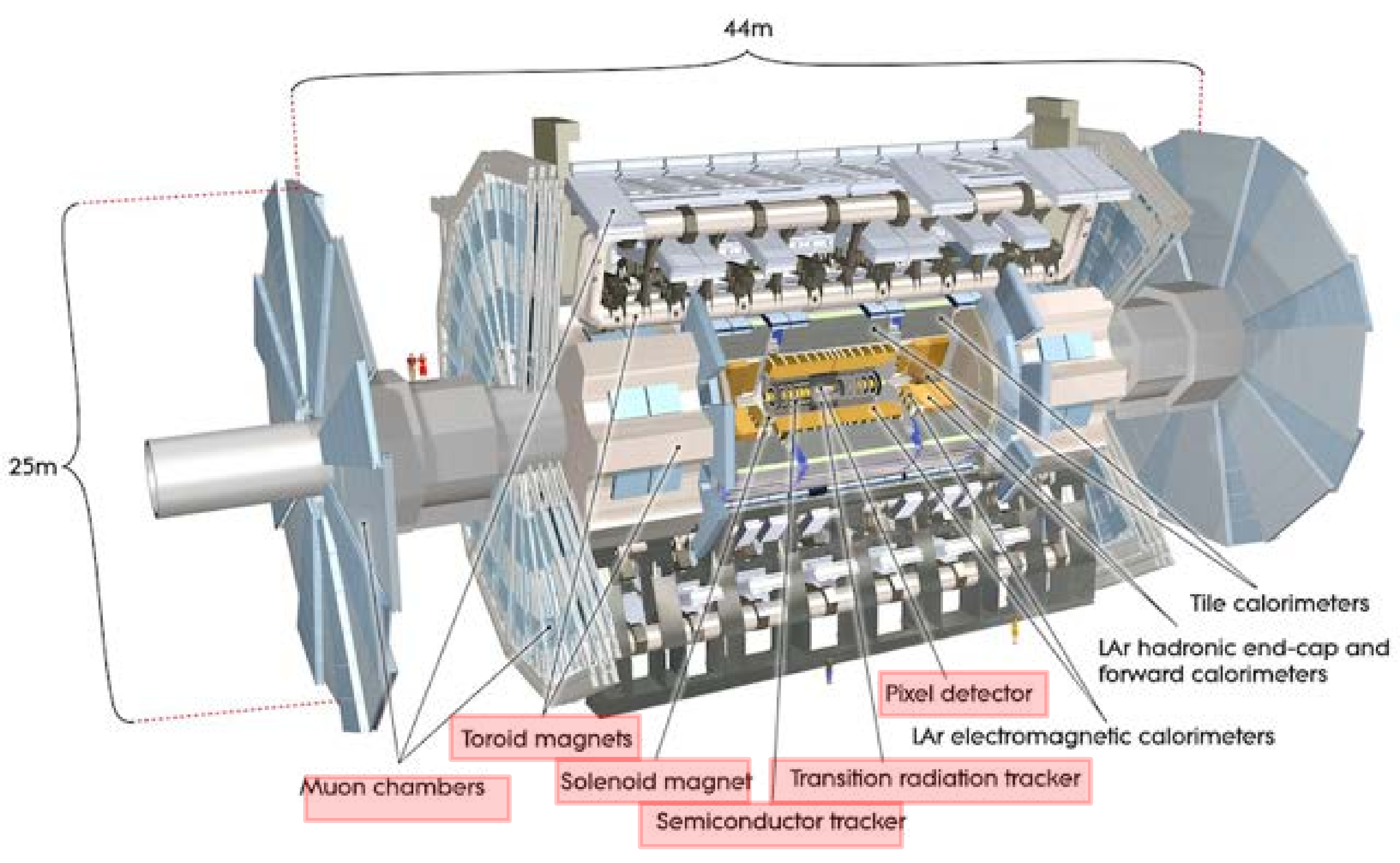
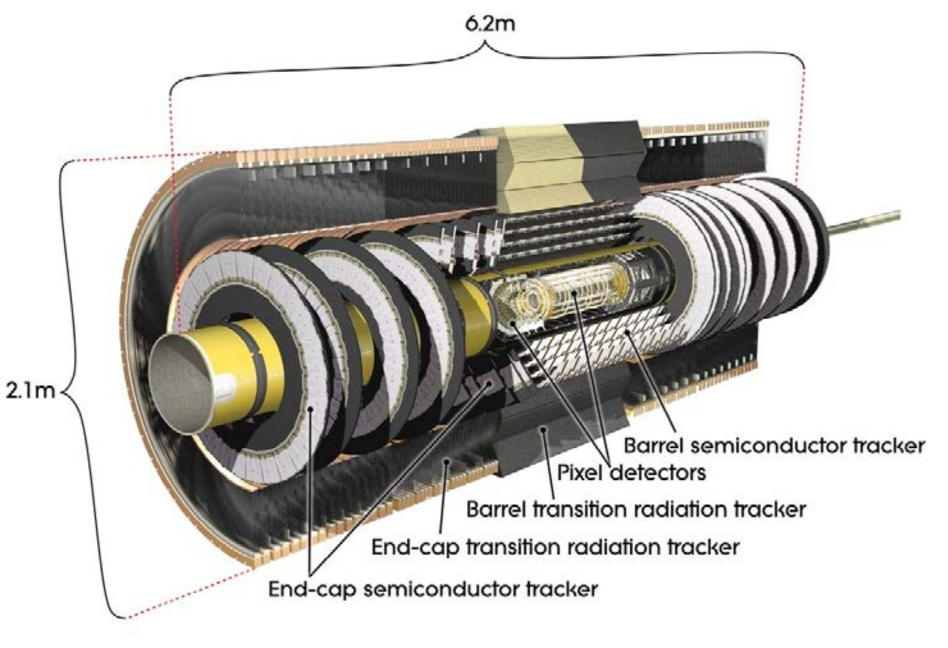
Spectroscopy of onia and hadrons with open beauty in ATLAS

