

# Quarkonium spectroscopy and production of excited states

Claus Buszello for the ATLAS Collaboration  
QWG 2013, Beijing



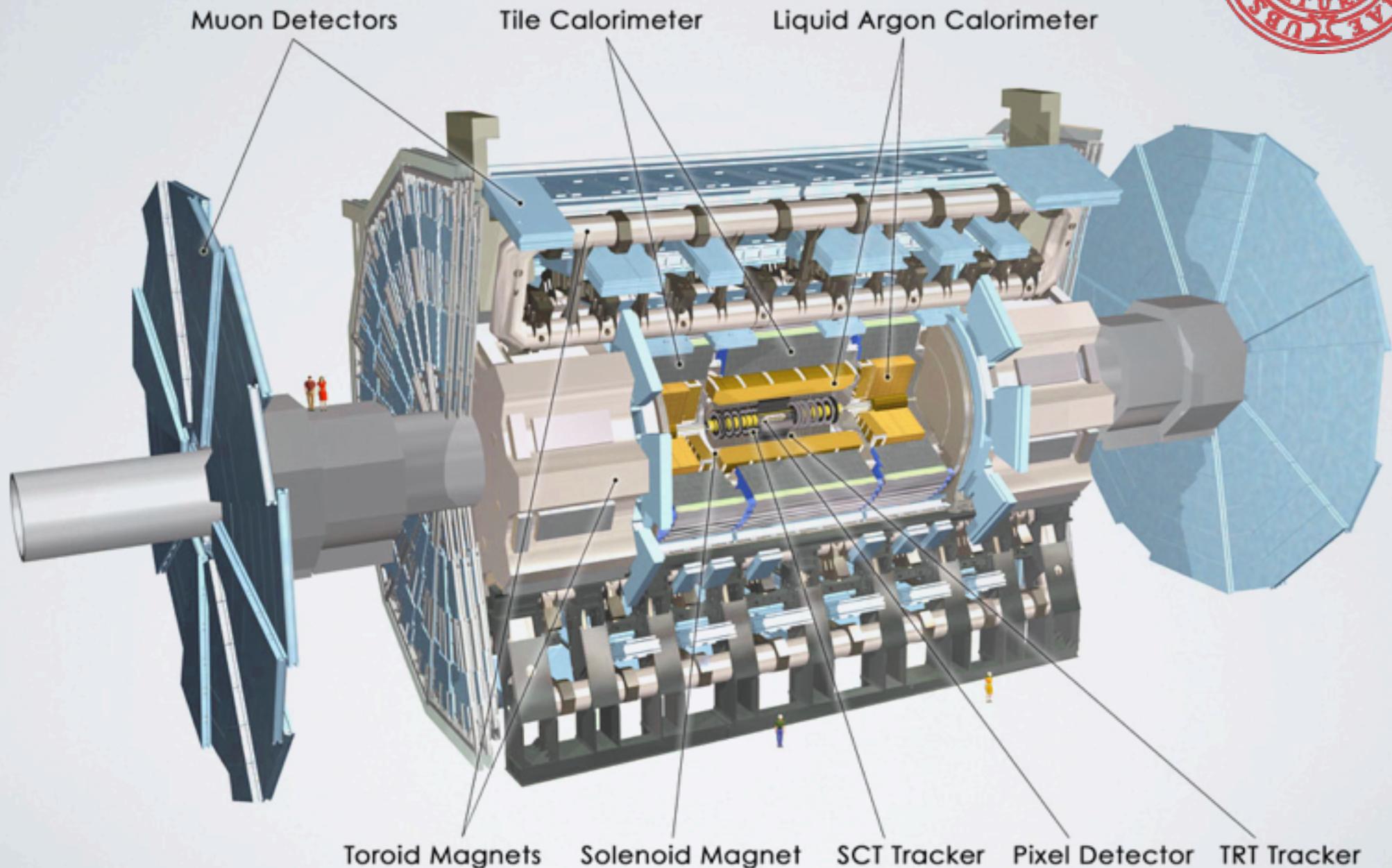


# Outline

---

- Introduction
  - Detector
  - Triggers
  - Muons and Photons
- $\chi_c$  Reconstruction
- $\chi_b(3P)$  Discovery
- $B_c$  Reconstruction

# ATLAS



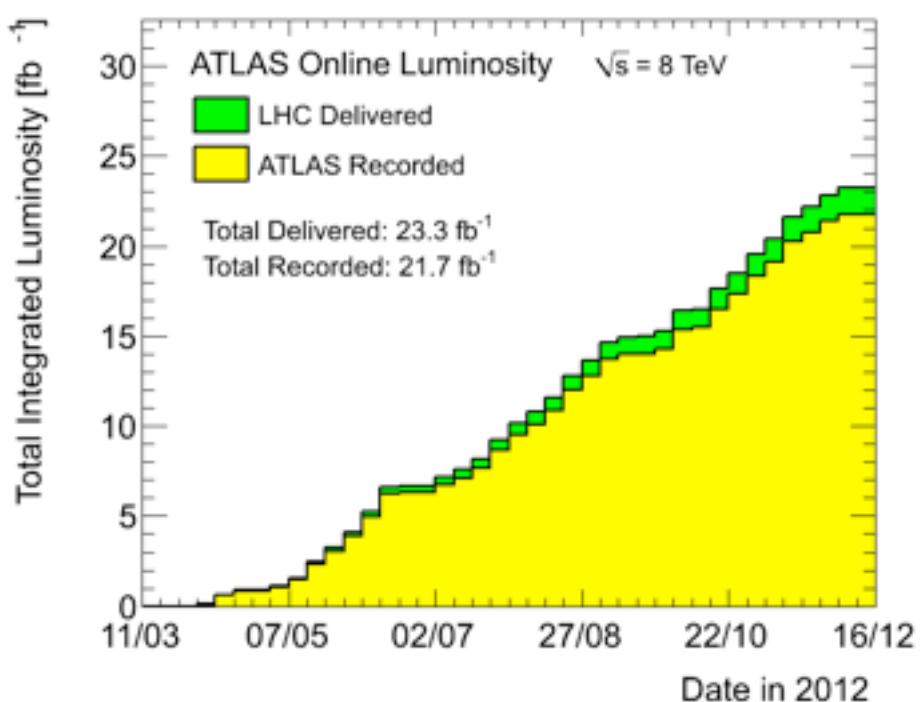
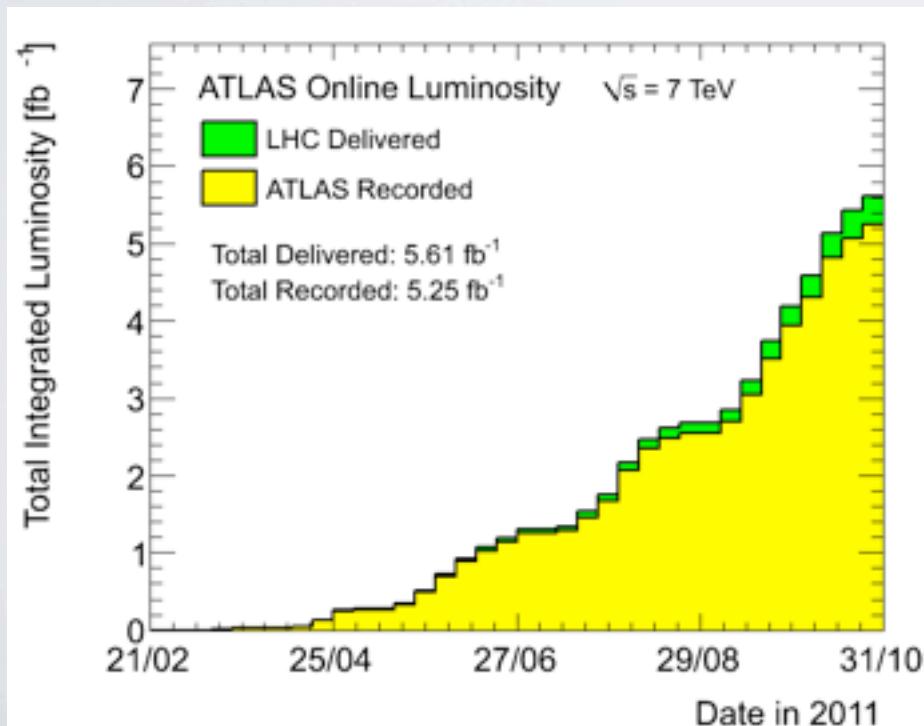
# Recorded Data



## ATLAS Recorded

- >  $5 \text{ fb}^{-1}$  of 7 TeV data in 2010 and 2011
- >  $21 \text{ fb}^{-1}$  of 8 TeV data in 2012

Available statistics for analysis also depends on selected triggers.

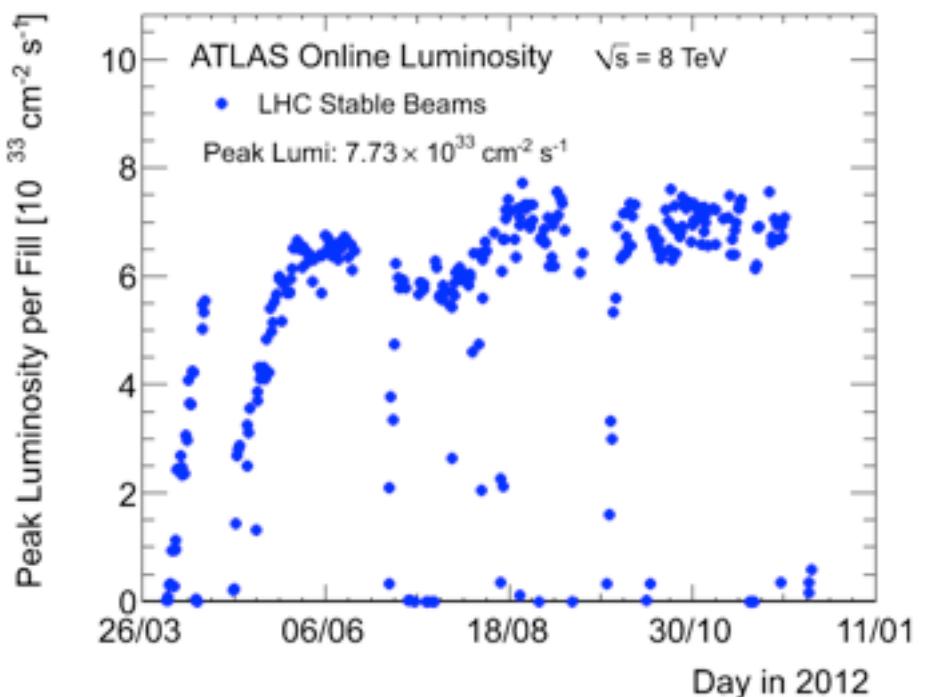
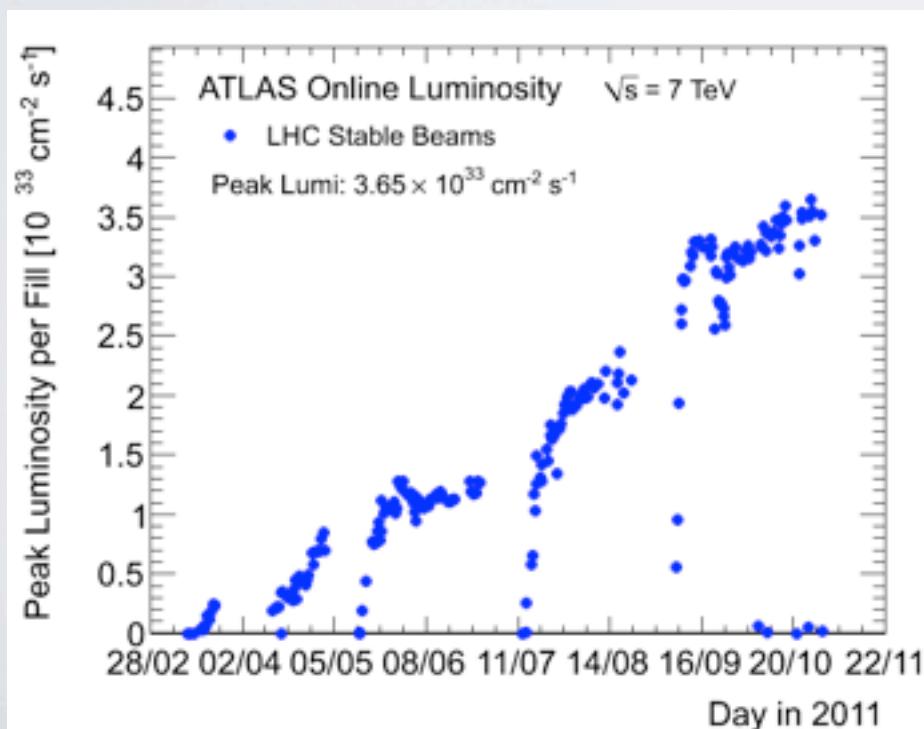


