# The $\mu$ problem
# &
# a non standard Higgs spectrum

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# Outline

**Main topics**

- Susy = light Higgs boson? The NMSSM with large $\lambda$
- The generation of the $\mu$ term (scale invariant superpotential)

- Experimental constraints
  - LEP bounds
  - EWPTs
  - DM direct detection
- The naturalness of the theory
- Higgs signatures at the LHC
- Conclusions & Outlook

Based on
R. Franceschini and S. Gori
"Solving the $\mu$ problem with a heavy Higgs boson"
**JHEP 1105:084,2011** [arXiv: 1005.1070]

# Susy = light Higgs boson?

## In the MSSM

- At the one loop

$$m_h^2 \leq m_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2} y_t^4 v^2 \sin^4 \beta \log \left( \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} \right)$$

- The MSSM is SM like in most part of the parameter space

⇨ LEP bound: $m_h \geq 114.4\,\text{GeV}$

Necessity of rather heavy stops!

**Fine tuning!**

( since the stops contribute at one loop also to $m_Z$ )

"Susy little hierarchy problem"

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## In the NMSSM

- At the one loop

$$m_h^2 \leq m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \frac{3}{4\pi^2} y_t^4 v^2 \sin^4\beta \log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$$

- If $\lambda$ is **perturbative** until $M_{GUT}$, we can gain only ~ **20 GeV** if compared to the MSSM

## What if we take large $\lambda$?

- **Effective field theory valid up to tens of TeV** (above which, one or more Higgs reveals its composite nature)

Barbieri, Hall, Nomura, Rychkov – PRD 75

- It can be still **compatible** with the **unification** of the gauge couplings

(Harnik, Kribs, Larson, Murayama - PRD 70, Chang, Kilic, Mahbubani -PRD 71, Birkedal, Chacko, Nomura - PRD 71)

# The model

## A particular fat Higgs model

Low energy effective field theory:

$$W = \lambda S H_1 \cdot H_2 + \frac{k}{3} S^3$$

$$\begin{aligned} V_{soft} &= m_1^2 |H_1|^2 + m_2^2 |H_2|^2 + \mu_S^2 |S|^2 - (A\lambda S H_1 H_2 + G\frac{k}{3} S^3 + h.c.) \\ &+ \frac{1}{8} g_1^2 (|H_2|^2 - |H_1|^2)^2 + \frac{1}{8} g_2^2 \left(H_1^\dagger T^i H_1 + H_2^\dagger T^i H_2\right)^2 \end{aligned}$$

λ perturbative until ~O(10 TeV)

**No dimensionfull parameters in the superpotential**

### The $\mu$ problem

$\mu = \lambda \langle S \rangle$

If λ is large, is μ still at (or just above) the EW scale?