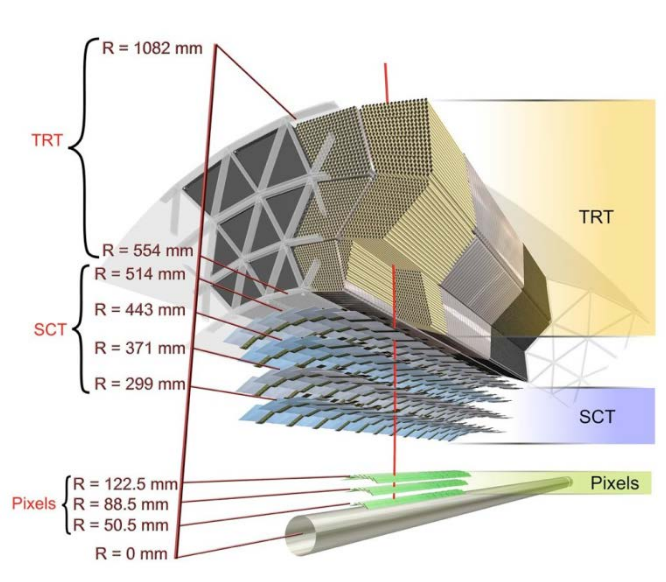
R Henderson (Lancaster) on behalf of the ATLAS Collaboration BEAUTY 14-18 July 2014



