Bottomonia at hadron colliders

Vato Kartvelishvili
Lancaster University, UK

Charmonium Workshop, LAL, Orsay, 6 March 2013

Scope and purpose

First observation of Υ

Υ studies at the Tevatron

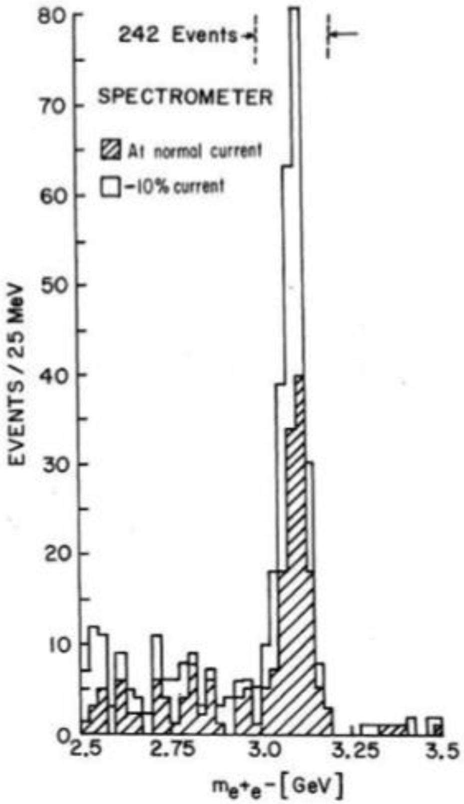
Dimuons in LHC experiments

Cross sections from CMS, LHCb and ATLAS

Bottomonium spectroscopy

Υ polarisation measurements, old and new

“High mass” dimuons in the 1970’s



Just a quick reminder:

J/psi discovery (hadronic side) on the left

Υ discovery on the right

Original picture formats are kept

VIEW LETTERS 1 AUGUST 1977

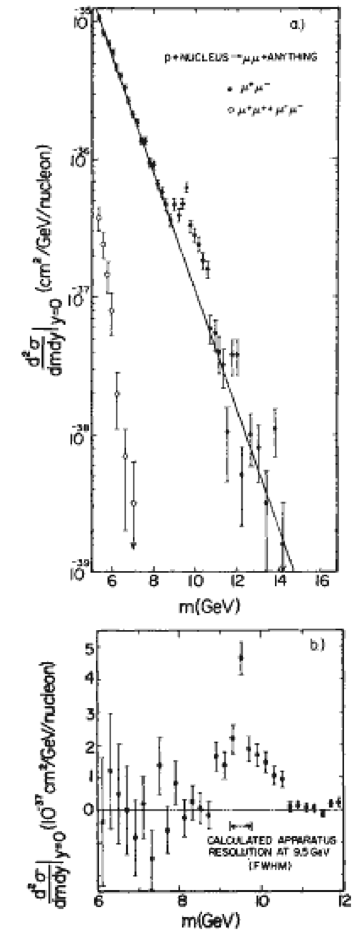
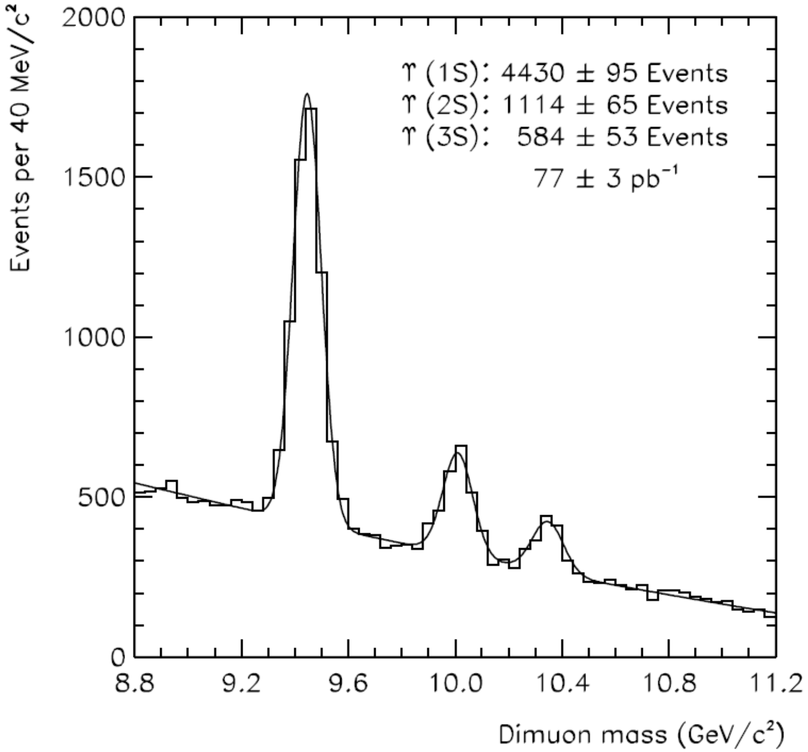
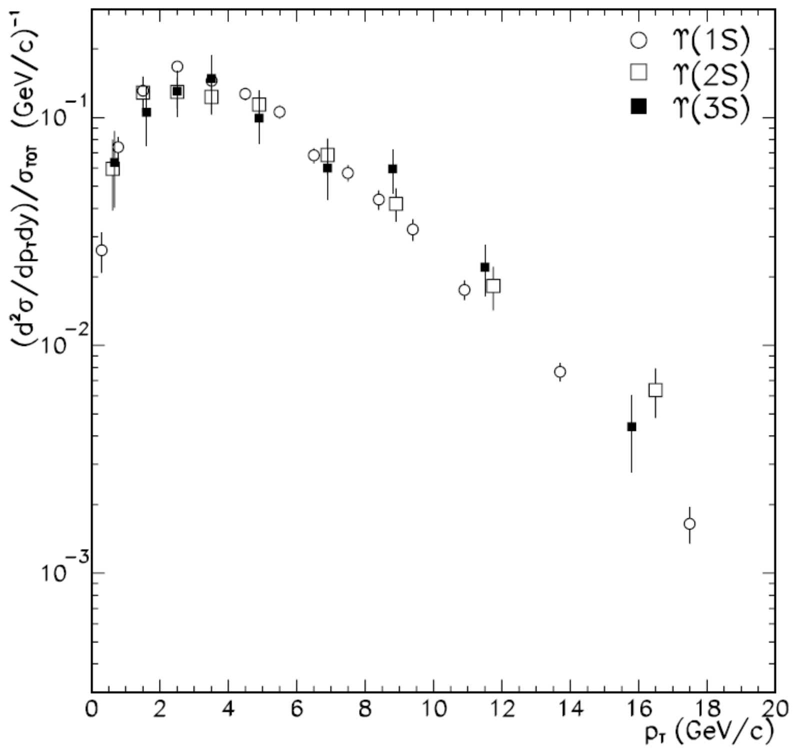


FIG. 3. (a) Measured dimuon production cross sections as a function of the invariant mass of the muon pair. The solid line is the continuum fit outlined in the text. The equal-sign–dimuon cross section is also shown. (b) The same cross sections as in (a) with the smooth exponential continuum fit subtracted in order to reveal the 9–10-GeV region in more detail.

