Higgs(es) in Triplet extended supersymmetric standard model at the LHC.

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JHEP 1310 (2013) 091 & Work in Progress
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November 11, 2013

Outline

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2. Standard Model Higgs
3. MSSM and its status
4. Triplet extended MSSM and its status
5. Constraint from rare decay
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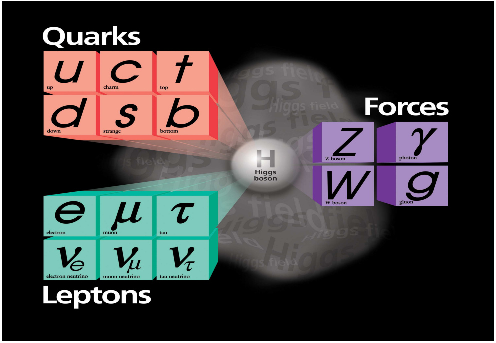
Outline

Introduction

- Standard Model (SM) of particle Physics is so far well established experimentally
- Standard Model is described by the local gauge invariance of $SU(2)_L \times U(1)_Y \times SU(3)_C$



Standard Model

- Gauge theory describes the interaction between gauge bosons (force carrier) and fermions.
- But this leaves all the fundamental and mediator particles as massless
- There must be some mechanism which generates the masses for these particles.
- Higgs mechanism is the mechanism that gives mass to the EW gauge bosons in a gauge invariant way.

SM Higgs

- In SM has a complex scalar $SU(2)_L$ doublet, Φ that coupled to the gauge fields,

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

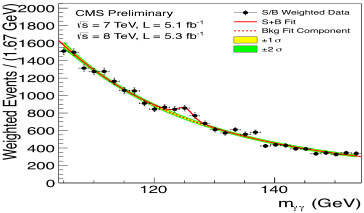
with a scalar potential given by

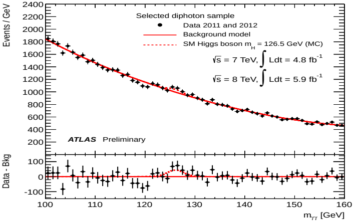
$$V(\Phi) = \mu^2 \mid \Phi^\dagger \Phi \mid + \lambda \Big(\mid \Phi^\dagger \Phi \mid \Big)^2$$

where, $\lambda \equiv \text{scalar self coupling},\ \lambda > 0 \quad \text{and}\ \mu^2 \equiv \text{scalar mass parameter}\mu^2 < 0.$

- Which when gets VEV at the minimum, $< \Phi^\dagger \Phi >= \sqrt{-\frac{\mu^2}{2\lambda}}$ the gauge bosons and fermions become massive.
- SM Higgs mass, $m_H = 2\lambda v^2$ is a free parameter.

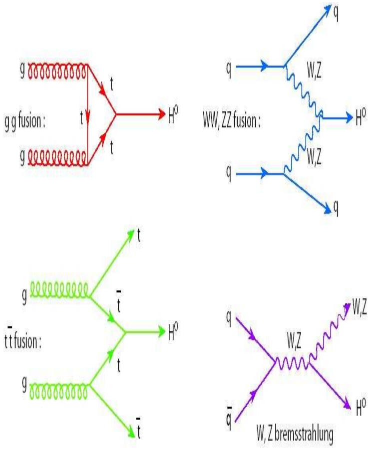
Experimental constraints: LHC on 4th July, 2012

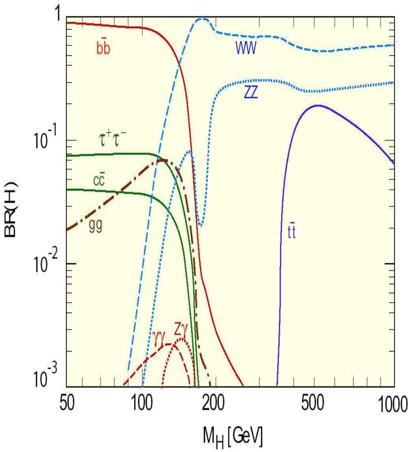




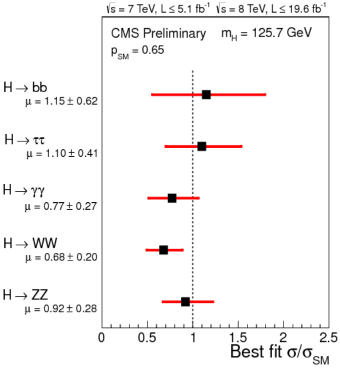
- Finally, on 4th of July 2012, we get evidence of a even-integer-spin particle similar to Higgs boson at the LHC.
- ATLAS has reported discovery of such a particle with best fit mass of 126.5 GeV at 5.0σ
- While CMS finds a particle with a mass of 125.3 ± 0.6 GeV with 4.9σ significance.

