Searching for a hidden-beauty counterpart to the X(3872) at ATLAS

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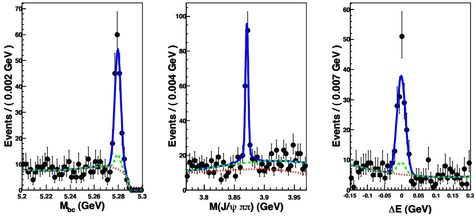
Outline

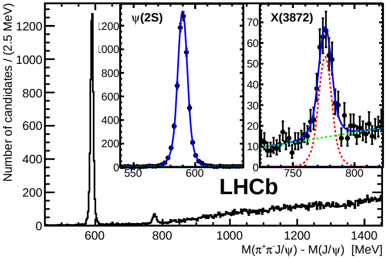
1. The X(3872) and the "X_b"
2. Quarkonium studies at ATLAS
3. The X_b search
   - $X_b \to \pi^+\pi^-\Upsilon(\to \mu^+\mu^-)$ reconstruction
   - discrimination in $(|y|, p_T, \cos\theta^*)$
   - background and signal modelling
   - calibration and validation
   - results as a function of mass
4. Bonus searches: $\Upsilon(1\,^3D_J)$, $\Upsilon(10860)$, and $\Upsilon(11020)$
5. Interpretation, and future plans
6. Summary

The X(3872) and the “X_b”

The X(3872) is the first (2003) & best-studied ($>$ 25 exp^{tal} papers) of the new hidden-charm states seen in the last decade.

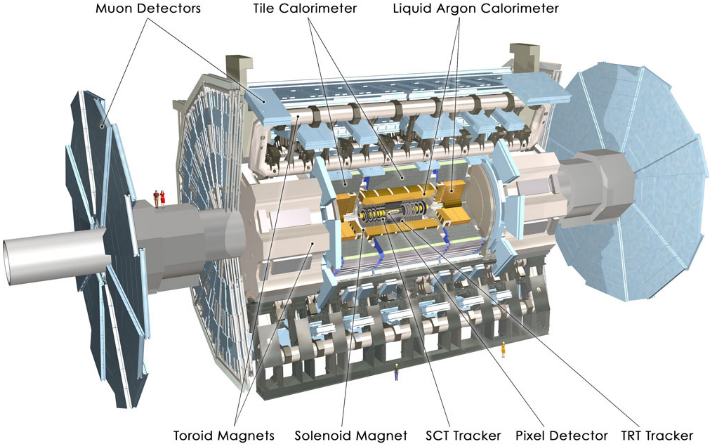
- $\pi\pi\psi$ [discovery] & other decays
- narrow: $\Gamma < 1.2\,\mathrm{MeV}$, 90% C.L.
- $J^{PC} = 1^{++}$ (2^{-+} finally excluded)
- direct $p\overline{p}$ & pp production seen
- very poor match to $c\overline{c}$ structure
- very close to $D^{*0}\overline{D}^0$ threshold:
  - $D^{*0}\overline{D}^0$ molecule, very weak $E_b \approx \frac{1}{10} E_b(^2H)$?
  - $\exists$ tetraquark, other models
- heavy-flavour symmetry: **expect a hidden-beauty analogue**





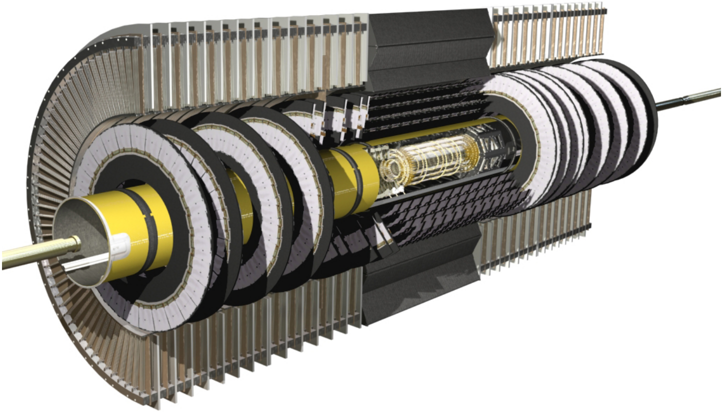
Quarkonium studies at ATLAS: the detector

huge, complex, multi-purpose detector optimized for a range of high-p_T discovery physics in $\sqrt{s} = 14\,\mathrm{TeV}$ pp collisions



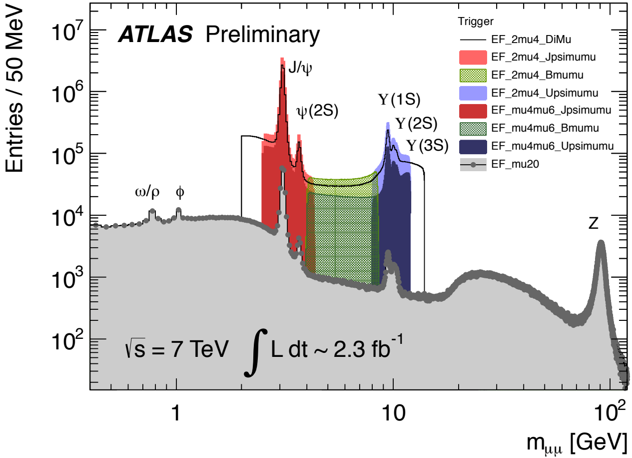
Quarkonium studies at ATLAS: the detector

for our special purposes, ATLAS is a large {Si pixel, Si strip, TRT} vertexing and tracking system, surrounded by trigger and muon ID



Quarkonium studies at ATLAS: trigger conditions

- rate limited by trigger bandwidth, especially at Level 1 (hardware)
- B-physics & onia: high-p_T μ, $M(\mu\mu)$-restricted-dimuon, ... triggers
- increasing $\mathcal{L} \longrightarrow$ higher-p_T triggers, prescaling, ...



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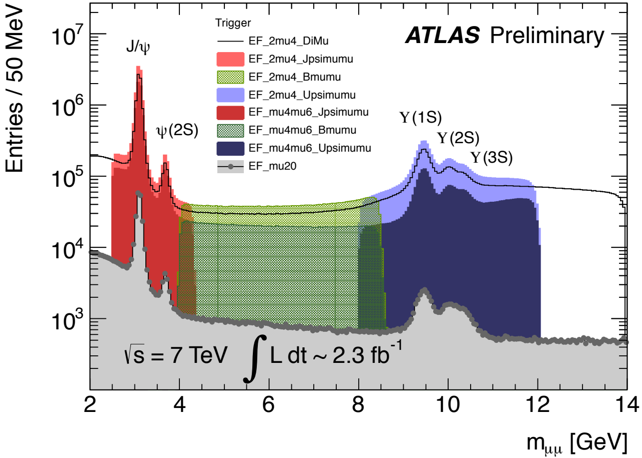


Quarkonium at ATLAS: acceptance for $V \to \mu^+\mu^-$

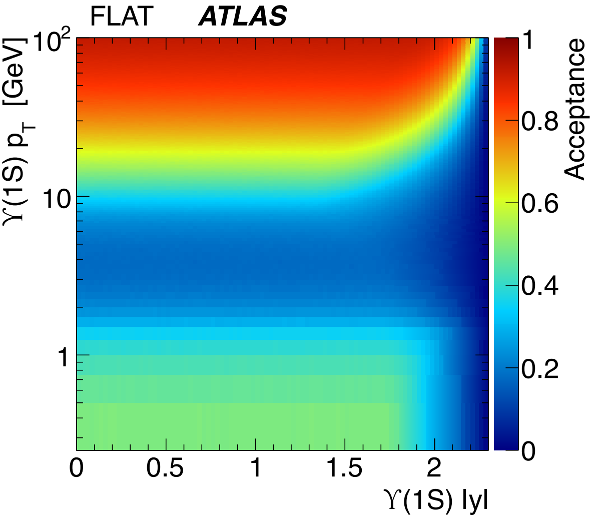
Υ(nS) cross-section measurement; ATLAS Collab., PRD 87, 052004 (2013)

for a given $(|y|, p_T)$, $\mathcal{A}$ is the probability that *both muons fall within the fiducial volume:*

- $p_T^\mu > 4\,\mathrm{GeV}$
- $|\eta^\mu| < 2.3$

$4\,\mathrm{GeV}$ trigger thresholds $\longrightarrow$ pronounced structure

straightforward extension to $\pi^+\pi^-\mu^+\mu^-$ and more complex final states



Quarkonium at ATLAS: polarization for V $\to \mu^+\mu^-$

Faccioli, Lourenço, Seixas, and Wöhri, EPJC 69, 657–673 (2010)

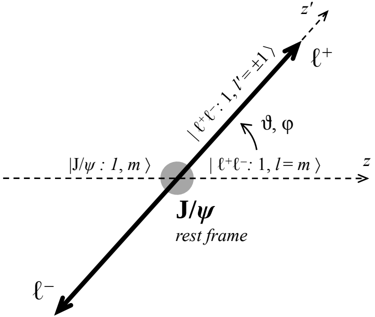
for $(J^{PC} = 1^{--})$ $|V\rangle = b_{+1}\,|+1\rangle + b_{-1}\,|-1\rangle + b_0\,|0\rangle$ decaying $\to \ell^+\ell^-$,

- the angular distribution $W(\cos\vartheta, \varphi)$

$$\propto \frac{\mathcal{N}}{(3+\lambda_\vartheta)} \left(1 + \lambda_\vartheta \cos^2\vartheta \right.$$

$$+ \lambda_\varphi \sin^2\vartheta \cos 2\varphi + \lambda_{\vartheta\varphi} \sin 2\vartheta \cos\varphi$$

$$\left. + \lambda_\varphi^\perp \sin^2\vartheta \sin 2\varphi + \lambda_{\vartheta\varphi}^\perp \sin 2\vartheta \sin\varphi \right)$$



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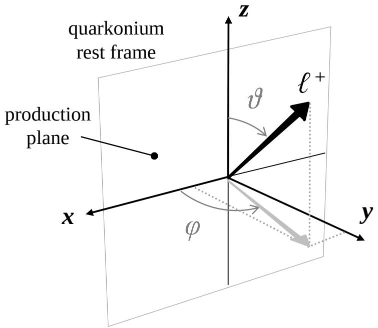
- inclusive production: p_1, p_2, and V only;
  we ($\sim$ must) choose (x, z) : production plane



