Charm, γ and ϕ_s at LHCb

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on behalf of the
LHCb Collaboration

Standard Model @ LHC 2024

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INFN
PADOVA
Istituto Nazionale di Fisica Nucleare
Sezione di Padova

LHCb

UNIVERSITAS STUDIORUM BERGOMENSIS

Unitarity Triangle Measurements

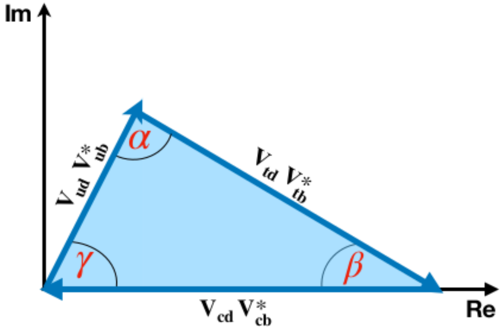
- The CKM matrix describes the quark charged current weak interactions

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \sim \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

- The unitarity of this matrix leads to

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

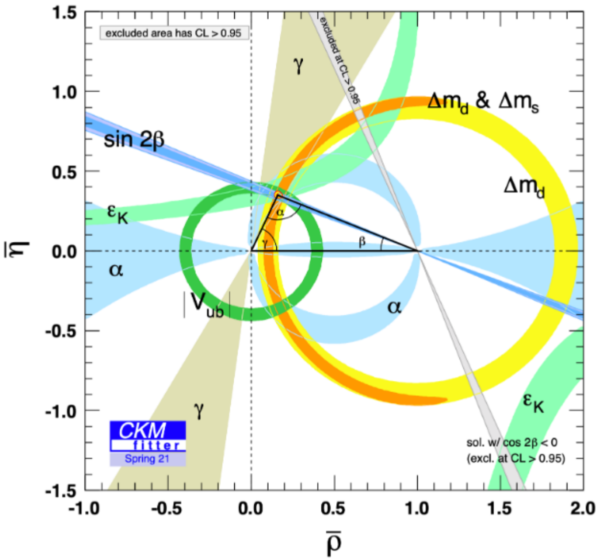
- It can be visualized as a triangle in the complex plane



- The key test of the SM is the check of the unitarity of the CKM matrix

- A single complex phase in the CKM matrix is the only measured source of CP violation (CPV)
  - Not enough to explain the matter-antimatter asymmetry in the universe.

- B and D meson decays are a great laboratory to probe CP violation and to test the unitarity of CKM matrix

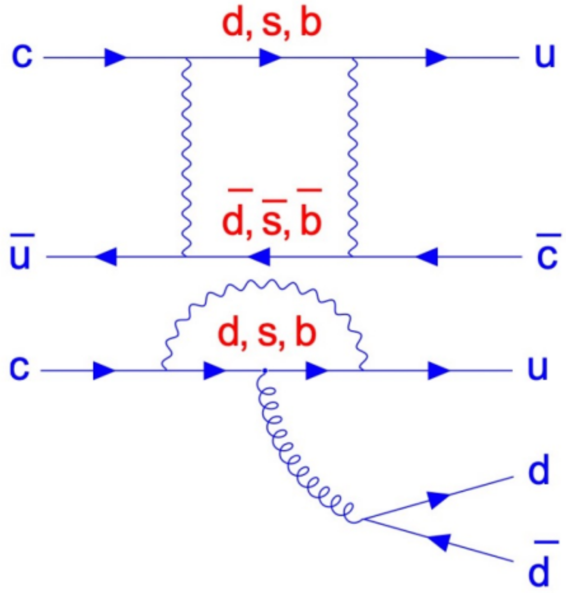


CPV in the Charm Sector

- Charm sector is an unique laboratory to study CPV in up-type quark decays
- CPV in charm is highly suppressed in the SM
  - beauty loop are suppressed by smallness of CKM elements

$$CPV \propto \mathrm{Im}\left(\frac{V_{cb}V_{bu}^{*}}{V_{cs}V_{su}^{*}}\right) \approx -6\times 10^{-4}$$

  - strange-down loops suppressed by GIM cancellation broken by *b* quark



- CPV in charm small O(10^{-4}) → sensitive to NP
- Theory predictions complicated by QCD effects, large and difficult to compute
- First observation of CPV in decay in $D^0 \rightarrow h^+h^-$ @LHCb(5.3σ)
[PRL122(2019)211803]
- First evidence for direct CP violation in specific D^0 decays:
[Phys. Rev. Lett. 131 (2023) 091802]
  - 3.8σ in $D^0 \rightarrow \pi^-\pi^+$
  - 1.4σ in $D^0 \rightarrow K^-k^+$

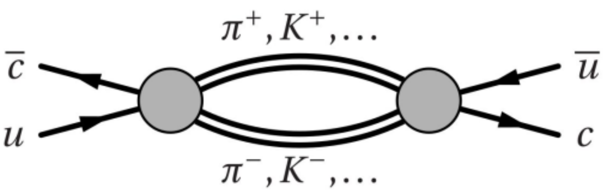
Mixing and CPV in $D^0 \rightarrow K^+\pi^-$

- $D^0 \rightarrow K^+\pi^-$ decays allows to simultaneously measure the mixing and all types of CPV.

- The SM prediction for the D^0 mixing amplitude governed by two contributions:

  - Short distance: suppressed by CKM *b* coupling and GIM mechanism

  - Long distances: low energy QCD through on-shell resonances → theoretical prediction of x and y very challenging

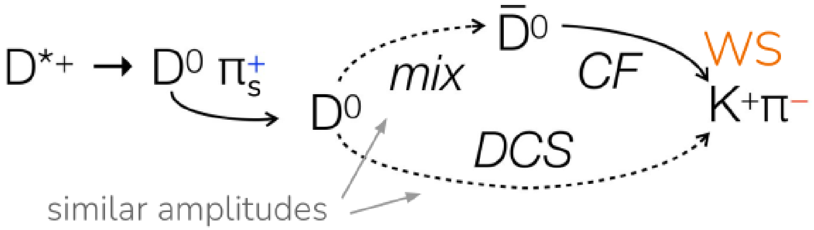


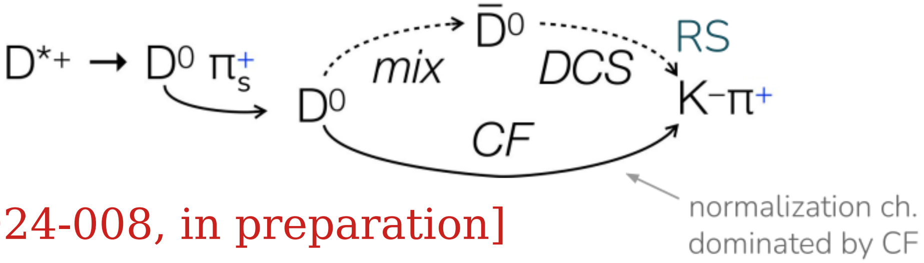
- Full run 2 LHCb analysis

- Time dependent analysis of $D^0 \rightarrow K^+\pi^-$ decays

- Reconstruct D^0 from $D^{*+} \rightarrow D^0\pi^-$ decays

- Distinguish two processes
  - Wrong sign (WS)
  - Right sign (RS)





[LHCb-PAPER-2024-008, in preparation]

Mixing and CPV in $D^0 \to K^+\pi^-$

[LHCb-PAPER-2024-008]

- In order to reduce the dependence on the mixing and CPV quantities a time dependent fit of WS/RS yield is performed:

$$R^{+}_{K\pi}(t) \equiv \frac{\Gamma(D^0(t) \to K^+\pi^-)}{\Gamma(\overline{D}^0(t) \to K^+\pi^-)} \qquad R^{-}_{K\pi}(t) \equiv \frac{\Gamma(\overline{D}^0(t) \to K^-\pi^+)}{\Gamma(D^0(t) \to K^-\pi^+)}$$

- Since $x_{1,2}$ and $y_{1,2}$ <<1 this ratio can be expanded as:

$$R^{\pm}_{K\pi}(t) = R_{K\pi}(1 \pm A_{K\pi}) + \sqrt{R_{K\pi}(1 \pm A_{K\pi})}\,(c_{K\pi} \pm \Delta c_{K\pi})\, t/\tau_{D^0} + (c'_{K\pi} \pm \Delta c'_{K\pi})\,(t/\tau_{D^0})^2$$

$$R_{K\pi} = \frac{1}{2}\left(\left|\frac{A_{\bar{f}}}{\bar{A}_{\bar{f}}}\right|^2 + \left|\frac{\bar{A}_f}{A_f}\right|^2\right),$$

$$A_{K\pi} = \frac{\left|A_{\bar{f}}/\bar{A}_{\bar{f}}\right|^2 - \left|\bar{A}_f/A_f\right|^2}{\left|A_{\bar{f}}/\bar{A}_{\bar{f}}\right|^2 + \left|\bar{A}_f/A_f\right|^2} \approx a^d_{\mathrm{DCS}}\,,$$

CPV in decay

$$c_{K\pi} \approx y_{12}\cos\phi^{\Gamma}_f \cos\Delta_f + x_{12}\cos\phi^M_f \sin\Delta_f\,,$$

$$\Delta c_{K\pi} \approx x_{12}\sin\phi^M_f \cos\Delta_f - y_{12}\sin\phi^{\Gamma}_f \sin\Delta_f\,,$$

