

# ATLAS Heavy-Flavour spectroscopy and exotic states

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## ATLAS results on heavy flavour spectroscopy

- ▶ Observation of an excited  $B_c^+$  meson state
  - ▶ *Phys. Rev. Lett.* **113** (2014) 212004 ([arXiv:1407.1032](#))
  - ▶ A new state observed compatible with a radial excitation  $B_c^+(2S)$
- ▶ Search for  $X_b$  and other hidden-beauty states using  $\pi^+\pi^-\Upsilon(1S)$  channel
  - ▶ *Phys. Lett. B* **740** (2015) 199-217 ([arXiv:1410.4409](#))
  - ▶ Aimed for bottomonium counterpart of  $X(3872)$
  - ▶ Also search for other states:  $\Upsilon(1^3D_J)$ ,  $\Upsilon(10860)$ ,  $\Upsilon(11020)$

## Older spectroscopy results (not in this talk)

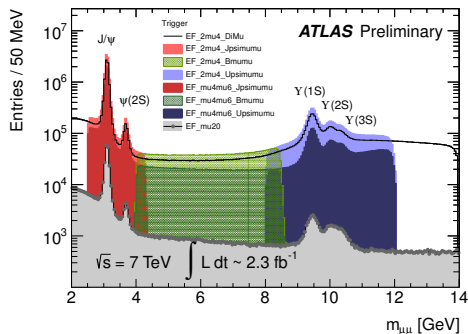
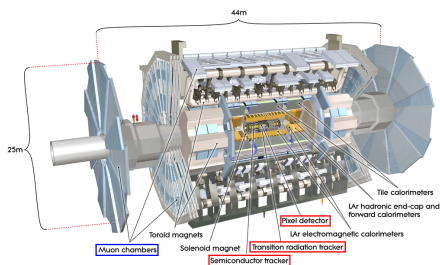
- ▶ Observation of a new  $\chi_b$  state in radiative transitions to  $\Upsilon(1S)$  and  $\Upsilon(2S)$ 
  - ▶ *Phys. Rev. Lett.* **108** (2012) 152001 ([arXiv:1112.5154](#))
  - ▶ A new state observed interpreted as  $\chi_b(3P)$  system

# ATLAS detector and trigger system

- ▶ Tracking **Inner Detector** in 2 T solenoid field
- ▶ **Muon system** put inside a toroid
- ▶ ATLAS **trigger system**: hardware *Level-1 trigger* and two-level software *High-Level Trigger*

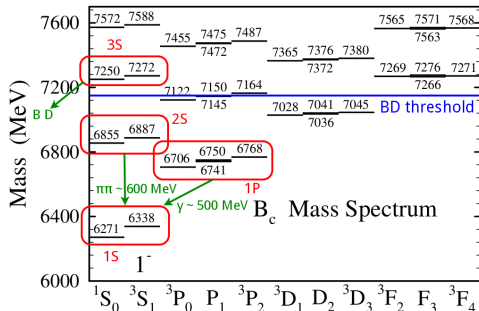
**Trigger selection for heavy flavour studies** is mostly based on di-muon signature

- ▶ muon  $p_T$  threshold (4 or 6 GeV)
- ▶ di-muon vertex reconstruction
- ▶ invariant mass window



# Search for $B_c^+$ excited states

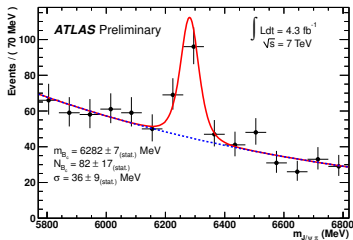
- ▶ No excited states of  $B_c^+$  reported previously
- ▶ The spectrum and properties of  $B_c^+$  family are predicted by non-relativistic potential models, perturbative QCD and lattice calculations
- ▶ Measurements of the ground and excited states → test of these predictions



