CP Violation in D→ $\pi\pi$,KK due to LR Mixing

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Outline

- Preamble
- CP asymmetry in D decays
- LR Mixing on $D^0 \rightarrow (K^+ K^-, \pi^+ \pi^-)$
- Summary

Observed CP Asymmetries

- The first event : 1964, indire ~~CP~~ is observed in K-meson, $\varepsilon \sim 2.2*10^{-3}$.
- nonzero D~~CP~~ in K-meson, $\varepsilon'/\varepsilon \sim 1.7*10^{-3}$
- indirect ~~CP~~ observed in $B \to J/\psi K_{S}$, $\sin 2\beta_d = 0.671 +/- 0.023$
- D~~CP~~ in $B \to K\pi$ was observed

  Data : $A_{CP}(B^- \to B \to \pi^+ K^-) - A_{CP}(B \to \pi^0 K^-) = -(14.8^{+1.3}_{-1.4})\%$

Kobayashi-Maskawa (KM) phase

- In the SM, the ~~CP~~ is arisen from the charged weak current,

$$-L_{int} = \bar{U}\gamma_\mu V_L^U V_L^{D^\dagger} P_L D\, W^\mu$$

$$V_{CKM} \equiv V_L^U V_L^{D^\dagger}$$

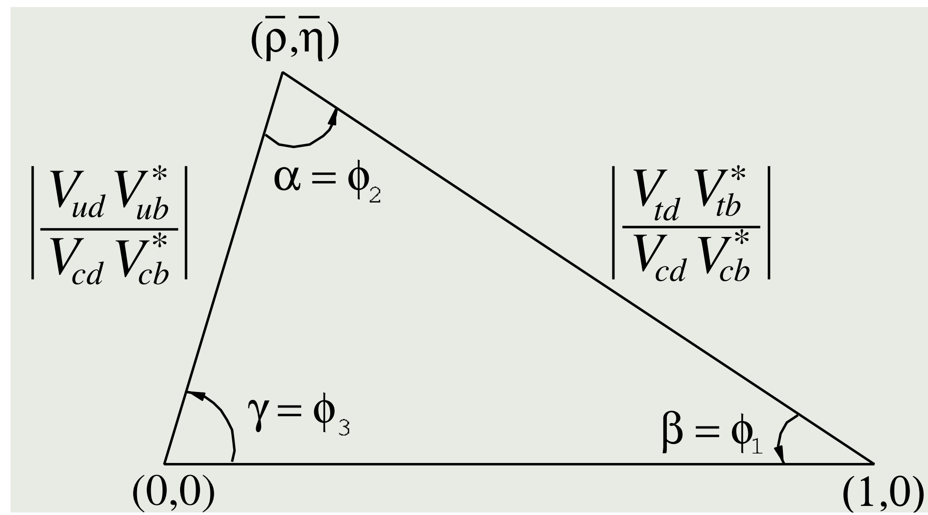
$$V_{CKM}V_{CKM}^\dagger = 1$$

$$\beta = \phi_1 = arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

$$\alpha = \phi_2 = arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

$$\gamma = \phi_3 = arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

$$\alpha + \beta + \gamma = \pi$$



With Wolfenstein's parametrization (83)

$$V_{CKM} \approx \begin{pmatrix} 1-\frac{\lambda^2}{2}-\frac{\lambda^4}{8} & \lambda & A\lambda^3(\rho - i\,\eta) \\ -\lambda+\frac{A^2\lambda^5}{2}[1-2(\rho+2i\eta)] & 1-\frac{\lambda^2}{2}-\frac{\lambda^4}{8}(1+4A^2) & A\lambda^2 \\ A\lambda^3\left[1-\left(1-\frac{\lambda^2}{2}\right)(\rho+i\,\eta)\right] & -A\lambda^2+\frac{A\lambda^4}{2}[1-2(\rho+i\eta)] & 1-\frac{A^2\lambda^4}{2} \end{pmatrix}$$

$$A \approx 0.808, \lambda \approx 0.2253, \rho \sim 0.13, \eta \sim 0.34$$

- In the SM, the mixing induced CP asymmetry (MICPA) is large in B_d decays
- The MICPAs in B_s and D mesons are small. The good places to probe the new CP mechanism

