CP Violation in Beauty to Open Charm Decays at LHCb

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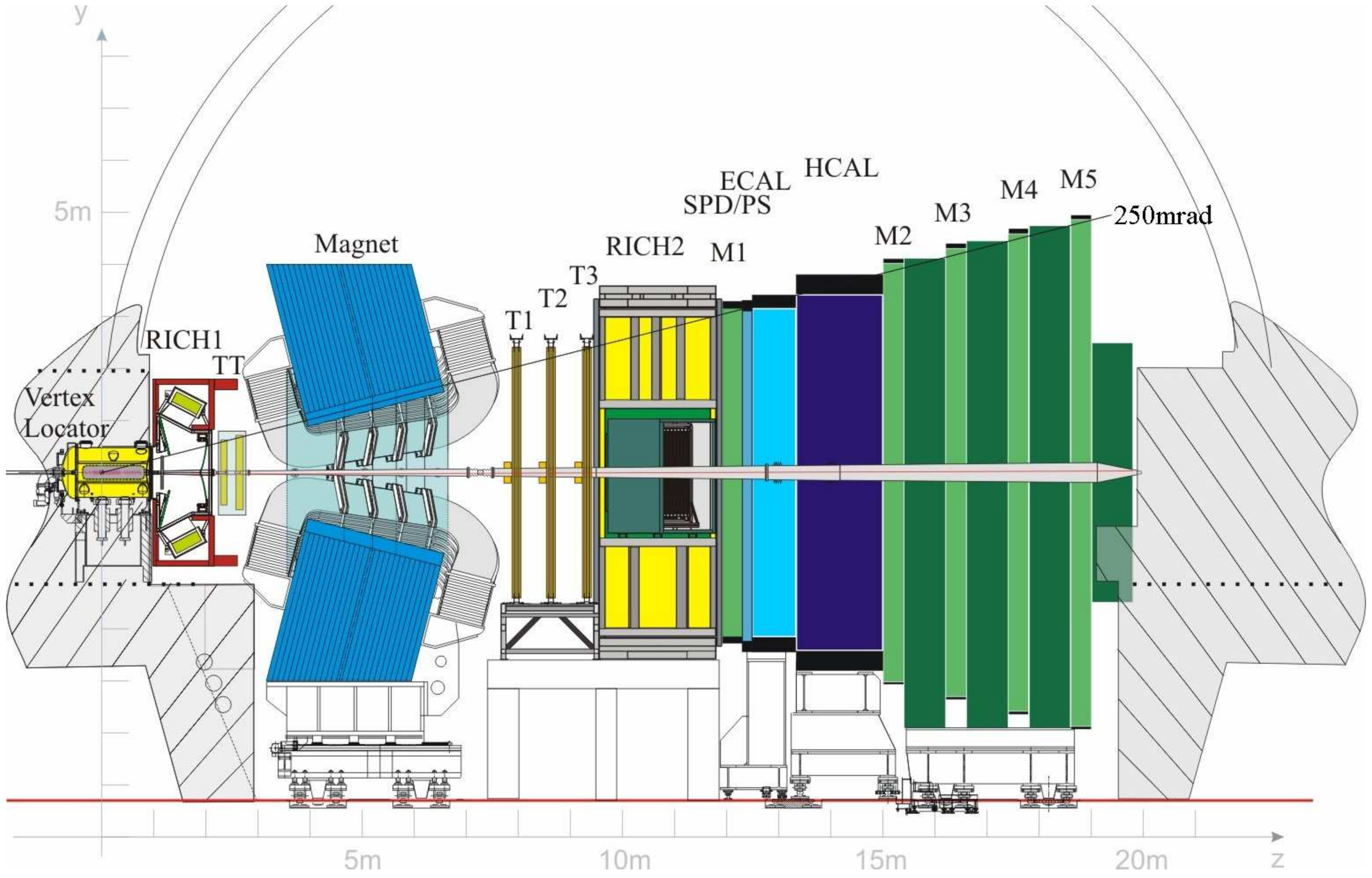
LHCb

- Detector designed for precision measurements of Beauty and Charm decays
- Doing our best to fully exploit our existing dataset
    - and preparing to do even more in Run 3!
- High precision vertexing and tracking
    - Excellent decay time and kinematics resolution
- High performance PID
    - $\sim 95\,\%\,K$ efficiency
- Precise measurement of γ is one primary focus of LHCb
    - Aiming for sub-degree uncertainty

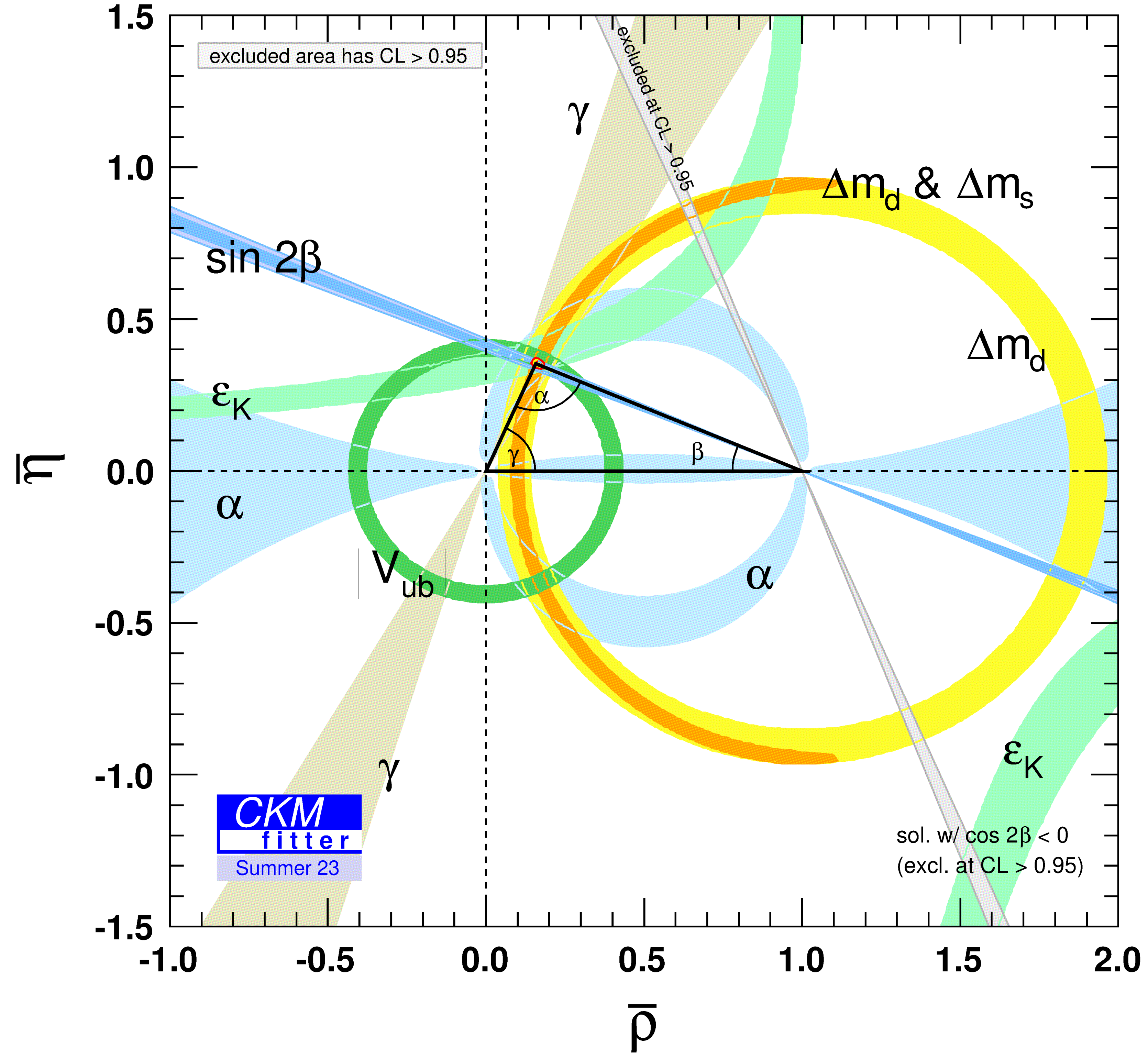


Schematic of the Run 1/2 LHCb detector [JINST]

CKM angle γ

- CKM matrix links quark mass and flavour eigenstates
- Unitary in the SM
  - $\implies$ triangles in the complex plane
- Use measurements to overconstrain them and search for new physics
- Also compare direct to indirect measurements
  - CKMfitter 2023 indirect world average $\gamma = (66.3^{+0.7}_{-1.9})^\circ$
  - HFLAV 2024 direct world average $\gamma = (66.4^{+2.8}_{-3.0})^\circ$
- γ measurements have very low theory uncertainties - excellent benchmark parameter [JHEP]

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

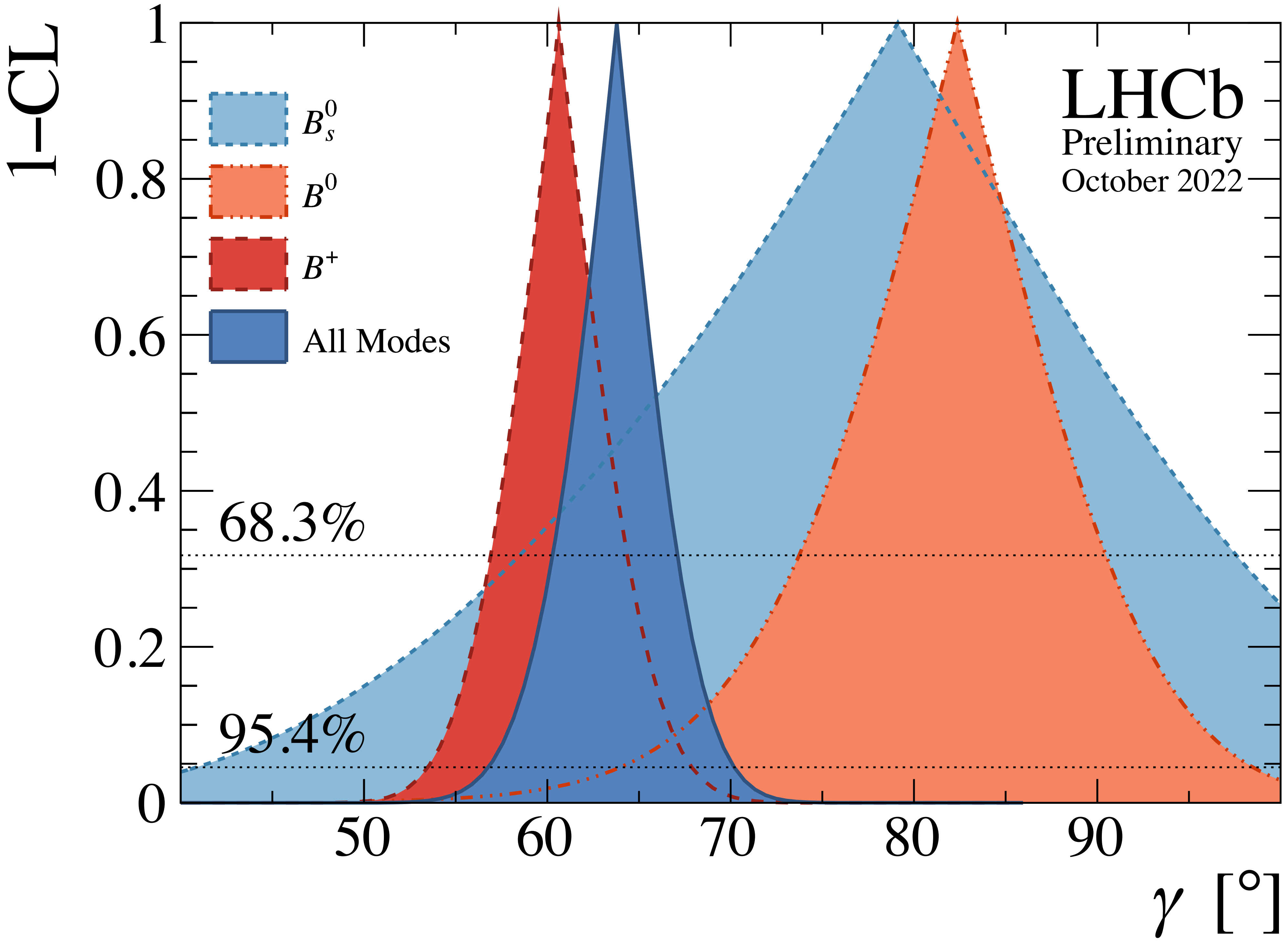


CKMfitter fit of the db unitarity triangle

New LHCb γ combination

[LHCb-CONF-2022-003]

2022



?

Species	Value [°]	68.3% CL Uncertainty [°]	95.4% CL Uncertainty [°]
B^+	60.6	$^{+4.0}_{-3.8}$	$^{+7.8}_{-7.5}$
B^0	82.0	$^{+8.1}_{-8.8}$	$^{+17}_{-18}$
B_s^0	79	$^{+21}_{-24}$	$^{+51}_{-47}$
All	63.8	$^{+3.5}_{-3.7}$	$^{+6.9}_{-7.5}$

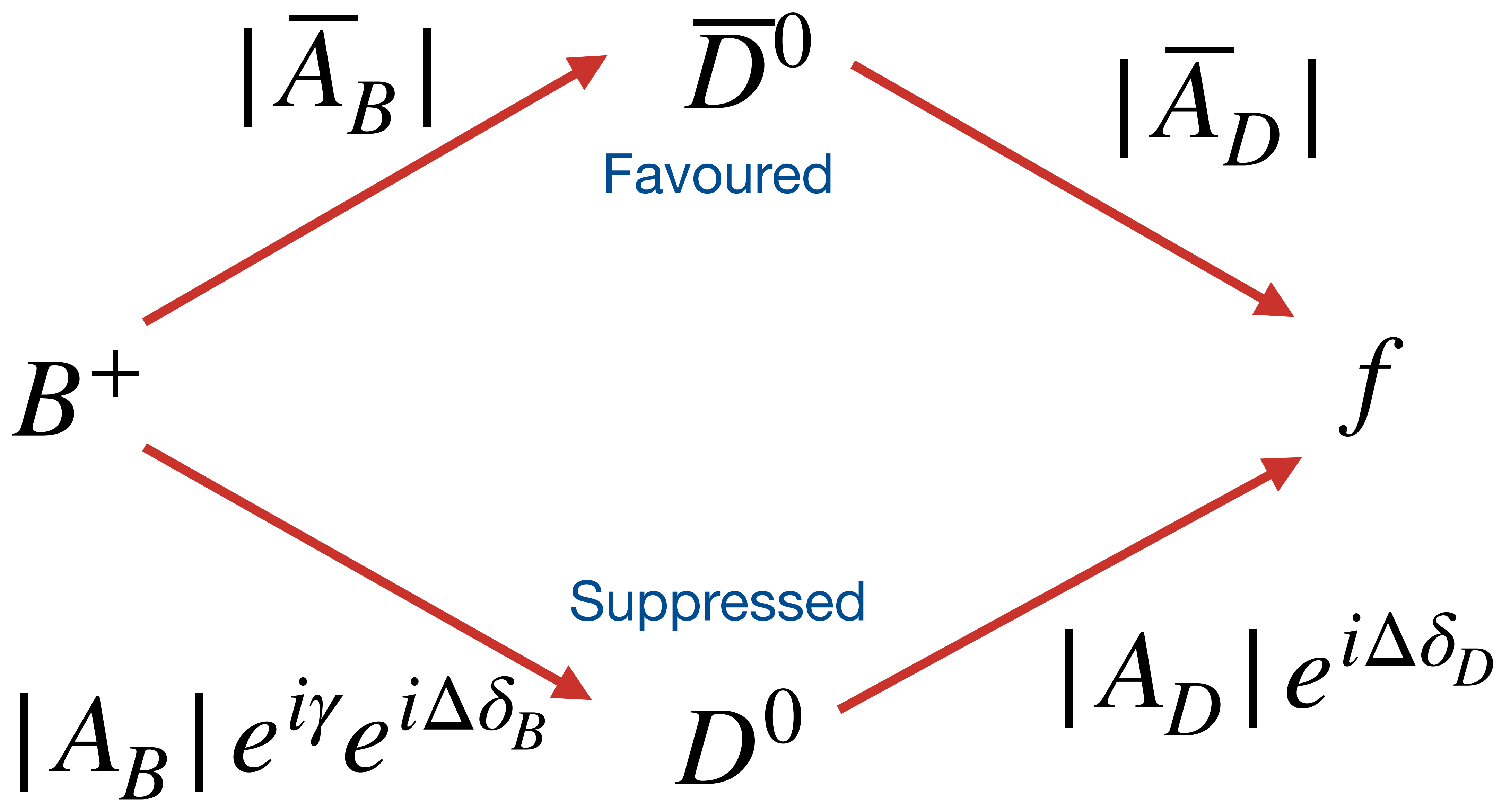
γ & time integrated CPV

- Interference between $b \to c$ and $b \to u$ transitions
  - Can't tell which flavour D in each event
- Squared amplitude depends on

  $\Delta\delta_B + \gamma$ for B^+/B^0

  $\Delta\delta_B - \gamma$ for $B^-/\overline{B}^0$

  $\implies$ asymmetries $\dfrac{\Gamma(B^- \to f) - \Gamma(B^+ \to f)}{\Gamma(B^- \to f) + \Gamma(B^+ \to f)}$
- Compare $B^\pm$ or $B^0/\overline{B}^0$ amplitudes to extract γ



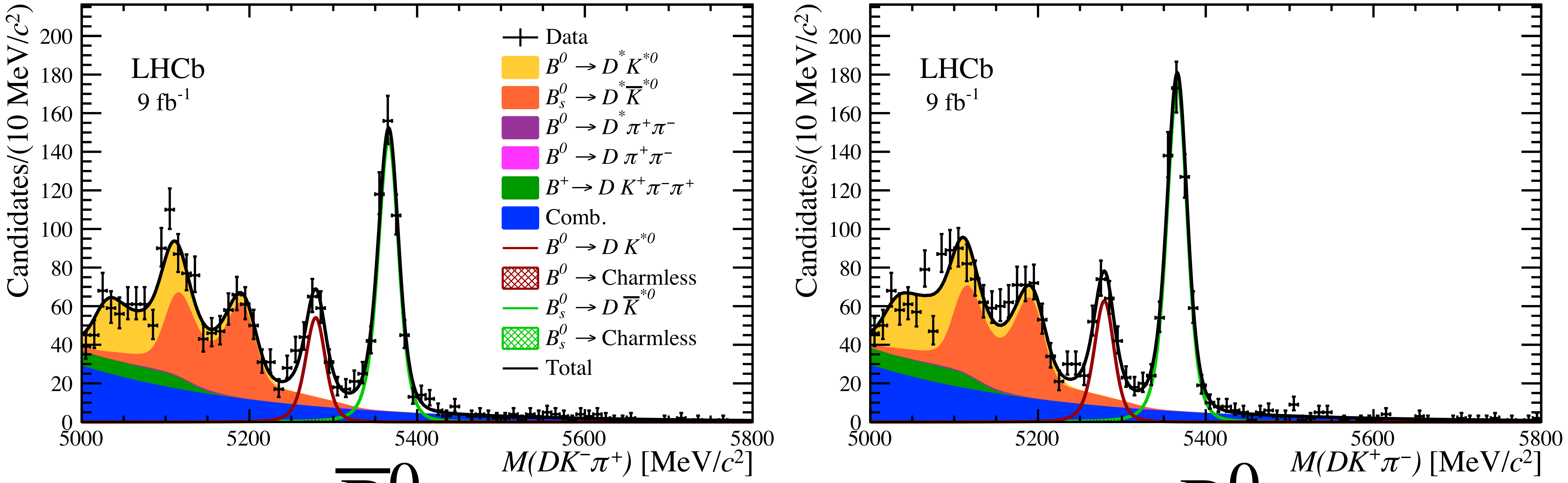
Sketch of the favoured and suppressed paths for a $B^+ \to DX, D \to f$ decay

