CP violation in heavy baryons: experimental results and prospects

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Implications of LHCb measurements and future prospect
CERN, 12-14 October 2016
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 $\rightarrow$ 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 $\Lambda_b^0 \to \Lambda D^0$, $\Lambda_b^0 \to \Lambda \bar{D}^0$, $\Lambda_b^0 \to \Lambda D_{CP}^0$
  and charge conjugate decays à la GLW

- Theory clean measurement of $\gamma$ using baryons

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

- Use $\Lambda_b^0 \to D^0 pK^-$ for improved reco efficiency
Search for CPV in charm baryons


- 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

$\Lambda_c^+ \rightarrow p\pi^-\pi^+$

- 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

\[A_P(B^0) = (-0.35 \pm 0.76 \pm 0.28)\%, \quad A_P(B_s^0) = (1.09 \pm 2.61 \pm 0.66)\%\]

\[A_{prod}(D_s^+) = (-0.33 \pm 0.13 \pm 0.18 \pm 0.10)\%, \quad A_{prod}(D^+) = (-0.96 \pm 0.19 \pm 0.18 \pm 0.18)\%\]

- Next step, measure $A_P(B^+)$ and obtain $A_P(\Lambda_b^0)$ 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
  \[ A_D(\pi^\pm) \sim 0.1\% \quad A_D(K^\pm) \sim 1\% \quad A_D(p/\bar{p}) \sim 1 - 2\% \]

- \( A_D \) can be measured using "ad hoc" abundant control samples, see Phys. 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:

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

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

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

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

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

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

\[
C_T = \vec{p}_p \cdot (\vec{p}_{h_1^-} \times \vec{p}_{h_2^+}) \\
\overline{C}_T = \vec{p}_p \cdot (\vec{p}_{h_1^+} \times \vec{p}_{h_2^-})
\]

\[
A_T(C_T) = \frac{N(C_T > 0) - N(C_T < 0)}{N(C_T > 0) + N(C_T < 0)}, \text{ for } \Lambda_b
\]

\[
\overline{A}_T(\overline{C}_T) = \frac{\overline{N}(-C_T > 0) - \overline{N}(-C_T < 0)}{\overline{N}(-C_T > 0) + \overline{N}(-C_T < 0)}, \text{ for } \overline{\Lambda}_b
\]

Largely insensitive to \(A_{\text{prod}}\) and \(A_{\text{reco}}\)

- 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 \(\pi\)

\[
a_{CP}^{\hat{T}\text{-odd}} = \frac{1}{2} (A_T - \overline{A}_T)
\]

\(\hat{T}\) = motion reversal operator

\(\delta\): strong phase

\(\varphi\): weak phase

\(\hat{T}\text{-even}\) \(\hat{T}\text{-odd}\) amplitudes

\(A_1\) \(A_2\) amplitudes


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 signal events

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

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

- Transitions governed by $b\rightarrow ud\bar{u}$ tree and $b\rightarrow du\bar{u}$ 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

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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:

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

\[ \overline{C}_{\hat{T}} = \bar{p}_p \cdot (\bar{p}_{h_1^+} \times \bar{p}_{h_2^-}) \propto \sin \Phi, \text{ for } \overline{\Lambda}_b^0 \]
First evidence for CP violation in baryons

![Graph showing Asymmetries (%) vs |Φ| [rad] for LHCb and Scheme B](image)

- Combined results of 2 binning schemes:
  - CP symmetry p-value=9.8×10^{-4}
  - 3.3σ deviation

- 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 $\gamma$

$\Lambda_b^0 \to D^0 pK^-$ \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 $D^0pK^-$, 20k $\bar{D}^0pK^-$, 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 $A_{\text{CP}}(pK^{*-}) \sim 20\%$ predicted in SM
  - Hsiao Y.K., Phys.Rev. D91 (2015) no.11, 116007

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

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

\[
\Lambda_b^0 \rightarrow (K_s^0 p)_{\Lambda_c^+} \pi^- \]

\[
\Lambda_b^0 \rightarrow \Lambda h^+ h^-, \Lambda_b^0 \rightarrow \Lambda \phi \]

$A_{\text{CP}} = 0.22 \pm 0.13 \pm 0.03$ 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

JHEP 05 (2016) 081  
Search CPV in rare $\Lambda_{b}^{0} \rightarrow pK^{-}\mu^{+}\mu^{-}$

- Rare FCNC decay with very small CPV in the SM, sensitive to new CPV sources via loop diagrams

