Introduction to Flavor Physics in and beyond the Standard Model

Lecture 4/4

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References:

The BaBar physics book, http://www.slac.stanford.edu/cgi-wrap/getdoc/slac-r-504-TOC-pdf.pdf

B physics at the Tevatron: Run II and beyond, hep-ph/0201071

The Discovery potential of a Super B Factory, hep-ph/0503261

Outline

- Key points from the previous lecture on CP violation
- General considerations on extending the SM
- Various New Physics models

CP violation in a nutshell

B meson mixing

- Schrodinger equation for two states that at t = 0 are pure B^0 and $\bar{B}^0$:

$$i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}|B^0(t)\rangle\\|\bar{B}^0(t)\rangle\end{pmatrix}=\left(M-i\frac{\Gamma}{2}\right)\begin{pmatrix}|B^0(t)\rangle\\|\bar{B}^0(t)\rangle\end{pmatrix}$$

mass matrix decay matrix

- The mass eigenstates are ($|p|^2+|q|^2=1$):

$$|B_L\rangle = p|B^0\rangle + q|\bar{B}^0\rangle$$
$$|B_H\rangle = p|B^0\rangle - q|\bar{B}^0\rangle$$

- For the B system we have $|\Gamma_{12}| \ll |M_{12}|$ and we can write:

$$\Delta m = 2|M_{12}| \qquad \Delta\Gamma = 2\,\mathrm{Re}\left(\frac{M_{12}}{|M_{12}|}\Gamma_{12}^*\right)$$

$$\frac{q}{p} = -\frac{M_{12}^*}{|M_{12}|}\left[1-\frac{1}{2}\mathrm{Im}\frac{\Gamma_{12}}{M_{12}}\right]$$

Time evolution

- The evolution of pure interaction eigenstates is:

$$|B^0(t)\rangle = g_+(t)|B^0\rangle + \frac{q}{p} g_-(t)|\bar{B}^0\rangle$$

$$|\bar{B}^0(t)\rangle = \frac{p}{q} g_-(t)|B^0\rangle + g_+(t)|\bar{B}^0\rangle$$

where

$$g_+(t) = e^{-imt}\, e^{-\Gamma t/2}\left[\cosh\frac{\Delta\Gamma t}{4}\cos\frac{\Delta m t}{2} - i\sinh\frac{\Delta\Gamma t}{4}\sin\frac{\Delta m t}{2}\right]$$

$$g_-(t) = e^{-imt}\, e^{-\Gamma t/2}\left[-\sinh\frac{\Delta\Gamma t}{4}\cos\frac{\Delta m t}{2} + i\cosh\frac{\Delta\Gamma t}{4}\sin\frac{\Delta m t}{2}\right]$$

- In the $\Delta\Gamma$=0 limit:

$$|B^0(t)\rangle = e^{-(im+\Gamma/2)t}\left[\cos\frac{\Delta m t}{2}\,|B^0\rangle + i\,\frac{q}{p}\sin\frac{\Delta m t}{2}\,|\bar{B}^0\rangle\right]$$

CP

$$|\bar{B}^0(t)\rangle = e^{-(im+\Gamma/2)t}\left[\cos\frac{\Delta m t}{2}\,|B^0\rangle + i\,\frac{q^*}{p^*}\sin\frac{\Delta m t}{2}\,|\bar{B}^0\rangle\right]$$

CP violation in mixing

$$|B^0\rangle \;\ldots\ldots t \ldots\ldots \;\; \beta\,|\bar{B}^0\rangle \quad \Rightarrow \beta = (q/p)\; g_-(t)$$
$$|\bar{B}^0\rangle \;\ldots\ldots t \ldots\ldots \;\; \bar{\beta}\,|B^0\rangle \quad \Rightarrow \bar{\beta} = (p/q)\; g_-(t)$$

- if $|\beta| \neq |\bar{\beta}|$, it is possible to measure CPV in decays to final states accessible only to B^0 or $\bar{B}^0$

$$|\beta| \neq |\bar{\beta}| \Leftrightarrow \left|\frac{q}{p}\right|^2 \neq 1$$

- An example is the neutral semileptonic decay asymmetry to wrong sign leptons:

$$a_{sl}(t) \;=\; \frac{\Gamma(\bar{B}^0(t) \to \ell^+\nu X) - \Gamma(B^0(t) \to \ell^-\bar{\nu} X)}{\Gamma(\bar{B}^0(t) \to \ell^+\nu X) + \Gamma(B^0(t) \to \ell^-\bar{\nu} X)}$$

CP violation in mixing

- Only 2 amplitudes do not vanish:

$$A = \langle \ell^+ \nu X | \mathcal{H}^d | B^0 \rangle \qquad \bar{A} = \langle \ell^- \bar{\nu} X | \mathcal{H}^d | \bar{B}^0 \rangle$$

- Their magnitude is the same: $|A|^2 = |\bar{A}|^2$

- The time dependent rates are:

$$\Gamma(\bar{B}^0(t) \to \ell^+ \nu X) = \left| \frac{p}{q} \, g_-(t) \, A \right|^2$$

$$\Gamma(B^0(t) \to \ell^- \bar{\nu} X) = \left| \frac{q}{p} \, g_-(t) \, \bar{A} \right|^2$$

- The asymmetry is:

$$a_{sl}(t) = \frac{1 - |q/p|^4}{1 + |q/p|^4} \simeq \mathrm{Im} \frac{\Gamma_{12}}{M_{12}}$$

small
time independent
large hadronic uncertainties

CP violation in decay

- It stems from the difference between the rates for $B \to f$ and $\bar{B} \to \bar{f}$

- We need two amplitudes with different weak and strong phases:

$$A_f = A_1 e^{i(\delta_1+\phi_1)} + A_2 e^{i(\delta_2+\phi_2)}$$
$$\bar{A}_{\bar{f}} = A_1 e^{i(\delta_1-\phi_1)} + A_2 e^{i(\delta_2-\phi_2)}$$

$$\mathcal{A} = \frac{\Gamma(B \to f) - \Gamma(\bar{B} \to \bar{f})}{\Gamma(B \to f) + \Gamma(\bar{B} \to \bar{f})}$$
$$= -\frac{2A_1A_2 \sin(\delta_2-\delta_1)\sin(\phi_2-\phi_1)}{A_1^2 + A_2^2 + 2A_1A_2\cos(\delta_2-\delta_1)\cos(\phi_2-\phi_1)}$$

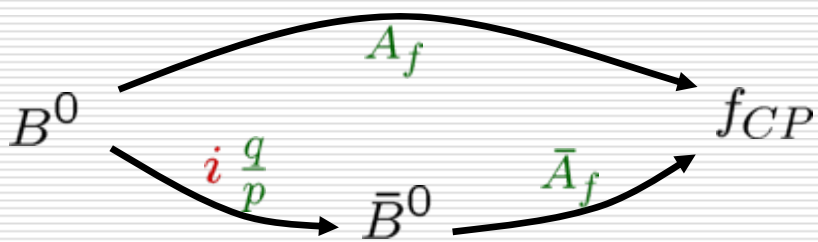
- We A_1, A_2 and δ_1-δ_2: all these quantities are sensitive to nonperturbative QCD

Interference in decays with and without and mixing

- We look at the time dependent CP asymmetries of neutral B decays to final states that are CP eigenstate:

$$\mathcal{A}_{f_{CP}} = \frac{\Gamma(\bar{B}^0(t) \to f_{CP}) - \Gamma(B^0(t) \to f_{CP})}{\Gamma(\bar{B}^0(t) \to f_{CP}) + \Gamma(B^0(t) \to f_{CP})}$$

- Same as CPV in decay, the only difference is that $|\bar{f}\rangle = \eta_f \, |f\rangle$
- *We need two amplitudes, with different weak and strong phases!*
- More amplitudes usually implies non-perturbative trouble...
- Even if $|A(B^0 \to f)| = |A(\bar{B}^0 \to f)|$ we can use $B^0 \to f_{CP}$ and $B^0 \to \bar{B}^0 \to f_{CP}$



A_f vs $i\frac{q}{p}\bar{A}_f$

Interference in decays with and without and mixing

- $A_f = Ae^{i\delta + i\phi}$

$$i\frac{q}{p}\bar{A}_f = A\left|\frac{q}{p}\right|e^{i[\delta+\frac{\pi}{2}]+i[\arg\frac{q}{p}-\phi]} = iA_f \underbrace{\frac{q}{p}\frac{\bar{A}_f}{A_f}}_{\equiv\lambda_f}$$

- In formulae:

$$\begin{aligned} A_{f_{CP}} &= \frac{\Gamma(\bar{B}^0(t)\to f) - \Gamma(B^0(t)\to f)}{\Gamma(\bar{B}^0(t)\to f) + \Gamma(B^0(t)\to f)} \\ &= \underbrace{\frac{2\mathrm{Im}\lambda_f}{1+|\lambda_f|^2}}_{S_f}\sin(\Delta m\, t) - \underbrace{\frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}}_{C_f}\cos(\Delta m\, t) \end{aligned}$$

