CP violation in heavy baryons: experimental results and prospects

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Implications of LHCb measurements and future prospect
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Outline

- CP violation in heavy baryon decays
- Experimental issues
- Experimental results
- Summary
CP violation in heavy baryon decays
Physics motivations

- At LHCb $b$-baryons are collected in unprecedented quantities → opens a new field in flavour physics for precision measurements

- CP violation (CPV) in $b$-baryons:
  - CKM mechanism predicts sizeable amount of CPV in $b$-baryons that can be precisely measured
  - complementary means to test Standard Model (SM) with respect to $B$ mesons
  - opportunities to search for new sources of CPV

- CPV in $c$-baryons:
  - null test for SM
CPV in \( b \)-hadrons

- Same underlying short distance physics for \( b \)-baryons and \( B \) mesons but with different spin and QCD structure

\[
\Lambda_b^0 \rightarrow p\pi^- \\
B_d^0 \rightarrow \pi^+\pi^-
\]

- Systematic study of CPV in \( b \)-baryons and in \( B \) mesons for a stringent test of CKM mechanism
CKM angle $\gamma$ using $\Lambda_b$ decays

- Extract $\gamma$ from BR of $\Lambda_b^0 \rightarrow \Lambda D^0$, $\Lambda_b^0 \rightarrow \Lambda \bar{D}^0$, $\Lambda_b^0 \rightarrow \Lambda D_{CP}^0$

  and charge conjugate decays à la GLW

- Theory clean measurement of $\gamma$ using baryons

- Small yields $BR = (\Lambda_b^0 \rightarrow \Lambda D^0) \sim 4 \cdot 10^{-6}$, $BR = (\Lambda_b^0 \rightarrow \Lambda \bar{D}^0) \sim 8 \cdot 10^{-7}$

- Use $\Lambda_b^0 \rightarrow D^0 pK^-$ for improved reco efficiency

Search for CPV in charm baryons

I. I. Bigi, arXiv:1206.4554  

- Null test for SM, sensitive to new physics effects
- CPV predictions for singly-Cabibbo suppressed (SCS) modes $\mathcal{O}(10^{-4})$ or less for doubly CS decays

$$\Lambda_c^+ \to p\pi^-\pi^+ \quad \Lambda_c^+ \to pK^-K^+$$

- Large samples allow probe for localised CPV in differential distributions for enhanced sensitivity. Signal events for SCS modes $\sim 10^5$ in RunI (3fb$^{-1}$)
Experimental issues
Particle-antiparticle production asymmetry

- Initial \( pp \) state not \( CP \) symmetric \( \rightarrow \) particle/antiparticle production asymmetries \( A_P \sim 1\% \)

- Initial asymmetry could mimic CPV and needs to be disentangled or measured

\[ A_P(B^0) = (-0.35 \pm 0.76 \pm 0.28)\%, \quad A_{prod}(D^+_s) = (-0.33 \pm 0.13 \pm 0.18 \pm 0.10)\% \]
\[ A_P(B^0_s) = (1.09 \pm 2.61 \pm 0.66)\%, \quad A_{prod}(D^+) = (-0.96 \pm 0.19 \pm 0.18 \pm 0.18)\% \]

- Next step, measure \( A_P(B^+) \) and obtain \( A_P(\Lambda^0_b) \) by means of a unitary relation

- Similarly in charm for \( D^0 \) and \( \Lambda^+_c \). \( A_P \) more relevant when probing small CPV asymmetries in charm
Detector reconstruction asymmetries

- Detector is made of matter, not CP symmetric
  → particle/antiparticle detection asymmetries
  \[ A_D(\pi^\pm) \sim 0.1\% \quad A_D(K^\pm) \sim 1\% \quad A_D(p/\bar{p}) \sim 1 - 2\% \]

- \( A_D \) can be measured using “ad hoc” abundant control samples, see
  Physics Rev. Lett. 110 (2013) 221601


