Studying the χ_b states with ATLAS

Birmingham HEP Seminar

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University of Birmingham

3rd October, 2012

Outline

- Introduction to the bottomonium system and some "History"
- Brief review of $b\bar{b}$ spectroscopy
- χ_b studies at ATLAS
- χ_b analyses from DØ and LHCb
- Further opportunities at the LHC

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

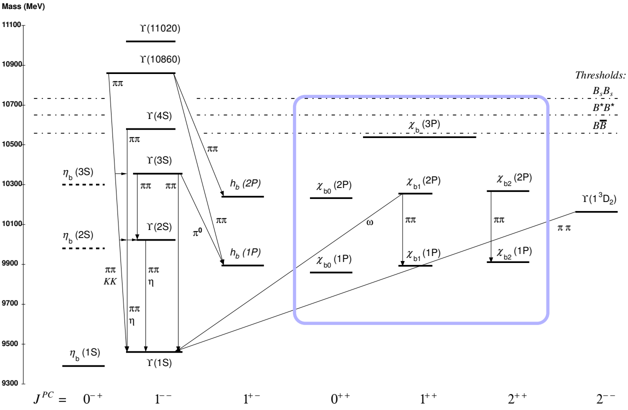

Figure: J. Beringer et al. (Particle Data Group), Phys. Rev. **D**86, 010001 (2012)

Radiative χ_b Decays

The radiative decays $\chi_b \to \Upsilon(nS)\gamma$ represent the most experimentally clean channels to reconstruct χ_b at the LHC:

- The radiative χ_b decays benefit from large branching fractions ✓
- $\mathcal{B}(\Upsilon(nS) \to \mu^+\mu^-)$ is $1-2\%$ and a di-muon signature is clean ✓
- Photons are *very* soft ✗ (<1 GeV in χ_b rest frame)

PDG Summary (masses rounded to nearest 1 MeV, E_γ in rest frame of χ_b)

	Mass [MeV]	E_γ [MeV]	$\mathcal{B}(\Upsilon(1S)\gamma)$	E_γ [MeV]	$\mathcal{B}(\Upsilon(2S)\gamma)$
$\chi_{b0}(1P)$	9859	391	<6%	-	-
$\chi_{b1}(1P)$	9893	423	35%	-	-
$\chi_{b2}(1P)$	9912	442	22%	-	-
$\chi_{b0}(2P)$	10233	743	1%	207	5%
$\chi_{b1}(2P)$	10255	764	9%	230	21%
$\chi_{b2}(2P)$	10269	777	7%	242	16%

Predictions from QCD inspired potential models:

1. Phys. Rev. D **36** 3401 (1987)
2. Phys. Rev. D **38** 279 (1988)
3. Eur. Phys. J. C. **4** 107 (1998)

- Just below the $B\bar{B}$ threshold (10.558 GeV)
- Narrow, $\Gamma < 1$ MeV if...
- ...$\Gamma(\chi_b(3P) \to \Upsilon(1,2,3S)\gamma)/\Gamma_{Tot.}$ is large (expected to be so)
- $\Gamma(\Upsilon(3S)\gamma) > \Gamma(\Upsilon(2S)\gamma) > \Gamma(\Upsilon(1S)\gamma)$

Publication	3^3P c.o.g	$\Delta 3^3P_0$	$\Delta 3^3P_1$	$\Delta 3^3P_2$
2.	10.520 GeV	-19 MeV	-4 MeV	+6 MeV
3.	10.525 GeV	-22 MeV	-4.9 MeV	+7.3 MeV

NAL PROPOSAL # 288

Scientific Spokesman:

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A Study of Di-Lepton Production in Proton Collisions at NAL

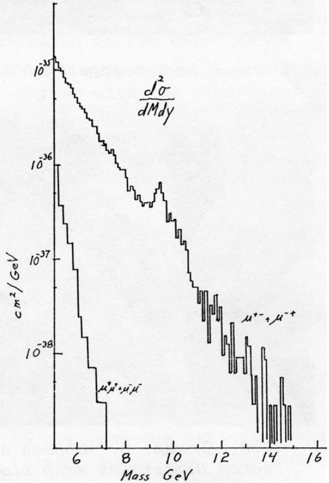
J. A. Appel, M. H. Bourquin, D. C. Hom, L. M. Lederman, J. P. Repellin, H. D. Snyder, J. K. Yoh (Columbia University); B. C. Brown, P. Limon, T. Yamanouchi (NAL).

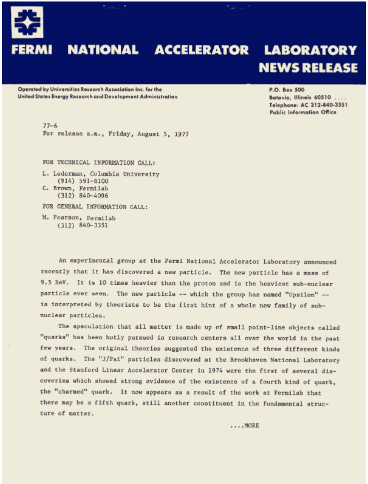
(Formerly #70 Phase III)

1. **Observe and measure the spectrum of virtual photons emitted in p-nucleon collisions via the mass distribution of e^+e^- pairs: $p + p \rightarrow e^+ e^- +$ anything. (1)**
   Study characteristics, e.g. parity violation, $p_\perp$ behavior.
2. **Search for structures in the above spectrum, publish these and become famous, e.g. W°, B°.**

5. **Extend the Experiment #70 study of single leptons in the double arm arrangement, i.e. $W^\pm$ etc. Publish these and become famous.**