$B^0 \to DK^{*0}, D \to h^+h^{'-}(\pi^+\pi^-)$

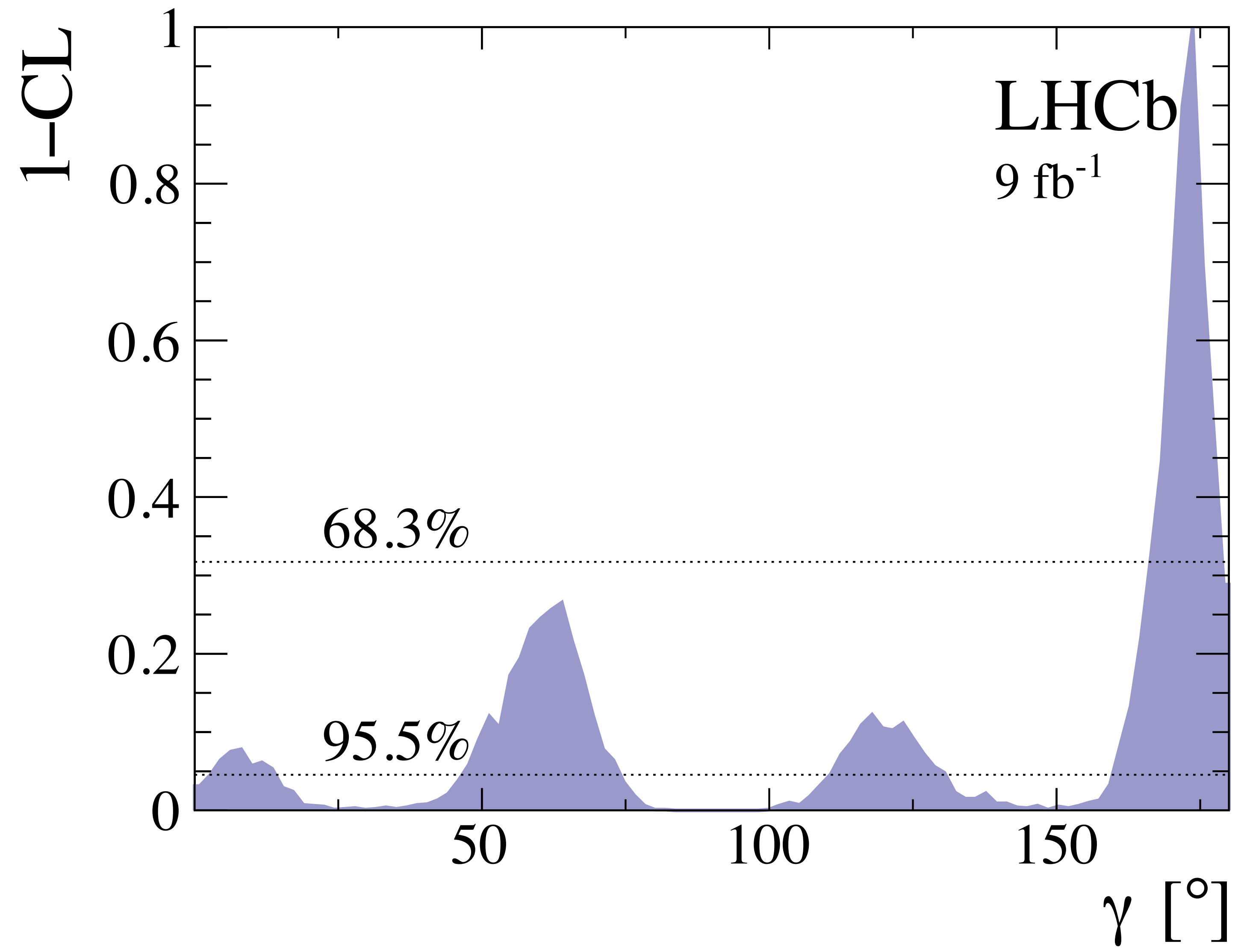
[JHEP]

- “Self-tagging”, the charges of the K^{*0} children depend on the flavour of the B
- Simultaneous measurement of
  - $D \to K^\pm\pi^\mp(\pi^+\pi^-)$
  - $D \to \pi^+\pi^-(\pi^+\pi^-)$
  - $D \to K^+K^-$
- Fit interference effects* to obtain 4 solutions of γ
  - Solution most compatible with existing measurements is $\gamma = (61.7 \pm 8.0)^\circ$
  - Require further input, such as $D \to K_S^0 h^+h^-$, to resolve the ambiguity

*See backup

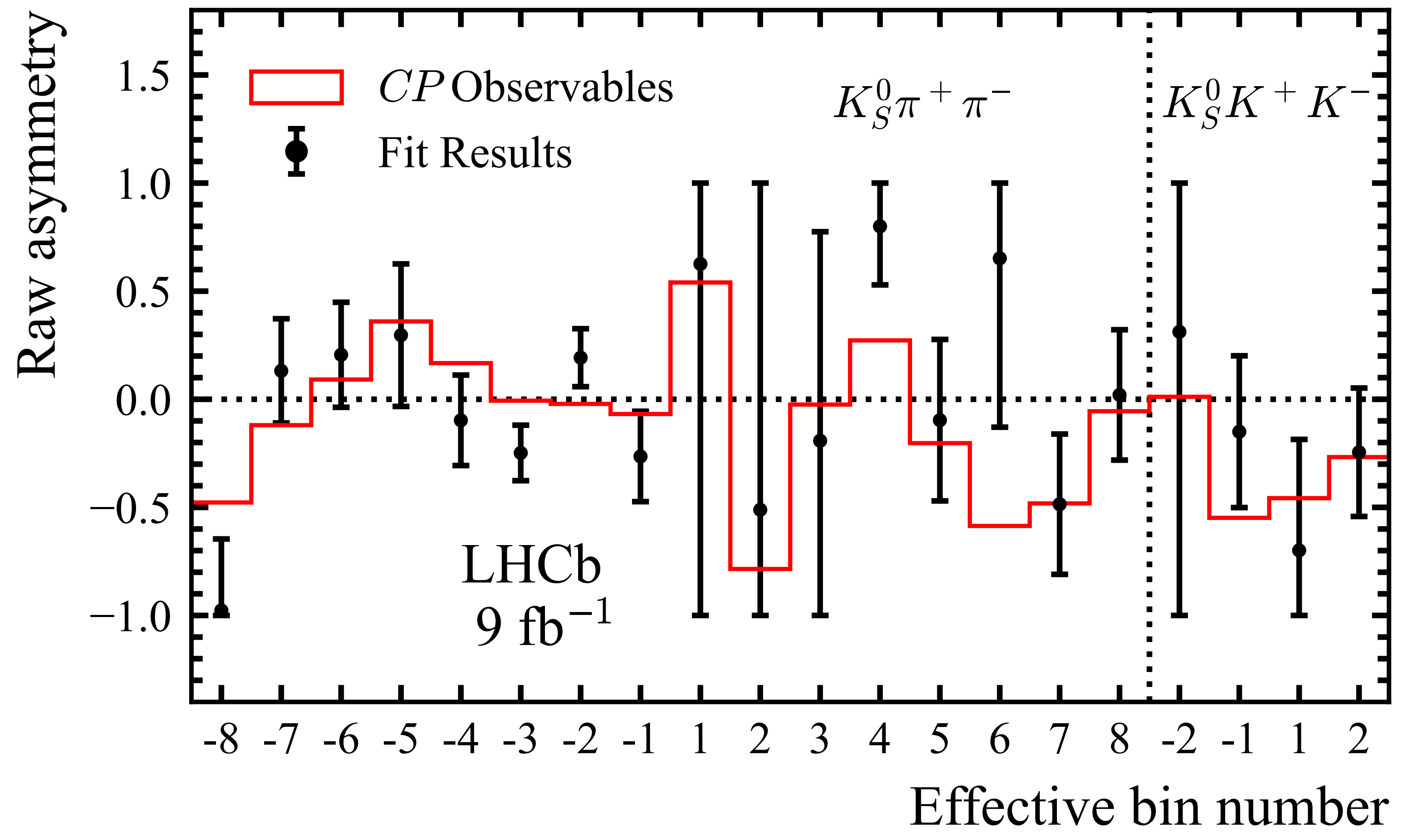


$\overline{B}^0$ Invariant mass fit result for $D \to K^+K^-$ B^0

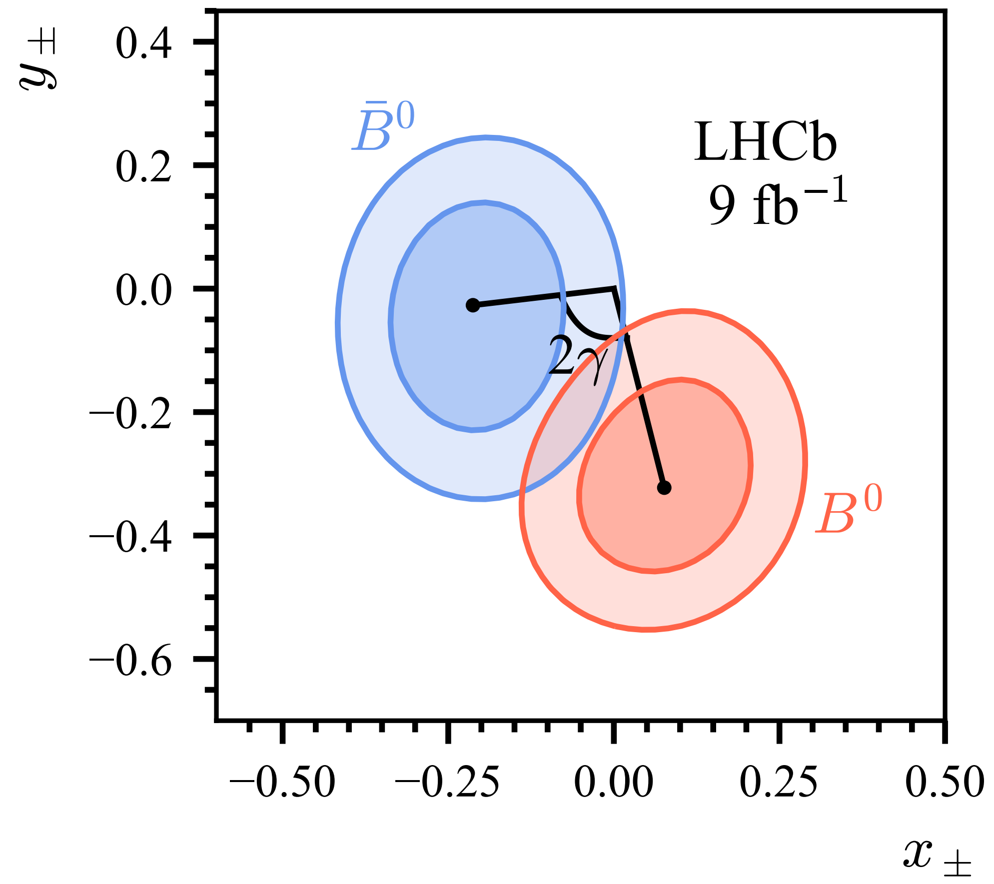


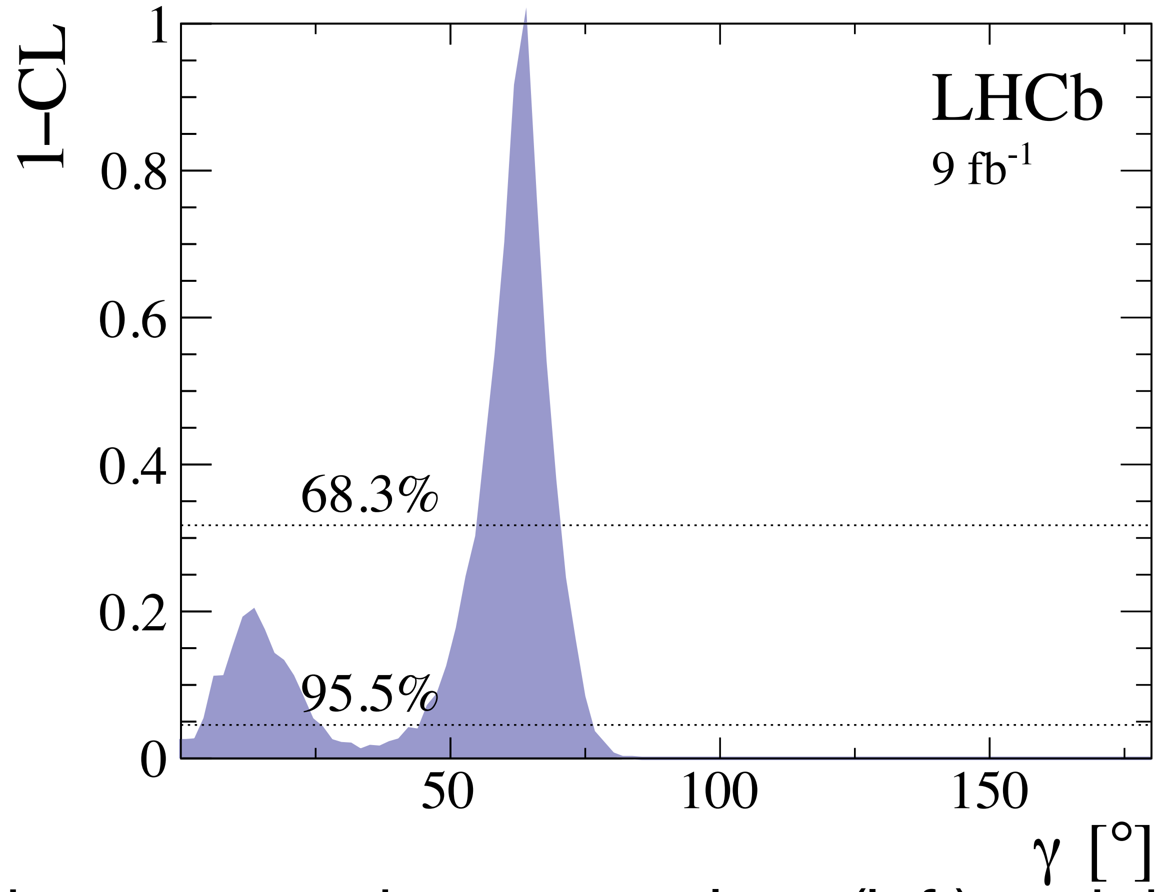
Confidence levels from the simultaneous interpretation in terms of $\gamma, r_{B^0}^{DK^*}, \delta_{B^0}^{DK^*}$

- Binned D decay Dalitz plane analysis*
    - Model independent
- Simultaneous mass fit to extract $x_\pm, y_\pm$
- Extract γ from $x_\pm = r_{B^0}^{DK^*}\cos(\Delta\delta_{B^0}^{DK^*} \pm \gamma)$, $y_\pm = r_{B^0}^{DK^*}\sin(\Delta\delta_{B^0}^{DK^*} \pm \gamma)$
- Combination with $D \to h^+ h'^-(\pi^+\pi^-)$ yields $\gamma = (63.2^{+6.9}_{-8.1})^\circ$
- Much closer to where B^+ was in the previous LHCb combination!



Per-bin asymmetries determined by the CP fit parameters (red) and signal yields when allowed to float freely (black) with statistical uncertainties





Statistical confidence regions for the measured $x_{\pm i}, y_{\pm i}$ values (left) and the confidence level profile for an extraction of γ from a combination of $D \to K^0_S h^+ h^-$ and $D \to hh(hh)$ (right)

*See backup

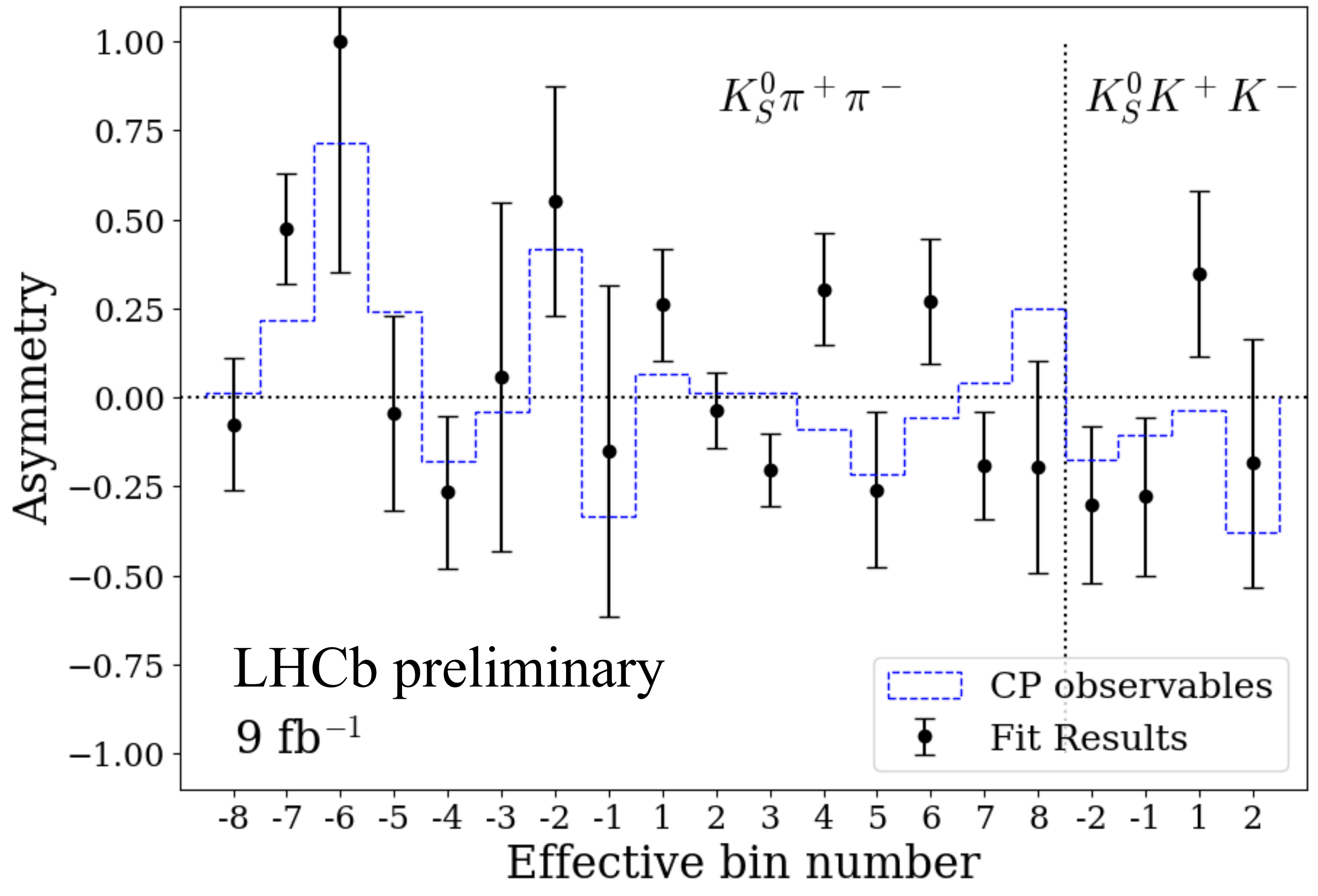
$B^\pm \to DK^{*\pm}$

[In preparation, LHCb-PAPER-2024-023]

NEW

- Simultaneous measurement of γ using
  - $D \to K^\pm\pi^\mp(\pi^+\pi^-)$
  - $D \to \pi^+\pi^-(\pi^+\pi^-)$
  - $D \to K^+K^-$
  - $D \to K^0_S h^+h^-$
- First time for $B^\pm \to DK^{*\pm}, D \to K^0_S h^+h^-$
- Interpretation in terms of γ yields

