χ_c and χ_b studies at ATLAS

IOP HEPP + APP Meeting

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Introduction: Quarkonium Production

Theoretical Motivation:

- Nearly 40 years after the discovery of the J/ψ, quarkonium production at hadron experiments is still not well understood...
- Advances in both theory and experiment are necessary to solve the many puzzles that remain
- The arrival of the LHC provides a great opportunity to improve this situation!

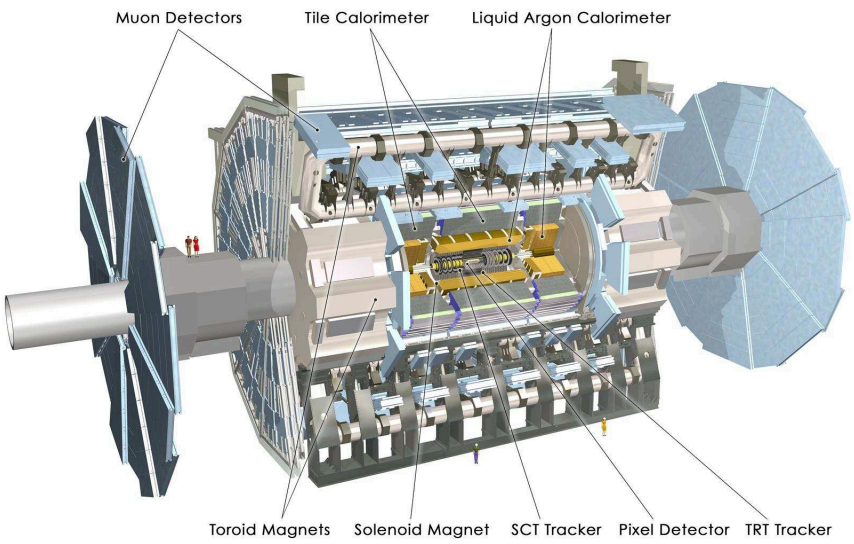
Theoretical Status:

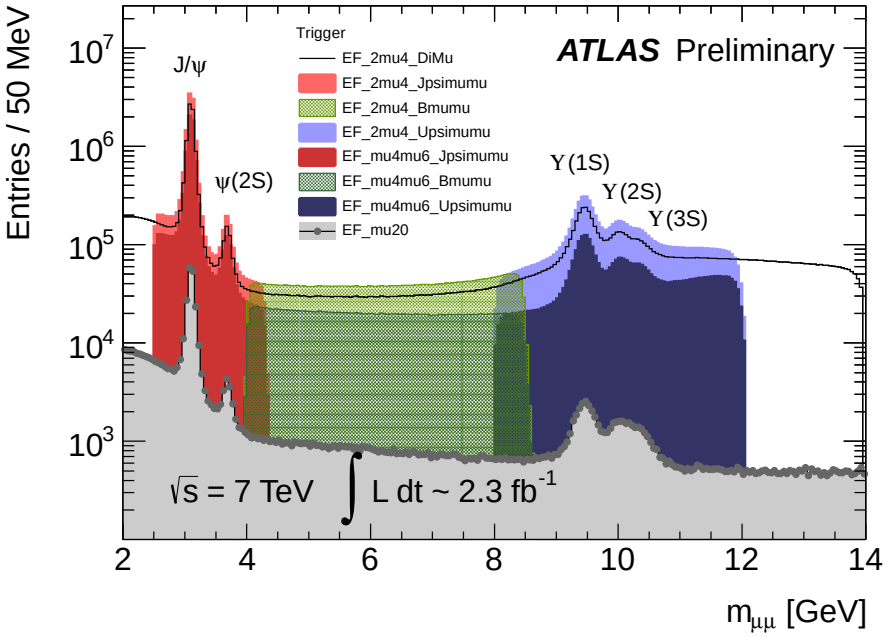
- The NRQCD factorisation approach (colour octet terms + other tricks) has had much success
- But, recent higher order calculations in the Colour Singlet Model (CSM) are also in reasonable agreement with the data
- Are colour octet processes necessary? Was the CSM right all along? Other ideas, i.e. Colour-Evaporation Model (CEM)?

Experimental input from the LHC experiments is neccesary to inform the future direction of theory!

The ATLAS Detector at the LHC

The ATLAS detector is a general purpose particle physics detector designed to study physics at the TeV scale. ATLAS is also well equipped to study quarkonium physics at the LHC!

