Synergy between LHCb and BESIII charm program (focusing on CKM physics)

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Outline

- Introduction
- Joint efforts on γ measurements
- Synergy on measurements of CKM matrix element magnitudes
- Conclusion

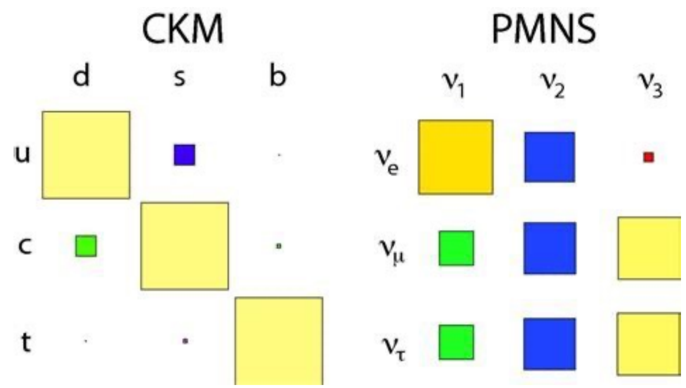
CP violation in SM

- CP violation essential in explaining matter-antimatter difference in universe
- Complex phases in CKM matrix and PMNS matrix generate CP violation in SM
- CKM matrix：unitary matrix connecting interaction and mass eigenstates

幺正矩阵，标准模型唯一限制条件

$$\begin{pmatrix} d^I \\ s^I \\ b^I \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

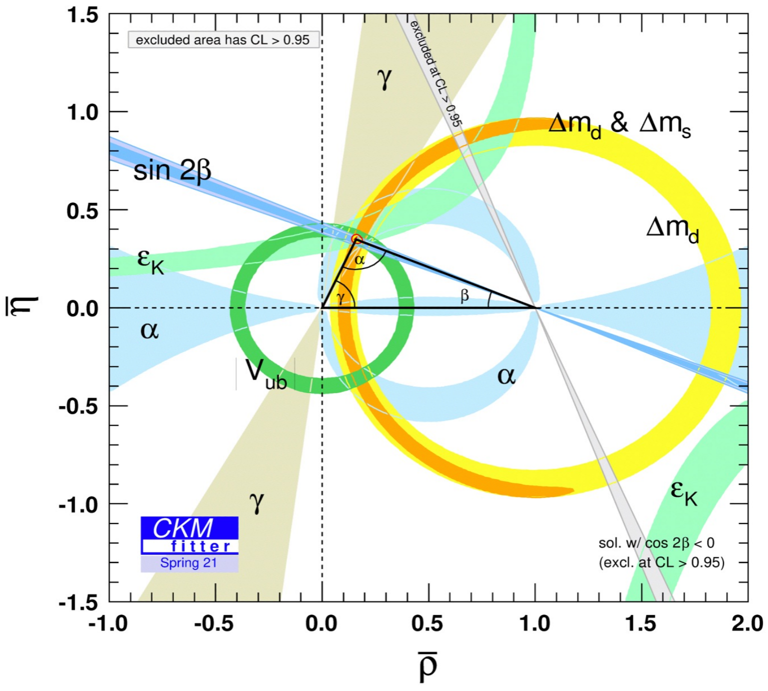
Interaction eigenstates   Mass eigenstates



- However, CP violation in SM model only contribute tiny to antimatter problem in universe
- Need more sources of CP violation

Unitary test

- Unitarity condition: only requirement in SM
- Closure test of unitary triangle etc $\sum_i V_{ij}^* V_{ij} = 1$ $\sum_i V_{ij}^* V_{ik} = 0$
- All measurements consistent with each other? Yes
- Is current precision enough? No



10^{-5}

$$V_{ud}V_{ud}^* + V_{us}V_{us}^* + V_{ub}V_{ub}^* - 1$$

$$= -0.00230^{+0.00218}_{-0.00023}\ (1\sigma)$$
$$-0.00230^{+0.00237}_{-0.00044}\ (2\sigma)$$
$$-0.00230^{+0.00242}_{-0.00065}\ (3\sigma)$$

Direct measurements:

$$\boldsymbol{\alpha + \beta + \gamma = (179^{+7}_{-6})^\circ}$$

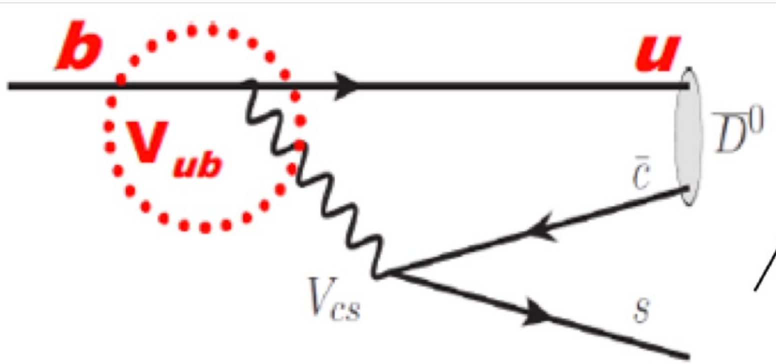
Global fits:

$$\boldsymbol{\alpha + \beta + \gamma = (179.9^{+1.9}_{-1.7})^\circ}$$

CKM angle γ

- **Measured through $b \to c$ and $b \to u$ interference**

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



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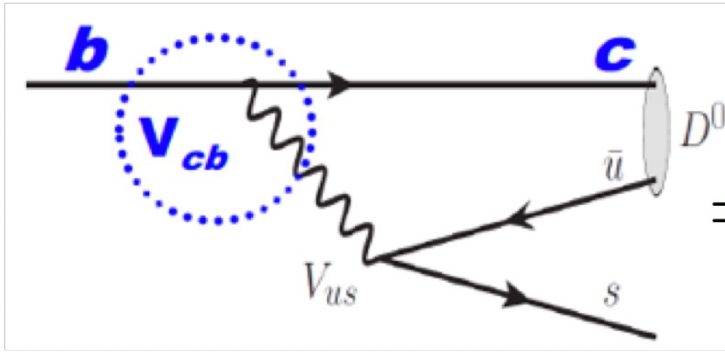


$$= r_B e^{i\delta_B}$$

$$A = a_1 e^{i(\delta_1+\phi_1)} + a_2 e^{i(\delta_2+\phi_2)} \qquad \bar{A} = a_1 e^{i(\delta_1-\phi_1)} + a_2 e^{i(\delta_2-\phi_2)}$$

