



# $\Lambda_b^0$ polarization and decay helicity amplitudes studies with the ATLAS detector

*Dongliang Zhang*  
**University of Michigan**

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# Outline

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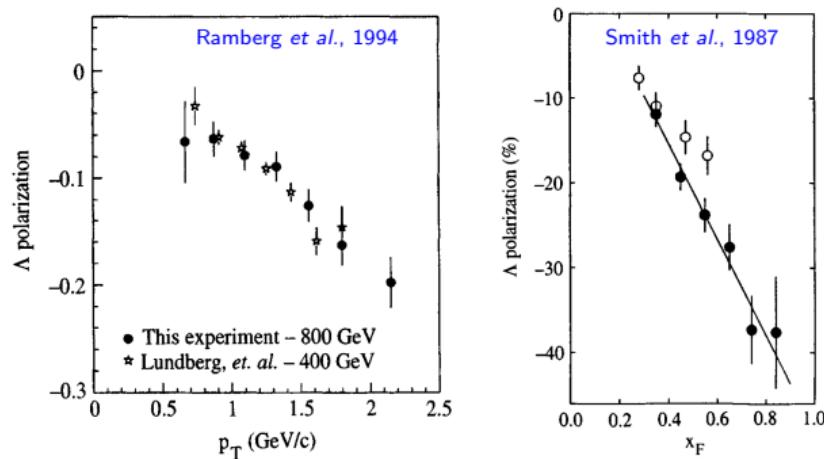
# Hyperon polarization mystery

- ❑ Asymmetric decay of polarized spin 1/2 particles

$$\frac{dN}{d \cos \theta} = \frac{1}{2}(1 + P \cdot \alpha \cos \theta)$$

- ❑ Mysterious hyperon polarization

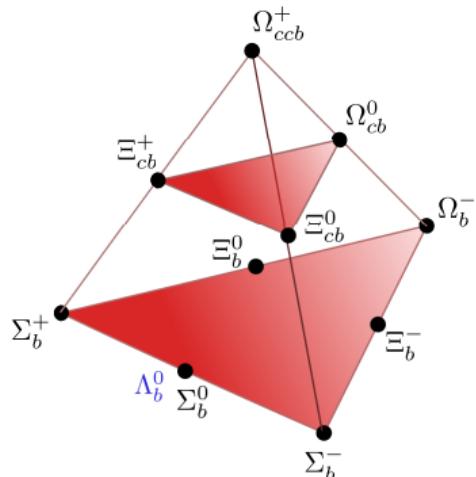
- ❑ No convincing theoretical explanation of large  $\Lambda$  polarization
- ❑ Mass dependent?



# $\Lambda_b^0$ polarization

- $\Lambda_b^0$  is the lightest  $b$ -baryon
  - $m \sim 5620$  MeV
  - Beyond the reach of  $B$ -factories
  - Could have higher polarization
    - Max. polarization of  $b \sim 10\%$  due to the larger mass
    - Kinematics dependent
- Decay asymmetry parameter  $\alpha_b$  for  $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$ 
  - pQCD and factorization:  $-(0.1 \sim 0.2)$
  - HQET: 0.78
- LHCb measurement<sup>1</sup>:
 
$$\alpha_b = 0.05 \pm 0.17(\text{stat}) \pm 0.07(\text{syst})$$

$$P = 0.06 \pm 0.07(\text{stat}) \pm 0.02(\text{syst})$$



<sup>1</sup>Phys. Lett. B 724, 27 (2013)