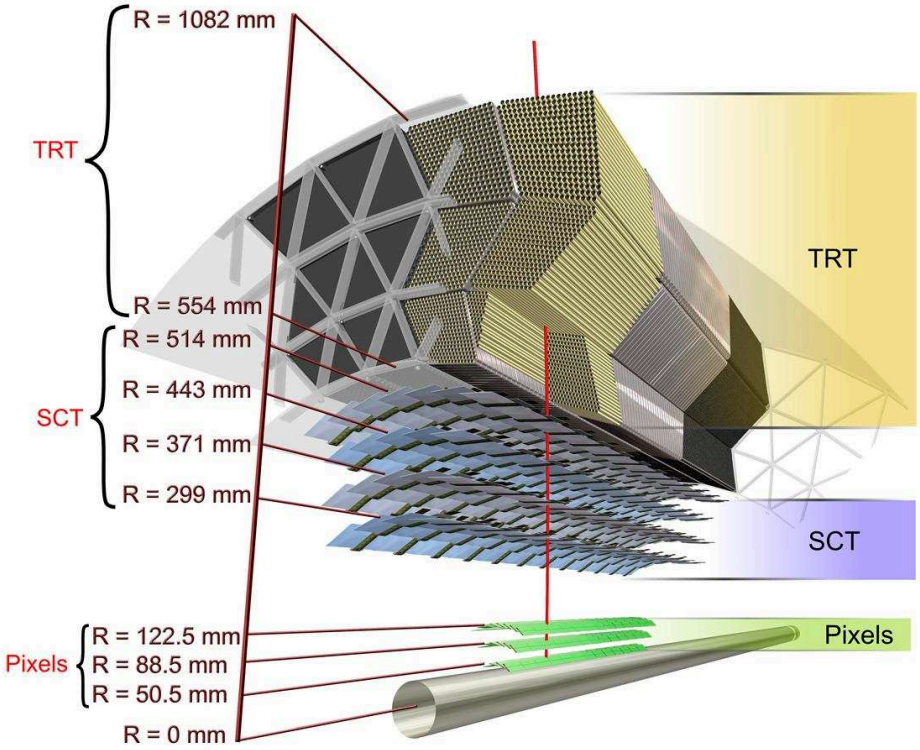


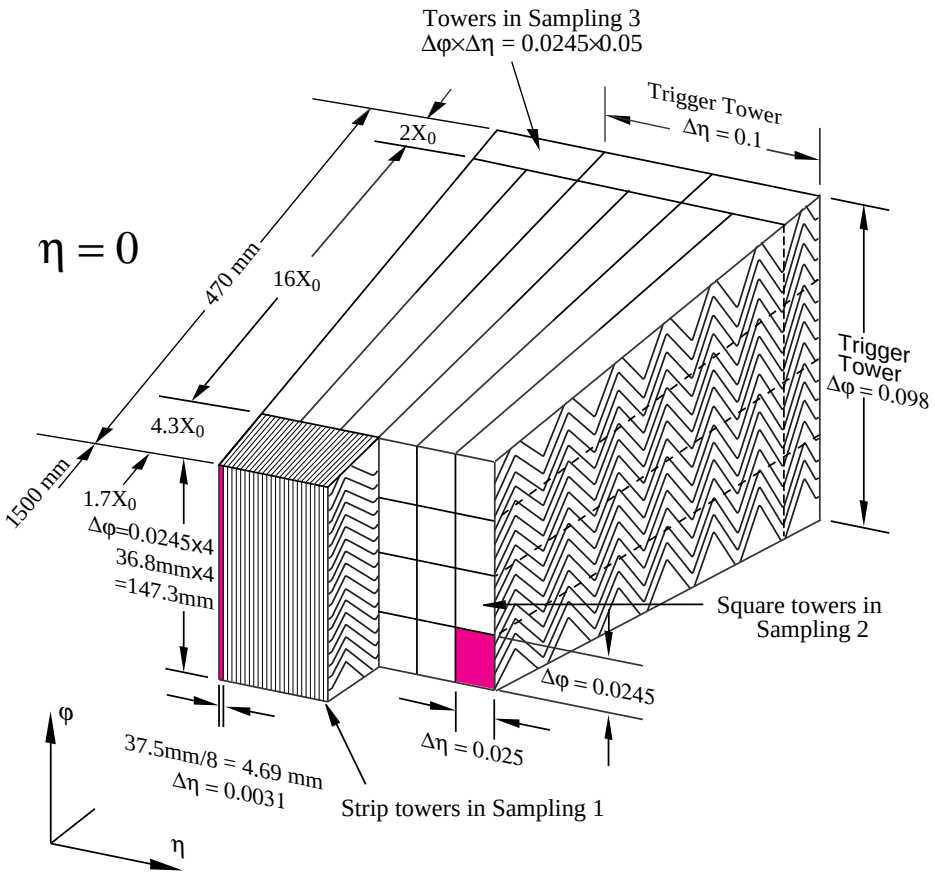


- Dedicated low p_T di-muon triggers are employed to record events containing J/ψ and Υ decays (gains w.r.t. high p_T single muon triggers shown on right)
- Unprecedentedly large J/ψ and Υ data samples (for a hadron experiment) were collected during LHC Run 1

Inner Detector (ID) ($|\eta| < 2.5$)

- Silicon Pixels and Strips (SCT) with Transition Radiation Tracker (TRT)





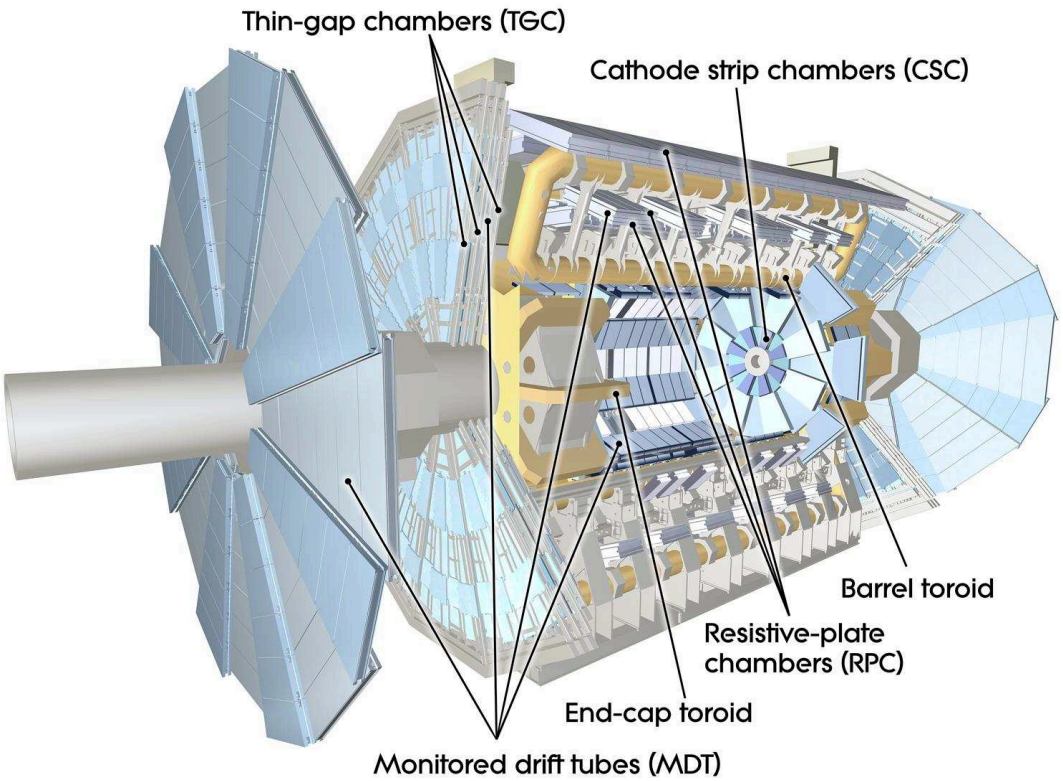
Liquid Argon EM Calorimeter ($|\eta| < 3.2$)

- Highly granular and **longitudinally segmented** in 3-4 layers

Detector Components II

Muon Spectrometer (MS) ($|\eta| < 2.7$)

- Toroid Magnet, 4 detector technologies, dedicated tracking and trigger chambers

