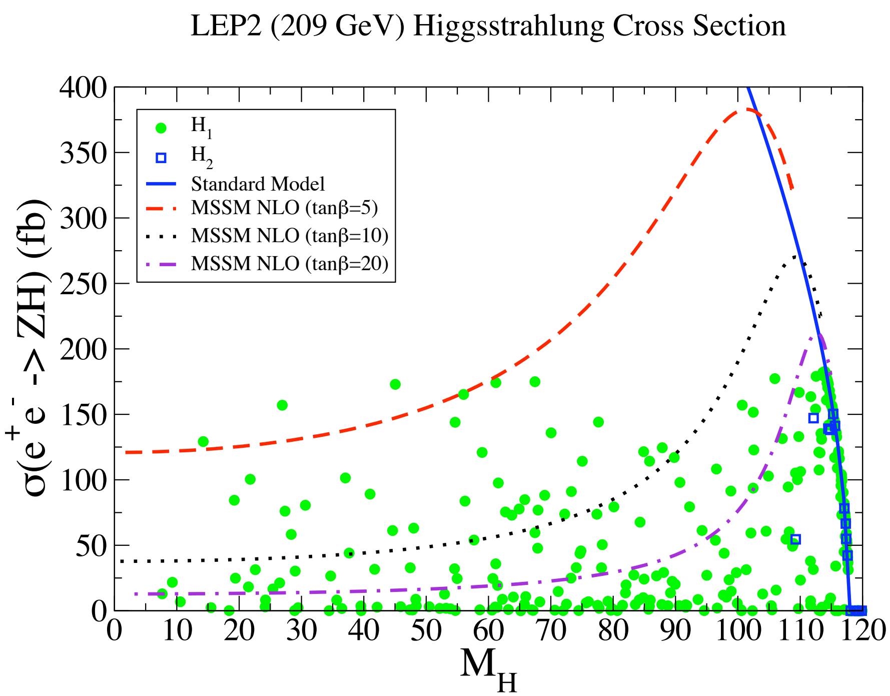
The Higgs Sector in a $U(1)'$ Extension of the MSSM



- **Motivations**
- **A (string-motivated) model**
- **Non-standard Higgs sector**
- **Nonstandard neutralino sector: CDM, $g_\mu - 2$**
- **Nonstandard Higgs potential and CP breaking: Electroweak baryogenesis**

References

- J. Erler, PL, and T. J. Li, hep-ph/0205001 (secluded sector)
- T. Han, B. McElrath, PL, hep-ph/0402064 (implications of Higgs sector)
- V. Barger, C. Kao, PL and H. S. Lee, hep-ph/0408120 (cold dark matter).
- V. Barger, C. Kao, PL and H. S. Lee, in preparation ($g_\mu - 2$)
- J. Kang, T. Li, T. Liu, and PL, hep-ph/0402068 (electroweak baryogenesis)

Beyond the MSSM

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

Most of the problems of standard model remain (hierarchy of electroweak and Planck scales is stabilized but not explained)

μ problem introduced

Could be that all new physics is at GUT/Planck scale, but there could be remnants surviving to TeV scale

Specific string constructions often have extended gauge groups, exotics

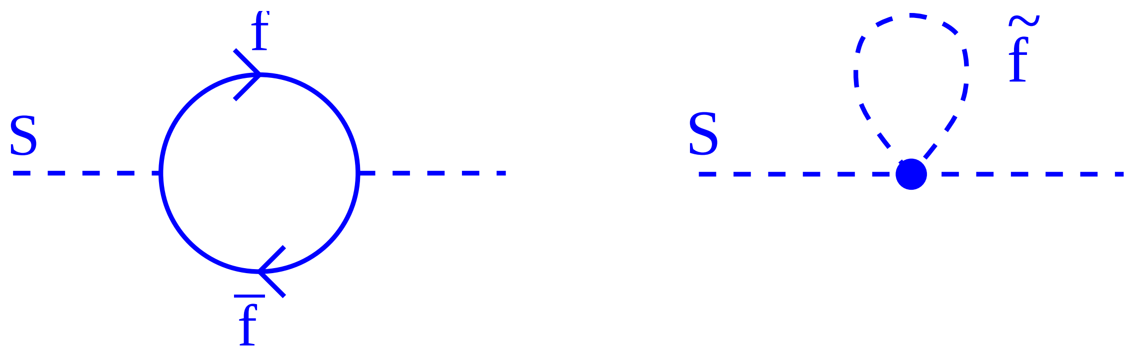
Important to explore alternatives/extensions to MSSM

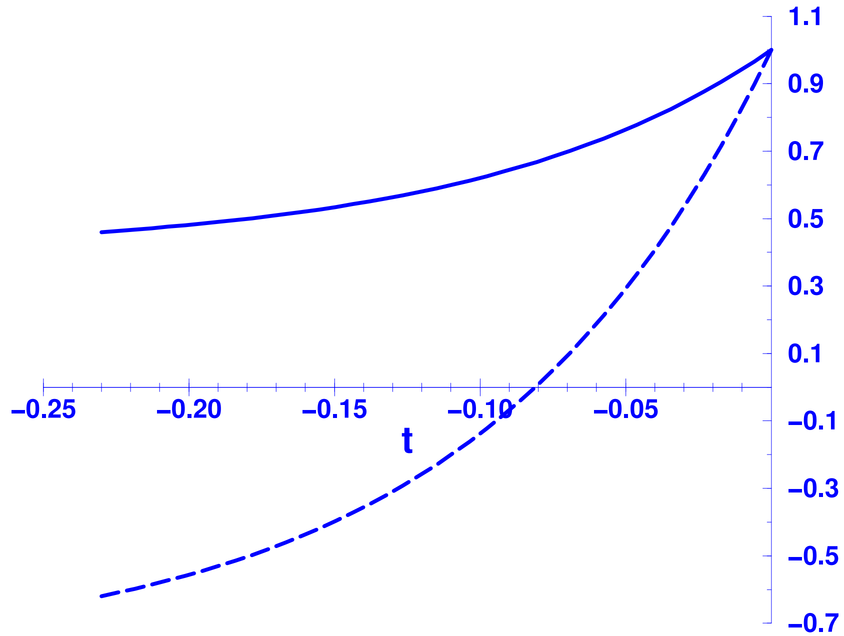
Motivations for a Z'

- Strings, GUTs, DSB, little Higgs, LED often involve extra Z'
  (GUTs require extra fine tuning for $M_{Z'} \ll M_{\rm GUT}$)

- String models

  - Extra $U(1)'$ and SM singlets extremely common
  - Radiative breaking of electroweak (SUGRA or gauge mediated) often yield EW/TeV scale Z' (unless breaking along flat direction $\longrightarrow$ intermediate scale)
  - Breaking due to negative mass^2 for scalar S (driven by large Yukawa) or by A term


f
S
f̄
S
f̃


1.1
0.9
0.7
0.5
0.3
0.1
–0.1
–0.3
–0.5
–0.7
–0.25
–0.20
–0.15
–0.10
–0.05
t

- Solution to μ problem (string-motivated extension of NMSSM)

$$W \sim hSH_uH_d,$$

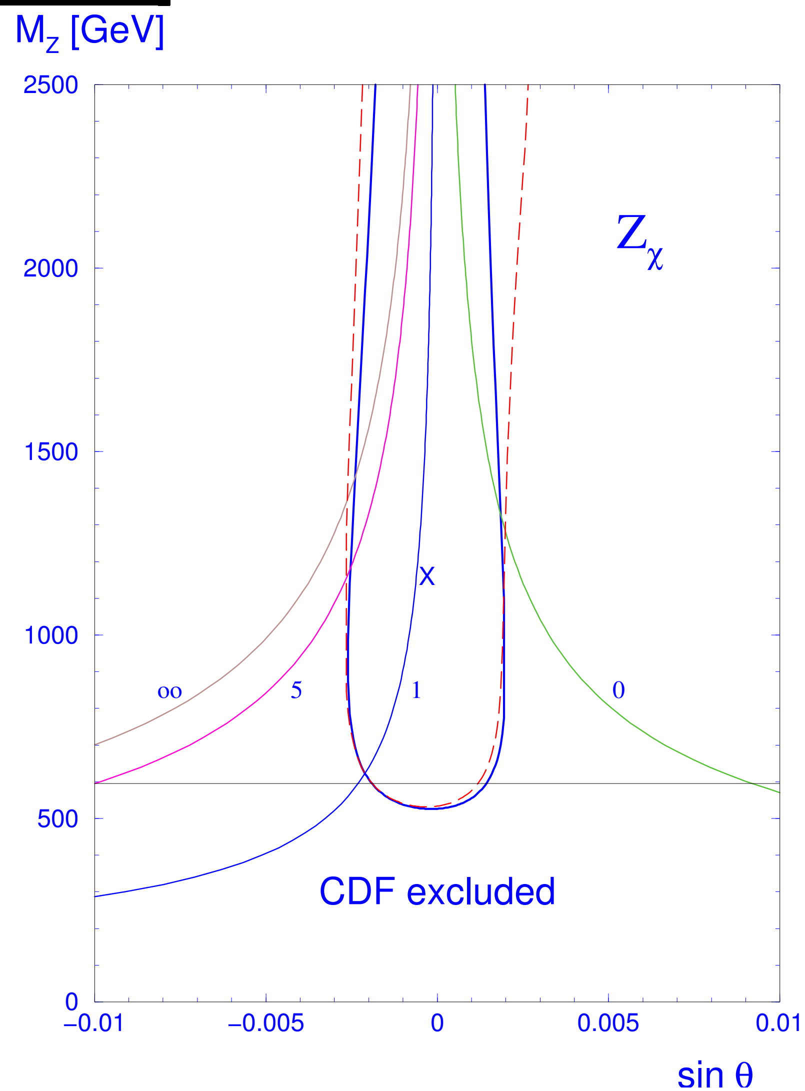
  - $U(1)'$ may forbid elementary μ or term in Kähler
  - S = standard model singlet, charged under $U(1)'$
  - $\langle S \rangle$ breaks $U(1)'$, $\mu_{eff} = h\langle S \rangle$
  - Like NMSSM, but no domain walls (Alternative: nMSSM)
  - Singlets don't have $W \sim \kappa S^3$ (cf. NMSSM) in constructions studied
  - SM-singlets usually have $U(1)'$ charges in constructions studied

Experiment

- Typically $M_{Z'} > 500 - 800$ GeV (Tevatron, LEP 2, WNC), $|\theta_{Z-Z'}| < \text{few} \times 10^{-3}$ (Z-pole)

- Discovery to $M_{Z'} \sim 5 - 8$ TeV at LHC, LC

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



Models

- **SUSY-breaking scale models** (Demir et al)
  - $M_{Z'} \sim M_Z$, leptophobic
  - $M_{Z'} \gtrsim 10 M_Z$ by modest tuning

- **Secluded sector models** (Erler, PL, Li)
  - Approximately flat direction, broken by small (~ 0.05) Yukawa
  - Z' breaking decoupled from effective μ term
  - Four SM singlets: $S, S_{1,2,3}$, doublets $H_{1,2}$
  - Off-diagonal Yukawas (string-motivated)
  - Can be consistent with minimal gauge unification

