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Measurements of the CKM angle γ at LHCb

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Summary. — The angle γ is the only complex phase of the Cabibbo-Kobayashi-Maskawa (CKM) matrix that can be measured at tree level. It therefore establishes a benchmark of the Standard Model (SM) against which loop-level measurements of the CKM parameters can be tested in order to reveal the presence of new physics. The LHCb experiment can determine γ from the analysis of both time-integrated and differential decay rates of B to D mesons. The combination of LHCb measurements represents the most precise determination of γ as of today and is going to reach the sub degree level of precision for a single measurement with the upgrade of the experiment.

1. – Direct *vs.* indirect measurements

The CKM matrix, which originates from the Yukawa interactions of the quarks in the SM, is a unitary matrix consisting of three real and one complex parameter. The unitarity condition can be represented on the complex plane as a unitarity triangle (UT) whose sides and angles can be determined experimentally in the decays of beauty quarks. The angle γ, which is the phase of the matrix element V_{ub}, is the only quantity which can be measured directly at tree level. Other quantities used to extract the value of γ indirectly, such as the angle β and the neutral B mesons oscillation frequencies Δm_s and Δm_d, which constrain the side of the triangle, can only be measured at loop level and are therefore more likely to be affected by new physics contributions.

The current determinations of γ from direct and indirect constraints, as represented graphically in fig. 1, give

$$\gamma_{direct} = (72.1^{+5.4}_{-5.7})^{\circ}, \tag{1a}$$

$$\gamma_{indirect} = (65.64^{+0.97}_{-3.42})^{\circ}. \tag{1b}$$

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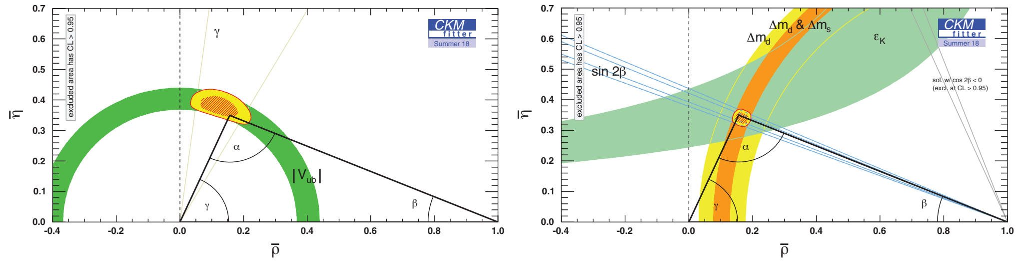

Fig. 1. – Comparison of the constraints to the UT from tree (left) and loop (right) quantities [1].

2. – Time-integrated *vs.* time-dependent measurements

The angle γ can be measured in the analysis of time-integrated and time-dependent decay rates of B to D mesons. In the first case the observable is the total decay rate of charged $B^{\pm}$ mesons:

$$\Gamma(B^{\pm} \to DK^{\pm}) \propto 1 + r_B^2 + 2r_B \cos(\delta_B \pm \gamma), \tag{2}$$

where r_B and δ_B are the magnitude ratio and strong phase difference of the $B^{\pm} \to \overline{D}^0 K^{\pm}$ and $B^{\pm} \to D^0 K^{\pm}$ amplitudes. In the second case, the information on γ is contained in the coefficients $A_f^{\Delta\Gamma}$, C_f and S_f of the differential decay rate equation of neutral B_s^0 mesons:

$$\frac{\mathrm{d}\Gamma_{B_s^0 \to f}}{\mathrm{d}t} \propto \cosh\left(\frac{\Delta\Gamma_s}{2}\right) + A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_s}{2}\right) + C_f \cos(\Delta m_s t) - S_f \sin(\Delta m_s t), \tag{3}$$

where $\Delta\Gamma_s$ and Δm_s are the B_s^0 mass eigenstates decay width and mass differences, while the coefficients C_f and S_f have opposite sign for initial $\overline{B}_s^0$ mesons. The value of γ is extracted from the coefficients of charge-parity (CP) conjugated final states $f = D_s^- K^+$ and $\bar{f} = D_s^+ K^-$:

$$C_f = \frac{1 - r_{DsK}^2}{1 + r_{DsK}^2} = -C_{\bar{f}}, \tag{4a}$$

$$A_{f(\bar{f})}^{\Delta\Gamma} = \frac{-2r_{D_sK} \cos(\delta \mp (\gamma - 2\beta_s))}{1 + r_{D_sK}^2}, \tag{4b}$$

$$S_{f(\bar{f})} = \frac{2r_{D_sK} \sin(\delta \mp (\gamma - 2\beta_s))}{1 + r_{D_sK}^2}, \tag{4c}$$

where r_{D_sK} and δ are the magnitude ratio and strong phase difference of the $\overline{B}_s^0 \to D_s^- K^+$ and $B_s^0 \to D_s^- K^+$ amplitudes, while β_s is the B_s^0 mixing phase.

In both cases, the value of γ is measured in the interference of two different transition amplitudes A_1, A_2 from the same initial to the same final state:

$$\frac{A_1}{A_2} = re^{i(\delta \pm \gamma)} \tag{5}$$

where r is the magnitude ratio, δ is the strong phase difference and γ is the weak phase difference of the two amplitudes. In the time-integrated case, the interference occurs in

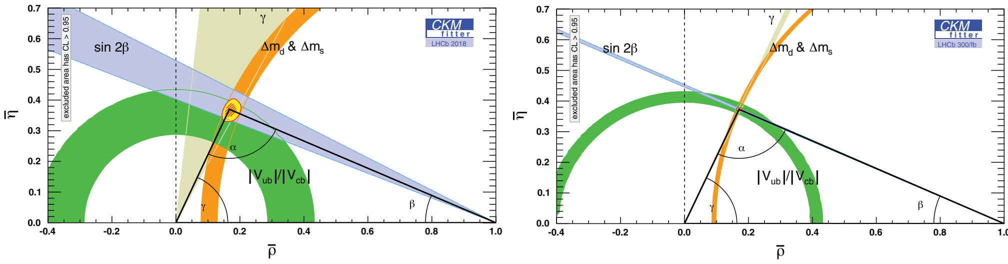

Fig. 2. – Comparison of the constraints to the UT from LHCb measurements as of today (left) and with the Phase II Upgrade (right) [2].

the decay of a D^0 or $\overline{D}^0$ meson produced from the charged $B^\pm$ meson in eq. (2) where both decay to the same final state f_D. In the time-dependent case, the interference occurs between a B_s^0 decaying directly into the final state f or following an oscillation into a $\overline{B}_s^0$ which decays into the same final state f. A non-zero value of γ results in an observable asymmetry of CP conjugated decay rates.

3. – Combination of γ measurements and the LHCb upgrade

The LHCb experiment is able to reconstruct decays of all B meson species and, due to excellent PID and secondary vertex reconstruction capabilities, is able to perform time-integrated as well as time-dependent measurements of γ. Since it is the least experimentally known angle of the UT, all the observables are combined to extract 13 hadronic parameters, such as r and δ of eq. (5), and one value of γ. The combination includes the observables from 16 measurements, of which 14 are time-integrated and 2 are time-dependent, for a total of 98 observables and 14 auxiliary parameters. The extracted value of γ is [3]

$$\gamma = (74.0^{+5.0}_{-5.8})^\circ. \tag{6}$$

The time-integrated measurements reached a 10° single-measurement precision by analyzing up to 2 of the 5 fb^{-1} collected during the LHC Run 2, while the time-dependent measurements have a 20° precision using only the statistics accumulated in Run 1. The current knowledge of the UT from both tree and loop-level quantities measured at LHCb is compared in fig. 2 with the projections for the LHCb Phase II Upgrade, corresponding to Run 5 of the LHC. Since theoretical uncertainty and knowledge of the external parameters are not expected to be limiting systematics, a single-measurement sub-degree level of precision on γ from both time-dependent and time-integrated approaches is expected.

REFERENCES

[1] CKM Fitter Group (Charles J. *et al.*), results and plots available at `http://ckmfitter.in2p3.fr`.

[2] LHCb Collaboration, *Physics case for an LHCb Upgrade II - Opportunities in flavour physics, and beyond, in the HL-LHC era*, LHCB-PUB-2018-009, LHCC-G-171, `https://cds.cern.ch/record/2636441`.

[3] LHCb Collaboration, *Update of the LHCb combination of the CKM angle γ*, LHCb-CONF-2018-002, `https://cds.cern.ch/record/2319289`.