CPV & mixing in beauty sector: experimental overview

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(for the ATLAS, CMS and LHCb collaborations)

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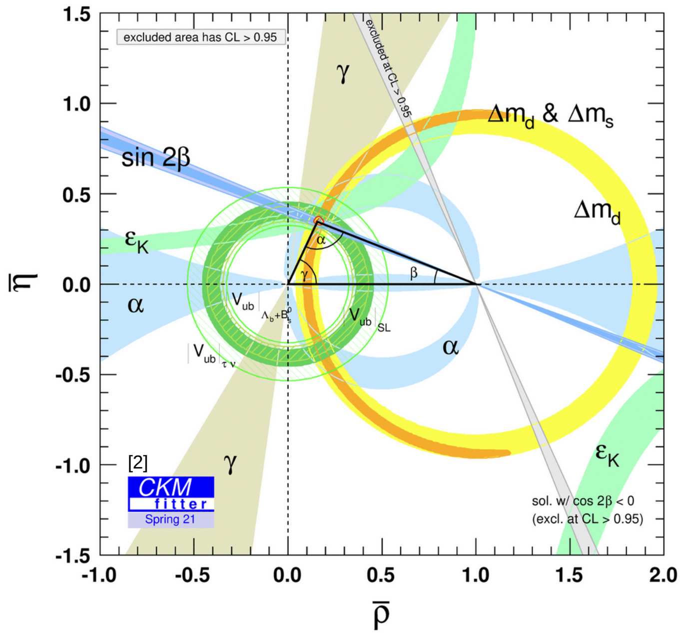
Motivation

- *CP*-violation observables are sensitive to Cabibbo–Kobayashi–Maskawa (CKM) angles α, $\beta_{(s)}$, γ.
- Precise measurements provide a strict test of the Standard Model (SM) predictions.
- Also allow for indirect searches for the New Physics (NP).
- Current status:

	HFLAV [1]	**CKMfitter** [2]	**UTfit** [3]
α [°]	$85.2\,^{+4.8}_{-4.3}$	$91.9\,^{+1.6}_{-1.2}$	90.1 ± 2.2
β [°]	22.2 ± 0.7	$23.41\,^{+1.53}_{-0.68}$	23.8 ± 1.3
γ [°]	$66.2\,^{+3.4}_{-3.6}$	$65.5\,^{+1.1}_{-2.7}$	65.8 ± 2.2
ϕ_s [rad]	-0.050 ± 0.019	$-0.03682\,^{+0.00060}_{-0.00086}$	-0.0370 ± 0.0010



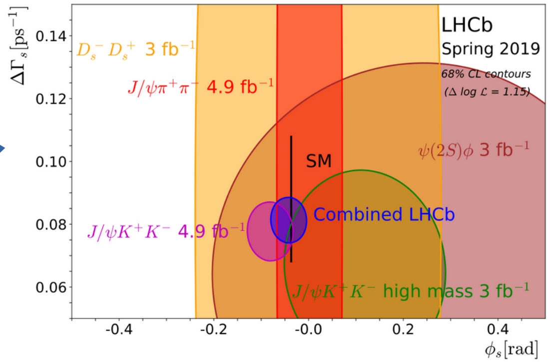
Disclaimer: Given the time constraint, only *selected* subjects are *summarized*.

[1] HFLAV Collaboration, Eur. Phys. J. C **81** (2021) no.3, 226, updated results: https://hflav.web.cern.ch.
[2] CKMfitter Group, Eur. Phys. J. C **41** (2005) no.1, 1-131, updated results: http://ckmfitter.in2p3.fr.
[3] UTfit Collaboration, JHEP **10** (2006) 081, updated results: http://utfit.org.

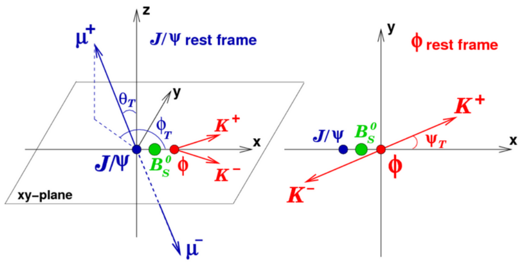
Measurement of the CPV phase ϕ_s in B_s decays

Eur. Phys. J. C 81 (2021) 342
Phys. Lett. B 816 (2021) 136188
Eur. Phys. J. C81 (2021) 1026

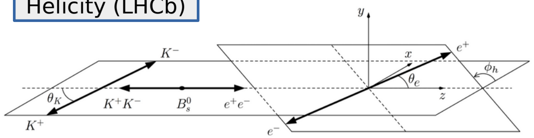
- *CP*-violating phase ϕ_s is defined as the weak phase difference between the B_s–$\overline{B}_s$ mixing amplitude and the $b \to c\bar{c}s$ decay amplitude (CPV in interference of mixing and decay).
- In the SM the phase ϕ_s is small and is related to the CKM matrix elements via the relation $\boldsymbol{\phi_s = -2\beta_s}$.
- LHCb: $B_s \to J/\psi\, K^+K^-$, both $J/\psi \to \mu^+\mu^-$ and $\boldsymbol{J/\psi \to e^+e^-}$; also $B_s \to J/\psi\, \pi^+\pi^-$, $B_s \to \psi(2S)\phi$, $\overline{B}_s \to D_s^+D_s^-$, see LHCb Public results.
- ATLAS, CMS: $B_s \to J/\psi(\mu^+\mu^-)\ \phi(K^+K^-)$.
- The golden mixing decay $B_s \to J/\psi(\mu^+\mu^-)\ \phi(K^+K^-)$ well known; less complicated environment to measure the phase (no direct CPV, only one weak phase).
- Pseudoscalar to vector-vector → final state: admixture of *CP*-odd and *CP*-even states. Distinguishable through **time-dependent angular analysis**.
- Opposite Side tagging (all experiments), Same Side tagging (so far LHCb only).