Superpotential : $W = hSH_1H_2 + \lambda S_1S_2S_3$

Potential : $V = V_F + V_D + V_{soft}$

$$
\begin{aligned}
V_F &= h^2\left(|H_1|^2|H_2|^2 + |S|^2|H_1|^2 + |S|^2|H_2|^2\right) \\
&+ \lambda^2\left(|S_1|^2|S_2|^2 + |S_2|^2|S_3|^2 + |S_3|^2|S_1|^2\right)
\end{aligned}
$$

$$
\begin{aligned}
V_D &= \frac{G^2}{8}\left(|H_2|^2 - |H_1|^2\right)^2 \\
&+ \frac{1}{2}g_{Z'}^2\left(Q_S|S|^2 + Q_{H_1}|H_1|^2 + Q_{H_2}|H_2|^2 + \sum_{i=1}^{3} Q_{S_i}|S_i|^2\right)^2
\end{aligned}
$$

where $G^2 = g_1^2 + g_2^2$,

$$
\begin{aligned}
V_{soft} &= m_{H_1}^2|H_1|^2 + m_{H_2}^2|H_2|^2 + m_S^2|S|^2 + \sum_{i=1}^{3} m_{S_i}^2|S_i|^2 \\
&- (A_h h S H_1 H_2 + A_\lambda \lambda S_1 S_2 S_3 + \text{H.C.}) \\
&+ (m_{SS_1}^2 S S_1 + m_{SS_2}^2 S S_2 + m_{S_1 S_2}^2 S_1^\dagger S_2 + \text{H.C.})
\end{aligned}
$$

- $\langle S_i \rangle \sim m_{S_i}/\lambda$ large for small λ
- Breaking along $D(U(1)') \sim 0$
- Smaller $\langle S \rangle$, $\langle H_i \rangle$, dominated by hA_h: $\tan\beta \sim 1, \langle S \rangle \sim \langle H_i \rangle$
- Large doublet-singlet mixing
- Two sectors nearly decoupled
- Mixed soft terms break two global symmetries
- Tree-level CP breaking in S, S_i sector in general (Important for baryogenesis; little effect on EDMs)

Nonstandard Higgs

(T. Han, PL, B. McElrath)

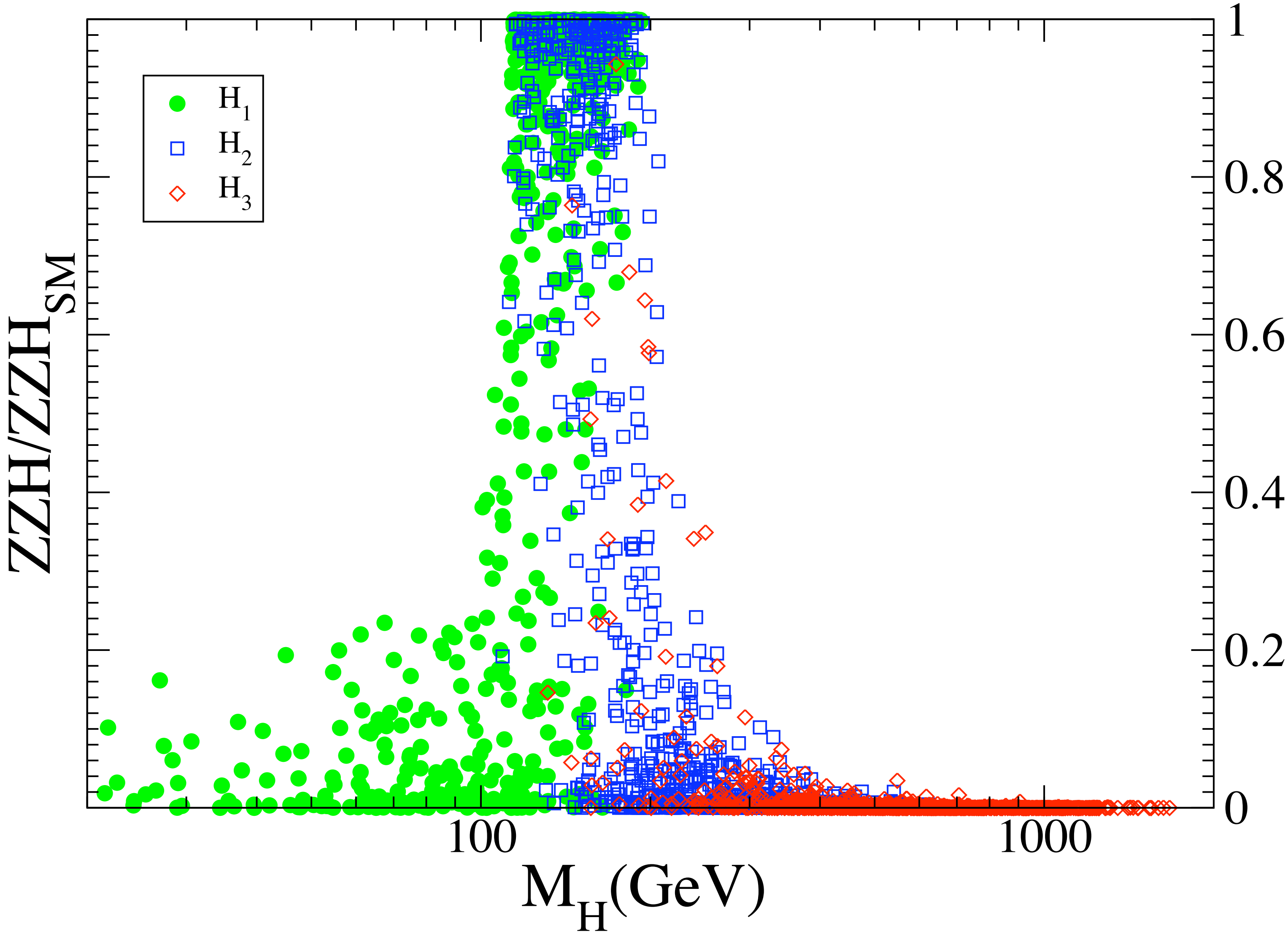
- **Complex Higgs, neutralino spectrum and decays, very different from MSSM and NMSSM because of small $\tan\beta$, mixing, and D terms**

- 6 neutral scalars and 4 pseudoscalars
  - Can have tree level CP breaking $\Rightarrow$ mixing
  - May separate into two sectors, one weakly coupled
  - Often light scalars with significant doublet admixture, but reduced coupling due to singlet admixture; often light pseudoscalar
  - Can have lightest Higgs up to $\sim$ 168 GeV with all couplings perturbative to M_P because of D terms

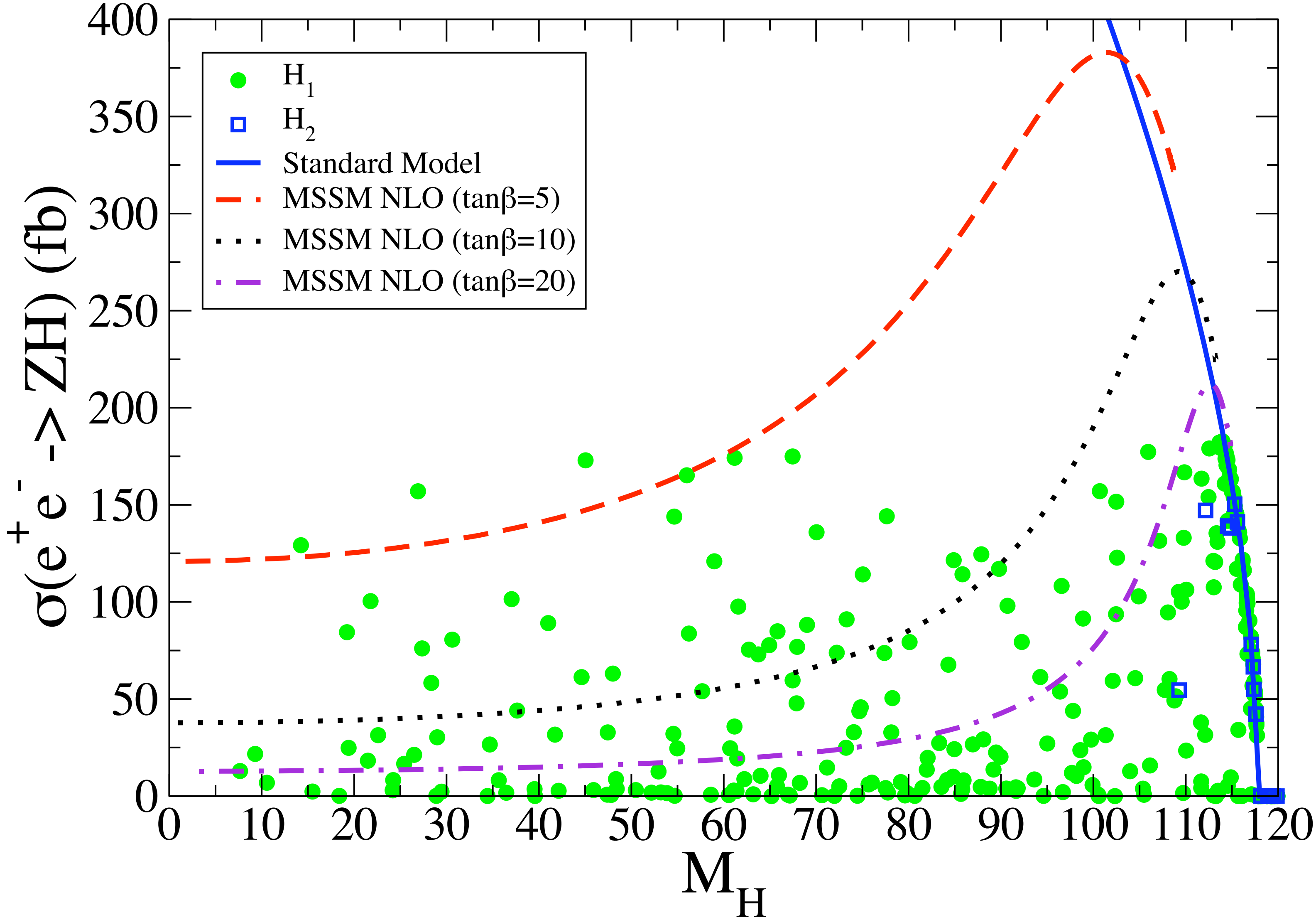
$$\begin{aligned} M_h^2 &\leq h^2v^2 + (M_Z^2 - h^2v^2)\cos^2 2\beta \\ &+ 2g_{Z'}^2 v^2 (Q_{H_2}\cos^2\beta + Q_{H_1}\sin^2\beta)^2 \\ &+ \frac{3}{4}\frac{m_t^4}{v^2\pi^2}\log\frac{m_{\tilde{t}_1}m_{\tilde{t}_2}}{m_t^2}. \end{aligned}$$

