The Higgs and neutralino sectors of the NMSSM

- Introduction: The NMSSM and its motivation
- The Higgs Sector
- The Neutralino Sector
- Conclusions & Summary

Introduction: The NMSSM and its motivation

The Next–to–Minimal Supersymmetric Standard Model

MSSM: two Higgs doublets [analyticity and anomaly cancellation]

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

H_d couples to down-type quarks and leptons
H_u couples to up-type quarks and leptons

NMSSM: two Higgs doublets, $\hat{H}_d$ and $\hat{H}_u$, and a new Higgs singlet superfield $\hat{S}$

$$\hat{S} \longrightarrow \begin{cases} \text{new scalar Higgs boson} \\ \text{new pseudoscalar Higgs boson} \\ \text{new higgsino} \end{cases}$$

- ♢ Well motivated by high scale theories
- ♢ Solves the μ-problem

The μ–problem

MSSM Superpotential:

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

Note the appearance of μ in W (the "Higgs-higgsino mass parameter")

- μ has dimensions of mass
- μ has no *a priori* link to EW scale

$\Big\}$ expect $\mu = 0$ or M_{Planck}

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

Why is $\mu \approx$ EW/SuSy scale?

This is known as the "μ-problem"

NMSSM Superpotential:

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

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

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

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

- $\frac{1}{3}\kappa S^3$ term is included to break additional $U(1)$ symmetry

  [provides extra mass for Higgs bosons]

The Higgs Sector

Relevant parameters:

λ	couplings to other Higgs [if $\lambda = 0$, new states decouple]
κ	contributes mass to new Higgs
A_λ, A_κ	associated soft SuSy-breaking parameters
$\langle S \rangle$, $\tan\beta = \langle H_u \rangle / \langle H_d \rangle$	vacuum-expectation-values

Today's scenario:

$$\boxed{\lambda = 0.3,\ \kappa = 0.1,\ A_\kappa = -100\text{GeV},\ \langle S \rangle = 3 \times 174\text{GeV},\ \tan\beta = 3}$$

A_λ replaced by heavy pseudoscalar mass M_{A_2} and allowed to vary

The Higgs Mass Spectrum

Spectrum like MSSM + 2 extra states

3 scalars:	H_1,	H_2,	H_3
2 pseudoscalars:	A_1,	A_2	
Charged:	$H^\pm$		

Approximate masses for $1/\tan\beta$ and M_Z/M_{A_2} small [tree-level]:

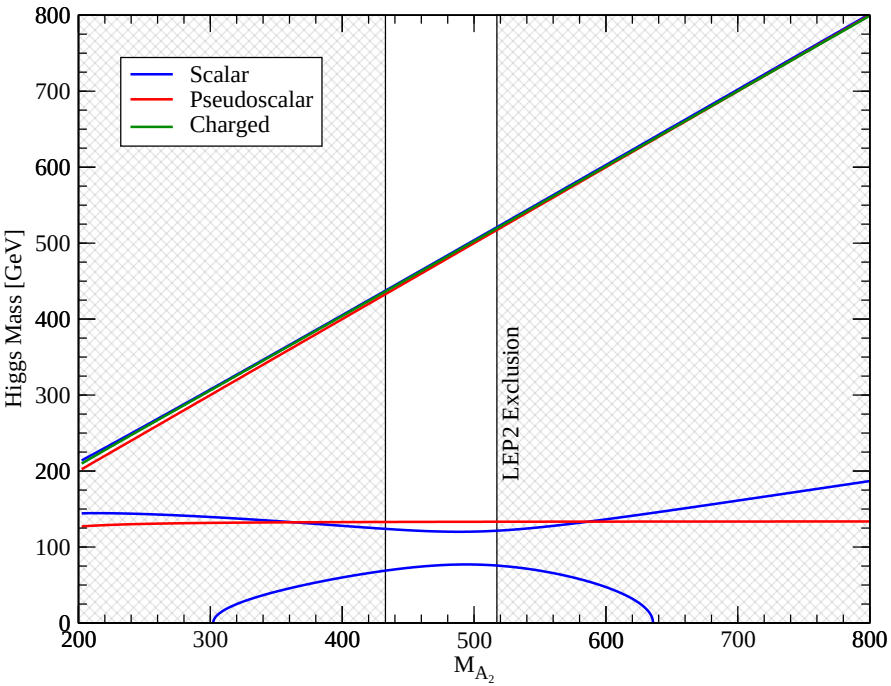
$$M_{H_3} \approx M_{H^\pm} \approx M_{A_2}$$

