Simultaneous determination of the CKM angle γ and parameters related to mixing and CP violation in the charm sector at LHCb

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DIS2026

Outlook:

- short introduction to γ
- the LHCb γ and charm combination
- first result with Run 3 data
- example of improved analysis
- summary and prospects

CP violation in the SM

SM charged current weak interactions between quarks are described by the Cabibbo-Kobayashi-Maskawa matrix V, 3 x 3, with V V* = I
⇔ 3 angles and 1 complex phase (or 3 real and **1 imaginary** parameters)
CP violation in the SM arise **only** through this complex phase
same phase/parameter in all (beauty, charm, …) CP violating processes

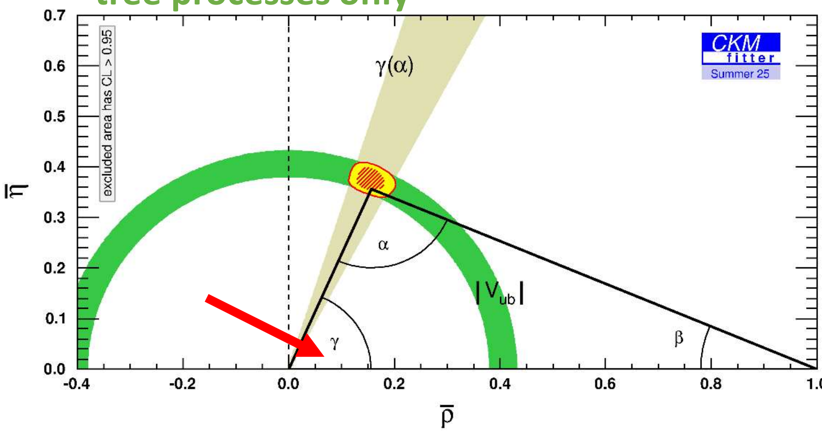
$$V_{ud}V_{ub}^{*}+V_{cd}V_{cb}^{*}+V_{td}V_{tb}^{*}=0$$

unitary condition relevant for beauty decays can be represented by a triangle in a complex plane, with angles α, β and γ

$$\gamma \equiv \arg\left[-\frac{V_{ud}V^{*}_{ub}}{V_{cd}V^{*}_{cb}}\right]$$

a.k.a. ϕ_3

tree processes only



[JHEP12(2021)141]

- γ only angle easily accessible in tree-level decays
- assuming no new physics in tree-level decays, the theoretical uncertainties are negligible in such direct measurements i.e., achievable accuracy dominated by experiments
- **deviations between these direct measurements and indirect determinations from global CKM fits**, which are based on independent observables and assume the validity of the SM and hence unitarity of the CKM matrix, **would be a clear indication of physics BSM** … due for example to new particles / mediators being exchanged in loops …
- at present these direct measurements have a larger uncertainty that the indirect determinations
- **closing this sensitivity gap is a key physics goal of the LHCb experiment**

http://ckmfitter.in2p3.fr/www/results/plots_summer25/ckm_res_summer25.html

how to measure γ

[JHEP12(2021)141]

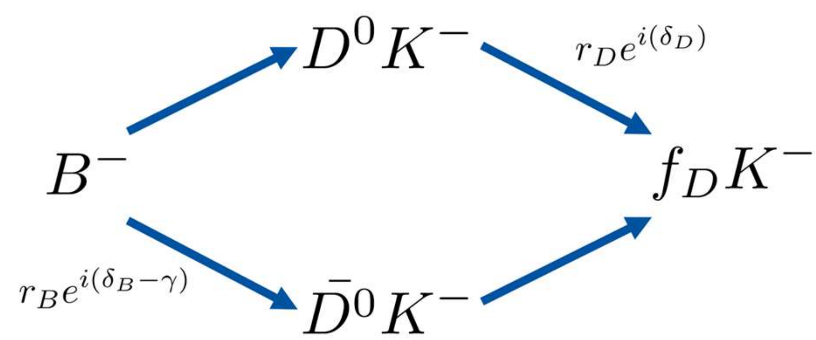
γ can be determined by exploiting the interference between

- b → c ubar s (V_{cb}), favored
- b → u cbar s (V_{ub}), suppressed

transition amplitudes

$$A_{sup}/A_{fav} = r^X_B \, e^{i(\delta^X_B \pm \gamma)}$$ (– is for b-quark, + for anti-b)

where r^X_B and δ^X_B are the ratio and the strong phase differences between the V_{cb} and V_{ub} transition amplitudes **for the specific final state X**
these must also be simultaneously determined



golden mode for illustration purposes

this interference effect is typically measured in B meson decays such as
$B^\pm \to D h^\pm$
where D is an admixture of the D^0 and anti-D^0 flavor states and $h^\pm$ is either a charged kaon or pion

$$\Gamma(B^\pm \to Dh^\pm) \propto |r_D e^{-i\delta_D} + r_B e^{i(\delta_B \pm \gamma)}|^2 \Rightarrow r_D^2 + r_B^2 + 2\kappa_D \kappa_B r_D r_B \cos(\delta_B + \delta_D \pm \gamma)$$

- r_D and δ_D are the ratio and the strong phase difference between the D^0 and anti-D^0 transition amplitudes to the same final state x
- $\kappa_{D/B}$ are the coherence factors of the B and D decays, equal to unity for two-body decays
- γ is shared by all decays

2 equations with 5 to 7 unknown => combine the results from many different D decay modes to overconstrain the parameters of the B meson decay **and fix the D decay parameters from other experiments / independent measurements**

