# *Plan* (in logical order)

*0. Introduction and preliminaries* (0)

*1. Higgsless: a "conservative" view* (1)

*2. The "naturalness" problem of the Fermi scale*

a. Supersymmetry (4)

b. Goldstone symmetry

c. Gauge symmetry in extraD ↕ (2)

*3. Dark Matter* (3)

*4. The Planck/Fermi hierarchy ⇔ extraD*

(No flavour for reasons of time)
Bs mixing and decays

# *Dark matter*

1. *Why at LHC: a numerical coincidence*
2. *Illustrative model 1*
3. *Illustrative model 2*

# Dark matter: a numerical coincidence

*Suppose you have a stable particle $\chi$*
*that decouples from the hot primordial plasma by $\chi\chi \to ff$*
*with a cross section σ. Then, for its relic density Ω*

$$\Omega h^2 = \frac{688\pi^{5/2} T_\gamma^3 (n+1) x_f^{n+1}}{99\sqrt{5g_*}(H_0/h)^2 M_{\rm Pl}^3 \sigma} \approx 0.2\frac{pb}{\sigma}$$ ⇐

*and $\sigma \approx pb$ is a typical weak interaction cross section*
*for a particle of mass* $m_\chi \approx G_F^{-1/2}$

*against the observed* $\Omega_{\rm DM} h^2 = 0.113 \pm 0.009$ ⇐

# 2 minimal illustrative models

*(unlike the susy case)*

# 1. A scalar-doublet model ("inert")

$$V = -\mu_1^2 H_1^\dagger H_1 + \mu_2^2 H_2^\dagger H_2 + \text{quartics}$$

For natural flavor conservation impose

$H_2 \to -H_2$

Only $H_1$ couples to matter

$$H_2 = \begin{pmatrix} H^+ \\ H + iA \end{pmatrix}$$

is "inert"

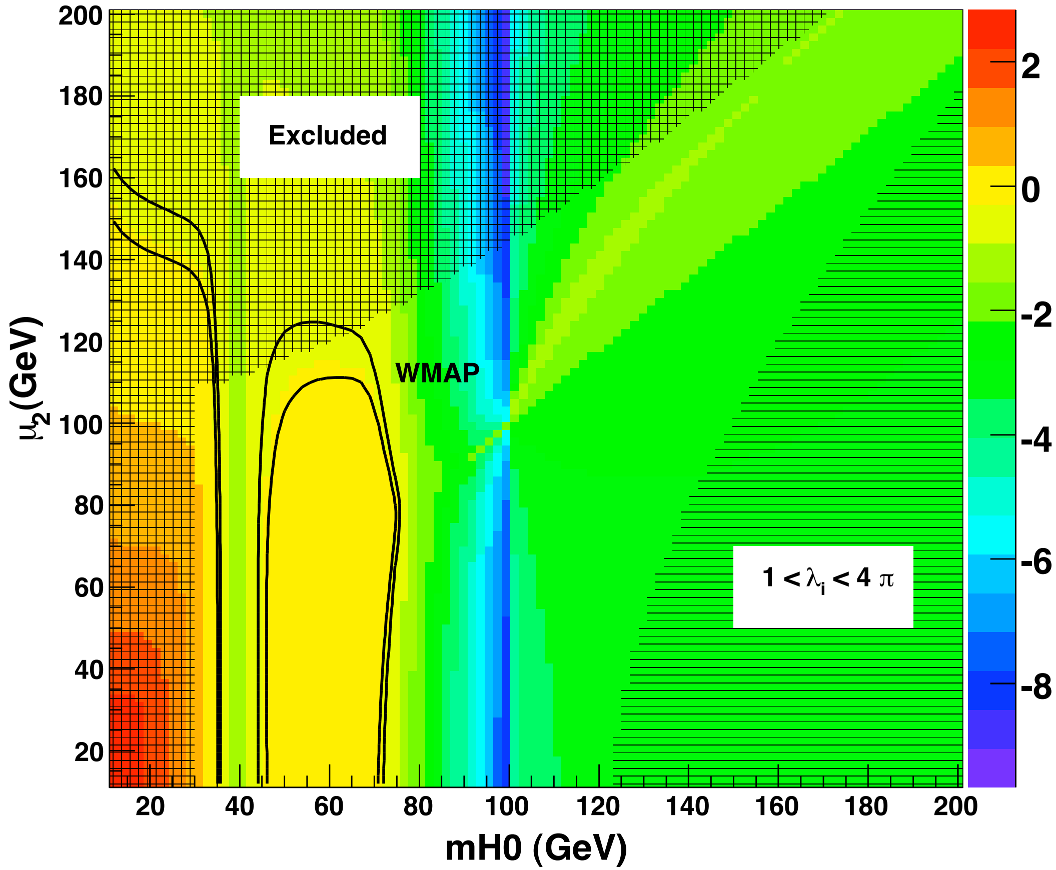
$v_2 = 0$

This is not the usual phase in the fine-tuned limit of $v_2 \ll v_1$

1. $H_1 = \begin{pmatrix} 0 \\ v + h \end{pmatrix}$ similar to SM Higgs
2. $H_2$ mass splittings lead to $\Delta T > 0$ *controlled by approximate* $SU(2)_V$
3. $H_2 \to -H_2$ is exact, and not spontaneously broken

Lightest Inert Particle (LIP) is stable and could be Dark Matter

$$\log_{10}(\Omega_M h^2)$$




Shouldn't one have seen S and A at LEP2 via

$$e^+e^- \to A + S \to (Z^* + S) + S \qquad \sigma \approx 0.1\ pb$$

What about direct DM detection

$$\sigma_h(\mathrm{L}p \to \mathrm{L}p) \approx 2 \times 10^{-9}\,\mathrm{pb}\ \left(\frac{\lambda_L}{0.5}\right)^2 \left(\frac{70\,\mathrm{GeV}}{m_L}\right)^2 \left(\frac{500\,\mathrm{GeV}}{m_h}\right)^4$$

currently $\sigma_h < 10^{-7} \div 10^{-8}\ pb$

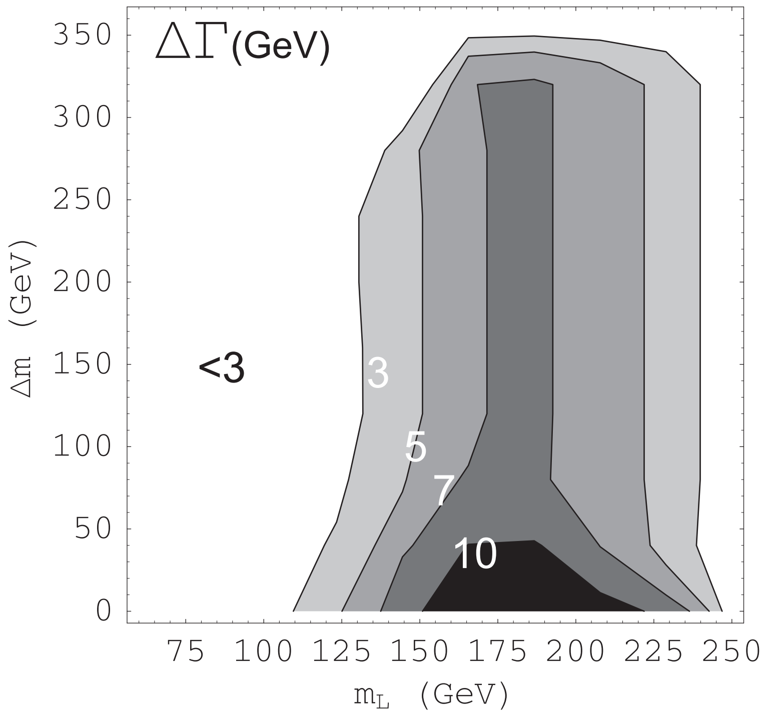
# Collider Signals (not easy)

1. $m_h = 400 \div 600\ GeV$

A standard Higgs boson?

$$h \to SS, AA, H^+H^-$$

$$\Gamma_h = 68\ GeV \quad \text{at} \quad m_h = 500\ GeV$$




2. $pp \to W^* \to HA$ or $HS$

$$H \to AW \text{ or } SW$$
$$A \to SZ^{(*)}$$

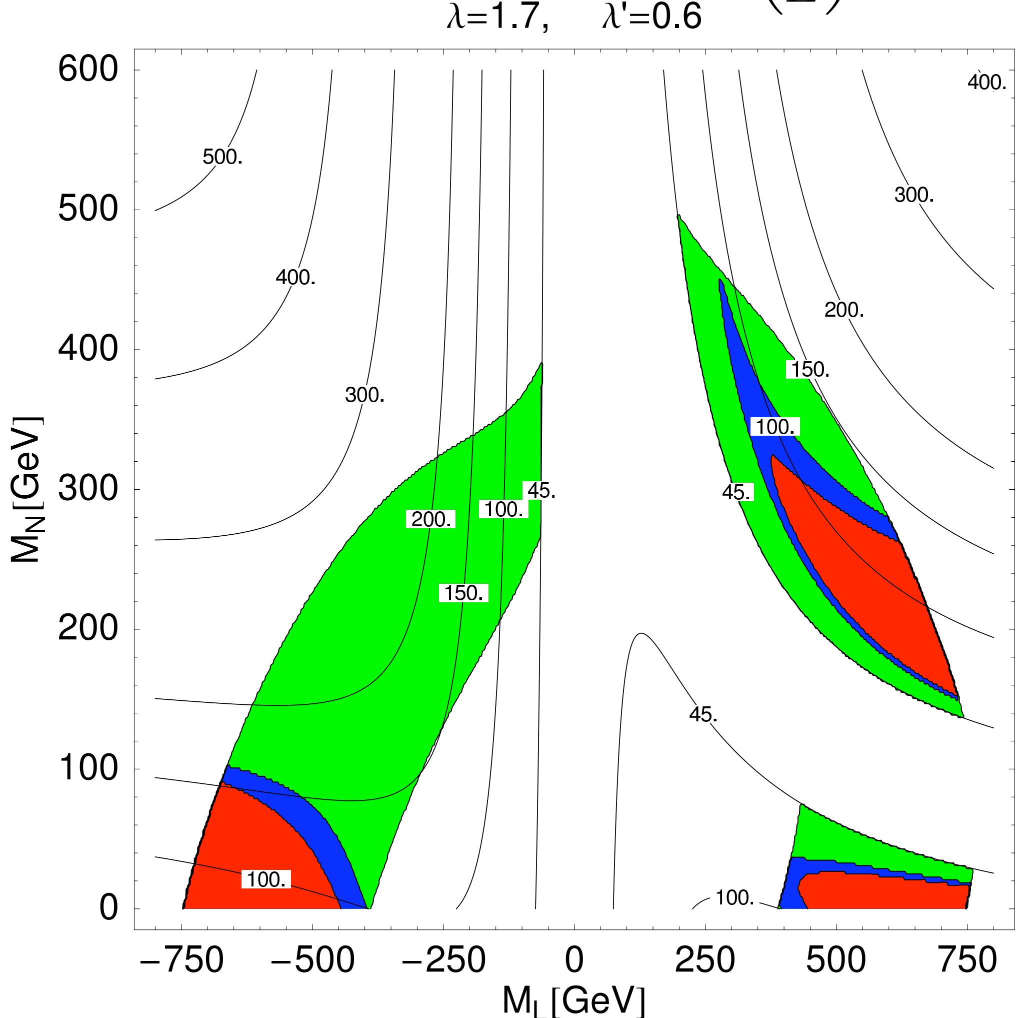
for the DM parameters, looking for 3 charged leptons

