University of Chinese Academy of Sciences

Measurement of the CKM angle γ using $B^{\pm} \to D^{*} h^{\pm}$ channels

arXiv: 2310.04277

Lei Hao
On behalf of the LHCb collaboration

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Outlines

- Motivation and introduction
- Data and simulation samples
- Selections
- Invariant mass fit
- Systematic uncertainty
- Interpretation
- Summary.

CKM matrix and CP violation

arXiv: 9612327
Phys. Rev. **D98** (2018) 030001

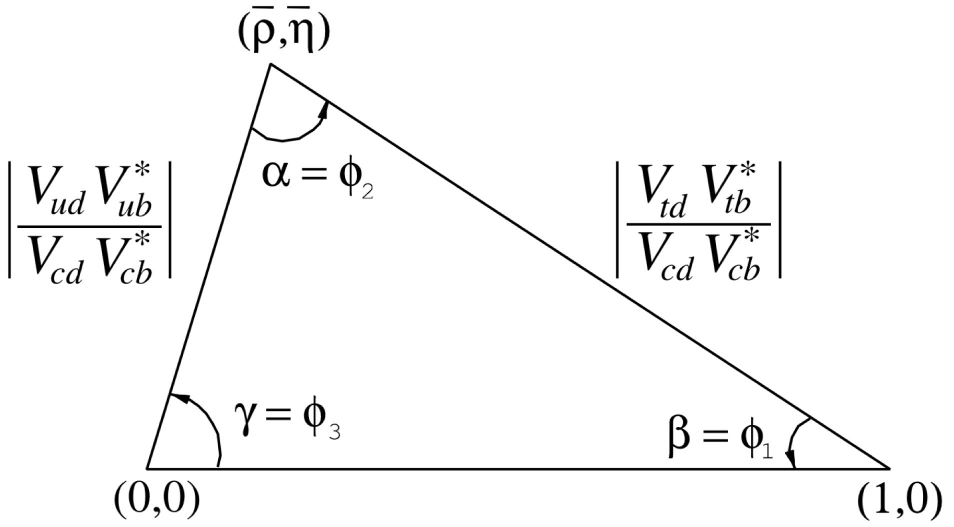
- CKM matrix is a 3×3 unitary matrix, elements represent the strength of flavor-changing weak interactions.

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = V_{\mathrm{CKM}} \begin{bmatrix} d \\ s \\ b \end{bmatrix}, \text{ where } V_{\mathrm{CKM}} = \begin{bmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{bmatrix}$$

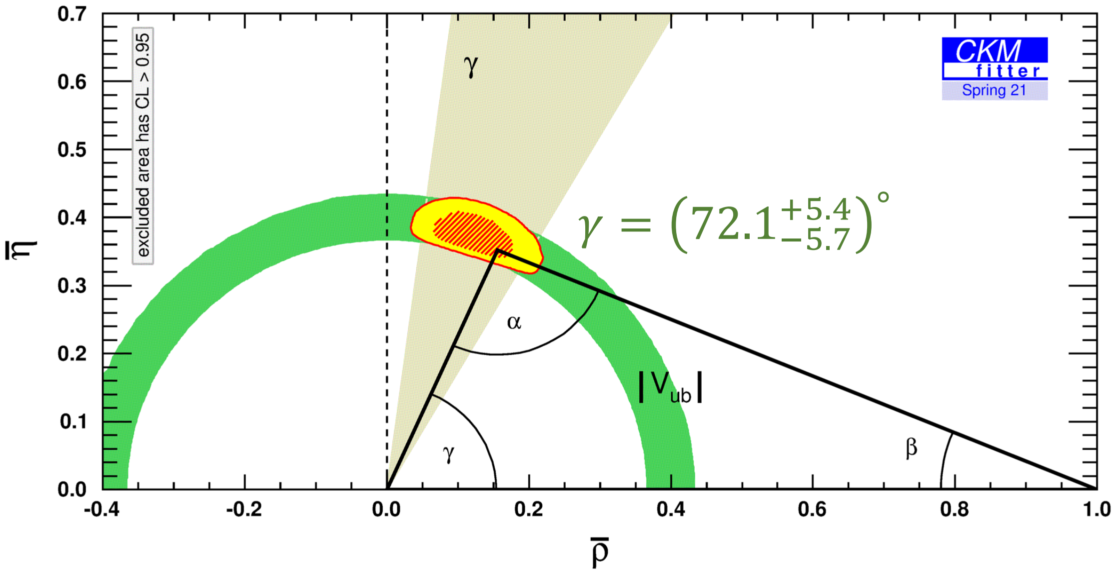
- Parameterized by 3 mixing angles and 1 CP violating phase.

