UNIVERSITY OF MICHIGAN

Studies of Λ_b^0 in ATLAS: decays to charmonium states and parity violating asymmetry

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on behalf of ATLAS Collaboration

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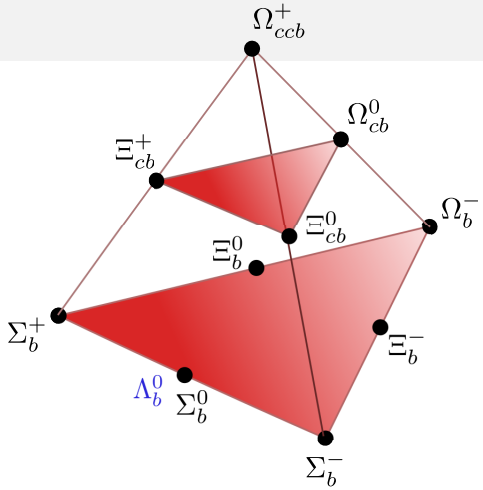
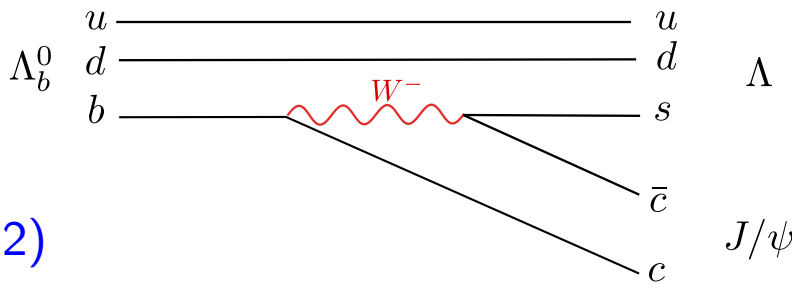
Outline

Introduction



- Λ_b^0 is the lightest b-baryon
  - $m \sim 5620$ MeV
  - Beyond the reach of B-factories
- A puzzle before LHC
  - Measurements of $\tau_{\Lambda_b^0}/\tau_{B_d^0}$ [1]
    - D0: $0.864 \pm 0.052(\text{stat}) \pm 0.033(\text{syst})$
    - CDF: $1.020 \pm 0.030(\text{stat}) \pm 0.008(\text{syst})$
  - Theory predictions [2]
    - HQE: $0.88 \sim 0.97$
    - NLO QCD: $(0.86 \sim 0.88) \pm 0.05$
- Decay asymmetry parameter α_b
  - Predictions [3]
    - pQCD and factorization: $-(0.1 \sim 0.2)$
    - HQET: 0.78
  - LHCb[4]: $0.05 \pm 0.17(\text{stat}) \pm 0.07(\text{syst})$



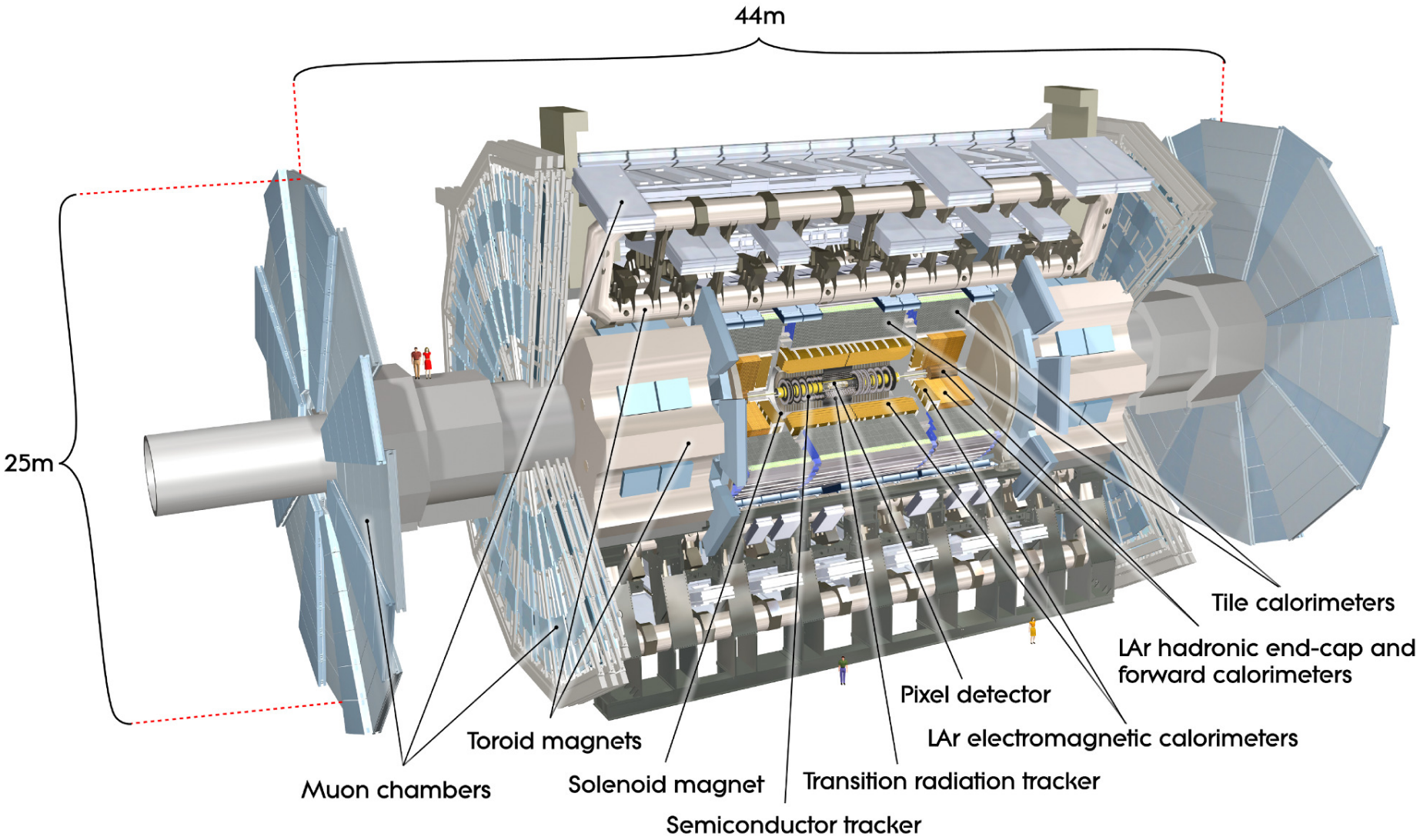
[1] Phys. Rev. D 85 (2012) 112003; Phys. Rev. Lett. 106 (2011) 121804 [updated in Phys. Rev. D 89 (2014) 072014]