History: 1977 - The CFS Collaboration discover the Υ with E288





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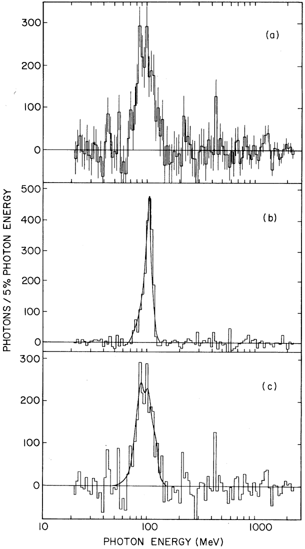
An experimental group at the Fermi National Accelerator Laboratory announced recently that it has discovered a new particle. The new particle has a mass of 9.5 BeV. It is 10 times heavier than the proton and is the heaviest sub-nuclear particle ever seen. The new particle -- which the group has named "Upsilon" -- is interpreted by theorists to be the first hint of a whole new family of sub-nuclear particles.

The speculation that all matter is made up of small point-line objects called "quarks" has been hotly pursued in research centers all over the world in the past few years. The original theories suggested the existence of three different kinds of quarks. The "J/Psi" particles discovered at the Brookhaven National Laboratory and the Stanford Linear Accelerator Center in 1974 were the first of several discoveries which showed strong evidence of the existence of a fourth kind of quark, the "charmed" quark. It now appears as a result of the work at Fermilab that there may be a fifth quark, still another constituent in the fundamental structure of matter.

....MORE

"An experimental group at the Fermi National Accelerator Laboratory announced recently that it has discovered a new particle. The new particle has a mass of 9.5 GeV..."



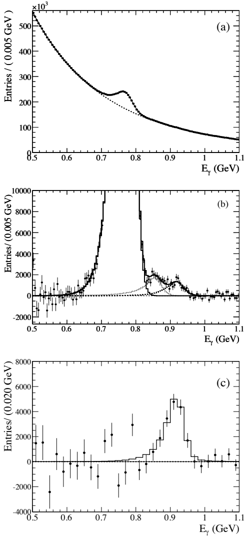
Phys. Rev. Lett. 49, 1612 and 1616 (1982)

- First saw evidence of $\Upsilon(3S) \rightarrow \chi_b(2P)\gamma$ (figure)
- Then observed the $\chi_b(2P) \rightarrow \Upsilon(1,2S)\gamma$

Phys. Rev. Lett. 51, 160 (1983)

- The next year, $\Upsilon(2S) \rightarrow \chi_b(1P)\gamma$ and $\chi_b(1P) \rightarrow \Upsilon(1S)\gamma$ were both observed

History: Some time later... BaBar and Belle find the η_b and h_b

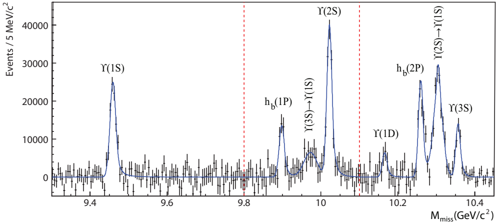


Phys. Rev. Lett. 101, 071801 (2008)

- Babar observed $\Upsilon(3S) \to \eta_b(1S)\gamma$ (left)

Phys. Rev. Lett. 108, 032001 (2012)

- Belle observed $\Upsilon(5S) \to h_b(1,2P)\pi^+\pi^+$ (below)



All discoveries in the bottomonium system since the Υ made by e^+e^- experiments!

Things get weird! Two charged bottomonium-like resonances!

Phys. Rev. Lett. 108, 122001 (2012) (arXiv:1110.2251)

Belle recently reported the observation of two narrow structures in $\pi^{\pm}\Upsilon(nS)$ (n = 1, 2, 3) and $\pi^{\pm}h_b(mS)$ (m = 1,2) pairs produced in association with a single charged pion in $\Upsilon(5S)$ decays!

Quarkonium physics can still surprise us!

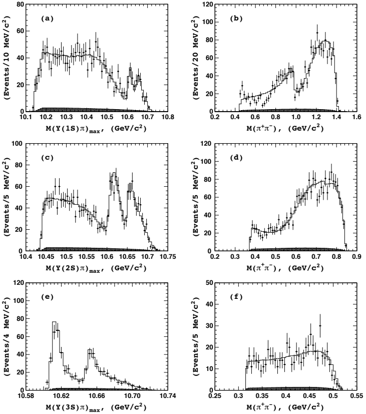
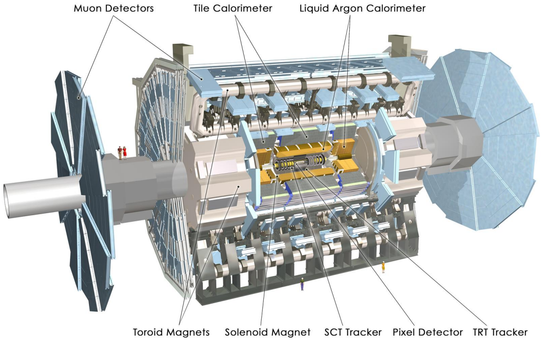


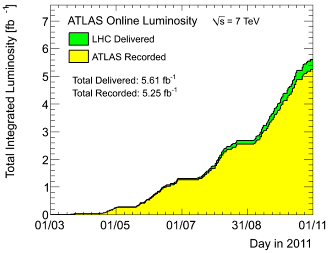
FIG. 2: Comparison of fit results (open histogram) with experimental data (points with error bars) for events in the $\Upsilon(1S)$ (a,b), $\Upsilon(2S)$ (c,d), and $\Upsilon(3S)$ (e,f) signal regions. The hatched histogram shows the background component.

