Search for CP violation in $\Lambda_b^0(\Xi_b^0) \to p3h$ (h = π,K) and study of $B_{(s)}^0 \to J/\psi p\bar{p}$

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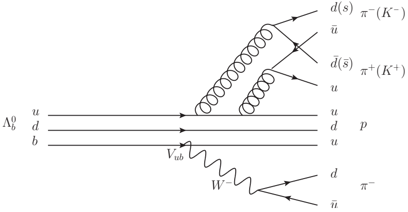
First observation of $\Lambda_b^0(\Xi_b^0) \to p h^- h^+ h^-$ decays and
First measurement of CP violation using triple product asymmetries in $\Lambda_b^0(\Xi_b^0) \to p h^- h^+ h^-$ decays.

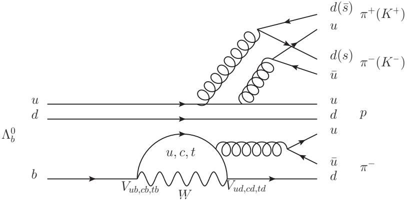
Physics Motivation

- CPV never observed in baryon sector, possible large CPV from interference between tree and penguin diagram.

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



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



- Triple products (TP) in Λ_b^0 decays particularly sensitive to new physics: "*Triple products which are expected to vanish in the SM can be enormous (50%) in the presence of new physics*"
Phys.Rev. D66 (2002) 094004; arXiv:hep-ph/0208054v2

Experimental Technique

- $\widehat{T}$-odd triple products: in Λ_b^0, Ξ_b^0 ($\overline{\Lambda}_b^0$, $\overline{\Xi}_b^0$) rest frame

  $C_T \equiv \vec{p}_p \cdot (\vec{p}_h \times \vec{p}_{h'})$, for Λ_b^0, Ξ_b^0; $\bar{C}_T \equiv \vec{p}_{\overline{p}} \cdot (\vec{p}_{\bar{h}} \times \vec{p}_{\bar{h}'})$, for $\overline{\Lambda}_b^0$, $\overline{\Xi}_b^0$
  choose the one with higher momentum for the identical charged tracks.

- $\widehat{T}$-odd observables:
  $A_{\widehat{T}} \equiv \frac{N(C_T>0)-N(C_T<0)}{N(C_T>0)+N(C_T<0)}$, for Λ_b^0, Ξ_b^0;
  $\bar{A}_{\widehat{T}} \equiv \frac{N(-\bar{C}_T>0)-N(-\bar{C}_T<0)}{N(-\bar{C}_T>0)+N(-\bar{C}_T<0)}$, for $\overline{\Lambda}_b^0$, $\overline{\Xi}_b^0$

  theoretical interests on TP: arXiv1506.01346,1508.03054

- True CP-violating observable: cancel FSI effects

$$a_{CP}^{\widehat{T}\text{-odd}} = \frac{1}{2}(A_{\widehat{T}} - \bar{A}_{\widehat{T}})$$

- $\Lambda_b^0/\overline{\Lambda}_b^0$ production asymmetry and $p/\overline{p}$, h^+/h^- reconstruction asymmetry cancel in definition $\Rightarrow$ low systematic uncertainty .

- Complementary approach to A_{CP} asymmetry method:
  $A_{CP} \propto \sin(\delta_1 - \delta_2)\sin(\phi_1 - \phi_2)$: 1,2 different amplitudes
  $a_{CP}^{\widehat{T}\text{-odd}} \propto \cos(\delta_k - \delta_j)\sin(\phi_k - \phi_j)$: k,j different partial wave amplitudes

Experimental status on b-baryon decays

- Previous measurements of A_{CP} consistent with no CPV.
- No experiment performed using $a_{CP}^{\widehat{T}\text{-odd}}$ method so far.

