Electroweak Breaking with Custodial Triplets

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- **Motivation**
- **The Model**
- **The Model at loop level**
- **Some results**
- **Summary**

Motivation

Thanks to the LHC, we are starting to unveil the true nature of EW symmetry breaking.

Two questions arise

Data (Higgs and nothing else) points towards a single doublet breaking the symmetry.

Could it be that the Electroweak breaking is triggered by something beyond the minimal model?

Is supersymmetry there? do we still think it should be as "natural" as possible?

If so, minimal models are under considerable experimental tension. Besides, the Higgs mass is still compatible with SUSY but heavier than expected.

There is still some room for modifications

How do we solve this?

An extended Higgs sector can help to make the Higgs mass heavier!

Extended Higgs sectors have been studied for a while. In particular triplet extensions can acommodate neutrino masses (via see-saw mechanism) and give rise to interesting phenomenology.

Extended Higgs sectors: The rho parameter

Triplets extensions of the Higgs sector are interesting but,

$$\boxed{\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1 + \ldots}$$

If we add anything <u>bigger than a doublet</u> and it acquires a vev,

$$\rho \neq 1$$

How can we fix this?

making the new vevs unnaturally small

in SUSY, making soft masses extra large

<u>With Symmetry</u>

The custodial symmetry protects $\rho = 1$ at tree level

$$SU(2)_L \otimes SU(2)_R \to SU(2)_V$$

<u>Add triplets, but! make the theory custodially invariant.</u>

Triplets + custodial symmetry

H. Georgi, M. Machacek '85

GM model

DOUBLY CHARGED HIGGS BOSONS

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Received 8 July 1985

We explore through two simple models, the first in which scalars are treated as fundamental and the second in which they are composite objects, the possibility that representations containing doubly charged scalars may participate in the spontaneous breakdown of the SU(2) × U(1) symmetry of electroweak interactions. We show that such exotic Higgs bosons may possess unsuppressed couplings to pairs of gauge vector bosons and comment on the observability of these charged Higgs bosons through the Cahn-Dawson mechanism in high-energy hadron colliders

one complex + one real SU(2)L scalar triplets ordered in such a way that custodial symmetry is preserved.

The non SUSY version of the GM model had issues that the Supersymmetry is expected to fix.

More on this later!

In a loop analysis, there is no natural scale to choose the custodial point

Quadratic divergences show up in the corrections to the rho parameter, making the SM fine tuning issue worse.

We have explicitly shown that SUSY takes care of these quadratic divergences, as it does with the usual ones.

J.F. Gunion, R. Vega, J. Wudka '90

It is interesting to explore the supersymmetric generalization of the GM model

The Model

The SUSY GM model

L. Cort, M. Quirós, MG '13

MSSM Higgs sector + 3 $SU(2)_L$ triplets

$SU(2)_L$

Doublets

$$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}$$

Y=-1/2

$$H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$$

Y=+1/2

Triplets

$$\Sigma_1 = \Sigma_1^i \sigma_i = \begin{pmatrix} \frac{\psi^+}{\sqrt{2}} & \psi^{++} \\ \psi^0 & -\frac{\psi^+}{\sqrt{2}} \end{pmatrix}$$

Y=+1

$$\Sigma_0 = \Sigma_0^i \sigma_i = \begin{pmatrix} \frac{\phi^0}{\sqrt{2}} & \phi^+ \\ \phi^- & -\frac{\phi^0}{\sqrt{2}} \end{pmatrix}$$

Y=0

$$\Sigma_{-1} = \Sigma_{-1}^i \sigma_i = \begin{pmatrix} \frac{\chi^-}{\sqrt{2}} & \chi^0 \\ \chi^{--} & -\frac{\chi^-}{\sqrt{2}} \end{pmatrix}$$

Y=-1

How does it work?

In order to write custodial invariants the Higgs sector SU(2)L multiplets are organized under SU(2)R multiplets.

$SU(2)_L \otimes SU(2)_R$

bidoublet $\mathbf{2} \otimes \bar{\mathbf{2}}$

$$\bar{H} = \left(\begin{array}{c} H_1 \\ H_2 \end{array} \right)$$

bitriplet $\mathbf{3} \otimes \bar{\mathbf{3}}$

$$\bar{\Delta} = \Sigma^i \bar{\sigma}_i = \left(\begin{array}{cc} -\frac{\Sigma_0}{\sqrt{2}} & -\Sigma_{-1} \\ -\Sigma_{-1} & \frac{\Sigma_0}{\sqrt{2}} \end{array} \right)$$

How do these objects behave?

Transformation rules under $SU(2)_L \otimes SU(2)_R$

$$\bar{H} \to (\bar{U}_R \otimes U_L)\, \bar{H} \qquad \bar{\Delta} \to (\bar{U}_R \otimes U_L)\, \bar{\Delta}\, (U_L^\dagger \otimes \bar{U}_R^\dagger)$$

the vacuum will be $SU(2)_V$ invariant if $\theta_R = \theta_L$. And the following identities are satisfied,

$$\langle \bar{H} \rangle = (\bar{U}_R \otimes U_L)\, \langle \bar{H} \rangle \qquad \langle \bar{\Delta} \rangle = (\bar{U}_R \otimes U_L)\, \langle \bar{\Delta} \rangle (U_L^\dagger \otimes \bar{U}_R^\dagger)$$

$$\langle \bar{H} \rangle = (\bar{U}_R \otimes U_L)\,\langle \bar{H} \rangle \qquad \langle \bar{\Delta} \rangle = (\bar{U}_R \otimes U_L)\,\langle \bar{\Delta} \rangle (U_L^\dagger \otimes \bar{U}_R^\dagger)$$

$$\theta_R = \theta_L$$

This relation is only satisfied if we choose a **custodially preserving direction of the vacuum,**

$$v_1 = v_2 \equiv v_H$$
$$v_\chi = v_\phi = v_\psi \equiv v_\Delta$$

Note that if we fix the vev of the triplet we also fix the vev that the doublet will acquire and viceversa:

$$v_{EW}^2 = 2v_H^2 + 8v_\Delta^2$$

What are the invariants that we can construct?

Superpotential

$$W_0 = \lambda \bar{H} \cdot \bar{\Delta} \bar{H} + \frac{\lambda_3}{3} \mathrm{Tr}(\bar{\Delta}^3) + \frac{\mu}{2} \bar{H} \cdot \bar{H} + \frac{\mu_\Delta}{2} \mathrm{tr}(\bar{\Delta}^2)$$

Soft terms

$$V_{\mathrm{Soft}} = m_H^2 |\bar{H}|^2 + m_\Delta^2 \mathrm{Tr}(|\bar{\Delta}|^2) + \frac{1}{2} m_3^2 \bar{H} \cdot \bar{H}$$
$$+ \left(\frac{1}{2} B_\Delta \mathrm{Tr}(\bar{\Delta}^2) + A_\lambda \bar{H} \cdot \bar{\Delta} \bar{H} + \frac{1}{3} A_{\lambda_3} \mathrm{Tr}(\bar{\Delta}^3) + h.c. \right)$$

Tree level features: scalar spectrum

Since the vacuum is custodially invariant the scalar spectrum will show some ordering under SU(2)V

$$SU(2)_L \otimes SU(2)_R \to SU(2)_V$$

$$\bar{\Delta} = \mathbf{3} \otimes \mathbf{3} = \delta_1 \oplus \delta_3 \oplus \delta_5$$

$$\bar{H} = \mathbf{2} \otimes \bar{\mathbf{2}} = \mathbf{h_1} \oplus \mathbf{h_3}$$

Fiveplets:

$F_S \quad F_P$

Singlets:

S_1 **Higgs-like state!**

$S_2 \quad P_1 \quad P_2$

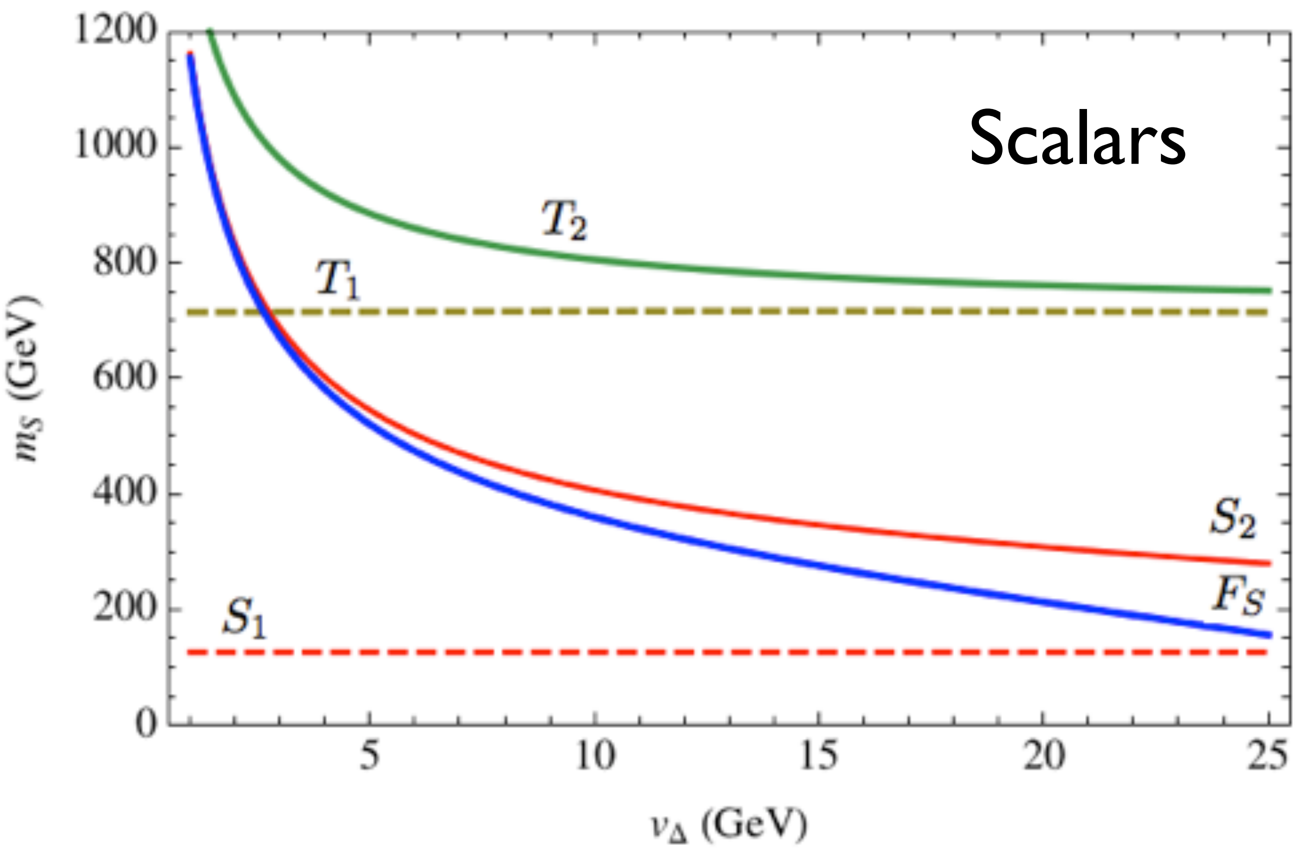
Triplets:

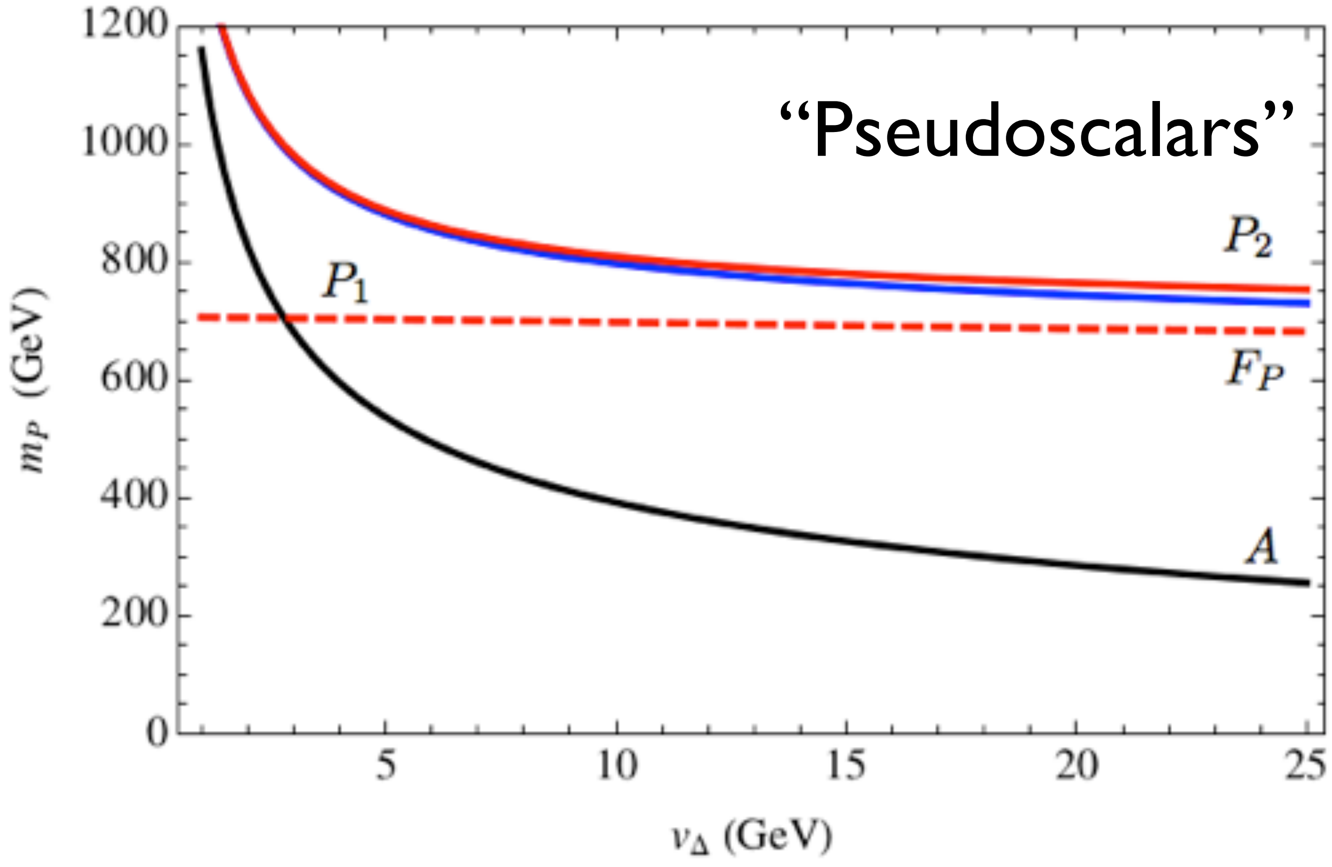
G **Goldstone triplet!**

$A \quad T_1 \quad T_2$

For a given point in the parameter space:

$$A_\lambda = A_{\lambda_3} = 0$$
$$B_\Delta = -m_3^2$$
$$\mu = \mu_\Delta = 250\,\mathrm{GeV}$$
$$m_3 = 500\,\mathrm{GeV}$$





The Model at loop level

The Model at loop level

U(1) and Yukawa couplings will break the custodial symmetry inducing a non custodial situation at loop level.

