Can the Higgs be supersymmetric and composite?

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Introduction: Models for EWSB

- Particle physics can be described with great accuracy with the SM.
- On the other hand EWSB is just accomplished with an ad-hoc potential:

$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$

- This fundamental scalar Higgs introduces a problem in the theory: the hierarchy problem.
- A complete description of EWSB should explain both the mechanism and the nature of the Higgs.

- There has been different suggestions to complete the SM in order to give a description to the EWSB sector:

  - Dynamical generation of the weak scale: Strongly interacting theories.

  - Radiative stable symmetry breaking: Supersymmetry.

- Let me briefly review the reasons why the first possibility is disfavoured with respect to the second.

- The idea of a dynamical origin of the EWS is natural in the sense that the rest of the spontaneous symmetry breaking of nature can be described in this way, e.g. BCS, chiral symmetry breaking in QCD,....

- There are two different approaches:

  - Strong dynamics that generate EWSB: Technicolour

  - Dynamical generation of a Higgs: PGB

- Let me discuss a bit both possibilities.

Technicolour

- The basic set-up is a theory analogous to QCD that condenses at Λ_{TC}, and due to that condensation EWS is broken.

- Unitarity of W^+W^- requires $\Lambda_{TC} \sim 1\ TeV$, whereas LEP bounds on EW observables tell us that any contribution to those observables with O(1) coefficients should be suppressed by a much bigger scale.

- This problems plus the lack of a complete model for flavour were the reasons why technicolour was abandoned.

Higgs as PGB

- Using the knowledge of the case of the pions in QCD the SM is embeded in a bigger global structure:

$$SM \subset G$$

- With the Higgs belonging to the coset of those two groups. When G is broken to the SM the Higgs arises as the goldstone of the broken generators.

- In order to give a potential to the Higgs, G should not be exact.

- These theories have their bigger problems in generating a viable quartic for the Higgs.
- The advantage of PSB with respect to technicolour is that one can postpone the scale of new physics to higher values so contributions to the EW parameters are in general smaller than in technicolor.
- This type of approach to the EWSB is been revisited recently thanks to the RS and the AdS/CFT correspondance.

MSSM: Blessings and curses

- The MSSM has been the most studied possibility of physics beyond SM because:
  - It provides a solution to the hierarchy problem
  - It naturally accomodates unification
  - It has a DM candidate
  - It has a relatively small impact on EW observables
  - EWSB can be triggered radiatively
  - It does not need a UV completion

- But not everything is as desired in the MSSM:
  - SUSY must be broken and there is no an unique way of doing it. Moreover none of the mechanism available in the market is a complete satisfaction.
  - Flavour is a big issue because most scenarios within the MSSM tend to predict to much FCNCs.
  - The amount of free parameters O(100) makes the model difficult to work with.

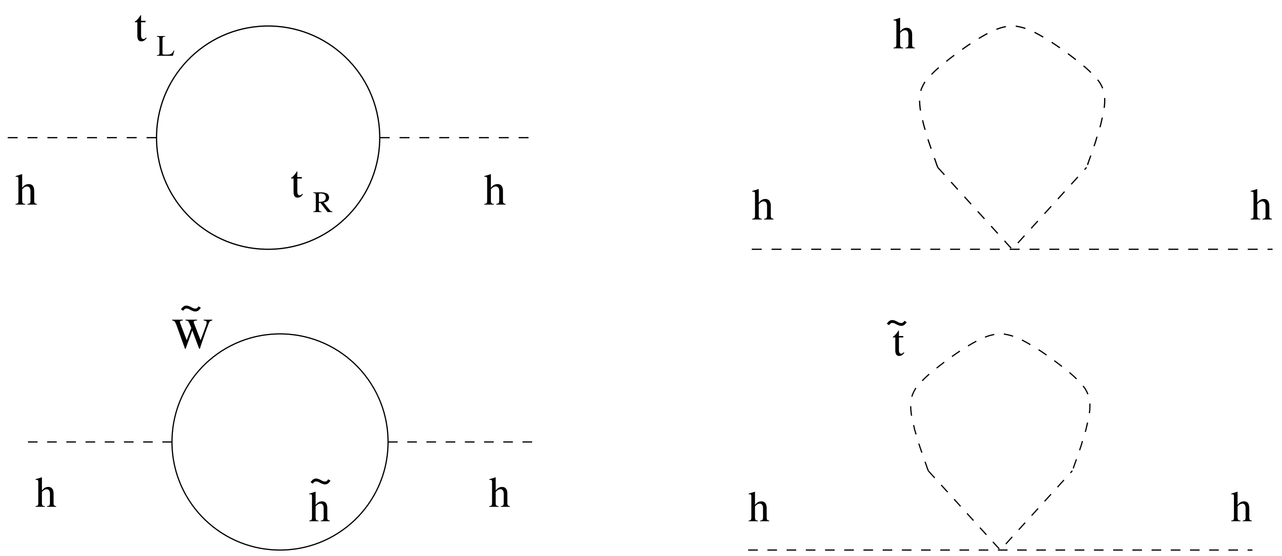
- But the bigger problem of the MSSM comes from the fact that neither the Higgs nor any sparticle has been discovered and the fine-tunning that this fact introduces in the theory.