Collaboration	A_{CP}
CDF	$A_{CP}(\Lambda_b^0 \to pK^-) = 0.37 \pm 0.17_{stat} \pm 0.03_{syst}$ [1]
	$A_{CP}(\Lambda_b^0 \to p\pi^-) = 0.03 \pm 0.17_{stat} \pm 0.05_{syst}$ [1]
LHCb	$A_{CP}(\Lambda_b^0 \to \overline{K^0}p\pi^-) = 0.22 \pm 0.13_{stat} \pm 0.03_{syst}$[2]
LHCb	$A_{CP}(\Lambda_b^0 \to J/\psi p\pi^-)$
	$-A_{CP}(\Lambda_b^0 \to J/\psi pK^-) = [5.7 \pm 2.4_{stat} \pm 1.2_{syst}]\%$ [3]

[1] Phys. Rev. Lett. 106 (2011) 181802
[2] JHEP 04 (2014) 087
[3] JHEP 1407 (2014)

Analysis Status

- Authors: Jinlin Fu, Maurizio Martinelli, Andrea Merli, Nicola Neri.
- Have completed the blind analysis on stripping21 data ($3fb^{-1}$).
- Received sign-off from WG reviewers.
- Waiting for 1st round of comments from RC (StevePlayfer, Mike Sokoloff).

Selection

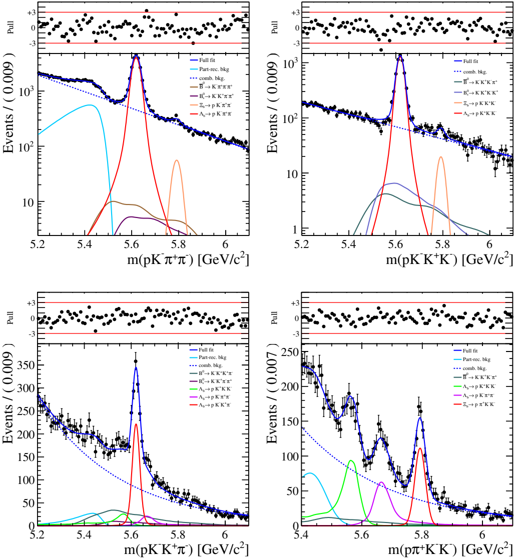
- Stripping21, Xb2phhhline
- Trigger requirement
  - L0: Hadron TOS or Global TIS on Λ_b^0
  - HLT1: TrackAllL0 TOS on Λ_b^0
  - HLT2: Topo(2,3,4)(Simple,BBDT) TOS on Λ_b^0
- Veto resonances, c-quark long lived particles.
- BDT selection:
  using $\Lambda_b^0 \to pK^-\pi^+\pi^-$ real data sample for all $p3h$ decays.
- $\mathrm{PID}_{\pi,K,p}$ optimization :
  use control samples composed of vetoed resonances after BDT.
- Multiple candidates: retain one candidate per event by random choice.

Fit Model

- Signal model: from MC(sum of Crystal Ball)
  $pdf_{sig} = f \cdot CB_1(\mu, \sigma, \alpha_1, n_1) + (1-f) \cdot CB_2(\mu, \sigma, \alpha_2, n_2)$
  tail parameters (α,n) and fraction (f) fixed from MC

- Background model:
  - Combinatorial background: exponential function
  - Partially-reconstructed backgrounds: Argus function convoluted with a Gaussian function
  - Cross-feed: $\Lambda_b^0 \to p3h, B^0/B_s^0 \to 4h$
    Described by MC shape (RooKeysPdf)
    Gaussian constraint yields from mass fit in data assuming particle misidentification.

Invariant mass fit



All first observations:

$\Lambda_b^0 \to pK^-\pi^+\pi^-$: 20121 ± 173

$\Lambda_b^0 \to pK^-K^+K^-$: 5332 ± 82

$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$: 6631 ± 105

$\Lambda_b^0 \to pK^+K^-\pi^-$: 1030 ± 56

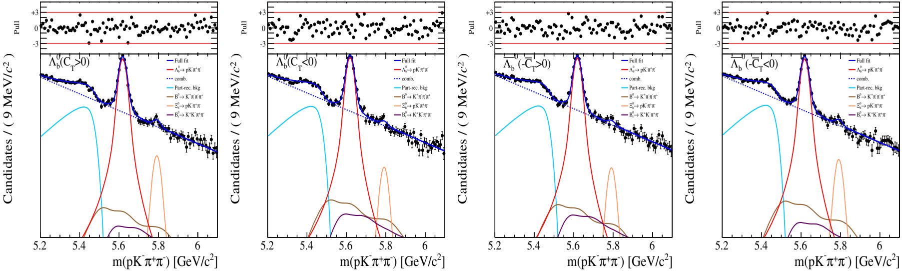
$\Xi_b^0 \to pK^-K^-\pi^+$: 719 ± 43

$\Xi_b^0 \to pK^-\pi^+\pi^-$: 277 ± 51

$\Xi_b^0 \to pK^-K^+K^-$: 82 ± 21

Simultaneous fit:

Example of $\Lambda_b^0 \to pK^-\pi^+\pi^-$, blind results.



$$A_{\widehat{T}} = (-3.29 \pm 1.12_{stat.}) \times 10^{-2}$$
$$\bar{A}_{\widehat{T}} = (-10.50 \pm 1.18_{stat.}) \times 10^{-2}$$
$$a_{CP}^{\widehat{T}\text{-odd}} = (3.60 \pm 0.81) \times 10^{-2}$$

Systematic Uncertainty Sources

- **Experimental bias**: induced by the experimental reconstruction, detector acceptance, and the selection criteria.
  - a possible experimental bias estimated using control sample (cs) $\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\pi^-$, CPV in SM expected to be consistent with zero.
  - assign the statistical uncertainty on $a_{CP}^{\widehat{T}\text{-odd}}$ $(\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\pi^-)$ as a systematic uncertainty on signal decays.
  - conservatively estimate systematic uncertainties on $A_{\widehat{T}}$ and $\bar{A}_{\widehat{T}}$ as $\sigma(A_{\widehat{T}}) = \sigma(\bar{A}_{\widehat{T}}) = \sqrt{2}\sigma(a_{CP}^{\widehat{T}\text{-odd}})_{cs}$.
- **Fit Model**: due to parametrisation of the signal and background shapes of reconstructed $m(p3h)$, estimated from toy studies.
- **Detector resolution**: due to the resolution on triple products C_T and $\bar{C}_T$, bias between the reconstructed and generated asymmetries in MC sample assumed as systematic uncertainties.

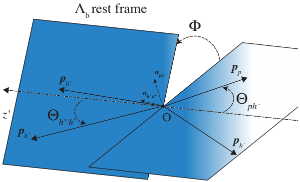
Main results of measurements integrated in the phase space

- First observations: $\Lambda_b^0 \to pK^-\pi^+\pi^-$, $\Lambda_b^0 \to pK^-K^+K^-$, $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$, $\Lambda_b^0 \to pK^+K^-\pi^-$, $\Xi_b^0 \to pK^-K^-\pi^+$, $\Xi_b^0 \to pK^-\pi^+\pi^-$, $\Xi_b^0 \to pK^-K^+K^-$.
- Best sensitivity to CPV in b-baryon decays, so far.

Decay	$A_{\widehat{T}}$ (%)	$\bar{A}_{\widehat{T}}$ (%)	$a_{CP}^{\widehat{T}\text{-odd}}$ (%)
$\Lambda_b^0 \to pK^-\pi^+\pi^-$	$x.x \pm 1.12_{\text{stat}} \pm 0.45_{\text{syst}}$	$x.x \pm 1.18_{\text{stat}} \pm 0.44_{\text{syst}}$	$x.x \pm 0.81_{\text{stat}} \pm 0.31_{\text{syst}}$
$\Lambda_b^0 \to pK^-K^+K^-$	$x.x \pm 2.10_{\text{stat}} \pm 0.70_{\text{syst}}$	$x.x \pm 2.14_{\text{stat}} \pm 0.46_{\text{syst}}$	$x.x \pm 1.50_{\text{stat}} \pm 0.41_{\text{syst}}$
$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$	$x.x \pm 2.06_{\text{stat}} \pm 0.45_{\text{syst}}$	$x.x \pm 2.06_{\text{stat}} \pm 0.44_{\text{syst}}$	$x.x \pm 1.45_{\text{stat}} \pm 0.32_{\text{syst}}$
$\Lambda_b^0 \to pK^+K^-\pi^-$	$x.x \pm 6.78_{\text{stat}} \pm 1.82_{\text{syst}}$	$x.x \pm 6.08_{\text{stat}} \pm 0.48_{\text{syst}}$	$x.x \pm 4.55_{\text{stat}} \pm 0.83_{\text{syst}}$
$\Xi_b^0 \to pK^-K^-\pi^+$	$x.x \pm 7.46_{\text{stat}} \pm 0.49_{\text{syst}}$	$x.x \pm 6.83_{\text{stat}} \pm 0.48_{\text{syst}}$	$x.x \pm 5.06_{\text{stat}} \pm 0.34_{\text{syst}}$

Measurements in the phase space regions

- In order to improve the sensitivity to CPV, a measurement is performed in 5D phase space regions: $m^2_{ph^-}$, $m^2_{h^+h^-}$, $\cos\Theta_{ph^-}$, $\cos\Theta_{h^+h^-}$, Φ.
- Two binning schemes:
  - divide into 8 or 4 regions with equal statistics.