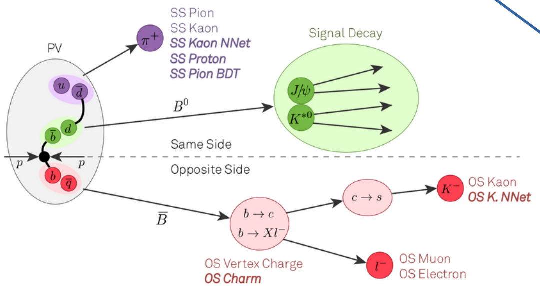


Transversity (ATLAS, CMS)



Helicity (LHCb)





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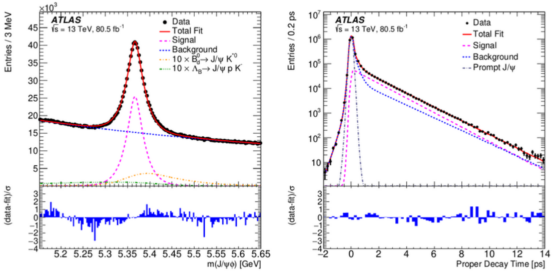
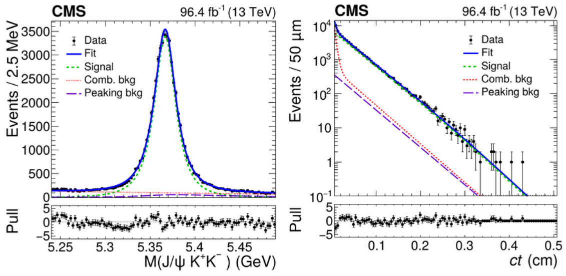
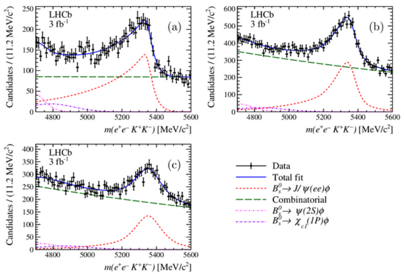
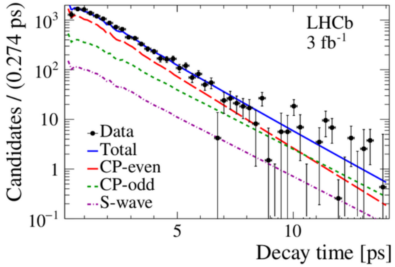
- Experiments are consistent with each other and with the SM prediction, however some tension occurs in other parameters especially in Γ_s ($\sim 3\sigma$).
- **LHCb (ee)**: Run-1. **ATLAS** and **CMS**: partial Run-2, combined with Run-1, working on **full Run-2** results.





LHCb: *ee* plots only!

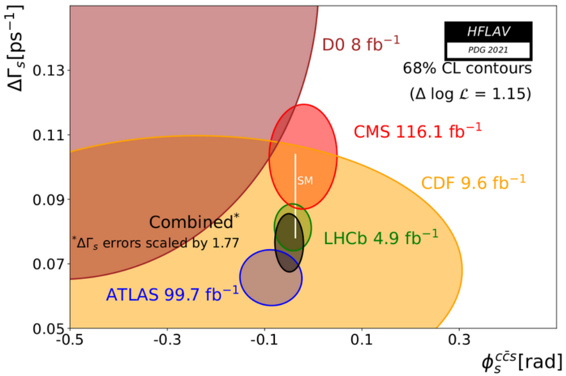


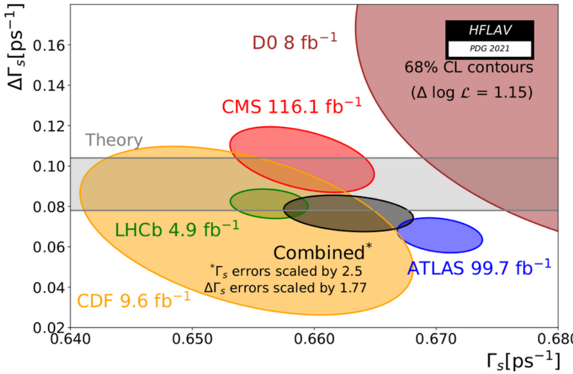


	ϕ_s [rad]	$\Delta\Gamma_s$ [ps^{-1}]
ATLAS	−0.087 ± 0.036 ± 0.021	0.0657 ± 0.0043 ± 0.0037
CMS	−0.021 ± 0.044 ± 0.010	0.1032 ± 0.0095 ± 0.0048
LHCb (all mumu)	−0.042 ± 0.025	0.0813 ± 0.0048
LHCb (ee)	0.00 ± 0.28 ± 0.07	0.115 ± 0.045 ± 0.011

Important check for the results with muons, because the systematic uncertainties are independent, while the studied mechanism of the CPV is the same.

LHCb (*ee*) not included





Simultaneous γ and charm mixing combination

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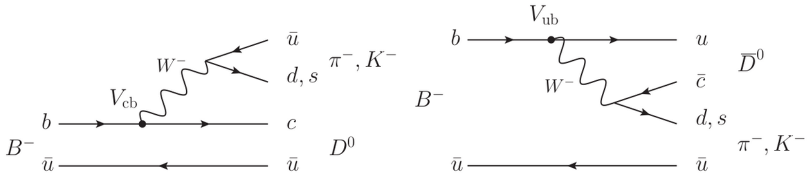
- CKM γ is the only angle that can be determined using solely measurements of tree-level B-meson decays with negligible theoretical uncertainty (assuming no sizeable new physics effects are present at tree level).
- Angle γ is measured in decays which are sensitive to interference between favoured $b \to c$ and suppressed $b \to u$ quark transition amplitudes (proportional to V_{cb} and V_{ub}, resp.).



- The results are obtained using a frequentist treatment, with a likelihood function built from the product of the probability density functions of experimental observables. The observables of each input are assumed to follow a multi-dimensional Gaussian distribution.

Many new/updated inputs

B decay	D decay	Ref.	Dataset	Status since Ref. [17]
$B^\pm \to Dh^\pm$	$D \to h^+h^-$	[20]	Run 1&2	**Updated**
$B^\pm \to Dh^\pm$	$D \to h^+\pi^-\pi^+\pi^-$	[21]	Run 1	As before
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^0$	[22]	Run 1	As before
$B^\pm \to Dh^\pm$	$D \to K^0_S h^+h^-$	[19]	Run 1&2	**Updated**
$B^\pm \to Dh^\pm$	$D \to K^0_S K^\pm\pi^\mp$	[23]	Run 1&2	**Updated**
$B^\pm \to D^*h^\pm$	$D \to h^+h^-$	[20]	Run 1&2	**Updated**
$B^\pm \to DK^{*\pm}$	$D \to h^+h^-$	[24]	Run 1&2(*)	As before
$B^\pm \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[24]	Run 1&2(*)	As before
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+h^-$	[25]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to h^+h^-$	[26]	Run 1&2(*)	**Updated**
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	[26]	Run 1&2(*)	**New**
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	[27]	Run 1	As before
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	[28]	Run 1	As before
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	[29]	Run 1	As before
$B^0_s \to D^\mp_s K^\pm\pi^+\pi^-$	$D^+_s \to h^+h^-\pi^+$	[30]	Run 1&2	**New**