LHCb-ANA-2015-055
$\Lambda_{b}^{0} \rightarrow pK^{-}\mu^{+}\mu^{-} = 600 \pm 44 \quad L_{\text{int}} = 3 \text{ fb}^{-1}$

- Measure $\Delta A_{CP}$ and $a_{T}^{CP}$
- Use abundant $J/\psi pK^{-}$ control mode
- Present precision on CPV is $5 \cdot 10^{-2}$
- Precision of $4 \cdot 10^{-3}$ is achievable with $300 \text{ fb}^{-1}$
\( b \) charmless decays

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

\[ \Xi^0_b \rightarrow p\pi^+K^-K^- \]
\[ N_{\text{sig}} = 709 \pm 45 \]

\[ \Xi^-_b \rightarrow pK^-K^- \]
\[ N_{\text{sig}} = 83 \pm 10 \]

LHCb unofficial
\[ L_{\text{int}} = 3 \text{ fb}^{-1} \]

LHCb-ANA-2014-077

not published yet

LHCb-ANA-2014-087
LHCb statistics and perspectives

LHCb data sample

From Chris Parkes at ECFA workshop, Oct16

- 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 $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ 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 $\mathcal{B}(\Lambda_b^0 \rightarrow p\bar{p}n) = (2.0^{+0.3}_{-0.2}) \times 10^{-6}$
- Other modes $\Lambda_b^0 \rightarrow p\bar{p}\Lambda, \Lambda_b^0 \rightarrow \Lambda\bar{\Lambda}\Lambda$
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 $\propto V_{tb}V_{td} \sim \lambda^3$ ($|V_{us}| = \lambda$)

$\Lambda_b^0 \rightarrow J/\psi p\pi^- \quad 2102 \pm 61$

$\Lambda_b^0 \rightarrow J/\psi pK^- \quad 11179 \pm 109$
Search for CP violation

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

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

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

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

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

- 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 $\times$ phase space factor

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

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

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

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

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

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

Candidates / ($20 \text{ MeV}/c^2$)
Signal yields

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

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

$$N_{\text{sig}}(\Lambda\pi^+\pi^-) = 64 \pm 14, 4.7\sigma$$
b→sâ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

\[ N_{\text{sig}}(\Lambda_b^0 \rightarrow \Lambda \phi) = 89 \pm 13, \quad 5.9\sigma \]
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

$\hat{n}_\Lambda = \frac{\hat{e}_Z \times \hat{n}_i}{|\hat{e}_Z \times \hat{n}_i|}$  \( i \in \{\Lambda, \phi\} \)

triple products:

$$\cos \Phi_{n_i} = \hat{e}_Y \cdot \hat{u}_i$$

$$\sin \Phi_{n_i} = \hat{e}_Z \cdot (\hat{e}_Y \times \hat{u}_i)$$


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

Figure 3: Decay angles for the $\bar{c}b \to \bar{c}J/\psi$ decay, where the angles are defined in the text.

Note that the basis $\{\vec{e}_X, \vec{e}_Y, \vec{e}_Z\}$ defines the $\bar{c}b$ rest frame, in which $\vec{e}_Z$ is parallel to $\vec{e}_3$, and $\vec{n}_\bar{c}$ ($V_{c\bar{c}}$) is the normal vector to the $\bar{c}b$ decay plane 1.

Asymmetries in $\cos n_i$ and $\sin n_i$, where $i \in \{\bar{c}, J/\psi\}$, are defined as

$$A_{\bar{c}} = \frac{N(\cos n_i > 0) - N(\cos n_i < 0)}{N(\cos n_i > 0) + N(\cos n_i < 0)} \quad (11)$$

$$A_{\bar{s}} = \frac{N(\sin n_i > 0) - N(\sin n_i < 0)}{N(\sin n_i > 0) + N(\sin n_i < 0)} \quad (12)$$

while Leitner and Ajaltouni provide no predictions for $\bar{c}b \to \bar{c}J/\psi$, predictions for $\bar{c}b \to \bar{c}\phi$ are determined to be

$$A_{\bar{c}}(\bar{c}b \to \bar{c}J/\psi) = 0.13\pm0.12\pm0.05 \quad (13)$$

$$A_{\bar{s}}(\bar{c}b \to \bar{c}J/\psi) = -0.22\pm0.12\pm0.06 \quad (14)$$

$$A_{\bar{c}}(\bar{c}b \to \bar{c}\phi) = -0.07\pm0.12\pm0.01 \quad (15)$$

$$A_{\bar{s}}(\bar{c}b \to \bar{c}\phi) = -0.01\pm0.12\pm0.03 \quad (16)$$

It should be noted that $A_{\bar{c}}(\bar{c}b \to \bar{c}J/\psi)$ are found to be zero.