$\sigma_{signal} \approx 3.5$ fb $\qquad \sigma_{bg} \approx 20$ fb

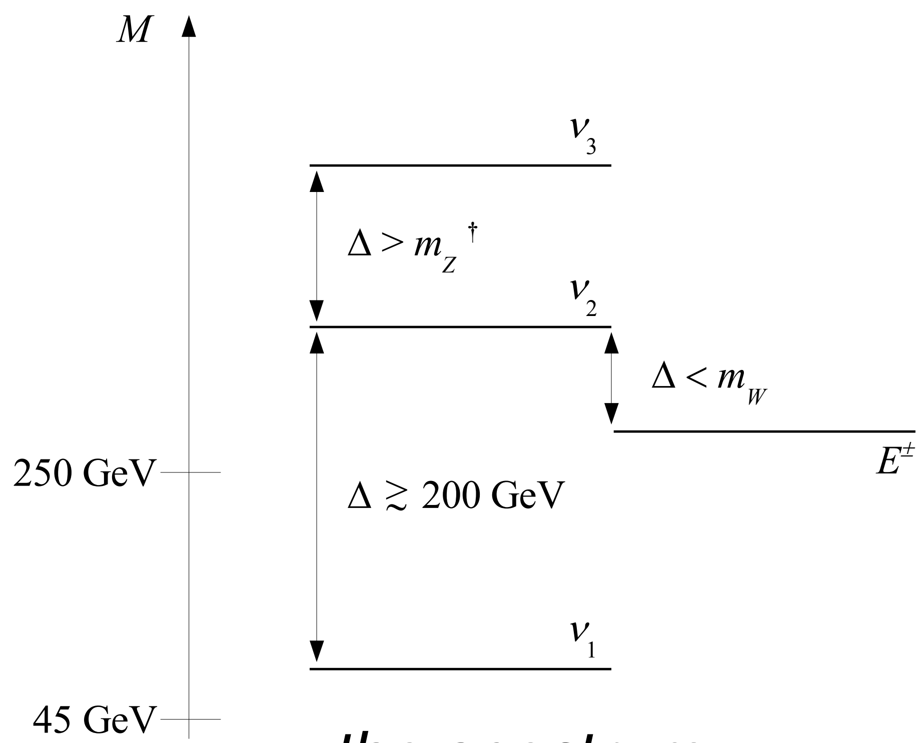
# 2 A neutrino-type model

$$\Delta\mathcal{L} = -\lambda LHN - \lambda' L^c \tilde{H} N + M_L L L^c + \frac{1}{2} M_N N^2 + h.c.$$

$$L = \begin{pmatrix} \nu \\ E \end{pmatrix}, \quad L^c = \begin{pmatrix} E^c \\ \nu^c \end{pmatrix}$$

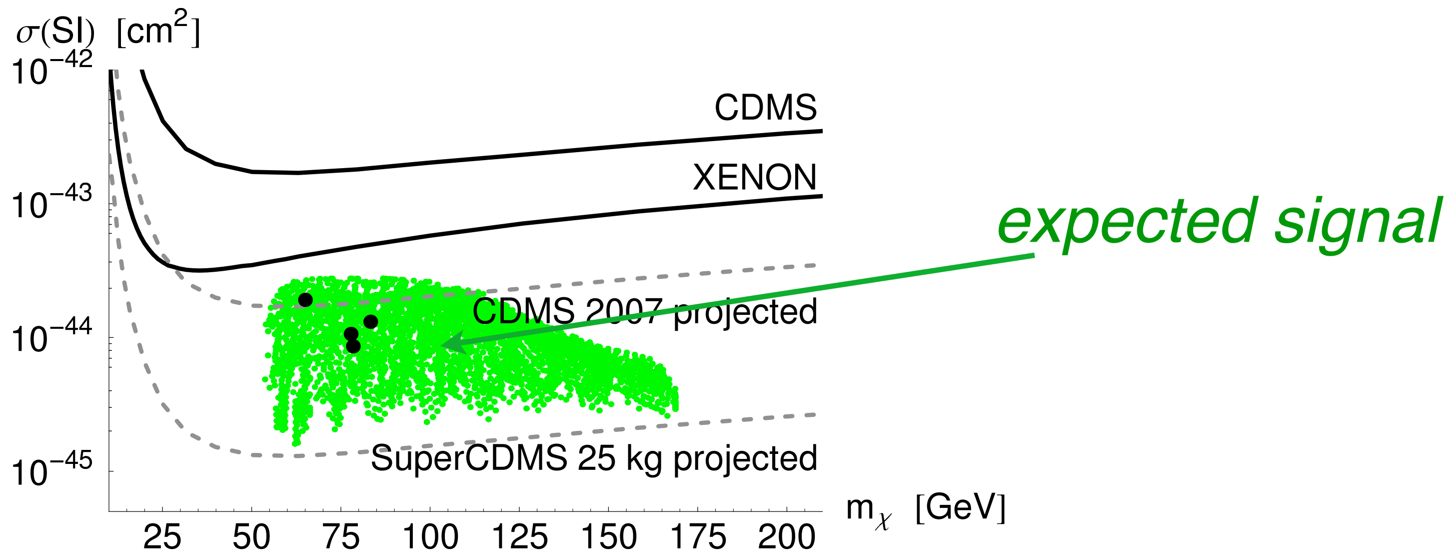



blue is the desired Ω

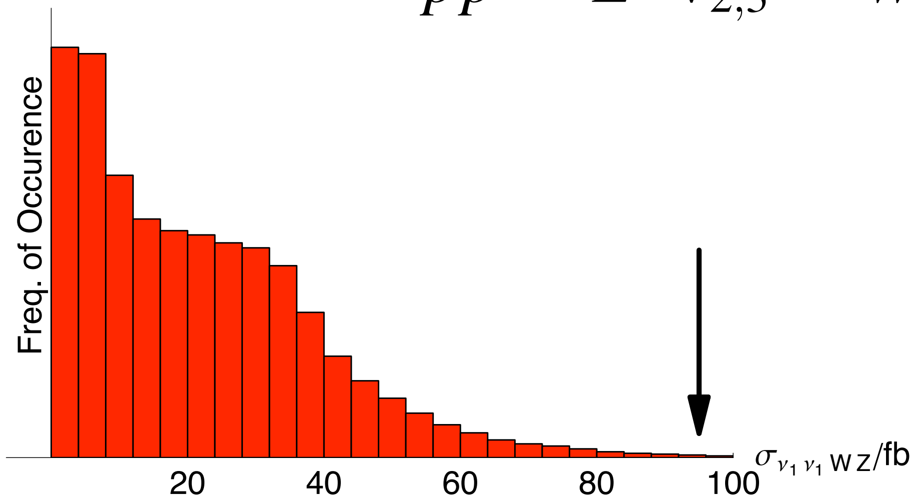


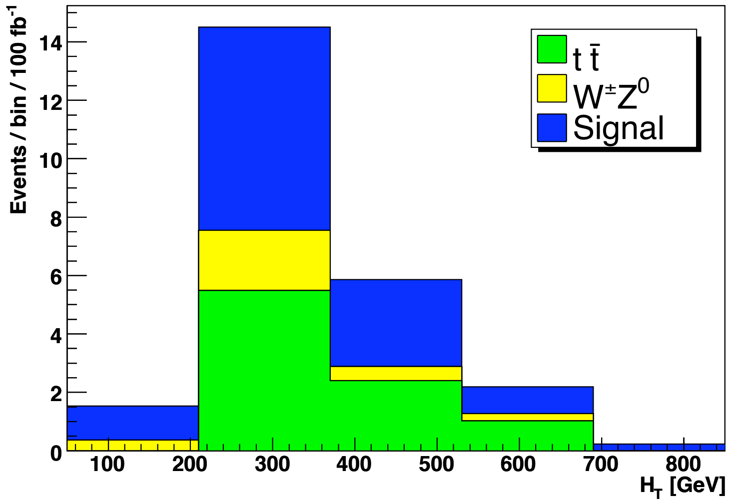

the spectrum

# Direct DM detection versus LHC




$$pp \to E^{\pm}\nu_{2,3} \to W^{\pm}Z\nu_1\nu_1 \to 3l + \not{E}_T$$



# Supersymmetry

*1. A (very fast) supersymmetry primer*

*2. An orientation on the signals*

*3. The Higgs system*

# A fast supersymmetry primer

## 1. The general Lagrangian

$$\mathcal{L} = i\bar{\psi}\,\not{D}\psi - (m\psi\psi + h.c.) + |D_\mu\phi|^2 - m^2|\phi|^2$$

has a supersymmetry, under which $\psi \Leftrightarrow \phi$

which can be extended to include gauge inv. int.s

$$V^\alpha = (A_\mu^\alpha, \lambda^\alpha) \qquad \hat{\phi}_a = (\psi_a, \phi_a)$$

$$\mathcal{L} = \mathcal{L}^{gauge} + \mathcal{L}^f$$

$$\mathcal{L}^f = \sum_a |f_a|^2 + (f_{ab}\psi_a\psi_b + \ h.c.)$$

(R-symmetry)

$\Rightarrow$ No $\Lambda^2$ div.s, even after inclusion of appropriate "soft" breaking terms

$$\mathcal{L} = \mathcal{L}^{gauge} + \mathcal{L}^f + \mathcal{L}^{soft}$$

## 2. The general MSSM

Standard particles into supermultiplets + $\hat{H}_1, \hat{H}_2$

$$f = \lambda_U Q u H_2 + \lambda_D Q d H_1 + \lambda_E L e H_1 + \mu H_1 H_2$$

$$\mathcal{L}^{soft} = \Sigma_\alpha m_\alpha^2 |\phi_\alpha|^2 + (\Sigma_\beta A_\beta^0 f_\beta + \Sigma_i m_{1/2i} \tilde{g}_i \tilde{g}_i + h.c.)$$

