



# Selected topics on beauty hadrons production and decay with the ATLAS detector at the LHC



**Andrea Ferretto Parodi**

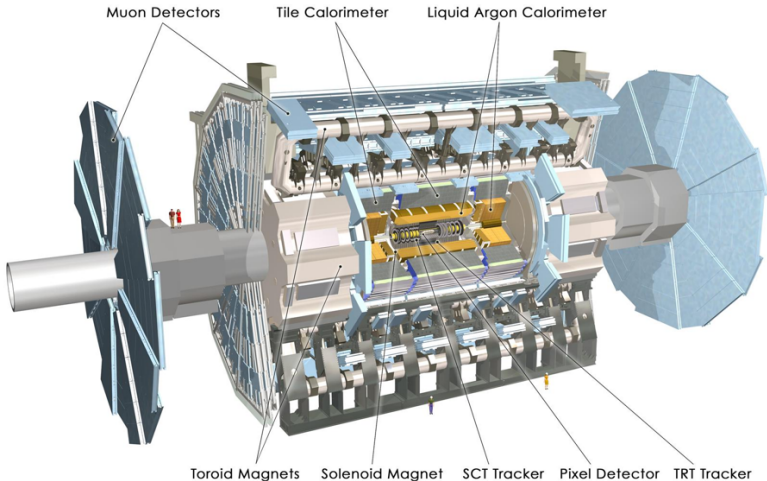
on behalf of the ATLAS Collaboration

7<sup>th</sup> International Workshop on Pion-Nucleon Partial Wave  
Analysis and the Interpretation of Baryon Resonances

Camogli, 23-27 September 2013

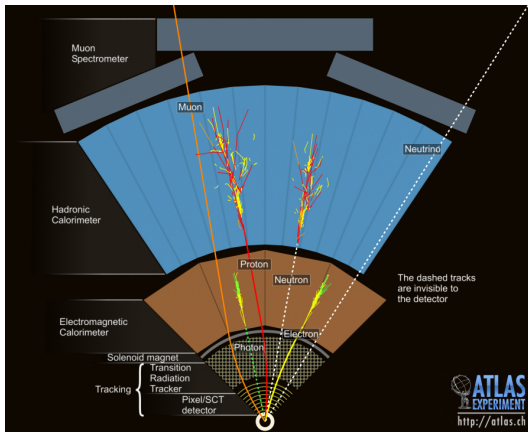


# The ATLAS Experiment at the LHC



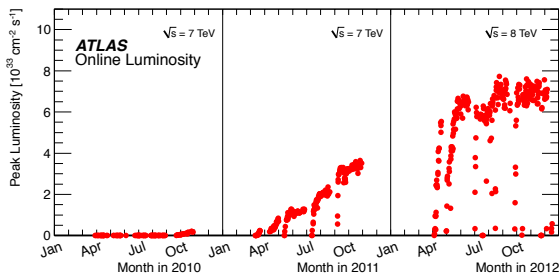
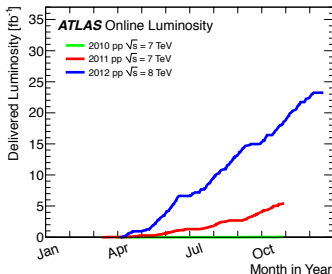
ATLAS is a general purpose detector, designed to be sensible to an extremely wide range of physics scenario (SM rediscovery, Higgs, SUSY, BSM,...)

# Detector overview



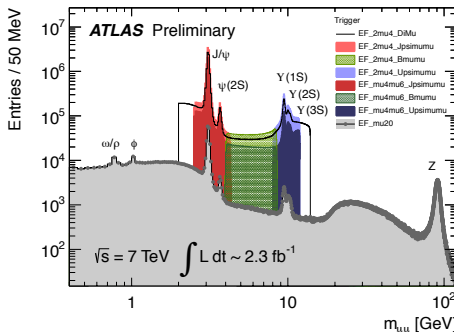
- ▶ **Tracking systems** (based on silicons+TRT) to reconstruct trajectories and momenta of charged particles
- ▶ **EM/hadronic calorimeters** to measure energy of particles and missing energy
- ▶ **Muon Spectrometers** to precisely measure muon momenta

