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

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# Little Hierarchy Problem

- SM Higgs ≧ 114.4 GeV    LEP
- If lighter MSSM Higgs ≧ 114.4 GeV

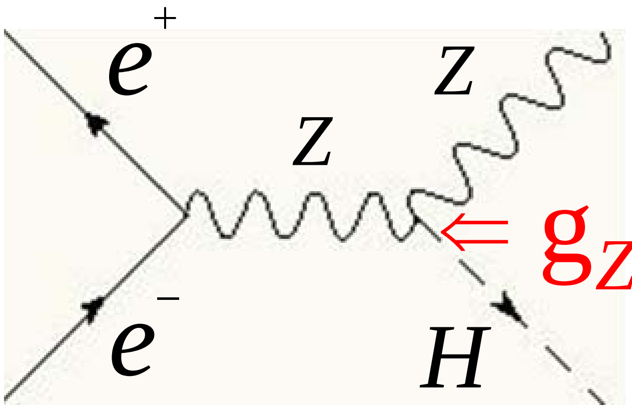
  ⇨ Large stop mass ≧ 500 GeV

  ⇨ Requires a tuning to obtain EW scale

  Little Hierarchy Problem
- But the Higgs bound at LEP is for SM, not for MSSM.
- We must examine the LEP results in MSSM.

# Higgs Search at LEP

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




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

$H$ ; SM Higgs

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

# LEP experiment for MSSM Higgs

- MSSM has two Higgs doublets.

  One of two Higgs have vanishing VEV.

- For simplicity, we take $\langle H_u \rangle >> \langle H_d \rangle$

  $H_u \rightarrow g_{ZZH_u} \sim g_{ZZH}$ SM like Higgs

  $H_d \rightarrow g_{ZZH_d} << g_{ZZH}$ cannot be seen in LEP

- If $m_{H_u} > m_{H_d}$, lighter Higgs becomes $H_d$

  Lighter Higgs $H_d$ cannot be seen.

Is it possible to realize the above situation in a natural way?

# Mass matrix of CP even Higgs (tree)

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

$m_{H_d}^2$ Small coupling

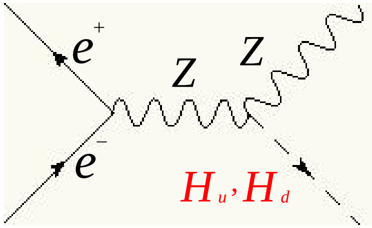
$$
m_{h,H}^2 = \begin{array}{c c} & \begin{array}{cc} H_d & H_u \end{array} \\ \begin{array}{c} H_d \\ H_u \end{array} & \begin{pmatrix} m_A^2 \sin^2\beta + m_Z^2 \cos^2\beta & -(m_A^2 + m_Z^2)\sin\beta\cos\beta \\ -(m_A^2 + m_Z^2)\sin\beta\cos\beta & m_Z^2 \sin^2\beta + m_A^2 \cos^2\beta \end{pmatrix}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