$\gamma = (63 \pm 13)^\circ$



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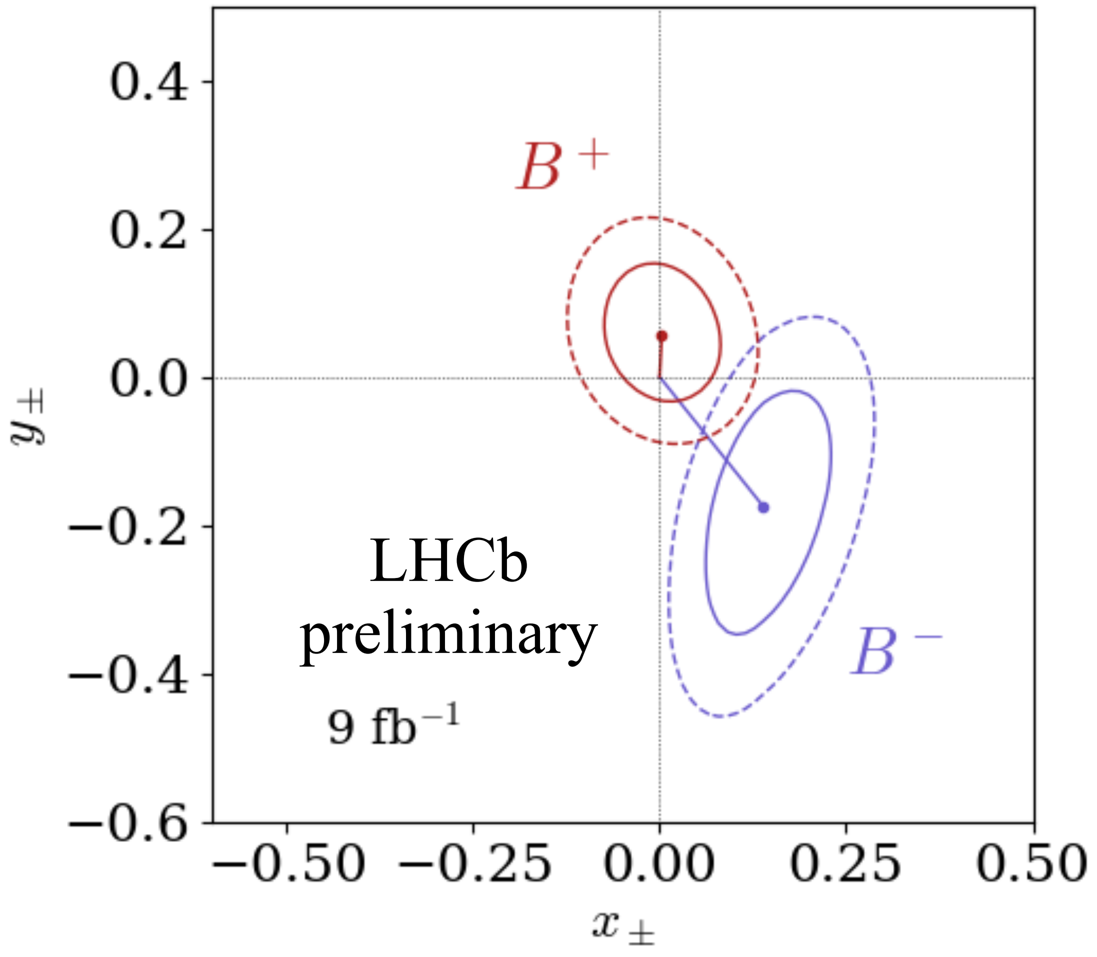
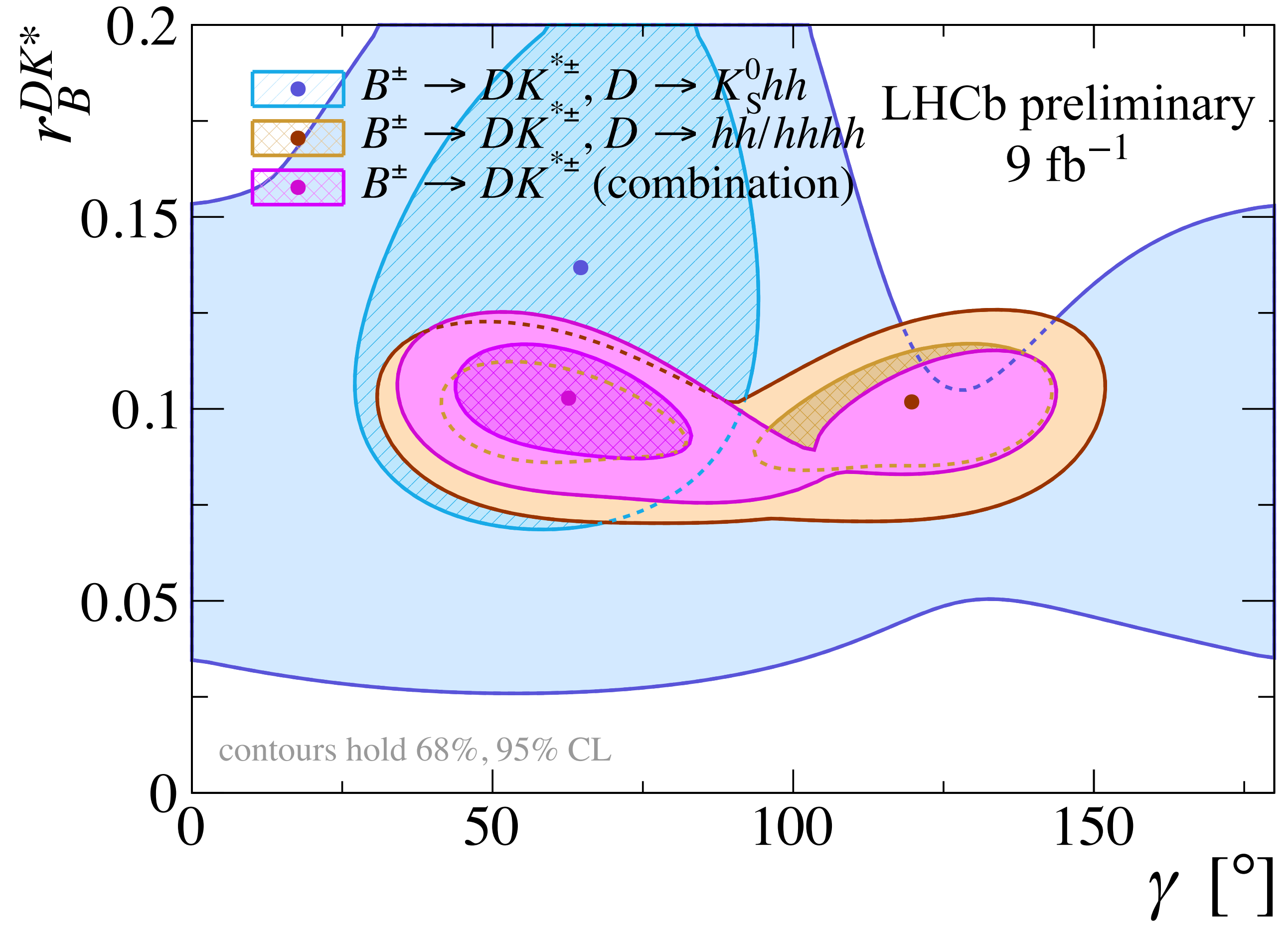


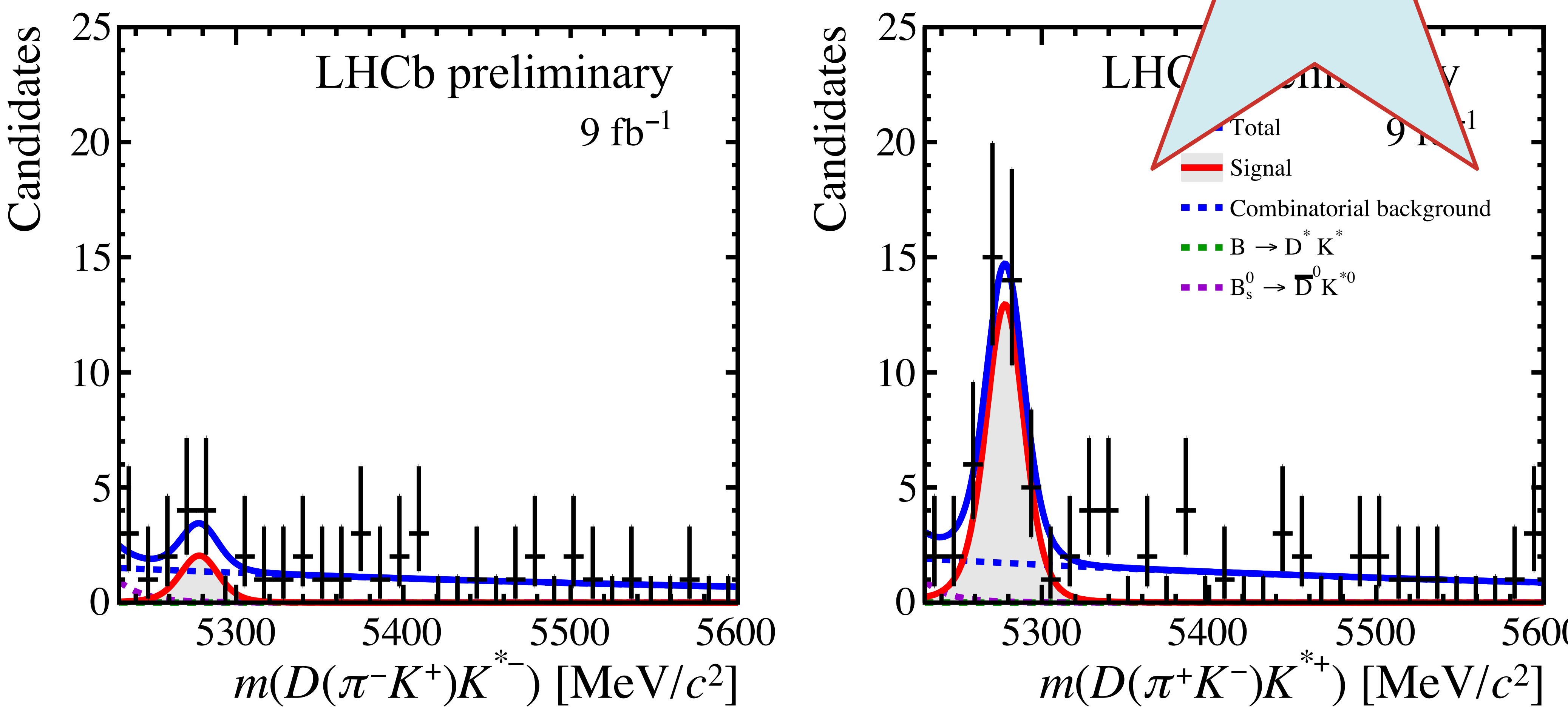


Statistical confidence regions for the measured $x_{\pm i}, y_{\pm i}$ values (left) and the contours for the extraction of $r_B^{DK^*}$ and γ (right)

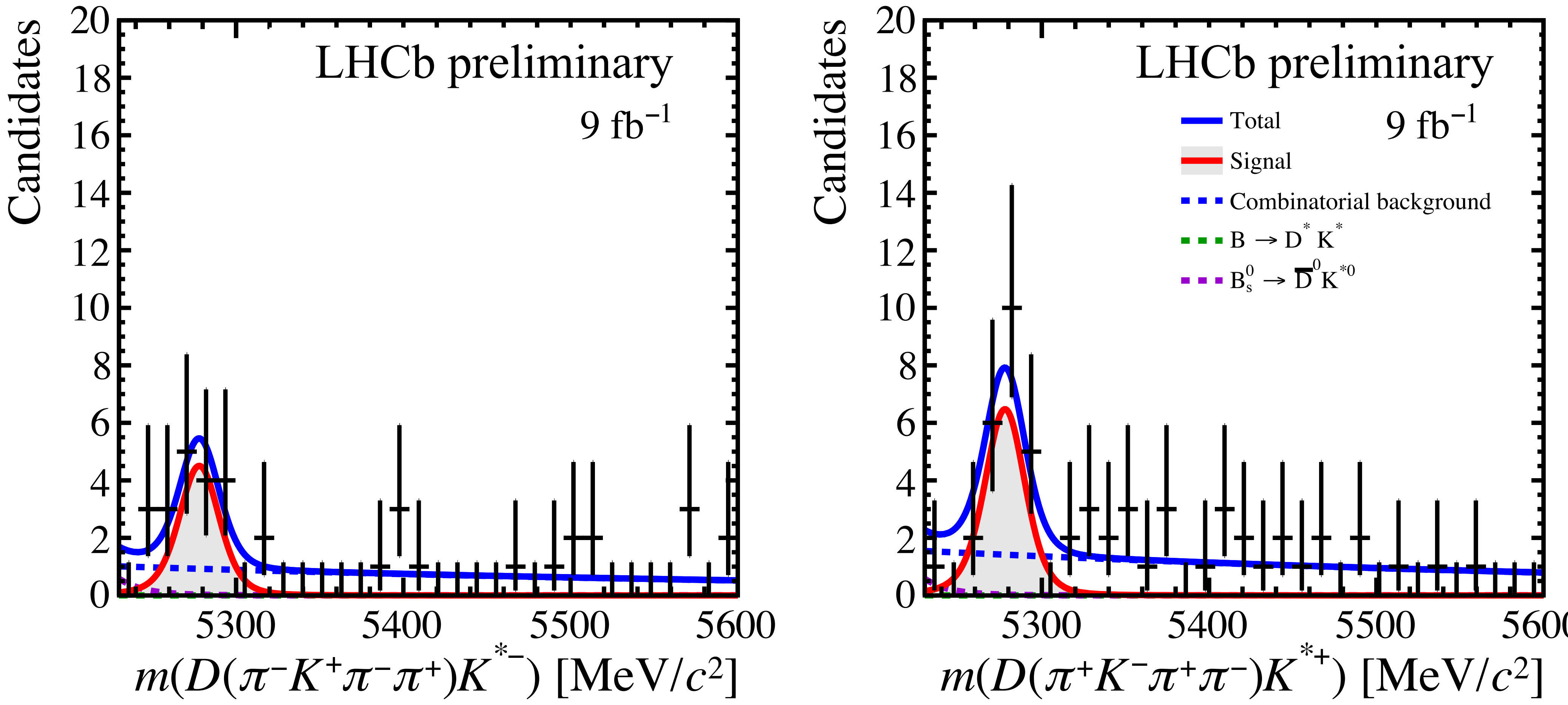
$B^\pm \to DK^{*\pm}$ [In preparation, LHCb-PAPER-2024-023]

NEW

- First observation of the doubly Cabibbo suppressed $B^\pm \to DK^{*\pm}, D \to \pi^\pm K^\mp(\pi^+\pi^-)$
- Amplitudes for favoured modes are of the form
  - $A^2 \propto 1 + r_B^2 r_D^2 + 2r_B r_D I$
  - $r_B, r_D < 1$
- Suppressed modes suffer from low statistics
  - But their amplitudes allow for large interference effects
  - $A^2 \propto r_D^2 + r_B^2 + 2r_B r_D I$
- We need more data!

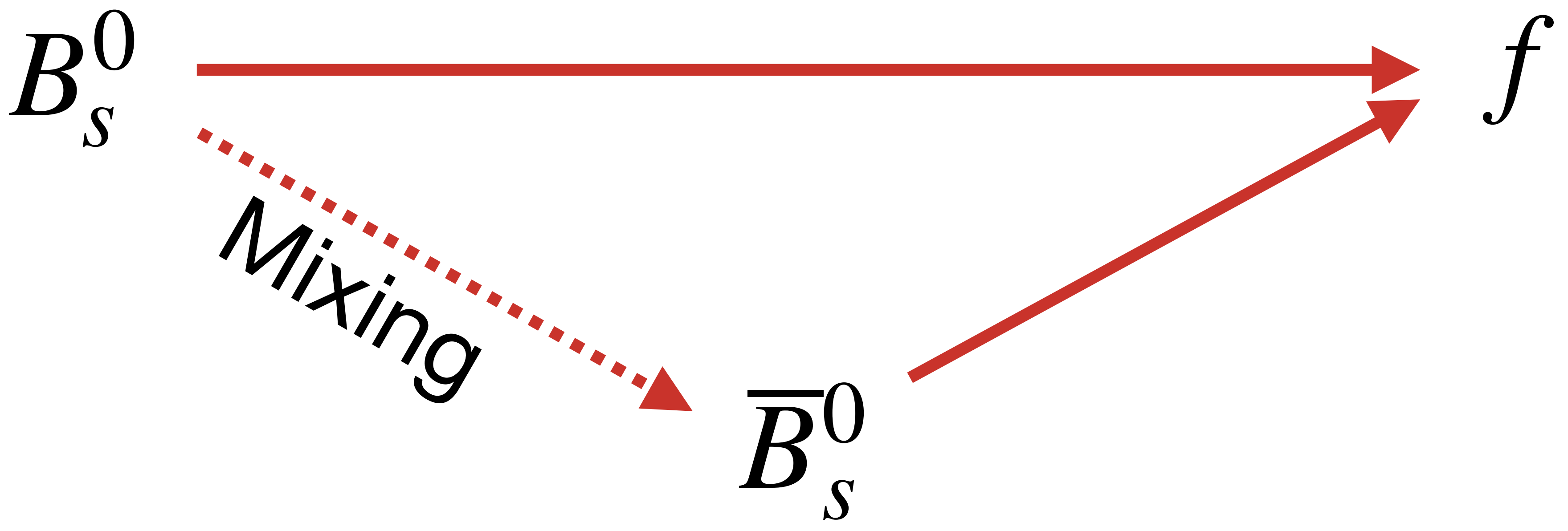


CP-mass fit result for suppressed $B^\pm \to DK^{*\pm}, D \to \pi^\pm K^\mp$



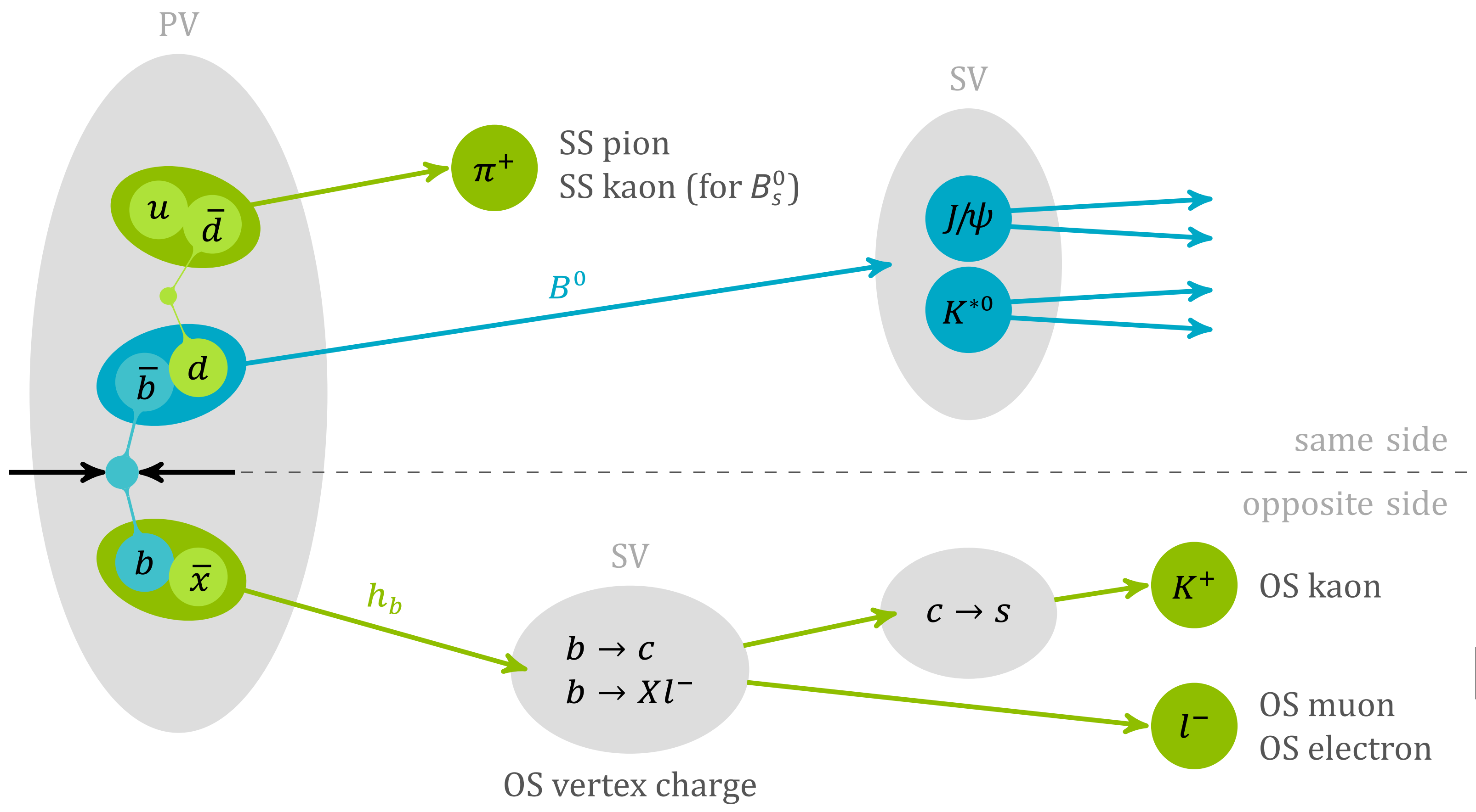
CP-mass fit result for suppressed $B^\pm \to DK^{*\pm}, D \to \pi^\pm K^\mp \pi^+\pi^-$