  - Typically, $\tan\beta \sim 1-3$

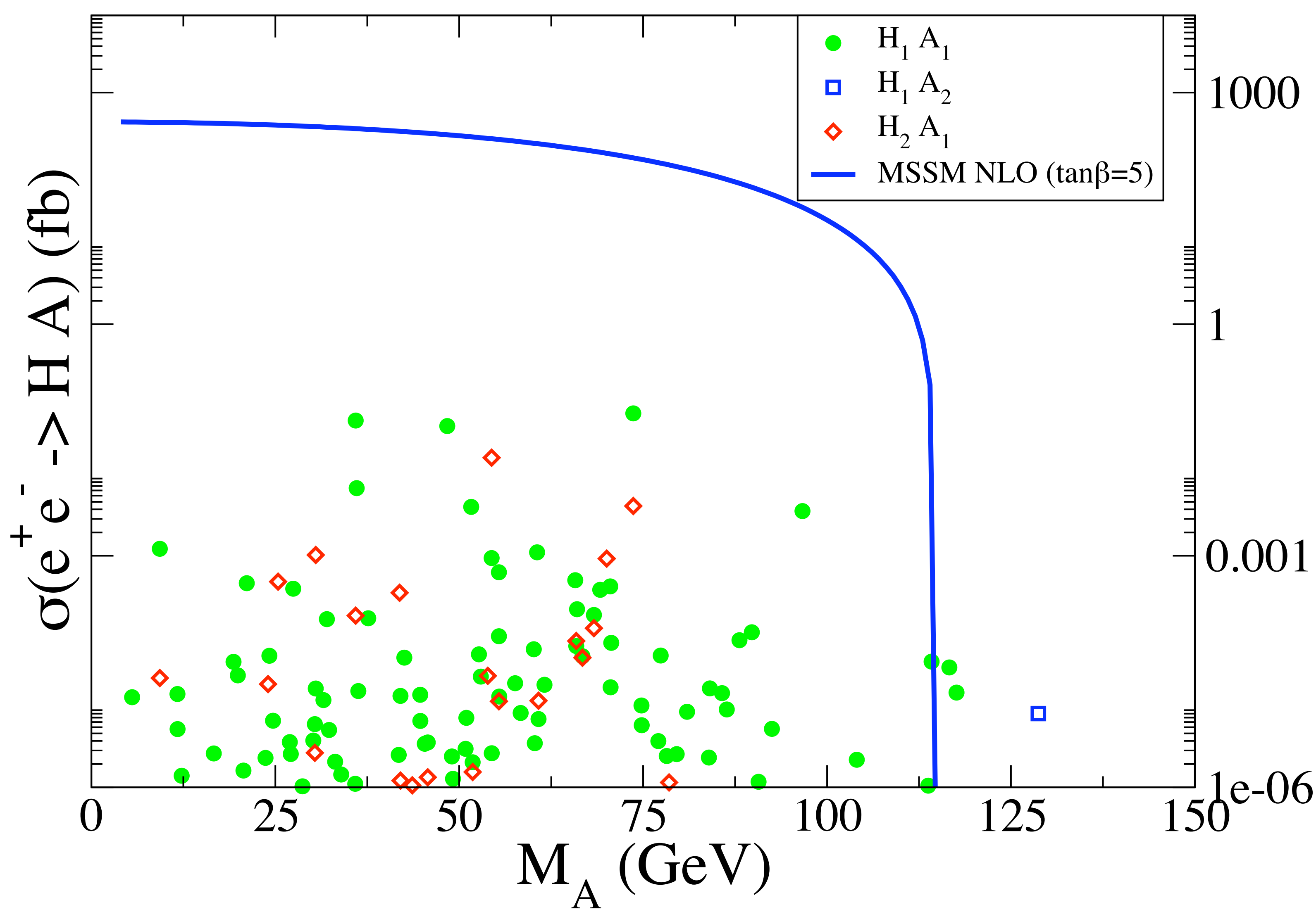
ZZH Coupling relative to Standard Model



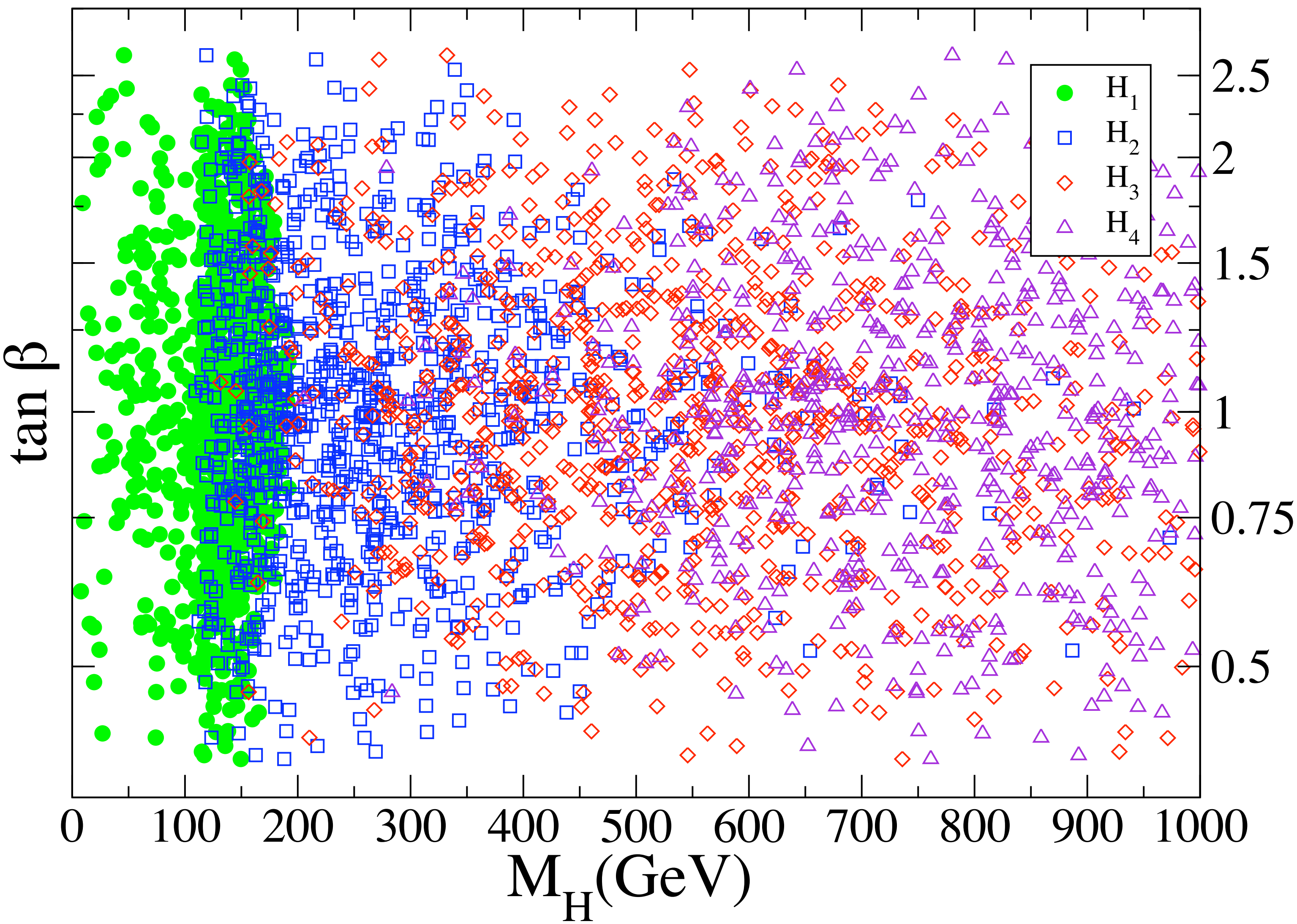
LEP2 (209 GeV) Higgsstrahlung Cross Section



