Search for $X_b \to \Upsilon(1S)\pi^+\pi^-$ with ATLAS
bottomonium counterpart to X(3872)

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Michael Beattie

Lancaster University
On Behalf of the ATLAS Collaboration

Outline

1) Introduction

- The ATLAS Detector
- Quarkonia physics with ATLAS
- $\psi(2S) \to J/\psi\pi^+\pi^-$ event reconstruction
- Background of X(3872)

Analysis published in Physics Letters B:
740 (2015) Pages 199 – 217

arxiv.org/pdf/1410.4409v2.pdf

2) Search for X_b in decays to $\Upsilon(1S)\pi^+\pi^-$

- Motivation
- Event reconstruction
- Binning
- Method validation with $\Upsilon(2S)$ and $\Upsilon(3S)$
- Local Significance and Upper Limits

3) Other states: $\Upsilon(1^3D_J)$, $\Upsilon(10860)$, $\Upsilon(11020)$

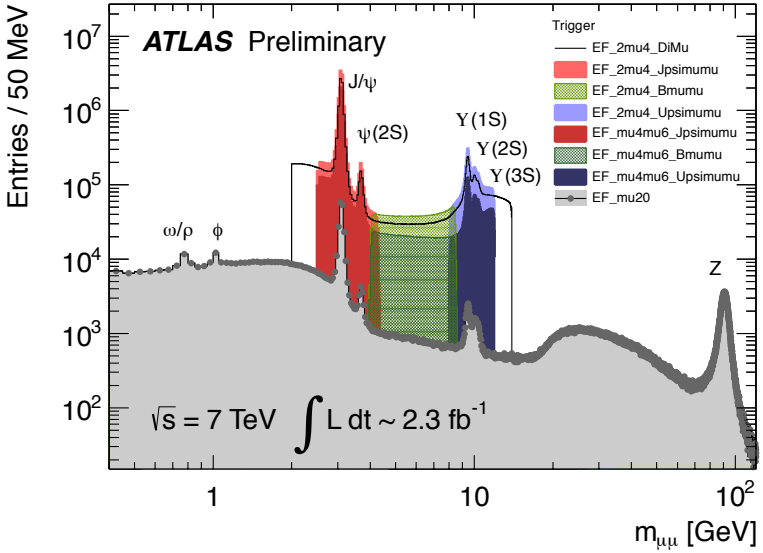
4) Summary and Future Plans

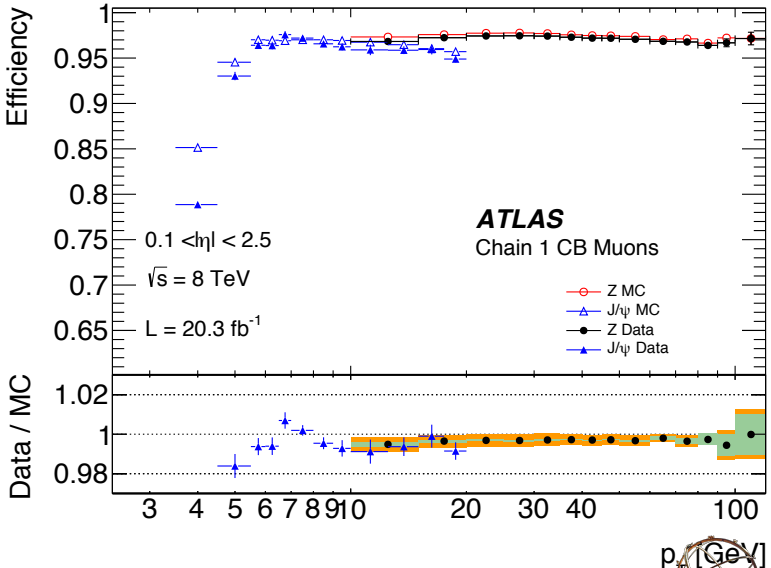
ATLAS Detector

- The ATLAS detector: a general purpose particle detector designed to study physics at the TeV scale [1]

- *Muon Spectrometer (MS):* air-core toroid magnet with separate tracking and trigger chambers
  - Barrel: MDT (precision tracking) and RPC (trigger)
  - Endcaps: MDT+CSC (precision tracking) and TGC (trigger)

- Detector is equipped with low p_T dimuon triggers in the MS specifically to record events containing J/ψ and ϒ decays





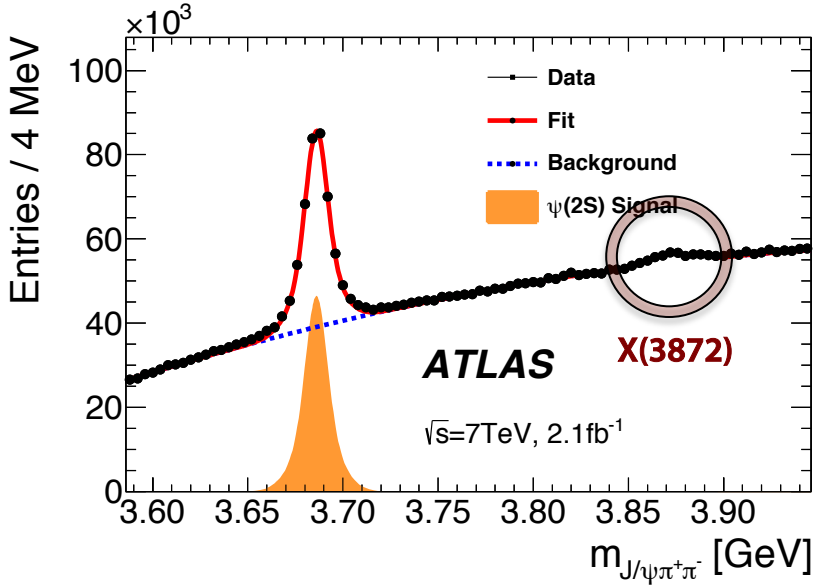
- Efficiency of reconstructing 'combined muons' (local track segments from MS and ID successfully matched) measured using data driven technique

- 'Tag and probe' using Z->μμ (higher muon p_T) and J/ψ->μμ (lower muon p_T) data samples
  - Require 'tag' to be a combined muon track

[1] arXiv:1110.1530 [2] http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/BPHYSICS/PUBLIC/DiMu_mas_diff_Triggers.png

ATLAS Measurements

ψ(2S)->J/ψπ⁺π⁻



X(3872) previously observed in 2011 ATLAS data as a resonance in $J/\psi\pi^+\pi^-$ invariant mass spectrum in ψ(2S) production cross section measurement[1]

- J/ψ candidates reconstructed through $\mu^+\mu^-$ vertex fits
- Four track vertex fits performed from reconstructed J/ψ muon tracks and pairs of hadronic tracks
  - Hadronic tracks given pion mass
  - Reconstructed J/ψ mass constrained to J/ψ PDG mass
  - Background dominated by mismatch of J/ψ and pion tracks 'combinatoral background

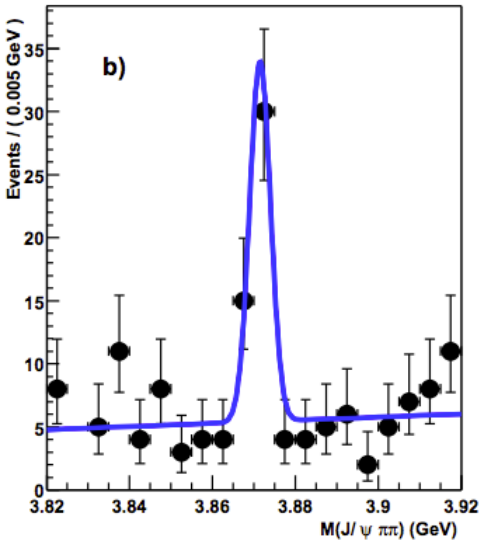
- **X(3872) ->J/ψπ⁺π⁻** - production measurements coming soon through the same $J/\psi\pi^+\pi^-$ decay channel. This talk will mainly focus on the X_b->Υ(1S) $\pi^+\pi^-$ search analysis
- **X_b->Υ(1S) $\pi^+\pi^-$** - search for candidates reconstructed in a similar manner using analogue decay X_b->Υ(1S) $\pi^+\pi^-$

[1] arXiv:1407.5532 / JHEP 09 (2014) 079

X(3872) Background

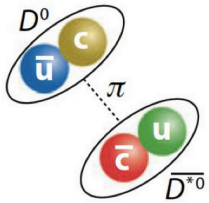
- X(3872): 'Exotic resonance' first observed in e^+e^- collider experiments (Belle[1] in 2003) and confirmed by BaBar[2] (via *b*-hadron decays) in decays to $J/\psi\pi^+\pi^-$
- Subsequently measured by the CDF II[3] experiment at the Tevatron $p\bar{p}$ collider
- Measured to be produced more abundantly through 'prompt' production processes

First observation of X(3872) at Belle[1]



What is X(3872)?

