Electroweak Breaking with Custodial Triplets

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In collaboration with:

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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?

There is still some room for modifications

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.

How do we solve this?

An extended Higgs sector can help making 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,

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

If we add anything bigger than a doublet 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

With Symmetry

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

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

Add triplets, but! make the theory custodially invariant.

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 $SU(2) \times U(1)$ 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

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

Due to new degrees of freedom getting vevs, tadpole diagrams not present in the minimal SM picture are present here and make the naturalness issue of the SM even worse.

J. Gunion, R. Vega, J. Wudka '91

+

Higgs mass in supersymmetry, interesting pheno...

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

The Model

A supersymmetric generalization of the GM model

The SUSY GM model

L. Cort, M. Quirós, MG '13
1308.4025

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

$$\bar{H} = \begin{pmatrix} H_1 \\ H_2 \end{pmatrix}$$

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

$$\bar{\Delta} = \Sigma^i \bar{\sigma}_i = \begin{pmatrix} -\frac{\Sigma_0}{\sqrt{2}} & -\Sigma_{-1} \\ -\Sigma_{-1} & \frac{\Sigma_0}{\sqrt{2}} \end{pmatrix}$$

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,

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

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

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

For the vacuum to respect SU(2)V we need to choose a custodially preserving direction.

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

Note that if we fix the vev of the triplet we also fix the vev that the doublet will acquire and viceversa: $v_{EW}^2 = 2 v_H^2 + 8 v_\Delta^2$

Tree level features: scalar spectrum

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

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

$\bar{\Delta} = \mathbf{3} \otimes \mathbf{3} = \delta_1 \oplus \delta_3 \oplus \delta_5$ → **Fiveplets:**

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

$F_S \quad F_P$

Singlets:

S_1 **Higgs-like state!**

$S_2 \quad P_1 \quad P_2$

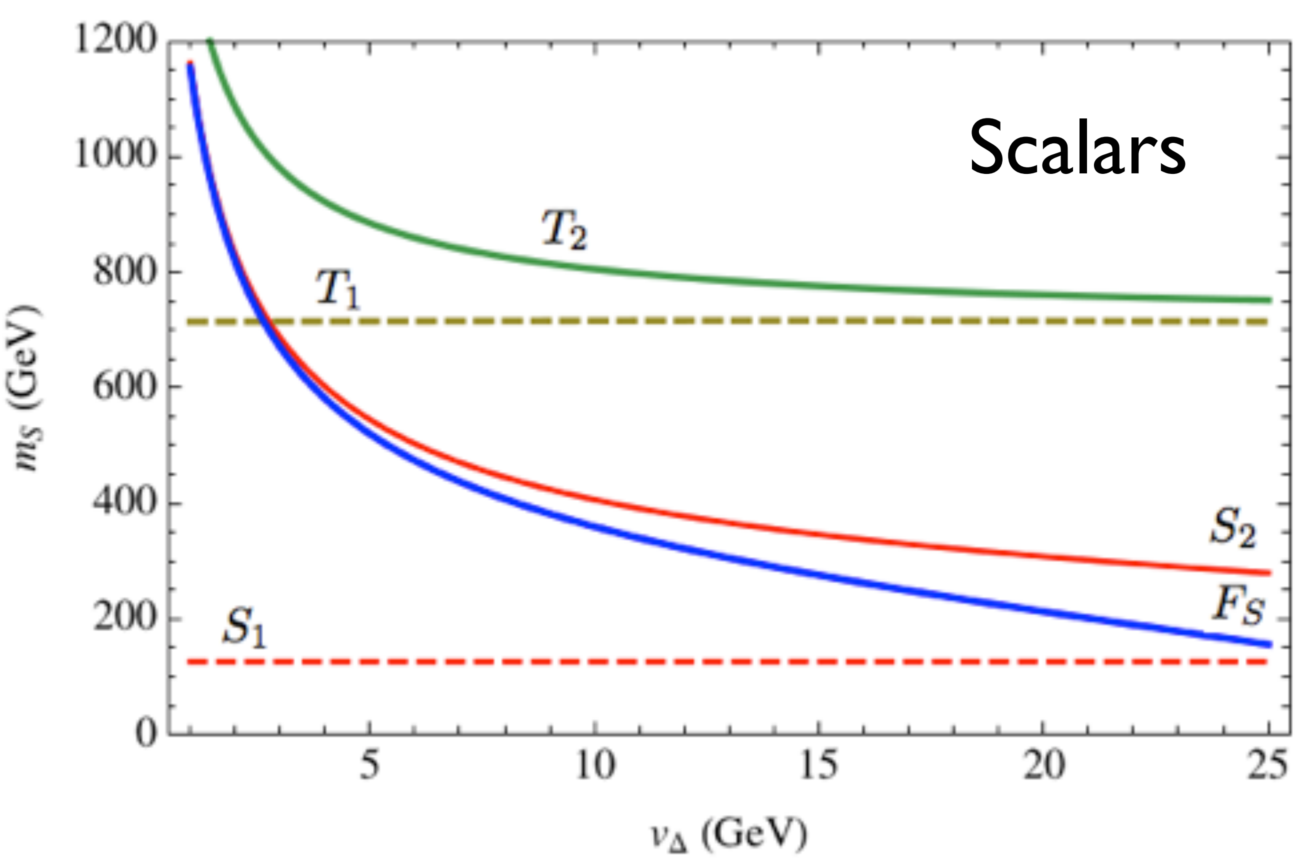
Triplets:

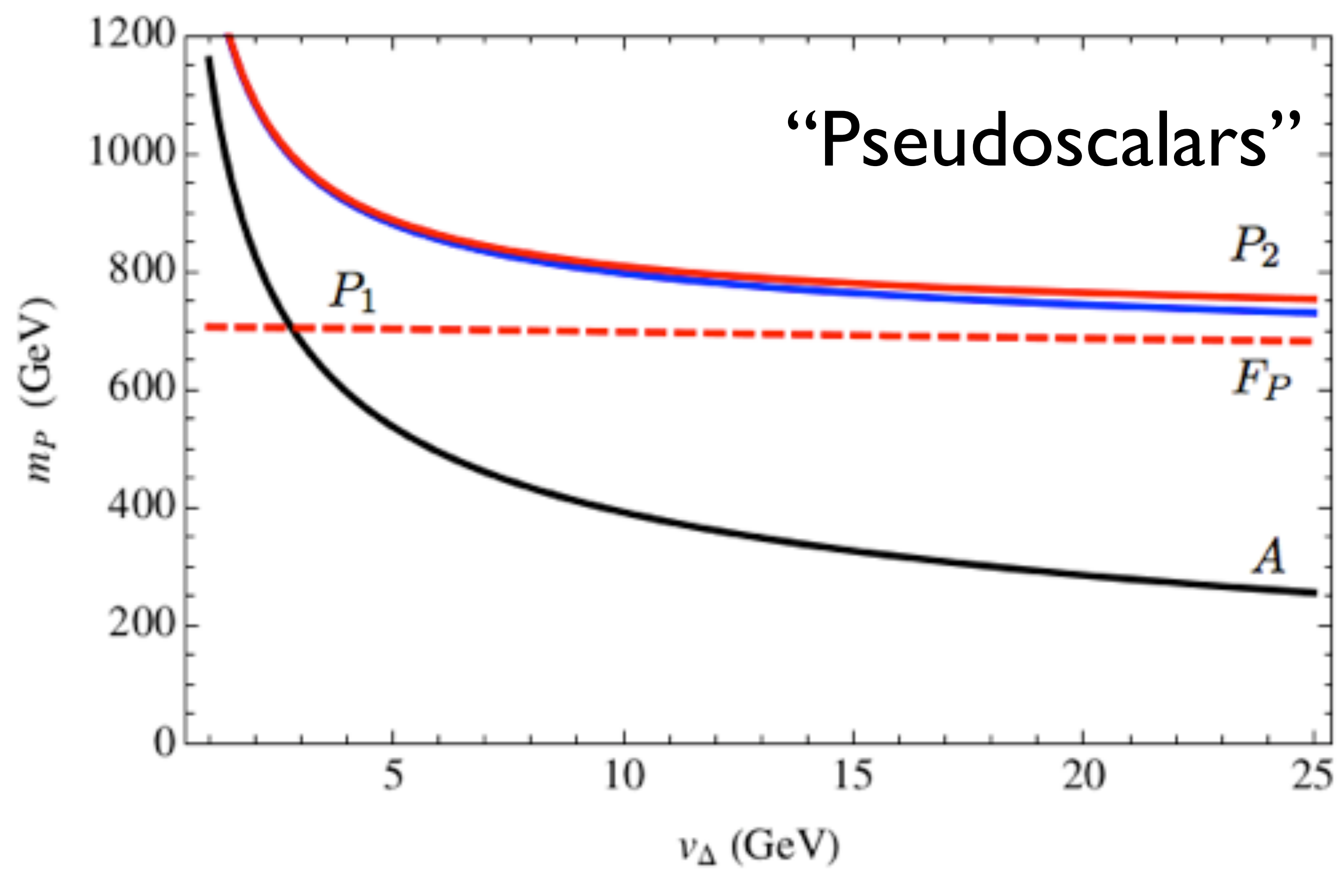
G **Goldstone triplet!**

$A \quad T_1 \quad T_2$

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”

Tree level (RG improved)

The Model at "loop level"

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

How bad? —**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

—**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!

