MSSM Higgs Sector with CP Violation

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TeV4LHC Higgs WG
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Motivation for CP-Violation in SUSY Models

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

- These CP-violating phases may induce effects on observables such as new contributions to the e.d.m. of the electron and the neutron.

  However, effects on observables are small in large regions of parameter space, where either first or second generation scalars are heavy, cancellations occur or simply the relevant CP-violating phase for such a given observable vanishes.

- 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.

Effects of CP-violation on Higgs physics associated with third generation scalars and/or gaugino-Higgsino sector, are worth studying.

Minimal Supersymmetric Extensions

- In the minimal SUSY extension, there are one charged and three neutral Higgs boson degrees of freedom.
- If CP is conserved, there are two CP-even and one CP-odd neutral Higgs bosons.
- At tree-level, all CP-violating phases, if present, may be absorbed into a redefinition of the fields.
- CP-violation in the Higgs sector appears at the loop-level, but can still have important consequences for Higgs physics

MSSM Higgs sector at Tree-Level

H_1, H_2 doublets $\Longrightarrow$ 2 CP-even Higgs h, H   1 CP-odd state A   2 charged Higgs $H^{\pm}$

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)

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

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

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

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

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. $\mathcal{O}(m_Z^2/m_A^2)$

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

$\Longrightarrow$ 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

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

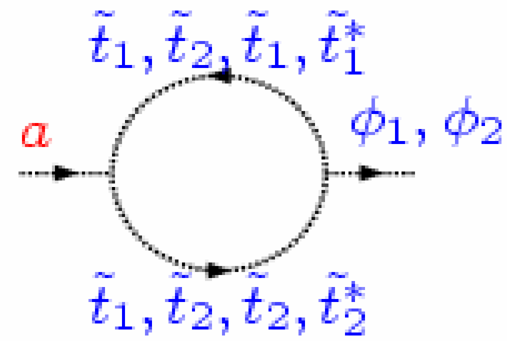
In the base (A, ϕ_1, ϕ_2):

$$M_N^2 = \begin{bmatrix} \mathbf{m}_A^2 & (\mathbf{M}_{SP}^2)^T \\ \mathbf{M}_{SP}^2 & \mathbf{M}_{SS}^2 \end{bmatrix}$$

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.

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

$$\mathbf{M}_{SP}^2 \propto \frac{\mathbf{m}_t^4}{16\pi^2 \, \mathbf{v}^2} \, \mathbf{Im}\left(\frac{\mu \mathbf{A}_t}{\mathbf{M}_S^2}\right)$$



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

Comments on Higgs Boson Mixing

- m_A^2 no longer a physical parameter, but the charged Higgs mass $M_{H^\pm}$ can be used as a physical parameter, together with M_S, $|\mu|$, $|A_t|$, $\arg(A_t)$ and $\arg(M_{\tilde{g}})$
- 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.
- Couplings of the Higgs bosons to vector bosons still depend on projection of Higgs that acquires v.e.v. to the different Higgs bosons.
- 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

$$g_{H_i VV} = \cos\beta\, \mathcal{O}_{1i} + \sin\beta\, \mathcal{O}_{2i}$$
$$g_{H_i H_j Z} = \mathcal{O}_{3i}\,(\cos\beta\, \mathcal{O}_{2j} - \sin\beta\, \mathcal{O}_{1j}) - \mathcal{O}_{3j}\,(\cos\beta\, \mathcal{O}_{2i} - \sin\beta\, \mathcal{O}_{1i})$$
$$g_{H_i H^- W^+} = \cos\beta\, \mathcal{O}_{2i} - \sin\beta\, \mathcal{O}_{1i} + i\mathcal{O}_{3i}$$
$$\mathcal{O}_{ij} \longrightarrow \text{analogous to } \sin(\beta-\alpha)\ \&\ \cos(\beta-\alpha)$$

$(V = W, Z)$

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

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

(equiv. to CP-conserv. case)

upper bound remains the same

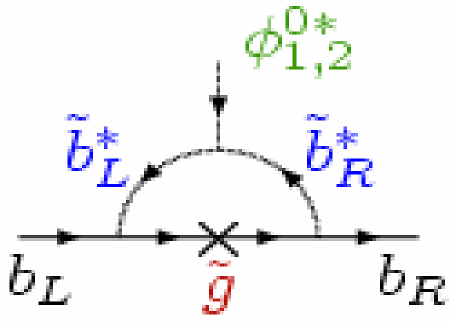
Decoupling limit: $m_{H^+} \gg M_Z$

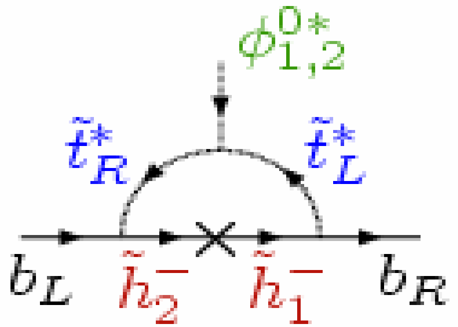
- **Effective mixing between the lightest Higgs and the heavy ones is zero → H_1 is SM-like**
- **Mixing in the heavy sector still relevant !**

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

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

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

$$\frac{\Delta h_b}{h_b} \sim \frac{2\alpha_s}{3\pi}\frac{m^*_{\tilde{g}}\mu^*}{\max\left(Q_{\tilde{b}}^2, |m_{\tilde{g}}|^2\right)} + \frac{|h_t|^2}{16\pi^2}\frac{A^*_t\mu^*}{\max\left(Q_{\tilde{t}}^2, |\mu|^2\right)}$$