CPV in the interference

$$c'_{K\pi} \approx \frac{1}{4}\left(x^2_{12} + y^2_{12}\right),$$

$$\Delta c'_{K\pi} \approx \frac{1}{2} x_{12} y_{12} \sin(\phi^M_f - \phi^{\Gamma}_f).$$

CPV in mixing

$$x_{12} \equiv 2|M_{12}|/\Gamma$$

$$\phi^M_2 \sim \arg(M_{12}),\ \phi^{\Gamma}_2 \sim \arg(\Gamma_{12}) \qquad y_{12} \equiv |\Gamma_{12}|/\Gamma$$

- CP violation measurements
- $A_{K\pi}$: rigorous null test of SM since c→uds doesn't receive any contribution from QCD nor chromomagnetic dipole operators
- Δ_f : improve the knowledge on $SU(3)_F$ breaking and rescattering effects at energy scale of the charm mass

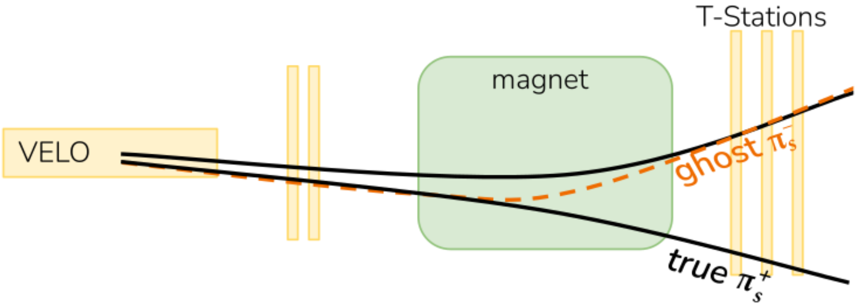
Strategy

[LHCb-PAPER-2024-008]

- Sample is divided between
  - D^0 final state ($K^-\pi^+$,$K^+\pi^-$),
  - 18 D^0 decay-time intervals
  - 3 data-taking period (2015-16, 2017 and 2018)

- Extracted values:
  - average D^0 decay time
  - WS-to-RS ratio, R, fitting D* mass to disentangle signal from combinatorial and ghost backgrounds
  - ghost backgrounds: misassociation of correctly-identified hits in VELO with hits in T-Stations from different particles)

- Correction them from the known systematic effects
  - bias to the ratio
  - bias to asymmetry
  - bias to D^0 decay-time



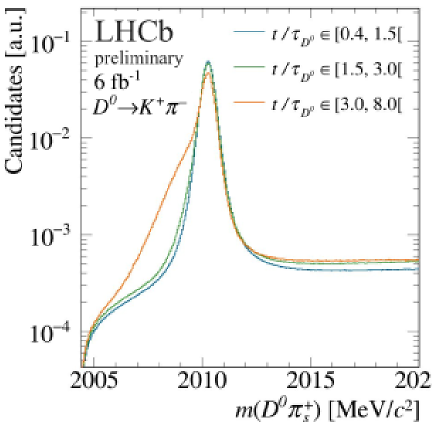
- Experimental challenges:
  - Backgrounds
  - Nuisance asymmetry

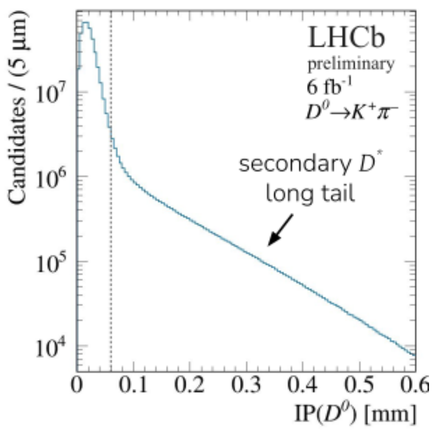
- Time dependence is fitted → extract mixing and CPV parameters

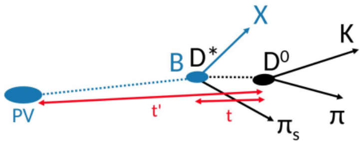
Biases

[LHCb-PAPER-2024-008]

- Bias of the decay time:
  - Poor D^* vertex resolution (1cm) → request to D^* to originate from primary vertex
    → contamination from secondary D^*
    - bias towards higher values
    - deformed D* shape







- Bias of charge asymmetry:
  - Originate by the differences in reconstruction efficiency between WS and RS, may mimic CPV

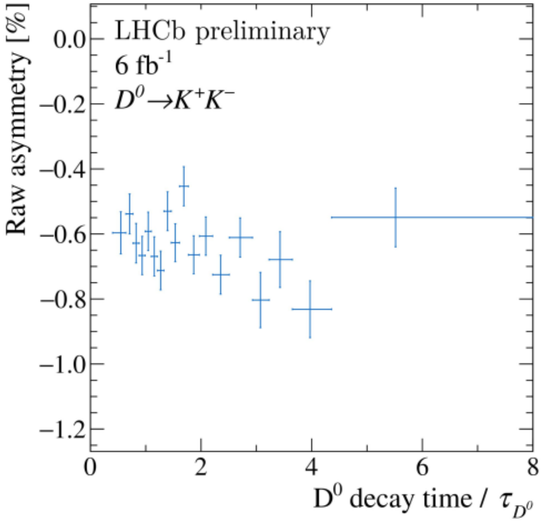
$$\widetilde{R'}^{\pm} = R'^{\pm}\frac{\int[1\pm A_P(D^*)]\epsilon(\pi_s^{\pm})\epsilon(K^{\pm}\pi^{\mp})\rho\, d\vec{p}_{D^0}\, d\vec{p}_{\pi_s}}{\int[1\mp A_P(D^*)]\epsilon(\pi_s^{\mp})\epsilon(K^{\pm}\pi^{\mp})\rho\, d\vec{p}_{D^0}\, d\vec{p}_{\pi_s}} \simeq R'^{\pm}\frac{1\pm[A_D(\pi_s)+A_P(D^*)]}{1\mp[A_D(\pi_s)+A_P(D^*)]}$$

  - Determinated with $D^0 \to K^+K^-$ control mode
  - To extract the raw asymmetry D^{*-} and D^{*+} are fitted simultaneously

$$A_D(\pi_s) + A_P(D^*) = A^{raw}(KK) - a^d_{KK} - \Delta Y\langle t\rangle$$

direct
CP asymmetry
in $D^0 \to K^+K^-$

time dependent
CP asymmetry
in $D^0 \to K^+K^-$



Strategy

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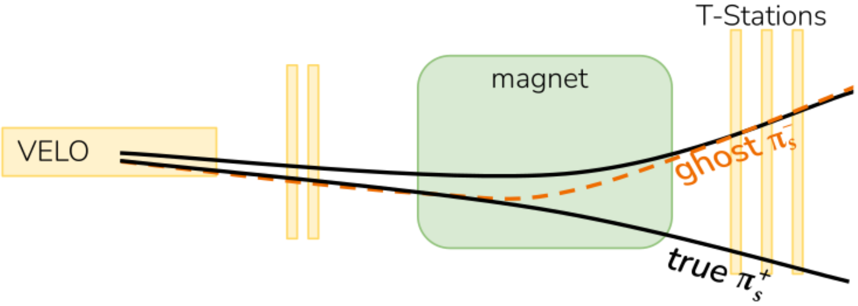


- Experimental challenges:
  - Backgrounds
  - Nuisance asymmetry

- Time dependence is fitted → extract mixing and CPV parameters

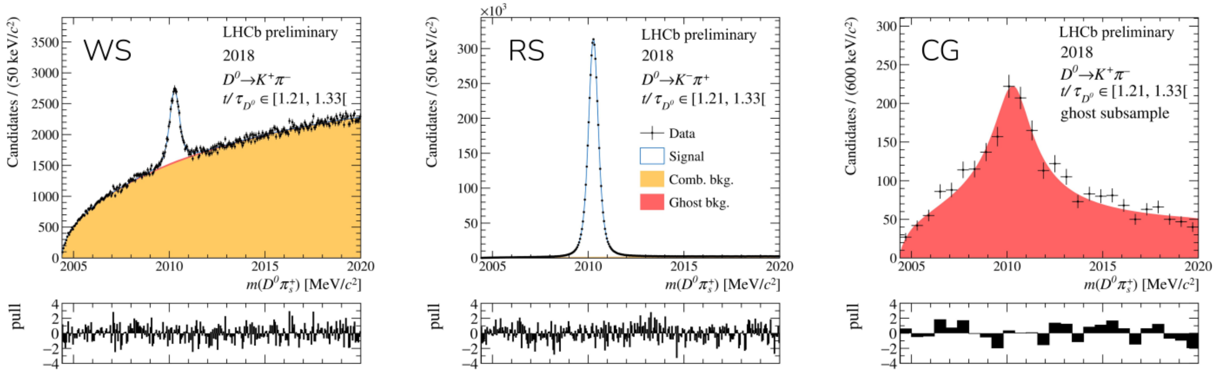
Results

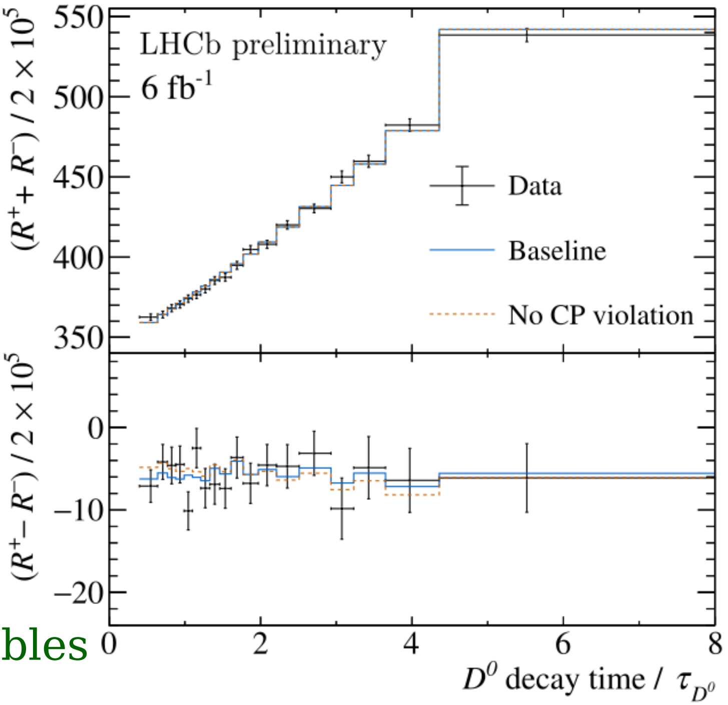
[LHCb-PAPER-2024-008]