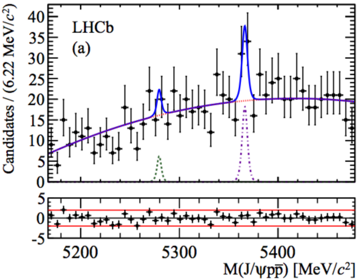
Decays	bins	variables
$\Lambda_b^0 \to pK^-\pi^+\pi^-$	8	$m^2_{pK^-}$, $m^2_{\pi^+\pi^-}$, $\phi_{(pK^-,\pi^+\pi^-)}$
$\Lambda_b^0 \to pK^-K^+K^-$	8	$m^2_{pK^-_{\text{fast}}}$, $m^2_{K^+K^-_{\text{slow}}}$, $\phi_{(pK^-_{\text{fast}},K^+K^-_{\text{slow}})}$
$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$	8	$m^2_{p\pi^-_{\text{fast}}}$, $m^2_{\pi^+\pi^-_{\text{slow}}}$, $\phi_{(p\pi^-_{\text{fast}},\pi^+\pi^-_{\text{slow}})}$
$\Lambda_b^0 \to pK^+K^-\pi^-$	4	$m^2_{p\pi^-}$, $m^2_{K^+K^-}$
$\Xi_b^0 \to pK^-K^-\pi^+$	4	$m^2_{pK^-_{\text{fast}}}$, $m^2_{\pi^+K^-_{\text{slow}}}$

  - divided into two regions with bin boundaries choosen at $\Phi = \frac{\pi}{2}$.
    arXiv:1508.03054v1
- To estimate the compatibility with the no CPV hypothesis, a χ^2 test w.r.t the hypothesis of $a_{CP}^{\widehat{T}\text{-odd}} = 0$ is performed.

Study of $B^0_{(s)} \to J/\psi p\bar{p}$

Physics Motivation (1)

- Never observed, UL with $1fb^{-1}$ at LHCb. arXiv:1306.4489



$$\mathcal{B}(B^0 \to J/\psi p\bar{p}) < 5.2 \times 10^{-7}$$

$$\mathcal{B}(B_s^0 \to J/\psi p\bar{p}) < 4.8 \times 10^{-6}$$

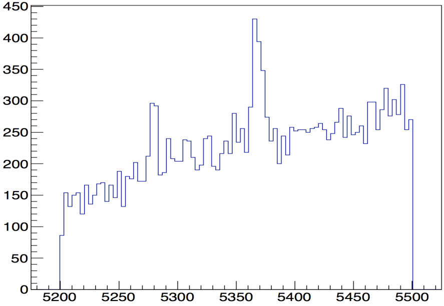
- $B_s^0 \to J/\psi p\bar{p}$ via $s\bar{s} \to p\bar{p}$ leads to OZI suppression w.r.t $B^0 \to J/\psi p\bar{p}$ via $d\bar{d} \to p\bar{p}$.
- The OZI suppression can be lifted by a possible tensor glueball condidate $f_J(2220) \to p\bar{p}$ in B_s^0 decay, while forbidden by the phase space in B^0 decay. arXiv:1412.4900

Physics Motivation (2)

- To investigate pentaquarks in $[J/\psi p]$ or $[J/\psi \bar{p}]$ system:
  - $B^0_{(s)}$ phase space does not allow $P_c(4380)/P_c(4450)$.
  - some lighter candidates: $[\Lambda_c \overline{D^*}] \sim 4295$MeV, $[\Sigma_c \bar{D}] \sim 4321$MeV. arXiv:1506.06386
  - a natural extension to $\Upsilon(1S) \to J\psi p\bar{p}$ with the same ntuple maker.
- To investigate near threshold enhancement in $p\bar{p}$ structure observed in many decays.

First look at data

- stripping21, `FullDSTDiMuonJpsi2MuMuDetachedLine`.
- decay chain constructed by detached J/ψ and StdAllNoPIDsProtons with kinematic cuts on $B^0_{(s)}$ candidates.
- Decay tree fitter with J/ψ mass constraint, and loose PID cuts.



- With hundreds of events, moment analysis could be exploited.