Decay	Parameters	Source	Ref.	Status since Ref. [17]
$B^\pm \to DK^{*\pm}$	$\kappa^{DK^{*\pm}}_{B^\pm}$	LHCb	[24]	As before
$B^0 \to DK^{*0}$	$\kappa^{DK^{*0}}_{B^0}$	LHCb	[45]	As before
$B^0 \to D^\mp\pi^\pm$	β	HFLAV	[11]	**Updated**
$B^0_s \to D^\mp_s K^\pm(\pi\pi)$	ϕ_s	HFLAV	[11]	**Updated**
$D \to h^+h^-\pi^0$	$F^+_{\pi\pi\pi^0}$, $F^+_{K\pi\pi^0}$	CLEO-c	[46]	As before
$D \to \pi^+\pi^-\pi^+\pi^-$	$F^+_{4\pi}$	CLEO-c	[46]	As before
$D \to K^+\pi^-\pi^0$	$r^{K\pi\pi^0}_D$, $\delta^{K\pi\pi^0}_D$, $\kappa^{K\pi\pi^0}_D$	CLEO-c+LHCb+BESIII	[47–49]	**Updated**
$D \to K^\pm\pi^\mp\pi^+\pi^-$	$r^{K3\pi}_D$, $\delta^{K3\pi}_D$, $\kappa^{K3\pi}_D$	CLEO-c+LHCb+BESIII	[41, 47–49]	**Updated**
$D \to K^0_S K^\pm\pi^\mp$	$r^{K^0_S K\pi}_D$, $\delta^{K^0_S K\pi}_D$, $\kappa^{K^0_S K\pi}_D$	CLEO	[50]	As before
$D \to K^0_S K^\pm\pi^\mp$	$r^{K^0_S K\pi}_D$	LHCb	[51]	As before

Assumptions:

- Neutral kaon mixing not considered, impact on γ negligible.
- CPV in D-meson decays not considered in the *beauty* part, except for $B^\pm \to D(h^+h^-)h^\pm$ or $B^\pm \to D^*(h^+h^-)h^\pm$.
- Strong phases in $D \to K_S h^+h^-$ decays – inputs from CLEO-c and BES-III treated as statistically independent.
- Various potential systematic correlations between input measurements are not accounted for.

Simultaneous γ and charm mixing combination

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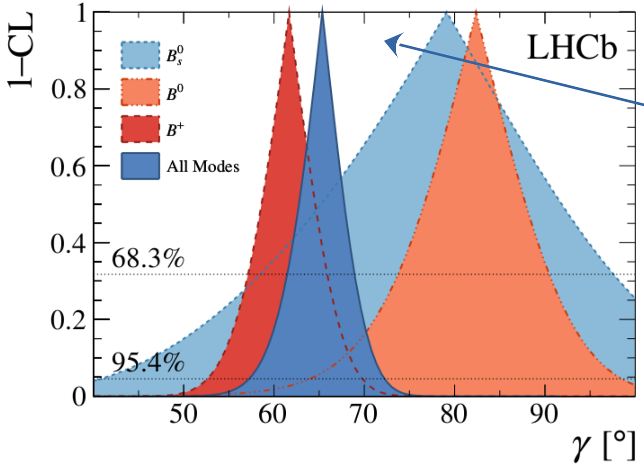
- The combination uses a total of 151 input observables to determine 52 free parameters, and the goodness of fit is found to be 84%, evaluated using the best-fit χ^2 and cross-checked with pseudoexperiments.

$$\gamma = (65.4^{+3.8}_{-4.2})^\circ$$

Compatible with, but lower than the previous LHCb combination $\gamma = (74^{+5.0}_{-5.8})^\circ$.

Good agreement between the frequentist and Bayesian statistical treatment.



Moderate tension 2.2σ between the charged and neutral B states. The uncertainties in the B and B_s modes are considerably larger than in the dominant B^+ modes.

Expected to improve by a factor of ~2 with the analysis of $B \to DK^+\pi^-$ and $B_s \to D_s^\mp K^\pm$ decays using the full LHCb data sample.

Inputs splitted by initial B-meson species

Species	Value [°]	68.3% CL		95.4% CL	
		Uncertainty	Interval	Uncertainty	Interval
B^+	61.7	$^{+4.4}_{-4.8}$	[56.9, 66.1]	$^{+8.6}_{-9.5}$	[52.2, 70.3]
B^0	82.0	$^{+8.1}_{-8.8}$	[73.2, 90.1]	$^{+17}_{-18}$	[64, 99]
B_s^0	79	$^{+21}_{-24}$	[55, 100]	$^{+51}_{-47}$	[32, 130]

Inputs splitted by time-dependent and time-integrated methods

Method	Value [°]	68.3% CL		95.4% CL	
		Uncertainty	Interval	Uncertainty	Interval
Time-dependent	79	$^{+21}_{-24}$	[55, 100]	$^{+51}_{-47}$	[32, 130]
Time-integrated	64.9	$^{+3.9}_{-4.5}$	[60.4, 68.8]	$^{+7.8}_{-9.6}$	[55.3, 72.7]

CKM angle γ from $B^{\pm} \to D(h^{\pm}h'^{\mp}\pi^0)\ h^{\pm}$

PAPER-2021-036, submitted to JHEP

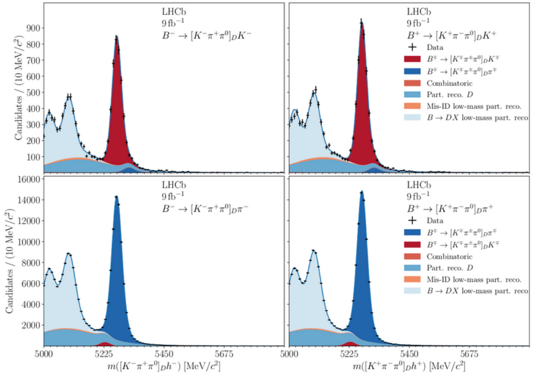
- (Came after the above combination was performed.)
- Data from Run-1 and Run-2 @ 7 TeV (1 fb^{-1}), 8 TeV (2 fb^{-1}), and 13 TeV (6 fb^{-1}).
- $B^- \to DK^-$ and $B^- \to D\pi^-$ decays studied using the $D \to \pi K \pi^0$, $D \to KK\pi^0$ and $D \to \pi\pi\pi^0$ final states.
- Measurement of γ using:
  - GLW modes: $B^- \to DK^-$, with *D*-meson decays to *CP* eigenstates.
  - ADS modes: with suppressed decays to non-charge-conjugate states.
    - Suppressed ADS decays: favoured (suppressed) $B \to DK$ decay followed by a suppressed (favoured) *D*-meson decay; **particularly sensitive to γ**.
    - Favoured ADS decays: favoured (suppressed) $B \to DK$ decay followed by a favoured (suppressed) *D*-meson decay.
  - Actually, *quasi-* modes are measured: *D*-meson decays to three or more hadrons.