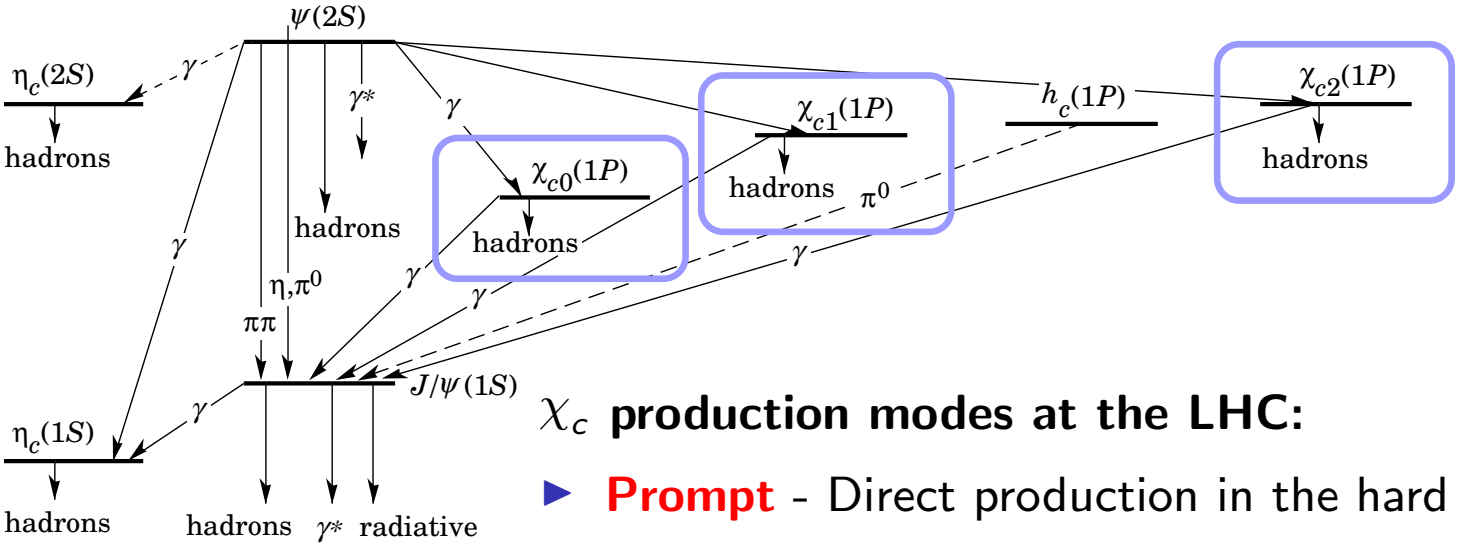


- Barrel: MDT (Tracking) and RPC (Trigger)
- Endcaps: MDT + CSC (Tracking) and TGC (Trigger)

What are the χ_c states?

Introduction:

- The χ_c states are a triplet of P-wave charmonium states with $J^{PC} = \{0, 1, 2\}^{++}$
- The $\chi_c(1P)$, with the J/ψ and $\psi(2S)$ are the only (easily) experimentally accessible charmonium states at the LHC
- The study of χ_c production can offer information complementary to production of the S-wave states



χ_c production modes at the LHC:

- **Prompt** - Direct production in the hard pp interaction
- **Prompt** - Feed down from higher charmonium states ($\psi(2S)$ dominant source, $\mathcal{B}(\psi(2S) \to \chi_c\,\gamma) \approx 10\%$)
- **Non-prompt** - Produced in the decay of a b hadron (e.g. $B^{\pm} \to \chi_c K^{\pm}$)

Radiative χ_c decays

Radiative Decays:

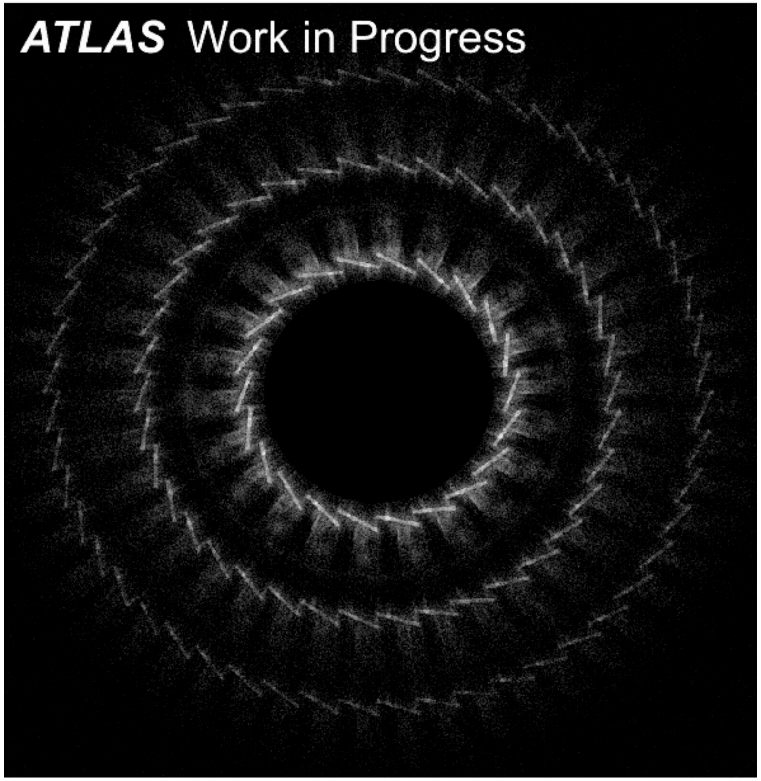
- The radiative decays $\chi_c \to J/\psi\,\gamma$ (with $J/\psi \to \mu^+\mu^-$) offer a clean experimental signature (very soft photons! $p_T(\gamma) < 5$ GeV)
- χ_{c1} and χ_{c2} have large radiative branching fractions of 34.4% and 19.5% (the value for χ_{c0} is significantly lower at 1.2%)

Photon Conversions ($\gamma \to e^+e^-$):

- Converted photons (an e^+e^- pair) are reconstructed from ID tracks alone
- Conversions offer superb mass resolution at the expense of a low reconstruction efficiency

Analysis Aims:

- Measure the absolute cross section and the ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ for prompt χ_{c1} and χ_{c2} production
- Measure non-prompt fraction of inclusive χ_c production



