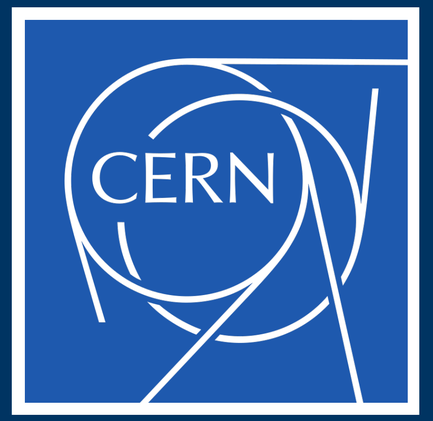
γ measurement and combination at LHCb

Federico Betti on behalf
of the LHCb collaboration

Implications of LHCb measurements
and future prospects

CERN — 22 October 2021



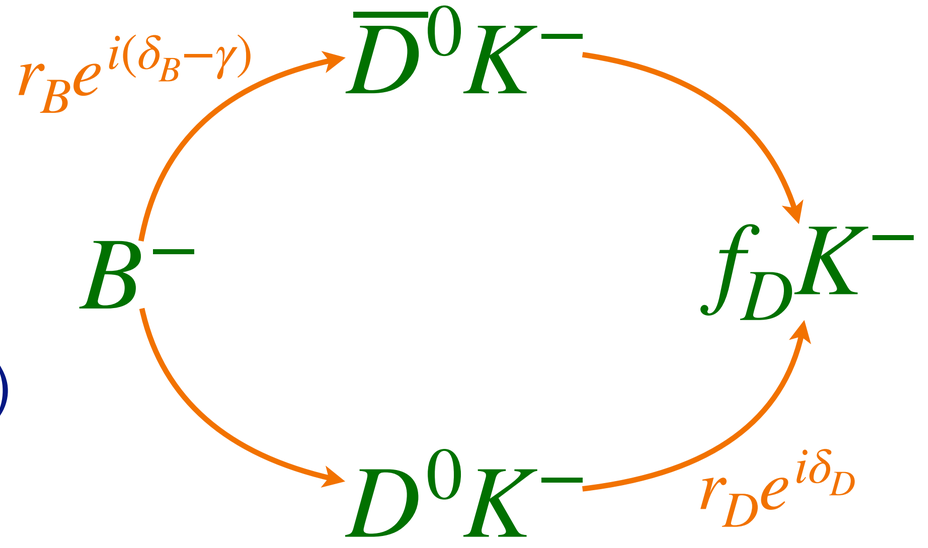
Introduction

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

- γ standard candle of SM
- Comparison between direct and indirect γ determinations is a test of SM
- γ measured in tree-level B decays that are theoretically clean
- SM uncertainties negligible $\sim (10^{-5})^\circ$ JHEP 01 (2014) 051
- New Physics can cause $\mathcal{O}(10^\circ)$ shift to γ PRD 92 (2015) 033002, JHEP 07 (2020) 177

Measuring γ

- γ measured in tree-level decays sensitive to interference between $b \to cW$ and $b \to uW$ transition amplitudes
- Golden modes: $B^{\pm} \to DK^{\pm}$
- Various methods according to D final state
  - GLW: CP eigenstates (e.g. KK, $\pi\pi$)
  - ADS: interference of CF and DCS transitions (e.g. $K\pi$)
  - BPGGSZ: 3-body final states (e.g. $K^0_s\pi\pi$)
- Time-dependent analyses of $B^0_{(s)}$ are also used



Previous status of γ

Unitarity constrained results:

CKMfitter

$$\gamma = (65.7^{+0.9}_{-2.7})^\circ$$

UTFit

$$\gamma = (65.8 \pm 2.2)^\circ$$

LHCb combination (2018): $\gamma = (74.4^{+5.0}_{-5.8})^\circ$

LHCb-CONF-2018-002

$B^- \to Dh^-, D \to K^0_s h^+ h^-$

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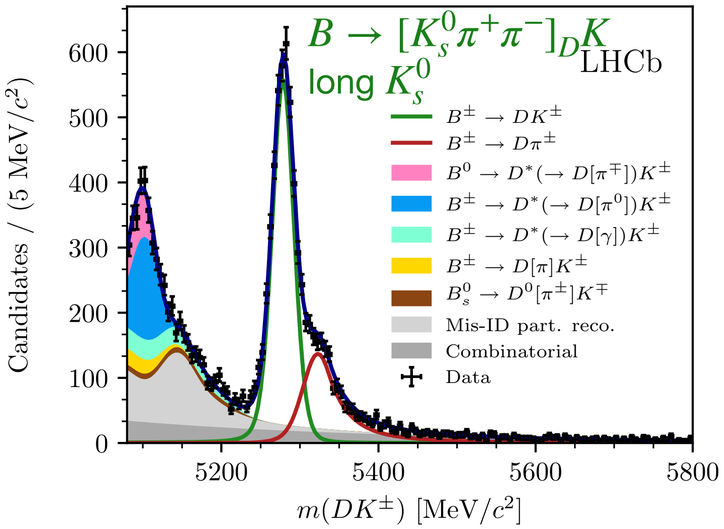
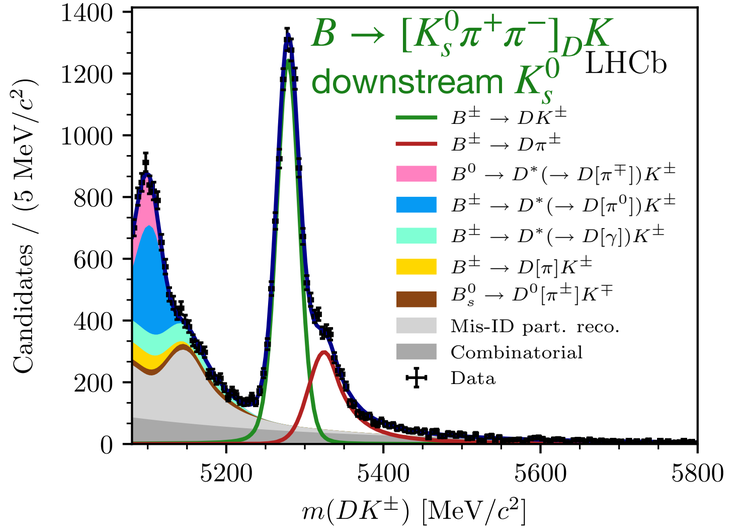
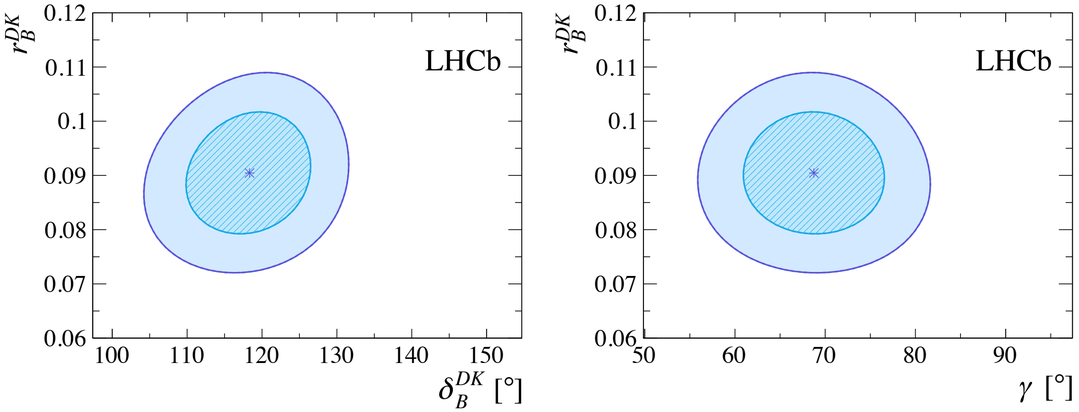
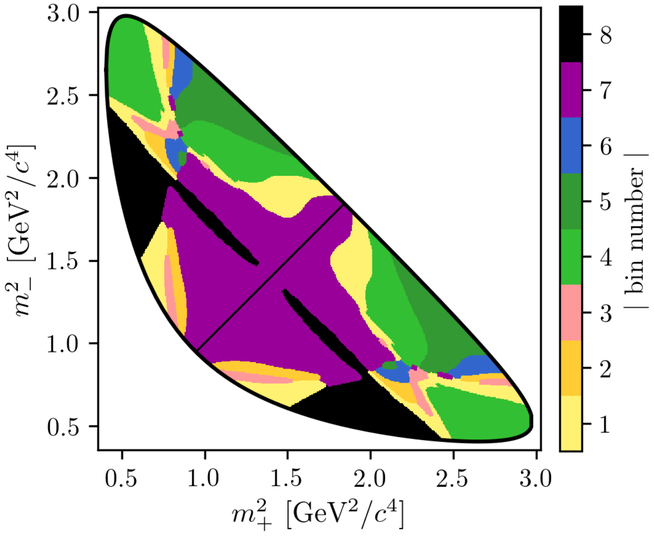
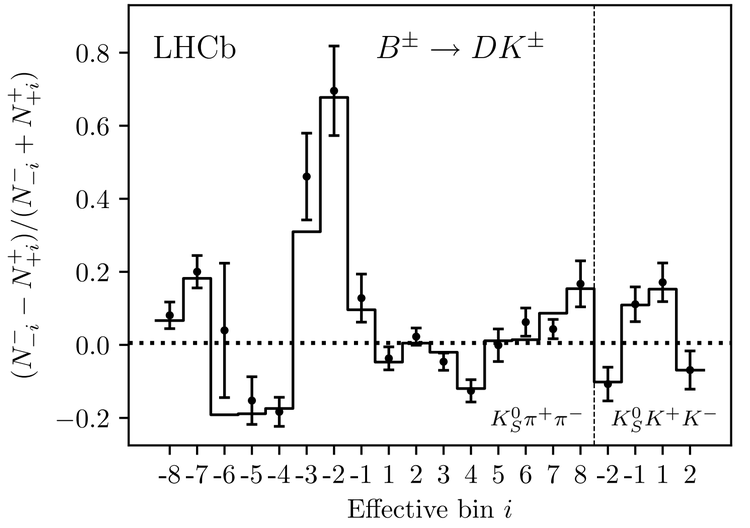
- Update with full Run 1 + Run 2
- Model-independent: analysis performed in Dalitz bins, using inputs from CLEO and BESIII
- $\gamma = (68.7^{+5.2}_{-5.1})^\circ$