CKM angle γ from $B^{\pm} \to D(h^{\pm}h'^{\mp}\pi^{0})\, h^{\pm}$

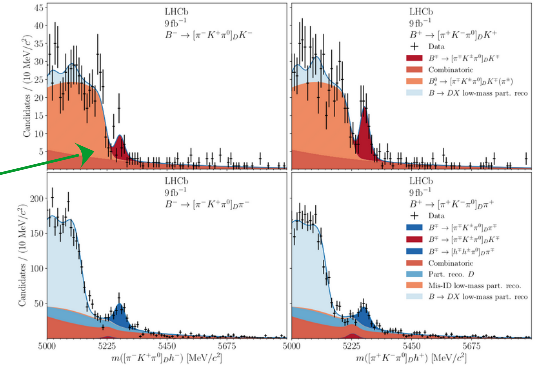
PAPER-2021-036, submitted to JHEP

- Experimentally robust *CP* observables formed from ratios of partial decay rates and measured with world-best precision:

$R^{KK\pi^0}$	$=$	1.021	$\pm\ 0.079$	$\pm\ 0.005$	GLW: double ratios of partial widths.
$R^{\pi\pi\pi^0}$	$=$	0.902	$\pm\ 0.041$	$\pm\ 0.004$	
$A_K^{K\pi\pi^0}$	$=$	-0.024	$\pm\ 0.013$	$\pm\ 0.002$	GLW: *CP*-asymmetry in the favoured mode.
$A_K^{KK\pi^0}$	$=$	0.067	$\pm\ 0.073$	$\pm\ 0.003$	GLW: *CP*-asymmetries.
$A_K^{\pi\pi\pi^0}$	$=$	0.109	$\pm\ 0.043$	$\pm\ 0.003$	
$A_\pi^{KK\pi^0}$	$=$	-0.001	$\pm\ 0.019$	$\pm\ 0.002$	
$A_\pi^{\pi\pi\pi^0}$	$=$	0.001	$\pm\ 0.010$	$\pm\ 0.002$	
R_K^{+}	$=$	0.0179	$\pm\ 0.0024$	$\pm\ 0.0003$	ADS: ratios of the rates of the suppressed and favoured decay modes.
R_K^{-}	$=$	0.0085	$\pm\ 0.0020$	$\pm\ 0.0004$	
R_π^{+}	$=$	0.00188	$\pm\ 0.00027$	$\pm\ 0.00005$	
R_π^{-}	$=$	0.00227	$\pm\ 0.00028$	$\pm\ 0.00004$	

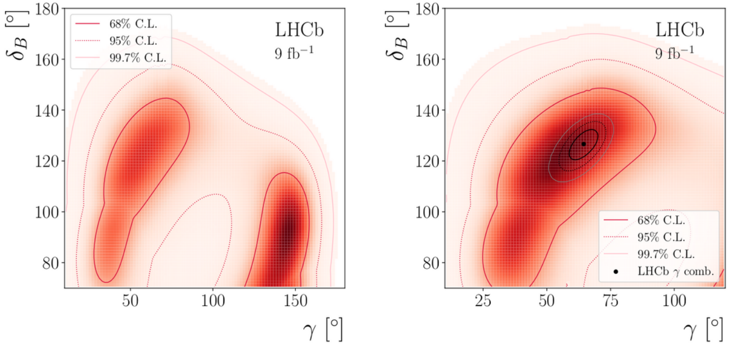


vs.



- Interpreted in terms of the fundamental parameters (angle γ, relative strong phase, ratio of the magnitudes of the $B^- \to DK^-$ to $B^- \to \overline{D}K^-$ amplitudes):

$$\begin{aligned} \gamma &= (56^{+24}_{-19})^\circ, \\ \delta_B &= (122^{+19}_{-23})^\circ, \\ r_B &= (9.3^{+1.0}_{-0.9}) \times 10^{-2} \end{aligned}$$



The suppressed $B^- \to D(\pi^- K^+\pi^0)K^-$ decay observed for the first time, with a significance of **7.8σ**!

- These measurements shall be used in future combinations to constrain the angle γ.

Observation of CPV in $B_{(s)} \to h^+h'^-$, $h^{(\prime)} = \pi, K$

JHEP 03 (2021) 075

- Using data 2015–2016 @ 13 TeV, L = 1.9 fb^{-1} for:
  - time-dependent *CP*-asymmetries in $B \to \pi^+\pi^-$ and $B_s \to K^+K^-$ decays,
  - time-integrated *CP*-asymmetries in $B \to K^+\pi^-$ and $B_s \to K^-\pi^+$ decays.
- *CP*-asymmetry in $B \to \pi^+\pi^-$: input to the isospin analysis → **CKM angle $\boldsymbol{\alpha}$**.
  - Can be extended by exploiting the approximate U-spin symmetry that relates the hadronic parameters of decay amplitudes of $B \to \pi^+\pi^-$ and $B_s \to K^+K^-$.
  - Stringent constraints on **CKM $\boldsymbol{\gamma}$** and on the $\boldsymbol{\phi_s = -2\beta_s}$ can be set.

Current experimental determinations confirm the SM expectation of negligible *CP*-violation in the $B_{(s)}$–$\overline{B}_{(s)}$ mixing (implying |q/p| = 1):
→ $C_f \neq 0$ → CPV in the decay,
→ $S_f \neq 0$ → CPV in the interference between mixing and decay.