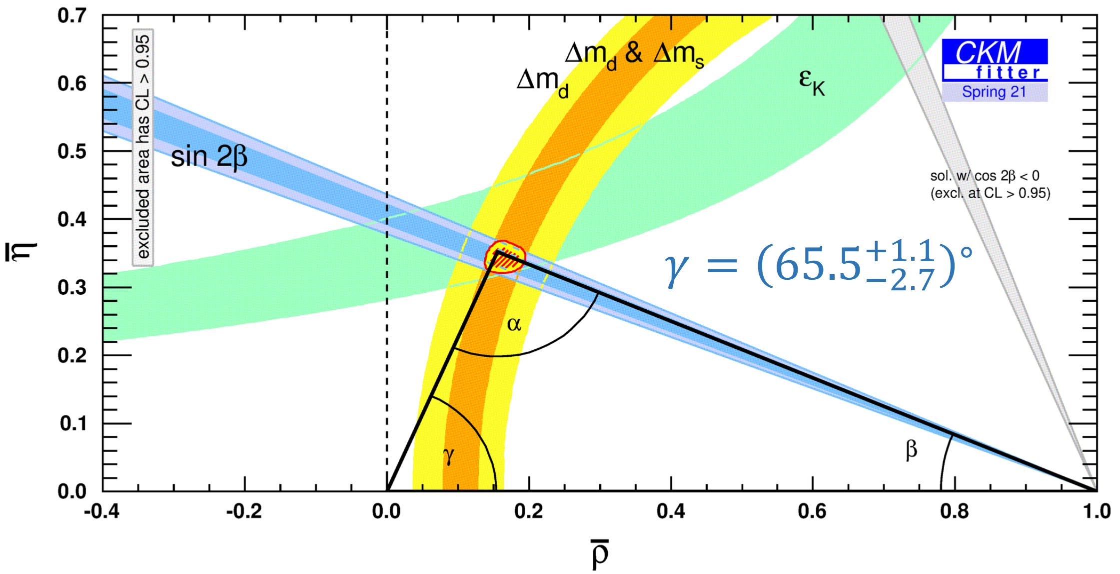
- $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$

- CKM phases are related to CP violation (CPV).
    - $\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$; $\beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$; $\boldsymbol{\gamma} = \mathbf{arg}\left(-\frac{\boldsymbol{V_{ud}V_{ub}^*}}{\boldsymbol{V_{cd}V_{cb}^*}}\right)$



CKM angle γ





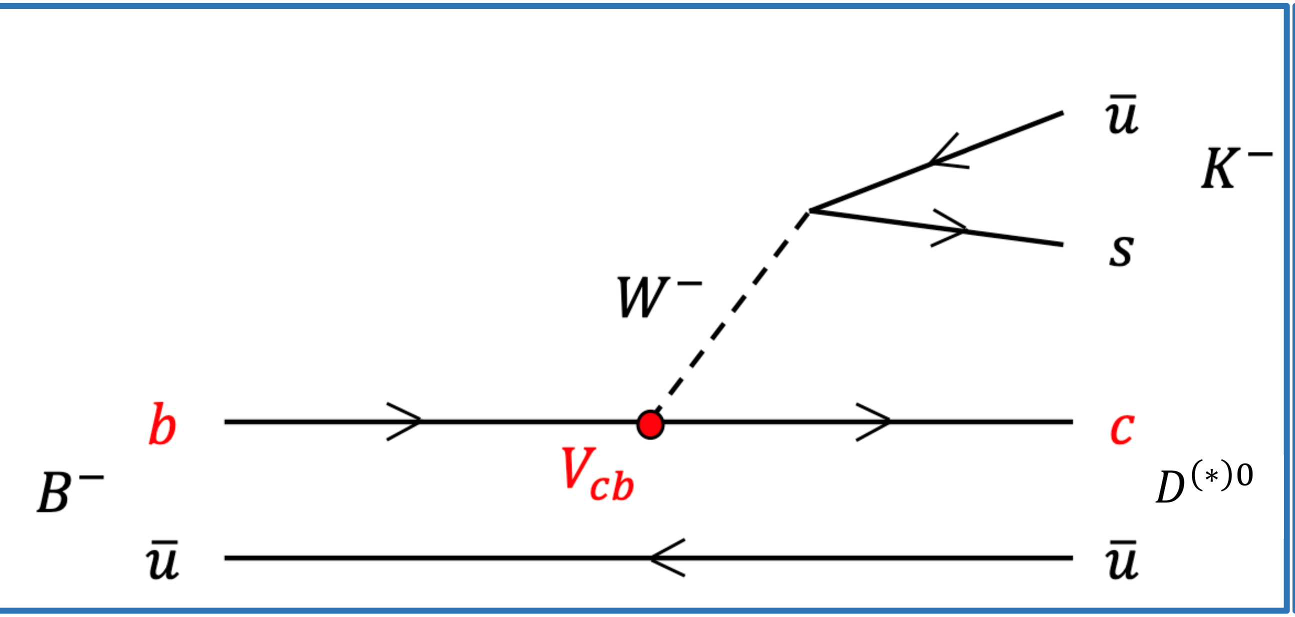
- Direct measurement of γ
  - Accessible at tree-level
  - Benchmarks of the standard model.