LHCb γ combination: B decay inputs

[JHEP12(2021)141]
[LHCb-CONF-2025-003]

B decay	D decay	Ref.	Dataset	Status since Ref. [16]
$B^\pm \to Dh^\pm$	$D \to h^\pm h'^\mp$	[29]	Run 1&2	*As before*
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^+\pi^-$	[30]	Run 1&2	*As before*
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^+\pi^-$	[20]	Run 1&2	**New**
$B^\pm \to Dh^\pm$	$D \to K^\pm\pi^\mp\pi^+\pi^-$	[24]	Run 1&2	*As before*
$B^\pm \to Dh^\pm$	$D \to h^\pm h'^\mp\pi^0$	[31]	Run 1&2	*As before*
$B^\pm \to Dh^\pm$	$D \to K^0_S h^+h^-$	[32]	Run 1&2	*As before*
$B^\pm \to Dh^\pm$	$D \to K^0_S K^\pm\pi^\mp$	[33]	Run 1&2	*As before*
$B^\pm \to D^*h^\pm$	$D \to h^\pm h'^\mp$ (PR)	[29]	Run 1&2	*As before*
$B^\pm \to D^*h^\pm$	$D \to K^0_S h^+h^-$ (PR)	[34]	Run 1&2	*As before*
$B^\pm \to D^*h^\pm$	$D \to K^0_S h^+h^-$ (FR)	[35]	Run 1&2	*As before*
$B^\pm \to DK^{*\pm}$	$D \to h^\pm h'^\mp$	[36]	Run 1&2	*As before*
$B^\pm \to DK^{*\pm}$	$D \to h^\pm\pi^\mp\pi^+\pi^-$	[36]	Run 1&2	*As before*
$B^\pm \to DK^{*\pm}$	$D \to K^0_S h^+h^-$	[36]	Run 1&2	*As before*
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^\pm h'^\mp$	[37]	Run 1	*As before*
$B^0 \to DK^{*0}$	$D \to h^\pm h'^\mp$	[38]	Run 1&2	*As before*
$B^0 \to DK^{*0}$	$D \to h^\pm\pi^\mp\pi^+\pi^-$	[38]	Run 1&2	*As before*
$B^0 \to DK^{*0}$	$D \to K^0_S h^+h^-$	[39]	Run 1&2	*As before*
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	[40]	Run 1	*As before*
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	[41, 42]	Run 1&2	*As before*
$B^0_s \to D^\mp_s K^\pm\pi^+\pi^-$	$D^+_s \to h^+h^-\pi^+$	[43]	Run 1&2	*As before*

❑ typical B meson final states (h=K,π) ?

$B^+ \to D\, h^+$
$B^+ \to D^*\, h^+$
$B^+ \to D\, K^{*+}$
$B^0 \to D\, K^{*0}$

❑ typical D meson final states ?

- CP-eigenstates, $D \to K^+K^-$ and $D \to \pi^+\pi^-$: GLW method
[Phys. Lett. B265 (1991) 172, Phys. Lett. B253 (1991) 483]
- non CP-eigenstates, $D^0 \to \pi^- K^+$: ADS method
[Phys. Rev. D63 (2001) 036005]
- self-conjugate multibody D meson decay, like $K^0_s\pi^+\pi^-$, with the D-Dalitz plot distributions: BPGGSZ method
[Phys. Rev. D 68, 054018 (2003), Eur. Phys. J. C 47, 347 (2006)]

current experimental status: most of the B decay inputs updated to Run 1&2 i.e. 9 /fb

LHCb γ combination: D decay inputs

[JHEP12(2021)141]
[LHCb-CONF-2025-003]

D decay	Observable(s)	Ref.	Dataset	Status since Ref. [16]
$D^0 \to h^+h^-$	ΔA_{CP}	[44–46]	Run 1&2	*As before*
$D^0 \to K^+K^-$	$A_{CP}(K^+K^-)$	[46–48]	Run 2	*As before*
$D^0 \to h^+h^-$	$y_{CP} - y_{CP}^{K^-\pi^+}$	[49,50]	Run 1&2	*As before*
$D^0 \to h^+h^-$	ΔY	[51–54]	Run 1&2	*As before*
$D^0 \to K^\pm\pi^\mp$ (double tag)	$R^\pm$, $(x'^\pm)^2$, $y'^\pm$	[21,27]	Run 1&2	**Updated**
$D^0 \to K^\pm\pi^\mp$ (single tag)	$R_{K\pi}$, $\overset{(\sim)}{A}_{K\pi}$, $c^{(\prime)}_{K\pi}$, $\Delta \overset{(\sim)}{c}{}^{(\prime)}_{K\pi}$	[55,56]	Run 1&2	*As before*
$D^0 \to K^\pm\pi^\mp\pi^+\pi^-$	r, $\kappa y'$, $(x^2+y^2)/4$	[28]	Run 1	*As before*
$D^0 \to K^\pm\pi^\mp\pi^+\pi^-$	$r_i^\pm$, $(\kappa y'^\pm)_i$, $x^{2\pm}+y^{2\pm}$	[22]	Run 2	**New**
$D^0 \to K^0_S\pi^+\pi^-$	x, y	[57]	Run 1	*As before*
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[58]	Run 1	*As before*
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[59,60]	Run 2	*As before*
$D^0 \to \pi^+\pi^-\pi^0$	ΔY^{eff}	[61]	Run 2	*As before*