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

$$C_f \equiv \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}, \quad S_f \equiv \frac{2\mathrm{Im}\lambda_f}{1+|\lambda_f|^2}, \quad A_f^{\Delta\Gamma} \equiv -\frac{2\mathrm{Re}\lambda_f}{1+|\lambda_f|^2} \quad \lambda_f \equiv \frac{q}{p}\frac{\overline{A}_f}{A_f}$$

$$(C_f)^2 + (S_f)^2 + \left(A_f^{\Delta\Gamma}\right)^2 = 1$$

Here: not a constraint, but a cross-check.

- *CP*-asymmetries and BFs of the $B \to K^+\pi^-$ and $B_s \to K^-\pi^+$ provides the test of the SM, assuming U-spin symmetry.
  - $B \to K^+\pi^-$: key input to the long-standing **$\boldsymbol{B \to K\pi}$ puzzle**.

Measurements of 4 possible $B^{(+)} \to \pi K$ decays in disagreement with SM (the amplitudes are expected to obey relations imposed by the isospin symmetry) → modification of the electroweak penguin amplitude? Examination through the "**sum rule**"...

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

$$\boxed{A_{CP}(K^+\pi^-) + A_{CP}(K^0\pi^+)\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+} = A_{CP}(K^+\pi^0)\frac{2\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+} + A_{CP}(K^0\pi^0)\frac{2\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}}$$

Observation of CPV in $B_{(s)} \to h^+h'^-$, $h^{(\prime)} = \pi, K$

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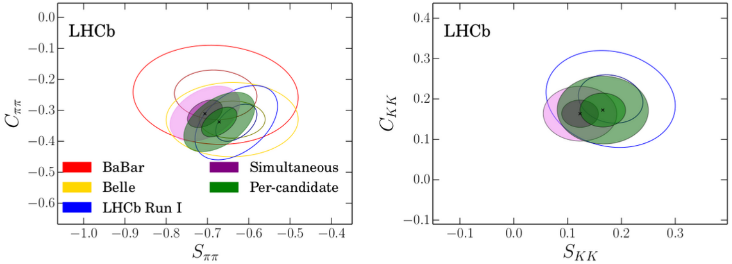
- Two independent fitting methods:
  - **Simultaneous**: a concurrent fit to all the final-state samples ($\pi^+\pi^-$, K^+K^- and $K^\pm\pi^\mp$). Used for all sub-measurements.
  - **Per-candidate**: independent fits to the $\pi^+\pi^-$ and K^+K^- samples with all background components statistically subtracted using the sFit technique. Used to determine CPV parameters in $B \to \pi^+\pi^-$ and $B_s \to K^+K^-$.
  - Comparison of their respective results serves as validation of the measurements.

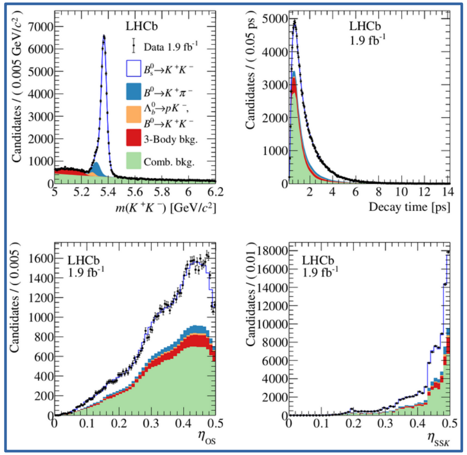


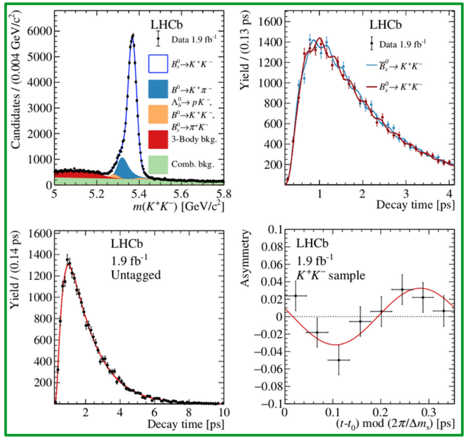
A χ^2 test used to determine the significance for:

→ (C_{KK}, S_{KK}, $A^{\Delta\Gamma}_{KK}$) to differ from (0, 0, -1) → **6.5σ**,

→ (C_{KK}, S_{KK}) to differ from (0, 0) → **6.7σ**.

The first observation of time-dependent CPV in decays of the B_s meson.





$$
\begin{aligned}
C_{\pi\pi} &= -0.311 \pm 0.045 \pm 0.015,\\
S_{\pi\pi} &= -0.706 \pm 0.042 \pm 0.013,\\
A_{CP}^{B^0} &= -0.0824 \pm 0.0033 \pm 0.0033,\\
A_{CP}^{B^0_s} &= 0.236 \pm 0.013 \pm 0.011,\\
C_{KK} &= 0.164 \pm 0.034 \pm 0.014,\\
S_{KK} &= 0.123 \pm 0.034 \pm 0.015,\\
\mathcal{A}_{KK}^{\Delta\Gamma} &= -0.83 \pm 0.05 \pm 0.09,
\end{aligned}
$$

Comb. with Run-1 →

$$
\begin{aligned}
C_{\pi\pi} &= -0.320 \pm 0.038,\\
S_{\pi\pi} &= -0.672 \pm 0.034,\\
A_{CP}^{B^0} &= -0.0831 \pm 0.0034,\\
A_{CP}^{B^0_s} &= 0.225 \pm 0.012,\\
C_{KK} &= 0.172 \pm 0.031,\\
S_{KK} &= 0.139 \pm 0.032,\\
\mathcal{A}_{KK}^{\Delta\Gamma} &= -0.897 \pm 0.087
\end{aligned}
$$

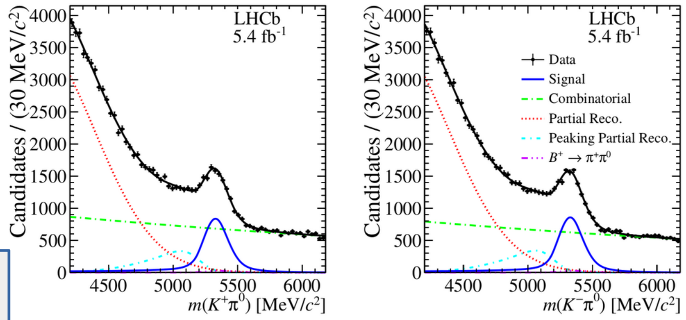
$$\sqrt{(C_{KK})^2 + (S_{KK})^2 + (\mathcal{A}_{KK}^{\Delta\Gamma})^2} = 0.93 \pm 0.08 \checkmark$$