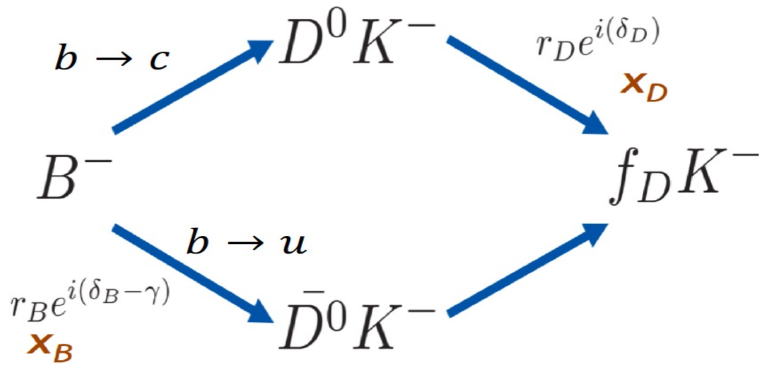
$$A_{CP} = \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2} \propto \sin(\delta_1 - \delta_2)\sin(\phi_1 - \phi_2)$$

- **Tree level processes → SM candle, NP normally enters loop diagrams**
- **Loop level processes suppressed, theoretically clean, $\delta\gamma/\gamma \sim 10^{-7}$**

JHEP 1401 (2014) 051

- **All QCD parameters (hard to calculate) obtained from experimental measurements (global fit)**

Probe γ in different methods



D^0 and $\overline{D}^0$ decay to same final states to interference

GLW: D = CP eigenstates, e.g. KK, ππ — PLB 253 (1991) 483, PLB 265 (1991) 172

ADS: D = quasi-flavour-specific states e.g. Kπ — PRL 78 (1997) 3257

GGSZ: D = self-conjugate multi(3)-body states e.g. $K_s\pi\pi$ — PRD 68 (2003) 054018

GLS: ADS variant with singly Cabbibo-suppressed decay $D \to K_s K\pi$ — PRD 67 (2003) 071301

time-dependent $B_s \to D_s K$, $B^0 \to D\pi$ etc — Nucl. phys. B 672 (2003) 459

Dalitz (GW) method: $B^0 \to DK\pi$ — PRD 79 (2009) 051301

Sensitivities of γ from many channels, important to measure as many as possible

Global combination

B decay	D decay	Ref.
$B^\pm \to Dh^\pm$	$D \to h^+h^-$	[29]
$B^\pm \to Dh^\pm$	$D \to h^+\pi^-\pi^+\pi^-$	[30]
$B^\pm \to Dh^\pm$	$D \to K^\pm\pi^\mp\pi^+\pi^-$	[18]
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^0$	[19]
$B^\pm \to Dh^\pm$	$D \to K^0_S h^+h^-$	[31]
$B^\pm \to Dh^\pm$	$D \to K^0_S K^\pm\pi^\mp$	[32]
$B^\pm \to D^*h^\pm$	$D \to h^+h^-$	[29]
$B^\pm \to DK^{*\pm}$	$D \to h^+h^-$	[33]
$B^\pm \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[33]
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+h^-$	[34]
$B^0 \to DK^{*0}$	$D \to h^+h^-$	[35]
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	[35]
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	[36]
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	[37]
$B^0_s \to D_s^\mp K^\pm$	$D_s^+ \to h^+h^-\pi^+$	[38]
$B^0_s \to D_s^\mp K^\pm\pi^+\pi^-$	$D_s^+ \to h^+h^-\pi^+$	[39]

Measurements from b-decays

Decay	Parameters	Source
$B^\pm \to DK^{*\pm}$	$\kappa_{B^\pm}^{DK^{*\pm}}$	LHCb
$B^0 \to DK^{*0}$	$\kappa_{B^0}^{DK^{*0}}$	LHCb
$B^0 \to D^\mp\pi^\pm$	β	HFLAV
$B^0_s \to D_s^\mp K^\pm(\pi\pi)$	ϕ_s	HFLAV
$D \to K^+\pi^-$	$\cos\delta_D^{K\pi}$, $\sin\delta_D^{K\pi}$, $(r_D^{K\pi})^2$, x^2, y	CLEO-c
$D \to K^+\pi^-$	$A_{K\pi}$, $A_{K\pi}^{\pi\pi\pi^0}$, $r_D^{K\pi}\cos\delta_D^{K\pi}$, $r_D^{K\pi}\sin\delta_D^{K\pi}$	BESIII
$D \to h^+h^-\pi^0$	$F^+_{\pi\pi\pi^0}$, $F^+_{KK\pi^0}$	CLEO-c
$D \to \pi^+\pi^-\pi^+\pi^-$	$F^+_{4\pi}$	CLEO-c+BESIII
$D \to K^+\pi^-\pi^0$	$r_D^{K\pi\pi^0}$, $\delta_D^{K\pi\pi^0}$, $\kappa_D^{K\pi\pi^0}$	CLEO-c+LHCb+BESIII
$D \to K^\pm\pi^\mp\pi^+\pi^-$	$r_D^{K3\pi}$, $\delta_D^{K3\pi}$, $\kappa_D^{K3\pi}$	CLEO-c+LHCb+BESIII
$D \to K^0_S K^\pm\pi^\mp$	$r_D^{K^0_S K\pi}$, $\delta_D^{K^0_S K\pi}$, $\kappa_D^{K^0_S K\pi}$	CLEO
$D \to K^0_S K^\pm\pi^\mp$	$r_D^{K^0_S K\pi}$	LHCb