$m_A$ CP odd Higgs mass

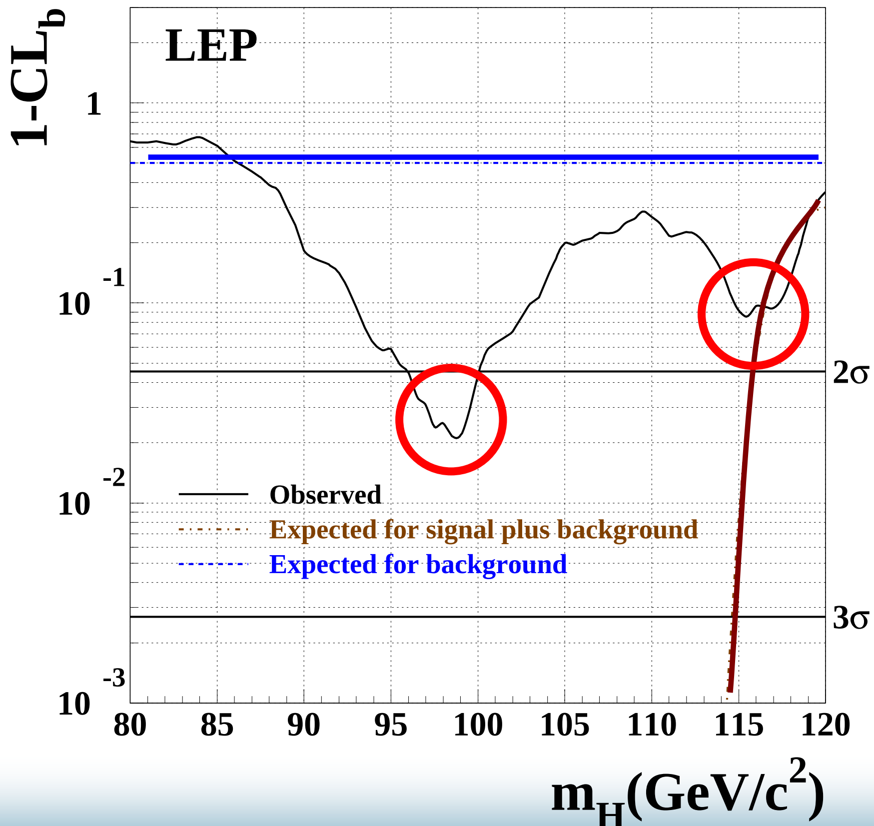
$m_{H_u}^2$ SM-like

- It is easy to satisfy $m_{Hu} > m_{Hd}$ , if we take $m_A^2 < m_Z^2$
  
  ⇒All the Higgs boson mass scales are EW scale!
- Is it possible to satisfy $m_{Hu} > 114.4\mathrm{GeV}$ naturally?
  
  → loop corrections and diagonalization of actual mass matrix must be taken into account

# Experimental aspect




◆ Results of LEP II




- □115 GeV ~1.7 $\sigma$ excess may be explained by the heavier (the SM like) CP-even MSSM Higgs boson
- □ 98 GeV ~2.3 $\sigma$ excess may be explained by the lighter CP-even MSSM Higgs 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.

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

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

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

e.g., large $\mu$ requires fine-tuning twice, because

$$m_1^2 = m_{H_d}^2 + \mu^2, m_2^2 = m_{H_u}^2 + \mu^2 \approx O((100\text{GeV})^2)$$

- It is not obvious whether it is possible within natural SUSY breaking parameters.

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

# Set up for numerical calculation

- Natural SUSY breaking parameters

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

- GUT relation for gaugino masses
- LEP bound $m_{\chi^0} \geq 46\text{GeV},\ m_{\chi^\pm} \geq 94\text{GeV}$
- Consistent with LEP Higgs search