Note that $\vec{e}_X, \vec{e}_Y, \vec{e}_Z$ are basis vectors in the $\bar{c}b$ rest frame, whereas $\vec{e}_1, \vec{e}_2, \vec{e}_3$ denote basis vectors in the laboratory frame.

Consistent with CP symmetry

See G. Durieux, arXiv:1608.03288
Asymmetry measurements

\[ A_{CP}^{\text{raw}} = \frac{N_{f}^{\text{corr}} - N_{\bar{f}}^{\text{corr}}}{N_{f}^{\text{corr}} + N_{\bar{f}}^{\text{corr}}} \]

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


\[ A_{CP} = A_{CP}^{\text{raw}} - (A_{P} + A_{D}) \]
\[ = A_{CP}^{\text{raw}}(\Lambda_{b}^{0} \rightarrow \Lambda h^{+} h^{-}) - A_{CP}^{\text{raw}}(\Lambda_{b}^{0} \rightarrow (\Lambda \pi^{+})_{\Lambda_{c}^{+}} \pi^{-}) \]

Use \( \Lambda_{b}^{0} \rightarrow (\Lambda \pi^{+})_{\Lambda_{c}^{+}} \pi^{-} \) as control model:

negligible CPV effect, production asymmetry \( A_{P} \) and most detection asymmetry \( A_{D} \) cancel

\[ A_{CP}(\Lambda_{b}^{0} \rightarrow \Lambda K^{+} \pi^{-}) = -0.53 \pm 0.23 \pm 0.11 \]
\[ A_{CP}(\Lambda_{b}^{0} \rightarrow \Lambda K^{+} K^{-}) = -0.28 \pm 0.10 \pm 0.07 \]
$\Lambda_b^0 \rightarrow p \pi^- \pi^+ \pi^-$ 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 [arXiv:1505.02771]

  ![Graph showing $f_{\Lambda_b^0}/f_d$ vs $p_T$ b-hadron](image)

  - LHCb hadronic
  - LHCb semileptonic
  - LEP average
  - LHCb Fit

  **Note:** LEP average not included in the fit. LHCb measurements are not independent

  - JHEP 08, 143 (2014)
  - PRD85, 032008 (2012)
Production kinematic dependence

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

- Measure

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

where $R(x) \equiv \frac{N_{\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-}(x)}{N_{\overline{B}^0 \rightarrow D^+\pi^-}(x)} \times \frac{\varepsilon_{\overline{B}^0 \rightarrow D^+\pi^-}(x)}{\varepsilon_{\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-}(x)}$, and $x = p_T, \eta$

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

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

Exponential dependence vs $p_T$

Linear dependence vs $\eta$
\( \Lambda^0_b \) production cross-section

- Measurement of differential production cross-section for \( \Lambda^0_b \) using \( \Lambda^0_b \to J/\psi \Lambda \) decays with \( J/\psi \to \mu^+ \mu^- \), \( \Lambda \to p\pi^- \)

- Cross-section ratio \( \sigma(\bar{\Lambda}^0_b) / \sigma(\Lambda^0_b) \) consistent with 1 and constant vs \( p_T \) and rapidity \( |y| \)

- \( p_T \) distribution falls faster than measured \( b \)-mesons spectra and than predicted spectra from NLO MC \textsc{powheg} and leading-order MC \textsc{pythia}
$\Lambda_b^0$ polarisation

- Polarisation measurements from LHCb are consistent with zero:

\[ P(\Lambda_b^0) = 0.06 \pm 0.07 \pm 0.02 \]
\[ P(\Lambda_b^0) = (-0.2 \pm 2.3)\% \]


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

JHEP 04 (2014) 087
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).

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

- $\Lambda_b^0$ 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 $\alpha$ from a simplified angular analysis with 5 independent parameters

\[
\alpha = |a_+|^2 - |a_-|^2 + |b_+|^2 - |b_-|^2 = 0.30 \pm 0.16 \pm 0.06
\]

- Negative helicity states for $\Lambda$ are preferred.

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

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

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

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

- Consistent with LHCb measurement

\[
\alpha = 0.05 \pm 0.17 \pm 0.07 \quad \text{PLB 724, 27 (2013)}
\]

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)