Flavor Physics and CP Violation

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Plan of the lectures

Lecture 1. Standard Model

What is flavor?
Flavor structure of the Standard Model (SM)
Glashow-Iliopoulos-Maiani (GIM) mechanism
Standard Model flavor problem
Tests of the Standard Model flavor and CP structure

Lecture 2. Effective theories beyond the Standard Model

Why to go beyond the Standard Model. TeV scale New Physics (NP)
The New Physics flavor problem
Testing high scale New Physics using flavor
The Minimal Flavor Violation (MFV) ansatz

Lecture 3. New Physics models

New Physics models and flavor implications
Prospects for the discovery of New Physics using flavor transitions at high energy:
Top flavor chaging decays
Higgs flavor changing decays

A few comments to start

Disclaimer: Some topics I will not cover:

- Lattice QCD
- Strong CP problem
- CP violation and baryogenesis

I will only mention:

- Neutrino flavor. Lectures of S. Petcov, September 12-14

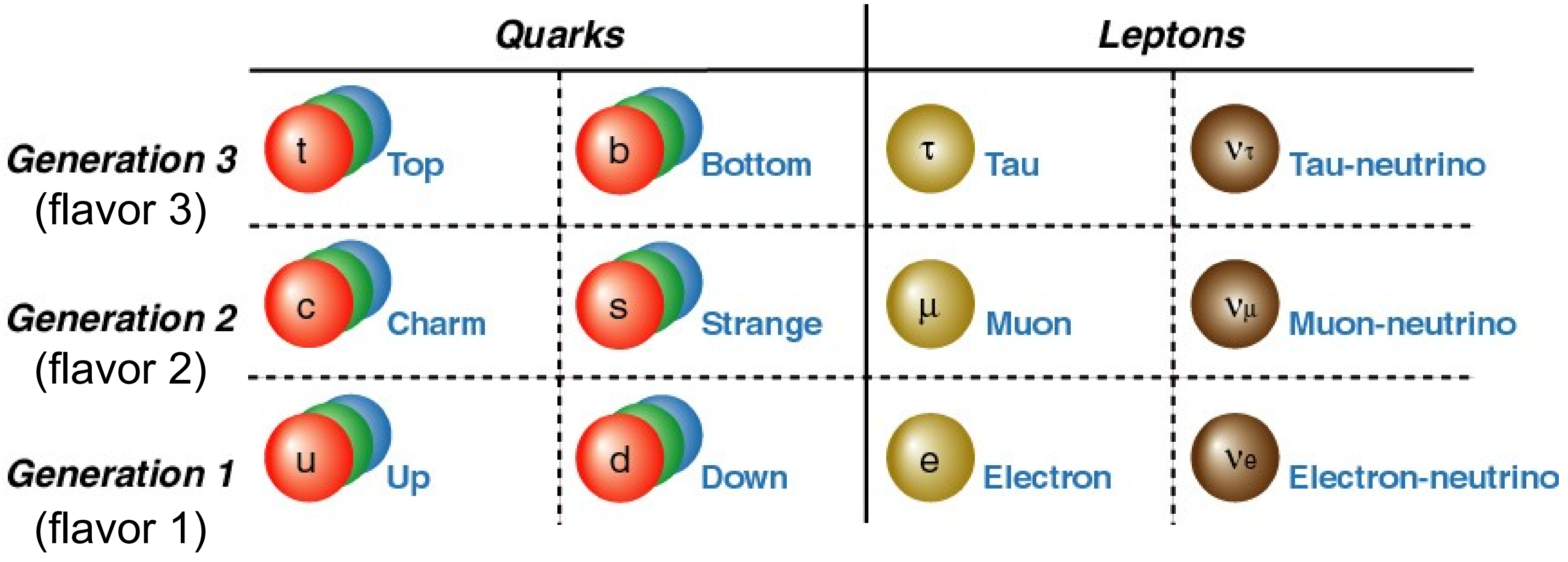
I will cover only the main ideas.
For more details, there are reviews and books:

- Y. Nir, arXiv: hep-ph/0510413;
- O. Gedalia and G. Perez, TASI 2009 Lectures - Flavor Physics," arXiv:1005.3106 [hep-ph].
- Z. Ligeti, TASI Lectures on Flavor Physics," arXiv:1502.01372 [hep-ph].
- G. Branco, L. Lavoura and J. Silva, CP Violation, Clarendon Press, Oxford, UK (1999)
- ...

Please ask questions!

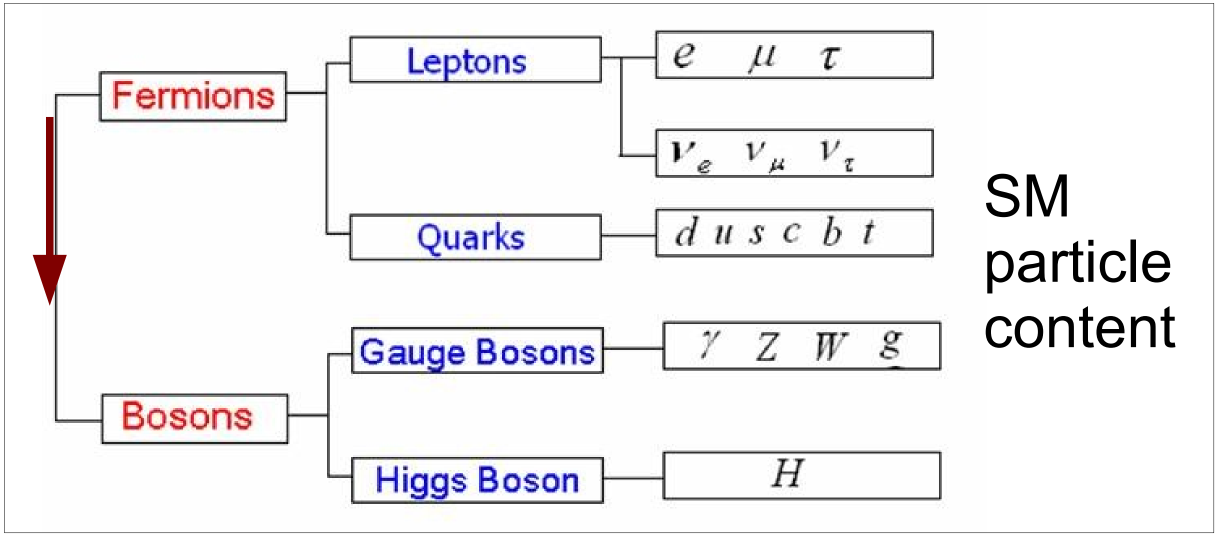
What is flavor?

Physics of the three generation Standard Model (SM) quarks and leptons



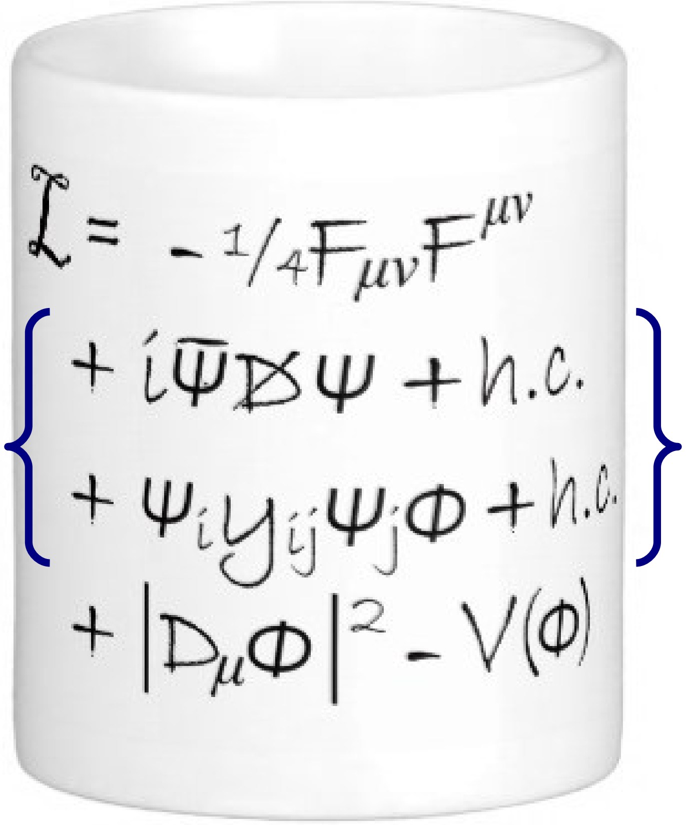
	Quarks		***Leptons***	
Generation 3 (flavor 3)	t Top	b Bottom	τ Tau	ν_τ Tau-neutrino
Generation 2 (flavor 2)	c Charm	s Strange	μ Muon	ν_μ Muon-neutrino
Generation 1 (flavor 1)	u Up	d Down	e Electron	ν_e Electron-neutrino

How do they interact with the other particles of the SM (and with New Physics particles (see 3rd lecture))?



