b hadron decay properties at ATLAS

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Outline

- Measurement of the parity-violating asymmetry parameter α_b *and the helicity amplitudes for the decay* $\Lambda_b^0 \to J/\psi \Lambda^0$ with the ATLAS detector
  Phys. Rev. D 89 (2014) 092009, arXiv:1404.1071
- Measurement of the *branching ratio* $\Gamma(\Lambda_b^0 \to \psi(2S)\Lambda^0)/\Gamma(\Lambda_b^0 \to J/\psi \Lambda^0)$ with the ATLAS detector
  Physics Letters B 751 (2015) 63-80, arXiv:1507.08202
- Study of the $B_c^+ \to J/\psi D_s^+$ *and* $B_c^+ \to J/\psi D_s^{*+}$ *decays* with the ATLAS detector
  Eur. Phys. J. C, 76(1), 1-24 (2016), arXiv:1507.07099

Angular analysis of $\Lambda_b^0 \to J/\psi\Lambda^0$ decay

Introduction

Motivation

- Parity violation in hadronic sector depends on the hadron constituents – strongly bound spectator quarks
- Measurement of parity-violating parameter α_b provides a test for several theoretical models:
  - pQCD: $\alpha_b = -0.17$ to -0.14 (PRD 65, 074030 (2002), arXiv:hep-ph/0112145)
  - HQET: $\alpha_b = 0.78$ (PLB 614, 165 (2005),arXiv:hep-ph/0412116)

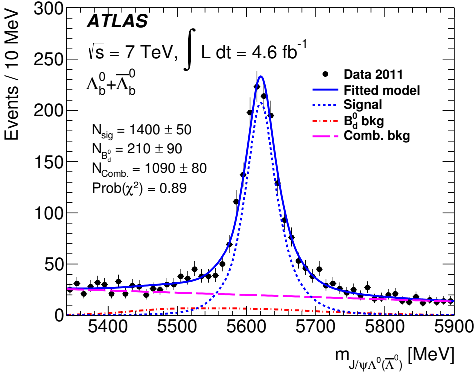
Strategy

- Measure the helicity amplitudes
  - $A(\lambda_\Lambda, \lambda_{J/\psi})$: $a_+ \equiv A(1/2, 0)$, $a_- \equiv A(-1/2, 0)$, $b_+ \equiv A(-1/2, -1)$, $b_- \equiv A(1/2, 1)$
  - $|a_+|^2 + |a_-|^2 + |b_+|^2 + |b_-|^2 = 1$
  - $\alpha_b = |a_+|^2 - |a_-|^2 + |b_+|^2 - |b_-|^2$
- Extract them using F_i moments

- Analysis uses 4.6 fb^{-1} of 7 TeV data

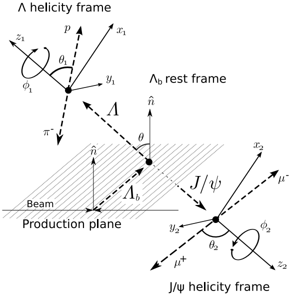
Reconstruction

- Cascade topology fit with $J/\psi \to \mu^+\mu^-$ and $\Lambda^0 \to p\pi^-$ mass constraints
  - Λ^0 momentum points back to dimuon vertex
  - $2.8 < m_{\mu\mu} < 3.4$ GeV, $1.08 < m_{p\pi} < 1.15$ GeV
  - $\chi^2/\mathrm{n.d.f.} < 3$
  - $L_{xy}(\Lambda^0) > 10$ mm, $\tau(\Lambda_b^0) > 0.35$ ps
  - $p_\mathrm{T}(\Lambda^0) > 3.5$ GeV



- Fit same tracks with $B^0 \to J/\psi K_S^0$ constraints
  - reject if χ^2-probabilities $\mathcal{P}(\Lambda_b^0) < \mathcal{P}(B^0)$
- Mass fit model:
  - *Signals:* MC templates
  - *Background:* linear