## 3. mSUGRA

$m_\alpha = m_0$, $m_{1/2i} = m_{1/2}$ universal at the GUT scale

LSP ≡ lightest neutralino ≡ $\chi^0$ stable

# 4. LSP and the susy breaking scale $\sqrt{F}$

$k = F/F_0$

The gravitino mass $m_{3/2} = \frac{F}{k\sqrt{3}M_P} = \frac{1}{k}\left(\frac{\sqrt{F}}{100\text{ TeV}}\right)^2 2.4\text{ eV}$

$\leftrightarrow m_V = gv$

In mSUGRA $\sqrt{F} \approx 10^8\, TeV \Rightarrow m_{3/2} \approx TeV$

In other schemes $\tilde{G} \equiv$ stable LSP

$$\Gamma(\chi_1^0 \to \gamma\tilde{G}) = \frac{k^2\ \kappa_\gamma m_{\chi_1^0}^5}{16\pi F^2} = k^2\ \kappa_\gamma \left(\frac{m_{\chi_1^0}}{100\text{ GeV}}\right)^5 \left(\frac{100\text{ TeV}}{\sqrt{F}}\right)^4\ 2\times 10^{-3}\text{ eV}$$

$$L = \frac{1}{\kappa_\gamma}\left(\frac{100\text{ GeV}}{m}\right)^5 \left(\frac{\sqrt{F/k}}{100\text{ TeV}}\right)^4 \sqrt{\frac{E^2}{m^2} - 1}\ \times 10^{-2}\text{ cm}$$

If phase space available

$\Gamma(\chi_1^0 \to h\tilde{G})$ and $\Gamma(\chi_1^0 \to Z\tilde{G})$ can be comparable to $\Gamma(\chi_1^0 \to \gamma\tilde{G})$

# *Supersymmetry at the LHC*

(if you care of the prediction!)

Pros

⇒ Neatly solves the naturalness problem of the Fermi scale

⇒ Gauge coupling unification

⇒ Alternatives in worse shape (EWPT)

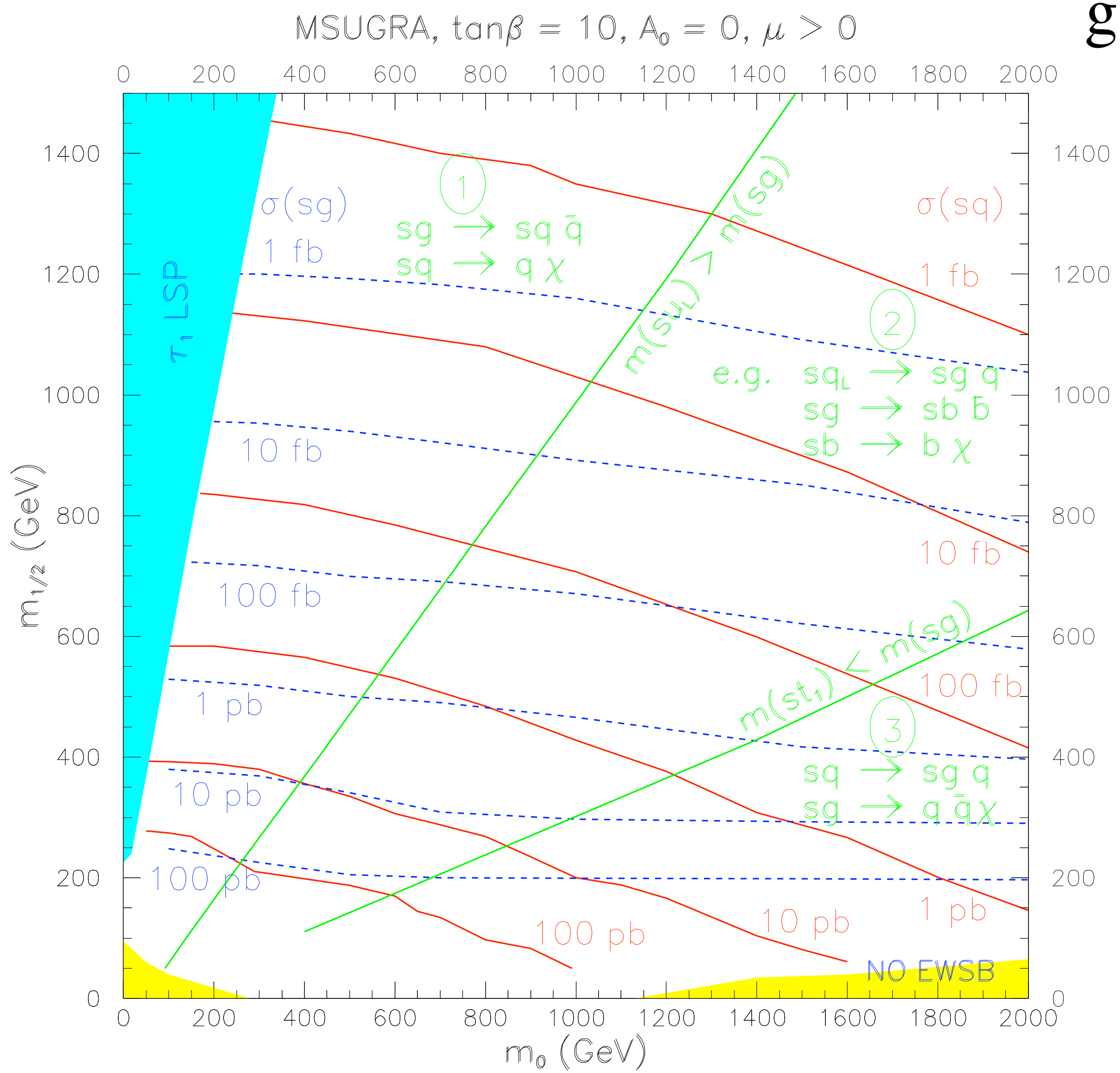
Contras (none decisive)

✓ ⇒ No Higgs boson ✓

⇒ No flavour effects (but follow $\mu \rightarrow e + \gamma$ at PSI)

⇒ No superpartners

# mSUGRA: gluinos, squarks decaying into lighter gauginos/higgsinos




a much studied case

$$m^2(\tilde{q}) \approx m_0^2 + 5m_{1/2}^2$$

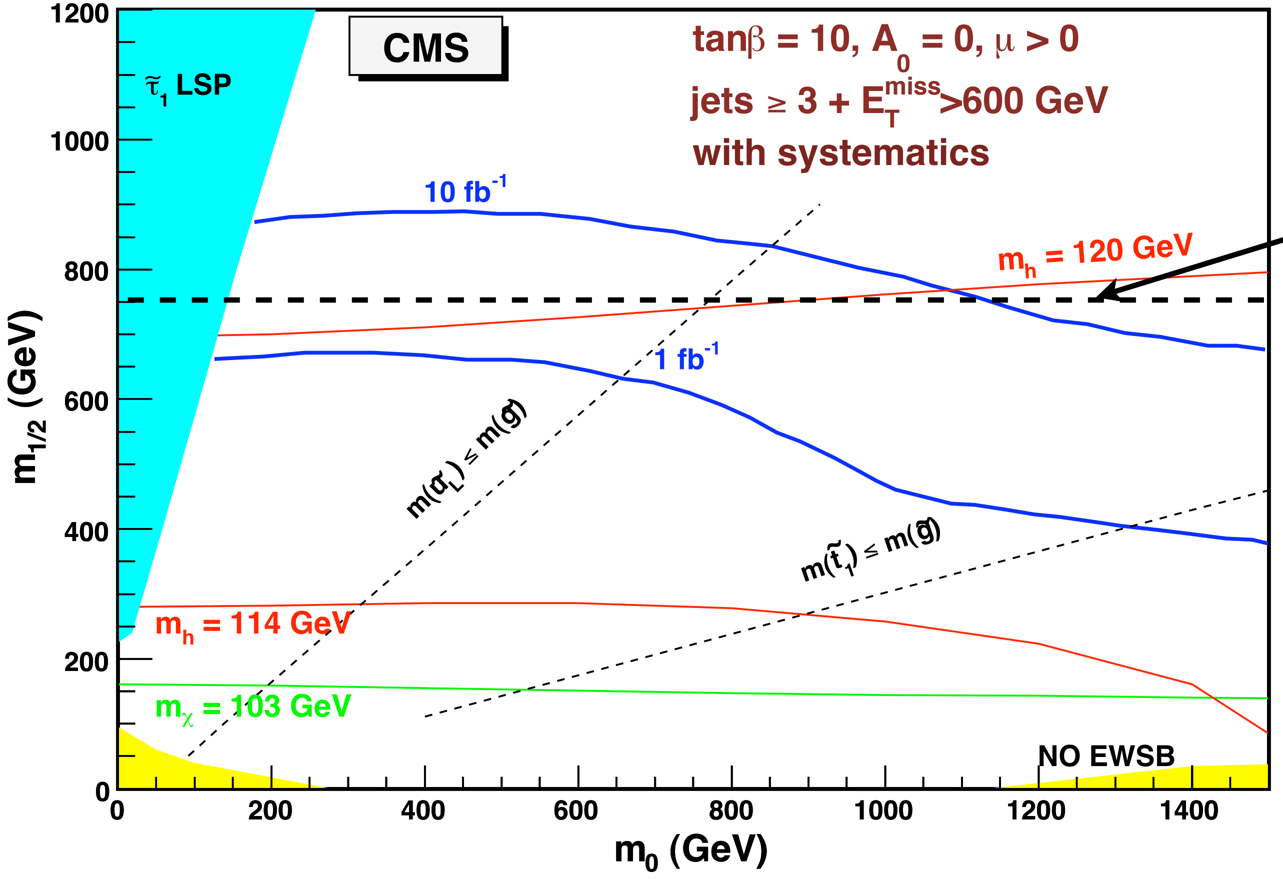
$$m(\tilde{g}) \approx 2.7m_{1/2}$$

$$m(\tilde{w}) \approx 0.8m_{1/2}$$

$$m(\tilde{b}) \approx 0.4m_{1/2}$$

$$pp \rightarrow \tilde{g}\tilde{g} \rightarrow /E_T + jets\ (+\mu^{\pm}/l^+l^-/Z/t)$$