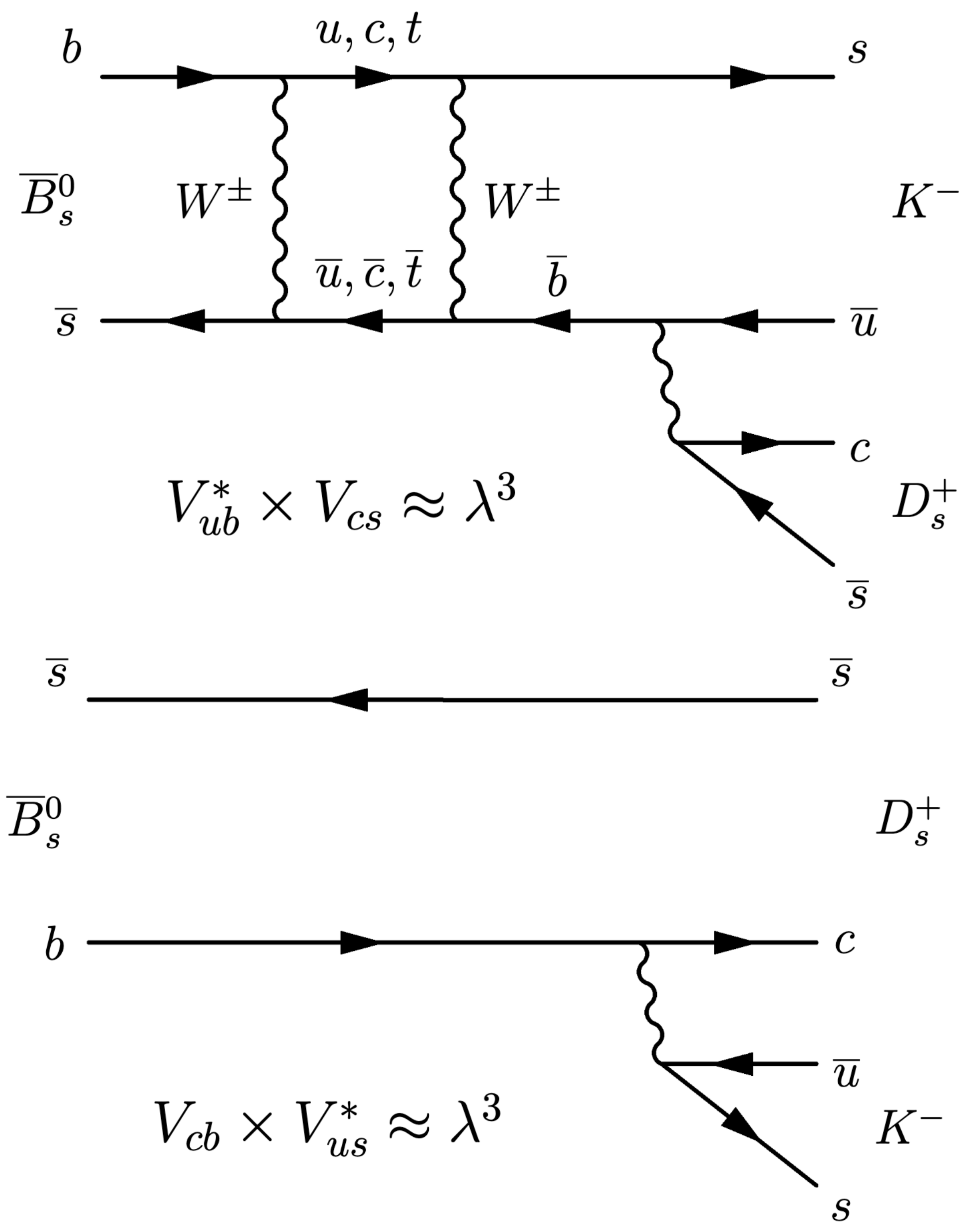
Time dependent CPV



- Interference between decay with and without mixing
  - Mass eigenstate is a superposition of the flavour eigenstates $\implies$ time-dependent mixing
  - Use flavour tagging to determine the initial flavour

- Difficult environment for flavour tagging
  - LHCb: $\epsilon_{\text{eff}} \equiv \epsilon(1-2\omega)^2 \sim 4-8\,\%$
  - Belle II: $\epsilon_{\text{eff}} \sim 30\,\%$, clean e^+e^- environment





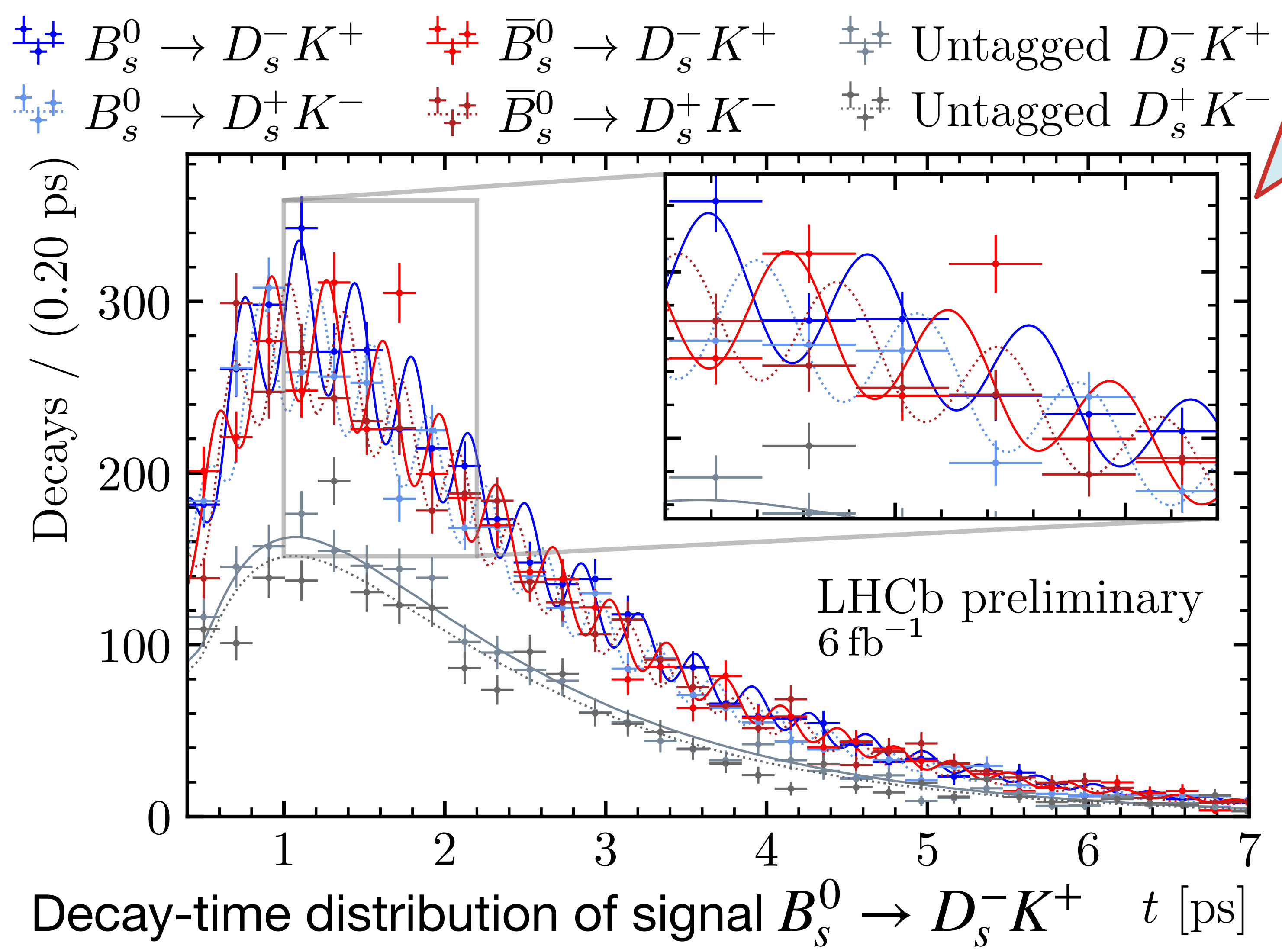
Feynman diagrams for a $\overline{B}_s^0 \to D_s^+ K^-$ decay with (top) and without (bottom) mixing

$B_s^0 \to D_s^- K^+$

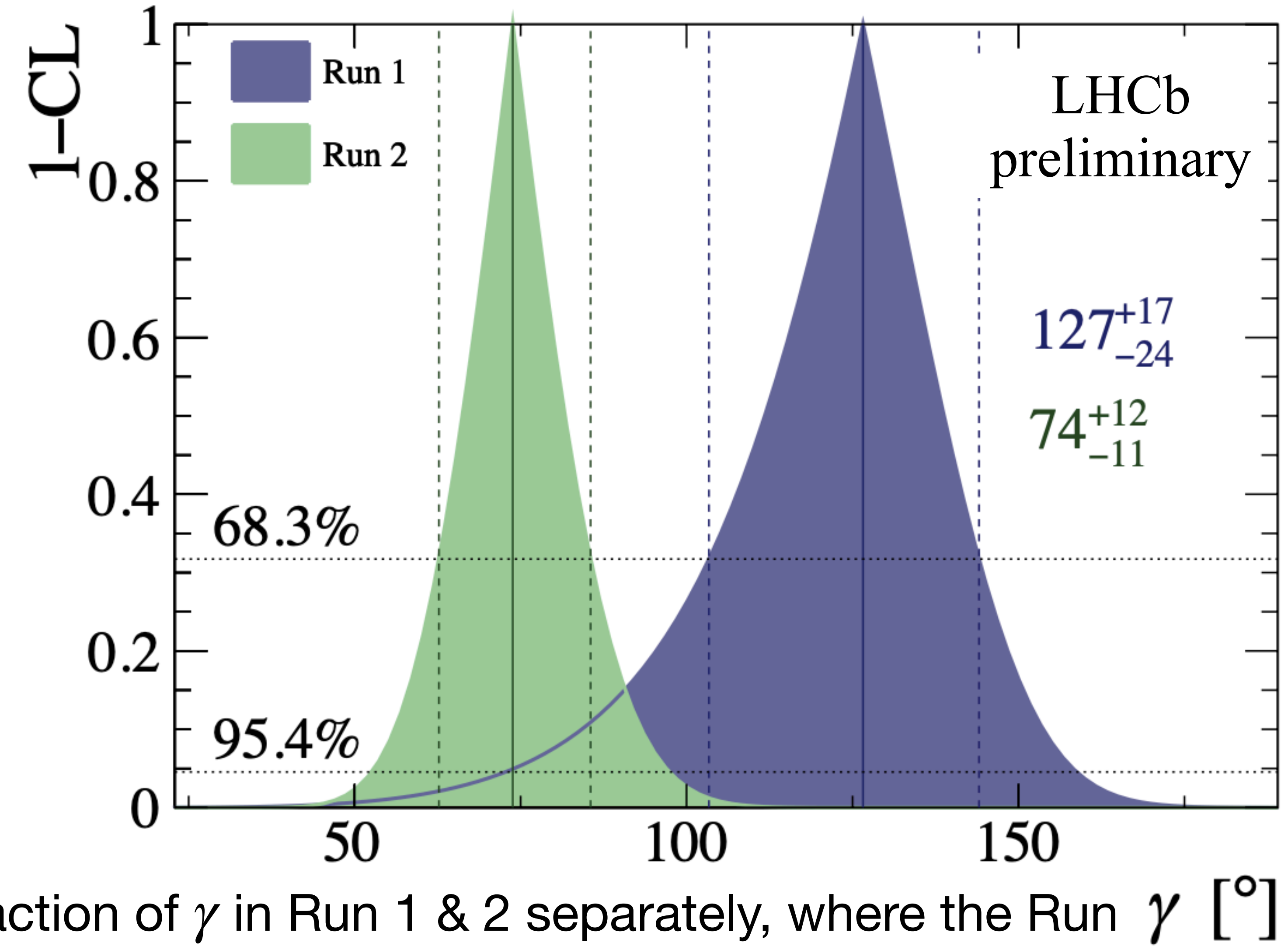
[In preparation, LHCb-PAPER-2024-020]

NEW

- CP observables depend on $\gamma - 2\beta_s$ (a.k.a $\gamma + \phi_s$)
- Simultaneous fit to B_s^0 and D_s^- invariant masses
  - Obtain sweights to project signal into decay time
- Fit decay time distribution to extract CP observables
- Run 1 was in tension with γ from $B_s^0 \to D_s^- K^+ \pi^+ \pi$ $\gamma = (44 \pm 12)^\circ \Longrightarrow$ poor constraint on γ from B_s^0
- Combination of Runs 1 & 2 yields $\gamma = (81^{+12}_{-11})^\circ$
- The most precise measurement of γ in B_s^0 decays from a single experiment



Decay-time distribution of signal $B_s^0 \to D_s^- K^+$ candidates per final state and flavour



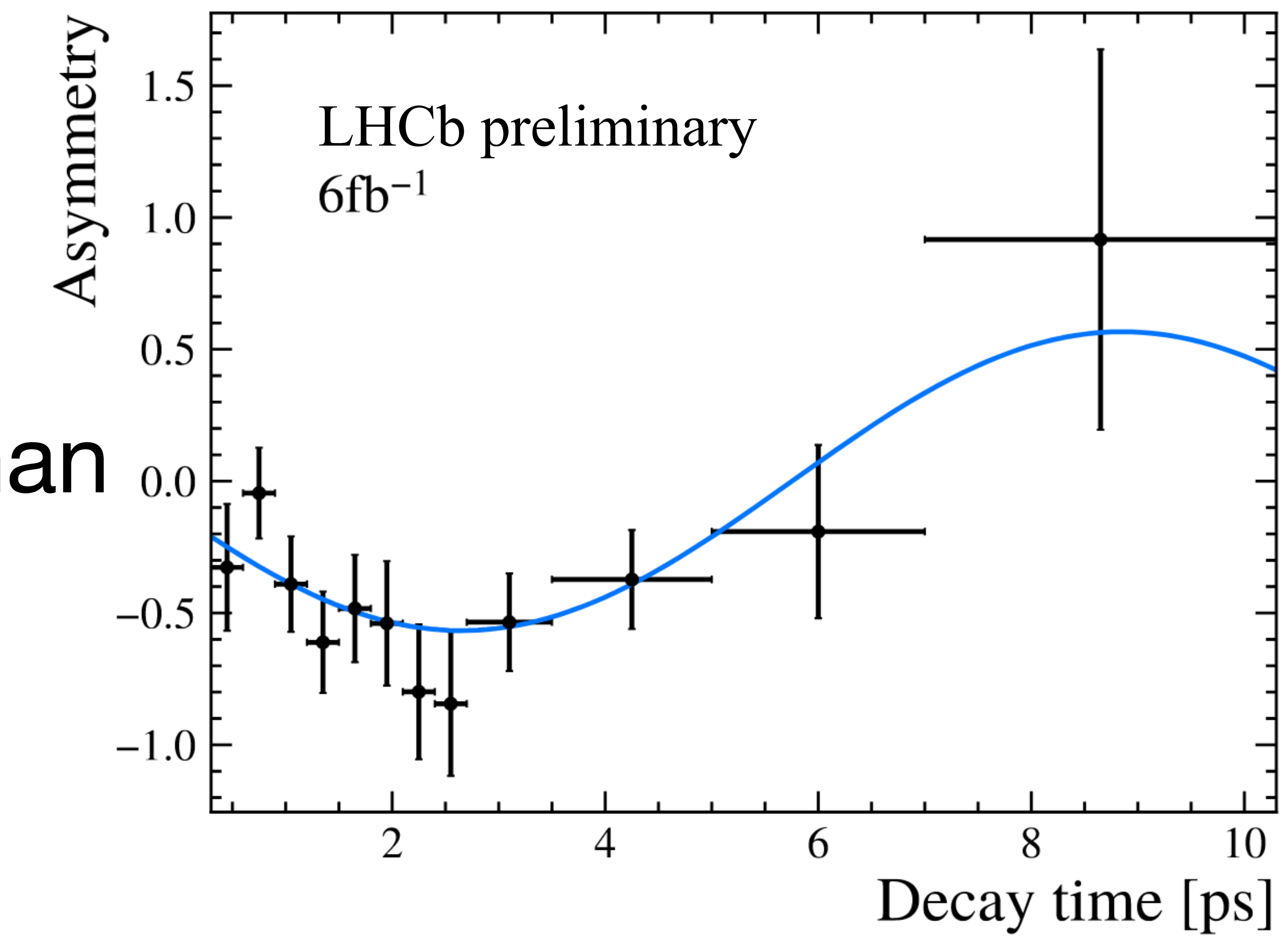
Extraction of γ in Run 1 & 2 separately, where the Run 1 fit has been updated with new inputs

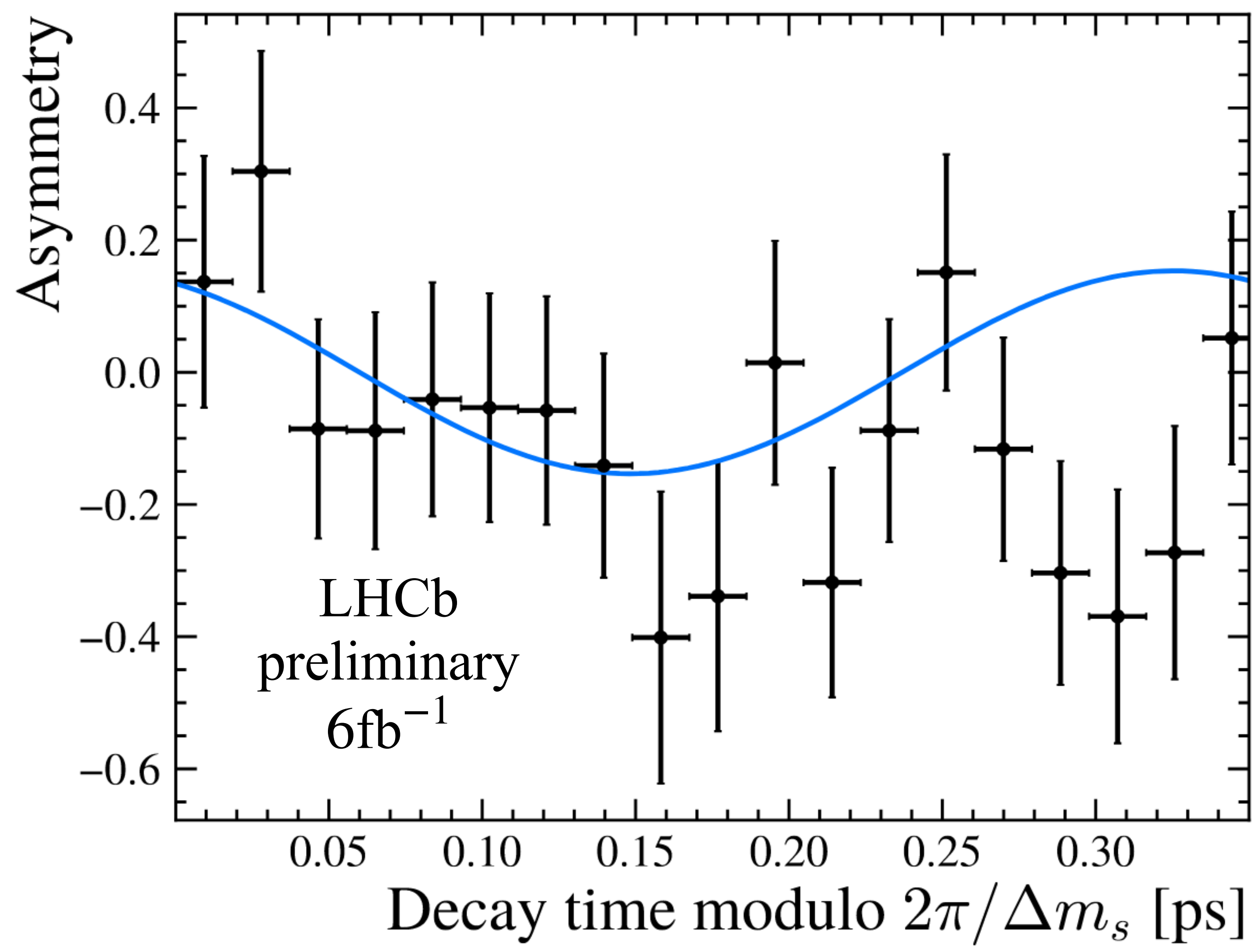
$B^0_{(s)} \to D^+_{(s)} D^-_{(s)}$

[In preparation, LHCb-PAPER-2024-027]

NEW

- Measurement of CP parameters related to β and β_s
- Similar analysis method
- Run 2 result is the first rejection of CP symmetry by more than 6σ in a single measurement of $B^0 \to D^+D^-$ decays
- For $B^0 \to D^+D^-$, combined with Run 1:
  - $S_{D^+D^-} = -0.55 \pm 0.09$
  - $C_{D^+D^-} = 0.16 \pm 0.09$
- For $B^0_s \to D^+_s D^-_s$, combined with Run 1:
  - $\phi_s = -0.05 \pm 0.09$ rad
  - $|\lambda_{D^+_s D^-_s}| = 1.05 \pm 0.10$
  - Consistent with CP symmetry



