Supersymmetry, Higgs Physics and CP Violation

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Outline

- Motivation for CP violation in SUSY models

- The MSSM Higgs Sector and explicit CP violation

  -- quantum corrections ➔ self energy and vertex effects

- Effects of CP violation in direct Higgs searches at Colliders

  -- new challenges for the Tevatron and LHC

- Higgs Mediated FCNC in the quark sector:

  a resummed effective Lagrangian

  -- Probing large tanb at the Tevatron➔ $B_s \to \mu^+ \mu-$

  -- Other applications searching for New Physics

  in B and K systems ΔM_{B_s}, ΔM_K and ε_K

CP Violation in the MSSM

- In low energy SUSY, there are extra CP-violating phases beyond the CKM ones, associated with complex SUSY breaking parameters

- One of the most important consequences of CP-violation is its possible impact on the explanation of the matter-antimatter asymmetry.

  Electroweak baryogenesis may be realized even in the simplest SUSY extension of the SM, but demands new sources of CP-violation associated with the third generation sector and/or the gaugino-Higgsino sector.

- These CP-violating phases may induce effects on observables such as
  -- new contributions to the e.d.m. of the electron and the neutron.
  -- Higgs mediated FCNC in the K and B –meson system

  Effects on observables can be small/sizeable depending on the SUSY parameter space

- In the Higgs sector at tree-level, all CP-violating phases, if present, may be absorved into a redefinition of the fields.

- CP-violation in the Higgs sector appears at the loop-level,
  associated with third generation scalars and/or the gaugino/Higgsino sector,
  but can still have important consequences for Higgs physics

MSSM Higgs Sector at Tree Level

2 Higgs SU(2) doublets
5 physical states → 2 CP-even **h, H** with mixing angle α
a CP-odd **A** and a charged pair $\mathbf{H}^{\pm}$

Higgs masses and couplings given in terms of two parameters:

m_A and $\tan\beta \equiv v_2/v_1$ mixing angle $\alpha \Longrightarrow \cos^2(\beta-\alpha) = \frac{m_h^2(m_Z^2-m_h^2)}{m_A^2(m_H^2-m_h^2)}$

Couplings to gauge bosons and fermions (norm. to SM)

$\mathrm{hZZ,\ hWW,\ ZHA,\ WH^{\pm}H} \longrightarrow \sin(\beta-\alpha)$
$\mathrm{HZZ,\ HWW,\ ZhA,\ WH^{\pm}h} \longrightarrow \cos(\beta-\alpha)$

$\mathrm{(h,H,A)}\ u\bar{u} \longrightarrow \cos\alpha/\sin\beta,\quad \sin\alpha/\sin\beta,\quad 1/\tan\beta$
$\mathrm{(h,H,A)}\ d\bar{d}/l^+l^- \longrightarrow -\sin\alpha/\cos\beta,\quad \cos\alpha/\cos\beta,\quad \tan\beta$

If $m_A \gg M_Z \rightarrow$ decoupling limit

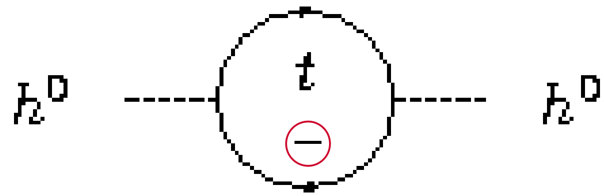
- $\cos(\beta-\alpha)=0$ up to correc. $\mathcal{O}(m_Z^2/m_A^2)$
- lightest Higgs has SM-like couplings and mass $m_h^2 \simeq m_Z^2\cos^2 2\beta$
- other Higgs bosons: heavy and roughly degenerate
$m_A \simeq m_H \simeq m_H^{\pm}$ up to correc. $\mathcal{O}(m_Z^2/m_A^2)$

- **Supersymmetric relations between couplings imply** $m_h \leq m_Z$

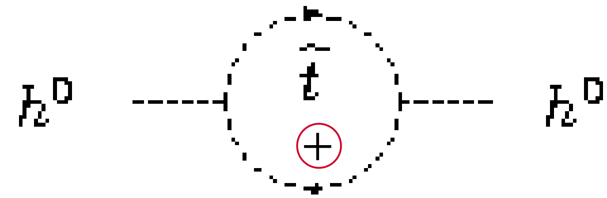
Quantum corrections ➔Higgs mass shifted due to incomplete cancellation of particles and superparticles in the loops

- Most important corrections come from the stop sector

$$M_{\tilde{t}}^2 = \begin{pmatrix} m_Q^2 + m_t^2 + D_L & m_t X_t \\ m_t X_t & m_U^2 + m_t^2 + D_R \end{pmatrix}$$



where the off-diagonal term depends on the stop-Higgs trilinear couplings, $X_t = A_t - \mu^* / \tan\beta$



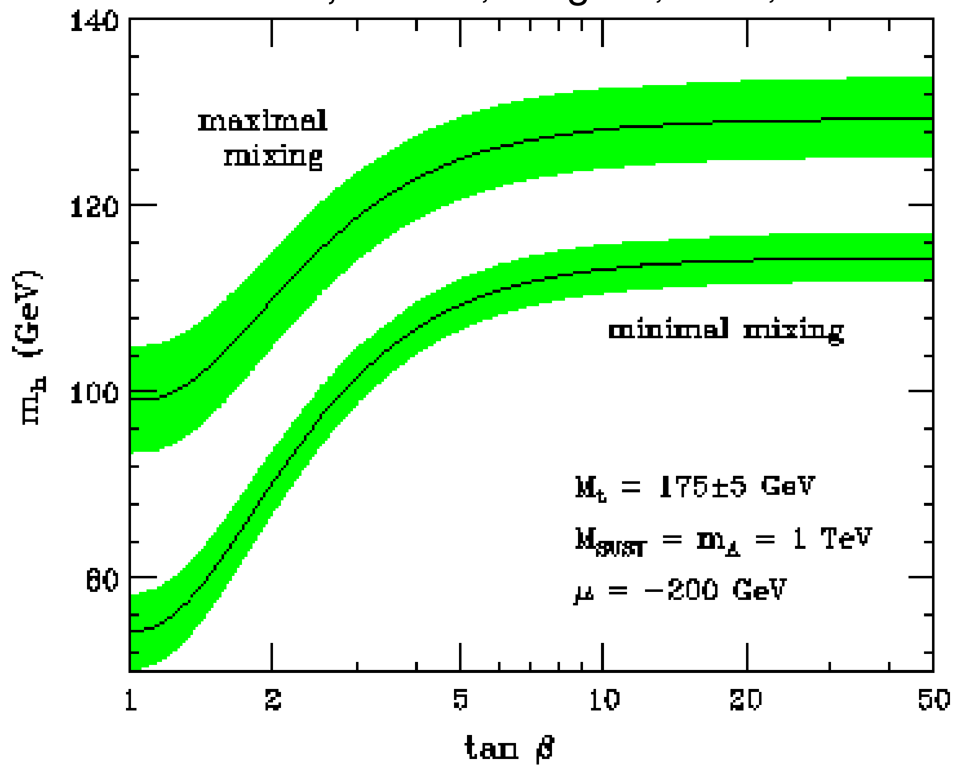
For large CP-odd Higgs boson masses, and with $M_S = m_Q = m_U$ the dominant one-loop corrections are given by,

$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12\, M_S^2}\right) \right)$$

Main Quantum effects:

- m_t^4 enhancement
- dependence on the stop mixing X_t
- logarithmic sensitivity to the stop mass (averaged: M_S)

M.C., Quiros, Wagner; M.C.,Haber



Upper bound :

$$m_h \leq 135 \quad \text{GeV}$$

stringent test of the MSSM

$$M_S = 1 \rightarrow 2 \text{ TeV} \Longrightarrow \Delta m_h \simeq 2 - 5 \text{ GeV}$$

$$\Delta m_t = 1 \text{ GeV} \Longrightarrow \Delta m_h \sim 1 \text{ GeV}$$

Carena, Haber, Hollik, Heinemeyer, Weiglein, C.W. '00
Heinemeyer, Hollik, Weiglein'02
Degrassi, Slavich, Zwirner '02

LEP MSSM HIGGS limits:

$$m_h > 91.0\text{GeV}; \qquad m_A > 91.9\text{GeV}$$

$$m_{H^\pm} > 78.6\text{GeV} \qquad m_h^{\text{SM}-\text{like}} > 114.6\text{GeV}$$

CP violation in the Higgs Sector

- at tree level $\Longrightarrow$ MSSM Higgs potential invariant under CP
- After radiative corrections: CP violation induced through loop effects via 3. generation sfermion and gaugino mass parameters

— Many possible relevant phases to Higgs sector

$m_{\tilde{g}}$ (one phase if Univ. gaugino masses) $\quad A_f \quad \mu \quad$ and $\quad m_{12}^2$

Due to U(1) symm.of the conformal inv. sector:

$\rightarrow$ one can redefine fields and absorb two phases

rephasing inv. combinations

if $\quad \mathrm{Im}\,((m_{12}^2)^* A_f \mu) \neq 0 \quad$ and/or $\quad \mathrm{Im}\,((m_{12}^2)^* m_{\tilde{g}} \mu) \neq 0$

$\Longrightarrow$ CP violating effects will be present in the MSSM

in practice, take m_{12}^2 and μ real and leave phases in A_f and $m_{\tilde{g}}$

Higgs Potential ➔ Quantum Corrections

Minimization should be performed with respect to real and imaginary parts of Higgs fluctuations $H_1^0 = \phi_1 + iA_1 \quad H_2^0 = \phi_2 + iA_2$

Performing a rotation: $A_1, A_2 \quad \Longrightarrow A, G^0$ (Goldstone)

Main effect of CP-Violation is the mixing of the three neutral Higgs bosons

$$\begin{pmatrix} A \\ \Phi_1 \\ \Phi_2 \end{pmatrix} = O \begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix}$$

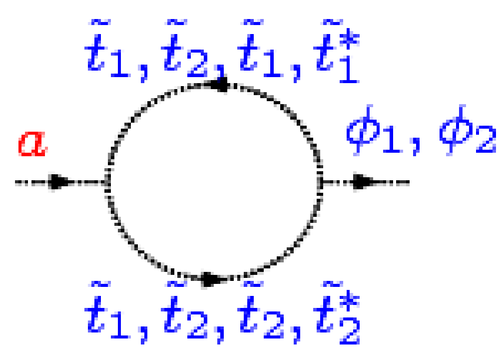
In the base (A, Φ_1, Φ_2)

$$M_N^2 = \begin{bmatrix} m_A^2 & (M_{SP}^2)^T \\ M_{SP}^2 & M_{SS}^2 \end{bmatrix}$$

M_{SS}^2 is similar to the mass matrix in the CP conserving case, and M_A^2 is the mass of the would-be CP-odd Higgs.

M_{SP}^2 **gives the mixing between would-be CP-odd and CP-even sates, predominantly governed by stop induced loop effects**

$$M_{SP}^2 \propto \frac{m_t^4}{16\pi^2 v^2} \, \mathrm{Im}\left(\frac{\mu A_t}{M_S^2}\right)$$



Gluino phase relevant at two-loop level. Guagino effects may be enhanced for large tan beta

Comments on Higgs Boson Mixing

- m_A no longer a physical parameter, but the charged Higgs mass $m_{H^\pm}$ can be used as a physical parameter, together with
$$M_S, |\mu|, |A_t|, |m_{\tilde{g}}| \arg(A_t), \arg(m_{\tilde{g}})$$
- Elements of matrix O are similar to $\cos\alpha$ **and** $\sin\alpha$ in the CP-conserving case. But third row and column are zero in the non-diagonal elements in such a case.
- Three neutral Higgs bosons can now couple to the vector bosons in a way similar to the SM Higgs.
- Similar to the decoupling limit in the CP-conserving case, for large values of the charged Higgs mass, light Higgs boson with Standard Model properties.

Interaction Lagrangian of W,Z bosons with mixtures of CP even and CP odd Higgs bosons

$$g_{H_i VV} = \cos\beta\, \mathcal{O}_{1i} + \sin\beta\, \mathcal{O}_{2i}$$

$$g_{H_i H_j Z} = \mathcal{O}_{3i}\,(\cos\beta\, \mathcal{O}_{2j} - \sin\beta\, \mathcal{O}_{1j}) - \mathcal{O}_{3j}\,(\cos\beta\, \mathcal{O}_{2i} - \sin\beta\, \mathcal{O}_{1i})$$

$$g_{H_i H^- W^+} = \cos\beta\, \mathcal{O}_{2i} - \sin\beta\, \mathcal{O}_{1i} + i\mathcal{O}_{3i}$$

$(V = W, Z)$

$O_{ij} \rightarrow$ analogous to $\sin\alpha$ and $\cos\alpha$

→ All couplings as a function of two: $g_{\mathrm{H_k VV}} = \varepsilon_{ijk}\; g_{\mathrm{H_i H_j Z}}$

and sum rules: $\sum_{i=1}^{3} g^2_{H_i ZZ} = 1 \qquad \sum_{i=1}^{3} g^2_{H_i ZZ}\, m^2_{H_i} = m^{2,\max}_{H_1} \lesssim 135$ GeV

(equiv. to CP-conserv. case)

upper bound remains the same

Decoupling limit: $m_{H^+} \gg M_Z$

- **Effective mixing between the lightest Higgs and the heavy ones is zero**

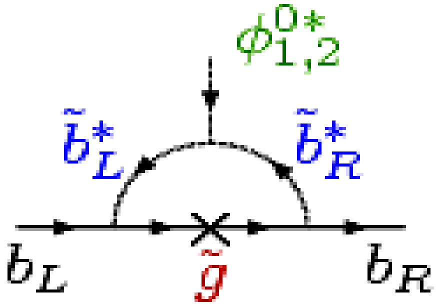
➔ H_1 is SM-like

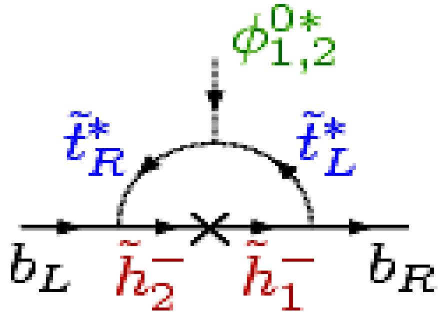
- **Mixing in the heavy sector still relevant !**

$$\longrightarrow \begin{pmatrix} m_A^2 & \Delta \\ \Delta & \Delta' + m_A^2 \end{pmatrix} \qquad \mathrm{w/} \qquad \Delta \sim \mathcal{O}(\Delta') \ll m_A^2$$

