Recent LHCb Results on Baryonic B Decays and b-Baryon Decays

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INSTITUT FÜR PHYSIK

LHCb

Cosmology and Baryons

Strong motivation: baryon antibaryon asymmetry in the universe

Sacharow Criteria

1. Baryon number violating processes
2. C and CP violation
3. Thermal non-equilibrium

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An open field of research
$\to$ concentrate on production and CP violation

QCD and Baryons

There are two phases for baryon production

- Produced at very large scales $\rightarrow$ Quark-Gluon-Plasma
- Produced in weak decays at lower scales

Argus Measurement (Z.Phys.C56:1-6,1992)

$$\mathcal{B}(B \rightarrow \text{baryons}) = (6.8 \pm 0.5\,(\text{stat}) \pm 0.3\,(\text{syst}))\%$$

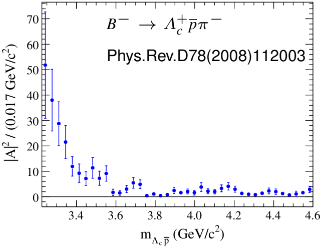
- B decays allow to study baryon production at low jet energies
- Realm of non-perturbative QCD $\rightarrow$ Help theorists to develop and test different models
- High statistics of the B Factories and LHCb also allow to search for very rare decays $\rightarrow$ Search for baryon number violation

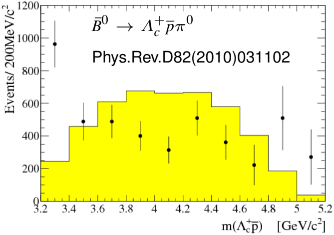
Baryonic B Decays

- Hierarchy in baryonic B decays ($\bar{B}^0/B^+ \to \Lambda_c^+ \bar{p}(n \times \pi)$ decays)

$$\mathcal{B}(2-\text{body}) \ll \mathcal{B}(3-\text{body}) < \mathcal{B}(4-\text{body}) \approx \mathcal{B}(5-\text{body})$$

- Different dynamics compared to mesonic Bdecays
  - Enhancement at the $m_{\mathrm{B_1\bar{B}_2}}$ threshold

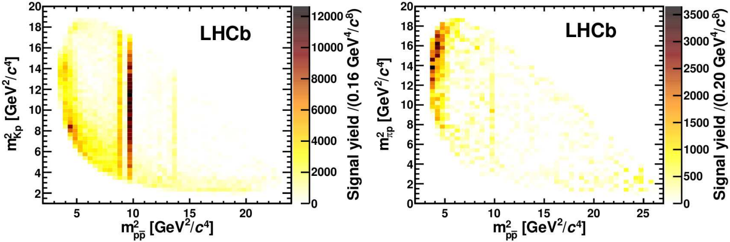




  - Seen in many decays:
    $\bar{B}^0 \to D^0 p\bar{p}$, $B^- \to p\bar{p}h^-$, $\bar{B}^0 \to \Lambda\bar{p}\pi^-$, $e^+e^- \to \gamma\Lambda\bar{\Lambda}$, $J/\psi \to \gamma p\bar{p}$
- Expand research to $\bar{B}_s^0$ and B_c^- mesons

Search for $B_c^- \to p\bar{p}\pi^-$

- Baryonic B_c^+ decays are an untouched field of research (inaccessible to *BABAR* and Belle)



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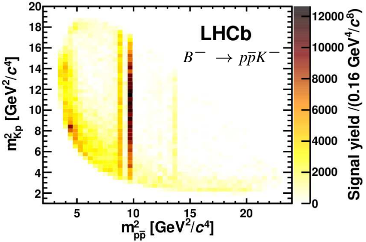
- Allows to apply what we learned from $\bar{B}^0$ and B^- decays

Phys. Rev. Lett. 113 (2014) 141801



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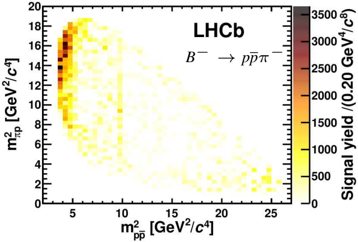

