Results on decays and *CP* violation from LHCb

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on behalf of the LHCb collaboration

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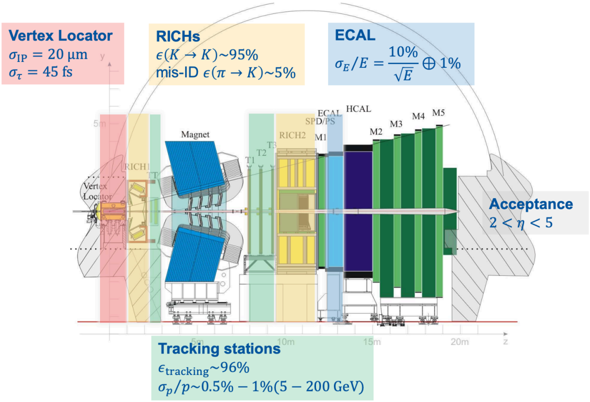
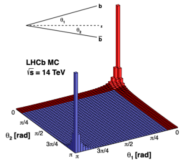
Overview

- Direct CP violation in three-body charm decays
  - $D^+_{(s)} \to K^- K^+ K^+$ [arXiv:2303.04062]
  - $D^0 \to \pi^+\pi^-\pi^0$ [LHCb-PAPER-2023-005 in preparation]
- CKM angles in beauty decays
  - $\sin 2\beta$ from $B^0 \to \psi K^0_{\mathrm{S}}$ [LHCb-PAPER-2023-013 in preparation]
  - ϕ_s from $B^0_s \to J/\psi K^+ K^-$ [LHCb-PAPER-2023-016 in preparation]
  - ϕ_s from $B^0_s \to \phi\phi$ [arXiv:2304.06198]
  - γ from $B^\pm \to [K^+ K^- \pi^+ \pi^-]_D h^\pm$ [arXiv:2301.10328]
  - Branching fractions of $B^0_{(s)} \to \bar{D}^{(*)0}\phi$ [LHCb-PAPER-2023-003 in preparation]
- Spectroscopy in hadron decays covered by other LHCb talks
  - Conventional meson [Tim Gershon] and baryon [Zhihao Xu]
  - Exotic hadrons [Elisabetta Spadaro Norella], [Yanxi Zhang], [Mindaugas Sarpis], [Bo Fang]

LHCb detector

- A single-arm forward spectrometer at LHC [JINST 3 (2008) S08005] [IJMPA 30 (2015) 1530022]





Direct CP violation in three-body charm decay

- Direct CP violation corresponds to

$$A_{CP} = \frac{|A_f|^2 - |\bar{A}_{\bar{f}}|^2}{|A_f|^2 + |\bar{A}_{\bar{f}}|^2} \neq 0 \Longleftarrow |A_f|^2 - |\bar{A}_{\bar{f}}|^2 = -2\sum_{i,j} |A_i||A_j| \sin(\delta_i - \delta_j)\sin(\phi_i - \phi_j)$$

- CP violation in charm hadrons only established recently
  - Difference in time-integrated CP asymmetries of $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ [PRL 122 211803]
  - Evidence for CP asymmetry of $D^0 \to \pi^+\pi^-$ [arXiv:2209.03179]
  - No broad consensus whether BSM contributions are required
- Three-body decays provide enhanced sensitivity in localised regions
  - Variation of strong phase across Dalitz plot
  - Model independent methods
    - Statistical test
    - Reduce systematic uncertainty on describing the resonant structure

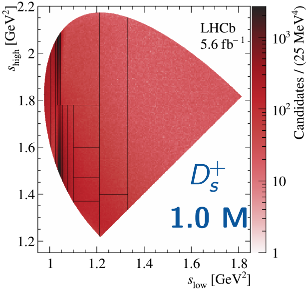
Search for CP violation in $D^+_{(s)} \to K^- K^+ K^+$

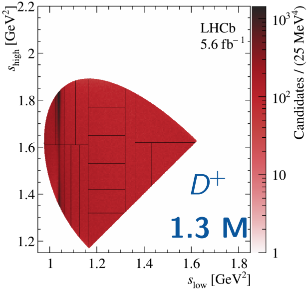
[arXiv:2303.04062]