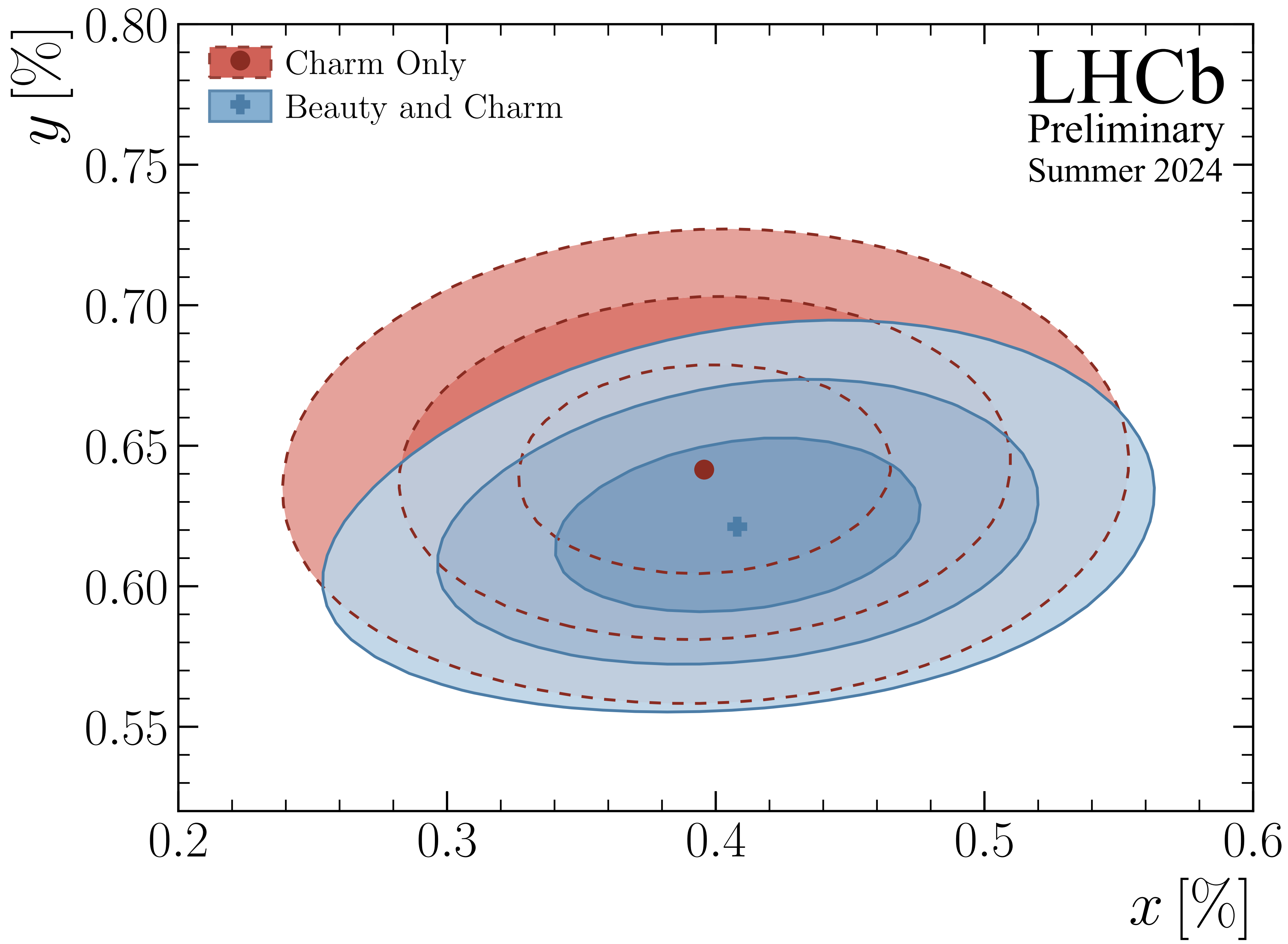


Decay-time-dependent asymmetry of $B^0 \to D^+D^-$ (top) and $B^0_s \to D^+_s D^-_s$ (bottom) candidates in sweighted data.

Beauty and Charm [In preparation, LHCb-CONF-2024-004]

NEW

- Combination of:
    - 19 LHCb B decay measurements (4 new, 3 superseded)*
    - 11 LHCb D decay measurements (1 new, 1 superseded)*
- 27 auxiliary inputs from LHCb, HFLAV, CLEO-c and BESIII (1 new, 2 updated)*
- Many Beauty and Charm measurements share parameters and provide complementary information
    - Detailed description of method in 2013
    - Added Charm in 2021
- Produces a single LHCb value for 29 physics parameters of interest (+ nuisance parameters)
- Latest update being released soon LHCb-CONF-2024-004



Charm mixing parameters when measured with and without complementary Beauty inputs

*See backup

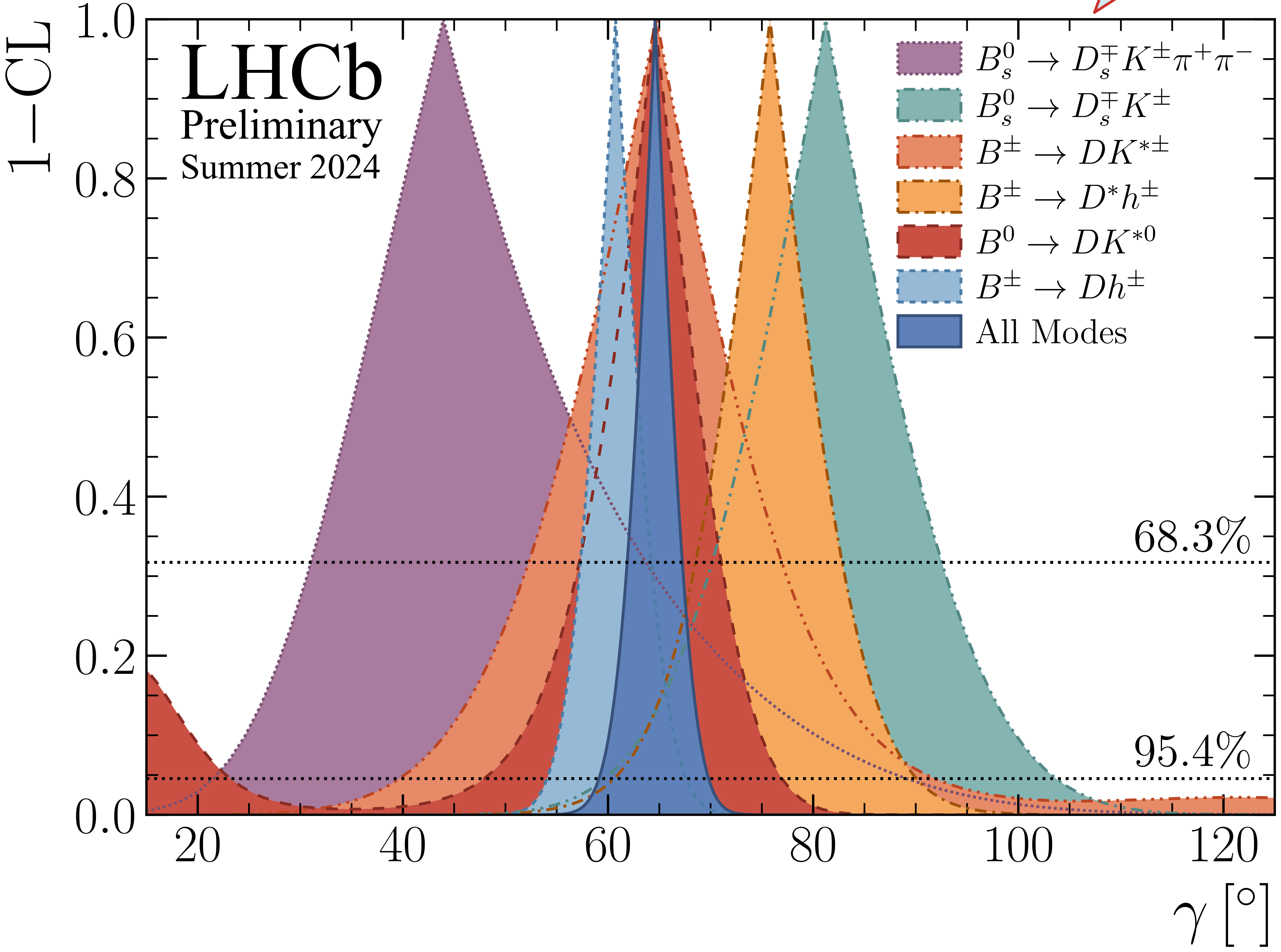
2024 LHCb γ

[In preparation, LHCb-CONF-2024-004]

NEW

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

- Decreased uncertainty by $\sim 0.7^\circ$ since 2022
- Reduced tension between the B_s^0 decays
- B^0 now sits amongst the B^+ measurements



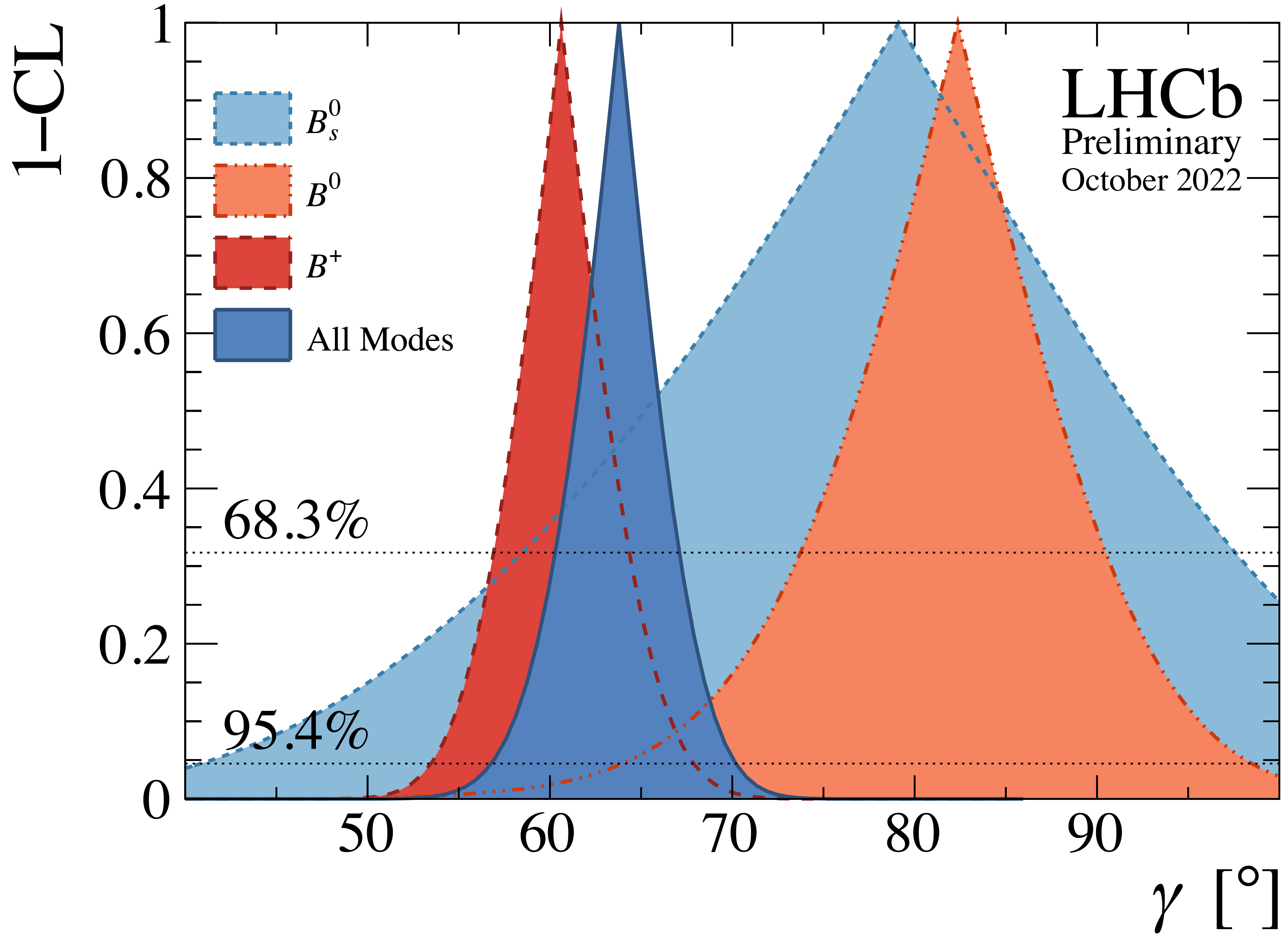
2024 LHCb γ combination per B decay

Per B species

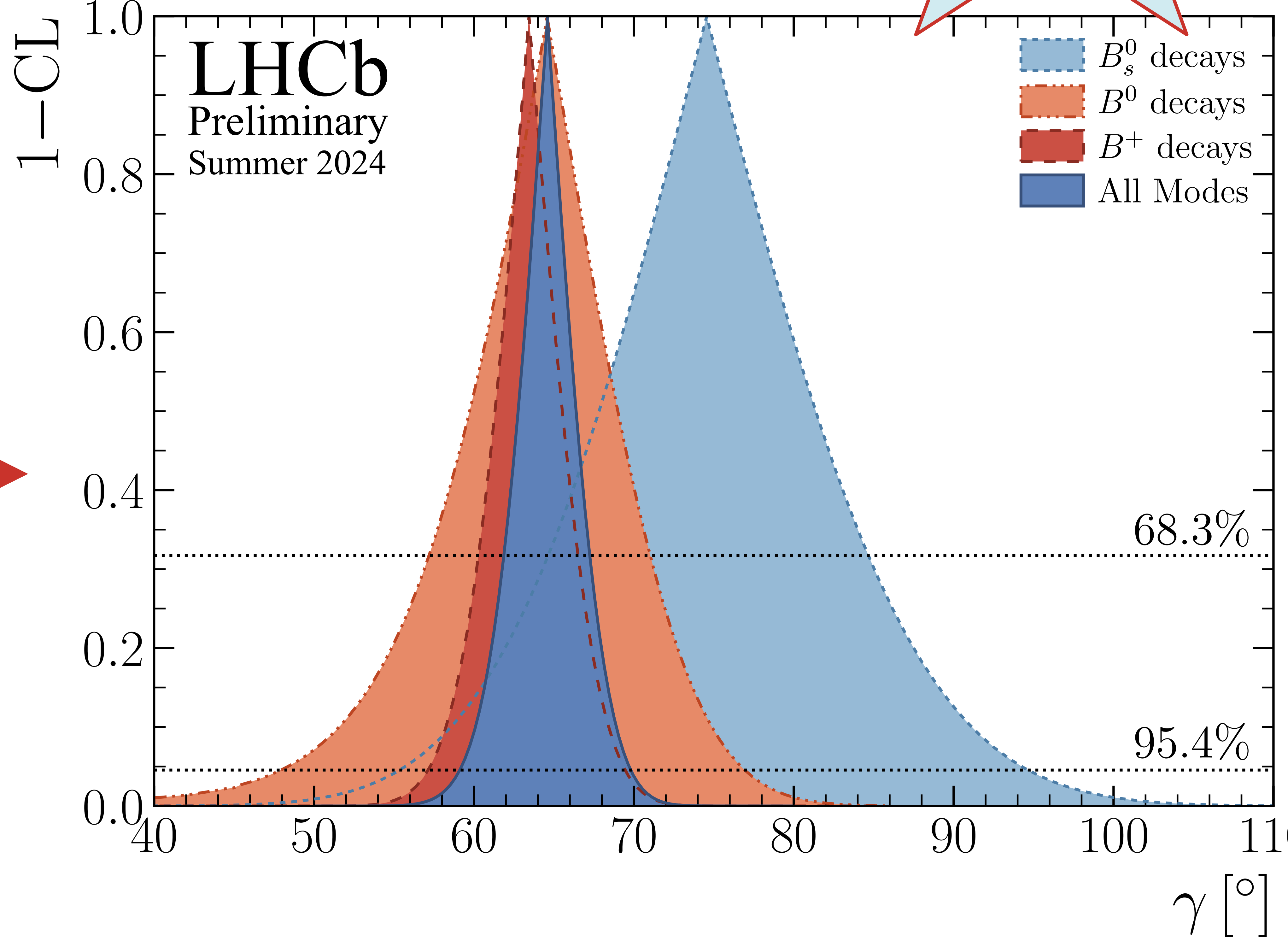
[In preparation, LHCb-CONF-2024-004]

NEW

2022



2024



Species	Value [°]	68.3% CL Uncertainty [°]	95.4% CL Uncertainty [°]
B^+	60.6	$^{+4.0}_{-3.8}$	$^{+7.8}_{-7.5}$
B^0	82.0	$^{+8.1}_{-8.8}$	$^{+17}_{-18}$
B_s^0	79	$^{+21}_{-24}$	$^{+51}_{-47}$
All	63.8	$^{+3.5}_{-3.7}$	$^{+6.9}_{-7.5}$

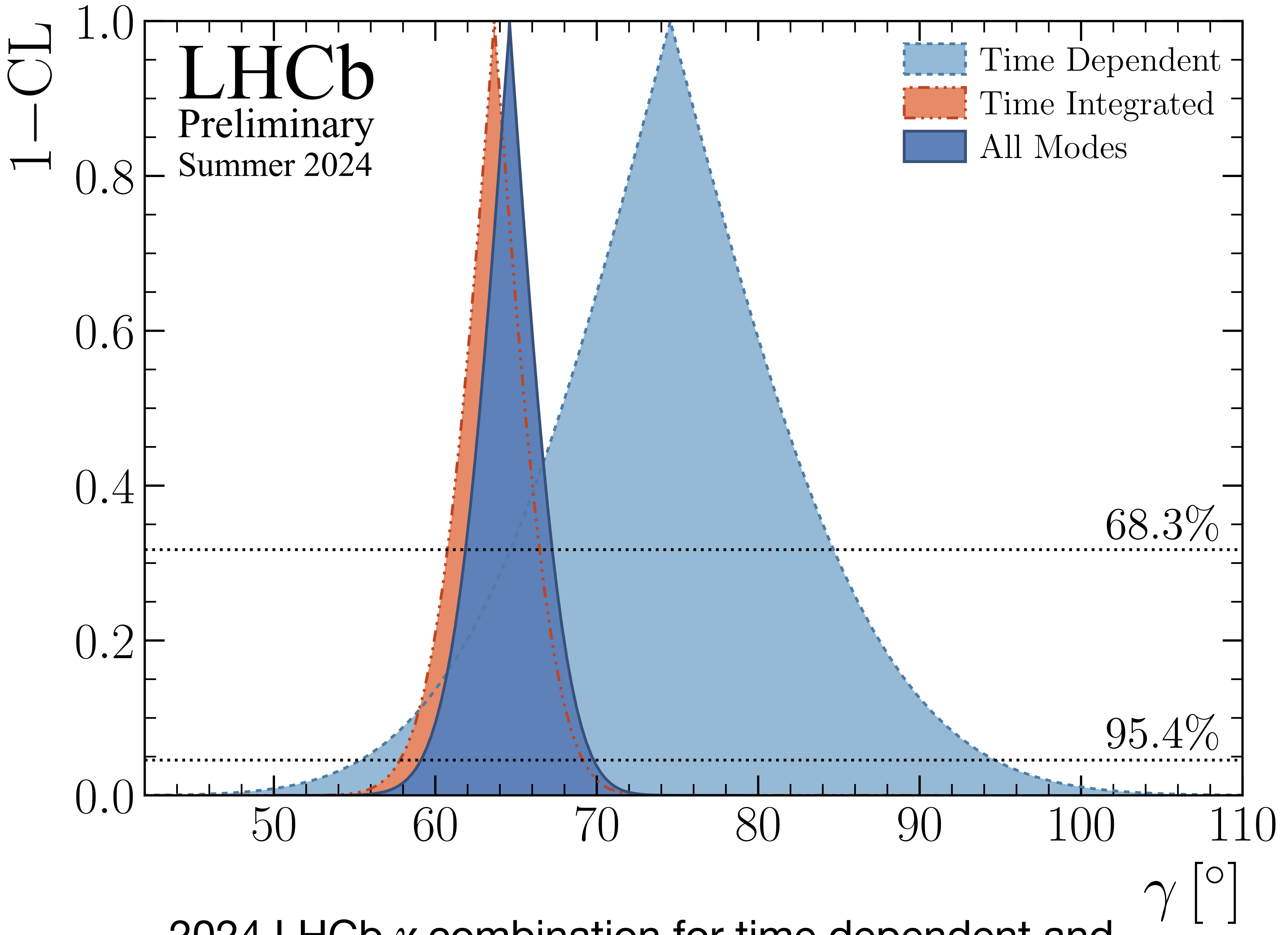
Species	Value [°]	68.3% CL Uncertainty [°]	95.4% CL Uncertainty [°]
B^+	63.4	$^{+3.2}_{-3.3}$	$^{+6.4}_{-6.5}$
B^0	64.6	$^{+6.5}_{-7.5}$	$^{+12}_{-17}$
B_s^0	75	$^{+10}_{-11}$	± 20
All	64.6	± 2.8	$^{+5.5}_{-5.7}$

A matter of time

[In preparation, LHCb-CONF-2024-004]

