Probing Supersymmetry through Higgs, Flavor Violation and Dark Matter Searches

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- Standard Model ⟶ works too well !

explains data collected & describes processes up to energies $\approx$ 100 GeV

- What is Beyond the SM ⟶ is certainly very exciting!

Some of the key open questions:

⋆ The origin of Electroweak Symmetry breaking: The Higgs Mechanism?

How to stabilize the Higgs quantum corrections: Why $v \ll M_{Pl}$?

⋆ The nature of Dark Matter

⋆ The explanation for the observed matter-antimatter asymmetry

⋆ The connection of electroweak and strong interactions with gravity

Are there New Symmetries in Nature, as SUPERSYMMETRY, which can provide the right answers?

Collider Experiments ⟶ **Tevatron, LHC, ILC**

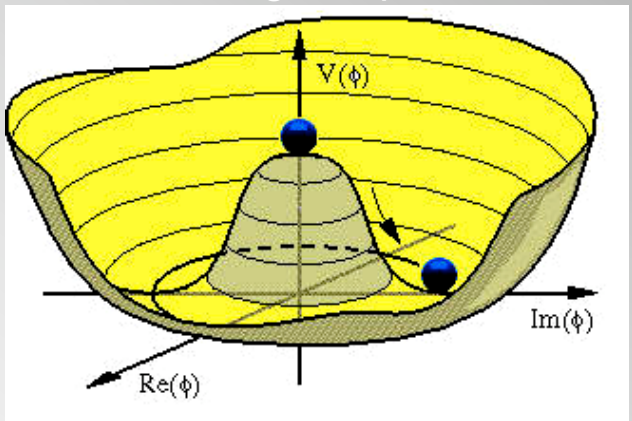
+

Dark Matter Detection Experiments ⟶ **CDMS**

==> our most robust handle to reveal the new physics that should answer these questions

In the Standard Model: The Higgs Mechanism

a self interacting complex scalar doublet with no trivial quantum numbers under $SU(2)_L \times U(1)_Y$



The Higgs field acquires a non-zero value to minimize its energy:

$$V(\phi) = -m^2\phi^2 + \frac{\lambda}{2}\phi^4$$

Higgs vacuum condensate $v \Longrightarrow$ scale of EWSB

- Spontaneous breakdown of the symmetry generates 3 massless Goldstone bosons which are absorbed to give mass to $V = W, Z$

  ⋆ interaction with gauge fields

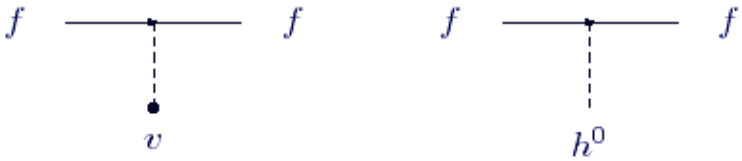
  $m_V^2 = g_{\phi\ VV}\ v/2 \quad \longrightarrow v = 174$ GeV

Higgs neutral under strong and electromagnetic interactions $\Longrightarrow$ $m_\gamma = 0$ $\quad m_g = 0$

exact symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y \quad \Longrightarrow \quad SU(3)_C \times U(1)_{em}$

⋆ mass to fermions via Yukawa interactions

$m_f = g_{\phi\ f\bar{f}}\ v$



- One state left in the spectrum: HIGGS Boson with mass $m_\phi^2 = 2\lambda v^2$

The Flavor Structure in the SM

- **The complete fermion Lagrangian**

$$\mathcal{L} = \sum_i \bar{\Psi}^i_{L,R} \mathcal{D}^\mu \gamma_\mu \Psi^i_{L,R} + \sum_{i,j} \left(\bar{\Psi}^i_L h^d_{ij} H d^j_R + \bar{\Psi}^i_L h^u_{ij} (i\sigma_2 H^*) u^j_R + h.c. \right)$$

In the mass eigenstate basis, the interactions of the Higgs field are also flavor diagonal

$$\bar{d}_i(\hat{m}_i + \hat{h}_i H) d_i, \qquad \text{with} \quad \hat{m}_i = \hat{h}_i v$$

Flavor Changing effects arise from charged currents, mixing left-handed up and down quarks:

$$\bar{u}_{L,i} V^{ij}_{CKM} \gamma_\mu d_{L,j} W^+_\mu + h.c.$$

where

$$V_{CKM} = U^\dagger_L D_L$$

- The CKM matrix is close to the identity ==> transitions between different flavors are suppressed in the SM

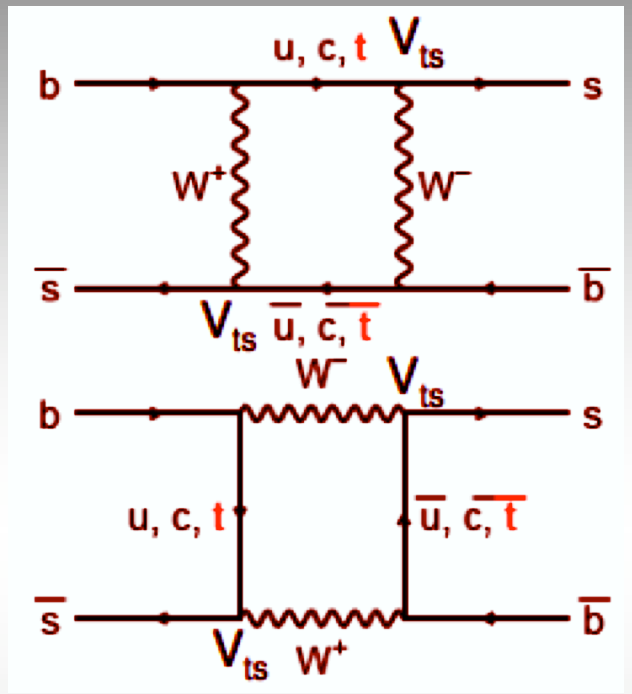
- The Higgs sector, as well as the neutral gauge interactions do not lead to FCNC

FC effects in B observables in the SM

A) Bs mixing

$$B_s^0 = (\bar{b}s) \qquad \bar{B}_s^0 = (b\bar{s})$$

Flavor eigenstates mix via weak interactions



Mass eigenstates:

$$B_H = pB_s^0 + q\bar{B}_s^0 \qquad B_L = pB_s^0 - q\bar{B}_s^0$$

B_H and B_L differ from CP eigenstates:

$$q/p = e^{-i2\beta_S} \text{ with } \beta_S = O(10^{-2})$$

The B meson mass matrix

$$M = \begin{bmatrix} M - i\Gamma/2 & M_{12} - i\Gamma_{12}/2 \\ M_{12}^* - i\Gamma_{12}^*/2 & M - i\Gamma/2 \end{bmatrix} \qquad \Gamma_{12} << M_{12}$$

$$\Delta M_s = M_{B_H} - M_{B_L} = 2\,|M_{12}| = \frac{G_F^2}{6\pi^2}\eta_B m_{B_S}\hat{B}_{B_S} f_{B_S}^2 M_W^2 S_0(m_t)\,|V_{ts}|^2$$

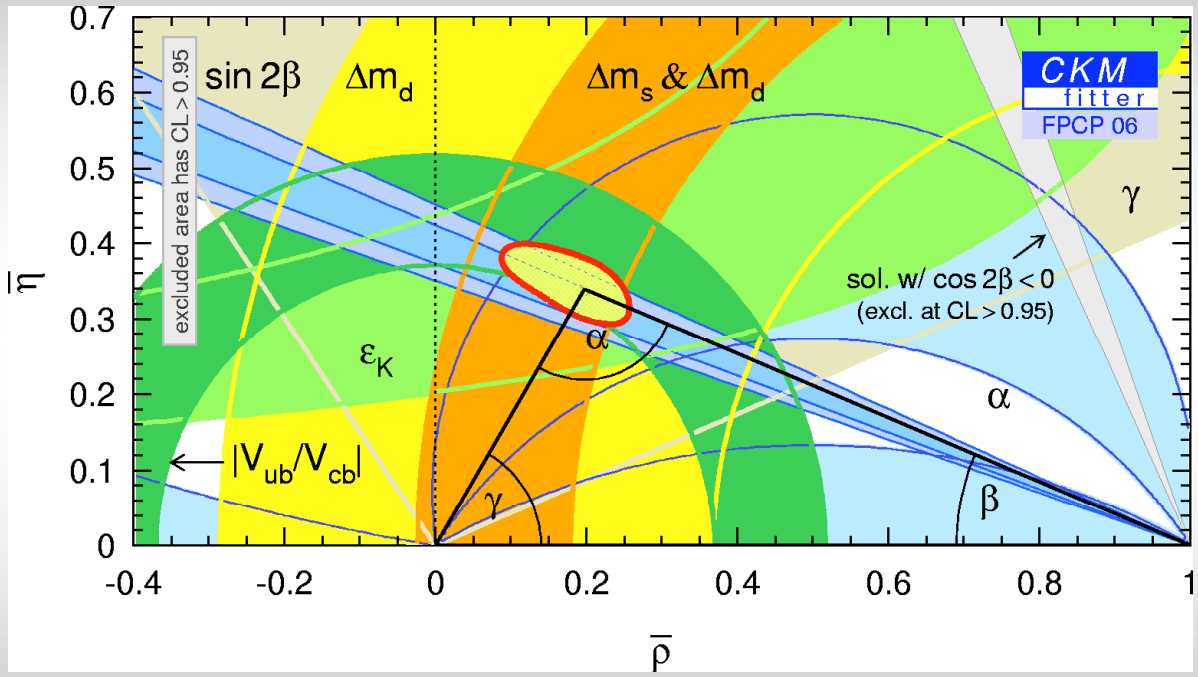
ΔM_S Direct Measurement and Global CKM Fit

$$\Delta M_S^{\text{CDF@95\%C.L.}} = 17.33^{+0.42}_{-0.21} \pm 0.07\, ps^{-1} \qquad \Delta M_S^{\text{D0@90\%C.L.}} = 17 \pm 2\, ps^{-1}$$