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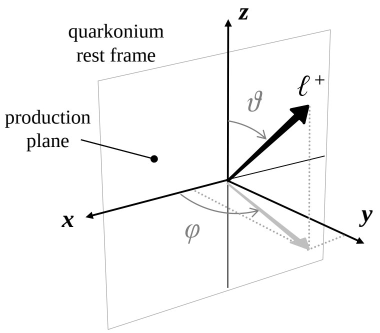

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- reflection-odd terms unobservable (parity)

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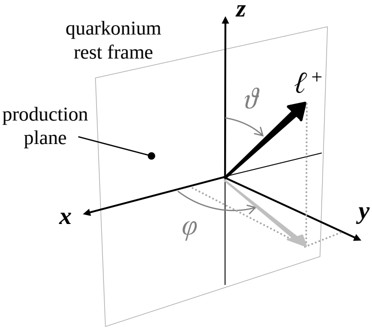

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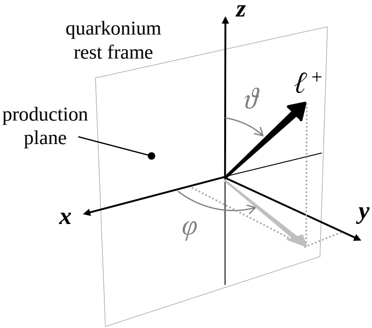

- inclusive production: p_1, p_2, and V only;
  we ($\sim$ must) choose (x, z) : production plane
- reflection-odd terms unobservable (parity)
- full angular distributions $(\lambda_\vartheta, \lambda_\varphi, \lambda_{\vartheta\varphi})$ in general needed ...

Quarkonium at ATLAS: polarization for $V \to \mu^+\mu^-$

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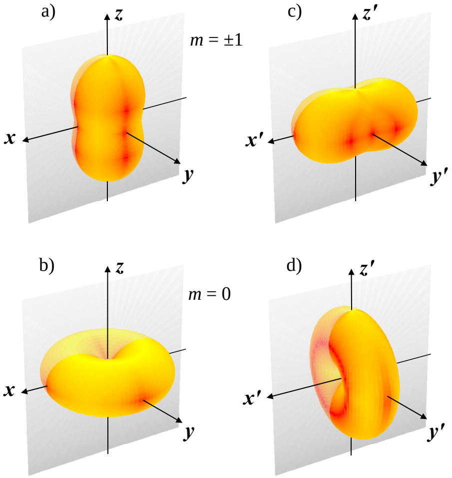
- L: polarized $\begin{cases} \text{transversely} \\ \text{longitudinally} \end{cases}$



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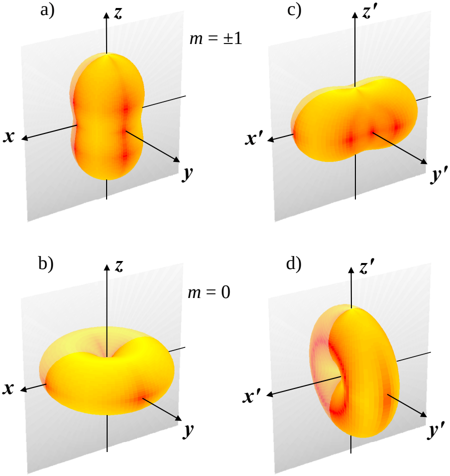

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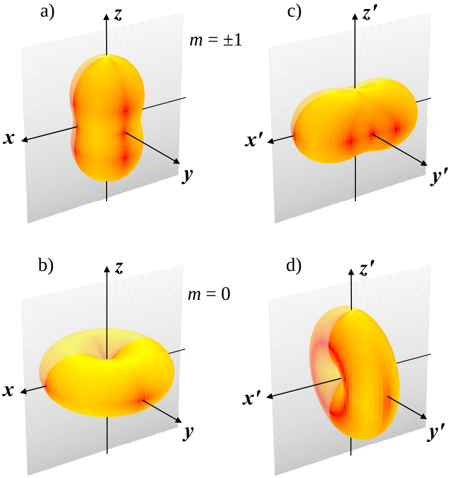

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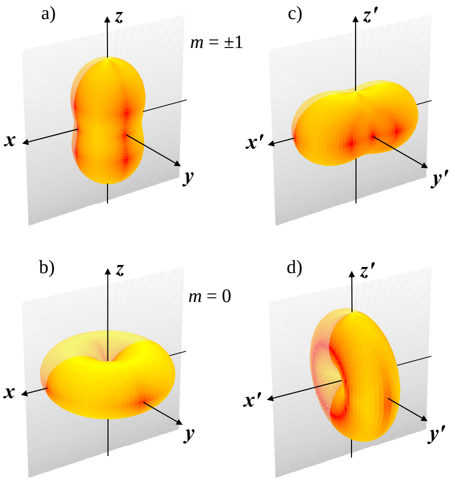
- integration over azimuth $\varphi \longrightarrow$ longitudinal dist^n (d) looks like



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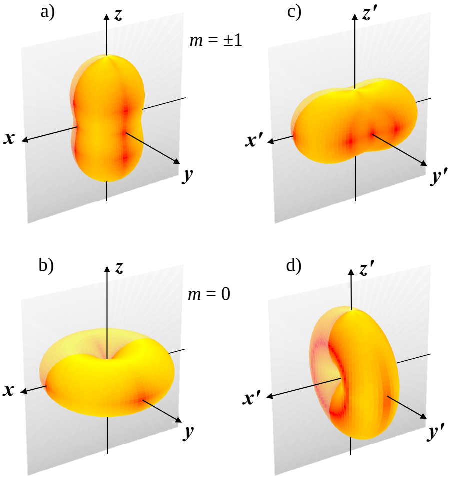
- integration over azimuth $\varphi \longrightarrow$ longitudinal dist^n (d) looks like *transverse* dist^n (a)



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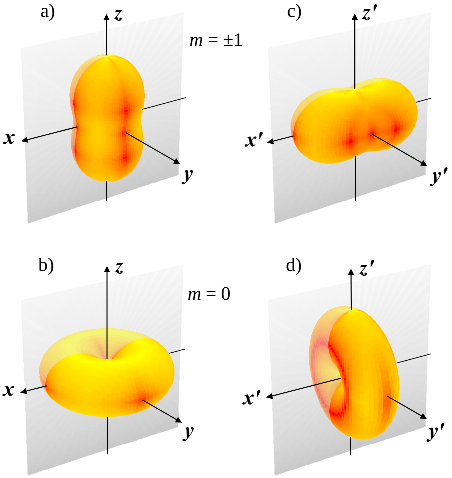

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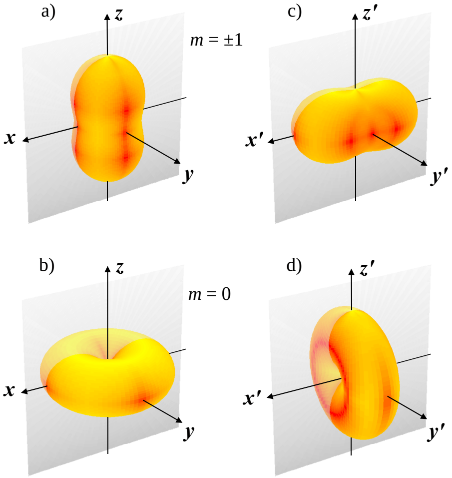
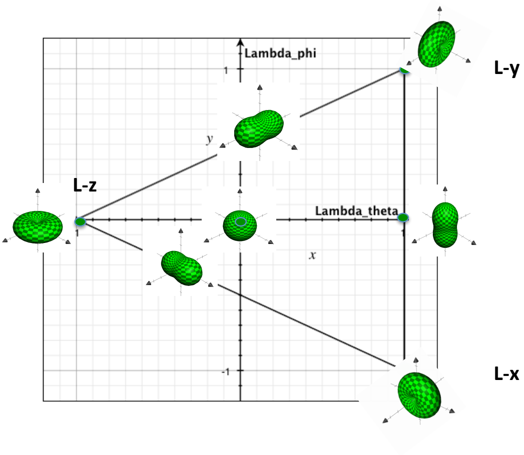
- integration over azimuth $\varphi \longrightarrow$ longitudinal dist^n (d) looks like *transverse* dist^n (a)
- λ_ϑ-only measurements (à la TeVatron Run I) can't be compared without assumptions about pol^n frame
- *experimental acceptance* is also typically a f^n of $(\lambda_\vartheta, \lambda_\varphi, \lambda_{\vartheta\varphi})$

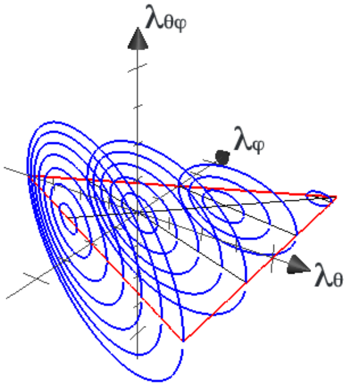


Quarkonium at ATLAS: polarization for V $\rightarrow \mu^+\mu^-$

Sandro Palestini, Physical Review D 83, 031503(R) (2011)

- limited range of $(\lambda_\vartheta,\ \lambda_\varphi,\ \lambda_{\vartheta\varphi})$ values allowed





Quarkonium at ATLAS: polarization for V $\to \mu^+\mu^-$

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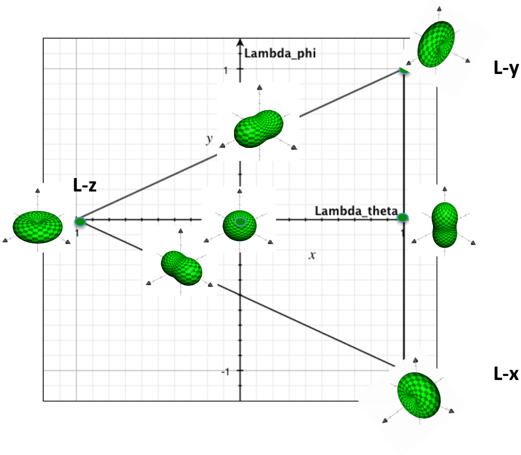
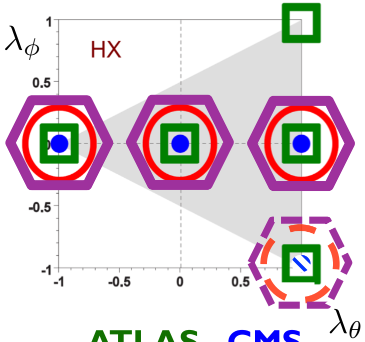
- limited range of $(\lambda_\vartheta, \lambda_\varphi, \lambda_{\vartheta\varphi})$ values allowed
- LHC experiments quote results for each of a set of working points





