Heavy Flavour Spectroscopy, Heavy Hadron Lifetimes

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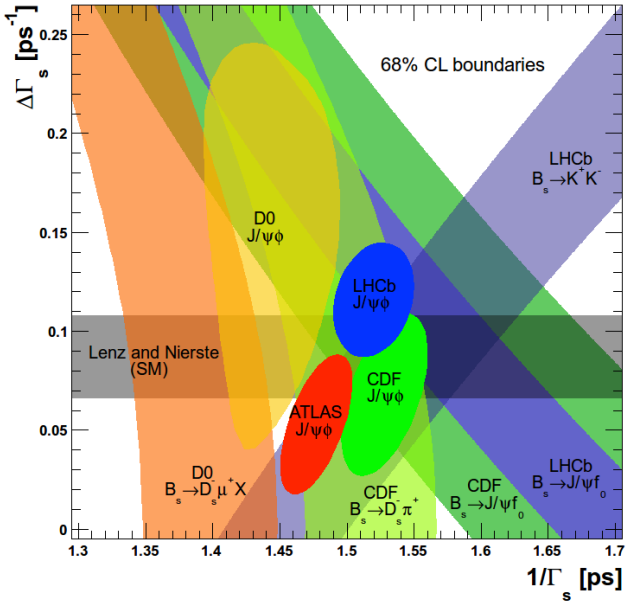
What this talk is – and isn't!

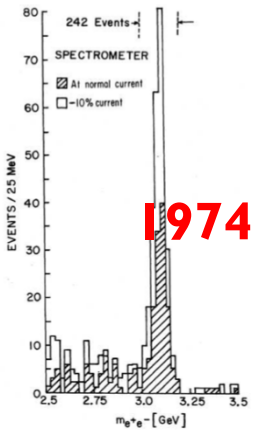
- Spectroscopy: but not the exotics – or open charm
- The most exciting part of heavy flavour lifetimes is in the heavy-light lifetime differences, covered by Greg and Guennadi
  - We see that using their 2011 data both ATLAS and LHCb are similar and already most precise in the 1/Γ -ΔΓ space
- I will cover some more conventional lifetime measurements
- I will also concentrate on the LHC results
- Some discussion of production & properties

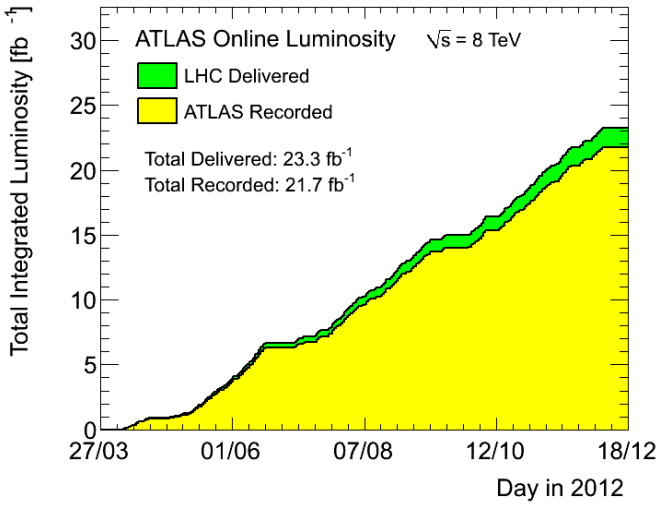


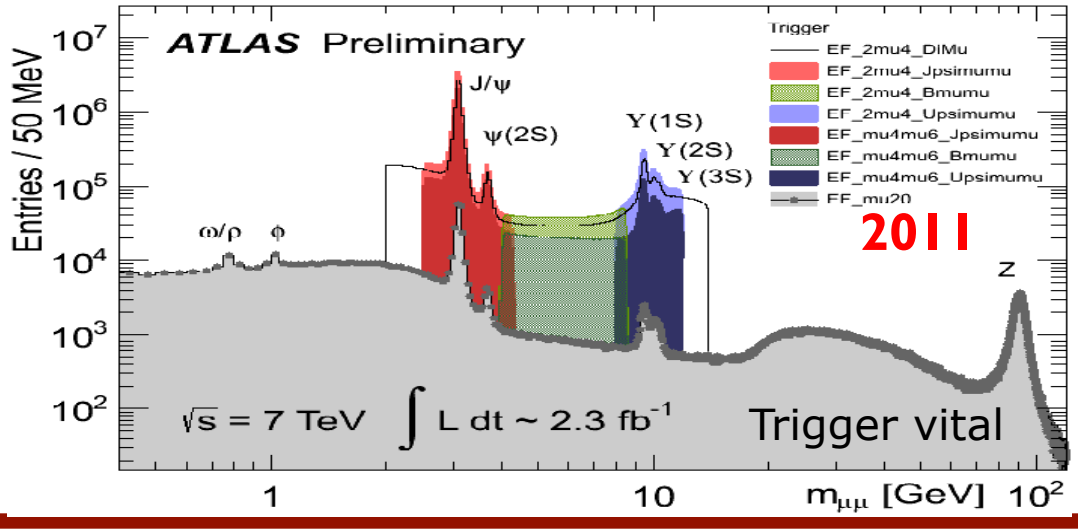
- Conventional apologies for biases and omissions

Heavy Flavour Spectroscopy

- HF sensitive to new physics
- LHCb advantage:
  - High cross-sections
  - Hadron triggers and PID
- ATLAS/CMS advantage:
  - High luminosity
  - Largely rely on muon/dimuon triggers
- Wide program
  - Charm production
  - Onia production
    - Υ (1,2,3S) production
    - χ_c and χ_b production
    - Polarisation measurements
  - B-hadron production
  - Lifetimes & CP violation

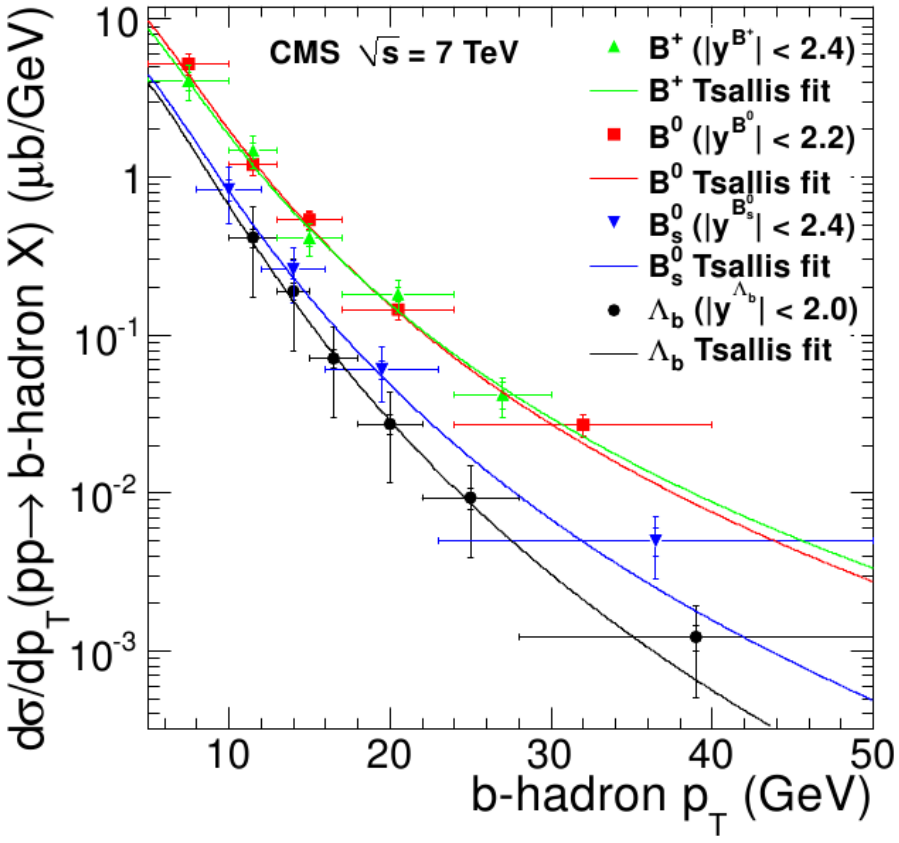


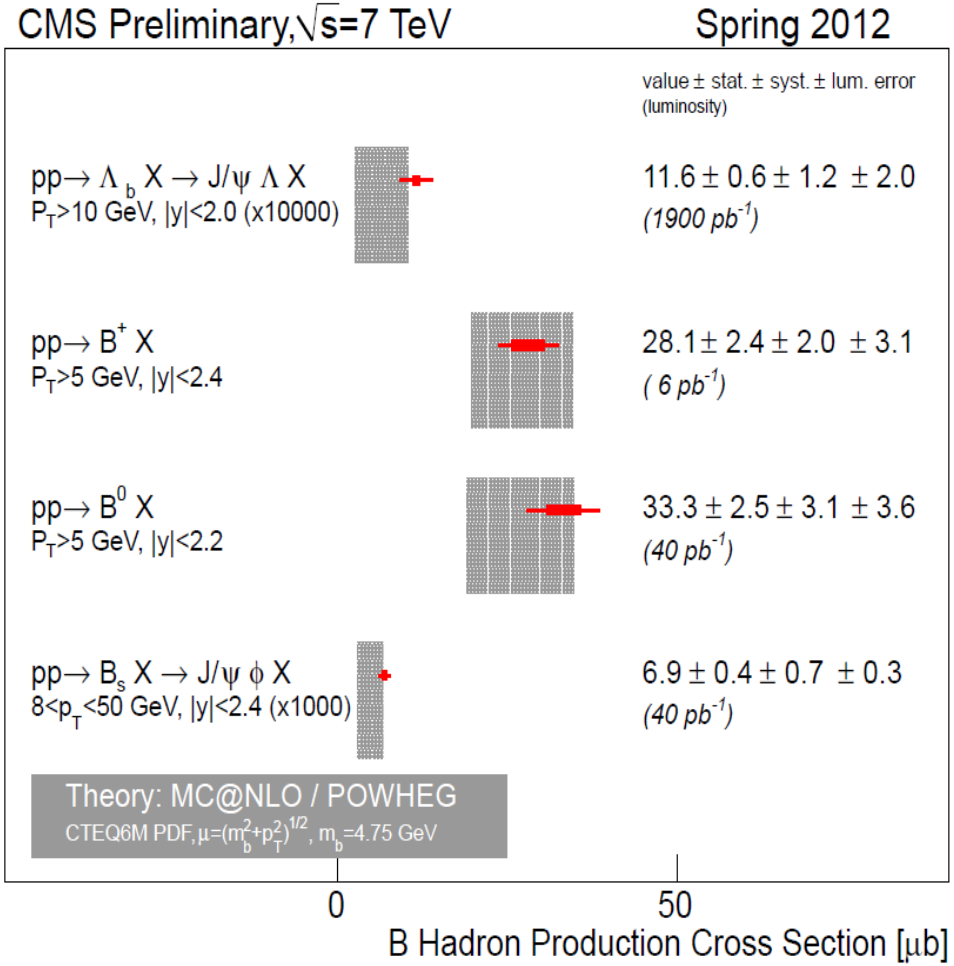




B hadron production

Compilation of CMS results on specific B hadron production:
The heavier the hadron, the steeper the pT spectrum...
Theory describes data well, but tends to be on the low side

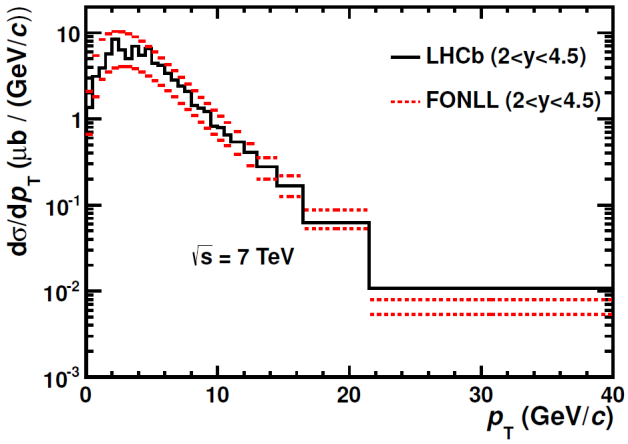




twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH

B^+ production

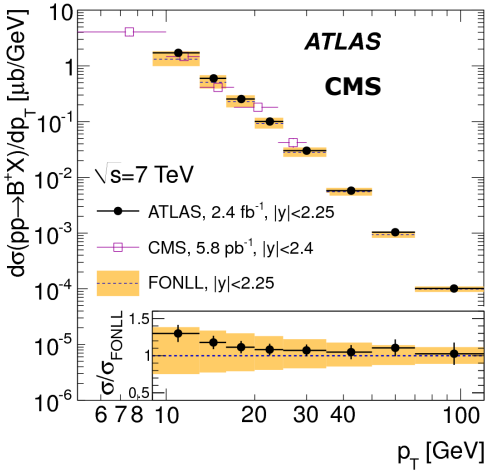
Charged B cross sections from ATLAS, CMS, LHCb

