Introduction to CP violation and the CKM matrix (I)

Jérôme Charles

Centre de Physique Théorique (Marseille)

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Preamble

Among the ~ 20 Nobel Prizes in/around particle physics since WWII, seven are related to flavor transitions:

1957 Lee & Yang (theory of parity violation in weak currents)

1980 Cronin & Fitch (discovery of *CP* violation)

1988 Lederman (discovery of ν_μ and parity violation)

2002 Koshiba (discovery of neutrino oscillations)

2008 Kobayashi & Maskawa (mechanism of CP violation)

2013 Englert & Higgs (EW symmetry breaking)

2015 Kajita & McDonald (neutrino oscillations)

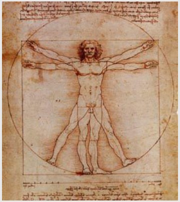
The Standard Model (SM) has $18 + 1 = 19$ parameters.

Three of them are completely flavor-blind: the gauge couplings g_S, g, g'.

The fourth, $\theta_{\rm QCD}$, violates CP but is flavor-blind (usually set to 0, experimental bound is about 10^{-11}); it is the coupling of the operator $\frac{1}{16\pi^2} G^{\mu\nu} \tilde{G}_{\mu\nu}$.

The remaining 15 parameters are all related to electroweak and flavor symmetry breaking, through the scalar sector of the SM: the Higgs expectation value v and mass m_H, the 9 fermions masses m_f, and the four quark mixing parameters A, λ, $\bar{\rho}$, $\bar{\eta}$.

the electroweak and flavor symmetry breaking sector is the most arbitrary and the least well understood part of the Standard Model

 $\Rightarrow$  ?

Outline

Today:

- A bit of history
- The flavor sector of the Standard Model
- *CP* violation and the CKM matrix
- Theory-free determination of the CKM elements

Tomorrow:

- Theoretical methods for heavy flavors
- Examples of predictions
- Beyond the SM and New Physics tests

The history of flavor physics

Antiquity

- 1896 discovery of the radioactivity of the uranium (Becquerel)
- 1898 thorium, polonium, radium (Curie^2)
- 1899 distinction between α and β decay (Rutherford)
- 1930 "invention" of the neutrino (Pauli)

Middle Age

- 1951-1954 CPT conservation theorem (Schwinger, Lüders & Pauli)
- 1956-1957 postulate and discovery of parity violation (Lee & Yang, Wu et al., Garwin & Lederman)
- 1964 discovery of charge $\times$ parity violation (Cronin & Fitch)
- 1973 mechanism(s) of CP violation in the "Standard" model (Kobayashi & Maskawa)

Modern Era

1998 discovery of time-reversal violation (CPLEAR)

1998 discovery of neutrino oscillations (Super-Kamiokande)

1999 direct CP violation in the kaon system (KTeV, Na48)

2001 mixing-induced CP violation in the B system (BaBar, Belle)

2004 direct CP violation in the B system (BaBar, Belle)

Postmodern Era

2008 Nobel Prize to Kobayashi and Maskawa for their successful mechanism of CP violation in the Standard Model

2014 first discovery of very rare FCNC decay $B_s \to \mu\mu$ (LHCb, CMS)

since $\sim$ 10 years a few hints against the SM are showing up (and down)

The Standard Model

It is defined by:

- The gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$.
- The fermion content: three generations of quarks and leptons
  $\Psi_Q = \begin{pmatrix} U_L \\ D_L \end{pmatrix}$, $\Psi_\ell = \begin{pmatrix} \nu_{\ell,L} \\ \ell_L \end{pmatrix}$, U_R, D_R, ℓ_R $(U = u, c, t,\ \ell = e, \mu, \tau)$
  where quarks (leptons) live in the fundamental (singlet) representation of $SU(3)_c$.
- The scalar sector $\Phi = \left(\phi^+, \phi^0\right)$
- the (by hand) choice of the vacuum $\langle \Phi \rangle = (0, v/\sqrt{2})$
  indeed this is the simplest way to give mass to the gauge bosons $W^\pm$, Z^0 in a gauge invariant way.

As soon as one requests that the SM is perturbatively renormalisable, all the kinetic and interaction terms follow from the above choices, ending with a Lagrangian depending on 19 free parameters.

No other model with less parameters and consistent with the data has been shown to exist so far. . .

The Yukawa sector

Because of weak chirality, naive ($L \times R$) mass terms for the fermions are forbidden by gauge symmetry; quadratic fermion terms comes from the Yukawa interactions with the Higgs doublet.

$$\mathcal{L}_Y = \bar{\Psi}_Q \Lambda_D D_R \Phi + \bar{\Psi}_Q \Lambda_U U_R \tilde{\Phi} + \bar{\Psi}_\ell \Lambda_\ell \ell_R \Phi + \mathrm{h.c.}$$

where the Λ's are 3×3 complex matrices in the family space.
Mass terms: replace the Higgs field by its expectation value;
diagonalization: $\Lambda = V \Delta W^\dagger$ where V, W are unitary and Δ is diagonal.
Consequences

- The mass eigenstates are $\hat{D}_L = V_D^\dagger D_L$, $\hat{D}_R = W_D^\dagger D_R$ and similarly for $U_{L,R}$, $\ell_{L,R}$.
- Tthe couplings of the weak current are given by the matrix $V_{\mathrm{CKM}} \equiv V_U^\dagger V_D$.
- The neutral current conserves the flavor (no FCNC at tree level).
- The massless neutrinos remain massless eigenstates in any basis.