- Indirect measurements
  - Some inputs include loop processes
  - Assuming closed triangle.
  - New Physics (NP) expected to contribute through loop processes.

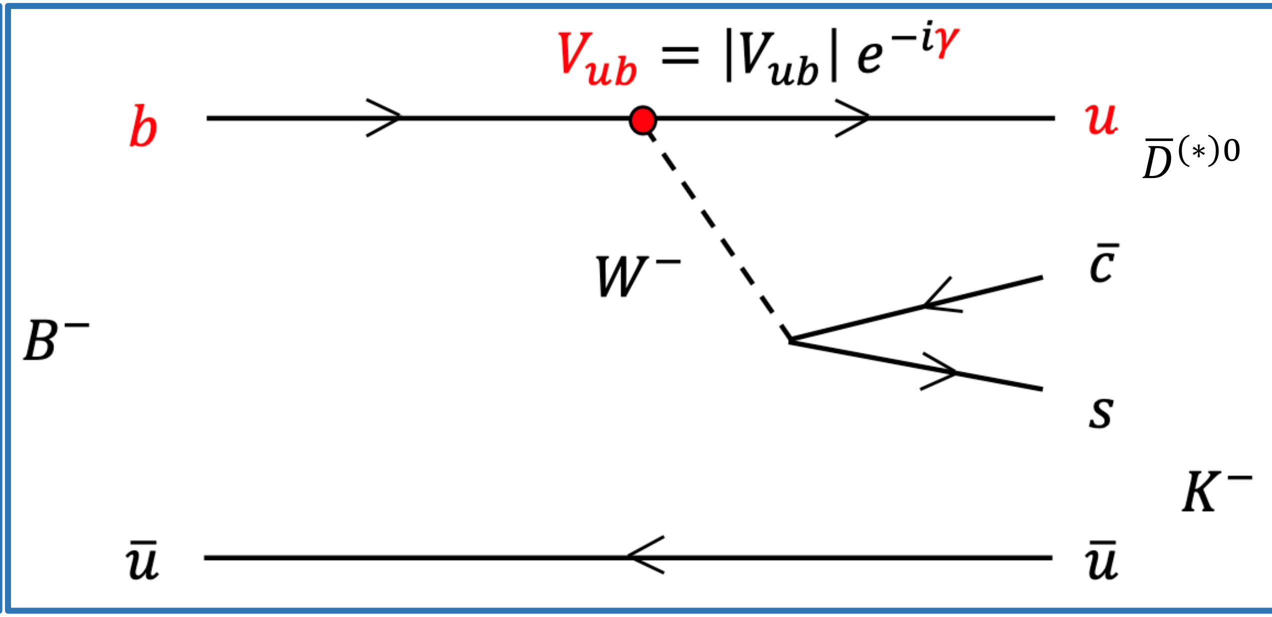
A discrepancy between direct and indirect measurements would be a clear sign of NP.

