechanism should be theoretically cleaner

Curiously, non-prompt fraction very similar to J/ψ

Prompt ψ(2S) /Jψ ratio close to constant

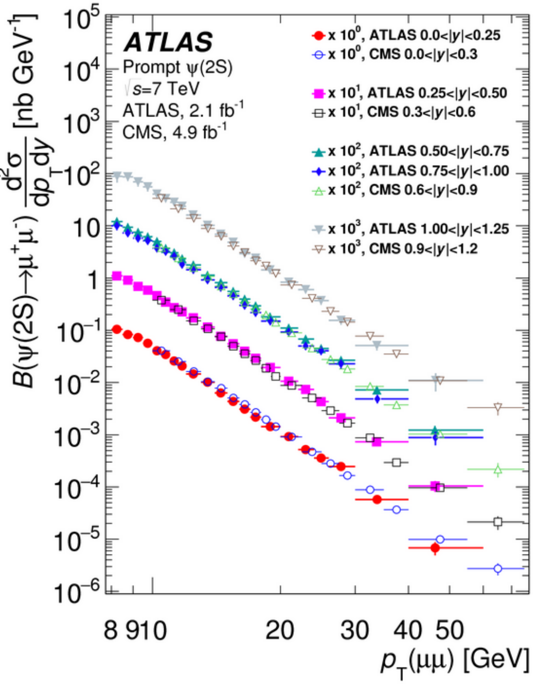
Can these facts be understood within our current picture?

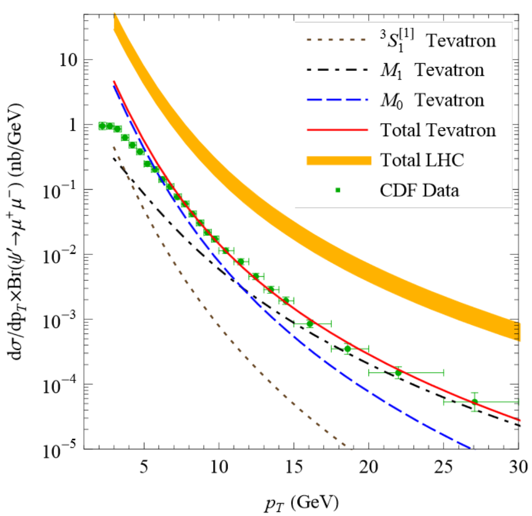




Prompt ψ(2S) production

Lancaster University

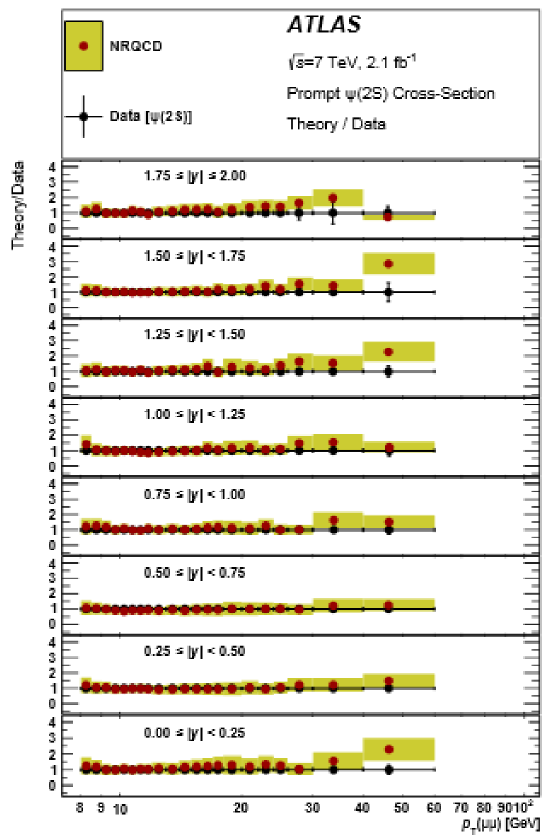


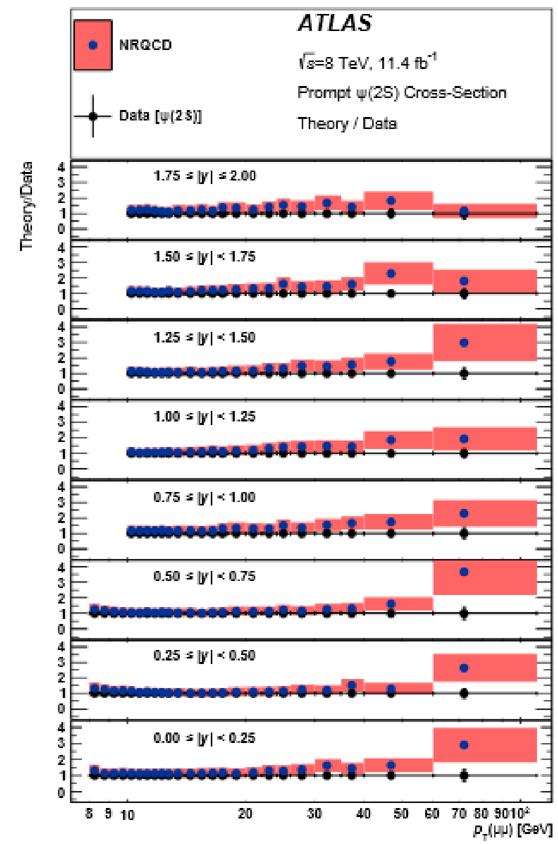


Again, ATLAS and CMS consistent

Could be used to extract some LDMEs (Ma,Wang,Chao,arXiv:1009.3655)

LDMEs from Tevatron fits in decent agreement with LHC data (maybe peeling slightly high at highest pT?)