# Recorded Data



Steady increase in instantaneous luminosity  
= greater number of collisions per bunch crossing

- slight degradation in tracking efficiency
- higher combinatoric background

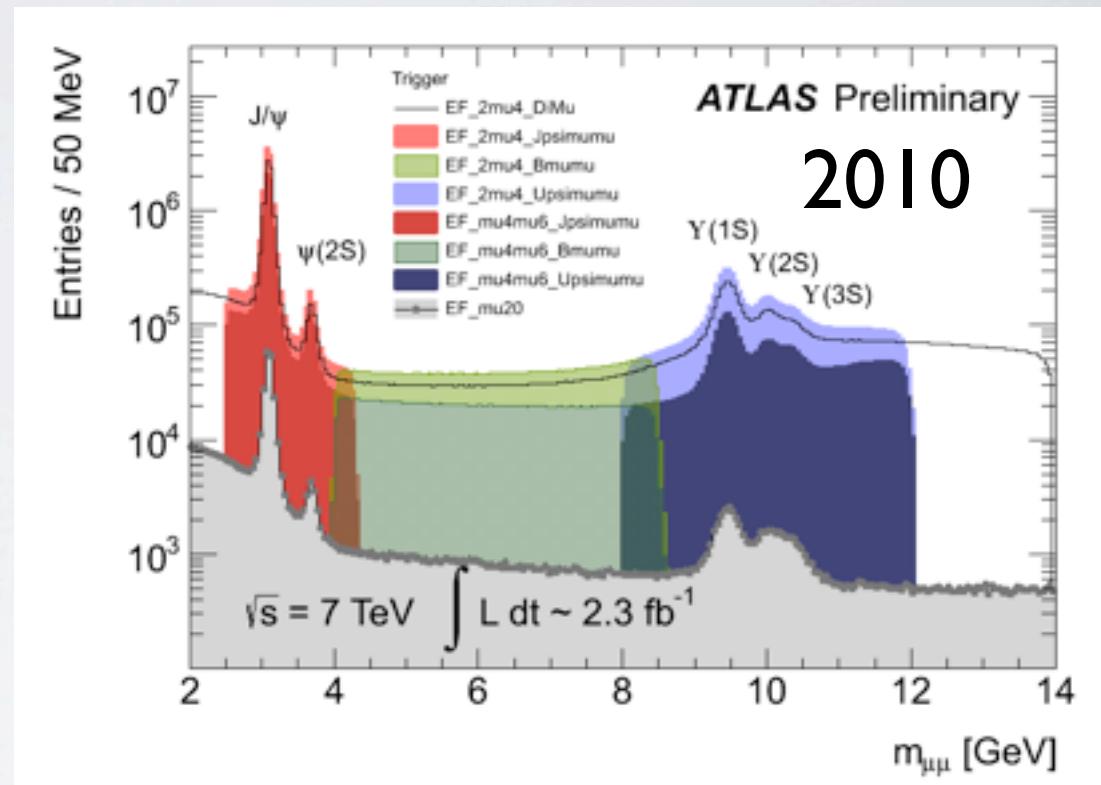


# B physics Triggers



- Seeded by high  $p_T$  muon,  $p_T > 4/6 \text{ GeV}$
- Additional muon  $p_T > 2.5/4 \text{ GeV}$

- $\mu\mu$  Mass windows
  - $J/\psi$
  - $Y$
  - $b \rightarrow \text{di-muon}$

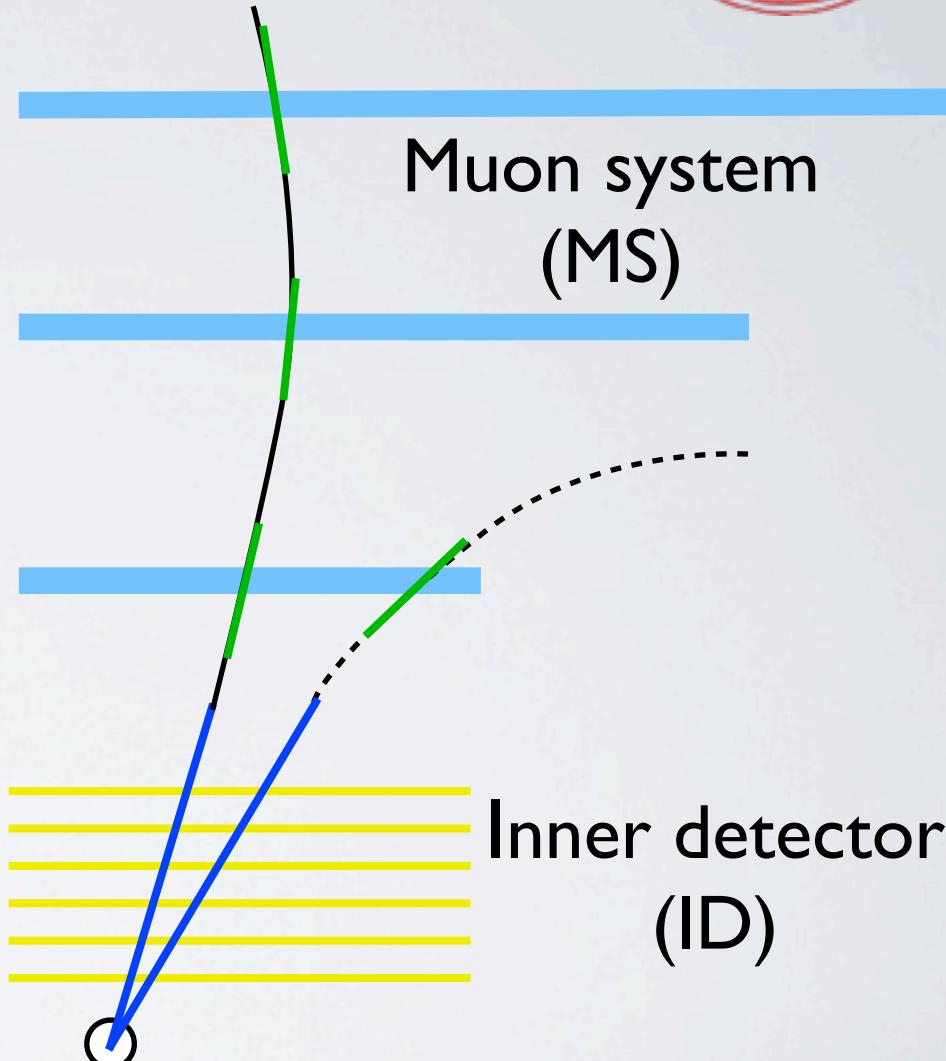


- Efficient and inclusive, moderate threshold
- No lifetime cuts or pre-scales in trigger

# Muons



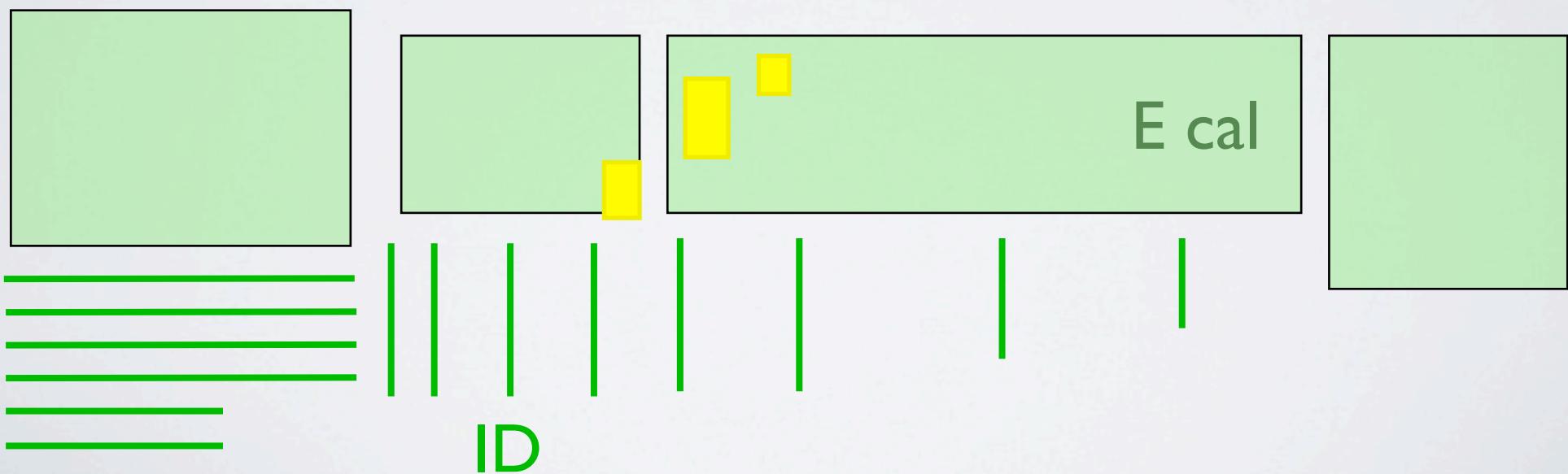
- Combined muons
  - Reconstructed MS muon
  - Combined with ID track
  - Resolution optimised for high  $p_T$  muons from MS
- Tagged Muon
  - Good ID track
  - Tagged with segment in MS
  - Good resolution and improved efficiency for lower  $p_T$  muons
- Only ID used for b-physics



