Measurements of CPV at LHCb

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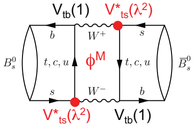
ICPPA-2018
Moscow

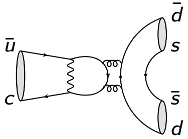
Outline

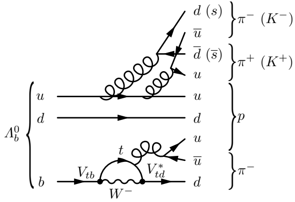
Introduction

Introduction

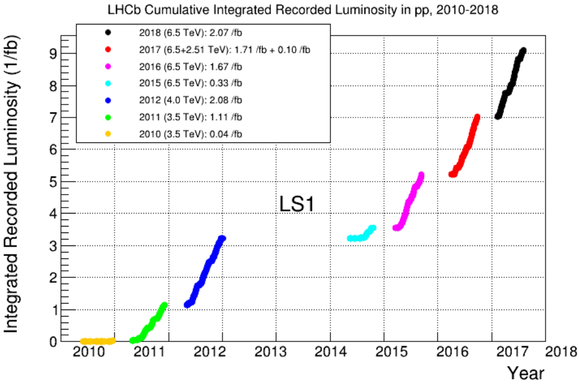
- Study of beauty and charm hadron decays is complementary to direct searches for new particles
- Can discover New Physics due to the effect of virtual new particles in quantum loops
- Through the study of the interference of different quantum paths $\rightarrow$ access to the magnitude of the couplings of NP and also to their phase (for instance, by measuring CP asymmetries)







LHCb collected data



Proton collisions at 7-13TeV:

- huge heavy flavour production cross-sections: 1.4×10^{11} $b\bar{b}$-pairs per fb^{-1} (Run 2)
- all beauty, charm and strange hadrons produced (B_s^0, Λ_b^0, B_c^+, D_s^+, Λ_c^+, Σ^+, ...)

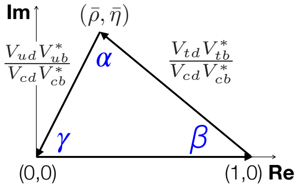
CP violation in the Standard Model

- In SM, CPV is accommodated in weak interactions

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$\cong \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

- The η is the only source of CPV in the SM.



Unitarity Triangle

(1st and 3rd CKM columns)

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

Over-constrain unitarity triangle apex coordinates for a stringent test of SM:

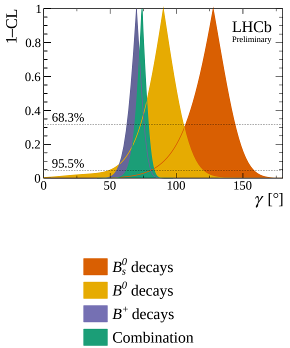
- CP violation measurements give angles
- CP conserving measurements give sides

The γ angle measurements

LHCb-CONF-2018-002

B decay	D decay	Method	Ref.	Dataset[†]	Status since last combination [3]
$B^+ \to DK^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2	Minor update
$B^+ \to DK^+$	$D \to h^+h^-$	ADS	[15]	Run 1	As before
$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[15]	Run 1	As before
$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS	[16]	Run 1	As before
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[17]	Run 1	As before
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[18]	Run 2	New
$B^+ \to DK^+$	$D \to K^0_S K^+\pi^-$	GLS	[19]	Run 1	As before
$B^+ \to D^*K^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2	Minor update
$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS	[20]	Run 1 & 2	Updated results
$B^+ \to DK^{*+}$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[20]	Run 1 & 2	New
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS	[21]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	[22]	Run 1	As before
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	[23]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ	[24]	Run 1	As before
$B^0_s \to D_s^{\mp}K^{\pm}$	$D_s^+ \to h^+h^-\pi^+$	TD	[25]	Run 1	Updated results
$B^0 \to D^{\mp}\pi^{\pm}$	$D^+ \to K^+\pi^-\pi^+$	TD	[26]	Run 1	New

