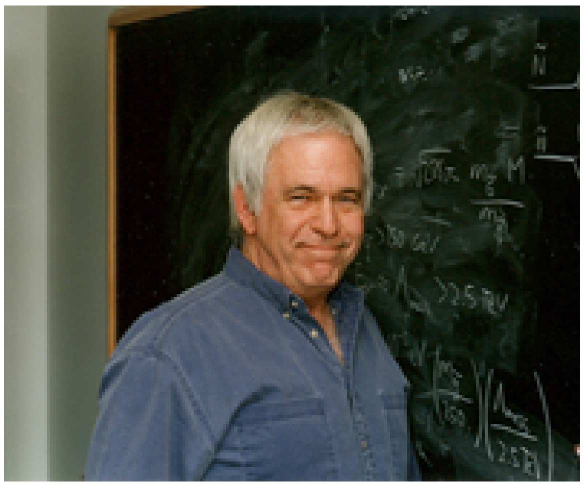
Beyond the Standard Paradigm



- **The standard paradigm or a landscape?**
- **Heavy Z'**
- **Extended Higgs**
- **Neutralinos**

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Massive neutrinos and (heterotic) string theory

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String theories in principle address the origin and values of the quark and lepton masses. Perhaps the small values of neutrino masses could be explained generically in string theory even if it is more difficult to calculate individual values, or perhaps some string constructions could be favored by generating small neutrino masses. We examine this issue in the context of the well-known three-family standard-like Z_3 heterotic orbifolds, where the theory is well enough known to construct the corresponding operators allowed by string selection rules, and analyze the D- and F-flatness conditions. Surprisingly, we find that a simple seesaw mechanism does not arise. It is not clear whether this is a property of this construction, or of orbifolds more generally, or of string theory itself. Extended seesaw mechanisms may be allowed; more analysis will be needed to settle that issue. We briefly speculate on their form if allowed and on the possibility of alternatives, such as small Dirac masses and triplet seesaws. The smallness of neutrino masses may be a powerful probe of string constructions in general. We also find further evidence that there are only 20 inequivalent models in this class, which affects the counting of string vacua.

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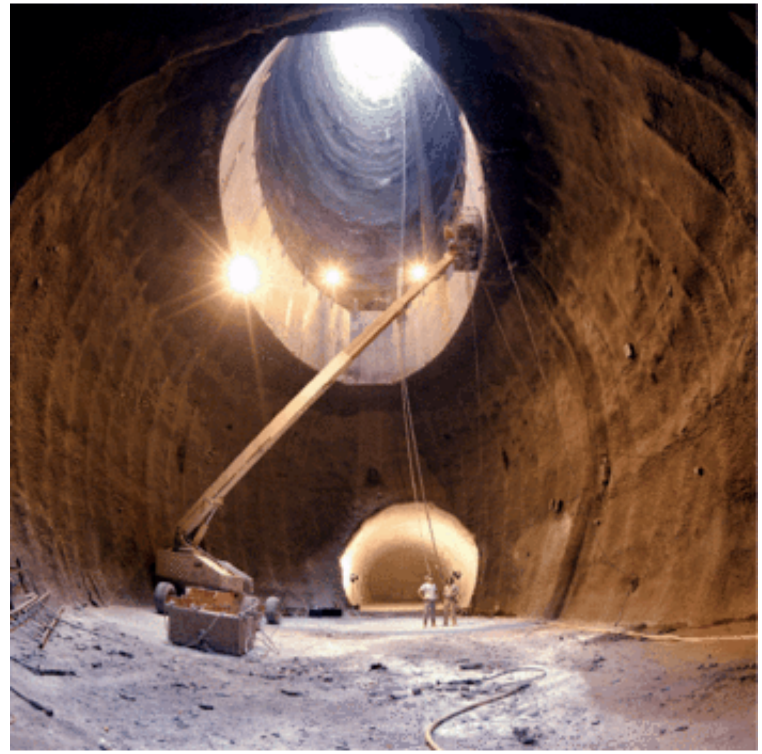
KANE



The standard paradigm

- MSSM at TeV scale
- LSP WIMPs
- (Possibly) GUT at unification scale
  - Gauge unification
- Seesaw model for m_ν
  - Leptogenesis
  - (Possibly) GUT relations for couplings (large representations?)
- SUSY breaking in hidden sector

Beyond the MSSM

Even if supersymmetry holds, MSSM may not be the full story

Most of the problems of standard model remain, new ones introduced (FCNC, EDM)

μ problem introduced: $W_\mu = \mu \hat{H}_u \cdot \hat{H}_d, \quad \mu = O(\text{electroweak})$

Remnants of GUT/Planck scale physics may survive to TeV scale

Ingredients of 4d GUTs hard to embed in string, especially large Higgs representations, Yukawa relations

Specific string constructions often have extended gauge groups, exotics, extended Higgs/neutralino sectors (Defect or hint?)

Important to explore alternatives/extensions to MSSM

Remnants Physics from the Top-Down

- Z' or other gauge
- Extended Higgs/neutralino (doublet, singlet)
- Quasi-Chiral Exotics
- Non-standard ν mass (enhanced symmetries)
- Quasi-hidden (Strong coupling? SUSY breaking? Composite family?)
- Charge $1/2$ (Confinement?, Stable relic?)
- Time varying couplings
- LED (TeV black holes, stringy resonances)
- LIV, VEP (speeds, decays, (oscillations) of HE γ, e, gravity waves (ν's))

A TeV-Scale Z'

- Strings, GUTs, DSB, little Higgs, LED often involve extra Z'

- Typically $M_{Z'} > 600 - 900$ GeV (Tevatron, LEP 2, WNC); $|\theta_{Z-Z'}| < \text{few} \times 10^{-3}$ (Z-pole)
  (CDF di-electron: 850 (Z_{seq}), 740 (Z_χ), 725 (Z_ψ), 745 (Z_η))

- Discovery to $M_{Z'} \sim 5 - 8$ TeV at LHC, ILC, $(pp \to \mu^+\mu^-, e^+e^-, q\bar{q})$ (depends on couplings, exotics, sparticles)

- Diagnostics to 1-2 TeV (asymmetries, y distributions, associated production, rare decays)

Implications of a TeV-scale $U(1)'$

- **Natural Solution to μ problem** $W \sim hSH_uH_d \rightarrow \mu_{eff} = h\langle S\rangle$
  (“stringy version” of NMSSM)

- **Extended Higgs sector**
  - Relaxed upper limits, couplings, parameter ranges (e.g., $\tan\beta$ can be close to 1)
  - Higgs singlets needed to break $U(1)'$
  - Doublet-singlet mixing $\longrightarrow$ highly non-standard collider signatures

- **Large A term and possible tree-level CP violation** (no new EDM constraints) $\longrightarrow$ **electroweak baryogenesis**

- Extended neutralino sector
  - Additional neutralinos, non-standard couplings, e.g., light singlino-dominated, extended cascades
  - Enhanced possibilities for cold dark matter, $g_\mu - 2$ (even small $\tan\beta$)

- Exotics (anomaly-cancellation)
  - May decay by mixing; by diquark or leptoquark coupling; or be quasi-stable

- Constraints on neutrino mass generation

- Z' decays into sparticles/exotics

- Flavor changing neutral currents (for non-universal $U(1)'$ charges)
  - Tree-level effects in B decay competing with SM loops (or with enhanced loops in MSSM with large $\tan\beta$)

Extended Higgs Sector

- Standard model singlets S_i and additional doublet pairs $H_{u,d}$ very common.

- Additional doublet pairs
  - Richer spectrum, decay possibilities
  - May be needed (or expand possibilities for) quark/lepton masses/mixings (e.g., stringy symmetries may restrict single Higgs couplings to one or two families)
  - Extra neutral Higgs $\longrightarrow$ FCNC (suppressed by Yukawas)
  - Significantly modify gauge unification (unless compensated)

Higgs singlets S_i

- Standard model singlets extremely common in string constructions

- Needed to break extra $U(1)'$ gauge symmetries

- Solution to μ problem ($U(1)'$, NMSSM, nMSSM, sMSSM)

$$W \sim h_s \hat{S} \hat{H}_u \hat{H}_d \rightarrow \mu_{eff} = h_s \langle S \rangle$$

- Relaxed upper limits, couplings, parameter ranges (e.g., $\tan\beta = v_u/v_d$ can be close to 1), singlet-doublet mixing

- Large A term and possible tree-level CP violation $\longrightarrow$ electroweak baryogenesis

Dynamical μ

- V. Barger, PL and H. S. Lee, "Lightest neutralino in extensions of the MSSM," Phys. Lett. B 630, 85 (2005), hep-ph/0508027
- V. Barger, PL, H.S. Lee and G. Shaughnessy, "Higgs Sector in Extensions of the MSSM", Phys. Rev. D 73, 115010 (2006), hep-ph/0603247.
- V. Barger, P. Langacker and G. Shaughnessy, "Neutralino signatures of the singlet extended MSSM," hep-ph/0609068.
- V. Barger, P. Langacker and G. Shaughnessy, "Collider signatures of singlet extended Higgs sectors," hep-ph/0611239.
- V. Barger, I. Lewis, M McCaskey, P. Langacker, G. Shaughnessy, and B. Yencho, "Detection of the Lightest Neutralino in Extended MSSM Models", to appear.