How bad? $\xrightarrow{\textbf{determined by}}$ **RG running**

At which scale do we impose custodial symmetry?

The natural choice seems the scale at which the soft terms are generated. Both superpotential and soft terms will be custodially invariant there.

In the non-SUSY version there is no natural choice for this scale.

<u>A picture of what will happen:</u>

Soft SUSY scale
custodially preserving lagrangian

$\xrightarrow{}$ **RG running**

EW scale
smooth deformation of a custodially preserving lagrangian

EW vacuum
aproximatelly custodial vacuum

Parametrize the breaking

Since the "true" vacuum will not be custodial we need a way to parametrize the deviation from the custodial one:

We perform a rotation from the custodial direction

$$v_2 = \sqrt{2}\sin\beta v_H$$
$$v_1 = \sqrt{2}\cos\beta v_H$$
$$\tan\beta = \frac{v_2}{v_1}$$

MSSM

+

$$v_\psi = 2\cos\theta_1\cos\theta_0 v_\Delta$$
$$v_\chi = 2\sin\theta_1\cos\theta_0 v_\Delta$$
$$v_\phi = \sqrt{2}\sin\theta_0 v_\Delta$$

$$\tan\theta_0 = \frac{\sqrt{2}v_\phi}{\sqrt{v_\psi^2 + v_\chi^2}}$$
$$\tan\theta_1 = \frac{v_\chi}{v_\psi}$$

Triplets

How do we compute things?

A set of custodially preserving parameters is given at the soft SUSY scale, using the RGEs, these parameters are run down to the EW scale where the EOMs are solved and the values of different observables are computed.

Since we are performing the RG running, not only parameters of the Higgs sector need to be fixed, other ones like gaugino and squark masses (that are crucial in the running) will be fixed too.

More on this later!

Some Results

RG running

We leave as free parameters the amount of running (by changing the scale at which soft couplings are generated, the messenger scale M) and the custodially invariant vev of the triplet. We compute for each observable a contour plot on the $(v_\Delta, \mathcal{M})$ plane.

Which point? An interesting one

Higgs sector

$$\lambda_3 = 0.35$$

$$\mu = \mu_\Delta = 250\,\mathrm{GeV}$$

$$A_\lambda = A_{\lambda_3} = 0$$

$$m_H = m_\Delta = 1000\,\mathrm{GeV}$$

Soft masses

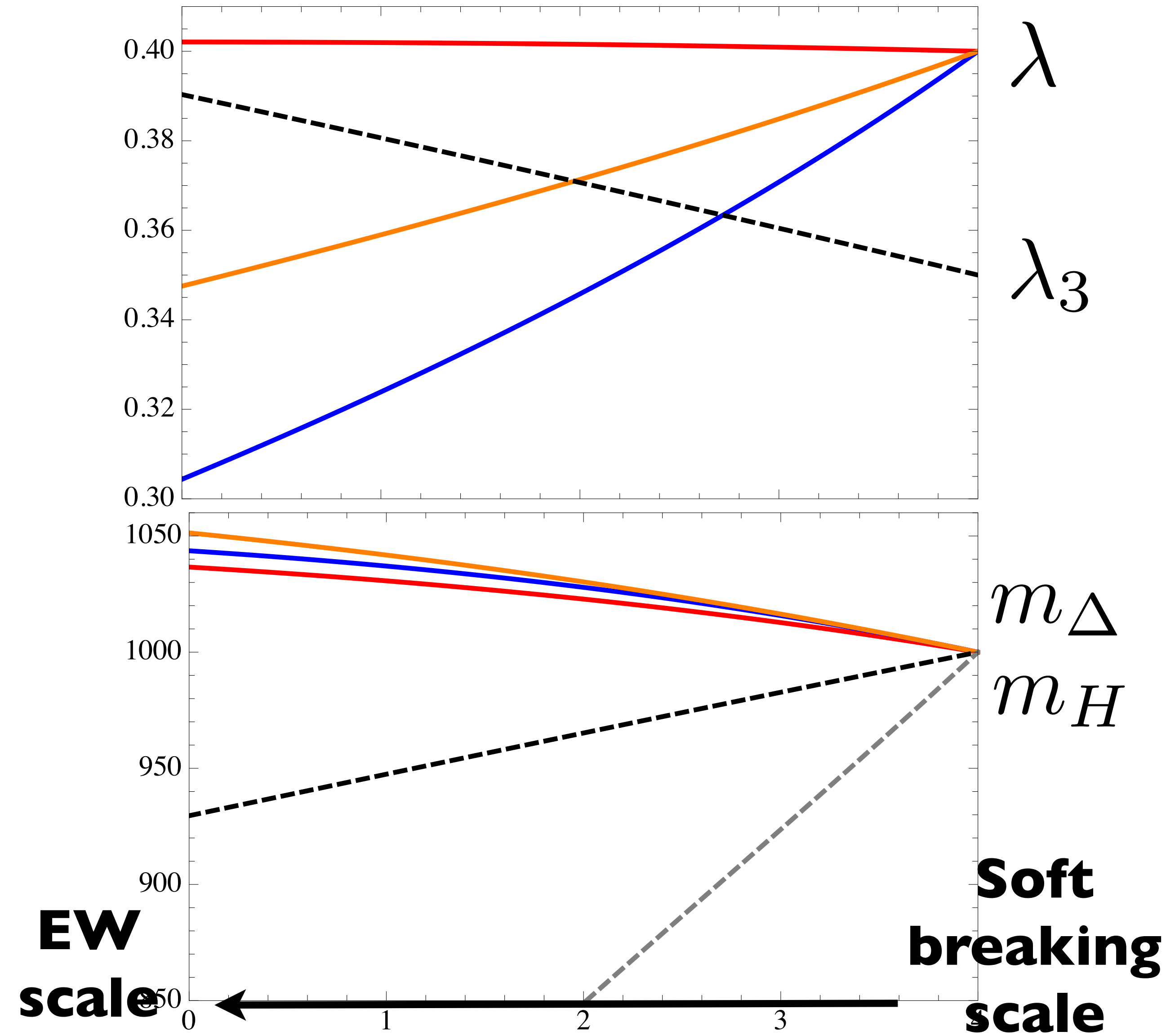
$$M_1 = M_2 = M_3 = 1000\,\mathrm{GeV}$$