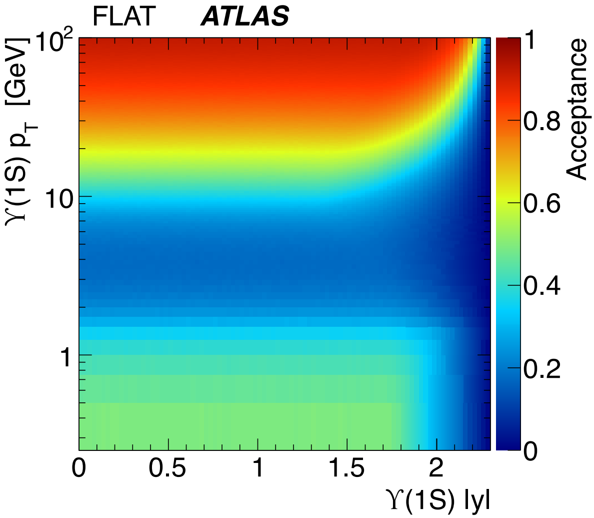
Quarkonium at ATLAS: acceptance $\mathcal{A}(|y|, p_T; \text{FLAT})$

$\Upsilon(nS)$ cross-section measurement; ATLAS Collab., PRD 87, 052004 (2013)

$(\lambda_\vartheta, \lambda_\varphi, \lambda_{\vartheta\varphi}) =$

$(\ \ 0,\ \ 0,\ \ 0)$

unpolarized production



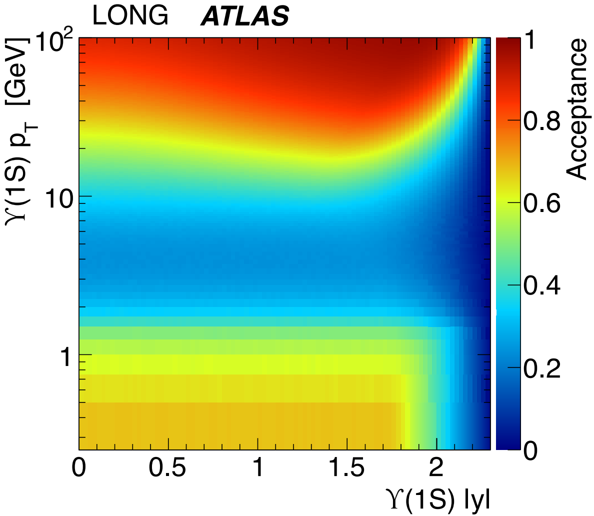
Quarkonium at ATLAS: acceptance $\mathcal{A}(|y|, p_T;$ LONG)

Υ(nS) cross-section measurement; ATLAS Collab., PRD 87, 052004 (2013)

$(\lambda_\vartheta, \lambda_\varphi, \lambda_{\vartheta\varphi}) =$

$(-1, \quad 0, \quad 0)$

polarization:
longitudinal along z



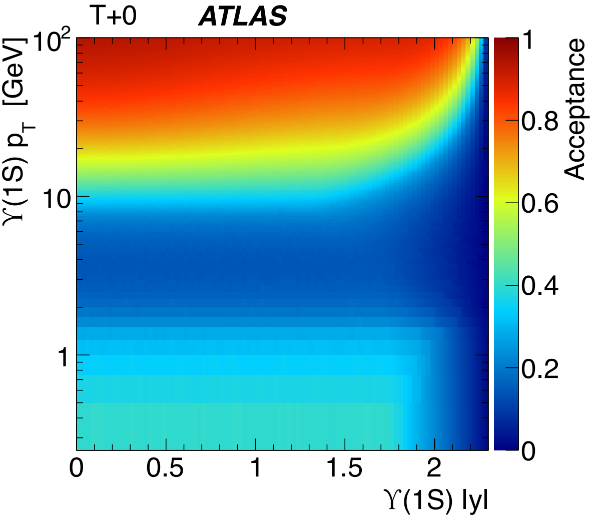
Quarkonium at ATLAS: acceptance $\mathcal{A}(|y|, p_T; T{+}0)$

$\Upsilon(nS)$ cross-section measurement; ATLAS Collab., PRD 87, 052004 (2013)

$(\lambda_\vartheta, \lambda_\varphi, \lambda_{\vartheta\varphi}) =$

$(+1, \quad 0, \quad 0)$

polarization:
transverse along z



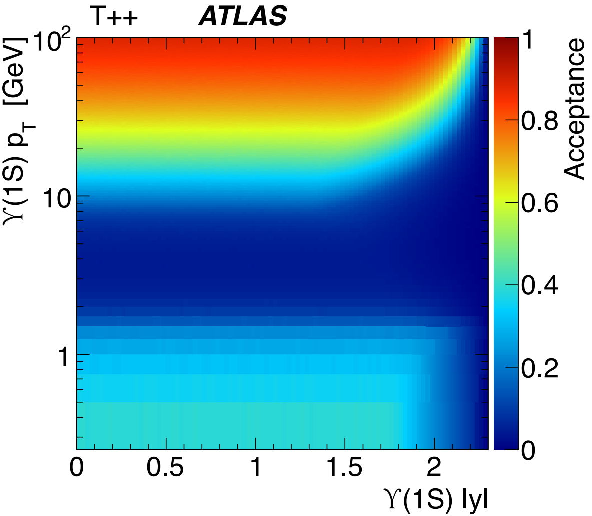
Quarkonium at ATLAS: acceptance $\mathcal{A}(|y|, p_T; T{+}{+})$

Υ(nS) cross-section measurement; ATLAS Collab., PRD 87, 052004 (2013)

$(\lambda_\vartheta, \lambda_\varphi, \lambda_{\vartheta\varphi}) =$

$(+1, +1, \quad 0)$

polarization:
longitudinal along y

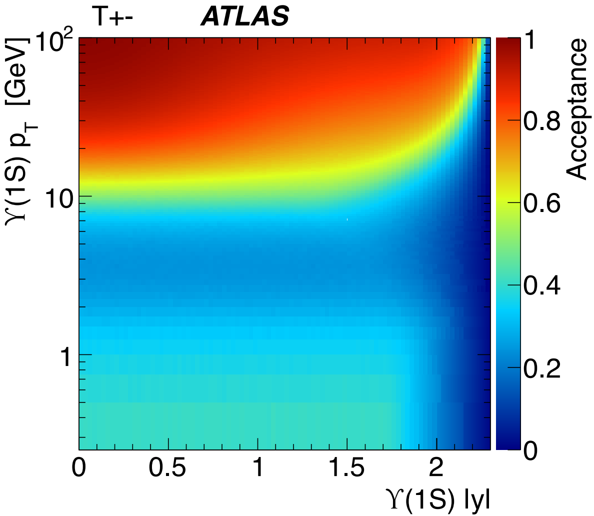


Quarkonium at ATLAS: acceptance $\mathcal{A}(|y|, p_T; T+-)$

Υ(nS) cross-section measurement; ATLAS Collab., PRD 87, 052004 (2013)

$(\lambda_\vartheta, \lambda_\varphi, \lambda_{\vartheta\varphi}) =$
$(+1, -1, \quad 0)$

polarization:
longitudinal along x

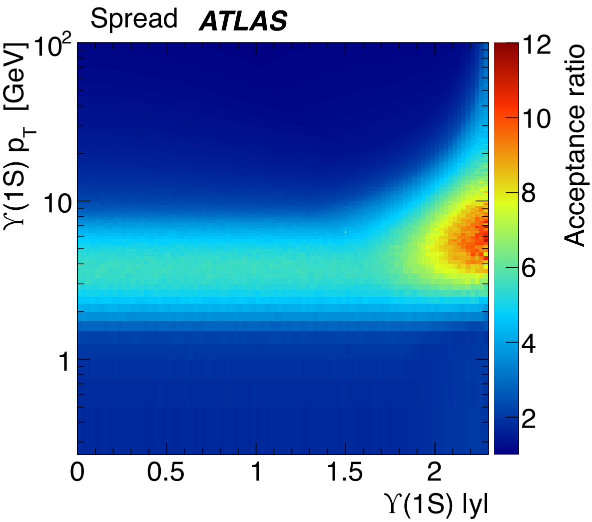


Quarkonium at ATLAS: acceptance spread

Υ(nS) cross-section measurement; ATLAS Collab., PRD 87, 052004 (2013)

maximum variation betw. the $(\lambda_\vartheta, \lambda_\varphi, \lambda_{\vartheta\varphi})$ working points

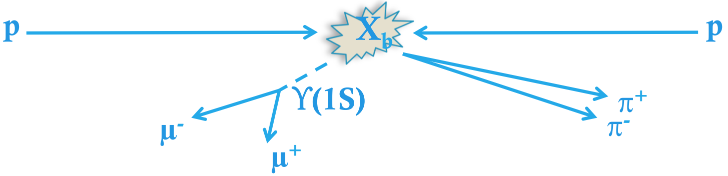
<u>*note:*</u>
CMS measurements are consistent with *unpolarized production* of the $\Upsilon(1S, 2S, 3S)$
PRL **110**, 081802 (2013)



The X_b search: outline

ATLAS Collab., Physics Letters B 740, 199–217 (2014); arXiv:1410.4409 [hep-ex]

The $\pi^+\pi^-\Upsilon(1S)$ (c.f. $\pi^+\pi^- J/\psi$) channel provides an **experimentally feasible search option:**



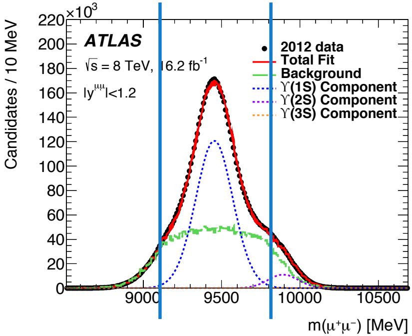
1. **Reconstruct** $X_b \to \pi^+\pi^-\Upsilon(\mu\mu)$ using large ATLAS $\Upsilon(\mu\mu)$ sample
2. Either **observe** X_b at mass M with significance z, or
3. **Set upper limits** for $X_b \to \pi^+\pi^-\Upsilon(\mu\mu)$ production
4. Also look for **$\Upsilon(1^3D_J)$, $\Upsilon(10860)$, and $\Upsilon(11020)$ decays**