- Abel, Bagger, Barger, Bastero-Gil, Batra, Birkedal, Carena, Chang, Choi, Cvetic, Dedes, Delgado, Demir, Dermisek, Dobrescu, Drees, Ellis, Ellwanger, Erler, Espinosa, Everett, Fox, Godbole, Gunion, Haber, Han, Hooper, Hugonie, Kaplan, King, Landsberg, Li, Matchev, McElrath, Menon, Miller, Moretti, Morrissey, Nevzorov, Panagiotakopoulos, Perelstein, Pilaftsis, Poppitz, Randall, Rosner, Roy, Sarkar, Sopczak, Tait, Tamvakis, Vempati, Wagner, Weiner, White, Zerwas, Zhang

Models with Dynamical μ

Model	Symmetry	Superpotential	CP-even	CP-odd
MSSM	–	$\mu \hat{H}_u \cdot \hat{H}_d$	H_1^0, H_2^0	A_2^0
NMSSM	Z_3	$h_s \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{\kappa}{3} \hat{S}^3$	H_1^0, H_2^0, H_3^0	A_1^0, A_2^0
nMSSM	Z_5^R, Z_7^R	$h_s \hat{S} \hat{H}_u \cdot \hat{H}_d + \xi_F M_{\rm n}^2 \hat{S}$	H_1^0, H_2^0, H_3^0	A_1^0, A_2^0
UMSSM	$U(1)'$	$h_s \hat{S} \hat{H}_u \cdot \hat{H}_d$	H_1^0, H_2^0, H_3^0	A_2^0
sMSSM	$U(1)'$	$h_s \hat{S} \hat{H}_u \cdot \hat{H}_d + \lambda_s \hat{S}_1 \hat{S}_2 \hat{S}_3$	$H_1^0, H_2^0, H_3^0, H_4^0, H_5^0, H_6^0$	$A_1^0, A_2^0, A_3^0, A_4^0$

- MSSM: gaugino unification but general μ
- NMSSM (“cubic”): may be domain wall problems (Z_2^R)
- nMSSM (“tadpole”): no domain walls; tadpoles from high order
- UMSSM: additional Z' ($\mu_{eff}, M_{Z'}$ generated by single S)
- sMSSM: stringy NMSSM w. decoupled μ_{eff}, $M_{Z'}$
  ($\hat{H}_u, \hat{H}_d, \hat{S}$ reduces to nMSSM in S_i decoupling limit $\longrightarrow$ n/sMSSM)

A Unified Analysis of Higgs and Neutralino Sectors

$$
\begin{aligned}
V_F &= |h_s H_u \cdot H_d + \xi_F M_n^2 + \kappa S^2|^2 + |h_s S|^2 \left(|H_d|^2 + |H_u|^2\right) \\
V_D &= \frac{G^2}{8}\left(|H_d|^2 - |H_u|^2\right)^2 + \frac{g_2^2}{2}\left(|H_d|^2|H_u|^2 - |H_u \cdot H_d|^2\right) \\
&+ \frac{{g_{1'}}^2}{2}\left(Q_{H_d}|H_d|^2 + Q_{H_u}|H_u|^2 + Q_S|S|^2\right)^2 \\
V_{\mathrm{soft}} &= m_d^2|H_d|^2 + m_u^2|H_u|^2 + m_s^2|S|^2 \\
&+ \left(A_s h_s S H_u \cdot H_d + \frac{\kappa}{3} A_\kappa S^3 + \xi_S M_n^3 S + h.c.\right)
\end{aligned}
$$

black = MSSM (with $\mu = h_s\langle S\rangle$); blue= extensions;
cyan = NMSSM; magenta = UMSSM; red= n/sMSSM

Mass matrices in $\{H_d, H_u, S\}$ basis

- **CP-even (tree level)** $(\langle H^0_{u,d}\rangle \equiv v_{u,d}/\sqrt{2}, \langle S\rangle \equiv s/\sqrt{2})$

$$
\begin{aligned}
(\mathcal{M}^0_+)_{dd} &= \left[\frac{G^2}{4} + Q^2_{H_d} g^2_{1'}\right] v_d^2 + (\frac{h_s A_s}{\sqrt{2}} + \frac{h_s \kappa s}{2} + \frac{h_s \xi_F M_{\rm n}^2}{s})\frac{v_u s}{v_d} \\
(\mathcal{M}^0_+)_{du} &= \left[-\frac{G^2}{4} + h_s^2 + Q_{H_d} Q_{H_u} g^2_{1'}\right] v_d v_u - (\frac{h_s A_s}{\sqrt{2}} + \frac{h_s \kappa s}{2} + \frac{h_s \xi_F M_{\rm n}^2}{s})s \\
(\mathcal{M}^0_+)_{ds} &= \left[h_s^2 + Q_{H_d} Q_S g^2_{1'}\right] v_d s - (\frac{h_s A_s}{\sqrt{2}} + h_s \kappa s) v_u \\
(\mathcal{M}^0_+)_{uu} &= \left[\frac{G^2}{4} + Q^2_{H_u} g^2_{1'}\right] v_u^2 + (\frac{h_s A_s}{\sqrt{2}} + \frac{h_s \kappa s}{2} + \frac{h_s \xi_F M_{\rm n}^2}{s})\frac{v_d s}{v_u} \\
(\mathcal{M}^0_+)_{us} &= \left[h_s^2 + Q_{H_u} Q_S g^2_{1'}\right] v_u s - (\frac{h_s A_s}{\sqrt{2}} + h_s \kappa s) v_d \\
(\mathcal{M}^0_+)_{ss} &= \left[Q_S^2 g^2_{1'} + 2\kappa^2\right] s^2 + (\frac{h_s A_s}{\sqrt{2}} - \frac{\sqrt{2}\xi_S M_{\rm n}^3}{v_d v_u})\frac{v_d v_u}{s} + \frac{\kappa A_\kappa}{\sqrt{2}} s
\end{aligned}
$$

- **Also CP-odd and charged Higgs** (CP breaking ignored)
- **Leading loop corrections (top-stop loops) are common**
- **Theoretical upper limits on H_1^0 relaxed** ($\rightarrow$ smaller $\tan\beta$ allowed)
  - MSSM

$$M^2_{H_1^0} \leq M_Z^2 \cos^2 2\beta + \tilde{\mathcal{M}}^{(1)}$$

$$\tilde{\mathcal{M}}^{(1)} = (\mathcal{M}_+^{(1)})_{dd} \cos^2\beta + (\mathcal{M}_+^{(1)})_{uu} \sin^2\beta + (\mathcal{M}_+^{(1)})_{du} \sin 2\beta$$

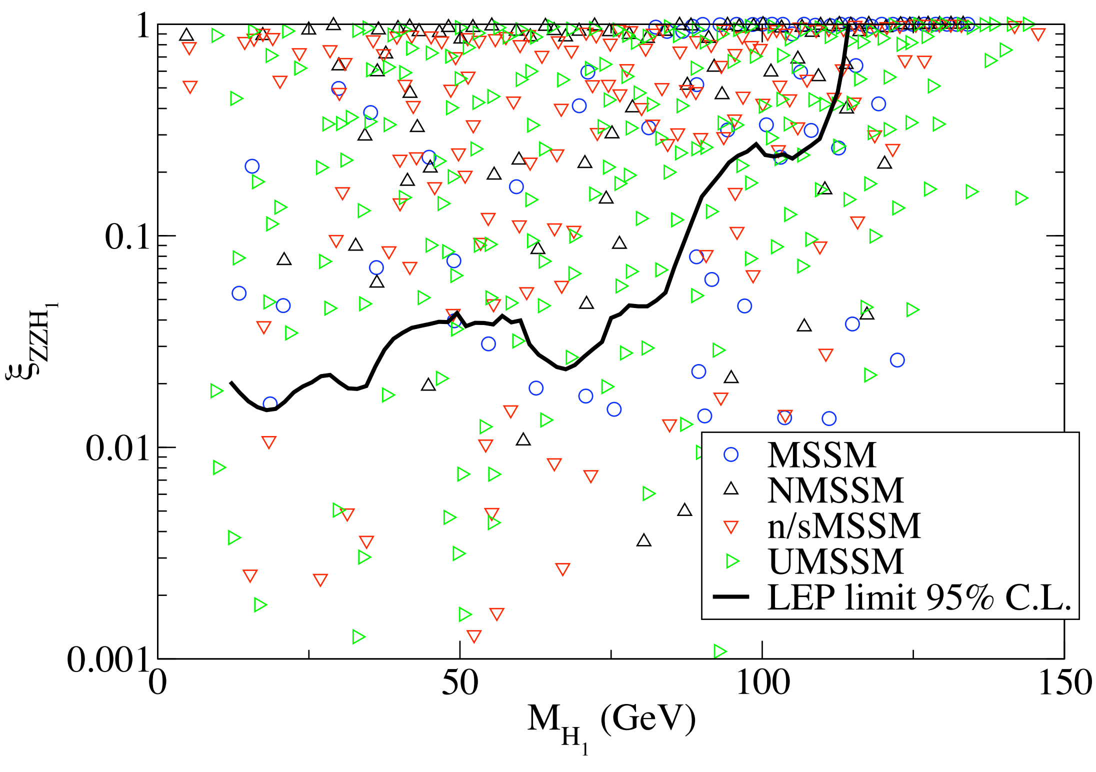
  - NMSSM, n/sMSSM, and Peccei-Quinn limits

$$M^2_{H_1^0} \leq M_Z^2 \cos^2 2\beta + \frac{1}{2} h_s^2 v^2 \sin^2 2\beta + \tilde{\mathcal{M}}^{(1)}$$

  - UMSSM

$$M^2_{H_1^0} \leq M_Z^2 \cos^2 2\beta + \frac{1}{2} h_s^2 v^2 \sin^2 2\beta + g_{Z'}^2 v^2 (Q_{H_d} \cos^2\beta + Q_{H_u} \sin^2\beta)^2 + \tilde{\mathcal{M}}^{(1)}$$

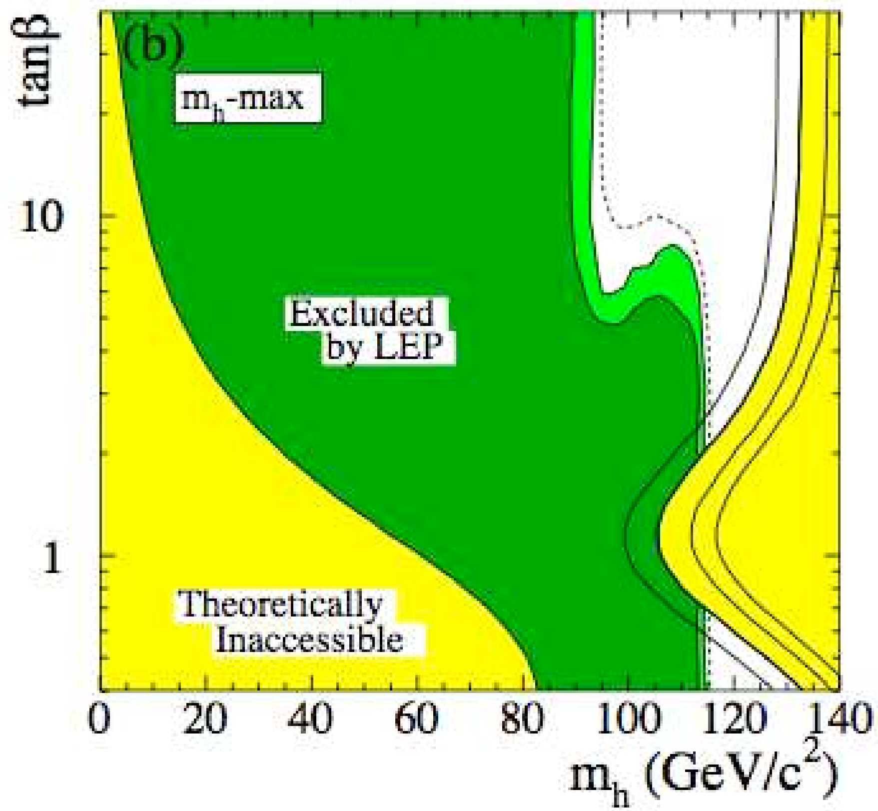
- **Experimental LEP SM and MSSM bounds may be relaxed by singlet-doublet mixing** (also by nonstandard decays)