# $\Lambda_b^0 \rightarrow J/\psi(\mu^+\mu^-)\Lambda^0(p\pi^-)$ decay

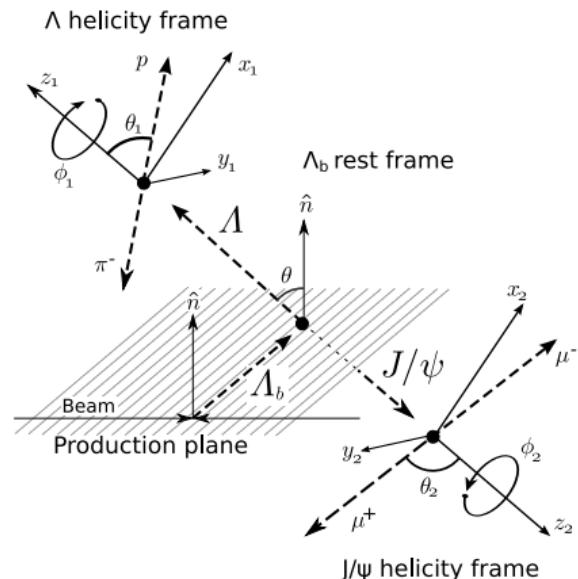
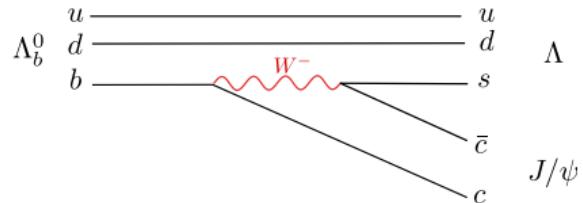
- ❑ Both  $P$  and  $\alpha_b$  not well determined
- ❑ In subsequent decay:
  - ❑ 4 helicity combination

Amplitude	$\lambda_\Lambda$	$\lambda_{J/\psi}$
$a_+ =  a_+ e^{i\omega_+}$	1/2	0
$a_- =  a_- e^{i\omega_-}$	-1/2	0
$b_+ =  b_+ e^{i\rho_+}$	-1/2	-1
$b_- =  b_- e^{i\rho_-}$	1/2	1

- ❑ Full PDF of  $\Omega = (\cos\theta, \phi, \cos\theta_1, \phi_1, \cos\theta_2, \phi_2)$ :

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

- ❑ 7 free parameters:  $P$ , 6 helicity parameters in  $\vec{A}$
- ❑ Overall  $P = 0$  for ATLAS detector
  - ❑ Measure  $\alpha_b$  using 2011 data



# Parametrization

- Using  $P = 0$ , reduced to 6 terms ( $i = 0, 2, 4, 6, 18$ , and  $19$ )

- Parameters  $\vec{A}$

- $\alpha_b = |a_+|^2 - |a_-|^2 + |b_+|^2 - |b_-|^2$

- $k_+ = \frac{|a_+|}{\sqrt{|a_+|^2 + |b_+|^2}}$

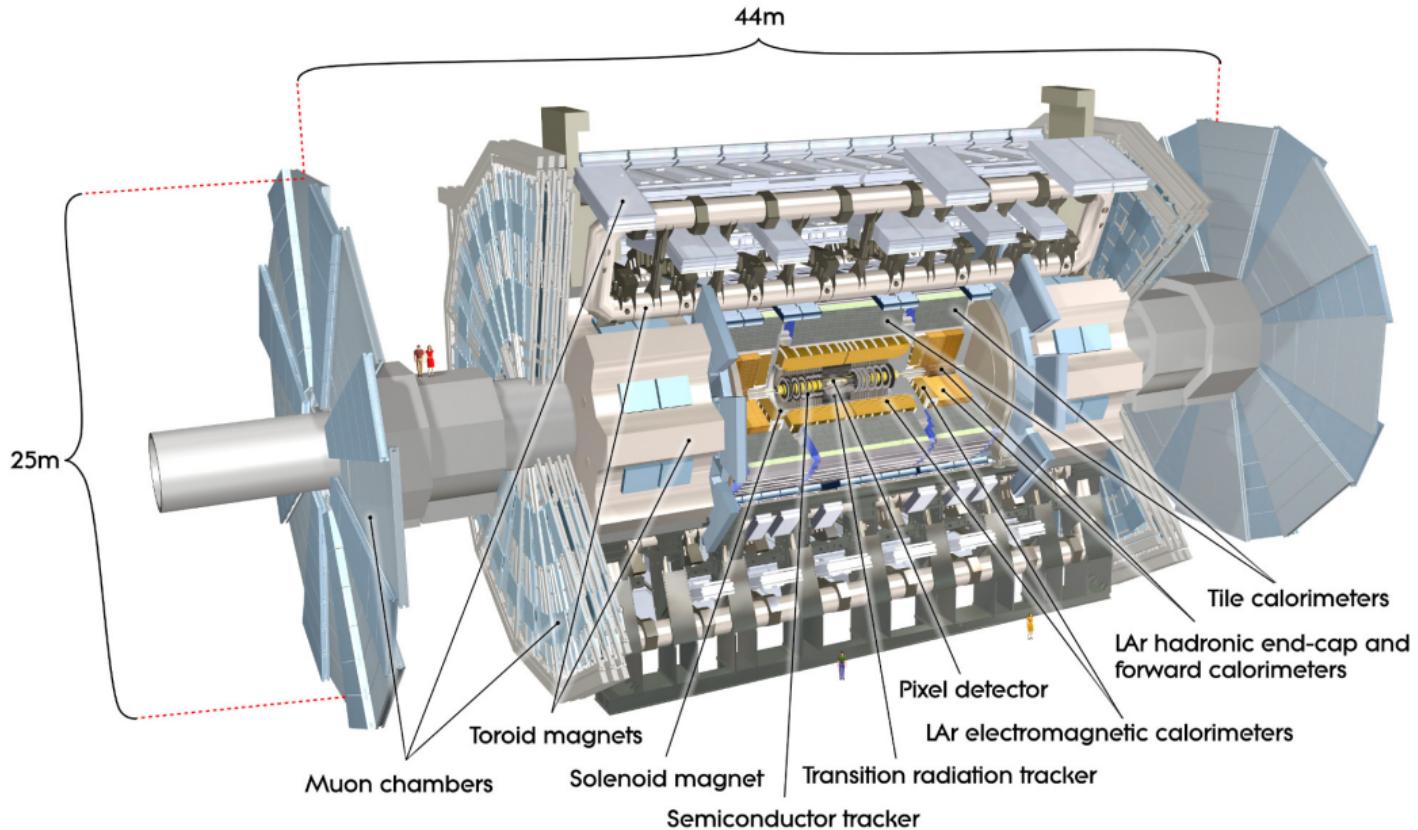
- $k_- = \frac{|b_-|}{\sqrt{|a_-|^2 + |b_-|^2}}$