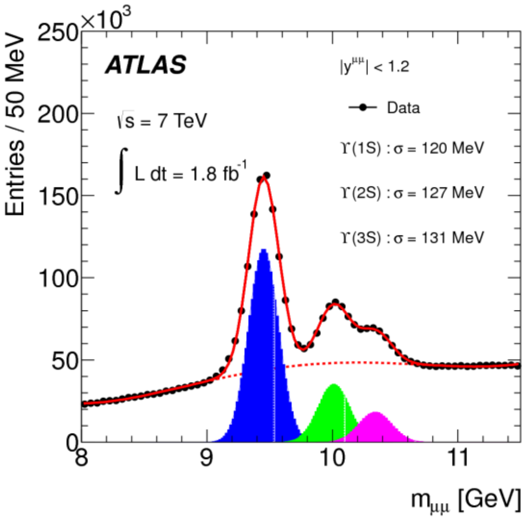


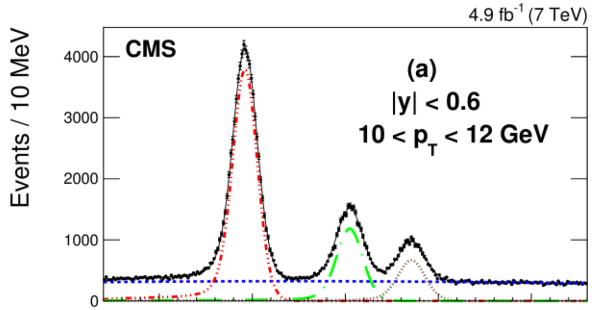


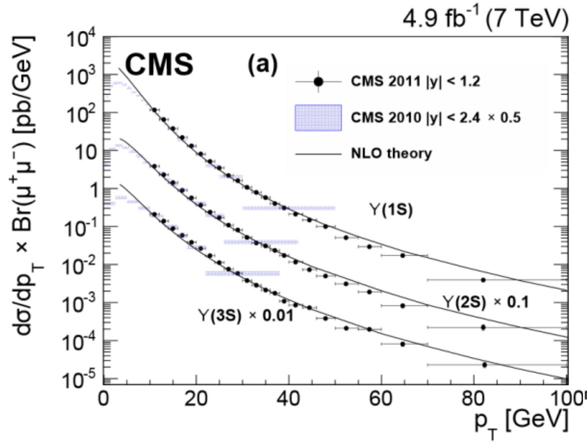
Υ(nS) production: references

ALICE: Υ production at 7 TeV, 1.35/pb (μμ, 2.5 <y<4)	EPJ C74 (2014) 2974
ALICE: Υ production at 8 TeV, 1.28/pb (μμ, 2.5 <y<4)	arXiv:1509.08258
ATLAS: Υ(1S) fiducial production at 7 TeV, 1.13/pb	PLB 705 (2011) 9
ATLAS: Υ production at 7 TeV, 1.8/fb	PR D87 (2013) 052004
CMS: Υ production at 7 TeV, 3.1/pb, |y|<2	PRD 83 (2011) 112004
CMS: Υ production at 7 TeV, 36/pb, |y|<2.4	PLB 727 (2013) 101
CMS: Υ production at 7 TeV, 4.9/fb, |y|<1.2	PLB 749 (2015) 14
LHCb: Υ production at 7 TeV (1/fb) and 8 TeV (2/fb) [pT<30 GeV, 2<y<4.5]	JHEP 1511 (2015) 103
LHCb: Υ production at 2.76 TeV (3.3/pb) [pT<15 GeV, 2<y<4.5]	EPJ C74 (2014) 2835
LHCb: Υ production at 8 TeV, 51/pb, 2 < y < 4.5	JHEP06(2013)064
LHCb: Υ production at 7 TeV, 25/pb, pT<15 GeV, 2<y<4.5	EPJ C72 (2012) 2025
D0: Υ production at 1.96 TeV,	PRL 94 (2005) 232001, PRL 100 (2008) 049902
CDF: Υ production at 1.8 TeV,	PRL 88 (2002) 161802, PRL 75 (1995) 4358

