THE FLAVOUR STRUCTURE IN THE SM, THE GIM MECHANISM, CP AND FCNC PROBES OF BSM

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Experimental observations		Theory
β decay	end 19^{th} century	
	1933	Fermi theory
μ decay	1936	
pions & kaons	1947-1950	
	1954	Yang-Mills theory
	1959	GWS model
	1960	symmetry breaking (Nambu-Goldstone)
	'60s	quark model
CP violation $K-\bar{K}$	1964	Higgs mechanism
	1970	GIM mechanism
	1973	CKM matrix
c quark	1974	
b quark	1977	
t quark	1995	
direct CPV ; $B-\bar{B}$ oscillations	2000s	
Higgs boson	2012	

Main experiments (recently active)

Belle	@	KEKB	8 GeV e^- - 3.5 GeV e^+	~ 1999 - 2010
Belle II	@	SuperKEKB	7 GeV e^- - 4 GeV e^+	~ 2018 - ...
BaBar	@	SLAC	9 GeV e^- - 3.1 GeV e^+	~ 1999 - 2008
LHCb	@	LHC	7 TeV pp , 13 TeV pp	~ 2002 - ...

WHY FLAVOUR PHYSICS ?

- provides precise determination of SM parameters
- can give indirect hints of new physics
- it's the only known source of CP violation

The Standard Model

Our model is composed of the following ingredients:

- Gauge symmetry: $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$
- Matter fields: [$i = 1, 2, 3$ generation]

quarks: $\begin{cases} Q_L^i & (3, 2)_{1/3} \\ U_R^i & (3, 1)_{-4/3} \\ D_R^i & (3, 1)_{2/3} \end{cases}$ doublets $\begin{pmatrix} u_L \\ d_L \end{pmatrix} \begin{pmatrix} c_L \\ s_L \end{pmatrix} \begin{pmatrix} t_L \\ b_L \end{pmatrix}$

$+ \quad H \quad (1, 2)_1$

leptons: $\begin{cases} L_L^i & (1, 2)_{-1} \\ E_R^i & (1, 1)_2 \end{cases}$ doublets $\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$

- Spontaneous Symmetry Breaking

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \longrightarrow SU(3)_c \otimes U(1)_{EM}$$

The most general Lagrangian includes all the terms that contain these ingredients, under the following additional constraints: Poincaré invariance and Renormalisability

$$\mathcal{L}_{SM} = \mathcal{L}_{kinetic} + \mathcal{L}_{Higgs} + \mathcal{L}_{Yukawa}$$

$\mathcal{L}_{kinetic}$ ↑ all $\bar{\psi} i \not{D} \psi$, all $\frac{1}{4} F_{\mu\nu}^a F^{\mu\nu a}$

$\mathcal{L}_{Higgs}$ ↑ $\frac{1}{2}\mu^2\phi^2 - \lambda\phi^4$

$\mathcal{L}_{Yukawa}$ ↑ terms of the type $y_u \bar{Q}_L \tilde{H} U_R$

Remarks:

- we do not impose *a priori* the conserved global symmetries of $\mathcal{L}_{SM}$; they are accidental symmetries

  $\psi_k \to e^{i\alpha_k} \psi_k$ $\quad [U(1)]^5$ of which: 3 are OK (Y, B, L)

  2 broken by m_f

- there are some "approximate symmetries"

  e.g. $SU(2)$ isospin or $SU(3)$ flavour

The CKM matrix

Let's consider the Yukawa terms in $\mathcal{L}_{SM}$:

$$\mathcal{L}_{Yukawa} = \bar{Q}_L^i \, y_{U\,ij} \, \tilde{H} \, U_R^j + \bar{Q}_L^i \, y_{D\,ij} \, H \, D_R^j + \bar{L}_L^i \, y_{L\,ij} \, H \, E_R^j + h.c.$$

- y_U, y_D matrices are in principle not (flavour) diagonal
- their entries can be complex numbers
- after SSB, these terms generate the fermion masses

$$\bar{Q}_L^i \, y_{D_{ij}} \, H \, D_R^j \longrightarrow \frac{v}{\sqrt{2}} \, \bar{d}_L^i \, y_{D\,ij} \, d_R^j$$

$$\bar{Q}_L^i \, y_{U\,ij} \, \tilde{H} \, \cancel{U}_R^j \longrightarrow \frac{v}{\sqrt{2}} \, \bar{u}_L^i \, y_{U\,ij} \, u_R^j$$

Rotate to the mass eigenstate basis:

$$u_L \to V_{uL} u_L \qquad d_L \to V_{dL} d_L$$
$$u_R \to V_{uR} u_R \qquad d_R \to V_{dR} d_R \qquad \to \text{new fields are mass-diagonal}$$

$V_{uL}, V_{uR}, V_{dL}, V_{dR}$ are unitary.