- The physical mass of the Higgs is given in the MSSM by this formula:

$$m_h^2 = m_z^2 \cos^2 2\beta + \frac{3m_t^4}{8\pi^2 v^2} \log \frac{\tilde{m}^2}{m_t^2}$$

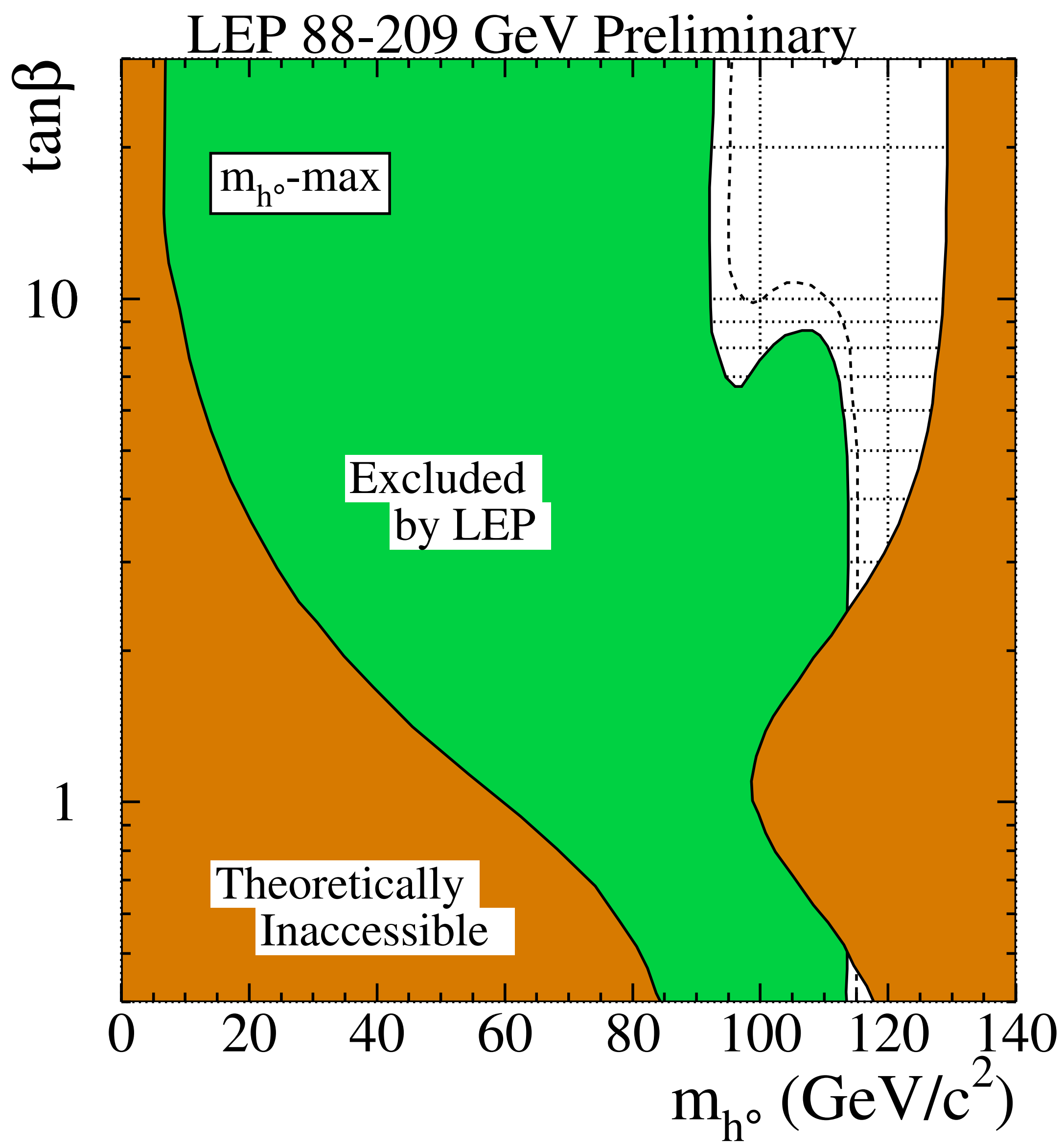
- Where $\tilde{m}$ is the mass of the stops.

- On the other hand hand susy particles (stops) play the rôle of cutting-off the quadratic divergence of the SM:



$$m_h^2 \sim (m_h^2)_0 + \frac{g^2}{16\pi^2}\tilde{m}^2$$

- So a big $\tilde{m}$ will make the physical mass higher, but inducing a bigger fine-tunning.

