Light Higgs in Upsilon Decays

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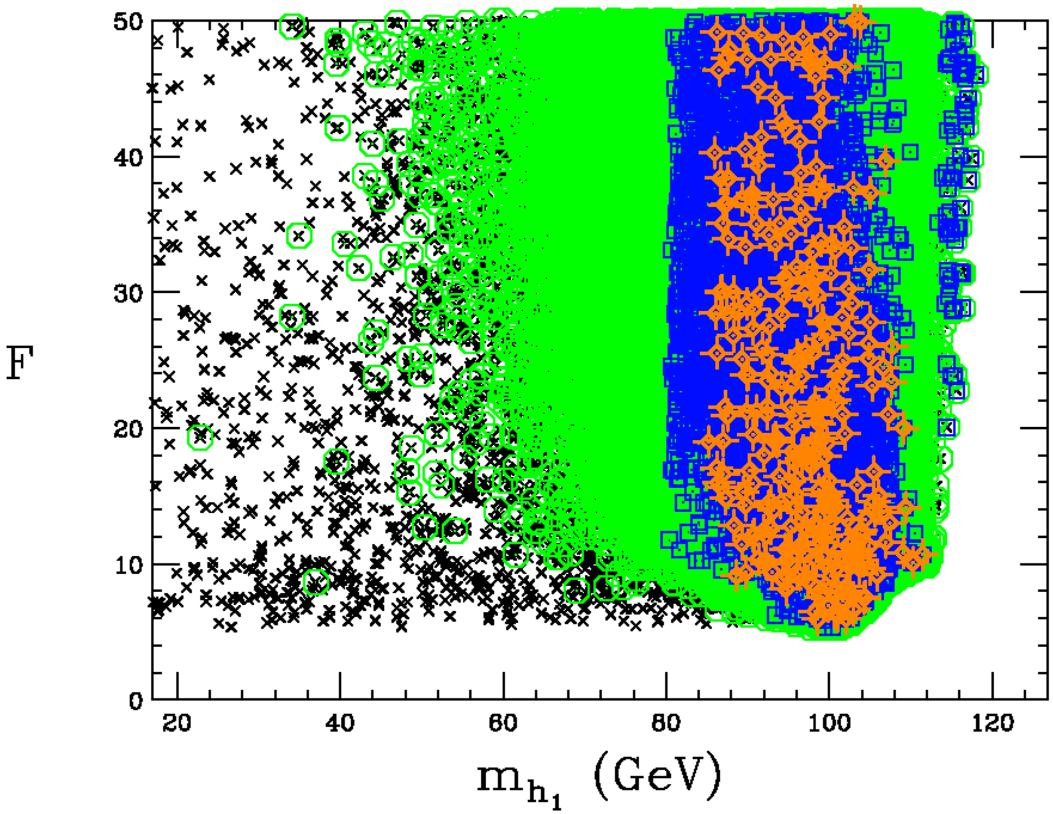
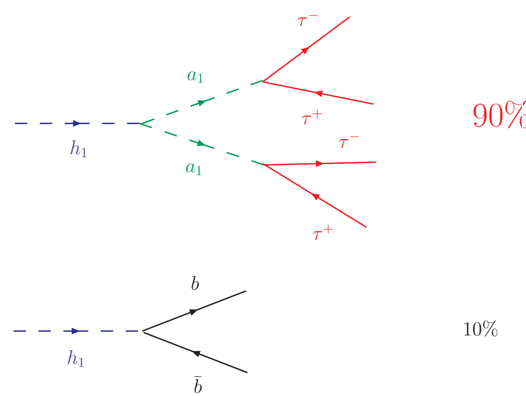
Natural Higgs mass in NMSSM

$\tan\beta = 10,\ M_3(M_Z) = 300$ GeV



- no constraints
- SUSY constraints
- $m_h > 114$ GeV or $h \to aa$
- $h \to aa,\ m_a < 2m_b$



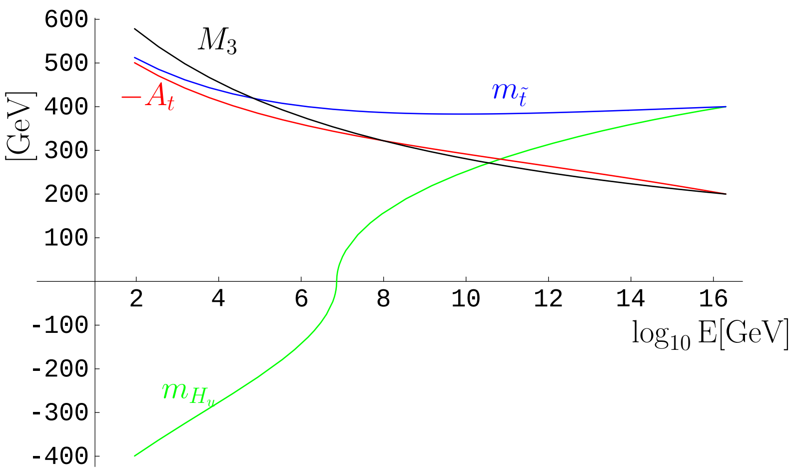
$$F = \max_p F_p = \max_p \left| \frac{p}{M_Z} \frac{dM_Z}{dp} \right|$$