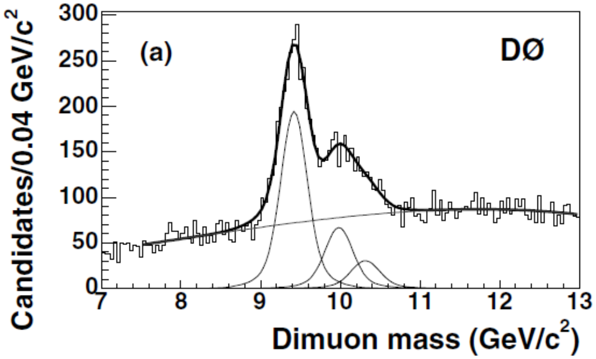
CDF results on Υ production

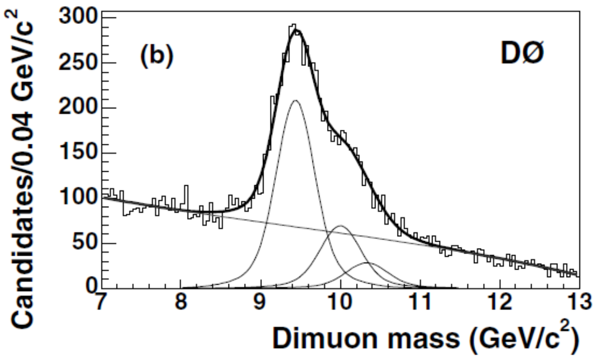


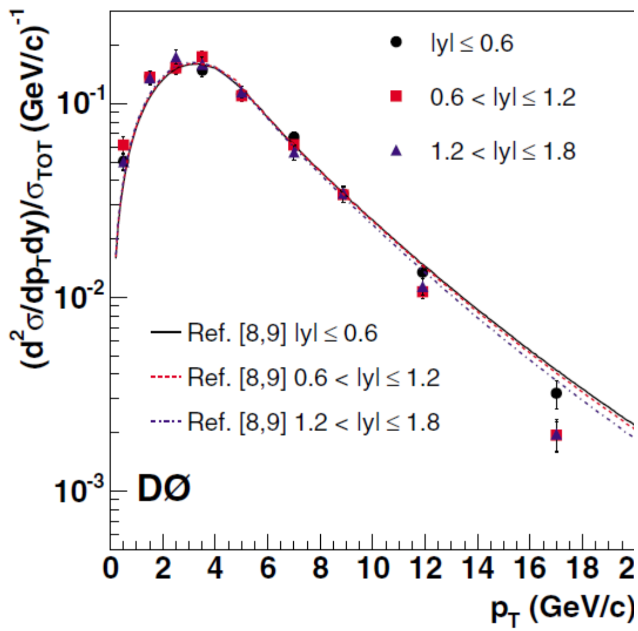


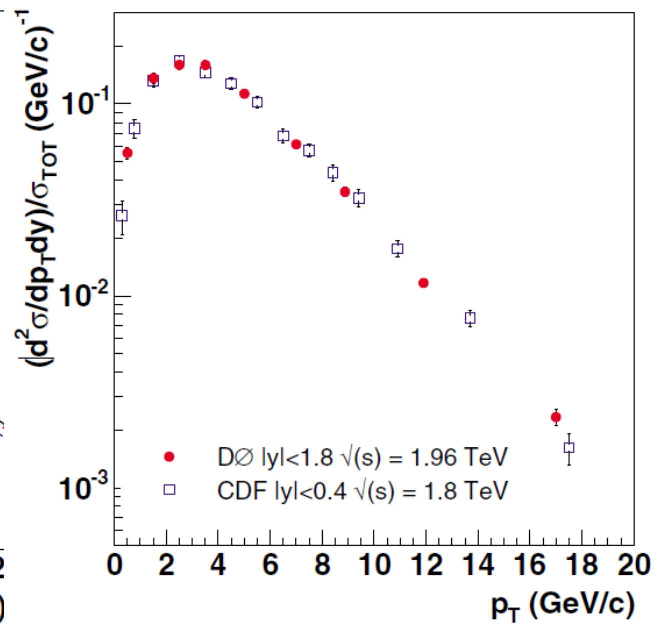
CDF detector:
good mass resolution, all three peaks resolved well
pT reach up to 18 GeV, but only at central rapidities
Hard to see any trend, but maybe 1S falls with pT steeper than the others?

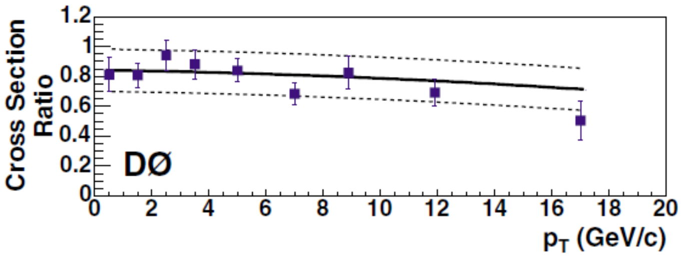
D0 results on Υ production











Clearly, mass resolution much worse in D0
Still good enough to separate the three peaks
Good agreement with CDF at central y
Three rapidity intervals studied
pT dependence slightly steeper at high rapidity

Ref.[8,9] is Berger et al: PRD 71 (2005) 034007
(large log resumm. at small pT, fixed LO at large pT)

More theory comparisons

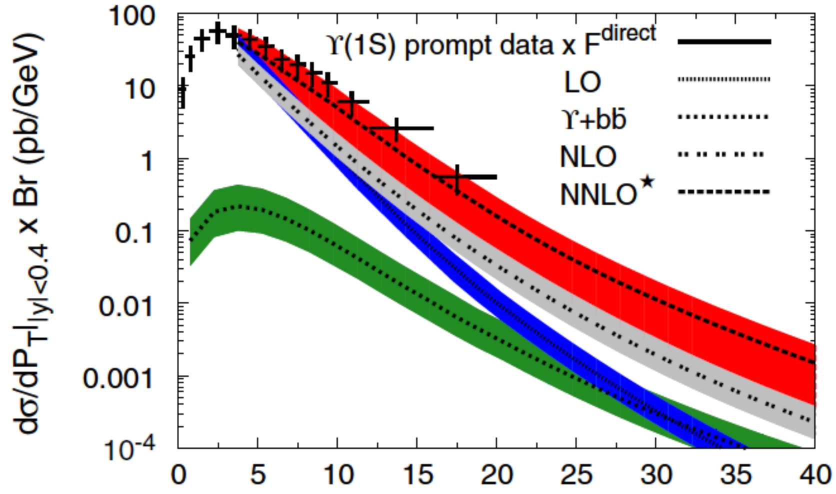
More familiar model, describing Tevatron data:

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

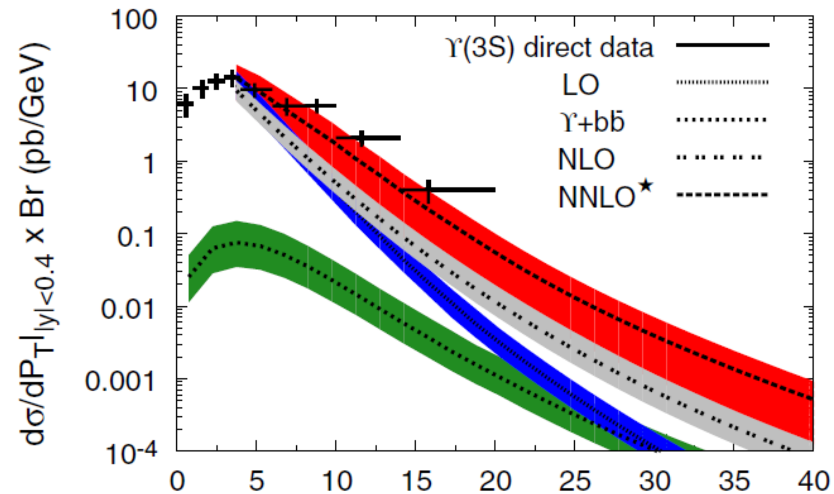
Evolution from LO to NNLO* can be clearly traced

Still lacks chi_b feeddown

Other talks in this session can help compare – and understand – various models

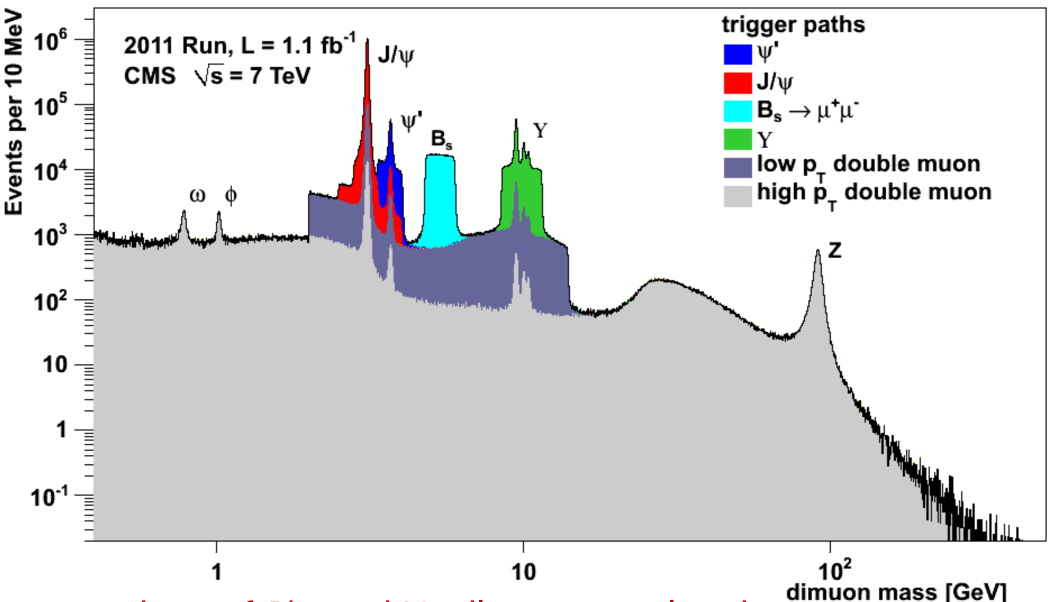


(a)



(b)

