Selected Topics in Higgs and Supersymmetry

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Selected Topics in Higgs and Supersymmetry

- **Introduction**
  - Motivation for SUSY at the TeV Scale
  - Some SUSY scenarios and signatures

- **The role of the Tevatron in shaping the next decade**
  - Precision Measurements
  - Discovery of new particles or new bosonic or fermionic (SUSY) dimensions
  - Indirect SUSY signatures

- **The MSSM Higgs Boson Phenomenology**
  - Radiative corrections to masses and couplings
  - Benchmark scenarios and Higgs opportunities at the LHC

- **Effects of explicit CP violation in the Higgs Sector**
  - How can this affect Higgs searches at Colliders

- **Outlook**

Introduction

• Standard Model $\Longrightarrow$ the pillar of particle physics that explains data collected in the past several years and provides description of physical processes up to energies of $\approx$ 100 GeV.

However, it is only an effective theory.

• Many open questions

- ⋆ origin of EWSB
- ⋆ generation of stabilization of hierarchies: M_{weak} Vs M_{Planck}
- ⋆ connection of electroweak and strong interactions with gravity
- ⋆ generation of fermion masses and mixings
- ⋆ explanation of baryon asymmetry of the universe
- ⋆ dark matter and dark energy

$\Longrightarrow$ crucial to get the complete picture valid up to higher energies, M_{Pl}

• **Collider Experiments**: Tevatron LHC, a Lepton Collider (TeV reach) our most robust handle to reveal the new physics that should answer these questions in this and the next decade

EWSB occurs at the TeV scale

In the absence of big fine-tuning of scales,

$\Longrightarrow$ New Phenomena should lie in the TeV range or below, within reach of LHC/LC

Numerous theories have been proposed:

two broad classes:

- weakly coupled dynamics
- strongly coupled dynamics

• Standard Model $\rightarrow$ example of weak EWSB

one extra physical state left in the spectrum $\equiv$ HIGGS Boson

Present Data $\rightarrow$ no direct evidence of Higgs [$m_h > 114.4$ GeV (LEP2)]

- SM with weakly coupled Higgs is in excellent agreement with precision data $\Longrightarrow$ $m_{H_{SM}} \leq 210$ GeV at 95 % C.L.

• In weakly coupled approach, SM most probably embedded in SUSY theory

• SUSY must be broken in the ground state – SUSY partners heavier than SM particles

If SUSY exists, many of its most important motivations demand some SUSY particles at the TeV range or below

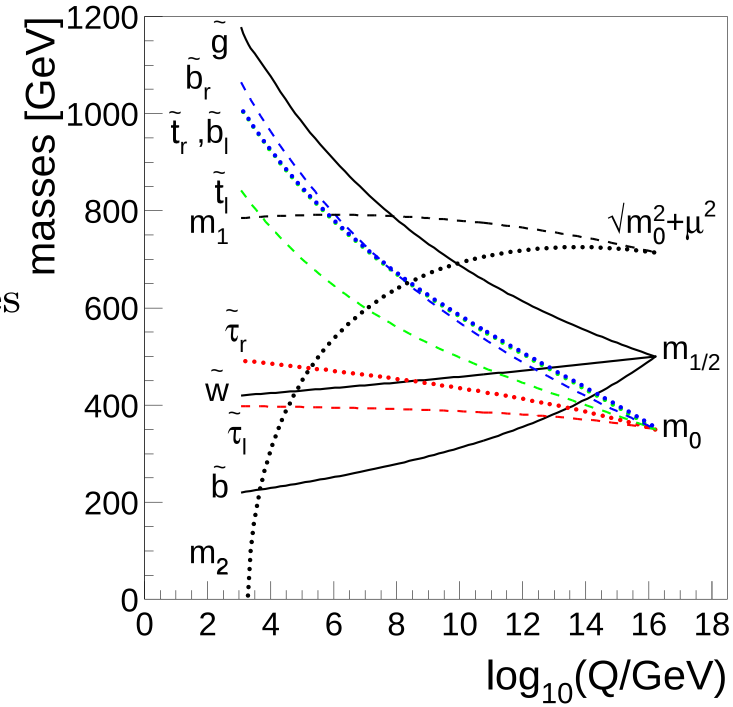
⋆ Solve hierarchy/naturalness problem

In low-energy SUSY: quadratic sensitivity to Λ_{eff} is replaced by quadratic sensitivity to SUSY breaking scale

⋆ EWSB is radiatively generated

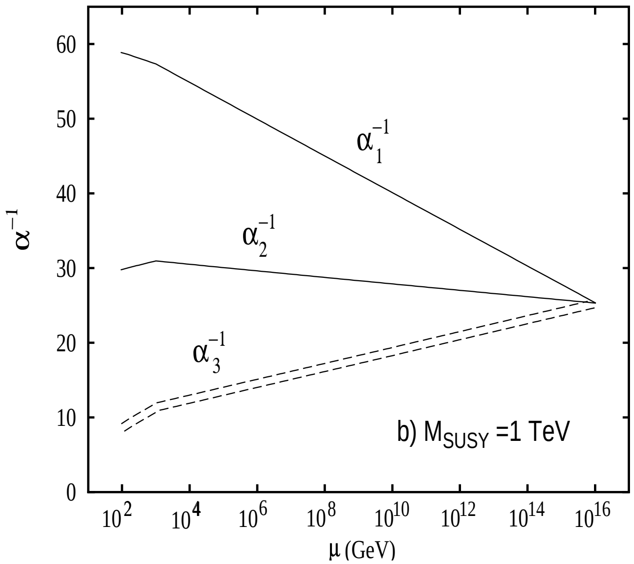
In the evolution of masses from high energy scales
$\longrightarrow$ a negative Higgs mass parameter is induced via radiative corrections

$\Longrightarrow$ *important top quark Yukawa effects!*



SUSY breaking scale must be at or below 1 TeV
if SUSY is associated with EWSB scale !

⋆ Play central role in unification of gauge couplings



Unification at $\alpha_{GUT} \simeq 0.04$ and $M_{GUT} \simeq 10^{16}$ GeV

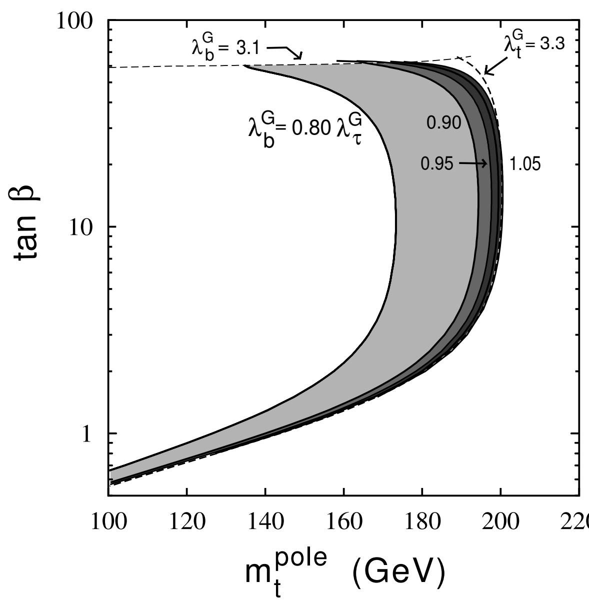
Experimentally, $\alpha_3(M_Z) \simeq 0.119 \pm 0.003$
in the MSSM:

$$\alpha_3(M_Z) = 0.127 - 4(\sin^2\theta_W - 0.2315) \pm 0.008$$

Remarkable agreement between Theory and Experiment!!

Langacker, Polonski — Bardeen, M.C., Pokorski, Wagner

⋆ Large value of m_t can be understood as resulting from quasi infrared fixed point of top-Higgs Yukawa coupling.



fixing m_b and α_s while varying $h_b(M_{GUT})$ and $h_\tau(M_{GUT})$ away from exact unification

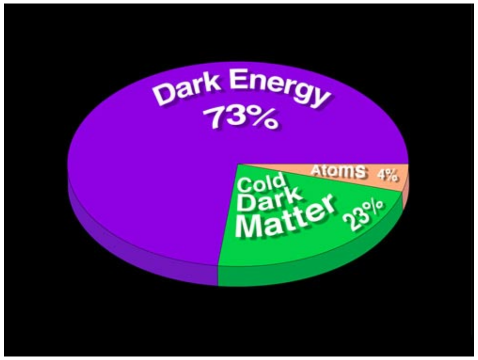
$\longrightarrow$ varying $h_t(m_t)$ prediction

$$\tan\beta = v_2/v_1; \quad m_t = h_t v_2$$

$$m_t^{pole} \simeq h_t(m_t) v \left[1 + \frac{4\alpha_s(m_t)}{3\pi}\right] \sin\beta$$
$$\sim (185 \text{ GeV}) h_t(m_t) \sin\beta$$

Bardeen, M.C., Pokorski, Wagner

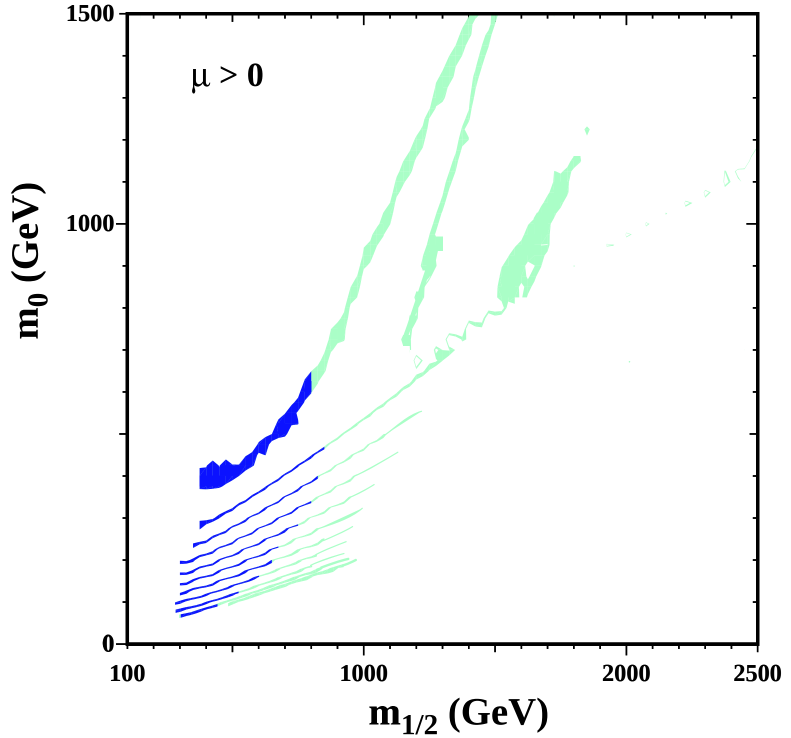
⋆ Provides a good dark matter candidate ⟶



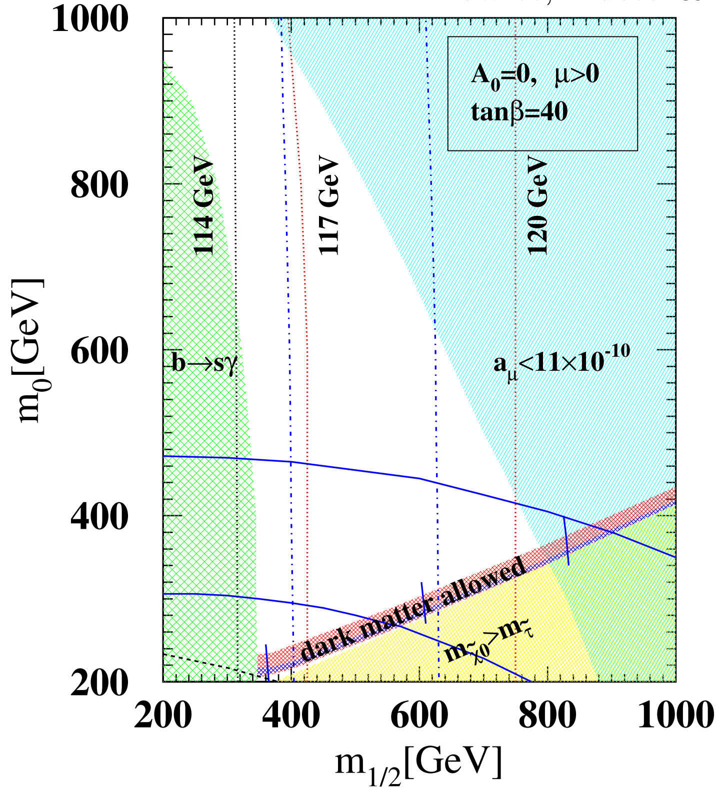
Present WMAP satellite data has confirmed with great accuracy the cold-dark matter density of the universe: $0.094 \leq \Omega_{CDM} h^2 \leq 0.13$

→ SUSY dark matter candidate is likely to be the lightest neutralino with mass possibly below 500 GeV and almost degenerate with the stau

Ellis, Olive, Santoso, Spanos



Arnowitt, Dutta & Hu



⋆ Provides a possible solution to the observed baryon asymmetry

Baryogenesis at the electroweak phase transition: (Start with B=L=0)

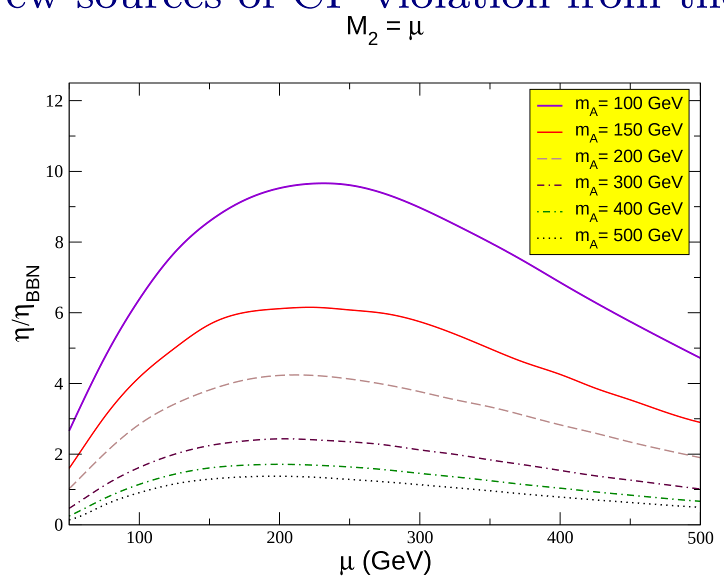
⋆ CP violating sources $\Longrightarrow$ create chiral baryon-antibaryon asymmetry in the symm. phase
⋆ Net Baryon number diffuse in the broken phase
⋆ Strong first order phase transition $\Longrightarrow$ baryon number violating processes are out of equilibrium in the broken phase $\Longrightarrow$ preserve the generated baryon asymmetry

In the SM:

- **EW Baryogenesis** demands a Higgs mass below 40 GeV $\Longrightarrow$ **ruled out by experiment**
- Independent problem: not enough CP violation

In Supersymmetry: both problems can be solved

- New bosonic degrees of freedom with coupling of order one to the Higgs
  $\Longrightarrow$ sufficiently strong first order phase transition with a Higgs mass up to 120 GeV
- New sources of CP violation from the sfermion sector



$\eta_{BBN} \simeq (6 \pm 3) 10^{-11}$

we plot for max. phase for μ, $\sin\phi_\mu = 1$
hence, from the figure
$\longrightarrow \sin\phi_\mu \geq 0.05$ preferred

M.C., Quiros, Seco, Wagner

The mechanism of SUSY breaking is not well understood.

