A brief review of the NMSSM

1. The basics
   — The NMSSM and the μ-problem
   — The parameters and mass spectrum
   — Fine tuning

2. NMSSM collider phenomenology
   — No lose theorems at the LHC
   — b-physics constraints on A_1
   — Distinguishing the NMSSM Higgs sector from the MSSM
   — The Neutralino Sector

3. Conclusions & Summary

Disclaimer: In 30 minutes, I can't cover every paper on the NMSSM, so apologies to anyone who has been left out.

Some background reading:

M. Dine, W. Fischler and M. Srednicki, Phys. Lett. B **104** (1981) 199.

H. P. Nilles, M. Srednicki and D. Wyler, Phys. Lett. B **120** (1983) 346.

J. P. Derendinger and C. A. Savoy, Nucl. Phys. B **237** (1984) 307.

J. Ellis, J. F. Gunion, H. Haber, L. Roszkowski, F. Zwirner, Phys. Rev. D **39** (1989) 844.

U. Ellwanger, M. Rausch de Traubenberg and C. A. Savoy, Phys. Lett. B **315** (1993) 331; Nucl. Phys. B **492** (1997) 21.

S. F. King and P. L. White, Phys. Rev. D **52** (1995) 4183.

F. Franke and H. Fraas, Int. J. Mod. Phys. A **12** (1997) 479.

The basics

The NMSSM and the μ-problem

MSSM Superpotential:

$$\boxed{W = \hat{u}^c \mathbf{h_u} \hat{Q} \hat{H}_u - \hat{d}^c \mathbf{h_d} \hat{Q} \hat{H}_d - \hat{e}^c \mathbf{h_e} \hat{L} \hat{H}_d + \mu \hat{H}_u \hat{H}_d}$$

Higgs Potential:

$$V = V_F + V_D + V_{\text{soft}}$$

$$\begin{aligned}
V_F &= \sum_i \left| \frac{\partial W}{\partial \phi_i} \right|^2 = |\mu|^2 (|H_d|^2 + |H_u|^2) \\
V_D &= \frac{1}{8} g^2 (H_d^\dagger \sigma H_d + H_u^\dagger \sigma H_u)^2 + \frac{1}{8} g' (|H_d|^2 - |H_u|^2)^2 \\
V_{\text{soft}} &= m_d^2 |H_d|^2 + m_u^2 |H_u|^2 + \mu B H_u H_d + \text{h.c.}
\end{aligned}$$

Note the appearance of μ in W

This is the "Higgs-higgsino mass parameter"

— adds mass to Higgs and higgsino states

$$\left.\begin{array}{l}\bullet\ \mu \text{ has dimensions of mass} \\ \bullet\ \mu \text{ has no } \textit{a priori} \text{ link to EW scale}\end{array}\right\} \text{expect } \mu = 0 \text{ or } M_{\text{Planck}}$$

But for correct phenomenology need $\mu \sim 100$ GeV $-$ 1 TeV

$\boxed{\text{Why is } \mu \approx \text{EW/SuSy scale?}}$

This is known as the "μ-problem"

The Next–to–Minimal Supersymmetric Standard Model

Introduce new Higgs singlet superfield $\widehat{S}$

$$\widehat{S}, \ \widehat{H}_d = \begin{pmatrix} \widehat{H}_d^0 \\ \widehat{H}_d^- \end{pmatrix}, \ \widehat{H}_u = \begin{pmatrix} \widehat{H}_u^+ \\ \widehat{H}_u^0 \end{pmatrix}$$

H_d and H_u are usual MSSM Higgs doublets

S is new neutral colorless singlet Higgs

$\rightsquigarrow$ two extra Higgs bosons + 1 extra neutralino:

3 scalar Higgs fields, H_1, H_2 and H_3

2 pseudoscalar Higgs field, A_1 and A_2

2 charged Higgs fields $H^\pm$

5 neutralinos, $\tilde{\chi}_i^0$, $i = 1, 5$

4 charginos, $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^\pm$

NMSSM Superpotential:

$$\boxed{W = \hat{u}^c \mathbf{h_u} \hat{Q} \hat{H}_u - \hat{d}^c \mathbf{h_d} \hat{Q} \hat{H}_d - \hat{e}^c \mathbf{h_e} \hat{L} \hat{H}_d + \lambda \hat{S} \hat{H}_u \hat{H}_d + \tfrac{1}{3} \kappa \hat{S}^3}$$

Now no dimensionful parameters $\Rightarrow$ No μ problem!

Effective μ term generated by dynamical symmetry breaking

When S develops a non-zero vacuum–expectation–value

$$\lambda S H_u H_d \longrightarrow \lambda \langle S \rangle H_u H_d = \mu_{\text{eff}} H_u H_d$$

$$\boxed{\mu_{\text{eff}} = \lambda \langle S \rangle}$$

MSSM limit: $\kappa = 0$, $\lambda \to 0$, keeping μ_{eff} fixed (ie. $\langle S \rangle \to \infty$)

If $\kappa = 0$, the lagrangian contains an extra global $U(1)$ "Peccei-Quinn" symmetry

$U(1)_{PQ}$ charges: $Q(-1)$, $u^c(0)$, $d^c(0)$, $L(-1)$, $e^c(0)$, $H_d(1)$, $H_u(1)$, $S(-2)$

model invariant under $\phi_i \to e^{iQ_i^{\mathrm{PQ}}\theta}\phi_i$

Symmetry broken by EWSB

$\Rightarrow$ massless Nambu–Goldstone boson, the Axion
(actually a pseudoscalar Higgs boson)

$\frac{1}{3}\kappa S^3$ term is included to break PQ symmetry
and provide extra mass for Higgs bosons

$\mathbb{Z}_3$ symmetry remains $\rightsquigarrow$ problems with domain walls in the early universe

$\longrightarrow$ Next Talk

The parameters

λ — couplings to other Higgs [if $\lambda = 0$, new states decouple]

κ — contributes mass to new Higgs

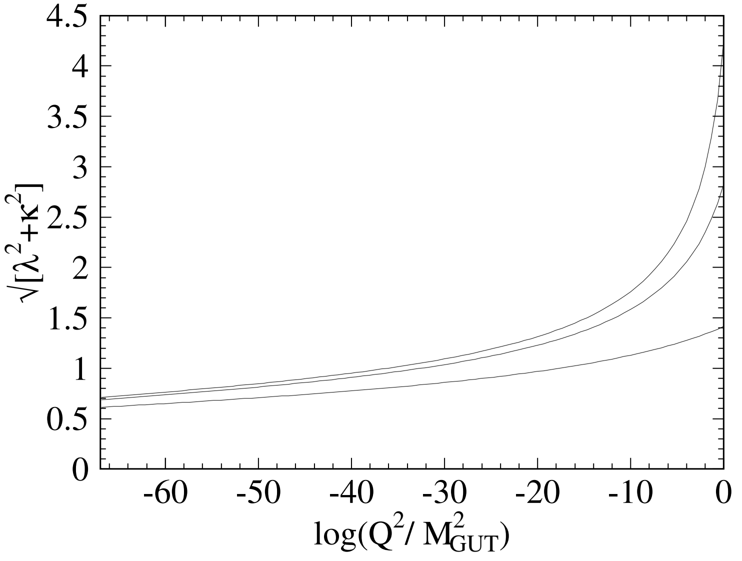
$$\left.\begin{array}{c} A_\lambda \\ A_\kappa \end{array}\right\} \text{ associated soft SuSy-breaking parameters}$$

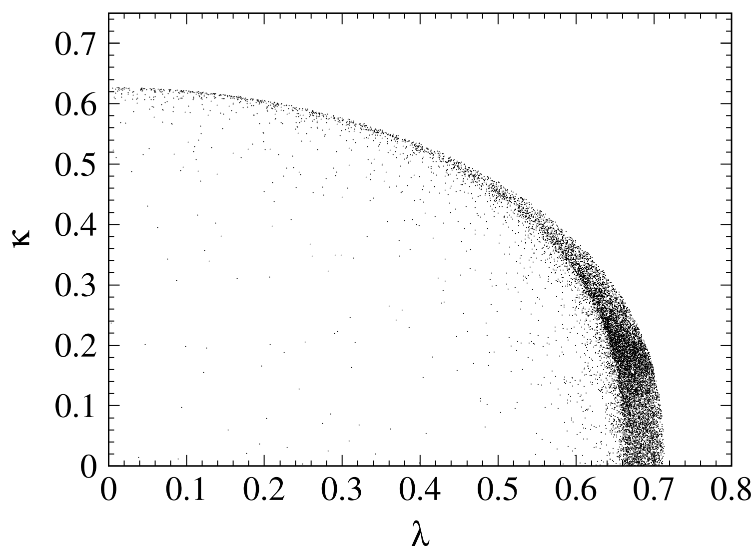
$$\left.\begin{array}{c} \langle S \rangle \\ \tan\beta = \langle H_u \rangle / \langle H_d \rangle \end{array}\right\} \text{ vacuum-expectation-values}$$

Often replace A_λ with mass $M_A = \dfrac{2\mu}{\sin 2\beta}(A_\lambda + \dfrac{\kappa\mu}{\lambda})$

[M_A is pseudoscalar mass in MSSM limit]

