CPV & CKM at LHCb:
status and prospect @ LHCb

Anna Lupato

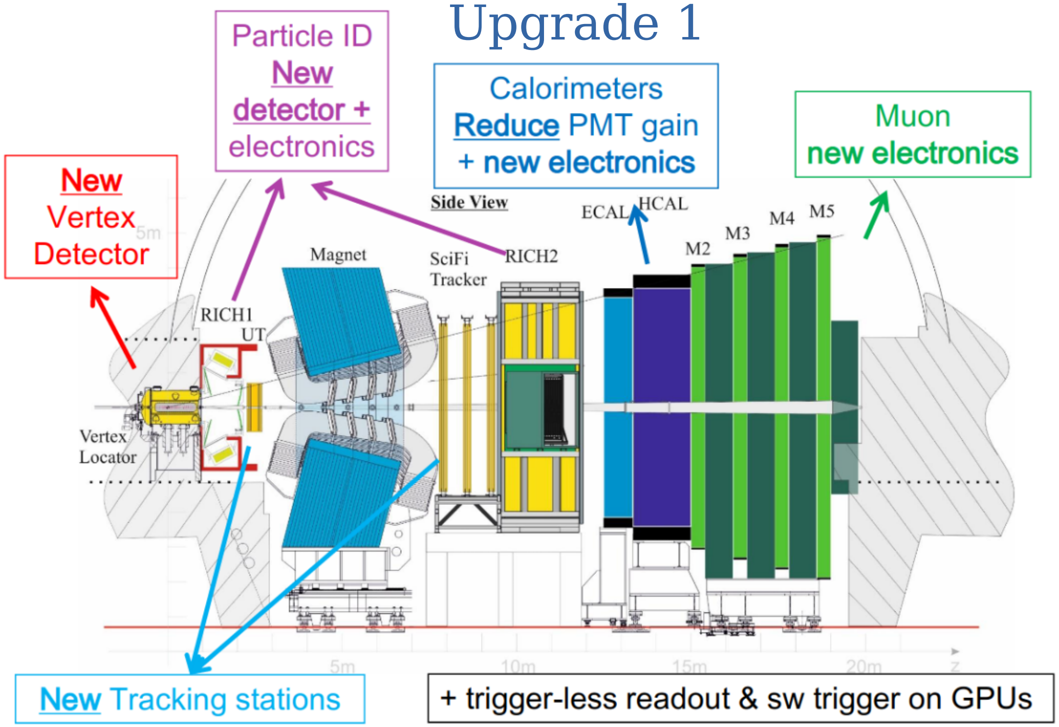
WIFAI,Incontro italiano sulla fisica ad alta intensità
Palazzo Hercolani, Bologna (Italy)
12-15 November 2024

UNIVERSITAS STUDIORUM BERGOMENSIS
LHCb
INFN PADOVA
Istituto Nazionale di Fisica Nucleare
Sezione di Padova

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…*

Upgrade 1



Particle ID
New detector + electronics

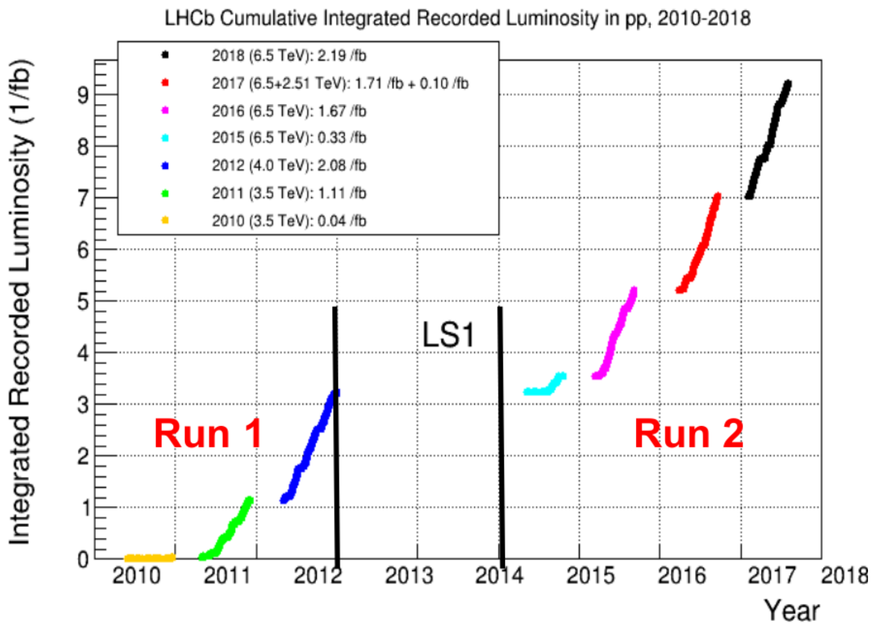
Calorimeters
Reduce PMT gain + new electronics

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

Unitarity Triangle Measurements

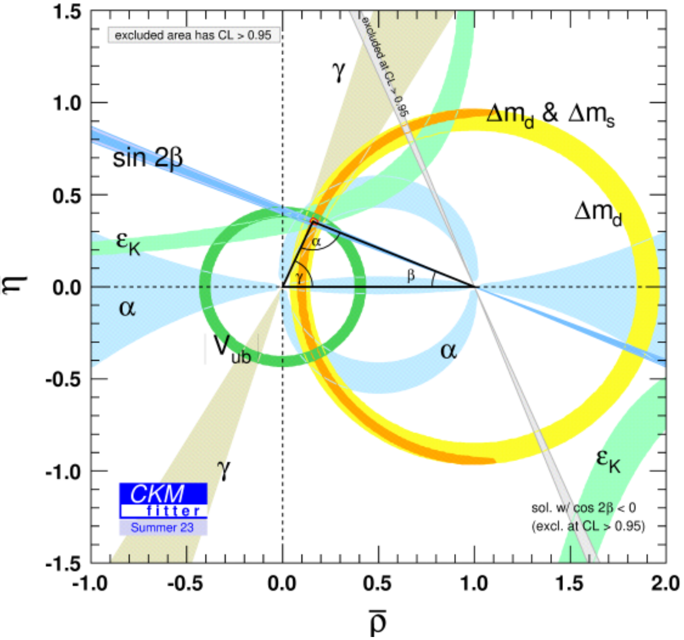
- The CKM matrix describes the quark charged current weak interactions

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

- The unitarity of this matrix leads , for instance, to

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

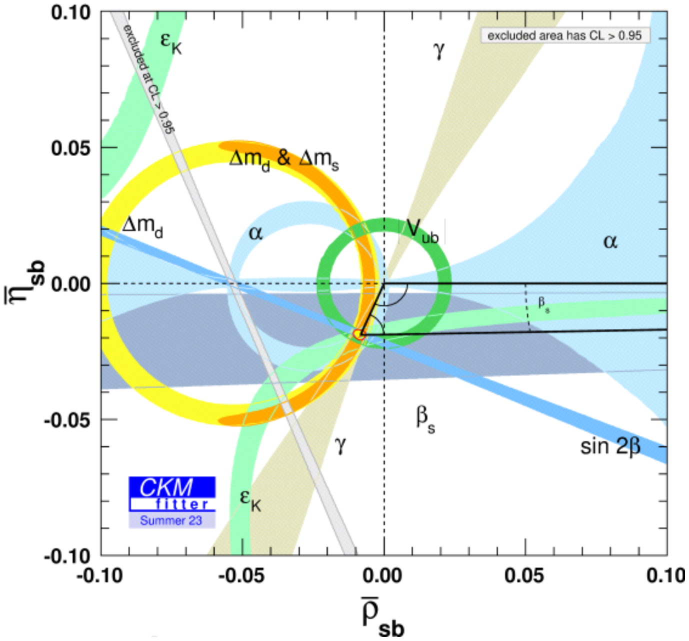
- It can be visualized as a triangle in the complex plane



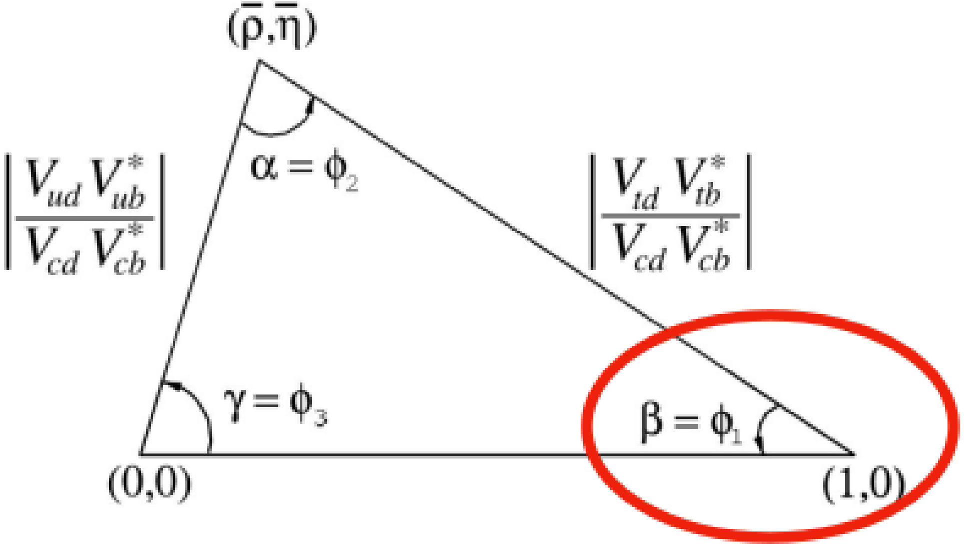
- The key test of the SM is the check of the unitarity of th CKM matrix

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



CKM-angle β


$(\bar{\rho},\bar{\eta})$
$\alpha = \phi_2$
$\left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right|$
$\left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right|$
$\gamma = \phi_3$
$\beta = \phi_1$
(0,0)
(1,0)

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
- $$\mathcal{A}^{CP}(t) = \frac{\Gamma(\overline{B}^0(t)\to f) - \Gamma(B^0(t)\to f)}{\Gamma(\overline{B}^0(t)\to f) + \Gamma(B^0(t)\to f)} = \frac{S\sin(\Delta m_d t) - C\cos(\Delta m_d t)}{\cosh\left(\frac{1}{2}\Delta\Gamma_d t\right) + \mathcal{A}_{\Delta\Gamma}\sinh\left(\frac{1}{2}\Delta\Gamma_d t\right)}$$

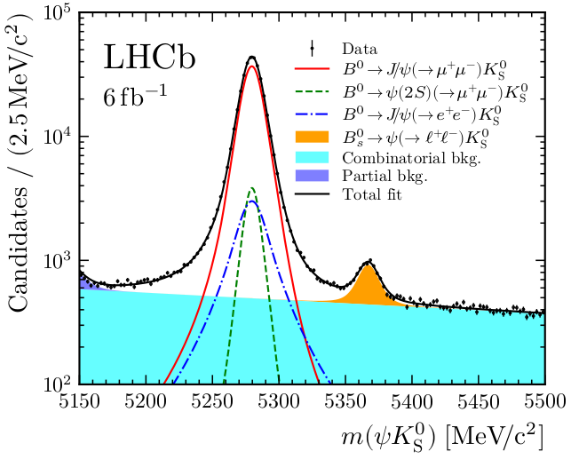
  where

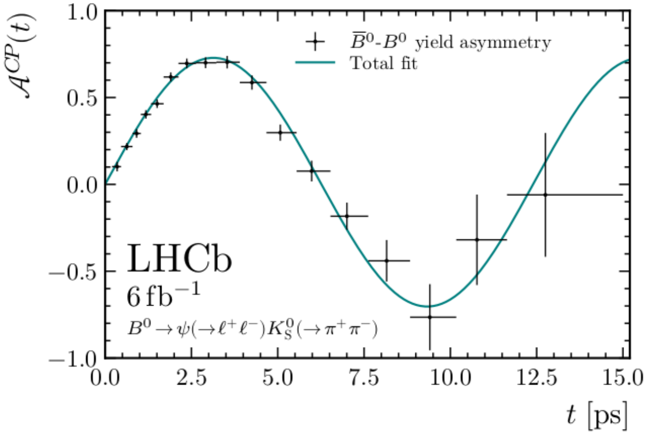
  $$S = \sin(2\beta + \Delta\phi_d + \Delta\phi_d{}^{\mathrm{NP}})$$

- Decay channels: $B^0 \to J/\psi(\to \mu^+\mu^-)K^0_s$, $B^0 \to \psi(2s)(\to \mu^+\mu^-)K^0_s$, $B^0 \to J/\psi(\to e^+e^-)K^0_s$ with $K^0_S \to \pi\pi$
- $$P(t,d,\eta) \propto \left[1 + \boxed{d\left(1-2\omega^+(\eta)\right)}\right]P_{B^0}(t) + \left[1 + \boxed{d\left(1-2\omega^-(\eta)\right)}\right]P_{\bar{B}^0}(t)$$

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

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





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

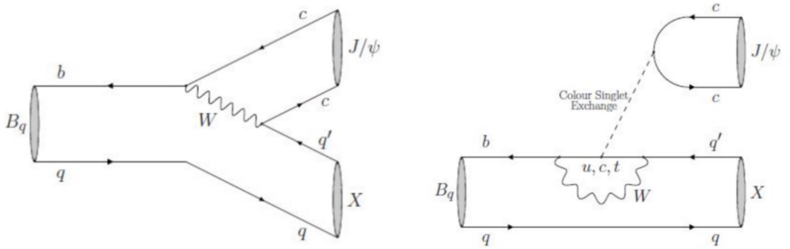
- Most precise single measurement
- Agreement with SM

[Phys.Rev.Lett.132(2024)021801]

Measurement of $BR(B^+ \to J/\psi\,\pi^+)$

[LHCb-PAPER-2024-031, in preparation]

- The $B^+ \to J/\psi\pi^+$ decay, proceeding via a $b \to \bar{c}cd$ transition, is enriched with penguin contributions



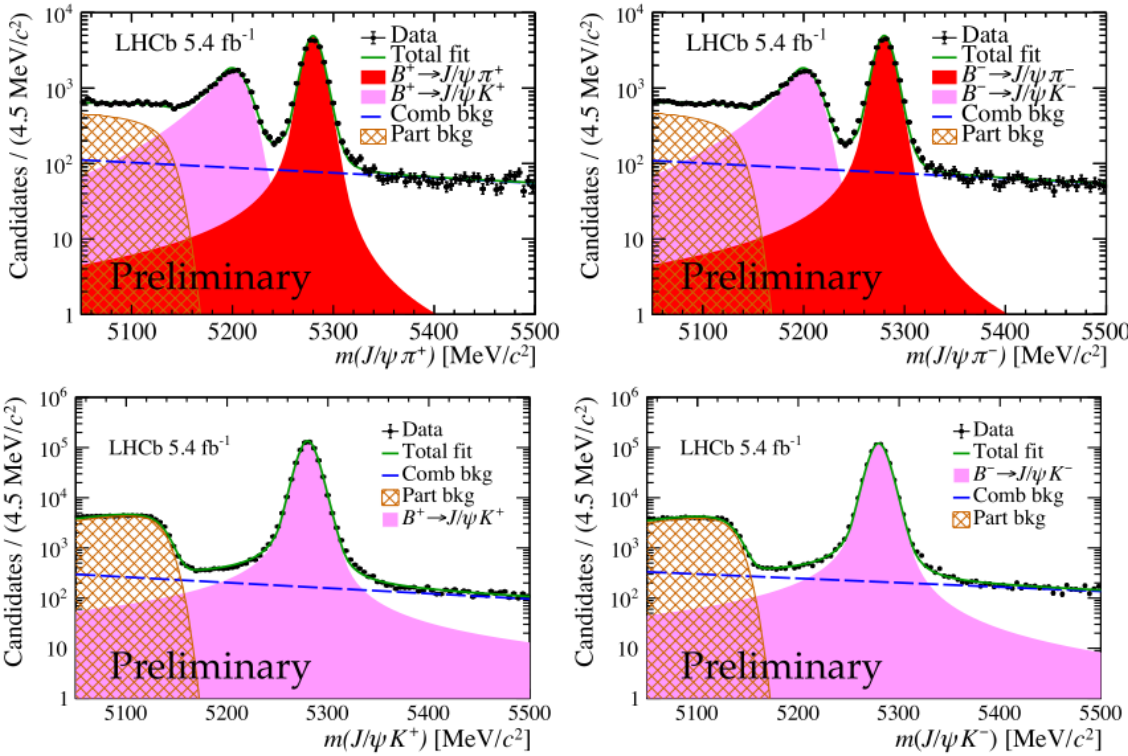
$(X = \pi, K)$

- Ideal place to look for yet unobserved direct CP violation in B decays to charmonia