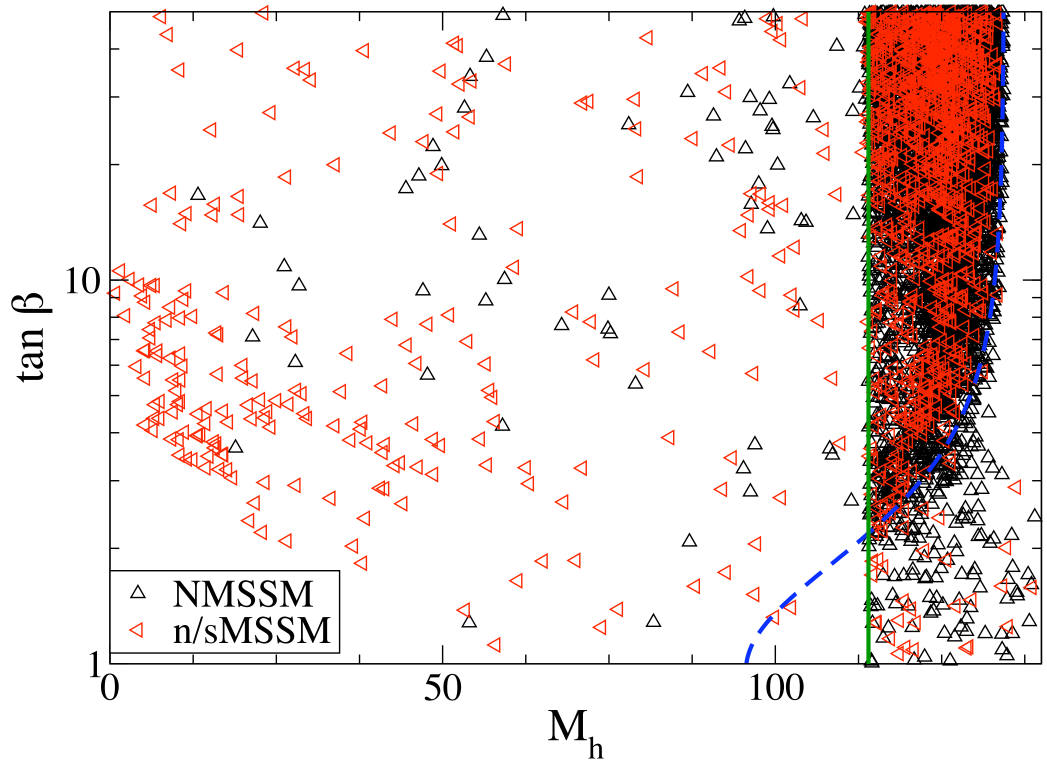


- **Reduced ZZH_i coupling**

$$\xi_{ZZH_i} = (R_+^{i1}\cos\beta + R_+^{i2}\sin\beta)^2$$

- **Also, $Z \to HA$, Z width, $\chi^\pm$ mass, $Z - Z'$ mixing, V minimum, RGE**


tanβ
(b)
m_h-max
Excluded by LEP
Theoretically Inaccessible
10
1
0
20
40
60
80
100
120
140
m_h (GeV/c^2)

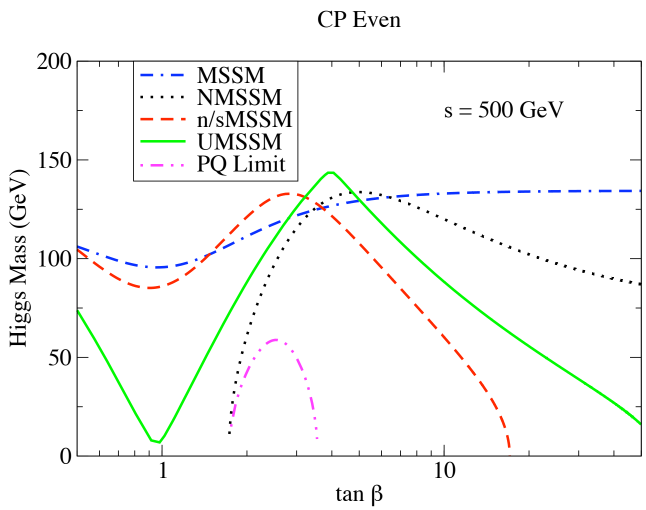

tan β
10
1
0
50
100
M_h
NMSSM
n/sMSSM

Limiting Cases

- **MSSM limit** ($s \rightarrow \infty$ with $\mu_{eff} = h_s s/\sqrt{2}$ fixed) $\longrightarrow$ **two MSSM-like CP-even Higgs and one largely singlet** (heavy in UMSSM, light in n/sMSSM, depends on κ in NMSSM)

- **PQ and R limits (massless pseudoscalar)**

Model	Limits	Symmetry	Effects
MSSM	$B \longrightarrow 0$	$U(1)_{PQ}$	$M_{A_1} \longrightarrow 0$
NMSSM	$\kappa, A_\kappa \longrightarrow 0$	$U(1)_{PQ}$	$M_{A_1} \longrightarrow 0$
NMSSM	$A_s, A_\kappa \longrightarrow 0$	$U(1)_R$	$M_{A_1} \longrightarrow 0$
n/sMSSM	$\xi_F, \xi_S \longrightarrow 0$	$U(1)_{PQ}$	$M_{A_1} \longrightarrow 0$
UMSSM	$g_{1'} \longrightarrow 0$	$U(1)$	$M_{Z'}, M_{A_1} \longrightarrow 0$



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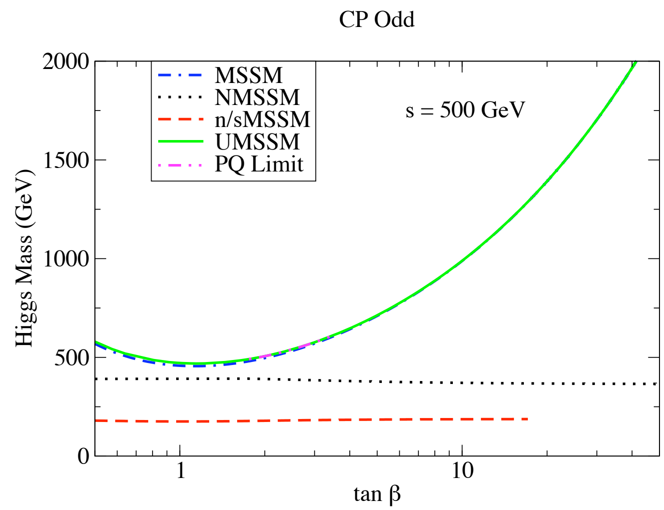

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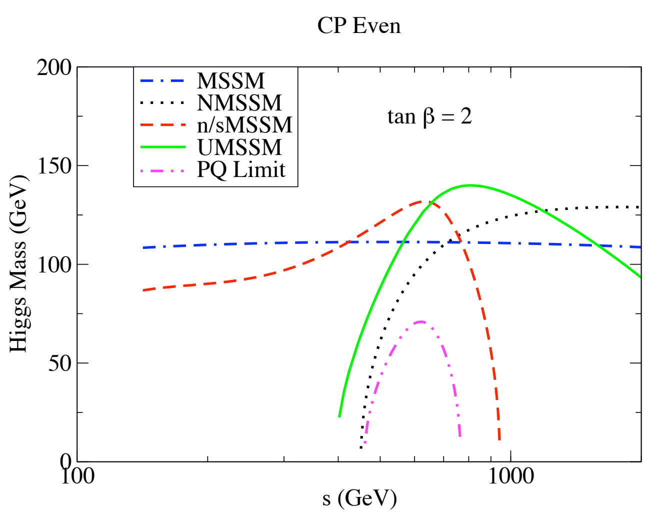