- Bias of ratio:
  - due to the contamination of doubly misidentified D^0 decays
  - removal of common candidates from the sample of WS decays

  → D^0 candidates used to reconstruct both WS D^{*+} and RS D^{*-}
    - RS D^{*-} kept but this removes a small fraction of WS biasing the ratio

- A binned fit is performed simultaneously to D^* mass distribution of WS, RS and common ghost





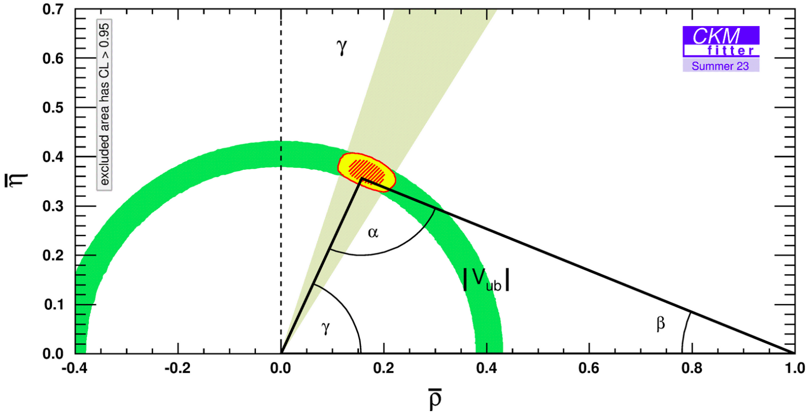
- The main systematic sources are D^* mass fit model and ghost bkg pdf

Parameters	
$R_{K\pi}$	$(342.7 \pm 1.9) \times 10^{-5}$
$c_{K\pi}$	$(52.8 \pm 3.3) \times 10^{-4}$
$c'_{K\pi}$	$(12.0 \pm 3.5) \times 10^{-6}$
$A_{K\pi}$	$(-6.6 \pm 5.7) \times 10^{-3}$
$\Delta c_{K\pi}$	$(2.0 \pm 3.4) \times 10^{-4}$
$\Delta c'_{K\pi}$	$(-0.7 \pm 3.6) \times 10^{-6}$

- 20% improvement on Φ_2^M
- Run 1 and run 2 results compatibles
- Total uncertainty improved by 1.6 with respect Run 1
- No evidence CPV neither in decays, mixing nor interference

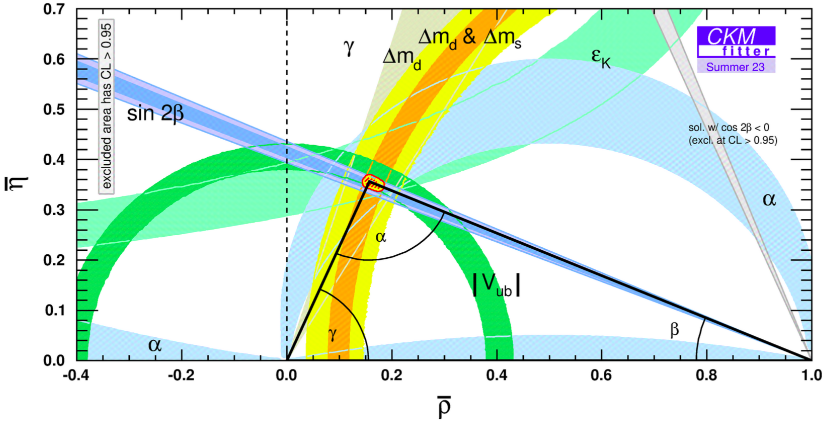
CKM γ angle

- γ is the phase difference between b→c and b→u quark transition
  - measurable in purely tree level o indirectly
  - negligible theoretical uncertainty ~10^{-7} [Zupan & Brod 1308.5663]
  - current experimental uncertainty is < 4°



Tree level direct measurements

$$\gamma_{\text{direct}} = (66.2^{+3.4}_{-3.6})^{\circ}$$



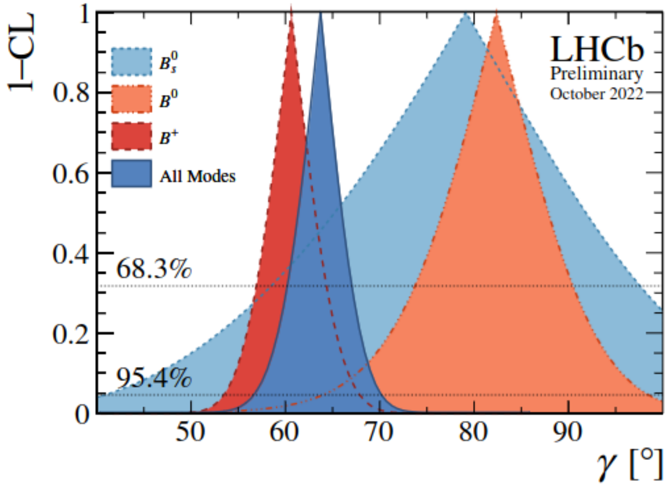
Loop-level indirect measurements

$$\gamma_{\text{indirect}} = (65.6^{+0.9}_{-2.7})^{\circ}$$

- LHCb combination:
  - simultaneous fit of γ and D^0 mixing parameters

$$\gamma = (63.8^{+3.5}_{-3.7})^{\circ}$$

[JHEP 12(2021)141]



γ angle

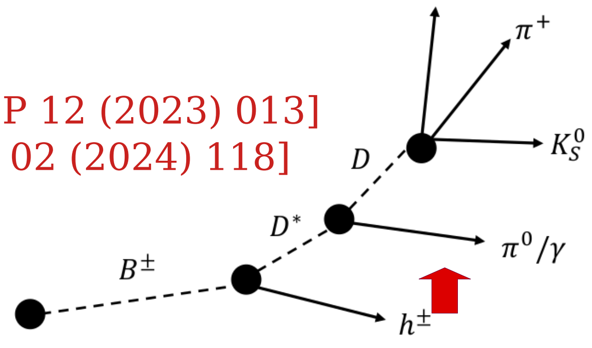
- It is typically measured in B decays such as B± → Dh± (where D= D^0, $\overline{D^0}$ and h=K, π)

$$|A(B^-)|^2 \propto A_D^2 + r_B^2 A_{\bar{D}}^2 + 2A_D A_{\bar{D}} r_B \cos(\delta_B - \gamma)$$

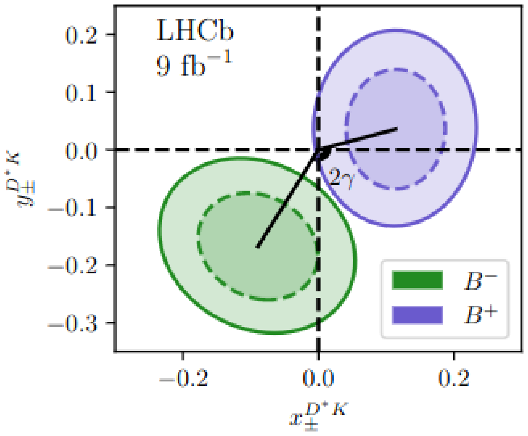
- Measurement technique depends on D-decay mode

$$|A(B^+)|^2 \propto A_D^2 + r_B^2 A_{\bar{D}}^2 + 2A_D A_{\bar{D}} r_B \cos(\delta_B + \gamma)$$

- **LHCb γ measurements with multibody D decays**
  - B± → D*K± (full reconstructed → better control of backgrounds) [JHEP 12 (2023) 013]
  - B± → D*K± (partially reconstructed → higher signal efficiency) [JHEP 02 (2024) 118] with D*→D^0 π or and D^0 → K^0_s h^+h^-



- The measurements are performed by analyzing the signal yields variation across the D decay phase space
  - They are independent of any amplitude model
  - direct measurement of D strong phase from BESIII and CLEO [JHEP05(2021)164]