Yukawa Couplings: CP violating vertex effects

$$-\mathcal{L}^{\rm eff}_{\phi^0 \bar{b} b} = (h_b + \delta h_b)\, \phi_1^{0*}\, \bar{b}_R b_L + \Delta h_b\, \phi_2^{0*}\, \bar{b}_R b_L \; + \; {\rm h.c.}$$





coupling Δh_b generated by SUSY breaking effects

M.C. Ellis, Pilaftsis , Wagner

$$\frac{\delta h_b}{h_b} \sim -\frac{2\alpha_s}{3\pi}\,\frac{m^*_{\tilde{g}} A_b}{\max\left(Q_b^2, |m_{\tilde{g}}|^2\right)} - \frac{|h_t|^2}{16\pi^2}\,\frac{|\mu|^2}{\max\left(Q_t^2, |\mu|^2\right)}$$

$$\frac{\Delta h_b}{h_b} \sim \frac{2\alpha_s}{3\pi}\,\frac{m^*_{\tilde{g}} \mu^*}{\max\left(Q_b^2, |m_{\tilde{g}}|^2\right)} + \frac{|h_t|^2}{16\pi^2}\,\frac{A_t^* \mu^*}{\max\left(Q_t^2, |\mu|^2\right)}$$

- The one loop effects to the Yukawa couplings introduce CP-violating effects which are independent of the Higgs mixing

the phase of the superfield b_R is real and positive:

$$h_b = \frac{g_w m_b}{\sqrt{2} M_W \cos\beta\, [\,1 + \delta h_b / h_b + (\Delta h_b / h_b)\tan\beta\,]}$$

Higgs boson-quark Lagrangian

- **taking into account both CP-violating self-energy and vertex effects**

(similar vertex effects in the up quark sector, but no tan β enhancement)

$$L_{\mathrm{Hf\bar{f}}} = -\sum_{i=1}^{3} \mathrm{H_i}[(g_{\mathrm{W}} m_{\mathrm{d}} / 2\mathrm{M_W})\, \bar{\mathrm{d}}\, (\mathrm{g}^{\mathrm{S}}_{\mathrm{H_i dd}} + \mathrm{g}^{\mathrm{P}}_{\mathrm{H_i dd}}\, \gamma_5)\, \mathrm{d}$$

$$+ (g_{\mathrm{W}} m_{\mathrm{u}} / 2\mathrm{M_W})\, \bar{\mathrm{u}}\, (\mathrm{g}^{\mathrm{S}}_{\mathrm{H_i uu}} + \mathrm{g}^{\mathrm{P}}_{\mathrm{H_i uu}}\, \gamma_5)\, \mathrm{u}]$$

with:

$$\mathrm{g}^{\mathrm{S}}_{\mathrm{H_i dd}} = \frac{1}{h_b + \delta h_b + \Delta h_b \tan\beta} \{\mathrm{Re}(h_b + \delta h_b) \frac{O_{1i}}{\cos\beta} + \mathrm{Re}(\Delta h_b) \frac{O_{2i}}{\cos\beta}$$

$$- [\mathrm{Im}(h_b + \delta h_b) \tan\beta - \mathrm{Im}(\Delta h_b)] O_{i3}\}$$

$$\mathrm{g}^{\mathrm{P}}_{\mathrm{H_i dd}} = \frac{1}{h_b + \delta h_b + \Delta h_b \tan\beta} \{[\mathrm{Re}(\Delta h_b) - \mathrm{Re}(h_b + \delta h_b) \tan\beta] O_{31}$$

$$- \mathrm{Im}(h_b + \delta h_b) \frac{O_{1i}}{\cos\beta} - \mathrm{Im}(\Delta h_b) \frac{O_{2i}}{\cos\beta}\}$$

- Decoupling limit: $M_{H^\pm} \gg M_Z$

CP violation effects in the Higgs-fermion couplings

$$O_{11} \to \cos\beta \qquad O_{21} \to \sin\beta \qquad O_{31} \to 0$$

hence:

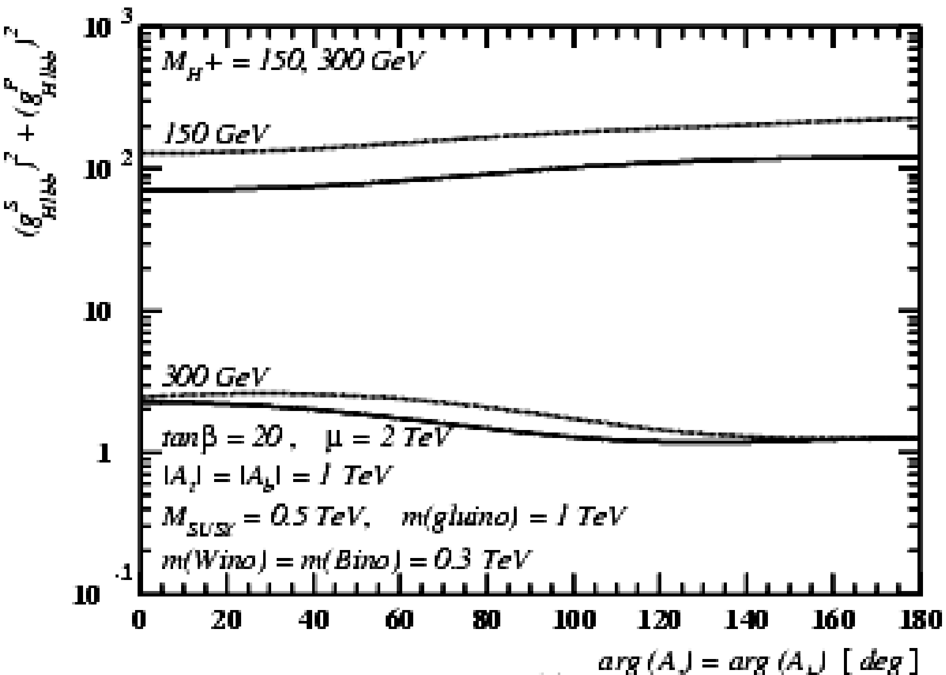
- H_1bb and H_1uu pseudoscalar couplings tend to zero while their scalar couplings tend to SM-like

with the bottom mass: $$h_b = \frac{g_w m_b}{\sqrt{2} M_W \cos\beta \,[1 + \delta h_b/h_b + (\Delta h_b/h_b)\tan\beta\,]}$$

- Heaviest Higgs Scalar and Pseudoscalar couplings to up and down quarks do not vanish

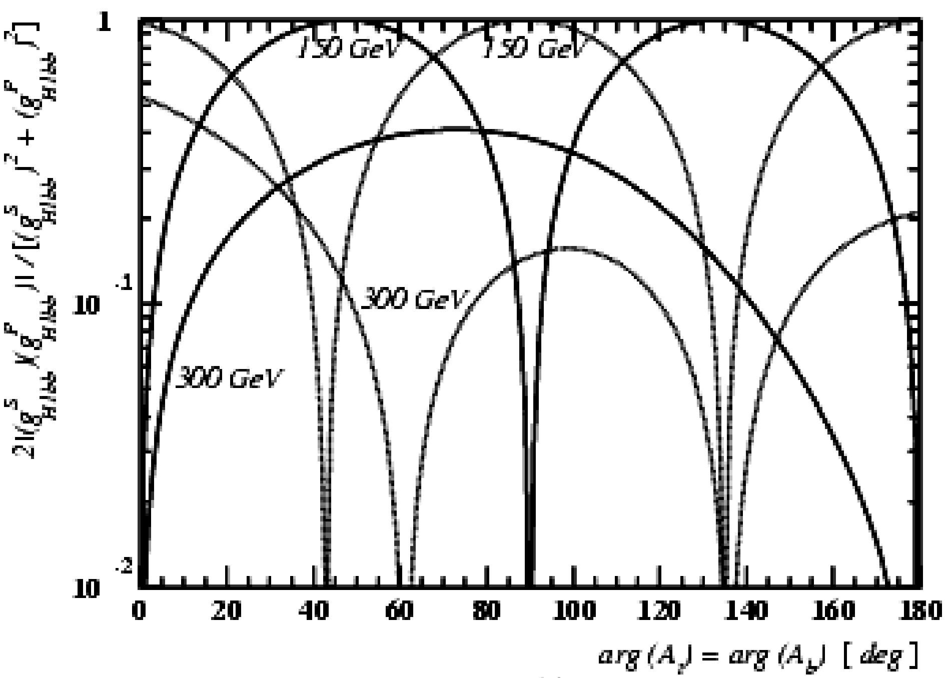
➔ non decoupling of CP-violating vertex effects as well as self energy ones

H_1bb Scalar and Pseudoscalar couplings as a function of phases



(a)

M.C., Ellis, Pilaftsis, Wagner



(b)

- **Analyze behaviour in term of CP-even quantities: BR's and CP- odd quatinties: Asymmetries**

- **Effects depend both on the dominant squark sector phases, as well as on the gaugino phases, affecting the vertex corrections.**

- **Cases with gluino mass phase zero (solid lines) and 90 degrees (dashed lines) shown in figures: stronger effects of gluino phase for larger tanb**

CP-Violating phases affect both masses and couplings in relevant ways.

CP-Violating Higgs bosons at LEP: challenging scenarios

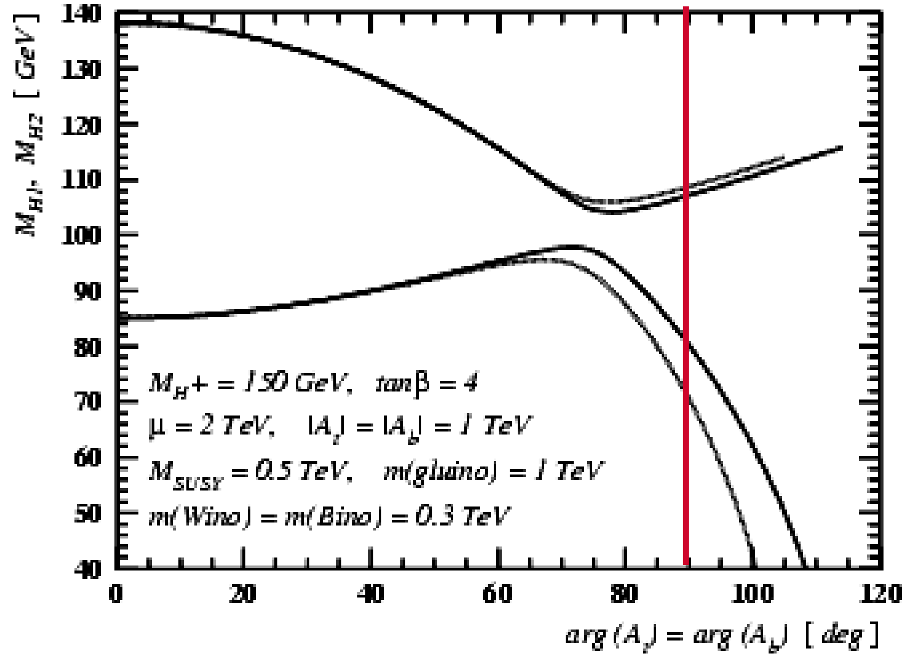
$$e^+e^- \longrightarrow H_i Z \text{ and } e^+e^- \longrightarrow H_i H_j$$

CPX Scenario:
$M_{SUSY} = 0.5,\ 1$ TeV
$\mu = 4\ M_{SUSY}$
$m_{\tilde{g}} = 1$ TeV
$|A_t| = |A_b| = 2 M_{SUSY}$

- interesting example:

$\arg(A_{t,b}) = 90^o$, $\arg(m_{\tilde{g}}) = 90^o$
$m_{H^\pm} \simeq 150$ GeV
$\longrightarrow m_{H_1} \simeq 70$ GeV
$m_{H_2} \simeq 105$ GeV

- M_{H_1} very small but $g_{h_1ZZ} \to 0$,
- $M_{H_1} + M_{H_2}$ too heavy for the given value of the $g_{H_1H_2Z}$ coupling
- M_{H_2} just at the edge of LEP reach



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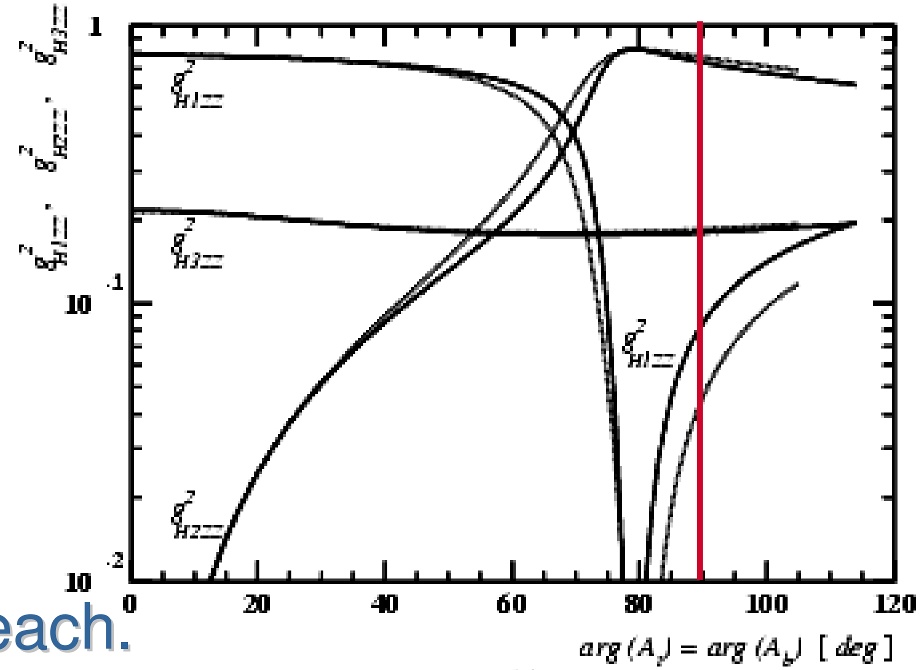


(b)

H_1 decouples from the Z and
H_2 and H_3 may be out of kinematic reach.