NEW

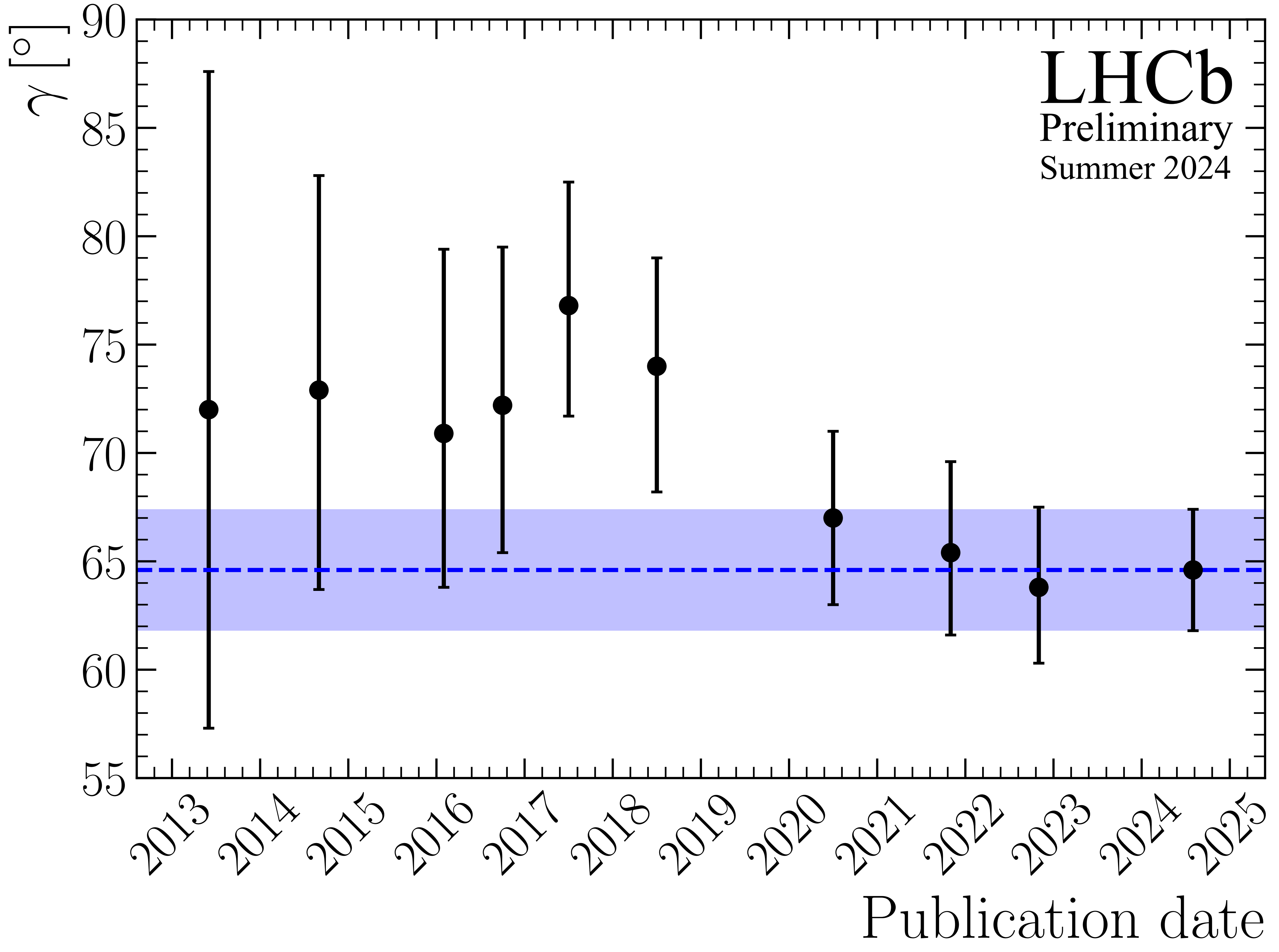
- Some small tension between time dependent and time integrated measurements
- Clearly need to push harder on time dependent analyses to get this uncertainty down



2024 LHCb γ combination for time dependent and time integrated analyses

Summary

- Several measurements of γ and one of β, β_s
  - Many new or improved methods
- Update of the Beauty and Charm combination, uncertainty on γ reduced significantly
- Still pushing our existing dataset as far as we can
  - Statistically limited - Run 3 will be even better!
- Thanks to all the proponents of these analyses
- Thanks for listening!

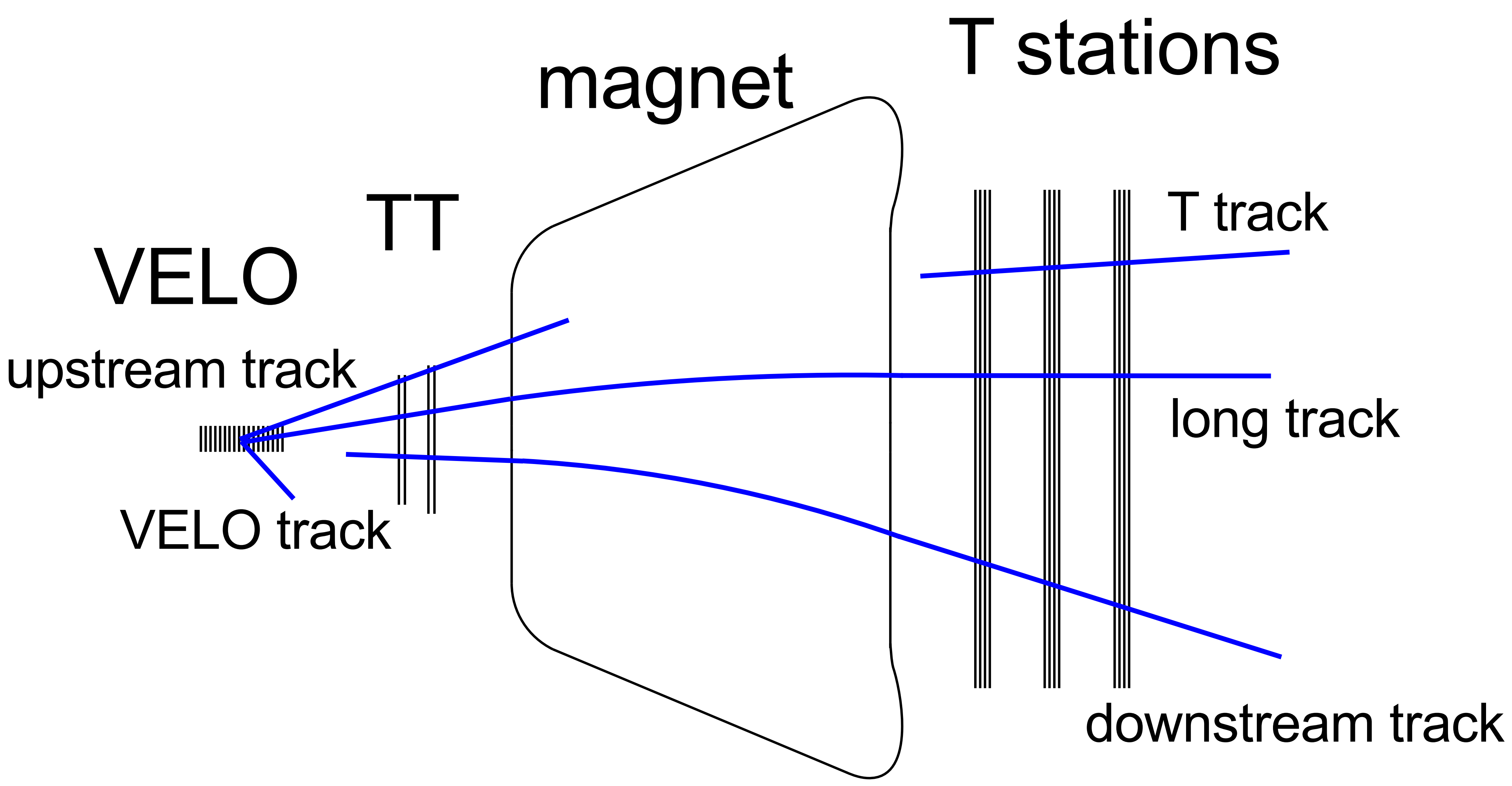


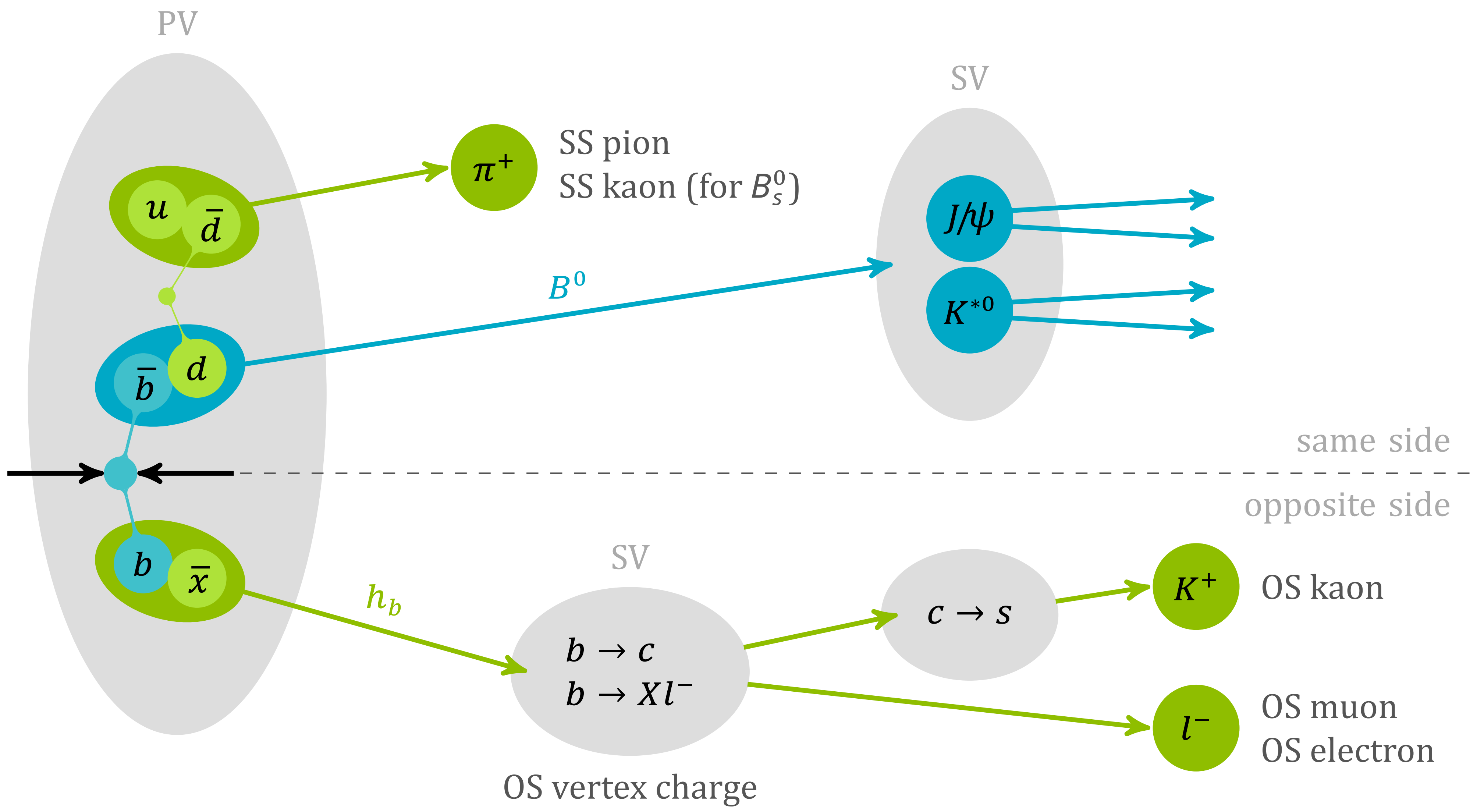
Evolution of the LHCb direct measurement of γ

Backup

LHCb

- For K_S^0 it's necessary to distinguish between those reconstructed with π tracks in different sub-detectors
  - Long-Long (LL) have hits in each tracking sub-detector
  - Down-Down (DD) are not seen in the VErtexLOcator (VELO) $\implies$ slightly worse resolution





- Flavour tagging for final states independent of initial flavour
- Difficult environment for it, results in a low effective tagging efficiency
  - LHCb: $\epsilon_{\text{eff}} \equiv \epsilon(1-2\omega)^2 \sim 4-8\,\%$
  - Belle II: $\epsilon_{\text{eff}} \sim 30\,\%$, clean e^+e^- environment
- ϵ tagging efficiency, ω wrong tag fraction
- Same side (SS) - uses particles in the hadronisation of the B
- Other side (OS) - assume another b quark (fair) and use its decay

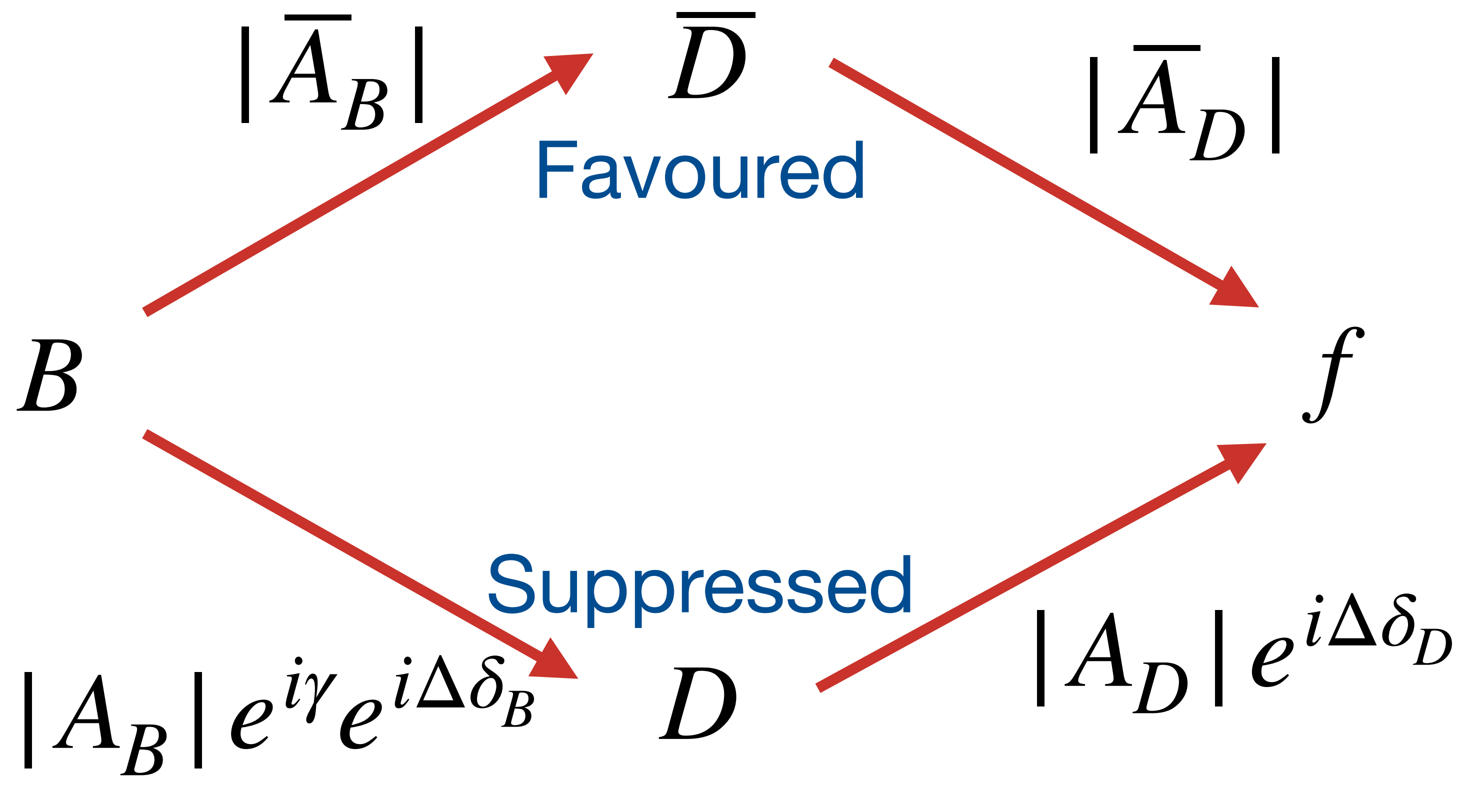
γ from 2 and 4-body D decays

- For any D final state can measure the charge asymmetry
  - $\dfrac{\Gamma(B^- \to f) - \Gamma(B^+ \to f)}{\Gamma(B^- \to f) + \Gamma(B^+ \to f)}$ "Difference in peak heights"
- For 2-body modes can also measure ratios such as
  - $\dfrac{\Gamma(B^- \to \overline{D}X, \overline{D} \to f) + \Gamma(B^+ \to DX, D \to f)}{\Gamma(B^- \to DX, D \to f) + \Gamma(B^+ \to \overline{D}X, \overline{D} \to f)}$ for $D \to K^\pm\pi^\mp$ ~sup./fav.
  - $\dfrac{\Gamma(B^- \to D_{CP}X) + \Gamma(B^+ \to D_{CP}X)}{\Gamma(B^- \to DX) + \Gamma(B^+ \to DX)}$ for CP-even modes, $D \to \pi^+\pi^-$ and $D \to K^+K^-$
- These extend fairly simply to 4-body modes, multiply interference terms by
  - $D \to \pi^+\pi^-\pi^+\pi^-$: CP-even fraction
  - $D \to K^\pm\pi^\mp\pi^+\pi^-$: coherence factor - to account for resonances
- The same for B^0 decays

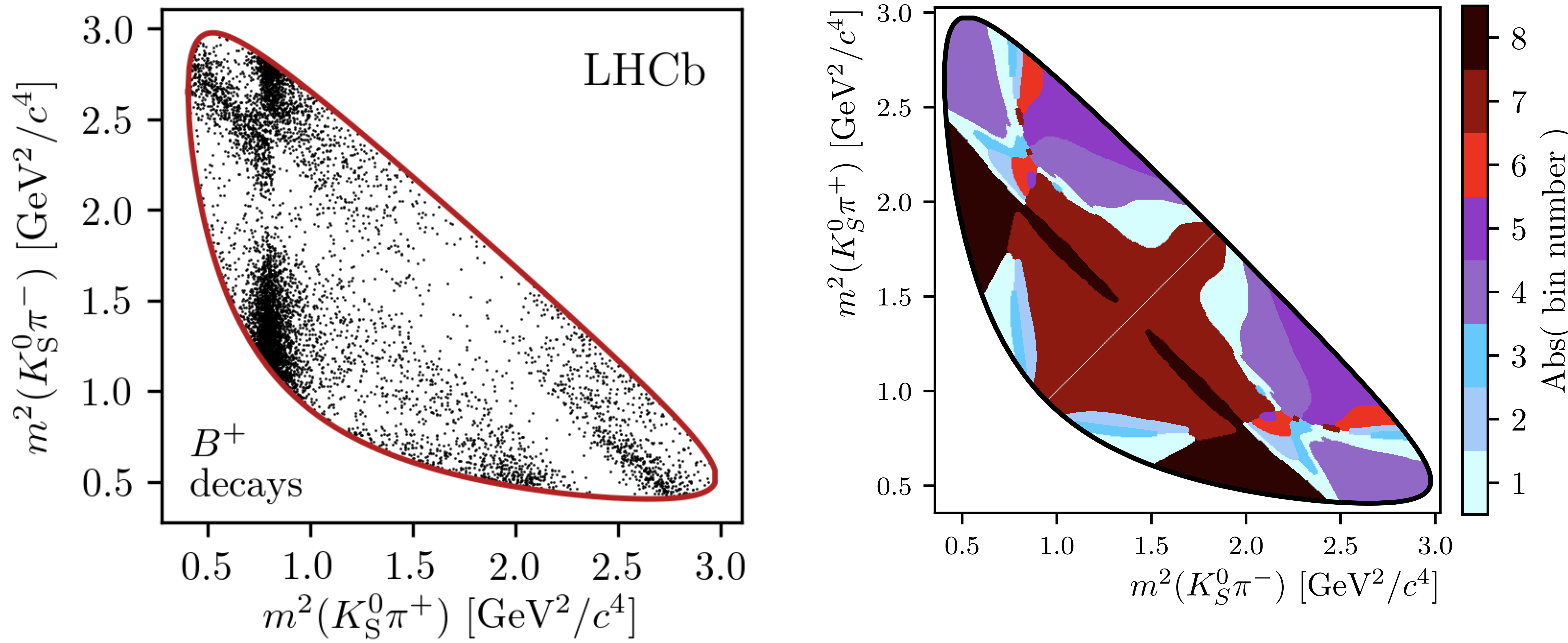
γ from $D \to K_S^0 h^+ h^-$ decays

- Resonances overlap across the Dalitz plane
- Bin the phase space to capture local asymmetries $\implies$ sensitivity to γ
  - For $D \to K_S^0 \pi^+ \pi^-$, $D \to K_S^0 K^+ K^-$ binning comes from CLEO-c
  - Obtained by maximising a binning quality factor

$$Q^2 = \frac{\sum_i N_i (c_i^2 + s_i^2)}{\sum_i N_i}$$



Sketch of the favoured and suppressed paths for a $B \to f$ decay with intermediate states containing a D or $\overline{D}$