$\Downarrow$

Different SUSY breaking scenarios $\longrightarrow$ crucially different patterns of low energy spectrum –production and decays–

- Important to develop a comprehensive search strategy to explore the main signals in different SUSY breaking scenarios.

SUGRA Scenarios

- Strongly interacting particles (due to RG effects) tend to be heavier than weakly interacting ones.

Supersymmetric particles odd under R-parity: $R_p = (-1)^{3B+L+2S}$

- If R-parity Conserved: Lightest Supersymmetric Particle (LSP) Stable

  $\Longrightarrow$ lots of $\not{E}_T \rightarrow$ distinctive SUSY signature

- LSP Stable $\Longrightarrow$ good Dark Matter candidate: *neutralinos*

Extensions of MSUGRA: — CP Violation

• Soft SUSY breaking parameters MAY BE COMPLEX and take any value allowed by phenomenological constraints

At least two complex phases cannot be rotated away, choosing those as ϕ_μ and ϕ_A

$\Longrightarrow$ six param. determine the sparticle spectrum:

$$m_0,\; M_{1/2},\; A_0,\; \tan\beta,\; \phi_\mu,\; \phi_A$$

• Interesting constraints on SUSY param. space from EDM's of electron and u,d quarks

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

To resolve the one-loop CP crisis:

• $\text{Im}\mu/|\mu|, \text{Im}A_f/A_f \leq 10^{-2}$, with $(m_{\tilde{f}}, m_\lambda) \sim 200\,\text{GeV}$

• CP phases ~ 1, but $m_{\tilde{f}} > 1$ TeV for $\tilde{f} = \tilde{e}, \tilde{u}, \tilde{d}, \tilde{\nu}_L$

• Cancellations between different EDM terms

$\Downarrow$

• Two-loop contributions to EDM's $\Longrightarrow$ constraints on CPV parameters of 3rd. gen. squarks, specially for large $\tan\beta$ $\longrightarrow$ important for Higgs physics

— CPV makes more challenging to reconstruct SUSY masses and couplings from experimental data

Gauge-Mediated Low-energy SUSY Breaking Scenarios

- Special feature $\longrightarrow$ LSP: light (gravitino) Goldstino: $m_{\tilde{G}} \sim 10^{-6} - 10^{-9}\text{GeV}$

If R-parity conserved, heavy particles cascade to lighter ones and

NLSP $\longrightarrow$ SM partner + $\tilde{G}$ $\quad$ $e.g.$, $\tilde{\chi}_1^0 \to (h, Z, \gamma)\,\tilde{G}$; $\quad \tilde{\ell}^\pm \to \ell^\pm\,\tilde{G}$; $\quad \tilde{q} \to q\,\tilde{G}$

Superpartner masses proportional to their gauge couplings.

- Signatures: decay length $\quad L \sim 10^{-2}\text{cm}\left(\frac{m_{\tilde{G}}}{10^{-9}\text{GeV}}\right)^2 \times \left(\frac{100\text{GeV}}{M_{\text{NLSP}}}\right)^5$

  ⋆ NLSP can have prompt decays:

  Signature of SUSY pair: 2 hard photons, (H's, Z's) + $\not{E}_T$ from $\tilde{G}$

  ⋆ macroscopic decay length but within the detector:

  displaced photons; high ionizing track with a kink to a minimum ionizing track

  (smoking gun of low energy SUSY)

  ⋆ decay well outside the detector: $\not{E}_T$ like SUGRA

Anomaly-Mediated SUSY Breaking Scenarios

- SUSY breaking masses determined by beta functions, proportional to gauge couplings
- Striking signature at colliders: $\quad \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 \pi^\pm$

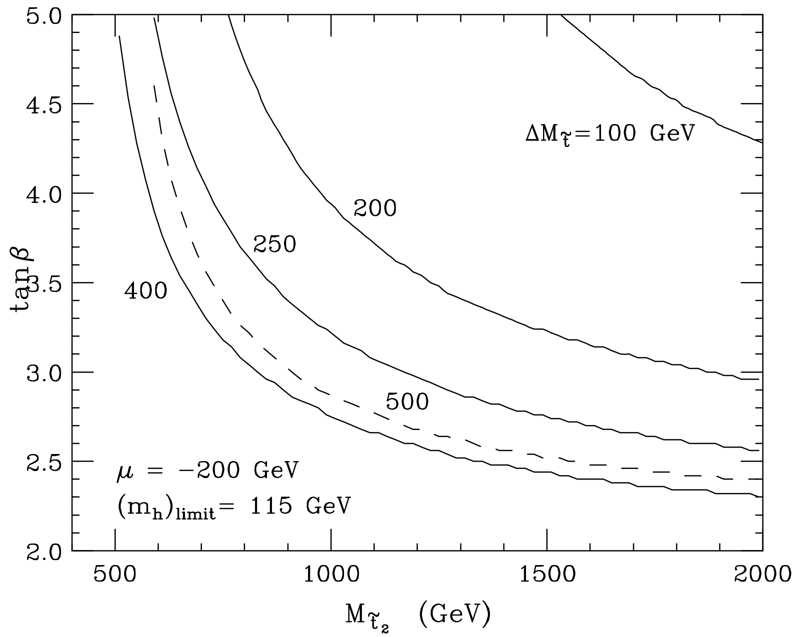
  at tree level, $M_{\tilde{\chi}_1^\pm} \approx M_{\tilde{\chi}_1^0}$ – mass degeneracy lifted by radiative corrections

  by about 150 MeV $\longrightarrow$ very soft pion (decay length of order 1 cm)

Indirect Information on SUSY from Experiment

- Higgs mass constraints from LEP

$\Longrightarrow$ impose important constraints on SUSY breaking models & 3rd gen. squark masses



Model independent bounds on $\tan\beta$ as a function of the heaviest stop mass for different values of the stop mass splitting

$$\Delta M_{\tilde{t}} = m_{\tilde{t}_2} - m_{\tilde{t}_1},$$

for $m_h = 115$ GeV,

large M_A, $M_t = 175$ GeV

M.C., Chankowski, Pokorski & Wagner

What Can We Learn from RUN 2?

– Precision measurements:

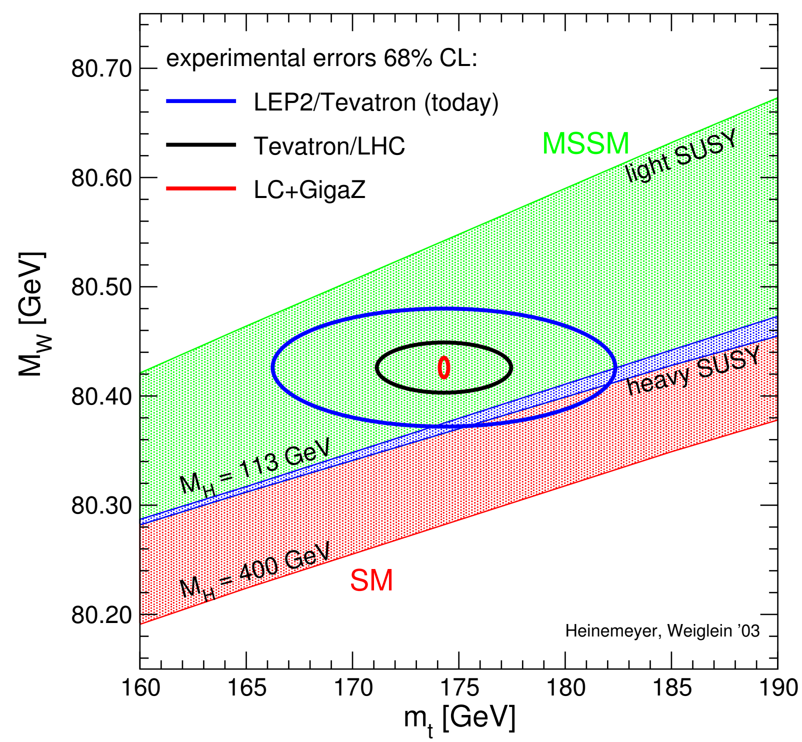
- top quark mass: $\delta M_t \simeq 3$ GeV with 2 fb^{-1}
- W mass: $\delta M_W \simeq 30$ MeV with 2 fb^{-1}

high precision for M_t is important to
$\Longrightarrow$ exploit precision on M_W in the context of electroweak precision measurements

M_t–M_W–M_H Correlation

- direct M_t and M_W measurements from LEP and the Tevatron
- Indirect M_t and M_W determination from SM fit to precision data (LEP, SLD, νN)
- SM relationship for M_t–M_W–M_H
  $\Longrightarrow$ crucial information on M_H

$\Longrightarrow$ A light SM Higgs Boson strongly favored by data



Stop and Sbottom Searches

In many models (MSUGRA, extended Gauge– and Anomaly–Mediated)
$\longrightarrow$ $\tilde{t}$**'s and** $\tilde{b}$**'s quite light**

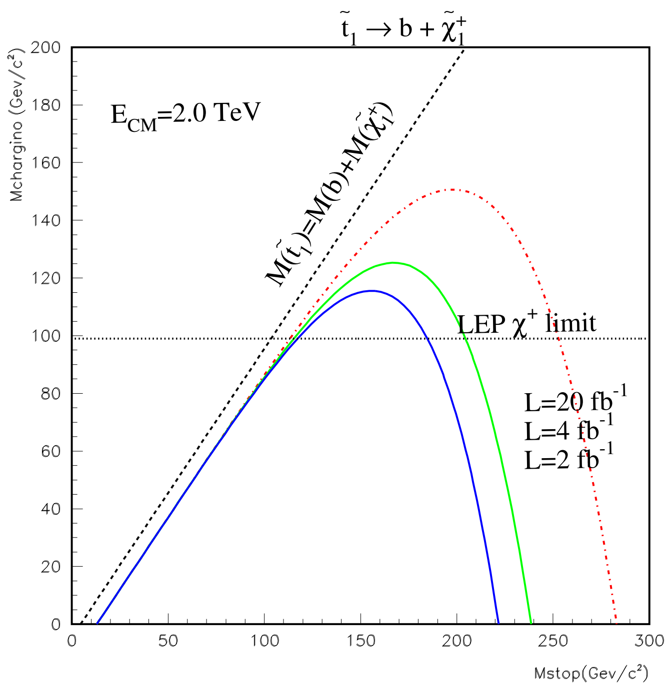
- If $m_{\tilde{t}_1} > m_{\tilde{\chi}_1^\pm} + m_b$ or $> M_W + m_{\tilde{\chi}_1^0} + m_b$
  or $> m_l + m_{\tilde{\nu}} + m_b$ or $> m_{\tilde{l}} + m_\nu + m_b$

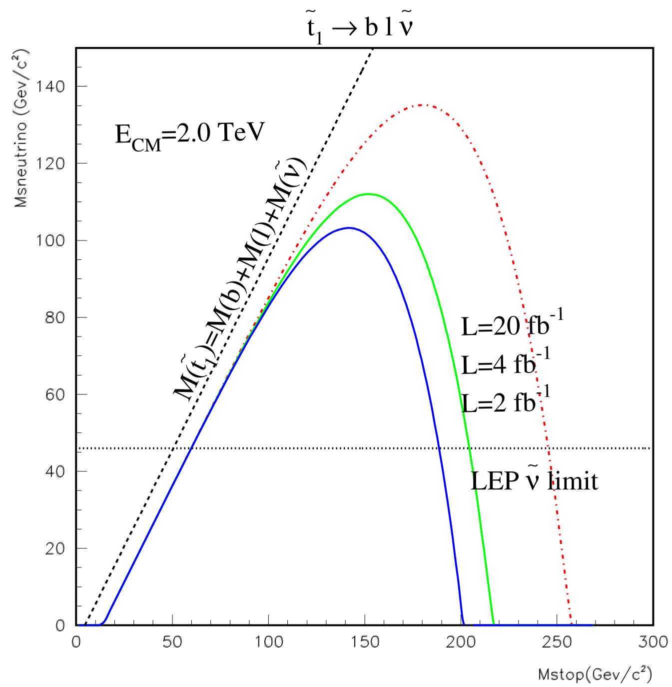
$$\Longrightarrow \tilde{t}_1 \to b\tilde{\chi}_1^{\pm(*)} \to b\tilde{\chi}_1^0 f\bar{f}' \qquad \text{with } f\bar{f}' = l\bar{\nu} \text{ or } q\bar{q}'$$

Signals: 2b jets + 2 W's + $\not{E}_T$, 2b jets + 2l's + $\not{E}_T$

Selection: b-jet + jet + l + $\not{E}_T$, 2l's + jet + $\not{E}_T$

Demina, Lykken, Matchev & Nomerotski

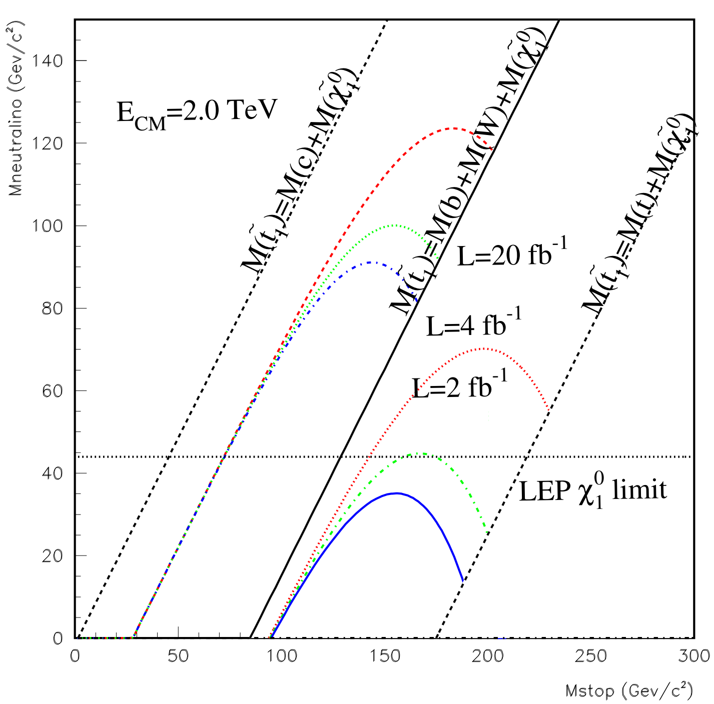




- If above modes kinematically disallowed,

  $\tilde{t}_1 \to c\tilde{\chi}^0_1$ (via $b\tilde{\chi}^\pm_1$ loop)