† Run 1 corresponds to an integrated luminosity of 3 fb^{-1} taken at centre-of-mass energies of 7 and 8 TeV . Run 2 corresponds to an integrated luminosity of 2 fb^{-1} taken at a centre-of-mass energy of 13 TeV .



$$\gamma = \left(74.0^{+5.0}_{-5.8}\right)$$

- Most precise determination of γ from a single experiment
- World average: $\gamma = \left(73.5^{+4.2}_{-5.1}\right)$ [HFLAV]

Introduction

CP tests in beauty

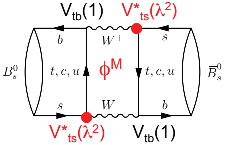
CP tests in charm

CP tests in baryons

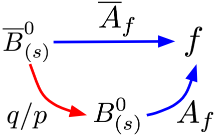
Summary

B_s^0 CP violating phase ϕ_s

Mass eigenstates $\neq$ flavour eigenstates:



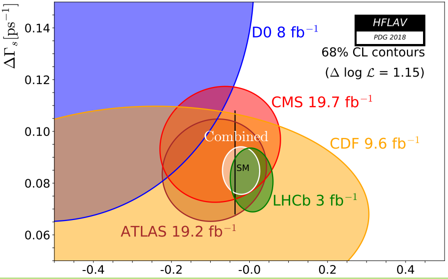
$$|B_L\rangle = p\,|B_s^0\rangle + q\,|\overline{B}_s^0\rangle$$
$$|B_H\rangle = p\,|B_s^0\rangle - q\,|\overline{B}_s^0\rangle$$
$\Rightarrow$ mixing



- CPV in mixing: $|q/p| \neq 1$, — q/p - complex number
- CPV in decays: $|A_f/\overline{A}_f| \neq 1$, — A_f, $\overline{A}_f$ - complex aplitudes

Even with no CPV in mixing or decay, one can generate CPV in the interference:

$$\phi_s \equiv -arg(\lambda_f) \equiv -arg\left(\frac{q}{p}\frac{\overline{A}_f}{A_f}\right) \neq 0$$



Two-body $B^0_{(s)}$ decays

Phys.Rev. D 98, 032004 (2018)

Simultaneous fit to to the distributions of reconstructed candidates: $B^0 \to \pi^+\pi^-$, $B^0_s \to K^+K^-$, $B^0 \to K^+\pi^-$ and $B^0_s \to \pi^+K^-$.

- Time-integrated asymmetries for $B^0 \to K^+\pi^-$ and $B^0_s \to \pi^+K^-$:

$$A_{CP} = \frac{\left|\bar{A}_{\bar{f}}\right|^2 - \left|A_f\right|^2}{\left|\bar{A}_{\bar{f}}\right|^2 + \left|A_f\right|^2}$$

- Time-dependent asymmetries for $B^0 \to \pi^+\pi^-$and $B^0_s \to K^+K^-$:

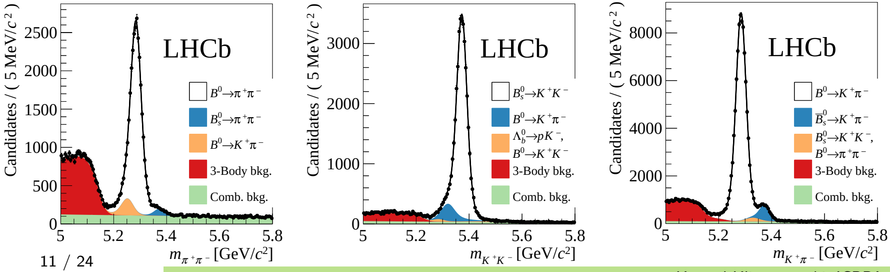
$$A_{CP}(t) = \frac{\Gamma_{\bar{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\bar{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)} = \frac{-C_f \cos(\Delta m_{d,s} t) + S_f (\Delta m_{d,s} t)}{\cosh\left(\frac{\Delta\Gamma_{d,s}}{2} t\right) + A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_{d,s}}{2} t\right)}$$