[2] See references of Phys. Rev. D 87 (2013) 032002

[3] See references of Phys. Rev. D 89 (2014) 092009

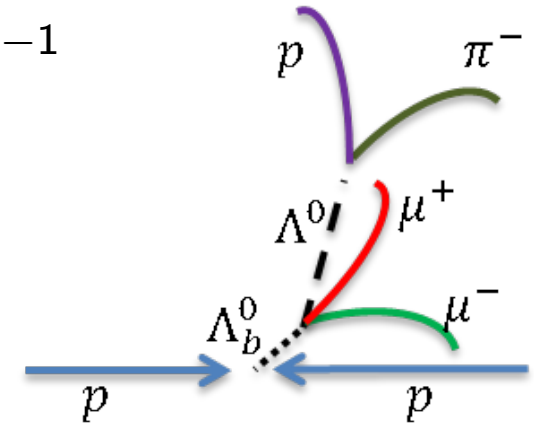
[4] Phys. Lett. B 724, 27 (2013)

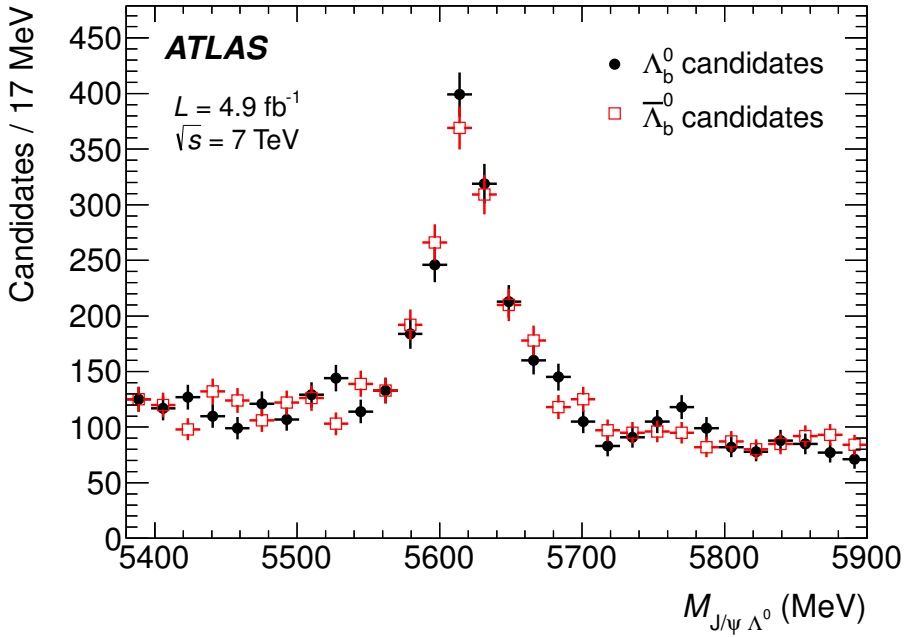
ATLAS detector



Event selection

- 2011 7 TeV data, J/ψ dimuon triggers, 5 fb^{-1}
- J/ψ preselection
  - $2.8 < m_{\mu\mu} < 3.4$ GeV
- Λ preselection
  - Track $p_T > 400$ MeV
  - $1.08 < m_{p\pi} < 1.15$ GeV
- Λ_b^0 fit
  - J/ψ and Λ masses fixed to PDG values
  - Dihadron vertex point to dimuon vertex
  - $\chi^2/N_{dof} < 3$
  - Refitted Λ: $p_T > 3.5$ GeV, $L_{xy} > 10$ mm
  - Veto B_d^0: $\mathcal{P}_{\Lambda_b^0} - \mathcal{P}_{B_d^0} > 0.05$





Λ_b^0 lifetime measurement

- Proper decay time

$$\tau = \frac{L_{xy}\, m^{\mathrm{PDG}}}{p_T}$$

- Mass-lifetime unbinned likelihood fit

$$L = \prod_{i=1}^{N} [f_{\mathrm{sig}} \mathcal{M}_{\mathrm{s}}(m_i|\delta_{mi}) \mathcal{T}_{\mathrm{s}}(\tau_i|\delta_{\tau i}) w_{\mathrm{s}}(\delta_{mi}, \delta_{\tau i}) + (1 - f_{\mathrm{sig}}) \mathcal{M}_{\mathrm{b}}(m_i|\delta_{mi}) \mathcal{T}_{\mathrm{b}}(\tau_i|\delta_{\tau i}) w_{\mathrm{b}}(\delta_{mi}, \delta_{\tau i})]$$

  - Mass
    - $\mathcal{M}_{\mathrm{s}}(m_i|\delta_{mi})$: Gaussian
    - $\mathcal{M}_{\mathrm{b}}(m_i|\delta_{mi})$: 1st order polynomial
  - Proper decay time
    - $\mathcal{T}_{\mathrm{s}}(\tau_i|\delta_{\tau i})$: exponential with efficiency correction
    - $\mathcal{T}_{\mathrm{b}}(\tau_i|\delta_{\tau i})$:
      – prompt: Dirac delta + symmetric exponential
      – non-prompt: two exponential
  - $w_{\mathrm{s,b}}(\delta_{mi}, \delta_{\tau i})$ is the PDF for δ_{mi} and $\delta_{\tau i}$, from data and same for signal and background

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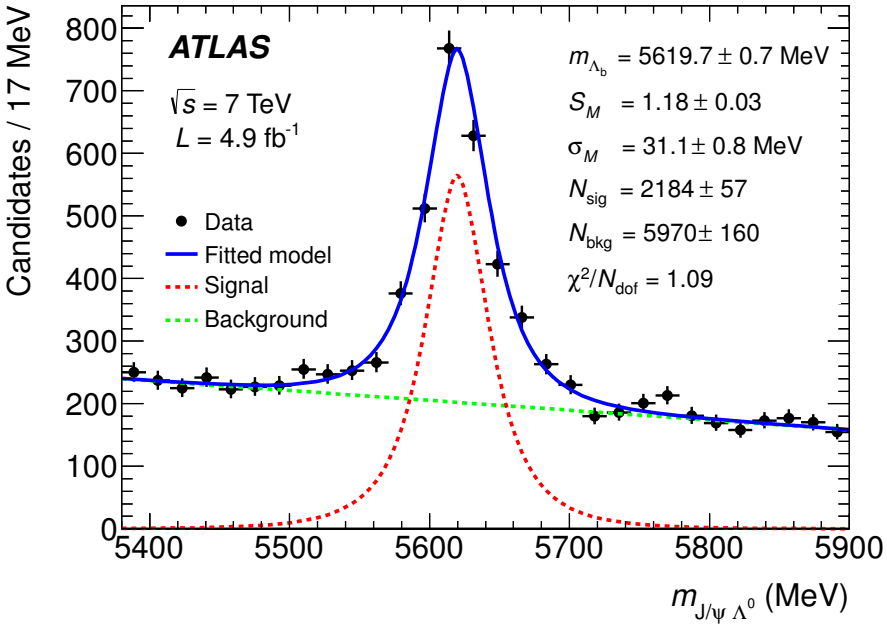
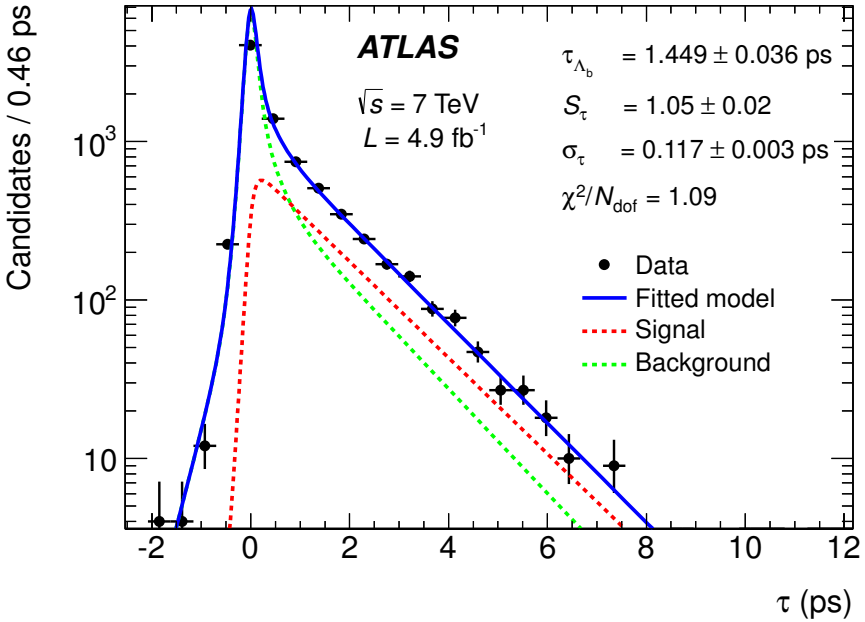
Results