### Free parameters

$$\lambda,\ k,\ A,\ G,\ \underbrace{m_1^2,\ m_2^2,\ \mu_S^2}$$

Traded for $\tan\beta,\ \mu,\ v$, thanks to the minimization conditions

# The mass of the lightest Higgs boson

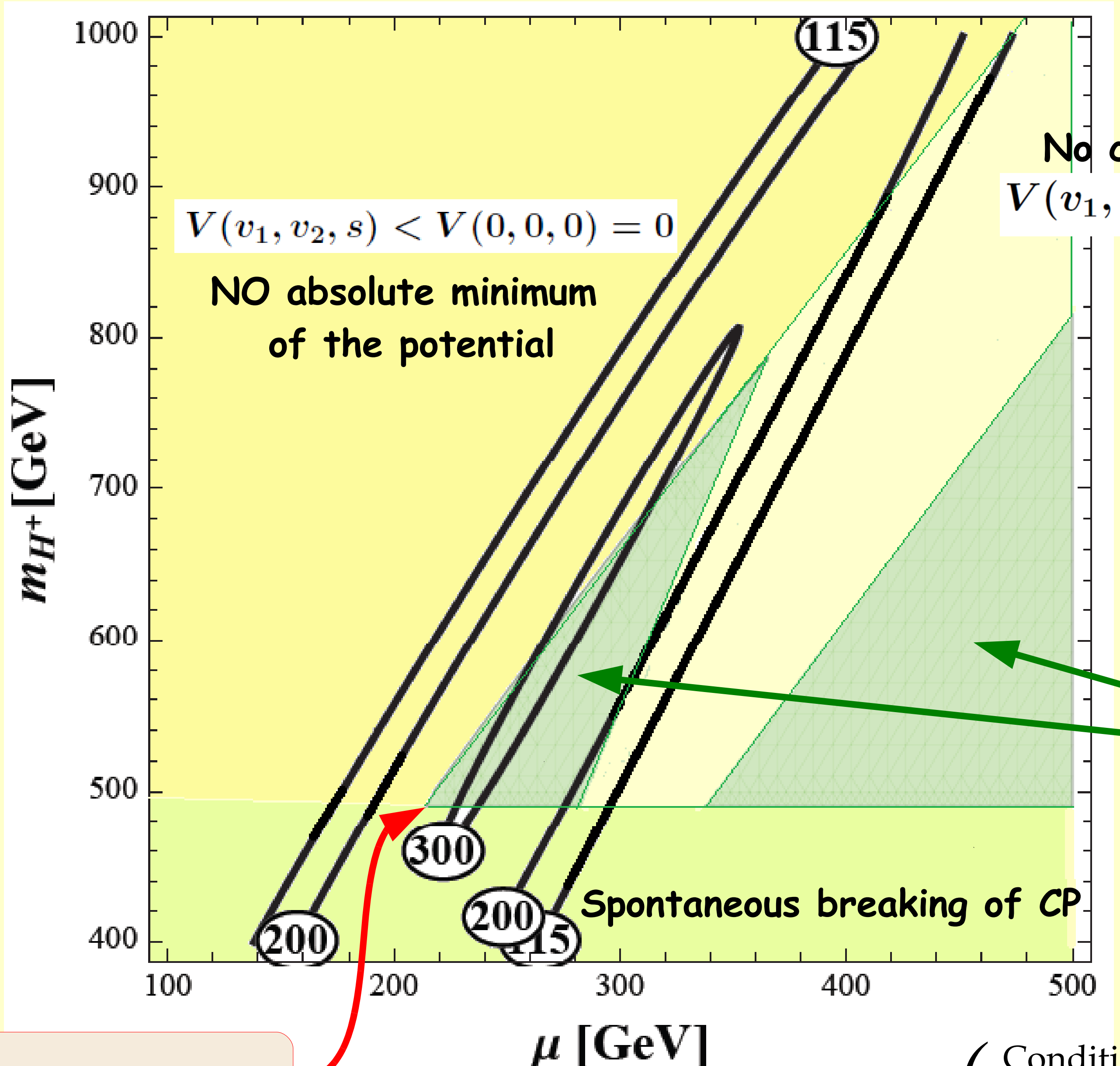
$\lambda = 2$

$k = 1.2$

$\tan\beta = 1.5$

Assuming
G=A

(large differences are not possible by the constraints on the potential)




Kanehata, T. Kobayashi, Y. Konishi, O. Seto, T. Shimomura arXiv:1103.5109

Minimum allowed value for μ

( Condition of conservation of EM is automatically satisfied )

# Generation of the μ term

$\mu = \lambda\, s$

**Is it constrained to be at around the EW scale by the conditions we have to impose to the scalar potential?**

- $V(v_1, v_2, s) < V(0,0,0) = 0$ and absence of spontaneous CP breaking. In the **large λ limit:**

$$\mu^2 \gtrsim \frac{\lambda^2 v^2}{2} \sin^2 2\beta - \frac{m_Z^2}{4} \cos^2 2\beta$$

- The absence of a tachionic Higgs and $V(v_1, v_2, s) < V(0,0,0) = 0$ in the large λ limit and for $k < \lambda$

$$\mu \lesssim \frac{v\lambda \sin 2\beta}{2} \frac{3(\rho-4)\rho + \sqrt{8(\rho-1)(5\rho-7)} + 9}{(\rho-5)(\rho-1)} \simeq \frac{3}{2} v\lambda \sin 2\beta + O(\rho)\, v\lambda$$

$\rho = k/\lambda$

**The mass of the chargino is rather constrained**

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

Where $\lambda v$ is the scale of the lightest Higgs mass

**Note:**

$\lambda \longrightarrow \infty$

$\mu \longrightarrow A \sin(2\beta)/2$

**μ is just above the EW scale**

Large λ

Higgs and chargino not seen at LEP

# Experimental constraints (1)

Is this theory viable in spite of the several experimental constraints?

- LEP bounds on Higgs, chargino and neutralino masses

Not strong constraints after having ensured that the Higgs is not tachionic

The lightest neutralino is massless for

$$\mu^2 = \frac{\lambda}{k}\frac{v^2\lambda^2 \sin 2\beta}{2}$$

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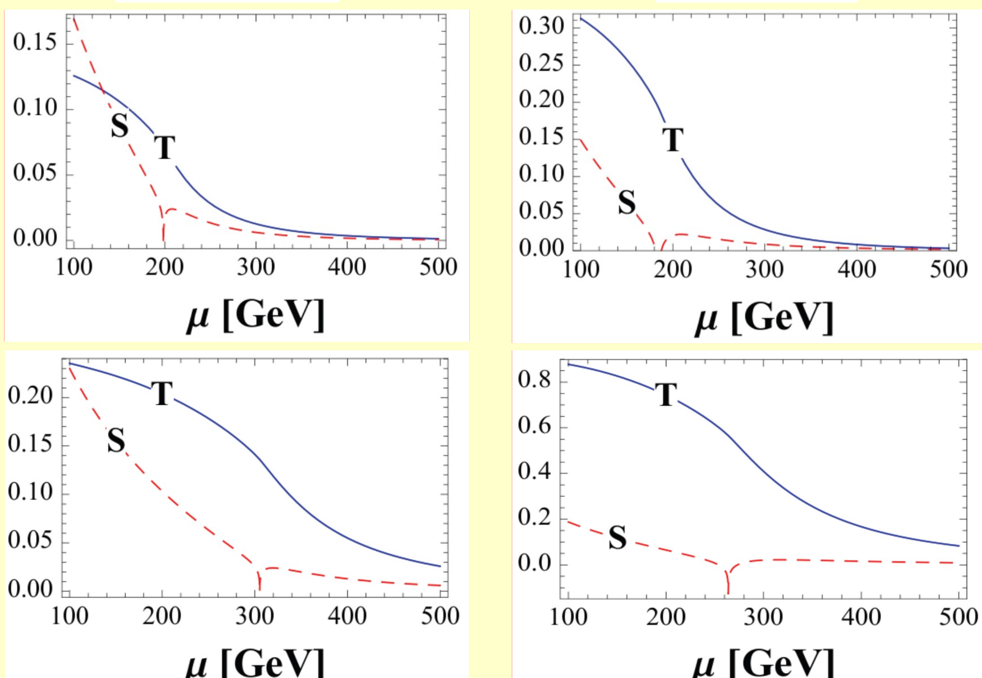
- EWPTs: main contribution to the T parameter is due to the Neutralinos

$\tan\beta = 1.5$ $\tan\beta = 2$

$\lambda = 1.5$

$\lambda = 2$




k = 1.2

perturbative until ~ 10TeV

**Preference for smaller values of tanβ and λ**

(We assume gauginos quite heavier than Higgsinos)

