11th Hellenic School and Workshops on
Elementary Particle Physics and Gravity

1st School of ITN
Unification in the LHC Era

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Flavour Physics

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P L A N

Lecture 1 and 2: the quark sector

- general properties of the flavour sector in the SM
- constraints on the V_{CKM} mixing matrix:
- from CP conserving observables
- from CP violating observables
- new physics and the flavour problem

Lecture 3 and 4: neutrinos masses, mixing and oscillations

- the data
- implications on the theory

1^{st} Lecture:

QUARKS: CP CONSERVING SECTOR

general remarks

$$L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\,\overline{\Psi}\gamma^{\mu} D_{\mu}\Psi$$

gauge sector

$$+ D_{\mu}\Phi^{+} D^{\mu}\Phi - V(\Phi)$$

symmetry breaking sector

$$+ (\overline{\Psi} Y \Phi \Psi + h.c.)$$

flavour sector

$$+ L_{NP}$$

Ψ = 3 copies of $q_L = (3,2,+1/6)$ $u_R = (3,1,+2/3)$ $d_R = (3,1,-1/3)$ $l_L = (1,2,-1/2)$ $e_R = (1,1,-1)$

From the first two lines of L, fermions are massless and the 3 generations cannot be distinguished. At the classical level this part of L has a $U(3)^5$ global symmetry. Transitions from one generation to the other are not allowed.

key properties of the flavour sector in the SM

$$L_Y = -\overline{d}_R y_d (\Phi^+ q_L) - \overline{u}_R y_u (\tilde{\Phi}^+ q_L) - \overline{e}_R y_e (\Phi^+ l_L) + h.c.$$

[most general d=4 allowed by gauge invariance]

in the unitary gauge $\Phi = \begin{pmatrix} 0 \\ \frac{h+v}{\sqrt{2}} \end{pmatrix}$ $L_Y = -\frac{h+v}{\sqrt{2}} \sum_{f=e,u,d} \overline{f}_R y_f f_L + h.c.$

y_f are diagonalized by $U_f^+ y_f V_f = y_f^D$

$f_L \to V_f f_L$ $f_R \to U_f f_R$
U_f and V_f unitary

y_f^D diagonal, real, positive

$m_f = \frac{y_f^D}{\sqrt{2}} v$ $f = u,d,e$

- Yukawa couplings are diagonal and proportional to fermion masses.

- gauge interactions of gluons, photon and Z remain diagonal (actually universal) in the new basis since only the combinations $U_f^+U_f=V_f^+V_f=1$ are involved.

- the charged current interaction becomes

$$-\frac{g}{\sqrt{2}} W_\mu^+ \left(\overline{u}_L \gamma^\mu V_u^+ V_d d_L + \overline{\nu}_L \gamma^\mu V_e e_L\right) + h.c.$$

V_e unphysical for massless ν

$$V_{CKM} = V_u^+ V_d$$

mixing matrix

parameter counting [N_g generations]

		N_g=3
masses	$3\,N_g$	9
mixing matrix		
angles	$\frac{N_g(N_g-1)}{2}$	3
phases	$\frac{N_g(N_g+1)}{2}-$	
$u_{Lk} \rightarrow e^{i\varphi_u^k} u_{Lk}$	$(2\,N_g-1)=$	
$d_{Lk} \rightarrow e^{i\varphi_d^k} d_{Lk}$	$\frac{(N_g-1)(N_g-2)}{2}$	1
		13

CP violation [Exercise]

$$\psi(x) \xrightarrow{C} i\gamma^0\gamma^2\psi^*(x)$$

$$\psi(t,\vec{x}) \xrightarrow{P} \gamma^0\psi(t,-\vec{x})$$

	P	C	CP
$\overline{\psi}_1\gamma^\mu\psi_2$	$\overline{\psi}_1\gamma_\mu\psi_2$	$-\overline{\psi}_2\gamma^\mu\psi_1$	$-\overline{\psi}_2\gamma_\mu\psi_1$
$\overline{\psi}_1\gamma^\mu\gamma_5\psi_2$	$-\overline{\psi}_1\gamma_\mu\gamma_5\psi_2$	$\overline{\psi}_2\gamma^\mu\gamma_5\psi_1$	$-\overline{\psi}_2\gamma_\mu\gamma_5\psi_1$
$W_\mu^\pm$	$W^{\pm\mu}$	$-W_\mu^\mp$	$-W^{\mp\mu}$

$$-\frac{g}{\sqrt{2}}W_\mu^+\,\overline{u}_{Li}\gamma^\mu\left(V_{CKM}\right)_{ij}d_{L_j}-\frac{g}{\sqrt{2}}W_\mu^-\,\overline{d}_{Li}\gamma^\mu\left(V_{CKM}^+\right)_{ij}u_{Lj}$$

CP

$$-\frac{g}{\sqrt{2}}W^{-\mu}\,\overline{d}_{Lj}\gamma_\mu\left(V_{CKM}\right)_{ij}u_{Li}-\frac{g}{\sqrt{2}}W^{+\mu}\,\overline{u}_{Lj}\gamma_\mu\left(V_{CKM}^+\right)_{ij}d_{Li}$$

invariance of the action $\Leftrightarrow$ $\boxed{V_{CKM}=V_{CKM}^*}$

- FCNC, i.e. flavour transitions mediated by higgs, photon, Z, gluons, are absent

- FC are only possible via charged-current interactions and are entirely described by a unitary mixing matrix V_{CKM}, depending on 4 parameters

- CP is violated in CC interactions if and only if V_{CKM} is complex
[with a single exception, this is the only source of CP violation in the SM. The other source, the so-called theta parameter, is bound to be very small by the limits on the electric dipole moment of the neutron.]

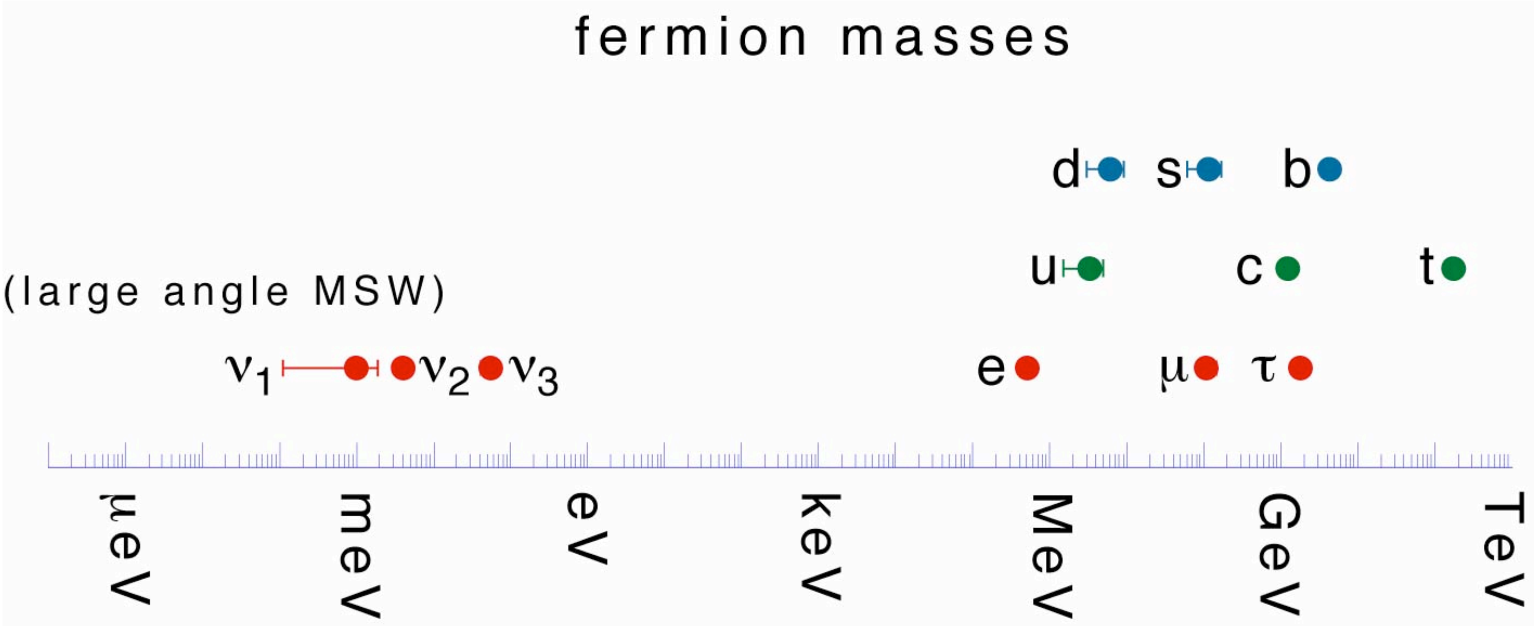
- neutrinos remain massless [more on this in lect. 3 and 4]

- The SM lagrangian, besides the SU(3)xSU(2)xU(1) gauge invariance possesses an accidental symmetry, at the classical level

$$U(1)_B \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$$

[this is broken by non-perturbative effects down to $U(1)^3$ associated to $B/3-L_i$. The effects are negligible at the available energies in the lab and possibly relevant in the early universe]

- fermion masses are not predicted by L_Y: there is one independent parameter for each fermion mass



- charged fermion mass ratios span 5-6 order of magnitudes [much more including neutrinos]
- hints of an underlying pattern:
  - in each generation the spread is by one-two order of magnitudes
  - when renormalized at the GUT scale, masses in the down sector and in the charged lepton sector are approximately equal, within factors of order one
  - mixing angles in V_{CKM} can be related to mass ratios

  .....
- a quantitative description of the observed hierarchies among fermion masses in terms of a reduced number of parameters is a formidable problem that have escaped any solution so far. [more comments later on...]

the mixing matrix

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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

[Wolfenstein parametrization, justified a posteriori by $\lambda \approx 0.22$]

- there are many processes sensitive to V_{ij}. We can use some of them to determine the independent parameters of V_{ij} and the remaining ones to perform tests.