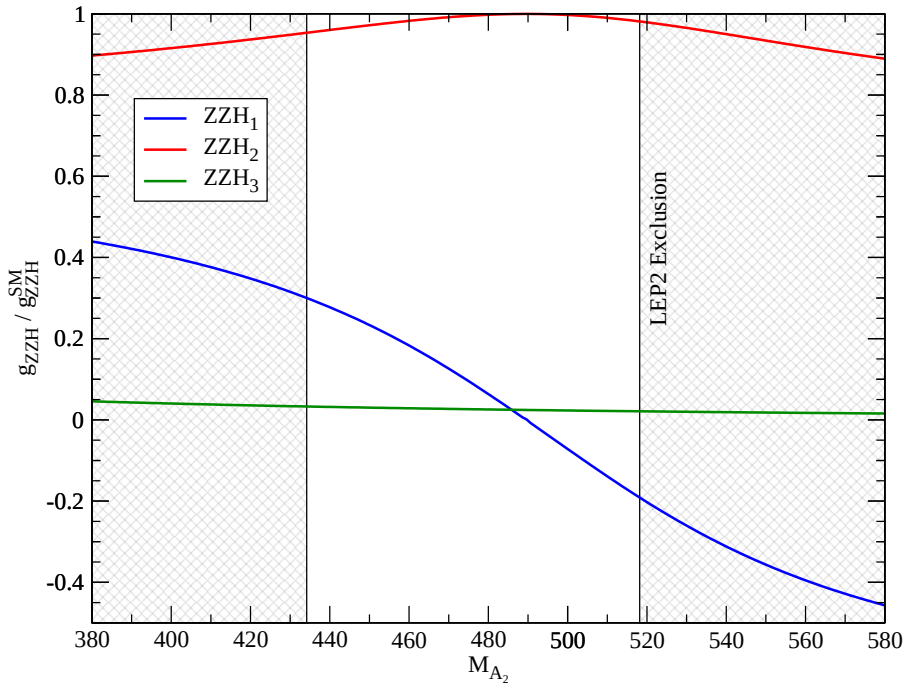
$$M_{H_2}^2 \approx M_Z^2 \cos^2 2\beta$$

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

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

At one-loop:





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

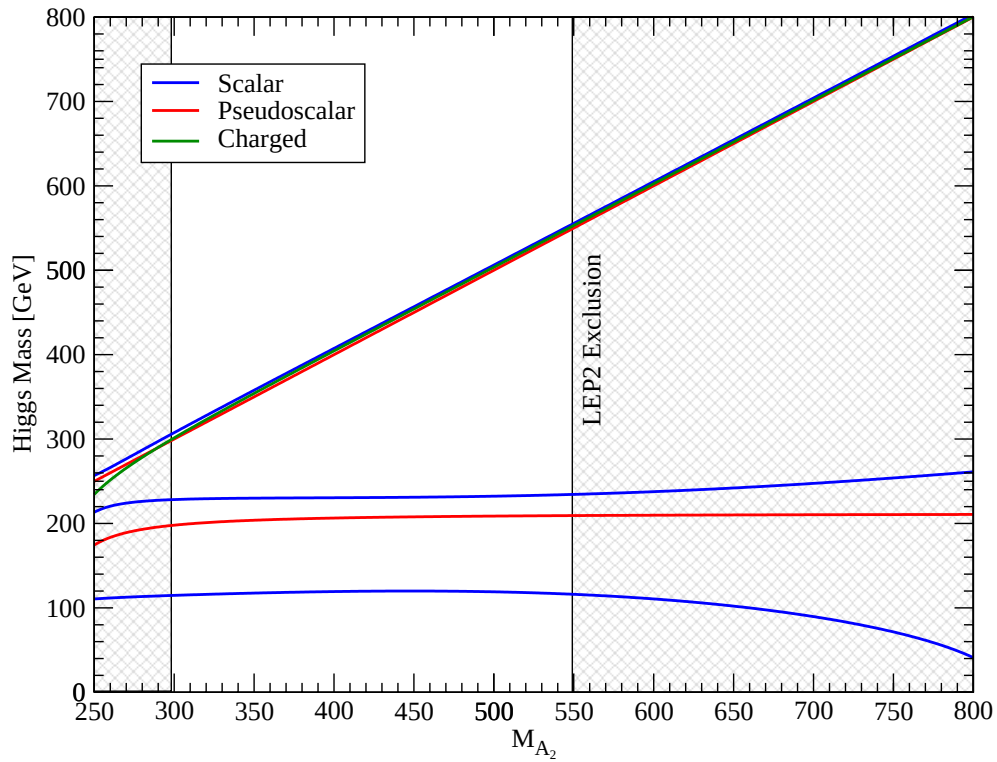
NMSSM H_1ZZ coupling small $\Rightarrow$ rather light Higgs is not ruled out