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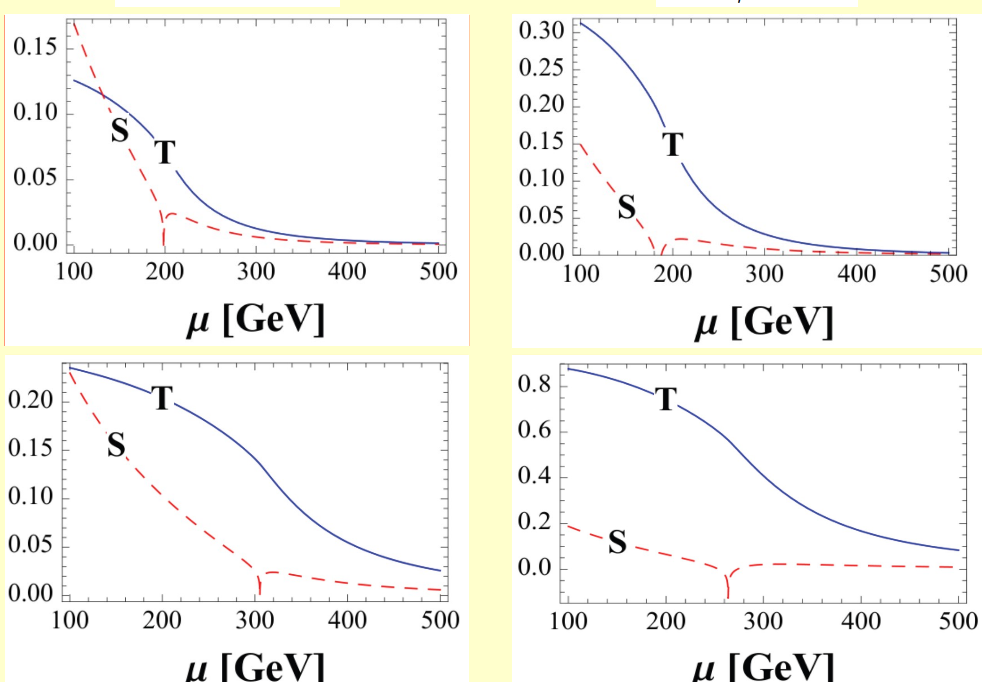
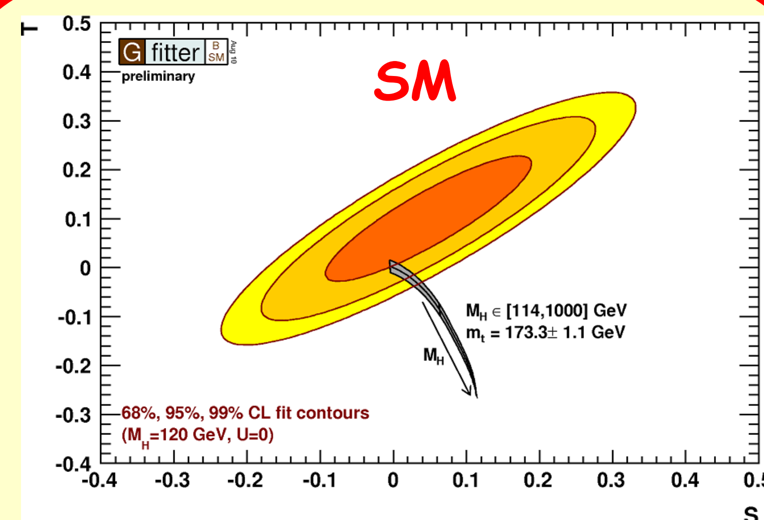


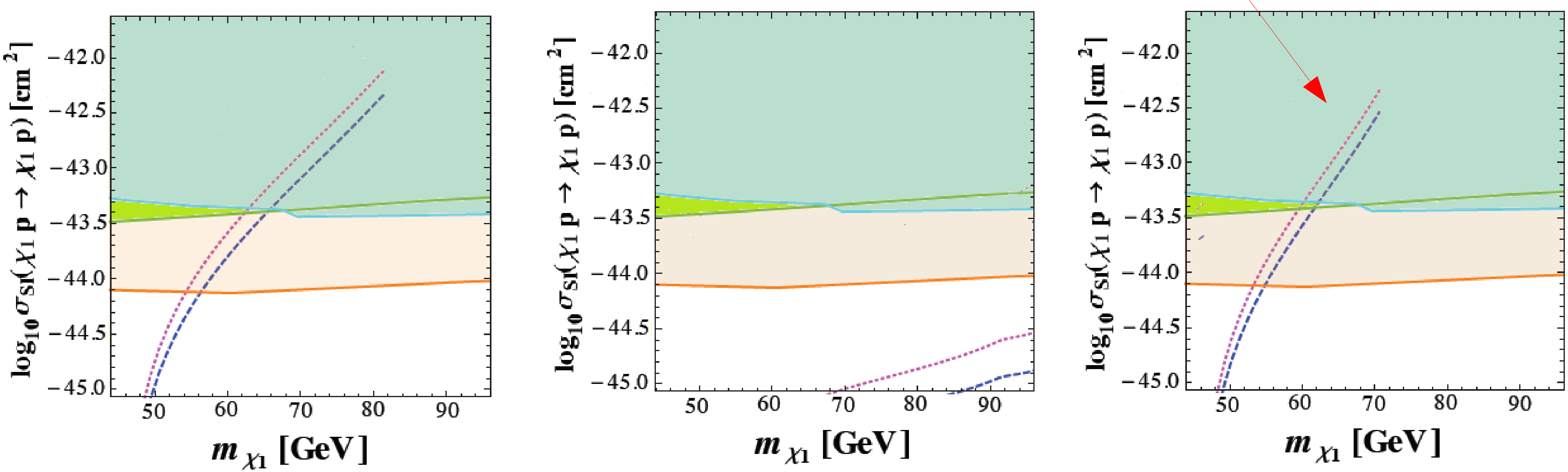




In spite of a large Higgs mass, the theory can be consistent with EWPTs because of the positive NP contributions to T

# Experimental constraints (2)

- Dark matter direct detection experiments

Computed using two different values for the quark form factors
(from chiral perturbation theory(arXiv:0801.3656),
or from QCD on the lattice(arXiv:0907.4177))