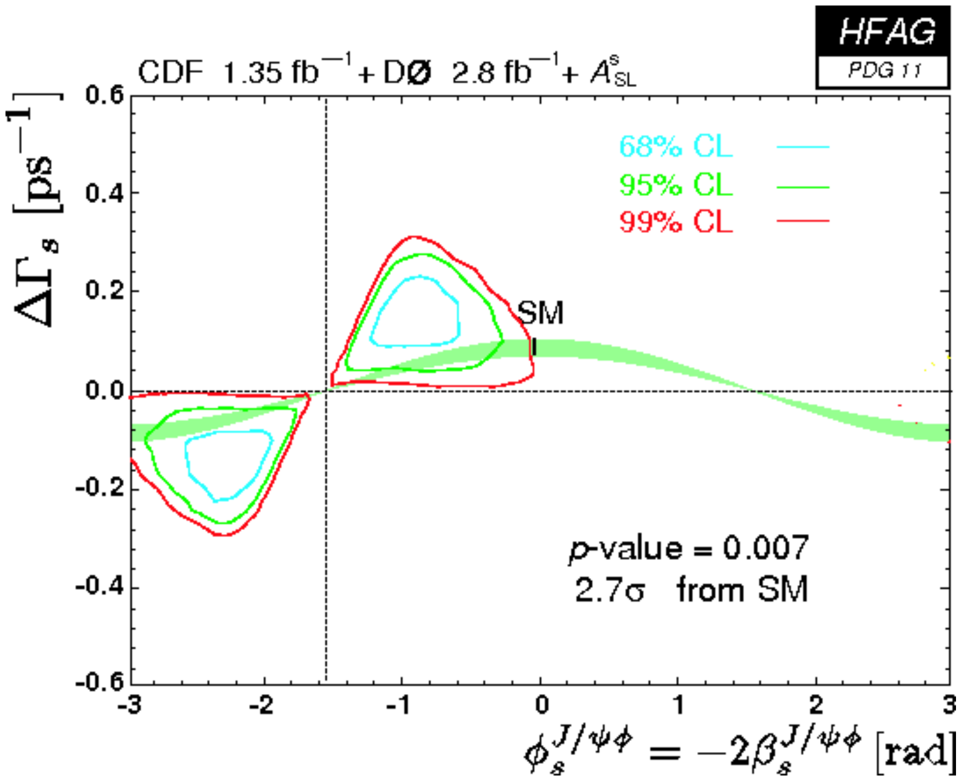
Why should we care the new CP phase?

- Faith, no reason to believe that there exists only one phase in nature
- KM phase can not explain the matter-antimatter asymmetry
- Motivated by current data : for instance,
  - the πK puzzle

Native estimation: $A_{CP}(B^- \to \pi^0 K^-) \approx A_{CP}(B \to \pi^+ K^-)$

Data : $A_{CP}(B^- \to B \to \pi^+ K^-) - A_{CP}(B \to \pi^0 K^-) = -(14.8^{+1.3}_{-1.4})\%$

❖ CDF+D0: a large phase in B_s oscillation ($B_s \rightarrow J/\phi$)



$$V_{ts} \approx -0.041\, e^{-i\beta_s}$$

$$\Delta\Gamma^s = 2|\Gamma_{12}^s| cos\phi_s, \phi_s \approx -2\beta_s$$

ϕ_s =[−1.17 ; −0.56] ∪ [−2.60 ; −2.01]

$\Delta\Gamma^s$=[+0.084 ; +0.224] ∪ [−0.230 ; −0.119] ps^{-1}

- D0 observed the like-sign charge asymmetry in dimuon events, defined by

$$A_{s\ell}^{b} = \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

$N^{++(--)}$: The number of events that b and $\bar{b}$-hadron semi-leptonically decay into two positive(negative) muons

D0 Co, PRD82(10)

Data & SM prediction

$$A_{s\ell}^{b} = (-0.787 \pm 0.172 \pm 0.093)\times 10^{-3}$$

PRD84(11)

$$A_{s\ell}^{b}(SM) = (-0.23^{+0.05}_{-0.06})\times 10^{-4}$$

Lenz & Nierste, JHEP0706(07)

Time-dependent CPA

- Two neutral strong eigenstates D, D-bar, with weak interactions the corresponding Hamiltonian is given by

$$H = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} - \frac{i}{2} \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{21} & \Gamma_{22} \end{pmatrix}$$

- The mass eigenstates:

$$|D_L\rangle = p|D\rangle + q|\overline{D}\rangle$$
$$|D_H\rangle = p|D\rangle - q|\overline{D}\rangle$$

- The time evolution of flavor states:

$$|D(t)\rangle = g_+(t)|D\rangle - \frac{q}{p} g_-(t)|\overline{D}\rangle$$
$$|\overline{D}(t)\rangle = g_+(t)|D\rangle - \frac{p}{q} g_-(t)|\overline{D}\rangle$$