SM particle content

The SM Lagrangian



$$\begin{aligned} \mathcal{L} = &-{}^{1}\!/_{4}F_{\mu\nu}F^{\mu\nu} \\ &\left\{ \begin{array}{l} + i\bar{\Psi}\not{D}\Psi + h.c. \\ + \Psi_i y_{ij}\Psi_j\Phi + h.c. \end{array} \right\} \\ &+ |D_\mu\Phi|^2 - V(\Phi) \end{aligned}$$

Flavor and the Proliferation of Parameters

$$-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$
$$i\bar{\Psi}\not{D}\Psi + h.c.$$

- Describes the gauge interactions of quarks and leptons

- Parametrized by 3 gauge couplings g_1, g_2, g_3

- Stable with respect to quantum corrections

- Highly symmetric

$$+|D_\mu\Phi|^2 - V(\Phi)$$

- Breaks electro-weak symmetry and gives mass to the $W^\pm$ and Z bosons

- 2 free parameters:
Higgs mass
Higgs vev

- Not stable with respect to quantum corrections

$$+\Psi_i y_{ij}\Psi_j\Phi + h.c.$$

- Leads to masses and mixings of the quarks and leptons

- 10+10 free parameters in the quark+lepton sector (12 in the lepton sector in case of Majorana masses)

- Stable with respect to quantum corrections

The gauge sector and flavor symmetries

$$-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

$$i\bar{\Psi}\not{D}\Psi + h.c.$$

Fermion representations under SU(3) × SU(2) × U(1):

$$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} = (3,2,1/6),\ u_R = (3,2,2/3),\ d_R = (3,1,-1/3)$$

$$L_L = \begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix} = (1,2,-1/2),\ e_R = (1,1,-1)$$

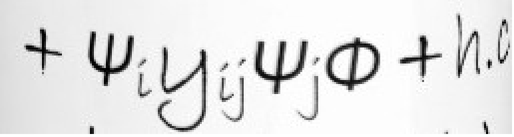
Flavor index

3 identical replica of the basic fermion family: $\sum_{\psi=Q_L,u_R,d_R,L_L,e_R} \sum_{i=1,2,3} \bar{\psi}_i \not{D} \psi_i$

The gauge Lagrangian is invariant under 5 independent U(3) global rotations for each of the 5 independent fields: $U(3)^5$ global symmetry

$$U(1)_L \times U(1)_B \times U(1)_Y \times U(1)_{PQ} \times U(1)_e \times$$
$$\times SU(3)_Q \times SU(3)_U \times SU(3)_D \times SU(3)_L \times SU(3)_e$$

The Higgs-flavor sector



$+\psi_i y_{ij} \psi_j \Phi + h.c$

$$\bar{Q}^i_L Y^{ij}_D d^j_R \Phi + \bar{Q}^i_L Y^{ij}_U u^j_R \tilde{\Phi} + \bar{L}^i_L Y^{ij}_E e^j_R \Phi + h.c.$$

$$\Phi = (1,2,1/2),\ \tilde{\Phi} = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \Phi^*$$

The Y are not hermitian

→ They are diagonalized by bi-unitary transformations

After Electroweak Symmetry Breaking (EWSB): $\langle \Phi \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$, $v = 246\,\mathrm{GeV}$

Mass eigenvalues $\quad M_f^{\rm diag} = U_{fL} M_f U^\dagger_{fR},\ (f = u, d)$

Mass eigenstates $\quad f_{Li} = U^{ij}_{fL} f^I_{Lj},\ f_{Ri} = U^{ij}_{fR} f^I_{Rj}$

Mass matrices diagonalized by different transformations for u_L and d_L, which are part of the same $SU(2)_L$ doublet, Q_L

CKM matrix

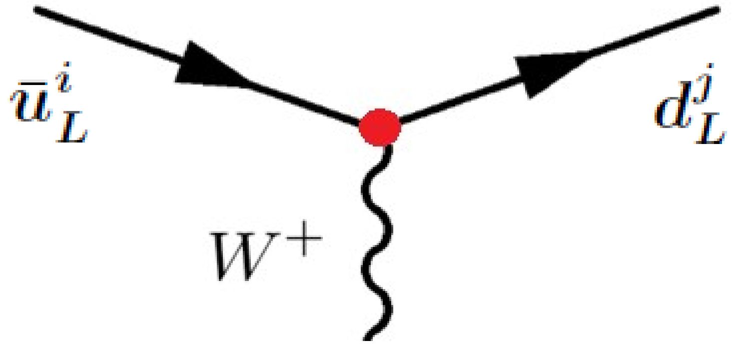
$$\begin{pmatrix} u^I_{Li} \\ d^I_{Li} \end{pmatrix} = (U^\dagger_{uL})_{ij} \begin{pmatrix} u_{Lj} \\ (U_{uL} U^\dagger_{dL})_{jk} d_{Lk} \end{pmatrix}$$

CKM matrix and the quark interactions

Cabibbo-Kobayashi-Maskawa

Interactions with the W boson:

$$-\frac{g}{2}\bar{Q}_{Li}\gamma^\mu W^a_\mu \tau^a Q_{Li} + h.c. \xrightarrow{u,d\ \text{mass-basis}} -\frac{g}{\sqrt{2}}(\bar{u}_L, \bar{c}_L, \bar{t}_L)\gamma^\mu W^+_\mu V \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + h.c.$$



Not to get confused: this mixing originates only from the Higgs sector: $V_{ij} \rightarrow \delta_{ij}$ if we switch-off the Yukawa interactions

Exercise: prove that neutral γ, Z and g currents stay flavor universal, since they don´t mix the chiralities

Interactions with the Higgs:

With (only) one Higgs doublet, the mass matrix is aligned with the Yukawa

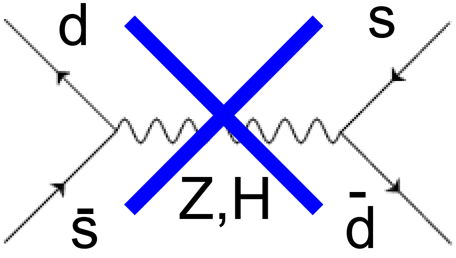
$$\mathcal{L}_m \sim Y v \bar{d}_L d_R, \quad \mathcal{L}_{\text{int}} \sim Y H \bar{d}_L d_R$$

With two doublets...see later (lecture 3)

Flavor Changing Neutral Currents (FCNCs)

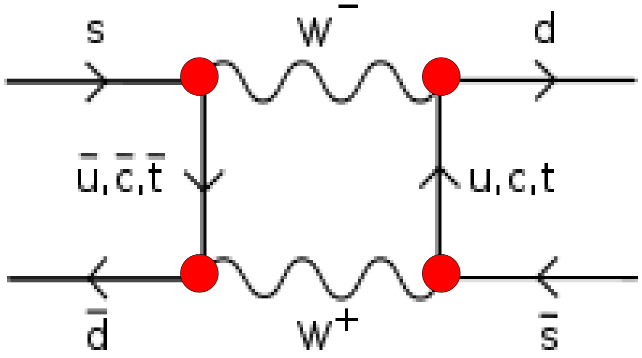
What did we learn?