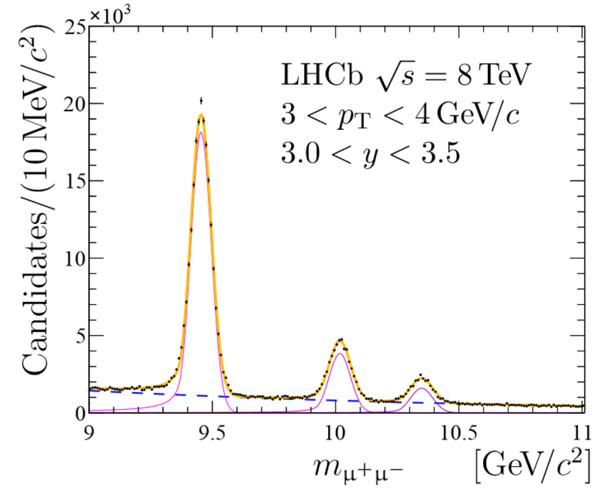
Recent results from LHC



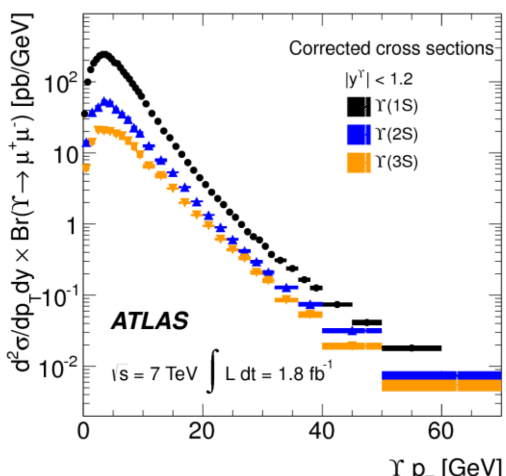


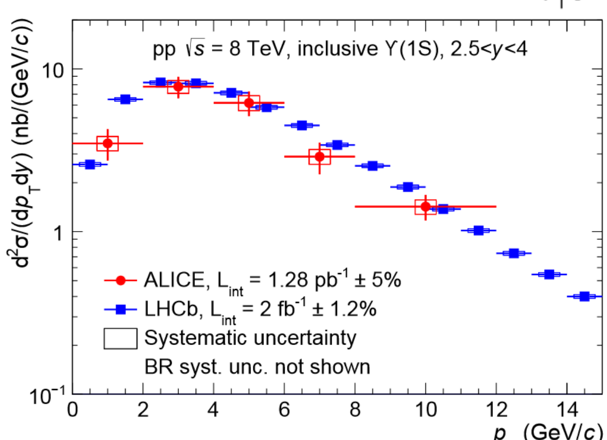


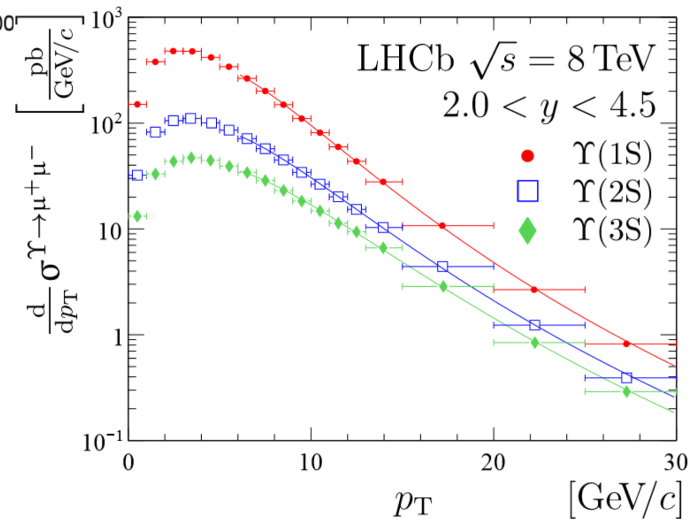
Good mass resolution allows for better separation between the Upsilon states



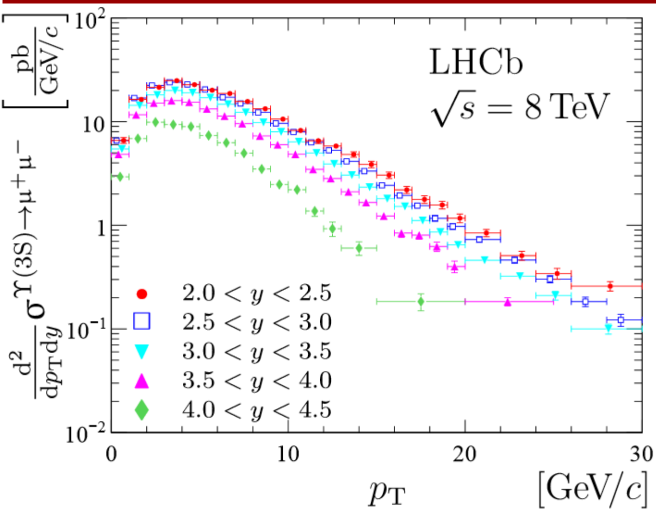
Very detailed data on production of all three ϒ states is available from all LHC collaborations