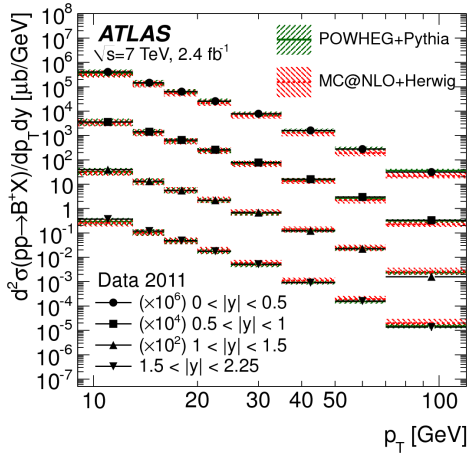


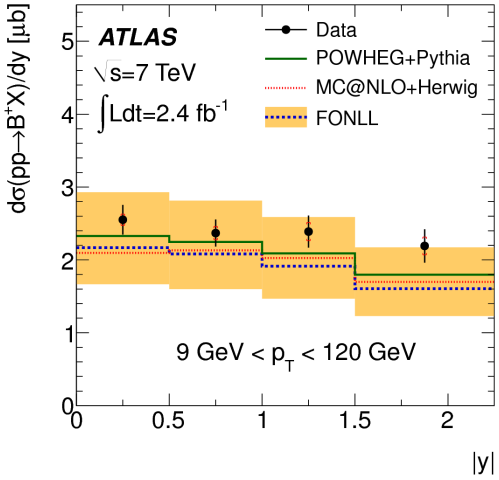
LHCb results agree with FONLL
So do ATLAS, CMS within errors
Evidence that MC@NLO is

- Too soft for |y|<1
- Too hard for |y|>1

Cross-section almost flat in |y|

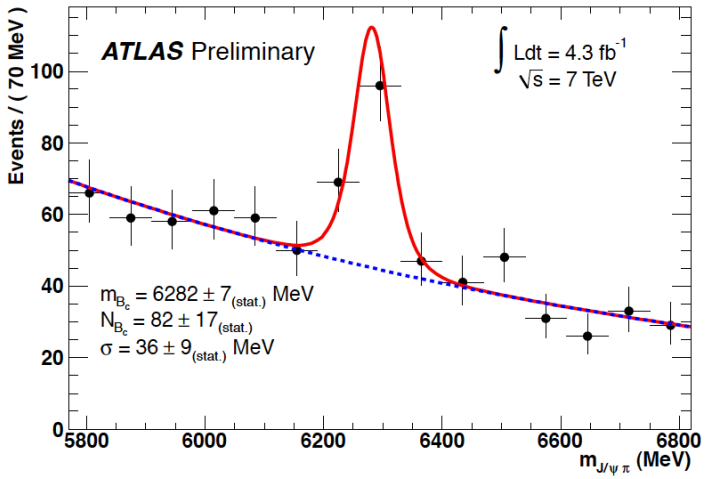






LHCb: JHEP 04 (2012) 093
CMS: PRL 106 (2011) 112001
ATLAS:arXiv:1307.0126

B_c production

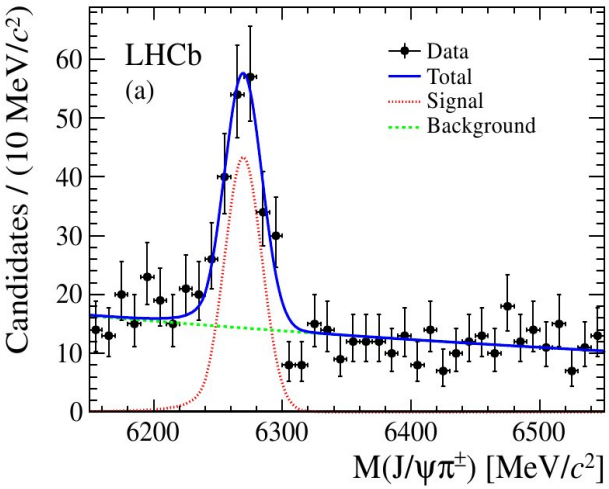


B_c: asymmetric, charged, weakly decaying heavy quarkonium

Studied by ATLAS, CMS, LHCb

CMS observed it in J/ψ π and J/ψ 3π

LHCb measured its production rate relative to B+



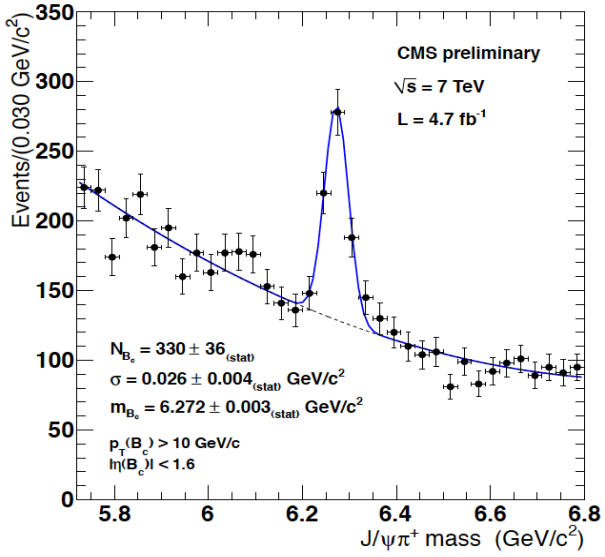
LHCb result at 7 TeV, 0.37 fb^{-1}

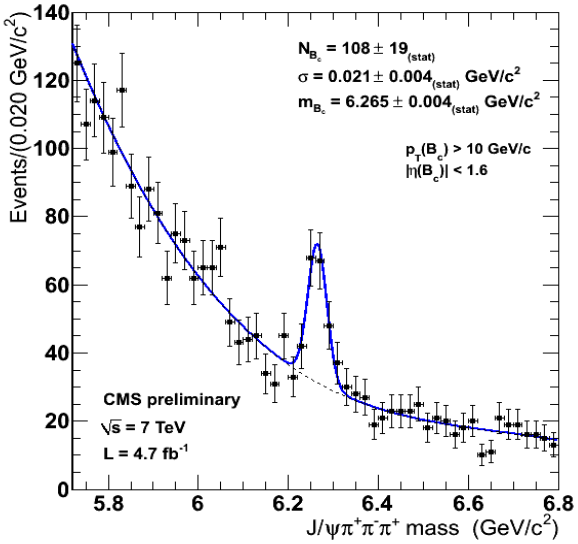
$$R_{c/u} = \frac{\sigma(B_c^+)\,\mathcal{B}(B_c^+ \to J/\psi\pi^+)}{\sigma(B^+)\,\mathcal{B}(B^+ \to J/\psi K^+)}$$

= 0.68 % ±0.10 % (stat)
±0.03 % (syst)
±0.05 % (lifetime)

for $p_T > 4$ GeV, $2.5<\eta<4.5$

Measurement provides valuable input for theory





LHCb: arXiv:1209.5634
CMS: PAS BPH-11-003
ATLAS:CONF-2012-028

B_c mass

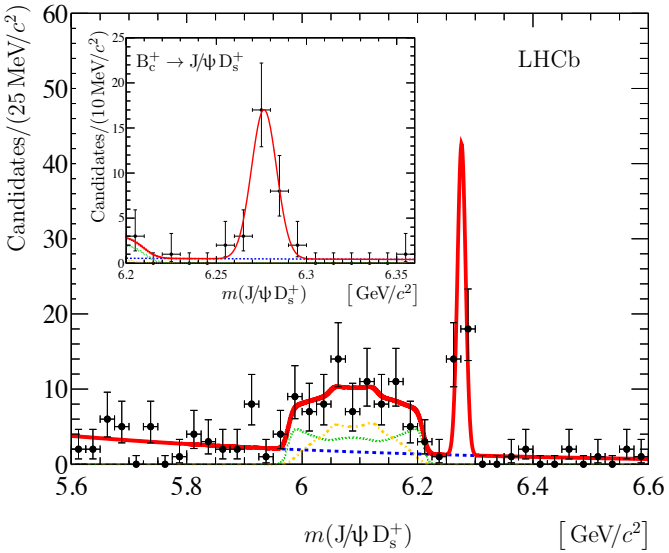
LHCb previously used $B_c^+ \rightarrow J/\Psi\ \pi^+$
$M(B_c)$ = 62737±1.3±1.6 MeV

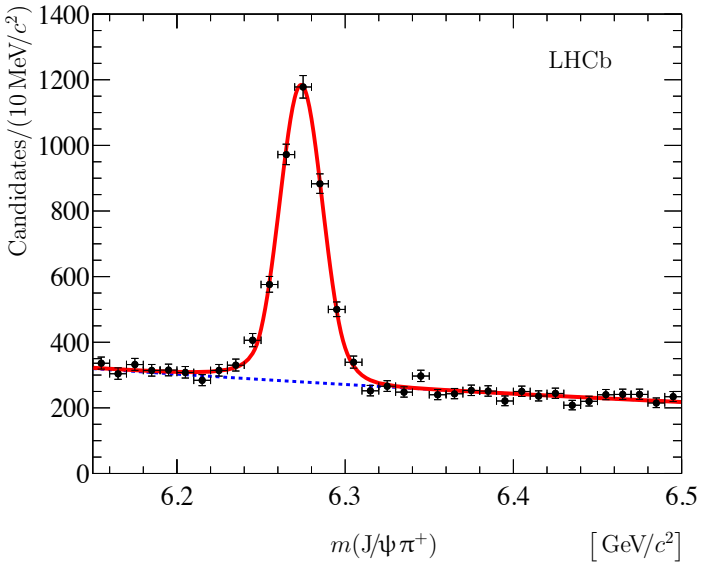
Now uses $B_c^+ \rightarrow J/\Psi\ D_s^+$
New Ds mass difference measurements reduce the systematics

$M(B_c)$ = 6276.28±1.44±0.36 MeV
$M(B_c)$-$M(D_s^+)$ = 4307.97±1.44±0.11 MeV

Below the previous PDG average uncertainty:

62745±1.6 MeV

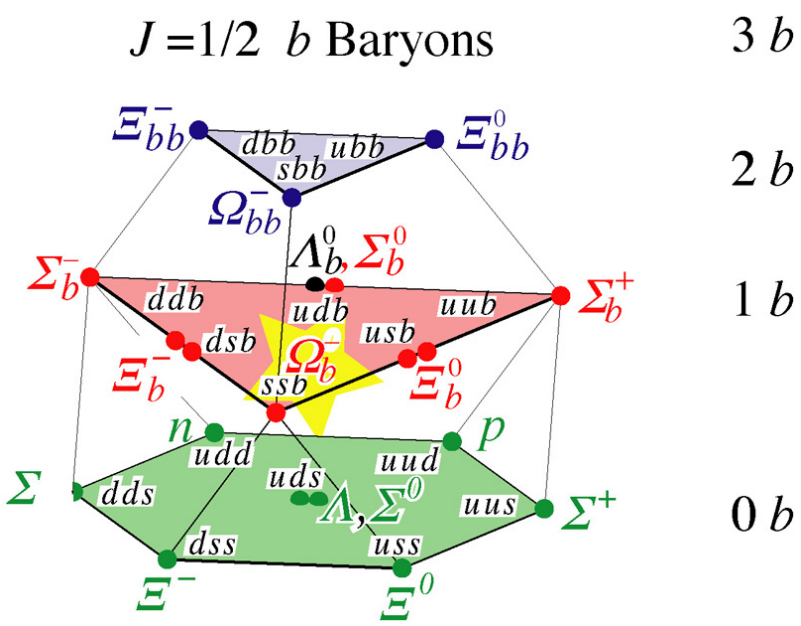




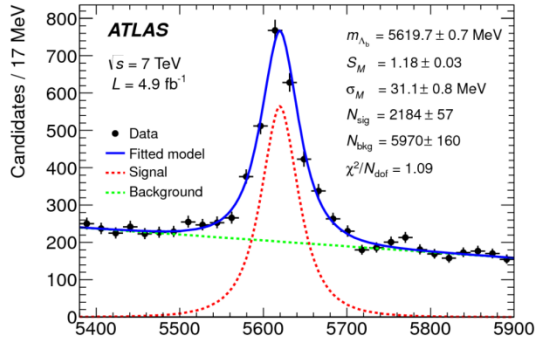
LHCb: PRD 87 (2013) 112012

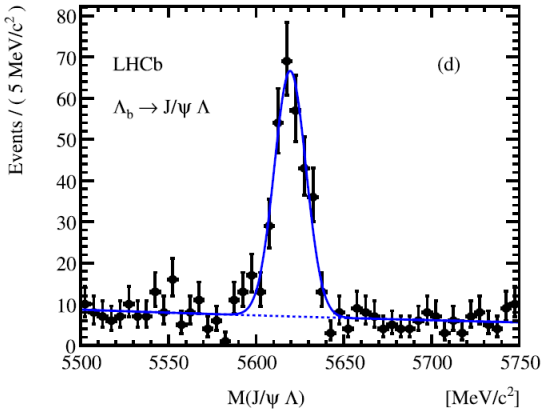
B Baryons

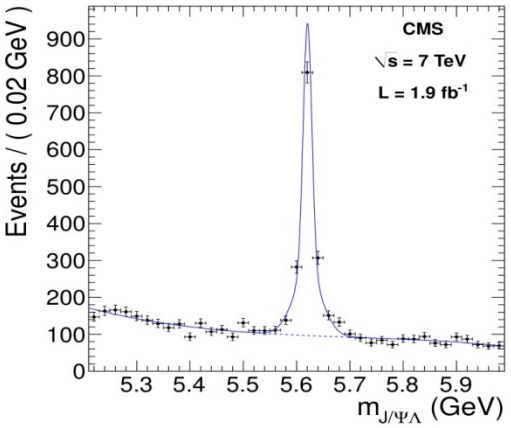
- B baryons are the preserve of hadron machines for now
- Nice results coming from the LHC
- New states observed
- Lots to be explored



