Observation of the χ_b states at ATLAS and a Ξ_b^{*0} baryon at CMS

FPCP2012, USTC - Hefei, China

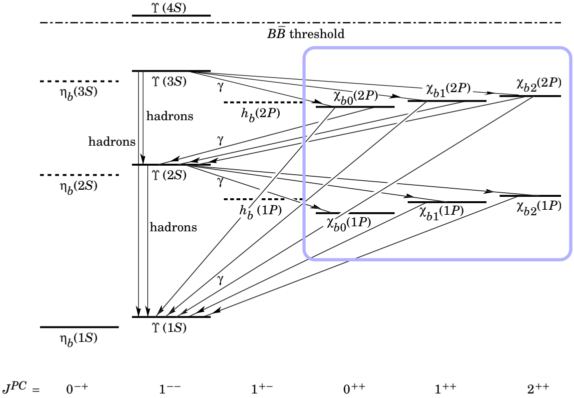
Andrew Chisholm, for the ATLAS and CMS Collaborations

University of Birmingham

21st May, 2012

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 $\mathcal{O}(10\%)$

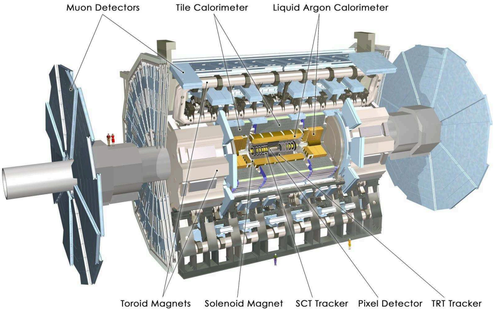


A third triplet, the $\chi_b(3P)$ is also expected below the $B\overline{B}$ threshold:

- 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**

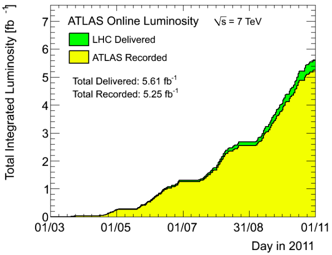
Figure: K. Nakamura et al. (Particle Data Group), J. Phys. G **37**, 075021 (2010)

The ATLAS detector is a general purpose particle physics detector designed to study physics at the TeV scale:



ATLAS has a diverse physics programme including Higgs Searches, SUSY + Exotics Searches, SM Physics, Heavy Flavour Physics and more!

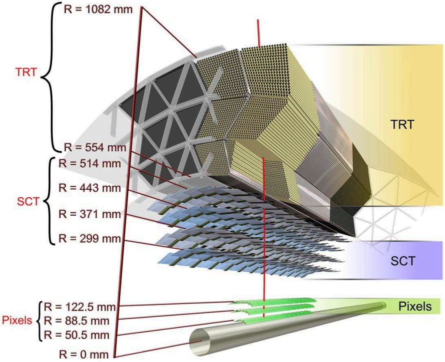
The LHC and ATLAS performed very well throughout 2011:

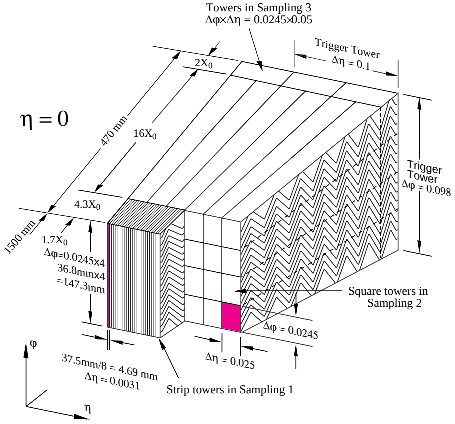


ATLAS collected over 5 fb^{-1} of data during the 2011 LHC run at $\sqrt{s} = 7$ TeV

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

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





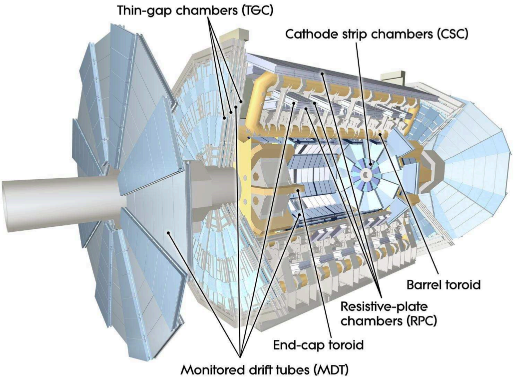
Liquid Argon EM Calorimeter ($|\eta| < 3.2$)

- 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)