# Data taking operations



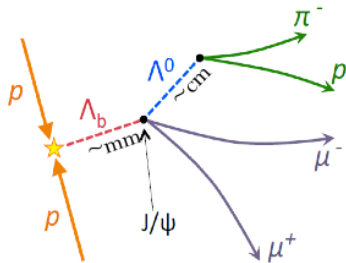
- ▶ LHC  $pp$  phase 1 ended (2010-2012), now preparing for phase 2 from 2015
- ▶ ATLAS recorded:
  - 45  $\text{pb}^{-1}$  in 2010 ( $\sqrt{s} = 7$  TeV, max lumi  $2 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ )
  - 5.3  $\text{fb}^{-1}$  in 2011 ( $\sqrt{s} = 7$  TeV, max lumi  $3.6 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ )
  - 22  $\text{fb}^{-1}$  in 2012 ( $\sqrt{s} = 8$  TeV, max lumi  $7.7 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ )
- ▶ excellent acquisition efficiency ( $> 90\%$ ) and detector performance
- ▶ heavy hadrons physics so far with 2010 and 2011 data at  $\sqrt{s} = 7$  TeV, due to the more suitable trigger (lower thresholds) and pileup conditions ( $\langle \mu \rangle = 1 - 3$  for 2010,  $\langle \mu \rangle \simeq 9$  for 2011), more complicated analyses for 2012 ( $\langle \mu \rangle \simeq 20$ )

# Trigger for heavy quark hadron physics



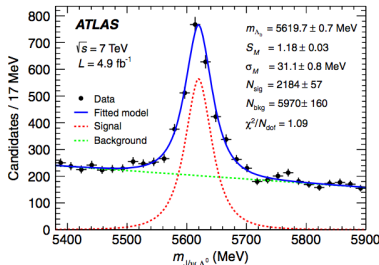
- ▶ trigger is a key ingredient for ATLAS physics program, to reduce the huge collision data flow from  $\sim 40$  MHz to  $\sim 500$  Hz
- ▶ most of the final states coming from heavy quark hadron decays contain muons (mainly from  $J/\psi$ ,  $\Upsilon$  or semileptonic decays)
- ▶ main triggers in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

# $\Lambda_b^0$ mass and lifetime measurement

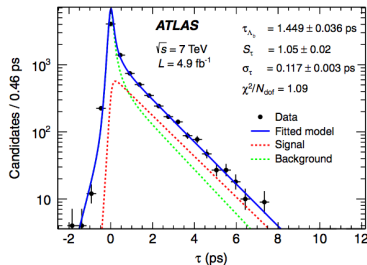


- ▶  $\Lambda_b^0$  reconstructed through the cascade decay topology  $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$  (with  $J/\psi \rightarrow \mu^+ \mu^-$  and  $\Lambda^0 \rightarrow p \pi^-$ )
- ▶ analysis made with  $4.9 \text{ fb}^{-1}$  of data collected in 2011 at  $\sqrt{s} = 7 \text{ TeV}$  using a topological  $J/\psi$  trigger chain
- ▶ simultaneous fit of the four final state tracks, with topological constraints
- ▶ each candidate must fulfill the selection:
  - global  $\chi^2/n_{\text{dof}} < 3$
  - $p_{T,\Lambda^0} > 3.5 \text{ GeV}$
  - $L_{xy,\Lambda^0} > 10 \text{ mm}$
  - $5.38 \text{ GeV} < m_{J/\psi \Lambda^0} < 5.90 \text{ GeV}$

# $\Lambda_b^0$ mass and lifetime measurement



Phys. Rev. D 87, 032002 (2013)



