Time integrated CP violation in b decays at LHCb

Jessy DANIEL, Université Clermont-Auvergne
On behalf of the LHCb collaboration

LHCP 2023
Belgrade, Serbia – 22-26 May 2023

OUTLINE

- **Simultaneous determination of the CKM angle ɣ**

- **A study of CP violation in the decays $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D h^{\pm}$ $(h = K, \pi)$ and $B^{\pm} \to [\pi^+\pi^-\pi^+\pi^-]_D h^{\pm}$**

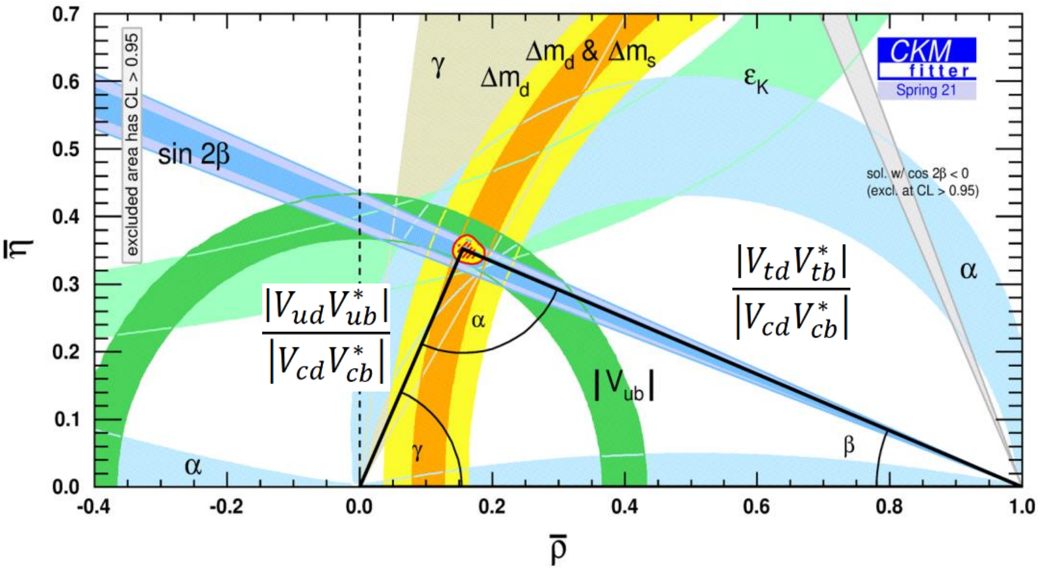
- **Evidence for the decay $B^0 \to \bar{D}^{(*)0}\phi$ and updated measurements of the branching fractions of the $B_s^0 \to \bar{D}^{(*)0}\phi$ decays**

The CKM Matrix, the Unitary Triangle and ɣ angle

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Unitary Equations and triangle :

$$\sum_{i=1}^{3} V_{ji}V_{ki}^* = \sum_{i=1}^{3} V_{ij}V_{ik}^* = 0$$



- CKM Matrix describes transition between quarks through weak interaction -> One of the main CP contribution to SM
- Its elements can be determined from experiment -> Parameterization with 4 independent parameters
- Goal : Sensitivity to BSM effects if Unitarity triangle different in direct and indirect measurements
- The current state of ɣ measurements (CONF-2022-003-001) :

Direct : $\gamma = (63.8^{+3.5}_{-3.7})^\circ$ -> Tree Level = Standard Candle

Indirect : $\gamma = (65.66^{+0.9}_{-2.65})^\circ$ -> Loops / Pinguin diagrams

$$\gamma \equiv arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right) \equiv arg(\bar{\rho} + i\bar{\eta})$$ = CKM Matrix complex phase = **The parameter to access CPV !**

The CKM Matrix, the Unitary Triangle and ɣ angle

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Unitary Equations and triangle :

$$\sum_{i=1}^{3} V_{ji}V_{ki}^{*} = \sum_{i=1}^{3} V_{ij}V_{ik}^{*} = 0$$

Couplings	NP loop order	Scales (in TeV) probed by B_d mixing	B_s mixing
$\lvert C_{ij}\rvert = \lvert V_{ti}V_{tj}^{*}\rvert$ (CKM-like)	tree level	17	19
	one loop	1.4	1.5
$\lvert C_{ij}\rvert = 1$ (no hierarchy)	tree level	2×10^3	5×10^2
	one loop	2×10^2	40

-> Test of global validity of the CKM formalism in tree level diagrams

Phys.Rev.D 89 (2014) 3, 033016

- CKM Matrix describes transition between quarks through weak interaction -> One of the main CP contribution to SM
- Its elements can be determined from experiment -> Parameterization with 4 independent parameters
- Goal : Sensitivity to BSM effects if Unitarity triangle different in direct and indirect measurements
- The current state of ɣ measurements (CONF-2022-003-001) :

Direct : $\gamma = (63.8^{+3.5}_{-3.7})^\circ$ -> Tree Level = Standard Candle

Indirect : $\gamma = (65.66^{+0.9}_{-2.65})^\circ$ -> Loops / Pinguin diagrams

- According to CKMfitter group, a 1° precision on direct measurement test SM up to dozens of TeV energy scales
  -> **Only possible in association of multiple analysis**

LHCb ɣ combination

- A combination of measurements sensitive to the CP violation angle ɣ including all relevant beauty and charm results from the LHCb detector included until October 2022

B decay	D decay	Ref.	Dataset	Status since Ref. [14]
$B^\pm \to Dh^\pm$	$D \to h^+h^-$	[29]	Run 1&2	As before
$B^\pm \to Dh^\pm$	$D \to h^+\pi^-\pi^+\pi^-$	[30]	Run 1	As before
$B^\pm \to Dh^\pm$	$D \to K^\pm\pi^\mp\pi^+\pi^-$	[18]	Run 1&2	**New**
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^0$	[19]	Run 1&2	**Updated**
$B^\pm \to Dh^\pm$	$D \to K^0_S h^+h^-$	[31]	Run 1&2	As before
$B^\pm \to Dh^\pm$	$D \to K^0_S K^\pm\pi^\mp$	[32]	Run 1&2	As before
$B^\pm \to D^*h^\pm$	$D \to h^+h^-$	[29]	Run 1&2	As before
$B^\pm \to DK^{*\pm}$	$D \to h^+h^-$	[33]	Run 1&2(*)	As before
$B^\pm \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[33]	Run 1&2(*)	As before
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+h^-$	[34]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to h^+h^-$	[35]	Run 1&2(*)	As before
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	[35]	Run 1&2(*)	As before
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	[36]	Run 1	As before
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	[37]	Run 1	As before
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	[38]	Run 1	As before
$B^0_s \to D^\mp_s K^\pm\pi^+\pi^-$	$D^+_s \to h^+h^-\pi^+$	[39]	Run 1&2	As before
D decay	Observable(s)	Ref.	Dataset	Status since Ref. [14]
$D^0 \to h^+h^-$	ΔA_{CP}	[24, 40, 41]	Run 1&2	As before
$D^0 \to K^+K^-$	$A_{CP}(K^+K^-)$	[16, 24, 25]	Run 2	**New**
$D^0 \to h^+h^-$	$y_{CP} - y_{CP}^{K^-\pi^+}$	[42]	Run 1	As before
$D^0 \to h^+h^-$	$y_{CP} - y_{CP}^{K^-\pi^+}$	[15]	Run 2	**New**
$D^0 \to h^+h^-$	ΔY	[43–46]	Run 1&2	As before
$D^0 \to K^+\pi^-$ (Single Tag)	$R^\pm$, $(x'^\pm)^2$, $y'^\pm$	[47]	Run 1	As before
$D^0 \to K^+\pi^-$ (Double Tag)	$R^\pm$, $(x'^\pm)^2$, $y'^\pm$	[48]	Run 1&2(*)	As before
$D^0 \to K^\pm\pi^\mp\pi^+\pi^-$	$(x^2+y^2)/4$	[49]	Run 1	As before
$D^0 \to K^0_S\pi^+\pi^-$	x, y	[50]	Run 1	As before
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[51]	Run 1	As before
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[52]	Run 2	As before
$D^0 \to K^0_S\pi^+\pi^-$ (μ^- tag)	x_{CP}, y_{CP}, Δx, Δy	[17]	Run 2	**New**

See plenary talk by Lei Hao

- Frequentist approach (Profile Likelihood + Plugin Feldman-Cousins)

\+ Auxiliary inputs from HFLAV, BESIII, CLEO and LHCb

173 input observables to determine 52 free parameters

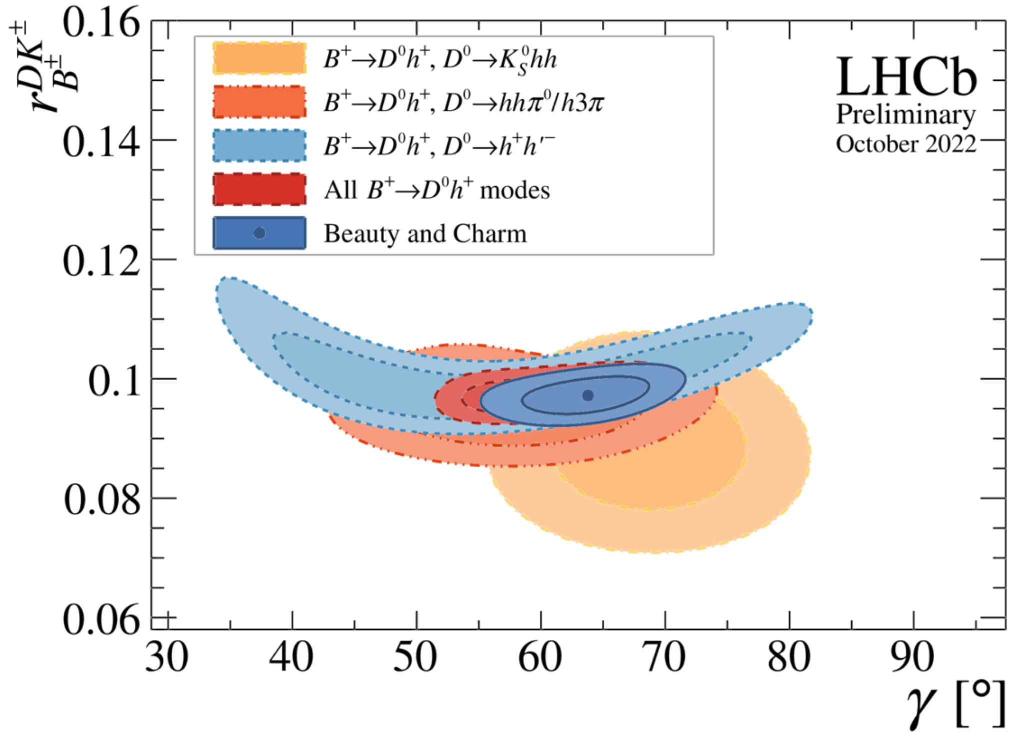
- Using two different and independent frameworks to crosscheck each other : gammadini & GammaCombo
- Simultaneous determination of ɣ and charm mixing parameters