Using ratio

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{Bs}}{m_{Bd}} \frac{f_{Bs}^2 B_{Bs}}{f_{Bd}^2 B_{Bd}} \frac{|V_{ts}|^2}{|V_{td}|^2}$$

Minimize QCD lattice uncertainty providing a measurement of $|V_{ts}|/|V_{td}|$

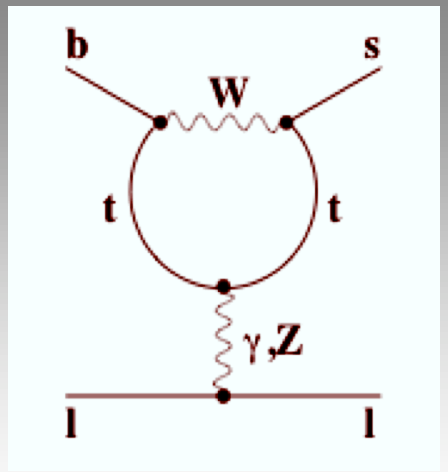


- Also, without CDF/D0 data

CMK fit $\Rightarrow \Delta M_S = 21.7^{+5.9(+9.7)}_{-4.2(-6.8)}\, ps^{-1}$ at 1(2) σ C.L. $\Rightarrow -14.1 < \Delta M_{B_s}^{NP}[ps^{-1}] < 2.4$

UT fit $\Rightarrow \Delta M_S = 21.5 \pm 2.6\, ps^{-1}$ at 1 σ C.L. $\Rightarrow -9.4 < \Delta M_{B_s}^{NP}[ps^{-1}] < 1$ at 2σ

B) Rare decay rate $B_S \to \mu^+\mu^-$

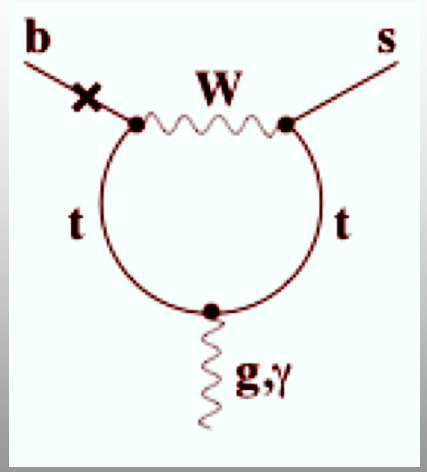


$$\text{SM amplitude} \propto V_{ts} \frac{m_\mu}{M_W}$$

$$BR(B_s \to \mu^+\mu-)_{SM} \approx (3.8 \pm 1.0)\ 10^{-9}$$

- Present CDF limit: $BR(B_s \to \mu^+\mu-) < 1.\ 10^{-7}$

C) Rare decay rate $B \to X_S\gamma$

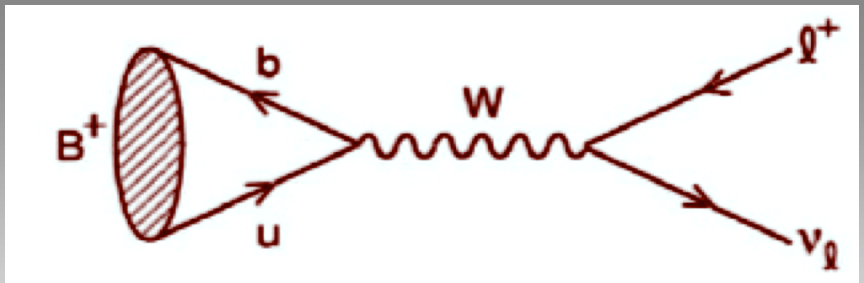


$$BR(B \to X_S\gamma)_{SM} = (3.38\ ^{+0.31}_{-0.42}\ ^{+0.32}_{-0.30})\ 10^{-4}$$

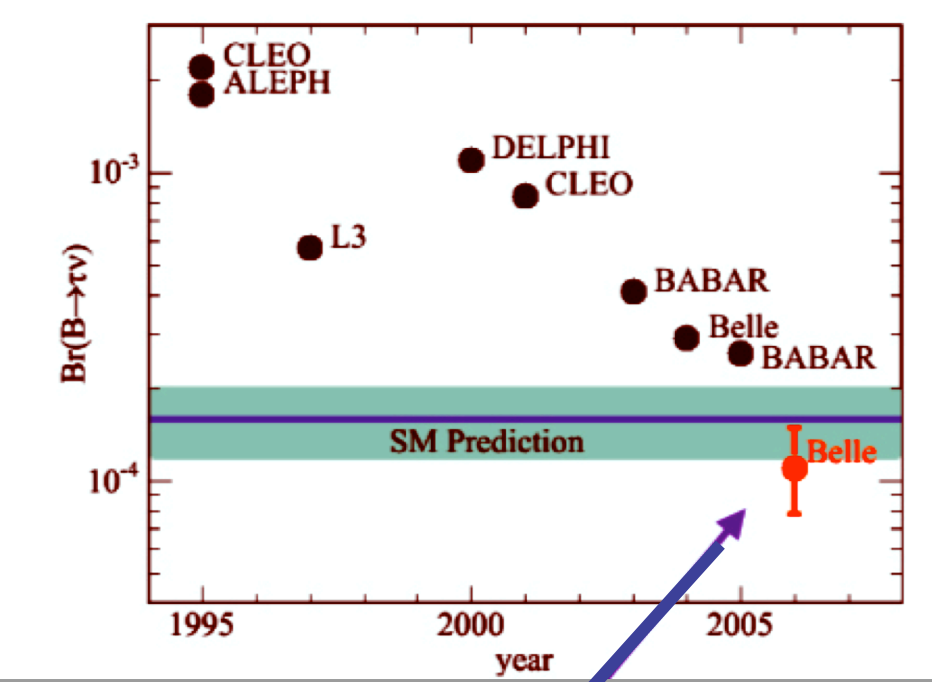
Estimated bound on New Physics using Belle results ==> Neubert 05

$$|BR(B \to X_S\gamma)^{exp} - BR(B \to X_S\gamma)^{SM}| < 1.3\ 10^{-4}$$

D) $B_u \to \tau\nu$ transition



$$BR(B_u \to \tau\nu)^{SM} = \frac{G_F^2 m_B m_\tau^2}{8\pi}\left(1-\frac{m_\tau^2}{m_B^2}\right) f_B^2 |V_{ub}|^2 \tau_B = (1.59 \pm 0.40)\ 10^{-4}$$



In agreement with SM within errors

$$BR(B_u \to \tau\nu)^{\exp} = (1.06\ ^{+0.34}_{-0.28}\ ^{+0.18}_{-0.16})\ 10^{-4}$$

Flavor Beyond the Standard Model

- **Two Higgs doublet Models:**

  Yukawa interactions ==> $\bar{d}_{R,i}\left(h^{ij}_{d,1}H_1 + h^{ij}_{d,2}H_2\right)d_{L,j}$

Both Higgs doublets acquire different v.e.v.'s and the mass matrix reads

==> $m^{ij}_d = h^{ij}_{d,1}v_1 + h^{ij}_{d,2}v_2$

Diagonalization of the mass matrix will not give diagonal Yukawa couplings

==> will induce large, usually unacceptable FCNC in the Higgs sector

Easiest solution: One Higgs doublet couples to down quarks and the other couples to up quarks only

Supersymmetry, at tree level

$$\mathcal{L} = \bar{\Psi}^i_L\left(h_{d,ij}H_1 d_R + h_{u,ij}H_2 u_R\right) + h.c.$$

Since the up and down sector are diagonalized independently, the Higgs Interactions remain flavor diagonal

The flavour problem in SUSY Theories

SUSY breaking mechanisms ==> can give rise to large FCNC effects

- Novel sfermion-gaugino-fermion interactions, e.g. for the down sector

$$\bar{d}^i_{L,R}\,\tilde{\lambda}\,\tilde{d}^j_{L,R} \rightarrow \bar{d}_{L,R} D^+_{L,R} \tilde{D}_{L,R} \tilde{\lambda}\,\tilde{d}_{L,R}$$

where $\tilde{D}_{L,R}$ come from the block diagonalization of the squark mass matrix

$$\left(\tilde{d}^{i\,*}_L\ \tilde{d}^{i\,*}_R\right) \begin{pmatrix} M_Q^2 + \mathrm{v}_1^2 h_d^+ h_d + D_{\tilde{d}_L} & \mathrm{v}_1\left(A_d - \mu^* \tan\beta\right) h_d \\ \mathrm{v}_1\left(A_d^* - \mu \tan\beta\right) h_d^+ & M_D^2 + \mathrm{v}_1^2 h_d^+ h_d + D_{\tilde{d}_R} \end{pmatrix} \begin{pmatrix} \tilde{d}^i_L \\ \tilde{d}^i_R \end{pmatrix}$$

- The diagonal entries are 3x3 matrices with M_Q^2, M_D^2 the soft SUSY breaking mass matrices and the rest proportional to the Yukawa or I
- The off diagonal matrices are proportional to the Yukawa and to the soft SUSY breaking matrices A_b coming from the trilinear interactions of the Higgs doublets with the sfermions

