Many light Higgs bosons in MSSM-like models

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R.D., arXiv:0806.0847 [hep-ph], arXiv:0807.2135 [hep-ph]

R.D. and J. Gunion, to appear

related to a series of papers with J. Gunion

Introduction:

- standard model (SM) - one complex scalar EW doublet
  - one Higgs boson in the spectrum: h
- minimal supersymmetric model (MSSM) - two EW doublets
  - five Higgs boson in the spectrum: h, H, A, $H^{\pm}$
- next-to-minimal-SSM (NMSSM) - two doublets + singlet
  - seven Higgs boson in the spectrum: $h_{1,2,3}$, $a_{1,2}$, $H^{\pm}$

In order to discover Higgs boson(s):

- we have to be able to produce them
  typically one of the CP even Higgses is SM-like in its coupling to Z
- we have to be able to detect them
  It is not necessarily true that SM-like Higgs decays in the same way as the SM Higgs!

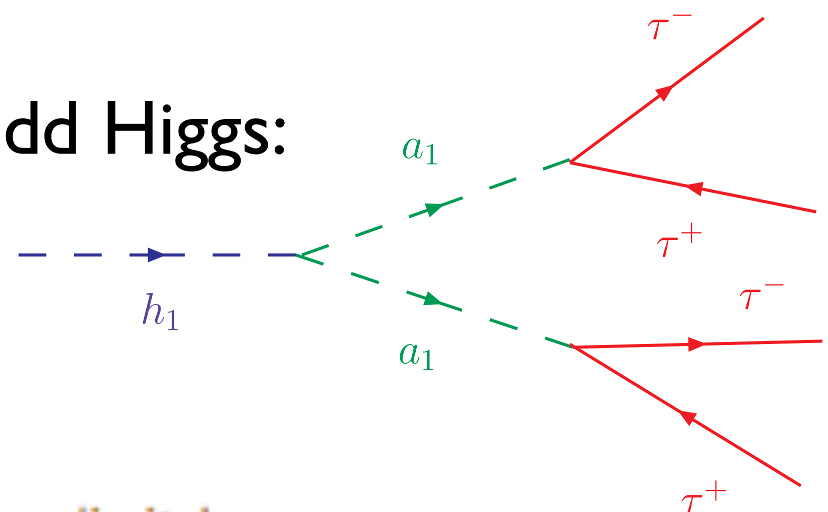
Motivation for non-standard Higgs decays:

Non-standard Higgs decays

- arise in many models BSM
- allow the Higgs significantly below LEP SM-limit
  - wanted by generic SUSY/natural EWSB
  - preferred by precision EW data
  - "indicated" by LEP data

e.g. NMSSM scenario with a light CP-odd Higgs:

series of papers with J. Gunion



90%

for $m_h \simeq 100$ GeV and $m_a \lesssim 10$ GeV there are no exp. limits!

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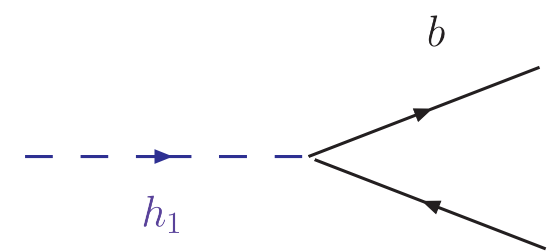


NMSSM - brief review

MSSM + one additional singlet superfield (results in one CP-even and one CP-odd neutral Higgs bosons, and one additional neutralino):

$$W \;=\; W_{MSSM} + \lambda\, \widehat{S}\widehat{H}_u\widehat{H}_d + \frac{\kappa}{3}\,\widehat{S}^3$$

$$\mathcal{L}^{SSB} \;=\; \mathcal{L}^{SSB}_{MSSM} + \lambda A_\lambda S H_u H_d + \frac{\kappa}{3} A_\kappa S^3 + m_S^2 S S^*$$

$$\tan\beta = \frac{v_u}{v_d}\,, \quad \mu_{eff} = \lambda s$$

light CP odd Higgs:

$$m_{a_1}^2 \simeq 3s\left(\kappa A_\kappa \sin^2\theta_A + \frac{3\lambda A_\lambda \cos^2\theta_A}{2\sin 2\beta}\right)$$

$$a_1 \equiv \cos\theta_A\, a_{MSSM} + \sin\theta_A\, a_S\,, \qquad \cos\theta_A \simeq \frac{2v}{s\tan\beta}$$

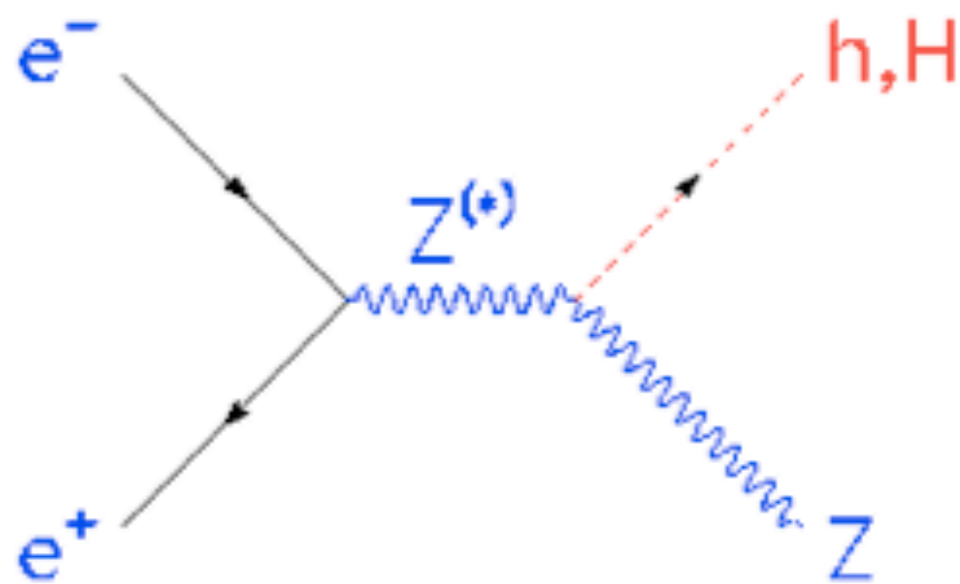
Can the light CP-odd Higgs be doublet like?

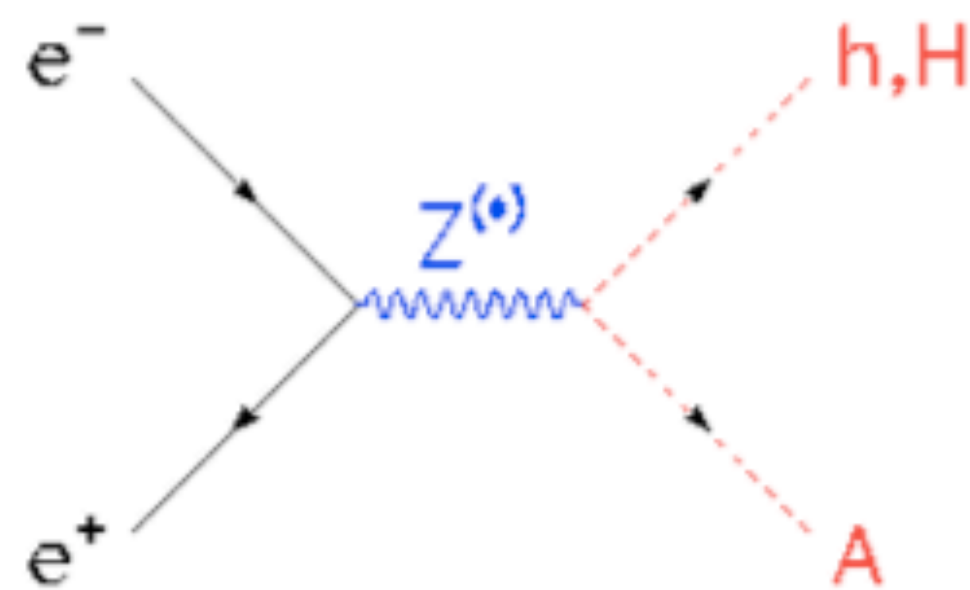
Higgs sector in the MSSM

$$M^2 \simeq \begin{pmatrix} m_A^2 s_\beta^2 + m_Z^2 c_\beta^2 & -(m_A^2 + m_Z^2) s_\beta c_\beta \\ -(m_A^2 + m_Z^2) s_\beta c_\beta & m_Z^2 s_\beta^2 + m_A^2 c_\beta^2 + \Delta \end{pmatrix}, \quad r_\Delta = \frac{\Delta}{m_Z^2}$$

diagonalized by $R(\alpha)$, and results in ZZh coupling: $C_{ZZh} = \frac{g^2_{ZZh}}{g^2_{ZZh_{SM}}} = \sin^2(\beta - \alpha)$

$$C_{ZZH} = \cos^2(\beta - \alpha), \quad C_{ZAh} = \cos^2(\beta - \alpha), \quad C_{ZAH} = \sin^2(\beta - \alpha)$$





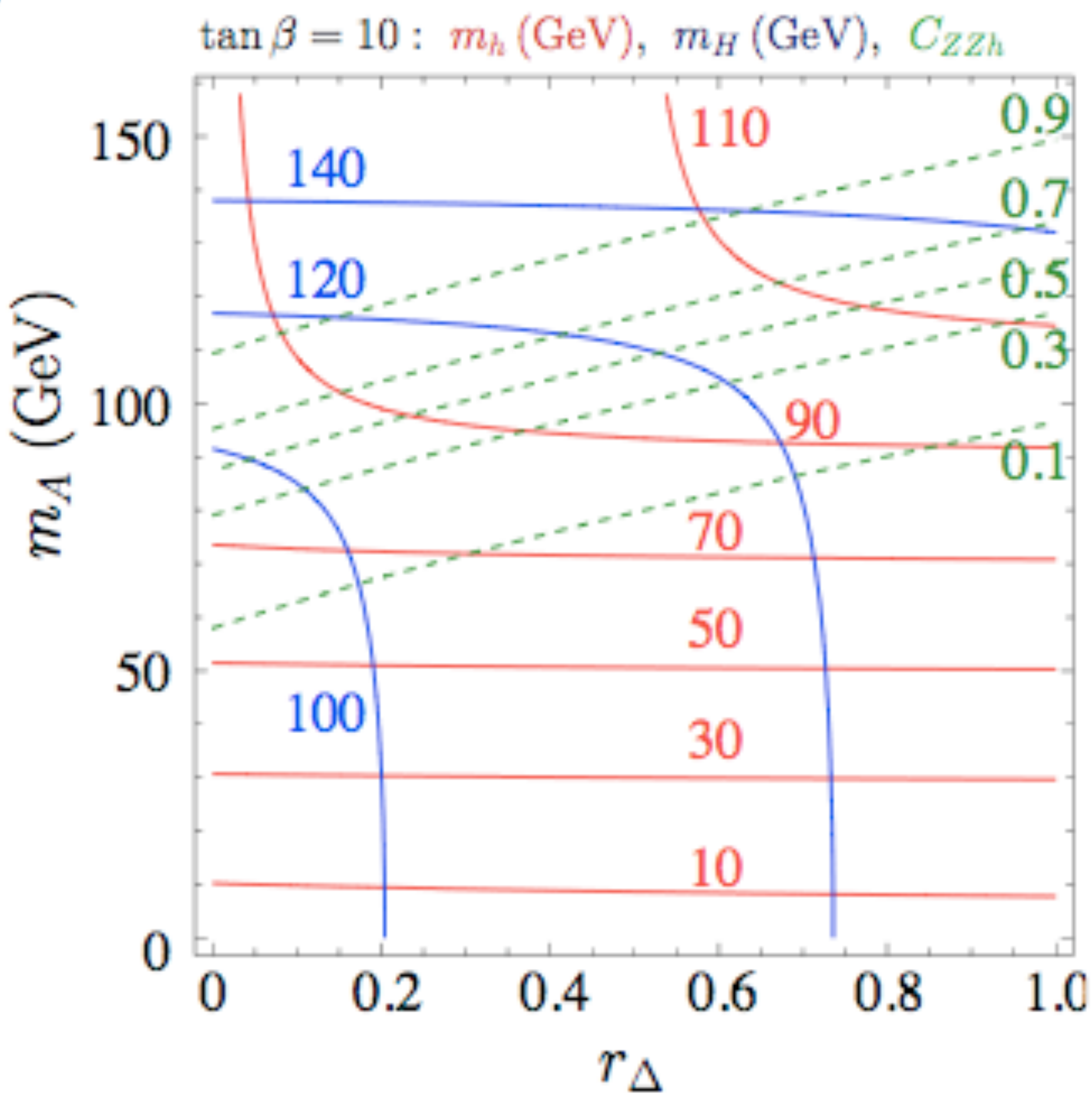
Higgs sector in the MSSM

- $m_A \ll m_Z$ for $\Delta \simeq 0$:

$$m_h^2 \simeq m_A^2 \cos^2 2\beta$$
$$m_H^2 \simeq m_Z^2$$
$$C_{ZZH} \simeq \cos^2 2\beta$$

$m_A \gg m_Z$:

$$m_h^2 \simeq m_Z^2 \cos^2 2\beta + \Delta \sin^2 \beta$$
$$m_H^2 \simeq m_A^2$$
$$C_{ZZh} \simeq 1$$



