Naturalness and Higgs decays in the MSSM with a singlet–

searching for a stealthy Higgs

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LBNL

Layout

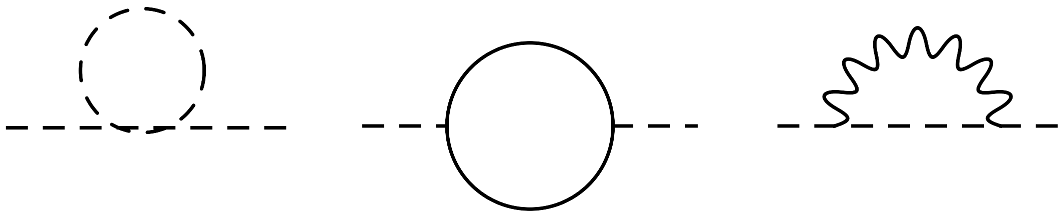
- SUSY little hierarchy problem and a possible solution
- Higgs limits from LEP
- MSSM+S$\neq$NMSSM and its new operators
- New phenomenology
- Conclusions and the future

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



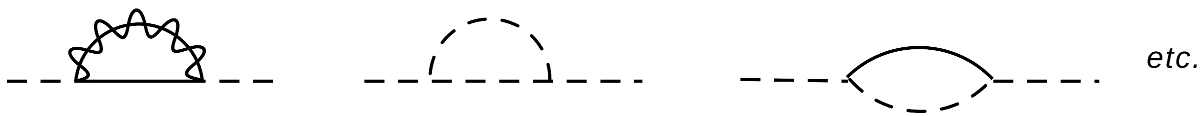
etc.

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

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

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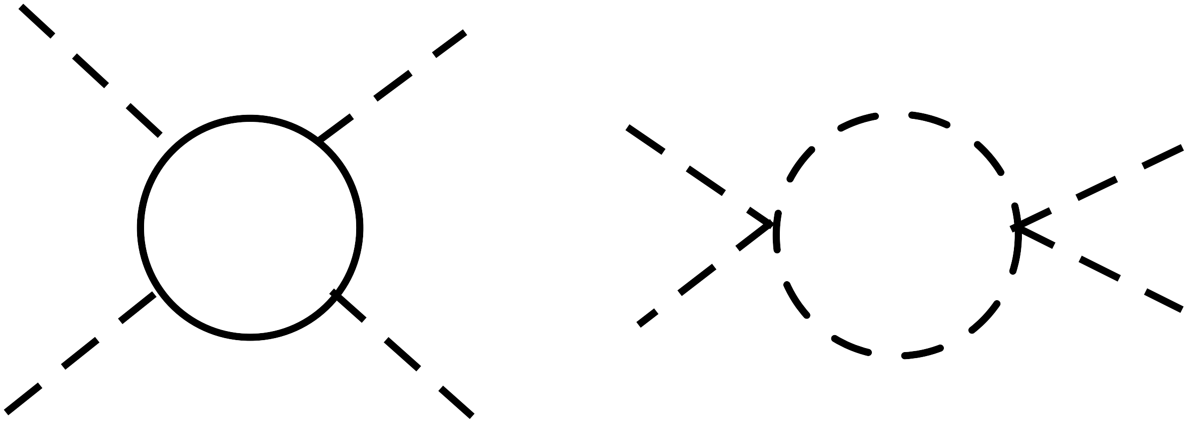
- The ugly(?): Need to raise Higgs mass, e.g. increase quartics. Loop corrections, NMSSM, Fat higgs, non-decoupling D-terms, little supersymmetry etc.

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 μ-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 [Gunion et al.]
- 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]
  - $S = s + ia + \theta\psi_s + \ldots$