# Photons



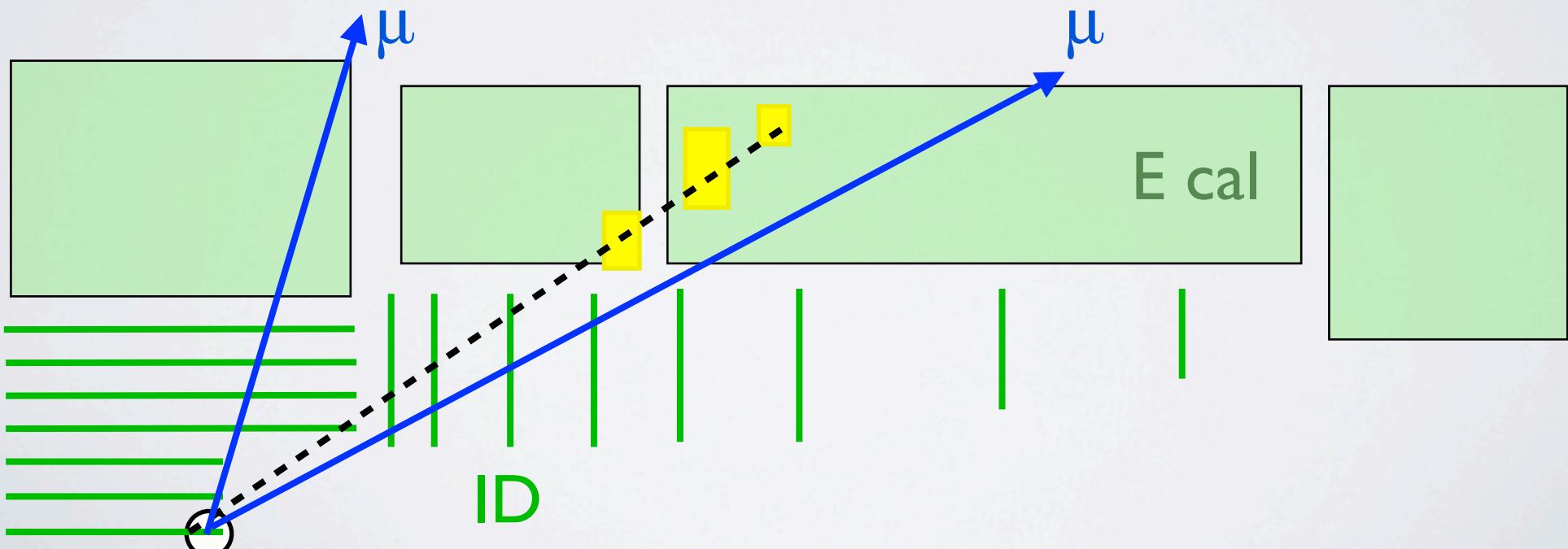
- Unconverted photons from E-cal



# Photons



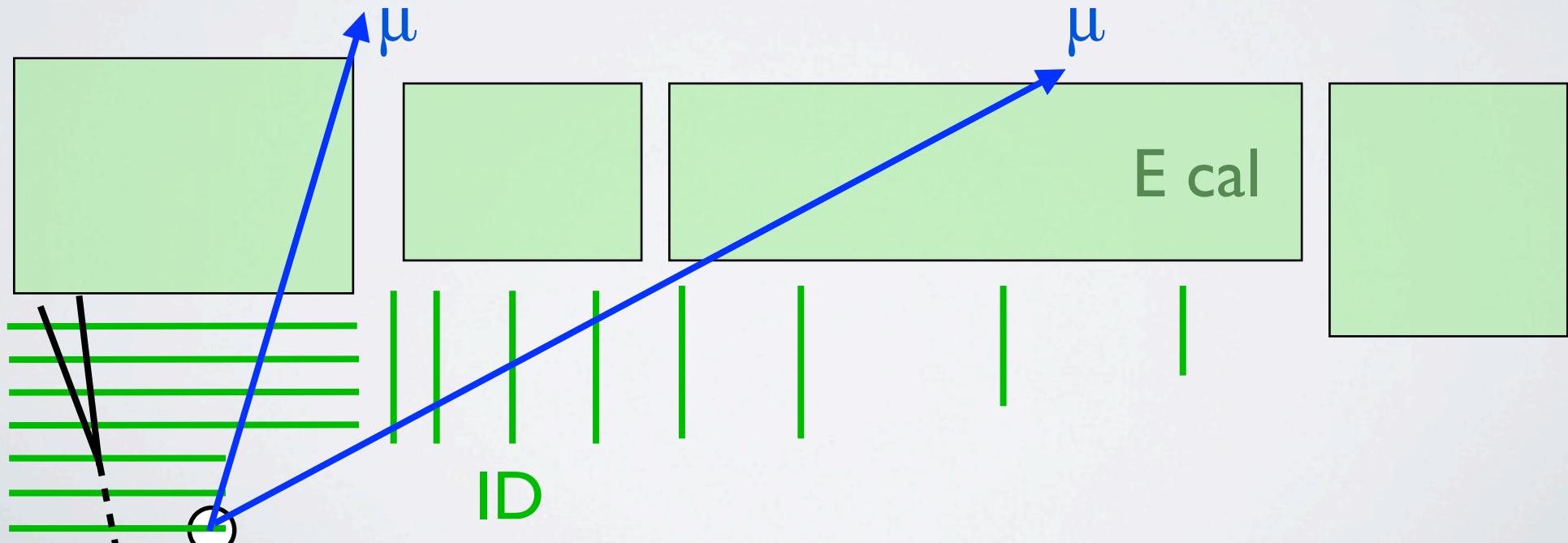
- Unconverted photons from E-cal
  - Fit polar angle fitted using E-cal and  $\mu\mu$  vertex



# Photons



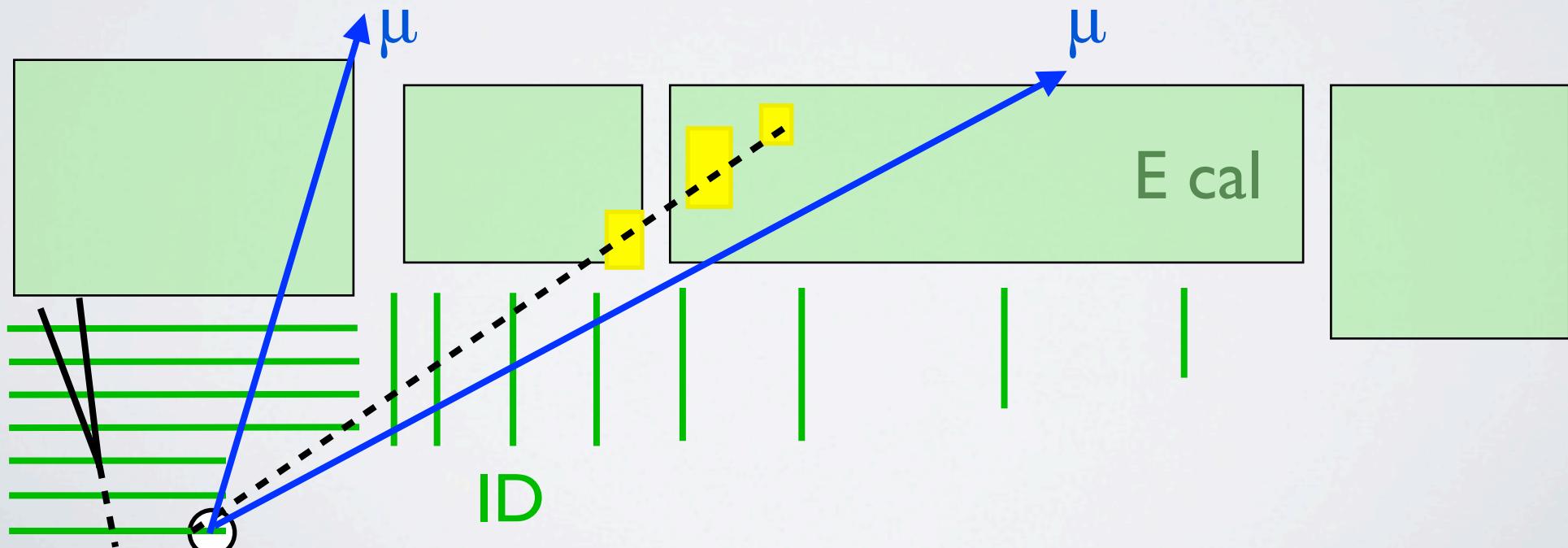
- Unconverted photons from E-cal
  - Fit polar angle fitted using E-cal and  $\mu\mu$  vertex
- Converted photons from ID tracks
  - Vertex inside ID, combined  $\gamma$  close to  $\mu\mu$  vertex



# Photons



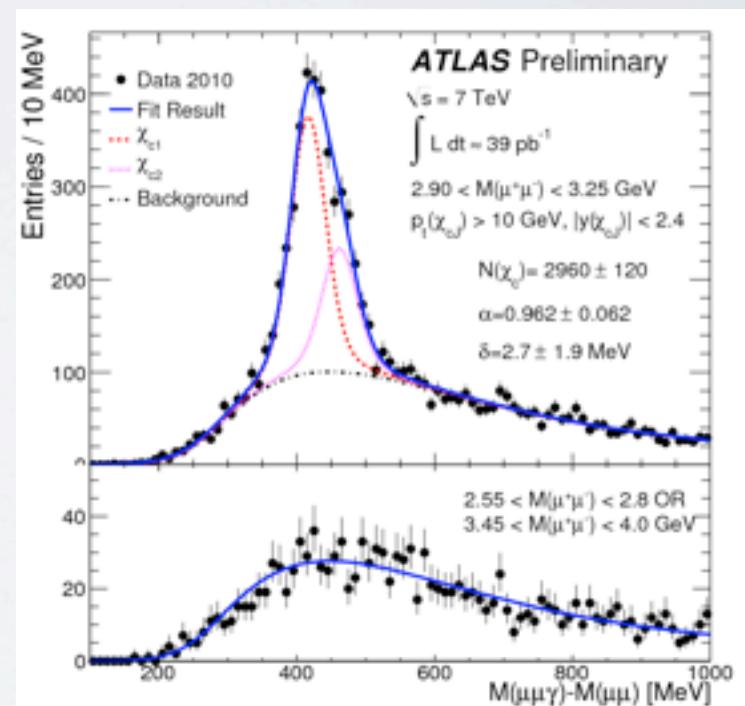
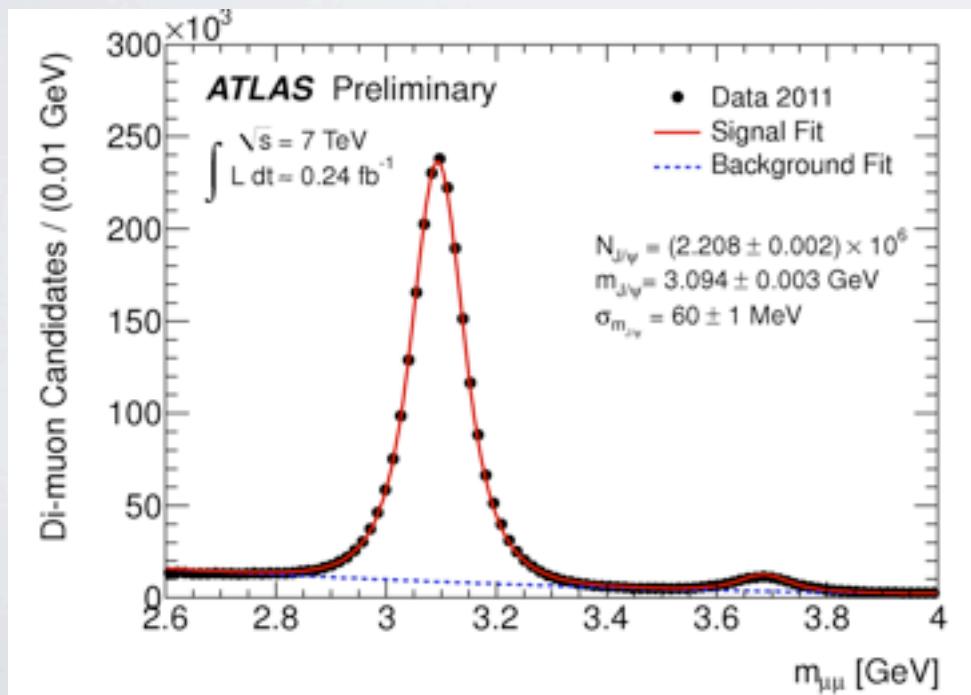
- Unconverted photons from E-cal
  - Fit polar angle fitted using E-cal and  $\mu\mu$  vertex
- Converted photons from ID tracks
  - Vertex inside ID, combined  $\gamma$  close to  $\mu\mu$  vertex
- For boosted state: small 3D opening angle  $\Phi(\mu\mu, \gamma)$





# $\chi_c \rightarrow J/\psi \gamma$ Signal

- Combined or tagged muons
  - $p_T(\mu) > 2.5 \text{ GeV}$ ,  $|\eta| < 2.5$ ,  $2.9 < M(\mu^+\mu^-)/\text{GeV} < 3.25$
- Unconverted photons
  - $E_T > 2.5 \text{ GeV}$ ,  $|\eta| < 2.5$
- $p_T(\mu\mu\gamma) > 10 \text{ GeV}$ ,  $|\eta(\mu\mu\gamma)| < 2.4$ ,  $\cos(\Phi(\mu\mu,\gamma)) > .99$