$$p \in \{M_i(0), i = 1,2,3; m_s^2(0), s = Q,u,d,L,e,H_u,H_d,S; A_t(0), A_\lambda(0), A_\kappa(0)\}$$

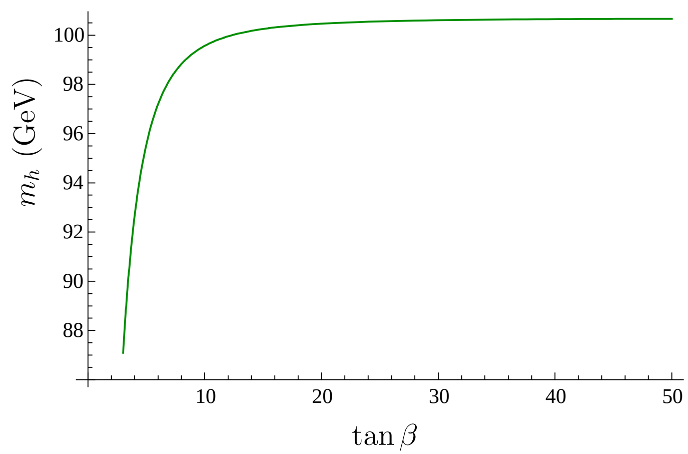
Higgs Mass in MSSM

$$m_h^2 \simeq M_Z^2 \cos^2 2\beta + \frac{3G_F m_t^4}{\sqrt{2}\pi^2}\left[\log\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{A_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{A_t^2}{12 m_{\tilde{t}}^2}\right)\right]$$

Typical mixing $|A_t/m_{\tilde{t}}| \simeq 1$



Typical Higgs mass



[FeynHiggs-2.5.1: $M_{SUSY} = m_A = \mu = 200$ GeV]

Higgs Mass in MSSM

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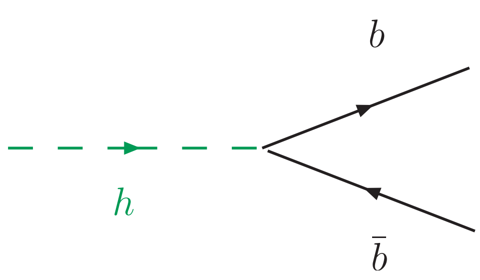
LEP limit: $m_h \gtrsim 114.4$ GeV