- Important control channel to understand penguin effects that affect sin2β measurement in $B^+ \to J/\psi K^+$ [PRD 79 (2009) 014030, JHEP 03 (2015) 145]

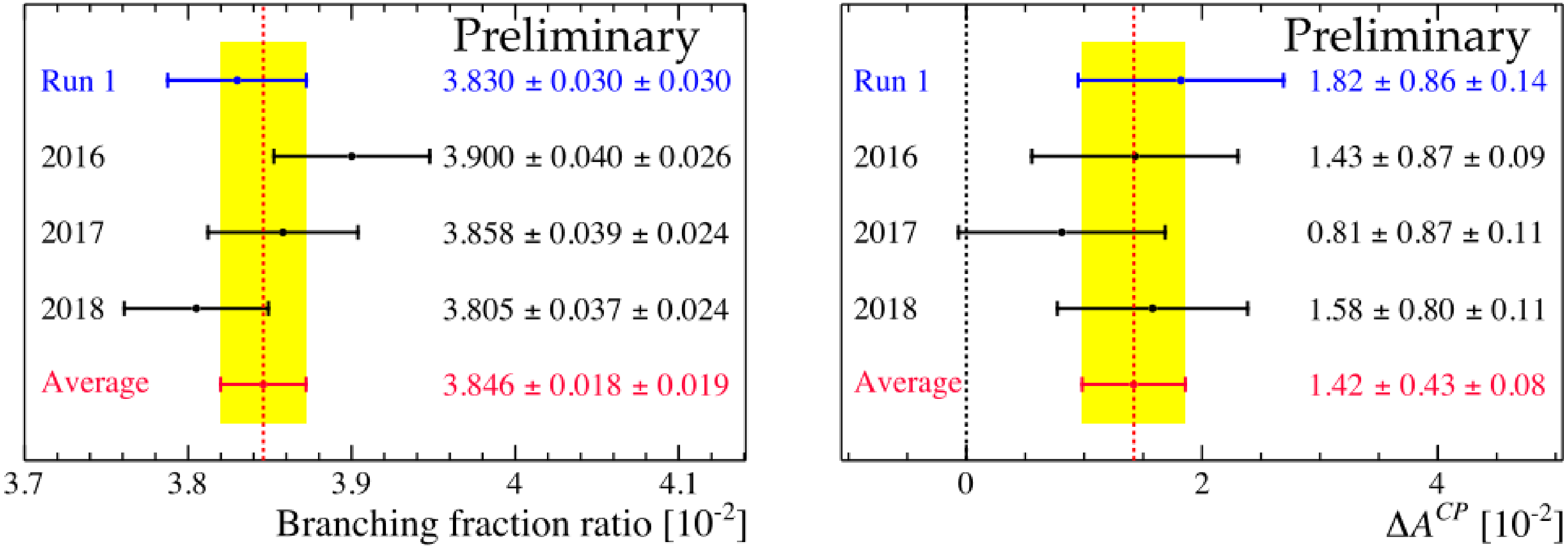
$$\Delta\mathcal{A}^{CP} \equiv \mathcal{A}^{CP}(B^+ \to J/\psi\pi^+) - \mathcal{A}^{CP}(B^+ \to J/\psi K^+).$$

$$\mathcal{R}_{K/\pi} \equiv \frac{\mathcal{B}(B^+ \to J/\psi\pi^+)}{\mathcal{B}(B^+ \to J/\psi K^+)},$$



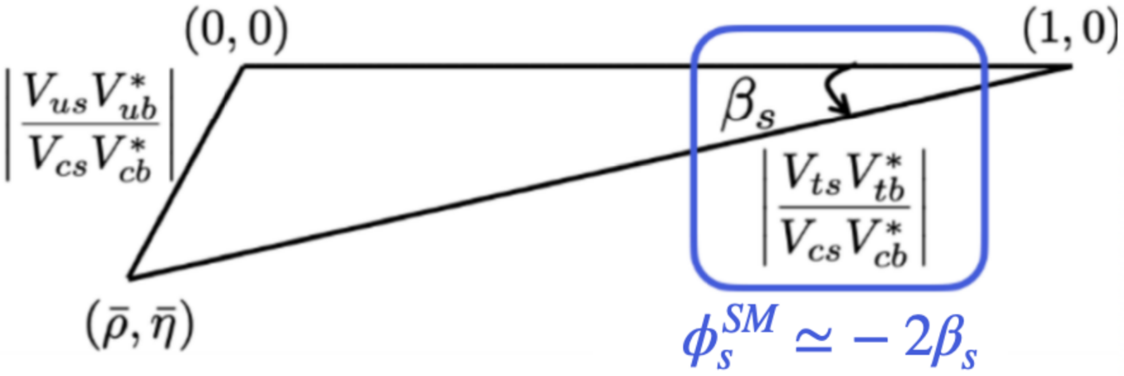
Measurement of $BR(B^+ \to J/\psi\,\pi^+)$

[LHCb-PAPER-2024-031, in preparation]



- Combination run2 and run1 data
- First observation of the direct CP violation in beauty to charmonia decays (3.2σ)

CKM-angle β_s



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

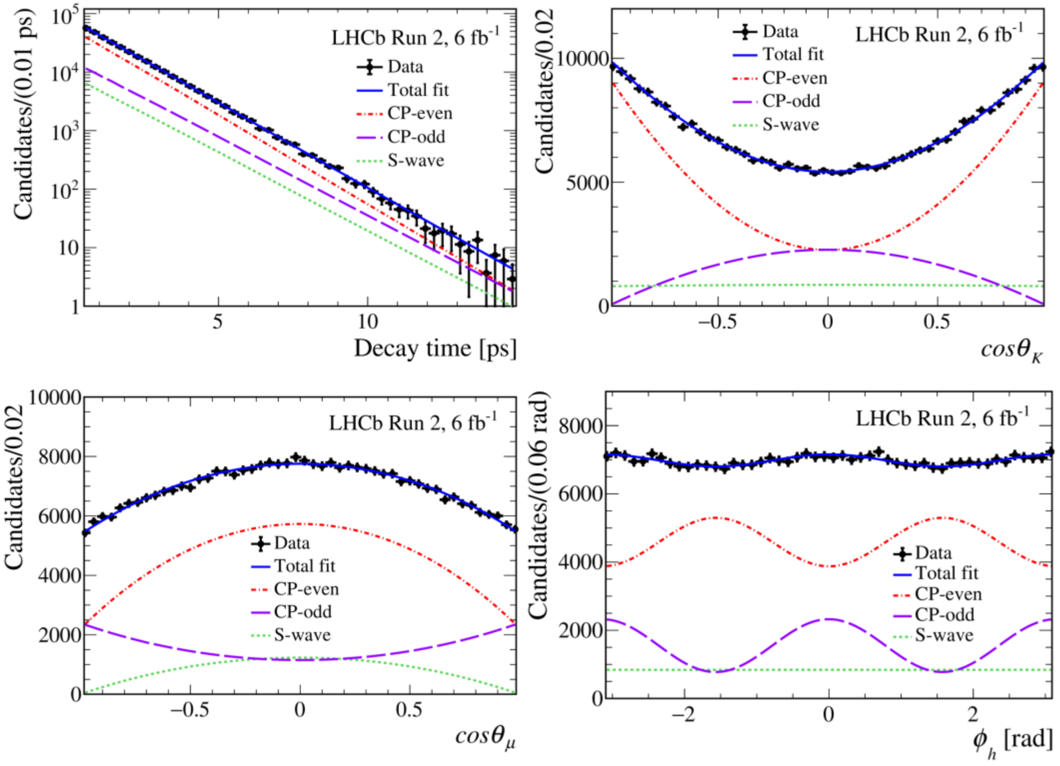
[PRL132(2024)051802]

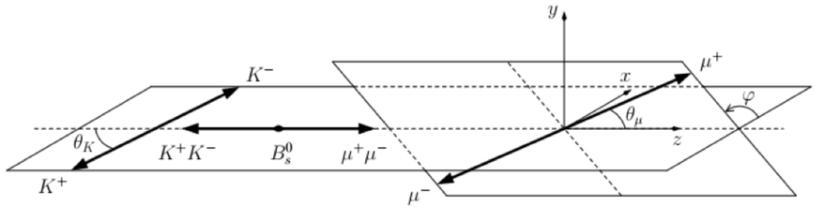
- B decays to CP eigenstates allow to probe the **mixing phase $\beta_s = -\phi_s/2$** through the interference between decays with and without mixing with a c-$\bar{c}$ resonance in the final state.

- $B_s \to J/\psi K^+K^-$ channel,in the vicinity of $\phi(1020)$ resonance with the full Run 2 dataset.

- 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

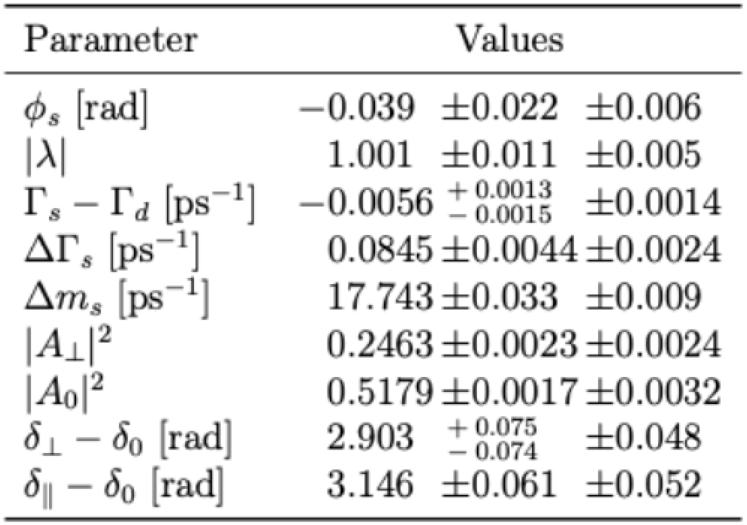




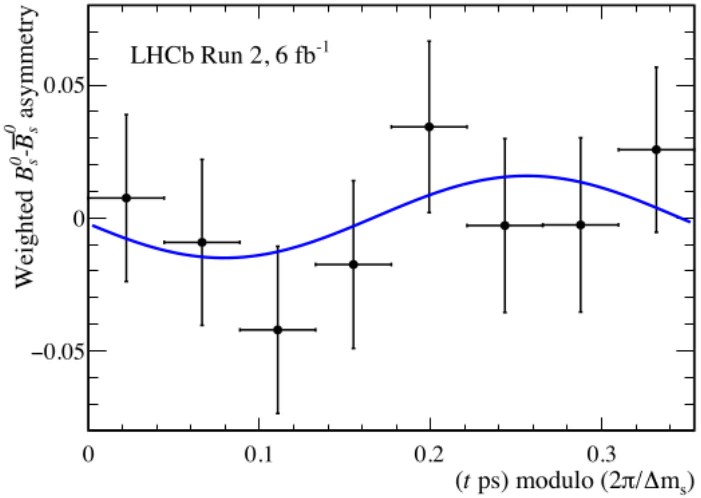
- The fit function accounts for :
  - Decay time resolution calibrated with prompt fake signals → $\sigma \sim 42$ps
  - Flavour tagging calibrated with $B^+ \to J/\psi K^+$ and $B_S \to D_s^-\pi^+$ → $\varepsilon \sim 4\%$
  - Angular acceptance

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
- $|\lambda|$: consistent with no direct CPV
- $\Gamma_s - \Gamma_d$: consistent with HQE expectation [JHEP12 (2017) 068]
- No polarization dependence

- Combination with run 1:

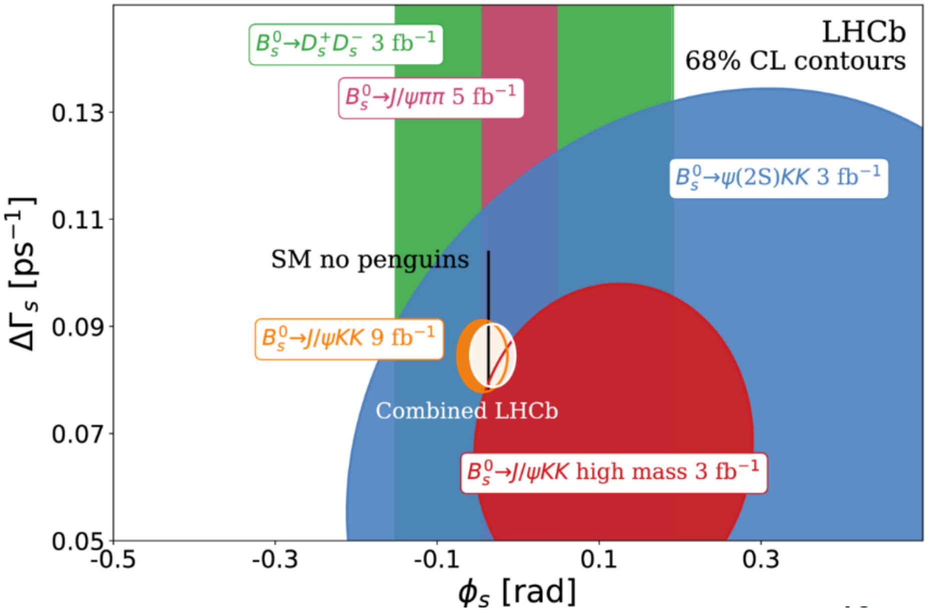
$$\phi_s = -0.044 \pm 0.020 \text{ rad}$$

$$|\lambda| = 0.990 \pm 0.010$$

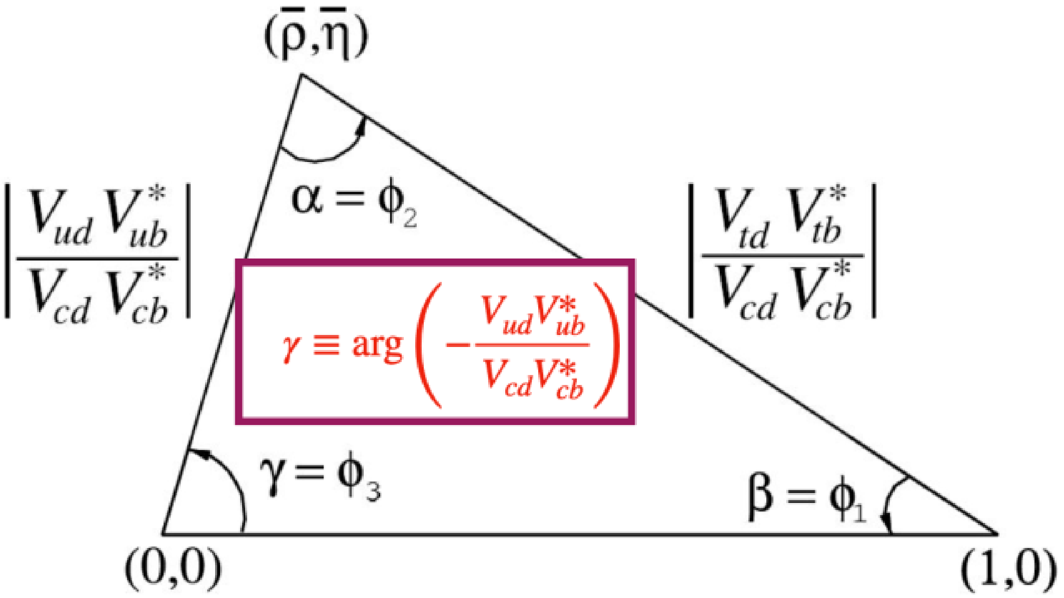
- LHCb combination:

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

[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]



CKM-angle γ



$$\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

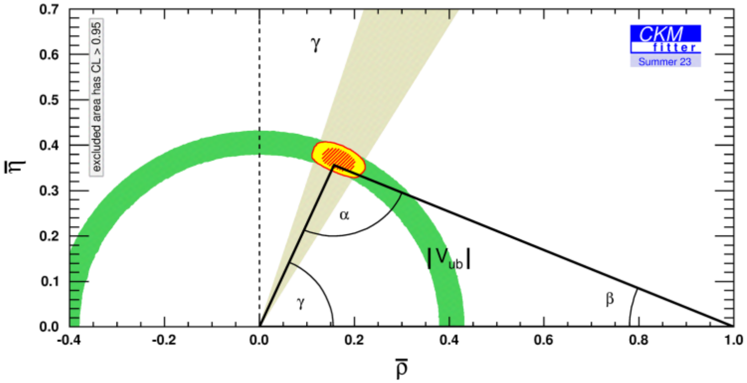
CKM γ angle

- γ is the phase difference between b→c and b→u quark transitions

$$\begin{tikzcd}
 & \overline{D^0}K^- \arrow[dr, bend left, "\mathcal{A}_{\overline{D^0}}"] & \\
B^- \arrow[ur, bend left, "\mathcal{A}_B r_B e^{i(\delta_B-\gamma)}"] \arrow[dr, bend right, "\mathcal{A}_B"'] & & (f)_D K^- \\
 & D^0K^- \arrow[ur, bend right, "\mathcal{A}_{D^0}"'] &
\end{tikzcd}
\qquad
\begin{tikzcd}
 & D^0K^+ \arrow[dr, bend left, "\mathcal{A}_{D^0}"] & \\
B^+ \arrow[ur, bend left, "\mathcal{A}_B r_B e^{i(\delta_B+\gamma)}"] \arrow[dr, bend right, "\mathcal{A}_B"'] & & (f)_D K^+ \\
 & \overline{D^0}K^+ \arrow[ur, bend right, "\mathcal{A}_{\overline{D^0}}"'] &
\end{tikzcd}$$

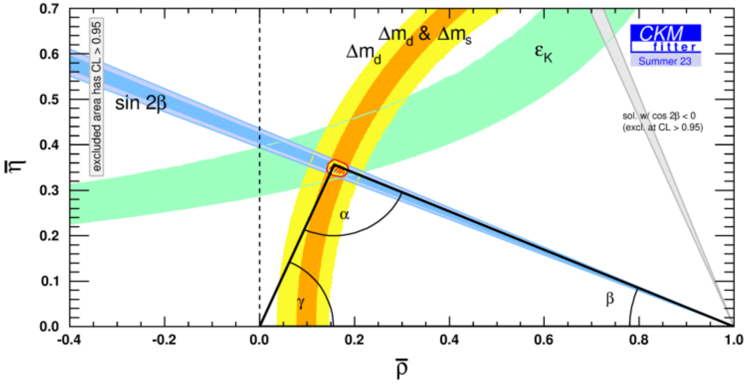
- measurable in purely tree level o indirectly

Tree level direct measurements



$$\gamma = (65.9^{+3.3}_{-3.5})^\circ$$

Loop-level indirect measurements



$$\gamma = (65.29^{+0.72}_{-1.86})^\circ$$

- negligible theoretical uncertainty ~10^{-7} [Zupan & Brod 1308.5663]

- current experimental uncertainty is < 4°:
  - thanks to the combination of many modes each with different sensitivities to γ
  - given the current precision also CPV and mixing effects in charm decays must be taken into account
  - knowledge of hadronic D decay parameters fundamental to improve sensitivity to γ [JHEP05(2021)164]

γ angle

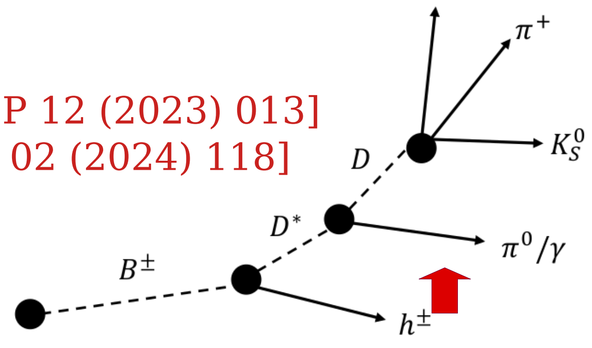
- It is typically measured in B decays such as B± → Dh± (where D= D^0, $\overline{D^0}$ and h=K, π)

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

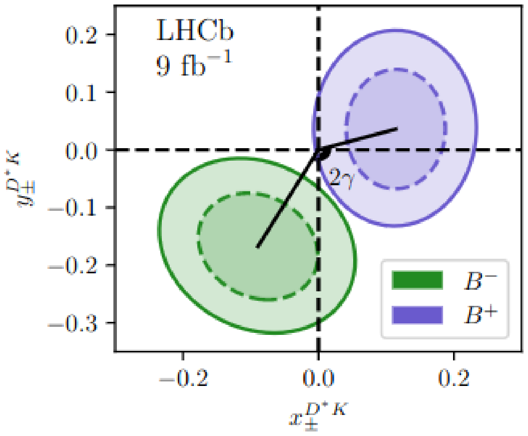
- Measurement technique depends on D-decay mode

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

- **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 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]

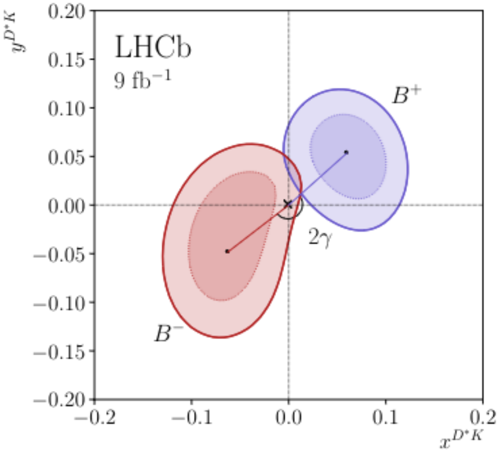


[JHEP 12 (2023) 013]

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

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

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



[JHEP 02 (2024) 118]

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

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

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

γ angle

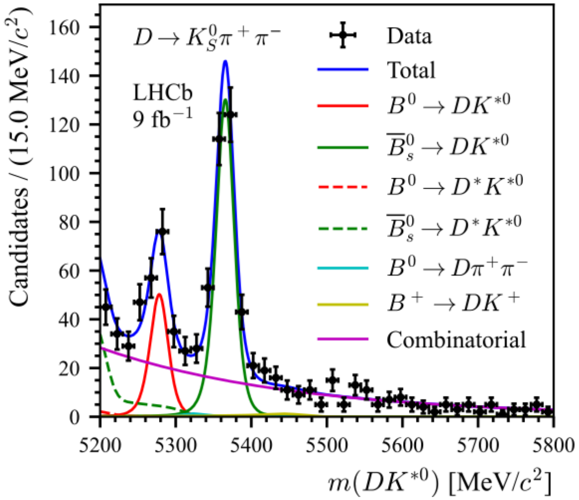
- Gain complementary info from $B^0 \to DK^*(892)^0$:
  - interference 3 times larger that for $B^\pm \to Dh^\pm$

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

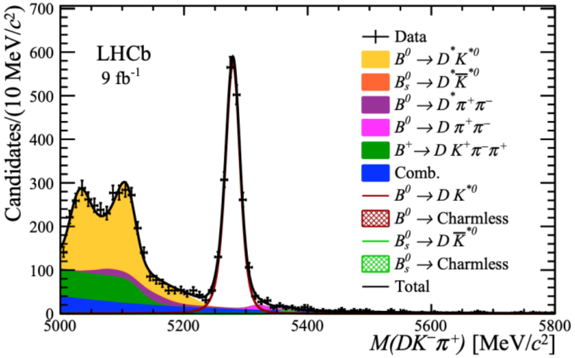
$$N_i(B^0) = h^{B^0}\left[F_{-i} + (x_+^2 + y_+^2)F_i + 2\kappa\sqrt{F_i F_{-i}}(x_+ c_i - y_+ s_i)\right]$$

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

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



- **$B^0 \to D^0K^*(892)^0$ with the ADS and GLW D-decays final states** [JHEP 05(2024) 025]
- 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

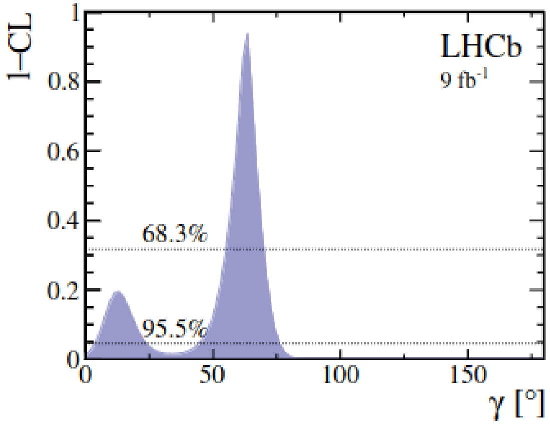


- Combination of the last two results
- Results from $D \to K^0_s\, h^+h$ broke the degeneracy

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

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

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



Decay-time dependent γ measurement

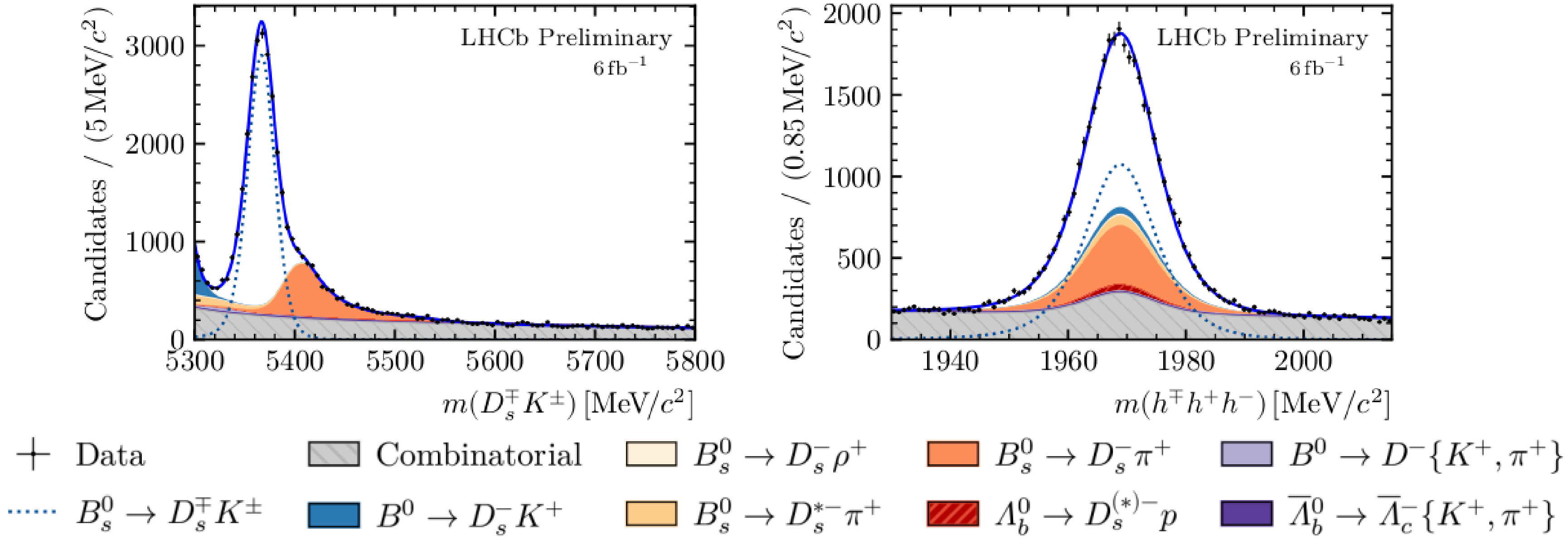
- **Measurement of CP asymmetry in $B^0_s \to D_s^- K^+$** [LHCb-PAPER-2024-020], in preparation
- With $D_s^- \to K^+\pi^+\pi^-$, $D_s^- \to K^-K^+\pi^-$, $D_s^- \to \pi^+\pi^-\pi^-$
- Time dependent measurement of γ

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

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

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

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



Decay-time dependent γ measurement

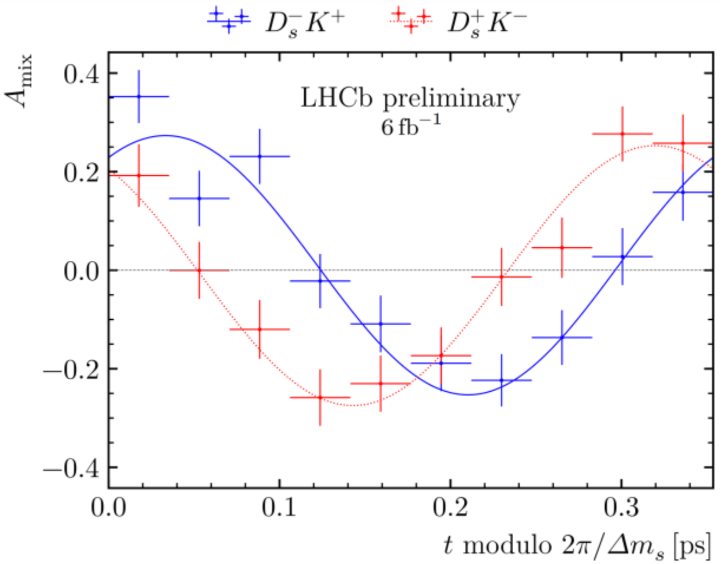
[LHCb-PAPER-2024-020], in preparation

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

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

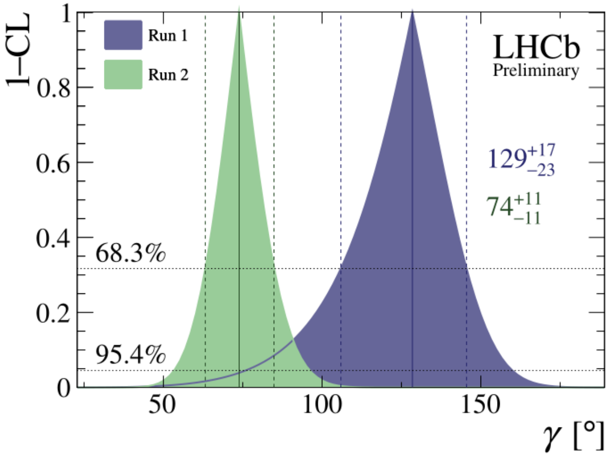
- External input: [PRL132(2024)051802] $\phi_s = -2\beta_s$