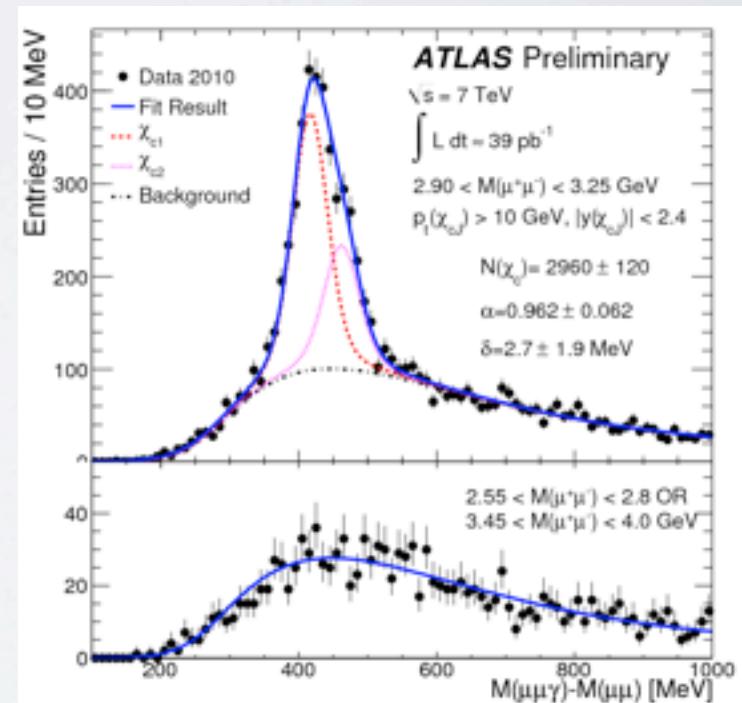
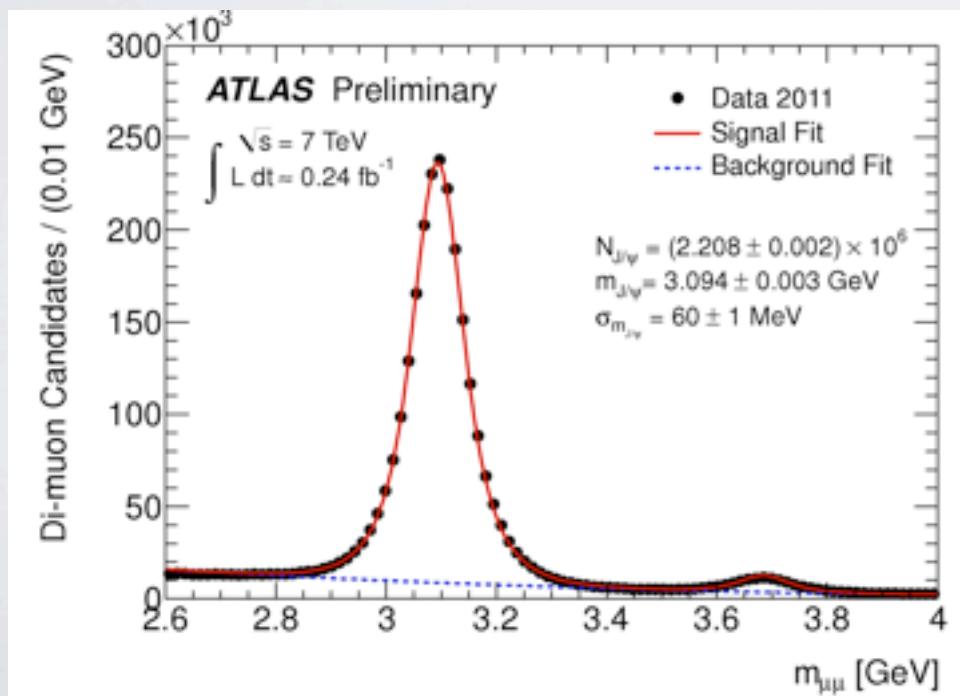


# $\chi_c \rightarrow J/\psi \gamma$ Signal



- Combined or tagged muons
  - $p_T(\mu) > 2.5 \text{ GeV}$ ,  $|\eta| < 2.5$ ,  $2.9 < M(\mu^+\mu^-)/\text{GeV} < 3.25$
- Unconverted photons
  - $E_T > 2.5 \text{ GeV}$ ,  $|\eta| < 2.5$
- $p_T(\mu\mu\gamma) > 10 \text{ GeV}$ ,  $|\eta(\mu\mu\gamma)| < 2.4$ ,  $\cos(\Phi(\mu\mu,\gamma)) > .99$

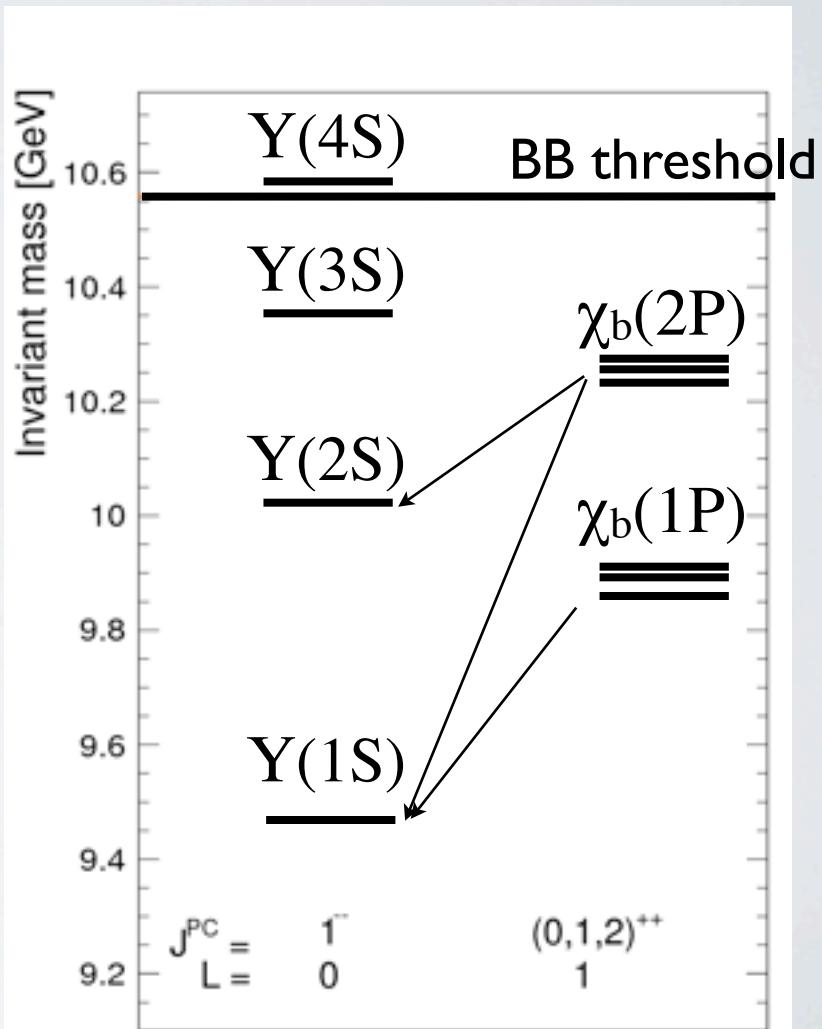
ATLAS-CONF-2011-136





# $\chi_b$ Search

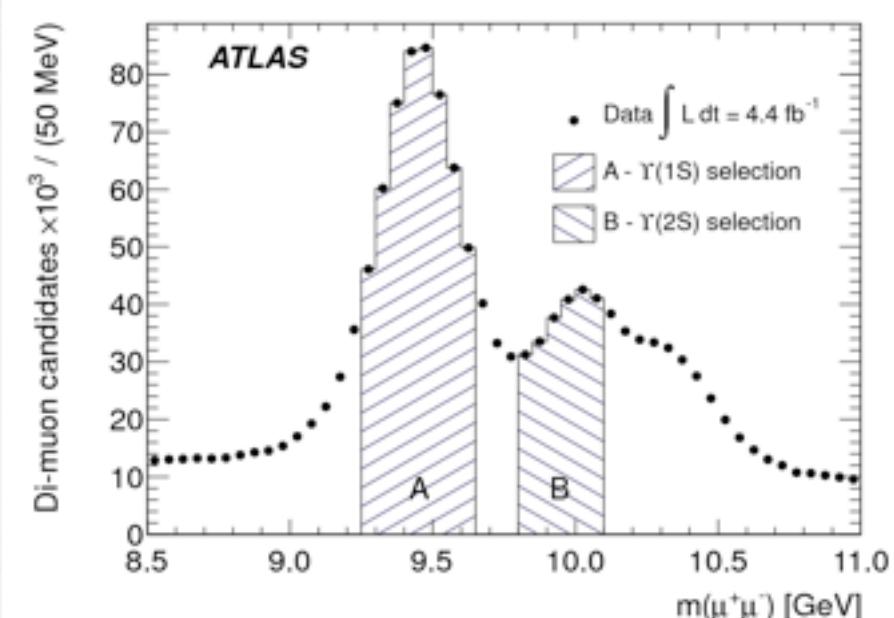
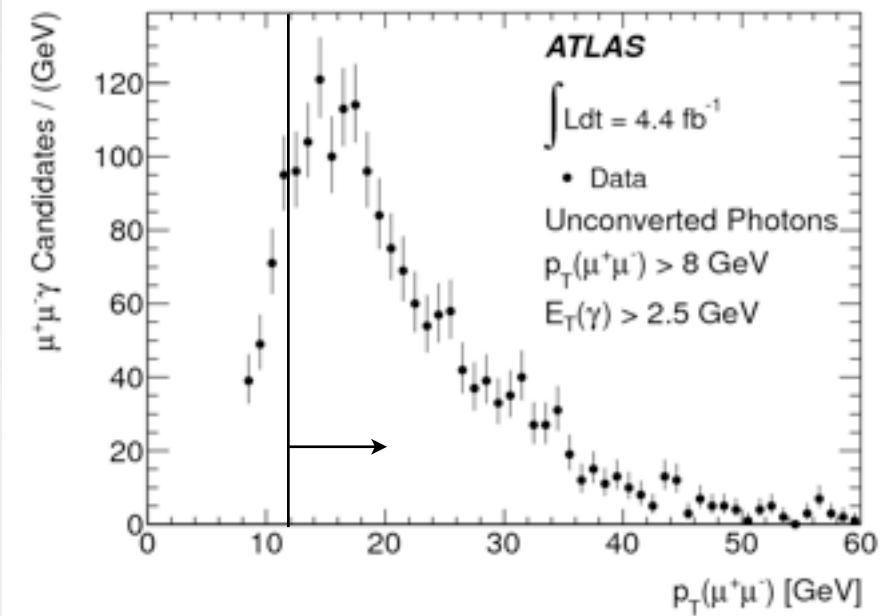
- 4.4  $\text{fb}^{-1}$  of 7 TeV data (2011)
  - Search for  $\chi_b$  in radiative decays to  $Y(1S), Y(2S)$
  - $Y(1,2S) \rightarrow \mu\mu$
  - Using converted and unconverted photons
  - $\chi_b(3P)$  predicted with
    - $m \approx 10.52 \text{ GeV}$
    - splitting  $\approx 10 - 20 \text{ MeV}$