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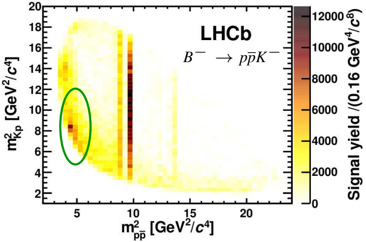

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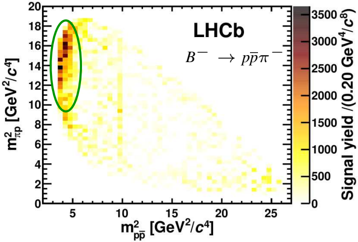

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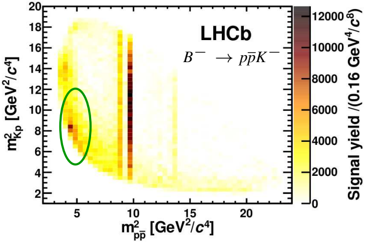

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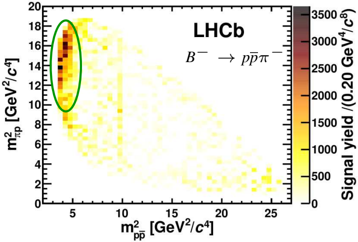
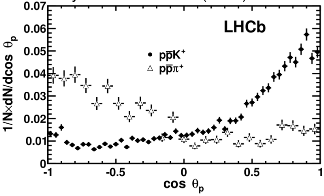


Angular distribution of the enhancement:

Phys. Rev. Lett. 113 (2014) 141801



Beauty Baryons

- Largely undeveloped field of research
- Experimental surge since the start of LHCb
- Unfortunately far ahead of theory
- Theorists more interest in fundamental things

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Focus on CPV and branching fractions

- Recent LHCb analyses
  - Branching fraction for $\Lambda_b^0 \to \Lambda\phi$ (Phys. Lett. B 759 (2016) 282)
  - Branching fraction for $\Lambda_b^0 \to \Lambda h_1^+ h_2^-$ (JHEP 05 (2016) 081)
  - CP violation in $\Lambda_b^0 \to p\pi^- h_1^+ h_2^-$ (LHCB-PAPER-2016-030-001)

External Effects

- Treatment of the hadronisation probabilities f_{Λ_b} and f_{Ξ_b}
- Lack of absolute branching fractions
- Limited knowledge of intermediate states

  Δ and N resonances in $m(p\pi)$
  $\Lambda^* and \Sigma^{0*}$ $resonances$ in $m(pK)$ and $m(\Lambda\pi)$
- Treatment of these resonances in Dalitz plot analyses
- Treatment of fermions in Dalitz plot analyses
- Fermion in the initial state

$$d\Gamma \propto |\mathcal{M}|^2 dm_{12}^2 dm_{23}^2 d\Omega_2 d\phi_{23}$$

- Implies five dimensional phase-space, two invariant masses and three angles

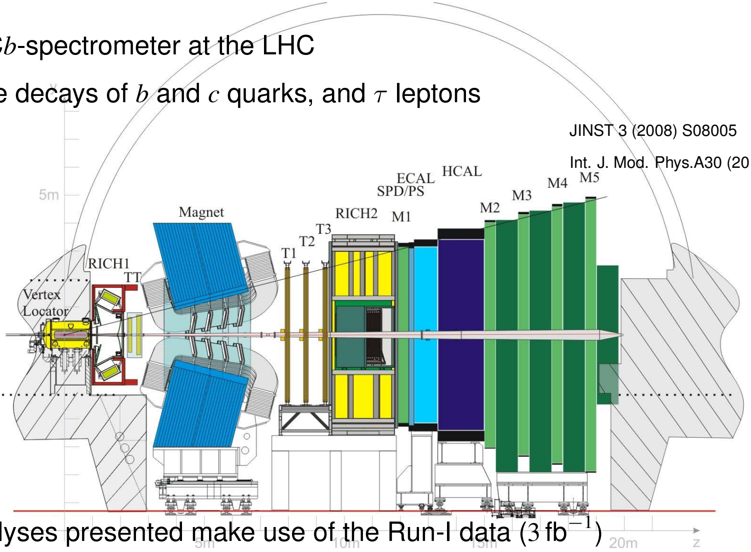
A lot of new things to learn!

