Emilian Dudas

CERN and CPhT-Ecole Polytechnique

# BEYOND THE STANDARD MODEL

Outline

- Hints from Higgs mass ?

- (meta)stability of the SM vacuum

- hierarchy problem and its solutions

- Flat and curved extra dimensions

- SUSY models after the last LHC results

- inverted hierarchy

- Beyond the MSSM

- low-scale SUSY breaking (non-linear MSSM)

- Hidden sector Z'

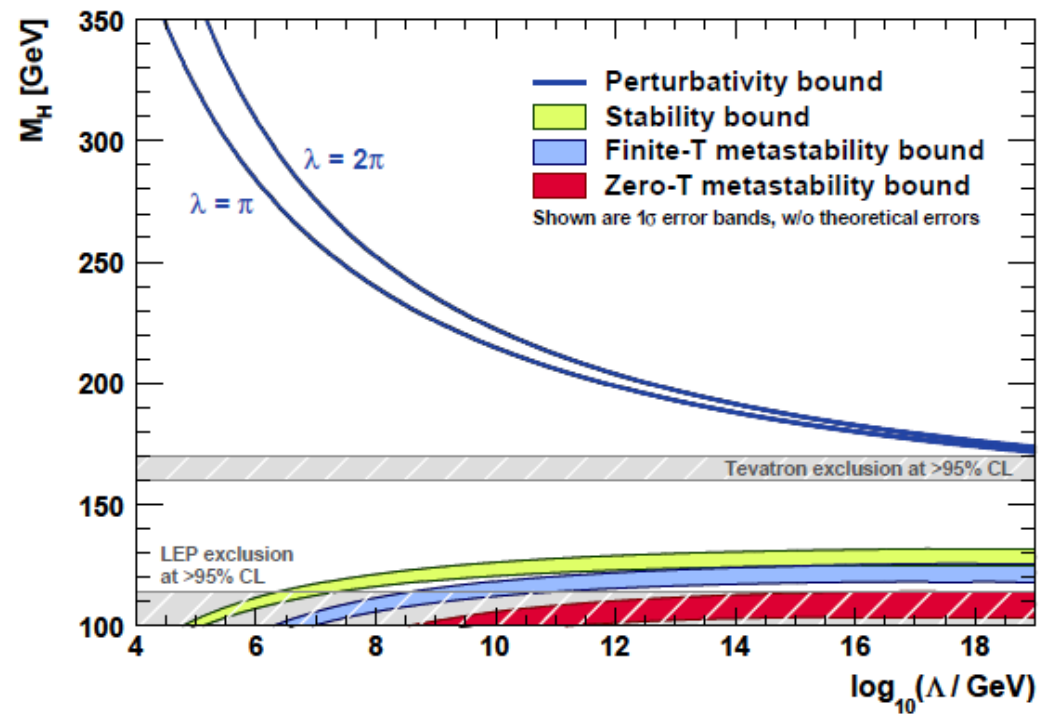- Conclusions and perspectives.

1. Hints from the Higgs mass ?

We all hope that Higgs hunting will suceeed soon (talks Djouadi,Zerwas)
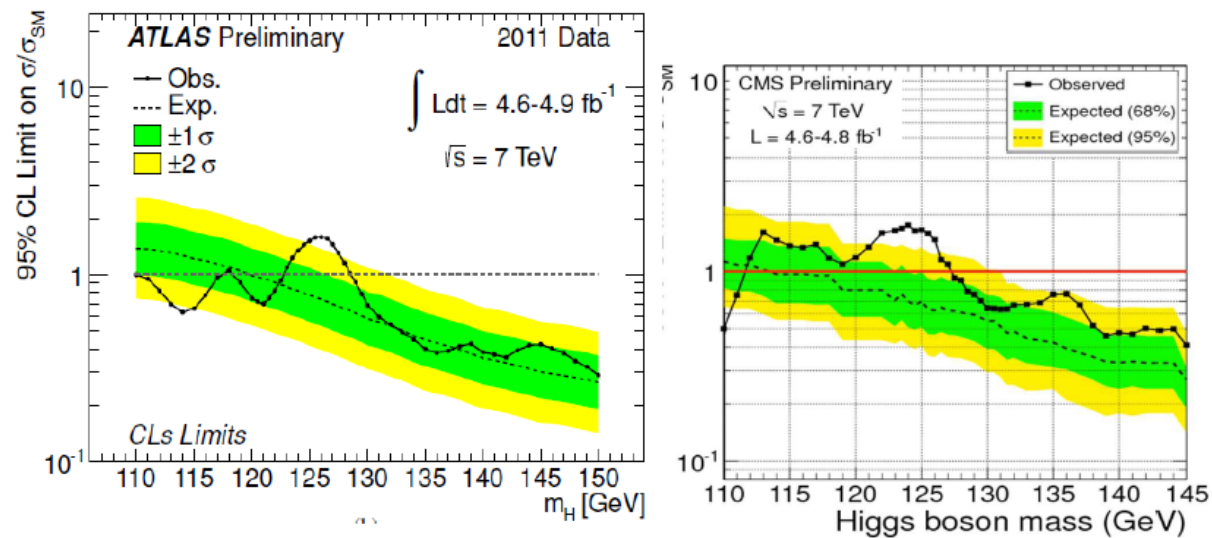

Evidence of a Higgs scalar with mass around 125 GeV (Moriond 2012).