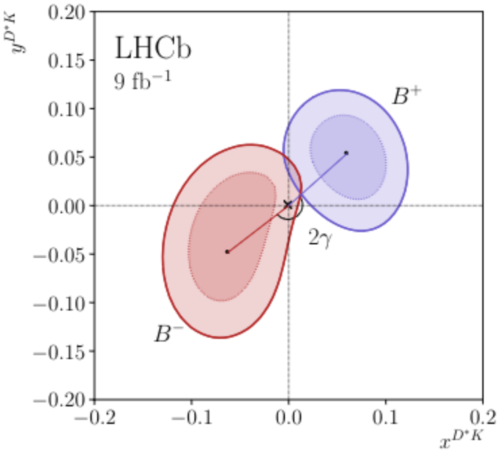


[JHEP 12 (2023) 013]

$$\gamma = (69^{+13}_{-14})^\circ$$

$$r_B^{D^*K} = 0.15 \pm 0.03$$

$$\delta_B^{D^*K} = (311 \pm 15)^\circ$$



[JHEP 02 (2024) 118]

$$\gamma = (92^{+21}_{-17})^\circ$$

$$r_B^{D^*K} = 0.080^{+0.022}_{-0.023}$$

$$\delta_B^{D^*K} = \left(310^{+15}_{-20}\right)^\circ$$

γ angle

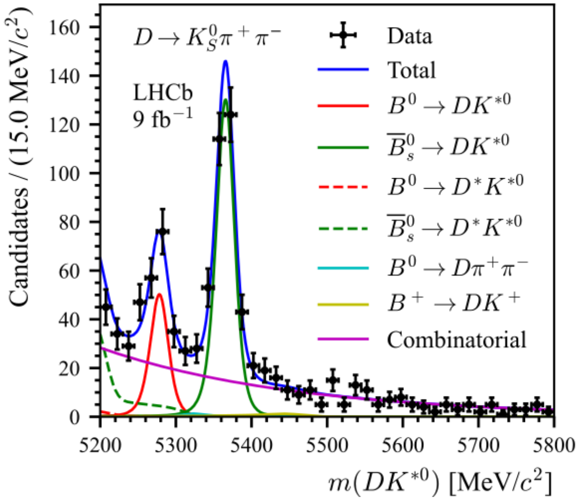
- Gain complementary info from $B^0 \rightarrow DK^*(892)^0$:
  - interference 3 times larger that for $B^\pm \rightarrow Dh^\pm$

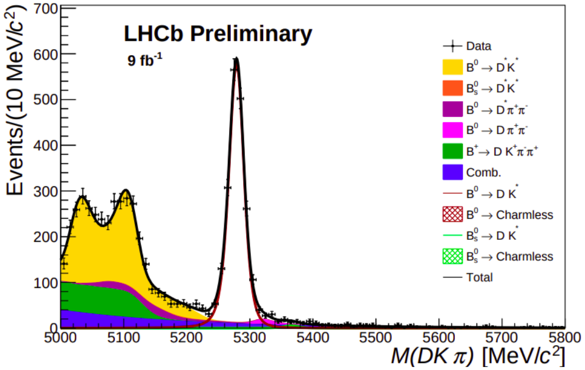
- **$B^0 \rightarrow DK^*(892)^0$ with $D \rightarrow K^0_s\, h^+h^-$** [Eur. Phys. J. C 84 (2024)
  - The γ angle is determined by examining the distributions of signal decays in phase space bins of $D^0 \rightarrow K^0_s\, h^+h^-$

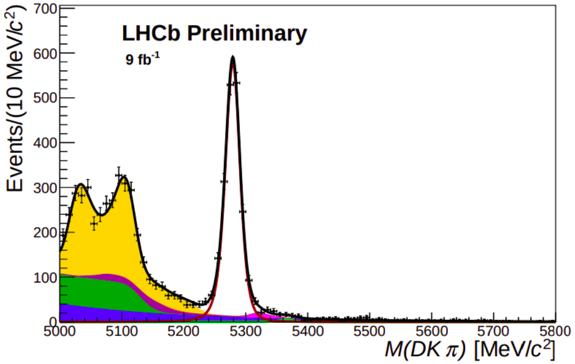
$$N_i(B^0) = h^{B^0}\left[F_{-i} + (x_+^2 + y_+^2)F_i + 2\kappa\sqrt{F_iF_{-i}}(x_+c_i - y_+s_i)\right]$$

$$x_\pm \equiv r_{B^0}\cos(\delta_{B^0} \pm \gamma)$$

$$y_\pm \equiv r_{B^0}\sin(\delta_{B^0} \pm \gamma)$$







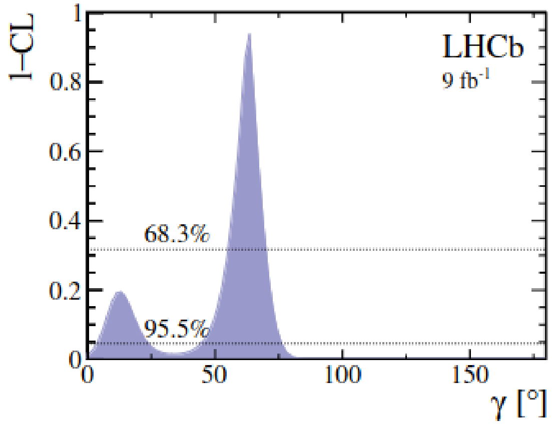
- **$B^0 \rightarrow D^0K^*(892)^0$ with the ADS and GLW D-decays final states**
  [arXiv:2401.17934]
  Fit to selected data through a simultaneous unbinned extended maximum-likelihood fit of the B^0 candidate reconstructed mass on each flavour of each D^0 final state
  - Statistical precision on the CP-violating observables has improved by around 60% comparison to the previous results

Combination of the last two results
Results from $D \rightarrow K^0_s\, h^+h$ broke the degeneracy

$$\gamma = (63.3 \pm 7.2)^\circ$$

$$r_{B^0}^{DK^*} = 0.233 \pm 0.016$$

$$\delta_{B^0}^{DK^*} = (191.8 \pm 6.0)^\circ$$



Decay-time dependent γ measurement

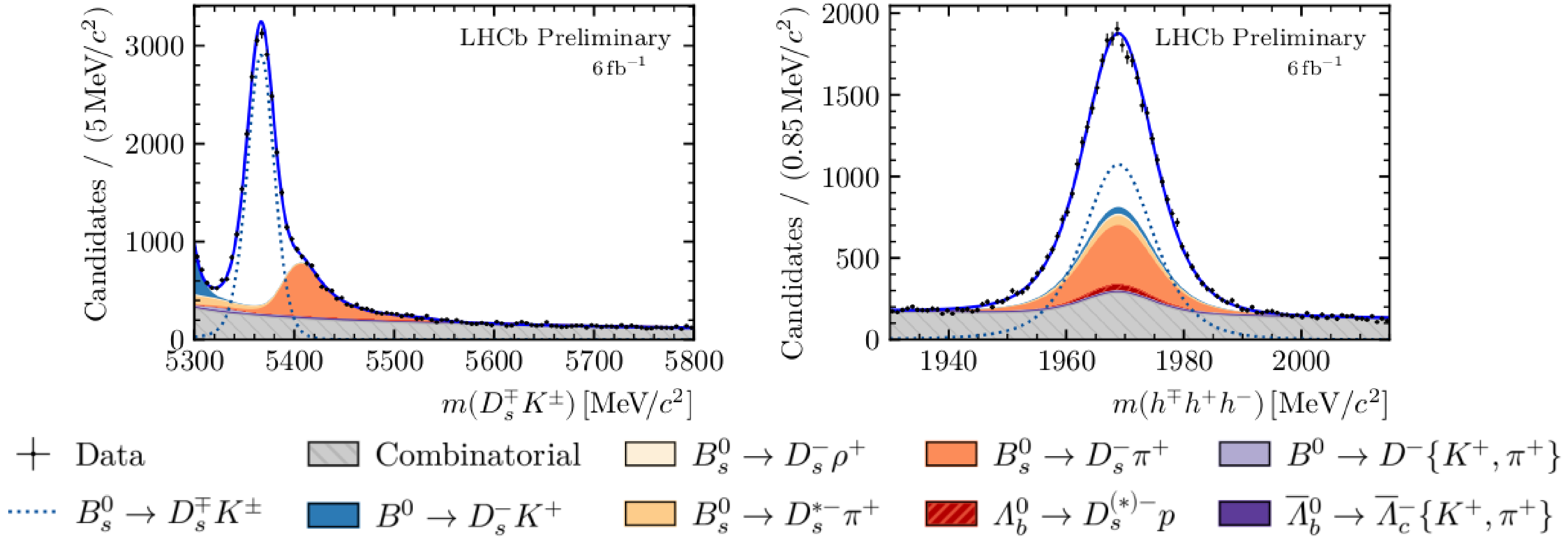
- **Measurement of CP asymmetry in $B^0_s \to D_s^- K^+$** [LHCb-CONF-2023-004]
- With $D_s^- \to K^+\pi^+\pi^-$, $D_s^- \to K^-K^+\pi^-$, $D_s^- \to \pi^{-+}\pi^-\pi^-$
- Time dependent measurement of γ

$$\Gamma\left(B_s^0(t) \to f/\bar{f}\right) \sim e^{-\Gamma_s t}\left(\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) + C_{f/\bar{f}}\cos\left(\Delta m_s t\right) + A^{\Delta\Gamma}_{f/\bar{f}}\sinh\left(\frac{\Delta\Gamma_s}{2}t\right) - S_{f/\bar{f}}\sin\left(\Delta m_s t\right)\right)$$

$$C_f = C_{\bar{f}} = \frac{1 - r^2_{D_sK}}{1 + r^2_{D_sK}} \qquad A^{\Delta\Gamma}_f = \frac{-2\,r_{D_sK}\cos\left(\delta - (\gamma - 2\beta_s)\right)}{1 + r^2_{D_sK}} \qquad S_f = \frac{2\,r_{D_sK}\sin\left(\delta - (\gamma - 2\beta_s)\right)}{1 + r^2_{D_sK}}$$

$$A^{\Delta\Gamma}_{\bar{f}} = \frac{-2\,r_{D_sK}\cos\left(\delta + (\gamma - 2\beta_s)\right)}{1 + r^2_{D_sK}} \qquad S_{\bar{f}} = \frac{2\,r_{D_sK}\sin\left(\delta + (\gamma - 2\beta_s)\right)}{1 + r^2_{D_sK}}$$