- 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	$-0.571 \pm 0.084 \pm 0.023$
$S_{\bar{f}}$	$-0.503 \pm 0.084 \pm 0.025$

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



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

- Compatible with run 1 @ 1.3σ
- run 1 and run 2 combination

$$\gamma = (81^{+12}_{-11})^\circ\,,$$
$$\delta = (347.6 \pm 6.3)^\circ\,,$$
$$r_{D_sK} = 0.318^{+0.034}_{-0.033}\,.$$

2024 LHCb γ and Charm Combination

[LHCb-CONF-2024-004]

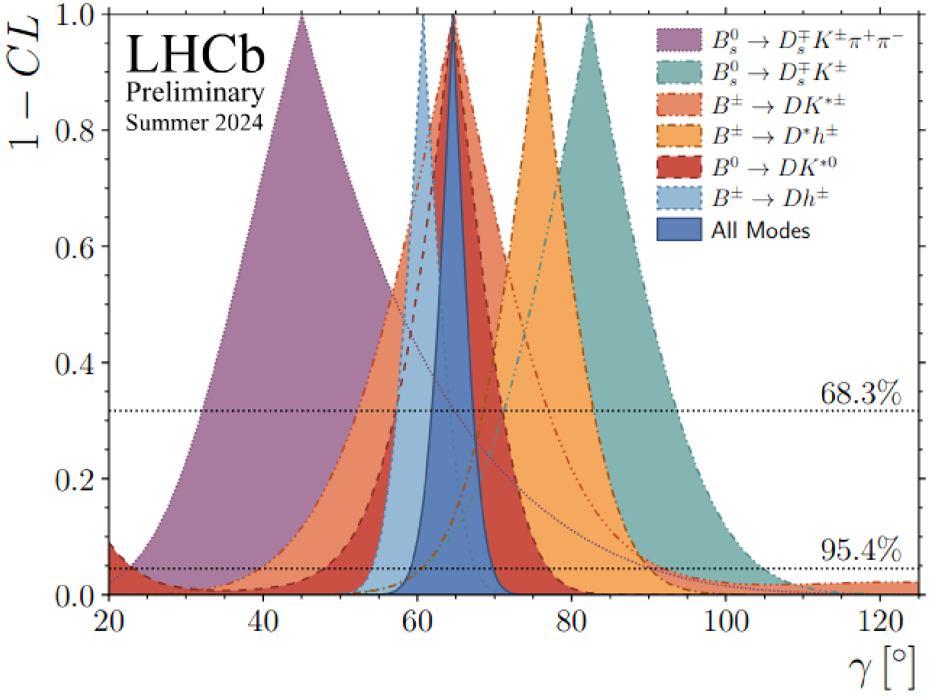
- Given the current precision also CPV and mixing effects in charm decays must be taken into account
  - 19 LHCb B decay measurements
  - 11 LHCb D decay measurements
  - 27 auxiliary inputs from LHCb,HFLAV, CLEO-c and BESIII

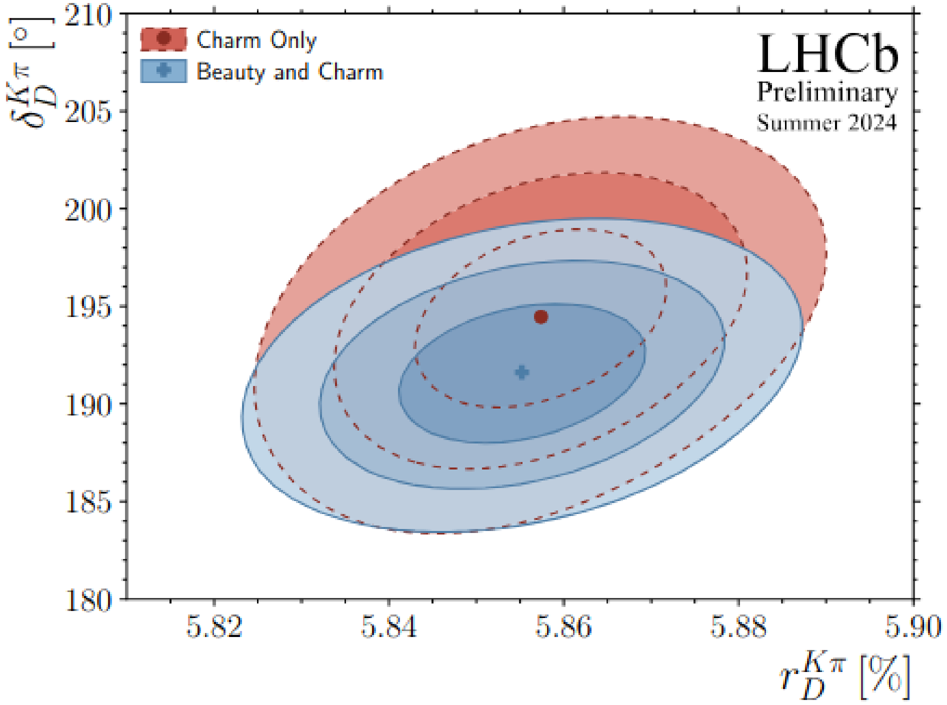
B decay	D decay
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^+\pi^-$
$B^\pm \to D^*h^\pm$ Full Reco	$D \to K^0_S h^+h^-$
$B^\pm \to D^*h^\pm$ Part. Reco	$D \to K^0_S h^+h^-$
$B^\pm \to DK^{*\pm}$	$D \to K^0_S h^+h^-, D \to h^+h'^-(\pi^+\pi^-)$
$B^0 \to DK^{*0}$	$D \to K^0_S h^+h^-$
$B^0 \to DK^{*0}$	$D \to h^+h'^-(\pi^+\pi^-)$
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$
–	$D^0 \to K^+\pi^-$, Charm Mixing
–	$D^0 \to \pi^+\pi^-\pi^0$, ΔY^{eff}

- Frequentis approach used

$$\gamma = (64.6 \pm 2.8)^\circ$$

- ~ 20% smaller uncertainty on y and $\delta^{K\pi}_D$ when including beauty





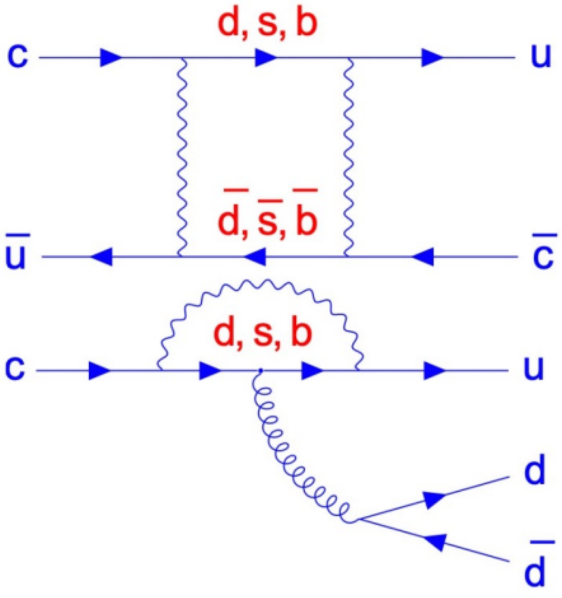
CPV in charm

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



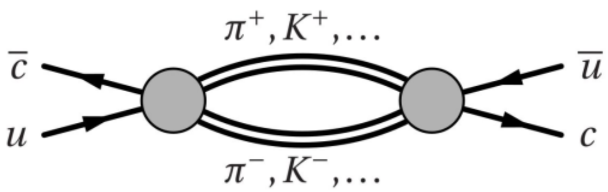
- CPV in charm small O(10^{-4}) → sensitive to NP
- Theory predictions complicated by QCD effects, large and difficult to compute
- First observation of CPV in decay in $D^0 \to h^+h^-$ @LHCb(5.3σ)
  [PRL122(2019)211803]
- First evidence for direct CP violation in specific D^0 decays:
  [Phys. Rev. Lett.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

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

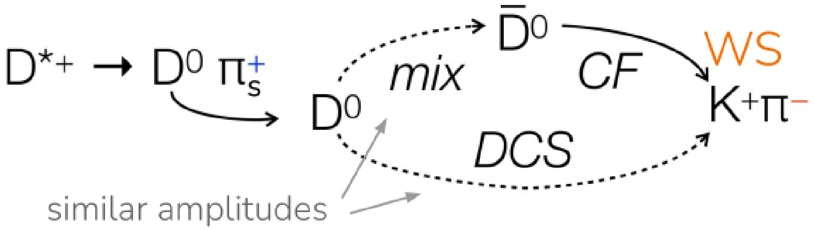


  - Long distances: low energy QCD through on-shell resonances → theoretical prediction of x and y very challenging

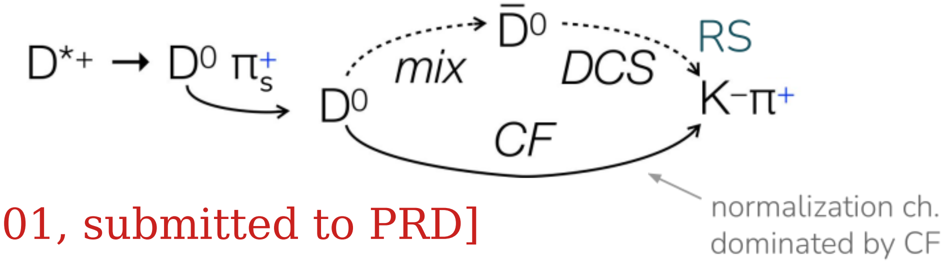
- Full run 2 LHCb analysis

- 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)



[arXiv 2407.18001, submitted to PRD]

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:

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

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

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

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

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

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

CPV in mixing

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

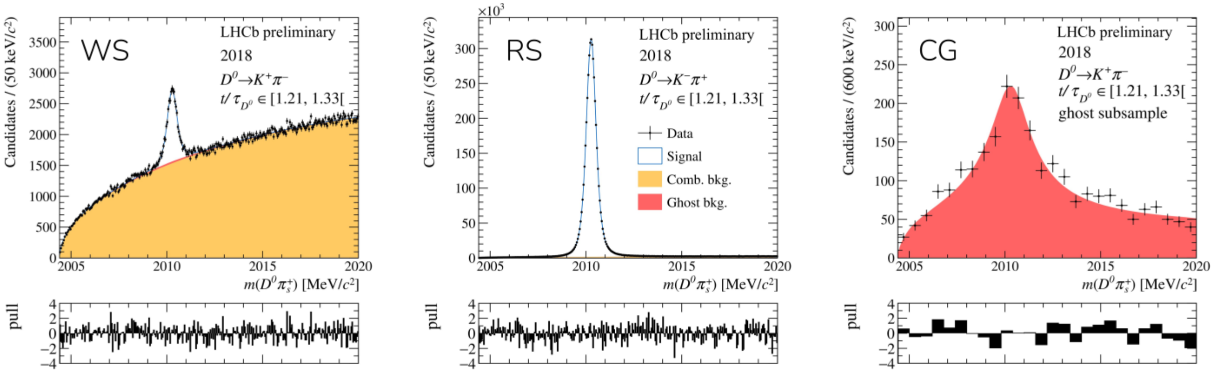
$$\phi^M_2 \sim \arg(M_{12}),\ \phi^\Gamma_2 \sim \arg(\Gamma_{12}) \qquad y_{12} \equiv |\Gamma_{12}|/\Gamma$$

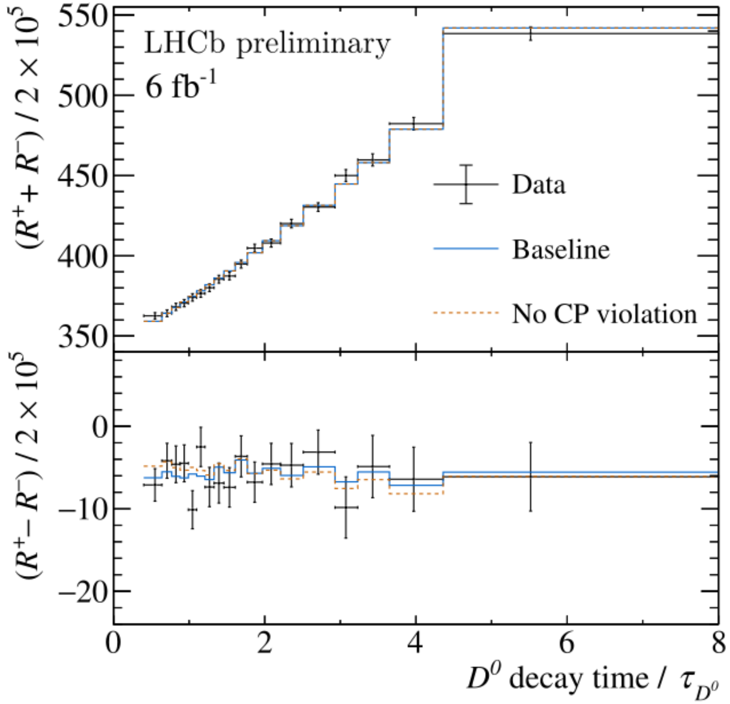
- CP violation measurements
- $A_{K\pi}$: rigorous null test of SM since c→uds doesn't receive any contribution from QCD nor chromomagnetic dipole operators
- Δ_f : improve the knowledge on $SU(3)_F$ breaking and rescattering effects at energy scale of the charm mass

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

[LHCb-PAPER-2024-008]

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





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

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

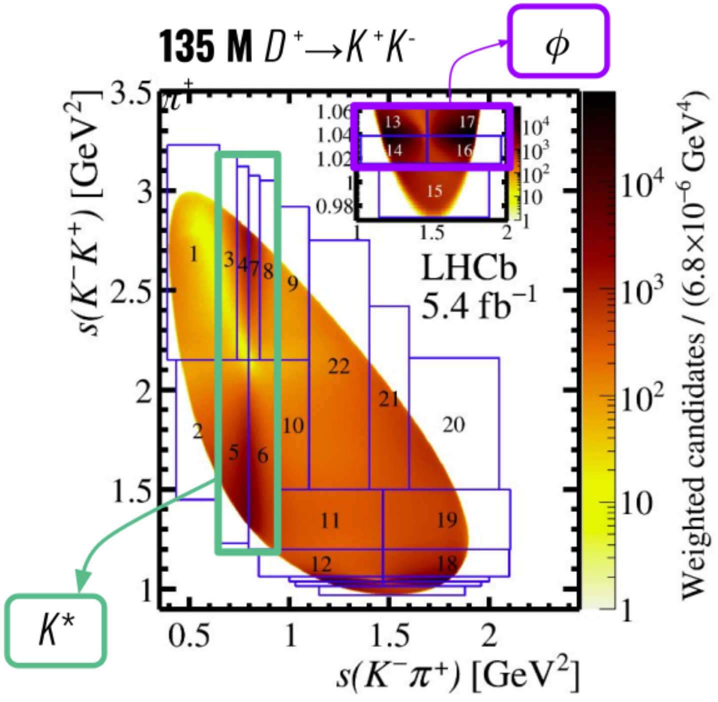
- Run 1 and run 2 results compatible
- Total uncertainty improved by 1.6 with respect Run 1
- No evidence CPV neither in decays, mixing nor interference