$$m_{\Lambda_b^0} = 5619.7 \pm 0.7(\text{stat}) \pm 1.1(\text{syst})\ \text{MeV}$$

$$\tau_{\Lambda_b^0} = 1.449 \pm 0.036(\text{stat}) \pm 0.017(\text{syst})\ \text{ps}$$

- **Systematic uncertainty** mainly come from muon trigger efficiency and Λ reconstruction bias

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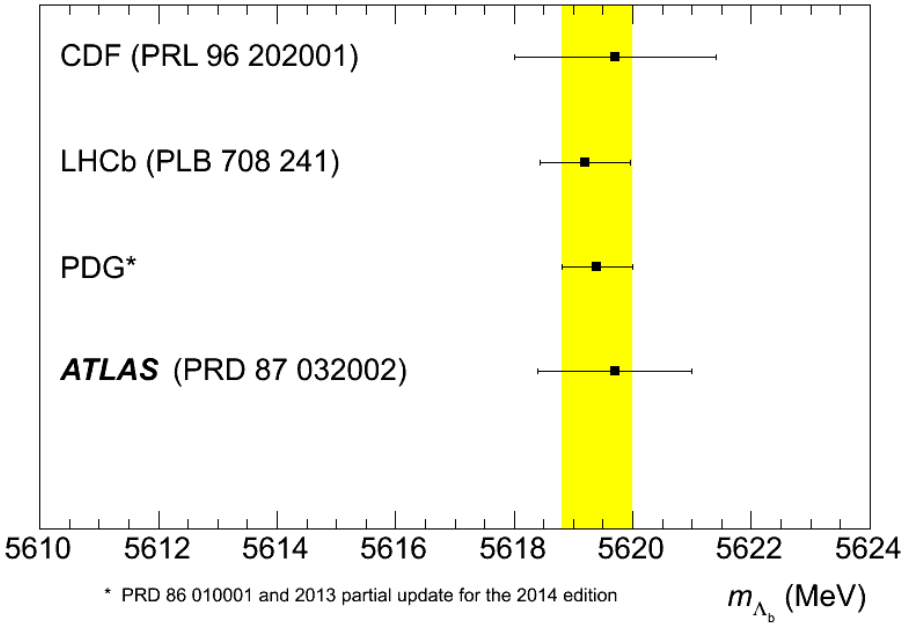
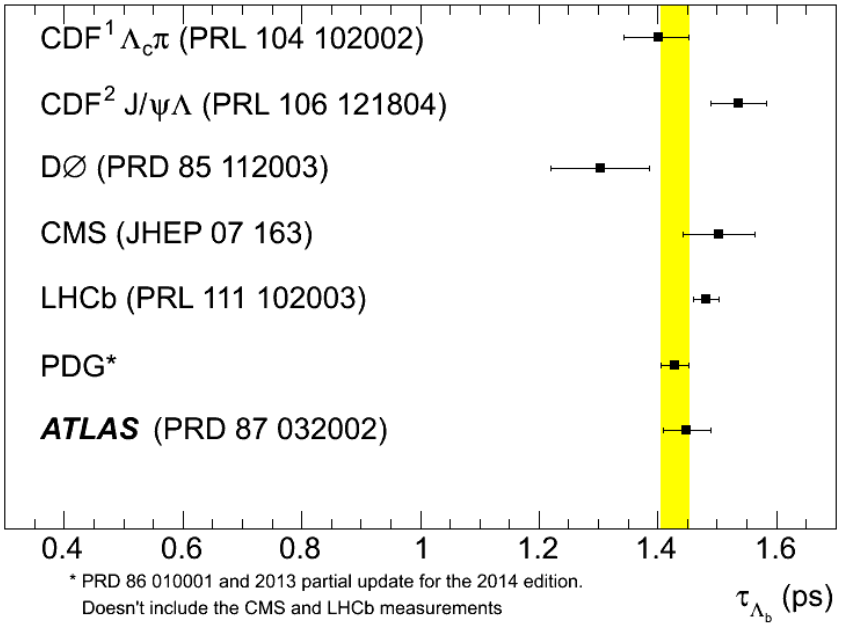


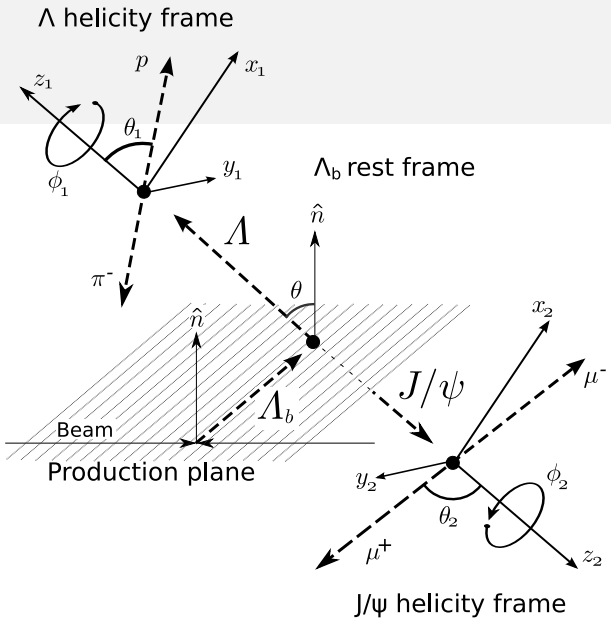


Normalize to the PDG value of $\tau_{B_d^0}$:

$$R = \tau_{\Lambda_b^0}/\tau_{B_d^0} = 0.960 \pm 0.025(\text{stat}) \pm 0.016(\text{syst})$$