- The relationship among p, q, M, Γ in B-meson:

$$\frac{q}{p} = \left(\frac{M_{12}^* - i\Gamma_{12}^*/2}{M_{12} - i\Gamma_{12}/2} \right)^{1/2}$$

CP Violation in D decays

- Final states are CP eigenstate
- Time-integrated CP asymmetry, defined by

$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D^0} \to \bar{f})}{\Gamma(D^0 \to f) + \Gamma(\overline{D^0} \to \bar{f})}$$

$$= a_{CP}^{dir}(f) + \frac{< t >}{\tau} a_{CP}^{ind}$$

The measurement of LHCb

$$A_{raw}(f) = \frac{N(D^{*+} \to D^0(f)\pi_s^+) - N(D^{*-} \to \overline{D^0}(f)\pi_s^-)}{N(D^{*+} \to D^0(f)\pi_s^+) + N(D^{*-} \to \overline{D^0}(f)\pi_s^-)}$$
$$= A_{CP}(f) + A_D(f) + A_D(\pi_s^+) + A_P(D^{*+})$$

$A_D(f)$: detection asymmetry of D^0
$A_D(\pi^+_s)$: detection asymmetry of soft pion
$A_P(D^{*+})$: production asymmetry for D^{*+}

- $A_D(K^+K^-) = A_D(\pi^+\pi^-) = 0$
- $A_D(\pi^+_s)$ and $A_P(D^{*+})$ are similar in KK and $\pi\pi$, i.e.

$$\Delta A_{CP} = A_{raw}(K^+K^-) - A_{raw}(\pi^+\pi^-)$$
$$\approx A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$

- robust against systematics

- The CP difference

$$\Delta A_{CP} = a_{CP}^{dir}(KK) - a_{CP}^{dir}(\pi\pi) + \frac{\Delta\langle t\rangle}{\tau} a_{CP}^{ind}$$

$$\frac{\Delta\langle t\rangle}{\tau} = (9.83 \pm 0.22 \pm 0.19)\%$$

$$\Delta A_{CP} \approx a_{CP}^{dir}(KK) - a_{CP}^{dir}(\pi\pi)$$

- LHCb result: arXiv:1112.0938

$$\Delta A_{CP} = (-0.82 \pm 0.21 \pm 0.11)\%$$

$$\Delta A_{CP} = (-0.62 \pm 0.21 \pm 0.10)\% \text{ (CDF note 10784)}$$

- CDF results: arXiv: 1111.5023

$$a_{CP}^{dir}(KK) = (-0.24 \pm 0.22 \pm 0.09)\%$$
$$a_{CP}^{dir}(\pi\pi) = (0.22 \pm 0.24 \pm 0.11)\%$$

Naïve estimation in the SM

- Direct CP asymmetry in D→(KK, π π)

$$Amp = \frac{G_F}{\sqrt{2}}\left[V_{cq}^* V_{uq}\left(T_{SM}^q + E_{SM}^q e^{i\delta_S^q}\right) - V_{cb}^* V_{ub} P_{SM}^q e^{i\phi_S^q}\right]$$

$$A_{CP}^{dir}(D^0 \to f) \sim -Im\left(\frac{V_{cb}^* V_{ub}}{V_{cq}^* V_{uq}}\right)\frac{2P_{SM}^q}{|T_{SM}^q + E_{SM}^q e^{i\delta_S^q}|^2}\left(T_{SM}^q \sin\phi_S^q + E_{SM}^q \sin(\delta_S^q - \phi_S^q)\right)$$

q=d → π π mode, q=s → KK mode

- E^q_{SM} stands for the W-exchange and long-distance effects are dominated

- With T^q_{SM} ~ E^q_{SM} and $Im(V^*_{cb}V_{ub}/V^*_{cq}V_{uq}) = \pm A^2 \lambda^4 \eta$

$$A_{CP}^{dir}(K^- K^+) \sim -A_{CP}^{dir}(\pi^- \pi^+) \sim -0.05\frac{P_{SM}^q}{T_{SM}^q}\%$$

- Unless $P^q_{SM}/T^q_{SM} > 1$, the large magnitude of ΔA_{CP} may imply the existence of new physics and new CP phase

- The detailed analysis with various approaches in the SM could be referred to

  Cheng & Chiang, 1201.0785, 1205.0580

  Feldmann, Nandi and Soni, 1202.3795

  Li, Lu, Yu, 1203.3120

  Franco, Mishima, Silvestrini,1203.3131

  Brod, Grossman, Kagan, Zupan, 1203.6659

LR Mixing in general $SU(2)_L xSU(2)_R xU(1)$

Chen, Geng, Wang

- Motivation: a^{ind}_{CP} usually induced by box diagrams is still consistent with no CP violation, for avoiding the constraint, we investigate the ΔA_{CP} is generated by tree, the same effects are suppressed at loop