- $\Delta_+ = \omega_+ - \rho_+$

- $\Delta_- = \omega_- - \rho_-$

$i$	$f_{1i}$	$F_i$
0	1	1
2	$(k_+^2 + k_-^2 - 1) + \alpha_b(k_+^2 - k_-^2)$	$\cos \theta_1$
4	$\frac{1}{4}[(3k_-^2 - 3k_+^2 - 1) + 3\alpha_b(1 - k_-^2 - k_+^2)]$	$0.5(3 \cos^2 \theta_2 - 1)$
6	$-\frac{1}{4}[(k_+^2 + k_-^2 - 1) + \alpha_b(3 + k_+^2 - k_-^2)]$	$0.5(3 \cos^2 \theta_2 - 1) \cos \theta_1$
18	$\frac{3}{\sqrt{2}}[\frac{1-\alpha_b}{2}\sqrt{k_-^2(1-k_-^2)}\cos(-\Delta_-) - \frac{1+\alpha_b}{2}\sqrt{k_+^2(1-k_+^2)}\cos(\Delta_+)]$	$\sin \theta_1 \sin \theta_2 \cos \theta_2 \cos(\phi_1 + \phi_2)$
19	$-\frac{3}{\sqrt{2}}[\frac{1-\alpha_b}{2}\sqrt{k_-^2(1-k_-^2)}\sin(-\Delta_-) - \frac{1+\alpha_b}{2}\sqrt{k_+^2(1-k_+^2)}\sin(\Delta_+)]$	$\sin \theta_1 \sin \theta_2 \cos \theta_2 \sin(\phi_1 + \phi_2)$