Recent times: high mass dimuons at LHC



Quite some progress since the dicoveries in 1974 and 1977

Can see the features of triggers used by ATLAS, CMS

Bandwidth limitations are a major concern:

Need to prescale low-pT triggers

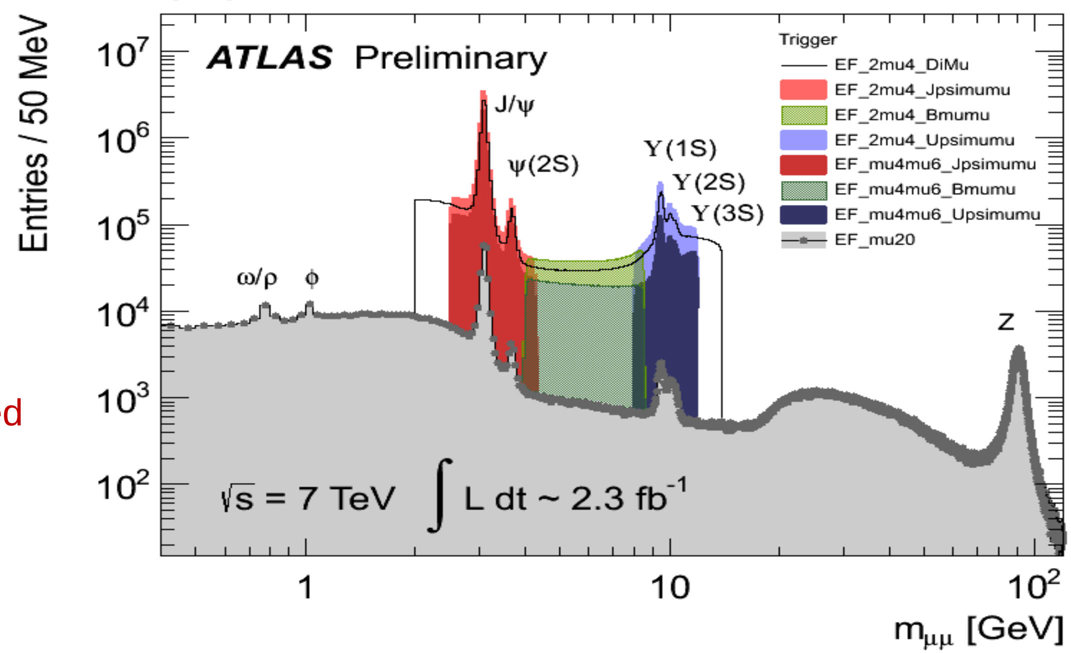
Huge numbers of J/ψ and Upsilon accumulated

Proven (at least in ATLAS) to be useful at any luminosity for checking data quality, measuring efficiencies etc.

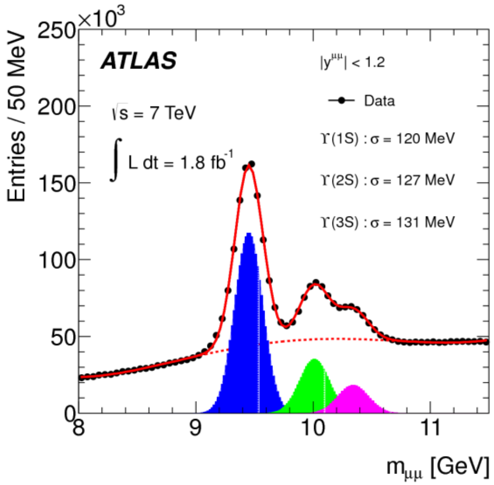
Should keep Onia/HF physics alive for the foreseeable future

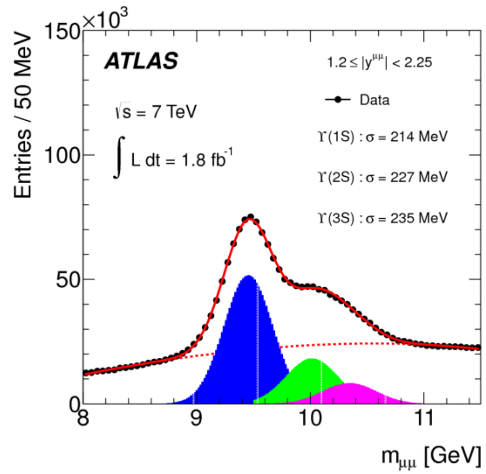
Many “basic” analyses already systematics-limited

Much more sophisticated analyses may become possible



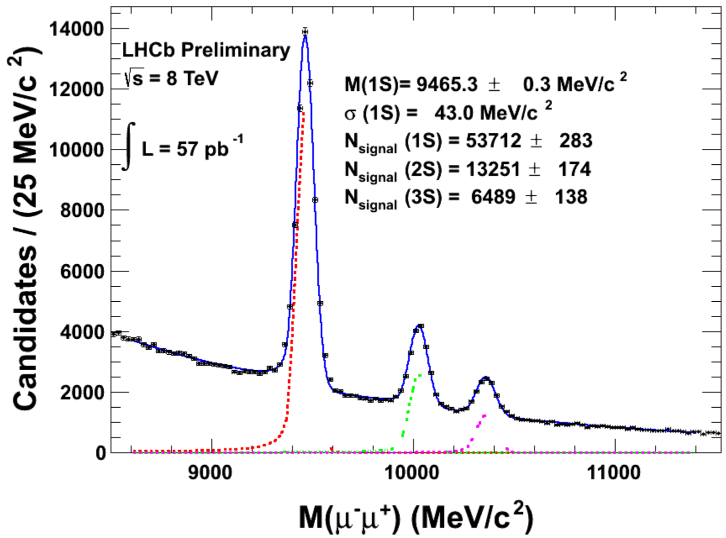
Dimuon mass resolution at LHC experiments

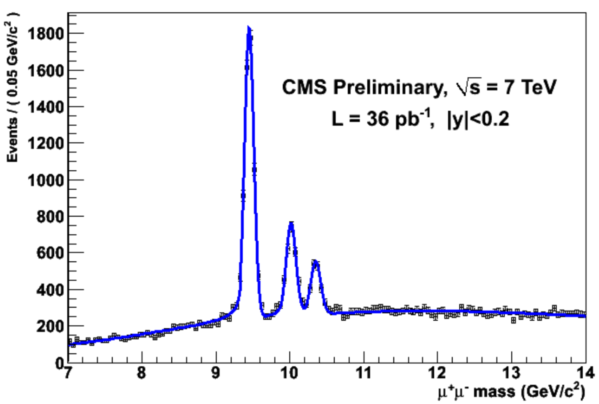


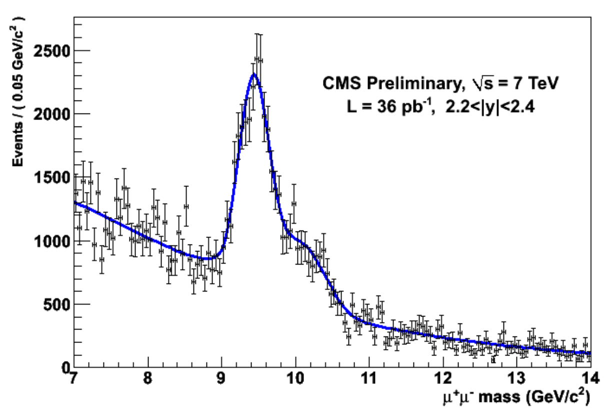


LHCb clearly a champion here

All three experiments are good enough to separate the three peaks







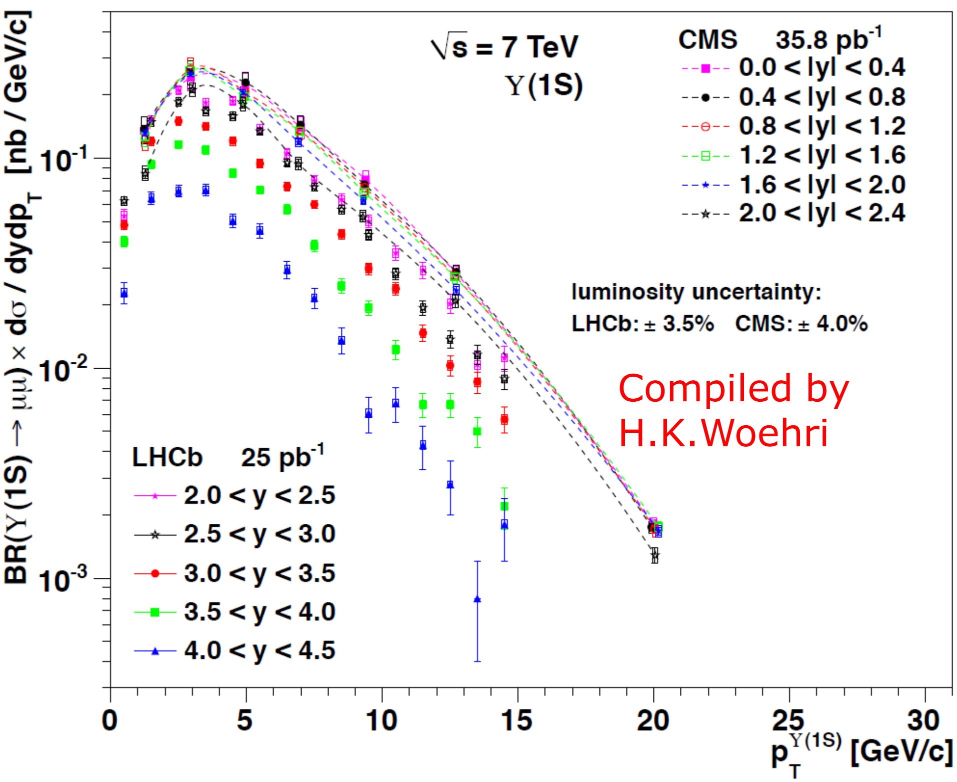
Production of Υ(1S), Υ(2S), Υ(3S): pT dependence