- Cabbibo-suppressed $D^+_{(s)}$ decays LHCb Run 2
- Signal purity 64% (D^+_s) and 78% (D^+)
- Model-independent binned techinique
  - Dalitz plot binning scheme: avoid potential sign-changing of CP asymmetry
  - Two-sample χ^2 test

$$\mathcal{S}^i_{CP} = \frac{N^i(D^+_{(s)}) - \alpha N^i(D^-_{(s)})}{\sqrt{\alpha(\delta^2_{N^i(D^+_{(s)})} + \delta^2_{N^i(D^-_{(s)})})}} \qquad \alpha = \frac{\sum_i N^i(D^+_{(s)})}{\sum_i N^i(D^-_{(s)})}$$

$$\chi^2(\mathcal{S}_{\mathcal{CP}}) = \sum (\mathcal{S}^i_{CP})^2$$





Search for CP violation in $D^+_{(s)} \to K^- K^+ K^+$

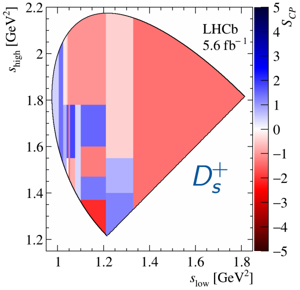
[arXiv:2303.04062]

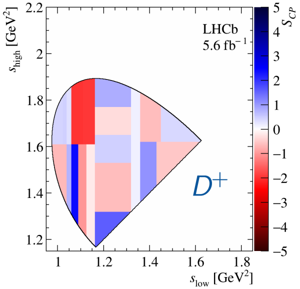
- No evidence for CP violation

$$p\text{-value}(D_s^+ \to K^- K^+ K^+) = 13.3\%$$

$$p\text{-value}(D^+ \to K^- K^+ K^+) = 31.6\%$$

  - p-value variations checked with Cabbibo-favored $D_s^+ \to K^- K^+ \pi^+$ and $D^+ \to K^- \pi^+ \pi^+$ decay
  - different invariant-mass fit models
  - different binning scheme



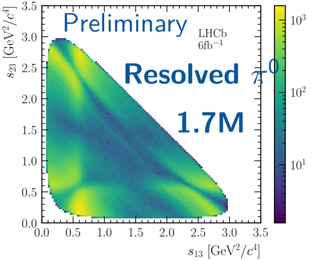


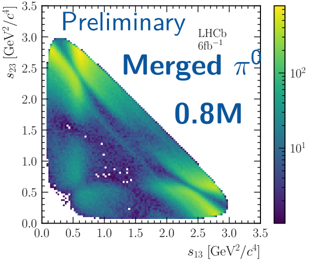
Search for CP violation in $D^0 \to \pi^+\pi^-\pi^0$ [LHCb-PAPER-2023-005 in preparation]

- Cabbibo-suppressed D^0 decays LHCb Run 2
  - $4\times$ LHCb Run 1 data [PLB 2014 11 043]
- Flavour tagged with $D^{*+} \to D^0\pi^+$
- Purity 81% (91%) for resolved (merged) π^0
- Equalisation procedure
  - Magnetic polarity
  - Fraction of merged and resolved π^0
- Model-independent unbinned technique

$$T \equiv \frac{1}{2n(n-1)}\sum_{i,j\neq i}^{n}\psi_{ij} + \frac{1}{2\bar{n}(\bar{n}-1)}\sum_{i,j\neq i}^{\bar{n}}\psi_{ij} - \frac{1}{n\bar{n}}\sum_{i,j}^{n,\bar{n}}\psi_{ij}$$

$$\psi_{ij} = e^{-d_{ij}^2/2\delta^2}, \quad \delta = 0.2\,\mathrm{GeV}^2$$



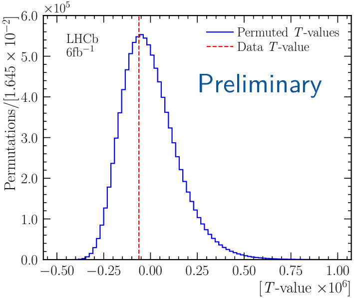


Search for CP violation in $D^0 \to \pi^+\pi^-\pi^0$ [LHCb-PAPER-2023-005 in preparation]