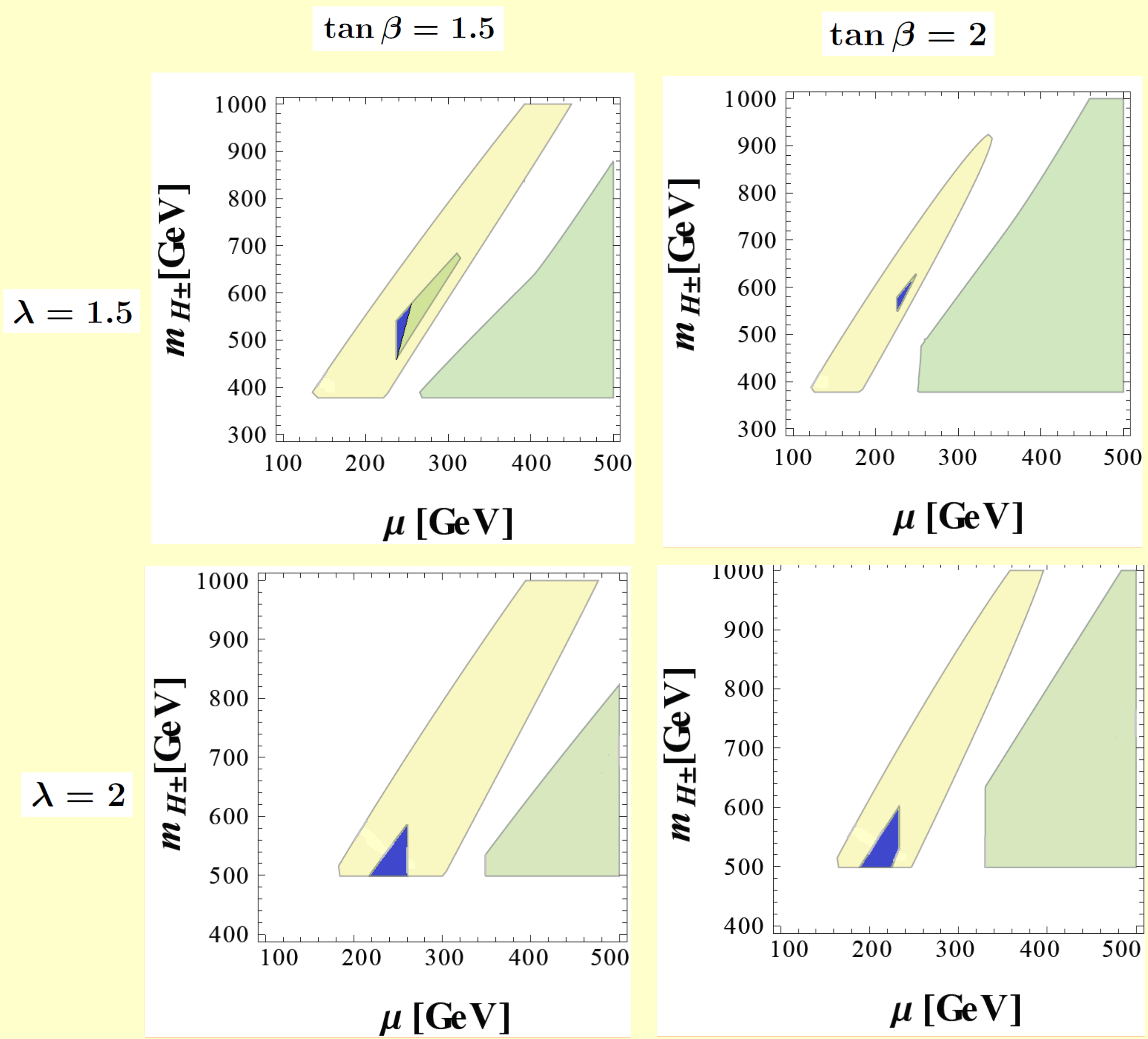

$m_{H^\pm} = 500$ GeV, $\lambda = 1.5$ — $m_{H^\pm} = 550$ GeV, $\lambda = 2$ — $m_{H^\pm} = 700$ GeV, $\lambda = 2$

CDMS-II Science 327 (2010) 1619-1621
Xenon100: Phys. Rev. Lett. 100, 021303 (2008)
Xenon100: Phys.Rev.Lett. (2011)

- Large values of $\lambda$ and small values of the charged Higgs mass are favored
- A large $m_{\chi_1}$ is typically excluded

**Both in the case of large/small Higgs mass μ~(200-300) GeV is favored**

# Summary of the constraints




k = 1.2
to have in general smaller contributions to the T parameter

- Correct EWSB;
- LEP bounds;
- EWPTs;
- DM direct detection

**In blue the allowed region**

Ranges for the mass of chargino and of the charged Higgs boson are rather limited