# mSUGRA discovery potential: Easy (?)




$m(\tilde{g}) \approx 2.5\ TeV$

# other "useful" Susy searches

⇒ gluino/stop decays (simple and motivated by naturalness)

1. $pp \to \tilde{t}\tilde{\bar{t}} \to t\bar{t} + \not{E}_T$
   $\quad \hookrightarrow t + \chi^0$

2. $pp \to \tilde{g}\tilde{g} \to jets + \not{E}_T$
   $\quad \hookrightarrow q\bar{q} + \chi^0$

$\sigma(\tilde{t}\tilde{\bar{t}}) \approx 1\ pb$
$m_{\tilde{t}} = 500\ GeV$

3. $pp \to \tilde{g}\tilde{g} \to 2t\ 2\bar{t} + \not{E}_T$
   $\quad \hookrightarrow \tilde{t}\ \bar{t}$
   $\quad\quad \hookrightarrow t + \chi^0$

4. $pp \to \tilde{t}\tilde{\bar{t}} \to t\bar{t} + jets + \not{E}_T$
   $\quad \hookrightarrow t + \tilde{g}$
   $\quad\quad \hookrightarrow q\bar{q} + \chi^0$

BR = 1

⇒ ew gauge/higgs-ino decays (simple in physical space)

5. $pp \to \chi_1^{\pm}\chi_2^0 \to 3leptons + \not{E}_T$
   $\quad \hookrightarrow l\bar{l} + \chi^0$
   $\quad \hookrightarrow l\nu + \chi^0$

$\sigma(\chi_1^{\pm}\chi_2^0) \approx 10 \div 100\ fb$
$m_\chi = 100 \div 200\ GeV$

⇒ light gravitino

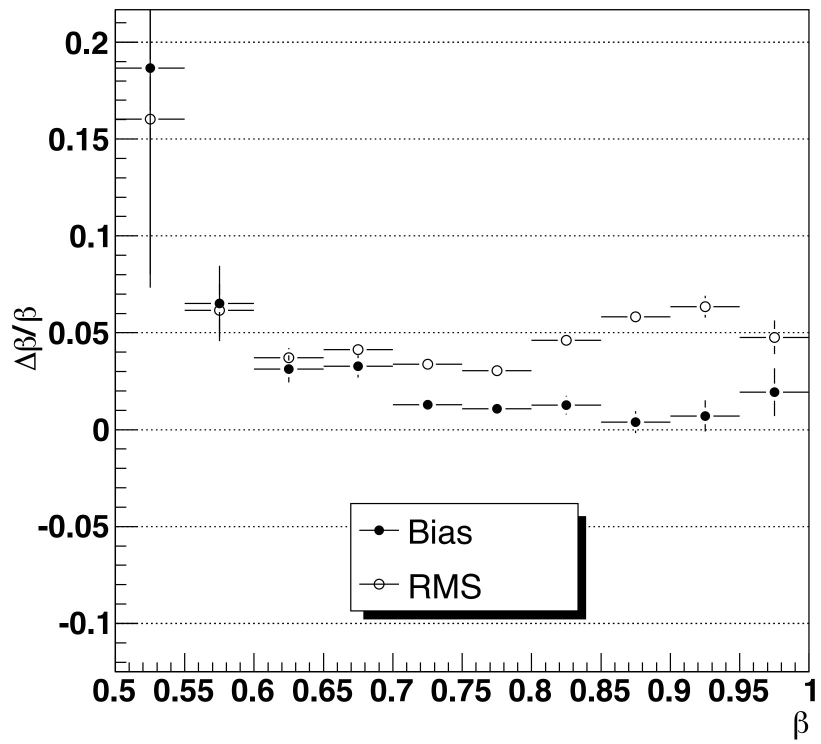
mSUGRA or above ⊕ $\chi^0 \to gravitino + \gamma,\ gravitino + \phi$
$\quad \hookrightarrow b\bar{b}$

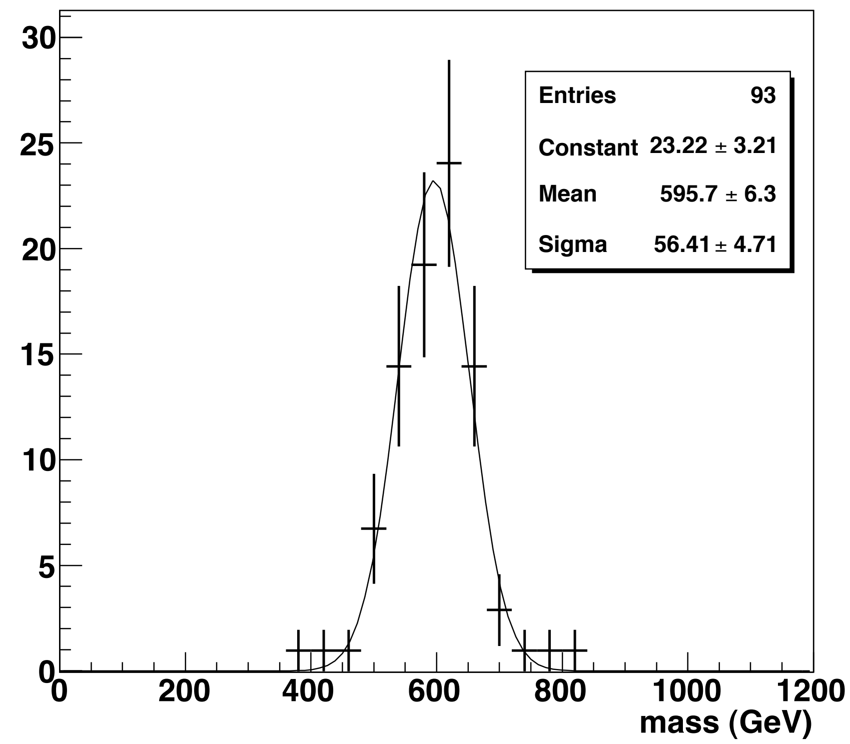
# “Stable” R-hadrons (made of $\tilde{g}$ or of $\tilde{t}$ )

because “LSP”, up to gravitino decays, or because of superheavy squarks (in the gluino case)

by dE/dx and time-of-flight

600 GeV gluino (0.5 $fb^{-1}$)




1 TeV gluino reachable with 1 $fb^{-1}$

# *Where is the supersymmetric Higgs boson?*

*View n⁰ 1*

**MSSM** 2x4 - (2+1) = 5 = 2 + 1 + 1 + 1

$H^{\pm}$ $h$ $H$ $A$

$$m_h^2 \leq M_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2}[\log \frac{m_{\tilde{t}}^2}{m_t^2} + \frac{A_t^2}{m_{\tilde{t}}^2}(1 - \frac{A_t^2}{12 m_{\tilde{t}}^2})]$$

$\Rightarrow$ *Take large tanβ (muon anomaly?) and large stop mass*

for $A_t/m_{\tilde{t}} \lesssim 1$ $m_{\tilde{t}} \gtrsim 900\,\mathrm{GeV}$

*to comply with the LEP bound*

$\Rightarrow$ *Swallow, e.g. in SUGRA,* $\Delta M_Z^2 \approx (2 \div 3) m_{\tilde{t}}^2 \geq 100\, M_Z^2$

$\Rightarrow$ *h just around the corner and quasi-standard*

# *Where is the supersymmetric Higgs boson?*

*View $n^0$ 2*

1. *Even assuming, for good reasons, that supersymmetry is relevant to nature, NO theorem that requires it to be visible at the LHC*

2. *For supersymmetry to be visible at the LHC, need a maximally natural solution of the hierarchy problem*

3. *Since the top, and so the stop, are the particles with the strongest coupling to the Higgs boson, insist on a moderate stop mass*

$\Rightarrow$ *Motivates search of (reasonably simple) alternatives*

$\Rightarrow$ *h not standard and not even light?*

# *A simple concrete possibility*

(others have been considered)

**NMSSM**

$$f = \mu H_1 H_2 \Rightarrow f = \lambda S H_1 H_2$$

$$\Delta V = |f_S|^2 = \lambda^2 |H_1 H_2|^2$$

(2x4 + 2)- (2+1) = 7 = 2 + 3 + 2

$H^{\pm}$ $h_i^{CP+}$ $A_k^{CP-}$

Out of the 3 CP even states,

take the only one coupled to ZZ, WW

$$m_h^2 = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \frac{3 m_t^4}{4\pi^2 v^2} \log \frac{m_{\tilde{t}}^2}{m_t^2}$$

before mixing with the other 2 states

1. What about $\lambda$?
2. What about mixing effects?

$$min[m(h_i^{CP+})] < m_h$$

# What about λ?

Two interesting alternatives:

1 $(\frac{\lambda}{4\pi})^2(10TeV) \leq 0.1 \quad \Rightarrow \quad \lambda(G_F^{-1/2}) \leq 2$