- If $|\lambda_f| = 1$ we get:

$$A_{f_{CP}} = \mathrm{Im}\lambda_f \sin(\Delta m\, t)$$

The three types of CP violation

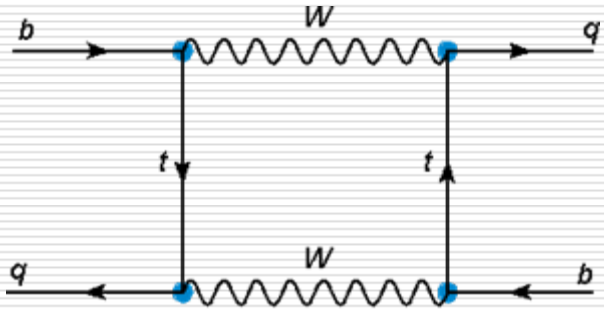
- There are three quantities that drive CPV effects:

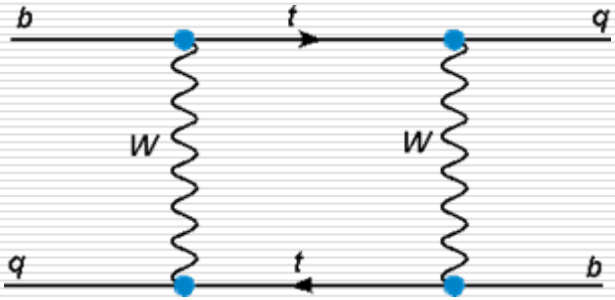
$$\left|\frac{q}{p}\right|, \quad \left|\frac{\bar{A}_{\bar{f}}}{A_f}\right|, \quad \lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

- CPV in mixing: $|q/p| \neq 1$
- CPV in decay: $|\bar{A}_{\bar{f}}/A_f| \neq 1$
- CPV in the interference between decay and mixing: $\lambda_f \neq \pm 1$

Calculation of M_{12}

- $\Delta B=2$ transitions need to go through a W loop





- As usual we write an effective Hamiltonian that captures the SD physics:

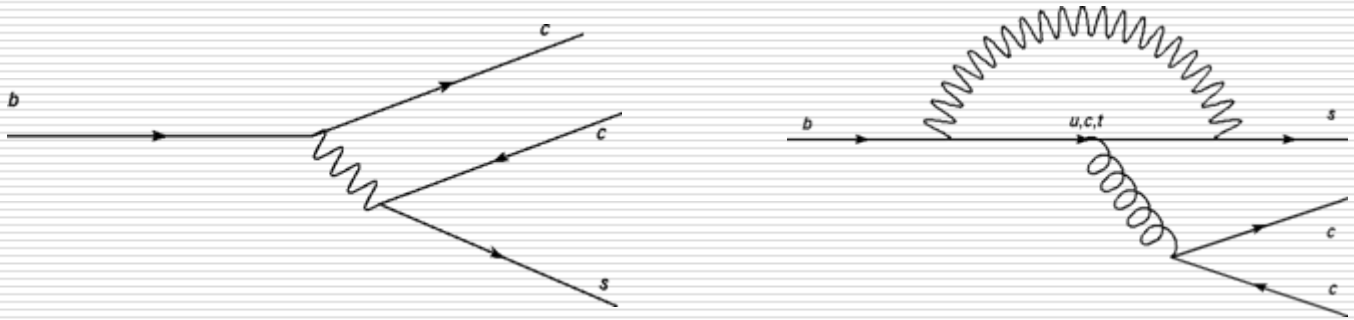
$$M_{12} = \frac{G_F^2 m_W^2}{12\pi^2} \eta_B m_B \left(f_B^2 \hat{B}_B\right) S_0\left(\frac{m_t^2}{m_W^2}\right) (V_{tb}V_{tq}^*)^2$$

$$\Delta m_B = \frac{G_F^2 m_W^2}{6\pi^2} \eta_B m_B \left(f_B^2 \hat{B}_B\right) S_0\left(\frac{m_t^2}{m_W^2}\right) \left|V_{tb}^* V_{tq}\right|^2$$

$$\frac{q}{p} = -\frac{(V_{tb}^* V_{tq})^2}{|V_{tb}^* V_{tq}|^2} = \begin{cases} -e^{-2i\beta} & \text{q=d} \\ -e^{-2i\beta_s} & \text{q=s} \end{cases}$$

$B \to J/\Psi K_s$

- This process is mediated by both tree and penguin operators:



$$A = (T_{c\bar{c}s} + P_s^c - P_s^t)\, V_{cb}V_{cs}^* + \underbrace{(P_s^u - P_s^t)\, V_{ub}V_{us}^*}_{\text{penguin pollution}}$$

- The last term is doubly suppressed:

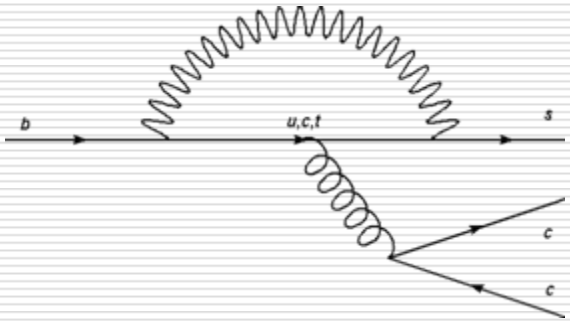
$$\frac{V_{ub}V_{us}^*}{V_{cb}V_{cs}^*} \simeq 10^{-2}$$

$$P/T \sim O(0.1)$$

$$\Rightarrow \quad \frac{A(B^0 \to J/\psi K^0)}{A(\bar{B}^0 \to J/\psi \bar{K}^0)} \simeq \frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}}$$

$B \to \phi K_s$

- This process is mediated by penguin operators only:



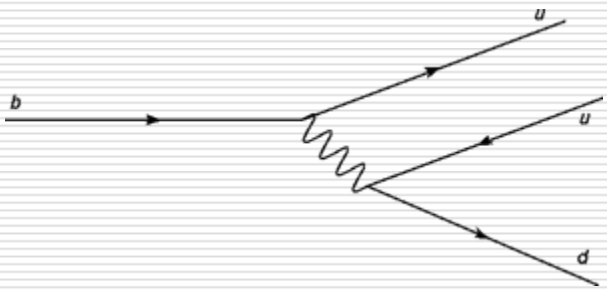
$$A = (P_s^c - P_s^t)\, V_{cb}V_{cs}^* + (P_s^u - P_s^t)\, V_{ub}V_{us}^*$$

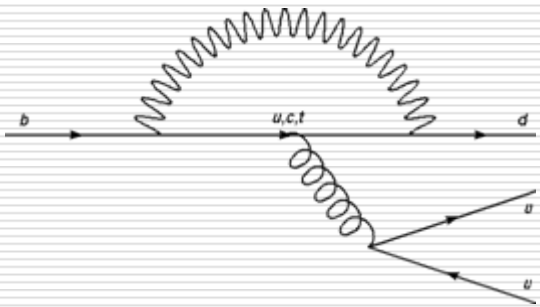
- The last term is only CKM suppressed:

$$\frac{V_{ub}V_{us}^*}{V_{cb}V_{cs}^*} \simeq 10^{-2} \quad \Rightarrow \quad \frac{A(B^0 \to \phi K^0)}{A(\bar{B}^0 \to \phi \bar{K}^0)} \simeq \frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}} + O(??)$$

$B \to \pi\pi$

- This process is mediated by both tree and penguin operators:





$$A = T_{\pi\pi}\, V_{ub}V_{ud}^* + \underbrace{P_{\pi\pi}\, V_{tb}V_{td}^*}_{\text{penguin pollution}} = T_{\pi\pi}\, V_{ub}V_{ud}^*\,(1 + r_{\pi\pi}\,\kappa)$$

- Is the last term suppressed?

$$\left|\frac{V_{tb}V_{td}^*}{V_{ub}V_{ud}^*}\right| \sim 2$$

$$r_{\pi\pi} \sim O(0.1)$$

$$\frac{A(B^0 \to \pi\pi)}{A(\bar{B}^0 \to \pi\pi)} \simeq \frac{V_{ub}V_{ud}^*}{V_{ub}^*V_{ud}}\,\underbrace{\frac{1 + r_{\pi\pi}\,\kappa}{1 + r_{\pi\pi}\,\kappa^*}}_{O(1)}$$