current experimental status:
most of the D decay inputs
updated to Run 1&2

LHCb γ combination: auxiliary inputs

	ers	Source	Ref.	Status since Ref. [16]
$B^\pm \to DK^{*\pm}$	$\kappa_{B^\pm}^{DK^{*\pm}}$	LHCb	[63]	*As before*
$B^0 \to DK^{*0}$	$\kappa_{B^0}^{DK^{*0}}$	LHCb	[64]	*As before*
$B^0 \to D^\mp\pi^\pm$	β	HFLAV	[14]	*As before*
$B^0_s \to D_s^\mp K^\pm(\pi\pi)$	ϕ_s	LHCb	[65]	*As before*
$D \to K^+\pi^-$	$\cos\delta_D^{K\pi}$, $\sin\delta_D^{K\pi}$, $(r_D^{K\pi})^2$, x^2, y	CLEO-c	[66]	*As before*
$D \to K^+\pi^-$	$A_{K\pi}$, $A_{K\pi}^{\pi\pi\pi^0}$, $r_D^{K\pi}\cos\delta_D^{K\pi}$, $r_D^{K\pi}\sin\delta_D^{K\pi}$	BESIII	[62,67,68]	**Updated**
$D \to h^+h^-\pi^0$	$F^+_{\pi\pi\pi^0}$, $F^+_{KK\pi^0}$	CLEO-c	[69]	*As before*
$D \to h^+h^-\pi^0$	$F^+_{\pi\pi\pi^0}$, $F^+_{KK\pi^0}$	BESIII	[70]	**New**
$D \to \pi^+\pi^-\pi^+\pi^-$	$F^+_{4\pi}$	CLEO-c+BESIII	[69,71]	*As before*
$D \to K^+K^-\pi^+\pi^-$	$F^+_{KK\pi\pi}$	BESIII	[72]	*As before*
$D \to K^+\pi^-\pi^0$	$r_D^{K\pi\pi^0}$, $\delta_D^{K\pi\pi^0}$, $\kappa_D^{K\pi\pi^0}$	CLEO-c+LHCb+BESIII	[25,26]	*As before*
$D \to K^\pm\pi^\mp\pi^+\pi^-$	$r_D^{K3\pi}$, $\delta_D^{K3\pi}$, $\kappa_D^{K3\pi}$	CLEO-c+LHCb+BESIII	[25,26]	*As before*
$D \to K^0_S K^\pm\pi^\mp$	$r_D^{K^0_S K\pi}$, $\delta_D^{K^0_S K\pi}$, $\kappa_D^{K^0_S K\pi}$	CLEO-c	[73]	*As before*
$D \to K^0_S K^\pm\pi^\mp$	$r_D^{K^0_S K\pi}$	LHCb	[74]	*As before*

synergy between LHCb – BESIII (and CLEO-c) is mandatory
if not the uncertainty on the auxiliary inputs will be a limiting factor in the accuracy of the LHCb γ combination

LHCb γ combination: results

- 235 input observables
- 64 free parameters
- **a few results worth to be highlighted:**
  - γ

γ [°]	62.8 ± 2.6

  - charm mixing parameters

$x \equiv (m_1 - m_2)/\Gamma$	x [%]	0.391 ± 0.042
$y \equiv (\Gamma_1 - \Gamma_2)/2\Gamma$	y [%]	0.625 ± 0.020

  - magnitude and phase of CP violation in charm mixing

$\lvert D_{1,2}\rangle \equiv p\lvert D^0\rangle \pm q\lvert \bar{D}^0\rangle$	$\lvert q/p \rvert$	$0.990^{+0.011}_{-0.012}$
$\phi \equiv \arg(q/p)$	ϕ [°]	-1.2 ± 0.9

- fit also many amplitude ratios and string phase differences

- 2 body and $K_s h^+ h^-$ D decays are dominating the combination

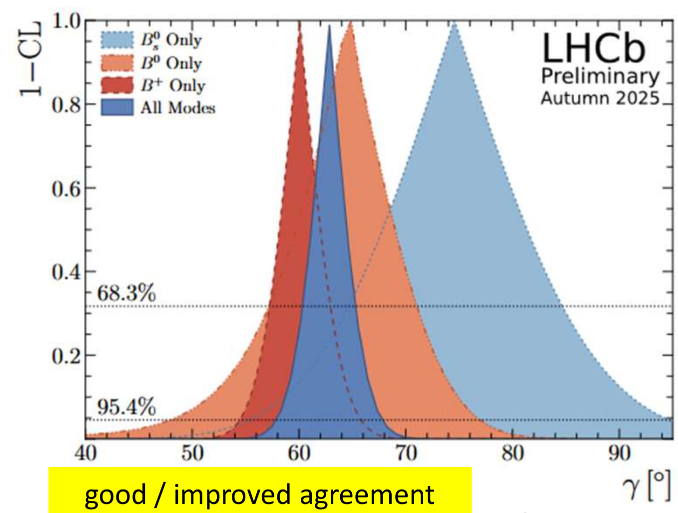
- most precise determination of γ from direct measurements to date

- the precision is primarily limited by the statistical uncertainties of the input measurements

- improved constraints on D hadronic parameter for K π and K 3π decays play a major role

