Spectroscopy of excited states at ATLAS

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Beauty 2013

Thursday 11th April

ATLAS

THE UNIVERSITY OF SYDNEY

Outline

- The ATLAS detector and B-Physics performance

- $J/\psi \rightarrow \mu^+\mu^-$ sample and cross-section
  - $\Lambda_b^0 \rightarrow J/\psi(\mu^+\mu^-)\Lambda(p\pi)$ mass and lifetime
  - $B_c \rightarrow J/\psi(\mu^+\mu^-)\,\pi$ observation

- $\Upsilon(nS) \rightarrow \mu^+\mu^-$ sample and cross-section
  - $\chi_b(nP) \rightarrow \gamma\Upsilon(1,2S)$, including $\chi_b(3P)$ discovery

The ATLAS Detector

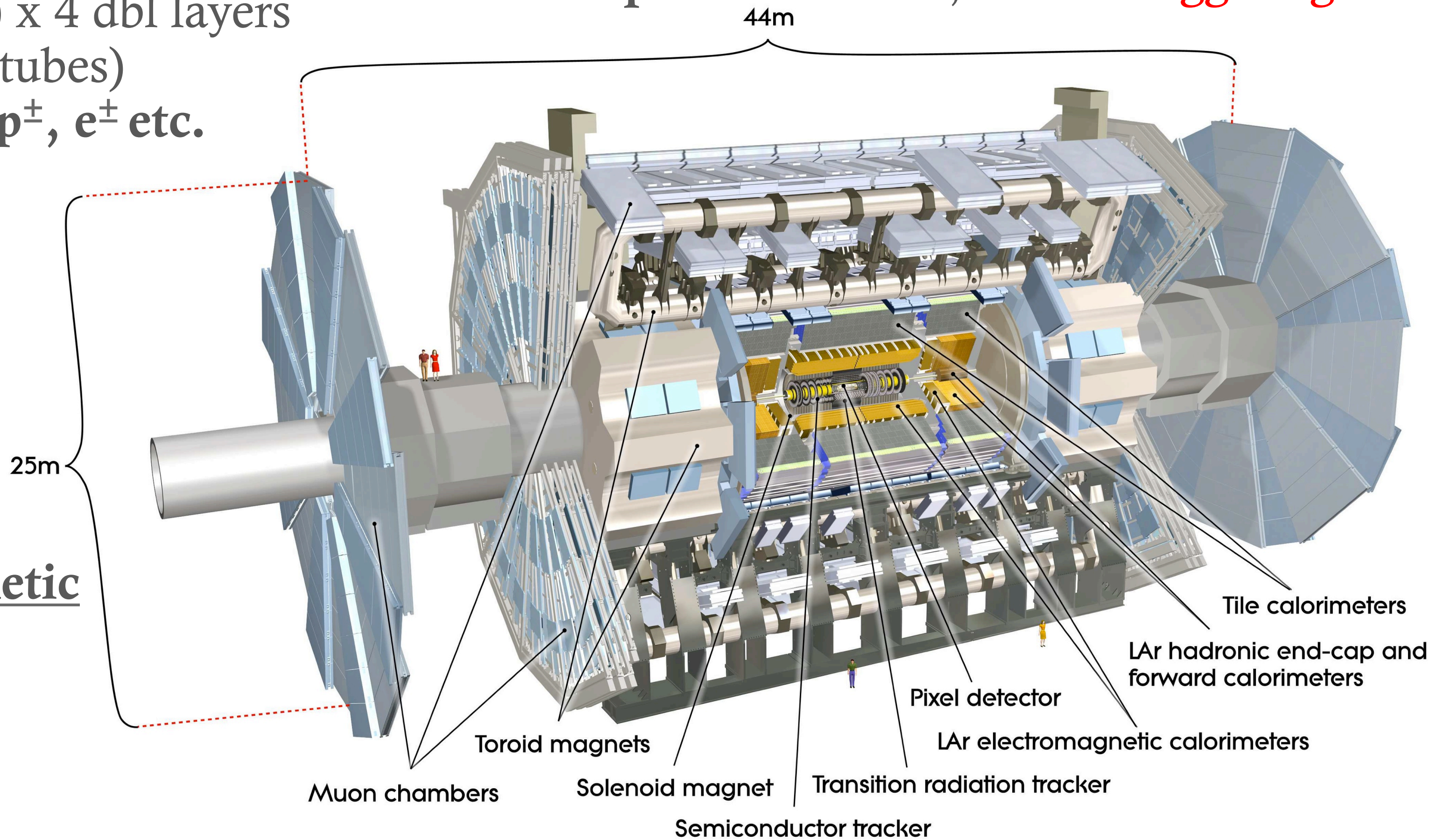
Inner Detector

- Pixels x 3 layers
- SCT (strip) x 4 dbl layers
- TRT (drift tubes)

$\mu^{\pm}$, $\pi^{\pm}$, $p^{\pm}$, $e^{\pm}$ etc.