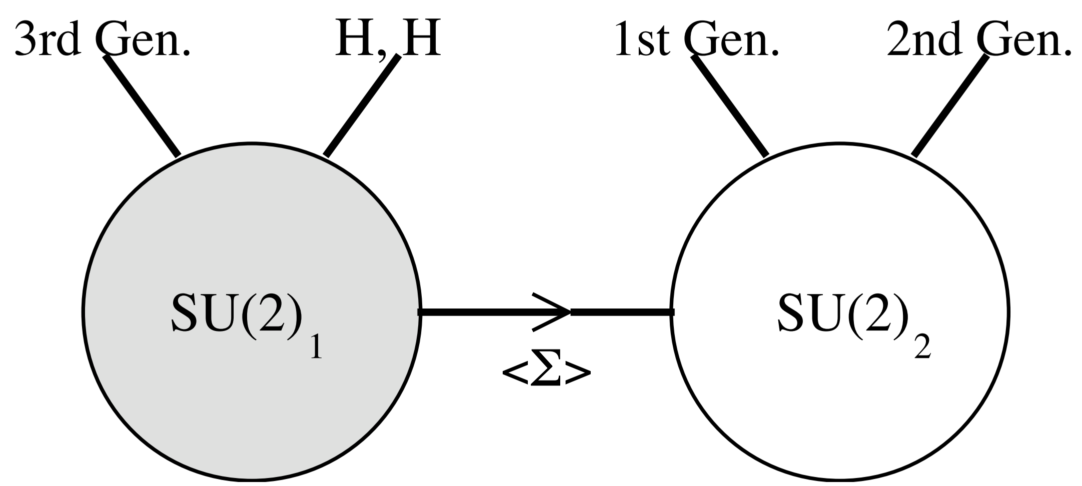


- The above plot supposes that $\tilde{m} \leq 1\ TeV$ which for the upper bound already gives something like 1% fine-tunning.

Raising the Higgs mass: D and F terms

- One way to try to alleviate that fine-tunning is to find a way to make the tree-level contribution to the Higgs mass bigger not to relay on the loop contribution to overcame the LEP bound so that stops can be lighter.
- I am going to present two models, one base on a new D-term contribution and the second one on a new superpotential contribution.

D-term (gauge extension)



- The model is based on a $SU(2)_1 \times SU(2)_2$ model broken to the diagonal at a similar scale where SUSY is broken.
- The matter content is such that the first $SU(2)$ is asymptotically free.
- Additional higgses are needed for yukawas in the second $SU(2)$.

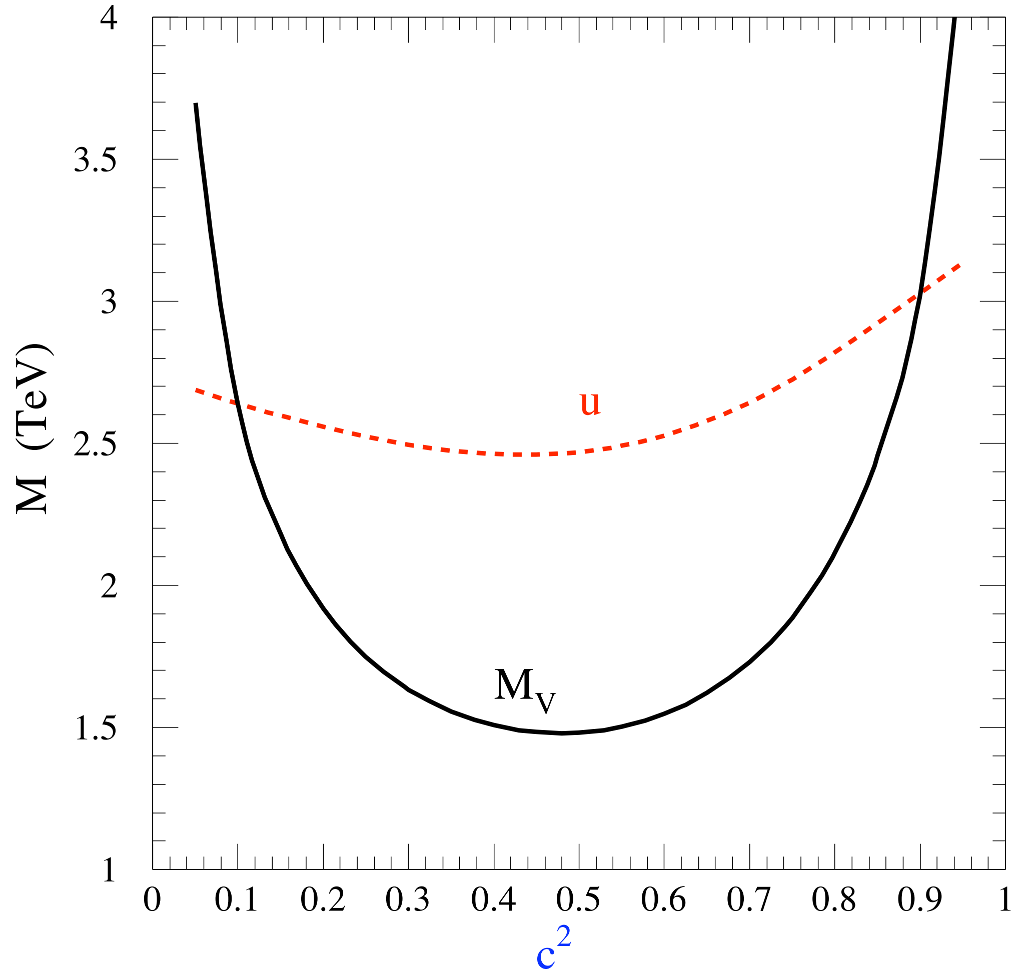
- Below the scale of SUSY(m) and diagonal(u) breaking, integrating out massive fields, the following quartic is generated:

$$\frac{g^2}{8}\Delta\left(H^\dagger\vec{\sigma}H-\overline{H}\vec{\sigma}\overline{H}^\dagger\right)^2+\frac{g_Y^2}{8}\left(|\overline{H}|^2-|H|^2\right)^2$$

$$\Delta=\frac{1+\frac{2m^2}{u^2}\frac{1}{g_2^2}}{1+\frac{2m^2}{u^2}\frac{1}{g_1^2+g_2^2}}\qquad\frac{1}{g^2}=\frac{1}{g_1^2}+\frac{1}{g_2^2}$$

- Upon EWSB the following tree-level mass is obtained:

$$m_{h^o}^2<\frac{1}{2}\left(g^2\Delta+g_Y^2\right)v^2\cos^2 2\beta$$



- A possible choice of parameters consistent with the EW fit, perturbativity and fine-tuning:

$$g_1(u) = 1.80,\ g_2(u) = .70,\ u = 2.4\ TeV\ \ M_{W'}, M_{Z'} \sim 4.5\ TeV m = 10\ TeV$$

- Leading to the following mass:

$$\Delta = 6.97 \Longrightarrow m_h = 214\ GeV$$

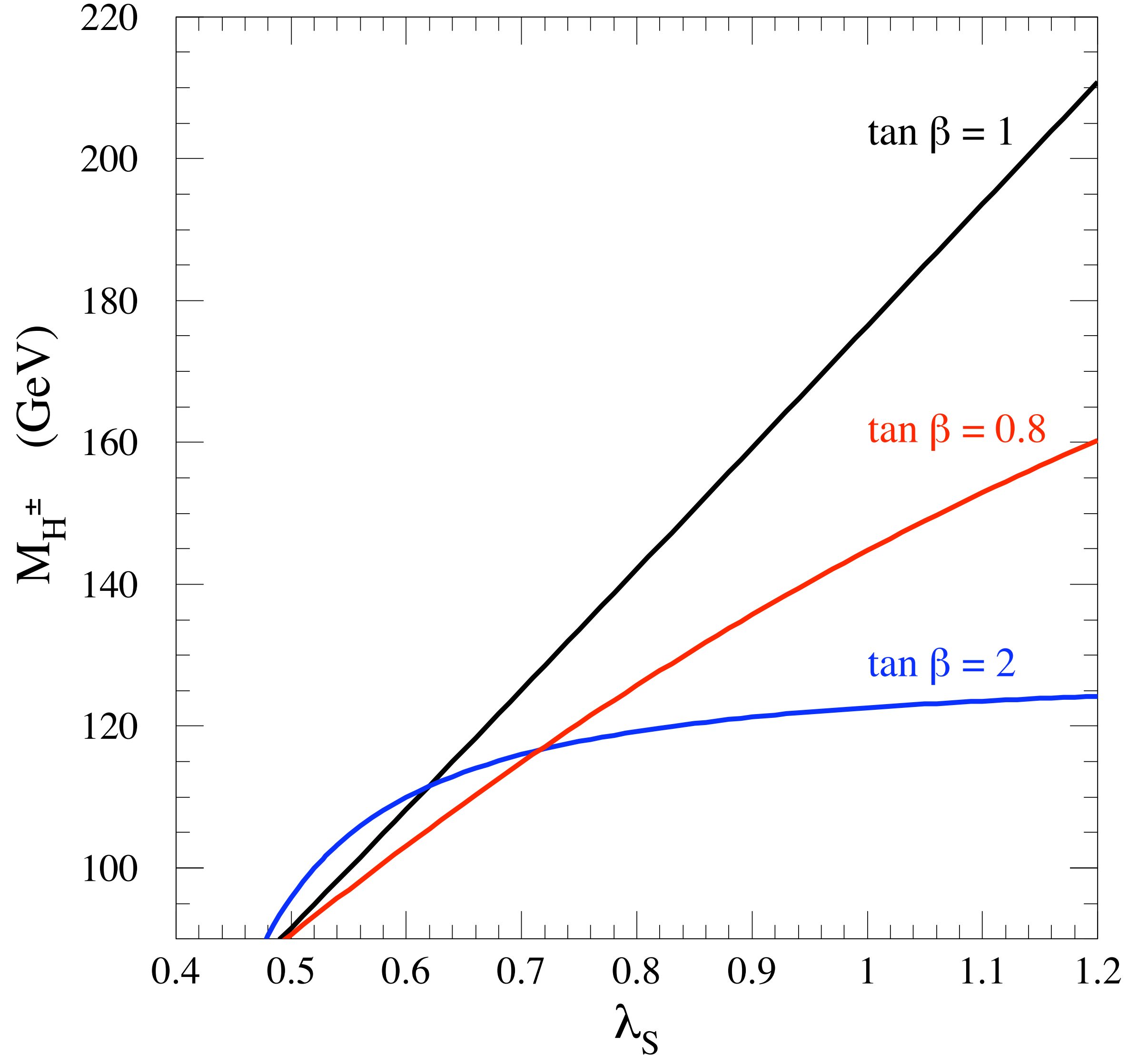
F-Term (NMSSM)