Measurement



$$w(\Omega, \vec{A}, P) = \frac{1}{(4\pi)^3} \sum_{i=0}^{19} f_{1i}(\vec{A}) f_{2i}(P, \alpha_\Lambda) F_i(\Omega)$$

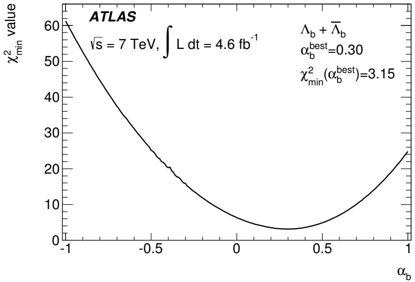
i	f_{1i}	f_{2i}	F_i
0	$a_+a_+^* + a_-a_-^* + b_+b_+^* + b_-b_-^*$	1	1
1	$a_+a_+^* - a_-a_-^* + b_+b_+^* - b_-b_-^*$	P	$\cos\theta$
2	$a_+a_+^* - a_-a_-^* - b_+b_+^* + b_-b_-^*$	α_Λ	$\cos\theta_1$
3	$a_+a_+^* + a_-a_-^* - b_+b_+^* - b_-b_-^*$	$P\,\alpha_\Lambda$	$\cos\theta\,\cos\theta_1$
4	$-a_+a_+^* - a_-a_-^* + \frac{1}{2}b_+b_+^* + \frac{1}{2}b_-b_-^*$	1	$\frac{1}{2}\,(3\cos^2\theta_2 - 1)$
5	$-a_+a_+^* + a_-a_-^* + \frac{1}{2}b_+b_+^* - \frac{1}{2}b_-b_-^*$	P	$\frac{1}{2}\,(3\cos^2\theta_2 - 1)\,\cos\theta$
6	$-a_+a_+^* + a_-a_-^* - \frac{1}{2}b_+b_+^* + \frac{1}{2}b_-b_-^*$	α_Λ	$\frac{1}{2}\,(3\cos^2\theta_2 - 1)\,\cos\theta_1$
7	$-a_+a_+^* - a_-a_-^* - \frac{1}{2}b_+b_+^* - \frac{1}{2}b_-b_-^*$	$P\,\alpha_\Lambda$	$\frac{1}{2}\,(3\cos^2\theta_2 - 1)\,\cos\theta\cos\theta_1$
8	$-3\mathrm{Re}(a_+a_-^*)$	$P\,\alpha_\Lambda$	$\sin\theta\,\sin\theta_1\,\sin^2\theta_2\,\cos\phi_1$
9	$3\mathrm{Im}(a_+a_-^*)$	$P\,\alpha_\Lambda$	$\sin\theta\,\sin\theta_1\,\sin^2\theta_2\,\sin\phi_1$
10	$-\frac{3}{2}\mathrm{Re}(b_-b_+^*)$	$P\,\alpha_\Lambda$	$\sin\theta\,\sin\theta_1\,\sin^2\theta_2\,\cos(\phi_1 + 2\,\phi_2)$
11	$\frac{3}{2}\mathrm{Im}(b_-b_+^*)$	$P\,\alpha_\Lambda$	$\sin\theta\,\sin\theta_1\,\sin^2\theta_2\,\sin(\phi_1 + 2\,\phi_2)$
12	$-\frac{3}{\sqrt{2}}\mathrm{Re}(b_-a_+^* + a_-b_+^*)$	$P\,\alpha_\Lambda$	$\sin\theta\,\cos\theta_1\,\sin\theta_2\,\cos\theta_2\,\cos\phi_2$
13	$\frac{3}{\sqrt{2}}\mathrm{Im}(b_-a_+^* + a_-b_+^*)$	$P\,\alpha_\Lambda$	$\sin\theta\,\cos\theta_1\,\sin\theta_2\,\cos\theta_2\,\sin\phi_2$
14	$-\frac{3}{\sqrt{2}}\mathrm{Re}(b_-a_-^* + a_+b_+^*)$	$P\,\alpha_\Lambda$	$\cos\theta\,\sin\theta_1\,\sin\theta_2\,\cos\theta_2\,\cos(\phi_1 + \phi_2)$
15	$\frac{3}{\sqrt{2}}\mathrm{Im}(b_-a_-^* + a_+b_+^*)$	$P\,\alpha_\Lambda$	$\cos\theta\,\sin\theta_1\,\sin\theta_2\,\cos\theta_2\,\sin(\phi_1 + \phi_2)$
16	$\frac{3}{\sqrt{2}}\mathrm{Re}(a_-b_+^* - b_-a_+^*)$	P	$\sin\theta\,\sin\theta_2\,\cos\theta_2\,\cos\phi_2$
17	$-\frac{3}{\sqrt{2}}\mathrm{Im}(a_-b_+^* - b_-a_+^*)$	P	$\sin\theta\,\sin\theta_2\,\cos\theta_2\,\sin\phi_2$
18	$\frac{3}{\sqrt{2}}\mathrm{Re}(b_-a_-^* - a_+b_+^*)$	α_Λ	$\sin\theta_1\,\sin\theta_2\,\cos\theta_2\,\cos(\phi_1 + \phi_2)$
19	$-\frac{3}{\sqrt{2}}\mathrm{Im}(b_-a_-^* - a_+b_+^*)$	α_Λ	$\sin\theta_1\,\sin\theta_2\,\cos\theta_2\,\sin(\phi_1 + \phi_2)$