Reconstructed conversions in the ATLAS Pixel layers

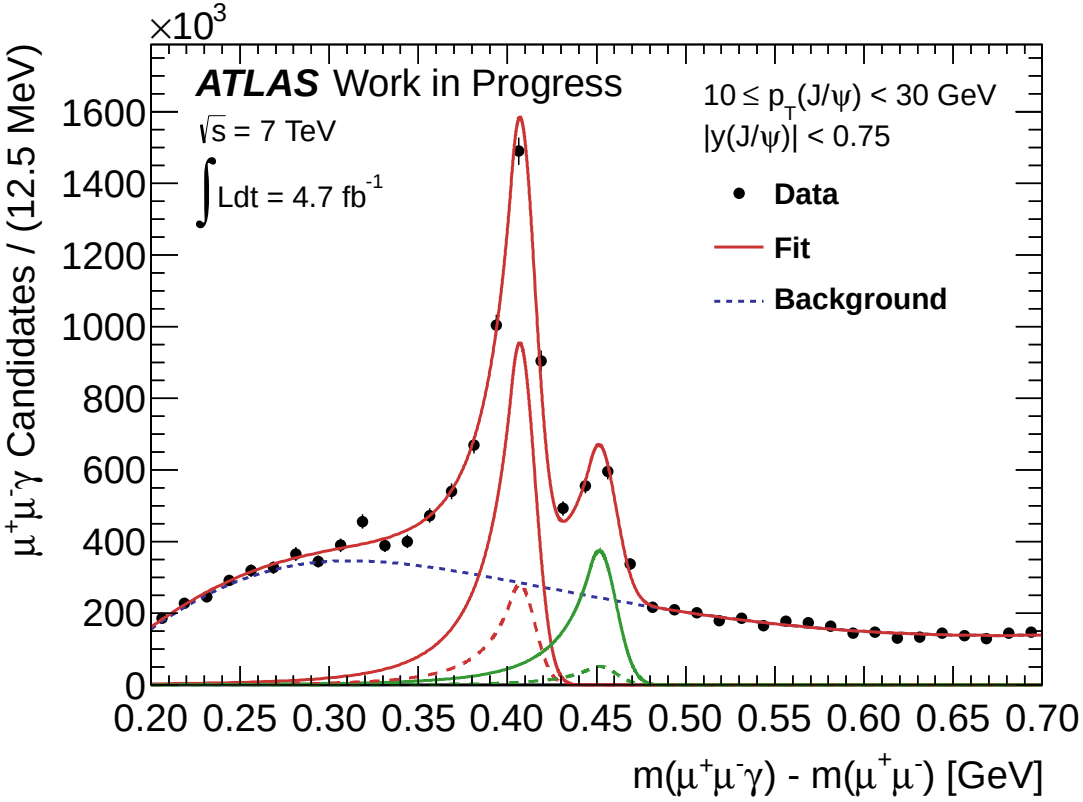
χ_c reconstruction

Dataset:

- Full 2011 dataset ($4.7\,\mathrm{fb}^{-1}$)
- Di-muon trigger (4 GeV single muon p_T threshold)

Event Selection:

- Di-muon pair compatible with J/ψ, reconstructed from both ID and MS measurements
- Photon conversion candidate with $p_T(\gamma) > 1.5$ GeV
- Conversion and $\mu^+\mu^-$ vertices compatible with χ_c decay (impact parameter cut)



Δm fit projection: Both χ_{c1} and χ_{c2} are well resolved, **dashed signal lines** (lower yield) represent non-prompt signal component

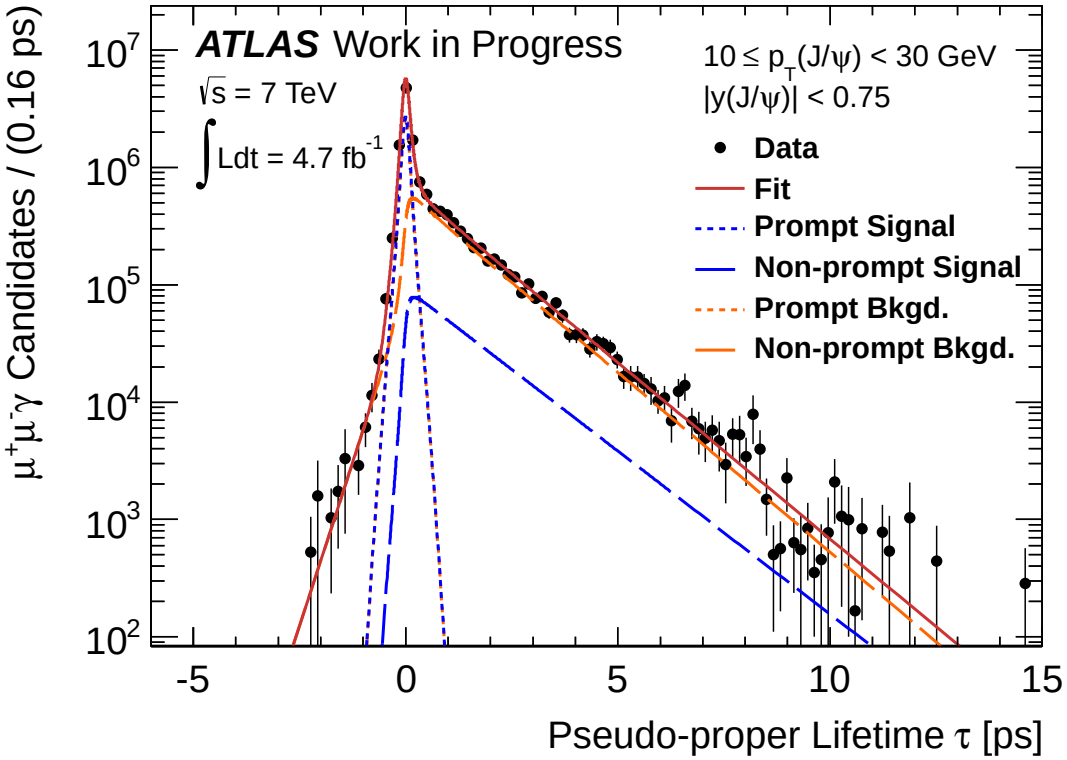
Analysis Strategy:

- Correct for experimental losses with a per-candidate weight, then perform a weighted fit to extract corrected χ_c yields
- Fit Δm and J/ψ lifetime distributions simultaneously to separate prompt component

Radiative χ_c decays

Corrections and Fit:

- Trigger and muon reconstruction efficiencies are taken from data-driven measurements
- Acceptance corrections are calculated for all χ_c polarisation scenarios
- Conversion reconstruction efficiencies calculated from MC simulation
- Simultaneous fit allows yields for prompt and non-prompt χ_{c1} and χ_{c2} to be extracted