- Still unknown – though knowledge of its properties increasing
- New excited charmonium ($\bar{c}c$) state?
- mass, small Γ, $J^{PC} = 1^{++}$, decays ->inconsistent with conventional cc
- Loosely bound $D^0 - \bar{D}^{0*}$ molecule?
- Tetraquark (diquark – anti-diquark)
- LHCb[4] measured $J^{PC} = 1^{++}$, making charmonium hypothesis less likely



D^0–$\overline{D^{*0}}$ "molecule"

diquark – anti-diquark

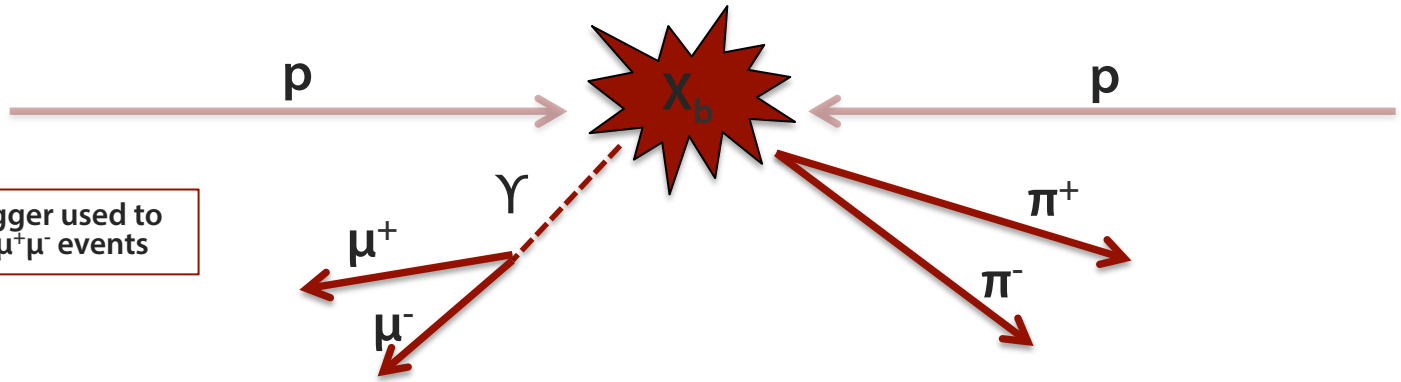
X(3872) production measurements from ATLAS coming soon

[1] arXiv:hep-ex/0309032v2 [2] arXiv:hep-ex/0406022v1 [3] arXiv:hep-ex/0312021v1 [4] arXiv:1302.6269 [hep-ex]

X_b Search Motivation

X_b

- Heavy quark symmetry -> expect bb 'X_b' analogue of X(3872)
- $J^{PC} = 1^{++}$, narrow width, produced in pp collisions
- The mass is model dependent e.g. Swanson model $m_{Xb} = 10.561$ GeV
- Measurement is experimentally feasible using existing framework to construct X_b candidates decaying to $\Upsilon(1S)\pi^+\pi^-$



Dimuon trigger used to collect $\Upsilon \to \mu^+\mu^-$ events

Additional

- Opportunity to measure production of $\Upsilon(1^3D_J)$ triplet states and $\Upsilon(10860)$, $\Upsilon(11020)$ using same analysis framework

$\Upsilon(1^3D_2)$ observed in radiative transitions by CLEO, BaBar

Analysis Data Sample

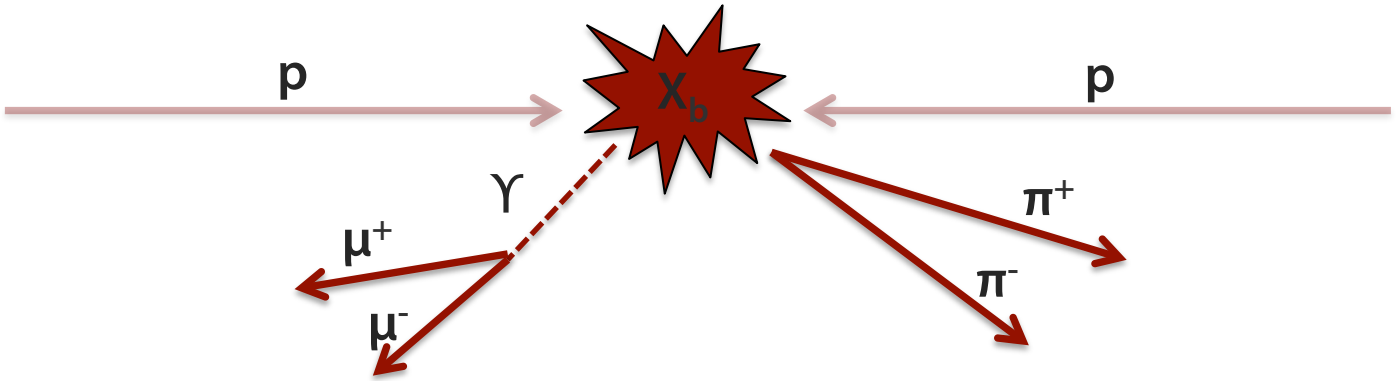
- Using events measured during the 2012 ATLAS data taking period $\sqrt{s} = 8$ TeV (~16.2fb^{-1})

$\Upsilon(1S) \to \mu\mu$

- $p_T(\mu^{\pm}) > 4$ GeV
- $|\eta(\mu^{\pm})| < 2.3$
- Upsilon dimuon trigger
- Muon track segments in tracker +calorimeter and muon spectrometer successfully combined
- $|m(\Upsilon(1S)) - m(\Upsilon(1S))_{PDG}| < 350$ MeV
- Opposite muon charge requirement
- Vertex $\chi^2 < 200$

