Phenomenology of the NMSSM with largish Higgs self-coupling

arXiv:1005.1070 with Stefania Gori
arXiv:0710.5750 with Leone Cavicchia and Vyacheslav S. Rychkov

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$W = \lambda S H_u \cdot H_d$ with $\lambda > 1$

Outline

- $m_h \sim \lambda v \sim 200 - 300$ GeV ... very non standard Higgs phenomenology
- dynamically generate $\mu \sim m_h \sim \lambda v$
- fine-tuning $\sim 1/\lambda \sim 1/m_h$
- experimental bounds from LEP and WIMP searches
- two representative cases of LHC (early) phenomenology

SUSY means a light Higgs(?)

MSSM

$m_h^2 < m_Z^2 \cos^2 2\beta$

- no contribution from the superpotential
- only some of the couplings of the general 2HDM are non-vanishing

large corrections

LO contribution to the rest of the potential at one loop

$\delta m_h^2 \sim \frac{m_{top}^4}{v^2} \log \frac{m_{stop}^2}{m_{top}^2}$

superpotential contributions: NMSSM

$W = \lambda S\, H_u \cdot H_d + ...$

- $m_h^2 < m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta$
- $\frac{d\lambda}{d \log \mu} \sim \lambda(\lambda^2 - g^2)$

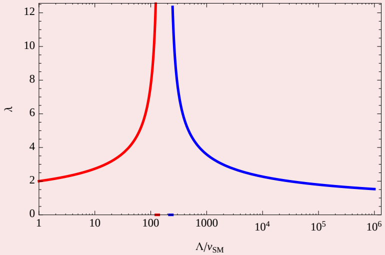
playing with the evolution of g

- $\lambda \sim 0.7$ at the Fermi scale still allows *perturbative* unification of the couplings.
- $m_h^{max} \simeq 150$ GeV

$m_h > 114$ GeV: a not so weak self coupling

$\lambda = 2$: let it go strong

- $m_h^2 \sim \lambda_{SM} v^2$
- λ_{SM} grows in the UV



- at some scale one or more Higgs bosons will reveal their composite nature

- below the strong coupling scale this looks like SUSY with a heavy Higgs boson

Unifcation can be preserved

$$W = \lambda S H_u H_d + f(S)$$

Harnik, Kribs, Larson, Murayama - PRD 70, Chang, Kilic, Mahbubani - PRD 71, Birkedal, Chacko, Nomura - PRD 71, Delgado, Tait - JHEP0507

λSUSY: a Heavy supersymmetric Higgs boson

- disregard the details of the UV models
- look at the low energy theory with a generic $W = \mu(S)H_uH_d + f(S)$

- $\mu = \mu(s)$
- $\lambda = \frac{\partial\mu(S)}{\partial S}$
- $M = \frac{\partial^2}{\partial S^2} f(S)$

$$V = \mu_1(S)|H_u|^2 + \mu_2(S)|H_d|^2 + \mu_3(S)H_u \cdot H_d + \lambda|H_u \cdot H_d|^2 + V(S)$$

Scalars: $M \gg \lambda v \quad \Rightarrow \quad$ 2HDM

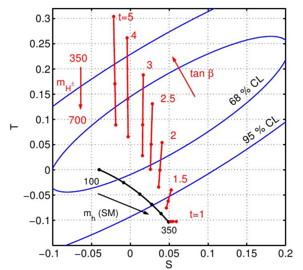
S and H_d, H_u are unmixed

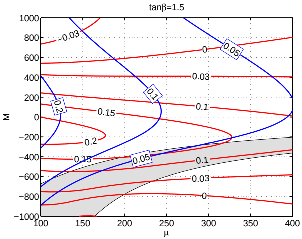
Fermions: $M_2, M_1 \gg \mu, \lambda v, M$

$m_{\chi^+} = \mu$

$$M_N = \begin{pmatrix} \mu & 0 & \frac{v\lambda(c_\beta - s_\beta)}{\sqrt{2}} \\ 0 & -\mu & -\frac{v\lambda(c_\beta + s_\beta)}{\sqrt{2}} \\ \frac{v\lambda(c_\beta - s_\beta)}{\sqrt{2}} & -\frac{v\lambda(c_\beta + s_\beta)}{\sqrt{2}} & M \end{pmatrix}$$

LEP prefers a light Higgs(?)