$$\xi = g_{ZZh} / g_{ZZH_{\text{SM}}} \leq 0.50$$

$$90\text{GeV} \leq m_h (\leq 117\text{GeV})$$

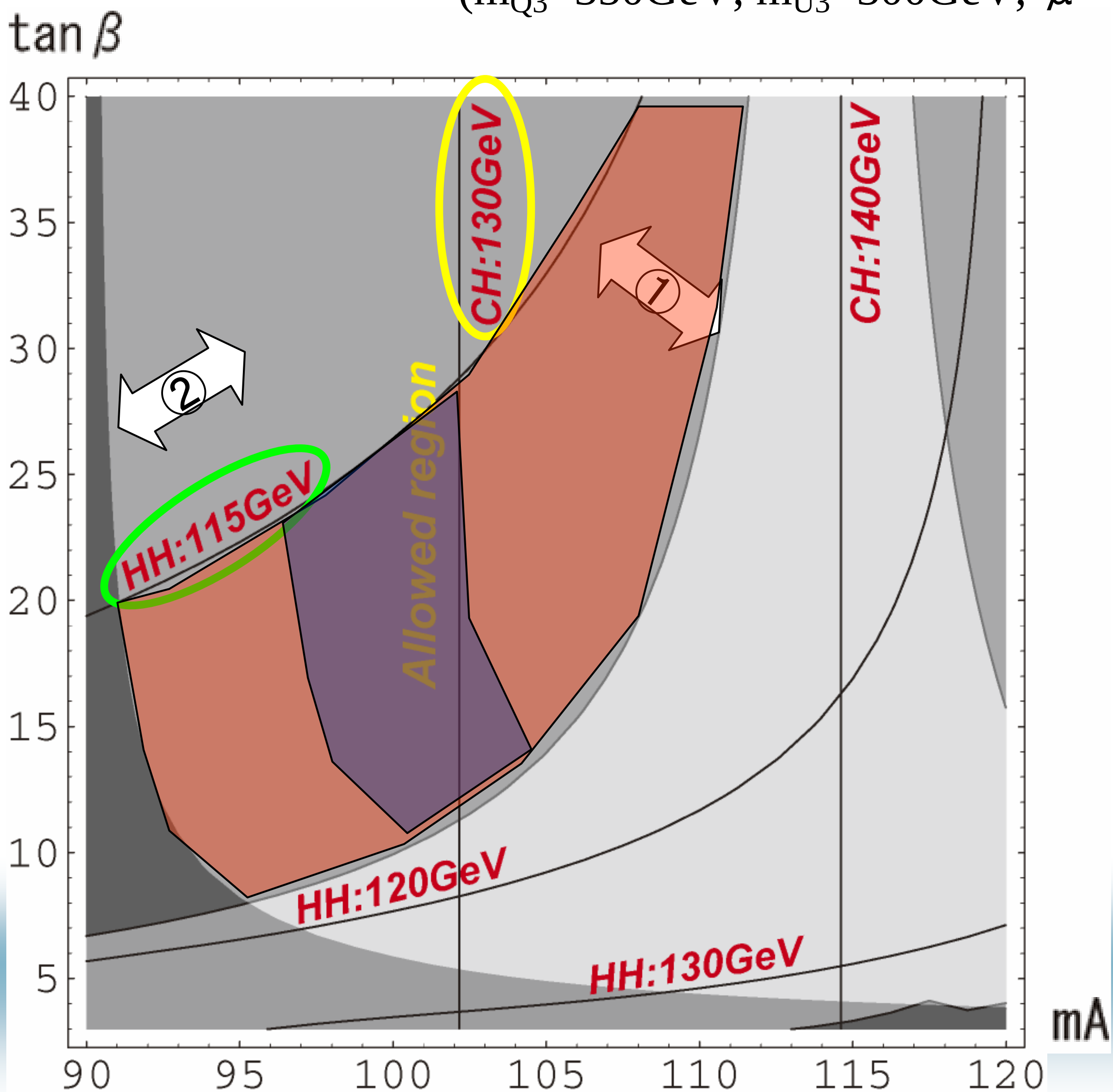
- Signal(98GeV)

$$\xi = g_{ZZh} / g_{ZZH_{\text{SM}}} \leq 0.50$$

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

# Results of numerical analyses

(m$_{Q3}$=350GeV, m$_{U3}$=300GeV, $\mu$ =200GeV, A=325GeV)




① $0 \le \xi \le 0.5$
② $90GeV \le m_h$

$0 \le \xi \le 0.50$
$95GeV \le m_h \le 101GeV$

*HH : heavy Higgs,*
*CH : Charged Higgs*

# $1^{st}$ summary and questions

- Light CP-even Higgs boson with small $g_{ZZh}$ coupling can be consistent with the LEP data in the MSSM with natural SUSY breaking parameters. (2 excesses can be signals.)
- Mass scales of the MSSM Higgs bosons are EW scale.

$$m_h \sim 98\text{GeV}, m_H \sim (115\text{-}120)\text{GeV}$$

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

○Is such a light charged Higgs boson consistent with Br(b→s $\gamma$)? [next topic]

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

○What is the essential point for obtaining lighter stop?

$$m_{\tilde{t}} \approx 300\text{GeV}$$

# Rich guy becomes richer

- The same radiative correction $\Delta(m_{\tilde{t}})$

① $m_{H_d}^2 \geq m_{H_u}^2 + \Delta(m_{\tilde{t}})$

$114\mathrm{GeV} \leq m_h$

② $m_{H_d}^2 \leq m_{H_u}^2 + \Delta(m_{\tilde{t}})$

$114\mathrm{GeV} \leq m_H$

$$\begin{pmatrix} m_{H_d}^2 & m_{12}^2 \\ m_{12}^2 & \underbrace{\boxed{m_{H_u}^2 + \Delta(m_{\tilde{t}})}}_{\text{SM-like}} \end{pmatrix}$$