- Between D0 and CDF
  - D0: $0.864 \pm 0.052(\text{stat}) \pm 0.033(\text{syst})$
  - CDF: $1.020 \pm 0.030(\text{stat}) \pm 0.008(\text{syst})$
- Compatible with theory Predictions
  - HQE: $0.88 \sim 0.97$
  - NLO QCD: $(0.86 \sim 0.88) \pm 0.05$
- Agree with the recent CMS and LHCb results

α_b measurement



- Asymmetric decay

$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta} = \frac{1}{2}(1 + P\alpha_b \cos\theta)$$

- Overall $P = 0$ at ATLAS
- Use the information of subsequent decays of Λ and J/ψ
  - Helicity amplitudes: $a_+ = A(\frac{1}{2}, 0)$, $a_- = A(-\frac{1}{2}, -1)$, $b_+ = A(-\frac{1}{2}, 0)$, $b_- = A(\frac{1}{2}, 1)$
  - Parameters $\vec{A}$: $\alpha_b = |a_+|^2 - |a_-|^2 + |b_+|^2 - |b_-|^2$, $k_+ = \frac{|a_+|}{\sqrt{|a_+|^2+|b_+|^2}}$, $k_- = \frac{|b_-|}{\sqrt{|a_-|^2+|b_-|^2}}$ and phases Δ_+, Δ_-.
  - Full PDF of $\Omega = (\cos\theta, \phi, \cos\theta_1, \phi_1, \cos\theta_2, \phi_2)$:

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

$i = 0, 2, 4, 6, 18,$ and 19.

$$F_0 = 1, \quad F_2 = \cos\theta_1$$
$$F_4 = 0.5(3\cos^2\theta_2 - 1)$$
$$F_6 = 0.5(3\cos^2\theta_2 - 1)\cos\theta_1$$
$$F_{18} = \sin\theta_1 \sin\theta_2 \cos\theta_2 \cos(\phi_1 + \phi_2)$$
$$F_{19} = \sin\theta_1 \sin\theta_2 \cos\theta_2 \sin(\phi_1 + \phi_2)$$

Method of moments

- Least square fit

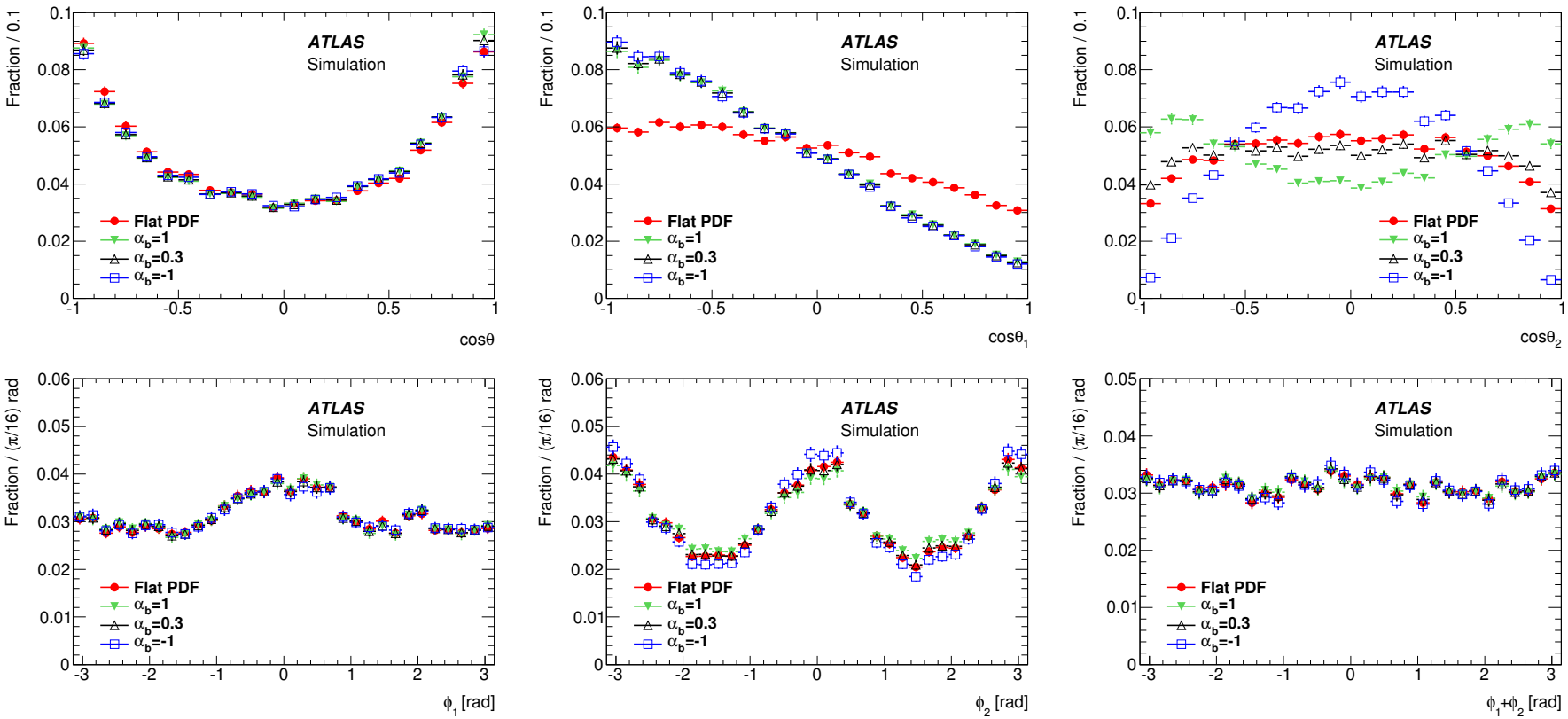
$$\chi^2 = \sum_i \sum_j (\langle F_i \rangle^{\text{expected}} - \langle F_i \rangle) V_{ij}^{-1} (\langle F_j \rangle^{\text{expected}} - \langle F_j \rangle)$$

  - $\langle F_j \rangle$ measured from data
  - V_{ij} is the covariance matrix
  - $\langle F_i \rangle^{\text{expected}}$ depends on the parameters $\vec{A}$

$$\langle F_i \rangle^{\text{expected}}(\vec{A}) = \sum_j \frac{1}{(4\pi)^3} \iint f_{1j}(\vec{A}) f_{2j}(\alpha_\Lambda) F_i(\Omega') T(\Omega', \Omega) F_j(\Omega) \, \mathrm{d}\Omega' \mathrm{d}\Omega$$
$$= \sum_j f_{1j}(\vec{A}) f_{2j}(\alpha_\Lambda) \mathbf{C}_{ij}$$

