CP violation with b baryons

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Flavour physics and CP violation (5-9 June 2017)

Why is CP violation in *b*-baryon decays interesting?

CP violation in the meson sector

- CP violation first observed in the kaon sector and since been observed and well measured in B^0, B^+ and B_s^0 decays.
- However no deviations from the SM have been conclusively established in the meson sector.

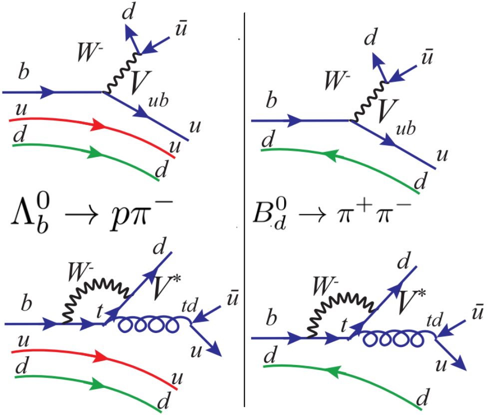
CP violation in the baryon sector

- Not yet observed but CKM mechanism predicts sizeable amount of CPV in *b* baryons.
- At the LHC *b*- baryons are now produced in unprecedented quantities facilitating searches for CPV in the baryon sector
- Important to measure CP asymmetries in as many decay modes as possible to check consistency of the CKM mechanism throughout

What exactly am I going to talk about?

- Discussion of the search for CPV in $\Lambda_b^0 \to p\pi^-$ (K^-) decays at CDF
  (Phys. Rev. Lett, 113:242001, 2014)
- Outline of recent results from the LHCb experiment namely:
  - CP searches in $\Lambda_b^0 \to \Lambda K^+ K^-$ (π^-) (JHEP 05 081 (2016)
  - First evidence for CP violation in baryons (Nature Physics 13, 391396 (2017))
  - Searches for CPV in rare $\Lambda_b^0 \to pK^-\mu^+\mu^-$ decays (arXiv:1703.00256, 2017)
- Discussion of potential future CPV measurements in the baryon sector at LHCb.

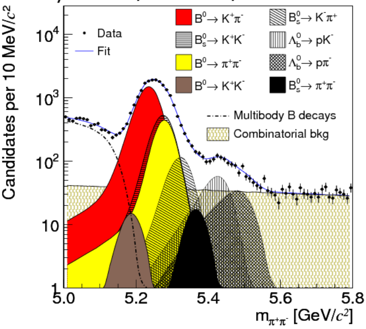
CPV in $\Lambda_b^0 \to pK^-$ (π^-) decays



- Baryon equivalent of $B^0 \to K^+$ $(\pi^+)\pi^-$ decays
- Receives contributions from penguins
- Theoretical predictions fairly precise at $\sim$ 3% uncertainty, Phys. Rev. D 91, 116007 (2015)
- CPV predicted to be around $\sim$ 5% Phys. Rev. D 91, 116007 (2015)

CPV in $\Lambda_b^0 \rightarrow pK^-$ (π^-) decays

Phys. Rev. Lett, 113:242001, 2014



Decay	$N_{b\to f}$	$N_{\bar{b}\to\bar{f}}$
$B^0 \to K^+\pi^-$	5313 ± 109	6348 ± 117
$B_s^0 \to K^-\pi^+$	560 ± 51	354 ± 46
$\Lambda_b^0 \to p\pi^-$	242 ± 24	206 ± 23
$\Lambda_b^0 \to pK^-$	271 ± 30	324 ± 31

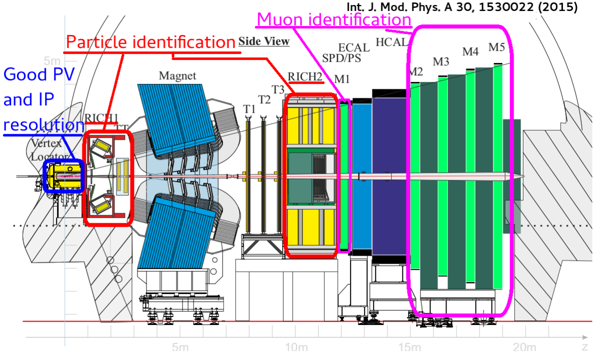
CDF results

$\mathcal{A}_{CP}(\Lambda_b^0 \to p\pi^-)$ =
$+0.06 \pm 0.07(stat) \pm 0.03(syst)$
$\mathcal{A}_{CP}(\Lambda_b^0 \to pK^-)$ =
$+0.10 \pm 0.08(stat) \pm 0.04(syst)$
$\mathcal{A}_{CP}$ consistent with zero

LHCb: Ongoing analysis but expect at least $\sim$ 10 times the statistics in Run 1 alone allowing for a 2-3% precision on $\mathcal{A}_{CP}$

Aside: the LHCb detector

The LHCb detector is a single arm spectrometer which covers the forward region ($2<\eta<5$) at the LHC.