Muon Spectrometer

- **p** measurement, id. and triggering

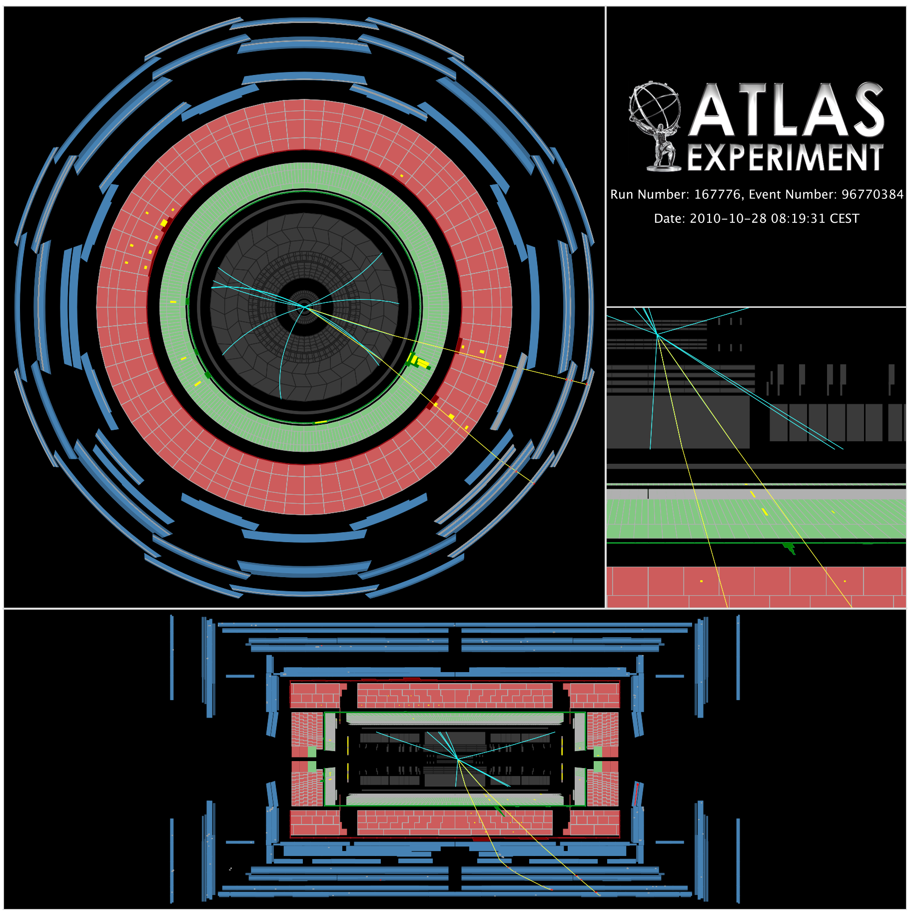


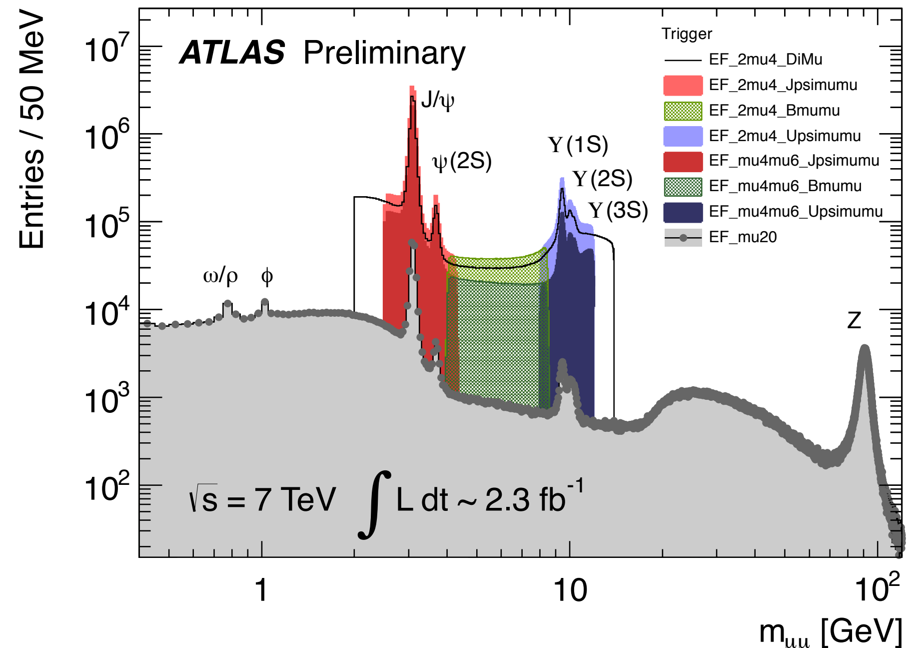
Electromagnetic Calorimeter

γ, $e^{\pm}$

Detector Performance

E.g. $\chi_{c1}(1P) \rightarrow \gamma\, \psi(\mu^{+}\mu^{-})$





- Dedicated B-Physics trigger menu
  - ~millions of $J/\psi \rightarrow \mu^{+}\mu^{-}$
  - ~millions of $\Upsilon(1,2,3S) \rightarrow \mu^{+}\mu^{-}$

(in 2011 alone)

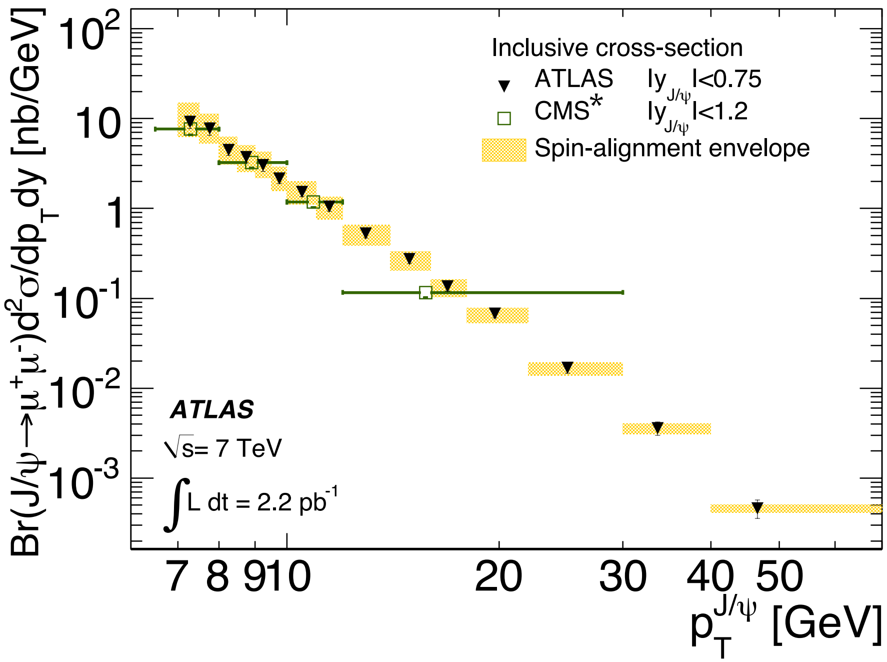
These samples form the basis for spectroscopic studies at ATLAS