- B field inversion is crucial to keep charged particle tracking asymmetries under control at \( 10^{-4} \) level
Experimental approaches

- Measure $\Delta A_{CP}$ difference of CP asymmetries:

$$A_{raw}(\Lambda_b^0 \to J/\psi p\phi^-) = A_{CP}(\Lambda_b^0 \to J/\psi p\phi^-) + A_{prod}(\Lambda_b^0) - A_{reco}(h^+) + A_{reco}(p)$$

$$\Delta A_{CP} = A_{raw}(\Lambda_b^0 \to J/\psi p\pi^-) - A_{raw}(\Lambda_b^0 \to J/\psi pK^-)$$

$$= A_{CP}(\Lambda_b^0 \to J/\psi p\pi^-) - A_{CP}(\Lambda_b^0 \to J/\psi pK^-) + A_{reco}(\pi^+) - A_{reco}(K^+)$$

Cancel $A_{prod}$ and $A_{reco}(p)$

Measured on data

$\Delta A_{CP} = (5.7 \pm 2.4 \pm 1.2)\%$

$2.2\sigma$ from zero

$L_{int} = 3 \text{ fb}^{-1}$
Experimental approaches

- Measure CPV via $(\hat{T}^{-})$ P-violating asymmetries:

$$C_{\hat{T}} = \vec{p}_{p} \cdot (\vec{p}_{h_{1}}^{-} \times \vec{p}_{h_{2}}^{+}) \quad \bar{C}_{\hat{T}} = \vec{p}_{p} \cdot (\vec{p}_{h_{1}}^{+} \times \vec{p}_{h_{2}}^{-})$$

$$A_{\hat{T}}(C_{\hat{T}}) = \frac{N(C_{\hat{T}} > 0) - N(C_{\hat{T}} < 0)}{N(C_{\hat{T}} > 0) + N(C_{\hat{T}} < 0)}, \text{ for } \Lambda_{b}^{0}$$

$$\bar{A}_{\hat{T}}(\bar{C}_{\hat{T}}) = \frac{\bar{N}(\bar{C}_{\hat{T}} > 0) - \bar{N}(\bar{C}_{\hat{T}} < 0)}{\bar{N}(\bar{C}_{\hat{T}} > 0) + \bar{N}(\bar{C}_{\hat{T}} < 0)}, \text{ for } \bar{\Lambda}_{b}^{0}$$

Largely insensitive to $A_{prod}$ and $A_{reco}$

- Complementary approach to $A_{CP}$ analysis

$$a_{CP}^{\hat{T}\text{-odd}} \propto \cos(\delta_{\text{even}} - \delta_{\text{odd}}) \sin(\varphi_{\text{even}} - \varphi_{\text{odd}})$$

not sensitive if $\delta_{\text{even}} - \delta_{\text{odd}} = \pi/2$ or $3\pi/2$

$$A_{CP} \propto \sin(\delta_{1} - \delta_{2}) \sin(\varphi_{1} - \varphi_{2})$$

not sensitive if $\delta_{1} - \delta_{2} = 0$ or $\pi$


More in G. Durieux talk at this workshop
Experimental results
CPV in $\Lambda_b^0 \rightarrow p\pi^-$ and $\Lambda_b^0 \rightarrow pK^-$

$\Lambda_b^0 \rightarrow pK^- \ 8,600 \text{ signal events}$

$\Lambda_b^0 \rightarrow p\pi^- \ 6,000 \text{ signal events}$

- Present sensitivity to CPV at $1 \cdot 10^{-2}$ level
- No irreducible systematic uncertainties identified so far
- Naive projections to $300 \text{ fb}^{-1}$ (assume 200x signal): $1 \cdot 10^{-3}$ precision on CPV asymmetries
CPV in 4-body charmless decays