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:

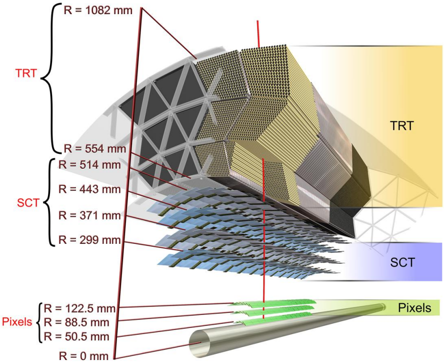


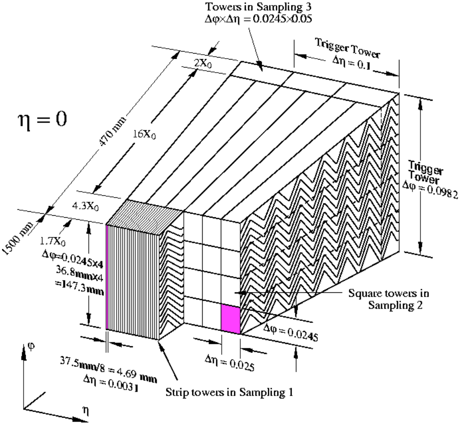
ATLAS collected over 5 fb^{-1} of data during the 2011 LHC run at $\sqrt{s} = 7$ TeV

Also, over 14 fb^{-1} collected to date at $\sqrt{s} = 8$ TeV during 2012!

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

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





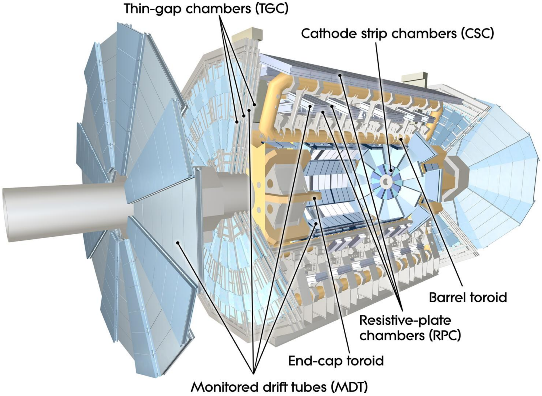
Liquid Argon EM Calorimeter ($|\eta| < 3.2$)

- 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:

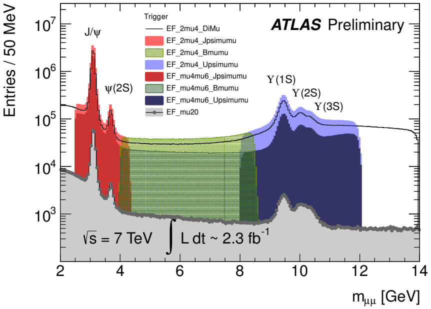
- The unconverted photon analysis is capable of reconstructing $\chi_b \to \Upsilon(1S)\gamma$ decays alone
- The converted photon analysis is capable of reconstructing both $\chi_b \to \Upsilon(1S)\gamma$ and $\chi_b \to \Upsilon(2S)\gamma$ decays

Data Sample and Trigger Selection

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)



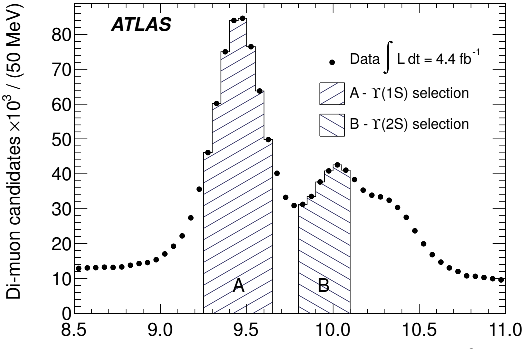
Selection of $\Upsilon(1,2S) \to \mu^+\mu^-$ candidates is common to both the unconverted and converted photon analyses:

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

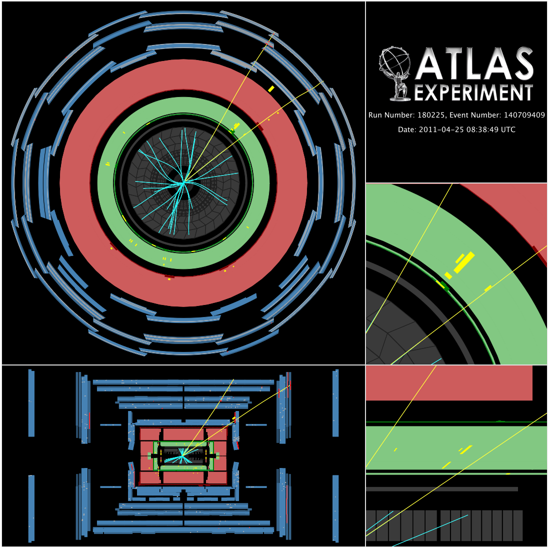
- Oppositely charged di-muon pair
- $\mu^+\mu^-$ common vertex fit $\chi^2/N_{D.o.F} < 20$
- $p_T(\mu^+\mu^-) > 12$ GeV
- Rapidity $|y(\mu^+\mu^-)| < 2.0$
- Both muons associated to same primary *pp* interaction



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

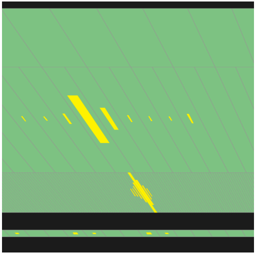
Unconverted Photon Selection

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"† 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