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

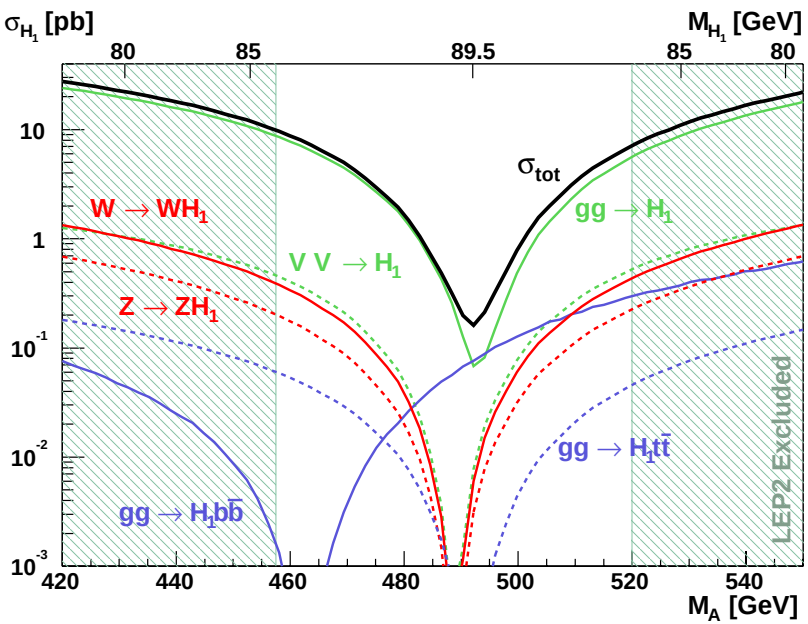
Allowed region opens up as κ is increased.

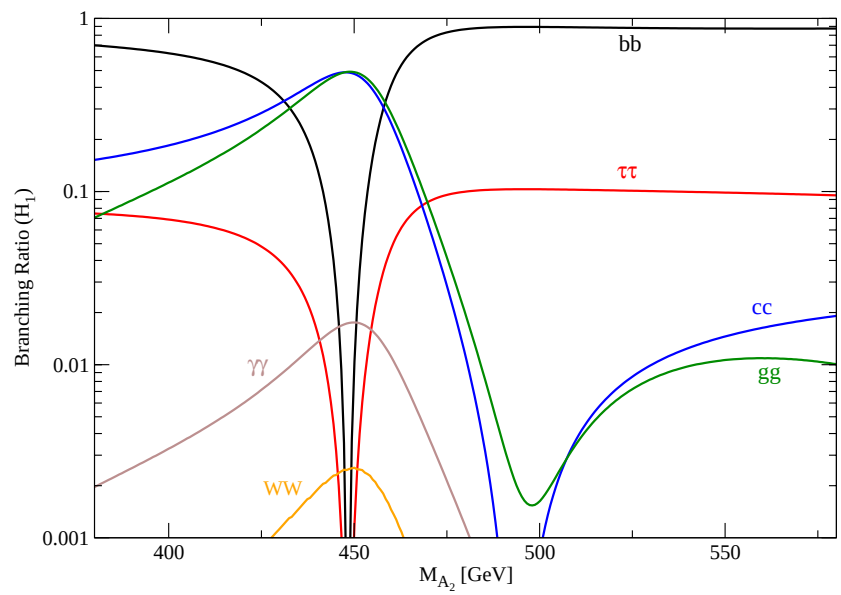
e.g. $\kappa = 0.25$ [with $\langle S \rangle = 3 \times 174$ GeV, $A_\kappa = -100$ GeV as before]