[DJM, Nevzorov, Zerwas, Nucl. Phys. **B** (2004) 3]





$$\lambda^2 + \kappa^2 \lesssim 0.5$$

Renormalization Group $\Rightarrow$ couplings λ and κ are small at LHC energies

- ◇ New Higgs bosons are not well coupled
- ◇ if κ is small $\Rightarrow$ extra Higgs bosons light

Approximate Higgs Masses

For $1/\tan\beta$ and M_Z/M_A small:

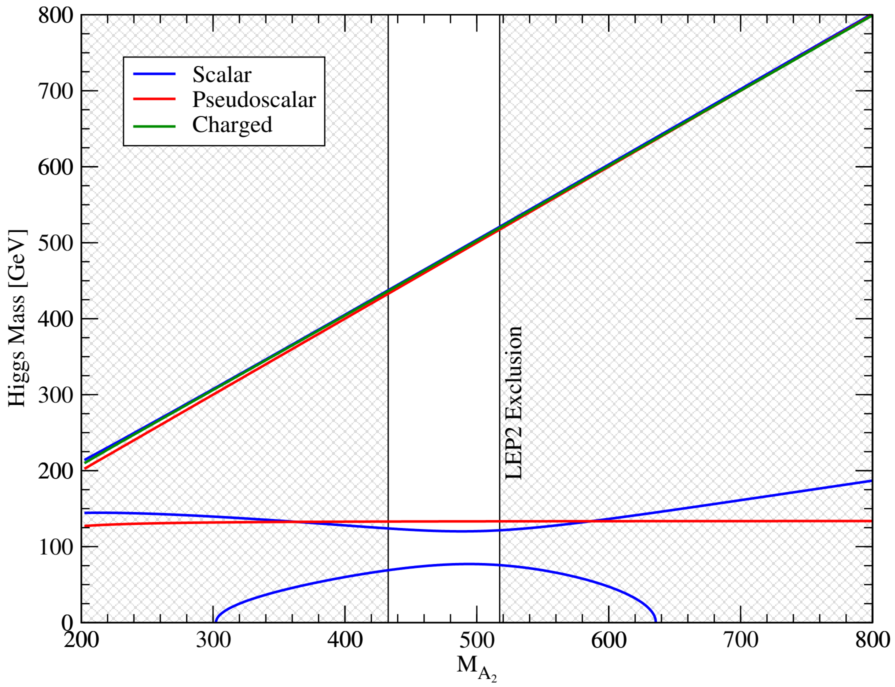
$$M_{H_3} \approx M_{H^\pm} \approx M_{A_2}$$

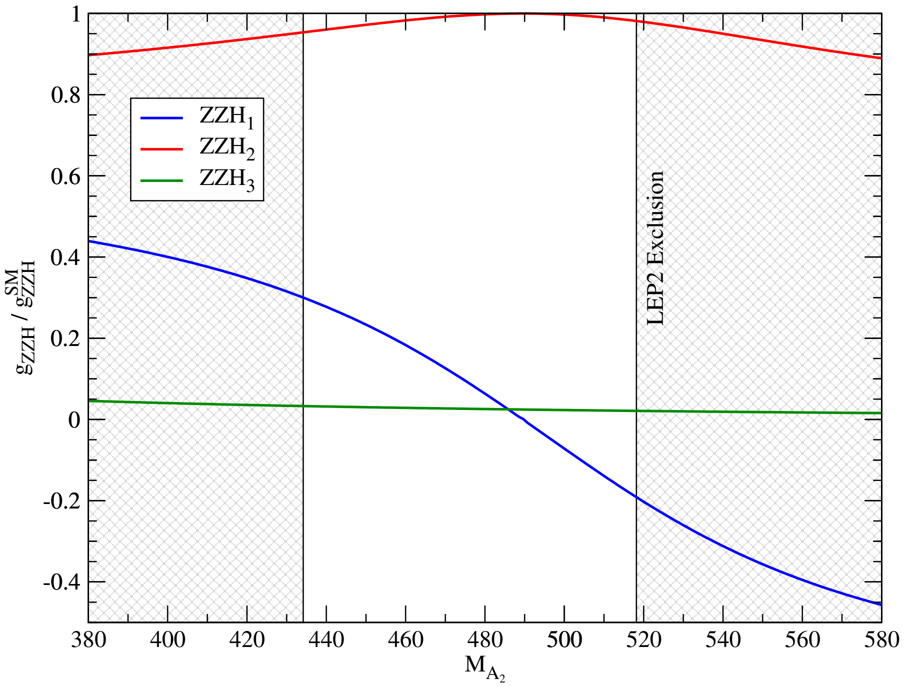
$$M_{H_2}^2 \approx M_Z^2 \cos^2 2\beta + \delta$$

$$M_{H_1}^2 \approx \kappa\langle S\rangle[4\kappa\langle S\rangle + A_\kappa] \qquad M_{A_1}^2 \approx -3\kappa\langle S\rangle A_\kappa$$

New bosons have mass depending on $\kappa\langle S\rangle$

e.g. at one-loop with $\lambda = 0.3$, $\kappa = 0.1$, $\langle S \rangle = 3 \times 174$ GeV, $A_\kappa = -100$ GeV:





LEP2 limits: Standard Model $M_H \gtrsim 114.4$ GeV

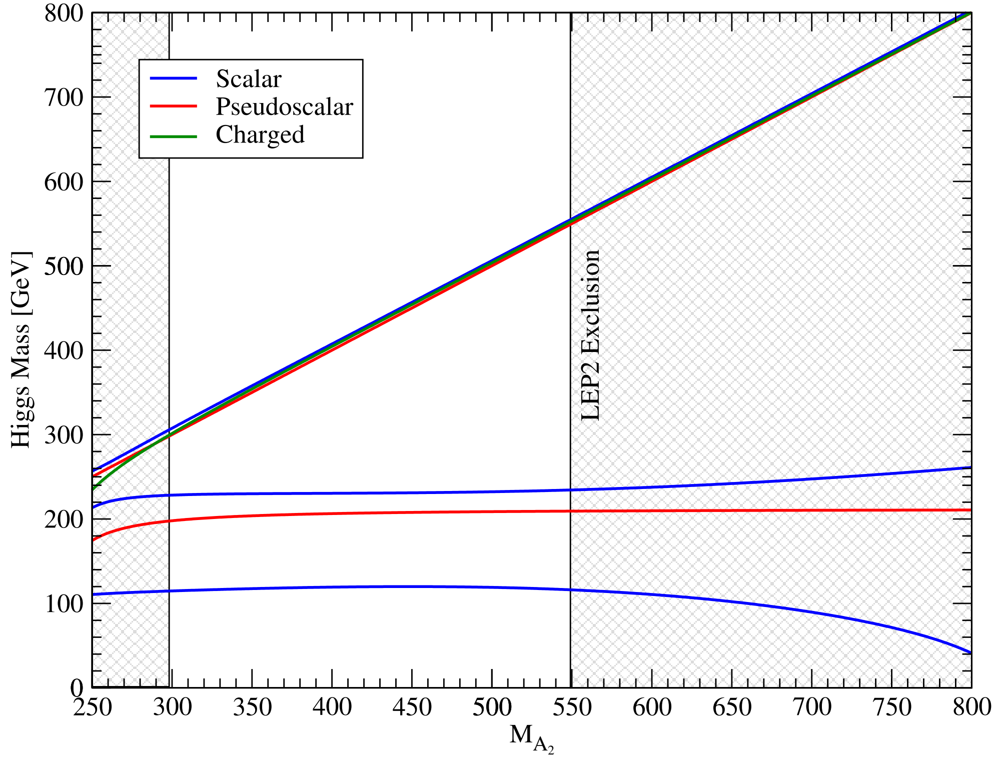
NMSSM $H_1 ZZ$ coupling small $\Rightarrow$ rather light Higgs is not ruled out

$\sigma(e^+e^- \to Z^* \to ZH_1) \approx 0$ for $M_{A_2} \approx 2\mu_{\text{eff}} / \sin 2\beta$

Allowed region opens up as κ is increased.

e.g. $\kappa = 0.25$ [with $\langle S \rangle = 3 \times 174$ GeV, $A_\kappa = -100$ GeV as before]

$$M_{H_2}^2 \approx \kappa \langle S \rangle [4\kappa \langle S \rangle + A_\kappa] \approx (235 \text{ GeV})^2 \qquad M_{A_1}^2 \approx -3\kappa \langle S \rangle A_\kappa \approx (198 \text{ GeV})^2$$



Fine tuning

The MSSM has large fine-tuning, caused by competing factors:

$$89.8 \text{ GeV} < M_h^2 < M_Z^2 \cos^2 2\beta + \frac{3m_t^4}{2\pi^2 v^2} \log \frac{M_{\text{SUSY}}^2}{m_t^2} + \ldots$$

$$\frac{M_Z^2}{2} = -\mu^2 + \frac{M_{H_d}^2 - M_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1}$$

Fine tuning is eased in the MSSM:

$$??? < M_h^2 < M_Z^2 \cos^2 2\beta + \tfrac{1}{2}\lambda^2 v^2 \sin^2 2\beta + \frac{3m_t^4}{2\pi^2 v^2} \log \frac{M_{\text{SUSY}}^2}{m_t^2} + \ldots$$