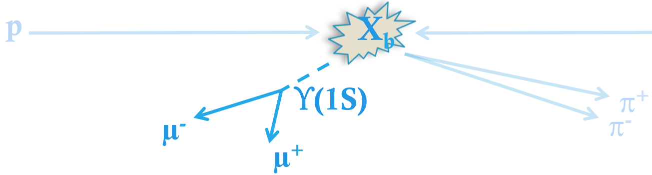
$X_b \to \pi^+\pi^-\Upsilon(\to \mu^+\mu^-)$ reconstruction

ATLAS Collab., Physics Letters B 740, 199–217 (2014); arXiv:1410.4409 [hep-ex]

I. Find $\Upsilon \to \mu^+\mu^-$ candidates:

- $p_T(\mu)>4$ GeV Υ trigger
- two "combined" μ tracks
- $|\eta(\mu)|<2.3$
- $|m(\mu\mu)-m_{1S}|<350$ MeV





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- two "combined" μ tracks
- $|\eta(\mu)|<2.3$
- $|m(\mu\mu)-m_{1S}|<350$ MeV

II. Add two tracks (ππ):

- $p_T(\pi)$>400 MeV
- $|\eta(\pi)|<2.5$
- 4-track vertex fit
  - $m(\mu\mu) = m_{1S}$ constraint
  - $\chi^2<20$
  - masses < 11.2 GeV

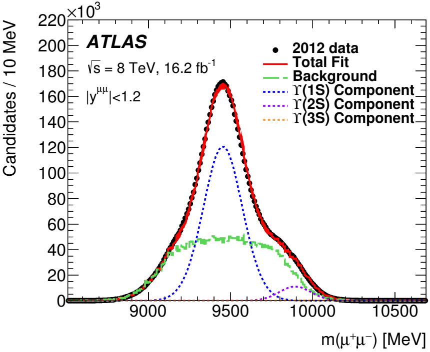
The X_b search: discrimination in ($|y|$, p_T, $\cos\theta^*$)

ATLAS Collab., Physics Letters B 740, 199–217 (2014); arXiv:1410.4409 [hep-ex]

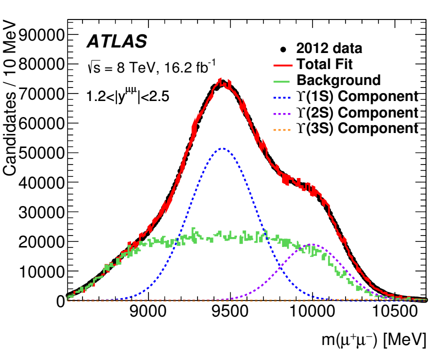
- **barrel ($|y| < 1.2$) resolut^n better than endcap ($1.2 < |y| < 2.4$)**
- constraint $\mu^+\mu^- \to \Upsilon$ mitigates this, but not higher bkgd under peak
- unknown X_b mass: $\pi\pi$ effect on $m(\pi\pi\Upsilon)$ resolution can't be removed

$\longrightarrow$ perform the analysis in bins of rapidity

BARREL



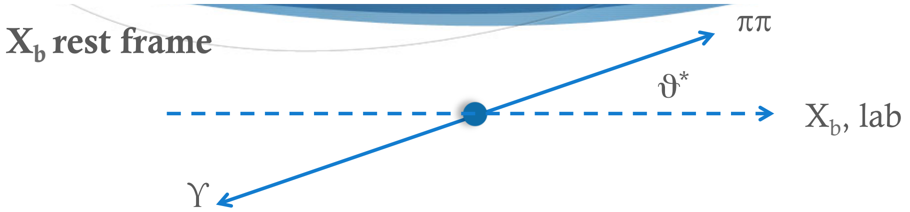
ENDCAP



The X_b search: discrimination in $(|y|, p_T, \cos\theta^*)$

ATLAS Collab., Physics Letters B 740, 199–217 (2014); arXiv:1410.4409 [hep-ex]

- **barrel ($|y| < 1.2$) resolut^n better than endcap ($1.2 < |y| < 2.4$)**
  $\longrightarrow$ perform the analysis in bins of rapidity
- **different signal and background distributions in (p_T, $\cos\theta^*$):**
  - $\cos\theta^*(\pi^+\pi^-)$ flat in parent rest frame for unpolarized signal
  - in background, $\pi^+\pi^-$ unrelated to $\mu^+\mu^-$, and has low $p_T^{\pi\pi}$
    $\longrightarrow$ background is lower in p_T, more backward in $\cos\theta^*$



[classic discrimination by decay angle for (quasi-)2-body decays]

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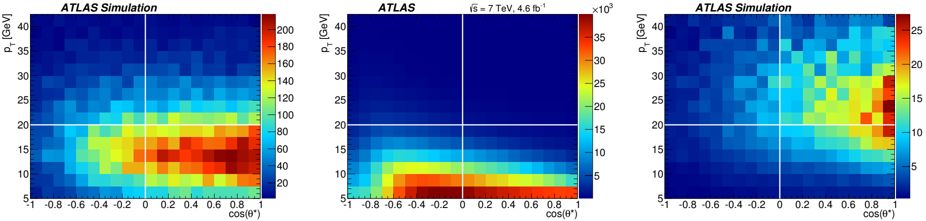

SIGNAL BACKGROUND $S/\sqrt{B}$

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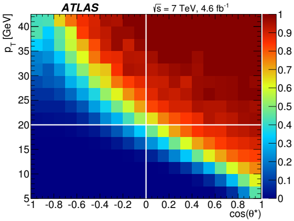
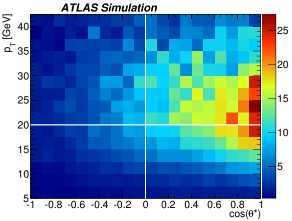


ΔR cut à la CMS

we chose bin boundaries at $(p_T, \cos\theta^*) = (20\,\mathrm{GeV}, 0)$
$\longrightarrow$ simult. fit to $2 \times 2 \times 2$ bins in $(|y|, p_T, \cos\theta^*)$:

considered ΔR cut [CMS]: less sensitive than binning



$S/\sqrt{B}$

The X_b search: background and signal modelling

ATLAS Collab., Physics Letters B 740, 199–217 (2014); arXiv:1410.4409 [hep-ex]

background:

- mix of inclusive $\Upsilon(1S)$ and combinatorial $\mu^+\mu^-$
- preliminary studies performed on 2011 ($7\,\mathrm{TeV}$) data: lower-sideband $\mu^+\mu^-$ and same-sign $\mu^\pm\mu^\pm$ samples
- $m(\pi^+\pi^-\Upsilon)$ distributions featureless above 9800 MeV
- confirmed in $\Upsilon \to \mu^+\mu^-$ signal region for various $m(\pi^+\pi^-\Upsilon)$ ranges

$\longrightarrow$ **polynomial fit** to $m(\pi^+\pi^-\Upsilon)$ region about each test mass

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signal:

- narrow state search: fit with $\mathbf{f \cdot \mathcal{G}(m, \sigma) + (1 - f) \cdot \mathcal{G}(m, r\sigma)}$
- f, r $\sim$ indep^t of mass; fixed to average over MC samples
- σ then found to be linear in mass
- *remaining issues:* division among analysis bins, acceptance, efficiency

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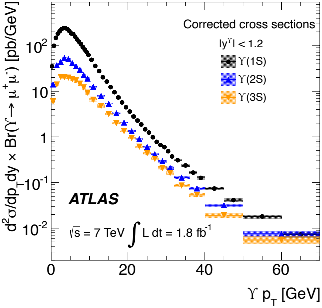
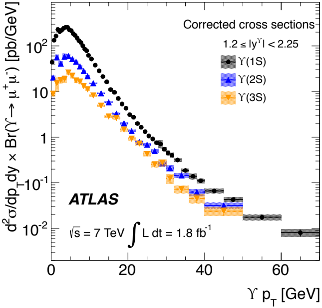
- σ then found to be linear in mass
- *remaining issues:* division among analysis bins, acceptance, efficiency — all depend on distribution of final-state particles in $(\eta,\, p_T,\, \phi)$

The X_b search: background and signal modelling

rely on $\Upsilon(nS)$ cross-section measurement; ATLAS Collab., PRD 87, 052004 (2013)

- use measured doubly-differential $\sigma \times \mathcal{B}$ for $\Upsilon(1S, 2S, 3S) \to \mu^+\mu^-$





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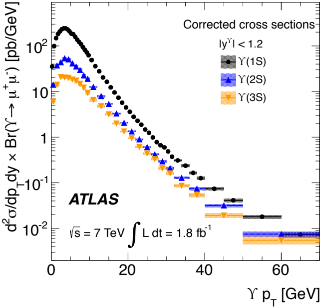
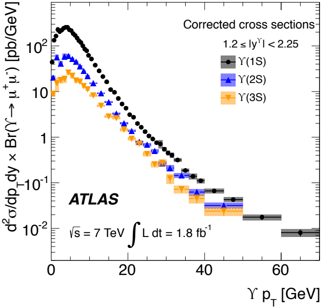


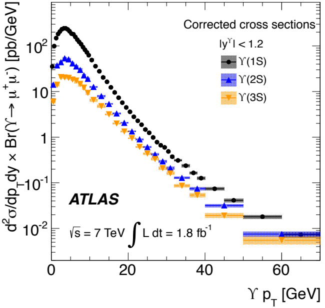


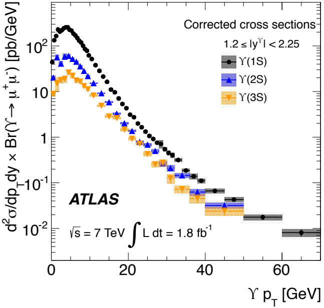
- extend $y \to 2.4$ (assumption), $p_T \to 100\,\mathrm{GeV}$ (CMS), $\sqrt{s} \to 8\,\mathrm{TeV}$ (PYTHIA)

The X_b search: background and signal modelling

rely on Υ(nS) cross-section measurement; ATLAS Collab., PRD 87, 052004 (2013)