The effect of these rotations on the Yukawa terms:

$$\mathcal{L}^q_{Yukawa} \to \frac{v}{\sqrt{2}} \, \bar{u}_L^i \left(V_{uL}^\dagger \, y_U \, V_{uR}\right)_{ij} u_R^j + \frac{v}{\sqrt{2}} \, \bar{d}_L^i \left(V_{dL}^\dagger \, y_D \, V_{dR}\right)_{ij} d_R^j$$

Singular Value Decomposition thm.: $\exists \, V_L, V_R$ such that $\tilde{y} = V_L^\dagger y V_R$ is diagonal with real elements > 0

The mass matrices are $\quad m_U = \frac{v}{\sqrt{2}} \tilde{y}_U \quad ; \quad m_D = \frac{v}{\sqrt{2}} \tilde{y}_D$

However, the effect is nontrivial on $\mathcal{L}_{kinetic}$. Most of the terms do not change (due to $V_{i_{L,R}}$ unitarity) except

$$\mathcal{L}_W \supset \frac{g_2}{\sqrt{2}} \bar{u}_L W_i \sigma^i d_L \to \frac{g_2}{\sqrt{2}} \bar{u}_L \underbrace{\left(V_{uL}^\dagger V_{dL}\right)}_{} W_i \sigma^i d_L$$

$$\boxed{V_{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

- involves only LH fields
- is unitary

Some flavour phenomenology

Flavour processes are mostly of two types: decays and oscillations.

A few interesting measurements can give hints on the structure of flavour physics:

- $B^+ \to X \mu^+ \nu$ B.R. $\cong 10\%$
  $B^+ \to X e^+ \nu$ B.R. $\cong 10\%$ } actually listed as the same on PDG

  $D^+ \to \bar{K}^0 e^+ \nu$ B.R. $\simeq 8.9\%$
  $D^+ \to \bar{K}^0 \mu^+ \nu$ B.R. $\simeq 9.3\%$

  $\hookrightarrow$ suggest lepton flavour universality

- $K^+ \to \pi^0 e^+ \nu$ B.R. $\simeq 5\%$
  $K^+ \to \pi^+ \ell^+ \ell^-$ B.R. $\simeq 4 \times 10^{-7}$

  $K^+ \to \mu^+ \nu$ B.R. $\simeq 63\%$
  $K^+ \to \mu^+ \mu^-$ B.R. $\simeq 6.8 \times 10^{-9}$

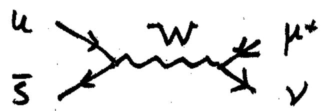
  $\hookrightarrow$ suggest that Flavour changing neutral currents undergo a suppression mechanism

- $B^+ \to D^0 \ell^+ \nu$ B.R. $\simeq 2 \times 10^{-2}$
  $B^+ \to \pi^0 \ell^+ \nu$ B.R. $\simeq 7.8 \times 10^{-5}$

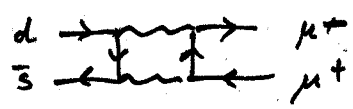
  $\hookrightarrow$ hierarchy between different generations

Heavy hadrons decays are usually classified based on their final state:

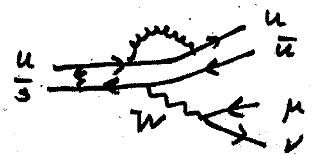
- leptonic $K^+ \to \mu^+ \nu$



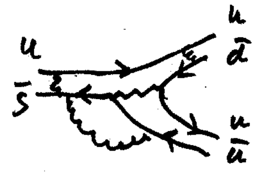
$K^0_L \to \mu \mu$



- semi-leptonic $K^+ \to \pi^0 \ell^+ \nu$



- non-leptonic $K^+ \to \pi^+ \pi^0$



GIM mechanism & FCNC suppression

Starting point: Cabibbo realisation of EW universality in pion and kaon decays ($d \to u$, $s \to u$)