Lifetime projection of fit on the previous slide. Prompt and non-prompt components can be well separated

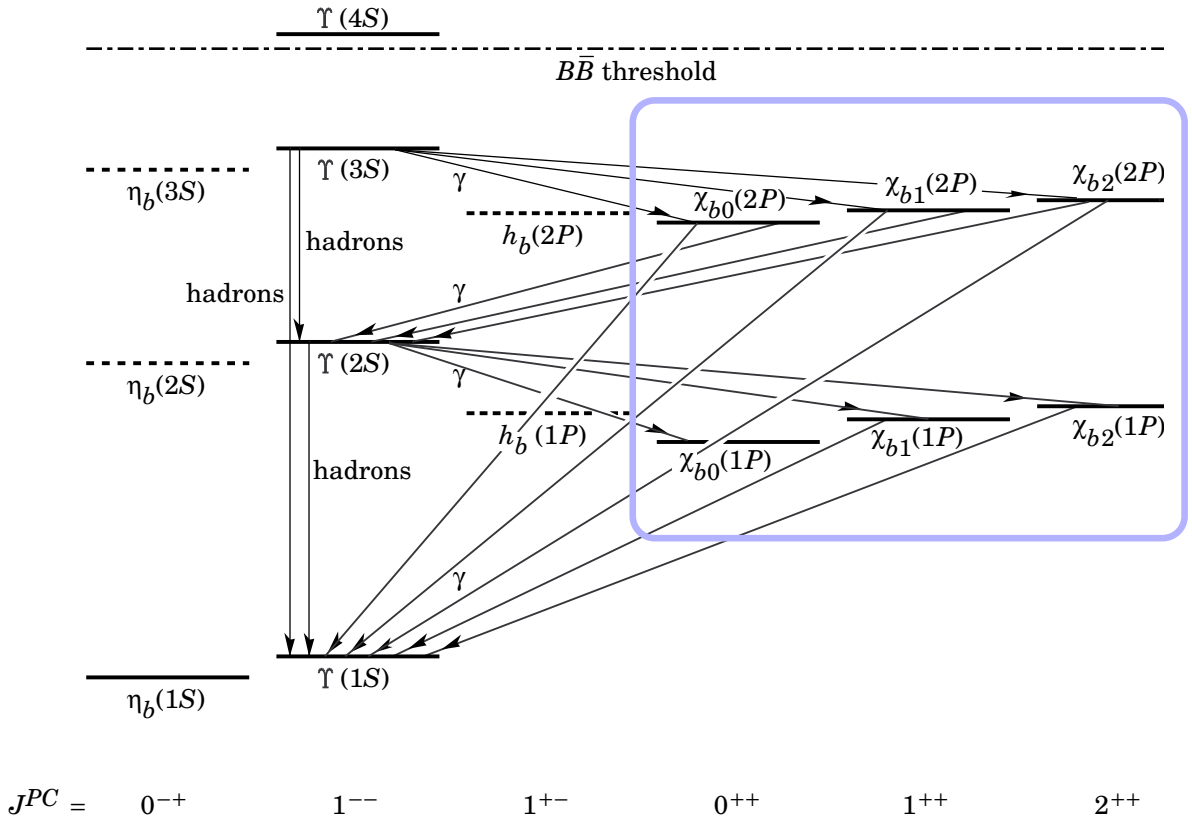
Measurement Status:

- Analysis is approaching completion, hope to publish results this year

What are the χ_b states?

The χ_b represent the spin triplet ($S = 1$) P-wave ($L = 1$) states of the bottomonium ($b\bar{b}$) spectrum.

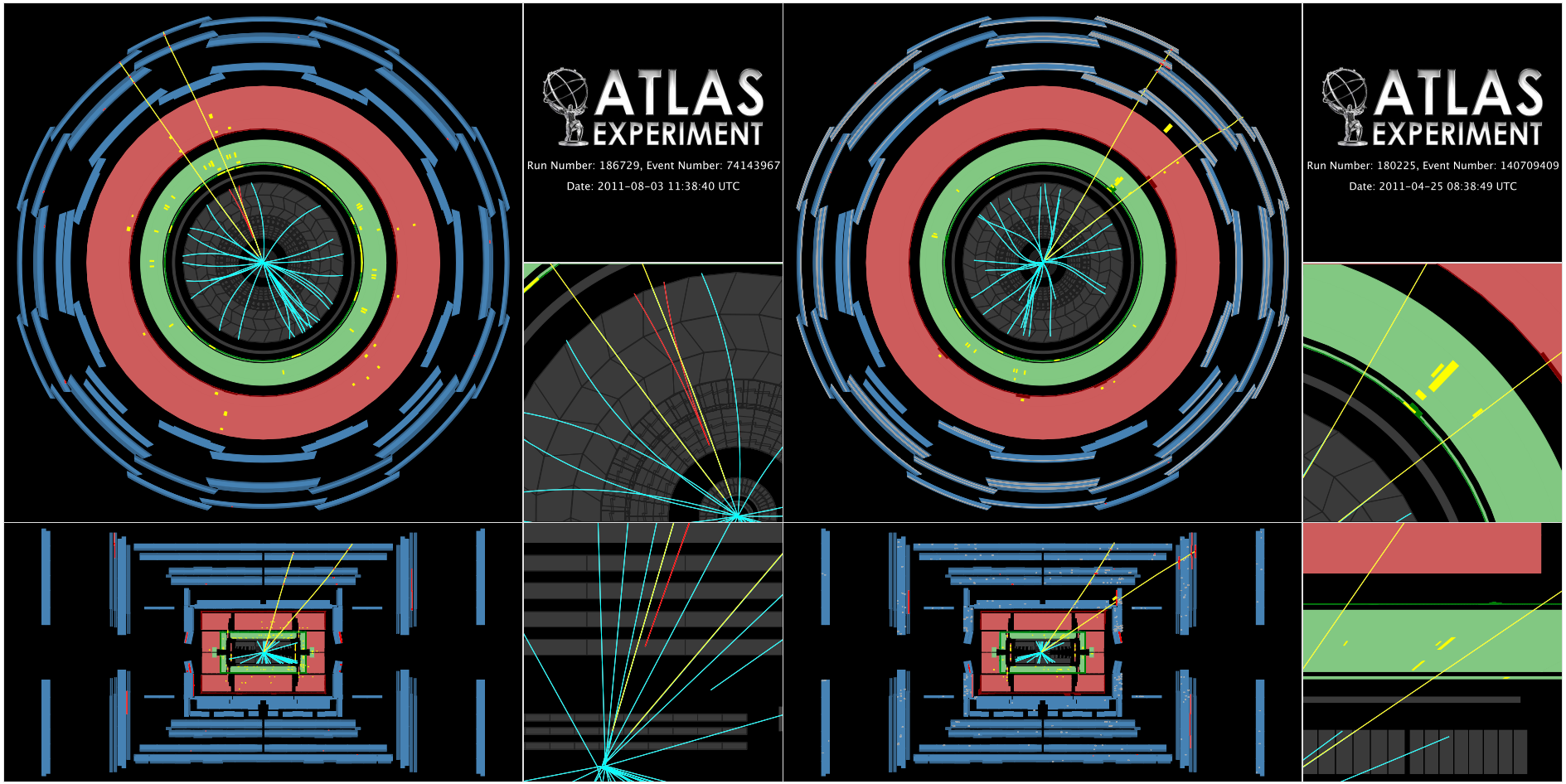
- Each χ_b is a triplet of states with $J^{PC} = 0^{++}, 1^{++}, 2^{++}$
- Hyperfine mass splittings between the 3 states are small $\mathcal{O}(10\text{ MeV})$
- Branching fractions for the radiative decays $\chi_b \to \Upsilon\gamma$ are large $\mathcal{O}(10\%)$