$$\Delta W = \lambda S \overline{H} H$$

- The usual NMSSM has a relatively small effect $\sim 150\ GeV$, due to perturbativity.
- We can make use of the previous set-up to increase the maximun value for λ since now runs with the strong SU(2) .
- Imposing pertubativity up to M_G, with similar parameters:

$$\lambda \leq 1.4$$

$$m_h^2 = m_z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta \Longrightarrow m_h \sim 250\ GeV$$



- Other interesting features of this asymptotically free NMSSM, is the opening of parameter space $\tan\beta < 1$ or charged higgs the lightest.

Composite Higgs?

- Having worked with strong interactions to increase the Higgs mass one may ask: what happens if we let the group confine?.
- I am going to present a model where the Higgs and the top quark are composites.
- With this set-up the large yukawa of the top can be explain due to the compositeness of those particle and thus related to the strong dynamics.
- EWSB is aided by a singlet and is generated at tree-level.

- The model is based on the gauge structure:

$$SU(3)_s \times SU(3)_c \times SU(2)_W \times U(1)_Y$$

- Where the $SU(3)_s$ will eventually condense and produce some of the SM particles as composites

- The preons of that groups are sumarized in the following table:

	$SU(3)_s$	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	Z_2
P_3	$\square$	$\square$	$\mathbf{1}$	0	$+$
P_1	$\square$	$\mathbf{1}$	$\mathbf{1}$	$-2/3$	$-$
$\overline{P}_2$	$\overline{\square}$	$\mathbf{1}$	$\square$	$+1/6$	$-$
$\overline{P}_1$	$\overline{\square}$	$\mathbf{1}$	$\mathbf{1}$	$+2/3$	$+$
$\overline{P}_{\tilde{1}}$	$\overline{\square}$	$\mathbf{1}$	$\mathbf{1}$	$-1/3$	$-$
P'	$\square$	$\mathbf{1}$	$\mathbf{1}$	$+1/3$	$-$
$\overline{P}'$	$\overline{\square}$	$\mathbf{1}$	$\mathbf{1}$	$-1/3$	$-$

- This model has anomalies with respect to the SM gauge group which simply show that NOT ALL of the SM fields are composite.

- We have the following fundamental fields:

	$SU(3)_s$	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	Z_2
L_i	$\mathbf{1}$	$\mathbf{1}$	$\square$	$-1/2$	$-$
e_i	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$+1$	$-$
$Q_{1,2}$	$\mathbf{1}$	$\square$	$\square$	$+1/6$	$-$
d_i	$\mathbf{1}$	$\overline{\square}$	$\mathbf{1}$	$+1/3$	$-$
$u_{1,2}$	$\mathbf{1}$	$\overline{\square}$	$\mathbf{1}$	$-2/3$	$-$
$\overline{q}_1$	$\mathbf{1}$	$\overline{\square}$	$\mathbf{1}$	$-2/3$	$+$
$\overline{q}_2$	$\mathbf{1}$	$\overline{\square}$	$\mathbf{1}$	$+1/3$	$-$
H'	$\mathbf{1}$	$\mathbf{1}$	$\square$	$+1/2$	$+$
$\overline{H}'$	$\mathbf{1}$	$\mathbf{1}$	$\square$	$-1/2$	$+$

- The strong group has 3 colours and 5 flavours so is in the conformal window, but if we include the following superpotential:

$$W = M\overline{P}'P'$$

- Below the scale M the theory will condense and can be described with the following fields:

		$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	Z_2
$B_1 \leftrightarrow t_R$	$P_3P_3P_1$	$\overline{\square}$	$\mathbf{1}$	$-2/3$	$-$
$B_2 \leftrightarrow S$	$P_3P_3P_3$	$\mathbf{1}$	$\mathbf{1}$	0	$+$
$\overline{B}_1 \leftrightarrow H$	$\overline{P}_2\overline{P}_1\overline{P}_{\tilde{1}}$	$\mathbf{1}$	$\square$	$+1/2$	$+$
$\overline{B}_2 \leftrightarrow \psi$	$\overline{P}_2\overline{P}_2\overline{P}_1$	$\mathbf{1}$	$\mathbf{1}$	$+1$	$+$
$\overline{B}_3 \leftrightarrow \chi$	$\overline{P}_2\overline{P}_2\overline{P}_{\tilde{1}}$	$\mathbf{1}$	$\mathbf{1}$	0	$-$
$M_1 \leftrightarrow Q_3$	$P_3\overline{P}_2$	$\square$	$\square$	$+1/6$	$-$
$M_2 \leftrightarrow q_1$	$P_3\overline{P}_1$	$\square$	$\mathbf{1}$	$+2/3$	$+$
$M_3 \leftrightarrow q_2$	$P_3\overline{P}_{\tilde{1}}$	$\square$	$\mathbf{1}$	$-1/3$	$-$
$M_4 \leftrightarrow \overline{H}$	$P_1\overline{P}_2$	$\mathbf{1}$	$\square$	$-1/2$	$+$
$M_5 \leftrightarrow \overline{\chi}$	$P_1\overline{P}_1$	$\mathbf{1}$	$\mathbf{1}$	0	$-$
$M_6 \leftrightarrow \overline{\psi}$	$P_1\overline{P}_{\tilde{1}}$	$\mathbf{1}$	$\mathbf{1}$	-1	$+$

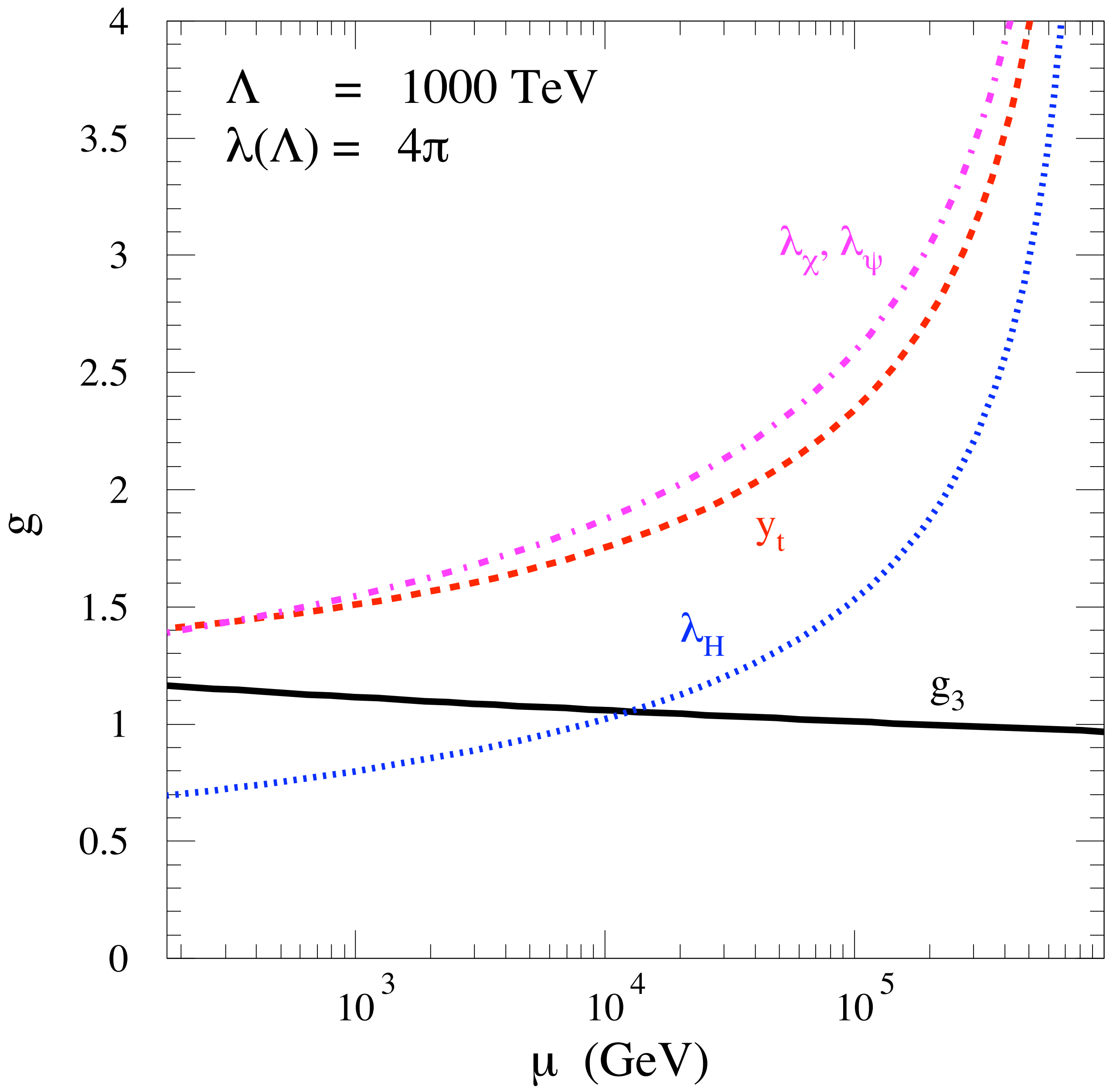
- Upon condensation the following superpotential is dynamically generated:

$$W = \frac{1}{\Lambda^3}(\overline{B}MB - detM)$$

$$\to \lambda(HQ_3t_R + H\overline{H}S + \ldots)$$

- So among some other terms we generate both the yukawa for the top and a quartic coupling for the Higgs.