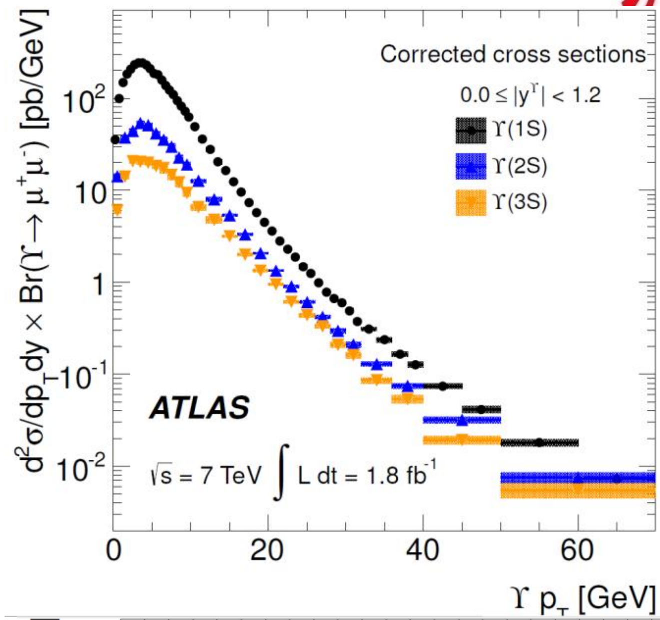
LANCASTER UNIVERSITY

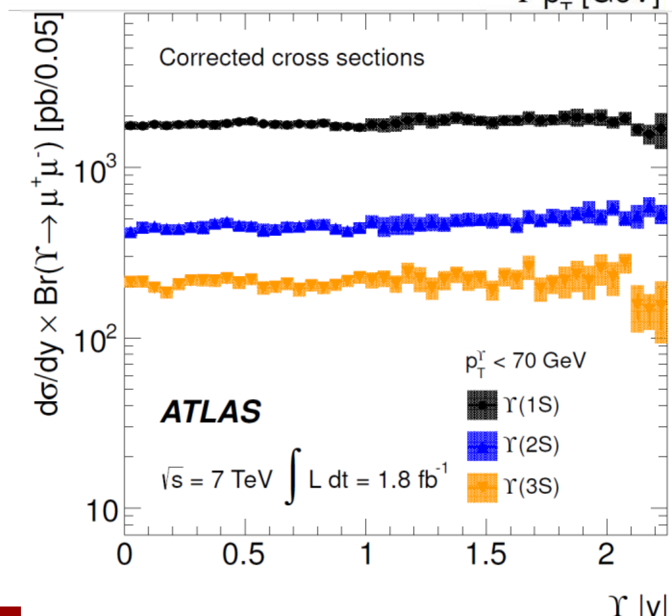
ATLAS: appeared in PRD yesterday
Differential cross section of Υ(1,2,3S) in pT and y with 1.8 fb^{-1}

Extended p_T range, finer pT binning, two rapidity ranges (fiducial cross section also provided)

Agrees well with existing data from CMS and LHCb, Wide space covered overall p_T: 0 to 70 GeV, |y| : < 4.5







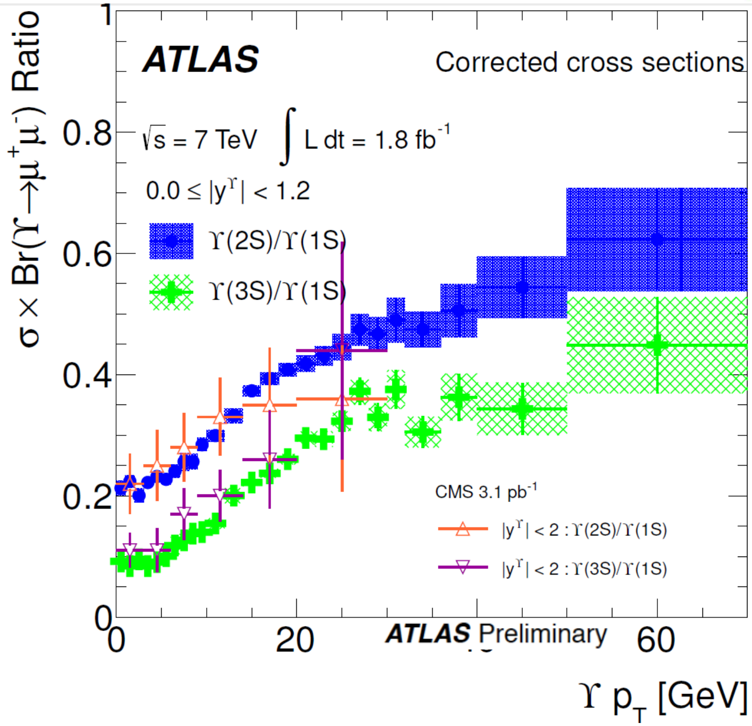
Production of Y(1S), Y(2S), Y(3S): ratios

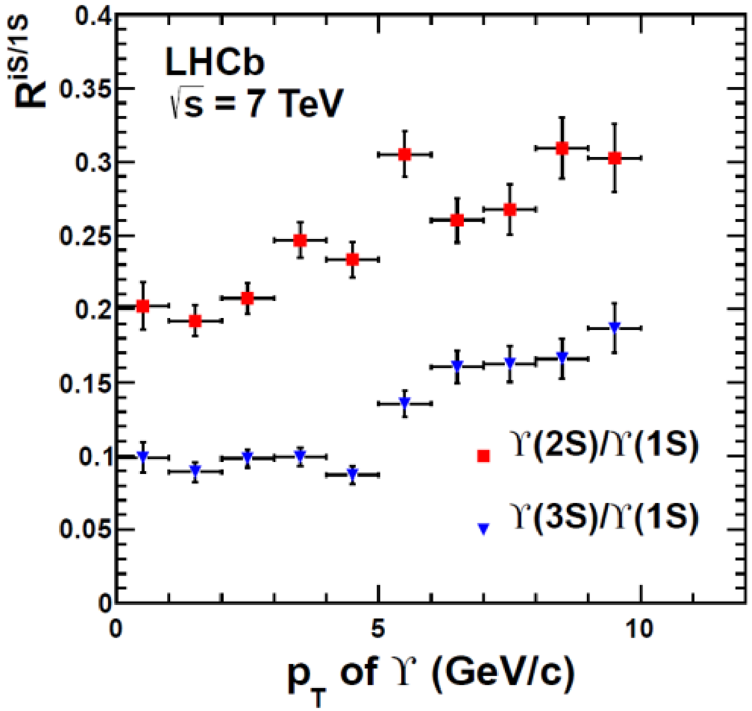
Intriguing: p_T dependence of ratios

Y(2S)/Y(1S), Y(3S)/Y(1S)

confirms existence of multiple mechanisms,

hints on their p_T evolution





Slightly worrying: Γ(ee) = 1.340, 0.612, 0.443 keV

Ratios: 0.46, 0.33 , well below measured ratios at high pT

Maybe direct production not dominant even there?

