# Naturalness and Higgs decays in the MSSM with a singlet–

## *searching for a stealthy Higgs*

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hep-ph/0511250

LBNL

# Layout

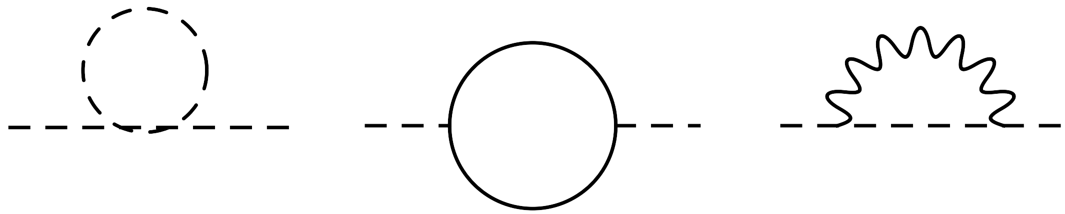
- SUSY little hierarchy problem and a possible solution
- Higgs limits from LEP
- MSSM+S$\neq$NMSSM and its new operators
- New phenomenology
- Conclusions and the future

# Hierarchy problem

- EWSB in SM driven by fundamental scalar, the Higgs

$$V_{classical} = \lambda(|\phi|^2 - v^2)^2$$

- Higgs potential receives large radiative corrections



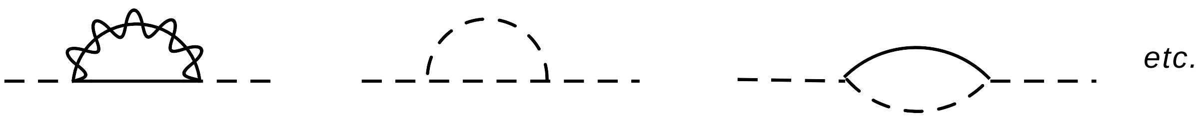
*etc.*

$$\Delta m_\phi^2 \sim \frac{\lambda^2}{16\pi^2}\Lambda^2$$

# Hierarchy problem

- Naturalness arguments tell us $\Lambda \sim \mathrm{TeV}$
- New physics at a TeV
- Technicolour, Little Higgs, Extra Dimensions, Supersymmetry

Low scale SUSY introduces superpartners below the TeV scale to cut off quadratic divergences



# Hierarchy problem

- The good: Superpartners soften divergence

$$\frac{\lambda^2}{16\pi^2}\Lambda^2 \to \frac{y^2}{16\pi^2} m_{\tilde{t}}^2 \log \frac{\Lambda}{m_{\tilde{t}}}$$

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- The bad: Higgs quartic interactions from D-terms. No longer a free parameter, $\lambda \to g$

$$m_h^2 \leq m_z^2 \cos^2 2\beta$$

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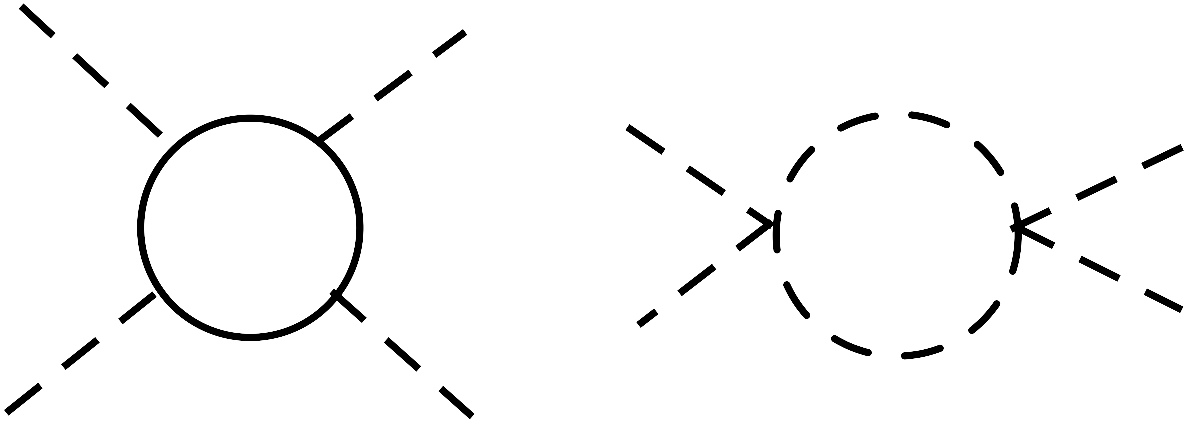
- The ugly(?): Need to raise Higgs mass, e.g. increase quartics. Loop corrections, NMSSM, Fat higgs, non-decoupling D-terms, little supersymmetry etc.

# SUSY little hierarchy problem

One loop corrections to Higgs quartic increase Higgs mass



$$\delta\lambda \to \Delta m_h^2 = \frac{3y_t^2}{4\pi^2} m_t^2 \log\left(\frac{\mathbf{m}_{\tilde{t}}^2}{m_t^2}\right)$$

Compare

$$\Delta m_H^2 = -\frac{3y_t^2}{4\pi^2} \mathbf{m}_{\tilde{t}}^2 \log\frac{\Lambda}{m_{\tilde{t}}}$$

# SUSY little hierarchy problem

- LEP bound on SM-like Higgs (much of MSSM parameter space) $m_h > 114\mathrm{GeV}$
- Requires heavy stops ($\mathcal{O}(400\mathrm{GeV})$), large quartic corrections
- Fine-tuning ($\mathcal{O}(5\%)$) of soft Higgs mass against $\mu$-term to get $v = 174\mathrm{GeV}$
- Alternative ways of raising quartic? e.g. NMSSM, little SUSY, fat Higgs, non-decoupling D-terms.....

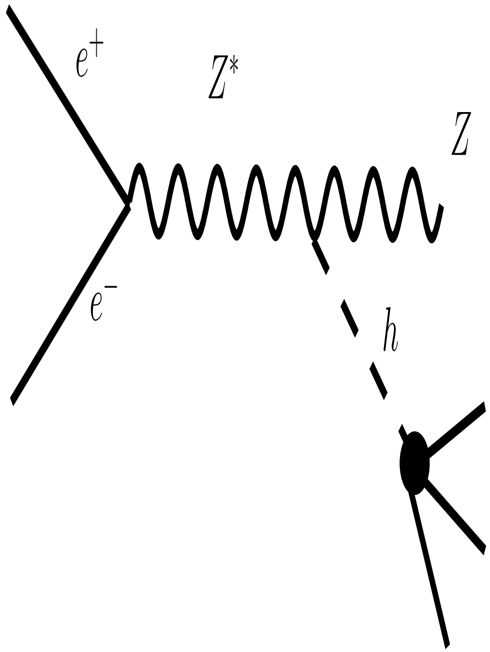
**Or, keep Higgs (and stops) light and instead evade LEP constraints**

Non-standard Higgs decays $\rightarrow$ new states coupled to Higgs, **not** invisible decays.