J/ψ Cross-section

Nucl. Phys. B 850 (2011) 387-344 arXiv:1104.3038v2

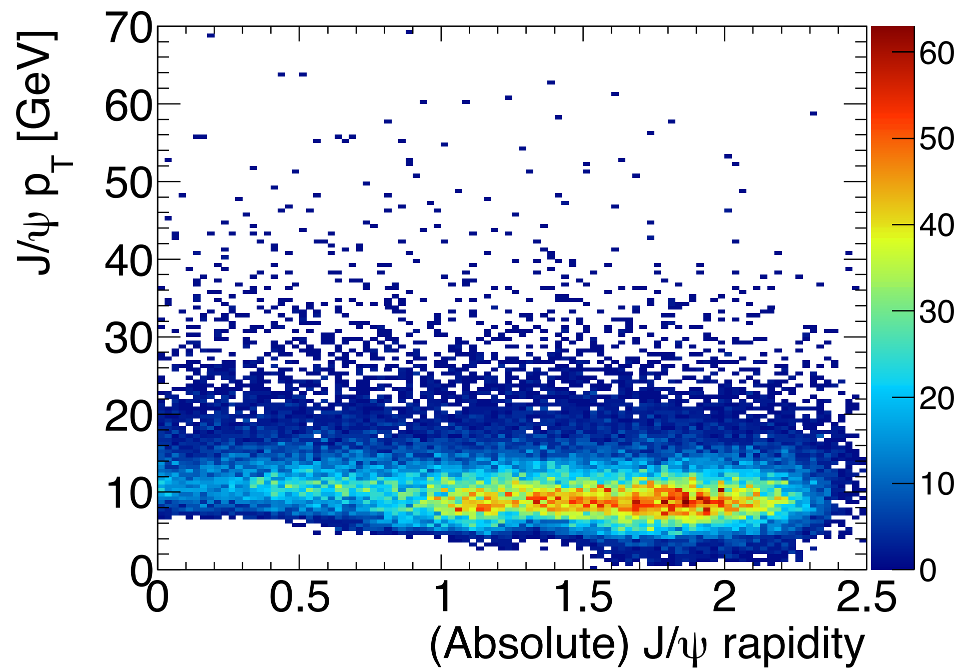
Differential cross-section measurement

- Large number of bins (4|y|x 15p_T)



Wide kinematic range

- p_T < 70 GeV, |y| < 2.5



- Single muon triggers (high acceptance in forward region)
- Subset of 2010 dataset (L=2.2 pb^{-1} – ~1×10^{-3} of 2011 data)
- Prompt/non-prompt production ratio measurement also

*CMS has since published an updated (though still consistent) measurement [1]

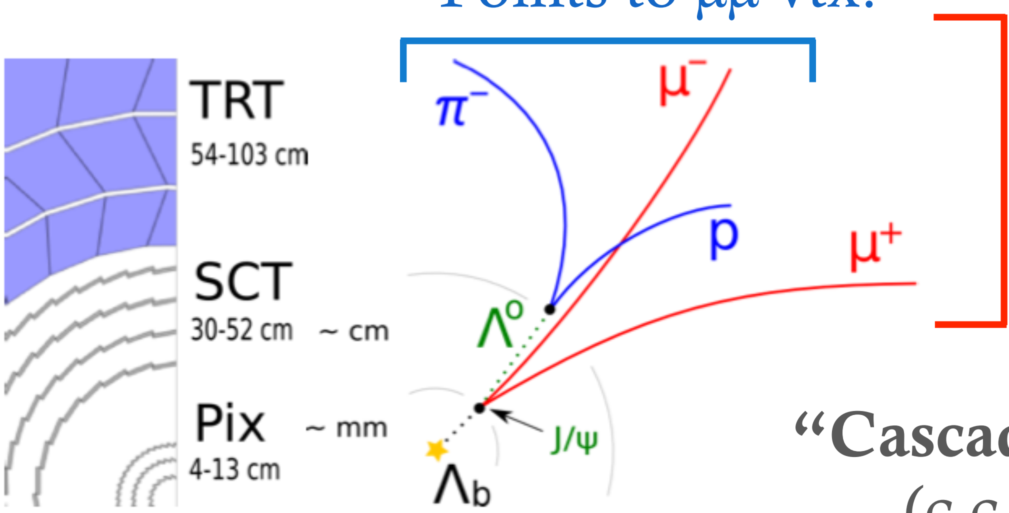
Λ_b^0 mass and lifetime

Phys. Rev. D 87 (2013) 032002 arXiv:1207.2284v2

More details from Carlo Schiavi (Friday 10:20am)

- Hadron colliders are only current place to study b-baryons
  - Λ_b^0 lifetime still has high (2-3%) experimental uncertainty
  - Discrepancy between CDF and DØ measurements (1.8 σ)
- The decay $\Lambda_b^0 \to J/\psi(\mu^+\mu^-)\Lambda^0(p^+\pi^-)$ (+ c.c.) was used here:

- $1.08 < m_{\Lambda 0} < 1.15$ GeV
- Fixed to $m_{\Lambda 0}$
- Points to μμ vtx.



- $2.8 < m_{J/\psi} < 3.4$ GeV
- Fixed to $m_{J/\psi}$
- J/ψ trigger

"Cascade topology vertex fit"

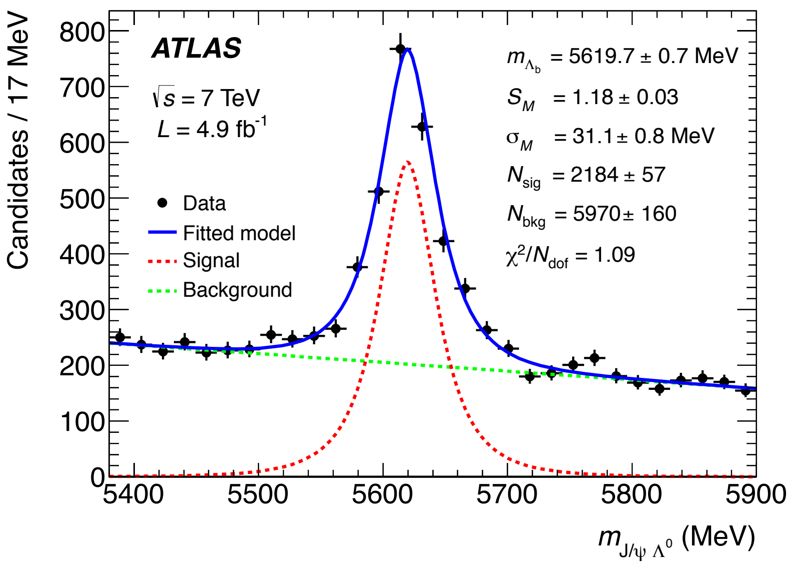
(c.c. fit also attempted)