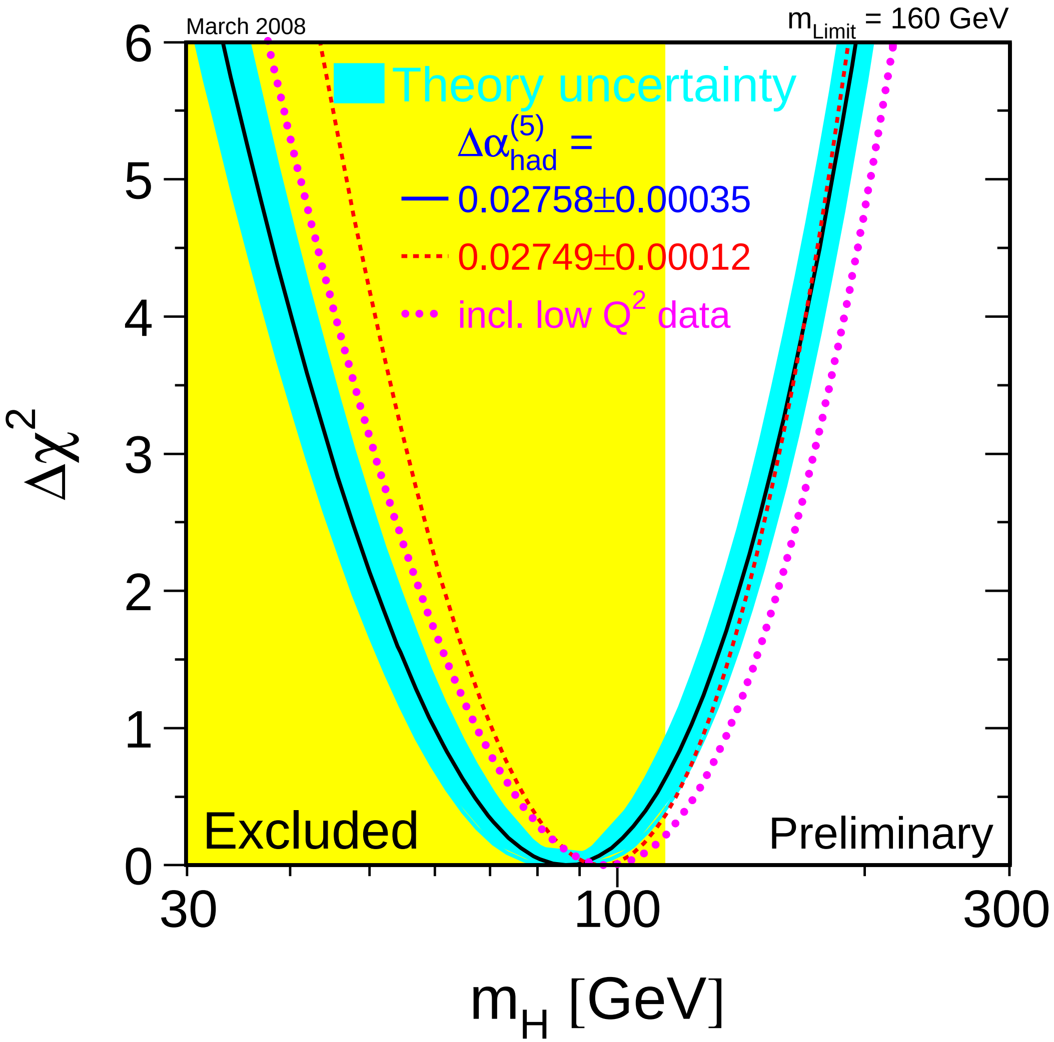


satisfied for $A_t/m_{\tilde{t}} \lesssim 1$ with:

$$m_{\tilde{t}} \gtrsim 1000\,\mathrm{GeV}$$

$\longrightarrow$ LEP puzzle!

Precision electroweak data



EWWG 2007

$m_h = 87^{+36}_{-27}$ GeV

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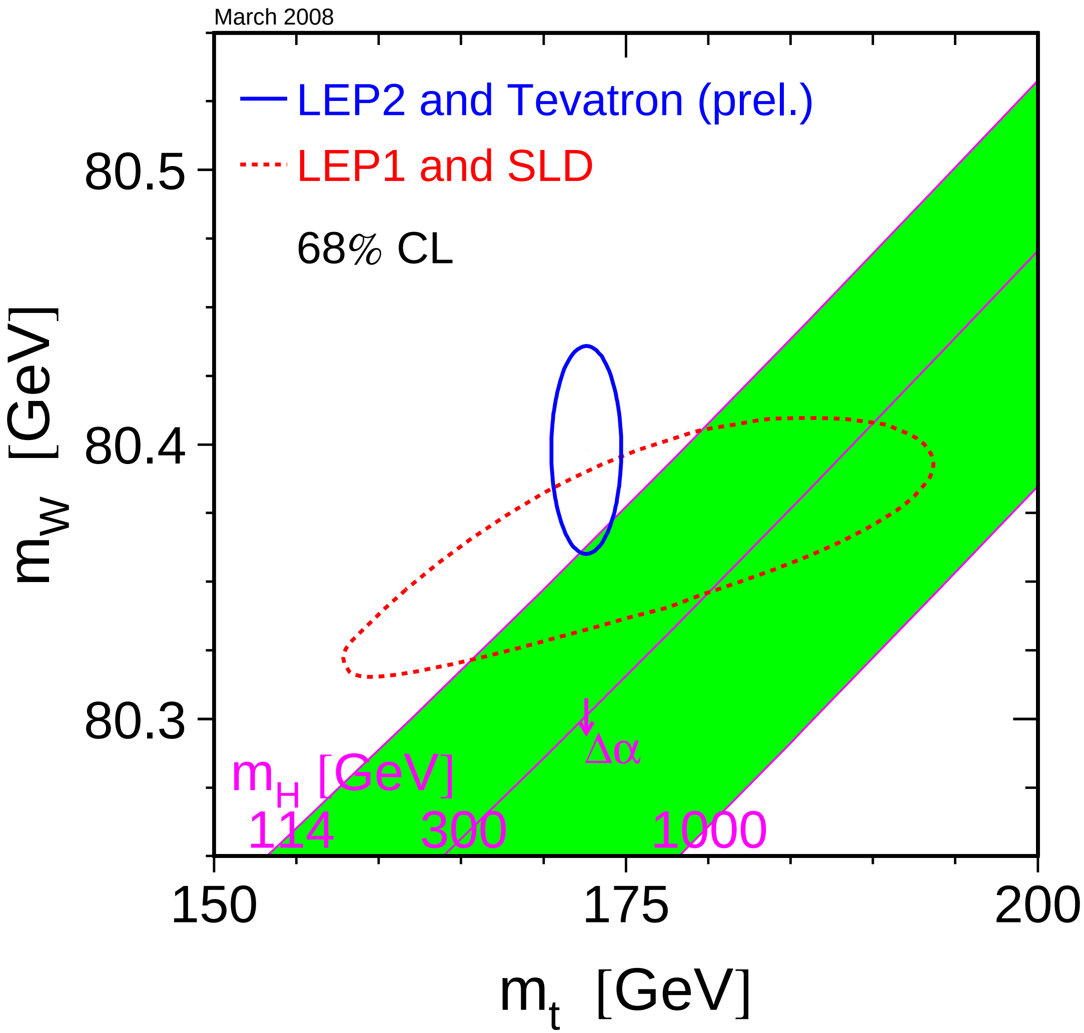