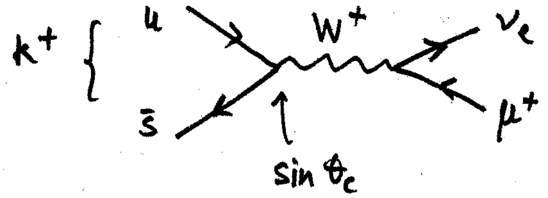
The hadronic current embeds a quantum superposition of d and s states:

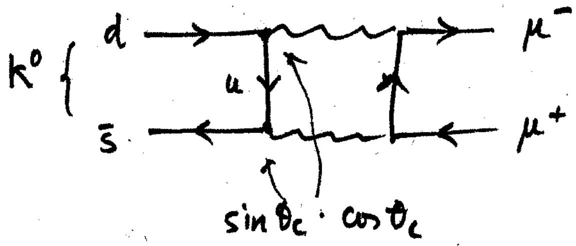
$$J^{\mu}_{(had)} = \bar{u}\,\gamma^{\mu}(1-\gamma^5)\,d'$$

where $d' = \cos\theta_c\, d + \sin\theta_c\, s$

θ_c is called Cabibbo angle ; $\theta_c \simeq 13^{\circ}$

But : compare with K^0 decay (NEUTRAL CURRENT)





thus naively: $\dfrac{BR(K^0 \to \mu^+\mu^-)}{BR(K^+ \to \mu^+\nu)} \sim \cos^2\theta_c \simeq 0.95$

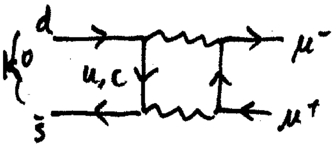
but experimental results: $\simeq 10^{-9}$!

Glashow - Iliopoulos - Maiani (GIM) 1970

Take the orthogonal combination to d' : $s' = -\sin\theta_c\, d + \cos\theta_c\, s$ and couple it to new particle c (charge $+\frac{2}{3}$)

$$J^{\mu}_{(had)} = \bar{u}\,\gamma^{\mu}(1-\gamma_5)\,d' + \bar{c}\,\gamma^{\mu}(1-\gamma_5)\,s'$$

Now we have to add c mediated diagram



$\sim \sin\theta_c \cdot \cos\theta_c - \sin\theta_c \cdot \cos\theta_c = 0$

This is exact in the limit of flavour symmetry, i.e. $m_i = 0$

↳ Neutral current is naturally suppressed

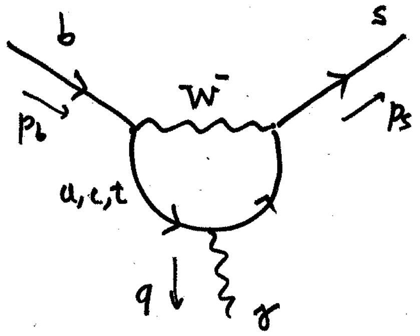
BUT other corrections must be small too ⟶ prediction $O(m_c^2/m_W^2)$

More FCNC suppression

Consider the process $b \to s\gamma$:

- it's a flavour changing neutral current ;
- first order is 1-loop diagrams ;
- use GIM mechanism to show its suppression .

The process is mediated via a so-called "PENGUIN DIAGRAM"



$$\simeq e q_\mu \epsilon_\nu \left[\bar{u}(p_s)\, \sigma^{\mu\nu} \frac{1+\gamma_5}{2} u(p_b) \right] \frac{m_b}{m_W^2} \frac{g^2}{16\pi^2} I(m_i)$$

with
$$q = p_b - p_s$$
$$\sigma^{\mu\nu} = \frac{i}{2}[\gamma^\mu, \gamma^\nu]$$
$$I(m_i) = \sum_i V_{ib} V_{is}^* \, F(m_i^2/m_W^2)$$

$F(x)$ is a complicated function :

