Naturalness and Higgs decays

Playing hide and seek with the Higgs

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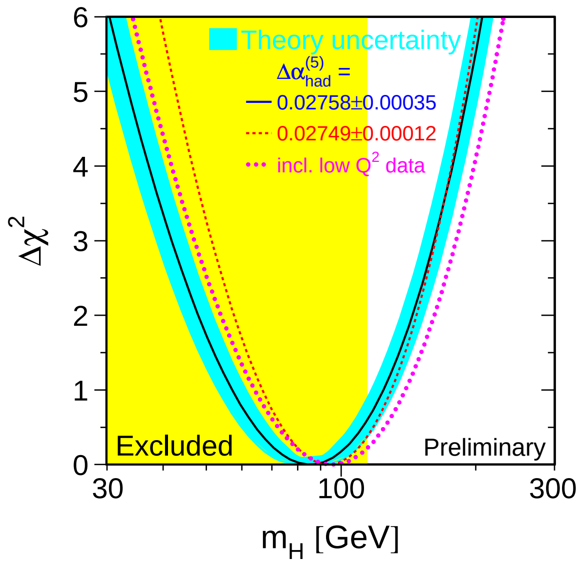
LBNL

Layout

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

LEP Legacy



- Electroweak precision measurements: $m_h \approx 89^{+42}_{-30}\mathrm{GeV}$
- LEP direct searches: $m_h > 114\mathrm{GeV}$
- Four fermion operators $\frac{1}{\Lambda^2}\overline{\psi}\psi\overline{\psi}\psi$: $\Lambda > 5\mathrm{TeV}$
- Hierarchy problem

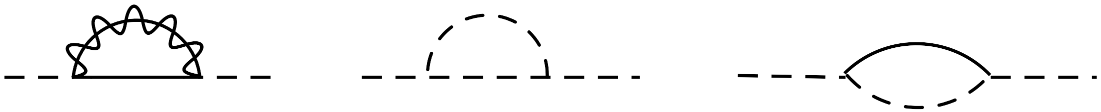
$$\Delta m_\phi^2 \sim \frac{\lambda^2}{16\pi^2}\Lambda^2$$

- Tensions? e.g. Chanowitz 02

Hierarchy problem

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

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



etc.

Hierarchy problem

- The good: Superpartners soften divergence

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

Hierarchy problem

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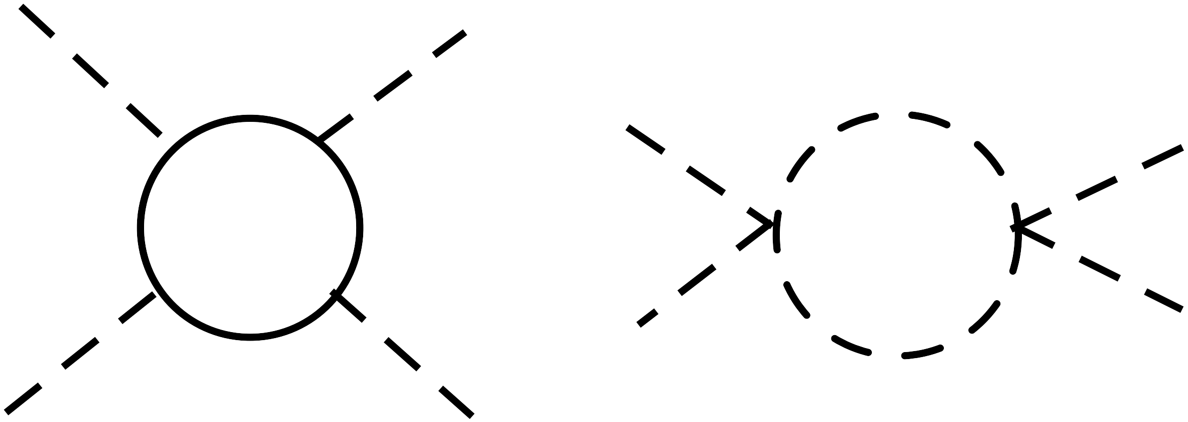
- The ugly(?): Need to raise Higgs mass, e.g. increase quartics. Loop corrections, NMSSM, Fat higgs, non-decoupling D-terms, little supersymmetry etc.

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) $m_h > 114\text{GeV}$
- Requires heavy stops ($\mathcal{O}(400\text{GeV})$), large quartic corrections
- Fine-tuning ($\mathcal{O}(5\%)$) of soft Higgs mass against μ-term to get $v = 174\text{GeV}$
- 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.