Measure γ in $B^{\pm} \to D^{*} K^{\pm}$

PhysicsLettersB265 (1991) 172-176



Favoured $b \to c$



Suppressed $b \to u$

- Access to γ via interference between $b \to c$ and $b \to u$.
  - $\frac{A(B^- \to \bar{D}^* K^-)}{A(B^- \to D^* K^-)} = r_B^{D^*K} e^{i(\delta_B^{D^*K} - \gamma)}$, $\frac{A(B^+ \to D^* K^+)}{A(B^+ \to \bar{D}^* K^+)} = r_B^{D^*K} e^{i(\delta_B^{D^*K} + \gamma)}$
  - Interference $\propto \cos[\delta_B^{D^*K} \pm \gamma]$.

BP-GGSZ method

Phys. Rev. D 68, 054018

- Multi-body D decays are used to study CPV in various regions over phase space, can be split into bins.

- $D \to K_S^0 h^+ h^-$ decays ($h = K, \pi$)

  Amplitude of $D(\bar{D})$ decay

  Square of mass of $K_S^0 h^\pm$

  - $A\left(B^\pm \to D^{(*)} h^\pm\right) \propto A_D(s_\pm, s_\mp) + A_{\bar{D}}(s_\pm, s_\mp) r_B^{D^{(*)}h} e^{i(\delta_B^{D^{(*)}h} \pm \gamma)}$

  - Presence of resonances in D decay provide variation of amplitude over phase space for extracting γ.

    - Knowledge of D decay is necessary to disentangle γ, from charm factory (BEIII and CLEO-c).

CP observables in BP-GGSZ method

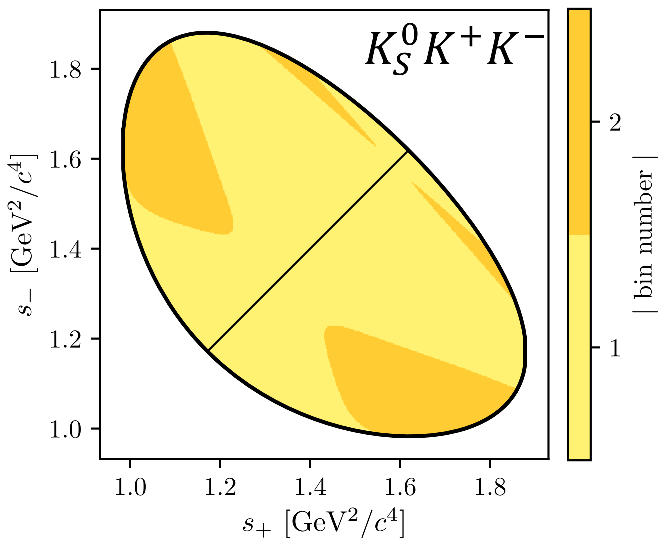
- Model-independent measurement.
  - The optimal binning scheme is used in this analysis.
- Signal yields in bin (i) are related to CP observables.
  - $N_i^- \propto \left(F_i + (x_-^2 + y_-^2)F_{-i} + 2f_{D^*}\sqrt{F_iF_{-i}}(c_ix_- + s_iy_-)\right)$
  - $N_i^+ \propto (F_{-i} + (x_+^2 + y_+^2)F_i + 2f_{D^*}\sqrt{F_iF_{-i}}(c_ix_+ - s_iy_+))$

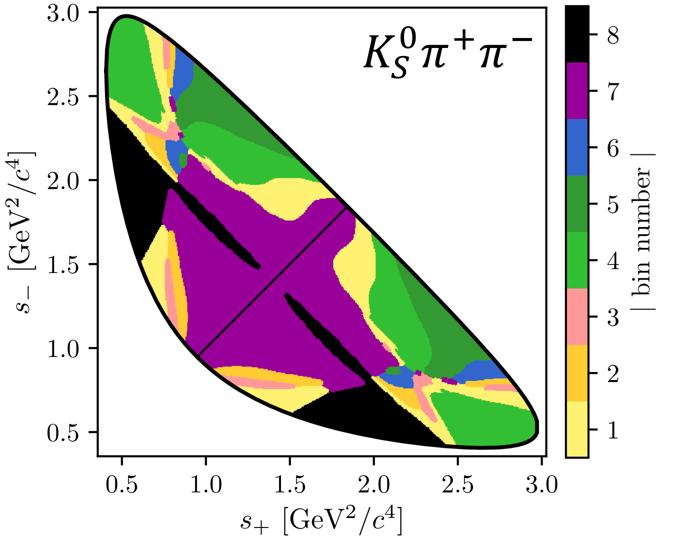
F_i: fractional yields of D^0 in bin i. determined mainly in $D^*\pi$ mode.

