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

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Outline

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

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

arxiv.org/pdf/1410.4409v2.pdf
The ATLAS detector: a general purpose particle detector designed to study physics at the TeV scale

**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 $J/\psi$ and $\Upsilon$ decays
- Efficiency of reconstructing ‘combined muons’ (local track segments from MS and ID successfully matched) measured using data driven technique
- ‘Tag and probe’ using $Z\rightarrow\mu\mu$ (higher muon $p_T$) and $J/\psi\rightarrow\mu\mu$ (lower muon $p_T$) data samples
  - Require ‘tag’ to be a combined muon track

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**ATLAS Measurements**

**ψ(2S)→J/ψπ⁺π⁻**

- $\sqrt{s}=7\text{TeV}$, 2.1 fb$^{-1}$
- Data, Fit, Background, $\psi(2S)$ Signal

- $X(3872)$ previously observed in 2011 ATLAS data as a resonance in $J/\psi\pi^+\pi^-$ invariant mass spectrum in $\psi(2S)$ production cross section measurement$^1$
  - J/$\psi$ candidates reconstructed through $\mu^+\mu^-$ vertex fits
  - Four track vertex fits performed from reconstructed $J/\psi$ muon tracks and pairs of hadronic tracks
    - Hadronic tracks given pion mass
    - Reconstructed $J/\psi$ mass constrained to $J/\psi$ PDG mass
    - Background dominated by mismatch of $J/\psi$ and pion tracks ‘combinatorial background

- $X(3872)$–→$J/\psi\pi^+\pi^-$ production measurements coming soon through the same $J/\psi\pi^+\pi^-$ decay channel. This talk will mainly focus on the $X_b$–→$\Upsilon(1S)\pi^+\pi^-$ search analysis

- $X_b$–→$\Upsilon(1S)\pi^+\pi^-$ search for candidates reconstructed in a similar manner using analogue decay $X_b$–→$\Upsilon(1S)\pi^+\pi^-$

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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

What is X(3872)?

- Still unknown – though knowledge of its properties increasing
- New excited charmonium ($\bar{c}c$) state?
- mass, small $\Gamma$, $J^{PC}=1^{++}$, 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

X(3872) production measurements from ATLAS coming soon

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**X_b Search Motivation**

- 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 $m_{X_b} = 10.561$ GeV
- Measurement is experimentally feasible using existing framework to construct $X_b$ candidates decaying to $ϒ(1S)\pi^+\pi^-$

**Additional**

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

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

$ϒ(1^3D_{2})$ observed in radiative transitions by CLEO, BaBar
Using events measured during the 2012 ATLAS data taking period $\sqrt{s} = 8$ TeV (~16.2fb$^{-1}$)

$\Upsilon(1S) \rightarrow \mu\mu$
- $p_T(\mu^\pm) > 4$ 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 $\chi^2 < 200$

$X_b \rightarrow \Upsilon(1S)\pi\pi$
- $p_T(\pi^\pm) > 400$ MeV
- $|\eta(\pi^\pm)| < 2.5$
- $\geq 1$ pixel hit & $\geq 6$ 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 \([p_T, \cos\theta^*]\)**

**X_b Rest Frame**

![ATLAS Simulation](image)

**Signal at 10.561 GeV:**
- high \(p_T\), high \(\cos \theta^*\)

**Bkg near 10.561 GeV:**
- low \(p_T\), spread in \(\cos \theta^*\)
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 \([p_T, \cos\theta*,|y|]\)

Bin boundaries optimize sensitivity for \(X_b = 10.561\) GeV mass hypothesis

Simultaneous fit performed in each \([p_T, \cos\theta*,|y|]\) bin to extract signal

MC simulation used to parameterize signal shape
Different bkg. shape in each bin: fit with 2\textsuperscript{nd}-order Chebychev polynomials

No obvious signs of additional signal peaks
Validation with $\Upsilon(2S)$, $\Upsilon(3S)$

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

$$N_{2S}^{\text{expected}} = (\sigma B)_{2S} \cdot L \cdot A \cdot \epsilon$$
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
- \(R = (\sigma B_{X_b})/(\sigma B_{\Upsilon(2S)})\)