- use measured doubly-differential $\sigma \times \mathcal{B}$ for $\Upsilon(1S, 2S, 3S) \to \mu^+\mu^-$





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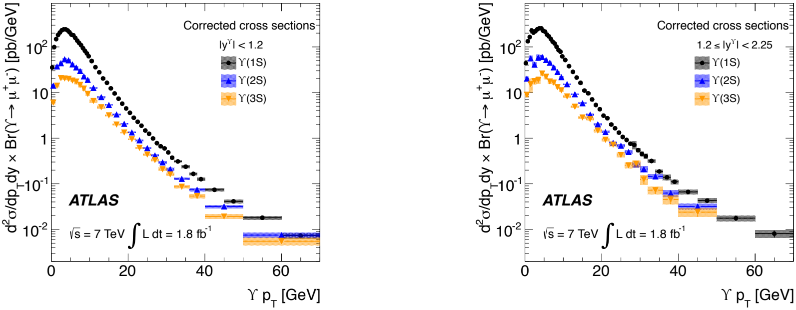
- assume (for now) that X_b production

The X_b search: background and signal modelling

rely on $\Upsilon(nS)$ cross-section measurement; ATLAS Collab., PRD 87, 052004 (2013)

- use measured doubly-differential $\sigma \times \mathcal{B}$ for $\Upsilon(1S, 2S, 3S) \to \mu^+\mu^-$



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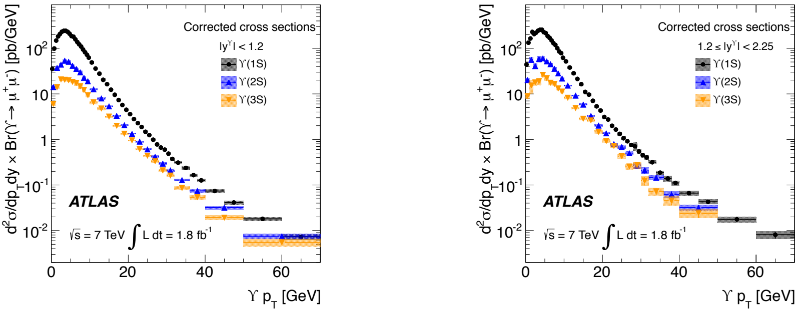

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  - is unpolarized [given parent (y, p_T), determines (η, p_T) of products]

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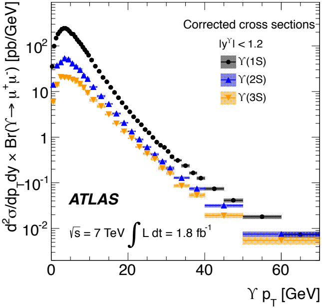

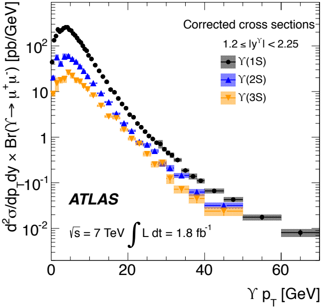

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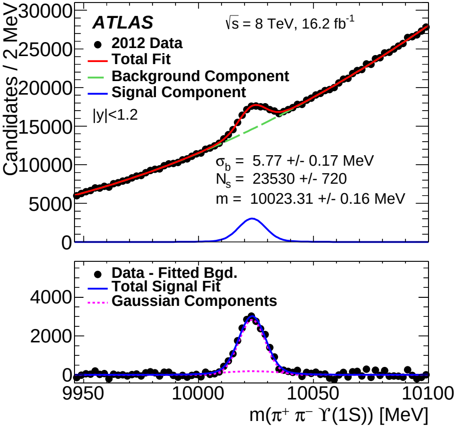
$\longrightarrow$ {division among bins, acceptance, efficiency} as functions of $m(X_b)$

The X_b search: calibration and validation: $\Upsilon(2S)$

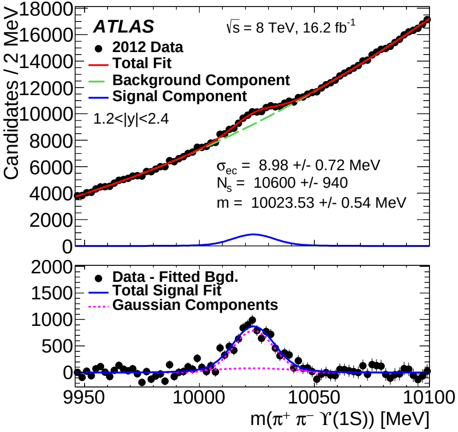
ATLAS Collab., Physics Letters B 740, 199–217 (2014); arXiv:1410.4409 [hep-ex]

1. **fit in 2 |y| bins, floated params:** m matches w.a.; σ matches MC

BARREL



ENDCAP



The X_b search: calibration and validation: $\Upsilon(2S)$

ATLAS Collab., Physics Letters B 740, 199–217 (2014); arXiv:1410.4409 [hep-ex]

1. **fit in 2 |y| bins, floated params:** m matches w.a.; σ matches MC

2. **separate fits in $2 \times 2 \times 2$ bins in ($|y|$, p_T, $\cos\theta^*$), fixed params:**
   - barrel fraction 0.67 ± 0.04 exceeds MC value 0.606 ± 0.004
   - in all subsequent fits, MC barrel fractions *rescaled* by $0.67/0.606$
   - division of signal among $2 \times 2 \times 2$ bins consistent with rescaled MC
   - sum of the eight yields:

$$N_{2S}^{fit} = 34300 \pm 800$$

$$\begin{aligned} N_{2S}^{pred} &= (\sigma\mathcal{B})_{2S} \cdot \mathcal{L} \cdot \mathcal{A} \cdot \epsilon \\ &= (0.504 \pm 0.038)\,\mathrm{nb} \cdot (16.2 \pm 0.3)\,\mathrm{fb}^{-1} \cdot (1.442 \pm 0.004)\% \cdot (0.283 \pm 0.002) \\ &= 33300 \pm 2500 \end{aligned}$$

   - all subsequent fits are performed
     - simultaneously over the $2 \times 2 \times 2$ bins
     - using the division of signal between the bins (as a function of mass) determined from MC

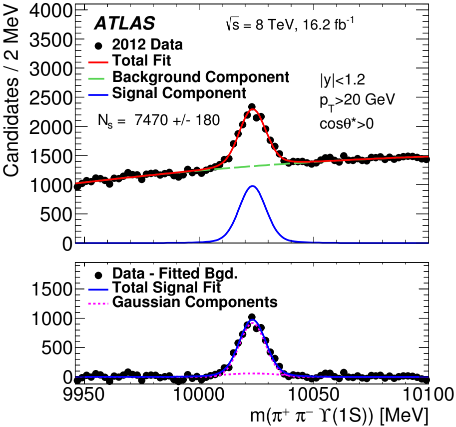
The X_b search: calibration and validation: $\Upsilon(2S)$

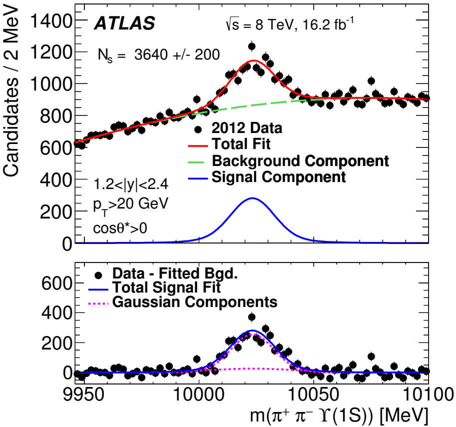
ATLAS Collab., Physics Letters B 740, 199–217 (2014); arXiv:1410.4409 [hep-ex]

- $p_T > 20\,\mathrm{GeV}$, $\cos\theta^* > 0$ (most sensitive bin):

BARREL

ENDCAP

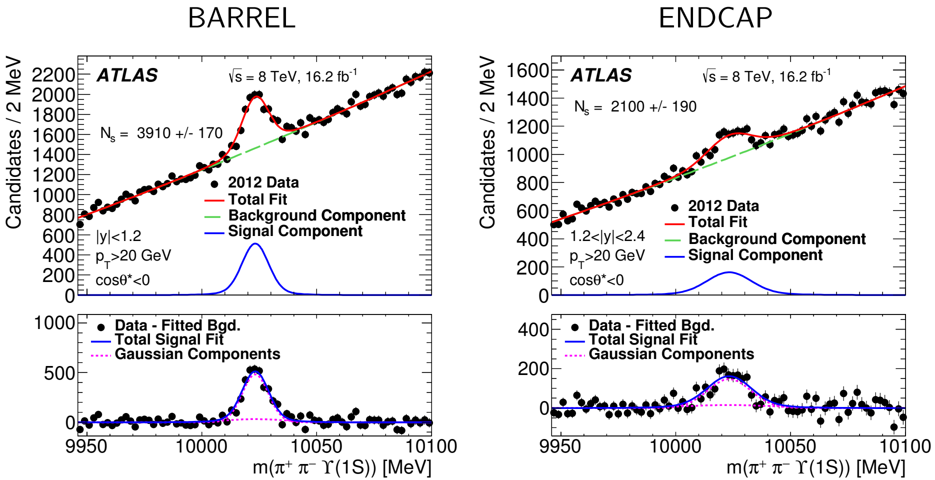




The X_b search: calibration and validation: $\Upsilon(2S)$

ATLAS Collab., Physics Letters B 740, 199–217 (2014); arXiv:1410.4409 [hep-ex]

- $p_T > 20\,\mathrm{GeV}$, $\cos\theta^* < 0$ (top-left bin):



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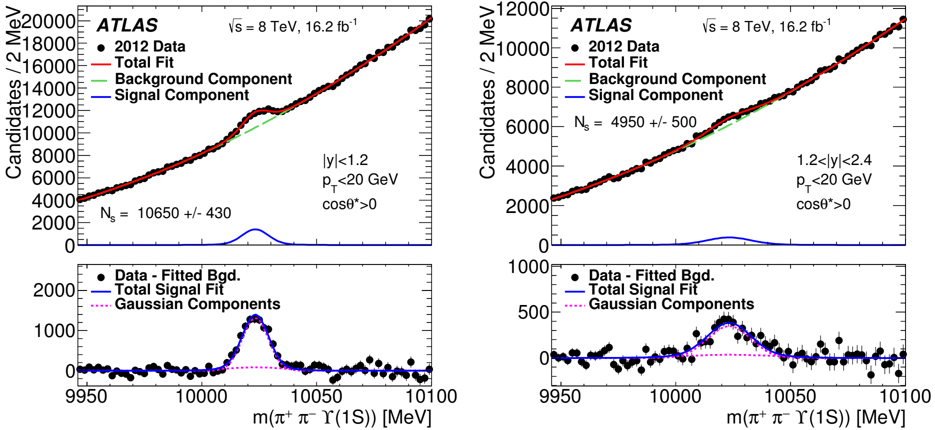
ATLAS Collab., Physics Letters B 740, 199–217 (2014); arXiv:1410.4409 [hep-ex]