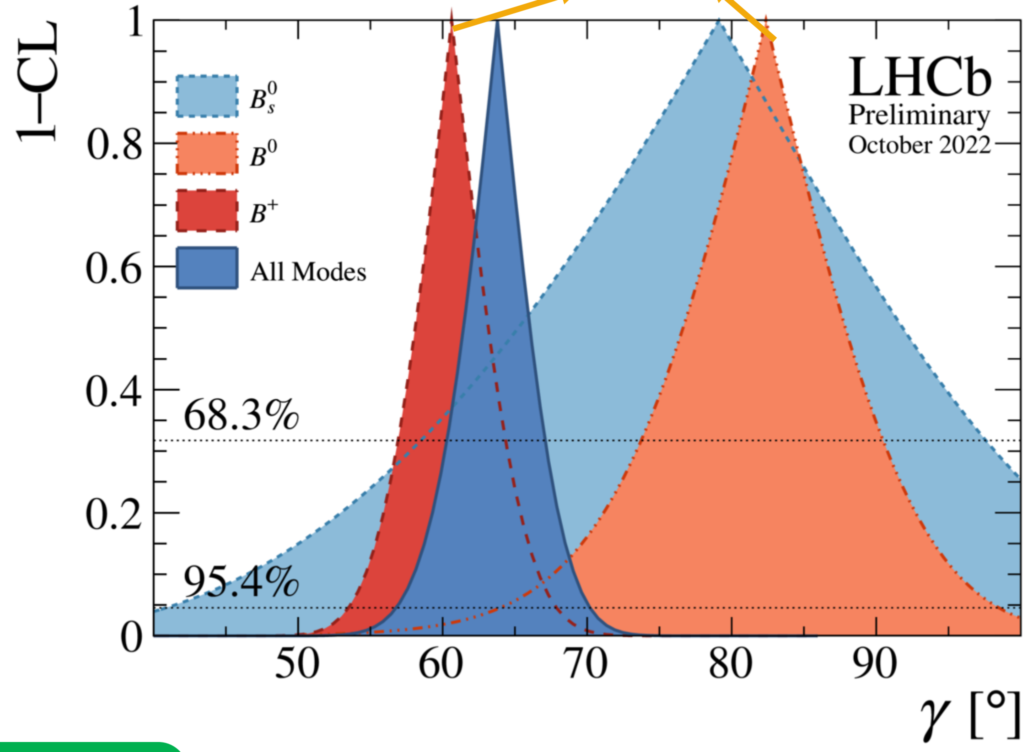
LHCb γ combination

Further details of the statistical procedure can be found in JHEP 12 (2021) 141

B_s^0 = we enter in a luminosity era enabling more precision

Moderate tension (2.2σ) between B^+ and B^0 modes



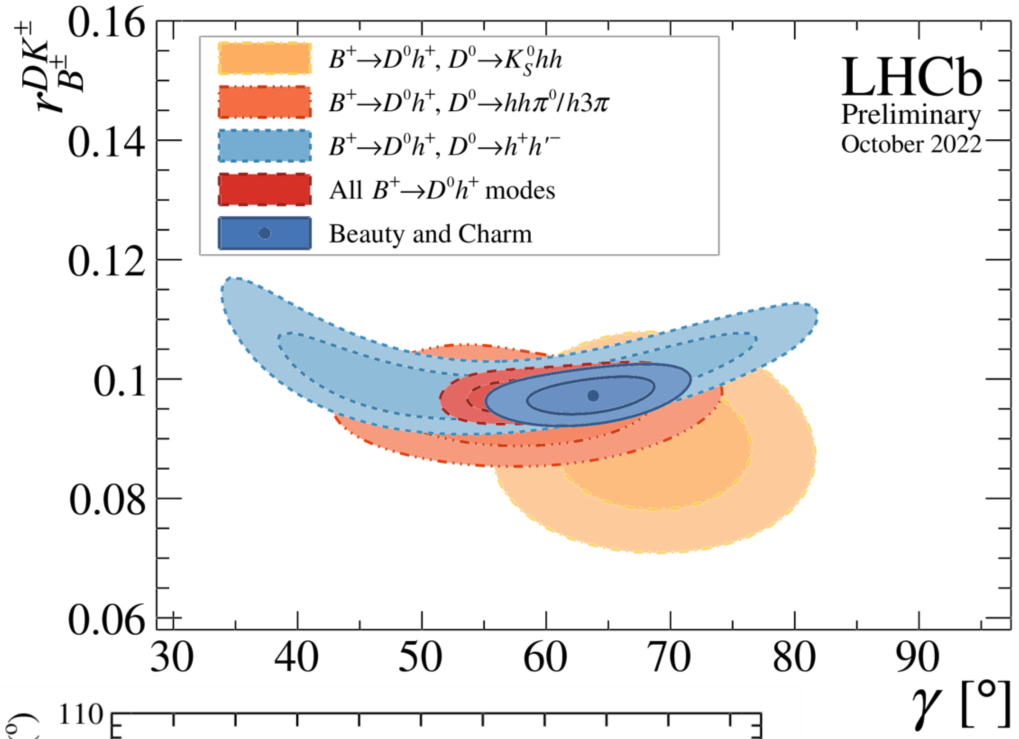


$$\gamma = (63.8^{+3.5}_{-3.7})^\circ$$

LHCb-CONF-2022-003

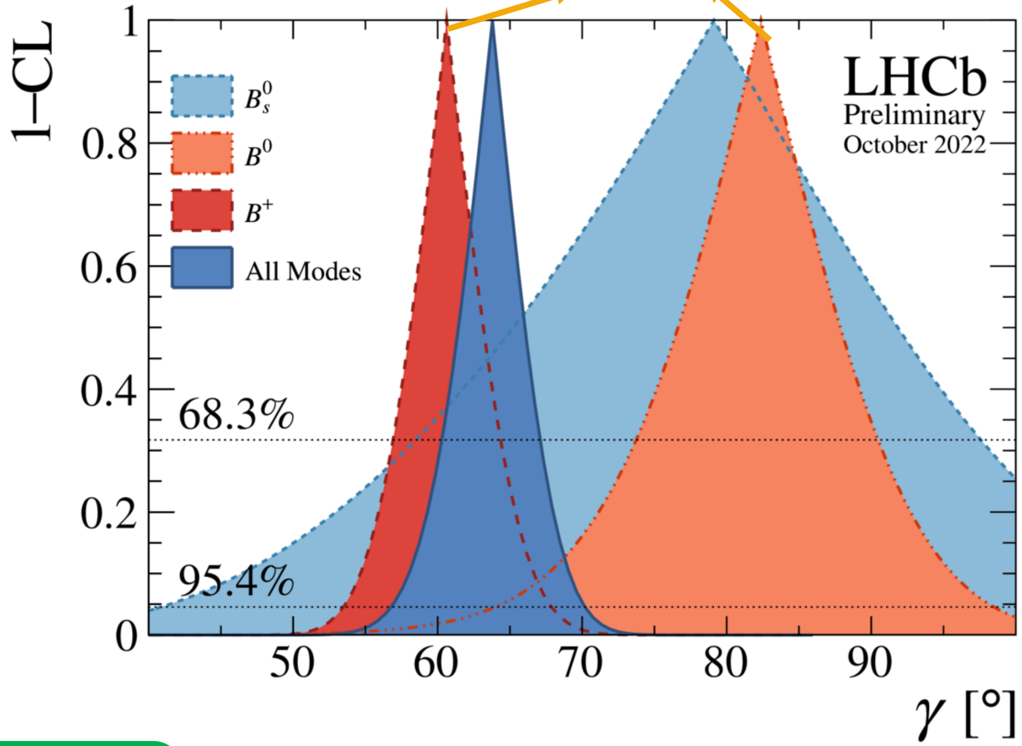
LHCb γ combination

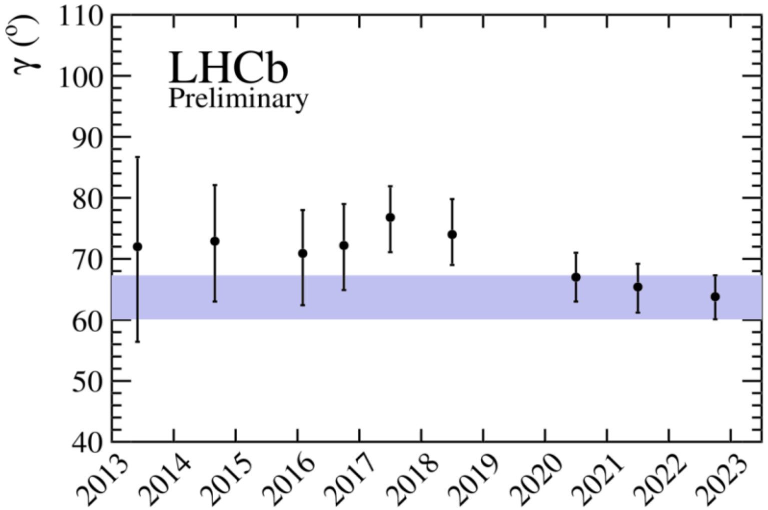
Further details of the statistical procedure can be found in JHEP 12 (2021) 141



B_s^0 = we enter in a luminosity era enabling more precision

Moderate tension (2.2σ) between B^+ and B^0 modes





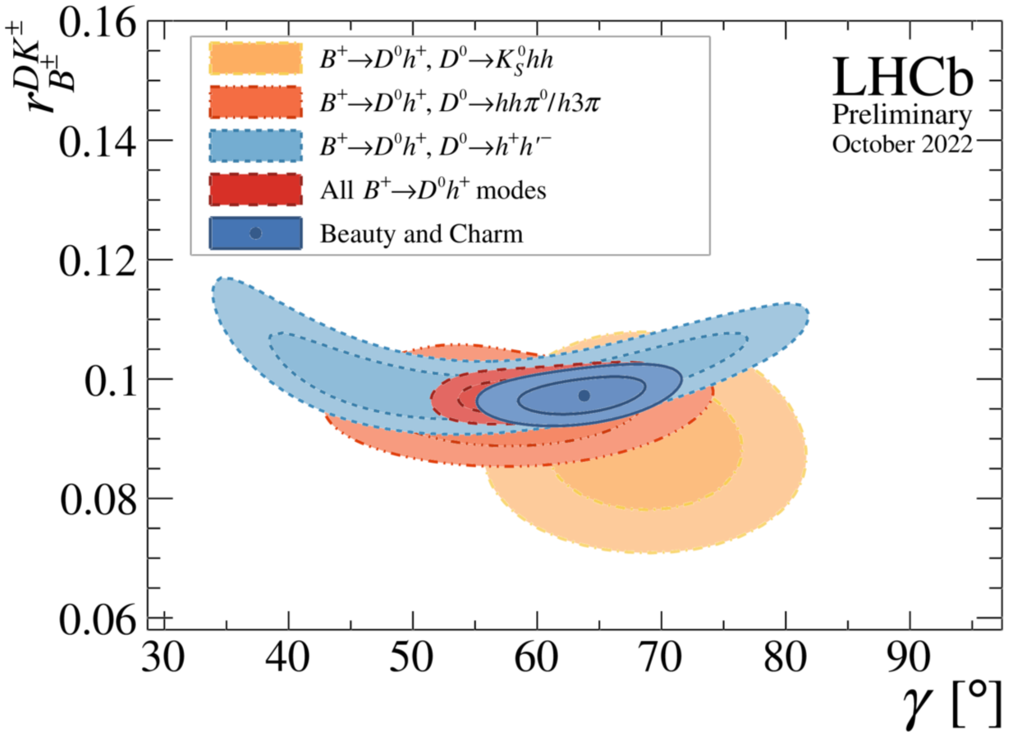
$$\gamma = (63.8^{+3.5}_{-3.7})^\circ$$

Compatible with the previous LHCb combination
In agreement with global CKM fit predictions

- Most precise determination of γ from a single experiment
- Uncertainties still in the regime of statistical dominance -> Systematic uncertainties account for ~1.4°
- Biggest improvement from the new $B \to Dh^\pm, D \to K^\pm\pi^\mp\pi^+\pi^-$ results arXiv:2209.03692 (submitted to PRD)-> **See Lei Hao's talk**

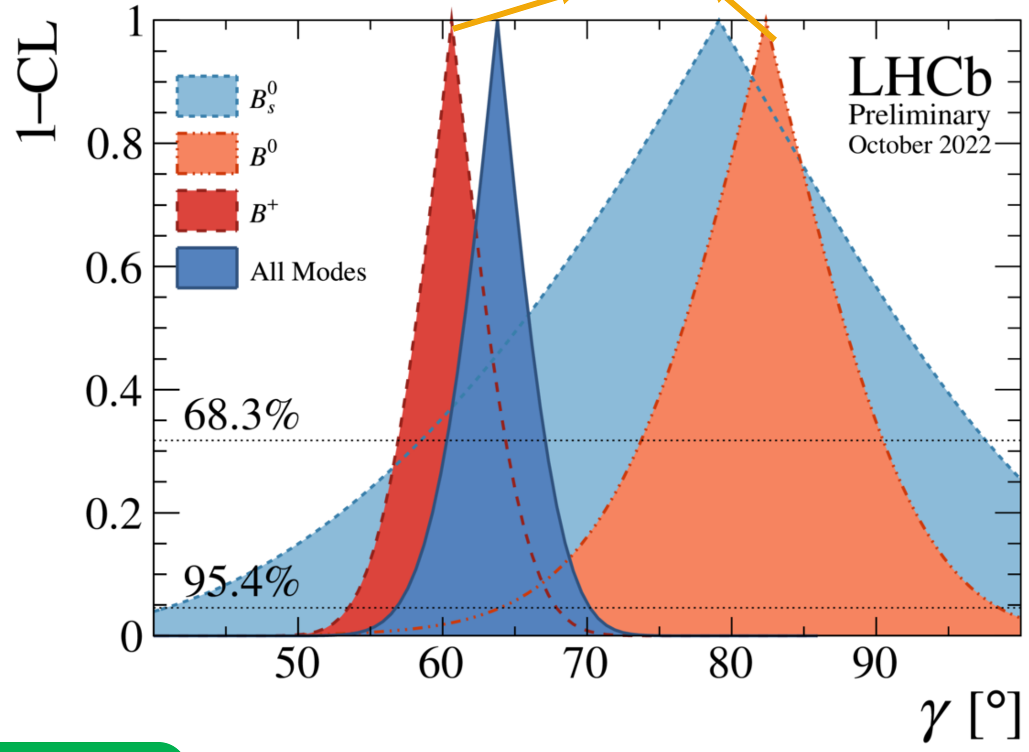
LHCb γ combination

Further details of the statistical procedure can be found in JHEP 12 (2021) 141



B_s^0 = **we enter in a luminosity era enabling more precision**

Moderate tension (2.2σ) between B^+ and B^0 modes



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

Compatible with the previous LHCb combination

In agreement with global CKM fit predictions

See talk by Yingrui Hou

Time integrated methods dominates the measure for now :

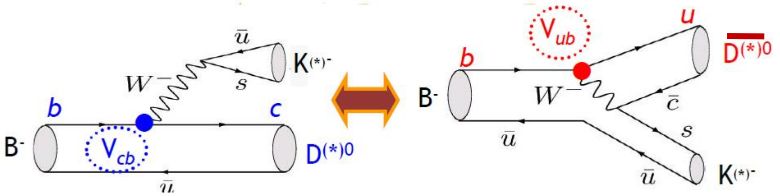
Method	Value [°]	68.3% CL Uncertainty	68.3% CL Interval	95.4% CL Uncertainty	95.4% CL Interval
Time-dependent	79	$^{+21}_{-23}$	[56, 100]	$^{+51}_{-48}$	[31, 130]
Time-integrated	63.3	$^{+3.7}_{-3.9}$	[59.4, 67.0]	$^{+7.1}_{-7.8}$	[55.5, 70.4]

CP Violation in the decays $B^{\pm} \to [h^+h^-\pi^+\pi^-]_D h^{\pm}$

- Aim of this analysis : Measure CP observables in $B^{\pm} \to [h^+h^-\pi^+\pi^-]_D h^{\pm}$ decays using **full Run1+2 ($9fb^{-1}$)**
  - First study of CP violation in this channel
  - Enhance sensitivity through sophisticated binning of 5D phase space
  - Provide input for future model-independent measurement of γ
  - + Measurements also performed of phase-space integrated observables

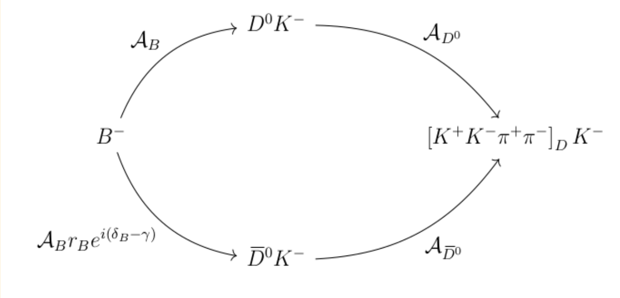
CP Violation in the decays $B^{\pm} \rightarrow [h^+h^-\pi^+\pi^-]_D h^{\pm}$