The Higgs boson

The Yukawa interactions, hence the Higgs, determine the flavor structure of the SM; what do we know about it ?

In the physical unitary gauge, only one degree of freedom survives: there is a single neutral Higgs boson in the SM, with unpredicted mass (depending on its self-coupling)

Until 2012 it was the only unobserved particle in the Standard Model.

When the Higgs become heavier and heavier, the Φ^4 interaction becomes larger and larger, up to the point it becomes non perturbative. However there are strong hints that the Φ^4 interaction is not defined in the non perturbative regime: it must be instead embedded in a well behaved theory, such as a gauge theory with asymptotic freedom.

The constraint that the scalar interaction remains perturbative up to the scale $\Lambda_{\rm NP}$ gives an upper bound on m_H. With $\Lambda_{\rm NP} \sim m_{\rm Planck}$ one finds $m_H \lesssim 180$ GeV.

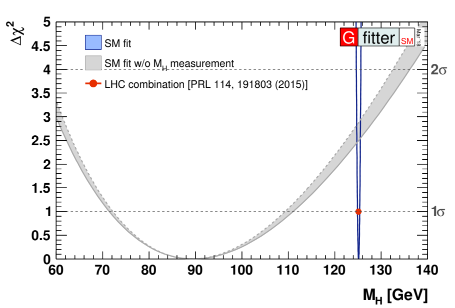
The constraint that the electroweak vacuum remains stable gives a lower bound on m_H. One finds $115\ {\rm GeV} \lesssim m_H$.

Experimental constraints on m_H

The experimental measurement (ATLAS, CMS) is $m_H = 125.18 \pm 0.16$ GeV ! Hence it is perfectly compatible with the naive expectations from the SM.

Even when unseen, the Higgs boson contribute virtually (loops) to the well measured electroweak observables (LEP, TeVatron, LHC): the latter cannot be described in the SM if one neglects the Higgs (or if it's too heavy).

Gfitter global analysis



The hierarchy problem

As in any non finite but renormalizable field theory, the bare Higgs mass receives divergent quantum corrections and must be renormalized.
However the scalar nature of the interaction produces quadratic instead of logarithmic divergences; regularizing these divergences with a cut-off that is interpreted as a New Physics scale, one finds

$$m_H^2 \sim (m_H^2)_{\rm bare} + \frac{\Lambda_{\rm NP}^2}{16\pi^2}$$

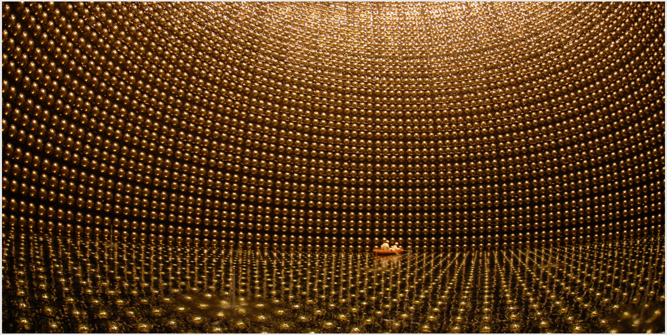
hence the Higgs mass is very sensitive to high scales: fine-tuning competition between the SM and the NP scale.
Requesting moderate fine-tuning leads to $\Lambda_{\rm NP} \sim 1$ TeV.
No evidence of such a low NP scale so far !
As we will see, flavor physics is a way to test for NP at much higher scales.

Aparté: neutrino masses

We have defined the SM with massless left-handed neutrinos; however it is known experimentally (Super-Kamiokande on solar neutrinos in 1998, then many other experiments using various sources of neutrinos) that they (flavor-)oscillate

$$P_{\mathrm{i}\leftrightarrow\mathrm{j}} \sim \sin^2(2\theta_{ij})\sin^2(\Delta m^2_{ij})$$

and hence they are massive (Pontecorvo)



Embedding neutrinos masses

Simplest solution: introduces a right-handed neutrino ν_R and the associated Dirac mass term from the Yukawa couplings, in full analogy with the quarks and charged leptons.
However ν_R has no SM charge, it is sterile: quite ugly solution !
Next-to-simplest solution: uses the antineutrino as the right-handed partner; then mass terms are generated from the gauge invariant dimension five operator (seesaw mechanism)

$$\frac{c}{\Lambda_{\rm NP}}(\bar{\Psi}_\ell \Phi)^2$$

This operator is not renormalizable so that $\Lambda_{\rm NP}$ must be considered as a New Physics scale.