$r_B^{D^*K}e^{i(\delta_B^{D^*K}\pm\gamma)} = x_\pm + iy_\pm$

Factor describing π phase difference between $D^* \to D\pi^0$ (1) and $D^* \to D\gamma$ (−1)

c_i, s_i: the cosine and sine of the strong phase difference of $D^0 - \overline{D}^0$ decay in bin i. inputs from BESIII and CLEO-c.





- $D^*\pi$ mode contributes to the measurement of γ.
  - $x_\xi^{D^*\pi}, y_\xi^{D^*\pi}$ =Re,Im$\left[\frac{r_B^{D^*\pi}e^{i\delta_B^{D^*\pi}}}{r_B^{D^*K}e^{i\delta_B^{D^*K}}}\right]$ arXiv:1804.05597

Data and simulation samples

- Samples: RUN1+RUN2 datasets.
- Simulation samples: obtain the shapes of signal and background
  - Signal simulation samples:
    - $B^{\pm} \to \left(D^{*} \to (D \to K_{S}^{0}hh)\pi^{0}/\gamma\right)h^{\pm},\ h = K,\pi$
  - Partially reconstructed background simulation samples

Constrain and selections

- The invariant masses of D, K_S^0 and π^0 are constrained to PDG value(Prog. Theor. Exp. Phys. 2022 (2022) 083C01), $B^{\pm}$ constrained to originate from PV.
- For the final-state charged tracks, requirements are placed on the track quality, momenta, IP and so on to suppress random tracks coming from the PV and backgrounds.
- Boosted decision trees (BDT) are used to reduce combinatorial background. J. Comput. Syst. Sci. 55 (1997) 119
  - Charged final-state tracks: the same as $B^{\pm} \to Dh^{\pm}$ GGSZ analysis, variables used include the momenta, vertex positions and so on.
  - Neutral BDT:
    - Reduce the combinatorial background with the $D^* \to D\pi^0/\gamma$ reconstruction.
    - Variables used include momentum, confidence level of γ and so on.
    - Optimized by the minimizing the uncertainty of the γ angle based on the toys.

Mass fit

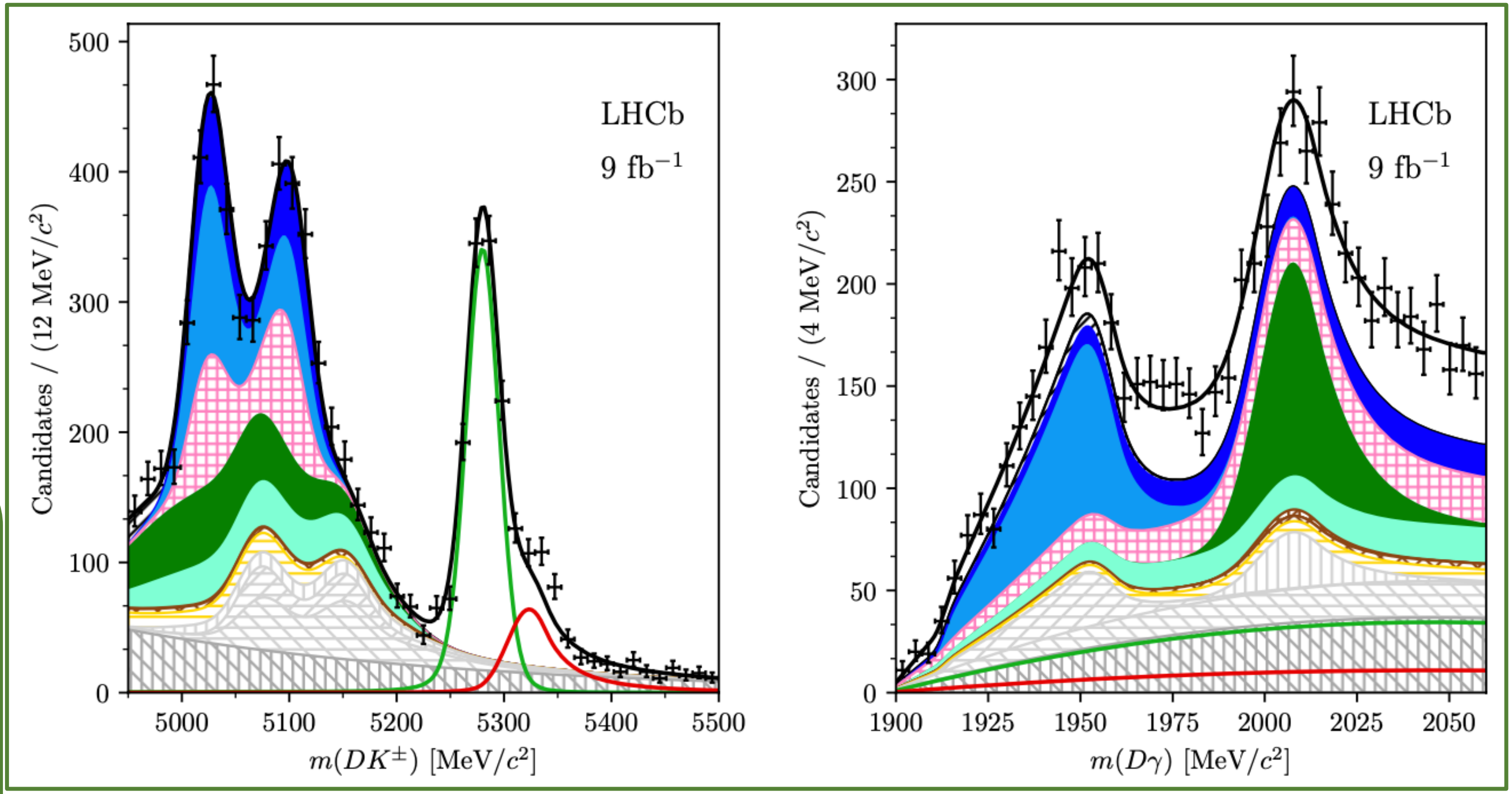
- Unbinned, extended maximum-likelihood 2D fit is performed simultaneously to mass distributions $m(Dh^{\pm}), m(D\pi^0/\gamma)$ in each of categories (D decay phase space bins, B charges, B decays, D decays, D^* decays).