$B^- \to D^{(*)}h^-, D \to h^+h'^-$

- Update with full Run 1 + Run 2
- Partial reconstruction method for $D^* \to D^0\pi^0, D^0\gamma$
- First observation of ADS $B^- \to (D\pi^0)_{D^*}\pi^-$
- $\gamma = (61.80 \pm 4.0)^\circ$ when combined with $K^0_S h^+h^-$ result

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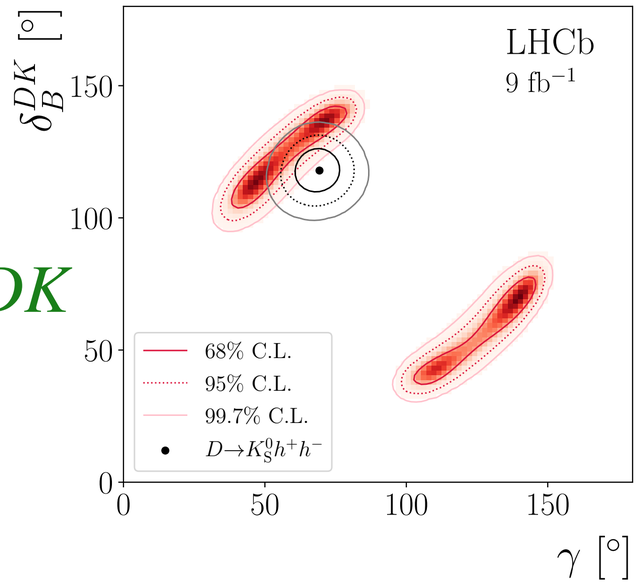
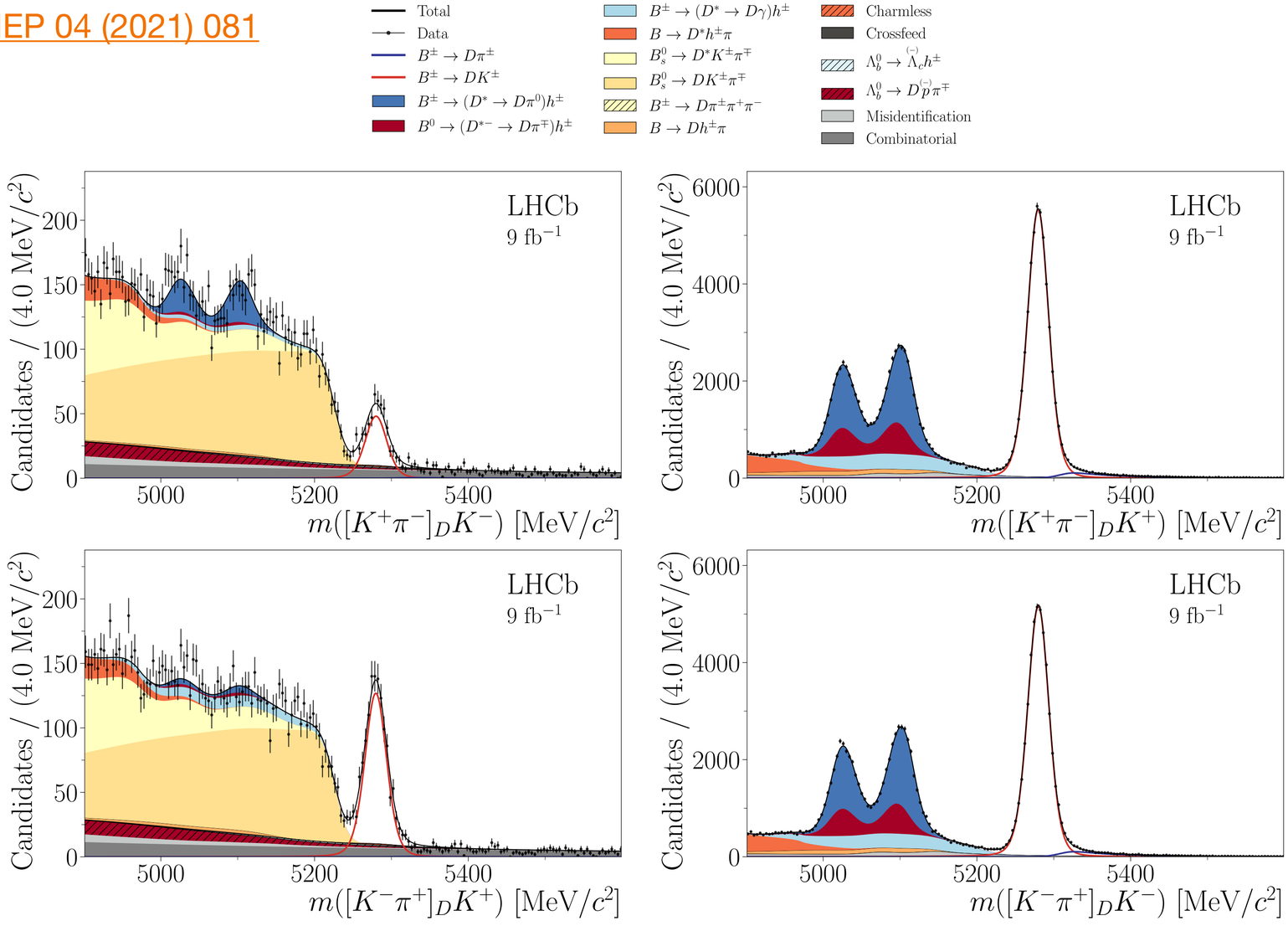
$B \to DK$





$B_s^0 \to D_s^{\mp} K^{\pm} \pi^+ \pi^-$, $D_s^+ \to h^+ h^- \pi^+$

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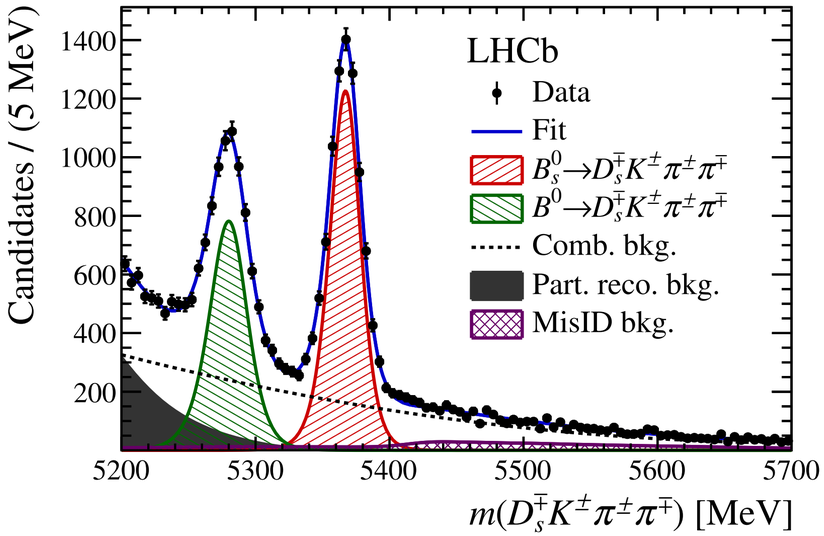
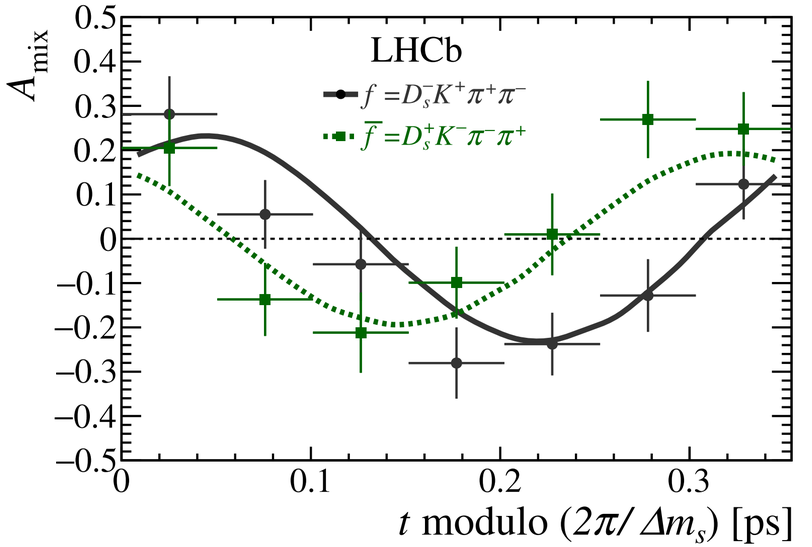
- New measurement with full Run 1 + Run 2
- Time-dependent amplitude analysis, takes ϕ_s as external input
- Less precise model-independent analysis
- $B_s^0 \to D_s^- \pi^+ \pi^+ \pi^-$ used as calibration
- $\gamma = (44^{+20}_{-13})^\circ$ modulo 180° with model-independent approach
- $\gamma = (44 \pm 12)^\circ$ modulo 180° with time-dependent amplitude analysis