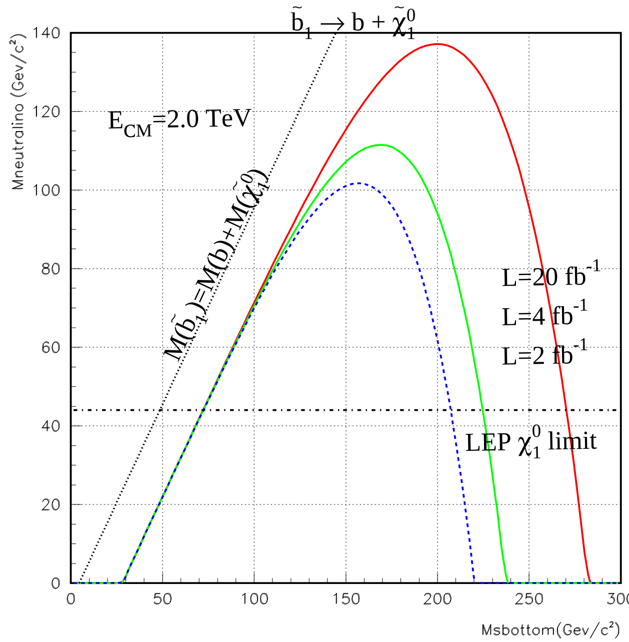
  Signal/Selection: 2c jets + $\not{E}_T$



- Sbottoms:

  $\Longrightarrow \tilde{b}_1 \to b\tilde{\chi}^0_1$

  100% BR if $m_{\tilde{\chi}^0_2} > m_{\tilde{b}} - m_b$



if $\tilde{b} \to b\tilde{\chi}^0_2$ allowed,
limit degraded in 30-40 GeV

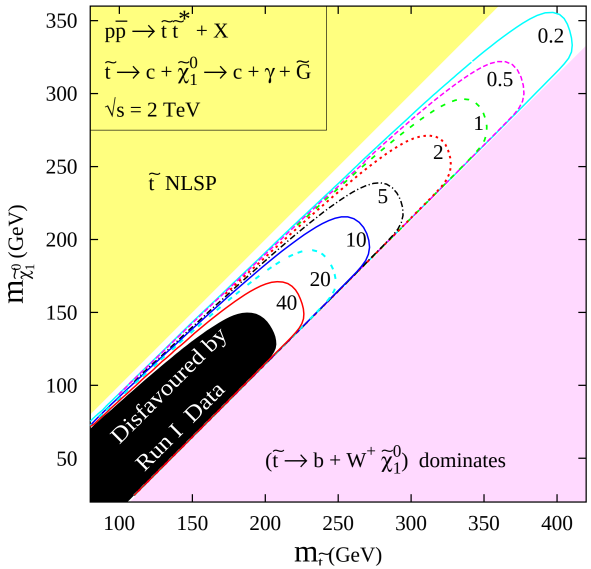
In summary: with $\int \mathcal{L}dt = 4$ fb^{-1}

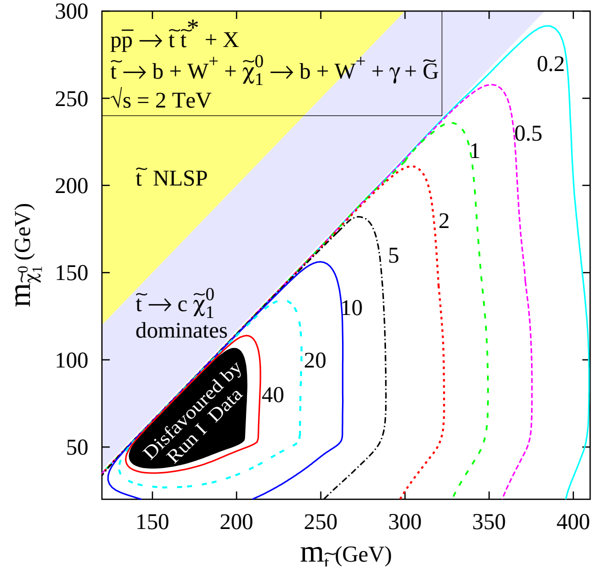
$m_{\tilde{t}_1} \leq 200/210$ GeV in $\tilde{t}_1 \to b\tilde{\chi}^\pm_1 / \tilde{t}_1 \to bl\tilde{\nu}$

$m_{\tilde{t}_1} \leq 180$ GeV in $\tilde{t}_1 \to c\tilde{\chi}^0_1$

$m_{\tilde{b}_1} \leq 230$ GeV in $\tilde{b}_1 \to b\tilde{\chi}^0_1$

Considering the stops to be the NLSP, look for signatures with jets, γ's and $\not\!\!E_T$ (small SM backgds.)   M.C, Choudhury, Diaz, Logan, Wagner





Cross sections for stop pair production in fb, with $\tilde{t} \to c\gamma\tilde{G}$ and Signal/selection $jj\gamma\gamma\not\!\!E_T$

$\int \mathcal{L}$	σ_S 5σ	Max. $m_{\tilde{t}}$ (2 body)
2 fb^{-1}	6 fb	290 GeV
4 fb^{-1}	3.5 fb	315 GeV

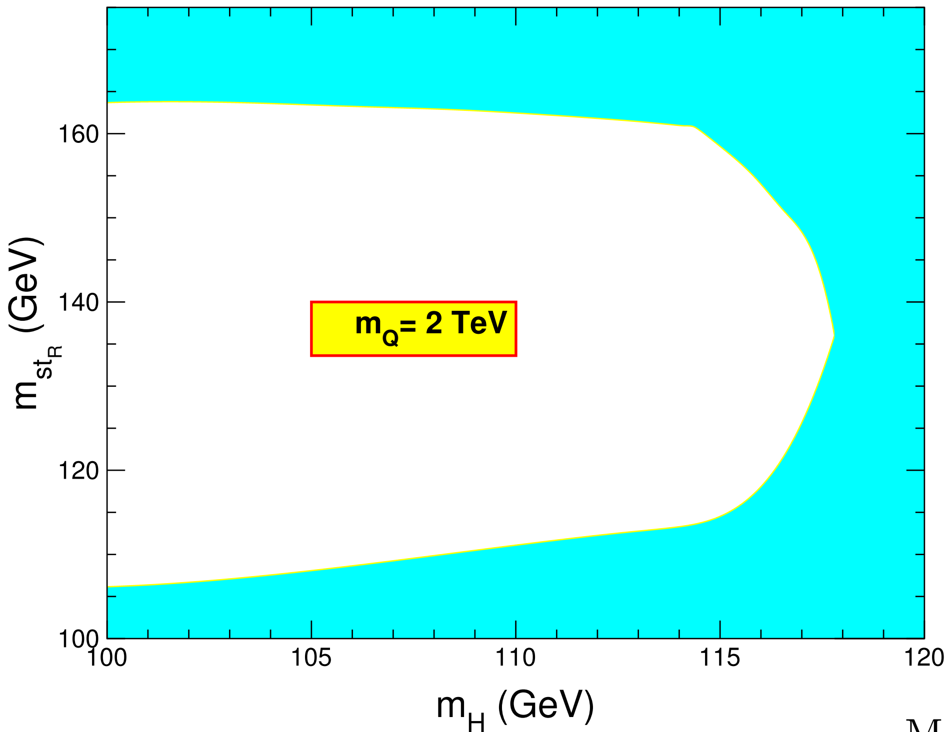
Cross sections for stop pair production in fb, with $\tilde{t} \to bW\gamma\tilde{G}$ and Signal/selection $bbWW\gamma\gamma\not\!\!E_T$

$\int \mathcal{L}$	σ_S	Max. $m_{\tilde{t}}$ (3 body)
2 fb^{-1}	2.5 fb	315 GeV
4 fb^{-1}	1.3 fb	330 GeV

$\star\ \tilde{q} \to q\gamma\tilde{G} \quad \Longrightarrow$ squark mass reach up to 400 GeV

An Interesting Highlight $\longrightarrow$ **Electroweak Baryogenesis**

predicts light right-handed stops $m_{\tilde{t}_R} \sim 150$ GeV
and MSSM Higgs bosons in the range $m_h \sim 100$-118 GeV



M.C., Quiros & Wagner

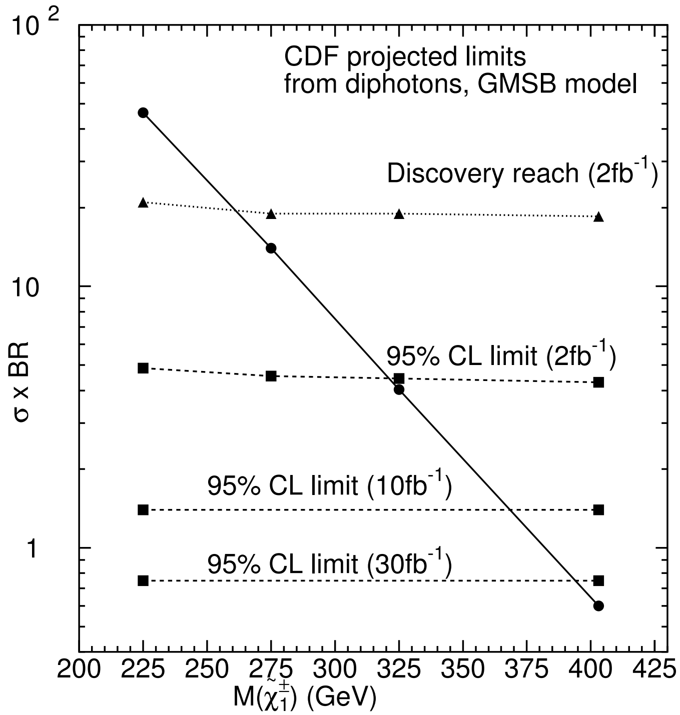
Tevatron Run II reach for Higgs and stops probes Baryogenesis at the Electroweak scale!

Gauge-Mediated Tevatron Reach

- Bino-like NLSP: $\tilde{\chi}_1^0 \to \gamma \tilde{G}$

  Signal: $\gamma\gamma X \not{E}_T$

  $X = \ell$'s and/or jets



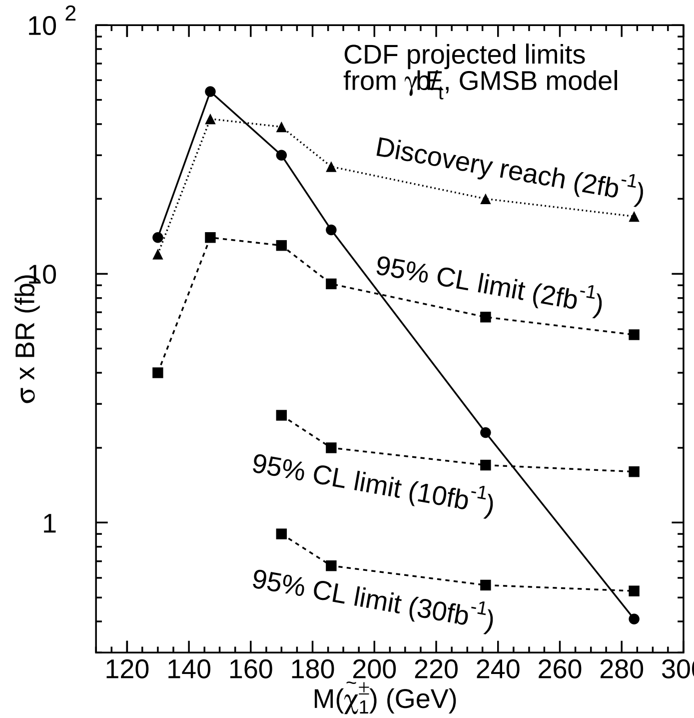
$M_{\tilde{\chi}^\pm} \sim 325$ GeV *(exclusion)* &

~ 260 GeV *(discovery)*

- Higgsino-like NLSP: $\tilde{\chi}_1^0 \to (h, Z, \gamma)\tilde{G}$

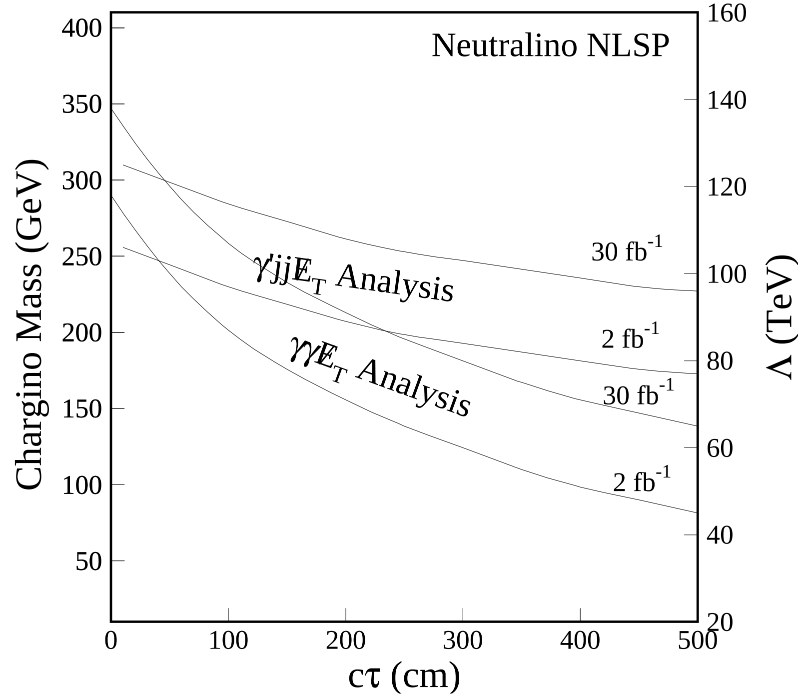
  Signal: γ b $\not{E}_T X$

  diboson signatures $(Z \to \ell\ell/\text{jj};\ h \to b\bar{b})\not{E}_T$



$M_{\tilde{\chi}_1^\pm}$ sensitivity up to 200 GeV for 2 fb^{-1}

- Non-prompt Decays



  - Few 100 TeV $\leq \sqrt{F} \leq$ few 1000 TeV

  – Bino-like NLSP

  Photon Pointing: it is possible to identify a displaced photon from a secondary vertex and possibly det. decay length using TOF

  Meas. of decay length $\rightarrow$ meas. of SUSY breaking scale

– Higgsino like-NLSP

$\Longrightarrow$ displaced γ's or secondary vertices from $b\bar{b}$, jj, $\ell^+\ell^-$

Search for displaced Z's using large E_T displaced jet with finite impact parameter or diplaced l's should be explored.