Then $m_\nu \sim v^2/\Lambda_{\rm NP}$; since neutrinos are very light ($\sum_\nu m_\nu \lesssim 1$ eV from cosmological constraints) $\Lambda_{\rm NP}$ must be large, of the order 10^{13} GeV or more (Grand Unification scale), unless the coupling is amazingly small.

Conclusion is that indeed neutrinos masses can be viewed as physics beyond the Standard Model, but presumably from very high scales that are not accessible with collider experiments.

The C, P and T symmetries

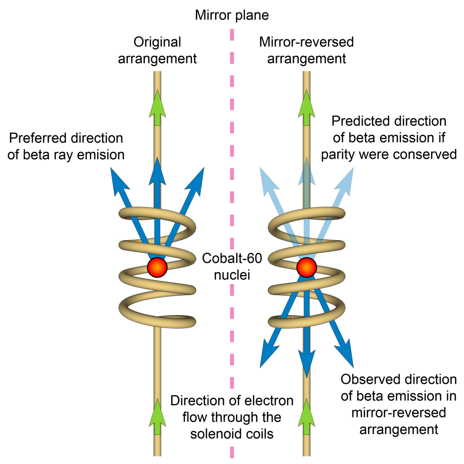
The Standard Model has been defined without imposing by hand global nor discrete symmetries; still, these symmetries are present, *e.g.* baryonic and leptonic global continuous symmetries, and CPT discrete symmetry from general properties of local and Lorentz-invariant Quantum Field Theories (Schwinger, Lüders & Pauli).

- C is the charge conjugation transformation particle $\leftrightarrow$ antiparticle
- P is the spatial parity transformation $(t, \mathbf{x}) \to (t, -\mathbf{x})$
- T is the time reversal transformation $(t, \mathbf{x}) \to (-t, \mathbf{x})$
- the product CPT is a mathematical exact invariance of any "viable" quantum field theory

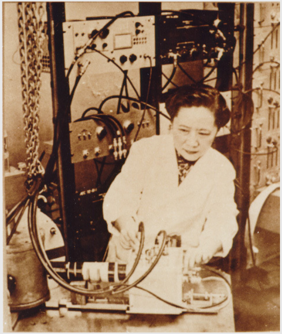
The precise transformation rules for the fields can be found in textbooks. Intuitively the distinction between left and right could be thought as a human invention, and so fundamental physics was postulated to be P-invariant.

Parity violation in the Cobalt weak decay

This is however not true (not even macroscopically: there are chiral molecules with chirality-dependent biological properties): weak interactions are chiral.



Wu experiment 1956-57



immediatly confirmed by Lederman & Garwin in pion decay

CP violation

If P is not conserved, why not postulate that CP is the "correct" interpretation of the left-right symmetry ?
CP was also found to be violated in 1964 (Cronin & Fitch) in kaon decays.

$$|K^0\rangle = \bar{s}d\,, \quad |\bar{K}^0\rangle = CP|K^0\rangle = s\bar{d}$$

CP-eigenstates

$$|K_\pm\rangle = (1/\sqrt{2})(|K^0\rangle \pm |\bar{K}^0\rangle)$$

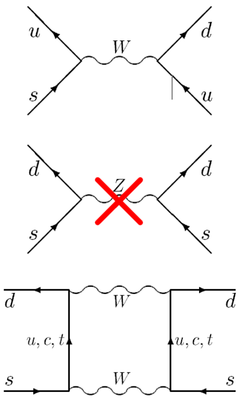
If CP were conserved, only $K_+ \to \pi\pi$ and $K_- \to \pi\pi\pi$ would be allowed

$$K_\pm \equiv K_{S,L}, \quad \tau(K_S) \ll \tau(K_L)$$

but $K_L \to \pi\pi$ was observed at the 10^{-3} level !
CP-asymmetries $\varepsilon_K \sim (K_L \to \pi\pi)/(K_S \to \pi\pi)$,
$\varepsilon' \sim (K_L \to \pi^+\pi^-) - (K_L \to \pi^0\pi^0)$
ε_K is indirect CP, while ε' comes from direct CP-violation in decay (found different from zero in 1999).

Kaon mixing

Kaon mixing is the prototype for FCNC transitions. It was used to predict the value of the charm mass from the value of Δm_K (Gaillard & Lee 1974).



Why CP-violation is a fundamental phenomenon ?

Because it is one of the three ingredients for baryogenesis (10^9 times more photons than baryons in the universe - vanishingly small quantities of antimatter): Sakharov 1967

1. baryon number violating interactions
2. C- and CP-violation
3. deviation from thermal equilibrium

Actually the SM interactions to be described later contain these ingredients, but in way too small quantities.

Warning: it is actually not proven that cosmological CP-violation has something to do with elementary particle physics.