- $p_T < 20\,\mathrm{GeV}$, $\cos\theta^* > 0$ (bottom-right bin):

BARREL | ENDCAP

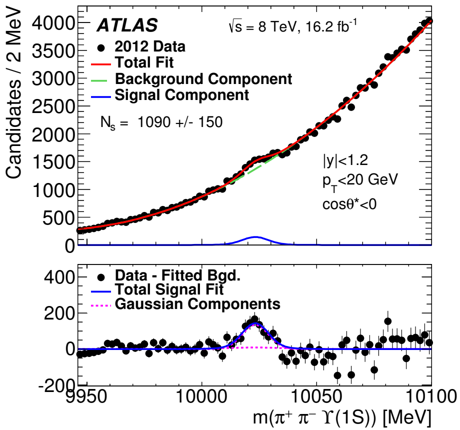


The X_b search: calibration and validation: $\Upsilon(2S)$

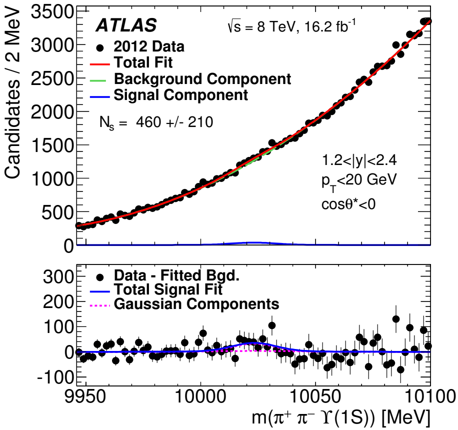
ATLAS Collab., Physics Letters B 740, 199–217 (2014); arXiv:1410.4409 [hep-ex]

- $p_T < 20\,\mathrm{GeV}$, $\cos\theta^* < 0$ (least sentitive bin):

BARREL



ENDCAP



The X_b search: calibration and validation: $\Upsilon(3S)$

ATLAS Collab., Physics Letters B 740, 199–217 (2014); arXiv:1410.4409 [hep-ex]

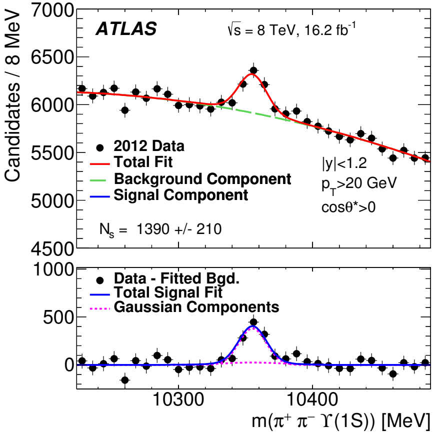
3. simultaneous fit to $2 \times 2 \times 2$ bins with fixed params:

- strong but not overwhelming signal: model for X_b search
- significance $z = 8.7$
- most sensitive bin $z = 6.5 \longrightarrow$:
  (for clarity: rebinned $2 \to 8\,\mathrm{MeV}$)
- $\chi^2/n_{dof} = 1.0$ for simult. fit: good signal division among bins
- overall fitted yield:

$$N^{fit}_{3S} = 11600 \pm 1300$$

$$N^{pred}_{3S} = (\sigma\mathcal{B})_{3S} \cdot \mathcal{L} \cdot \mathcal{A} \cdot \epsilon = 11400 \pm 1500$$

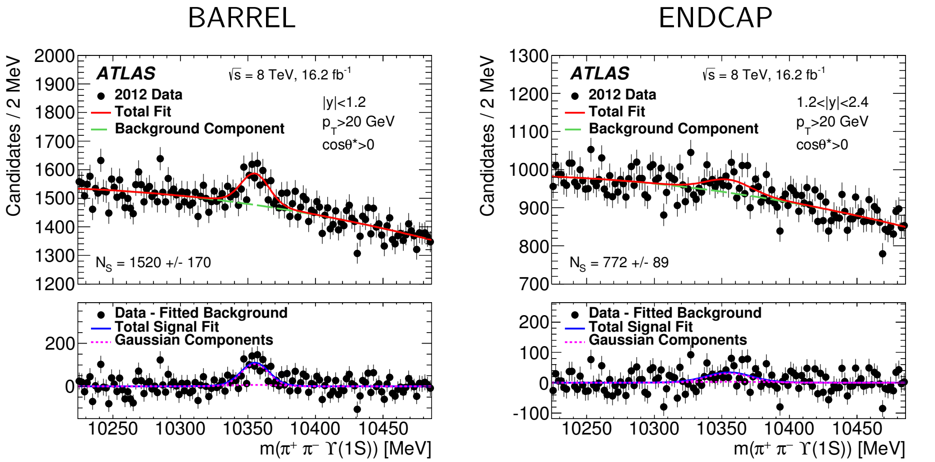
BARREL, HIGH-p_T, HIGH-$\cos\theta^*$



The X_b search: calibration and validation: $\Upsilon(3S)$

ATLAS Collab., Physics Letters B 740, 199–217 (2014); arXiv:1410.4409 [hep-ex]

- $p_T > 20\,\mathrm{GeV}$, $\cos\theta^* > 0$ (most sensitive bin):



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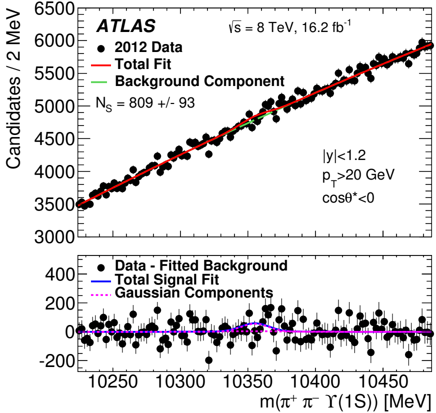
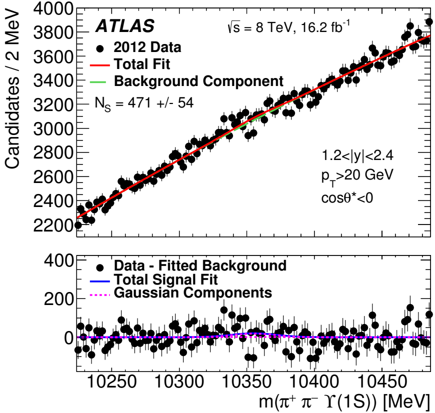
BARREL



ENDCAP



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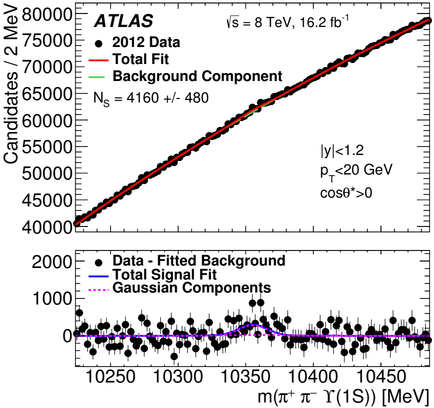
- $p_T < 20\,\mathrm{GeV}$, $\cos\theta^* > 0$ (bottom-right bin):

BARREL



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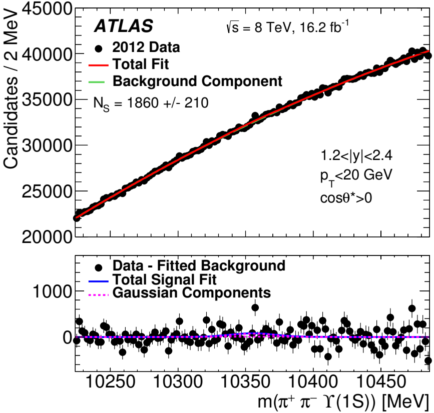

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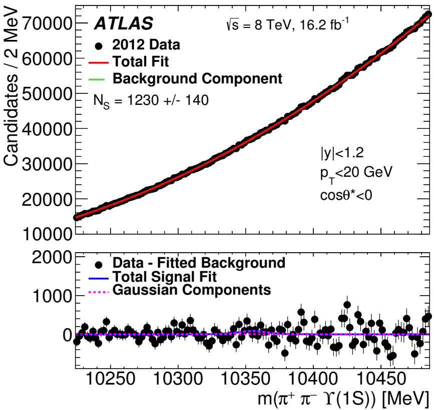

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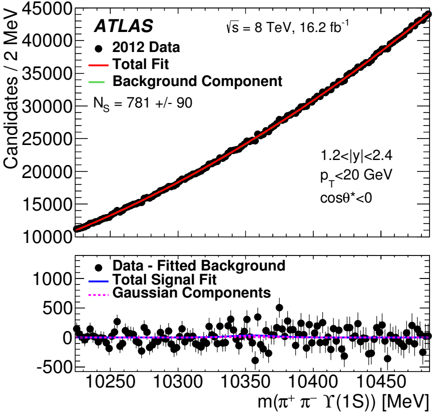

The X_b search: results as a function of mass

ATLAS Collab., Physics Letters B 740, 199–217 (2014); arXiv:1410.4409 [hep-ex]

- hypothesis test every $10\,\mathrm{MeV}$ from 10–$11\,\mathrm{GeV}$, excluding $\Upsilon(2S, 3S)$
- fit range $m \pm 8\sigma_{\mathrm{endcap}}$: $\pm 72\,\mathrm{MeV}$ at $10\,\mathrm{GeV}$; $\pm 224\,\mathrm{MeV}$ at $10.9\,\mathrm{GeV}$
- simultaneous fit to the 8 ($|y|$, p_T, $\cos\theta^*$) bins, for $R = \sigma\mathcal{B}/(\sigma\mathcal{B})_{2S}$