- No evidence for local CP violation

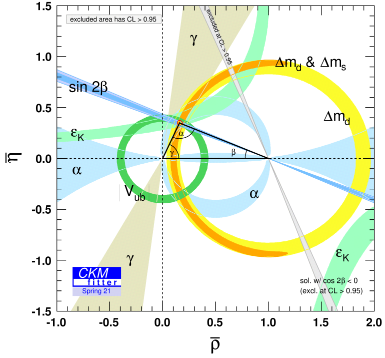
$$p\text{-value} = 62\%$$

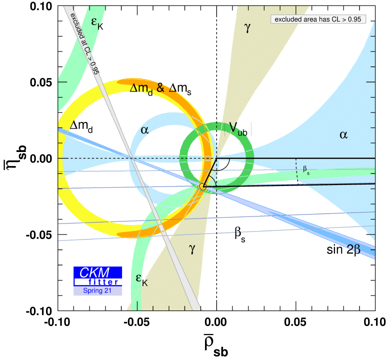
  - Cross-checks with $D^0 \to K^-\pi^+\pi^0$ decay
  - background-dominated samples
  - pseudoexperiments



Angles of CKM unitarity triangle

[CKMFITTER GROUP]





$$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0 \qquad V_{us}V_{ub}^{*} + V_{cs}V_{cb}^{*} + V_{ts}V_{tb}^{*} = 0$$

Measurements of $\beta_{(s)}$ with time-dependent analysis

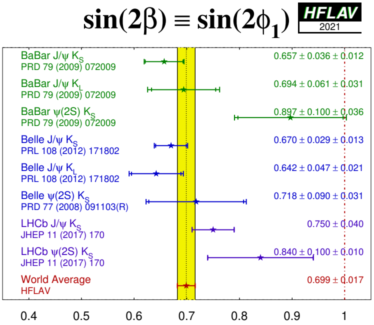
- Neutral B meson decays into CP eigenstates

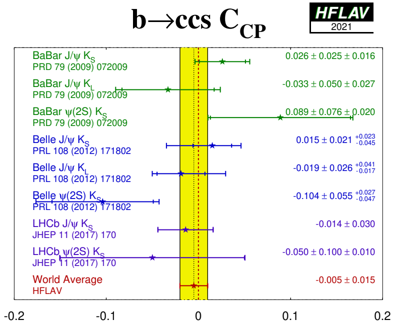
$$A_{CP}(t) = \frac{\Gamma\left(\bar{B}^0_{(s)} \to f\right) - \Gamma\left(B^0_{(s)} \to f\right)}{\Gamma\left(\bar{B}^0_{(s)} \to f\right) + \Gamma\left(B^0_{(s)} \to f\right)} = \frac{S_f^{d(s)} \sin\left(\Delta m_{d(s)} t\right) - C_f^{d(s)} \cos\left(\Delta m_{d(s)} t\right)}{\cosh\left(\Delta\Gamma_{d(s)}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

  - $b \to c\bar{c}s$: golden channels
    - $\sin 2\beta$ from $B^0 \to \psi K^0_{\mathrm{S}}$
    - $\phi_s^{c\bar{c}s}$ from $B^0_s \to J/\psi KK$
  - $b \to s\bar{s}s$: penguin-dominated decay

- CKM angle β known to a high precision
  - Clean experimental signature of $B^0 \to \psi K^0_{\mathrm{S}}$ decay
  - $S_f \approx \sin 2\beta$

[EPJC81 (2021) 226]



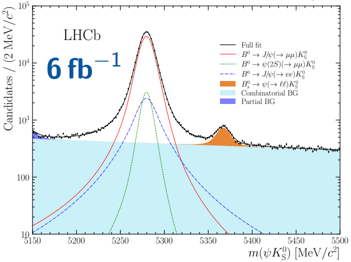


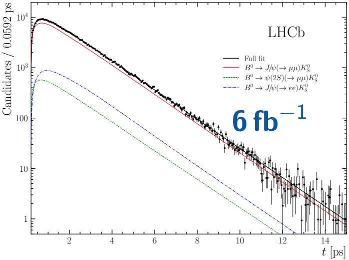
$\sin 2\beta$ from $B^0 \to \psi K^0_S$

[LHCb-PAPER-2023-013 in preparation]

- Three decay modes LHCb Run 2 data
  - $B^0 \to J/\psi(\to \mu\mu)K^0_S$ 306K
  - $B^0 \to \psi(2S)(\to \mu\mu)K^0_S$ 24K
  - $B^0 \to J/\psi(\to ee)K^0_S$ 43K
- Selection improved w.r.t. Run 1
- Flavour tagging calibrated with $B^0 \to J/\psi K^*$ and $B^+ \to J/\psi K^+$
- Correct decay-time distribution for detector misalignment biases