- **Another interesting example within the CPX Scenario:**

(1) $m_{H^{\pm}} = 160\,\mathrm{GeV} \quad \tan\beta = 4$

(2) $m_{H^{\pm}} = 150\,\mathrm{GeV} \quad \tan\beta = 5$

(3) $m_{H^{\pm}} = 140\,\mathrm{GeV} \quad \tan\beta = 6$

$$\arg(A_{t,b}) = 110^{\circ} \text{ and case (3)}$$

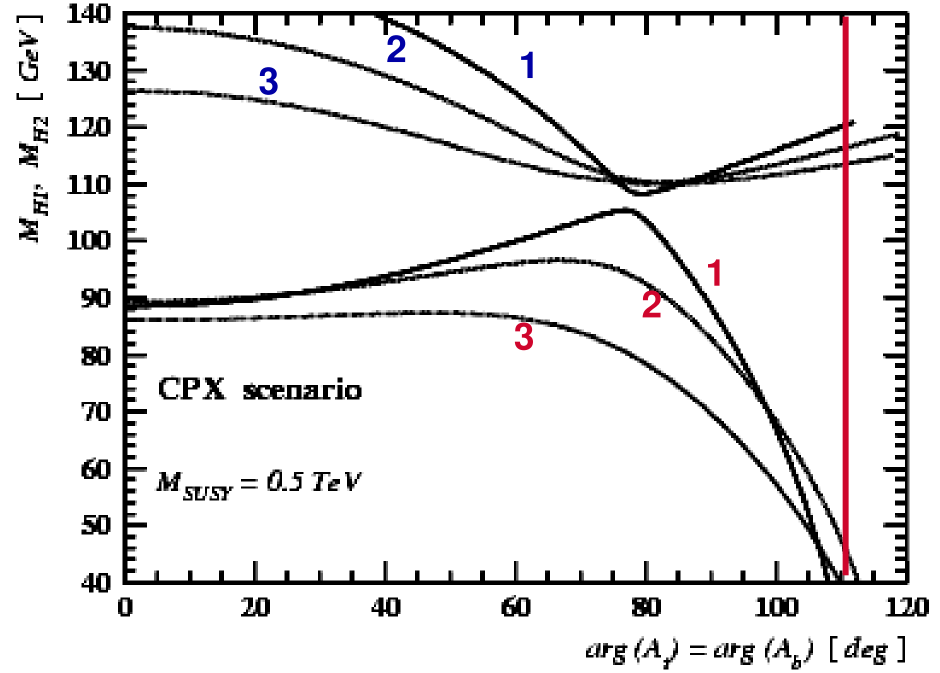
$$\Rightarrow m_{H_2} = 112\,\mathrm{GeV} \text{ and } m_{H_1} = 40\,\mathrm{GeV}$$

g_{H_1ZZ} too small to detect H_1

H_2 is produced via Higgs-strahlung but, it has sizeable decay rate into H_1H_1

New search mode opens up:

$$ZH_2 \to ZH_1H_1 \to Zb\bar{b}b\bar{b}$$



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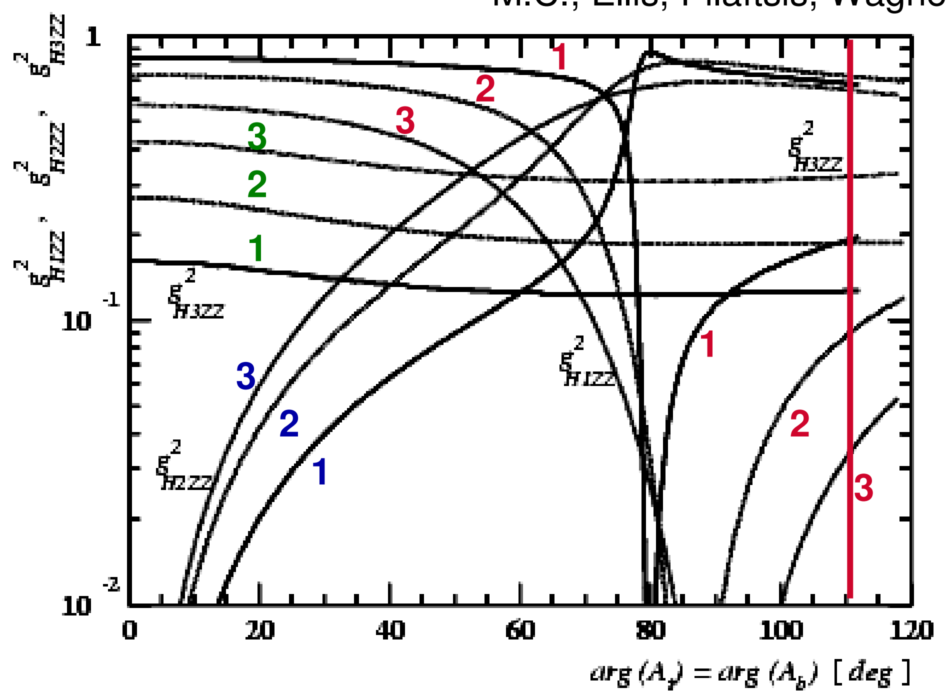
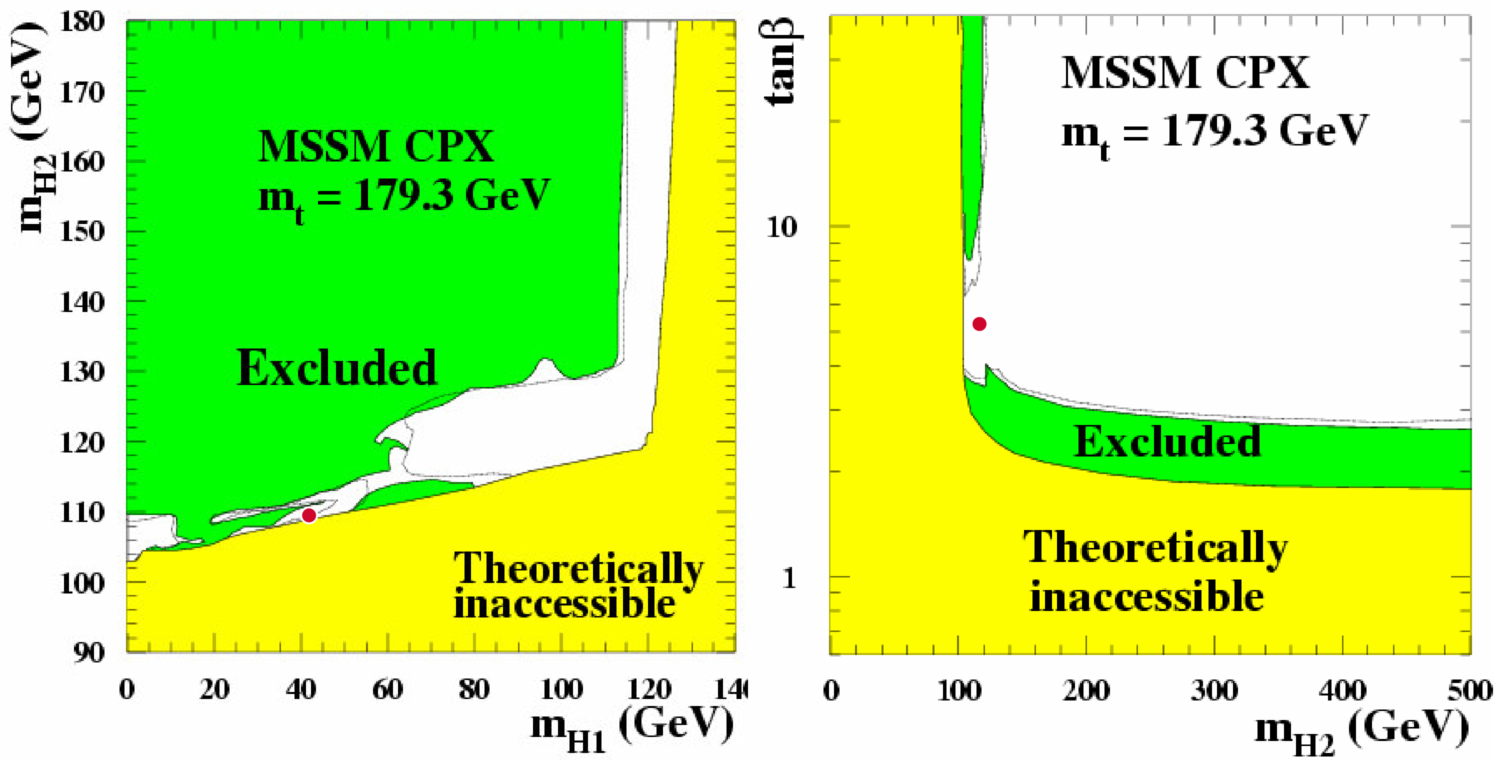


(b)

CPX scenario: no lower bound on M_{H_1} from LEP!

- H_1 decouples from the Z and H_2 and H_3 may be out of kinematic reach.
- or reduced couplings of H_i to Z and extended regions were H_2 decays H_1H_1 and the H_1's decay into b's



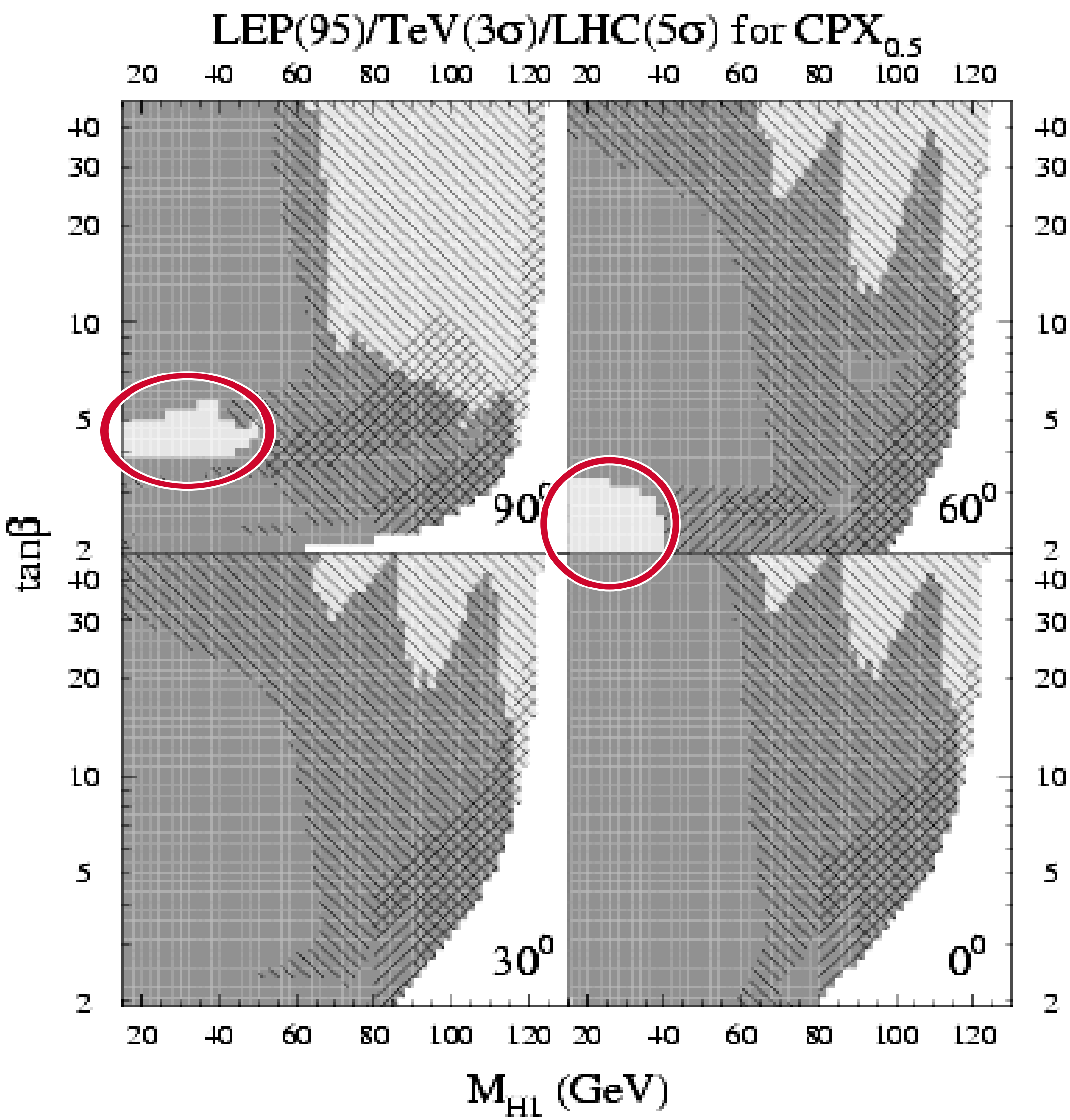
Including ZH_2 and H_1H_2 with $H_2 \to H_1H_1 \to b\bar{b}b\bar{b}$ in the analyses

$m_{H2} < 130$ GeV ➔ major role of CP-violating effects

Example: m_{H1} = 40-45GeV, m_{H2} = 110 GeV, $\tan\beta = 4-7$ Not excluded

No Universal lower limit on mH_1 but $\tan\beta > 2.6-2.9$ **(mt dep.)**

Approximate LEP exclusion and Tevatron (3σ / 5 fb^{-1}) and LHC (5σ discovery) limits in the m_{H_1} – $\tan\beta$ plane for CPX scenarios with different phases (arg $M_{\tilde{g}}$) = arg($A_{t,b}$)



45° lines → Tevatron: W/Z $H_i(\to b\bar{b})$

135° lines → LHC:

$gg \to H_i \to \gamma\gamma$ (100 fb^{-1})

$t\bar{t}H_i(\to b\bar{b})$ (100 fb^{-1})

WW/ZZ $H_i(\to \tau^+\tau^-)$ (30 fb^{-1})

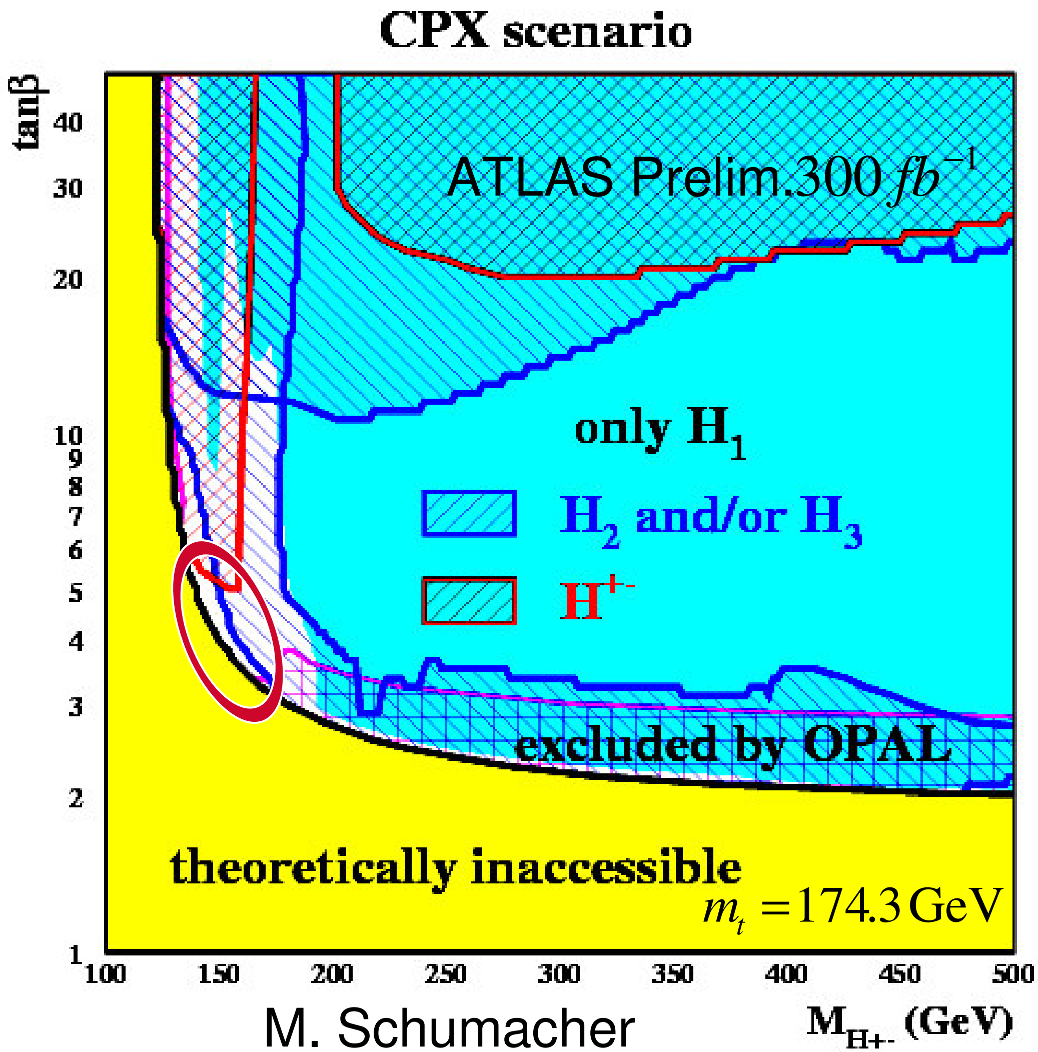
dark grey → LEP exclusion.