Λ_b production







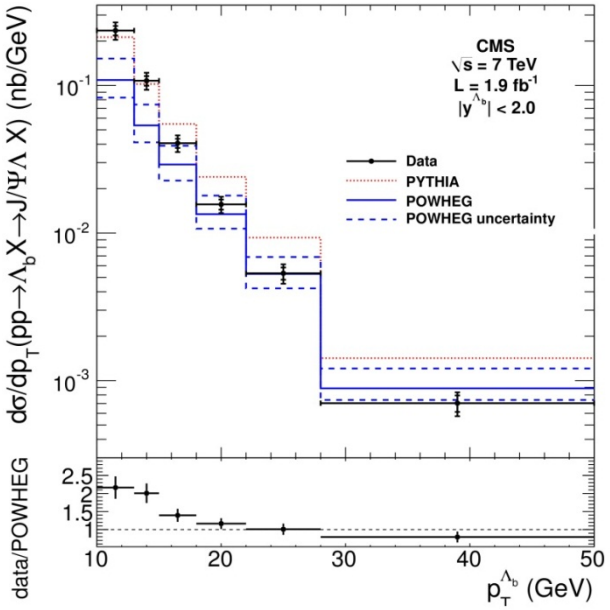
Λ_b : prominent peak in $J/\psi^+\Lambda$ decay mode, competitive measurements of properties by LHC experiments

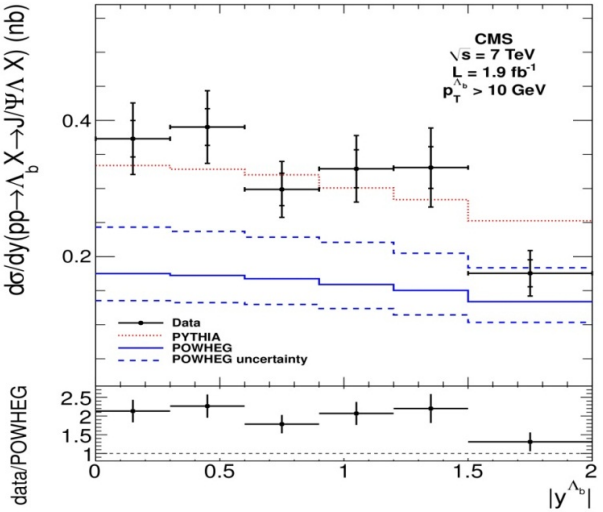
Differential cross section measured by CMS

New decay modes seen by LHCb

Description of p_T spectrum by theory not perfect, but reasonable

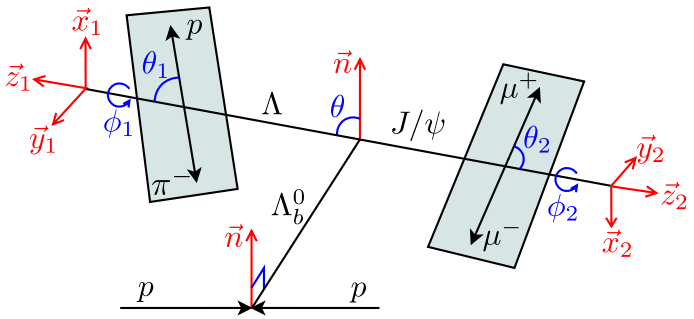
Shape of rapidity dependence reproduced well





CMS: PLB 714 (2012) 136
LHCb: PLB 708 (2012) 241
ATLAS: PRD 87 (2013) 032002

Λ_b polarization



4 decay amplitudes measured: a+, a-, b+, b-

Combined to a single parity sensitive observable:

$\alpha_b = |a+|^2-|a-|^2+|b+|^2-|b-|^2$

2011 data

LHCb:

α_b = 0.05 ± 0.17 ± 0.07

$|a+|$ = 0.01±0.04 ± 0.03

$|a-|$ = 0.57±0.06 ± 0.03

$|b+|$ = 0.51±0.05 ± 0.02

$|b-|$ = 0.10±0.04 ± 0.03

ATLAS:

α_b = 0.28 ± 0.16 ± 0.06

$|a+| = 0.17^{+0.12}_{-0.17} \pm 0.06$

$|a-| = 0.59^{+0.06}_{-0.07} \pm 0.04$

$|b+| = 0.79^{+0.04}_{-0.05} \pm 0.02$

$|b-|$ = 0.08 ± 0.13 ± 0.05

Reasonable experimental agreement

Transverse polarization not excluded at ~10%

Disagrees with HQET predictions

ATLAS: ATLAS-CONF-2013-071
LHCb: PLB 724 (2013) 27

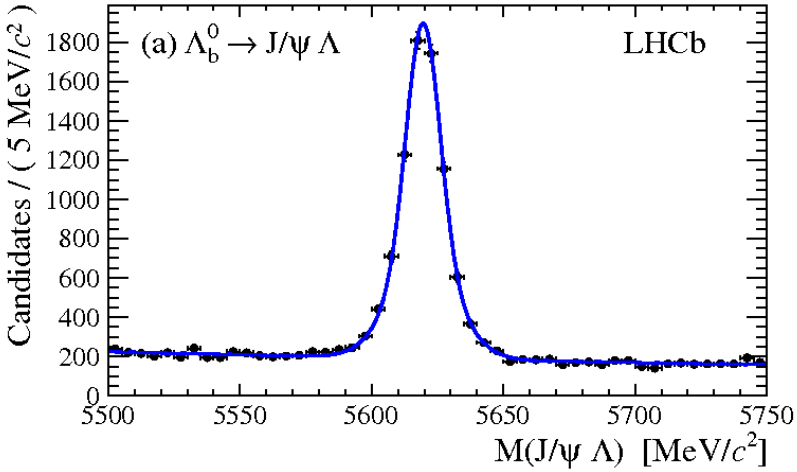
Higher mass b baryons

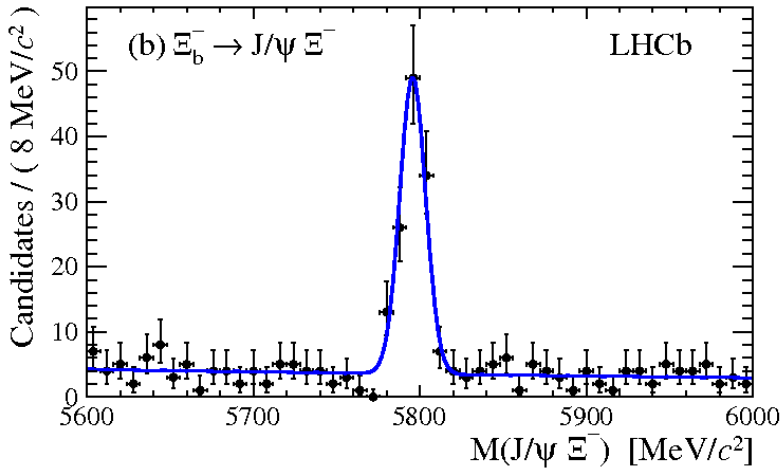
- Nice observations & mass determinations of Λ_b^0, Ξ_b^-, Ω_b^- from LHCb
  - $1fb^{-1}$ of data
  - Decays involving the J/Ψ
  - Good control of momentum scale- but sets systematic

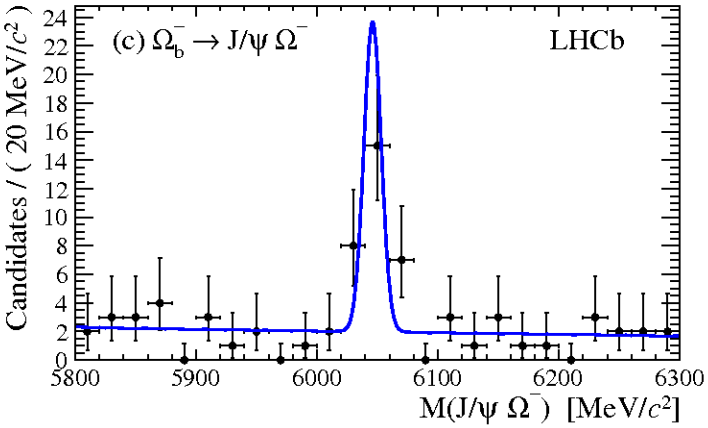
$M(\Lambda_b^0)=5619.53\pm0.13\pm0,45MeV$

$M(\Xi_b^-)=5795.8\pm0.9\pm0.4MeV$

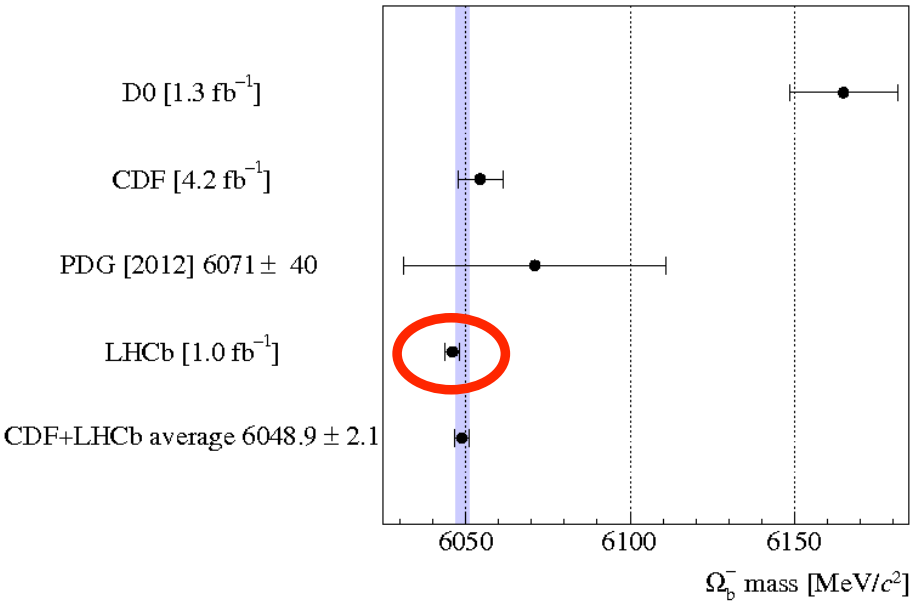
$M(\Omega_b^-)=6046.0\pm2.2\pm0.5MeV$







Ω_b^- Mass Mystery Resolved?



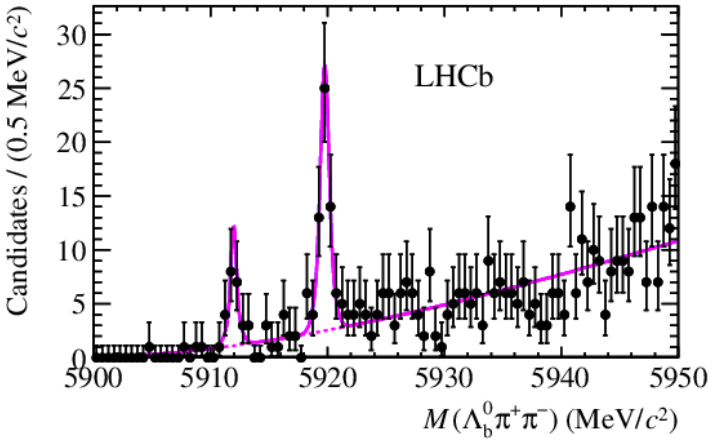
Seems to resolve the mass dispute:
Agrees with CDF not D-Zero

New high mass b baryon states

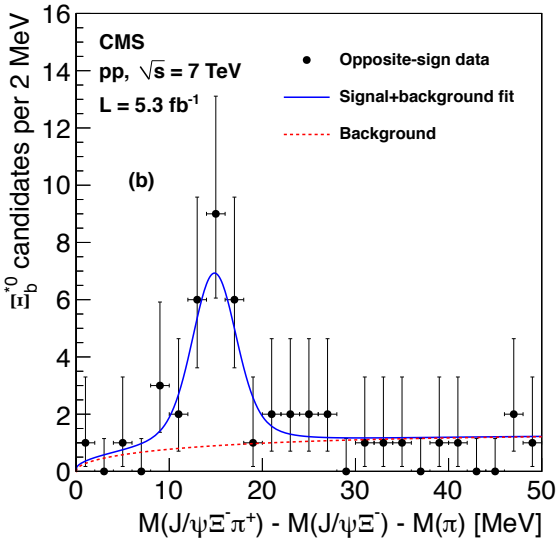
- Excited Λ_b^0 states from LHCb
  - Extracted from 1fb^{-1} 2011 7TeV data
  - Signals in $\Lambda_b\pi^+\pi^-$ spectrum
  - Believed to be two orbital excitations
  - Predictions are spread around the observed masses of

5911.97±0.12±0.02±0.66(M(Λ_b))

5919.77±0.08±0.02±0.66(M(Λ_b))