- We should carefully select among the relevant processes those that can be both accurately measured and accurately described by the theory. Dominant theoretical uncertainties come from our difficulty in dealing with strong interactions in the non-perturbative regime.

unitarity constraints

Due to unitarity the elements of V_{CKM} are not independent. Many tests are based on the unitarity relations. Most useful are:

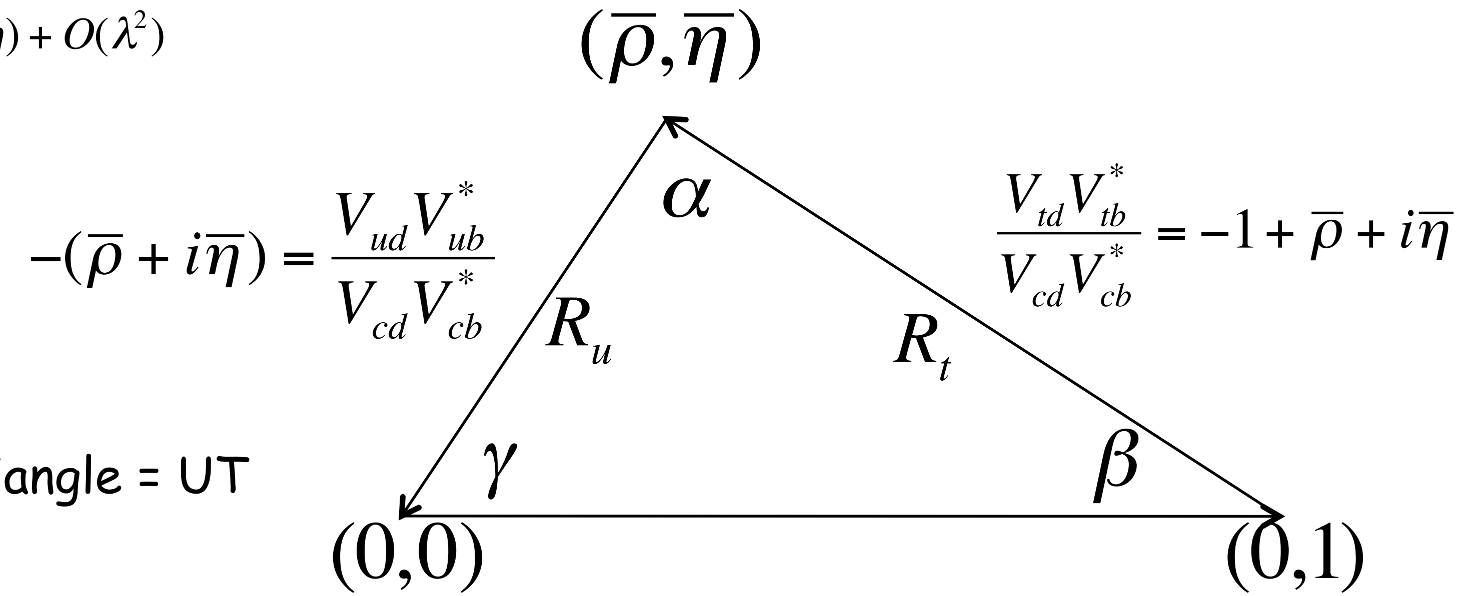
$$\sum_k V_{ik} V_{jk}^* = \delta_{ij}$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

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

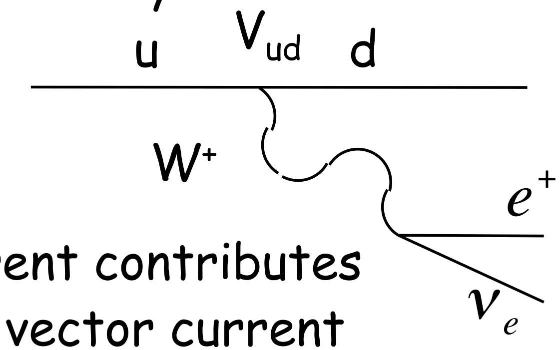
$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + 1 + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0$$

$$(\bar{\rho},\bar{\eta}) = (\rho,\eta) + O(\lambda^2)$$



unitarity triangle = UT

$|V_{ud}|$ from super-allowed Fermi transitions in nuclear beta decay
such as $^{14}O \rightarrow {}^{14}N^* + e^+ + \nu_e \qquad u \rightarrow d + e^+ + \nu_e$



$$\left\langle {}^{14}N^*(k) \right| \bar{d}\gamma^\mu(1-\gamma_5)u \left| {}^{14}O(p) \right\rangle \approx F(0)(p+k)^\mu$$

$$J^P({}^{14}O) = J^P({}^{14}N^*) = 0^+$$

$$\left| {}^{14}O \right\rangle = |1,1\rangle \qquad \left| {}^{14}N^* \right\rangle = |1,0\rangle$$

only the vector current contributes
conservation of the vector current
implies $\quad F(0) = \sqrt{2}$

$$|V_{ud}| = 0.97425(22)$$ [0.0002 relative precision]

$|V_{us}|$ from the semileptonic decay of K^0_L

$$K_L^0 \rightarrow \pi^- + e^+ + \nu_e \qquad K_L^0 \rightarrow \pi^+ + e^- + \bar{\nu}_e \qquad s \rightarrow u + e^- + \bar{\nu}_e$$

in the hadronic matrix element only the vector current survives.

$$\left\langle \pi^-(k) \right| \bar{s}\gamma^\mu(1-\gamma_5)d \left| K_L^0(p) \right\rangle$$

This current is conserved in the SU(3) limit ($m_s=m_d=m_u\approx 0$) and it normalizes the relevant form factors at vanishing momentum transfer. Corrections from the symmetry limit are under control.

$$|V_{us}| = 0.2254(13)$$ [0.6 % precision]

$|V_{ub}|$ inclusive semileptonic B decays $\quad B \to X_u l \nu \quad |V_{ub}| = 0.00432(27)$

exclusive semileptonic B decays, e.g. $\quad B \to \pi\, l \nu \quad |V_{ub}| = 0.00351(47)$

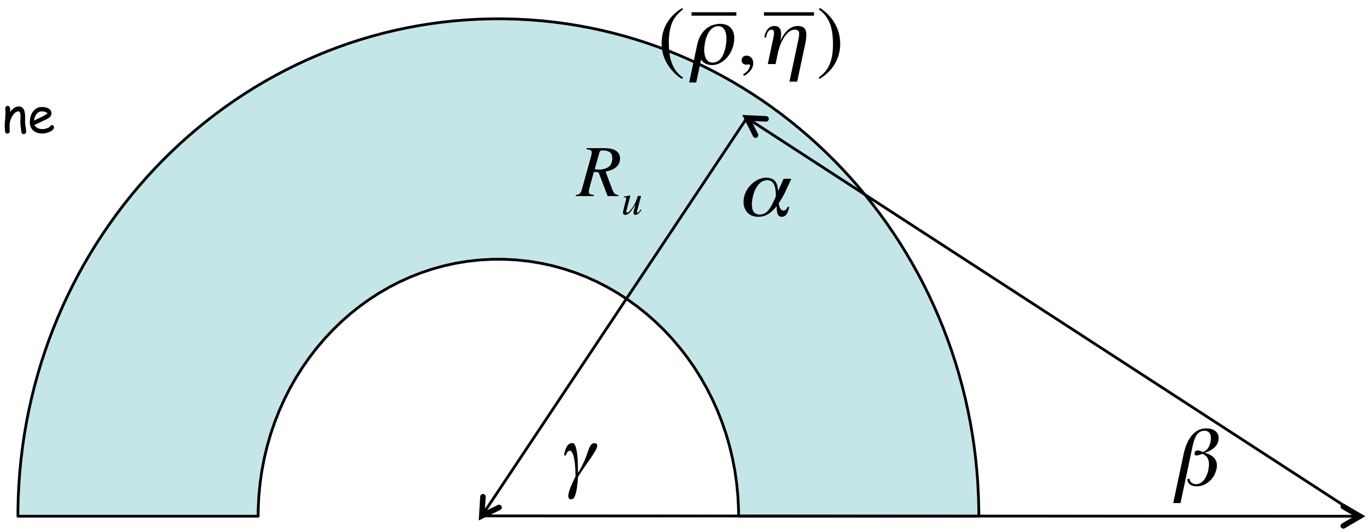
leptonic B decay $\quad B \to \tau \nu \quad |V_{ub}| = 0.00510(59)$

[much less control from theory viewpoint.
No heavy-light quark symmetry of strong interactions.]

$$\sqrt{1 - |V_{ud}|^2 - |V_{us}|^2} = 0.00564^{+0.02669}_{-0.00564}$$

1[st] unitarity relation well satisfied
[errors on $|V_{ub}|$ have no impact on it]

$|V_{ub}|$ determines one side of the UT, R_u its uncertainty is relevant here



$|V_{cb}|$ the most precisely known element after V_{ud} and V_{us}

based on both exclusive and inclusive semileptonic B decays into charm

$$|V_{cb}| = (40.6 \pm 1.3) \times 10^{-3}$$

[3 % precision]

$|V_{us}|$ and $|V_{cb}|$ fix $\lambda \approx 0.22$ and $A \approx 0.8$

other constraints on (ρ,η) plane

mixing in neutral pseudoscalar system M^0 $[B^0_d, B^0_s, K^0, D^0]$

- convention:
  M^0 decays into e^+X and $\overline{M}^0$ into e^-X.

$$B_d^0 \equiv \bar{b}d \qquad B_s^0 \equiv \bar{b}s$$
$$\overline{B}_d^0 \equiv \bar{d}b \qquad \overline{B}_s^0 \equiv \bar{s}b$$

M^0 and $\overline{M}^0$ are related by CP conjugation

$$CP\left|M^0\right\rangle = e^{i\xi}\left|\overline{M}^0\right\rangle$$
$$CP\left|\overline{M}^0\right\rangle = e^{-i\xi}\left|M^0\right\rangle$$