Extraction of CKM angles

- For $B \to J/\psi(\phi) K_s$ we have:

$$\lambda_{\psi K_s} = \frac{q}{p}\frac{A_{\psi K^0}}{\bar{A}_{\psi \bar{K}^0}}\frac{p_K}{q_K} = \eta_{\psi K_s}\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}}\frac{V_{cs} V_{cd}^*}{V_{cs}^* V_{cd}} = \eta_{\psi K_s} e^{-2i\beta}$$

$$\begin{aligned}\mathcal{A}_{\psi K_s} &= \frac{\Gamma(\bar{B}^0(t) \to J/\psi K_s) - \Gamma(B^0(t) \to J/\psi K_s)}{\Gamma(\bar{B}^0(t) \to J/\psi K_s) + \Gamma(B^0(t) \to J/\psi K_s)} \\ &= -\eta_{\psi K_s} \sin(2\beta)\ \sin(\Delta m_{B_d} t)\end{aligned}$$

- For $B \to \pi\pi$ we have:

$$\lambda_{\pi\pi} = \frac{q}{p}\frac{A_{\pi\pi}}{\bar{A}_{\pi\pi}} = \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\frac{V_{ub} V_{ud}^*}{V_{ub}^* V_{ud}}\frac{1 + r_{\pi\pi}\,\kappa}{1 + r_{\pi\pi}\,\kappa^*} = e^{2i\alpha}\frac{1 + r_{\pi\pi}\,\kappa}{1 + r_{\pi\pi}\,\kappa^*}$$

$$\begin{aligned}\mathcal{A}_{\pi\pi} &= -C_{\pi\pi}\ \cos(\Delta m_{B_d} t) + S_{\pi\pi}\ \sin(\Delta m_{B_d} t) \\ S_{\pi\pi} &= \sin(2\alpha) + O(r_{\pi\pi}) \\ C_{\pi\pi} &= O(r_{\pi\pi})\end{aligned}$$

New Physics effects

General considerations

- The Standard Model is the most general renormalizable theory given its particle content

- New physics enters via new particles:
  - Higgs bosons
  - fermions
  - scalars
  - gauge bosons

- In order to escape present bounds, new particles can be
  - very heavy with large couplings (e.g. stop)
  - relatively lighter with smaller couplings (e.g. neutralino)

- If masses are larger than energies presently accessible we have to look for virtual effects

- In order for these effects to be visible we have to look for processes that are suppressed within the Standard Model

General considerations

- Interesting processes:
  - rare decays
  - CP asymmetries
  - proton decay (accidentally protected in the SM)
  - neutrino oscillations
  - dark matter
  - muon anomalous magnetic moment
  - ....
- Hadronic uncertainties might be large enough to hide a possible new physics signal

Example: a fourth generation

- We have now eight quarks:

$$\mathcal{L} = \underbrace{\bar{U}_R\, i\not{D}\, U_R + \bar{D}_R\, i\not{D}\, D_R + \bar{Q}_L\, i\not{D}\, Q_L}_{\text{invariant under } U_R \to R_u\, U_R\,,\; D_R \to R_d\, D_R \text{ and } Q_L \to S_u\, Q_L} - \left(\bar{Q}_L\, \tilde{\phi}\, \hat{y}^u U_R + \bar{Q}_L\, \phi\, \hat{y}^d D_R + \text{h.c.}\right)$$

where $R_u\,,\, R_d\,,\, S_u \in U(4)$

- Using this U(4)^3 symmetry we can write:

$$\begin{aligned}\mathcal{L} \;=\; & \bar{U}'_R\, i\not{D}\, U'_R + \bar{D}'_R\, i\not{D}\, D'_R + \bar{Q}'_L\, i\not{D}\, Q'_L \\ & -\left(\bar{Q}'_L\, \tilde{\phi}\, y^u\, U'_R + \bar{Q}'_L\, \phi\, V y^d\, D'_R + \text{h.c.}\right).\end{aligned}$$

4x4 CKM matrix

- The eight quark masses are:

$$m_u = \frac{v}{\sqrt{2}} y_u, \quad m_d = \frac{v}{\sqrt{2}} y_d$$

Example: a fourth generation

- Mass eigenstate basis:

$$\begin{pmatrix} U_L \\ D_L \end{pmatrix} \to \begin{pmatrix} U_L \\ V D_L \end{pmatrix}$$

$$-\bar{U}_L m^u U_R - \bar{D}_L V m^d D_R + \text{h.c.} \to -\bar{U}_L m^u U_R - \bar{D}_L m^d D_R + \text{h.c.}$$

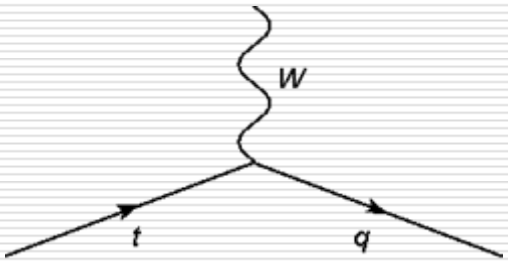
- There are no Flavor Changing Neutral Currents

$$a_R\, \bar{D}_R \not{Z} D_R + a_L\, \bar{D}_L \not{Z} D_L \to a_R\, \bar{D}_R \not{Z} D_R + a_L\, \bar{D}_L \underbrace{V^\dagger \not{Z} V}_{\not{Z}} D_L$$

- Flavour Changing Charged Currents follow a pattern similar to the SM:

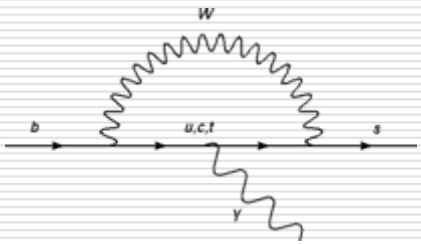
$$-\frac{g_2}{\sqrt{2}}\left[\bar{U}_L \not{W}^+ D_L + \bar{D}_L \not{W}^- U_L\right] \to -\frac{g_2}{\sqrt{2}}\left[\bar{U}_L \not{W}^+ V D_L + \bar{D}_L V^\dagger \not{W}^- U_L\right]$$

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{uB} \\ V_{cd} & V_{cs} & V_{cb} & V_{cB} \\ V_{td} & V_{ts} & V_{tb} & V_{tB} \\ V_{Td} & V_{Ts} & V_{Tb} & V_{TB} \end{pmatrix}$$



Example: a fourth generation

- What happens to the 9 entries of the standard CKM matrix?
- Some entries have been measured directly (tree level decays proportional to a single coupling). Since the fourth generation is necessarily heavy, these direct determinations are still valid.
- On V_{td} and V_{ts} we have only indirect constraints (i.e. Δm_B, $b \rightarrow s\gamma$, ...)
- Note that loop processes are always proportional to combination of CKM entries:



$$\propto V_{tb}^{*} V_{ts}$$

- Before the measurement of V_{tb}, it was possible to arrange the masses and couplings of the 4th generation in such a way that V_{tb} as small as 0.1 was possible.

Example: a fourth generation

- Physical parameters in the 4x4 CKM matrix:

$$4n_f^2 - (3n_f^2 - 1) = \underset{y^u}{n_f} + \underset{y^d}{n_f} + \underset{V}{(n_f - 1)^2}$$

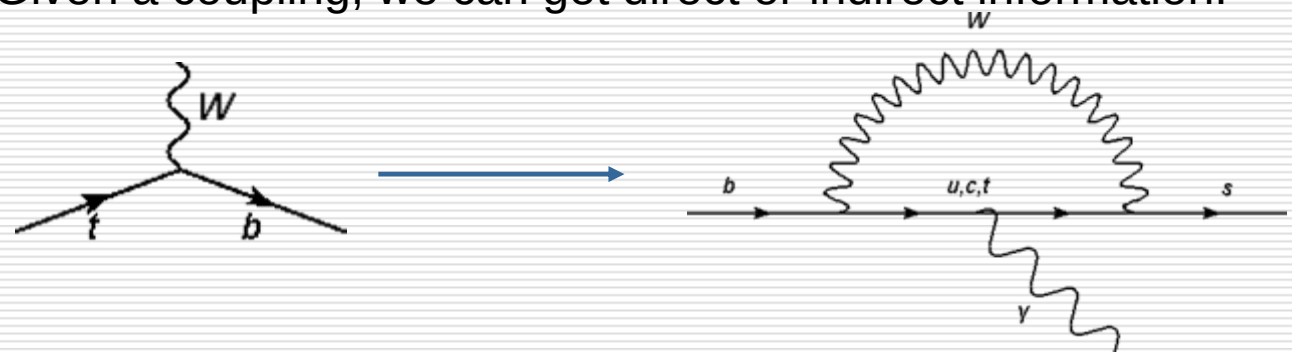
Separating angles and phases in V we get:

$$(n_f - 1)^2 = \underbrace{n_f(n_f - 1)/2}_{\text{6 real}} + \underbrace{(n_f - 1)(n_f - 2)/2}_{\text{3 imaginary}}$$