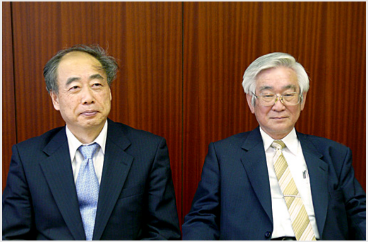
The Cabibbo-Kobayashi Maskawa matrix

Recall the diagonalization of the quadratic (mass) terms in the Yukawa Lagrangian:

$$V_{\rm CKM} \equiv V_U^\dagger V_D = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

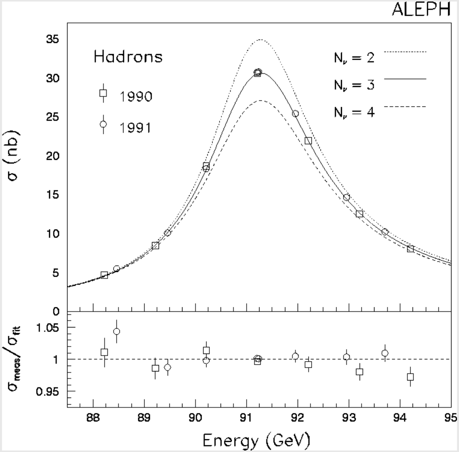
This matrix is unitary and since some of the phases can be reabsorbed into the quark fields it only has $n(n-1)/2$ mixing angles and $(n-1)(n-2)/2$ complex phases:

These phases can generate *CP*-violation ! (Kobayashi-Maskawa)



From parameter counting $n = 3$ is the minimal number of families that are needed to generate CP-violation through the KM mechanism.

It also happens that $n = 3$ is the number of massless neutrinos found at LEP, and more generally the number of observed fermion generation: is it a coincidence ?



Parametrization of the CKM matrix

With the mixing angles $\cos, \sin(\theta_{ij}) \equiv c_{ij}, s_{ij}$ the CKM matrix is the product of three 2x2 rotation matrices with one phase

$$V_{\rm CKM} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{23} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

However it will experimentally be found that $s_{12} \sim \lambda \sim 0.2$, $s_{23} \sim \lambda^2 \sim 0.04$, $s_{13} \sim \lambda^3 \sim 0.008$.

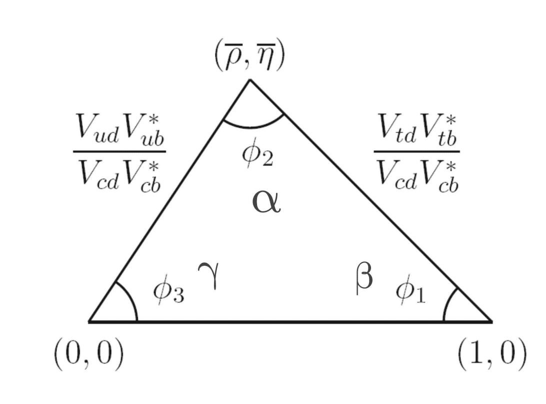
LKet us make this hierarchy explicit by defining the exact version of the Wolfenstein parametrization

$$\lambda^2 \equiv \frac{|V_{us}|^2}{|V_{ud}|^2 + |V_{us}|^2} \qquad A^2\lambda^4 \equiv \frac{|V_{cb}|^2}{|V_{ud}|^2 + |V_{us}|^2}$$

$$\bar\rho + i\,\bar\eta \equiv -\frac{V_{ud}\,V_{ub}^*}{V_{cd}\,V_{cb}^*}$$

3×3 unitarity implies six triangle relations in the complex plane; because of the λ suppression, four of these triangles are quasi-flat, and the remaining two are almost degenerate. One defines "the" Unitarity Triangle by

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



NB: $\beta, \alpha, \gamma = \phi_1, \phi_2, \phi_3$ in the Japanese notation

The Jarlskog invariant

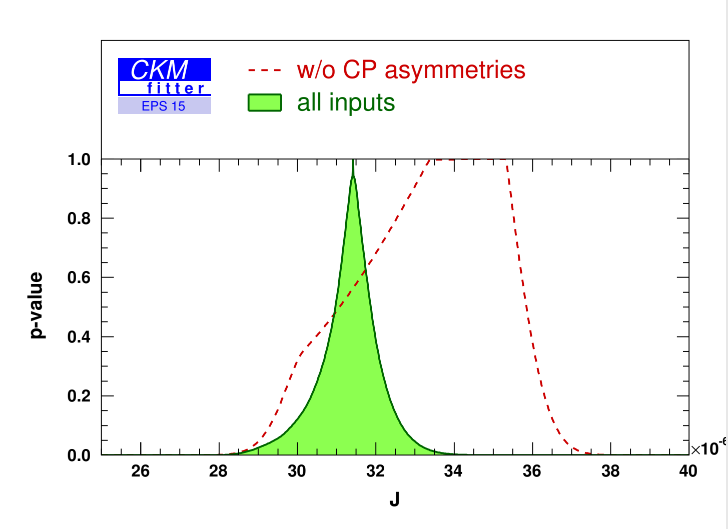
In the SM, CP violation is driven by the Jarlskog invariant

Jarlskog '85

$$\begin{aligned} \mathrm{Im}\left(V_{ij} V_{kl} V_{il}^* V_{kj}^*\right) &= J \sum_{m,n=1}^{3} \varepsilon_{ikm} \varepsilon_{jln} \\ J &= c_{12} c_{23} c_{13}^2 s_{12} s_{23} s_{13} \sin\delta \end{aligned}$$

where we see that three generation mixing ((12), (23), (13)) and CP-violating phase (δ) are necessary ingredients for CP violation.