- OLD SOLUTION : assuming $m_u < m_c < m_t \ll m_W$ (!)
  we can Taylor-expand $F(x) = F(0) + x F'(0) + \dots$

$$I \simeq -F'(0) \sum_{i=u,c} \left[\frac{m_t^2 - m_i^2}{m_W^2} V_{is}^* V_{ib} \right]$$

$$\sim O\left(\lambda^2 \frac{m_t^2}{m_W^2} \right) \longrightarrow$$

Why did it work ?
G.I.M. studied K mesons, so terms :
$$m_t^2 V_{td} V_{ts} \sim \lambda^5 m_t^2$$
$$m_c^2 V_{cd} V_{cs} \sim \lambda m_c^2$$
No need of knowing about t !

One is able to obtain good prediction for m_c : $m_c \simeq 1{,}5$ GeV

- MODERN SOLUTION :
  We now know that
  $$m_u < m_c \ll m_W < m_t$$
  so we can't Taylor expand $F(x)$.

However, using $\sum_i V_{ib} V_{is}^* = 0$, we note that I is invariant under $F(x) \to F(x) + \text{const}$. Doing the math :

$F(0) = 0 \Leftarrow$ $\quad I \simeq F\left(\frac{m_t^2}{m_W^2}\right) V_{tb} V_{ts}^*$

- we expect $F(x) \sim O(1)$
- top still dominates

Parameter counting in the SM

Back to our formulation of the SM, and we try to fix its parameters.

[Which of the parameters in $\mathcal{L}_{SM}$ are <u>physical</u>?
i.e. What do we need to measure?

So far:

$\mathcal{L}_{kin}$ $\quad g_1, g_2, g_3$

$\mathcal{L}_{Higgs}$ $\quad v, \lambda$

$\mathcal{L}_{Yukawa}$ $\quad m_e, m_\mu, m_\tau$

$\quad y_{U_{ij}}, y_{D_{ij}}$

These are two complex $N \times N$ matrices $\longrightarrow$ $2N^2$ real parameters
$2N^2$ phases

To count the physical parameters we can use the paradygm:

$$\boxed{N(\text{physical par.}) = N(\text{all par.}) - N(\text{broken generators})}$$

i.e. generators broken by y_U, y_D

If $y_U, y_D = 0$, $\mathcal{L}_{SM}$ has $\underline{U(N)^3}$ symmetry.

$\mathcal{L}_{Yukawa}$ explicitly breaks $U(N)^3 \longrightarrow U(1)_B$

Let's count:

real: $3 \times \frac{1}{2} N(N-1) \longrightarrow 0$

phases: $3 \times \frac{1}{2} N(N+1) \longrightarrow 1$

So we obtain

$$N_{phys}^{real} = 2N^2 - \frac{3}{2} N(N-1) = \frac{1}{2} N(N+3)$$

$$N_{phys}^{phases} = 2N^2 - \frac{3}{2} N(N+1) + 1 = \frac{1}{2}(N-1)(N-2)$$

<u>Examples</u>:

$N=2 \longrightarrow$ 5 real, 0 phases

$N=3 \longrightarrow$ 9 real, 1 phase $\longrightarrow$ [complex Yukawas i.e. CP violation only for $N \geq 3$!

$N=4 \longrightarrow$ 14 real, 3 phases

In our model $N=3$

$\hookrightarrow$ 9 real = 6 masses + 3 CKM angles ; 1 CKM phase

Parametrisations of the CKM

We showed that V_{CKM} depends on 4 parameters : 3 real + 1 phase

- Unitary parametrisation :

$$V_{CKM} = R_{uc}\, R^{\delta}_{ut}\, R_{ct} =$$

$$= \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} =$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$\dashrightarrow$ Cabibbo matrix : $\theta_{12} \simeq$ Cabibbo angle

- 5 complex entries
- fit $\longrightarrow$ $\sin\theta_{12} \simeq 0.225$; $\sin\theta_{23} \simeq 0.0423$; $\sin\theta_{13} \simeq 0.0037$
  $\delta \simeq 69^{\circ}$
- $s_{13} \ll s_{23} \ll s_{12}$ $\longrightarrow$ flavour hierarchy
- magnitude of V_{CKM} entries :

$$|V_{CKM}| \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \quad \text{with} \quad \lambda \sim 0.2$$

badly known (~10%)