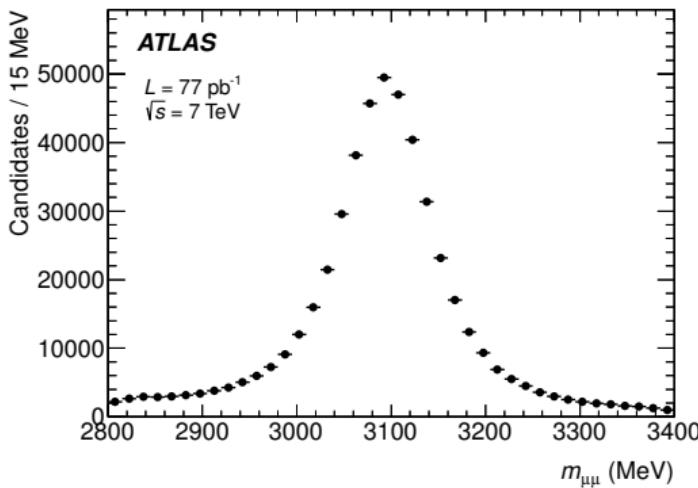
# ATLAS detector



# $J/\psi$ and $\Lambda$ candidates

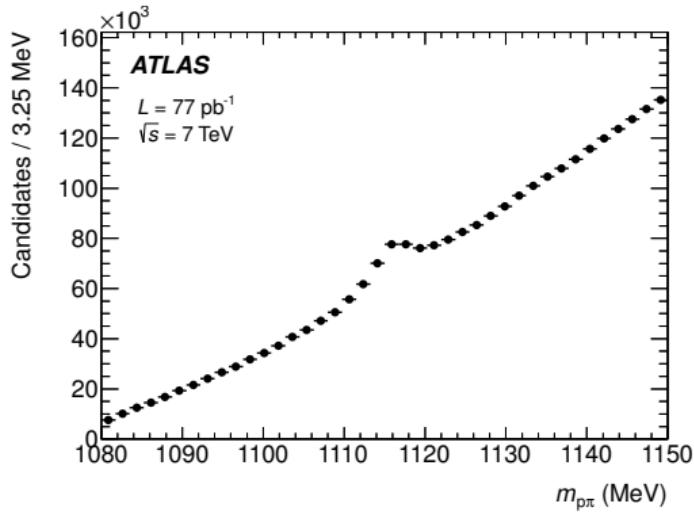
## $J/\psi$ candidates

- Combined muons,  $|\eta| < 2.5$
- ID + MS segment muons,  $|\eta| < 2.2$
- Sufficient Inner Detector hits
- $2.8 < m_{\mu\mu} < 3.4$  GeV



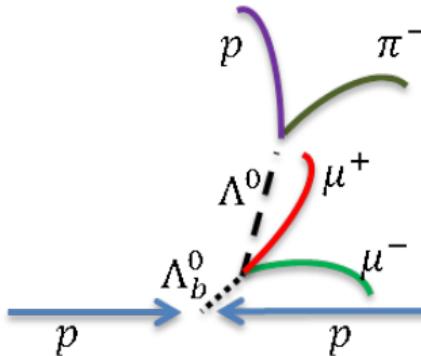
## $\Lambda$ candidates

- Two ID tracks,  $p_T > 400$  MeV
- Sufficient Inner Detector hits
- $1.08 < m_{p\pi} < 1.15$  GeV
- Both  $p\pi^-$  and  $\bar{p}\pi^+$  combinations



# Event selection

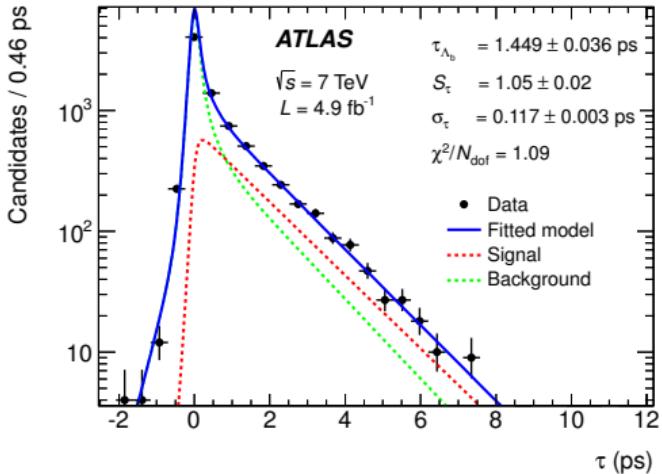
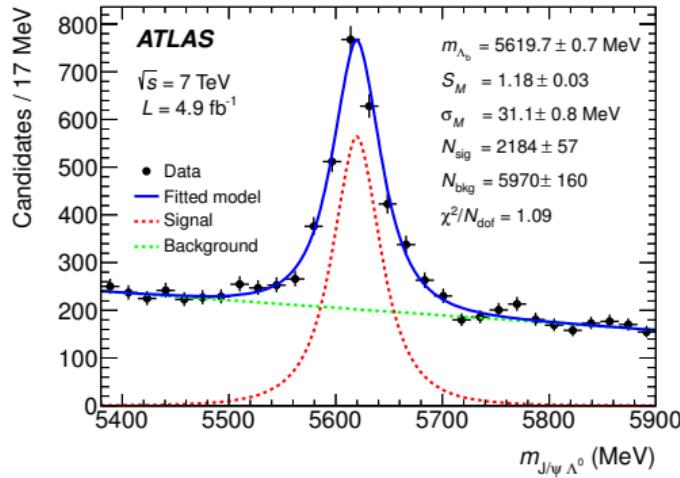
- Pass  $J/\psi$  dimuon triggers
- $\Lambda_b^0$  fit
  - $J/\psi$  and  $\Lambda$  masses fixed to PDG values
  - Dihadron vertex point to dimuon vertex
  - $\chi^2/N_{dof} < 3$
  - Refitted  $\Lambda$ :  $p_T > 3.5$  GeV,  $L_{xy} > 10$  mm
- Also fitted to  $B_d^0 \rightarrow J/\psi(\mu^+\mu^-)K_S^0(\pi^+\pi^-)$  hypothesis for  $B_d^0$  background rejection cuts