- evolution of M^0 and $\overline{M}^0$ in the relative rest frame is governed by the non-hermitian hamiltonian

$$H = M - i\frac{\Gamma}{2}$$

M and Γ are 2x2 hermitian matrices in $(M^0, \overline{M}^0)$ basis
$M_{11}=M_{22}$ and $\Gamma_{11}=\Gamma_{22}$ by CPT

- eigenstates of the hamiltonian, with definite masses $M_H > M_L$ and widths Γ_H, Γ_L

$$\left|M_L\right\rangle = p\left|M^0\right\rangle + q\left|\overline{M}^0\right\rangle$$
$$\left|M_H\right\rangle = p\left|M^0\right\rangle - q\left|\overline{M}^0\right\rangle$$

$$|p|^2 + |q^2| = 1$$

- in general CP is not conserved in this system. Equivalent conditions for CP conservation are [Exercise]

$$\varphi \equiv \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right) = 0 \quad (\mathrm{mod}\ \pi) \quad \Longleftrightarrow \quad a \equiv 1 - \left|\frac{q}{p}\right|^2 = 0$$

useful approximate expressions [Exercise]

$K^0 - \overline{K}^0$

$$a = \frac{4|M_{12}||\Gamma_{12}|}{4|M_{12}|^2 + |\Gamma_{12}|^2}\varphi + O(\varphi^2)$$

$B^0 - \overline{B}^{0\,0}$

$$a = \frac{|\Gamma_{12}|}{|M_{12}|}\sin\varphi + O\left(\frac{|\Gamma_{12}|^2}{|M_{12}|^2}\right)$$

- relevant (convention-independent) parameters $|M_{12}|$ $|\Gamma_{12}|$ $\varphi \leftrightarrow a$
  they can be related to observable quantities

$$\Delta M \equiv M_H - M_L \approx 2|M_{12}| \qquad \Delta\Gamma \equiv \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos\varphi$$

$$\frac{\Gamma(K_L \to l^+\nu\pi^-) - \Gamma(K_L \to l^-\overline{\nu}\pi^+)}{\Gamma(K_L \to l^+\nu\pi^-) + \Gamma(K_L \to l^-\overline{\nu}\pi^+)} \approx \frac{a}{2} \approx 2\,\mathrm{Re}\,\varepsilon_K$$

$$A_{sl}^b = \frac{N_b(l^+l^+) - N_b(l^-l^-)}{N_b(l^+l^+) + N_b(l^-l^-)} \approx a + O(a^2)$$

	K^0	B_d^0	B_s^0
[average width] $\Gamma\ (ps^{-1})$	$\approx 5.6 \times 10^{-3}$	≈ 0.66	≈ 0.68
$\Delta M\ (ps^{-1})$	$5.292(9) \times 10^{-3}$	$0.507(5)$	$17.725 \pm 0.041 \pm 0.026$ [LHC$_b$ 341 pb^{-1} CONF-2011-050]
$\Delta\Gamma\ (ps^{-1})$	$11.144(6) \times 10^{-3}$	–	$0.123 \pm 0.029 \pm 0.008$ [LHC$_b$ 337 pb^{-1} CONF-2011-049] $B_s \to J/\psi\,\varphi$
φ	$6.77(12) \times 10^{-3}$	–	–

[hints from D0 of a non-vanishing combination. More later on…]

[mixing has been established also in D^0 systems, with large errors on ΔM, $\Delta\Gamma$]

part of QCD uncertainty cancels in the ratio $\Delta M_d/\Delta M_s$

	K^0	B_d^0		B_s^0
$\Delta M\ (ps^{-1})$	large uncertainties from low-energy QCD	$\lvert V_{tb}V_{td}^*\rvert$	constraint on (ρ,η) plane	$\lvert V_{tb}V_{ts}^*\rvert$
$\Delta\Gamma\ (ps^{-1})$	large uncertainties from low-energy QCD	$(26.7^{+5.8}_{-6.5})\times 10^{-4}$		$0.088(17)$
φ	$\approx 2\dfrac{\mathrm{Im}\,M_{12}}{\Delta M}$ constraint on (ρ,η) plane	$-0.091^{+0.026}_{-0.038}$		$(4.2\pm 1.4)\times 10^{-3}$

small in the SM
here New Physics can manifest
by modifying $\arg(-M_{12}/\Gamma_{12})_{SM}$

[more on this when discussing CP]

an example: limits on (ρ,η) from $\Delta M_d/\Delta M_s$

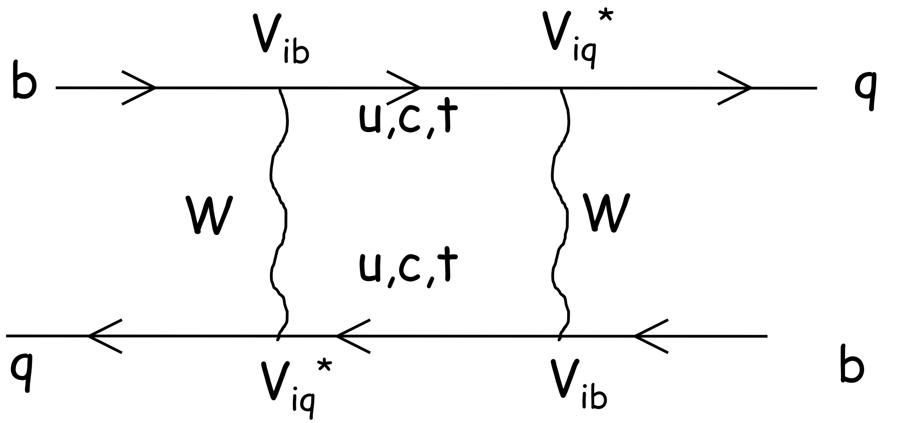
$$\Delta M \approx 2|M_{12}| \qquad M_{12} = \frac{\langle B^0|H|\overline{B}^0\rangle}{2M_B}$$

where only the dispersive part of H should be considered

in the SM M_{12} is dominated by the operator

$$O(|\Delta B|=2) = \overline{q}_L\gamma^\mu b_L\ \overline{q}_L\gamma_\mu b_L \qquad (q=d,s)$$

arising in the low-energy limit from the box diagram



\+ crossed

After inclusion of QCD corrections and running from M_W down to m_b

$$H(|\Delta B|=2) = \frac{G_F^2}{4\pi^2}M_W^2(V_{tb}V_{tq}^*)^2 S\left(\frac{m_t^2}{M_W^2}\right)\eta_B b_B(\mu) O(|\Delta B|=2) + h.c. + \ldots$$

small contributions $O\left(\frac{m_c^2}{M_W^2}\right)$

$$\eta_B \approx 0.55 \qquad S\left(\frac{m_t^2}{M_W^2}\right) = \frac{m_t^2}{4M_W^2} + \ldots \approx 2.3$$

main uncertainty from hadronic matrix element

$$b_B(\mu)\left\langle B^0 \left| O\left(|\Delta B| = 2\right) \right| \overline{B}^0 \right\rangle = \frac{2}{3} M_B^2 f_B^2 \widehat{B}$$

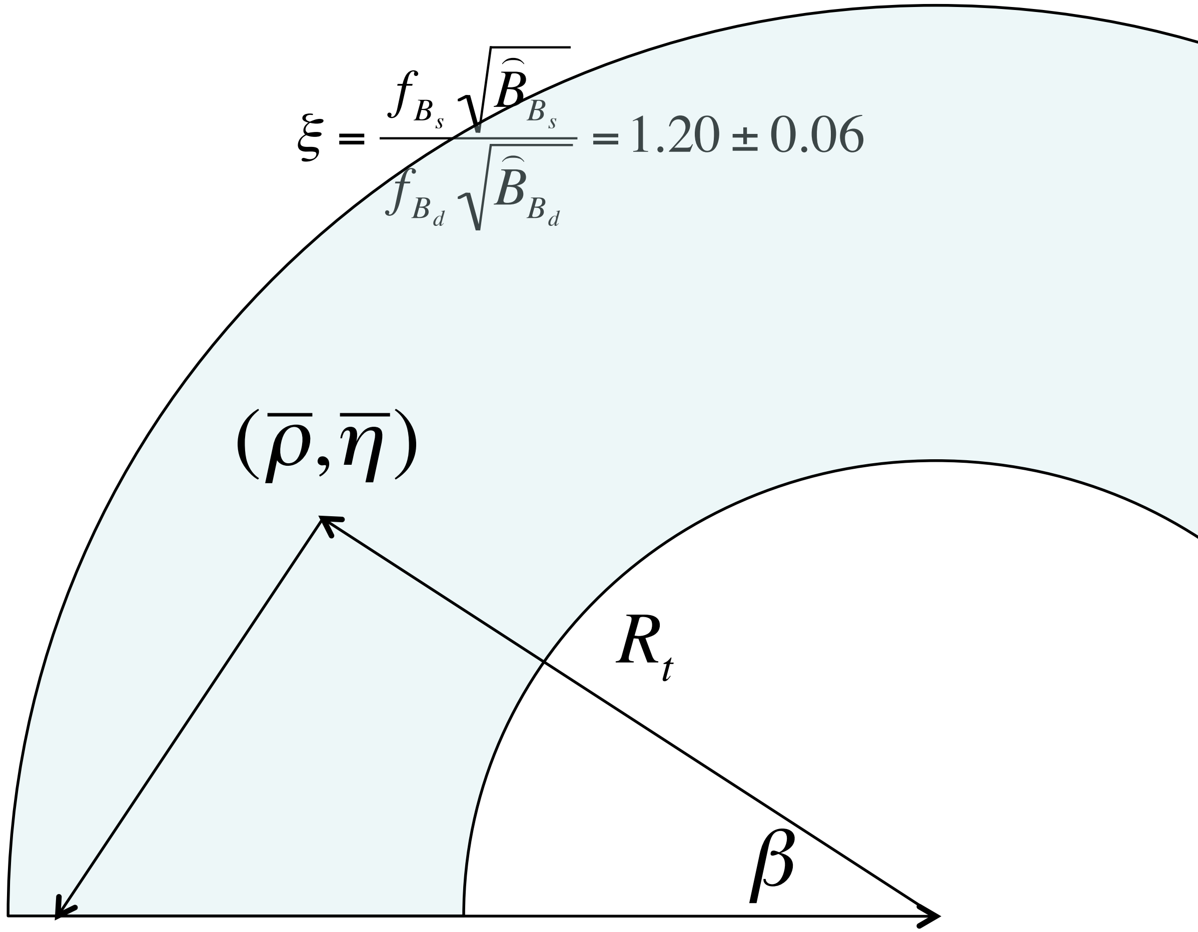
$$f_B \sqrt{\widehat{B}} = \begin{cases} (225 \pm 35)\ \text{MeV} & B_d^0 \\ (270 \pm 45)\ \text{MeV} & B_s^0 \end{cases}$$

from lattice

part of the uncertainties cancel in the ratio

$$\frac{\Delta M_{B_d}}{\Delta M_{Bs}} = \left|\frac{V_{td}}{V_{ts}}\right|^2 \frac{M_{B_d}}{M_{B_s}} \xi^{-2}$$

$$\xi = \frac{f_{B_s}\sqrt{\widehat{B}_{B_s}}}{f_{B_d}\sqrt{\widehat{B}_{B_d}}} = 1.20 \pm 0.06$$

