Spectroscopy and decay properties of b-hadrons with the ATLAS experiment

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on behalf of the ATLAS Collaboration

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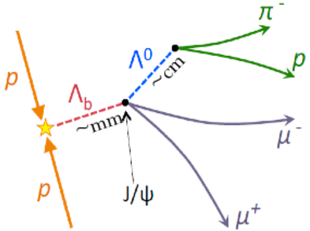
Introduction

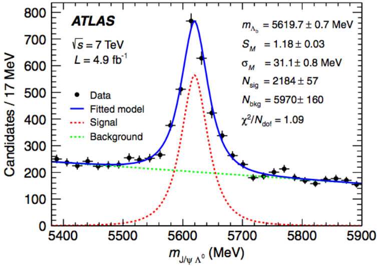
- the various QCD models differ in the predictions on observables related to hadrons containing heavy quarks (like mass, lifetime, spin, ...)
- several aspects of weak decays SM expectations are waiting confirmation from experiments
- hadronic spectroscopy provides the possibility to test heavy quarks interaction models
- the observation of new particles or new decay channels allows to further constraint the present theoretical framework
- selection of related topics discussed today:
  - **Measurement of the Λ_0^b lifetime and mass** (Phys. Rev. D 87, 032002 (2013))
  - **Measurement of the parity-violating asymmetry parameter α_b and the helicity amplitudes for the decay $\Lambda_0^b \to J/\psi\Lambda^0$ with the ATLAS detector** (Phys. Rev. D 89 (2014) 092009)
  - **Flavour tagged time dependent angular analysis of the $B_s^0 \to J/\psi\phi$ decay and extraction of $\Delta\Gamma_s$ and the weak phase ϕ_s in ATLAS** (ATLAS-CONF-2013-039)
  - **Observation of a new χ_b state in radiative transitions to $\Upsilon(1S)$ and $\Upsilon(2S)$** (Phys. Rev. Lett. 108, 152001 (2012))

Λ_b^0 mass and lifetime measurement

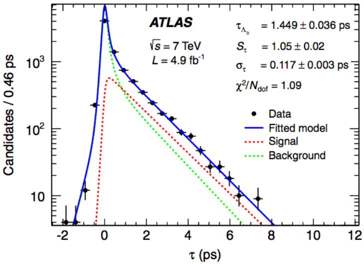


- Λ_b^0 baryon is the lightest baryon containing a b quark (5620 MeV), and is not produced at B factories $\Rightarrow$ currently hadron colliders are the only facilities to study b-baryons properties
- Λ_b^0 reconstructed through the decay $\Lambda_b^0 \to J/\psi(\to \mu^+\mu^-)\Lambda^0(\to p\pi^-)$
- analysis made with 4.9 fb^{-1} of data collected in 2011 at $\sqrt{s} = 7$ TeV using a topological J/ψ trigger chain
- simultaneous fit of the four final state tracks, with topological constraints
- each candidate must fulfill the selection:
  - global $\chi^2/n_{dof} < 3$
  - $p_{T,\Lambda^0} > 3.5$ GeV
  - $L_{xy,\Lambda^0} > 10$ mm
  - 5.38 GeV $< m_{J/\psi\Lambda^0} <$ 5.90 GeV

Λ_b^0 mass and lifetime measurement



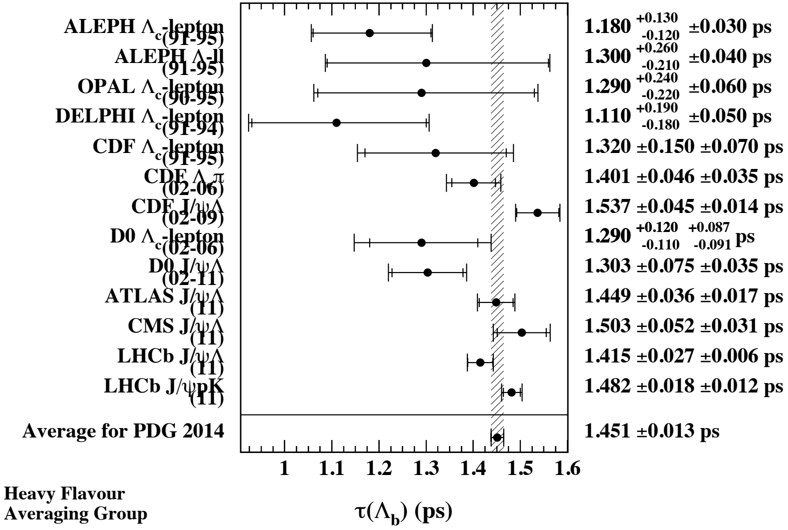
Phys. Rev. D 87, 032002 (2013)