# Y Selection

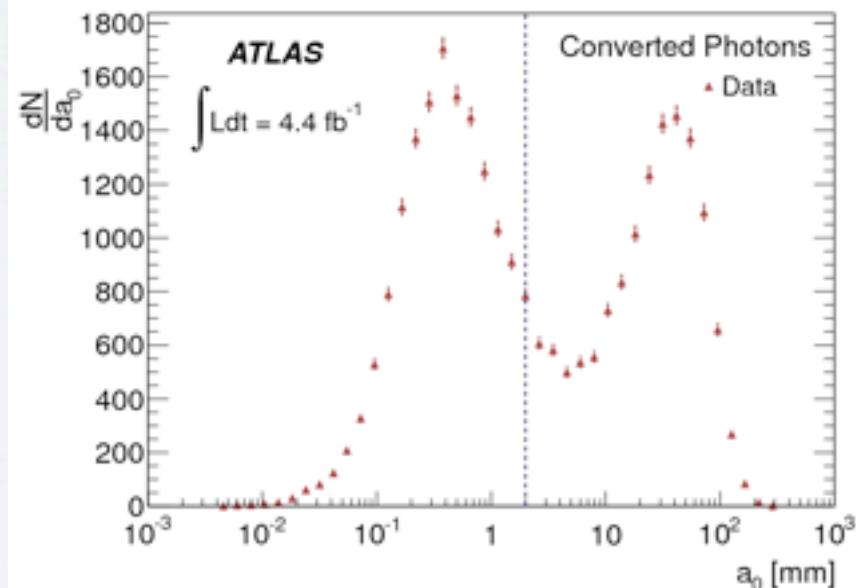
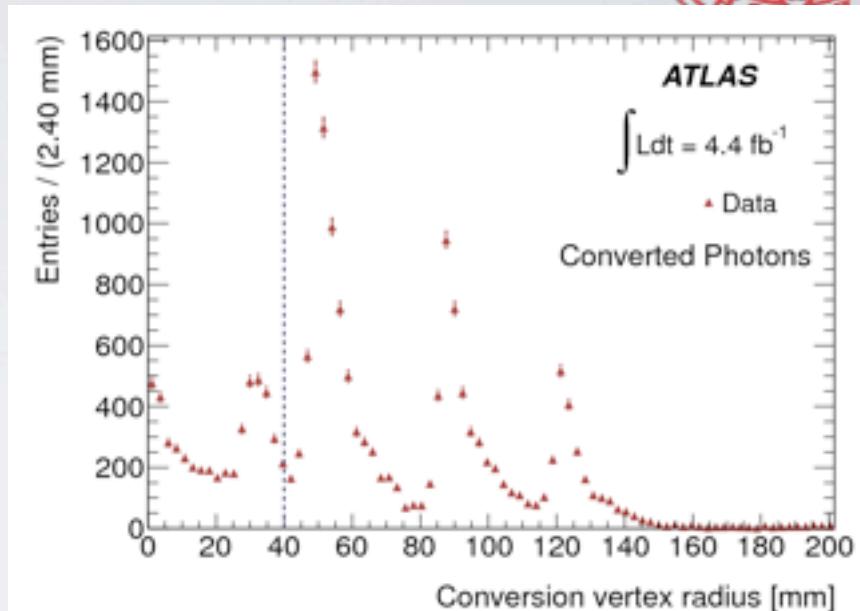
- Two track matched muons
  - Opposite charge
  - $p_T > 4 \text{ GeV}$ ,  $|\eta| < 2.3$
- Di-muon Vertex
  - $\chi^2/N_{\text{d.o.f}} < 20$
  - $p_T > (12) 20 \text{ GeV}$   
(un)converted
  - $|\eta| < 2.0$
  - Mass windows:  
 $9.25 < m(\mu\mu)/\text{GeV} < 9.65$   
 $9.80 < m(\mu\mu)/\text{GeV} < 10.10$



# Converted Photons



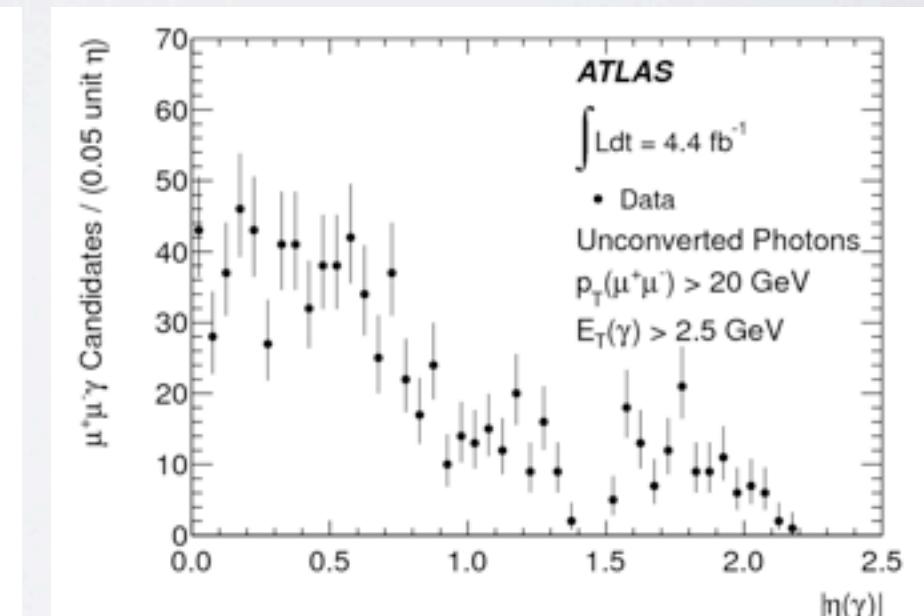
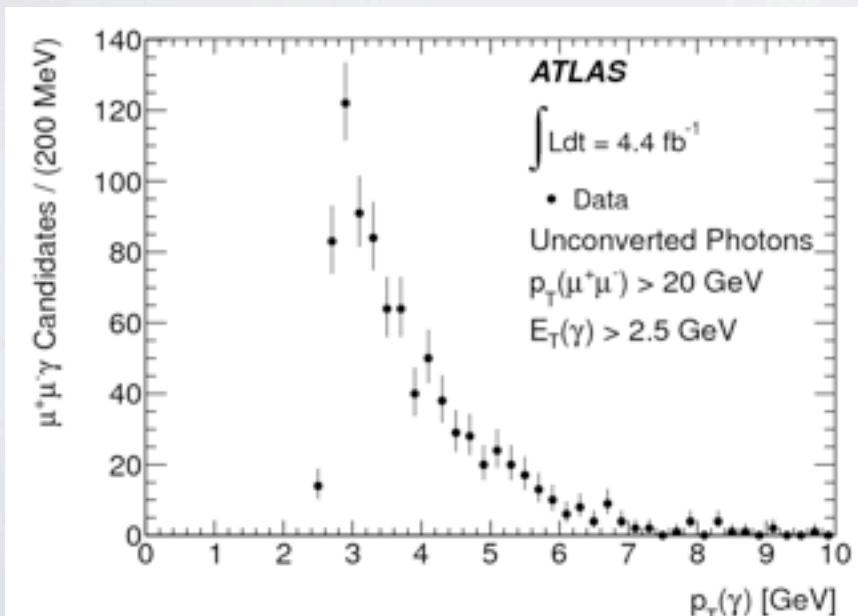
- Two ID tracks, opposite sign
  - $p_T > 500 \text{ MeV}$
  - electron ID from TRT
- Vertex fit:
  - opening angle constrained
  - $\chi^2$  probability  $> 0.01$
  - 40 mm from beam axis
  - $\text{IP}(\gamma) < 2 \text{ mm}$
  - $|\eta(\gamma)| < 2.3$

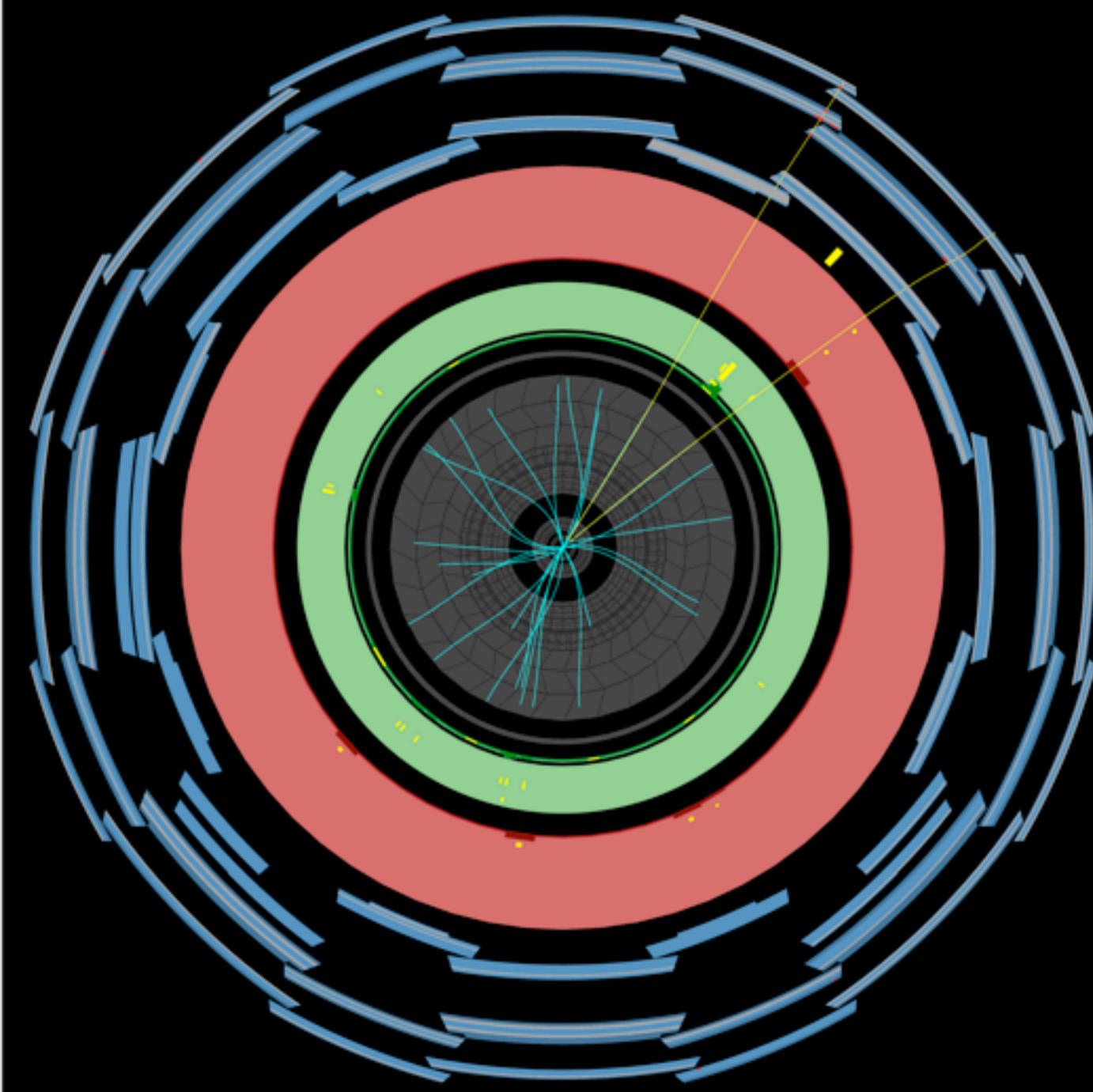


# Unconverted Photons



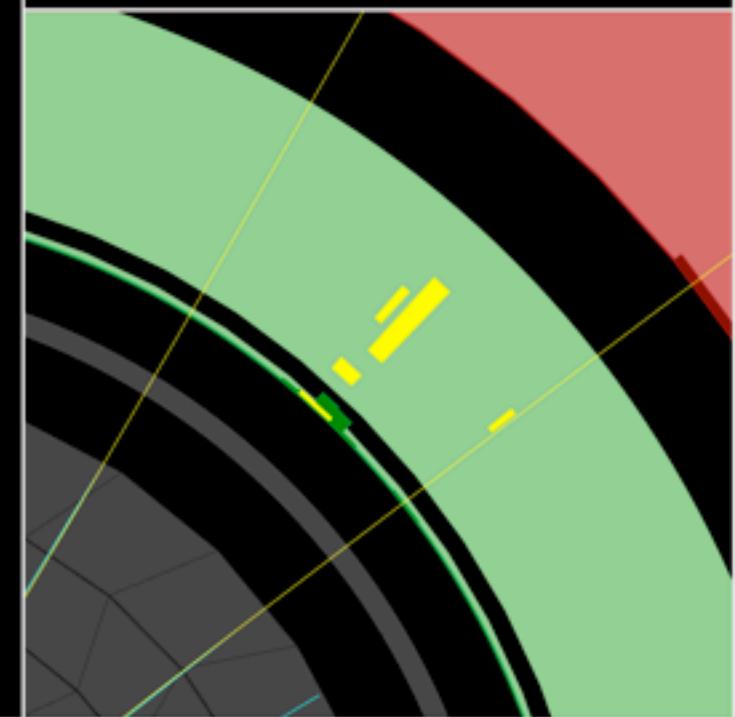
- “Loose” photon selection using E-cal
  - low H-cal fraction
  - Narrow shower shape
  - $|\eta| < 2.37$ , crack at  $1.37 < |\eta| < 1.52$  excluded
  - $E_T > 2.5 \text{ GeV}$
  - Fit to E-cal clusters and  $\mu\mu$  Vertex:  $\chi^2/N_{\text{d.o.f.}} < 200$