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



Lightest Higgs boson production at the LHC & its decay





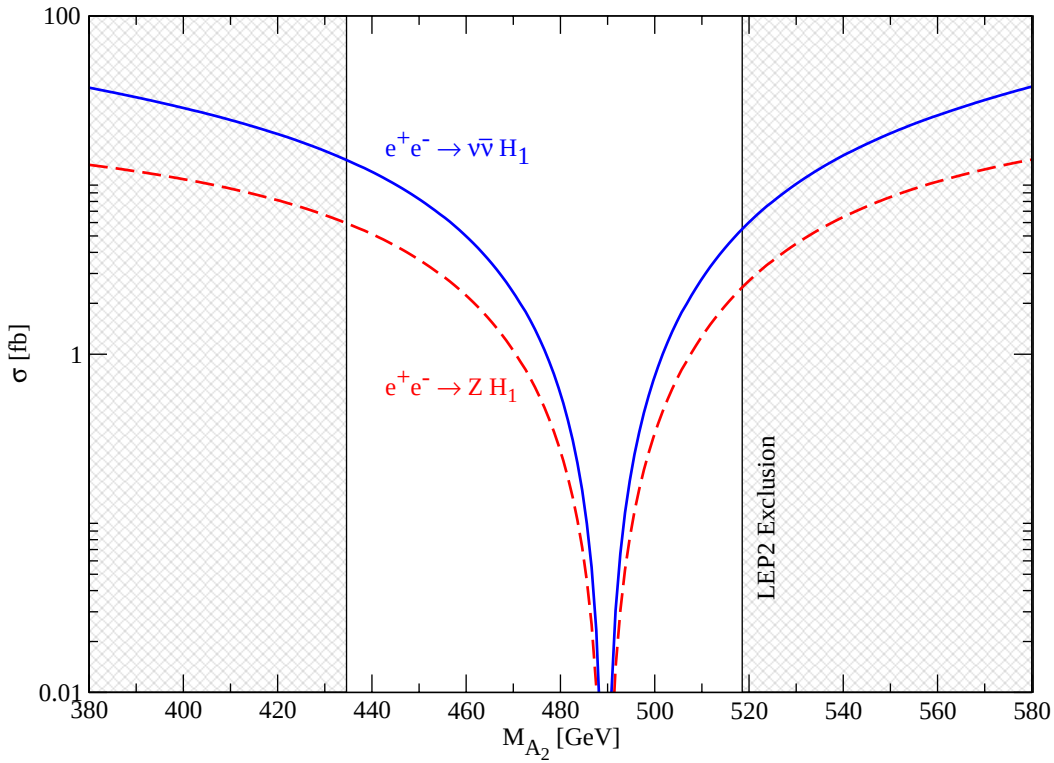
Cross-sections reasonable but decay dominated by $H_1 \to b\bar{b}$

Hadronic decay $\Rightarrow$ Huge SM backgrounds

Very difficult to see at the LHC

Can an e^+e^- Linear Collider close this gap?

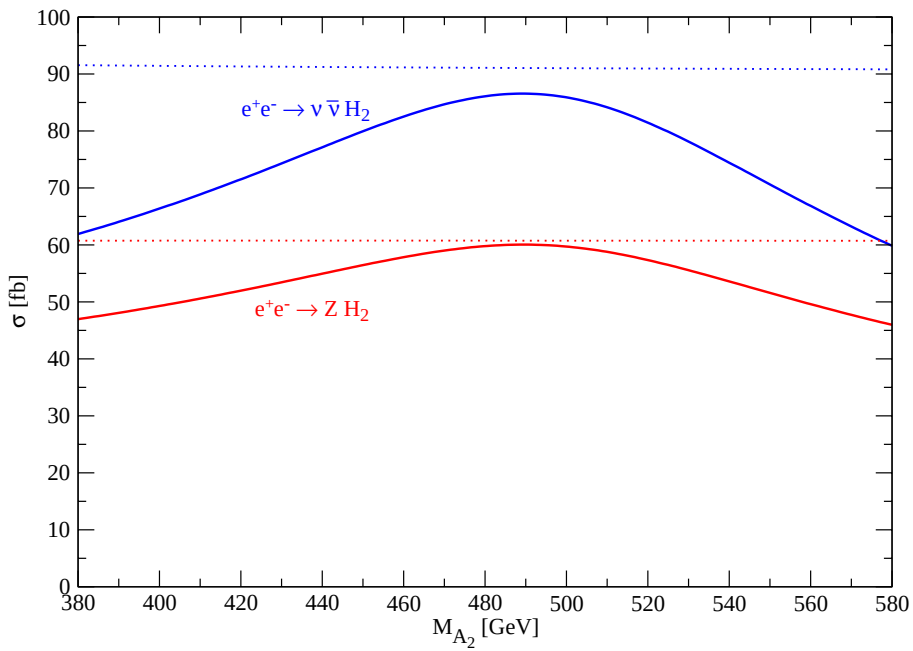
Lightest Higgs production at a $\sqrt{s} = 500$ GeV e^+e^- Linear Collider