Δ p/p $\sim$ 0.4% at 5 GeV, $\boldsymbol{\sigma_{IP}}$ = 20 $\mu\mathrm{m}$ for high p_T tracks.

$\boldsymbol{\pi/K}$ **separation:** ϵ_K $\sim$90%, 5% $\pi \rightarrow K$ mis-id.

$\boldsymbol{\pi/\mu}$ **separation:** ϵ_μ $\sim$97%, 1-3% $\pi \rightarrow \mu$ mis-id.

Experimental issues

Particle-antiparticle production asymmetry

- Initial *pp* state not CP symmetric $\rightarrow$ particle/antiparticle production (A_P) asymmetric
- This initial asymmetry could mimic CPV and needs to be well understood
- First value of $A_P(\Lambda_b^0)$ only recently obtained at LHCb (March 2017, arXiv:1703.08464)

Detector reconstruction efficiency of daughters

- As detector is made of matter, not CP symmetric.
- Reconstruction efficiency asymmetries of $\sim$ 1%
- These are comparatively well handled and understood

Experimental approaches

- Measure ΔA_{CP} difference of CP asymmetries:

$$\mathcal{A}_{\rm raw}(\Lambda_b^0 \to J/\psi p h^-) = \mathcal{A}_{CP}(\Lambda_b^0 \to J/\psi p h^-) + \boxed{\mathcal{A}_{\rm prod}(\Lambda_b^0)} - \mathcal{A}_{\rm reco}(h^+) + \boxed{\mathcal{A}_{\rm reco}(p)}$$

$$\begin{aligned}\Delta A_{CP} =& \mathcal{A}_{\rm raw}(\Lambda_b^0 \to J/\psi p \pi^-) - \mathcal{A}_{\rm raw}(\Lambda_b^0 \to J/\psi p K^-) \\ =& \mathcal{A}_{CP}(\Lambda_b^0 \to J/\psi p \pi^-) - \mathcal{A}_{CP}(\Lambda_b^0 \to J/\psi p K^-) + \boxed{\mathcal{A}_{\rm reco}(\pi^+) - \mathcal{A}_{\rm reco}(K^+)}\end{aligned}$$

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

Measured on data

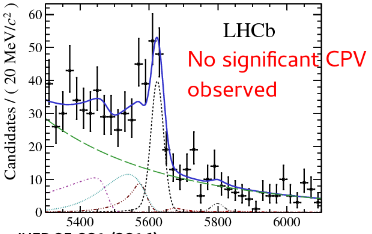
Experimental approaches

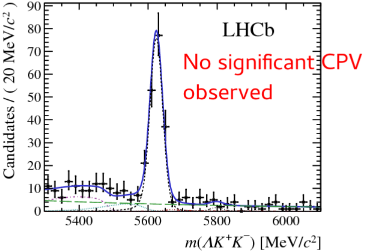
- Measure difference of A_{CP} between different Λ_b^0 decay modes
- Measure CPV via ($\hat{T}$-)P-violating asymmetries which are largely insensitive to A_P $\rightarrow$ triple products (detailed definition later)

LHCb results: CPV in $\Lambda_b^0 \to \Lambda\, h^+ h^-$

- Search for the charmless decays $\Lambda_b^0 \to \Lambda\, h^+ h^-$
- First observation of $\Lambda_b^0 \to \Lambda K^+ K^-$ and $\Lambda_b^0 \to \Lambda K^+ \pi^-$
- Searches also made for $\Lambda_b^0 \to \Lambda \pi^+ \pi^-$ but no significant excess observed.
- Control decays mediated via a Λ_c^+: $\Lambda_b^0 \to \Lambda_c^+ (\to \Lambda \pi^+) \pi^-$ or $\Lambda_b^0 \to \Lambda_c^+ (\to \Lambda K^+) \pi^-$ (expect minimal CP violation.)
- Measure relative to control decays to minimize sensitivity to the Λ_b^0 production asymmetry as well as dependence on the reconstruction asymmetries.