- Simultaneous fit of all modes and run 2 years
- Two dimensional invariant mass fit: 20950±180 candidates



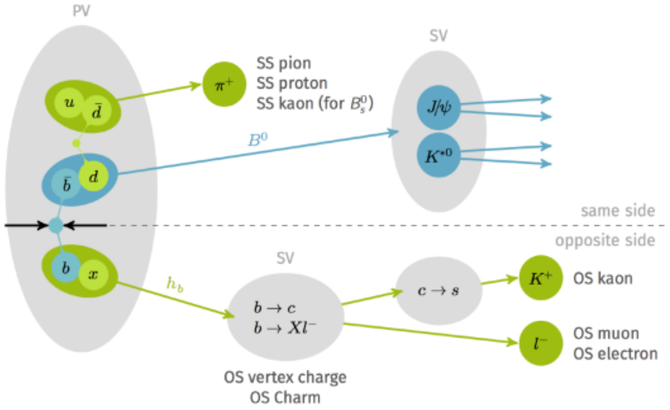
Decay-time dependent γ measurement

- The decay time fit has to be corrected for:

[LHCb-CONF-2023-004]

To **separate $B_s^0/\bar{B}_s^0$ candidates** ⟶ **flavour-tagging**

- estimates initial flavour
- exploits various fragmentation processes
- MVA-based mistag probability



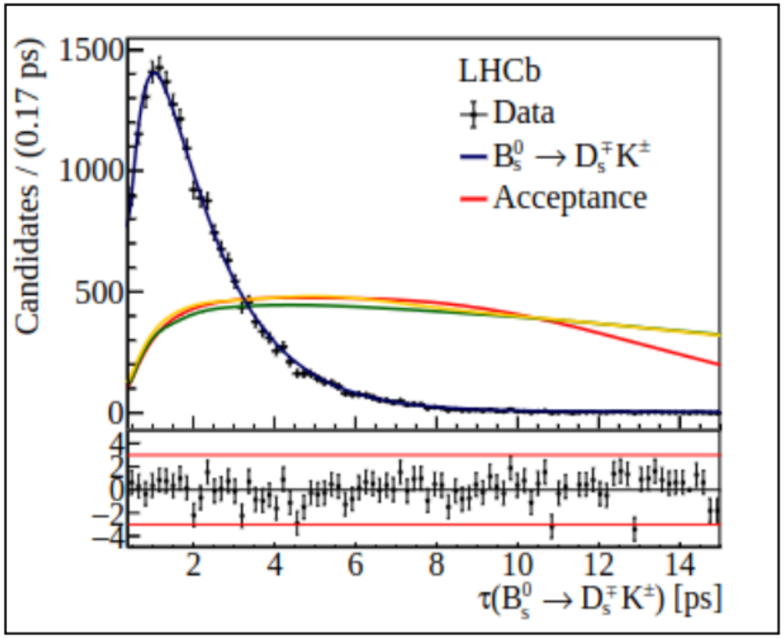
Decay-time resolution

- Finite decay-time resolution in the detector leads to a dilution of the observed oscillation
- The prompt sample of $D_s^-\pi^+$ was exploited

$$D_{res} \approx e^{-\frac{1}{2}\Delta m_s^2 \sigma^2}$$

Decay-time acceptance

- Decay-time distorted by selection requirements
- Heavily correlated with the CP observable D_f, $D_{\bar{f}}$
- Acceptance fixed to $B^0 \to D_s^-\pi^+$ fit and corrected by the ratio of the decay-time acceptances of $D_s^-K^+$ and $D_s^-\pi^+$



Decay-time dependent γ measurement

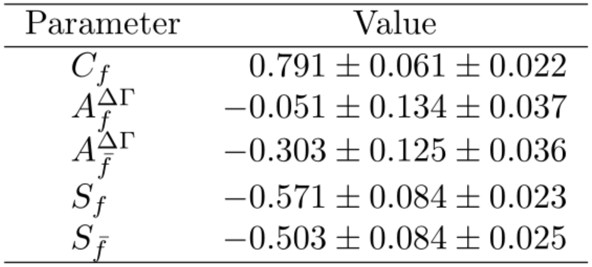
- External input: $\Delta\Gamma_s$, Γ_s, detection asymmetry

- Input from $B^0 \rightarrow D_s^- \pi^+$ [Nature Physics 18, (2022) 1-5]
    - Resolution calibration
    - Decay time acceptance
    - Tagging calibration
    - Production asymmetry
    - Δm_s

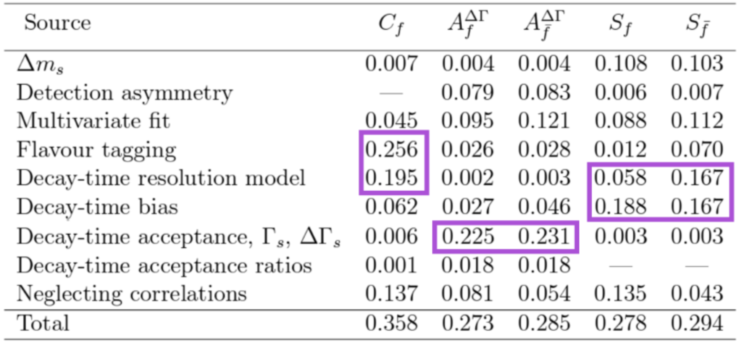
- External input: [arXiv:2308.01468]

$$\phi_s = -2\beta_s$$

- Significant CP violation in the interference (8.8σ)
- Measured CPV observables

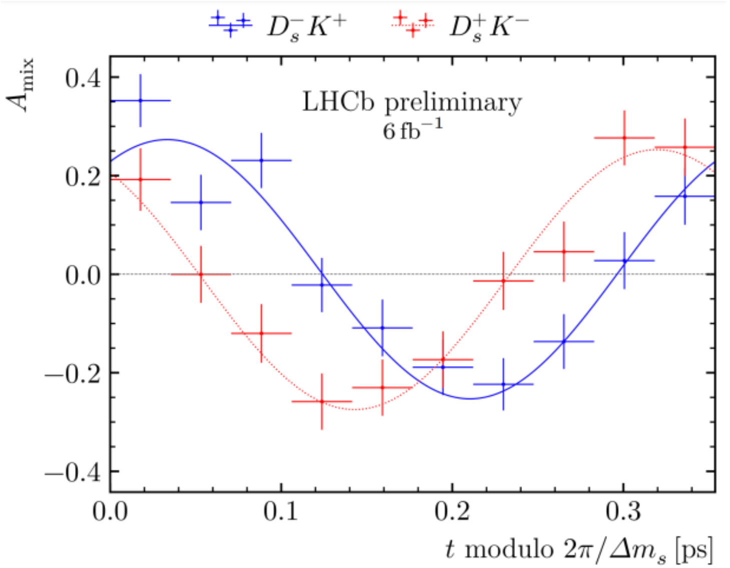


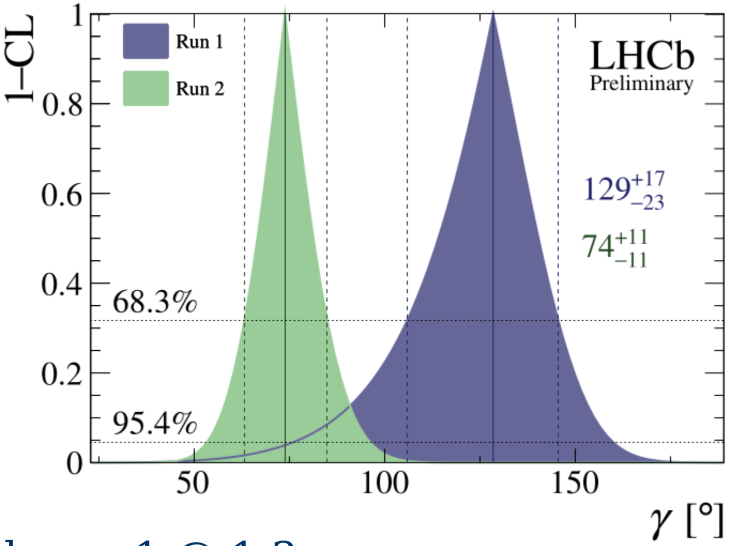
Parameter	Value
C_f	$0.791 \pm 0.061 \pm 0.022$
$A_f^{\Delta\Gamma}$	$-0.051 \pm 0.134 \pm 0.037$
$A_{\bar{f}}^{\Delta\Gamma}$	$-0.303 \pm 0.125 \pm 0.036$
S_f	$-0.571 \pm 0.084 \pm 0.023$
$S_{\bar{f}}$	$-0.503 \pm 0.084 \pm 0.025$