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

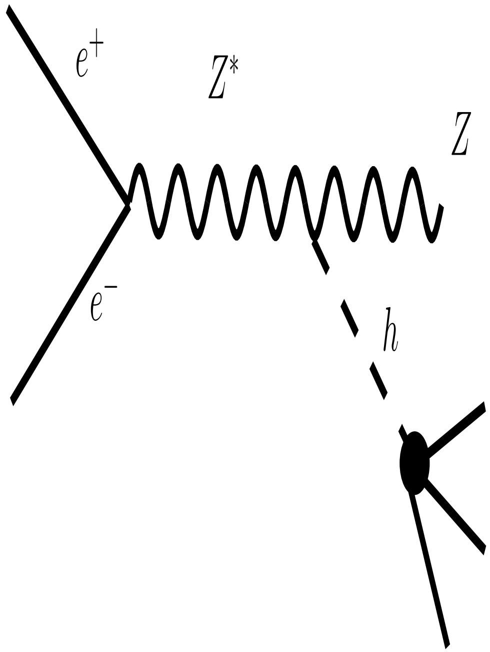
Mass eigenstates related to interaction eigenstates by,

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

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

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

LEP limits



LEP limits usually quoted as limits on ξ^2 (or c^2 or k or $\ldots$)

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

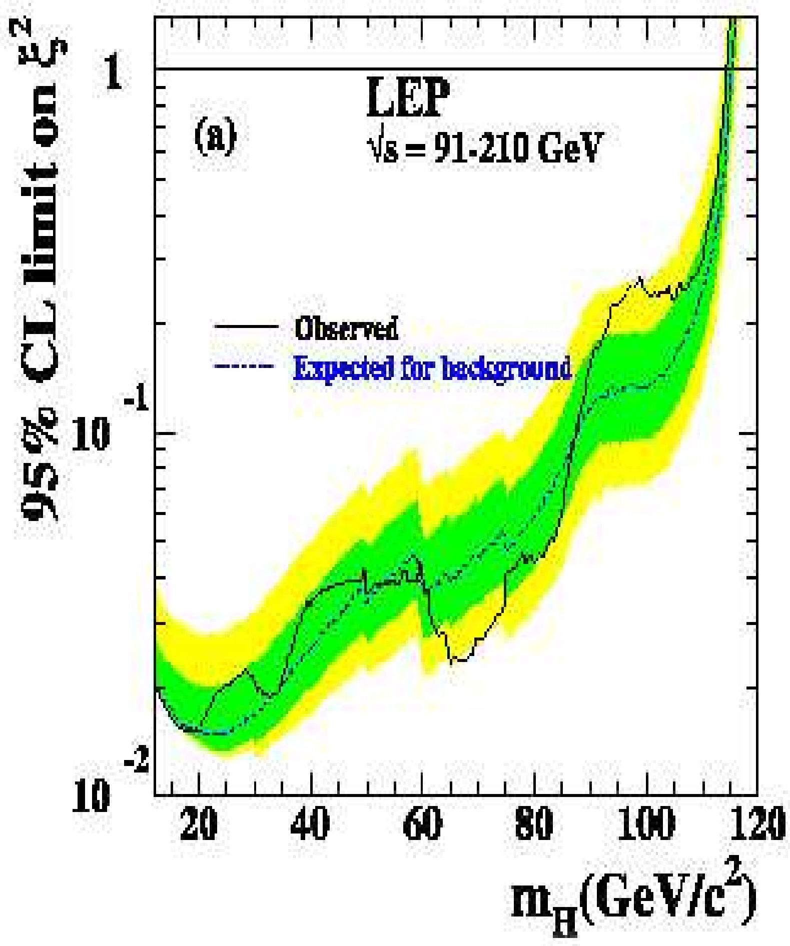
$$\left(\begin{array}{cc} \text{SM higgs :} & m_h \geq 114.4\text{GeV} \\ \text{Invis. higgs :} & m_h \geq 114\text{GeV} \\ \text{Model indep. :} & m_h \geq 81\text{GeV} \end{array} \right)$$