Non-standard Higgs decays

Higgs width:

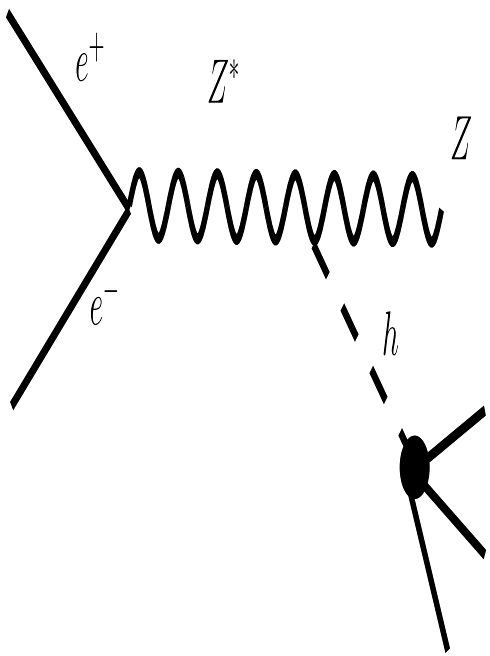
$$\Gamma = (2.34 \times 10^{-5} m_h + .206\text{MeV})$$

- CP violating MSSM Carena et al.
- $h \to 2a \to 4\gamma$ at Tevatron Dobrescu et al.
- $h \to 4b$ in the NMSSM Gunion and Dermisek
- $h \to 4\tau$ in the NMSSM Ellwanger et al., Graham et al.
- $h \to 6j$ in the MSSM with R-parity violation Carpenter et al.

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]
  - $S = s + ia + \theta\psi_s + \ldots$

LEP limits



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

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

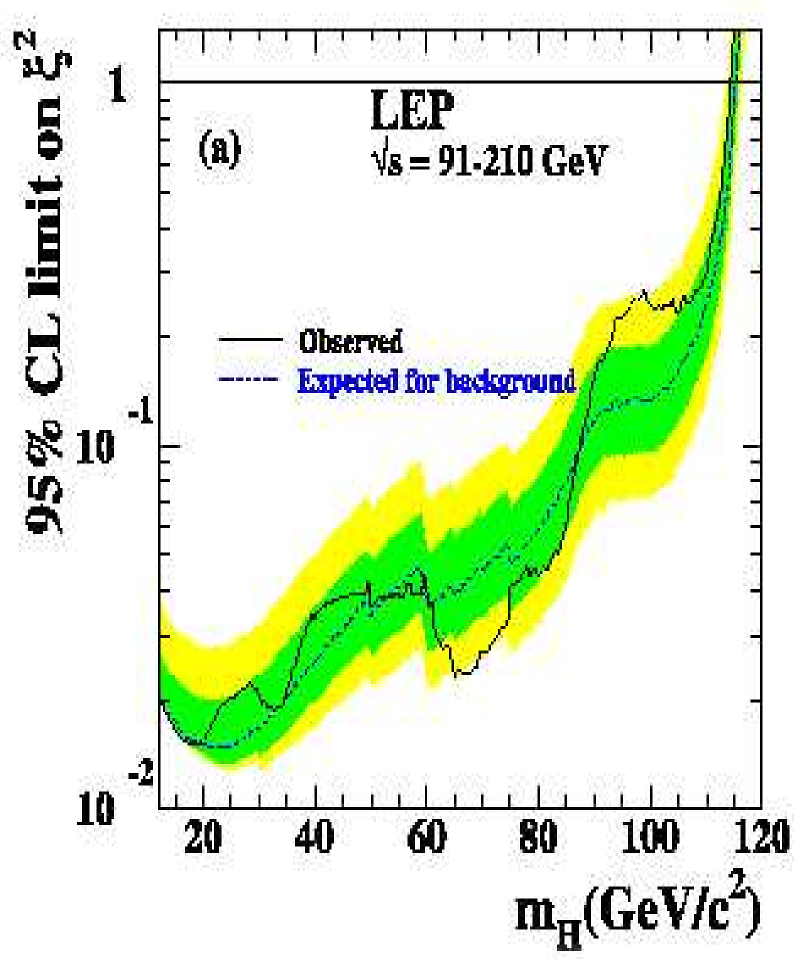
$$\begin{pmatrix} \text{SM higgs :} & m_h \geq 114.4\text{GeV} \\ \text{Invis. higgs :} & m_h \geq 114\text{GeV} \\ \text{Model indep. :} & m_h \geq 81\text{GeV} \end{pmatrix}$$