Source	C_f	$A_f^{\Delta\Gamma}$	$A_{\bar{f}}^{\Delta\Gamma}$	S_f	$S_{\bar{f}}$
Δm_s	0.007	0.004	0.004	0.108	0.103
Detection asymmetry	—	0.079	0.083	0.006	0.007
Multivariate fit	0.045	0.095	0.121	0.088	0.112
Flavour tagging	0.256	0.026	0.028	0.012	0.070
Decay-time resolution model	0.195	0.002	0.003	0.058	0.167
Decay-time bias	0.062	0.027	0.046	0.188	0.167
Decay-time acceptance, Γ_s, $\Delta\Gamma_s$	0.006	0.225	0.231	0.003	0.003
Decay-time acceptance ratios	0.001	0.018	0.018	—	—
Neglecting correlations	0.137	0.081	0.054	0.135	0.043
Total	0.358	0.273	0.285	0.278	0.294

[LHCb-CONF-2023-004]





$$\gamma = (74 \pm 11)^\circ\,,$$
$$\delta = (346.9 \pm 6.6)^\circ\,,$$
$$r_{D_sK} = 0.327 \pm 0.038\,,$$

- Compatible with run 1 @ 1.3σ
- Combination between run 1 and run 2 ongoing

Measurement of ϕ_s in $B^0_s \to J/\psi K^+K^-$

[PRL132(2024)051802]

- B decays to CP eigenstates allow to probe the mixing phase $\beta_s = \phi_s/2$ through the interference between decays with and without mixing with a $c\text{-}\bar{c}$ resonance in the final state.

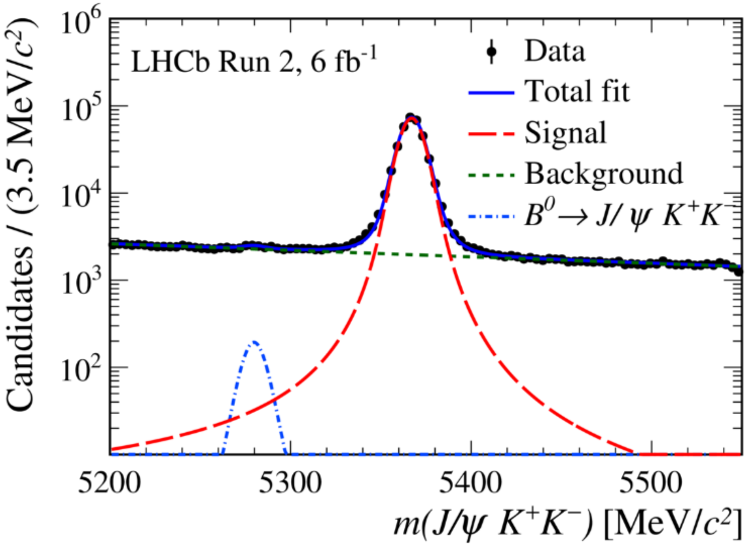
$$\beta_s \equiv \arg\left[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)\right]$$

- Unique opportunity to LHC due to Lorentz boost in p-p collisions

- $B^0_s \to J/\psi K^+K^-$ channel,in the vicinity of $\phi(1020)$ resonance

- Full run II analysis

- The data sample is divided in 48 independent subsamples:
  - 6 bins in the of invariant mass in the [990,1050] MeV/c^2
  - 2 trigger categories,
  - 4 years of data taking



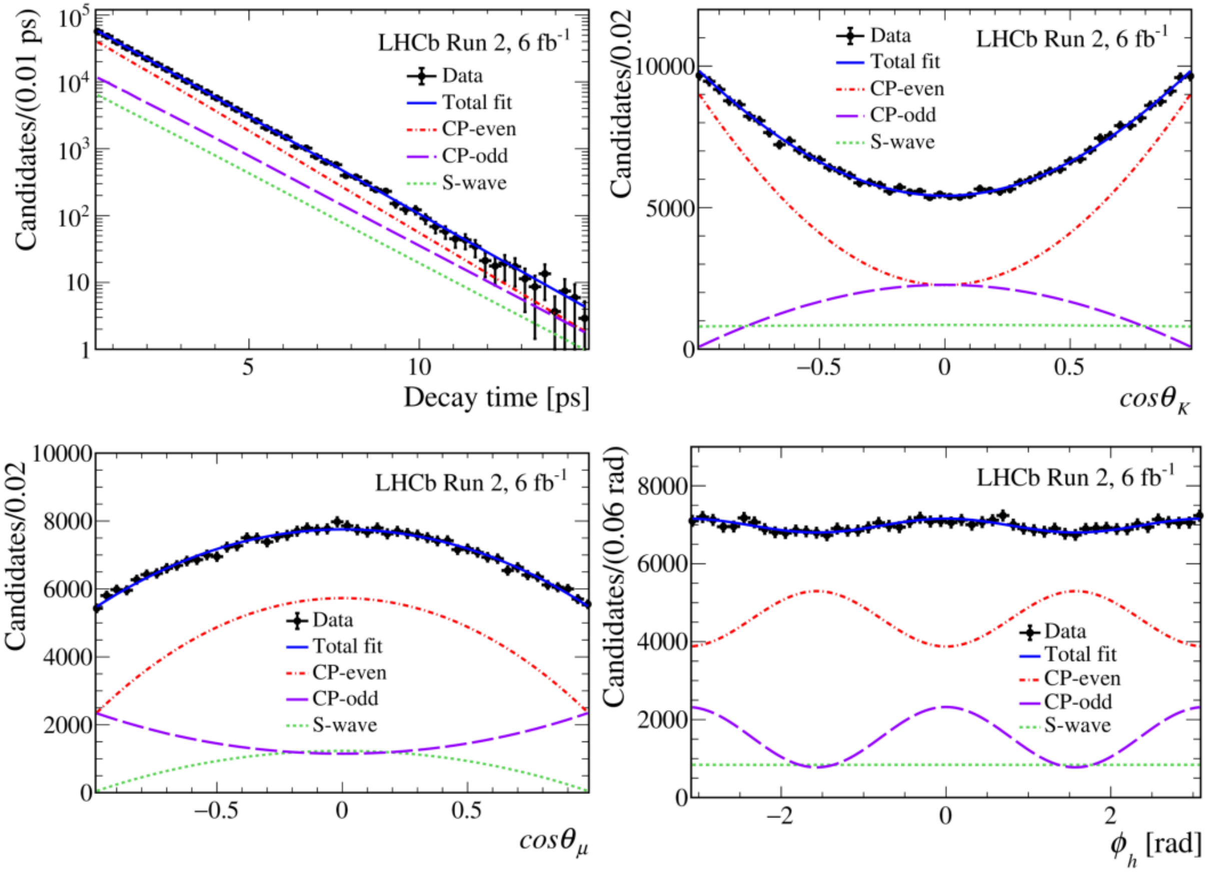
- Extended maximum likelihood fit to extract the signal yields

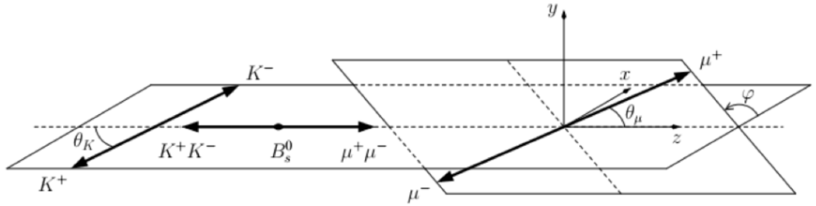
Measurement of ϕ_s in $B^0_s \to J/\psi K^+K^-$

[PRL132(2024)051802]

- To extract ϕ_s, CP even and CP-odd decay amplitude need to be disentangled since they depend on angular momentum between J/ψ and the kaons pair

  → A weighted simultaneous fit to decay time distribution and decays angles ($\cos\theta_K$, $\cos\theta_\mu$, ϕ_h) in the helicity basis is performed



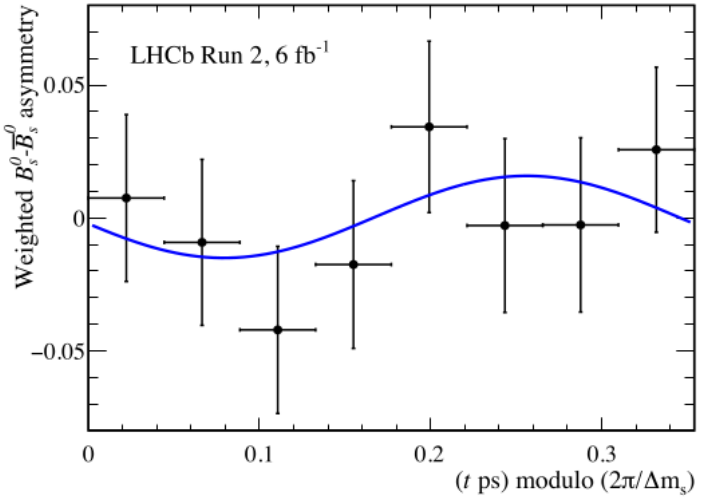


- The fit function account for :
  - Decay time resolution calibrated with prompt fake signals → $\sigma \sim$ 42ps
  - Flavour tagging calibrated with $B^+ \to J/\psi K^+$ and $B_S \to D_s^- \pi^+ \to \varepsilon \sim 4\%$
  - Angular efficiencies