$$m_{\tilde{Q}} = m_{\tilde{u}} = m_{\tilde{d}} = 500\,\mathrm{GeV}$$

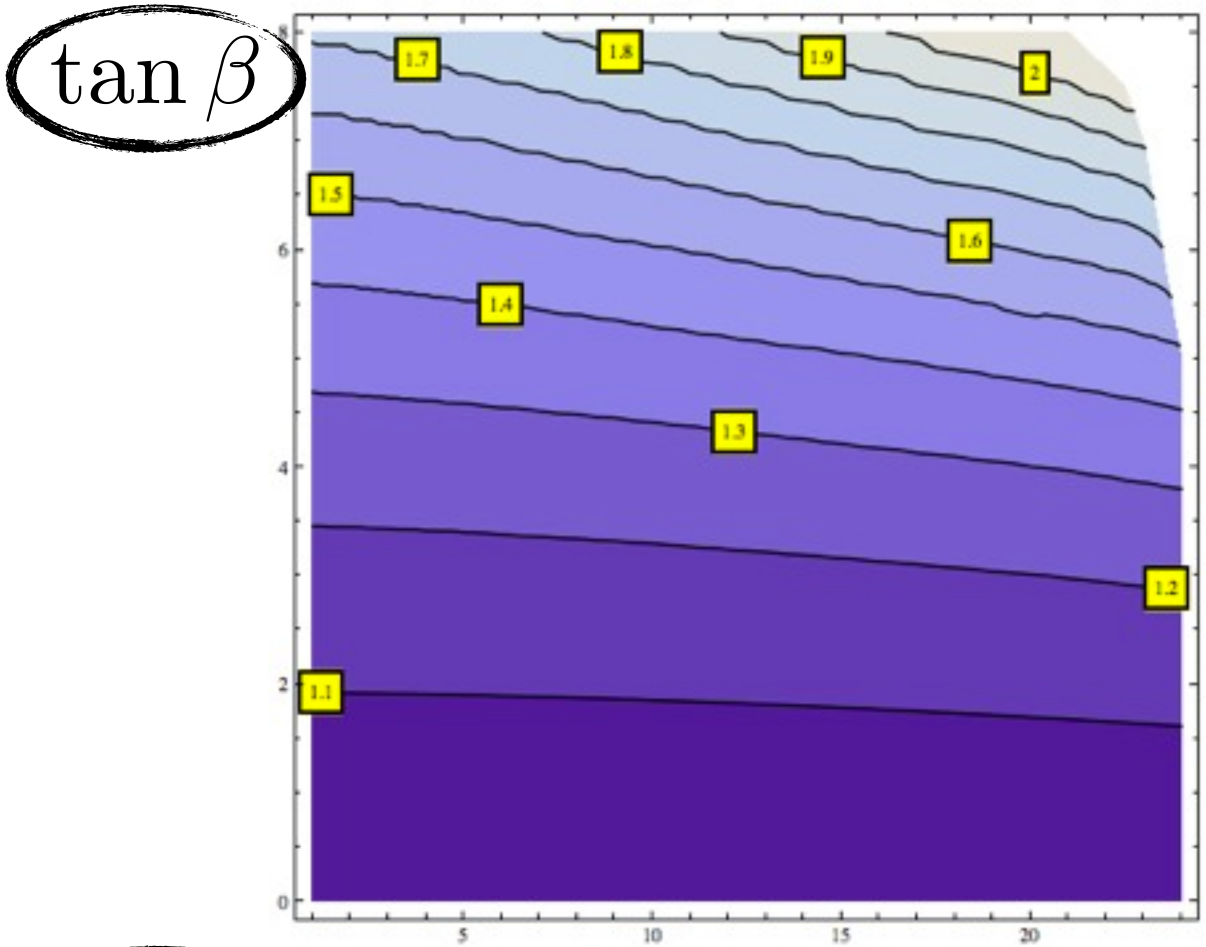
$$a_u = a_d = 0$$

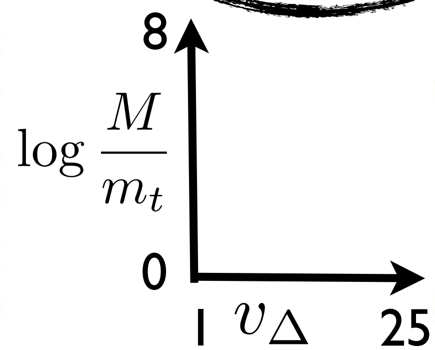
λ is adjusted so that the Higgs mass is correctly reproduced at the weak scale for every point in the $(v_\Delta, \mathcal{M})$ plane.

The introduction of new matter d.o.f. makes the theory develop Landau poles sooner than in minimal models. Also, the bigger the running the bigger the custodial breaking so low-med scale SUSY breaking is expected!