Fit simultaneously and drawn with the B charges and D decay phase space bins merged.

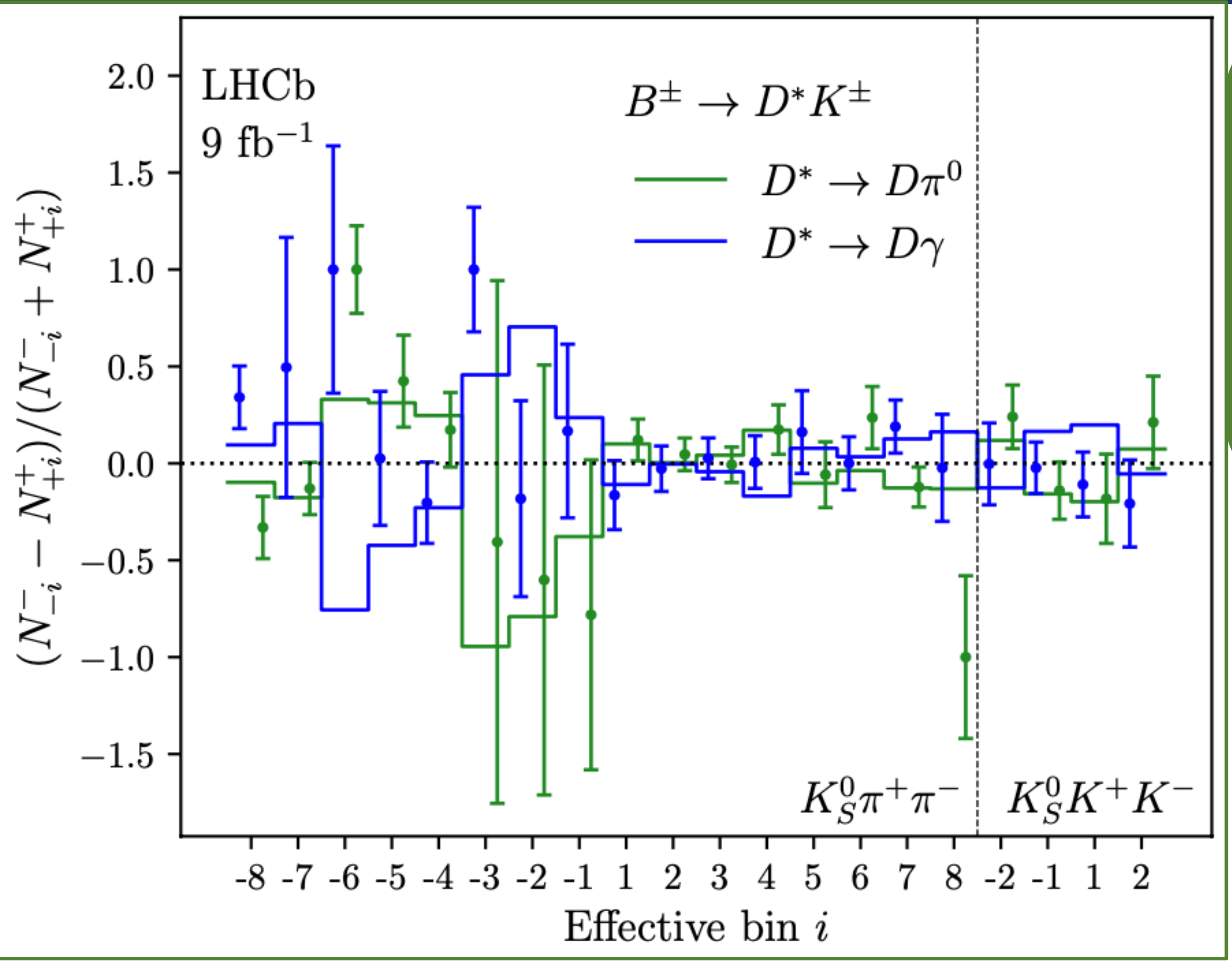
Solid color components contribute to the CKM angle γ measurement dominantly.