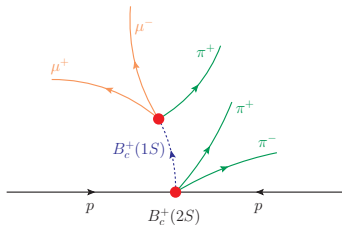
Phys. Rev. D 70 (2004) 054017

- ▶ Ground state  $B_c^+$  was earlier observed in  $B_c^+ \rightarrow J/\psi\pi^+$  mode

▶ ATLAS-CONF-2012-028



- ▶ The analysis uses *7 TeV and 8 TeV pp collisions data*
  - ▶  $4.9 \text{ fb}^{-1}$  and  $19.2 \text{ fb}^{-1}$ , respectively
- ▶ Selection optimized using  $S/\sqrt{S+B}$  criterion on *Monte Carlo* (both signal and backgrounds)



- ▶  $J/\psi$  candidates reconstructed by fitting a muon pair to a common vertex
- ▶ Combining a  $J/\psi$  candidate with another track  $\rightarrow B_c^+(1S)$  candidate
  - ▶ Di-muon mass is constrained to the  $J/\psi$  world average in 3-prong vertex fit
- ▶  $B_c^+(2S)$  candidates formed from  $B_c^+(1S)$  and two tracks from primary vertex with  $\pi^\pm$  masses assigned
  - ▶ Cascade fit with  $B_c^+(1S)$  combined momentum *constrained to point to  $B_c^+(2S)$  vertex*

# $B_c^+(1S)$ selection and fit

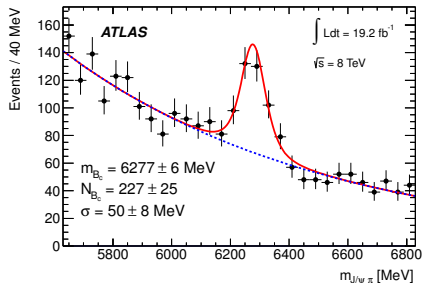
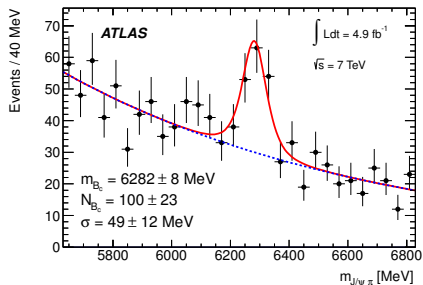
## $B_c^+(1S)$ selection for 7 TeV (8 TeV) data

- ▶  $p_T(\mu_1, \mu_2) > 4, 6$  GeV
- ▶  $\chi^2/\text{n.d.f.}(J/\psi) < 15$
- ▶  $m(J/\psi)$  within  $\pm 3\sigma$  of the nominal ( $\sigma$  depending on the rapidity range)

- ▶  $\chi^2/\text{n.d.f.}(B_c^+) < 2.0$  (1.5)
- ▶  $p_T(B_c^+) > 15$  GeV (18 GeV)
- ▶  $\frac{d_{xy}^0}{\sigma(d_{xy}^0)}(\pi^+) > 5$  (4.5)