- The extension of SM based on the gauge symmetry $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

- Two charged gauge bosons, $W_{L,}$ $W_{R,}$

- Fermion masses are from

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_1^+ \\ \phi_2^- & \phi_2^0 \end{pmatrix} = (2,2^*,0)$$

- Break $SU(2)_{L,R}$, one can introduce doublets $\delta_{L,R}$ and triplets $\Delta_{L,R}$

- The mass matrix for W_L-W_R is

$$M^2 = \begin{pmatrix} M_L^2 & M_{LR}^2 e^{i\alpha} \\ M_{LR}^2 e^{-i\alpha} & M_R^2 \end{pmatrix}$$

$$M_{1,2}^2 = \frac{1}{2}\left[M_L^2 + M_R^2 \mp \sqrt{(M_R^2 - M_L^2)^2 + 4\, M_{LR}^4}\right]$$

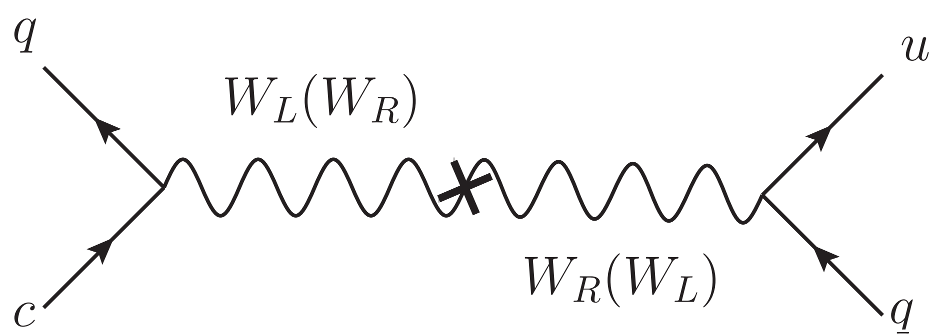
- Mass eigenstates vs gauge eigenstates

$$\begin{pmatrix} W_L^+ \\ W_R^+ \end{pmatrix} = \begin{pmatrix} cos\xi & -sin\xi \\ e^{i\omega} sin\xi & e^{i\omega} cos\xi \end{pmatrix} \begin{pmatrix} W_1^+ \\ W_2^+ \end{pmatrix}$$

$$tan2\xi = \frac{\mp 2 M_{LR}^2}{M_R^2 - M_L^2}$$

$$m_R \gg m_L, m_{LR}, \xi \sim M_{LR}^2 / M_R^2$$

- LR mixing effects on D decays



q=d, s

- Pure W_R contributions are g^2_R / m^2_R suppressed, hereafter we don't discuss the effects.

- If $M_R \sim$ 1TeV, $M_{LR} \sim 0.1$ TeV, $\xi \sim O(10^{-2})$, if no further constraint, it is large enough to enhance the CP in D decays
- In manifest or pseudo-manifest LR model, $V^L = V^{R(*)}$, $\xi < O(10^{-3})$ Wolfenstein PRD(84)
- The constraint could be released when flavor mixing effects are more arbitrary and carry large CP phases (nonmanifest LR model) Langacker & Sankar PRD(89)
- Sizable ξ and large phase in V^R could lead to large CP in Hyperon decays, Chang, He, Pakavasa PRL(95)
- We study the impact on the CP in $D^0 \rightarrow \pi\pi$, KK decays

Decay Amplitudes

$$\mathcal{H}^q_{\chi\chi'} = \frac{4G_F}{\sqrt{2}}\frac{g_R}{g_L}\xi\Big[V^{\chi'}_{uq}V^{\chi^*}_{cq}\left(C'_1(\mu)(\bar{u}q)_{\chi'}(\bar{q}c)_\chi\right) + C'_2(\mu)(\bar{u}_\alpha q_\beta)_{\chi'}(\bar{q}_\beta c_\alpha)_\chi)$$
$$+ V^{\chi}_{uq}V^{\chi'^*}_{cq}\left(C'_1(\mu)(\bar{u}q)_{\chi}(\bar{q}c)_{\chi'}\right) + C'_2(\mu)(\bar{u}_\alpha q_\beta)_{\chi}(\bar{q}_\beta c_\alpha)_{\chi'})\Big] \,.$$