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

We will be most interested in the constraints on cascade decays

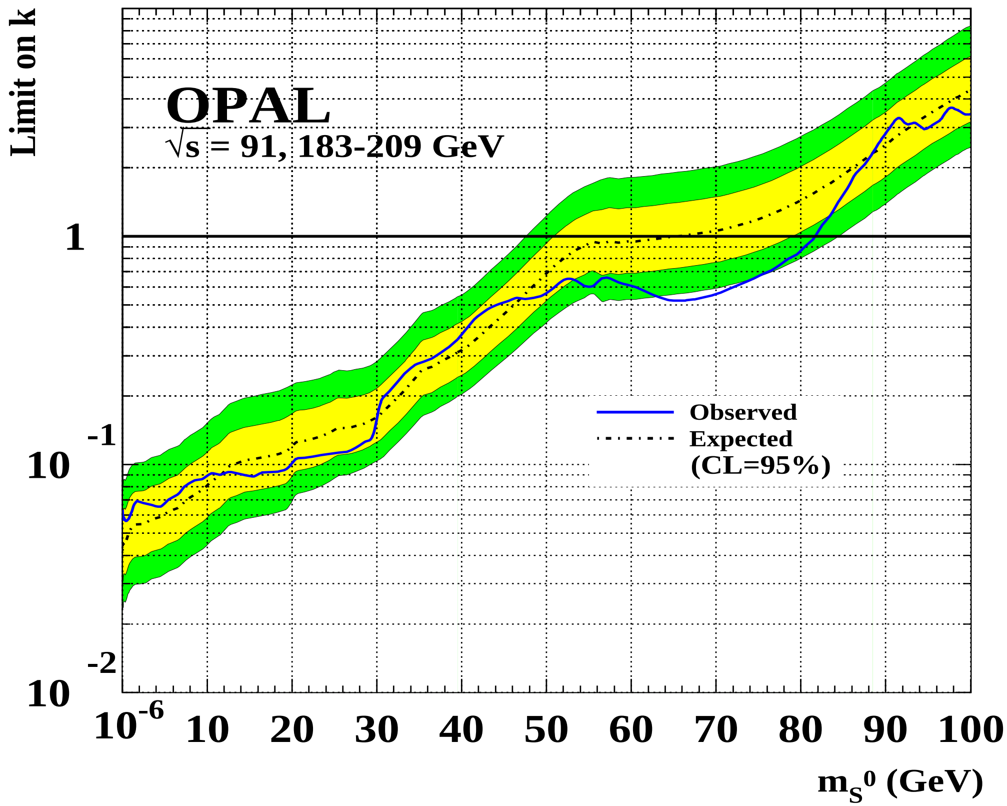
LEP constraints–SM like

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



Model Independent