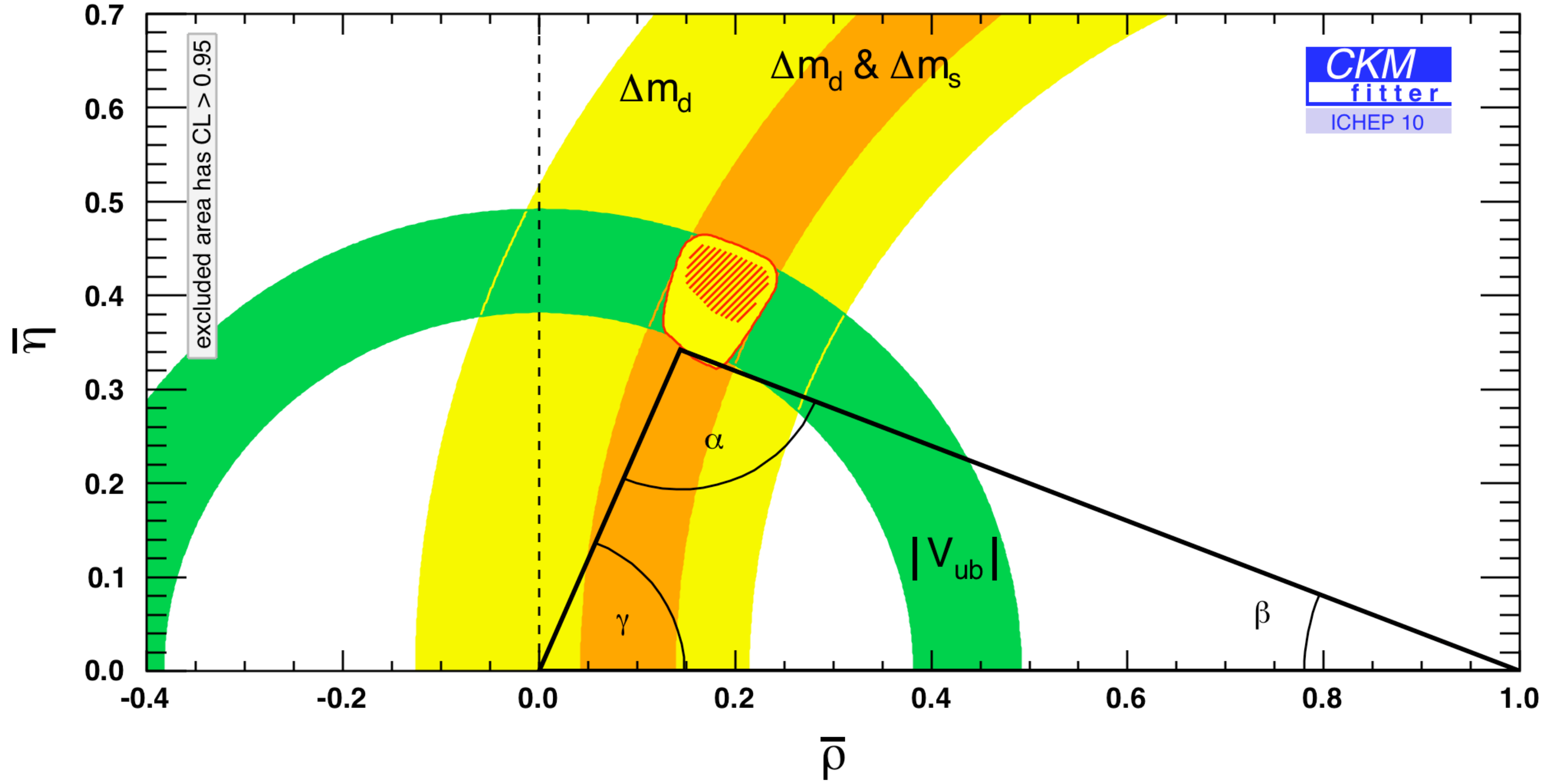


this constrains the size of one side of the UT

$$\left|\frac{V_{td}}{V_{ts}}\right| = R_t \lambda + O(\lambda^3)$$

improved accuracy on Δm_s by new LHC_b measurement not useful since the error is dominated by the uncertainty on ξ

Now with true data



sofar, only CP invariant quantities

2^{nd} Lecture:
QUARKS: CP VIOLATING SECTOR

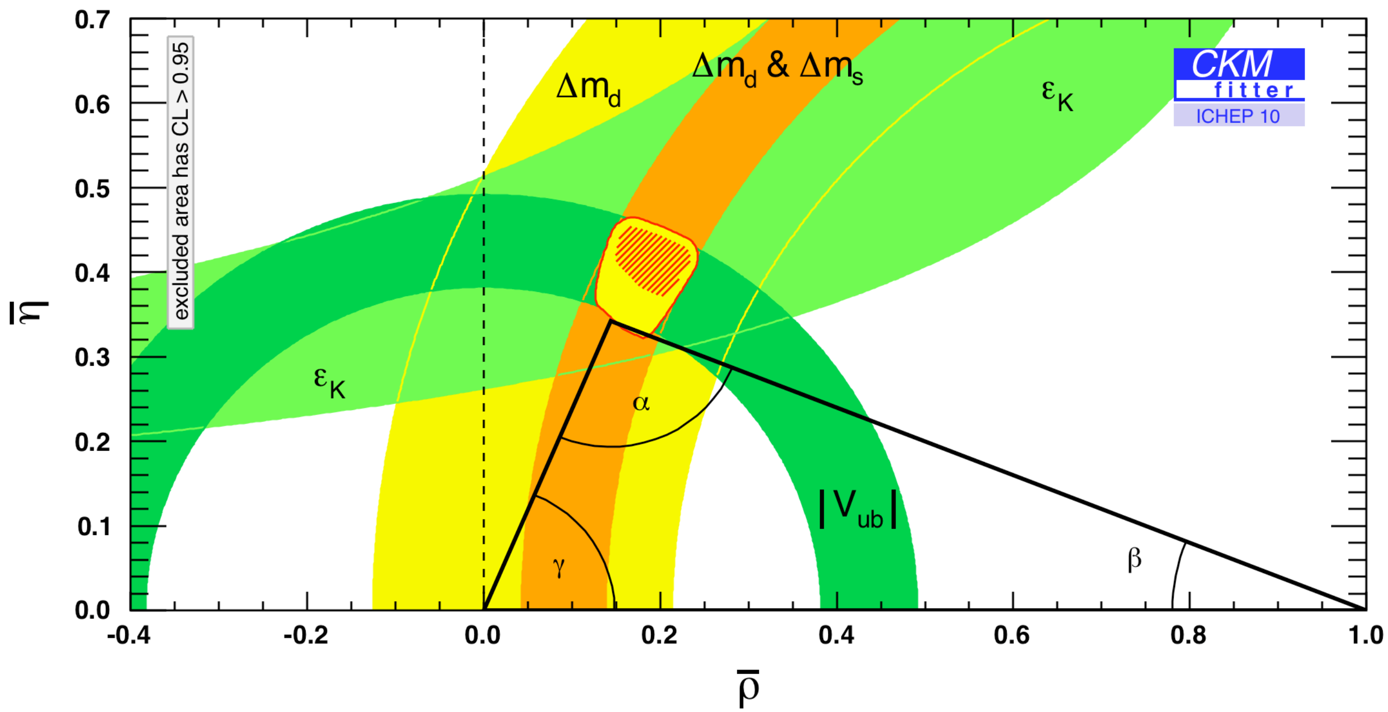
constraints from CP violating observables

K system: not discussed here

constraint from the ϵ_K parameter:

$$(1.66 \pm 0.02) \times 10^{-3} = \mathrm{Re}(\varepsilon_K) \approx \frac{a}{4} \approx \frac{\mathrm{Im}\, M_{12}}{2\Delta M} \leftrightarrow \overline{\eta}[(1-\overline{\rho}) + const]$$

estimate of Im M_{12} in the SM as seen in the B system



CP violation in the B system

- consider the decay of a B meson (charged or neutral) into a final state f, B->f, and the process related by CP conjugation. Relevant amplitudes

$$A_f = \langle f|H|B\rangle \quad \bar{A}_{\bar{f}} = \langle \bar{f}|H|\bar{B}\rangle \qquad \text{if} \quad \left|\frac{\bar{A}_{\bar{f}}}{A_f}\right| \neq 1$$