- Average polarization P is taken as 0
- Measure $\langle F_i \rangle = \frac{1}{N^{\text{data}}} \sum_{n=1}^{N^{\text{data}}} F_i(\Omega_n)$, $i = 2, 4, 6, 18, 19$
  - Background subtraction bases on sidebands and B^0 MC
- Expected values: $\langle F_i \rangle^{\text{expected}} = \sum_j f_{1i}(\vec{A}) f_{2i}(\alpha_\Lambda) C_{ij}$ with
  $\mathrm{C}_{ij} \sim \iint F_i(\Omega') T(\Omega', \Omega) F_j(\Omega)\,\mathrm{d}\Omega'\mathrm{d}\Omega$ for detector effects
- Fit $\chi^2 = \sum_i \sum_j (\langle F_i \rangle^{\text{expected}} - \langle F_i \rangle) V_{ij}^{-1} (\langle F_j \rangle^{\text{expected}} - \langle F_j \rangle)$
  - to constrain the solution within physical boundaries

Results

- Helicity amplitudes:

$$|a_+| = 0.17^{+0.12}_{-0.17}(\text{stat}) \pm 0.09(\text{syst}),$$
$$|a_-| = 0.59^{+0.06}_{-0.07}(\text{stat}) \pm 0.03(\text{syst}),$$
$$|b_+| = 0.79^{+0.04}_{-0.05}(\text{stat}) \pm 0.02(\text{syst}),$$
$$|b_-| = 0.08^{+0.13}_{-0.08}(\text{stat}) \pm 0.06(\text{syst}).$$



- Parity violation parameter:
  - $\alpha_b = 0.30 \pm 0.16(\text{stat}) \pm 0.06(\text{syst})$
  - Consistent with LHCb measurement $\alpha_b = 0.05 \pm 0.17(\text{stat}) \pm 0.07(\text{syst})$ (PLB 724, 27 (2013))
  - Difference with both pQCD and HQET expectations by $+2.6\sigma$ and -2.8σ, respectively

Observation of $\Lambda_b^0 \to \psi(2S)\Lambda^0$ decay

Introduction

Motivation

- $\Lambda_b^0 \to \psi(2S)\Lambda^0$ was not seen before
- Expectations for $\Gamma(\Lambda_b^0 \to \psi(2S)\Lambda^0)/\Gamma(\Lambda_b^0 \to J/\psi\Lambda^0)$:
  - Similar B meson decays: 0.5 – 0.8
  - Covariant quark model prediction Few Body Syst. 21, 131 (1996), arXiv:hep-ph/9602372: 0.8 ± 0.1