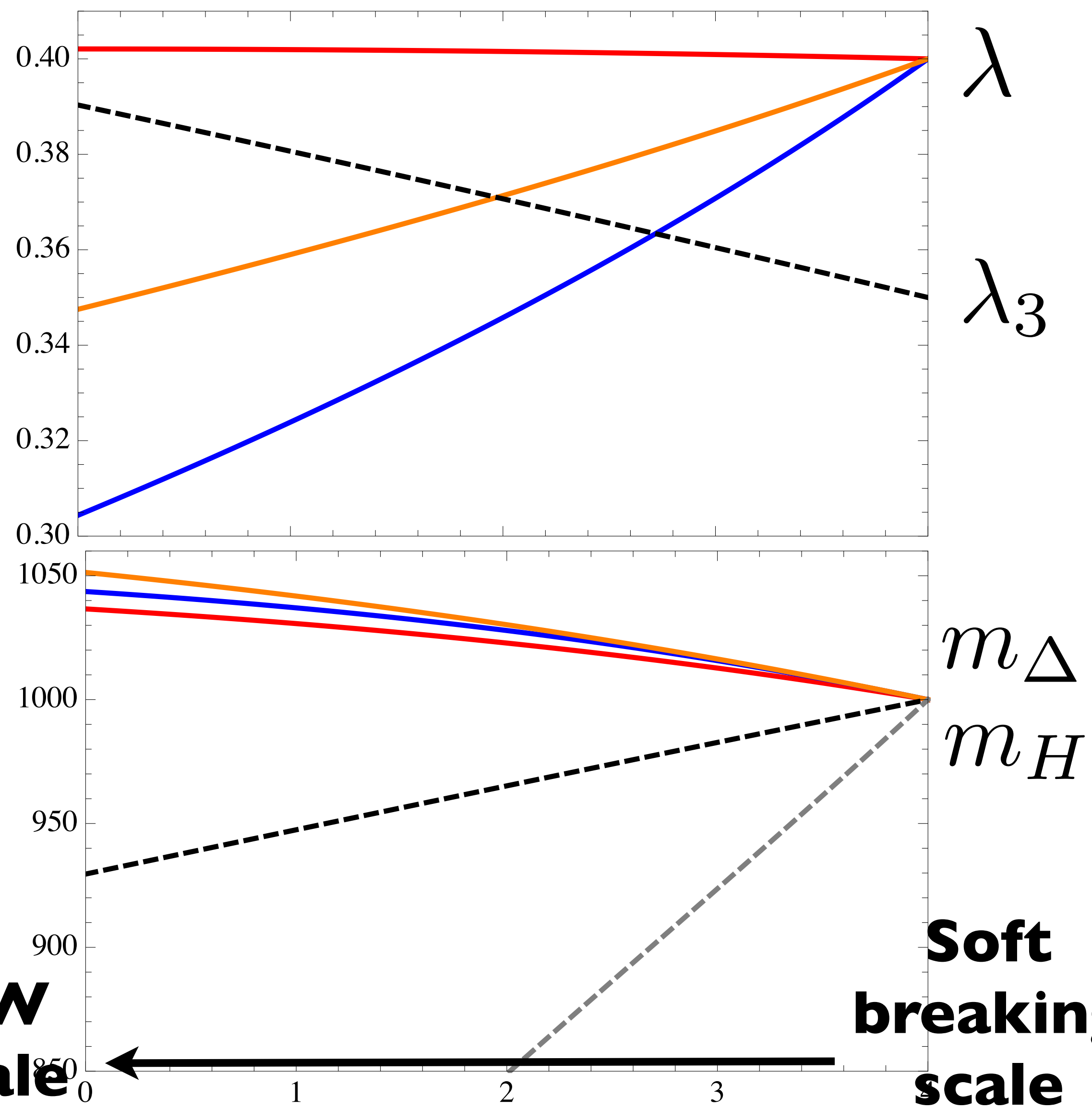
Some Results

Preliminary

RG running

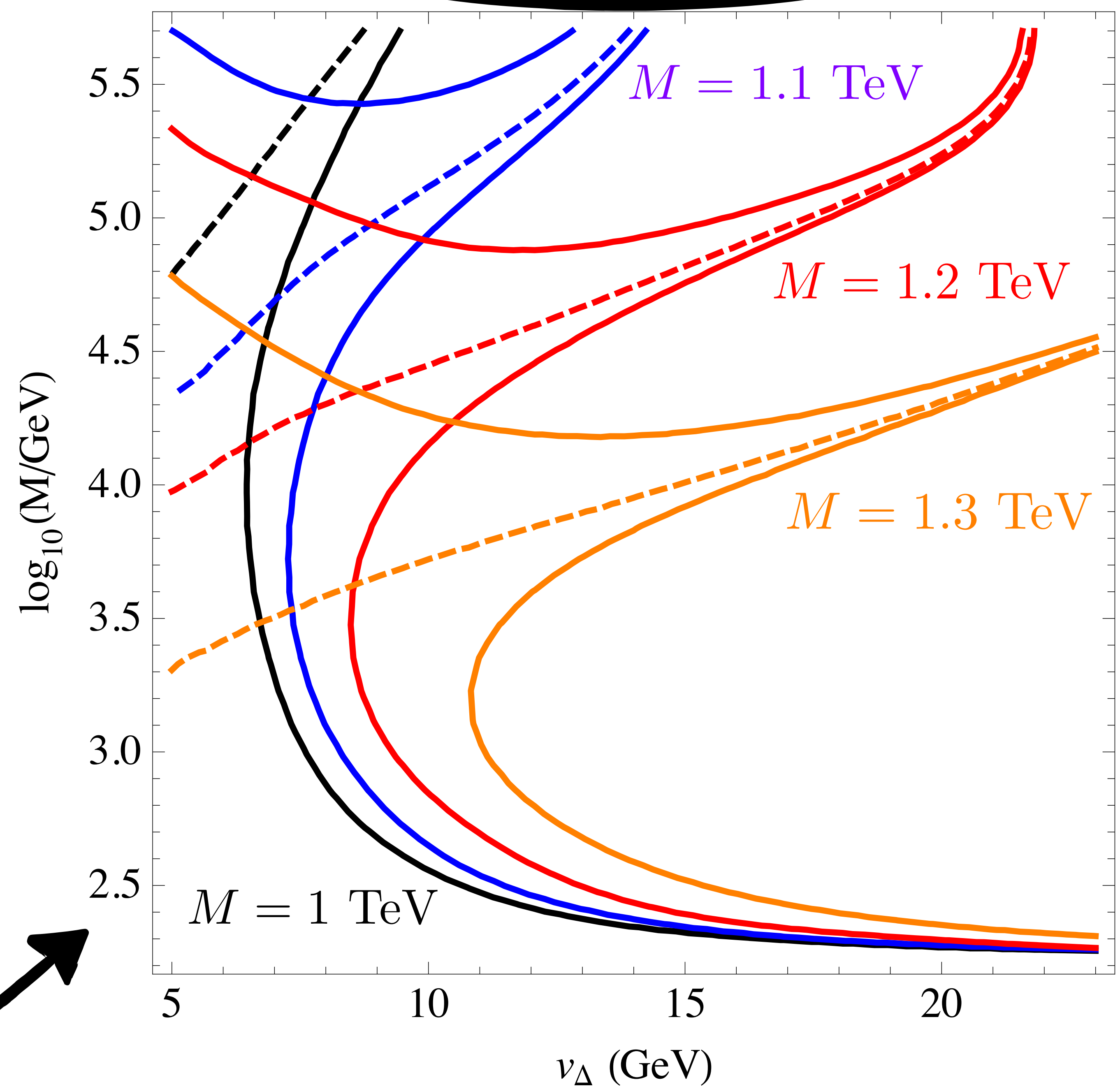
$$m_H = m_\Delta = 1000\,\mathrm{GeV} \;//\; m_{\tilde{Q}} = m_{\tilde{u}} = m_{\tilde{d}} = 500\,\mathrm{GeV} \;//\; a_u = a_d = 0$$