- Transitions governed by $b \rightarrow u\bar{d}\bar{u}$ tree and $b \rightarrow d\bar{u}\bar{u}$ penguin amplitudes of similar magnitude. Large relative weak phase in SM from CKM elements, $\arg(V_{tb}V_{td}^*/V_{ub}V_{ud}^*) = \alpha$

- Potential non negligible CPV effects in the SM

Tree diagram $\propto V_{ub} \sim \lambda^3$

Penguin diagram $\propto \sum_{x=u,c,t} V_{bx} V_{xd} \sim \lambda^3$

I.I. Bigi, arXiv:1608.06528
CPV in $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$ decays

- Search for localised CPV effects, enhanced sensitivity
- Use 4-body topology to build P-violating asymmetries

$N_{\text{sig}}(p\pi^-\pi^+\pi^-) = 6646 \pm 105$

$L_{\text{int}} = 3 \text{ fb}^{-1}$

- P-odd, $\hat{T}$-odd triple products:

$$C_{\hat{T}} = \vec{p}_p \cdot (\vec{p}_{h_1^-} \times \vec{p}_{h_2^+}) \propto \sin \Phi, \text{ for } \Lambda_b^0$$

$$\bar{C}_{\hat{T}} = \vec{p}_{\bar{p}} \cdot (\vec{p}_{\bar{h}_1^+} \times \vec{p}_{\bar{h}_2^-}) \propto \sin \bar{\Phi}, \text{ for } \bar{\Lambda}_b^0$$
First evidence for CP violation in baryons

Very low systematic uncertainties. Sensitivity expected to scale with statistics i.e. $10^{-3}$ precision on CPV at 300 fb$^{-1}$

CPV predictions, at least for some regions of phase space, very welcome

G. Durieux, arXiv:1608.03288
Towards the measurement of $\gamma$

$$\Lambda_b^0 \to D^0 pK^- \quad \text{sig} = 163 \pm 18$$

$$\mathcal{L}_{int} = 1 \text{fb}^{-1}$$

- Interesting decay modes for the future $\text{BR} = (4.8 \pm 0.9) \times 10^{-5}$
- Expect 100k $D^0 pK^-$, 20k $\bar{D}^0 pK^-$, 16k $D_{CP} pK^-$ signal events with 300 fb$^{-1}$
- $D^0 \to K^- \pi^+$; $D_{CP}^0 \to \pi^+ \pi^-, K^+ K^-$
- Hard to estimate the impact on $\gamma$ determination at present
Search for CPV in $\Lambda_b^0 \rightarrow K_s^0 p\pi^-$

- Large $A_{CP}(pK^{*-}) \sim 20\%$ predicted in SM
  
  \[ A_{CP} = 0.22 \pm 0.13 \pm 0.03 \]
  
  use $\Lambda_b^0 \rightarrow (K_s^0 p)_{\Lambda_c^+} \pi^-$ as control mode
  
  - Precision on CPV at $5 \cdot 10^{-3}$ is achievable with 300 fb$^{-1}$
  
  - Other interesting results: $\Lambda_b^0 \rightarrow \Lambda h^+ h^-, \Lambda_b^0 \rightarrow \Lambda\phi$ decays
charmless decays

- First observation of several decay modes
- Search for CPV in $\Xi_b$ decays is next step

$\Xi_b^0 \rightarrow p\pi^+ K^- K^-$

$N_{\text{sig}} = 709 \pm 45$

$\Xi_b^- \rightarrow pK^- K^-$

$N_{\text{sig}} = 83 \pm 10$

not published yet

LHCb unofficial

$L_{\text{int}} = 3 \text{ fb}^{-1}$

LHCb-ANA-2014-077

LHCb-ANA-2014-087
In 2016 collected almost twice $b$-baryon signal yields wrt Run1

Possibility to increase yields x30 UpgradeI and x200 UpgradeII
Summary

• LHCb opens a new window to search for CPV in baryon decays. Many $b$-baryon decays observed for the first time

• Evidence for CPV found in $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$ decays with a statistical significance of $3.3\sigma$. This represents the first evidence for CPV in baryon sector. Eagerly looking for a $5\sigma$ observation.