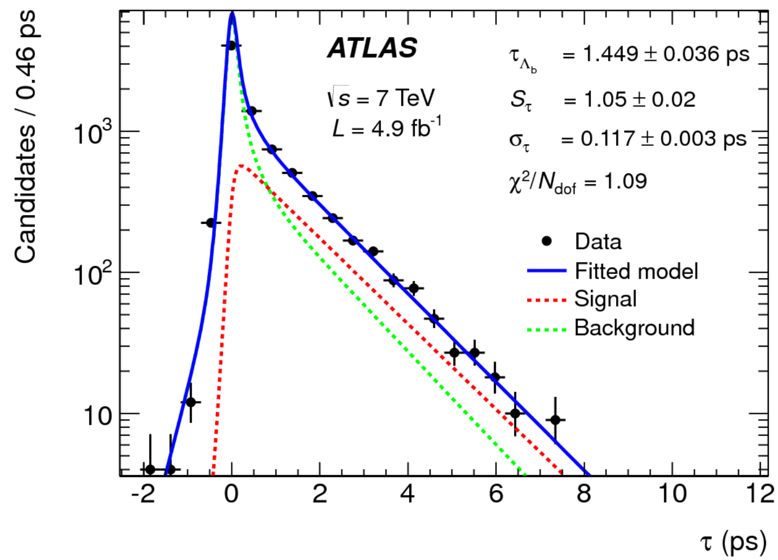
Λ_b^0 mass and lifetime

Phys. Rev. D 87 (2013) 032002 arXiv:1207.2284v2

- Vertex fit → m, δ_m, $\tau = (L_{xy} m_{PDG})/p_T$, δ_τ
- Un-binned, m.l. fit simultaneously to m, τ :

$$L = \prod_{i=1}^{N} \left[f_{\mathrm{sig}} \mathcal{M}_{\mathrm{s}}(m_i|\delta_{m_i}) \mathcal{T}_{\mathrm{s}}(\tau_i|\delta_{\tau_i}) w_{\mathrm{s}}(\delta_{m_i}, \delta_{\tau_i}) + (1 - f_{\mathrm{sig}}) \mathcal{M}_{\mathrm{b}}(m_i|\delta_{m_i}) \mathcal{T}_{\mathrm{b}}(\tau_i|\delta_{\tau_i}) w_{\mathrm{b}}(\delta_{m_i}, \delta_{\tau_i}) \right]$$

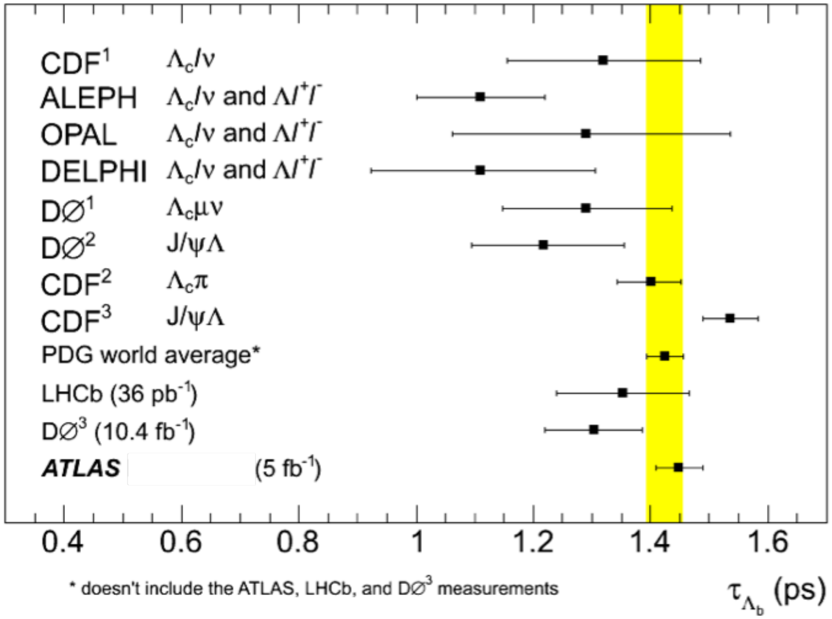




Λ_b^0 mass and lifetime

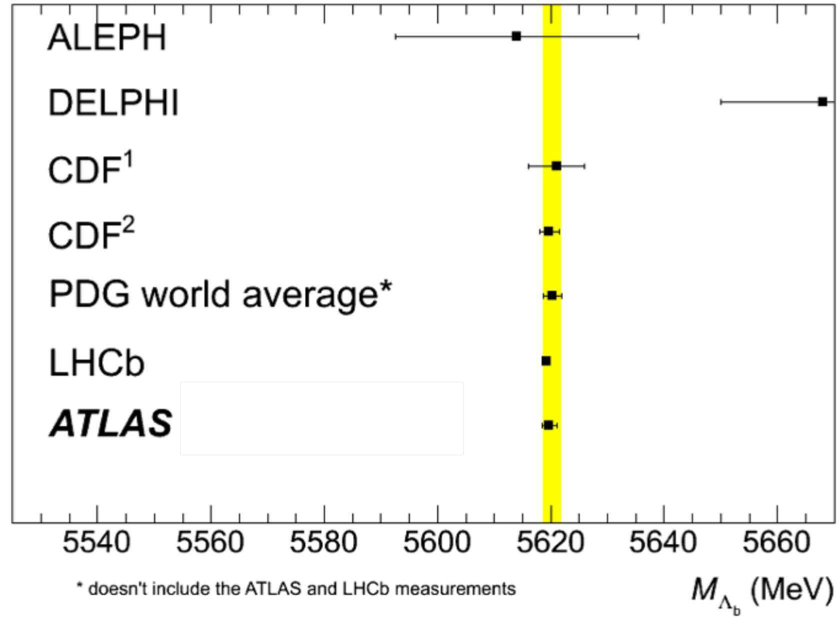
Phys. Rev. D 87 (2013) 032002 arXiv:1207.2284v2

τ = 1.449 ± 0.036(stat) ± 0.017(syst) ps



n.b. CMS recently reported a measurement τ = 1.503±0.052(stat.)±0.031(syst.) ps [2]

m = 5619.7 ± 0.7 (stat) ± 1.1 (syst) MeV



- Analysis was cross-checked with $B_d \rightarrow J/\psi(\mu^+\mu^-)K_S^0(\pi^+\pi^-)$
- Lifetime ratio to Λ_b^0 gives insight into b-qq vs. b-qbar dynamics
- Measure:

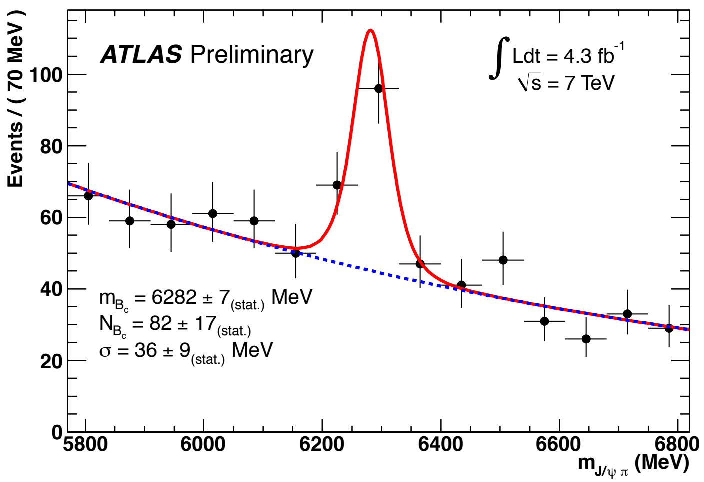
$$\mathbf{R = \tau_{\Lambda b0} / \tau_{Bd} = 0.960 \pm 0.025(stat) \pm 0.016(syst)}$$

c.f. 0.864 ± 0.052 (DØ [3]), 1.020 ± 0.030 (CDF [4]), 0.88-0.97 (HQET [5])

Prelim. $B_c^{\pm}$ observation

ATLAS-CONF-2012-028

- B_c = lowest bound state of c,b quarks
  - → probe of heavy quark dynamics inaccessible to bbar, ccbar states.
- Predicted by all usual (NR potential, pQCD, lattice etc.) models
  - First observed by CDF: m = 6275.6 ± 2.9 (stat.) ± 2.5 (syst.) MeV (latest [6])
  - Then DØ: m = 6300 ± 14 (stat.) ± 5 (syst.) MeV (latest [7])
  - And LHCb: m = 6276.28 ± 1.44 (stat) ± 0.36 (syst.) [8]
- ATLAS adds to this* using $B_c^{\pm} \to J/\psi\,(\mu^+\mu^-)\,\pi^{\pm}$ with 4.3 fb^{-1} (full 2011 dataset)



$$L = \prod_{i=1}^{N} \left[\mathcal{F}_{signal}(m^i_{J/\psi\pi}) + \mathcal{F}_{bkg}(m^i_{J/\psi\pi}) \right]$$

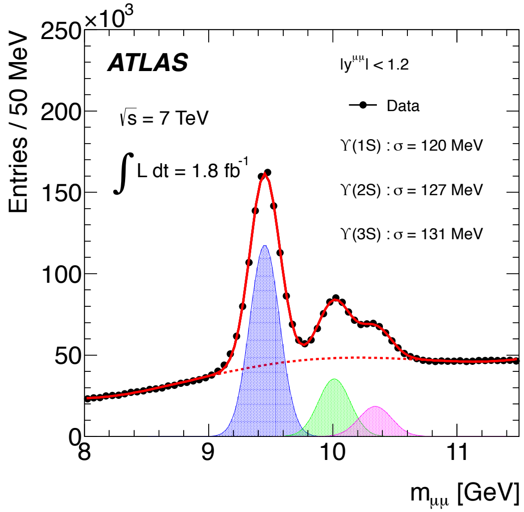
m = 6277 ± 6 (stat.) MeV

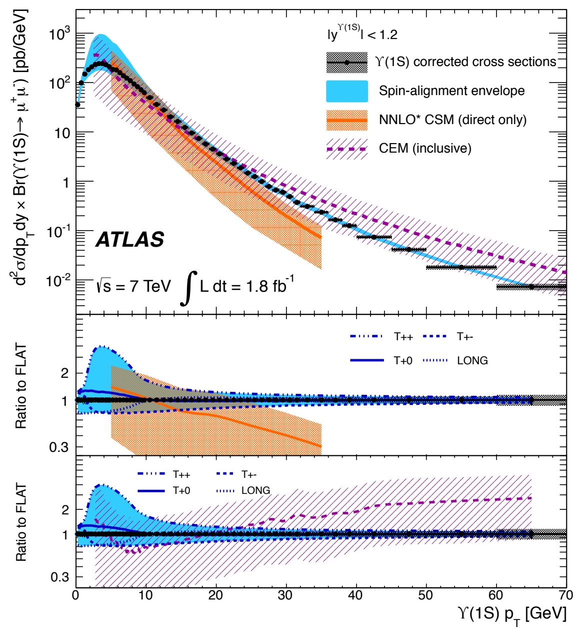
- Errors statistical only
- Can be extended using 2012 dataset

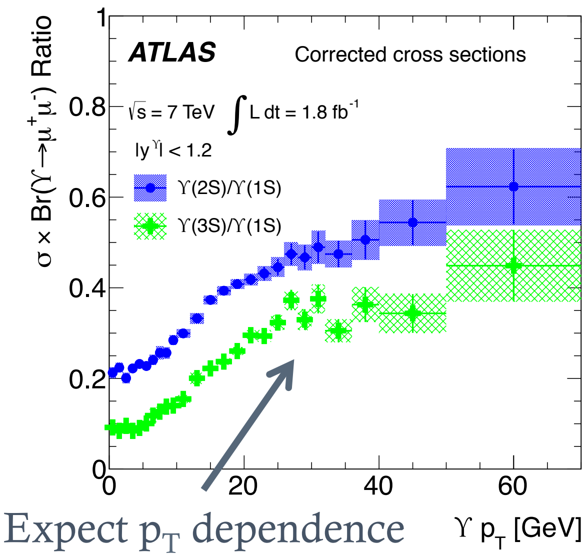
*CMS has a similar observation and prelim. meas. [9]

Υ(nS) production

Phys. Rev. D 87 (2013) 052004 arXiv:1211.7255







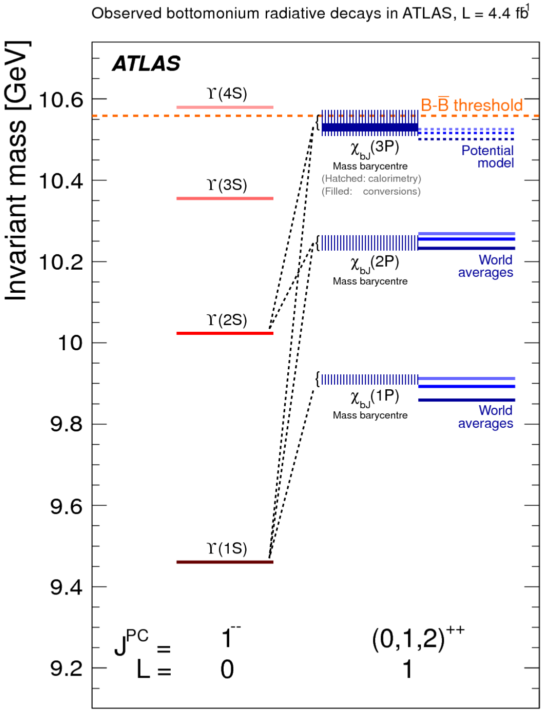
Expect p_T dependence due to χ_b feed-down (see later)