A third triplet, the $\chi_b(3P)$ is also expected below the $B\overline{B}$ threshold:

- Theoretical Predictions: Phys. Rev. D **36** 3401 (1987), Phys. Rev. D **38** 279 (1988), Eur. Phys. J. C. **4** 107 (1998)
- Mass centre of gravity expected around **10.525 GeV**

χ_b studies at ATLAS



Two events containing candidate $\chi_b \to \Upsilon\gamma$ decays:

- Left - The photon has converted and is reconstructed in the ID
- Right - The photon is unconverted and is reconstructed in the EM Calorimeter

First χ_b studies at ATLAS

Observation of a new χ_b state in radiative transitions to $\Upsilon(1S)$ and $\Upsilon(2S)$ at ATLAS

Phys. Rev. Lett. 108, 152001 (2012) (arXiv:1112.5154 [hep-ex])

Radiative χ_b decays are studied with two simultaneous analyses which exploit different reconstruction methods and detectors:

- Photons reconstructed using the EM calorimeter (unconverted)
- $\gamma \to e^+e^-$ conversions reconstructed with the Inner Detector (converted)
- Both share a common $\Upsilon \to \mu^+\mu^-$ selection

The two reconstruction methods have their own advantages and disadvantages. In particular, the minimum $p_T(\gamma)$ threshold (2.5 GeV and 1.0 GeV respectively) determines which radiative decays can be reconstructed:

- The unconverted photon analysis is capable of reconstructing $\chi_b \to \Upsilon(1S)\,\gamma$ decays alone
- The converted photon analysis is capable of reconstructing both $\chi_b \to \Upsilon(1S)\,\gamma$ and $\chi_b \to \Upsilon(2S)\,\gamma$ decays

Common Υ selection

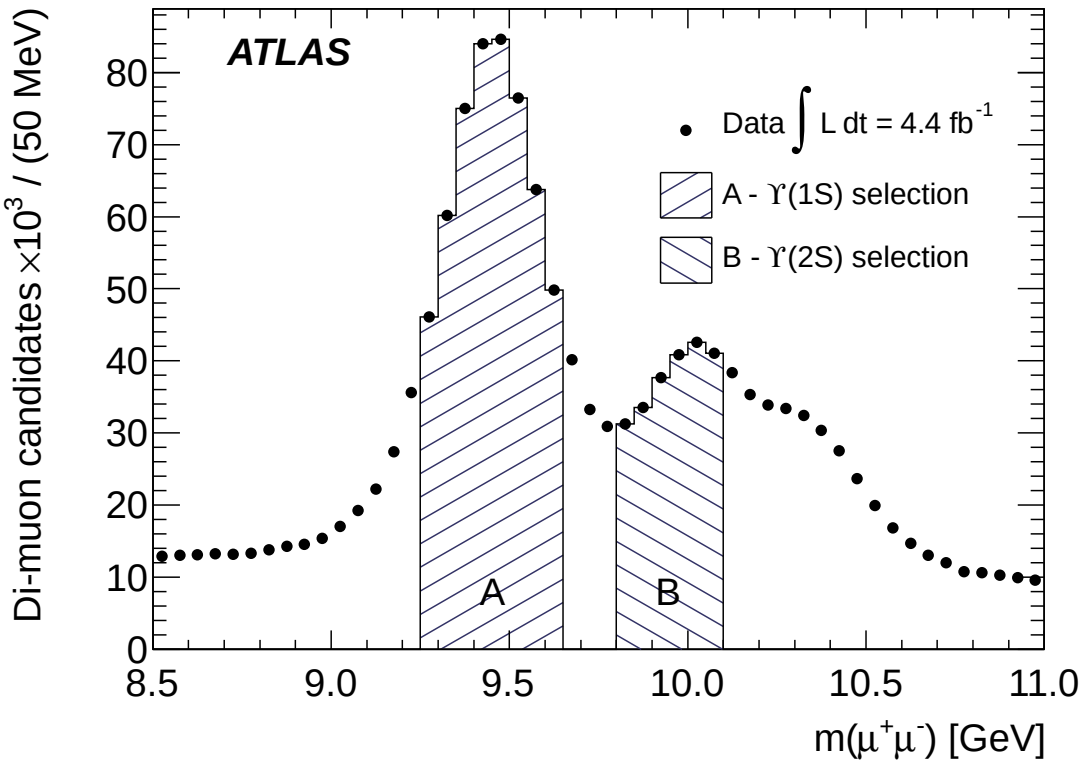
Selection of $\Upsilon(1,2S) \to \mu^+\mu^-$ candidates is common to both the unconverted and converted photon analyses:

Muon Selection

- $p_T(\mu^\pm) > 4.0$ GeV
- $|\eta(\mu^\pm)| < 2.3$
- Reconstructed from track in ID combined with MS track

$\Upsilon \to \mu^+\mu^-$ Selection

- Oppositely charged di-muon pair
- $\mu^+\mu^-$ common vertex fit $\chi^2/N_{D.o.F} < 20$
- $p_T(\mu^+\mu^-) > 12$ GeV
- Rapidity $|y(\mu^+\mu^-)| < 2.0$
- Both muons associated to same primary pp interaction