- Aim of this analysis : Measure CP observables in $B^{\pm} \rightarrow [h^+h^-\pi^+\pi^-]_D h^{\pm}$ decays using **full Run1+2 (9fb^{-1})**
    - First study of CP violation in this channel
    - Enhance sensitivity through sophisticated binning of 5D phase space
    - Provide input for future model-independent measurement of γ
    - + Measurements also performed of phase-space integrated observables



Phys. Rev. D (2003) 68, 054018
Eur.Phys.J.C (2008) 55:51-56

BPGGSZ formalism



- Overall Amplitude of this decay :

$$\begin{cases} \mathcal{A}_{B^-}(\phi) = \mathcal{A}_{B^-}^{D^0K^-}(\mathcal{A}_{D^0}(\phi) + r_B^{DK} exp(i(\delta_B^{DK} - \gamma))\mathcal{A}_{\bar{D}^0}(\phi)) \\ \mathcal{A}_{B^+}(\phi) = \mathcal{A}_{B^+}^{D^0K^+}(\mathcal{A}_{\bar{D}^0}(\phi) + r_B^{DK} exp(i(\delta_B^{DK} + \gamma))\mathcal{A}_{D^0}(\phi)) \end{cases}$$

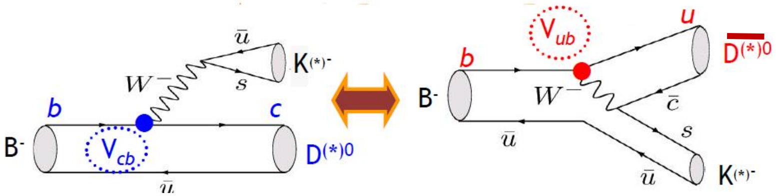
- Strong-phase difference of D^0 and $\bar{D}^0$ decays inaccessible at LHCb (OK at BESIII and Cleo-C)
- D-decay phase-space split into bins -> yields of B^+ in each bin *i* :

$$\begin{cases} N_{+i}^{+} = h_{B^+}^{DK}(F_{-i} + ((x_+^{DK})^2 + (y_+^{DK})^2)F_{+i} + 2\sqrt{F_{+i}F_{-i}}(x_+^{DK}c_i - y_+^{DK}s_i)) \\ N_{-i}^{-} = h_{B^-}^{DK}(F_{-i} + ((x_-^{DK})^2 + (y_-^{DK})^2)F_{+i} + 2\sqrt{F_{+i}F_{-i}}(x_-^{DK}c_i - y_-^{DK}s_i)) \end{cases}$$

- CP observables :
    - $\begin{cases} x_{\pm}^{DK} = r_B^{DK} cos(\delta_B^{DK} \pm \gamma) \\ y_{\pm}^{DK} = r_B^{DK} sin(\delta_B^{DK} \pm \gamma) \end{cases}$
    - $\begin{cases} x_{\xi}^{D\pi} = Re(\xi^{D\pi}) \\ y_{\xi}^{D\pi} = Im(\xi^{D\pi}) \end{cases}$ $\left(\xi^{D\pi} = \frac{r_B^{D\pi}}{r_B^{DK}} e^{i(\delta_B^{D\pi} - \delta_B^{DK})}\right)$
- Fractional bin yield :
    - $F_i = \frac{\int_i d\phi \eta(\phi) |\mathcal{A}(D^0)|^2}{\sum_j \int_j d\phi \eta(\phi) |\mathcal{A}(D^0)|^2}$
    - Floated in the fit, mostly constrained by $B^{\pm} \rightarrow D\pi^{\pm}$
- Amplitude averaged strong phases :
    - $c_i = \frac{\int_i d\phi |\mathcal{A}(D^0)||\mathcal{A}(\bar{D}^0)| cos(\Delta\delta_D)}{\sqrt{\int_i d\phi |\mathcal{A}(D^0)|^2 \int_i d\phi |\mathcal{A}(\bar{D}^0)|^2}}$
    - $s_i = \frac{\int_i d\phi |\mathcal{A}(D^0)||\mathcal{A}(\bar{D}^0)| sin(\Delta\delta_D)}{\sqrt{\int_i d\phi |\mathcal{A}(D^0)|^2 \int_i d\phi |\mathcal{A}(\bar{D}^0)|^2}}$

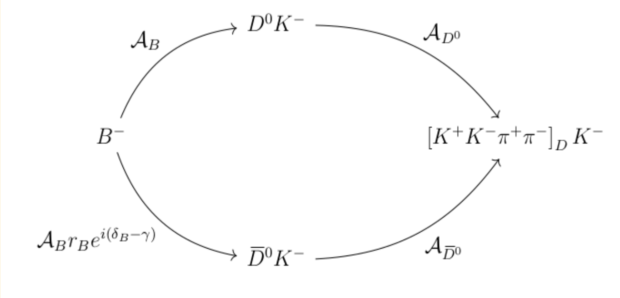
CP Violation in the decays $B^{\pm} \to [h^+h^-\pi^+\pi^-]_D h^{\pm}$

- Aim of this analysis : Measure CP observables in $B^{\pm} \to [h^+h^-\pi^+\pi^-]_D h^{\pm}$ decays using **full Run1+2 (9fb^{-1})**
  - First study of CP violation in this channel
  - Enhance sensitivity through sophisticated binning of 5D phase space
  - Provide input for future model-independent measurement of γ
  - + Measurements also performed of phase-space integrated observables



Phys. Rev. D (2003) 68, 054018
Eur.Phys.J.C (2008) 55:51-56

BPGGSZ formalism



- Overall Amplitude of this decay :

$$\begin{cases} \mathcal{A}_{B^-}(\phi) = \mathcal{A}_{B^-}^{D^0K^-}(\mathcal{A}_{D^0}(\phi) + r_B^{DK}exp(i(\delta_B^{DK}-\gamma))\mathcal{A}_{\bar{D}^0}(\phi)) \\ \mathcal{A}_{B^+}(\phi) = \mathcal{A}_{B^+}^{\bar{D}^0K^+}(\mathcal{A}_{\bar{D}^0}(\phi) + r_B^{DK}exp(i(\delta_B^{DK}+\gamma))\mathcal{A}_{D^0}(\phi)) \end{cases}$$

- Strong-phase difference of D^0 and $\bar{D}^0$ decays inaccessible at LHCb (OK at BESIII and Cleo-C)
- D-decay phase-space split into bins -> yields of B^+ in each bin *i* :

$$\begin{cases} N_{+i}^{+} = h_{B^+}^{DK}(F_{-i} + ((x_+^{DK})^2 + (y_+^{DK})^2)F_{+i} + 2\sqrt{F_{+i}F_{-i}}(x_+^{DK}c_i - y_+^{DK}s_i)) \\ N_{-i}^{-} = h_{B^-}^{DK}(F_{-i} + ((x_-^{DK})^2 + (y_-^{DK})^2)F_{+i} + 2\sqrt{F_{+i}F_{-i}}(x_-^{DK}c_i - y_-^{DK}s_i)) \end{cases}$$

- CP observables :
  - $\begin{cases} x_{\pm}^{DK} = r_B^{DK}cos(\delta_B^{DK} \pm \gamma) \\ y_{\pm}^{DK} = r_B^{DK}sin(\delta_B^{DK} \pm \gamma) \end{cases}$
  - $\begin{cases} x_{\xi}^{D\pi} = Re(\xi^{D\pi}) \\ y_{\xi}^{D\pi} = Im(\xi^{D\pi}) \end{cases}$ $\left(\xi^{D\pi} = \frac{r_B^{D\pi}}{r_B^{DK}} e^{i(\delta_B^{D\pi}-\delta_B^{DK})}\right)$

- Fractional bin yield :
  - $F_i = \dfrac{\int_i d\phi\eta(\phi)|\mathcal{A}(D^0)|^2}{\sum_j \int_j d\phi\eta(\phi)|\mathcal{A}(D^0)|^2}$
  - Floated in the fit, mostly constrained by $B^{\pm} \to D\pi^{\pm}$

- Amplitude averaged strong phases :
  - $c_i = \dfrac{\int_i d\phi|\mathcal{A}(D^0)||\mathcal{A}(\bar{D}^0)|cos(\Delta\delta_D)}{\sqrt{\int_i d\phi|\mathcal{A}(D^0)|^2 \int_i d\phi|\mathcal{A}(\bar{D}^0)|^2}}$
  - $s_i = \dfrac{\int_i d\phi|\mathcal{A}(D^0)||\mathcal{A}(\bar{D}^0)|sin(\Delta\delta_D)}{\sqrt{\int_i d\phi|\mathcal{A}(D^0)|^2 \int_i d\phi|\mathcal{A}(\bar{D}^0)|^2}}$

Taken from an amplitude model JHEP 02 (2019) 126

CP Violation in the decays $B^{\pm} \to [h^+h^-\pi^+\pi^-]_D h^{\pm}$

- Here are the invariant-mass distributions integrated over phase-space :
- Gives possibility to also do the measurements of phase-space integrated observables ---> Another statistically independent analysis
  - $A_h^{KK\pi\pi} \equiv \frac{\Gamma(B^- \to Dh^-) - \Gamma(B^+ \to Dh^+)}{\Gamma(B^- \to Dh^-) + \Gamma(B^+ \to Dh^+)} = \frac{2 r_B^{Dh} \kappa sin(\delta_B^{Dh}) sin(\gamma)}{1 + (r_B^{Dh})^2 + 2 r_B^{Dh} \kappa cos(\delta_B^{Dh}) cos(\gamma)}$

    where $\kappa = 2F_+^{KK\pi\pi} - 1$

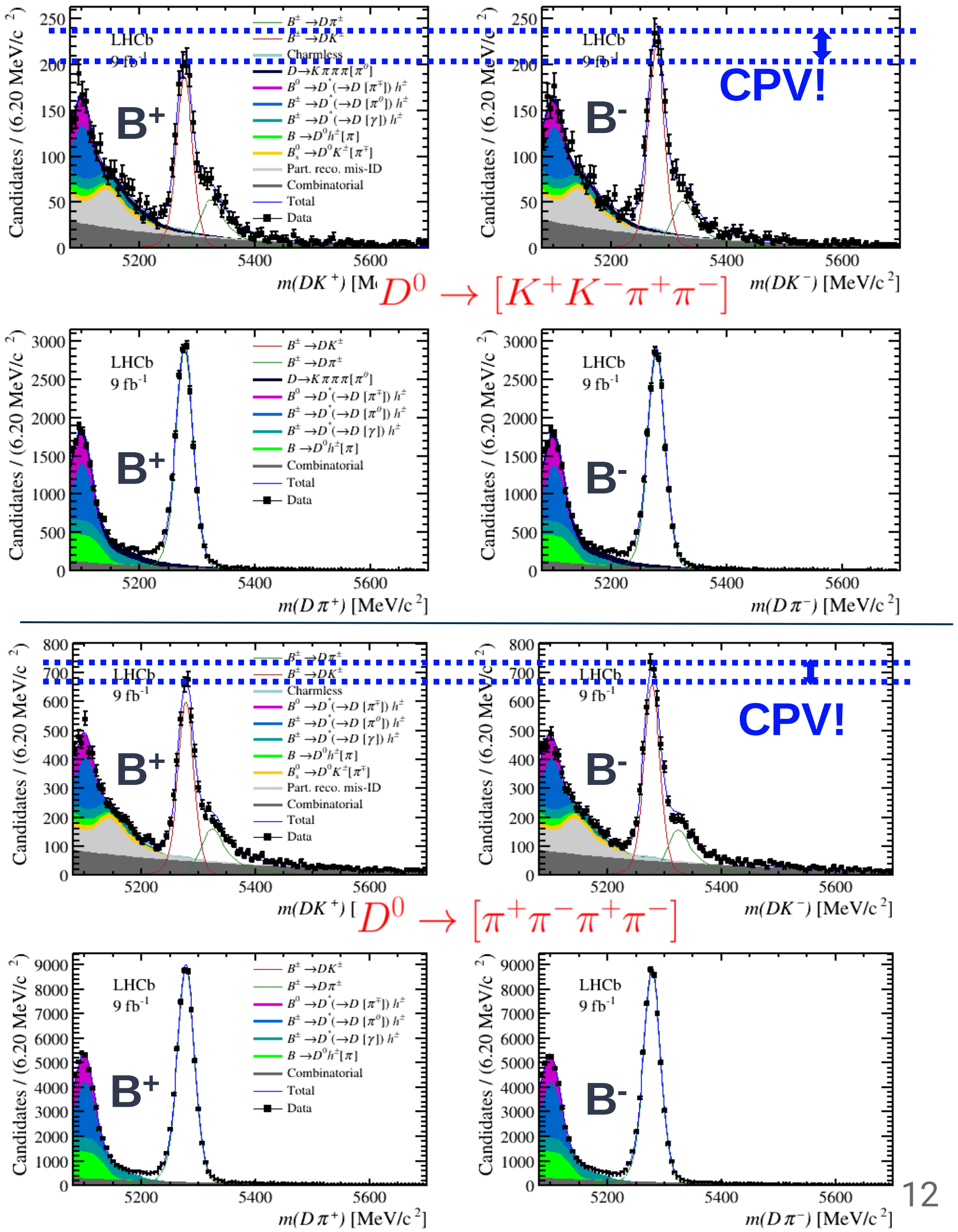
    CP-even fraction of the decay, taken from Phys. Rev. D 107, 032009 (BES III) Phys. Rev. D 106, 092004 (BES III)
  - $R_{CP}^{KK\pi\pi} \equiv \frac{R_{KK\pi\pi}}{R_{K\pi\pi\pi}} = 1 + (r_B^{DK})^2 + 2 r_B^{DK} \kappa cos(\delta_B^{DK}) cos(\gamma)$

    from arXiv:2209.03692(submitted to PRD)

with $R_f \equiv \frac{\Gamma(B^- \to [f]_D K^-) + \Gamma(B^+ \to [f]_D K^+)}{\Gamma(B^- \to [f]_D \pi^-) + \Gamma(B^+ \to [f]_D \pi^+)}$