# MSSM + singlet

- Extend the Higgs sector in the simplest possible way: MSSM + S $\neq$ NMSSM
- NMSSM assumes $\langle S \rangle = \mu$. Make assumptions about UV theory
- We are interested in phenomenological questions about Higgs decays
- New, previously ignored operators, new decays
  - Supersoft [Nelson, Weiner and PF]
  - New vector-like matter coupled to $S$ [Dobrescu, Landsberg, Matchev]
  - $S = s + ia + \theta\psi_s + \ldots$

# LEP limits




LEP limits usually quoted as limits on $\xi^2$ (or $c^2$ or $k$ or ...)

$$\xi_X^2 \equiv \frac{\sigma(e^+e^- \to hZ)}{\sigma(e^+e^- \to hZ)_{SM}} \times BR(h \to X)$$

$$\begin{pmatrix} \text{SM higgs :} & m_h \geq 114.4\text{GeV} \\ \text{Invis. higgs :} & m_h \geq 114\text{GeV} \\ \text{Model indep. :} & m_h \geq 81\text{GeV} \end{pmatrix}$$

$$@\ 95\%\ CL\ (\xi^2 = 1)$$

We will be most interested in the constraints on cascade decays

# Rough calculation

## Can non-standard decays dominate?

$\Gamma_{h\to 2a} \gtrsim 4 \times \Gamma_{h\to bb}$

$$\mathcal{L} \supset \frac{c}{\sqrt{2}} v h a^2$$

$$\Gamma_{h\to 2a} = \frac{c^2 v^2}{16\pi m_h}\left(1 - 4\frac{m_a^2}{m_h^2}\right)^{1/2}$$

$$\Gamma_{h\to 2b} = \frac{3m_b^2}{16\pi v^2} m_h \left(1 - 4\frac{m_a^2}{m_h^2}\right)^{3/2}$$

$\Gamma_{h\to 2a} \gtrsim 4 \times \Gamma_{h\to bb} \Rightarrow \frac{cv}{\sqrt{2}} \gtrsim 5\mathrm{GeV}$

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$\Gamma_{h\to 2a} \gtrsim 4 \times \Gamma_{h\to bb} \Rightarrow \frac{cv}{\sqrt{2}} \gtrsim 5\mathrm{GeV}$

Yes!

# Effects of mixing

Mass eigenstates related to interaction eigenstates by,

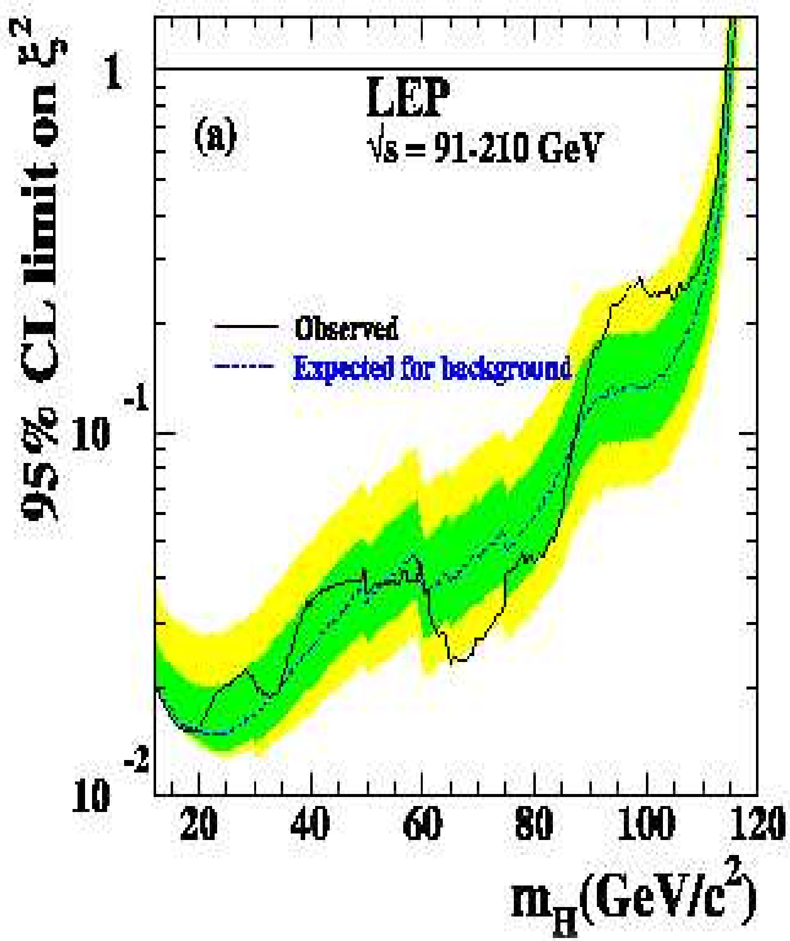
$$\begin{pmatrix} \tilde{s} \\ \tilde{h} \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} s \\ h \end{pmatrix}$$

$$m_{\tilde{h}}^2 = \frac{m_{mssm}^2 - m_{\tilde{s}}^2 \sin^2\theta}{\cos^2\theta}$$

An increase in mass through mixing without radiative corrections, alleviates tuning.