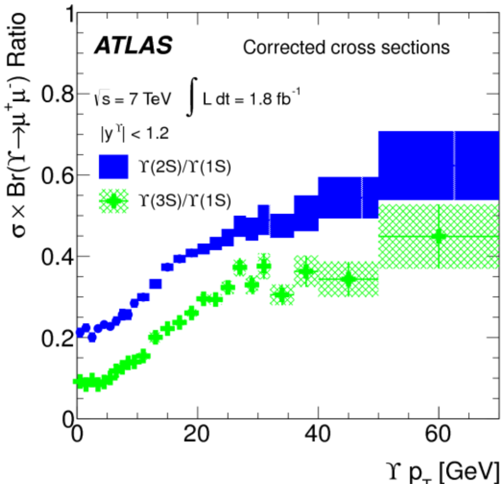


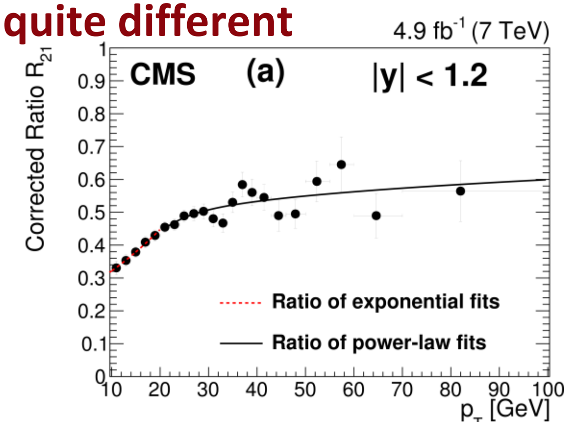
Ratios

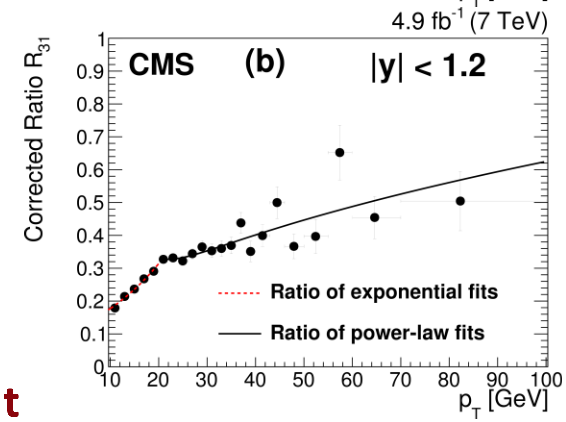


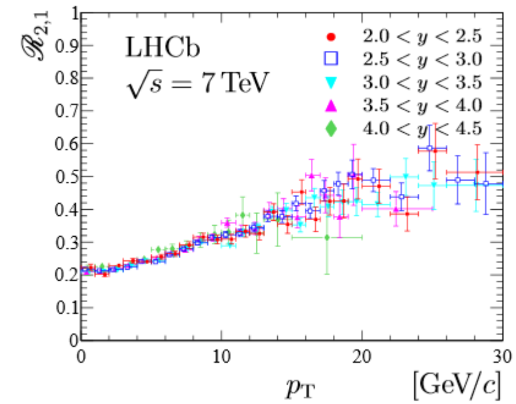
Ratios Υ(3S)/Υ(1S) and Υ(2S)/Υ(1S) show strong dependence on pT, hinting on a superposition of several mechanisms

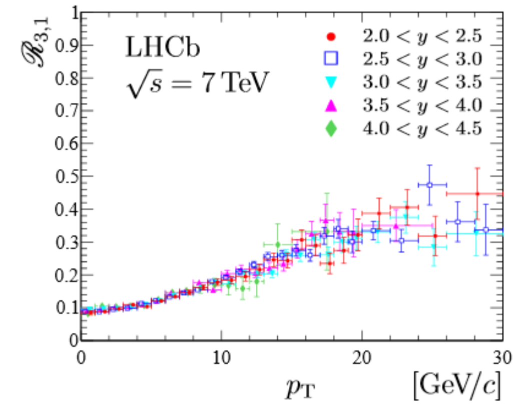
But no dependence on y, even at high y where pT spectra are quite different











LHCb (EPJ C74 (2014) 3092):

feed-down from C-even states is about 50% for all three Υ(nS) states

There is no "clean" state here like ψ(2s)

Can these experimental facts be reconciled within our current picture of production?