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

We will be most interested in the constraints on cascade decays

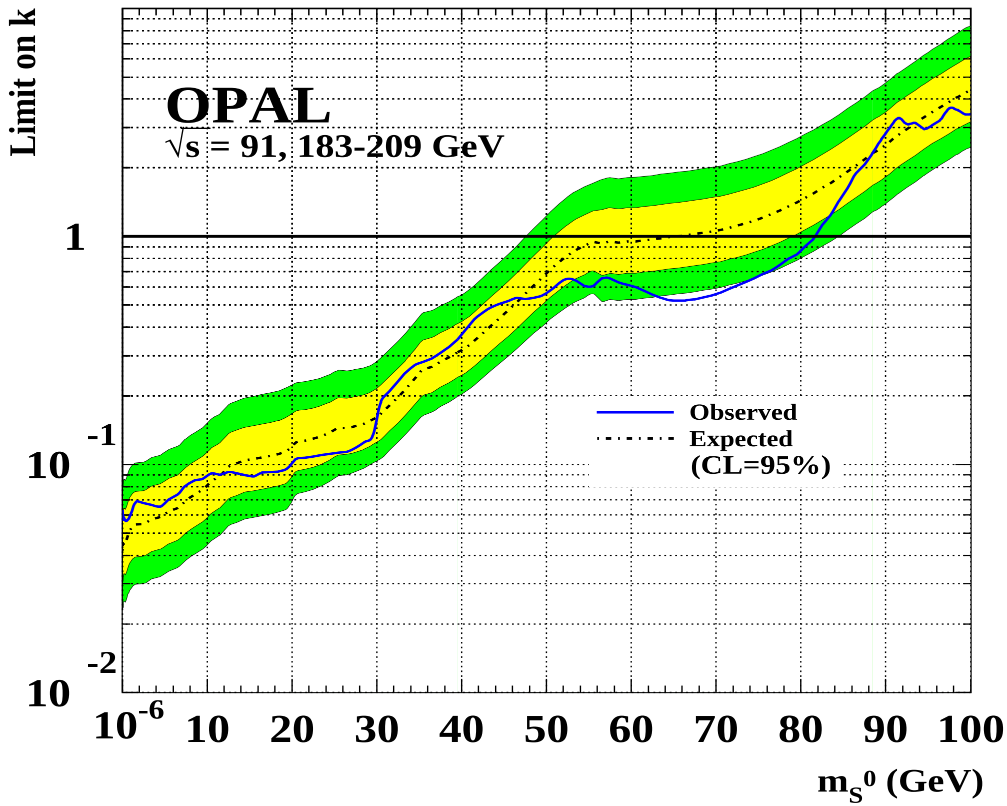
LEP constraints–SM like

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



Model Independent

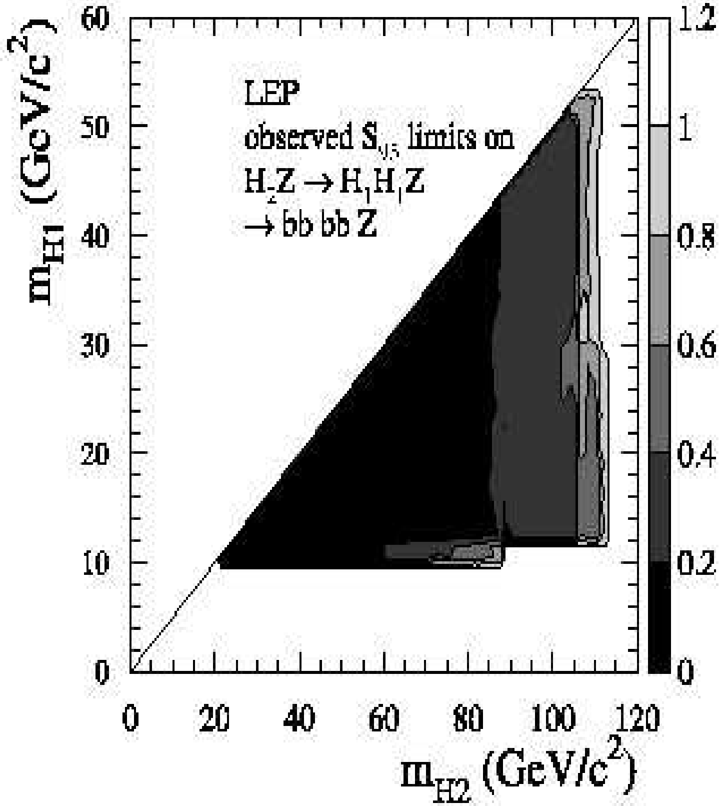
$m_h \geq 81\text{GeV}$

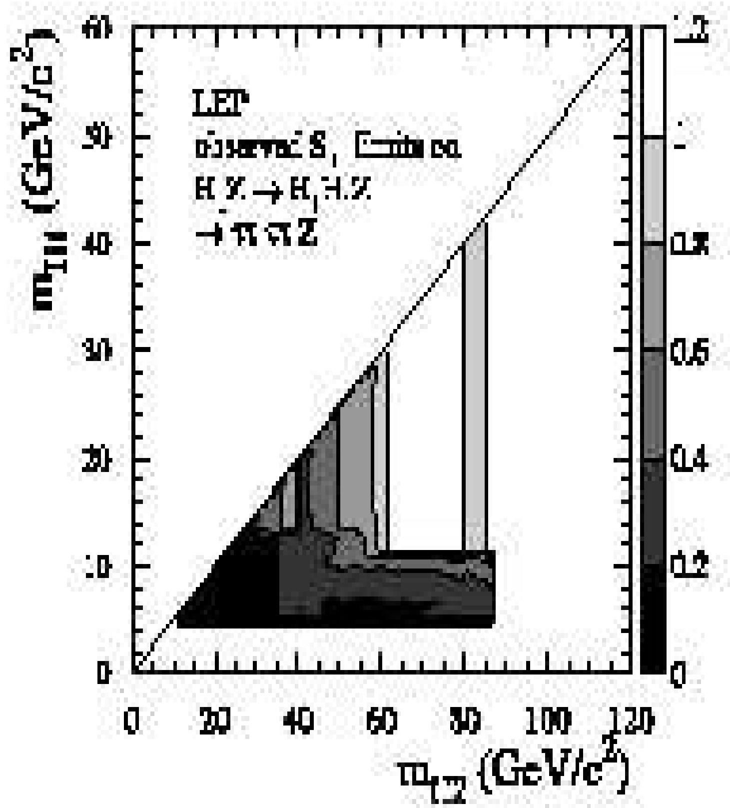


[*Eur. Phys. J.* **C27** (2003) 311-329; hep-ex/0206022]