ATLAS: PRD 87 (2013) 052004
CMS: PRD 83 (2011) 112004
LHCb: EPJC 72 (2012) 2025

Production of Υ: more theory comparisons

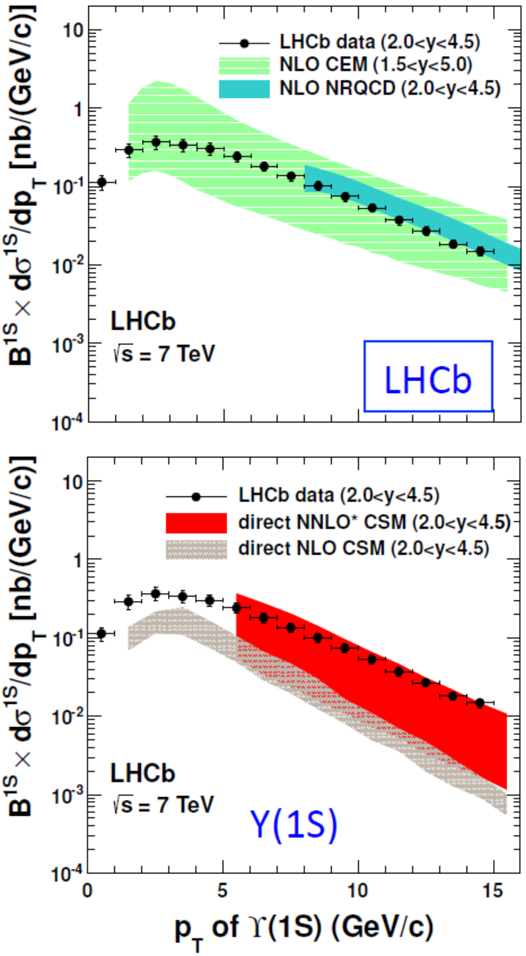
All the usual models – CSM, COM, CEM, etc -- do a reasonable job, but neither can reproduce the full range

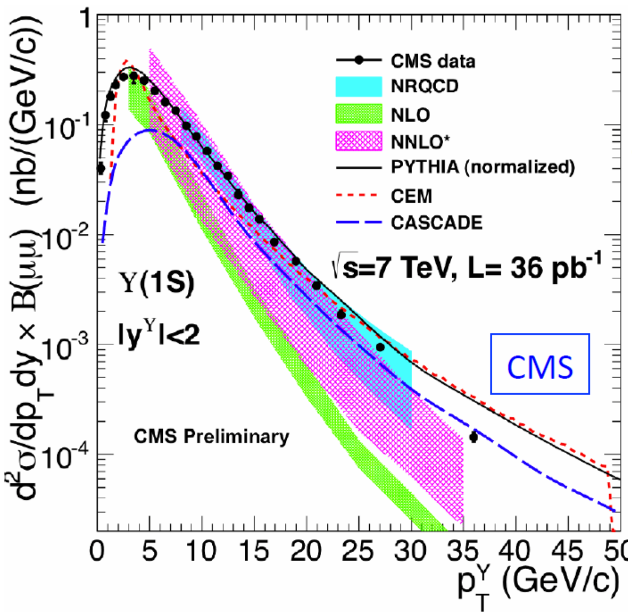
ATLAS: PRD 87 (2013) 052004
CMS: PRD 83 (2011) 112004
LHCb: EPJC 72 (2012) 2025

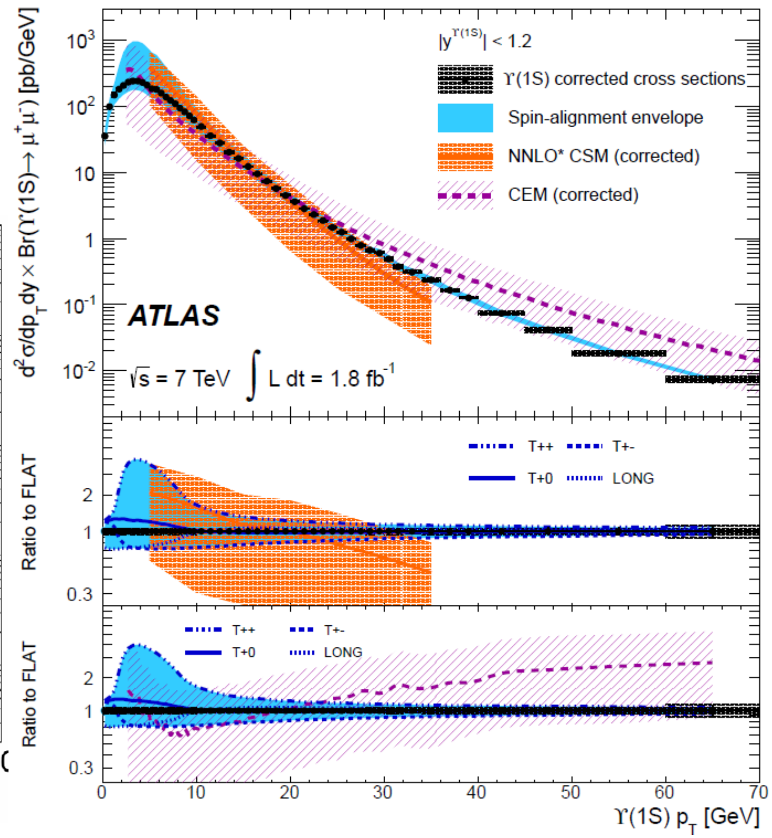
NNLO* CSM doing better than in case of J/ψ

p_T, y spectra alone not enough to make a judgement

Tough times for theorists!