The Jarlskog invariant is precisely known from global analyses:



The possibility to predict J from CP conserving observables only is a peculiar feature of the SM, related to the three generation KM mechanism.

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c, b and t are *heavy* with respect to the typical strong interaction scale $\Lambda \lesssim m_p \sim 1$ GeV.

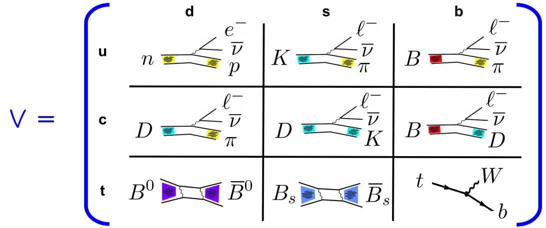
However the top quark doesn't hadronize, and the c quark is not that heavy.

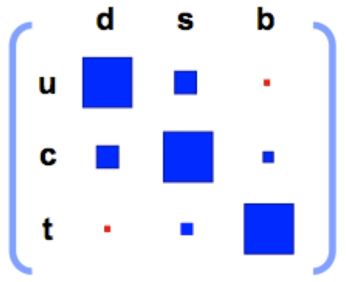
Also the b sector is the only quark sector that can involve the three generations (needed to observe CP violation) 'democratically', *i.e.* with the same Cabibbo suppression in λ.

The b system has very specific properties with respect to flavor !

Extracting CKM couplings

$$V_{\mathrm{CKM}} \equiv V_U^\dagger V_D = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$





In contrast to leptons, quarks are confined into non perturbative bound states (hadrons).

One does not measure directly the weak couplings of quarks, but rather matrix elements of quark operators taken between hadron states, that need to be calculated by means of theoretical methods.

There are however a few examples in the B meson system where one can get rid of strong interaction effects, by taking advantage of the fact that QCD conserves CP (at the 10^{-11} level).

The most beautiful example is the time-dependent CP-asymmetry in $B \to J/\psi K_S$.

$B^0 - \bar{B}^0$ mixing

B^0 and $\bar{B}^0$ have the same quantum numbers from the point of view of the weak interaction, so they mix.

Mass eigenstates

$$|B_{H,L}\rangle = p|B^0\rangle \mp q|\bar{B}^0\rangle$$

Time evolution

$$i\frac{d}{dt}\begin{pmatrix} |B^0(t)\rangle \\ |\bar{B}^0(t)\rangle \end{pmatrix} = [M - (i/2)\Gamma]\begin{pmatrix} |B^0(t)\rangle \\ |\bar{B}^0(t)\rangle \end{pmatrix}$$

In practice, both theoretically and experimentally $\Gamma_{12} \ll M_{12}$, so that the solution of the diagonalization reduces to

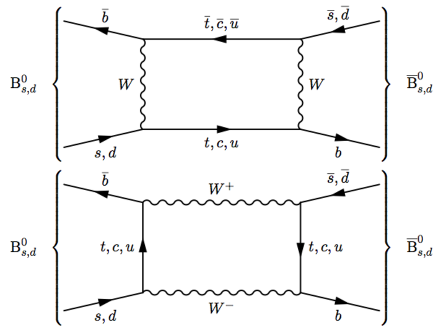
$$q/p = -\sqrt{M_{12}^*/M_{12}}$$

M_{12} is dominated by box (loop) diagrams where the top is virtual, hence

$$M_{12} \sim V_{td}^* V_{tb} \times (QCD)$$

Thus independently of the QCD matrix element, one has

$$q/p = \frac{V_{td} V_{tb}^*}{V_{td}^* V_{tb}} \simeq e^{-2i\beta}$$



Mixing-induced time-dependent CP-asymmetry

One defines

$$a_{CP}(t) = \frac{\Gamma(\bar{B}^0(t) \to f_{CP}) - \Gamma(B^0(t) \to f_{CP})}{\Gamma(\bar{B}^0(t) \to f_{CP}) + \Gamma(B^0(t) \to f_{CP})}$$
$$= \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2} \cos \Delta m t + \frac{2 \mathrm{Im} \lambda_f}{1 + |\lambda_f|^2} \sin \Delta m t$$

where

$$\lambda_f = \eta_f \frac{q}{p} \frac{\bar{A}_f}{A_f}$$

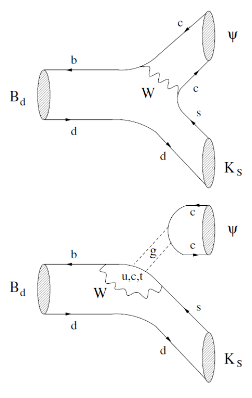
In the above expression, the coefficient of $\cos \Delta m t$ is the direct CP-asymmetry, while the $\sin \Delta m t$ is the mixing-induced one