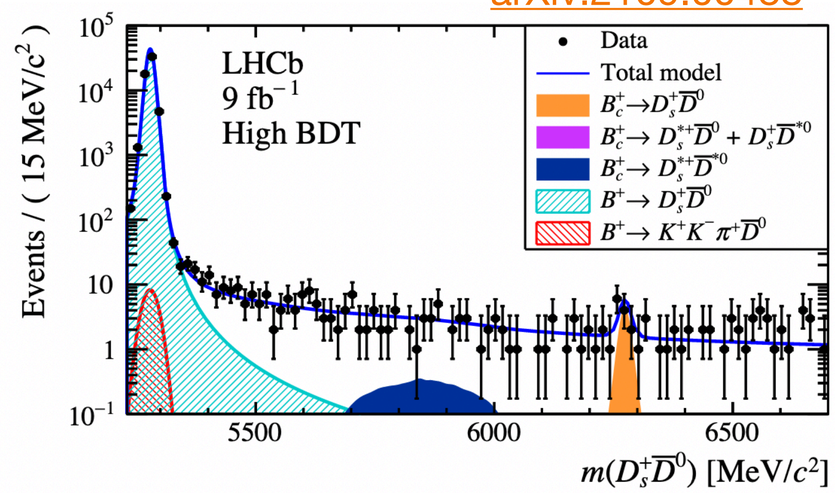


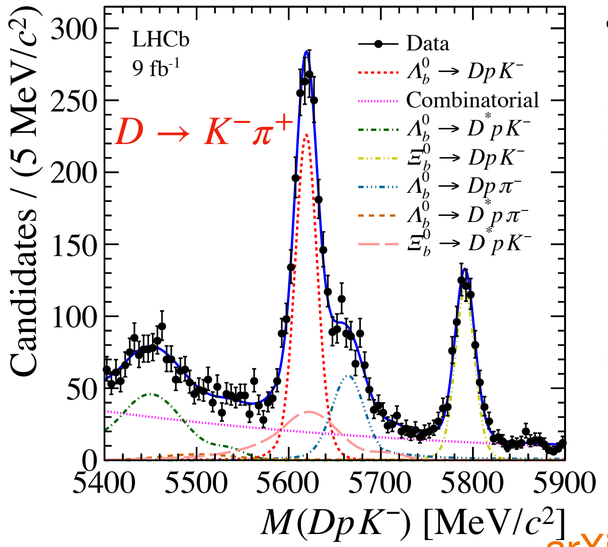


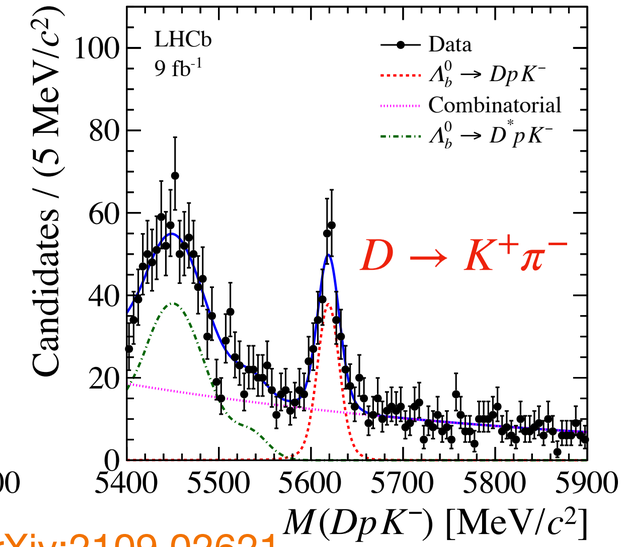
Other decay modes

- Recent measurements with full Run 1 + Run 2:
  - A_{CP} of $\Lambda_b^0 \to [K\pi]_D pK^-$
  - Search for $B_c^+ \to D_{(s)}^{(*)+} D^{(*)}$
- Potential to be sensitive to γ with future runs

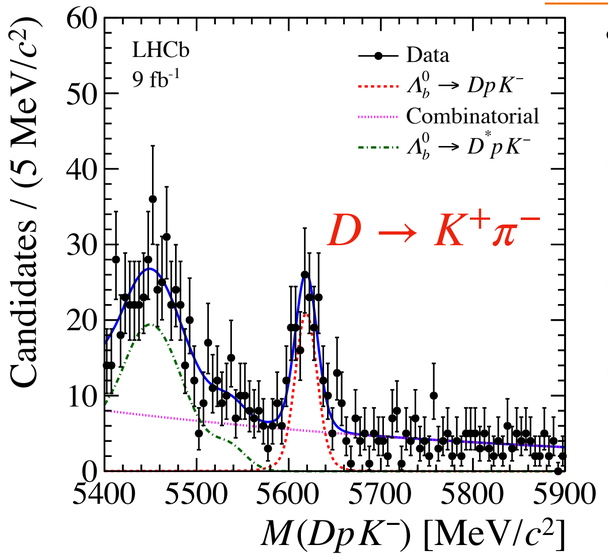
arXiv:2109.00488

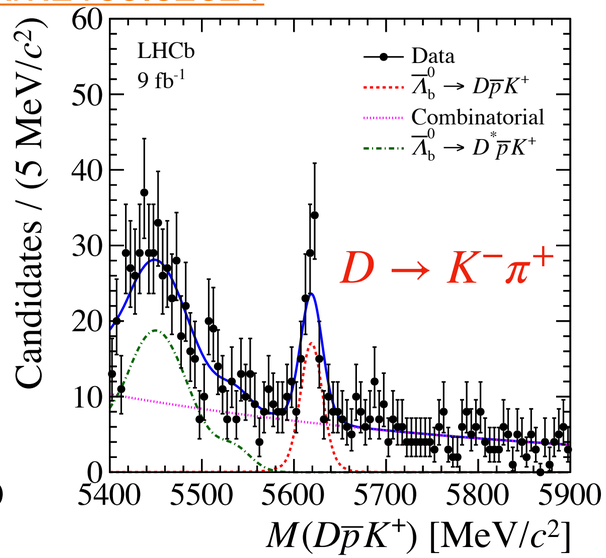






arXiv:2109.02621





LHCb γ + charm combination

- In the past, charm parameters (x_D, y_D, $\delta_D^{K\pi}$, $r_D^{K\pi}$) have been taken as external input from HFLAV
- $B^\pm \to DK^\pm$ with $D \to K^\pm\pi^\mp$ are sensitive to $\delta_D^{K\pi}$, if x_D, y_D and $r_D^{K\pi}$ are taken as input

$$A_{\text{fav}}^{K\pi} = \frac{2r_B^K r_D^{K\pi} \sin\left(\delta_B^K - \delta_D^{K\pi}\right) \sin\gamma}{1 + (r_B^K r_D^{K\pi})^2 + 2r_B^K r_D^{K\pi} \cos\left(\delta_B^K - \delta_D^{K\pi}\right) \cos\gamma}$$

$\Rightarrow$ best option is to combine LHCb charm+beauty results to constrain all four parameters

$\Rightarrow$ 8 charm measurements are included

arXiv:2110.02350

LHCb γ + charm combination

$$\frac{\Gamma(D^0 \to K^+\pi^-, t)}{\Gamma(D^0 \to K^-\pi^+, t)} \approx (r_D^{K\pi})^2 + r_D^{K\pi}(x_D \sin\delta_D^{K\pi} - y_D \cos\delta_D^{K\pi})\frac{t}{\tau}$$

- In charm measurements of $D^0 \to K^+\pi^-$ to $D^0 \to K^-\pi^+$ ratio, y_D and $\delta_D^{K\pi}$ are highly correlated ⇒ the charm+beauty combination improves precision on y_D
- Further motivation to include charm measurements: D mixing has significant effects on $B^\pm \to D\pi^\pm$

arXiv:2110.02350

LHCb γ + charm combination

- 7 new/updated beauty measurements
- 151 observables
- 52 free parameters
- Frequentist treatment (*Plugin* method)
- Cross-checked with Bayesian framework

B decay	D decay	Ref.	Dataset	Status since Ref. [24]
$B^\pm \to Dh^\pm$	$D \to h^+h^-$	[27]	Run 1&2	**Updated**
$B^\pm \to Dh^\pm$	$D \to h^+\pi^-\pi^+\pi^-$	[28]	Run 1	As before
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^0$	[29]	Run 1	As before
$B^\pm \to Dh^\pm$	$D \to K^0_S h^+h^-$	[26]	Run 1&2	**Updated**
$B^\pm \to Dh^\pm$	$D \to K^0_S K^\pm\pi^\mp$	[30]	Run 1&2	**Updated**
$B^\pm \to D^*h^\pm$	$D \to h^+h^-$	[27]	Run 1&2	**Updated**
$B^\pm \to DK^{*\pm}$	$D \to h^+h^-$	[31]	Run 1&2(*)	As before
$B^\pm \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[31]	Run 1&2(*)	As before
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+h^-$	[32]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to h^+h^-$	[33]	Run 1&2(*)	**Updated**
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	[33]	Run 1&2(*)	**New**
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	[34]	Run 1	As before
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	[35]	Run 1	As before
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	[36]	Run 1	As before
$B^0_s \to D^\mp_s K^\pm\pi^+\pi^-$	$D^+_s \to h^+h^-\pi^+$	[37]	Run 1&2	**New**
–	$D^0 \to h^+h^-$	[38–40]	Run 1&2	**New**
–	$D^0 \to h^+h^-$	[41]	Run 1	**New**
–	$D^0 \to h^+h^-$	[42–45]	Run 1&2	**New**
–	$D^0 \to K^+\pi^-$	[46]	Run 1	**New**
–	$D^0 \to K^+\pi^-$	[47]	Run 1&2(*)	**New**
–	$D^0 \to K^\pm\pi^\mp\pi^+\pi^-$	[48]	Run 1	**New**
–	$D^0 \to K^0_S\pi^+\pi^-$	[49,50]	Run 1&2	**New**
–	$D^0 \to K^0_S\pi^+\pi^-$	[51]	Run 1	**New**