C_f - CPV in the decay, S_f - CPV in interference between decay and mixing

Two-body $B^0_{(s)}$ decays

Phys.Rev. D 98, 032004 (2018)

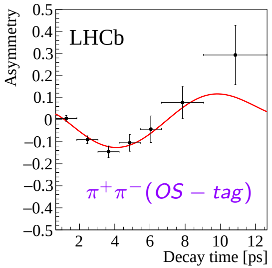
- Analysis performed using full Run 1 data sample ($\sim 3\text{fb}^{-1}$)
- Time-dependent asymmetries ingredients:
  - flavour tagging
  - decay-time resolution
  - decay-time acceptance
- Time-independent asymmetries ingredients:
  - final state detection asymmetries
  - production asymmetry

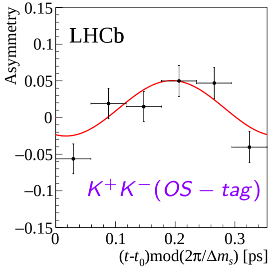


Two-body $B^0_{(s)}$ decays

- First measurement of $A^{\Delta\Gamma}_{K^+K^-}$
- Strongest evidence of CPV in B^0_s sector: confirmed at 4σ

$$
\begin{aligned}
C_{\pi^+\pi^-} &= -0.34 \pm 0.06 \pm 0.01 \\
S_{\pi^+\pi^-} &= -0.63 \pm 0.05 \pm 0.01 \\
C_{K^+K^-} &= 0.20 \pm 0.06 \pm 0.02 \\
S_{K^+K^-} &= 0.18 \pm 0.06 \pm 0.02 \\
A^{\Delta\Gamma}_{K^+K^-} &= -0.79 \pm 0.07 \pm 0.10 \\
A^{B^0}_{CP} &= (-8.4 \pm 0.4 \pm 0.3)\% \\
A^{B^0_s}_{CP} &= (21.3 \pm 1.5 \pm 0.3)\%
\end{aligned}
$$





Introduction

CP tests in beauty

CP tests in charm

CP tests in baryons

Summary

$D^0 \to K_s^0 K_s^0$ decays

arXiv:1806.01642

- D^0 mixing is established
- CP violation yet unobserved!
  - Small value expected from SM $\mathcal{O}(V_{ub}V_{cb}^* V_{us}V_{cs}^*) \sim \mathcal{O}(10^{-3})$

$A_{CP}(K_s^0 K_s^0)$

- Define $A_{raw}(D^0 \to f) = \frac{ND^0 - N\overline{D}^0}{ND^0 + N\overline{D}^0}$
- Measure $A_{CP}(D^0 \to K_s^0 K_s^0)$
- Tag with prompt $D^{*+} \to D^0 \pi_s^+$

$$A_{CP} = A_{raw} - A_P(D^{*+}) - A_D(\pi_s^+)$$

- Eliminate detection/production asymmetries using control channel:

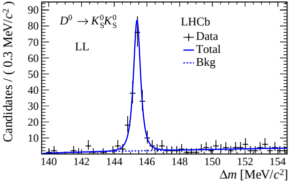
$$\Delta A_{CP} \equiv A_{raw}(D^0 \to K_s^0 K_s^0) - A_{raw}(D^0 \to K^+K^-) = A_{CP}(D^0 \to K_s^0 K_s^0) - A_{CP}(D^0 \to K^+K^-)$$

- The $A^{CP}(D^0 \to K^+K^-)$ has been measured by LHCb with a precision of 0.2%: Phys. Lett. B767 (2017) 177

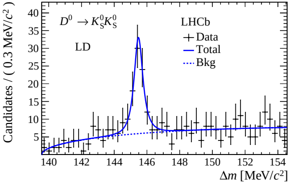
$D^0 \to K^0_s K^0_s$ decays

arXiv:1806.01642

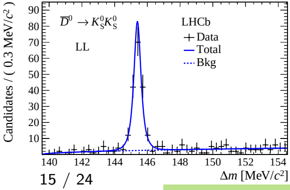
$\mathcal{L} = 2\,\text{fb}^{-1} @ \sqrt{s} = 13\text{TeV} \quad \Rightarrow$
1067 $D^0 \to K^0_s K^0_s$ candidates