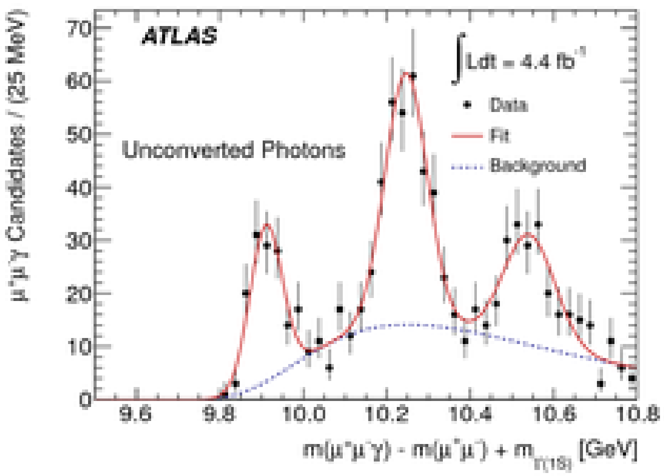


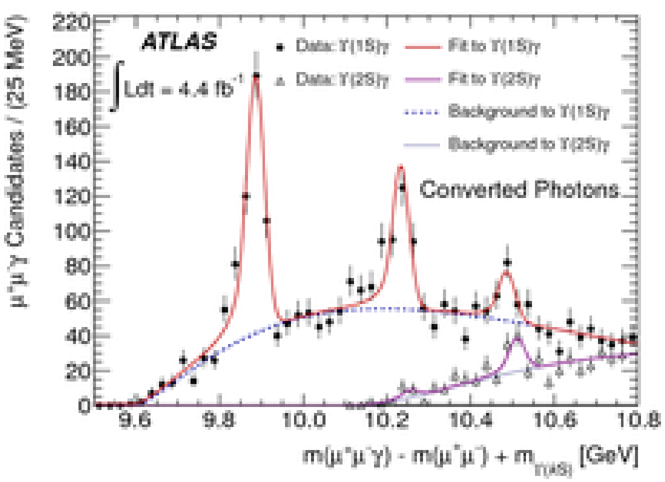


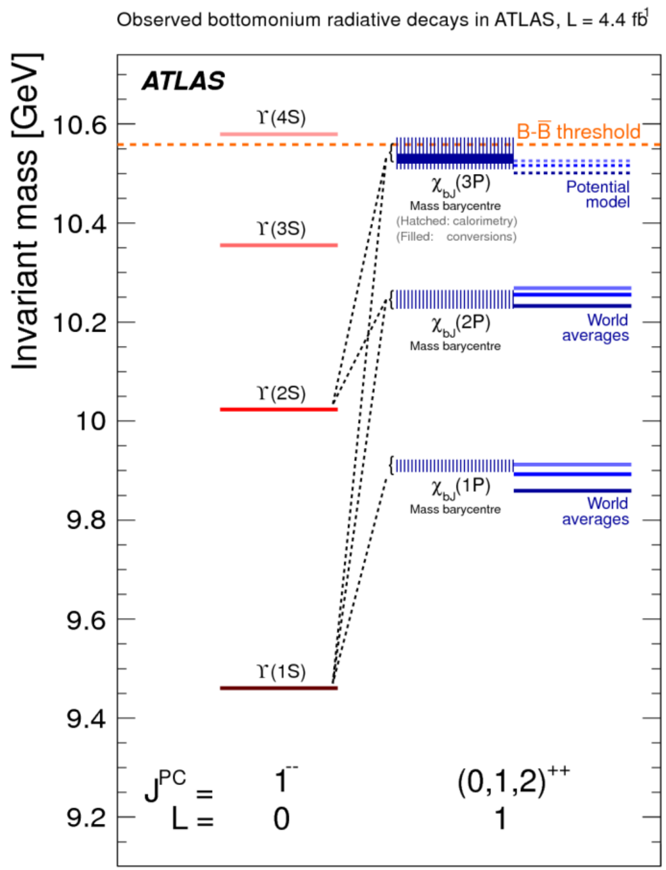


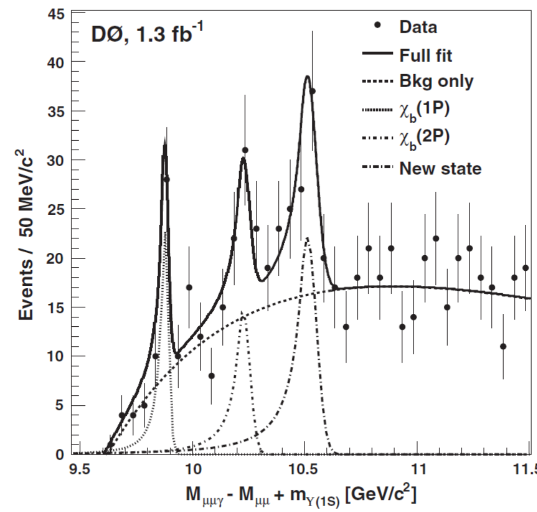
Radiative transitions in Υ system

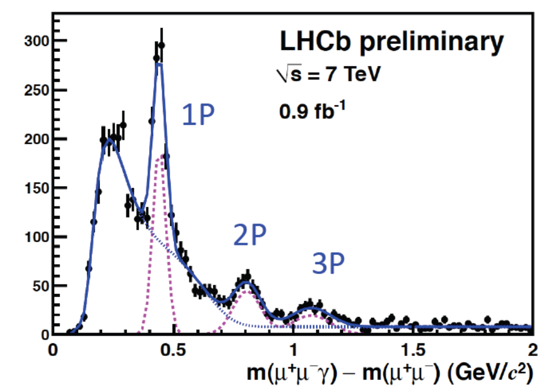
ATLAS: $\chi_b(3P)$
– first discovery of LHC,
now confirmed by D0, LHCb











Υ production: fraction of feeddown

Feeddown pattern in Υ much more complicated.

LHCb singled out $\chi_b(1P)$ contribution to Υ(1S)

LHCb: (20.7 ± 5.7(stat) ± 2.1(syst) $^{+2.7}_{-5.4}$(pol))% at forward rapidity and pT range shown above, with no significant pT dependence

In agreement with CDF measurements at 1.8 TeV

CDF: (27.1 ± 6.9 ± 4.4)% at central rapidity

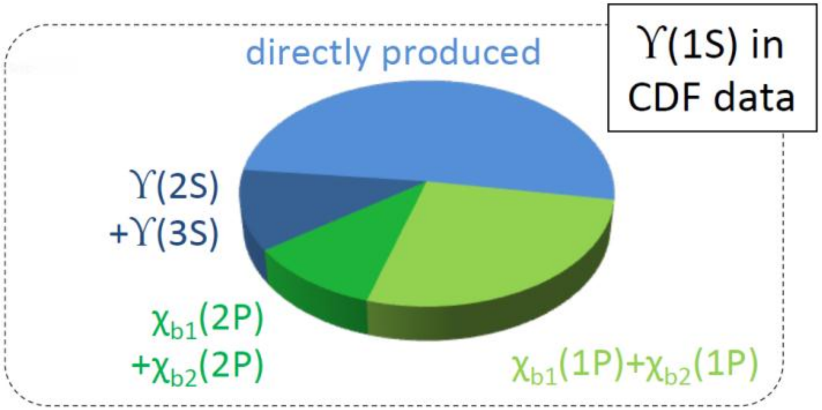
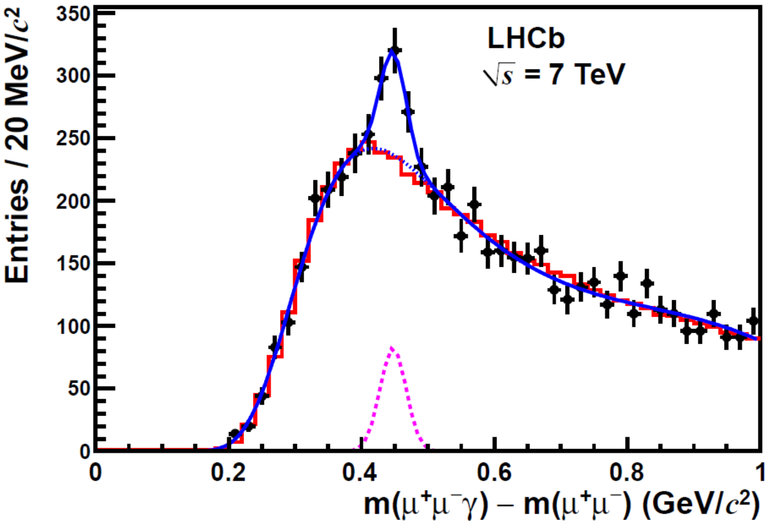
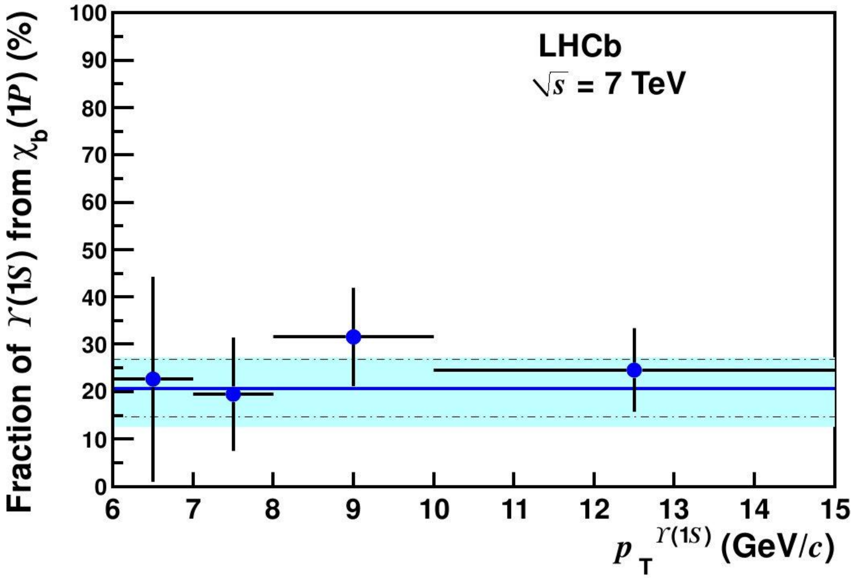


Diagram from P. Faccioli





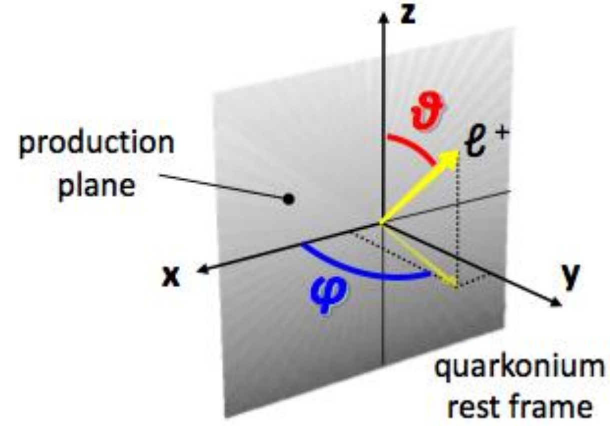
LHCb: arXiv:1209.0282
CDF: PRL 84 (2000) 2094

Developments in spectroscopy (from PDG)