The academic case is when the decay amplitude is dominated by a single CKM coupling, such that $A \sim V_{\rm CKM} \times {\rm QCD}$; then

$$a_{CP}(t) = {\rm Im} \left(\frac{V^*_{\rm CKM}}{V_{\rm CKM}} \right) \sin \Delta m t$$

$B_d \to J/\psi K_S$

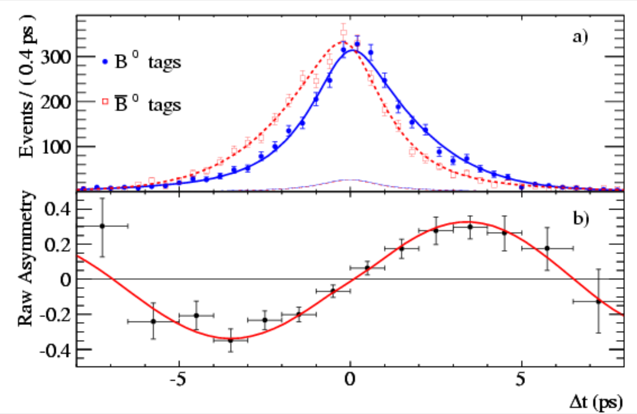
Let $B^0 \to J/\psi K_S$ interfere with $B^0 \to \bar{B}^0 \to J/\psi K_S$. The 'tree' diagram is, by far, dominant over the 'penguin' one. It is proportional to $V_{cb}V_{cs}^*$. Corrections are suppressed by both CKM ($\lambda^2 \sim 4\%$) and strong interaction effects (a few % at most).



$$
\begin{aligned}
a_{CP}(t) &= -\mathrm{Im}\left(\frac{V_{td}V_{tb}^*}{V_{td}^*V_{tb}}\right)\left(\frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}}\right)\left(\frac{V_{cs}V_{cd}^*}{V_{cs}^*V_{cd}}\right)\sin\Delta mt \\
&= \sin 2\beta \sin\Delta mt
\end{aligned}
$$

Time-dependent *CP* violation

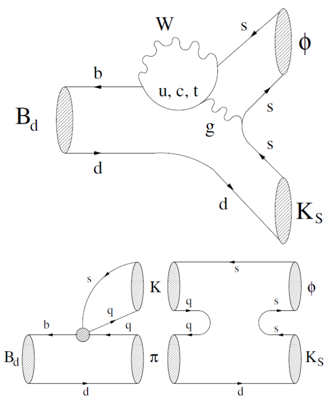
BaBar 2009



Other 'sin 2β' channels

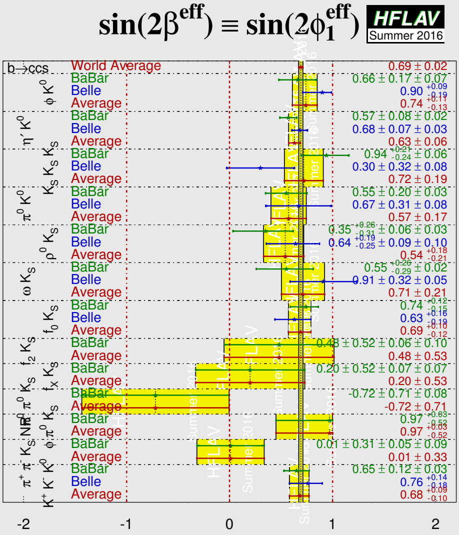
In $B \to \phi K_S$ the dominant topology is the penguin one, because of the CKM couplings. Same argument also leads to the extraction of $\sin 2\beta$ from the time-dependent *CP* asymmetry.

However hadronic corrections are typically larger than for $J/\psi K_S$.



These penguin decays are crucial for testing the SM since new particles may run in the penguin loop, with a drastic impact on the *CP*asymmetry.