Barbieri, Hall, Nomura, Rychkov - PRD 75

- the heavy Higgs contributes to $S \sim \lambda$
- Higgsinos and Higgs contribute to $T \sim \lambda$

heavy Higgs:

- less FT
- no need for a special 3rd gen

dynamical generation of a μ term in λSUSY

$W = \lambda S H_u H_d + \frac{k}{3} S^3$ with large λ

- dynamical generation of μ
- naturalness
- experimental constraints
- LHC phenomenology

$$V_{\text{soft}} = m_1^2 \left|H_1\right|^2 + m_2^2 \left|H_2\right|^2 + \mu_S^2 \left|S\right|^2 - (A\lambda S H_1 H_2 + G\frac{k}{3} S^3 + h.c.)$$

$$V = V_{\text{soft}} + V_D + \lambda^2 \left|H_u H_d\right|^2 + k^2 \left|S^2\right|^2 + \lambda^2 \left(\left|H_u S\right|^2 + \left|H_d S\right|^2\right)^2 + \lambda k (S^2 H_u H_d + h.c)$$

Generation of $\mu = \lambda s$ and the soft terms

- $4k^2 s^3 - 2Gks^2 + 2s\left(\lambda^2 v^2 + v^2 \lambda k \sin 2\beta + \mu_S^2\right) - Av^2 \lambda \sin 2\beta = 0$
- $\mu_S^2 s^2 + k^2 s^4 - 2G\frac{k}{3}s^3 - \frac{\lambda^2}{4}v^4 \sin^2 2\beta - \frac{m_Z^2}{4}v^2 \cos^2 2\beta < 0$
- $2Gs(A - ks) - 3A\lambda v^2 \sin 2\beta > 0$

small λ : $v/s \ll 1$

$$s \simeq \frac{1}{4k}\left(G + \sqrt{G - 8\mu_S}\right)$$

- EWSB triggered by $V_G = -\frac{k}{3}GS^3$
- tends to give unmixed singlets

$\lambda \gg 1$: $s \lesssim v$

$$s \simeq \frac{A \sin 2\beta}{2\left(\lambda + k \sin 2\beta\right)}$$

- EWSB triggered by $V_A = -\lambda A S H_u H_d$
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$$V(vev) \simeq -\frac{\lambda^2}{4} v^4 \sin^2 2\beta + -k^2 s^4 + \frac{1}{3} kGs^3 < 0$$

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$$G/s < O(\lambda^2/k)$$

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$$Gs/v^2 > O(\lambda)$$

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$$G/A < O(\lambda/k)$$

$$GA > O(\lambda^2 v^2)$$

$$A > \lambda v$$

a heavy Higgs boson: $m_h \sim \lambda v \sim \mu$

Parameters: μ, m_{H^+}

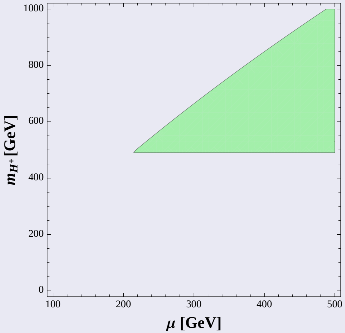
$$\mu \equiv \lambda s\,, \quad m_{H^+}^2 = \frac{2\mu(A - \frac{k}{\lambda}\mu)}{\sin 2\beta} - \lambda^2 v^2 + mW^2$$

$$G = A$$

$$m_{H^+}^2 > 2\lambda^2 v^2 + m_W^2$$

$$m_{H^+}^2 < 4\frac{\mu^2}{\sin^2 2\beta} + m_W^2 + \frac{m_Z^2}{\tan^2 2\beta} + O\left(\frac{1}{\lambda}\right)$$

$\lambda = 2,\ k = 1.2,\ \tan\beta = 1.5$



$\mu \sim m_h$

$$\frac{\lambda v}{\sqrt{2}} \sin 2\beta < \mu < \frac{3}{2}\lambda v \sin 2\beta$$

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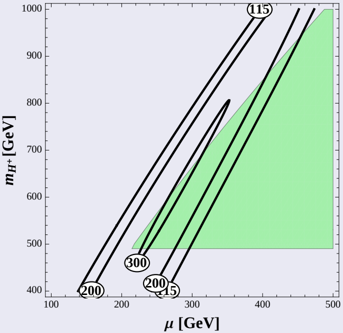