Cascade decays

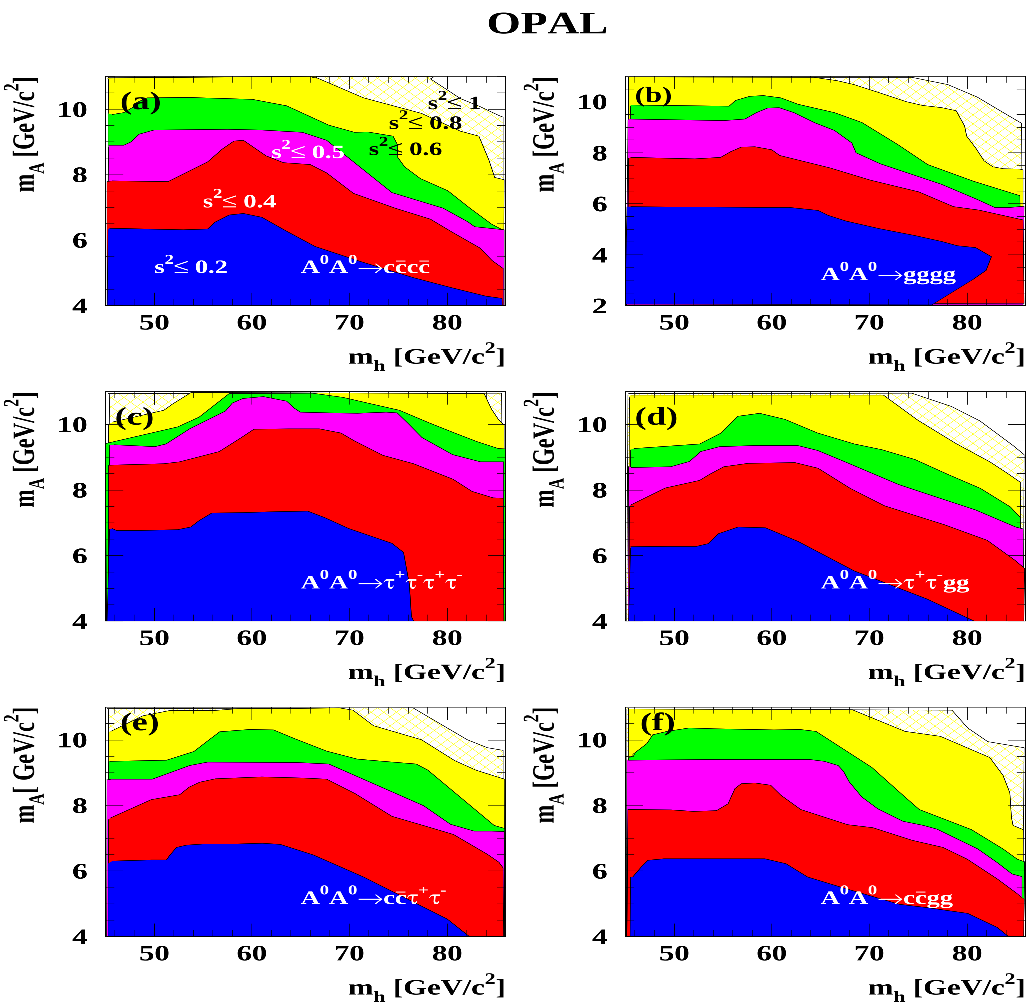
$m_h \geq 110\text{GeV}$ for 4b final state [André Sopczak, SUSY05]





Cascade decays

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



[*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: $W'_\alpha W^\alpha S$

Operators with singlet

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

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

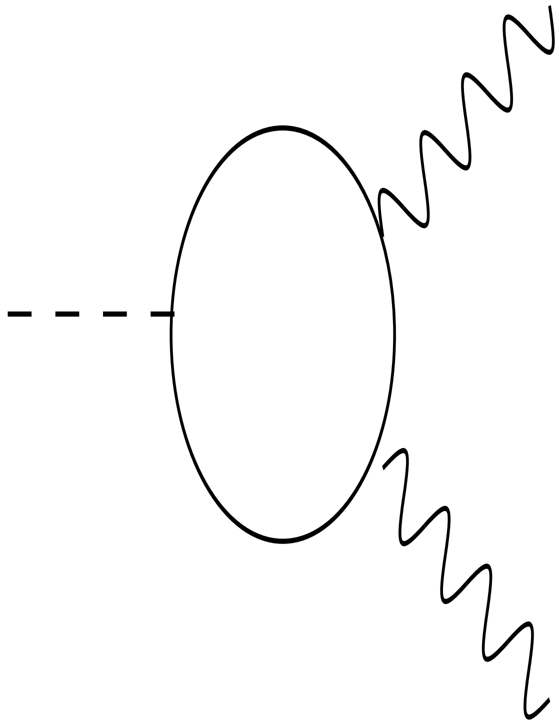
Decays $h \to 2s, 2a$ and $s \to 2a$

A-term: $A_h S H_u H_d$
Mixes A^0 and a, allows $a \to 2b/2\tau$ $h \to 2s, 2a$ and $s \to 2a$

Mixing term: $m_{CP}^2 sa$
Can induce $h \to sa$ if $h \to 2s$ kinematically forbidden.