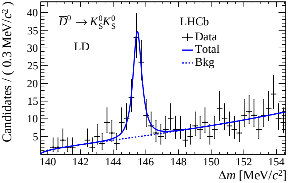


$A_{CP}(K^0_s K^0_s) = 0.042 \pm 0.034 \pm 0.010$



Combined with the LHCb Run 1 measurement
$A_{CP}(K^0_s K^0_s) = 0.020 \pm 0.029 \pm 0.010$





CPV in $\Lambda_b^0 \to p3h$

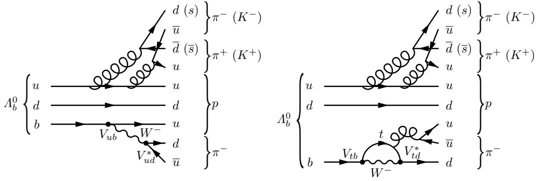
Nature Physics 13, 391 (2017)

- Only direct CPV in baryon sector
- Test CPV by comparison of baryon and anti-baryon decay yields

$$A_{CP} = \frac{N(A \to f) - N(\overline{A} \to \overline{f})}{N(A \to f) + N(\overline{A} \to \overline{f})} \propto sin(\delta_1 - \delta_2) sin(\varphi_1 - \varphi_2)$$

$\delta-$strong phase, $\varphi-$weak phase

- Effect visible with contributions from at least two amplitudes: $A_1 e^{i\delta_1} e^{i\varphi_1}$, $A_2 e^{i\delta_2} e^{i\varphi_2}$
- Requires non-vanishing strong and weak phase difference



CPV in $\Lambda_b^0 \to p3h$

Nature Physics 13, 391 (2017)

Utilise 4-body final state to construct:

$$C_{\hat{T}} = \vec{p_p} \cdot (\vec{p_{h_1^-}} \times \vec{p_{h_2^+}}), \qquad \overline{C}_{\hat{T}} = \vec{p_{\overline{p}}} \cdot (\vec{p_{h_1^+}} \times \vec{p_{h_2^-}})$$

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

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

CP-violating observable:

$$a_{CP}^{\hat{T}-odd} = \frac{1}{2}(A_{\hat{T}} - \overline{A}_{\hat{T}})$$

$$a_{P}^{\hat{T}-odd} = \frac{1}{2}(A_{\hat{T}} + \overline{A}_{\hat{T}})$$

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

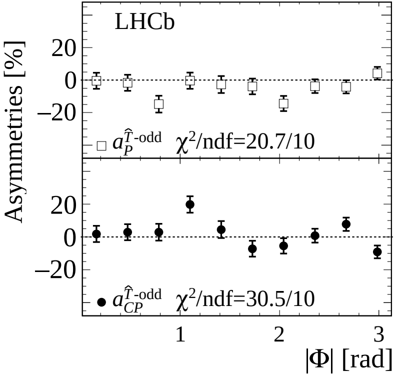
Complementary approach to A_{CP} analysis

- $a_{CP}^{P-odd} \propto cos(\delta_{even} - \delta_{odd}) sin(\varphi_{even} - \varphi_{odd})$ not sensitive if $\delta_{even} - \delta_{odd} = {}^{\pi}/_{2}$ 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 π

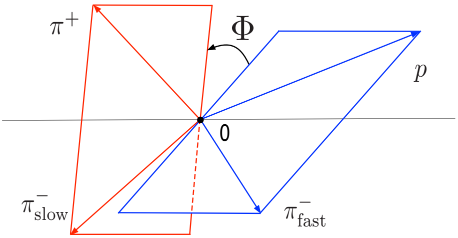
CPV in $\Lambda_b^0 \to p3h$

Nature Physics 13, 391 (2017)