Measurement of ϕ_s in $B^0_s \to J/\psi K^+K^-$

[PRL132(2024)051802]

Parameter	Values		
ϕ_s [rad]	-0.039	± 0.022	± 0.006
$\lvert\lambda\rvert$	1.001	± 0.011	± 0.005
$\Gamma_s - \Gamma_d$ [ps^{-1}]	-0.0056	$^{+0.0013}_{-0.0015}$	± 0.0014
$\Delta\Gamma_s$ [ps^{-1}]	0.0845	± 0.0044	± 0.0024
Δm_s [ps^{-1}]	17.743	± 0.033	± 0.009
$\lvert A_\perp\rvert^2$	0.2463	± 0.0023	± 0.0024
$\lvert A_0\rvert^2$	0.5179	± 0.0017	± 0.0032
$\delta_\perp - \delta_0$ [rad]	2.903	$^{+0.075}_{-0.074}$	± 0.048
$\delta_\parallel - \delta_0$ [rad]	3.146	± 0.061	± 0.052



- Most precise measurement to date and consistent with SM
- $\lvert\lambda\rvert$: consistent with no direct CPV
- $\Gamma_s - \Gamma_d$: consistent with HQE expectation [JHEP12 (2017) 068]
- No polarization dependence

- Combination with run 1:

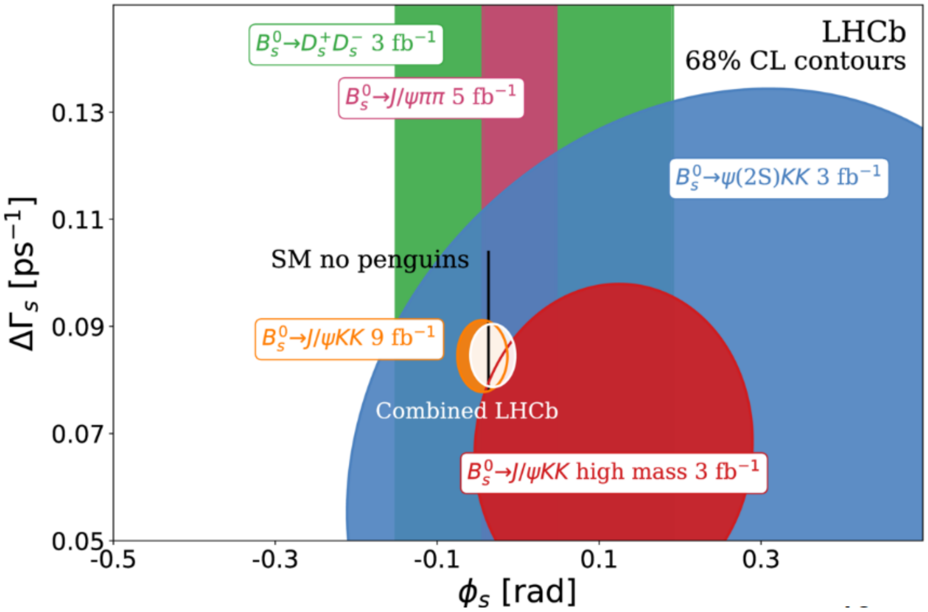
$$\phi_s = -0.044 \pm 0.020 \text{ rad}$$

$$\lvert\lambda\rvert = 0.990 \pm 0.010$$

- LHCb combination:

$$\phi_s = -0.031 \pm 0.018 \text{ rad}$$

[PRL 114 (2015) 041801,EPJC 79 (2019) 706, EPJC81 (2021) 1026]
[PLB 736 (2014) 186, PLB 797 (2019) 134789, PLB 762 (2016) 253, PRL 113 (2014) 211801]



Conclusion

A lot of results are still being produced with LHCb Run1+Run2 sample

- World leading measurements of mixing phases of neutral B mesons
- New measurements of $B \to Dh$ decays continuously improving the constraints on the γ angle

- LHCb is still exploiting its enormous charm data sample to look for CP violation in this sector
  - No evidence of discrepancies is observed with respect to SM expectations

- LHCb Upgrade I is going to start to collect data with the potential to more than double its sample in the next two years

- Complementarity and cross-check with Belle II will be fundamental as well

Original
2009-2018

Upgrade I
2022-2032

Upgrade II
2033-

Measurement of $\Delta\Gamma_s$ in $B^0_s \to J/\psi\, \pi^+\pi^-$ and $B^0_s \to J/\psi\, \eta'$

- The decay-width difference between the light and heavy mass eigenstates
- $\Delta\Gamma_s$ can be determined from the decay-width difference between a CP-odd and a CP-even B^0_s mode.

- If CP violation is negligible:

$$\Gamma(B^0_s(t) \to f) \propto e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + \eta_{CP}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right)\right]$$

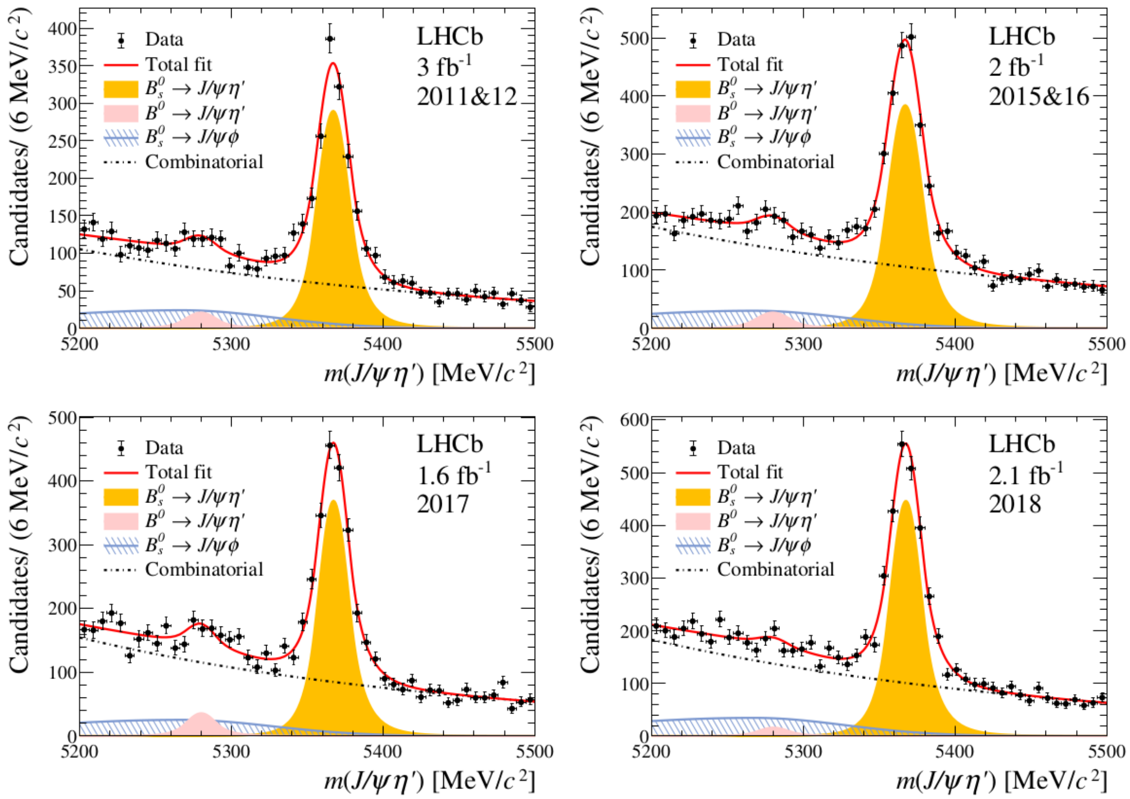
- integrating over a time bin

$$R_i = \frac{N_{\rm L}}{N_{\rm H}} \propto \frac{\left[e^{-\Gamma_s t(1+y)}\right]_{t_1}^{t_2}}{\left[e^{-\Gamma_s t(1-y)}\right]_{t_1}^{t_2}} \cdot \frac{(1-y)}{(1+y)} \quad \longrightarrow \quad R_i = A_i \cdot \frac{N_{\rm L}^{\rm RAW}}{N_{\rm H}^{\rm RAW}}$$

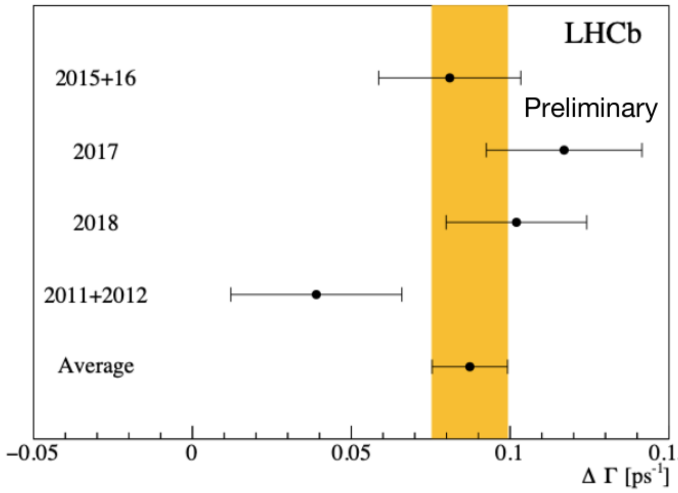
$y = \Delta\Gamma_s / 2\Gamma_s$

$N_{L(H)}$: CP-even(odd) modes

efficiency in each decay time bin



$$\Delta\Gamma_s = 0.087 \pm 0.012 \pm 0.009\ \text{ps}^{-1}$$



Orange band is 1σ error band

- 1st measurement using η′ channel
- In agreement with the SM

[LHCb-PAPER-2023-025]