arXiv:2110.02350

Auxiliary inputs

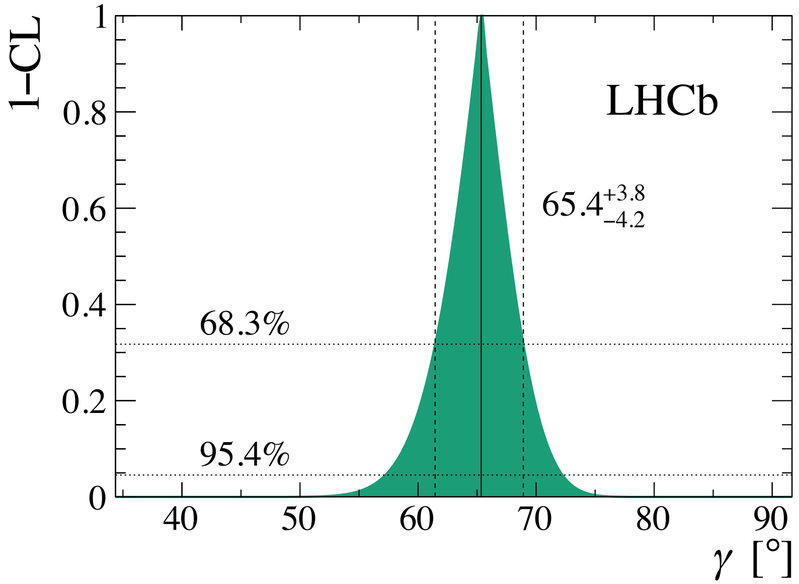
External constraints needed for hadronic parameters and coherence factors in multibody B and D decays

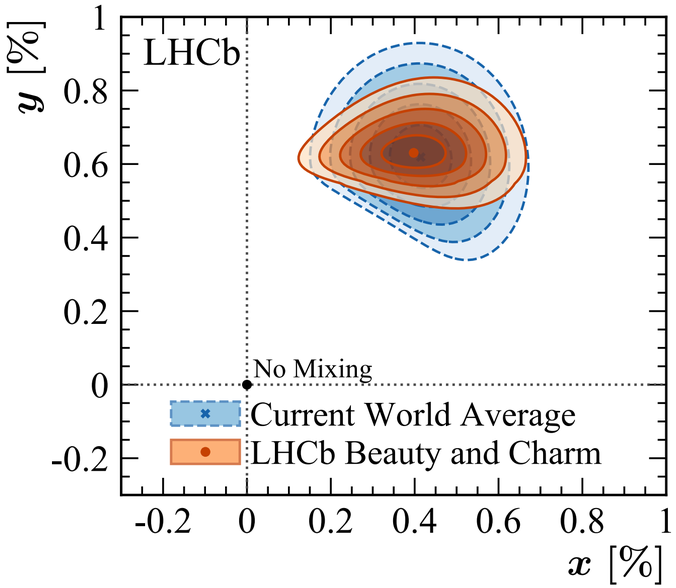
arXiv:2110.02350

Decay	Parameters	Source	Ref.	Status since Ref. [24]
$B^\pm \to DK^{*\pm}$	$\kappa_{B^\pm}^{DK^{*\pm}}$	LHCb	[31]	As before
$B^0 \to DK^{*0}$	$\kappa_{B^0}^{DK^{*0}}$	LHCb	[52]	As before
$B^0 \to D^\mp\pi^\pm$	β	HFLAV	[18]	**Updated**
$B_s^0 \to D_s^\mp K^\pm(\pi\pi)$	ϕ_s	HFLAV	[18]	**Updated**
$D \to h^+h^-\pi^0$	$F^+_{\pi\pi\pi^0}$, $F^+_{K\pi\pi^0}$	CLEO-c	[53]	As before
$D \to \pi^+\pi^-\pi^+\pi^-$	$F^+_{4\pi}$	CLEO-c	[53]	As before
$D \to K^+\pi^-\pi^0$	$r_D^{K\pi\pi^0}$, $\delta_D^{K\pi\pi^0}$, $\kappa_D^{K\pi\pi^0}$	CLEO-c+LHCb+BESIII	[48, 54–56]	**Updated**
$D \to K^\pm\pi^\mp\pi^+\pi^-$	$r_D^{K3\pi}$, $\delta_D^{K3\pi}$, $\kappa_D^{K3\pi}$	CLEO-c+LHCb+BESIII	[48, 54–56]	**Updated**
$D \to K^0_S K^\pm\pi^\mp$	$r_D^{K^0_S K\pi}$, $\delta_D^{K^0_S K\pi}$, $\kappa_D^{K^0_S K\pi}$	CLEO	[57]	As before
$D \to K^0_S K^\pm\pi^\mp$	$r_D^{K^0_S K\pi}$	LHCb	[58]	As before

Results

$$\gamma = (65.4^{+3.8}_{-4.2})^\circ$$





arXiv:2110.02350

$$x_D = (4.00^{+0.52}_{-0.53}) \times 10^{-3}$$

$$y_D = (6.30^{+0.33}_{-0.30}) \times 10^{-3}$$

$$\delta_D^{K\pi} = (190.0^{+4.2}_{-4.1})^\circ$$

$$r_D^{K\pi} = (58.67 \pm 0.15) \times 10^{-3}$$

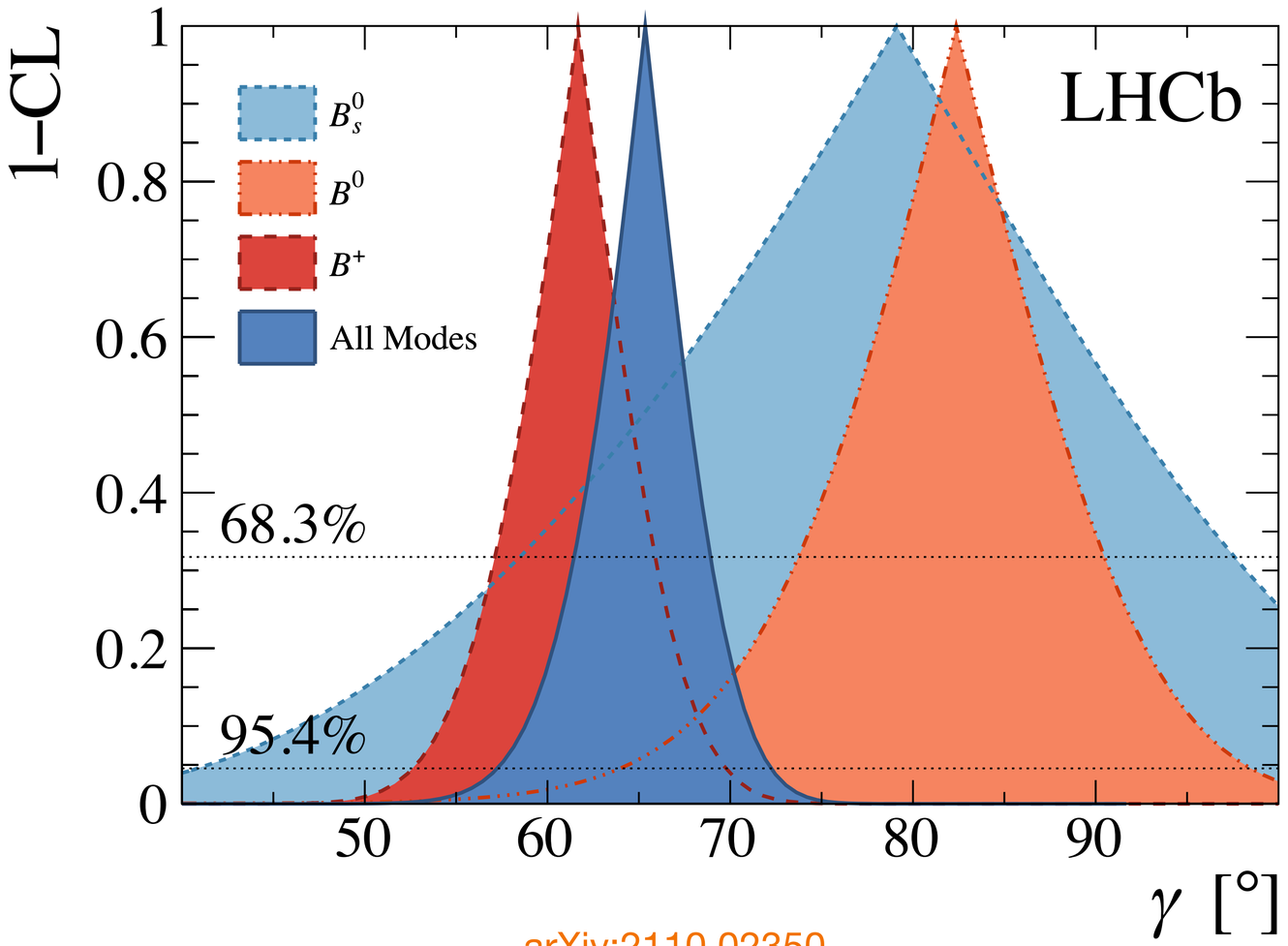
- Excellent precision on γ
- Agreement with indirect global CKM fitters: CKMfitter $\gamma = (65.7^{+0.9}_{-2.7})^\circ$ UTFit $\gamma = (65.8 \pm 2.2)^\circ$

New world average: HFLAV $\gamma = (66.2^{+3.4}_{-3.6})^\circ$

Breakdowns

Combinations for different B species

Species	Value [°]	68.3% CL	
		Uncertainty	Interval
B^+	61.7	$^{+4.4}_{-4.8}$	$[56.9, 66.1]$
B^0	82.0	$^{+8.1}_{-8.8}$	$[73.2, 90.1]$
B^0_s	79	$^{+21}_{-24}$	$[55, 100]$