The ATLAS detector is a general purpose detector (GPD) with almost 4π coverage

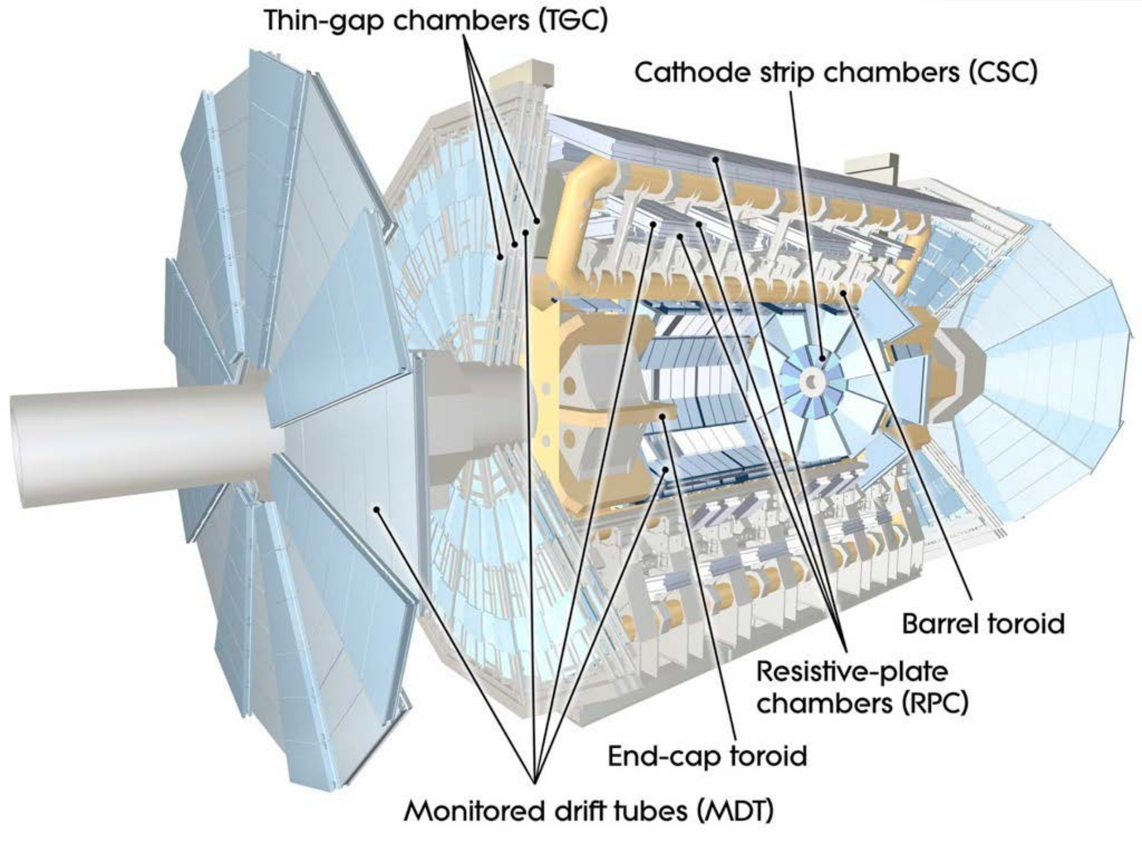
ATLAS Inner Detector ID





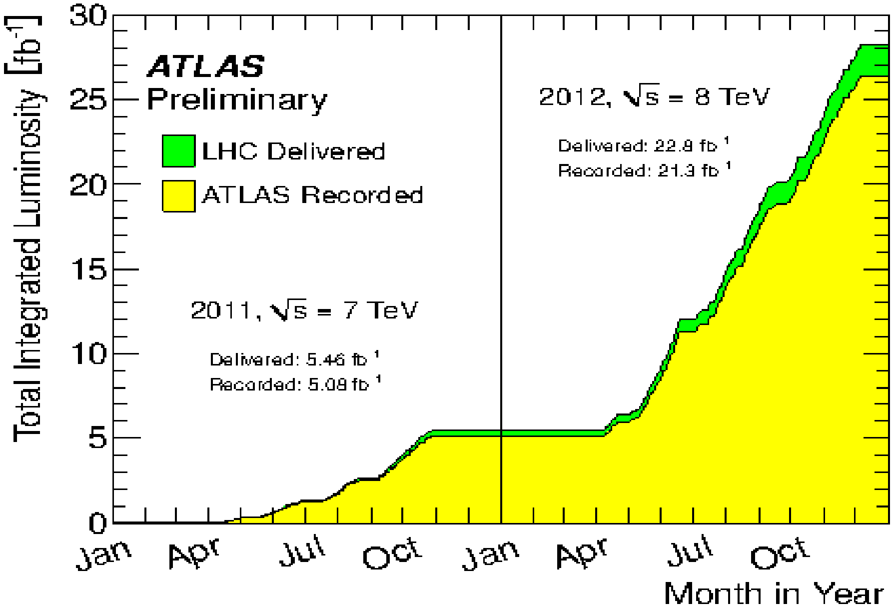
- 2T magnetic field, coverage $|\eta| < 2.5$
- Momentum scale: ~0.1% at low energy, ~1% up to ~100 GeV
- Momentum resolution: $\sigma/p_T = 3.8 \times 104$ (GeV) $\oplus$ 0.015
- Primary vertex resolution: ~30 µm transverse, ~50 µm longitudinal

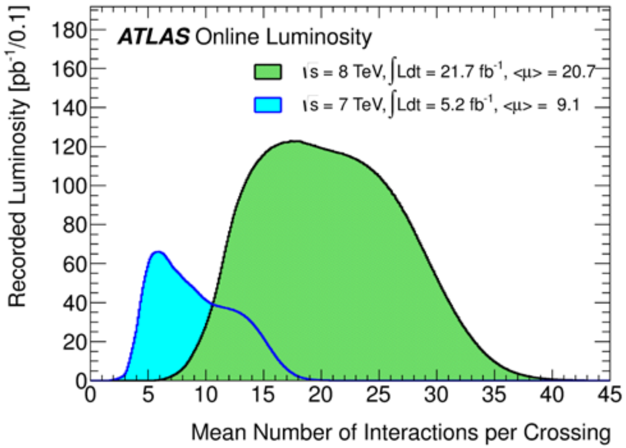
The ATLAS Muon Spectrometer (MS)



- Coverage |η| < 2.7
- Average field 0.5T
- Momentum resolution <10% for muons with energy < 1 TeV
- **Essential for onia analyses for both trigger and offline muon identification, the track parameters coming enitrely from the ID however.**

Luminosity and Pileup





Vertexing : The ID vertex precision (show above) can resolve the increasing number of primary vertices from increasing pileup

Trigger: The ATLAS trigger has been able efficiently to process increasing luminosity. Vital to onia and b physics is the b-physics di-muon trigger.

B-Trigger

The ATLAS trigger system comprises of three levels

- **Level 1 :** Hardware based , resistive Plate Chambers (RPC) , thin gap chambers(TGC), trigger on muons in $|\eta|<1.05$ and $1.05 < |\eta|<2.5$ respectively.
- **High-Level Trigger:** Software based**,** Level 2 trigger and the Event Filter (EF)