Charm (and b) inputs

D decay	Observable(s)	Ref.
$D^0 \to h^+h^-$	ΔA_{CP}	[24, 40, 41]
$D^0 \to K^+K^-$	$A_{CP}(K^+K^-)$	[16, 24, 25]
$D^0 \to h^+h^-$	$y_{CP} - y_{CP}^{K^-\pi^+}$	[42]
$D^0 \to h^+h^-$	$y_{CP} - y_{CP}^{K^-\pi^+}$	[15]
$D^0 \to h^+h^-$	ΔY	[43–46]
$D^0 \to K^+\pi^-$ (Single Tag)	$R^\pm$, $(x'^\pm)^2$, $y'^\pm$	[47]
$D^0 \to K^+\pi^-$ (Double Tag)	$R^\pm$, $(x'^\pm)^2$, $y'^\pm$	[48]
$D^0 \to K^\pm\pi^\mp\pi^+\pi^-$	$(x^2+y^2)/4$	[49]
$D^0 \to K^0_S\pi^+\pi^-$	x, y	[50]
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[51]
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[52]
$D^0 \to K^0_S\pi^+\pi^-$ (μ^- tag)	x_{CP}, y_{CP}, Δx, Δy	[17]

Also constrain D mixing parameters

A table for strong phase measurements

Decay modes	Strategy	Quantities	BESIII status	LHCb status
$D \to K_S^0 h^+ h^-$	binned	c_i, s_i	3 fb^{-1} published; 8 fb^{-1} ongoing;	9 fb^{-1} published; (5° VS 1°)
$D \to K_S^0 h^+ h^-$	Fourier	$a_c^i, a_s^i, b_c^i, b_s^i$	8 fb^{-1} ongoing;	9 fb^{-1} ongoing
$D \to K^\pm \pi^\mp \pi^+ \pi^-$	global and binned	$R_{K3\pi}, \delta_{K3\pi}$, $R_{K3\pi}^i, \delta_{K3\pi}^i$	3 fb^{-1} published; New data ongoing	9 fb^{-1} published; (6° VS 6°)
$D \to K^+ K^- \pi^+ \pi^-$	global and binned	F_+, c_i, s_i	16 fb^{-1} ongoing	9 fb^{-1} published (MD); 9 fb^{-1} ongoing (MI); (12° VS 10°)
$D \to \pi^+ \pi^- \pi^+ \pi^-$	global and binned	F_+, c_i, s_i	3 fb^{-1} ongoing	9 fb^{-1} ongoing (MI); (9° VS 3°)
$D \to K^\pm \pi^\mp \pi^0$	global	$R = 0.792 \pm 0.033$	3 fb^{-1} published New data ongoing	9 fb^{-1} published;
$D \to K_S^0 K^\mp \pi^\pm$	global	$R = 0.70 \pm 0.08$	8 fb^{-1} ongoing	9 fb^{-1} published;
$D \to K_S^0 \pi^+ \pi^- \pi^0$	global and binned	$F_+ = 0.238 \pm 0.017$, c_i, s_i	3 fb^{-1} ongoing	9 fb^{-1} ongoing
$D \to K^+ K^- \pi^0$	global	$F_+ = 0.73 \pm 0.06$, c_i, s_i	8 fb^{-1} published	9 fb^{-1} published;
$D \to K^+ \pi^-$	global	δ	3 fb^{-1} published	9 fb^{-1} published;

Charm mixing data

- Neutral charm meson can mix and thus affect the decay rate

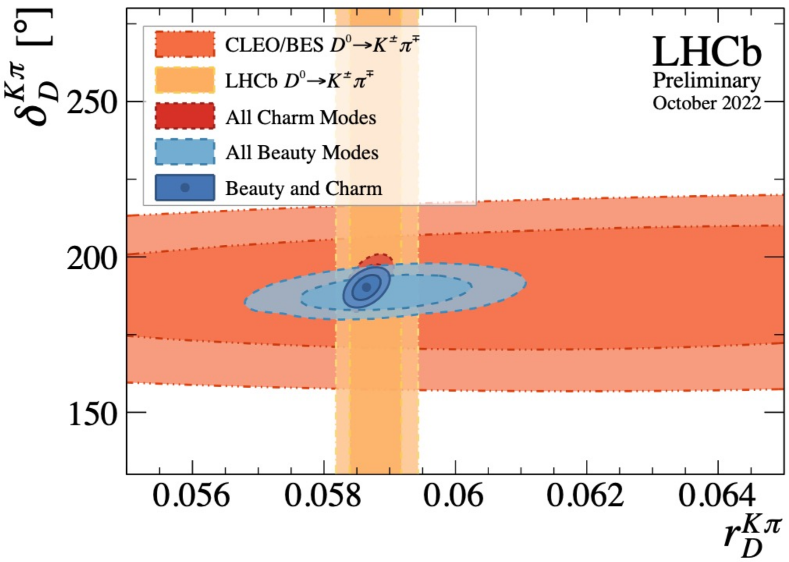
$$\Gamma\left(D^0(t)\to f\right)_\Omega \simeq \left[\mathcal{A}^2\left(1+\frac{y^2-x^2}{4}(\Gamma t)^2\right)+\mathcal{B}^2\left(\left|\frac{q}{p}\right|^2\frac{x^2+y^2}{4}(\Gamma t)^2\right)\right.$$
$$\left.+\mathcal{A}\mathcal{B}\left(y\,Re\left(\mathcal{Z}_\Omega^f\frac{q}{p}\right)+x\,Im\left(\mathcal{Z}_\Omega^f\frac{q}{p}\right)\right)(\Gamma t)\right]e^{-\Gamma t}$$