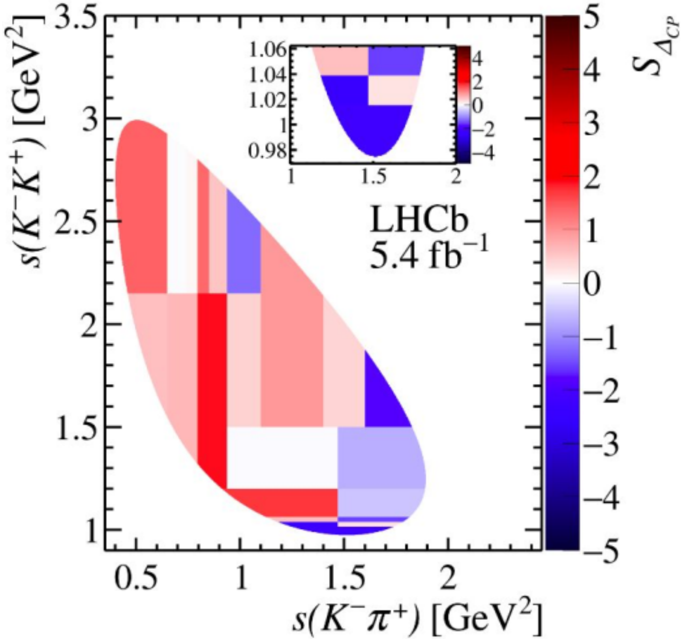
CPV measurement in $D^+ \to K^+K^-\pi^-$

- $D^+ \to K^+K^-\pi^-$ is the cabibbo suppressed decay with largest BR
- Measurement of A_{CP} around K* and φ resonances

$$A_{CP|S} = \frac{1}{2}\left[\left(\Delta A_{\text{raw}}^{\text{top-left}} + \Delta A_{\text{raw}}^{\text{bottom-right}}\right) - \left(\Delta A_{\text{raw}}^{\text{top-right}} + \Delta A_{\text{raw}}^{\text{bottom-left}}\right)\right]$$

- CP asymmetry significance measured in Dalitz-plot bins
- No CPV evidence





[arXiv 2409.01414, submitted to PRD]

Study of Λ^0_b (Ξ^0_b) → $\Lambda h^+ h^-$ final states

[LHCb-PAPER-2024-043], in preparation

- Measurements of Branching fractions and A_{CP}

- Charmeless baryonic decays are ideal to search for CP violation:
  - Similar level of amplitudes from penguin and tree diagram
  - Different weak phase

$$\frac{\mathcal{B}\left(\Lambda_b^0\,(\Xi_b^0) \to \Lambda h^+ h'^-\right)}{\mathcal{B}\left(\Lambda_b^0 \to \Lambda_c^+\,(\to \Lambda\pi^+)\,\pi^-\right)} = \frac{N_{\Lambda_b^0(\Xi_b^0) \to \Lambda h^+ h'^-}}{N_{\Lambda_b^0 \to \Lambda_c^+(\to\Lambda\pi^+)\pi^-}} \times \frac{\epsilon_{\Lambda_b^0 \to \Lambda_c^+(\to\Lambda\pi^+)\pi^-}}{\epsilon_{\Lambda_b^0(\Xi_b^0) \to \Lambda h^+ h'^-}} \times \frac{f_{\Lambda_b^0}}{f_{\Lambda_b^0(\Xi_b^0)}},$$

$$\Delta A_{CP}(\Lambda_b^0/\Xi_b^0 \to f) = A_{CP}(\Lambda_b^0/\Xi_b^0 \to f) - A_{CP}(\Lambda_b^0 \to \Lambda_c^+(\to \Lambda\pi^+)\pi^-)$$

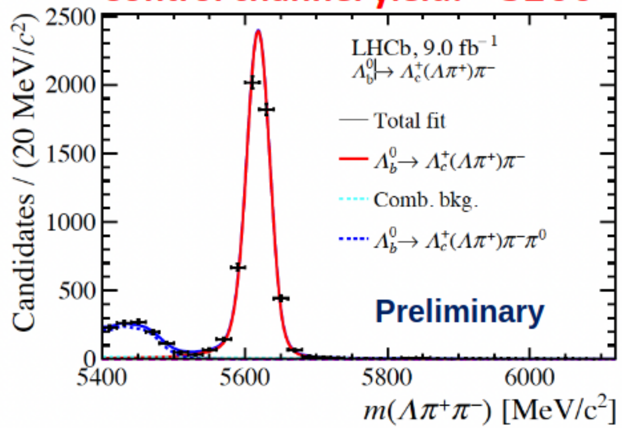
- Run 1+2 data

- Yields extracted from invariant mass fits

-
$$A_{CP}^f = \frac{\Gamma(\Lambda_b^0 \to f) - \Gamma(\bar{\Lambda}_b^0 \to \bar{f})}{\Gamma(\Lambda_b^0 \to f) + \Gamma(\bar{\Lambda}_b^0 \to \bar{f})}$$

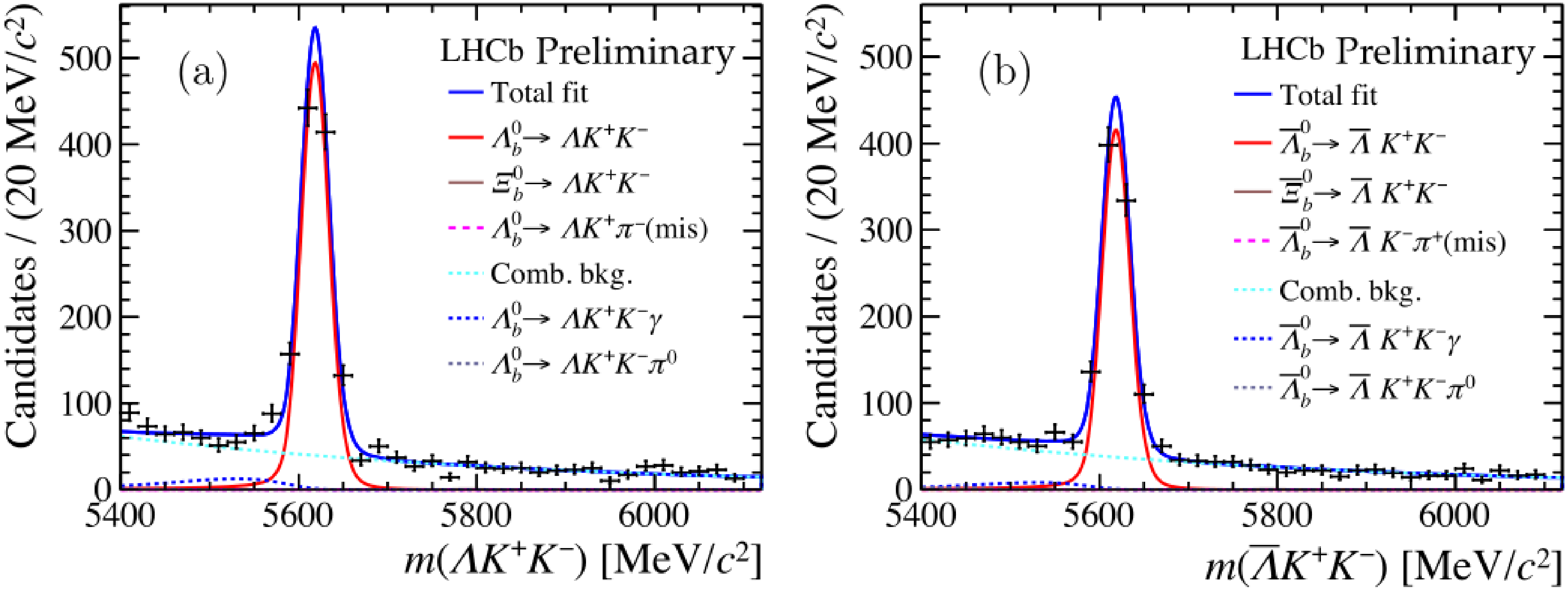
$$A_{CP}^f = A_{\mathrm{Raw}}^f - A_{\mathrm{P}}^{\Lambda_b^0} - A_{\mathrm{D}}^f$$

Control channel yield: ~5200



Study of Λ^0_b (Ξ^0_b) → Λh^+h^- final states

[LHCb-PAPER-2024-043], in preparation



- First evidence of direct CP violation in baryon decays (3.1σ)

$$
\begin{aligned}
\Delta\mathcal{A}^{CP}\left(\Lambda_b^0 \to \Lambda\pi^+\pi^-\right) &= -0.013 \pm 0.053 \pm 0.018, \\
\Delta\mathcal{A}^{CP}\left(\Lambda_b^0 \to \Lambda K^+\pi^-\right) &= -0.118 \pm 0.045 \pm 0.021, \\
\boxed{\Delta\mathcal{A}^{CP}\left(\Lambda_b^0 \to \Lambda K^+K^-\right) = 0.083 \pm 0.023 \pm 0.016,} \\
\Delta\mathcal{A}^{CP}\left(\Xi_b^0 \to \Lambda K^-\pi^+\right) &= 0.27 \pm 0.12 \pm 0.05\ ,
\end{aligned}
$$

$\mathcal{B}(\Lambda_b^0 \to \Lambda\pi^+\pi^-) = (5.3 \pm 0.4 \pm 0.5 \pm 0.5(norm)) \times 10^{-6}$ First observation

$\mathcal{B}(\Lambda_b^0 \to \Lambda K^+\pi^-) = (4.6 \pm 0.2 \pm 0.4 \pm 0.5(norm)) \times 10^{-6}$ Confirmed

$\mathcal{B}(\Lambda_b^0 \to \Lambda K^+K^-) = (10.7 \pm 0.3 \pm 0.4 \pm 1.1(norm)) \times 10^{-6}$ Confirmed

$\mathcal{B}(\Xi_b^0 \to \Lambda\pi^+\pi^-) = (11.0 \pm 2.6 \pm 1.4 \pm 3.8(norm)) \times 10^{-6}$ First evidence (4σ)

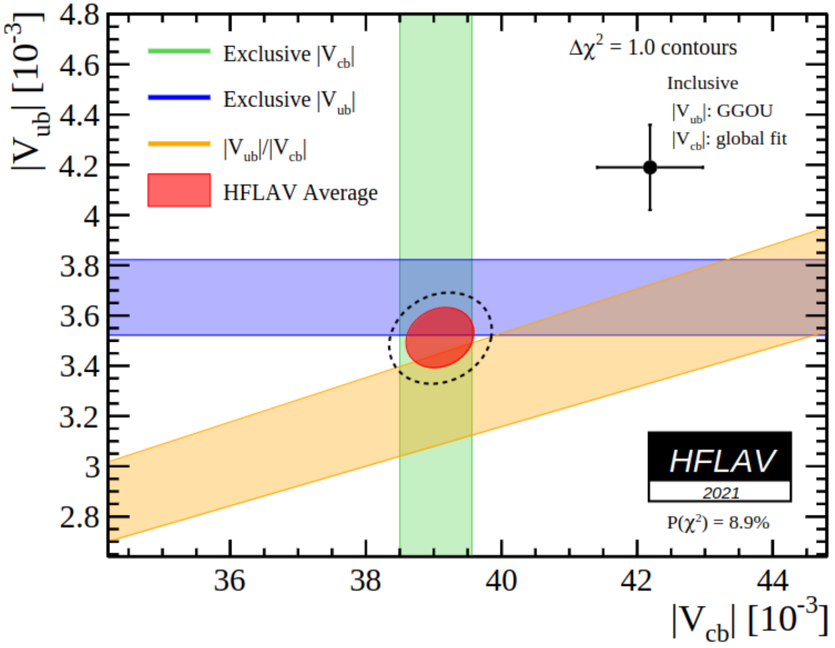
$\mathcal{B}(\Xi_b^0 \to \Lambda K^-\pi^+) = (10.4 \pm 1.4 \pm 1.2 \pm 3.5(norm)) \times 10^{-6}$ First observation

$\mathcal{B}(\Xi_b^0 \to \Lambda K^-K^+) < 2.4 \times 10^{-6}$ (90% CL) No evidence

- If confirmed, may provide useful insights on sources of CPV in baryon dynamics

Measurement of $|V_{xb}|$

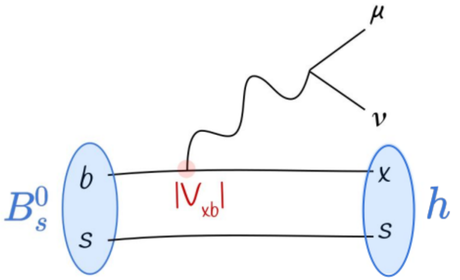
Measurement of $|V_{xb}|$



- Measurements of $|V_{xb}|$ provide a crucial input for indirect searches of New Physics

- Discrepancy between exclusive and inclusive measurements: ≈ 3σ tension
→ new complementary measurements

Measurement of $|V_{xb}|$



- Two main ways to measure $|V_{ub}|$ and $|V_{cb}|$:
  - **Inclusive decays**:
    - $B^+ \rightarrow X_c l\nu, B^0 \rightarrow X_u l\nu$
    - Focus on all final states
    - Need to know QCD correction to parton level decay rate
  - **Exclusive decays**:
    - Focus on a single final state
    - Exclusive determinations rely on form factors (FF) to parameterize hadronic current as function of q^2 ($\mu\nu$ invariant mass): LQCD or QCD sum rules
      - Extracted in experimental measurement from data
- **Ground state hadrons** in the final are the golden modes for lattice QCD predictions and have the lowest theoretical uncertainties.
- **B_s decays are advantageous compared to $B^{0/+}$**
  - Easier to calculate in LQCD due to heavier spectator quark → more precise predictions

Measurement of $|V_{ub}/V_{cb}|$

- The strategy:

[Phys. Rev. Lett. 126 081804 (2021)]

  - Dataset: 2012, 2 fb^{-1} @ 8TeV

  - Signal: $B_s^0 \to K^-\mu^+\nu$
  - Normalization: $B_s^0 \to D_s^-\mu^+\nu$ where $D_s \to K^+K^-\pi^-$

  - CKM extraction strategy:

$$\underbrace{\frac{\mathcal{B}(B_s^0 \to K^-\mu^+\nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^-\mu^+\nu_\mu)}}_{\text{Experiment}} = \frac{|V_{ub}|^2}{|V_{cb}|^2} \times \underbrace{\frac{\mathrm{FF}_K}{\mathrm{FF}_{D_s}}}_{\text{Theory}}$$

  - The $|V_{ub}|/|V_{cb}|$ ratio is derived in two regions of q^2 ($\mu\nu$ invariant mass) to exploit different FF_K calculation method:
    - Light cone sum rules (LCSR) @ low q^2 ($q^2<7$ GeV^2/c^4)
    - LQCD @ high q^2 ($q^2>7$ GeV^2/c^4)

Normalization mode FF_{Ds} fully described by LQCD [Phys Rev D. 101 074513]

Signal and normalization fits

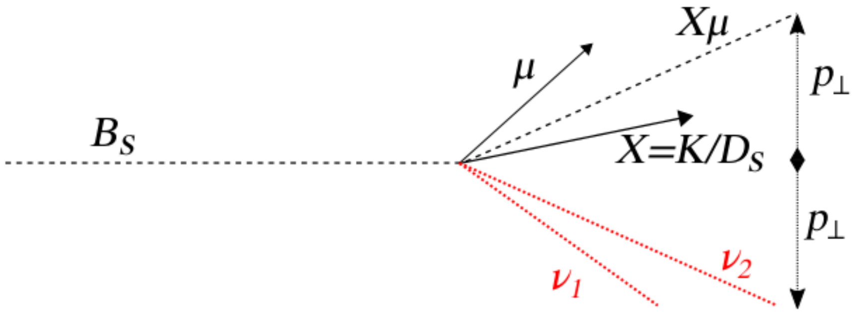
[Phys. Rev. Lett. 126 081804]