- If $\sqrt{F} \geq$ few 1000 TeV $\Longrightarrow$ outside detector decay looks like traditional $\tilde{\chi}_1^0$ LSP

– Stau NLSP:

- prompt decays

  2 high-p_T τ's and high $\not{E}_T$

  mass sensitivity for 2 fb^{-1}

  $m_{\tilde{\tau}} < 80$ GeV (5σ) DØ

  $m_{\tilde{\tau}} \sim 100$ GeV (95% CL) CDF

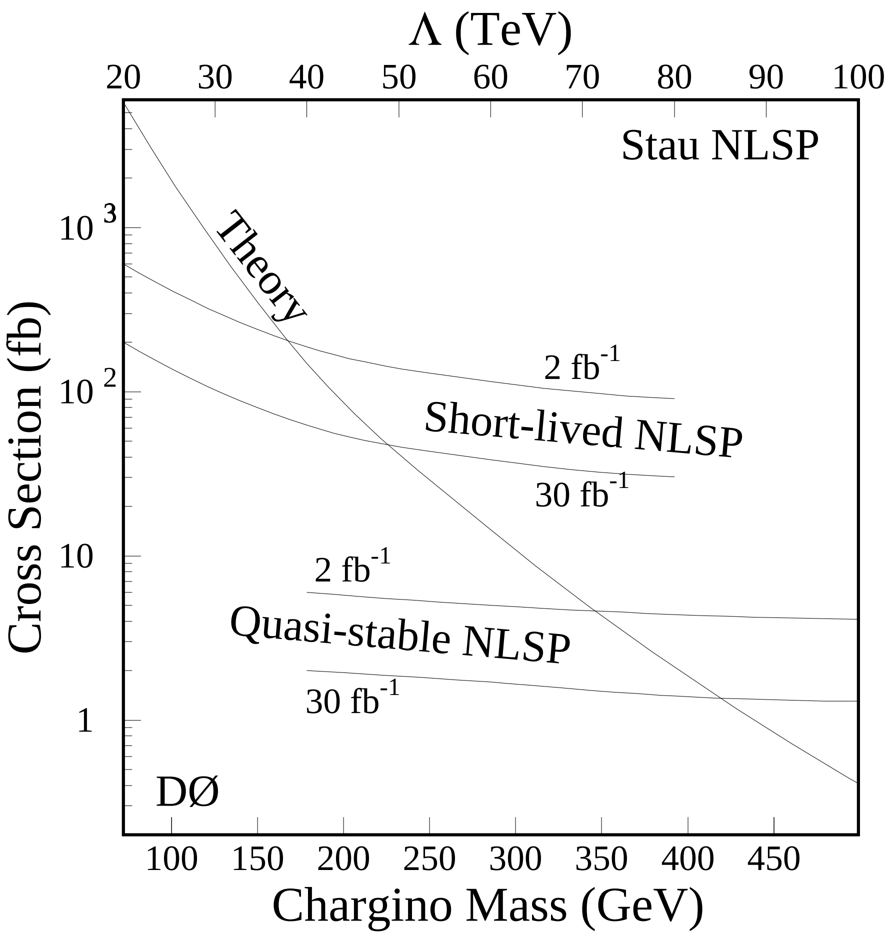
- quasi-stable τ's

  highly-ionizing tracks, extra μ-like tracks

  for 2 fb^{-1},

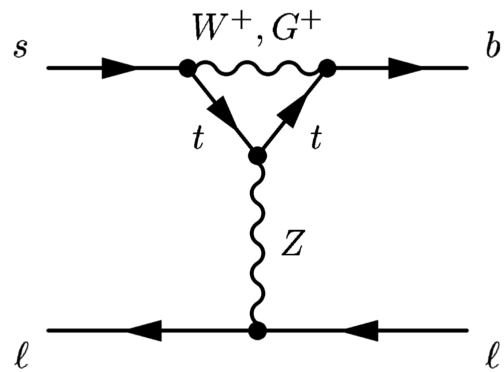
  CDF $\Longrightarrow$ $m_{\tilde{\tau}} > 150$ GeV *excl.*
  ~ 110 GeV *disc.*
  (40 GeV improvement with ToF)

  DØ $\Longrightarrow$ ~ 175 GeV *disc.*



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

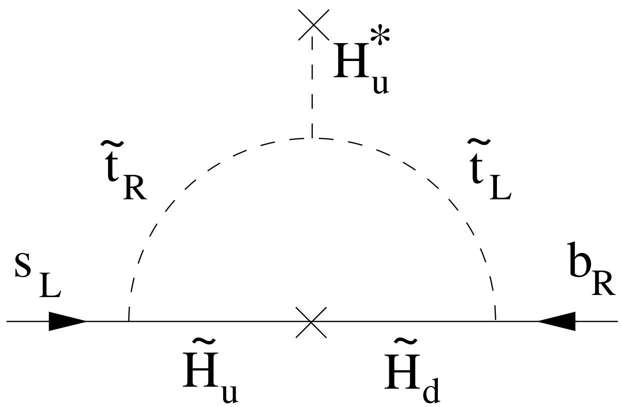
SM sample diagram:



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)

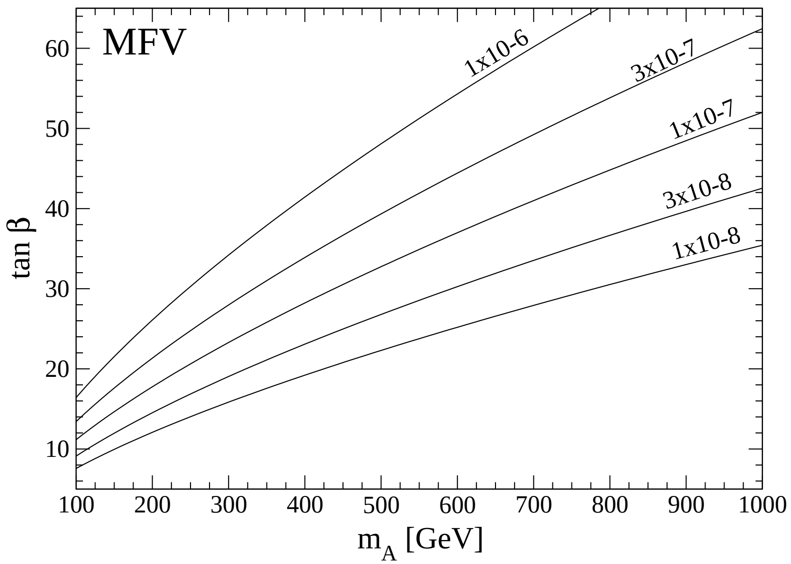
$Br(B \to \mu^+\mu^-)_{\rm MSSM} \propto \tan^6\beta\,\frac{1}{M^2_{A^0}}\,f(\mu A_t, M_{\tilde{t}_i}, M_{\tilde{\chi}^+_i})$

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 paraneters

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

Radiative Corrections to Higgs Masses

important quantum correc. due to loops of particles and their superpartners: incomplete cancellation due to SUSY breaking $\Longrightarrow$ main effects: top and stop loops; bottom and sbottom loops in large $\tan\beta$ regime

The stop mass matrix:

$$\begin{pmatrix} M_Q^2 + m_t^2 + D_L & m_t X_t \\ m_t X_t & M_U^2 + m_t^2 + D_R \end{pmatrix}$$

$D_L \equiv (\frac{1}{2} - \frac{2}{3}\sin^2\theta_W) M_z^2 \cos 2\beta$ and
$D_R \equiv \frac{2}{3}\sin^2\theta_W M_z^2 \cos 2\beta$

$$m_h^2 = M_Z^2 \cos^2 2\beta + \frac{2\, g_2^2\, m_t^4}{8\pi^2\, M_W^2} \left[\ln(M_S^2/m_t^2) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12\, M_S^2}\right)\right] + \text{h.o.}$$

$M_S^2 = \frac{1}{2}(m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2)$ and $X_t = A_t - \mu/\tan\beta \longrightarrow$ stop mixing

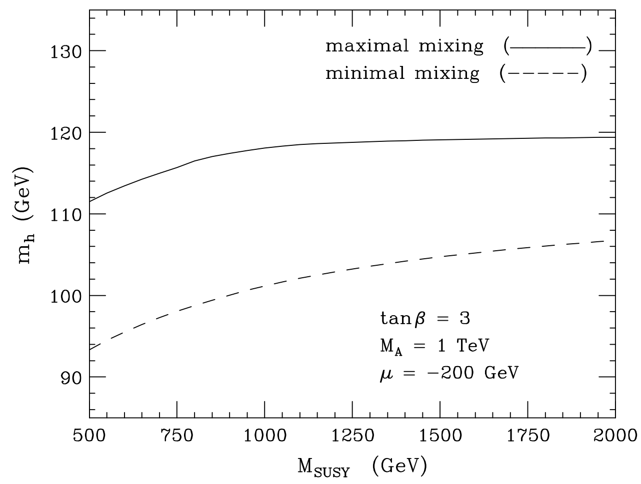
- two-loop log. and non-log.effects are numerically important $\rightarrow$ computed by different methods:
  - diagrammatic
  - effective potential
  - RG-improved effective potential

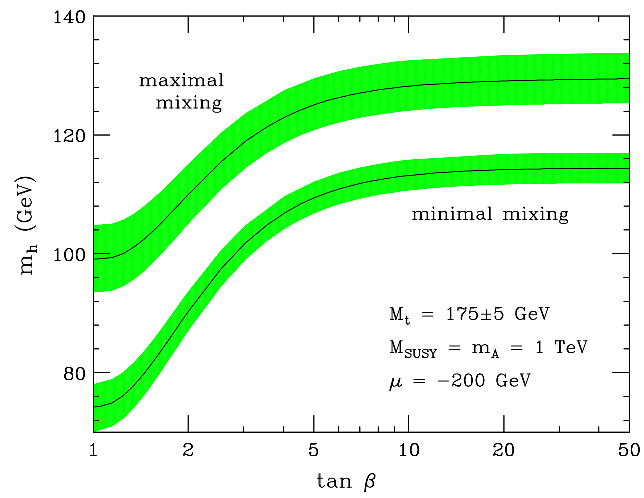
- upper limit on Higgs mass:

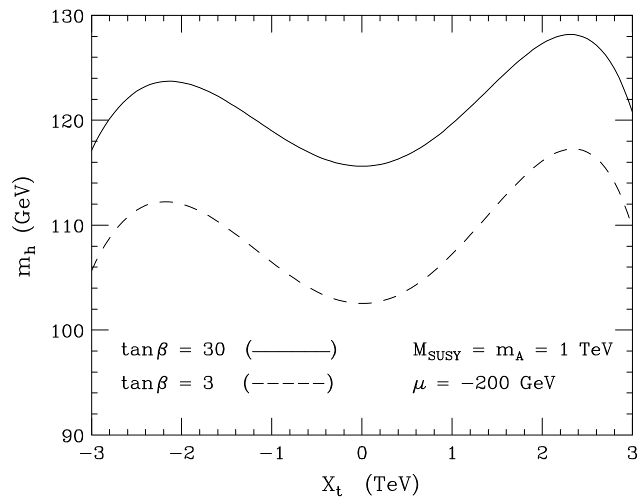
$m_h \lesssim 135$ GeV

$M_S = 1 \rightarrow 2$ TeV $\Longrightarrow \Delta m_h \simeq 2 - 5$ GeV
$\Delta m_t = 1$ GeV $\Longrightarrow \Delta m_h \sim 1$ GeV

main effects already present in one-loop formulae







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

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

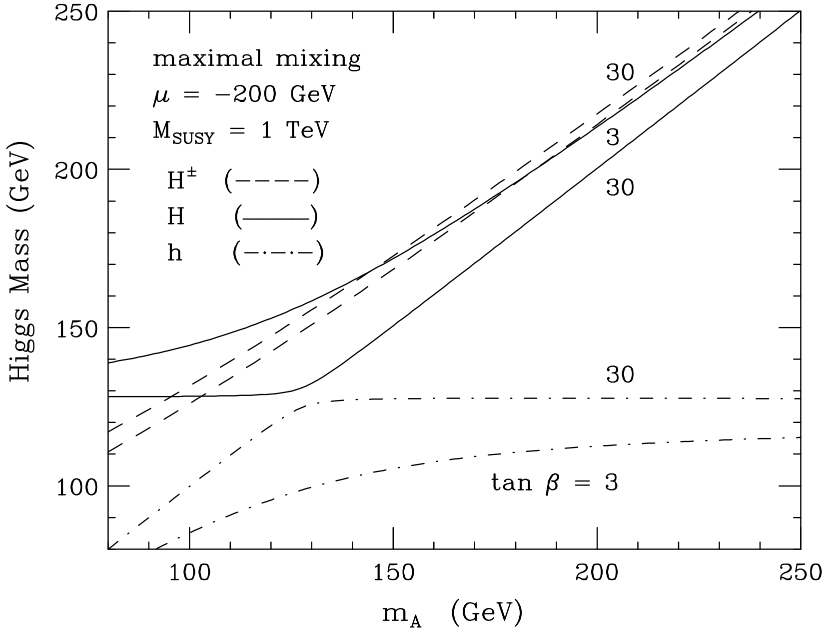
(scheme depend.) small asym. at h.o.