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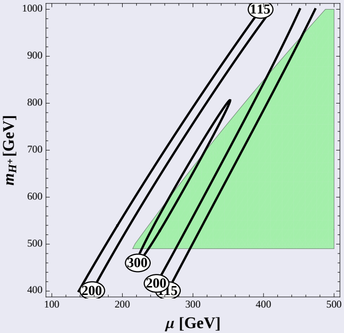

- $\mu/m_Z \gtrsim 1$
- Higgs and Chargino not at LEP

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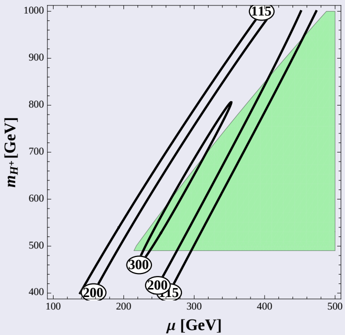


- $\mu/m_Z \gtrsim 1$
- Higgs and Chargino not at LEP

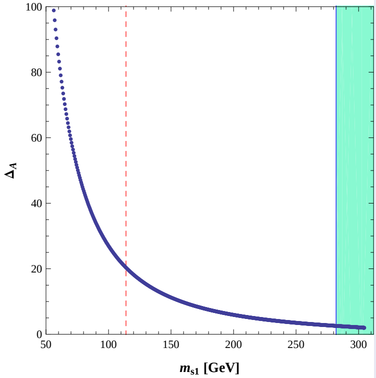
the heavier the Higgs the better

$$\lambda^2 v^2 = \frac{2s\lambda(A - ks)}{\sin 2\beta} + \frac{m_1^2 - m_2^2}{\cos 2\beta} + m_Z^2$$

$$v \sim m_{soft}/\lambda$$

$$FT \sim 1/m_{s_1}$$

FT



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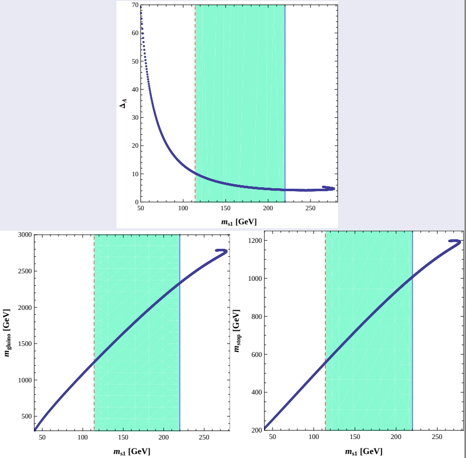
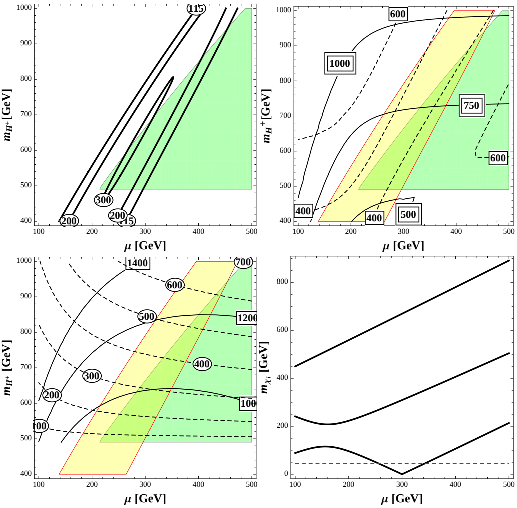
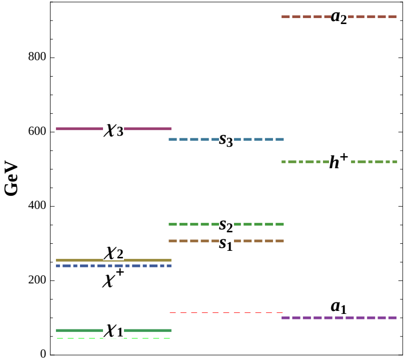
FT and Naturalness bounds



see also Barbieri, Bertuzzo, Farina, Lodone, Pappadopulo - 1004.2256

a rather heavy SUSY spectrum

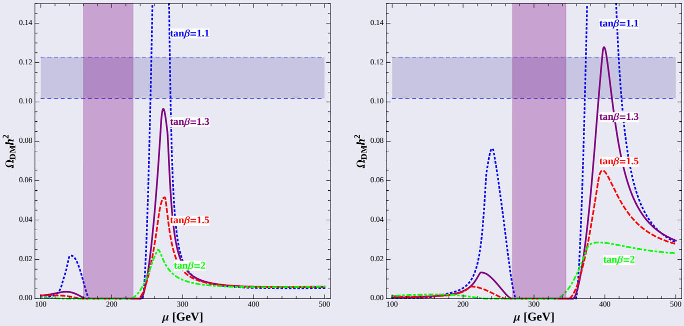




- s_1, χ^+, h^+ tipically above LEP reach
- χ_1^0 excluded by LEP in some region
- a_1 is typically light