- we use the hierarchy of the V_{CKM} to define the Wolfenstein parametrisation :

$$\begin{cases} \sin\theta_{12} \equiv \lambda = \dfrac{|V_{us}|}{\sqrt{|V_{us}|^2 + |V_{ud}|^2}} \\ \sin\theta_{13} \equiv A\lambda^2 = \lambda \left| \dfrac{V_{cb}}{V_{us}} \right| \\ \sin\theta_{13}\, e^{i\delta} \equiv A\lambda^3(\rho + i\eta) = V_{ub}^{*} \end{cases}$$

CKM fitter :

$\lambda = 0.22509^{+0.00029}_{-0.00028}$

$A = 0.8250^{+0.0071}_{-0.0111}$

$\bar{\rho} = 0.1598^{+0.0076}_{-0.0072}$

$\bar{\eta} = 0.3499^{+0.0063}_{-0.0061}$

With these definitions and expanding in powers of λ :

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

- the approximation of V_{CKM} up to $O(\lambda^4)$ is not a unitary matrix anymore.

  ↳ useful if one wants to release unitarity constraint

- often used: $$\bar{\rho} + i\bar{\eta} = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \simeq (\rho + i\eta)\left(1 - \frac{\lambda^2}{2}\right)$$

  because it is phase-convention independent.

  The V_{CKM} is again unitary in $\lambda, A, \bar{\rho}, \bar{\eta}$ parametrisation (but has a horrible expression).

- this parametrisation acknowledges the fact that, to very good approximation, CP violation occurs only in interactions involving the first and third generations.

In order to quantify the amount of CP violation in a parametrisation-independent way, we can define the Jarlskog invariant:

$$J \sum_{m,n} \epsilon_{ikm}\epsilon_{jln} = \mathrm{Im}\left(V_{ij}V_{kl}V_{il}^*V_{kj}^*\right)$$

↑ not summed over

In particular, $J = c_{12}c_{23}c_{13}^2 s_{12}s_{13}s_{23}\sin\delta \simeq \lambda^6 A^2 \eta$

CKMfitter: $J \simeq 3.1 \times 10^{-5}$

Observations:

- J depends on all angles: if $\theta_i = 0 \Rightarrow$ no CP violation
- CP violation is small not because δ is small ($\sin\delta \sim 1$) but rather because the angles are small.

The unitarity triangle(s)

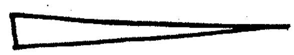
Since V_{CKM} is a unitary matrix, its entries obey six homogeneous equations, e.g. $\sum_i V_{id} V_{is}^* = 0$

complex homogeneous equations $\Longrightarrow$ unitarity triangles in the complex plane

Putting the measured V_{ij} in these triangles, one finds that most of them are almost degenerate:

- $\sum_k V_{ku} V_{kc}^* = 0 \quad \longrightarrow \quad O(\lambda) + O(\lambda) + O(\lambda^5) = 0$

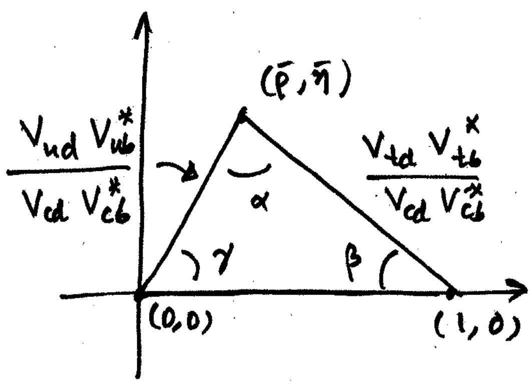
- $\sum_k V_{kc} V_{kt}^* = 0 \quad \longrightarrow \quad O(\lambda^2) + O(\lambda^2) + O(\lambda^4) = 0$



- $\boxed{\sum_k V_{ku} V_{kt}^* = 0} \quad \longrightarrow \quad O(\lambda^3) + O(\lambda^3) + O(\lambda^3) = 0$