Phys. Rev. D 87, 032002 (2013)

- for mass fit, background described with a first order polynomial, signal with a Gaussian
- for lifetime fit, signal and non-prompt background modeled as exponential functions, prompt background modeled as sum of a Dirac δ function and a symmetric exponential distribution (for non-Gaussian tails)
- unbinned maximum likelihood mass/lifetime fit: $m = 5619.7 \pm 0.7(stat) \pm 1.1(syst)$ MeV $\tau = 1.449 \pm 0.036(stat) \pm 0.017(syst)$ ps
- CMS: $\tau = 1.503 \pm 0.052(stat) \pm 0.031(syst)$ ps (JHEP 07 (2013) 163)
- LHCb: $\tau = 1.482 \pm 0.018(stat) \pm 0.012(syst)$ ps (Phys. Rev. Lett. 111, 102003)
- LHCb: $\tau = 1.415 \pm 0.027(stat) \pm 0.006(syst)$ ps (JHEP 04 (2014) 114)

Λ_b^0 mass and lifetime measurement



Λ_b^0 parity violating asymmetry parameter

- parity violation is a well-known feature of weak interactions
- in hadrons weak decays it is not maximal and depends on the hadron's constituents (e.g. for $\Lambda_0 \to p\pi^-$ parity violating decays asymmetry parameter $\alpha_\Lambda \approx 0.6$)
- strong interaction effects in hadron decays are non-perturbative, making it difficult to predict α values for light hadrons
- for heavy baryons (like Λ_b^0) the energy release in the b-quark decay is large enough and theoretical predictions are possible
- pQCD predicts α_b to be in the range from -0.17 to -0.14, while calculations based on HQET predicts a value of ~ 0.78
- LHCb measured $\alpha_b = 0.05 \pm 0.17(stat) \pm 0.07(syst)$ (Phys. Lett. B 724 (2013) 27)
- ATLAS measured α_b with comparable precision using 4.6 fb^{-1} of 2011 data

Λ_b^0 parity violating asymmetry parameter

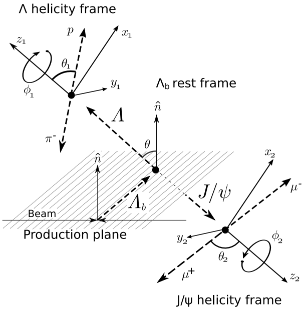
- decay described by 4 helicity amplitudes $A(\lambda_\Lambda, \lambda_{J/\psi})$, normalized to 1:

$$a_+ = (1/2, 0) \quad a_- = (-1/2, 0)$$
$$b_+ = (-1/2, -1) \quad b_- = (1/2, 1)$$

- dynamics described by the angles: $\Omega = (\theta, \phi, \theta_1, \phi_1, \theta_2, \phi_2)$
- full angular PDF of the decay angles Ω:

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

  - $f_{1i}(\vec{A})$: bilinear combination of helicity amplitudes
  - $f_{2i}(P, \alpha_\Lambda) \equiv P\alpha_\Lambda, P, \alpha_\Lambda$ or 1
  - $F_i(\Omega)$: orthogonal functions of decay angles