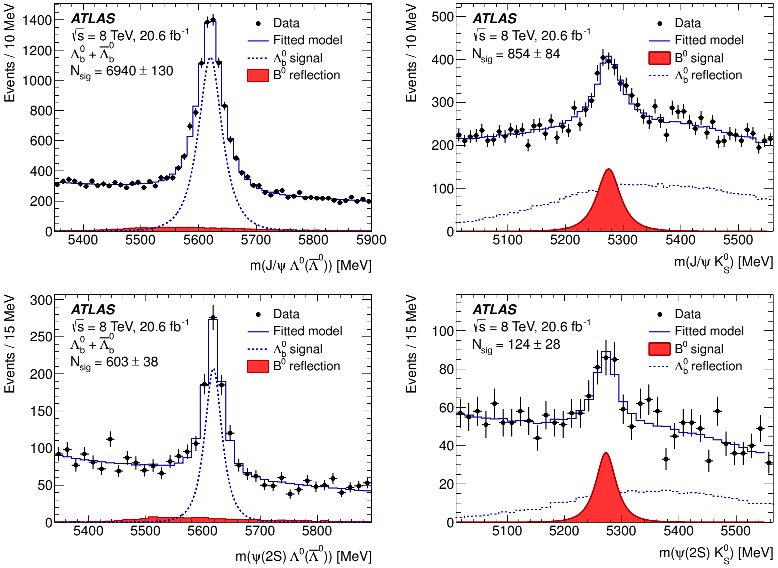
Reconstruction

- Signal and reference modes have the same topology
- Reconstruction and selection similar to the previous analysis
  - Mass constraints for intermediate resonances are used
  - Kinematic region: $p_{\mathrm{T}}(\Lambda_b^0) > 10$ GeV, $|\eta(\Lambda_b^0)| < 2.1$
  - To suppress $B^0 \to J/\psi K_S^0$, require *fit χ^2-probabilities* $\mathcal{P}(\Lambda_b^0) > \mathcal{P}(B^0)$

- Use 20.6 fb^{-1} of 8 TeV data

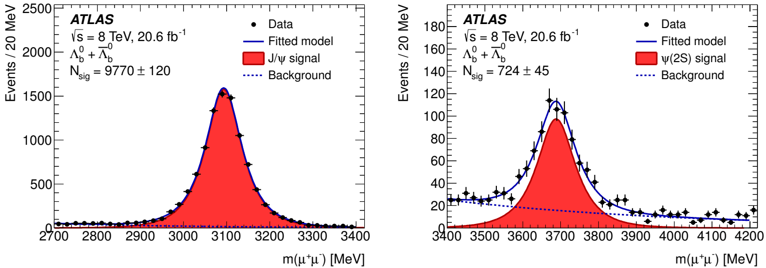
Signal fits

Simultaneous binned ML fit of Λ_b^0 and B^0 mass distributions



Signal fits (cont.)

To verify the signal corresponds to decays through the intermediate resonances, the analysis repeated without mass constraints



Results

	$\Lambda_b^0 \to J/\psi \Lambda^0$	$B^0 \to J/\psi K_S^0$	$\Lambda_b^0 \to \psi(2S)\Lambda^0$	$B^0 \to \psi(2S)K_S^0$
N_{sig}	6940 ± 130	854 ± 84	603 ± 38	124 ± 28
m_{sig} [MeV]	5620.4 ± 0.4	5274.7 ± 2.3	5618.2 ± 1.2	5272.4 ± 4.9
σ_{sig} [MeV]	19.7 ± 0.5	19.2 ± 2.2	14.3 ± 1.1	16.7 ± 4.1

