ATLAS SEARCHES FOR NEW HEAVY FLAVOUR STATES

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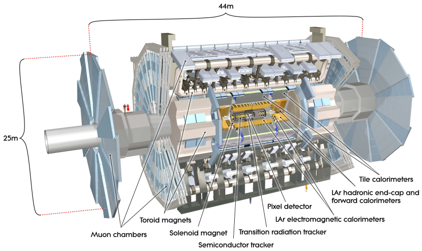
Outline

1. Observation of an excited $B_c^{\pm}$ meson state with the ATLAS Detector
   - Phys. Rev. Lett. **113**, no. 21, 212004 (2014), arXiv:1407.1032 [hep-ex]
   - 4.9 fb^{-1} of $\sqrt{s} = 7$ TeV and 19.2 fb^{-1} of $\sqrt{s} = 8$ TeV pp collision data
2. Search for the X_b and other hidden-beauty states in the $\pi^+\pi^-\Upsilon(1S)$ channel at ATLAS
   - Phys. Lett. B **740**, 199 (2015), arXiv:1410.4409 [hep-ex]
   - 16.2 fb^{-1} of $\sqrt{s} = 8$ TeV pp collision data

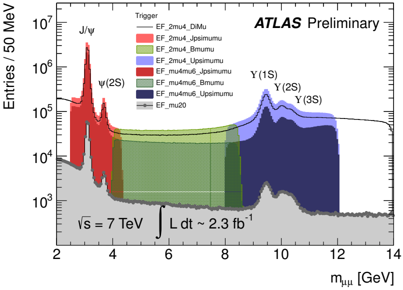
ATLAS: general purpose detector:

- Subsystems essential for B-physics: Inner detector and Muon spectrometer,
- Inner detector: tracking, momentum and vertexing, $|\eta| < 2.5$, d_0 resolution $\sim 10\mu m$,
- Muon spectrometer: trigger and muon identification,
- J/ψ mass resolution ~ 60 MeV, $\Upsilon(1S) \sim 120$ MeV,
- ATLAS trigger system: hardware *Level-1 trigger* and two-level software *High-Level Trigger*

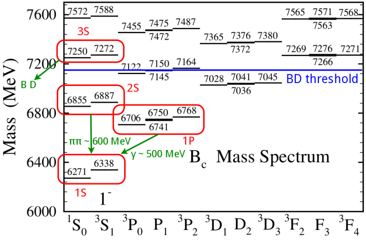


Trigger selection for heavy flavour studies is mostly based on di-muon signature:

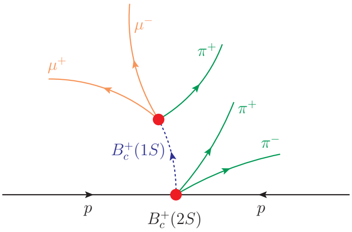
- muon p_T threshold (4 or 6 GeV)
- di-muon vertex reconstruction
- invariant mass window



B_c STATES



The B_c mass spectrum, taken from Phys. Rev. D 70, 054017 (2004).



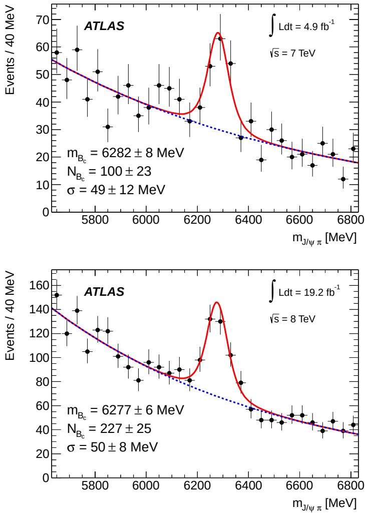
- Excited states of $B_c^{\pm}$ are predicted by nonrelativistic potential models, pertubative QCD and lattice calculations,
- mass of $B_c^{\pm}(2S)$ in range 6835–6917 MeV,
- both the $1S$ and $2S$ states have pseudoscalar (0^-) and vector (1^-) spin states that are predicted to differ in mass by about 20–50 MeV,
- ATLAS not sensitive enough to distinguish 0^- and 1^- states: missing soft gamma, mass resolution.