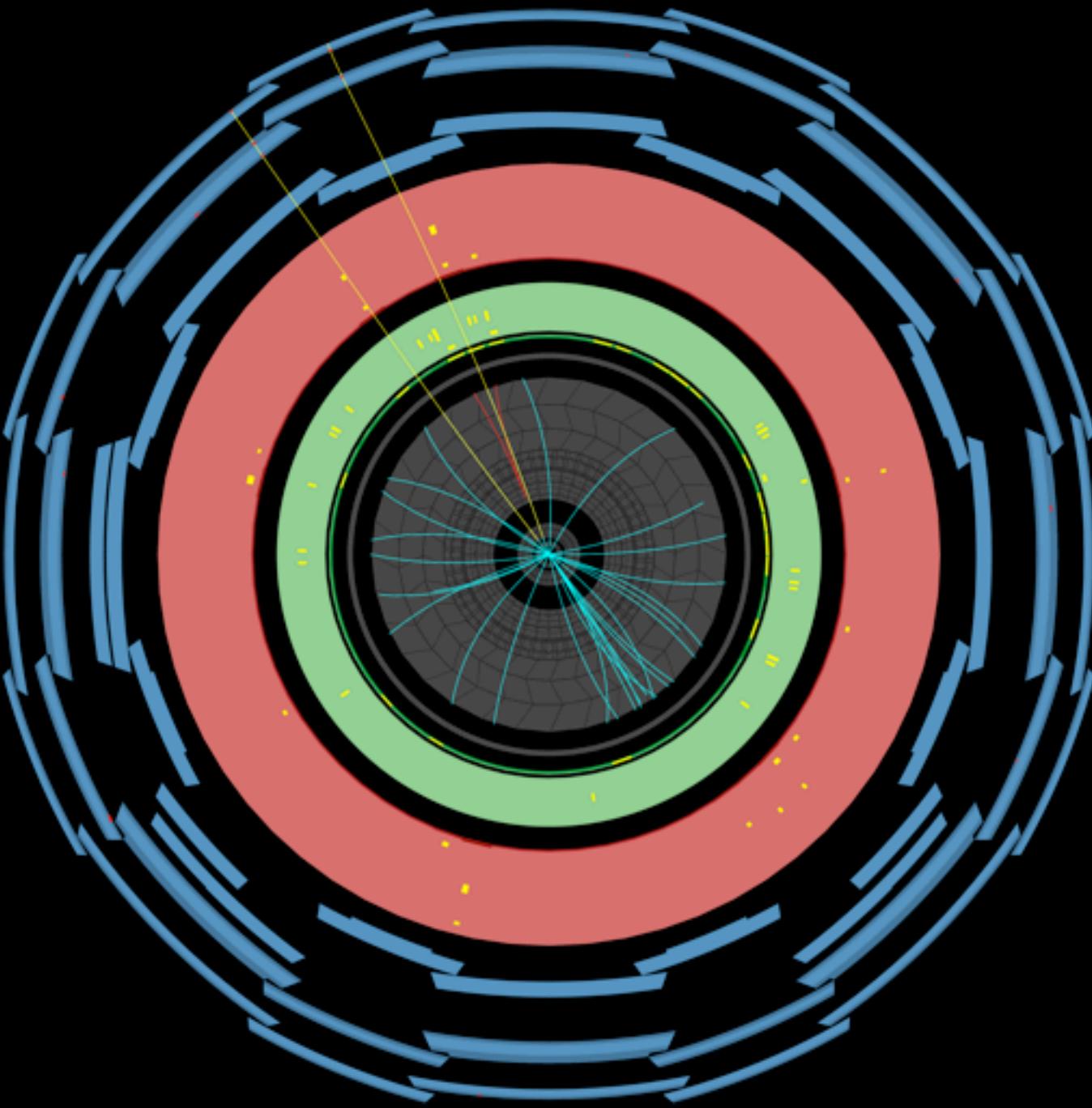




Run Number: 180225, Event Number: 140709409

Date: 2011-04-25 08:38:49 UTC

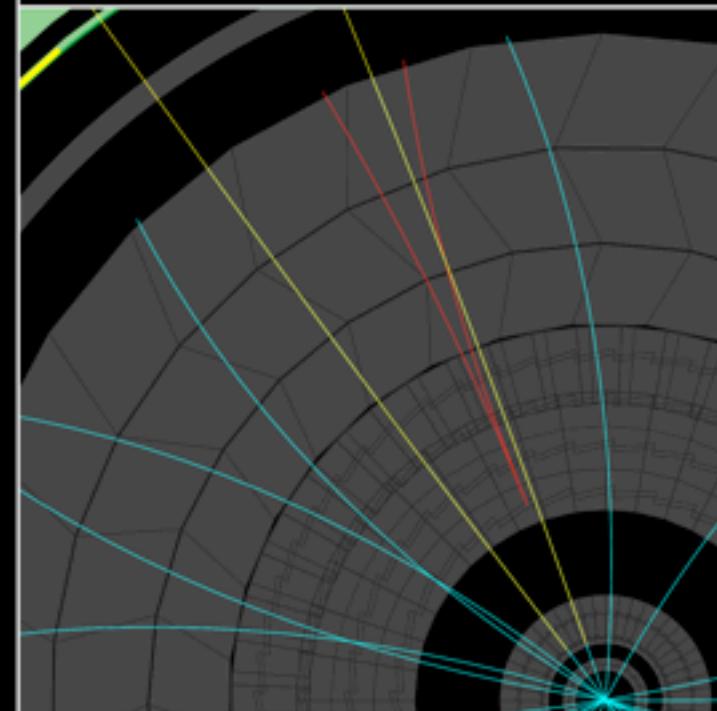




# ATLAS EXPERIMENT

Run Number: 186729, Event Number: 74143967

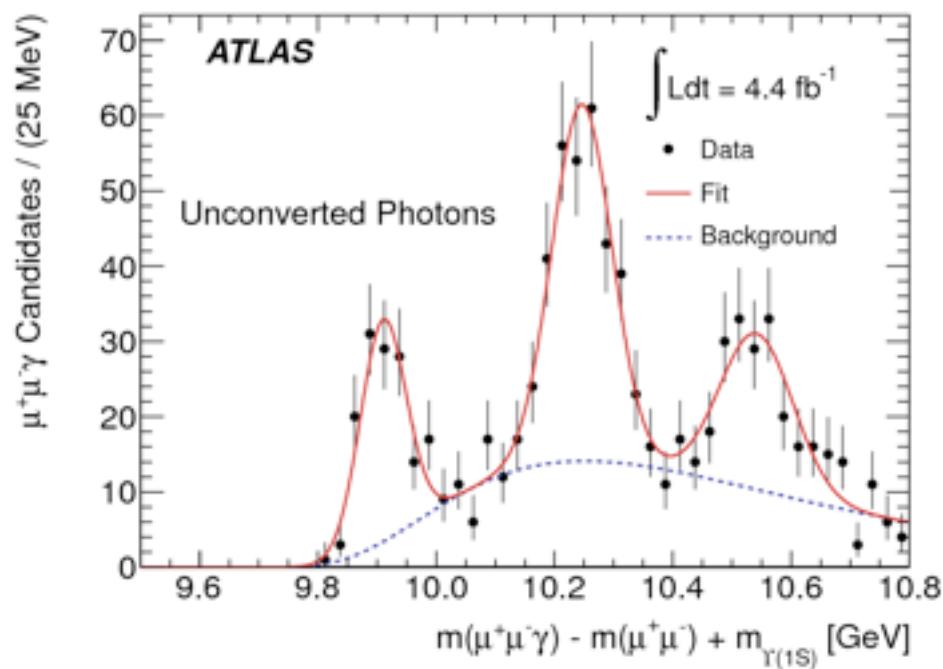
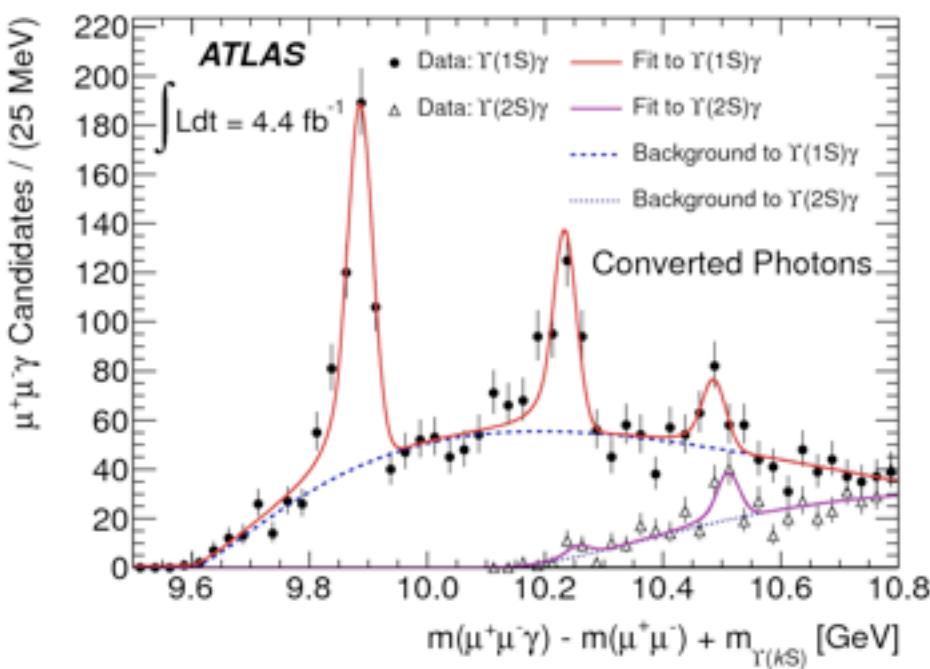
Date: 2011-08-03 11:38:40 UTC





# $\chi_b$ Selection

- For combined di-muon and photon candidates
  - use  $m_k = m(\mu\mu\gamma) - m(\mu\mu) + m_{Y(kS)}$  for  $k=1,2$
  - Additional peak at  $\approx 10.5$  GeV
  - using  $\log(L_{\max}/L_0)$ : Significance  $> 6\sigma$  in each channel