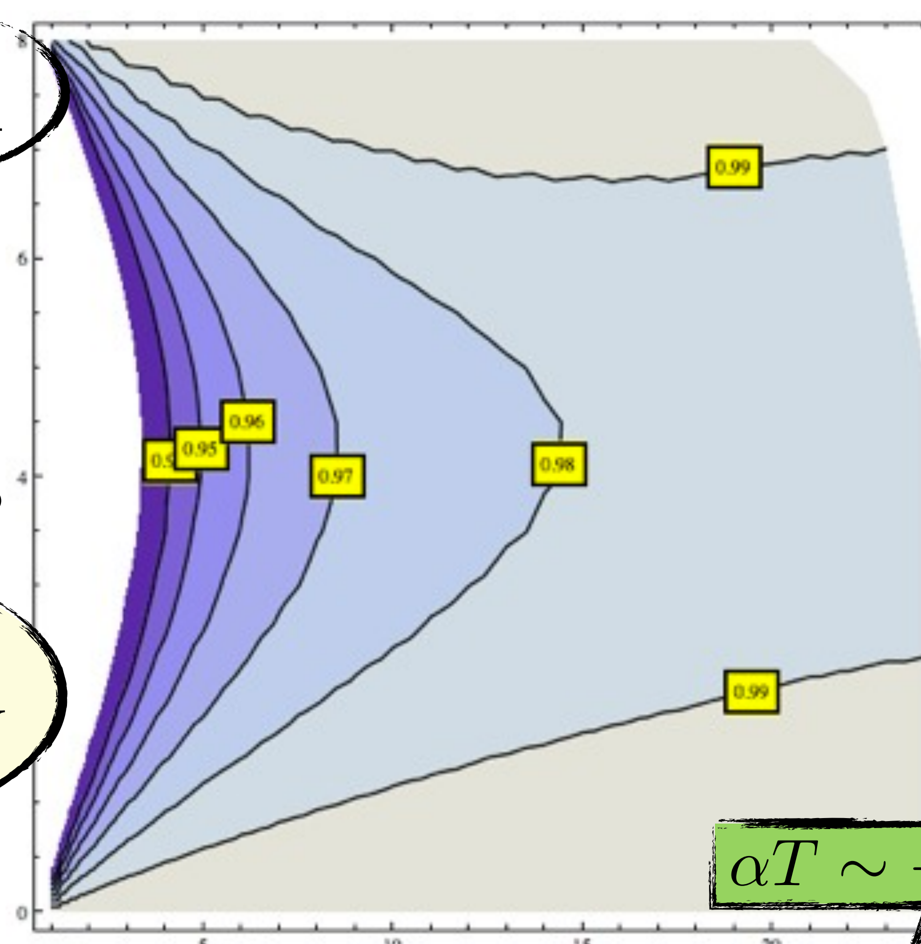


Some results: Angles and custodial breaking

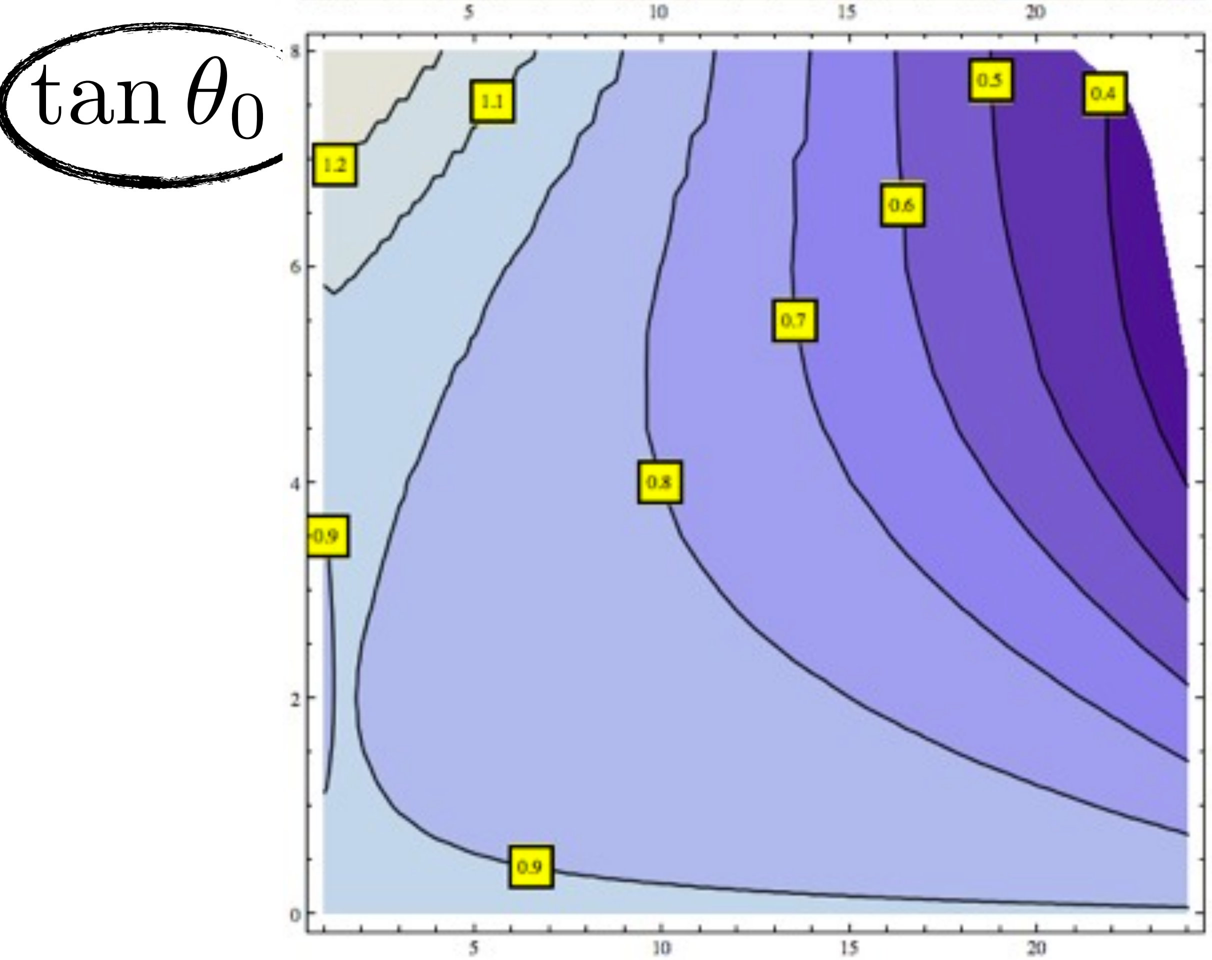


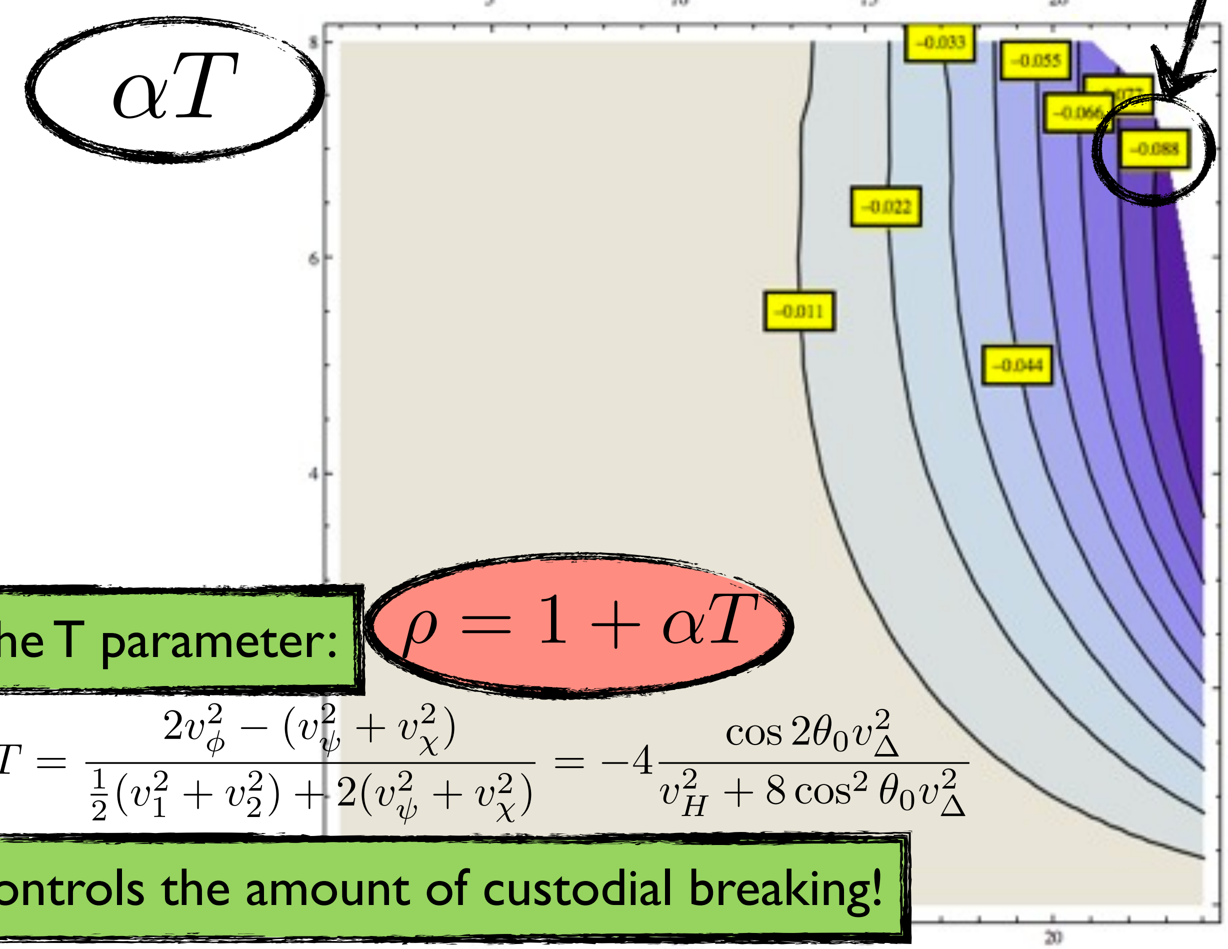


$\log\frac{M}{m_t} = 8$
$\to M \sim 500\,\mathrm{TeV}$



$\alpha T \sim -0.09$





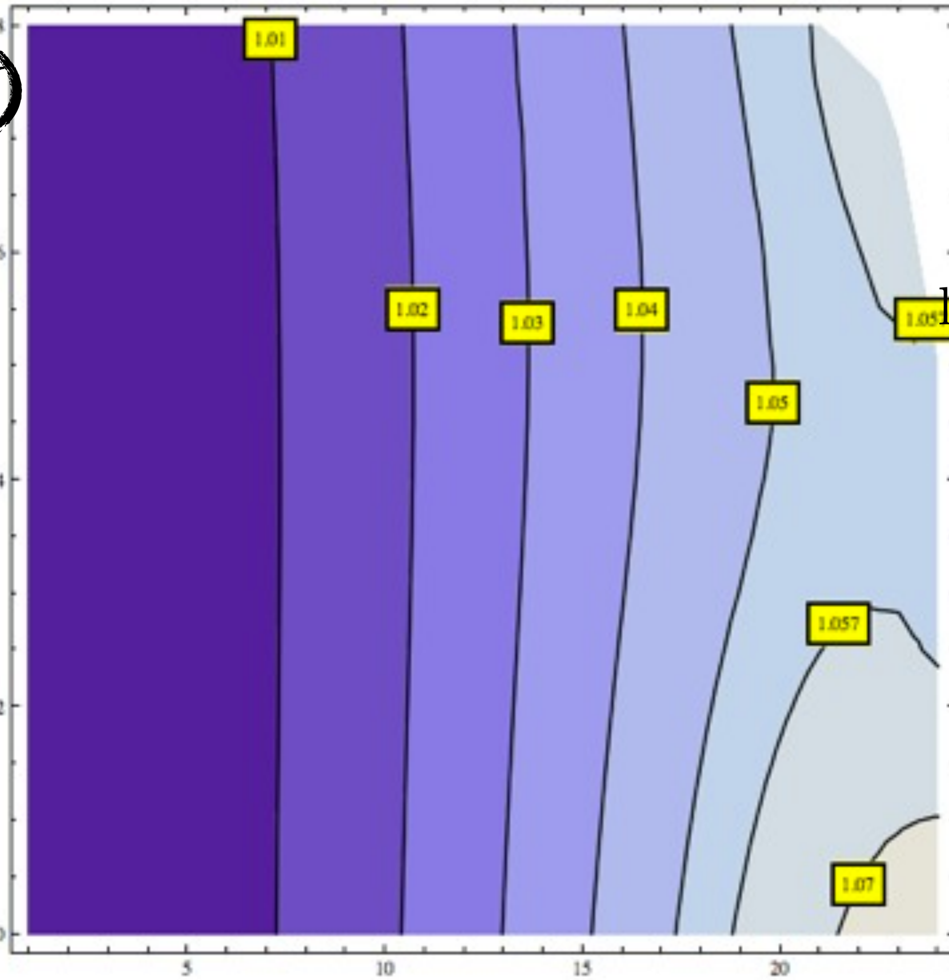
The T parameter: $\rho = 1 + \alpha T$

$$\alpha T = \frac{2v_\phi^2 - (v_\psi^2 + v_\chi^2)}{\frac{1}{2}(v_1^2 + v_2^2) + 2(v_\psi^2 + v_\chi^2)} = -4\frac{\cos 2\theta_0 v_\Delta^2}{v_H^2 + 8\cos^2\theta_0 v_\Delta^2}$$

Controls the amount of custodial breaking!