Here, $\chi = L(R)$ and $\chi' = R(L)$ while $q = s(d)$, and $(\bar{q}q')_{L(R)} = \bar{q}\gamma^\mu P_{L(R)}q'$. The Wilson coefficients $C'_1 = \eta_+$ and $C'_2 = (\eta_+ - \eta_-)/3$ with QCD corrections could be estimated by [25, 26]

$$\eta_+ = \left(\frac{\alpha_s(\mu)}{\alpha_s(m_c)}\right)^{-3/27}\left(\frac{\alpha_s(\mu)}{\alpha_s(m_b)}\right)^{-3/25}\left(\frac{\alpha(m_b)}{\alpha_s(m_W)}\right)^{-3/23} ,$$
$$\eta_- = \eta_+^{-8} \,. \tag{14}$$

Based on the decay constants and transition form factors, defined by

$$\begin{aligned}\langle 0|\bar{q}'\gamma^\mu\gamma_5 q|P(p)\rangle &= i f_P p^\mu \,,\\ \langle P(p_2)|\bar{q}\gamma_\mu c|D(p_1)\rangle &= F_+^{DP}(k^2)\left\{Q_\mu - \frac{Q\cdot k}{k^2}k_\mu\right\}\\ &\quad + \frac{Q\cdot k}{k^2}F_0^{DP}(k^2)\,k_\mu \,,\end{aligned}$$

$$A^q_{LR}(D^0\to f) = \left(V^{L*}_{cq}\bar{V}^R_{uq} - \bar{V}^{R*}_{cq}V^L_{uq}\right)T^q_{\chi\chi'}$$

$$\begin{aligned}T^d_{RL} &= \frac{G_F}{\sqrt{2}}\frac{g_R}{g_L}\xi a_1' f_\pi F_0^{D\pi}(m_D^2 - m_\pi^2)\,,\\ T^s_{LR} &= \frac{f_K}{f_\pi}\frac{F_0^{DK}}{F_0^{D\pi}}\frac{m_D^2 - m_K^2}{m_D^2 - m_\pi^2}T^d_{RL}\,,\end{aligned}$$

$$a_1' = C_1' + C_2'/N_c.$$

- CP asymmetries :

$$A_{CP}(D^0 \to f) \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)}$$

- With $V^L_{ud}=-V^L_{us}\sim-\lambda$

$$|A^d|^2 - |\bar{A}^d|^2 = -4E^d_{SM}T^d_{RL}\sin\delta^d_S\left(\lambda^2 Im\bar{V}^{R*}_{ud} + \lambda Im\bar{V}^R_{cd}\right) ,$$

$$|A^s|^2 - |\bar{A}^s|^2 = -4E^s_{SM}T^s_{LR}\sin\delta^s_S\left(\lambda Im\bar{V}^{R*}_{us} - \lambda^2 Im\bar{V}^R_{cs}\right) .$$

$$\bar{V}^R = e^{i\omega}V^R$$

- The CPAs depend on the pattern of V^R

Constraint from ε'/ε

- The tree induced CP also contributes to direct CP violation in K→ π π

$$(\epsilon'/\epsilon)_K \sim 1.25 \times 10^{-3} g_R/g_L \xi Im(\bar{V}^R_{us} - \lambda \bar{V}^{R*}_{ud}).$$

He, McKellar, Pakvasa, PRL(88)

- To avoid the constraint from DCPV in K decays, we consider two cases:

  - $Im(\bar{V}^R_{us,ud}) \approx 0$
  - $Im\,\bar{V}^R_{us} \approx \lambda Im\,\bar{V}^{R*}_{ud}$