Measurement of sin(2β)

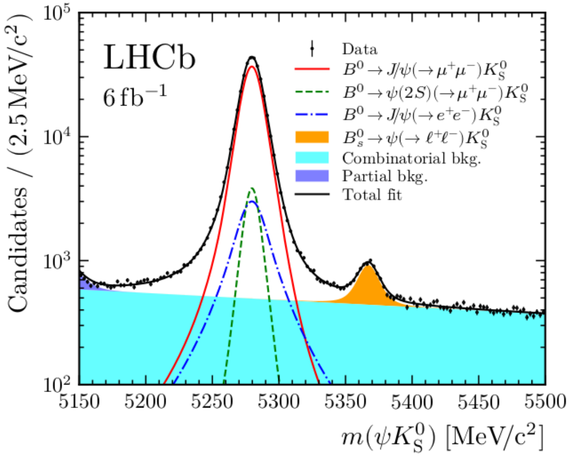
- B decays to CP eigenstates allow to probe the mixing phase β through the interference between decays with and without mixing
- $$\mathcal{A}^{CP}(t) = \frac{\Gamma(\overline{B}^0(t) \to f) - \Gamma(B^0(t) \to f)}{\Gamma(\overline{B}^0(t) \to f) + \Gamma(B^0(t) \to f)} = \frac{S\sin(\Delta m_d t) - C\cos(\Delta m_d t)}{\cosh\left(\frac{1}{2}\Delta\Gamma_d t\right) + \mathcal{A}_{\Delta\Gamma}\sinh\left(\frac{1}{2}\Delta\Gamma_d t\right)}$$

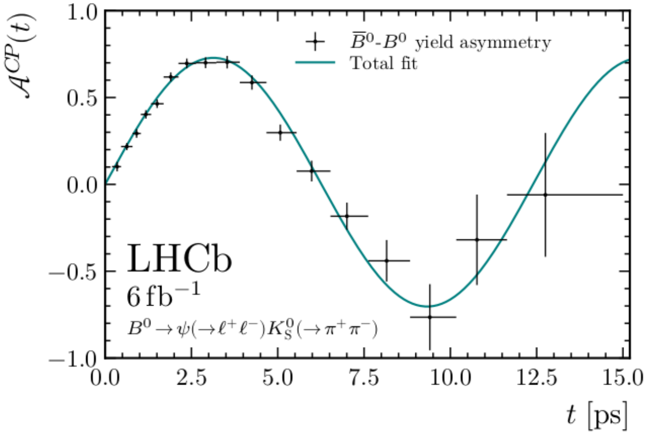
  where

  $$S = \sin(2\beta + \Delta\phi_d + \Delta\phi_d{}^{\mathrm{NP}})$$
- Decay channels: $B^0_s \to J/\psi(\to \mu^+\mu^-)K^0_s$, $B^0_s \to \psi(2s)(\to \mu^+\mu^-)K^0_s$, $B^0_s \to J/\psi(\to e^+e^-)K^0_s$ with $K^0_S \to \pi\pi$
- $$P(t,d,\eta) \propto [1 + d(1 - 2\omega^+(\eta))]P_{B^0}(t) + [1 + d(1 - 2\omega^-(\eta))]P_{\bar{B}^0}(t)$$

  $$P_{B^0(\bar{B}^0)}(t) \propto \{(1 \mp A_P)(1 \mp \Delta\epsilon_{tag})e^{-\Gamma_d t'}(1 \mp S\sin(\Delta m_d t') \pm C\cos(\Delta m_d t'))\} \otimes R(t - t') \cdot \epsilon(t)$$

- Simultaneous fit of all channels
- Combination run2 and run1 data





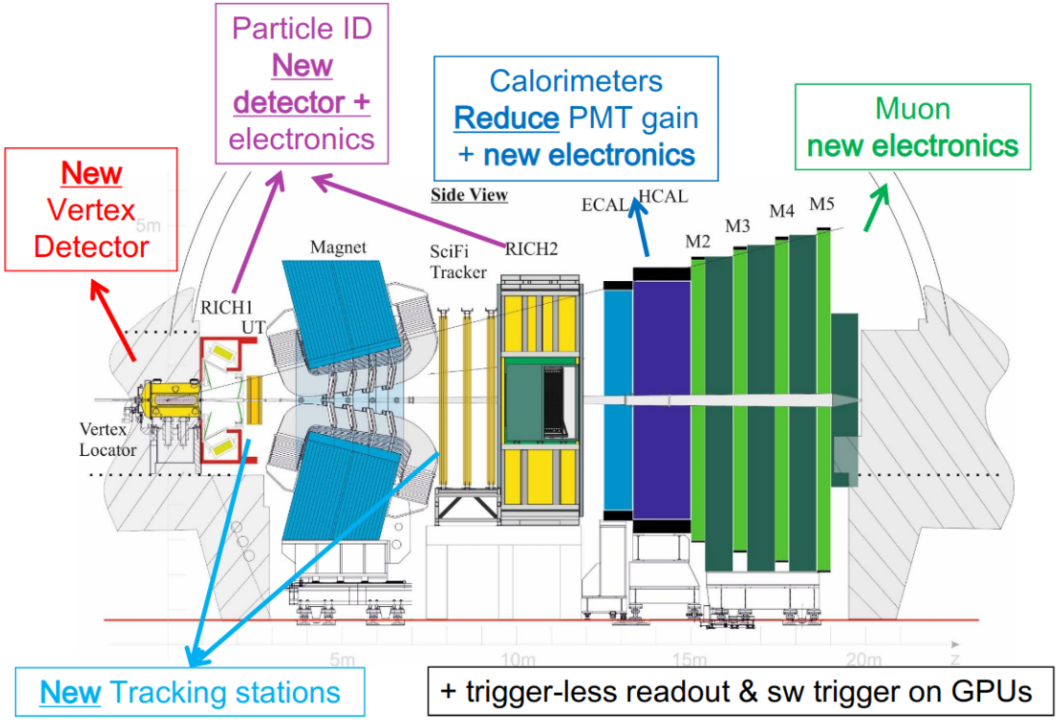
$$S^{\text{Run 1\&2}}_{J/\psi K^0_S} = 0.726 \pm 0.014\,(\text{stat+syst})$$
$$C^{\text{Run 1\&2}}_{J/\psi K^0_S} = 0.010 \pm 0.012\,(\text{stat+syst})$$

- Most precise single measurement
- Agreement with CKMfitter predictions

[LHCb-PAPER-2023-013]

LHCb

- LHCb was originally designed for CP violation and rare beauty & charm decays
- But now it is a general purpose detector: *exotic spectroscopy, EW precision physics, heavy ions, fixed target program…*



Particle ID
New detector + electronics

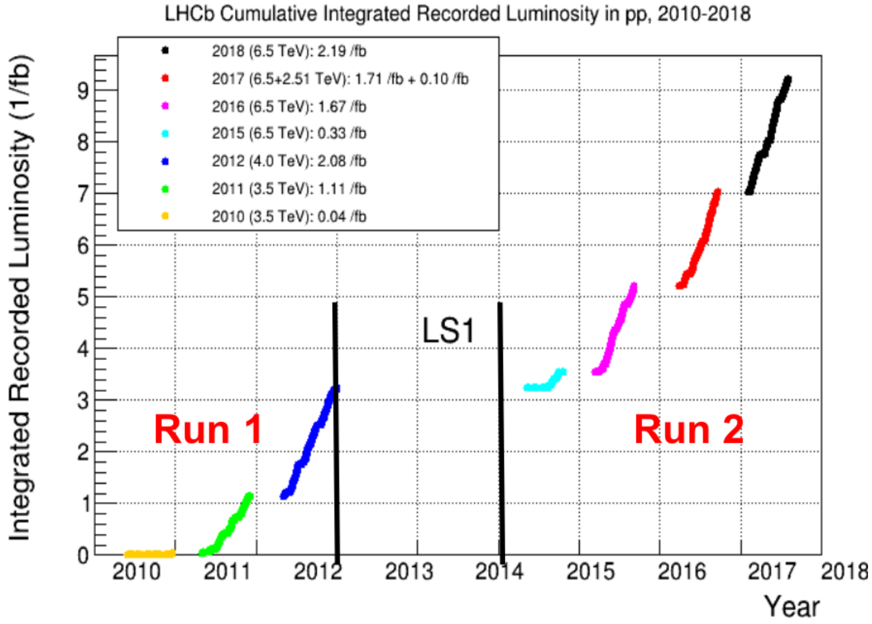
Calorimeters
Reduce PMT gain
+ new electronics

Muon
new electronics

New
Vertex
Detector

New Tracking stations

+ trigger-less readout & sw trigger on GPUs



Run1: 3 fb^{-1} @ $\sqrt{s}$ =7-8 TeV
Run2: 6 fb^{-1}@ $\sqrt{s}$ =13 TeV

- LHCb is a spectrometer in the forward direction $(2<\eta<5)$

- Excellent vertexing, tracking and particle identification
- Low trigger threshold on hadrons, muons and photons
- Production of all types of *b* and *c* hadrons