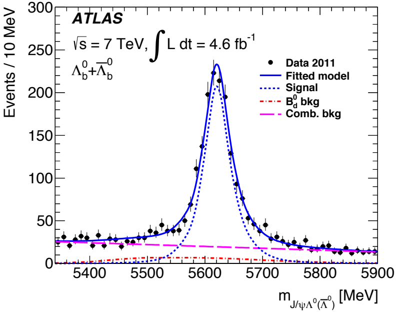
Phys. Rev. D 89 (2014) 092009

- parity violating decay asymmetry parameter: $\alpha_b = |a_+|^2 - |a_-|^2 + |b_+|^2 - |b_-|^2$
- analysis extracts α_b and helicity amplitudes from measured averages of each F_i:

$$\langle F_i \rangle = \frac{1}{N^{data}} \sum_{n=1}^{N^{data}} F_i(\Omega_n)$$

Λ_b^0 parity violating asymmetry parameter

Sample selection and fit



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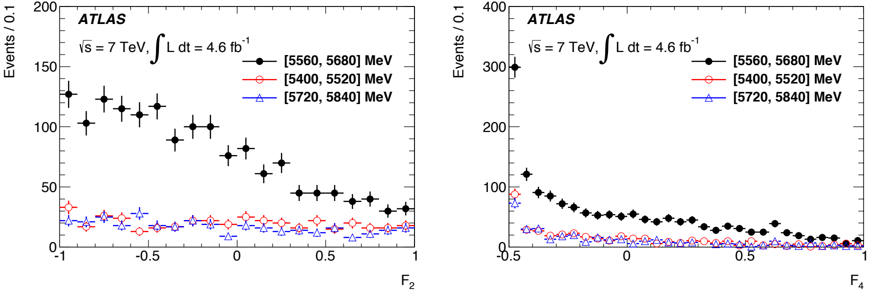
- Λ_b^0 selection similar as for mass and lifetime analysis (plus few specific requirements)
- α_b and helicity amplitudes extracted through a χ^2 fit to the measured $\langle F_i \rangle$:

$$\chi^2 = \sum_{i=1}^{5} \sum_{j=1}^{5} (\langle F_i \rangle^{exp} - \langle F_i \rangle) V_{ij}^{-1} (\langle F_j \rangle^{exp} - \langle F_j \rangle)$$

where V_{ij} is the covariance matrix of measured $\langle F_i \rangle$, and $\langle F_i \rangle^{exp}$ is evaluated from models including detector effects and depends on the helicity amplitudes

Λ_b^0 parity violating asymmetry parameter

Background subtraction



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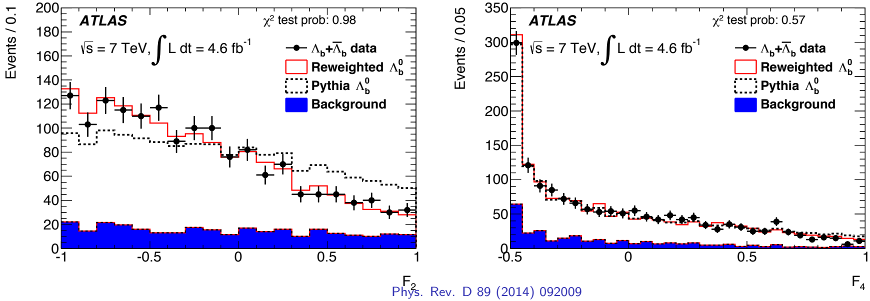
- the background contribution to the $\langle F_i \rangle$ values in the signal region can be estimated as an average of the values in the two sidebands and subtracted from the measured $\langle F_i \rangle$
- as a check, the F_i distributions of the two sidebands are compared and found to be in agreement

Λ_b^0 parity violating asymmetry parameter

Check of fit results



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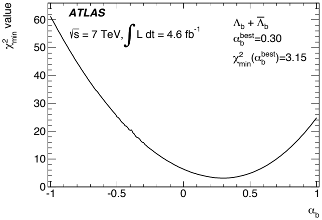
- fit results are checked by comparing F_i distributions for data with weighted signal MC plus sideband background
- MC events weighted with signal PDF and parameters from the fit, and normalized to the number of events of sideband-subtracted data
- agreement between data and simulation

Λ_b^0 parity violating asymmetry parameter

Fit results

- fit results:

$$\alpha_b = 0.30 \pm 0.16(stat) \pm 0.06(syst)$$
$$|a_+| = 0.17^{+0.12}_{-0.17}(stat) \pm 0.09(syst)$$
$$|a_-| = 0.59^{+0.06}_{-0.07}(stat) \pm 0.03(syst)$$
$$|b_+| = 0.79^{+0.04}_{-0.05}(stat) \pm 0.02(syst)$$
$$|b_-| = 0.08^{+0.13}_{-0.08}(stat) \pm 0.06(syst)$$



