A Solution for the Little Hierarchy Problem and $b \to s\gamma$

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The little hierarchy problem

The little hierarchy problem

- The MSSM
  - 2 Higgs doublet model
  - 4 Higgs bosons (h, H, A and $H^{\pm}$)
  - $m_h < m_Z$ at tree level
- LEP bound : $m_{\text{SM Higgs}} > 114.4\text{GeV}$
- If we require $m_h > 114.4\text{GeV}$

  => stop mass > 500GeV

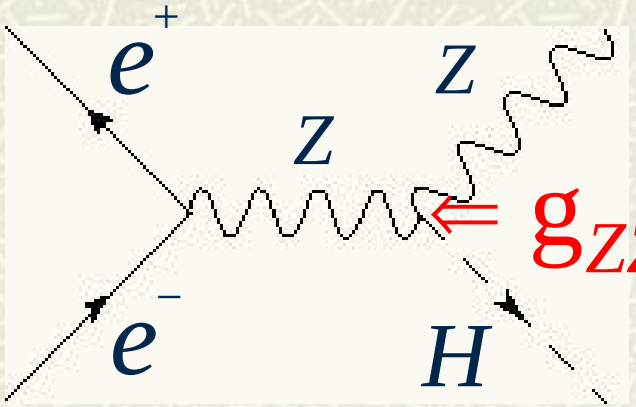
  => 0.5% fine tuning

We examine g_{ZZH} and g_{ZZh}

A solution

LEP experiments for the SM Higgs

- g_{ZZH} coupling



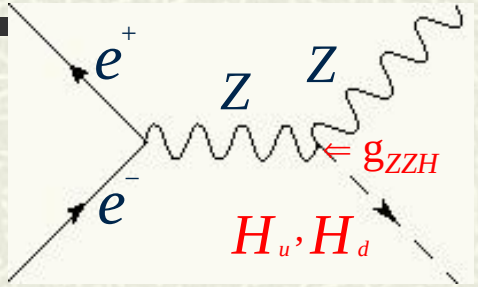
$\Leftarrow g_{ZZH} \propto \langle v \rangle$

H ; the SM Higgs

$$|D_\mu H|^2 \rightarrow g^2 ZZHH \rightarrow g^2 \langle H \rangle ZZH = g_{ZZH} ZZH$$

The SM Higgs boson mass > 114.4 GeV (95% CL)

LEP exp. for the MSSM Higgs



- The MSSM has two Higgs doublets.
  For simplicity, we take $\langle H_u \rangle >> \langle H_d \rangle$

  $H_u \to g_{ZZHu} \sim g_{ZZH}$: It looks like the SM Higgs (LEP bound)

  $H_d \to g_{ZZHd} << g_{ZZH}$: <u>hard to find it at LEP</u>

- Moreover, if $m_{H_d} < m_{H_u}$, then H_d becomes lighter CP-even Higgs boson h and it cannot be found using above process (m_h<114.4GeV is allowed).

  How is it realized in terms of parameters of Higgs sector?

Details : Mass matrix of CP even Higgs bosons (tree level)

- When $\langle H_u \rangle >> \langle H_d \rangle$ (i.e. $\tan\beta >> 1$)

$$m^2_{h,H} = \begin{array}{c} H_d \\ H_u \end{array} \overset{\begin{array}{cc} H_d & H_u \end{array}}{\begin{pmatrix} m_A^2\sin^2\beta + m_Z^2\cos^2\beta & -(m_A^2 + m_Z^2)\sin\beta\cos\beta \\ -(m_A^2 + m_Z^2)\sin\beta\cos\beta & m_Z^2\sin^2\beta + m_A^2\cos^2\beta \end{pmatrix}} \sim \begin{pmatrix} m_A^2 & 0 \\ 0 & m_Z^2 \end{pmatrix}$$

$m^2_{H_d}$ weakly couple

$m^2_{H_u}$ SM-like

- Hence when $m_A^2 < m_Z^2$, $m_{Hd}^2 < m_{Hu}^2$ can be realized

  ⇒All the Higgs boson mass scales are EW scale

- Is it possible to satisfy $m_{Hu} > 114.4\text{GeV}$ naturally?