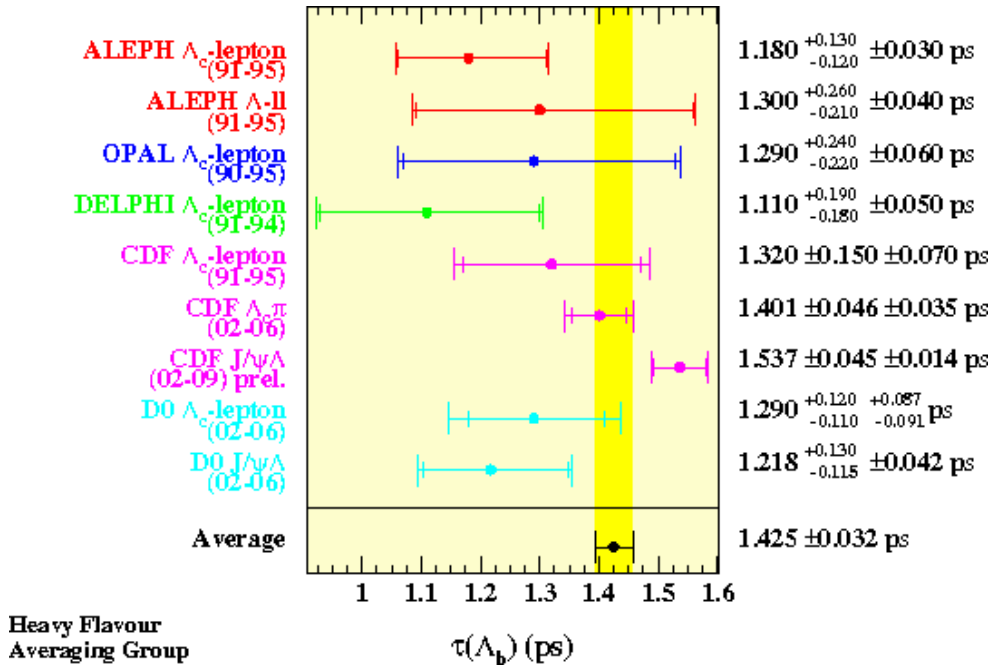


- Excited Ξ_b^0 state from CMS
  - Seen in $\Xi_b^-\pi^+$ mode
  - Usual mass difference technique
  - More than 5σ
  - Probable 3/2$^+$ partner of the Ξ_b ?



Λ_b lifetime

- Only currently accessible at hadron machines
- Tension between
  - Tevatron measurements
  - HQE expectation
- Lots of LHC activity!
- N.B. For $\tau(B_s)$ see Greg Cowan's talk



Situation in 2010

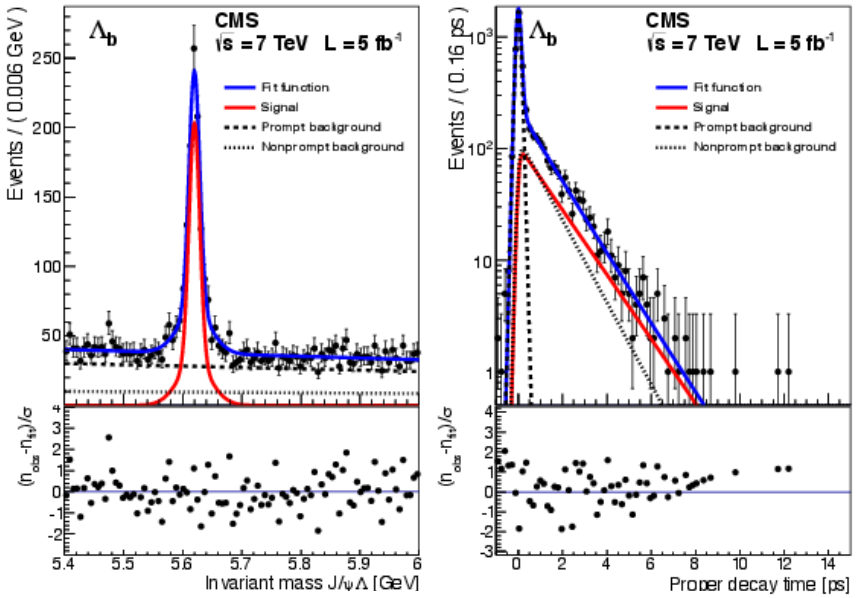
$$\frac{\tau_{B^+}}{\tau_{B^0}} = 1.06 \pm 0.03; \quad \frac{\tau_{B_s}}{\tau_{B^0}} = 1.00 \pm 0.01; \quad \frac{\tau_{\Lambda_b}}{\tau_{B^0}} = 0.88 \pm 0.05$$

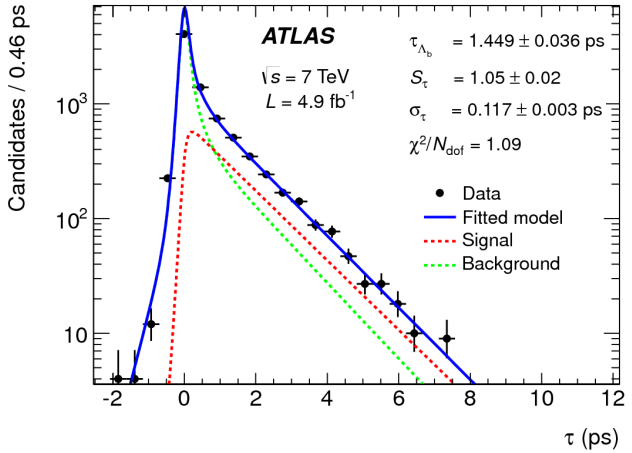
Λ_b lifetime: ATLAS, CMS

- Each ~5fb^{-1} 2011 7TeV data
- Use $\Lambda_b \rightarrow J/\Psi\Lambda$
- Unbinned mass/pseudo proper time fit
- Control: $B_d \rightarrow J/\Psi K_s$
- Different largest systematics, but both MC in origin

CMS:
$\tau(\Lambda_b)=1.503\pm0.052\pm0.031$ps

ATLAS:
$\tau(\Lambda_b)=1.449\pm0.036\pm0.017$ps

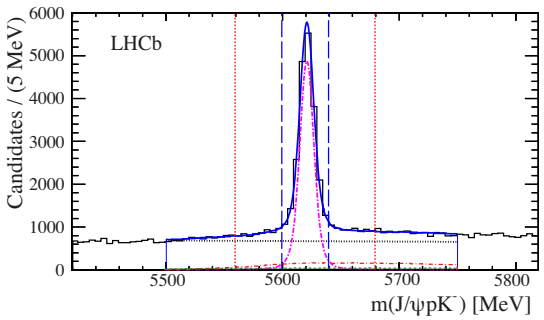


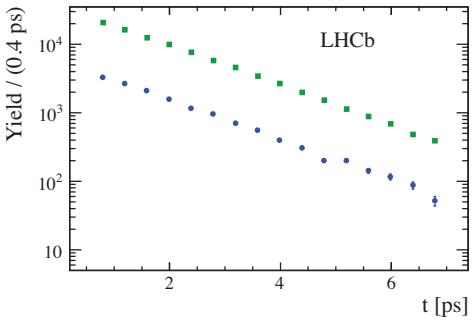


ATLAS: PRD 87 (2013) 032002
CMS: JHEP 07 (2013) 163

Λ_b lifetime: LHCb

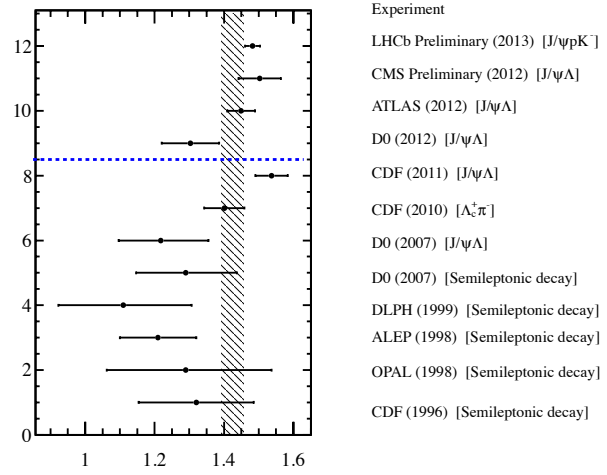
- Uses new mode:
- $\Lambda_b \rightarrow J/\Psi pK$
- Avoids Λ reconstruction inefficiency
- Normalize to $B \rightarrow J/\Psi K^*$ (topologically similar)
- Extract Λ_b and B fractions in lifetime bins





- Lifetime ratio well determined
  - $\tau(\Lambda_b)$ requires B lifetime to be known
- Sensitive to acceptance slope slope

$\tau(\Lambda_b) = 1.482 \pm 0.018 \pm 0.012$ ps



Onward to B_c lifetime measurements?