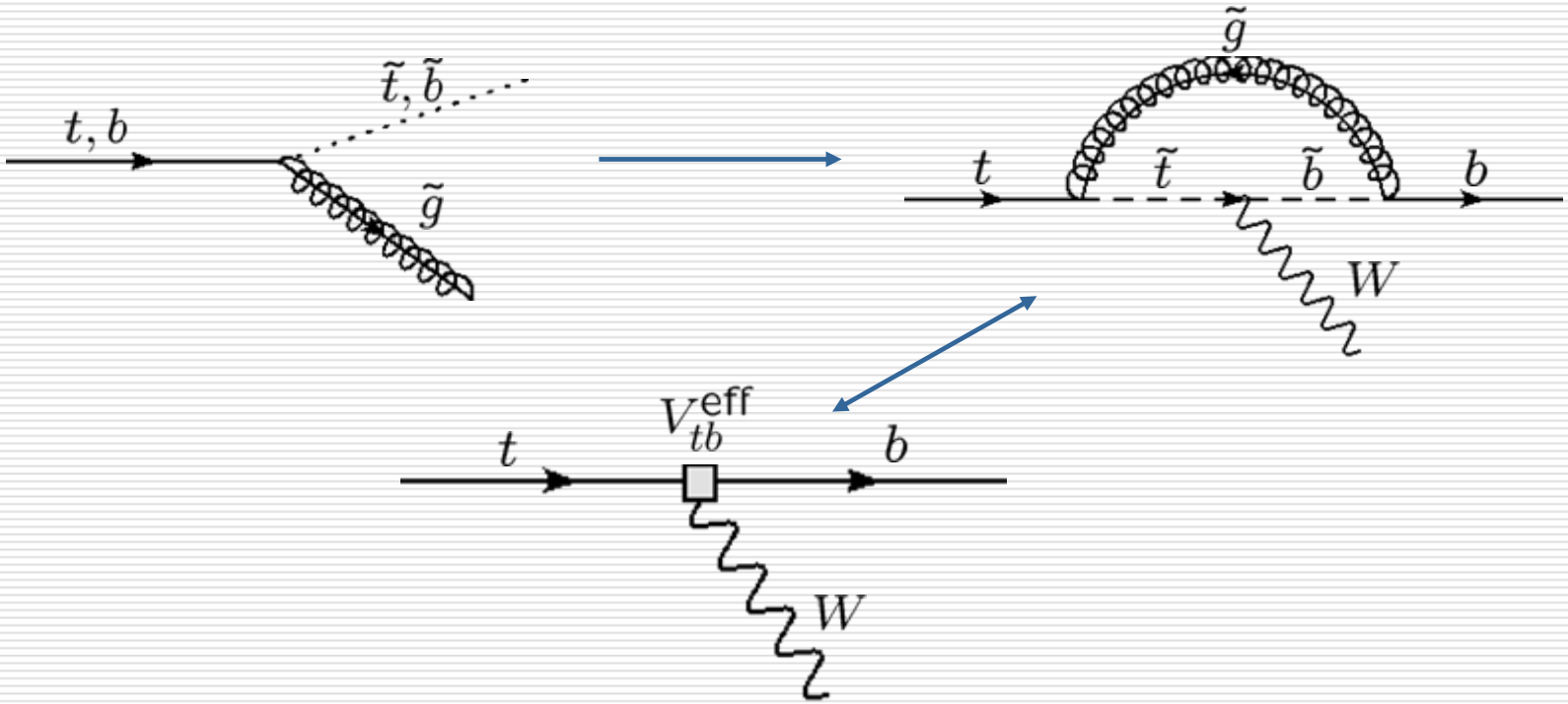
- What part of the phenomenology might drastically change?
  - CP asymmetries
  - Unitarity triangle fits (the 3x3 u-c-t submatrix is not unitary anymore)
- Smoking gun: direct production and detection of 4th generation quarks

More on loop effects

- Given a coupling, we can get direct or indirect information:

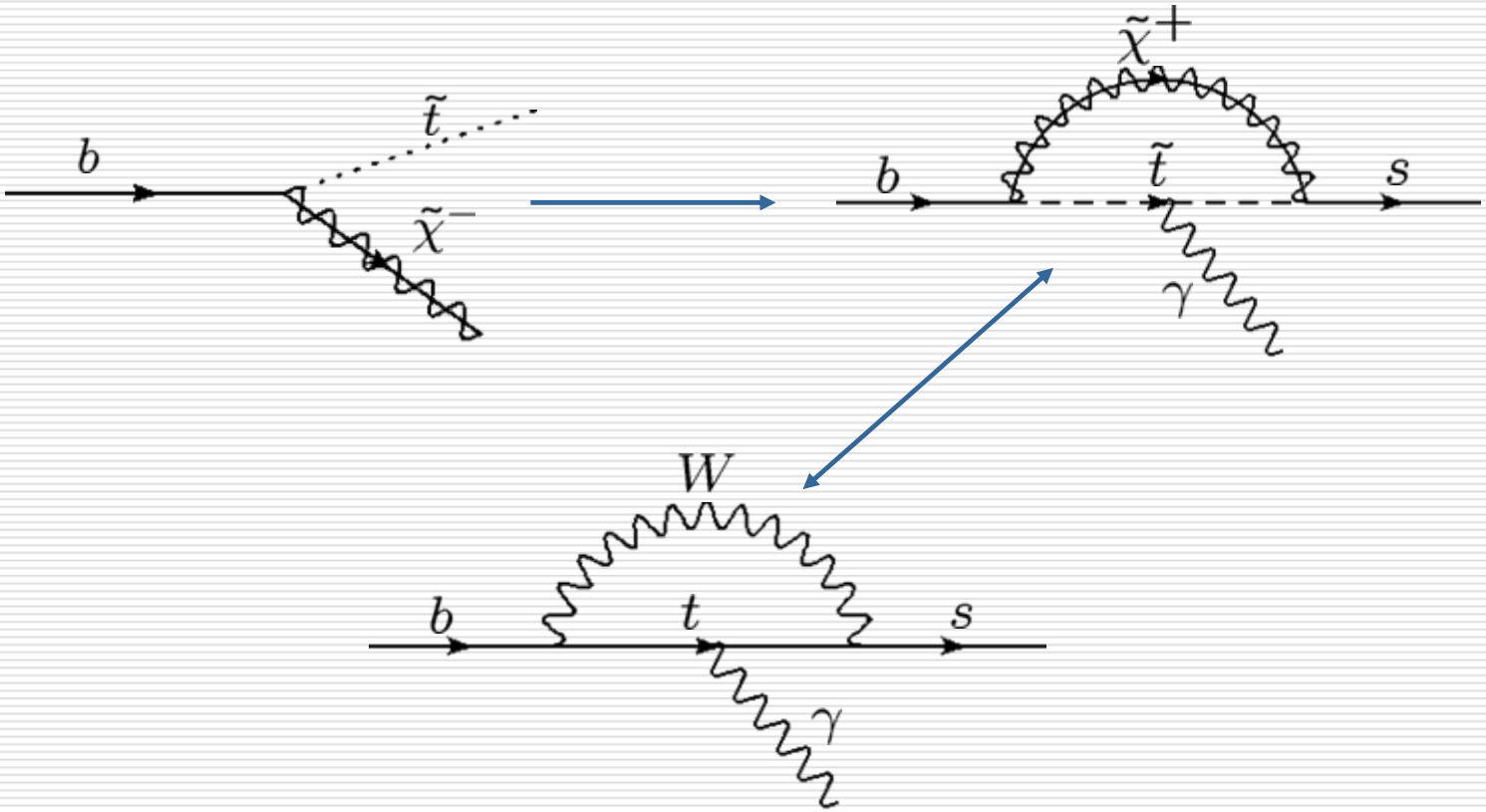


- Kinematically forbidden flavor-conserving interactions:



More on loop effects

- Kinematically forbidden flavor-changing interactions:



- The SM contribution is loop and CKM suppressed
- CKM-like new physics contributions are sizable even with heavy new particles. If the t-s coupling is not suppressed, this new physics diagram easily outguns the SM one.

The delicate structure

- The SM pattern of Flavor Changing Neutral Currents and CP violation follows directly from the choice of using one single Higgs doublet to give masses to all the fermions

- The two Yukawas (that contain 36 real parameters) break almost completely the flavor symmetry of the SM: U(3)xU(3)xU(3)→U(1). Because of the latter, 26 of the 36 parameters are unphysical.

- The introduction of additional fields capable of interacting with quarks, lead often to new flavor changing interactions. The latter cannot be usually rotated away since we already used all the freedom allowed by the $U(3)^3$ symmetry to simplify the Yukawas.

- *The SM has a very delicate structure: almost any addition to it will result in a proliferation of flavor changing interactions and CP violating phases.*

Why one doublet?