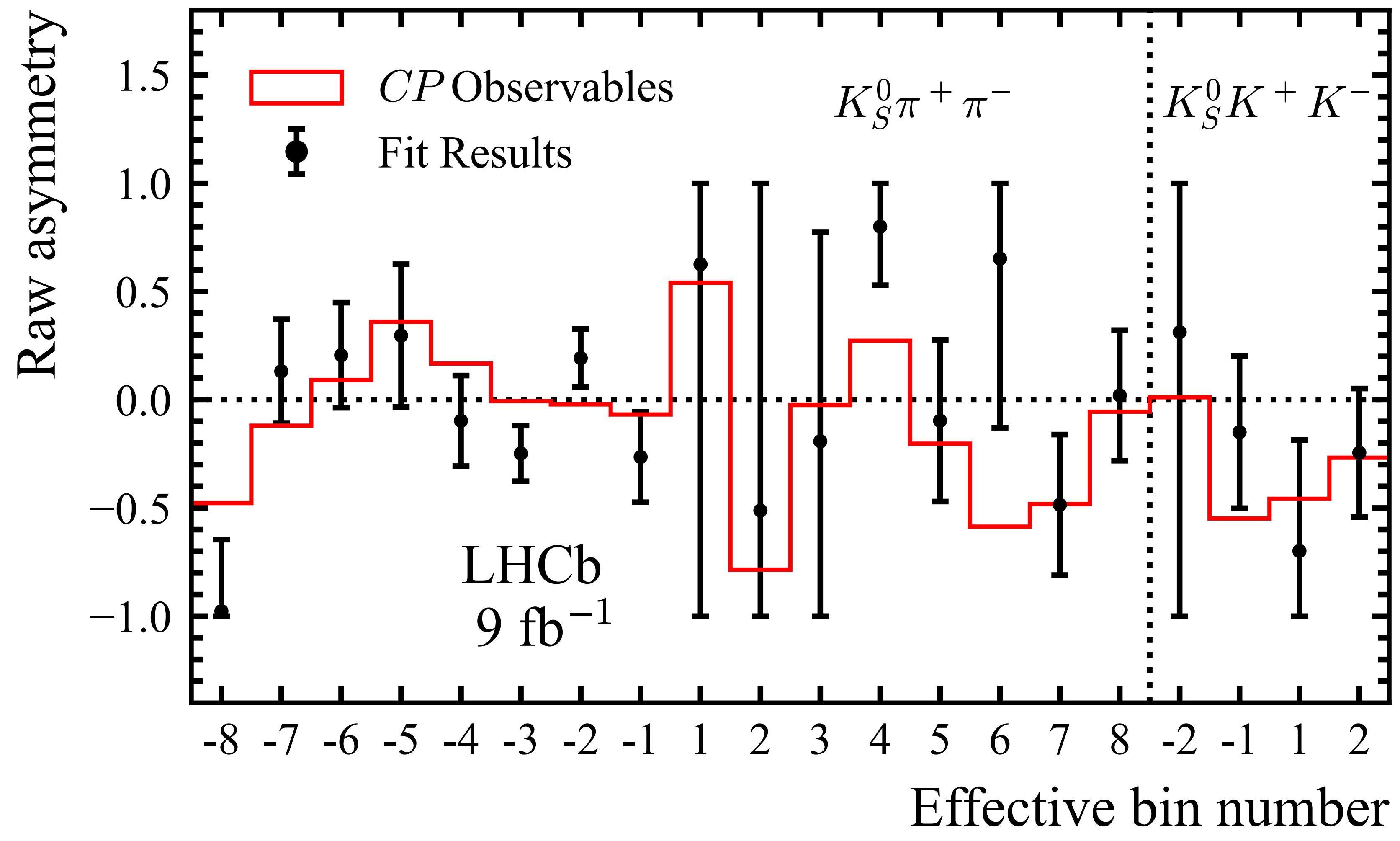


$B^+ \to DK^+, D \to K_S^0 \pi^+ \pi^+$ Dalitz distribution in LHCb data (left) and optimal binning scheme from CLEO-c (right)

- Bin population expectation equation

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

- Simultaneous mass fit to extract $x_{\pm}, y_{\pm}$
  - $\kappa, F_{\pm i}, c_i, s_i$ are fixed to values from previous measurements of LHCb, CLEO/BES
- Extract γ from $x_{\pm} = r_{B^0}^{DK^*}\cos(\Delta\delta_{B^0}^{DK^*} \pm \gamma)$, $y_{\pm} = r_{B^0}^{DK^*}\sin(\Delta\delta_{B^0}^{DK^*} \pm \gamma)$
- Combination with $D \to hh(hh)$ yields $\gamma = (63.2^{+6.9}_{-8.1})^{\circ}$
- Much closer to where B^+ was in the previous LHCb combination!



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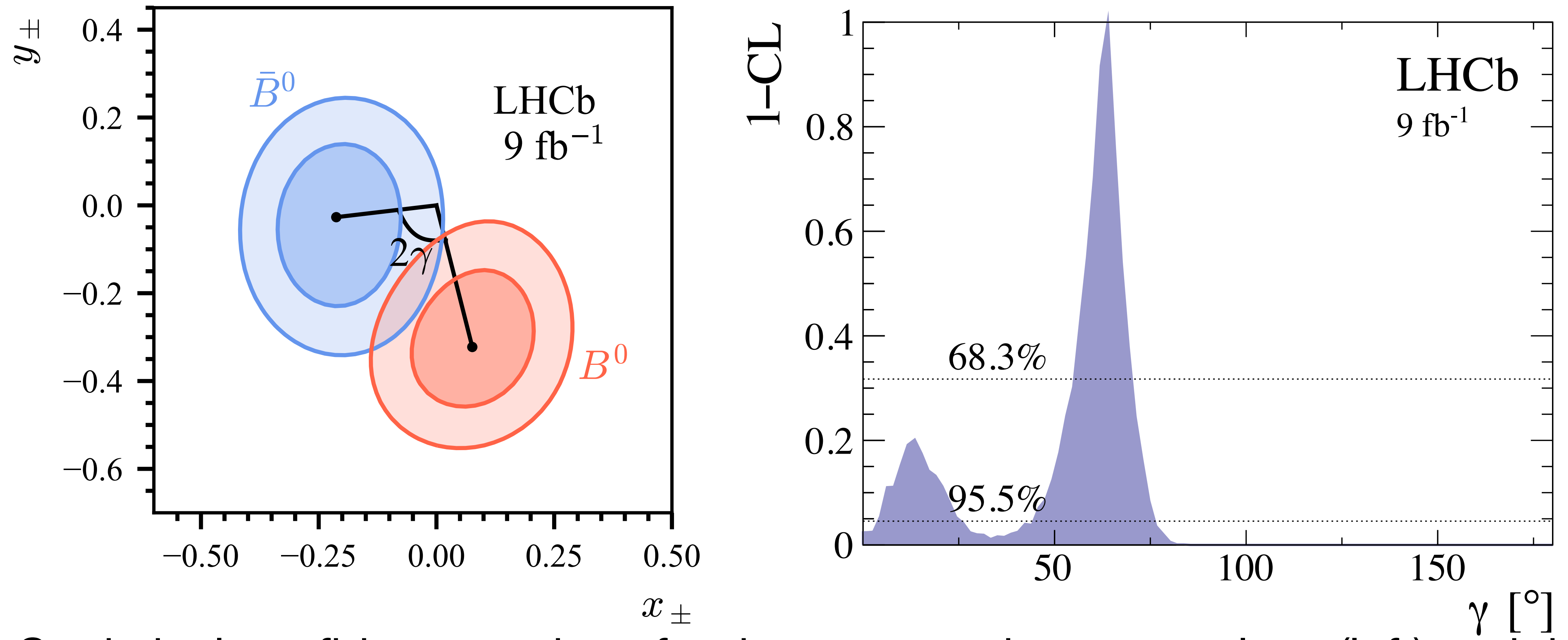


Statistical confidence regions for the measured $x_{\pm i}, y_{\pm i}$ values (left) and the confidence level profile for an extraction of γ from a combination of $D \to K_S^0 h^+ h^-$ and $D \to hh(hh)$ (right)

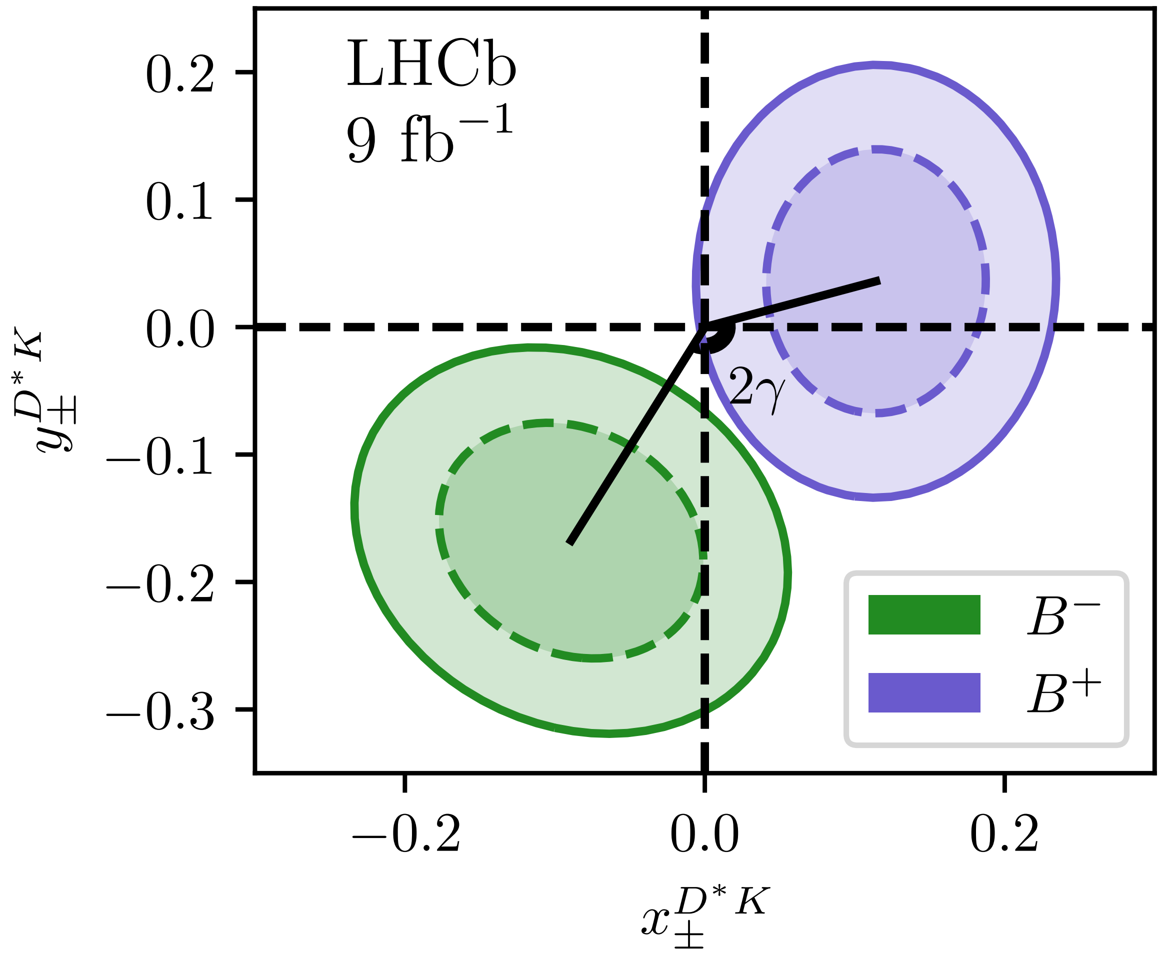
Fully reconstructed $B^{\pm} \to D^{*}h^{\pm}$ decays

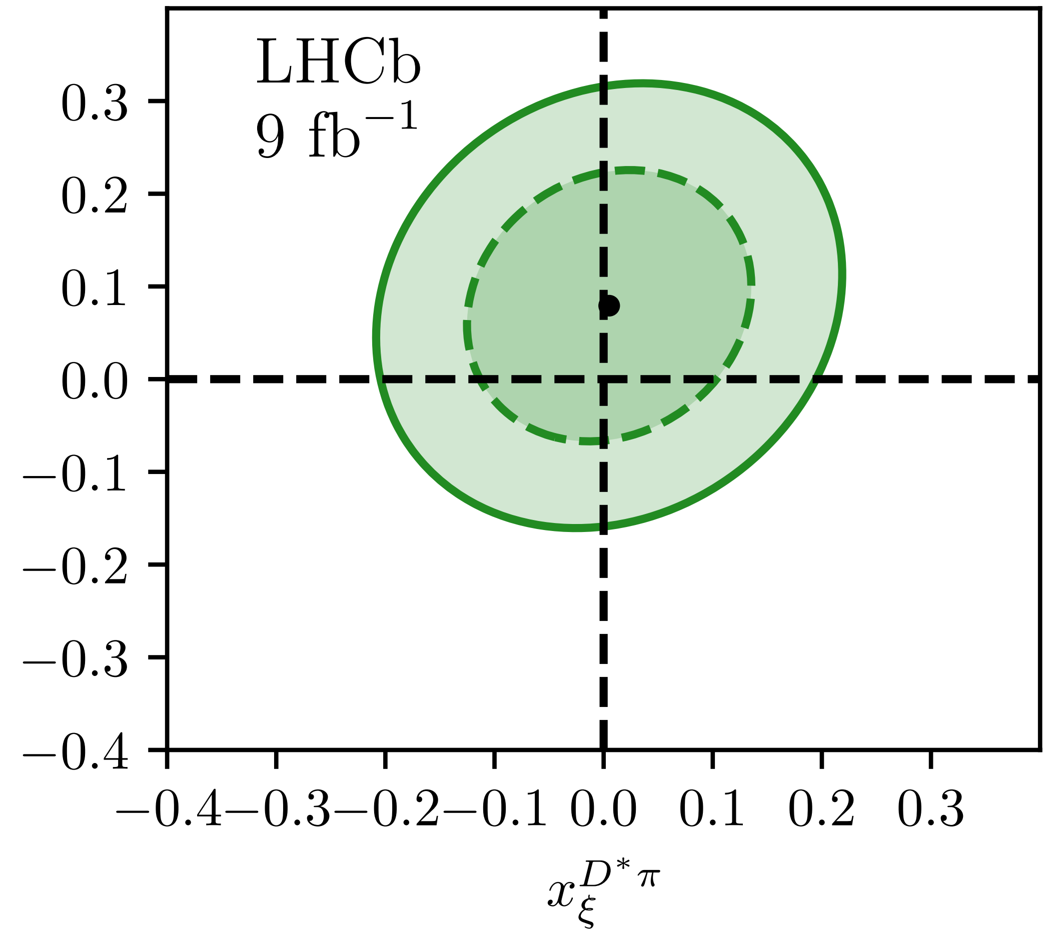
[JHEP]

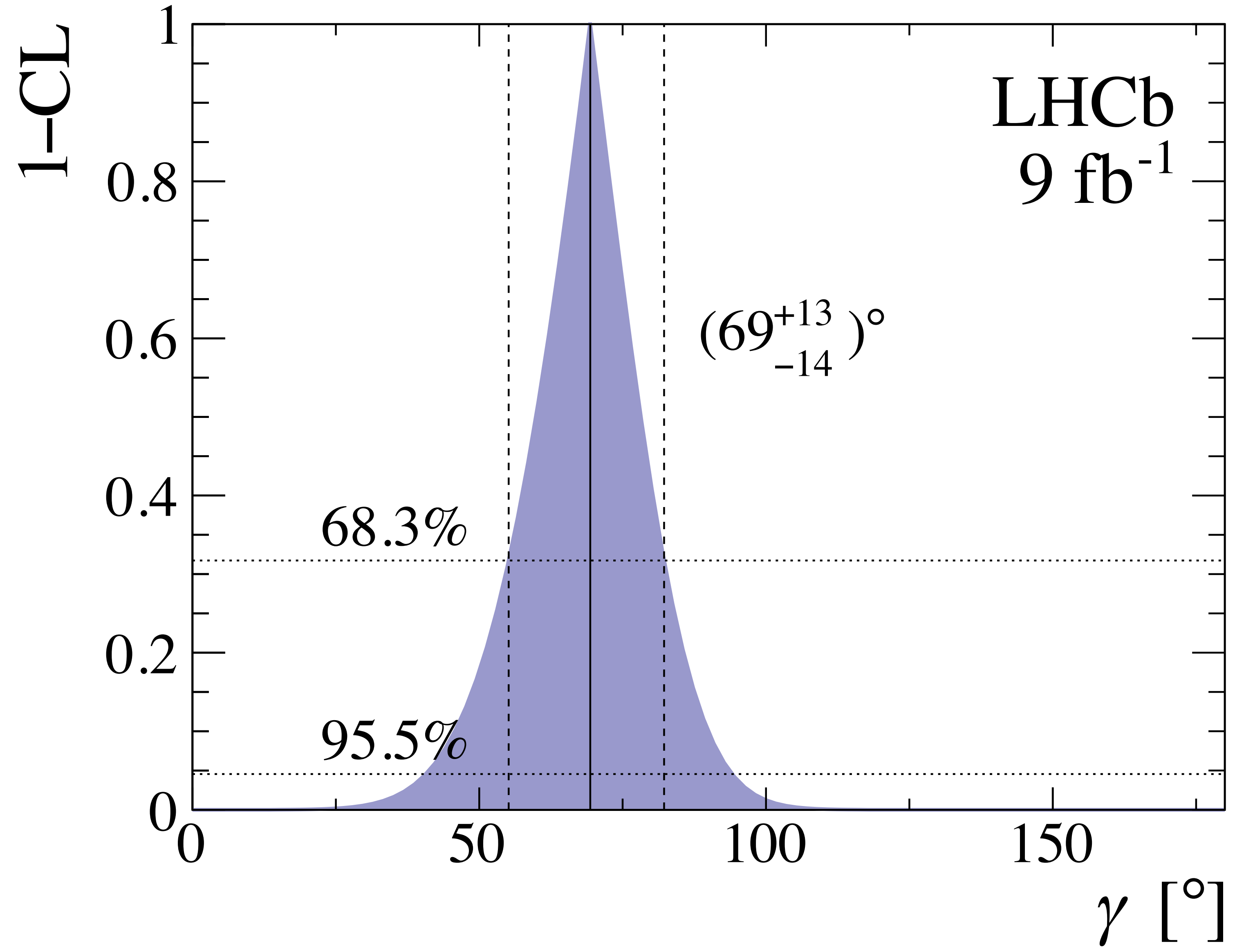
- $D \to K_S^0 h^+ h^-$ final state
- D originates from $D^* \to D\pi^0$ or $D^* \to D\gamma$
- LL and DD K_S^0 datasets are merged due to low statistics
- $B^{\pm} \to D^* K^{\pm}$ drives the sensitivity to γ
- $B^{\pm} \to D^* \pi^{\pm}$ provides a relatively large dataset with low CPV $\Longrightarrow$ good sensitivity to $F_{\pm i}$
    - Parameterise $B^{\pm} \to D^* \pi^{\pm}$ Cartesian parameters in terms of $B^{\pm} \to D^* K^{\pm}$

$$x_{\pm}^{D^*\pi} = x_\xi x_{\pm}^{D^*K} - y_\xi y_{\pm}^{D^*K}$$
$$y_{\pm}^{D^*\pi} = x_\xi y_{\pm}^{D^*K} - y_\xi x_{\pm}^{D^*K}$$