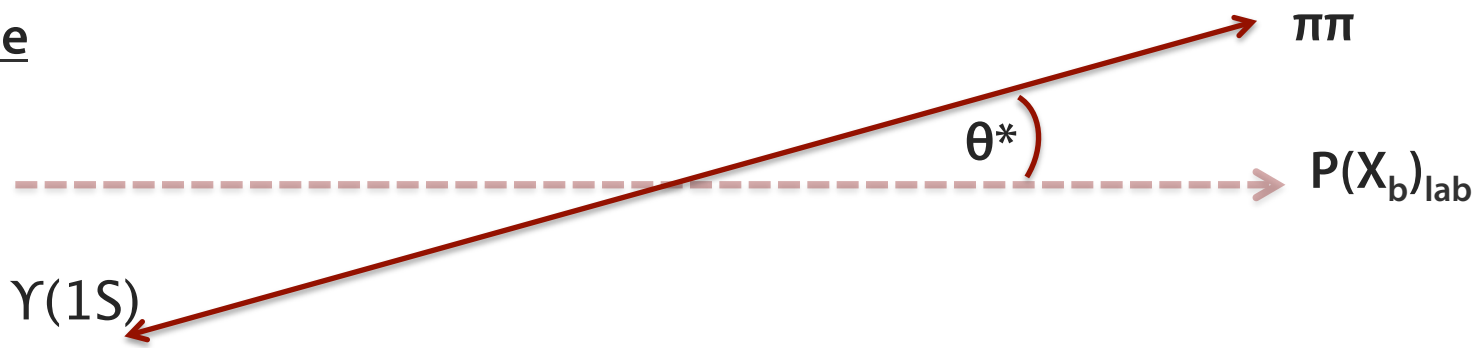
$X_b \to \Upsilon(1S)\pi\pi$

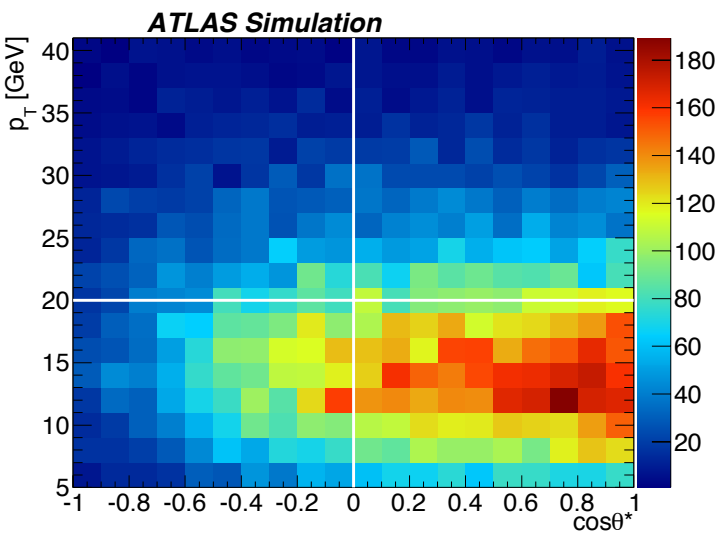
- $p_T(\pi^{\pm}) > 400$ MeV
- $|\eta(\pi^{\pm})| < 2.5$
- ≥ 1 pixel hit & ≥ 6 SCT for pion tracks
- 4-track vertex fit
  - $m_{\mu\mu} = m_{\Upsilon(1S)}$
  - Vertex $\chi^2 < 20$
  - $m_{\mu\mu\pi\pi} < 11.2$ GeV



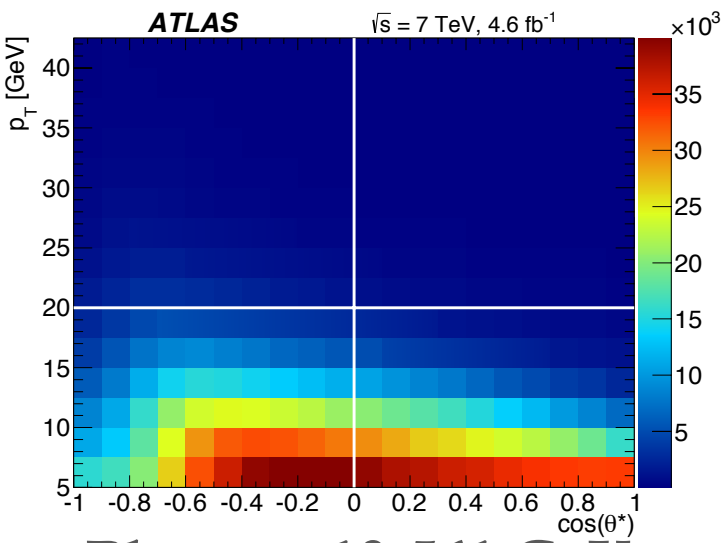
X_b: S/B Separation in [p_T, cosθ*]

X_b Rest Frame





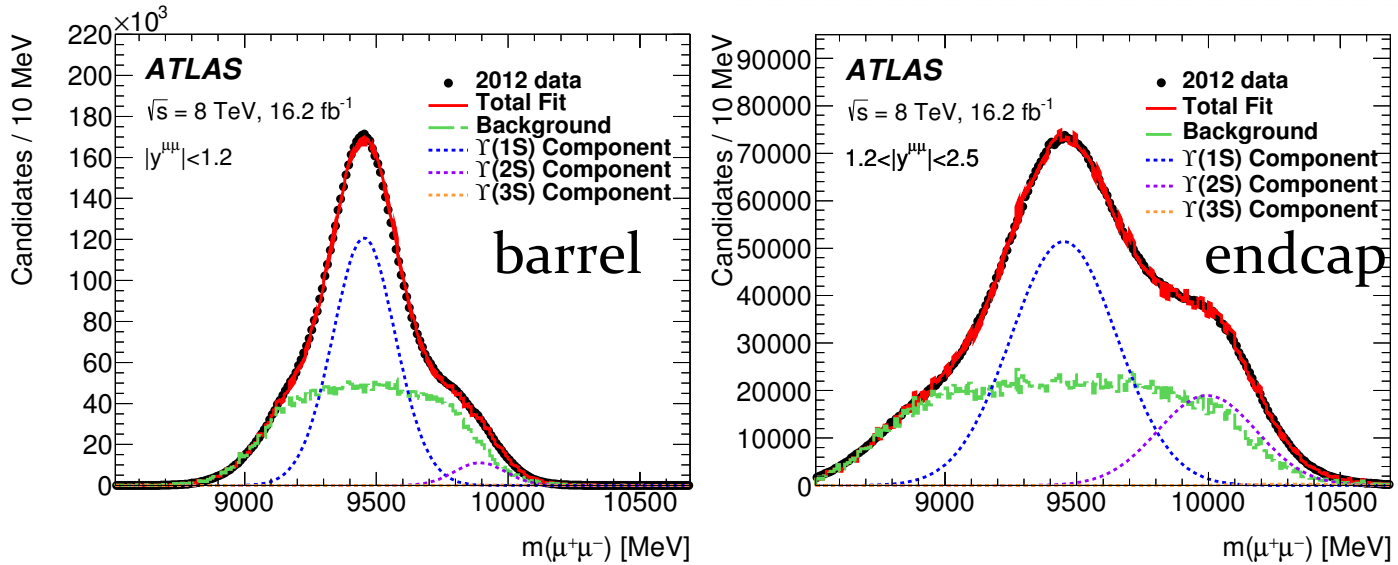
Signal at 10.561 GeV:
high p_T, high cos ϑ^*



Bkg near 10.561 GeV:
low p_T, spread in cosϑ^*

X_b: S/B Separation in Rapidity

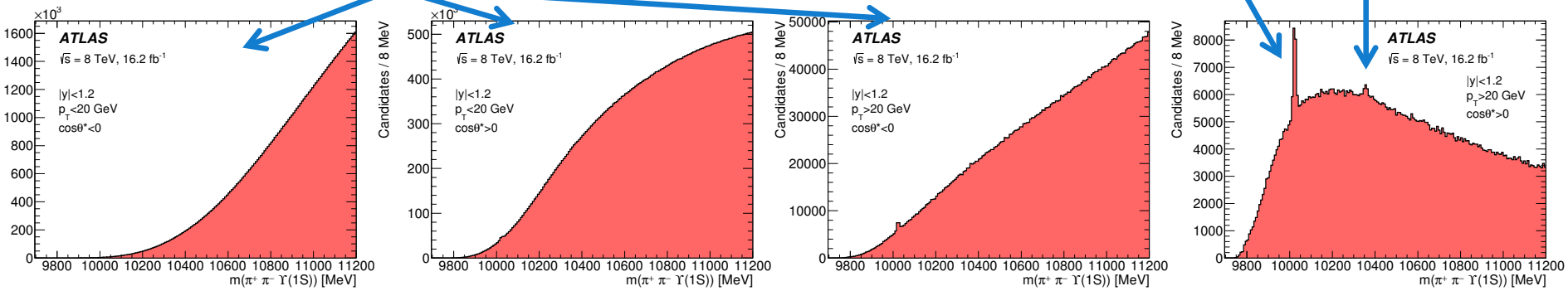
- Invariant mass reconstruction resolution depends on rapidity (worse at larger |y|)
- Split into barrel (|y| < 1.2) and endcap (|y| > 1.2) regions