# $\Lambda_b^0$ mass and lifetime

- ❑ Veto  $B_d^0$ :  $\mathcal{P}_{\Lambda_b^0} - \mathcal{P}_{B_d^0} > 0.05$
- ❑ Mass and lifetime 2D fit

[Phys. Rev. D 87 \(2013\) 032002](#)



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

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

- ❑ Consistent with results from other experiments

# Final selection & Background

## Event selection

- ❑ Exclude tracks from primary vertex
- ❑  $\tau > 0.35$  ps
- ❑ Loose  $B_d^0$  veto:  $\mathcal{P}_{\Lambda_b^0} > \mathcal{P}_{B_d^0}$
- ❑  $5560 < m < 5680$  MeV

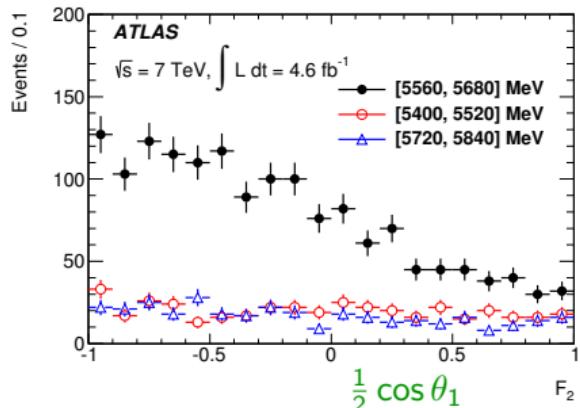
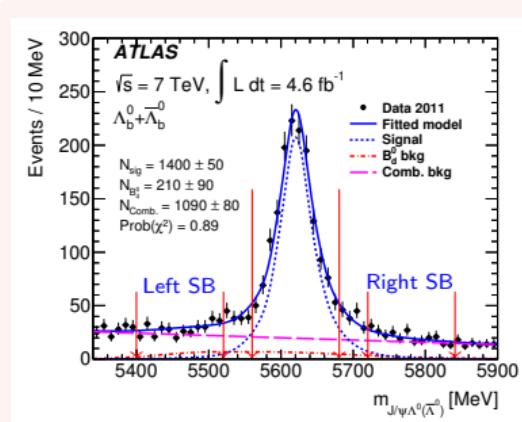
## Combinatorial background