Phys. Rev. D 89 (2014) 092009

- Λ^0 and J/ψ from Λ_b^0 decay are highly polarized in the direction of their momenta
- large $|a_-|$ and $|b_+|$ $\Rightarrow$ negative helicity states for Λ^0 are preferred
- α_b value consistent with LHCb measurement: $0.05 \pm 0.17(stat) \pm 0.07(syst)$ (Phys. Lett. B 724 (2013) 27)
- intermediate between pQCD and HQET predictions:
  - $\sim 2.6\sigma$ difference w.r.t. pQCD ($-(0.14 - 0.17)$)
  - $\sim 2.8\sigma$ difference w.r.t. HQET (0.78)
- more accurate measurements will follow with 2012 data (~ 20 fb^{-1})

$B_s^0 \to J/\psi\phi$ angular analysis

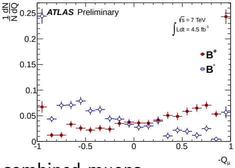
- $B_s^0 \to J/\psi\phi$ decay parameters measured with 4.9 fb^{-1} of 2011 data $\to$ channel expected to be sensitive to new physics
- CP violation in interference between direct decays and decays occurring through $B_s^0 - \overline{B_s^0}$ mixing
- an angular analysis of the decay products is needed to decompose the decay into CP-odd and CP-even components
- decay parameters:
  - $\Gamma_s, \Delta\Gamma_s$: average width and width difference of the two B_s mass eigenstates B_L and B_H
  - ϕ_s: phase arising from CP-violation
  - $|A_\perp|, |A_\parallel|, |A_0|$: CP eigenstate amplitudes of which the final state is an admixture
  - $\delta_\perp, \delta_\parallel, \delta_0$: corresponding phases
  - $|A_s|, \delta_s$: S-wave components
- analysis makes use of flavour tagging to determine the initial B-meson flavour and improve ϕ_s sensitivity (this is inserted in the fit as a probability for $B_s - \overline{B_s}$)

$B_s^0 \to J/\psi\phi$ angular analysis

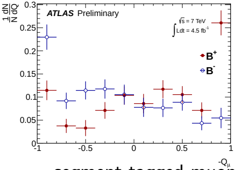
Flavour tagging

- initial flavour of neutral B-meson can be inferred by information from the other B-meson of the event (Opposite-Side Tagging) $\to$ studied and calibrated on $B^\pm \to J/\psi K^\pm$ sample, where flavour of the B-meson is provided by the kaon
- *muon cone charge* tagger: $\Delta R < 0.5$ cone around muon track
- *jet charge* tagger: b-tagged jet in absence of a muon

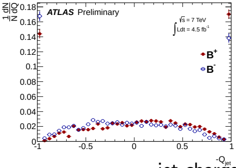
$$Q = \frac{\sum_i^{N_{trk}} q_i \cdot (p_T^i)^k}{\sum_i^{N_{trk}} (p_T^i)^k}$$



combined muons



segment tagged muons



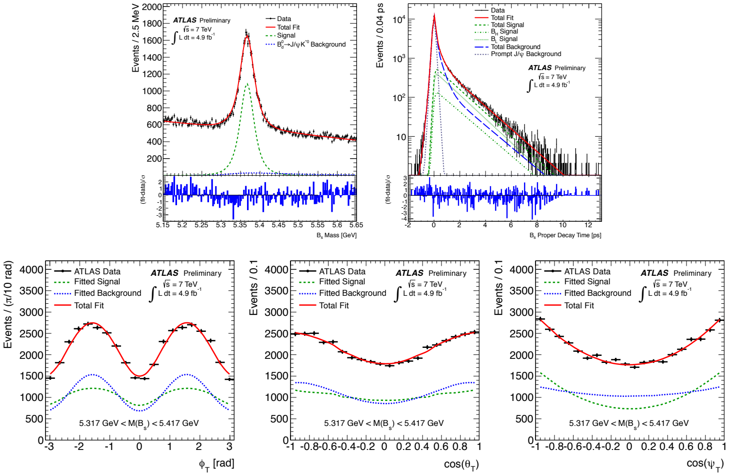
jet charge

Tagger	Efficiency [%]	Dilution [%]	Tagging Power [%]
Segment Tagged muon	1.08 ± 0.02	36.7 ± 0.7	0.15 ± 0.02
Combined muon	3.37 ± 0.04	50.6 ± 0.5	0.86 ± 0.04
Jet charge	27.7 ± 0.1	12.68 ± 0.06	0.45 ± 0.03
Total	32.1 ± 0.1	21.3 ± 0.08	1.45 ± 0.05