- We are left to calculate the value of the condensation scale.



- For $\Lambda = 1000\ TeV$ we manage to reproduce the observed top mass.

- EWSB is not radiative but tree-level adding the following superpotential coupling:

$$W_s = -y_s \epsilon_{\alpha\beta\gamma} P_3^\alpha P_3^\beta P_3^\gamma$$

$$\to - \left(\frac{y_s}{4\pi} \Lambda^2 \right) S$$

- This will add up to the following Higgs potential:

$$V = \lambda_H S (H\overline{H} - v_0^2)$$

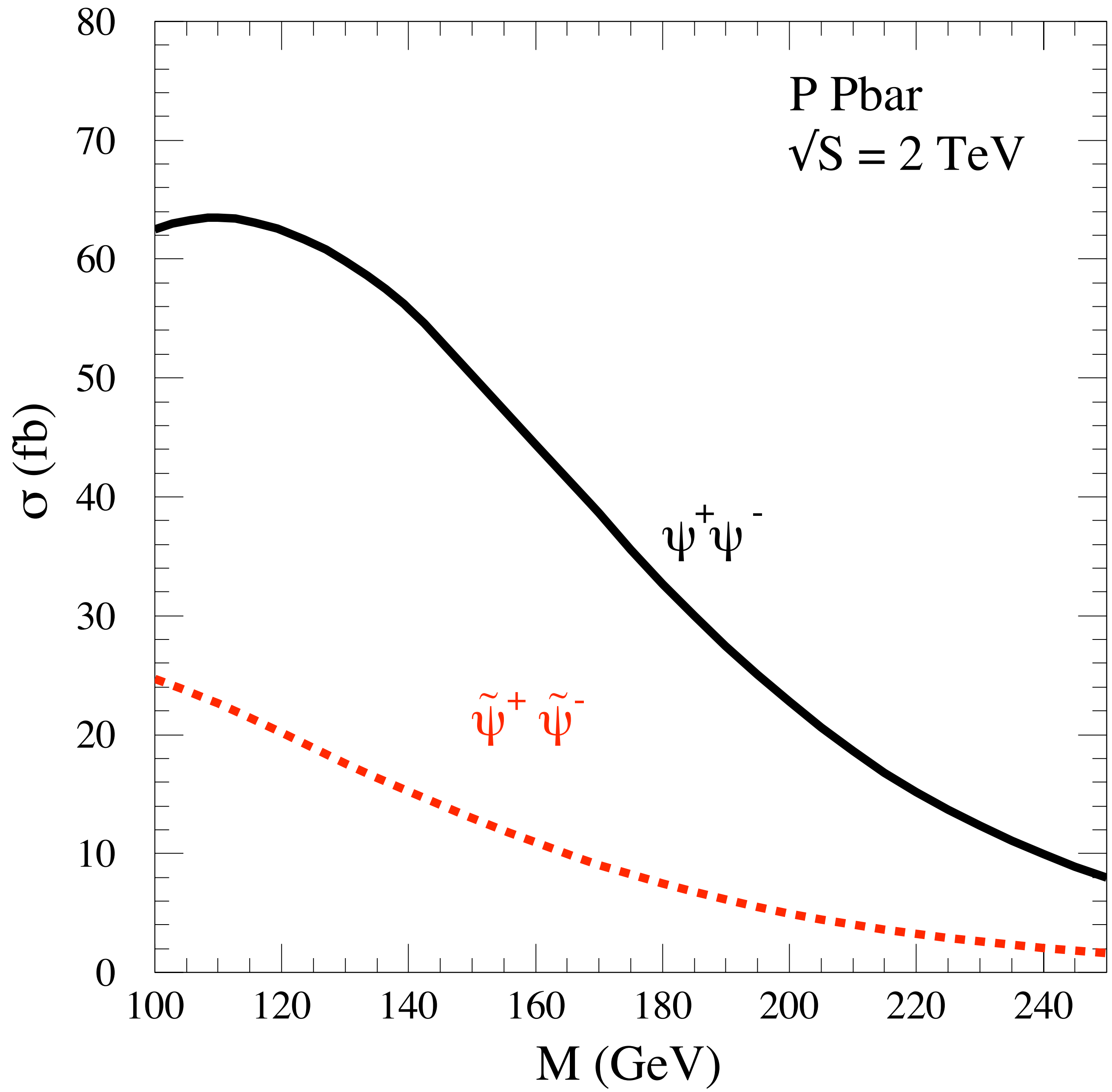
- Where $v_0^2 = \frac{y_s}{16\pi^2}\Lambda^2$

- The rest of yukawa couplings for the fundamental fermions are generated through superpotential couplings between preons, they are naturally smaller than the yukawa coupling of the top.