It the signal is real, is SM consistent until the GUT/Planck scale ?

Perturbativity/stability Higgs mass limits. Λ=scale of new physics

- In the SM, for $124 - 126$ GeV mass, the Higgs potential develops an instability around 10^{11} GeV. Lifetime of our vacuum $>>$ age of the universe.
- Can derive upper limits on the right-handed neutrino masses from SM vacuum stability
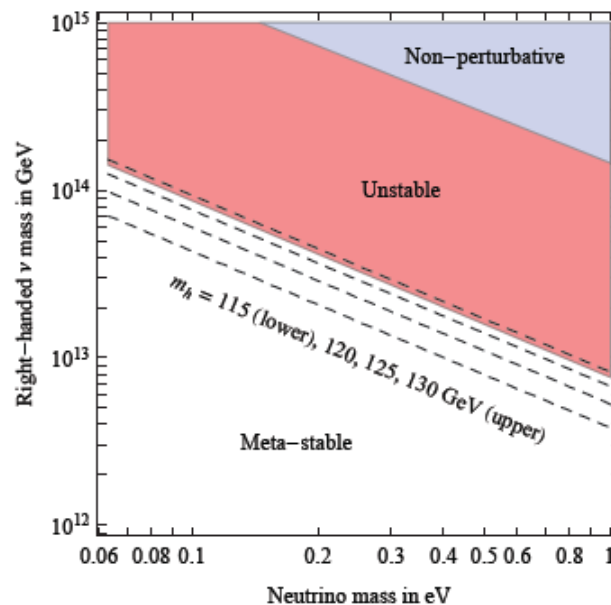
Quantum corrections to the Higgs mass in the SM, coming from diagrams in Fig. 29, are quadratically divergent

$$\delta m_h^2 \simeq \frac{3\Lambda^2}{8\pi^2 v^2}(4m_t^2 - 4M_W^2 - 2M_Z^2 - m_h^2) \ .$$
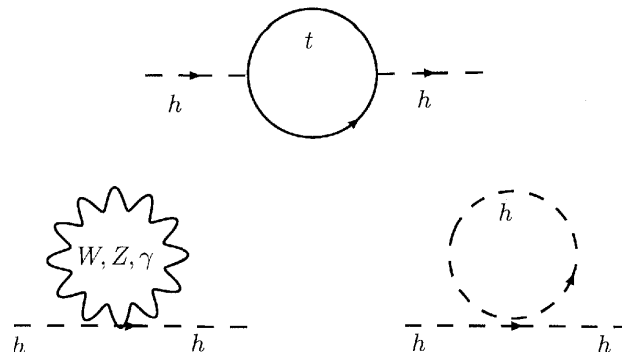
Quadratic divergences to the Higgs mass in the SM, leading to the *hierarchy problem*.

In a theory including gravity or GUT's, Λ is a physical mass scale $\Lambda = M_P, M_{GUT}$. It is then difficult to understand why

$$m_h^2 = (m_h^0)^2 + \frac{3\Lambda^2}{8\pi^2 v^2}(4m_t^2 - 4M_W^2 - 2M_Z^2 - m_h^2) \sim v^2 \ll \Lambda^2$$

This is the the hierarchy problem. Traditional solutions fall into three categories:

- low-energy supersymmetry (SUSY)

- strong dynamics (technicolor, RS, composite Higgs models)

- large extra dimensions

2. Flat and curved extra dimensions

Large-extra dimensional scenario (ADD) solves hierar-chy problem by having a low (TeV) fundamental scale