- For *phenomenological* reasons we *needed* to introduce LR interactions among fermion fields:

$$\bar{Q}_L \, \phi \, \hat{y}^d \, D_R \qquad\qquad \bar{Q}_L \, \tilde{\phi} \, \hat{y}^u \, U_R$$

$Y_Q = \frac{1}{6}$ $\quad Y_\phi = \frac{1}{2}$ $\quad Y_D = -\frac{1}{3}$ $\qquad\qquad$ $Y_Q = \frac{1}{6}$ $\quad Y_{\tilde{\phi}} = -\frac{1}{2}$ $\quad Y_D = \frac{2}{3}$

- The hypercharges of the two Higgs doublets are opposite to each other and we decided to use one doublet only:

$$\tilde{\phi} \equiv i\sigma_2 \phi^* = \begin{pmatrix} \bar{\phi}^0 \\ -\phi^- \end{pmatrix}$$

- This choice does not follow from any symmetry or principle, it is just the minimal option

- We are completely free to add more doublets (not so for triplets)

The Two-Higgs Doublet Model (2HDM)

- Let us introduce two Higgses with opposite Hypercharge: ϕ_1 and ϕ_2

- After electroweak symmetry breaking 3 of their 8 degrees of freedom will be eaten by the W and Z, the other 5 remain physical.

- The Higgs spectrum contains now a charged Higgs ($H^{\pm}$), a pseudo-scalar Higgs (A), and two scalar Higgses (h, H)

- The neutral components of *both* Higgs doublets acquire a vacuum expectation value:

$$|\langle\phi_1\rangle| = \begin{pmatrix} 0 \\ v_1/\sqrt{2} \end{pmatrix} \qquad |\langle\phi_2\rangle| = \begin{pmatrix} v_2/\sqrt{2} \\ 0 \end{pmatrix} \qquad \tan\beta = \frac{v_2}{v_1}$$

- Additional parameters up to now:
  - $m_{H^{\pm}}$, m_A, m_H
  - $\tan\beta$
  - α (mixing angle between H and h)

The Two-Higgs Doublet Model (2HDM)

- Now we have to decide how to couple the Higgs doublets to the quarks
  - Type-I : ϕ_1 couples to up and down quarks, ϕ_2 doesn't couple to quarks

$$\mathcal{L}_{\text{type-I}} = -\bar{Q}_L\, \phi_1\, \hat{y}^d\, D_R - \bar{Q}_L\, \tilde{\phi}_1\, \hat{y}^u\, U_R$$

  - Type-II : ϕ_1 couples to the up quarks, ϕ_2 to the down quarks

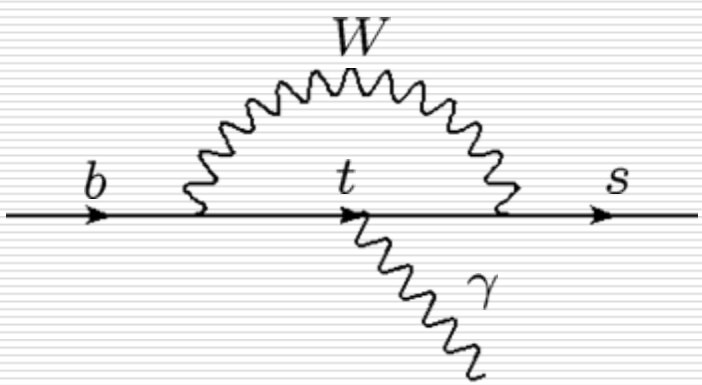
$$\mathcal{L}_{\text{type-II}} = -\bar{Q}_L\, \phi_1\, \hat{y}^d\, D_R - \bar{Q}_L\, \phi_2\, \hat{y}^u\, U_R$$

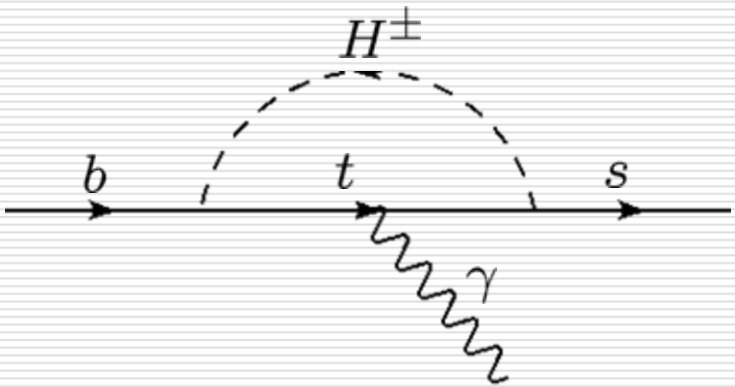
  - Type-III: both doublets couple to up and down quarks

$$\begin{aligned}\mathcal{L}_{\text{type-III}} \;=\; & -\bar{Q}_L\, \phi_1\, \hat{y}_1^d\, D_R - \bar{Q}_L\, \tilde{\phi}_1\, \hat{y}_1^u\, U_R \\ & -\bar{Q}_L\, \tilde{\phi}_2\, \hat{y}_2^d\, D_R - \bar{Q}_L\, \phi_2\, \hat{y}_2^u\, U_R\end{aligned}$$

The Two-Higgs Doublet Model: type-II

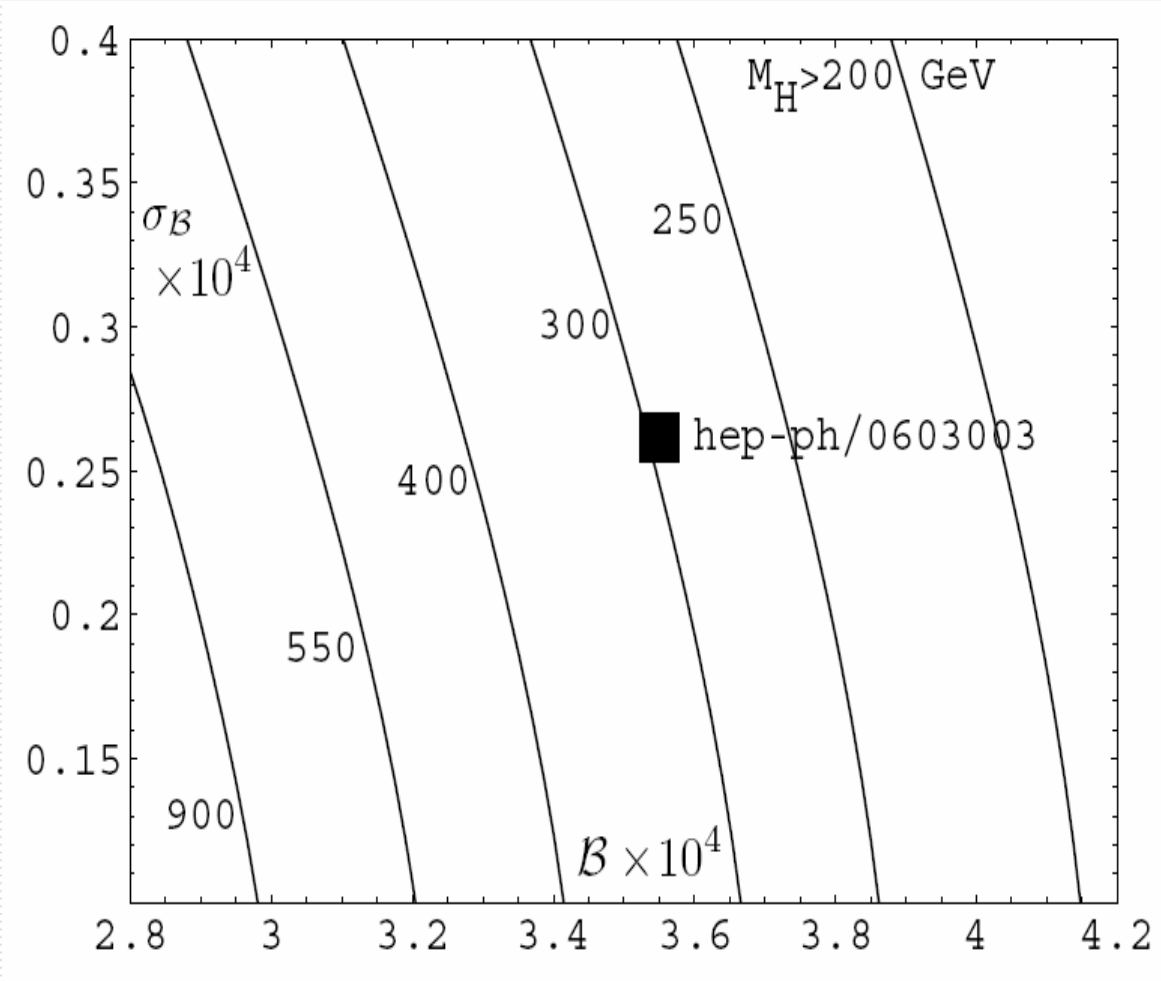
- We have again only two arbitrary complex Yukawas:
  - the CKM matrix is again the only source of flavor changing interactions
  - there are no Flavor Changing Neutral Currents
  - *we have new Flavor Changing Charged Currents (charged Higgs)*
- Charged Higgs FC interactions are CKM-like
- Charged Higgs loops contribute to several rare decays:





The Two-Higgs Doublet Model: type-II

- Rare decays put a strong constraint on the charged Higgs mass:



[Misiak et al., 06]

The Two-Higgs Doublet Model: type-III

- The (non-diagonal) quark mass matrices are:

$$\hat{m}_u = \frac{v_1}{\sqrt{2}}\hat{y}_1^u + \frac{v_2}{\sqrt{2}}\hat{y}_2^u, \quad \hat{m}_d = \frac{v_1}{\sqrt{2}}\hat{y}_1^d + \frac{v_2}{\sqrt{2}}\hat{y}_2^d$$

- In the mass eigenstate basis:
  - The unitary transformations that diagonalize the mass matrices do not diagonalize any of the four Yukawa matrices

$$S_u^\dagger \left(\frac{v_1}{\sqrt{2}}\hat{y}_1^u + \frac{v_2}{\sqrt{2}}\hat{y}_2^u \right) R_u = m_u^{\text{diag}} \quad \not\Rightarrow \quad S_u^\dagger \, \hat{y}_{1,2}^u \, R_u = y_{1,2}^{u,\text{diag}}$$

  - Unitarity again leads to the cancellation of flavor changing neutral currents involving gauge bosons

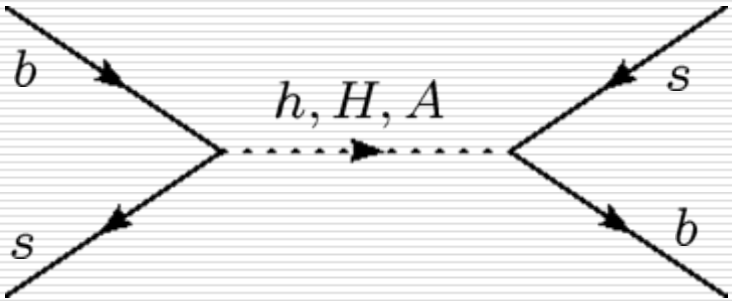
  - The CKM matrix again appears in the W vertices:

$$V = S_u^\dagger S_d$$

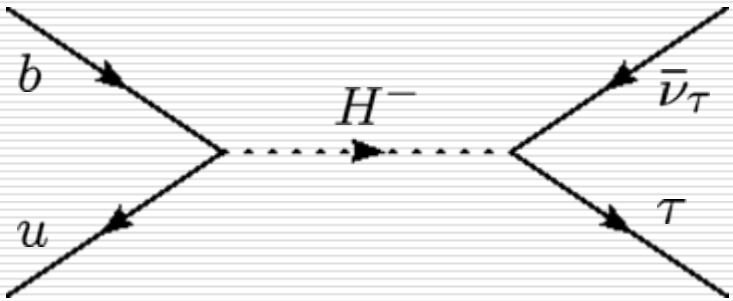
The Two-Higgs Doublet Model: type-III

- The delicate flavor structure of the SM is completely destroyed and phenomenology imposes strong constraints on the various FC and CPV parameters

- We have new flavor changing neutral and charged currents involving the neutral and charged Higgses, respectively.



Δm_{B_q}



$B^- \to \tau \bar{\nu}_\tau$

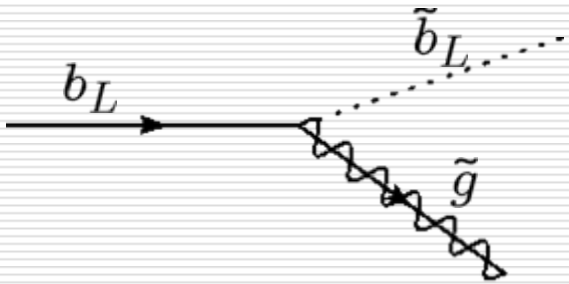
The Minimal Supersymmetric Standard Model (MSSM)

- The MSSM is the minimal SUSY theory that contains the SM gauge group and matter content
- To each SM particle is associated a sparticle
- SUSY predicts sparticles degenerate in mass with the respective particles; hence we expect SUSY to be broken at low energies
- We do not know the mechanism of SUSY breaking and we parametrize it with soft breaking terms
  - this rises the number of parameters to about 124
- A truly fundamental theory would fix most of them

The Minimal Supersymmetric Standard Model (MSSM)

- For deep reasons it is necessary to couple up and down quarks to distinct Higgs doublets (as in the 2HDM type-II)

- Particles and sparticles interact via gauge bosons (and their partners, the gauginos). As in the SM these interactions are, initially, flavor diagonal:

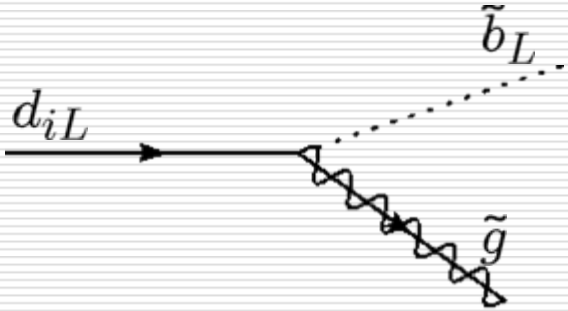


- The soft breaking terms introduce new flavor structures. Here are the terms involving the squarks:

$$\mathcal{L}_{\text{soft}}^{squarks} = \tilde{Q}^\dagger M_Q^2 \tilde{Q} + \tilde{U}^\dagger M_U^2 \tilde{U} + \tilde{D}^\dagger M_D^2 \tilde{D} + \tilde{Q} Y_U^A \phi_1 \tilde{U} + \tilde{Q} Y_D^A \phi_2 \tilde{D}$$

The Minimal Supersymmetric Standard Model (MSSM)

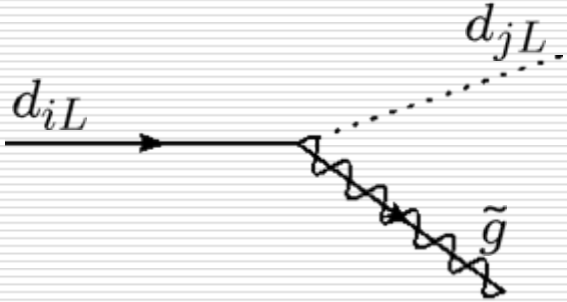
- After diagonalizing the quark Yukawas (i.e. switch to quark mass eigenstates), particle-sparticle interactions are no-longer flavor diagonal:



$$(S_d^\dagger)_{ib}$$

- Unless a miracle happens, the diagonalization of the sdown-left mass matrix will require a different matrix ($\tilde{S}_d$)

- In the quark and squark mass eigenstate basis, we have



$$(S_d^\dagger \tilde{S}_d)_{ij} \neq \delta_{ij}$$

- This is the supersymmetric flavor problem

Minimal Flavor Violation (MFV)

- In the SM the quark Yukawas are:

$$\hat{y}_u = S_u \, y_u \, R_u^\dagger$$
$$\hat{y}_d = S_u \, V y_d \, R_d^\dagger$$

  and the three unitary matrices S_u, R_u and R_d are unobservable

- In several new physics models (type-III 2HDM, MSSM, ...) these matrices become observable

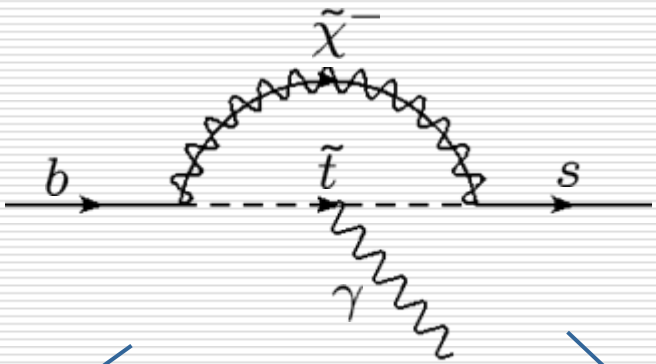
- *The MFV principle requires these matrices to remain unobservable*

- In the MSSM this implies $S_d = \tilde{S}_d$, hence the absence of extra sources of flavor changing

Minimal Flavor Violation (MFV)

- This means that all flavor changing interactions are controlled by the CKM matrix

- For instance:



General MSSM:

$$\delta_{ts}\, f(m_{\tilde{t}}/m_{\tilde{g}})$$

MSSM with MFV:

$$V_{tb}^* V_{ts}\, f(m_{\tilde{t}}/m_{\tilde{g}})$$

MFV: Model Independent Analysis

- Once we decide to walk the MFV road, the structure of new physics contributions to rare decays and CP violating observables is very strongly constrained