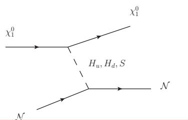
Relic Dark matter (singlino-higgsino)

- typically $m_{LSP} < m_Z$
- mainly annihialtes into fermions

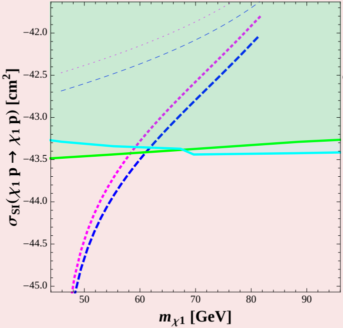


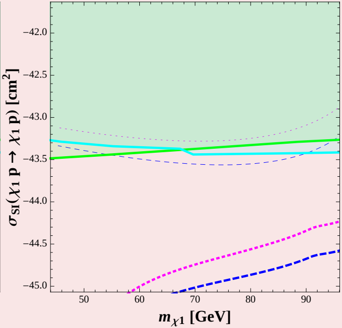
Spin independent scattering on nuclei

strongish higgs exchange in direct detection experiments



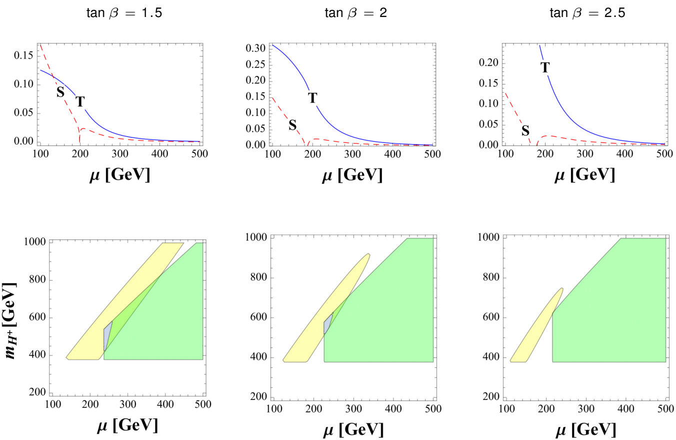
- the large mixing in the scalar sector gives important effects





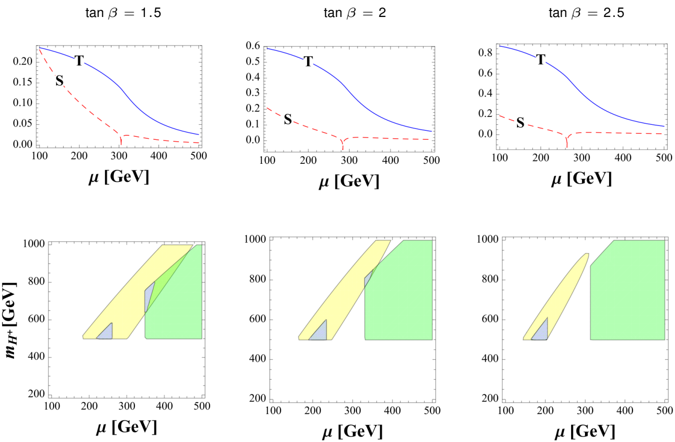
Experimental constraints for $\lambda = 1.5$

- LEP direct serches
- WIMP searches
- EWPT



Experimental constraints for $\lambda = 2$

- LEP direct serches
- WIMP searches
- EWPT



LHC: a strongish self-coupling in the Higgs sector

largish λ

- the Higgs/Higgsino phenomenology is mainly governed by λ
- Higgs/Higgsino with large $\mathcal{B}$ into other Higgs/Higgsino states

singlet mixing in the Higgs sector

- in the decoupled singlet case the Higgs sector has some resemblance with the MSSM (if not for the mass!)
- when the singlet is mixed the Higgs phenomenolgy is completely changed

colored super partners

- squarks and gluinos do not experience the largish couplings of the Higgs sector
- colored particles phenomenology is as in the MSSM