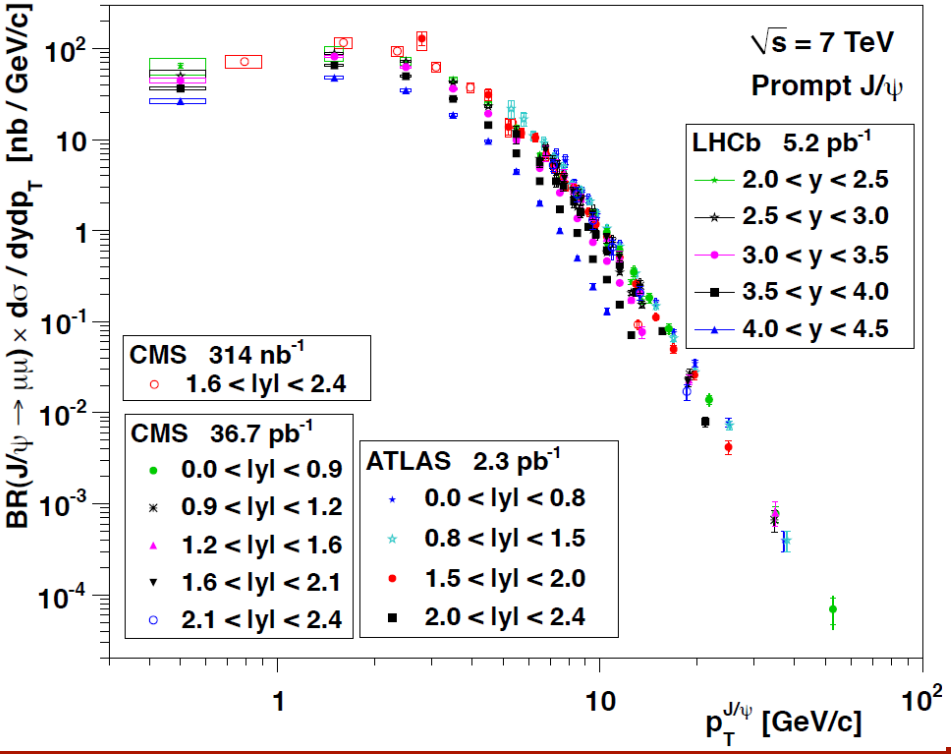
LHCb: arXiv:1307.2476

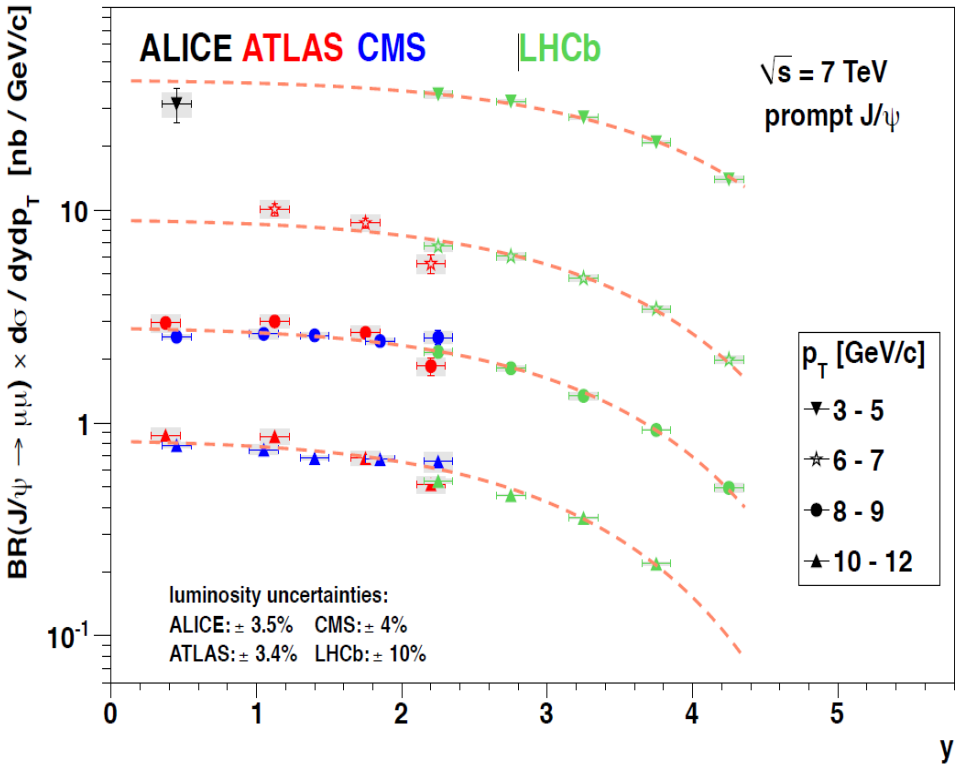
Onia studies: Prompt J/ψ

LHC experiments cover a huge kinematic range $|y| < 4.5$, $0<p_T<70$ GeV

Over 6 orders of magnitude in p_T

Measurements mostly consistent when overlap, some differences in rapidity shapes





Compiled by Hermine K. Woehri

ALICE: arXiv:1205.5880
ATLAS: NPB850 (2011) 387
CMS: JHEP02 (2012) 011
LHCb: EPJC71 (2011) 1645

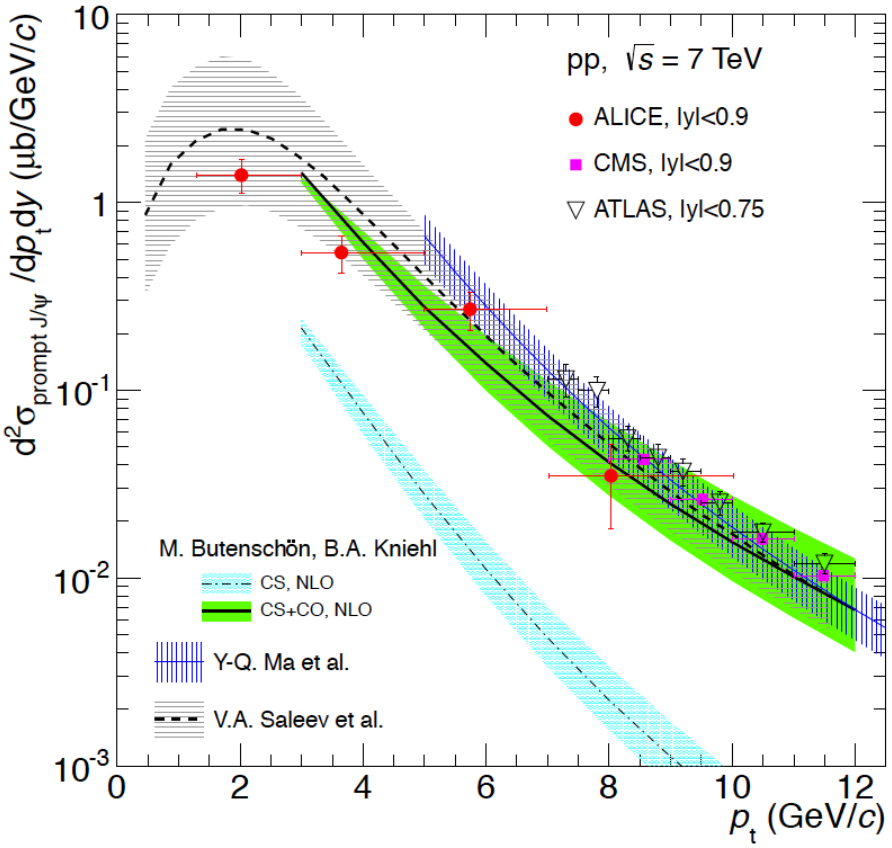
Prompt J/ψ vs theory

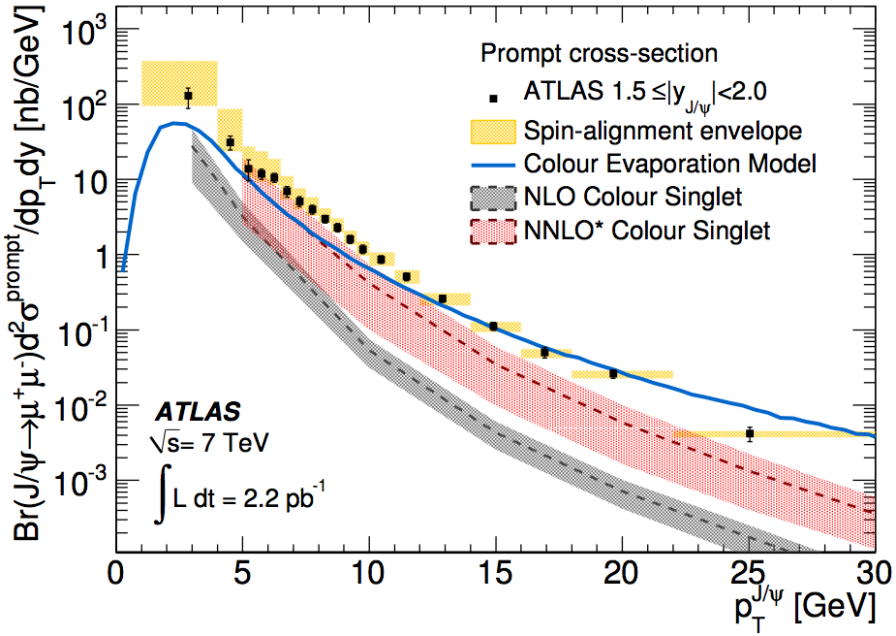
Multitude of models (CSM, CEM, COM) in various incarnations all do a reasonable job, but none is perfect

Some have virtually no parameters (CSM, CEM)

Others (NRQCD-based) have have quite a few

p_T spectra alone not enough to distinguish between models

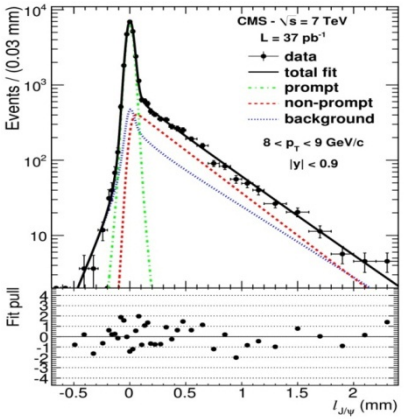




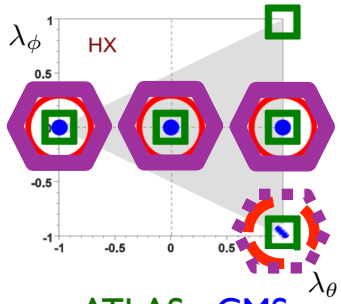
Alice: arXiv:1205.5880
ATLAS: NPB850 (2011) 387
CMS: JHEP (2012) 011
Also LHCb: EPJC71 (2011) 1645

Fraction of J/ψ from B decays

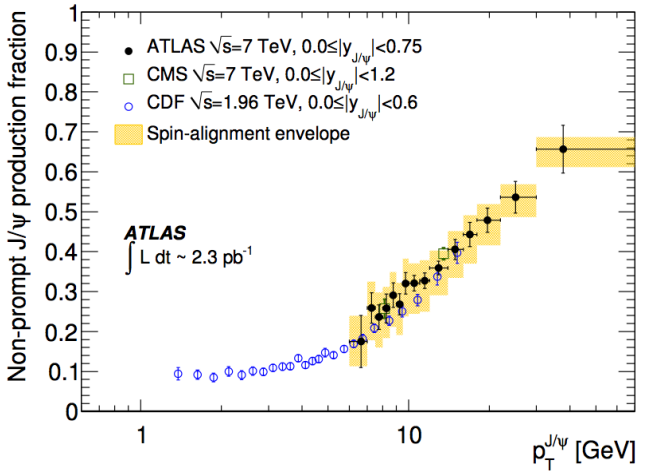
Use (pseudo) proper time to separate prompt and non-prompt charmonium

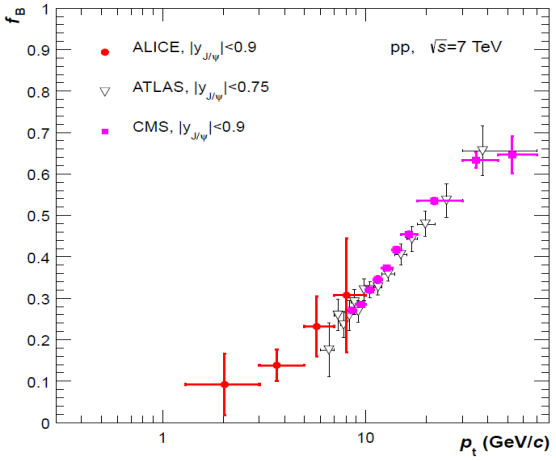


J/ψ: now measured by CDF and all four LHC experiments
Below 10% at low p_T, central rapidity, increasing with p_T to ~70%
This increase slows down at forward rapidities
Weak energy dependence (if any at all)

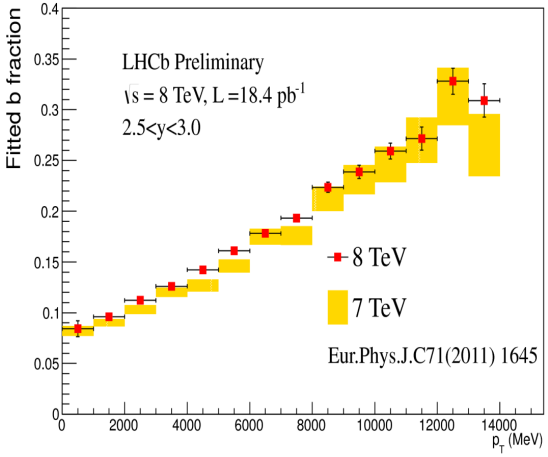


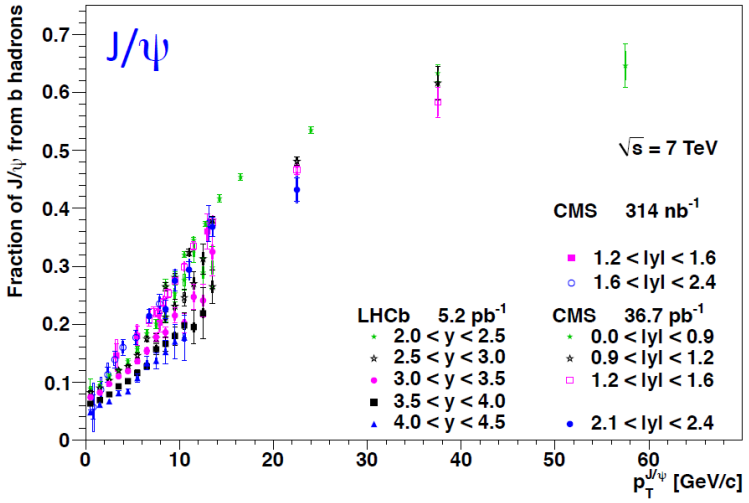
ATLAS CMS
LHCb ALICE





At high p_T, non-prompt approaches plateau of ~60%





ALICE: arXiv:1205.5880
CMS: EPJ C71 (2011) 1575
ATLAS: NPB 850 (2012) 387
CMS: JHEP 02 (2012) 011
CDF: PRD 71 (2005) 032001
CDF: PRD 80 (2009) 031103
LHCb: EPJ C71 (2011) 1645
LHCb: arXiv:1204.1258

ψ(2S): unique case

ATLAS: ATLAS-CONF-2013-097
CMS Collaboration, JHEP 1202 (2012) 011, arXiv:1111.1557
LHCb Collaboration, Eur.Phys.J. C72 (2012) 2100, arXiv:1204.1258

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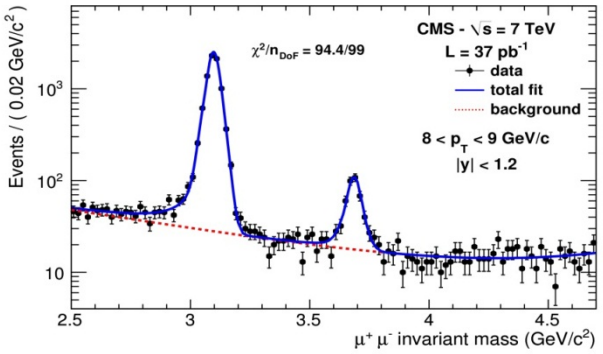
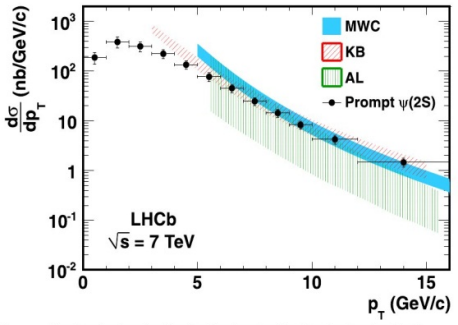
Dimuons from ψ(2S):
~30 times fewer than J/ψ

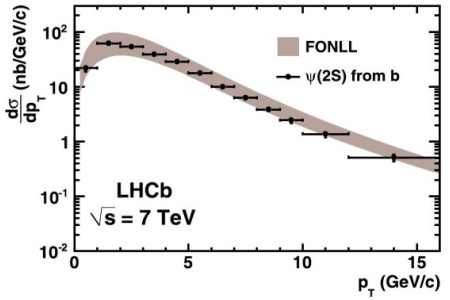
Some ψ(2S) are **non-prompt**, but there is **no** feeddown from heavier states

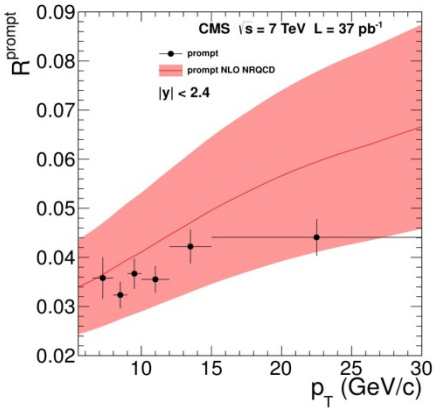
ψ(2S) to J/ψ ratio R (corrected for BR(μμ)) is measured separately for prompt and non-prompt -- a good testbed for production models