matter trapped on the brane

gravitons escape into the bulk

brane   bulk
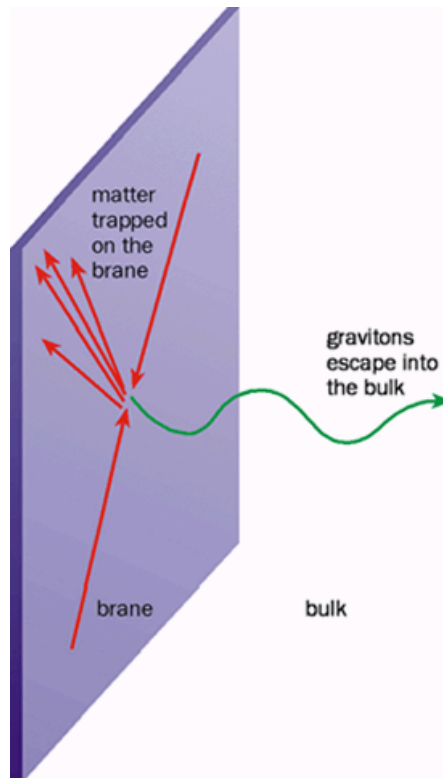
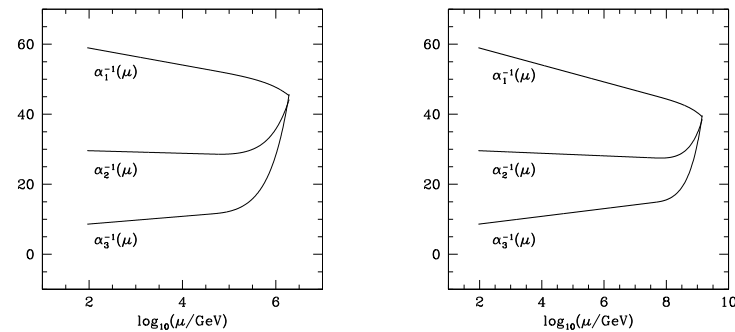# There are large dims. where only gravity propagates
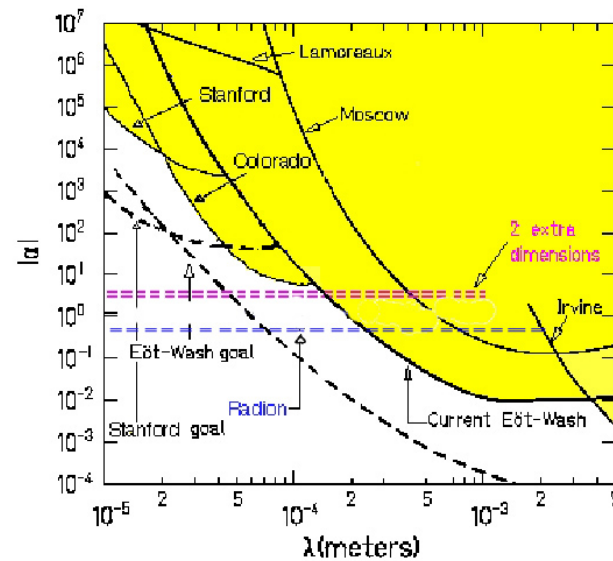
Searches for deviations from Newton law, with

$$V(r) \;=\; G_N \, \frac{m_1 m_2}{r} \, (1 + \alpha \, e^{-r/\lambda})$$

Current limits: $R_\perp^{-1} > 0.1$ mm

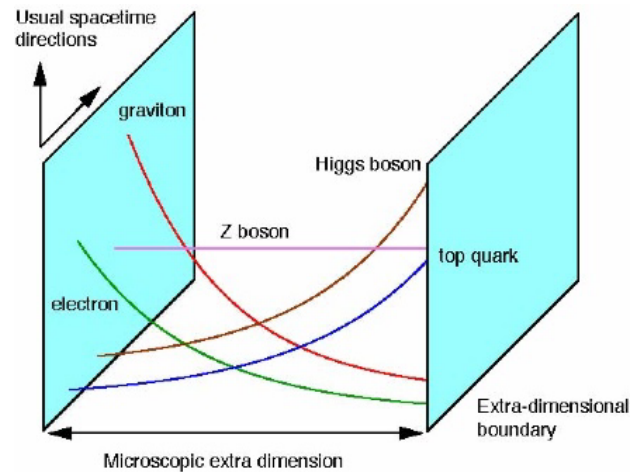TeV extra dims. can provide:

- low-energy unification of gauge couplings

- Kaluza-Klein dark matter (UED)

Unification with extra dims. $R^{-1} = 10^5/10^8$ GeV (left/right). Current UED limits: $R^{-1} > 700$ GeV.

Modern reincarnation of technicolor: holography. Ex:

Randall-Sundrum brane-world model

There is a 5d-4d (AdS/CFT holographic dictionary:

- states localized on TeV (IR) brane: composite.

- states localized on Planck (UV) brane: elementary.

• KK states in 5d $\Leftrightarrow$ resonances of 4d strongly coupled theory.

Nice features:

Different localization of fermions $\rightarrow$ flavor structure which can explain fermion masses and mixings.

Some problems:

• KK states affect SM observables: electroweak precision tests, FCNC effects $\rightarrow \Lambda_{IR} > 3$ TeV.

Models with $\Lambda_{IR} \sim$ TeV exist, with deformed metric in the infrared: soft-wall (Cabrer,Gersdorff,Quiros)

3. SUSY models after the last LHC results (talks Djouadi,Drieu la Rochelle)

SUSY : every fermion (boson) $\leftrightarrow$ boson (fermion)