- ❑ Estimated from sidebands (SB)
- ❑ [5400, 5520] MeV and [5720, 5840] MeV

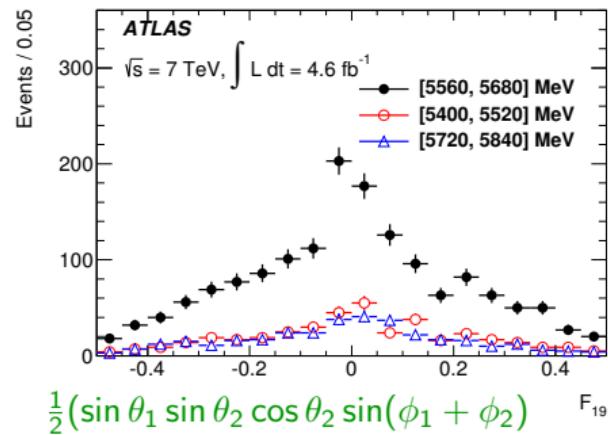
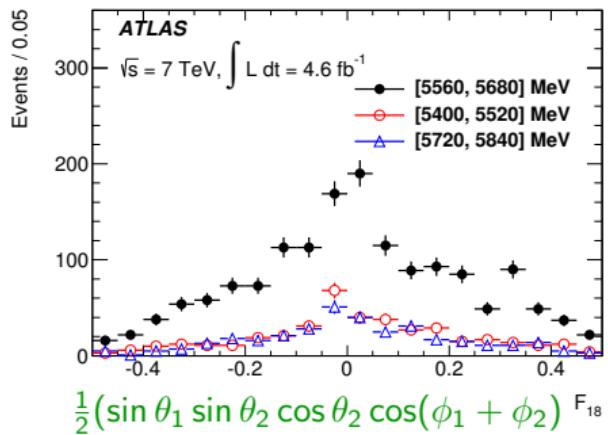
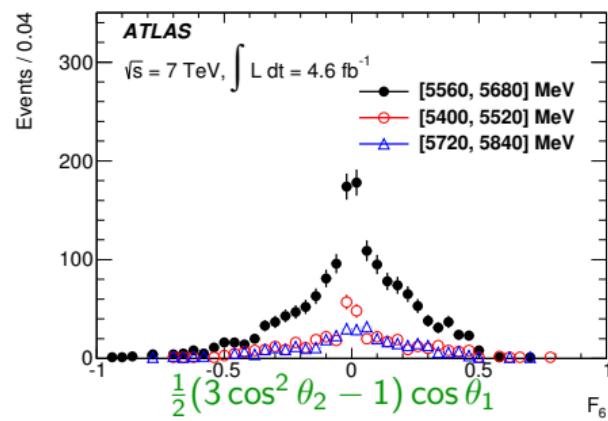
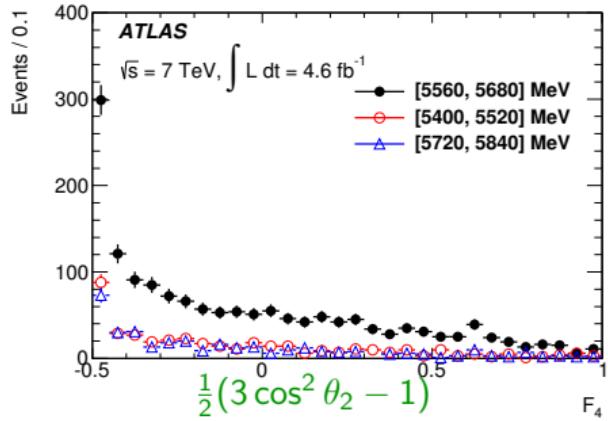
## Peaking background

- ❑  $B_d^0 \rightarrow J/\psi(\mu^+\mu^-)K_S^0(\pi^+\pi^-)$
- ❑ Yield from the mass fit
- ❑  $\langle F_i \rangle$  from Mont Carlo

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



# Sidebands comparison



# 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  $\vec{A}$

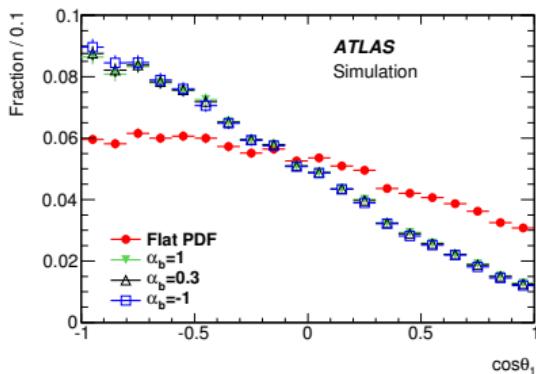
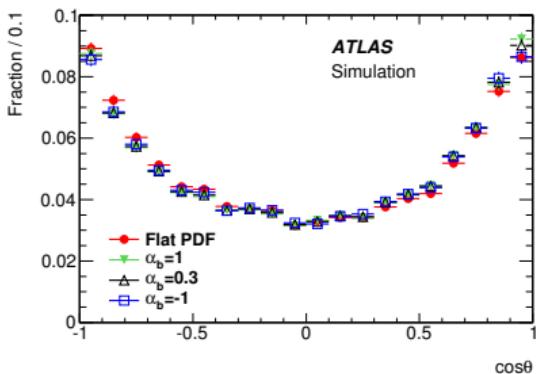
$$\begin{aligned}\langle F_i \rangle^{\text{expected}}(\vec{A}) &= \int F_i(\Omega') \int T(\Omega', \Omega) w(\vec{A}, \Omega) d\Omega d\Omega' \\ &= \sum_j \frac{1}{(4\pi)^3} \iint f_{1j}(\vec{A}) f_{2j}(\alpha_\Lambda) F_i(\Omega') T(\Omega', \Omega) F_j(\Omega) d\Omega' d\Omega \\ &= \sum_j f_{1j}(\vec{A}) f_{2j}(\alpha_\Lambda) C_{ij}\end{aligned}$$