LHCb results: CPV in $\Lambda_b^0 \to \Lambda h^+ h^-$



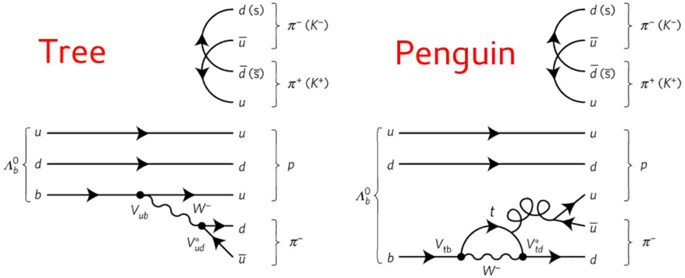


Measured values of A_{CP}

$A_{CP}(\Lambda K^+\pi^-) = 0.53 \pm 0.23 \pm 0.11$

$A_{CP}(\Lambda K^+K^-) = 0.28 \pm 0.10 \pm 0.07$

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



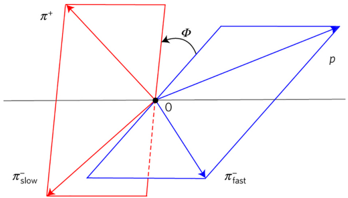
$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ and $\Lambda_b^0 \to p\pi^- K^+ K^-$ decays are particular sensitive to CP affects as penguin and diagrams $\sim$ magnitude and the potential interference of resonances, e.g. $N^* \to p\pi$ and $\rho(770)^0 \to \pi^+\pi^-$

Triple products (TP):

$\Lambda_b^0 : C_{\hat{T}} = \mathbf{p}_p.(\mathbf{p}_{h_1^-} \times \mathbf{p}_{h_2^+}) \propto sin(\phi)$

$\overline{\Lambda_b^0} : \overline{C}_{\hat{T}} = \mathbf{p}_{\overline{p}}.(\mathbf{p}_{h_1^+} \times \mathbf{p}_{h_2^-}) \propto sin(\overline{\phi})$

$\hat{T}$ reverses 3 vectors of momentum and spin



$p\pi^- K^+ K^- : h_1 = \pi, h_2 = K$

$p\pi^- \pi^+ \pi^- : h_1 = \pi_{\text{fast}_{\Lambda_b^0 \text{rest fr.}}}, h_2 = \pi$

Asymmetries:

$$A_{\hat{T}} = \frac{N^+_{C_{\hat{T}}} - N^-_{C_{\hat{T}}}}{N^+_{C_{\hat{T}}} + N^-_{C_{\hat{T}}}}, \overline{A}_{\hat{T}} = \frac{\overline{N}^+_{-\overline{C}_{\hat{T}}} - \overline{N}^-_{-\overline{C}_{\hat{T}}}}{\overline{N}^+_{-\overline{C}_{\hat{T}}} + \overline{N}^-_{-\overline{C}_{\hat{T}}}}$$

P, CP violating observables:

$$a_P^{\hat{T}-odd} = \frac{1}{2}(A_{\hat{T}} + \overline{A}_{\hat{T}}) \text{ if: } \neq 0 \rightarrow PV$$

$$a_{CP}^{\hat{T}-odd} = \frac{1}{2}(A_{\hat{T}} - \overline{A}_{\hat{T}}) \text{ if: } \neq 0 \rightarrow CPV$$

A non-zero CP-odd observable implies CP violation

Search for CPV in $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$ and $\Lambda_b^0 \rightarrow p\pi^-K^+K^-$ decays

