Beauty baryons in ATLAS

Maria Smizanska
on behalf of the ATLAS collaboration

Lancaster University

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Outline

- Production polarisation of Λ_b^0 and Parity-violating asymmetry parameter and the helicity amplitudes in $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$
  Phys. Rev. D 89, 092009, May 2014
- Measurement of Λ_b^0 lifetime
  PhysRevD.87.032002, 2013
- J/ψ p resonances in the $\Lambda_b^0 \rightarrow J/\psi K^-$
  ATLAS-CONF-2019-48
- Summary and outlook

Parity-violating asymmetry parameter, Polarisation and helicity amplitudes in $\Lambda_b^0 \to J/\psi \Lambda^0$

Phys. Rev. D 89, 092009, May 2014

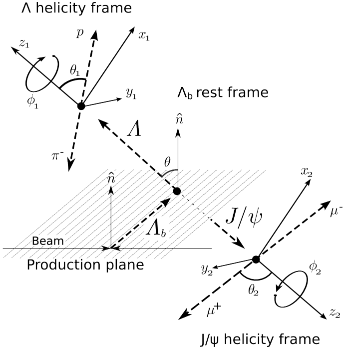
Physics motivation

- Production polarisation: in the symmetric p-p collisions hyperons are produced with spin perpendicular to the production plane. A Polarisation means an asymmetry between probabilities of spin oriented up versus down. Λ_b^0 production polarisation in ATLAS been measured using the decay $\Lambda_b^0 \to J/\psi \Lambda^0$. In the central p-p collisions covered by ATLAS detector this polarisation is expected to be larger than in forward oriented LHCb. So measuring it in ATLAS is a synergy between LHC experiments.
- Another property of hyperons is a parity violation, some of them exhibit in their decays. For example, $\Lambda \to p\pi$ has an asymmetry parameter of over 60%.
- $\Lambda_b^0 \to J/\psi \Lambda^0$ Decay Probability depends on production polarisation P and 4 helicity amplitudes $\mathrm{a}_+ \equiv$ A(1/2, 0), $\mathrm{a}_- \equiv$ A(-1/2, 0), $\mathrm{b}_+ \equiv$ A(-1/2,1) and $\mathrm{b}_+ \equiv$ A(1/2, -1), where 1/2 and 1 are spin projections of Λ and J/ψ. The parity violating parameter is defined as: $\alpha_b \equiv |\mathrm{a}_+|^2 - |\mathrm{a}_-|^2 + |\mathrm{b}_+|^2 - |\mathrm{b}_-|^2$

- $\Lambda_b^0 \to J/\psi\Lambda^0$ Decay Probability contain 20 terms, shown in figure, left. To extract all physics parameters in the PDF, the 5 angles are used, shown in Fig right.

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	$-3Re(a_+a_-^*)$	$P\alpha_\Lambda$	$\sin\theta\sin\theta_1\sin^2\theta_2\cos\phi_1$
9	$3Im(a_+a_-^*)$	$P\alpha_\Lambda$	$\sin\theta\sin\theta_1\sin^2\theta_2\sin\phi_1$
10	$-\frac{3}{2}Re(b_-b_+^*)$	$P\alpha_\Lambda$	$\sin\theta\sin\theta_1\sin^2\theta_2\cos(\phi_1 + 2\phi_2)$
11	$\frac{3}{2}Im(b_-b_+^*)$	$P\alpha_\Lambda$	$\sin\theta\sin\theta_1\sin^2\theta_2\sin(\phi_1 + 2\phi_2)$
12	$-\frac{3}{\sqrt{2}}Re(b_-a_+^* + a_-b_+^*)$	$P\alpha_\Lambda$	$\sin\theta\cos\theta_1\sin\theta_2\cos\theta_2\cos\phi_2$
13	$\frac{3}{\sqrt{2}}Im(b_-a_+^* + a_-b_+^*)$	$P\alpha_\Lambda$	$\sin\theta\cos\theta_1\sin\theta_2\cos\theta_2\sin\phi_2$
14	$-\frac{3}{\sqrt{2}}Re(b_-a_-^* + a_+b_+^*)$	$P\alpha_\Lambda$	$\cos\theta\sin\theta_1\sin\theta_2\cos\theta_2\cos(\phi_1 + \phi_2)$
15	$\frac{3}{\sqrt{2}}Im(b_-a_-^* + a_+b_+^*)$	$P\alpha_\Lambda$	$\cos\theta\sin\theta_1\sin\theta_2\cos\theta_2\sin(\phi_1 + \phi_2)$
16	$\frac{3}{\sqrt{2}}Re(a_-b_+^* - b_-a_+^*)$	P	$\sin\theta\sin\theta_2\cos\theta_2\cos\phi_2$
17	$-\frac{3}{\sqrt{2}}Im(a_-b_+^* - b_-a_+^*)$	P	$\sin\theta\sin\theta_2\cos\theta_2\sin\phi_2$
18	$\frac{3}{\sqrt{2}}Re(b_-a_-^* - a_+b_+^*)$	α_Λ	$\sin\theta_1\sin\theta_2\cos\theta_2\cos(\phi_1 + \phi_2)$
19	$-\frac{3}{\sqrt{2}}Im(b_-a_-^* - a_+b_+^*)$	α_Λ	$\sin\theta_1\sin\theta_2\cos\theta_2\sin(\phi_1 + \phi_2)$