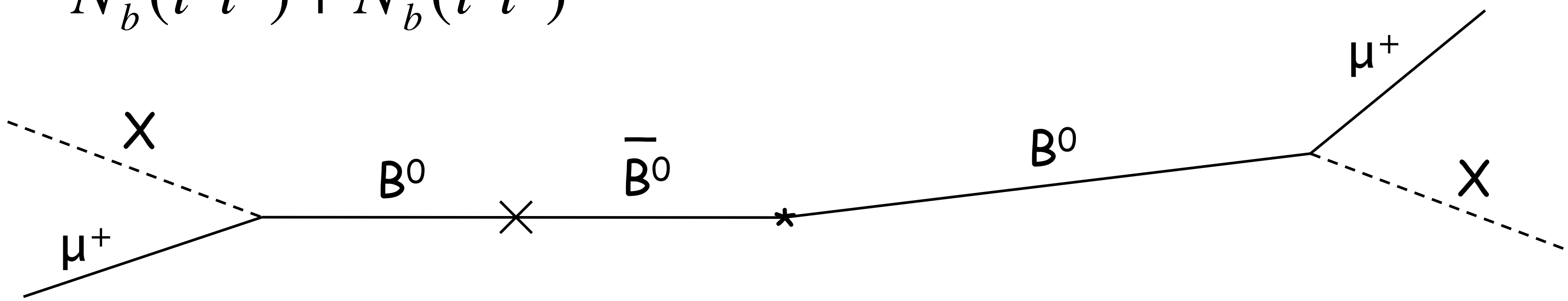
CP is violated in decay (direct) the only possibility if B is charged

direct CP violation has been observed in B meson decays, both in neutral and charged cases: e.g. $\bar{B}^0 \to K^-\pi^+ \quad B^- \to K^-\rho^0$

- if B is neutral CP violation can occur through mixing in some case it is entirely controlled by the parameter a as, for instance, the like-sign dilepton charge asymmetry

$$a = \frac{|\Gamma_{12}|}{|M_{12}|}\sin\varphi$$

$$A_{sl}^b = \frac{N_b(l^+l^+) - N_b(l^-l^-)}{N_b(l^+l^+) + N_b(l^-l^-)} \approx a + O(a^2)$$



not interesting to constrain the UT, but to search for New Physics

- a is very small in the SM, for both B^0_d and B^0_s [Exercise]

$$\frac{|\Gamma_{12}|}{|M_{12}|} = O\left(\frac{m_b^2}{m_t^2}\right) << 1 \qquad \varphi \equiv \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right) = O\left(\frac{m_c^2}{m_b^2}\right) \times [V_{CKM} \text{ factors}]$$

$$a_d = (-4.8^{+1.0}_{-1.2}) \times 10^{-4} \qquad a_s = (2.06 \pm 0.57) \times 10^{-5}$$

- D0 has recently updated the results on the like-sign dimuon asymmetry [1106.6308] 9.0 pb^{-1}

$$A_{sl}^b = (-0.787 \pm 0.172 \pm 0.093)\%$$

- at the Tevatron collider both B^0_d and B^0_s are produced and A_{sl}^b is an average between a_d and a_s

$$A_{sl}^b \approx 0.6\, a_d + 0.4\, a_s \approx (-0.023^{+0.005}_{-0.006})\%$$

waiting for a cross check…

- … in the following we will set a_d=a_s=0 ➡ $$\frac{q}{p} = -\frac{M_{12}^*}{|M_{12}|} = -\frac{V_{tb}^* V_{tq}}{V_{tb} V_{tq}^*}$$ [Exercise]

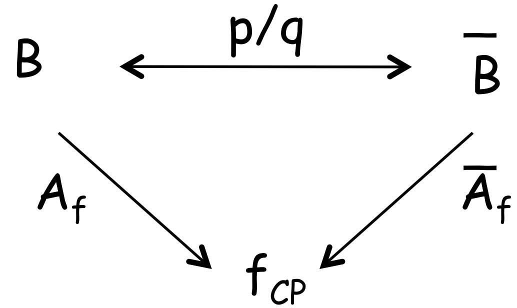
mixing induced CP asymmetry

- an interesting CP asymmetry arises when both B^0 and $\overline{B}^0$ can decay into a common final state f_{CP}, eigenstate of CP. The key parameter in this case is

$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f} \qquad A_f = \langle f|H|B\rangle \quad \overline{A}_f = \langle f|H|\overline{B}\rangle$$

- in the simplest case [golden mode] the decay amplitudes carry the same weak phase, so that $|A_f|=|A_f|$ and there is no direct CP violation: $|\lambda_f|=1$
Defining

$$a_{f_{CP}}(t) = \frac{\frac{d\Gamma(\overline{B}^0(t)\to f_{CP})}{dt} - \frac{d\Gamma(B^0(t)\to f_{CP})}{dt}}{\frac{d\Gamma(\overline{B}^0(t)\to f_{CP})}{dt} + \frac{d\Gamma(B^0(t)\to f_{CP})}{dt}}$$



we have
$$a_{f_{CP}}(t) = \frac{\mathrm{Im}\,\lambda_f \sin(\Delta M t)}{\cosh(\Delta\Gamma t/2) - \mathrm{Re}\,\lambda_f \sinh(\Delta\Gamma t/2)}$$

in the B^0_d system, where $\Delta\Gamma$ is negligible $\quad a_{f_{CP}}(t) = \mathrm{Im}\,\lambda_f \sin(\Delta M t)$

in $\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$ both $\frac{q}{p} = -\frac{M_{12}^*}{|M_{12}|} = -\frac{V_{tb}^* V_{tq}}{V_{tb} V_{tq}^*}$ and $\frac{\bar{A}_f}{A_f}$

are weak phases, combination of V_{CKM} elements, whose combination can be directly tested

$B_d \rightarrow J/\psi\, K_S \rightarrow J/\psi\, (\pi^+\pi^-)$

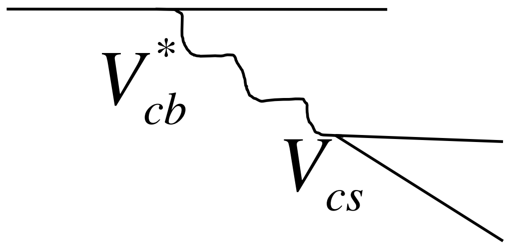
$$\frac{q}{p} = -\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} \qquad \frac{\bar{A}_f}{A_f} = \frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}} \frac{V_{us} V_{ud}^*}{V_{us}^* V_{ud}}$$

$$\lambda_{J/\psi K_S} \approx -e^{-2i\beta}$$

[Exercise]