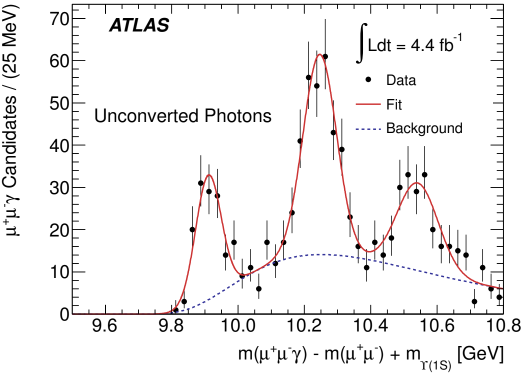
$\chi_b \to \Upsilon(1S)\gamma$ Selection

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

† 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 $\Upsilon \rightarrow \mu^+\mu^-$ 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

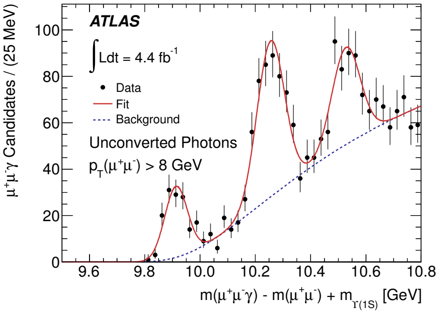
- Unconverted photon energy scale uncertainty (estimated at $\pm 2\%$ of the ΔM position)
- Modelling of the background distribution (estimated from refitting with various alternative models)

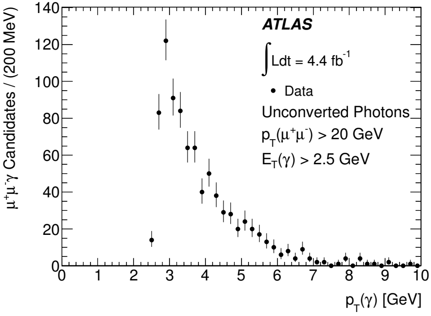
	Fitted Mass (MeV)
$\chi_b(1P)$	9910 ± 6 (stat.) ± 11 (syst.)
$\chi_b(2P)$	10246 ± 5 (stat.) ± 18 (syst.)
$\chi_b(3P)$	10541 ± 11 (stat.) ± 30 (syst.)

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

Unconverted Photon Result III

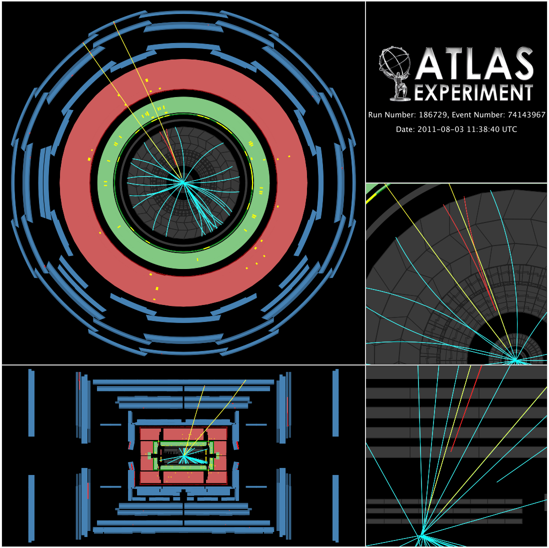
Left: $m\left(\mu^+\mu^-\gamma\right) - m\left(\mu^+\mu^-\right) + m^{PDG}_{\Upsilon(1S)}$ distribution without a lower $p_T(\mu^+\mu^-) > 8$ GeV cut.





Right: Unconverted photon $p_T(\gamma)s$ distribution for $\Upsilon(1S)\gamma$ candidates.

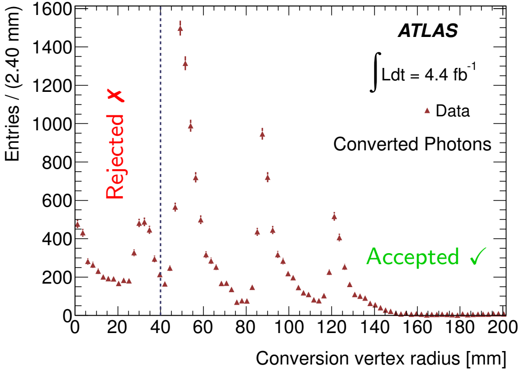
Converted Photon Analysis



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

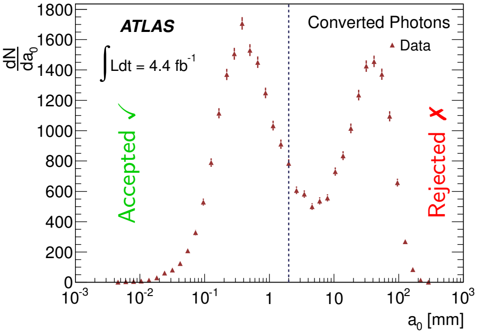
Reconstructing photons from e^+e^- conversions in the Inner Detector (ID) offers improved resolution and access to softer photons:

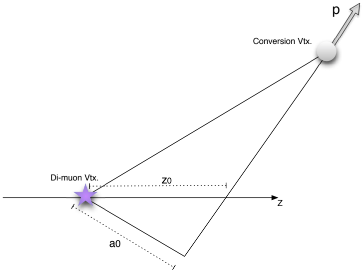
- Reconstructed from ID measurements *alone* (no EM cluster matching)
- Minimum track momentum $p_T(e^\pm) > 500$ MeV
- $p_T(\gamma) > 1$ GeV
- $|\eta(\gamma)| < 2.3$
- Only two-track conversions are retained
- 4 silicon detector hits required for each electron track



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

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:

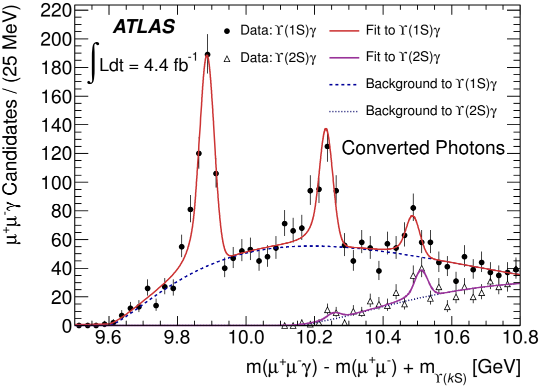




- $a_0 < 2$ mm is required to **reject photon combinatorics not compatible with having originated from the di-muon vertex**
- The χ^2 probability of the conversion vertex fit is required to be greater than 0.01

Converted Photon Result I

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

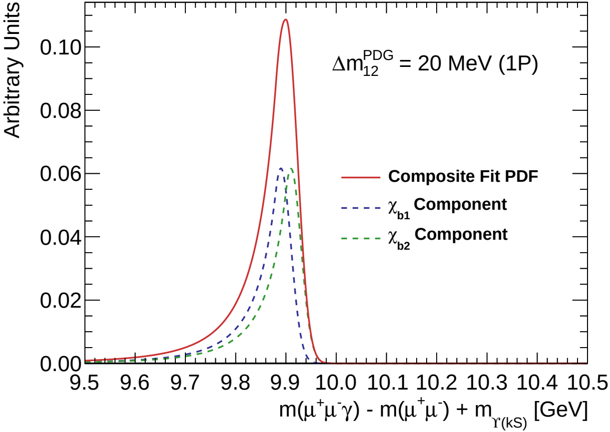
Under the interpretation of the third signal as $\chi_b(3P)$, the experimental mass barycentre is measured from a simultaneous unbinned extended maximum likelihood fit to both the $\Upsilon(1S)\gamma$ and $\Upsilon(2S)\gamma$ mass distributions:

- 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 $(\Delta m - q_0)^{\alpha} \cdot \exp\{(\Delta m - q_0) \cdot \beta\}$

Signal Fit Model



- For demonstration, $\sigma = 20$ MeV (i.e. $1P$ $J = 1, 2$ splitting)
- No knowledge of $\sigma \cdot \mathcal{B}$ for any of the states
- Relative normalisation of χ_{b1} and χ_{b2} components is fixed to be equal

Converted Photon Result II

Assigned Systematic Uncertainties:

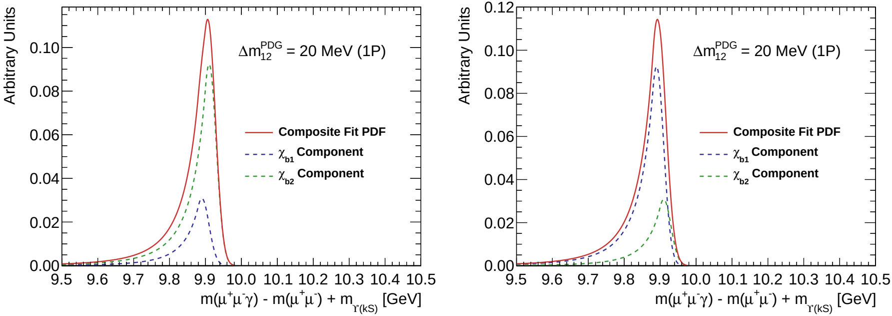
- Vary relative $J = 1, 2$ signal normalisation by ± 0.25 (or left free in fit): ± 5 MeV
- Alternative signal and background models: ± 5 MeV
- Decoupled fits to the $\Upsilon(1S)$ and $\Upsilon(2S)$ distributions: ± 5 MeV
- Individually releasing constraints to the PDG values for the $\chi_b(1P)$ and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

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

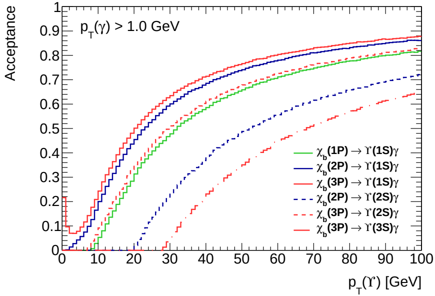
Demonstration of $J = 1, 2$ Normalisation Systematic

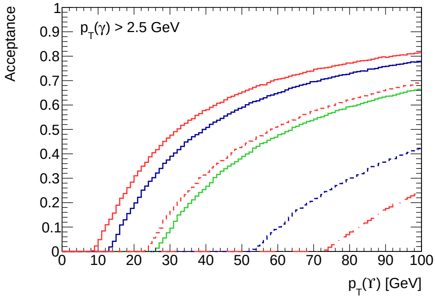


Fit result is not very sensitive to $J = 1, 2$ normalisation as $\sigma \sim \Delta M_{12}$

- Bye eye, difficult to notice any difference in the shape of the composite PDF!
- Reflected in small systematic shift in measured mass ($\pm$5 MeV)

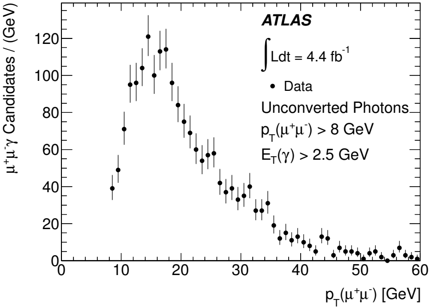
Relative Acceptance





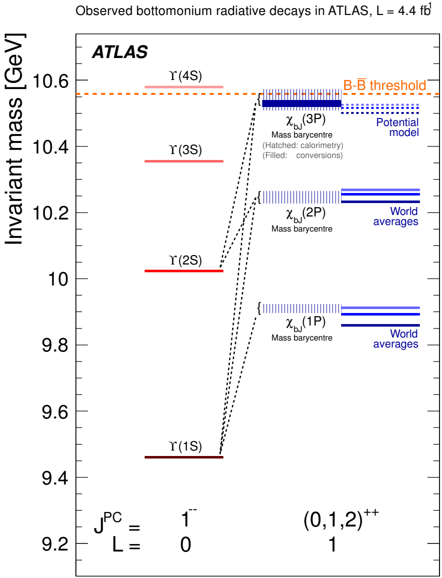
Large difference in acceptance between the three states due to minimum $p_T(\gamma)$ reconstruction threshold:

- Converted photons have much larger acceptance for all decays at low $p_T(\Upsilon)$
- Unconverted photons have a much reduced acceptance due to the $p_T(\gamma) > 2.5$ GeV reconstruction threshold



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

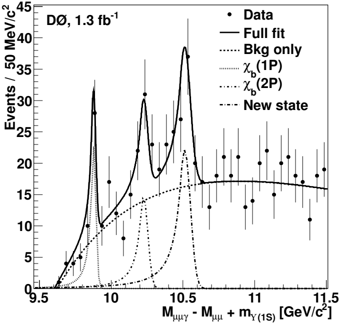


Confirmation by $D\O$

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

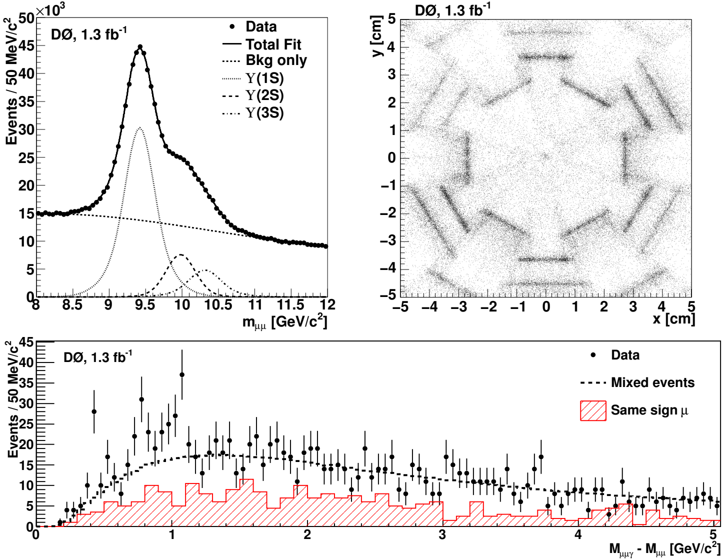
Observation of a narrow state decaying into $\Upsilon(1S) + \gamma$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

Phys. Rev. D **86**, 031103(R) (2012) (arXiv:1203.6034 [hep-ex])



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

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

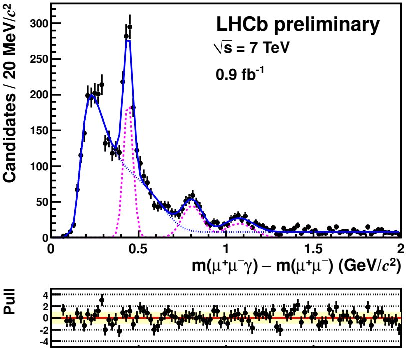

DØ, 1.3 fb^{-1}
Data
Total Fit
Bkg only
Υ(1S)
Υ(2S)
Υ(3S)
Events / 50 MeV/c^2
×10^3
$m_{\mu\mu}$ [GeV/c^2]
DØ, 1.3 fb^{-1}
y [cm]
x [cm]
DØ, 1.3 fb^{-1}
Data
Mixed events
Same sign μ
Events / 50 MeV/c^2
$M_{\mu\mu\gamma}$ - $M_{\mu\mu}$ [GeV/c^2]

Confirmation by LHCb

LHCb later confirmed the observation at ICHEP2012 in a preliminary conference note:

Observation of the $\chi_b(3P)$ state at LHCb in *pp* collisions at $\sqrt{s} = 7$ TeV

LHCb-CONF-2012-020

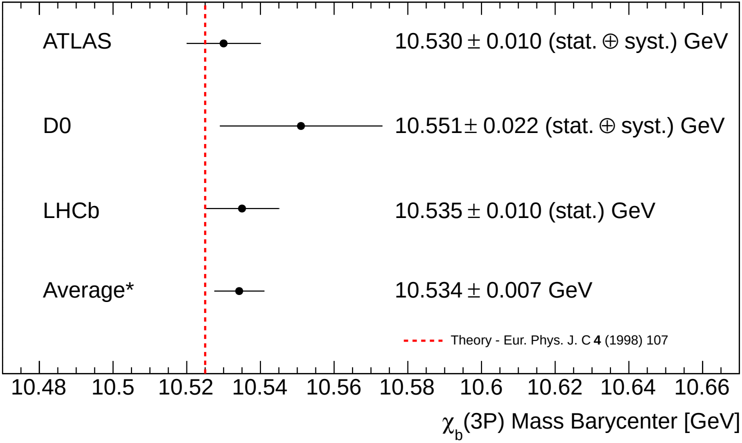


"Three peaks are clearly visible, corresponding to the $\chi_b(1P)$, $\chi_b(2P)$, and the new $\chi_b(3P)$ state recently observed by the ATLAS experiment and confirmed by $D\text{Ø}$."

$$\overline{m}_3 = 10.535 \pm 0.010\ (\text{stat.})\ \text{GeV}$$

Unofficial Combination!

Warning! This is my own† DIY "World Average"



†Nothing to do with the PDG, ATLAS, *DØ* or LHCb!