Full Run I sample: $\mathcal{L} = 3\,\text{fb}^{-1}$
$N_{sig}(p\pi^-\pi^+\pi^-) = 6646 \pm 105$
$N_{sig}(p\pi^-K^+K^-) = 1030 \pm 56$



- Scheme A - binning in invariant mass combinations, to focus on dominant resonance contributions
- Scheme B- binning in angle Φ between decay planes



Combined result from 2 binning schemes:

CP symmetry p-value$=9.8 \times 10^{-4}$

3.3σ deviation

$\Lambda_b^0 \to pK^-\pi^+\pi^-, \Lambda_b^0 \to pK^-K^+K^-$, $\Xi_b^0 \to pK^-K^+\pi^-$ JHEP 08 (2018) 039

- Analysis uses Triple Product Asymmetries
- TPA integrated over all phase space for $\Lambda_b^0 \to pK^-\pi^+\pi^-$:

$$a_P^{\hat{T}-odd} = (-0.60 \pm 0.84 \pm 0.31)\%$$

$$a_{CP}^{\hat{T}-odd} = (-0.81 \pm 0.84 \pm 0.31)\%$$

- TPA integrated over all phase space for $\Lambda_b^0 \to pK^-K^+K^-$:

$$a_P^{\hat{T}-odd} = (-1.56 \pm 1.51 \pm 0.32)\%$$

$$a_{CP}^{\hat{T}-odd} = (1.12 \pm 1.51 \pm 0.32)\%$$

- TPA integrated over all phase space for $\Xi_b^0 \to pK^-K^+\pi^-$:

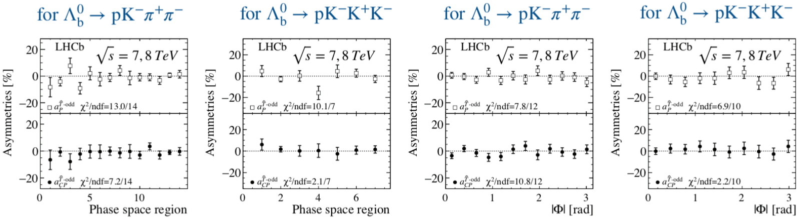
$$a_P^{\hat{T}-odd} = (-3.04 \pm 5.19 \pm 0.36)\%$$

$$a_{CP}^{\hat{T}-odd} = (-3.58 \pm 5.19 \pm 0.36)\%$$

- All phase space integrated results are consistent with P and CP conservation

$\Lambda_b^0 \to pK^-\pi^+\pi^-, \Lambda_b^0 \to pK^-K^+K^-,$ $\Xi_b^0 \to pK^-K^+\pi^-$ JHEP 08 (2018) 039

- Binned analysis for $\Lambda_b^0 \to pK^-\pi^+\pi^-$ and $\Lambda_b^0 \to pK^-K^+K^-$ is performed
- Two binning schemes as in previous results
- All binned measurement consistent with P and CP conservation



Summary and Outlook

- Many great results from Run I and Run II
  - First evidence of CPV in baryons
- Very successful Run II: in total LHCb already collected $\mathcal{L} = 10\,\text{fb}^{-1}$

	LHC era			HL-LHC era	
	Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2021-24)	Run 4 (2027-30)	Run 5+ (2031+)
ATLAS, CMS	25 fb^{-1}	100 fb^{-1}	300 fb^{-1}	$\longrightarrow$	3000 fb^{-1}
LHCb	3 fb^{-1}	8 fb^{-1}	25 fb^{-1}	50 fb^{-1}	*300 fb^{-1}

* assumes a future LHCb upgrade to raise the instantaneous luminosity to $2 \times 10^{34}\ \text{cm}^{-2}$

- The LHCb upgraded detector after Run-2 will handle $\times 5$ instantaneous luminosity, from $4 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$ to $2 \times 10^{33}\text{cm}^{-2}\text{s}^{-1}$
- The hardware trigger stage will be eliminated, and trigger become fully software based. Many detectors will be replaced.