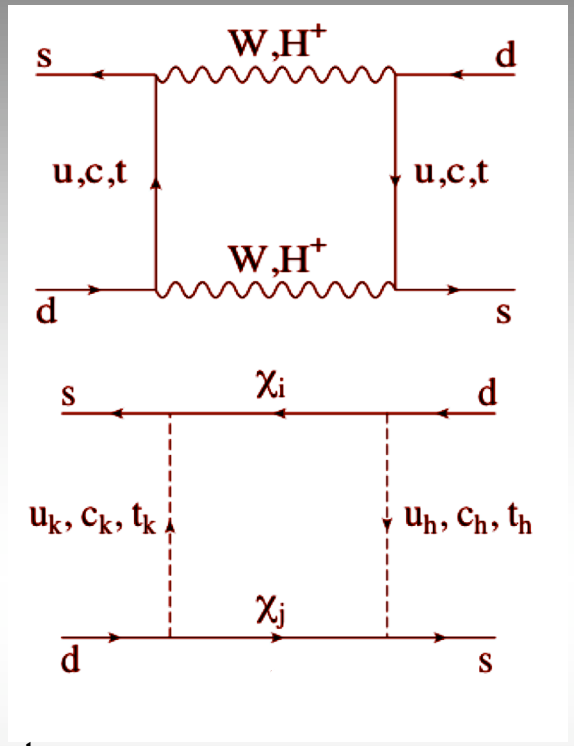
$$\tilde{u}^*_L h_u (A_u H_2 - \mu^* H_1) \tilde{u}_R + \tilde{d}^*_L h_d (A_d H_1 - \mu^* H_2) \tilde{d}_R + h.c.$$

Minimal Flavor Violation (MFV)

- At tree level, the quarks and squarks diagonalized by the same matrices

$$\tilde{D}_{L,R} = D_{L,R}; \quad \tilde{U}_{L,R} = U_{L,R}$$

Hence, in the quark mass eigenbasis the squark masses are block diagonal and the Only FC effects arise from charged currents via V_{CKM} as in the SM .



- At loop level , FCNC generated by two main effects:

1) Both Higgs doublets couple to the up and down sectors
==> important effects in the B system at large tan beta

2) Soft SUSY breaking parameters obey Renormalization Group equations: given their values at the SUSY scale, they change significantly at low energies
==> RG evolution adds terms prop. to $h_d h_d^+$ and $h_u h_u^+$

In both cases the effective coupling governing FCNC processes

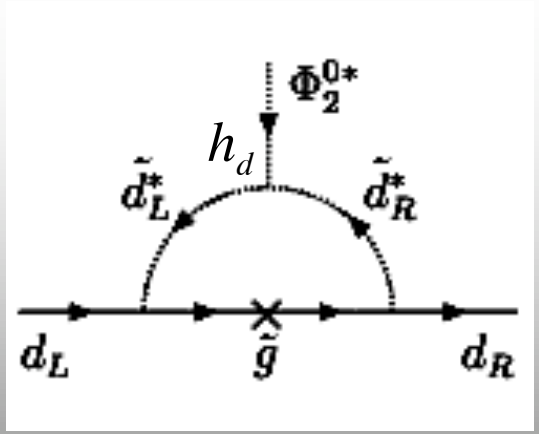
$$(\chi_{FC})_{ij} = (h_u h_u^+)_{ij} \propto m_t^2 \, \mathrm{V}_{3i}^{\mathrm{CKM}*} \mathrm{V}_{3j}^{\mathrm{CKM}} \qquad \text{for } i \neq j$$

$\tan\beta$ enhanced loop corrections to neutral Higgs-fermion couplings

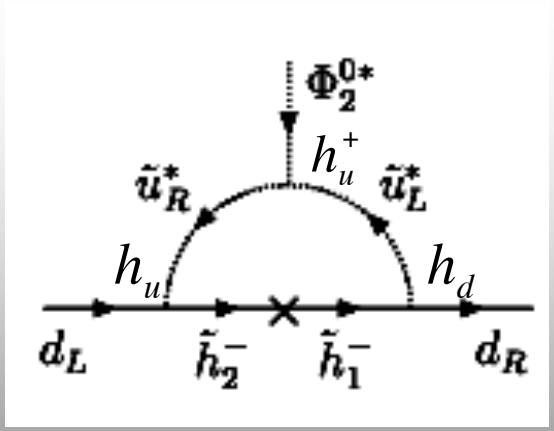
$$-\mathcal{L}_{eff} = \bar{d}_R^0 \hat{\mathbf{Y}}_d [\Phi_d^{0*} + \Phi_u^{*0}\left(\hat{\epsilon}_0 + \hat{\epsilon}_Y \hat{\mathbf{Y}}_u^\dagger \hat{\mathbf{Y}}_u\right)] d_L^0 + \Phi_u^0 \bar{u}_R^0 \hat{\mathbf{Y}}_u u_L^0 + h.c.$$

The ε factors correspond to the diagrams:

$\hat{\mathbf{Y}}_d \hat{\epsilon}_0$



$\hat{\mathbf{Y}}_d \hat{\epsilon}_Y \hat{\mathbf{Y}}_u^\dagger \hat{\mathbf{Y}}_u$



The ε loop factors are intimately connected to the assumed structure of the squark mass matrices

In terms of the mass eigenstates:

$$-L_{eff} = \frac{\sqrt{2}}{v_2}\left(\tan\beta\,\Phi_1^{0^*} - \Phi_2^{0^*}\right)\bar{d}_R M_d V^+ R^{-1} V d_L + \frac{\sqrt{2}}{v_2}\Phi_2^{0^*}\bar{d}_R M_d d_L + \Phi_2^0 \bar{u}_R h_u u_L + h.c.$$

where M_u, M_d are the physical quark mass matrices, $h_u = M_u\sqrt{2}/v_2$

V is the physical CKM matrix and the matrix R:

$$R = 1 + \varepsilon_0 \tan\beta + \varepsilon_Y \tan\beta |h_u|^2$$

- Considering the squark masses flavour diagonal ➔ R diagonal

Dependence on the SUSY parameters

$$\varepsilon_0^i \approx \frac{2\alpha_s}{3\pi}\frac{\mu M_{\tilde{g}}}{\max\left[m^2_{\tilde{d}_1^i}, m^2_{\tilde{d}_2^i}, M^2_{\tilde{g}}\right]} \rightarrow \text{gluino contribution}$$

$$\varepsilon_Y \approx \frac{\mu A_t}{16\pi^2 \max\left[m^2_{\tilde{t}_1^i}, m^2_{\tilde{t}_2^i}, \mu^2\right]} \rightarrow \text{higgsino contribution}$$

Neglecting h_u and h_c compared with h_t one can define

$$\rightarrow \varepsilon_J = \varepsilon_0^J + \varepsilon_Y h_t^2 \delta^{J3}$$

Flavor Conserving Non-Standard Higgs-fermion couplings

$$-L_{eff} = \frac{\sqrt{2}}{v_2}\left(\tan\beta\,\Phi_1^{0^*} - \Phi_2^{0^*}\right)\bar{d}_R M_d \frac{1}{R^{33}} d_L + \frac{\sqrt{2}}{v_2}\Phi_2^{0^*}\bar{d}_R M_d d_L + h.c.$$

$$R^{33} = 1 + \varepsilon_3 \equiv 1 + \Delta_b \qquad\qquad V \cong I$$

2 Higgs SU(2) doublets ϕ_1 and ϕ_2 : after Higgs Mechanism

==> 5 physical states: 2 CP-even h, H with mixing angle α

1 CP-odd A and a charged pair $H^{\pm}$

such that :

$$\phi_1^0 = -\sin\alpha\, h + \cos\alpha\, H + i\sin\beta\; A$$
$$\phi_2^0 = \cos\alpha\, h + \sin\alpha\, H - i\cos\beta\; A$$

and at large $tan\beta$, $m_A > m_h^{max}$:

$\cos\alpha \approx \sin\beta;\;\; \sin\alpha \approx -\cos\beta$

Hence: $H + iA \cong \sin\beta\;\phi_1^0 - \cos\beta\,\phi_2^0$

$$-L_{eff} = \frac{\sqrt{2}}{v}\tan\beta\,\phi_1^{0*}\bar{d}_R \frac{m_b}{1+\Delta_b} d_L + h.c.$$

$$g_{Abb} \cong g_{Hbb} \cong \frac{m_b \tan\beta}{(1+\Delta_b)v}$$

destroy basic relation

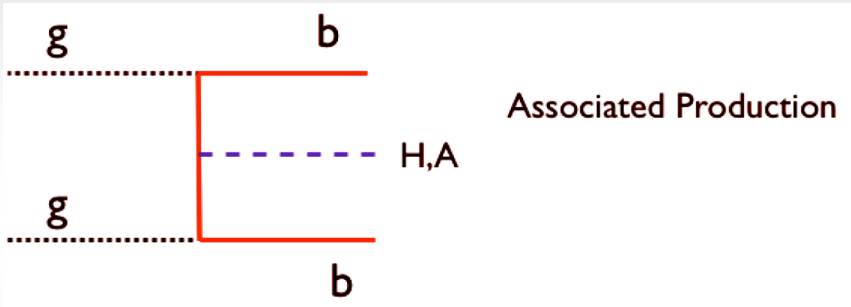
$$g_{A/H\,bb}/g_{A/H\,\tau\tau} \neq m_b/m_\tau$$