Parameter	Value
γ [°]	62.8 ± 2.6
$r_{B^\pm}^{DK^\pm}$ [%]	$9.72^{+0.19}_{-0.18}$
$\delta_{B^\pm}^{DK^\pm}$ [°]	$123.3^{+2.8}_{-3.0}$
$r_{B^\pm}^{D\pi^\pm}$ [%]	$0.49^{+0.06}_{-0.05}$
$\delta_{B^\pm}^{D\pi^\pm}$ [°]	$282.9^{+9.8}_{-10.4}$
x [%]	0.391 ± 0.042
y [%]	0.625 ± 0.020
$r_D^{K\pi}$ [%]	5.857 ± 0.009
$\delta_D^{K\pi}$ [°]	192.7 ± 2.3
$\lvert q/p \rvert$	$0.990^{+0.011}_{-0.012}$
ϕ [°]	-1.2 ± 0.9

[LHCb-CONF-2025-003]



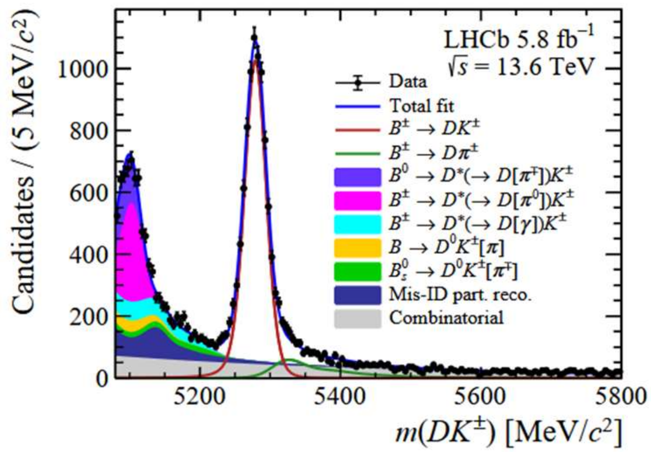
good / improved agreement between the different B flavors

First measurement of γ using Run 3 data: $B^+ \to D h^+$ with $D \to K^0_s h^+ h^-$ with $h = \pi$ or K

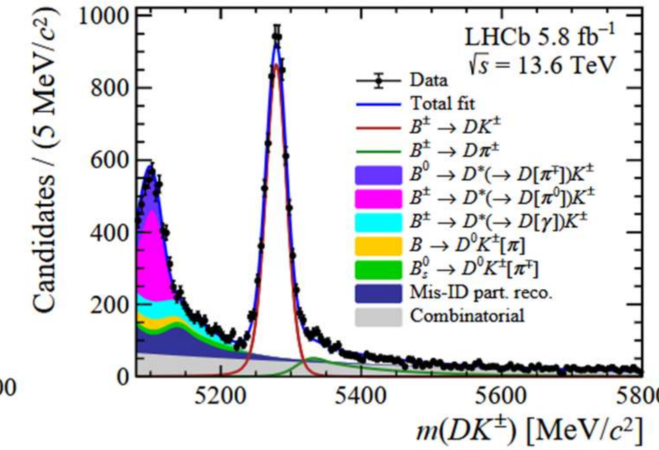
[LHCb-PAPER-2026-010]

- 5.8 \fb collected in 2024
- first measurement of γ with Run 3 (Morionw EW 2026)
- Run3 advantages: higher luminosity, higher trigger efficiency (removal of L0 + dedicated exclusive HLT2 lines for this decay)
- CP violation is observed through differences in the D-Dalitz plot between B^+ and B^- mesons

long K0s



downstream K0s

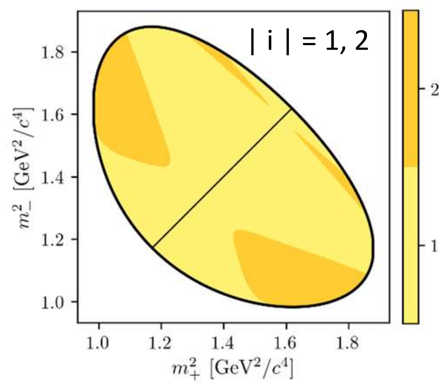


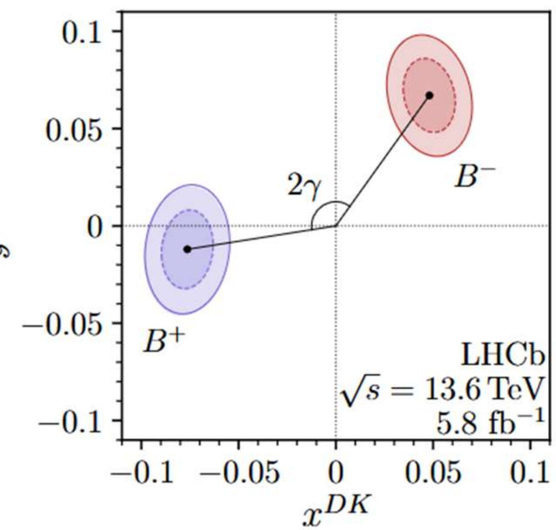
$$x_\pm^{DK} \equiv r_B^{DK}\cos(\delta_B^{DK} \pm \gamma)$$
$$y_\pm^{DK} \equiv r_B^{DK}\sin(\delta_B^{DK} \pm \gamma)$$

$$N^+_{+i} = h^{DK}_{B^+}\left[F_{-i} + \left(\left(x_+^{DK}\right)^2 + \left(y_+^{DK}\right)^2\right)F_{+i} + 2\sqrt{F_{+i}F_{-i}}\left(x_+^{DK}c_{+i} - y_+^{DK}s_{+i}\right)\right]$$

c (s) ≡ cosine (sine) of the strong-phase difference between the D0 and anti-D0-decay amplitudes at a given point on the Dalitz plot

for $D \to K^0_s K^+ K^-$ these are obtained from a combination of BESIII and CLEO data [Phys. Rev. D 102, 052008]