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

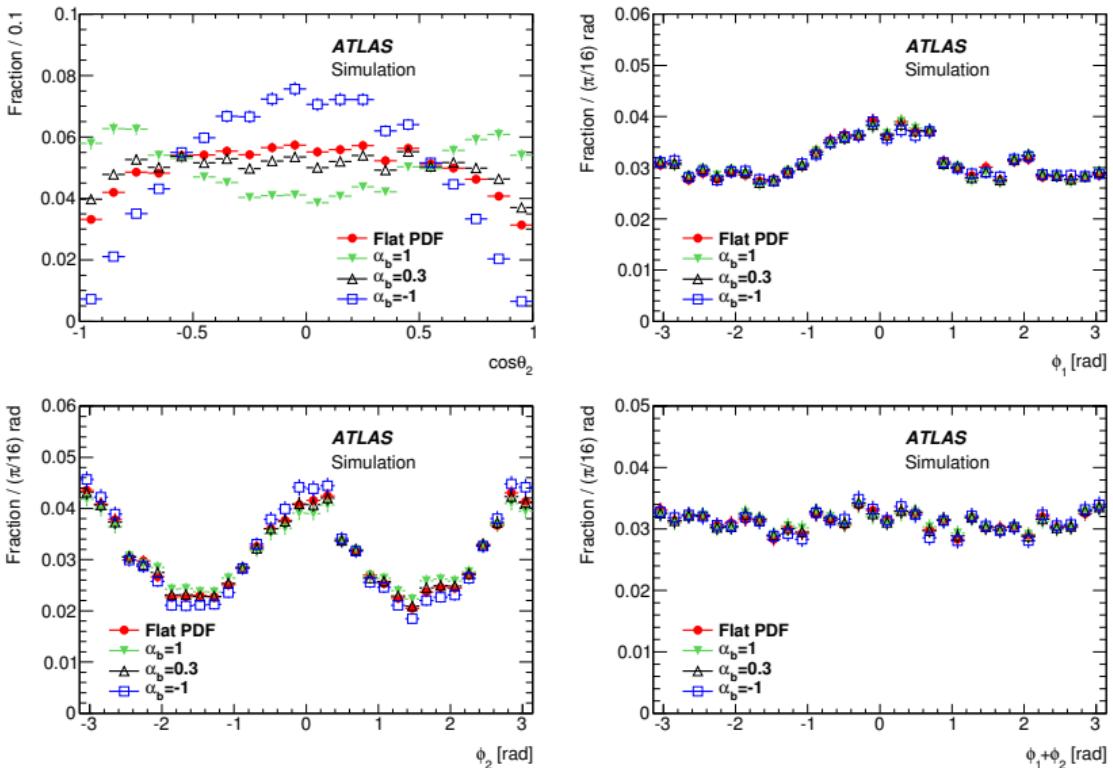
# Efficiency correction from MC

$$\begin{aligned} \mathbf{C}_{ij} &= \frac{1}{(4\pi)^3} \iint F_i(\Omega') F_j(\Omega) T(\Omega', \Omega) d\Omega' d\Omega \\ &\approx \frac{\epsilon_T}{N^{\text{mc}}} \sum_{n=1}^{N^{\text{mc}}} F_i(\Omega'_n) F_j(\Omega_n) \end{aligned}$$

- ✓ Trigger correction
- ✓ Kinematics correction



## □ Other angular variables



# 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

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

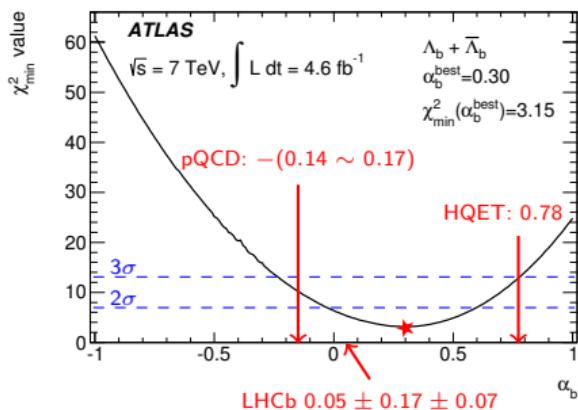
$$|A(-1/2, -1)| = 0.59^{+0.06}_{-0.07} \pm 0.03$$