- With generally, MFV contributions can be absorbed in the following parameters:

$$M_{12}^{d} \to M_{12}^{d,SM}\left(1 + h_d e^{2i\sigma_d}\right) = M_{12}^{d,SM}\, r_d^2 e^{2i\theta_d}$$

$$M_{12}^{s} \to M_{12}^{s,SM}\left(1 + h_s e^{2i\sigma_s}\right) = M_{12}^{s,SM}\, r_s^2 e^{2i\theta_s}$$

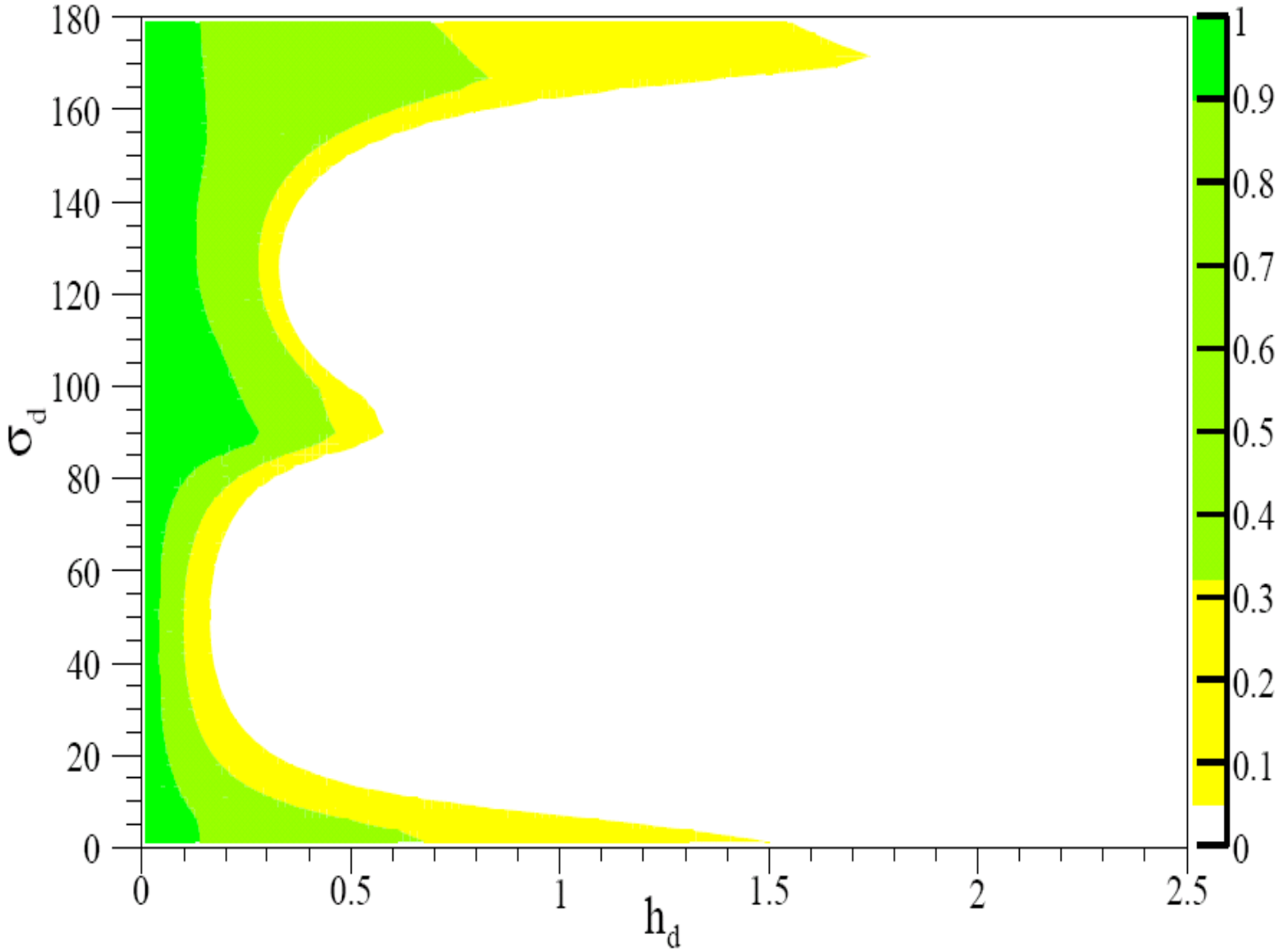
$$M_{12}^{K} \to M_{12}^{K,SM}\left(1 + h_K e^{2i\sigma_K}\right) = M_{12}^{K,SM}\, r_K^2 e^{2i\theta_K}$$

- Some predictions for several observables change:

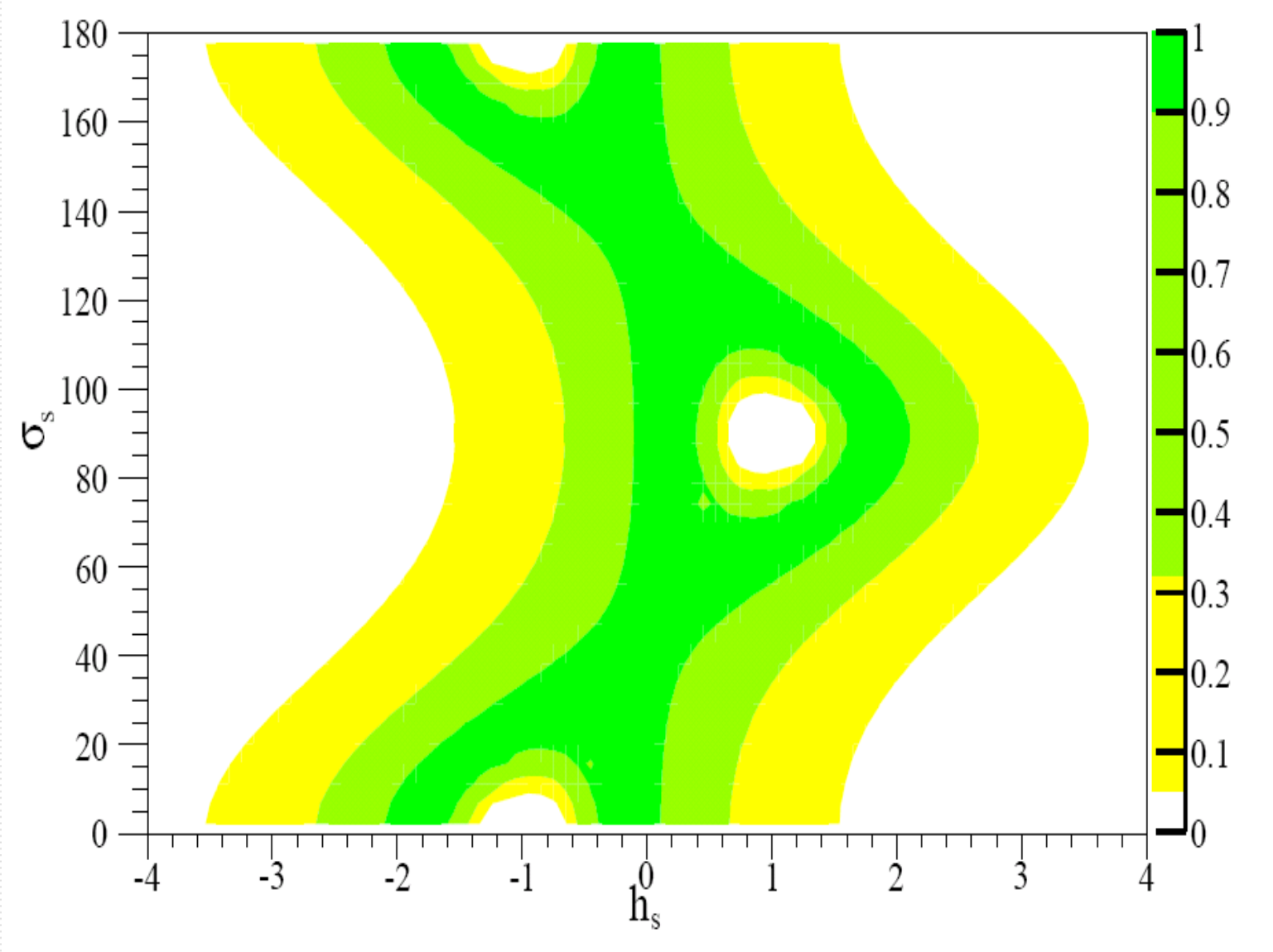
$$\Delta m_{B_d} \to \Delta m_{B_d}^{SM} r_d^2 \qquad \frac{\Delta m_{B_s}}{\Delta m_{B_d}} \to \left(\frac{\Delta m_{B_s}}{\Delta m_{B_d}}\right)^{SM} \frac{r_s^2}{r_d^2}$$