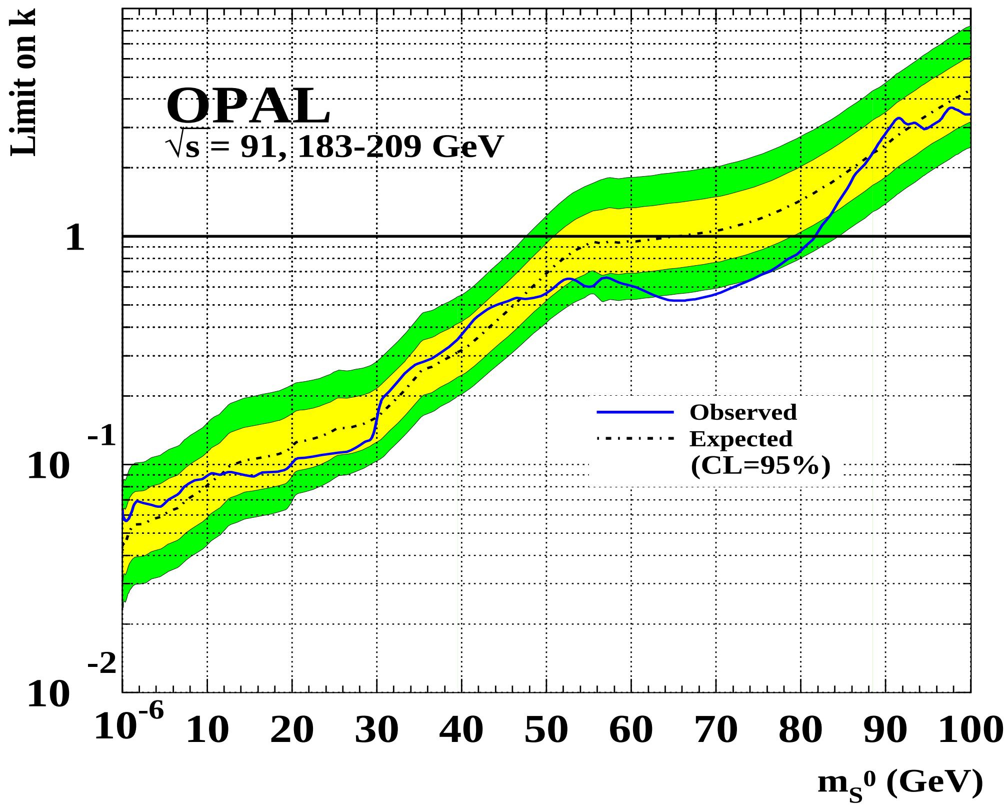
# LEP constraints–SM like

$m_h \geq 114.4\text{GeV}$ [André Sopczak, SUSY05]



# Model Independent

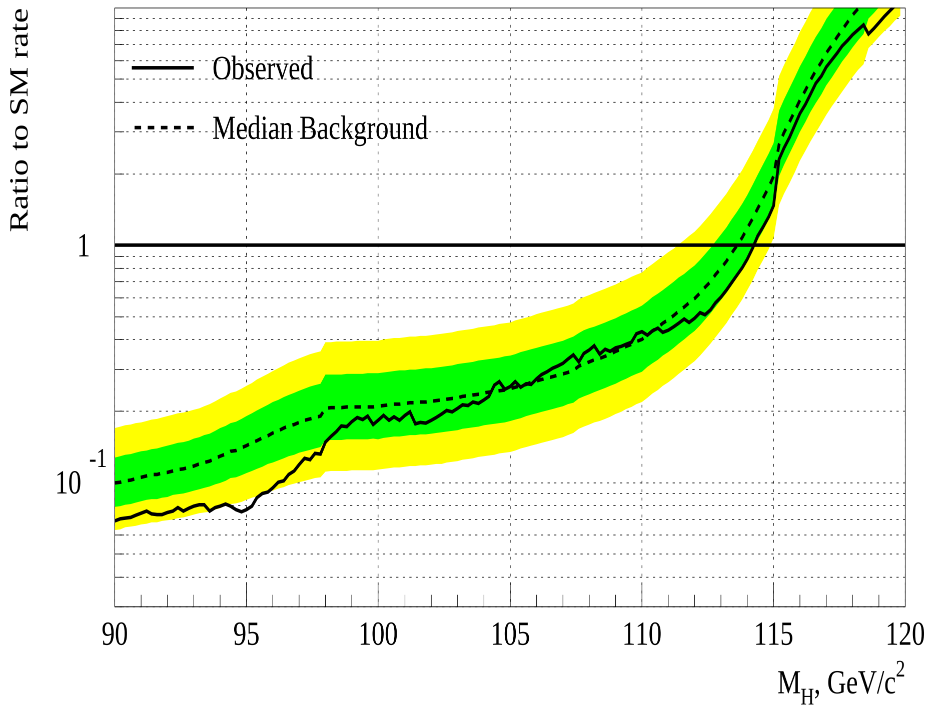
$m_h \geq 81\text{GeV}$




[*Eur. Phys. J.* **C27** (2003) 311-329; hep-ex/0206022]

# Invisible decay

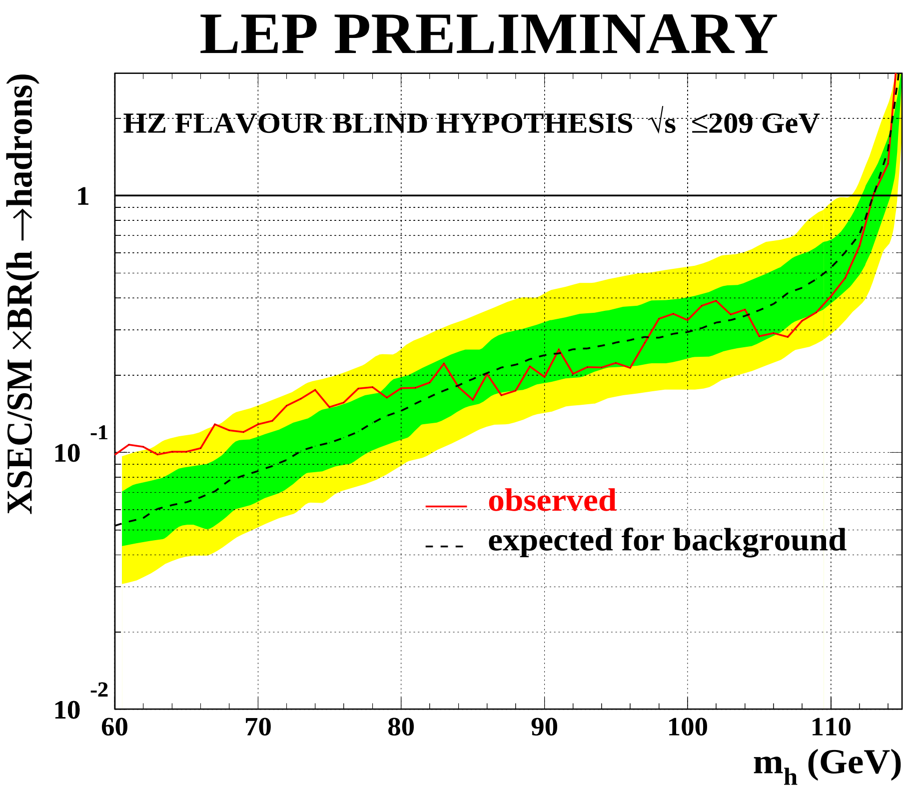
$m_h \geq 114\text{GeV}$




LEP-wide analysis. [hep-ex/0107032]