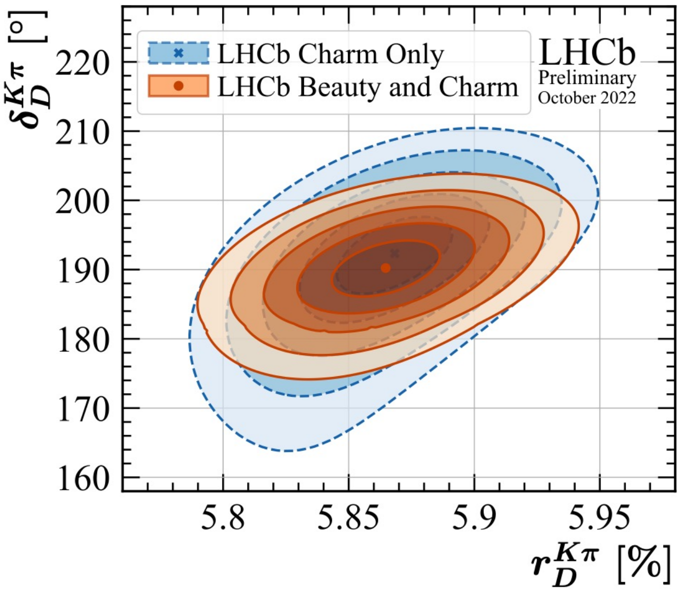
x, y : mixing parameters

q/p : CP parameters

- Strong parameters same as those from charm threshold data
- With the inputs of charm mixing related parameters, strong parameters can be constrained: global determination
- Charm mixing offers valuable constrains even with current LHCb data for ADS modes

Constraints from global fit

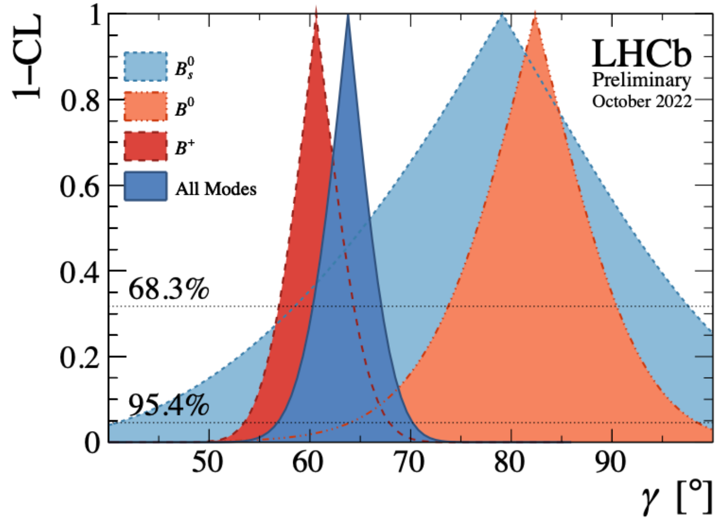




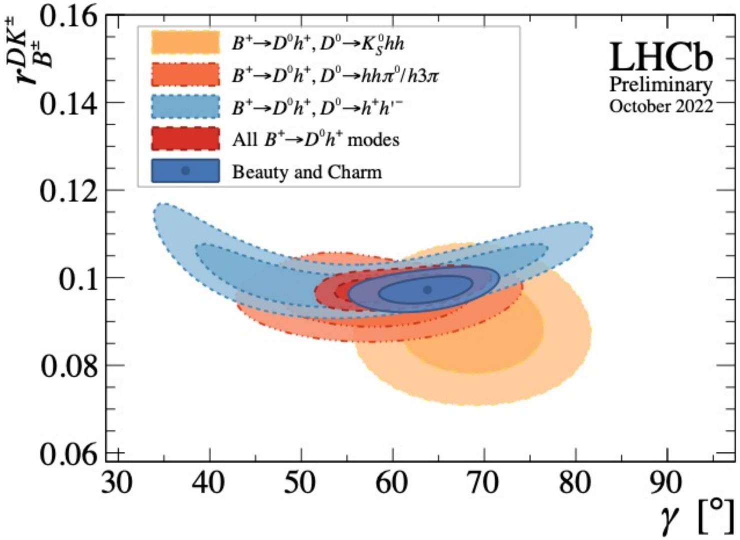
- Uncertainties from charm threshold around 8°, while including LHCb measurements from charm and beauty gives around 3°
- With 20 fb^{-1}, BESIII will give around 4°

- Strong parameters receive more constrains from charm decays
- Add beauty part further help reducing uncertainties

Global combination results



$$\gamma = (63.8^{+3.5}_{-3.7})°$$



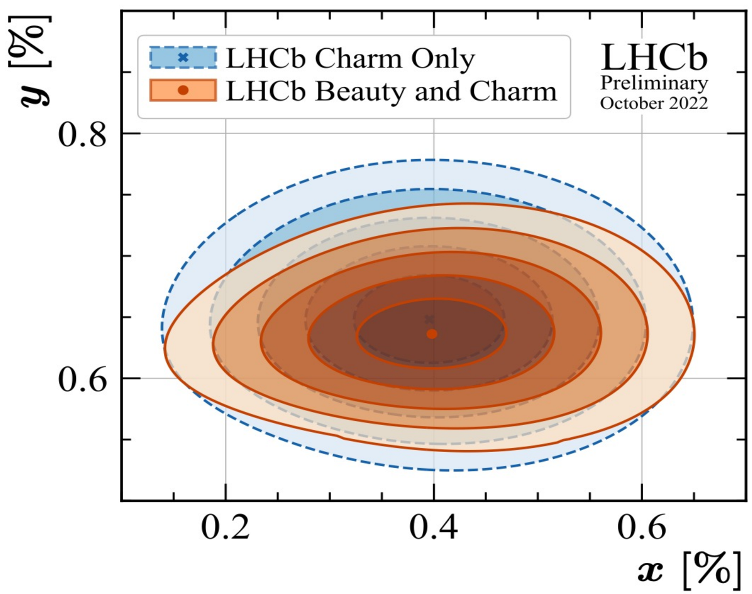
- **Compatible with indirect determination**