- The effects of detector are in $\mathbf{C}_{ij}$
- $T(\Omega', \Omega)$ is the resolution and efficiency function

Efficiency correction from MC



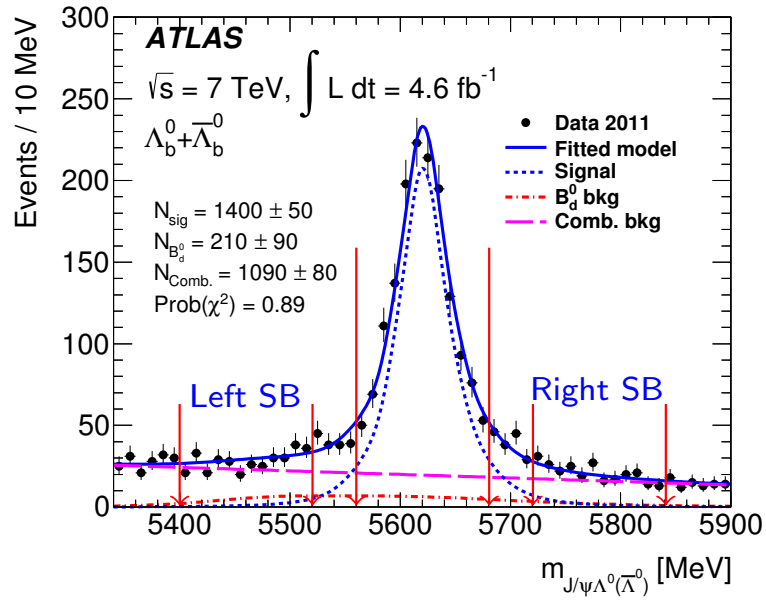
$$\mathbf{C}_{ij} = \frac{1}{(4\pi)^3} \iint F_i(\Omega') F_j(\Omega) T(\Omega', \Omega) \, \mathrm{d}\Omega' \mathrm{d}\Omega$$

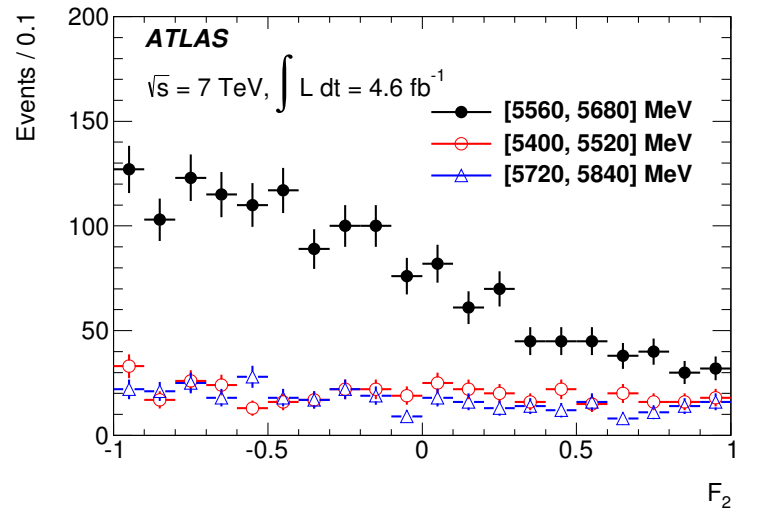
$$\approx \frac{\epsilon_{\mathrm{T}}}{N^{\mathrm{mc}}} \sum_{n=1}^{N^{\mathrm{mc}}} F_i(\Omega'_n) F_j(\Omega_n)$$

- ✓ Trigger correction
- ✓ Kinematics correction

Background

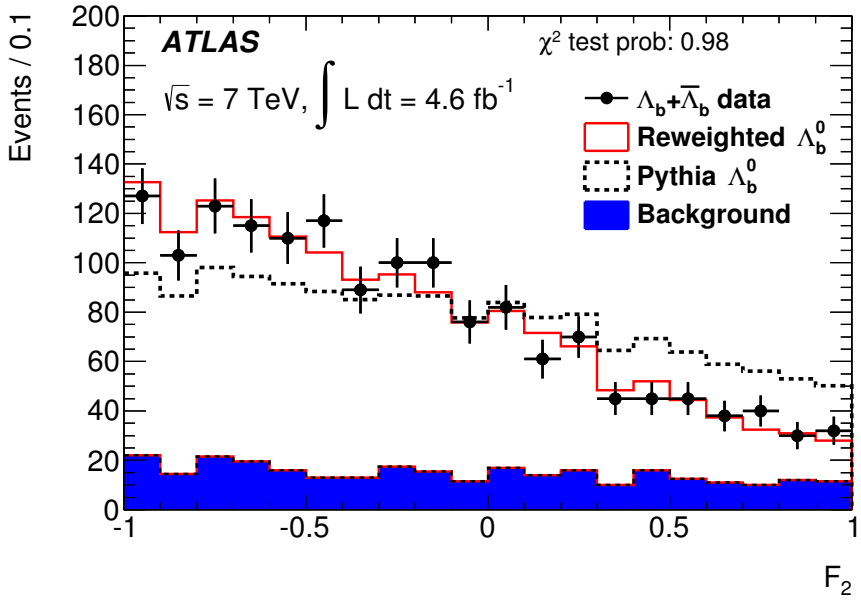
- Event selection
  - Exclude hadron tracks from primary vertex
  - $\tau > 0.35$ ps
  - Loose B_d^0 veto: $\mathcal{P}_{\Lambda_b^0} > \mathcal{P}_{B_d^0}$
- Combinatorial background
  - Estimated from sidebands (SB)
  - $[5400, 5520]$ MeV and $[5720, 5840]$ MeV
- Peaking background
  - $B_d^0 \to J/\psi(\mu^+\mu^-)K_S^0(\pi^+\pi^-)$
  - Yield from the mass fit
  - $\langle F_i \rangle$ from Mont Carlo