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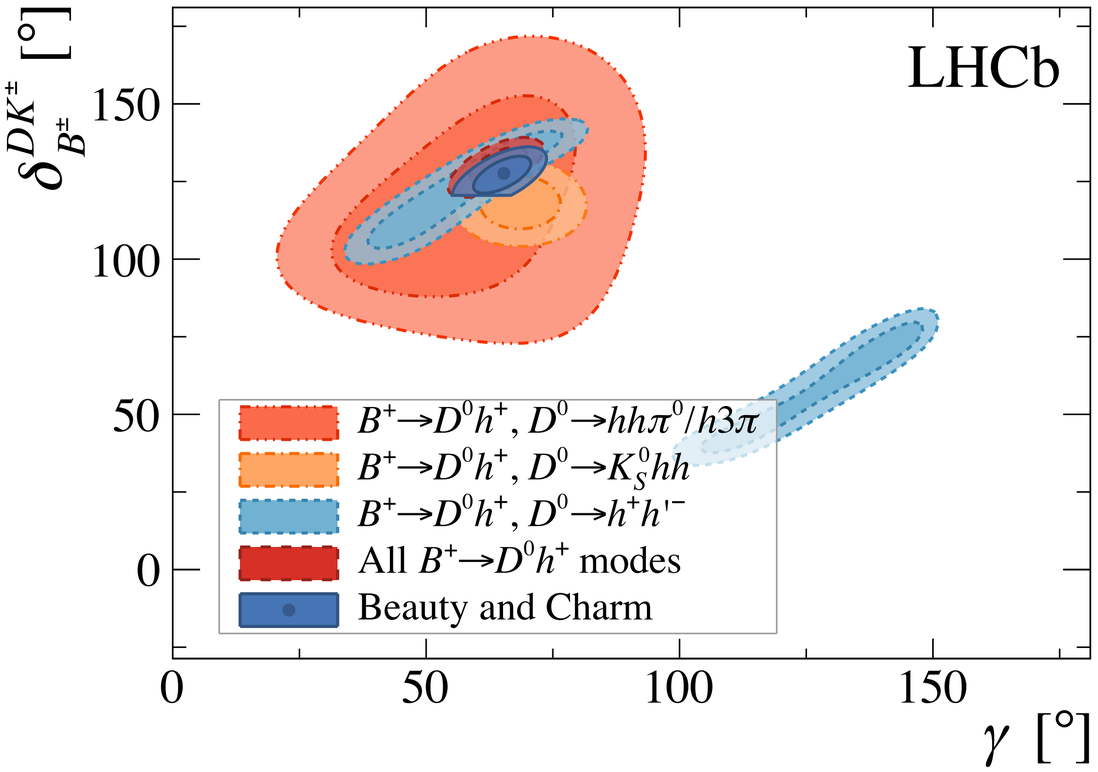
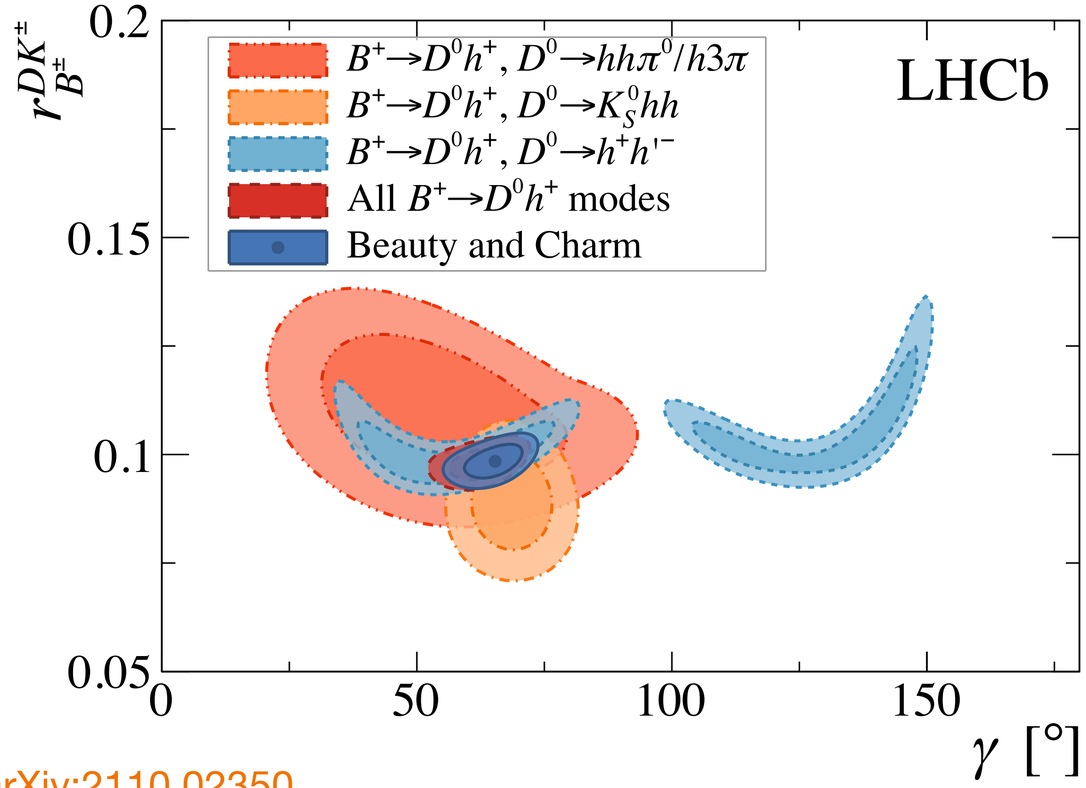
Breakdowns

Combinations for different D decays for most sensitive modes





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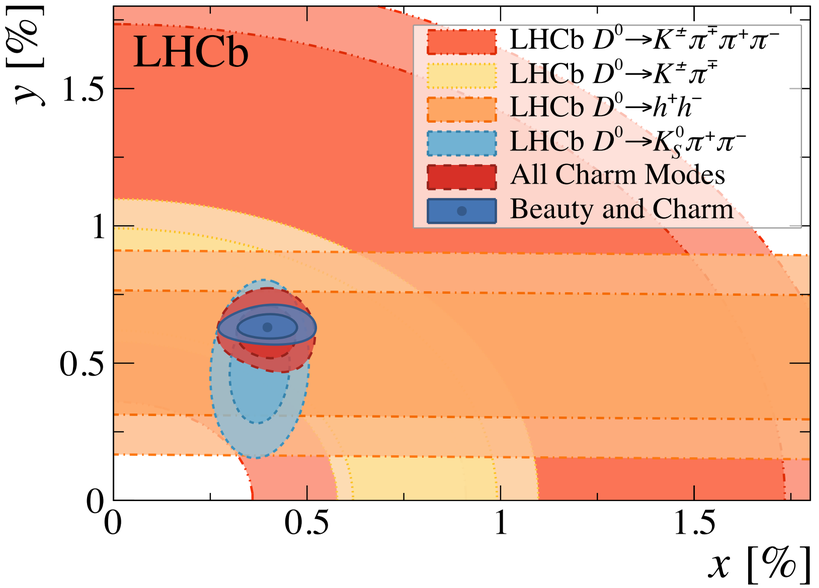
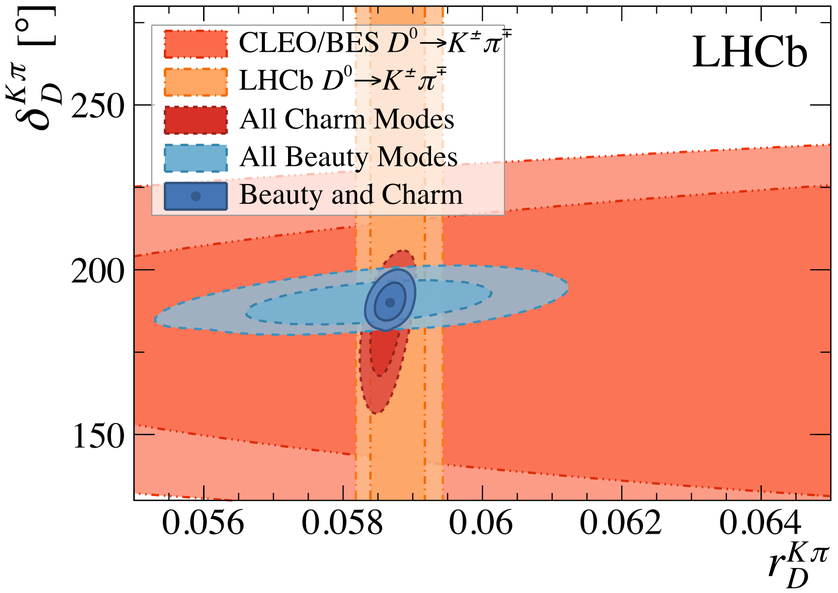
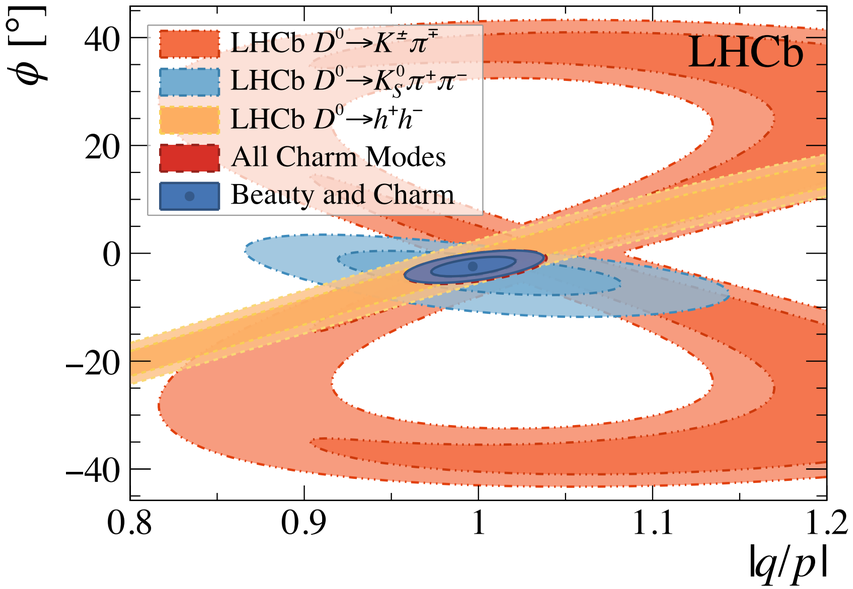
Breakdowns