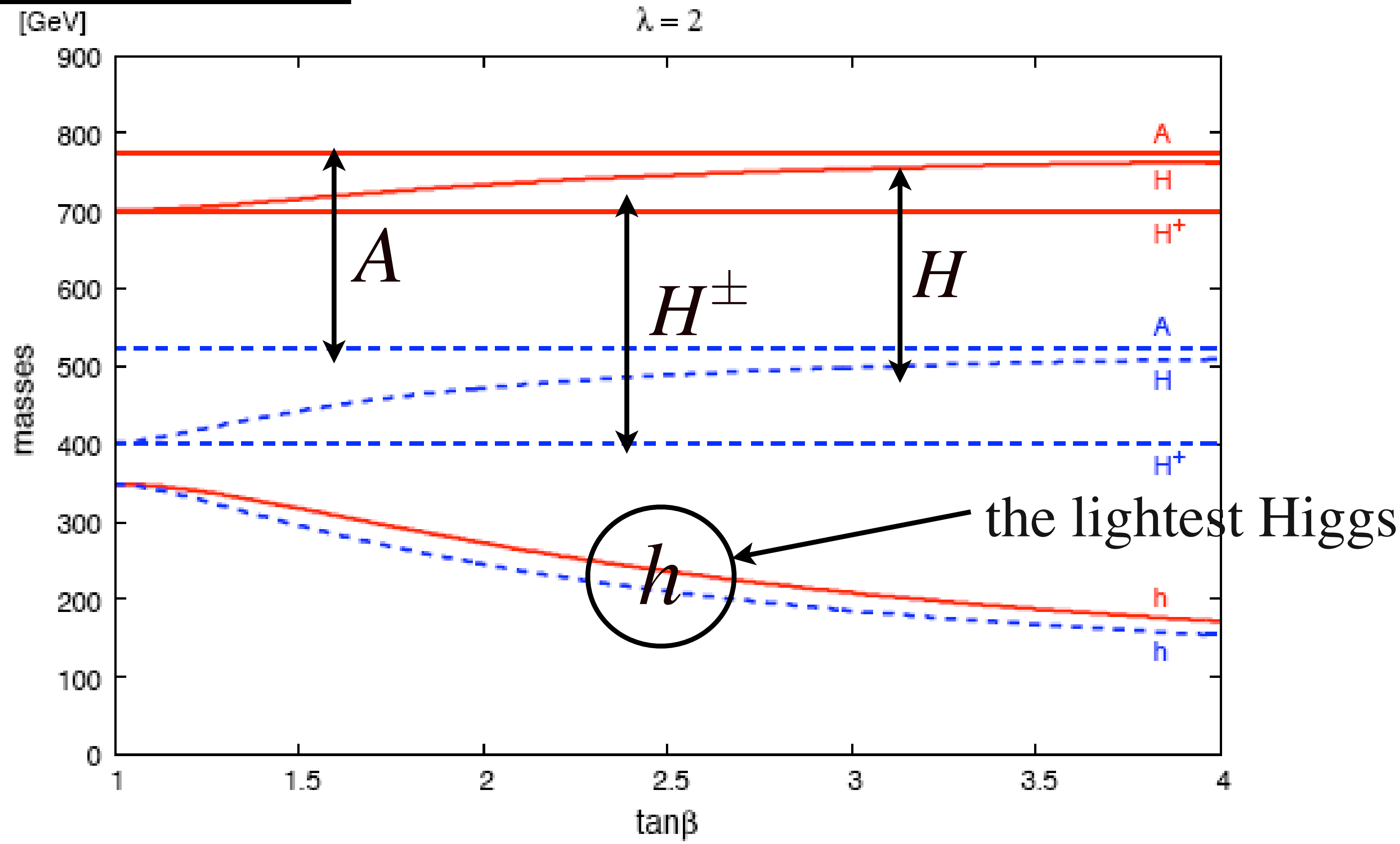
To respect the EWPT (unification?)

2 $(\frac{\lambda}{4\pi})^2(M_{GUT}) \leq 0.1 \quad \Rightarrow$ See below

To maintain manifest perturbative unification

$\lambda(G_F^{-1/2}) \approx 2$

# The Higgs boson spectrum




$h \to ZZ \to l^+l^-\ l^+l^-$ easy, but very much NON-susy

$H \to hh \to 4V \to l^+l^-\ 6j$

$A \to hZ \to VV\ Z \to l^+l^-\ 4j$

possible with $100\ fb^{-1}$ (see below)