# 2 jets

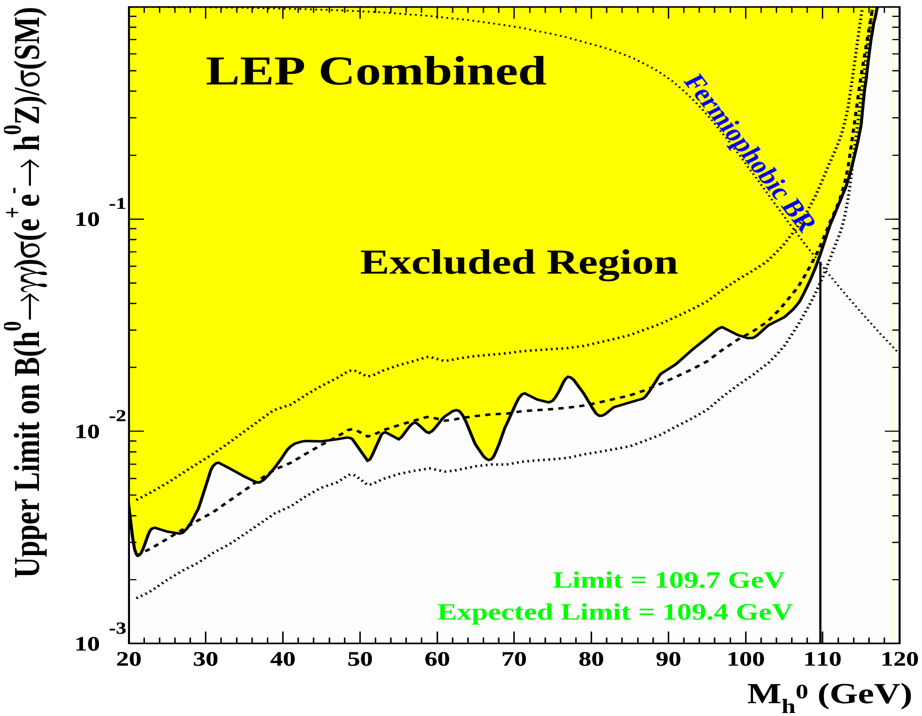
$m_h \geq 113\text{GeV}$




[hep-ex/0107034]

# 'Fermiophobic'

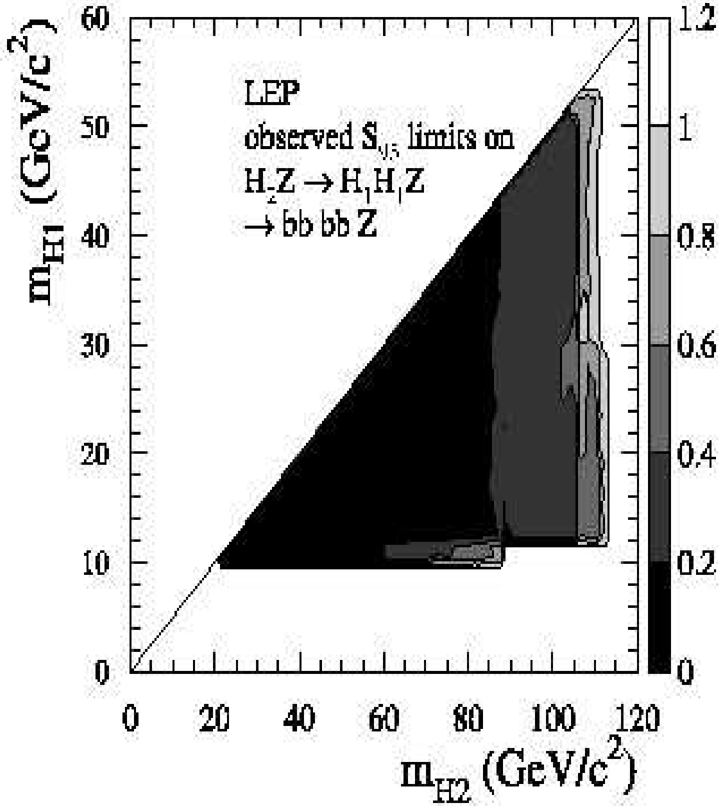
$m_h \geq 109.7\mathrm{GeV},\ 117\mathrm{GeV}$ if exclusively to photons

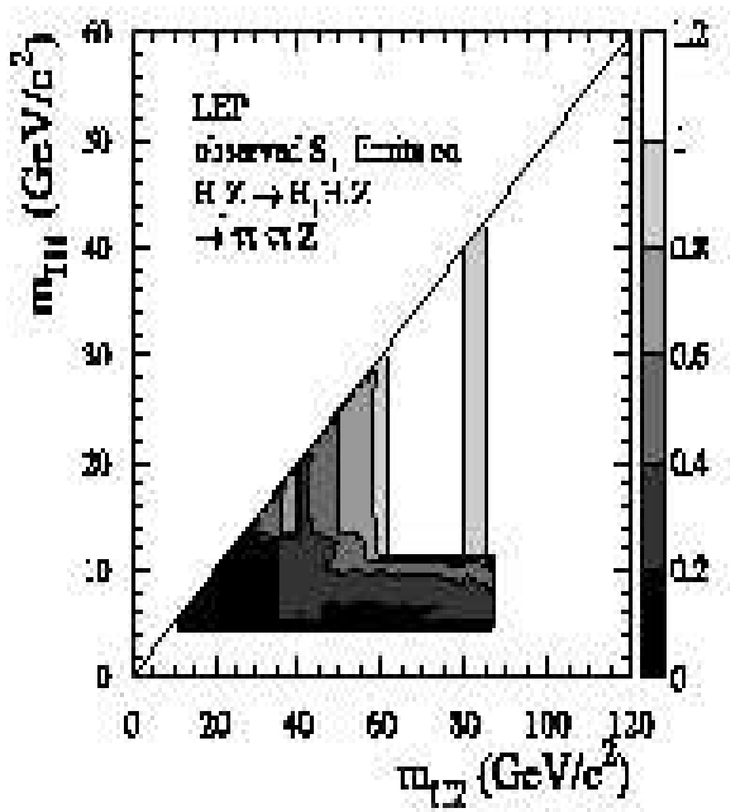



[hep-ex/0212038]