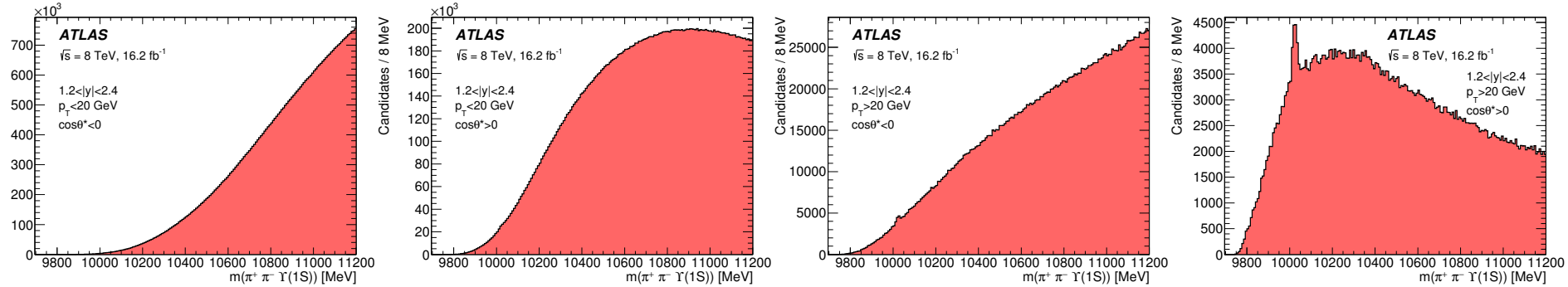
- Data split into different bins depending on **[p_T, cosθ*,|y|]**
- **Bin boundaries optimize sensitivity for X_b = 10.561 GeV mass hypothesis**
- Simultaneous fit performed in each **[p_T, cosθ*,|y|]** bin to extract signal
- MC simulation used to parameterize signal shape

Summary of data selection

Different bkg. shape in each bin:
fit with 2nd-order Chebychev polynomials



(a) Barrel, low p_T, low $\cos\theta^*$ **(b)** Barrel, low p_T, high $\cos\theta^*$ **(c)** Barrel, high p_T, low $\cos\theta^*$ **(d)** Barrel, high p_T, high $\cos\theta^*$

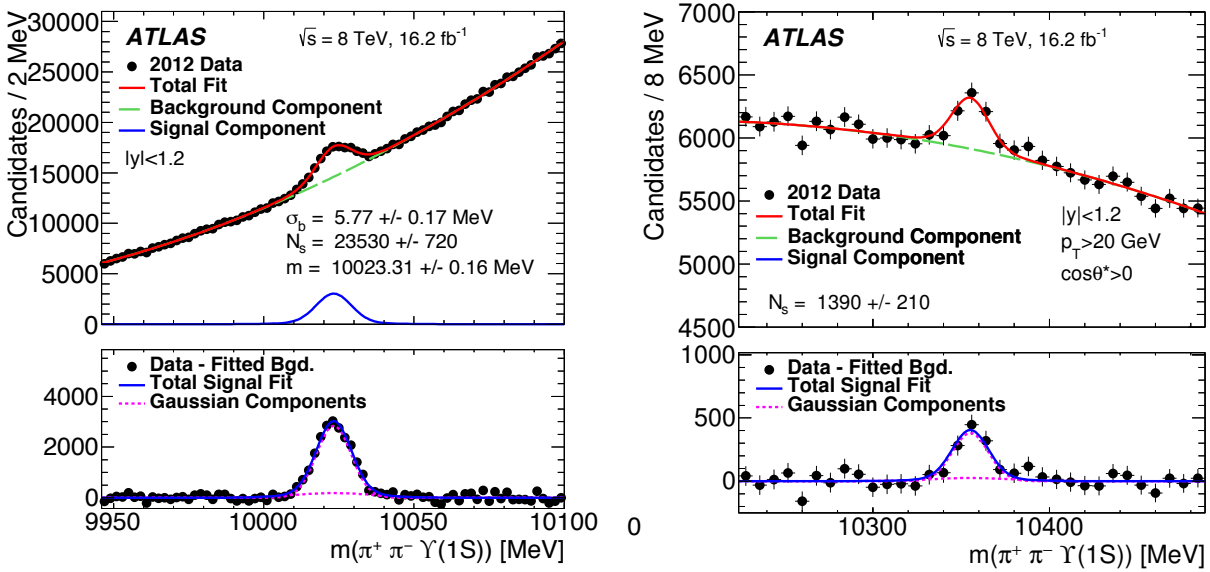


(e) Endcap, low p_T, low $\cos\theta^*$ **(f)** Endcap, low p_T, high $\cos\theta^*$ **(g)** Endcap, high p_T, low $\cos\theta^*$ **(h)** Endcap, high p_T, high $\cos\theta^*$

No obvious signs of additional signal peaks

Validation with Υ(2S), Υ(3S)

- Invariant mass reconstruction resolution depends on rapidity (worse at larger |y|)
- Split into barrel (|y| < 1.2) and endcap (|y| > 1.2) regions

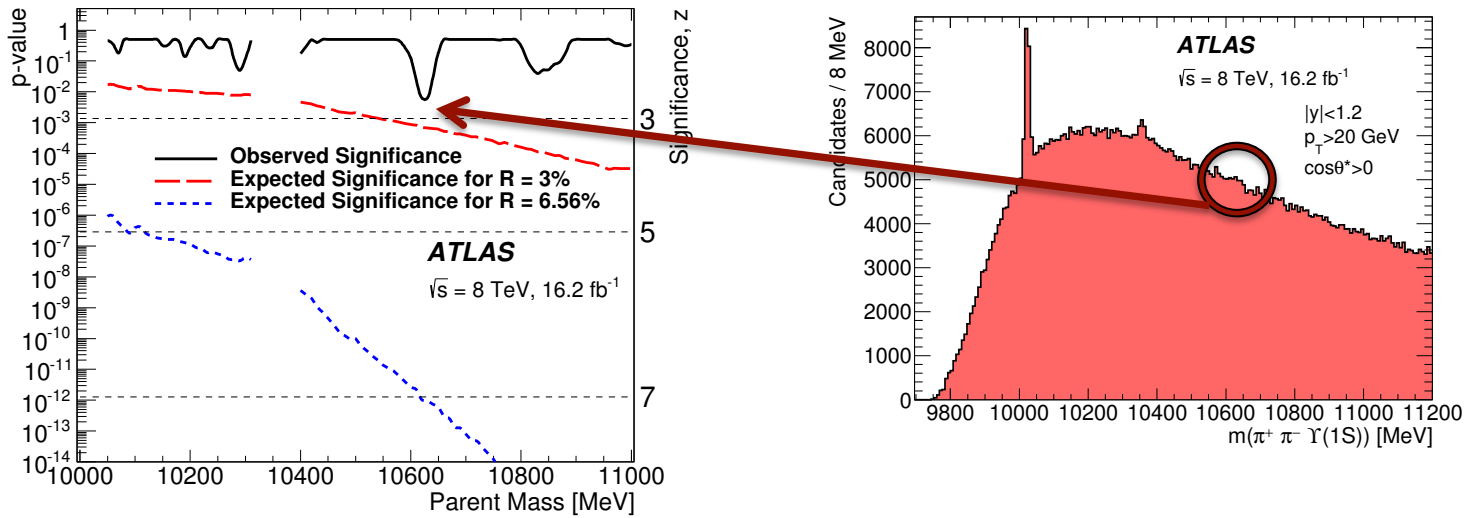


- Mass and σ parameters consistent between data and MC for Υ(nS) within error
- **Signal parameters fixed to simulation values and fits performed in each bin for Υ(1S), Υ(2S)**
- Extracted yields agree with estimates :

$$N_{2S}^{\text{expected}} = (\sigma\mathcal{B})_{2S} \cdot \mathcal{L} \cdot \mathcal{A} \cdot \epsilon$$

X_b: Local Significance

- Perform binned mass likelihood fits in all 8 [p_T, $\cos\theta^*$,$|y|$] bins simultaneously



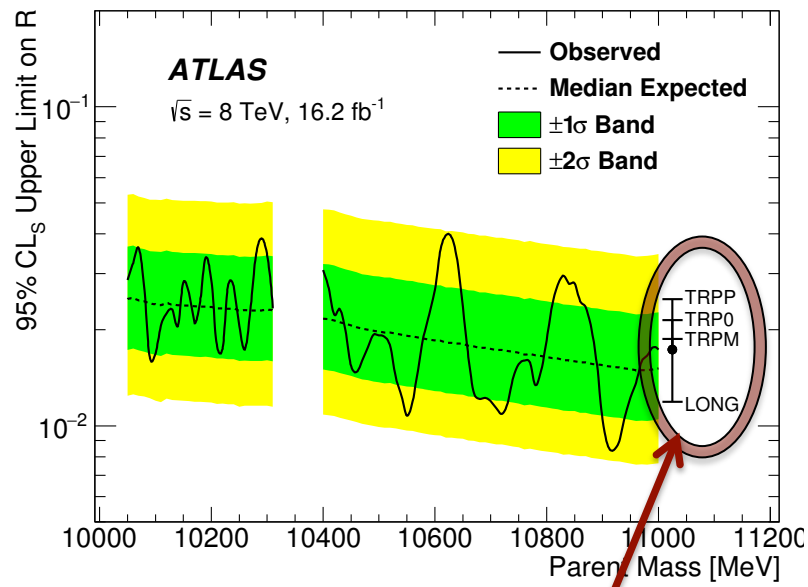
- X_b mass hypothesis changed in increments of 10 MeV
- $R = (\sigma B_{Xb})/(\sigma B_{\Upsilon(2S)})$