- 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:

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

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

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

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

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

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:

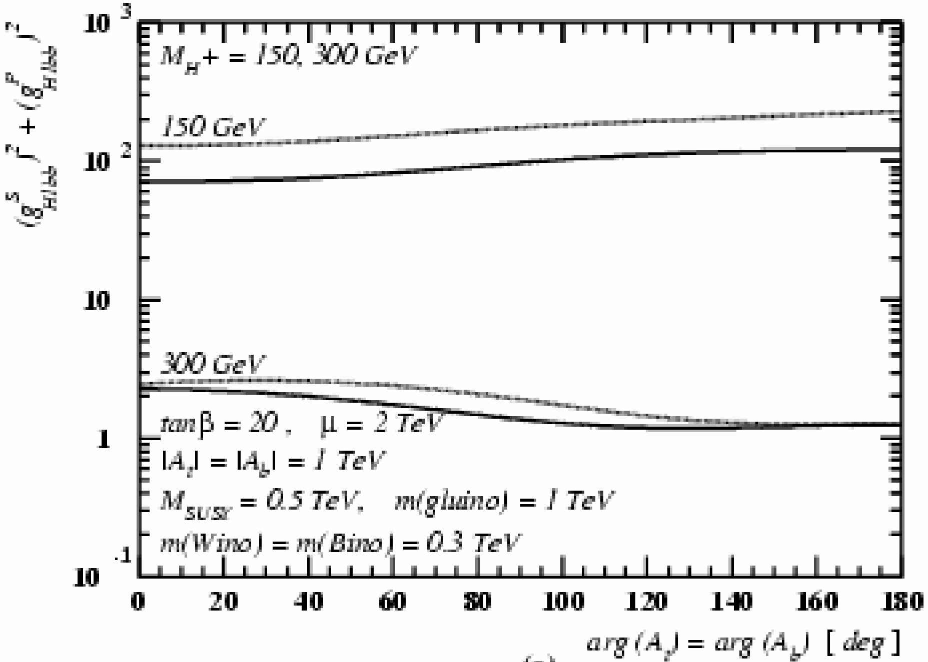
- H_1bb and H_1uu pseudoscalar couplings tend to zero while their scalar couplings tend to SM-like

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

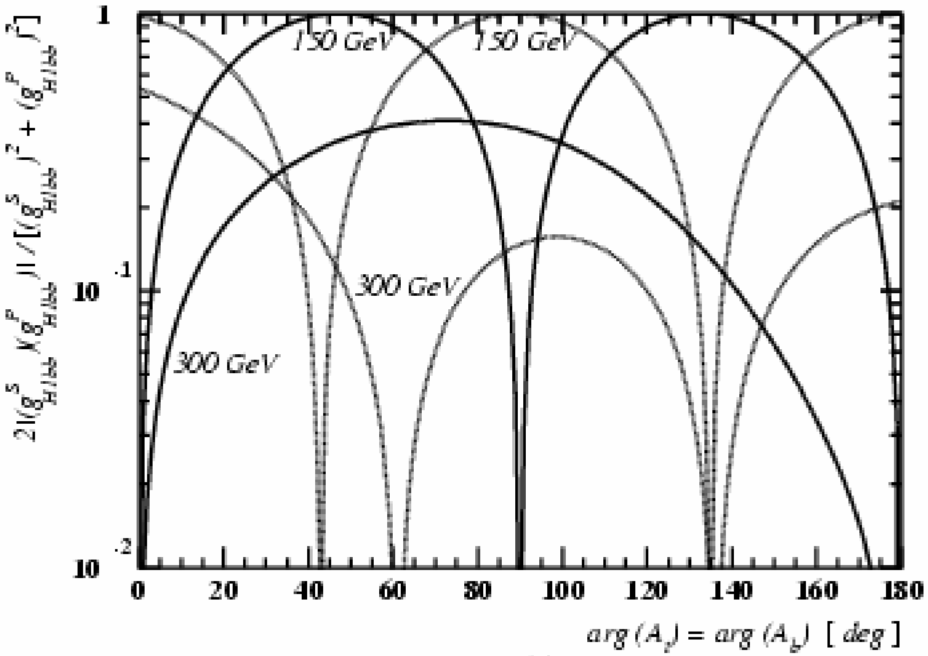
- Heaviest Higgs Scalar and Pseudoscalar couplings to up and down quarks do not vanish

➔ 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)



(b)