Helicity studies using 5 angles



- Supposing production polarisation is P=0, leaves only 5 out of 20 terms of PDF.
- The Parity-violating asymmetry parameter α_b and 4 helicity amplitudes were measured for Λ_b^0, for anti Λ_b^0 and for the combination of both, combining Λ_b^0 and anti-Λ_b^0 samples, under the assumption of CP conservation.

- both Λ_b^0 anti Λ_b^0
- $\alpha_b = 0.28 \pm 0.16 \pm \pm 0.06$

$|a_+| = 0.17^{+0.12}_{-0.17}(\text{stat}) \pm 0.09(\text{syst})$

$|a_-| = 0.59^{+0.06}_{-0.07}(\text{stat}) \pm 0.03(\text{syst})$

$|b_+| = 0.79^{+0.04}_{-0.05}(\text{stat}) \pm 0.02(\text{syst})$

$|b_-| = 0.08^{+0.13}_{-0.08}(\text{stat}) \pm 0.06(\text{syst})$

- Λ_b^0
- $\alpha_b = 0.24 \pm 0.22 \pm 0.28$

$|a_+| = 0.26^{+0.11}_{-0.26}(\text{stat})$

$|a_-| = 0.60^{+0.08}_{-0.09}(\text{stat})$

$|b_+| = 0.75^{+0.06}_{-0.07}(\text{stat})$

$|b_-| = 0.14^{+0.10}_{-0.14}(\text{stat})$

- anti Λ_b^0
- $\alpha_b = 0.33 \pm 0.17 \pm 0.17$

$|a_+| = 0.008^{+0.227}_{-0.008}(\text{stat})$

$|a_-| = 0.58^{+0.07}_{-0.08}(\text{stat})$

$|b_+| = 0.81^{+0.05}_{-0.05}(\text{stat})$

$|b_-| = 0.004^{+0.168}_{-0.004}(\text{stat})$

- If parity is conserved, one should get $|a_+| = |a_-|$ and $|b_+| = |b_-|$. The different values of $|a_+| / |a_-|$ and $|b_+| / |b_-|$ shows the parity conservation is broken in the $\Lambda_b^0 \to J/\psi\Lambda^0$ decay.
- Large amplitudes $|a_-|$ and $|b_+|$ mean the negative-helicity states for Λ are preferred. The Λ and Jψ from Λ_b^0 decay are highly polarized.
- The parameters from Λ_b^0 and anti-Λ_b^0 are consistent with each other, showing no indication of the CP violation. In this case, the results of the combination of Λ_b^0 and anti-Λ_b^0 is justified, which are more

Comparison of asymmetry parameter with others.

- ATLAS α_b = 0.28 $\pm$ 0.16(stat) $\pm$ 0.06(syst)

- Comparison with LHCb:
  - Adding in quadrature stat. and syst. uncertainties , ATLAS α_b is consistent with early LHCb measurement 0.05 $\pm$ 0.17(stat) $\pm$ 0.07(syst) [Phys.Lett.B724,27(2013)] ,
  - while it is in tensions at level of 1.6 σ with new LHCb measurement: JHEP 06 (2020), in which the parity-violating parameter α_b was found to be consistent with zero, with a 68% credibility interval from -0.048 to 0.005.

- Theory models predict α_b values:
  - pQCD[C.-H.Chou,etal, Phys.Rev.D65, 074030(2002)] (α_b in the range -0.17 to -0.14
  - HQET[Z.Ajaltouni,etal, Phys.Lett.B614,165(2005)] (α_b=$\pm$ 0.78)

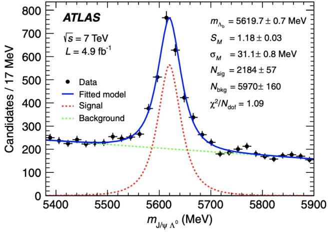
- Fit results when allowing Polarisation parameter non-zero for Λ_b^0, antiΛ_b^0 and combined.

Table 13: Fit results when allowing polarization parameter free.