Summary of sin 2β-like measurements

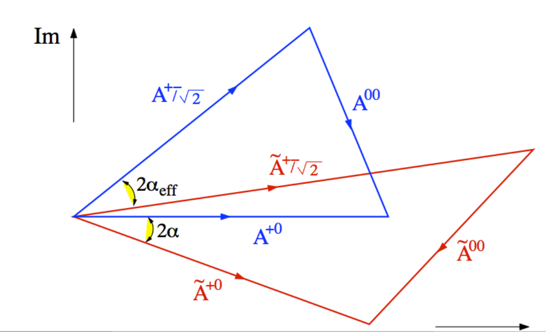


The extraction of the angle α

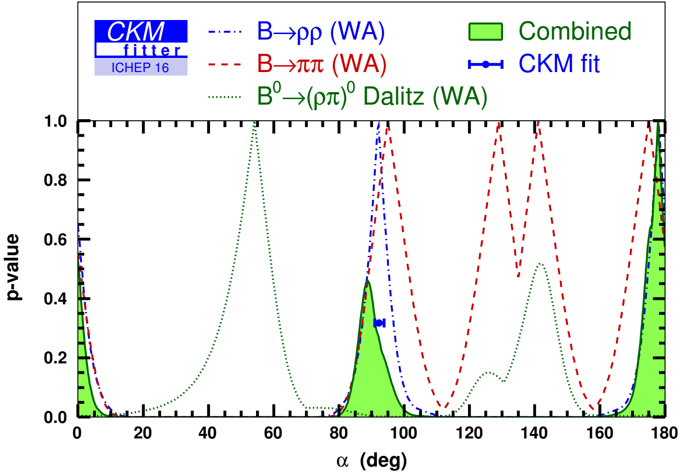
It follows the same logic but in this case subdominant penguin diagrams can reach 10% or even more, and cannot be neglected.

Instead one uses the fact that the unwanted diagrams have different isospin properties than tree diagrams, and one reconstruct α as the phase between different linear combinations of decay amplitudes. Gronau London 1990

For $B \to \pi\pi$ and $B \to \rho\rho$ there are three assignements of charges and thus three amplitudes



α Grand combination



The extraction of γ

Construct interferences between CP conjugate decay modes that differ by phase γ.
The necessary hadronic information (ratio of matrix elements) doesn't cancel but is directly taken from data (of B and/or D decays):

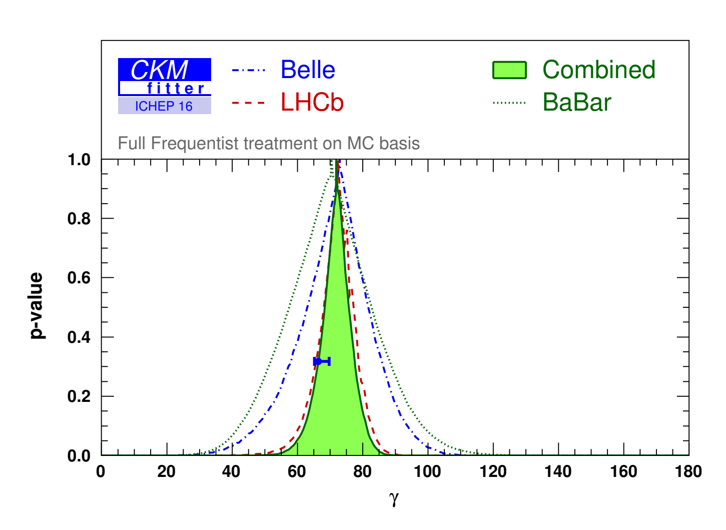
GLW: use $B^\pm \to D_{\rm CP} K^\pm$ to let $b \to c\bar{u}s$ interfere with $b \to u\bar{c}s$
Gronau, London, Wyler '91

ADS: use $B^\pm \to (D^0, \overline{D}^0) K^\pm \to (K^+\pi^-)K^\pm$ that is
$(b \to c\bar{u}s) \times (c \to d\bar{u}s)$ vs. $(b \to u\bar{c}s) \times (\bar{c} \to \bar{s}u\bar{d})$
Atwood, Dunietz, Soni '96

GGSZ: use instead three body decay of D, that is either described by a resonance (isobar) model, or by a binned Dalitz plot analysis
Giri, Grossman, Soffer, Zupan '03; Bondar, Poluetkov '05

Many variants (D^*, K^*, more particles in the final state...).

γ Grand combination



γ (direct) $= (72.1^{+5.4}_{-5.8})^\circ$ vs. γ (indirect) $= (65.33^{+0.96}_{-2.54})^\circ$

QCD driven extraction of CKM couplings

Beyond UT angles, most of the time the flavor observables depend non trivially on both the CKM couplings (weak part) and the QCD matrix elements (strong part).

When working at low energies (wrt the weak scale) the first step is to use the Operator Product Expansion to simplify the computation.

W-mediated product of two currents

$$g^2 \int d^4x\, J_\mu(0) D_W^{\mu\nu}(x) J_\nu(x)$$

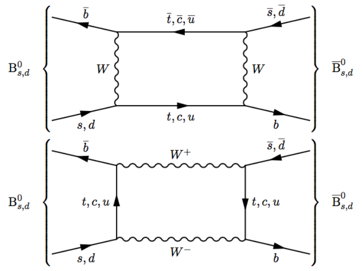
with the propagator

$$D_W^{\mu\nu}(x) = \int d^4q\, e^{iqx} \frac{ig^{\mu\nu}}{q^2 - m_W^2 + i\epsilon}$$

In the low energy limit $q^2 \ll m_W^2$ one recovers the Fermi interaction

$$\frac{g^2}{m_W^2} J^\mu(0) J_\mu(0)$$

The $\Delta B = 2$ SM operator



$$\sim (V^*_{td}V_{tb})^2\langle\bar{B}^0|\bar{b}\gamma^\mu(1-\gamma_5)d\bar{b}\gamma_m u(1-\gamma^5)d|B^0\rangle \sim (V^*_{td}V_{tb})^2(m_B)^2 f_B^2 B_B^2$$

where f_B is the B decay constant and B_B is the bag factor, both of them being complicated non perturbative quantities

The calculation of this kind of QCD matrix elements is a field of research by itself; actually the particular structure of the weak interaction generate a variety of operators (Dirac and Lorentz structures) that do not appear in purely strong interaction processes.