In the SM, there are no FCNCs at the tree level



(example for Kaon mixing)

Only loop mediated processes with charged interactions



(example for Kaon mixing)

The CKM matrix (parametrization)

The standard parametrization of the CKM matrix

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$
$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -s_{23}c_{12} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$ $(i, j = 1, 2, 3)$

Wolfenstein parametrization λ ~ 0.23 (Cabibbo angle)

$$V = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\varrho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \varrho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$A,\ \varrho,\ \eta = \mathcal{O}(1)$

Counting of the free parameters:
3 real parameters (rotational angles) + 1 complex phase (CP violation (CPV))
+ 6 physical masses   Exercise: check this is true

Why CP violation (CPV)

How to simply understand why a physical phase in the Yukawa couplings means CP violation?

$$Y_D^{ij}\bar{Q}_{Li}\Phi D_R^j + h.c. = Y_D^{ij}\bar{Q}_{Li}\Phi D_R^j + Y_D^{ij*}\bar{D}_R^j\Phi^\dagger Q_{Li}$$

Under CP:

$$Y_D^{ij}\bar{D}_R^j\Phi^\dagger Q_{Li} + Y_D^{ij*}\bar{Q}_{Lj}\Phi D_R^i$$

CP is conserved if $Y_D^{ij} = Y_D^{ij*}$

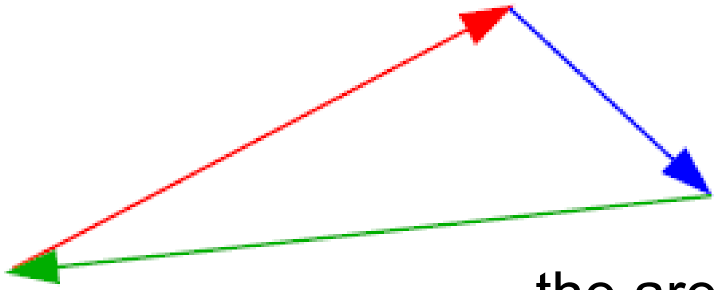
Having a phase $\longrightarrow$ CP violation (the only source of CP violation in the SM (excluding the CP strong phase)

Not a full proof, since there is still a basis choice...

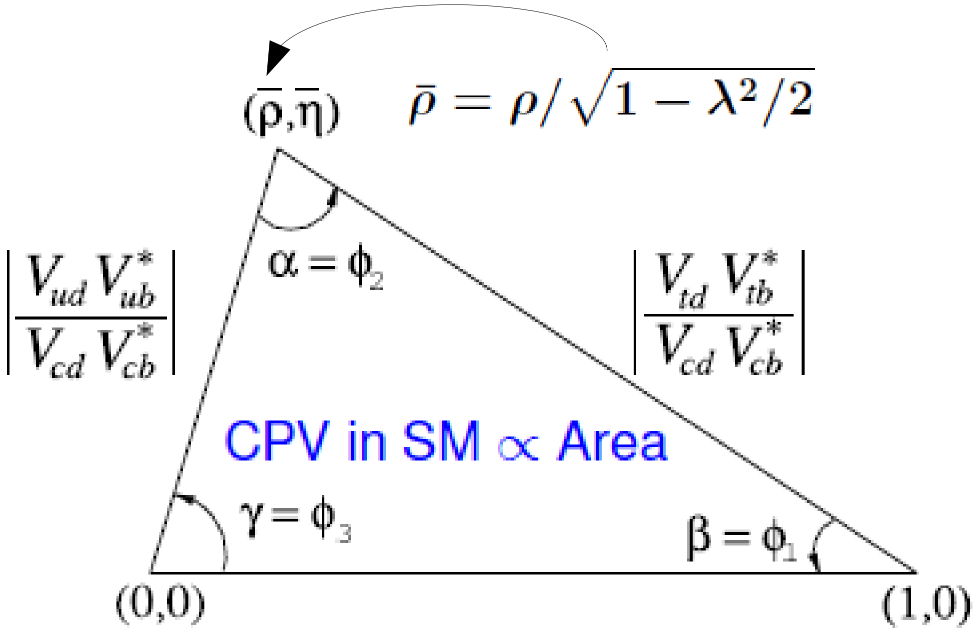
Properties of the CKM matrix

It is unitary: $V_{a1}(V^{+})_{1b} + V_{a2}(V^{+})_{2b} + V_{a3}(V^{+})_{3b} = 0$

6 unitary triangles:



the area of these triangles is:
- always the same
- zero in absence of CP violation



CPV in SM $\propto$ Area

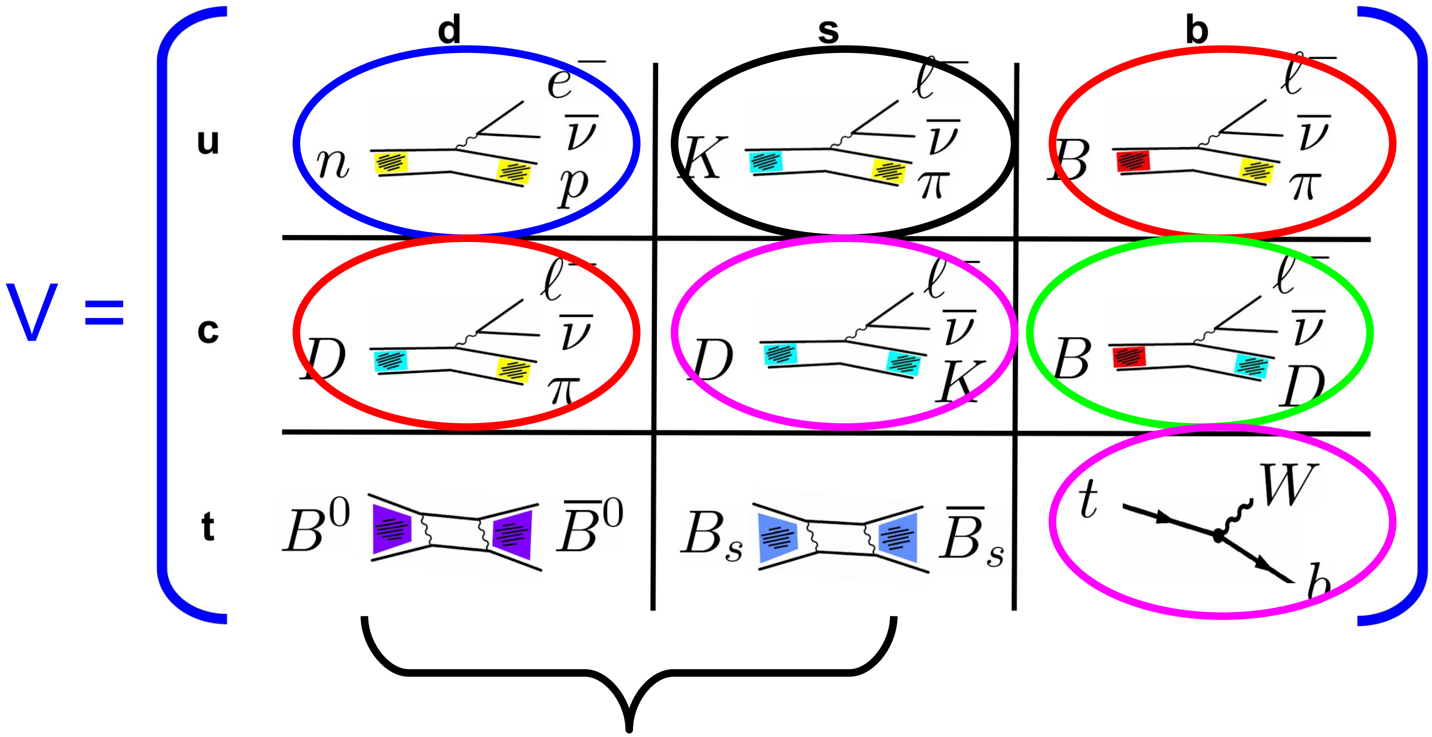
the most stringent test is provided by

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

Goal:

Overconstrain sides and angles by many measurements sensitive to different short distance physics