• CPV searches ongoing in several $b$-baryon decays. Next step, amplitude analysis to determine source of CPV. Important effort needed for development of phenomenological models

• At high luminosity $300\text{fb}^{-1}$ reach $10^{-3}$ precision on CPV in several $b$-baryon decays. Systematic study of CPV in baryons, angle $\gamma$

• Theoretical predictions for CPV in $b$-baryon decays are needed to confront with precision measurements
Backup slides
Explore purely baryonic decays


- No such type of decay has ever been observed
- Prediction $\mathcal{B}(\Lambda_b^0 \to p\bar{p}n) = (2.0^{+0.3}_{-0.2}) \times 10^{-6}$
- Other modes $\Lambda_b^0 \to p\bar{p}\Lambda$  $\Lambda_b^0 \to \Lambda\bar{\Lambda}\Lambda$

Dibaryon invariant mass spectra prediction

![Diagram showing dibaryon invariant mass spectra prediction.](image-url)
Observation of $\Lambda_b^0 \rightarrow J/\psi p\pi^-$ decay

- Large interference between tree and penguin amplitudes.
  Measure relative BR wrt $\Lambda_b^0 \rightarrow J/\psi pK^-$ and search for CPV.

$\Lambda_b^0 \rightarrow J/\psi p\pi^-$ tree $\propto V_{cb} V_{cd} \sim \lambda^3$

$\Lambda_b^0 \rightarrow J/\psi p\pi^-$ penguin $\propto V_{tb} V_{td} \sim \lambda^3$  ($|V_{us}| = \lambda$)

$\Lambda_b^0 \rightarrow J/\psi p\pi^-$

\[ m_{J/\psi p\pi} \text{ [MeV/c}^2\text{]} \]

LHCb

$\Lambda_b^0 \rightarrow J/\psi pK^-$

\[ m_{J/\psi pK} \text{ [MeV/c}^2\text{]} \]

LHCb
Search for CP violation

- Measurement of $\Delta A_{CP}$ cancel production and proton reconstruction asymmetries

$$A_{\text{raw}}(\Lambda_b^0 \to J/\psi p h^-) = A_{CP}(\Lambda_b^0 \to J/\psi p h^-) + A_{\text{prod}}(\Lambda_b^0) - A_{\text{reco}}(h^+) + A_{\text{reco}}(p)$$

$$\Delta A_{CP} = A_{\text{raw}}(\Lambda_b^0 \to J/\psi p \pi^-) - A_{\text{raw}}(\Lambda_b^0 \to J/\psi p K^-)$$

$$= A_{CP}(\Lambda_b^0 \to J/\psi p \pi^-) - A_{CP}(\Lambda_b^0 \to J/\psi p K^-) + A_{\text{reco}}(\pi^+) - A_{\text{reco}}(K^+)$$

$$= (5.7 \pm 2.4 \pm 1.2)\% \ 2.2\sigma \text{ from zero}$$

- No indications of large local CP asymmetries in Dalitz plane

- Rich resonant structure in $m(p\pi^-)$, and 2 pentaquark in $m(J/\psi p)$ distributions

- BR compatible with expected value 0.08: CKM x phase space factor

$$\frac{\mathcal{B}(\Lambda_b^0 \to J/\psi p \pi^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = 0.0824 \pm 0.0025 \text{ (stat)} \pm 0.0042 \text{ (syst)}$$
Search for CPV in $\Lambda_b^0 \rightarrow \Lambda h^+ h'^- \text{ decays}$