  "the" unitarity triangle

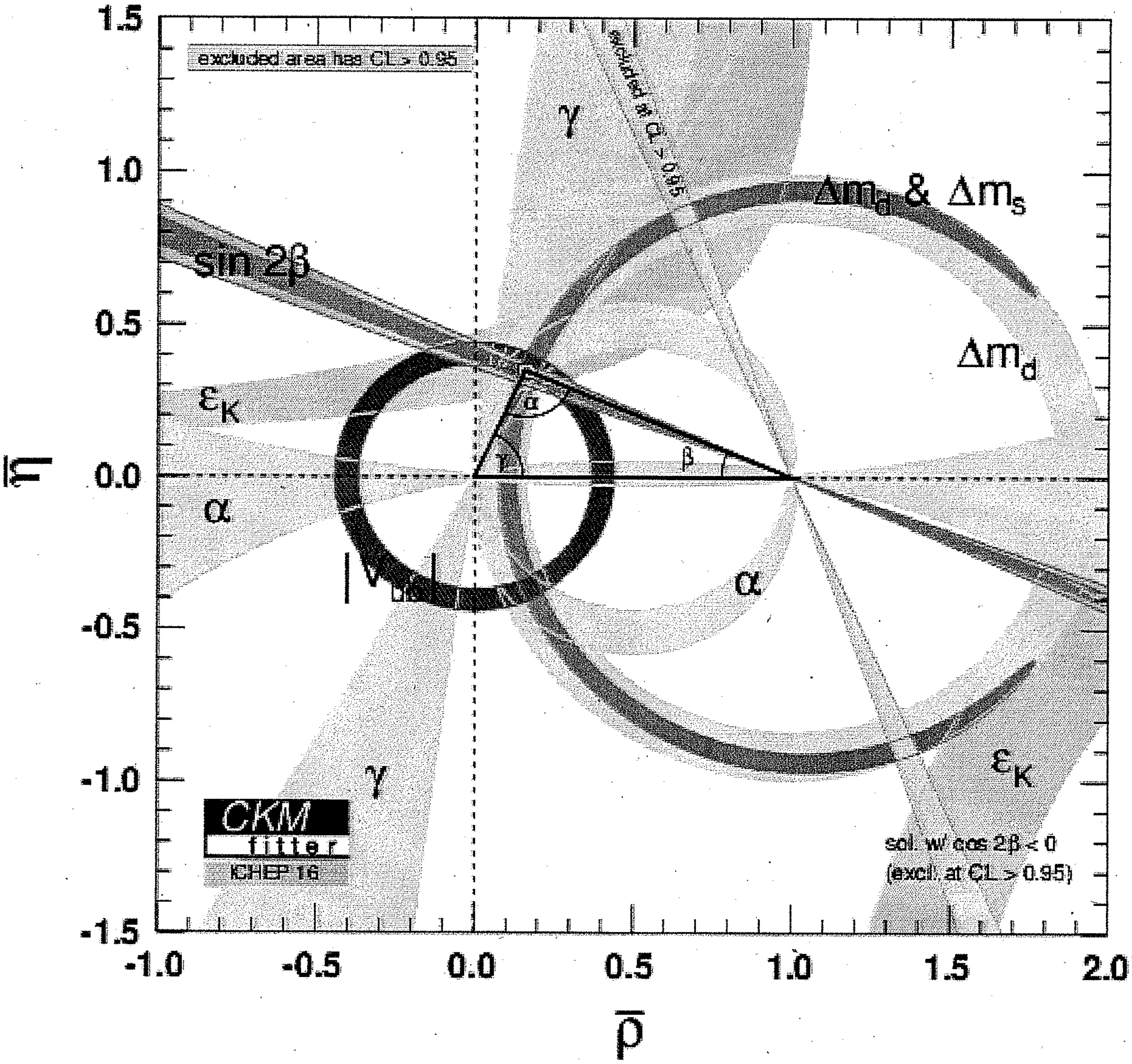
Usually normalised to $\dfrac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} + 1 + \dfrac{V_{td} V_{tb}^*}{V_{cd} V_{cb}^*} = 0$