# Cascade decays

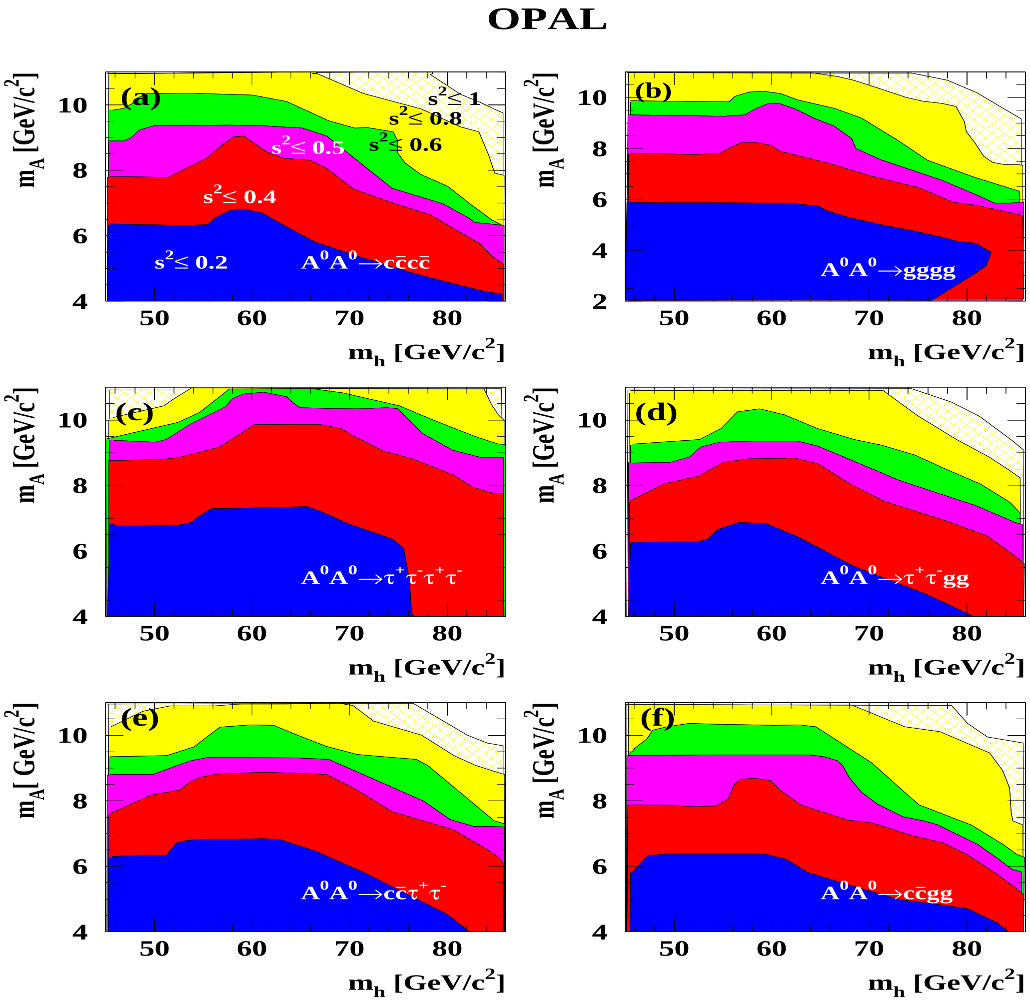
$m_h \geq 110\mathrm{GeV}$ for 4b final state [André Sopczak, SUSY05]



# Cascade decays

$m_h \geq 86\text{GeV}, \text{ if} m_a \lesssim 12\text{GeV}$




[*Eur. Phys. J.* **C27** (2003) 483-495; hep-ex/0209068]

# New Operators with singlets

| | |
|---|---|
| $\delta_s^2$ | $XX^\dagger(S+S^\dagger)^2_D$ |
| $\delta_a^2$ | $XX^\dagger(S-S^\dagger)^2_D$ |
| $m_D$ | $(W'_\alpha W^\alpha S)_F$ |
| $\lambda_h$ | $(SH_uH_d)_F$ |
| $A_s$ | $(XS^3)_F \ + \ h.c.$ |
| $A_h$ | $(XSH_uH_d)_F \ + \ h.c.$ |
| $m^2_{CP}$ | $XX^\dagger(S+S^\dagger)(S-S^\dagger)_D$ |
| $M_Q^{-1}$ | $(SQ\bar{Q}+M_QQ\bar{Q})_F$ |

SUSY breaking spurions:

$$X=\theta^2F_X \qquad W'_\alpha=\theta_\alpha D$$

# Scalar masses

- $\delta_s^2$, $\delta_a^2$–Scalar/pseudo-scalar masses

$$X^\dagger X \left(S + S^\dagger\right)^2\Big|_{\theta^4} = \frac{\delta_s^2}{2} s^2$$

$$X^\dagger X \left(S - S^\dagger\right)^2\Big|_{\theta^4} = \frac{\delta_a^2}{2} a^2$$

No reason for $\delta_a = \delta_s$, no symmetry

# New operators with a singlet

- $\delta_s^2$, $\delta_a^2$–Scalar/pseudo-scalar masses
- $m_D$–Supersoft operator

# Supersoft

Source of SUSY breaking is a D-term in a hidden sector $U(1)$. [Nelson, Weiner and PF]

In presence of SM adjoints, (e.g. $S$),

$$\int d^2\theta \sqrt{2} \frac{W'_\alpha W_j^\alpha A_j}{M} + \text{h.c.} \rightarrow$$

$$\mathcal{L} \supset -m_D \lambda_j \tilde{a}_j - \sqrt{2} m_D (a_j + a_j^*) D_j - D_j (\sum_i g_k q_i^* t_j q_i) - \frac{1}{2} D_j^2$$

offshell, and onshell ($m_D = D'/M$)

$$\mathcal{L} \supset -m_D \lambda_j \tilde{a}_j - m_D^2 (a_j + a_j^*)^2 - m_D (a_j + a_j^*)(\sum_i g_k q_i^* t_j q_i)$$

# Supersoft

- ESPs marry gauginos $\rightarrow$ Dirac gaugino masses
- Real scalar piece of ESP gets a tree level mass
- New scalar trilinear interaction, no analogue in MSSM
- Scalar masses not even log sensitive to high scale, running stops at gaugino mass.