Thank You

[CERN]

Backup

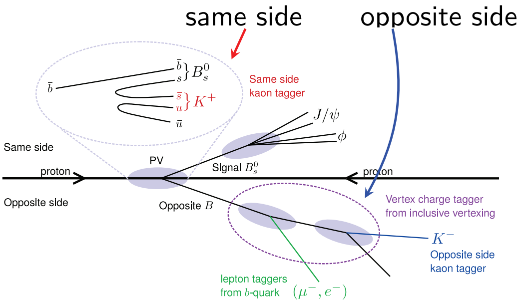
B_s^0 or $\overline{B}_s^0$ - tagging the flavour

Same side

- s quark in B_s^0 is produced with $\overline{s}$
- $\sim 50\,\%$ of $\overline{s}$ forms a charged K
- charge of the K identifies flavour of B_s^0

Opposite side

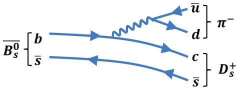
- in pp collisions b produced mostly in $b\overline{b}$ pairs
- flavour determined by the charge of decay products of opposite B:
  - leptons
  - kaons
  - global charge of secondary vertex



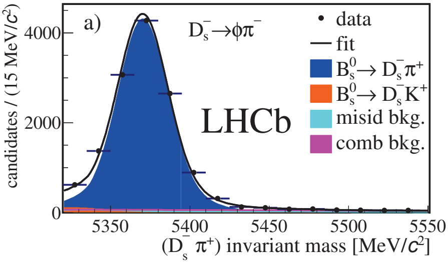
- Total effective tagging efficiency: $\epsilon(1-2\omega)^2$
- ϵ - efficiency of tagging algorithm
- ω - frequency of events with wrong tagging
- $Eff = (3.9 \pm 0.25)\%$

$B_s^0 - \overline{B}_s^0$ oscillations

Δm_s measured from 1fb^{-1} $B_s^0 \to D_s^- \pi^+$ decays



- High statistics:
  N $\sim$ 34000 signal candidates
- Self tagging channel
- Five different D_s^- decay modes:
  ($\phi\pi^-$, $K^* K^-$, $K^- K^+ \pi^-$,
  $K^- \pi^+ \pi^-$, $\pi^- \pi^+ \pi^-$)
- Very low background



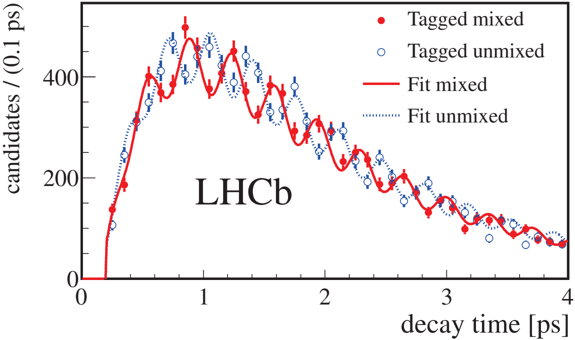
[New J. Phys. 15 (2013) 053021]

$B_s^0 - \overline{B}_s^0$ oscillations

The measured oscillation frequency:

$$\Delta m_s = 17.768 \pm 0.023(stat) \pm 0.006(syst)\,\text{ps}^{-1}$$

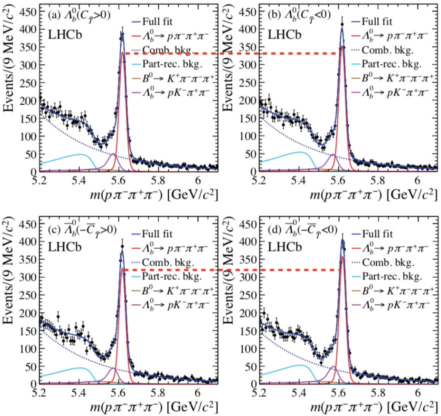
- Based on $\mathcal{L} = 1\text{fb}^{-1}$ data
- The most precise measurement to date
- Agrees with world average: $17.69 \pm 0.08\,\text{ps}^{-1}$