- Uses 1.8 fb^{-1} from 2011 (~1/3 of total available) with un-prescaled triggers
- **Large, ~10^6 Υ(1S), sample** covering **broad rapidity range** - |y|<2.25
- Inclusive differential production cross-sections are calculated for
  - **Fiducial phase space** (p_T > 4 GeV and |η|<2.3 for each muon), and
  - **Full phase space**, including polarisation uncertainty.

First $\chi_b(3P)$ observation

Phys. Rev. Lett. 108 (2012) 152001 arXiv:1112.5154

- $\chi_{bJ}(nP)$ are S=1, L=1 bottomonium (J=0,1,2)
- n=1,2 already observed in:
  - $\chi_{bJ}(1P) \rightarrow \gamma\Upsilon(1S)$ at m=9.90 GeV
  - $\chi_{bJ}(2P) \rightarrow \gamma\Upsilon(1,2S)$ at m=10.26 GeV
- The $\chi_{bJ}(3P)$ was predicted [10] to have
  - Mass of ~10.52 GeV < $2m_B$
  - Hyperfine splitting of 10-20 MeV



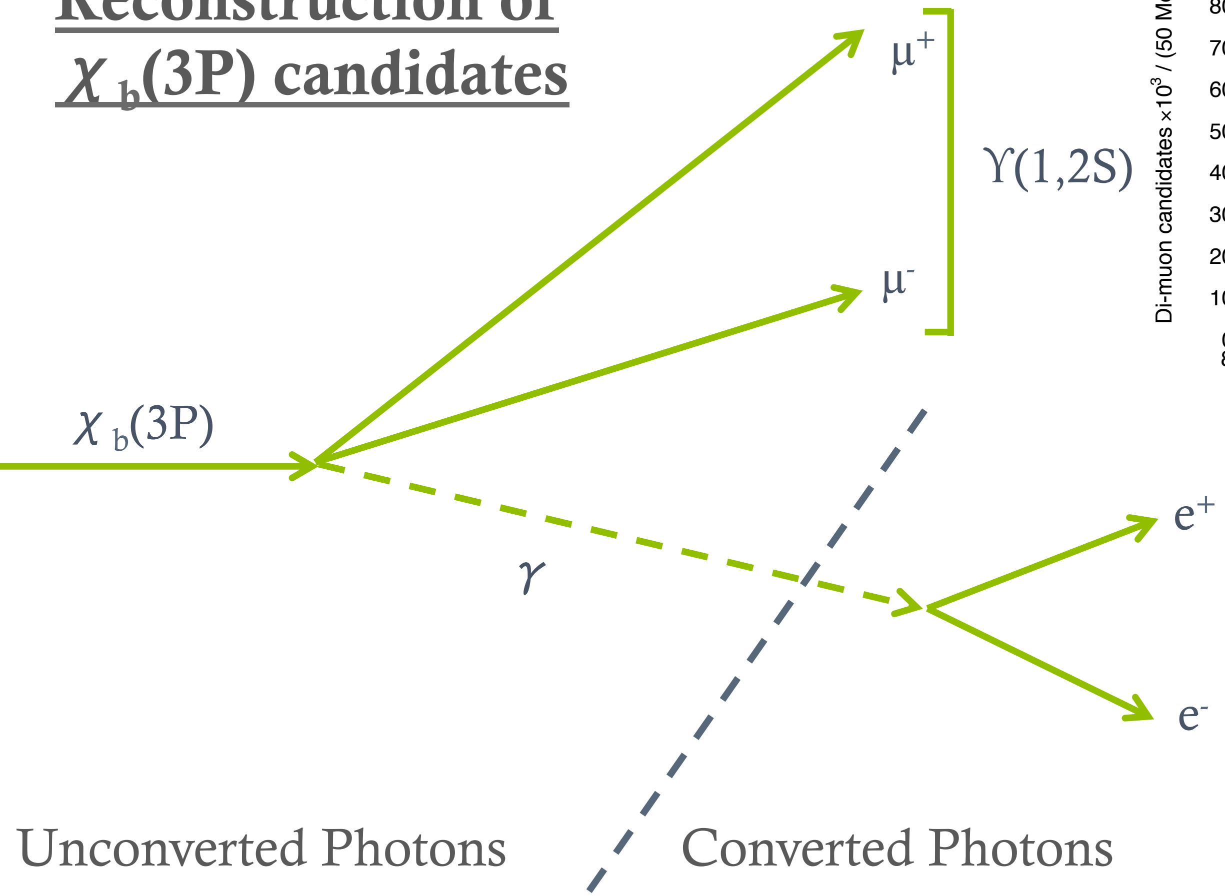
ATLAS performed a search for $\chi_b(nP) \rightarrow \gamma\Upsilon(1,2S)$

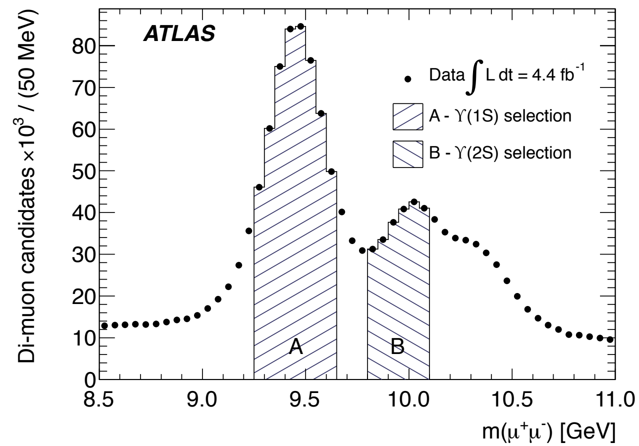
- Observe structure at m=10.530 ± 0.005 (stat.) ±0.008 (syst.) GeV
  - Significance >6 σ in two independent analysis channels
  - Confirmed by:
    - LHCb: m = 10.535 ± 0.010 (stat.) GeV [11]
    - DØ: m = 10.551 ± 0.014 (stat.) ± 0.017 (syst.) GeV [12]