Complementarity of beauty and charm on charm parameters







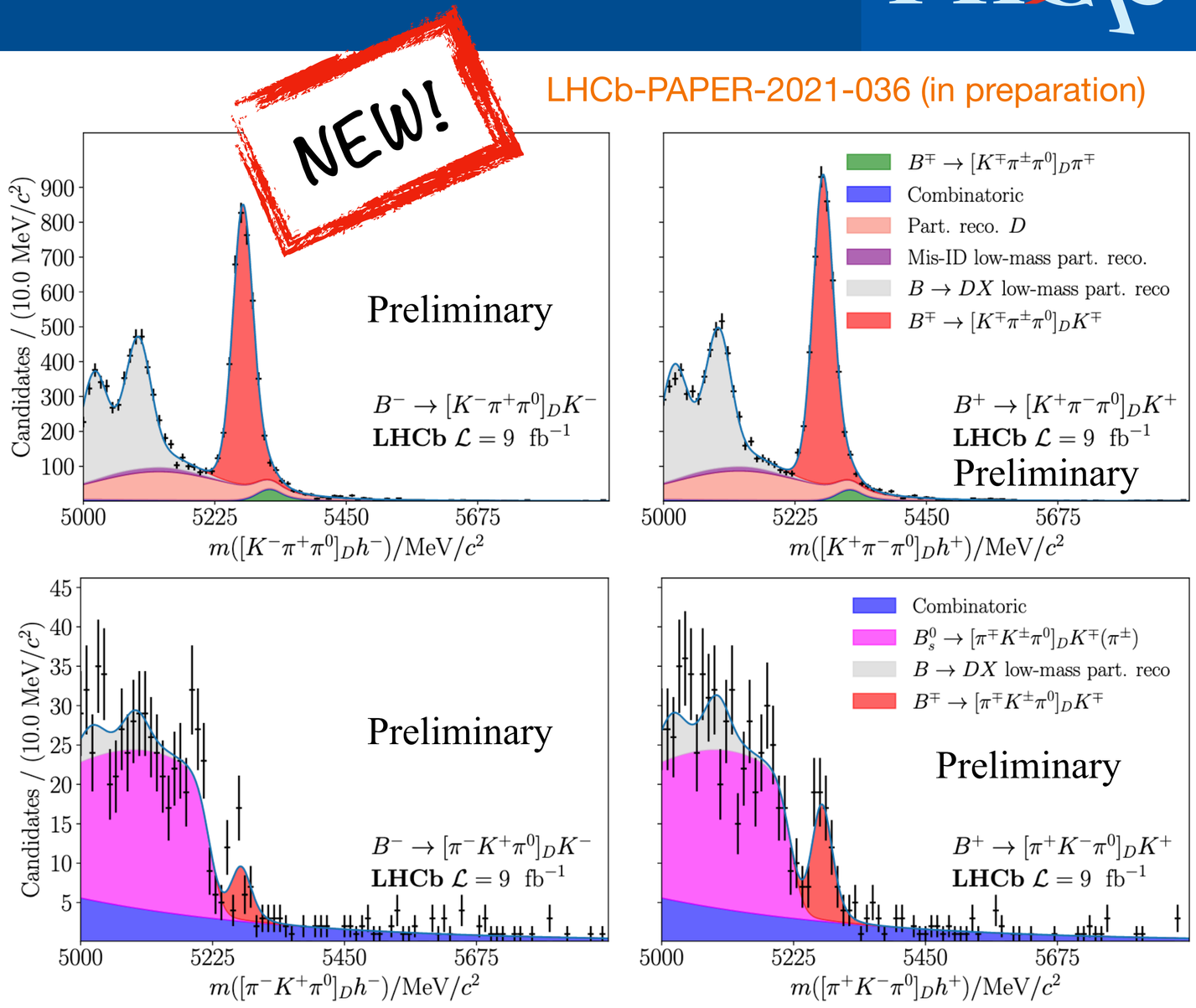
Precision on $\delta_D^{K\pi}$ and y_D improved by almost a factor 2

arXiv:2110.02350

$B^- \to Dh^-, D \to h^+h^-\pi^0$

- Update with full Run 1 + Run 2
- Quasi-ADS and quasi-GLW modes ⇒ use dilution factors taken from external inputs
- Observation of suppressed $B^- \to [\pi^-K^+\pi^0]_D K^-$ with more than 7σ significance

LHCb-PAPER-2021-036 (in preparation)



$B^- \to Dh^-, D \to h^+h^-\pi^0$

- Global minimum at $\gamma = (145^{+9}_{-39})^\circ$
- Second solution consistent with combination

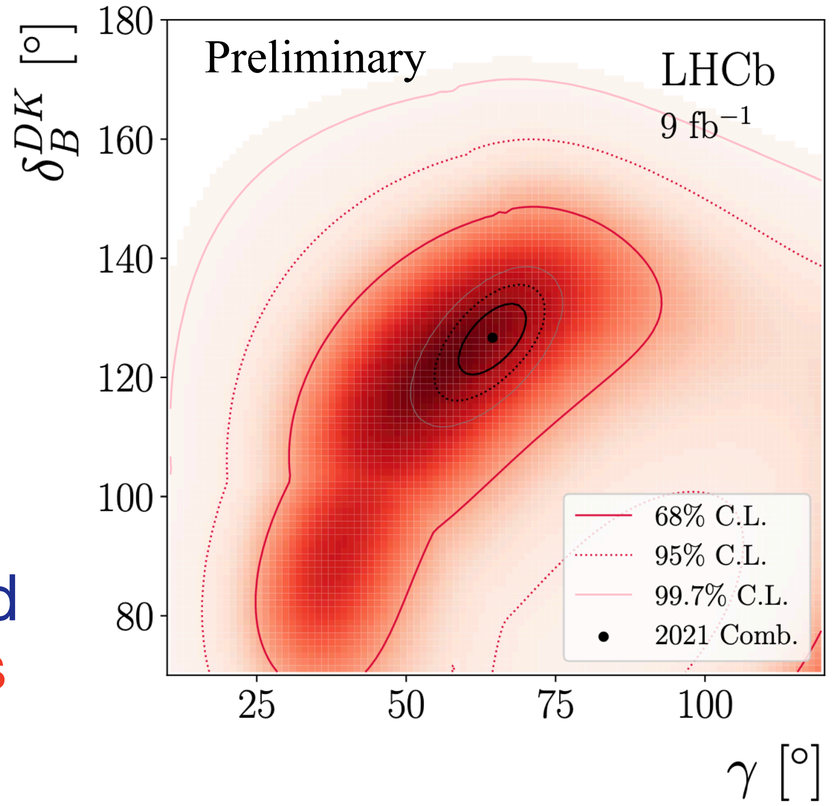
$$\gamma = (56^{+24}_{-19})^\circ$$

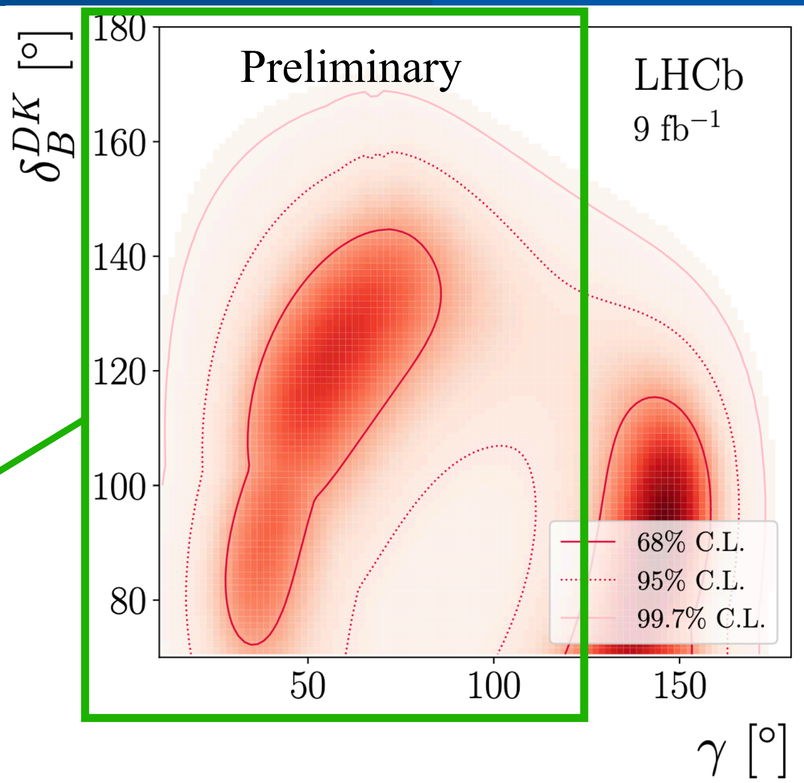
$$\delta_B = (122^{+19}_{-23})^\circ$$

$$r_B = (9.25^{+1.04}_{-0.85}) \times 10^{-2}$$

- This result will be used in future combinations

NEW!