$$\gamma = (65.5^{+1.1}_{-2.7})° \quad \text{CKMfitter}$$

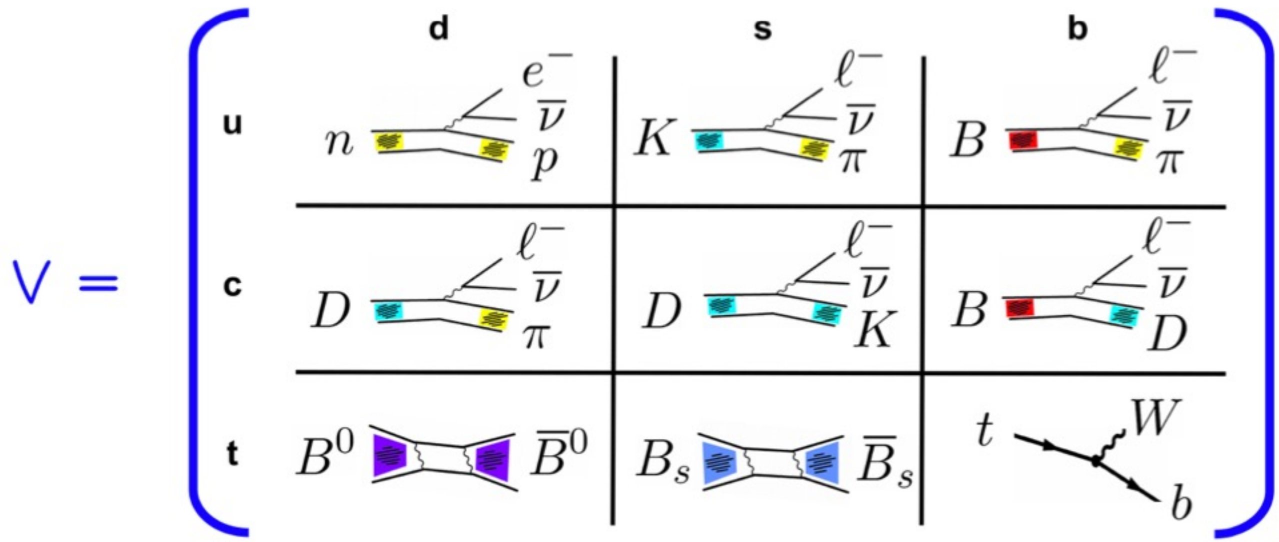
- **Dominant by B^+ decays**

- **Different decays contribute differently, global combination gives best sensitivity**

- **Sensitivity on y parameters improves**



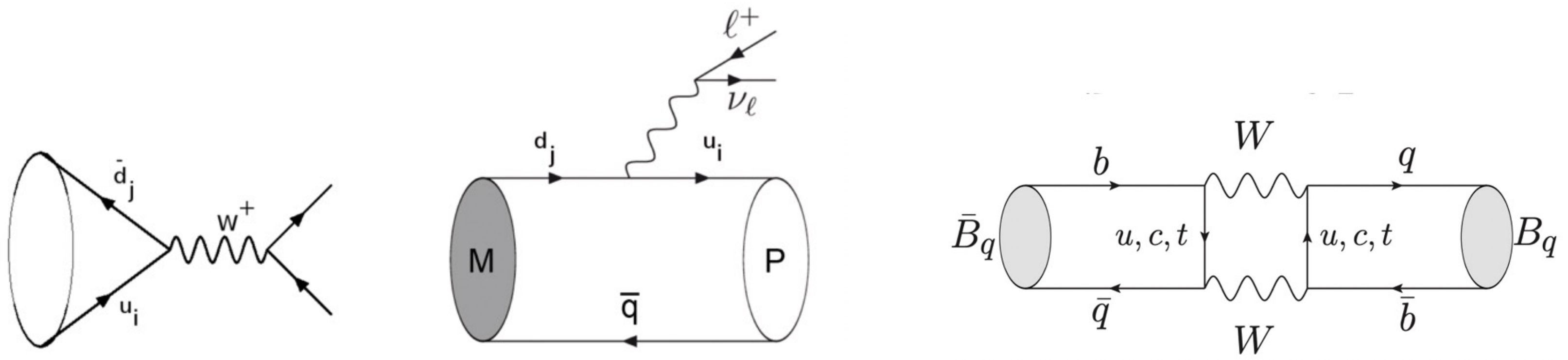
CKM observables: magnitude



From S. Descotes-Genon

- $|V_{ud}|$: superallowed nuclear β decays
- $|V_{us}|$: $K \to \pi l\nu, K \to l\nu, \tau \to K\nu$ etc. + form factors, decay constants
- $|V_{cs}|, |V_{cd}|$: (semi-)leptonic charm decays + Lattice inputs
- $|V_{ub}|, |V_{cb}|$: (semi-)leptonic B decays + Lattice inputs
- $|V_{td}|, |V_{ts}|$: $\Delta m_d, \Delta m_s$ + bag parameters, decay constants

General on magnitude measurements



- **Leptonic decays, only need decay constant of the decaying particle**

Precise BF measurements

$$B[M \to \ell\nu_\ell]_{\rm SM} = \frac{G_F^2 m_M m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_M^2}\right)^2 |V_{q_u q_d}|^2 f_M^2 \tau_M (1 + \delta_{em}^{M\ell 2})$$

- **Semi-leptonic decays, form factor needed** **(2 when P is Pseudo-scalar, more for vector and fermions)**