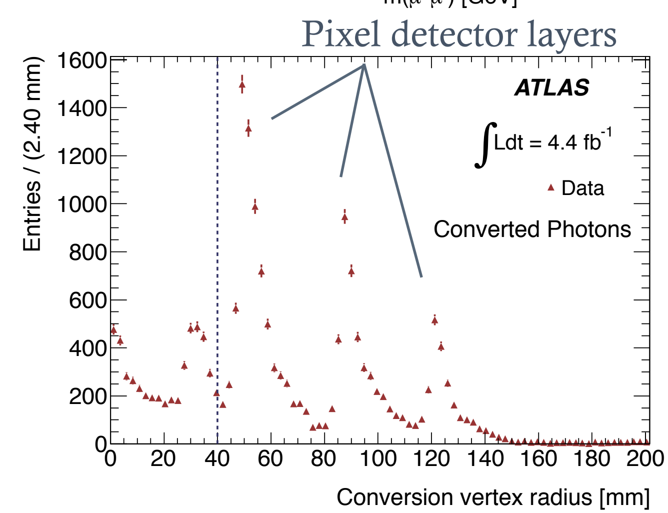
First $\chi_b(3P)$ observation

Phys. Rev. Lett. 108 (2012) 152001 arXiv:1112.5154

Reconstruction of $\chi_b(3P)$ candidates

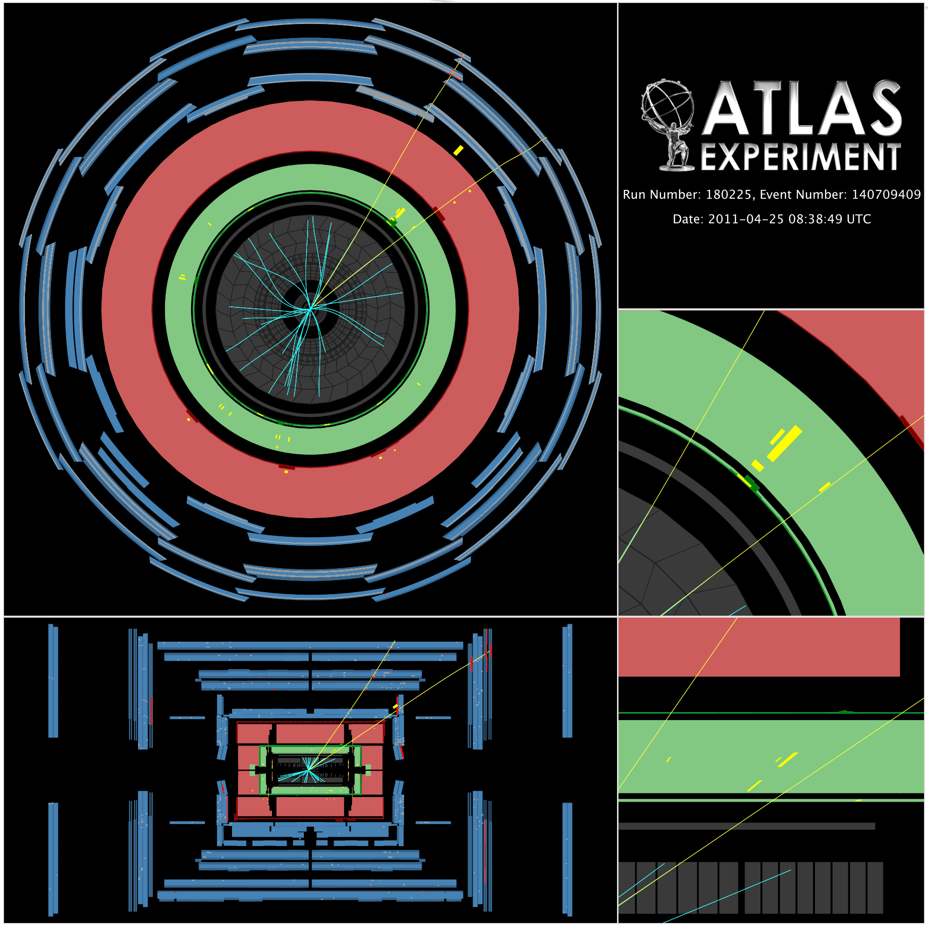




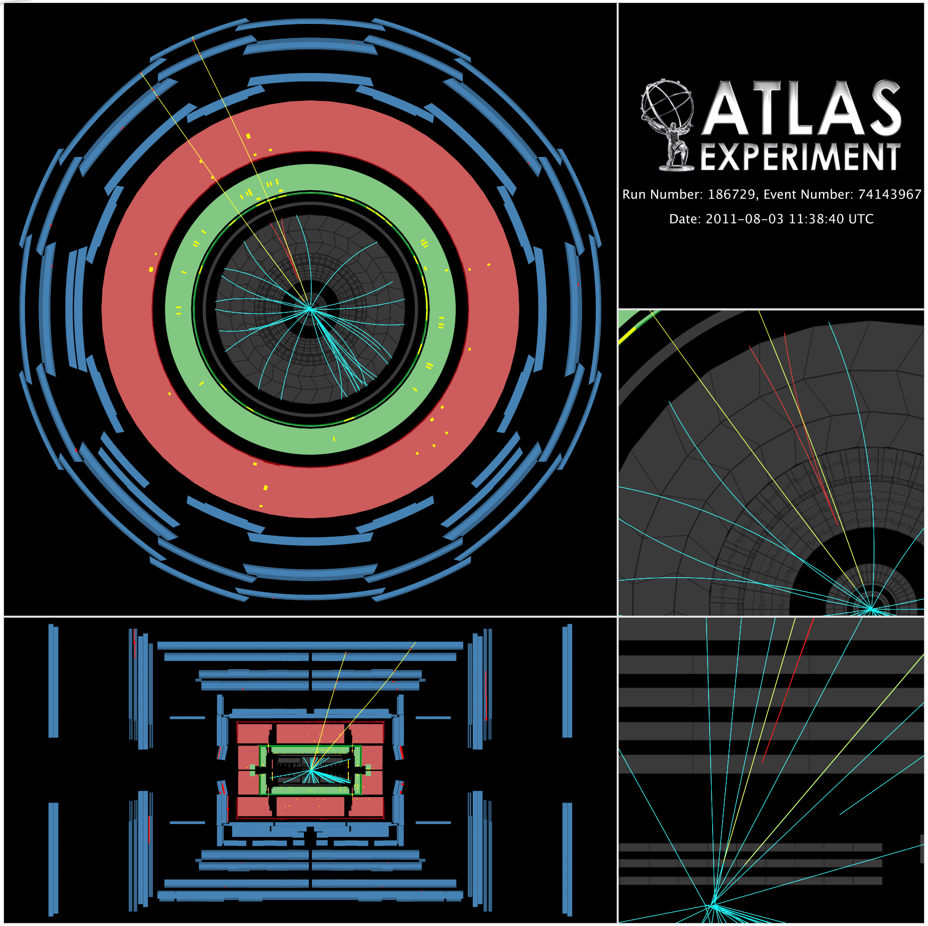


First $\chi_b(3P)$ observation

Phys. Rev. Lett. 108 (2012) 152001 arXiv:1112.5154



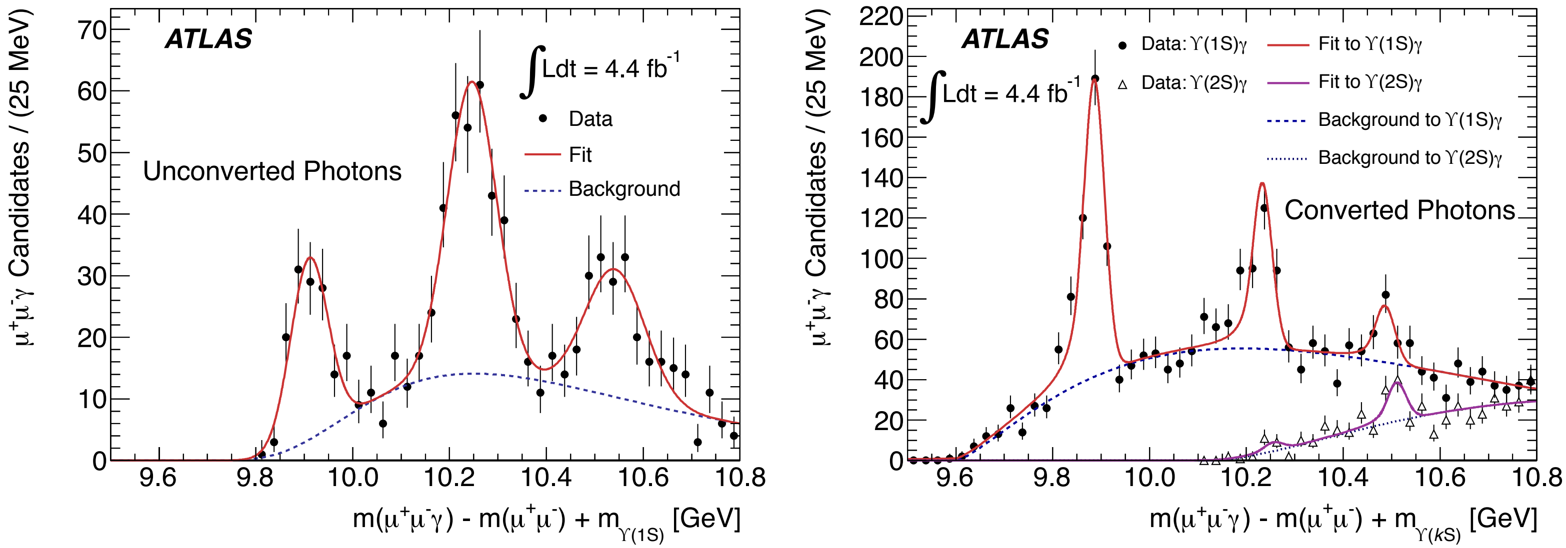
Unconverted, γ
m=10.54 GeV



Converted, e^+e^-
m=10.54 GeV

First $\chi_b(3P)$ observation

Phys. Rev. Lett. 108 (2012) 152001 arXiv:1112.5154



- To minimise effect of muon resolution, use $\mathbf{m_{\mu\mu\gamma} - m_{\mu\mu} + m_{\Upsilon,PDG}}$
- For conversion sample, $\Upsilon(2S)\gamma$ can be reconstructed
- Significance calculated with $\mathbf{(-2\log(L_{max}/L_0))^{0.5} > 6}$ under all syst. variations

State	Model predictions [3, 4] [MeV]	Fitted masses [MeV] Unconverted Photons	Fitted masses [MeV] Converted Photons
$\chi_b(1P)$	9900	9910 ± 6 (stat.) ± 11 (syst.)	Fixed to χ_{b1} = 9892.78 & χ_{b2} = 9912.21 [9]