Preliminary





$\sin 2\beta$ from $B^0 \to \psi K^0_S$

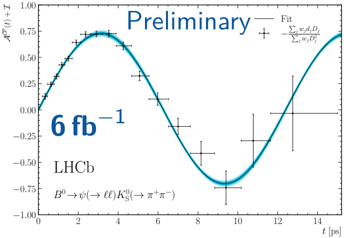
[LHCb-PAPER-2023-013 in preparation]

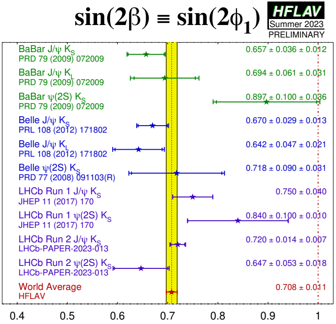
- Time-dependent *CP* asymmetry

$$S_{\psi K^0_S} = 0.7158 \pm 0.0133\ \text{(stat)}\ \pm 0.0078\ \text{(syst)}$$

$$C_{\psi K^0_S} = 0.0120 \pm 0.0123\ \text{(stat)}\ \pm 0.0029\ \text{(syst)}$$

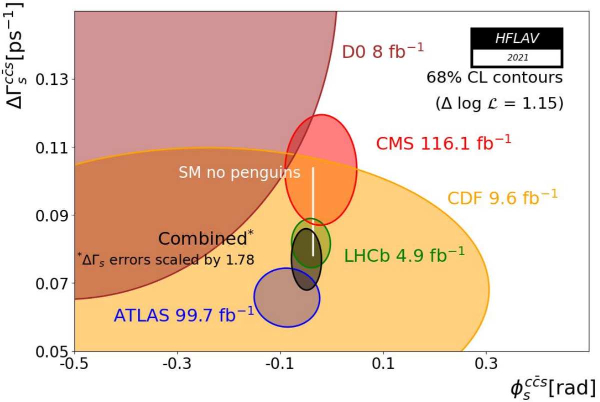
  - Most precise single measurement of β
  - Dominate the world average
  - Consistent between three modes
- Consider contributions of penguin diagrams when converting to $\sin 2\beta$
  - Measurements from penguin-free $b \to c\bar{u}d$ transitions helpful





ϕ_s from $b \to c\bar{c}s$

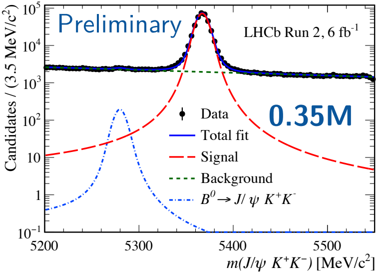
- Indirect measurement $\phi_s = 0.0368^{+0.0006}_{-0.0009}$ [PRD84 2011 033005, updated with Spring 2021 results]
- Direct measurement $\phi_s^{c\bar{c}s} = 0.049 \pm 0.019$ [HFLAV2021]

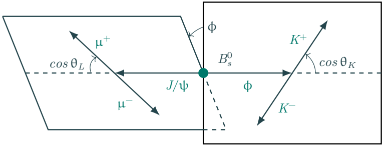


ϕ_s from $B_s^0 \to J/\psi K^+ K^-$

[LHCb-PAPER-2023-016 in preparation]

- Legacy analysis of LHCb Run 2 data
- $m(K^+K^-)$ in the vicinity of $\phi(1020)$
- Flavour tagging calibrated with $B_s^0 \to D_s^+\pi^+$ and $B^+ \to J/\psi K^+$
- Correct decay-time distribution for detector misalignment biases
- Weighted simultaneous fit to decay time and decay angles





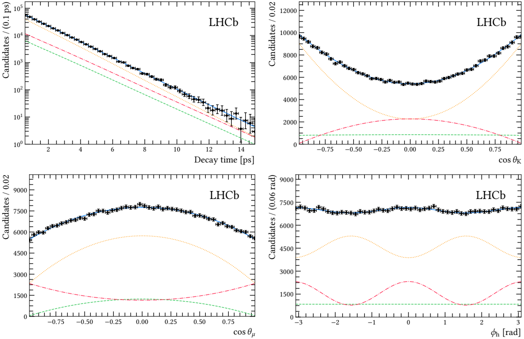
ϕ_s from $B_s^0 \to J/\psi K^+ K^-$

[LHCb-PAPER-2023-016 in preparation]

$$\phi_s = -0.039 \pm 0.022\ (\text{stat})\ \pm 0.006\ (\text{syst})\ \text{rad}$$
$$\Delta\Gamma_s = 0.0848^{+0.0044}_{-0.0045}\ (\text{stat})\ \pm 0.0024\ (\text{syst})\ \text{ps}^{-1}$$
$$\Gamma_s - \Gamma_d = -0.0059^{+0.0013}_{-0.0014}\ (\text{stat})\ \pm 0.0014\ (\text{syst})\ \text{ps}^{-1}$$