- pair production and observation of decays chains with jets,leptons and mET
- TeV-ish discovery potential with $\mathcal{L} = 1/fb$ (end of 2011) or above TeV for $\mathcal{L} \sim 10/fb$

the mixed singlet scenario, $\mu_{eff} = \lambda s$

lightest CP-even Higgs

- $\mathcal{O}(1)$ coupled to the top
- gluon fusion production
- prefers decays in the Higgs/Higgsino sector
- $\mathcal{B} \sim 1/N_{ch}$

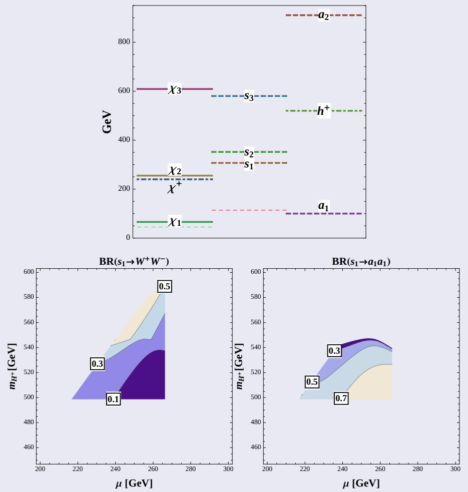
$\lambda \gtrsim k > 1$

- $\Gamma(s_1 \to a_1 a_1) > \Gamma(s_1 \to WW)$
- $gg \to s_n \to a_1 a_1,\ Za_1,\ invisible$

the lightest Higgs state

$$a_1 \to b\bar{b}, \tau^- \tau^+$$

$m_{H^+} = 550\ GeV, \mu = 250\ GeV$

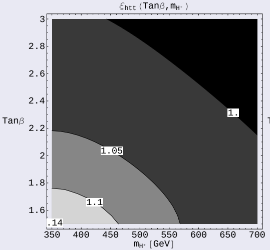


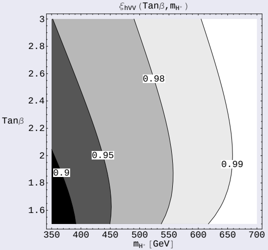
The unmixed singlet scenario

- the H_u, H_d sector looks like the MSSM at low $\tan\beta$
- S is decoupled

the lightest Higgs

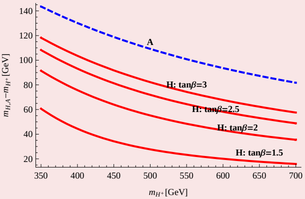
- h is very SM-like and decays into VV
- gluon fusion σ has only limited deviations from the SM value



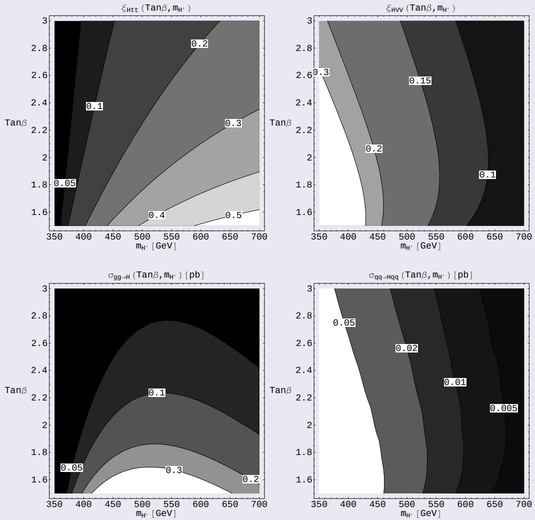


puzzle after $\mathcal{L} = 10/fb$

- SM-like h boson
- colored superpartners
- heavy Higgs bosons to tell the full story



the heavy CP-even H



H properties

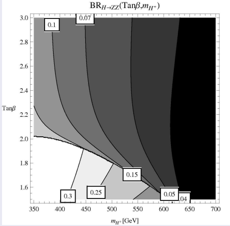
- $m_H \sim 500$ GeV
- rather decoupled
- VBF is subdominant