# ElectroWeak Precision Tests in λSUSY

$$\lambda(G_F^{-1/2}) \approx 2$$

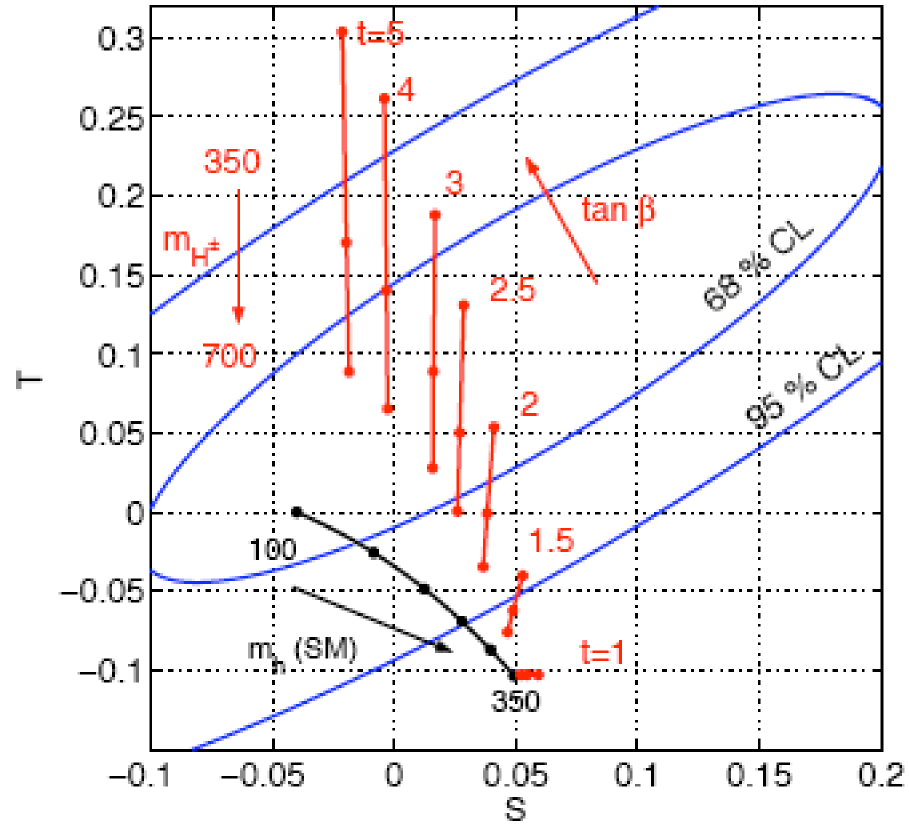
S and T from Higgs's

*one loop effects but*

$$\Delta T \propto \lambda^4$$

$$\lambda \uparrow \Rightarrow m_h \uparrow$$

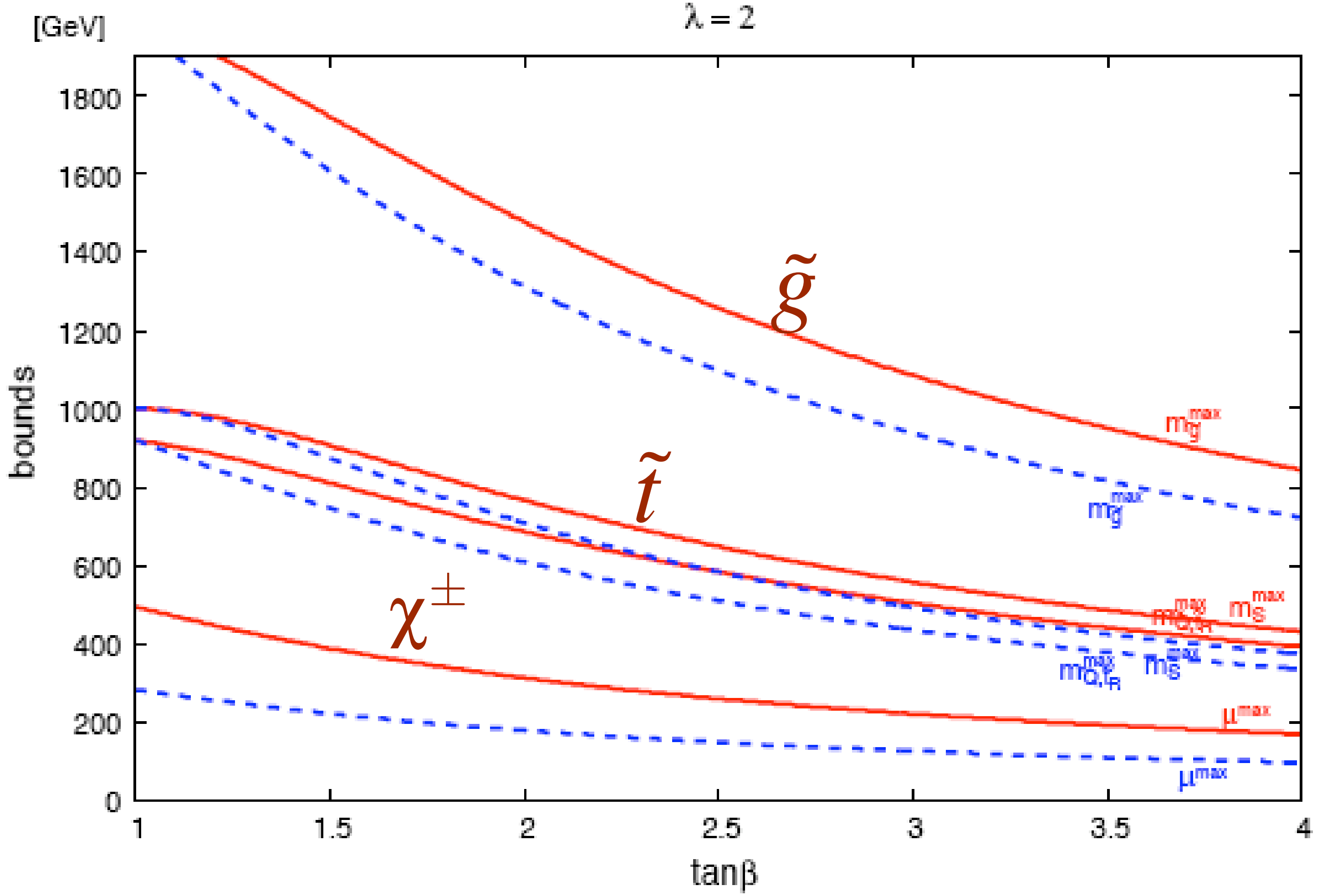
*compensated by* $\Delta T \uparrow$




*(an example of how we could be fouled by the EWPT)*

# $\lambda$Susy $\equiv$ NMSSM with $\lambda_{low\ energy} \leq 2$

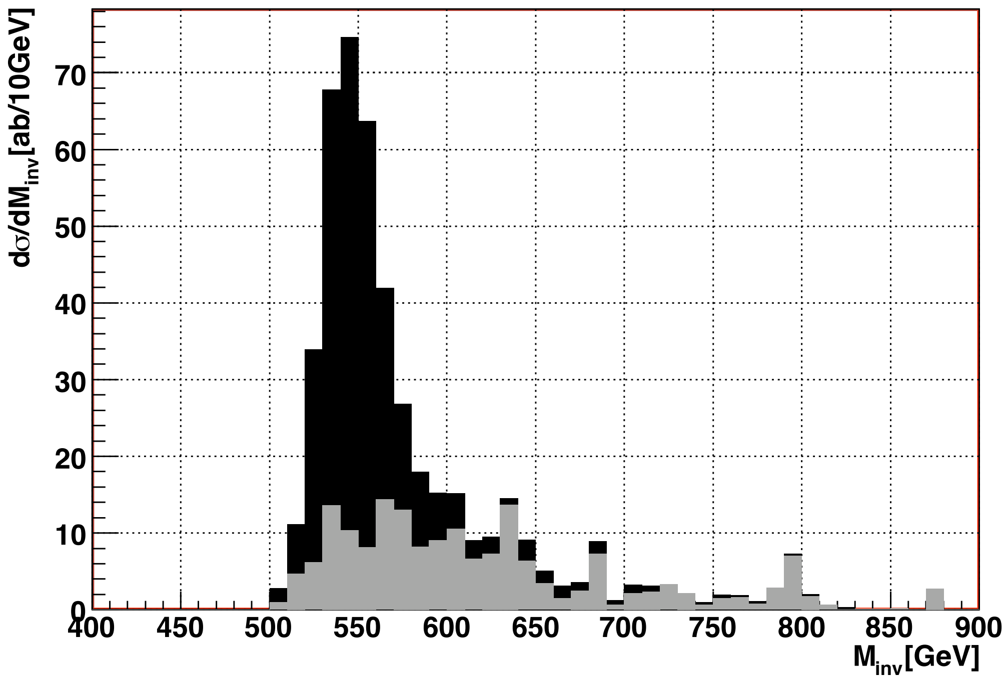
naturalness bounds




with up to 20% tuning $(m^{max} \propto \sqrt{\Delta/5})$

*No problem with the EWPT; Unification subject to what happens above 10 TeV*

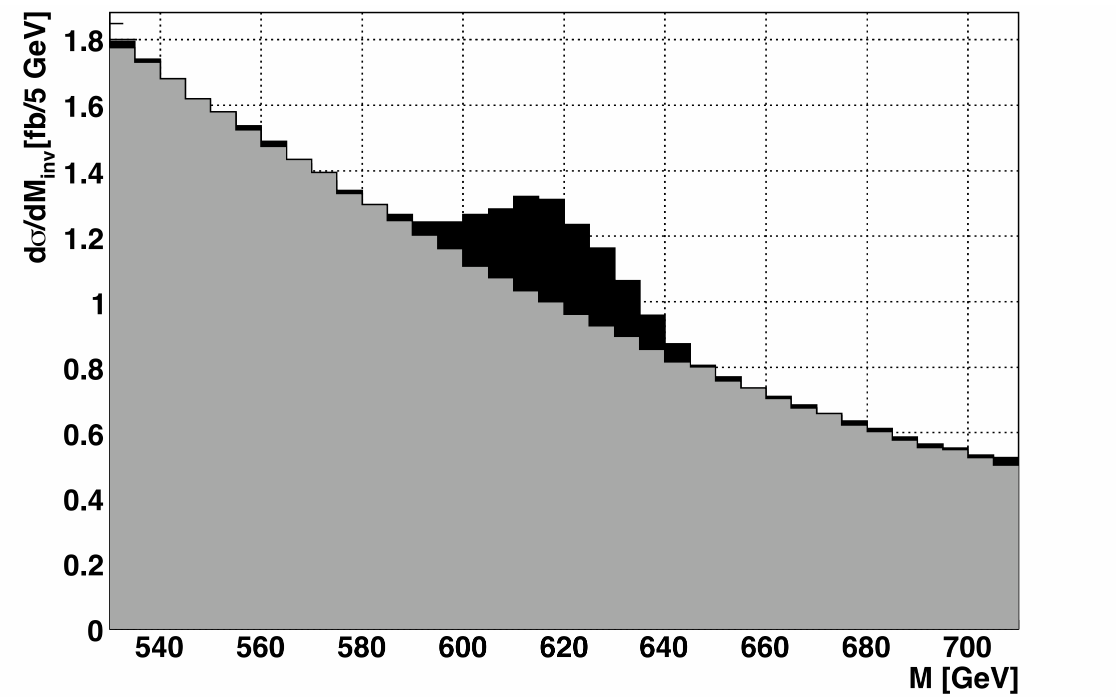
## $\lambda_{low\ energy} \leq 2$




$$\sigma(gg \to H) \approx 100\ fb$$

$$m_H = 500 \div 600\ GeV$$

$$H \to hh \to 4V \to 2l\ 6\,jets$$



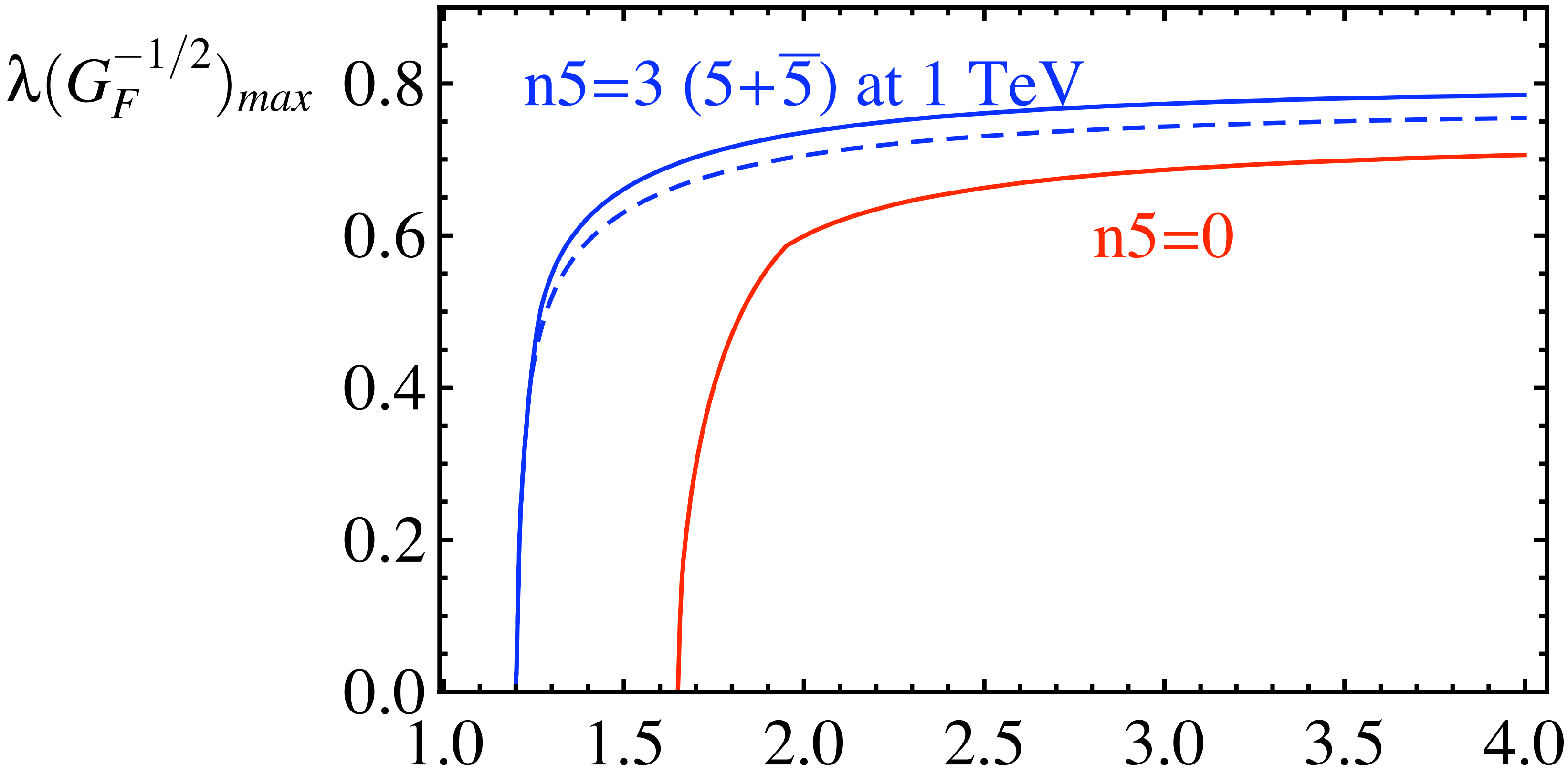

$$m_A \approx 600\ GeV$$

$$\sigma\ BR \approx 10\ fb$$

$$A \to Zh \to Z\ 2V \to 2l\ 4\,jets$$

$$\left(\frac{\lambda}{4\pi}\right)^2 (M_{GUT}) \leq 0.1$$

*by RGE running:*

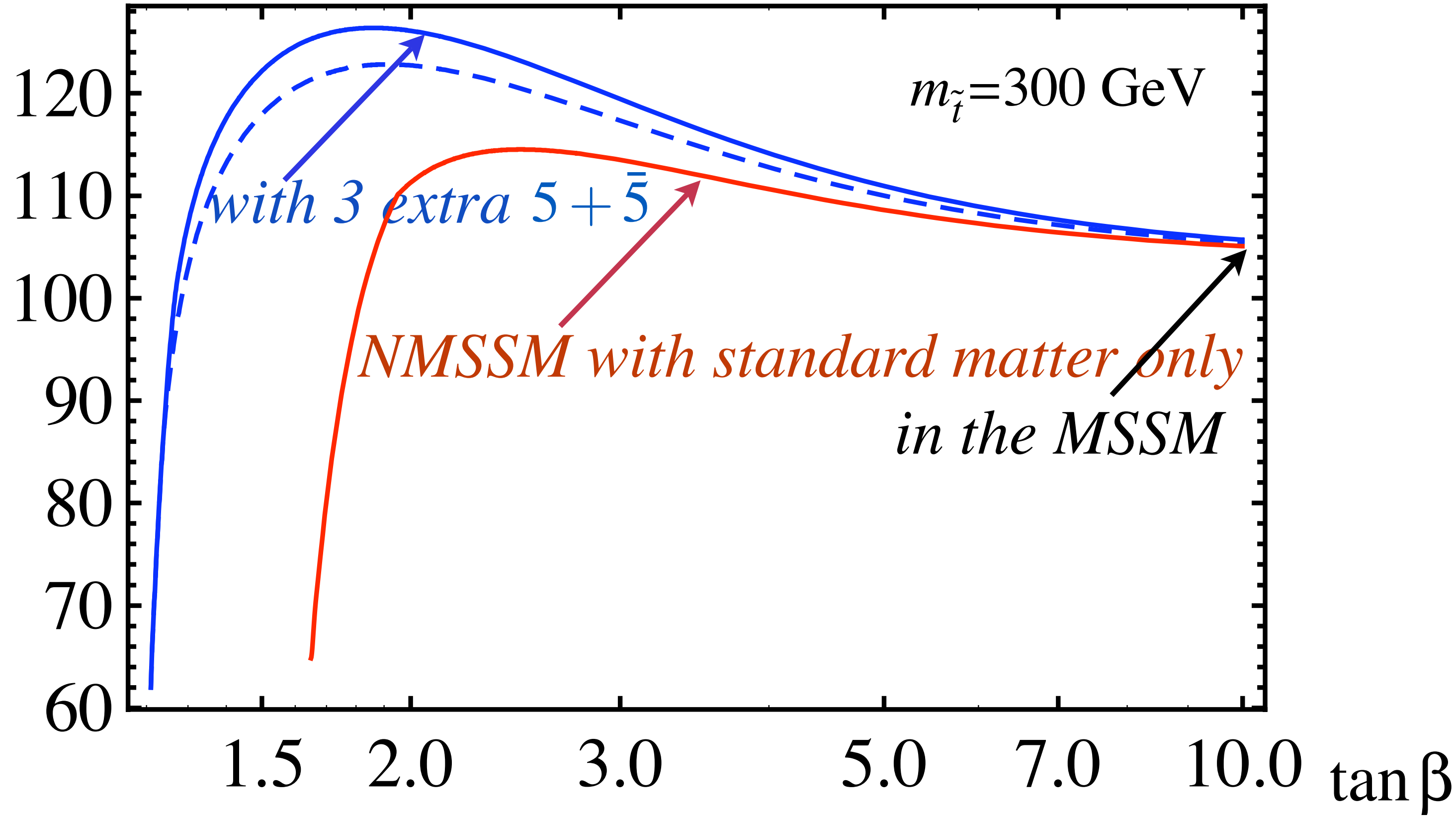



*with standard matter only*