LHCb -Detector

- LHCb-spectrometer at the LHC
- Rare decays of b and c quarks, and τ leptons

JINST 3 (2008) S08005

Int. J. Mod. Phys.A30 (2015) 1530022



- Analyses presented make use of the Run-I data ($3\,\text{fb}^{-1}$)
- corresponds to about 20×10^9 Λ_b baryons)

Search for $B_c^- \to p\bar{p}\pi^-$

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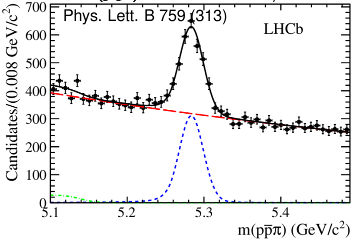
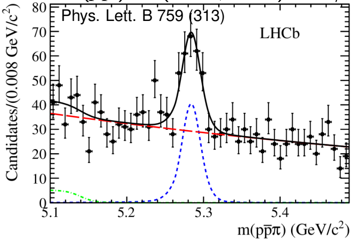
Analysis Strategy

Use $B^- \to p\bar{p}\pi^-$ as normalisation

$m(p\bar{p}) < 2.85\,\mathrm{GeV}/c^2$



$m(p\bar{p}) \in (2.85, 3.15)\,\mathrm{GeV}/c^2$



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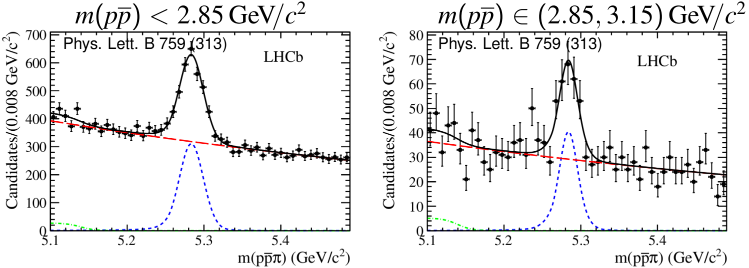


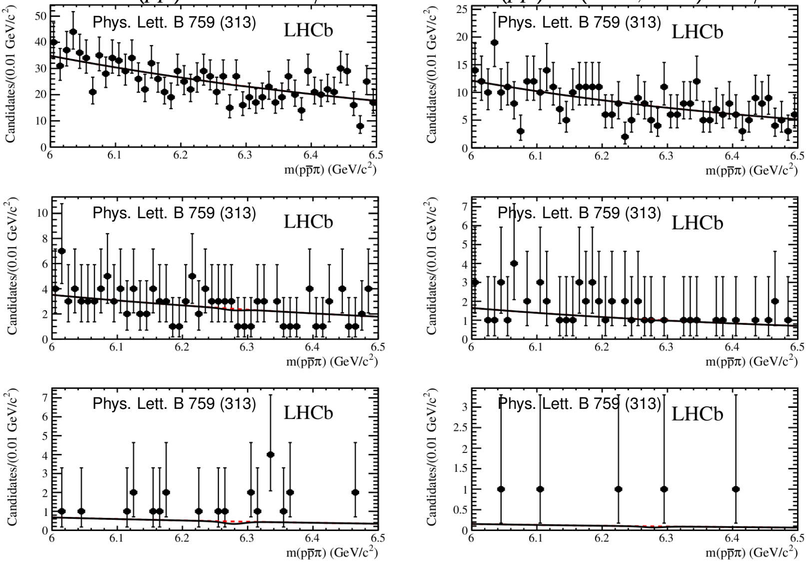
Determine

$$\frac{f_c}{f_u}\mathcal{B}(B_c^- \to p\bar{p}\pi^-) = \frac{N(B_c^- \to p\bar{p}\pi^-)}{N(B^- \to p\bar{p}\pi^-)} \times \frac{\varepsilon_u}{\varepsilon_c} \times \mathcal{B}(B^- \to p\bar{p}\pi^-)$$

- Limit to the enhancement region and J/ψ region as cross check
- `PID` and `BDT` selection making use of topological variables
- Simultaneous fit in three `BDT` regions with similar expected yields