($m_t = 174.3$ GeV)

low tanb and low m_{Hi} region remains uncover in the absence of the $H_2 \to H_1H_1$ analysis

M.C., Ellis, Mrenna, Pilaftsis, Wagner

Can LHC discover the SM-like Higgs in the MSSM with explicit CP violation?



$m_{H1} < 70$ GeV

m_{H2} : 105 to 120 GeV

m_{H3} : 140 to 180 GeV

- H_2/H_3 channels: VBF and ttHi

Present limitations:

VBF only for mass > 110 GeV

No study for H_1 below 70 GeV

- Encourage the study of $gg \to H_2$, $t\bar{t}H_2$, W/Z H_2 and WW/ZZ H_2 with subsequent decay $H_2 \to H_1 H_1$, using the extra leptons from W/Z's.

Also $t\bar{t} \to WbH^{\pm}b$ with $H^{\pm} \to WH_1 \to Wb\bar{b}$

Looking for $\mathbf{H_2 \rightarrow H_1\ H_1}$

- Standard signatures not sufficient to probe the presence of a SM-like Higgs bosons decaying into lighter Higgs states.
- Lighter states have weak couplings to the weak gauge bosons, but large couplings to third generation down quarks and leptons.
- Possibility of looking for two taus and two bottoms (jets) signatures at LHC in the weak boson fusion production channel of two CP-odd like Higgs bosons. (J. Gunion et al. with 300 fb-1 at the LHC, NMSSM)
- A detailed experimental simulation should be performed to test this possibility.

Higgs Mediated FCNC in the quark sector

In terms of the mass eigenstates:

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

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:

$$R = 1 + E_{\tilde{g}} \tan\beta + E_u \tan\beta |h_u|^2$$

- Considering the squark masses flavour diagonal and universal ➔ R diagonal and $E_{\tilde{g}}$ is given by gluino contribution to Δh_b and E_u is given by the higgsino one
- Considering just the 3rd generation, we recover the effective Yukawa interactions presented above in the $\Phi^0 \overline{b} b$ effective Lagrangian

$$\text{in general: } R^{-1} = \frac{1}{1 + E_{\tilde{g}} \tan\beta} + \chi_{FC} \quad \text{with} \quad \chi_{FC} = -\frac{E_u |h_u|^2 \tan\phi}{(1 + E_{\tilde{g}} \tan\beta)R}$$

$$-L_{FCNC} = \frac{\sqrt{2}}{v_2}\left(\tan\beta\,\Phi_1^{0^*} - \Phi_2^{0^*}\right)\overline{d}_{iR} m_{di} (V_{ti}^* \chi_{FC}^{(t)} V_{tj} + V_{ci}^* \chi_{FC}^{(c)} V_{cj} + V_{ui}^* \chi_{FC}^{(u)} V_{uj}) d_{jL}.$$

$\chi_{FC}^{(u,c,t)}$ are the diagonal entries of χ_{FC} and summation over $i = d, s, b$ is understood

- Expressing the Higgs fields in terms of their mass eigenstates $H_{1,2,3}$
  ➔ general resummed Lagrangian for the diagonal and off-diagonal Higgs interactions Lagrangian:

$$-L_{H_i\bar{d}d'} = -\frac{g}{2M_w}\sum_{i=1}^{3} H_i \bar{d}\left(M_d g^L_{H_i\bar{d}d'} P_L + g^R_{H_i\bar{d}d'} M_{d'} P_R \right) d'$$

with
$$g^L_{H_i\bar{d}d'} = V^+R^{-1}V\frac{O_{1i}}{\cos\beta} + \left(1 - V^+R^{-1}V\right)\frac{O_{2i}}{\sin\beta} - i\left(1 - \frac{1}{\cos^2\beta}V^+R^{-1}V\right)\frac{O_{3i}}{\tan\beta}$$

$$g^R_{H_i\bar{d}d'} = \left(g^L_{H_i\bar{d}d'}\right)^+$$

- The above $\tan^2\beta$ enhanced FCNC terms properly take into account resummation, non-universality in the squark sector and CP violation effects

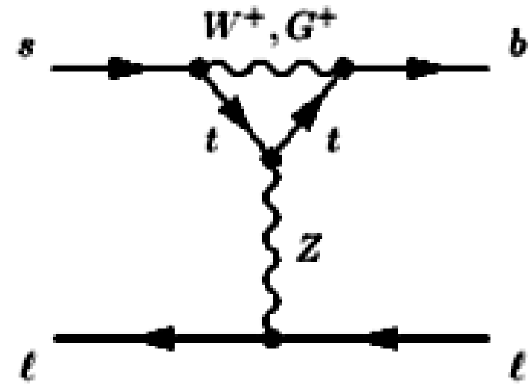
- The resummation matrix R controls the strength of the Higgs-mediated FCNC effects
  If R proportional to unity➔ a kind of GIM mechanism cancellation occurs and all Higgs-mediated FCNC vanish identically

- The one-loop resummed Lagrangian captures the bulk of the one-loop induced radiative effects for large tanb and Msusy above the electrowek scale

Probing the large tanb region at the Tevatron

$$B_s \rightarrow \mu^+ \mu-$$

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

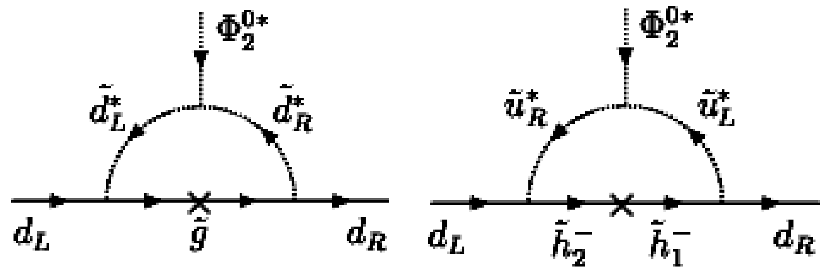


$$BR(B_s \rightarrow \mu^+ \mu-)_{SM} \approx (3.8 \pm 1.0)\ 10^{-9}$$

- Present CDF limit: $BR(B_s \rightarrow \mu^+ \mu-) < 2.\quad 10^{-7}$

- In the MSSM with two Higgs doublets:

$$BR(B_s \rightarrow \mu^+ \mu-)_{MSSM} \propto \left| V_{tb} V_{ts}^* \right| \frac{\tan^6 \beta}{m_{H_i}^4}$$



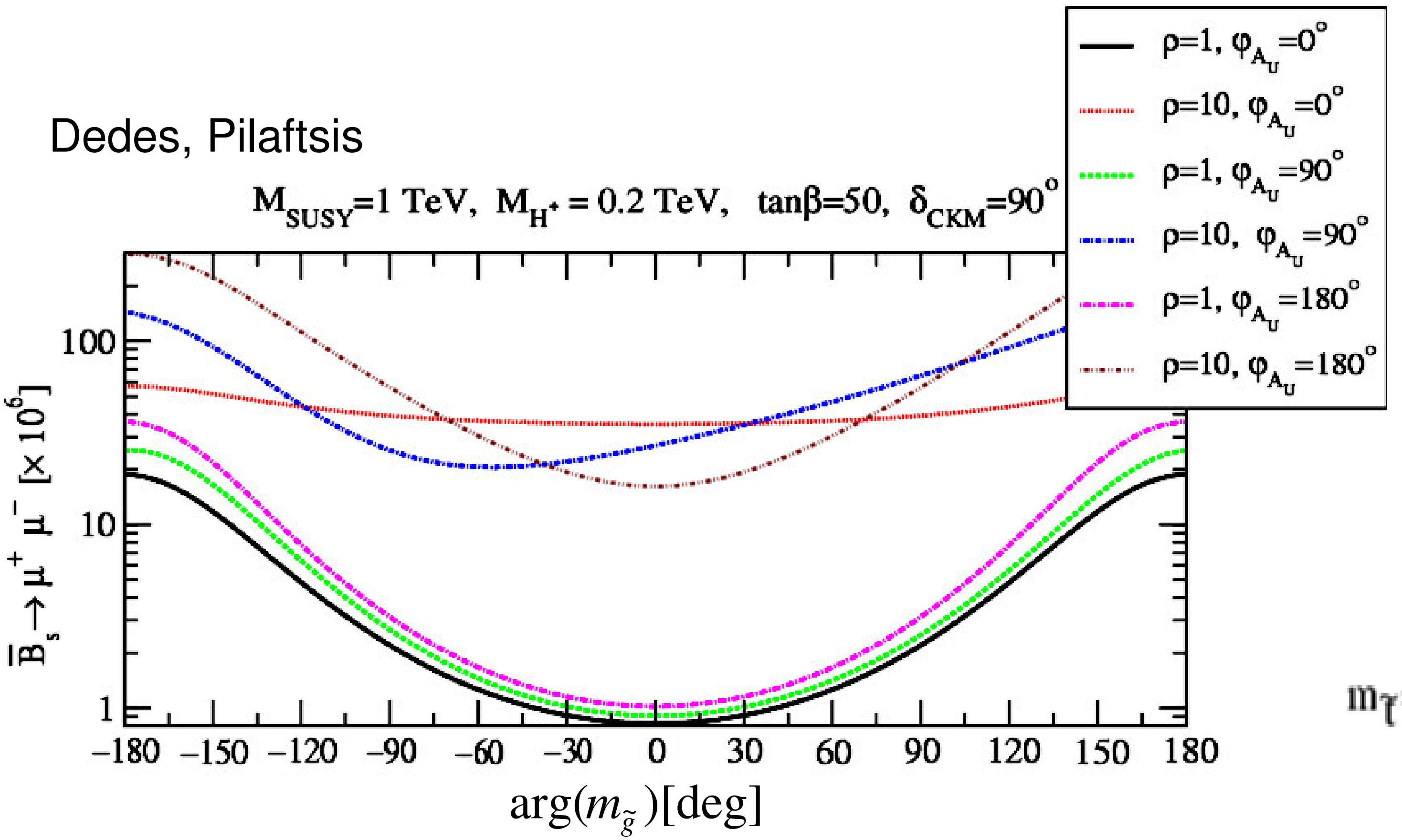
- Higgs mediated FCNC contributions can enhance the Branching ratio by 3 orders of magnitude

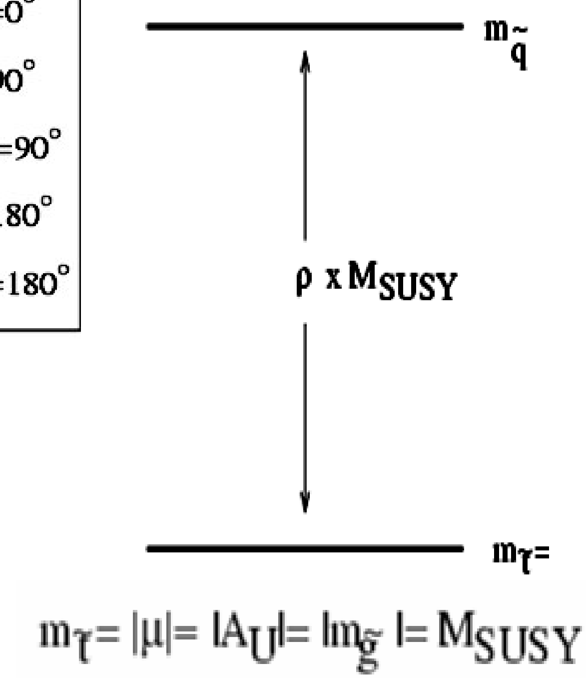
- Searches at the Tevatron explore regions of the tanb-Higgs masses parameter space in a very efficient way!