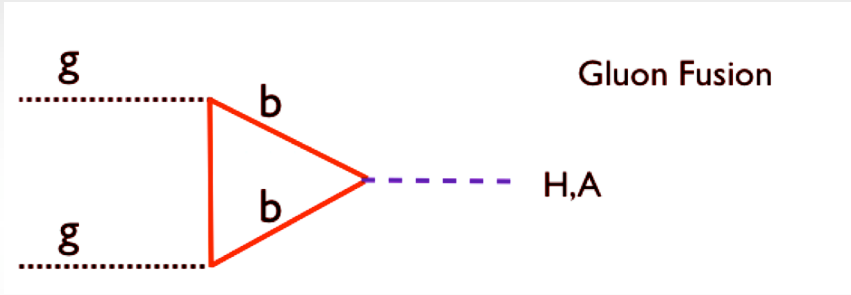
$$|\Delta_\tau| << |\Delta_b| \Rightarrow \quad g_{A\tau\tau} \cong g_{H\tau\tau} \cong m_\tau \tan\beta/v$$

Non-Standard Higgs Production at the Tevatron and LHC

- Enhanced couplings to b quarks and tau-leptons
- Considering value of running bottom mass and 3 quark colors

$$BR(A \to b\bar{b}) \cong \frac{9}{9+(1+\Delta_b)^2} \qquad BR(A \to \tau^+\tau^-) \cong \frac{(1+\Delta_b)^2}{9+(1+\Delta_b)^2}$$





$$\sigma(b\bar{b}A) \times BR(A \to b\bar{b}) \simeq \sigma(b\bar{b}A)_{\rm SM} \frac{\tan^2\beta}{(1+\Delta_b)^2} \times \frac{9}{(1+\Delta_b)^2+9}$$

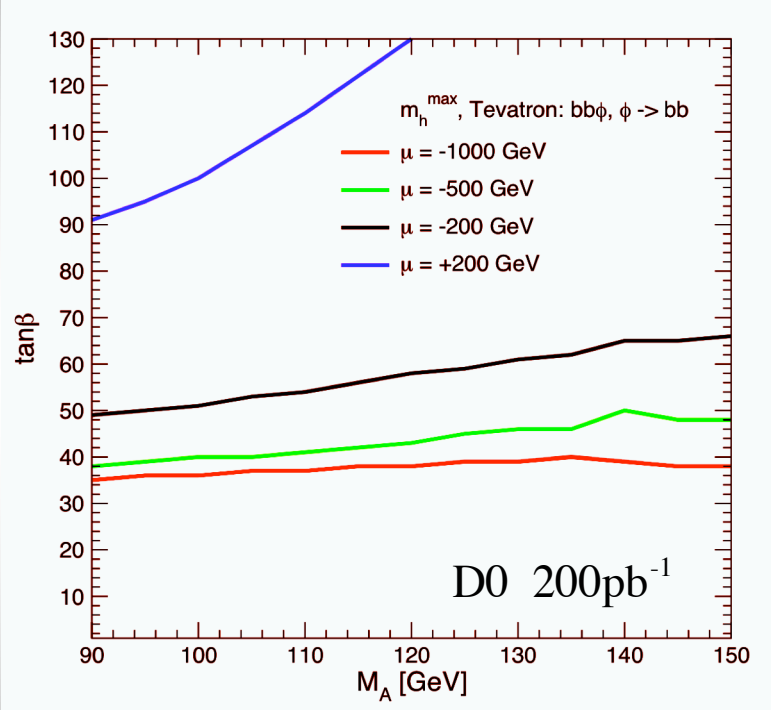
$$\sigma(b\bar{b}, gg \to A) \times BR(A \to \tau\tau) \simeq \sigma(b\bar{b}, gg \to A)_{\rm SM} \frac{\tan^2\beta}{(1+\Delta_b)^2+9}$$

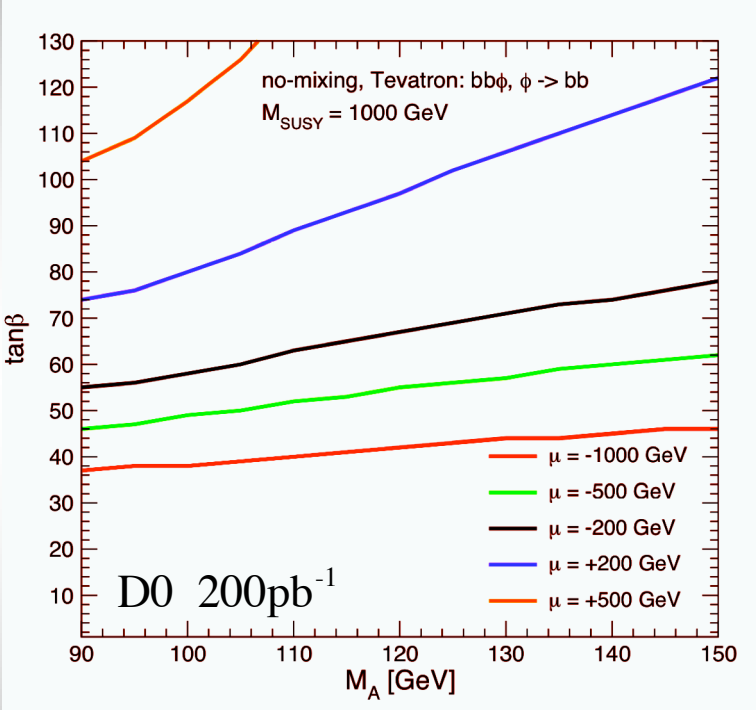
There may be a strong dependence on the parameters in the bb search channel, which is strongly reduced in the tau-tau channel

Searches for Non-Standard Higgs bosons at the Tevatron

A) In the bb mode ==> probe large region of $\tan\beta - m_A$ **plane**

$$p\bar{p} \to b\bar{b}\phi, \quad \phi \to b\bar{b}$$



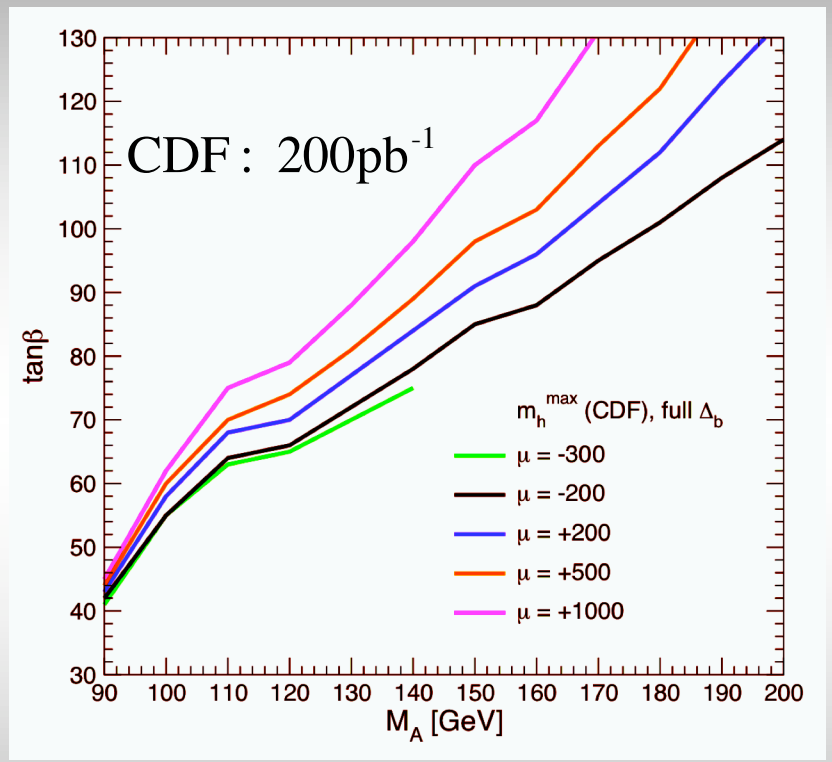


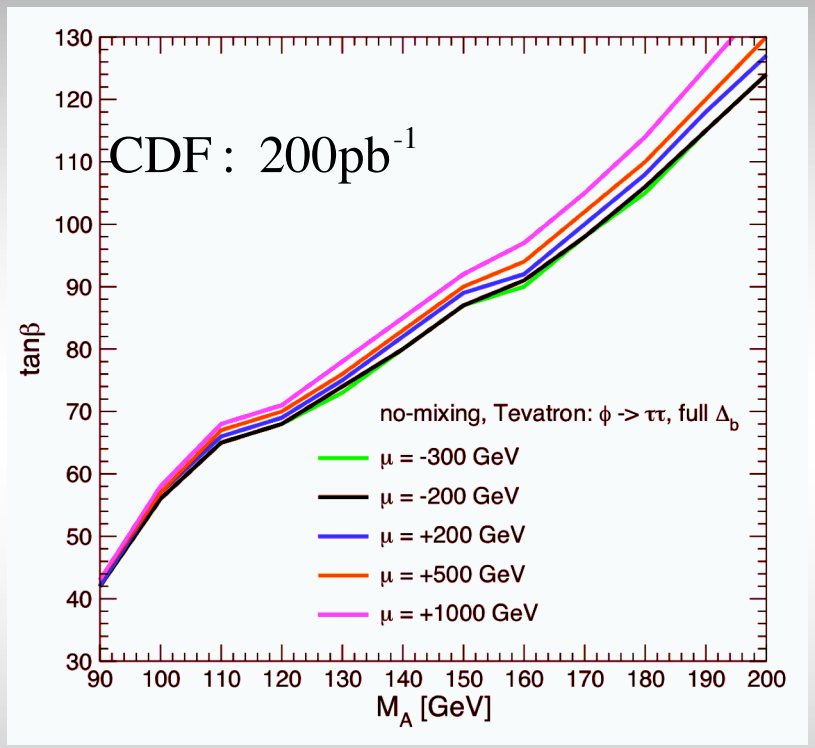
- Enhanced reach for negative values of μ
- Strong dependence on SUSY parameters

$$\sigma(b\bar{b}\phi)BR\left(\phi \to b\bar{b}\right) \propto 1/\left(1+\Delta_b\right)^2 \Rightarrow \text{enhanced for } \Delta_b < 0 \;\Leftrightarrow \mu < 0 \text{ if } A_t \text{ and } M_{\tilde{g}} > 0$$