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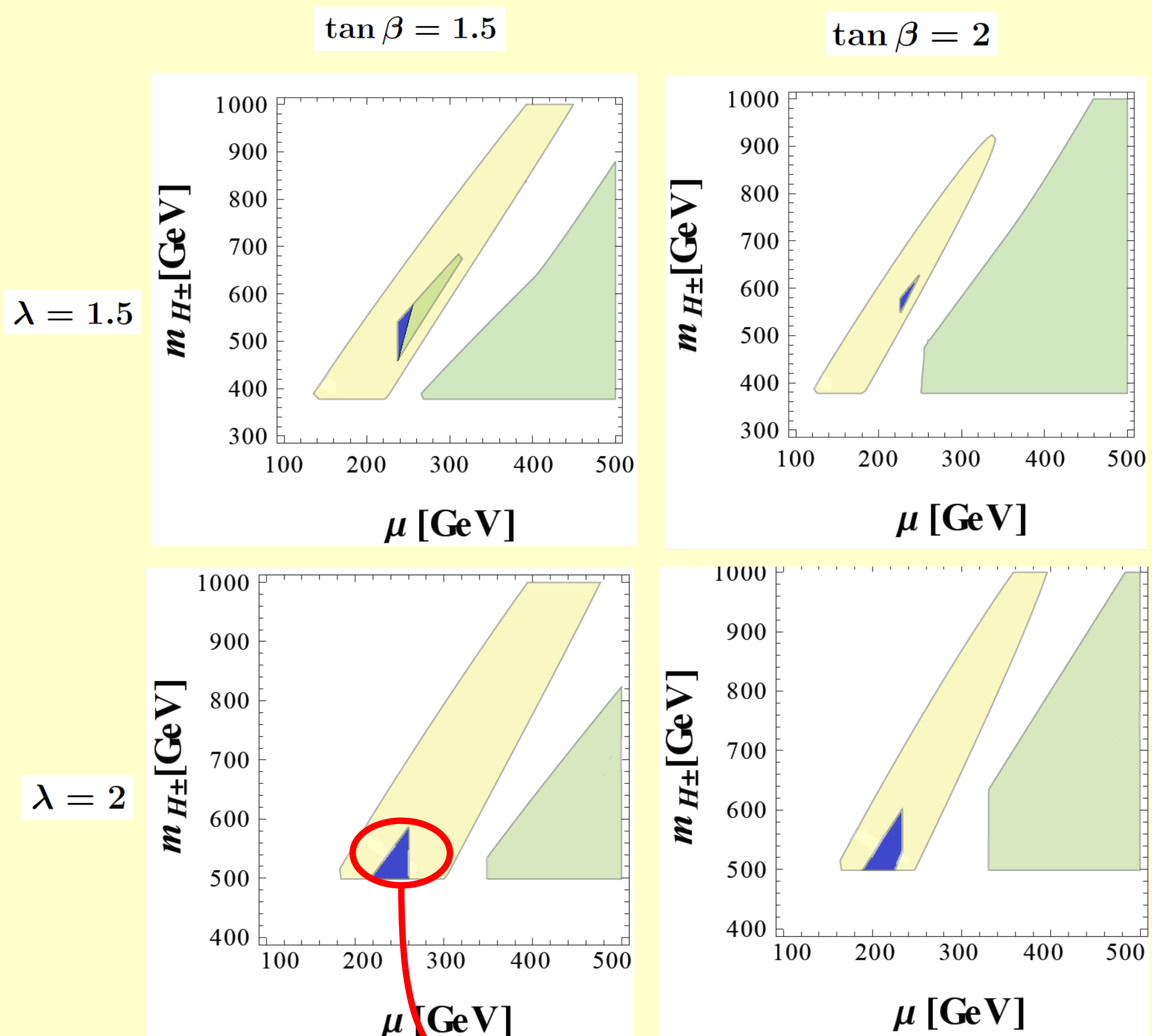


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Here we will do our analysis

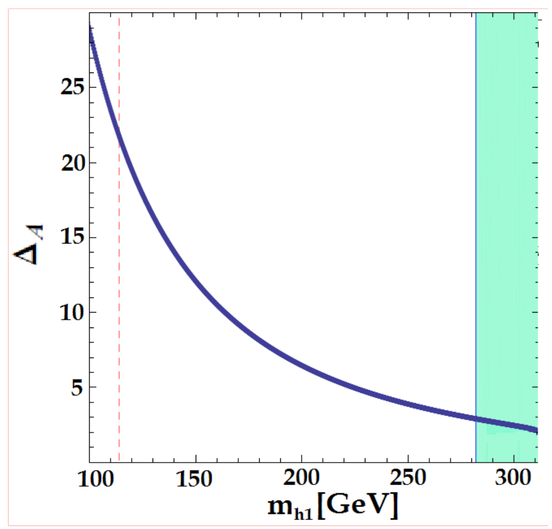
# Naturalness and heavy sparticles

- In a generic theory the EW scale depends on several dimensionful parameters $v^2 = v^2(a_j)$
- For small variations of these parameters it is natural to have also small variations of the EW scale
- Definition of fine tuning $\Delta_{ai}$

$$\boxed{\Delta_{a_j} \equiv \left| \frac{a_j^2}{v^2} \frac{d\, v^2(a_i)}{d\, a_j^2} \right|}$$

Barbieri, Giudice, Nucl.Phys.B306

- In our theory, we have to compute the fine tuning with respect to ($\mu_S$,$m_1$,$m_2$,G,A)
- Only the latter is relevant:




Theory is much less tuned for a heavy Higgs boson

- Heavy squarks are allowed (but not required) with a moderate level of fine tuning:

$$\Delta = \left| \frac{m_{\tilde{Q}}^2}{v^2} \frac{d\, v^2}{d\, m_{\tilde{Q}}^2} \right| \sim \left| \frac{m_{\tilde{Q}}^2}{v^2} \frac{d\, v^2}{d\, m_2^2} \frac{d\, m_2^2}{d\, m_{\tilde{Q}}^2} \right| \Rightarrow \Delta \sim \frac{m_{\tilde{Q}}^2}{v^2} \frac{3 \log^2 \frac{\Lambda_{\rm mess}}{\rm TeV}}{4\pi^2 \sin^2\beta} \frac{dv^2}{dm_2^2}$$