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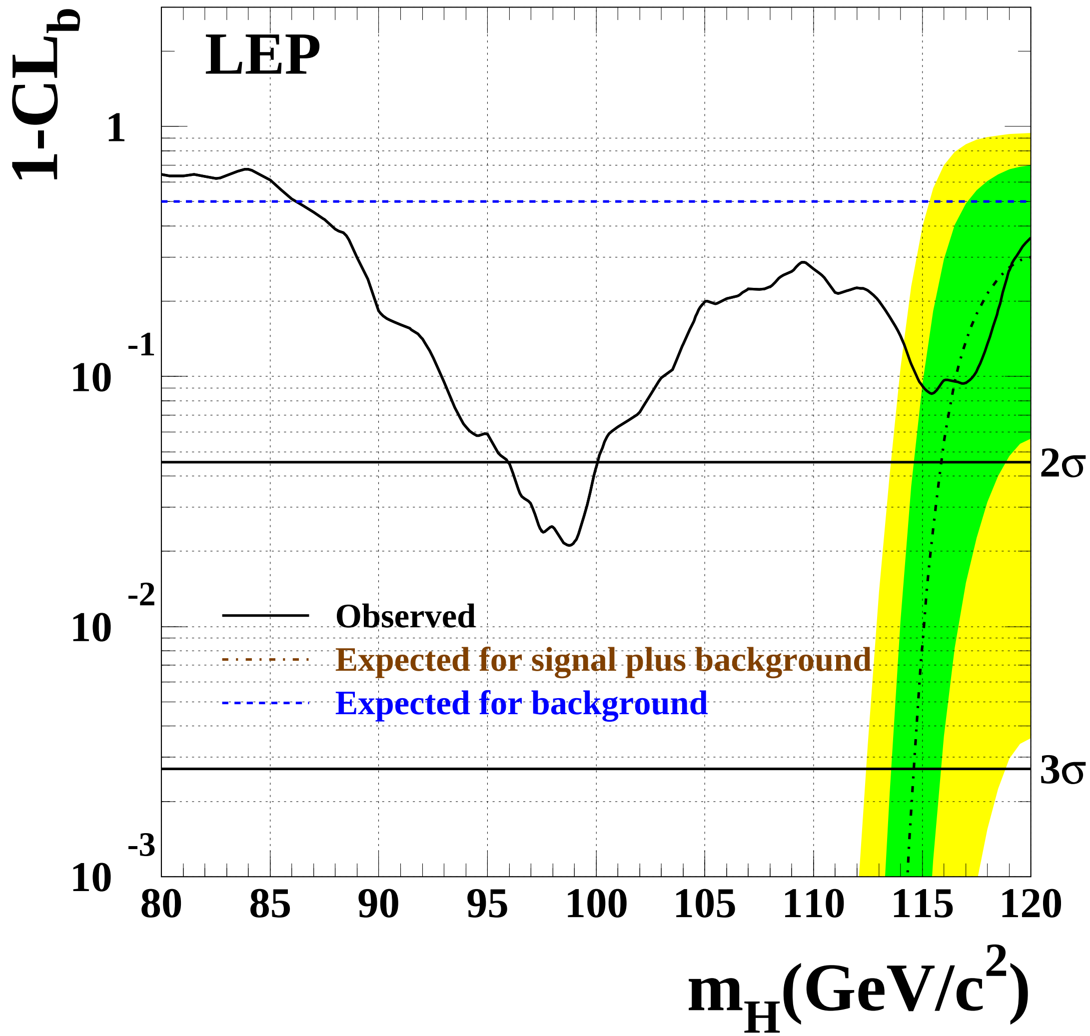
Search for the SM Higgs at LEP