Summary of theoretical work prompted by the observation of the $\chi_b(3P)$ candidate:

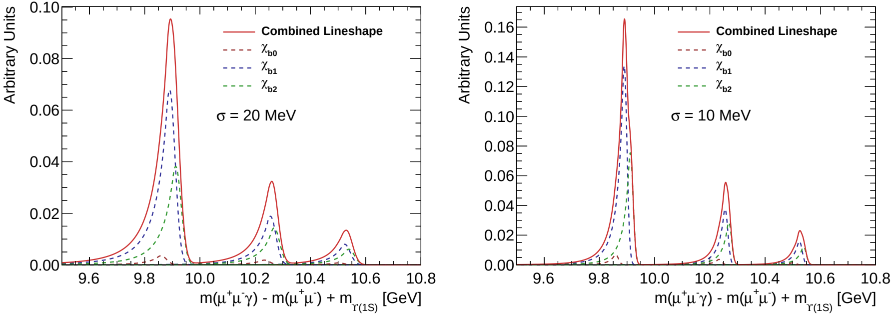
- **Potential model results for the newly discovered $\chi_b(3P)$ states**
- arXiv:1201.4096
- **Production of χ_b mesons at LHC**
- arXiv:1203.4893
- **Comment on "Observation of a New χ_b State in Radiative Transitions to $\Upsilon(1S)$ and $\Upsilon(2S)$ at ATLAS"**
- arXiv:1204.1984
- **Developments in heavy quarkonium spectroscopy**
- arXiv:1205.4189
- **$\chi_b(3P)$ splitting predictions in potential models**
- arXiv:1208.2186

Perhaps the most important implication:

- Another source of feed down into the inclusive $\Upsilon(nS)$ cross section
- The inclusive $\Upsilon(3S)$ cross section was previously thought to be free from significant feed down, $\mathcal{B}(\chi_b(3P) \to \Upsilon(3S)\gamma)$ expected to be large

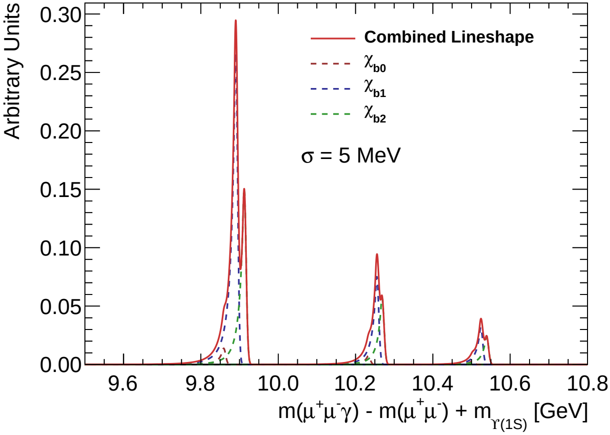
Will we ever resolve hyperfine structure (in $\Upsilon(nS)\gamma$) at the LHC?

You may need to squint!



- Investigate with a **crude** model and purely **qualitative** analysis!
- Relative normalisation of $J = 0, 1, 2$ taken from PDG branching fractions (assume equal production ratio and assume $2P$ values for $3P$)
- Relative production of $n = 1, 2, 3$ taken from recent ATLAS Υ production paper
- No acceptance effects, resolution modelled by CB with various different Gaussian widths σ

It looks difficult! Need $\sigma < 10$ MeV at least!



- Mass resolution of around 5 MeV very challenging at the LHC (for ATLAS at least!)

Important to look in other channels!

The (non-)observation of the new state in other decays could shed more light on its nature and confirm / rule out the $\chi_b(3P)$ interpretation. Some channels that might be possible at the LHC include:

- $\chi_b \to \Upsilon + \omega$
- $\chi_b \to \Upsilon + \Phi$
- $\chi_b \to J/\psi J/\psi$
- Other VV final states?

Cross section $(1, 2P)$ and $3P$ $\sigma \cdot \mathcal{B}(\chi_b(3P) \to \Upsilon(1S)\,\gamma)$ measurements

- Possible with 2012 dataset

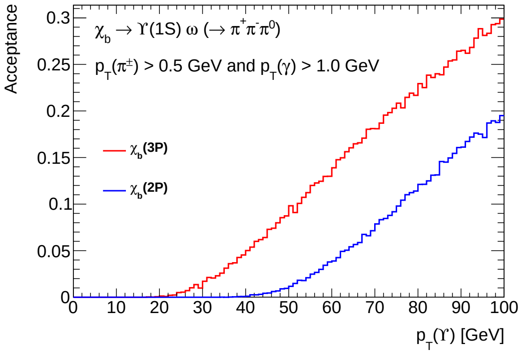
Spin, Parity and Polarization measurements

- Likely to require more data, complex analyses...
- Polarization is accessible through an angular analysis of final state di-muons in $\chi_b \to \Upsilon(nS)\gamma$ (arXiv:1103.4882)

$\chi_b \to \Upsilon(1S)\,\omega$

CLEO has observed $\chi_b(2P) \to \Upsilon(1S)\,\omega$ decays (Phys. Rev. Lett. 92, 222002 (2004))

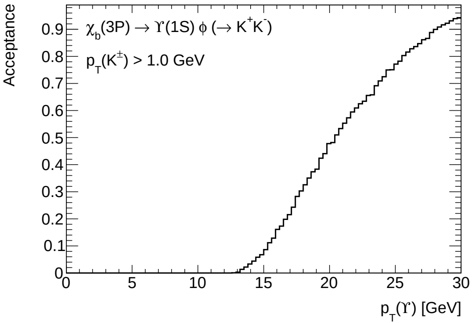
- Only $\chi_{b1}(2P)$ and $\chi_{b2}(2P)$ are above the $\Upsilon(1S)\,\omega$ threshold
- $\mathcal{B}(\chi_b(2P) \to \Upsilon(1S)\,\omega) = 1 - 2\%$! ✓
- ω momentum in χ_b rest frame only 135(94) MeV! ✗



Bottom Line - Low acceptance with ATLAS, huge backgrounds! Possible with LHCb?