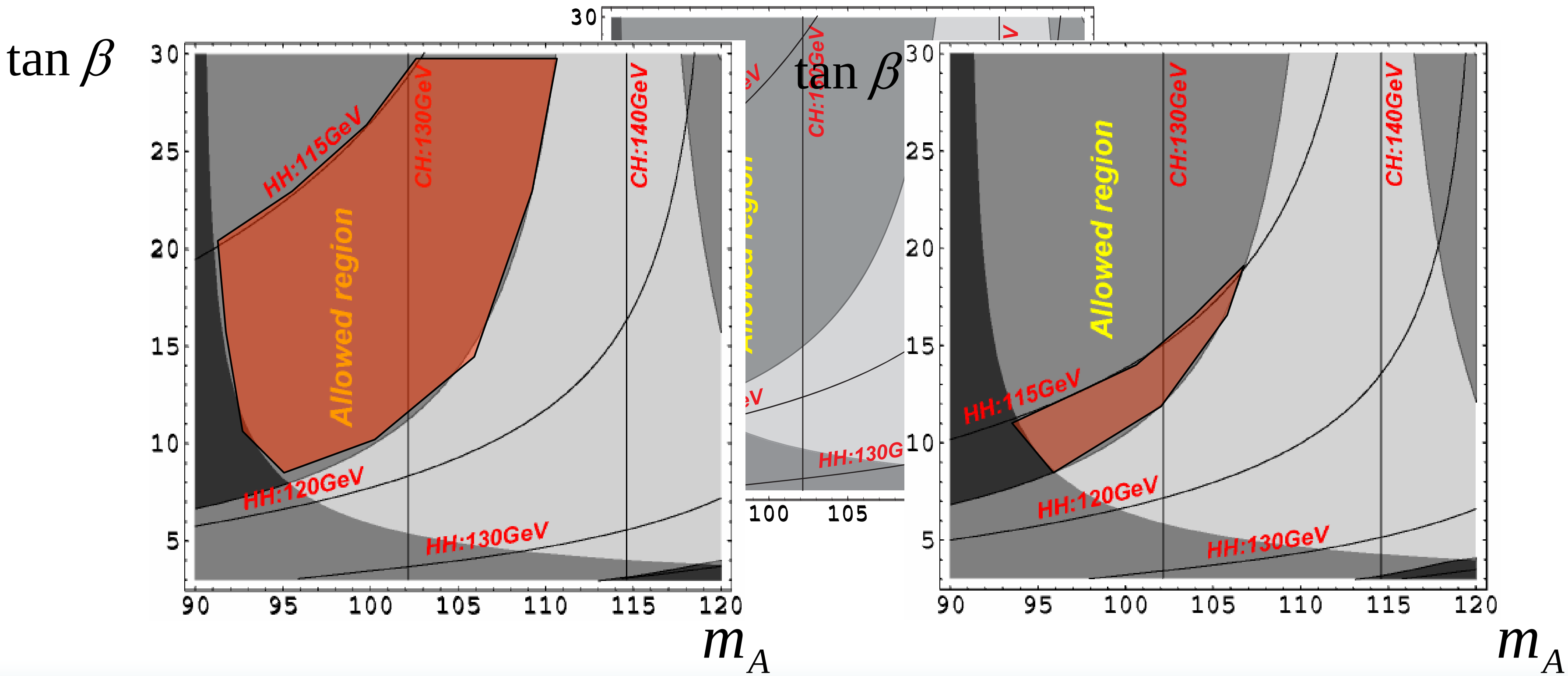
- Off diagonal element $m_{12}^2 \propto \cot\beta$ increases (decreases) $m_H (m_h)$
- The usual case ① needs larger $\Delta(m_{\tilde{t}})$ and smaller $m_{12}^2$ (larger $\tan\beta$) to satisfy the lower bound of SM like Higgs.