M.C. & Haber

$M_{SUSY} \equiv M_Q = M_U = M_D$ if $M_{SUSY} \gg m_t \rightarrow M_S^2 \simeq M_{SUSY}^2$

- at 2 loops $\rightarrow M_{\tilde{g}}$ dependence

MSSM Higgs Masses as a function of M_A



$$m_H^2 \cos^2(\beta - \alpha) + m_h^2 \sin^2(\beta - \alpha) = [m_h^{max}(\tan\beta)]^2$$

- $\cos^2(\beta - \alpha) \to 1$ for large $\tan\beta$, low m_A
  $\Longrightarrow$ H has SM-like couplings to W,Z
- $\sin^2(\beta - \alpha) \to 1$ for large m_A
  $\Longrightarrow$ h has SM-like couplings to W,Z

Hence, for large $\tan\beta$:
$\to$ always one CP-even Higgs with SM-like couplings to W,Z
and mass below $m_h^{max} \leq 135$ GeV

if $m_A > m_h^{max}$ $\quad\to\quad$ $m_h \simeq m_h^{max}$ and $m_H \simeq m_A$

if $m_A < m_h^{max}$ $\quad\to\quad$ $m_h \simeq m_A$ and $m_H \simeq m_h^{max}$

Radiative Corrections to Higgs Boson Couplings

[1] Through rad. correc. to the CP-even Higgs mass matrix, $\delta\mathcal{M}^2_{ij}$, which defines the mixing angle α

$$\sin\alpha\cos\alpha = \mathcal{M}^2_{12} \,/\, \sqrt{(\mathrm{Tr}\mathcal{M}^2)^2 - 4\,\det\mathcal{M}^2}$$

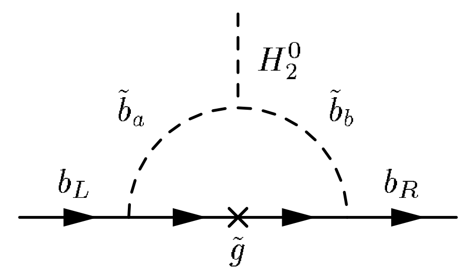
important effects of rad. correc. on $\sin\alpha$ or $\cos\alpha$ depending on sign of $\mu\, A_t$ and magnitude of A_t/M_S.

$\Longrightarrow$ govern couplings of Higgs to fermions

$\Longrightarrow$ via rad. correc. to $\underline{\cos(\beta-\alpha) \text{ and } \sin(\beta-\alpha)}$ governs Higgs couplings to vector bosons

[2] SUSY vertex correc. to Yukawa couplings, which modify the effective Lagrangian, coupling Higgs to fermions

$$\mathcal{L}_{\rm eff} \longrightarrow h_b\, H^0_1\, b\bar{b} + \Delta h_b\, H^0_2\, b\bar{b}$$



Δh_b modifies the m_b–h_b relation

$$m_b \simeq h_b v_1 + \Delta h_b v_2 = h_b\, v\, \cos\beta \left(1 + \frac{\Delta h_b}{h_b} \tan\beta\right)$$

$$\Delta_b = \frac{\Delta h_b}{h_b} \tan\beta \sim \frac{2\alpha_S}{3\pi} \frac{\mu\, M_{\tilde{g}}}{\max(m^2_{\tilde{b}_1}, m^2_{\tilde{b}_2}, M^2_{\tilde{g}})} \tan\beta + \Delta_b^{\tilde{t}\tilde{\chi}^+}$$

$\Delta_b \sim \mathcal{O}(1)$ if $\tan\beta$ large

$$\Delta_b^{\tilde{t}\tilde{\chi}^+} \sim \frac{h_t^2}{16\pi^2} \frac{\mu\, A_t}{\max(m^2_{\tilde{t}_1}, m^2_{\tilde{t}_2}, \mu^2)} \tan\beta$$

Modified Higgs Boson Couplings to b-quarks

$$g_{h\,b\bar{b}} \simeq \frac{-\sin\alpha\, m_b}{v\,\cos\beta(1+\Delta_b)}\,(1-\Delta_b/\tan\alpha\tan\beta)$$

$$g_{H\,b\bar{b}} \simeq \frac{\cos\alpha\, m_b}{v\,\cos\beta(1+\Delta_b)}\,(1-\Delta_b\tan\alpha/\tan\beta)$$

$$g_{A\,b\bar{b}} \simeq \frac{m_b}{v(1+\Delta_b)}\,\tan\beta$$

- similar effects on τ coupling but $|\Delta_\tau| \ll |\Delta_b|$

Important modifications of couplings occur for regions of MSSM parameter space

$\longrightarrow$ dep. on sign and values of μA_t, μA_b, $\mu M_{\tilde{g}}$ and magnitudes of $M_{\tilde{g}}/M_S$, μ/M_S

- destroy the basic relation: $g_{h\,b\bar{b}}/g_{h\,\tau\tau} \sim m_b/m_\tau$

- strong suppression of coupling of h (H) to bottoms if

  $\tan\alpha \simeq \Delta_b/\tan\beta$ $\quad ((\tan\alpha)^{-1} \simeq -\Delta_b/\tan\beta)$

  $g_{h\,b\bar{b}} \simeq 0$; $g_{h\,\tau\tau} \simeq -\frac{m_\tau}{v}\Delta_b$ $\quad$ (h $\leftrightarrow$ H)

$\Longrightarrow$ main decay modes of SM-like MSSM Higgs: $b\bar{b} \sim 80\%$ $\quad \tau^+\tau^- \sim 7-8\%$

drastically changed $\Longrightarrow$ other decay modes enhanced

$\Longrightarrow$ Higgs phenomenology at colliders revisited!!

More generally we can write the Effective Lagrangian:

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

The resulting interaction Lagrangian defining the couplings of the physical Higgs bosons to third generation fermions:

$$\mathcal{L}_{\rm int} = -\sum_{q=t,b,\tau}\left[g_{hq\bar{q}}hq\bar{q} + g_{Hq\bar{q}}Hq\bar{q} - ig_{Aq\bar{q}}A\bar{q}\gamma_5 q\right] + \left[\bar{b}g_{H^-t\bar{b}}tH^- + \text{h.c.}\right].$$

$g_{(h/H/A),b\bar{b}}$ as given before. Similarly, $g_{(h/H/A),\tau^+\tau^-}$ replacing $m_b \to m_\tau$, $\Delta_b \to \Delta_\tau$ and $g_{(h/H/A),t\bar{t}}$ replacing $m_b \to m_t$, $\Delta_b \to \Delta_t$, $\tan\beta, \tan\alpha \to 1/\tan(\beta), 1/\tan(\alpha)$ (no $\tan\beta$ enhancement in Δ_t; $\Delta_\tau \ll \Delta_b$)

Similar to neutral Higgs case, for the charged Higgs one has important radiative corrections for large $\tan\beta$

$$g_{H^-t\bar{b}} \simeq \left\{\frac{m_t}{v}\cot\beta\left[1 - \frac{1}{1+\Delta_t}\frac{\Delta h_t}{h_t}\tan\beta\right]P_R + \frac{m_b}{v}\tan\beta\left[\frac{1}{(1+\Delta_b)}\right]P_L\right\}$$

also Δm_τ corrections in $g_{H^-\tau\nu_\tau}$ may be included.

MSSM Higgs Boson Searches at Hadron Colliders

- Due to large number of free parameters, a complete analysis of MSSM param. is too involved
- different initial states $\rightarrow$ production and decay channels relevant at lepton colliders are different from hadron colliders
- different enviroment at the Tevatron and LHC $\rightarrow$ different relevant Higgs production and decay channels as well

Main Neutral Higgs Boson Production Processes

Tevatron:

vector-boson bremsstrahlung: $p\bar{p} \rightarrow Vh/VH \rightarrow Vb\bar{b}$

associated production: $p\bar{p} \rightarrow \phi b\bar{b} \rightarrow b\bar{b}b\bar{b}$ with $\phi =$ A/h or A/H

LHC:

vector-boson fusion: $qq \rightarrow qqV^*V^* \rightarrow qqh,\ qqH$, with $h, H \rightarrow VV, \tau^+\tau^-, \gamma\gamma$

gluon fusion: $gg \rightarrow \phi \rightarrow \gamma\gamma$

associated production $gg, q\bar{q} \rightarrow \phi t\bar{t}$ with subsequent decay $\phi \rightarrow b\bar{b}, \gamma\gamma\ VV^*$

Benchmark Scenarios for the Search of the SM-like Neutral MSSM Higgs

SM-like → MSSM Neutral Higgs with stronger coupling to the W,Z bosons (also to top for intermediate/large $\tan\beta$)
for $m_A > m_h^{max} \rightarrow h$
for $m_A < m_h^{max}$ (and $\tan\beta \geq 10$) $\rightarrow H$
and $m_{h(H)} \leq m_h^{max} \leq 135$ GeV

Scenarios proposed: designed to study MSSM Higgs Sector

- without any assumptions of a particular soft SUSY breaking scenario
- taking into account only constraints from the Higgs sector itself

For each scenario:

- Fix values of $\tilde{t}$, $\tilde{b}$ sectors and gaugino masses
- Vary $\tan\beta$ and m_A
$0.5 \geq \tan\beta \leq 50$ and $m_A \leq 1$ TeV.
- Present results in terms of

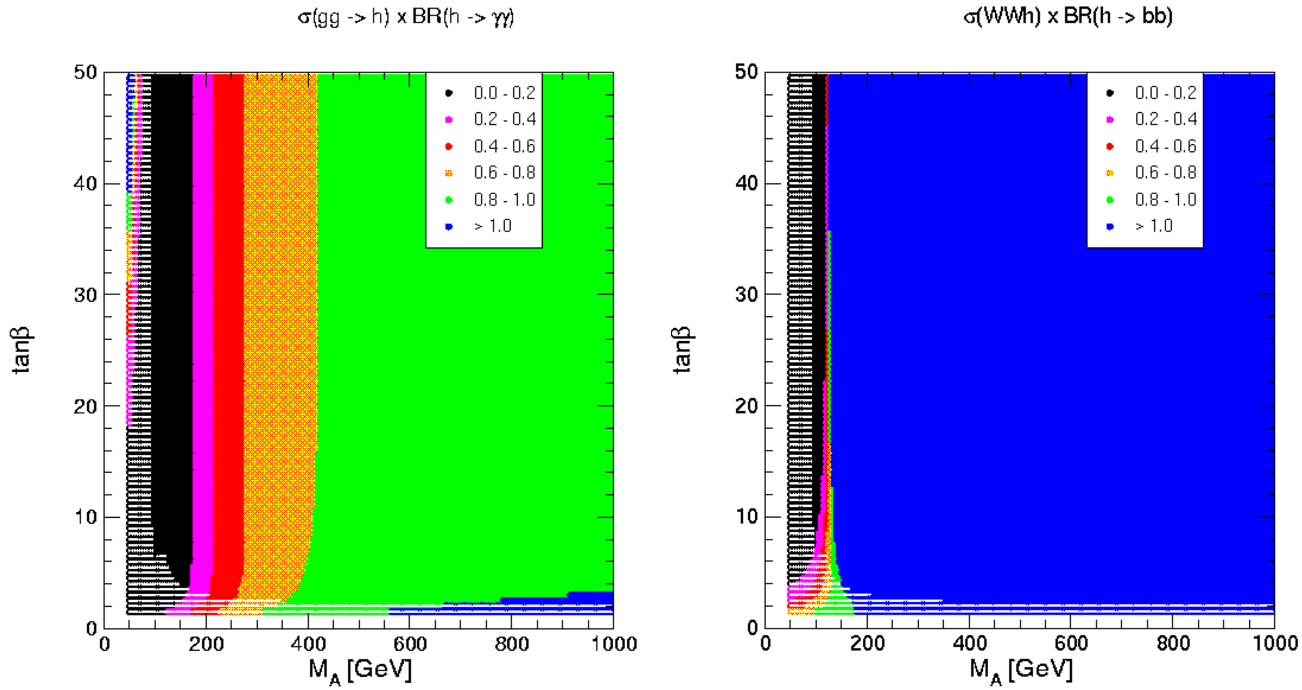
$$\frac{[\sigma \times BR]_{MSSM}}{[\sigma \times BR]_{SM}}$$

for various production channels

The m_h^{max} Scenario

- maximizes the value of the lightest Higgs mass & allows conservative $\tan\beta$ exclusion bounds
  $M_{SUSY} = 1$ TeV, $X_t = \sqrt{6}\, M_{SUSY}$, $\mu = M_2 = 200$ GeV, $A_b = A_t$, $M_{\tilde{g}} = 0.8\, M_{SUSY}$

LHC
$h \to \gamma\gamma$



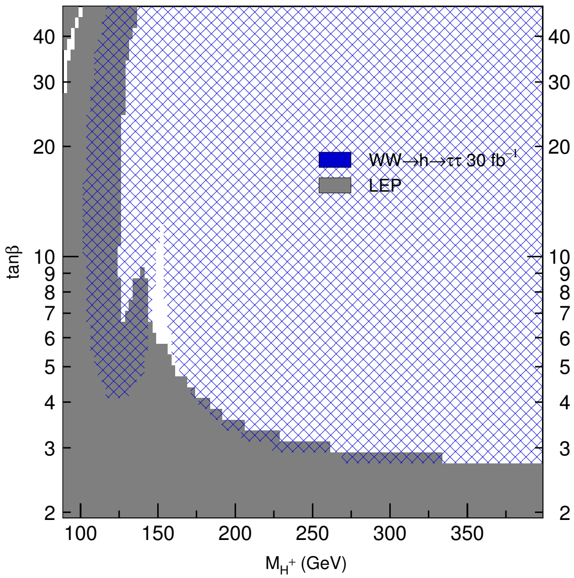
Tevatron:
$h \to b\bar{b}$

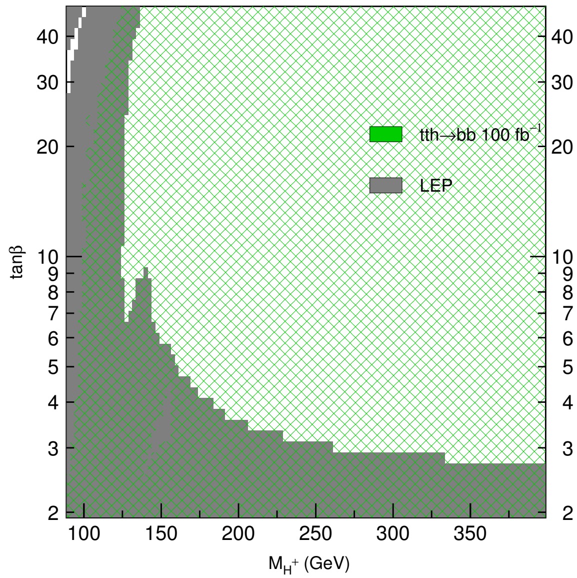
- $g_{hb\bar{b}}$, $g_{h\tau\tau}$ enhanced due to $\sin\alpha_{eff}/\cos\beta$ factor for low m_A and intermediate/large $\tan\beta \Longrightarrow$ strong suppression of $h \to \gamma\gamma$