## Extended unbinned fit of the mass distribution

- ▶ *Signal*: Gaussian with per-candidate errors
- ▶ *Background*: exponential



# $B_c^+(2S)$ selection and fit

## Selection of $B_c^+(2S) \rightarrow B_c^+(1S)\pi^+\pi^-$ candidates

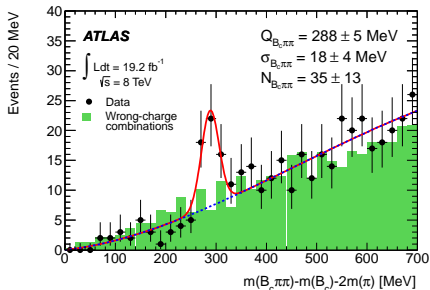
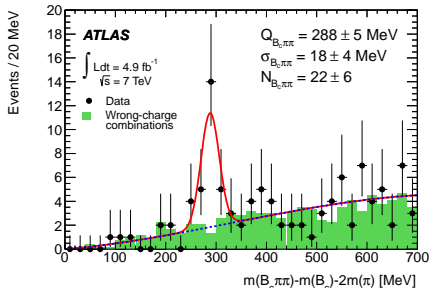
- ▶  $B_c^+(1S)$  candidates within  $\pm 3\sigma$  of the fitted mass
- ▶  $p_T(\pi^+, \pi^-) > 400$  MeV
- ▶ for several candidates in event, the one with the best cascade fit  $\chi^2$  is kept

## Extended unbinned fit of Q-value distribution

$$Q_{B_c^+\pi\pi} = m(B_c^+\pi^+\pi^-) - m(B_c^+) - 2m(\pi^+)$$

- ▶ *Signal*: Gaussian
- ▶ *Background*: 3rd order polynomial

*Wrong charge combination* (same-sign  $\pi$ )  
used for background control

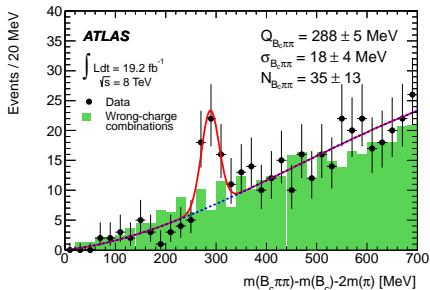
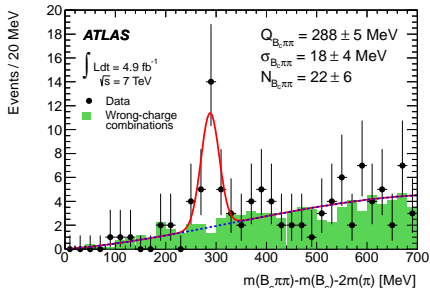


# $B_c^+(2S)$ observation

- ▶ Significance of the observed signal calculated with toy studies accounting for a “*look elsewhere effect*”
  - ▶ Combined significance is  $5.2\sigma$
  - ▶ ( $3.7\sigma$  and  $4.5\sigma$  in 7 and 8 TeV data, respectively)
- ▶ Dominant source of systematic of the  $Q$ -value is the *fitting procedure*

## Summary of the analysis

- ▶ A new state observed at  $Q = 288.3 \pm 3.5$  (stat.)  $\pm 4.1$  (syst.) MeV (error-weighted mean of 7 and 8 TeV values)
- ▶ Corresponds to a mass  $6842 \pm 4$  (stat.)  $\pm 5$  (syst.) MeV, that is consistent with the predicted mass of  $B_c^+(2S)$



- ▶  $X(3872)$  is the best-studied new **hidden-charm** state, observed by many experiments
- ▶ Mass, narrow width,  $J^{PC} = 1^{++} \rightarrow$  unlikely a conventional quarkonium
  - ▶ weakly bound  $D^0 \bar{D}^{*0}$  *molecule*?
  - ▶  $[qc][\bar{q}\bar{c}]$  *tetraquark*?

▶

$$\frac{\sigma(pp \rightarrow X(3872))\mathcal{B}(X(3872) \rightarrow \pi^+\pi^- J/\psi)}{\sigma(pp \rightarrow \psi(2S))\mathcal{B}(\psi(2S) \rightarrow \pi^+\pi^- J/\psi)} = (6.56 \pm 0.29 \pm 0.65)\%$$

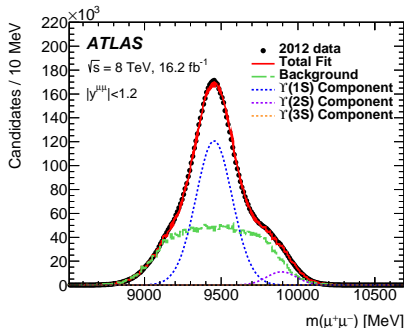
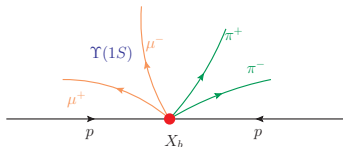
(CMS, [JHEP 04 \(2013\) 154](#), [arXiv:1302.3968](#))