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$h_c(1P)$	3525.41 ± 0.16	<1	1^{+-}	$\psi(2S) \to \pi^0 (\gamma\eta_c(1S))$	CLEO [8–10] (13.2)	2004	OK
				$\psi(2S) \to \pi^0 (\gamma...)$	CLEO [8–10] (10), BES [11] (19)		
				$p\bar{p} \to (\gamma\eta_c) \to (\gamma\gamma\gamma)$	E835 [12] (3.1)		
				$\psi(2S) \to \pi^0 (...)$	BESIII [11] (9.5)		
$\eta_c(2S)$	3638.9 ± 1.3	10±4	0^{-+}	$B \to K (K^0_S K^- \pi^+)$	Belle [13, 14] (6.0)	2002	OK
				$e^+e^- \to e^+e^- (K^0_S K^- \pi^+)$	*BABAR* [15, 16] (7.8), CLEO [17] (6.5), Belle [18] (6)		
				$e^+e^- \to J/\psi (...)$	*BABAR* [19] (np), Belle [20] (8.1)		
$\chi_{c2}(2P)$	3927.2 ± 2.6	24±6	2^{++}	$e^+e^- \to e^+e^- (D\bar{D})$	Belle [21] (5.3), *BABAR* [22, 23] (5.8)	2005	OK
B_c^+	6277 ± 6	-	0^-	$\bar{p}p \to (\pi^+ J/\psi)...$	CDF [24, 25] (8.0), DØ [26] (5.2)	2007	OK
$\eta_b(1S)$	9395.8 ± 3.0	$12.4^{+12.7}_{-5.7}$	0^{-+}	$\Upsilon(3S) \to \gamma (...)$	*BABAR* [27] (10), CLEO [28] (4.0)	2008	OK
				$\Upsilon(2S) \to \gamma (...)$	*BABAR* [29] (3.0)		
				$\Upsilon(5S) \to \pi^+\pi^-\gamma (...)$	Belle [30] (14)		
$h_b(1P)$	9898.6 ± 1.4	?	1^{+-}	$\Upsilon(5S) \to \pi^+\pi^- (...)$	Belle [30, 31] (5.5)	2011	NC!
				$\Upsilon(3S) \to \pi^0 (...)$	*BABAR* [32] (3.0)		
$\Upsilon(1^3D_2)$	10163.7 ± 1.4	?	2^{--}	$\Upsilon(3S) \to \gamma\gamma (\gamma\gamma\Upsilon(1S))$	CLEO [33] (10.2)	2004	OK
				$\Upsilon(3S) \to \gamma\gamma (\pi^+\pi^-\Upsilon(1S))$	*BABAR* [34] (5.8)		
				$\Upsilon(5S) \to \pi^+\pi^- (...)$	Belle [31] (2.4)		
$h_b(2P)$	$10259.8^{+1.5}_{-1.2}$	?	1^{+-}	$\Upsilon(5S) \to \pi^+\pi^- (...)$	Belle [31] (11.2)	2011	NC!
$\chi_{bJ}(3P)$	10530 ± 10	?	?	$pp \to (\gamma\mu^+\mu^-)...$	ATLAS [35] (>6)	2011	NC!

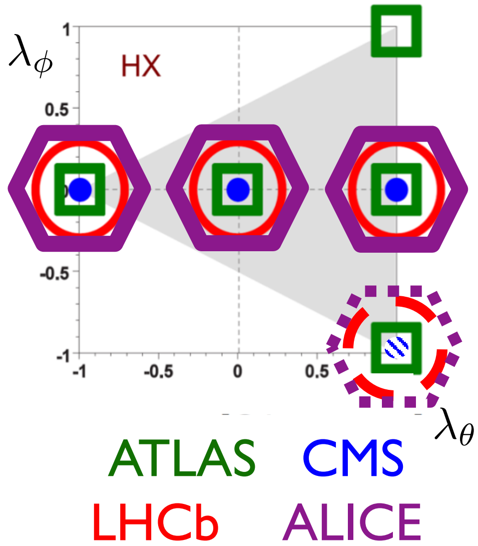
A vector state $|\psi\rangle = a_{-1}\,|1,-1\rangle + a_0\,|1,0\rangle + a_{+1}\,|1,+1\rangle$

produced in a single exclusive process, and decaying into a pair of fermions, has the general angular distribution:



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

$$\lambda_{\theta^\star} = \frac{1-3|a_0|^2}{1+|a_0|^2} \qquad \lambda_{\phi^\star} = \frac{2Re\,a_{+1}^* a_{-1}}{1+|a_0|^2} \qquad \lambda_{\theta^\star\phi^\star} = \frac{\sqrt{2}Re\,[a_0^*(a_{+1}-a_{-1})]}{1+|a_0|^2}$$



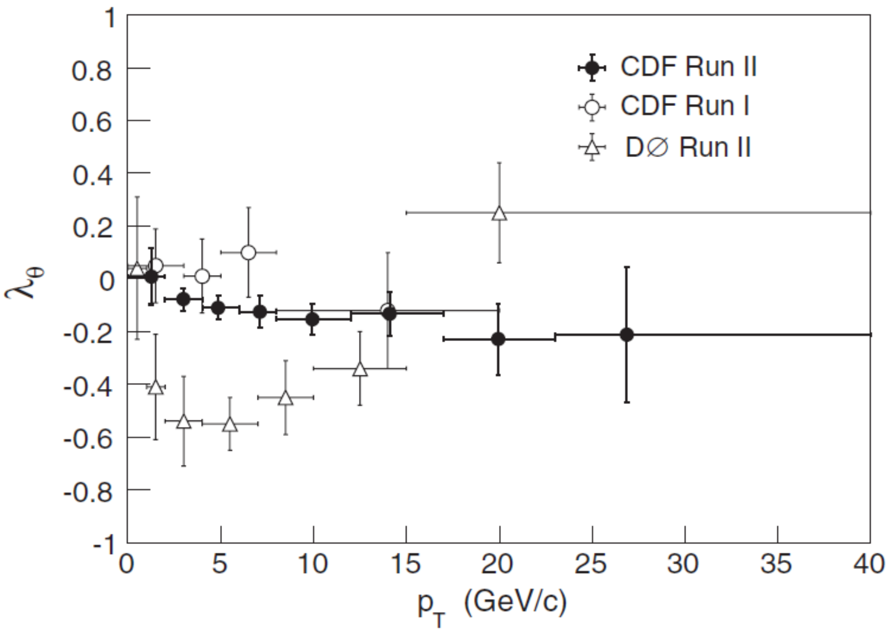
In cross section measurements, detector acceptance depends on polarisation, and if the polarisation is unknown, the acceptance-corrected cross section varies with the polarisation hypothesis used

Different experiments use slightly different range of hypotheses

In the two-angle treatment, a move from helicity frame to e.g. Collins-Soper frame is accoplished by a simple rotation

Polarisation measurements: need for 2 angles

In polarisation measurements it is **not safe** to integrate over φ^*, because fiducial cuts can -- and do! -- introduce non-trivial and sometimes strong φ^*-dependence, thus affecting θ^* dependence and hence the extracted value of λ_θ



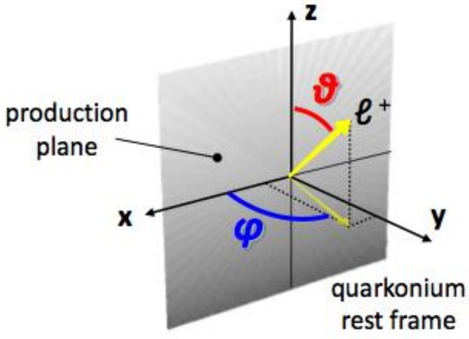
Clear contradictions between CDF Run I, CDF Run II and D0 Run II measurements of ϒ polarisation is a clear illustration:

Only CDF Run II result here uses 2-angle analysis

CMS: Υ polarisation

General angular dependence of decay muons in Υ rest frame:

$$1 + \lambda_{\theta^\star} \cos^2\theta^\star + \lambda_{\phi^\star} \sin^2\theta^\star \cos 2\phi^\star + \lambda_{\theta^\star\phi^\star} \sin 2\theta^\star \cos\phi^\star$$