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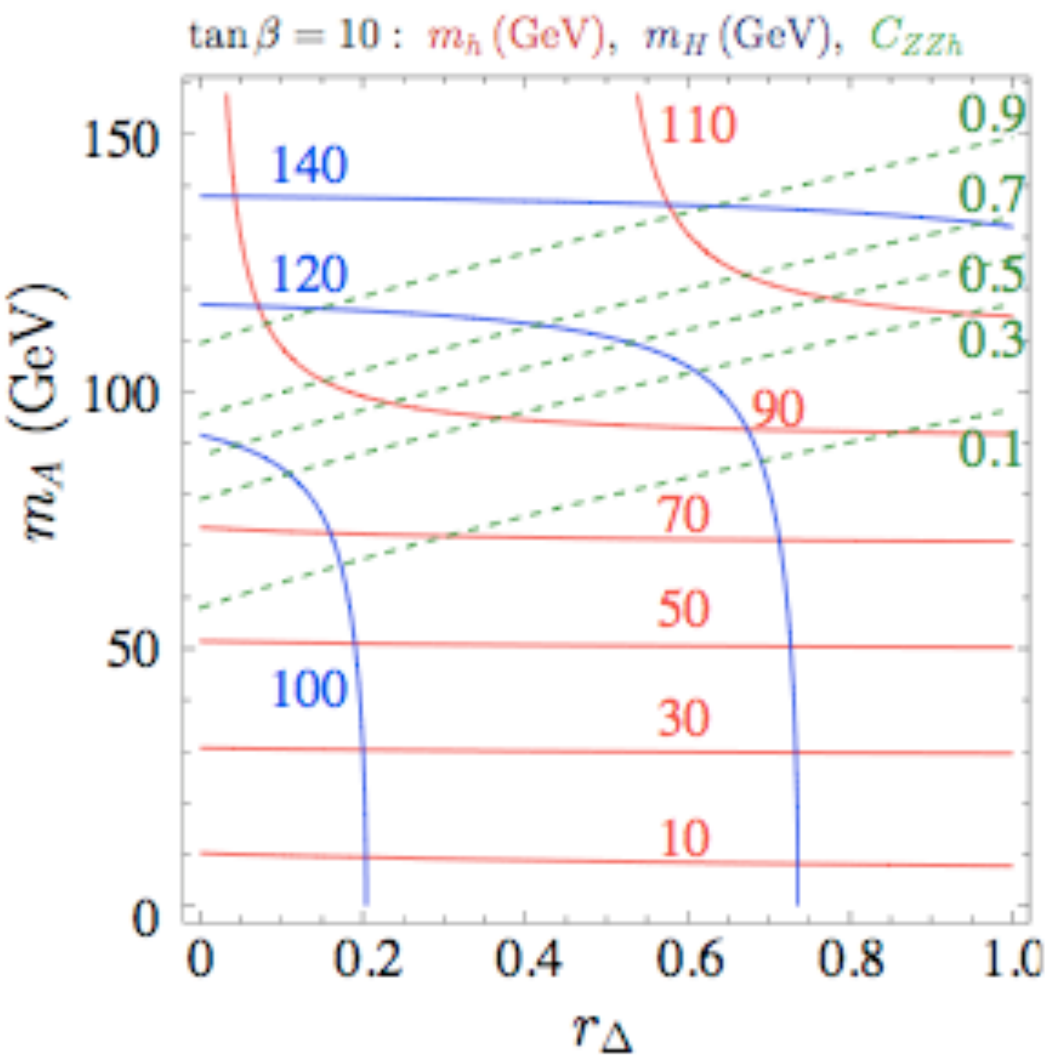
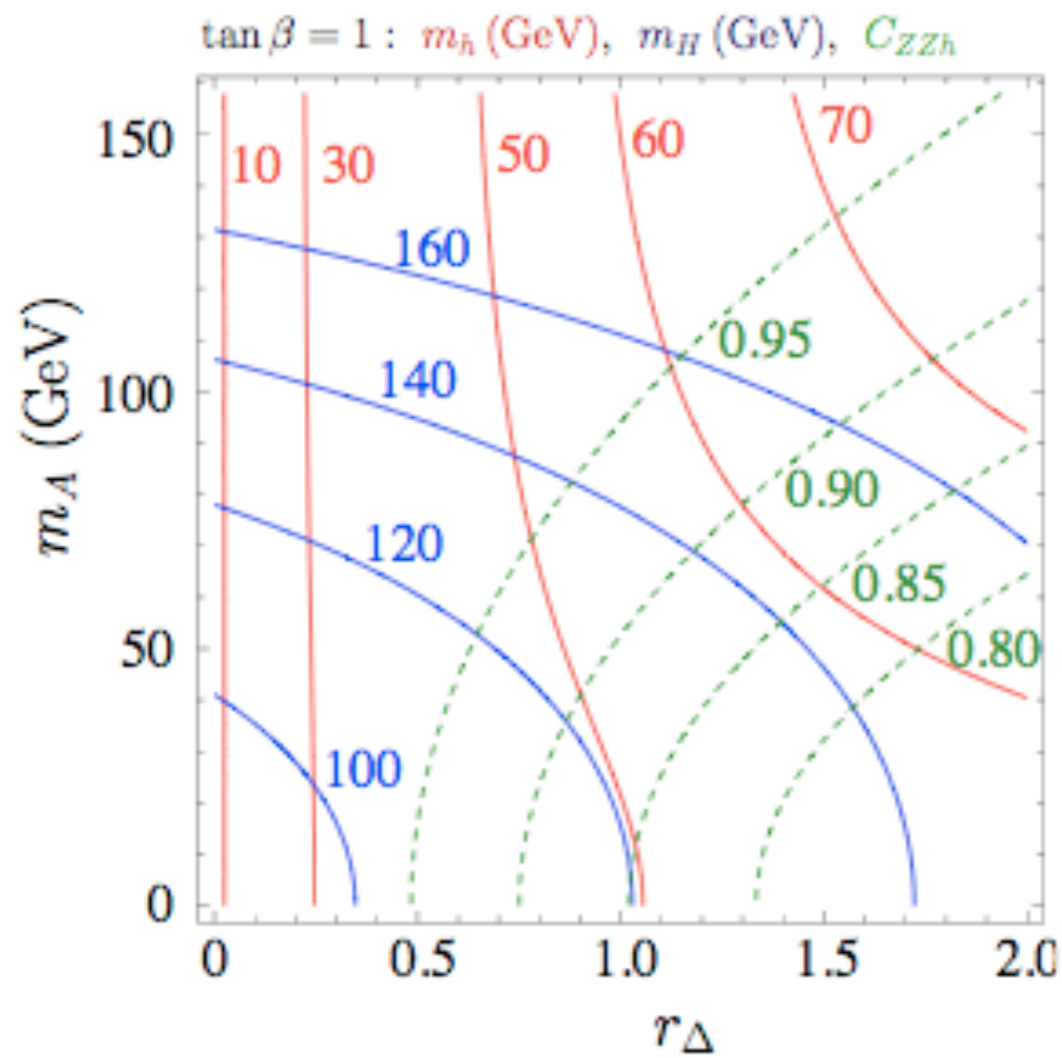
  $m_h^2 \simeq m_A^2 \cos^2 2\beta$
  $m_H^2 \simeq m_Z^2$
  $C_{ZZH} \simeq \cos^2 2\beta$

$m_A \ll m_Z$ at $\tan\beta \simeq 1$:

$m_h^2 \simeq \Delta/2$
$m_H^2 \simeq m_Z^2 + m_A^2 + \Delta/2$
$C_{ZZH} \simeq 0, \quad C_{ZZh} \simeq 1$





MSSM at $m_A \ll m_Z$ and $\tan\beta \simeq 1$

$m_h^2 \simeq \Delta/2$ $\quad$ $m_h \simeq 38 - 56$ GeV

$m_H^2 \simeq m_Z^2 + m_A^2 + \Delta/2$ $\quad$ $m_H \simeq 108 - 150$ GeV

$C_{ZZh} \simeq 1$ $\quad$ $C_{ZZh} \simeq 0.84 - 0.97$

$m_{H^\pm} = \sqrt{m_W^2 + m_A^2 - \Delta'} \simeq m_W^2$ $\quad$ $m_{H^\pm} \simeq 78 - 80$ GeV

FeynHiggs2.6.3, with $m_t = 172.6$ GeV

($m_A = 8$ GeV, $\tan\beta = 1.01$, $\mu = 100$ GeV, $M_{SUSY} < 1$ TeV, $-2 < X_t/m_{\tilde{t}} < 0$)

$B(h \to AA,\ b\bar{b}) \simeq 90\%,\ 10\%$

$B(A \to \tau^+\tau^-,\ c\bar{c},\ gg) \simeq 50\%,\ 40\%,\ 10\%$

fixed by $\tan\beta$ for $2m_\tau \lesssim m_A \lesssim 10$ GeV

$B(H \to ZA,\ AA,\ hh,\ b\bar{b}) \simeq 37\%,\ 34\%,\ 28\%,\ 0.4\%$

for 1 TeV SUSY and $X_t/m_{\tilde{t}} = 0$

$B(H^+ \to W^{+\star}A,\ \tau^+\nu,\ c\bar{s}) \simeq 70\%,\ 20\%,\ 10\%$

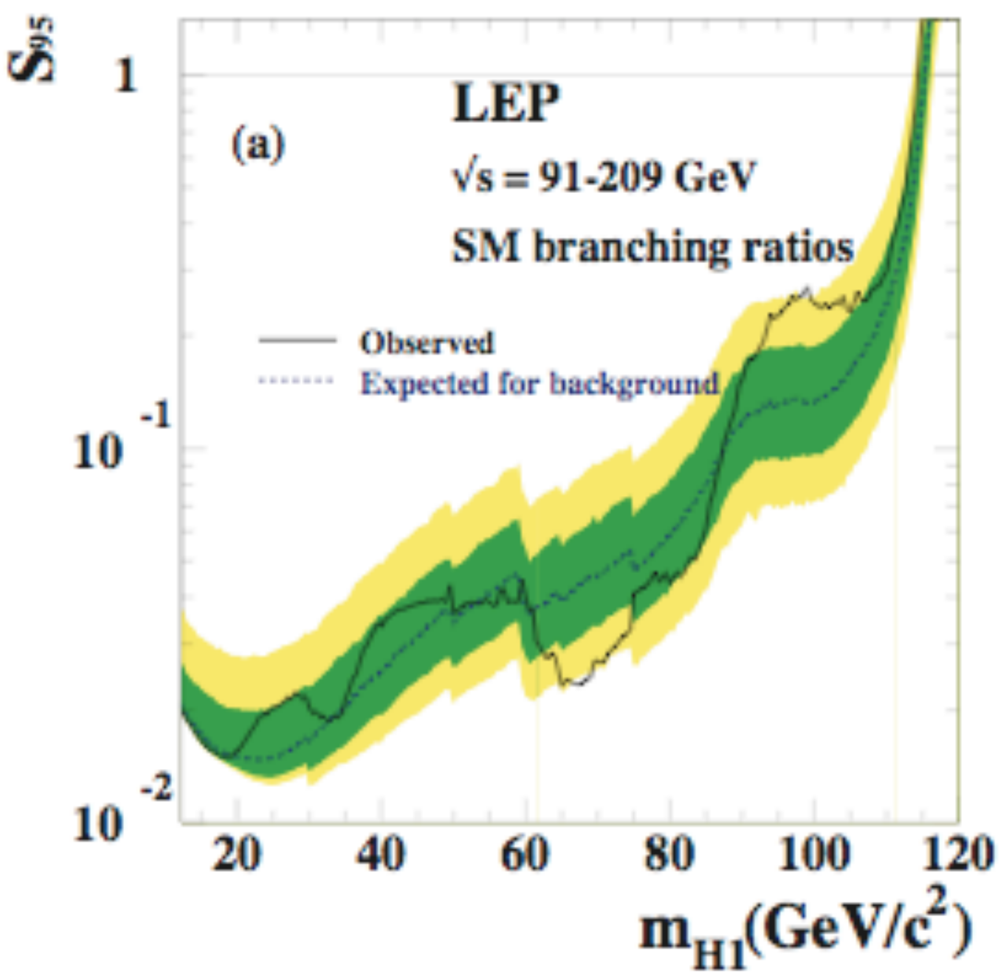
$B(t \to H^+ b) \simeq 40\%$, $\quad B(t \to W^+ b) \simeq 60\%$