Large $\tan\beta$ is unfavored in case ②

# Numerical calculation

$m_Q = 350GeV, m_U = 300GeV,$
$\mu = 200GeV, A = 325GeV$

$m_Q = 300GeV, m_U = 250GeV,$
$\mu = 300GeV, A = 300GeV$




$0 \le \xi \le 0.50$

$90GeV \le m_h (\le 117GeV)$

# $b \to s\gamma$ constraint

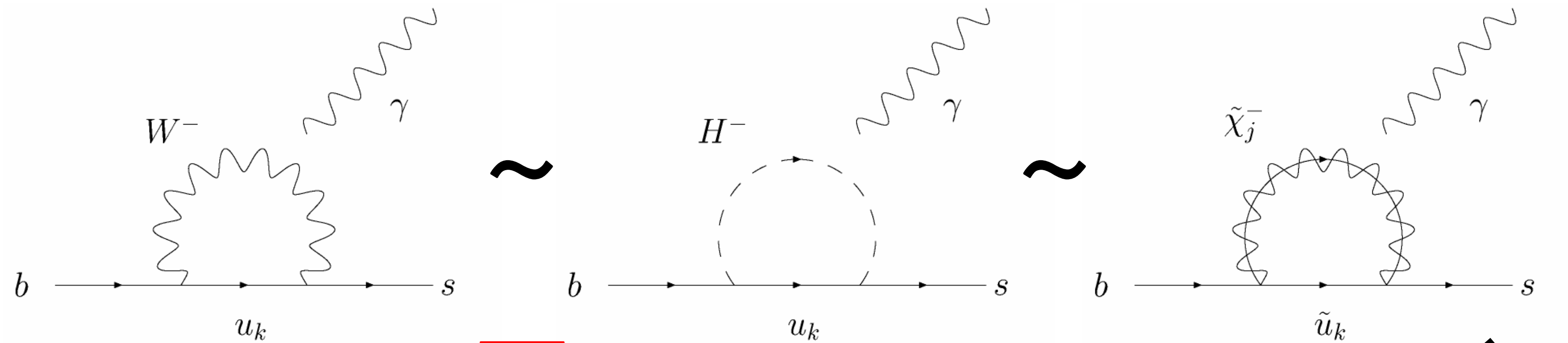
Is this scenario consistent with $b \to s\gamma$?

$$m_{H^\pm} \approx 130\mathrm{GeV} \Leftrightarrow m_{H^\pm} \geq 350\mathrm{GeV}$$

# Branching ratio of b→s $\gamma$

$\text{Pre}: (3.60 \pm 0.30) \times 10^{-4}$

$\text{Exp}: (3.39 \pm 0.27) \times 10^{-4}$




Standard model + additive Charged Higgs negative Chargino $\neq 0$

Fact: no b→s $\gamma$ process if SUSY is exact [Ferrara and Remiddi '74]

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

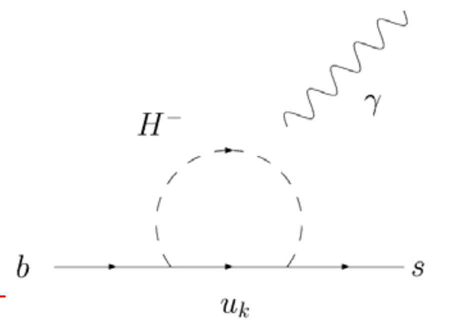
Naturalness ⇒The masses of every fields in the loops are the weak scale.

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

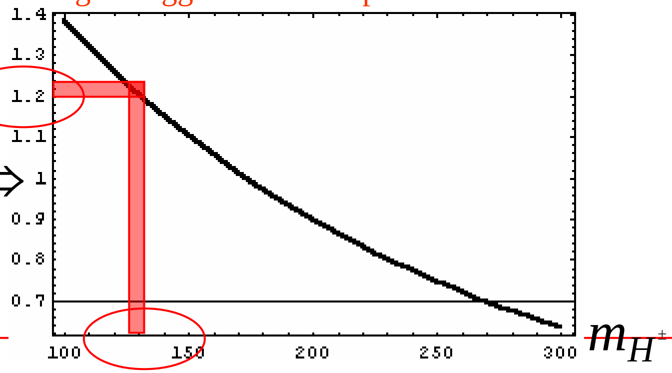
The cancellation between charged Higgs contribution and the chargino's is expected.