*with 3 extra* $5+\bar{5}$

$$(\frac{\lambda}{4\pi})^2(M_{GUT}) \leq 0.1$$

$m_h[GeV]_{max}$ with a moderate stop mass

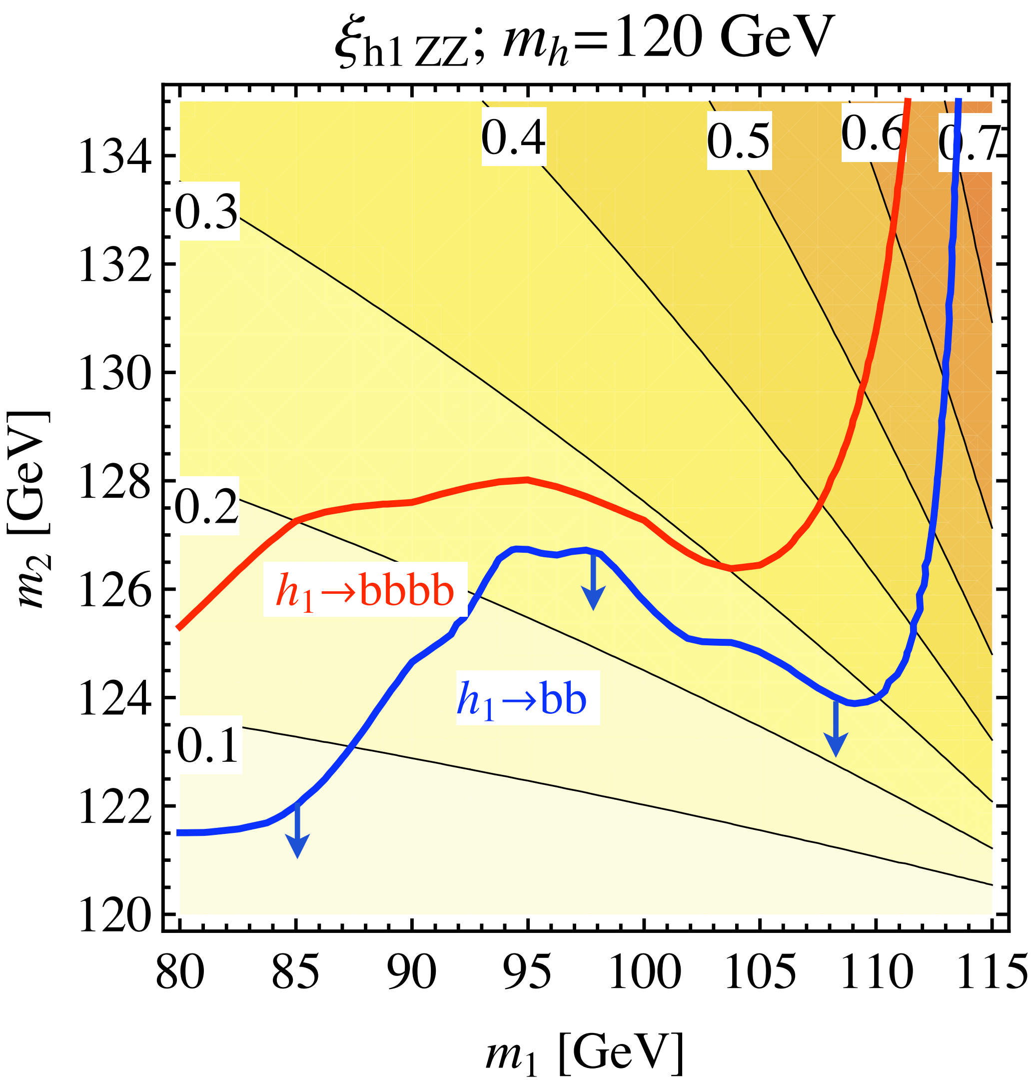



| $n_5 = 0$ | | $n_5 = 3$ | | |
|---|---|---|---|---|
| $\alpha_S(M_Z)$ | $\alpha_G$ | $\alpha_S(M_Z)$ | $\alpha_G$ | |
| **0.117** | 0.041 | **0.117** | 0.103 | 1-loop |
| **0.130** | 0.043 | **0.123** | 0.154 | 2-loop |

$$\alpha_S(M_Z)|_{exp} = 0.1176(20)$$

## *The NMSSM with extra matter and a light stop*

$$\mathcal{M}^2_{2\times 2} = \begin{pmatrix} m_h^2 & \Delta m^2 \\ \Delta m^2 & m_{s_1}^2 \end{pmatrix}$$




*can rather easily be made compatible with the LEP bounds while keeping manifest perturbative unification*

# In an explicit NMSSM quasi-PQ symmetric

(hence with a light pseudo-Goldstone G)

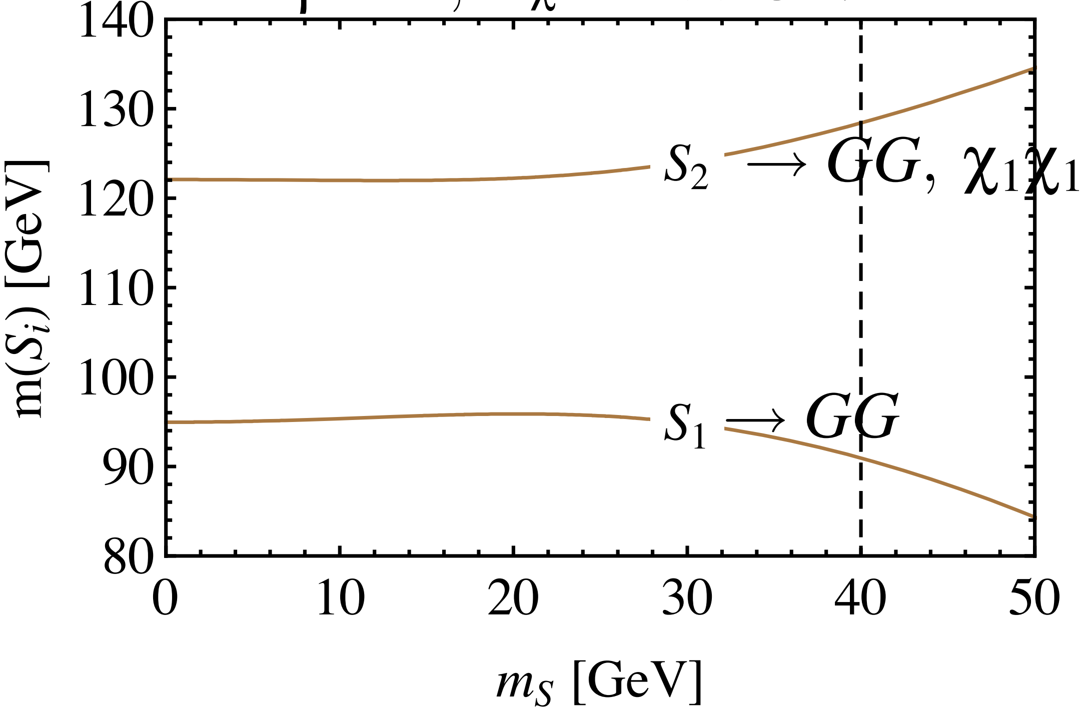
$$f = \lambda\ S\ H_1 H_2 + \kappa/3\ S^3$$

$\lambda \approx 0.7 \div 0.8,\ \kappa \leq 0.1$
$(\lambda_G \approx 1 \div 3,\ \kappa_G \leq 1)$

parameter counting: $m_1^2, m_2^2, m_S^2, A_\lambda, A_k$

$\kappa \to 0,\ A_\kappa \to 0\ \Rightarrow$ a PQ-symmetry $\Rightarrow v,\ \tan\beta,\ m_S^2,\ A_\lambda;\ m_G$