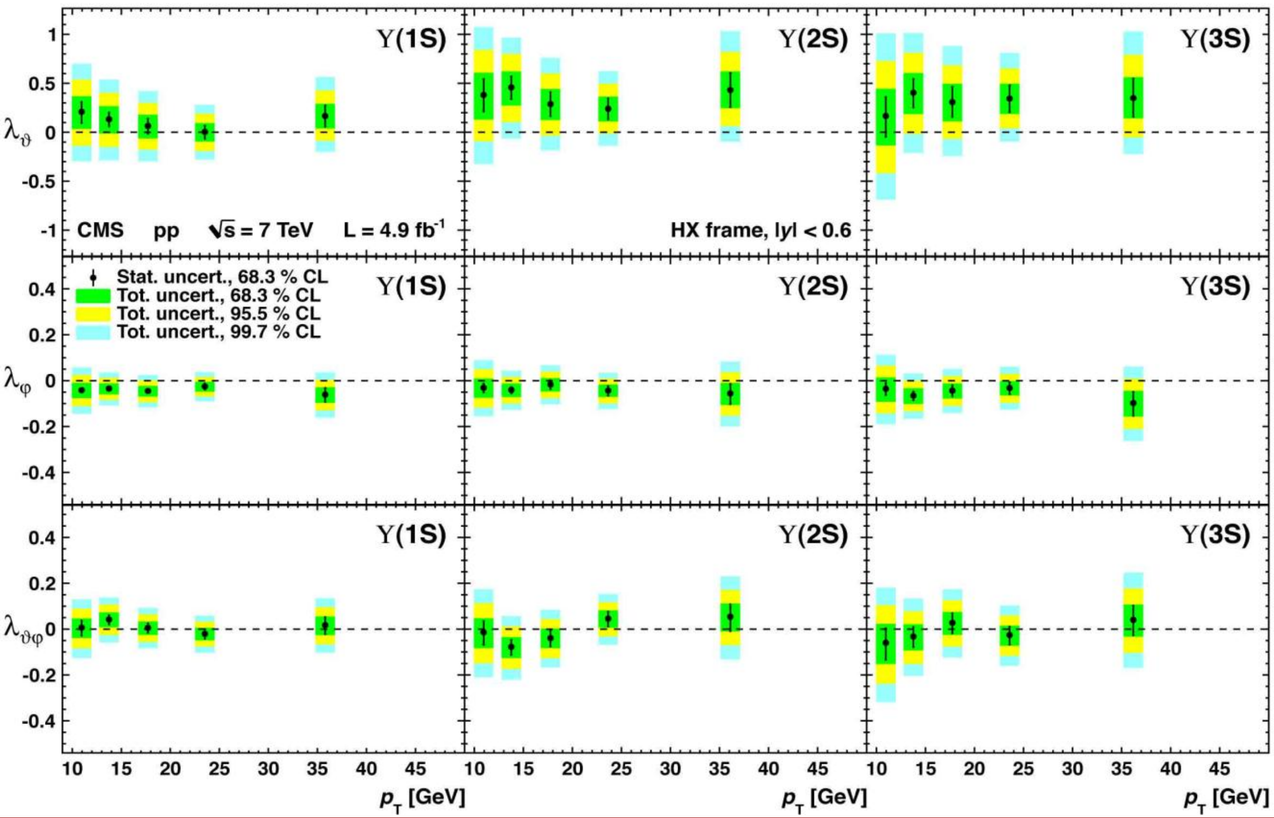


Helicity frame: z axis along the Υ momentum in the lab frame

CMS have made a full 2-angle measurement of the polarisation of all three Υ states, in two rapidity bins, and three different frames, as a function of Υ transverse momentum

Only helicity frame results are shown here, results in others are similar: spin alignment for Υ(1S) is not strong, if any at all

Possible hints of slightly increasing transverse polarisation when moving from Υ(1S) to Υ(2S) to Υ(3S)



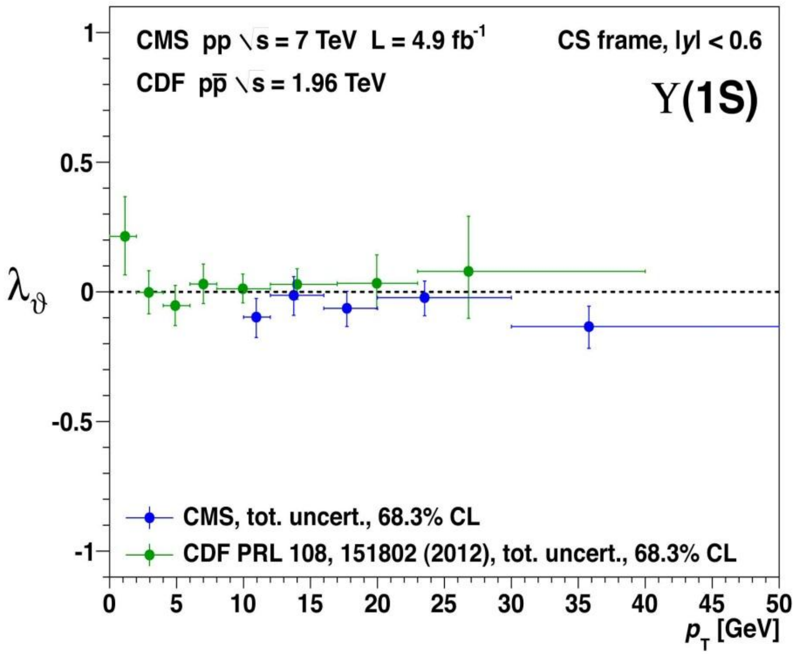
CMS: PRL 110 (2013) 081802

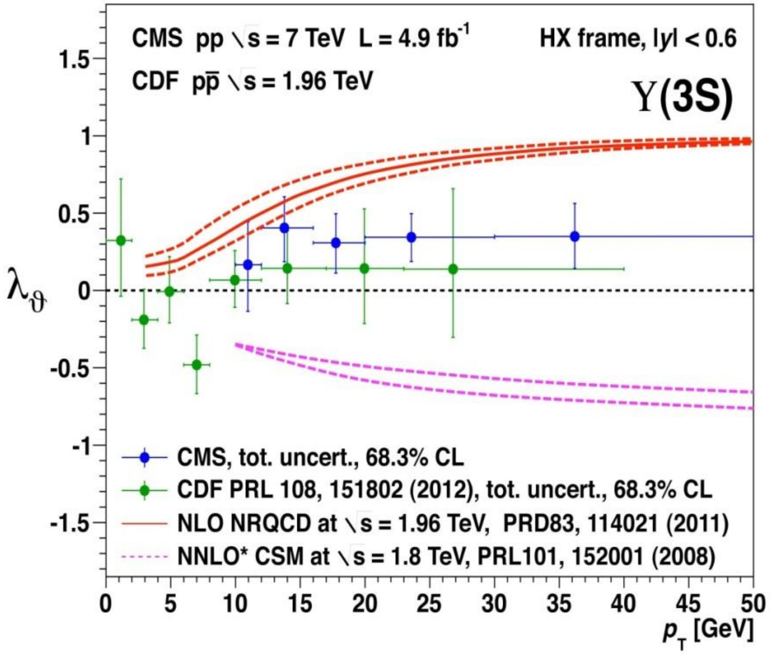
CMS results in good agreement with recent results from CDF

Theoretical predictions are notoriously difficult to make, partly due to feeddown

Model curves below made under assumption that Υ(3S) is direct, however after the observation of $\chi_b(3P)$ we know that's not true!

In any case, measured polarisation levels are not as large as those predicted by the theoretical models shown





LHC: quarkonium factory?

- Production properties of the **three families of Υ** states are being studied in detail, with a huge range of p_T and y covered, and the LHC experiments nicely complementing each other.
- These measurements provide lots of input for theorists, and plenty of questions, but no clear answers yet
- First **"two-angle" measurements of vector quarkonium spin alignment** show no signs of strong polarisation, against the expectations of leading models
- pT and rapidity distributions alone are not enough to discriminate between various models
- First LHC measurements of **"new observables"** -- studies of Onia associations with other Onia, open HF, underlying event characteristics – have become available for J/ψ, providing new challenges to theory
- Similar measurements with Υ will also show up in due course – "watch this space"
- **No sign of η_b or h_b so far at LHC.** Looks like a very tough task – please convince me that it's worth the effort...

Now about the future

- Exciting times at LHC: Huge amounts of data together with good understanding of the detectors!
- Many new measurements to be presented at Moriond next month, surely some of them will include heavy flavours and quarkonia!
- Further down the line: higher statistics measurements for various B-hadrons at ever higher pT
- Polarisation of prompt J/ψ, $\psi(2S)$, and more of Υ
- χ_c and χ_b production cross sections, although individual χ_{bJ} (NP) may not be resolved (χ_{cJ} will be), more for J/ψ, $\psi(2S)$
- Bc production (and spectroscopy!) in some detail
- Much more on di-onia production: cross sections, resonances?
- Much more on "new observables": Onia + open HF, Onia + tracks, Onia + jets or photons
- Other things...

List of references (most certainly incomplete...)

- Υ discovery: Phys. Rev. Lett. 39 (1977) 252

CDF:
- Υ polarisation: PRL 108 (2012) 151802
- Υ cross section & polarisation: PRL 88 (2002) 161802
- Υ feeddown from chi_b: PRL 84 (2000) 2094

D0
- χ_b(3P) confirmation: PRD 86 (2012) 031103(R)
- Υ cross section: PRL 94 (2005) 232001
- Υ polarisation: PRL 101 (2008) 182004

ATLAS
- χ_b(3P) first observation: PRL 108 (2012) 152001
- Υ cross section: PRD 87 (2013) 052004
- Υ fiducial cross section: PL B703 (2011) 428

CMS
- Υ polarization arXiv:1209.2922; PRL 110 (2013) 081802
- Υ cross section: PRD 83 (2011) 112004

LHCb
- Υ feeddown from chi_b: arXiv:1209.0282
- χ_b(3P) confirmation: LHCb: CONF-2012-020
- Υ cross section: EPJC 72 (2012) 2025

THANK YOU!