Analysis Strategy

- proponents: Biplab Dey, Jinlin Fu, Nicola Neri.
- Establish decay modes, measure branching fraction, and investigate $J/\psi p\bar{p}$ Dalitz plot, with $3fb^{-1}$.
- BDT selection:
  - signal: MC, background: right sideband.
  - few kinematic variables, ProbNNp and isolation variables to build classifier.
- FOM: for branching fraction, $\frac{\epsilon}{\frac{\alpha}{2}+\sqrt{B}}$; for angular analysis, $\frac{S}{\sqrt{S+B}}$.
- Normalisation mode: $B_s \to J/\psi K^+ K^-$.

THANK YOU

Backup

Analysis Strategy

- Dataset splitted into 4 samples depending on Λ_b^0 flavor and C_T value.
- The number of signal events retrieved by simultaneous fit to the four distributions of $m(p3h)$. Asymmetry parameters $A_{\widehat{T}}$, $\bar{A}_{\widehat{T}}$ extracted from the fit.

$$
\begin{aligned}
N_{\Lambda_b^0, C_T>0} &= \tfrac{1}{2} N_{\Lambda_b^0}(1 + A_{\widehat{T}}), \\
N_{\Lambda_b^0, C_T<0} &= \tfrac{1}{2} N_{\Lambda_b^0}(1 - A_{\widehat{T}}), \\
N_{\overline{\Lambda}_b^0, -\bar{C}_T>0} &= \tfrac{1}{2} N_{\overline{\Lambda}_b^0}(1 + \bar{A}_{\widehat{T}}), \\
N_{\overline{\Lambda}_b^0, -\bar{C}_T<0} &= \tfrac{1}{2} N_{\overline{\Lambda}_b^0}(1 - \bar{A}_{\widehat{T}}).
\end{aligned}
$$

- Two measurements
  - Measurement integrated in the phase space.
  - Measurement in different regions of the phase space.
- $A_{\widehat{T}}$, $\bar{A}_{\widehat{T}}$ are masked with different unknown random offsets, until the systematics have been measured and the results approved by referees.

Checks on other possible sources

- Stability checks: different year, magnet polarity, data taking period, and different L0 trigger requirements, compatible with statistical fluctuations.
- Checks on Multiple Candidates treatment:
  different random seed for different choice, compatible with statistical fluctuations.
- Checks on signal reconstruction efficiency versus C_T value:
  - No correlations among discriminating variables and C_T (data, MC),
  - Raito of efficiencies w.r.t different sign of C_T is compatible with one (signal MC and Control sample $\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\pi^-$).
- Checks on PID effects:
  Using control sample, PID criteria for final particles are varied. Differences of asymmetries are compatible with statistical fluctuations.

Summary of Systematic Uncertainties

The main contribution is from experimental bias or fit model.

Decay	Contribution	$\Delta A_{\widehat{T}}(\%)$	$\Delta \bar{A}_{\widehat{T}}(\%)$	$\Delta a_{CP}^{\widehat{T}\text{-odd}}(\%)$
$\Lambda_b^0 \to pK^-\pi^+\pi^-$	Experimental bias	±0.44	±0.44	±0.31
	C_T resolution	±0.01	±0.01	±0.01
	Fit model	±0.09	±0.04	±0.02
	Total	±0.45	±0.44	±0.31
$\Lambda_b^0 \to pK^+K^-\pi^-$	Experimental bias	±0.44	±0.44	±0.31
	C_T resolution	±0.10	±0.03	±0.06
	Fit model	±1.76	±0.18	±0.77
	Total	±1.82	±0.48	±0.83
$\Lambda_b^0 \to pK^-K^+K^-$	Experimental bias	±0.44	±0.44	±0.31
	C_T resolution	±0.00	±0.10	±0.05
	Fit model	±0.55	±0.06	±0.26
	Total	±0.70	±0.46	±0.41
$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$	Experimental bias	±0.44	±0.44	±0.31
	C_T resolution	±0.09	±0.01	±0.05
	Fit model	±0.06	±0.06	±0.04
	Total	±0.45	±0.44	±0.32
$\Xi_b^0 \to pK^-K^-\pi^+$	Experimental bias	±0.44	±0.44	±0.31
	C_T resolution	±0.06	±0.01	±0.02
	Fit model	±0.21	±0.20	±0.15
	Total	±0.49	±0.48	±0.34