Extracting the CKM parameters



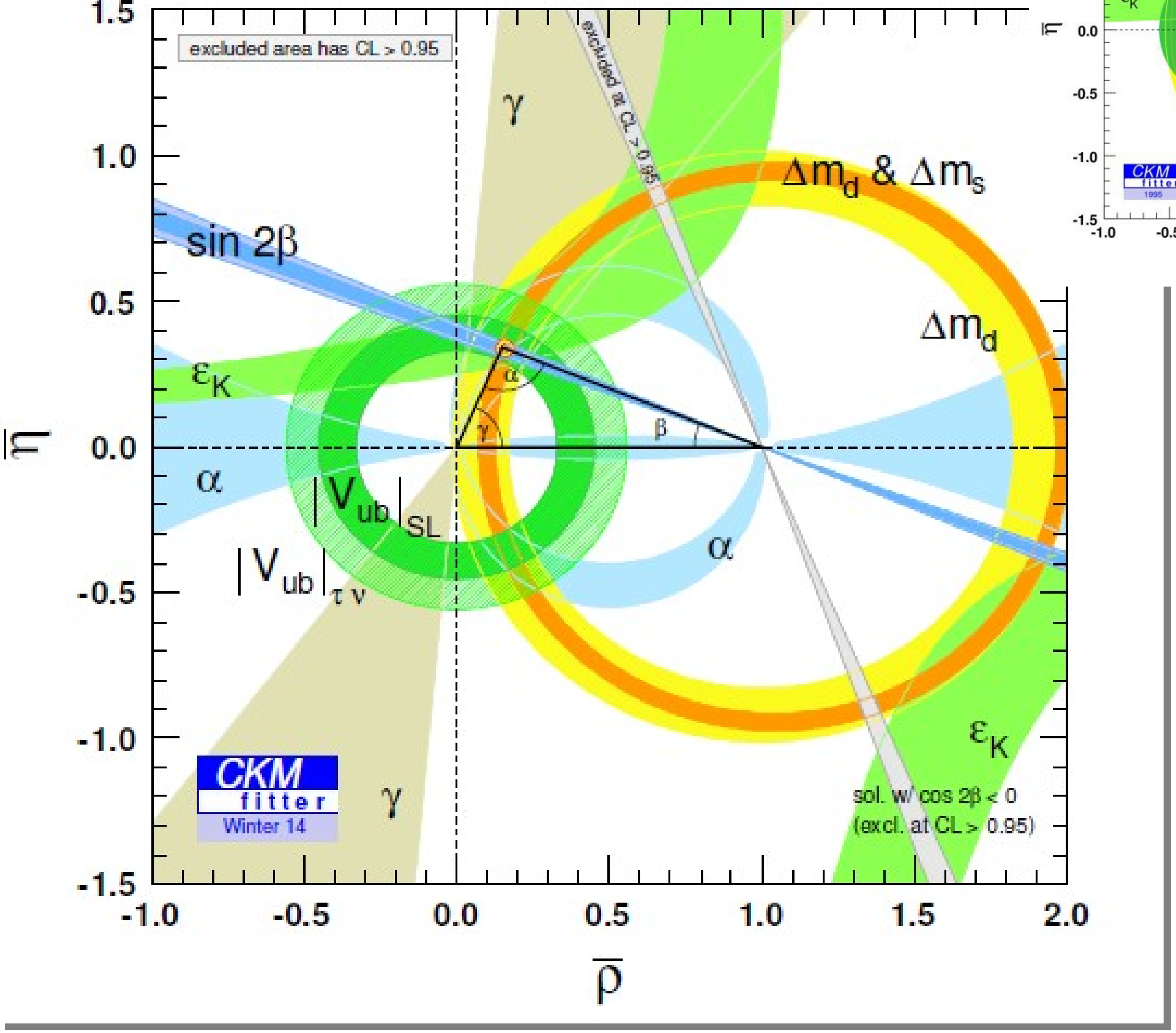
Only two not accessible
at the tree level

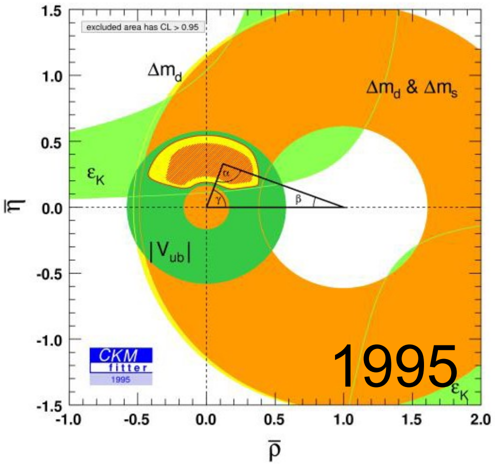
Excellent determination (error ~ 0.01 %)
Very good determination (error ~ 0.1%)
Good determination (error ~ 2 %)
Sizable error (5-15 %)
Not competitive with unitarity constraints

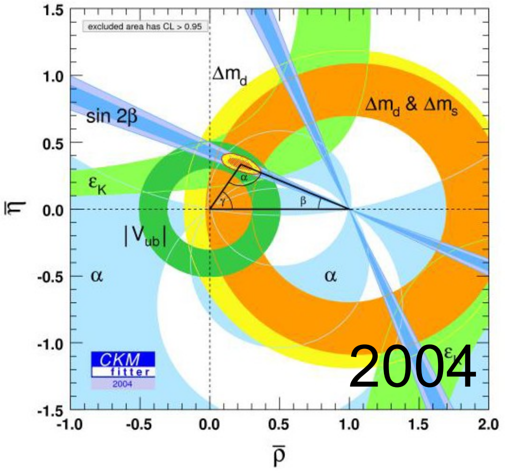
Experimental feasibility and theoretical cleanliness are the key ingredients
work our way around QCD
(We calculate with quark, but we measure hadrons!)

Experimental tests (latest results)

http://ckmfitter.in2p3.fr/







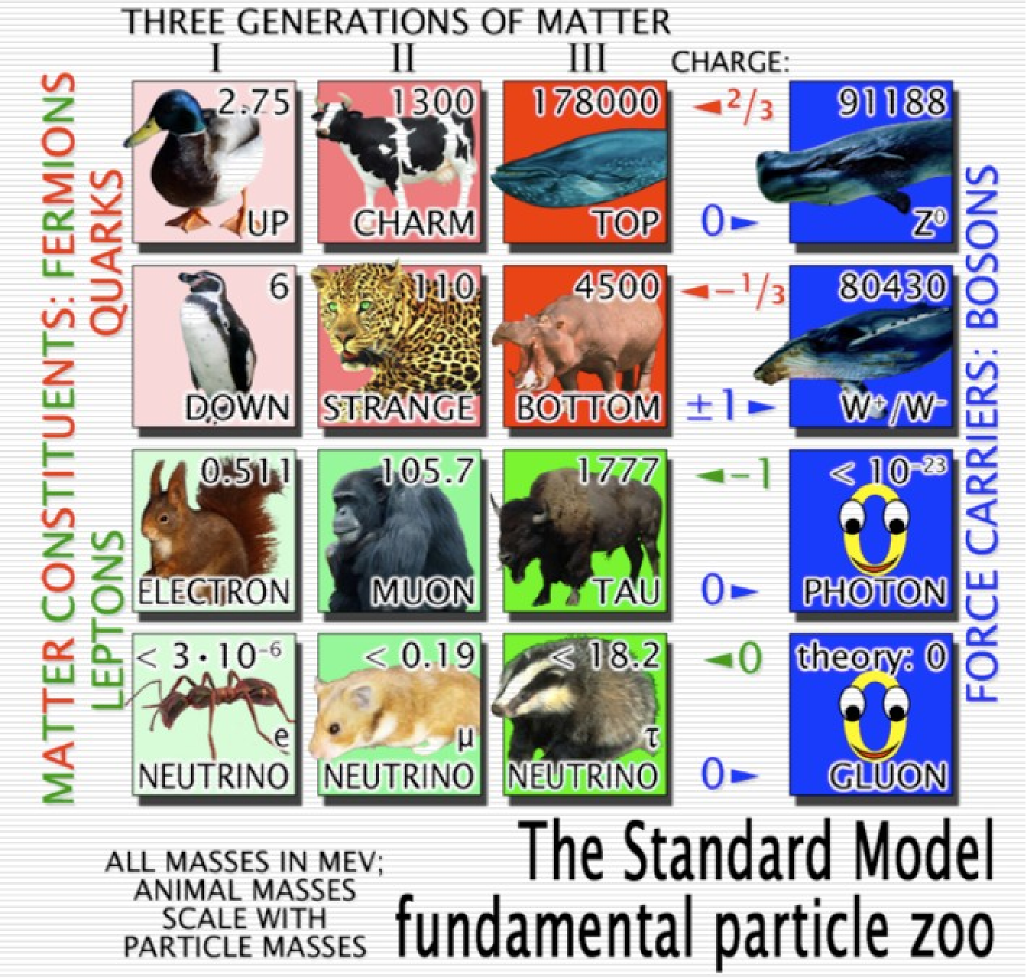
$$A = 0.813^{+0.015}_{-0.027}$$
$$\lambda = 0.2255^{+0.0007}_{-0.0003}$$
$$\bar\rho = 0.149^{+0.016}_{-0.008}$$
$$\bar\eta = 0.342^{+0.013}_{-0.011}$$
(68% CL)