Fit to the Run-I Data

$m(p\bar{p}) < 2.85\,\mathrm{GeV}/c^2$ $m(p\bar{p}) \in (2.85, 3.15)\,\mathrm{GeV}/c^2$



Results for the Run-I Data

Analysis published in Phys. Lett. B 759 (313)

Upper Limits

- Enhancement region

$$\frac{f_c}{f_u} \times \mathcal{B}(B_c^- \to p\bar{p}\pi^-) < 3.6 \times 10^{-8} \text{ @95\%CL.}$$

- J/ψ control region accounting for $\mathcal{B}(J/\psi \to p\bar{p})$

$$\frac{f_c}{f_u} \times \mathcal{B}(B_c^- \to J/\psi\,\pi^-) < 8.6 \times 10^{-6} \text{ @95\%CL.}$$

- Fist search for $b\bar{c}$ annihilation into a baryonic final state
- Limits on the J/ψ region in agreement with the previous measurement (Phys. Rev. Lett. 114 (2015) 132001)

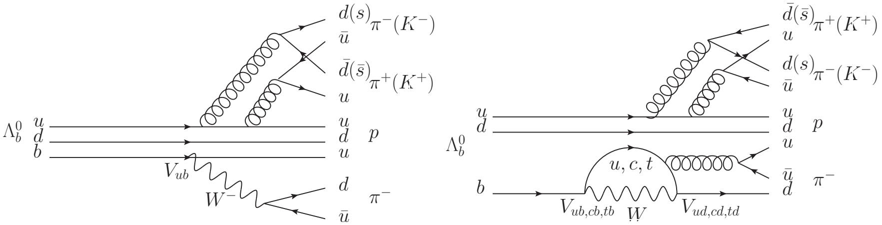
$$\frac{f_c}{f_u} \times \mathcal{B}(B_c^- \to J/\psi\,\pi^-) = (7.0 \pm 0.3) \times 10^{-6}$$

Search for CPV in $\Lambda_b^0 \to p\pi^- h_1^+ h_2^-$

Search for CPV in $\Lambda_b^0 \to p\pi^- h_1^+ h_2^-$

Physics of $\Lambda_b \to p\pi^- h_1^+ h_2^-$ decays

- Inference of a $b \to u$ tree and a $b \to d$ penguin amplitude
- Interference is proportional to γ
- Amplitude $A(b \to d) < A(b \to s)$ →larger interference effect



CPV in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ and $\Lambda_b^0 \to p\pi^-K^-K^+$

- Several methods of measuring direct P, T, and CP violation
- Scalar Triple Products allow study all three symmetries

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Use Triple Products to Measure P Violation

- Measure the expectation value of P-odd observables

$$\mathcal{O} = \boldsymbol{p}_1 \cdot (\boldsymbol{p}_2 \times \boldsymbol{p}_3) \quad \text{with} \quad \mathrm{T}\boldsymbol{p} = -\boldsymbol{p}, \mathrm{P}\boldsymbol{p} = -\boldsymbol{p}$$

- A non-vanishing expectation value is evidence for P and T violation
- Experimentally easy to access

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Use Triple Products to Measure T and CP Violation

- Measure instead the T-odd observable

$$\mathcal{O} = \boldsymbol{s}_1 \cdot (\boldsymbol{p}_1 \times \boldsymbol{p}_2) \quad \text{with} \quad \mathrm{T}\boldsymbol{s} = -\boldsymbol{s}, \mathrm{P}\boldsymbol{s} = +\boldsymbol{s}$$

- A non-vanishing expectation value is an evidence for T violation
- Not sensitive to Parity violation $\mathrm{P}\boldsymbol{s} = +\boldsymbol{s}$
- Experimentally difficult to access

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- Goal is to search for CP violation:

$$\mathcal{O} = \boldsymbol{p}_p \cdot (\boldsymbol{p}_{h_1^+} \times \boldsymbol{p}_{h_2^-}) \text{ with } h_1 = h_2 = \pi \text{ and } h_1 = \pi, h_2 = K$$

- Pion ambiguity solved by choosing the higher momentum pion

From Triple Product to CP Violation

Use the Triple Product $\mathcal{O} = \boldsymbol{p}_p \cdot (\boldsymbol{p}_{h_1^+} \times \boldsymbol{p}_{h_2^-})$