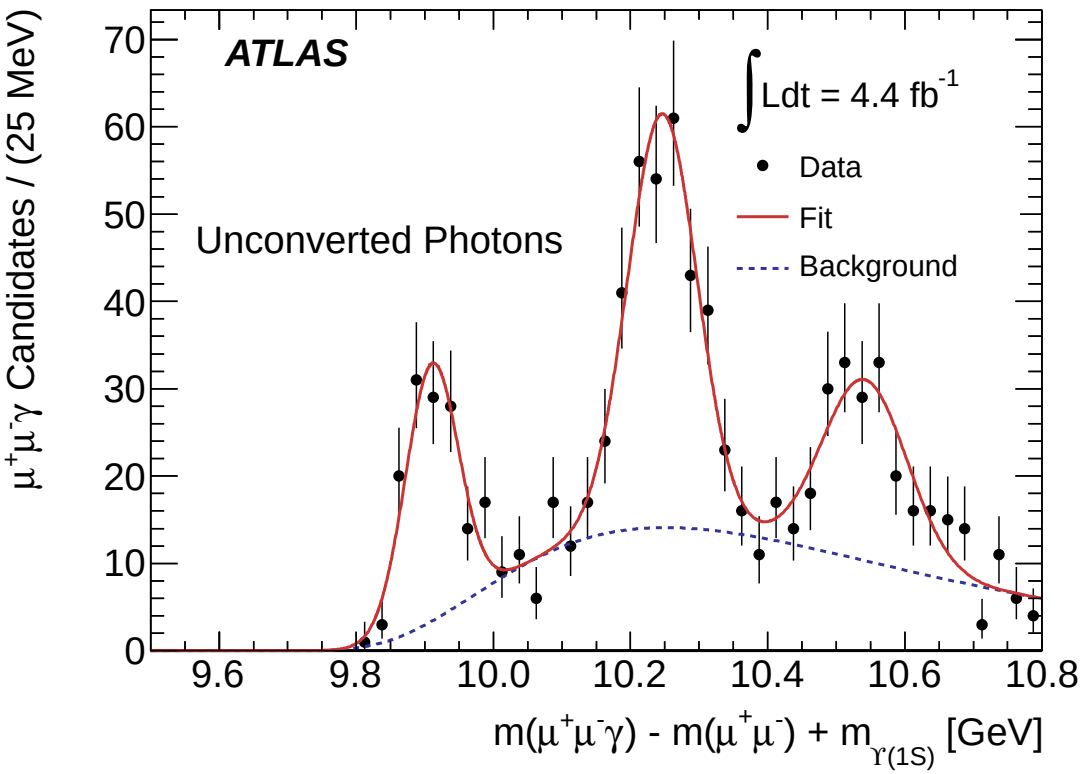


$\Upsilon \to \mu^+\mu^-$ invariant mass selection

- A - $\Upsilon(1S)$: $9.25 < m(\mu^+\mu^-) < 9.65$ GeV
- B - $\Upsilon(2S)$: $9.80 < m(\mu^+\mu^-) < 10.10$ GeV

χ_b reconstruction with unconverted photons

The $m\left(\mu^+\mu^-\gamma\right) - m\left(\mu^+\mu^-\right) + m^{PDG}_{\Upsilon(1S)}$ distribution exhibits three peaks:



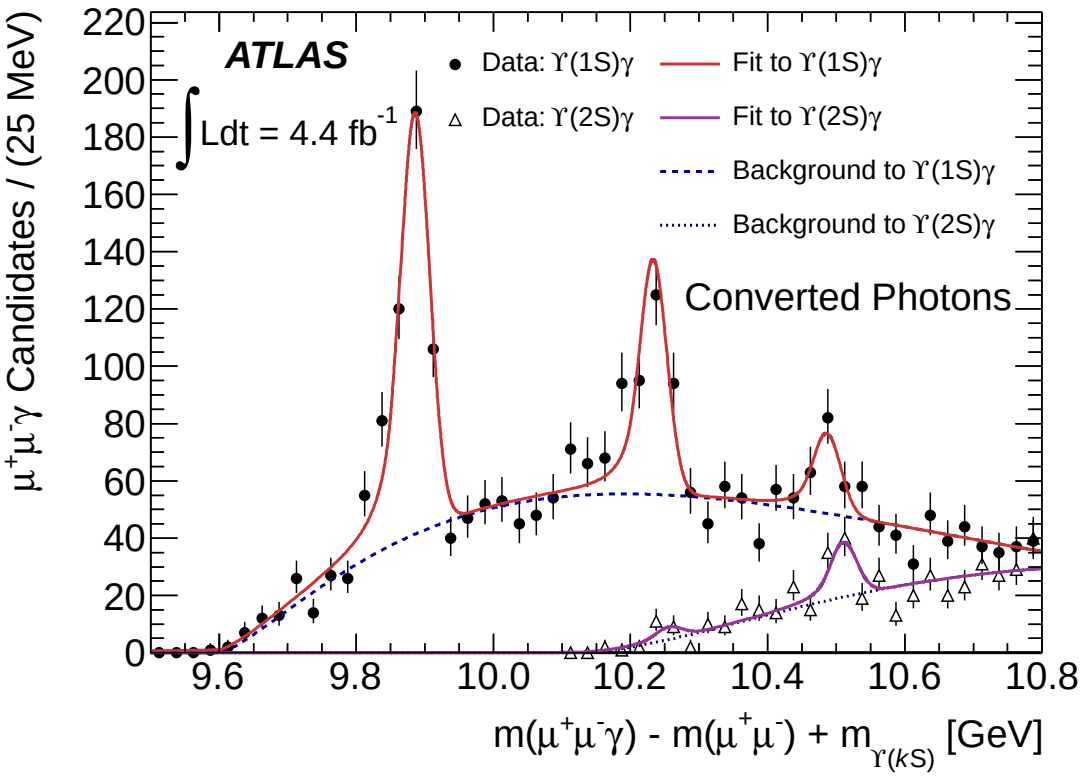
- **Mass difference** distribution is analysed to minimise the effects of experimental $\Upsilon \to \mu^+\mu^-$ resolution
- Mass resolution is further improved by correcting the photon η direction to point back to the $\mu^+\mu^-$ vertex
- The first two peaks are compatible with the $\chi_b(1P)$ and $\chi_b(2P)$ states, the third peak has a **significance** $> 6\sigma$