Light CP even Higgs

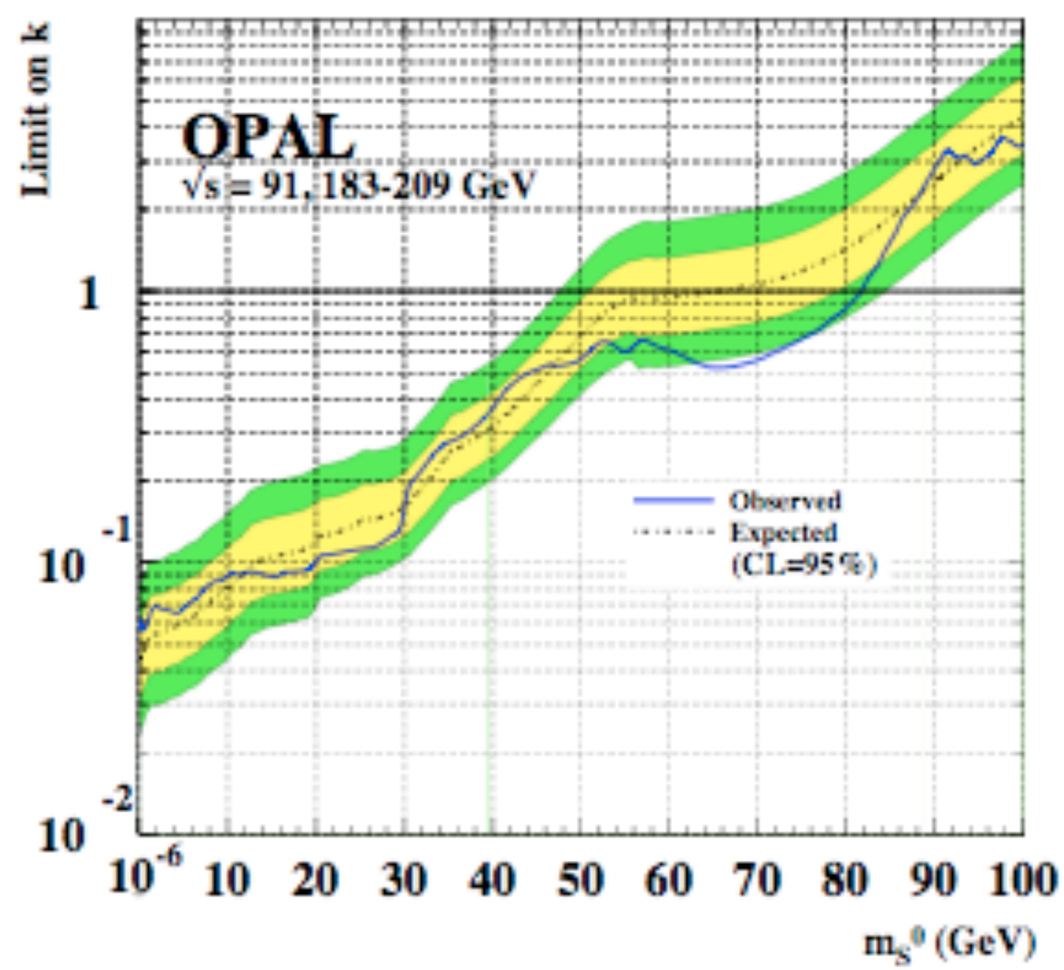
h could have been produced at LEP in $e^+e^- \to Zh$ with
$B(h \to 2\tau 2c,\ 4\tau,\ 4c,\ b\bar{b},\ \dots) \simeq 36\%,\ 23\%,\ 14\%,\ 10\%,\ \dots$

Strongest limits from:

$h \to b\bar{b}$



decay-mode independent



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we need: $m_h \gtrsim 82$ GeV

ruled out in MSSM!

can easily be viable in beyond MSSM, e.g. singlet extensions:

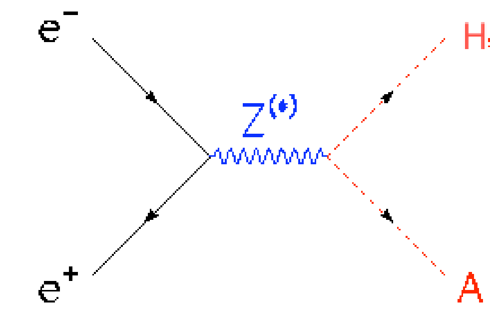
$$W \supset \lambda S H_u H_d$$

increases Higgs quartic coupling, and

$$m_h^2 \simeq \dots + \lambda^2 v^2 \sin^2 2\beta + \dots$$

$v = 174$ GeV

Heavy CP even Higgs



H could have been produced at LEP in $e^+e^- \to HA$ with

$B(H \to ZA,\ AA) \simeq 50\%,\ 50\%$ — if $H \to hh$ not open

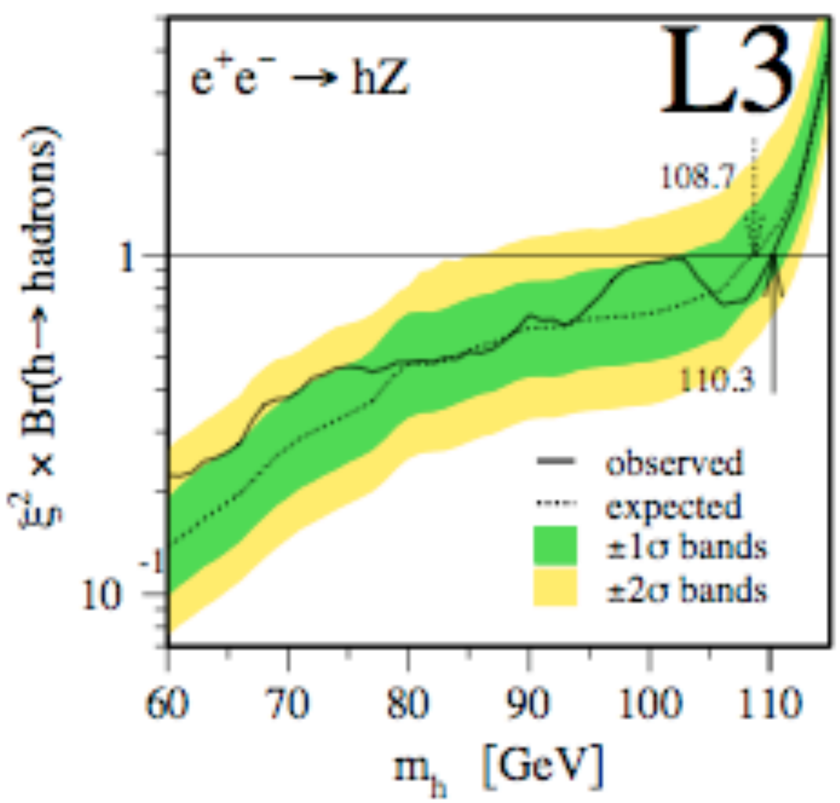
NO SEARCH for: $e^+e^- \to HA \to (ZA)A$

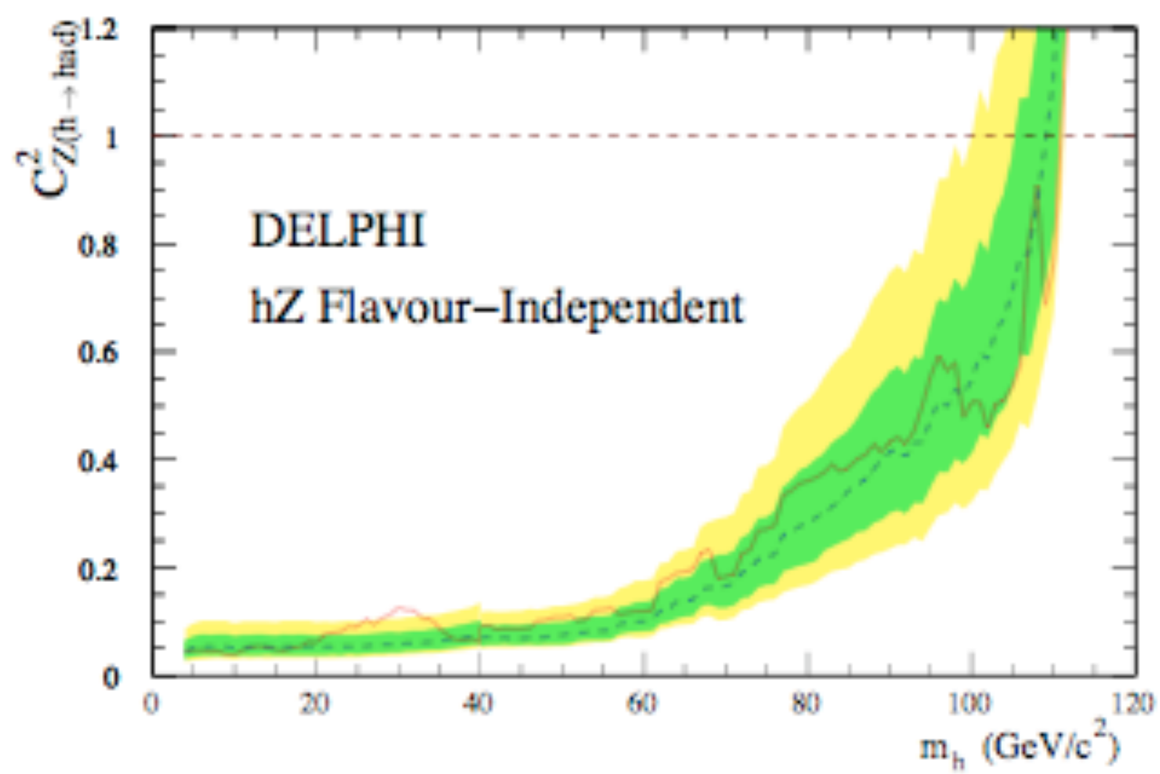
however, it would contribute to:

$e^+e^- \to Zh \to Z(AA)$ or $e^+e^- \to Zh \to Z + jets$

with wrong reconstructed Higgs mass!

e.g. in flavor independent searches:





Heavy CP even Higgs

H could have been produced at LEP in $e^+e^- \to HA$ with

$B(H \to ZA,\ AA) \simeq 50\%,\ 50\%$ if $H \to hh$ not open

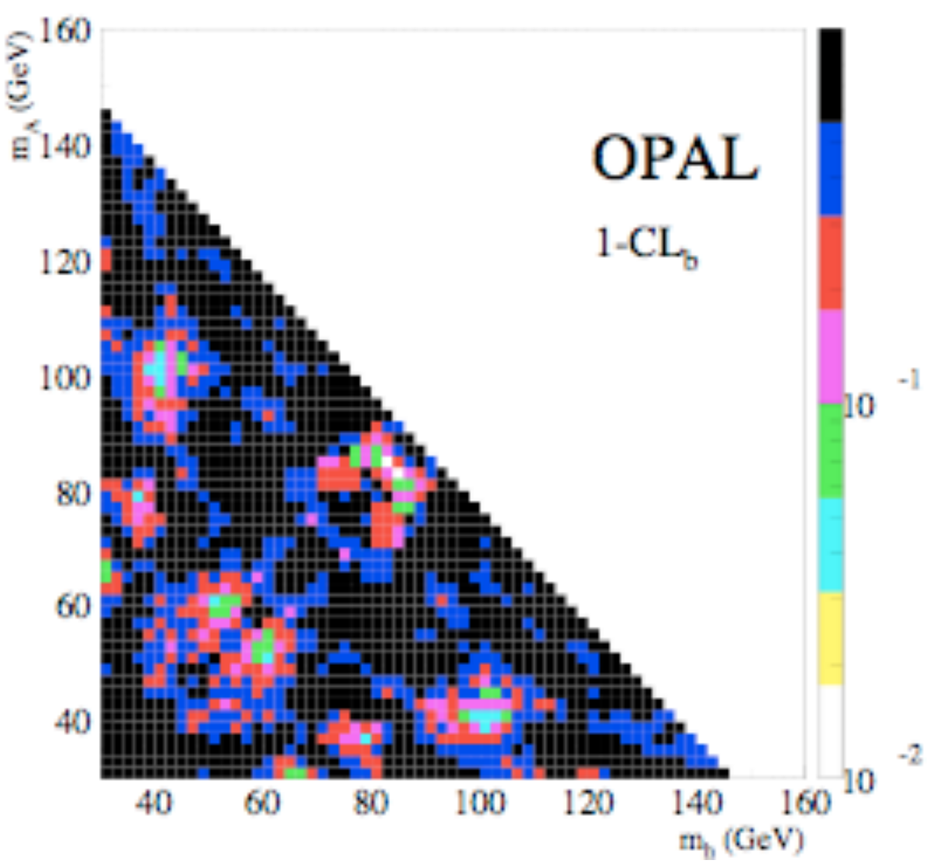
LIMITED SEARCH for: $e^+e^- \to HA \to (AA)A$

however, it would contribute to:

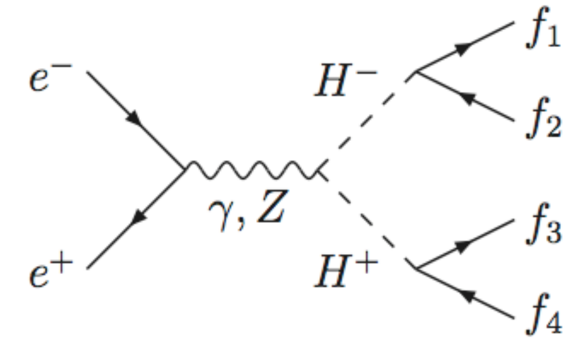
$$e^+e^- \to Ah \to 4jets$$

with wrong reconstructed Higgs mass!

e.g. in flavor independent searches:



Charged Higgs



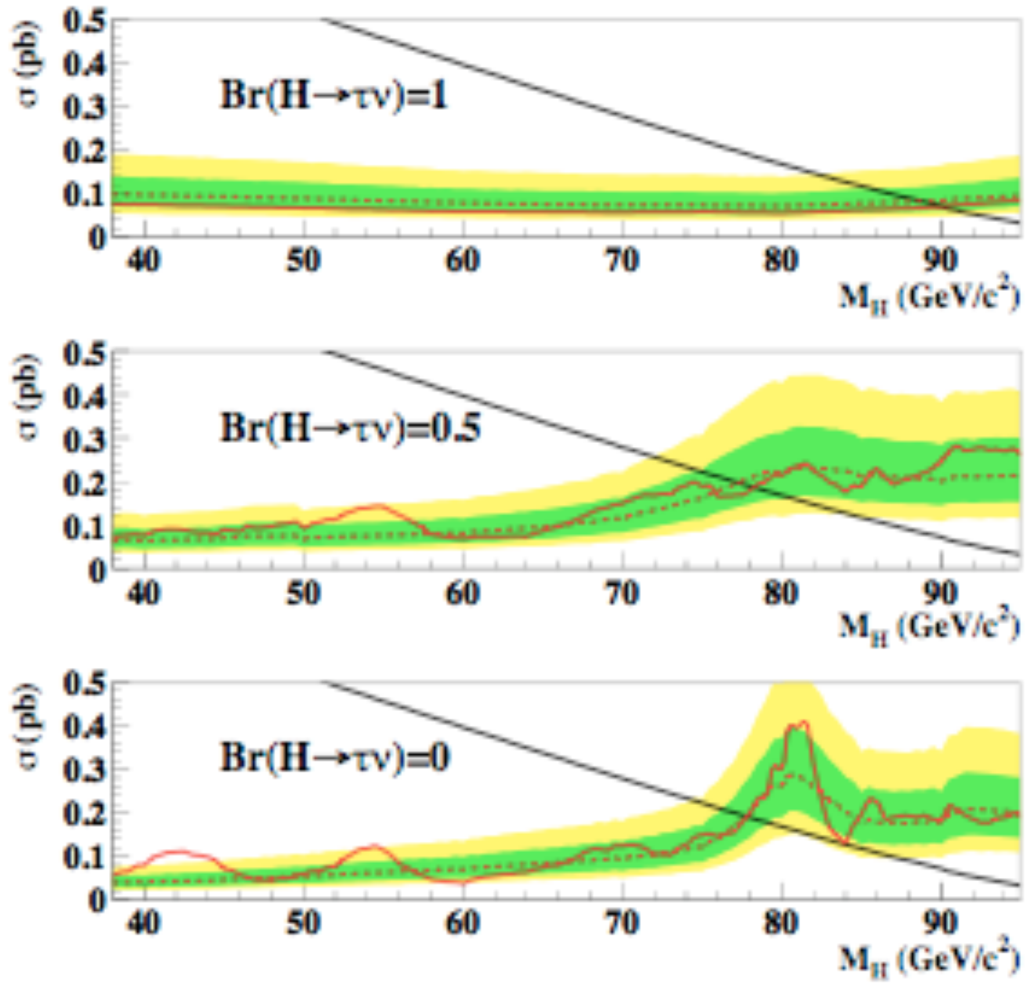
$H^\pm$ could have been produced at LEP: $e^+e^- \to H^+H^-$ with

$B(H^+ \to W^{+\star}A,\ \tau^+\nu,\ c\bar{s}) \simeq 70\%,\ 20\%,\ 10\%$

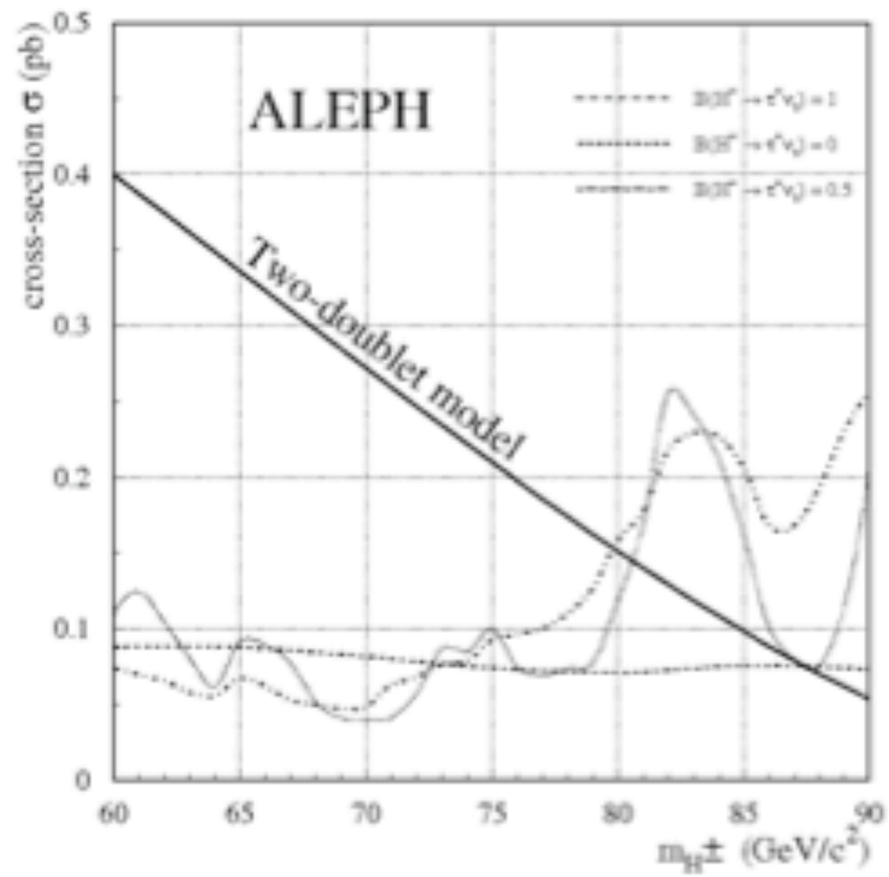
NO SEARCH for: $H^\pm \to W^{\pm\star}A$ with $A \to \tau^+\tau^-,\ c\bar{c},\ gg$

Strongest limits from ALEPH: $m_{H^\pm} > 79.3$ GeV

DELPHI



assuming $B(H^+ \to \tau^+\nu) + B(H^+ \to c\bar{s}) = 1$



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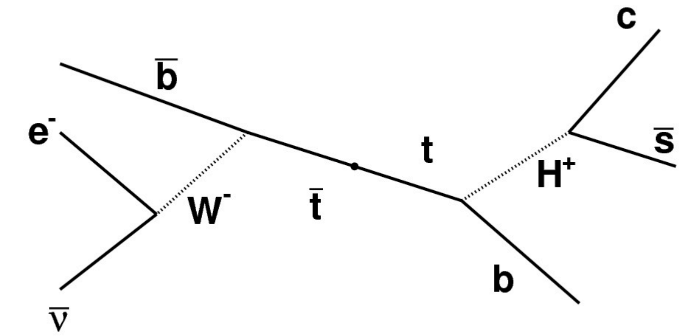


$H^{\pm}$ could have been produced at Tevatron: $t \to H^{+}b$ with

$B(t \to H^{+}b) \simeq 40\%, \quad B(H^{+} \to W^{+\star}A,\ \tau^{+}\nu,\ c\bar{s}) \simeq 70\%,\ 20\%,\ 10\%$

NO SEARCH for: $H^{\pm} \to W^{\pm\star}A$ with $A \to \tau^{+}\tau^{-},\ c\bar{c},\ gg$

Strongest limits from CDF: from 193 pb^{-1} of data!!!

- $B(t \to H^{+}b) < 0.4$

  assuming $B(H^{+} \to \tau^{+}\nu) = 1$

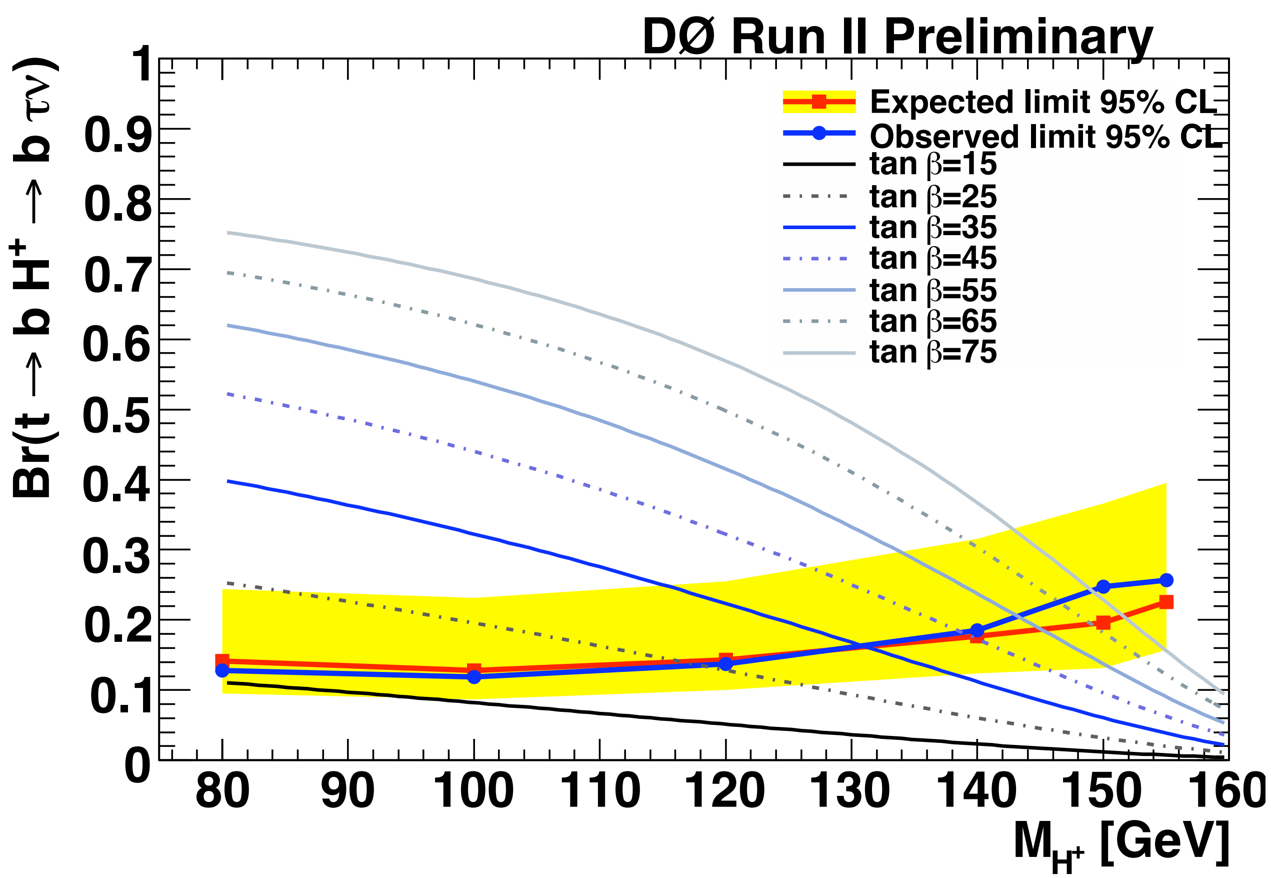
- $B(t \to H^{+}b) < 0.8$ for $m_{H^{\pm}} \simeq 80$ GeV

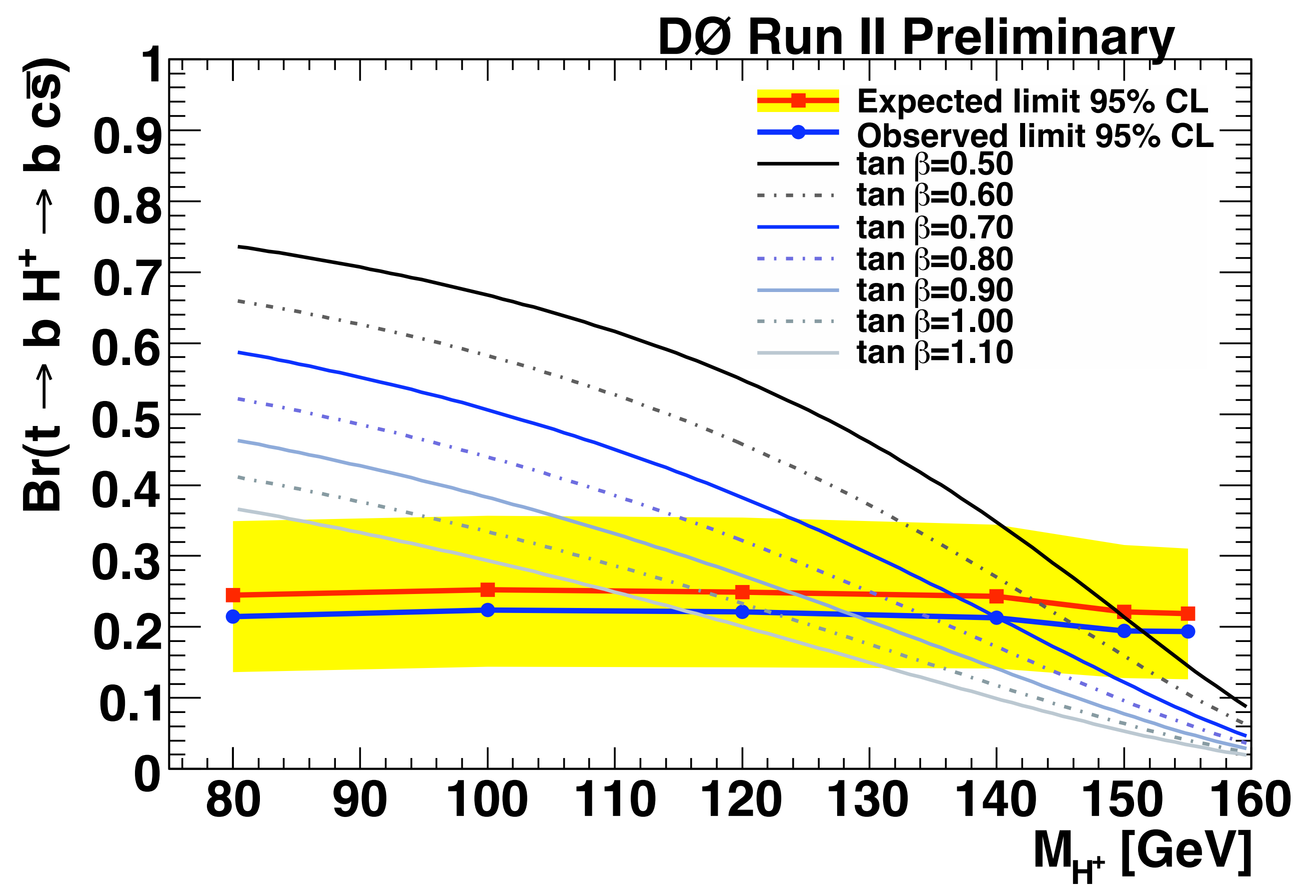
  assuming $H^{+} \to \tau^{+}\nu,\ c\bar{s},\ t^{\star}\bar{b}$ or $W^{+}A$ with $A \to b\bar{b}$

No limits for $m_{H^{\pm}} \gtrsim 75$ GeV from LEP or Tevatron!