See also
http://www.utfit.org/UTfit/

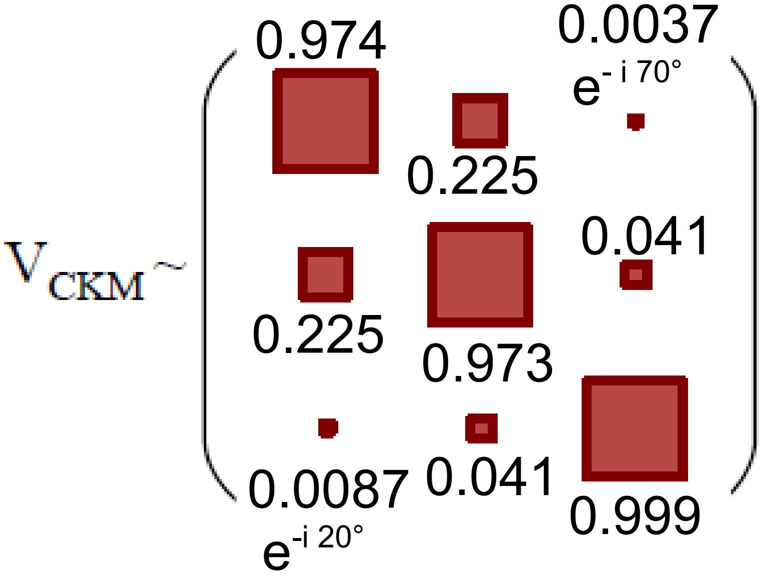
Remarkable success of the CKM picture

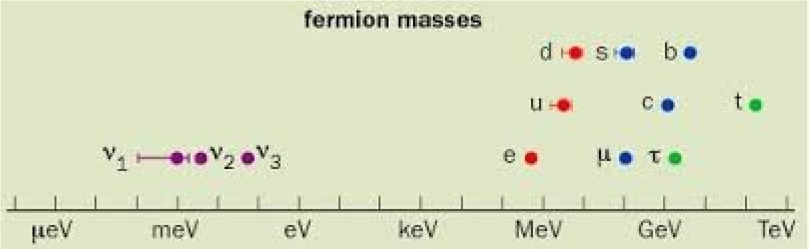
The SM flavor problem

Measurements tell us that:



E.Lunghi





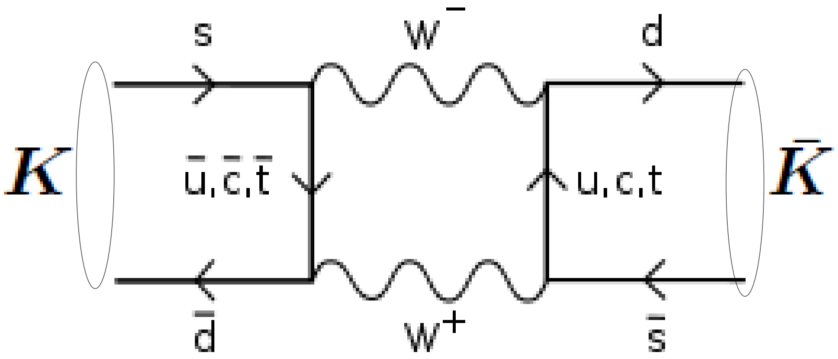
Reminder for the gauge couplings: $g_1 \sim 0.35$; $g_2 \sim 0.65$; $g_3 \sim 1.2$

This structure does not seem accidental. New dynamics?

Kaon mixing and the GIM mechanism

S. L. Glashow, J. Iliopoulos and L. Maiani, Phys. Rev. D 2, 1285 (1970).

We have learned that flavor changing neutral processes are suppresed by ~1/(16π^2) in the SM (loop suppression). But not only...



(Kaon mixing)

$$\mathcal{A} \sim \frac{1}{16\pi^2} \sum_{ij} V_{is} V_{id}^* V_{js} V_{jd}^* f(m_i, m_j)$$

ij = u,c,t

Loop function

- The mass-independent part cancels thanks to the unitarity of the CKM matrix.
- The leading term will have a further mass suppression: $f \sim m_i^2/m_W^2$

In summary: suppression by

- Loop
- CKM elements
- Mass ratios

Meson mixing (generalities)

Two quark bound state

D mesons: $|u\bar{c}\rangle, |\bar{u}c\rangle$ (M~ 1.9 GeV)
Kaons: $|s\bar{d}\rangle, |\bar{s}d\rangle$ (M~ 0.5 GeV)
B mesons: $|(s,d)\bar{b}\rangle, |(\bar{s},\bar{d})b\rangle$ (M ~ 5.3 GeV)

Let´s focus now on B_d mixing: $\psi(t) = \begin{pmatrix} B_d(t) \\ \bar{B}_d(t) \end{pmatrix}$

$$\begin{aligned} CP(B_d) &= \bar{B}_d \\ CP(\bar{B}_d) &= B_d \end{aligned}$$

Time evolution

$$\hat{H} = \hat{M} - i\frac{\hat{\Gamma}}{2} = \begin{pmatrix} M - i\Gamma/2 & M_{12} - i\Gamma_{12}/2 \\ M_{12}^* - i\Gamma_{12}^*/2 & M - i\Gamma/2 \end{pmatrix}$$

Hermitian and with positive eigenvalues

$$i\frac{d\psi(t)}{dt} = \hat{H}\psi(t) \Rightarrow \psi(t) = e^{-i\hat{H}t}\psi(0)$$

Counting the degrees of freedom:
4 CP conserving and 1 phase

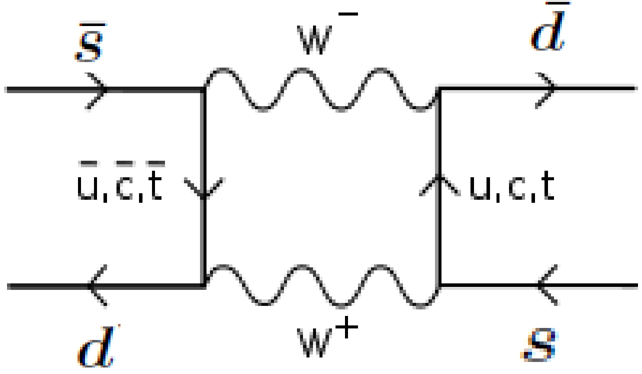
If we define $Q = \sqrt{\left(M_{12} - i\frac{\Gamma_{12}}{2}\right)\left(M_{12}^* - i\frac{\Gamma_{12}}{2}^*\right)} \sim |M_{12}| + \cdots$ (only valid for B mixing)