Solid color ⟶ signal contributions (fully and partially reconstructed D^*)

Hashed color ⟶ background contributions



CP asymmetry



Points with error bar are obtained from the alternative fit where the signal yield in each category is a free parameter.

Solid line indicate the CP asymmetry predicted with the CP observables.

CP violation to be observed.

Good agreement between individual bin asymmetries from alternative fit and prediction with CP observables.

Bin asymmetries between $D^* \to D\pi^0$ and $D^* \to D\gamma$ are opposite in sign.

Systematic uncertainty

Fitted with correlation in the $B^{\pm} \to D^{*}h^{\pm}, D^{*} \to D\pi^{0}$ component in γ mode.

The strategy for assessing these is similar to past $B^{\pm} \to Dh^{\pm}$ analysis.

All uncertainties are quoted with implicit: $\times 10^{-2}$

Source	$\sigma(x_{+}^{D^{*}K})$	$\sigma(x_{-}^{D^{*}K})$	$\sigma(y_{+}^{D^{*}K})$	$\sigma(y_{-}^{D^{*}K})$	$\sigma(x_{\xi}^{D^{*}\pi})$	$\sigma(y_{\xi}^{D^{*}\pi})$
Neglecting correlations	0.05	0.03	0.19	0.04	0.70	1.48
Efficiency correction of (c_i, s_i)	0.53	0.18	0.18	0.20	0.64	1.73
Invariant mass shape parameter	0.09	0.16	0.20	0.05	0.39	0.06
Fixed yield ratios	0.09	0.03	0.03	0.01	0.33	0.15
Bin dependence of the invariant-mass shape	0.40	0.38	0.41	0.33	1.78	1.57
DP bin migration	0.32	0.70	0.03	0.17	1.20	2.00
Λ_b^0 background	0.97	1.34	0.55	0.77	1.13	1.43
Semileptonic B backgrounds	0.27	1.29	0.02	0.67	0.03	0.04
Merging data subsamples	0.06	0.02	0.12	0.03	0.06	0.34
CP violation in $B^{\pm,0} \to DK^{\pm}\pi^{0,\mp}$	0.03	0.13	1.97	0.99	0.13	0.68
Total systematic	1.26	2.04	2.12	1.48	2.66	3.78
Strong-phase inputs (external)	0.41	0.23	0.30	0.64	0.93	0.83
Statistical	3.16	3.55	4.41	3.98	5.00	5.04

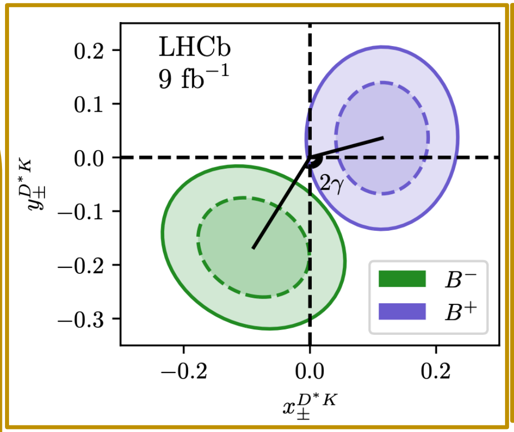
Fitted with CPV in $B^{\pm,0} \to DK^{\pm}\pi^{0,\mp}$ components.