$\boldsymbol{B_c^+(1S)}$ selection for 7 TeV (8 TeV) data:

- $p_T(\mu_1) > 4$ GeV and $p_T(\mu_2) > 6$ GeV,
- J/ψ vertex fit $\chi^2/\mathrm{NDF} < 15$,
- $m(J/\psi)$ within $\pm 3\sigma$ of the nominal (σ depending on the rapidity range),
- B_c^+ vertex fit $\chi^2/\mathrm{NDF} < 2.0$ (1.5) with dimuon mass constrained to mass J/ψ,
- $p_T(B_c^+) > 15$ GeV (18 GeV),
- pion candidate from B_c^+ $p_T(\pi^+) > 4$ GeV and its impact $d^0/\sigma(d^0)(\pi^+) > 5$ (4.5)

Extended unbinned fit of the mass distribution

- *Signal*: Gaussian with per-candidate errors
- *Background*: exponential
- the stability of $B_c^{\pm}$ yield was checked through its normalization to $B^{\pm} \to J/\psi K^{\pm}$ that were reconstructed with similar requirements.

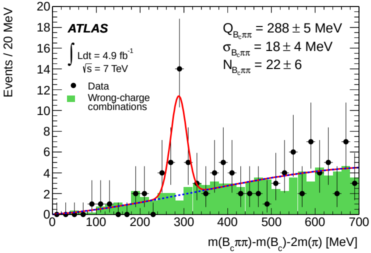


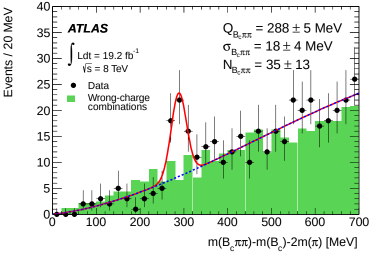
Selection of $B_c^{\pm}(2S)$ candidates:

- $B_c^{+}(1S)$ candidates within $\pm 3\sigma$ of the fitted mass
- pion tracks from primary vertex with $p_T(\pi^+, \pi^-) > 400$ MeV,
- cascade vertex fitter was applied to build decay topology: the refitted triplet of $B_c^{+}(1S)$ tracks and the pair of PV pion tracks must intersect in two separate vertices,
- for several candidates in event, the one with the best cascade fit χ^2 is kept

Extended unbinned fit of Q-value distribution:

- use $Q = m(B_c^+\pi^+\pi^-) - m(B_c^+) - 2m(\pi^+)$ to improve resolution,
- *Signal*: Gaussian,
- *Background*: 3rd order polynomial,
- *Wrong charge combination* (same-sign π) used for background control





Summary of $B_c^{\pm}(2S) \to B_c^{\pm}(1S)\pi^+\pi^-$ analysis

- Significance of the observed signal calculated with toy studies accounting for a "look elsewhere effect" ,
- combined significance is 5.2σ (3.7σ and 4.5σ in 7 and 8 TeV data, respectively),
- dominant source of systematic of the Q-value is the *fitting procedure*,
- a new state observed at $Q = 288.3 \pm 3.5$ (stat.) ± 4.1 (syst.) MeV (error-weighted mean of 7 and 8 TeV values),
- this new state corresponds to a mass 6842 ± 4 (stat.) ± 5 (syst.) MeV, and is consistent with the predicted mass of $B_c(2S)$.

Search for X_b state

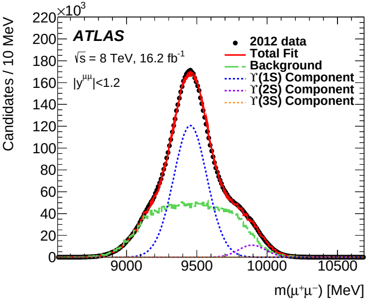
- $X(3872)$ is the best-studied new hidden-charm state, observed by many experiments
  - mass, narrow width, $J^{PC} = 1^{++}$ → unlikely a conventional quarkonium,
  - weakly bound $D^0\bar{D}^{*0}$ *molecule* or $[qc][\bar{q}\bar{c}]$ *tetraquark*
  - the relative production rate R for $X(3872)$ (CMS, JHEP **1304**, 154 (2013))