LHWG-2003-011



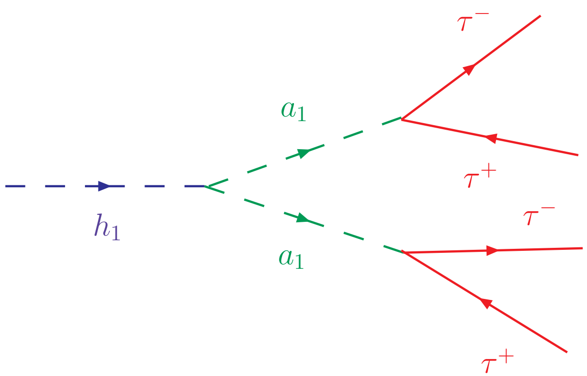
Non-standard Higgs decays

R.D. and J. Gunion

LEP puzzle solved in models with non-standard Higgs decays, e.g.:

$$h_1 \to a_1 a_1 \to 4\tau, \quad 4j, \quad 4g, \quad \ldots$$

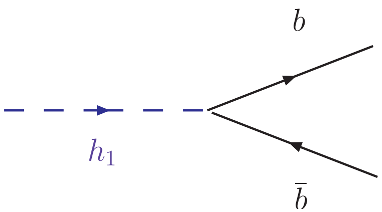
for $m_h \simeq 100$ GeV and $m_a \lesssim 10$ GeV there are no exp. limits!



90%

search at LEP - L3, C. Tully

10%



can fully explain LEP Higgs excess at $m_h \simeq 100$ GeV

NMSSM - brief review

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

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

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

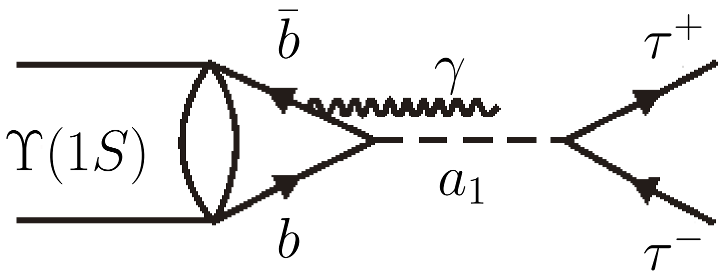
$$\tan\beta = \frac{v_u}{v_d}\,, \quad \mu_{eff} = \lambda s$$

light CP odd Higgs:

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

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

Light CP-odd Higgs at B factories



Many ways to search, e.g.:

$\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$

with

$\sigma_{eff} = 179\, pb.$

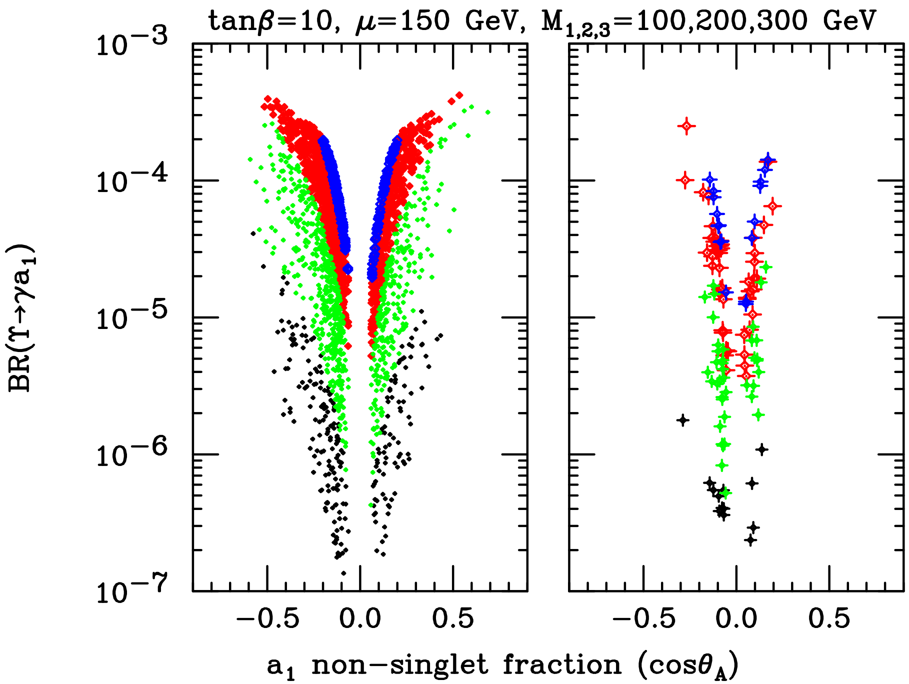
To limit

$Br(\Upsilon(1S) \to \gamma a_1) \lesssim 10^{-6}$

we need

$5.6 fb^{-1}/\epsilon$ collected on $\Upsilon(3S)$.