# Supersoft

In MSSM+S we have an adjoint.

$$\mathcal{L} = \int d^2\theta \frac{W'_\alpha}{M} W_Y^\alpha S + h.c. \rightarrow -\frac{1}{2}(m_D s + D_Y)^2 + \frac{m_D}{2}\psi_S \lambda$$

$D_Y = \sum_i g_Y q_i \phi_i^* \phi_i$ Mixing from this operator leads to,

$$\begin{pmatrix} m_D^2 + \Delta_s^2 & \frac{g m_D v s_{\alpha+\beta}}{\sqrt{2}} & -\frac{g m_D v c_{\alpha+\beta}}{\sqrt{2}} \\ \frac{g m_D v s_{\alpha+\beta}}{\sqrt{2}} & m_h^2 & 0 \\ -\frac{g m_D v c_{\alpha+\beta}}{\sqrt{2}} & 0 & m_H^2 \end{pmatrix}$$

Also leads to $h \rightarrow ss$ decays

# New operators with a singlet

- $\delta_s^2$, $\delta_a^2$–Scalar/pseudo-scalar masses
- $m_D$–Supersoft operator
- $\lambda_h S H_u H_d$

# Superpotential: $\lambda_s S H_u H_d$

Since we are not restricting to NMSSM also include a $\mu$-term. Can be removed by

$$S \rightarrow S - \sqrt{2}\frac{\mu}{\lambda_h}$$

With additional mass term for $S$,

$$\mu_{eff} = \mu \left( \frac{\delta_s^2}{\delta_s^2 + \lambda_h^2 v^2} \right)$$

Mixing:

$$\begin{pmatrix} \lambda_h^2 v^2 + \delta_s^2 & -2\lambda_h v \tilde{\mu} s_{\alpha-\beta} & 2\lambda_h v \tilde{\mu} c_{\alpha-\beta} \\ -2\lambda_h v \tilde{\mu} s_{\alpha-\beta} & m_h^2 & 0 \\ 2\lambda_h v \tilde{\mu} c_{\alpha-\beta} & 0 & m_H^2 \end{pmatrix}$$

# Superpotential: $\lambda_s S H_u H_d$

Decays: $h \longrightarrow 2s, 2a$ and $s \longrightarrow 2a$

# New operators with a singlet

- $\delta_s^2$, $\delta_a^2$–Scalar/pseudo-scalar masses
- $m_D$–Supersoft operator
- $\lambda_h S H_u H_d$
- $A_S S^3 + c.c.$

# New operators with a singlet

- $\delta_s^2$, $\delta_a^2$–Scalar/pseudo-scalar masses
- $m_D$–Supersoft operator
- $\lambda_h S H_u H_d$
- $A_S S^3 + c.c.$

$X A_S S^3\big|_{\theta^2}$: Alone this does little, (opposite) contribution to scalar masses.

With mixing gives $h \to 2s, 2a$

# New operators with a singlet

- $\delta_s^2$, $\delta_a^2$–Scalar/pseudo-scalar masses
- $m_D$–Supersoft operator
- $\lambda_h S H_u H_d$
- $A_S S^3 + c.c.$
- $A_h S H_u H_d + c.c.$

# A-term: $A_h S H_u H_d$

$$XSH_uH_d|_{\theta^2}$$

- Generated at the loop level if $\lambda_h S H_u H_d$ is present
- Mixes $A^0$ and $a$, allows $a \to 2b/2\tau$
- Have $h \to 2s, 2a$ and $s \to 2a$

$$\begin{pmatrix} \delta_s^2 & A_h v\cos(\alpha+\beta) & A_h v\sin(\alpha+\beta) \\ A_h v\cos(\alpha+\beta) & m_h^2 & 0 \\ A_h v\sin(\alpha+\beta) & 0 & m_H^2 \end{pmatrix}$$

$$\begin{pmatrix} m_a^2 & -A_h v \\ -A_h v & m_A^2 \end{pmatrix}$$

# New operators with a singlet

- $\delta_s^2$, $\delta_a^2$–Scalar/pseudo-scalar masses
- $m_D$–Supersoft operator
- $\lambda_h S H_u H_d$
- $A_S S^3 + c.c.$
- $A_h S H_u H_d + c.c.$
- $m_{CP}^2 sa$–CP mixing mass

# Mixing term: $m_{CP}^2 sa$

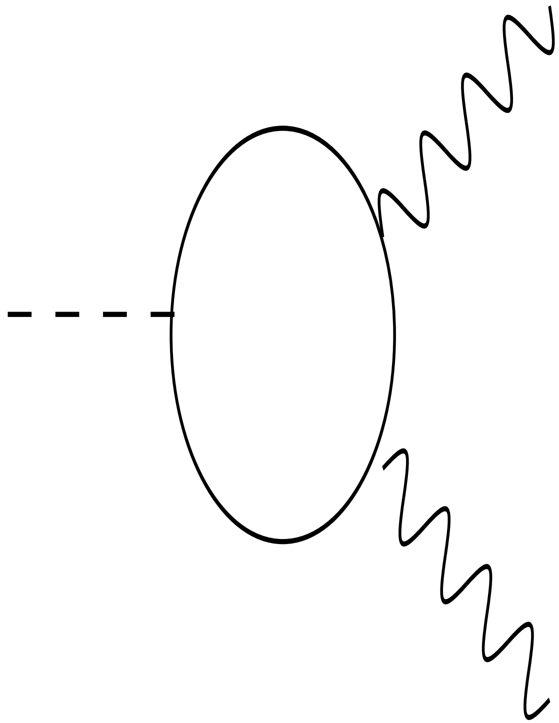
$$XX^\dagger \left(S+S^\dagger\right)\left(S-S^\dagger\right)\Big|_{\theta^4}$$

- Does *not* violate CP by itself, only if $a$ couples to fermions or gauge bosons, or mixes with $A^0$–no EDM problems.
- Can induce $h \to sa$ if $h \to 2s$ forbidden. e.g. with supersoft

# New operators with a singlet

- $\delta_s^2$, $\delta_a^2$–Scalar/pseudo-scalar masses
- $m_D$–Supersoft operator
- $\lambda_h S H_u H_d$
- $A_S S^3 + c.c.$
- $A_h S H_u H_d + c.c.$
- $m_{CP}^2 sa$–CP mixing mass
- $\lambda_Q S Q\bar{Q} + M_Q Q\bar{Q}$–Fermiophobic decays

# Fermiophobic decays



- Integrate out heavy coloured matter, loop induced $s, a \to 2g/2\gamma$ decays
- Dominant for $a$, if small mixing between $a$ and $A^0$ through loop-induced $A_h$
- Branching ratios for $h \to 2a \to (4g, 2g2\gamma, 4\gamma) = (0.99, 7.6 \times 10^{-3}, 1.5 \times 10^{-5})$
- Viable search channel at LHC?–possibly

  [Dobrescu, Landsberg, Matchev]

# Necessary operators

- $a$ should decay: $A_h$, $m_{CP}^2$, $M_Q^{-1}$
- $h$ should have cascade decays: $m_D$, $\lambda_h$, $A_s$ (with source of mixing from another operator), $A_h$
- If $s$ is light it also needs cascade decays (unless below 12 GeV ): $\lambda_h$ (with source of mixing from another operator), $A_s$, $A_h$ (with source of mixing from another operator), $m_{CP}^2$