# Results (small coupling, naturalness)

- Charged Higgs ($m_{Q3}$=350GeV, $m_{U3}$=300GeV, $\mu_R$=200GeV, $\tan\beta$=10)

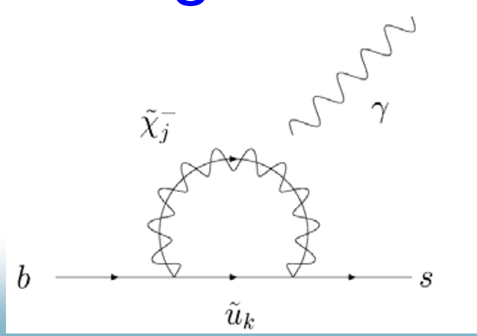



Charged Higgs induced amplitude

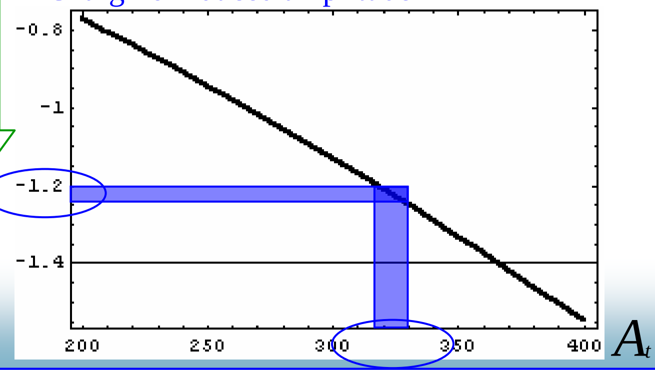



SM $\Rightarrow$

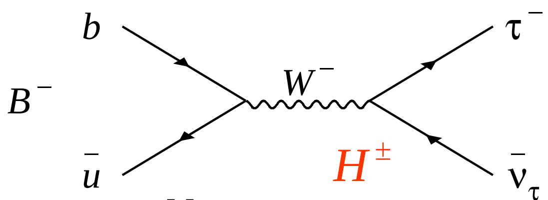
- Chargino




Chargino induced amplitude



$$B^- \to \tau^- \overline{\nu}_\tau$$




- Charged Higgs contribution in tree diagram.

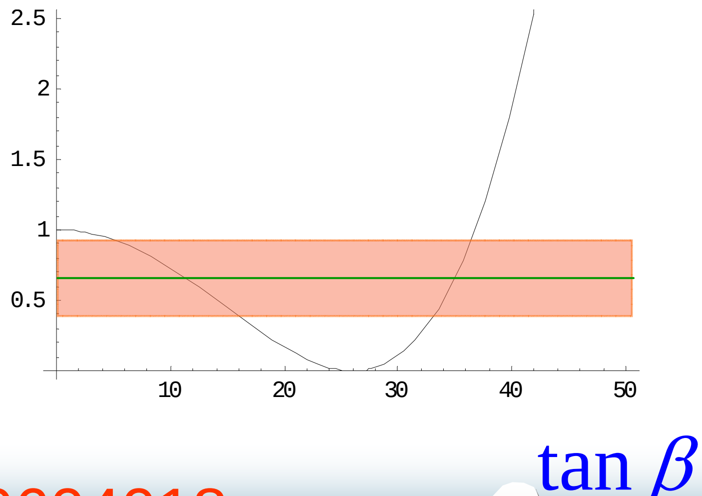
*There are no SUSY particle contributions at tree level.

i.e., no cancellations as in the case of b→s$\gamma$!

$$\boxed{Br(B^- \to \tau^- \overline{\nu}_\tau)_{SM+CH} = Br(B^- \to \tau^- \overline{\nu}_\tau)_{SM} \times r_H}$$

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

$$m_{H^\pm} = 130\mathrm{GeV}$$




$$^*Br(B^- \to \tau^- \overline{\nu}_\tau)_{SM} = \frac{G_F^2 m_B m_\tau^2}{8\pi}\left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

$$= (1.59 \pm 0.40) \times 10^{-4}$$

$$\boxed{Br(B^- \to \tau^- \overline{\nu}_\tau)_{Exp} = (1.06^{+0.34}_{-0.28}(stat)^{+0.18}_{-0.16}(syst)) \times 10^{-4}}$$

Belle hep-ex/0604018

$$r_H \approx 0.67, m_{H^\pm} \approx 130\mathrm{GeV} \Rightarrow \tan\beta \approx 10{,}35$$

# Summary

- Little hierarchy problem can be solved by lighter Higgs with smaller ZZh coupling.

  Rich (poor) guy becomes richer (poorer).

- Every Higgs in MSSM have the weak scale masses.

$$m_h \sim 98\mathrm{GeV}, m_H \sim (115\text{-}120)\mathrm{GeV}$$

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

- Such small charged Higgs mass is consistent with Br(b→s$\gamma$) because of cancellation.

  Naturalness requirement plays an important role in the cancellation.