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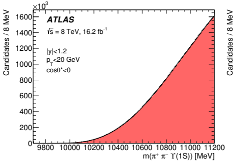
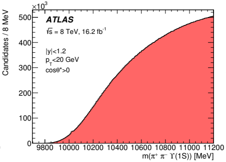
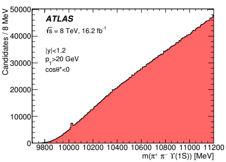


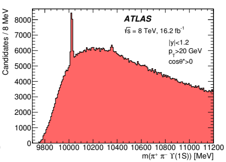
(a) Barrel, low p_T, low $\cos\theta^*$



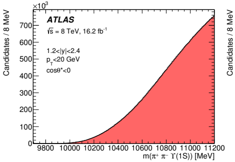
(b) Barrel, low p_T, high $\cos\theta^*$



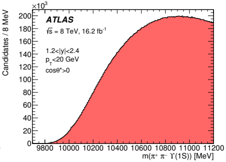
(c) Barrel, high p_T, low $\cos\theta^*$



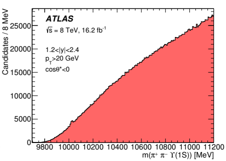
(d) Barrel, high p_T, high $\cos\theta^*$



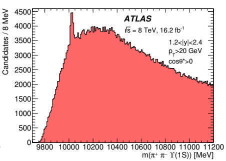
(e) Endcap, low p_T, low $\cos\theta^*$



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



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



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

The X_b search: results as a function of mass

ATLAS Collab., Physics Letters B 740, 199–217 (2014); arXiv:1410.4409 [hep-ex]

- hypothesis test every 10 MeV from 10–11 GeV, excluding $\Upsilon(2S, 3S)$
- fit range $m \pm 8\sigma_{\text{endcap}}$: ± 72 MeV at 10 GeV; ± 224 MeV at 10.9 GeV
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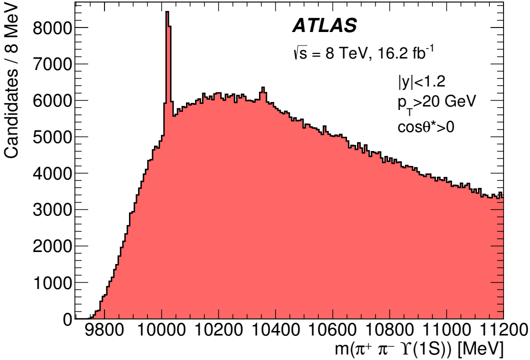

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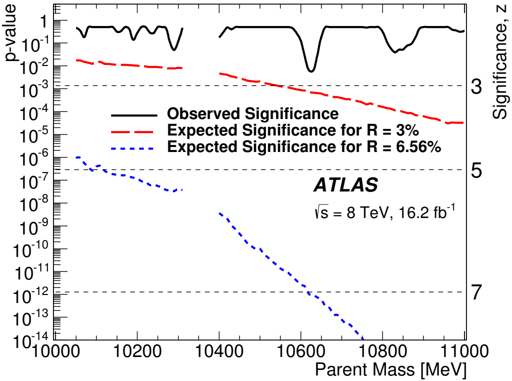

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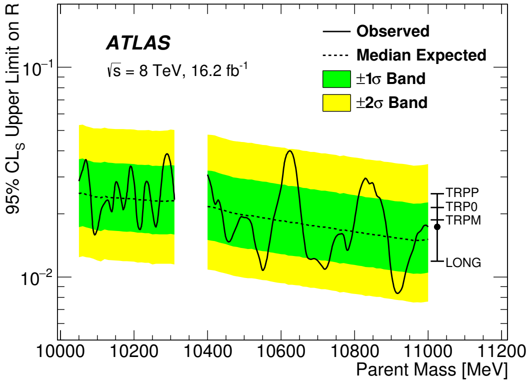

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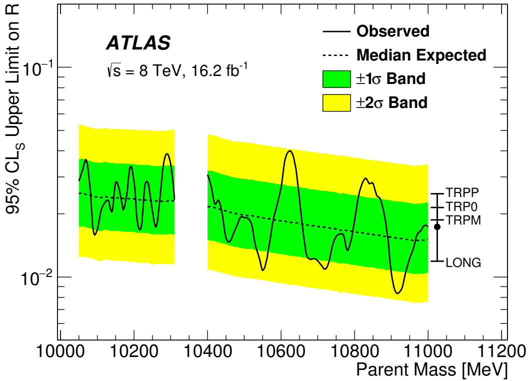

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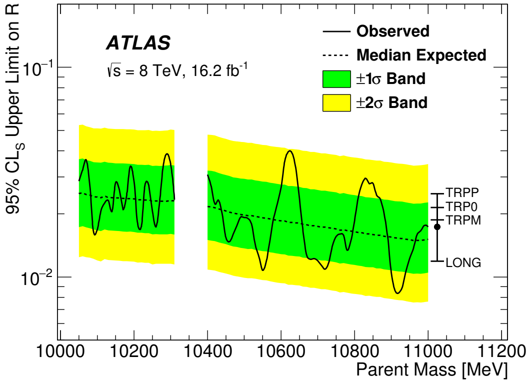

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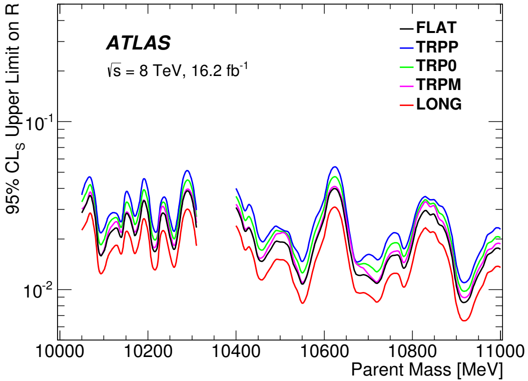
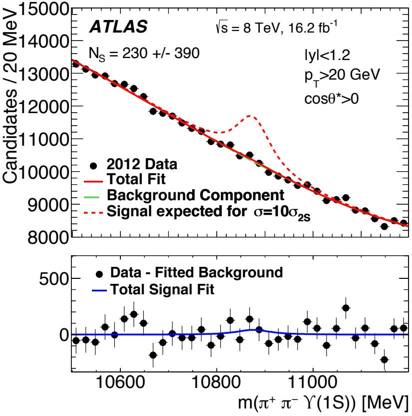
- reported in detail



Bonus searches: $\Upsilon(1\,^3D_J)$, $\Upsilon(10860)$, and $\Upsilon(11020)$

ATLAS Collab., Physics Letters B 740, 199–217 (2014); arXiv:1410.4409 [hep-ex]



Projection of fit to $\Upsilon(10860)$

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

- Tried triplet fit → z=0.12
- J=2:

$$\sigma\,[\Upsilon(1^3D_2)] < 0.55\ \ \sigma\,[\Upsilon(2S)]$$

using known $\pi^+\pi^-\Upsilon(1S)$ branching (observed at CLEO+BaBar)

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

- Broad – different fitting model
- $\Gamma_{\pi\pi\Upsilon}$ large for $\Upsilon(10860)$
- No evidence for either state

Interpretation, and future plans

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- I-allowed modes — $\{\gamma, \pi\pi\pi^0\}\Upsilon$, $\pi\pi\chi_b$ — have severe $\mathcal{A}\cdot\epsilon$ problems

Summary

- ATLAS has searched for an X_b in inclusive $\pi\pi\Upsilon$ at $8\,\mathrm{TeV}$ pp collisions
- the analysis is subject to spin-alignment-dependent acceptance effects due to p_T thresholds, *cf.* soft onia production spectrum
- $\pi^+\pi^-\mu^+\mu^-$ combinations vtx-fitted with $m(\mu^+\mu^-) = m_\Upsilon$ constraint
- discrimination in $(|y|, p_T, \cos\theta^*)$ is exploited by $2 \times 2 \times 2$ binning
- simultaneous binned UML fit to resulting $m(\pi^+\pi^-\Upsilon)$ distributions
- local $P_2 + {}^2\mathcal{G}$ fit every $10\,\mathrm{MeV}$, with parameters
  - fixed to combination of $7\,\mathrm{TeV}$ pp data and MC
  - calibrated and validated on the $\Upsilon(2S, 3S) \to \pi^+\pi^-\Upsilon$ peaks

  and systematics included using Gaussian constraints
- no signal seen, and $\sigma\mathcal{B}/(\sigma\mathcal{B})_{2S} = 6.56\%$ excluded everywhere
- I-allowed decay modes — with difficult $\mathcal{A}\cdot\epsilon$ conditions — under study

BACKUP: systematics

The upper limit calculation depends indirectly on signal and background fitting parameters, including the fraction of the signal falling in each of the analysis bins. From Eq. (2), the upper limit on R is proportional to the inverse fitted $\Upsilon(2S)$ yield, N_{2S}^{-1}, and the ratios $\mathcal{A}_{2S}/\mathcal{A}$ and ϵ_{2S}/ϵ. For each source of systematic uncertainty, the impact on these factors is quantified to find the maximum shift across the mass range. These are then summed in quadrature and included in the fit as Gaussian-constrained nuisance parameters.

The $X(3872) \to \pi^+\pi^- J/\psi$ dipion mass distribution favours high mass [6, 9]; for a potential hidden-beauty counterpart this distribution is unknown. For $\psi(2S) \to \pi^+\pi^- J/\psi$ [42], and both $\Upsilon(2S)$ [39] and $\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S)$ [43, 44], the dipion mass distributions are concentrated near the upper boundary; those for $Y(4260) \to \pi^+\pi^- J/\psi$ [45] and $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$ [40] are double-humped. The results quoted here assume decay according to three-body phase space; $\Upsilon(2S)$- and $\Upsilon(3S)$-like distributions change the splitting functions by up to 35%, decrease the efficiency ratio by up to 17%, and produce modest changes in other parameters.

The next largest contribution is due to the linear extrapolation of the acceptance between the $\Upsilon(2S)$ and $\Upsilon(3S)$ values. Alternative extrapolations between the $\Upsilon(1S)$ and $\Upsilon(2S)$, and between $\Upsilon(1S)$ and $\Upsilon(3S)$, are also tried; the greatest change in the acceptance ratio, 12%, is assigned as the uncertainty.