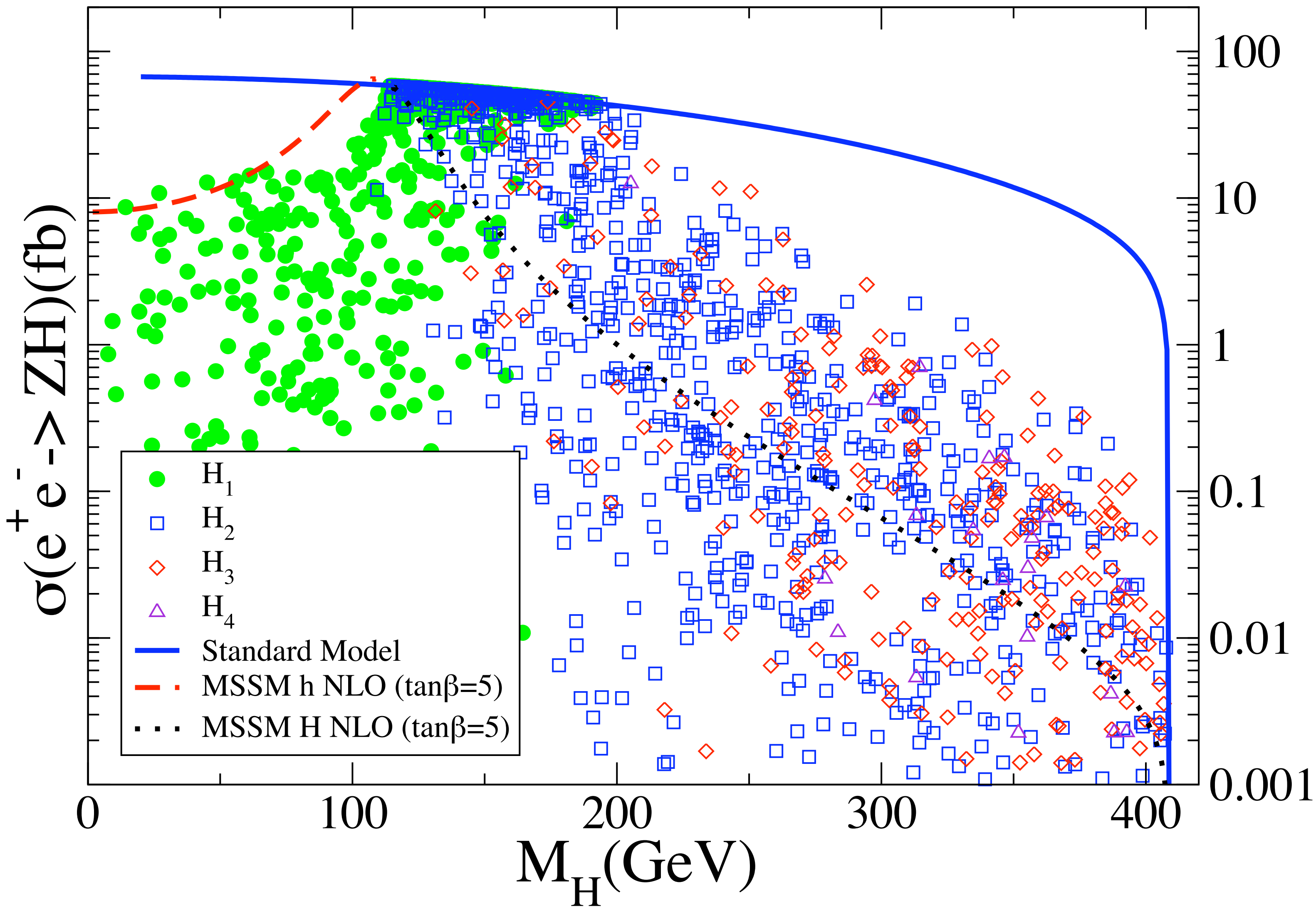
LEP2 H A Cross Section



M_H vs. $\tan\beta$



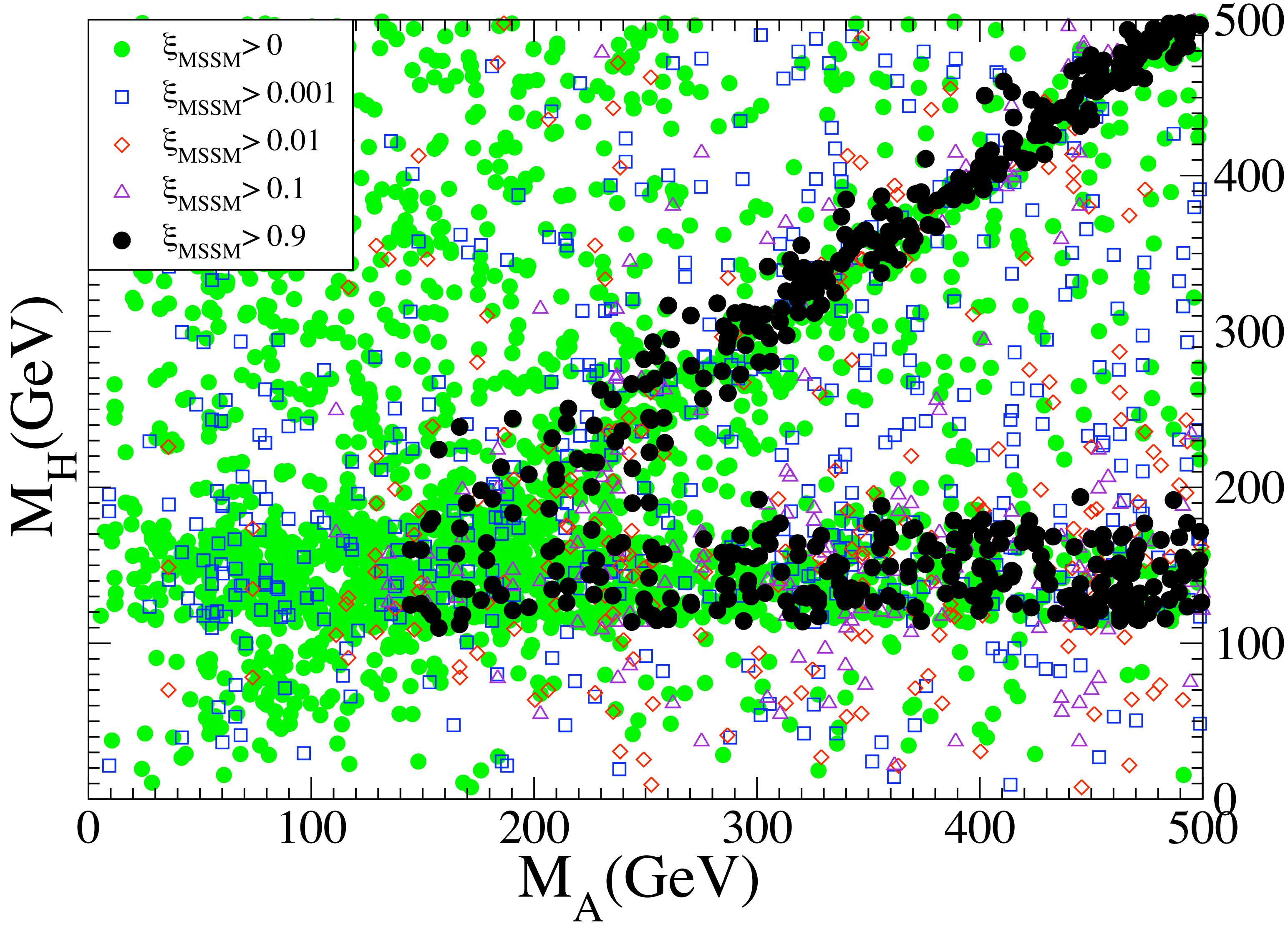
Linear Collider (500 GeV)Higgsstrahlung Cross Section



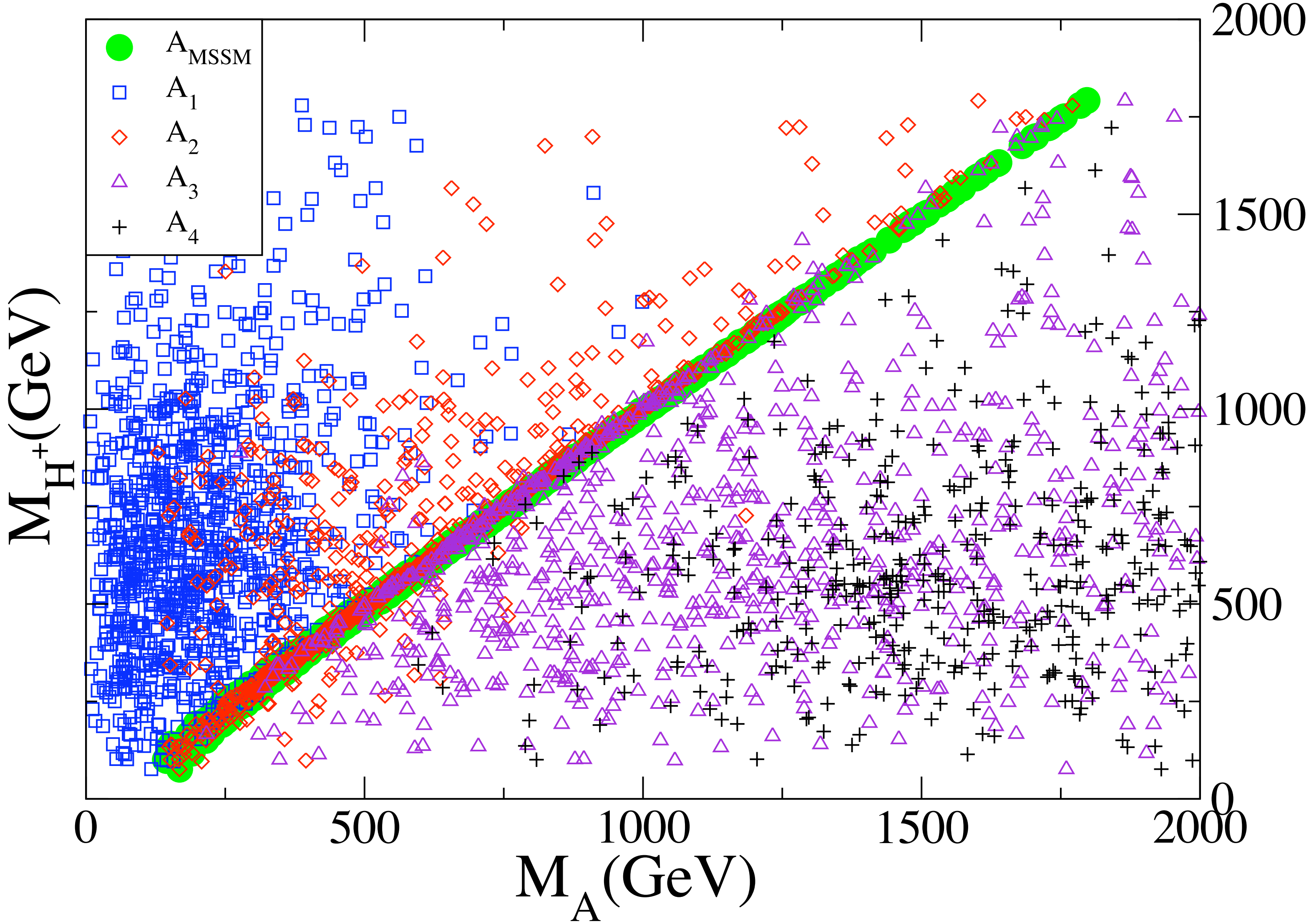
- **Wide range of spectra, including light or heavy H_1, A_1; usually light χ_1^0**

- **Complex neutralino spectrum (9 in model)** **(Implications for CDM, $g_\mu - 2$)**

M_H vs. M_A by MSSM fraction



Charged Higgs Mass vs. A Masses



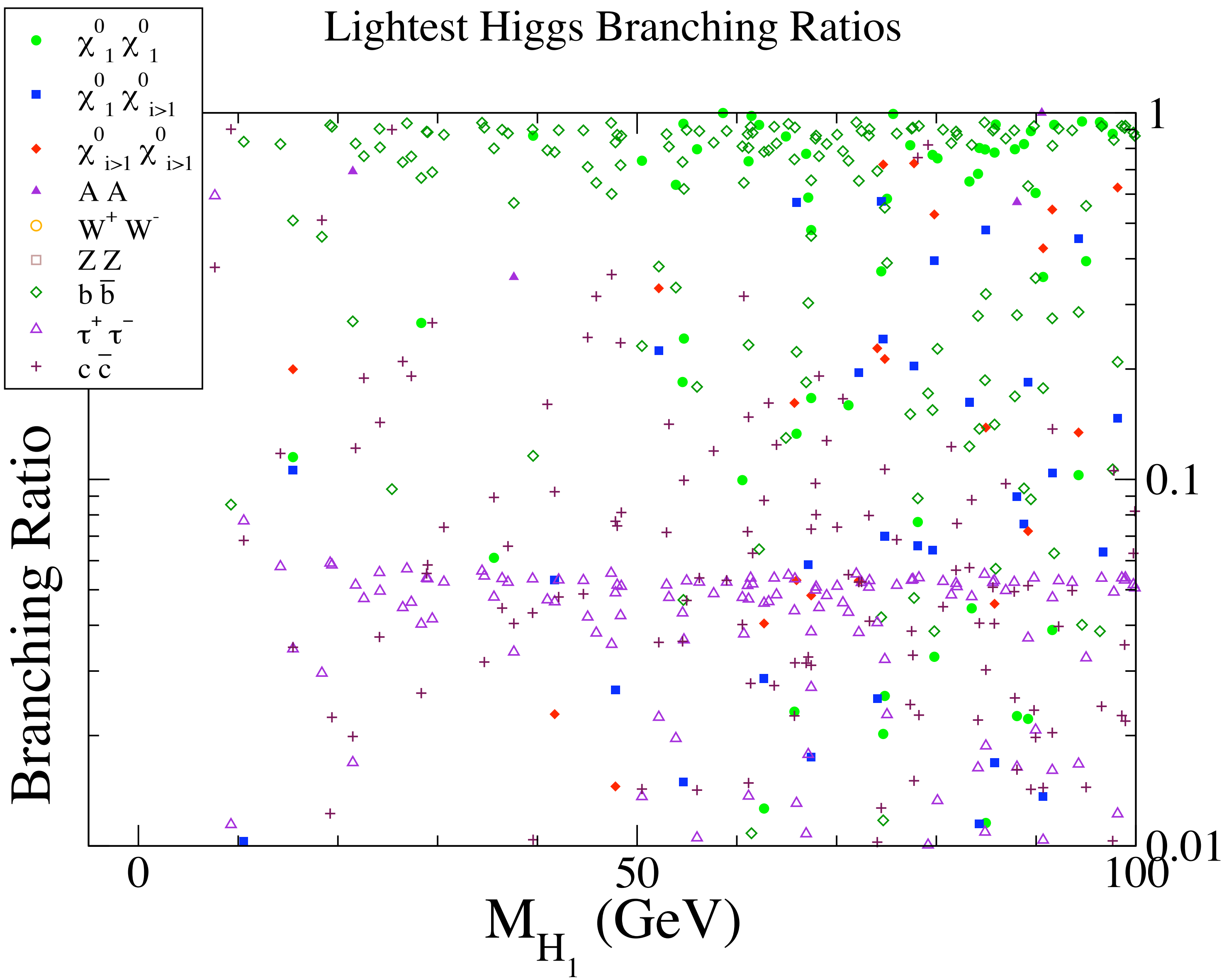
A-8. TYPICAL LIGHT $A_1 \rightarrow$ INVISIBLE DOMINANT