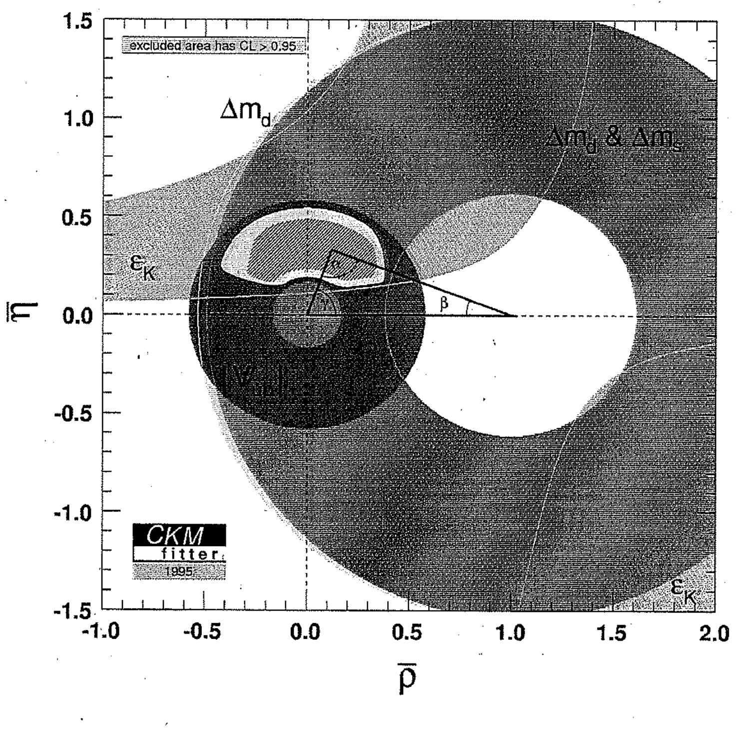


Observations:

- very good check of the SM parameters consistence
- α, β, γ are invariant under phase redefinition
- each of the unitarity triangles has the same area: $J/2$

[note: other convention
$\phi_1 = \beta$
$\phi_2 = \alpha$
$\phi_3 = \gamma$


excluded area has CL > 0.95
γ
excluded at CL > 0.95
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
|V_ub|
CKM
fitter
ICHEP 16
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
η̄
ρ̄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Constraining V_{CKM} in the $\bar{\rho}$-$\bar{\eta}$ plane

Strategy: compare experimental values for some flavor observables to theory predictions with $\bar{\rho}, \bar{\eta}$ as free parameters, then plot the constraint on the complex plane.

- $|V_{ub}|$ from $B \to X_u e \bar{\nu} \quad \propto |V_{ub}|^2$

  By definition $\quad \bar{\rho}^2 + \bar{\eta}^2 = \left| \frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} \right|^2$

  therefore this constraint is approximately a circle centered in $(0,0)$.

- Δm_d, Δm_s from B-$\bar{B}$ mixing : $\Delta m_d \propto |V_{td}|^2$

  $$\frac{BR(B \to \bar{B})}{BR(B_s \to \bar{B}_s)} \propto |V_{td}|^2$$

  Since $|V_{td}|^2 \propto (\rho - 1)^2 + \eta^2$,

  this constraint is another circle, centered in $(1,0)$.

- ϵ_K ~~from~~ indirect CP violation in K-$\bar{K}$ mixing.

  The contraint is approx. an hyperbola

- α, β, γ from CP asymmetries

  "gold-plated mode"

  $A_{CP}(B_d \to J/\psi + K_S) \longrightarrow \sin 2\beta$ good measurement

  status : $\quad \sin 2\beta = 0.740^{+0.020}_{-0.025}$ well known

  $\alpha = (88.8^{+2.3}_{-2.3})^\circ \parallel (-2.2^{+3.7}_{-4.9})^\circ$

  $\gamma = (72.1^{+5.4}_{-5.8})^\circ$

  room for improvement

CP Violation

Discrete symmetries :
- CP violation $\Rightarrow$ $p(a\to b) \neq p(\bar{a}\to\bar{b})$
- T violation $\Rightarrow$ $p(a\to b) \neq p(b\to a)$
- CPT violation $\Rightarrow$ $p(a\to b) \neq p(\bar{b}\to\bar{a})$

We have good reasons to believe that CPT is a symmetry of Nature. Therefore T violation $\Leftrightarrow$ CP violation.

- CPV is only observed in the quark sector
- other possible sources : θ_{QCD} , complex Higgs sector
- in the quark sector, CPV caused by V_{CKM} phases.