Heavy vector-like matter

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



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]

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.

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

$D_Y = \sum_i g_Y q_i \phi_i^* \phi_i$ 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 $h \to ss$ decays

Necessary operators

- a should decay: A_h, m^2_{CP}, 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^2_{CP}

Some operators better than others. 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, $m_{\tilde{t}} = 325\mathrm{GeV} \Rightarrow$

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

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

Single stage cascades

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

- 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), $m_{\tilde{t}} = 175\text{GeV} \Rightarrow$

$\sin^2\theta$	$m_{\tilde{h}}$	$m_{\tilde{s}}$	$m_{\tilde{a}}$	$B_{\tilde{h}\to 2\tilde{a}}$	$B_{\tilde{s}\to 2\tilde{a}}$	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

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

- 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

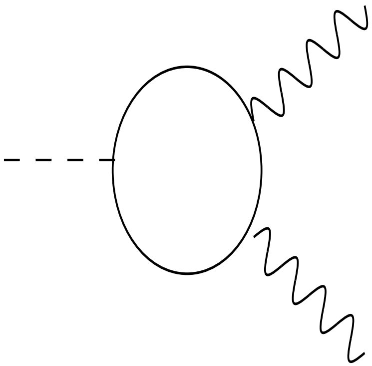
Simple(st?) extension of MSSM greatly enhances Higgs phenomenology, different from NMSSM.

- $h \to 2a \to 4b$ 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.

INTERLUDE

Fermiophobic Higgs



$$\mathcal{L} = \frac{cv}{2} h a^2 + \bar{\psi}(M + i\lambda\gamma_5 a)\psi$$

Higgs can be as light as $82\mathrm{GeV}$

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

- Allows discovery of both a and h
- $Br(h \to 4\gamma) \sim 10^{-5} - 10^{-3}$ $\left[Br(h_{SM} \to 2\gamma) \sim 10^{-3}\right]$
- Displaced vertices Strassler and Zurek
- LHC: large reach in Br across much of parameter space
- TeVatron: hope for $m_h > 120\mathrm{GeV}$ (or $Br > 5 \times 10^{-3}$)

Signal

Do a partonic analysis in PYTHIA with cuts:

- Transverse Momentum: $p_T > 20$ GeV for all photons.
- Isolation: $\delta R > .4$ between all photons
- Rapidity Acceptance: $|\eta| < 2.5$
- Consistent Pairing: Require a photon pairing such that $|m_{\rm pair1} - m_{\rm pair2}| < 5\ {\rm GeV}$.

Typical acceptances 1%-10%. Could be improved by lowering p_T cut at TeVatron can go to $10{\rm GeV}$.
Multiple photons above $15{\rm GeV}$ trigger?
Mass resolutions: $\Delta m_{h(a)} \sim 0.1\sqrt{m_{h(a)}}$

$$\Delta m_h = \mathcal{O}(1{\rm GeV})$$
$$\Delta m_a = \mathcal{O}(0.5{\rm GeV})$$