Fit Hypothesis

- Narrow state
- $\sigma_{Xb}(|y|,p_T)$ is $\Upsilon(1S)$, $\Upsilon(2S)$ like (linear interpolation/extrapolation used for signal width)
- $m_{\pi\pi}$ shape from three-body phase space

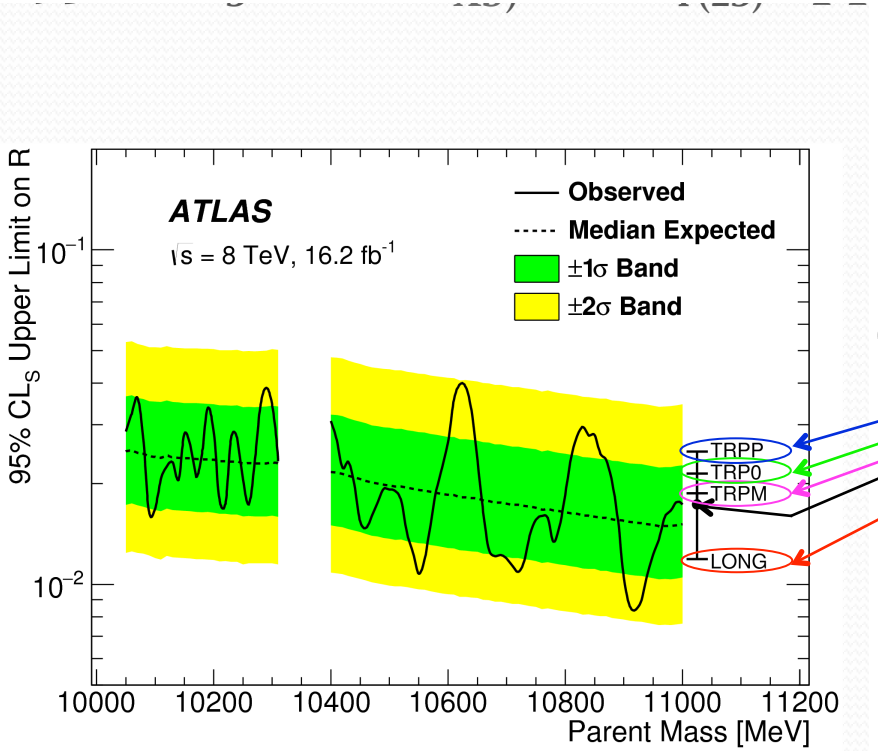
X_b: Upper Limits

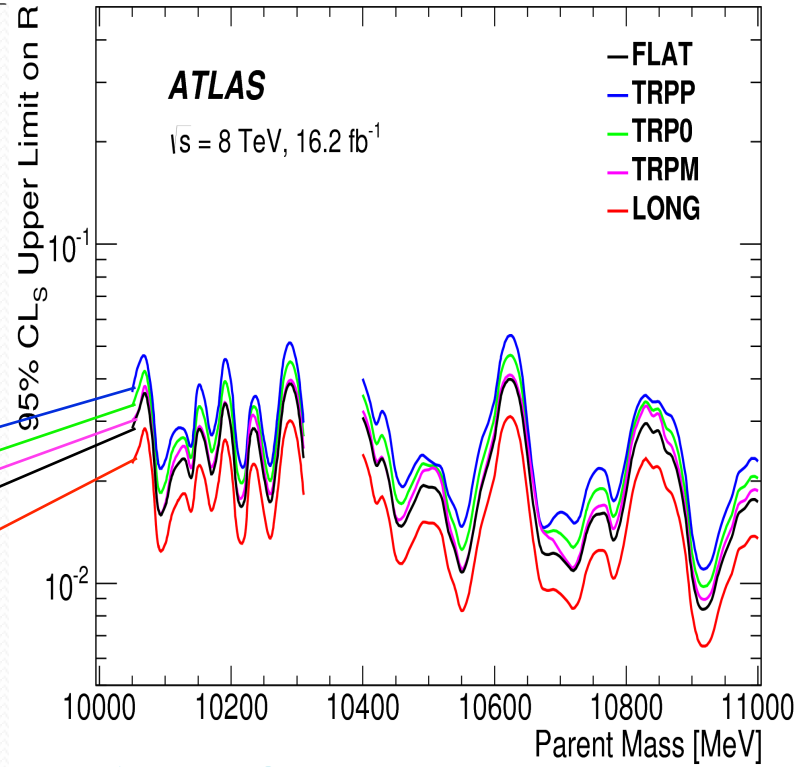
- Upper limits evaluated at 95% confidence level using CL_s method
- Upper limits found in every 10 MeV mass interval
- Systematic errors increase upper limit by up to 13%
- Upper limit of $\sigma B_{Xb}(X_b \to \Upsilon(1S)\pi^+\pi^-)$ found to be smaller than charm-analogue $X(3872) \to J/\psi\pi^+\pi^-$ production
- Most restrictive limits to date for $m(X_b) > 10.1$ GeV



Upper Limit depends on polarisation (unknown..) Assumed to be flat for central hypothesis