The SM inputs : arXiv:1201.0785, Cheng & Chiang

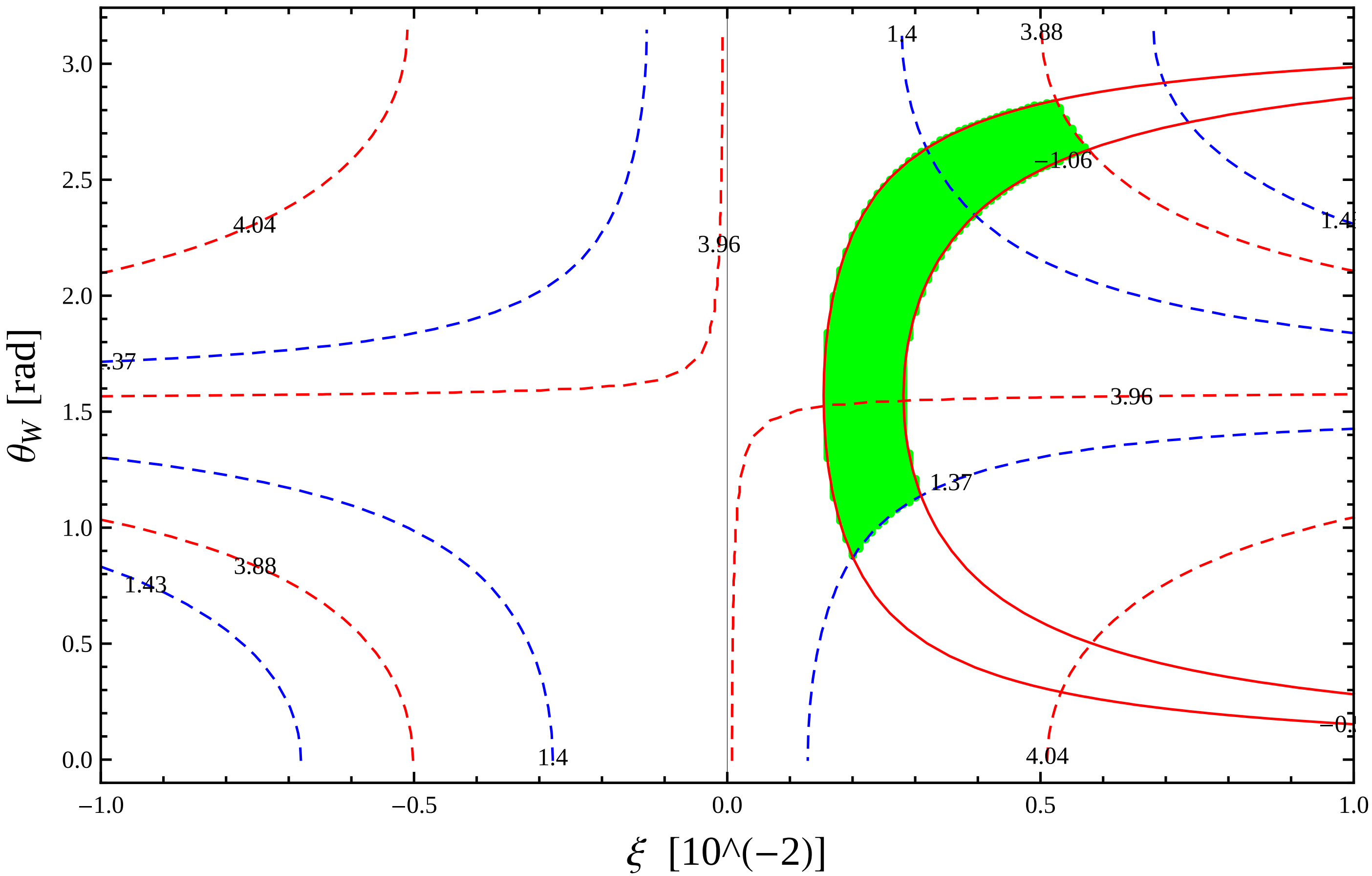
TABLE I. Numerical inputs for the parameters in the SM.

T^d_{SM}	T^s_{SM}	E^d_{SM}	E^s_{SM}	δ^d_S	δ^s_S
3.0×10^{-6}GeV	4.0×10^{-6}GeV	1.3×10^{-6}GeV	1.6×10^{-6}GeV	$145°$	$108°$
V^L_{us}	$m_{\pi(K)}$	m_D	$f_{\pi(K)}$	$F_0^{D\pi(K)}$	m_t
0.22	0.139(0.497)GeV	1.863GeV	0.13(0.16)GeV	0.666(0.739)	162.8 GeV

The BRs for D→ (KK, π π) in the SM are

$$\mathcal{B}(D^0\to K^-K^+) = 4.0[3.94\pm0.07]\times10^{-3}$$
$$\mathcal{B}(D^0\to \pi^-\pi^+) = 1.4[1.397\pm0.026]\times10^{-3}$$

Results: Case I $Im(\bar{V}^R_{us,ud}) \approx 0$



$$\bar{V}^R_{cd} = -\lambda \bar{V}^R_{cs}$$
$$= -\lambda e^{i\theta}$$

$$A_{CP}(K^+K^-) \approx -A_{CP}(\pi^+\pi^-)$$

$$\xi \to g_R/g_L \xi$$

Case II: $Im\,\bar{V}^R_{us} \approx \lambda Im\,\bar{V}^{R*}_{ud}$

- We get

$$|A^d|^2 - |\bar{A}^d|^2 = -4E^d_{SM}T^d_{RL}\sin\delta^d_S\left(\lambda^2 Im\bar{V}^{R*}_{ud} + \lambda Im\bar{V}^R_{cd}\right)$$

$$|A^s|^2 - |\bar{A}^s|^2 = 4\lambda^2 E^s_{SM}T^s_{LR}\sin\delta^s_S\left(Im\bar{V}^{R*}_{ud} + Im\bar{V}^R_{cs}\right)$$