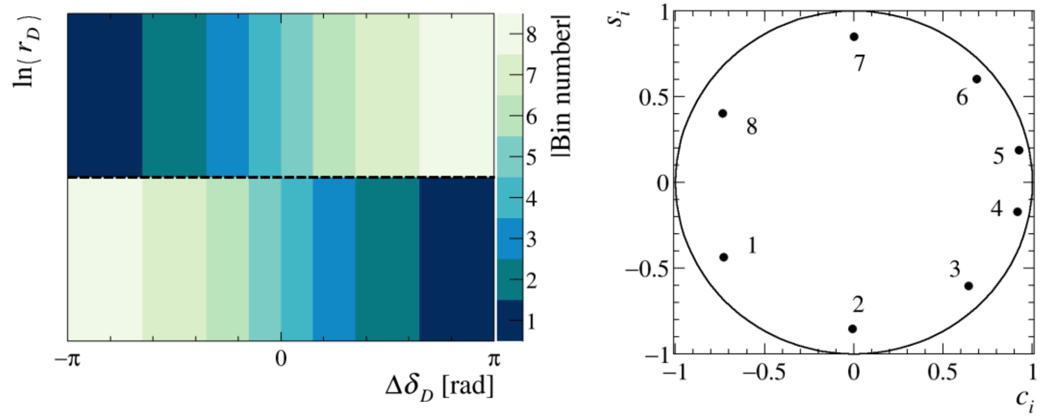
CP-violating observable	Fit results
$A_K^{KK\pi\pi}$	$0.093 \pm 0.023 \pm 0.002$
$A_\pi^{KK\pi\pi}$	$-0.009 \pm 0.006 \pm 0.001$
$A_K^{\pi\pi\pi\pi}$	$0.060 \pm 0.013 \pm 0.001$
$A_\pi^{\pi\pi\pi\pi}$	$-0.0082 \pm 0.0031 \pm 0.0007$
$R_{CP}^{KK\pi\pi}$	$0.974 \pm 0.024 \pm 0.015$
$R_{CP}^{\pi\pi\pi\pi}$	$0.978 \pm 0.014 \pm 0.010$

Consistent with Phys.Let.B 760 (2016),117-131



CP Violation in the decays $B^{\pm} \to [h^+h^-\pi^+\pi^-]_D h^{\pm}$

- The binning scheme is defined in a 2D surface defined by : $\Delta\delta_D \equiv arg(\frac{\mathcal{A}_{D^0}}{\mathcal{A}_{\bar{D}^0}}), \quad r_D \equiv |\frac{\mathcal{A}_{D^0}}{\mathcal{A}_{\bar{D}^0}}|$
  Bins are chosen to be symmetric around $\Delta\delta_D = 0$ and $ln(r_D) = 0$
  Enhance sensibility to γ, following the procedure described in JHEP 01 (2018), 144 , by maximizing the Q-value :



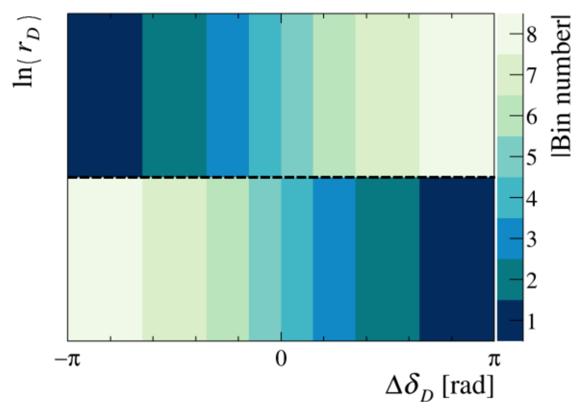
$$Q^2 \equiv (Q_+^2 + Q_-^2)/2$$

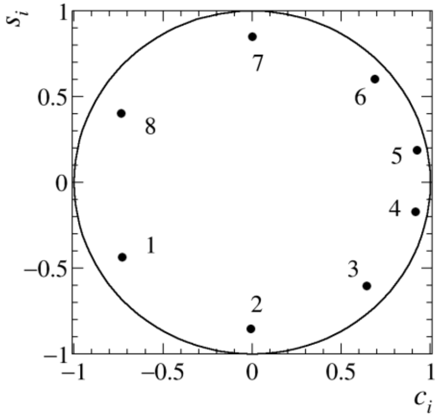
$$Q_\pm^2 \equiv 1 - (1 - \sum_i \frac{F_i F_{-i}(1-c_i^2-s_i^2)}{N_i^\pm})(\sum_i F_i)^{-1}$$

Calculated from the amplitude model + input of physical parameters

CP Violation in the decays $B^{\pm} \to [h^+h^-\pi^+\pi^-]_D h^{\pm}$

- The binning scheme is defined in a 2D surface defined by : $\Delta\delta_D \equiv arg(\frac{\mathcal{A}_{D^0}}{\mathcal{A}_{\bar{D}^0}}), \quad r_D \equiv |\frac{\mathcal{A}_{D^0}}{\mathcal{A}_{\bar{D}^0}}|$
  Bins are chosen to be symmetric around $\Delta\delta_D = 0$ and $ln(r_D) = 0$
  Enhance sensibility to γ , following the procedure described in JHEP 01 (2018), 144 , by maximizing the Q-value :



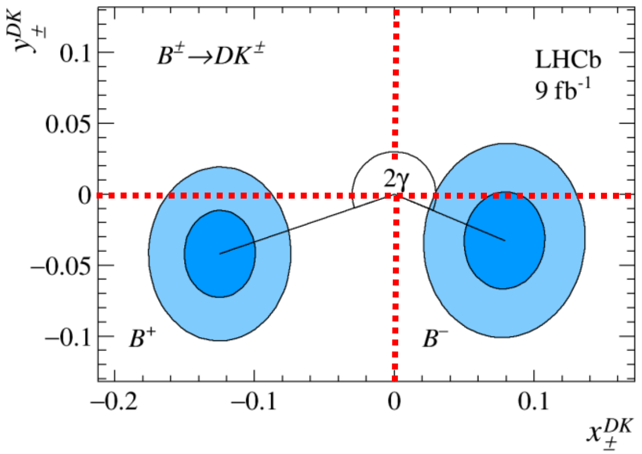


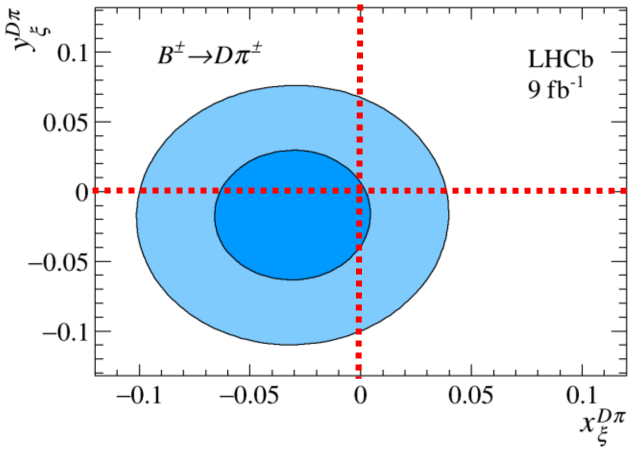
$$Q^2 \equiv (Q_+^2 + Q_-^2)/2$$

$$Q_{\pm}^2 \equiv 1 - (1 - \sum_i \frac{F_i F_{-i}(1-c_i^2-s_i^2)}{N_i^{\pm}})(\sum_i F_i)^{-1}$$

Calculated from the amplitude model + input of physical parameters

- CP Fit Results from binned analysis :

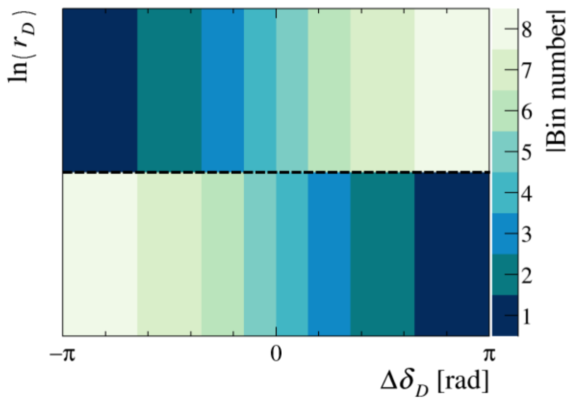


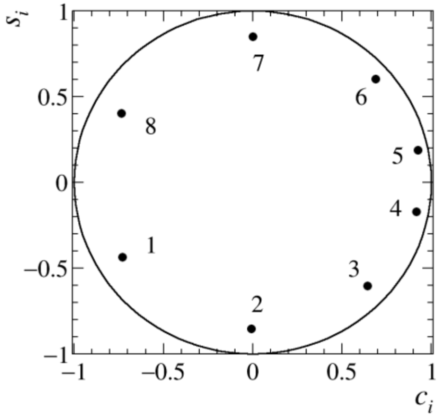


-> The distinct $B^{\pm} \to DK^{\pm}$ contours indicate CPV while the mode $B^{\pm} \to D\pi^{\pm}$ has very low sensitivity to CPV

CP Violation in the decays $B^{\pm} \to [h^+h^-\pi^+\pi^-]_D h^{\pm}$

- The binning scheme is defined in a 2D surface defined by : $\Delta\delta_D \equiv arg(\frac{\mathcal{A}_{D^0}}{\mathcal{A}_{\bar{D}^0}})$, $r_D \equiv |\frac{\mathcal{A}_{D^0}}{\mathcal{A}_{\bar{D}^0}}|$
  Bins are chosen to be symmetric around $\Delta\delta_D = 0$ and $ln(r_D) = 0$
  Enhance sensibility to γ, following the procedure described in JHEP 01 (2018), 144 , by maximizing the Q-value :



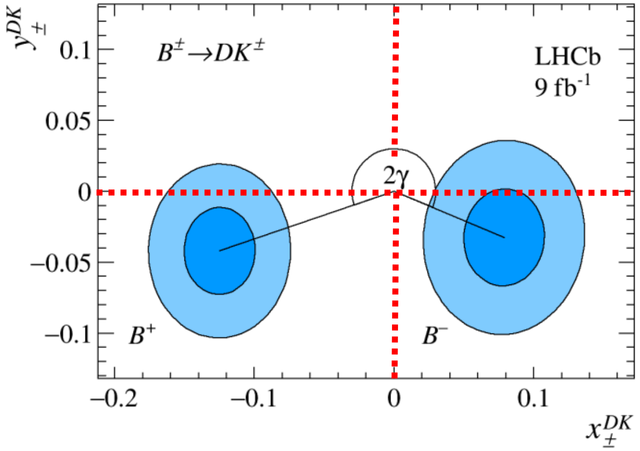


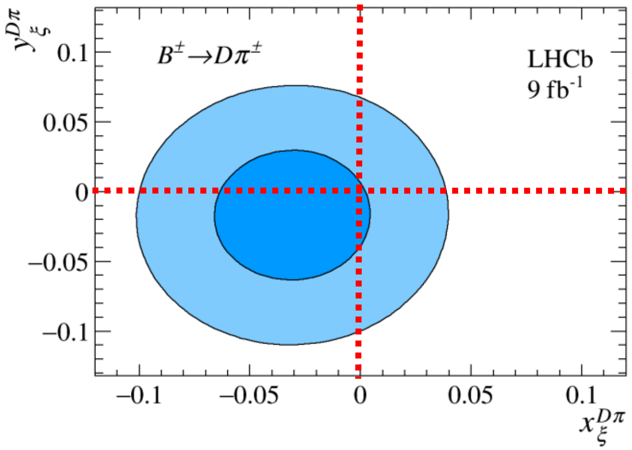
$$Q^2 \equiv (Q_+^2 + Q_-^2)/2$$

$$Q_{\pm}^2 \equiv 1 - (1 - \sum_i \frac{F_i F_{-i}(1-c_i^2-s_i^2)}{N_i^{\pm}})(\sum_i F_i)^{-1}$$

Calculated from the amplitude model + input of physical parameters

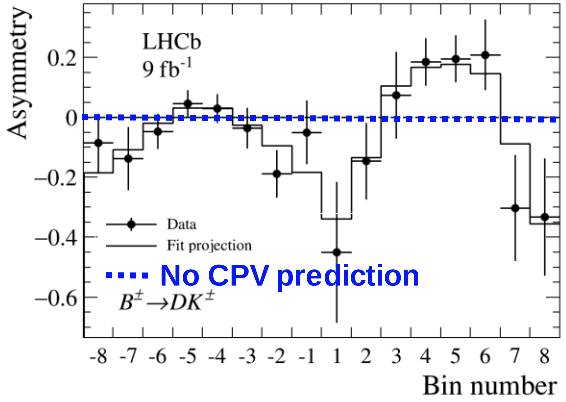
- CP Fit Results from binned analysis :

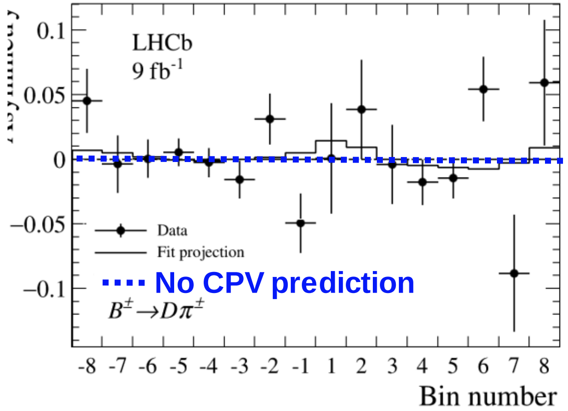




-> The distinct $B^{\pm} \to DK^{\pm}$ contours indicate CPV while the mode $B^{\pm} \to D\pi^{\pm}$ has very low sensitivity to CPV