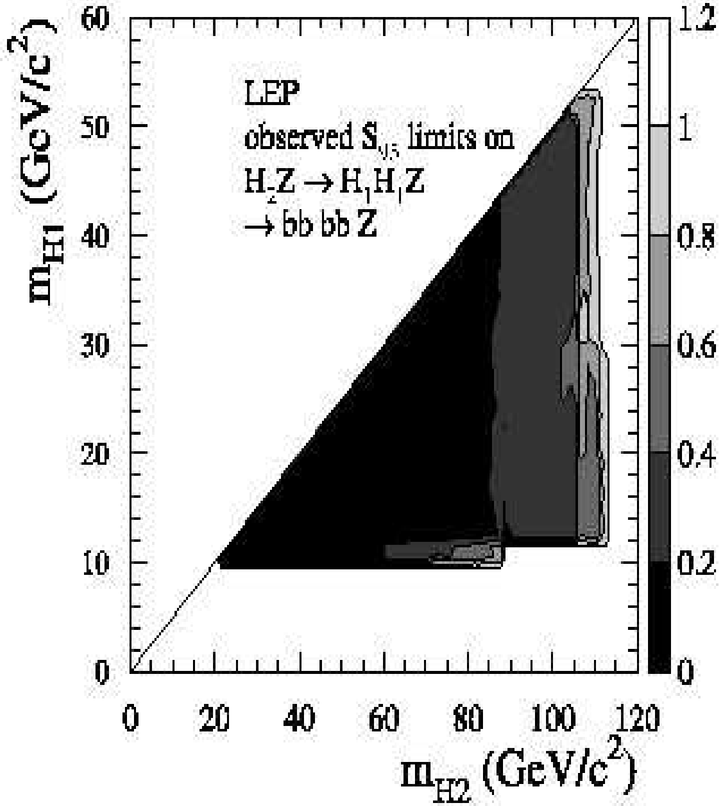
$m_h \geq 81\text{GeV}$

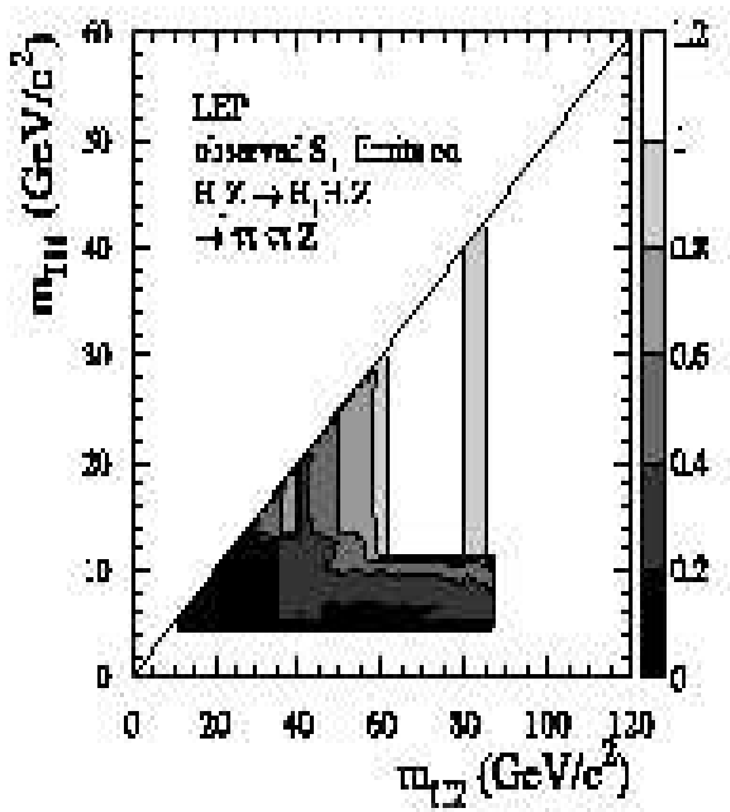


[*Eur. Phys. J.* **C27** (2003) 311-329; hep-ex/0206022]

Cascade decays

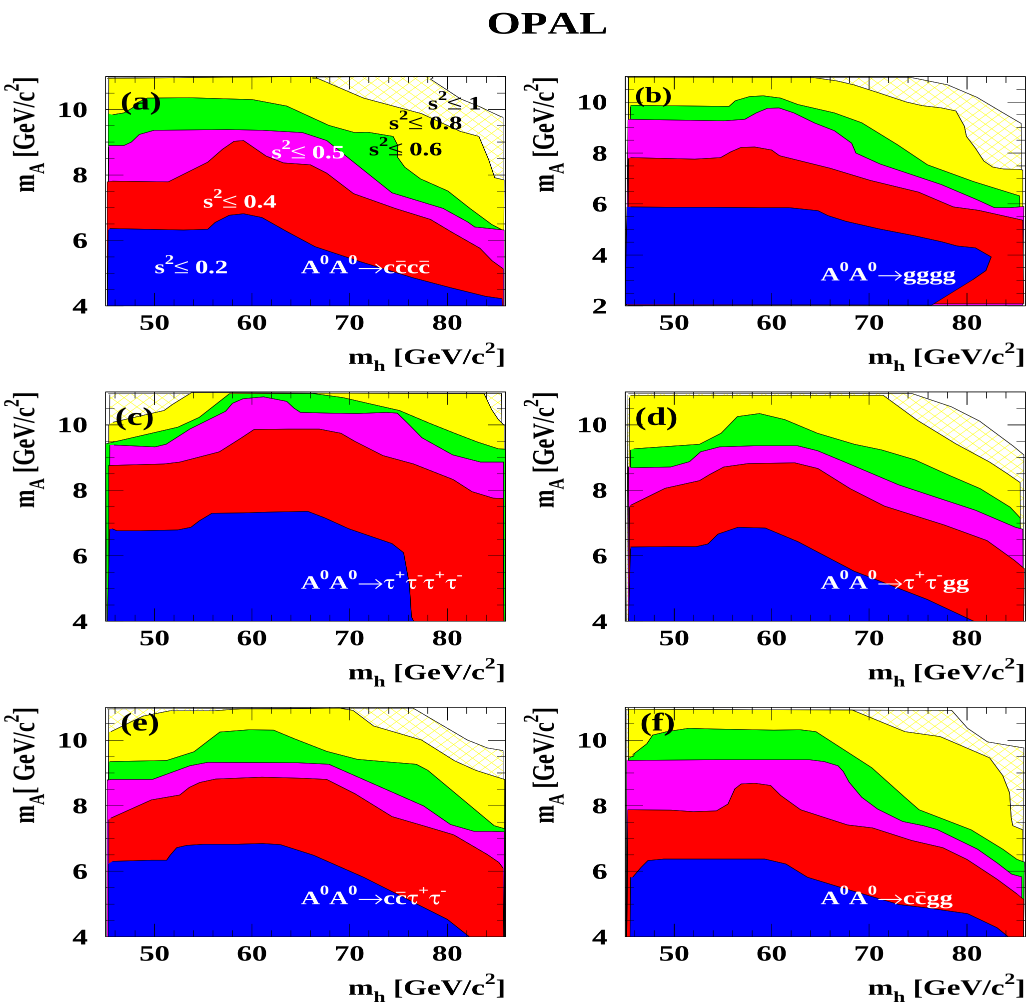
$m_h \geq 110\mathrm{GeV}$ for 4b final state [André Sopczak, SUSY05]