- We adopt the patterns for the numerical analysis

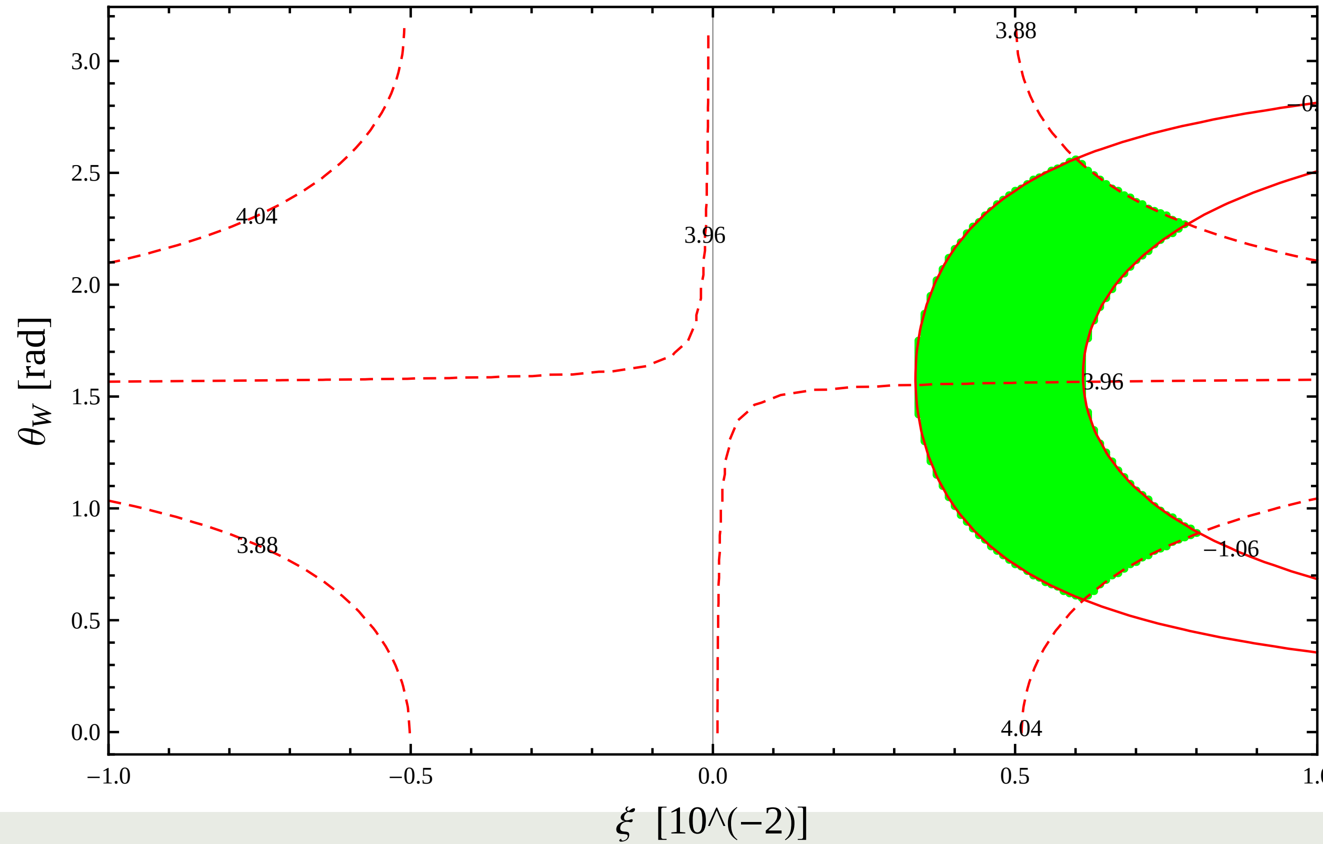
$$V^R_A(\alpha) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_\alpha & \pm s_\alpha \\ 0 & s_\alpha & \mp c_\alpha \end{pmatrix}, \quad V^R_B(\alpha) = \begin{pmatrix} 0 & 1 & 0 \\ c_\alpha & 0 & \pm s_\alpha \\ s_\alpha & 0 & \mp c_\alpha \end{pmatrix}$$

we adopt α=0 for the numerical analysis

Langacker & Sankar PRD(89)