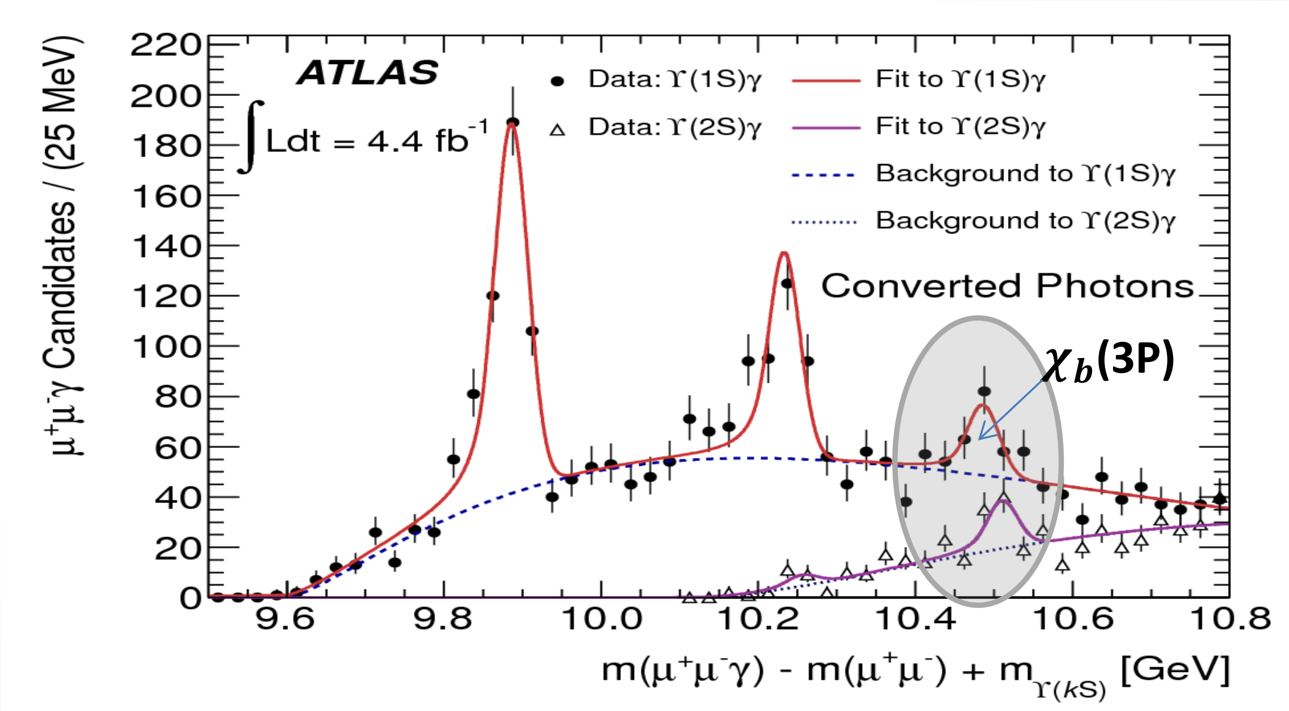
B-Trigger : All Onia and open B relies on this

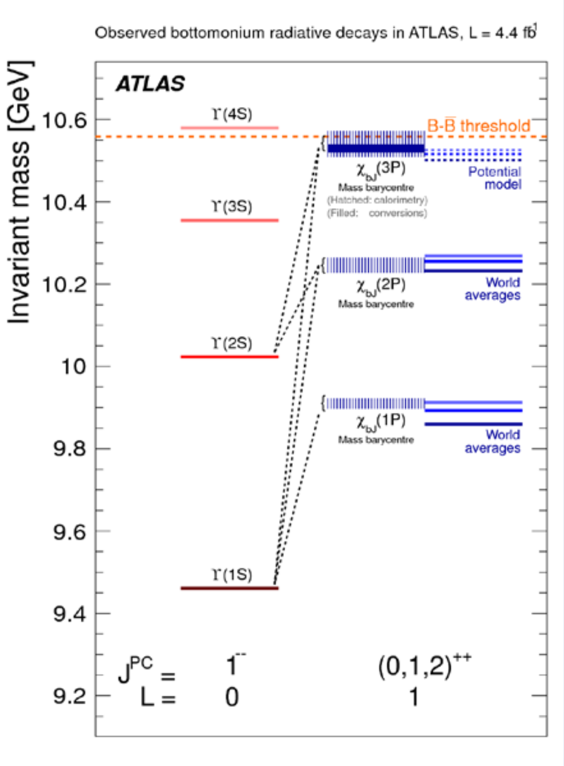
- One or more regions of interest (**RoI)** are identified by the Level 1 muon trigger which seed the HLT muon online reconstruction algorithms, which combine the response from both ID and MS.
- HLT J/ψ - μ_1 μ_2 , common vertex , 2.5 GeV<mass<4.3 GeV and $p_T(\mu_1)>6$ GeV ;$p_T(\mu_2)>4$ GeV

The success of this trigger means that despite increased luminosity we are able to maintain an un-prescaled J/ψ→μμ and ϒ→μμ trigger without any J/ψ lifetime cuts, even at full luminosity.