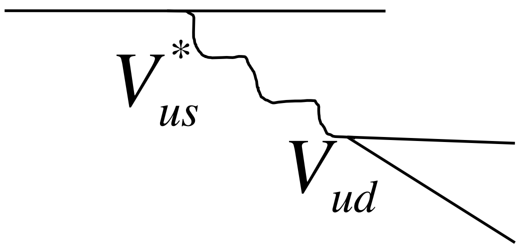
$\bar{b} \rightarrow c\bar{c}\,\bar{s}$

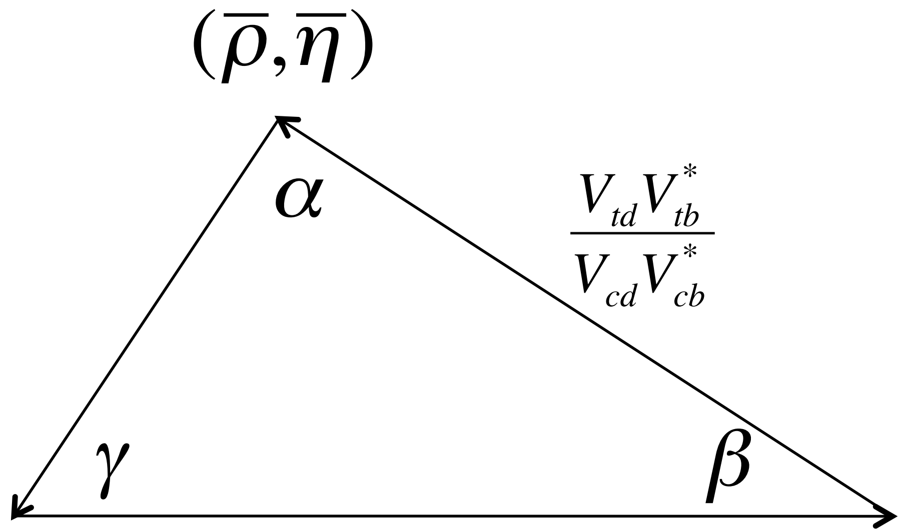
$V_{cb}^* V_{cs}$



$\bar{s} \rightarrow u\bar{u}\,\bar{d}$

$V_{us}^* V_{ud}$

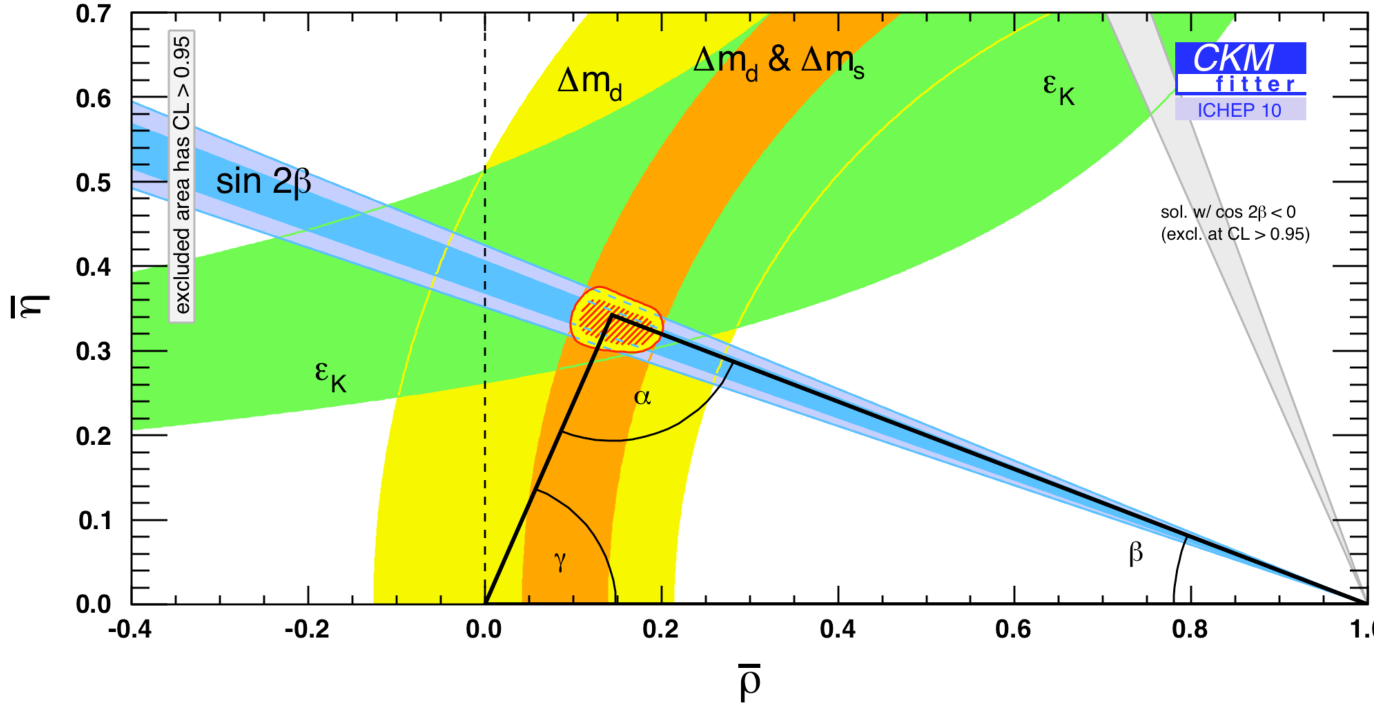




$$a_{J/\psi K_S}(t) = \sin 2\beta \sin(\Delta M_{B_d} t)$$

there is also a one-loop penguin contribution to A_f, which can be neglected to an accuracy better than 1%

$$\sin 2\beta = 0.673 \pm 0.023$$



mixing induced CP asymmetries sensitive to sin2β has been measured in B_d decays in many other channels, where the contribution from penguin diagrams $\bar{b} \to q\bar{q}\bar{s} \quad (q = u, d, s)$ is dominant, with consistent results

$B_s \to J/\psi\ \phi$

more difficult to analize:
- two spin 1 particles in the final state: angular correlations needed to separate CP eigenstates

interesting:
- in B_s system $\Delta\Gamma$ cannot be neglected
- sensitive to a small angle, β_s

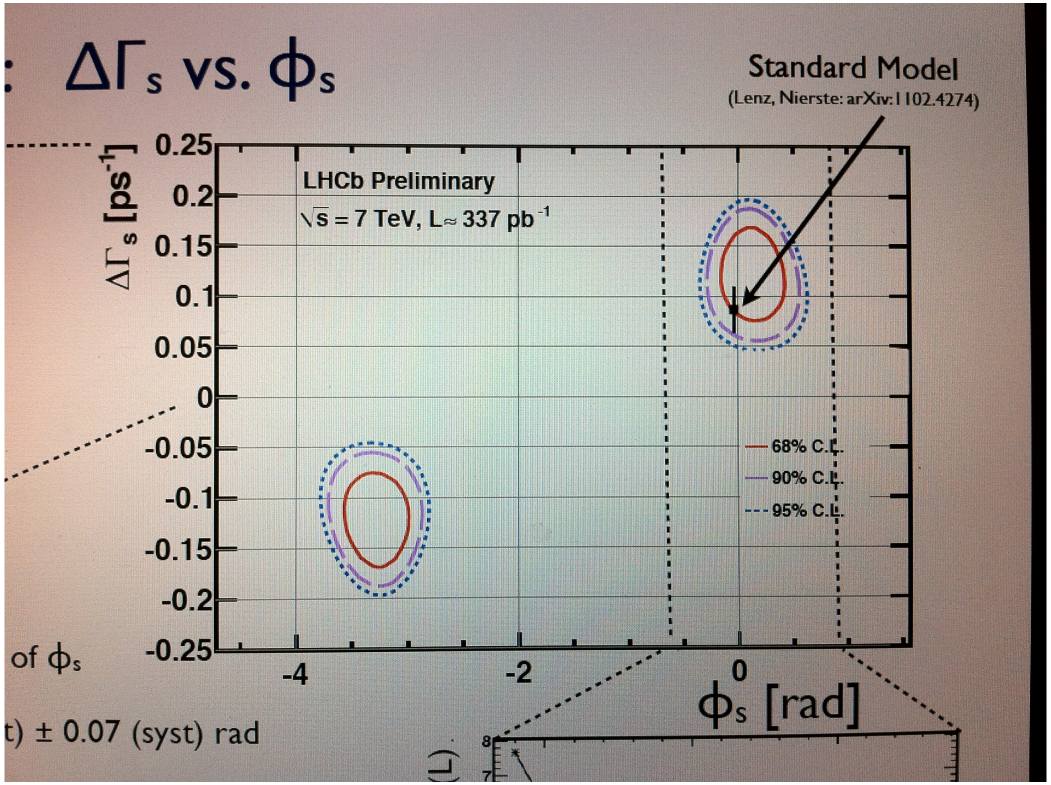
$$\frac{q}{p} = -\frac{V_{tb}^* V_{ts}}{V_{tb} V_{ts}^*} \qquad \frac{\overline{A}_f}{A_f} = -\eta_{CP}\frac{V_{cb}V_{cs}^*}{V_{cb}^* V_{cs}}$$

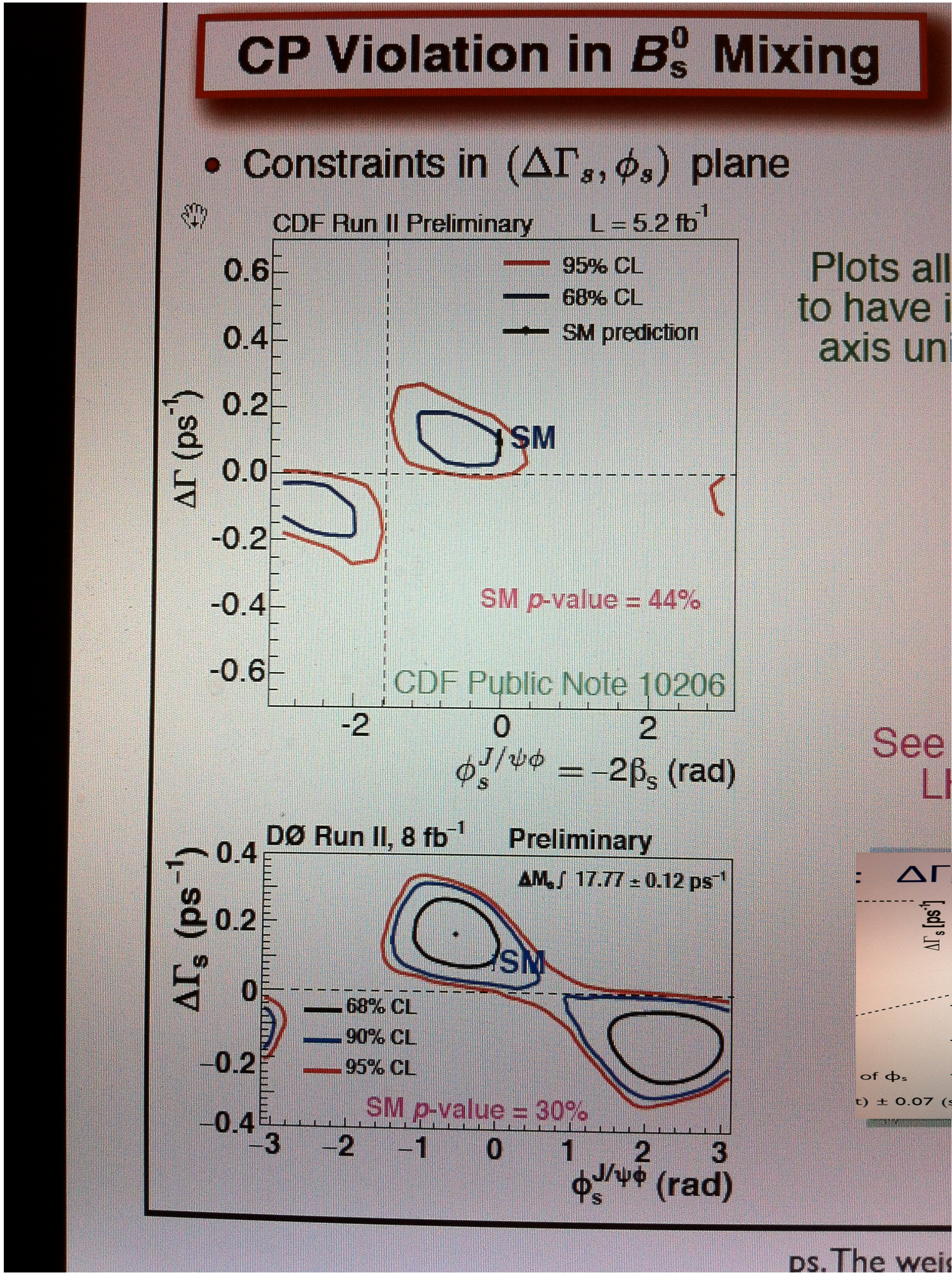
[LHC$_b$ 337 pb^{-1} CONF-2011-049]

$$\lambda_{J/\psi\phi} \approx \eta_{CP} e^{2i\beta_s}$$

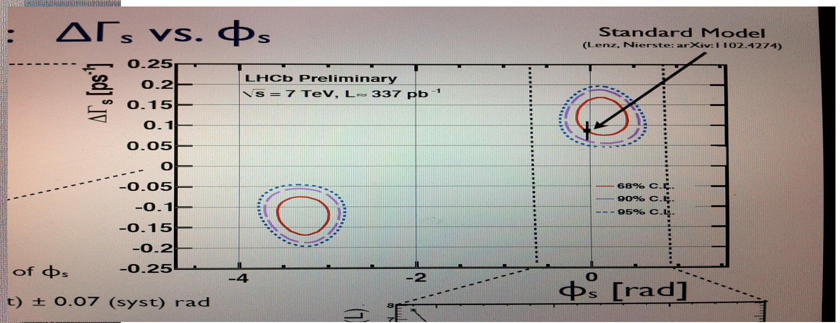
$$\beta_s \equiv \arg\left[-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right] = \lambda^2\overline{\eta} + O(\lambda^4) \approx 0.02$$

$$\Delta\Gamma = 0.123 \pm 0.029 \pm 0.008 ps^{-1}$$
$$\phi_s \equiv -2\beta_s = 0.13 \pm 0.18 \pm 0.07\ rad$$