**Fit Hypothesis**
- **Narrow state**
- \(\sigma_{X_b}(|y|, p_T)\) 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 CLs method
- Upper limits found in every 10 MeV mass interval
- Systematic errors increase upper limit by up to 13%
- Upper limit of $\sigma B_{X_b}(X_b \rightarrow \Upsilon(1S)\pi^+\pi^-)$ found to be smaller than charm-analogue $X(3872) \rightarrow J/\psi\pi^+\pi^-$ 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 $m_{X_b} > 10.1$ GeV

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**ATLAS**

$\sqrt{s} = 8$ TeV, 16.2 fb$^{-1}$

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**Flat**

**Longitudinal**

**Transverse**
ϒ(1^{3}D_{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: \(\sigma(\Upsilon(1^{3}D_{J})) < 0.55\) \(\sigma(\Upsilon(2S))\) (using known BR)

ϒ(10860) and ϒ(11020)
- Much broader natural width than \(\Upsilon(1S)\), \(\Upsilon(2S)\) etc
- Extended mass range and fit model changes
- No evidence found for either state
  - Signal significance: 0.6σ and 0.3σ respectively
Perform search of $X_b \rightarrow Y(1S)\pi^+\pi^-$ for numerous mass hypotheses across the 10 – 11 GeV
- $Y(2S)$ and $Y(3S)$ signal used for validation and ‘calibration’
- No evidence found for existence of new states
- 95% CL Upper Limits on $R = (\sigma_{X_b})/(\sigma_{\psi(2S)})$. Ranges between 0.8 – 4%
- This is the most sensitive limit to data

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

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

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Back Up
Binning: $X_b$ significance

$S/\sqrt{B}$ estimate [arb. units]

$\Delta R<0.7$ cut imprint on background near 10.561 GeV
Y(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 $\cos \theta^*$

$\gamma(1S)$ mass spectra in various regions, with signal mass fixed to world-average and simulation-based values used for mass fixing and background predictions.
**Y(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 $\cos \theta$
Y(1S), Y(2S) Yield Validation

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

<table>
<thead>
<tr>
<th></th>
<th>Predicted</th>
<th>Observed</th>
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<tbody>
<tr>
<td>Y(2S)</td>
<td>33300 ± 2500</td>
<td>34300 ± 800</td>
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<tr>
<td>Y(3S)</td>
<td>11400 ± 1500</td>
<td>11600 ± 1300</td>
</tr>
</tbody>
</table>
$\Upsilon(11020)$ Fit

\begin{align*}
\text{Candidates / 20 MeV} \\
\hline
17000 & 16000 & 15000 & 14000 & 13000 & 12000 & 11000 & 10000 & 9000 & 8000
\end{align*}

$N_S = 150 \pm 560$

$\sqrt{s} = 8\text{ TeV}, 16.2\text{ fb}^{-1}$

$|y|<1.2$

$p_T>20\text{ GeV}$

$\cos\theta^*>0$

$\Upsilon^{-}\pi^+\pi^-\Upsilon(1S)$

$\sigma B = (\sigma B)_2S$

$\text{Total Fit}$

$\text{Background Component}$

$\text{Total Signal Fit}$

15/09/2015

M. Beattie – ATLAS Collaboration

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## Systematics

### Signal shape parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\sigma_b$ [%]</th>
<th>$\sigma_{ec}$ [%]</th>
<th>$f_b$ [%]</th>
<th>$f_{ec}$ [%]</th>
<th>$r_b$ [%]</th>
<th>$r_{ec}$ [%]</th>
<th>$S_{y}$ [%]</th>
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<td>16.3</td>
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### Signal bin splitting parameters

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<th>Parameter</th>
<th>$N_{2S}$ [%]</th>
<th>$\epsilon/\epsilon_{2S}$ [%]</th>
<th>$A/A_{2S}$ [%]</th>
<th>$\epsilon/\epsilon_{2S} \cdot A/A_{2S}$ [%]</th>
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<td>$m_{\pi+\pi}$ shape</td>
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</table>
Polarisation Uncertainty

ATLAS
\( \sqrt{s} = 8 \text{ TeV}, 16.2 \text{ fb}^{-1} \)

Left:

95% CL Upper Limit on R

Right:

Median Upper Limit (relative to FLAT)

\( \sqrt{s} = 8 \text{ TeV}, 16.2 \text{ fb}^{-1} \)