Observation of χ_b(nP) in radiative decays to ϒ(1S) and ϒ(2S) [2011]

doi:10.1103/PhysRevLett.108.152001





χ_b(nP)→ ϒ(1S,2S) (→μμ) +γ(→e^+e^-)(converts in ID)

Search for an excited B_c meson

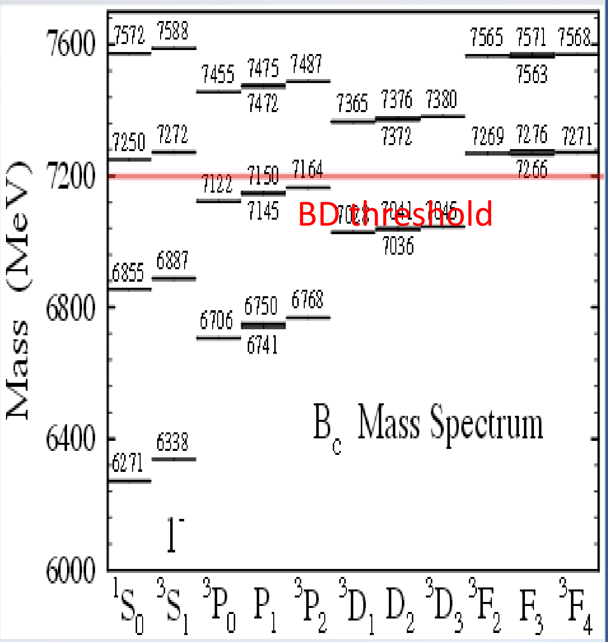
The $\boldsymbol{B_c^\pm}$ has been observed in both semi-leptonic decay and hadron decay modes, but excited states have not been previously reported.

- The spectrum and properties of the $\boldsymbol{B_c^\pm}$ are predicted by NRQCD , and lattice calculations.
- Measurements of the ground and excited states will provide tests of the predictions of these models and ultimately provide the opportunity to extract information on the strong interaction potential

Theoretical predictions for excited B_c states

- **1S ground state**: both 1^1S_0 and 1^3S_1 (pseudoscalar, vector) mass difference ~20-70 Mev transitions via soft undetectable soft gamma.
- **2P states**: soft undetectable gamma radiation to 1S, contributes to ground state cross section.

- **2S state**:
  - $\boldsymbol{B}_c^{\pm *}$(2S) predicted mass in range 6835-6917 MeV
  - $\boldsymbol{B}_c^{\pm}{*}(2S_0) \rightarrow \boldsymbol{B}_c^{\pm}(1S_0)$ + ππ;
  - $\boldsymbol{B}_c^{\pm}{*}(2S_1) \rightarrow \boldsymbol{B}_c^{\pm}(1S_1)$ + ππ; $\boldsymbol{B}_c^{\pm}{*}(1S_1) \rightarrow \boldsymbol{B}_c^{\pm}(1S_0)$+$\gamma_{\text{invisible}}$
  - Mass difference m(2S)-m(1S)~600 MeV
  - π π from PV should follow $\boldsymbol{B}_c^{\pm}$ direction



http://arxiv.org/abs/hep-ph/9703341

S. Godfrey,
PRD 70, 054017 (2004)

Data and MC samples

This study uses pp collision data samples :

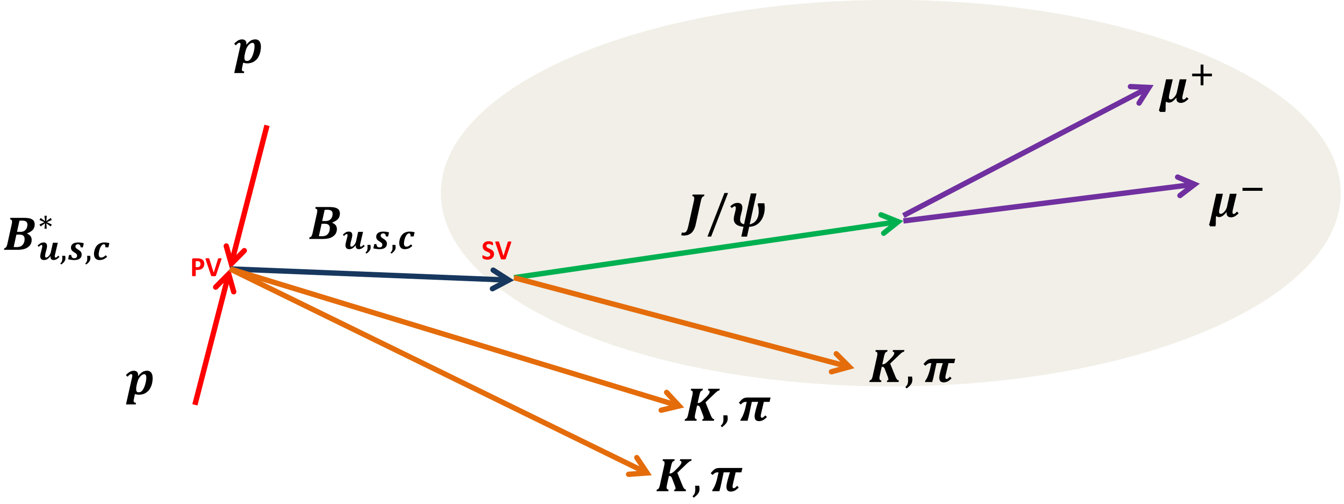
- 2011 ($\sqrt{s}$ = 7 TeV) integrated luminosity 4.9 fb^{-1}
- 2012 ($\sqrt{s}$ = 8 TeV) integrated luminosity 19.2 fb^{-1}