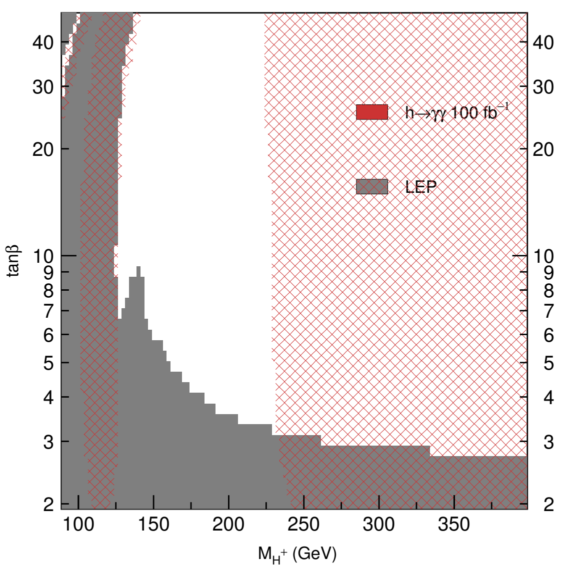
$\Longrightarrow gg \to h \to \gamma\gamma$ strongly suppressed compared to SM
and $W^*/Z^* \to W/Zh \to W/Zb\bar{b}$ nearly always enhanced
(WWh/ZZh coupling is SM-like for $m_A \geq m_h^{max}$)

For $m_A \leq m_h^{max}$, $\tan\beta \geq 10 \Longrightarrow W^*/Z^* \to W/ZH \to W/Zb\bar{b}$ similar behavior

LHC Prospects for Neutral Higgs searches: the m_h^{max} scenario



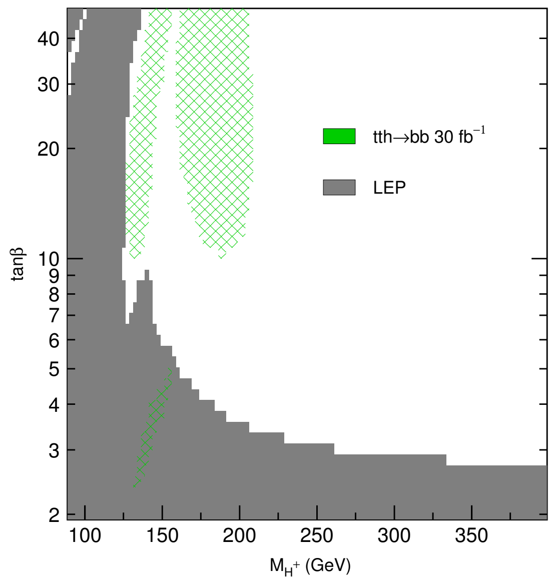


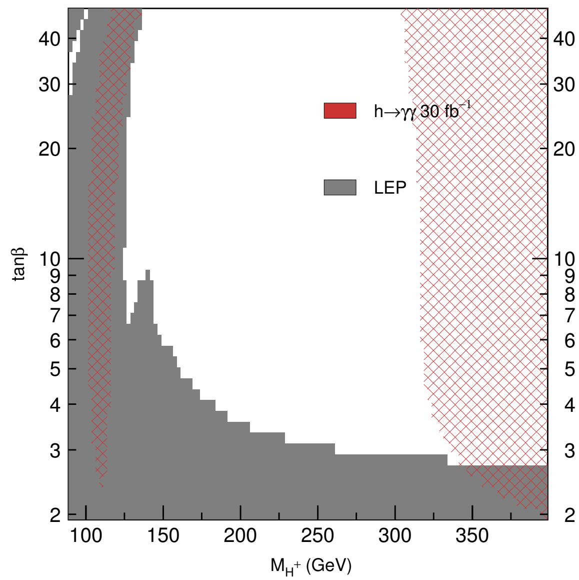


- vector-boson fusion with decay into taus is the decisive channel with 30 fb^{-1}

- $h \to \gamma\gamma$, from gluon fusion and associated production with top quarks, and $h \to b\bar{b}$ from associated production with top quarks, need 100 fb^{-1}

The m_h^{max} scenario at LHC with 30 fb^{-1}





Small α_{eff} Scenario

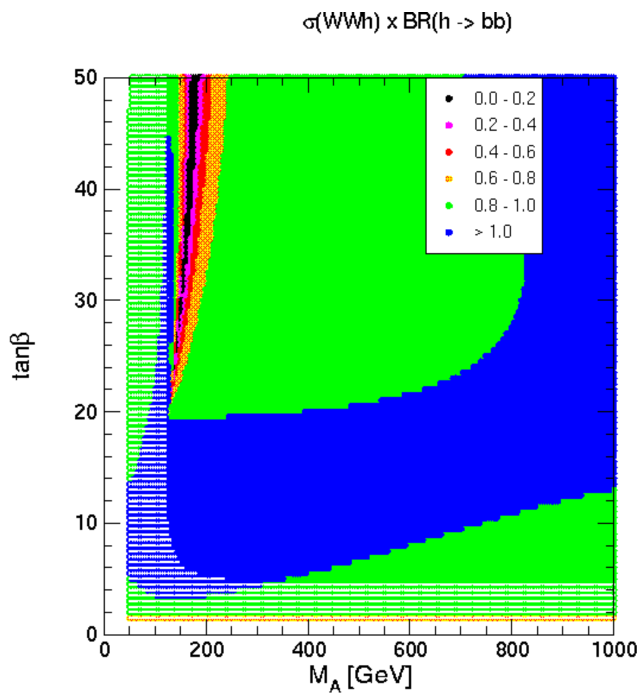
Besides $gg \to h \to \gamma\gamma$, most channels at the Tevatron and LHC rely on $h \to b\bar{b}, \tau^+\tau^-$

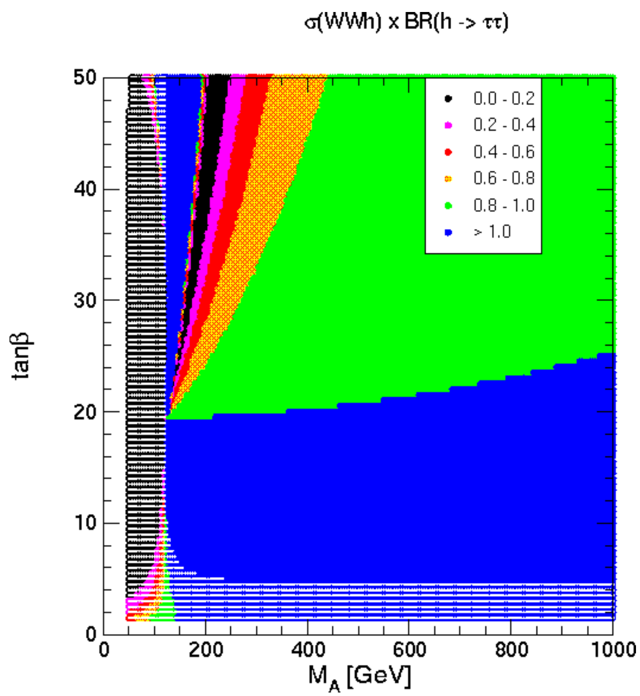
If α_{eff} (rad. corrected α) is small $\Longrightarrow$ $g_{hb\bar{b}}$ and $g_{h\tau\tau}$ couplings can be importantly suppressed : Suppression occurs for moderate/large $\tan\beta$ and small/moderate m_A

Also, $h \to b\bar{b}$ can have large corrections from $\tilde{b}/\tilde{g}$ and $\tilde{t}/\tilde{\chi}^{\pm}$ loops (Δ_b)

$M_{\text{SUSY}} = 800$ GeV, $X_t = -1.2$ TeV, $\mu = 2.5 M_{\text{SUSY}}$, $M_2 = 500$ GeV, $A_b = A_t$, $M_{\tilde{g}} = 500$ GeV

Tevatron: $h \to b\bar{b}$





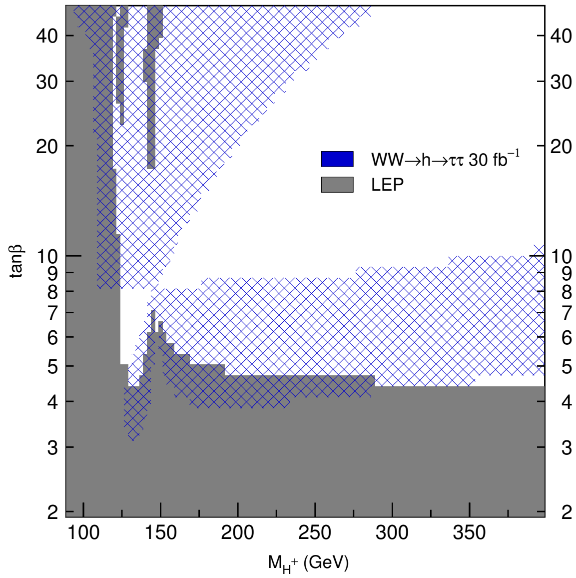
LHC: $h \to \tau^+\tau^-$

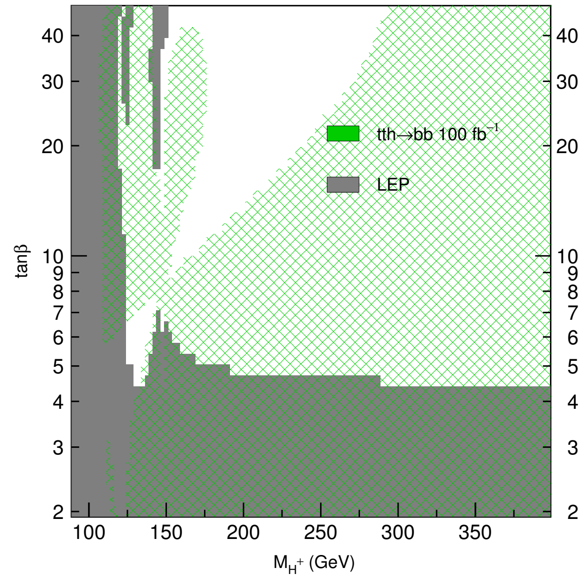
M.C., Heinemeyer, Wagner & Weiglein

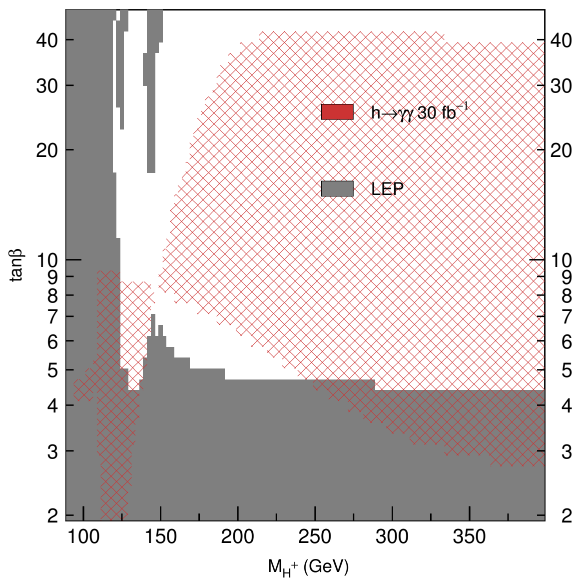
- Significant suppression for $\tan\beta \geq 20$ and $m_A \leq 200$ (400) GeV for $h \to b\bar{b}$ ($\tau\tau$)

$\Longrightarrow$ Searches via W/Zh, WWh and $t\bar{t}h$ will be more difficult than in the SM. Instead, the $h \to \gamma\gamma$ channel will be enhanced compared to the SM.

LHC Prospects for Neutral Higgs searches: Small $\alpha_{\rm eff}$ scenario



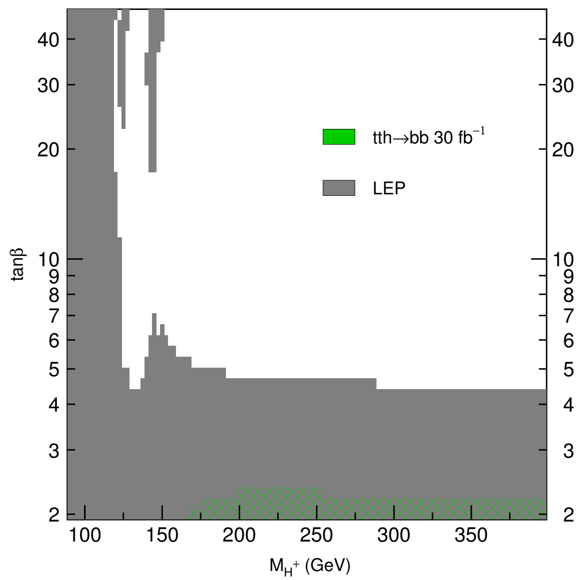


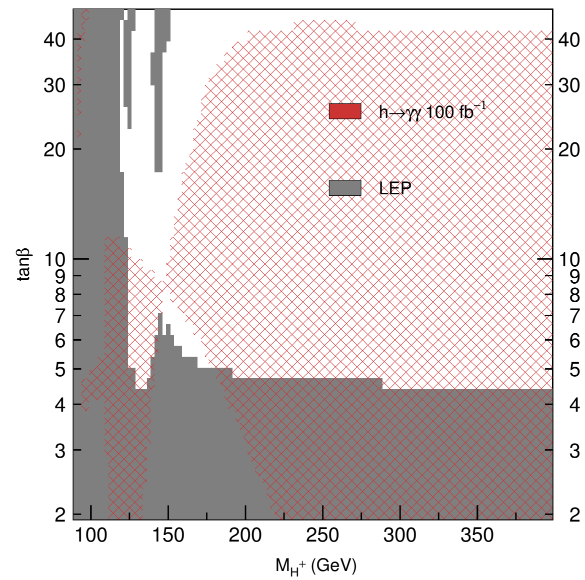


- Complementarity between the vector boson fusion and the $h \rightarrow \gamma\gamma$ channels for 30 fb^{-1}

- $t\bar{t}h \rightarrow t\bar{t}\,b\bar{b}$ channel relevant only with high luminosity

The α_{eff} scenario at LHC: tth with 30 fb^{-1}, $h \to \gamma\gamma$ with 100 fb^{-1}

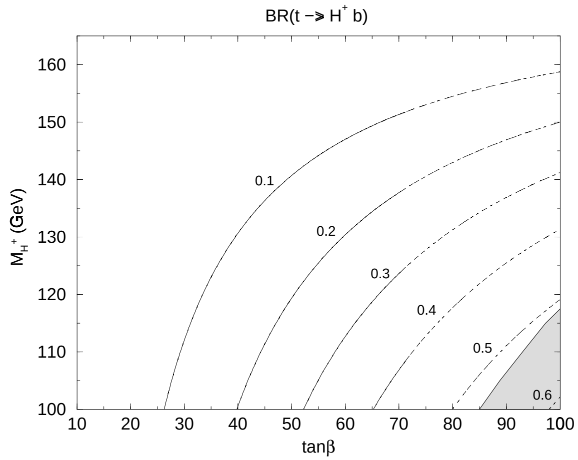




Charged Higgs searches at the Tevatron

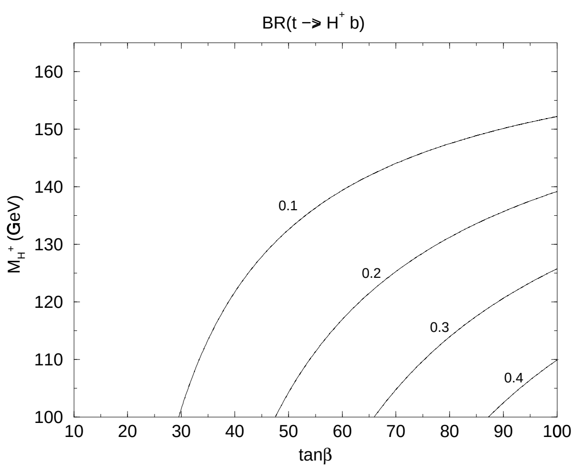
- Curves of constant BR for $t \rightarrow bH^+$ after resummation of LO and NLO logarithms of QCD corrections included applying OPE