  → loop corrections and diagonalization of actual mass matrix must be taken into account

Rich guy becomes richer, poor…

- Off diagonal entries and quantum correction

$$\begin{pmatrix} m_{H_d}^2 (\sim m_A^2) & -(m_A^2 + m_Z^2)\sin\beta\cos\beta \\ -(m_A^2 + m_Z^2)\sin\beta\cos\beta & m_{H_u}^2 (\sim m_Z^2) + \Delta(\ln(m_{\tilde{t}})) \end{pmatrix}$$

- Diagonalization

$$a > b \qquad E > e$$

$$\begin{pmatrix} a & c \\ c & b \end{pmatrix} \Rightarrow \begin{pmatrix} E & 0 \\ 0 & e \end{pmatrix}$$

$$E > a \text{ and } e < b \quad \text{since} \quad \begin{matrix} \mathrm{E} \\ \mathrm{e} \end{matrix} = (a + b \pm \sqrt{(a-b)^2 + 4c^2})/2$$

Rich guy becomes richer, poor…

- "Normal case" $m_{H_d}^2 > m_{H_u}^2 + \Delta(m_{\tilde{t}})$

$$\begin{array}{c} \\ H_d \\ H_u \end{array} \begin{array}{c} \begin{array}{cc} H_d & H_u \end{array} \\ \begin{pmatrix} m_{H_d}^2 (\sim m_A^2) & -(m_A^2 + m_Z^2)\sin\beta\cos\beta \\ -(m_A^2 + m_Z^2)\sin\beta\cos\beta & m_{H_u}^2 (\sim m_Z^2) + \Delta(\ln(m_{\tilde{t}})) \end{pmatrix} \end{array}$$

  - H~Hd and h~Hu $m_h > 114.4\text{GeV}$
  - $m_H^2 > m_{H_d}^2 (\sim m_A^2)$, $m_h^2 < m_{H_u}^2 (\sim m_Z^2) + \Delta(\ln(m_{\tilde{t}}))$
  - needs large stop mass => the fine-tuning problem

*In this case, large tan β is preferable

Rich guy becomes richer, poor…

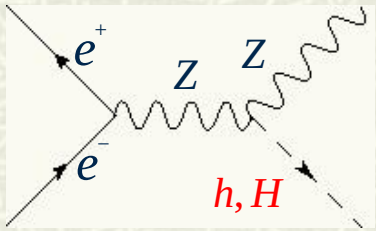
- "Inverse case" $m_{H_d}^2 < m_{H_u}^2 + \Delta(m_{\tilde{t}})$

$$\begin{array}{c} \\ H_d \\ H_u \end{array} \begin{array}{c} \begin{array}{cc} H_d & H_u \end{array} \\ \begin{pmatrix} m_{H_d}^2 (\sim m_A^2) & -(m_A^2 + m_Z^2)\sin\beta\cos\beta \\ -(m_A^2 + m_Z^2)\sin\beta\cos\beta & m_{H_u}^2 (\sim m_Z^2) + \Delta(\ln(m_{\tilde{t}})) \end{pmatrix} \end{array}$$

- H~Hu and h~Hd $m_H > 114.4\text{GeV}$
- $m_h^2 < m_{H_d}^2 (\sim m_A^2)$, $m_H^2 > m_{H_u}^2 (\sim m_Z^2) + \Delta(\ln(m_{\tilde{t}}))$
- needs no large stop mass