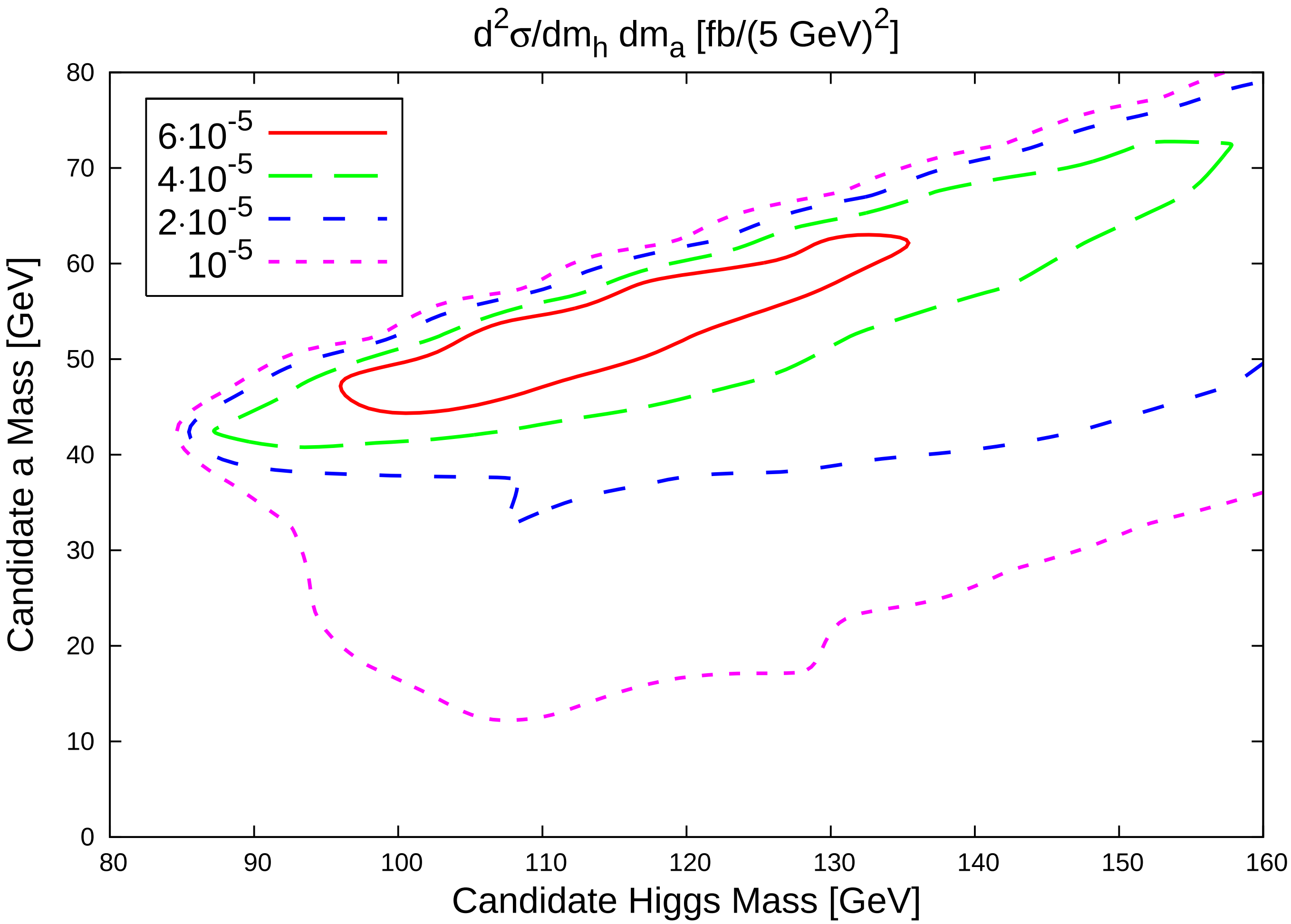
Background

Use ALPGEN

- Type I: 4γ and $n\gamma + (4-n)\gamma_j$
  Mis-id rate is 1 in $\min(3067, -1333 + 110 p_T/\mathrm{GeV})$
  Can we go lower that $p_T = 20\mathrm{GeV}$?
  Thankfully small
- Type II: Pileup
  e.g. $2\gamma_j \oplus 2\gamma_j$
  Resolve with pointing information?

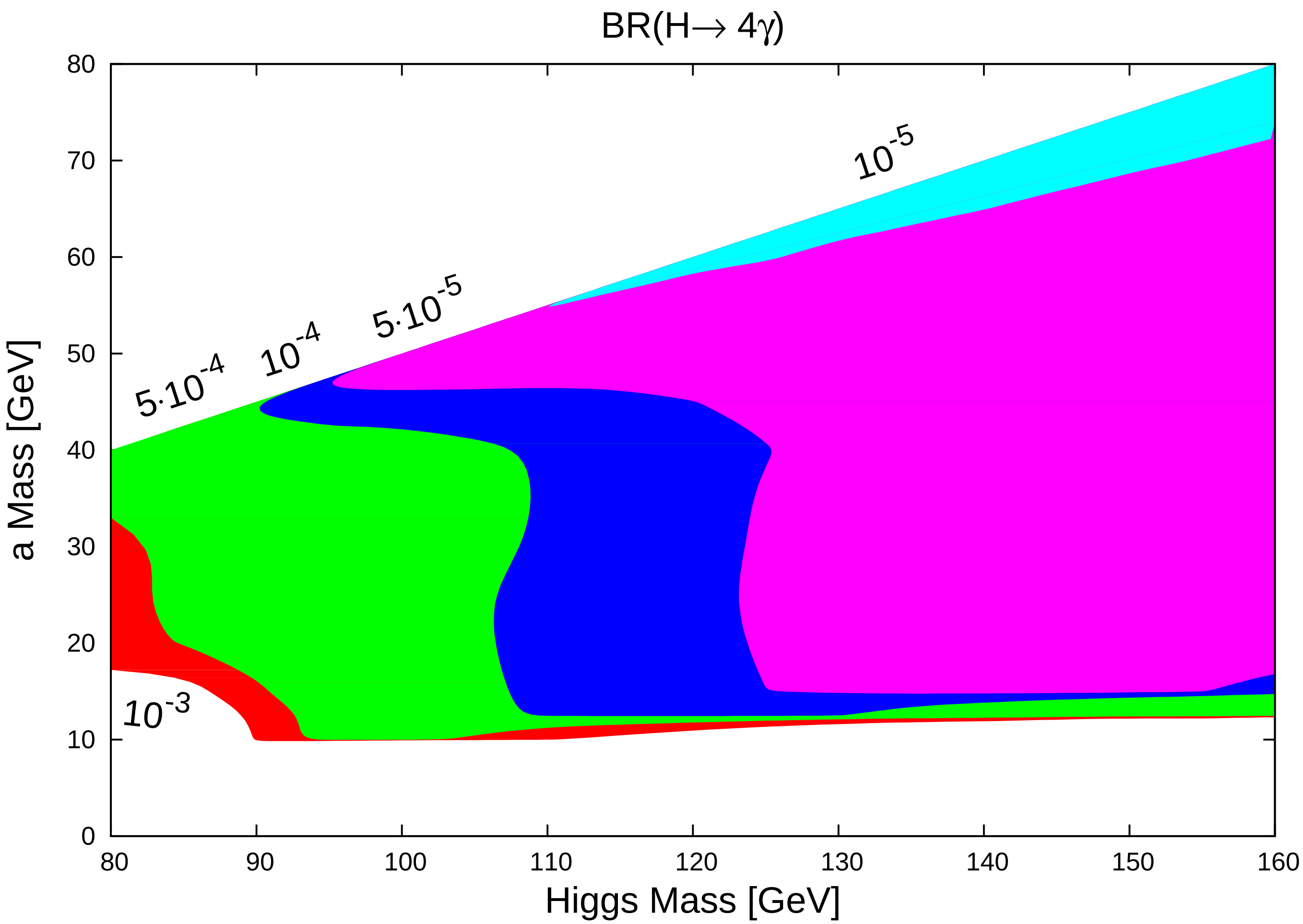
Bottom line: **Background is small** Expect $\ll 1$ event after 300 fb^{-1}
Will require ≥ 5 events for discovery (Poisson $5\sigma \sim 2$)