$B_s^0 \to J/\psi\phi$ angular analysis

Fit results

- unbinned maximum likelihood simultaneous fit to mass, proper-time, tag probability, transverse angles



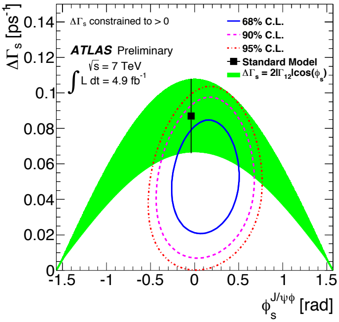
ATLAS-CONF-2013-039

$B_s^0 \to J/\psi\phi$ angular analysis

Fit results

- uncertainty of ϕ_s improved by 40% compared to untagged analysis
- likelihood contour in the $\phi_s - \Delta\Gamma_s$ plane shows agreement with SM prediction
- measured values:

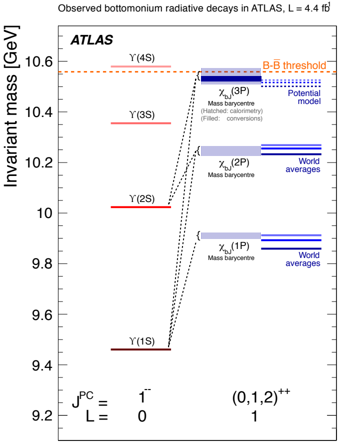
$$\phi_s = 0.12 \pm 0.25(stat) \pm 0.11(syst) rad$$
$$\Delta\Gamma_s = 0.053 \pm 0.021(stat) \pm 0.009(syst)\ \text{pb}^{-1}$$
$$\Gamma_s = 0.677 \pm 0.007(stat) \pm 0.003(syst)\ \text{pb}^{-1}$$
$$|A_0(0)|^2 = 0.529 \pm 0.006(stat) \pm 0.011(syst)$$
$$|A_{\|}(0)|^2 = 0.220 \pm 0.008(stat) \pm 0.009(syst)$$
$$\delta_\perp = 3.89 \pm 0.46(stat) \pm 0.13(syst)\ \text{rad}$$



ATLAS-CONF-2013-039

Observation of $\chi_b(3P)$ state

- heavy quarkonia states provide a insight into the nature of QCD close to strong decay threshold
- ATLAS studied χ_b quarkonia states through the radiative decay modes $\chi_b(nP) \to \Upsilon(1S, 2S)(\to \mu^+\mu^-)\gamma$
- $\chi_b(1P)$ (9.90 GeV) and $\chi_b(2P)$ (10.26 GeV) observed by previous experiments
- $\chi_b(3P)$ never observed, but predicted to have a mass around 10.52 GeV
- data sample recorded during 2011 p-p collisions at $\sqrt{s} = 7$ TeV, corresponding to 4.4 fb^{-1}, and collected with muon triggers

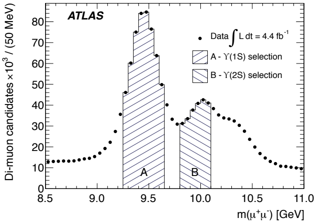


Phys. Rev. Lett. 108, 152001 (2012)

Observation of $\chi_b(3P)$ state

Selection of the sample

- high quality muons with $p_T > 4$ GeV and $|\eta| < 2.3$
- oppositely charged muon pairs fitted to a common vertex (loose vertex requirement $\chi^2/n_{dof} < 20$), no mass or momentum constraint
- dimuon candidate must have $p_T > 12$ GeV and $|y| < 2.0$
- dimuon candidates are selected as $\Upsilon(1S)$ if $9.25 < m_{\mu\mu} < 9.64$ GeV, as $\Upsilon(2S)$ if $9.80 < m_{\mu\mu} < 10.10$ GeV (asymmetric mass window to reduce contamination from $\Upsilon(3S)$)
- converted (unconverted) photons are required to be within $|\eta| < 2.30$ (2.37)
- χ_b candidates reconstructed by associating a candidate Υ with a photon