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







Fully reconstructed $B^{\pm} \to D^{*}h^{\pm}$ decays

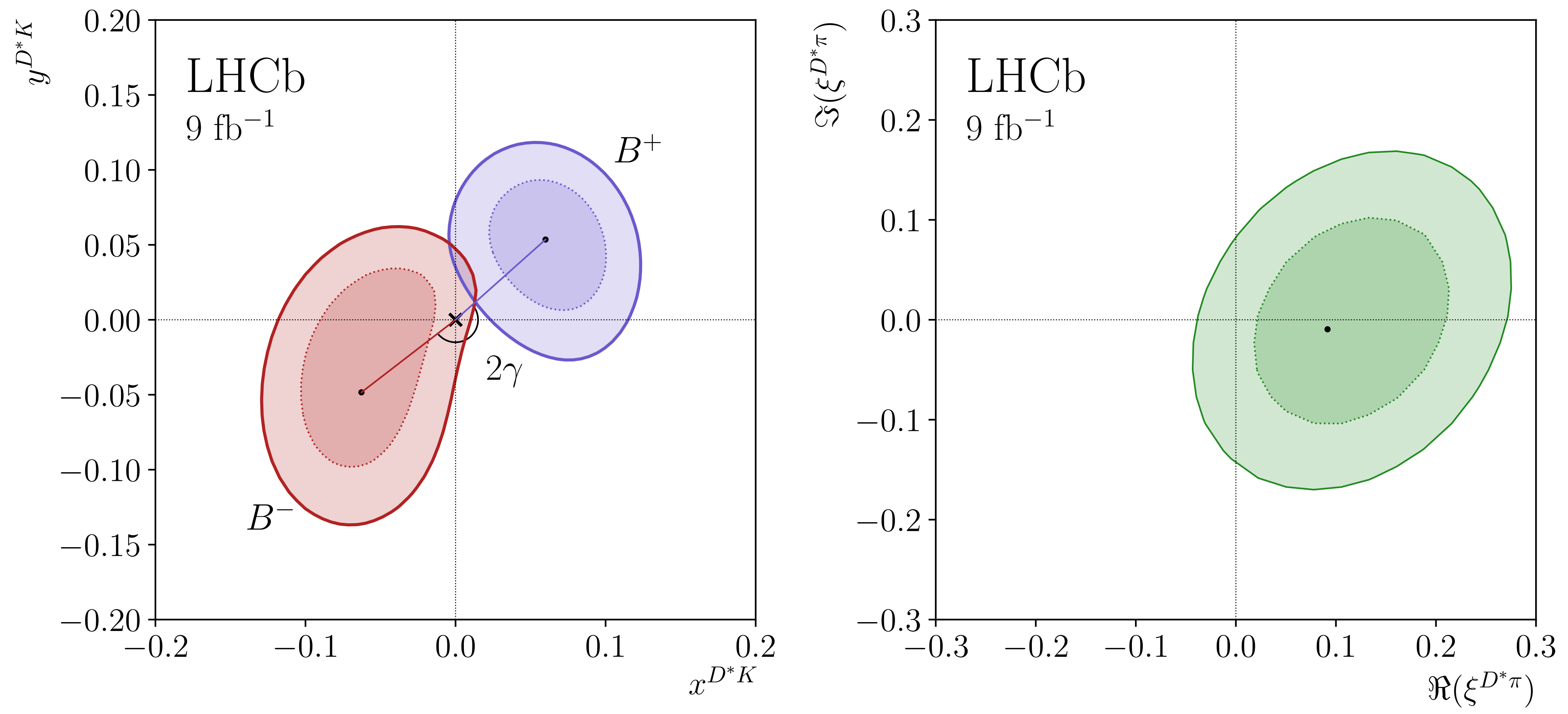
- Parameterise $B^{\pm} \to D^{*}\pi^{\pm}$ binned expectations with $\xi = \frac{r_B^{D^*\pi}}{r_B^{D^*K}} \exp[i(\delta_B^{D^*\pi} - \delta_B^{D^*\pi})]$ such that

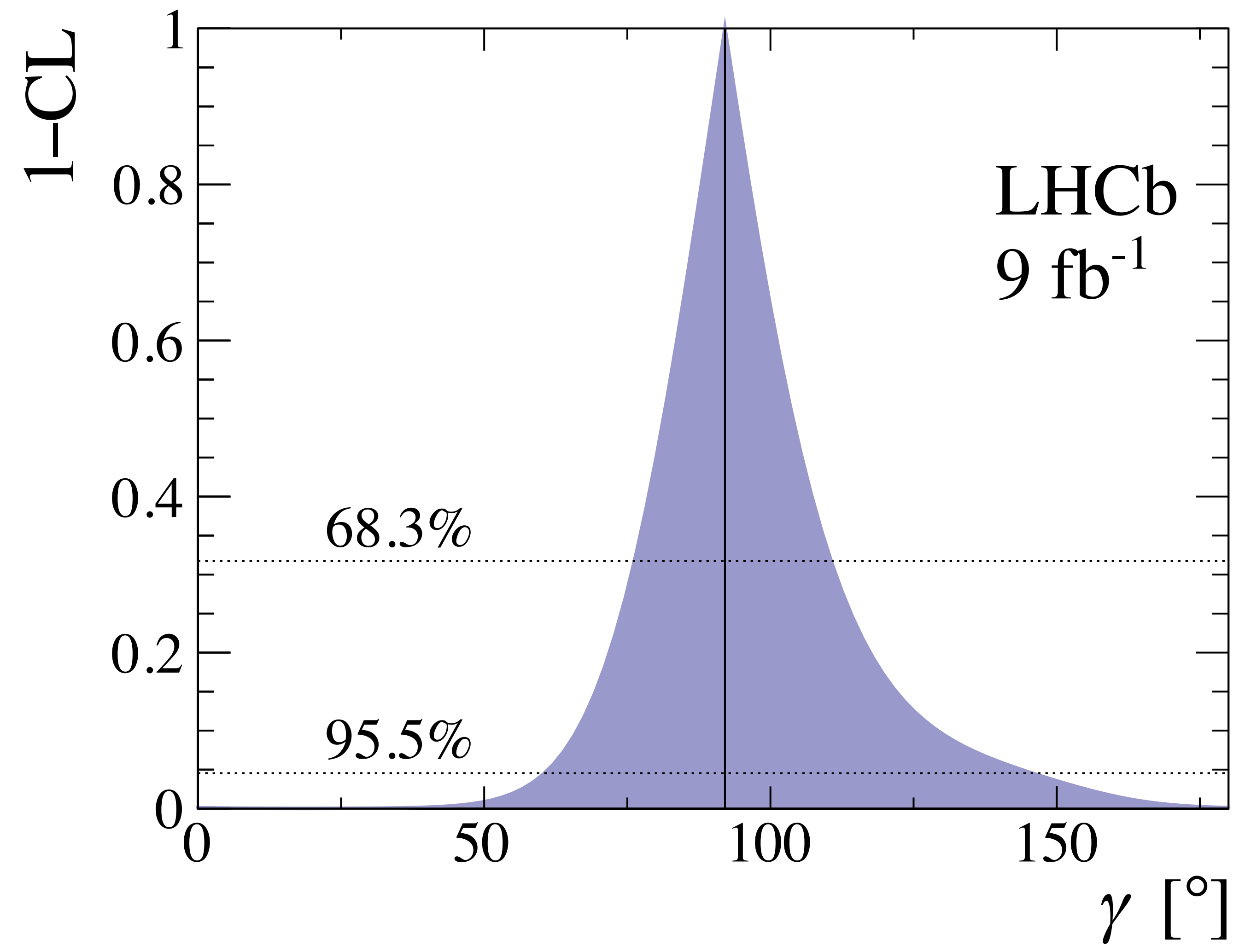
$$x_{\pm}^{D^*\pi} = \mathrm{Re}(\xi) x_{\pm}^{D^*K} - \mathrm{Im}(\xi) y_{\pm}^{D^*K}$$
$$y_{\pm}^{D^*\pi} = \mathrm{Re}(\xi) y_{\pm}^{D^*K} - \mathrm{Im}(\xi) x_{\pm}^{D^*K}$$

- Also done in the $B^{\pm} \to Dh^{\pm}$ analysis
- Known from a general derivation [arxiv]

Partially reconstructed $B^\pm \to D^* h^\pm$ decays [JHEP]

- The π^0/γ is missed during the reconstruction of the decay
  - Greater signal efficiency, and background pollution
- Greater statistics enables considering the LL and DD K_S^0 datasets separately
  - Allows separate F_i values
- Maximal correlation with fully reconstructed analysis determined to be $4\ \%$, corresponds to a shift of only 0.2° in the uncertainty
- $\gamma = (92^{+21}_{-17})^\circ$





Time dependent parameter explanations

$$\frac{\mathrm{d}\Gamma(t,d)}{\mathrm{d}t} \propto e^{-t/\tau_{B^0_{(s)}}} \left(\cosh \frac{\Delta\Gamma_q t}{2} + D_f \sinh \frac{\Delta\Gamma_q t}{2} + d\, C_f \cos \Delta m_q t - d\, S_f \sin \Delta m_q t \right)$$

The CP-violation parameters are defined as

$$D_f = -\frac{2|\lambda_f| \cos \phi_q}{1+|\lambda_f|^2},\ C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2},\ S_f = \frac{2|\lambda_f| \sin \phi_q}{1+|\lambda_f|^2},$$

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f} \text{ and } \phi_q = \arg \lambda_f,$$

Combination updates [In preparation, LHCb-CONF-2024-004]

B decay	D decay	Ref.	Dataset	Status since Ref. [13]
$B^{\pm} \to Dh^{\pm}$	$D \to h^+h'^-$	[32]	Run 1&2	*As before*
$B^{\pm} \to Dh^{\pm}$	$D \to h^+h^-\pi^+\pi^-$	[19]	Run 1&2	**New**
$B^{\pm} \to Dh^{\pm}$	$D \to K^{\pm}\pi^{\mp}\pi^+\pi^-$	[33]	Run 1&2	*As before*
$B^{\pm} \to Dh^{\pm}$	$D \to h^+h'^-\pi^0$	[34]	Run 1&2	*As before*
$B^{\pm} \to Dh^{\pm}$	$D \to K^0_S h^+h^-$	[35]	Run 1&2	*As before*
$B^{\pm} \to Dh^{\pm}$	$D \to K^0_S K^{\pm}\pi^{\mp}$	[36]	Run 1&2	*As before*
$B^{\pm} \to D^*h^{\pm}$	$D \to h^+h'^-$ (PR)	[32]	Run 1&2	*As before*
$B^{\pm} \to D^*h^{\pm}$	$D \to K^0_S h^+h^-$ (PR)	[20]	Run 1&2	**New**
$B^{\pm} \to D^*h^{\pm}$	$D \to K^0_S h^+h^-$ (FR)	[21]	Run 1&2	**New**
$B^{\pm} \to DK^{*\pm}$	$D \to h^+h'^-$	[22]	Run 1&2	**Updated**
$B^{\pm} \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[22]	Run 1&2	**Updated**
$B^{\pm} \to DK^{*\pm}$	$D \to K^0_S h^+h^-$	[22]	Run 1&2	**New**
$B^{\pm} \to Dh^{\pm}\pi^+\pi^-$	$D \to h^+h'^-$	[37]	Run 1	*As before*
$B^0 \to DK^{*0}$	$D \to h^+h'^-$	[23]	Run 1&2	**Updated**
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	[23]	Run 1&2	**Updated**
$B^0 \to DK^{*0}$	$D \to K^0_S h^+h^-$	[24]	Run 1&2	**Updated**
$B^0 \to D^{\mp}\pi^{\pm}$	$D^+ \to K^-\pi^+\pi^+$	[38]	Run 1	*As before*
$B^0_s \to D_s^{\mp}K^{\pm}$	$D_s^+ \to h^+h^-\pi^+$	[25,39]	Run 1&2	**Updated**
$B^0_s \to D_s^{\mp}K^{\pm}\pi^+\pi^-$	$D_s^+ \to h^+h^-\pi^+$	[40]	Run 1&2	*As before*

Beauty measurements in the combination

D decay	Observable(s)	Ref.	Dataset	Status since Ref. [13]
$D^0 \to h^+h^-$	ΔA_{CP}	[41–43]	Run 1&2	*As before*
$D^0 \to K^+K^-$	$A_{CP}(K^+K^-)$	[43–45]	Run 2	*As before*
$D^0 \to h^+h^-$	$y_{CP} - y_{CP}^{K^-\pi^+}$	[46,47]	Run 1&2	*As before*
$D^0 \to h^+h^-$	ΔY	[48–51]	Run 1&2	*As before*
$D^0 \to K^+\pi^-$ (double tag)	$R^{\pm}$, $(x'^{\pm})^2$, $y'^{\pm}$	[52]	Run 1	*As before*
$D^0 \to K^+\pi^-$ (single tag)	$R_{K\pi}$, $A_{K\pi}$, $c_{K\pi}^{(\prime)}$, $\Delta c_{K\pi}^{(\prime)}$	[27,53]	Run 1&2	**Updated**
$D^0 \to K^{\pm}\pi^{\mp}\pi^+\pi^-$	$(x^2+y^2)/4$	[54]	Run 1	*As before*
$D^0 \to K^0_S\pi^+\pi^-$	x, y	[55]	Run 1	*As before*
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[56]	Run 1	*As before*
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[57,58]	Run 2	*As before*
$D^0 \to \pi^+\pi^-\pi^0$	ΔY^{eff}	[26]	Run 2	**New**

Charm measurements in the combination

Combination updates [In preparation, LHCb-CONF-2024-004]

Decay	Parameters	Source	Ref.	Status since Ref. [13]
$B^\pm \to DK^{*\pm}$	$\kappa_{B^\pm}^{DK^{*\pm}}$	LHCb	[59]	*As before*
$B^0 \to DK^{*0}$	$\kappa_{B^0}^{DK^{*0}}$	LHCb	[60]	*As before*
$B^0 \to D^\mp\pi^\pm$	β	HFLAV	[14]	**Updated**
$B_s^0 \to D_s^\mp K^\pm(\pi\pi)$	ϕ_s	LHCb	[61]	**Updated**
$D \to K^+\pi^-$	$\cos\delta_D^{K\pi}$, $\sin\delta_D^{K\pi}$, $(r_D^{K\pi})^2$, x^2, y	CLEO-c	[62]	*As before*
$D \to K^+\pi^-$	$A_{K\pi}$, $A_{K\pi}^{\pi\pi\pi^0}$, $r_D^{K\pi}\cos\delta_D^{K\pi}$, $r_D^{K\pi}\sin\delta_D^{K\pi}$	BESIII	[63]	*As before*
$D \to h^+h^-\pi^0$	$F_{\pi\pi\pi^0}^+$, $F_{KK\pi^0}^+$	CLEO-c	[64]	*As before*
$D \to \pi^+\pi^-\pi^+\pi^-$	$F_{4\pi}^+$	CLEO-c+BESIII	[64, 65]	*As before*
$D \to K^+K^-\pi^+\pi^-$	$F_{KK\pi\pi}^+$	BESIII	[66]	**New**
$D \to K^+\pi^-\pi^0$	$r_D^{K\pi\pi^0}$, $\delta_D^{K\pi\pi^0}$, $\kappa_D^{K\pi\pi^0}$	CLEO-c+LHCb+BESIII	[67–69]	*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	[54, 67–69]	*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	[70]	*As before*
$D \to K_S^0K^\pm\pi^\mp$	$r_D^{K_S^0K\pi}$	LHCb	[71]	*As before*

Auxiliary inputs to the combination

Quantity	Value	68.3% CL		95.4% CL	
		Uncertainty	Interval	Uncertainty	Interval
$\gamma[^\circ]$	64.6	±2.8	$[61.8, 67.4]$	${}^{+5.5}_{-5.7}$	$[58.9, 70.1]$
$r_{B^\pm}^{DK^\pm}[\%]$	9.73	${}^{+0.21}_{-0.20}$	$[9.53, 9.94]$	${}^{+0.42}_{-0.40}$	$[9.33, 10.15]$
$\delta_{B^\pm}^{DK^\pm}[^\circ]$	127.4	${}^{+2.8}_{-3.0}$	$[124.4, 130.2]$	${}^{+5.6}_{-6.2}$	$[121.2, 133.0]$
$r_{B^\pm}^{D\pi^\pm}[\%]$	0.49	${}^{+0.06}_{-0.05}$	$[0.44, 0.55]$	${}^{+0.12}_{-0.10}$	$[0.39, 0.61]$
$\delta_{B^\pm}^{D\pi^\pm}[^\circ]$	292	${}^{+10}_{-11}$	$[281, 301]$	${}^{+19}_{-22}$	$[269, 310]$
$r_{B^\pm}^{D^*K^\pm}[\%]$	10.6	±1.0	$[9.6, 11.6]$	±2.0	$[8.6, 12.6]$
$\delta_{B^\pm}^{D^*K^\pm}[^\circ]$	312	${}^{+6}_{-7}$	$[304, 318]$	${}^{+12}_{-16}$	$[296, 324]$
$r_{B^\pm}^{D^*\pi^\pm}[\%]$	0.74	${}^{+0.41}_{-0.32}$	$[0.42, 1.15]$	${}^{+0.87}_{-0.62}$	$[0.12, 1.61]$
$\delta_{B^\pm}^{D^*\pi^\pm}[^\circ]$	37	${}^{+39}_{-20}$	$[17, 76]$	${}^{+94}_{-31}$	$[6, 131]$
$r_{B^\pm}^{DK^{*\pm}}[\%]$	10.6	${}^{+0.9}_{-1.0}$	$[9.6, 11.5]$	${}^{+1.7}_{-2.0}$	$[8.6, 12.3]$
$\delta_{B^\pm}^{DK^{*\pm}}[^\circ]$	49	${}^{+14}_{-11}$	$[38, 63]$	${}^{+30}_{-23}$	$[26, 79]$
$r_{B^0}^{DK^{*0}}[\%]$	23.4	${}^{+1.5}_{-1.6}$	$[21.8, 24.9]$	${}^{+2.9}_{-3.3}$	$[20.1, 26.3]$
$\delta_{B^0}^{DK^{*0}}[^\circ]$	192	±6	$[186, 198]$	${}^{+13}_{-12}$	$[180, 205]$
$r_{B_s^0}^{D_s^\mp K^\pm}[\%]$	33.3	${}^{+3.7}_{-3.5}$	$[29.8, 37.0]$	${}^{+7.5}_{-7.1}$	$[26.2, 40.8]$
$\delta_{B_s^0}^{D_s^\mp K^\pm}[^\circ]$	349	±6	$[343, 355]$	±12	$[337, 361]$
$r_{B_s^0}^{D_s^\mp K^\pm\pi^+\pi^-}[\%]$	46	±8	$[37, 54]$	${}^{+16}_{-17}$	$[29, 62]$
$\delta_{B_s^0}^{D_s^\mp K^\pm\pi^+\pi^-}[^\circ]$	345	${}^{+13}_{-12}$	$[333, 358]$	${}^{+26}_{-25}$	$[320, 371]$
$r_{B^0}^{D^\mp\pi^\pm}[\%]$	3.0	${}^{+1.3}_{-1.2}$	$[1.8, 4.3]$	${}^{+3.1}_{-2.7}$	$[0.3, 6.1]$
$\delta_{B^0}^{D^\mp\pi^\pm}[^\circ]$	30	${}^{+25}_{-36}$	$[-6, 55]$	${}^{+45}_{-77}$	$[-47, 75]$
$r_{B^\pm}^{DK^\pm\pi^+\pi^-}[\%]$	8.0	${}^{+2.7}_{-3.3}$	$[4.7, 10.7]$	${}^{+4.9}_{-8.0}$	$[0.0, 12.9]^*$
$r_{B^\pm}^{D\pi^\pm\pi^+\pi^-}[\%]$	6.2	${}^{+2.2}_{-3.0}$	$[3.2, 8.4]$	${}^{+3.7}_{-6.2}$	$[0.0, 9.9]^*$
$x[\%]$	0.41	±0.05	$[0.36, 0.45]$	±0.09	$[0.31, 0.50]$
$y[\%]$	0.621	${}^{+0.022}_{-0.021}$	$[0.600, 0.643]$	${}^{+0.044}_{-0.042}$	$[0.579, 0.665]$
$r_D^{K\pi}[\%]$	5.855	${}^{+0.010}_{-0.009}$	$[5.846, 5.865]$	${}^{+0.020}_{-0.019}$	$[5.836, 5.875]$
$\delta_D^{K\pi}[^\circ]$	191.6	${}^{+2.5}_{-2.4}$	$[189.2, 194.1]$	${}^{+4.9}_{-5.1}$	$[186.5, 196.5]$
$\lvert q/p\rvert$	0.989	±0.015	$[0.974, 1.004]$	${}^{+0.031}_{-0.030}$	$[0.959, 1.020]$
$\phi[^\circ]$	-2.5	±1.2	$[-3.7, -1.3]$	±2.5	$[-5.0, 0.0]$
$a_{K^+K^-}^{\mathrm{d}}[\%]$	0.06	${}^{+0.06}_{-0.05}$	$[0.01, 0.12]$	±0.11	$[-0.05, 0.17]$
$a_{\pi^+\pi^-}^{\mathrm{d}}[\%]$	0.22	±0.06	$[0.16, 0.28]$	±0.12	$[0.10, 0.34]$
$a_{K^+\pi^-}^{\mathrm{d}}[\%]$	-0.60	${}^{+0.27}_{-0.26}$	$[-0.86, -0.33]$	${}^{+0.53}_{-0.54}$	$[-1.14, -0.07]$

Combination results for Beauty and Charm parameters of interest