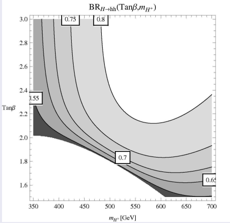
large λ

- largish coupling with the Higgs bosons and higgsinos

the heavy CP-even

$H \to hh$ tends to dominate





$m_{H^\pm} = 500$ GeV, $\tan\beta = 2$

$$\sigma_H^{GF} = 150 \text{ fb}, \quad \sigma_H^{VBF} = 27 \text{ fb},$$
$$m_H = 555\,\text{GeV}, \quad m_h = 250\,\text{GeV},$$
$$\Gamma_H = 21\,\text{GeV}, \quad \Gamma_h = 3.8\,\text{GeV},$$
$$\xi^2_{Htt} = 0.058, \quad \xi^2_{HVV} = 0.060,$$
$$BR(H \to hh) = 0.76, \quad BR(H \to VV) = 0.2$$

- a chance to obsere the largness of λ in the dominance of $H \to hh$

$gg \to H \to hh \to 2Z2V \to 6j\ell\bar{\ell}$

$$\Delta R_{JJ} > 0.7,\ p_T^J > 20\text{ GeV},\ \eta_J < 2.5,\ 80 < \frac{m_{ll}}{\text{GeV}} < 100,\ \eta_l < 10,$$

Signal $\sigma \simeq 2.7$ fb

- at best one leptonic decay to get tens of events in 100/fb
- fully recontructible final state $\Rightarrow$ mass measurement
- other final states with mET can be considered ($Z \to \nu\bar{\nu}, W \to \ell\bar{\nu}$)

Backgrounds (AlpGen and Madgraph)

Process	specific cuts	σ
$(Z \to l^+l^-)6j$	—	1118(2) fb
$(Z \to l^+l^-)b\bar{b}4j$	$p_T^l > 10$ GeV	94(2) fb
$(Z \to l^+l^-)c\bar{c}4j$	$p_T^l > 10$ GeV	92(1) fb
$(Z \to l^+l^-)(t\bar{t} \to 6J)$	$\eta_l < 2.5, p_T^l > 10$ GeV	5.86(2) fb

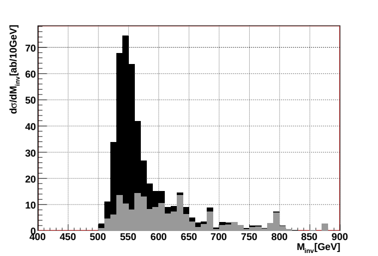
Process	σ
$H \to 6Jl^+l^-$	0.286(9) fb
$(Z \to l^-l^+)6j$	0.15(1) fb
$(Z \to l^-l^+)Q\bar{Q}4j$	0.032(5) fb
$(Z \to l^-l^+)(t\bar{t} \to 6J)$	0.022(1) fb

Analysis for $\mathcal{L} = 100/fb$

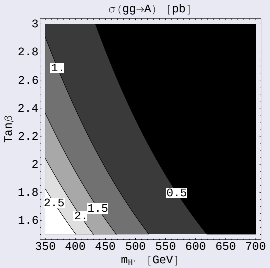
- run over the pairing of the jets
- require all the pairs within 8 GeV from the W or the Z
- make pairs with the leptons and the jets and with the jets only
- require two resonances within 33 GeV from the h mass