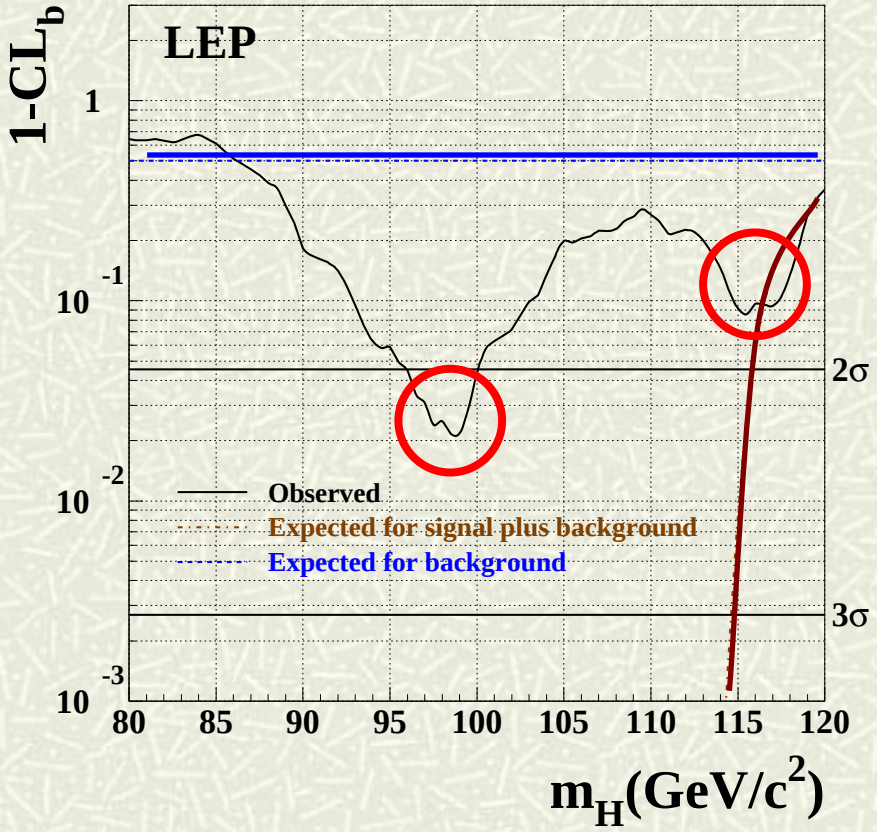
*In this case, small $\tan\beta$ is preferable

Experimental aspects



- Results of LEP exp.

$m_{\text{SM Higgs}} > 114.4$ GeV



- 115 GeV ~1.7 σ excess may be explained by the heaviest (SM like) CP-even Higgs boson H
- 98 GeV ~2.3 σ excess may be explained by the lightest CP-even Higgs boson h with small coupling

Previous works

Kane-Wang-Nelson-Wang '04
Drees '05

- Both excesses can be explained in the MSSM, if SUSY breaking parameters have not mSUGRA type boundaries.

$$90\text{GeV} \le m_A \le 175\text{GeV}, \quad 110\text{GeV} \le m_{H^\pm} \le 200\text{GeV}$$

- They didn't take care about the tuning problem enough.

$$100\text{GeV} \le m_{\tilde{t}}, m_{H_u}, m_{H_d}, \mu, A_t \le 2\text{TeV}$$

*Large values require fine tuning

$$\frac{m_Z^2}{2} \sim -\mu^2 - m_{Hu}^2 (\Delta m_{Hu}^2 (m_{\tilde{t}}^2))$$

- It is not obvious whether the Inverse case is possible using "natural" SUSY breaking parameters.

$$m_{\tilde{t}}, m_{H_u}, m_{H_d}, \mu, A_t \approx O((100\text{GeV})^2)$$

Setup of numerical analyses

- GUT relations for gaugino masses
- Exp. bounds $m_{\chi^0} \geq 46\text{GeV},\ m_{\chi^\pm} \geq 94\text{GeV},\ m_{\tilde{\tau}} \geq 82\text{GeV}$
- Natural SUSY, - breaking parameters

  $M_{1/2}$=145GeV, m_0=100GeV (at GUT scale)
  => m_{Q3}=350GeV, m_{U3}=300GeV, μ =200GeV (at EW scale)
- Consistencies with LEP Higgs search