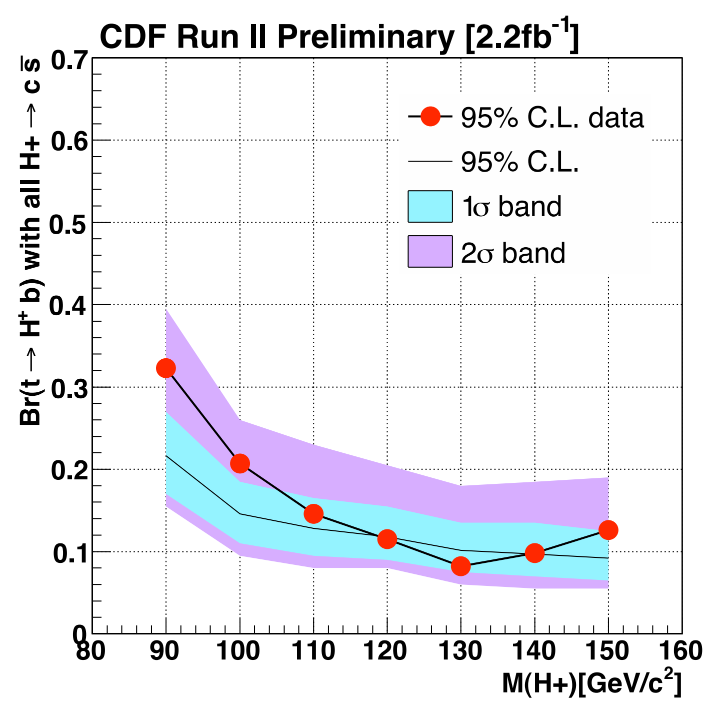
New D0 and CDF limits on charged Higgs

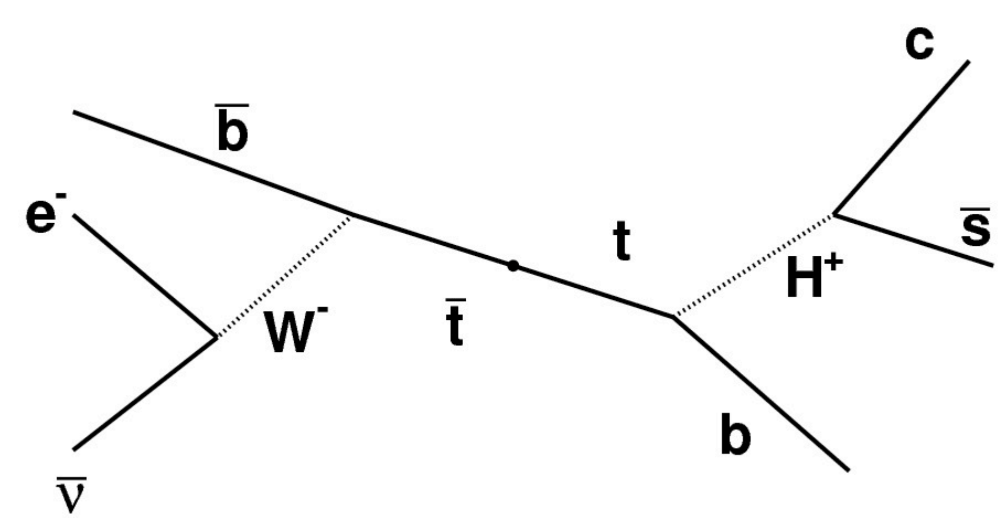
Aug 08





limits do not constrain our scenario!





Light CP-odd Higgs at B factories

A could have been produced at B-factories: $\Upsilon \to A\gamma$

(it is advantageous to search in $\Upsilon(1S)$, $(2S)$ and $(3S)$ data)

results obtained from R.D., J. F. Gunion and B. McElrath, hep-ph/0612031

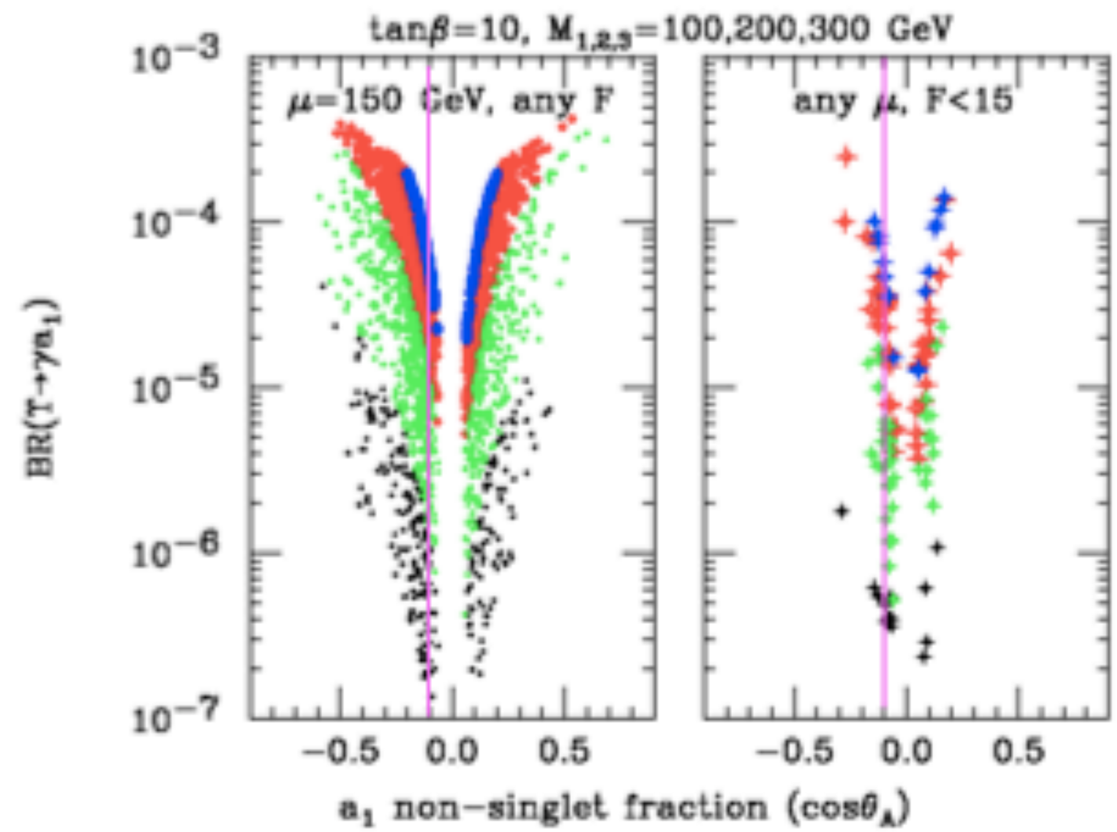
taking $\tan\beta \cos\theta_A \simeq 1$:

$B(\Upsilon(1S) \to A\gamma) \simeq 5 \times 10^{-5}$

for $m_A \simeq 2m_\tau$

$B(\Upsilon(1S) \to A\gamma) \simeq 10^{-7}$

for $m_A \simeq 9.2$ GeV



$m_{a_1} < 2m_\tau$

$2m_\tau < m_{a_1} < 7.5\,GeV$

$7.5\,GeV < m_{a_1} < 8.8\,GeV$

$8.8\,GeV < m_{a_1} < 9.2\,GeV$

CLEO preliminary limits:

assuming $B(A \to \tau^+\tau^-) = 1$

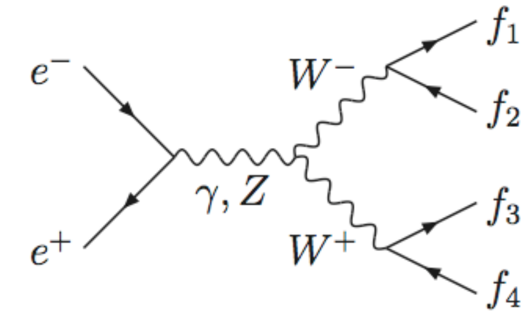
$B(\Upsilon(1S) \to A\gamma) < 7 \times 10^{-5} \;-\; 8 \times 10^{-6}$

depending on exact m_A

Lepton universality in W boson decays

- measured at LEP in $e^+e^- \to W^+W^-$ arXiv:hep-ex/0412015

$$B(W \to \mu\nu)/B(W \to e\nu) = 0.994 \pm 0.020$$
$$B(W \to \tau\nu)/B(W \to e\nu) = 1.070 \pm 0.029$$
$$B(W \to \tau\nu)/B(W \to \mu\nu) = 1.076 \pm 0.028$$



$$R_{\tau/l} \equiv 2B(W \to \tau\nu)/(B(W \to e\nu) + B(W \to \mu\nu))$$

2.8σ deviation from lepton universality:

$$R^{exp}_{\tau/l} = 1.073 \pm 0.026$$

- measured at Tevatron in inclusive W production $p\bar{p} \to WX$

CDF, Nucl. Phys. Proc. Suppl. **144**, 323 (2005)

agrees with lepton universality:

$$Br(W \to \tau\nu)/Br(W \to e\nu) = 0.99 \pm 0.04(stat) \pm 0.07(syst)$$

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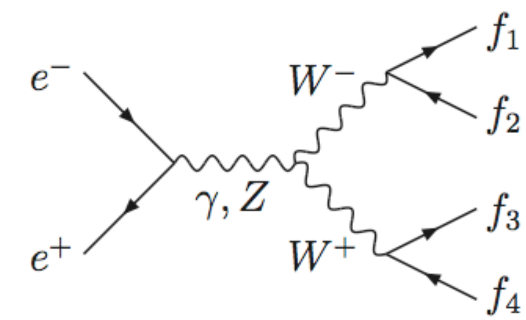

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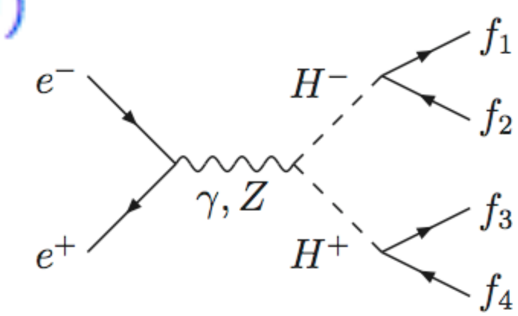

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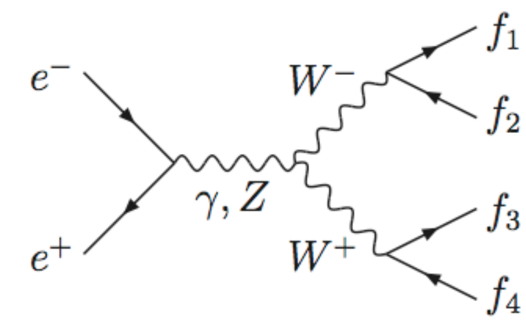

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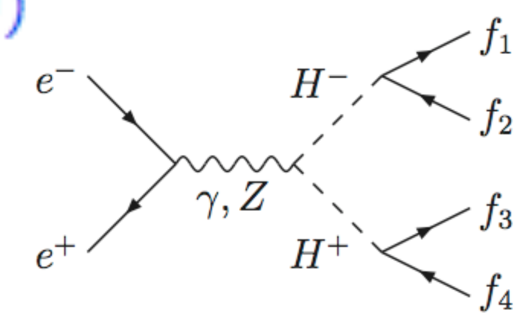

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$$Br(W \to \tau\nu)/Br(W \to e\nu) = 0.99 \pm 0.04(stat) \pm 0.07(syst)$$

$H^\pm$ NOT expected to contribute!