$\tan\beta = 1.08$		$M_{Z'} = 2831$ GeV		$M_{H^+} = 622$ GeV		$\alpha_{ZZ'} = 2.7\cdot10^{-5}$			
M_H	116	564	629	2739	3077	8917			
$\xi_{\rm MSSM}$	1	$1.9\cdot10^{-4}$	1	$4.3\cdot10^{-5}$	$1.3\cdot10^{-4}$	0			
$\sigma(H_i Z)$	58								
$\sigma(H_i \nu\overline{\nu})$	88								
$\sigma(H_i e^+e^-)$	8.5								
M_A	78	621	3045	8916	0	0			
$\xi_{\rm MSSM}$	$3.0\cdot10^{-4}$	1	$1.5\cdot10^{-4}$	0	1	$1.0\cdot10^{-4}$			
$\sigma(H_1 A)$	$5.0\cdot10^{-6}$								
M_{χ^0}	36	159	176	191	335	666	696	2236	3630
$\xi_{\rm MSSM}$	0.17	1	0.83	1	1	0	0	$5.2\cdot10^{-5}$	$4.1\cdot10^{-5}$
$\xi_{\tilde{s}}$	0.83	$4.1\cdot10^{-4}$	0.17	$9.0\cdot10^{-4}$	0	1	1	0.63	0.38
$\xi_{\tilde{Z}'}$	0	0	0	0	0	$4.9\cdot10^{-3}$	$3.0\cdot10^{-3}$	0.37	0.62
M_{χ^+}	154	335							

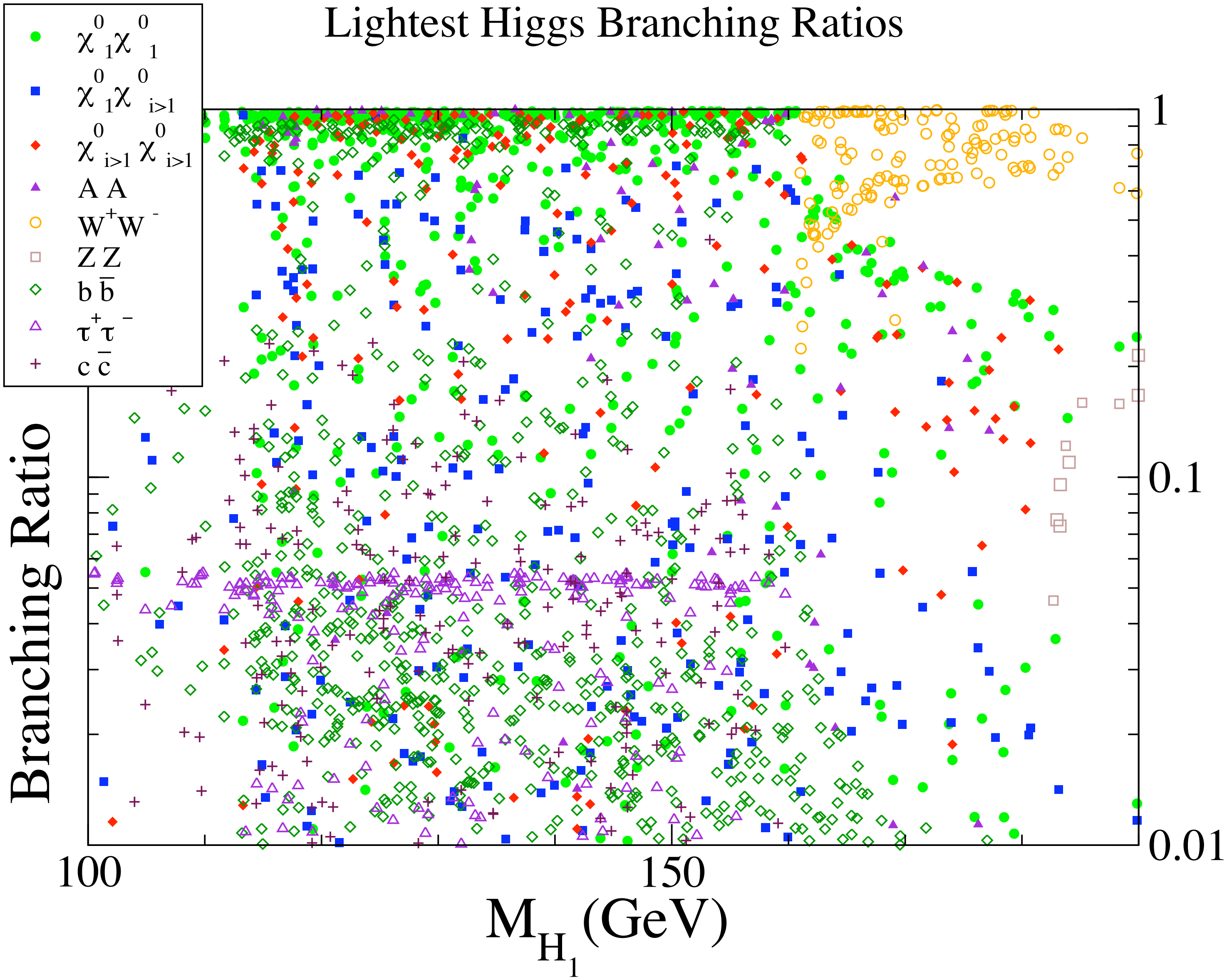
- **Many possible decay channels for light and heavy, including MSSM-like, Higgs, neutralino (invisible), cascade**

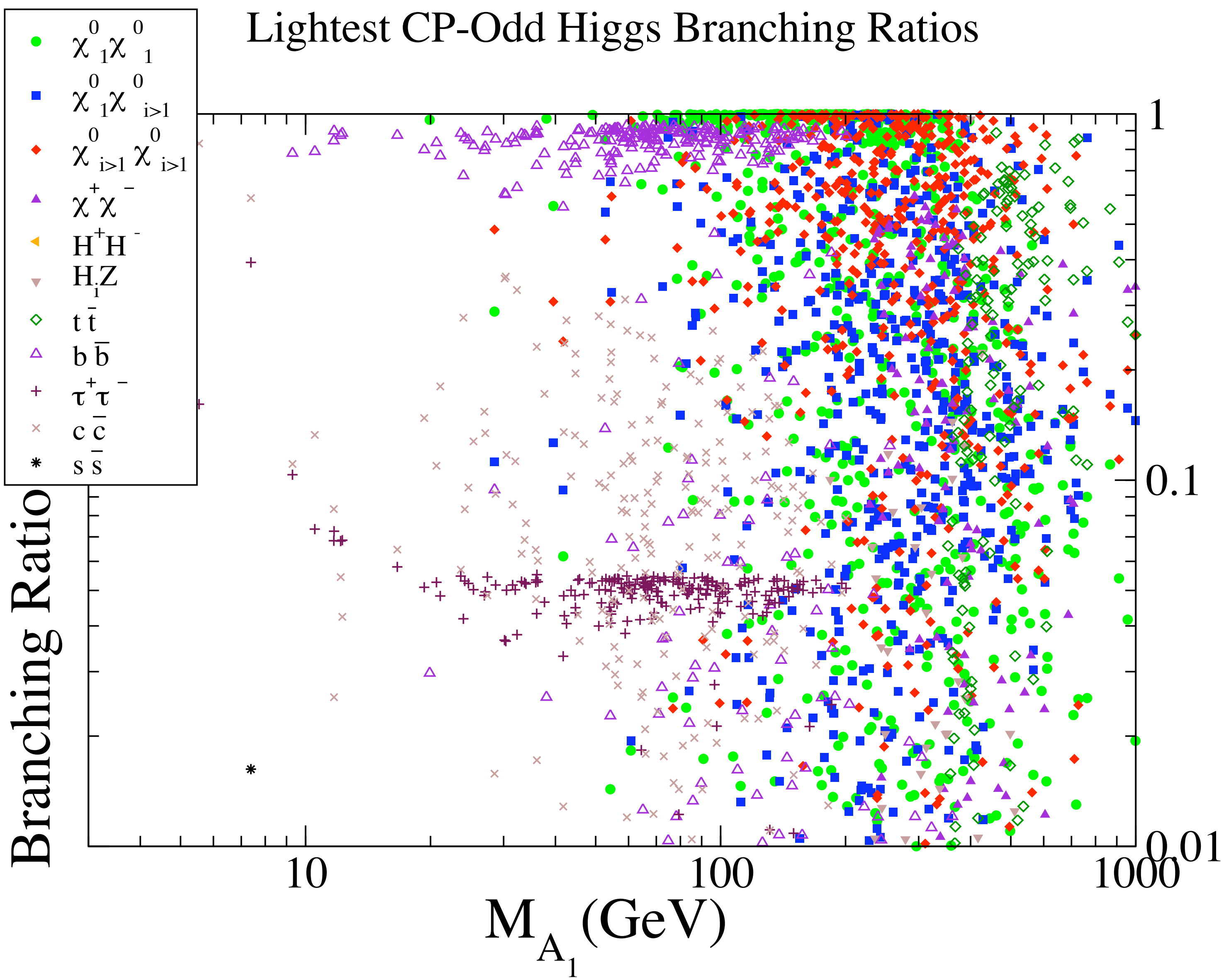
- **Usually** $H_1 \rightarrow \chi_1^0 \chi_1^0$ **or** $A_1 A_1$ **when kinematically possible**

- **Also,** $H \rightarrow b\bar{b}$, $\tau^+\tau^-$, $c\bar{c}$; $H_i \rightarrow H_j H_k$, $A_j A_k$