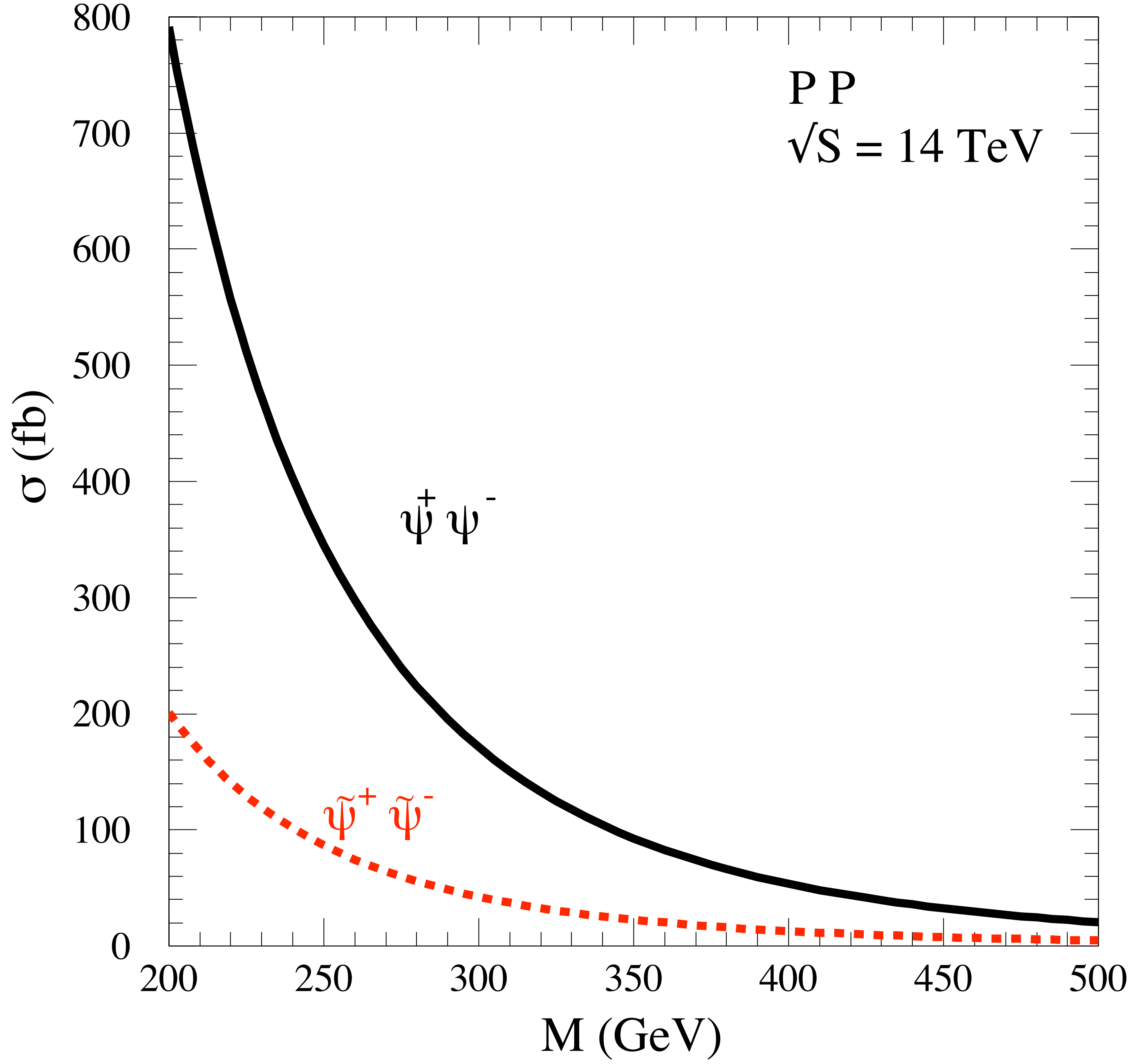
- Phenomenology of the model include an extra stable particle apart from the LSP, and a long lived one.

- The Higg mass is naturally greater than the LEP bound.

- Unification can be accomodated but not in a GUT.



- Here we have the cross-section for production of the charged quasi-stable particle for the TEVATRON



- Here we have the cross-section for production of the charged quasi-stable particle for LHC

Conclusions

- The breaking of EW symmetry remains as the only ingredient left to be discover within the SM.
- Although the real mechanism of generation of that breaking is part of the realm of physics BSM.
- There has been during the last decades different possibilities to explain the origin of that breaking.
- Among them perhaps SUSY has been the most studied, but nowadays the MSSM is not in the healthy shape it was before LEP-II.

- In this sort of review talk I have tried to go through the different possibilities in the market.
- NONE of them is complete, and moreover if we allowed for 10% fine-tunning MANY of them are allowed.
- I have also showed how the fine-tunning of SUSY theories related to the Higgs mass can be reduced in theories with enhanced gauge symmetries.
- Even maybe the Higgs can be both composite and supersymmetric getting benefits from both worlds.