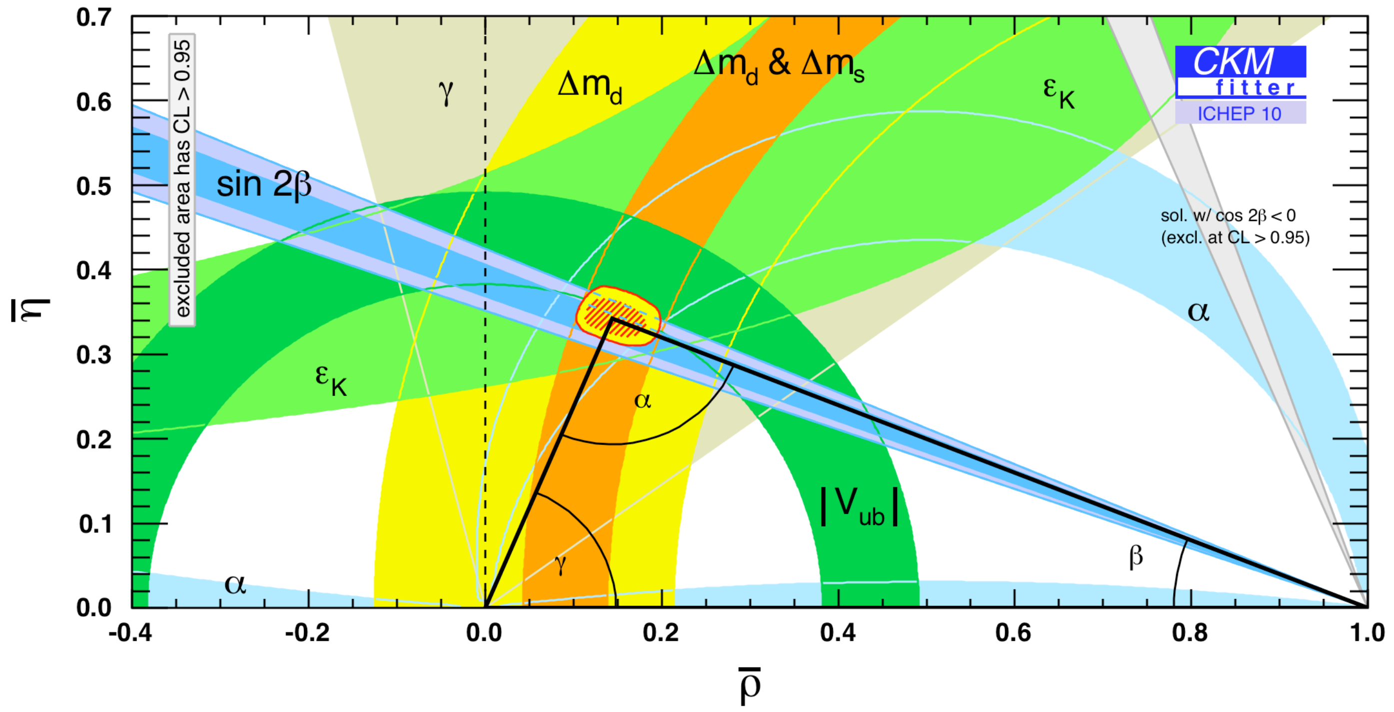




a new phase in M_{12}^s would show up both in A_{sl}^b and in β_s



Putting everything together [as 2010]



- overall consistency among many different measurements
- looking at details, there is a tension between the direct determination of the angle β, which is very precise, and other observables, in particular $|V_{ub}|$ and ϵ_K.

New physics in ΔB=2 transitions ?

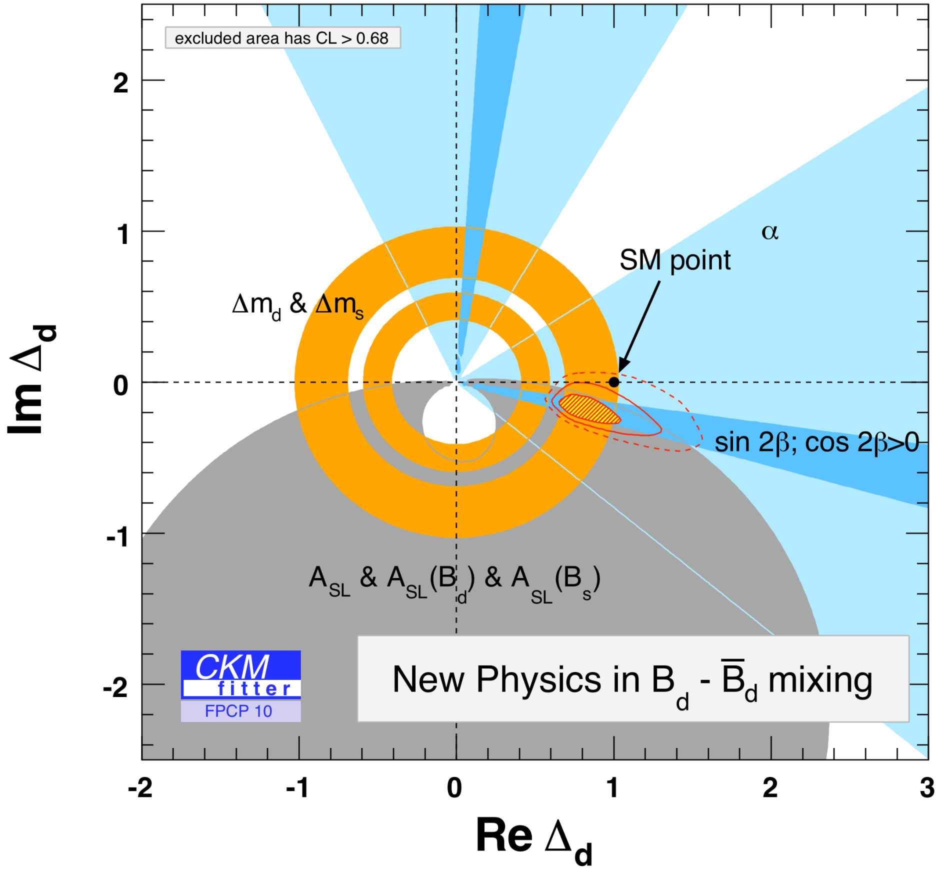
define 2 New Physics parameters

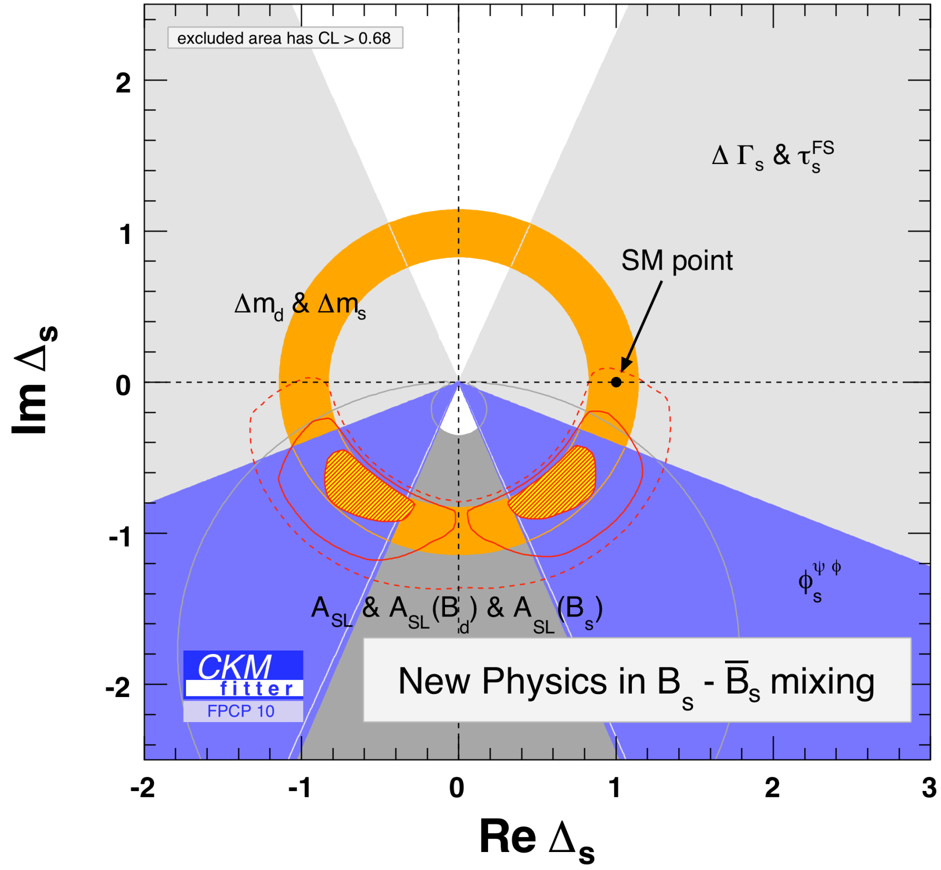
$$\Delta_q \equiv \frac{M_{12}^q}{M_{12}^{q,SM}} \qquad \Delta_q = |\Delta_q| e^{i\phi_q^\Delta}$$

(q=d,s)

2010 fits

large negative Φ_q^Δ preferred by both old D0 like-sign dimuon asymmetry and by Tevatron data on $B_s \to J/\psi\ \Phi$





SM OK within 3 σ…

New physics: effective lagrangian approach

$$L = L_{SM} + \sum_i c_i^5 \frac{O_i^5}{\Lambda} + \sum_i c_i^6 \frac{O_i^6}{\Lambda^2} + \ldots$$

O^d_i gauge invariant operators of dimension d

here: constraints from flavour physics on $|\Delta F|=2$ operators

FLAVOUR PROBLEM

Operator	Bounds on Λ in TeV ($c_{ij}=1$)		Bounds on c_{ij} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L \gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}

TABLE I: Bounds on representative dimension-six $\Delta F = 2$ operators. Bounds on Λ are quoted assuming an effective coupling $1/\Lambda^2$, or, alternatively, the bounds on the respective c_{ij}'s assuming $\Lambda = 1$ TeV. Observables related to CPV are separated from the CP conserving ones with semicolons. In the B_s system we only quote a bound on the modulo of the NP amplitude derived from Δm_{B_s} (see text). For the definition of the CPV observables in the D system see Ref. [15].