Lightest Higgs Branching Ratios
$\chi^0_1 \chi^0_1$
$\chi^0_1 \chi^0_{i>1}$
$\chi^0_{i>1} \chi^0_{i>1}$
A A
$W^+ W^-$
Z Z
$b \bar{b}$
$\tau^+ \tau^-$
$c \bar{c}$
Branching Ratio
1
0.1
0.01
0
50
100
M_{H_1} (GeV)

Lightest Higgs Branching Ratios





Lightest CP-Odd Higgs Branching Ratios
$\chi^0_1\chi^0_1$
$\chi^0_1\chi^0_{i>1}$
$\chi^0_{i>1}\chi^0_{i>1}$
$\chi^+\chi^-$
H^+H^-
H_iZ
$t\bar{t}$
$b\bar{b}$
$\tau^+\tau^-$
$c\bar{c}$
$s\bar{s}$
Branching Ratio
1
0.1
0.01
10
100
1000
M_{A_1} (GeV)

Branching Ratios for dominant decay modes (greater than 1% excluding model-dependent squark, slepton, Z' and exotic decays; $\chi^0_{i>1}$ are summed):

H_1	$\chi^0_1\chi^0_1$	97%	$b\bar{b}$	3%								
H_2	H_1H_1	26%	W^+W^-	21%	$\chi^+_1\chi^-_1$	15%	$\chi^0_{i>1}\chi^0_{i>1}$	12%	ZZ	10%	$t\bar{t}$	8%
H_3	$t\bar{t}$	70%	$\chi^0_1\chi^0_{i>1}$	14%	$\chi^0_{i>1}\chi^0_{i>1}$	10%	$\chi^+_1\chi^-_2$	4%	H_1H_1	1%		
H_4	A_1A_2	40%	H_3H_3	19%	$\chi^+_1\chi^-_1$	13%	$\chi^0_{i>1}\chi^0_{i>1}$	13%	H_1H_1	4%	W^+W^-	4%
H_5	$\chi^+_1\chi^-_1$	37%	$\chi^0_{i>1}\chi^0_{i>1}$	33%	$\chi^0_1\chi^0_{i>1}$	7%	A_1A_2	7%	H_1H_1	4%	W^+W^-	4%
H_6	$\chi^0_{i>1}\chi^0_{i>1}$	96%	H_2H_4	2%	H_2H_2	1%						
A_1	$\chi^0_1\chi^0_1$	99%	$b\bar{b}$	1%								
A_2	$t\bar{t}$	73%	$\chi^0_{i>1}\chi^0_{i>1}$	12%	$\chi^0_1, \chi^0_{i>1}$	7%	$\chi^0_1\chi^0_1$	5%	$\chi^+_1\chi^-_1$	2%		
A_3	H_2Z	100%										
A_4	$\chi^0_{i>1}\chi^0_{i>1}$	67%	H_5Z	27%	A_1H_2	4%	A_2H_5	1%				

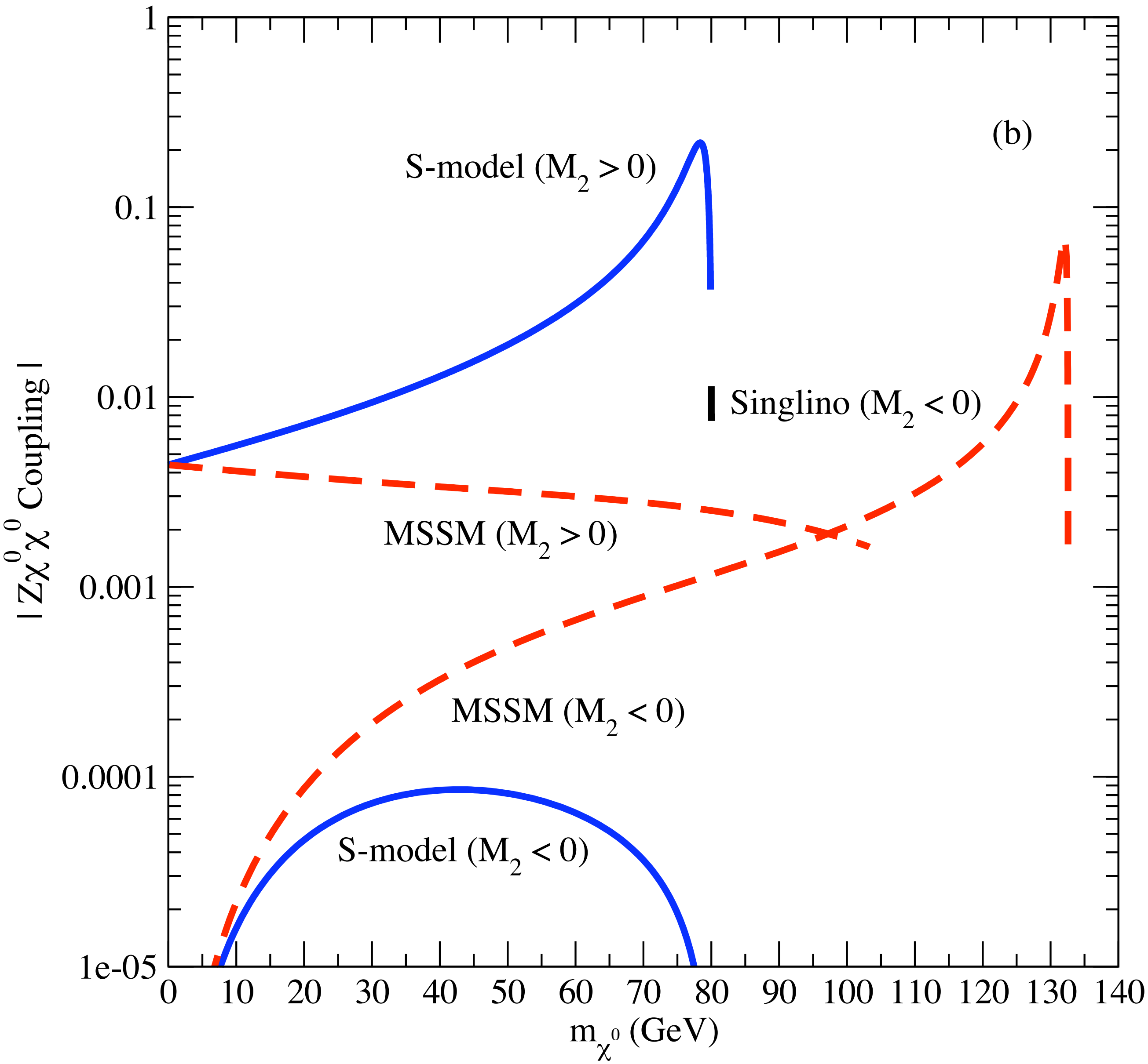
Conclusions

- Important to explore alternatives to MSSM
- Top-down string constructions very often contain extra Z' and SM singlets S
- Elegant solution to μ problem (string-motivated extension of NMSSM)
- Many implications, including nonstandard Higgs (spectrum, couplings, decays, CP breaking), CDM, $g_\mu - 2$, efficient EW baryogenesis, $B_s - \bar{B}_s$ mixing, rare B decays, neutrino masses
- But, must observe Z'

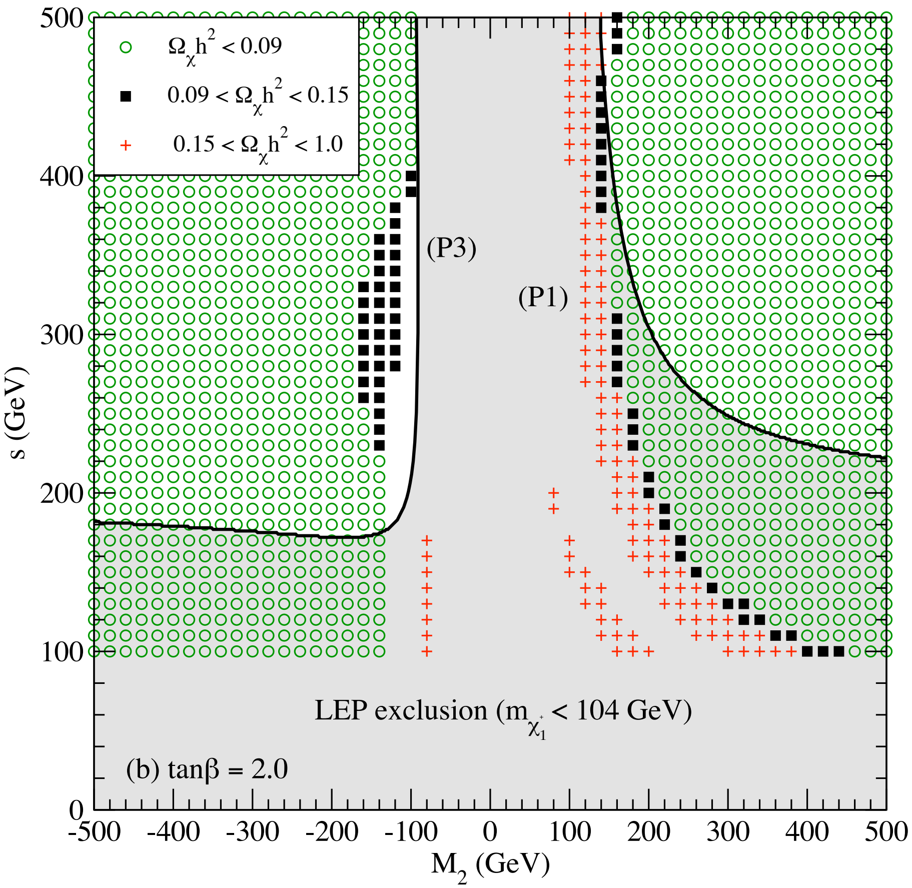
Cold Dark Matter

(V. Barger, C. Kao, PL, H.-S. Lee)