Charged Higgs contribution to $R_{\tau/l}$

- $H^{\pm}$ contribution to $\tau\nu\tau\nu$:

$$R^{l}_{\tau/l} = \sqrt{1 + \frac{\sigma_{H^+H^-} B(H^+ \to \tau^+\nu)^2}{\sigma_{W^+W^-} B(W^+ \to l^+\nu)^2}}$$

efficiency of $W \to \tau\nu$ event to pass as $W \to l\nu$ event is not negligible and so $H^{\pm}$ effectively contributes also to mixed $\tau\nu l\nu$ channels

- $H^{\pm}$ contribution (simplified!) to $\tau\nu + \mathrm{hadrons}$:

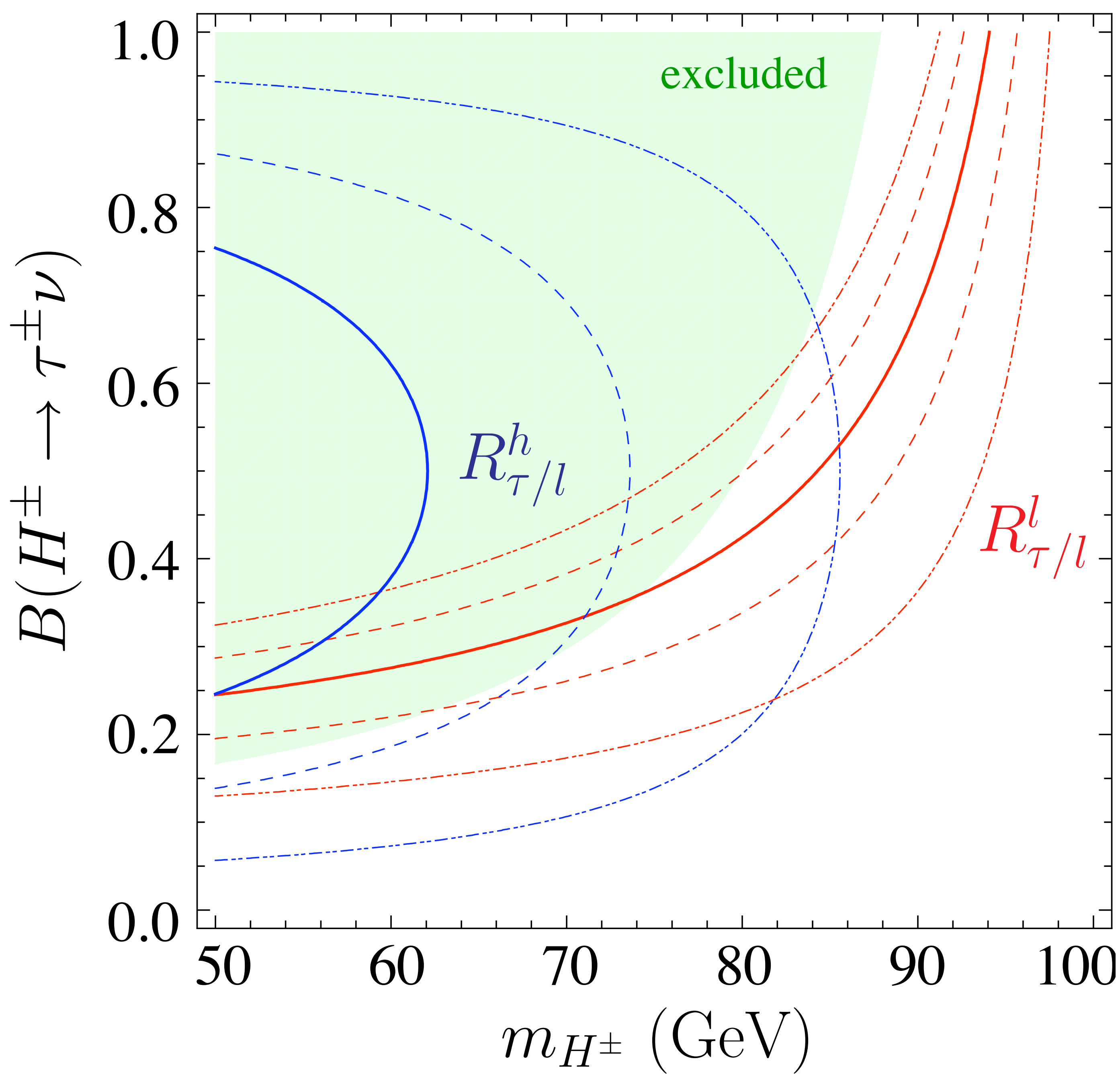
$$R^{h}_{\tau/l} = 1 + \frac{\sigma_{H^+H^-} B(H^+ \to \tau^+\nu) B(H^+ \to hadrons)}{\sigma_{W^+W^-} B(W^+ \to l^+\nu) B(W^+ \to hadrons)}$$

underestimates by not including $H^+H^- \to c\bar{s}W^{-*}A,\ \bar{c}sW^{+*}A,\ W^{+*}AW^{-*}A$ with one $A \to \tau^+\tau^-$ that could mimic $WW \to \tau\nu + hadrons$

$$B(H^+ \to hadrons) \simeq 1 - B(H^+ \to \tau^+\nu)$$

overestimates $B(H^+ \to hadrons)$ by including $B(H^+ \to W^{+*}A)$ with $A \to \tau^+\tau^-$, $\tau \to leptons$ and $W^{+*} \to leptons$

Charged Higgs contribution to $R_{\tau/l}$



$$R^{exp}_{\tau/l} = 1.073 \pm 0.026$$

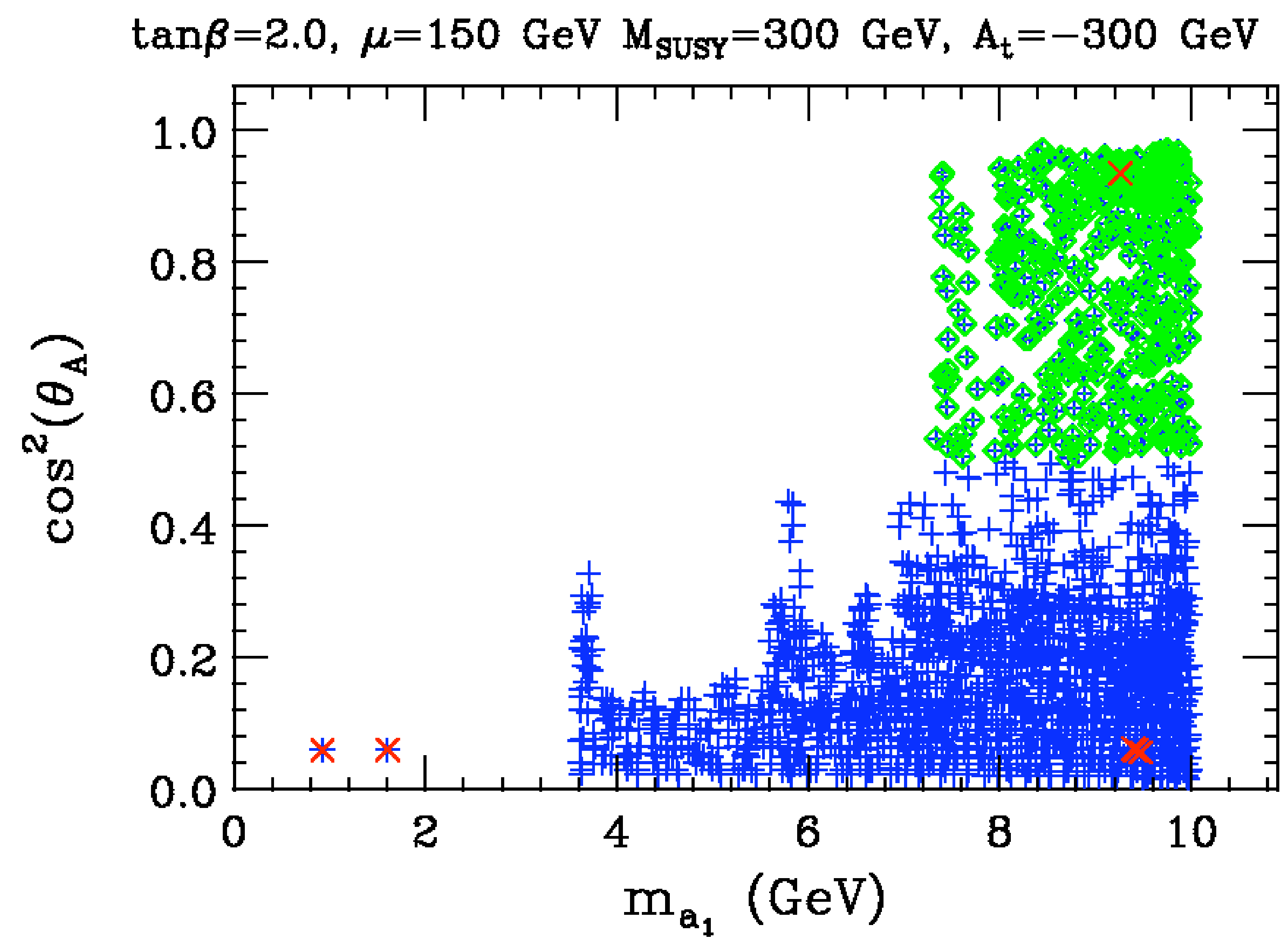
shaded is excluded by $H^\pm \to \tau^\pm \nu$ limits;

other limts not showed but not effective for $m_{H^\pm} \gtrsim 75$ GeV

$m_{H^\pm} \simeq 75 - 85$ GeV with $B(H^+ \to \tau^+ \nu) \simeq 20 - 40\%$ seems to explain $R_{\tau/l}$

NMSSM with a light doublet-like CP-odd Higgs:

R.D. and J. Gunion, to appear



SM-like CP-even Higgs

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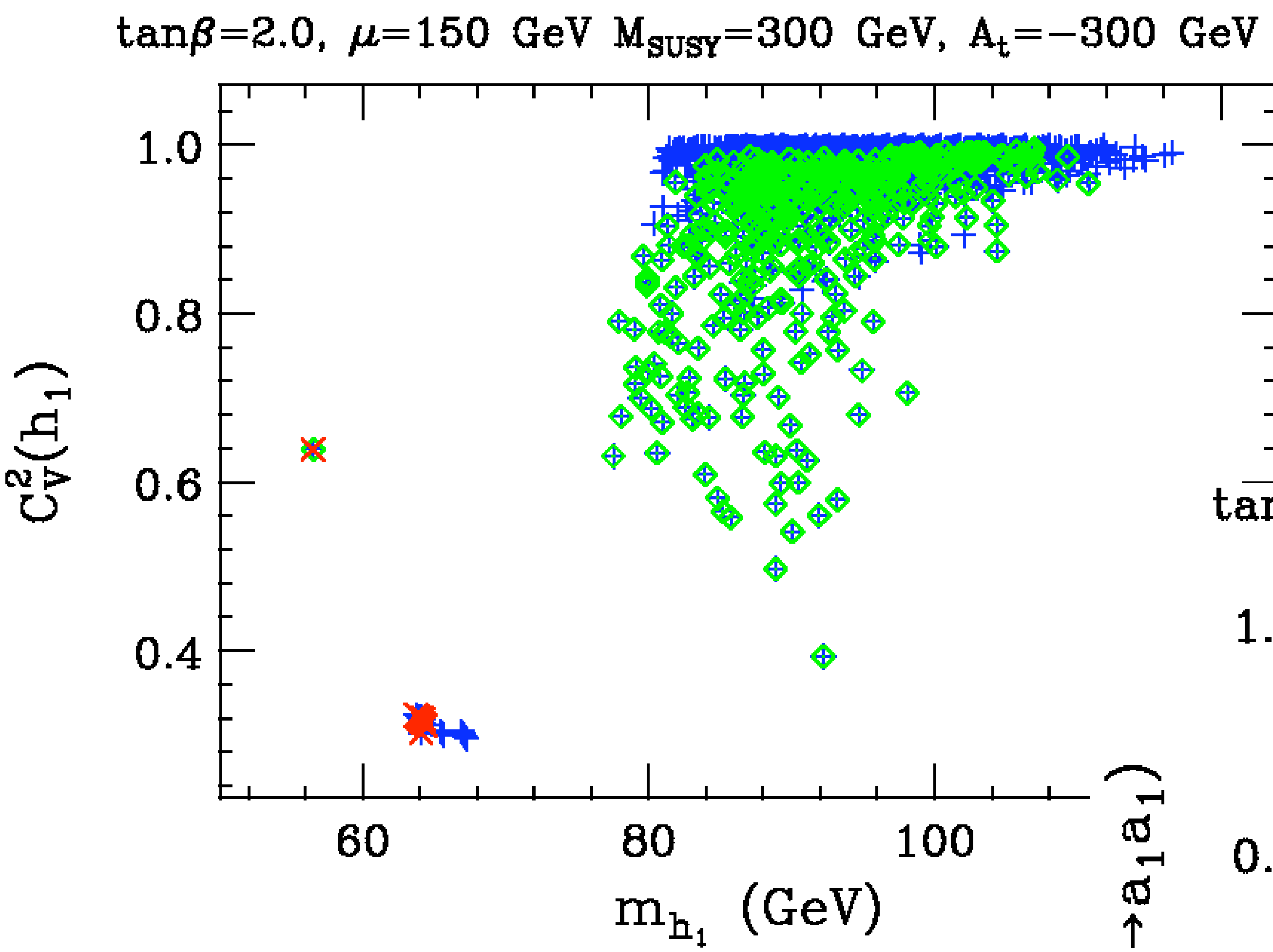
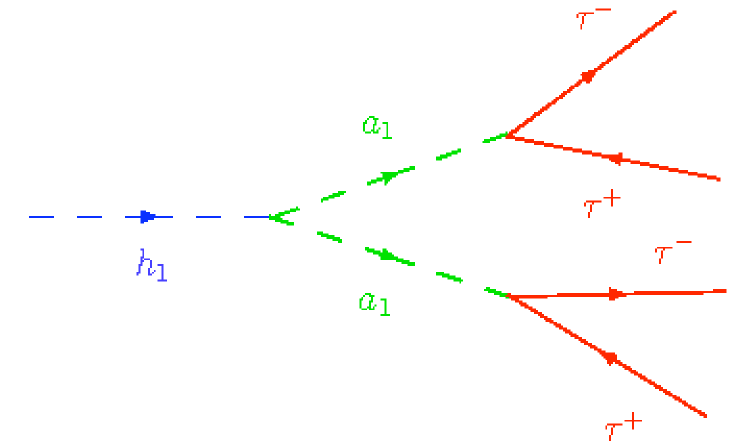
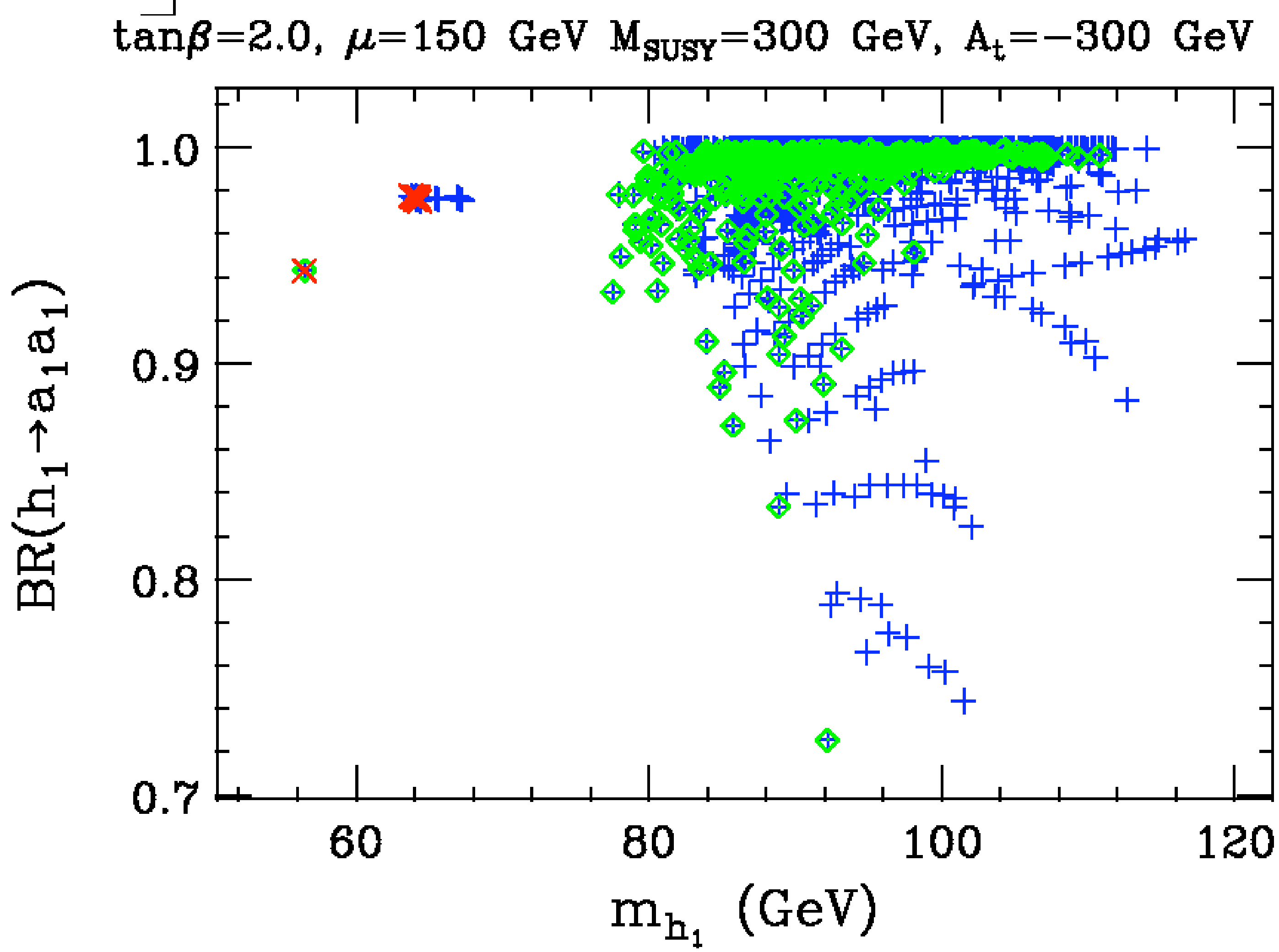
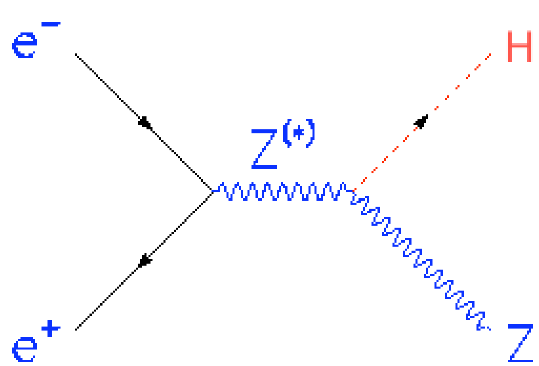