B) In the tau tau inclusive mode

$$p\bar{p} \rightarrow X\phi, \quad \phi \rightarrow \tau^+\tau^-$$





- Important reach in the large tanb-mA plane
- Softer dependence on SUSY parameters via radiative corrections

Higgs Mediated FCNC in the down-quark sector

- **In the MFV scenario, the neutral Higgs flavor changing Lagrangian**

$$-L_{FCNC} = \bar{d}_R^J \left(X_{RL}^S\right)^{JI} d_L^I \; \phi_S + h.c. \qquad \text{with } \mathrm{I} \neq \mathrm{J}$$

$$\text{and} \quad \left(\mathrm{X}_{\mathrm{RL}}^{\mathrm{S}}\right)^{JI} = \frac{\overline{m}_{d\,J}\; h_t^2\; \Gamma^{JI}\; \left(x_2^S - x_1^S \tan\beta\right)\tan\beta}{\mathrm{v}\left(1+\varepsilon_0^{\mathrm{J}}\tan\beta\right)\left(1+\Delta_b \tan\beta\right)} \mathrm{V}_{\mathrm{CKM}}^{3\mathrm{J}^*} \mathrm{V}_{\mathrm{CKM}}^{3\mathrm{I}}$$

$\Gamma^{JI} = \varepsilon_Y$ in the case of universal soft SUSY squark mass parameters

x_1^S, x_2^S are the components of the h, H and A in ϕ_1^0, ϕ_2^0
==> $\tan\beta^2$ enhanced coupling for H/A or h/A, depending on value of m_A

- Non- Minimal Flavor Violation, using the CKM matrix

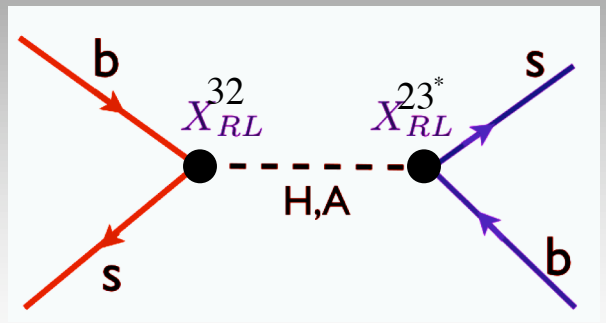
Equivalent to allow for effects of RG evolution proportional to $h_u h_u^+$ in M_Q

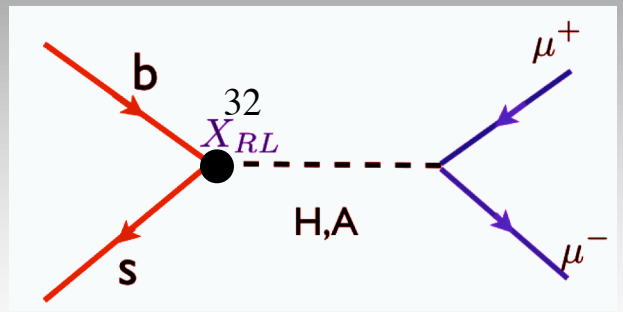
$\Gamma^{JI} = \Delta_b - \varepsilon^{1,2}$ **==>**FC depends on the difference between loop factors

- L-H. squarks are not diagonalized by the same rotation as L-H. quarks
==> induces FC in the left-handed quark-squark-gluino vertex prop V_{CKM}

Correlation between Bs mixing and $\mathrm{BR}(B_S \to \mu^+\mu^-)$

due to $\tan\beta$ enhanced Higgs mediated flavor violating effects





$$\left(\Delta M_{B_S}\right)^{SUSY} \propto \ominus \frac{X_{RL}^{32} X_{LR}^{32}}{m_A^2}$$

Negative sign with respect to SM

$$BR(B_S \to \mu^+\mu^-)^{SUSY} \propto \frac{\left|X_{RL}^{32}\right|^2 \tan\beta^2}{m_A^4}$$

- SUSY contributions strongly correlated, and for universal squark masses

$$\frac{\Delta M_{B_S}}{BR(B_S \to \mu^+\mu^-)} \propto \frac{m_A^2}{\tan\beta^2}$$

to maximize ΔM_{B_S} for a given value of $\mathrm{BR}(B_S \to \mu^+\mu^-)$ $\Leftrightarrow$ minimize $\tan\beta$ (for fixed m_A)

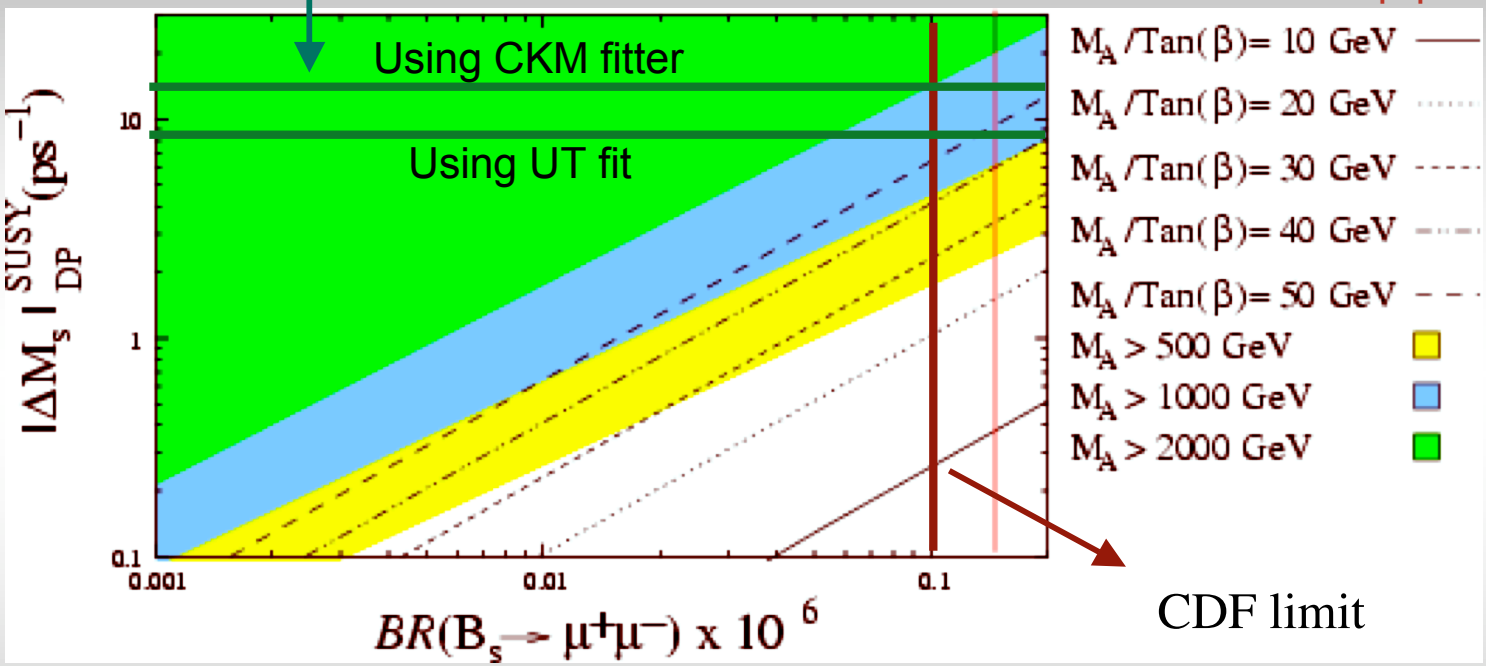
$\Rightarrow$ choose large, negative values of ε_0 and ε_Y (large implies $\mu \approx M_{\tilde{g}} \approx 2M_{\tilde{q}} \approx \frac{2}{3} A_t$)

• What can we learn from Bs-mixing?

How strong is the bound on $\mathrm{BR}(B_s \to \mu^+\mu-)$?