- Important effects of CP violation

SUSY Higgs-penguin contribution to $\mathrm{BR}(B_s \to \mu^+ \mu-)$ as a function of CP phases

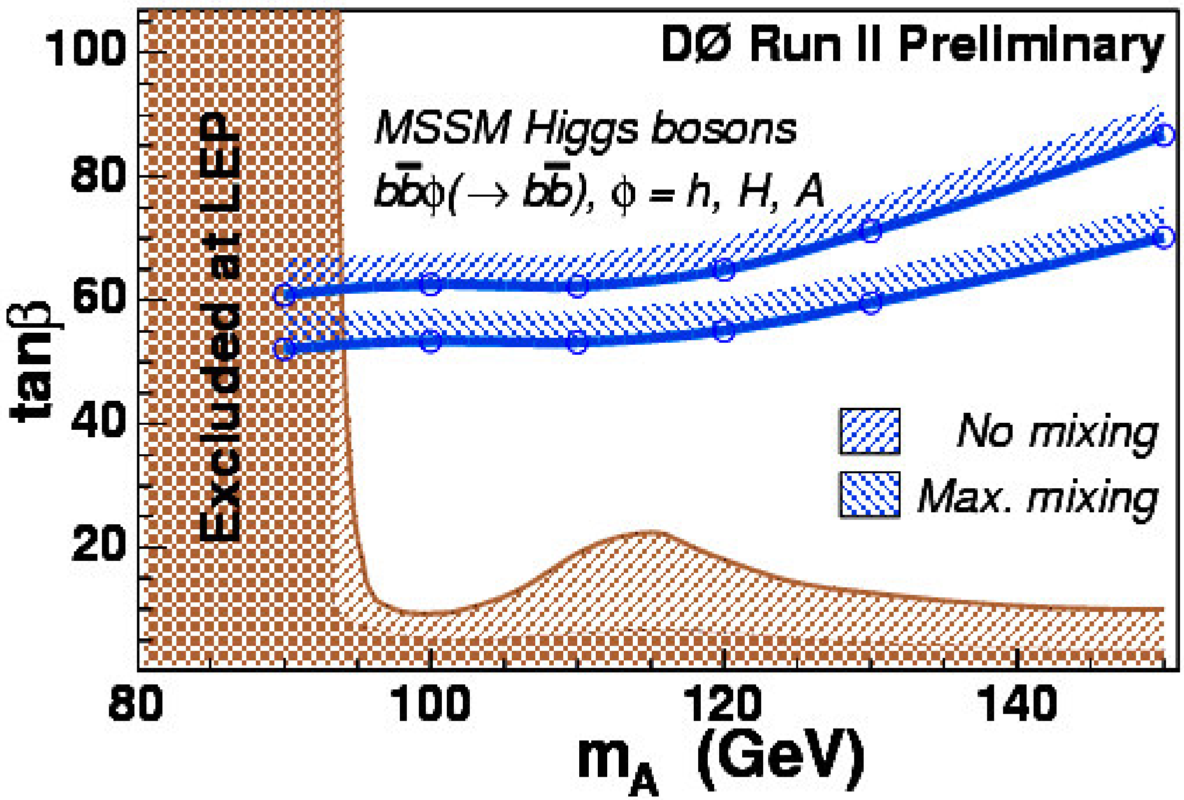
Dedes, Pilaftsis





- Predictions for other inputs of tanb and charged Higgs mass can be easily estimated rescaling the above values by a factor: $(\tan\beta/50)^6 \times (0.2/m_{H^\pm}[\mathrm{TeV}])^4$
- Bounds become more restrictive for phases of order π

Present Tevatron reach in the CP conserving MSSM Higgs sector



$200\,\mathrm{pb}^{-1}$

$p\,\bar{p} \rightarrow \phi b\bar{b} \rightarrow b\bar{b}b\bar{b}$ with

ϕ = A/h or A/H

With about 5 fb-1 one can expect to test the regime with:

$$\tan\beta \approx 10 \text{ and } \mathrm{m_A} \approx 100\,\mathrm{GeV} --- \tan\beta \approx 50 \text{ and } \mathrm{m_A} \approx 250\,\mathrm{GeV}$$

• Interesting to study the direct reach in tanb-CP-odd Higgs mass/ Hi masses and compare with indirect reach via sensitivity to $\mathrm{BR}(B_s \rightarrow \mu^+\mu-)$

M.C. Noriega, Szynkman: in progress

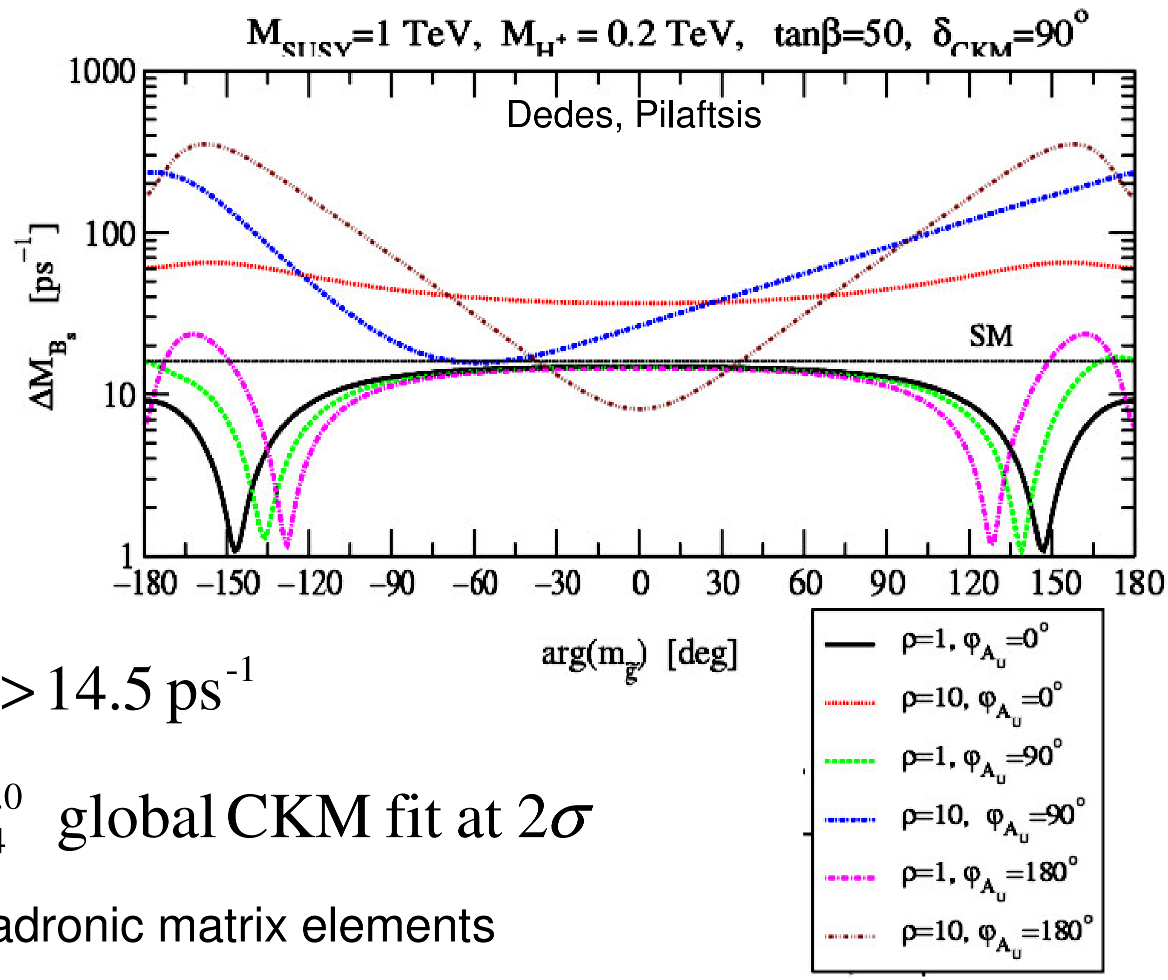
Other Applications of the resummed Effective Lagrangian for Higgs mediated FCNC to K and B systems

Dependece on CP phases of the mass difference ΔM_{B_s}

- SUSY contributions from Higgs mediated double penguin diagrams

Predictions for other inputs of tanb and charged Higgs mass can be easily estimated rescaling the above values by a factor:

$$(\tan\beta/50)^4 \times \left(0.2/m_{H^\pm}[\mathrm{TeV}]\right)^2$$



- LEP/SLD 95% C.L. limit: $\Delta M_{B_s}^{exp} > 14.5\ \mathrm{ps}^{-1}$

- SM prediction : $\Delta M_{B_s}^{SM} = 17.9^{+11.0}_{-2.4}$ global CKM fit at 2σ

  Uncertainties due to calculation of hadronic matrix elements

SM and Higgs double penguin effects may add constructively or destructively
➔ possible sizable new physics contributions

Other Applications of the resummed Effective Lagrangian for Higgs mediated FCNC to K and B systems

Dependece on CP phases of the

$K^0 - \overline{K}^0$ mass difference ΔM_K

and the CP violating mixing parameter ε_K

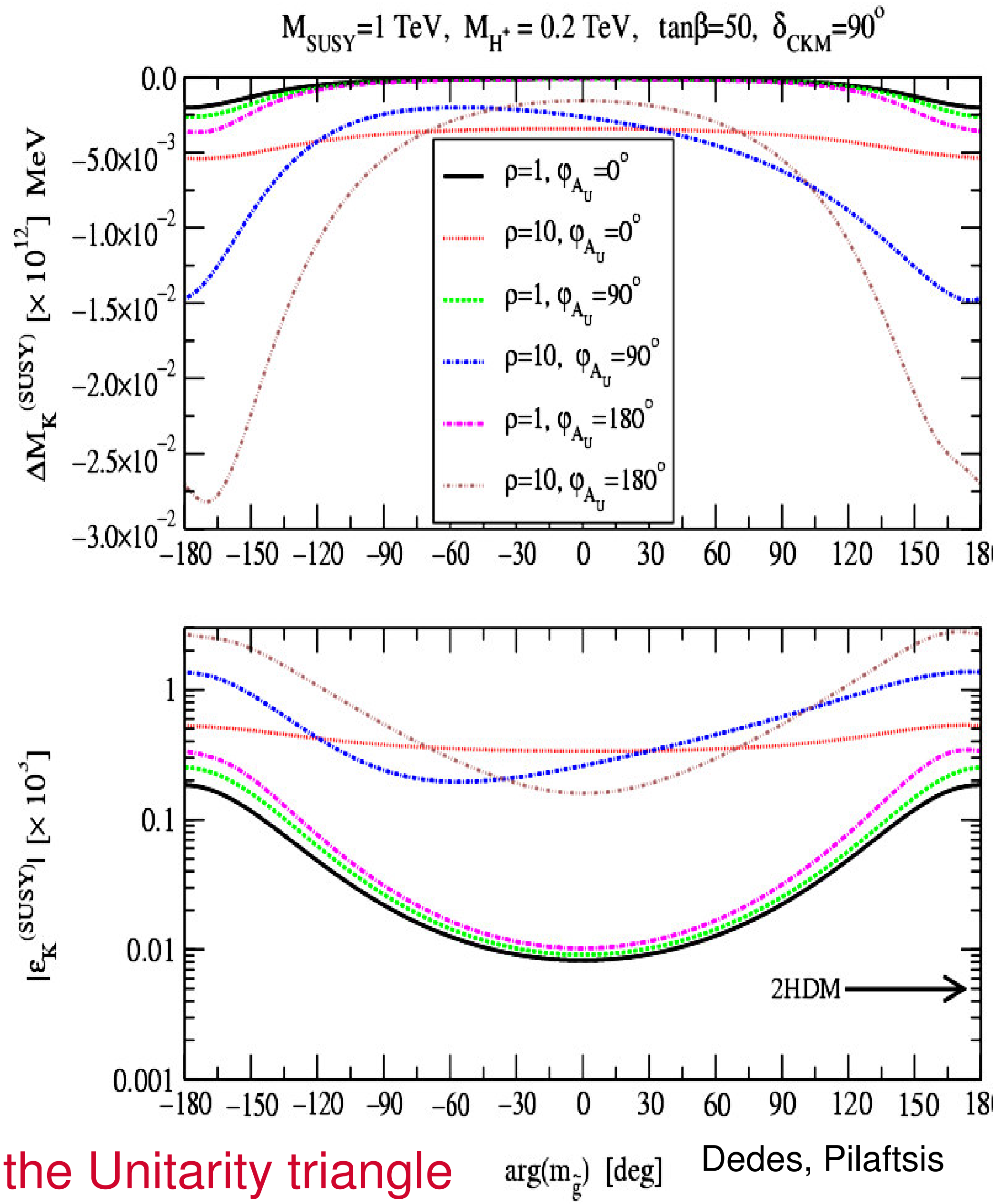
- SUSY contributions from Higgs mediated double penguin diagrams, $\tan^4 b$ enhanced
- box diagrams: t-H^+ and chargino-stop

Isidori,Retico; Buras et al.

$$\Delta M_K^{exp} = (3.490 \pm 0.006) \times 10^{-12}\,\mathrm{MeV}$$

ΔM_K is a poor laboratory to search for the impact for new physics

$$\left|\varepsilon_K^{exp}\right| = (2.282 \pm 0.017) \times 10^{-3}$$



Dedes, Pilaftsis

If $\delta\varepsilon_K^{NP} \approx \varepsilon_K^{SM}$, NP can change the fit to the Unitarity triangle

Conclusions

- Low energy supersymmetry has an important impact on Higgs physics.
- It leads to definite predictions to the Higgs boson couplings to fermions and gauge bosons.
- Such couplings, however, are affected by radiative corrections induced by supersymmetric particle loops.
- CP-violation in the Higgs sector is well motivated and should be studied in detail. It affects the searches for Higgs bosons at hadron and lepton colliders in an important way.
- At a minimum, it stresses the relevance of studying non-standard Higgs boson production and decay channels at lepton and hadron colliders.

Interaction Lagrangian of W,Z vector bosons with mixtures of CP even and CP odd Higgs bosons

$$L_{\mathrm{H_iVV}} = g_{\mathrm{H_iVV}}\, g_W M_W\, \mathrm{H_i}[\mathrm{W}_\mu \mathrm{W}^\mu + \mathrm{Z}_\mu \mathrm{Z}^\mu/(2\mathrm{M_W}/\mathrm{M_Z})]$$

$$L_{\mathrm{H_iH_jZ}} = g_{\mathrm{H_iH_jV}}\, g_W /(4M_W/\mathrm{M_Z})\; \mathrm{Z}^\mu \mathrm{H_i}\, i\overleftrightarrow{\partial}_\mu \mathrm{H_j}$$