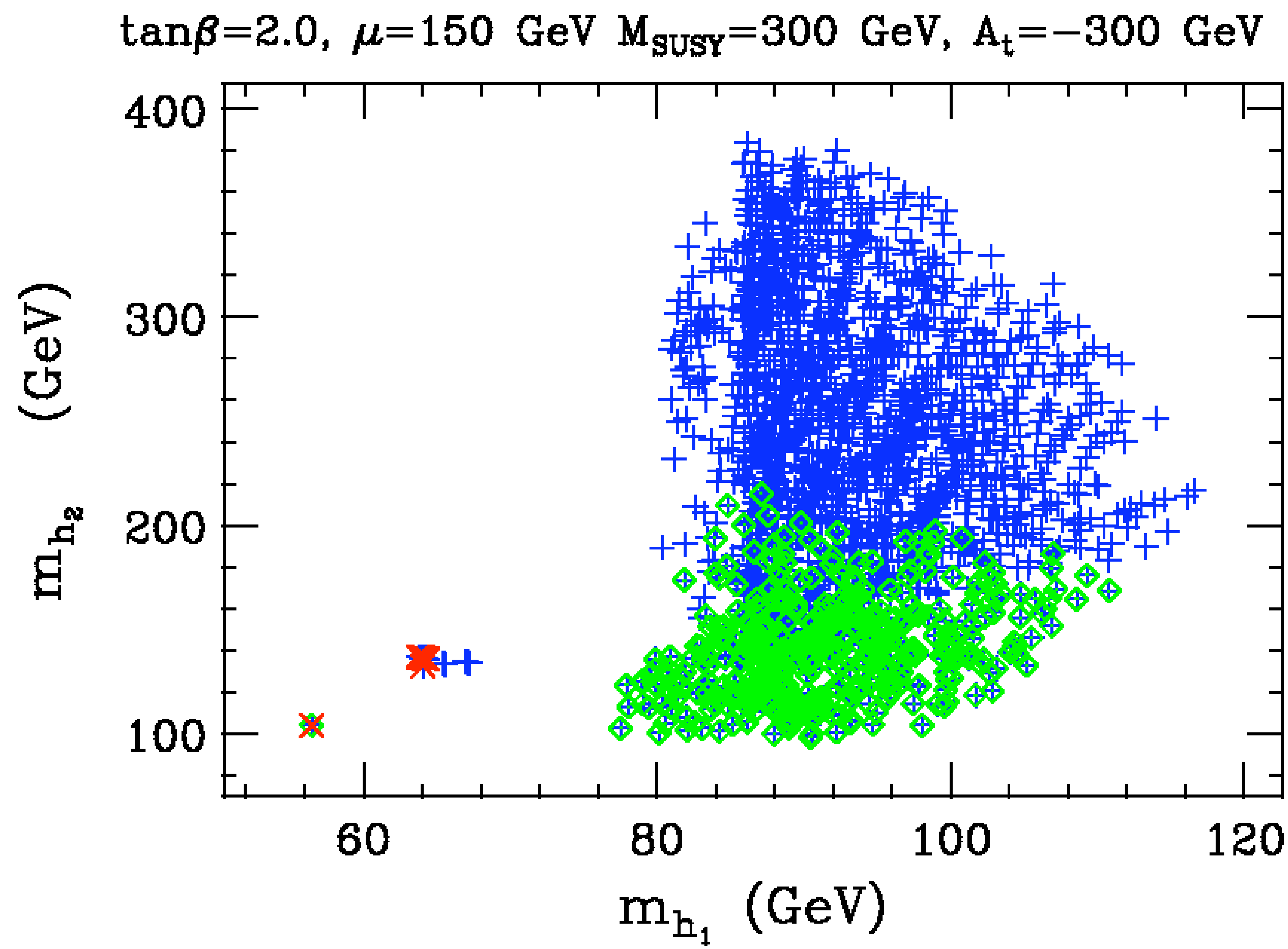






Heavy CP-even Higgs

R.D. and J. Gunion, to appear



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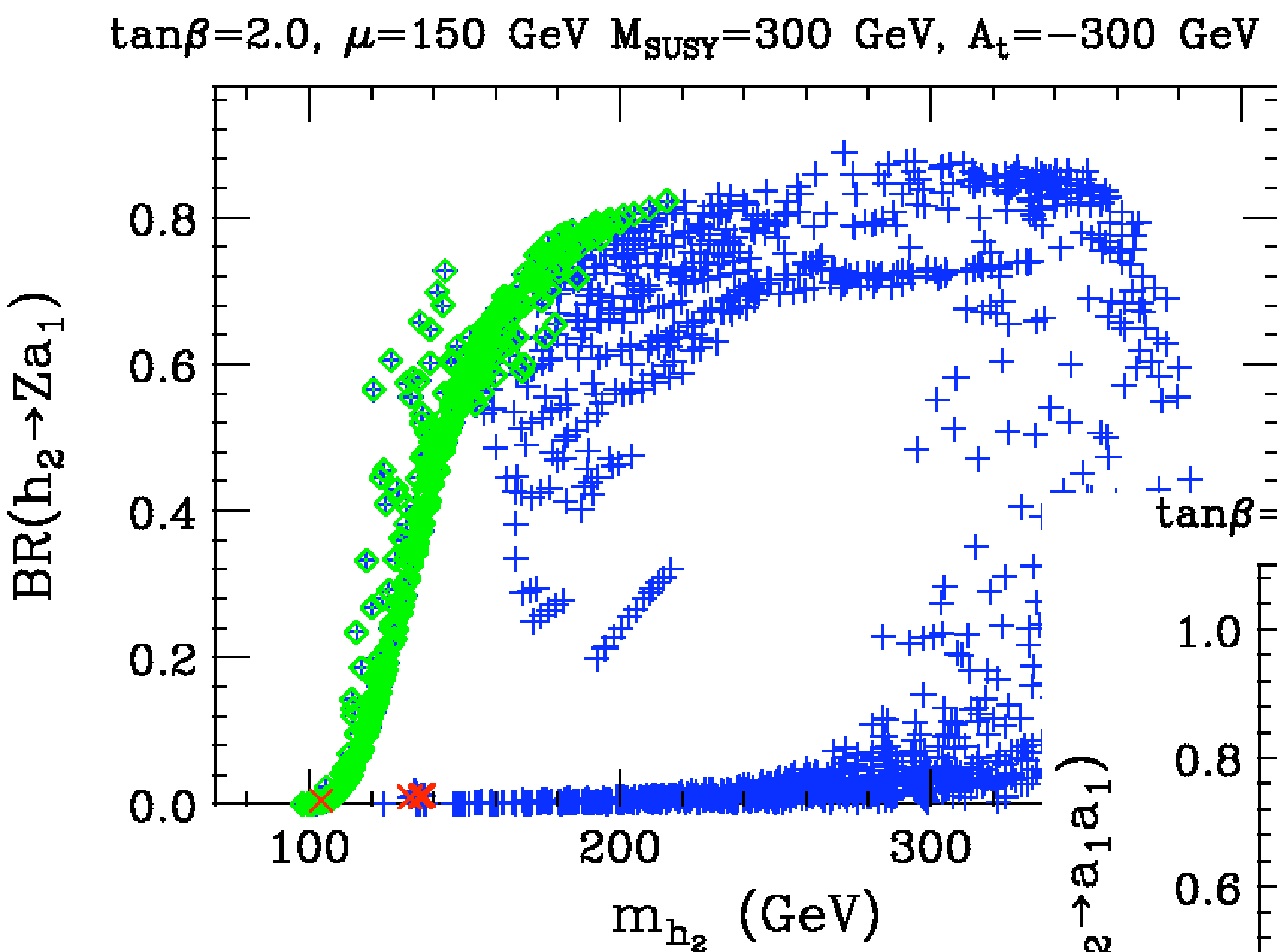
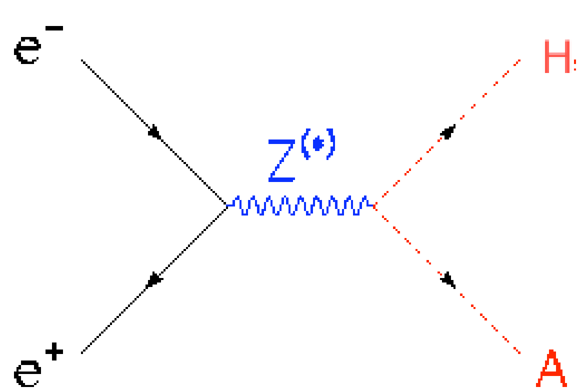
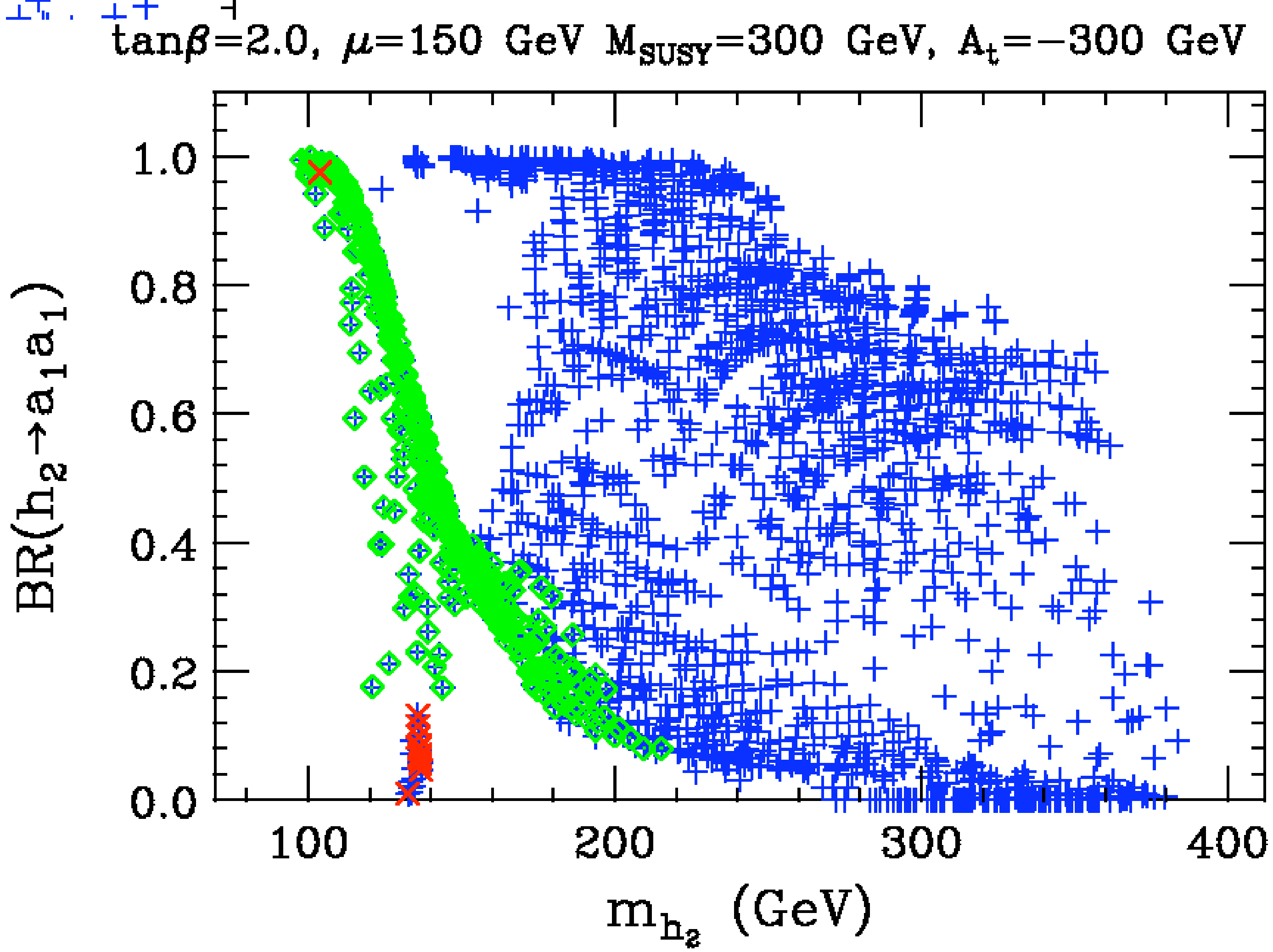
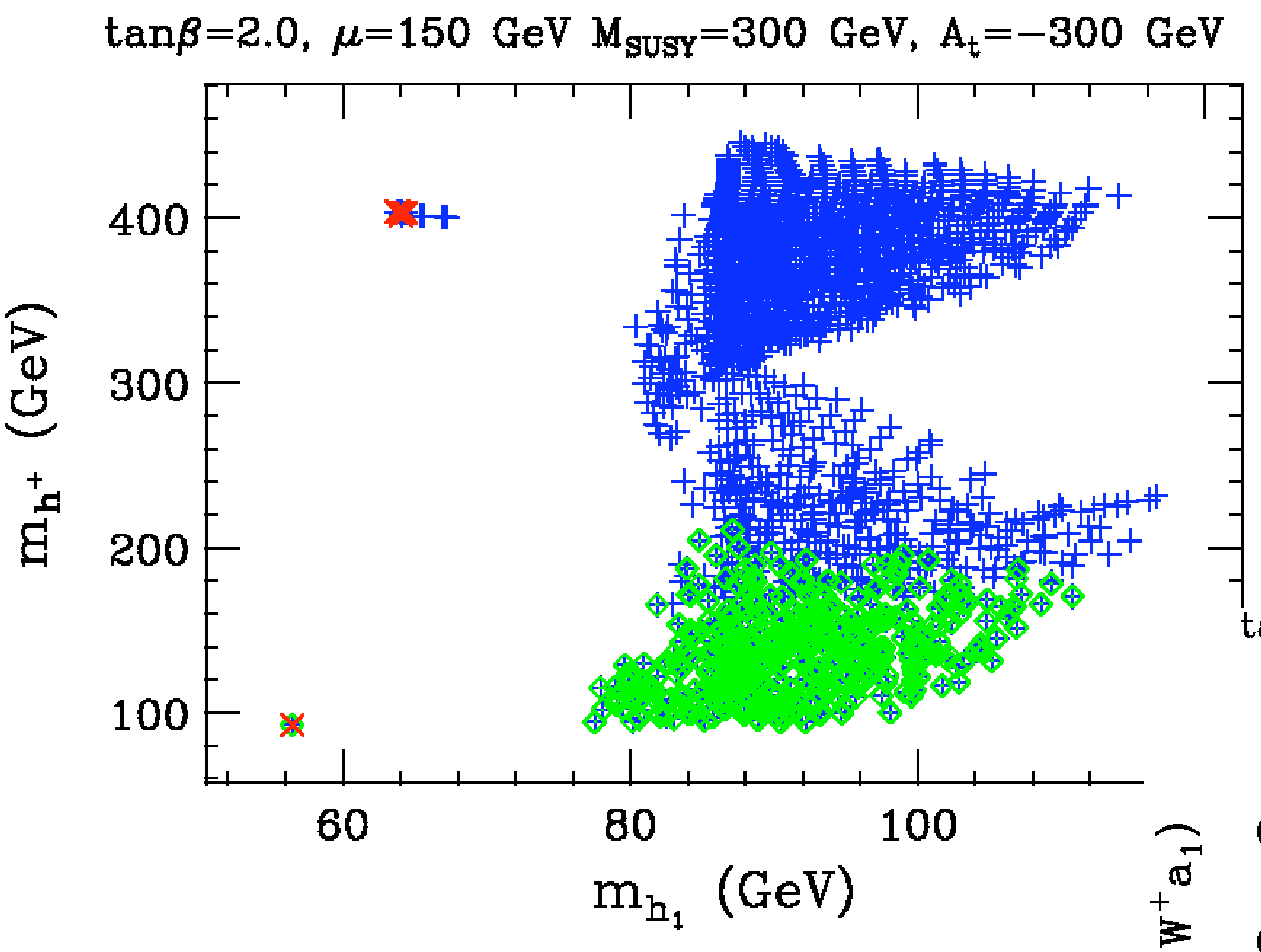


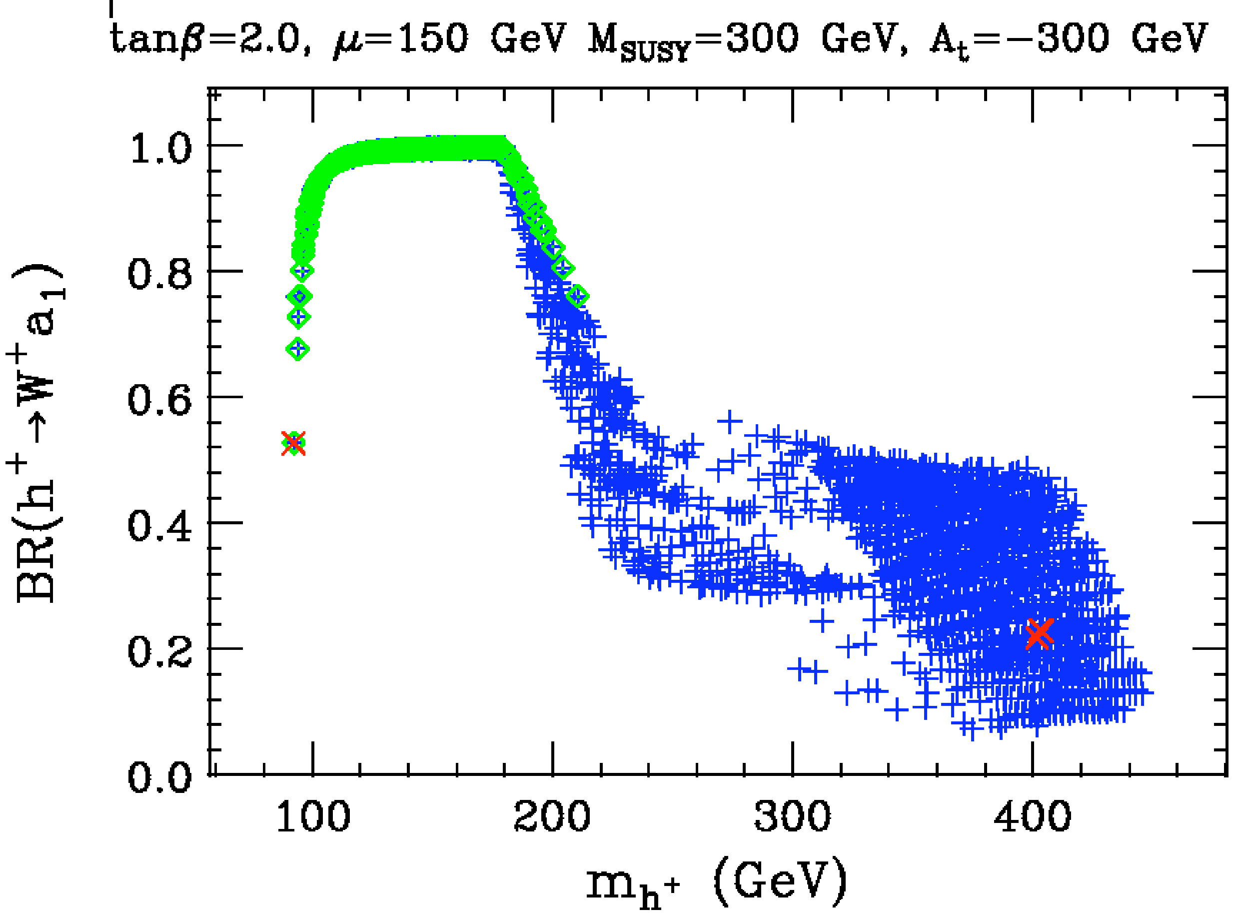




Charged Higgs

R.D. and J. Gunion, to appear





Conclusions

$m_A \ll m_Z$ at $\tan\beta \simeq 1$ scenario viable in extensions of the MSSM; presents an opportunity to discover Higgs bosons at LEP, Tevatron, CLEO, BaBar, Belle:

- SM like CP even Higgs, $m_h \gtrsim 82$ GeV
  - produced in $e^+e^- \to Zh$
    - effective search would require combining $h \to 4\tau, 2\tau 2c, 4c, 2b$ modes
- heavy CP even Higgs, $m_h \simeq 108 - 150$ GeV
  - produced in $e^+e^- \to HA$
    - search in $H \to ZA$ and $H \to AA$
- CP odd Higgs, $m_A \lesssim 10$ GeV
  - produced also at B-factories $\Upsilon \to A\gamma$
    - requires combined search in $A \to \tau^+\tau^-, c\bar{c}, gg$
- charged Higgs, $m_{H^\pm} \simeq m_W$
  - produced in $e^+e^- \to H^+H^-$ at LEP and $t \to H^+b$ at Tevatron
    - search in $H^+ \to W^{+*}A$ with $A \to \tau^+\tau^-, c\bar{c}$

      can explain $B(W \to \tau\nu)/B(W \to l\nu) = 1.073 \pm 0.026$!

requires modified strategies for Higgs discovery at the LHC