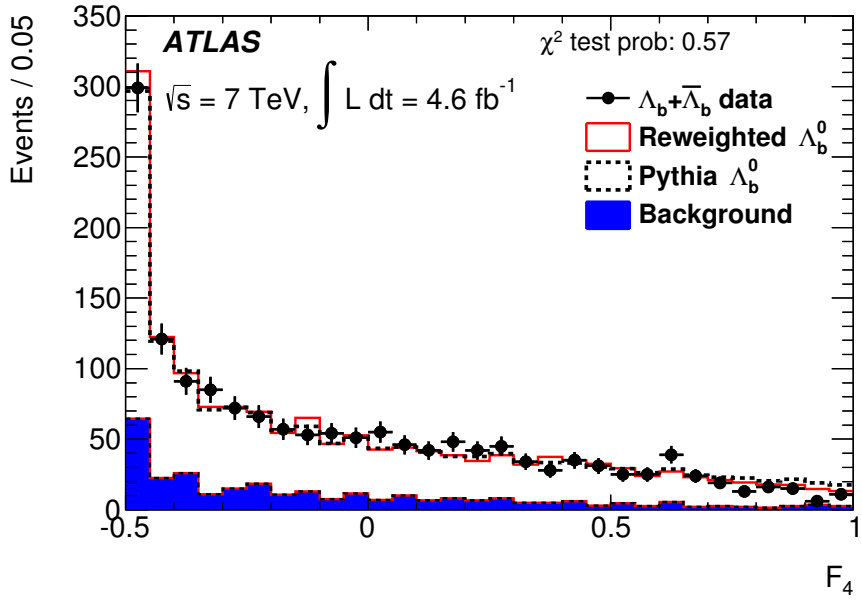


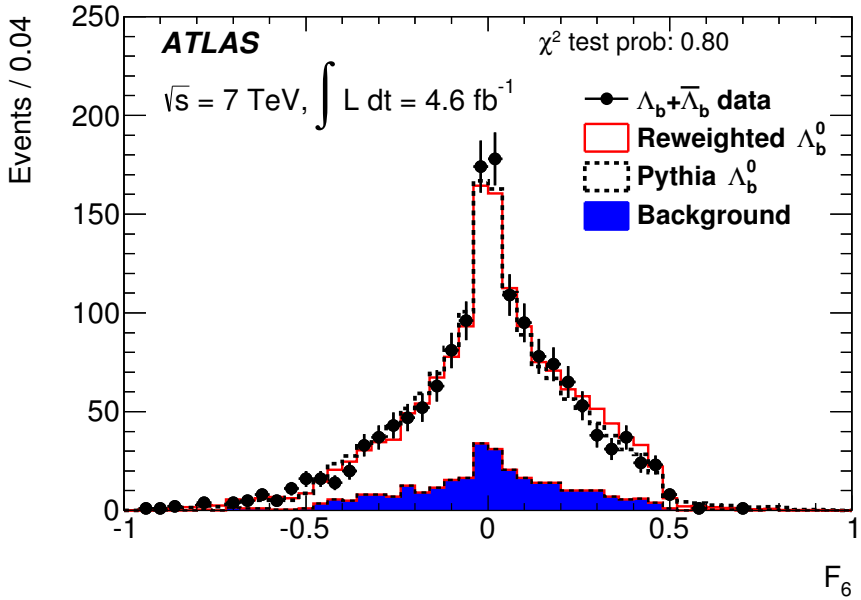


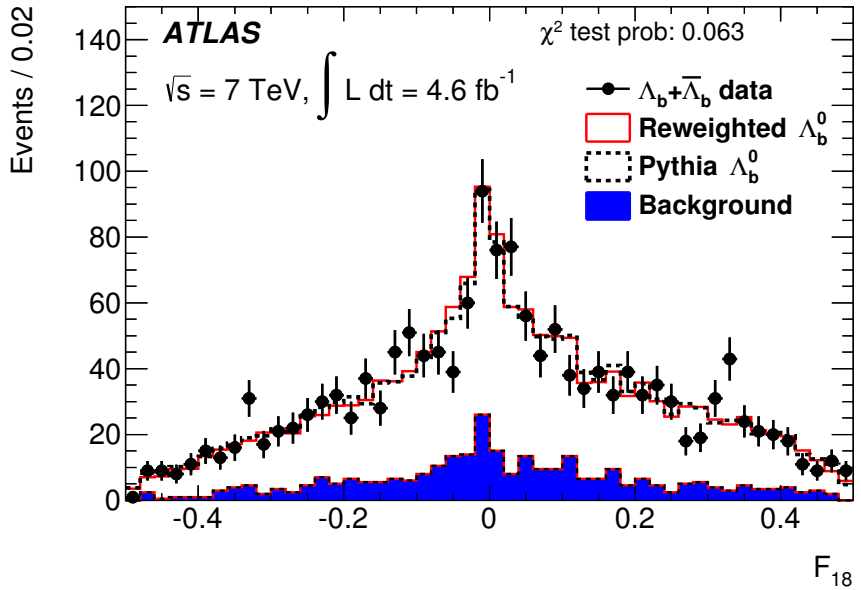
Parameter	$[5340, 5900]$ MeV	$[5560, 5680]$ MeV
N_{sig}	1400 ± 50	1240 ± 40
N_{Comb}	1090 ± 80	234 ± 16
$N_{B_d^0}$	210 ± 90	73 ± 30

- MC weighted using the fit results









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Results

Fit results

$\alpha_b = 0.30 \pm 0.16(\text{stat}) \pm 0.06(\text{syst})$

$k_+ = 0.21^{+0.14}_{-0.21}(\text{stat}) \pm 0.13(\text{syst})$

$k_- = 0.13^{+0.20}_{-0.13}(\text{stat}) \pm 0.15(\text{syst})$

corresponding to

$|A(\ 1/2,\ 0)| = 0.17^{+0.12}_{-0.17} \pm 0.09$

$|A(-1/2,-1)| = 0.59^{+0.06}_{-0.07} \pm 0.03$

$|A(-1/2,\ 0)| = 0.79^{+0.04}_{-0.05} \pm 0.02$

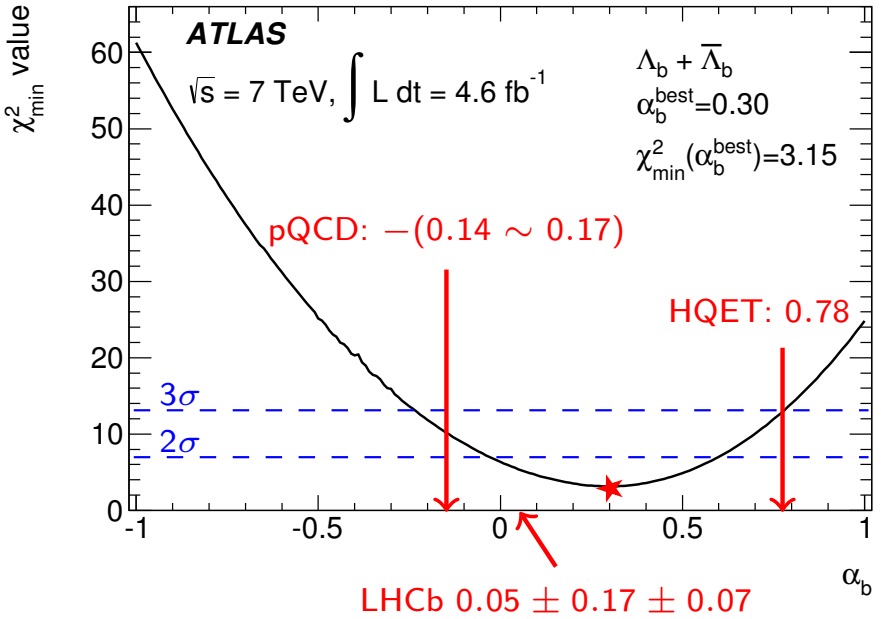
$|A(\ 1/2,\ 1)| = 0.08^{+0.13}_{-0.08} \pm 0.06$