- nice gauge coupling unification

- natural dark matter candidate (neutralino)
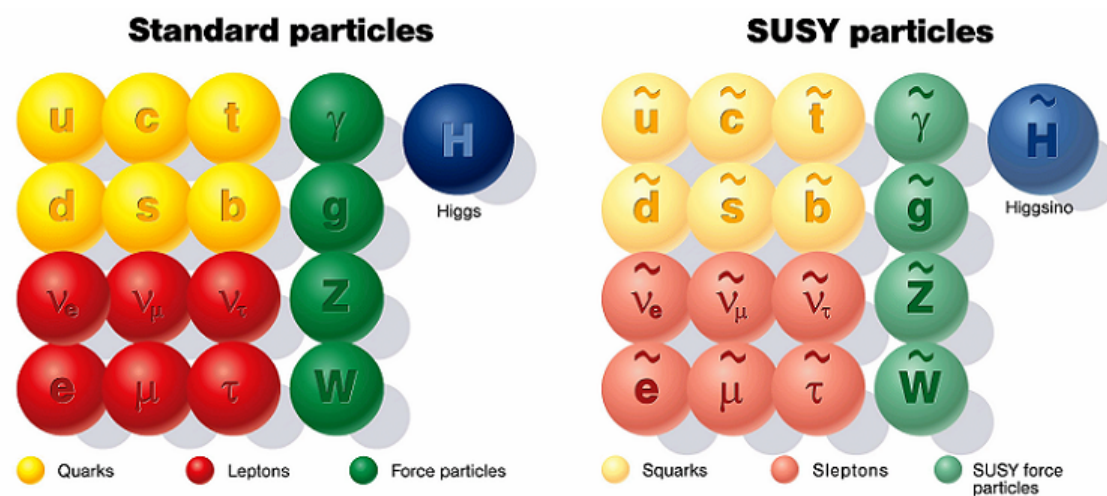
There are two main new informations from LHC :

1) Direct SUSY searches restrict :

- masses of squarks of first two generations and gluino to have masses > 1 TeV

- third generation squarks can be much lighter (> 300 GeV)

2) SUSY spectrum specific, since MSSM prefers a light scalar (at tree-level $m_h^0 < M_Z$):

$$\delta m_h^2 \approx \frac{3g^2 m_t^4}{8\pi^2 m_W^2} \left[\ln\left(\frac{M_{\text{SUSY}}^2}{m_t^2}\right) + \frac{X_t^2}{M_{\text{SUSY}}^2}\left(1 - \frac{X_t^2}{12 M_{\text{SUSY}}^2}\right)\right]$$

where and M_{SUSY} (A_t) denotes the average stop mass (mass mixing in the stop sector).
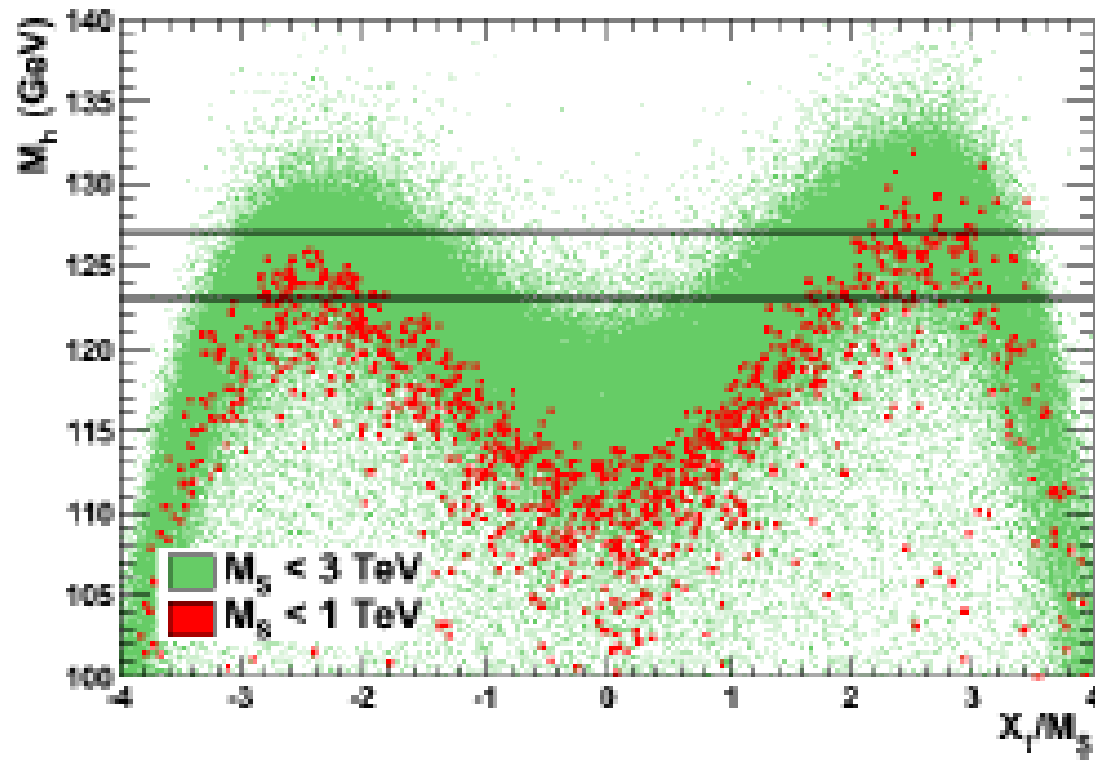
Higgs boson mass versus X_t/M_{SUSY}. Heavier Higgs easier for $X_t > 0$, but negative values more natural from RGE from M_{GUT}.

A 125 GeV Higgs not natural in CMMSM/mSUGRA, since:

- for $A_t \sim M_{SUSY}$ it requires $M_{SUSY} > 3 - 4$ TeV $\Rightarrow$ big fine-tuning of the electroweak scale

- for $M_{SUSY} < 1$ TeV, it requires large A-terms. Difficult to conceive, starting from M_{GUT} or M_{Planck}.