The new state at 10.53 GeV is above the $\Upsilon(1S)\,\phi(1020)$ threshold...

- Not yet observed...
- $\mathcal{B}(\chi_b(3P) \to \Upsilon(1S)\,\phi)$ not measured or calculated! (as far as I am aware) ✗
- High acceptance with $\phi \to K^+K^-$ ($\mathcal{B}(\phi \to K^+K^-)$ is also large $\sim 50\%$) ✓
- $\Upsilon(1S) + 2$ tracks with ATLAS's limited PID might be messy! ✗



Bottom Line - $\mathcal{B}$ may be very low! LHCb (with good PID) more sensitive?

$\chi_b \to J/\psi\, J/\psi$

$\chi_b \to J/\psi\, J/\psi$: a potentially a very clean signal at the LHC

- 4 Lepton (4μ more realistic at low p_T) very clean, low background ✓
- $\chi_{b1} \to J/\psi\, J/\psi$ is Landau-Yang forbidden, $\Delta m_{0,2} \approx 53$ MeV large enough to be resolved? ✓
- $\mathcal{B}(\chi_{b0} \to J/\psi\, J/\psi) \approx 2 \times 10^{-4}$ (Phys. Rev. **D72** (2005) 094018) ✗
- $\mathcal{B}(J/\psi \to \mu^+\mu^-)^2 \approx 3.6 \times 10^{-3}$ ✗

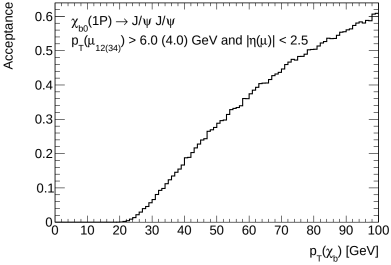
The inclusive cross section for χ_{b0} at the LHC is estimated to be as much as $\sigma(pp \to \chi_{b0} + X) \approx 1\mu\mathrm{b}$:

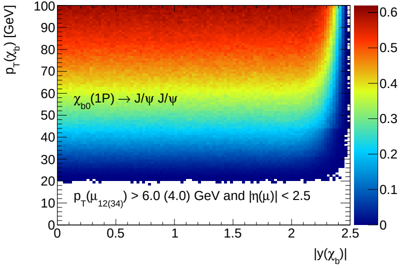
- Rough estimate of 700 events per fb^{-1} (before trigger, acceptance and reconstruction)
- Strong potential for observation with $> 20\mathrm{fb}^{-1}$ from 2011 + 2012 (ATLAS / CMS)

$\chi_b \to J/\psi\, J/\psi$

Estimates suggest a large raw event yield, but how many χ_b are likely to be reconstructed?

- Require $p_T(\mu) > 6$ GeV for triggered J/ψ and $p_T(\mu) > 4$ GeV for the other with all muons required to be within $|\eta(\mu)| < 2.5$



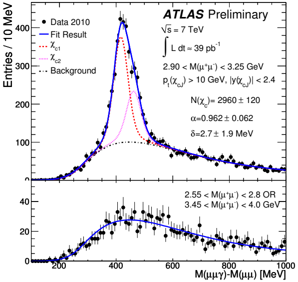


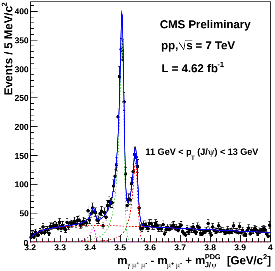
- Acceptance and trigger thresholds allow only very boosted ($p_T > 20 GeV$) χ_b to be reconstructed
- This will significantly (factor of ~ 100) reduce the yields on the previous slide!

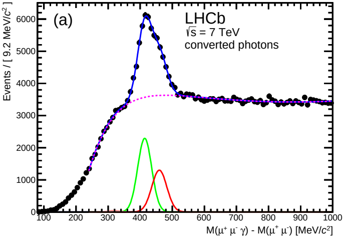
Bottom Line - Likely to need 10s fb^{-1} data for an observation, possible in 2012?

- The known $\chi_b(1,2P)$ states are observed in radiative decays to $\Upsilon(1S)\,\gamma$ at ATLAS
- **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
- Many more interesting opportunities at the LHC!

Thank you for listening!


ATLAS Preliminary
√s = 7 TeV
∫ L dt ≈ 39 pb^-1
2.90 < M(μ+μ-) < 3.25 GeV
pt(χcJ) > 10 GeV, |y(χcJ)| < 2.4
N(χc)= 2960 ± 120
α=0.962 ± 0.062
δ=2.7 ± 1.9 MeV
Data 2010
Fit Result
χc1
χc2
Background
Entries / 10 MeV
2.55 < M(μ+μ-) < 2.8 OR
3.45 < M(μ+μ-) < 4.0 GeV
M(μμγ)-M(μμ) [MeV]


CMS Preliminary
pp,√s = 7 TeV
L = 4.62 fb^-1
11 GeV < pT (J/ψ) < 13 GeV
Events / 5 MeV/c²
mγμ+μ- - mμ+μ- + m PDG J/ψ [GeV/c²]


(a)
LHCb
√s = 7 TeV
converted photons
Events / [9.2 MeV/c²]
M(μ+ μ- γ) - M(μ+ μ-) [MeV/c²]