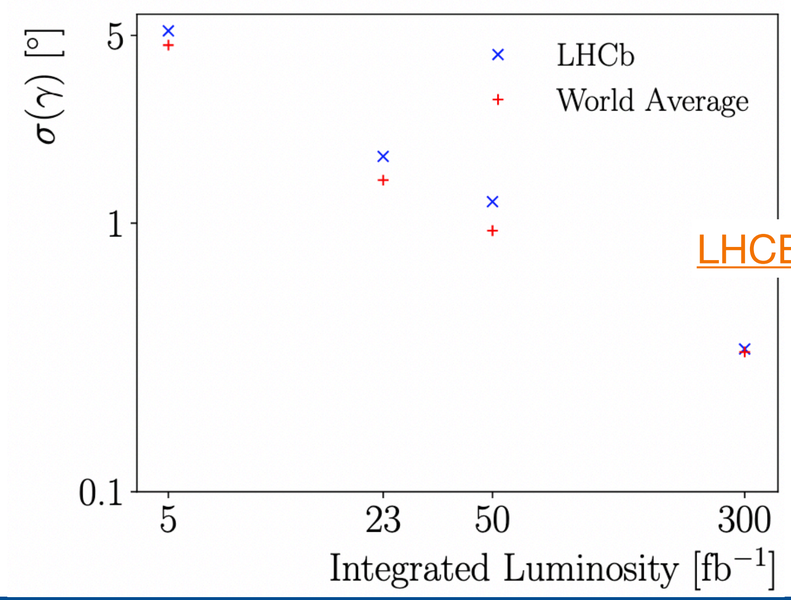




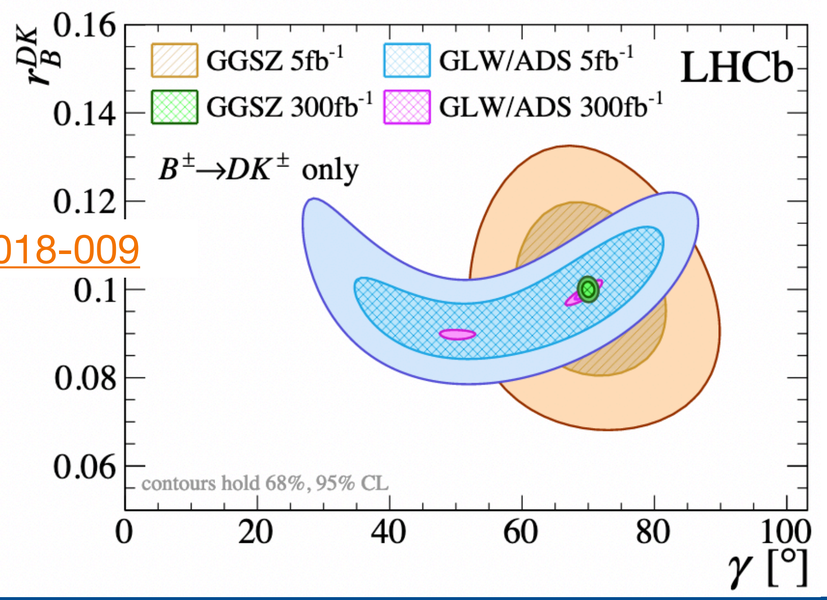
LHCb-PAPER-2021-036 (in preparation)

Future prospects

- Other $B \to Dh$ measurements ongoing with Run 2 data (e.g. $B \to [K\pi\pi\pi]_D h$)
- Sensitivity of $B^0 \to [K^0_s h^+ h^-]_D K^+\pi^-$ and $B^0_s \to D^\mp_s K^\pm$ is expected to increase by a factor 2 with Run 2 data
- Upgrades will be fundamental to increase precision on γ



LHCB-PUB-2018-009



Conclusions

- Many recent results by LHCb with full data sample to determine γ
- LHCb combination: $\gamma = (65.4^{+3.8}_{-4.2})^\circ$
- New measurements and updates with Run 2 data still ongoing
- LHCb upgrades aim for $< 1^\circ$ precision on γ

Backup

Assumptions

- $K^0 - \overline{K}^0$ mixing
  - For $D \to K^0_S h^+ h^-$: $\mathcal{O}(10^{-3})$ relative shift on γ, also taken into account in systematics
  - For $D \to K^0_S K^\pm \pi^\mp$: larger effect, but sensitivity of the related measurement to γ is low
- Assume $U-$spin symmetry when considering CP violation in $D \to h^+ h^-$ in the beauty sector: 0.3° effect
- Neglect CP violation in charm mixing in beauty sector: 0.1° effect
- Correlation of systematics between measurements: negligible effect because the combination is statistically dominated (3.3° out of 3.6°)

Results

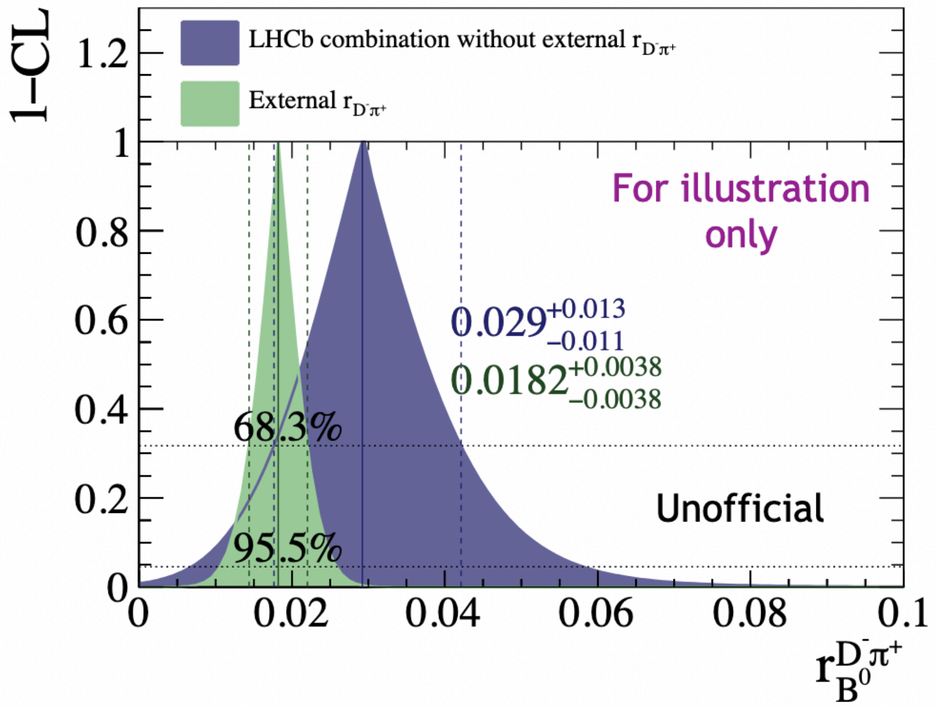
Quantity	Value	68.3% CL		95.4% CL	
		Uncertainty	Interval	Uncertainty	Interval
γ [°]	65.4	$^{+3.8}_{-4.2}$	[61.2, 69.2]	$^{+7.5}_{-8.7}$	[56.7, 72.9]
$r_{B^\pm}^{DK^\pm}$	0.0984	$^{+0.0027}_{-0.0026}$	[0.0958, 0.1011]	$^{+0.0056}_{-0.0052}$	[0.0932, 0.1040]
$\delta_{B^\pm}^{DK^\pm}$ [°]	127.6	$^{+4.0}_{-4.2}$	[123.4, 131.6]	$^{+7.8}_{-9.2}$	[118.4, 135.4]
$r_{B^\pm}^{D\pi^\pm}$	0.00480	$^{+0.00070}_{-0.00056}$	[0.00424, 0.00550]	$^{+0.0017}_{-0.0011}$	[0.0037, 0.0065]
$\delta_{B^\pm}^{D\pi^\pm}$ [°]	288	$^{+14}_{-15}$	[273, 302]	$^{+26}_{-31}$	[257, 314]
$r_{B^\pm}^{D^*K^\pm}$	0.099	$^{+0.016}_{-0.019}$	[0.080, 0.115]	$^{+0.030}_{-0.038}$	[0.061, 0.129]
$\delta_{B^\pm}^{D^*K^\pm}$ [°]	310	$^{+12}_{-23}$	[287, 322]	$^{+20}_{-71}$	[239, 330]
$r_{B^\pm}^{D^*\pi^\pm}$	0.0095	$^{+0.0085}_{-0.0061}$	[0.0034, 0.0180]	$^{+0.017}_{-0.0089}$	[0.0006, 0.026]
$\delta_{B^\pm}^{D^*\pi^\pm}$ [°]	139	$^{+22}_{-86}$	[53, 161]	$^{+32}_{-129}$	[10, 171]
$r_{B^\pm}^{DK^{*\pm}}$	0.106	$^{+0.017}_{-0.019}$	[0.087, 0.123]	$^{+0.031}_{-0.040}$	[0.066, 0.137]
$\delta_{B^\pm}^{DK^{*\pm}}$ [°]	35	$^{+20}_{-15}$	[20, 55]	$^{+57}_{-28}$	[7, 92]
$r_{B^0}^{DK^{*0}}$	0.250	$^{+0.023}_{-0.024}$	[0.226, 0.273]	$^{+0.044}_{-0.052}$	[0.198, 0.294]
$\delta_{B^0}^{DK^{*0}}$ [°]	197	$^{+10}_{-9.3}$	[187.7, 207]	$^{+24}_{-18}$	[179, 221]
$r_{B_s^0}^{D_s^\mp K^\pm}$	0.310	$^{+0.098}_{-0.092}$	[0.218, 0.408]	$^{+0.20}_{-0.21}$	[0.10, 0.51]