Polarisation measurements: references

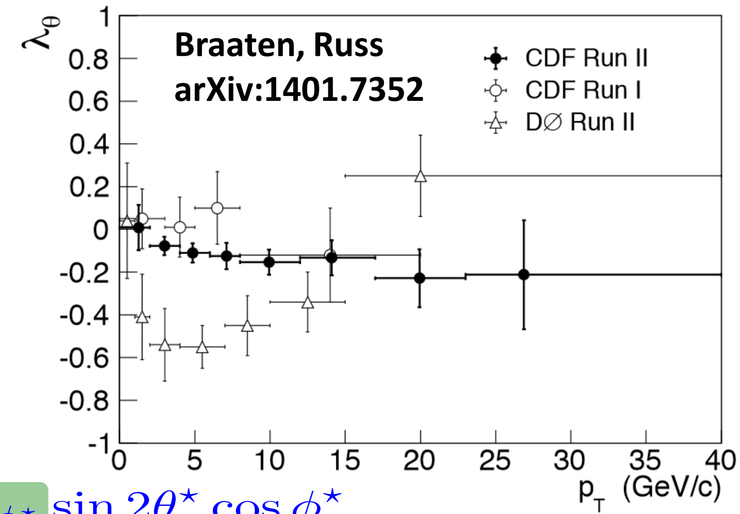
Lancaster University

LHCb: ψ(2S) polarisation, 7 TeV, 1/fb, $2 < y < 4.5$	EPJ C74 (2014) 2872
LHCb: J/ψ polarisation, 7 TeV, 0.37/fb, $2 < y < 4.5$	EPJ C73 (2013) 2631
CMS: Υ polarisation, 7 TeV, 4.9/fb, $\|y\|<1.2$	PRL 110 (2013) 081802
CMS: J/ψ and ψ(2S) polarisation, 7 TeV, 4.9/fb, $\|y\|<1.2$	PLB 727 (2013) 381
ALICE: J/ψ polarisation, 7 TeV, $2.5 < y < 4$	PRL108 (2012) 082001

CDF: J/ψ and ψ(2S) polarisation, 1.96 TeV	PRL 99 (2007) 132001
CDF: J/ψ and ψ(2S) polarisation, 1.8 TeV	PRL 85 (2000) 2886
CDF: Υ polarisation, 1.96 TeV	PRL 108 (2012) 151802
D0: Υ polarisation, 1.96 TeV	PRL 101 (2008) 182004

Polarisation measurements with ϒ

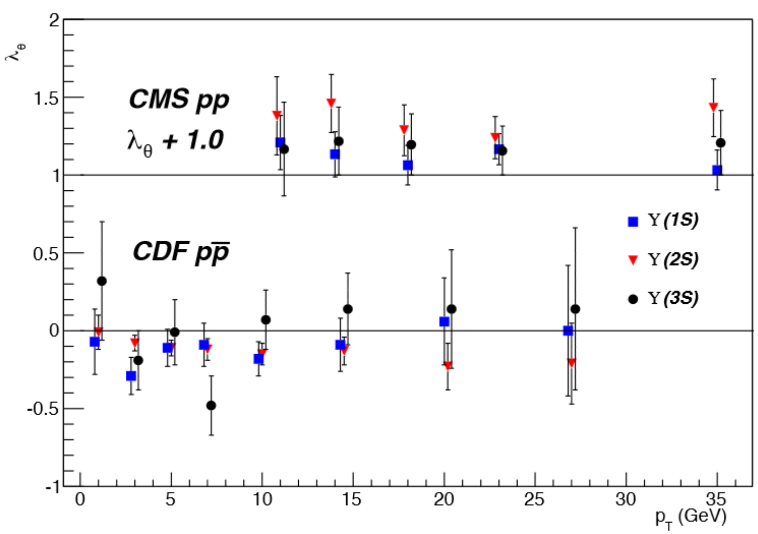
Troubled history, single-angle Tevatron analyses yielded contradictory results



Likely due to biases caused by implied ϕ* integration

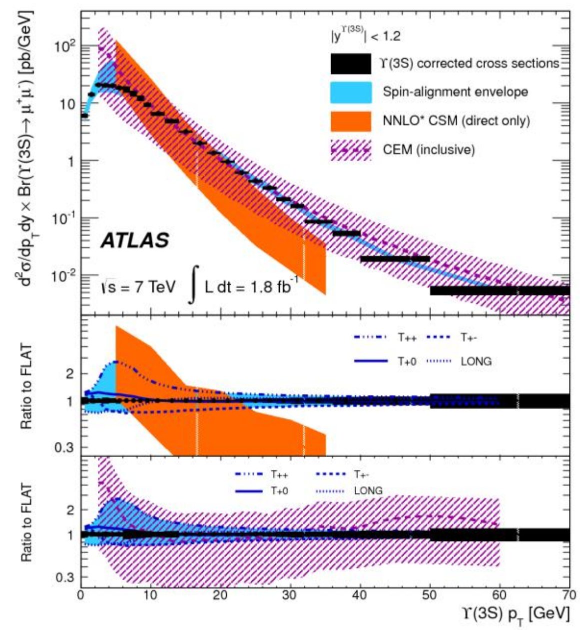
"Full'' double angle analyses pioneered by CMS

$$\frac{dN}{d\Omega} = 1 + \lambda_{\theta^\star} \cos^2\theta^\star + \lambda_{\phi^\star} \sin^2\theta^\star \cos 2\phi^\star + \lambda_{\theta^\star\phi^\star} \sin 2\theta^\star \cos\phi^\star$$



Polarisation can affect measured cross section:

Acceptance incomplete, especially at low pT and cosθ* close to ±1



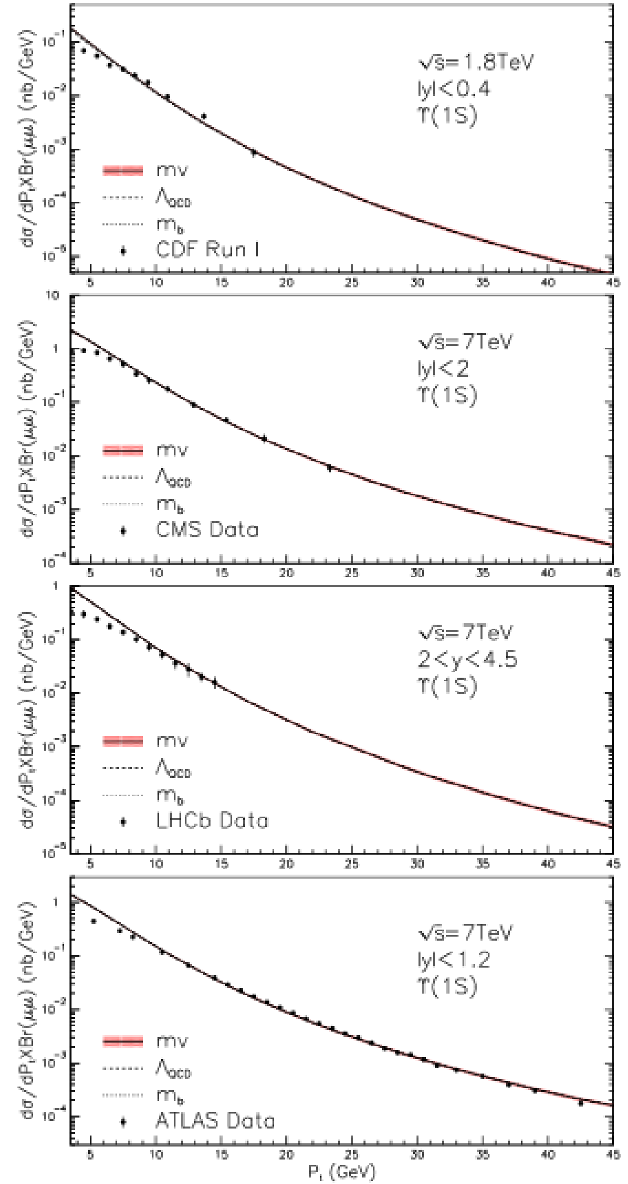
Upsilon – "global fit" attempt

Attempt to describe ϒ(nS) production cross sections and polarisations within a single fit

Fitting LDMEs to describe Tevatron and LHC data at NLO

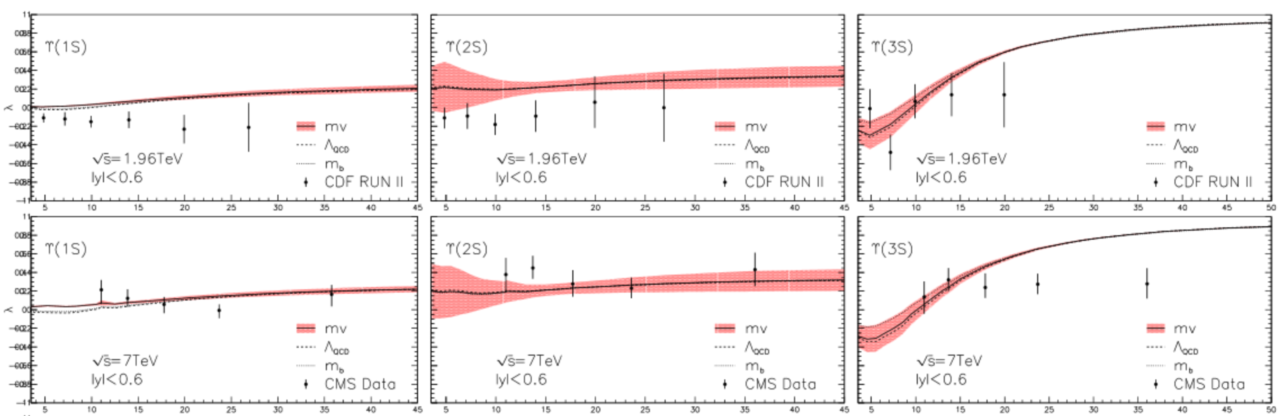
Assumes no feed-down for ϒ(3S) – and gets its polarisation wrong