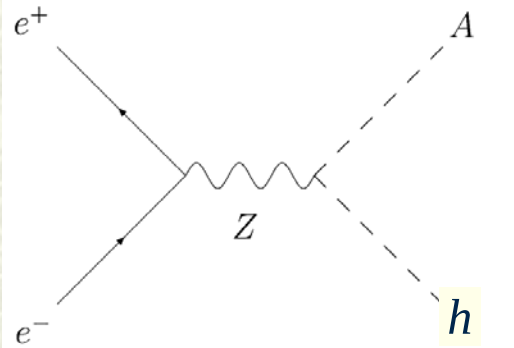
$$90\text{GeV} \leq m_h$$

$$(95\text{GeV} \leq m_h \leq 101\text{GeV})$$

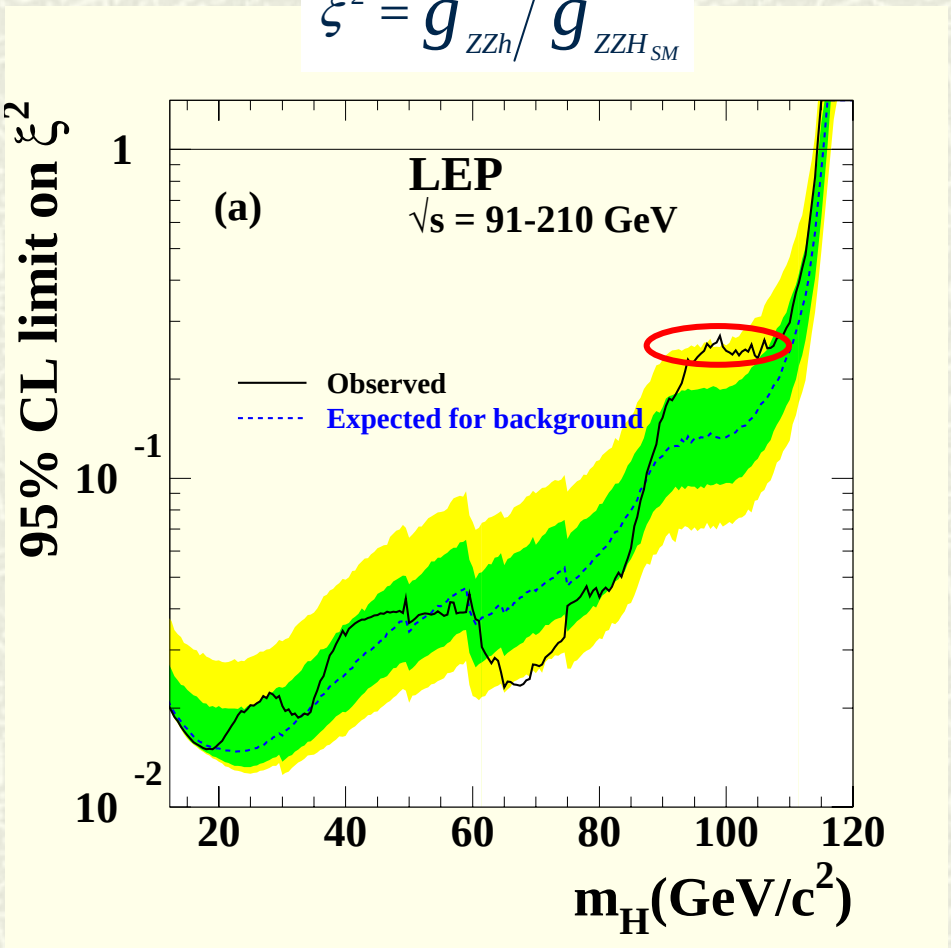
$$\xi^2 = g^2_{ZZh} \Big/ g^2_{ZZH_{SM}} \leq 0.25$$

Consistencies with LEP Higgs search

*m_h < nearly 90GeV is excluded from ZhA production process.