- Determine the asymmetry

$$A_T = \frac{N(\mathcal{O} > 0) - N(\mathcal{O} < 0)}{N(\mathcal{O} > 0) + N(\mathcal{O} < 0)}$$

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$$a_{T-\mathrm{odd}}^{\mathrm{P}} = {}^1\!/\!_2(A_T + \bar{A}_T)$$

$$a_{T-\mathrm{odd}}^{\mathrm{CP}} = {}^1\!/\!_2(A_T - \bar{A}_T) \propto \sin\phi_{\mathrm{weak}} \cos\delta_{\mathrm{strong}}$$

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- $\mathcal{A}_{T-\mathrm{odd}}^{\mathrm{CP}}$ is maximal in the vanishing limit of δ_{strong}
- All variables are largely insensitive to production and detector induced asymmetries

Extracting $\mathcal{A}_{T-\mathrm{odd}}^{\mathrm{CP}}$ and $\mathcal{A}_{T-\mathrm{odd}}^{\mathrm{P}}$

- Split the data into additional four sets
  - $(\Lambda_b^0, \mathcal{O} > 0)$, $(\Lambda_b^0, \mathcal{O} < 0)$, $(\overline{\Lambda}_b^0, \bar{\mathcal{O}} > 0)$, $(\overline{\Lambda}_b^0, \bar{\mathcal{O}} < 0)$
  - Fit for the asymmetry by modifying the individual yields
- Decay modes until now unobserved

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- Decay modes observed for the first time

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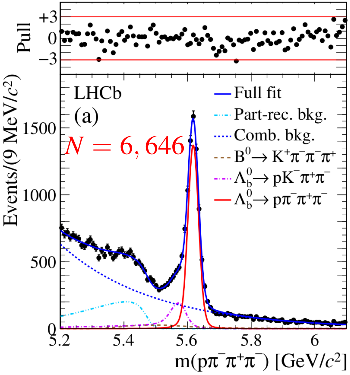

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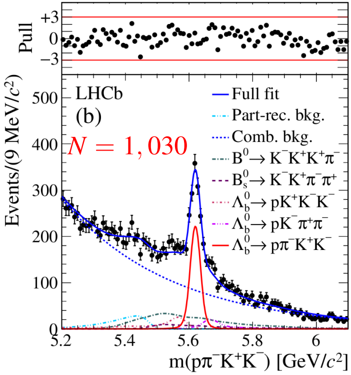

Results for $\mathcal{A}_{T-\mathrm{odd}}^{\mathrm{CP}}$ and $\mathcal{A}_{T-\mathrm{odd}}^{\mathrm{P}}$

- Results for the global fit

Λ_b^0 decay	$a_{T-\mathrm{odd}}^{\mathrm{CP}}$ [%]	$a_{T-\mathrm{odd}}^{\mathrm{P}}$ [%]
$p\pi^-\pi^+\pi^-$	$-1.15 \pm 1.45 \pm 0.32$	$-3.71 \pm 1.45 \pm 0.32$
$p\pi^-K^+K^-$	$-0.93 \pm 4.54 \pm 0.42$	$-3.62 \pm 4.54 \pm 0.42$

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- Larger $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ statistics allow further studies
- CP violation often dependent on resonances in the phase space

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- Global asymmetries consistent with neither CP nor P violation
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- CP violation often dependent on resonances in the phase space
- Introduce two binning schemes

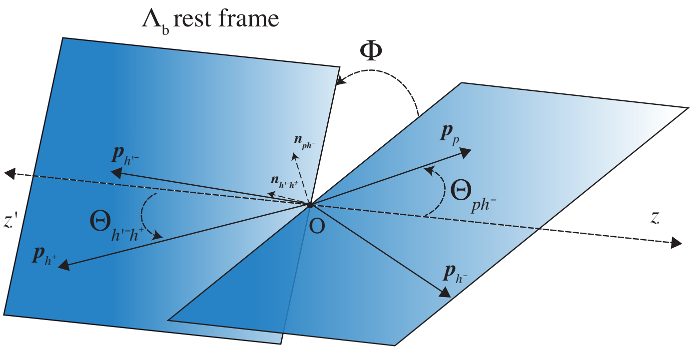
Phase space: Binning scheme chosen to reflecting known resonances