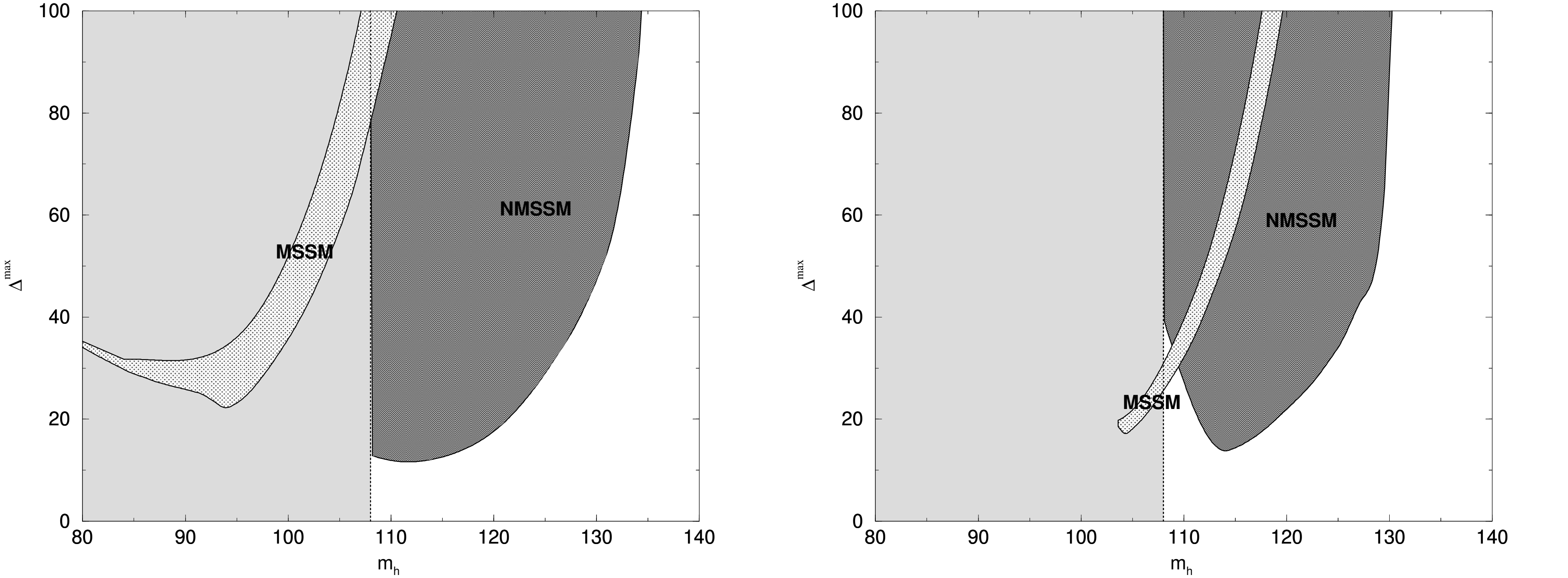
NMSSM H_1 LEP lower bounds relaxed

[Bastero-Gil, Hugonie, King, Roy, Vempati, Phys. Lett. B **489** (2000) 359]

Define 'tuning' with respect to each parameter 'a' as

$$\Delta_a \equiv \left| \frac{a}{M_Z^2} \frac{\partial M_Z^2}{\partial a} \right| \text{ and } \Delta^{\max} \equiv \text{maximum value of all the } \Delta_a$$

$\tan\beta = 3$: $\tan\beta = 5$:



NMSSM Collider Phenomenology

[Ellwanger, Gunion, Hugonie, hep-ph/0111179
Ellwanger, Gunion, Hugonie, Moretti, hep-ph/0401228]

No–lose theorems

If the NMSSM is true, can we be sure that we see any Higgs boson at the LHC?

Is the LHC guaranteed to see at least one Higgs boson?

NMSSM is different from the MSSM because:

♢ Higgs couplings are shared out with new state

WW/ZZ couplings can be greatly reduced

$$\Rightarrow \begin{cases} \text{Golden channel } H \to Z^* Z \to 4l \text{ becomes small} \\ W^\pm \text{ contribution and } t \text{ contributions to } H \to \gamma\gamma \text{ rate may cancel} \end{cases}$$

♢ For some parameter choices have very light particles:

- escape the LEP limits (and LHC detection) due to reduced couplings
- still have sizable Higgs-Higgs couplings

⇒ Can have new decay channels, such as $H_{1,2} \to A_1 A_1$

♢ May have Higgs states which overlap in mass:

"Such overlaps can obviate many of the standard discovery modes."

They perform a scan over the free parameters:

$$\lambda,\ \kappa,\ A_\lambda,\ A_\kappa,\ \mu_{\text{eff}},\ \tan\beta$$

and require:

- $\mu_{\text{eff}} = \lambda\langle S\rangle \geq 100$ GeV to avoid light charginos
- $e^+e^- \to ZH_i$ and $e^+e^- \to H_iA_j$ small enough to avoid LEP contraints
- $m_{H^\pm} > 155$ GeV to avoid $t \to H^+b$ decays

They include decays to Higgs bosons but exclude decays to sparticles

They looked at the "usual" LHC channels:

1) $gg \to h/a \to \gamma\gamma$;
2) associated Wh/a or $t\bar{t}h/a$ production with $\gamma\gamma\ell^{\pm}$ in the final state;
3) associated $t\bar{t}h/a$ production with $h/a \to b\bar{b}$;
4) associated $b\bar{b}h/a$ production with $h/a \to \tau^+\tau^-$;
5) $gg \to h \to ZZ^{(*)} \to$ 4 leptons;
6) $gg \to h \to WW^{(*)} \to \ell^+\ell^-\nu\bar{\nu}$;
7) $WW \to h \to \tau^+\tau^-$;
8) $WW \to h \to WW^{(*)}$.

Result: Most parameter choices allow at least one Higgs boson to be seen at the LHC ($S/\sqrt{B} > 10$)

They give 6 representative points where LHC discovery is very difficult

Point Number	1	2	3	4	5	6
Bare Parameters						
λ	0.2872	0.2124	0.3373	0.3340	0.4744	0.5212
κ	0.5332	0.5647	0.5204	0.0574	0.0844	0.0010
$\tan\beta$	2.5	3.5	5.5	2.5	2.5	2.5
$\mu_{\rm eff}$ (GeV)	200	200	200	200	200	200
A_λ (GeV)	100	0	50	500	500	500
A_κ (GeV)	0	0	0	0	0	0
CP-even Higgs Boson Masses and Couplings						
m_{h_1} (GeV)	115	119	123	76	85	51
R_1	1.00	1.00	-1.00	0.08	0.10	-0.25
t_1	0.99	1.00	-1.00	0.05	0.06	-0.29
b_1	1.06	1.05	-1.03	0.27	0.37	0.01
Relative gg Production Rate	0.97	0.99	0.99	0.00	0.01	0.08
$BR(h_1 \to b\overline{b})$	0.02	0.01	0.01	0.91	0.91	0.00
$BR(h_1 \to \tau^+\tau^-)$	0.00	0.00	0.00	0.08	0.08	0.00
$BR(h_1 \to a_1 a_1)$	0.98	0.99	0.98	0.00	0.00	1.00
m_{h_2} (GeV)	516	626	594	118	124	130
R_2	-0.03	-0.01	0.01	-1.00	-0.99	-0.97
t_2	-0.43	-0.30	-0.10	-0.99	-0.99	-0.95
b_2	2.46	-3.48	3.44	-1.03	-1.00	-1.07
Relative gg Production Rate	0.18	0.09	0.01	0.98	0.99	0.90
$BR(h_2 \to b\overline{b})$	0.01	0.04	0.04	0.02	0.01	0.00
$BR(h_2 \to \tau^+\tau^-)$	0.00	0.01	0.00	0.00	0.00	0.00
$BR(h_2 \to a_1 a_1)$	0.04	0.02	0.83	0.97	0.98	0.96
m_{h_3} (GeV)	745	1064	653	553	554	535
CP-odd Higgs Boson Masses and Couplings						
m_{a_1} (GeV)	56	7	35	41	59	7
t'_1	0.05	0.03	0.01	-0.03	-0.05	-0.06
b'_1	0.29	0.34	0.44	-0.20	-0.29	-0.39
Relative gg Production Rate	0.01	0.03	0.05	0.01	0.01	0.05
$BR(a_1 \to b\overline{b})$	0.92	0.00	0.93	0.92	0.92	0.00
$BR(a_1 \to \tau^+\tau^-)$	0.08	0.94	0.07	0.07	0.08	0.90
m_{a_2} (GeV)	528	639	643	560	563	547
Charged Higgs Mass (GeV)	528	640	643	561	559	539
Most Visible of the LHC Processes 1)-8)	2 (h_1)	2 (h_1)	8 (h_1)	2 (h_2)	8 (h_2)	8 (h_2)
$N_{SD} = S/\sqrt{B}$ Significance of this process at L =300 fb^{-1}	0.48	0.26	0.55	0.62	0.53	0.16
$N_{SD}(L = 300$ fb$^{-1})$ for $WW \to h \to aa \to jj\tau^+\tau^-$ at LHC	50	22	69	63	62	21