Preliminary

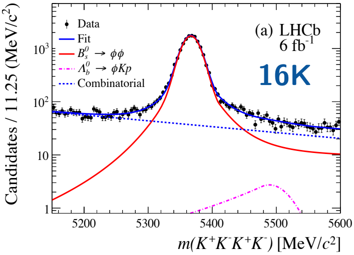
- Most precise single measurements
- Consistent with SM expectations
- Supersede LHCb measurement with 2015-16 data [EPJC79 2019 706]

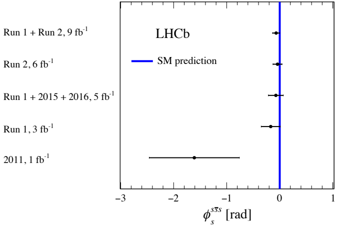


- Penguin-dominated decay via $b \to s\bar{s}s$
  - Benchmark FCNC channel
- Same analysis technique as $b \to c\bar{c}s$
- Results from simultaneous fit

$$\phi_s^{s\bar{s}s} = -0.042 \pm 0.075\ (\text{stat})\ \pm 0.009\ (\text{syst})\ \text{rad}$$
$$|\lambda| = 1.004 \pm 0.030\ (\text{stat})\ \pm 0.009\ (\text{syst})$$

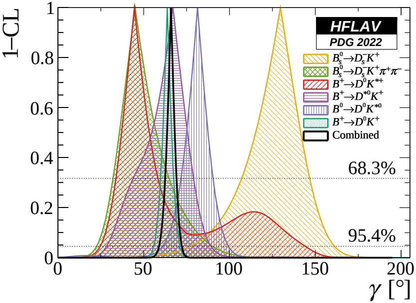
  - Most precise measurement with penguin-dominated decay
  - Consistent with SM expectation
  - No significant polarisation dependence





CKM angle γ from $B \to DK$

- $\gamma = \left(65.9^{+3.3}_{-3.5}\right)^{\circ}$ [arXiv:2206.07501]
- Favoured $b \to c\bar{u}s$ and suppressed $b \to u\bar{c}s$ transitions
- Interference occurs when D decays to a common final state

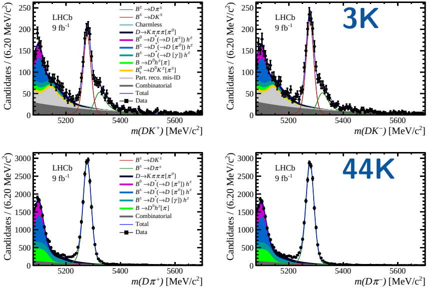


- LHCb has pursued this strategy with a wide range of D final states
  - $K\pi$, $K\pi\pi\pi$, $\pi\pi\pi\pi$ [PLB760 (2016) 117], [arXiv:2209.03692]
  - $K^0_S K\pi$, $K^0_S hh$ [JHEP06 (2020) 58], [JHEP 02 (2021) 0169]
  - $hh\pi^0$ [JHEP 07 (2022) 099]
  - $B^{\pm} \to D^{(*)} h^{\pm}$ [JHEP 04 (2021) 081]

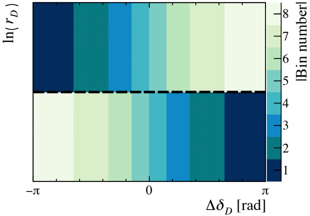
γ from $B^\pm \to [K^+K^-\pi^+\pi^-]_D h^\pm$

[arXiv:2301.10328]

- $h = K, \pi$ with LHCb Run 1 and 2
- Binning scheme of $(\Delta\delta_D, r_D)$
  - Minimise dilution of strong phases
  - Maximise interference effects
- *CP*-violating observables from measurement of yields in bins of phase space