$\chi_b(2P)$	10260	10246 ± 5 (stat.) ± 18 (syst.)	Fixed to χ_{b1} = 10255.46 & χ_{b2} = 10268.65 [9]
$\chi_b(3P)$	10525	10541 ± 11 (stat.) ± 30 (syst.)	10530 ± 5 (stat.) ± 9 (syst.)

Conclusion and future plans

- ATLAS has an **active and rich B-Physics and Quarkonium program**.
- Recent (spectroscopy-related) results include
  - J/ψ, $\Upsilon(nS)$ differential cross-section measurement
  - Λ_b^0 lifetime and mass measurement
  - B_c observation and preliminary mass measurement
  - First $\chi_b(3P)$ observation and mass measurement.
- Watch this space!
  - Lots of interesting ongoing analyses currently underway
  - Lots of data –
    - up to 4.9 fb^{-1} at 7 TeV and >20 fb^{-1} at 8 TeV
    - Dedicated B-Physics/Onia triggers

References

[1] JHEP 02 (2012) 011

[2] CMS BPH-11-013

[3] Phys. Rev. D 85, 112003 (2012)

[4] Phys.Rev.Lett.106:121804,2011

[5] Phys.Lett. B376 (1996) 303-308

[6] Phys.Rev.Lett.100:182002,2008

[7] Phys.Rev.Lett.101:012001,2008

[8] LHCb-TALK-2013-048

[9] CMS-PAS-BPH-11-003

[10] Eur.Phys.J.C4:107-114,1998

[11] LHCb-CONF-2012-020

[12] Phys.Rev. D86 (2012) 031103