Global constraints on the CKM matrix

Goal: determine the value of the fundamental coupling constants from the measurement of experimental observables.

In order to be conservative when testing the Standard Model, one uses as experimental and theoretical inputs only the ones one thinks are well understood quantitatively.

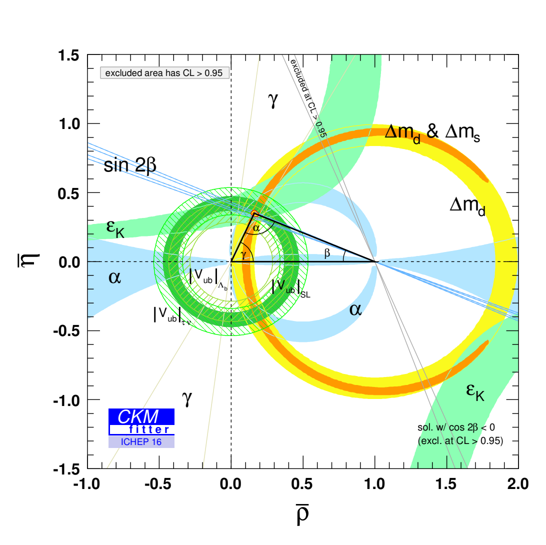
A global statistical analysis is performed, with the best possible treatment of experimental and theoretical errors; for the latter, a model has to be defined and used.

Here the results by the CKMfitter group, based on the frequentist approach, are presented.

The main physical ingredients are the following

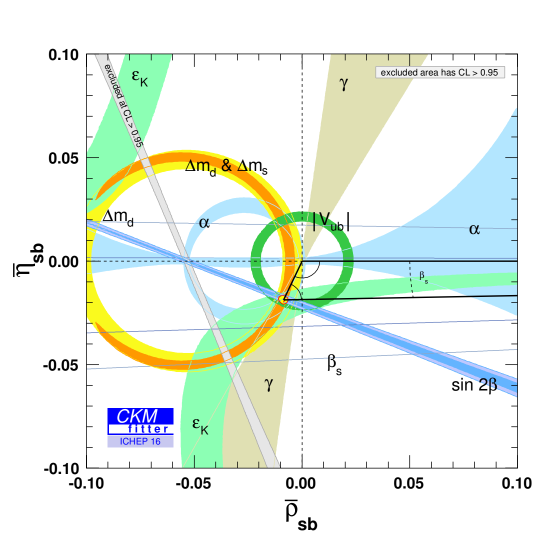
- $|V_{ud}|$, $|V_{us}|$, $|V_{cb}|$ and $|V_{ub}|$ from the relevant charged current, tree level weak decays; the needed strong interaction parameters are taken from Lattice QCD or other methods where necessary
- Δm_{ds} from $B_{d,s} - \bar{B}_{d,s}$ oscillation measurements and Lattice QCD
- the CP-violating angles α, β, γ from the corresponding experimental analyses; very little theoretical input is needed here
- the CP-violating asymmetry ε_K, the interpretation of which depends on the $K - \bar{K}$ mixing parameter B_K computed on the lattice

The global CKM analysis in the B_d UT plane



all constraints together

The global CKM analysis in the B_s UT plane



all constraints together

The global CKM analysis

Wolfenstein parameters from the fit

$$A = 0.8250^{+0.0071}_{-0.0111}(1\%) \qquad \lambda = 0.22509 \pm 0.00029(0.1\%)$$

$$\bar{\rho} = 0.1598^{+0.0076}_{-0.0072}(5\%) \qquad \bar{\eta} = 0.3499^{+0.0063}_{-0.0061}(2\%)$$

Clearly the big picture is that the CKM couplings are the dominant contribution to the physical flavor transitions, whereas the KM phase is the dominant contribution to *CP*-asymmetries.

More accurate tests can be done by comparing the indirect fit prediction for a given quantity, with its direct determination (experimental measurement or theoretical calculation).

example: $\sin 2\beta$ in 2001

indirect prediction $0.50 < \sin 2\beta < 0.86$

first measurements $\sin 2\beta_{\mathrm{BaBar}} = 0.59 \pm 0.14 \pm 0.05$,
$\sin 2\beta_{\mathrm{Belle}} = 0.99 \pm 0.14 \pm 0.06$

now

indirect prediction $\sin 2\beta = 0.740^{+0.020}_{-0.025}$

World Average measurement $\sin 2\beta = 0.699 \pm 0.017$

Pull values for the CKM observables