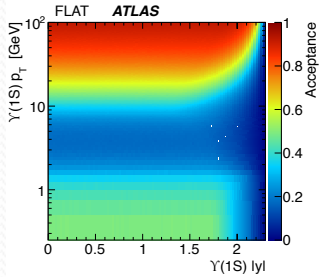
X_b: Spin Alignment Uncertainty



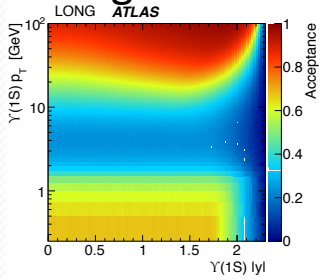


Most restrictive limits to date for m_{Xb}>10.1 GeV

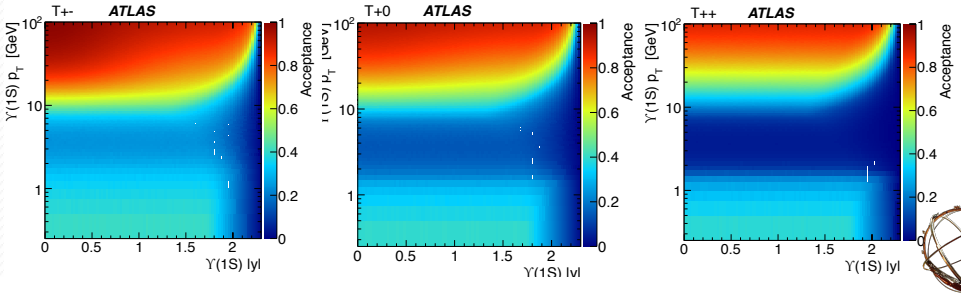
Flat



Longitudinal



Transverse



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

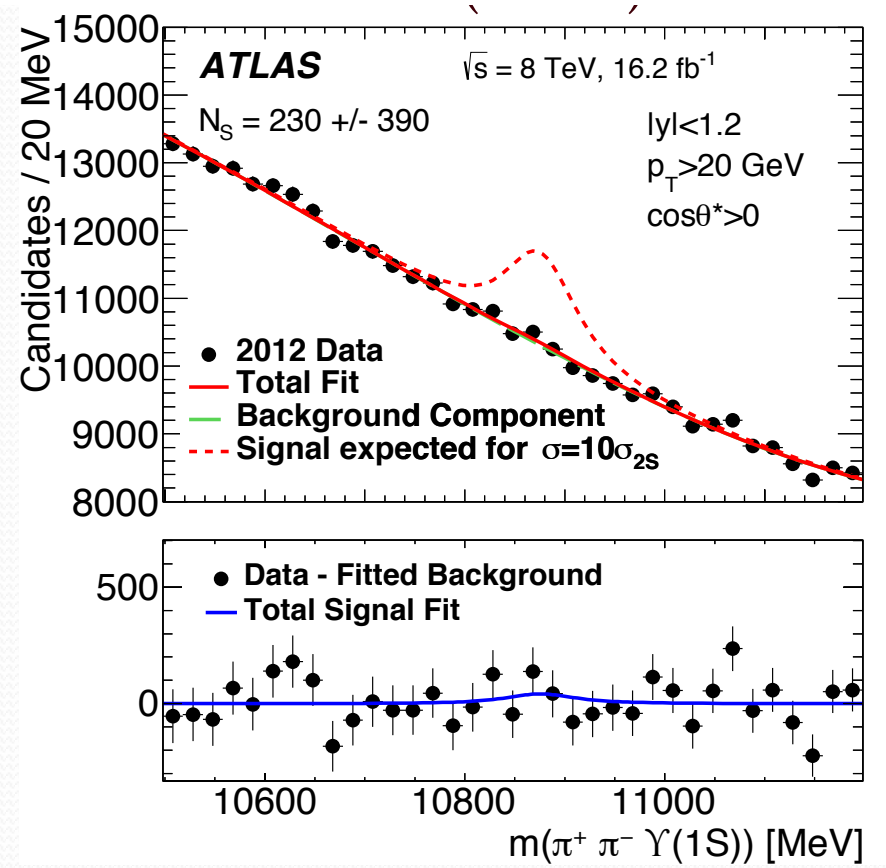
$\Upsilon(1^3D_J)$ Triplet states

- Extra peaks added for closely spaced states, with masses of 10156, 10164, 10170 MeV (averaged from several models)
- Signal significance < 0.12σ
- UL for J=2 state: **σ($\Upsilon(1^3D_J)$) < 0.55 σ(Υ(2S)) (using known BR)**

$\Upsilon(10860)$ and $\Upsilon(11020)$

- Much broader natural width than **Υ(1S), Υ(2S) etc**
- Extended mass range and fit model changes
- No evidence found for either state
  - Signal significance: 0.6σ and 0.3σ respectively

Simultaneous Fit to $\Upsilon(10860)$ and $\Upsilon(11020)$



Summary

- **Performed search of $X_b \to \Upsilon(1S)\pi^+\pi^-$ for numerous mass hypotheses across the 10 – 11 GeV**
  - $\Upsilon(2S)$ and $\Upsilon(3S)$ signal used for validation and 'calibration'
  - No evidence found for existence of new states
  - 95% CL Upper Limits on $R = (\sigma B_{Xb})/(\sigma B_{\psi(2S)})$. Ranges between 0.8 – 4%
  - This is the most sensitive limit to data

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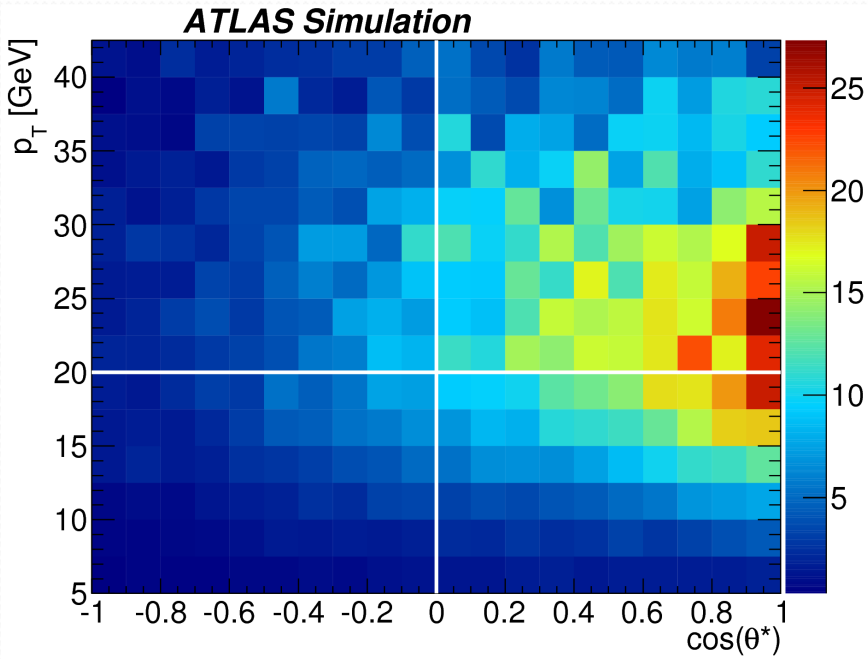
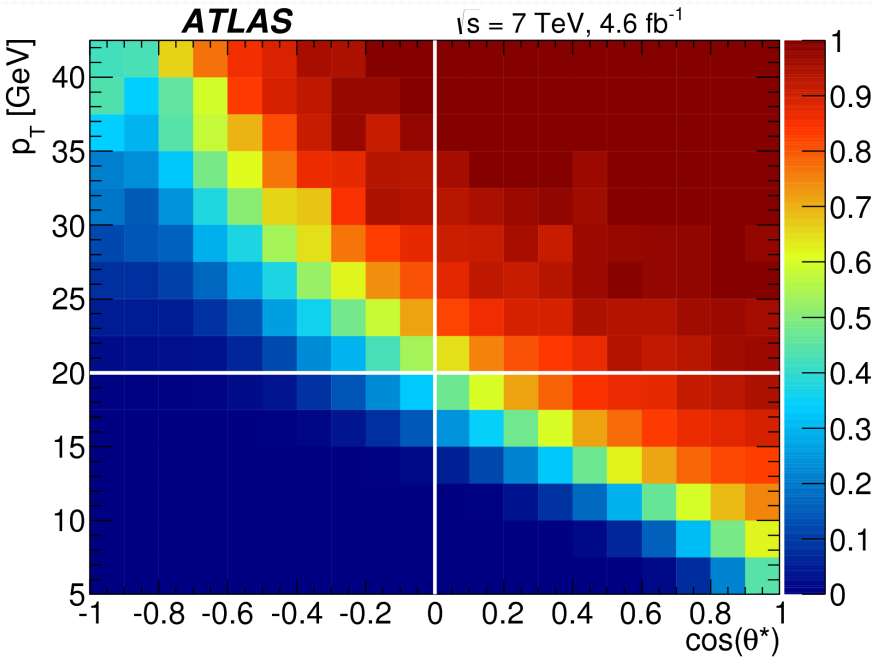
- **Search for $\Upsilon(1^3D_J)$, $\Upsilon(10860)$, $\Upsilon(11020)$**
  - **No evidence for any of these states**
  - **Upper limit set on $\Upsilon(1^3D_2)$ production: $\sigma(\Upsilon(1^3D_J)) < 0.55\ \sigma(\Upsilon(2S))$**

- **Next steps**
  - **Expect $X_b \to \Upsilon(1S)\pi^+\pi^-$ is strongly isospin suppressed**
  - **Other channels e.g. $X_b \to \chi_b(nP)\pi^+\pi^-$ are experimentally challenging but worth exploring**

Back Up

Binning: X_b significance

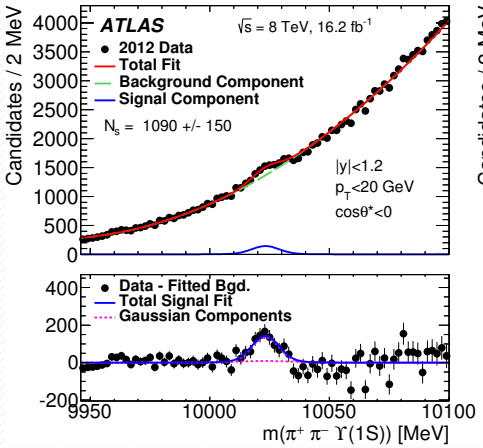




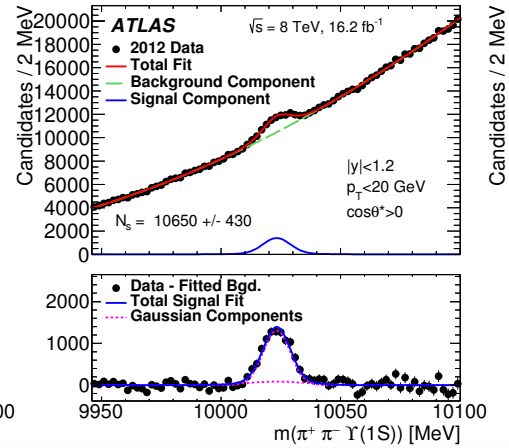
S/√B estimate [arb. units]