- ▶ Heavy-quark symmetry suggests a **hidden-beauty** partner  $X_b$ 
  - ▶ Mass predictions vary (e.g. 10561 MeV for the molecular model of Swanson, [Phys. Rep. 429 \(2006\) 243](#), [arXiv:hep-ph/0601110](#))
- ▶ Decay  $X_b \rightarrow \pi^+\pi^-\Upsilon(1S)$  is a straightforward way to reconstruct  $X_b$ 
  - ▶ As by-product,  $\Upsilon(1^3D_J)$ ,  $\Upsilon(10860)$ ,  $\Upsilon(11020)$  can be studied with the same final state

# $X_b$ reconstruction and selection

## $\Upsilon(1S)$ reconstruction

- ▶ Muon pairs matched to those passed trigger with  $p_T(\mu) > 4$  GeV
- ▶  $|\eta(\mu)| < 2.3$
- ▶ Dimuons in mass range  $\pm 350$  MeV around  $\Upsilon(1S)$  mass



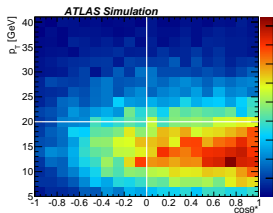
## Adding two tracks

- ▶  $p_T(\pi) > 400$  MeV
- ▶  $|\eta(\mu)| < 2.5$
- ▶ Fit a 4-track vertex:
  - ▶ Dimuon mass is constrained to nominal  $\Upsilon(1S)$  mass – substantially improves resolution
  - ▶  $\chi^2 < 20$
  - ▶ Candidates with mass  $< 11.2$  GeV are retained

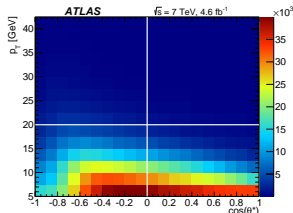
# Analysis binning

The analysis is performed in 8 bins

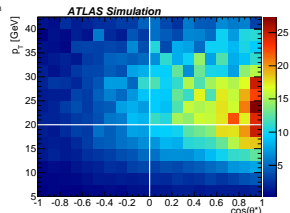
- ▶  $|y(X_b)|$ : barrel ( $|y| < 1.2$ ) and endcap ( $1.2 < |y| < 2.4$ ) due to different mass resolution
- ▶  $(p_T(X_b), \cos\theta^*)$ : split into 4 quadrants – different S/B ratio
  - ▶  $\theta^*$  is an angle between  $\pi^+\pi^-$  momentum in the parent rest frame and the parent momentum in lab frame
- ▶ Fraction of the signal in each bins are defined by *splitting functions* derived from the simulation



Signal



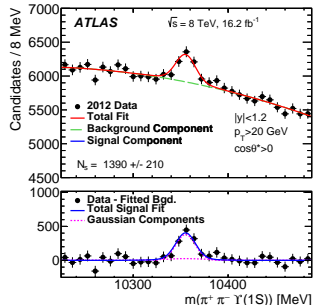
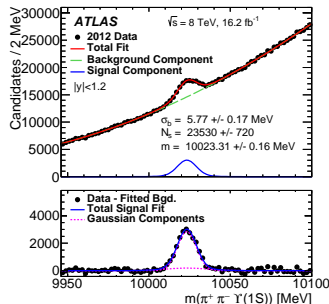
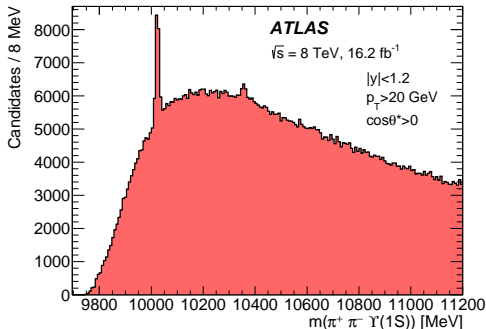
Background