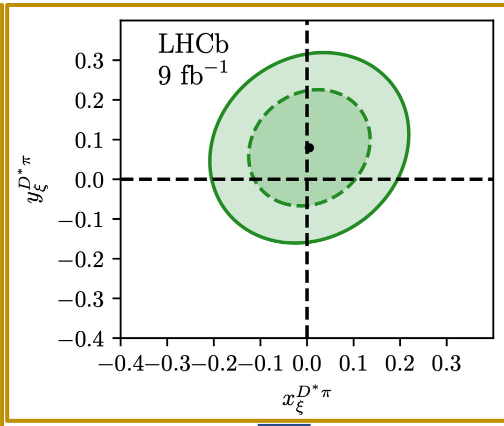
Simultaneous fit performed to data subsamples.

The systematic uncertainties are smaller than statistical uncertainty.

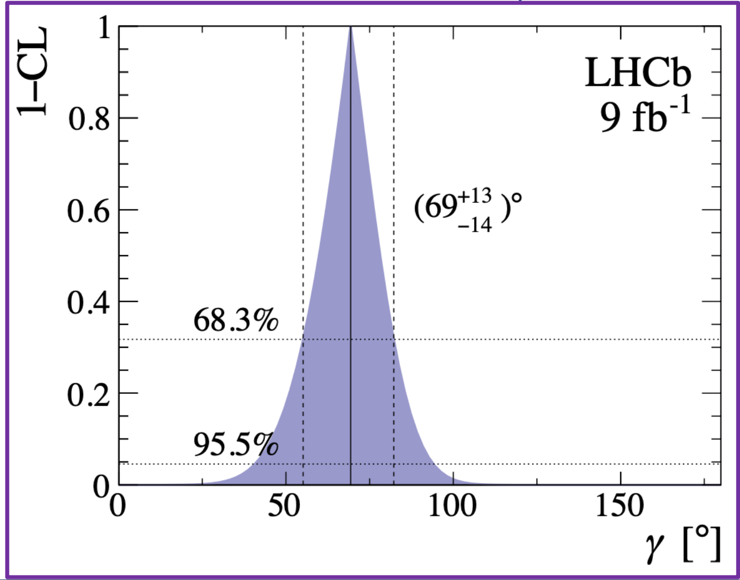
CP observables and measured γ

- CP observables measured, uncertainties are statistical, systematic and due to external inputs.
  - $x_{+}^{D^*K} = (\ 11.42 \pm 3.16 \pm 1.26 \pm 0.41\ )\times 10^{-2}$
  - $x_{-}^{D^*K} = (\ -8.91 \pm 3.55 \pm 2.04 \pm 0.23\ )\times 10^{-2}$
  - $y_{+}^{D^*K} = (\ 3.60 \pm 4.41 \pm 2.12 \pm 0.30\ )\times 10^{-2}$
  - $y_{-}^{D^*K} = (-16.75 \pm 3.98 \pm 1.48 \pm 0.64\ )\times 10^{-2}$
  - $x_{\xi}^{D^*\pi} = (\ 0.51 \pm 5.00 \pm 2.66 \pm 0.93\ )\times 10^{-2}$
  - $y_{\xi}^{D^*\pi} = (\ 7.92 \pm 5.04 \pm 3.78 \pm 0.83\ )\times 10^{-2}$





$\gamma = (69 \pm 14)^\circ$



- Consistent with world average.
- The most precise determination using this channel.
- Improve sensitivity on γ combination.

Summary

- RUN1+2 data analysed.
- Model-independent method used to measure γ.
  - Yields measured in bins of phase space.
  - External measurements of strong phases used to access γ.
- Measured value is $\gamma = (69 \pm 14)^\circ$, in agreement with other results and the most precise in $B^\pm \to D^* h^\pm$ channels. Statistical uncertainty dominates.
- $B^\pm \to D^* h^\pm$ is an important channel for γ measurement.

BACKUP