Monte Carlo data

Treated exactly as collision data

- PYTHIA 6 (tuned for LHC) is used to generate exclusive $\boldsymbol{B_c^{\pm}}$ channels
- PYTHIA 8 is used to generate inclusive J/ψX channels
- The following channel samples are used to optimize the event selection criteria: (J/ψπ, J/ψK, J/ψρ ($\rho \to \pi^0\pi^{\pm}$), J/ψμν, J/ψπ^0 π, J/ψπππ, and J/ψX produced from $b\bar{b}$)
- Difference between 7 and 8 TeV data is due to higher centre of mass energies of production and higher pileup , thus separate selection optimizations between 2011 and 2012 are required.

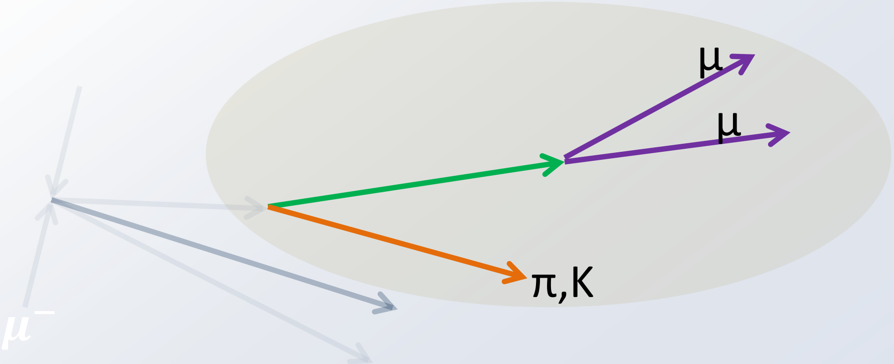
Searching for an excited B_c meson state



Analysis overview:

- A B candidate is constructed from a $\mu^+\mu^-$ pair and a hadronic track using both π and K hypotheses forming a secondary vertex (SV).
- A B^*candidate is the formed from the B candidate and two oppositely charged hadrons from the primary vertex (PV) using both π and K hypotheses.
- The wrong sign B^* candidates formed from same sign charged hadron from the primary vertex are also kept.

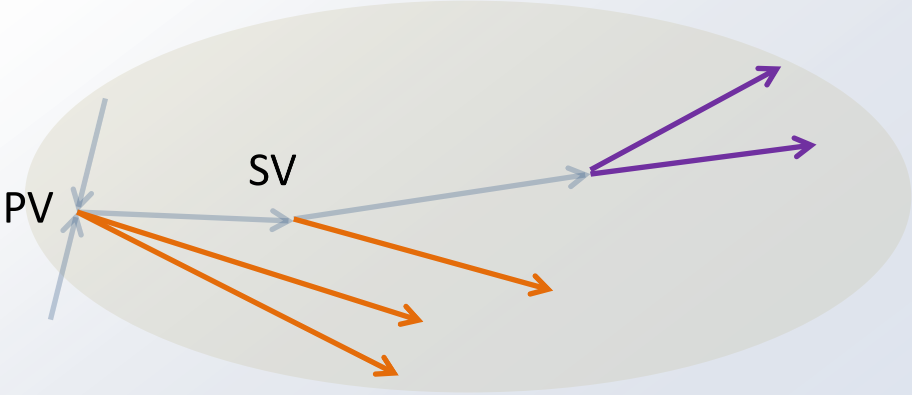
Searching for B meson Candidates



B candidates:

- J/ψ μμ vertex must have χ^2<15 per degree of freedom
- Hadronic tracks $p_T > 4$ GeV
- $p_T(B) > 15$GeV (7 TeV data); $p_T(B) > 18 GeV$ (8 TeV data).
- Cut on hadron track impact parameter quantity $(d_o)\,/\sigma(d_o)$ > 5 or 4.5 for 7 and 8 TeV data respectively where d_o with respect to PV.
- Cut on B vertex (sv)
  $\chi^2 < 2$ or 1.5 per degree of freedom for 7 and 8 TeV data respectively
- Primary vertex (PV) ; 7 TeV vertex with highest p_T ; 8 TeV vertex most closely pointed at by the $B^{\pm}c$ candidate