Running of the parameters



Rho parameter constrain

$$\rho = 1 + \Delta\rho_{tree}$$

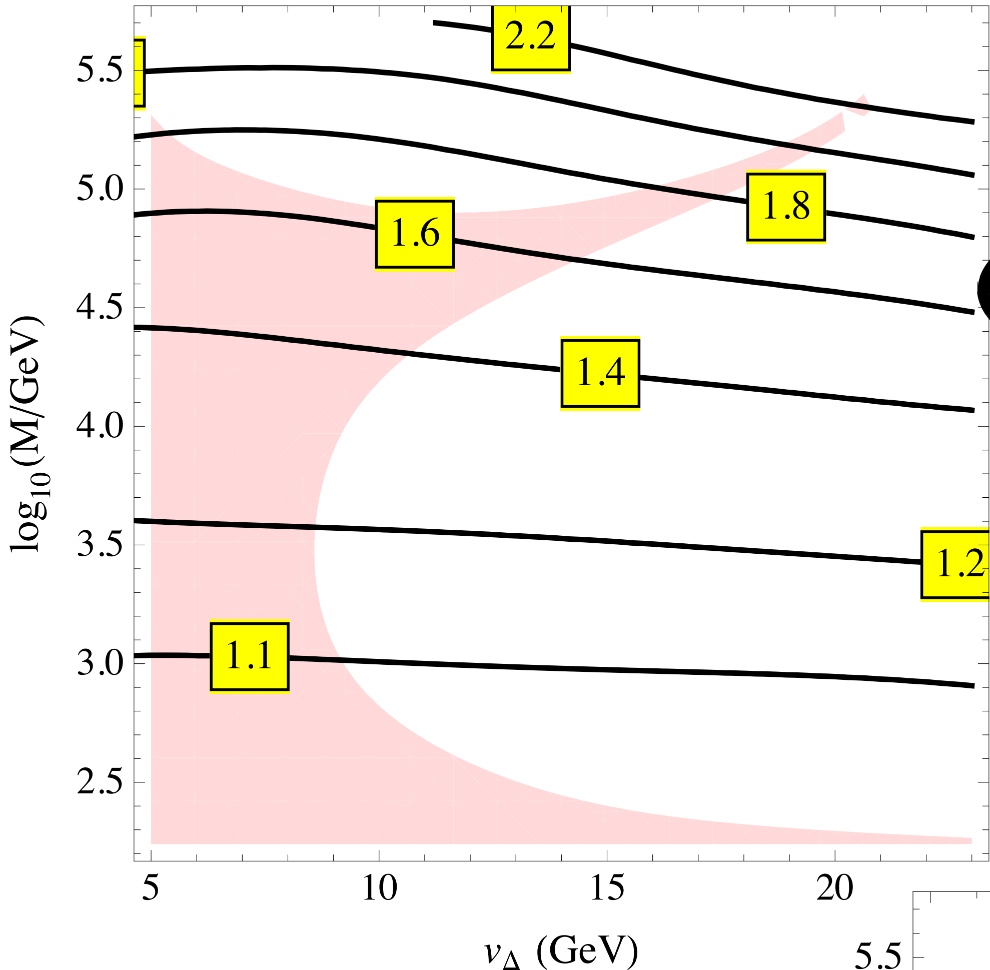


Dashed lines correspond to,

$$\rho = 1 \;\; ; \;\; 2v_\phi^2 = v_\psi^2 + v_\chi^2$$

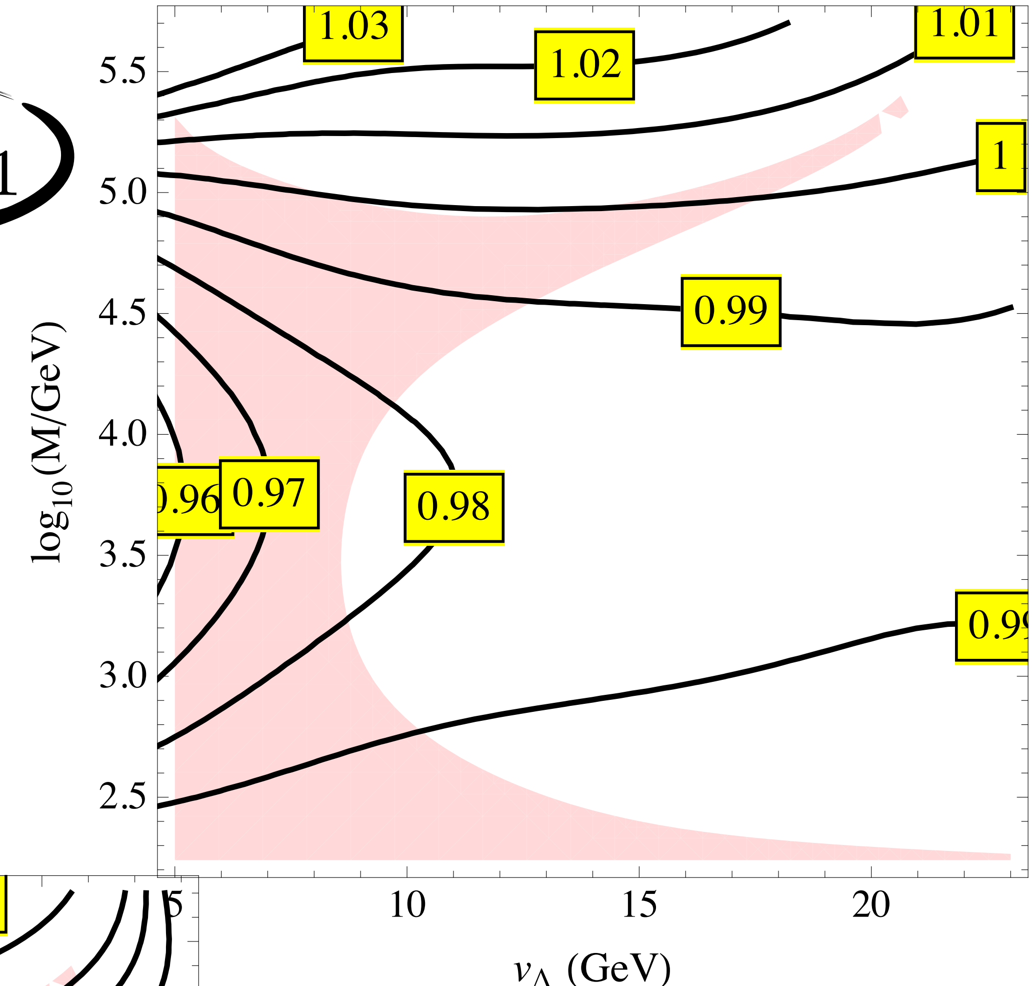
$$\Delta\rho_{tree} = \frac{2v_\phi^2 - (v_\psi^2 + v_\chi^2)}{\frac{1}{2}(v_1^2 + v_2^2) + 2(v_\psi^2 + v_\chi^2)} = -4\frac{\cos 2\theta_0 v_\Delta^2}{v_H^2 + 8\cos^2\theta_0 v_\Delta^2}$$