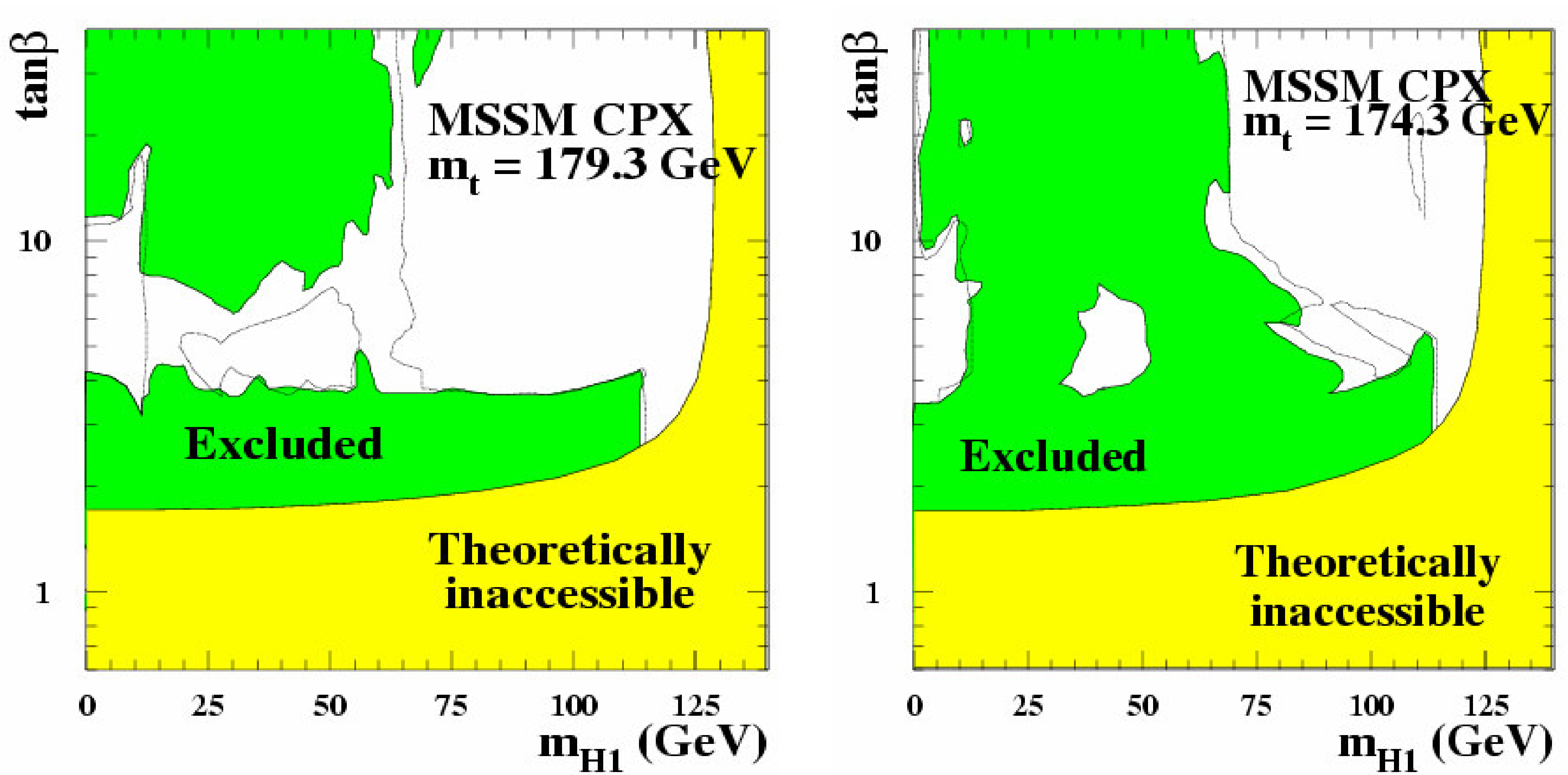
$$\begin{aligned} g_{H_iVV} &= \cos\beta\, O_{1i} + \sin\beta\, O_{2i} \\ g_{H_iH_jZ} &= O_{3i}\,(\cos\beta\, O_{2j} - \sin\beta\, O_{1j}) - \\ &\quad O_{3j}\,(\cos\beta\, O_{2i} - \sin\beta\, O_{1i}) \\ g_{H_iH^-W^+} &= \cos\beta\, O_{2i} - \sin\beta\, O_{1i} + iO_{3i} \end{aligned}$$

Yukawa Interactions

More generally we can write the Effective Lagrangian:

$$\begin{aligned} -\mathcal{L}_{\mathrm{eff}} &= \epsilon_{ij}\left[(h_b + \delta h_b)\bar{b}_R H_d^i Q_L^j + (h_t + \delta h_t)\bar{t}_R Q_L^i H_u^j\right] \\ &\quad + \Delta h_t \bar{t}_R Q_L^k H_d^{k*} + \Delta h_b \bar{b}_R Q_L^k H_u^{k*} + \mathrm{h.c.} \end{aligned}$$

Impact of the top quark mass on the results



main effect for $\tan\beta = 4 - 10$ is due to opening of H_1Z, H_2Z channels as well as H_1H_2

CP-Violating Higgs bosons at the Tevatron

Example:

• MH1 about 90 GeV but out of the reach of LEP.

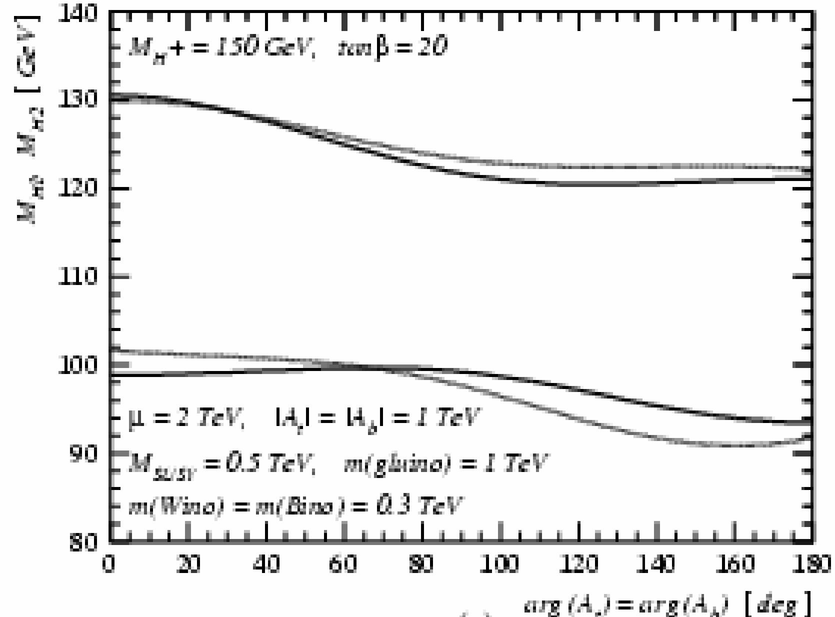
• All other channels kinematically unaccessible

• MH1 also hopeless at the Tevatron due to reduced W/Z H1 coupling

• H1 and H2 masses have little variation with phase of At, but couplings to gauge bosons vary importantly

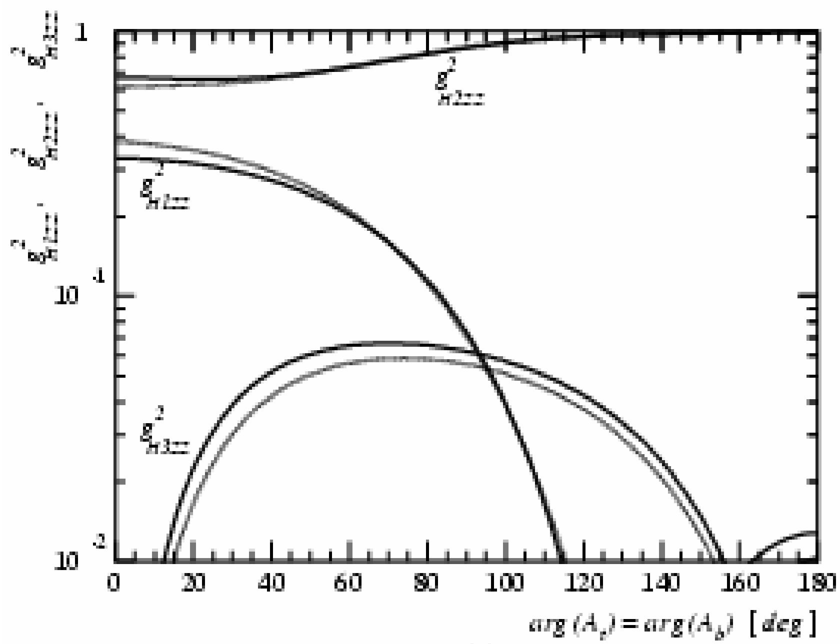
The Tevatron has a chance of having a first glance at H2.

Most crucial however, explore similar regions but for $M_{H_2} \geq 2M_{H_1}$



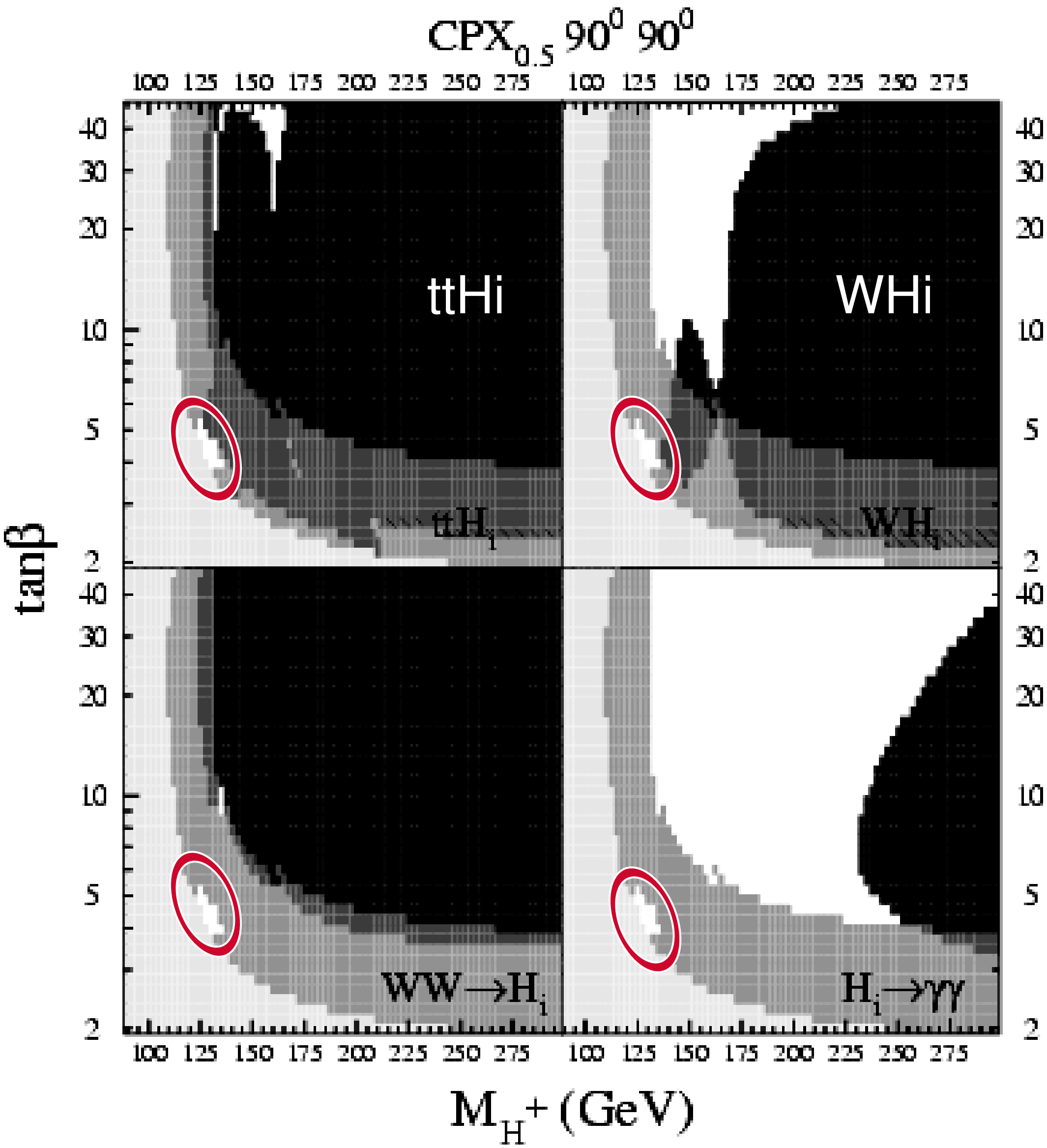
(a)

M.C., Ellis, Pilaftsis, Wagner



(b)

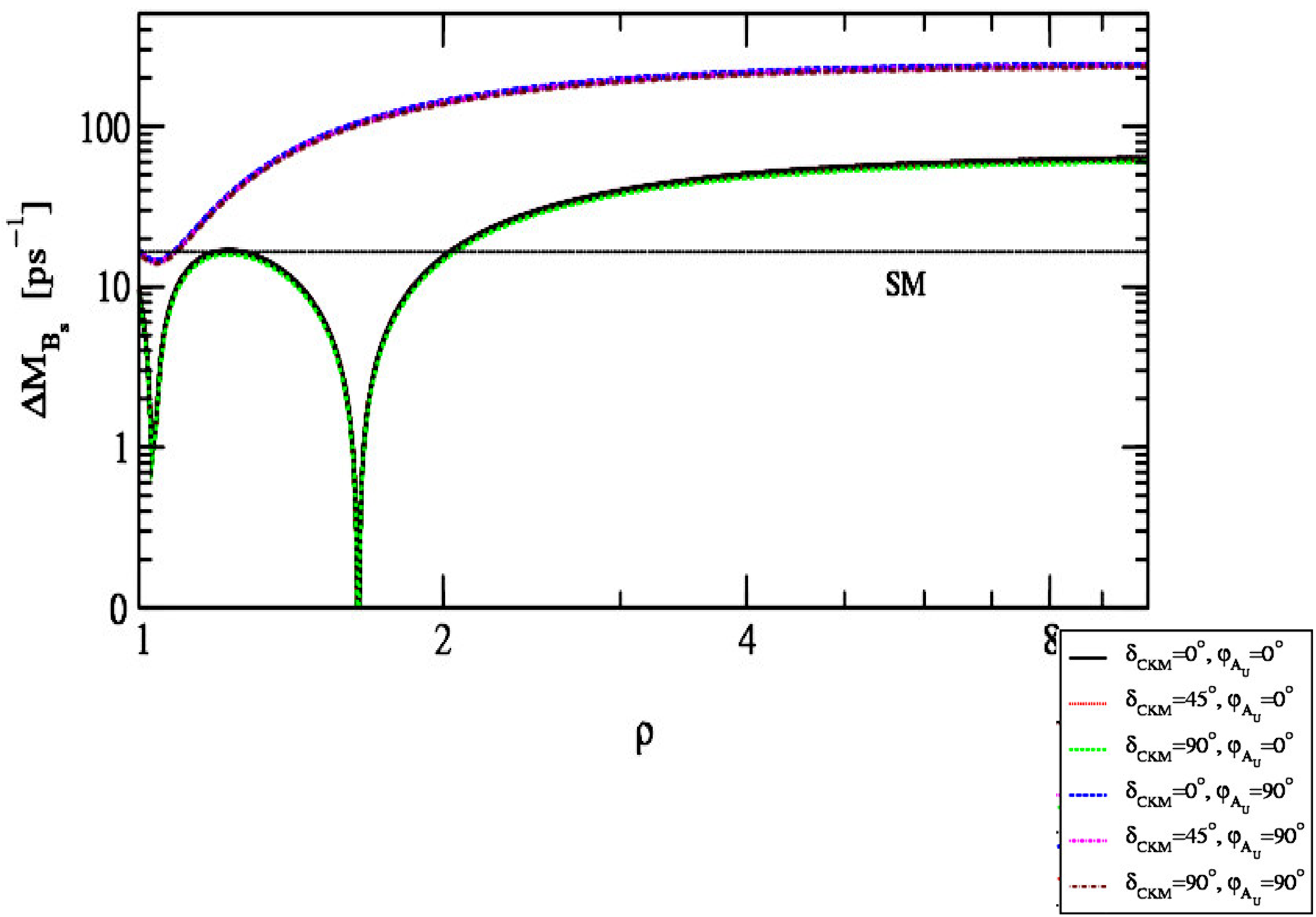
Similar plot as above but showing different channels separately and in the tan β–m_{H^+} plane



- The Tevatron could see a 3 σ hint with 5 fb^{-1} in a sizeable area of parameter space
- If arg($M\tilde{g}$)= 0 instead, stronger suppression of BR($H_{1,2}$) → $b\bar{b}$ and both upper channels less competitive

- vector boson fusion Higgs production with subsequent decay into taus still crucial channel at first years of LHC!