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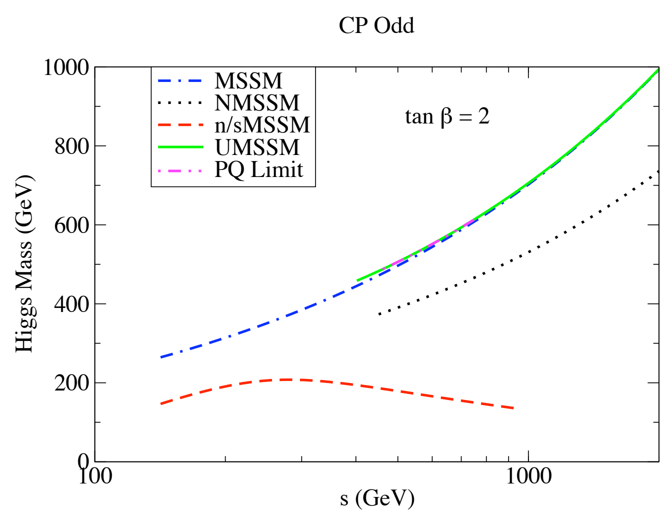
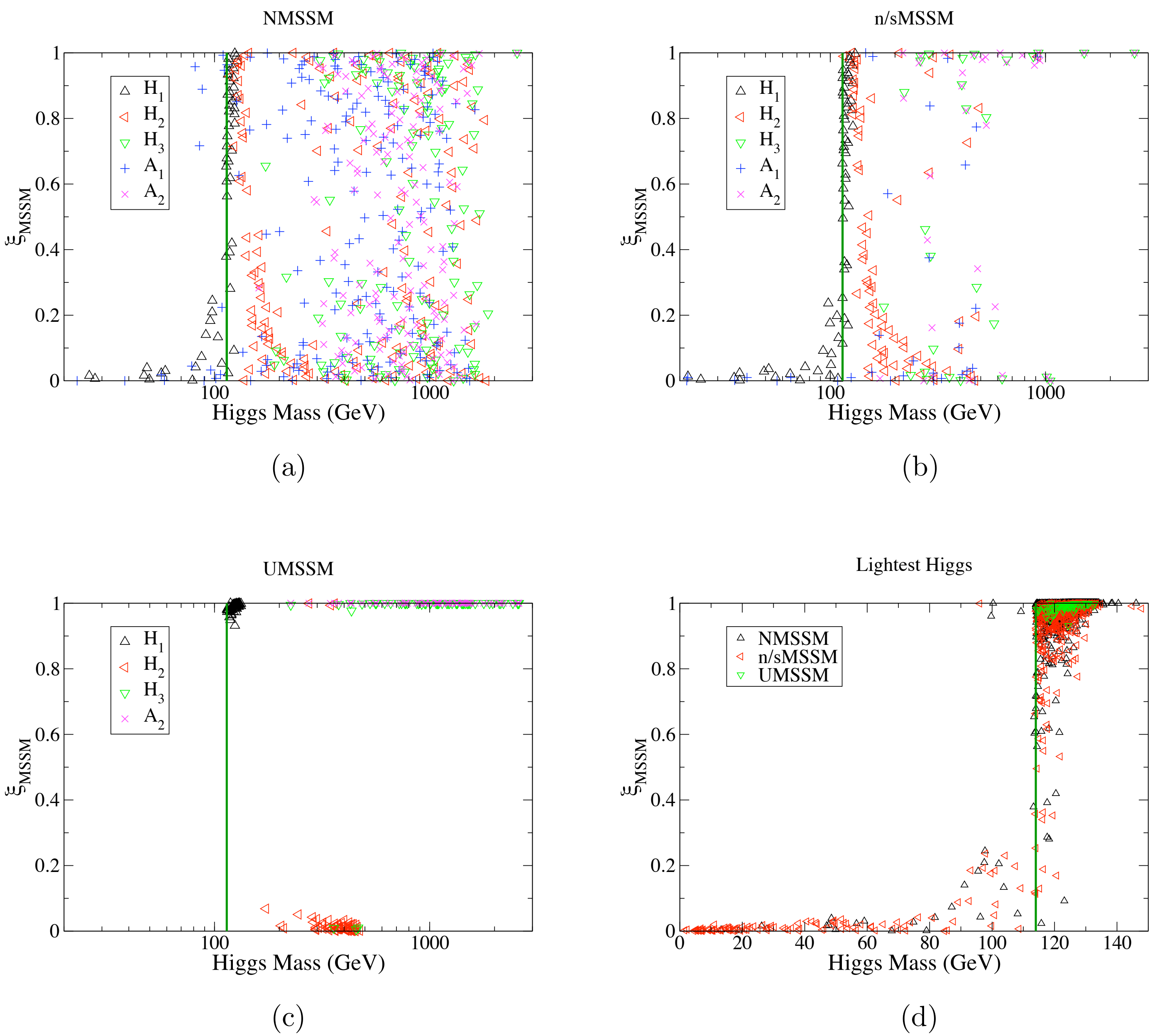
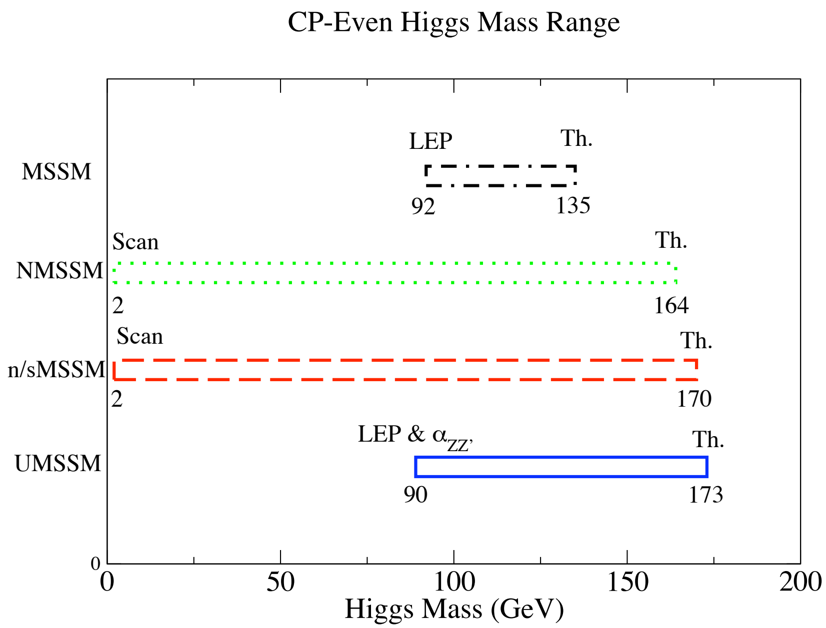


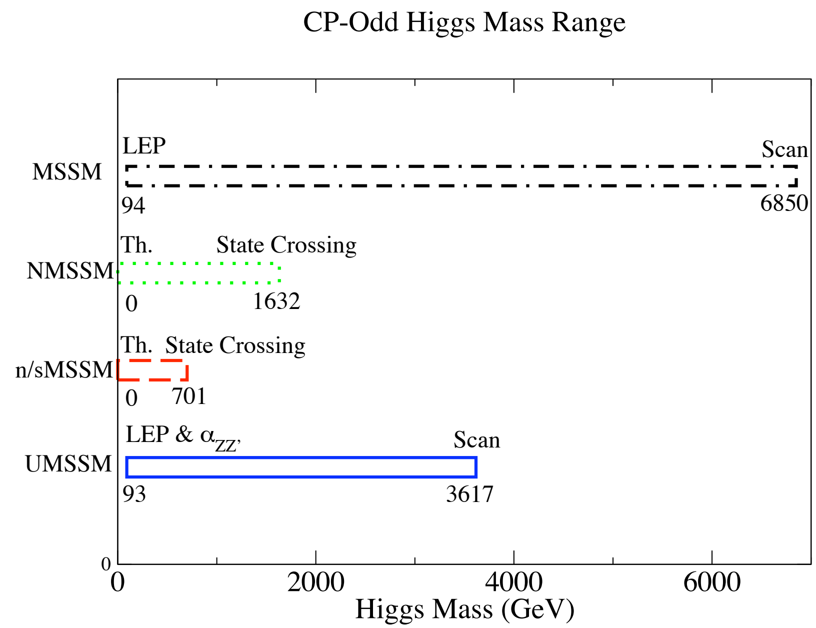
(d)

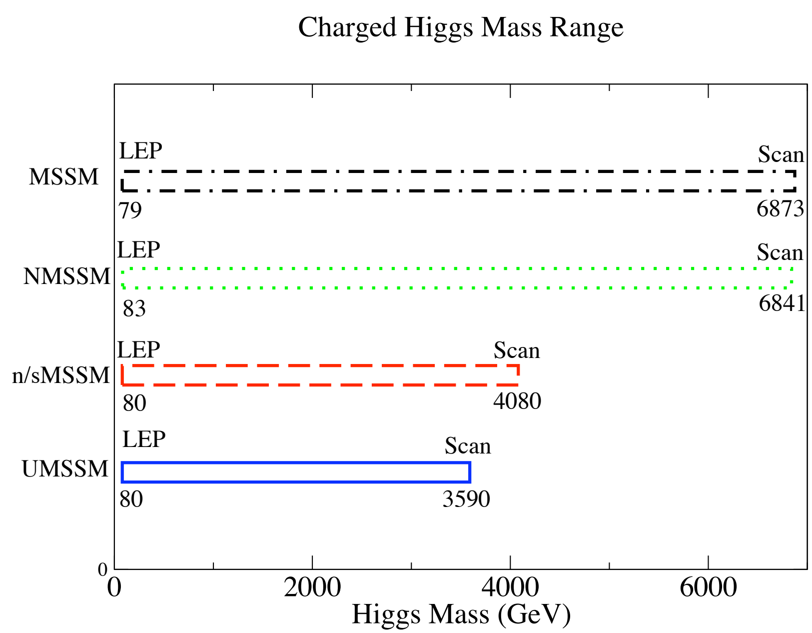
$$A_s = M_n = 500 \text{ GeV}, \; A_\kappa = -250 \text{ GeV}, \; h_s = \kappa = 0.5, \; \xi_{F,S} = -0.1$$

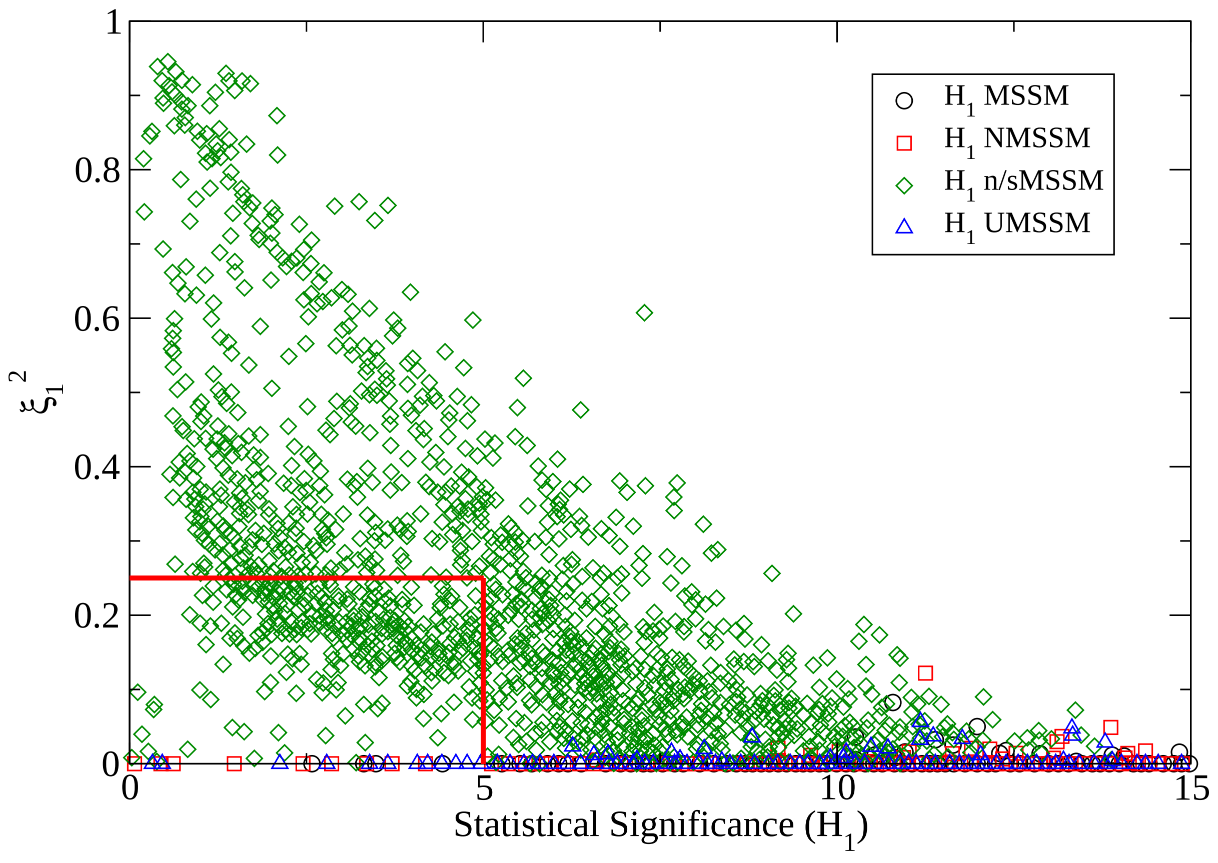


MSSM fraction $\xi^{H_i}_{\mathrm{MSSM}} = \sum_{j=d}^{u} (R_{+}^{ij})^2$


CP-Even Higgs Mass Range
MSSM
NMSSM
n/sMSSM
UMSSM
LEP
Th.
92
135
Scan
Th.
2
164
Scan
Th.
2
170
LEP & $\alpha_{ZZ'}$
Th.
90
173
Higgs Mass (GeV)


CP-Odd Higgs Mass Range
MSSM
NMSSM
n/sMSSM
UMSSM
LEP
Scan
94
6850
Th.
State Crossing
0
1632
Th.
State Crossing
0
701
LEP & $\alpha_{ZZ'}$
Scan
93
3617
Higgs Mass (GeV)


Charged Higgs Mass Range
MSSM
NMSSM
n/sMSSM
UMSSM
LEP
Scan
79
6873
LEP
Scan
83
6841
LEP
Scan
80
4080
LEP
Scan
80
3590
Higgs Mass (GeV)



Production and decay rates modified. Standard Model modes (5σ), vs invisible decays, $H \rightarrow \chi^0\chi^0$ (or AA), via WBF ($\xi^2 \gtrsim 0.25$).