Tree diagram $\propto V_{ub} \sim \lambda^3$

Penguin diagram $\propto \sum_{x=u,c,t} V_{bx} V_{xd} \sim \lambda^3$

JHEP 05 (2016) 081
Signal yields

- First observation of $\Lambda_b^0 \rightarrow \Lambda K^\pm \pi^\mp$ and $\Lambda_b^0 \rightarrow \Lambda K^+ K^-$

$$N_{\text{sig}}(\Lambda K^\pm \pi^\mp) = 97 \pm 14, \ 8.1\sigma$$

$$N_{\text{sig}}(\Lambda K^+ K^-) = 185 \pm 15, \ 15.8\sigma$$
Signal yields

- Evidence of $\Lambda_b^0 \to \Lambda\pi^+\pi^-$, control model $\Lambda_b^0 \to (\Lambda\pi^+)\Lambda_c^+\pi^-$ selected from $\Lambda_b^0 \to \Lambda\pi^+\pi^-$ phase space.
- No evidence of any $\Xi_b^0 \to \Lambda h^+ h'$

$N_{\text{control}}(\Lambda_c^+\pi^-) = 471 \pm 22$

$N_{\text{sig}}(\Lambda\pi^+\pi^-) = 64 \pm 14, \ 4.7 \sigma$
Search for CPV using triple-product asymmetries in $\Lambda_b^0 \rightarrow \Lambda \phi$

$b \rightarrow s\bar{s}s$ transition has been the subject of theoretical and experimental interest in $B^0$, $B_s$ decays, since new physics in the loop could induce non-SM CPV
Signal yields

- First observation

\[ N_{\text{sig}}(\Lambda_b^0 \to \Lambda \phi) = 89 \pm 13, \quad 5.9\sigma \]
Triple-product asymmetries

5 angles describe decay, considering $\Lambda_b^0$ possibly produced with a transverse polarisation

$\theta_\Lambda$: polar angle of $p$ in $\Lambda$ rest frame
$\theta_\phi$: polar angle of $K^+$ in $\phi$ rest frame
$\Phi_1$: angle between $\hat{n}$ and $\hat{n}_\Lambda$
$\Phi_2$: angle between $\hat{n}$ and $\hat{n}_\phi$
$\theta$: polar angle of $\Lambda$ in $\Lambda_b^0$ rest frame w.r.t. $\hat{n}$
Triple-product asymmetries

\[ \hat{n}_\Lambda \]

\[ \vec{u}_i = \frac{\vec{e}_Z \times \hat{n}_i}{|\vec{e}_Z \times \hat{n}_i|} \quad i \in \{\Lambda, \phi\} \]

triple products:

\[ \cos \Phi_{n_i} = \vec{e}_Y \cdot \vec{u}_i \]
\[ \sin \Phi_{n_i} = \vec{e}_Z \cdot (\vec{e}_Y \times \vec{u}_i) \]

CPV observables, untagged sample:

\[ A^c_i = \frac{N_i(\cos \Phi_{n_i} > 0) - N_i(\cos \Phi_{n_i} < 0)}{N_i(\cos \Phi_{n_i} > 0) + N_i(\cos \Phi_{n_i} < 0)} \]
\[ A^s_i = \frac{N_i(\sin \Phi_{n_i} > 0) - N_i(\sin \Phi_{n_i} < 0)}{N_i(\sin \Phi_{n_i} > 0) + N_i(\sin \Phi_{n_i} < 0)} \]

Results

\[ \hat{n}_\Lambda \]

\[ \hat{n}_\phi \]

\[ \vec{e}_X \]

\[ \vec{e}_Y \]

\[ \vec{e}_Z \]

\[ \Lambda_b \]

\[ p \]

\[ \pi^- \]

\[ \Lambda \]

\[ \theta_\Lambda \]

\[ \Phi_1 \]

\[ \theta \]

\[ \Phi_2 \]

\[ K^+ \]

\[ K^- \]

\[ p \]

\[ \hat{n} \]

\[ A_s^\Lambda = 0.13 \pm 0.12 \pm 0.05 \]

\[ A_c^\Lambda = -0.22 \pm 0.12 \pm 0.06 \]

\[ A_s^\phi = -0.07 \pm 0.12 \pm 0.01 \]

\[ A_c^\phi = -0.01 \pm 0.12 \pm 0.03 \]