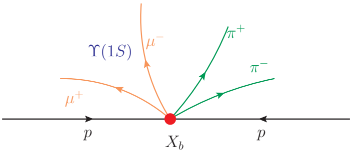
$$R = \frac{\sigma_{pp\to X(3872)} \cdot \mathcal{B}_{X(3872)\to J/\psi\pi^+\pi^-}}{\sigma_{pp\to\psi(2S)} \cdot \mathcal{B}_{\psi(2S)\to J/\psi\pi^+\pi^-}} = (6.56 \pm 0.29 \pm 0.65)\%$$

- Heavy-quark symmetry suggests a hidden-beauty partner X_b;
  - mass predictions vary (e.g. 10561 MeV for the molecular model of Swanson, while tetraquark predicts 10492, 10593, or 10682 MeV, depending on the flavour of the light quarks)
  - Decay $X_b \to \pi^+\pi^-\Upsilon(1S)$ 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.

$\Upsilon(1S)$ reconstruction

- Pairs of oppositely charged muons with $p_T(\mu) > 4$ GeV and $|\eta(\mu)| < 2.3$ are fitted to the common vertex,
- require the matching between the reconstructed and trigger-level muons,
- dimuons in mass range ±350 MeV around $\Upsilon(1S)$ mass are retained.





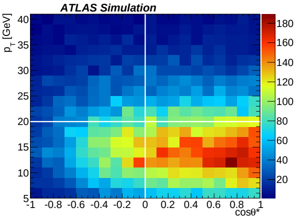
Build X_b candidate

- Dipion candidate are formed from oppositely charged pions with $p_T(\pi) > 400$ MeV and $|\eta(\pi)| < 2.5$
- $\Upsilon(1S) \to \mu^+\mu^-$ candidate and dipion system are combined by performing a four-track common-vertex fit ($\chi^2 < 20$),
- the $\mu^+\mu^-$ mass constrained to mass $\Upsilon(1S)$; this significantly improve the mass resolution,
- candidates with mass < 11.2 GeV are retained.

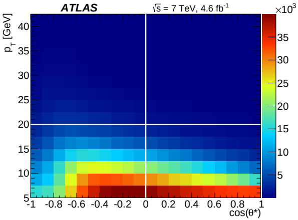
The analysis is performed in 8 bins

- $|y(X_b)|$: 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, (θ^* 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,
- optimize the expected significance for a weak signal at 10561 MeV,
- binned, extended maximum-likelihood fit is performed simultaneously to the 8 bins ($|y|$, p_T, $\cos\theta^*$) in a local region around the mass of interest.

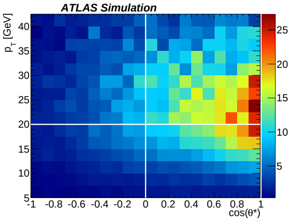
MC sample $m(X_b) = 10.561\,\mathrm{GeV}$



Background



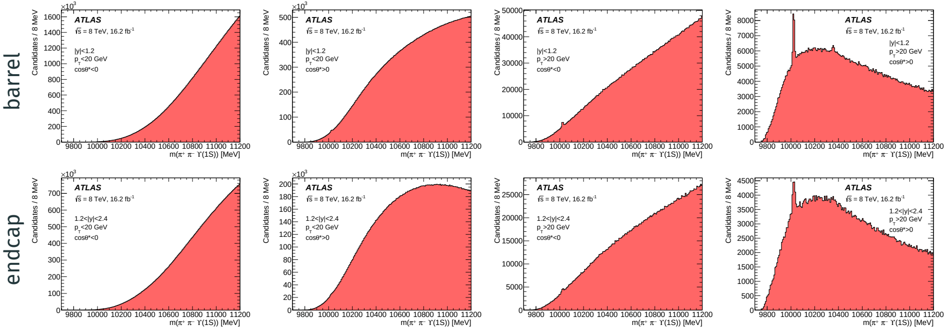
Significance $\sim S/\sqrt{B}$



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

- Clear peaks of $\Upsilon(2S)$ and $\Upsilon(3S)$ are observed; no other visible signals,
- kinematic bin most sensitive to an X_b signal: $|y| < 1.2$, $p_T > 20\,\mathrm{GeV}$ and $\cos\theta^*$,
- normalized to $\Upsilon(2S)$ yields and validated on $\Upsilon(3S)$.