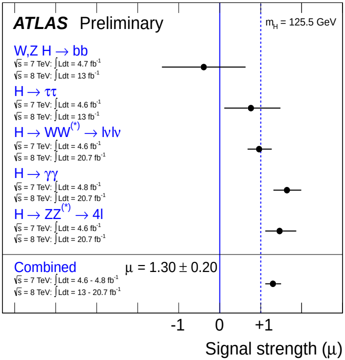
Higgs Production Processes at the LHC and its decay





Status of Higgs at the LHC





s

- CMS: $H \rightarrow ZZ \Rightarrow m_H = 125.8 \pm 0.4(\mathrm{stat}) \pm 0.2(\mathrm{sys})$
- ATLAS: $H \rightarrow ZZ \Rightarrow m_H = 124.3 \pm 0.6(\mathrm{stat}) \pm 0.4(\mathrm{sys})$
  $H \rightarrow \gamma\gamma \Rightarrow m_H = 126.8 \pm 0.2(\mathrm{stat}) \pm 0.7(\mathrm{sys})$

Problems of Standard Model

- Higgs mass is not protected by any symmetry $\Rightarrow$ Hierarchy problem.
- No cold dark matter candidate.
- Neutrinos are massless in SM.
- Does not explain fermion mass hierarchy.
- It can not explain baryogenesis and leptogenesis.
- SM has 19 unknown parameters whose value are to be set experimentally.
- It does not give the gauge coupling unification at some high scale.
- Finally, it does not include gravity.
- ...

Hierarchy Problem

- Standard Model Higgs mass is not protected by any symmetry!

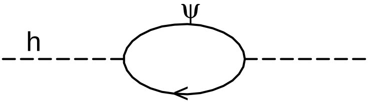


Figure : Scalar mass renormalization from a fermion loop.

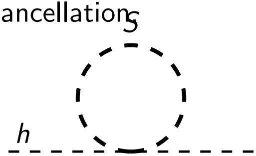
$$\delta M_h^2 = -\frac{\lambda_F^2}{8\pi^2}\Lambda^2 + \dots$$

- the quantum correction to the Higgs boson mass depends *quadratically* on the high scale cut off Λ.

Outline

Motivation

- Supersymmetry protects the Higgs mass by giving possible cancellations



- For each particle there is a super partner differing by spin $1/2$.

Particle content of MSSM

Names		spin 0	spin 1/2	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
squarks, quarks	$\hat{Q}$	$(\widetilde{u}_L\ \ \widetilde{d}_L)$	$(u_L\ \ d_L)$	$(\,\mathbf{3},\ \mathbf{2}\,,\ \frac{1}{6})$
($\times$3 families)	$\hat{u}$	$\widetilde{u}_R^*$	$u_R^\dagger$	$(\,\overline{\mathbf{3}},\ \mathbf{1},\ -\frac{2}{3})$
	$\hat{d}$	$\widetilde{d}_R^*$	$d_R^\dagger$	$(\,\overline{\mathbf{3}},\ \mathbf{1},\ \frac{1}{3})$
sleptons, leptons	$\hat{L}$	$(\widetilde{\nu}\ \ \widetilde{e}_L)$	$(\nu\ \ e_L)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ -\frac{1}{2})$
($\times$3 families)	$\hat{e}$	$\widetilde{e}_R^*$	$e_R^\dagger$	$(\,\mathbf{1},\ \mathbf{1},\ 1)$
Higgs, higgsinos	$\hat{H}_u$	$(H_u^+\ \ H_u^0)$	$(\widetilde{H}_u^+\ \ \widetilde{H}_u^0)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ +\frac{1}{2})$
	$\hat{H}_d$	$(H_d^0\ \ H_d^-)$	$(\widetilde{H}_d^0\ \ \widetilde{H}_d^-)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ -\frac{1}{2})$

Names	spin 1/2	spin 1	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
gluino, gluon	$\widetilde{g}$	g	$(\,\mathbf{8},\ \mathbf{1}\,,\ 0)$
winos, W bosons	$\widetilde{W}^\pm\ \ \widetilde{W}^0$	$W^\pm\ \ W^0$	$(\,\mathbf{1},\ \mathbf{3}\,,\ 0)$
bino, B boson	$\widetilde{B}^0$	B^0	$(\,\mathbf{1},\ \mathbf{1}\,,\ 0)$

MSSM other features

- R-parity, for each particle is defined as

$$P_R = (-1)^{3(\mathrm{B-L})+2\mathrm{s}}$$

- With R-parity is conservation, LSP(Lightest supersymmetric particle) can not decay.
  $\Rightarrow$ Have a dark matter candidate.
- Unlike Standard Model, MSSM has five Higgs bosons,
  h, H the CP-even neutral Higgs bosons
  A the CP-odd neutral Higgs bosons
  $H^{\pm}$ charged Higgs bosons

MSSM Higgs sector

- In the large m_A limit, the lightest CP-even neutral Higgs mass at tree-level is $m_h^2 \simeq m_Z^2 \cos^2 2\beta$
  $\Rightarrow m_h$ cannot be greater than m_Z.
- With the radiative correction at one-loop the lightest Higgs mass becomes,

$$m_h^2 \lesssim m_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[ln\frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2}(1 - \frac{X_t^2}{12M_S^2})\right]$$

where $M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$,
the stop mixing parameter is $X_t = A_t - \mu \cot\beta$
and for maximal mixing scenario: $X_t^{max} = \sqrt{6} M_S$.