From a theoretical viewpoint, this requires some departure from the standard SUSY breaking mediation scenarios:

• gravity mediation: generically $A \sim M_{SUSY}$

• gauge mediation: $A << M_{SUSY}$.

One old possibility which became popular recently: inverted hierarchy / natural SUSY:

- third generation scalars in the TeV range

- first two generations much heavier $(10 - 15 \text{ TeV})$

This is actually natural in flavor and holographic models. Good ex: abelian flavor models. Quark mass matrices are given by

$$h_{ij}^U \sim \epsilon^{q_i + u_j + h_u} \quad , \quad h_{ij}^D \sim \epsilon^{q_i + d_j + h_d} \ ,$$

where $\epsilon << 1$, q_i (u_i, d_i, h_u, h_d) denote the $U(1)_X$ charges of the left-handed quarks (right-handed up-quarks, right-handed down-quarks, H_u and H_d, respectively).

Quark masses and mixings are

$$\frac{m_u}{m_t} \sim \epsilon^{q_{13}+u_{13}} \ , \ \ \frac{m_c}{m_t} \sim \epsilon^{q_{23}+u_{23}} \ , \ \ \frac{m_d}{m_b} \sim \epsilon^{q_{13}+d_{13}} \ , \ \ \frac{m_s}{m_b} \sim \epsilon^{q_{23}+d_{23}}$$

$$\sin\theta_{12} \sim \epsilon^{q_{12}} \ \ \ , \ \ \ \sin\theta_{13} \sim \epsilon^{q_{13}} \ \ \ , \ \ \ \sin\theta_{23} \sim \epsilon^{q_{23}} \ .$$

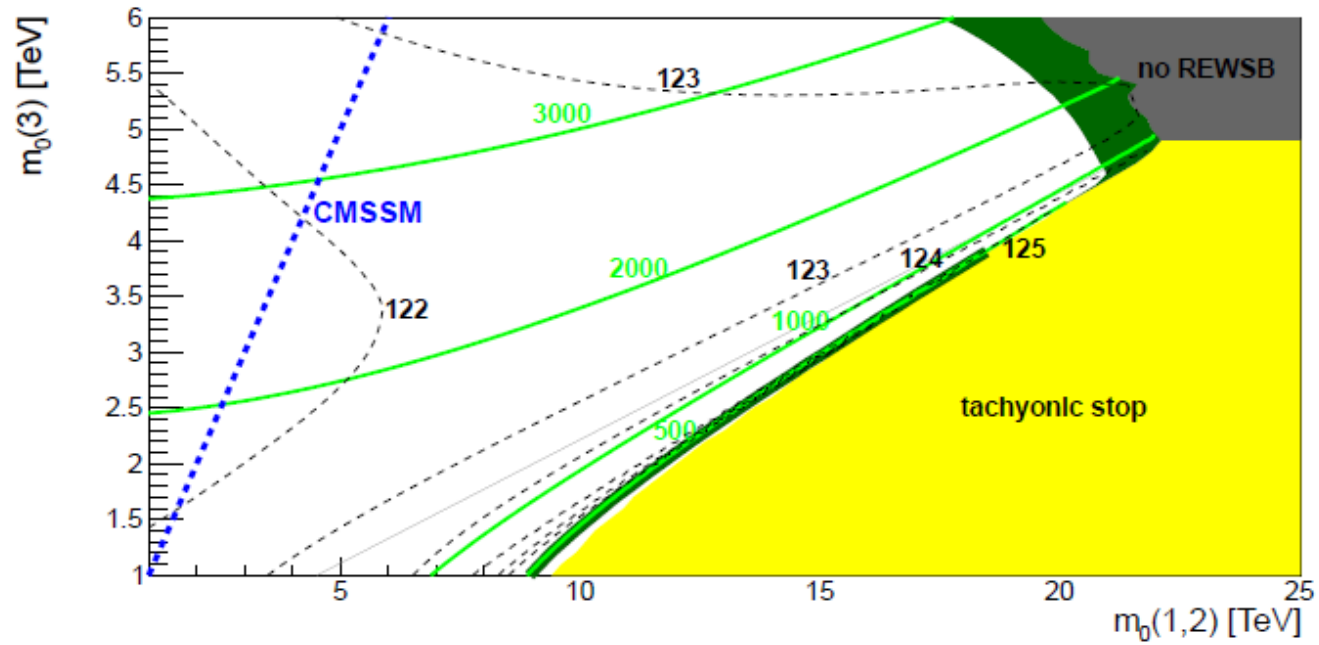Good fit to data $\Rightarrow$ larger charges for lighter generations

$$q_1 \ > q_2 \ > q_3 \ \ \ , \ \ \ u_1 \ > u_2 \ > u_3 \ \ \ , \ \ \ d_1 \ > d_2 \ > d_3 \ .$$

Scalar masses in abelian flavor models are of the form

$$m_{ij}^2 \ = \ X_i \langle D \rangle \ + \ a_{ij} \langle F \rangle \ .$$

If $D >> F$, inverted hierarchy is generated.

If $m_{1,2}/m_3$ is too large, stops became tachyonic $\rightarrow$ natural way to generate large stop mixing.