$\tan\beta = 2,\ A_\lambda = 400\ GeV$




$S_3(\approx 300\ GeV) \to GG,\ \chi\chi,\ t\bar{t}$

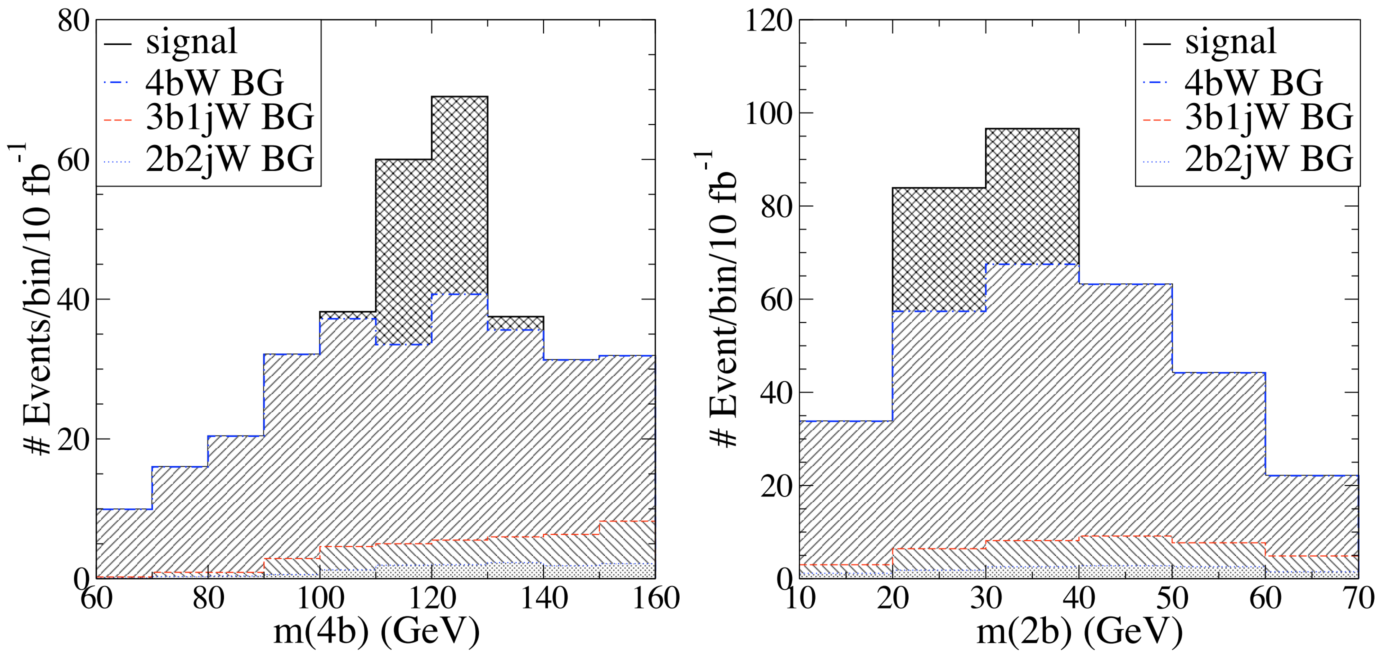
$\Rightarrow v,\ \tan\beta,\ m_S^2,\ A_\lambda$

$GG \to b\bar{b},\ \tau\bar{\tau}$

A pretty non-standard Higgs-boson phenomenology

$$pp \rightarrow Wh \rightarrow l\nu\ GG \rightarrow l\nu\ 4b$$

$$\sigma\ BR \approx 50\ fb$$




$m_h = 120\ GeV$ $\qquad$ $m_G = 30\ GeV$

# *Summary*

# *The road map again*

(my own vote)

*1. Higgsless: a "conservative" view* ☺ ☺

*2. The "naturalness" problem of the Fermi scale*

a. Supersymmetry ☺ ☺ ☺

b. Goldstone symmetry ☺ ☺

c. Gauge symmetry in extraD ☺ ☺

*3. Dark Matter* ☺ ☺

*4. The Planck/Fermi hierarchy ⇔ extraD*

a. Gravity weak by flux in extraD ☺

b. $G_F^{-1/2}/M_{Pl}$ as a red shift effect ☺

c. Symmetry breaking by boundary conditions ☺ ☺

# Final Summary of signals

TENTATIVE and biased
(and obviously not all compatible with each other)

$$\int Ldt \leq 1 fb^{-1}$$

1. mSUGRA
2. gluino/stop decays
3. "stable" R-hadrons
4. light gravitino

$B_s \to l^+ l^-$

$$\int Ldt = 1 \div 30 fb^{-1}$$

5. SM-like Higgs boson
6. KK quarks

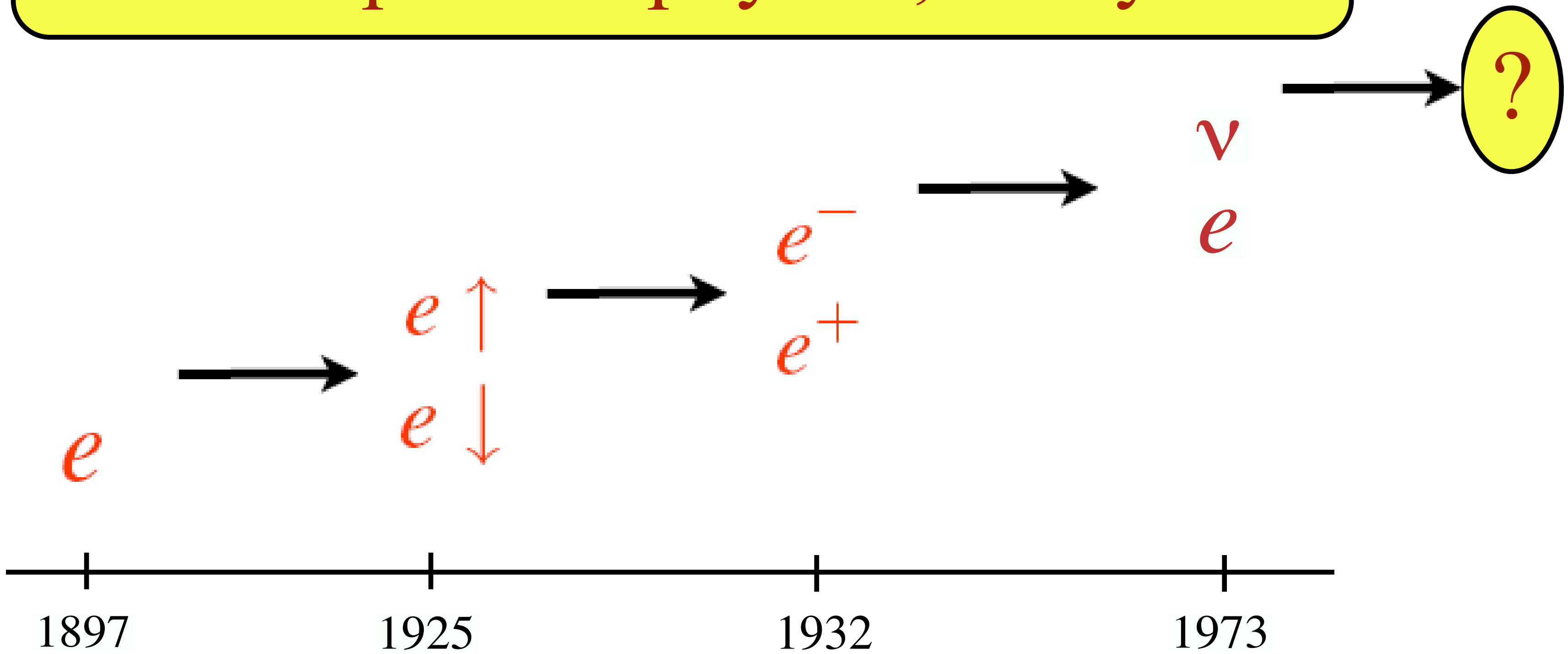
( a 15-20% consistency check between $m_h$ and the EWPT)

$$\int Ldt \geq 30 fb^{-1}$$

7. ew gauge/higgs-ino decays
8. extra-Susy Higgs bosons
9. Minimal Dark Matter
10. KK gluons
11. KK W, Z
12. Heavy vectors

# The central question of particle physics

**What is the next relevant symmetry in particle physics, if any?**

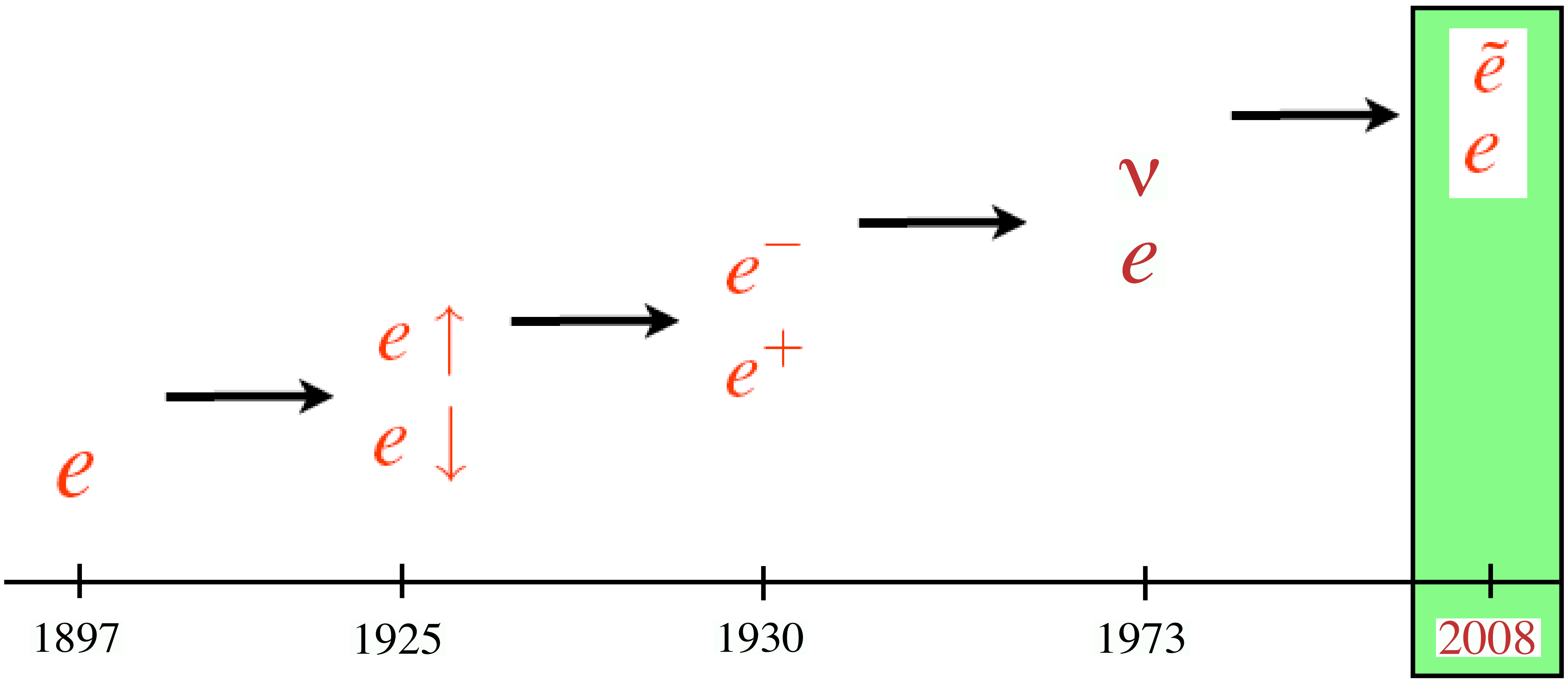



(The key to the economy of equations)

## The LHC should shed some light here

# The key to the economy of equations

(the merit of space-time and internal symmetries)




Supersymmetry as the most interesting theoretical candidate

not unique, however