Some operators better than others

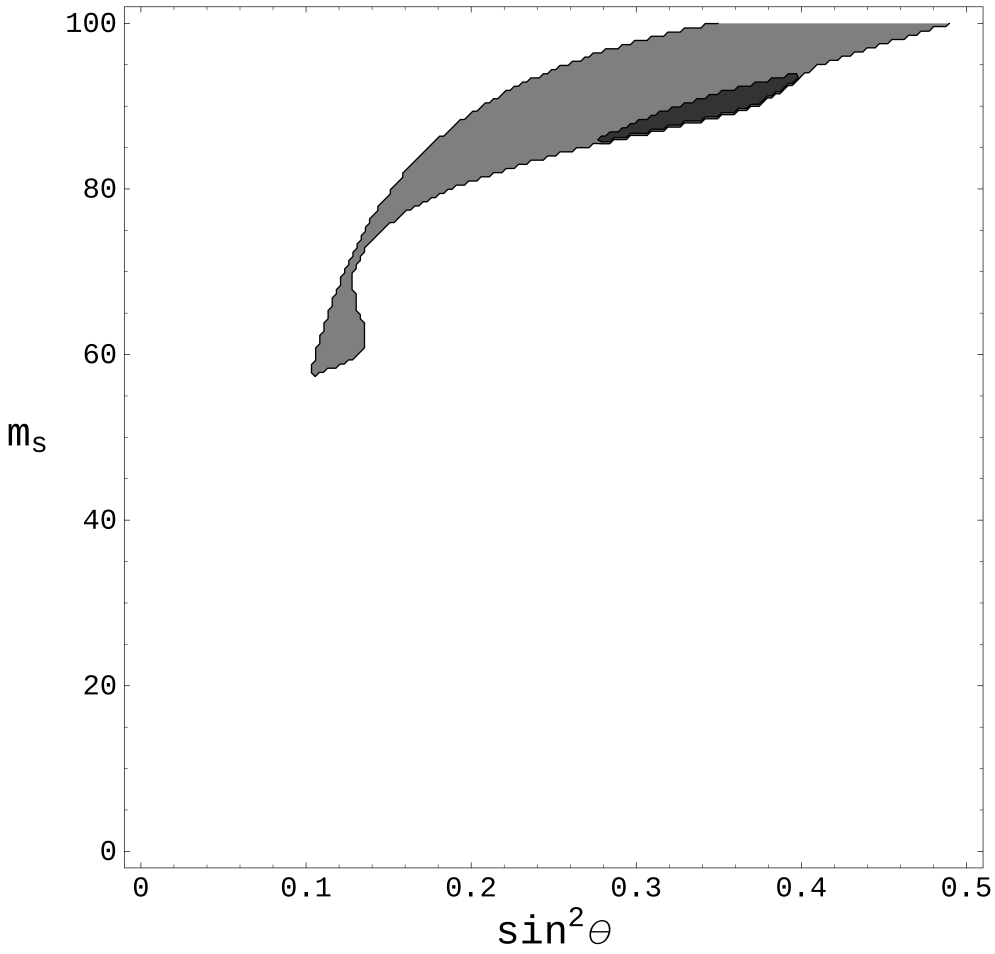
# Scenarios

- Mixing with $s$ pushes higgs heavy, $m_h \geq 114\mathrm{GeV}$, or $110\mathrm{GeV}$ for 4b final state
- Single stage higgs decays $h \to 2a \to 2X$. If $X = b\bar{b}$, $m_h \geq 110\mathrm{GeV}$, if $X = 2\tau$ (tuned), $m_h \gtrsim 86\mathrm{GeV}$ or $X = 2g$ $m_h \gtrsim 82\mathrm{GeV}$
- Double stage decay $h \to 2s \to 4a \to 4X$ or $h \to as \to 3a \to 3X$, $m_h \geq 82\mathrm{GeV}$

Two types of tuning

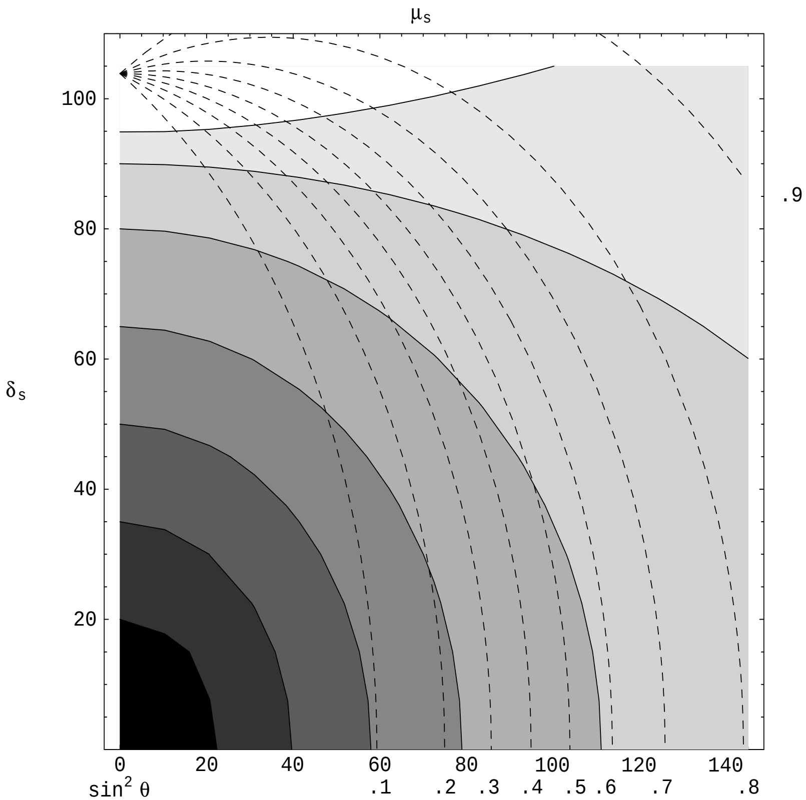
- $\frac{\partial \log m_Z}{\partial \log \text{“parameter”}}$ $\sim$stop mass
- Spectral tuning to avoid experimental constraints