M.C. Ellis, Mrenna, Pilaftsis, Wagner



100
10
1
0
1
2
4
8
SM
ΔM_{B_s} [ps^{-1}]
ρ
$\delta_{CKM}=0°, \varphi_{A_U}=0°$
$\delta_{CKM}=45°, \varphi_{A_U}=0°$
$\delta_{CKM}=90°, \varphi_{A_U}=0°$
$\delta_{CKM}=0°, \varphi_{A_U}=90°$
$\delta_{CKM}=45°, \varphi_{A_U}=90°$
$\delta_{CKM}=90°, \varphi_{A_U}=90°$

CPsuperH

- Code to compute Higgs spectrum, couplings and decay modes in the presence of CP-violation

Lee, Pilaftsis, M.C., Choi, Drees,Ellis, Lee,Wagner.'03

- CP-conserving case: Set phases to zero. Similar to HDECAY, but with the advantage that charged and neutral sector treated with same rate of accuracy.

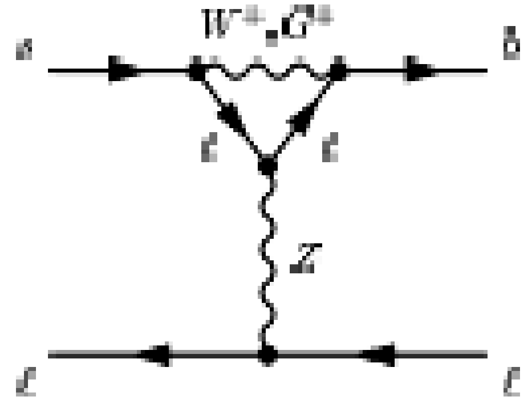
- Combines calculation of masses and mixings by M.C., Ellis, Pilaftsis, Wagner. with analysis of decays by Choi, Drees, Hagiwara, Lee and Song.

- Available at

http://theory.ph.man.ac.uk/~jslee/CPsuperH.html

$B_s \to \mu^+\mu^-$ as a probe of $\tan\beta$ at the Tevatron

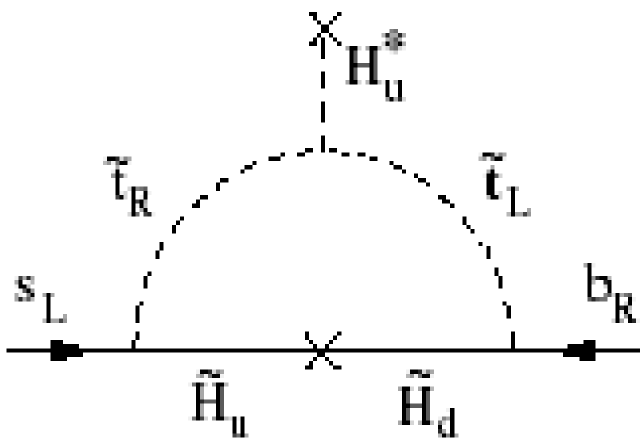
SM sample diagram:



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

$Br(B \to \mu^+\mu^-)_{\rm SM} = (3.8 \pm 1.0) \times 10^{-9}$

- In the MSSM, with two Higgs doublets, the Higgs Mediated contribution can put this BR at the reach of the Tevatron!



After SUSY breakdown, new contributions to d-type quark masses are generated even in a Minimal Flavor Model (CKM-induced)

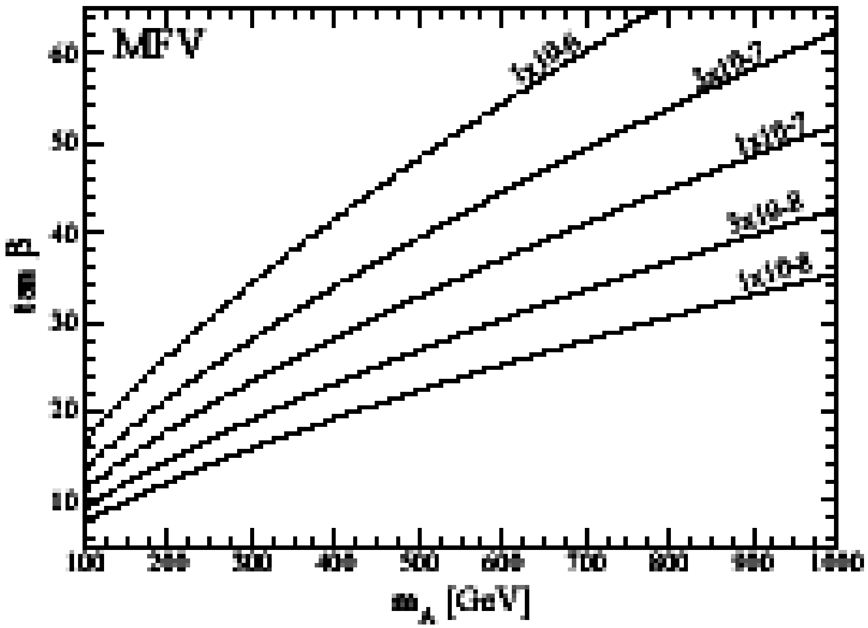
$Br(B \to \mu^+\mu^-)_{\rm MSSM} \propto \tan^6\beta\frac{1}{M^2_{A^0}}f(\mu A_t, M_{\tilde{t}_i}, M_{\tilde{\chi}_i^+})$

where $f \to$ const. $\neq 0$ for $M_{\rm SUSY} \to \infty$.

Babu, Kolda

$\Rightarrow$ branching fraction can be enhanced by three orders of magnitude!

Contours of Maximun allowed value of BR($B_s \to \mu\mu$) as a function of M_A and $\tan\beta$.



- $Br(B_s \to \mu^+\mu^-) < 2.6 \cdot 10^{-6}$ from Run 1.
- Single event sensitivity at Run 2 is 10^{-8} for 2 fb^{-1}

Kane, Kolda, Lennon

If a signature is observed at the Tevatron $\Longrightarrow$ lower bound on the value of $\tan\beta$

$$\tan\beta > 11 \left(\frac{M_A}{100GeV}\right)^{2/3} \left[\frac{Br(B_s \to \mu^+\mu^-)}{10^{-7}}\right]^{1/6}$$

Interesting to study direct reach in M_A via $b\bar{b}$ A/H production for large $\tan\beta$ and reach in $Br(B_s \to \mu^+\mu^-)$ for different sets of MSSM parameters

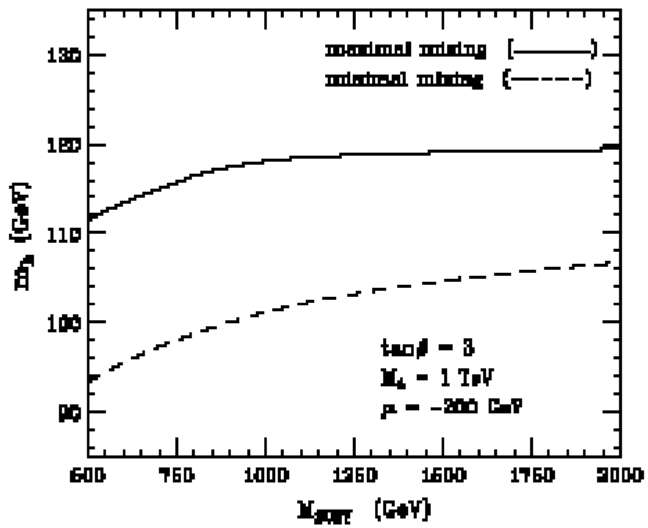
Two-loop effects

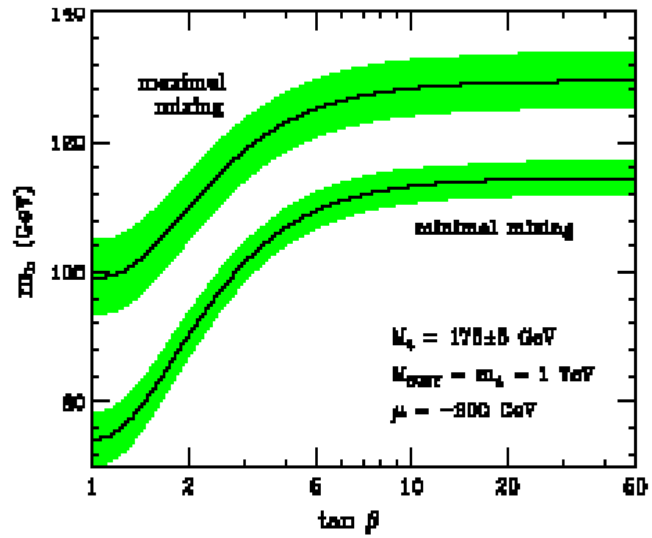
- At one loop, Higgs masses up to 150 GeV may be obtained for stop masses of order 1 TeV.

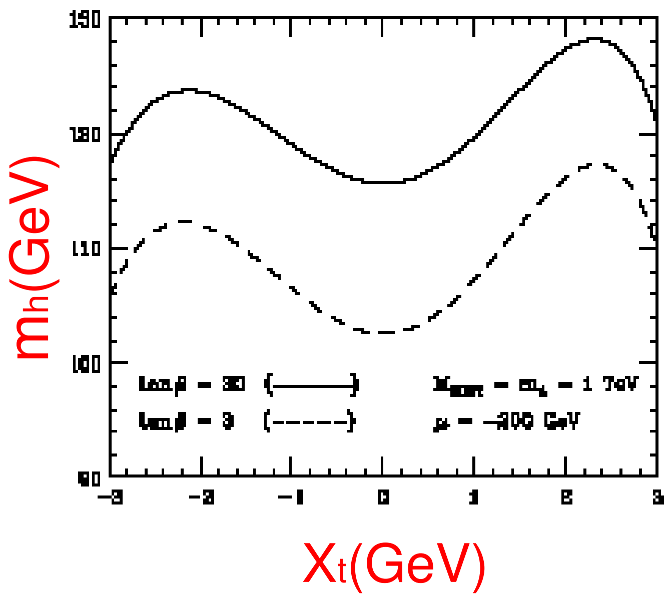
- Apart from lowering the Higgs mass by about 10--15 percent of its tree – level value by log. corrections, an asymmetry in the Higgs mass under change of sign of Xt appears at the two-loop level

- Such an asymmetry is induced by one-loop corrections to the relation between the top-quark mass and the top Yukawa coupling, which depend on the product of Xt and the gluino mass.

$$\frac{\Delta m_t}{m_t} \approx \frac{2\alpha_3}{3\pi} \frac{X_t M_{\tilde{g}}}{\max(m_{\tilde{t}}^2, M_{\tilde{g}}^2)}$$







$M_{SUSY} \equiv M_Q = M_U = M_D$

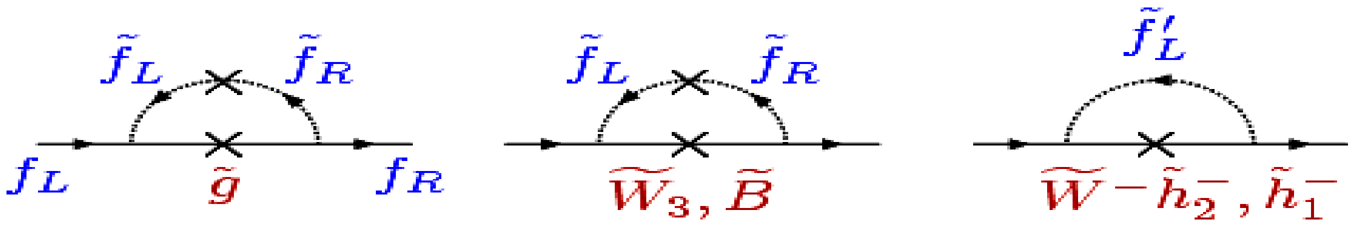
- m_t^4 enhancement
- logarithmic sensitivity to $m_{\tilde{t}_i}$
- depend. on $\tilde{t}$-mixing X_t

$\Longrightarrow$ max. value $X_t \sim \sqrt{6} M_S$

Carena, Haber, Hollik, Heinemeyer, Weiglein, C.W. '00
Heinemeyer, Hollik, Weiglein'02
Degrassi, Slavich, Zwirner '02

Allowing 2 -- 3 TeV stop masses, the revised top-quark mass value, and playing with all other parameters, upper bound on the lightest Higgs mass can be pushed up to about 145 GeV.

One-loop contributions to the EDMs:



with $f = e,\ u,\ d$.