- The measured ratio is

$$R_{\rm BF} \equiv \frac{\mathcal{B}(B_s^0 \to K^-\mu^+\nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^-\mu^+\nu_\mu)} = \overbrace{\frac{N_K}{N_{D_s}}}^{\text{Ratio of yields}} \underbrace{\frac{\epsilon_{D_s}}{\epsilon_K}}_{\text{Efficiency ratio}} \times \underbrace{\mathcal{B}(D_s^- \to K^+K^-\pi^-)}_{\text{[Prog. Theor. Exp. Phys. 2020, 083C01 (2020)]}}$$

- A binned maximum likelihood fit to the B_s corrected mass

$$m_{\rm corr} = \sqrt{m^2(Y\mu) + p_\perp^2(Y\mu)} + p_\perp(Y\mu),\ Y = K^-, D_s^-$$

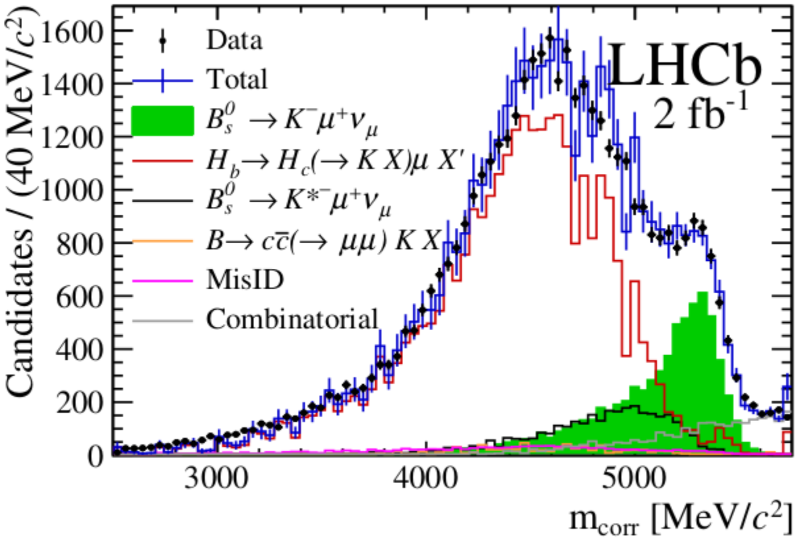


- If only missing particle is a neutrino the corrected mass distribution will peak at the B_s mass

Signal and normalization fits

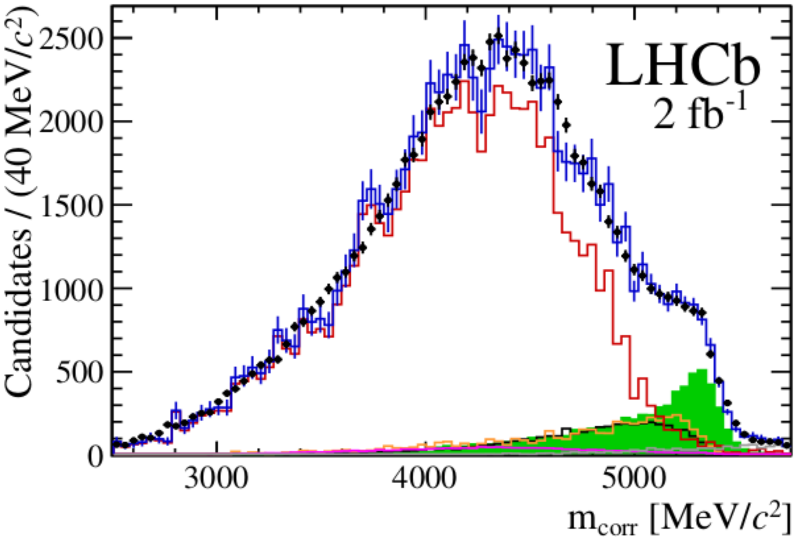
[Phys. Rev. Lett. 126 081804]

$B_s^0 \to K^-\mu^+\nu_\mu$ low q^2



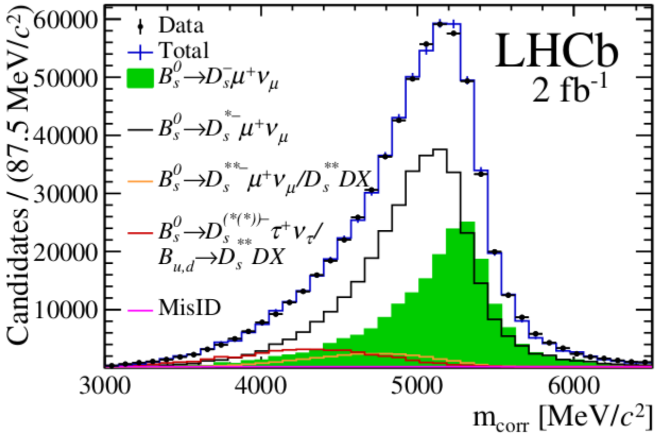
$N(B_s^0 \to K^-\mu^+\nu_\mu)_{low} = 6922 \pm 285$

$B_s^0 \to K^-\mu^+\nu_\mu$ high q^2



$N(B_s^0 \to K^-\mu^+\nu_\mu)_{high} = 6399 \pm 370$

$B_s^0 \to D_s^-\mu^+\nu_\mu$



$N(B_s^0 \to D_s^-\mu^+\nu_\mu) = 201450 \pm 5200$

- The largest systematic uncertainty is from the fit templates
- First observation of the decay $B_s^0 \to K^-\mu^+\nu$

Extraction of $|V_{ub}|/|V_{cb}|$

[Phys. Rev. Lett. 126 081804 (2021)]

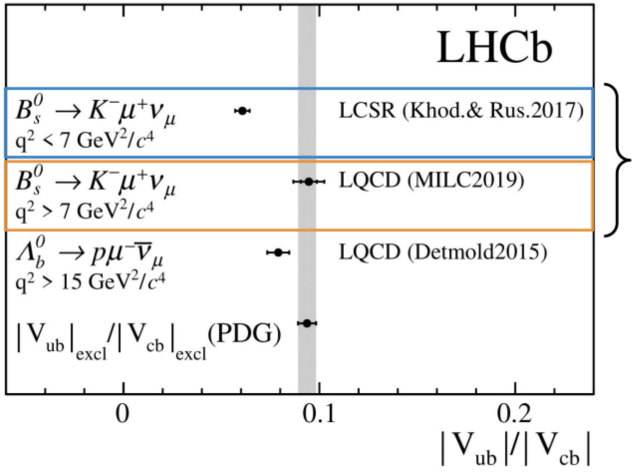
- The obtained values are

$$\underbrace{\frac{\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)}}_{\text{Experiment}} = \frac{|V_{ub}|^2}{|V_{cb}|^2} \times \underbrace{\frac{\text{FF}_K}{\text{FF}_{D_s}}}_{\text{Theory}}$$

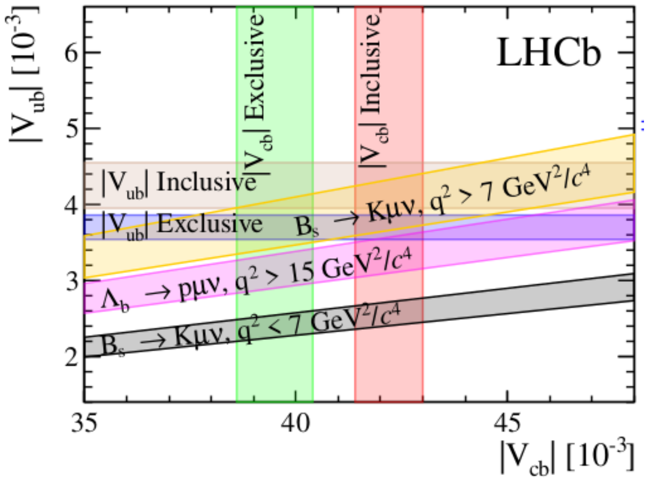
- $q^2 > 7\ \text{GeV}^2/c^4$: $$\frac{\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)} = 1.66 \pm 0.08(stat) \pm 0.07(syst) \pm 0.05(D_s) \times 10^{-3}$$
- $q^2 < 7\ \text{GeV}^2/c^4$: $$\frac{\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)} = 3.25 \pm 0.21(stat)^{+0.16}_{-0.17}(syst) \pm 0.09(D_s) \times 10^{-3}$$

$$\boxed{|V_{ub}|/|V_{cb}|_{(\text{low})} = 0.0607 \pm 0.0015(\text{stat}) \pm 0.0013(\text{syst}) \pm 0.0008(D_s) \pm 0.0030(\text{FF})}$$

$$\boxed{|V_{ub}|/|V_{cb}|_{(\text{high})} = 0.0946 \pm 0.0030(\text{stat})^{+0.0024}_{-0.0025}(\text{syst}) \pm 0.0013(D_s) \pm 0.0068(\text{FF})}$$



Discrepancy related to the difference in the theoretical calculations of the form factors.



$|V_{cb}|$: with $B_s^0 \to D_s^{*-}\mu^+\nu$ decays

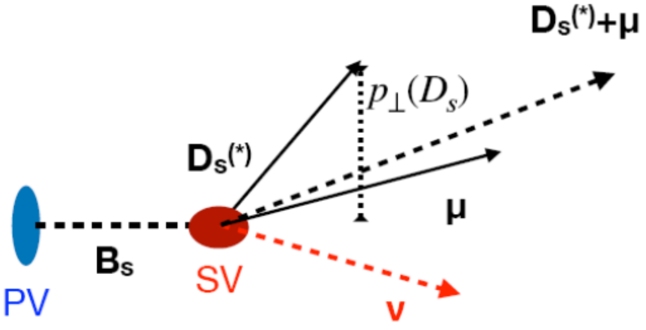
[Phys. Rev. D 101 072004 (2020)]

- Signal: $B_s^0 \to D_s^{(*)-}\mu^+\nu$ where $D_s \to \varphi(\to K^+K^-)\pi$, γ or π^0 not reconstructed
- Normalization: $B^0 \to D^{(*)-}\mu^+\nu$
- Both channels reconstructed in the same final states
- Extract $|V_{cb}|$ from

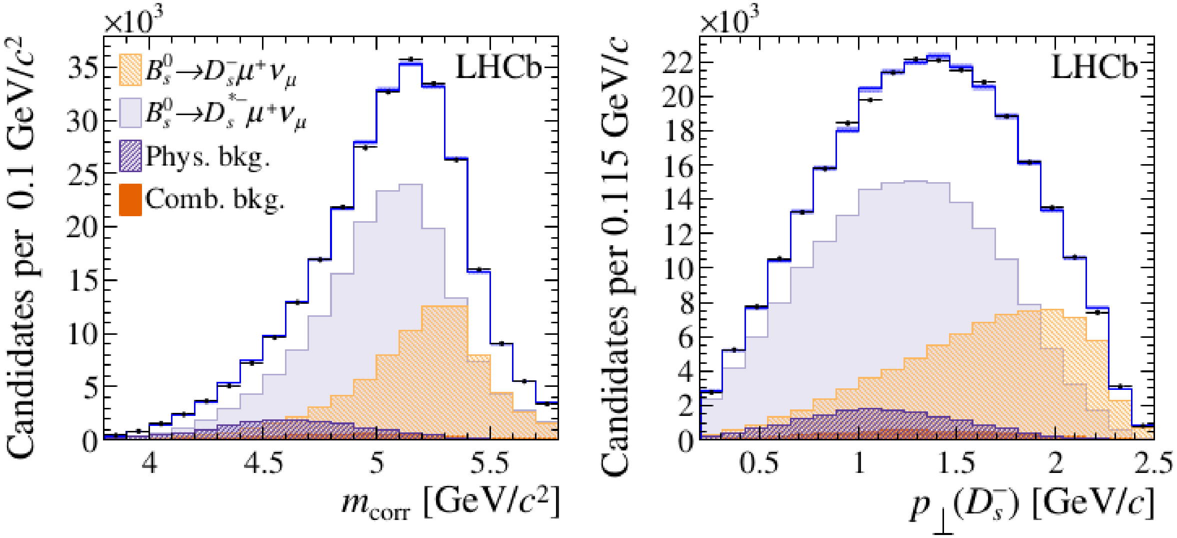
$$\mathcal{R}^* \equiv \frac{\mathcal{B}(B_s^0 \to D_s^{*-}\mu^+\nu_\mu)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)} \qquad \mathcal{R} \equiv \frac{\mathcal{B}(B_s^0 \to D_s^{-}\mu^+\nu_\mu)}{\mathcal{B}(B^0 \to D^{-}\mu^+\nu_\mu)}$$

- external input:
  - hadronization fractions f_s/f_d [PRD(2019)031102]
  - branching fractions [PDG]

- Due to the undetected neutrino we cannot determine precisely the q^2 → use variable $p_\perp(D_s)$ with respect to B flight distance



$|V_{cb}|$: with $B_s^0 \to D_s^{*-}\mu^+\nu$ decays

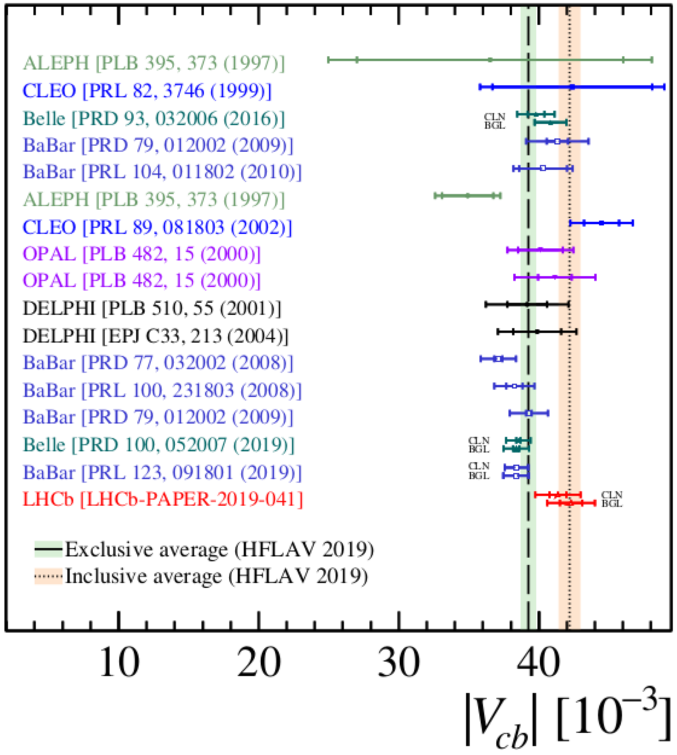


- 2-D template fit to M_{corr} and $p_\perp(D_s)$ identify thesignal yield and provides a simultaneous measurement of the ratios $R^{(*)}$ and the form factors