Upper bound on new physics from CDF measurement

M. C. et al. hep-ph/0603106



large ε factors implies heavy squarks and trilinear terms

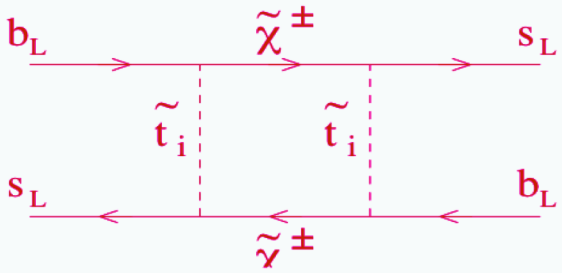
- For natural values of m_A< 1000 GeV ==> largest contributions at most a few ps-1

$$\left|\Delta M_{B_S}\right|^{SUSY}_{DP} \approx 3ps^{-1} \Rightarrow \text{resolve the discrepancy between the SM and experiment}$$

$$\Rightarrow \text{imply that } \mathrm{BR}(B_S \to \mu^+\mu^-) \text{ should be at the Tevatron reach}$$

Stop-Chargino Contributions to ΔM_s in MFV

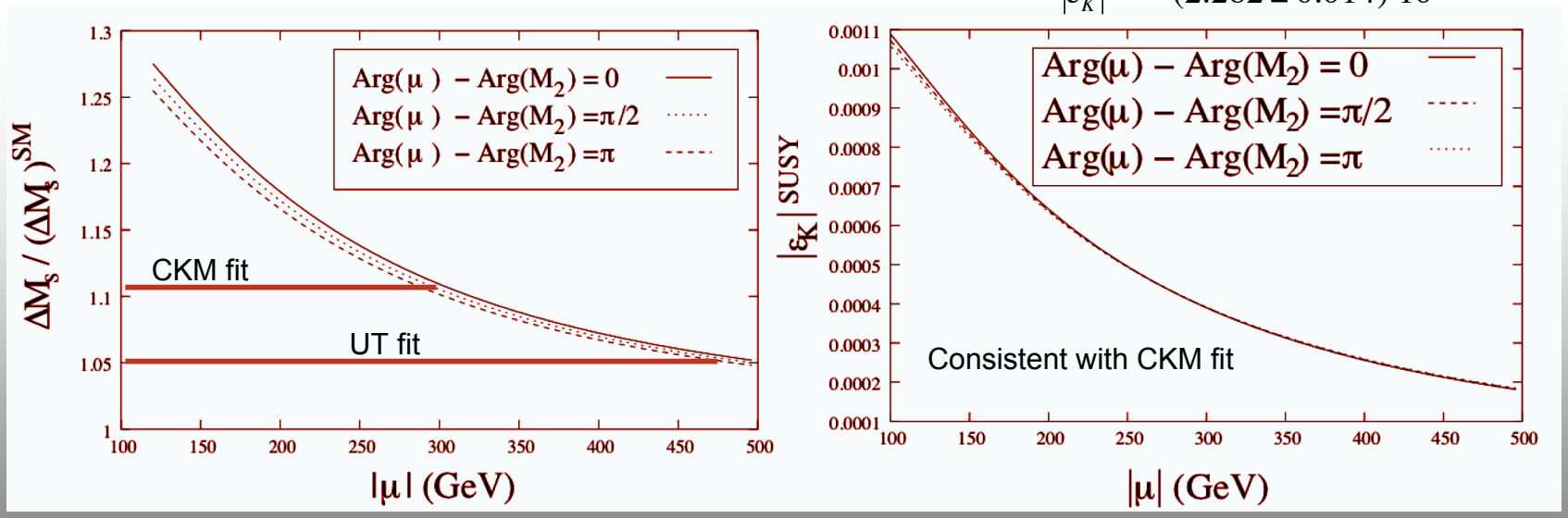
- Light stops and charginos can give substantial contributions to ΔM_s even for low values of $\tan\beta$.



Light stop scenario==> compatible with Electroweak Baryogenesis

- However these kinds of SUSY particle spectra can also induce large contributions to ϵ_K if SM CP phase is order $\pi/3$.

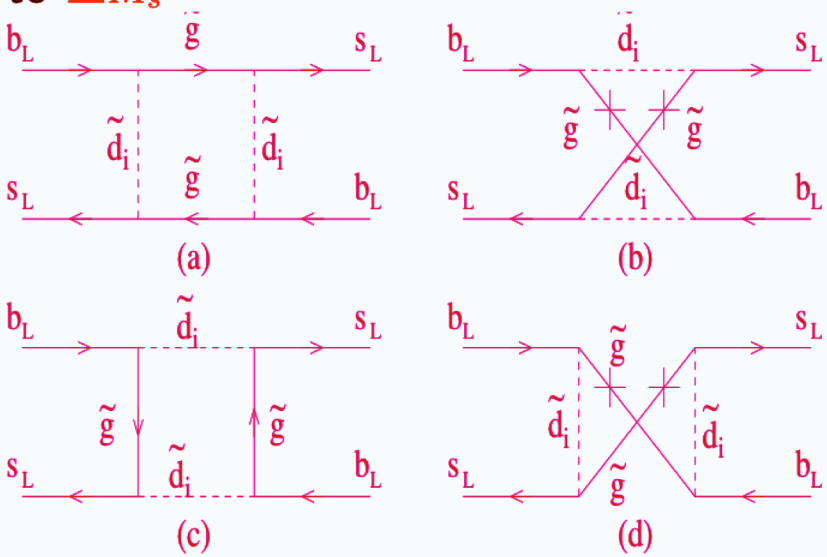
$$|\varepsilon_K|^{\exp} = (2.282 \pm 0.014)\ 10^{-3}$$



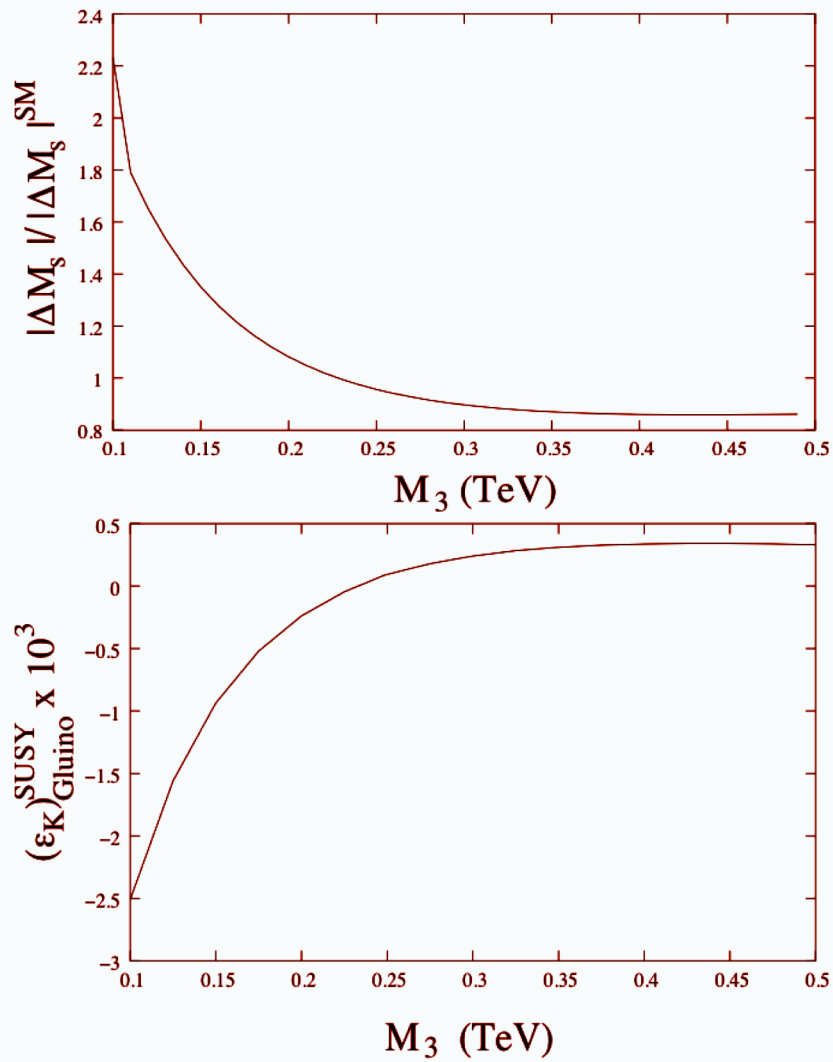
Within this scenario, small values of mu (< 250 GeV) are strongly disfavour by bounds from Bs-mixing

Gluino Contributions to ΔM_s for the Non Miminal Flavor Violation

- In Non Minimal Flavor Violation the gluino-quark-squark vertex is not diagonal and so box diagrams with light gluinos and sbottoms can give substantial contributions to ΔM_s



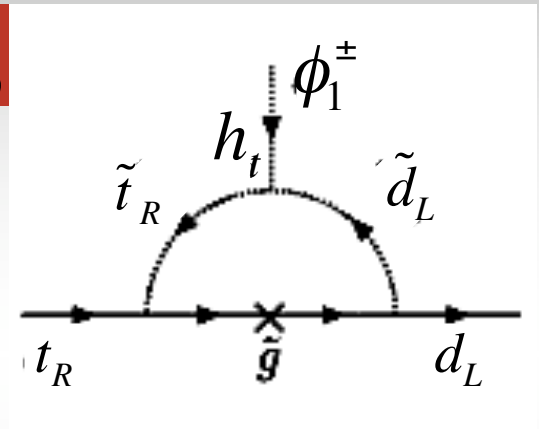
- Generating these large contributions needs extremely constrained SUSY parameter region.