[New J. Phys. 15 (2013) 053021]

Search for CPV in $\Lambda_b^0, \Xi_b^0 \to p3h$ decays using TPA

Nature Phys. 13 (2017) 391-396



Search for CPV in $\Lambda_b^0, \Xi_b^0 \to p3h$ decays using TPA

Nature Phys. 13 (2017) 391-396

- Phase space integrated results for $\Lambda_b^0 \to p\pi^-\pi^+\pi-$

$$a_P^{\hat{T}-odd} = (-3.71 \pm 1.45 \pm 0.32)\%$$
$$a_{CP}^{\hat{T}-odd} = (1.15 \pm 1.45 \pm 0.32)\%$$

- Phase space integrated results for $\Lambda_b^0 \to p\pi^- K^+ K-$

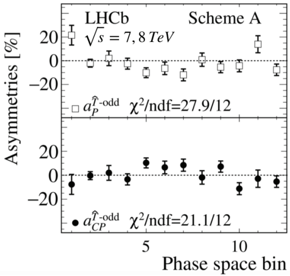
$$a_P^{\hat{T}-odd} = (3.62 \pm 4.54 \pm 0.42)\%$$
$$a_{CP}^{\hat{T}-odd} = (-0.93 \pm 4.54 \pm 0.42)\%$$

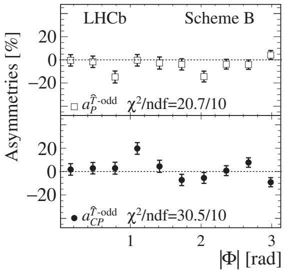
- Phase space integrated results consistent with P and CP conservation

Search for CPV in $\Lambda_b^0, \Xi_b^0 \to p3h$ decays using TPA

Nature Phys. 13 (2017) 391-396

- Two binning schemes used to measure $a_{CP}^{\hat{T}-odd}$ in different regions of phase space
- Scheme A- binning in two-body mass combinations
- Scheme B- Uniform binning in Φ angle between decay planes
- First evidence of CPV in baryons with 3.3σ significance





A_{CP} in $D^0 \to K_S^0 K_S^0$ - Data Sample

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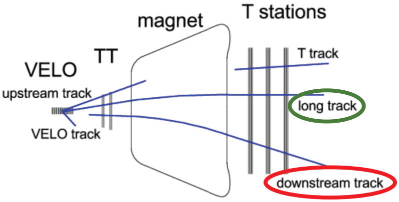
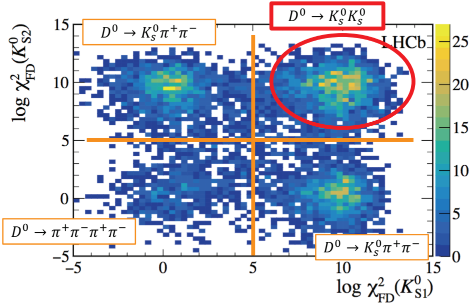
arXiv:1806.01642
submitted to JHEP

- 2015+2016 data → $\mathbf{2.0\ fb^{-1}}$
- Two independent samples:
  1. **LD**: one K_S^0 is reconstructed from **long** tracks and the other from **downstream** tracks
  2. **LL**: both K_S^0 are reconstructed from **long** tracks
- Different **resolution** between the two samples



A_{CP} in $D^0 \to K_S^0 K_S^0$ - Data Sample

- Important **background** due to $D^0 \to K_S^0 \pi^+ \pi^-$ and $D^0 \to \pi^+ \pi^- \pi^+ \pi^-$
- Selection on LL:
  $[\log \chi^2_{FD}(K^0_{S1}) - 10]^2 + [\log \chi^2_{FD}(K^0_{S2}) - 10]^2 < 16$
- Selection on LD:
  $\log \chi^2_{FD}(K^0_{SL}) > 2.5$