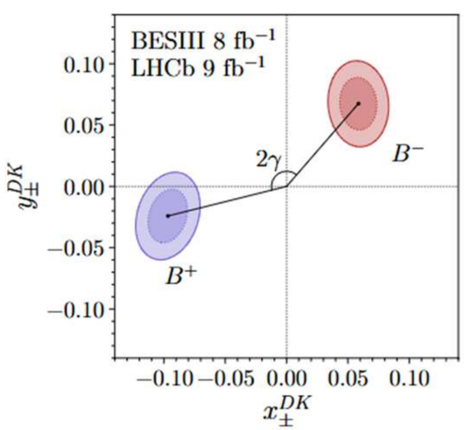
$$\gamma = (68.1 \pm 6.7)^\circ$$

- in good agreement with the corresponding Run 1&2, 9 \fb, result and the LHCb combination
- this 5.8 \fb data set show a yield exceeding the one of the previous Run 1&2 analysis (6 solar years of data taking)

Precise measurement of γ using a novel approach

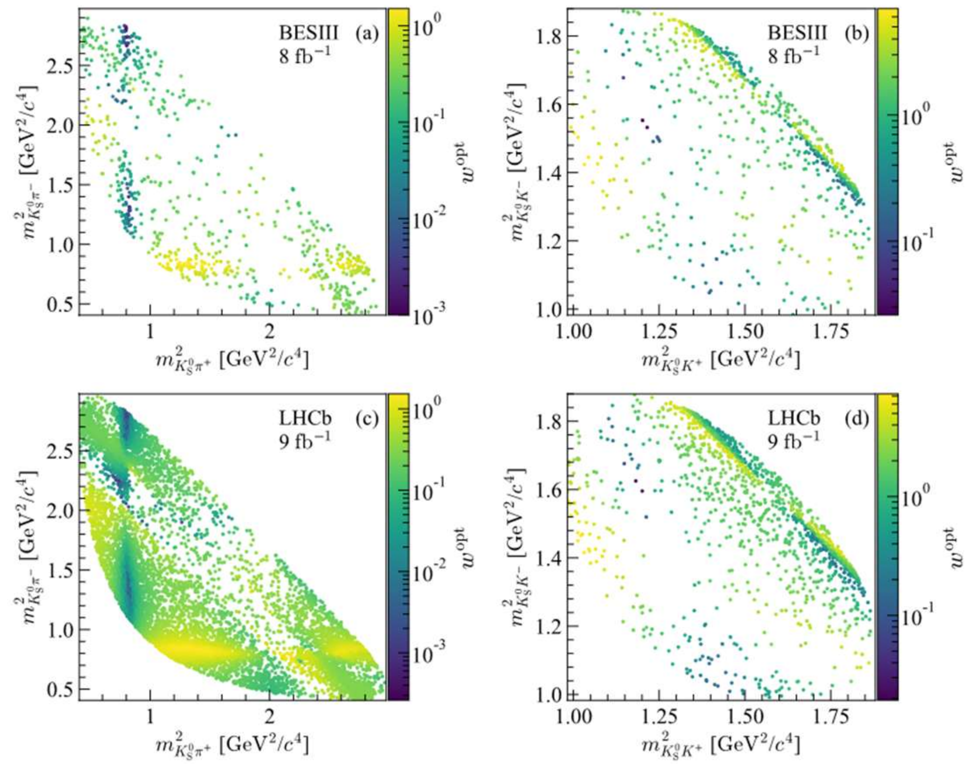
[submitted to PRL] [submitted to PRD]

- process: $B^+ \to D\,h^+$ with $D \to K^0_s h^+ h^-$ with $h = \pi$ or K
- CP violation is observed through differences in the D-Dalitz plot between B^+ and B^- mesons
- **unbinned, optimized, joint fit to both datasets**
  - Fourier expansion (2nd order for $K^0_s \pi^+ \pi^-$, 1rst order for $K^0_s K^+ K^-$) of the strong-phase difference to capture its variation across the Dalitz plot, smooth irregularities of the binned approach
  - optimal weight incorporating sensitivity changes due to decay amplitudes, efficiency and background distributions in the D-Dalitz plane
  - 8 /fb of BESIII data, 9 /fb of LHCb data, Run 1&2



$$\gamma = (71.3 \pm 5.0)^\circ$$

optimal weights



$K^0_s \pi^+ \pi^-$ $K^0_s K^+ K^-$

- the statistical uncertainty is reduced by 5 % wrt the binned analysis performed on the same Run 1&2 data set
- BESIII has collected 20 \fb (2021-2024), LHCb will end Run3 (this year) with ≈ 27 \fb

$\Rightarrow$ higher-order Fourier expansions

- could be extended to other B decays

✦ summary and prospects

- 2025 LHCb γ combination based on 9 /fb: $(62.8 \pm 2.6)^o$
- 20 beautiful input measurements that can cross check each other
- LHCb result is driving the world average
- present uncertainty is not yet what we need