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

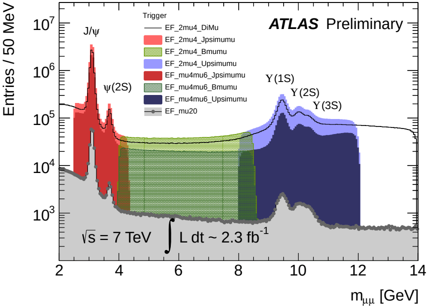
The two reconstruction methods have their own advantages and disadvantages. In particular, the minimum $p_T(\gamma)$ threshold (2.5 GeV and 1.0 GeV respectively) determines which radiative decays can be reconstructed:

- 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

The analysis uses 4.4 fb^{-1} of pp collision data at $\sqrt{s} = 7$ TeV recorded throughout the 2011 LHC run:

Trigger Strategy:

- Events containing radiative χ_b decays are **triggered by the di-muon decay** $\Upsilon \to \mu^+\mu^-$ (the photons are too soft to trigger the event)
- The trigger records events which contain di-muon pairs or single high p_T muons
- The majority of events are selected by dedicated $\Upsilon \to \mu^+\mu^-$ di-muon triggers (blue shaded histograms)



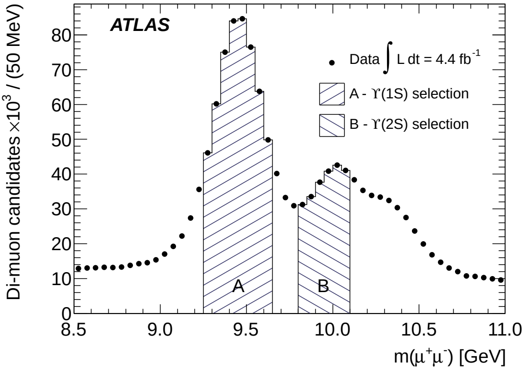
Selection of $\Upsilon(1,2S) \to \mu^+\mu^-$ candidates is common to both the unconverted and converted photon analyses:

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

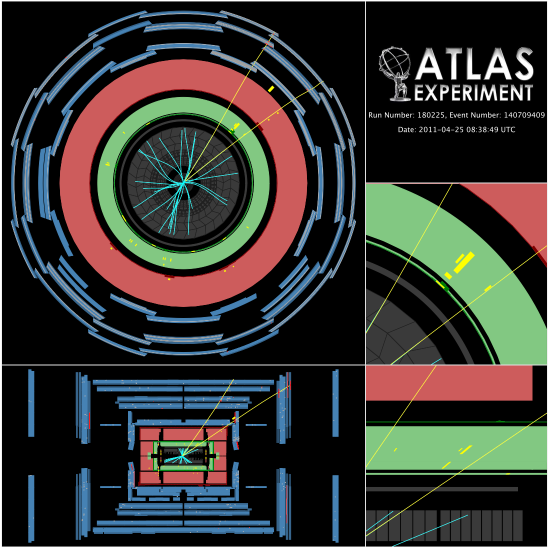
- Oppositely charged di-muon pair
- $\mu^+\mu^-$ common vertex fit $\chi^2/N_{D.o.F} < 20$
- $p_T(\mu^+\mu^-) > 12$ GeV
- Rapidity $|y(\mu^+\mu^-)| < 2.0$
- Both muons associated to same primary *pp* interaction



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

Unconverted Photon Analysis



An event containing a candidate $\chi_b \to \Upsilon\gamma$ decay in which the photon is unconverted

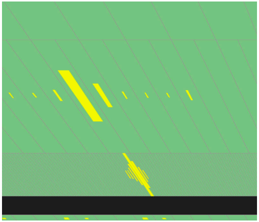
Unconverted Photon Selection

EM calorimeter energy deposits not matched to any track are considered as unconverted photon candidates:

- $E_T(\gamma) > 2.5$ GeV
- $|\eta(\gamma)| < 2.37$ (Barrel-Endcap transition region $1.37 < |\eta| < 1.52$ excluded)
- "Loose"[1] photon ID selection: Including limits on hadronic leakage and requirements on the EM shower shape (designed to reject backgrounds from narrow jets and π^0 decays)

Unconverted Photon Pointing Correction

- The polar angle of the photon 3-vector is corrected to point back to $\mu^+\mu^-$ vertex
- Loose cut of $\chi^2/N_{D.o.F} < 200$ rejects photons not compatible with having originated from the $\mu^+\mu^-$ vertex



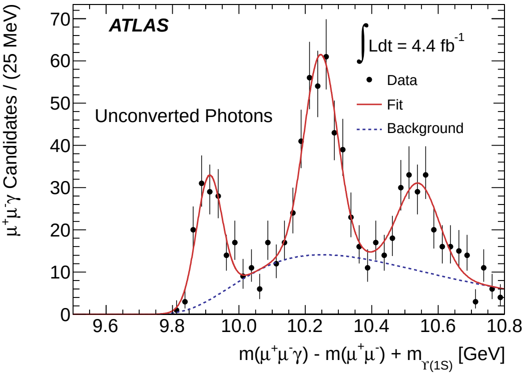
$\chi_b \to \Upsilon(1S)\gamma$ Selection