Parameter	Λ_b only	$\bar{\Lambda}_b$ only	Λ_b and $\bar{\Lambda}_b$
α_b	$0.17^{+0.21}_{-0.20}$	$0.32^{+0.17}_{-0.16}$	$0.29^{+0.15}_{-0.15}$
P	$-0.26^{+0.23}_{-0.23}$	$-0.11^{+0.16}_{-0.16}$	$-0.13^{+0.13}_{-0.13}$
$\lvert a_+\rvert$	$0.20^{+0.11}_{-0.16}$	$0.05^{+0.18}_{-0.05}$	$0.15^{+0.04}_{-0.15}$
$\lvert a_-\rvert$	$0.61^{+0.06}_{-0.07}$	$0.58^{+0.07}_{-0.08}$	$0.59^{+0.06}_{-0.06}$
$\lvert b_+\rvert$	$0.74^{+0.07}_{-0.07}$	$0.81^{+0.05}_{-0.06}$	$0.79^{+0.04}_{-0.05}$
$\lvert b_-\rvert$	$0.20^{+0.13}_{-0.20}$	$0.012^{+0.157}_{-0.012}$	$0.07^{+0.13}_{-0.07}$

- Within precision of measurement, the Polarisations of Λ_b^0, antiΛ_b^0 and combined are identical with zero.
- Under conditions of Polarisation parameter free, the asymmetry parameters of Λ_b^0, antiΛ_b^0 and combined are consistent with the measurement if Polarisation supposed to be 0.
- Total Run2/Run3 statistics to improve precision of these important parameters of Λ_b^0 baryon.

- Based on 4.9 fb^{-1} of p-p collisions in ATLAS.
- Simultaneous un-binned maximum likelihood fit applied to mass and proper-decay time to $\Lambda_b^0 \to J/\psi\Lambda^0$ candidates.



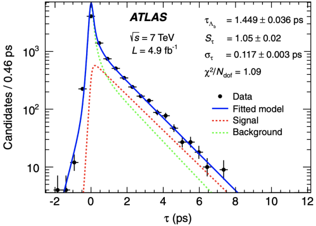


TABLE II. Summary of the systematic uncertainties of the lifetime measurement, σ_τ^{syst}, and the mass measurement, σ_m^{syst}, for Λ_b^0.

Systematic uncertainty	σ_τ^{syst} (fs)	σ_m^{syst} (MeV)
Selection/reco. bias	12	0.9
Background fit models	9	0.2
B_d^0 contamination	7	0.2
Residual misalignment	1	···
Extra material	3	0.2
Tracking p_T scale	···	0.5
Total systematic error	17	1.1

- mass and lifetime result:

$$\tau_{\Lambda_b} = 1.449 \pm 0.036(\text{stat}) \pm 0.017(\text{syst})\ \text{ps},$$
$$m_{\Lambda_b} = 5619.7 \pm 0.7(\text{stat}) \pm 1.1(\text{syst})\ \text{MeV}.$$

- PDG: mass (5619.60 $\pm$ 0.17) MeV , Lifetime (1.471$\pm$0.009) ps

- Ratio of Λ_b^0 and B_d^0 lifetimes:

$$R = \tau_{\Lambda_b}/\tau_{B_d} = 0.960 \pm 0.025(\text{stat}) \pm 0.016(\text{syst}).$$

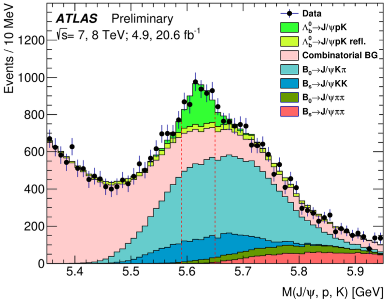
- PDG: 0.970$\pm$0.009

$\Lambda_b^0 \to J/\psi p K^-$ decay channel used to search for J/ψ p resonances with the Run1 data ATLAS-CONF-2019-48

- LHCb (PRL 115 (2015) 072001 W) observed 2 structures, $P_c(4380)^+$ and $P_c(4450)^+$ in J/ψ p mass of $\Lambda_b^0 \to J/\psi p K^-$. Later, PRL 117 (2016) 082003 W LHCb claimed one new narrow $P_c(4312)$ state, and the previous Pc(4450) split into two close narrow peaks.
- Using Run1 data ATLAS use $\Lambda_b^0 \to J/\psi p K^-$ channel for this search.