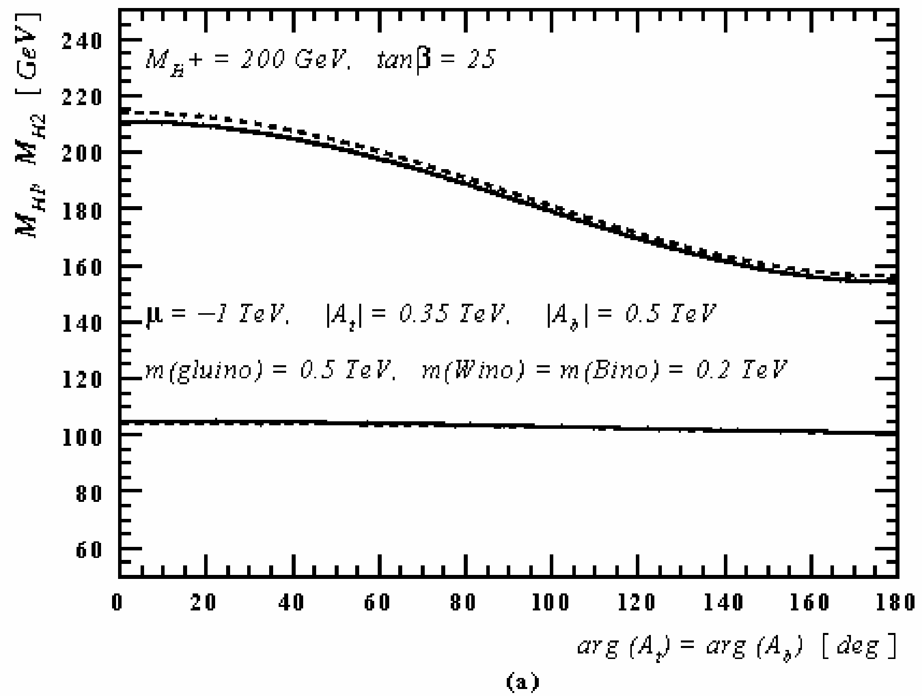
- **Analyze behaviour in term of CP-even quantities: BR's and CP- odd quatinties: Asymmetries**

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

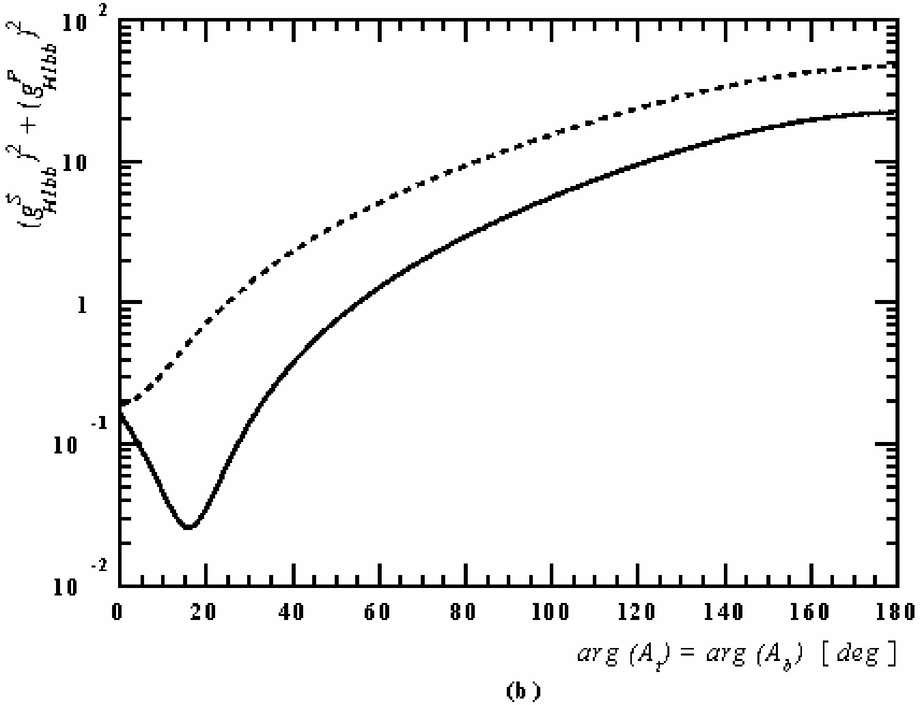
- **Cases with gluino mass phase zero (solid lines) and 90 degrees (dashed lines) shown in figures: stronger effects of gluino phase for larger tanb**

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

Strong suppresion of H_1bb Coupling depending on the gluino phase



(a)



(b)

- 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

CP-Violating Higgs bosons at LEP: a challenging scenario

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

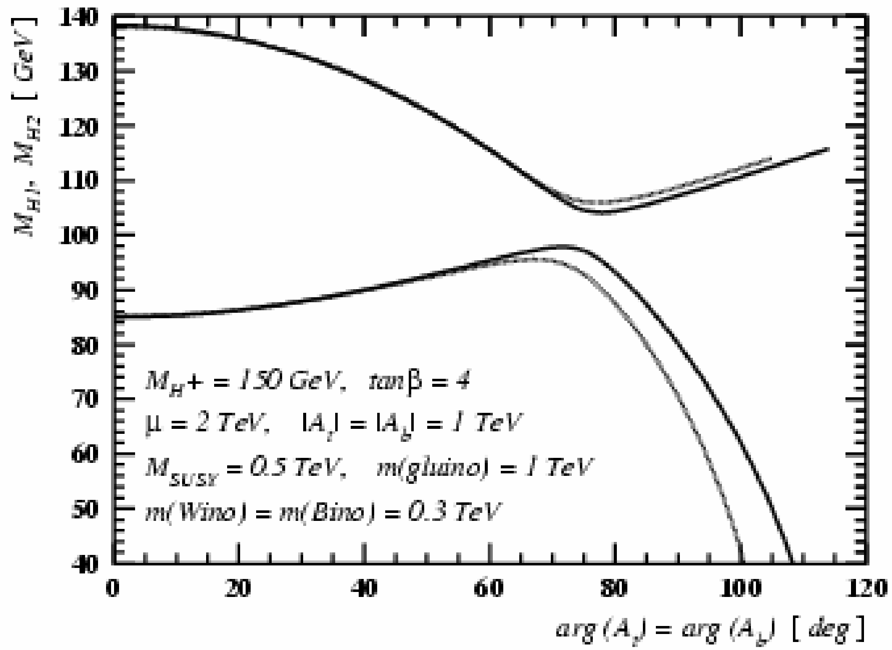
CPX Scenario:

$M_{SUSY} = 0.5,\ 1$ TeV

$\mu = 4\, M_{SUSY}$

$m_{\tilde{g}} = 1$ TeV

$|A_t| = |A_b| = 2M_{SUSY}$



(a)

- interesting example:

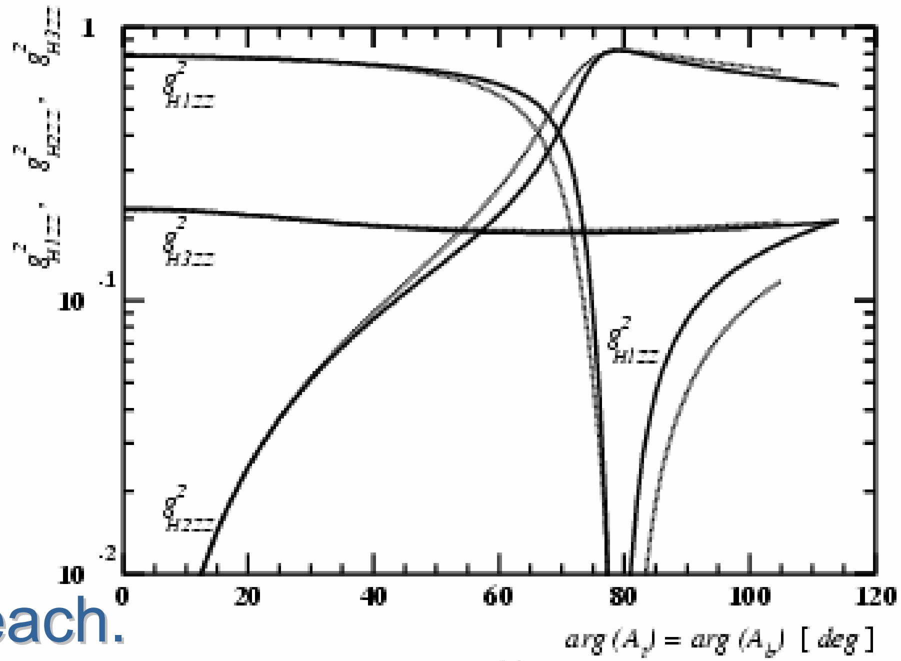
$\arg(A_{t,b}) = 90^o$, $\arg(m_{\tilde{g}}) = 90^o$

$m_{H^\pm} \simeq 150$ 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

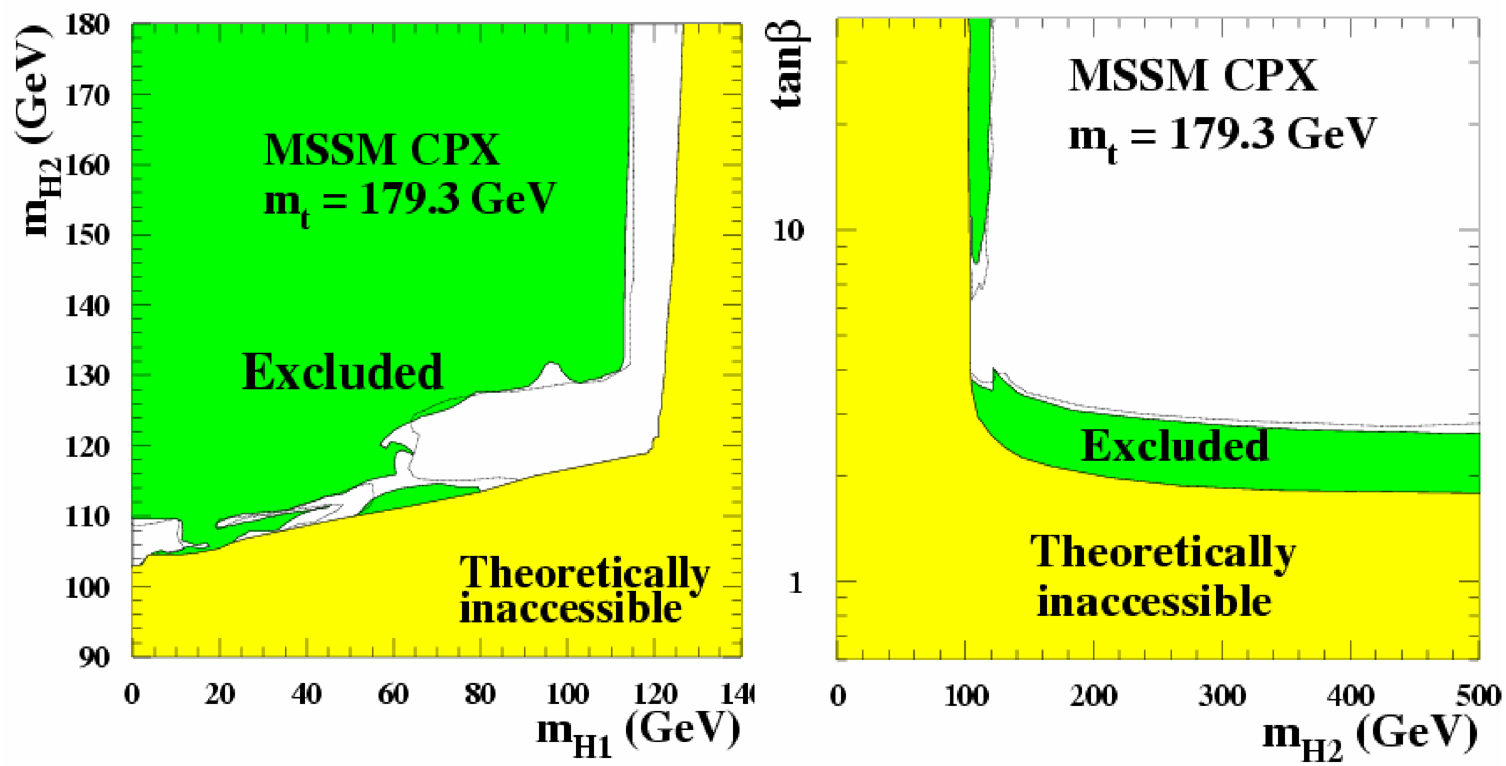


(b)