- Reconstructed $\Upsilon(1S) \to \mu^+\mu^-$ candidates are associated with corrected unconverted photons to form χ_b candidates

[1] Described in detail in: Phys. Rev. D **83**, 052005 (2011) (arXiv:1012.4389)

Unconverted Photon Result I

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



- **Mass difference** distribution is analysed to minimise the effects of experimental $\Upsilon \to \mu^+\mu^-$ resolution
- The first two peaks (around 9.90 GeV and 10.25 GeV) are compatible with the $\chi_b(1P)$ and $\chi_b(2P)$ states
- **The third peak (around 10.55 GeV)** is compatible with theoretical predictions for the $\chi_b(3P)$ states

- Final selection of $p_T(\mu^+\mu^-) > 20$ GeV chosen to maximise $\chi_b(1P)$ and $\chi_b(2P)$ significance irrespective of effect on the third peak
- Statistical significance of third signal is **greater than** 6σ calculated from a likelihood ratio approach (including systematic variations)

Unconverted Photon Result II

An extended unbinned maximum likelihood fit is performed to the $m\left(\mu^+\mu^-\gamma\right) - m\left(\mu^+\mu^-\right) + m^{PDG}_{\Upsilon(1S)}$ distribution to extract an estimate of the $\chi_b(3P)$ mass barycentre:

Fit Model

- **Signal:** Single Gaussian for each $\chi_b(nP)$ peak, each with a free mean value and width
- **Background:** Described by $\exp\left(A \cdot (\Delta M) + B \cdot (\Delta M)^{-2}\right)$ where A and B are free parameters

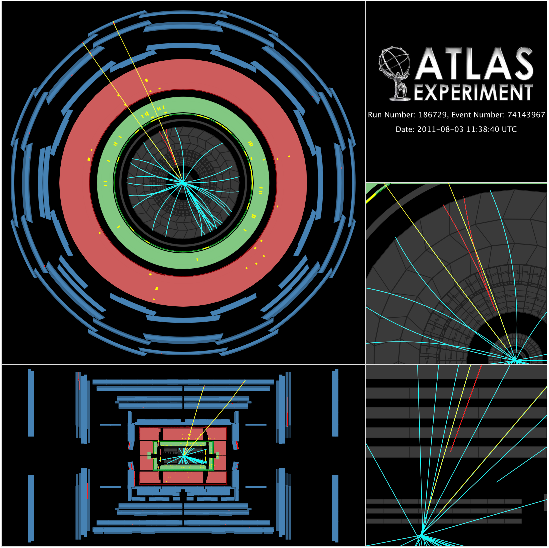
Assigned Systematic Uncertainties

- Unconverted photon energy scale uncertainty (estimated at $\pm 2\%$ of the ΔM position)
- Modelling of the background distribution (estimated from refitting with various alternative models)

	Fitted Mass (MeV)
$\chi_b(1P)$	9910 ± 6 (stat.) ± 11 (syst.)
$\chi_b(2P)$	10246 ± 5 (stat.) ± 18 (syst.)
$\chi_b(3P)$	10541 ± 11 (stat.) ± 30 (syst.)

The statistical significance of third signal remains greater than 6σ with each systematic variation

Converted Photon Analysis

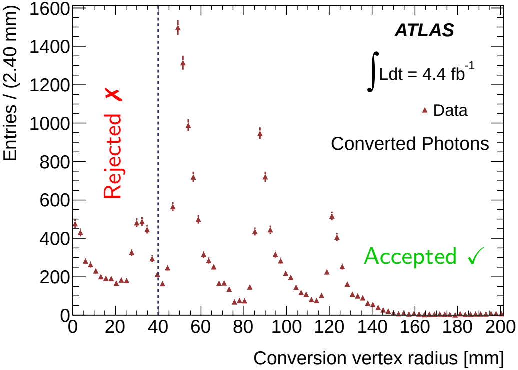


An event containing a candidate $\chi_b \to \Upsilon\gamma$ decay in which the photon has converted ($\gamma \to e^+e^-$)

Converted Photon Selection I

Reconstructing photons from e^+e^- conversions in the Inner Detector (ID) offers improved resolution and access to softer photons:

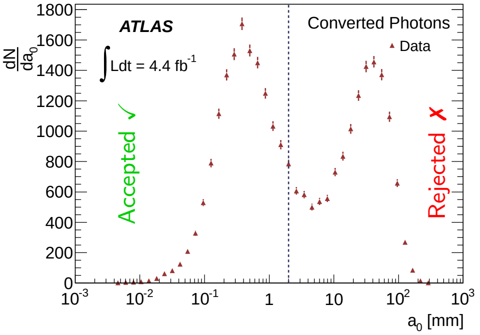
- Reconstructed from ID measurements *alone* (no EM cluster matching)
- Minimum track momentum $p_T(e^\pm) > 500$ MeV
- $p_T(\gamma) > 1$ GeV
- $|\eta(\gamma)| < 2.3$
- Only two-track conversions are retained
- 4 silicon detector hits required for each electron track

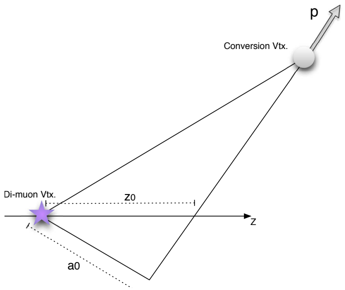


- Candidate electron tracks must **not** already be selected as di-muon candidate tracks
- Radius of conversion vertex $R > 40$ mm to reduce background contamination

Converted Photon Selection II

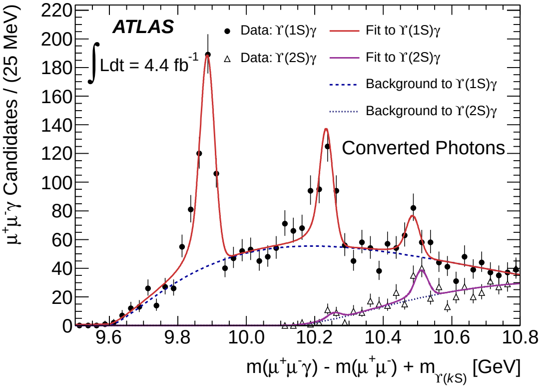
The 3D impact parameter of the converted photon with respect to the di-muon vertex, a_0, is a powerful variable which can be used to select photons associated with the di-muon vertex:





- $a_0 < 2$ mm is required to **reject photon combinatorics not compatible with having originated from the di-muon vertex**
- The χ^2 probability of the conversion vertex fit is required to be greater than 0.01

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



- Statistical significance of the **third signal** (around 10.5 GeV) is **greater than** 6σ calculated from a likelihood ratio approach (including systematic variations)
- Data points are **not** corrected for energy losses due to Bremsstrahlung (taken into account in fit)

Converted Photon Fit Description

Under the interpretation of the third signal as $\chi_b(3P)$, the experimental mass barycentre is measured from a simultaneous unbinned extended maximum likelihood fit to both the $\Upsilon(1S)\gamma$ and $\Upsilon(2S)\gamma$ mass distributions:

- The simultaneous fit allows a number of parameters to be shared across the two samples to help constrain the model, with additional constraints applied from the known masses (PDG)

Fit Model:

- As the $J = 0$ branching fraction is significantly smaller than for $J = 1, 2$ its contribution can be neglected
- The $\chi_b(nP)$ state is therefore modelled by **two Crystal Ball (CB)** functions to describe the low-mass Bremsstrahlung tail
- For $n = 1, 2$, the masses of the individual J=1,2 states are fixed to the known PDG values, and for n=3 the hyperfine splitting is fixed to the theoretically predicted value of 12 MeV
- The relative normalisations of the J=1 and J=2 components are fixed to be equal
- A free parameter λ, common to all the peaks, accounts for additional energy losses and appears in the form $\overline{\Delta m} \cdot \lambda$
- The background is modelled by $(\Delta m - q_0)^{\alpha} \cdot \exp\{(\Delta m - q_0) \cdot \beta\}$

Converted Photon Result II

Assigned Systematic Uncertainties:

- Vary relative $J = 1, 2$ signal normalisation by ± 0.25 (or left free in fit): ± 5 MeV
- Alternative signal and background models: ± 5 MeV
- Decoupled fits to the $\Upsilon(1S)$ and $\Upsilon(2S)$ distributions: ± 5 MeV
- Individually releasing constraints to the PDG values for the $\chi_b(1P)$ and $\chi_b(2P)$ masses: ± 3 MeV

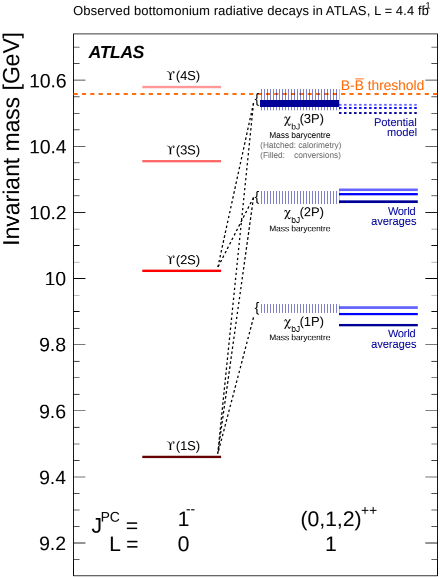
Fit Result:

- Energy scale factor $\lambda = 0.961 \pm 0.003$
- Experimental mass barycentre for $\chi_b(3P)$ signal determined by fit to converted photon candidates **alone** is:

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

Summary

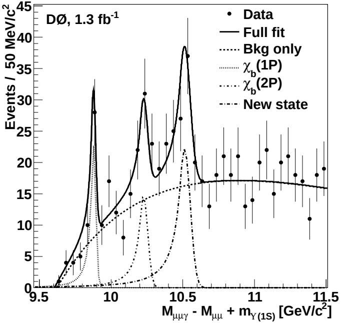
- The known $\chi_b(1,2P)$ states are observed in radiative decays to $\Upsilon(1S)\gamma$
- **A new structure** at a higher mass is also observed in the $\Upsilon(1S)\gamma$ and $\Upsilon(2S)\gamma$ spectra
- The interpretation of this as the $\chi_b(3P)$ states is consistent with theoretical predictions
- The mass of the structure is measured with two separate analyses using converted and unconverted photons with compatible results
- The mass measurement with smaller systematic uncertainties from the converted photon analysis is chosen to represent the final measurement



Shortly after the publication of the ATLAS result, the $D\emptyset$ collaboration confirmed the observation of a new structure in the $\Upsilon(1S)\gamma$ mass spectrum:

Observation of a narrow state decaying into $\Upsilon(1S) + \gamma$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

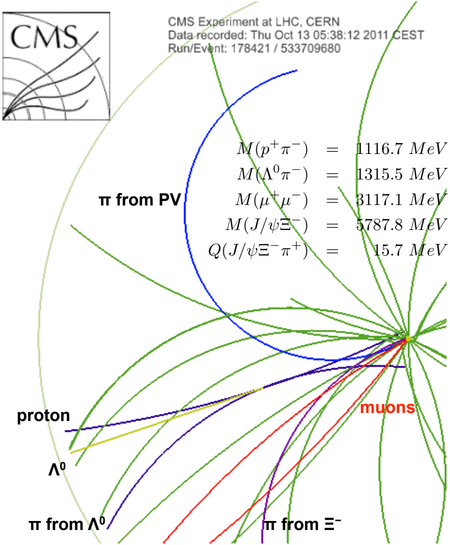
Submitted to Phys. Rev. D - Rapid Communications arXiv:1203.6034 [hep-ex]



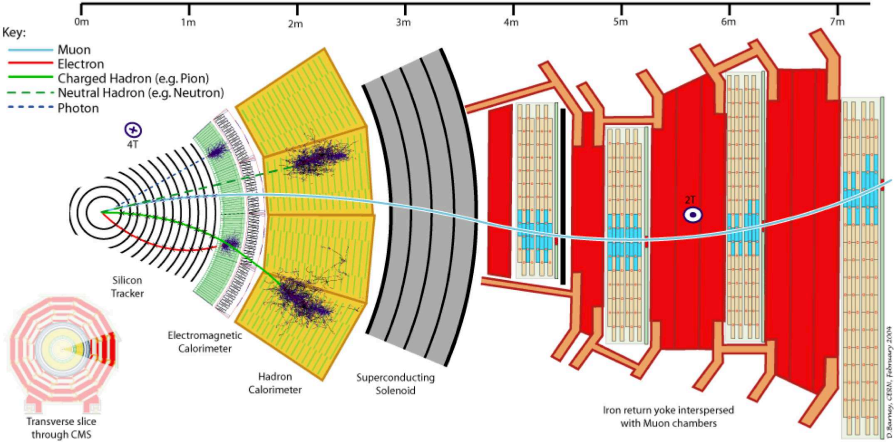
"...a third peak is observed at a mass consistent with the new state observed by the ATLAS collaboration."

$$\overline{m}_3 = 10.551 \pm 0.014\ (\text{stat.}) \pm 0.017\ (\text{syst.})\ \text{GeV}$$

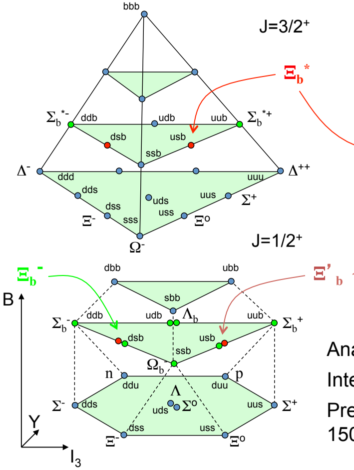
Observation of a new Ξ_b^{*0} baryon at CMS