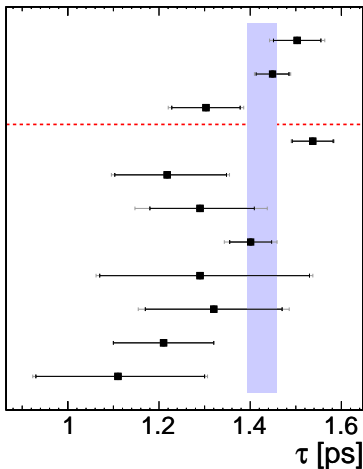
Phys. Rev. D 87, 032002 (2013)

- ▶ 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  $\delta$  function and a symmetric exponential distribution (for non-Gaussian tails)
- ▶ unbinned maximum likelihood mass/lifetime fit:  
 $m = 5619.7 \pm 0.7(stat) \pm 1.1(syst) \text{ MeV}$   
 $\tau = 1.449 \pm 0.036(stat) \pm 0.017(syst) \text{ ps}$
- ▶ CMS:  $\tau = 1.503 \pm 0.052(stat) \pm 0.031(syst) \text{ ps}$  (JHEP 07 (2013) 163)
- ▶ LHCb:  $\tau = 1.482 \pm 0.018(stat) \pm 0.012(syst) \text{ ps}$  (LHCb-PAPER-2013-032)



# $\Lambda_b^0$ mass and lifetime measurement

## $\Lambda_b$ lifetime



CMS.	(2011)	$J/\psi \Lambda$
ATLAS	(2011)	$J/\psi \Lambda$
D0	(02-11)	$J/\psi \Lambda$
CDF2	(02-09)	$J/\psi \Lambda$
D0	(02-06)	$J/\psi \Lambda$
D0	(02-06)	$\Lambda_c^+ \mu$
CDF2	(02-06)	$\Lambda_c^+ \pi$
OPAL	(90-95)	$\Lambda_c^+ l, \Lambda \bar{l} l^+$
CDF1	(91-95)	$\Lambda_c^+ l$
ALEPH	(91-95)	$\Lambda l$
DELPHI	(91-94)	$\Lambda_c^+ l$

errors in black: statistical only  
 errors in grey: syst. added in quadrature  
 band: current best value (PDG)  
 --- values below used for best value

J. Beringer et al. (Particle Data Group)  
 Phys. Rev. D86, 010001 (2012)

# Parity violation for $\Lambda_b^0 \rightarrow J/\psi(\mu\mu)\Lambda^0(p\pi^-)$

- decay described by 4 helicity amplitudes

$A(\lambda_\Lambda, \lambda_{J/\psi})$ , normalized to 1:

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

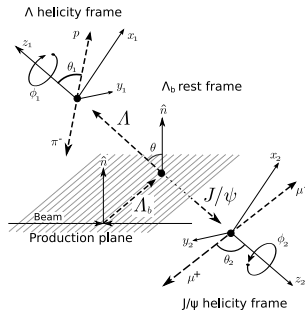
$$b_+ = (-1/2, -1) \quad b_- = (1/2, 1)$$

- dynamics described by 5 angles:  $\theta, \theta_1, \phi_1, \theta_2, \phi_2$
- parity violating decay asymmetry parameter:  $\alpha_b = |a_+|^2 - |a_-|^2 + |b_+|^2 - |b_-|^2$
- full angular PDF of the decay angles  $\Omega$ :

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

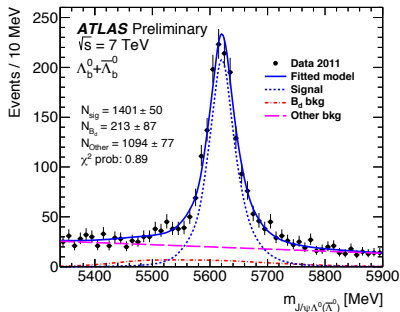
- $f_{1i}(\vec{A})$ : bilinear combination of helicity amplitudes
- $f_{2i}(P, \alpha_\Lambda) \equiv P\alpha_\Lambda, P, \alpha_\Lambda$  or 1
- $F_i(\Omega)$ : orthogonal functions of decay angles

- analysis extracts  $\alpha_b$  and helicity amplitudes from measured averages of each  $F_i$