Within reach at existing facilities!



A_κ, A_λ, κ, λ scan $\quad$ $F < 15$ scan

$m_{a_1} < 2m_\tau$

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

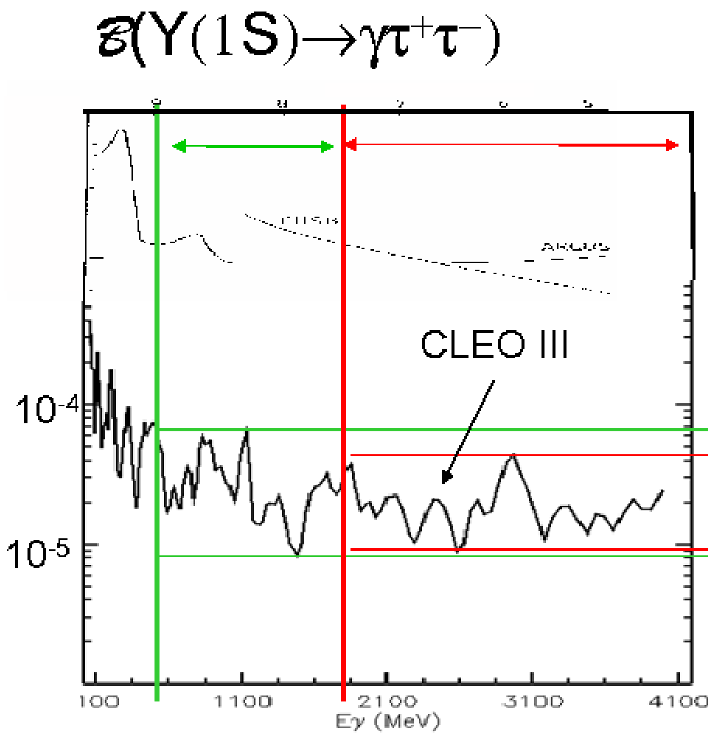
$7.5\, GeV < m_{a_1} < 8.8\, GeV$

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

CLEO limits

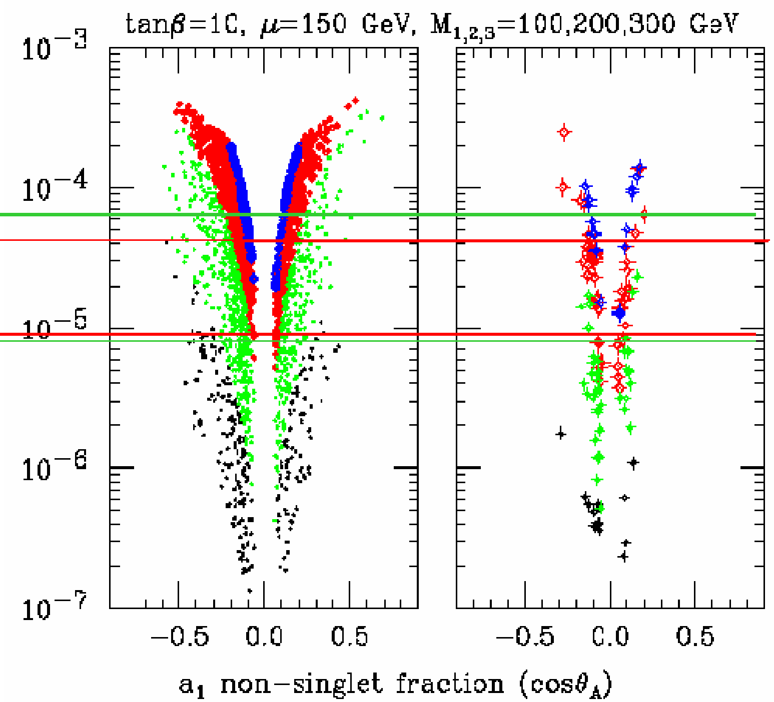
S. Stone, FPCP, May 2008

Constraints on NMSSM from $\gamma\tau^+\tau^-$



From
Dermisek, Gunion, McElrath: hep-ph/0612031

NMSSM consistent with
all previous results



Many models with $2m_\tau < m_a < 7.5$ GeV (represented by red points) ruled out by our results.