Phase space bin	$m(p\pi^+)$	$m(p\pi_{slow}^-)$	$m(\pi^+\pi_{slow}^-)$, $m(\pi^+\pi_{fast}^-)$	$\lvert\Phi\rvert$
1	(1.07, 1.23)			$(0, \frac{\pi}{2})$
2	(1.07,1.23)			$(\frac{\pi}{2}, \pi)$
3	(1.23,1.35)			$(0, \frac{\pi}{2})$
4	(1.23,1.35)			$(\frac{\pi}{2}, \pi)$
5	(1.35,5.34)	(1.07,2.00)	$m(\pi^+\pi_{slow}^-) < 0.78$ or $m(\pi^+\pi_{fast}^-) < 0.78$	$(0, \frac{\pi}{2})$
6	(1.35,5.34)	(1.07,2.00)	$m(\pi^+\pi_{slow}^-) < 0.78$ or $m(\pi^+\pi_{fast}^-) < 0.78$	$(\frac{\pi}{2}, \pi)$
7	(1.35,5.34)	(1.07,2.00)	$m(\pi^+\pi_{slow}^-) > 0.78$ and $m(\pi^+\pi_{fast}^-) > 0.78$	$(0, \frac{\pi}{2})$
8	(1.35,5.34)	(1.07,2.00)	$m(\pi^+\pi_{slow}^-) > 0.78$ and $m(\pi^+\pi_{fast}^-) > 0.78$	$(\frac{\pi}{2}, \pi)$
9	(1.35,5.34)	(2.00,4.00)	$m(\pi^+\pi_{slow}^-) < 0.78$ or $m(\pi^+\pi_{fast}^-) < 0.78$	$(0, \frac{\pi}{2})$
10	(1.35,5.34)	(2.00,4.00)	$m(\pi^+\pi_{slow}^-) < 0.78$ or $m(\pi^+\pi_{fast}^-) < 0.78$	$(\frac{\pi}{2}, \pi)$
11	(1.35,5.34)	(2.00,4.00)	$m(\pi^+\pi_{slow}^-) > 0.78$ and $m(\pi^+\pi_{fast}^-) > 0.78$	$(0, \frac{\pi}{2})$
12	(1.35,5.34)	(2.00,4.00)	$m(\pi^+\pi_{slow}^-) > 0.78$ and $m(\pi^+\pi_{fast}^-) > 0.78$	$(\frac{\pi}{2}, \pi)$

Resonances:

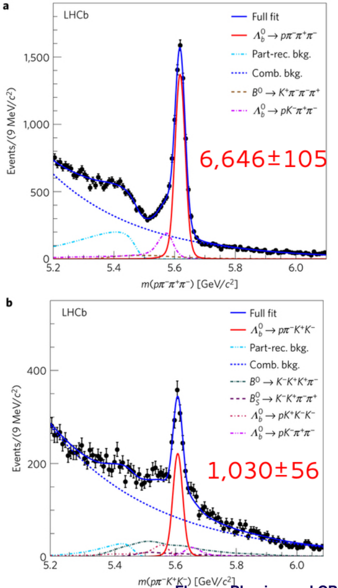
CP asymmetries may vary over phsp $\implies$ may cancel when integrating over phsp

Binning:

Scheme A: Split into phsp bins $\{m(p\pi^+), m(p\pi^-{}_{\rm slow}), m(\pi^+\pi^-{}_{\rm slow}), m(\pi^+\pi^-{}_{\rm fast}), |\phi|\}$ to increase CPV sensitivity Phys. Rev. D92 (2015) 076013, Gronau, Michael *et al.*

Scheme B: $|\phi|$ - interference visible as a function of ϕ

Event selection and yields



- Combine tracks identified as protons, pions, or kaons that originate from a common vertex and tag using proton charge.
- Remove backgrounds from $b \to c$ transitions with vetoes and use BDT to reduce combinatorial background.
- All selections and binning schemes selected before looking at signal region.
- Use $\Lambda_b^0 \to \Lambda_c^+ (p\pi^+\pi^- (K^+K^-))\pi^-$ as a control mode.

Efficiencies and systematic uncertainties

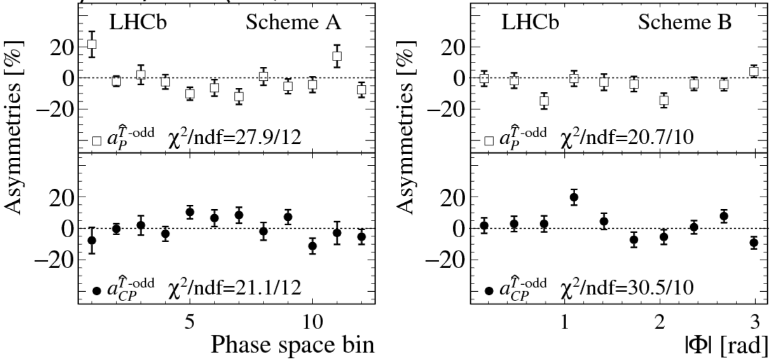
- Signal candidates are split into four categories, $C_{\hat{T}}^{+/-}$ and Λ_b^0 or $\overline{\Lambda_b^0}$.
- The reconstruction efficiency for $C_{\hat{T}}^{+}$ is = $C_{\hat{T}}^{-}$ within uncertainties.
- The asymmetries in the signal samples are measured with a simultaneous unbinned maximum likelihood fit to the mass distribution

Systematic uncertainties

- Experimental effects $\rightarrow$ biases in the measured asymmetries $\rightarrow$ quantified using control modes in data.
- Uncertainty statistically dominated.