H$_1$ decouples from the Z and
H$_2$ and H$_3$ may be out of kinematic reach.

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

$H_2 \to H_1H_1 \to b\bar{b}b\bar{b}$

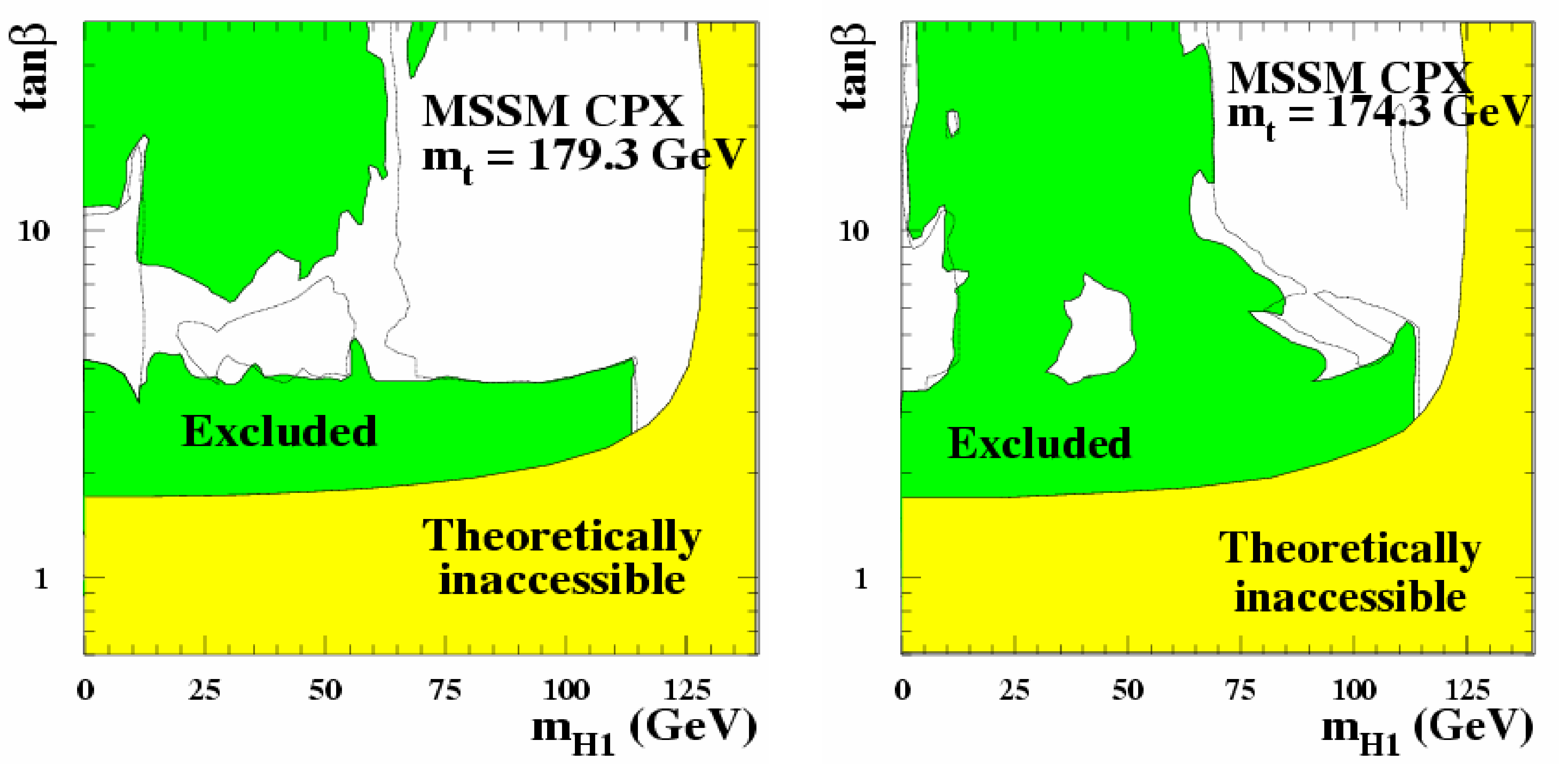
in the analyses

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

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

No Universal lower limit on mH1 but $\tan\beta > 2.6 - 2.9$ **(mt dep.)**