ΔR<0.7 cut imprint on background near 10.561 GeV

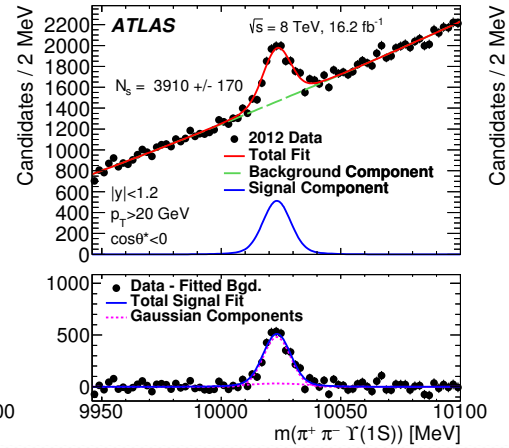
Υ(2S) Fit Projections



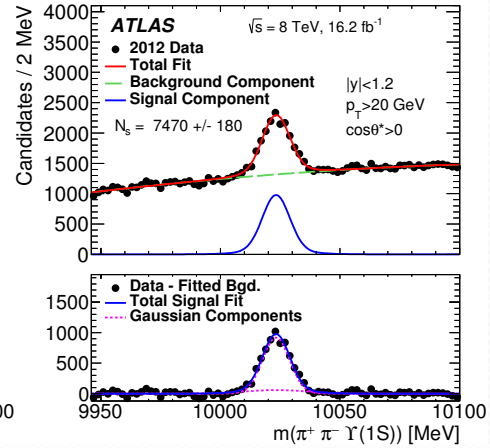
(a) Barrel, low p_T, low $\cos\theta^*$



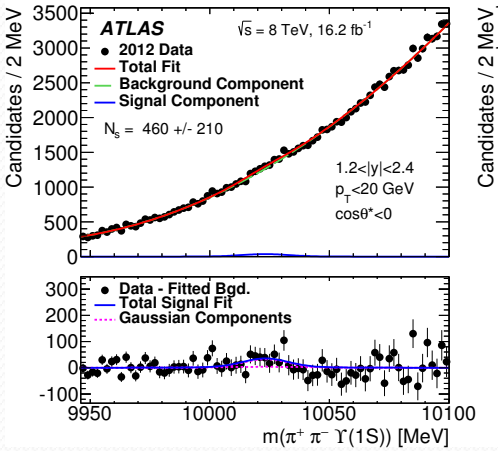
(b) Barrel, low p_T, high $\cos\theta^*$



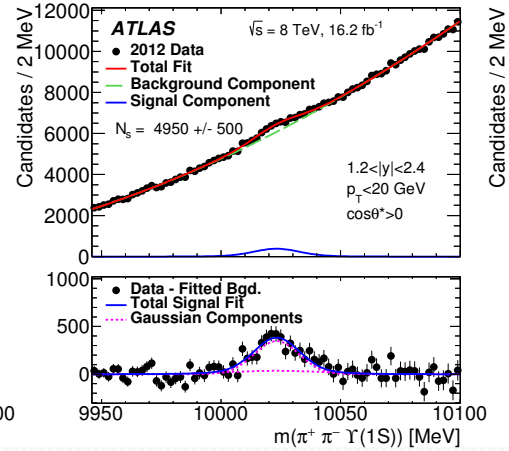
(c) Barrel, high p_T, low $\cos\theta^*$



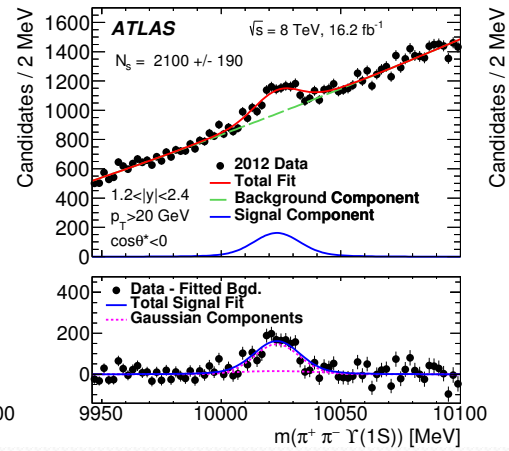
(d) Barrel, high p_T, high $\cos\theta^*$



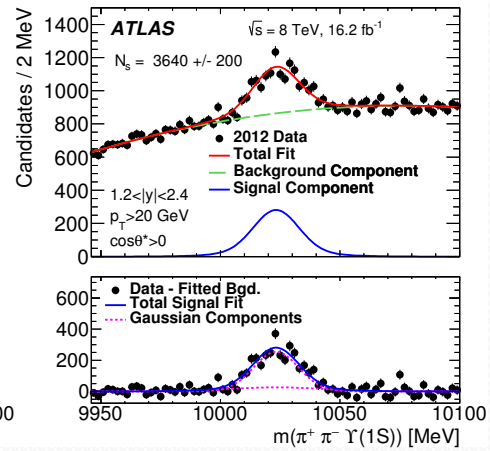
(e) Endcap, low p_T, low $\cos\theta^*$



(f) Endcap, low p_T, high $\cos\theta^*$

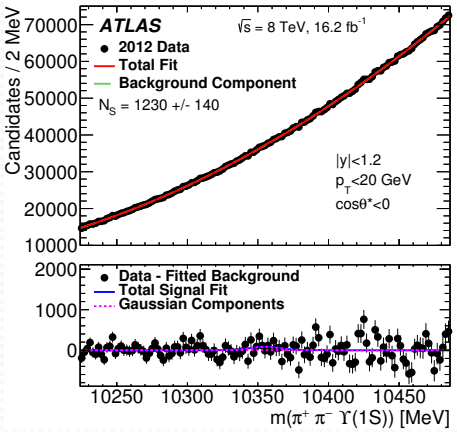


(g) Endcap, high p_T, low $\cos\theta^*$

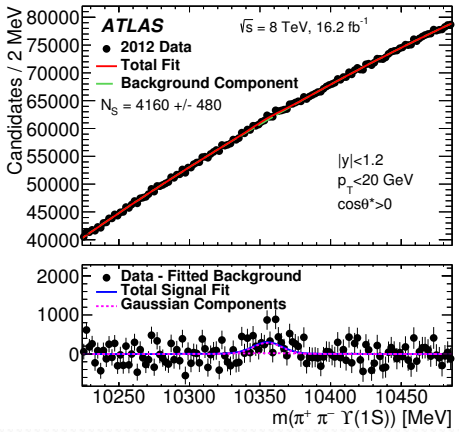


(h) Endcap, high p_T, high $\cos\theta^*$

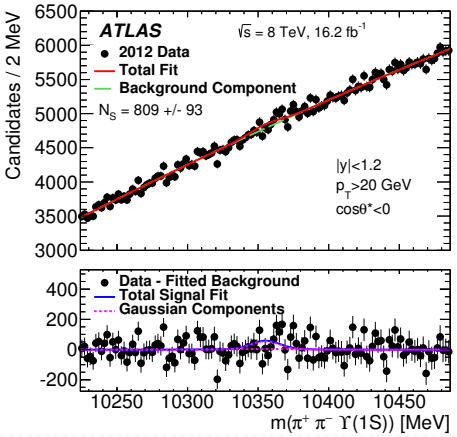
Υ(3S) Fit Projections



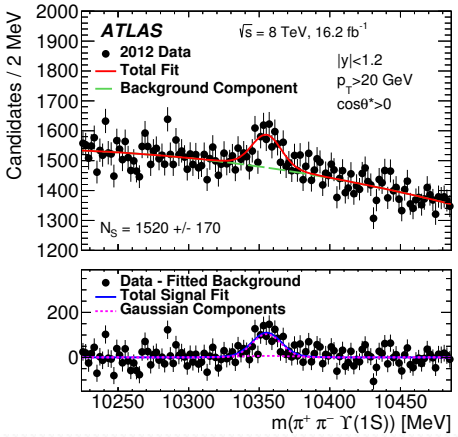
(a) Barrel, low p_T, low $\cos\theta^*$



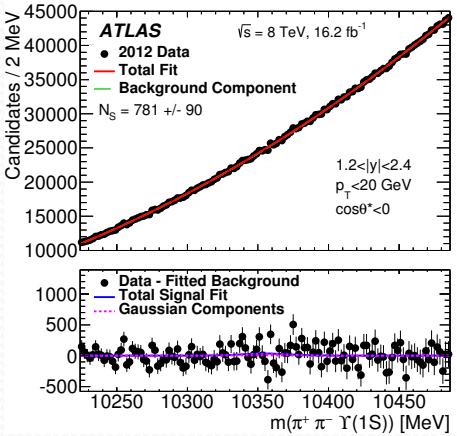
(b) Barrel, low p_T, high $\cos\theta^*$