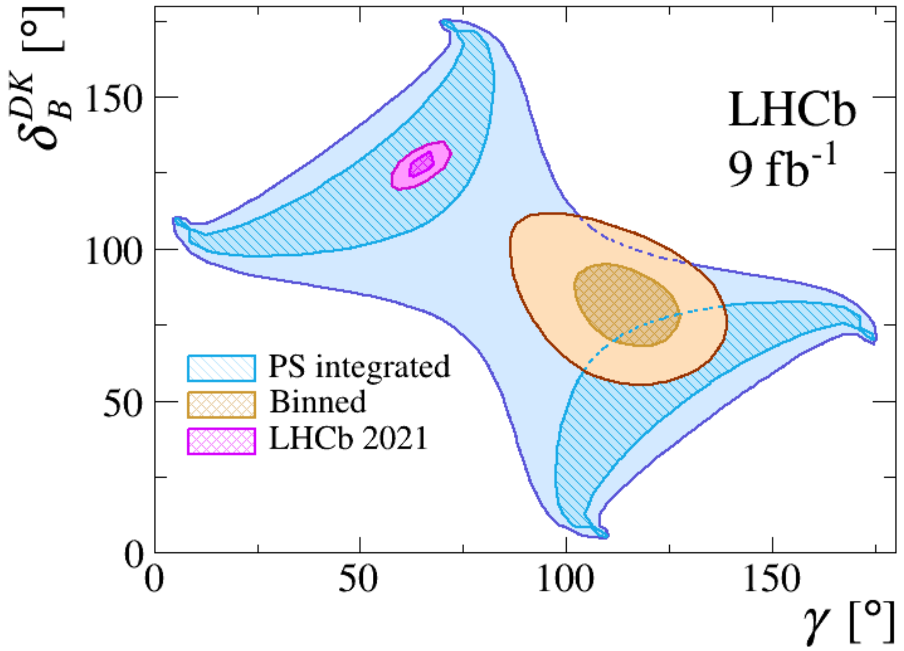
- Useful crosscheck to compare measured bin asymmetries against prediction by the fitted CP observables
- The $B^{\pm} \to DK^{\pm}$ mode shows non-zero bin asymmetries !
- Non-trivial distribution driven by strong phase variations

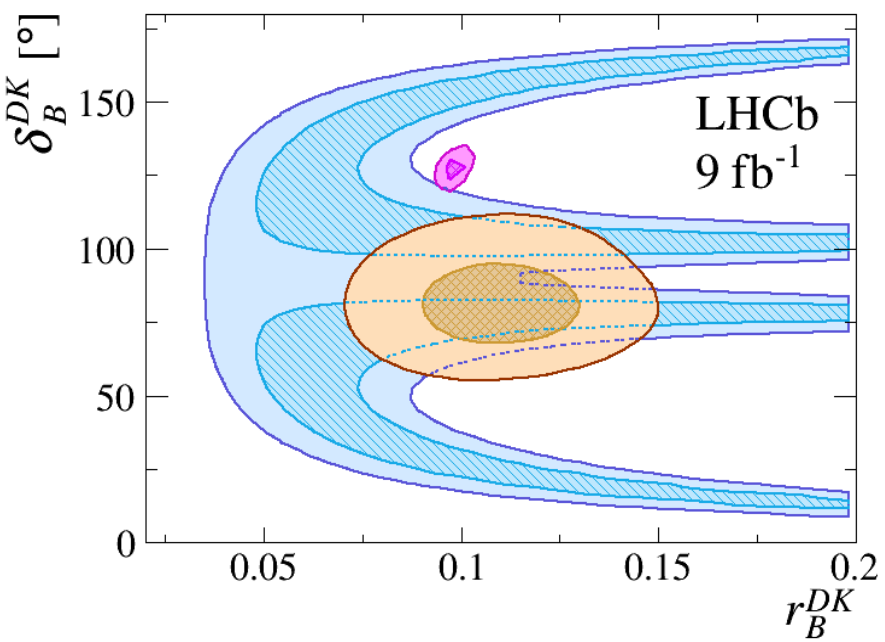




CP Violation in the decays $B^{\pm} \to [h^{+}h^{-}\pi^{+}\pi^{-}]_{D}h^{\pm}$

- Those results can then be interpreted in term of the underlying physics parameters :





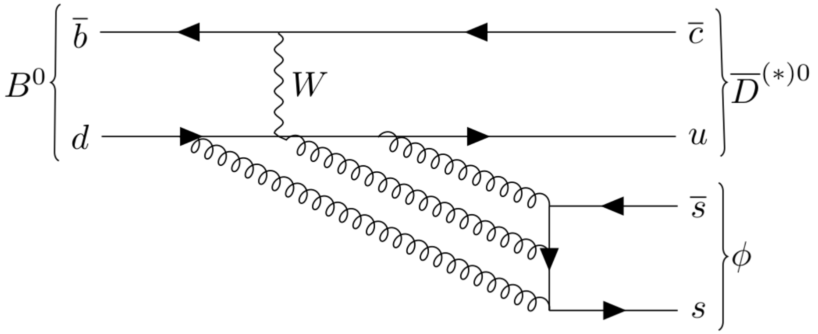
Numerical results for the binned analysis :

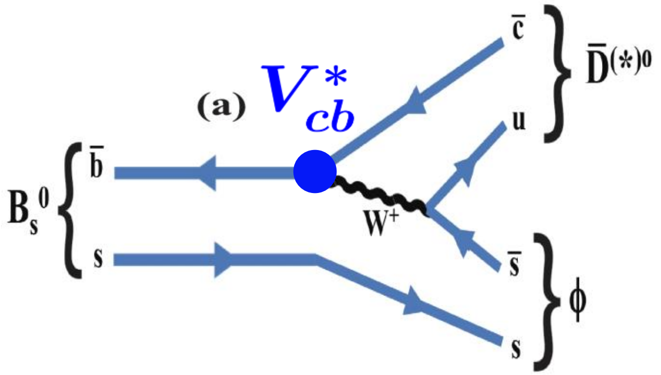
$$\gamma = (116^{+12}_{-14})^{\circ},$$
$$\delta_B^{DK} = (81^{+14}_{-13})^{\circ},$$
$$r_B^{DK} = 0.110^{+0.020}_{-0.020},$$
$$\delta_B^{D\pi} = (298^{+62}_{-118})^{\circ},$$
$$r_B^{D\pi} = 0.0041^{+0.0054}_{-0.0041},$$

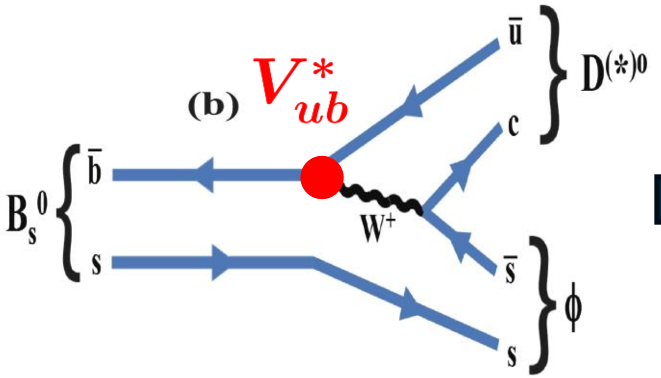
- Values of ɣ from binned analysis high, but falls within the 3σ asymmetric contours
- Phase-space inclusive measurement are compatible with expectation
- This publication is model dependent BUT **strong phases will be available from BESIII soon**
  -> This paper allows a model independent update when c_i and s_i become available

Branching Fractions of $B^0 \to \bar{D}^{(*)0}\phi$ and $B_s^0 \to \bar{D}^{(*)0}\phi$

- Aim of this analysis :
  - First evidence for the decay $B^0 \to \bar{D}^{(*)0}\phi$ (Suppressed by the Okubo-Zweig-Iizuka rules)
    - Such mode not been observed in b-hadron yet !
    - Constrain the $\omega - \phi$ mixing angle (with information from $B^0 \to D^{(*)0}\omega$)
  - Updated measurement of the BF of the $B_s^0 \to \bar{D}^{(*)0}\phi$ decays
    - Two color-suppressed interfering diagrams **with amplitudes similar in size**
    - Can be used to measure CKM angle ɣ ! Chin. Phys. C45 (2021) 023003





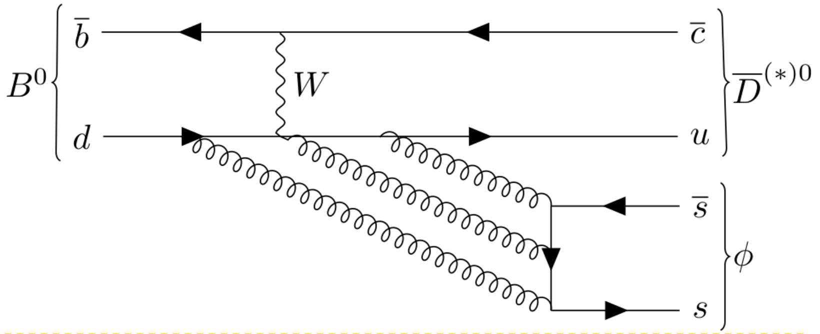


Really similar to
$B^0 \to \bar{D}^0 K^{*0}$

Note : The decays used for reconstruction are : $\bar{D}^0 \to K^+\pi^-$, $\phi \to K^+K^-$, $\bar{D}^{*0} \to \bar{D}^0\pi^0$ or $\bar{D}^{*0} \to \bar{D}^0\gamma$

Branching Fractions of $B^0 \to \bar{D}^{(*)0}\phi$ and $B^0_s \to \bar{D}^{(*)0}\phi$

- Aim of this analysis :
  - First evidence for the decay $B^0 \to \bar{D}^{(*)0}\phi$ (Suppressed by the Okubo-Zweig-Iizuka rules)
    - Such mode not been observed in b-hadron yet !
    - Constrain the $\omega - \phi$ mixing angle (with information from $B^0 \to D^{(*)0}\omega$)
  - Updated measurement of the BF of the $B^0_s \to \bar{D}^{(*)0}\phi$ decays
    - Two color-suppressed interfering diagrams **with amplitudes similar in size**
    - Can be used to measure CKM angle γ ! Chin. Phys. C45 (2021) 023003



Parenthesis : The $\omega - \phi$ mixing angle

- The physical states ω and ϕ can be written as a function of the ideally states $\omega^I \equiv \frac{(u\bar{u}+d\bar{d})}{\sqrt{2}}$ and $\phi^I \equiv s\bar{s}$

$$\begin{pmatrix}\omega \\ \phi\end{pmatrix} = \begin{pmatrix}cos(\delta) & sin(\delta) \\ -sin(\delta) & cos(\delta)\end{pmatrix}\begin{pmatrix}\omega^I \\ \phi^I\end{pmatrix}$$

- The mixing angle can be determined with the branching fractions : $tan^2\delta = \frac{\mathcal{B}(B^0\to\bar{D}^{(*)0}\phi)}{\mathcal{B}(B^0\to\bar{D}^{(*)0}\omega)} \times \frac{\Phi(\omega)}{\Phi(\phi)}$

Integrals of the phase space factors

Input from Phys.Rev.D 98, 071103 (2018)