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

NMSSM

$W = \lambda_S S H_u H_d + \kappa_S S^3 \leftarrow$ Supersymmetric

$V = \lambda_S A_\lambda S H_u H_d + \kappa_S A_\kappa S^3 + m_S^2 |S|^2 + c.c. \leftarrow$ soft SUSY breaking

Additional possible terms

- $\delta_s^2 s^2$, $\delta_a^2 a^2$–Scalar/pseudo-scalar masses
- Mixing term: $m_{CP}^2 sa$
- $\lambda_Q S Q \bar{Q} + M_Q Q \bar{Q}$–Fermiophobic decays
- Supersoft operator: $W'_\alpha W^\alpha S$

NMSSM-like operators

Superpotential: $\lambda_s S H_u H_d$
Leads to mixing

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

Decays $h \to 2s, 2a$ and $s \to 2a$

NMSSM-like operators

A-term: $A_h S H_u H_d$

- 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 $s \to 2a$

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

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

NMSSM-like operators

Superpotential and A-term have similar affect on Higgs physics

$A_S S^3$

- Alone this does little, (opposite) contribution to scalar masses.
- With another source of mixing gives $h \to 2s, 2a$

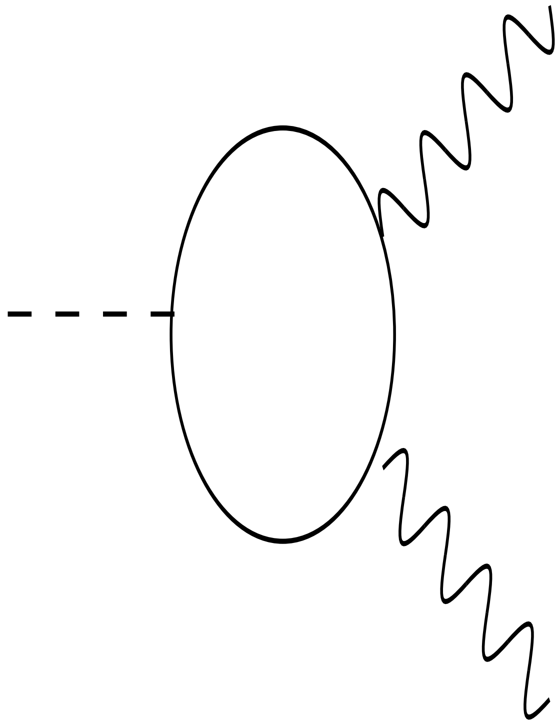
Other Operators

Mixing term: $m^2_{CP} sa$

- 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

Other Operators

$\lambda_Q S Q\bar{Q} + M_Q Q\bar{Q}$



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 TeVatron/LHC?–possibly [Dobrescu, Landsberg Matchev]

Other operators–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

Necessary operators

- a should decay: A_h, m_{CP}^2, M_Q^{-1}
- h should have cascade decays: m_D, λ_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): λ_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

Single stage cascades

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

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

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

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

Single stage cascades

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

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

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

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

Fermiophobic Higgs

$h \to 2a \to 4g, 2g2\gamma, 4\gamma$

- Very hard to see at TeVatron/LHC
- To reconstruct Higgs at LHC need 4γ channel
- Dominant backgrounds (small) are $n\ jets + (4-n)\gamma$, pileup events
- Consistent pairs trick
- Br $\gtrsim few \times 10^{-4}$ discoverable with $300 fb^{-1}$

Double stage cascades

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

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

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

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

$\sin^2_{\theta_{sh}}$	$\sin^2_{\theta_{ah}}$	$m_{\tilde{h}}$	$m_{\tilde{s}}$	$m_{\tilde{a}}$	$B_{\tilde{h}\to\tilde{a}\tilde{s}}$	$B_{\tilde{s}\to 2\tilde{a}}$	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 4γ 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.