Inverted hierarchy example. Higgs mass (black dashed),stop

mass (solid green) for $\mu > 0, \tan\beta = 10, M_{1/2} = 1, A_0 = -2$

(TeV). Yellow "tachyonic stop" and grey "no REWSB" ($\mu^2 < 0$)

regions are excluded. Dark green region: $\Omega_{DM}h^2 < 0.1288$.

4. Beyond the MSSM

There are various approaches/frameworks:

1) SUSY models with different gauge groups and/or field content:

- MSSM + light singlet(s) : NMSSM (Ellwanger,Hugonie,etc) and its variants

There are new contributions to Higgs self coupling.

2) strongly coupled models : SUSY-RS models, $\lambda MSSM$,etc

3) MSSM with higher dimensional operators (talk Drieu de la Rochelle), low-scale SUSY breaking.

- MSSM + goldstino: Non-linear MSSM.

Usually we parameterize SUSY breaking in MSSM by a coupling to a spurion

$$S = \theta^2 m_{soft}$$

If SUSY breaking scale f is low, we consider SUSY matter sector coupled to the goldstino. This can be done by replacing S with a constrained superfield X, satisfying $X^2 = 0$

$$X = \frac{GG}{2F_X} + \sqrt{2}\theta G + \theta^2 F_X.$$

new MSSM couplings, correction to the higgs potential.

The main difference in non-linear MSSM is the replacement $S \rightarrow \frac{m_{soft}}{f} X$.

This reproduces the MSSM soft terms, but it adds new dynamics :

- F_X is a dynamical auxiliary field $\rightarrow$ new couplings from

$$-\bar{F}_X = f + \frac{B}{f} h_1 h_2 + \frac{A_u}{f} q u h_2 + \cdots$$

- it contains in a compact form the goldstino couplings to matter.

All couplings to the Goldstino are proportional to soft-terms. The lagrangian is

$$\mathcal{L} = \mathcal{L}_{MSSM} + \mathcal{L}_X + \mathcal{L}_m + \mathcal{L}_{AB} + \mathcal{L}_g \quad \text{where}$$

$$\mathcal{L}_H = \sum_{i=1,2} \frac{m_i^2}{f^2} \int d^4\theta \; X^\dagger X \; H_i^\dagger e^{V_i} H_i \;,$$

$$\mathcal{L}_m = \sum_\Phi \frac{m_\Phi^2}{f^2} \int d^4\theta \; X^\dagger X \Phi^\dagger e^V \Phi \;, \quad \Phi = Q, U_c, D_c, L, E_c$$

$$\mathcal{L}_{AB} = \frac{B}{f} \int d^2\theta \; X H_1 H_2 + (\frac{A_u}{f} \int d^2\theta \; X Q U_c H_2 + \cdots)$$

$$\mathcal{L}_g = \sum_{i=1}^{3} \frac{1}{16\, g_i^2\, \kappa} \frac{2\, m_{\lambda_i}}{f} \int d^2\theta\, X \, \text{Tr}\, [W^\alpha W_\alpha]_i + h.c.$$

Matter terms coming from solving for F_X are new compared to MSSM. Ex : the scalar potential is modified:

$$V = \left(|\mu|^2 + m_1^2\right) |h_1|^2 + \left(|\mu|^2 + m_2^2\right)|h_2|^2 + (B\, h_1.h_2 + \text{h.c.})$$
$$+ \frac{g_1^2 + g_2^2}{8} \left[|h_1|^2 - |h_2|^2\right]^2 + \frac{g_2^2}{2} |h_1^\dagger\, h_2|^2$$
$$+ \frac{1}{f^2} \left| m_1^2\, |h_1|^2 + m_2^2\, |h_2|^2 + B\, h_1.h_2 \right|^2$$

The last term is new , generated by integrating out the sgoldstino.

Physical interpretation : new couplings of the Higgs to the (low-scale) SUSY breaking sector.
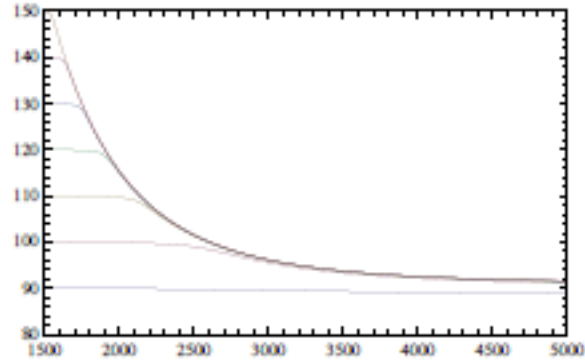
Implications for Higgs masses.