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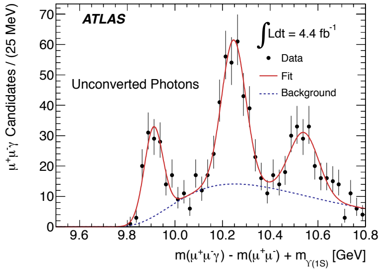
Observation of $\chi_b(3P)$ state



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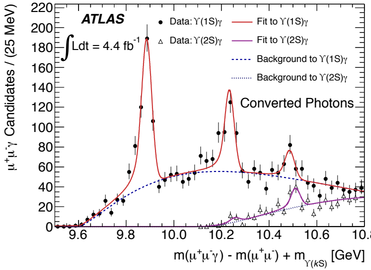


Phys. Rev. Lett. 108, 152001 (2012)

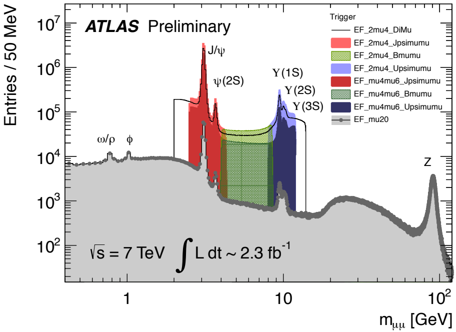
- to minimize the effect of Υ resolution and compare both $\Upsilon(1S)\gamma$ and $\Upsilon(2S)\gamma$ decays, signal is studied as $\Delta m = m(\mu^+\mu^-\gamma) - m(\mu^+\mu^-) + m_{\Upsilon(kS)}$
- structures observed and interpreted as $\chi_b(3P)$ states
- $\chi_b(3P) \to \Upsilon(1S)\gamma$ observed for both converted and uncoverted photons, $\chi_b(3P) \to \Upsilon(2S)\gamma$ only for converted photons due to the higher threshold of unconverted photons
- fitted mass value: $m_{\chi_b(3P)} = 10.530 \pm 0.005(stat) \pm 0.009(syst) GeV$
- observation confirmed by LHCb and D0, with fitted mass values in agreement:
  - LHCb: $m_{\chi_b(3P)} = 10.535 \pm 0.010(stat)$ GeV (LHCb-CONF-2012-020)
  - D0: $m_{\chi_b(3P)} = 10.551 \pm 0.014(stat) \pm 0.017(syst)$ GeV (arXiv:1203.6034)

Conclusions

- heavy quark hadrons spectroscopy measurements proceed vigorously in ATLAS
- Λ_b^0 mass and lifetime measurement in agreement with other experiment
- Λ_b^0 parity violation parameter in agreement with LHCb but in disagreement with theoretical predictions $\Rightarrow$ need updated analysis with 2012 data
- measurement of ϕ_s and $\Delta\Gamma_s$ in $B_s^0 \to J/\psi\phi$, in agreement with SM expectations
- observation of a new $\chi_b(3P)$ state, subsequently confirmed by LHCb and D0 (ATLAS measurement is still the most precise)
- this talk covers only few selected topics, in general much effort is ongoing studying heavy flavour baryons, charmonium and bottomonium states
- much more results on ATLAS flavour physics available in the public results page

Backup slides

Trigger for heavy quark hadron physics



- trigger is a key ingredient for ATLAS physics program, to reduce the huge collision data flow from $\sim$ 40 MHz to $\sim$ 500 Hz
- most of the final states coming from heavy quark hadron decays contain muons (mainly from J/ψ, Υ or semileptonic decays)
- main triggers in ATLAS:
  - single and di-muon
  - topological triggers for $J/\psi, \Upsilon, B_s, \ldots$: specific invariant mass region or vertex requirements

Λ_b^0 parity violating asymmetry parameter

Table 1: The coefficients f_{1i}, f_{2i} and F_i of the probability density function in Eqn. 2 [7].