- First measurement of $|V_{cb}|$ using B_s and in a hadronic environment

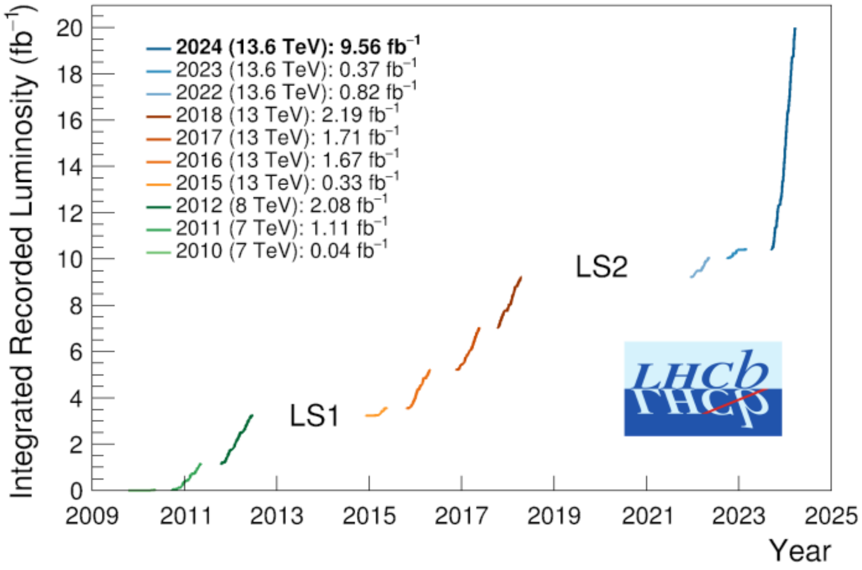
- Compatible with world average for both inclusive and exclusive determinations
- Confirms trend that parametrisation is not responsible for inclusive vs exclusive disagreements
- New $f_s/f_d \to V_{cb}$ [arXiv:2103.06810]

$$|V_{cb}|_{CLN} = (40.8 \pm 0.6(stat) \pm 0.9(syst) \pm 1.1(ext))\text{x}10^{-3}$$
$$|V_{cb}|_{BGL} = (41.7 \pm 0.8(stat) \pm 0.9(syst) \pm 1.1(ext))\text{x}10^{-3}$$



Run 3

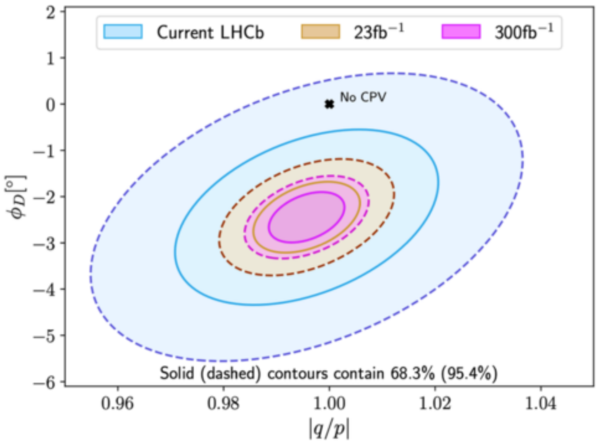
- Changing from an hardware trigger to a fully software based one.
- Read-out whole detector at 40 MHz with a brand new detector [PID,Tracking] to cope with higher lumi and radhardness constraints
- 2024 Close to Run1+Run2 in one year of data taking



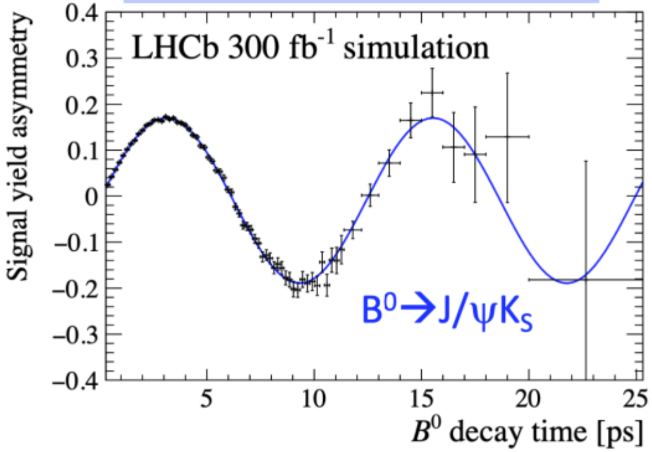
	Run 2	Run 3	Run 4	Run 5	Run 6
Total LHCb recorded luminosity at end of each Run [fb^{-1}]	9	23	53	211	300

LHCb upgrade II Physics case: CP Violation

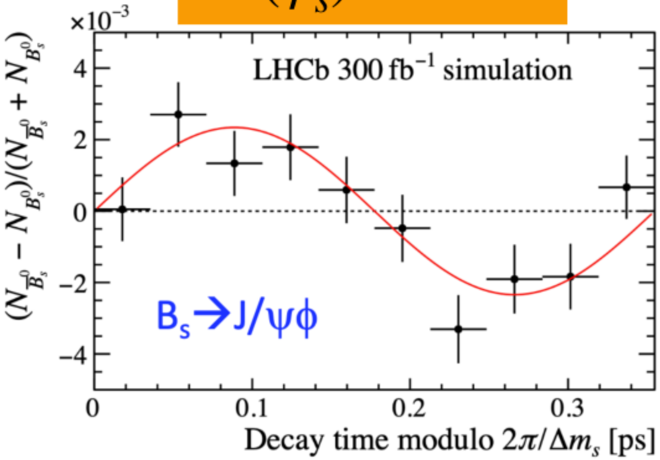
- $\sigma(\text{Charm CPV}) : \mathcal{O}(10^{-5})$



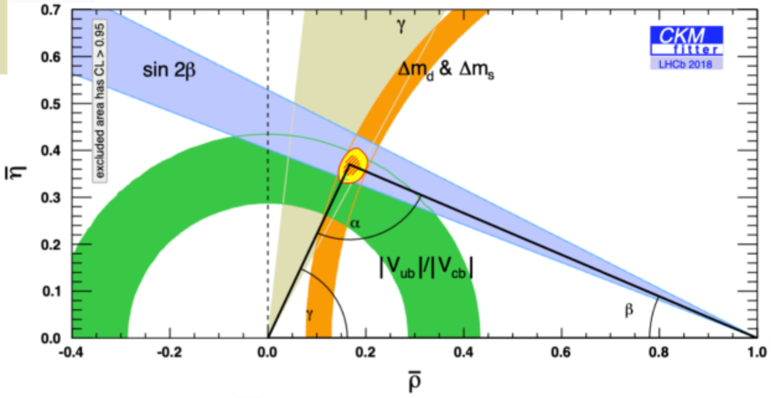
- $\sigma(\sin(2\beta)) : 0.003$

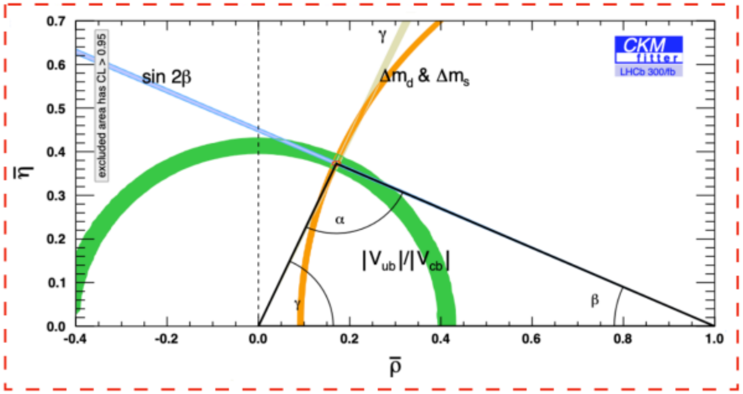


- $\sigma(\phi_s)$: 4 mrad



- $\sigma(\gamma) : 0.4°$





- LHCb has outperformed expected Run 2 sensitivities for both β and γ

- LHCb Upgrade II will make the most precise measurement of all of CP violation parameters in the B system

Conclusion

- Flavour physics at hadron colliders is able to probe indirectly NP high energy scales
- 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 $B \rightarrow Dh$ 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
- $b \rightarrow ul\nu$ and $b \rightarrow cl\nu$ exclusive analysis under study
- LHCb Upgrade I 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

Back up

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:

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

- integrating over a time bin

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

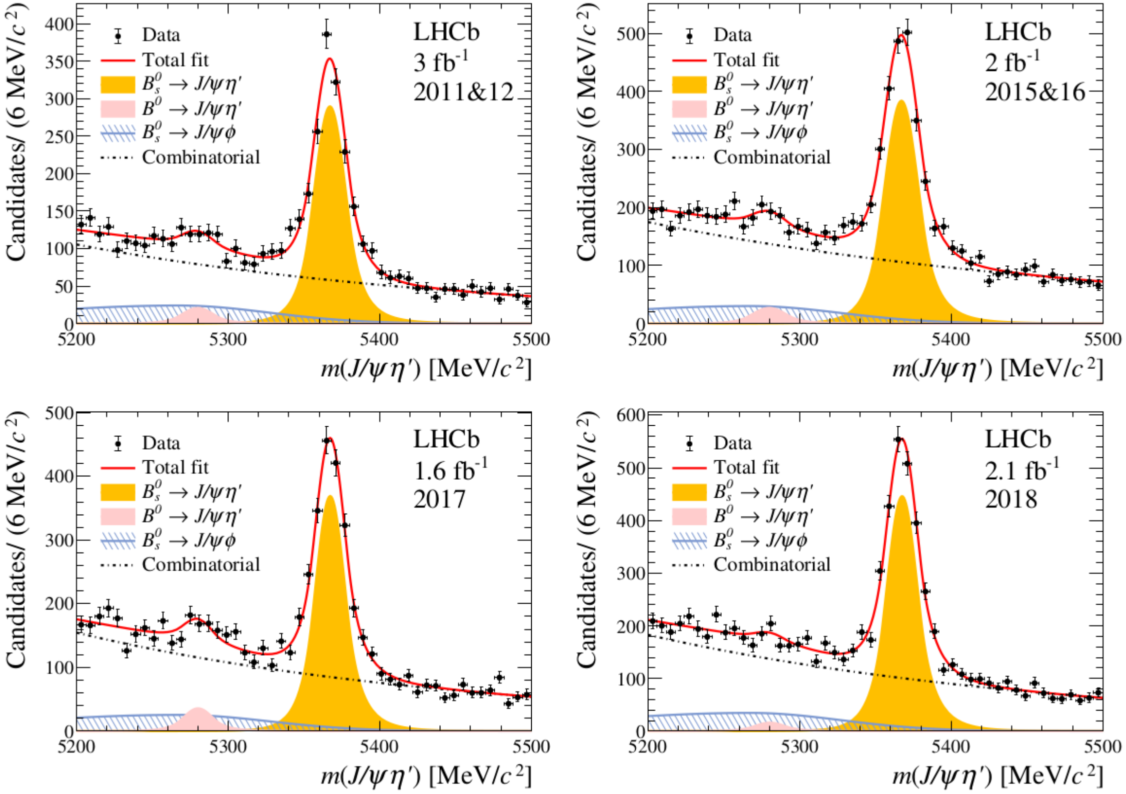
→

$$R_i = A_i \cdot \frac{N_\mathrm{L}^\mathrm{RAW}}{N_\mathrm{H}^\mathrm{RAW}}$$

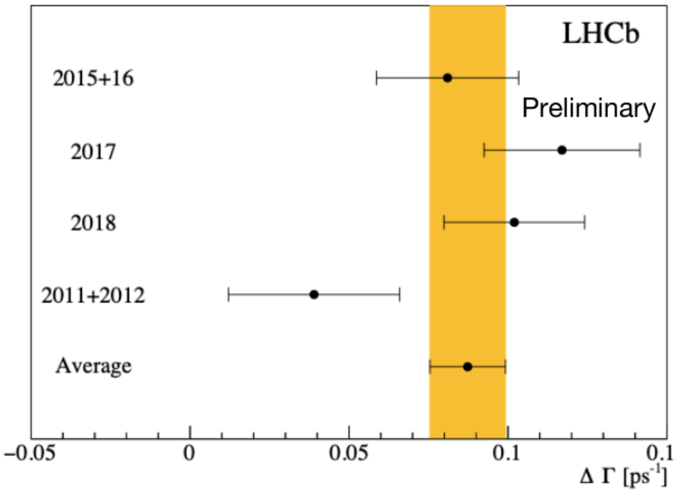
$y = \Delta\Gamma_s / 2\Gamma_s$

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

efficiency in each decay time bin



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



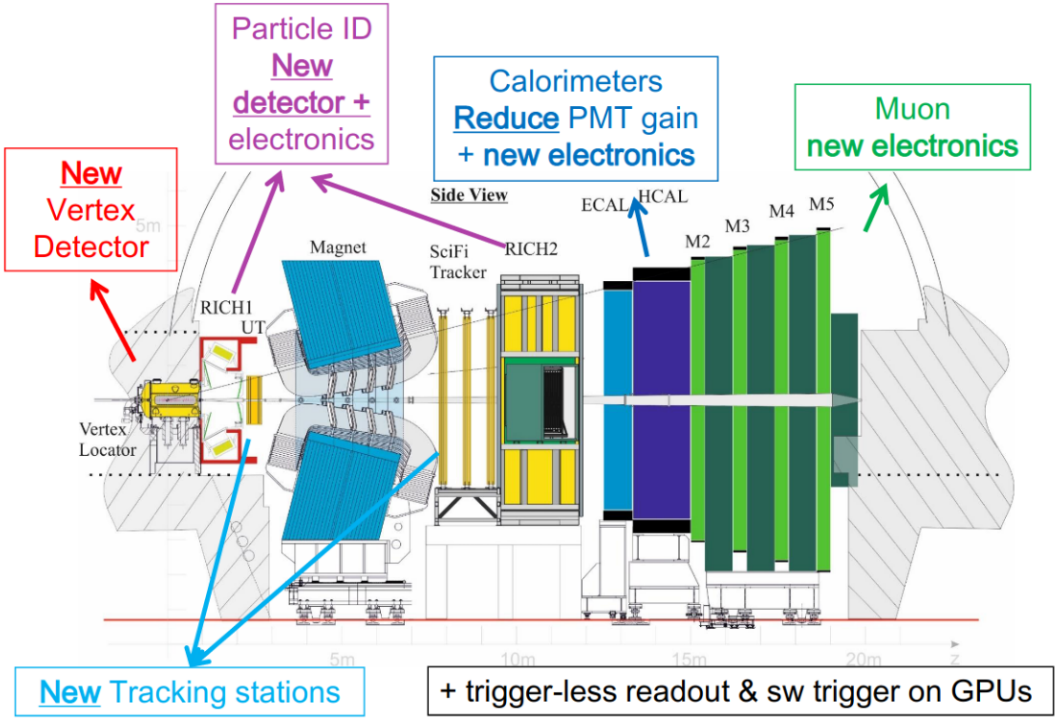
Orange band is 1σ error band

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

[LHCb-PAPER-2023-025]

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

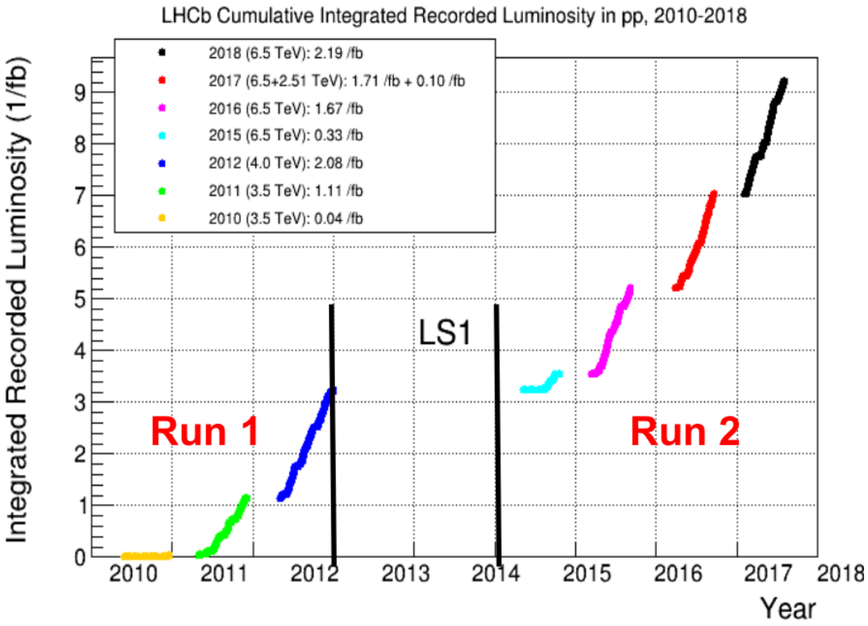
Calorimeters
Reduce PMT gain + new electronics