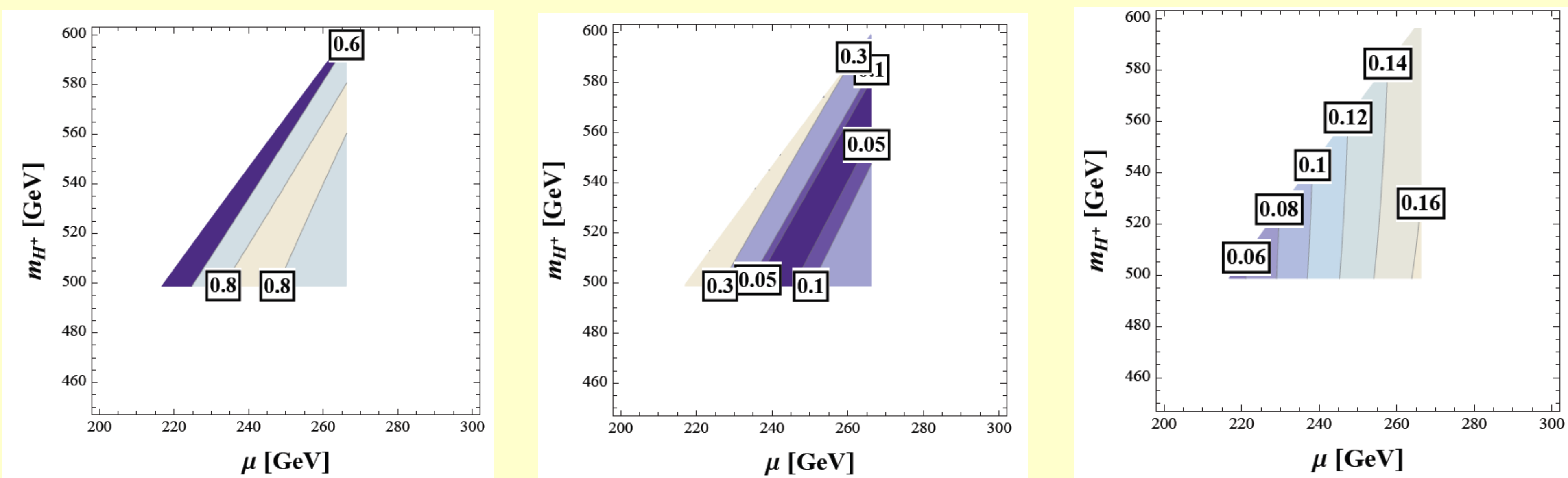
Not huge dependence for large values of λ

# Production of the Higgs bosons at the LHC

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

## 1.Gluon gluon fusion

Reduced couplings squared with up-type quarks:




$h_1$ $h_2$ $h_3$

Significantly coupled

The two heavier states are sufficiently coupled

Possibility of producing at the LHC all the three Higgs bosons through gluon gluon fusion

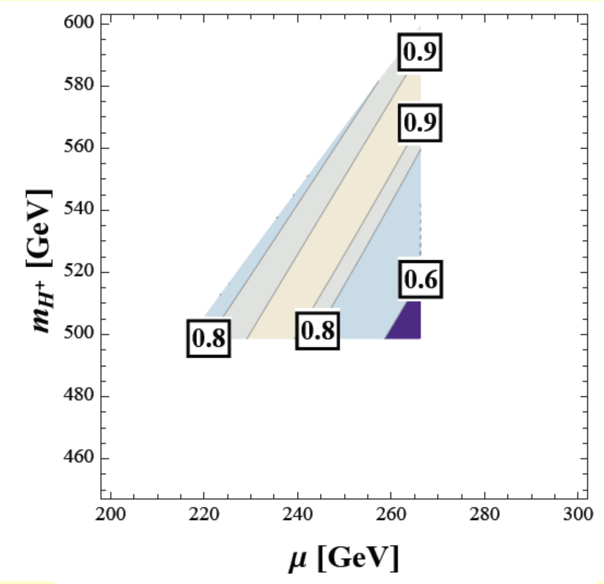
$\lambda = 2$

$k = 1.2$

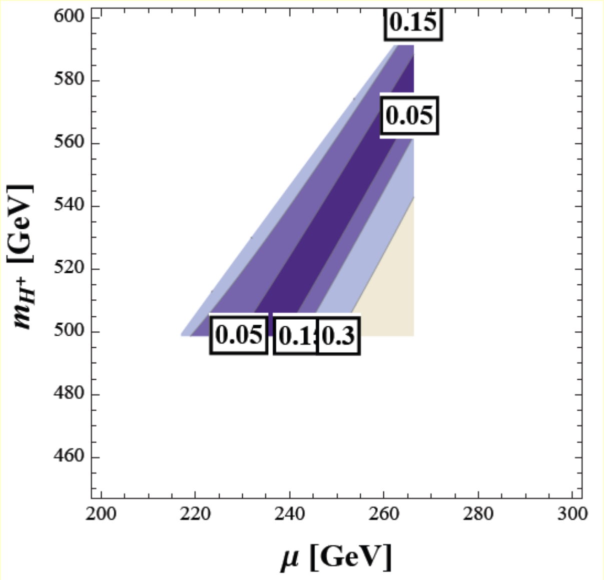
$\tan\beta = 1.5$

## 2.Vector boson fusion

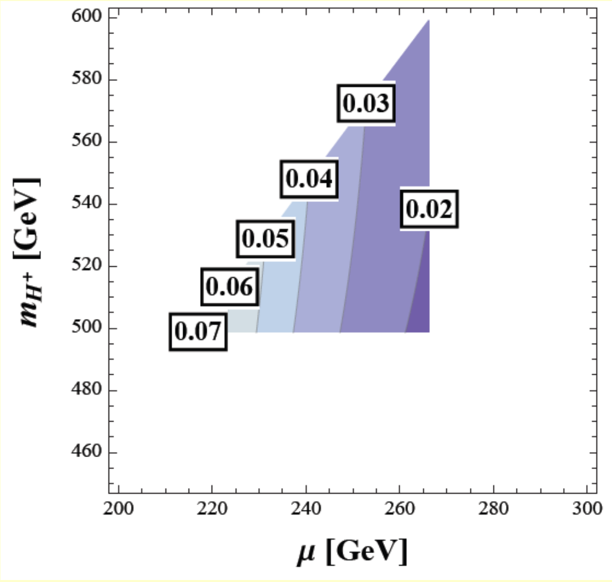
Reduced couplings squared with gauge bosons:




h$_1$




h$_2$




h$_3$

Significantly coupled

The heaviest state is rather decoupled

Difficulty of producing the heaviest Higgs boson at the LHC through vector boson fusion