Impact of the top quark mass on the results

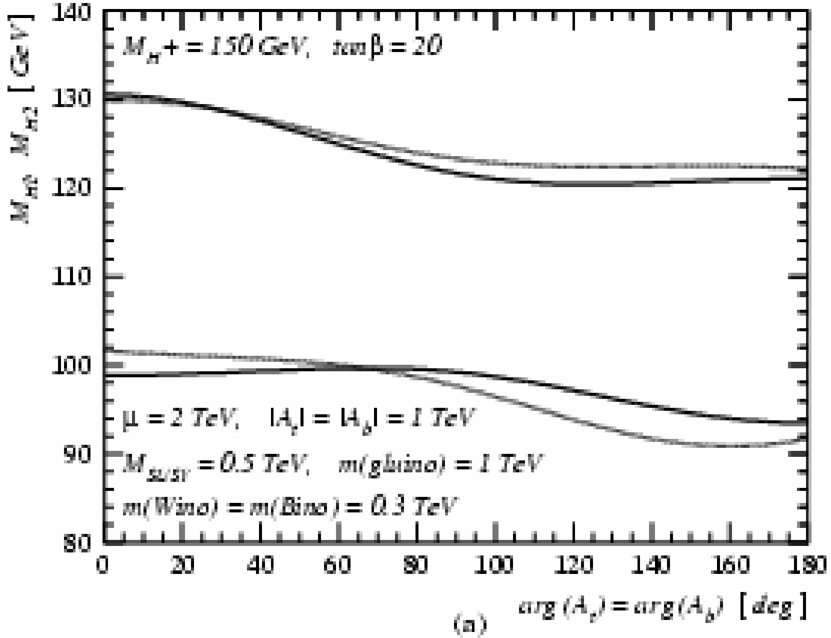


main effect for $\tan\beta = 4-10$ is due to opening of H_1Z, H_2Z channels as well as H_1H_2

CP-Violating Higgs bosons at the Tevatron

Example:

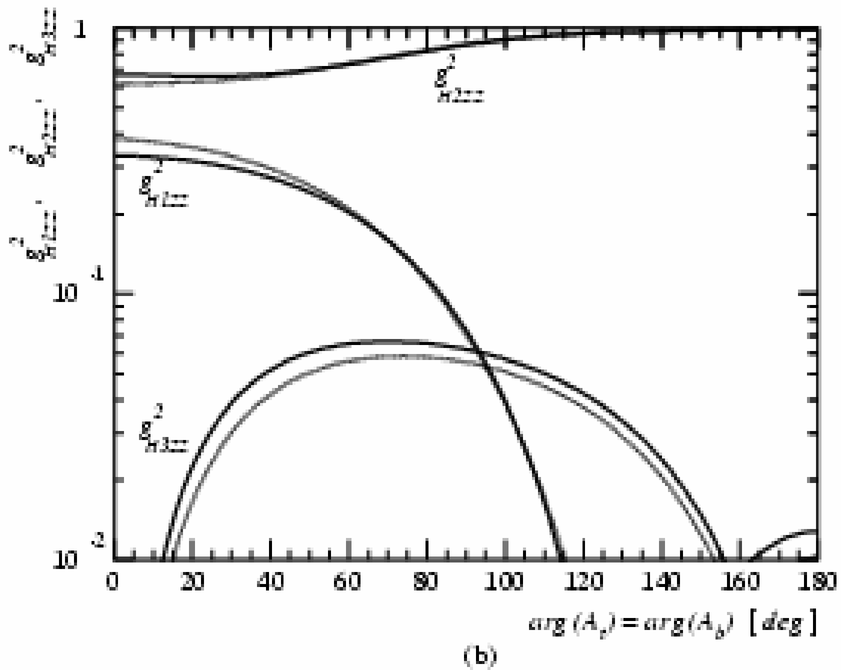
- MH1 about 90 GeV but out of the reach of LEP.
- All other channels kinematically unaccessible



(a)