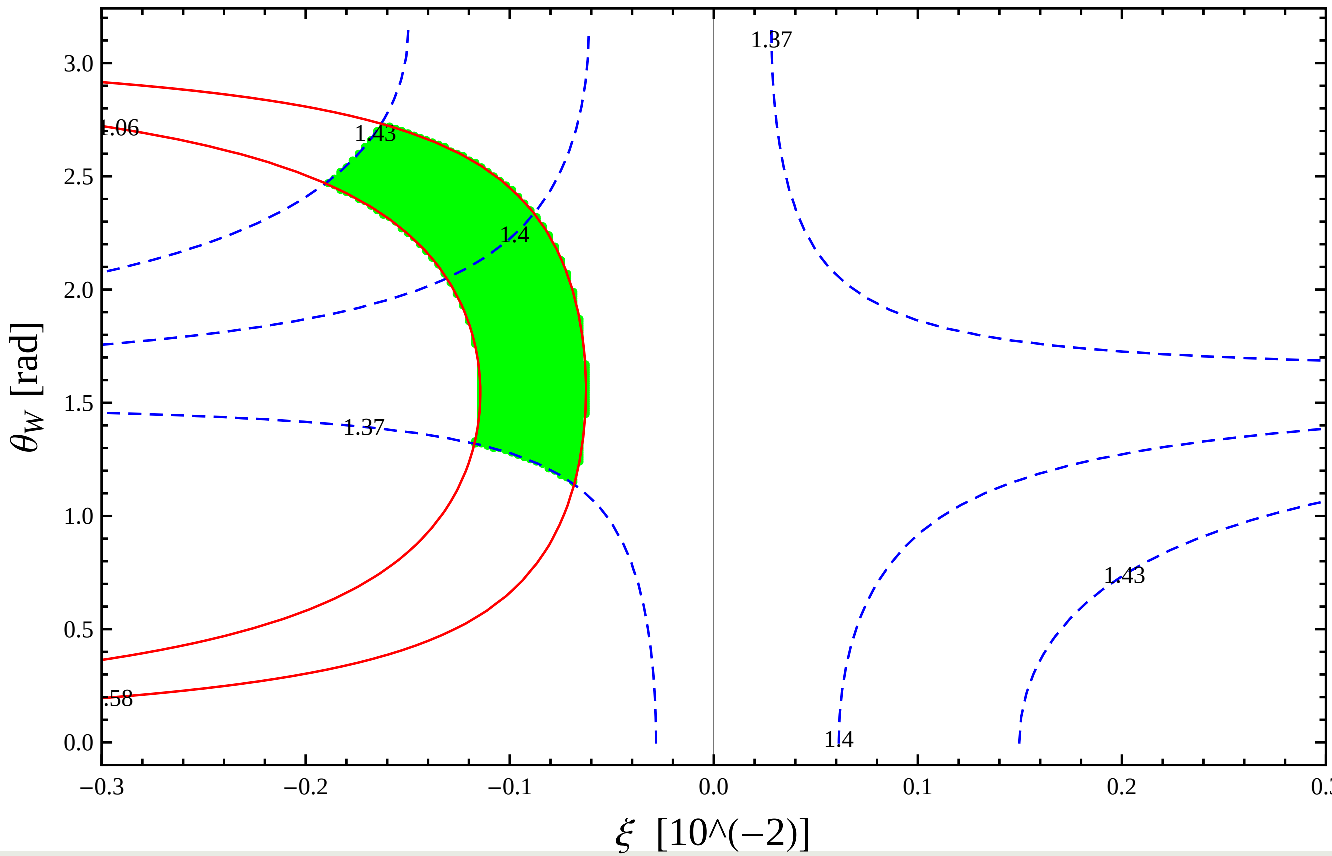
$V^R_A(\alpha=0)$

- $V^R_{cd}\to 0$ and $\mathrm{Im}(V^R_{ud})\approx 0$ due to ε'/ε. As a result, CPA in $D^0\to\pi\pi\to 0$



$V^R_B(\alpha=0)$

- $V^R_{ud,cs} \to 0$, $A_{CP}(D^0 \to KK) \to 0$



Summary

- LHCb and CDF show the direct CP violation in D decays with 3.8σ deviation from the no CP violation. The “anomaly” could be explained by the LR mixing in the general LR model

- The same effects could predict large CPA in doubly Cabibbo suppressed process, such as $D^0 \rightarrow \pi^- K^+$ decays