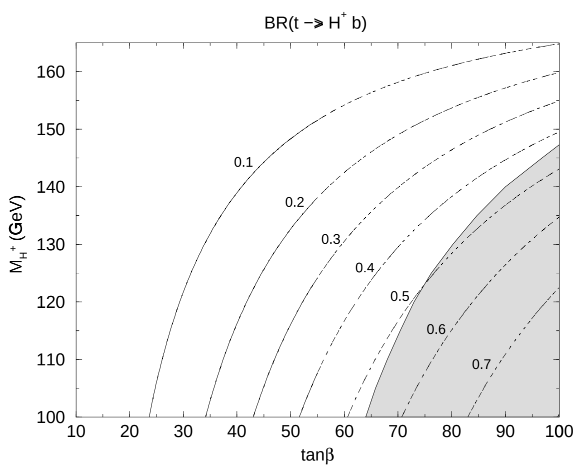
  Shaded area excluded by Run1 DØ frequentist analysis from $H^{\pm}$ searches in top decays



- Including dominant SUSY correc. for large $\tan\beta$ and a heavy SUSY spectrum

based on $\mathcal{L} \simeq \frac{g}{\sqrt{2}M_W} \frac{\bar{m}_b(Q)\tan\beta}{1+\Delta m_b} \left[V_{tb}H^+\bar{t}_L b_R(Q) + \mathrm{h.c.}\right] \Longrightarrow \Gamma_{MSSM} \simeq \frac{\Gamma^{imp.}_{QCD}}{(1+\Delta mb)^2}$

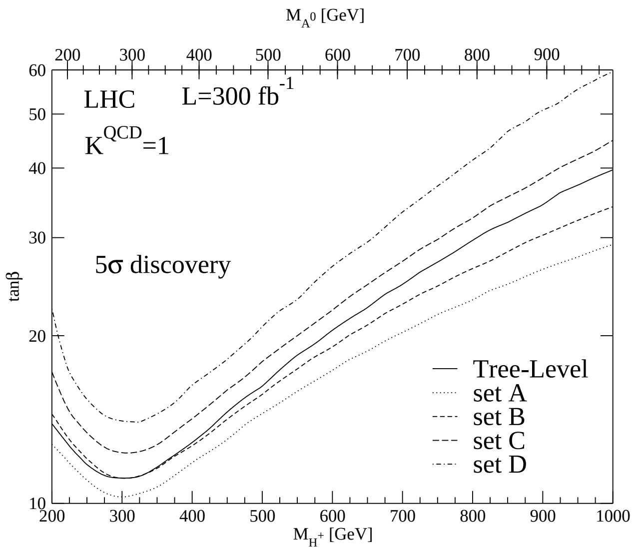




Drastic variations on $\tan\beta - m_{H^\pm}$ plane bounds, depending on MSSM parameter space

M.C., Garcia, Nierste, Wagner

Similar analysis for $pp \to H^+ tb + X$ at LHC for large $\tan\beta$



Discovery reach at the LHC for different sets of SUSY parameters, which can enhance or suppress the $H^{\pm}tb$ coupling

Discovery reach at LHC with 300 fb^{-1} and $\tan\beta > 30$

- best case scenario: $m_{H^+} \leq 1$ TeV
- worst case scenario: $m_{H^+} \leq 450$ GeV

Belyaev, Garcia, Gausch, Sola

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

$\Longrightarrow$ 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 between the three neutral Higgs boson states

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

In the base (A, ϕ_1, ϕ_2):

$$\mathcal{M}_N^2 = \begin{bmatrix} m_A^2 & \left(M_{SP}^2\right)^T \\ M_{SP}^2 & M_{SS}^2 \end{bmatrix}$$

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.

where $M_{SP}^2 \propto \mathrm{Im}(\mu A_t)$

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 $\arg(M_{\tilde{g}})$

Interaction Lagrangian of W, Z vector bosons
with mixtures of $\mathcal{CP}$-even & $\mathcal{CP}$-odd Higgs bosons.

$$\Downarrow$$

$$\begin{aligned}
g_{H_i VV} &= \cos\beta\,\mathcal{O}_{1i} + \sin\beta\,\mathcal{O}_{2i} \qquad\qquad (V = W, Z) \\
g_{H_i H_j Z} &= \mathcal{O}_{3i}\,(\cos\beta\,\mathcal{O}_{2j} - \sin\beta\,\mathcal{O}_{1j}) - \\
&\quad \mathcal{O}_{3j}\,(\cos\beta\,\mathcal{O}_{2i} - \sin\beta\,\mathcal{O}_{1i}) \\
g_{H_i H^- W^+} &= \cos\beta\,\mathcal{O}_{2i} - \sin\beta\,\mathcal{O}_{1i} + i\mathcal{O}_{3i}
\end{aligned}$$

$\mathcal{O}_{ij} \longrightarrow$ analogous to $\sin(\beta-\alpha)$ & $\cos(\beta-\alpha)$

$\longrightarrow$ all couplings as a fc. of two: $\boxed{g_{H_k VV} = \epsilon_{ijk}\, g_{H_i H_j V}}$

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

(equiv. to CP-conserv. case)

upper bound remains the same

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

- effective mixing between the lightest Higgs H_1 and the heavy ones is zero: $H_1 \longrightarrow$ SM-like
- Due to high degeneracy between the would-be m_A & m_H

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

$\longrightarrow$ *mixing still relevant*

Yukawa Couplings

$$-\mathcal{L}_{\phi b\bar{b}} = \left(h_b H_1^0 + \Delta h_b H_2^0\right) \bar{b}_L b_R + h.c.$$

Coupling Δh_b generated by SUSY breaking effects $\quad \Delta h_b \simeq \frac{\alpha_3}{3\pi} \frac{M_{\tilde{g}}^* \mu^*}{M_S^2}$

The one loop corrections to the Yukawa couplings introduce CP-violating effects which are independent of Higgs mixing (like ϵ and $\epsilon^{'}$)

$$g^S_{H_i dd} = \frac{1}{h_d \cos\beta + \Delta h_d \sin\beta} \left[Re(h_d) O_{1i} + Re(\Delta h_d) O_{2i} + \left(Im(h_d) \sin\beta - Im(\Delta h_d) \cos\beta \right) O_{3i} \right]$$

$$g^P_{H_i dd} = \frac{1}{h_d \cos\beta + \Delta h_d \sin\beta} \left[Im(h_d) O_{1i} + Im(\Delta h_d) O_{2i} + \left(Re(h_d) \cos\beta - Re(\Delta h_d) \sin\beta \right) O_{3i} \right]$$

where we have defined the phase of the superfield b_R

$$m_b^2 \propto h_b + \delta h_b + \Delta h_b \tan\beta$$

to be real and positive

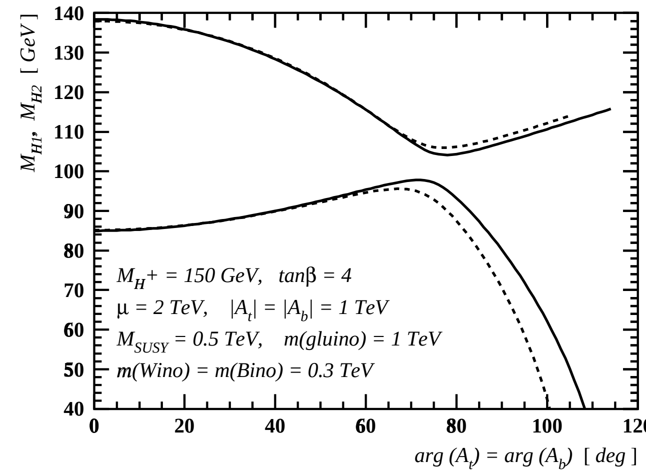
CP-Violating Higgs Bosons in the light of LEP2

Production Mechanism: $e^+e^- \to H_iZ$ and $e^+e^- \to H_iH_j$

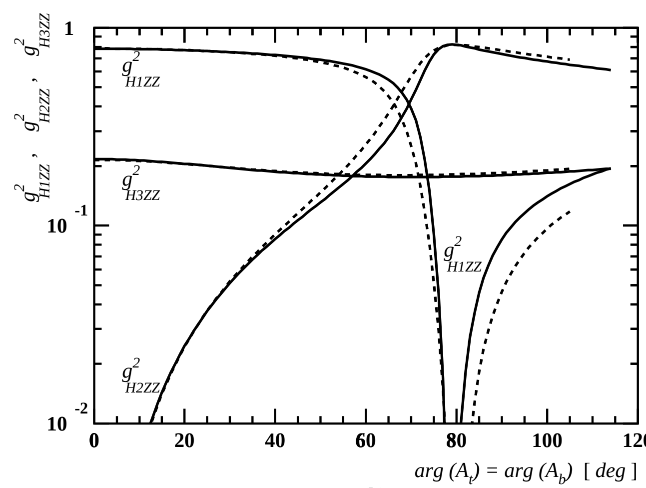
CPX Scenario:
$M_{SUSY} = 0.5,\ 1$ TeV
$\mu = 4\ M_{SUSY}$
$m_{\tilde{g}} = 1$ TeV
$|A_t| = |A_b| = 2M_{SUSY}$

• 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



(a)

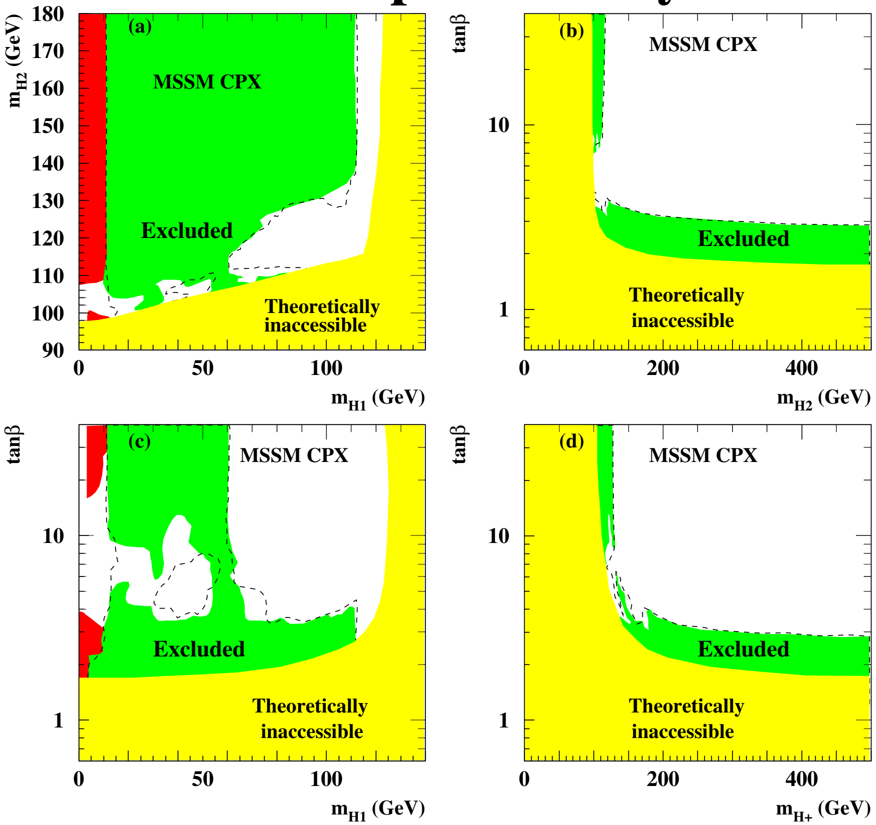


(b)

Pilaftsis

Other cases may require extra studies: { *e.g.* if $H_1 H_2$ kinematically allowed and $H_2 \to H_1 H_1$ open, then present LEP bounds may be challenged.