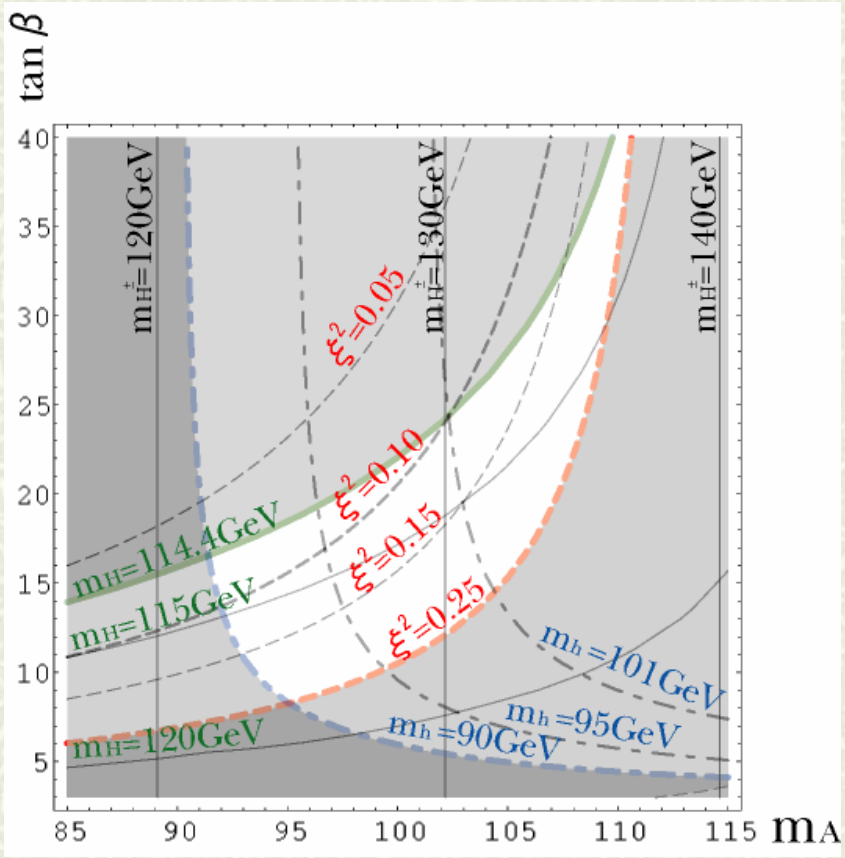
$$\xi^2 = g^2_{ZZh} / g^2_{ZZH_{SM}}$$



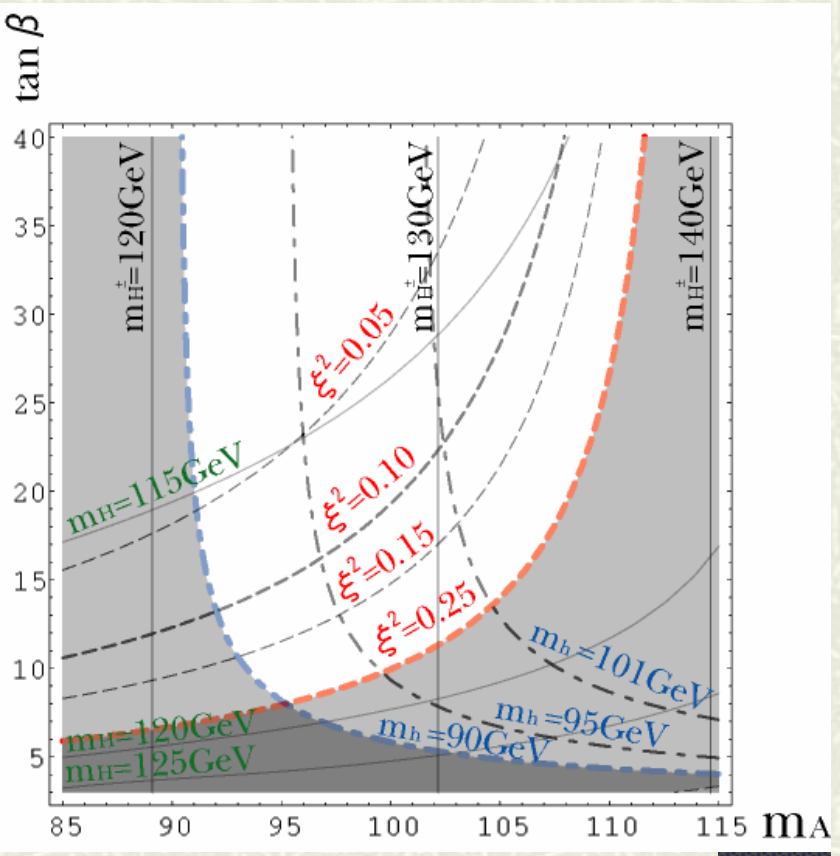
Results of numerical analyses

(m_{Q3}=350GeV, m_{U3}=300GeV, μ =200GeV)

- A=300GeV



- A=325GeV



1st Summary and questions

- Light h with small g_{ZZh} coupling can be consistent with the LEP data in the MSSM with natural μ and SUSY breaking parameters. (2 excesses can be signals.)