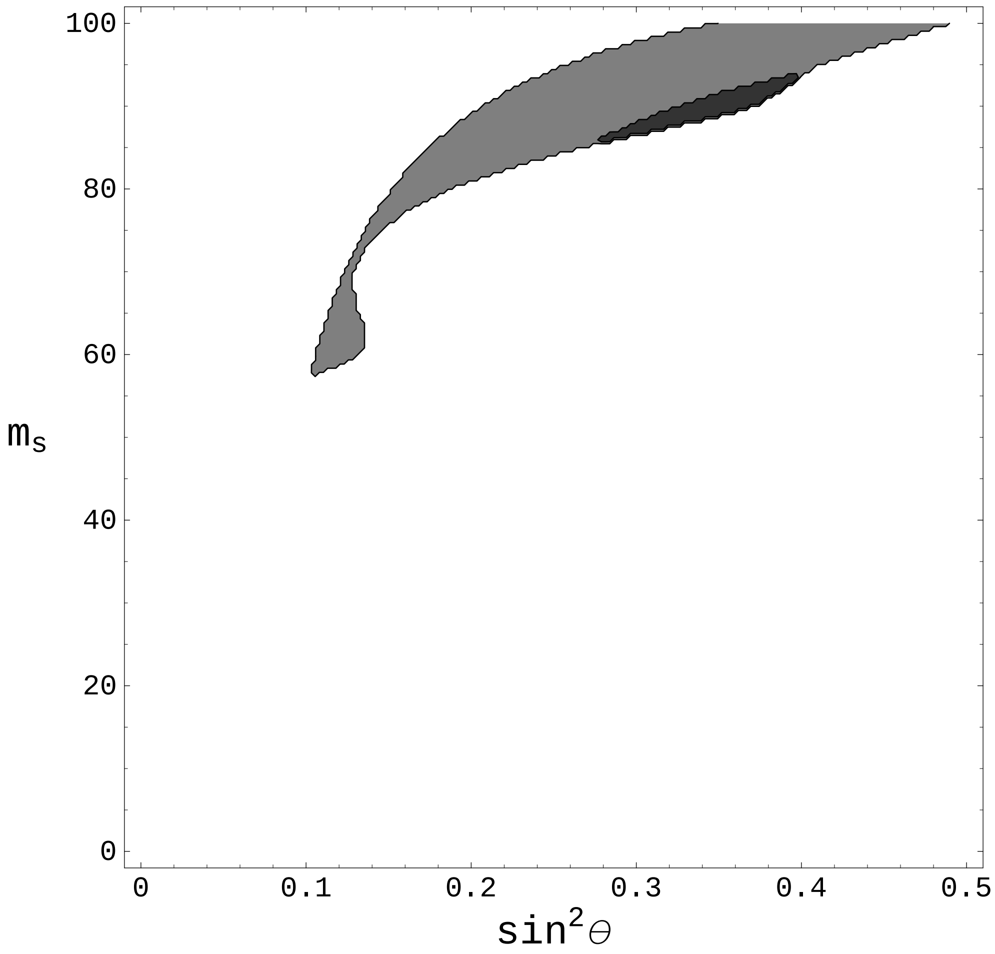
Conclusions and the future

- 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

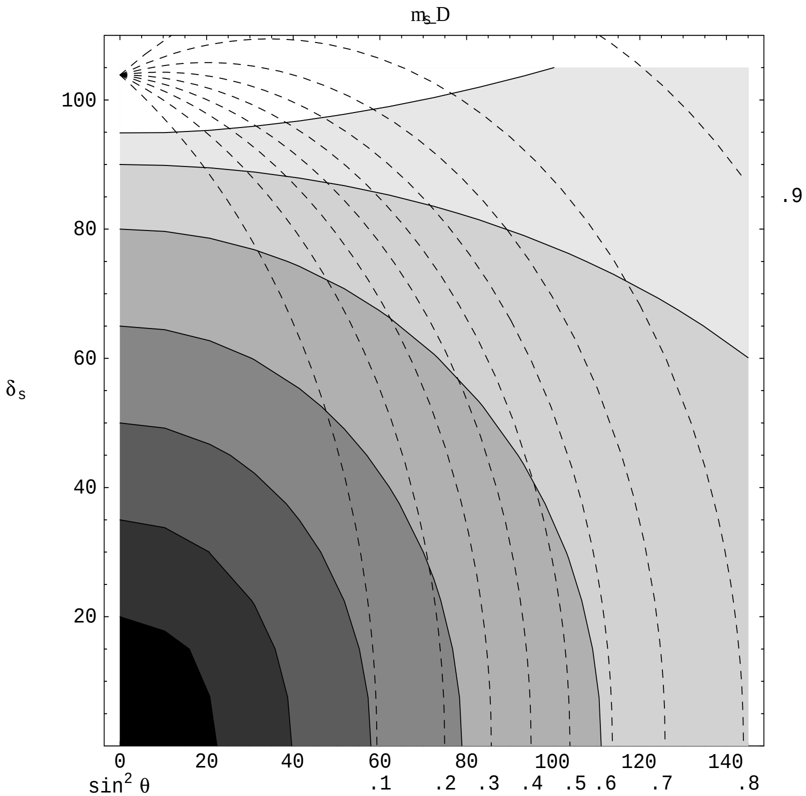
- New signals from general analysis
- New signals demand new analyses e.g. model independent, low a mass
- New scenarios with light (stealthy) higgs **and** light superpartners