- After efficiency/acceptance corrections

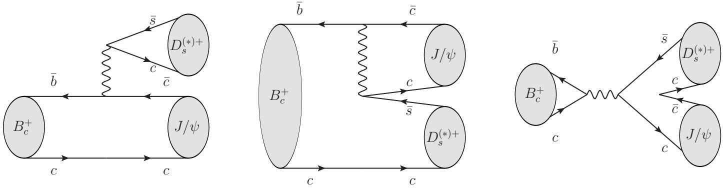
$$\frac{\Gamma(\Lambda_b^0 \to \psi(2S)\Lambda^0)}{\Gamma(\Lambda_b^0 \to J/\psi \Lambda^0)} = 0.501 \pm 0.033\,(\text{stat.}) \pm 0.016\,(\text{syst.}) \pm 0.011(\mathcal{B})$$

- Largest systematics sources:
  - Signal extraction
  - $\mathcal{B}(J/\psi \to \mu^+\mu^-)$ and $\mathcal{B}(\psi(2S) \to e^+e^-)$
- The ratio *within the range 0.5–0.8 for analogous B meson decays*
- The only available prediction – *covariant quark quark model:* 0.8 ± 0.1 *is higher than data*

Study of $B_c^+ \to J/\psi D_s^{(*)+}$ decays

Motivation

- B_c^+ is the only weakly decaying particle consisted of two heavy quarks
- Decays with charmonia and $D_s^{(*)+}$ represent $\bar{b} \to \bar{c}c\bar{s}$ transition in B_c^+ sector
  - Can go through annihilation diagram (suppressed for lighter B mesons)



Spectator **Colour-suppressed spectator** **Annihilation**

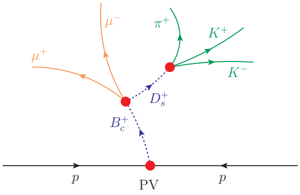
- Various model predictions available: *branching ratios*, *polarization*
- Earlier observed only in LHCb (PRD 87 (2013) 112012)

- ATLAS studied these decays with full Run-1 data of 25 fb^{-1}

Analysis in a nutshell

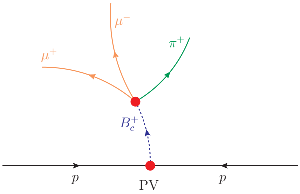
Signal channels: $B_c^+ \to J/\psi D_s^{(*)+}$

- Intermediate resonances via $J/\psi \to \mu^+\mu^-$ and $D_s^+ \to \phi(K^+K^-)\pi^+$
- Two distinct vertices of B_c^+ and D_s^+ decays
- *Mass constraints for J/ψ and D_s^+* in cascade fit
- $D_s^{*+} \to D_s^+\gamma/\pi^0$, neutral particle escapes detection



Reference channel: $B_c^+ \to J/\psi\pi^+$

- Measures ratios are
  $\mathcal{R}_{D_s^+/\pi^+} = \mathcal{B}(B_c^+ \to J/\psi D_s^+)/\mathcal{B}(B_c^+ \to J/\psi\pi^+)$,
  $\mathcal{R}_{D_s^{*+}/\pi^+} = \mathcal{B}(B_c^+ \to J/\psi D_s^{*+})/\mathcal{B}(B_c^+ \to J/\psi\pi^+)$,
  $\mathcal{R}_{D_s^{*+}/D_s^+} = \mathcal{B}(B_c^+ \to J/\psi D_s^{*+})/\mathcal{B}(B_c^+ \to J/\psi D_s^+)$



Polarization in $B_c^+ \to J/\psi D_s^{*+}$ decay

- Pseudoscalar B_c^+ decays into two vectors $\to$ *3 helicity amplitudes* A_{00}, A_{++}, A_{--}
- Longitudinally A_{00} and transversely $A_{\pm\pm}$ polarized components – different kinematics: $J/\psi D_s^+$ mass shape and J/ψ helicity angle
- Are distinguished by fit of these variables $\to$ measure $\Gamma_{\pm\pm}/\Gamma$