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	$-3Re(a_+a_-^*)$	$P\alpha_\Lambda$	$\sin\theta\sin\theta_1\sin^2\theta_2\cos\varphi_1$
9	$3Im(a_+a_-^*)$	$P\alpha_\Lambda$	$\sin\theta\sin\theta_1\sin^2\theta_2\sin\varphi_1$
10	$-\frac{3}{2}Re(b_-b_+^*)$	$P\alpha_\Lambda$	$\sin\theta\sin\theta_1\sin^2\theta_2\cos(\varphi_1 + 2\varphi_2)$
11	$\frac{3}{2}Im(b_-b_+^*)$	$P\alpha_\Lambda$	$\sin\theta\sin\theta_1\sin^2\theta_2\sin(\varphi_1 + 2\varphi_2)$
12	$-\frac{3}{\sqrt{2}}Re(b_-a_+^* + a_-b_+^*)$	$P\alpha_\Lambda$	$\sin\theta\cos\theta_1\sin\theta_2\cos\theta_2\cos\varphi_2$
13	$\frac{3}{\sqrt{2}}Im(b_-a_+^* + a_-b_+^*)$	$P\alpha_\Lambda$	$\sin\theta\cos\theta_1\sin\theta_2\cos\theta_2\sin\varphi_2$
14	$-\frac{3}{\sqrt{2}}Re(b_-a_-^* + a_+b_+^*)$	$P\alpha_\Lambda$	$\cos\theta\sin\theta_1\sin\theta_2\cos\theta_2\cos(\varphi_1 + \varphi_2)$
15	$\frac{3}{\sqrt{2}}Im(b_-a_-^* + a_+b_+^*)$	$P\alpha_\Lambda$	$\cos\theta\sin\theta_1\sin\theta_2\cos\theta_2\sin(\varphi_1 + \varphi_2)$
16	$\frac{3}{\sqrt{2}}Re(a_-b_+^* - b_-a_+^*)$	P	$\sin\theta\sin\theta_2\cos\theta_2\cos\varphi_2$
17	$-\frac{3}{\sqrt{2}}Im(a_-b_+^* - b_-a_+^*)$	P	$\sin\theta\sin\theta_2\cos\theta_2\sin\varphi_2$
18	$\frac{3}{\sqrt{2}}Re(b_-a_-^* - a_+b_+^*)$	α_Λ	$\sin\theta_1\sin\theta_2\cos\theta_2\cos(\varphi_1 + \varphi_2)$
19	$-\frac{3}{\sqrt{2}}Im(b_-a_-^* - a_+b_+^*)$	α_Λ	$\sin\theta_1\sin\theta_2\cos\theta_2\sin(\varphi_1 + \varphi_2)$

Λ_b^0 parity violating asymmetry parameter

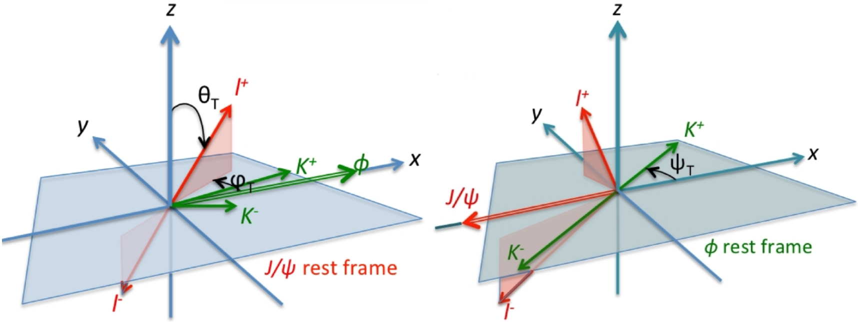
Systematic uncertainties

TABLE VI. Systematic uncertainties.