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

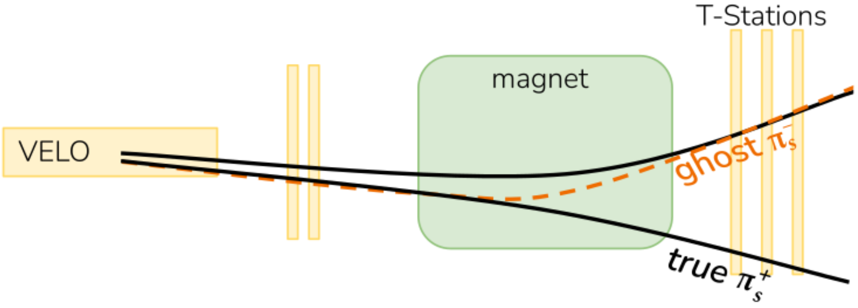
Strategy

[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



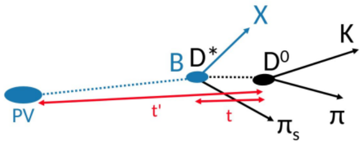
- Experimental challenges:
  - Backgrounds
  - Nuisance asymmetry

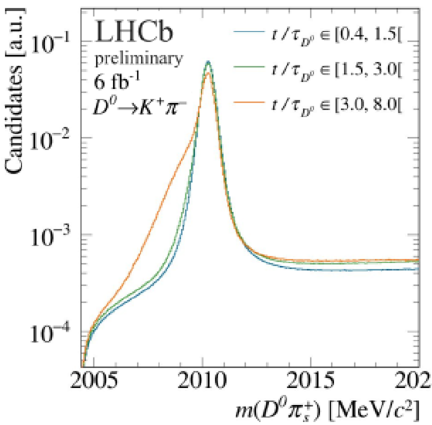
- Time dependence is fitted → extract mixing and CPV parameters

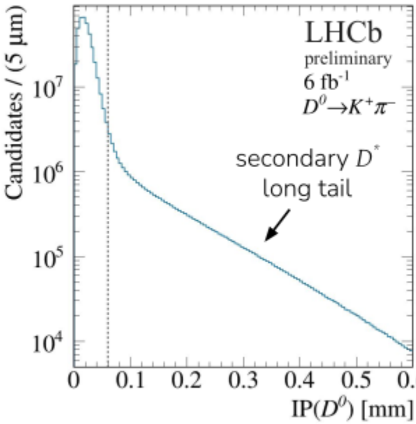
Biases

[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

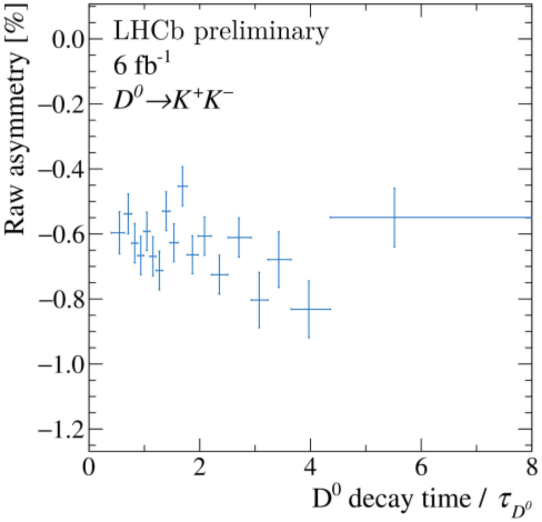
$$\widetilde{R'}^{\pm} = R'^{\pm}\frac{\int[1 \pm A_P(D^*)]\epsilon(\pi_s^{\pm})\epsilon(K^{\pm}\pi^{\mp})\rho\, d\vec{p}_{D^0}\, d\vec{p}_{\pi_s}}{\int[1 \mp A_P(D^*)]\epsilon(\pi_s^{\mp})\epsilon(K^{\pm}\pi^{\mp})\rho\, d\vec{p}_{D^0}\, d\vec{p}_{\pi_s}} \simeq R'^{\pm}\frac{1 \pm [A_D(\pi_s) + A_P(D^*)]}{1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

  - 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 $D^0 \to K^+K^-$

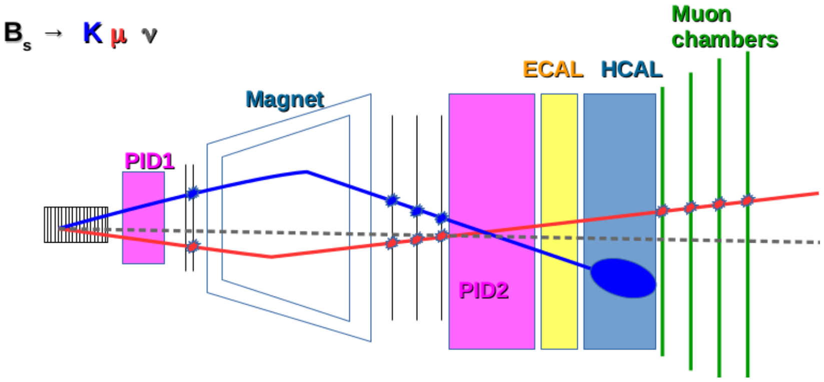
time dependent
CP asymmetry
in $D^0 \to K^+K^-$



The backgrounds

[Phys. Rev. Lett. 126 081804]

- $B_s^0 \to K^-\mu^+\nu$
  - main background originates from $H_b \to H_c(\to K^-X)\mu^+X'$ (unreconstructed particles)
  - $B_s^0 \to K^{*-}(\to K^-\pi^0)\mu^+\nu$
  - $B_s^0 \to [cc]^-(\to \mu^+\mu^-)K^-X$



- $B_s^0 \to D_s^-\mu^+\nu$
  - $B_s^0 \to D_s^{*-}(\to D_s\gamma)\mu^+\nu$
  - $B_s^0 \to D_s^{**-}\mu^+\nu$, $B_{u,s,d} \to D_sDX$ and $B_s^0 \to D_s^{*-}\tau^+\nu$

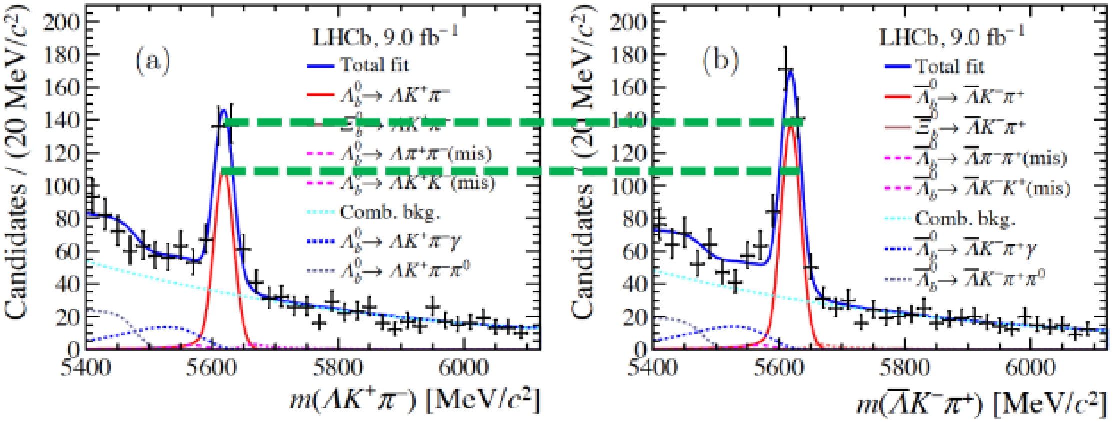
- To suppress background
  - the candidates are required to be isolated from the other tracks in the event
  - BDT classifiers exploit the kinematics of the decays

- The B_s^0 momentum can be calculated with a two fold ambiguity → regression model that exploit the B_s flight information [JHEP 02 (2017) 021]
  - Ambiguity solved by selection the solution most consistent with the regression value
  - $\varepsilon \approx 70\%$

Study of Λ^0_b (Ξ^0_b) → Λh^+h^- final states

[LHCb-PAPER-2024-043], in preparation

Preliminary

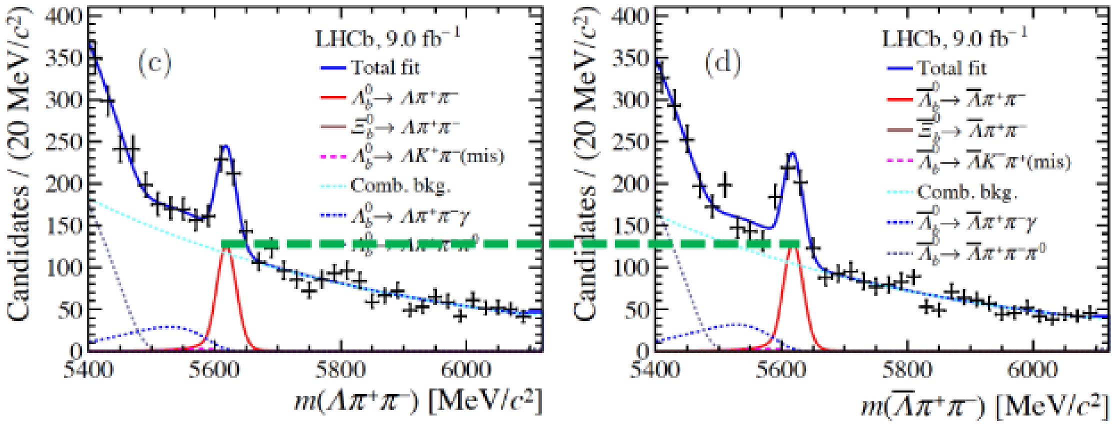


$$\Lambda_b^0 \to \Lambda K^+\pi^-$$

$$\Delta A_{CP} = -0.118 \pm 0.045 \pm 0.021$$

Consistent with 0 within 2.4σ

Preliminary



$$\Lambda_b^0 \to \Lambda\pi^+\pi^-$$

$$\Delta A_{CP} = -0.013 \pm 0.053 \pm 0.018$$

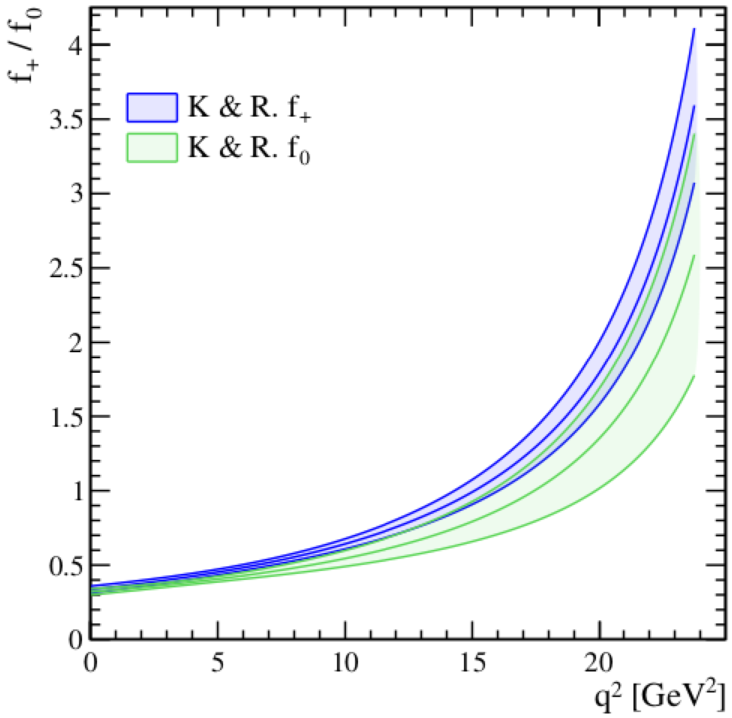
Consistent with 0

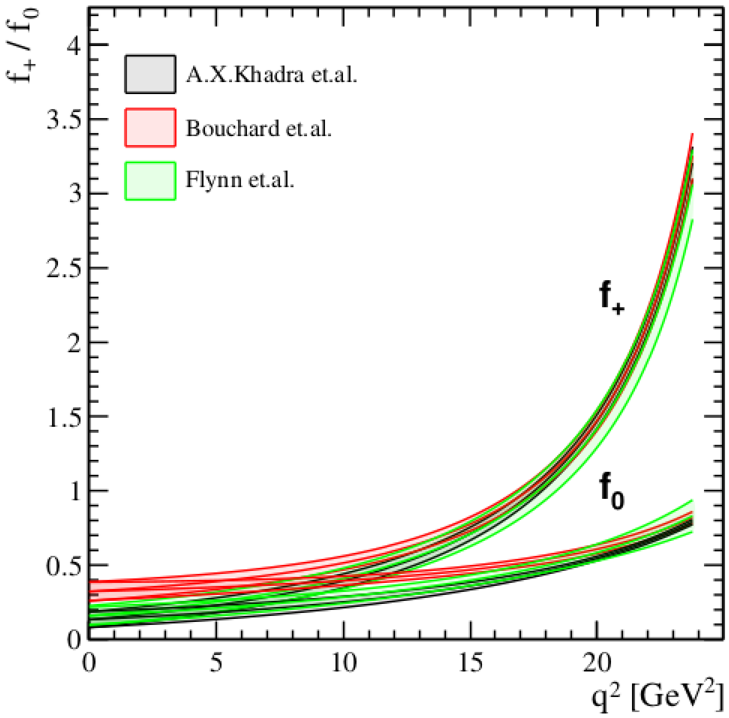
The FF_K

[Phys. Rev. Lett. 126 081804 (2021)]

- Calculations from QCD light-cone sum rules are most precise at large recoil (low q^2)
  [JHEP 08 (2017) 112]

- Lattice QCD predictions provide a precise determination of the form factors at low recoil transfer (high q^2)
  [Phys. Rev. D 90, 054506] [Phys. Rev. D 91, 074510] [Phys. Rev. D 100, 034501]





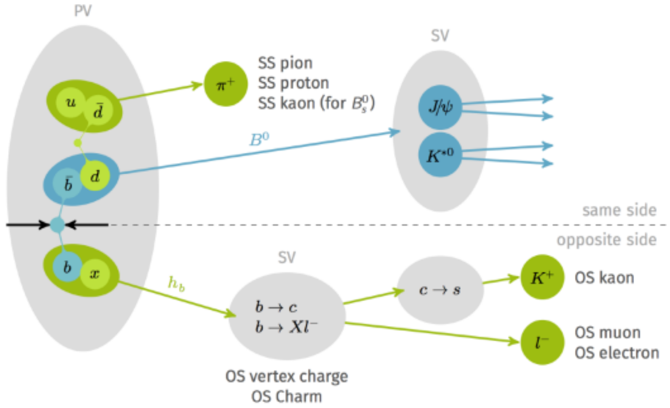
Decay-time dependent γ measurement

- The decay time fit has to be corrected for:

[LHCb-PAPER-2024-020], in preparation

To **separate** $B_s^0/\bar{B}_s^0$ **candidates** $\longrightarrow$ **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 $D_s^-\pi^+$