BF as function of q^2

$$\frac{d\Gamma(M \to P\ell\nu)}{dq^2} = \frac{G_F^2 |V_{q_u q_d}|^2}{24\pi^3} \frac{(q^2 - m_\ell^2)^2 \sqrt{E_P^2 - m_P^2}}{q^4 m_H^2} \times \left[\left(1 + \frac{m_\ell^2}{2q^2}\right) m_M^2 (E_P^2 - m_P^2) |f_+(q^2)|^2 + \frac{3m_\ell^2}{8q^2}(m_M^2 - m_P^2)^2 |f_0(q^2)|^2\right]$$

- **Meson mixing, decay constant and bag parameters**

$$\Delta m_q = \frac{G_F^2}{6\pi^2} |V_{tq}^* V_{tb}|^2 M_W^2 S_0(x_t) B_q f_{Bq}^2 M_{Bq} \widehat{\eta_B}$$

BESIII contributions

(Semi-)Leptonic decays

Pure leptonic decays:

$D_s^+ \to \tau^+\nu_\tau, \tau^+ \to e^+\nu_e\bar{\nu}_\tau$, Phys. Rev. Lett. 127, 171801 (2021)

$D_s^+ \to \tau^+\nu_\tau, \tau^+ \to \pi^+\bar{\nu}_\tau$ & $D_s^+ \to \mu^+\nu_\mu$, Phys. Rev. D 104, 052009 (2021)

$D_s^+ \to \tau^+\nu_\tau, \tau^+ \to \pi^+\pi^0\bar{\nu}_\tau$, Phys. Rev. D 104, 032001 (2021)

$D_s^+ \to \tau^+\nu_\tau, \tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$, arXiv:2303.12468

$D_s^+ \to \tau^+\nu_\tau, \tau^+ \to \pi^+\bar{\nu}_\tau$, arXiv:2303.12600

$D_s^{*+} \to e^+\nu_e$, arXiv:2304.12159, first experimental result on $f_{D_s^{*+}}$

Semi-leptonic decays:

$D^0 \to K_1(1270)^- e^+\nu_e$, Phys. Rev. Lett. 127, 131801 (2021)

$D_s^+ \to a_0(980)^0 e^+\nu_e$, Phys. Rev. D 103, 092004(2021)

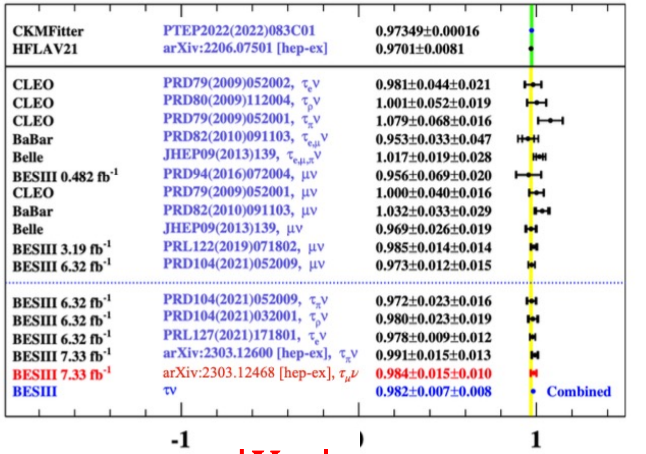
$D^0 \to K^- e^+\nu_e$ & $D^+ \to \bar{K}^0 e^+\nu_e$, Phys. Rev. D 104, 052008 (2021)

$D_s^+ \to \pi^0\pi^0 e^+\nu_e$ & $K_S^0 K_S^0 e^+\nu_e$, Phys. Rev. D 105, L031101 (2022)

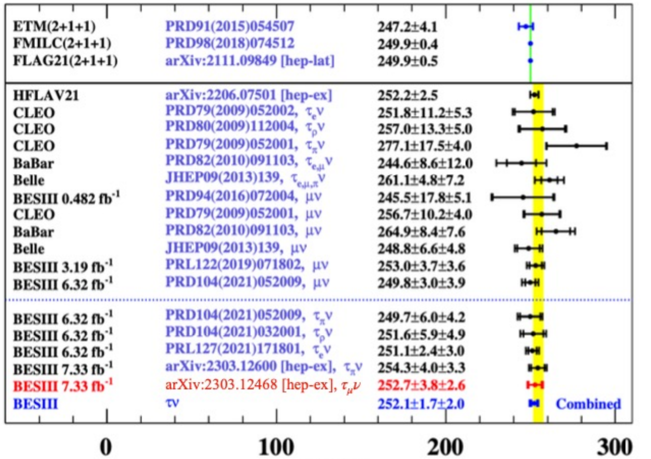
$D_s^+ \to \pi^0 e^+\nu_e$, Phys. Rev. D 106, 112004 (2022)

$D_s^+ \to \pi^+\pi^- e^+\nu_e$, arXiv:2303.12927

$D_s^+ \to \eta e^+\nu_e, \eta' e^+\nu_e$, arXiv:2306.05194



$|V_{cs}|$



$f_{D_s^+}$

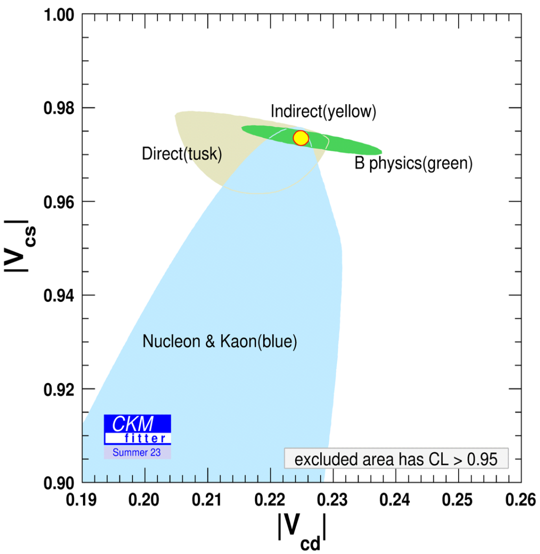
Gives the magnitudes of the triangles; could also be used to test QCD