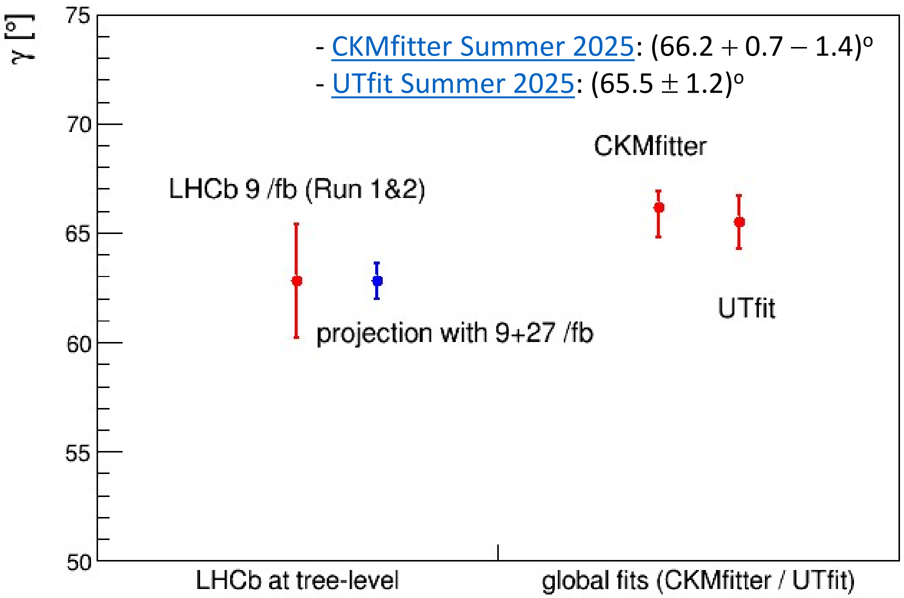
- LHCb integrated lumi. increase by mid 2026: + 27 /fb

&& boost in yields due to the fully software Run 3 trigger

$\Rightarrow \pm 0.8^o$ to $\pm 1.3^o$

expect a gradual decrease of the γ uncertainty in the coming releases, to $< 1.5^o$ when all Run 3 measurements will be available

uncertainty will be comparable to CKMfitter / UTfit



moving ahead in the future, LHCb expects to reach an integrated lumi.:

- of 50 /fb by the end of Run 4, i.e. 2033
- of 300 /fb by the end of Run 5, i.e. 2041

by then, if the accuracy of the external inputs will not be a limiting factor, the γ uncertainty could reach 0.35^o

$\Rightarrow$ synergy with BESIII is mandatory

other experiments:

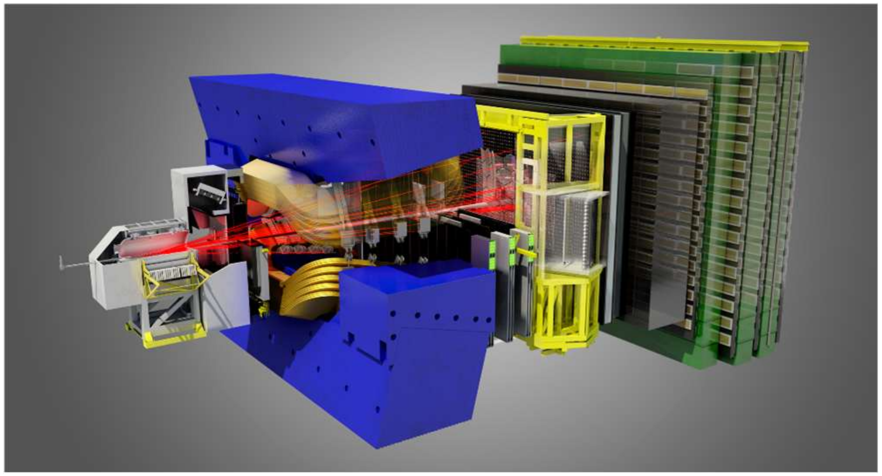
- BaBar: $(69 + 17 - 16)^o$ [Phys. Rev. D87 (2013) 052015]
- Belle && Belle II: $(75.2 \pm 7.6)^o$ [JHEP 10 (2024) 143]