- MH1 also hopeless at teh 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

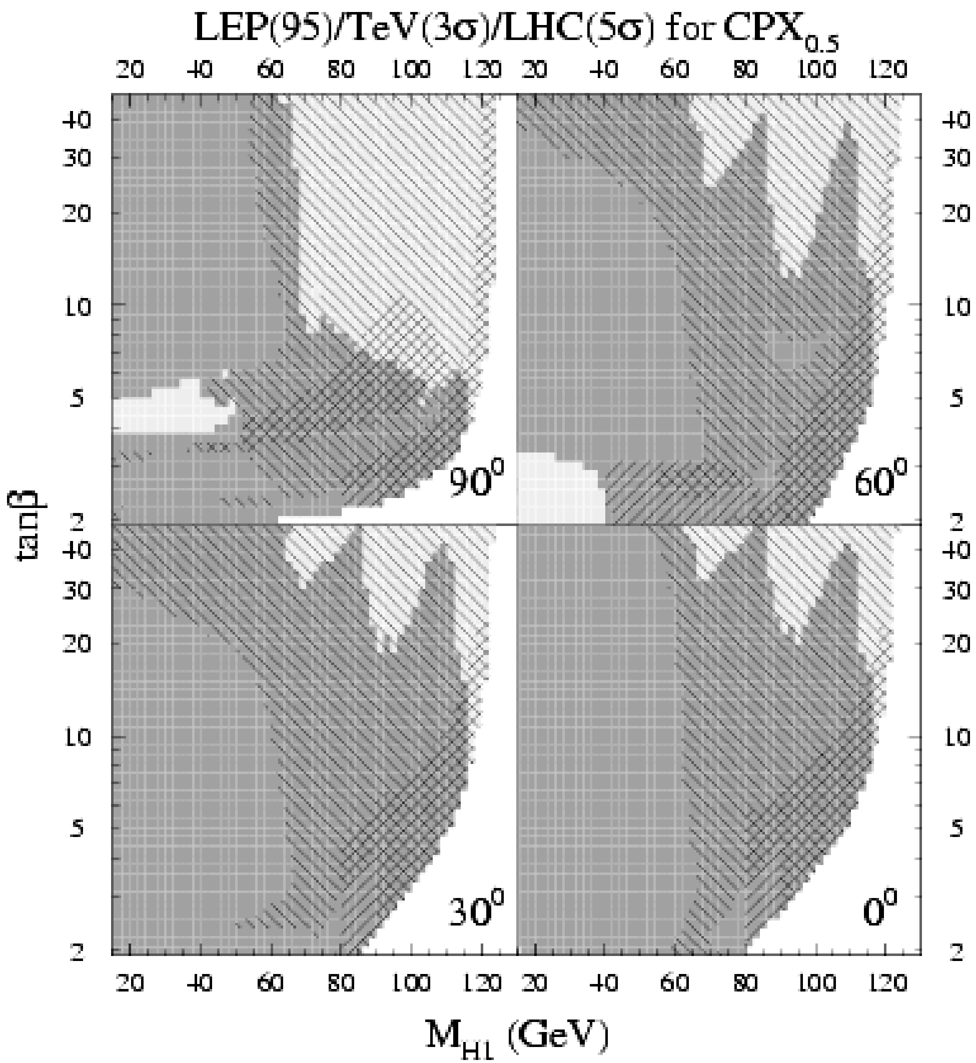


(b)

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

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

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 $H_i(\rightarrow b\bar{b})$

135° lines → LHC: $gg \rightarrow H_i \rightarrow \gamma\gamma$ (100 fb^{-1})

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

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

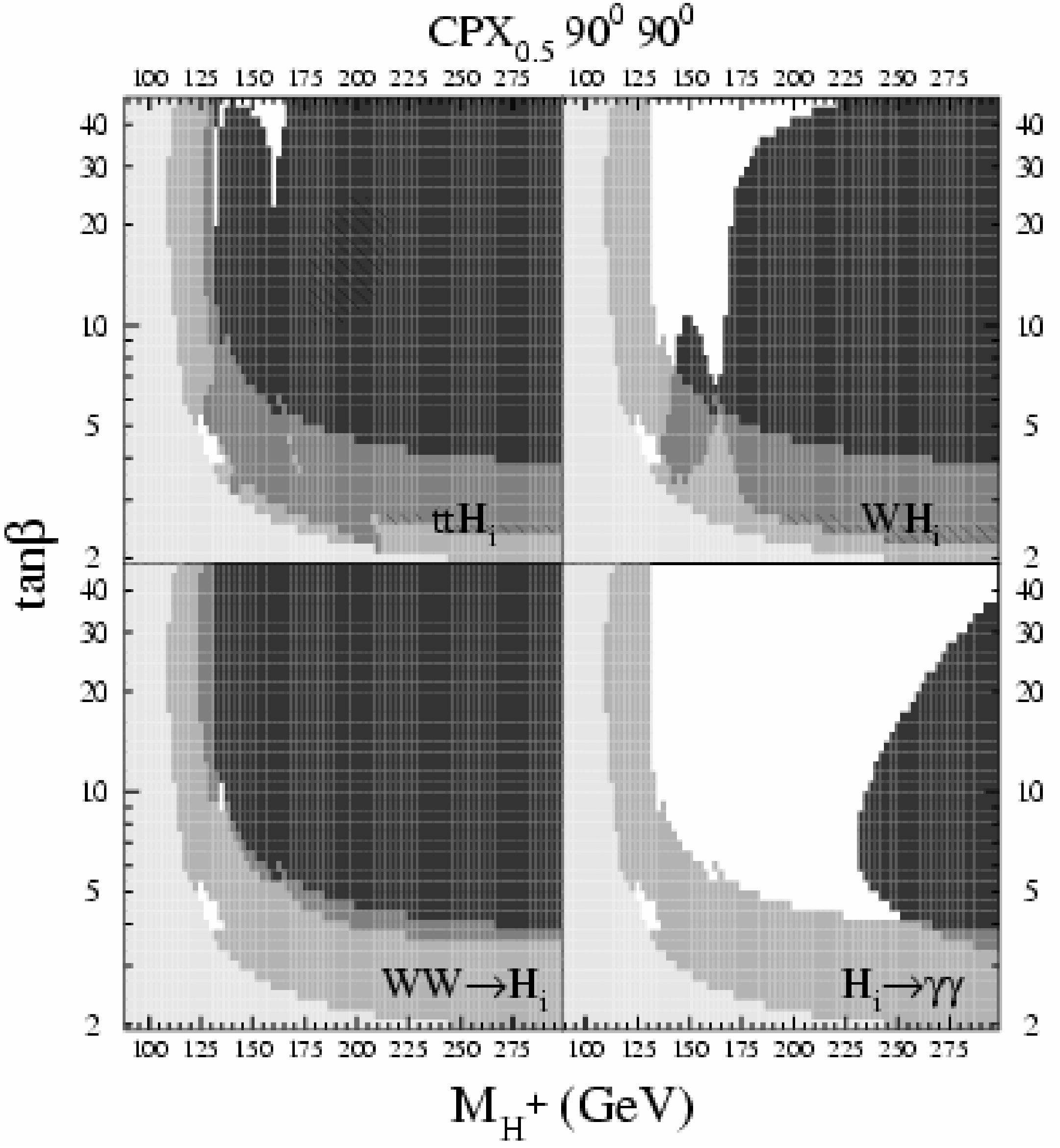
grey → LEP exclusion.