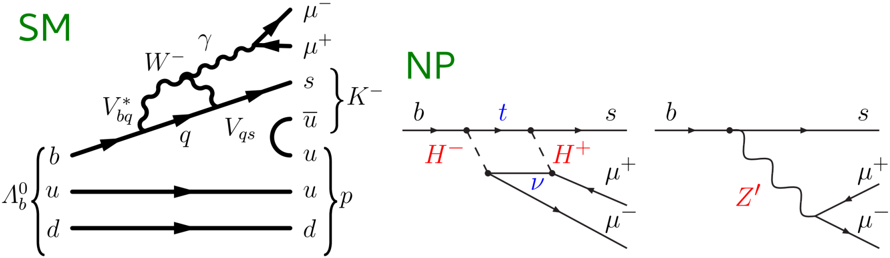
Results for $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$

Nature Physics 13, 391396 (2017)



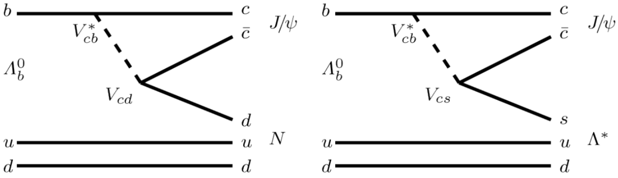
- $a_{CP}^{\hat{T}-odd}$: A = 2.0 σ, B = 3.4 σ
- $a_{P}^{\hat{T}-odd}$: A = 2.8 σ, B = 2.3 σ
- Global: 3.3σ $\rightarrow$ First evidence for CP violation in baryon sector
- Cross check with alternative binning schemes yield, global $\rightarrow$ 3.1σ

Search for CPV in $|V_{ts}|$ transitions

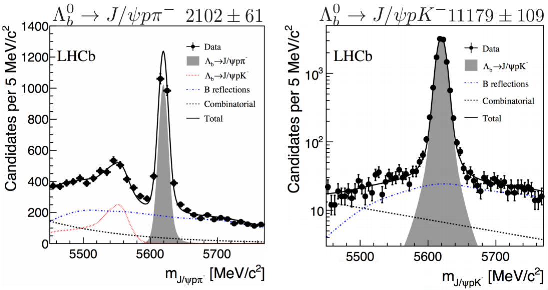


- Decay occurs via a Flavour Changing Neutral Current.
- Sensitive to NP effects

Aside: search for CPV in equivalent charmounium modes



JHEP 07 (2014) 103



$$\Delta\mathcal{A}_{\mathcal{CP}} = \mathcal{A}_{\mathcal{CP}}(\Lambda_b^0 \to J/\psi\, p\pi^-) - \mathcal{A}_{\mathcal{CP}}(\Lambda_b^0 \to J/\psi\, pK^-) = (5.7 \pm 2.4 \pm 1.2)\%$$

Using $\mathcal{A}_{CP}$ vs using triple products to look for CPV

$\hat{T}_{even}$, $\hat{T}_{odd}$ amplitudes

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

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

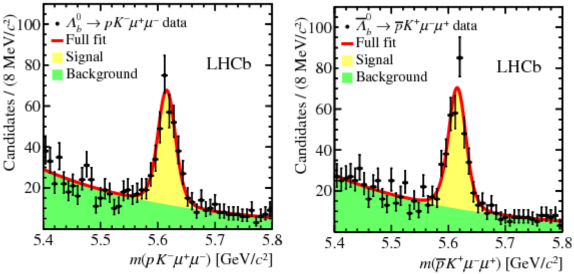
A_1, A_2 amplitudes

$$\mathcal{A}_{CP} \propto sin(\delta_1 - \delta_2) sin(\phi_1 - \phi_2)$$

not sensitive if $\delta_1 - \delta_2 = 0$ or π

δ = strong phase, ϕ = weak phase

Search for CPV in $|V_{ts}|$ transitions



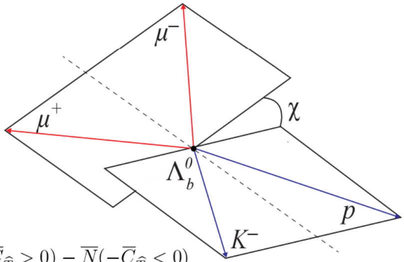
arXiv:1703.00256 (2017)