  (not $m_{\tilde{t}} \sim 500\text{GeV}$ but $m_{\tilde{t}} \sim 300\text{GeV}$)

- Mass scales of the MSSM Higgs bosons are EW scale.

$$m_h \sim 100\text{GeV}, \quad m_H \sim 115\text{GeV}$$

$$m_A \sim 100\text{GeV}, \quad m_{H^\pm} \sim 130\text{GeV}$$

- Is existence of light charged Higgs boson consistent with Br(b→s γ) constraint? [next topic]

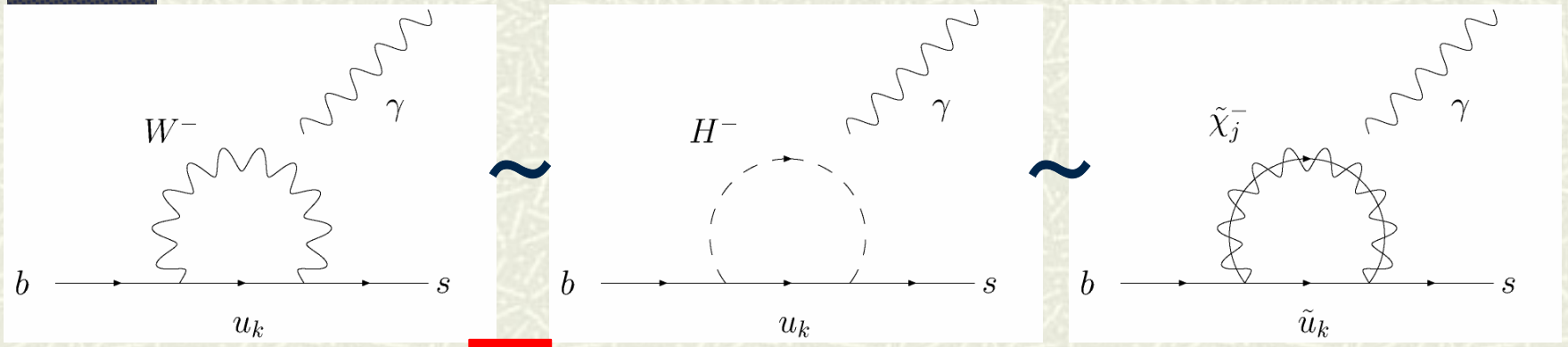
  cf. $m_{H^\pm} \geq 350\text{GeV}$ in the type II 2HDM

Br(b→s γ) constraint

Branching ratio of b→s γ

Pre : $(3.60\pm0.30)\times10^{-4}$

Exp : $(3.55\pm0.24)\times10^{-4}$



Standard model | additive | Charged Higgs | negative | Chargino

*No b→s γ process occurs if SUSY is exact [Ferrara and Remiddi '74]

$$m_W = m_{\tilde{W}}, m_{H^\pm} = m_{\tilde{H}^\pm}, m_t = m_{\tilde{t}}$$

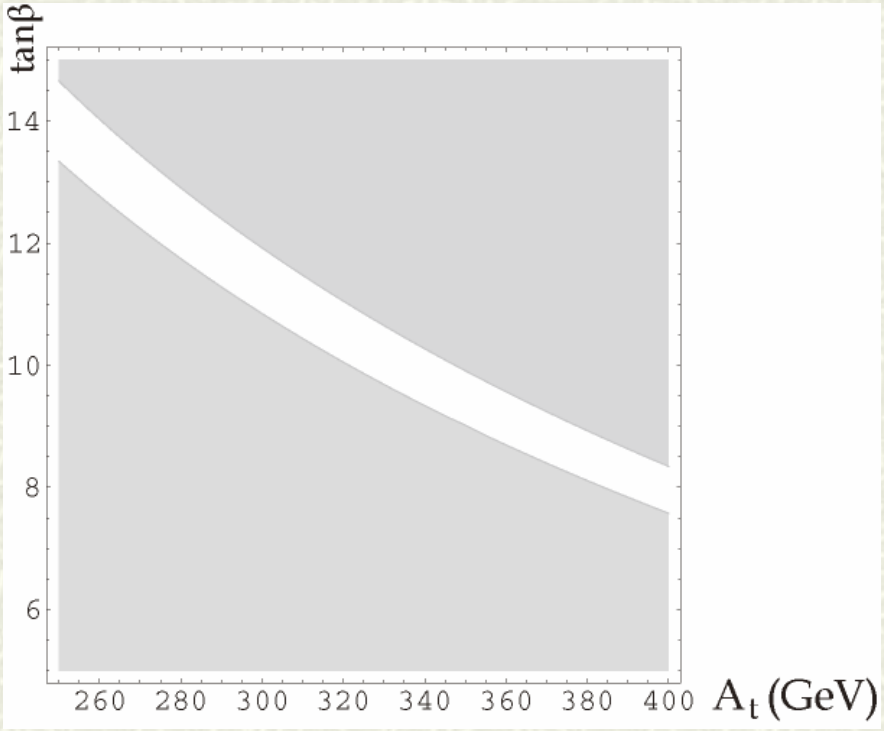
Naturalness ⇒ The mass scales of every fields in the loops are now all EW scale.