Main **systematic Uncertainties**

- MC statistics
- Background shape modeling

Correlation

Parameter	α_b	k_+	k_-
α_b	1	0.41	−0.19
k_+		1	0.20
k_-			1



- Between two theory predictions
- Consistent with LHCb results

Summary

- Λ_b^0 decaying to charmonium studied at ATLAS
- Lifetime measurement

$$\tau_{\Lambda_b^0} = 1.449 \pm 0.036(\text{stat}) \pm 0.017(\text{syst}) \text{ ps}$$
$$\tau_{\Lambda_b^0}/\tau_{B_d^0} = 0.960 \pm 0.025(\text{stat}) \pm 0.016(\text{syst})$$

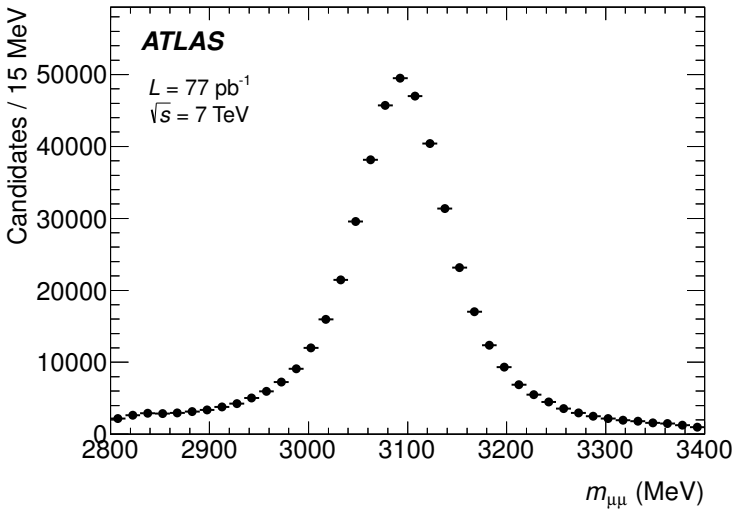
- α_b measurement

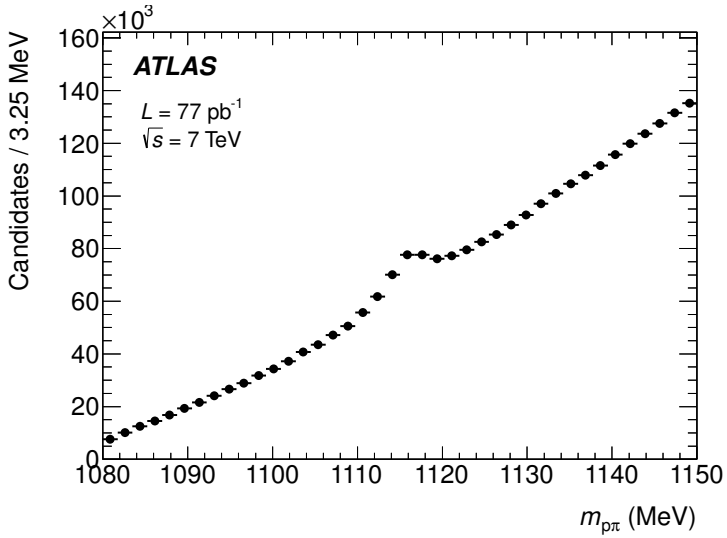
$$\alpha_b = 0.30 \pm 0.16(\text{stat}) \pm 0.06(\text{syst})$$
$$|a_+| = 0.17^{+0.12}_{-0.17}(\text{stat}) \pm 0.09(\text{syst})$$
$$|a_-| = 0.59^{+0.06}_{-0.07}(\text{stat}) \pm 0.03(\text{syst})$$
$$|b_+| = 0.79^{+0.04}_{-0.05}(\text{stat}) \pm 0.02(\text{syst})$$
$$|b_-| = 0.08^{+0.13}_{-0.08}(\text{stat})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

- 2012 data analysis is ongoing
  - Improve the α_b measurement
  - And more...