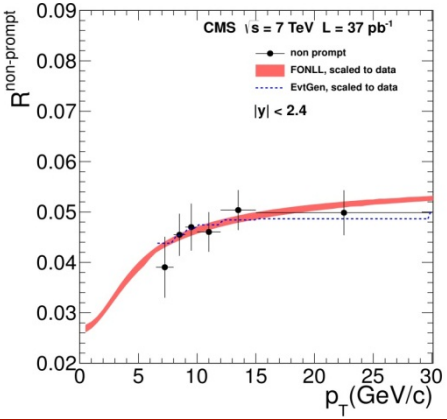
Fraction still rises to ~60%
Less so at high rapidity

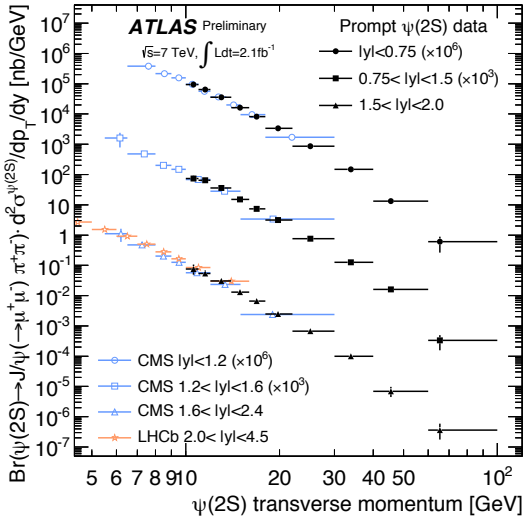


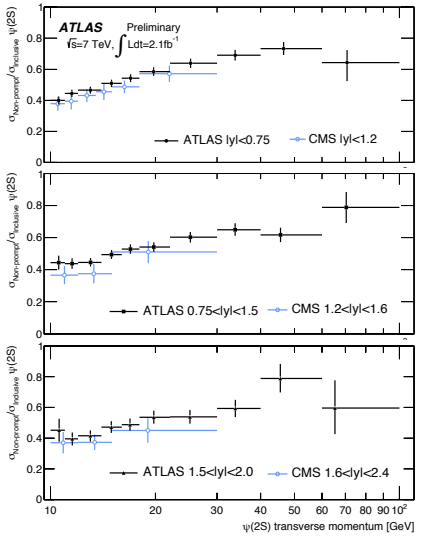






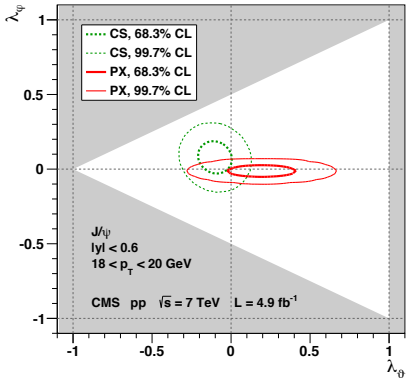


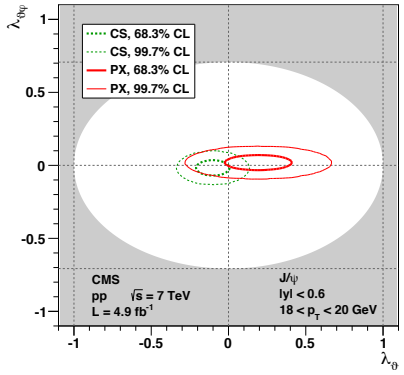


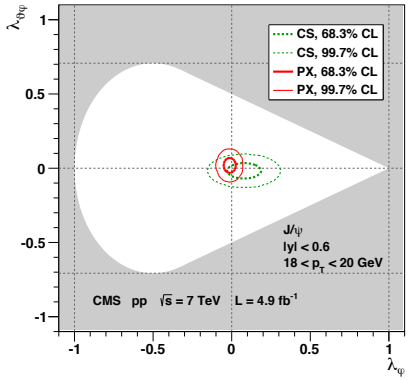


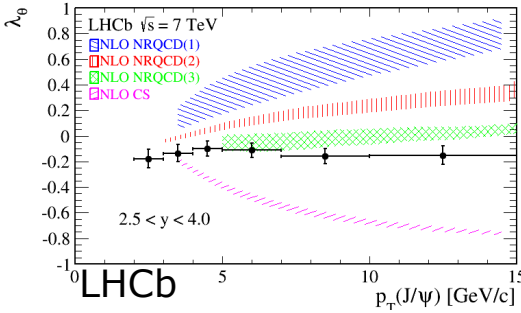
J/Ψ polarization: ALICE, LHCb, CMS at 7TeV

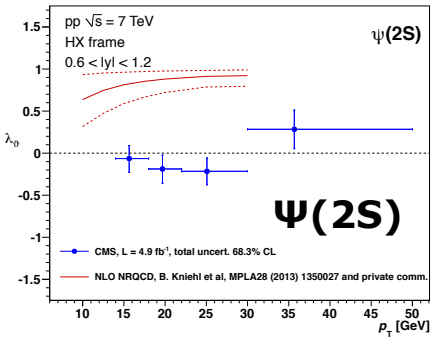
- LHCb results using early 2011 data
- ALICE 100nb^{-1} of 2010 data
- Now nice study from CMS of J/Ψ and Ψ(2S) polarization (2011 data)
- General conclusion: little evidence for polarization in prompt J/Ψ , some issues for NLO NRQCD models
- Non-result for Ψ(2S) interesting – no feed-down







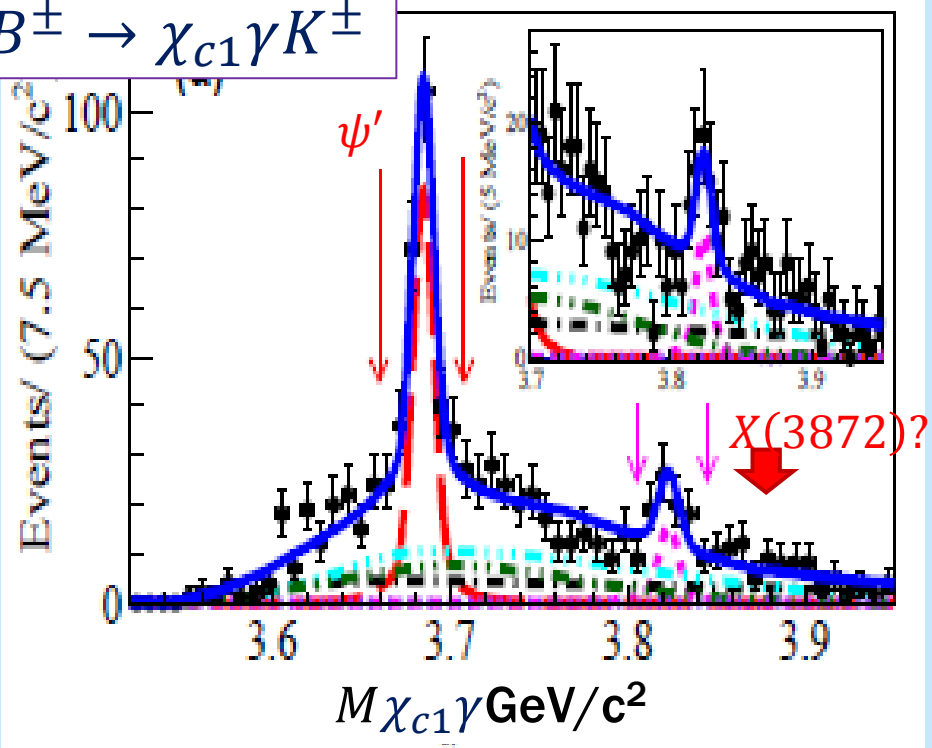




CMS Collaboration: CMS-BPH-13-003
LHCb Collaboration: LHCb-PAPER-2013-008
ALICE Collaboration: PRL 108 (2012) 082001

Belle: Missing $\Psi_2(1D)$ state?

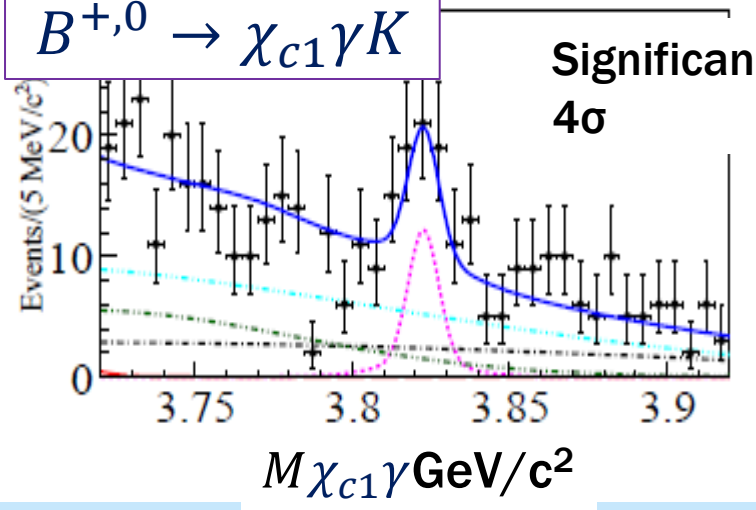
$B^{\pm} \to \chi_{c1}\gamma K^{\pm}$



arXiv:1304.3975
To appear in PRL

Simultaneous fit to $B^{\pm} \to \chi_{c1}\gamma K^{\pm}$ and $B^0 \to \chi_{c1}\gamma K_S$ modes

$B^{+,0} \to \chi_{c1}\gamma K$



Significance 4σ

Again no evidence for C-odd partner of $X(3872)$.

But we found narrow peak at 3823 MeV.

Mass is $3823.1 \pm 1.8 \pm 0.7$ MeV

Production of Υ(1S), Υ(2S), Υ(3S)

ATLAS: PRD 87 (2013) 052004CMS: EPJ C72 (2012) 2251; also LHCb: EPJC 72 (2012) 2025

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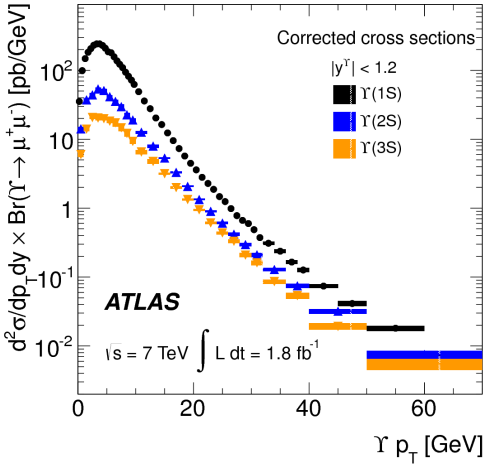
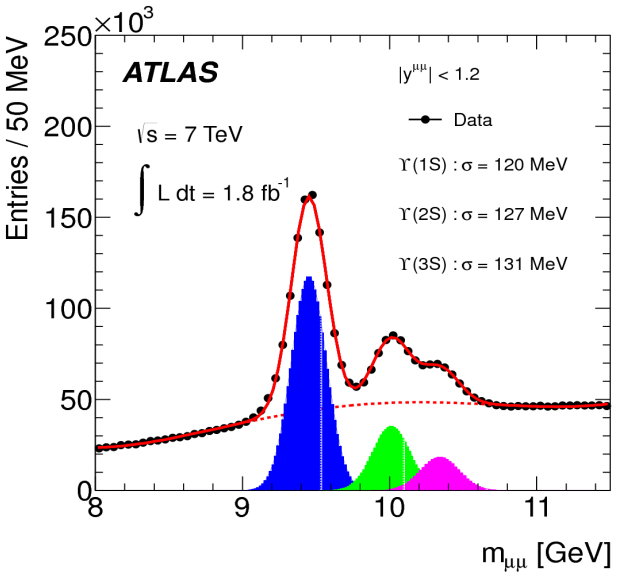


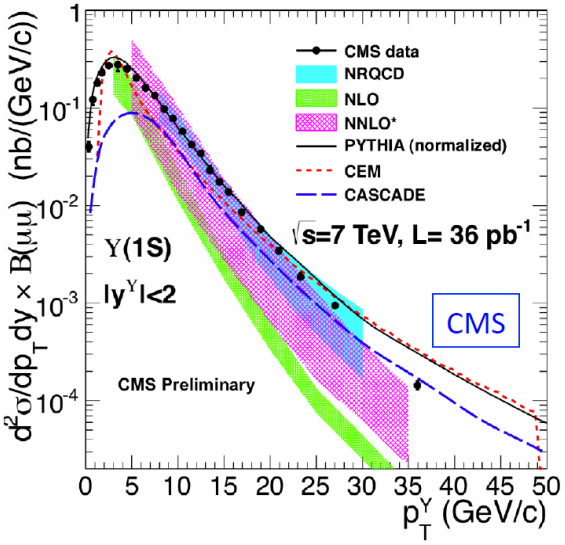
Wide p_T range, fine binning

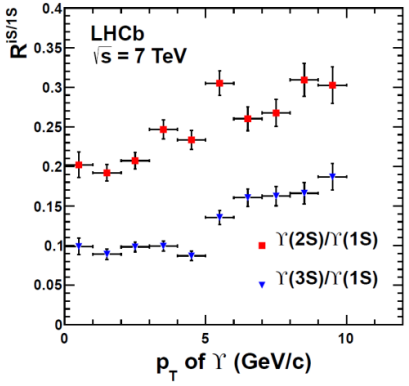
Good agreement between ATLAS, CMS and LHCb, wide coverage
p_T: 0 to 70 GeV, |y| : < 4.5

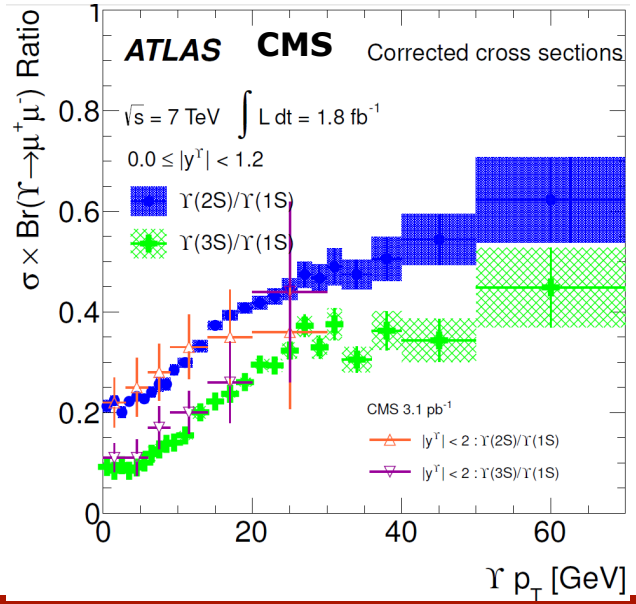
CSM, COM, CEM, etc - doing a reasonable job but none perfect

p_T dependence of ratios Y(2S)/Y(1S), Y(3S)/Y(1S) confirms existence of multiple mechanisms, hints on their p_T evolution
Tough times for theorists!