	Fit result $(\times 10^2)$
x_-^{DK}	7.9 ± 2.9 (stat) ± 0.4 (syst) ± 0.4
y_-^{DK}	-3.3 ± 3.4 (stat) ± 0.4 (syst) ± 3.6
x_+^{DK}	-12.5 ± 2.5 (stat) ± 0.3 (syst) ± 1.7
y_+^{DK}	-4.2 ± 3.1 (stat) ± 0.3 (syst) ± 1.3
$x_\xi^{D\pi}$	-3.1 ± 3.5 (stat) ± 0.7 (syst) ± 0.1
$y_\xi^{D\pi}$	-1.7 ± 4.7 (stat) ± 0.6 (syst) ± 1.1



γ from $B^\pm \to [K^+K^-\pi^+\pi^-]_D h^\pm$

[arXiv:2301.10328]

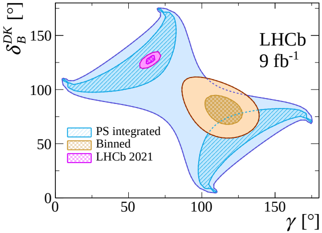
- Interpretation in terms of underlying physics parameters

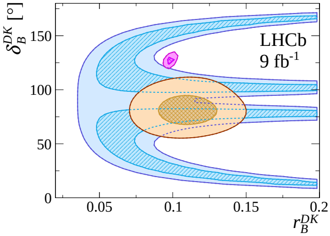
$$\gamma = \left(116^{+12}_{-14}\right)^\circ$$

$$\delta_B^{DK} = \left(81^{+14}_{-13}\right)^\circ, \quad r_B^{DK} = 0.110^{+0.020}_{-0.020}$$

$$\delta_B^{D\pi} = \left(298^{+62}_{-118}\right)^\circ, \quad r_B^{D\pi} = 0.0041^{+0.0054}_{-0.0041}$$

  - γ and δ_B^{DK} consistent with other channels within 3σ
  - Good agreement for r_B^{DK}, $\delta_B^{D\pi}$, $r_B^{D\pi}$
  - Model-independent determination can be achieved with future measurement of D-meson strong-phase parameters from BESIII [CPC44 (2020) 040001]
  - Measurements integrated over phase space also performed





Branching fractions of $B^0_{(s)} \to \bar{D}^{(*)0}\phi$

[LHCb-PAPER-2023-003 in preparation]

- Evidence for $B^0 \to \bar{D}^{(*)0}\phi$ with LHCb Run 1 and 2 data

$$\mathcal{B}\left(B^0 \to \bar{D}^0\phi\right) = (7.7 \pm 2.1\ (\text{stat})\ \pm 0.7\ (\text{syst})\ \pm 0.7\ (\text{ext})\ ) \times 10^{-7}$$

$$\mathcal{B}\left(B^0 \to \bar{D}^{*0}\phi\right) = (2.2 \pm 0.5\ (\text{stat})\ \pm 0.2\ (\text{syst})\ \pm 0.2\ (\text{ext})\ ) \times 10^{-6}$$

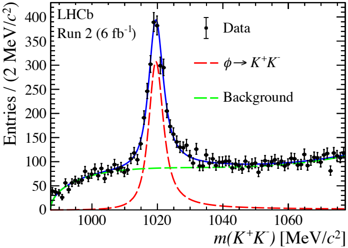
- Update branching fraction of $B^0_s \to \bar{D}^{(*)0}\phi$

$$\mathcal{B}\left(B^0_s \to \bar{D}^0\phi\right) = (2.30 \pm 0.10\ (\text{stat})\ \pm 0.11\ (\text{syst})\ \pm 0.20\ (\text{ext})\ ) \times 10^{-5}$$

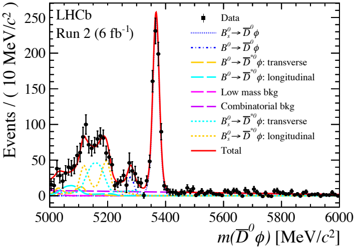
$$\mathcal{B}\left(B^0_s \to \bar{D}^{*0}\phi\right) = (3.17 \pm 0.16\ (\text{stat})\ \pm 0.17\ (\text{syst})\ \pm 0.27\ (\text{ext})\ ) \times 10^{-5}$$

  - Sensitivity to γ: 8-19°

[CPC45 (2021) 023003]



Preliminary



LHCb upgrades

- Two phases of upgrade are scheduled for the LHCb detector
  - Boost of statistics