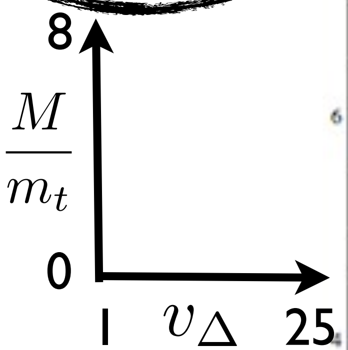
Some results: Couplings

r_{S_1WW}

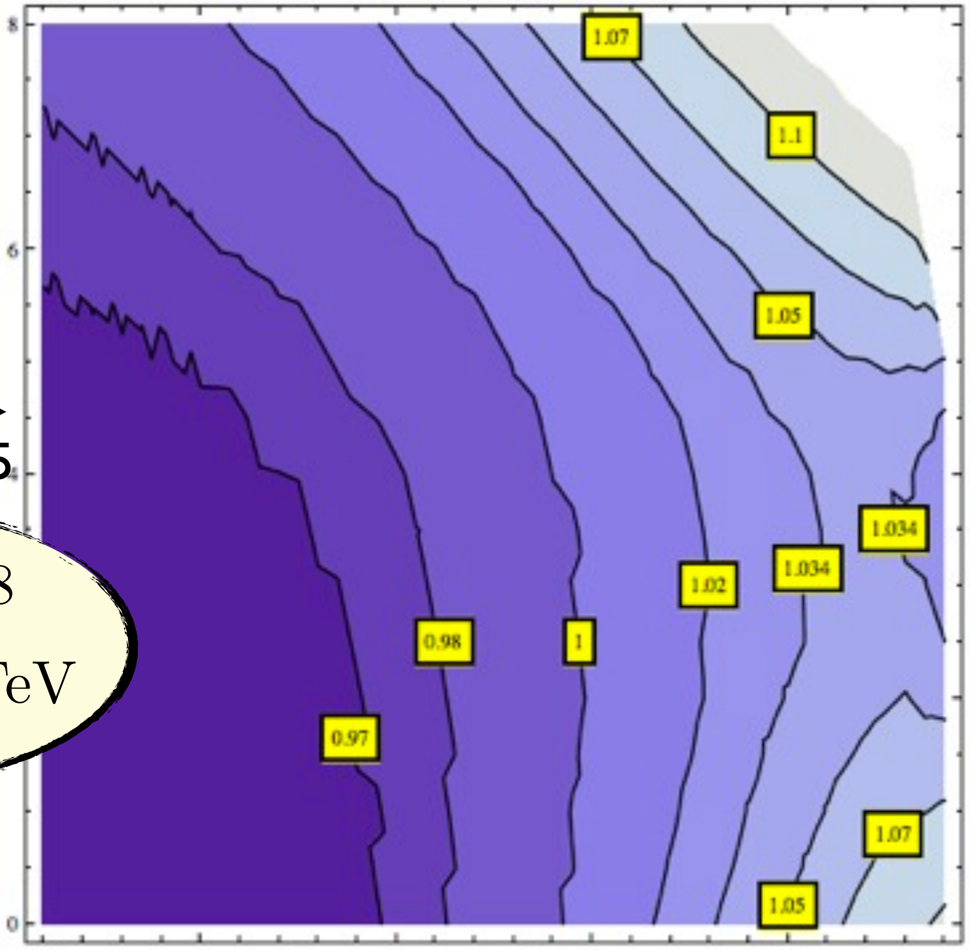


$S_1 = h$

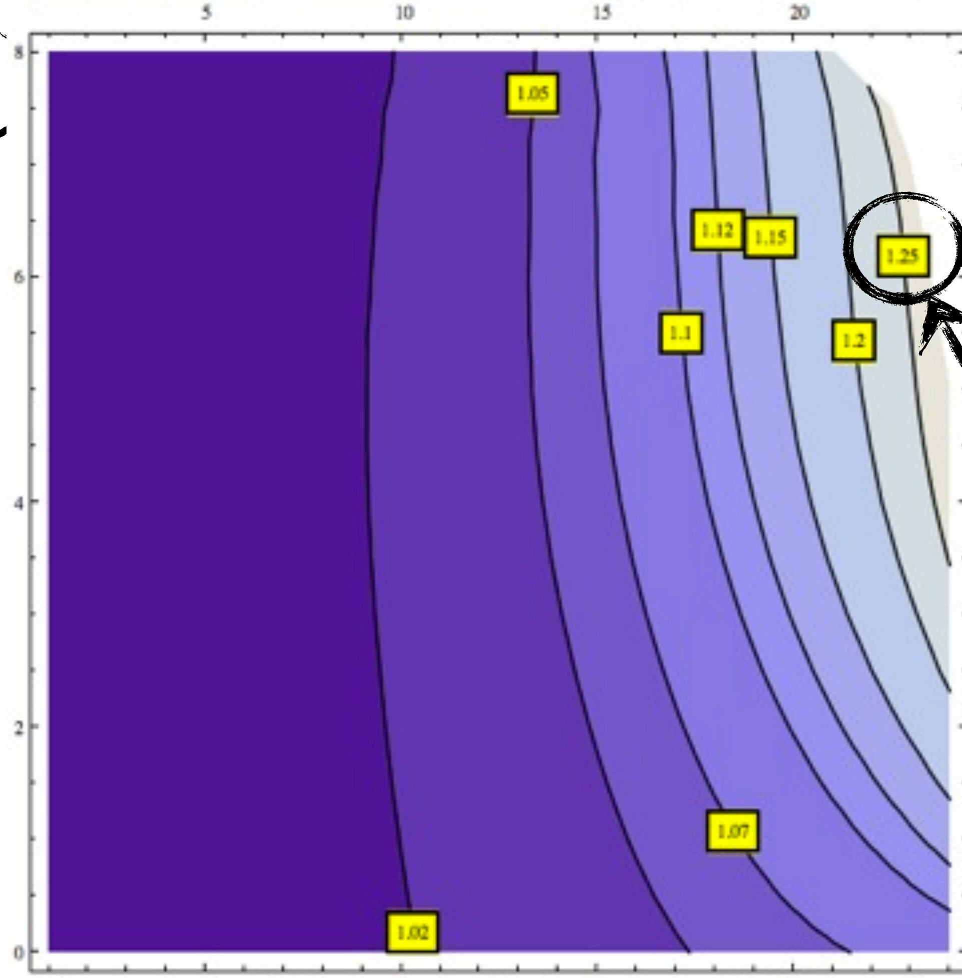
$r_{S_1\gamma\gamma}$



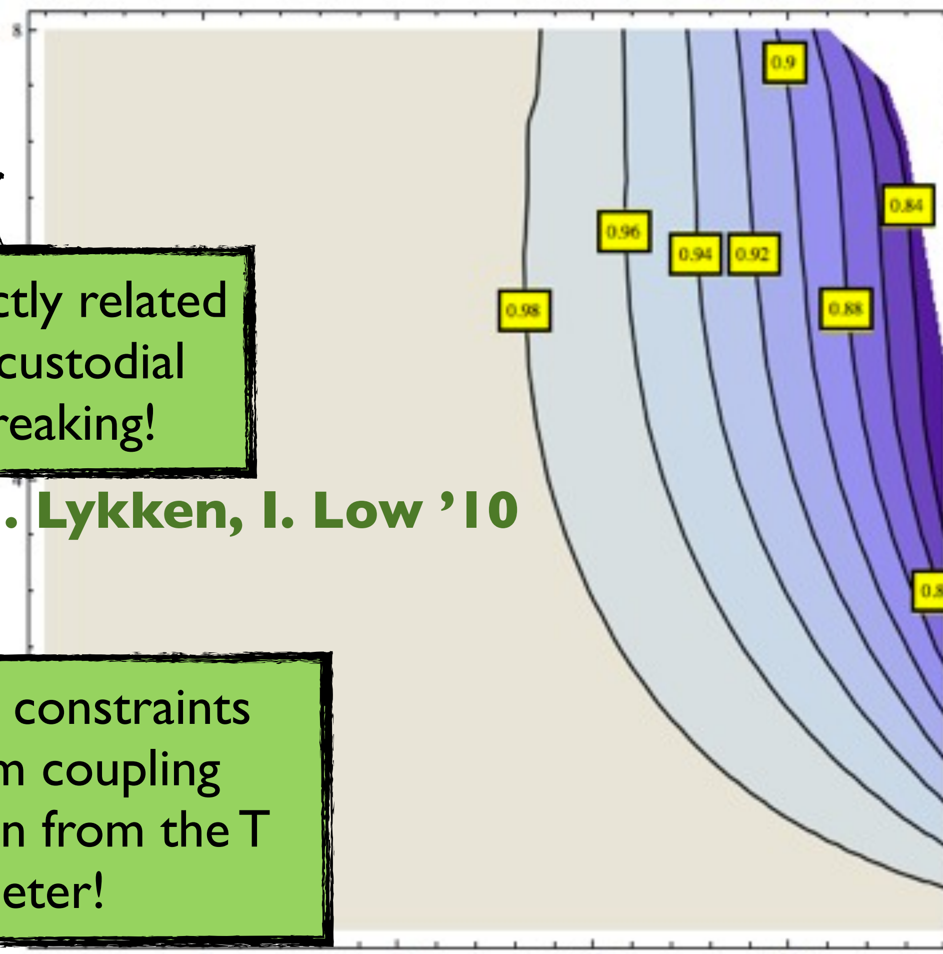
$$\log \frac{M}{m_t} = 8 \rightarrow M \sim 500\,\mathrm{TeV}$$



r_{S_1ZZ}



$$\frac{r_{S_1WW}}{r_{S_1ZZ}}$$



Directly related to custodial breaking!

J. Lykken, I. Low ’10

1.25! Harder constraints coming from coupling deviations than from the T parameter!

Summary

Summary

- We are working on the SUSY generalization of the GM model (triplets + custodial symmetry). The triplets raise the tree level contribution to the Higgs mass allowing for a 126 GeV value while keeping stops light.

- One of the main points of this work is to see if it is still possible for the EW breaking to happen with something bigger than a doublet while keeping tunings under control.

- Custodial symmetry seems to work pretty well even at loop level and the constrains will come from coupling deformations rather than T parameter deviations.

- We have performed a numerical analysis of an interesting (almost excluded) parameter space, the breaking will be smoothed out if soft masses are larger, making the derived constraints even milder.

- Features of triplet models are also present (or can be acommodated) here: Interesting phenomenology, neutrino masses, etc.

- It is crucial to consistently take into account the loop situation in this model since the properties it shows at tree level are lost if the breaking induced by loop corrections is high enough. In particular, the custodial ordering and degeneracy of the mass eigenstates at tree level is going to be affected, so phenomenological studies should take this into account.

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Thank you!

BACK UP SLIDES

Custodial basis:

Doublets

$$h_1^0 = \frac{1}{\sqrt{2}}(H_1^0 + H_2^0)$$

$$h_3^+ = H_2^+, \quad h_3^0 = \frac{1}{\sqrt{2}}(H_1^0 - H_2^0), \quad h_3^- = H_1^-$$

Triplets

$$\delta_1^0 = \frac{\phi^0 + \chi^0 + \psi^0}{\sqrt{3}}$$

$$\delta_3^+ = \frac{\psi^+ - \phi^+}{\sqrt{2}}, \ \delta_3^0 = \frac{\chi^0 - \psi^0}{\sqrt{2}}, \ \delta_3^- = \frac{\phi^- - \chi^-}{\sqrt{2}}$$

$$\delta_5^{++} = \psi^{++}, \ \delta_5^+ = \frac{\phi^+ + \psi^+}{\sqrt{2}}, \ \delta_5^0 = \frac{-2\phi^0 + \psi^0 + \chi^0}{\sqrt{6}}, \ \delta_5^- = \frac{\phi^- + \chi^-}{\sqrt{2}}, \ \delta_5^{--} = \chi^{--}$$

BACK UP SLIDES

Tree level mass spectrum:

SINGLETS

scalars

$$\begin{pmatrix} S_1 \\ S_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha_S & -\sin\alpha_S \\ \sin\alpha_S & \cos\alpha_S \end{pmatrix} \begin{pmatrix} h^0_{1R} \\ \delta^0_{1R} \end{pmatrix}$$

pseudoscalars

$$\begin{pmatrix} P_1 \\ P_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha_P & -\sin\alpha_P \\ \sin\alpha_P & \cos\alpha_P \end{pmatrix} \begin{pmatrix} h^0_{1I} \\ \delta^0_{1I} \end{pmatrix}$$