49 events instead of 20 in the SM

- at least 7 σ significance



the CP-odd: $gg \rightarrow A \rightarrow Zh \rightarrow 4j\ell\bar{\ell}$



$m_{H^+} = 500$ GeV, $\tan\beta = 2$

$m_A = 615$ GeV, $\Gamma_A = 11$ GeV, $\sigma \times \mathrm{BR} = 5.5$ fb

$$p_T^j > 20 \text{ GeV},\ p_T^l > 10 \text{ GeV},\ \eta^{j,l} < 2.5$$

$$\Delta R_{jj,lj,ll} > 0.4,\ 80 \text{ GeV} < m_{ll} < 100 \text{ GeV}$$

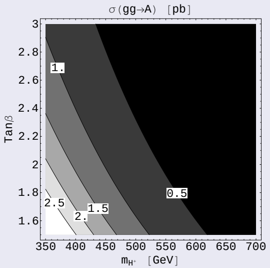
$\mathcal{L} = 100/fb$

- resonance structure reconstruction as in the case of H

the CP-odd: $gg \to A \to Zh \to 4j\ell\bar{\ell}$

$m_{H^+} = 500$ **GeV**, $\tan\beta = 2$

$m_A = 615$ GeV, $\Gamma_A = 11$ GeV, $\sigma \times \mathrm{BR} = 5.5$ fb



$$p_T^j > 20 \text{ GeV}, \; p_T^l > 10 \text{ GeV}, \; \eta^{j,l} < 2.5$$

$$\Delta R_{jj,lj,ll} > 0.4, \; 80 \text{ GeV} < m_{ll} < 100 \text{ GeV}$$

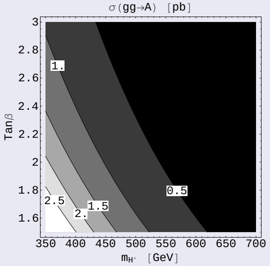
$\mathcal{L} = 100/fb$

Channel	σ
$A \to (Z \to l^+l^-)4J$	3.02(4) fb
$(Z \to l^+l^-)4J$	7.006(4) pb
$(Z \to l^+l^-)W2j$	176.0(8) fb
Sum of neglected	$\simeq$ 90 fb

the CP-odd: $gg \to A \to Zh \to 4j\ell\bar{\ell}$

$m_{H^+} = 500$ **GeV,** $\tan\beta = 2$

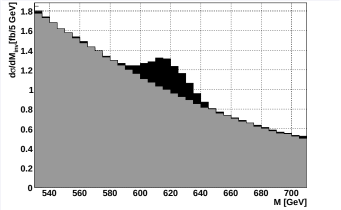
$m_A = 615$ GeV, $\Gamma_A = 11$ GeV, $\sigma \times \mathrm{BR} = 5.5$ fb



$$p_T^j > 20 \text{ GeV},\ p_T^l > 10 \text{ GeV},\ \eta^{j,l} < 2.5$$

$$\Delta R_{jj,lj,ll} > 0.4,\ 80 \text{ GeV} < m_{ll} < 100 \text{ GeV}$$

$\mathcal{L} = 100/fb$



Conclusions

λSUSY: the NMSSM with largish λ ($\lambda \gtrsim k > 1$)

- lightest Higgs around 200-300 GeV
- strong coupling onset in the Higgs sector at 10-100 TeV
- UV completions compatible with gauge coupling unification exist

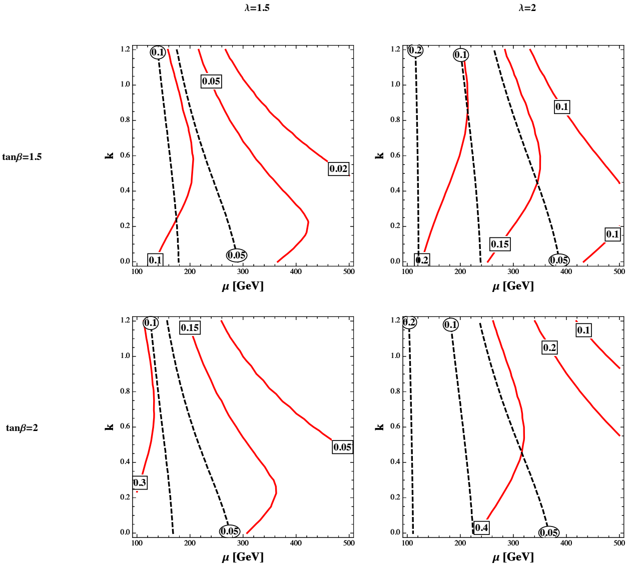
- mixed or unmixed singlet in the low energy theory
- $\lambda v \sim m_h$ is the only relevant scale of the model
- FT is low because $v \sim m_{soft}/\lambda$

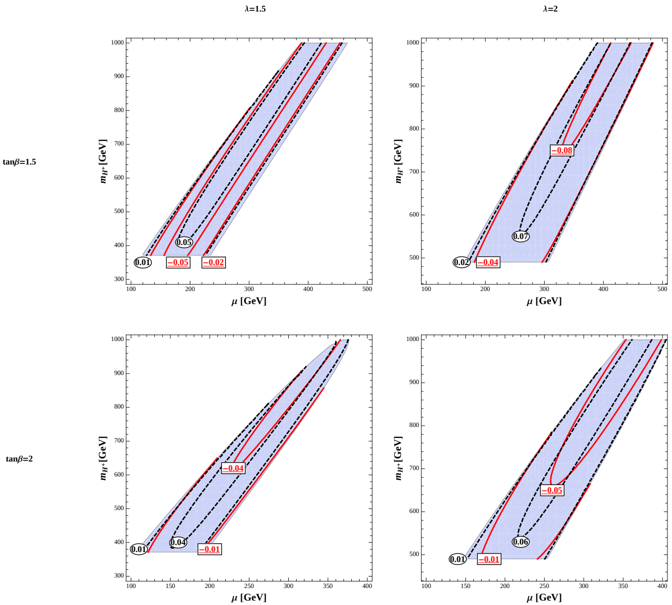
mixed singlet case

- dynamics for $\mu \sim m_h \sim \lambda v$
- reduced $gg \to h \to VV$ rate
- $h \to aa, aZ$ invisible decays
- larger SI cross-section on nuclei