$S/\sqrt{B}$

# $\Upsilon(2S)$ and $\Upsilon(3S)$ fits

- ▶ Clear peaks of  $\Upsilon(2S)$  and  $\Upsilon(3S)$  are observed; no other visible signals
- ▶  $\Upsilon(2S)$ : signal shape and distribution over bins found consistent with MC
- ▶  $\Upsilon(3S)$ : simultaneous fit in all bins (significance  $z = 8.7$ , cf. 6.5 in one bin)
- ▶ Both yields agree with predictions



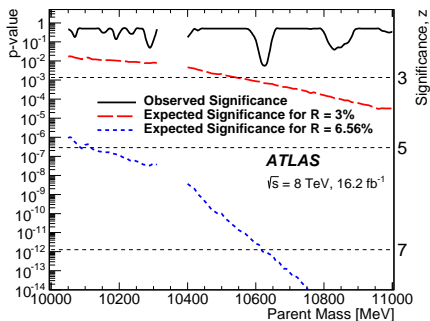
# $X_b$ local significance

## Strategy:

- ▶ Test for signal presence across 10–11 GeV range every 10 MeV
- ▶ Simultaneous fit in 8 analysis bins
  - ▶ Binned ML fit
- ▶ For each mass, extract  $p$ -value and significance

## Assumptions:

- ▶ Look for *narrow state*
- ▶ Resolution dependence on  $|y|$ ,  $p_T$  is  $\Upsilon(nS)$ -like
- ▶ Phase-space shape of  $m(\pi^+\pi^-)$



Mass ranges near  $\Upsilon(2S)$  and  $\Upsilon(3S)$  are excluded

# $X_b$ upper limits

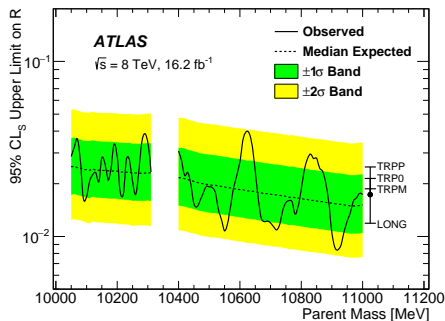
$CL_s$  limit on  $(\sigma\mathcal{B})/(\sigma\mathcal{B})_{2S}$  at 95% CL is evaluated as a function of mass

## Systematic uncertainties

- ▶ Included as Gaussian-constrained nuisance parameters

## Unknown $X_b$ production polarisation

- ▶ Assumed unpolarised
- ▶ Various assumptions shift the limits
- ▶ Shifts depend weakly on mass
- ▶ Shown with error bars



Mass ranges near  $\Upsilon(2S)$  and  $\Upsilon(3S)$  are excluded

*The limit is most restrictive to date for  $m > 10.1 \text{ GeV}$*

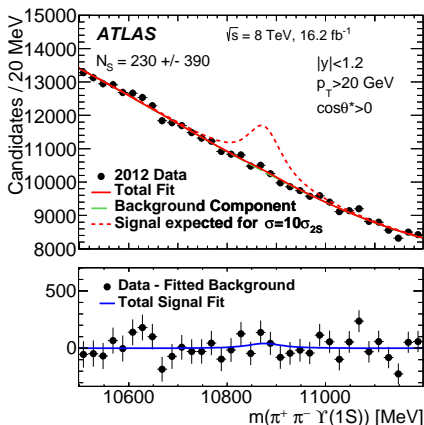
# Results for $\Upsilon(1^3D_J)$ , $\Upsilon(10860)$ , $\Upsilon(11020)$