2 mass (and width) eigenstates with

$$\begin{aligned} |B_{H,L}\rangle &= p|B_d\rangle \mp q|\bar{B}_d\rangle \\ \frac{q}{p} &= -\frac{2M_{12}^* - i\Gamma_{12}^*}{\Delta m - \frac{i}{2}\Delta\Gamma} \end{aligned}$$

Mass $M_{H,L} = M \pm \mathrm{Re(Q)}$
Width $\Gamma_{H,L} = \Gamma \mp 2\mathrm{Im(Q)}$

Meson mixing (SM predictions)



$$x_t = \frac{m_t^2}{m_W^2}$$

Formalism of effective Hamiltonians:

$$\mathcal{H}_{\Delta B=2} = \frac{G_F^2}{16\pi^2} m_W^2 (V_{tb}^* V_{td})^2 S_0(x_t) (\bar{b}\gamma_\mu(1-\gamma_5)d)^2$$

$$\langle \bar{B}_d | (\bar{b}\gamma_\mu(1-\gamma_5)d)^2 | B_d \rangle \equiv \frac{8}{3} B_B F_B^2 m_{B_d}^2$$

Exercise: show that this is the dominant contribution

The full expression, including loop corrections:

$$\Delta m_B = \frac{G_F^2}{6\pi^2} \eta_B m_{B_d} m_W^2 B_B F_B^2 S_0(x_t) |V_{tb} V_{td}^*|^2$$

For the Kaon system, we cannot neglect the other contributions:

$$\Delta m_K = \frac{G_F^2}{6\pi^2} m_K m_W^2 B_K F_K^2 \left| \eta_1 S_0(x_c) (V_{cs} V_{cd}^*)^2 + \right.$$
$$\left. \eta_2 S_0(x_t) (V_{ts} V_{td}^*)^2 + 2\eta_3 S_0(x_c, x_t) (V_{cs} V_{cd}^*)(V_{ts} V_{td}^*) \right|$$

CP violation in the meson system

Let us consider now a meson decay.

We define the decay amplitudes to the final state f

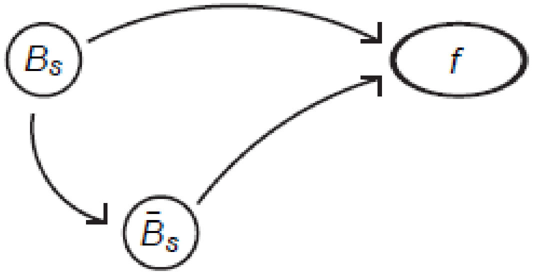
$$\mathcal{A}_f = \langle f|\mathcal{H}|B\rangle, \ \bar{\mathcal{A}}_f = \langle f|\mathcal{H}|\bar{B}\rangle$$

In general, there are 3 types of CP violation in meson decays:

(i) CP violation in mixing, when the two neutral mass eigenstate admixtures cannot be chosen to be CP-eigenstates

(ii) CP violation in decay, when the amplitude for a decay and its CP-conjugate process have different magnitudes;

(iii) CP violation in the interference of decays with and without mixing, which occurs in decays into final states that are common to B and $\bar{B}$



(i) CP violation in mixing

Reminder from
3 slides ago:

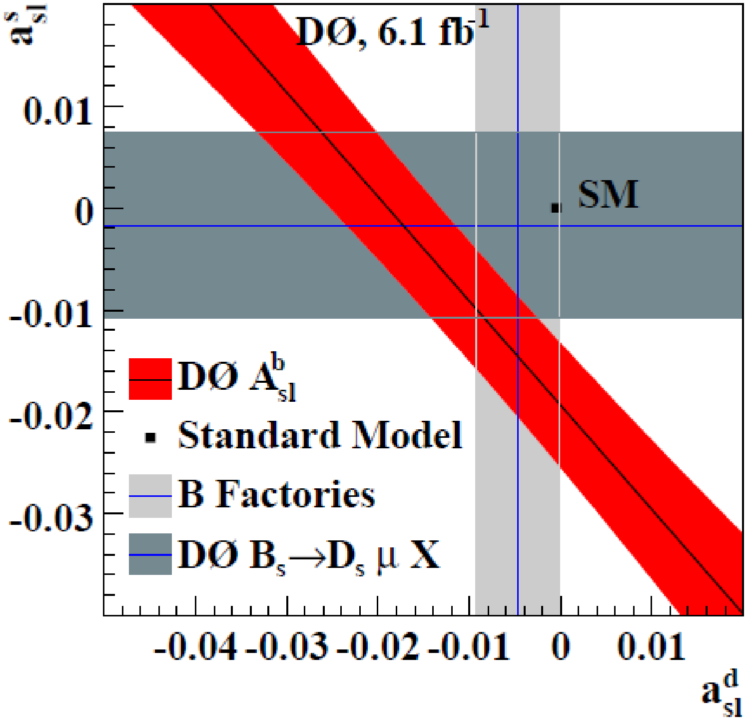
$$|B_{H,L}\rangle = p|B_d\rangle \mp q|\bar{B}_d\rangle$$
$$\frac{q}{p} = -\frac{2M_{12}^* - i\Gamma_{12}^*}{\Delta m - \frac{i}{2}\Delta\Gamma}$$

$$B_d = \bar{b}d,\ \bar{B}_d = b\bar{d}$$

This type of CP violation arises if |q/p|≠1

$$a_{SL} = \frac{\Gamma(\bar{B}_d(t) \to \ell^+\nu X) - \Gamma(B_d(t) \to \ell^-\bar{\nu} X)}{\Gamma(\bar{B}_d(t) \to \ell^+\nu X) + \Gamma(B_d(t) \to \ell^-\bar{\nu} X)} = \frac{1-|q/p|^4}{1+|q/p|^4}$$

One example of measurement of these asymmetries:



D0, 1007.0395

(ii) CP violation in decay

Reminder from
2 slides ago: $\mathcal{A}_f = \langle f|\mathcal{H}|B\rangle,\ \bar{\mathcal{A}}_{\bar{f}} = \langle \bar{f}|\mathcal{H}|\bar{B}\rangle$

$$\boxed{a_{f\pm} = \frac{\Gamma(B^+ \to f^+) - \Gamma(B^- \to f^-)}{\Gamma(B^+ \to f^+) + \Gamma(B^- \to f^-)} = \frac{1 - |\bar{\mathcal{A}}_{f-}/\mathcal{A}_{f+}|}{1 + |\bar{\mathcal{A}}_{f-}/\mathcal{A}_{f+}|}}$$

This type of CP violation arises if $|\bar{\mathcal{A}}_{\bar{f}}/\mathcal{A}_f| \neq 1$

This arises only if we have both a "CP weak" and a "CP strong" phase and more than one amplitude interfering

$$\left|\frac{\bar{A}_{\bar{f}}}{A_f}\right| = \left|\frac{\sum_i A_i e^{i(\delta_i - \phi_i)}}{\sum_i A_i e^{i(\delta_i + \phi_i)}}\right|$$

Non-zero CP asymmetries observed in few B meson decay modes (e.g. $B^+ \longrightarrow K^+ K^- K^+$ and $B^+ \longrightarrow K^+ K^- \pi^+$ @ LHCb)

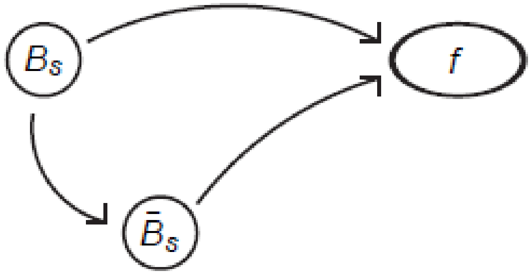
(iii) CP violation in the interference

Reminder from 3 slides ago: $\lambda_{CP} \equiv \frac{q}{p}\frac{\bar{\mathcal{A}}_f}{\mathcal{A}_f}$

$$|B_{H,L}\rangle = p|B_d\rangle \mp q|\bar{B}_d\rangle$$
$$\frac{q}{p} = -\frac{2M_{12}^* - i\Gamma_{12}^*}{\Delta m - \frac{i}{2}\Delta\Gamma}$$

$$\mathcal{A}_f = \langle f|\mathcal{H}|B\rangle,\ \bar{\mathcal{A}}_f = \langle f|\mathcal{H}|\bar{B}\rangle$$