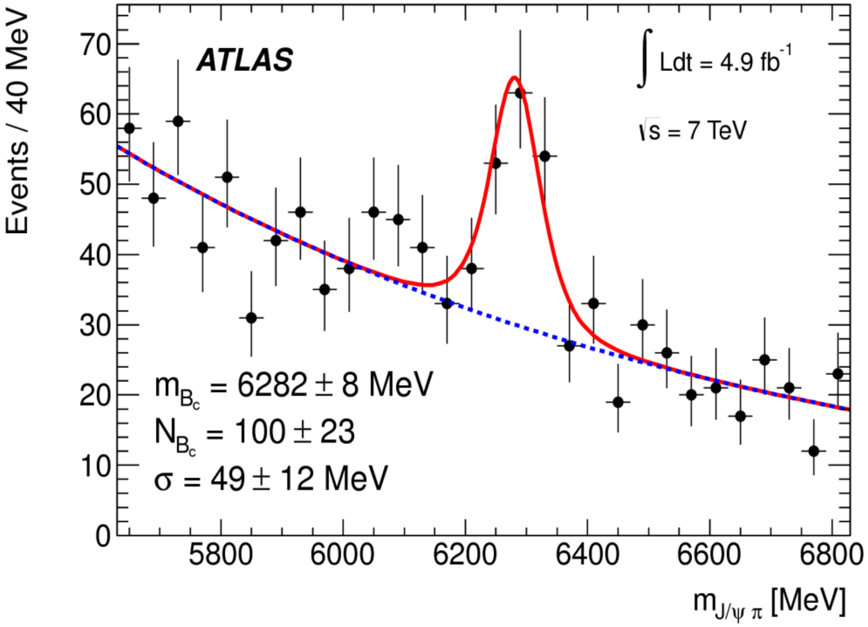
Finding B_c^* (2S) Candidates



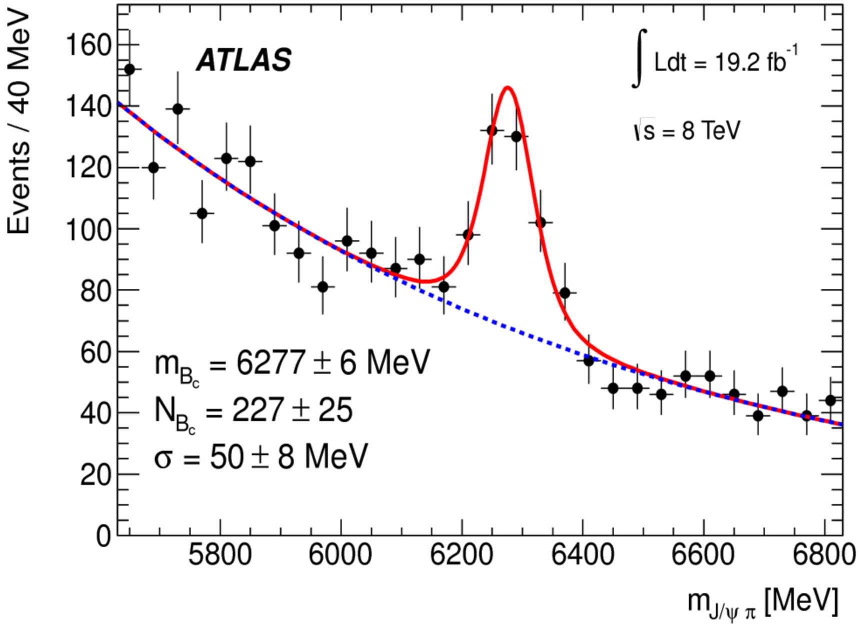
$B_c^*(2S)$ candidates:

- Previously found B candidates within a 3σ mass window around the J/ψ mass are selected (this allows for the different resolutions from the Barrel and Endcap components of the ID)
- The three B candidate tracks and two hadrons from the PV are fitted simultaneously.
- The muon pair is constrained to the $\mathrm{m}(J/\psi)$.
- The B and B^* candidates must have a significantly displaced vertices.
- When there are more than one B* candidates in an event the one with the best χ^2 to the B_c^* cascade vertices fit is chosen.