$$m_W \sim m_{\tilde{W}}, m_{H^\pm} \sim m_{\tilde{H}^\pm}, m_t \sim m_{\tilde{t}}$$

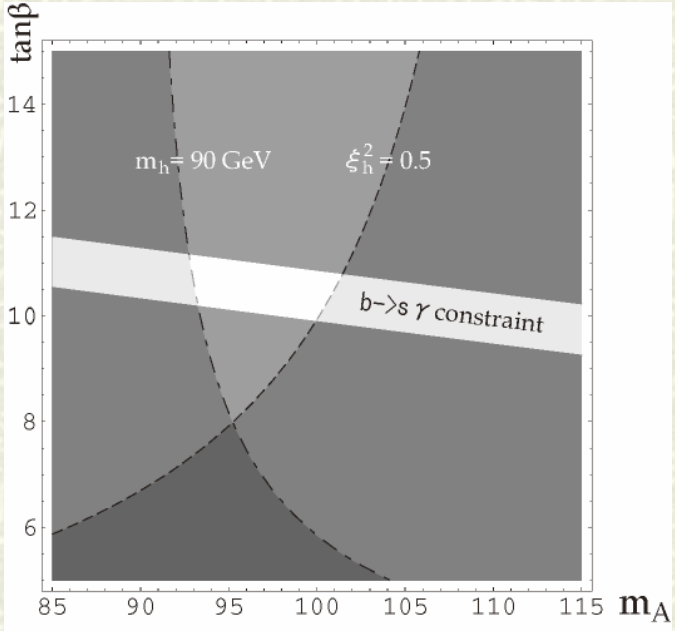
Cancellation between charged Higgs and chargino contributions can be expected

Numerical analyses

(m_{Q3}=350GeV, m_{U3}=300GeV, μ =200GeV)



$m_{H^{\pm}} = 125\text{GeV}$



$A_t = 325\text{GeV}$

2nd Summary

- It is possible to cancel charged Higgs contribution using chargino contribution

  Naturalness

  → low SUSY breaking scale

  → approximately same order contributions to $b \to s\gamma$ process

  → cancellation

Summary and discussion

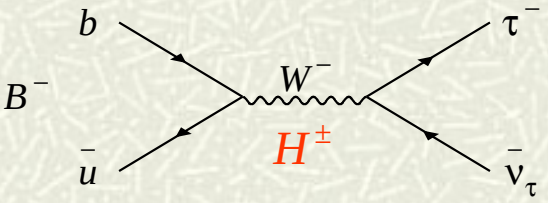
Summary

- The little hierarchy problem can be solved by light CP-even Higgs boson with small ZZh coupling
- Every Higgs boson in the MSSM has all the weak scale mass
- Small $\tan\beta$ is preferable
- A small charged Higgs boson mass is consistent with the Br($b \to s\gamma$) because of cancellation

  Naturalness requirement realizes the cancellation
- We hope discoveries of the MSSM Higgs bosons in near future experiments

Discussion/Br of $B^- \to \tau^- \bar{\nu}_\tau$

Constraints on $m_{H^\pm}$ and $\tan\beta$



*There are no SUSY particle contributions at tree level.

i.e., no cancellations as in the case of b→s γ !

$$Br(B^- \to \tau^- \bar{\nu}_\tau)_{NP} = Br(B^- \to \tau^- \bar{\nu}_\tau)_{SM} \times r_H$$