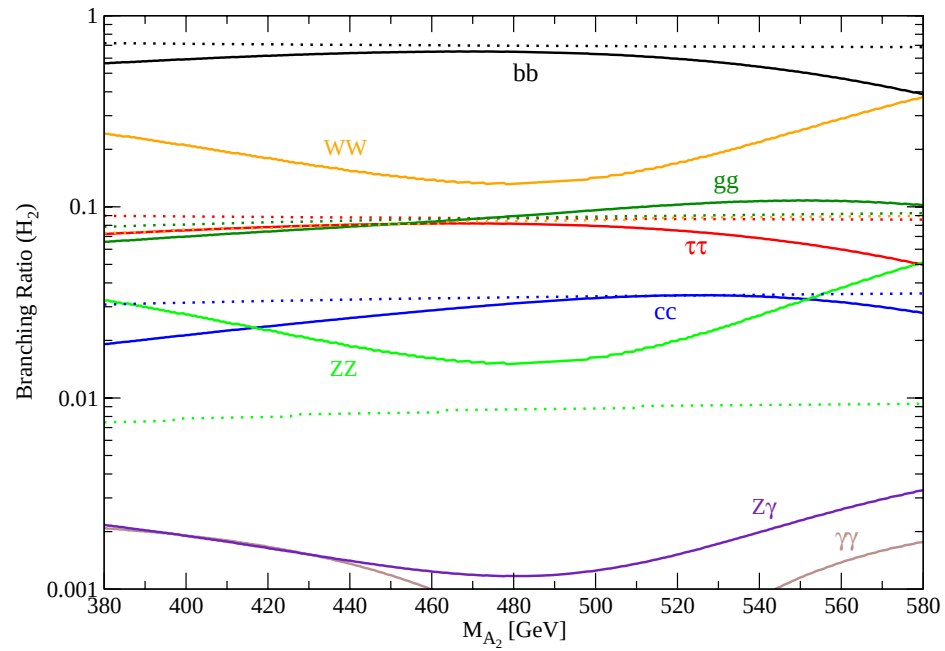


Visible for most of the allowed range

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

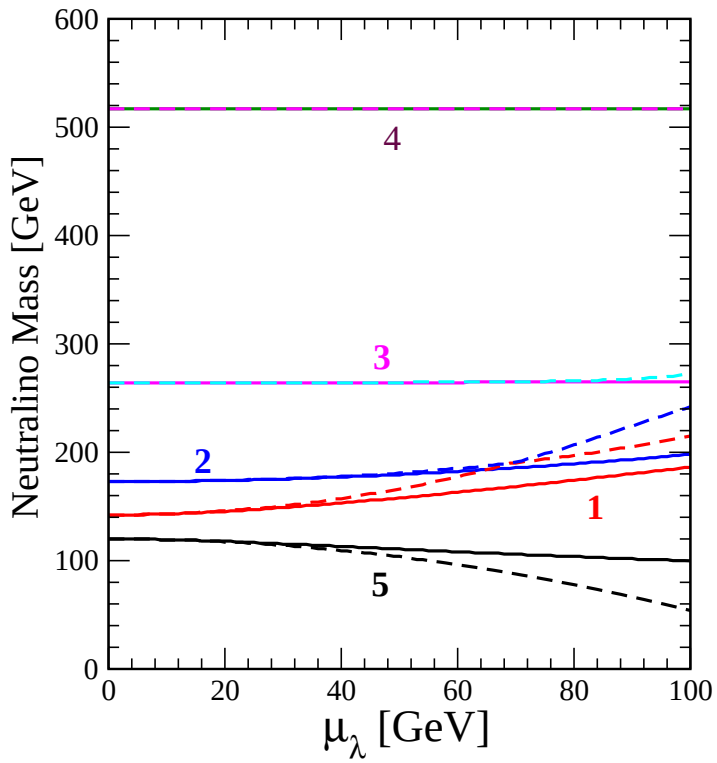




Dotted lines show MSSM [for corresponding parameters]