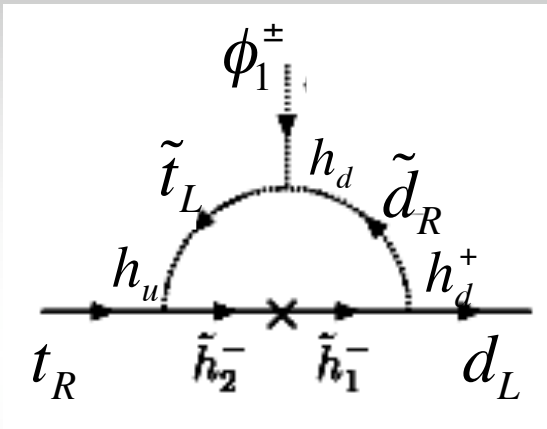


Flavor Changing in the charged Higgs coupling

- Similarly to the neutral Higgs case, we have $\tan\beta$ enhanced loop corrections which depend on SUSY parameters

$\hat{Y}_u \; \varepsilon_0'$





$\hat{Y}_u \; \varepsilon_Y' \hat{Y}_d \hat{Y}_d$

$$-L_{eff}^{H^{\pm}} = \bar{u}_R^J \, P_{RL}^{JI} \, d_L^I \, H^+ + \bar{u}_L^J \, P_{LR}^{JI} \, d_R^I \, H^+ + h.c.$$

$$P_{LR}^{3I} \approx \frac{\sqrt{2}}{\mathrm{v}} \bar{m}_t \cot\beta \, V_{CKM}^{3I} \left(1 - \tan\beta\left(\varepsilon_0' - \varepsilon_Y' h_b^2\right)\right)$$

$$P_{LR}^{J3} = \frac{\sqrt{2}}{\mathrm{v}} \frac{\bar{m}_b \tan\beta}{\left(1 + \varepsilon_0^{3^*} \tan\beta\right)} V_{CKM}^{J3}$$

$$P_{LR}^{33} = P_{LR}^{J3}(J \to 3, \; \varepsilon_0^{3^*} \to \Delta_b^*)$$

This type of corrections are most important in constraining new physics from $B \to X_S \gamma$ and $B_u \to \tau\nu$

Contributions to $BR(B \to X_s \gamma)$

B and Higgs Physics at the Tevatron and the LHC:

explore complementary regions of SUSY parameter space

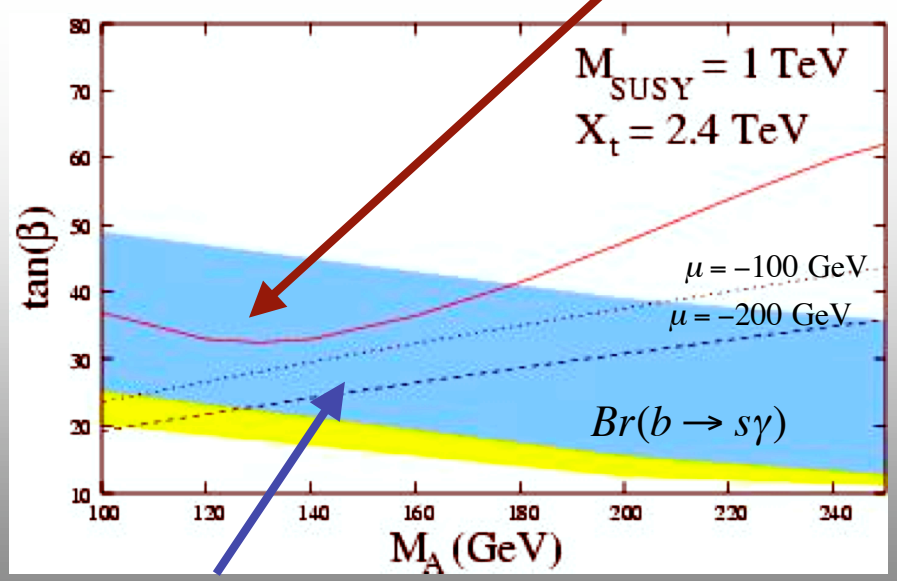
- MSSM Higgs searches probe large tan β and M_A regions via the inclusive process $p\bar{p} \to H/A \to \tau^+\tau^-$ => only small SUSY model dependence

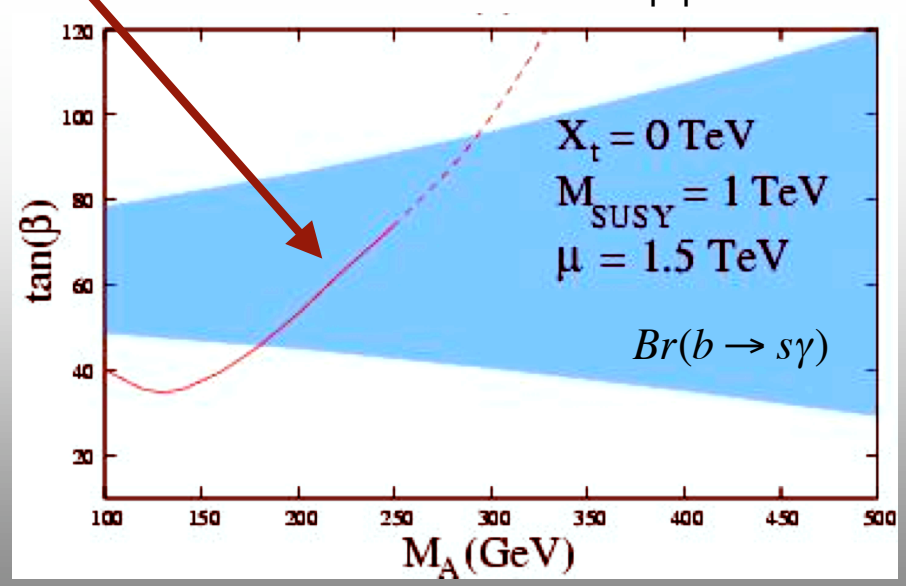
M. Carena et al. hep-ph/0511023

- Higgs mediated FCNC can enhance the rare decay rate $B_S \to \mu^+\mu^-$ up to levels accessible at the Tevatron => explores efficiently large tanβ and M_A region

Tevatron Higgs reach with 1fb^{-1}

M. Carena et al. hep-ph/0603106





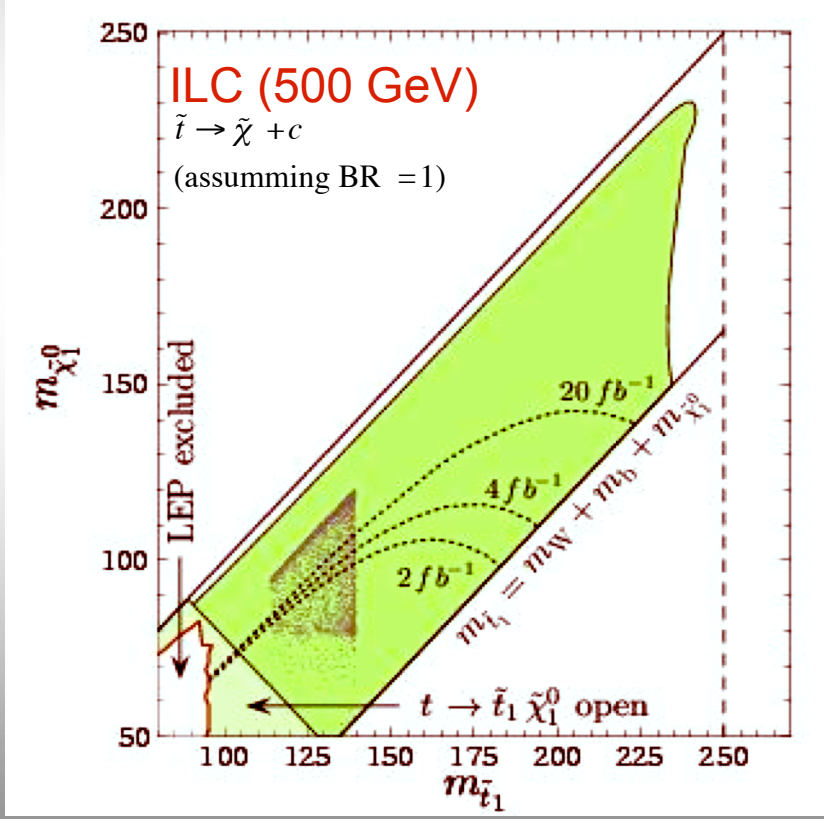
CDF limit : $BR(B_S \to \mu^+\mu^-) < 1 \times 10^{-7}$

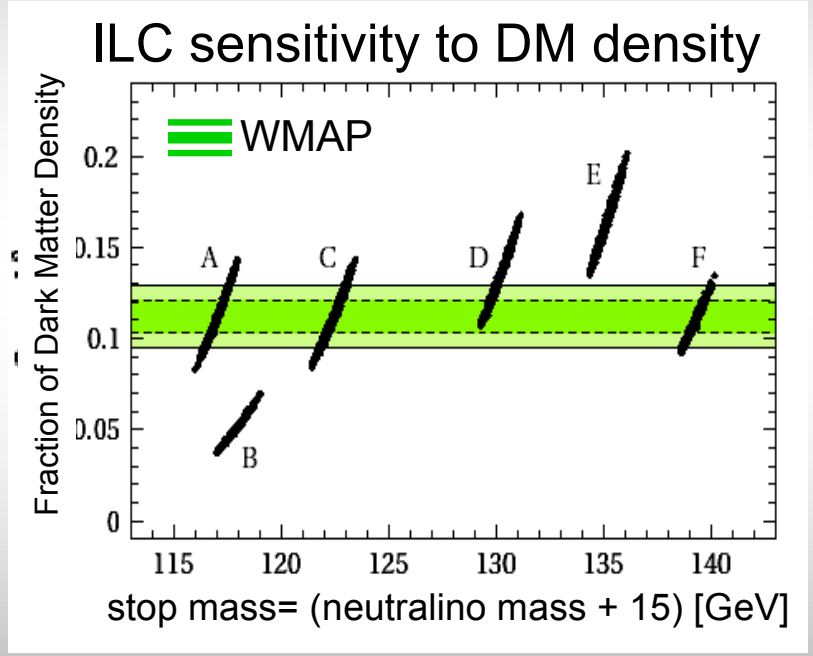
- **Enhanced reach at the LHC**

Dark Matter at Colliders

The LHC will probably find evidence of DM particles through missing momentum and missing energy analyses

The ILC will determine its properties with extreme detail, allowing to compute which fraction of the total DM density of the universe it makes





SUSY models which explain DM and Matter-Antimatter Asymmetry

M. Carena et al. hep-ph/0508152

A particle physics understanding of cosmological questions!