Selection and fit

Combinatorial background suppression

- Cascade fit quality and vertices displacement ($L_{xy}(B_c^+)$ and $L_{xy}(D_s^+)$)
- Decay kinematics, intermediate resonance mass windows (J/ψ, D_s^+, ϕ)
- Decay angular properties

$B_s^0 \to J/\psi\phi$ background

- Explicit $J/\psi\phi$ mass veto

2D extended unbinned ML fit of $m(J/\psi D_s^+)$ and $|\cos\theta'(\mu^+)|$ distributions

- Helicity angle $\theta'(\mu^+)$ is the angle between μ^+ and D_s^+ momenta in the J/ψ rest frame

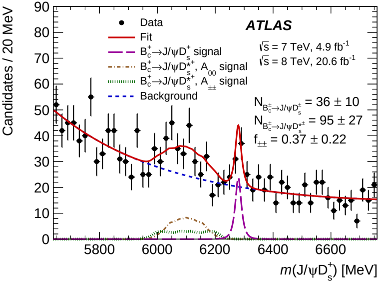
Mass part

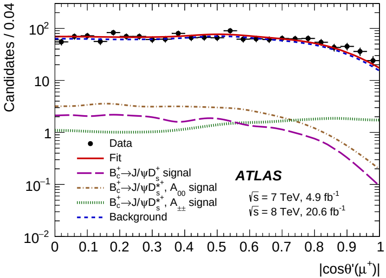
- $B_c^+ \to J/\psi D_s^+$ *signal:* modified Gaussian function
- $B_c^+ \to J/\psi D_s^{*+}$ A_{00} *and* $A_{\pm\pm}$ *signals:* templates from MC
- *Background:* quadratic exponential

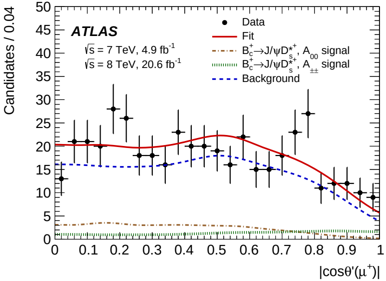
Angular part

- *Singals:* MC templates to account for detector effects
- *Background:* templates from $m(J/\psi D_s^+)$ sidebands

$B_c^+ \to J/\psi D_s^{(*)+}$ signal

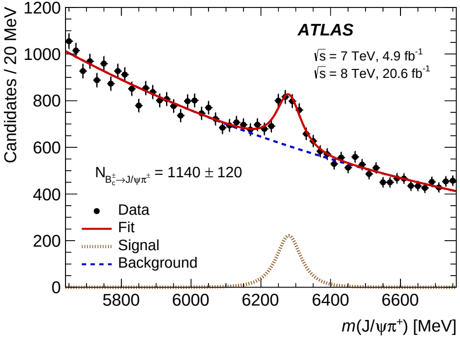






- Signal yields agree with 1D mass fit
- Fit correctness checked with toy MC studies
  - 2D fit is much more sensitive to $f_{\pm\pm}$ than 1D
- Statistical significance of the two signals: 4.9σ

Reference channel $B_c^+ \to J/\psi\pi^+$



- Selection as close as possible to the signal mode
- Veto π^+ candidates identified as muons to suppress $B_c^+ \to J/\psi\mu^+\nu_\mu$