Decays of mesons and anti-mesons to the same final state:



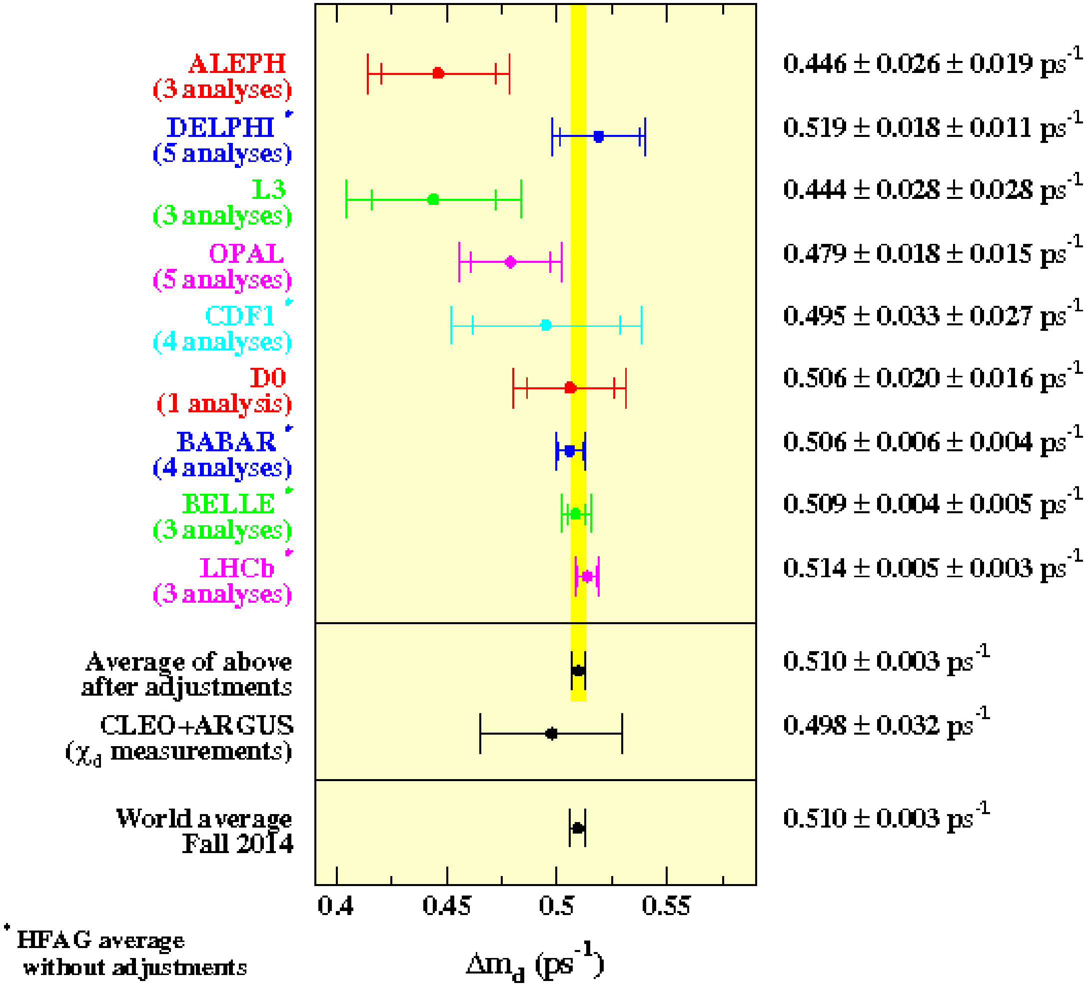
This type of CP violation arises if $|\lambda_f| = 1,\ \mathrm{Im}(\lambda_f) \neq 0$

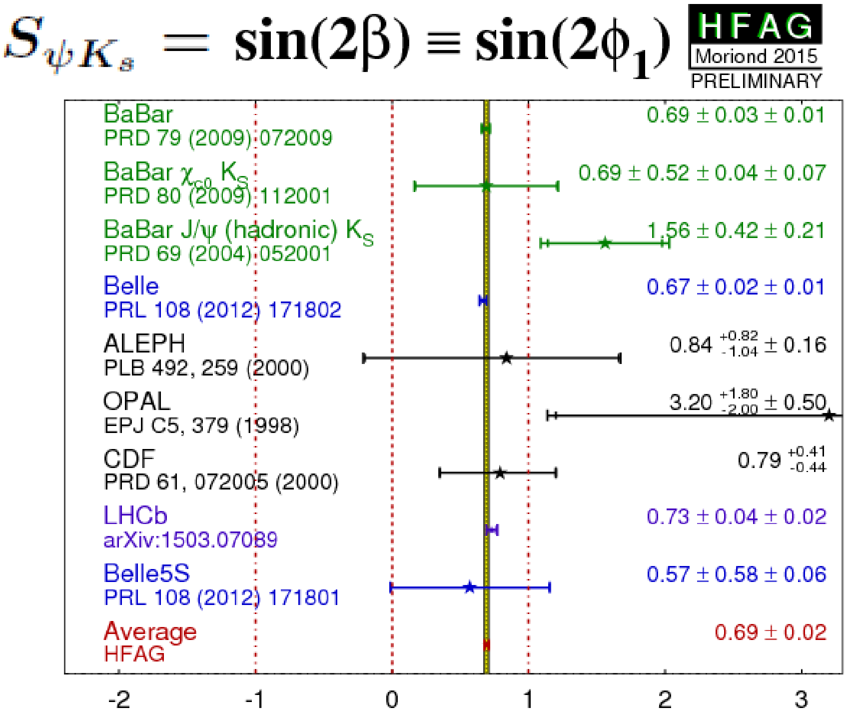
$$a_{f_{CP}} = \frac{\Gamma(\bar{B}_d(t) \to f_{CP}) - \Gamma(B_d(t) \to f_{CP})}{\Gamma(\bar{B}_d(t) \to f_{CP}) + \Gamma(B_d(t) \to f_{CP})} = -\mathrm{Im}(\lambda_{CP})\sin(\Delta m_B\, t)$$