with improvements expected in the coming years

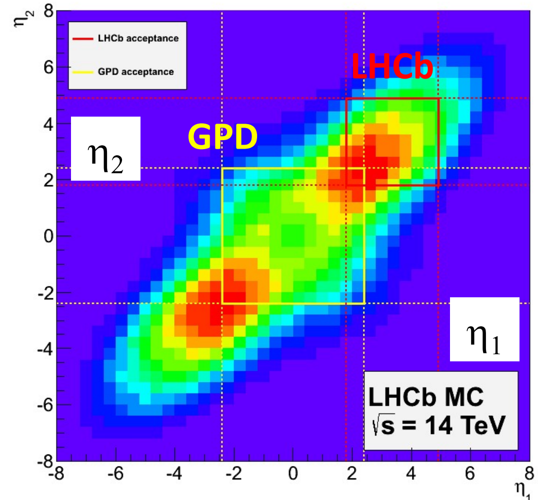
Backup material

LHCb: the detector and its performances up to Run 2

single-arm forward spectrometer at the LHC



b anti-b pairs produced



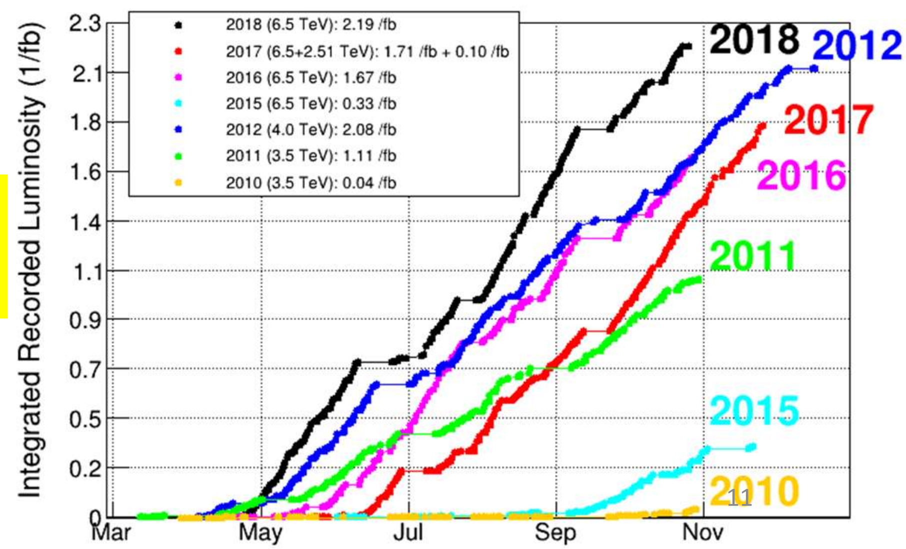
• detector paper:
JINST 3 (2008) S08005
• Run 1 performance:
Int. J. Mod. Phys. A30 (2015) 1530022
• Run 2 performance:
JINST 14 (2019) P04013
• Run 3 performance:
In preparation

optimized for beauty and charm physics at $2 < \eta < 5$

key points:

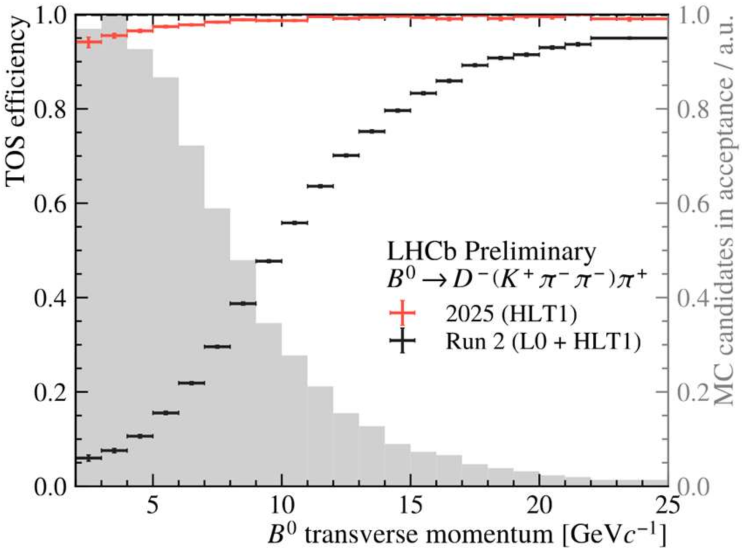
- momentum resolution
  ($\sigma(p)/p \approx 0.5$ % (low momentum) to 1 % @ 200 GeV/c)
- impact parameter resolution
  ($\sigma(IP) \approx 15$ μm at high p_T)
- primary and secondary vertices reco.
- decay time resolution ($\sigma(t) \approx 50$ fs)
- 'global' PID: e / μ / π / K
  (K id ≈ 95 % π mis-id ≈ 5 %, p < 100 GeV/c)
- γ and π^0 reconstruction

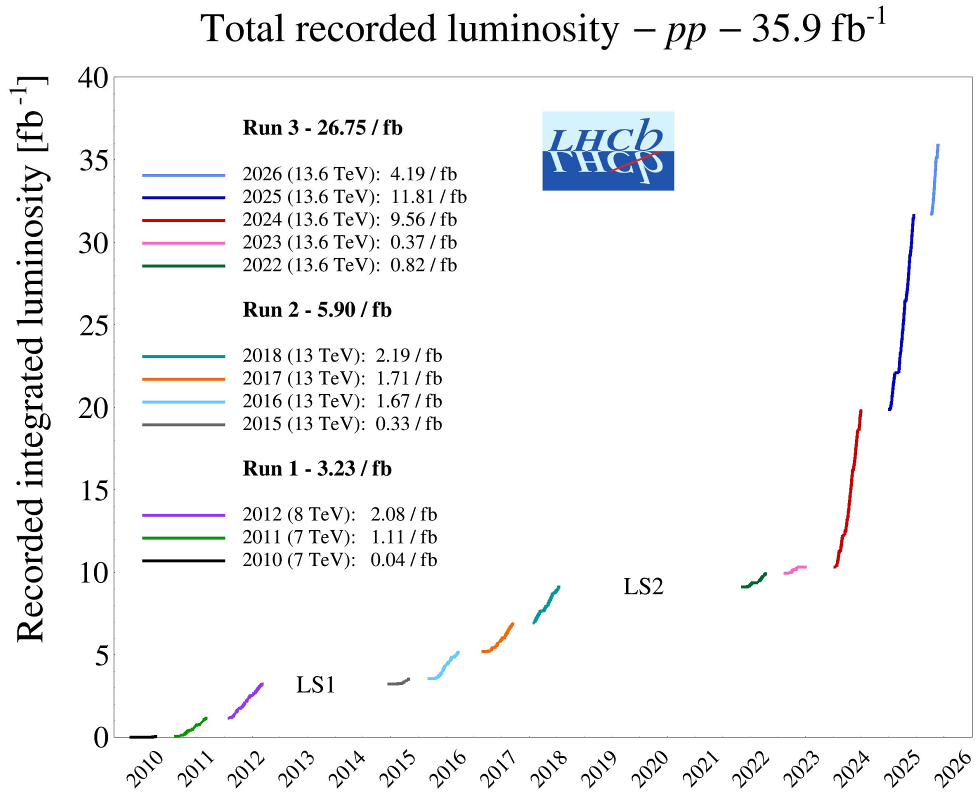
recorded lumi.:
2011→ 2012 (Run 1): 3 /fb
2015 → 2018 (Run 2): 6 /fb