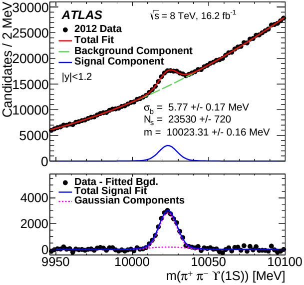
low p_T, low $\cos\theta^*$ | low p_T, high $\cos\theta^*$ | high p_T, low $\cos\theta^*$ | high p_T, high $\cos\theta^*$



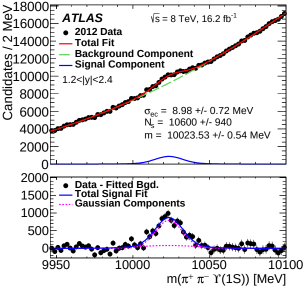
$\Upsilon(2S)$ and $\Upsilon(3S)$ fits

- Differential production cross section $\mathrm{d}^2\sigma/\mathrm{d}y\mathrm{d}p_T$ for $\Upsilon(2S)$ and $\Upsilon(3S)$ measured by ATLAS/CMS at 7 TeV were used to calculate production weights, which are applied to 8 TeV $\Upsilon(2S)/\Upsilon(3S)$ simulated sample,
- $\Upsilon(2S)$ total fitted yield $N_{2S} = 34300 \pm 800$ is consistent with expected $N_{2S}^{\text{expected}} = (\sigma\mathcal{B})_{2S} \cdot \mathcal{L} \cdot \mathcal{A} \cdot \epsilon = 33300 \pm 2500$,
- $\Upsilon(3S)$ total fitted yield $N_{3S} = 11600 \pm 1300$ agrees with $N_{3S}^{\text{expected}} = 11400 \pm 1500$, statistical significance for simultaneous fit to the analysis bins is $z = 8.7$ while for individual fit to the most sensitive bin $z = 6.5$.

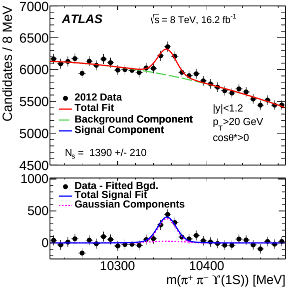
$\Upsilon(2S)$ in barrel



$\Upsilon(2S)$ in endcap



$\Upsilon(3S)$ in the most sensitive bin

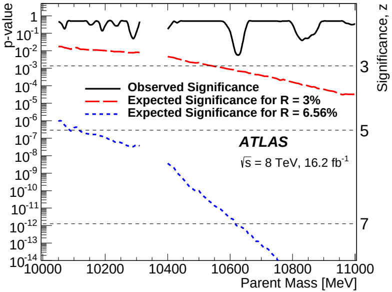


Strategy:

- A hypothesis test for signal presence across 10–11 GeV range every 10 MeV,
- simultaneous fit in 8 analysis bins
- for each mass, extract p-value and significance.

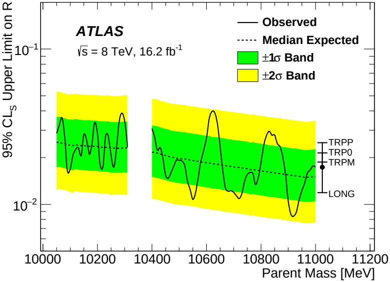
Assumptions:

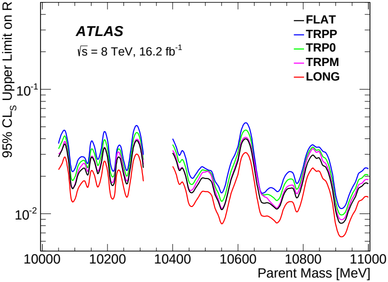
- Look for narrow state,
- resolution dependence on $|y|$, p_T is $\Upsilon(nS)$-like,
- phase-space shape of $m(\pi^+\pi^-)$.