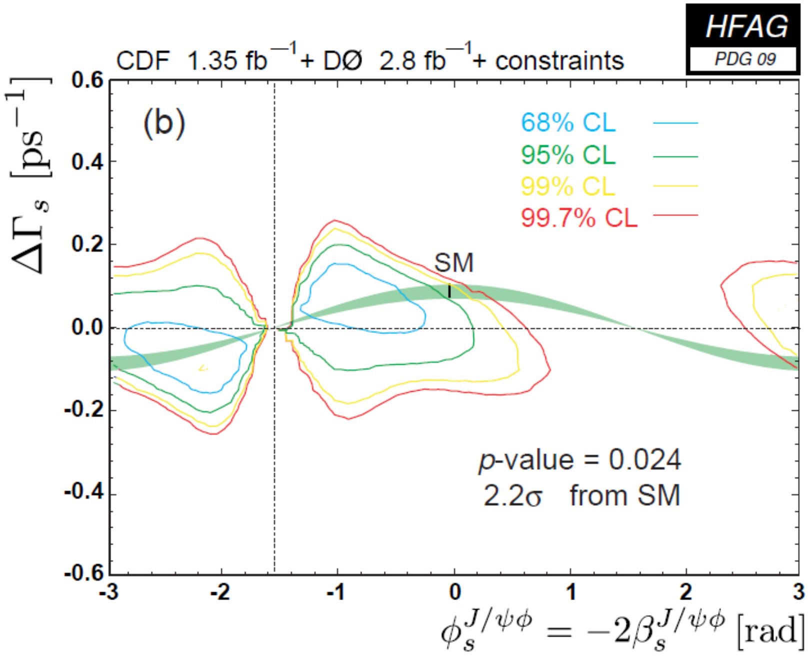
Some example of measured CP observables

$$a_{\psi K_s} = S_{\psi K_s}\sin(\Delta m_{B_d} t)$$

Experimental status

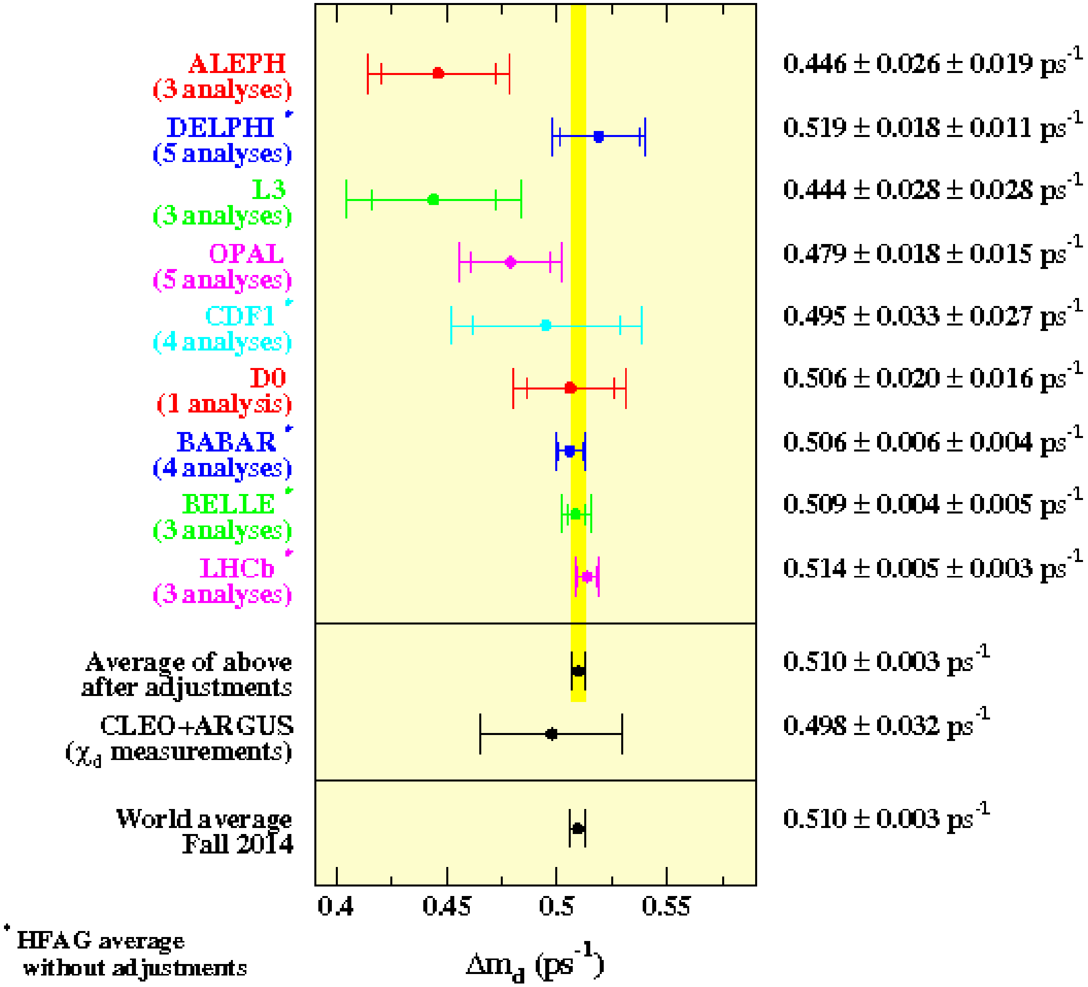


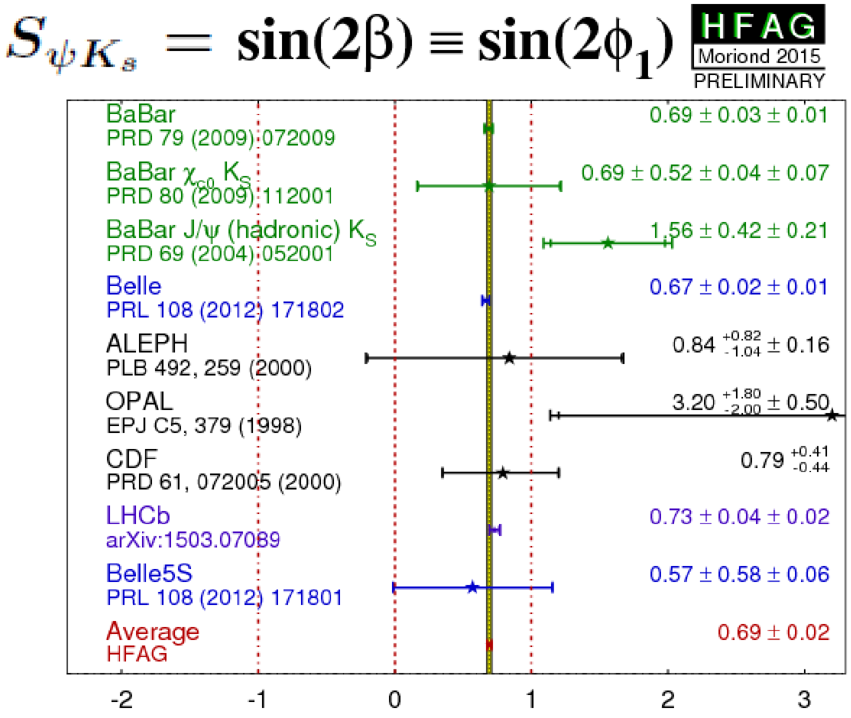


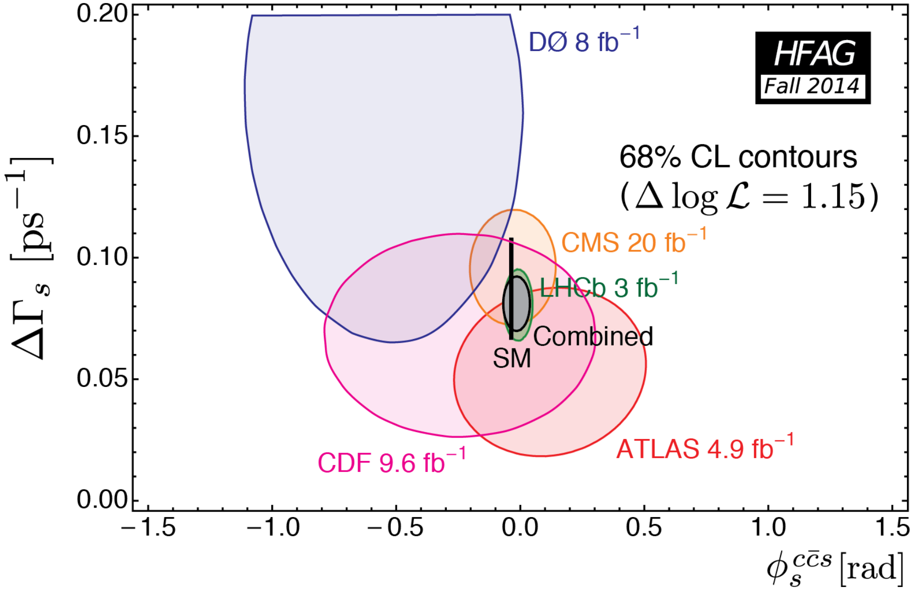


For a complete list of observables:
http://www.slac.stanford.edu/xorg/hfag/
http://pdg.lbl.gov/

Experimental status







For a complete list of observables:
http://www.slac.stanford.edu/xorg/hfag/
http://pdg.lbl.gov/

What we have learned?

- Flavor structure of the Standard Model:

  Question: what is the global flavor symmetry broken by the SM Yukawa couplings?

- Glashow-Iliopoulos-Maiani (GIM) mechanism:

  FCNCs suppressed by loops, CKM elements and quark masses.

- Standard Model flavor problem:

  new dynamic beyond the SM?

- Tests of the Standard Model flavor and CP structure:

  Meson mixing.
  Three types of CP violation.

Next:
Effective theories beyond the SM...