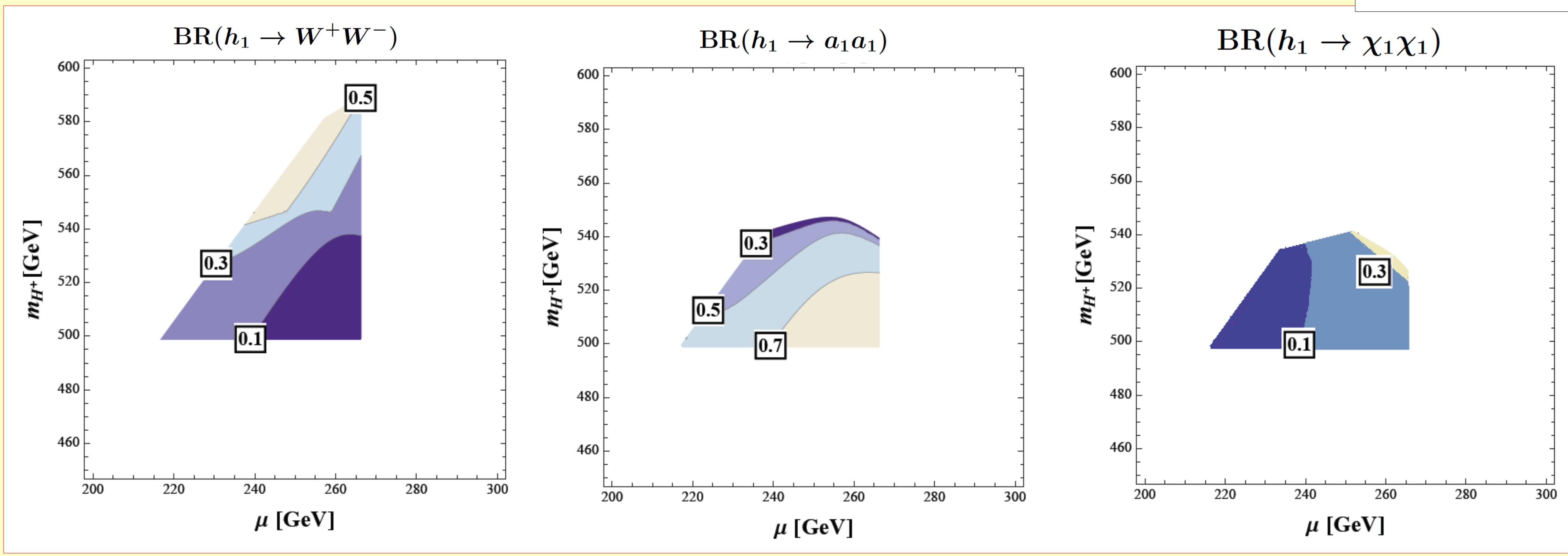
# Decays of the lightest Higgs boson

$\lambda = 2$

$k = 1.2$

$\tan\beta = 1.5$

**Three main decay modes:**

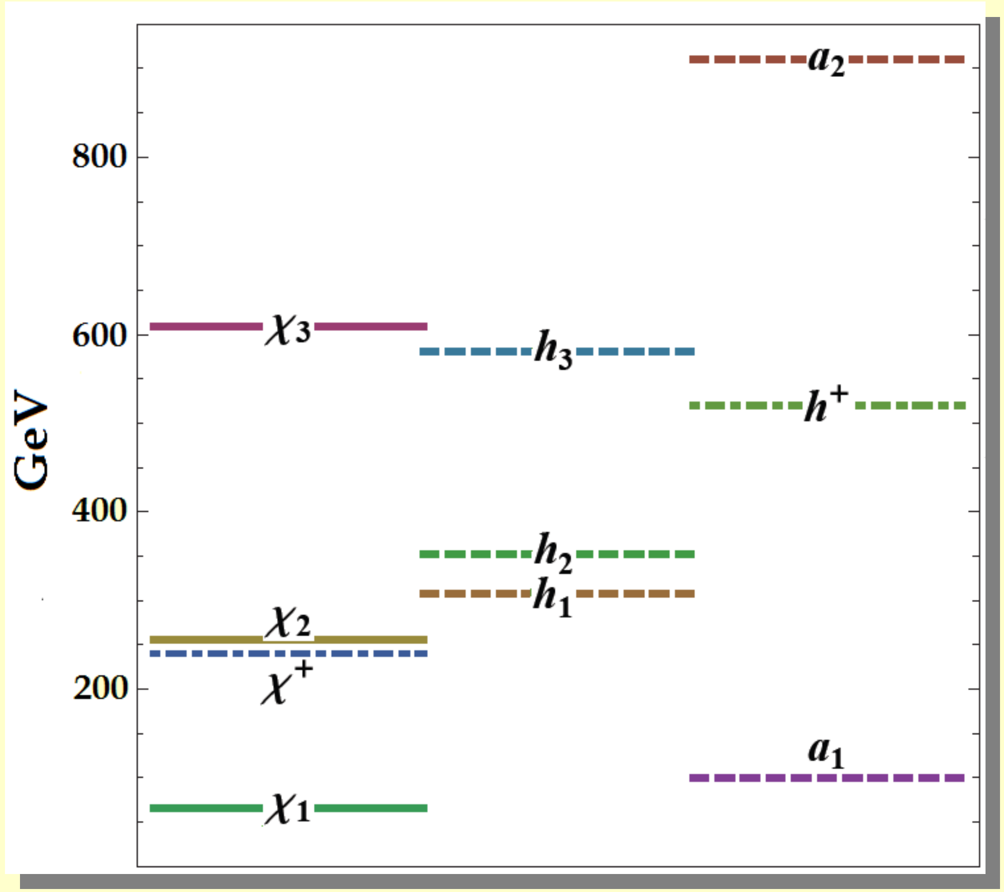



- Rather reduced decay of the Higgs into WW ⇨ Higgs not found at the LHC yet.
- Higgs could be observed earlier in the non-SM decay $h \to a_1 a_1 \to \tau\bar{\tau}b\bar{b}$
  Still not for a early LHC
- A large fraction of Higgs bosons decay invisibly into two LSPs