It can be measured in various processes :

- oscillations generate indirect CPV through mixing Hamiltonian

$$|\epsilon| = (2.228 \pm 0.011) \times 10^{-3} \qquad K-\bar{K}$$

- decays include direct CPV through weak phases

$$B \to f \qquad \left.\begin{array}{l} A_f = A(B\to f) \\ \bar{A}_f = A(\bar{B}\to\bar{f}) \end{array}\right\} \text{ CPV if } |A_f| \neq |\bar{A}_f|$$

Usually measure

$$A_{CP} \equiv \frac{\Gamma(B\to f) - \Gamma(\bar{B}\to\bar{f})}{\Gamma(B\to f) + \Gamma(\bar{B}\to\bar{f})} = \frac{|A/\bar{A}|^2 - 1}{|A/\bar{A}|^2 + 1}$$

exp: in $K-\bar{K}$ $\quad \mathrm{Re}\,\frac{\epsilon'}{\epsilon} = (1.66 \pm 0.23) \times 10^{-3}$

in $B \to DK$ $\quad A_{CP} = 0.11 \pm 0.04$

$B \to K\pi\pi$ $\quad A_{CP} = 0.027 \pm 0.008$

- interference of decays & mixing

$$B \to \bar{B} \to f$$

- another possible ~~process~~ instance of CPV : EDMs

(chromo-EDMs)

Probes of BSM

CP violation and FCNCs are sensitive probes of high-energy physics in the SM and for new physics.

↳ test the SM : unitarity triangle "closes"
i.e. $\alpha + \beta + \gamma = 180°$ EXP : $(183^{+7}_{-8})°$

Parametrise new physics using higher-dimensional operators in SMEFT :

- $\Delta F = 0$ operators (CP-odd), e.g. $\theta_{QCD}\, \tilde{G}_{\mu\nu} G^{\mu\nu}$

or $d_i\, \bar{\psi}\, (F\cdot\sigma)\gamma_5\, \psi \; + \; \tilde{d}_i\; \bar{\psi}\, g_s\, (G\cdot\sigma)\, \gamma_5\, \psi$

↳ · $(g-2)_\mu$ currently $\sim 3.6\sigma$ discrepancy

· EDMs (electron) SM $< 10^{-38}$ e·cm
exp $< 10^{-28}$ e·cm
(neutron) SM $< 10^{-31}$ e·cm
exp $< 10^{-25}$ e·cm

- $\Delta F = 1$ operators, e.g. penguins

$$O_9 = \bar{s}\gamma_\mu b \sum_\ell \bar{\ell}\gamma^\mu \ell$$
$$O_{10} = \bar{s}\gamma_\mu b \sum_\ell \bar{\ell}\gamma^\mu\gamma^5 \ell$$

→ combined constraints on C_9 & C_{10} $\sim 4\sigma$

- $\Delta F = 2$ operators $\frac{c_{ij}}{\Lambda^2}\left(\bar{q}_{i_L}\gamma^\mu q_{j_L}\right)^2$ & $\frac{c_{ij}}{\Lambda^2}\left(\bar{q}_{iR}\, q_{jL}\right)\left(\bar{q}_{iL}\, q_{jR}\right)$

i, j	Λ $(c_{ij} = 1)$	c_{ij} $(\Lambda = 1$ TeV$)$
s, d	$> 10^4$ TeV	$< 10^{-9}$
c, u	$> 10^3$ TeV	$< 10^{-8}$
b, d	> 500 TeV	$< 10^{-7}$
b, s	> 100 TeV	$< 10^{-5}$

from [Isidori '10]

Other interesting measurements

- the famous $R_{D^{(*)}}$ anomaly : $R_{D^{(*)}} = \dfrac{BR(B \to D^{(*)} \tau \nu)}{BR(B \to D^{(*)} \ell \nu)}$
  - small theory uncertainty
  - $\sim 4\sigma$ discrepancy
- P_5' anomaly in angular moments expansion of $B \to K^* \mu^+ \mu^-$
- dimuon charge asymmetry in $B_{s,d} \to X \ell \nu$

  DØ $3-4\sigma$ $\dfrac{N_{\mu^+\mu^+} - N_{\mu^-\mu^-}}{N_{\mu^+\mu^+} + N_{\mu^-\mu^-}}$

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