TRIPLETS

scalars

$$T_H = \begin{pmatrix} \frac{1}{\sqrt{2}}(h_3^+ + h_3^{-*}) \\ h^0_{3R} \\ \frac{1}{\sqrt{2}}(h_3^- + h_3^{+*}) \end{pmatrix}, \quad T_\Delta = \begin{pmatrix} \frac{1}{\sqrt{2}}(\delta_3^+ + \delta_3^{-*}) \\ \delta^0_{3R} \\ \frac{1}{\sqrt{2}}(\delta_3^- + \delta_3^{+*}) \end{pmatrix}$$

$$\begin{pmatrix} T_1 \\ T_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha_T & -\sin\alpha_T \\ \sin\alpha_T & \cos\alpha_T \end{pmatrix} \begin{pmatrix} T_H \\ T_\Delta \end{pmatrix}$$

pseudoscalars

$$G^0 = \cos\theta\, h^0_{3I} + \sin\theta\, \delta^0_{3I}$$

$$G^\mp = \cos\theta\, \frac{h_3^{\pm *} - h_3^\mp}{\sqrt{2}} + \sin\theta\, \frac{\delta_3^{\pm *} - \delta_3^\mp}{\sqrt{2}}$$

$$A^0 = -\sin\theta\, h^0_{3I} + \cos\theta\, \delta^0_{3I}$$

$$A^\mp = -\sin\theta\, \frac{h_3^{\pm *} - h_3^\mp}{\sqrt{2}} + \cos\theta\, \frac{\delta_3^{\pm *} - \delta_3^\mp}{\sqrt{2}}$$

FIVEPLETS

scalars

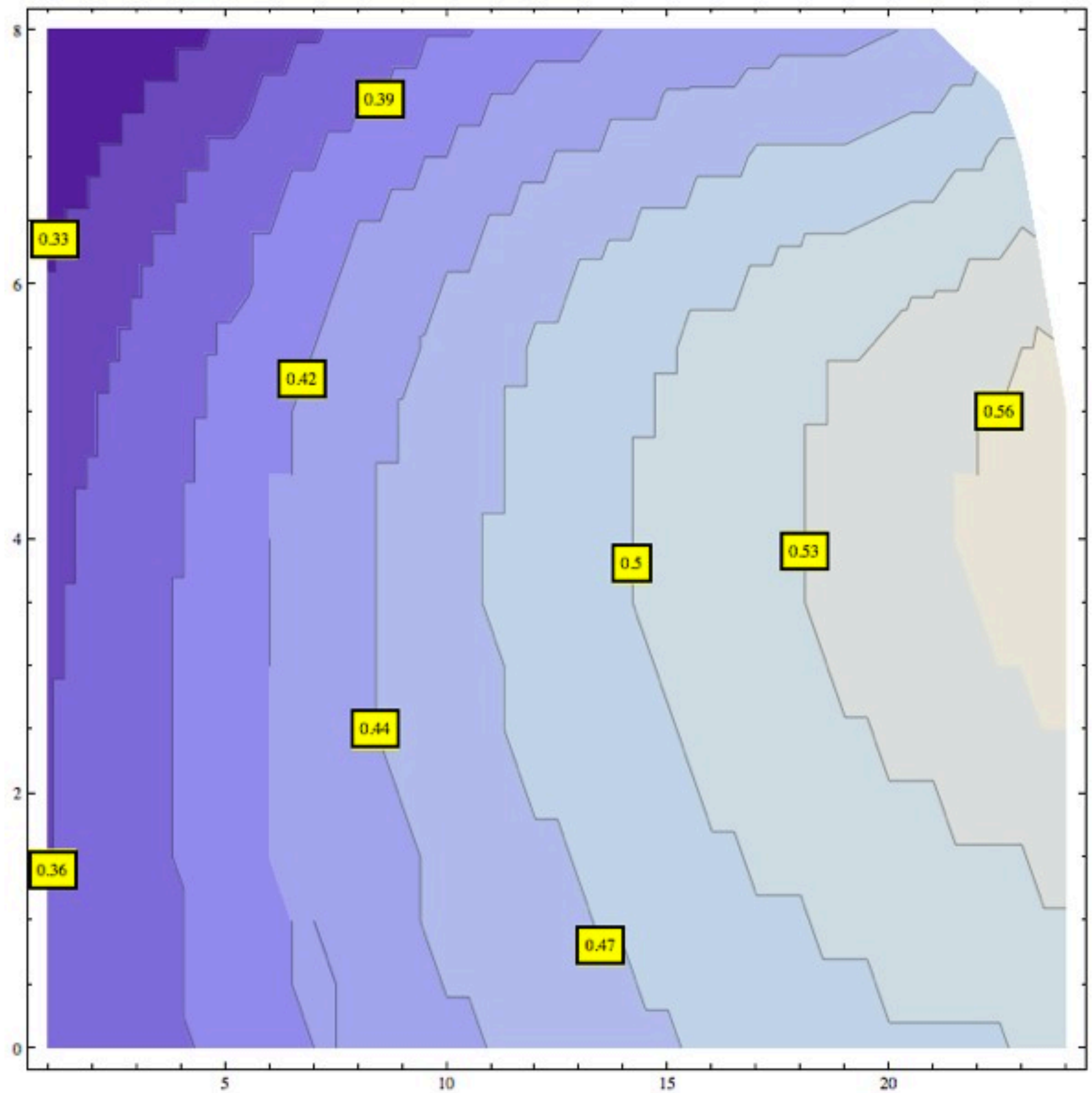
$$F_S = \begin{pmatrix} \frac{1}{\sqrt{2}}(\delta_5^{++} + \delta_5^{--*}) \\ \frac{1}{\sqrt{2}}(\delta_5^{+} + \delta_5^{-*}) \\ \delta^0_{5R} \\ \frac{1}{\sqrt{2}}(\delta_5^{-} + \delta_5^{+*}) \\ \frac{1}{\sqrt{2}}(\delta_5^{--} + \delta_5^{++*}) \end{pmatrix}$$

pseudoscalars

$$F_P = \begin{pmatrix} \frac{1}{\sqrt{2}}(\delta_5^{--*} - \delta_5^{++}) \\ \frac{1}{\sqrt{2}}(\delta_5^{-*} - \delta_5^{+}) \\ \delta^0_{5I} \\ \frac{1}{\sqrt{2}}(\delta_5^{+*} - \delta_5^{-}) \\ \frac{1}{\sqrt{2}}(\delta_5^{++*} - \delta_5^{--}) \end{pmatrix}$$

BACK UP SLIDES

Lambda values for getting the correct Higgs mass:



The status of the MSSM Higgs light boson

$$m_h^2 = m_Z^2 \cos 2\beta^2 + \frac{3m_t^4}{4\pi^2 v^2}\left[\log\left(\frac{m_S^2}{m_t^2}\right) + \frac{X_t^2}{m_S^2}\left(1 - \frac{X_t^2}{12 m_S^2}\right)\right] \overset{\text{LHC}}{=} 126 \text{ GeV}$$

- Enhance the logarithm by making the stop masses large.
- Enhance the threshold correction by living close to the maximal mixing.
- **Enhance the tree level contribution**

A way of keeping light stops while also having a naturally heavy Higgs

D-terms
Extended Gauge groups

F-terms
Extended Higgs sectors

Parameter space range and Landau Poles

The introduction of new matter d.o.f. helps the RG running of the top yukawa coupling to develop a Landau pole sooner than in minimal models, this sets bounds on the scale of SUSY breaking M.

Also, the bigger the running the bigger the custodial breaking so low-med scale SUSY breaking is expected!

UV completions?

SUSY breaking should be transmitted to the observable sector in a custodially invariant way (at least aproximately).

What breaking mechanism is suitable?

Gravity mediation leaves universal soft parameters but we expect it to happen in higher scales. Could we bring down gravity mediation? Maybe with some extra dimension?

Low scale **Gauge mediation** mechanisms could do the job, hypercharge contributions will break custodial invariance but this is in the exact nature of the mechanism and the breaking is expected to be small.