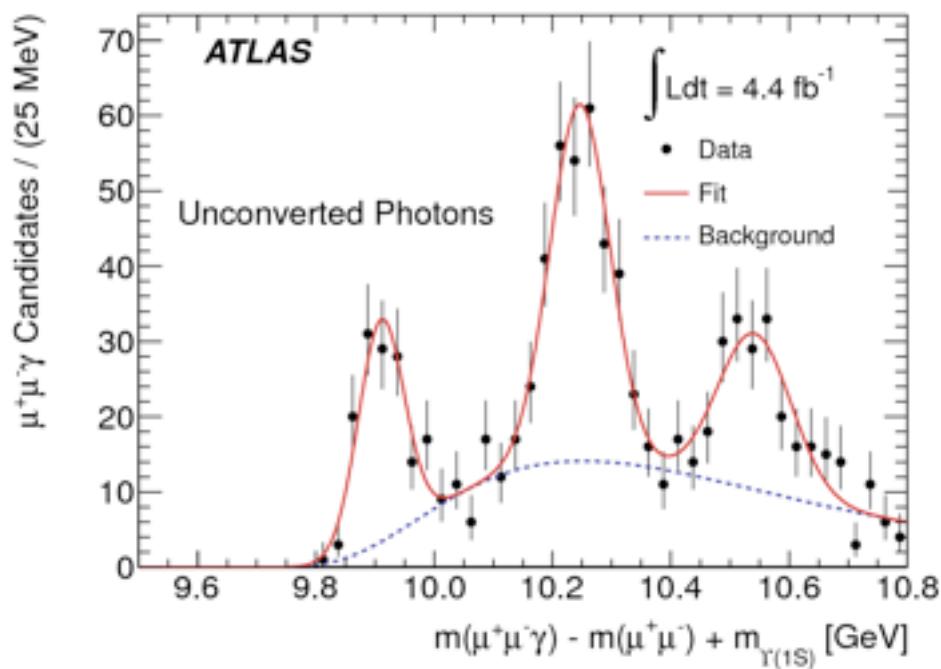
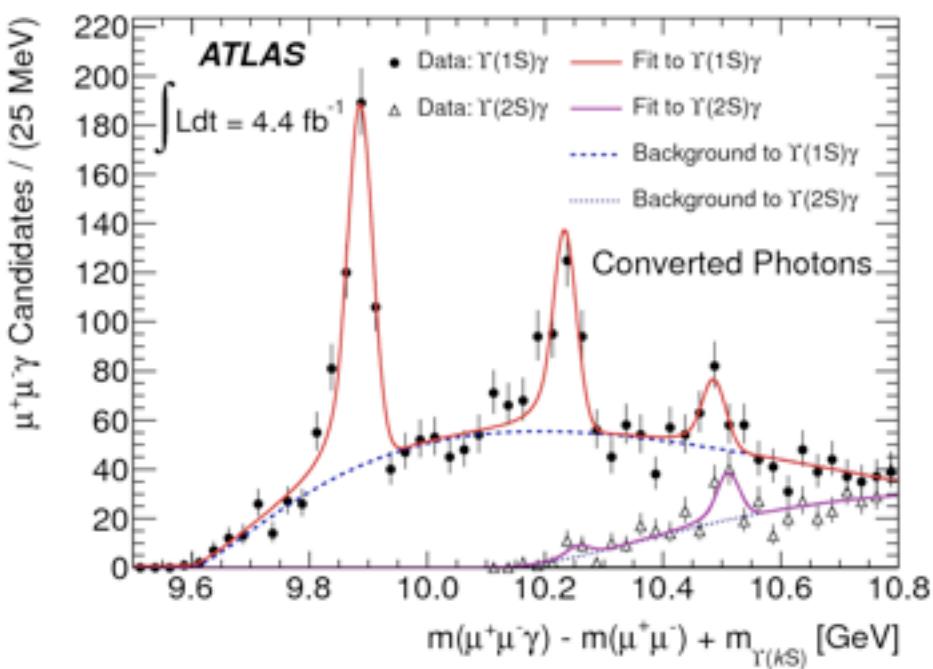


# $\chi_b$ Selection

Phys. Rev. Lett. 108  
(2012) 152001



- For combined di-muon and photon candidates
  - use  $m_k = m(\mu\mu\gamma) - m(\mu\mu) + m_{Y(kS)}$  for  $k=1,2$
  - Additional peak at  $\approx 10.5$  GeV
  - using  $\log(L_{\max}/L_0)$ : Significance  $> 6\sigma$  in each channel





# $\chi_b(3P)$ Mass

- Unbinned extended likelihood fit
  - Signals: doublets of Crystal Ball Functions (alternatively Gaussians for unconverted photons)
    - $J=1$  and  $J=2$  components set equal
    - suppressed state  $J=0$  excluded
  - Background: exponential with turn-on
$$N_B \cdot (\Delta m - q^0)^A \cdot \exp(B(\Delta m - q^0))$$
  - Masses of known  $\chi b$  states fixed:  $\lambda \cdot m(\chi b(1P, 2P))$

unconverted:  $m(\chi b(3P)) = 10.541 \pm .011_{\text{(stat.)}} \pm .03_{\text{(syst.)}}$  GeV  
converted:  $m(\chi b(3P)) = 10.530 \pm .005_{\text{(stat.)}} \pm .009_{\text{(syst.)}}$  GeV

Main systematics unconv.	
BG model	$\pm 21$ MeV
mass scale $\lambda$	$\pm 2\% \rightarrow 22$ MeV
$\chi_{b1,2,3}$ mixture	$\pm 5$ MeV

# Masses

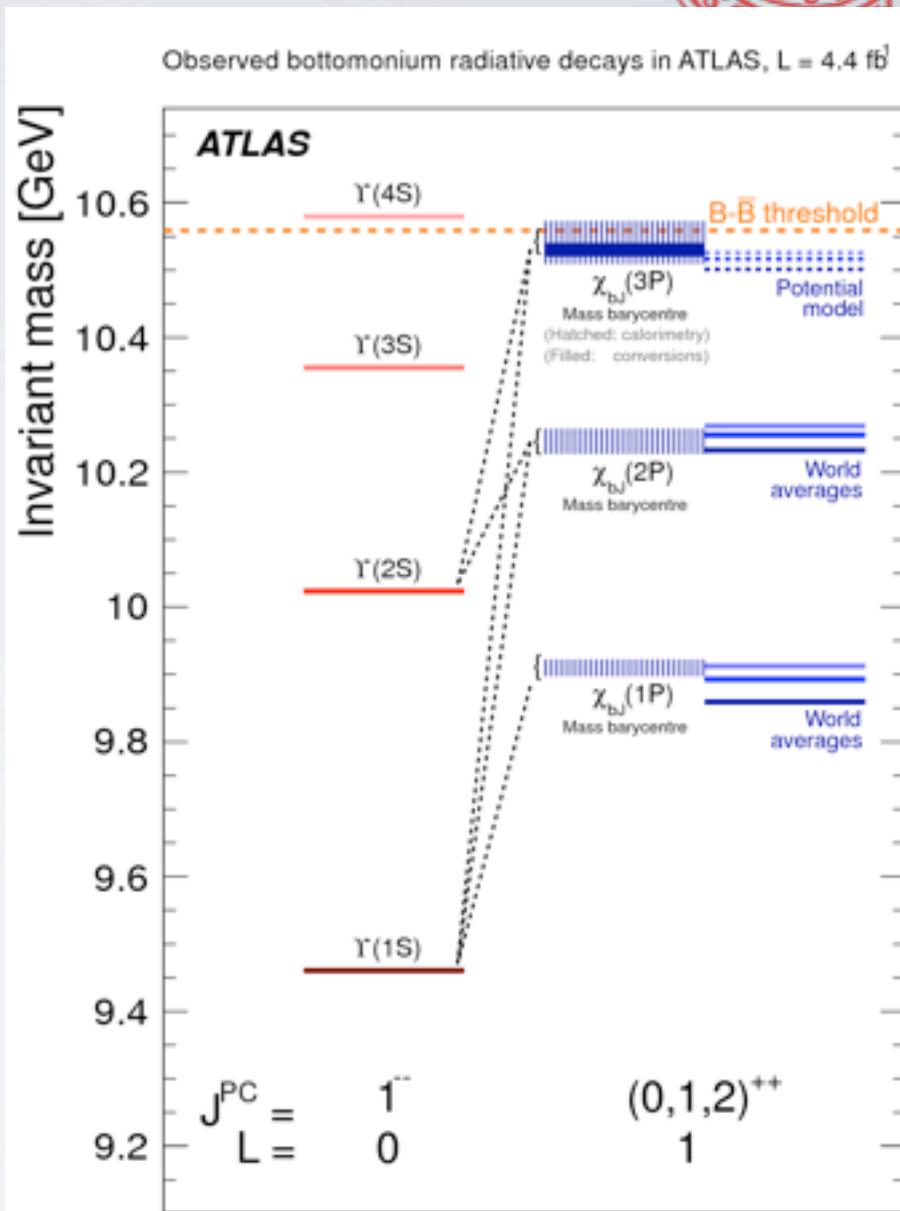


## Unconverted

m/MeV	predicted	measured
$\chi b(1P)$	9900	$9910 \pm 6 \pm 11$
$\chi b(2P)$	10260	$10246 \pm 5$
$\chi b(3P)$	10525	10541

## Converted

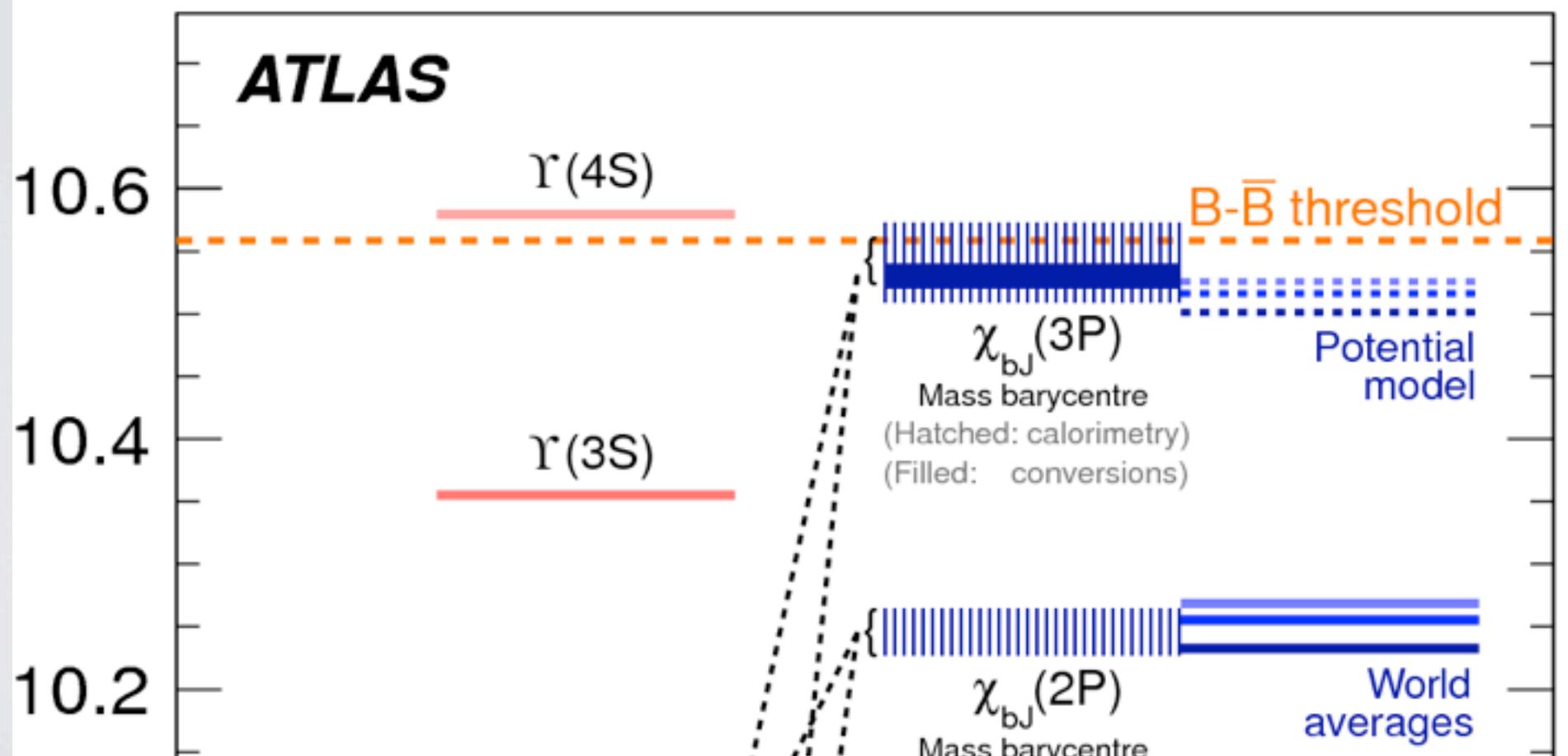
m/MeV	predicted	measured
$\chi b(1P)$	9900	fixed
$\chi b(2P)$	10260	fixed
$\chi b(3P)$	10525	$10530 \pm 5 \pm 9$