# A benchmark point

**A typical configuration:**

$$\lambda = 2$$
$$k = 1.2$$
$$\tan\beta = 1.5$$
$$\mu = 240\ \text{GeV}$$
$$m_{H^+} = 520\ \text{GeV}$$




| | $ZZ$ | $WW$ | $t\bar{t}$ | $\chi_1\chi_1$ | $\chi_1\chi_2$ | $a_1 Z$ | $a_1 a_1$ | $\Gamma$ [GeV] |
|---|---|---|---|---|---|---|---|---|
| $h_1$ | 0.088 | 0.196 | 0 | 0.090 | 0 | 0.059 | 0.568 | 30.3 |
| $h_2$ | 0.004 | 0.008 | 0.002 | 0.179 | 0.027 | 0.001 | 0.782 | 33.6 |
| $h_3$ | 0.023 | 0.047 | 0.039 | 0.461 | 0.013 | 0.165 | 0.255 | 48.2 |

# Conclusions

What

**Scale invariant NMSSM as an effective field theory valid up to ~10 TeV**

Main Consequences

- It raises dramatically the mass of the lightest Higgs boson: **$M_{h1}$ ~ (200-300) GeV**
- It generates a μ term that scales as the lightest Higgs mass (it addresses naturally the **μ problem**)

- In spite of the large Higgs mass, EWPTs can be easily satisfied

Predictions

Predictions in the region of parameter space allowed by the experiments (LEP, EWPTs, DM direct detection)

- Lightest chargino rather close in mass to the lightest Higgs boson
- Lightest neutralino with a mass smaller than ~100 GeV
- Lightest Higgs boson mainly decaying into two pseudoscalars $h \to a_1 a_1 \to \tau\bar{\tau}b\bar{b}$

- Possibility of discovery the heavier Higgs bosons produced through gluon gluon fusion

**Outlook**: detailed study of the collider signature of the model

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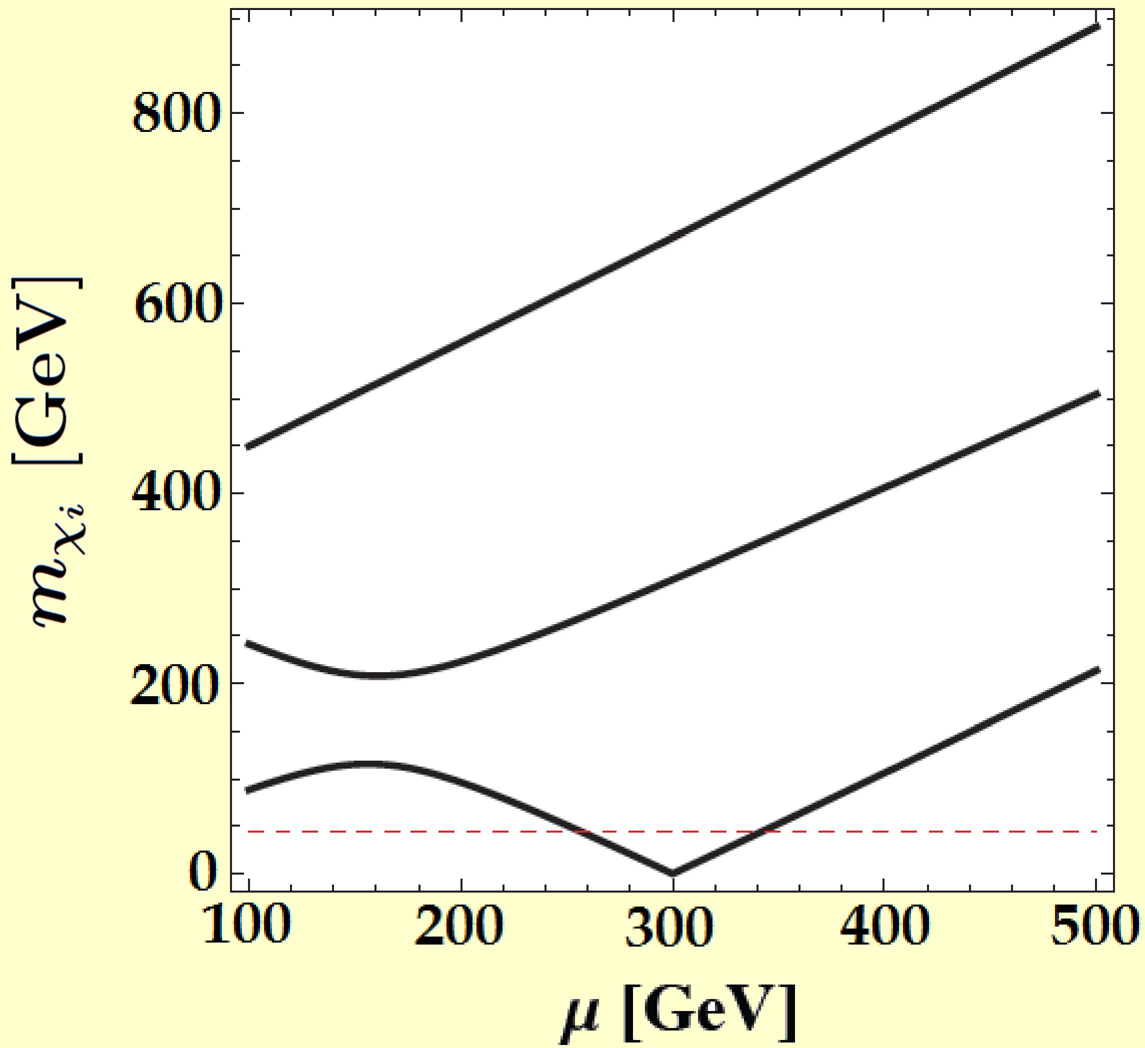
$\tan\beta = 1.5$



# Backup (2)

$k = 1.2$
$\lambda = 1.5$

$k = 1.2$
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