M.C., Ellis, Pilaftsis, Wagner

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

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

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



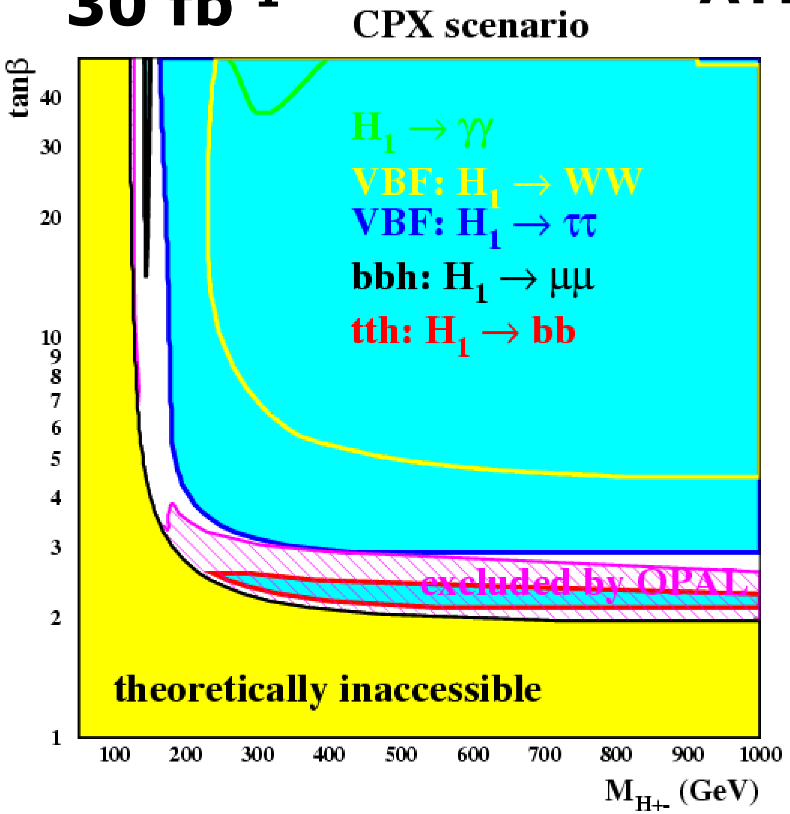
- The Tevatron could see a 3 σ hint with 5 fb^{-1} in a sizeable area of parameter space
- If $\arg(M_{\tilde{g}})=0$ instead, stronger suppression of $BR(H_{1,2}) \to b\bar{b}$ and both upper channels less competitive

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

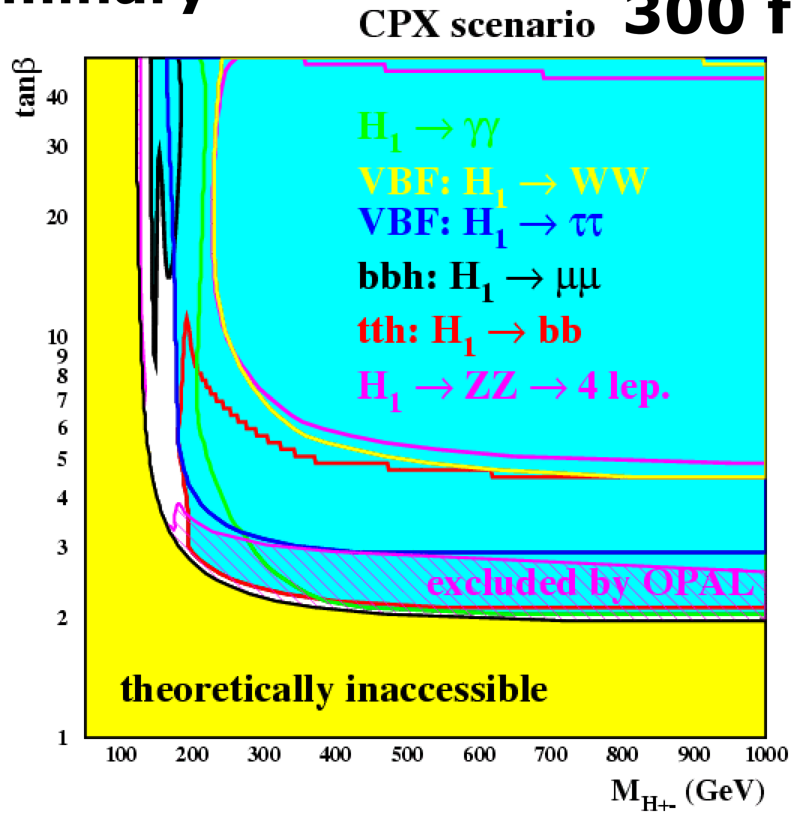
Light Higgs Boson H_1

ATLAS preliminary

30 fb^{-1}



300 fb^{-1}



- **border of discovery region at low tanb mostly determined by availability of inputs (VBF >110 GeV, ttH and $\gamma\gamma$ > 70 GeV)**
- **border at low M_{H+-} due to decoupling of H_1 from W,Z and t**
- **for VBF channels: assume same efficiencies for contribution of CP even and CP odd states (needs to be checked)**
- **for ttH: efficiencies for CP even and odd bosons are the same**

M. Schumacher, SUSY 04

Looking for $H_2 \rightarrow H_1 H_1$

- Standard signatures not sufficient to probe the presence of 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 inverse fb at the LHC)
- A detailed experimental simulation should be performed to test this possibility.

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

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 low energy SUSY: Electroweak Baryogenesis.
- 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:

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