Υ production: fraction of feeddown

Feeddown pattern in Υ very complicated.

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

LHCb: $(20.7 \pm 5.7(\text{stat}) \pm 2.1(\text{syst}) \, ^{+2.7}_{-5.4}(\text{pol}))\%$
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

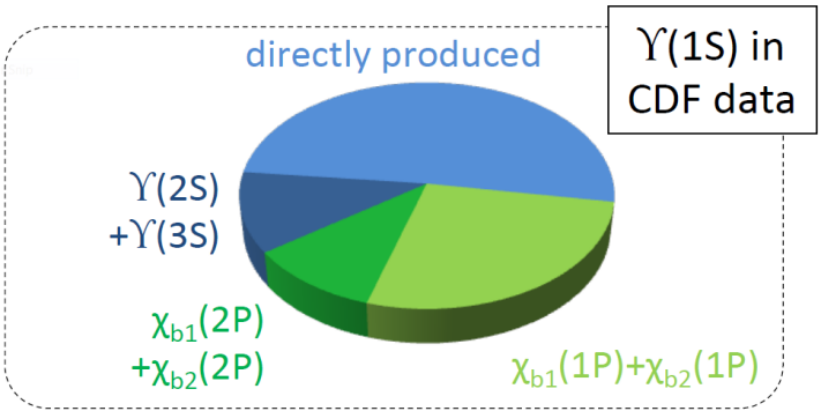
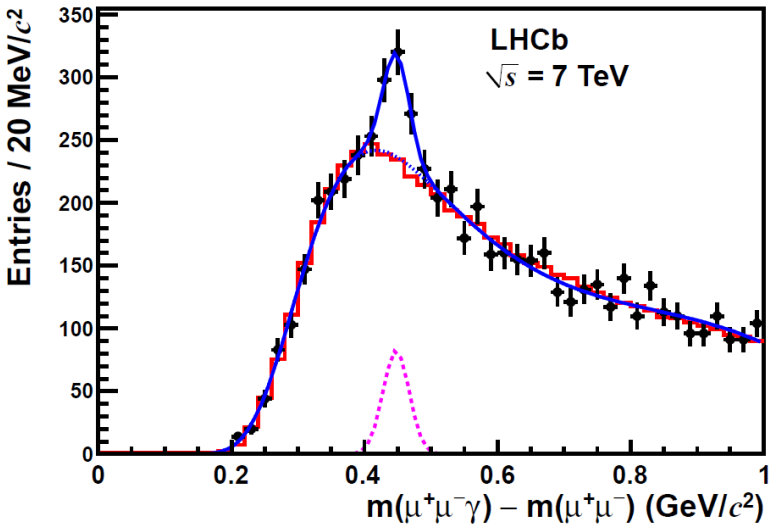
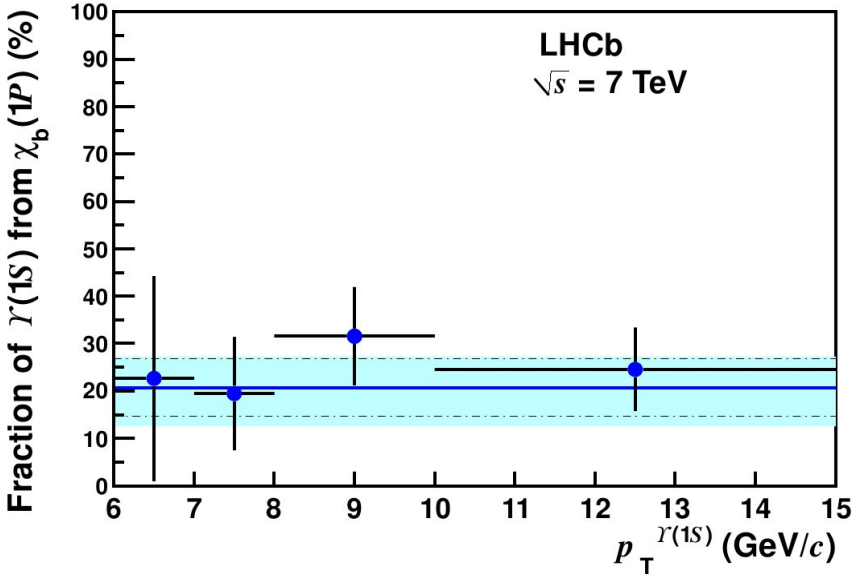


Diagram from P. Faccioli





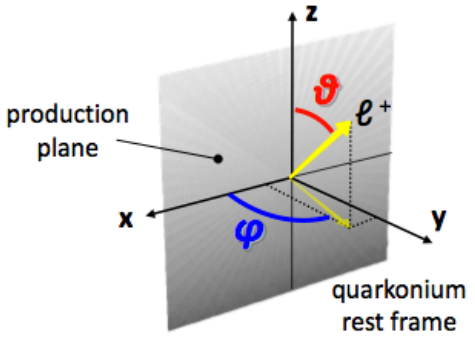
LHCb: arXiv:1209.0282
CDF: PRL 84 (2000) 2094

CMS: Υ polarisation

General angular dependence of decay muons in Υ rest frame:

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

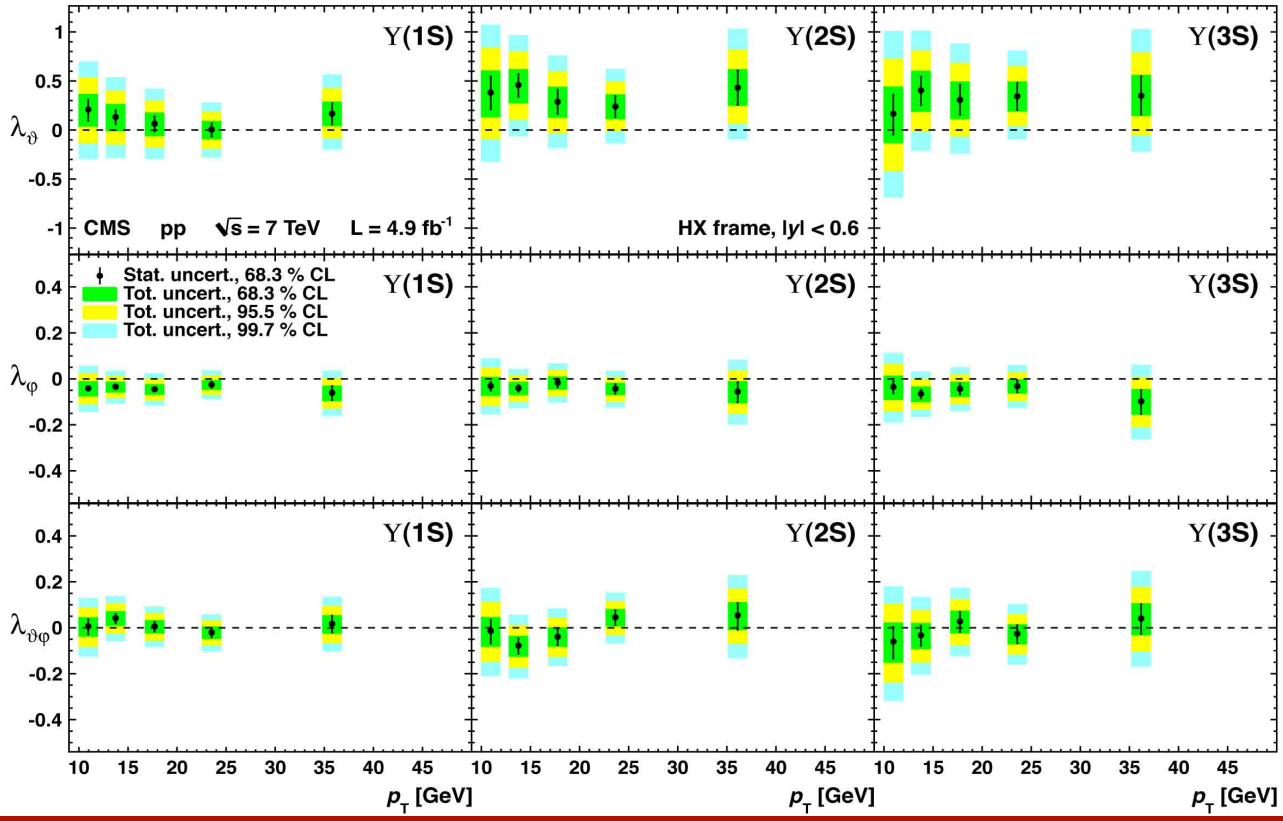
Helicity frame: z axis along the Υ momentum in the lab frame



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

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: arXiv:1209.2922

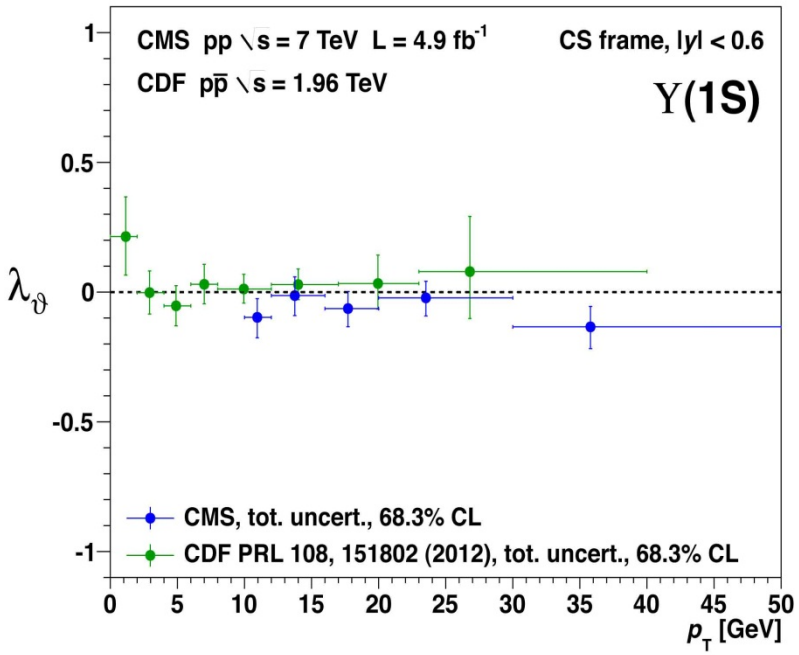
Υ polarisation vs energy, and theory comparison

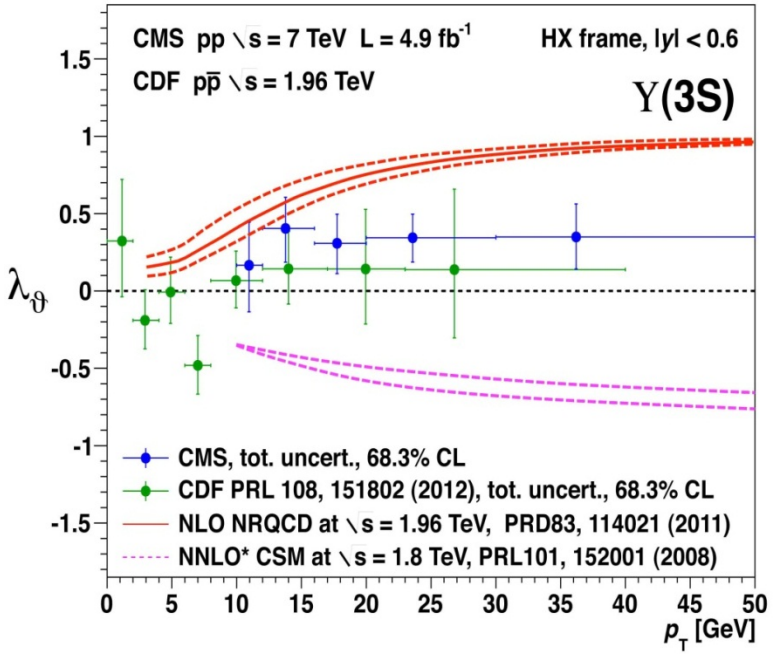
CMS results in good agreement with recent results from CDF

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

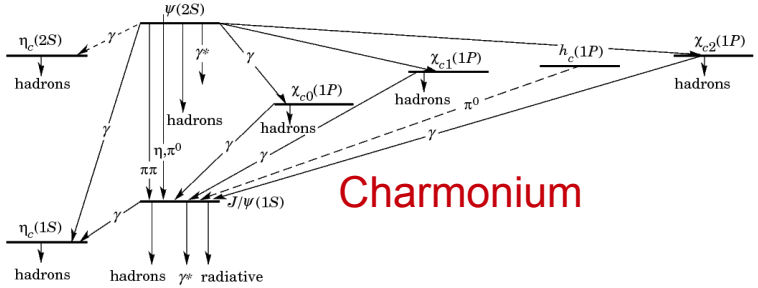
Model curves below made under assumption that Υ(3S) is direct, however after the observation of χ_b(3P) we know that's not true!