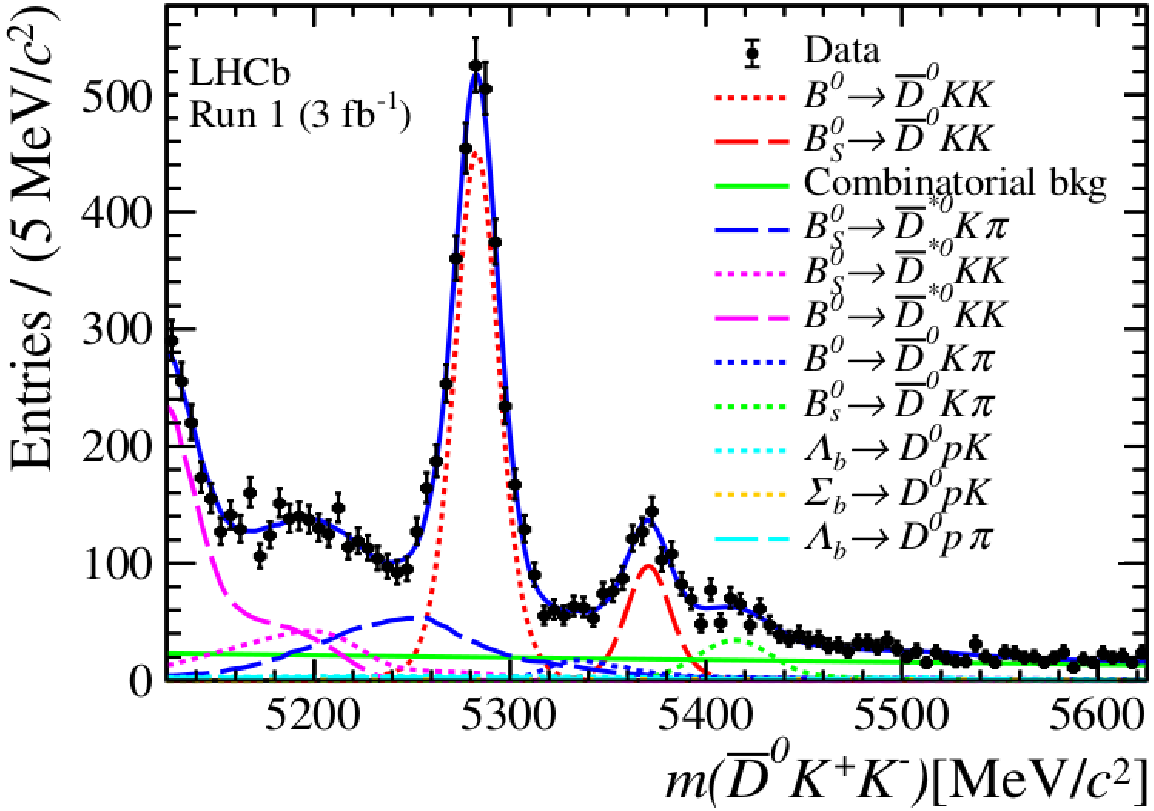
From current world average

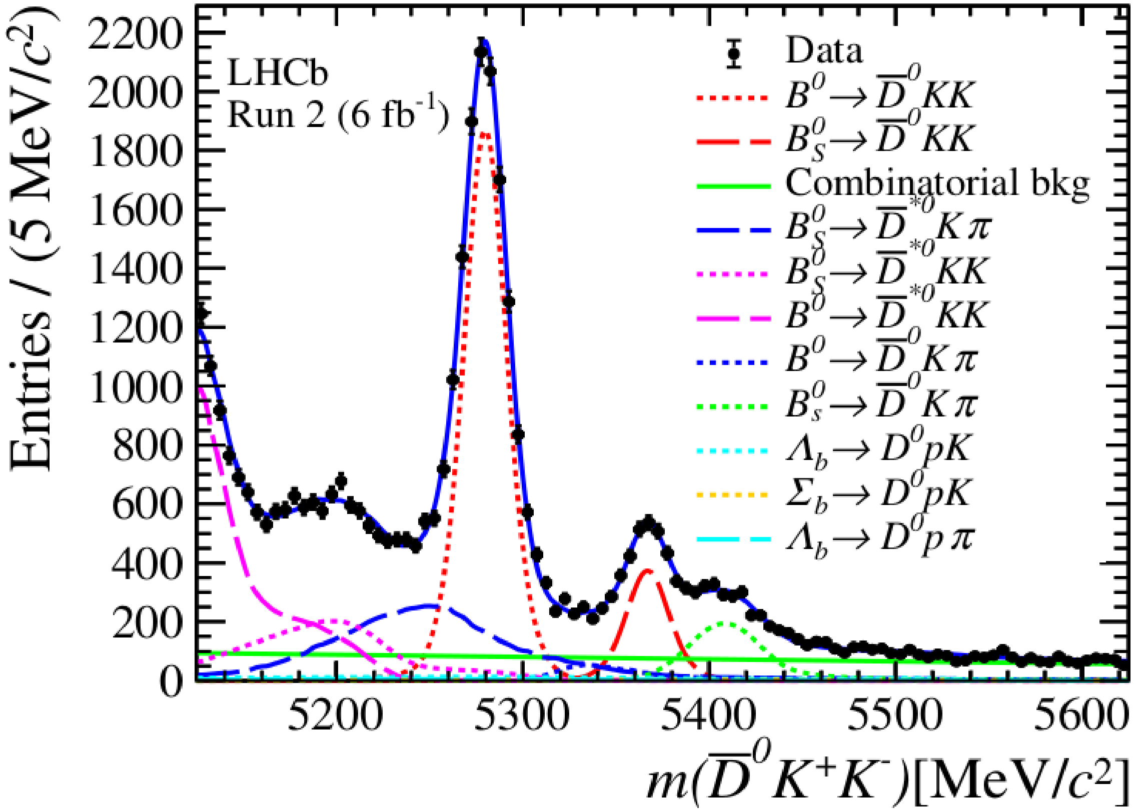
- Angle recently observed in charmonium resonance decays $\chi_{cJ} \to \omega\phi$ **BUT** still not in b-hadron decays

Phys.Rev.D 99, 012015 (2019) (BESIII)

Branching Fractions of $B^0 \to \bar{D}^{(*)0}\phi$ and $B_s^0 \to \bar{D}^{(*)0}\phi$

- Invariant-mass fit for the decay $B^0 \to \bar{D}^0 K^+ K^-$ == Normalisation mode

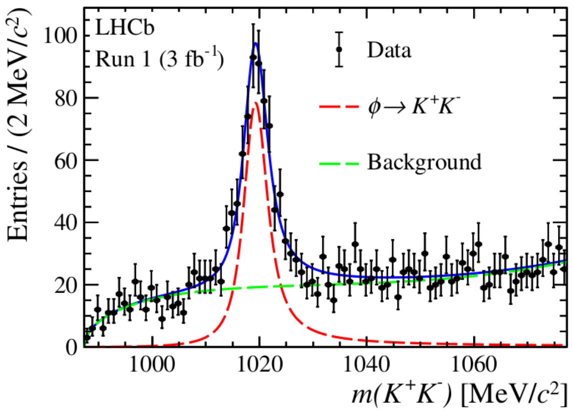


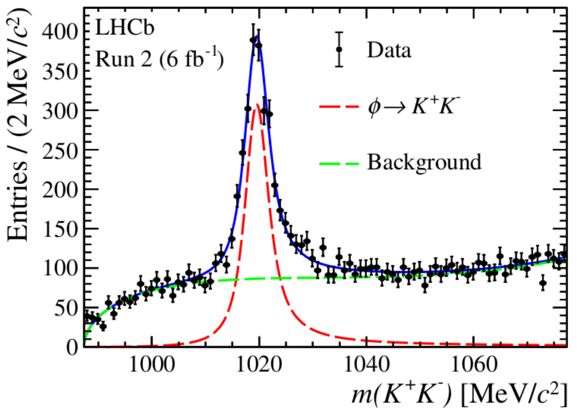


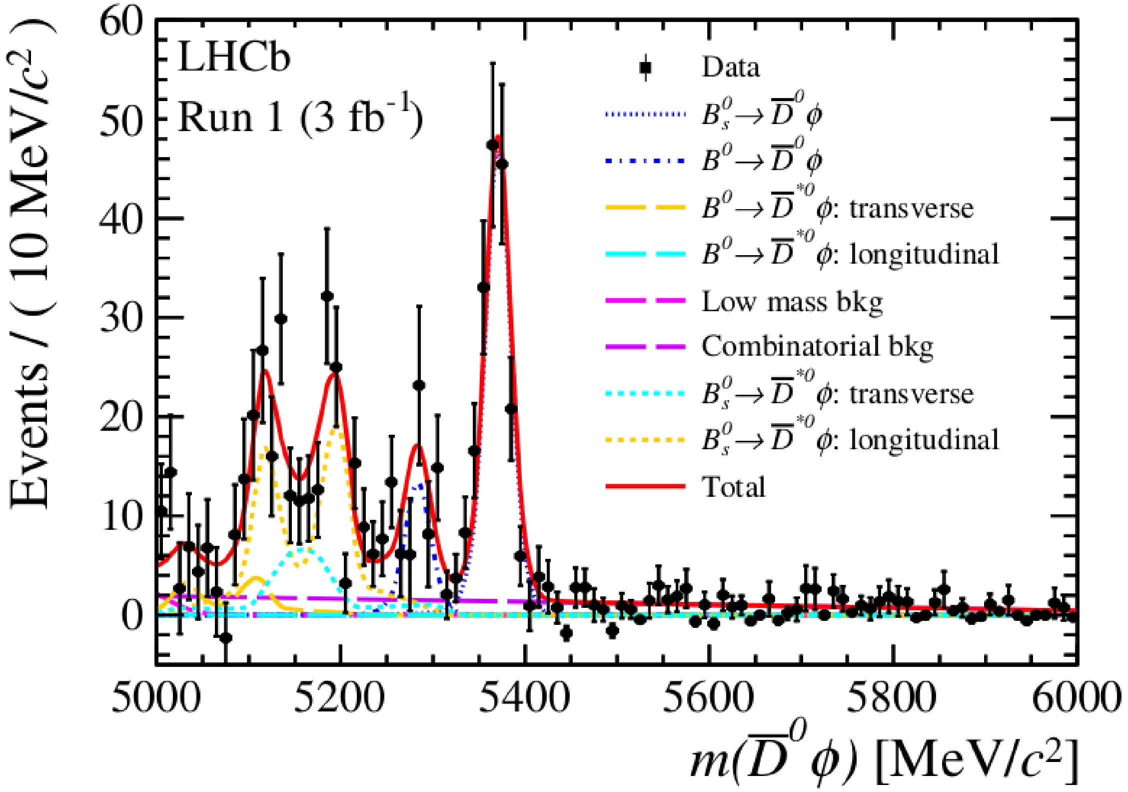
Branching Fractions of $B^0 \to \bar{D}^{(*)0}\phi$ and $B_s^0 \to \bar{D}^{(*)0}\phi$

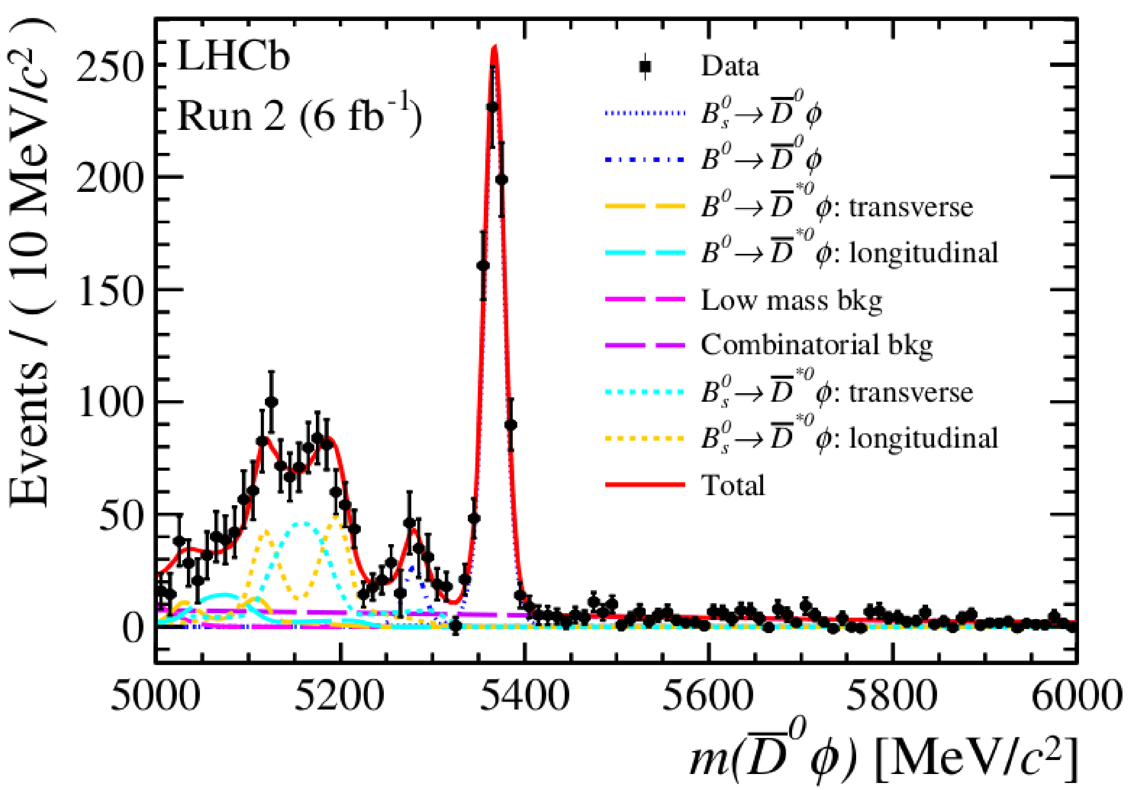
- Invariant-mass fit for the decay $B^0 \to \bar{D}^0 K^+ K^-$
- Fit on $m(K^+K^-)$ to remove non - ϕ background
- s-Weight method to project on $m(\bar{D}^0\phi)$
- Note that the ratio between transverse and longitudinal components are free parameters for both $B^0 \to \bar{D}^{(*)0}\phi$ and $B_s^0 \to \bar{D}^{(*)0}\phi$

Two steps fit









Branching Fractions of $B^0 \to \bar{D}^{(*)0}\phi$ and $B_s^0 \to \bar{D}^{(*)0}\phi$

- The results are :
  - **First evidence** for $B^0 \to \bar{D}^{(*)0}\phi$

$$\mathcal{B}(B^0 \to \bar{D}^0\phi) = (7.7 \pm 2.1 \pm 0.7 \pm 0.7) \times 10^{-7} \longrightarrow 3.6\sigma \text{ significance}$$

$$\mathcal{B}(B^0 \to \bar{D}^{*0}\phi) = (2.2 \pm 0.5 \pm 0.2 \pm 0.2) \times 10^{-6} \longrightarrow 4.3\sigma \text{ significance}$$

statistic sytematic from normalisation mode

Branching Fractions of $B^0 \to \bar{D}^{(*)0}\phi$ and $B_s^0 \to \bar{D}^{(*)0}\phi$

- The results are :
  - **First evidence** for $B^0 \to \bar{D}^{(*)0}\phi$

    $\mathcal{B}(B^0 \to \bar{D}^0\phi) = (7.7 \pm 2.1 \pm 0.7 \pm 0.7) \times 10^{-7}$ → 3.6σ significance

    $\mathcal{B}(B^0 \to \bar{D}^{*0}\phi) = (2.2 \pm 0.5 \pm 0.2 \pm 0.2) \times 10^{-6}$ → 4.3σ significance

    statistic, sytematic, from normalisation mode

  - A combined study of the two decay modes gives $\omega - \phi$ mixing angle

    $tan^2\delta = (3.6 \pm 0.7 \pm 0.4) \times 10^{-3}$ → consistent with theoretical prediction Phys.Lett.B 666 (2008) 185-188

Branching Fractions of $B^0 \to \bar{D}^{(*)0}\phi$ and $B_s^0 \to \bar{D}^{(*)0}\phi$

- The results are :
  - **First evidence** for $B^0 \to \bar{D}^{(*)0}\phi$

    $\mathcal{B}(B^0 \to \bar{D}^0\phi) = (7.7 \pm 2.1 \pm 0.7 \pm 0.7) \times 10^{-7}$ → 3.6σ **significance**