Some results: Angles and custodial breaking

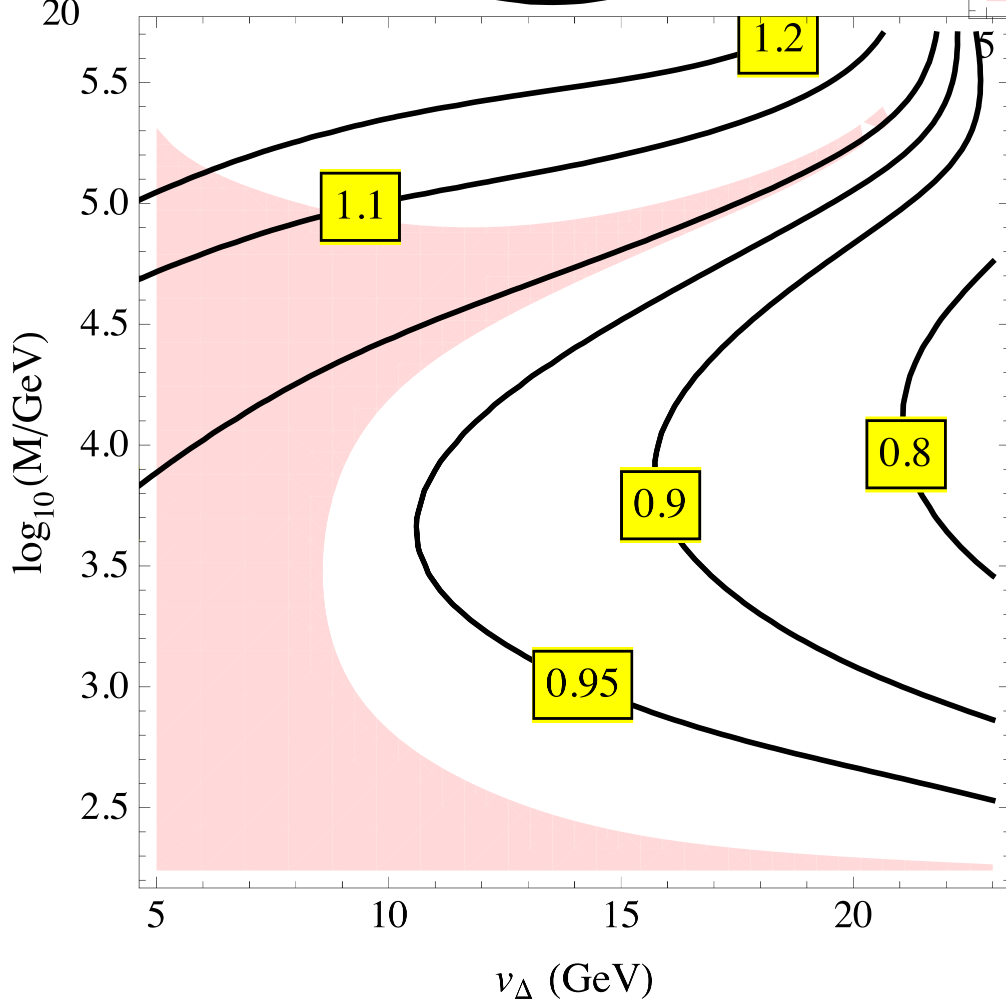


$\tan\beta$

$\tan\theta_1$



$\tan\theta_0$

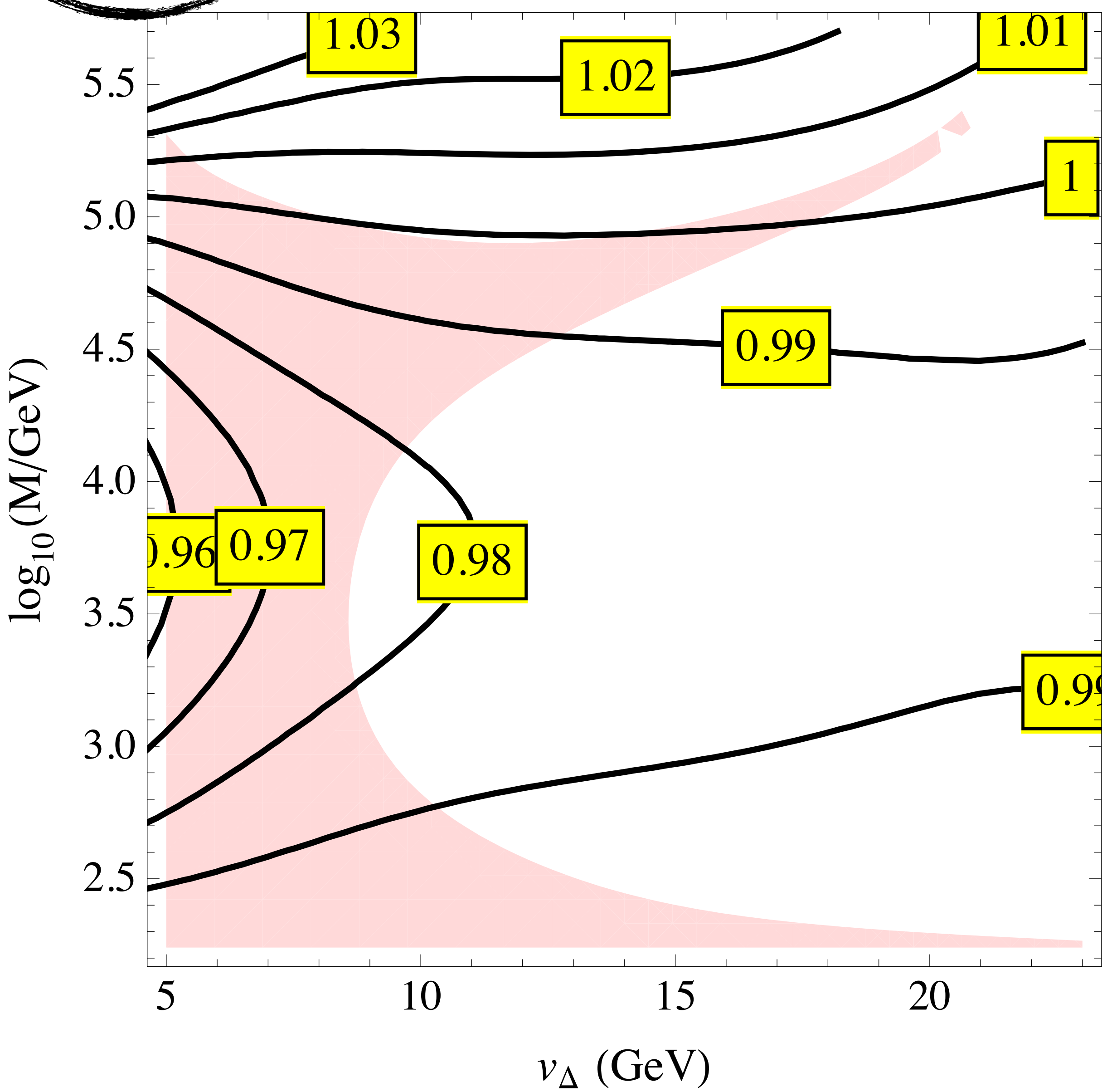


λ is adjusted so that the Higgs mass is correctly reproduced at the weak scale for every point in the $(v_\Delta, \mathcal{M})$ plane.