The Neutralino Sector

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



$m_1 \approx \mu - \ldots$

$m_2 \approx \mu + \ldots$

$m_3 \approx M_1 + \ldots$

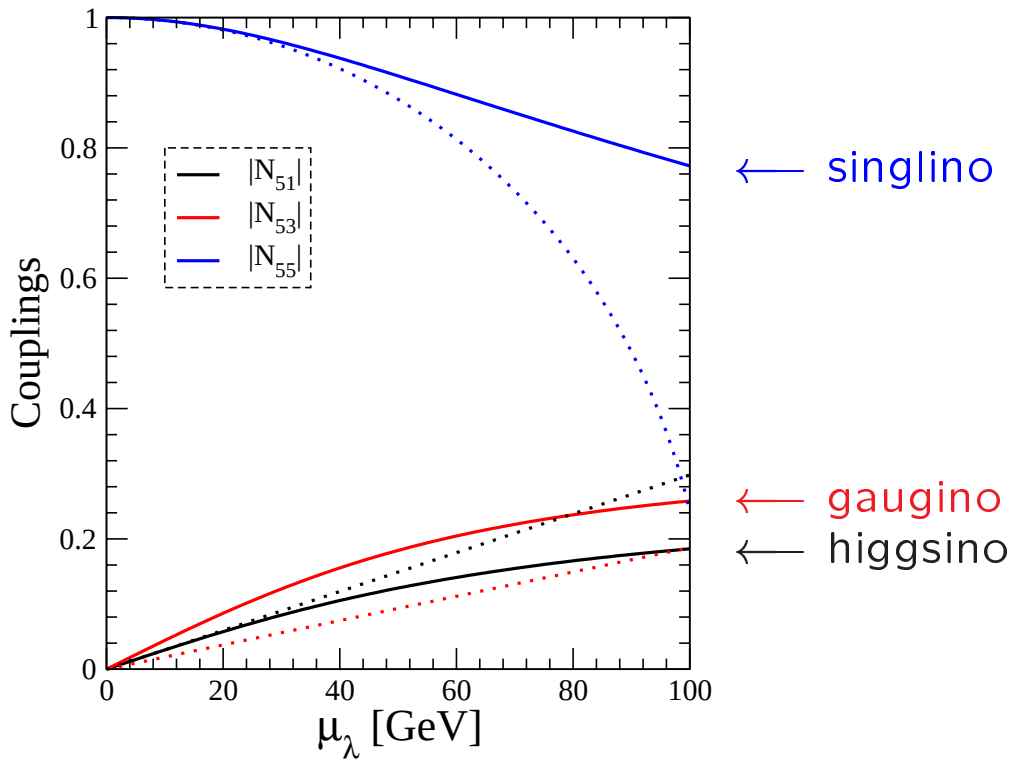
$m_4 \approx M_2 + \ldots$

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

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

$M_1 = 250$ 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

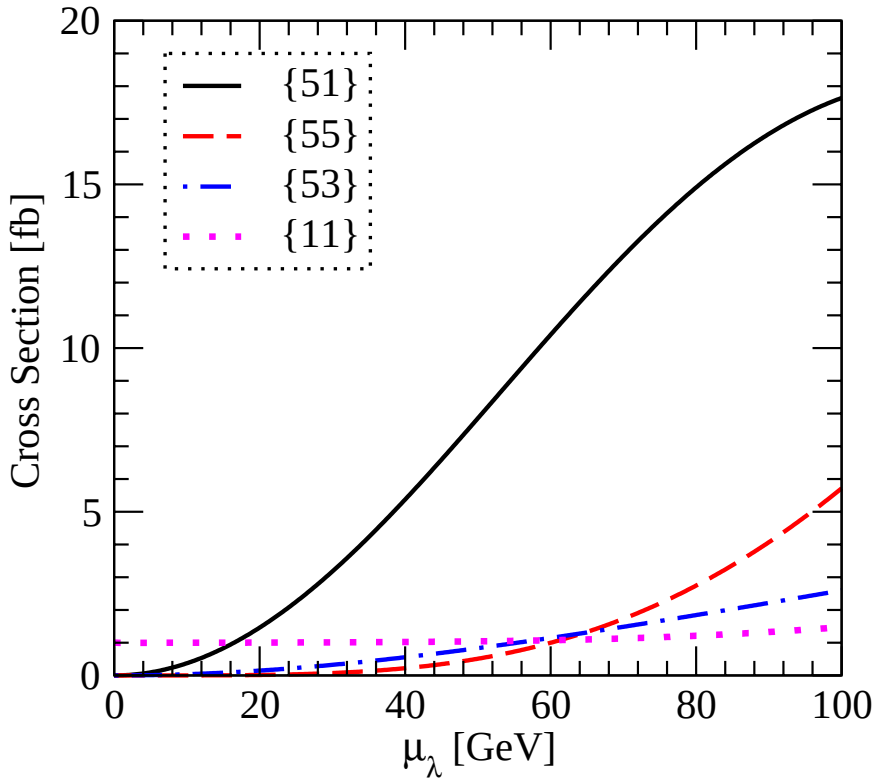
Heavy states are unaffected by precence of singlino (as expected)

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?