Measured polarisation levels are not as large as those predicted by the theoretical models shown



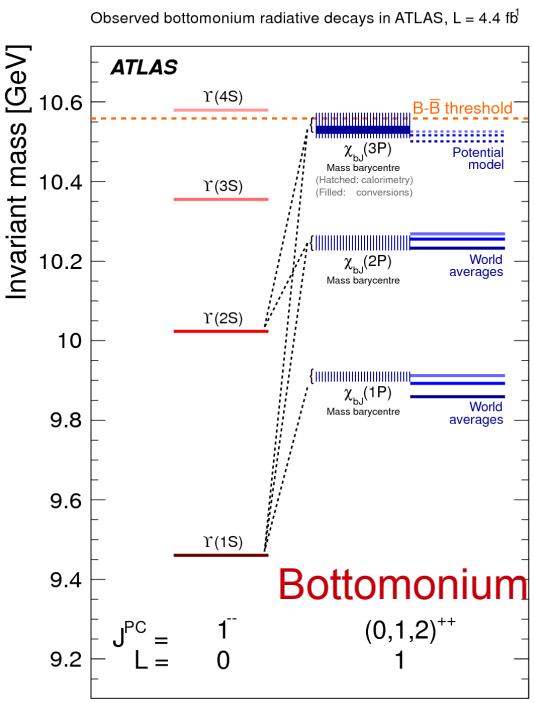


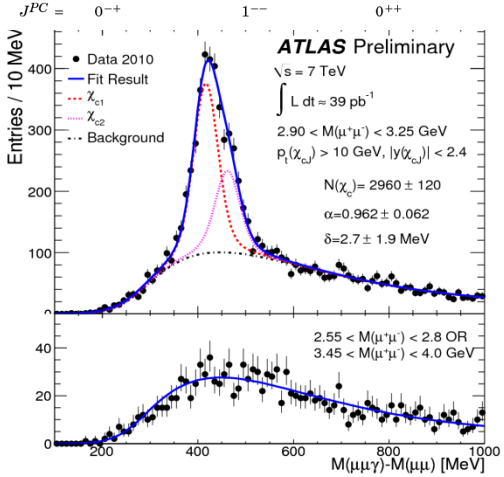
Quarkonium spectroscopy and χ feeddown



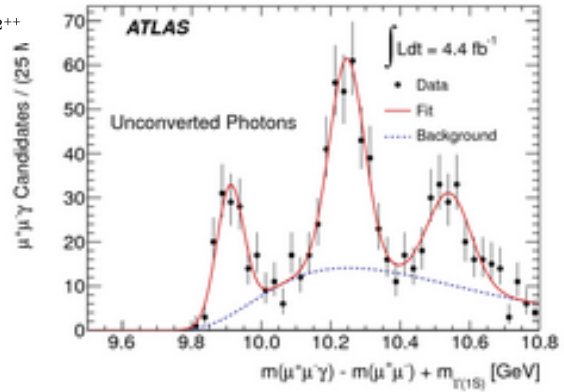
Charmonium

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

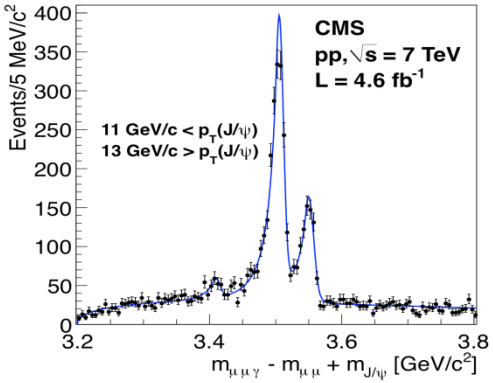




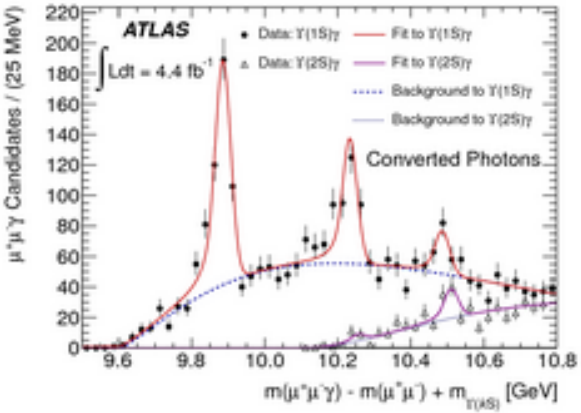
Unconverted photons

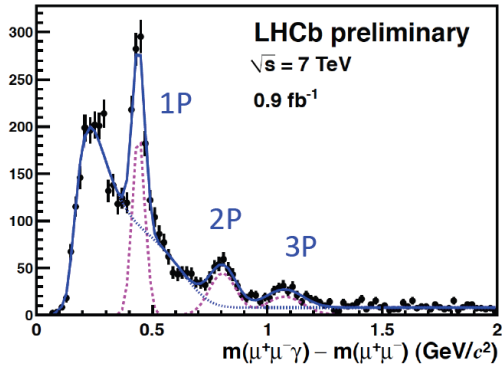


ATLAS: PRL 108 (2012) 152001
CMS: EPJ C 72 (2012) 2251
LHCb: CONF-2012-020

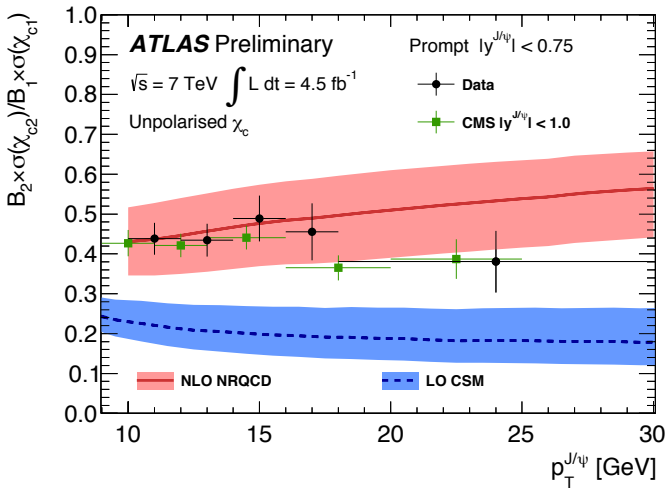


Converted photons





Ratio of prompt χ_c production

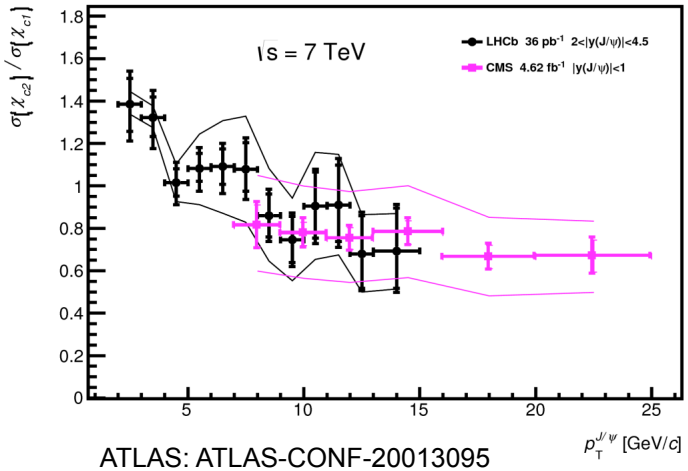


Relative production of prompt χ_{c2} to χ_{c1} in their $J/\psi + \gamma$ decays
Various theoretical models predict different polarisation of χ_c
Acceptance corrections depend on assumed polarisation

Smooth transition from low p_T, high y region studied by ATLAS, LHCb to higher p_T, low y range studied in CMS

Thin lines show the range with extreme polarisation assumptions

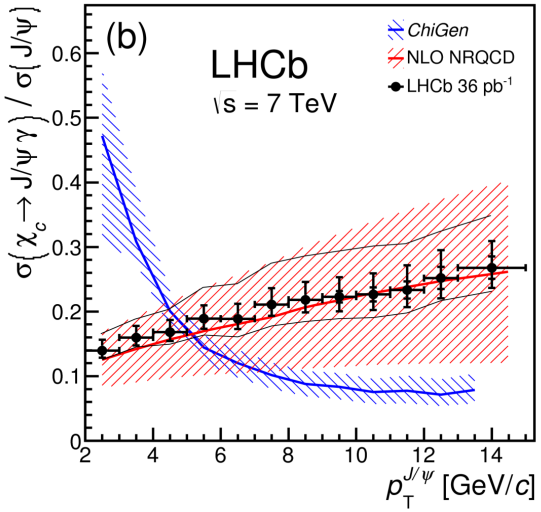
p_T dependence trend follows qualitative expectations from naive perturbative QCD



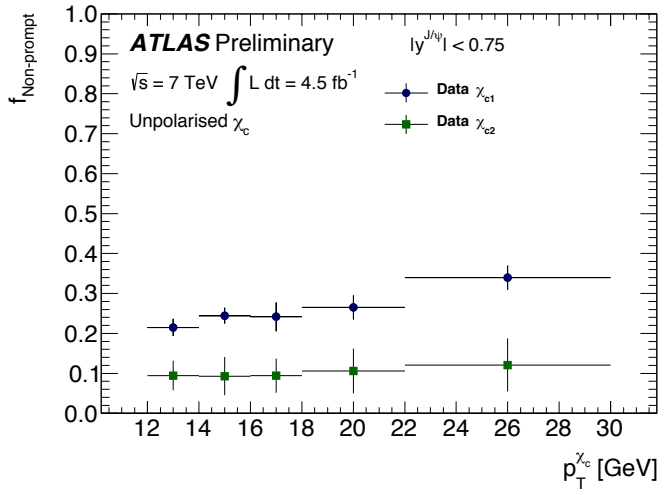
ATLAS: ATLAS-CONF-20013095
CMS: arXiv:1209.2922
LHCb: arXiv: 1204.1452
LHCb: PLB 714 (2012) 215

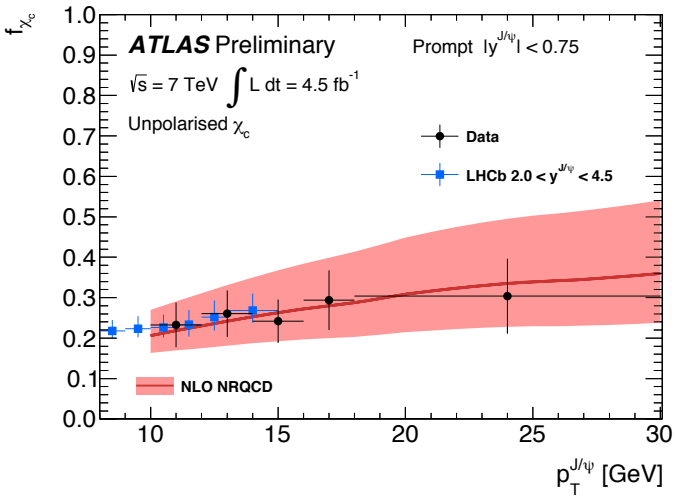
LHCb & ATLAS have measured the fraction of J/ψ produced from χ_c radiative decays

COM describes data well, but perturbative CSM-style calculations are in contrast with both



χ_c fractions





- The non-prompt fraction measurement, shows that the production of $\chi_{c1,2}$ is mostly prompt
  - This is opposite to what is seen in J/ψ and ψ(2S)
- Fraction of prompt J/ψ produced in χ_c decays is the sum of χ_{c1} & χ_{c2} (Without χ_{c0} it is still a good approximation)
  - This provides an estimate of the contribution to prompt J/ψ

ATLAS Collaboration, ATLAS-CONF-2013-95
LHCb Collaboration, Phys.Lett. B718 (2012) 431–440

A very active time for LHC HF Studies

- Much more data awaiting analysis
  - More than ‘just another year’
  - Experiments increased trigger rates in 2012 to analyze during shut-down
- Much more data to come
  - Higher energy, interesting for production
  - Detectors will have significant upgrades
    - E.g. ATLAS insertable B-layer
    - Much improved lifetime resolution
- Interesting programme continues well into the luminosity upgrades
- Keep watching for results, and guide us to the interesting things to study