E.g. Point 2

$$\lambda = 0.2124,\ \kappa = 0.5647,\ \tan\beta = 3.5,\ \mu_{\text{eff}} = 200\ \text{GeV},\ A_\lambda = A_\kappa = 0$$
$$[\Rightarrow M_A = 634.5\ \text{GeV},\ \kappa\langle S\rangle = 531.7\ \text{GeV}]$$

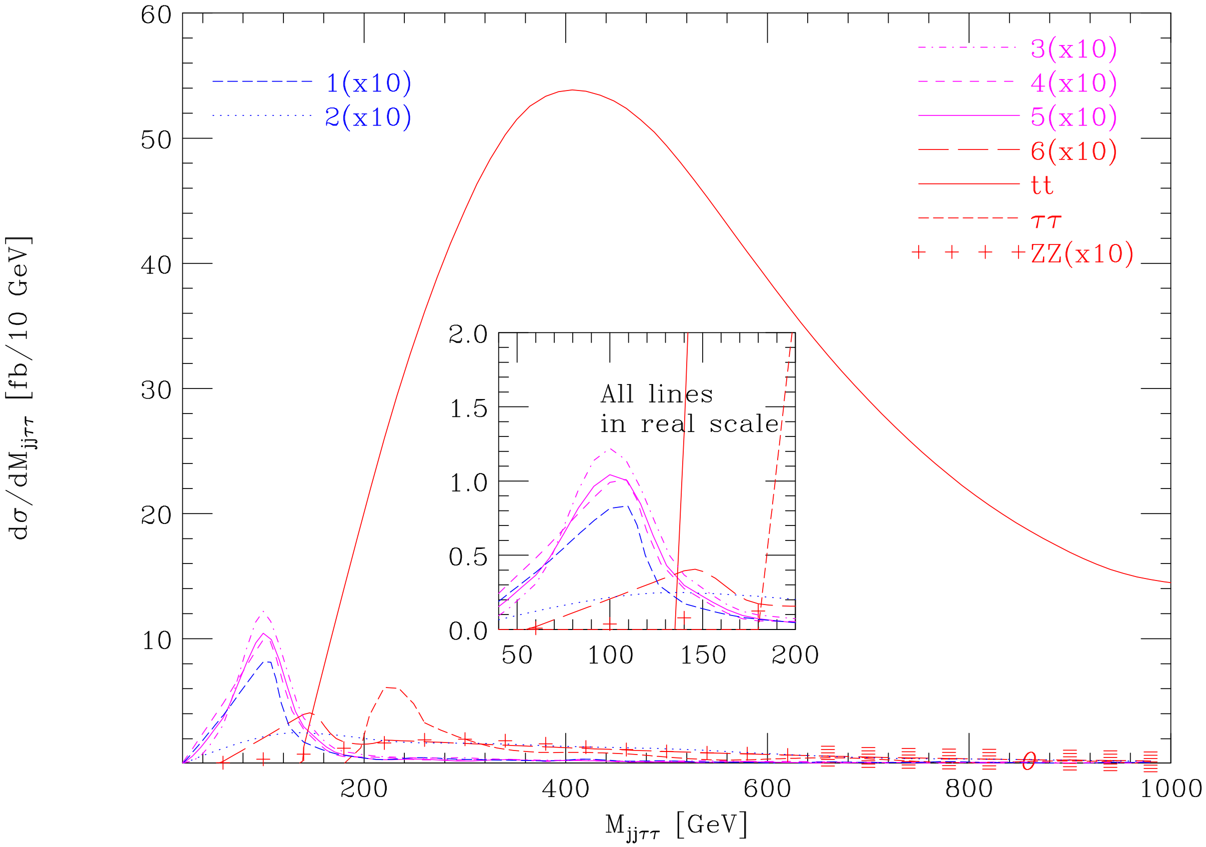
$$\begin{array}{ll}
M_{H_3} = 1064\,\text{GeV} & [M_{H_3}^2 \approx \kappa\langle S\rangle\,(4\kappa\langle S\rangle + A_\kappa)] \\
\left.\begin{array}{l} M_{H_2} = 626\,\text{GeV} \\ M_{A_2} = 639\,\text{GeV} \\ M_{H^\pm} = 640\,\text{GeV} \end{array}\right\} & [M_{H_3} \approx M_{H^\pm} \approx M_{A_2} \approx M_A] \\
M_{H_1} = 119\,\text{GeV} & [M_{H_1}^2 \approx M_Z^2 \cos^2 2\beta + \delta] \\
M_{A_1} = 7\,\text{GeV} & [M_{A_1}^2 \approx -3\kappa\langle S\rangle A_\kappa]
\end{array}$$

Main features:

$$\text{BR}(H_1 \to A_1 A_1) = 0.99 \qquad \text{BR}(A_1 \to \tau^+\tau^-) = 0.99$$

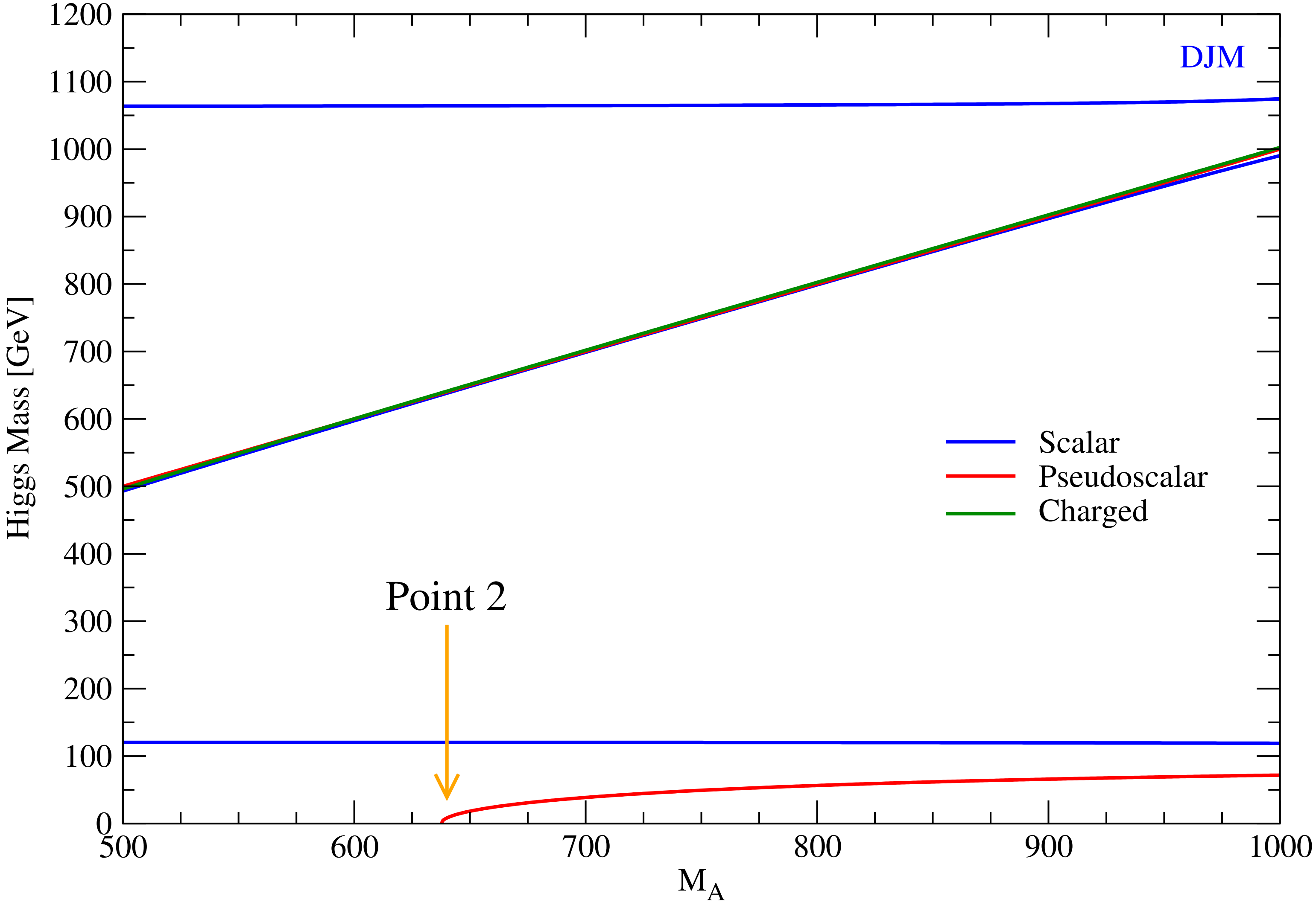
$$\text{Look at } WW \to H_1 \to A_1 A_1 \to \tau^+\tau^-\tau^+\tau^- \to \tau^+\tau^- jj\nu_\tau\bar{\nu}_\tau$$

Heavily exploit forward & backward jet tagging on light quarks from W-strahlungs



For point 2, $S/\sqrt{B} = 22$

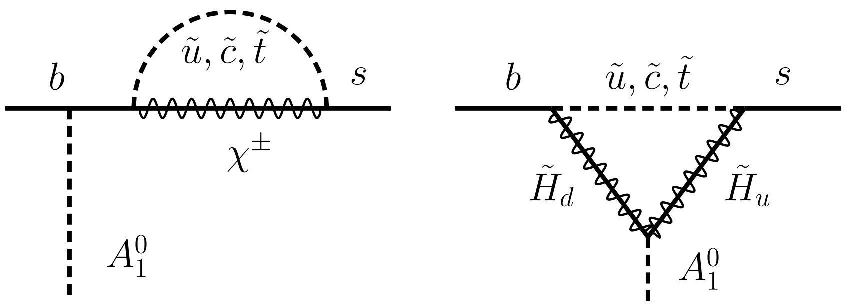
These points aren't exactly "typical"



b-physics constraints on A [or how light can A_1 get?]