## $\Upsilon(1^3D_J)$ triplet

- ▶ Two extra peaks added to the fit model (masses fixed to theoretical predictions)
- ▶ Significance  $z = 0.12$
- ▶  $\sigma(\Upsilon(1^3D_J))/\sigma(\Upsilon(2S)) < 0.55$   
(use known  $\mathcal{B}$  from BaBar)

## $\Upsilon(10860)$ , $\Upsilon(11020)$

- ▶ Broad states  $\rightarrow$  different fit model
- ▶ No evidence for either state found

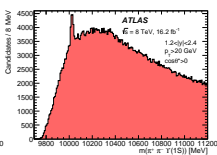
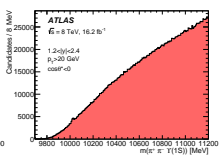
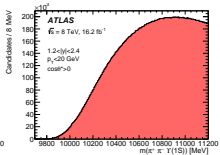
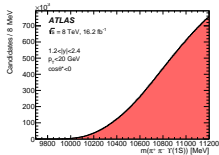
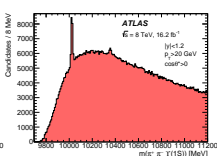
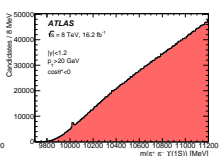
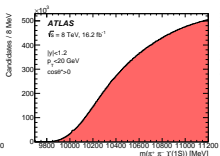
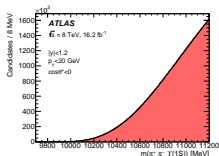


Two analyses performed by ATLAS are reported:

- ▶ Observation of a *new state decaying into*  $B_c^+ \pi^+ \pi^-$  with a mass consistent with the predictions for the  $B_c^+(2S)$  state in 7 TeV and 8 TeV data
  - ▶ First observation of an excited state in  $B_c^+$  sector
  - ▶ Measured mass  $6842 \pm 4$  (stat.)  $\pm 5$  (syst.) MeV
- ▶ Search for  $X_b$  state in  $\pi^+ \pi^- \Upsilon(1S)$  channel
  - ▶ No signal found
  - ▶ Upper limits on  $(\sigma \mathcal{B})/(\sigma \mathcal{B})_{2S}$  @ 95% CL are set at **0.8–4.0%**
  - ▶ No evidences for other searched states  $\Upsilon(1^3D_J)$ ,  $\Upsilon(10860)$ ,  $\Upsilon(11020)$
  - ▶ Limit  $\sigma(\Upsilon(1^3D_J))/\sigma(\Upsilon(2S)) < 0.55$  is set

# Backup slides

# $\pi^+\pi^-\Upsilon(1S)$ mass distributions



# Systematic uncertainties

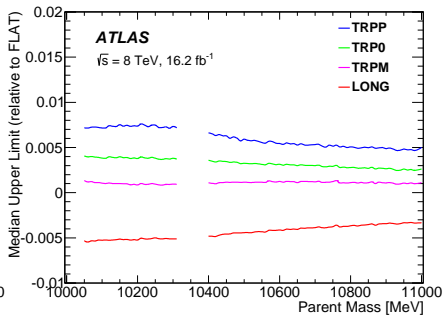
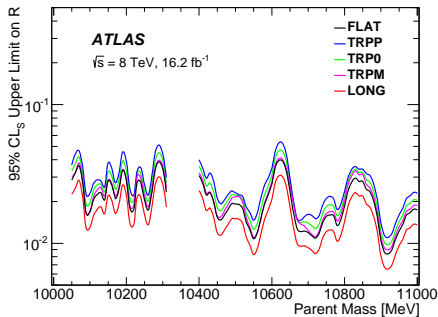
$$R = (\sigma_{\mathcal{B}})/(\sigma_{\mathcal{B}})_{2S}$$

$$N = N_{2S} \cdot R \cdot \frac{\mathcal{A}}{\mathcal{A}_{2S}} \cdot \frac{\epsilon}{\epsilon_{2S}}$$