LHCb: the new Run 3 era

https://lbfence.cern.ch/alcm/figure/details/5590





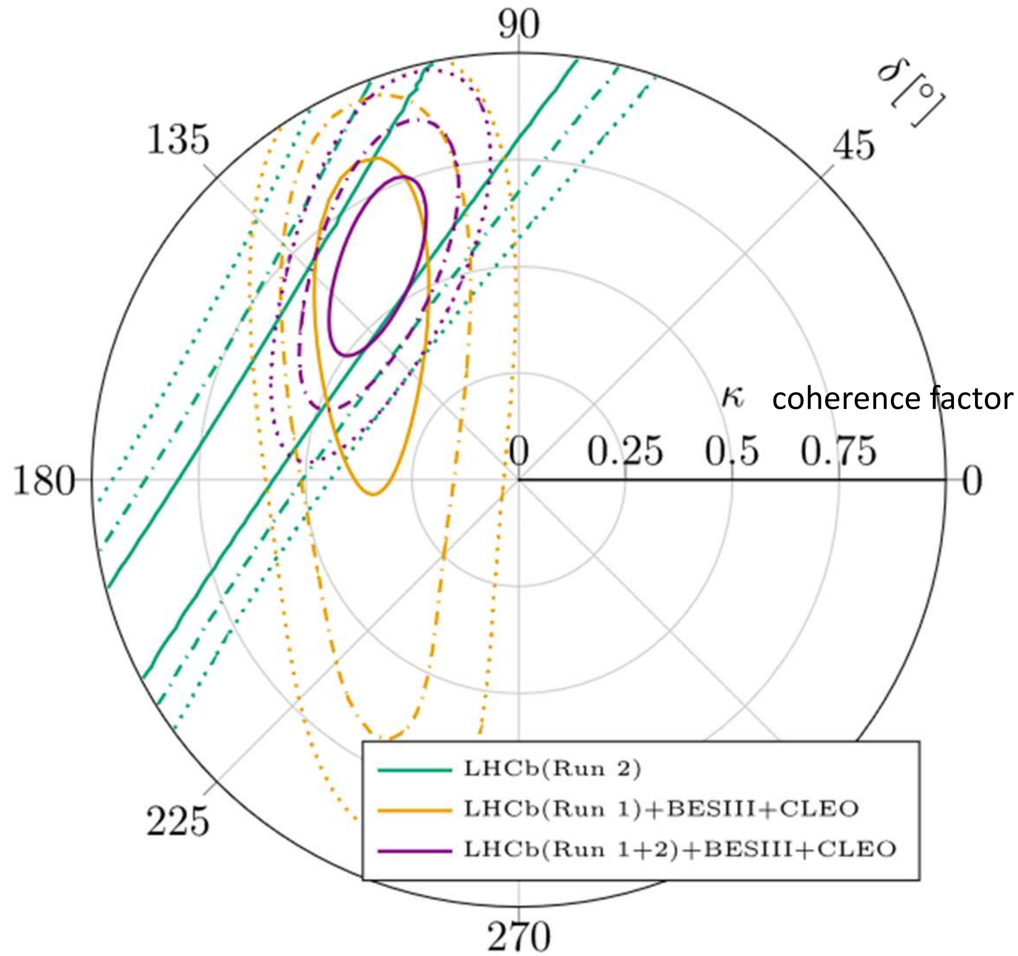
trigger efficiencies for hadronic B decays since 2024 are much more favorable wrt Run 2

yield per luminosity of hadronic B decays in Run 3 are up to 3 times the corresponding Run 2 ones

⇒ expect a significant boost in statistic

LHCb γ combination: phase of CP violation in charm mixing

[https://arxiv.org/pdf/2510.04963]



First measurement of γ using Run 3 data: [LHCb-PAPER-2026-010]

$B^+ \to D h^+$ with $D \to K^0_s h^+ h^-$ with $h = \pi$ or K

$$N^+_{+i} = h^{DK}_{B^+}\left[F_{-i} + \left(\left(x^{DK}_+\right)^2 + \left(y^{DK}_+\right)^2\right)F_{+i} + 2\sqrt{F_{+i}F_{-i}}\left(x^{DK}_+ c_{+i} - y^{DK}_+ s_{+i}\right)\right]$$
$$N^+_{-i} = h^{DK}_{B^+}\left[F_{+i} + \left(\left(x^{DK}_+\right)^2 + \left(y^{DK}_+\right)^2\right)F_{-i} + 2\sqrt{F_{+i}F_{-i}}\left(x^{DK}_+ c_{+i} + y^{DK}_+ s_{+i}\right)\right]$$
$$N^-_{+i} = h^{DK}_{B^-}\left[F_{+i} + \left(\left(x^{DK}_-\right)^2 + \left(y^{DK}_-\right)^2\right)F_{-i} + 2\sqrt{F_{+i}F_{-i}}\left(x^{DK}_- c_{+i} + y^{DK}_- s_{+i}\right)\right]$$
$$N^-_{-i} = h^{DK}_{B^-}\left[F_{-i} + \left(\left(x^{DK}_-\right)^2 + \left(y^{DK}_-\right)^2\right)F_{+i} + 2\sqrt{F_{+i}F_{-i}}\left(x^{DK}_- c_{+i} - y^{DK}_- s_{+i}\right)\right]$$

LHC / LHCb schedule up to 2041 …