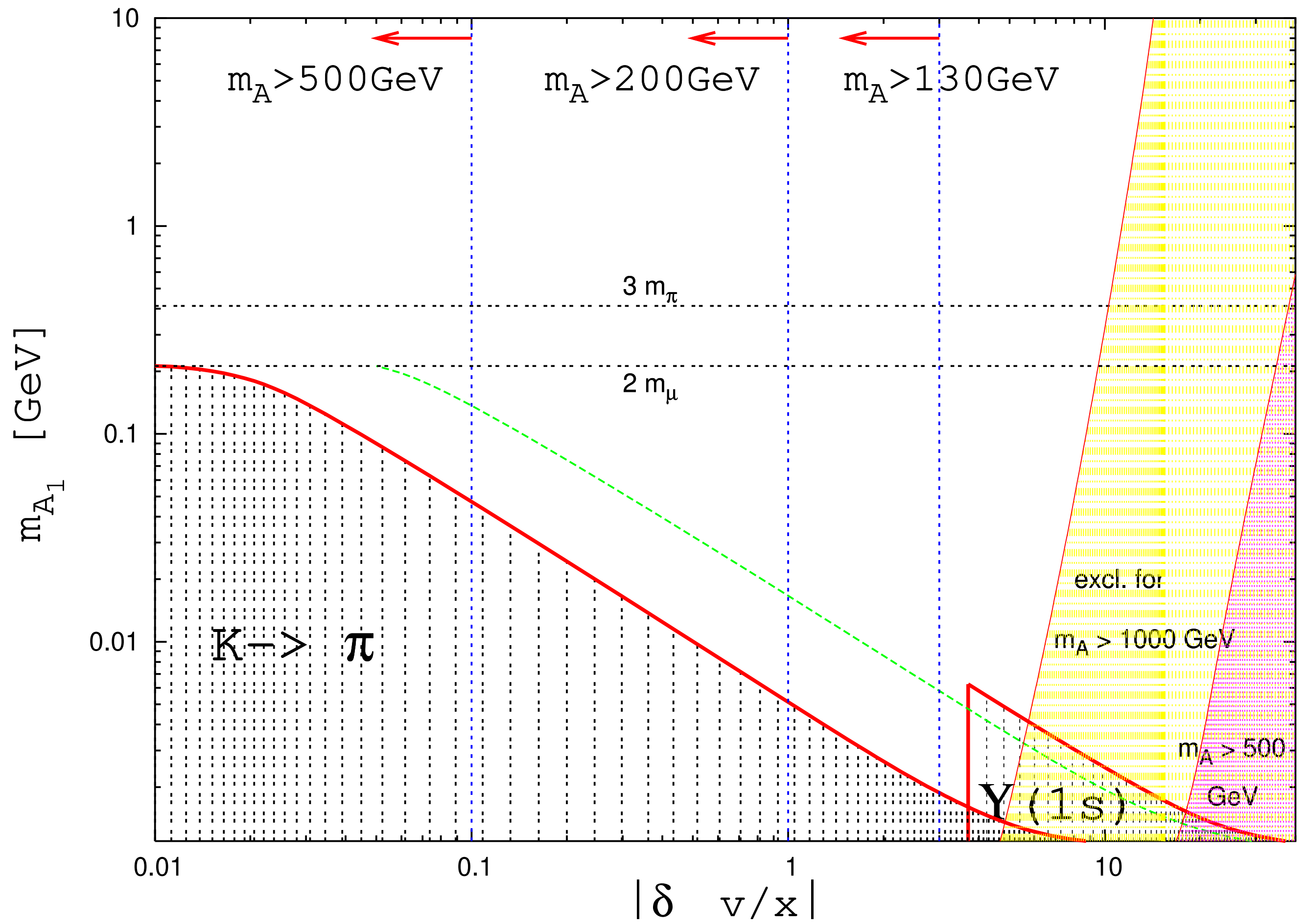
[Hiller hep-ph/0404220]

If A_1 is very light then we may have $b \to sA_1$ decays:



Contributes to:

- Rare K, B and radiative Υ decays
- $B - \bar{B}$ mixing



[$|\delta_{-}v/x|$ is a scaled $A_1 f\bar{f}$ vertex]

Distinguishing the NMSSM Higgs sector from the MSSM

Change in philosophy from "no-lose theorems":

If we do see a Higgs boson(s) at the LHC, how can we tell if it is the NMSSM?

Can we see the "singlet"-like Higgs bosons?

For most NMSSM scenarios,

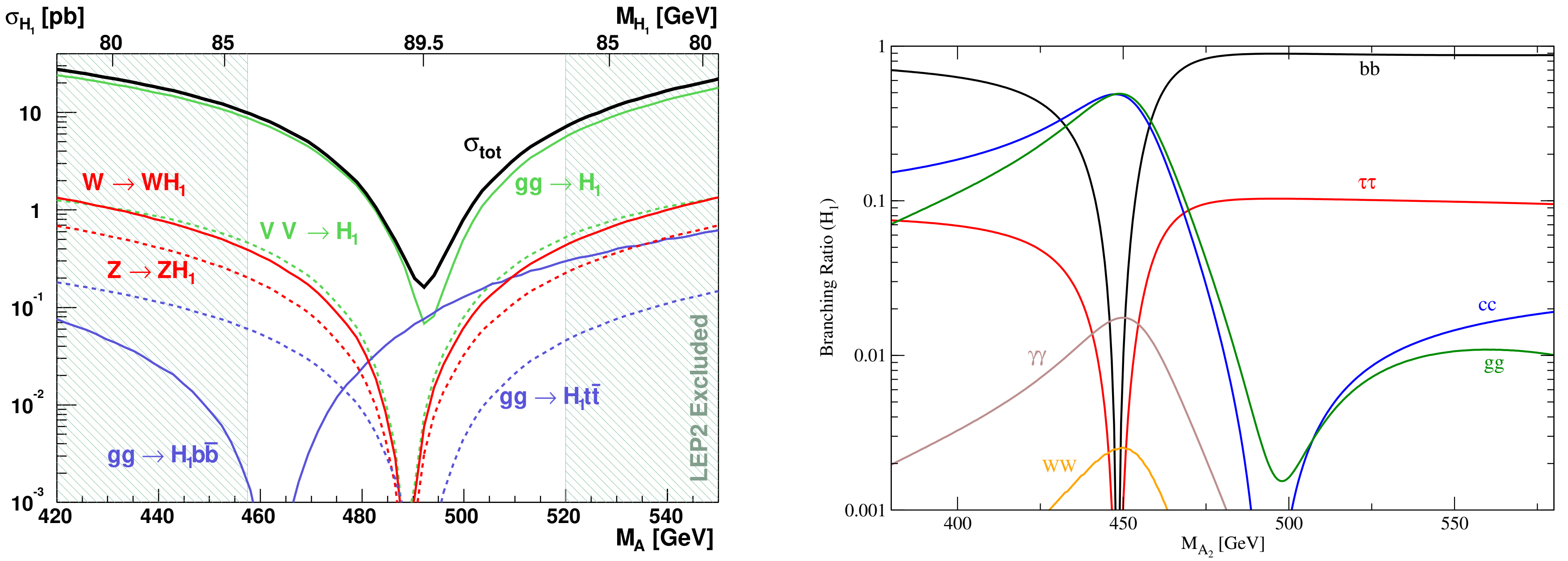
- ♢ "doublet-like" scalar is not much more difficult to see than in the MSSM
- ♢ "singlet-like" scalar can be seen if it is heavy enough to decay $H \to Z^* Z$

[There is clearly an interplay between how hard/easy each of these is.]