Due to the new quartic couplings, the Higgs masses change

$$\Delta m_h^2 = \frac{v^2}{16\,f^2}\frac{1}{\sqrt{w}}\Big[16 m_A^2\mu^4 + 4\,m_A^2\,\mu^2\,m_Z^2 + (m_A^2 - 8\,\mu^2)\,m_Z^4$$

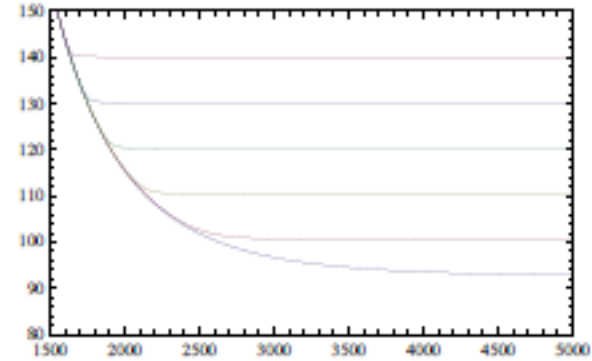$$-2\,m_Z^6 + 2\,(-2\,m_A^2\,\mu^2 + 8\mu^4 + 4\mu^2\,m_Z^2 + m_Z^4)\,\sqrt{w} + \cdots\Big]$$

with $w = (m_A^2 + m_Z^2)^2 - 4m_A^2 m_Z^2\cos^2 2\beta$. The increase in the Higgs mass is significant for
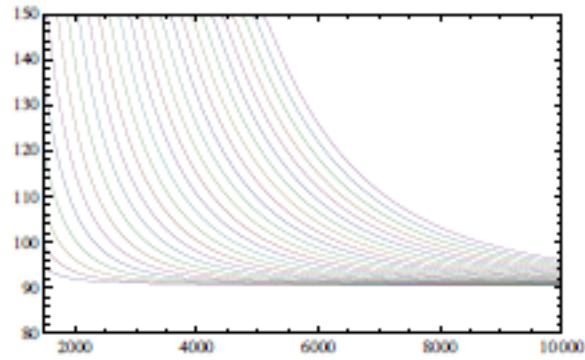
$$1.5\ TeV \leq f \leq 10\ TeV$$

The fine-tuning of the electroweak scale is also reduced.

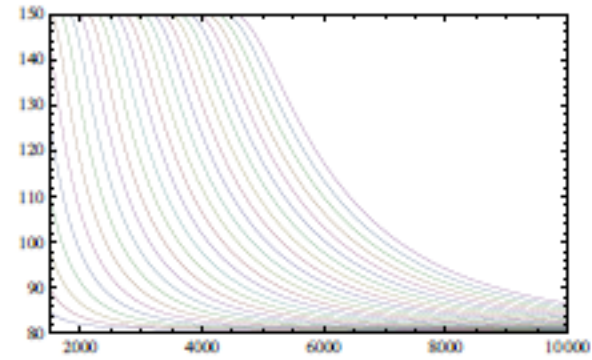(a) m_h in function of $\sqrt{f}$, m_A parameter

(b) m_H in function of $\sqrt{f}$, m_A parameter

(c) m_h in function of $\sqrt{f}$, μ parameter

(d) m_h in function of $\sqrt{f}$, μ parameter

Higgs mass in non-linear MSSM. In (a), (b) $\mu = 900$ GeV, $\tan\beta = 50$. In (c), (d), $m_A = 150$ GeV. In (c) $\tan\beta = 50$.

5. Hidden Z'

Additional neutral gauge bosons can be light if hidden from SM. Natural communication hidden/SM sectors :
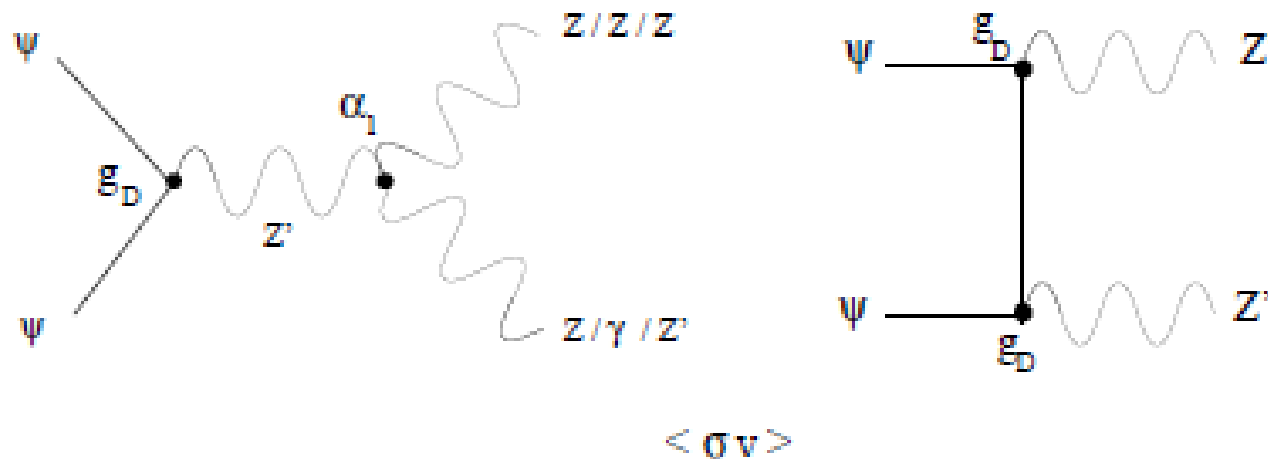
- Kinetic mixing

$$\mathcal{L}_{\mathsf{mix}} \;=\; \epsilon\; F^Y_{mn}\; F^{Z'}_{mn}$$

- Chern-Simons terms (loops of heavy fermions or string theory Green-Schwarz mechanism)

$$\mathcal{L}_{\mathsf{CS}} \;=\; \alpha_1\; \epsilon^{mnpr}\; Z'_m\; Z_n\; F^Y_{pr}$$

• If DM is the lightest charged fermion in the hidden sector, these models have specific signatures.