Measurement of the direct CPV in $B^+ \to K^+\pi^0$

Phys. Rev. Lett. 126 (2021) 091802

$$A_{CP} = \frac{\Gamma(B^- \to K^-\pi^0) - \Gamma(B^+ \to K^+\pi^0)}{\Gamma(B^- \to K^-\pi^0) + \Gamma(B^+ \to K^+\pi^0)}$$

- Data 2016-2018 @ 13 TeV, L = 1.9 fb^{-1}.
- Candidates fitted separately in 2x2 categories:
  - in order to reduce uncertainties due to non-uniformity of the detector, candidates are separated according to whether the LHCb dipole magnetic field (MF) is aligned vertically **upward** or **downward**.
  - Candidates are further separated by B-meson charge.
- The combined effect of the nuisance asymmetries is measured with a control sample of $B^+ \to J/\psi(\mu^+\mu^-)K^+$ decays: $A_{CP}(B^+ \to K^+\pi^0) = A_{\rm raw}(B^+ \to K^+\pi^0) - A^{B}_{\rm prod.} - A^{K}_{\rm det.}$
- Averaging the MF Up and MF Down results…



$$A_{CP}(B^+ \to K^+\pi^0) = 0.025 \pm 0.015 \pm 0.006 \pm 0.003$$

Consistent with the world average and with zero at ~1.5σ.

$$\Delta A_{CP}(K\pi) \equiv A_{CP}(B^+ \to K^+\pi^0) - A_{CP}(B^0 \to K^+\pi^-)$$

From HFLAV

0.108 ± 0.017

New world average of $\boldsymbol{A_{CP}(B^+ \to K^+\pi^0) = 0.031 \pm 0.013}$
→ corresponds to $\boldsymbol{\Delta A_{CP}(K\pi) = 0.115 \pm 0.014}$
(nonzero with a significance > 8σ).

Updated **sum rule** prediction for $\boldsymbol{A_{CP}(B \to K^0\pi^0) = -0.138 \pm 0.025}$
(departing from zero with a significance of ~**5.5σ**).

Systematic uncertainties

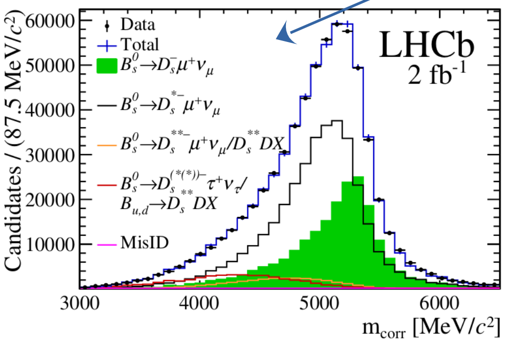
Systematic	Value ($\times 10^{-3}$)
Signal modeling shape	4.3
Combinatorial background shape	1.3
Partial reco. background shape	1.3
Peaking partial reco. background shape	1.2
Peaking partial reco. background offset	1.3
Peaking partial reco. background resolution	1.4
$B^+ \to \pi^+\pi^0$ yield	1.3
$B^+ \to \pi^+\pi^0$ CP asymmetry	1.5
Multiple candidates	1.3
Production/detection asymmetry stat.	2.1
Production/detection asymmetry weights	0.5
Sum in quadrature	6.1

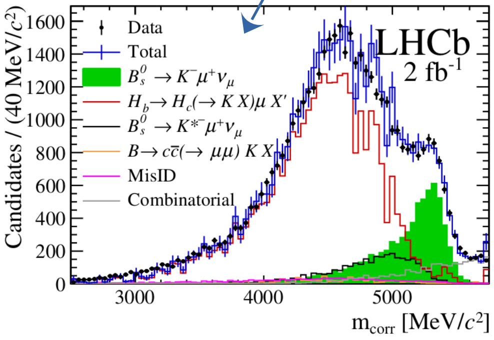
First observation of $B_s \to K^- \mu^+ \nu_\mu$

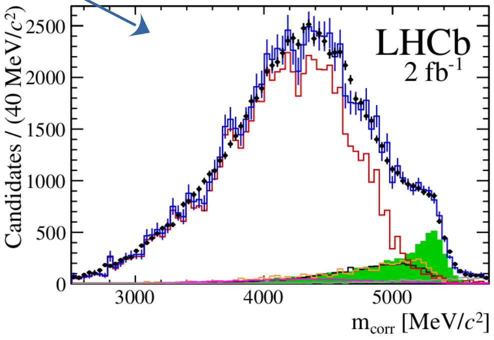
Phys. Rev. Lett. 126 (2021) 081804

- Observed hierarchy $|V_{ub}|/|V_{cb}| \sim 0.1$, i.e., $b \to c l \nu$ favored over $b \to u l \nu$.
- Semileptonic b-hadron decays are an excellent ground for measuring $|V_{ub}|$ and $|V_{cb}|$ (factorization of the hadronic and leptonic parts of the amplitudes eases theoretical calculations).
- Existing $|V_{ub}|$ and $|V_{cb}|$ measurements show a **discrepancy between** those performed with **exclusive decays**, where all the visible particles are reconstructed, and **inclusive decays** where only the lepton is reconstructed.
- Data 2012 @ 8 TeV, L = 2 fb^{-1}. Normalization channel $B_s \to D^-_s(K^-K^+\pi^-)\mu^+\nu_\mu$.
- *BR* and $|V_{ub}|/|V_{cb}|$ measured in the two regions of $q^2 = m(\mu^+\nu_\mu)^2$: **below** and **above** 7 GeV^2.