[DJM, Moretti, hep-ph/0403137]

Lightest Higgs boson production at the LHC & its decay

for $\lambda = 0.3$, $\kappa = 0.1$, $\langle S \rangle = 3 \times 174$ GeV, $A_\kappa = -100$ GeV:

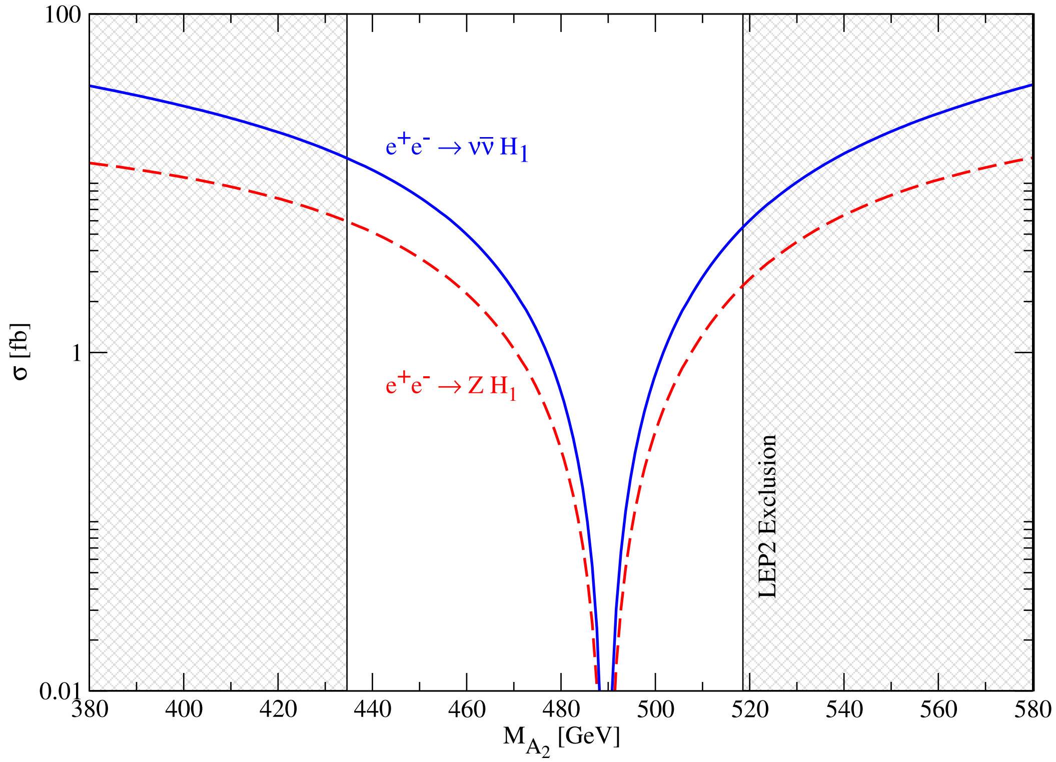


Cross-sections reasonable but decay dominated by $H_1 \to b\bar{b}$

Hadronic decay $\Rightarrow$ Huge SM backgrounds

Very difficult to see at the LHC

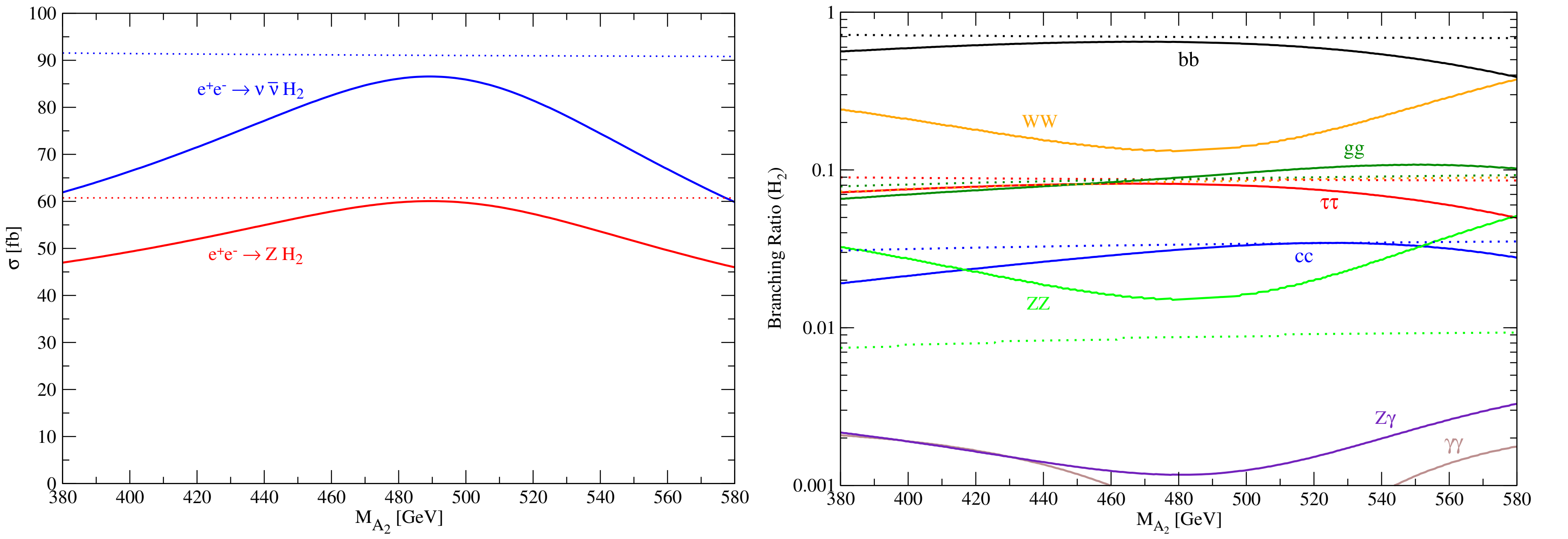
Lightest Higgs production at a $\sqrt{s} = 500$ GeV e^+e^- Linear Collider



Visible for most of the allowed range

These scale with s just like in the SM $\begin{cases} \sigma(e^+e^- \to ZH_1) \;\propto 1/s \\ \sigma(e^+e^- \to \nu\bar{\nu}H_1) \propto \log(s/M_{H_1}^2) \end{cases}$

Production and decay for second lightest (“h”-like) Higgs

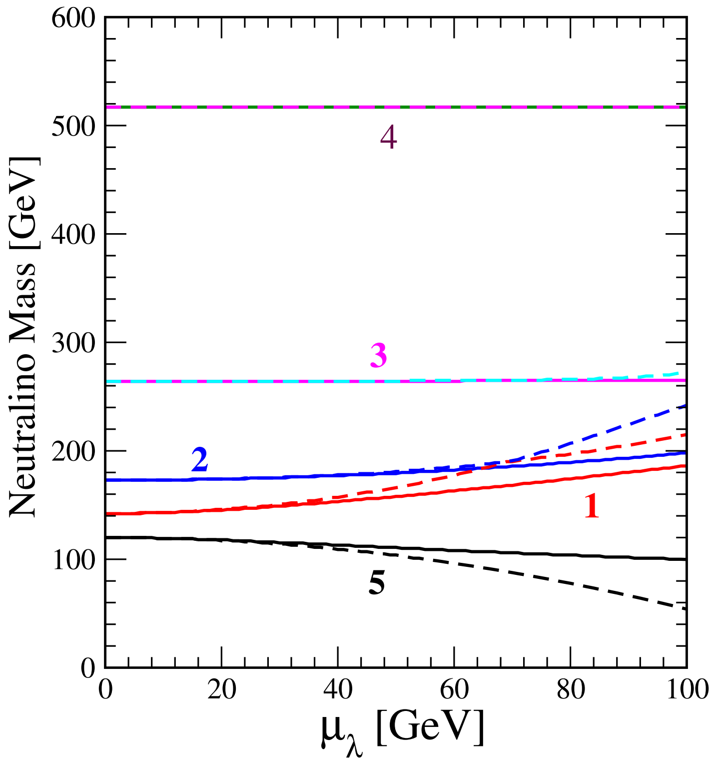


Dotted lines show MSSM [for corresponding parameters]

The Neutralino Sector

[Choi, DJM, Zerwas, preliminary]

2 gauginos + 2 higgsinos + "singlino" $\rightarrow$ 5 neutralinos



$m_1 \approx \mu - \ldots$

$m_2 \approx \mu + \ldots$

$m_3 \approx M_1 + \ldots$

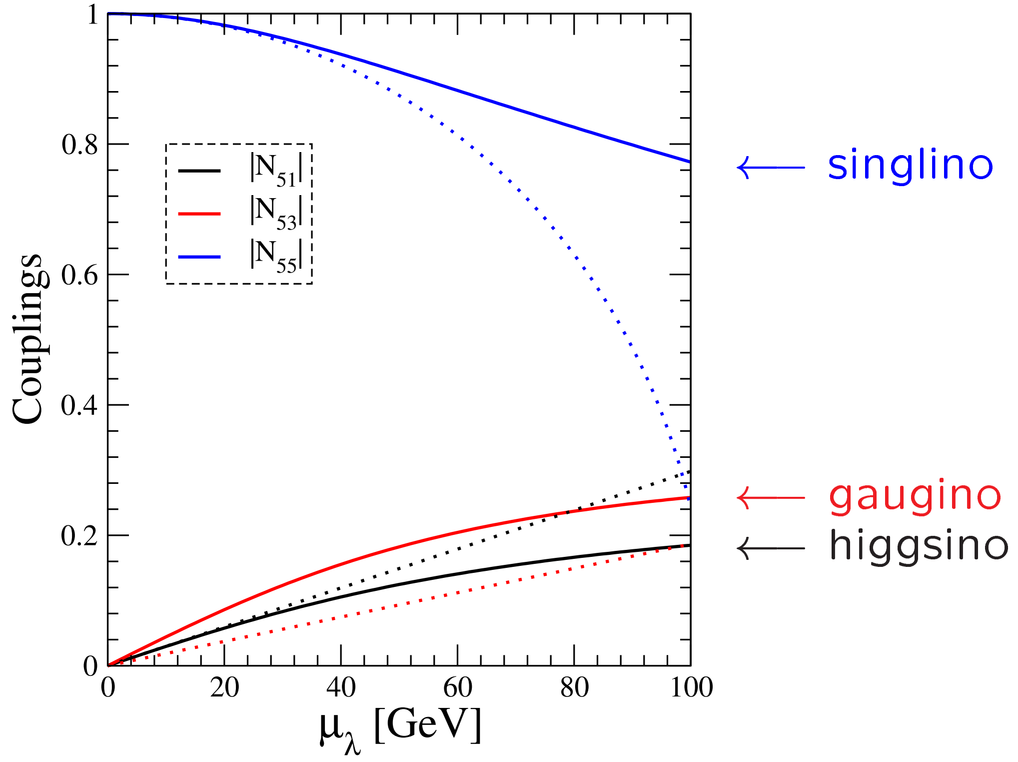
$m_4 \approx M_2 + \ldots$

$m_5 \approx 2\kappa\langle S\rangle + \ldots$

$$\mu_\lambda = \lambda v/\sqrt{2}$$

$M_1 = 250$ GeV, $M_2 = 500$ GeV, $\tan\beta = 3$, $\mu = 170$ GeV, $\kappa\langle S\rangle = 60$ GeV

Ingredients of lightest Neutralino



In this scenario LSP is singlino!