unmixed singlet case

- SM-like Higgs boson
- $H \to hh \to 6j\ell\bar{\ell}$ with $\mathcal{L} \lesssim 100/fb$
- $A \to hZ \to 4j\ell\bar{\ell}$ with $\mathcal{L} \lesssim 100/fb$


λ=1.5
λ=2
tanβ=1.5
tanβ=2
k
μ [GeV]
0.1
0.05
0.02
0.2
0.15
0.3
0.4



λ=1.5
λ=2
tanβ=1.5
tanβ=2
m_{H+} [GeV]
μ [GeV]
0.01
0.05
−0.05
−0.02
0.02
0.07
−0.04
−0.08
0.04
−0.01
0.06
−0.05

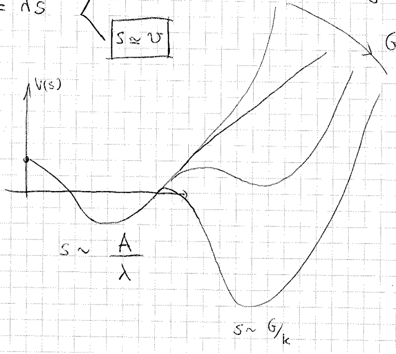
$\lambda \gtrsim 1$

$k \simeq 1$

$$W = \lambda H_u H_d S + \frac{k}{3} S^3$$

$$V = m_1^2 |H_u|^2 + m_2^2 |H_d|^2 + \mu_s^2 |S|^2 - \left(A \lambda H_u H_d S + \frac{k}{3} G S^3 + h.c. \right)$$
$$+ k^2 |S^2|^2 + \lambda^2 |H_u H_d|^2 + \lambda^2 \left(|H_u S|^2 + |H_d S|^2 \right) + \lambda k \left(S^2 H_u H_d + h.c. \right)$$
$$+ \text{D-terms}$$

$\mu = \lambda s$
- $s \gg v$ pert. NMSSM $\Rightarrow$ large μ $\Rightarrow$ FT
- $s \simeq v$

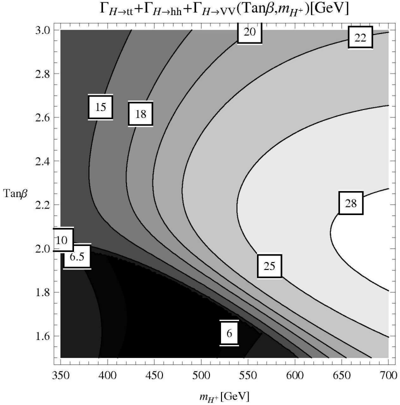


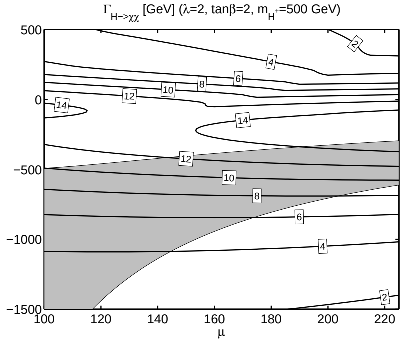
upper bound on G

$$\frac{G}{A} < \frac{\lambda}{k}$$

$$A \gtrsim \lambda v$$

$$A G > \lambda^2 v^2$$


ΓH→tt+ΓH→hh+ΓH→VV(Tanβ,mH+)[GeV]
Tanβ
mH+[GeV]
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
350
400
450
500
550
600
650
700
20
22
15
18
28
10
6.5
25
6


ΓH->χχ [GeV] (λ=2, tanβ=2, mH+=500 GeV)
M
μ
500
0
−500
−1000
−1500
100
120
140
160
180
200
220
2
4
6
8
10
12
14
14
12
10
8
6
4
2