With "moderate" success otherwise



Gong,Wan,Wang,Zhang

PRL112 (2014) 032001

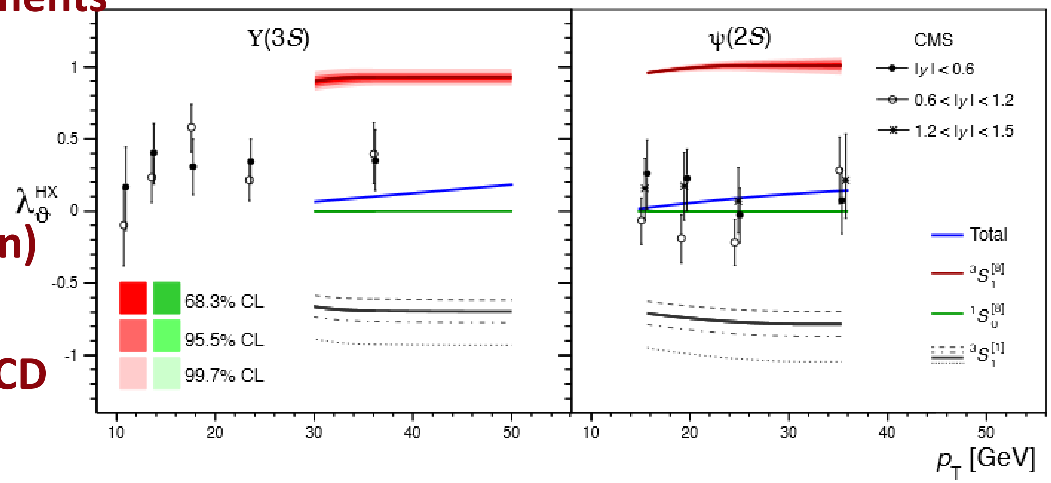


Change of perspective?

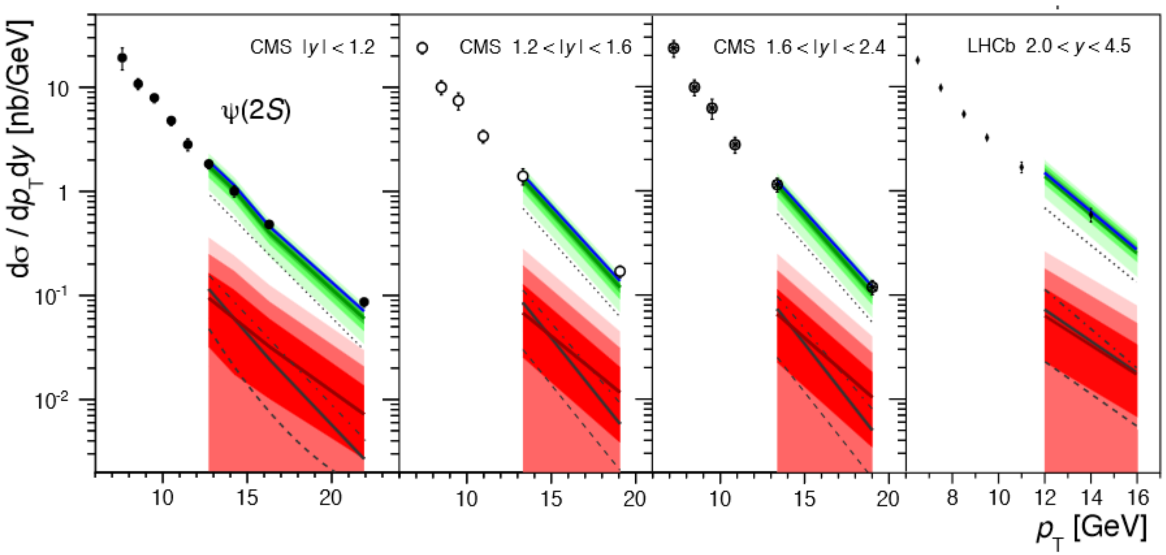
An attempt to bring polarisation measurements into the global fits of production LDMEs

Trying to identify areas with fewest contributions: ψ(2S) , ϒ(3S)
(the latter may not be a correct assumption)

Claim that cross section and polarisation description may be reconciled within NRQCD approach at high pT



Faccioli,Knünz,Lourenco,Seixas,Wöhri PLB736(2014)98



However, at high pT, both polarisation-dependent variations and differences between various LDME contributions are small

More comprehensive analysis needed to be convincing

Charmonium polarisation

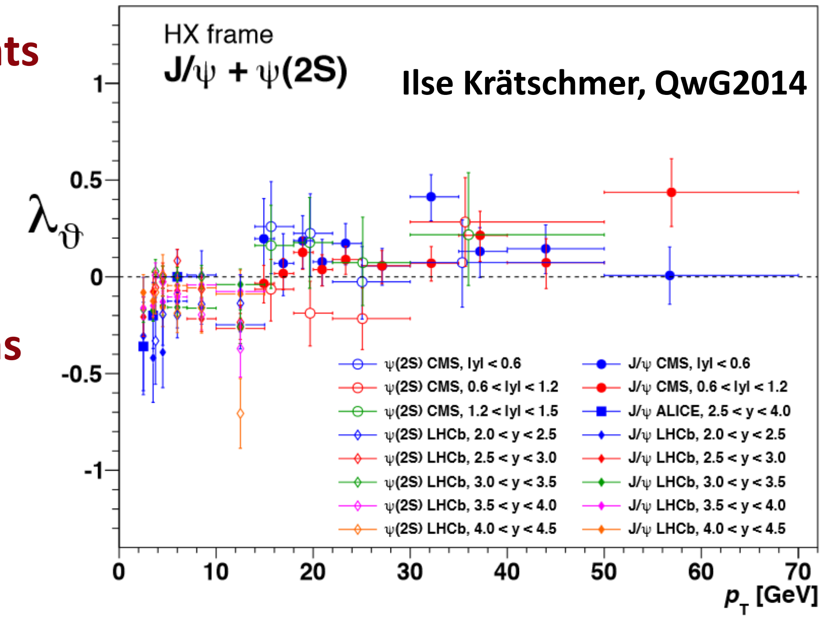
Latest measurements consistent between experiments