Colors represent different mass ranges

FPCP May, 2008

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:

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

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

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$H^\pm$ 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

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

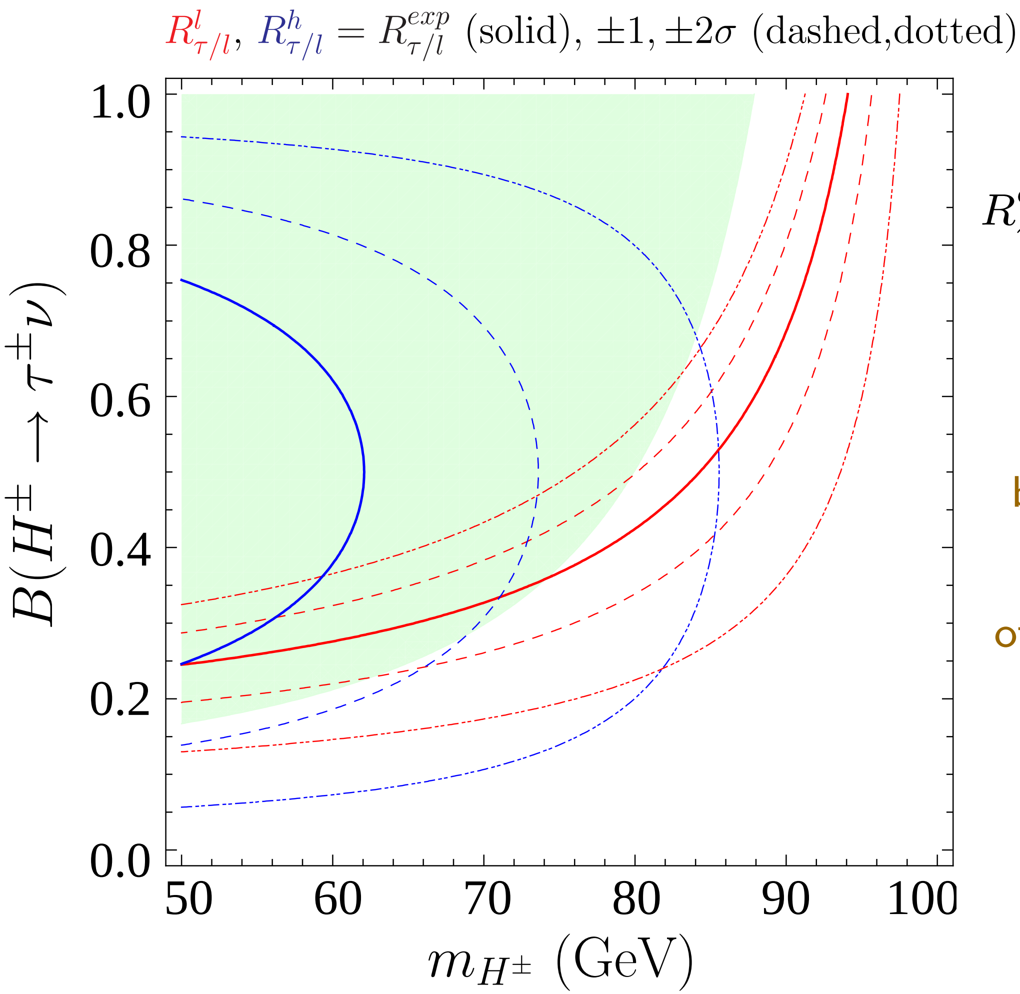
$$R^h_{\tau/l} = 1 + \frac{\sigma_{H^+H^-} B(H^+ \to \tau^+\nu) B(H^+ \to hadrons)}{\sigma_{W^+W^-} B(W^+ \to l^+\nu) B(W^+ \to hadrons)}$$

underestimates by not including $H^+H^- \to c\bar{s}W^{-\star}A$, $\bar{c}sW^{+\star}A$, $W^{+\star}AW^{-\star}A$ 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 $B(H^+ \to W^{+\star}A)$ with $A \to \tau^+\tau^-$, $\tau \to leptons$ and $W^{+\star} \to leptons$

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 $R_{\tau/l}$

Light Charged Higgs in the MSSM

mass of the charged Higgs in the MSSM:

$$m_{H^\pm} = \sqrt{m_W^2 + m_A^2 - \Delta'}$$

Δ' is SUSY correction - typically small

for $m_A \ll m_W$:

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

In the MSSM this possibility is ruled out by Higgs searches, MSSM predicts $m_h \lesssim 60$ GeV, but it is viable in simple extensions of the MSSM, e.g. NMSSM.
The scenario requires $m_A < 2m_b$ and $\tan\beta \simeq 1$.