    $\mathcal{B}(B^0 \to \bar{D}^{*0}\phi) = (2.2 \pm 0.5 \pm 0.2 \pm 0.2) \times 10^{-6}$ → 4.3σ **significance**

    statistic, sytematic, from normalisation mode

  - A combined study of the two decay modes gives $\omega - \phi$ mixing angle

    $tan^2\delta = (3.6 \pm 0.7 \pm 0.4) \times 10^{-3}$ → **consistent with theoretical prediction** Phys.Lett.B 666 (2008) 185-188

  - Precision improved for $B_s^0 \to \bar{D}^{(*)0}\phi$ **+ consistent with previous LHCb results** Phys. Rev. D 98, 071103 (2018)

    $\mathcal{B}(B_s^0 \to \bar{D}^0\phi) = (2.30 \pm 0.10 \pm 0.11 \pm 0.20) \times 10^{-5}$

    $\mathcal{B}(B_s^0 \to \bar{D}^{*0}\phi) = (3.17 \pm 0.16 \pm 0.17 \pm 0.27) \times 10^{-5}$

    The fraction of the longitudinal polarisation of $B_s^0 \to \bar{D}^{*0}\phi$:

    $f_L(B_s^0 \to \bar{D}^{*0}\phi) = (53.1 \pm 6.0 \pm 1.9)\%$

Branching Fractions of $B^0 \to \bar{D}^{(*)0}\phi$ and $B_s^0 \to \bar{D}^{(*)0}\phi$

- The results are :
  - **First evidence** for $B^0 \to \bar{D}^{(*)0}\phi$

    $\mathcal{B}(B^0 \to \bar{D}^0\phi) = (7.7 \pm 2.1 \pm 0.7 \pm 0.7) \times 10^{-7}$ → 3.6σ **significance**

    $\mathcal{B}(B^0 \to \bar{D}^{*0}\phi) = (2.2 \pm 0.5 \pm 0.2 \pm 0.2) \times 10^{-6}$ → 4.3σ **significance**

    statistic sytematic from normalisation mode

  - A combined study of the two decay modes gives $\omega - \phi$ mixing angle

    $tan^2\delta = (3.6 \pm 0.7 \pm 0.4) \times 10^{-3}$ → **consistent with theoretical prediction** Phys.Lett.B 666 (2008) 185-188

  - Precision improved for $B_s^0 \to \bar{D}^{(*)0}\phi$ **+ consistent with previous LHCb results** Phys. Rev. D 98, 071103 (2018)

    $\mathcal{B}(B_s^0 \to \bar{D}^0\phi) = (2.30 \pm 0.10 \pm 0.11 \pm 0.20) \times 10^{-5}$

    $\mathcal{B}(B_s^0 \to \bar{D}^{*0}\phi) = (3.17 \pm 0.16 \pm 0.17 \pm 0.27) \times 10^{-5}$

    The fraction of the longitudinal polarisation of $B_s^0 \to \bar{D}^{*0}\phi$:

    $f_L(B_s^0 \to \bar{D}^{*0}\phi) = (53.1 \pm 6.0 \pm 1.9)\%$

- **This can be used to measure CKM angle ɣ**

Branching Fractions of $B^0 \to \bar{D}^{(*)0}\phi$ and $B_s^0 \to \bar{D}^{(*)0}\phi$

- The results are :
  - **First evidence** for $B^0 \to \bar{D}^{(*)0}\phi$

    $$\mathcal{B}(B^0 \to \bar{D}^0\phi) = (7.7 \pm 2.1 \pm 0.7 \pm 0.7) \times 10^{-7}$$

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

    statistic sytematic from norm:
  - A combined study of the two decay modes gives ω -

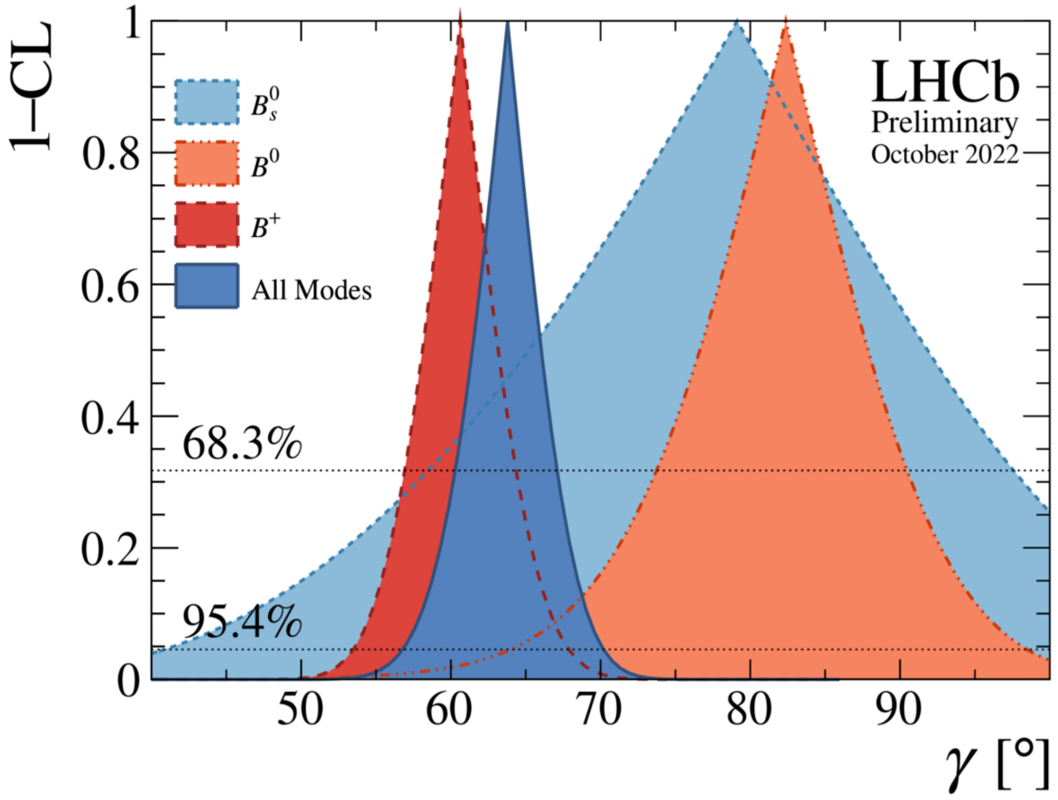
    $$tan^2\delta = (3.6 \pm 0.7 \pm 0.4) \times 10^{-3}$$

  - Precision improved for $B_s^0 \to \bar{D}^{(*)0}\phi$

    $$\mathcal{B}(B_s^0 \to \bar{D}^0\phi) = (2.30 \pm 0.10 \pm 0.11 \pm 0.20) \times 10^{-5}$$

    $$\mathcal{B}(B_s^0 \to \bar{D}^{*0}\phi) = (3.17 \pm 0.16 \pm 0.17 \pm 0.27) \times 10^{-5}$$

Reminder : ɣ not yet accurately measured in B_s^0



- **This can be used to measure CKM angle ɣ**
  - Additional methods employing another B_s^0 decay !
  - Notable difference with $B_s^0 \to D_s K$ JHEP 03 (2018) 059 : No tagging and pure final state
  - **Expected sensitivity on ɣ with this decay is about 8° to 19° with LHCb dataset** Chin. Phys. C45 (2021) 023003

Conclusion and prospects

- New combination of LHCb results gives the most precise determination of ɣ

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

- First study of the CP violation with the channel $B^\pm \to [h^+h^-\pi^+\pi^-]_D h^\pm$
  - Both with a D phase-space binning scheme and integrated
  - To be improved after BESIII strong-phase measurements

- First evidence for $B^0 \to \bar{D}^{(*)0}\phi$

- Branching fraction precision improved for $B_s^0 \to \bar{D}^{(*)0}\phi$ -> Possible ɣ measurement (Stay tuned !)

- Coming soon (or later) :
  - Studies of new decay modes
  - Updates with Run3 data set (expected $23 fb^{-1}$) -> Room for improvement as all measurements are still limited by statistics

Conclusion and prospects

- New combination of LHCb results gives the most precise determination of γ

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

- First study of the CP violation with the channel $B^\pm \to [h^+h^-\pi^+\pi^-]_D h^\pm$
  - Both with a D phase-space binning scheme and integrated
  - To be improved after BESIII strong-phase measurements

Thank you for your attention !

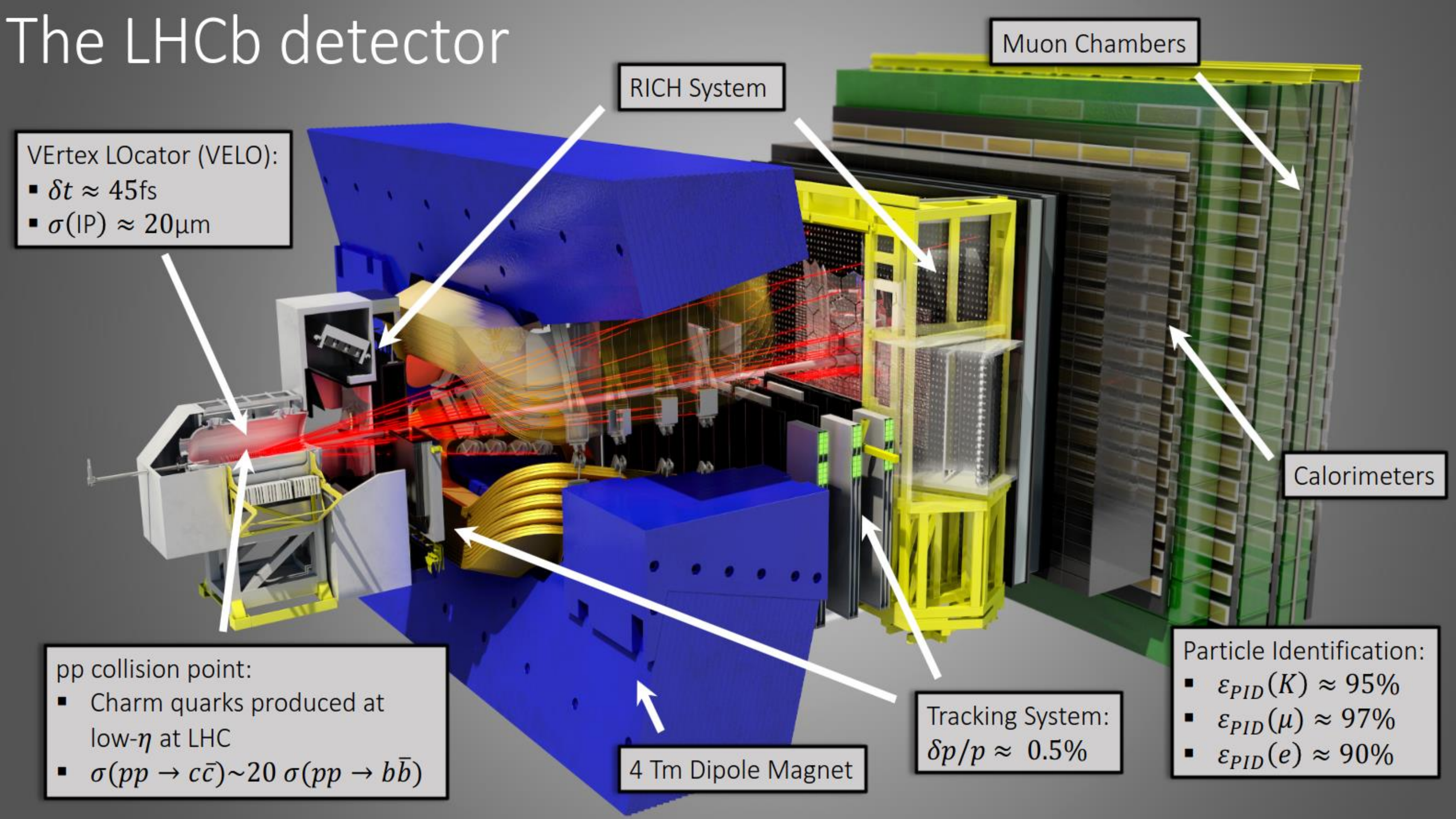
- First evidence for $B^0 \to \bar{D}^{(*)0}\phi$

- Branching fraction precision improved for $B_s^0 \to \bar{D}^{(*)0}\phi$ -> Possible γ measurement (Stay tuned !)

- Coming soon (or later) :
  - Studies of new decay modes
  - Updates with Run3 data set (expected 23fb^{-1}) -> Room for improvement as all measurements are still limited by statistics

BACKUP

The LHCb detector



LHCb γ combination

Table 2: Auxiliary inputs used in the combination. Those highlighted in bold have changed since the previous combination [14].