Feynman diagrams contributing to the dark matter annihilation. First diagram generates a gamma-ray line, the second accommodates WMAP relic density.
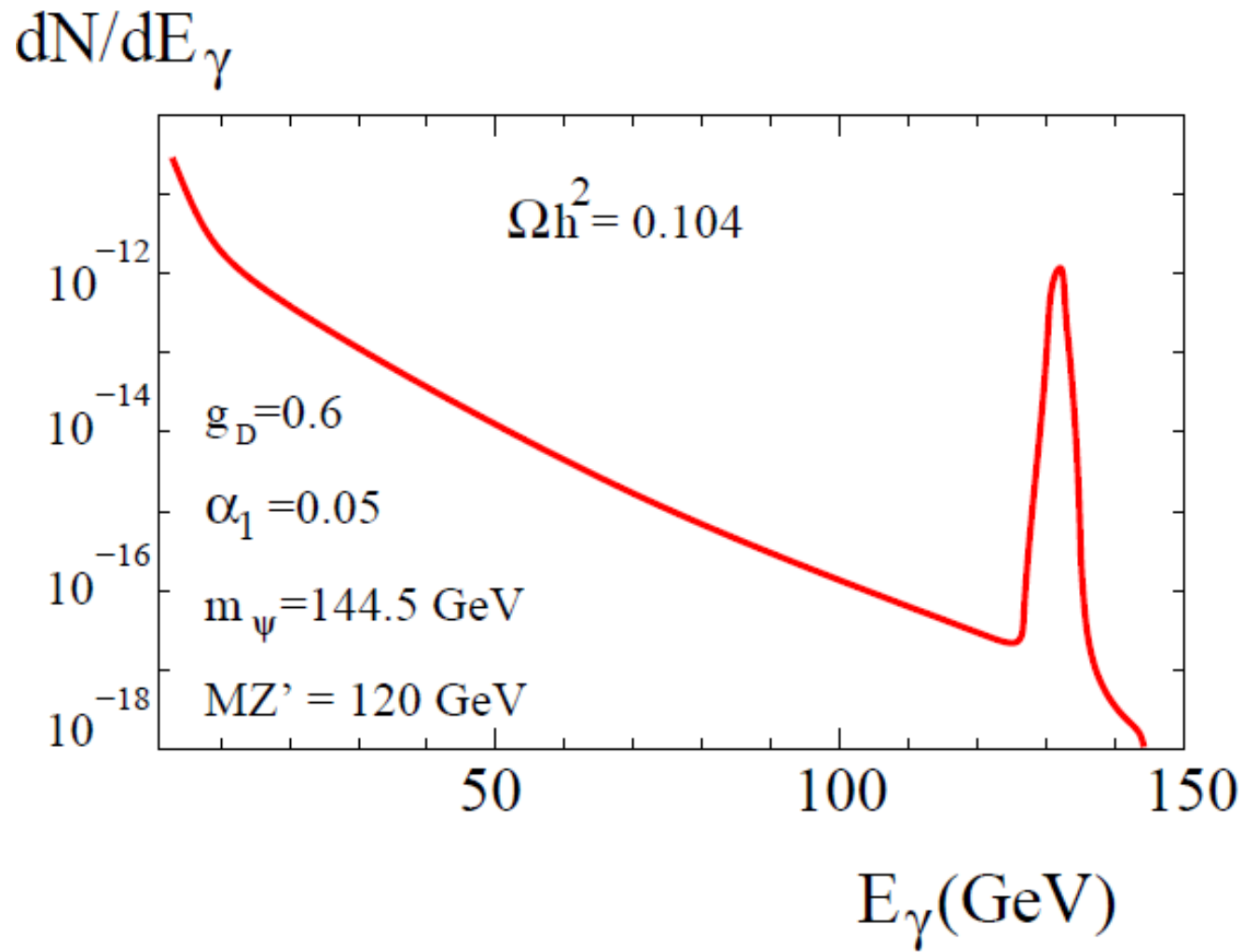
Photon spectrum from the annihilation of dark matter

Conclusions and perspectives

- With 125 GeV Higgs and if SM , we live in a metastable vacuum.

- Additional couplings are restricted by lifetime of our vacuum

- ± 3 GeV in the Higgs mass change drastically both phenomenology and model builindg !

- Simplest SUSY models (mSUGRA,CMMSM) less and less viable. Non-standard models are needed.

- Inverted hierarchy models are natural and predictive in flavor models.

- Non-linear MSSM: new quartic Higgs coupling: contribution to Higgs mass,important for $\sqrt{f} < 10$ TeV.

- Alleviated fine-tuning of the electroweak scale.

- Hidden Z' can be the mediator between hidden sector and our sector.

- Chern-Simons couplings can generate gamma ray lines in the dark matter annihilation (signal in FERMI) ?

Thank you !