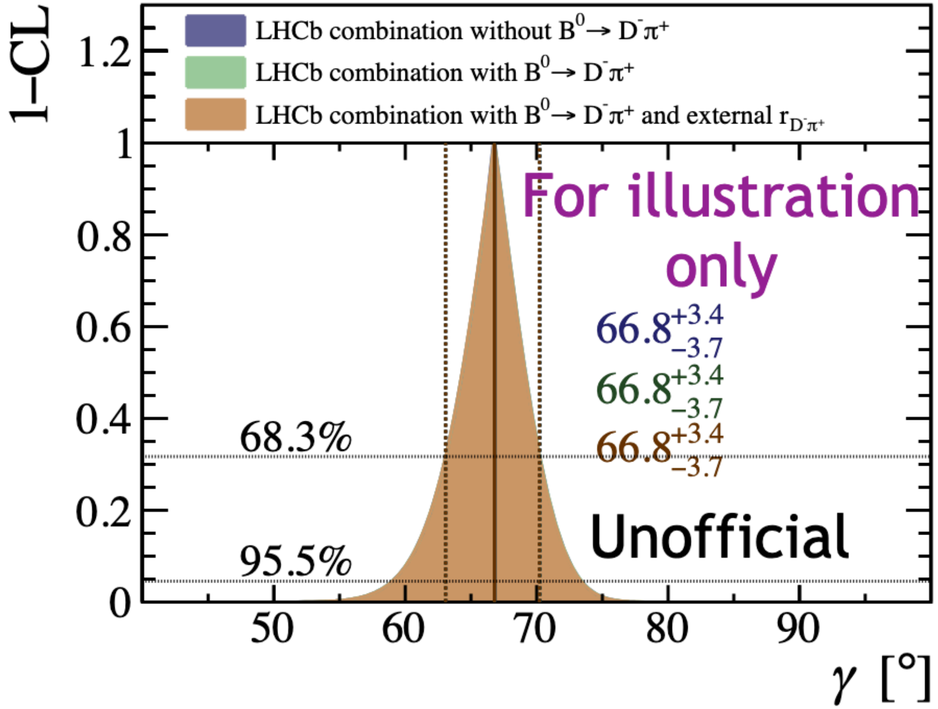
Results

Quantity	Value	68.3% CL		95.4% CL	
		Uncertainty	Interval	Uncertainty	Interval
$\delta_{B_s^0}^{D_s^\mp K^\pm}$ [°]	356	$^{+19}_{-18}$	[338, 375]	$^{+39}_{-39}$	[317, 395]
$r_{B_s^0}^{D_s^\mp K^\pm\pi^+\pi^-}$	0.460	$^{+0.081}_{-0.084}$	[0.376, 0.541]	$^{+0.16}_{-0.17}$	[0.29, 0.62]
$\delta_{B_s^0}^{D_s^\mp K^\pm\pi^+\pi^-}$ [°]	345	$^{+13}_{-12}$	[333, 358]	$^{+26}_{-25}$	[320, 371]
$r_{B^0}^{D^\mp\pi^\pm}$	0.030	$^{+0.014}_{-0.012}$	[0.018, 0.044]	$^{+0.036}_{-0.028}$	[0.002, 0.066]
$\delta_{B^0}^{D^\mp\pi^\pm}$ [°]	30	$^{+26}_{-37}$	[−7, 56]	$^{+45}_{-81}$	[−51, 75]
$r_{B^\pm}^{DK^\pm\pi^+\pi^-}$	0.079	$^{+0.028}_{-0.034}$	[0.045, 0.107]	$^{+0.050}_{-0.079}$	[0.000, 0.129]*
$r_{B^\pm}^{D\pi^\pm\pi^+\pi^-}$	0.067	$^{+0.025}_{-0.029}$	[0.038, 0.092]	$^{+0.040}_{-0.067}$	[0.000, 0.107]*
x [%]	0.400	$^{+0.052}_{-0.053}$	[0.347, 0.452]	$^{+0.10}_{-0.11}$	[0.29, 0.50]
y [%]	0.630	$^{+0.033}_{-0.030}$	[0.600, 0.663]	$^{+0.069}_{-0.058}$	[0.572, 0.699]
$r_D^{K\pi}$	0.05867	$^{+0.00015}_{-0.00015}$	[0.05852, 0.05882]	$^{+0.00031}_{-0.00030}$	[0.05837, 0.05898]
$\delta_D^{K\pi}$ [°]	190.0	$^{+4.2}_{-4.1}$	[185.9, 194.2]	$^{+8.6}_{-8.3}$	[181.7, 198.6]
$\lvert q/p\rvert$	0.997	$^{+0.016}_{-0.016}$	[0.981, 1.013]	$^{+0.033}_{-0.033}$	[0.964, 1.030]
ϕ [°]	−2.4	±1.2	[−3.6, −1.2]	±2.5	[−4.9, 0.1]
ΔA_{CP}	−0.00152	±0.00029	[−0.00181, −0.00123]	±0.00058	[−0.00210, −0.00094]

Input for $B^0 \to D^-\pi^+$

- Previously $r_B^{D^-\pi^+}$ was taken as external input from theory
- Now $r_B^{D^-\pi^+}$ is determined by the combination
- $r_B^{D^-\pi^+}$ found to be consistent with theoretical value
- γ totally unaffected by how $r_B^{D^-\pi^+}$ is treated





$B^- \to Dh^-, D \to h^+h^-\pi^0$

$R_{F+}^{KK\pi^0}$	$=$	1.021	$\pm$	0.079	$\pm$	0.005
$R_{F+}^{\pi\pi\pi^0}$	$=$	0.902	$\pm$	0.041	$\pm$	0.004
$A_K^{K\pi\pi^0}$	$=$	-0.024	$\pm$	0.013	$\pm$	0.002
$A_K^{KK\pi^0}$	$=$	0.067	$\pm$	0.073	$\pm$	0.003
$A_K^{\pi\pi\pi^0}$	$=$	0.109	$\pm$	0.043	$\pm$	0.003
$A_\pi^{KK\pi^0}$	$=$	-0.001	$\pm$	0.019	$\pm$	0.002
$A_\pi^{\pi\pi\pi^0}$	$=$	0.001	$\pm$	0.010	$\pm$	0.002
R_K^+	$=$	0.0179	$\pm$	0.0024	$\pm$	0.0003
R_K^-	$=$	0.0085	$\pm$	0.0020	$\pm$	0.0004
R_π^+	$=$	0.00188	$\pm$	0.00027	$\pm$	0.00005
R_π^-	$=$	0.00227	$\pm$	0.00028	$\pm$	0.00004
$R_{\mathrm{ADS}(K)}$	$=$	0.0127	$\pm$	0.0016	$\pm$	0.0002
$A_{\mathrm{ADS}(K)}$	$=$	-0.38	$\pm$	0.12	$\pm$	0.02
$R_{\mathrm{ADS}(\pi)}$	$=$	0.00207	$\pm$	0.00020	$\pm$	0.00003
$A_{\mathrm{ADS}(\pi)}$	$=$	0.069	$\pm$	0.094	$\pm$	$0.016,$

NEW!

LHCb-PAPER-2021-036 (in preparation)

$$R_{F+}^{KK\pi^0} \approx R_{K/\pi}^{KK\pi^0}/R_{K/\pi}^{K\pi\pi^0}, \qquad R_{F+}^{\pi\pi\pi^0} \approx R_{K/\pi}^{\pi\pi\pi^0}/R_{K/\pi}^{K\pi\pi^0}$$

$$A_K^{K\pi\pi^0} = \frac{\Gamma(B^- \to [K^-\pi^+\pi^0]_D K^-) - \Gamma(B^+ \to [K^+\pi^-\pi^0]_D K^+)}{\Gamma(B^- \to [K^-\pi^+\pi^0]_D K^-) + \Gamma(B^+ \to [K^+\pi^-\pi^0]_D K^+)}$$

$$A_{F+(K)}^{hh\pi^0} = \frac{\Gamma(B^- \to [hh\pi^0]_D K^-) - \Gamma(B^+ \to [hh\pi^0]_D K^+)}{\Gamma(B^- \to [hh\pi^0]_D K^-) + \Gamma(B^+ \to [hh\pi^0]_D K^+)}$$

$$A_{F+(\pi)}^{hh\pi^0} = \frac{\Gamma(B^- \to [hh\pi^0]_D \pi^-) - \Gamma(B^+ \to [hh\pi^0]_D \pi^+)}{\Gamma(B^- \to [hh\pi^0]_D \pi^-) + \Gamma(B^+ \to [hh\pi^0]_D \pi^+)}$$

$$R_K^{\mp} = \frac{\Gamma(B^\mp \to [\pi^\mp K^\pm \pi^0]_D K^\mp)}{\Gamma(B^\mp \to [K^\mp \pi^\pm \pi^0]_D K^\mp)},$$

$$R_\pi^{\mp} = \frac{\Gamma(B^\mp \to [\pi^\mp K^\pm \pi^0]_D \pi^\mp)}{\Gamma(B^\mp \to [K^\mp \pi^\pm \pi^0]_D \pi^\mp)}.$$

$$R_{\mathrm{ADS}(h)} = \frac{\Gamma(B^- \to [\pi^- K^+ \pi^0]_D h^-) + \Gamma(B^- \to [\pi^- K^+ \pi^0]_D h^-)}{\Gamma(B^- \to [K^- \pi^+ \pi^0]_D h^-) + \Gamma(B^- \to [K^- \pi^+ \pi^0]_D h^-)}$$

$$A_{\mathrm{ADS}(h)} = \frac{\Gamma(B^- \to [\pi^- K^+ \pi^0]_D h^-) - \Gamma(B^- \to [\pi^- K^+ \pi^0]_D h^-)}{\Gamma(B^- \to [\pi^- K^+ \pi^0]_D h^-) + \Gamma(B^- \to [\pi^- K^+ \pi^0]_D h^-)}.$$

History of LHCb combinations