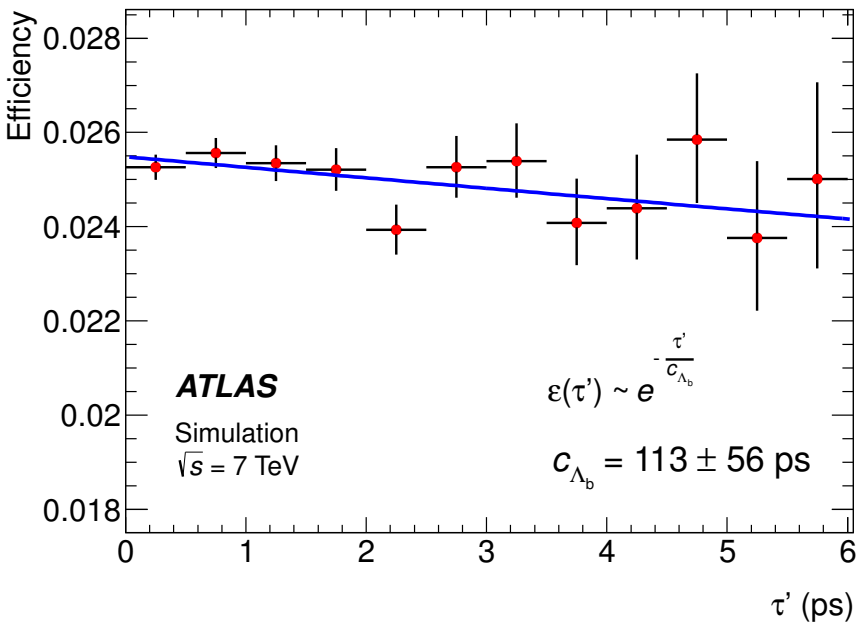
Backup

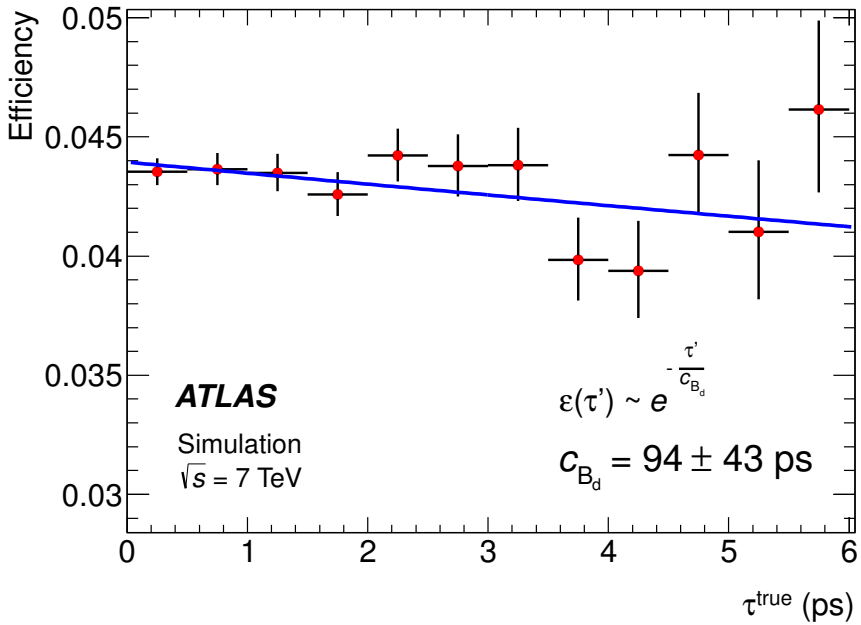
Backup: J/ψ and Λ preselection



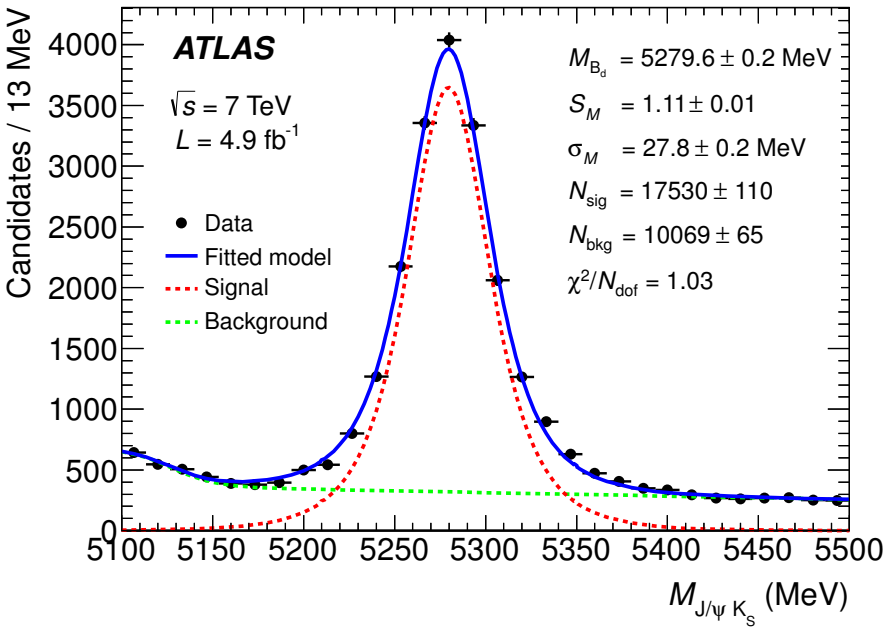


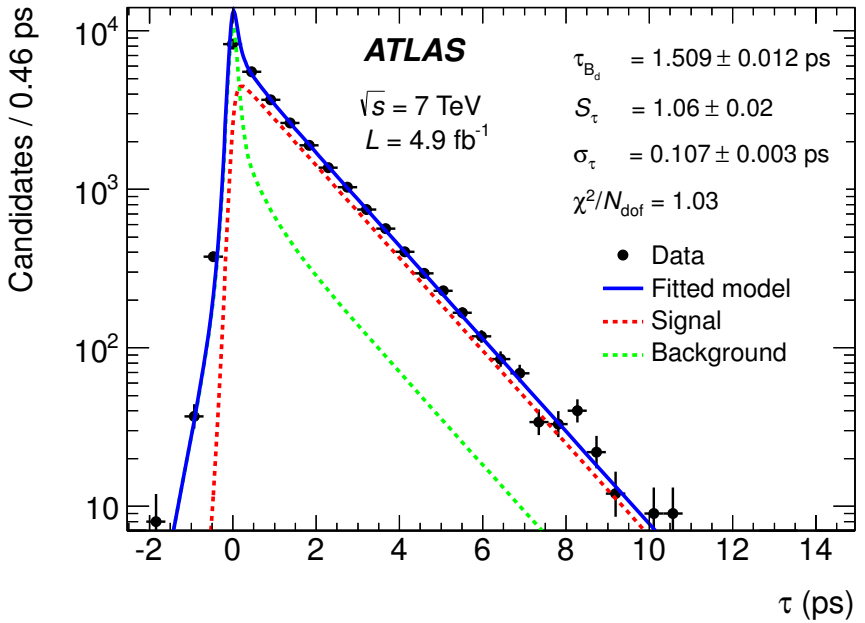
Backup: Efficiency correction of lifetime measurement





Backup: B_d^0 lifetime measurement





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	$\frac{1}{2}\left(3\cos^2\theta_2 - 1\right)$
5	$-a_+a_+^* + a_-a_-^* + \frac{1}{2}b_+b_+^* - \frac{1}{2}b_-b_-^*$	P	$\frac{1}{2}\left(3\cos^2\theta_2 - 1\right)\cos\theta$
6	$-a_+a_+^* + a_-a_-^* - \frac{1}{2}b_+b_+^* + \frac{1}{2}b_-b_-^*$	α_Λ	$\frac{1}{2}\left(3\cos^2\theta_2 - 1\right)\cos\theta_1$
7	$-a_+a_+^* - a_-a_-^* - \frac{1}{2}b_+b_+^* - \frac{1}{2}b_-b_-^*$	$P\,\alpha_\Lambda$	$\frac{1}{2}\left(3\cos^2\theta_2 - 1\right)\cos\theta\cos\theta_1$
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	$\sin\theta_1\ \sin\theta_2\ \cos\theta_2\ \sin(\phi_1 + \phi_2)$

Backup: reparameterized f_{1i}

i	f_{1i}
0	1
2	$(k_+^2 + k_-^2 - 1) + \alpha_b(k_+^2 - k_-^2)$
4	$\frac{1}{4}[(3k_-^2 - 3k_+^2 - 1) + 3\alpha_b(1 - k_-^2 - k_+^2)]$
6	$-\frac{1}{4}[(k_+^2 + k_-^2 - 1) + \alpha_b(3 + k_+^2 - k_-^2)]$
18	$\frac{3}{\sqrt{2}}[\frac{1-\alpha_b}{2}\sqrt{k_-^2(1-k_-^2)}\cos(-\Delta_-) - \frac{1+\alpha_b}{2}\sqrt{k_+^2(1-k_+^2)}\cos(\Delta_+)]$
19	$-\frac{3}{\sqrt{2}}[\frac{1-\alpha_b}{2}\sqrt{k_-^2(1-k_-^2)}\sin(-\Delta_-) - \frac{1+\alpha_b}{2}\sqrt{k_+^2(1-k_+^2)}\sin(\Delta_+)]$

Backup: Sidebands comparison