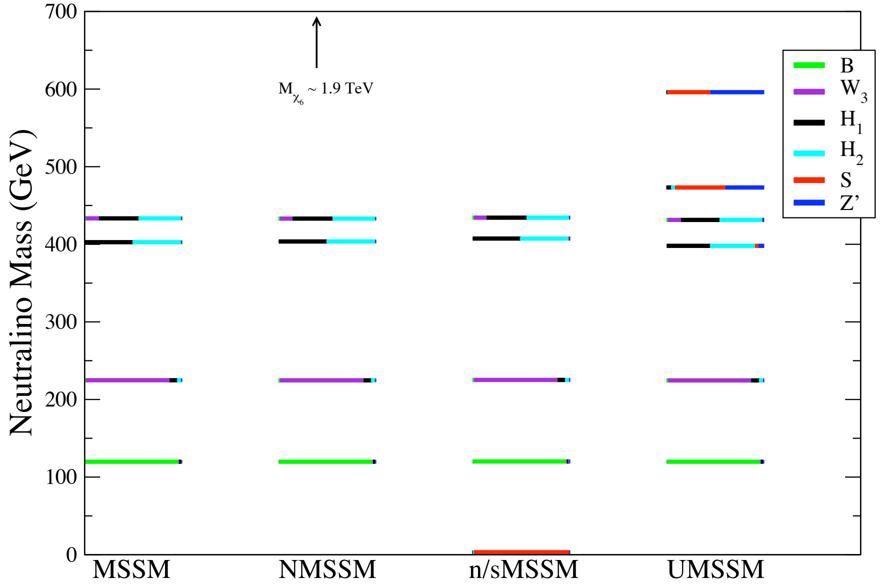
Lightest Neutralino

Mass matrix (M_{χ^0}) in basis $\{\tilde{B}, \tilde{W}_3, \tilde{H}_1^0, \tilde{H}_2^0, \tilde{S}, \tilde{Z}'\}$:

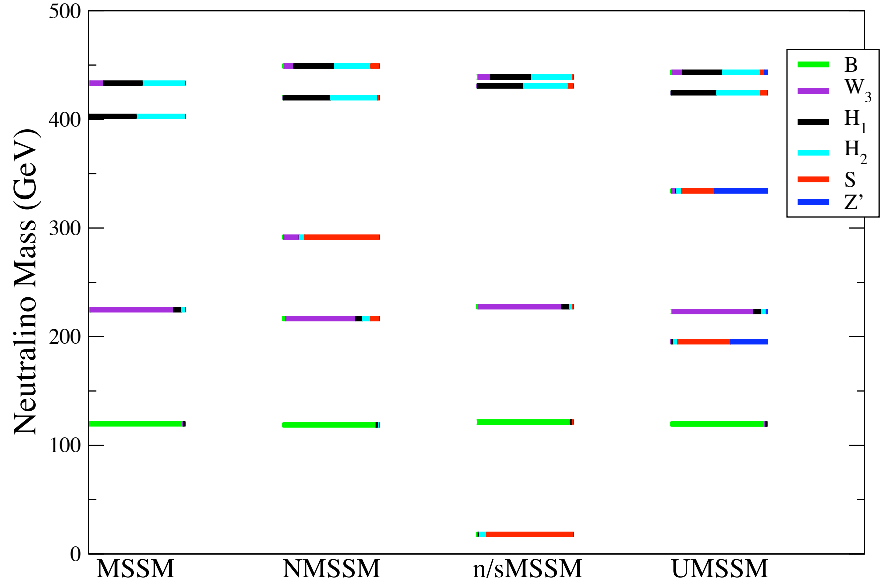
$$\begin{pmatrix} M_1 & 0 & -g_1 v_1/2 & g_1 v_2/2 & 0 & 0 \\ 0 & M_2 & g_2 v_1/2 & -g_2 v_2/2 & 0 & 0 \\ -g_1 v_1/2 & g_2 v_1/2 & 0 & -\mu_{eff} & -\mu_{eff} v_2/s & g_{Z'} Q'_{H_1} v_1 \\ g_1 v_2/2 & -g_2 v_2/2 & -\mu_{eff} & 0 & -\mu_{eff} v_1/s & g_{Z'} Q'_{H_2} v_2 \\ 0 & 0 & -\mu_{eff} v_2/s & -\mu_{eff} v_1/s & \sqrt{2}\kappa s & g_{Z'} Q'_S s \\ 0 & 0 & g_{Z'} Q'_{H_1} v_1 & g_{Z'} Q'_{H_2} v_2 & g_{Z'} Q'_S s & M_{1'} \end{pmatrix}$$

($\langle S \rangle \equiv \frac{s}{\sqrt{2}}$, $\langle H_i^0 \rangle \equiv \frac{v_i}{\sqrt{2}}$, $\sqrt{v_1^2 + v_2^2} \equiv v \simeq 246$ GeV, $Q'_\phi = \phi$ $U(1)'$ charge)

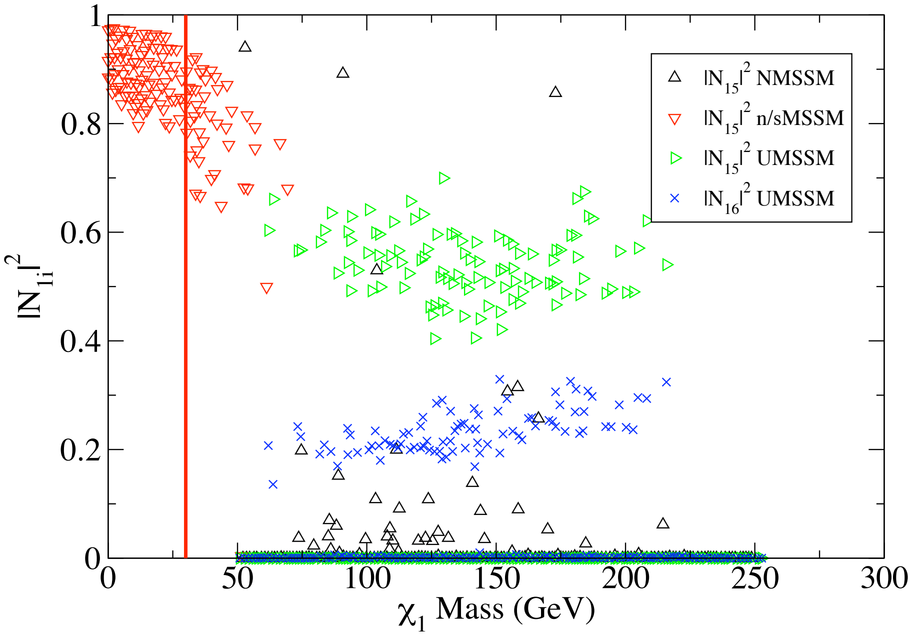
(black = MSSM; blue= extensions; cyan = NMSSM; magenta = UMSSM)