7

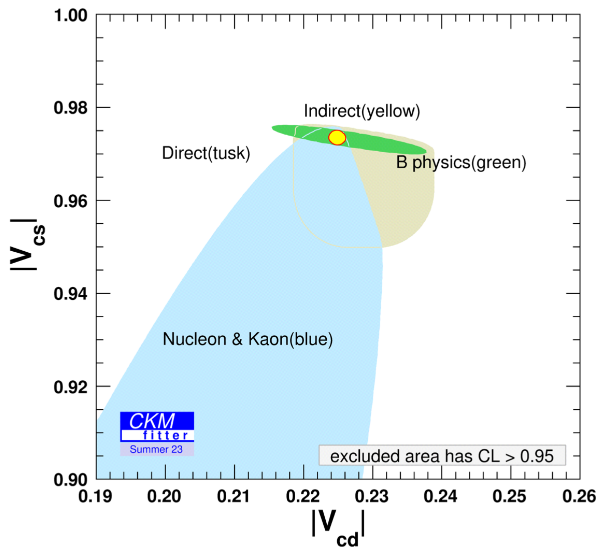
Talk by Z. Lu

Contribution of BESIII to CKM global fit

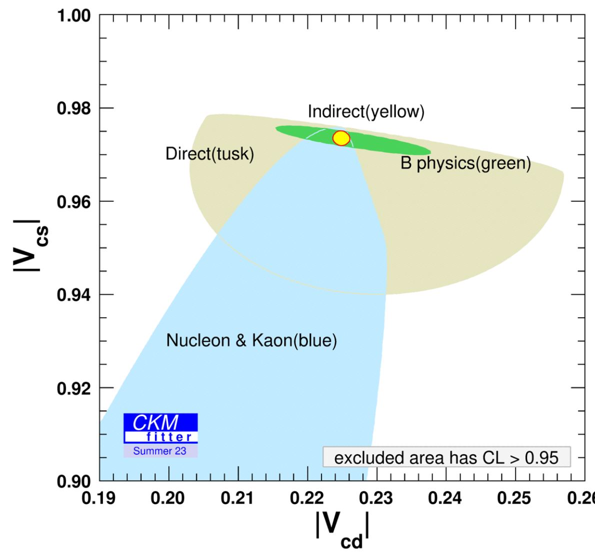
Indirect: $V_{cs} = 0.97358^{+0.00014}_{-0.00028}$ $V_{cd} = 0.22483^{+0.00031}_{-0.00023}$



Leptonic decays



Semi-leptonic decays



Neutrino-nuclear + $W \to cs$ no lattice needed

$$V_{cs} = 0.984 \pm 0.010$$
$$V_{cd} = 0.2185 \pm 0.0060$$

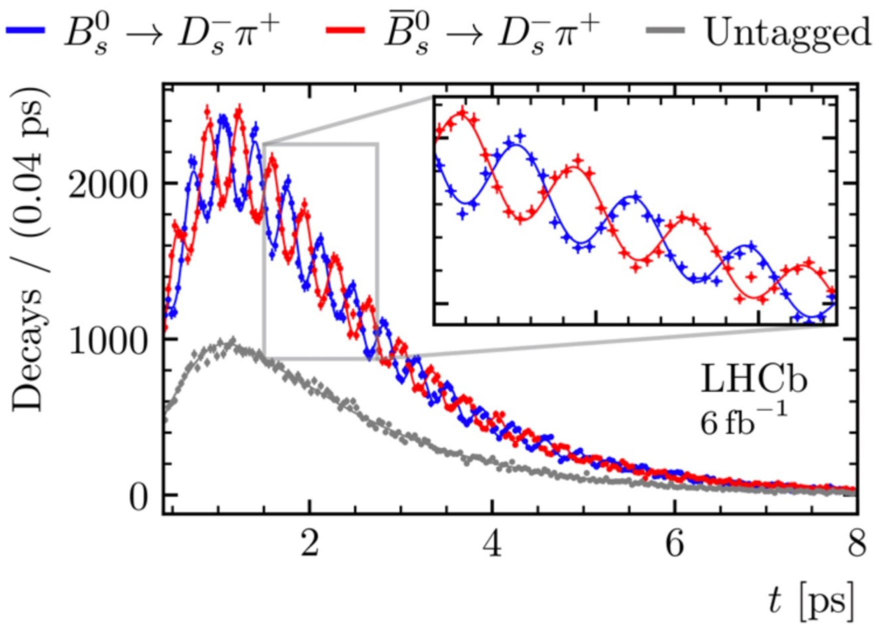
$$V_{cs} = 0.9729^{+0.0012}_{-0.0007}$$
$$V_{cd} = 0.2285 \pm 0.0054$$

$$V_{cs} = 0.9670 \pm 0.0080$$
$$V_{cd} = 0.230 \pm 0.011$$

- **BESIII offers the world best direct measurements on $|V_{cd}|$ and $|V_{cs}|$**
- **However, still much worse than from indirect constrain; need improvements**

LHCb contributions

Nature Physics 18 (2022) 1-5



- Measured using $B_S^0 \to D_S^- \pi^+$, $B^0 \to D^{(*)} \mu \nu X$

$$\Delta m_d = 0.5065(19)\text{ps}^{-1}$$
$$\Delta m_s = 17.7656(57)\text{ps}^{-1}$$