The parameters of the efficiency, the splitting functions, and the widths of the narrow signal components σ_b and σ_{ec} as functions of mass, are varied by the uncertainties on their fitted values; alternative functional forms are also tried. In each case, the largest deviation is assigned as the systematic uncertainty. The use of production weights (described in Section 4) relies on assumptions regarding rapidity dependence, and evolution from $\sqrt{s} = 7$ TeV to 8 TeV. Removing these weights produces a ~1% change in efficiency ratio (most of the differences cancel), but changes the values of the splitting functions by up to 8%.

Data versus simulation differences in the $\Upsilon(2S)$ width parameters in the barrel and endcap (1.9% and 4.2%, respectively) are incorporated as a source of uncertainty, as is the statistical uncertainty on the averages used for signal shape parameters f and r (0.5–1.4%). The background shape model is also altered, allowing a third-order term comparable in size to typical values of the second-order terms. Finally, uncertainties on N_{2S} and the barrel/endcap scaling factor are assigned based on uncertainties from the $\Upsilon(2S)$ fits.

BACKUP: systematics

Table 1. The contribution of the various sources of systematic uncertainty to the fitting-type parameters influencing the upper limit calculation. The subscripts on σ, f, and r specify whether they are shape parameters for the barrel ("b", $|y| < 1.2$) or endcap ("ec", $1.2 < |y| < 2.4$) regions. The parameters labelled with an S refer to the splitting functions. Their values are the fraction of the signal in the lower bin of the subscript variable within the kinematic range specified by the superscript: "b" and "ec" as above, "(1)" for ($|y| < 1.2$, $p_{\mathrm{T}} < 20\,\mathrm{GeV}$), "(2)" for ($|y| < 1.2$, $p_{\mathrm{T}} > 20\,\mathrm{GeV}$), "(3)" for ($1.2 < |y| < 2.4$, $p_{\mathrm{T}} < 20\,\mathrm{GeV}$), and "(4)" for ($1.2 < |y| < 2.4$, $p_{\mathrm{T}} > 20\,\mathrm{GeV}$). All values are relative uncertainties, expressed as a percentage.

	σ_{b} [%]	σ_{ec} [%]	f_{b} [%]	f_{ec} [%]	r_{b} [%]	r_{ec} [%]	$S_{|y|}$ [%]	$S^{\mathrm{b}}_{p_{\mathrm{T}}}$ [%]	$S^{\mathrm{ec}}_{p_{\mathrm{T}}}$ [%]	$S^{(1)}_{\cos\theta^*}$ [%]	$S^{(2)}_{\cos\theta^*}$ [%]	$S^{(3)}_{\cos\theta^*}$ [%]	$S^{(4)}_{\cos\theta^*}$ [%]
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											
$|y|$ 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
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

Table 2. The contribution of the various sources of systematic uncertainty to the scaling-type parameters influencing the upper limit calculation. All values are relative uncertainties, expressed as a percentage.

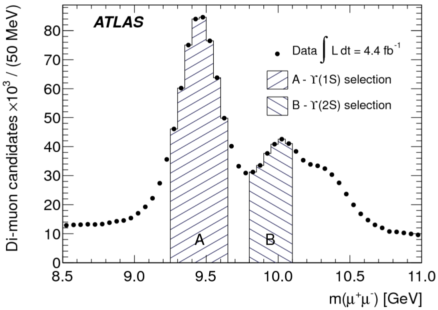
	N_{2S} [%]	ϵ/ϵ_{2S} [%]	$\mathcal{A}/\mathcal{A}_{2S}$ [%]	$\epsilon/\epsilon_{2S} \cdot \mathcal{A}/\mathcal{A}_{2S}$ [%]
N_{2S} yield	2.3			
ϵ vs. m: fit		1.0		
ϵ vs. m: parameterisation		0.5		
Production weighting		1.0		
Acceptance Extrapolation			11.7	
$m_{\pi^+\pi^-}$ shape				17.3
Total	2.3	1.5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

BACKUP: observation of the $\chi_b(nP)$ states

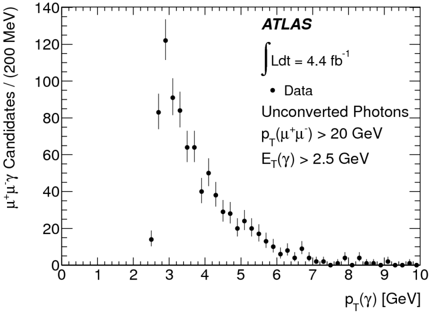
ATLAS: PRL 108, 152001 (2012); arXiv:1112.5154 [hep-ex]

from 2011 data: "combined" muon tracks, $p_T > 4\,\mathrm{GeV}$, $|\eta| < 2.3$;
well-vertexed $\mu^+\mu^-$: $p_T > 12\,\mathrm{GeV}$, $|y| < 2.0$

$\Upsilon(1S)$ and $(2S) \to \mu^+\mu^-$ sel^n



unconverted photon selection



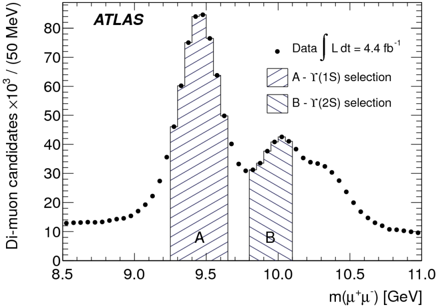
poor acceptance due to $p_T^\gamma > 2.5\,\mathrm{GeV}$ threshold

BACKUP: observation of the $\chi_b(nP)$ states

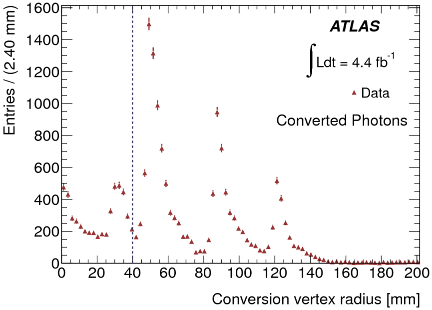
ATLAS: PRL 108, 152001 (2012); arXiv:1112.5154 [hep-ex]

from 2011 data: "combined" muon tracks, $p_T > 4\,\mathrm{GeV}$, $|\eta| < 2.3$;
well-vertexed $\mu^+\mu^-$: $p_T > 12\,\mathrm{GeV}$, $|y| < 2.0$

$\Upsilon(1S)$ and $(2S) \to \mu^+\mu^-$ sel^n



converted photon vertices (xy)



now $p_T^\gamma > 1.0\,\mathrm{GeV}$,
but low conversion efficiency

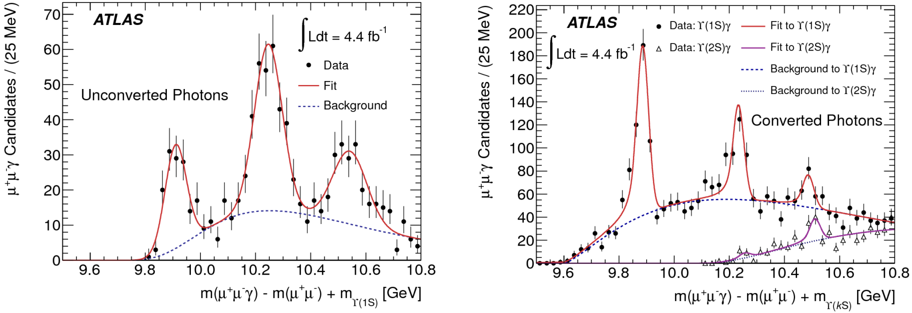
BACKUP: observation of the $\chi_b(nP)$ states

ATLAS: PRL 108, 152001 (2012); arXiv:1112.5154 [hep-ex]

<u>from 2011 data:</u> "combined" muon tracks, $p_T > 4\,\mathrm{GeV}$, $|\eta| < 2.3$;

well-vertexed $\mu^+\mu^-$: $p_T > 12\,\mathrm{GeV}$, $|y| < 2.0$

$\chi_b \to \gamma_{\rm uncon}\Upsilon(1S)$ fit $\qquad$ $\chi_b \to \gamma_{\rm convert}\Upsilon(nS)$ fit

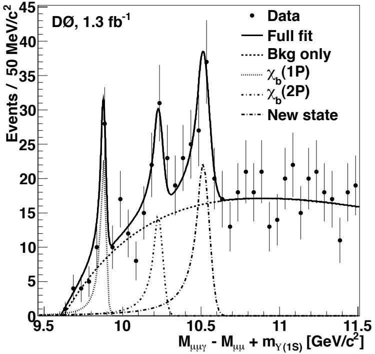


BACKUP: observation of the $\chi_b(nP)$ states

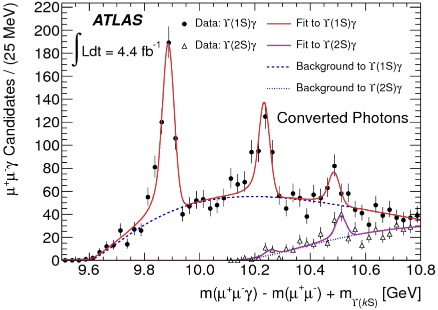
ATLAS: PRL 108, 152001 (2012); arXiv:1112.5154 [hep-ex]

from 2011 data: "combined" muon tracks, $p_T > 4\,\mathrm{GeV}$, $|\eta| < 2.3$;
well-vertexed $\mu^+\mu^-$: $p_T > 12\,\mathrm{GeV}$, $|y| < 2.0$

DØ confirmation (also conversions)



$\chi_b \to \gamma_{\text{convert}} \Upsilon(nS)$ fit



BACKUP: first observation of the $\chi_{bJ}(3P)$

ATLAS: PRL 108, 152001 (2012); arXiv:1112.5154 [hep-ex]

$\chi_b(3P)$ significance $> 6\sigma$ in each sample;

for the photon conversions:

- $\chi_{b0} \to \gamma\Upsilon$ suppressed: omitted
- $\chi_{b1,b2}(1P, 2P)$ fixed to WA
- $\chi_{b1,b2}(3P)$ splitting $= 12\,\mathrm{MeV}$ assumed

$\chi_b(3P)$ barycenter $\tilde{m}_3$ determination:

calo.	$10.541 \pm 0.011 \pm 0.030\,\mathrm{GeV}$
conv^{ns}	$10.530 \pm 0.005 \pm 0.009\,\mathrm{GeV}$
predicted	10.525

(PRD 36, 3401 (1987); 38, 279 (1988); EPJC 4, 107 (1998))

there will be indirect $\Upsilon(3S)$ production !