OPAL preliminary



a) $M_{H_2} \leq 130$ GeV $\Longrightarrow$ { major role of CP-violating effects.

b) $\tan\beta$ <2.8 excluded

c) region of $M_{H_1} \leq 50$ GeV $\longrightarrow$ open channels:

ZH_2 and $H_1 H_2$ with $H_2 \to H_1 H_1 \to b\bar{b}b\bar{b}$

(broaden signal with reduced sensitivity)

example: $m_{H_1} = 39$ GeV, $m_{H_2} = 105$ GeV

$\tan\beta = 8.5$ not excluded

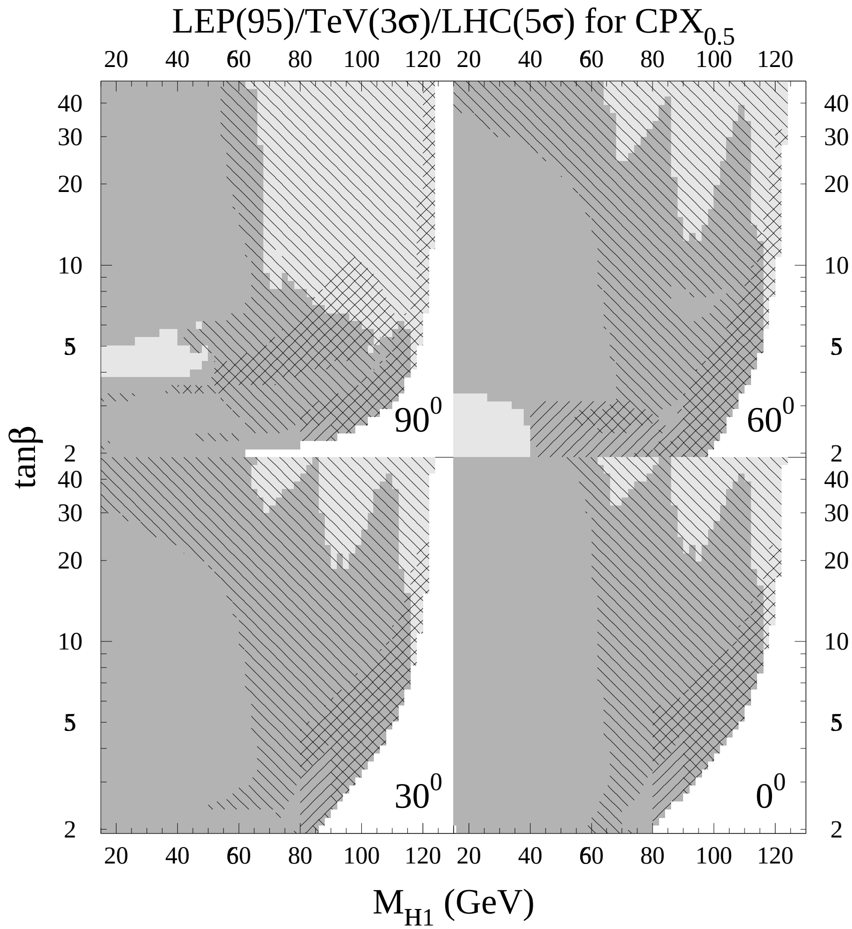
- Due to reduced couplings of H_i to W/Z gauge bosons
  and to extended regions where $H_2 \to H_1 H_1$ dominates

No limit on lightest Higgs can be given independent of $\tan\beta$

(May change after combination of 4 experiments)

- Can Such decay chain be seen at the Tevatron? $gg \to H_2 \to H_1 H_1$?
  Some studies at parton level. . . also for LHC

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 $\rightarrow H_i \rightarrow \gamma\gamma b$ (100 fb^{-1})

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

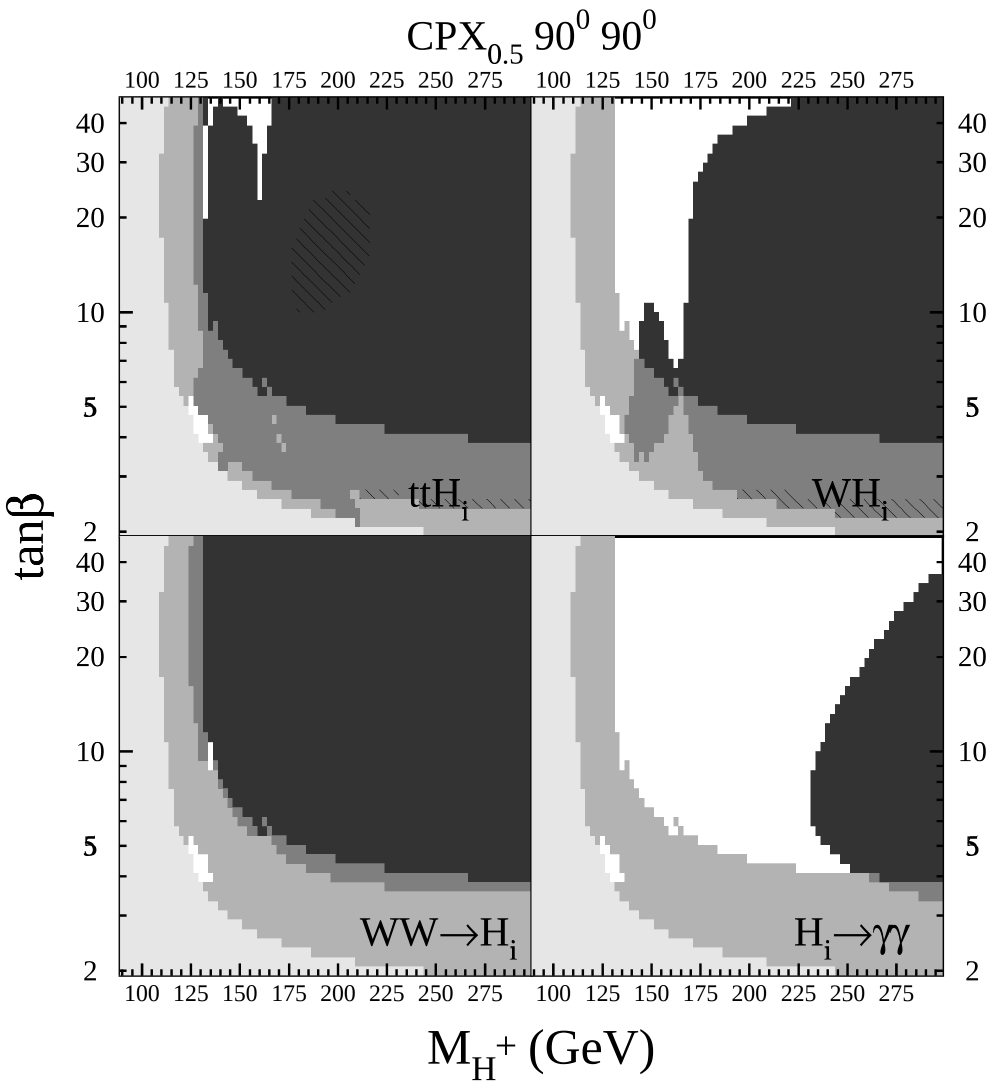
WW/ZZ $H_i(\rightarrow \tau^+\tau^-)$ (30 fb^{-1})

grey → LEP exclusion.

M.C., Ellis, Pilaftsis, Wagner

- low $\tan\beta$ and low m_{H_i} region remains uncovered in the absence of the $H_2 \rightarrow H_1 H_1$ analysis
- Encourage the study of $gg \rightarrow H_2 \rightarrow H_1 H_1$ and $t\bar{t}H_2$ and W/Z H_2 with subsequent decay $H_2 \rightarrow H_1 H_1$ using the extra leptons from the W/Z's.

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

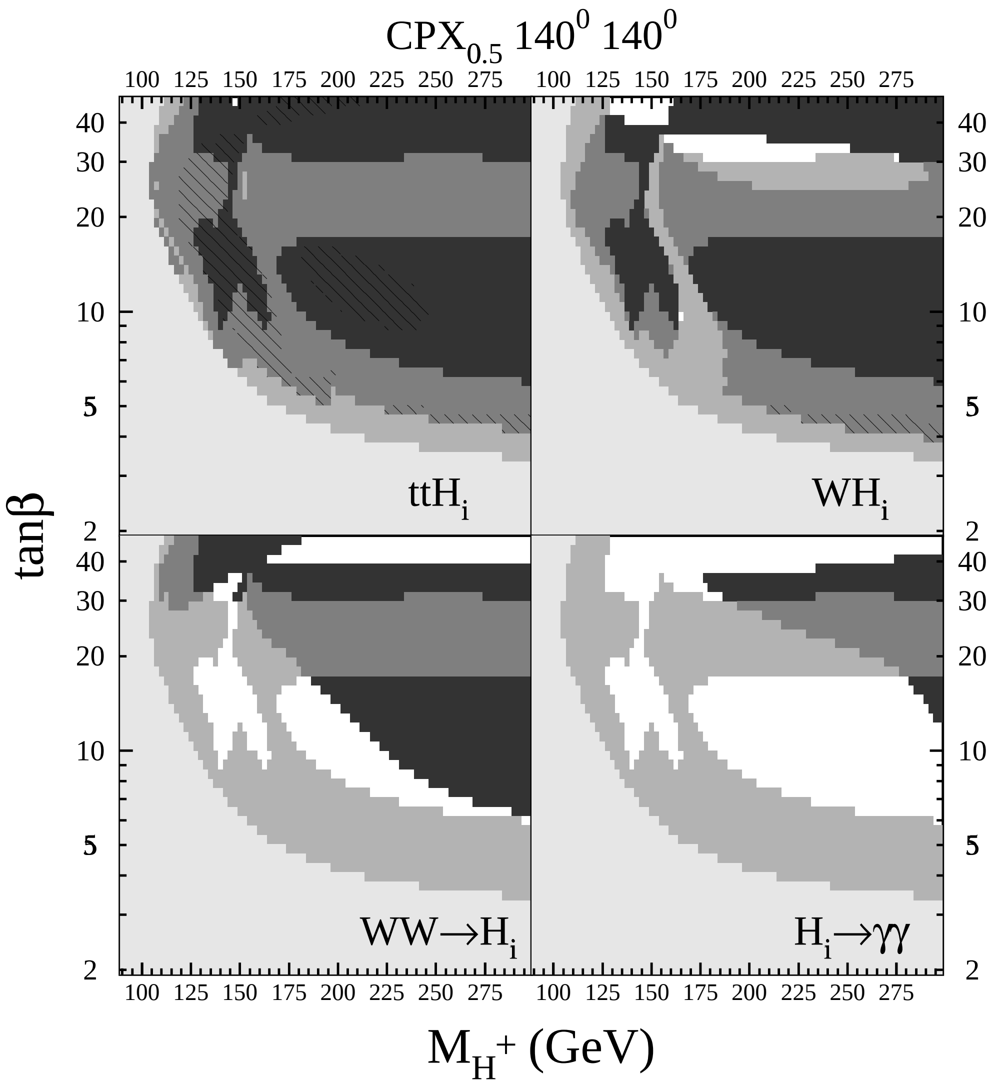


- The Tevatron could see a 3 σ hint with 5 fb^{-1} in a sizeable area of parameter space

If arg($M\tilde{g}$)= 0 instead, stronger suppression of BR($H_{1,2}$) $\rightarrow b\bar{b}$ and both upper channels less competitive

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

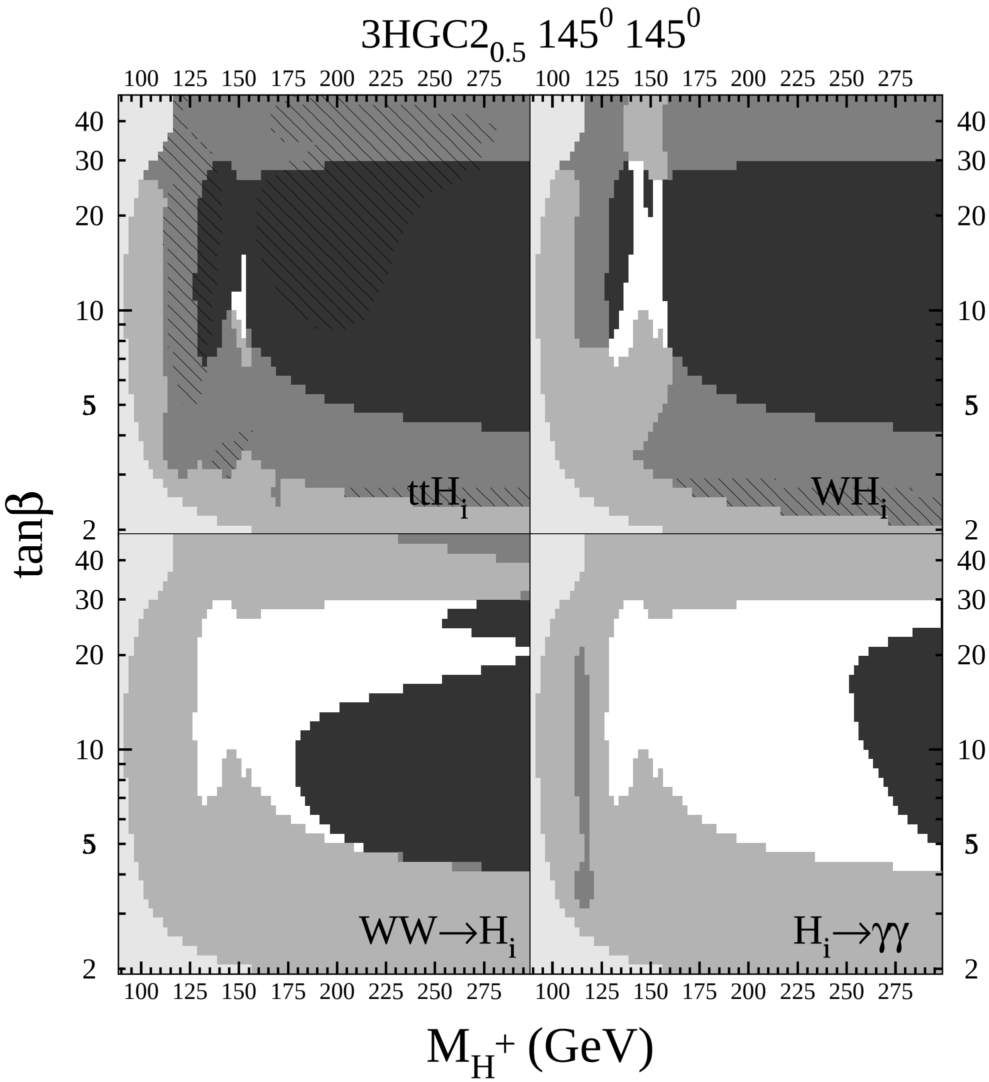
In some regions of parameter space → strong $H_1 \to \tau^+\tau^-$ suppression



However, depending on the charged Higgs mass and $\tan\beta$ values $\longrightarrow b\bar{b}$ becomes suppressed with respect to $\tau^+\tau^-$

- Complementarity of Tevatron and low luminosity LHC could be crucial for early discovery in this type of scenarios.

In MSSM with CP violation: mass splitting among neutral Higgs bosons can be sizeable and they can share their couplings to W/Z's



⟹ 3 signatures with very low significance

⟹ they can be very close in mass and "one signal" can be the background to the other.

⋆ MSSM SM-like Higgs studies show that

- Tevatron $W/ZH_i(\to b\bar{b})$ and LHC $WWH_i(\to \tau^+\tau^-)$
  $\Longrightarrow$ direct test of Higgs mechanism,
  can be affected very differently by radiative corrections.
  $\Longrightarrow$ nice complementarity

- $t\bar{t}H_i(\to b\bar{b})$ needs high luminosity option at LHC $\mathcal{O}(100\ \text{fb}^{-1})$

- $h \to \gamma\gamma$ channel may be difficult depending on SUSY parameter space (especially in CPX scenarios)

- LHC discovery reach in the first years relies strongly on vector-boson fusion Higgs production, with $H_i \to \tau^+\tau^-$.

It will be useful to study this channel with detailed detector simulations including specially challenging cases.

Outlook

By the End of This Decade

– Tevatron

• will have measured M_t, M_W to unprecedented accuracy $\longrightarrow$ indirect constraints on $M_{H_{\rm SM}}$

• If Nature is kind, discovery of new particles.

• If Nature, the accelerator and the detectors are kind, and physicists very smart, we may learn something about EWSB!

In the Next Decade

– LHC: A *sure* window to new physics:

• Higgs • SUSY • New Dimensions • New Particles & Interactions

• If Higgs & SUSY are there, we will find out.

• If Nature is kind, we will know exactly which type of SUSY is there.

– LC

• unique capabilities to do precision Physics

• open the window to Planck scale physics

• unique connection with Cosmology