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CPV observables

- Time-integrated *CPV* asymmetries in $B^0 \to K^+\pi^-$ and $B_s \to \pi^+K^-$ decays are defined as:

$$A_{CP} = \frac{|\bar{A}_{\bar{f}}|^2 - |A_f|^2}{|\bar{A}_{\bar{f}}|^2 + |A_f|^2}$$

- The main *CPV* observables are the time-dependent asymmetries of $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ decays:

$$A(t) = \frac{\Gamma_{\bar{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\bar{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)} = \frac{-\mathbf{C_f}\cos\left(\Delta m_{d(s)}t\right) + \mathbf{S_f}\sin\left(\Delta m_{d(s)}t\right)}{\cosh\left(\frac{\Delta\Gamma_{d(s)}}{2}t\right) + A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_{d(s)}}{2}t\right)}$$

$$C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} \qquad S_f = \frac{2Im\lambda_f}{1+|\lambda_f|^2} \qquad A_f^{\Delta\Gamma} = \frac{2Re\lambda_f}{1+|\lambda_f|^2}$$

direct *CPV* — mixing induced *CPV*

$$|C_f|^2 + |S_f|^2 + |A_f^{\Delta\Gamma}|^2 = 1 \text{ (condition not imposed)}$$

- The knowledge of the flavour of the *B* candidate at production is required $\Longrightarrow$ flavour tagging tool is a key ingredient of the analysis

[Davide Fazzini, 10th International Workshop on the CKM Unitarity Triangle, 2018]

Other sources of asymmetry

- The time dependent asymmetry is measured as:

$$A_{raw}(t) \approx A_{CP} + A_D + A_{PID} + A_P \cos(\Delta m_{d(s)} t)$$

- The **production asymmetry** A_P can be extracted by means of the time-dependent fit from the *CP* asymmetries in $B^0 \to K^+\pi^-$ and $B_s \to \pi^+ K^-$ decays
- A correction is required taking into account:
  - **asymmetry induced by the PID requirements** ($A_{PID}^{K\pi}$)
  - **detection asymmetry** ($A_D^{K\pi}$)
- $A_{PID}^{K\pi}$ estimated using $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$
- $A_D^{K\pi}$ measured using raw asymmetries of Cabibbo-favoured charm decays $D^+ \to K^-\pi^+\pi^+$ and $D^+ \to K^0\pi^+$ [JHEP 07 (2014) 041]
- Asymmetries are convoluted with the $B^0_{(s)} \to h^+h'^-$ phase space

$A_{PID}^{K\pi}(B^0_{(s)} \to K^\pm\pi^\mp)$	=	$(-0.04 \pm 0.25)\%$
$A_D^{K\pi}(B^0 \to K^+\pi^-)$	=	$(-0.900 \pm 0.141)\%$
$A_D^{K\pi}(B_s \to \pi^+K^-)$	=	$(-0.924 \pm 0.142)\%$

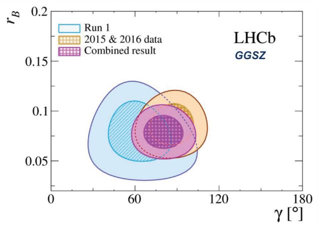
[Phys. Rev. D 98 (2018) 032004]

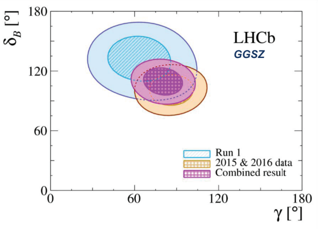
JHEP 08 (2018) 176

- Combine with Run 1 results (3 fb^{-1} at $\sqrt{s} = 7{,}8$ TeV) to give constraint on γ: JHEP 10 (2014) 097

$$\gamma = \left(80^{+10}_{-9}\right)^{\circ}$$

GGSZ





Run 1: $\gamma = \left(62^{+15}_{-14}\right)^{\circ}$

2015 & 2016: $\gamma = \left(87^{+11}_{-12}\right)^{\circ}$