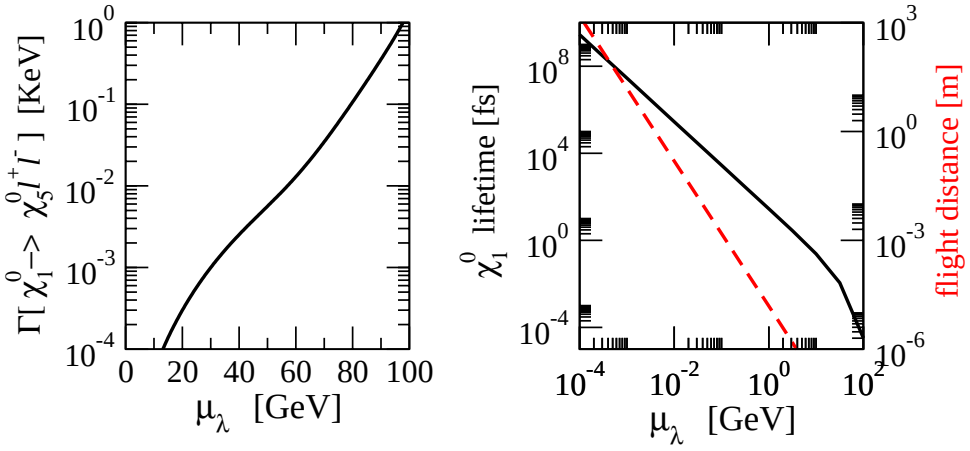
Production at an e^+e^- Linear Collider



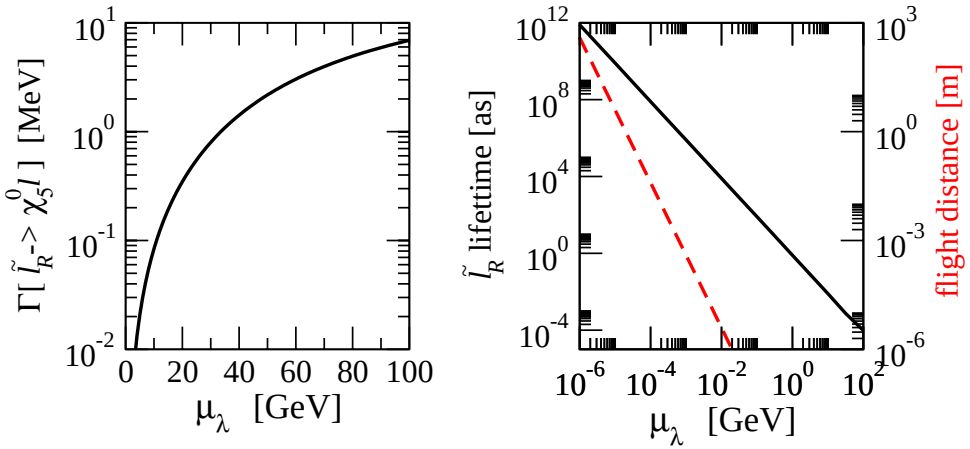
mediated by $\begin{cases} \text{s-channel } Z \text{ exchange (higgsino-like)} \\ \text{t/u-channel } \tilde{e} \text{ exchange (gaugino-like)} \end{cases}$

Singlino LSP as a decay product

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

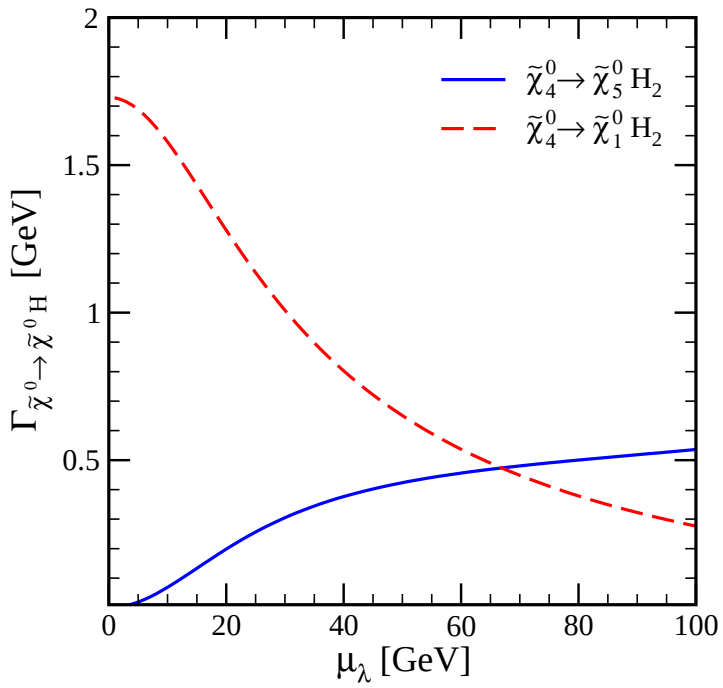


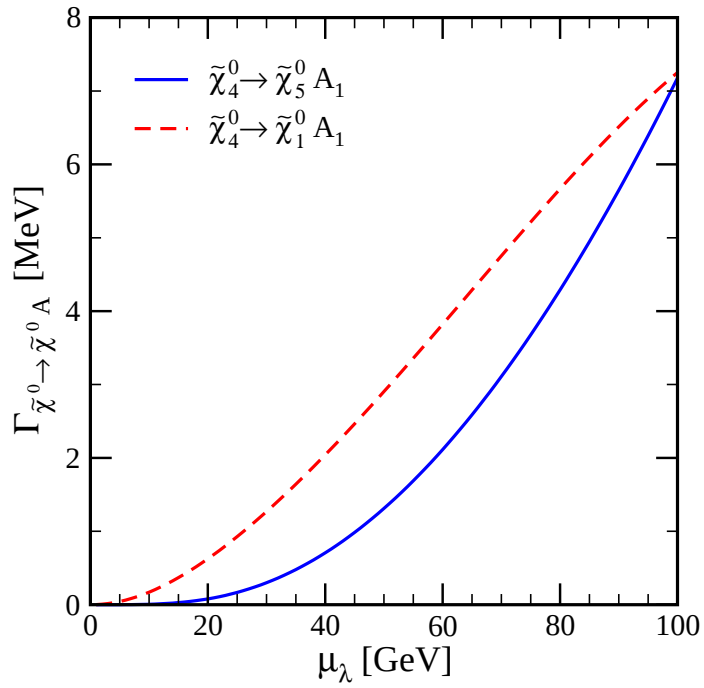
$\tilde{l}_R$ decays:



No displaced vertices unless μ_λ is *very* small

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

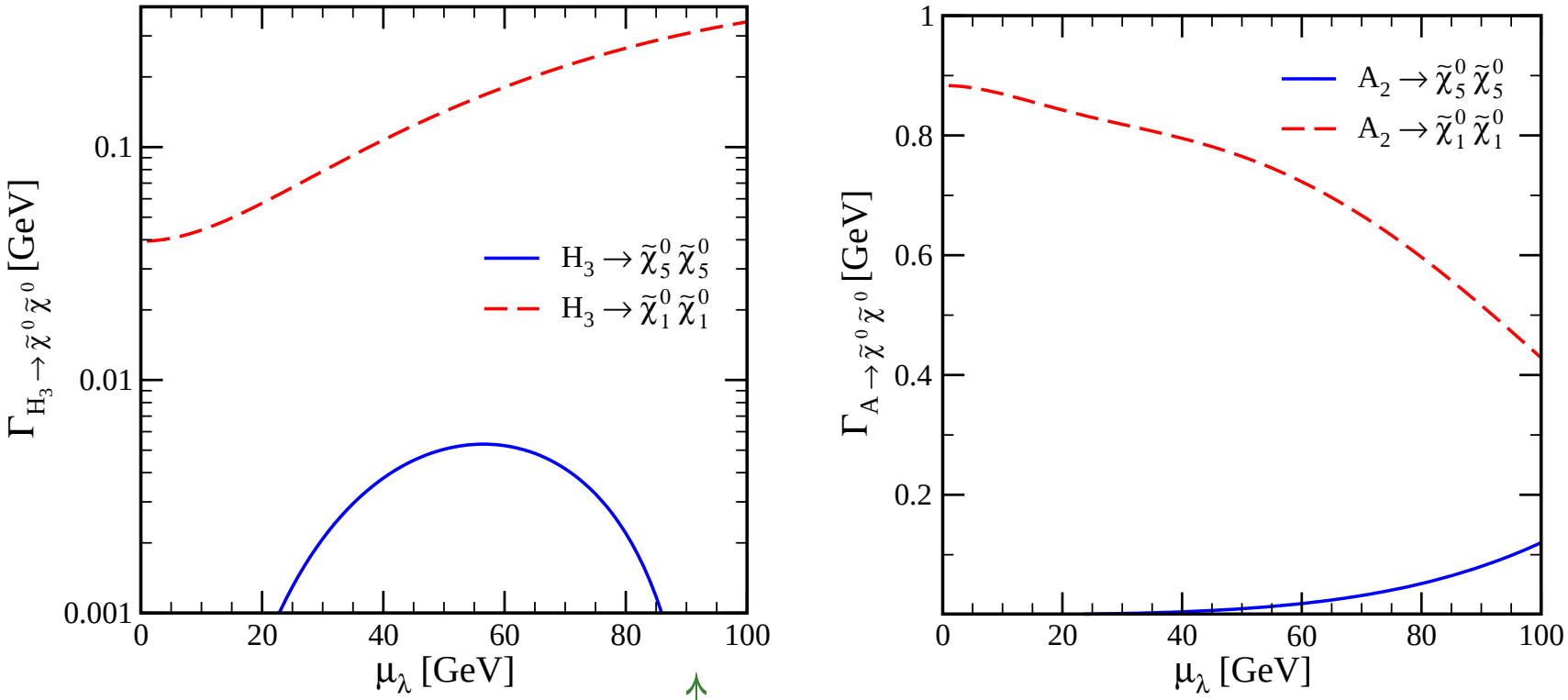




Here H_2 and A_1 are singlet dominated:

$M_{H_2} \sim 100 - 120$ 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

- NMSSM is a well motivated extension of MSSM: solves μ-problem
- New superfield $\hat{S} \Rightarrow$ 3 new particles, H, A, $\tilde{\chi}^0$, with $M \sim \kappa\langle S\rangle$
- Higgs sector:
  - — light H with reduced Z couplings would escape LEP2 limits
  - — difficult to see at LHC $\longrightarrow$ need an e^+e^- LC
  - — even LC has a blind spot where Z-coupling vanishes
- Neutralino sector:
  - — light $\tilde{\chi}^0_5$ could be singlino LSP
  - — 'usual' LSP decays to $\tilde{\chi}^0_5$ rapidly (eg. $\tilde{\chi}^0_1 \to \tilde{\chi}^0_5 l^+ l^-$)