- New analyses for LHC and beyond e.g. 4γ final state

Allowed regions



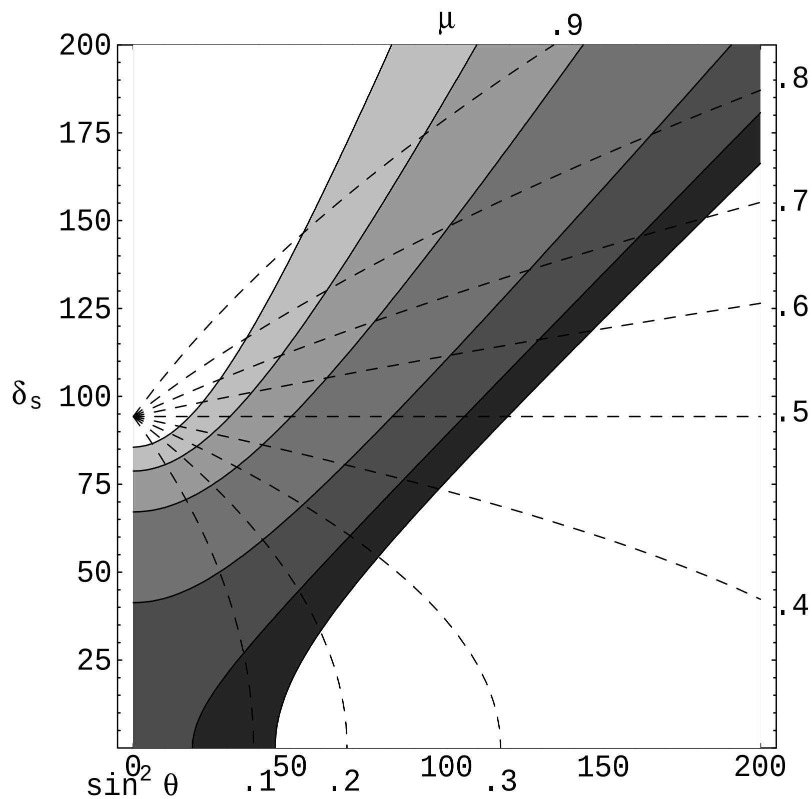
Allowed regions if $h \to 2a \to 4b$, $s \to 4b$, $m_{\tilde{t}} = 300\text{GeV}$

Possible realisations



Using supersoft operator

darkest to lightest–20,25,50,65,80,90,95 GeV



Using superpotential ($\lambda_h = 0.25$)

darkest to lightest–20,40,60,80,90,96 GeV