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

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

## Correlation

Parameter	$\alpha_b$	$k_+$	$k_-$
$\alpha_b$	1	0.41	-0.19
$k_+$		1	0.20
$k_-$			1



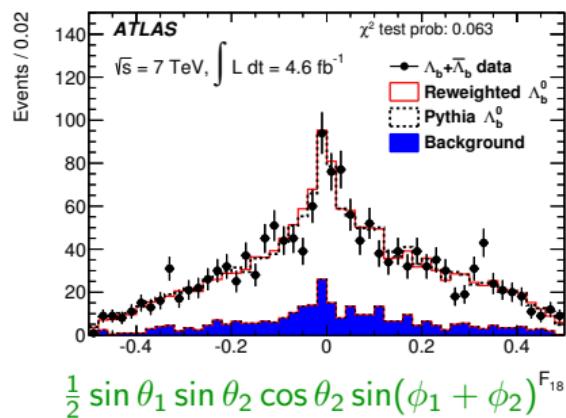
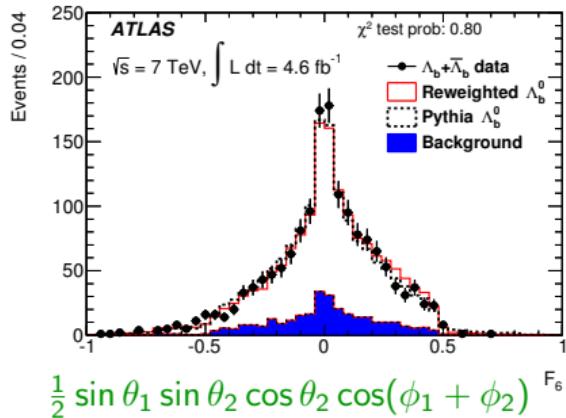
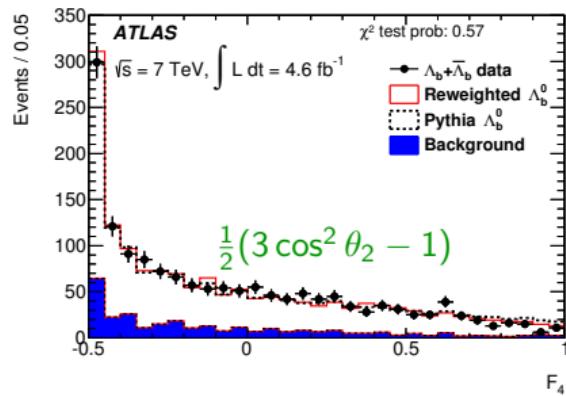
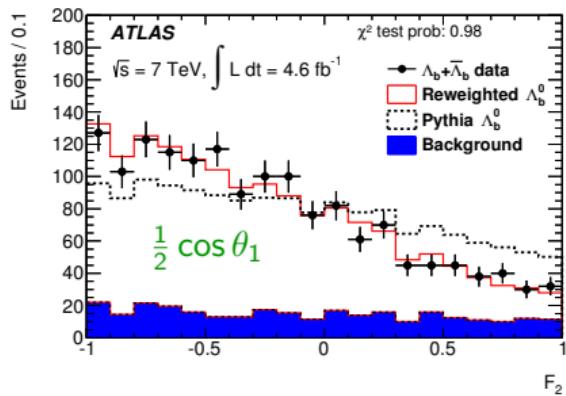
- Between two theory predictions
- Consistent with LHCb results

# Systematic uncertainties

Source	$\alpha_b$	$k_+$	$k_-$	$ a_+ $	$ a_- $	$ b_+ $	$ b_- $
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	0.020	0.004	0.004	0.002	0.008	0.007	0.002
MC weight (model)	0.007	0.010	0.008	0.008	0.007	0.002	0.005
MC weight (data)	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 $\alpha_\Lambda$	0.009	0.023	0.023	0.019	0.005	0.001	0.014
<b>Total</b>	0.064	0.130	0.147	0.086	0.028	0.020	0.061

- Estimated by performing the fit after varying the parameters
- MC statistics and background estimation

## MC weighted using the fit results



# Summary

- ❑ Mystery of the hyperon polarization and various theoretical predictions of  $\alpha_b$
- ❑  $\alpha_b$  measurement using  $5 \text{ fb}^{-1}$  7 TeV ATLAS data

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

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

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

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

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

- ❑ Analyzing the whole run 1 data

# Backup: full PDF

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