[Isidori, Nir, Perez, 2010]

Minimal Flavour Violation

- either the scale of new physics is very large or flavour violation from New Physics is highly non-generic. Useful benchmark: a framework where the only source of flavour violation beyond the SM are the Yukawa coupling

- The Yukawa couplings Y_u and Y_d of the quark sector are promoted to non-dynamical fields (spurions) in such a way that the SM lagrangian is formally invariant under the flavour group G_q

$$G_q = SU(3)_{u_R} \times SU(3)_{d_R} \times SU(3)_{q_L} \qquad y_u = (3,1,\overline{3})$$

$$q_L = (1,1,3) \quad u_R = (3,1,1) \quad d_R = (1,3,1) \qquad y_d = (1,3,\overline{3})$$

- MFV assumes that new operators coming from New Physics do not involve any additional field/spurions and that they are still invariant under G_q
[additional assumption: no additional sources of CPV other than those in $y_{u,d}$]

- in this way operators that contribute to FC automatically carry some suppression from the small y_u and y_d and one can hope to lower the allowed scale of New Physics.

Exercise: build the leading operator with ΔF=2 in MFV

choose, e.g. the basis where

$$y_d = y_d^{Diag} \qquad y_u = y_u^{Diag} V_{CKM} \qquad y_{u,d}^{Diag} \text{ diagonal}$$

we can form the MFV invariant

$$\bar{q}_{Li}\gamma^{\mu}(y_u^+ y_u)_{ij} q_{Lj}\, \bar{q}_{Lk}\gamma_{\mu}(y_u^+ y_u)_{kl} q_{Ll}$$

looking at the down quark sector and selecting i=k=d,s and j=l=b
we get the MFV operators contributing to ΔB=2

$$O_{MFV}(|\Delta B| = 2) = \frac{c}{\Lambda_{NP}^2} y_t^4 (V_{tb}V_{tq}^*)^2\, \bar{q}_L\gamma^{\mu} b_L\, \bar{q}_L \gamma_{\mu} b_L \qquad (q = d,s)$$

where we used $y_u^{Diag} \approx \text{diag}(0,0,y_t)$

same CKM suppression as in the SM. Now the bound on the scale of New Physics reads

$$\Lambda_{NP} > 5.9\ TeV \qquad \Lambda_{NP} \leftrightarrow \frac{\Lambda_{NP}}{4\pi} \leftrightarrow \frac{4\pi}{g}\Lambda_{NP}$$

[this would modify M_{12} for B_d and B_s in the same way:
i.e Δ_d and Δ_s are identical and real in MFV]

SUMMARY

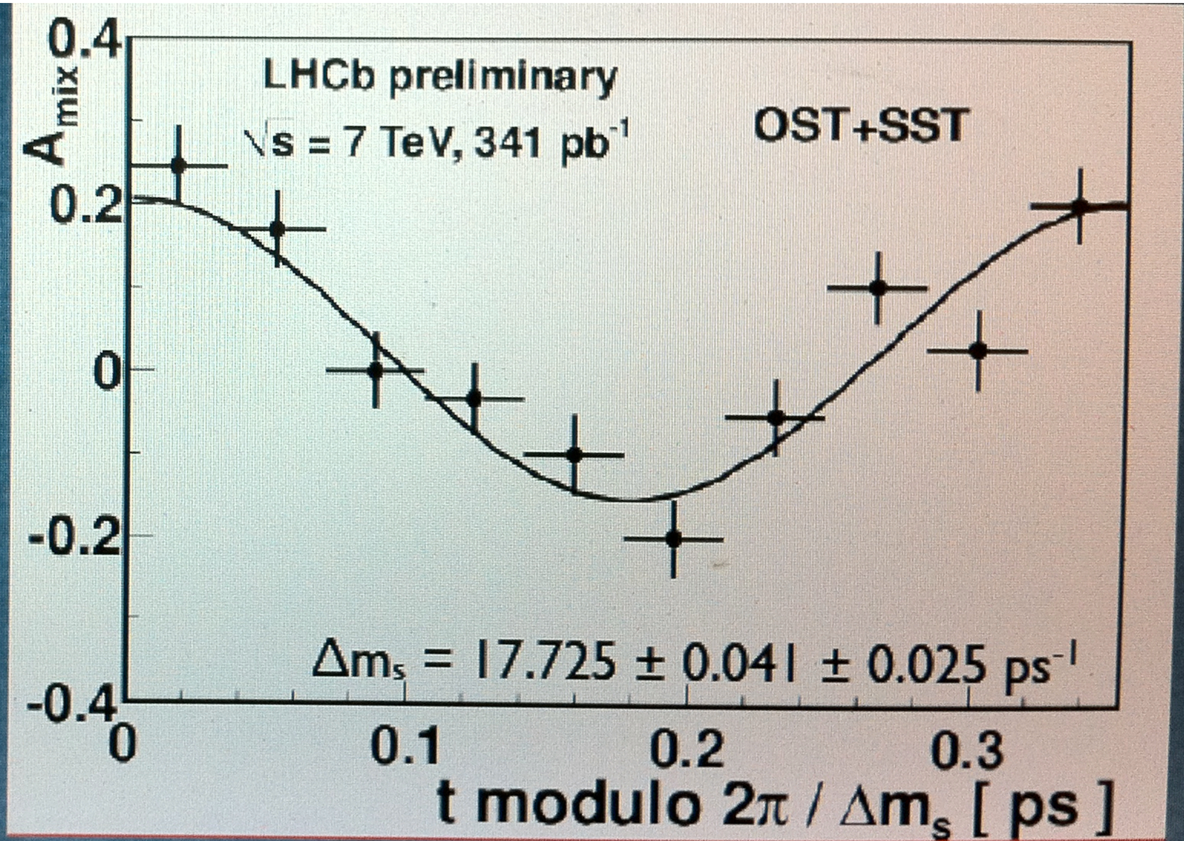
- The flavour sector brings many new parameters into the theory:
13 [in SM with vanishing neutrino masses and up to 22 for massive neutrinos].
Part of them displays a clear pattern calling for a more fundamental explanation. None of the explanations proposed so far is fully satisfactory.
We speak of a FLAVOUR MYSTERY.

- One of the key property of the flavour sector of the SM is the absence of flavour changing neutral currents [FCNC].
Many FC transitions can only occur through electroweak loop, sensitive to New Physics at the TeV scale.

- In the quark sector there are many tests of the SM flavour picture.
The parameter space is over-constrained and the SM description is robust.
Only small deviations from the SM picture are allowed.

- This poses strong constraints on the flavour structure of most SM extensions.
Either the scale of New Physics is very large and the new contributions are decoupled or this scale is accessible, i.e. at the LHC, and the new contributions are highly non-generic, to avoid conflict with existing tests.
We speak of a FLAVOUR PROBLEM.

$A_{mix}(B_s \to D_s \pi)$



bound on the scale of New Physics in MFV

Operator	Bound on Λ	Observables
$H^\dagger\left(\overline{D}_R Y^{d\dagger} Y^u Y^{u\dagger} \sigma_{\mu\nu} Q_L\right)\left(e F_{\mu\nu}\right)$	6.1 TeV	$B \to X_s\gamma$, $B \to X_s\ell^+\ell^-$
$\frac{1}{2}(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L)^2$	5.9 TeV	ϵ_K, Δm_{B_d}, Δm_{B_s}
$H_D^\dagger\left(\overline{D}_R Y^{d\dagger} Y^u Y^{u\dagger} \sigma_{\mu\nu} T^a Q_L\right)\left(g_s G^a_{\mu\nu}\right)$	3.4 TeV	$B \to X_s\gamma$, $B \to X_s\ell^+\ell^-$
$\left(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L\right)\left(\overline{E}_R \gamma_\mu E_R\right)$	2.7 TeV	$B \to X_s\ell^+\ell^-$, $B_s \to \mu^+\mu^-$
$i\left(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L\right) H_U^\dagger D_\mu H_U$	2.3 TeV	$B \to X_s\ell^+\ell^-$, $B_s \to \mu^+\mu^-$
$\left(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L\right)\left(\overline{L}_L \gamma_\mu L_L\right)$	1.7 TeV	$B \to X_s\ell^+\ell^-$, $B_s \to \mu^+\mu^-$
$\left(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L\right)\left(e D_\mu F_{\mu\nu}\right)$	1.5 TeV	$B \to X_s\ell^+\ell^-$

TABLE II: Bounds on the scale of new physics (at 95% C.L.) for some representative $\Delta F = 1$ [27] and $\Delta F = 2$ [12] MFV operators (assuming effective coupling $\pm 1/\Lambda^2$), and corresponding observables used to set the bounds.

[Isidori, Nir, Perez, 2010]

of new physics not far from the TeV region. These bounds are very similar to the bounds on