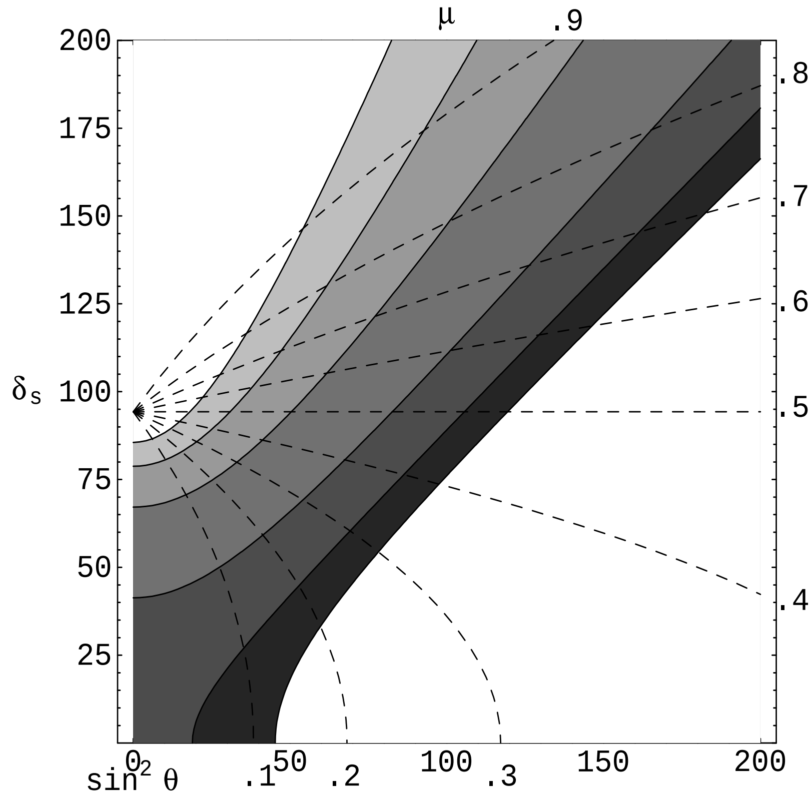
# Allowed regions




Allowed regions if $h \rightarrow 2a \rightarrow 4b$, $s \rightarrow 4b$, $m_{\tilde{t}} = 300\mathrm{GeV}$

# Possible realisations




Using supersoft operator

darkest to lightest–20,25,50,65,80,90,95 $\mathrm{GeV}$

Using superpotential ($\lambda_h = 0.25$)

darkest to lightest–20,40,60,80,90,96 $\mathrm{GeV}$

# Single stage cascades

$$h \longrightarrow 2a \longrightarrow 4b$$

Least tuning with supersoft: $m_D$, $A_s$, $m_{\tilde{t}} = 325\mathrm{GeV} \Rightarrow$

| $\sin^2\theta$ | $m_{\tilde{h}}$ | $m_{\tilde{s}}$ | $m_{\tilde{a}}$ | $B(\tilde{h} \longrightarrow 2\tilde{a})$ | $B(\tilde{s} \longrightarrow 2\tilde{a})$ | tuning |
|---|---|---|---|---|---|---|
| 0.1 | 109 | 73.8 | 32.6 | 0.86 | .99 | 3% |

Light stops, but still “tuned"–Just so region

# Single stage cascades

$$h \longrightarrow 2a \longrightarrow 4g, 4\tau$$

- Possible with $\lambda_h$ and $M_Q^{-1}$ but need $A_h$ small.
- Less tuned with $m_D$, $A_s$ and $M_Q^{-1}$ ($A_h$ for $4\tau$), $m_{\tilde{t}} = 175\text{GeV} \Rightarrow$

| $\sin^2\theta$ | $m_{\tilde{h}}$ | $m_{\tilde{s}}$ | $m_{\tilde{a}}$ | $B_{\tilde{h}\to 2\tilde{a}}$ | $B_{\tilde{s}\to 2\tilde{a}}$ | tuning |
|---|---|---|---|---|---|---|
| .22 | 94.9 | 76.2 | 28.3 | .92 | .99 | 100% |
| | | | (8.37) | (.93) | | (10%) |

Tuning comes about from making $m_a < 12\text{GeV}$

# Double stage cascades

$$h \rightarrow 2s \rightarrow 4a \rightarrow 8g, 8b, 8\tau$$

- Tough to get with $\lambda_h$ since $s$ lighter than $a$.
- Final states never searched for, complicated
- $m_D$, $A_s$ and $M_Q^{-1}$ or $A_h$, $m_{\tilde{t}} = 360\mathrm{GeV} \Rightarrow$

| $\sin^2\theta$ | $m_{\tilde{h}}$ | $m_{\tilde{s}}$ | $m_{\tilde{a}}$ | $B_{\tilde{h}\rightarrow 2\tilde{a}}$ | $B_{\tilde{h}\rightarrow 2\tilde{s}}$ | $B_{\tilde{s}\rightarrow 2\tilde{a}}$ | tuning |
|---|---|---|---|---|---|---|---|
| .06 | 111 | 39.3 | 16.2 | .35 | .50 | .99 | 4% |
| | | | (7.13) | (0.36) | (0.49) | | (2%) |

$$\tilde{h} \rightarrow \tilde{a}\tilde{s} \rightarrow 3\tilde{a} \rightarrow 6b, 6\tau$$

| $\sin^2_{\theta_{sh}}$ | $\sin^2_{\theta_{ah}}$ | $m_{\tilde{h}}$ | $m_{\tilde{s}}$ | $m_{\tilde{a}}$ | $B_{\tilde{h}\rightarrow\tilde{a}\tilde{s}}$ | $B_{\tilde{s}\rightarrow 2\tilde{a}}$ | tuning |
|---|---|---|---|---|---|---|---|
| 0.10 | .01 | 103 | 67.0 | 18.4 | .70 | .91 | 100% |
| | | | (66.6) | (9.87) | (0.69) | (0.96) | 18% |

# Benchmark summary

Simple(st?) extension of MSSM greatly enhances Higgs phenomenology, different from NMSSM.

- $h \to 2a \to 4b$ Just so, less tuned with supersoft
- $h \to 2s/2a \to 4\tau$ Requires spectral tuning. OPAL limits stop at $86\mathrm{GeV}$–Why?–new analysis
- $h \to 2a \to 4g$ Higgs as light as $82\mathrm{GeV}$, only OPAL did model independent. Possible $2g2\gamma$ or $4\gamma$ signals
- $\tilde{h} \to \tilde{a}\tilde{s} \to 3\tilde{a} \to 6b, 6\tau$ little tuning with supersoft, not present in NMSSM. Higgs as light as $82\mathrm{GeV}$
- $h \to 2s \to 4a \to 8g, 8b, 8\tau$ only with supersoft, not in NMSSM

Lesson: pheno first model later.

# Conclusions and the future

- MSSM suffers from LHP
- *Lowering* Higgs mass and giving it novel decays also solves problem, allows for light stops
- MSSM+S$\neq$NMSSM
- Consider all operators, in particular supersoft and new coloured matter
- Tunings come in two forms

# Conclusions and the future

- New signals from general analysis
- New signals demand new analyses e.g. model independent, low $a$ mass
- New scenarios with light (stealthy) higgs **and** light superpartners
- New analyses for LHC and beyond e.g. $4\gamma$ final state