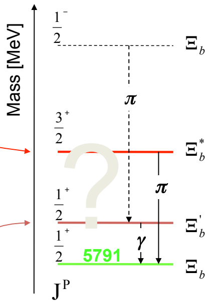


The CMS Detector



Submitted to Phys. Rev. Lett. (arXiv:1204.5955 [hep-ex])





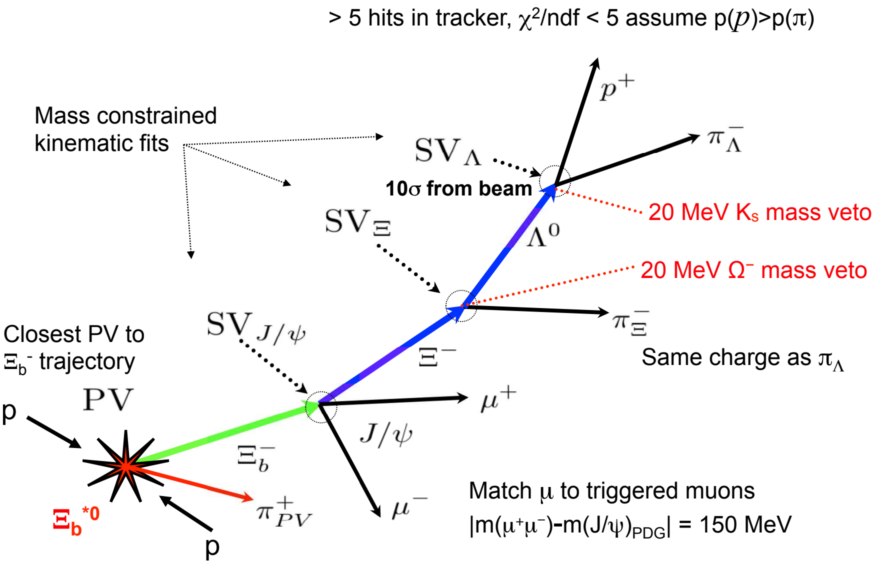
Analog to charmed baryon spectrum

Inter-quark potential + color hyperfine

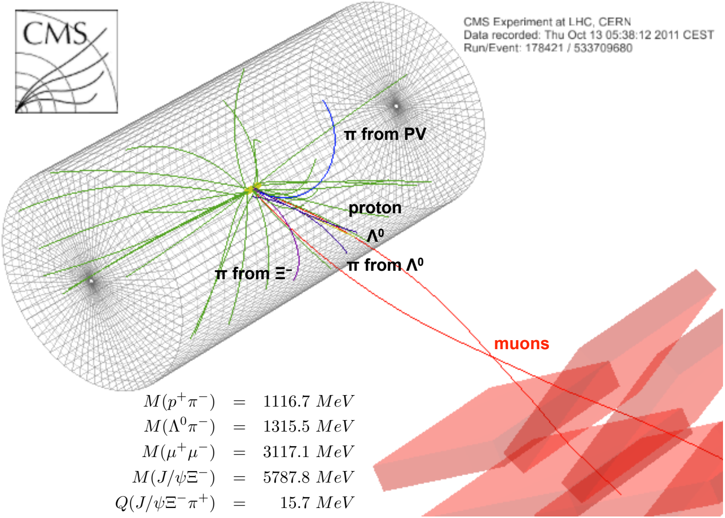
Predicted masses for higher states:
150 – 160 MeV higher, width ~ 1MeV

Ξ_b^- (+ C.C.) Reconstruction

Data recorded from the 2011 LHC run at $\sqrt{s} = 7$ TeV corresponding to 5.3 fb^{-1}



Event containing a Ξ_b^{*0} candidate



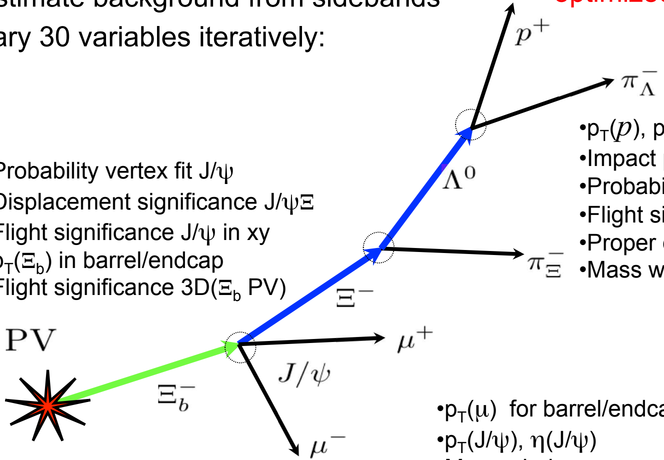
$$M(p^+\pi^-) = 1116.7\ MeV$$
$$M(\Lambda^0\pi^-) = 1315.5\ MeV$$
$$M(\mu^+\mu^-) = 3117.1\ MeV$$
$$M(J/\psi\Xi^-) = 5787.8\ MeV$$
$$Q(J/\psi\Xi^-\pi^+) = 15.7\ MeV$$