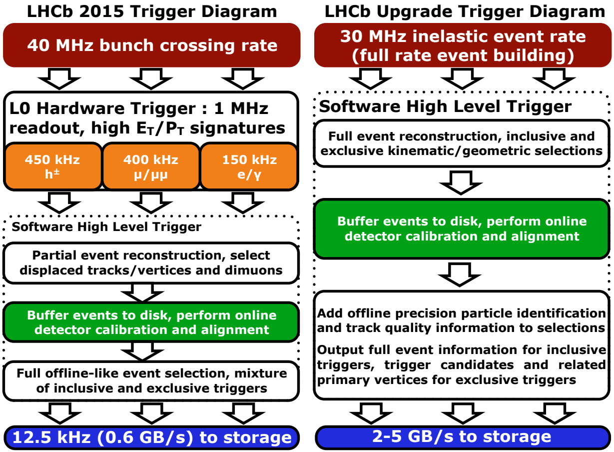
LHC Run	Period	$\sqrt{s}$ [TeV]	Instantaneous lumi. [$\mathrm{cm}^2\ \mathrm{s}^1$]	Integrated lumi. [fb^{-1}]	Pile-up
Upgrade I	2019-2021				
Run 3	2022-2024	14	2×10^{33}	50	5
Run 4	2027-2030				
Upgrade II	2031				
Run 5	2032 $\rightarrow$	14	2×10^{34}	300	50

[CERN-LHCC-2011-001, CERN-LHCC-2012-007, CERN-LHCC-2017-003, CERN-LHCC-2018-027]

Trigger-less readout

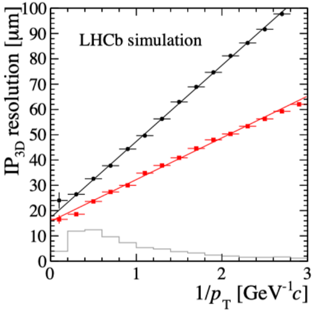
[CERN-LHCC-2011-001, CERN-LHCC-2012-007, CERN-LHCC-2017-003]

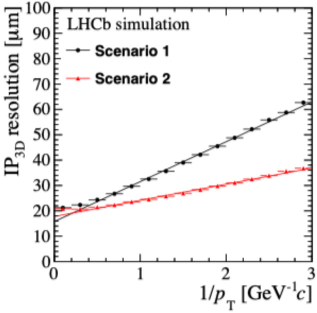
- From Upgrade I onward: trigger-less readout and fully software trigger
  - Price: little sensitivity for unprepared things
  - Careful plan ahead of data taking



[CERN-LHCC-2012-007, CERN-LHCC-2017-003]

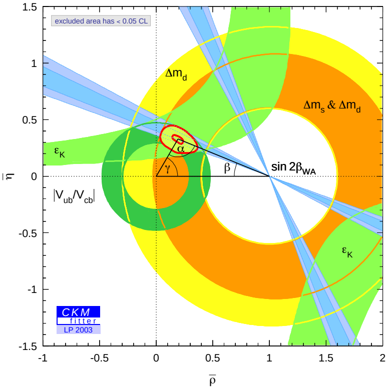
- IP resolution improved thanks to the upgrade of tracking systems
  - Decrease of 5 fs in decay-time resolution for $B_s^0 \to J/\psi\,\phi$ mode
  - (Left) Upgrade I: Run 2 VS Run 3
  - (Right) Upgrade II: Scenario 1 VS Scenario 2

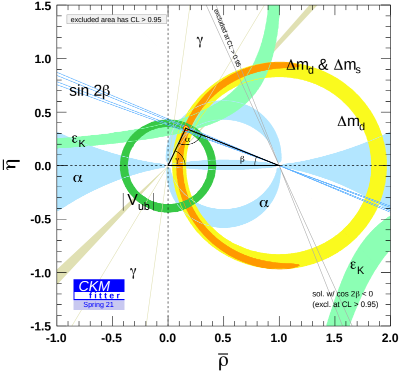




Summary

- Fruitful recent results of *CP* violation from LHCb
  - Direct *CP* violation in three-body charm decays
  - CKM angles in beauty decays





Backup

$\sin 2\beta$ from $B^0 \to \psi K^0_{\mathrm{S}}$

- Systematic uncertainties

Source	$\sigma(S)$	$\sigma(C)$
Fitter validation	0.0004	0.0006
$\Delta\Gamma_d$ uncertainty	0.0055	0.0017
FT calibration portability	0.0053	0.0001
FT $\Delta\epsilon_{\mathrm{tag}}$ portability	0.0014	0.0017
Decay-time bias model	0.0007	0.0013