No dramatic polarisation observed anywhere

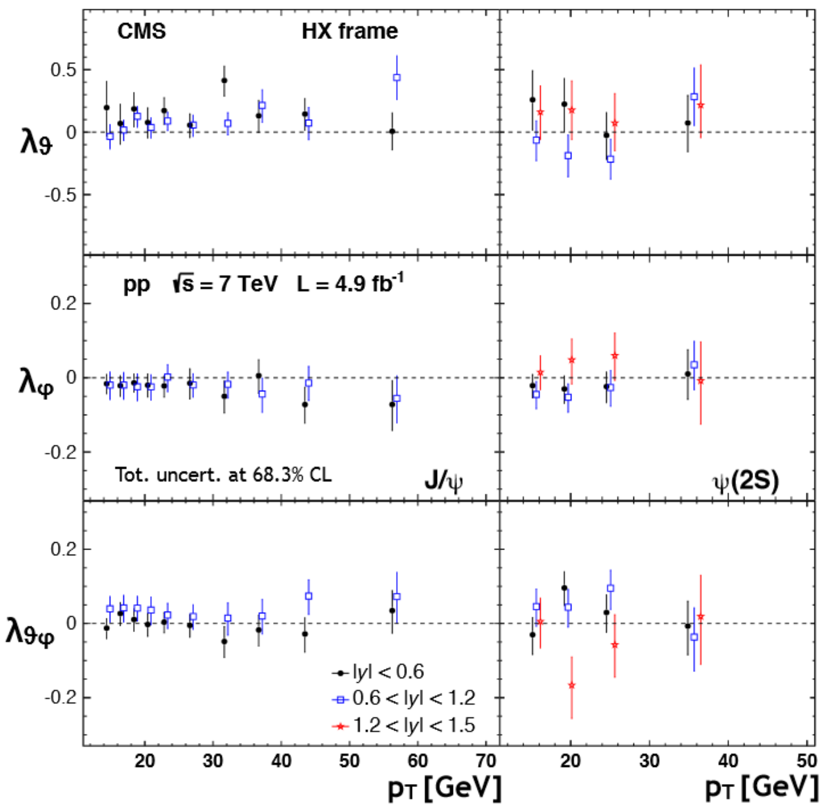
No strong dependence on pT or rapidity

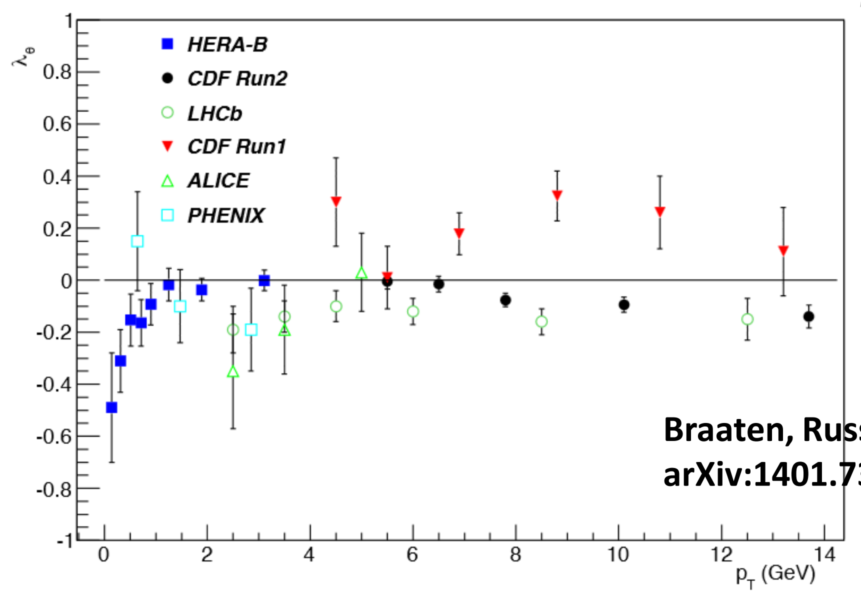
No sizeable difference between J/ψ and ψ(2S)

Not much help in figuring out production mechanisms



Ilse Krätschmer, QwG2014





Braaten, Russ
arXiv:1401.7352

Instead of conclusions

The big puzzle is still there – how are quarkonium states produced in hadronic collisions?

Vast amounts of data are now available from both the Tevatron and the LHC experiments

In general, very good synergy between the LHC experiments – complement each other in pT and rapidity, covering a huge range between them

More and more bits of the puzzle are becoming available

Maybe we are (slowly) getting (slightly) closer to the point of a big breakthrough in understanding?