Angle between decay planes Φ: Binning scheme depending on the relative angle between the the $p\pi^-{}_{\mathrm{fast}}$ and $\pi^+\pi^-{}_{\mathrm{slow}}$ decay planes

Phase Space Binning

- Making use of a 5D phase space
- Define twelve bins describing
  - The $\Delta^{++}(1232) \to p\pi^+$ region in four bins
    - Left and right hand side of the Δ peak
    - Separate two Φ intervals $(0, \pi/2)$, $(\pi/2, \pi)$
  - Nucleon resonances $N^* \to p\pi^-{}_{\text{slow}}$ and $\rho \to \pi^+\pi^-{}_{\text{slow/fast}}$
    - $m(p\pi^+) > m(\Delta^{++})$
    - Separate $m(p\pi^-{}_{\text{slow}})$ at $2\,\text{GeV}/c^2$ since $m(N^*) < 2\,\text{GeV}/c^2$
    - Pion pair compatible with ρ hypothesis and above
    - Each separated into two Φ intervals $(0, \pi/2)$, $(\pi/2, \pi)$
- Binning depending on the angle Φ integrating over the invariant masses

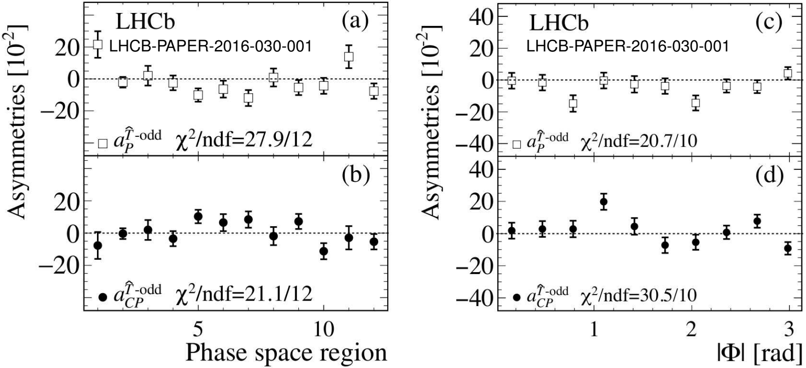
Angular Binning



- Chosen Binning

$$\left(\frac{i-1}{10}\pi, \frac{i}{10}\pi\right) \quad \text{with} \quad i = 1, 2, \ldots, 10$$

Phase Space Dependence



- CP violation determined by several global χ^2 tests against the CP conservation hypothesis
- Combined statistical significance against CP conservation

$$\mathcal{S} = 3.3\sigma$$

Results for the Run-I data

Observation of two $\Lambda_b^0 \to p\pi^- h_1^+ h_2^-$ modes

- Observation of $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ and $\Lambda_b^0 \to p\pi^- K^- K^+$

$$
\begin{aligned}
N(\Lambda_b^0 \to p\pi^-\pi^+\pi^-) &= 6,646 \\
N(\Lambda_b^0 \to p\pi^- K^- K^+) &= 1,030
\end{aligned}
$$

- Next step: determination of the branching fractions

Evidence for CP violation in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$

- Using triple products no phase space integrated CP violation
- Phase space dependent CP violation of $\mathcal{S} = 3.3\sigma$
- No local or global evidence for parity violation

Evidence for CP violation in $\Lambda_b^0 \to p\pi^- K^+ K^-$

- No local or global evidence for P or CP violation

Conclusions

- Small overview of the LHCb activities in this field of research

Search for $B_c^- \to p\bar{p}\pi^-$

$$\frac{f_c}{f_u} \times \mathcal{B}(B_c^- \to p\bar{p}\pi^-) < 3.6 \times 10^{-8} \text{ @95\%CL.}$$

Search for CP violation in $\Lambda_b^0 \to p\pi^- h_1^+ h_2^-$ decays

- Observation of $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ and $\Lambda_b^0 \to p\pi^- K^+ K^-$
- Phase space dependent CP violation for $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$

$$\mathcal{S} = 3.3\sigma$$

- Update using the Run-II data as soon as possible

- A lot of interesting analyses in the pipeline

Thank you for your attention