Cut & count optimizing FOM $S/\sqrt{S+B}$

Estimate background from sidebands

Vary 30 variables iteratively:

Only the Ξ_b^- selection is optimized (not Ξ_b^* signal)

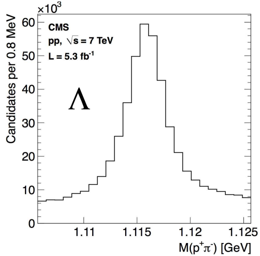


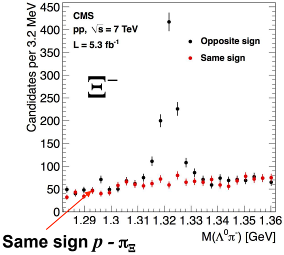
- Probability vertex fit J/ψ
- Displacement significance $J/\psi\Xi$
- Flight significance J/ψ in xy
- $p_T(\Xi_b)$ in barrel/endcap
- Flight significance 3D(Ξ_b PV)

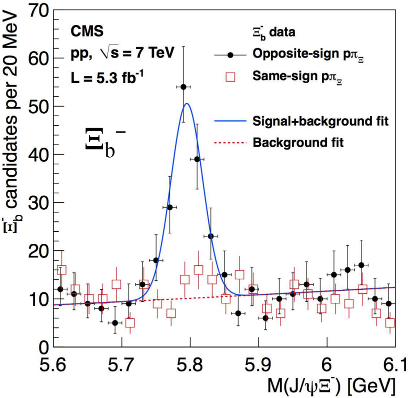
- $p_T(p)$, $p_T(\pi)$
- Impact parameter 3D I/σ_I
- Probability of vertex fit
- Flight significance Λ in xy
- Proper decay time
- Mass window

- $p_T(\mu)$ for barrel/endcap
- $p_T(J/\psi)$, $\eta(J/\psi)$
- Mass window

Ξ_b^- Reconstruction





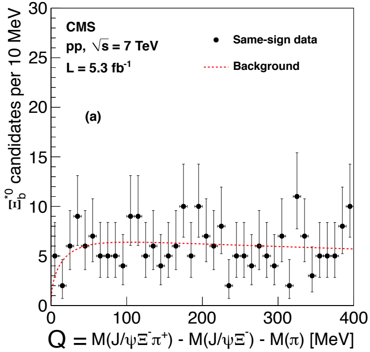


m = 5795.0 ± 3.1 MeV

σ = 23.7 MeV in agreement with MC

Next: Combine Ξ_b^- candidate with a track from the primary interaction vertex...

Background Model



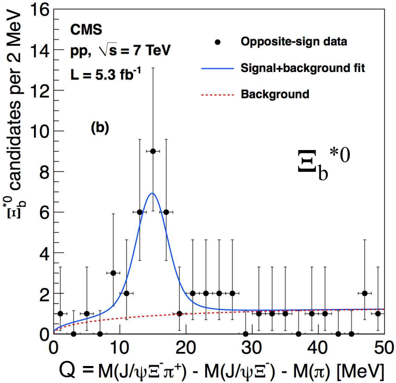
Background expected to be dominated by combinations of Ξ_b^- candidates and prompt tracks:

- Extract randomly $p(\Xi_b^-)$, $p(\pi)$, α (angle between Ξ_b^- and π) from their same-sign distributions 10^8 times
- Due to low statistical precision of the $p(\Xi_b^-)$ distribution, it is fit with an analytical distribution
- Calculate Ξ_b^{*0} background candidate mass from the three variables to get Q distribution

- Fit the distribution with $f(Q) = Q^{a_1} * (exp(-a_2 Q) + exp(-a_3 Q) + exp(-a_4 Q))$ (red dashed line)
- The $p(\Xi_b^-)$ distribution is fitted to several functions to estimate the systematic uncertainty on the background function parameters a_i
- This uncertainty is then propagated into the significance calculation

Ξ_b^{*0} Result

Combine Ξ_b^- candidate (mass within 2.5σ of fitted mean) with track of opposite sign with at least 2 pixel (5 tracker) hits and 3D distance to PV within $3\sigma_{PV}$:



Voigtian (σ=1.9±0.1 MeV from MC)
+combinatorial background

Significance: 6.9 σ

Width: Γ = 2.1±1.7 MeV

(Theory: 0.93 MeV)

Mean: Q = 14.84 + 0.74 MeV

Simulation → no excess due to other b-hadrons (B^0, B^+, B_s, Λ_b)

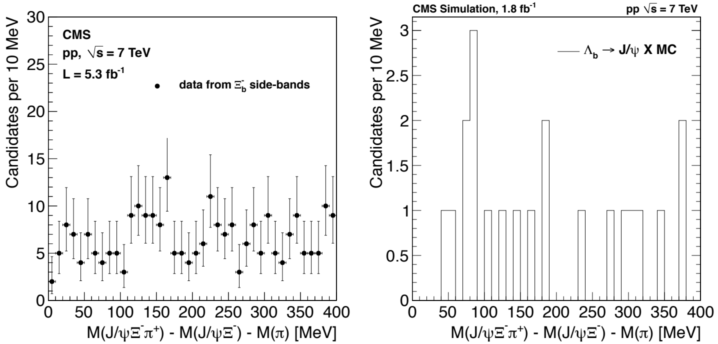
Systematic Uncertainties

- different background models
- differences data – simulation

➔ $m = 5945.0 \pm 2.7_{PDG} \pm 0.7_{stat} \pm 0.3_{syst}$ MeV

.. the first particle discovered by CMS, and the first baryon at the LHC

- **No excess seen from Ξ_b^- candidates from the mass distribution side-bands**
- **No excess seen in inclusive $\Lambda_b \to J/\psi X$ MC samples**



Additionally, no events are seen in the Q distribution from MC for other B hadron species: B^+, B^0, B_s

Conclusion

The ATLAS experiment has observed a new structure in the $\Upsilon(1S)\gamma$ and $\Upsilon(2S)\gamma$ mass spectra at a mass of around 10.53 GeV:

- The observed structure is compatible with theoretical predictions for the $\chi_b(3P)$ system
- Under this interpretation, the experimental mass barycentre is measured to be:

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

- Further measurements by ATLAS and other experiments will help to shed more light on the nature of the new state(s)

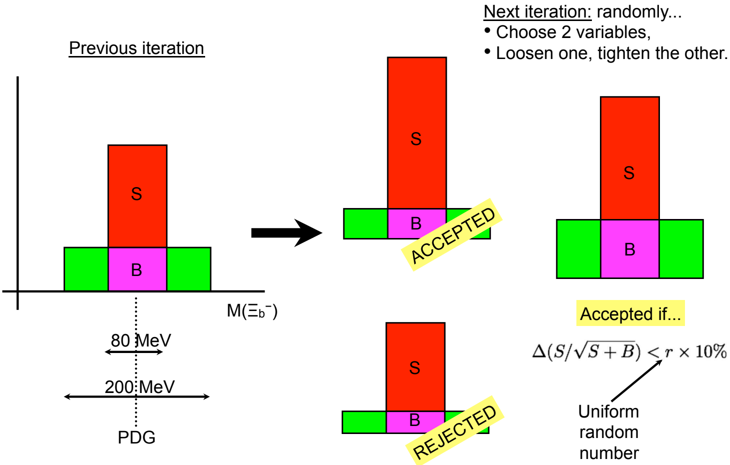
The CMS experiment has observed a new neutral Ξ_b^* baryon:

- The mass of the new baryon is measured to be:

$$m_{\Xi_b^{*0}} = 5945.0 \pm 0.7\ (\text{stat.}) \pm 0.3\ (\text{syst.}) \pm 2.7(PDG)\ \text{MeV}$$

Supplementary Material

CMS Ξ_b^{*0}: Ξ_b^- Selection Algorithm



CMS Ξ_b^{*0}: Systematic uncertainty on measurement of Ξ_b^{*0} fitted Q value

The systematic uncertainty on the measured Q value is first evaluated through a detailed MC simulation:

- The reconstructed Q value in MC is measured to be 0.23 ± 0.10 MeV above the generated value
- This is consistent with the observation that the measured Λ^0 and Ξ^- masses are above their world-averages by 0.16 ± 0.05 and 0.18 ± 0.14 MeV respectively
- The sum in quadrature of the shift and its statistical uncertainty, 0.25 MeV, is considered as the systematic uncertainty due to this effect

The systematic uncertainty is also estimated from variations in the fit model:

- As an extreme fitting scenario, a flat function is used for the background shape, leading to a Q value 0.12 MeV higher than the value measured

Adding these two uncertainties in quadrature gives a total Q systematic uncertainty of 0.28 MeV