Extremely important to study – end product of all SuSy decay chains.

Comparison of NMSSM at $\mu_\lambda = 60$ GeV with the MSSM ($\mu_\lambda = 0$ limit)

Mass(GeV)	5	1	2	3	4
MSSM		142	173	264	517
NMSSM	108	163	182	264	517

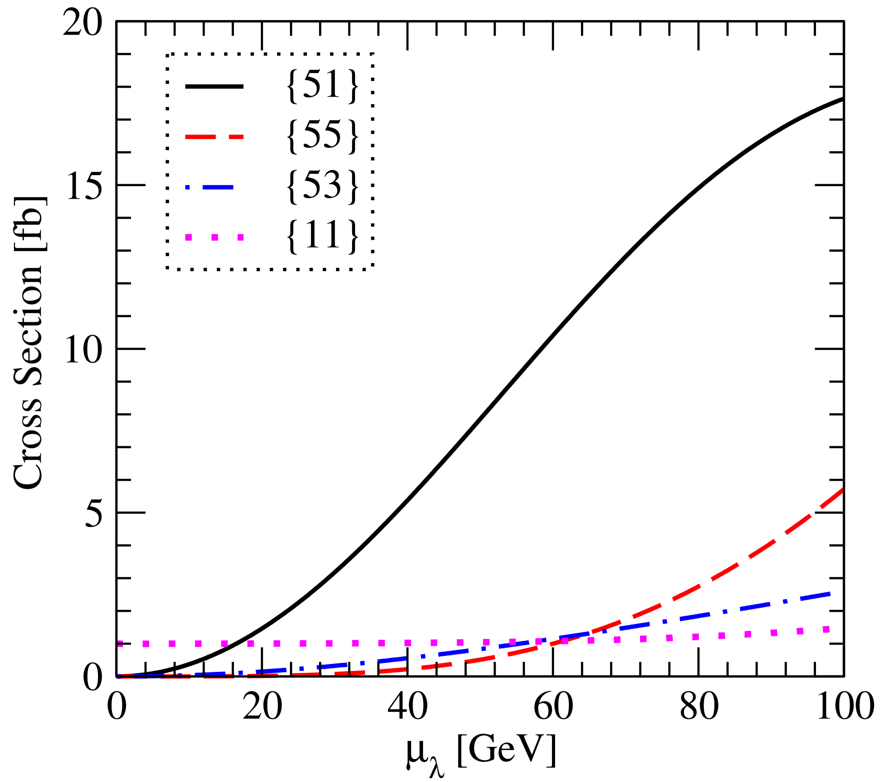
Heavy states are unaffected by precence of singlino (as expected)

If we see (e.g.) 3 $\tilde{\chi}^0$ states at the LHC, are we seeing

$\tilde{\chi}^0_1$, χ^0_2 and $\tilde{\chi}^0_4$ of the MSSM

or $\tilde{\chi}^0_5$, $\tilde{\chi}^0_1$ and $\tilde{\chi}^0_2$ of the NMSSM?

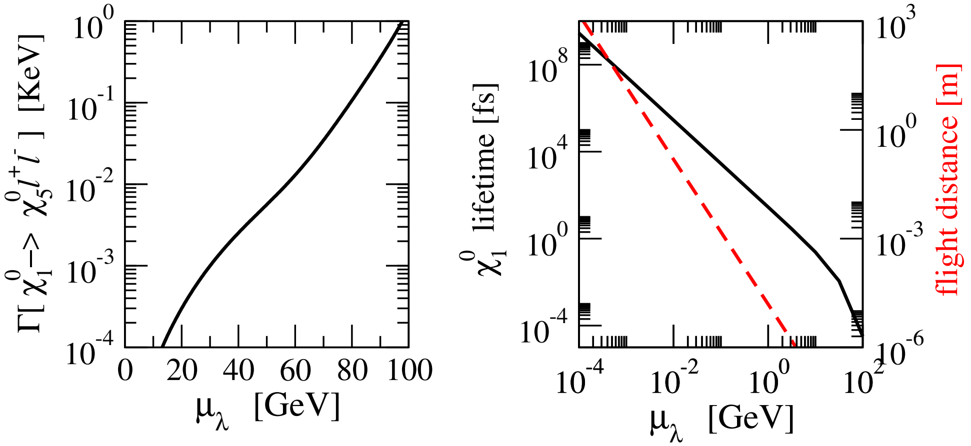
Production at an e^+e^- Linear Collider



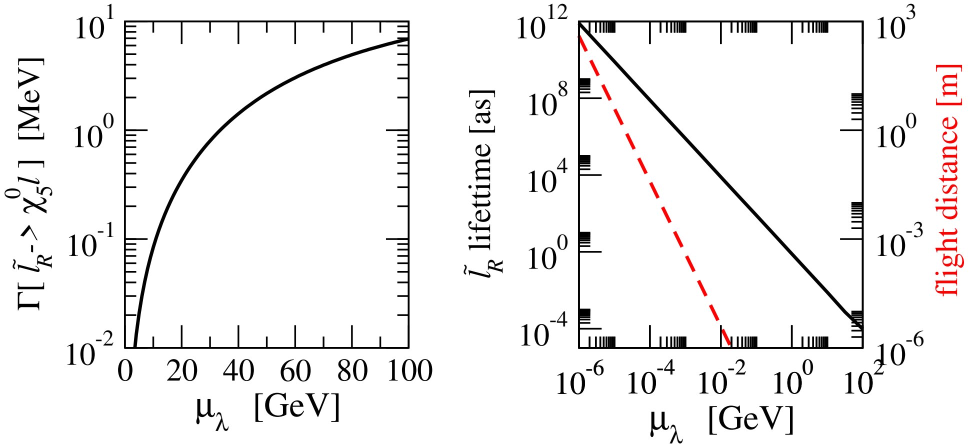
mediated by $\begin{cases} \text{s-channel } Z \text{ exchange (higgsino-like)} \\ \text{t/u-channel } \tilde{e} \text{ exchange (gaugino-like)} \end{cases}$

Singlino LSP as a decay product

$\tilde{\chi}_1^0$ decays:

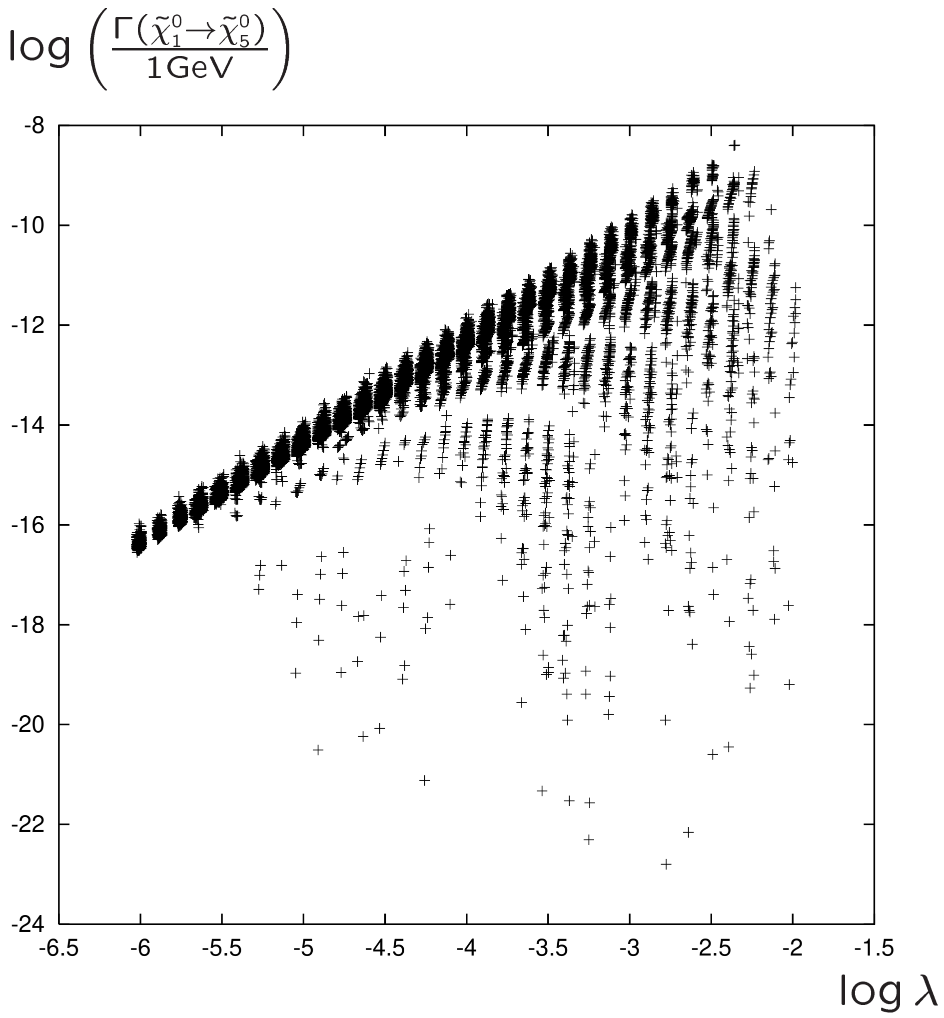


$\tilde{l}_R$ decays:

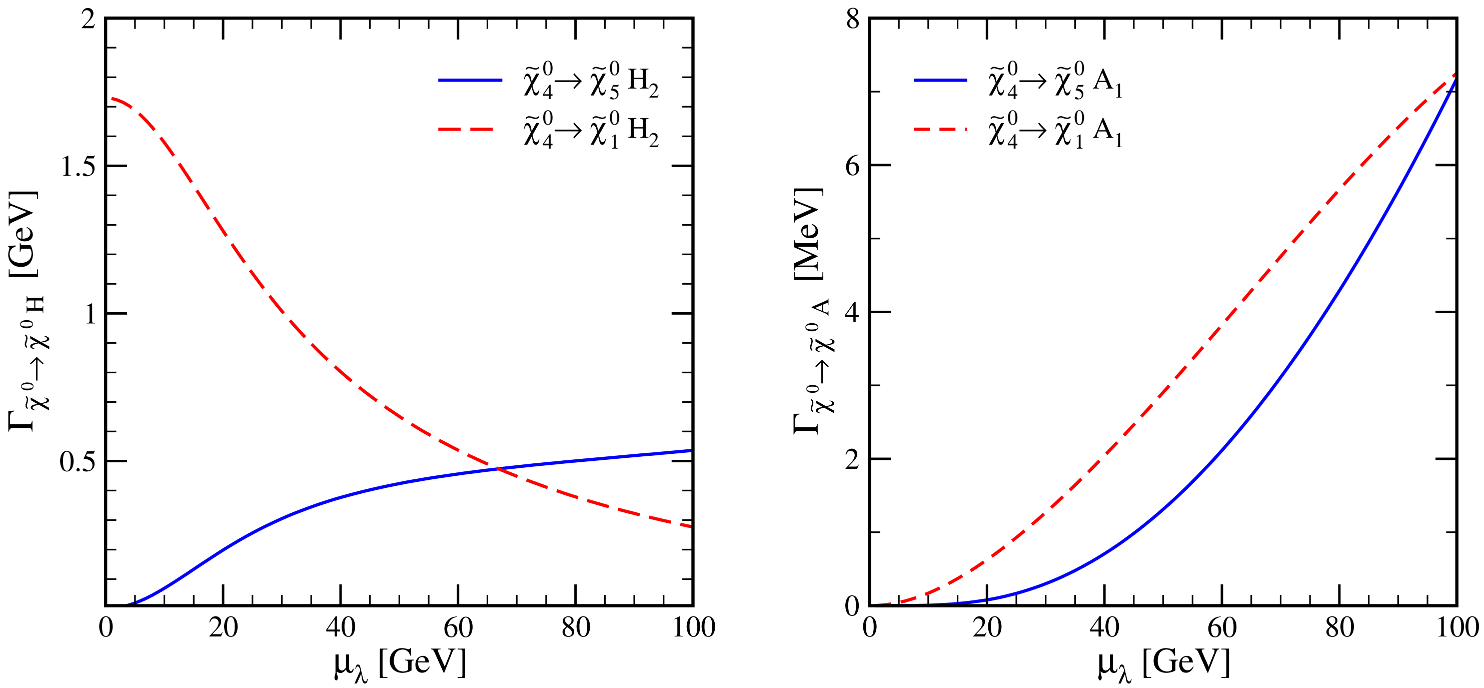


No displaced vertices unless μ_λ is *very* small

Ellwanger, Hugonie, Eur.Phys.J. C5 (1998) 723



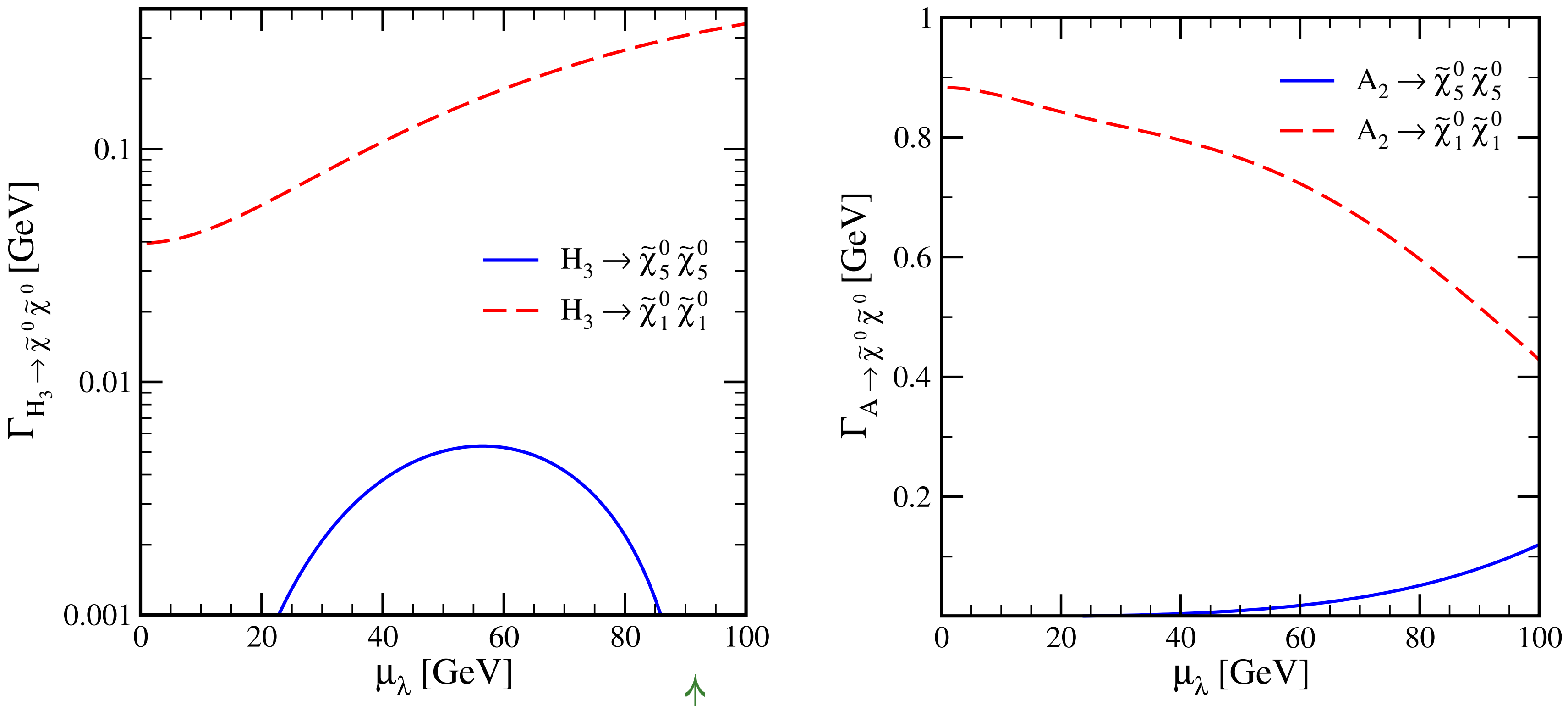
$\tilde{\chi}^0$'s may also be produced in association with Higgs bosons...



Here H_2 and A_1 are singlet dominated:

$M_{H_2} \sim 100 - 120$ GeV, $M_{A_1} \sim 130 - 150$ GeV

... or in decays of heavy Higgs bosons



$H_3\,\tilde{\chi}^0_5\,\bar{\tilde{\chi}}^0_5$ coupling switches off here

Conclusions & Summary

◇ The NMSSM is a well motivated extension of minimal supersymmetry

— solves the μ-problem
— less fine tuned than the MSSM

◇ Extra scalar, pseudoscalar and neutralino.

◇ "No-lose theroem" for all but some retricted corners of parameter space.

◇ b-physics constrains $M_{A_1} \gtrsim \mathcal{O}(10\text{MeV})$

◇ NMSSM Higgs can escapes LEP limits by having reduced ZZH coupling

◇ If "singlet" Higgs light

— difficult to see at LHC in most scenarios
— can be seen at a e^+e^- LC except for small areas of parameter space

◇ Extra neutralino is often LSP

— no displaced vertices unless λ very small