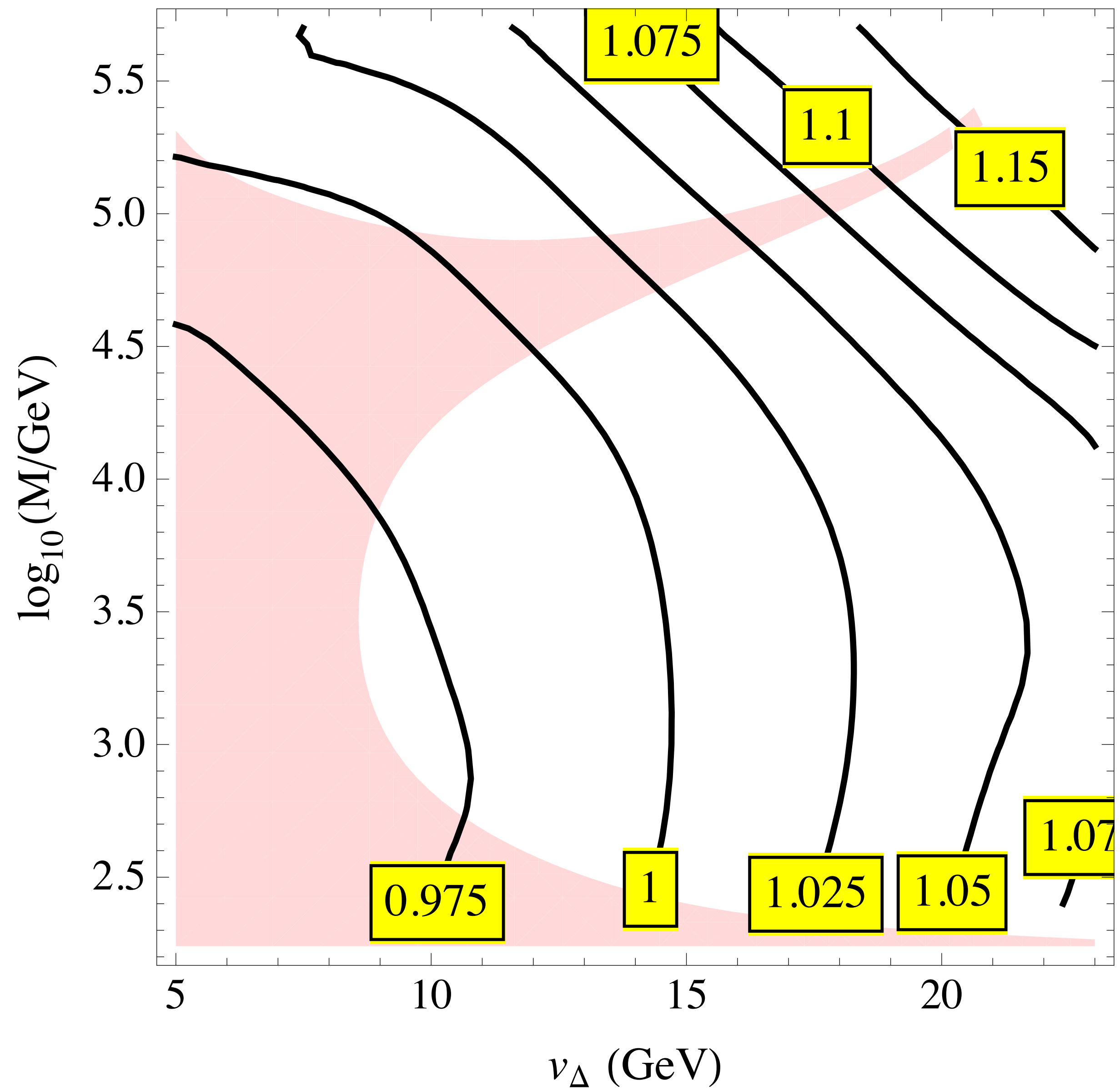
$$M_{gaugino} = 1.2 \text{ TeV}$$

Some results: Couplings

$$\frac{r_{hWW}}{r_{hZZ}}$$



$$r_{h\gamma\gamma}$$



$$\frac{r_{hWW}}{r_{hZZ}} \neq 1$$

Directly related to custodial breaking!