$B_c^{\pm} \rightarrow J/\psi\pi^{\pm}$



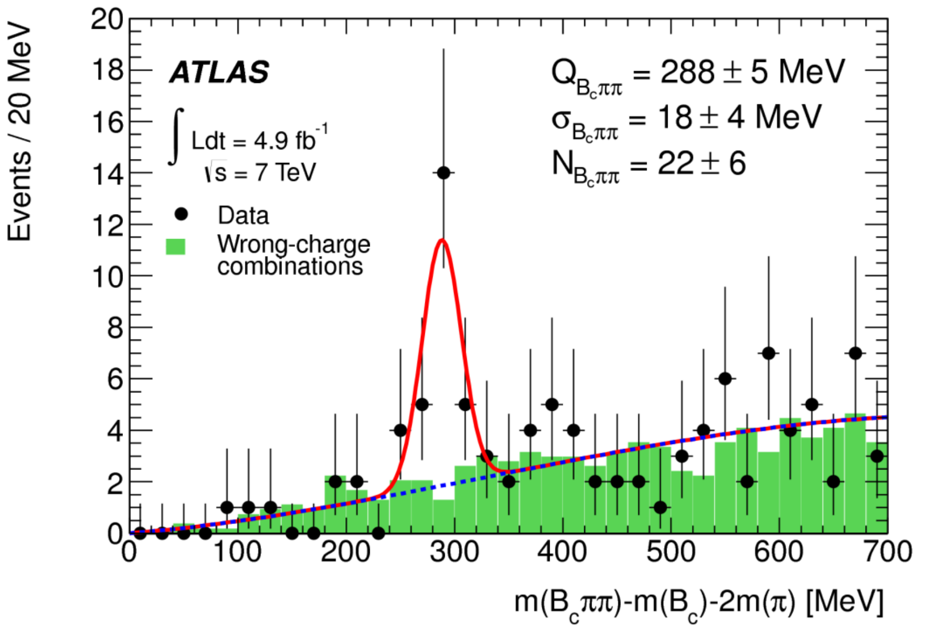
7 TeV



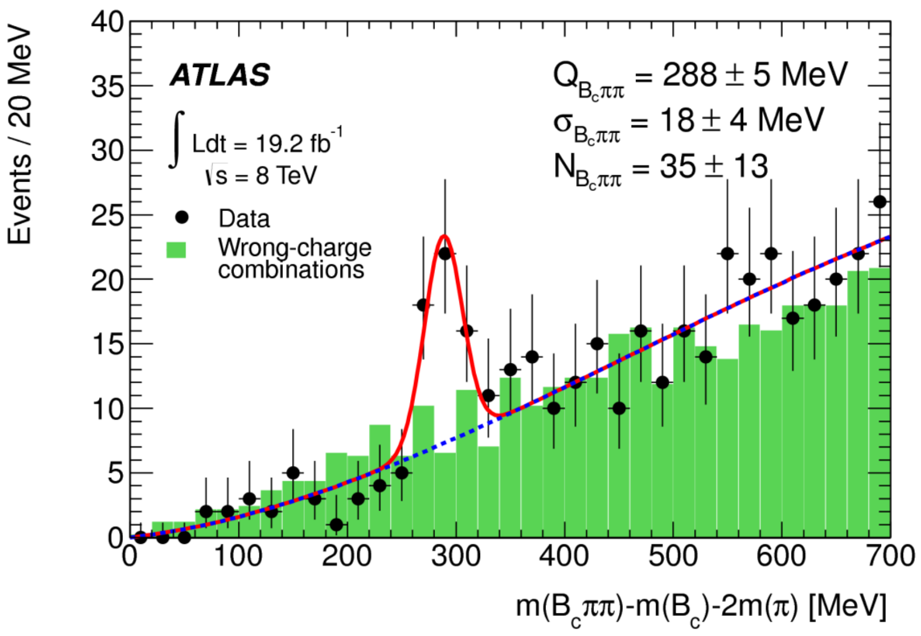
8 TeV

- The solid line is the projection of the results of the unbinned maximum likelihood fit **(Gaussian plus exponential background)** to all candidates in the range 5620-6820 MeV.
- The dashed line is the projection of the background to that fit.

$Q = m\left(B_c^{\pm}\pi^{+}\pi^{-}\right) - m\left(B_c^{\pm}\right) - 2m(\pi \pm)$



7 TeV
significance: 3.7σ



8 TeV
significance: 4.5σ

Lower yield due to harder p_T cuts

- The solid line is the projection of the results of the unbinned maximum likelihood fit **(Gaussian plus third order polynomial)** to all candidates in the range 0-700 MeV.
- The dashed line is the projection of the background to that fit and the green shaded histogram are for the wrong pion charge combination normalised to the same yield.

Systematics

So far all errors shown have been statistical. The systematic errors are assumed to be independent and added in quadrature giving ~4.1 MeV

There are two dominant sources of systematic uncertainty

- Uncertainty in the $\boldsymbol{B_c^*}$ candidate ground state largely cancelled out by the Q (mass difference) distribution
- Uncertainty in the fitting of the mass difference distributions.
    - $\boldsymbol{B_c^*}$ candidate mass systematic from procedure below 3MeV
    - Pion momentum scale relative to the B candidate 1.2 MeV
    - Residual B candidate mass uncertainty adds about 1.7 MeV

Q fitting systematic error estimated by

- Varying the background model using an exponential threshold function, and higher order polynomial. (3.4 MeV contribution)
- Varying the fit mass range from 0-700 to 0-1500 MeV (1.2 MeV contribution)
- Using different models for the signal (eg. Breit-Wigner, BW convoluted with Gaussian, double Gaussian) This was found to have a negligible effect.

B_c^* signal significance

The new structure significance is evaluated by pseudo-experiment.

- Generate a large number of toy-MC experiments following the background only hypothesis
  (Using data determined parameters)
- Background shape scaled to observed number of events.
- Fit not constrained to the theoretically expected mass range ;"look elsewhere effect".
- Significance calculated from the fraction of pseudo-experiments in which the difference ΔlnL with and without signal is larger than in the data.

Conclusions

The observation of excited $\boldsymbol{B_c^*}$ state with

- Q =288.3 ±3.5±4.1
- Corresponding to a mass of 6842±4±5 MeV
- With a significance of 5.2σ for 2011 and 2012 data combined
- Consistent with predicted mass of $\boldsymbol{B_c^*}$ (2S)
- This result will help refine the details NRQCD and lattice models

http://arxiv.org/abs/1407.1032