- Measure $\Delta\mathcal{A}_{CP} = \mathcal{A}_{CP}(\Lambda_b^0 \to pK^-\mu^+\mu^-) - \mathcal{A}_{CP}(\Lambda_b^0 \to J/\psi\, pK^-)$
- $\Delta\mathcal{A}_{CP}$ = (-3.5 $\pm$ 5.0 (stat) $\pm$ 0.2 (syst)) $\times 10^{-2}$ $\to$ no significant CPV

Search for CPV in $|V_{ts}|$ transitions

$$C_{\widehat{T}} \equiv \vec{p}_{\mu^+} \cdot (\vec{p}_p \times \vec{p}_{K^-}),$$
$$\overline{C}_{\widehat{T}} \equiv \vec{p}_{\mu^-} \cdot (\vec{p}_{\overline{p}} \times \vec{p}_{K^+}),$$

proportional to

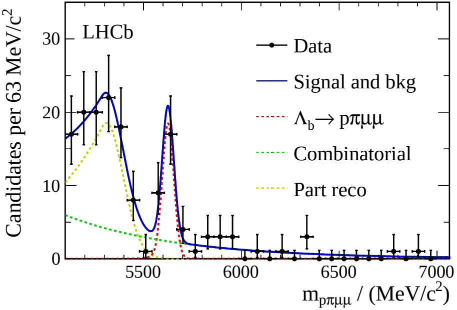


$$A_{\widehat{T}} \equiv \frac{N(C_{\widehat{T}} > 0) - N(C_{\widehat{T}} < 0)}{N(C_{\widehat{T}} > 0) + N(C_{\widehat{T}} < 0)}, \quad \overline{A}_{\widehat{T}} \equiv \frac{\overline{N}(-\overline{C}_{\widehat{T}} > 0) - \overline{N}(-\overline{C}_{\widehat{T}} < 0)}{\overline{N}(-\overline{C}_{\widehat{T}} > 0) + \overline{N}(-\overline{C}_{\widehat{T}} < 0)},$$

$$a_{CP}^{\widehat{T}\text{-odd}} \equiv \frac{1}{2}\left(A_{\widehat{T}} - \overline{A}_{\widehat{T}}\right), \qquad a_{P}^{\widehat{T}\text{-odd}} \equiv \frac{1}{2}\left(A_{\widehat{T}} + \overline{A}_{\widehat{T}}\right),$$

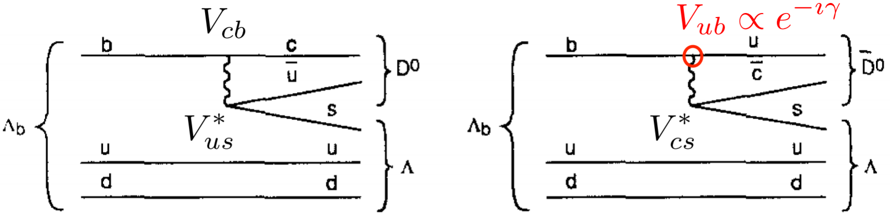
$a_{CP}^{\hat{T}-odd} = (1.2 \pm 5.0(\mathrm{stat}) \pm 0.7(\mathrm{syst})) \times 10^{-2} \rightarrow$ no significant CPV

Potential future measurements: First observation of a $b \to d$ transition in the baryon sector



- The Cabibbo-suppressed equivalent channel of $\Lambda_b^0 \to pK^-\mu^+\mu^-$ is $\Lambda_b^0 \to p\pi^-\mu^+\mu^-$.
- This channel has recently been observed for the first time and is the first observation of a $b \to d$ transition in the baryon sector (JHEP 04 (2017) 029).
- With more data this channel could also be used in CPV searches.