Fit to $m(K^+K^-\pi^-)$ in 40 intervals of $m_{corr} \to N(D^-_s) = f(m_{corr})$.







$$m_{\rm corr} = \sqrt{m^2_{Y\mu} + p^2_{\perp}/c^2} + p_{\perp}/c$$

where $Y = K^-$ or D^-_s

First observation of $B_s \to K^- \mu^+ \nu_\mu$

Phys. Rev. Lett. 126 (2021) 081804

- BMLF to m_{corr}: $N_K(\mathrm{low}) = 6922 \pm 285$, $N_K(\mathrm{high}) = 6399 \pm 370$ and $N_{D_s} = 201450 \pm 5200$.

$$R_{\mathrm{BF}} \equiv \frac{\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)} = \frac{N_K}{N_{D_s}} \frac{\epsilon_{D_s}}{\epsilon_K} \times \mathcal{B}(D_s^- \to K^+ K^- \pi^-)$$

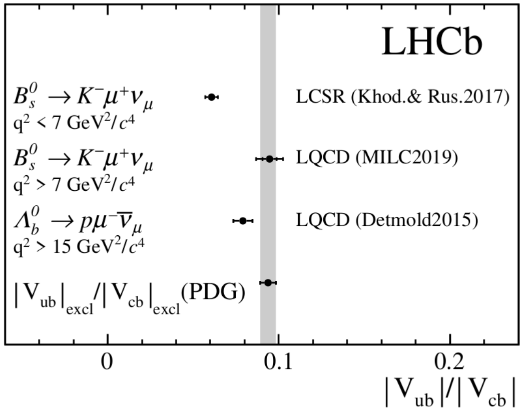
$$\mathrm{FF}_Y = |V_{xb}|^{-2} \int \frac{d\Gamma(B_s^0 \to Y \mu^+ \nu_\mu)}{dq^2} dq^2$$

$$\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu) = \tau_{B_s} \times |V_{cb}|^2 \times \mathrm{FF}_{D_s} \times R_{\mathrm{BF}}$$

$$\boxed{\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu) = (1.06 \pm 0.05\,(\mathrm{stat}) \pm 0.04\,(\mathrm{syst}) \pm 0.06\,(\mathrm{ext}) \pm 0.04\,(\mathrm{FF})) \times 10^{-4}}$$

$$R_{\mathrm{BF}} = |V_{ub}|^2/|V_{cb}|^2 \times \mathrm{FF}_K/\mathrm{FF}_{D_s}$$

$$|V_{ub}|/|V_{cb}|(\mathrm{low}) = 0.0607 \pm 0.0015\,(\mathrm{stat}) \pm 0.0013\,(\mathrm{syst}) \pm 0.0008\,(D_s) \pm 0.0030\,(\mathrm{FF})$$
$$|V_{ub}|/|V_{cb}|(\mathrm{high}) = 0.0946 \pm 0.0030\,(\mathrm{stat})^{+\,0.0024}_{-\,0.0025}\,(\mathrm{syst}) \pm 0.0013\,(D_s) \pm 0.0068\,(\mathrm{FF})$$



R_{BF} in the two q^2 regions represent the first experimental ingredient to the FF calculations of the $B_s \to K^- \mu^+ \nu_\mu$ decay.

The $|V_{cb}|/|V_{ub}|$ results will improve both the averages of the exclusive measurements in the ($|V_{cb}|$, $|V_{ub}|$) plane and the precision on the least known side of the CKM UT.

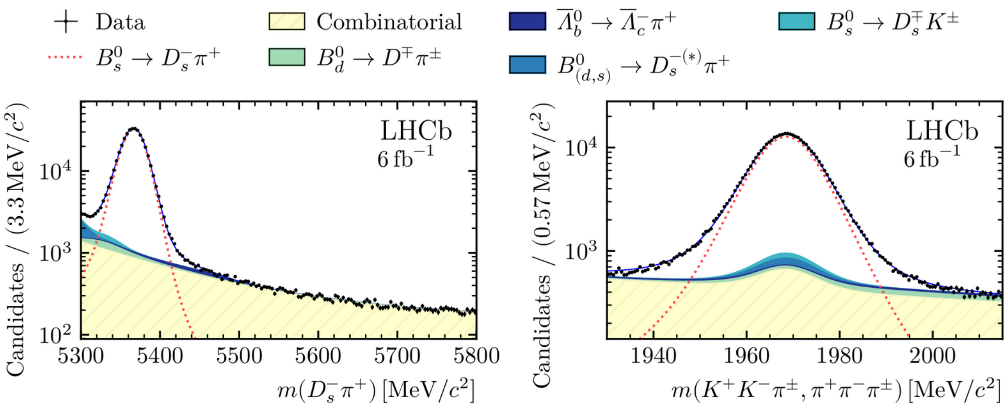
Relative systematic uncertainties of R_{BF}

Uncertainty	All q^2	low q^2	high q^2
Tracking	2.0	2.0	2.0
Trigger	1.4	1.2	1.6
Particle identification	1.0	1.0	1.0
$\sigma(m_{\mathrm{corr}})$	0.5	0.5	0.5
Isolation	0.2	0.2	0.2
Charged BDT	0.6	0.6	0.6
Neutral BDT	1.1	1.1	1.1
q^2 migration	–	2.0	2.0
Efficiency	1.2	1.6	1.6
Fit template	$^{+2.3}_{-2.9}$	$^{+1.8}_{-2.4}$	$^{+3.0}_{-3.4}$
Total	$^{+4.0}_{-4.3}$	$^{+4.3}_{-4.5}$	$^{+5.0}_{-5.3}$

Precise measurement of Δm_s

Nature Physics 18, (2022) 1-5

- B_s mesons can oscillate between particle and antiparticle **flavour** eigenstates.
- Frequency given by the mass difference $\boldsymbol{\Delta m_s = m_H - m_L}$ between heavy (H) and light (L) **mass** eigenstates. (Recall slide 2: "Measurement of the CPV phase ϕ_s in B_s decays".)
- Decay channel $\boldsymbol{B_s \to D^-_s \pi^+}$ (with $D^-_s \to K^- K^+ \pi^-$ or $D^-_s \to \pi^- \pi^+ \pi^-$). Data 2015–2018 @ 13 TeV, L = 6 fb^{-1}.
- Decay-time distribution constructed in the absence of background:
  2D UMLF to $D^-_s \pi^+$ and $K^- K^+ \pi^-$ or $\pi^- \pi^+ \pi^-$ distributions → yields, weights → sPlot.