Outlook

- Direct Higgs search at LEP

$$e^+e^- \xrightarrow{Z^*} H_{SM} Z \qquad m_{H_{SM}} > 114.6\text{GeV at } 95\% \text{ C.L.}$$

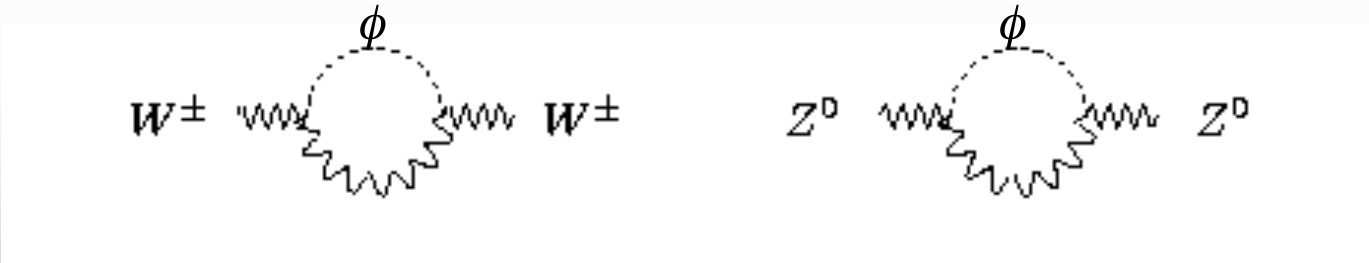
with $H_{SM} \to b\bar{b}, \tau^+\tau^-; Z \to q\bar{q}, l^+l^-, \nu\bar{\nu}$

final LEP result, 2003

- Constraints on m_H from precision tests of the SM

(accuracy at the per mille level) from CERN, Fermilab, SLAC

Although the Higgs boson has not been seen and its mass is unknown, it enters via loop corrections in electroweak observables: particle masses, decay rates, etc



All electroweak parameters have at most logarithmic dependence on m_ϕ
However, preferred value of m_ϕ can be determined

$$m_\phi < 200 \text{ GeV at } 95\ \% \text{ C.L}$$

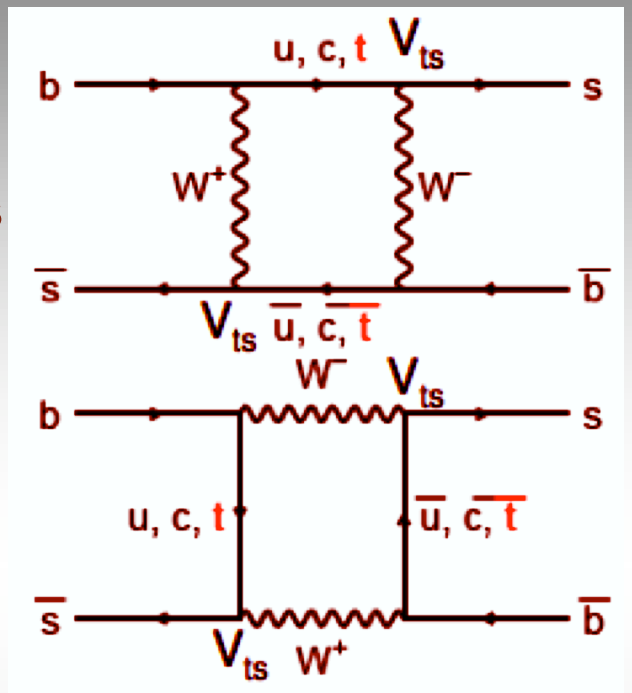
To avoid a light Higgs Boson, must have new phenomena below 1 TeV

SM express review on B_s Mixing

$$B_s^0 = (\bar{b}s); \quad \bar{B}_s^0 = (b\bar{s})$$

Flavor eigenstates ==> mix via weak interactions

$$i\frac{d\psi(t)}{dt} = \hat{H}\psi(t) \qquad \psi(t) = \begin{vmatrix} |B_s^0(t)\rangle \\ |\bar{B}_s^0(t)\rangle \end{vmatrix}$$

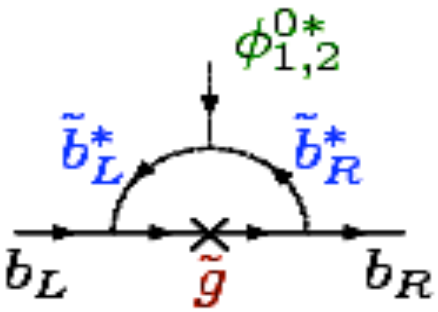


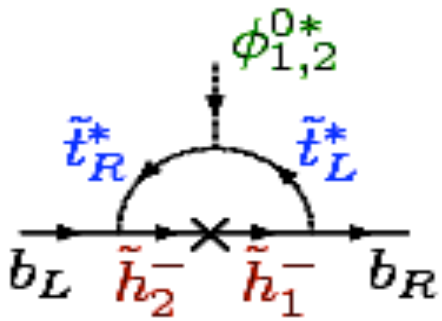
Mass eigenstates: $B_{H,L} = pB_s^0 \pm q\bar{B}_s^0$

$$p = \frac{1+\varepsilon_B}{\sqrt{2(1+|\varepsilon_B|^2)}} \qquad q = \frac{1-\varepsilon_B}{\sqrt{2(1+|\varepsilon_B|^2)}}$$

With

$$\Delta M_s = \frac{G_F^2}{6\pi^2}\eta_B m_{B_S}\hat{B}_{B_S} f_{B_S}^2 M_W^2 \frac{2.46\ m_t^{1.52}}{(170\ \text{GeV})^{1..52}}|V_{td}|^2$$


$\phi^{0*}_{1,2}$
$\tilde{b}^*_L$
$\tilde{b}^*_R$
b_L
$\tilde{g}$
b_R


$\phi^{0*}_{1,2}$
$\tilde{t}^*_R$
$\tilde{t}^*_L$
b_L
$\tilde{h}^-_2$
$\tilde{h}^-_1$
b_R

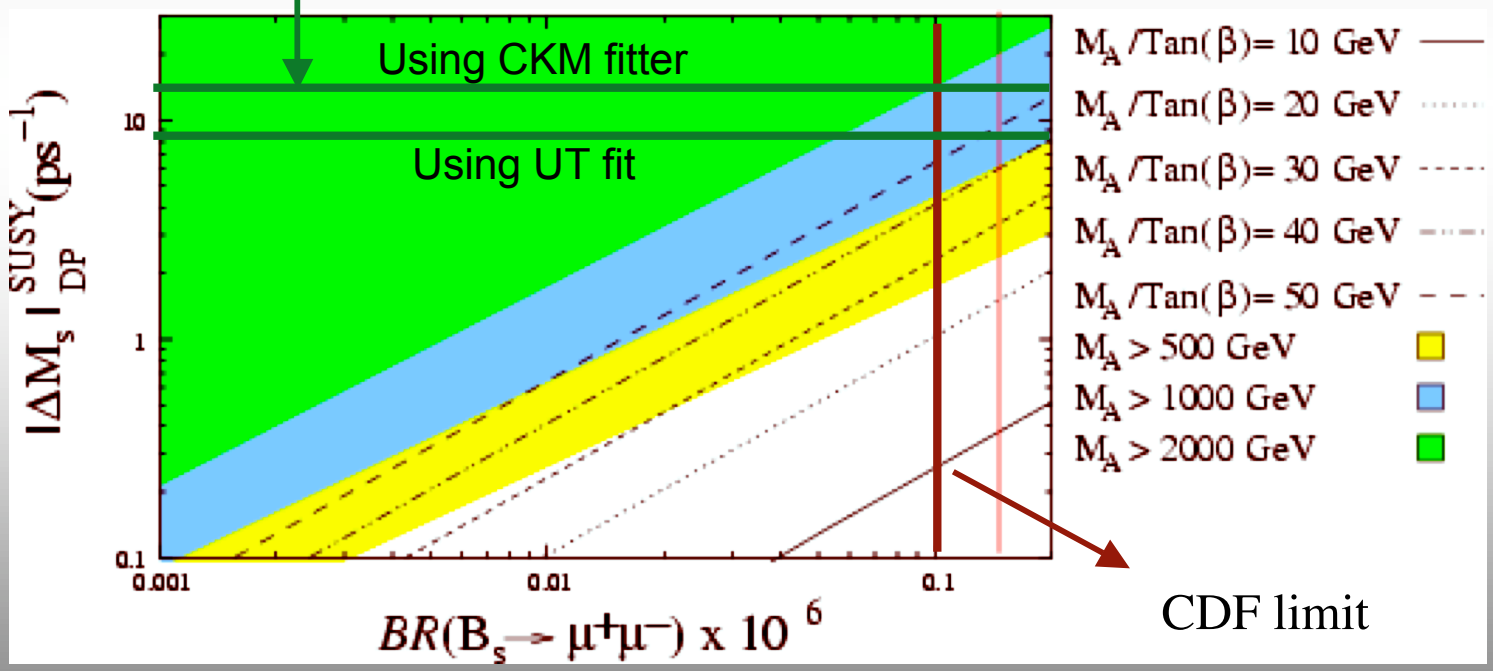
▪Correlation between Bs mixing and $\mathrm{BR}(B_S \to \mu^+\mu^-)$ due to Higgs mediated flavor violating effects

$$BR(B_s \to \mu^+\mu^-)^{MSSM} \propto |V_{ts}^* V_{tb}|^2 \left(\tan\beta^6 / m_{A/H}^4\right)$$

$$\Delta M_s^{MSSM} \propto |V_{ts}^* V_{tb}|^2 \left(\tan\beta^4 / m_{A/H}^2\right)$$

$$\Delta M_s^{CDF} = 17.34^{+0.49}_{-0.20}$$

Upper bound on new physics contribution based on CDF measurement:



M. Carena et al. hep-ph/0603106