Source	α_b	k_+	k_-	$\lvert a_+\rvert$	$\lvert a_-\rvert$	$\lvert b_+\rvert$	$\lvert b_-\rvert$
Background shape	0.034	0.020	0.042	0.018	0.017	0.010	0.024
B_d^0 background	0.011	0.085	0.061	0.069	0.008	0.008	0.036
Angles resolution	0.005	0.017	0.026	0.014	0.004	0.002	0.015
MC mass resolution modeling	0.020	0.004	0.004	0.002	0.008	0.007	0.002
MC kin. weighting (MC parametrization)	0.007	0.010	0.008	0.008	0.007	0.002	0.005
MC kin. weighting (data sample size)	0.011	0.017	0.014	0.014	0.005	0.003	0.008
MC sample size	0.047	0.090	0.121	0.039	0.016	0.013	0.037
Value of α_Λ	0.009	0.023	0.023	0.019	0.005	0.001	0.014
Total	0.064	0.130	0.147	0.086	0.028	0.020	0.061

$B_s^0 \to J/\psi\phi$ angular analysis

Transversity angles



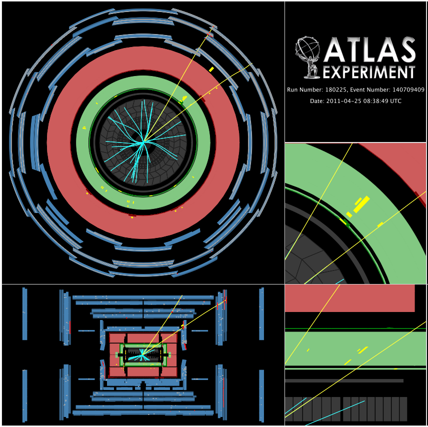
$B_s^0 \to J/\psi\phi$ angular analysis

Systematic uncertainties

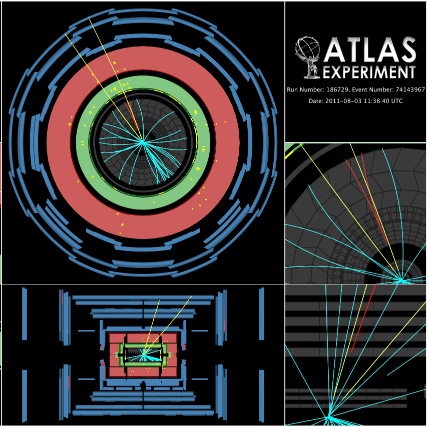
	ϕ_s (rad)	$\Delta\Gamma_s$ (ps^{-1})	Γ_s (ps^{-1})	$\lvert A_\parallel(0)\rvert^2$	$\lvert A_0(0)\rvert^2$	$\lvert A_S(0)\rvert^2$	$\delta_\perp$ (rad)	$\delta_\parallel$ (rad)	$\delta_\perp - \delta_S$ (rad)
ID alignment	$<10^{-2}$	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	-	$<10^{-2}$	$<10^{-2}$	-
Trigger efficiency	$<10^{-2}$	$<10^{-3}$	0.002	$<10^{-3}$	$<10^{-3}$	$< 10^{-3}$	$<10^{-2}$	$<10^{-2}$	$<10^{-2}$
B_d^0 contribution	0.03	0.001	$<10^{-3}$	$<10^{-3}$	0.005	0.001	0.02	$<10^{-2}$	$<10^{-2}$
Tagging	0.10	0.001	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	0.002	0.05	$<10^{-2}$	$<10^{-2}$
Models:									
default fit	$<10^{-2}$	0.002	$<10^{-3}$	0.003	0.002	0.006	0.07	0.01	0.01
signal mass	$<10^{-2}$	0.001	$<10^{-3}$	$<10^{-3}$	0.001	$<10^{-3}$	0.03	0.04	0.01
background mass	$<10^{-2}$	0.001	0.001	$<10^{-3}$	$<10^{-3}$	0.002	0.06	0.02	0.02
resolution	0.02	$<10^{-3}$	0.001	0.001	$<10^{-3}$	0.002	0.04	0.02	0.01
background time	0.01	0.001	$<10^{-3}$	0.001	$<10^{-3}$	0.002	0.01	0.02	0.02
background angles	0.02	0.008	0.002	0.008	0.009	0.027	0.06	0.07	0.03
Total	0.11	0.009	0.003	0.009	0.011	0.028	0.13	0.09	0.04

Observation of a new χ_b state

Event displays



uncoverted photon



converted photon

Observation of $\chi_b(3P)$ state