	$\sigma_b$ [%]	$\sigma_{ec}$ [%]	$f_b$ [%]	$f_{ec}$ [%]	$r_b$ [%]	$r_{ec}$ [%]	$S_{ y }$ [%]	$S_{pr}^b$ [%]	$S_{pr}^{ec}$ [%]	$S_{\cos\theta^*}^{(1)}$ [%]	$S_{\cos\theta^*}^{(2)}$ [%]	$S_{\cos\theta^*}^{(3)}$ [%]	$S_{\cos\theta^*}^{(4)}$ [%]
Extracting $f, r$			0.5	1.1	1.2	1.4							
Extrapolating $\sigma$	0.1	0.2											
Data/MC difference in $\sigma$	1.9	4.2											
$ y $ scale factors							5.8						
Production weighting							0.3	8.4	7.0	0.9	2.8	2.1	3.4
Bin splittings: fit							0.2	0.5	0.8	2.4	4.2	2.8	6.0
Bin splittings: parameterisation							1.8	1.0	1.2	0.2	0.2	0.4	0.2
$m_{\pi^+\pi^-}$ shape							0.2	8.0	11.5	34.7	16.2	15.9	15.0
<b>Total</b>	2.0	4.2	0.5	1.1	1.2	1.4	6.1	11.6	13.6	34.8	17.0	16.3	16.6

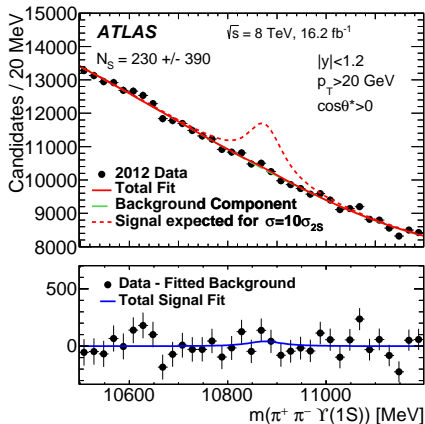
	$N_{2S}$ [%]	$\epsilon/\epsilon_{2S}$ [%]	$\mathcal{A}/\mathcal{A}_{2S}$ [%]	$\epsilon/\epsilon_{2S} \cdot \mathcal{A}/\mathcal{A}_{2S}$ [%]
$N_{2S}$ yield	2.3			
$\epsilon$ vs. $m$ : fit		1.0		
$\epsilon$ vs. $m$ : parameterisation		0.5		
Production weighting		1.0		
Acceptance Extrapolation			11.7	
$m_{\pi^+\pi^-}$ shape				17.3
<b>Total</b>	2.3	1.5	11.7	17.3

# Accounting for the polarisation



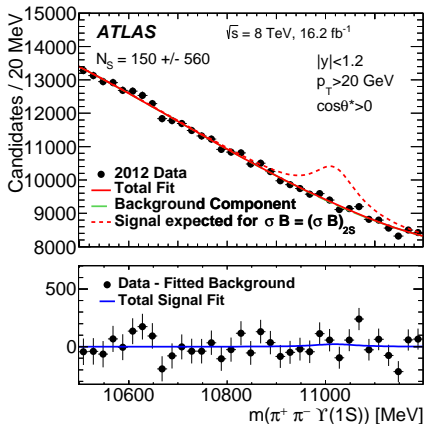
# Wide resonance search

$\Upsilon(10860)$



For world-average values:  $z = 0.6$   
 Maximum significance:  $z = 1.1$   
 at  $m = 10856 \text{ MeV}$ ,  $\Gamma = 55 \text{ MeV}$

$\Upsilon(11020)$



For world-average values:  $z = 0.3$   
 Maximum significance:  $z = 0.6$   
 at  $m = 11039 \text{ MeV}$ ,  $\Gamma = 95 \text{ MeV}$