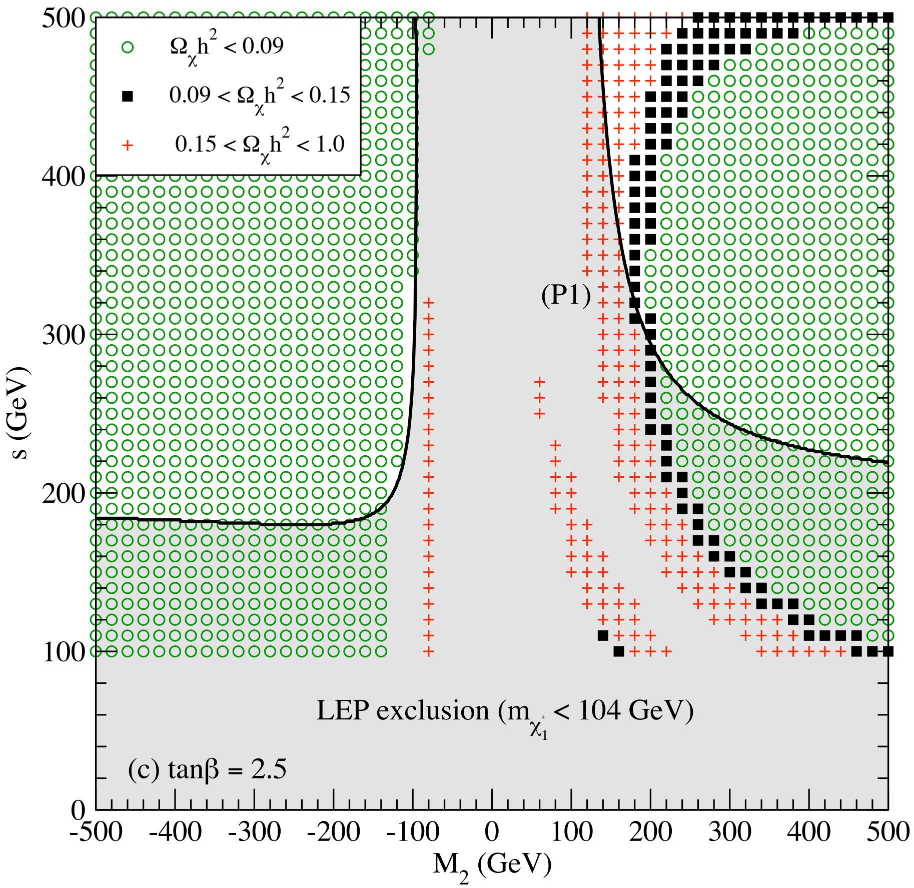
- $0.09 < \Omega_{\chi^0} h^2 < 0.15$
- MSSM: limited parameter space for sufficient LSP (co)annihilation; mainly bino in most of parameter space.
- $U(1)'$: additional Z'-ino and singlino. ((n)NMssm: additional singlino) →may have enhanced annihilation coupling to Z
- Solutions compatible with observations for most m_{χ^0} (only examined for large Z'-ino mass)



(b)
S-model ($M_2 > 0$)
Singlino ($M_2 < 0$)
MSSM ($M_2 > 0$)
MSSM ($M_2 < 0$)
S-model ($M_2 < 0$)
$|Z\chi^0\chi^0$ Coupling$|$
m_{χ^0} (GeV)
1
0.1
0.01
0.001
0.0001
1e-05
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140



$\Omega_\chi h^2 < 0.09$
$0.09 < \Omega_\chi h^2 < 0.15$
$0.15 < \Omega_\chi h^2 < 1.0$
(P3)
(P1)
LEP exclusion ($m_{\chi_1} < 104$ GeV)
(b) tanβ = 2.0
s (GeV)
M_2 (GeV)
500
400
300
200
100
0
-500
-400
-300
-200
-100
0
100
200
300
400
500



$\Omega_\chi h^2 < 0.09$
$0.09 < \Omega_\chi h^2 < 0.15$
$0.15 < \Omega_\chi h^2 < 1.0$
(P1)
LEP exclusion ($m_{\chi_1} < 104$ GeV)
(c) tanβ = 2.5
s (GeV)
M_2 (GeV)
500
400
300
200
100
0
-500
-400
-300
-200
-100
0
100
200
300
400
500

Muon $g_\mu - 2$

(V. Barger, C. Kao, PL, H.-S. Lee)

- **BNL E821:** $a_\mu(\text{exp}) = (11659208.0 \pm 5.8) \times 10^{-10}$

- 2.4σ deviation from its Standard Model (SM) prediction $\Delta a_\mu \equiv a_\mu(\text{exp}) - a_\mu(\text{SM}) = 23.9(7.2)(3.5)(6) \times 10^{-10}$, assuming $e^+e^- \to$ hadrons value for hadronic vacuum polarization

- **MSSM:**

$$\Delta a_\mu(\text{SUSY}) \sim 13 \times 10^{-10} \frac{\tan\beta \ \text{sign}(\mu)}{(M_{\text{SUSY}}/100 \text{ GeV})^2},$$

  for common superpartner masses M_{SUSY}, favoring large $\tan\beta$ and/or small M_{SUSY}

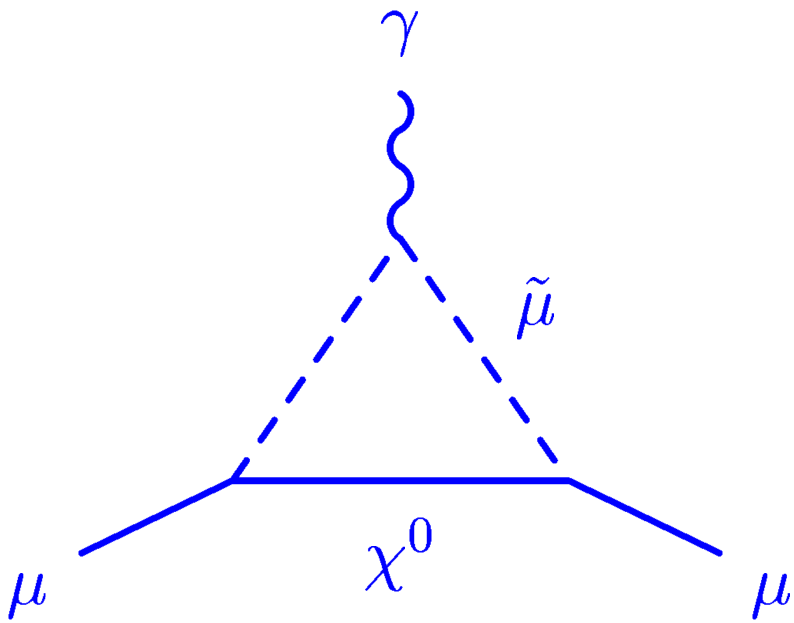
- **LEP2:** $m_{\tilde{\mu}} \gtrsim 95$ GeV

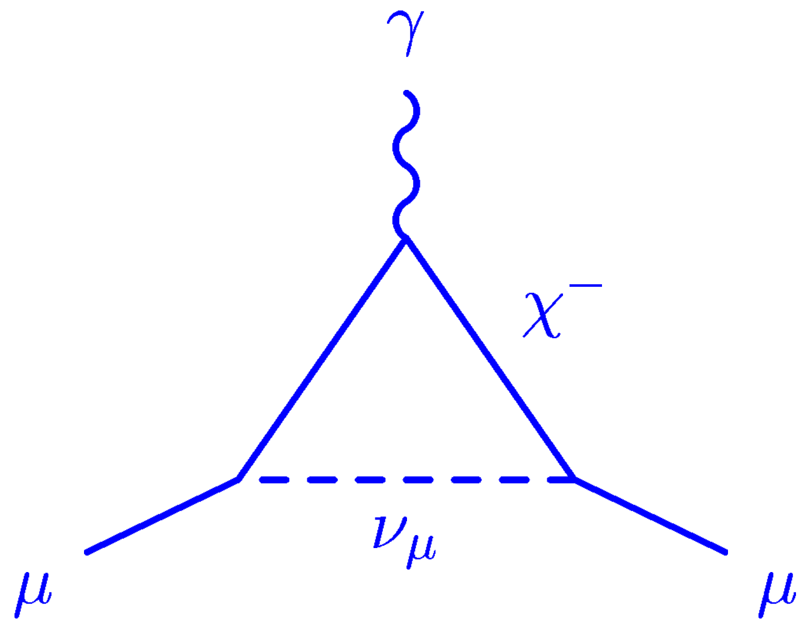
- Z' diagrams small for allowed $M_{Z'}$

- New Z'-ino and singlino contributions in $U(1)'$, and different parameter range

- Neutralino mass matrix in $\left\{\tilde{B}, \tilde{W}_3, \tilde{H}_1^0, \tilde{H}_2^0, \tilde{S}, \tilde{Z}'\right\}$ basis

$$\begin{pmatrix} M_1 & 0 & -g_1 v_1/2 & g_1 v_2/2 & 0 & 0 \\ 0 & M_2 & g_2 v_1/2 & -g_2 v_2/2 & 0 & 0 \\ -g_1 v_1/2 & g_2 v_1/2 & 0 & -h_s s/\sqrt{2} & -h_s v_2/\sqrt{2} & g_{Z'} Q'(H_1^0) v_1 \\ g_1 v_2/2 & -g_2 v_2/2 & -h_s s/\sqrt{2} & 0 & -h_s v_1/\sqrt{2} & g_{Z'} Q'(H_2^0) v_2 \\ 0 & 0 & -h_s v_2/\sqrt{2} & -h_s v_1/\sqrt{2} & 0 & g_{Z'} Q'(S) s \\ 0 & 0 & g_{Z'} Q'(H_1^0) v_1 & g_{Z'} Q'(H_2^0) v_2 & g_{Z'} Q'(S) s & M_{1'} \end{pmatrix}$$

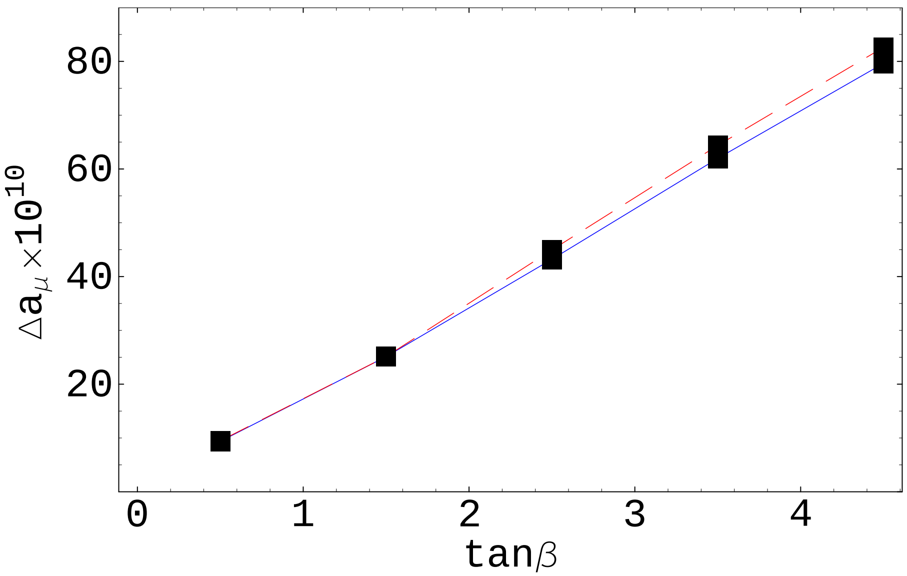


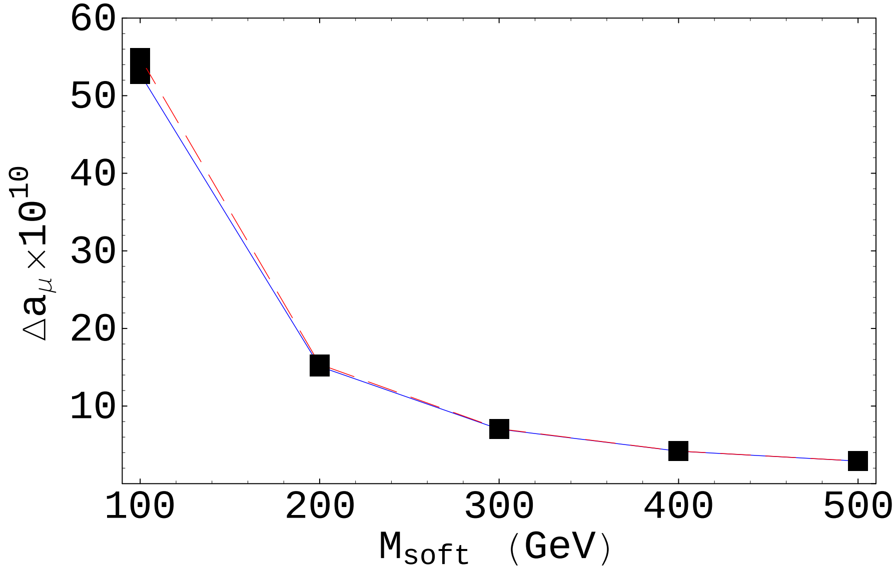


$$\chi^0 = \left\{ \tilde{B}, \tilde{W}_3, \tilde{H}_1^0, \tilde{H}_2^0, \tilde{S}, \tilde{Z}' \right\}$$

$$\chi^- = \left\{ \tilde{W}^-, \tilde{H}^- \right\}$$

Adequate $g_\mu - 2$ possible, even with small $\tan\beta$, consistent with $m_{\tilde{\mu}}$ constraints, while also giving observed CDM