Decay	Parameters	Source	Ref.	Status since Ref. [14]
$B^{\pm} \to DK^{*\pm}$	$\kappa_{B^{\pm}}^{DK^{*\pm}}$	LHCb	[33]	As before
$B^0 \to DK^{*0}$	$\kappa_{B^0}^{DK^{*0}}$	LHCb	[53]	As before
$B^0 \to D^{\mp}\pi^{\pm}$	β	HFLAV	[13]	As before
$B_s^0 \to D_s^{\mp}K^{\pm}(\pi\pi)$	ϕ_s	HFLAV	[13]	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	[27]	**New**
$D \to K^+\pi^-$	$A_{K\pi}$, $A_{K\pi}^{\pi\pi\pi^0}$, $r_D^{K\pi}\cos\delta_D^{K\pi}$, $r_D^{K\pi}\sin\delta_D^{K\pi}$	BESIII	[28]	**New**
$D \to h^+h^-\pi^0$	$F_{\pi\pi\pi^0}^+$, $F_{KK\pi^0}^+$	CLEO-c	[54]	As before
$D \to \pi^+\pi^-\pi^+\pi^-$	$F_{4\pi}^+$	CLEO-c+BESIII	[26, 54]	**Updated**
$D \to K^+\pi^-\pi^0$	$r_D^{K\pi\pi^0}$, $\delta_D^{K\pi\pi^0}$, $\kappa_D^{K\pi\pi^0}$	CLEO-c+LHCb+BESIII	[55–57]	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	[49, 55–57]	As before
$D \to K_S^0K^{\pm}\pi^{\mp}$	$r_D^{K_S^0K\pi}$, $\delta_D^{K_S^0K\pi}$, $\kappa_D^{K_S^0K\pi}$	CLEO	[58]	As before
$D \to K_S^0K^{\pm}\pi^{\mp}$	$r_D^{K_S^0K\pi}$	LHCb	[59]	As before

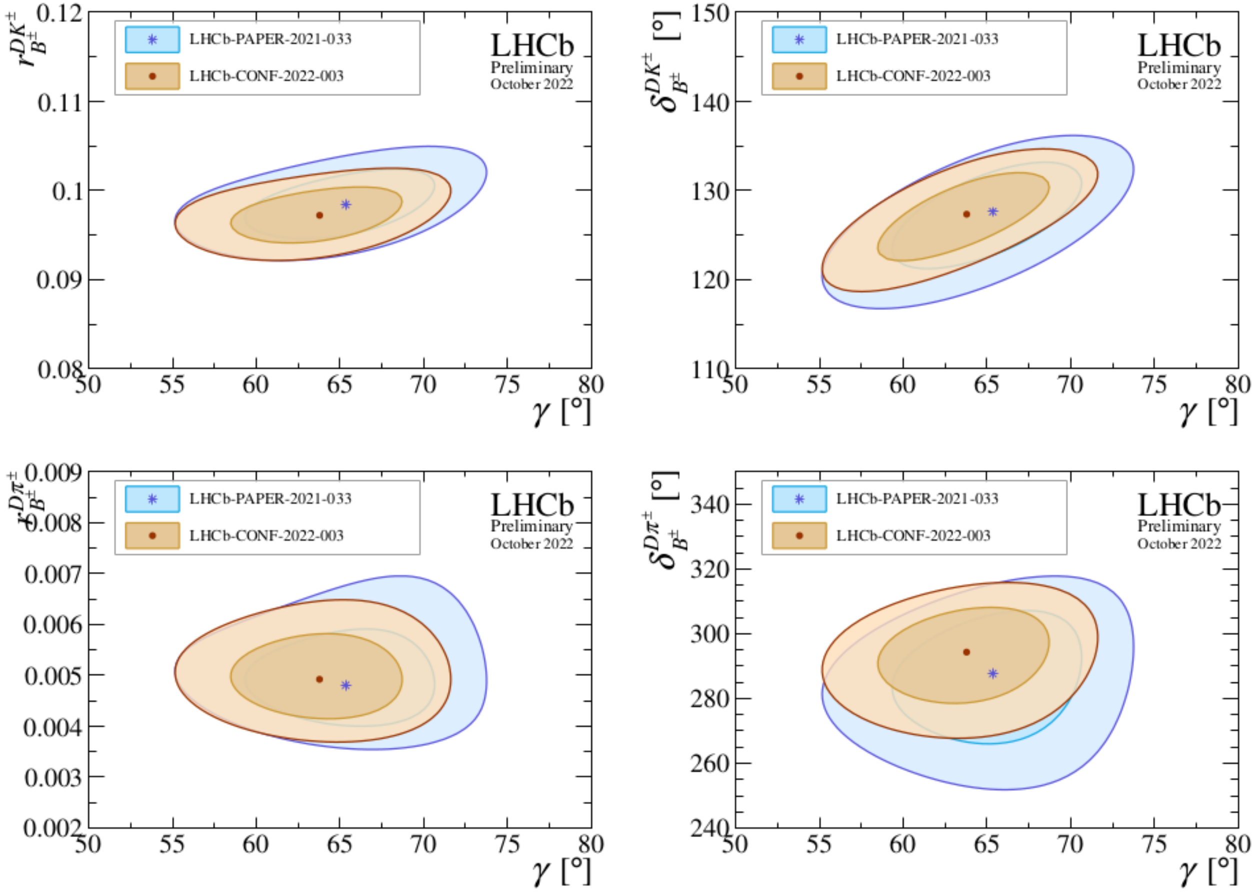
Table 3: Confidence intervals and central values for each of the parameters of interest, computed using the Feldman-Cousins *Plugin* method [63]. Entries marked with an asterisk show where the scan has hit a physical boundary at the lower limit.

Quantity	Value	68.3% CL		95.4% CL	
		Uncertainty	Interval	Uncertainty	Interval
$\gamma[^\circ]$	63.8	$^{+3.5}_{-3.7}$	[60.1, 67.3]	$^{+6.9}_{-7.5}$	[56.3, 70.7]
$r_{B^{\pm}}^{DK^{\pm}}$	0.0972	$^{+0.0022}_{-0.0021}$	[0.0951, 0.0994]	$^{+0.0045}_{-0.0042}$	[0.0930, 0.1017]
$\delta_{B^{\pm}}^{DK^{\pm}}[^\circ]$	127.3	$^{+3.4}_{-3.5}$	[123.8, 130.7]	$^{+6.5}_{-7.3}$	[120.0, 133.8]
$r_{B^{\pm}}^{D\pi^{\pm}}$	0.00490	$^{+0.00059}_{-0.00053}$	[0.00437, 0.00549]	$^{+0.0013}_{-0.0010}$	[0.0039, 0.0062]
$\delta_{B^{\pm}}^{D\pi^{\pm}}[^\circ]$	294.0	$^{+9.7}_{-11}$	[283, 303.7]	$^{+19}_{-22}$	[272, 313]
$r_{B^{\pm}}^{D^*K^{\pm}}$	0.098	$^{+0.017}_{-0.019}$	[0.079, 0.115]	$^{+0.031}_{-0.037}$	[0.061, 0.129]
$\delta_{B^{\pm}}^{D^*K^{\pm}}[^\circ]$	308	$^{+12}_{-25}$	[283, 320]	$^{+21}_{-69}$	[239, 329]
$r_{B^{\pm}}^{D^*\pi^{\pm}}$	0.0091	$^{+0.0081}_{-0.0056}$	[0.0035, 0.0172]	$^{+0.016}_{-0.0085}$	[0.0006, 0.025]
$\delta_{B^{\pm}}^{D^*\pi^{\pm}}[^\circ]$	137	$^{+22}_{-83}$	[54, 159]	$^{+32}_{-130}$	[7, 169]
$r_{B^{\pm}}^{DK^{*\pm}}$	0.108	$^{+0.016}_{-0.019}$	[0.089, 0.124]	$^{+0.030}_{-0.039}$	[0.069, 0.138]
$\delta_{B^{\pm}}^{DK^{*\pm}}[^\circ]$	34	$^{+20}_{-15}$	[19, 54]	$^{+54}_{-28}$	[6, 88]
$r_{B^0}^{DK^{*0}}$	0.249	$^{+0.022}_{-0.025}$	[0.224, 0.271]	$^{+0.044}_{-0.051}$	[0.198, 0.293]
$\delta_{B^0}^{DK^{*0}}[^\circ]$	198	$^{+10}_{-9.6}$	[188.4, 208]	$^{+24}_{-19}$	[179, 222]
$r_{B_s^0}^{D_s^{\mp}K^{\pm}}$	0.310	$^{+0.096}_{-0.094}$	[0.216, 0.406]	$^{+0.20}_{-0.22}$	[0.09, 0.51]
$\delta_{B_s^0}^{D_s^{\mp}K^{\pm}}[^\circ]$	356	$^{+19}_{-18}$	[338, 375]	$^{+39}_{-38}$	[318, 395]
$r_{B_s^0}^{D_s^{\mp}K^{\pm}\pi^+\pi^-}$	0.460	$^{+0.081}_{-0.085}$	[0.375, 0.541]	$^{+0.16}_{-0.17}$	[0.29, 0.62]
$\delta_{B_s^0}^{D_s^{\mp}K^{\pm}\pi^+\pi^-}[^\circ]$	346	$^{+12}_{-12}$	[334, 358]	$^{+26}_{-25}$	[321, 372]
$r_{B^0}^{D^{\mp}\pi^{\pm}}$	0.030	$^{+0.016}_{-0.012}$	[0.018, 0.046]	$^{+0.041}_{-0.027}$	[0.003, 0.071]
$\delta_{B^0}^{D^{\mp}\pi^{\pm}}[^\circ]$	32	$^{+26}_{-40}$	[−8, 58]	$^{+45}_{-86}$	[−54, 77]
$r_{B^{\pm}}^{DK^{\pm}\pi^+\pi^-}$	0.079	$^{+0.028}_{-0.034}$	[0.045, 0.107]	$^{+0.049}_{-0.079}$	[0.000, 0.128]*
$r_{B^{\pm}}^{D\pi^{\pm}\pi^+\pi^-}$	0.068	$^{+0.026}_{-0.030}$	[0.038, 0.094]	$^{+0.039}_{-0.068}$	[0.000, 0.107]*
$x[\%]$	0.398	$^{+0.050}_{-0.049}$	[0.349, 0.448]	$^{+0.099}_{-0.10}$	[0.30, 0.497]
$y[\%]$	0.636	$^{+0.020}_{-0.019}$	[0.617, 0.656]	$^{+0.041}_{-0.039}$	[0.597, 0.677]
$r_D^{K\pi}[\%]$	5.865	$^{+0.014}_{-0.015}$	[5.850, 5.879]	$^{+0.029}_{-0.030}$	[5.835, 5.894]
$\delta_D^{K\pi}[^\circ]$	190.2	$^{+2.8}_{-2.8}$	[187.4, 193.0]	$^{+5.6}_{-6.1}$	[184.1, 195.8]
$\lvert q/p \rvert$	0.995	$^{+0.015}_{-0.016}$	[0.979, 1.010]	$^{+0.032}_{-0.032}$	[0.963, 1.027]
$\phi[^\circ]$	−2.5	$^{+1.2}_{-1.2}$	[−3.7, −1.3]	$^{+2.4}_{-2.5}$	[−5.0, −0.1]
$a_{K^+K^-}^{\mathrm{d}}[\%]$	0.090	$^{+0.057}_{-0.057}$	[0.033, 0.147]	$^{+0.11}_{-0.12}$	[−0.03, 0.20]
$a_{\pi^+\pi^-}^{\mathrm{d}}[\%]$	0.240	$^{+0.061}_{-0.062}$	[0.178, 0.301]	$^{+0.12}_{-0.12}$	[0.12, 0.36]

Table 4: Confidence intervals and best-fit values for γ when splitting the combination inputs by initial B meson species, computed using the Feldman-Cousins *Plugin* method [63].

Species	Value [°]	68.3% CL		95.4% CL	
		Uncertainty	Interval	Uncertainty	Interval
B^+	60.6	$^{+4.0}_{-3.8}$	[56.8, 64.6]	$^{+7.8}_{-7.5}$	[53.1, 68.4]
B^0	82.0	$^{+8.1}_{-8.8}$	[73.2, 90.1]	$^{+17}_{-18}$	[64, 99]
B_s^0	79	$^{+21}_{-24}$	[55, 100]	$^{+51}_{-47}$	[32, 130]

LHCb γ combination



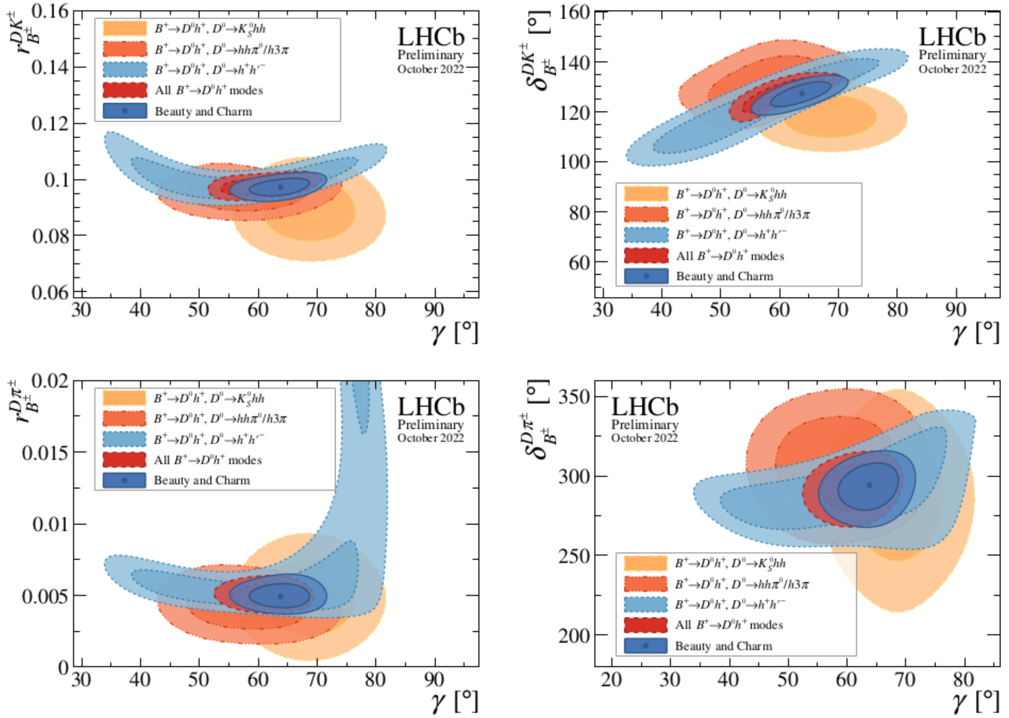


Figure 4: Profile likelihood contours for the components which contribute towards the γ part of the combination, showing the breakdown of sensitivity amongst different sub-combinations of modes. The contours shown are the two-dimensional 1σ and 2σ contours which correspond to the areas containing 68.3% and 95.4% of the distribution.