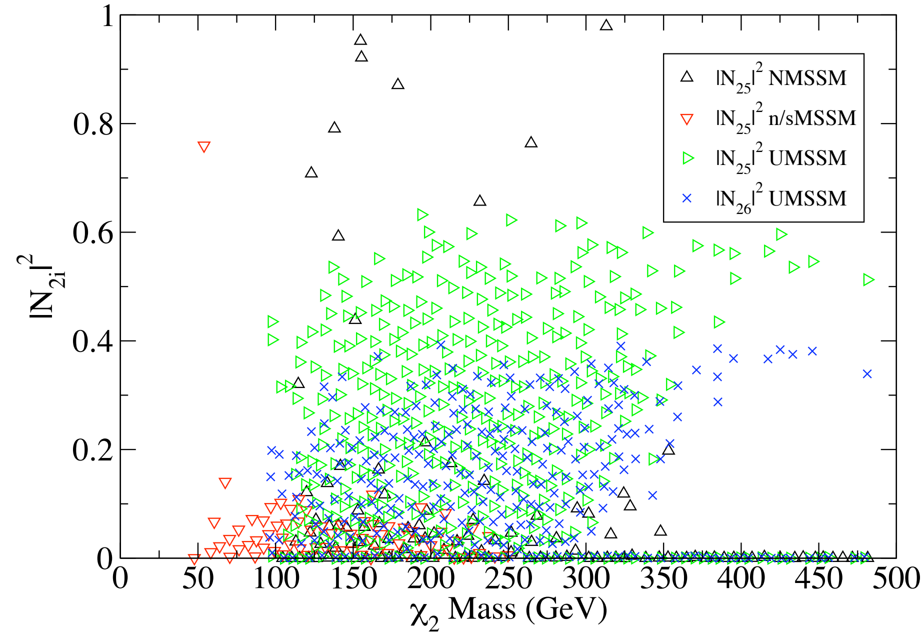


(nearly) decoupled singlino

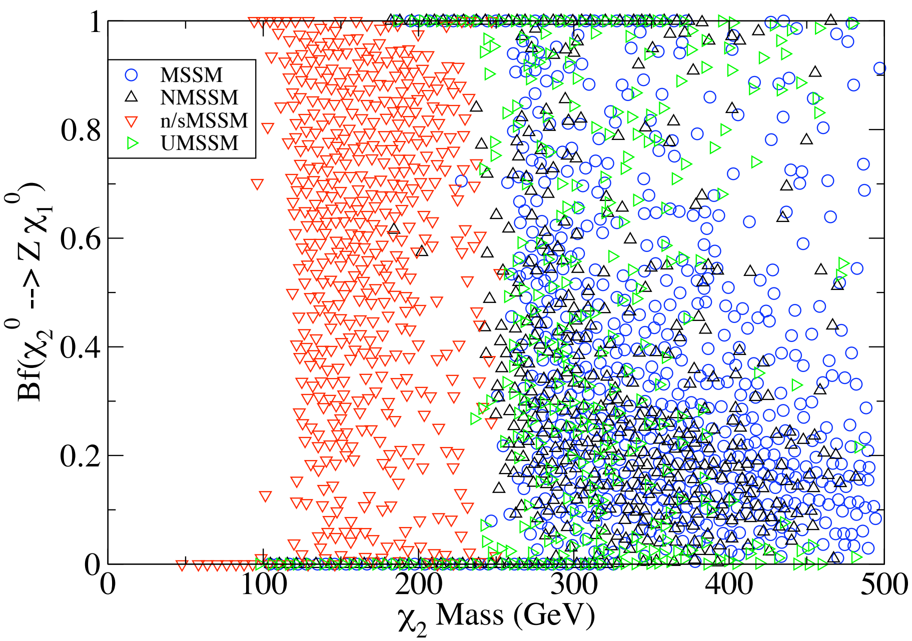


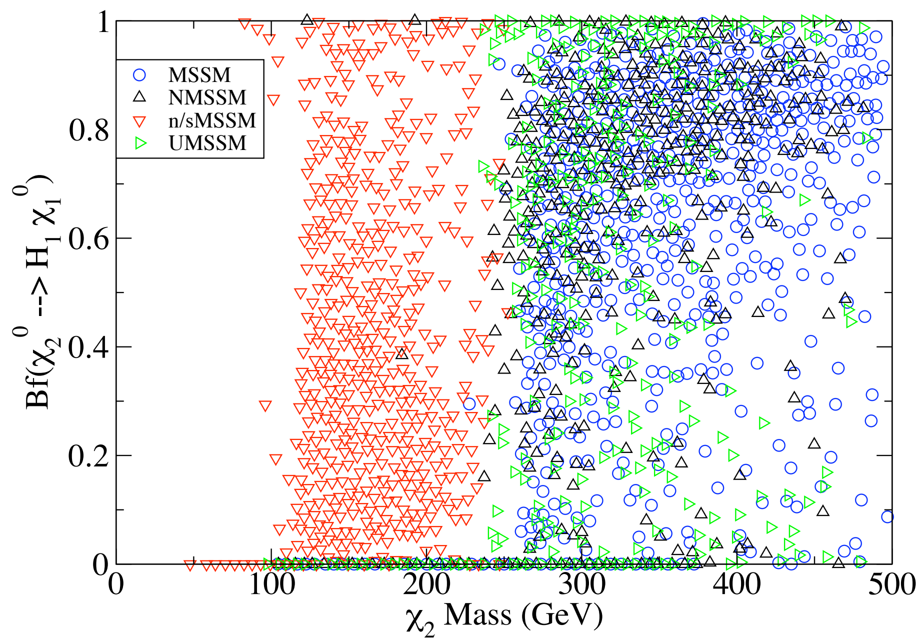
strongly mixed singlino



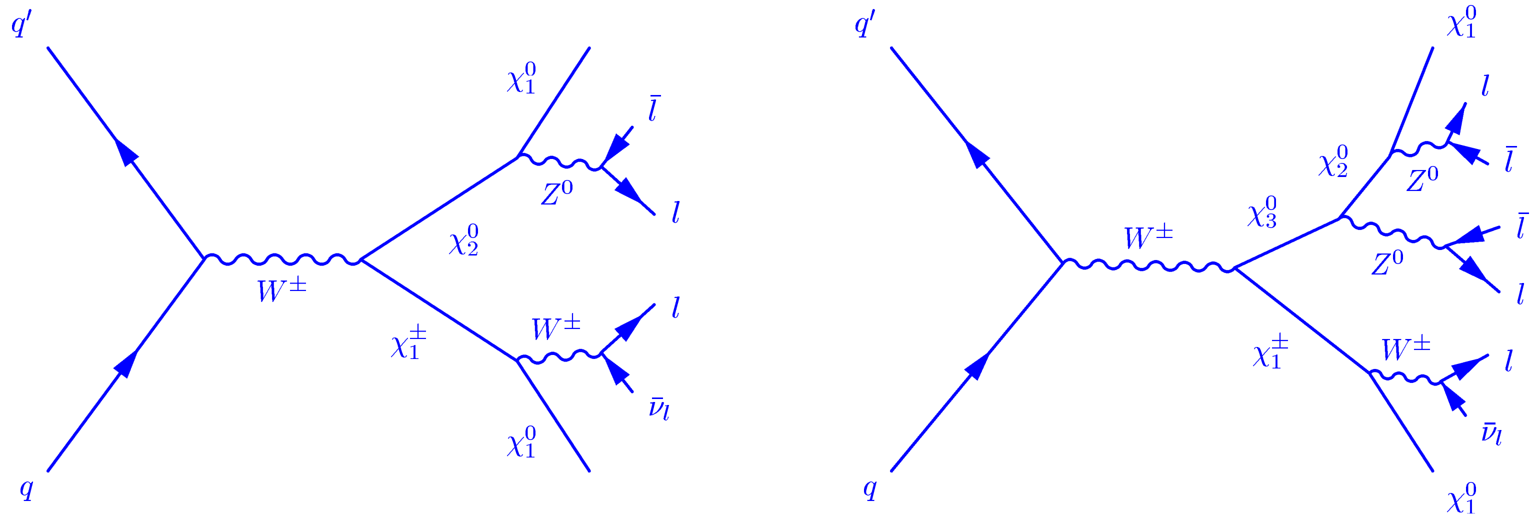


singlino and gaugino fractions of $\chi_{1,2}$

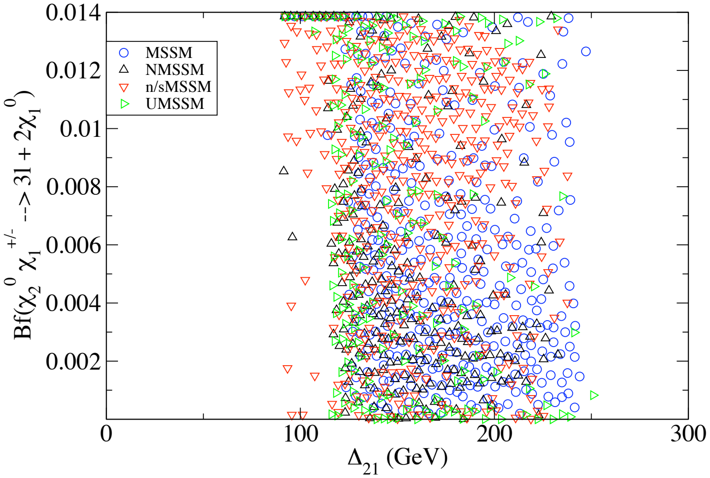




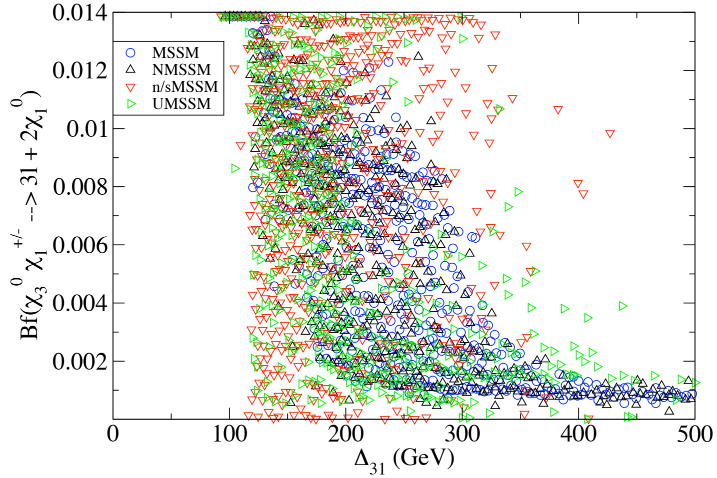
branching fractions of $\chi_2 \longrightarrow (Z, H_1)\ \chi_1$



Extended cascade diagrams for 3, 5, or 7 charged leptons



(a)



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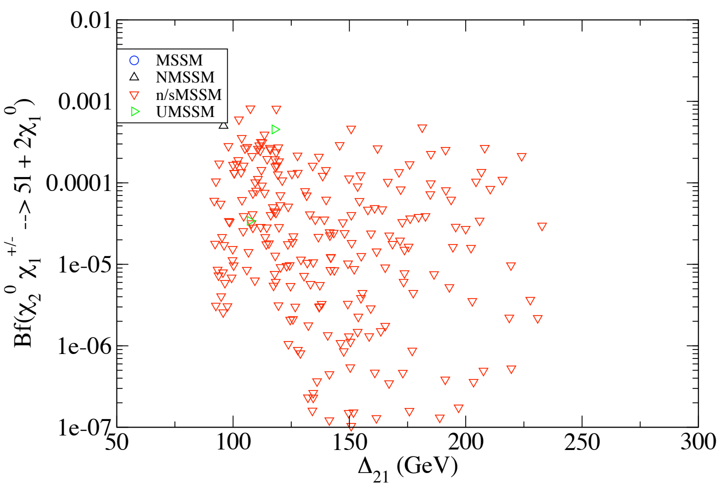