Potential future measurements: measuring γ with $b-$ baryons



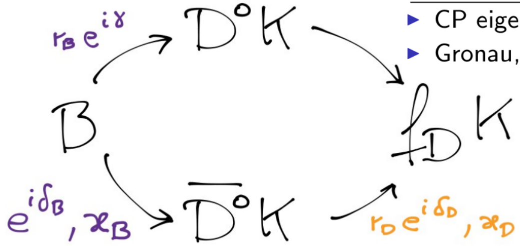
- $\Lambda_b^0 \to \Lambda D$ decays can be used to determine the CKM angle γ through CP violation caused by the interference of the $b \to u$ and $b \to c$ tree-level transitions, as done in the meson sector.
- $\mathcal{B}(\Lambda_b^0 \to \Lambda D) \sim 10^{-6}$, $\mathcal{B}(\Lambda_b^0 \to \Lambda \overline{D}) \sim 10^{-7}$, not observed to date.
- Related decay $\Lambda_b^0 \to DpK^-$ however has been seen.

Conclusions

- Searches for CPV *b* baryons are still in the early stages but with increased data from the LHC this area is becoming more of interest.
- CP violation is expected in the baryon sector and first evidence of it has been seen by LHCb.
- Looking for CP violation in baryons can provide an important range of CPV searches which can complement those being undertaken in the meson sector and could be an important tool in the search for new physics.

Back-up slides

GLW method of measuring the CKM angle γ



- GLW method
  - CP eigenstates e.g. $D \to KK$
  - Gronau, London, Wyler (1991)

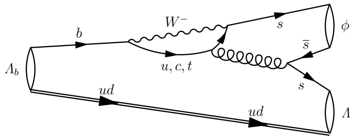
$$A_f = |F|e^{i(\delta_F - \phi_F)} + |S|e^{i(\delta_S - \phi_S)}$$
$$\bar{A}_{\bar{f}} = |F|e^{i(\delta_F + \phi_F)} + |S|e^{i(\delta_S + \phi_S)}$$

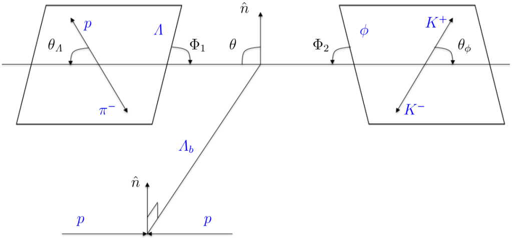
because strong phases (δ) don't change sign under CP while weak phases (ϕ) do

$$\mathcal{A}_{CP} = \frac{|\bar{A}_{\bar{f}}|^2 - |A_f|^2}{|\bar{A}_{\bar{f}}|^2 + |A_f|^2}$$
$$= \frac{2|F||S|\sin(\delta_F - \delta_S)\sin(\phi_F - \phi_S)}{|F|^2 + |S|^2 + 2|F||S|\cos(\delta_F - \delta_S)\cos(\phi_F - \phi_S)}$$

γ is the weak phase difference $\phi_F - \phi_S$

CPV in $\Lambda_b^0 \to \Lambda\,\phi$ triple products



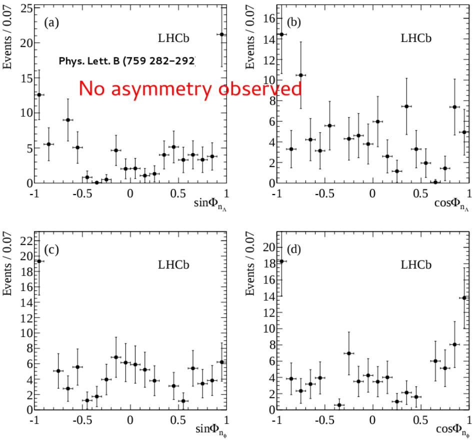


$b \to s\bar{s}s$ loop (penguin) process

$$A(cos(\phi_i)) = \frac{N(cos(\phi_i) > 0) - N(cos(\phi_i < 0))}{N(cos(\phi_i) > 0) + N(cos(\phi_i < 0))}$$

$$A(sin(\phi_i)) = \frac{N(sin(\phi_i) > 0) - N(sin(\phi_i < 0))}{N(sin(\phi_i) > 0) + N(sin(\phi_i < 0))}$$

Results



$A(cos(\phi_\Lambda)) = 0.22 \pm 0.12 \pm 0.05$

$A(sin(\phi_\Lambda)) = 0.13 \pm 0.12 \pm 0.06$

$A(cos(\phi_\phi)) = 0.01 \pm 0.12 \pm 0.01$

$A(sin(\phi_\phi)) = 0.07 \pm 0.12 \pm 0.03$