ATLAS-CONF-2013-071

# Parity violation for $\Lambda_b^0 \rightarrow J/\psi(\mu\mu)\Lambda^0(p\pi^-)$



ATLAS-CONF-2013-071

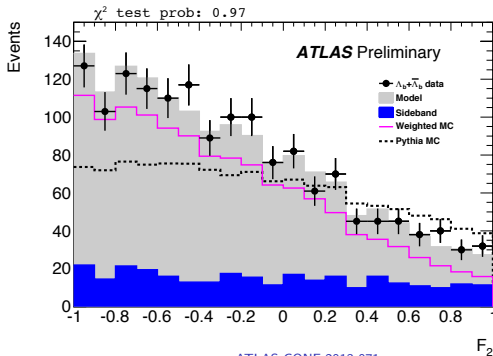
- ▶  $\Lambda_b^0$  selection similar as for mass and lifetime analysis (plus few specific requirements)
- ▶  $\alpha_b$  and helicity amplitudes extracted through a  $\chi^2$  fit to the measured  $\langle F_i \rangle$ :

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

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

# Parity violation for $\Lambda_b^0 \rightarrow J/\psi(\mu\mu)\Lambda^0(p\pi^-)$

## Fit results



ATLAS-CONF-2013-071

- 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
- systematics mainly from calculation of correction matrix and uncertainties on background contribution to  $\langle F_i \rangle$

# Parity violation for $\Lambda_b^0 \rightarrow J/\psi(\mu\mu)\Lambda^0(p\pi^-)$

## Fit results

- fit results:

$$\alpha_b = 0.28 \pm 0.16(stat) \pm 0.06(syst)$$

$$|a_+| = 0.17_{-0.17}^{+0.12}(stat) \pm 0.06(syst)$$

$$|a_-| = 0.59_{-0.07}^{+0.06}(stat) \pm 0.04(syst)$$

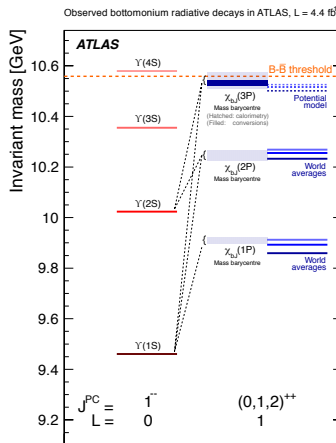
$$|b_+| = 0.78_{-0.05}^{+0.04}(stat) \pm 0.02(syst)$$

$$|b_-| = 0.08_{-0.08}^{+0.13}(stat) \pm 0.05(syst)$$

- $\Lambda^0$  and  $J/\psi$  from  $\Lambda_b^0$  decay are highly polarized in the direction of their momenta
- large  $|a_-|$  and  $|b_+| \Rightarrow$  negative helicity states for  $\Lambda^0$  are preferred
- $\alpha_b$  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:
  - $\sim 2.5\sigma$  disagreement w.r.t. pQCD ( $-(0.14 - 0.18)$ )
  - $\sim 2.9\sigma$  disagreement w.r.t. HQET (0.78)
- more accurate measurements will follow with 2012 data ( $\sim 20 \text{ fb}^{-1}$ )

# Observation of a new $\chi_b$ state

- ▶ heavy quarkonia states provide a insight into the nature of QCD close to strong decay threshold
- ▶ ATLAS studied  $\chi_b$  quarkonia states through the radiative decay modes  $\chi_b(nP) \rightarrow \Upsilon(1S, 2S)(\rightarrow \mu^+ \mu^-) \gamma$
- ▶  $\chi_b(1P)$  (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  $4.4 \text{ fb}^{-1}$ , and collected with muon triggers

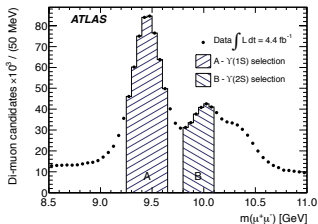


Phys. Rev. Lett. 108, 152001 (2012)