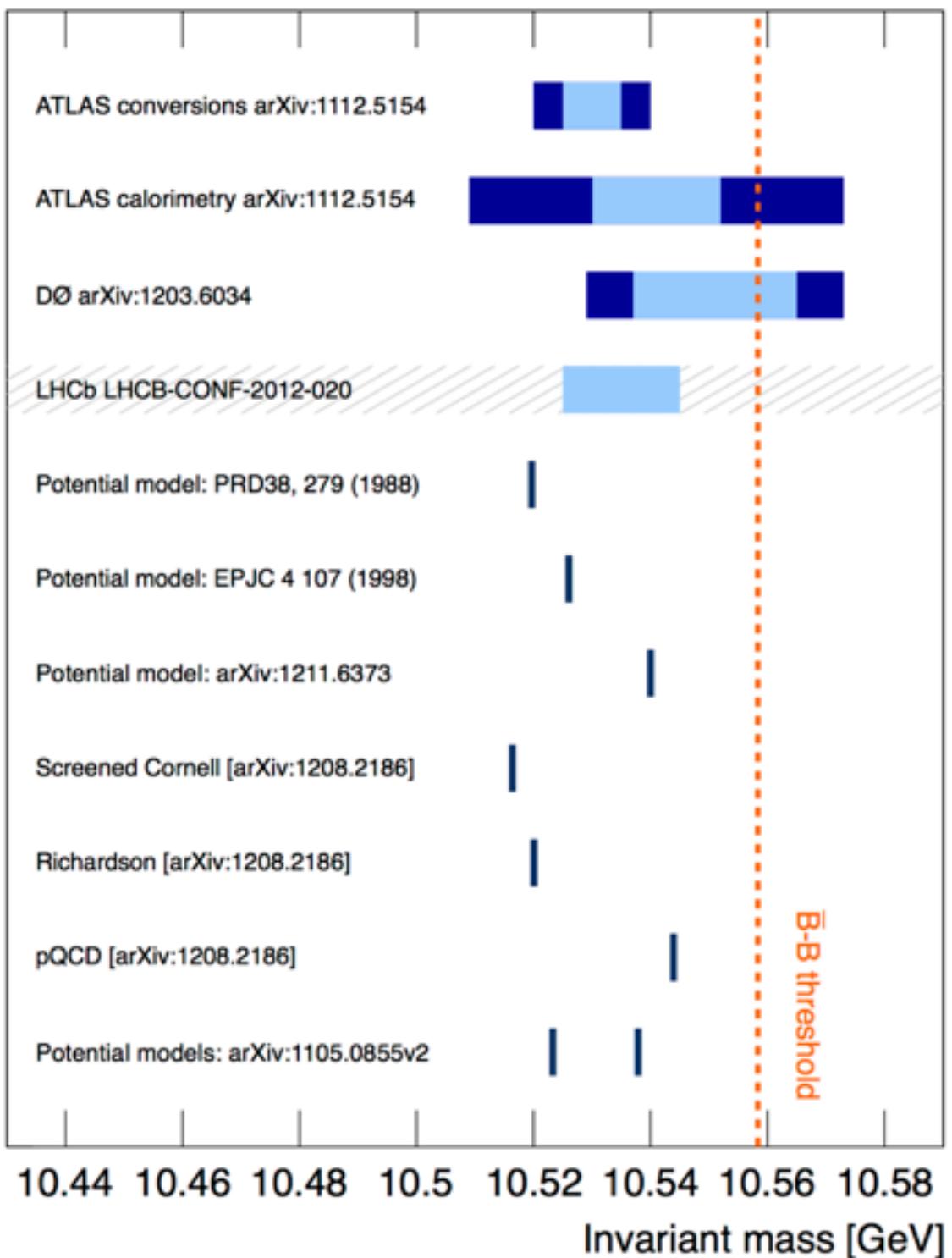
# Spectrum



Observed bottomonium radiative decays in ATLAS,  $L = 4.4 \text{ fb}^{-1}$



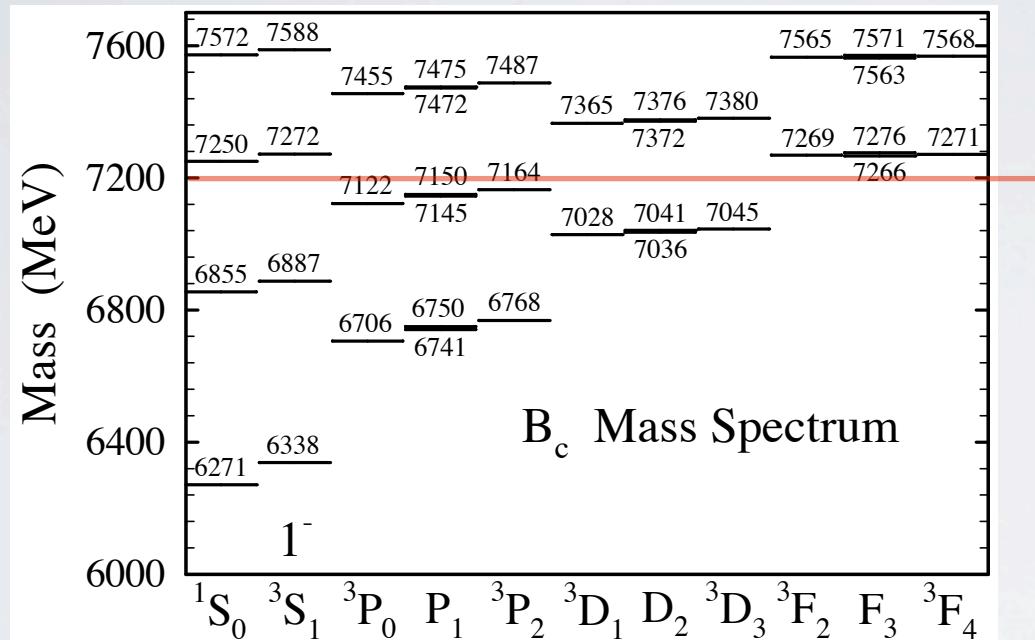
$\chi_{cJ}(3P)$  mass barycentre measurements and model predictions





# B<sub>c</sub> measurements

- B<sub>c</sub> mass predicted in various models
  - Measure ground and excited states to test them



BD threshold

From: S. Godfrey,  
PRD 70, 054017 (2004)

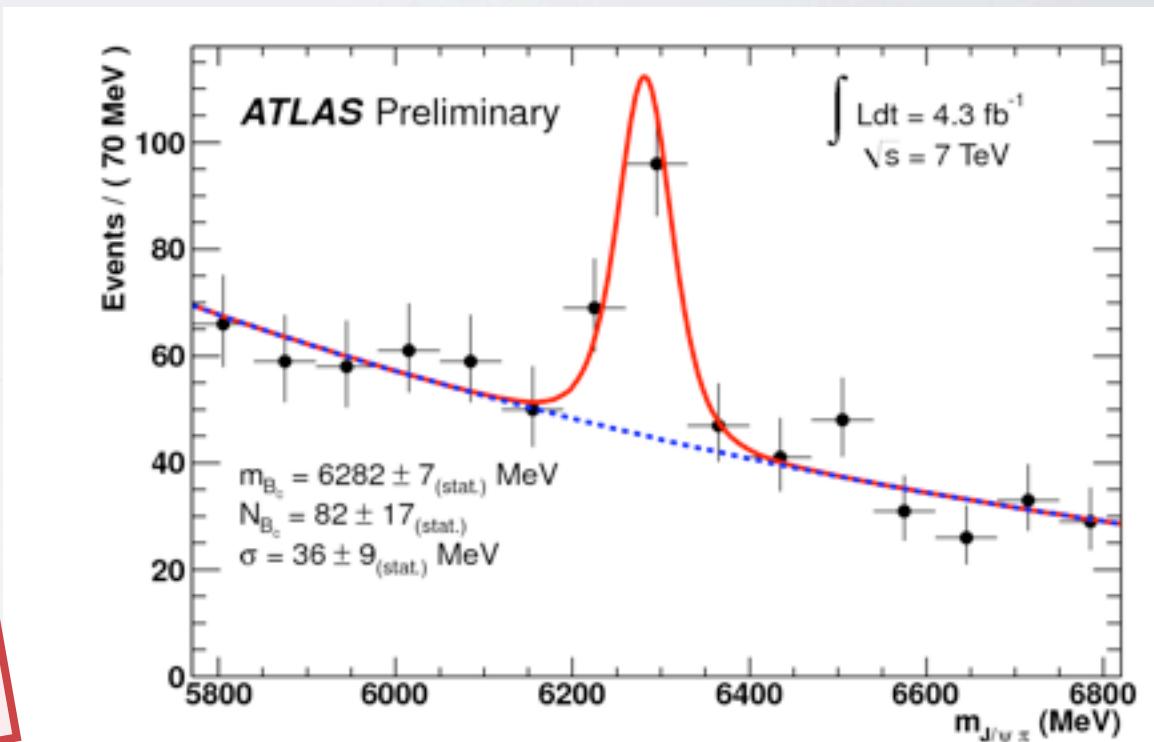
- Using decay mode B<sub>c</sub><sup>±</sup> → J/ψ π<sup>±</sup>
- Using 4.3 fb<sup>-1</sup> of 7 TeV data, triggered by
  - di-muon p<sub>T</sub>(μ1) > 4/6 GeV, p<sub>T</sub>(μ2) > 4 GeV
  - single muon p<sub>T</sub>(μ) > 6 GeV

# J/ $\psi$ Selection



- Two oppositely charged muons:
  - $p_T(\mu 1) > 6 \text{ GeV}$ ,  $p_T(\mu 2) > 4 \text{ GeV}$ ,  $|\eta| < 2.5$
- Good  $\mu\mu$  Vertex:  $\chi^2/N_{\text{d.o.f}} < 15$
- $M(\mu\mu)$  mass window: 180 MeV around  $m(J/\psi)$
- $\pi^\pm$  candidate
  - 1 Pixel, 6 SCT hits
  - $p_T(\pi^\pm) > 4 \text{ GeV}$
  - IPS:  $d^0_{xy}/\sigma(d^0_{xy}) > 5$
- $\mu\mu\pi$  Vertex:
  - $\chi^2/N_{\text{d.o.f}} < 15$
  - $p_T(\mu\mu\pi) > 15 \text{ GeV}$

ATLAS-CONF-2012-028





# B<sub>c</sub> Mass

- Unbinned extended likelihood fit
  - Signal: Gaussian fit of
    - mass:  $m_{J/\psi\pi}^i - m_{B_c}$
    - width:  $S \cdot \delta m_{J/\psi\pi}^i$
    - signal fraction
  - Background: exponential
  - Signal events given for  $\pm 3 \sigma$  around central mass

**$m(B_c) = 6282 \pm 7 \text{ MeV}$**   
World avg.:  $6277 \pm 6 \text{ MeV}$   
 **$\sigma = 36 \pm 9 \text{ (stat.) GeV}$**   
 **$N_{\text{sig}} = 82 \pm 17$**

- Starting point for excited B<sub>c</sub> states



# Summary

ATLAS allows for quality b-physics program  
mainly through muon and di-muon triggers  
in the central rapidity region  
> 4 times more luminosity (i.e.  $J/\psi$ ) in 2012 data.

Converted and unconverted photons allow  
spectroscopy in charmonium and bottomonium

Large number of reconstructed  $B_c$   
⇒ search for excited  $B_c$  states possible.

- $>6 \sigma$  observation of  $\chi_b(3P)$
- $m(\chi_b(3P)) = 10.530 \pm 0.005 \text{ (stat.)} \pm 0.009 \text{ (syst.) GeV}$