Background



d²σ/dm_h dm_a [fb/(5 GeV)²]
6·10^-5
4·10^-5
2·10^-5
10^-5
Candidate a Mass [GeV]
Candidate Higgs Mass [GeV]
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160

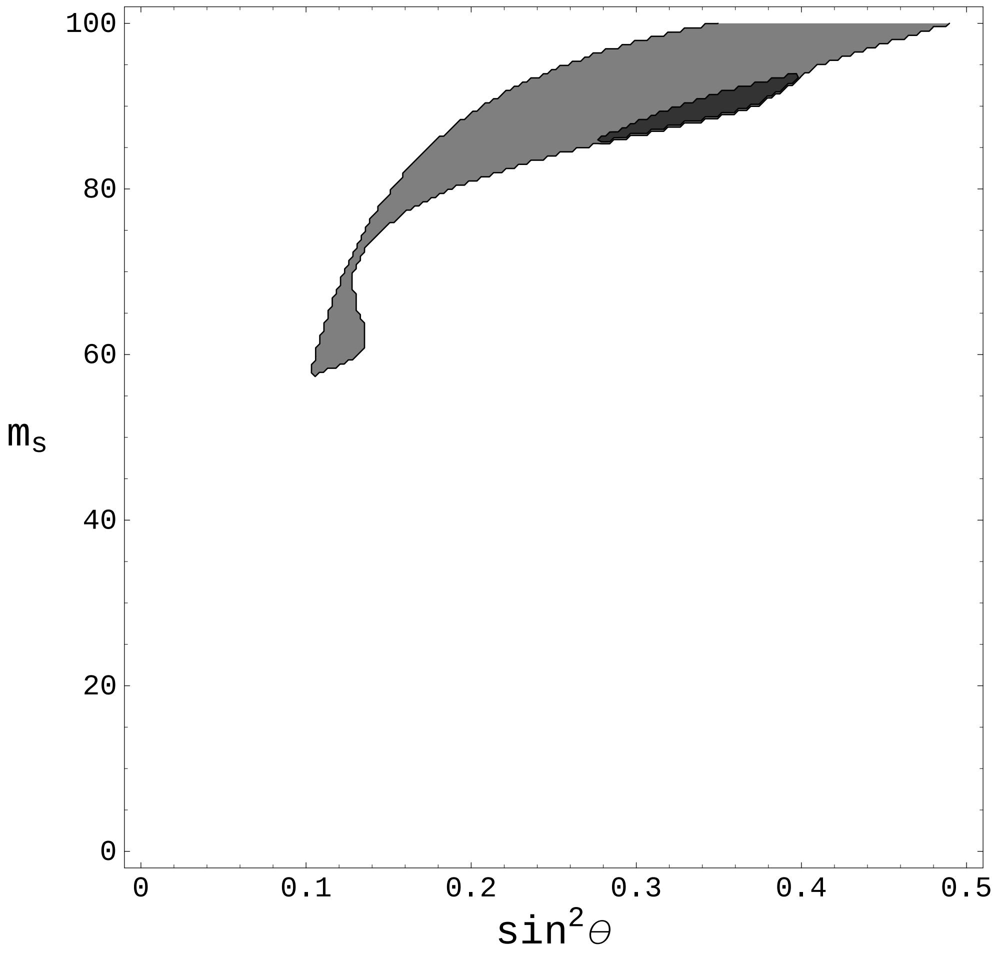
Signal


BR(H→ 4γ)
a Mass [GeV]
Higgs Mass [GeV]
0
10
20
30
40
50
60
70
80
80
90
100
110
120
130
140
150
160
10-3
5·10-4
10-4
5·10-5
10-5