# Observation of a new $\chi_b$ state

## Selection of the sample

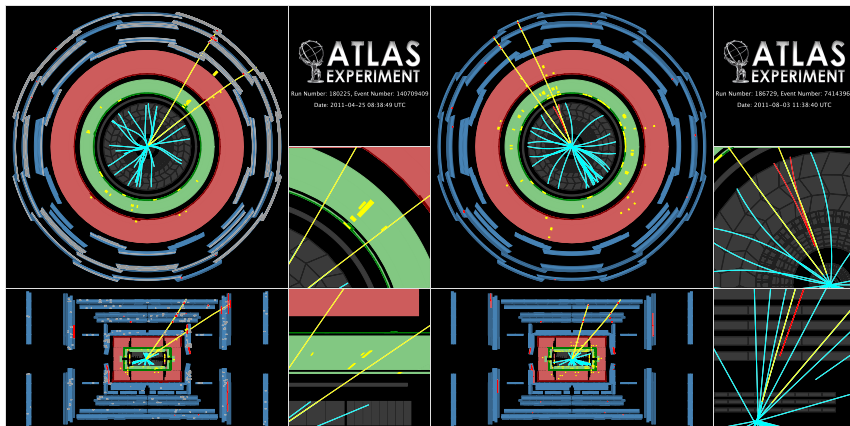
- ▶ high quality muons with  $p_T > 4$  GeV and  $|\eta| < 2.3$
- ▶ oppositely charged muon pairs fitted to a common vertex (loose vertex requirement  $\chi^2/n_{dof} < 20$ ), no mass or momentum constraint
- ▶ dimuon candidate must have  $p_T > 12$  GeV and  $|y| < 2.0$
- ▶ dimuon candidates are selected 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)
- ▶  $\chi_b$  candidates reconstructed by associating a candidate  $\Upsilon$  with a photon



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

# Observation of a new $\chi_b$ state

## Event displays

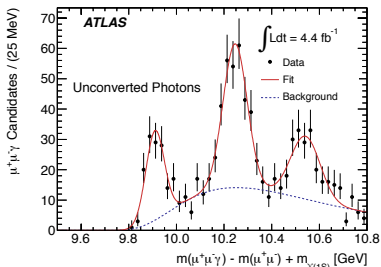


uncovered photon

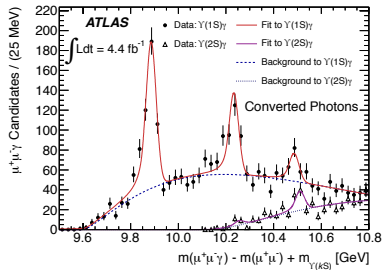
converted photon



# Observation of a new $\chi_b$ state



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



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

- ▶ to minimize the effect of  $\Upsilon$  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
- ▶  $\chi_b(3P) \rightarrow \Upsilon(1S)\gamma$  observed for both converted and uncovered photons,  $\chi_b(3P) \rightarrow \Upsilon(2S)\gamma$  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 quite active in ATLAS
- ▶ analyses published so far with  $\sqrt{s} = 7$  TeV data, ongoing updates or new analyses with 2012 data
- ▶  $\Lambda_b^0$  mass and lifetime measurement in agreement with other experiment
- ▶  $\Lambda_b^0$  parity violation parameter in agreement with LHCb but in disagreement with theoretical predictions  $\Rightarrow$  need updated analysis with 2012 data
- ▶ observation of a new  $\chi_b(3P)$  state, subsequently confirmed by LHCb and D0 (ATLAS measurement is still the most precise)
- ▶ further plan is to try to observe separate  $\chi_b(3P)$  substructures corresponding to  $J = 1$  and  $J = 2$  states, maybe possible with 2012 data using only the barrel detector region, where mass resolution is higher
- ▶ in general much effort is ongoing studying heavy flavour baryons, charmonium and bottomonium states
- ▶ much more public results on ATLAS flavour physics available [here](#)

## Backup slides

# Parity violation for $\Lambda_b^0 \rightarrow J/\psi(\mu\mu)\Lambda^0(p\pi^-)$

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