Crude estimate of the one-loop contributions to the ne
and electron EDMs:

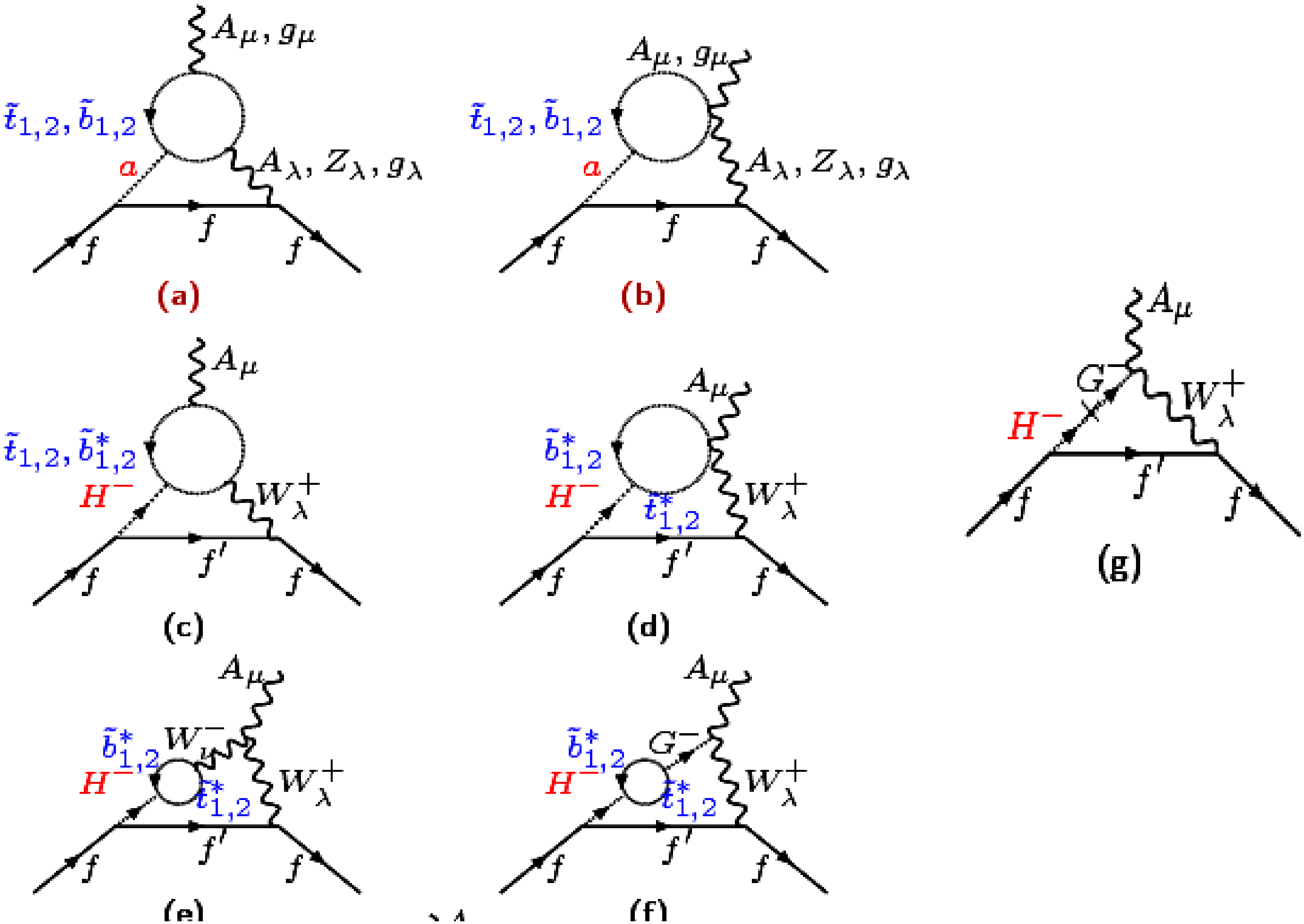
$$\left(\frac{d_f}{e}\right)^{1-\text{loop}} \sim (10^{-25}\ \text{cm}) \times \frac{\{\text{Im}\,\mu,\ \text{Im}\,A_f\}}{\max(M_{\tilde{f}}, m_\lambda)} \times \left(\frac{1\ \text{TeV}}{\max(M_{\tilde{f}}, m_\lambda)}\right)^2 \Big(\frac{m_f}{10\ \text{MeV}}$$

with $\lambda = \tilde{g}, \widetilde{W}^-, \tilde{h}^-_{1,2}$.

Schemes for resolving the one-loop CP crisis:

- $\text{Im}\,\mu/|\mu|,\ \text{Im}\,A_f/|A_f| \lesssim 10^{-2}$, with $M_{\tilde{f}}, m_\lambda \sim 200$ (
- CP phases ~ 1, but $M_{\tilde{f}} \gtrsim 1$ TeV, for $\tilde{f} = \tilde{u}, \tilde{d}, \tilde{e}, \tilde{\nu}_L$
- Cancellations between the different EDM terms

Higgs-boson two-loop contributions to EDM and CEDM of a fermion in the Feynman–'t Hooft gauge; f' represents the conjugate fermion of f under T_z^f



MSSM tree-level Higgs spectrum and properties

Minimal model: 2 Higgs SU(2) doublets

5 physical states: 2 CP-even h, H with mixing angle
1 CP-odd A and a charged pair $H^{\pm}$

- Two Higgs doublets, H_1 and H_2 mix, with a mixing angle α, leading to the two CP-even Higgs bosons.

$$h = -\sin\alpha\, H_1^0 + \cos\alpha\, H_2^0$$

$$H = \cos\alpha\, H_1^0 + \sin\alpha\, H_2^0$$

- The charged and complex neutral parts of the two Higgs doublets lead to the Goldstone as well as the CP-odd and charged Higgs bosons

- Ratio of Higgs vacuum expectation values, $\tan\beta = \frac{v_2}{v_1}$, determines the mixing angle between Goldstones and Higgs states.

Higgs masses and couplings given in terms of two parameters:

m_A and $\tan\beta \equiv v_2/v_1$ mixing angle $\alpha \Longrightarrow \cos^2(\beta - \alpha) = \frac{m_h^2(m_Z^2 - m_h^2)}{m_A^2(m_H^2 - m_h^2)}$

Couplings to gauge bosons and fermions (norm. to SM)

hZZ, hWW, ZHA, $WH^{\pm}H$ $\longrightarrow \sin(\beta-\alpha)$

HZZ, HWW, ZhA, $WH^{\pm}h$ $\longrightarrow \cos(\beta-\alpha)$

(h,H,A) $u\bar{u} \longrightarrow \cos\alpha/\sin\beta,\quad \sin\alpha/\sin\beta,\quad 1/\tan\beta$

(h,H,A) $d\bar{d}/l^+l^- \longrightarrow -\sin\alpha/\cos\beta,\quad \cos\alpha/\cos\beta,\quad \tan\beta$

For moderate or large values of the CP-odd Higgs boson mass:

$$(m_A \gg M_Z \rightarrow \text{decoupling limit})$$

- $\cos(\beta-\alpha)=0$ up to correc. $\mathcal{O}(m_Z^2/m_A^2)$
- lightest Higgs has SM-like couplings and mass $m_h^2 \simeq m_Z^2\cos^2 2\beta$
- other Higgs bosons: heavy and roughly degenerate

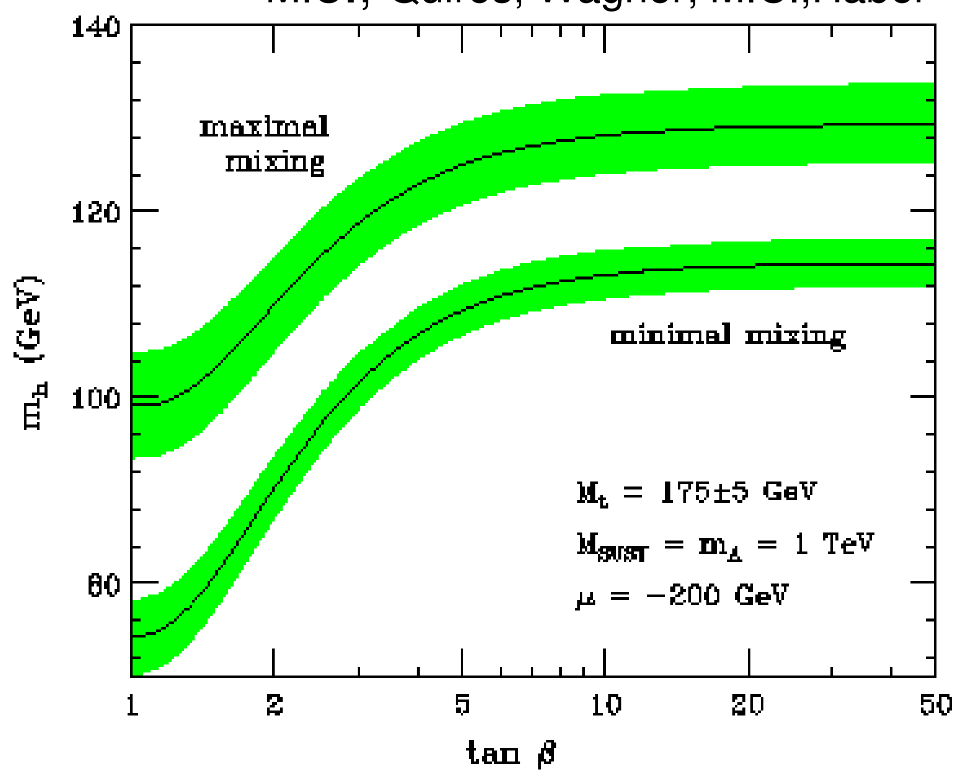
$m_A \simeq m_H \simeq m_H^{\pm}$ up to correc. $\mathcal{O}(m_Z^2/m_A^2)$

- **Supersymmetric relations between couplings imply** $m_h \leq m_Z$

After quantum corrections, Higgs mass shifted due to incomplete cancellation of particles and superparticles in the loops

Main Quantum effects: m_t^4 **enhancement ; dependence on the stop mixing** X_t **; logarithmic sensitivity to the stop mass (averaged:** M_S **)**

M.C., Quiros, Wagner; M.C.,Haber



Upper bound :

$$m_h \leq 135 \quad \text{GeV}$$

stringent test of the MSSM

LEP MSSM HIGGS limits:

$$m_h > 91.0\text{GeV}; m_A > 91.9\text{GeV}$$

$$m_{H^\pm} > 78.6\text{GeV}$$

$$m_h^{\text{SM-like}} > 114.6\text{GeV}$$

Loop Corrections to Higgs boson masses

- Most important corrections come from the stop sector,

$$\mathbf{M}^2_{\tilde{t}} = \begin{pmatrix} \mathbf{m}^2_Q + \mathbf{m}^2_t + \mathbf{D}_L & \mathbf{m}_t\,\mathbf{X}_t \\ \mathbf{m}_t\,\mathbf{X}_t & \mathbf{m}^2_U + \mathbf{m}^2_t + \mathbf{D}_R \end{pmatrix}$$

  where the off-diagonal term depends on the stop-Higgs trilinear couplings, $\mathbf{X}_t = \mathbf{A}_t - \mu^* / \tan\beta$

- For large CP-odd Higgs boson masses, and with $\mathbf{M}_S = \mathbf{m}_Q = \mathbf{m}_U$ dominant one-loop corrections are given by,

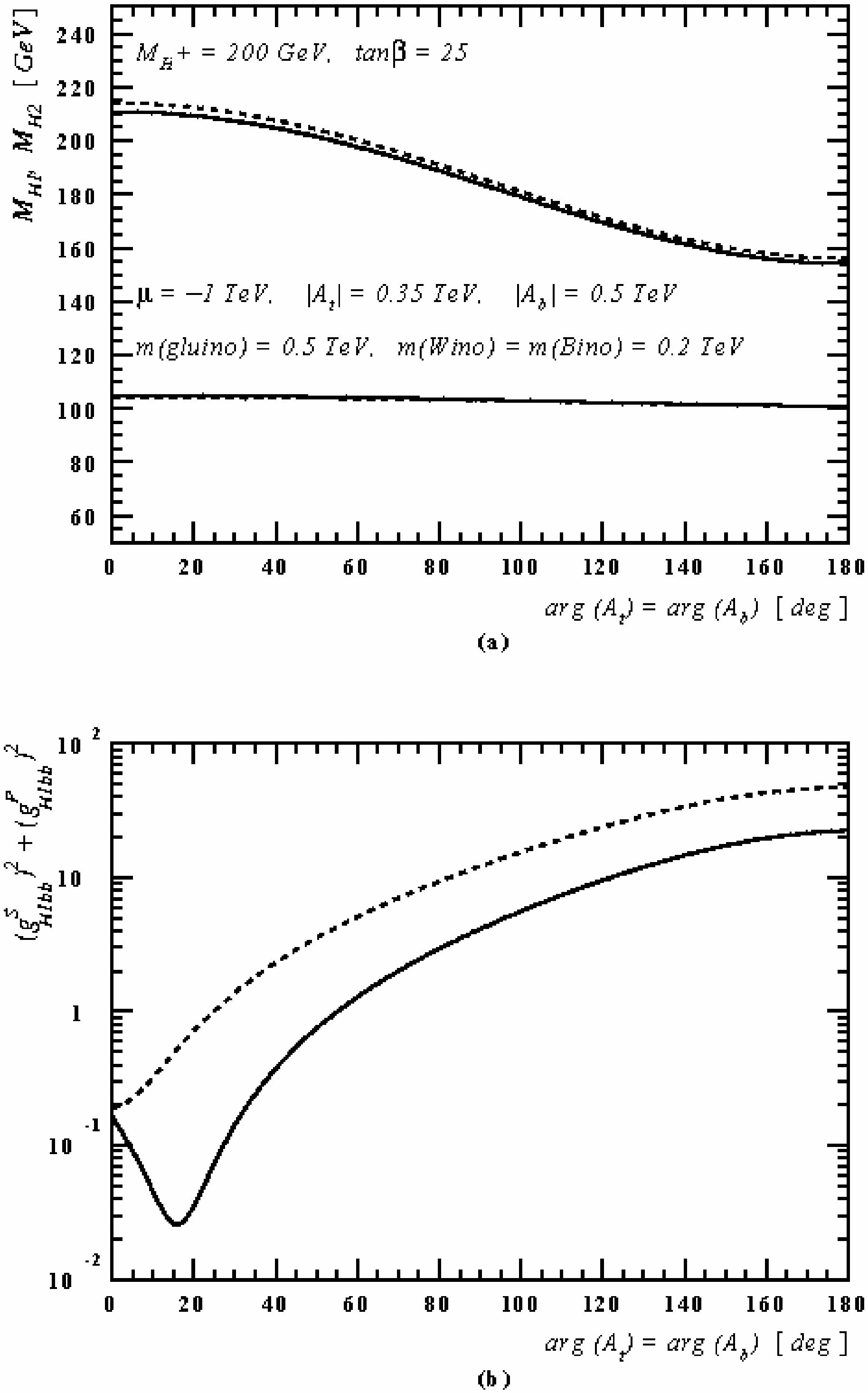
$$\mathbf{m}^2_h \approx \mathbf{M}^2_Z \cos^2 2\beta + \frac{3\mathbf{m}^4_t}{4\pi^2 \mathbf{v}^2}\left(\log\left(\frac{\mathbf{M}^2_S}{\mathbf{m}^2_t}\right) + \frac{\mathbf{X}^2_t}{\mathbf{M}^2_S}\left(1 - \frac{\mathbf{X}^2_t}{12\,\mathbf{M}^2_S}\right)\right)$$

- After two-loop corrections:

  - upper limit on Higgs mass:
    $m_h \lesssim 135$ GeV

$$M_S = 1 \to 2 \text{ TeV} \Longrightarrow \Delta m_h \simeq 2-5 \text{ GeV}$$
$$\Delta m_t = 1 \text{ GeV} \Longrightarrow \Delta m_h \sim 1 \text{ GeV}$$

Strong suppresion of H_1bb Coupling depending on the gluino phase



- Suppression of Higgs coupling to bb for a Higgs with SM-like couplings to vector bosons

⬇

Region of parameter space consistent with electroweak Baryogenesis

Searches at LEP excluded a mass up to about 112 GeV in the flavour independent analysis