$$a_{\psi K_s} \to \sin 2(\beta + \theta_d)$$

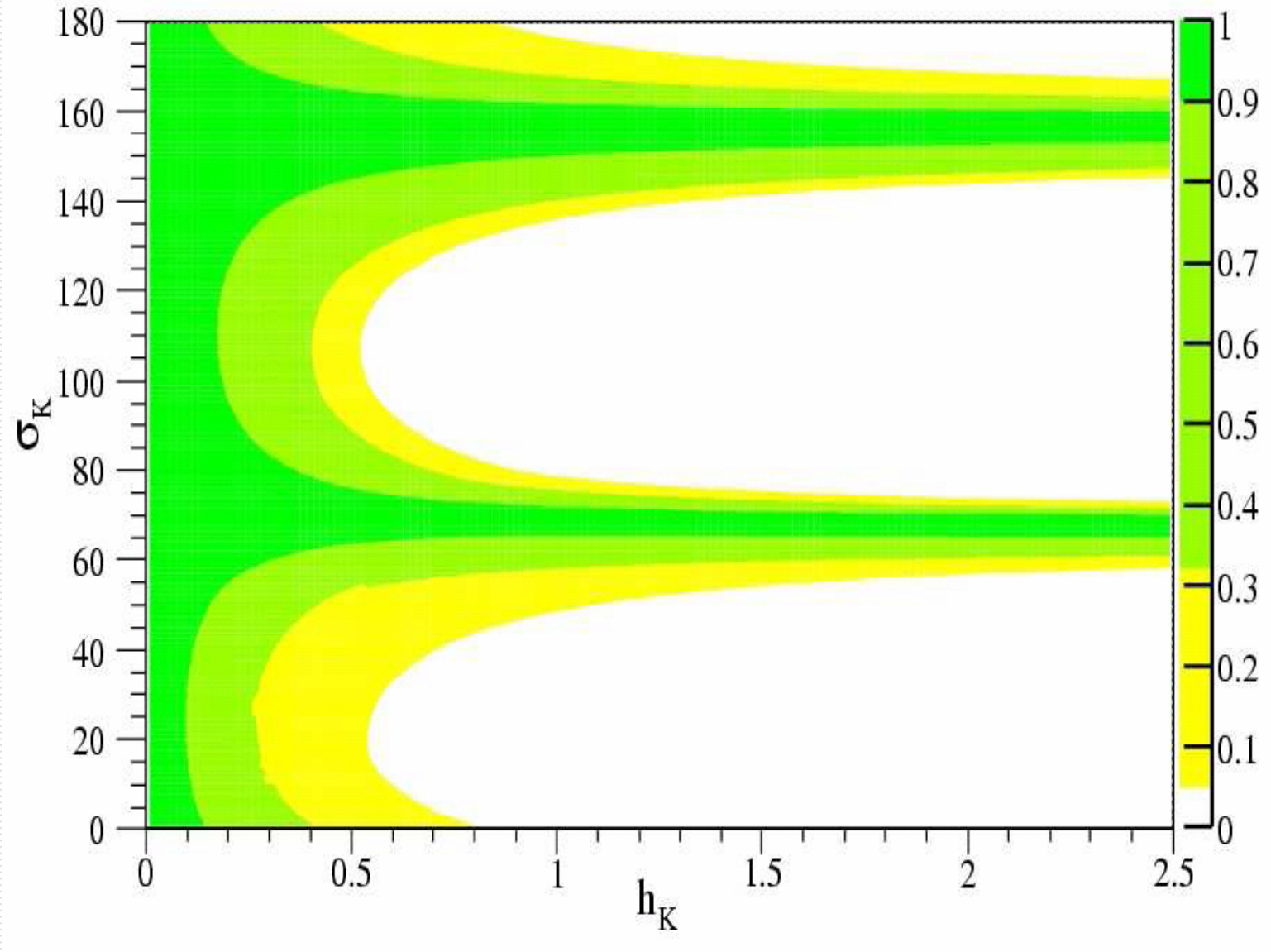
Model Independent Analysis: b→d sector (B_d)



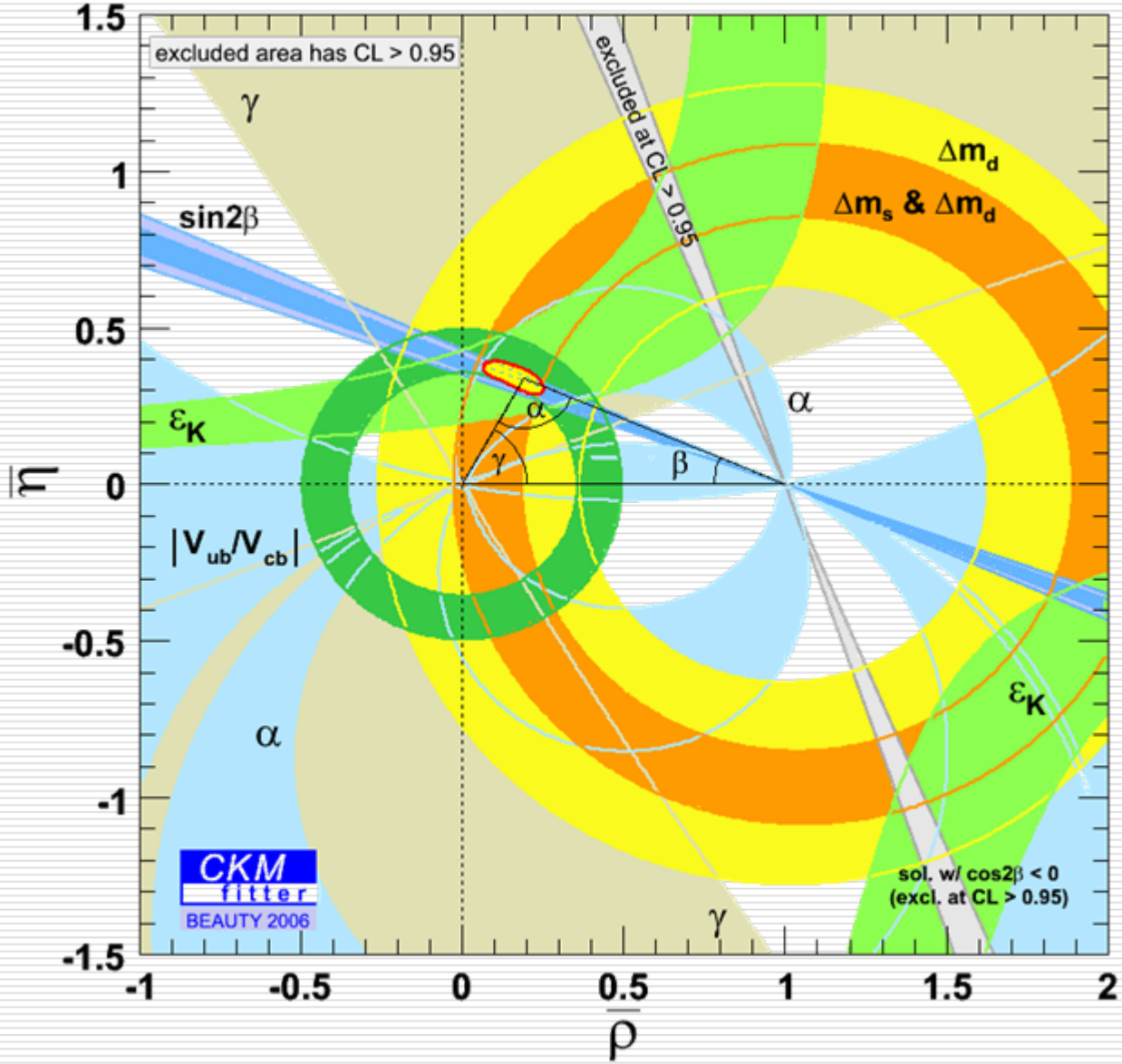
Model Independent Analysis: b→s sector (B_s)



Model Independent Analysis: s→d sector (K)



The UT fit


excluded area has CL > 0.95
excluded at CL > 0.95
γ
sin2β
Δm_d
Δm_s & Δm_d
α
ε_K
β
$|V_{ub}/V_{cb}|$
CKM fitter
BEAUTY 2006
sol. w/ cos2β < 0
(excl. at CL > 0.95)
$\bar{\eta}$
$\bar{\rho}$
1.5
1
0.5
0
-0.5
-1
-1.5
-1
-0.5
0
0.5
1
1.5
2

What do we learn?

- The Unitarity Triangle fit is a tremendous check of the CKM mechanism

- Arbitrary new physics is amazingly constrained

- If new physics is MFV (i.e. shows proper respect to the CKM) the UT fit constraints are partially lifted: in these models the scale at which new physics enters (read: the masses of the new particles) can be reasonably low.

- Complementarity between direct and indirect searches

- NP scale is identified
- little information on FC structure

- NP scale is poorly constrained
- completely explore FC interactions

Both necessary to pin down the New Standard Model