J. Lykken, I. Low '10
1005.0872

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 be triggered by something bigger than a doublet while keeping tunings under control.

- We have performed a numerical analysis for different points in the parameter space, we see that the scale at which SUSY breaking is transmitted to the observable sector is predicted by the need to respect the rho parameter experimental limits.

- 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

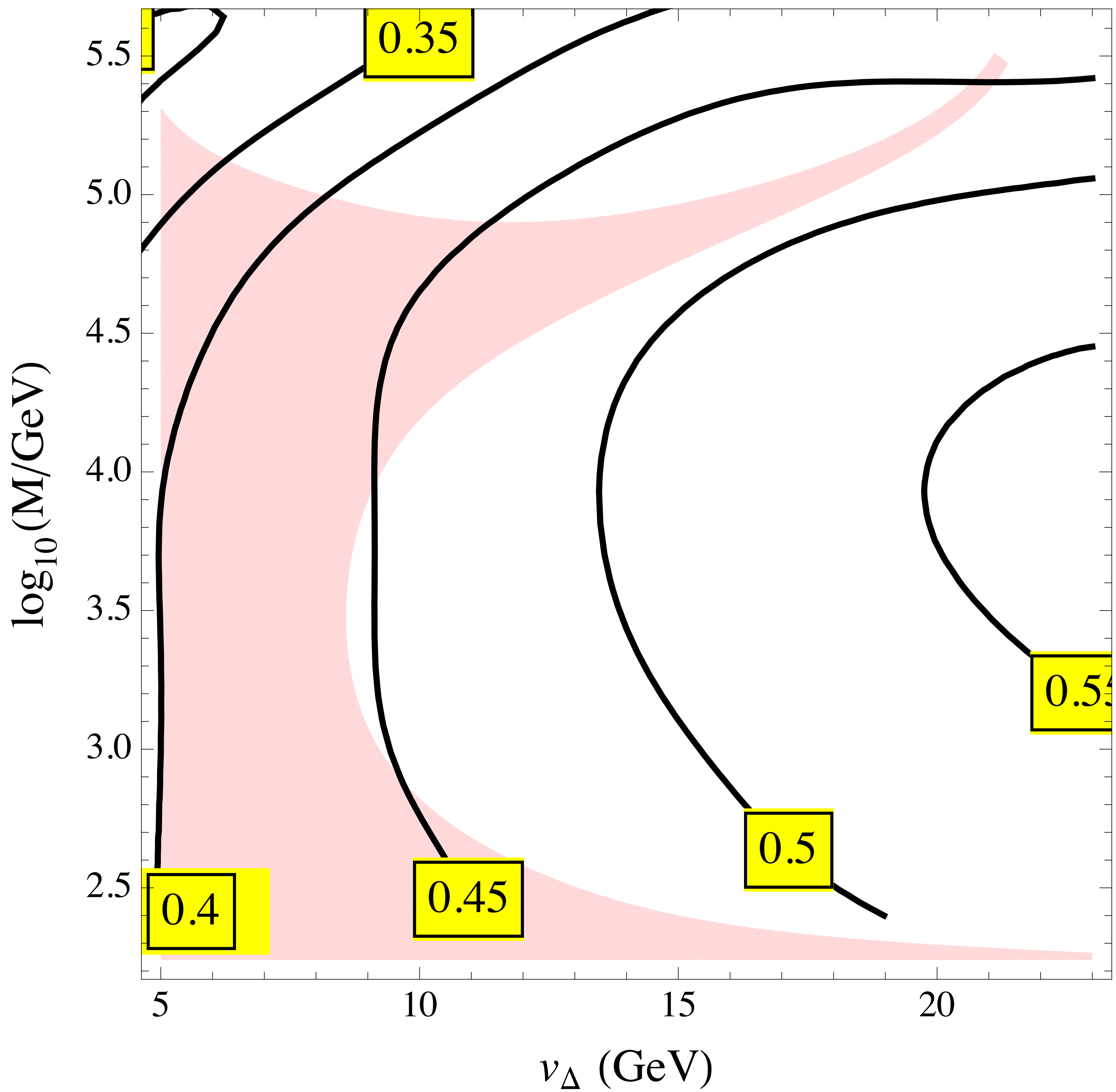
$$F_S = \begin{pmatrix} \frac{1}{\sqrt{2}}(\delta_5^{++} + \delta_5^{--*}) \\ \frac{1}{\sqrt{2}}(\delta_5^{+} + \delta_5^{-*}) \\ \delta^0_{5R} \\ \frac{1}{\sqrt{2}}(\delta_5^{-} + \delta_5^{+*}) \\ \frac{1}{\sqrt{2}}(\delta_5^{--} + \delta_5^{++*}) \end{pmatrix}$$

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 at mSOFT that give the correct Higgs mass:



The status of the MSSM Higgs light boson

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

LHC

- 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

F-terms

Extended Higgs sectors

D-terms

Extended Gauge groups

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.