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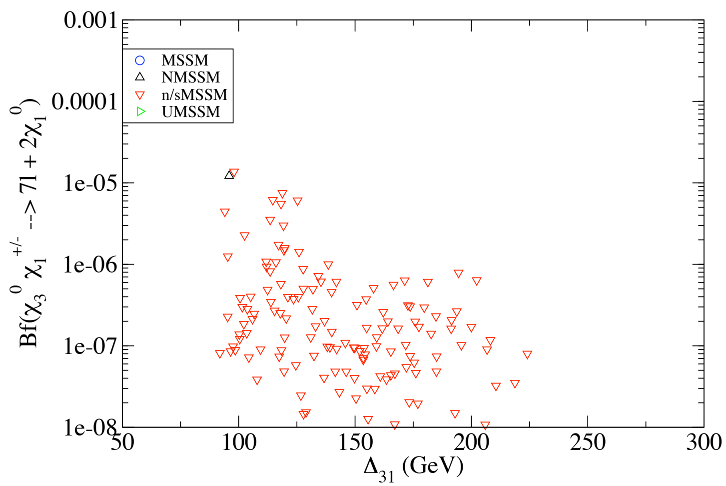
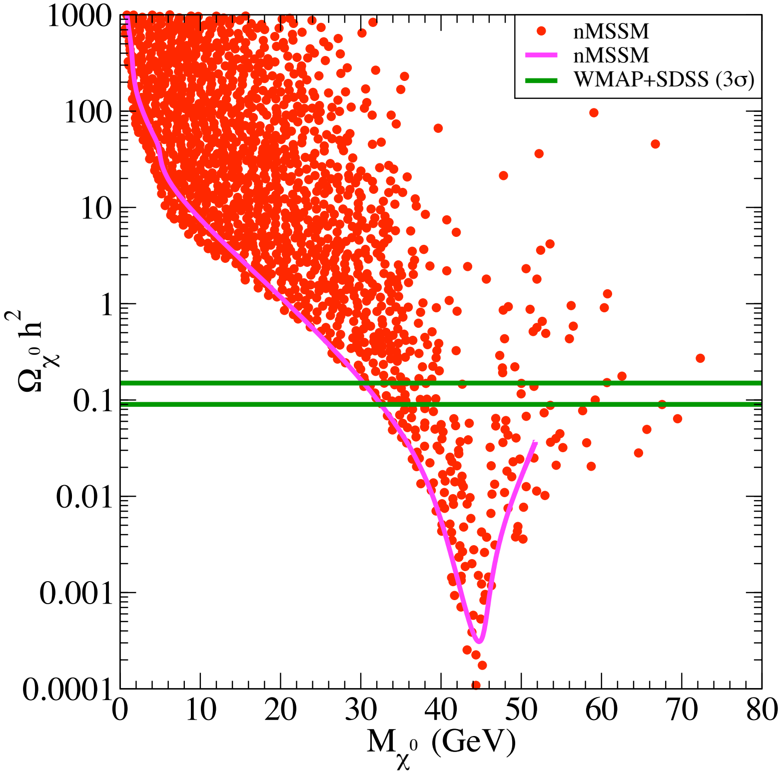
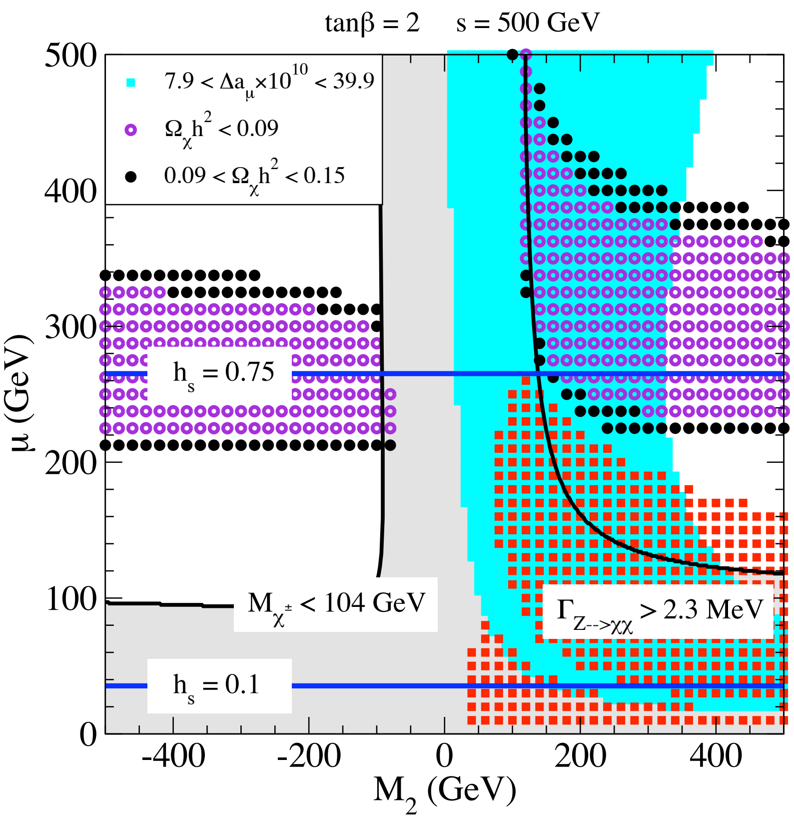


(d)

Decays into 3, 5, or 7 charged leptons





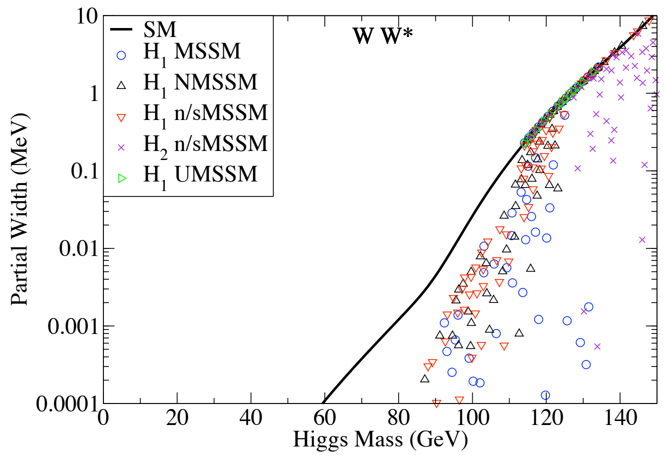
Relic density in nMSSM from $\chi_1^0 \chi_1^0 \rightarrow Z$ only
(may be $\chi_1^0 \rightarrow$ secluded in sMSSM)

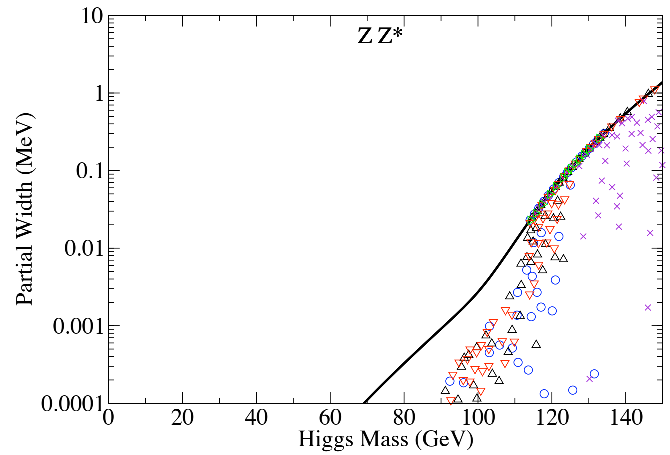
Relic density and $g_\mu - 2$ in n/sMSSM

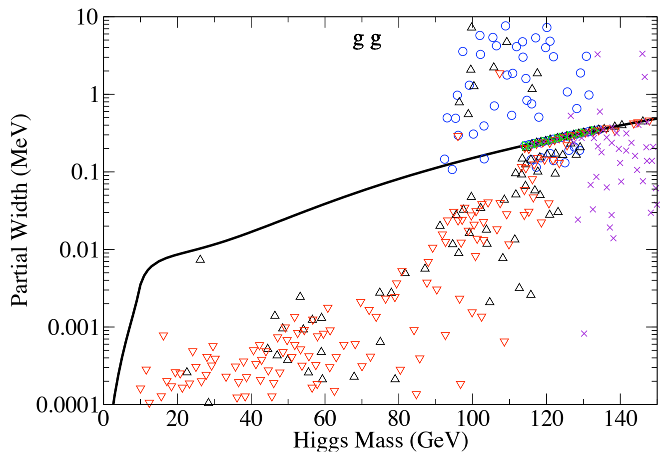
Conclusions

- Combination of theoretical ideas and new experimental facilities may allow testable theory to Planck scale
- From the bottom up: there may be more at TeV scale than (minimal SUGRA) MSSM (e.g., Z', extended Higgs/neutralino, quasi-chiral exotics)
- From the top down: there may be more at TeV scale than (minimal SUGRA) MSSM
- Dynamical μ term leads to very rich Higgs/neutralino physics at colliders and for cosmology
- Consider alternatives to the minimal seesaw