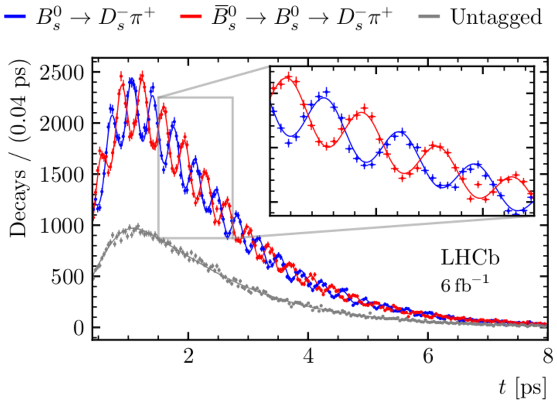
Precise measurement of *Δm*$_s$

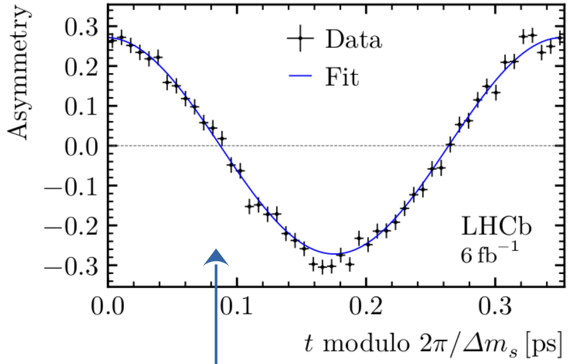
Nature Physics 18, (2022) 1-5

- Initial B_s flavour:
  - OS + SS tagging.
  - Combined efficiency ε = (80.30 ± 0.07)%, mistag fraction ω = (36.21 ± 0.02 ± 0.17)%.
- UMLF to the decay-time distribution

$$P(t) \sim e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + C \cdot \cos(\Delta m_s t)\right]$$

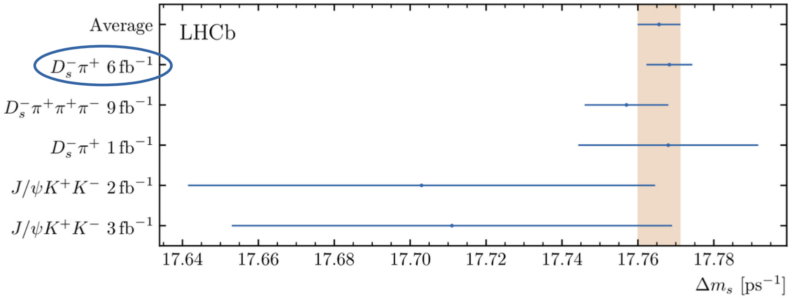
+ modified to account for the detector effects





$$A(t) = \frac{N(B_s^0 \to D_s^-\pi^+, t) - N(\overline{B}_s^0 \to D_s^-\pi^+, t)}{N(B_s^0 \to D_s^-\pi^+, t) + N(\overline{B}_s^0 \to D_s^-\pi^+, t)}$$

- ***Δm*$_s$ = 17.7683 ± 0.0051 (stat) ± 0.0032 (syst) ps^{-1}**, the most precise measurement!
- Combination with the previous LHCb result: ***Δm*$_s^{comb}$ = 17.7656 ± 0.0057 ps^{-1}**.
- Compatible with, and considerably more precise than, the predicted value from lattice QCD and sum rule calculations.



Systematic uncertainties

Description	Systematic uncertainty [ps^{-1}]
Reconstruction effects:	
momentum scale uncertainty	0.0007
detector length scale	0.0018
detector misalignment	0.0020
Invariant mass fit model:	
background parametrisation	0.0002
$B_s^0 \to D_s^{*-}\pi^+$ and $B^0 \to D_s^-\pi^+$ contributions	0.0005
Decay-time fit model:	
decay-time resolution model	0.0011
neglecting correlation among observables	0.0011
Cross-checks:	
kinematic correlations	0.0003
Total systematic uncertainty	0.0032

Measurement of $\Lambda_b \to D(K^+\pi^-)pK^-$

Phys. Rev. D104 (2021) 112008

- Both $D \to K^+\pi^-$ and $D \to K^-\pi^+$ considered, the singly-Cabibbo-suppressed $\Lambda_b \to D(K^+\pi^-)pK^-$ decay **observed for the first time**.
- Data from Run-1 and Run-2 @ 7, 8 and 13 TeV (9 fb^{-1} in total).
- **Full** vs. **restricted** region $M^2(pK^-) < 5\ \mathrm{GeV}^2$ (enhanced sensitivity to γ expected).

Ratio of BFs between the favoured and suppressed modes

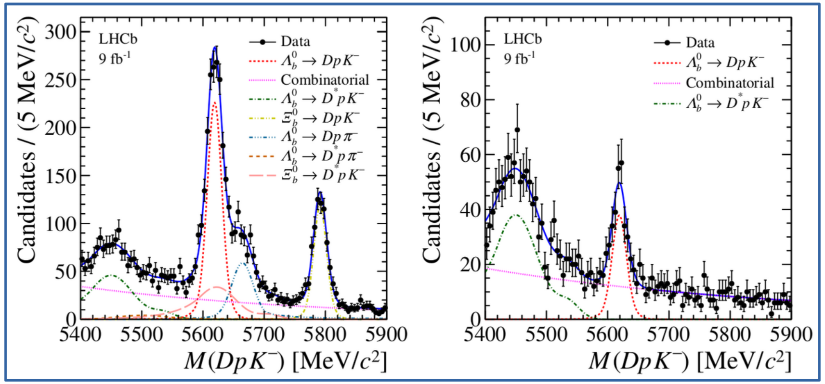
Full:

$$R = 7.1 \pm 0.8\,(\mathrm{stat.})^{+0.4}_{-0.3}\,(\mathrm{syst.}),$$
$$A = 0.12 \pm 0.09\,(\mathrm{stat.})^{+0.02}_{-0.03}\,(\mathrm{syst.})$$

Restricted:

$$R = 8.6 \pm 1.5\,(\mathrm{stat.})^{+0.4}_{-0.3}\,(\mathrm{syst.}),$$
$$A = 0.01 \pm 0.16\,(\mathrm{stat.})^{+0.03}_{-0.02}\,(\mathrm{syst.})$$

CP asymmetry in the suppressed mode (expected to be sensitive to γ)



R consistent with the estimate: $R \approx \left|\dfrac{V_{cb}V_{us}^*}{V_{ub}V_{cs}^*}\right|^2 = 6.0$

- Present signal yields are too low to be used to extract γ; larger samples are expected in the coming years.

Summary

- CPV and mixing in beauty is a great place to look for the new physics!
- CKM γ measurement slowly enters the precision area.
- More data (precision) needed for ϕ_s measurements.
- More public results:
  - ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults,
  - CMS: https://cms-results.web.cern.ch/cms-results/public-results/publications/BPH/index.html,
  - LHCb: https://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_all.html.

Thank you!