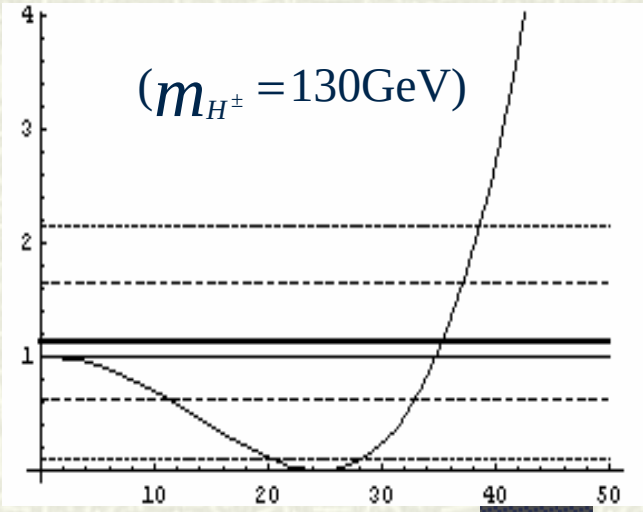
$$\mathrm{Br}(B^- \to \tau^- \bar{\nu}_\tau)_{Exp} = (1.59 \pm 0.40) \times 10^{-4}$$

$$r_H = (1 - m_B^2 \frac{\tan^2\beta}{m_{H^\pm}^2})^2$$

$$Br(B^- \to \tau^- \bar{\nu}_\tau)_{Exp} = (1.79 \,^{+0.56}_{-0.49}(stat) \,^{+0.39}_{-0.46}(syst)) \times 10^{-4}$$

hep-ex/0604018 and T.Browder's talk at ICHEP 2006

$r_H = 1.13 \pm 0.51$



Back up files

The little hierarchy problem

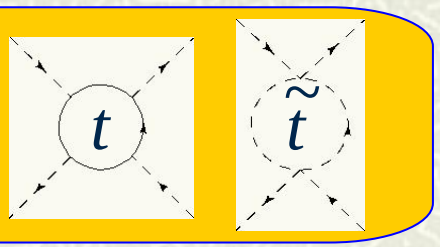
- MSSM prediction

$h^0, H^0, A^0, H^\pm$

$$m_{h^0}^2 \le m_Z^2 + \frac{3Y_t^4 v^2}{4\pi^2} \log \frac{m_{\tilde{t}}^2}{m_t^2}$$

tree

1-loop



*quartic couplings ⇒ gauge couplings

present bound; the SM Higgs ≧ 114.4 GeV

⇒ stop ≧ 500 GeV

$\Rightarrow$ stop $\geqq$ 500GeV

$$\Delta m_{Hu}^2 \sim -\frac{3Y_t^2}{4\pi^2} m_{\tilde{t}}^2 \log\frac{\Lambda_{UV}}{m_{\tilde{t}}} \leq -(850GeV)^2$$

From the conditions of extremum

$$\frac{m_Z^2}{2} \sim -\mu^2 - m_{Hu}^2 \left(\Delta m_{Hu}^2\right)$$

$$\sim \Delta m_{Hu}^2 (1.005 - 1.000)$$

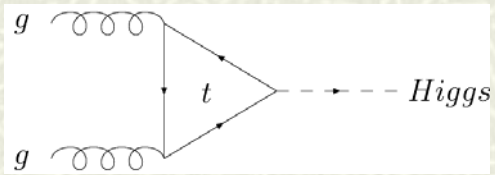
$$\frac{m_Z^2/2}{\left|\Delta m_{Hu}^2\right|} \sim 0.5\%$$

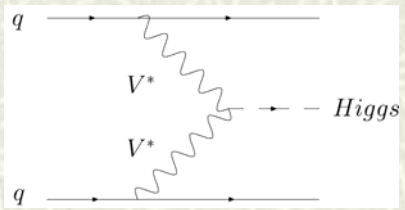
"little hierarchy problem"

$$m_H^2 = \Delta m_H^2 (1.00000000000000000000000000001 - 1.00000000000000000000000000000)$$

Discussion 1. Observabilities of CP-even Higgs bosons

- Heavy CP-even Higgs boson (*the SM like)
  - It must be discovered under O(120GeV) at LHC
  - It may be difficult to distinguish whether discovered particle is the MSSM Higgs boson or not





- Light CP-even Higgs boson
  - Minimal g_{ZZh} means maximal g_{ZhA}

    ⇒ h may be easily discovered at ILC