R.D. arXiv:0806.0847

MSSM-like CP-odd Higgs at B factories

MSSM-like A could be 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

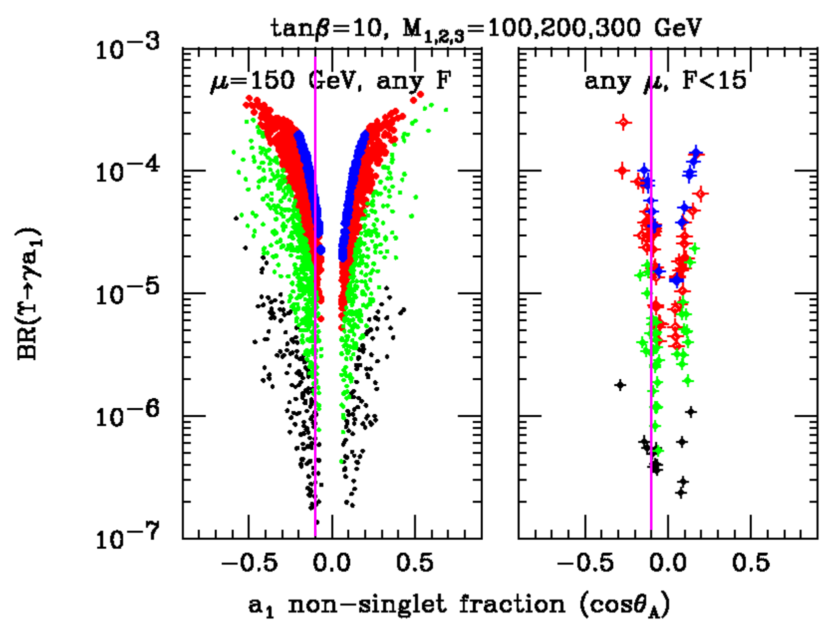
taking $\tan\beta \cos\theta_A \simeq 1$:

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

for $m_A \simeq 2m_\tau$

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

for $m_A \simeq 9.2$ GeV



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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

General case

light CP odd Higgs coupling to SM fermions:

normalized to SM Higgs coupling

$ab\bar{b}$, $a\tau^+\tau^-$:

$$\tan\beta\,\cos\theta_A$$

$ac\bar{c}$:

$$\cot\beta\,\cos\theta_A$$

for large $\tan\beta$:

$$B(a\to\tau^+\tau^-)\;\simeq\;100\%$$

for $\tan\beta\simeq 1$:

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

for $\tan\beta\ll 1$:

$$B(a\to c\bar{c})\;\simeq\;100\%$$

Possibility of cascade decays

assuming more than one light scalar, $< 2m_b$, cascade decays would dominate:

$$a_N \;\rightarrow\; 2a_{N-1} \;\rightarrow\; 4a_{N-2} \;\rightarrow\; \ldots \;\rightarrow\; 2^{N-1}a_1$$

typically the heaviest scalar, a_N, produced in Upsilon decays

$$\Upsilon \;\rightarrow\; a_N\,\gamma$$

but the decay product determined by the lightest, a_1, e.g.:

$$\Upsilon \;\rightarrow\; 2^{N-1}a_1 \;+\; \gamma \;\rightarrow\; 2^{N-1}jj \;+\; \gamma$$

$$\Upsilon \;\rightarrow\; 2^{N-1}a_1 \;+\; \gamma \;\rightarrow\; 2^{N-1}e^+e^- \;+\; \gamma$$

$$\Upsilon \;\rightarrow\; 2^{N-1}a_1 \;+\; \gamma \;\rightarrow\; 2^{N-1}\gamma\gamma \;+\; \gamma$$

depending on the mass of a_1.

a_1 can also decay into a stable neutral particles: $a_1 \;\rightarrow\; \chi\chi$

Conclusions

Light Higgs bosons present a unique opportunity for B factories:

- motivated by relations to other Higgs bosons
  - modifying the SM Higgs decays, $h \to aa$
  - possibility of a light charged Higgs

    can explain $B(W \to \tau\nu)/B(W \to l\nu) = 1.073 \pm 0.026$!
- it is advantageous to search in $\Upsilon(1S)$, $(2S)$ and $(3S)$ data

  $$\Upsilon(3S, 2S) \to \pi^+\pi^-\Upsilon(1S), \qquad \Upsilon(1S) \to a\gamma$$
- decay modes: $a \to \tau^+\tau^-$, $c\bar{c}$, gg
- possibility of cascade decays, $a_N \to 2^{N-1} a_1 + \gamma$
  - $a_1 \to jj$
  - $a_1 \to e^+e^-$
  - $a_1 \to \gamma\gamma$
- possible connection to dark matter

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search for light scalar particles should be a serious part of the Super B factory program

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