$B_c^+ \to J/\psi\pi^+$ fit

1D extended unbinned ML fit

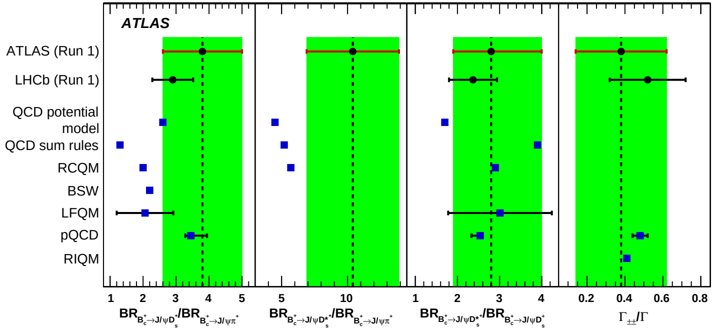
- *Background:* exponential
- *Signal:* modified Gaussian

- For $\mathcal{B}$ ratio measurement, the B_c^+ kinematic region used:
  - $p_{\mathrm{T}}(B_c^+) > 15$ GeV
  - $|\eta(B_c^+)| < 2.0$

Results

- $\mathcal{R}_{D_s^+/\pi^+} = \frac{\mathcal{B}_{B_c^+ \to J/\psi D_s^+}}{\mathcal{B}_{B_c^+ \to J/\psi \pi^+}} = 3.8 \pm 1.1\ (\text{stat.}) \pm 0.4\ (\text{syst.}) \pm 0.2\ (\text{BF})$
- $\mathcal{R}_{D_s^{*+}/\pi^+} = \frac{\mathcal{B}_{B_c^+ \to J/\psi D_s^{*+}}}{\mathcal{B}_{B_c^+ \to J/\psi \pi^+}} = 10.4 \pm 3.1\ (\text{stat.}) \pm 1.5\ (\text{syst.}) \pm 0.6\ (\text{BF})$
- $\mathcal{R}_{D_s^{*+}/D_s^+} = \frac{\mathcal{B}_{B_c^+ \to J/\psi D_s^{*+}}}{\mathcal{B}_{B_c^+ \to J/\psi D_s^+}} = 2.8^{+1.2}_{-0.8}\ (\text{stat.}) \pm 0.3\ (\text{syst.})$
- $\Gamma_{\pm\pm}/\Gamma = 0.38 \pm 0.23\ (\text{stat.}) \pm 0.07\ (\text{syst.})$

Dominant systematics contribution from the fit model uncertainties



Conclusion

- Three heavy hadron decay analyses performed by ATLAS were presented:
  - α_b and helicity amplitudes in $\Lambda_b^0 \to J/\psi \Lambda^0$ measurement *(7 TeV)*
  - First observation and measurement of $\Lambda_b^0 \to \psi(2S)\Lambda^0$ *(8 TeV)*
  - Study of $B_c^+ \to J/\psi D_s^{(*)+}$ decays *(7 TeV + 8 TeV)*
- Potential of Run 1 data is still not fully exploited
- Many new interesting results expected with 13 TeV data!

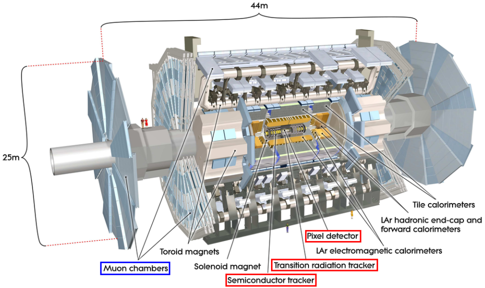
Backup slides

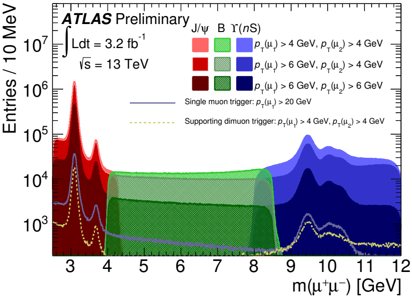
ATLAS detector and trigger system

- Tracking **Inner Detector** in 2 T solenoid field
- **Muon system** put inside a toroid
- ATLAS **trigger system**: hardware *Level-1 trigger* and 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





J/ψ and D_s^+ signals in $B_c^+ \to J/\psi D_s^{(*)+}$ decays