Conclusions and the future

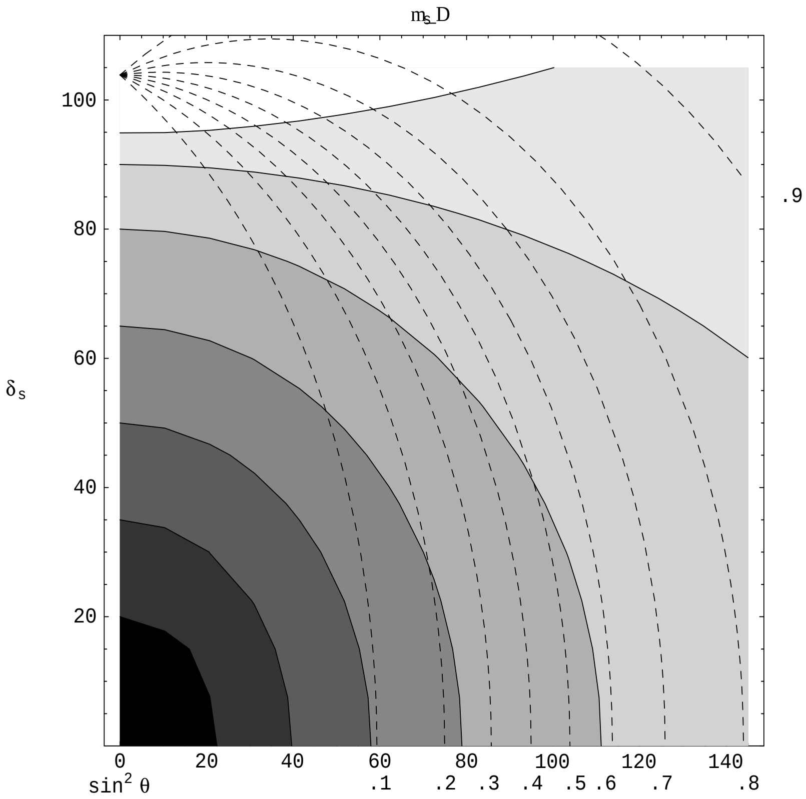
- MSSM suffers from LHP
- *Lowering* Higgs mass and giving it novel decays also solves problem, allows for light stops
- Consider all operators, in particular supersoft and new coloured matter
- New signals from general analysis
- New signals demand new analyses e.g. model independent, low a mass
- New scenarios with light (stealthy) higgs **and** light superpartners
- New analyses for LHC and beyond e.g. 4γ final state

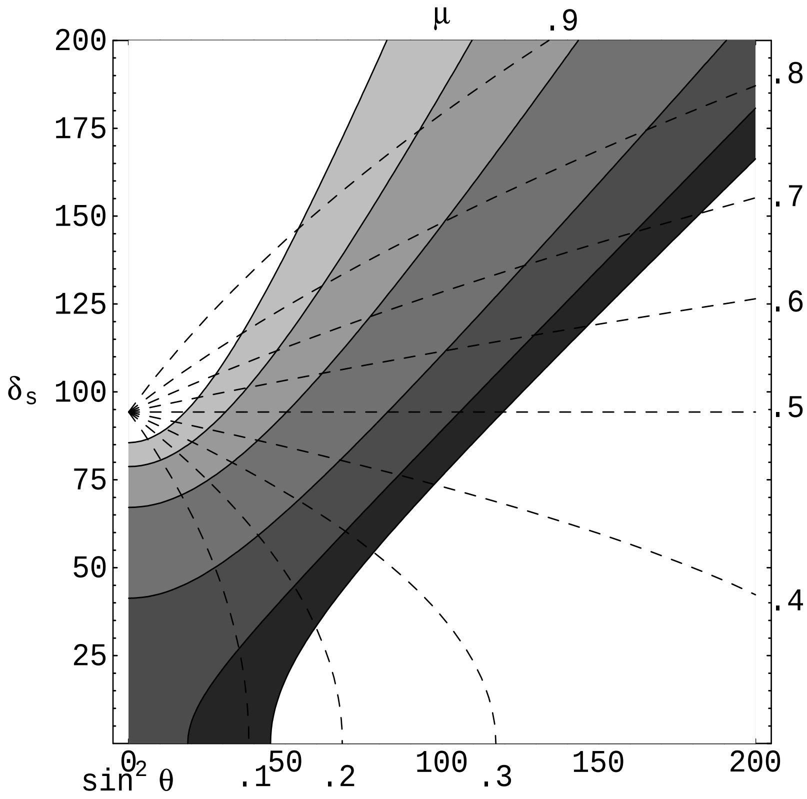
Allowed regions



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