Maximum Δa_μ

Observation: $(13.9 - 33.9) \times 10^{-10}$

Electroweak Baryogenesis

(J. Kang, PL, T. Li, T. Liu)

- Baryon asymmetry $n_B/n_\gamma \sim 6 \times 10^{-10}$
- Basic ideas worked out by Sakharov in 1967, but no concrete model
- Possible mechanisms
  - Affleck-Dine baryogenesis
  - GUT baryogenesis (wiped out by sphalerons for $B - L$=0)
  - Leptogenesis
  - Electroweak baryogenesis (Off the wall scenario: CP breaking in interactions with expanding bubble wall; sphalerons outside bubble)

Implementation of "off the wall"

Standard model: no strong first order phase transition for $M_h > 114.4$ GeV; CP violation too small

Minimal supersymmetric extension (MSSM): small parameter space for light Higgs and light stop; new sources for CP violation

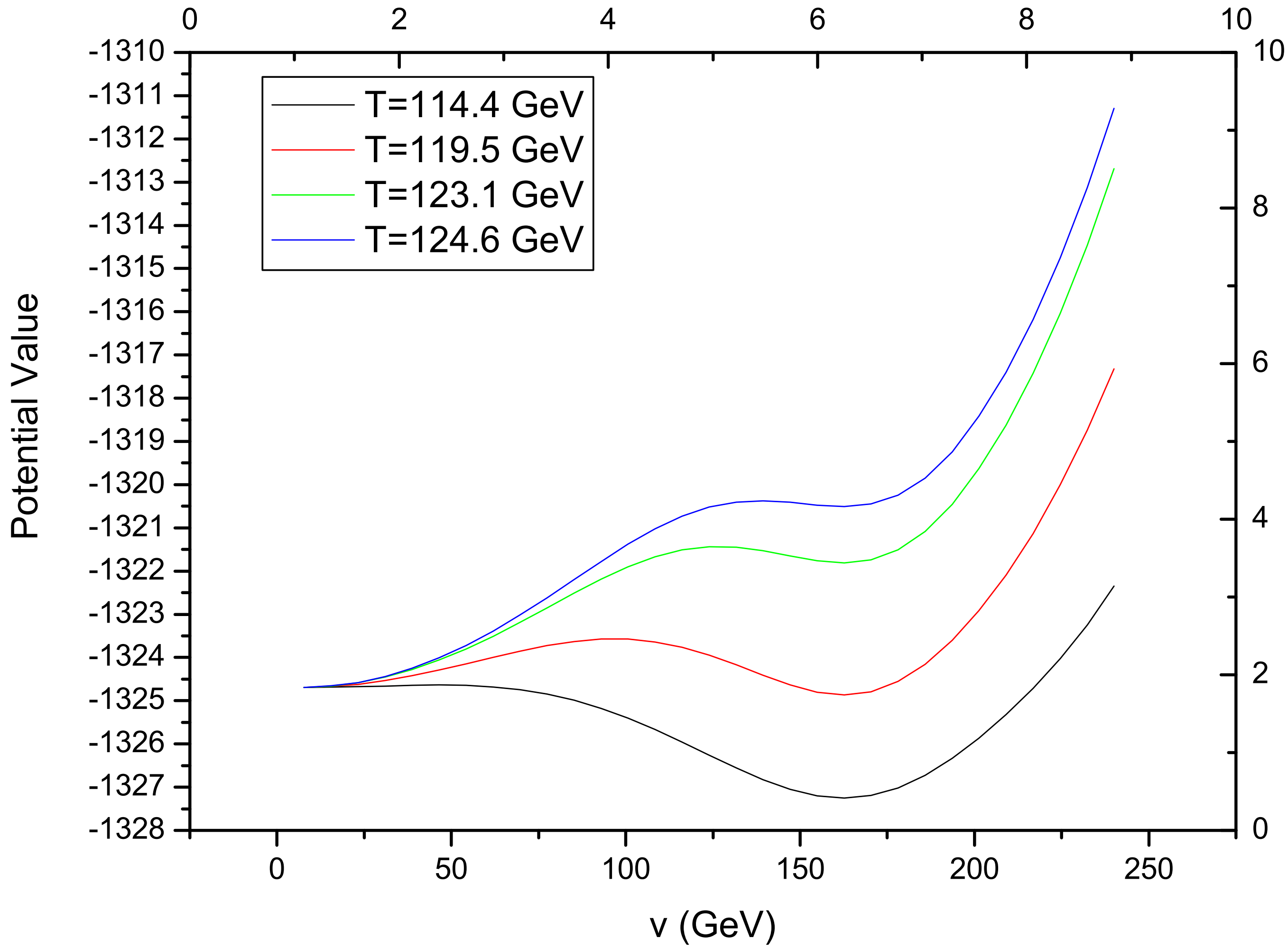
NMSSM (extension to include extra Higgs fields): can have strong first order for large $hA_hSH_1H_2$ but cosmological domain walls

nMSSM: strong transition without domain walls

Secluded sector $U(1)'$:

- **Symmetry breaking driven by large $hA_hSH_1H_2$**
- **Tree level CP breaking in Higgs sector associated with soft SM singlet terms**
- **New contributions to electric dipole moments negligible**
- **First phase transition breaks $U(1)'$, second breaks $SU(2)\times U(1)$**

- **Phase transition strongly first order**

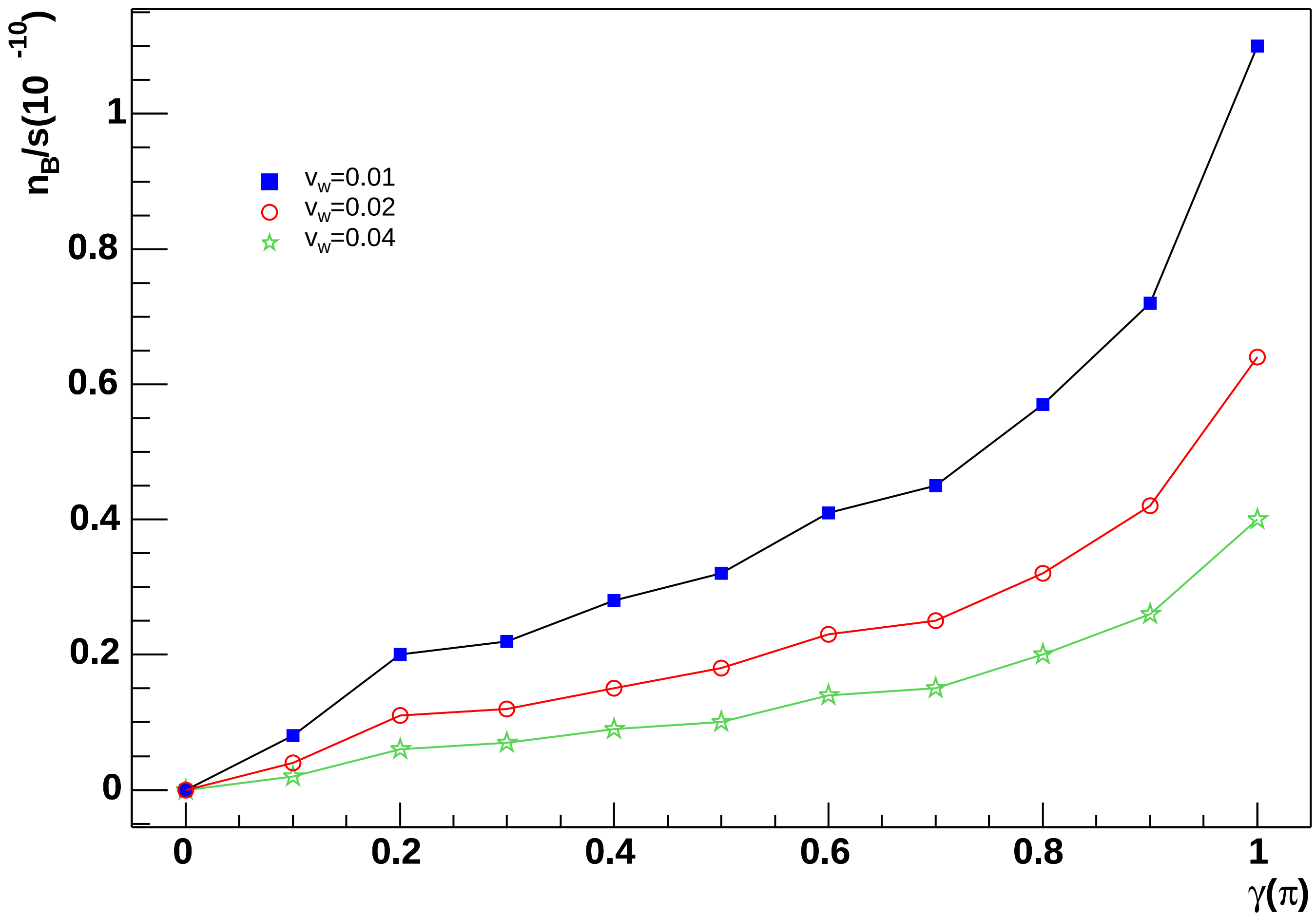


Transition at $T_c = 120$ GeV, $v(T_c)/T_c = 1.31$

- For τ lepton use thin wall approximation (justified)
- For reasonable parameters, can obtain adequate asymmetry, even for large $\tilde{t}$ mass, from τ alone

$$\frac{n_B}{s} = -90\gamma_w^3(1 + \frac{v_w}{\langle v_L \rangle})\frac{\xi_L m^2 \delta \Delta\theta_{CP} h(\delta, T)\Gamma_s^{'}}{(2\pi)^4 v_w g_* T^3}$$

- Larger contributions from neutralinos/charginos if not too heavy



$\gamma =$ **explicit CP phase. Exp:** $n_B/s \sim (0.8 - 0.9)\times 10^{-10}$.