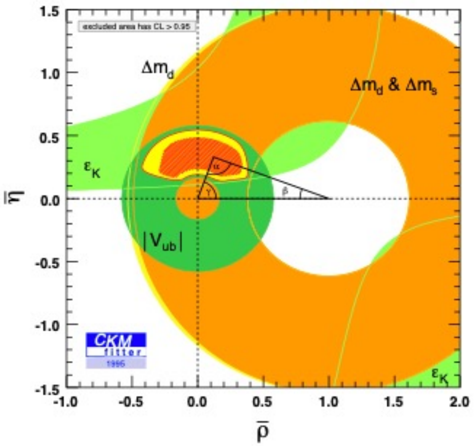
Precision of 0.38% and 0.03%!!!

$$\Delta \mathrm{m_q} = \frac{G_F^2}{6\pi^2} \left| V_{tq}^* V_{tb} \right|^2 M_W^2 S_0(x_t) B_q f_{Bq}^2 M_{Bq} \widehat{\eta_B}, \quad x_t = \frac{m_t^2}{M_W^2}$$

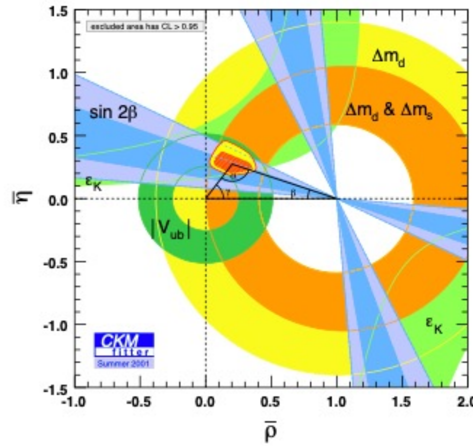
$$S_0(x) = x \left[\frac{1}{4} + \frac{9}{4} \frac{1}{1-x} - \frac{3}{2} \frac{1}{(1-x)^2} \right] - \frac{3}{2} \left[\frac{x}{1-x} \right]^3 \ln x$$

- **LHCb not only contributes to $|V_{ub}|$ and $|V_{cb}|$, but also $|V_{tq}|$**
- **Uncertainties mainly from Bag parameters (3%) obtained from lattice**

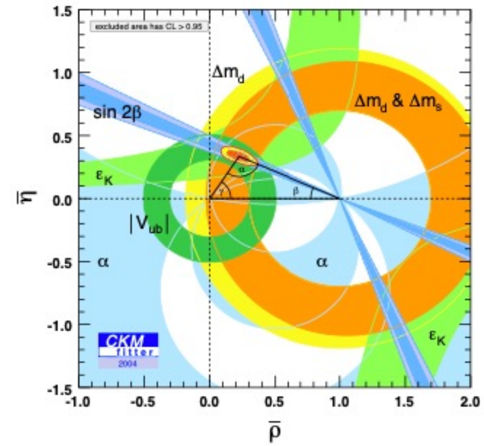
CKM status over years



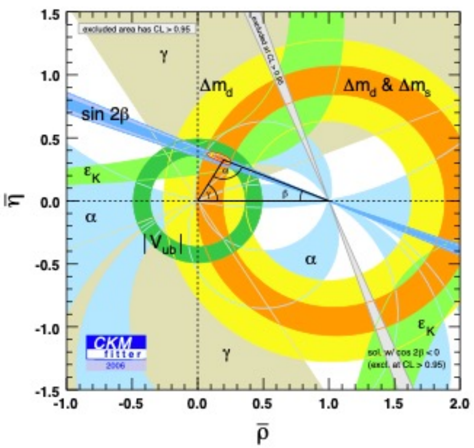
1995



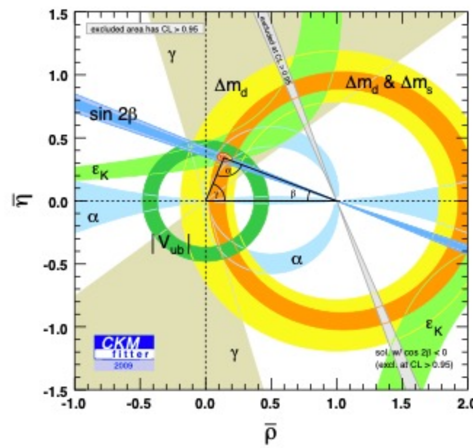
2001



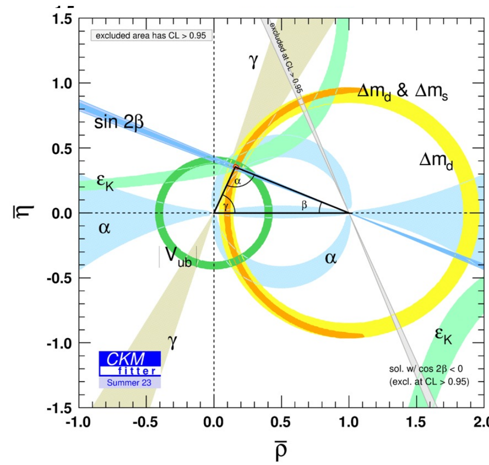
2004



2006



2009



2023

Conclusion

- **Understanding matter-antimatter problem through unitarity test of CKM matrix is important**
- **Joint efforts from beauty to charmed data (LHCb), charm threshold data (BESIII) and charm mixing data (LHCb) are key to establish world-best sensitivity on γ angle and on charm mixing parameters**
- **Global efforts also needed on measurements of CKM matrix element magnitude, especially from charmed data**

Thank You for Your Attention

QCD: key inputs to extract EW parameters

- **Factorization assumption:**

Physics of interest

Lattice

$$\Gamma = (\text{Weak})\,(\text{EM})\,(\text{QCD})$$

Experimental measurements

Precisely calculated by QED

Theoretical inputs as important as experimental measurements

$$\frac{\Gamma_1}{\Gamma_2} = \frac{(\text{Weak})_1}{(\text{Weak})_2}\,\frac{(\text{EM})_1}{(\text{EM})_2}\,\frac{(\text{QCD})_1}{(\text{QCD})_2}$$

Ratios generally preferred both experimentally and theoretically