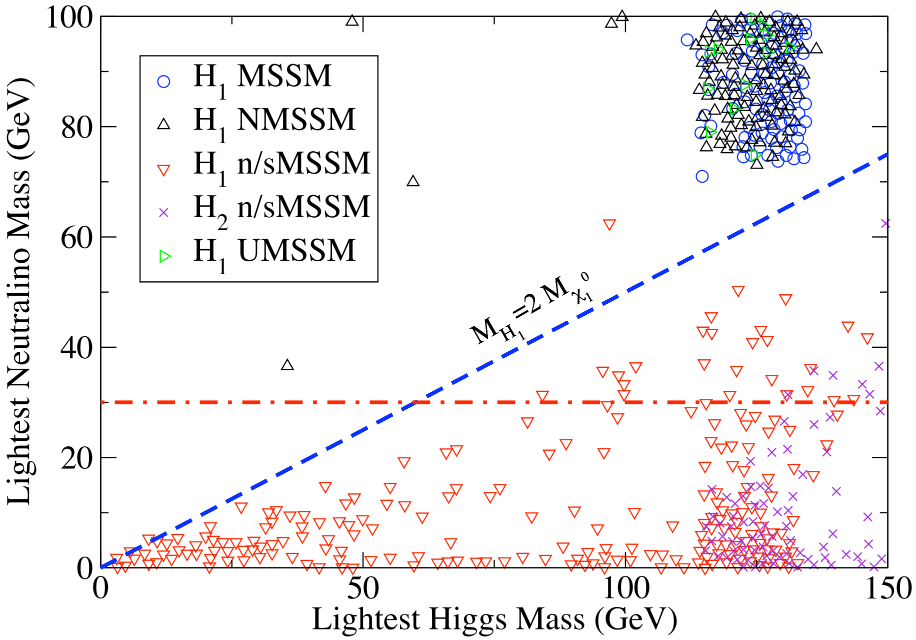
Lightest Higgs Decays



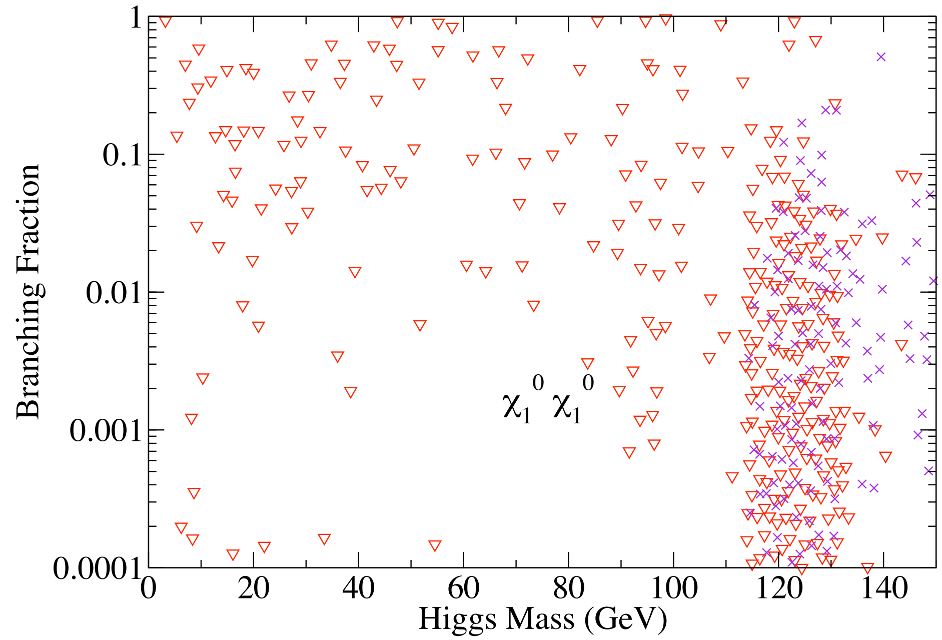




Invisible Decays

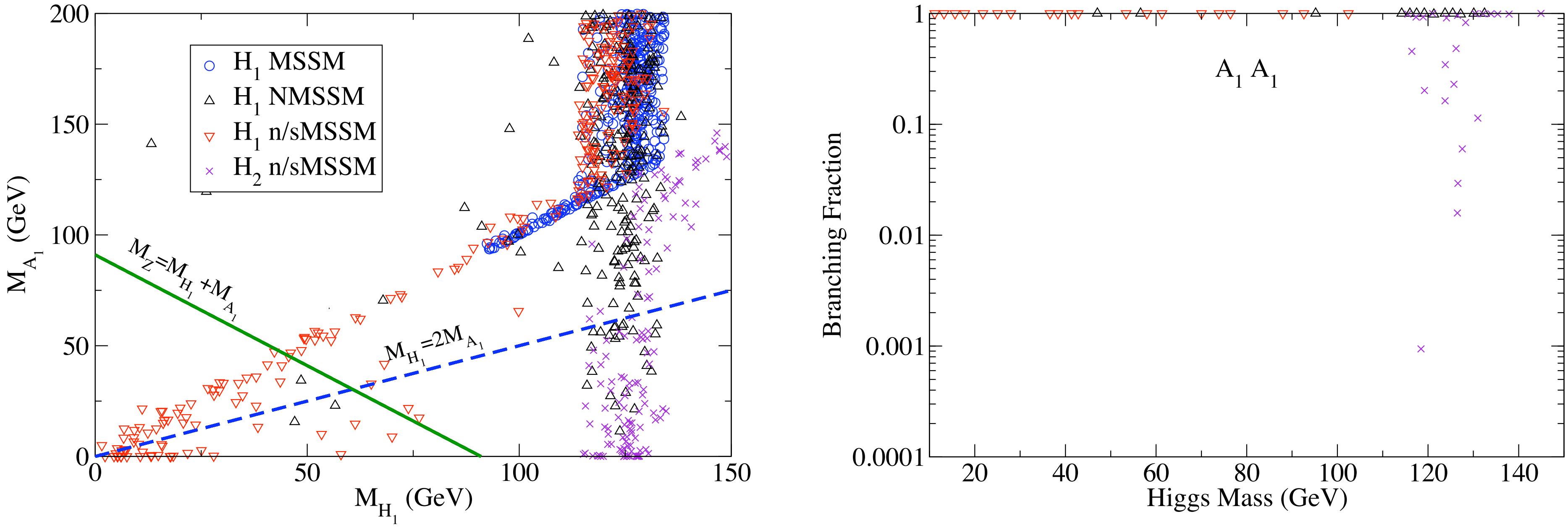


(a)



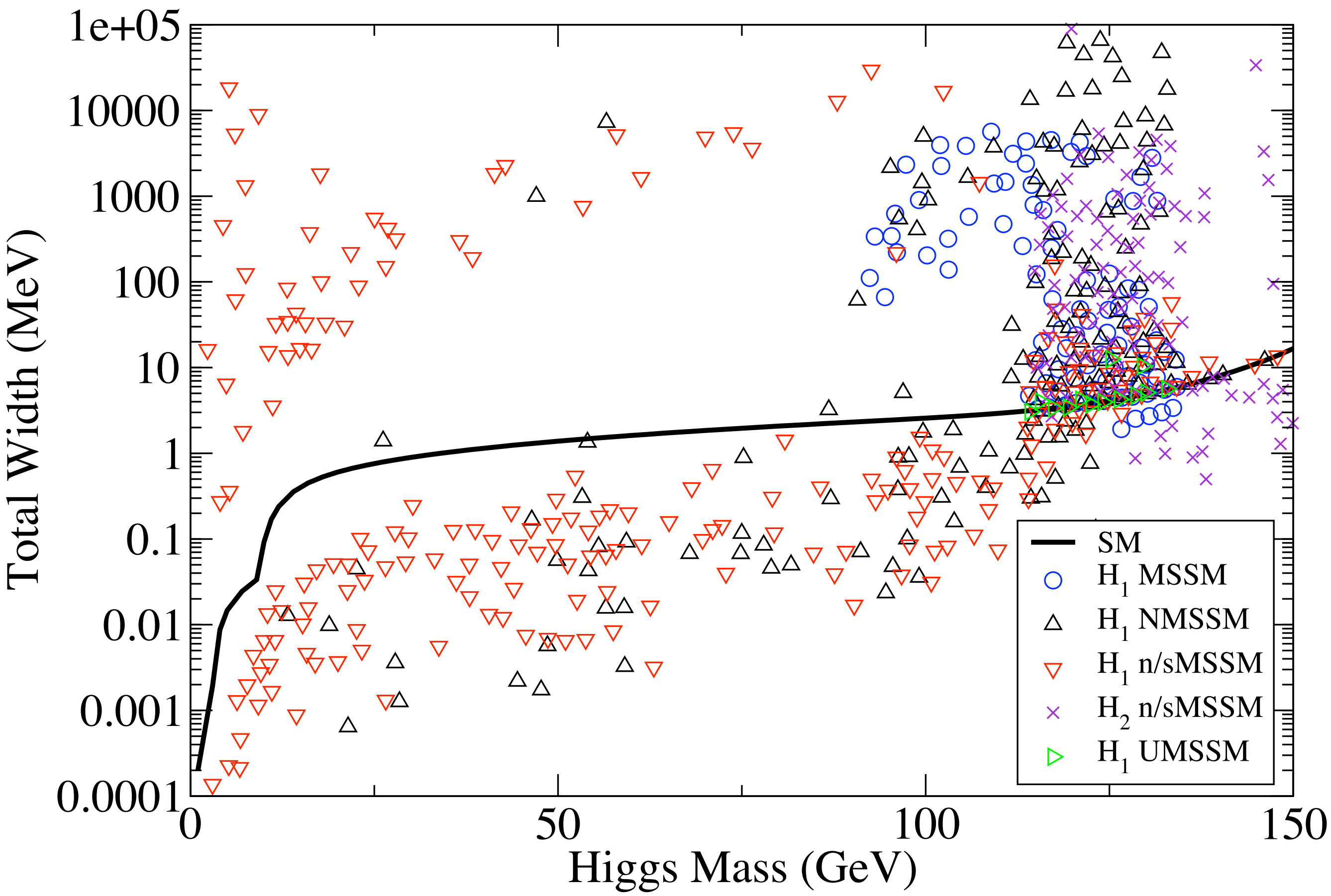
(b)

$H_{1,2} \rightarrow A_1 A_1$



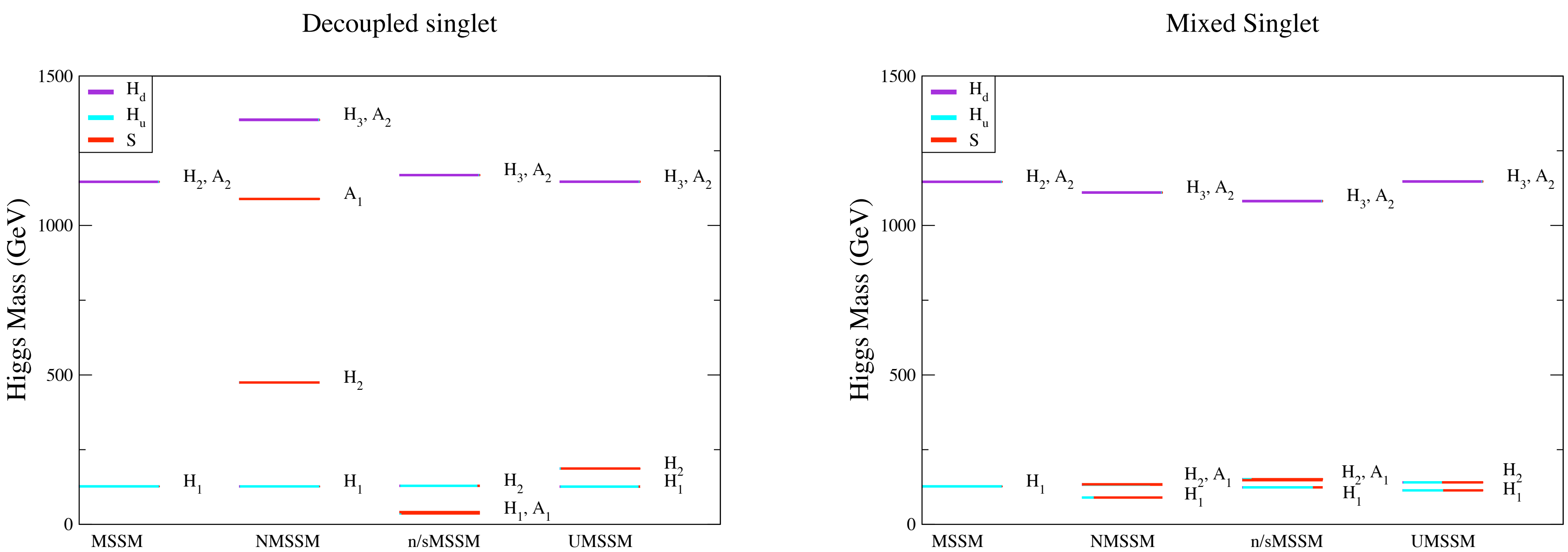
(a) (b)

Total Width



1e+05
10000
1000
100
10
1
0.1
0.01
0.001
0.0001
Total Width (MeV)
0
50
100
150
Higgs Mass (GeV)
SM
H1 MSSM
H1 NMSSM
H1 n/sMSSM
H2 n/sMSSM
H1 UMSSM

Higgs Composition



(a) (b)