Consistent with CP symmetry

See G. Durieux, arXiv:1608.03288

a simultaneous unbinned
maximum likelihood fit to the
datasets with positive or
negative triple products

Consistent with CP symmetry
Asymmetry measurements

\[ \mathcal{A}_{\text{raw}}^{CP} = \frac{N_f^{\text{corr}} - N_{\bar{f}}^{\text{corr}}}{N_f^{\text{corr}} + N_{\bar{f}}^{\text{corr}}} \]

\( N_f^{\text{corr}}(N_{\bar{f}}^{\text{corr}}) \): efficiency-corrected yield for \( \Lambda_b^0(\overline{\Lambda}_b^0) \) decays, since efficiencies various across phase space.


\[ \mathcal{A}_{CP} = \mathcal{A}_{\text{raw}}^{CP} - (\mathcal{A}_P + \mathcal{A}_D) \]

\[ = \mathcal{A}_{\text{raw}}^{CP}(\Lambda_b^0 \rightarrow \Lambda h^+ h^-) - \mathcal{A}_{\text{raw}}^{CP}(\Lambda_b^0 \rightarrow (\Lambda\pi^+)\Lambda_c^+\pi^-) \]

Use \( \Lambda_b^0 \rightarrow (\Lambda\pi^+)\Lambda_c^+\pi^- \) as control model:

negligible CPV effect, production asymmetry \( \mathcal{A}_P \) and most detection asymmetry \( \mathcal{A}_D \) cancel

\[ \mathcal{A}_{CP}(\Lambda_b^0 \rightarrow \Lambda K^+\pi^-) = -0.53 \pm 0.23 \pm 0.11 \]

\[ \mathcal{A}_{CP}(\Lambda_b^0 \rightarrow \Lambda K^+K^-) = -0.28 \pm 0.10 \pm 0.07 \]
\[ \Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^- \] phase space distributions

background-subtracted using the sPlot method
b-baryon production

- Production cross-section strongly depends on $p_T$ of $b$-hadron:

  - different $b$-quark fragmentation function ratio $f_{\Lambda_b^0}/f_d$ measured at LEP and at LHC, where $f_{\Lambda_b^0} = P(b \rightarrow \Lambda_b^0)$ and $f_d = P(b \rightarrow B_d^0)$

  - measurement of $f_{\Lambda_b^0}/f_d$ vs $p_T$ of $b$-quark is cleaner to interpret. Expected a slow dependence in that case

Note: LEP average not included in the fit. LHCb measurements are not independent.
Production kinematic dependence

- Use clean $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ (45K), $\bar{B}^0 \rightarrow D^+ \pi^-$ (106K) exclusive decays to measure dependance of $f_{\Lambda_b^0}/f_d$ on $b$-hadron kinematics, e.g. $p_T$, pseudorapidity $\eta$.

- Measure

$$\frac{f_{\Lambda_b^0}(x)}{f_d(x)} = \frac{B(\bar{B}^0 \rightarrow D^+ \pi^-)}{B(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-)} \times \frac{B(D^+ \rightarrow K^- \pi^+ \pi^+)}{B(\Lambda_c^+ \rightarrow pK^- \pi^+)} \times R(x)$$

where

$$R(x) \equiv \frac{N_{\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-}(x)}{N_{\bar{B}^0 \rightarrow D^+ \pi^-}(x)} \times \frac{\epsilon_{\bar{B}^0 \rightarrow D^+ \pi^-}(x)}{\epsilon_{\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-}(x)},$$

and $x = p_T, \eta$

Data sample 1fb$^{-1}$ at 7 TeV - JHEP08(2014)143

\[ \Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-, \quad 3.05 < \eta < 3.2 \]
Production kinematic dependence