- The **third signal** is compatible with theoretical predictions for the $\chi_b(3P)$ states
- Mass of third structure measured to be (unconverted photons alone):

$$\overline{m}_3 = 10.541 \pm 0.011\ (\text{stat.}) \pm 0.030\ (\text{syst.})\ \text{GeV}$$

χ_b reconstruction with converted photons

Both the $\chi_b \to \Upsilon(1S)\,\gamma$ and $\chi_b \to \Upsilon(2S)\,\gamma$ mass distributions are shown together:



- Conversions reconstructed from ID tracks alone (no EM cluster information)
- The 3D impact parameter between the conversion and $\mu^+\mu^-$ vertices is required to be compatible with a χ_b decay
- Both $(\Upsilon(1,2S)\gamma)$ mass distributions are fitted simultaneously to measure the mass of third signal

- Statistical significance of the **third signal** (around 10.5 GeV) is also $> 6\sigma$
- Mass of third structure measured to be (converted photons alone):

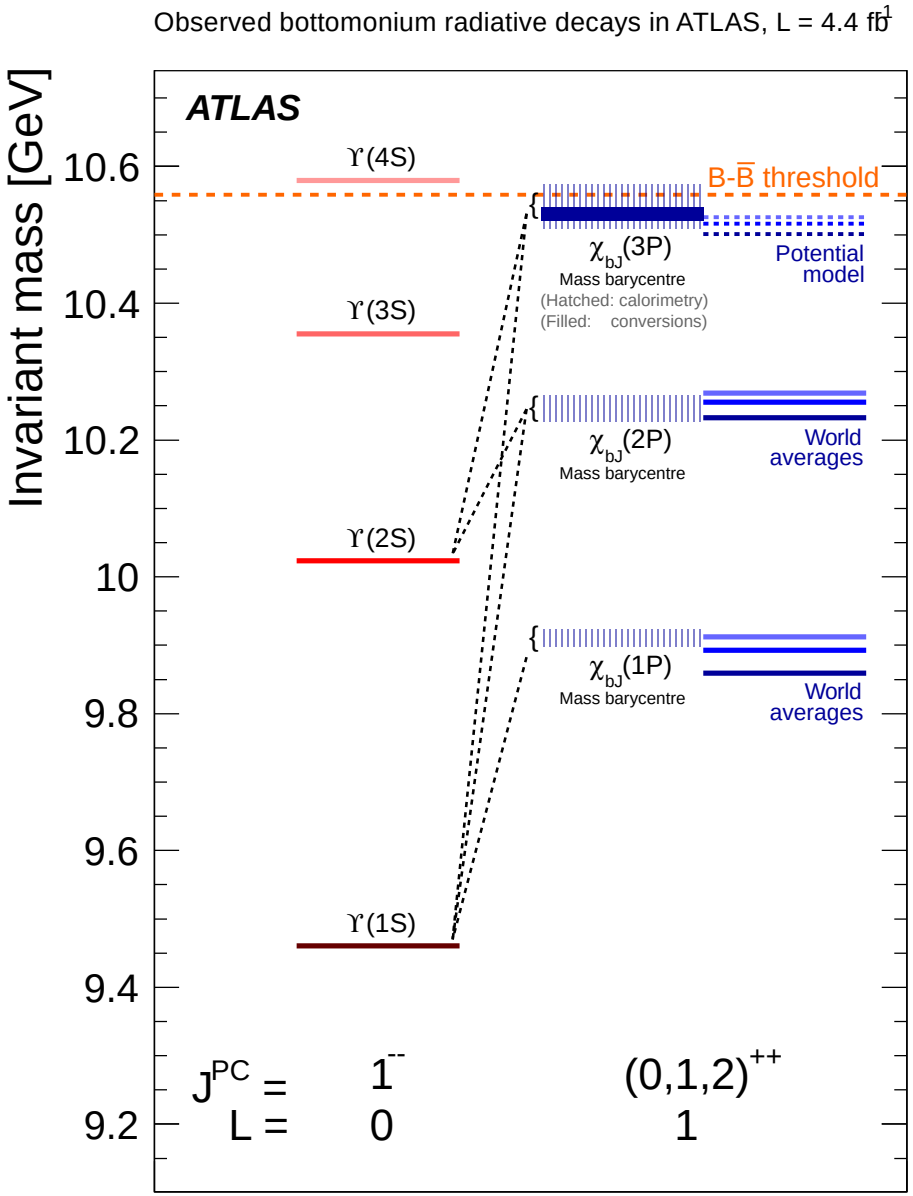
$$\overline{m}_3 = 10.530 \pm 0.005\ (\text{stat.}) \pm 0.009\ (\text{syst.})\ \text{GeV}$$

χ_b Summary

- The known $\chi_b(1,2P)$ states are observed in radiative decays to $\Upsilon(1S)\gamma$
- **A new structure** at a higher mass is also observed in the $\Upsilon(1S)\gamma$ and $\Upsilon(2S)\gamma$ spectra
- The interpretation of this as the $\chi_b(3P)$ states is consistent with theoretical predictions
- The mass of the structure is measured with two separate analyses using converted and unconverted photons with compatible results
- Now confirmed by $D\emptyset^{\dagger}$ and LHCb‡

† Phys. Rev. D **86**, 031103(R) (2012)

‡ LHCb-CONF-2012-020



What can we learn from this?

What are the consequences of the observation of this "new" state?

- Another source of feed-down into the inclusive Υ cross section - must be taken into account in theoretical models
- Decays of $\chi_b(3P)$ states at $\sim$ 10.5 GeV to $\Upsilon(3S)$ are kinematically allowed
- The $\Upsilon(3S)$ cross section was thought to be free from significant feed-down - now not the case
- $\mathcal{B}(\chi_b(3P) \to \Upsilon(3S)\gamma)$ should be large $\mathcal{O}(10\%)$
- Polarisation of $\Upsilon(3S)$ no longer "clean" probe of direct production mechanisms
- Recent production calculations now include $\chi_b(3P)$ feed-down (Phys. Rev. D **86**, 054015 (2012))

Summary

- Many exciting and interesting opportunities in quarkonium physics at the LHC
- Analysis of χ_c production at ATLAS is in progress
- The $\chi_b(3P)$ states have recently been observed at ATLAS
- This observation has significant implications on our understanding of inclusive bottomonium production