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

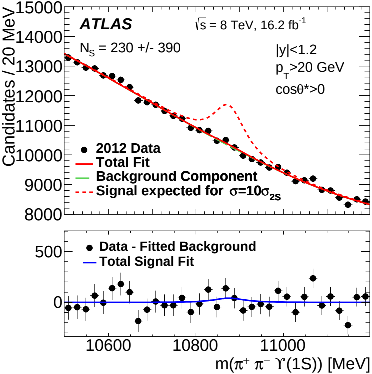
- CL_s limit on $R = (\sigma\mathcal{B})/(\sigma\mathcal{B})_{2S}$ at 95% CL is evaluated as a function of mass,
- various assumptions on X_b production polarization shift the limits (1 longitudinal and 3 transverse spin-alignment scenarios),
- this is the most sensitive X_b production search for $m > 10.1\,\mathrm{GeV}$,
- the null result of the search $X_b \to \pi^+\pi^-\Upsilon(1S)$ decay does not tell us if the X_b exists, because for an isoscalar with $J^{PC} = 1^{++}$ such a decay is forbidden by G-parity conservation.

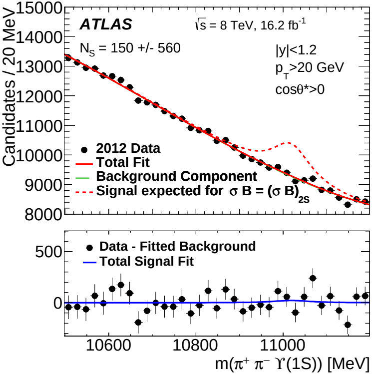




Results for $\Upsilon(1^3D_J)$, $\Upsilon(10860)$, $\Upsilon(11020)$

- $\Upsilon(1^3D_J)$ triplet fit attempted with additional signal shapes for the three masses: 10156, 10164, and 10170 MeV; a significance of $z = 0.12$ is found,
- upper limit of relative cross-section $\sigma(\Upsilon(1^3D_2))/\sigma(\Upsilon(2S)) < 0.55$ (using known $\mathcal{B}(\Upsilon(1^3D_2) \to \pi^+\pi^-\Upsilon(1S)) = (6.6 \pm 1.6) \times 10^{-3}$ from BaBar)
- broad resonances $\Upsilon(10860)$, $\Upsilon(11020)$ searched for in grid of mass and width, (using world-average masses and uncertainties), largest significances of $z = 1.1$ and 0.6
- plots shown with rates $\sigma_{10860} = 10\sigma(2S)$ and $\sigma_{10860} = \sigma(2S) \cdot \mathcal{B}(2S)$





Two analyses performed by ATLAS are reported:

1. Observation of a new state decaying into $\boldsymbol{B_c^+ \pi^+ \pi^-}$ in 7 TeV and 8 TeV data
    - First observation of an excited state in B_c^+ sector
    - Measured mass **6842 ± 4 (stat.) ± 5 (syst.) MeV** is consistent with the predicted mass of the $B_c^+(2S)$ state
2. Search for $\boldsymbol{X_b}$ state in $\boldsymbol{\pi^+\pi^-\Upsilon(1S)}$ channel in 8 TeV data
    - No evidence for new narrow state is found for masses 10.05–10.31 GeV and 10.40–11.00 GeV
    - Upper limits are set on the ratio $R = [\sigma(pp \to X_b)\mathcal{B}(X_b \to \pi^+\pi^-\Upsilon(1S))]/[\sigma(pp \to \Upsilon(2S))\mathcal{B}(\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S))]$, with results ranging from **0.8%** to **4.0%**, depending on the X_b mass
    - No evidences for other searched states $\boldsymbol{\Upsilon(1^3D_J)}$ triplet, $\boldsymbol{\Upsilon(10860)}$ and $\boldsymbol{\Upsilon(11020)}$
    - Upper limit on relative cross section is set $\sigma(\Upsilon(1^3D_2))/\sigma(\Upsilon(2S)) < 0.55$
    - The searches for the isospin-conserving X_b decays are in progress