ϕ_s from $B_s^0 \to J/\psi K^+ K^-$

[LHCb-PAPER-2023-016 in preparation]

- Systematic uncertainties

Source	$\lvert A_0\rvert^2$	$\lvert A_\perp\rvert^2$	ϕ_s [rad]	$\lvert\lambda\rvert$	$\delta_\perp - \delta_0$ [rad]	$\delta_\parallel - \delta_0$ [rad]	$\Gamma_s - \Gamma_d$ [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	Δm_s [ps^{-1}]
Mass parameterization	0.04	0.03	–	0.02	0.15	0.12	0.02	0.04	–
Mass factorization	0.11	0.10	0.42	0.19	0.54	0.60	0.12	0.16	0.18
Mass: shape statistical	0.04	0.04	0.05	0.09	0.62	0.33	0.02	0.01	0.11
B_c^+ contamination[1]	0.04	0.05	–	0.02	–	0.17	(0.02)	(0.07)	–
f_2 component	0.04	0.04	0.02	–	0.07	0.13	0.01	0.03	0.02
Clone candidates	0.07	0.04	0.02	0.10	0.18	0.18	0.02	–	0.01
Multiple candidates	0.01	–	0.27	0.22	0.90	0.41	0.01	0.01	0.24
Particle identification	0.06	0.09	0.27	0.27	1.31	0.51	0.05	0.15	0.46
C_{SP} factors	–	0.01	–	0.03	0.73	0.41	–	0.01	0.04
DTR[2] calibration	–	–	0.03	0.02	0.11	0.07	–	–	0.05
DTR model applicalibity	–	–	0.08	0.03	0.26	0.09	–	–	0.09
Time bias correction	0.04	0.05	0.06	0.05	0.77	0.11	0.03	0.05	0.44
Angular efficiency	0.05	0.14	0.25	0.32	0.42	0.44	0.01	0.02	0.13
Angular resolution	0.01	0.01	0.02	0.01	0.02	0.08	-	0.01	0.02
Kinematic weighting	0.24	0.09	0.01	0.01	0.98	0.86	0.02	0.03	0.31
Momentum uncertainty	0.08	0.04	0.04	–	0.07	0.11	0.01	–	0.13
Position uncertainty	0.07	0.04	0.04	–	0.10	0.09	0.02	–	0.31
Neglected correlations	–	–	–	–	4.20	4.96	–	–	–
Total syst.	0.31	0.24	0.63	0.54	4.82	5.17	0.14	0.24	0.80
Stat.	0.17	0.23	2.15	1.1	7.5	6.1	0.14	0.44	3.3

γ from $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D h^{\pm}$

[arXiv:2304.06198]

- Systematic uncertainties

	Uncertainty ($\times 10^2$)					
Source	x_-^{DK}	y_-^{DK}	x_+^{DK}	y_+^{DK}	$x_\xi^{D\pi}$	$y_\xi^{D\pi}$
Mass shape	0.02	0.02	0.03	0.06	0.02	0.04
Bin-dependent mass shape	0.11	0.05	0.10	0.19	0.68	0.16
PID efficiency	0.02	0.02	0.03	0.06	0.02	0.04
Low-mass background model	0.02	0.02	0.03	0.04	0.02	0.02
Charmless background	0.14	0.15	0.12	0.14	0.01	0.02
CP violation in low-mass background	0.01	0.10	0.08	0.12	0.07	0.26
Semi-leptonic b-hadron decays	0.05	0.27	0.06	0.01	0.07	0.19
Semi-leptonic charm decays	0.02	0.07	0.03	0.15	0.06	0.24
$D \to K^{\mp}\pi^{\pm}\pi^+\pi^-$ background	0.11	0.05	0.07	0.04	0.09	0.05
$\Lambda_b^0 \to pD\pi^-$ background	0.01	0.25	0.14	0.04	0.06	0.34
$D \to K^{\mp}\pi^{\pm}\pi^+\pi^-\pi^0$ background	0.30	0.05	0.19	0.07	0.05	0.01
Fit bias	0.06	0.05	0.13	0.02	0.06	0.13
Total LHCb systematic	0.37	0.43	0.34	0.32	0.70	0.57
c_i, s_i	0.35	3.64	1.74	1.29	0.14	1.10
Total systematic	0.51	3.67	1.78	1.33	0.72	1.24
Statistical	2.87	3.40	2.51	3.05	4.24	5.17