- Absolute value of $f_{\Lambda_b^0} / f_d$ from LHCb semileptonic analysis
  
  - obtain most precise branching ratio measurement of $b$-baryon to date (8% precision)

\[ \mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-) = \left( 4.30 \pm 0.03 ^{+0.12}_{-0.11} \pm 0.26 \pm 0.21 \right) \times 10^{-3} \]

(a) LHCb

Exponential dependence vs $p_T$

(b) LHCb

Linear dependence vs $\eta$
$\Lambda_b^0$ production cross-section

- Measurement of differential production cross-section for $\Lambda_b^0$ using $\Lambda_b^0 \rightarrow J/\psi \Lambda$ decays with $J/\psi \rightarrow \mu^+ \mu^-$, $\Lambda \rightarrow p\pi^-$

**PLB 714 (2012) 136–157**

- $p_T$ distribution falls faster than measured $b$-mesons spectra and than predicted spectra from NLO MC **POWHEG** and leading-order MC **PYTHIA**

- Cross-section ratio $\sigma(\Lambda_b^0)/\sigma(\Lambda_b^0)$ consistent with 1 and constant vs $p_T$, and rapidity $|y|$
$\Lambda^0_b$ polarisation

- Polarisation measurements from LHCb are consistent with zero:

\[
P(\Lambda^0_b) = 0.06 \pm 0.07 \pm 0.02 \quad \text{Phys.Lett.B 724 (2013) 27}
\]
\[
P(\Lambda^0_b) = (-0.2 \pm 2.3)\% \quad \text{Phys.Rev.Lett 115 (2015) 072001}
\]

- Effect of $\Lambda^0_b$ polarisation estimated to be negligible on CPV asymmetries

\[
\text{JHEP 04 (2014) 087} \quad \text{JHEP 1407 (2014) 103}
\]

- Effect studied using MC sample polarised at generation level and control samples
Parity violation in $\Lambda_b^0 \rightarrow J/\psi \Lambda$

- Parity violation is not maximal in hadron weak decays and depends on hadron constituents. In $b$-baryons can be predicted by perturbative QCD (pQCD) and heavy quark effective theory (HQET).

\[ w(\cos \theta) = \frac{1}{2} \left( 1 + \alpha P \cos \theta \right) \]

- $\Lambda_b^0$ polarisation allowed only to be perpendicular to production plane, due to parity conservation in pp strong interaction.

- Use 4 helicity amplitudes to describe the $\Lambda_b^0 \rightarrow J/\psi \Lambda$ decay.

\[ A(\lambda_\Lambda, \lambda_{J/\psi}) : a_+ = A(1/2, 0), a_- = A(-1/2, 0), \]
\[ b_+ = A(-1/2, -1), b_- = A(1/2, 1) \]
Parity violation results

- <P>=0 in a symmetric interval in pseudorapidity
- Assume CP conservation and extract α from a simplified angular analysis with 5 independent parameters

\[ \alpha = |a_+|^2 - |a_-|^2 + |b_+|^2 - |b_-|^2 \]

\[ = 0.30 \pm 0.16 \pm 0.06 \]

- Consistent with LHCb measurement
  \[ \alpha = 0.05 \pm 0.17 \pm 0.07 \]
  but not with pQCD [-0.17,-0.14] and HQET predictions 0.78
- LHCb measured \( P = 0.06 \pm 0.07 \pm 0.02 \)
LHCB tracking system

TT: 500µm thick, single sided Si strip detector, pitch~100-200µm, vertical and stereo angle strips arrangement (x-u-v-x)=(0°,-5°,+5°,0°)
Ghost track = is a fake track. For example it can be formed by matching a real track segment in the VELO (VELO seed) with a real track segment in the downstream tracker (T seed)