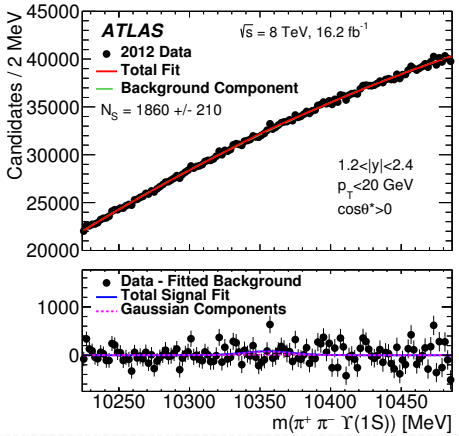
(c) Barrel, high p_T, low $\cos\theta^*$



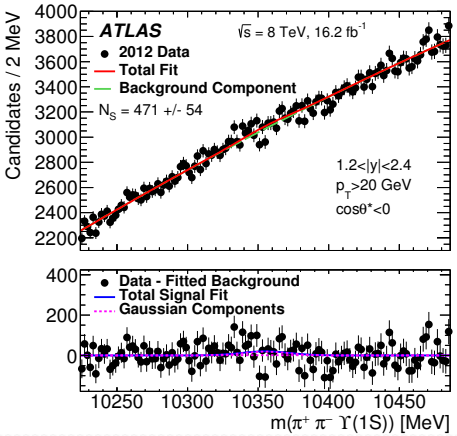
(d) Barrel, high p_T, high $\cos\theta^*$



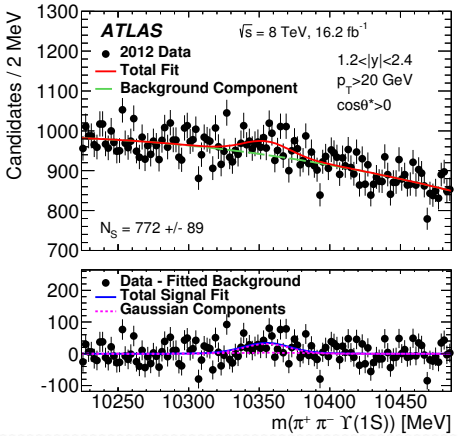
(e) Endcap, low p_T, low $\cos\theta^*$



(f) Endcap, low p_T, high $\cos\theta^*$



(g) Endcap, high p_T, low $\cos\theta^*$



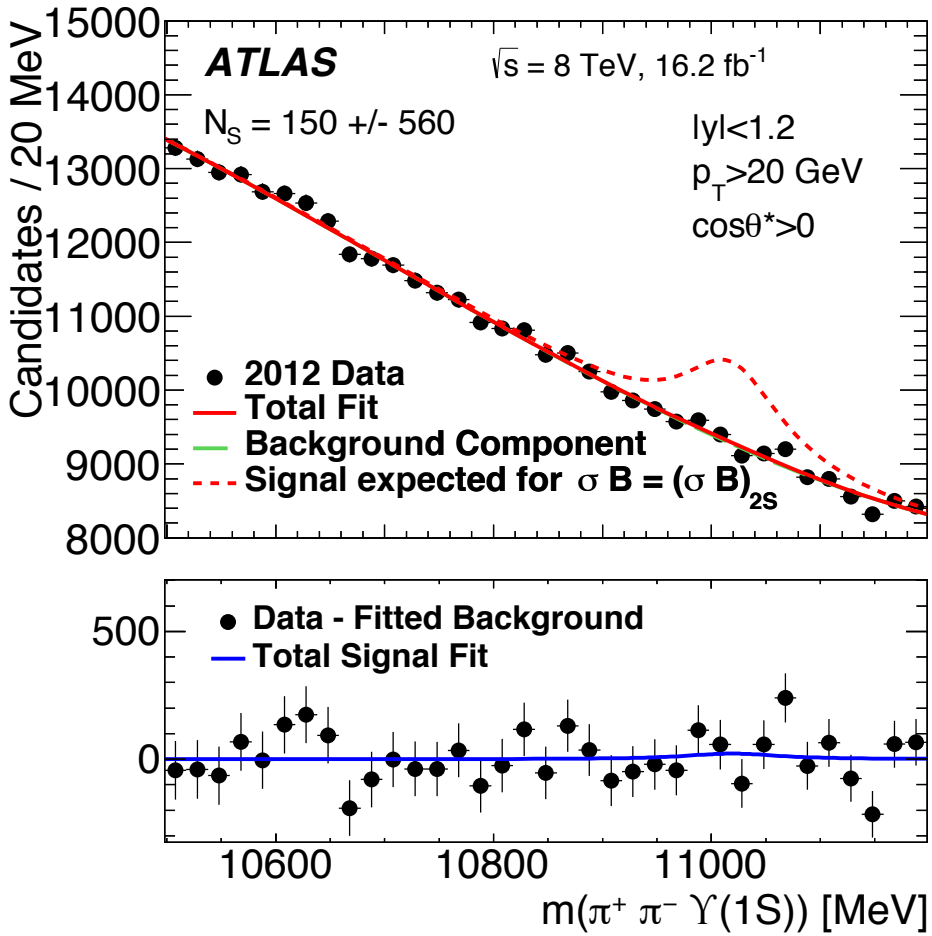
(h) Endcap, high p_T, high $\cos\theta^*$

Υ(1S), Υ(2S) Yield Validation

$$N_{2S}^{\text{expected}} = (\sigma\mathcal{B})_{2S} \cdot \mathcal{L} \cdot \mathcal{A} \cdot \epsilon$$

	Predicted	Observed
Υ(2S)	33300 ± 2500	34300 ± 800
Υ(3S)	11400 ± 1500	11600 ± 1300

Υ(11020) Fit


ATLAS
√s = 8 TeV, 16.2 fb-1
NS = 150 +/- 560
|y|<1.2
pT>20 GeV
cosθ*>0
2012 Data
Total Fit
Background Component
Signal expected for σ B = (σ B)2S
Candidates / 20 MeV
15000
14000
13000
12000
11000
10000
9000
8000
Data - Fitted Background
Total Signal Fit
500
0
10600
10800
11000
m(π+ π− Υ(1S)) [MeV]

Systematics

Signal shape parameters ← → Signal bin splitting parameters

	σ_{b} [%]	σ_{ec} [%]	f_{b} [%]	f_{ec} [%]	r_{b} [%]	r_{ec} [%]	$S_{\lvert y\rvert}$ [%]	$S^{\mathrm{b}}_{p_{\mathrm{T}}}$ [%]	$S^{\mathrm{ec}}_{p_{\mathrm{T}}}$ [%]	$S^{(1)}_{\cos\theta^*}$ [%]	$S^{(2)}_{\cos\theta^*}$ [%]	$S^{(3)}_{\cos\theta^*}$ [%]	$S^{(4)}_{\cos\theta^*}$ [%]
Extracting f, r			0.5	1.1	1.2	1.4							
Extrapolating σ	0.1	0.2											
Data/MC difference in σ	1.9	4.2											
$\lvert y\rvert$ 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
Total	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

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

Polarisation Uncertainty