Analyze signal process after the background decay parameters fixed at the step 1

- Fit the $M(J/\psi p K)$ distribution in the "global scope"
  - $N(\Lambda_b^0 \to J/\psi p K^-) = 2270 \pm 300$
  - $N(B^0 \to J/\psi K^+ \pi^-) \approx 10770$
  - $N(B_s^0 \to J/\psi K^+ K^-) \approx 2290$
  - $N(B^0 \to J/\psi \pi^+ \pi^-) \approx 1070$
  - $N(B_s^0 \to J/\psi \pi^+ \pi^-) \approx 1390$
- Further $\Lambda_b^0 \to J/\psi p K$ study is done in the SR (fit steps 3, 4)



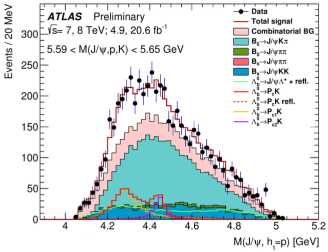
- $\Lambda_b^0 \to J/\psi p K$ yields in the SR:
  - 1010 ± 140 for right mass assignment
  - 160 ± 20 for wrong mass assignment

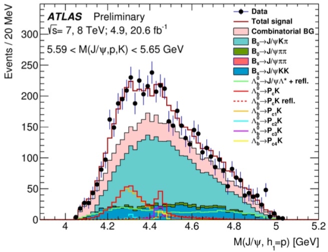
ATLAS fits of J/ψ p mass from the events in signal region of $\Lambda_b^0 \to J/\psi p K^-$

- Fit under 2 pentaquarks hypothesis yields

Parameter	Value	LHCb value [5]
$N(P_{c1})$	$400^{+130}_{-140}(\text{stat})^{+110}_{-100}(\text{syst})$	–
$N(P_{c2})$	$150^{+170}_{-100}(\text{stat})^{+50}_{-90}(\text{syst})$	–
$N(P_{c1}+P_{c2})$	$540^{+80}_{-70}(\text{stat})^{+70}_{-80}(\text{syst})$	–
$\Delta\phi$	$2.8^{+1.0}_{-1.6}(\text{stat})^{+0.2}_{-0.1}(\text{syst})$ rad	–
$m(P_{c1})$	$4282^{+33}_{-26}(\text{stat})^{+28}_{-7}(\text{syst})$ MeV	$4380 \pm 8 \pm 29$ MeV
$\Gamma(P_{c1})$	140^{+77}_{-50} (stat)$^{+41}_{-33}$ (syst) MeV	$205 \pm 18 \pm 86$ MeV
$m(P_{c2})$	4449^{+20}_{-29} (stat)$^{+18}_{-10}$ (syst) MeV	$4449.8 \pm 1.7 \pm 2.5$ MeV
$\Gamma(P_{c2})$	51^{+59}_{-48} (stat)$^{+14}_{-46}$ (syst) MeV	$39 \pm 5 \pm 19$ MeV

  - $\chi^2/\text{n.d.f.} = 31.7/39$ ($p = 55.7\%$)
  - Fixing M and Γ of the two P_c to LHCb values yields $\chi^2/\text{n.d.f.} = 49.0/43$ ($p = 24.5\%$)
- The new narrow P_c states cannot be distinguished by ATLAS due to a worse mass resolution and low stats
- Check the hypothesis by fixing their parameters to the LHCb results
  - $\chi^2/\text{n.d.f.} = 31.7/42$





ATLAS search for J/ψ p resonances in $\Lambda_b^0 \to J/\psi p K^-$ with the Run1 data

- Model with 2 penta-quarks yields 400 events $P_c(4282)^+$ and 150 $P_c(4449)^+$, with their parameters consistent with the LHCb results, arriving to χ^2/n.d.f. = 31.7/39 (p = 55.5%)
- Fixing M and Γ of the two P_c to the LHCb values yields χ^2/n.d.f. = 49.0/43 (p = 24.5%).
- The two new LHCb (2016) narrow P_c states cannot be distinguished by ATLAS due to a worse mass resolution and low stats
- Checking the hypothesis by fixing parameters to LHCb results gives χ^2/n.d.f. = 31.7/42
- The no penta-quarks model fit to data was also performed. In this case the fit describes data poorly, but this hypothesis still cannot be excluded (p = 9.1 x 10^{-3}).
- This ATLAS research continues with lager Run2 statistics - allows more precise determination.

Conclusions about ATLAS Λ_b^0 studies

- Λ_b^0 research in ATLAS with RUN1 data covered wide spear of analysis:
- Λ_b^0 Production polarisation in 7 and 8 TeV p-p collisions
- Λ_b^0 Parity violation measured in $\Lambda_b^0 \to J/\psi\Lambda^0$ decay
- Λ_b^0 lifetime in $\Lambda_b^0 \to J/\psi\Lambda^0$ and its ratio to Bd lifetime
- Less favourable $\Lambda_b^0 \to J/\psi pK^-$ decay channel (due to hadrons in the final state) was successfully used to search for J/ψ p pentaquark resonances
- Improvements with Run2 statistics in all these projects vital.
- ATLAS opened to new ideas for analysis and searches in Beauty Baryons. New theory ideas very welcome !