MSSM Higgs in a Nutshell

Lightest Higgs in MSSM

- While in the SM the Higgs mass is essentially a free parameter (and should simply be smaller than about 1 TeV), the lightest CP–even Higgs particle in the MSSM is bounded from above.
- Depending on the SUSY parameters that enter the radiative corrections, it is restricted to values

$$M_h^{\max} \approx M_Z |\cos 2\beta| + \text{radiative corrections} \lesssim 110\text{--}135 \text{ GeV}$$

- "Observed $M_h \approx 125$ GeV" at the LHC, would place very strong constraints on the MSSM parameters through their contributions to the radiative corrections to the Higgs sector.

MSSM Higgs sector

- After $\sim$ 125 GeV Higgs boson discovery, the parameter spaces of MSSM like theories are stringently constrained. Let's consider two well known theories: mSUGRA/cMSSM, pMSSM.
- mSUGRA/cMSSM Soft SUSY breaking parameters are unified at the high scale (GUT). Parameter space of the theory contains only sign(μ), $\tan\beta$, A_0, m_0, $m_{1/2}$.
- Phenomenological MSSM: CP conservation, flavor diagonal mass and coupling matrices, universality of the 1st and 2nd generations are imposed. Parameter space of the model (22 parameters) : $\tan\beta$, μ, M_A, gaugino Masses: M_1,M_2,M_3 A_f (3 for the 3rd generation+3 for 1st and 2nd generations) $m_{\tilde{f}_L}$ and $m_{\tilde{f}_R}$ $(5 \oplus 5)$

Outline

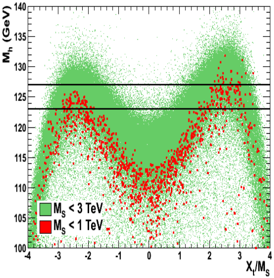
∼ 125 GeV Higgs in MSSM

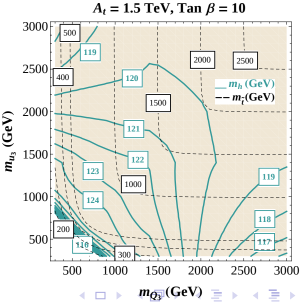
M_h^{max} in pMSSM, Djouadi et al. PLB708 (2012) 162-169

- Only the scenarios with large X_t/M_S values and, in particular, those close to the maximal mixing scenario $A_t/M_S \approx \sqrt{6}$ survive.
- The no–mixing scenario is ruled out for $M_S \lesssim 3$ TeV.
- The typical mixing scenario needs large M_S and moderate to large $\tan\beta$ values.
- $M_h^{\rm max}$=136, 123 and 126 GeV have been obtained in, the maximal, zero and typical mixing scenarios.

M_h^{max} in pMSSM, Carena et al. JHEP 1203 (2012) 014

- With the significant splitting of the stop soft masses, the mass of the heaviest stop is of the order of the largest soft stop mass, and the lightest stop mass can be as low as ∼ 100 GeV
- ∼ 125 GeV Higgs does not imply a hard lower bound on the squark masses.
- A_t larger than ∼ 2 TeV are required to achieve ∼ 125 GeV Higgs.
- In the case of no splitting between the two stop soft masses, values of A_t above ∼ 1.5 TeV are needed to achieve Higgs masses in the region of interest.
- In this case the mass of the lightest stop is naturally above a few hundred GeV.



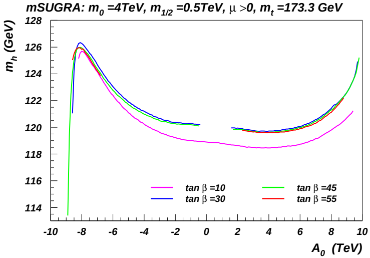


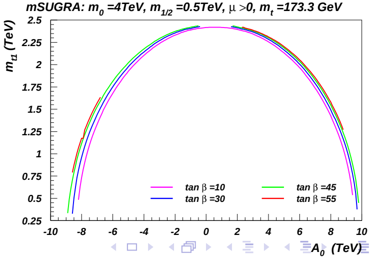
mSUGRA with ∼125 GeV Higgs Baer et al.

With ∼125 GeV Higgs

- For $A_0 = 0$, m_0 versus $m_{1/2}$ planes are excluded (only possible ∼ 125 GeV solutions with $m_{1/2} \sim m_0 \sim 10$ TeV; corresponding squark/gaugino masses ∼ 20 TeV).
- For $A_0 = \pm 2m_0$ and $m_0 \sim 4 - 10$ TeV: Possible to get desired Higgs mass. Result: heavy scalars but light gauginos are still possible.
- $|A_0| \lesssim 1.8m_0$ is excluded for $m_0 < 5$ TeV
- $|A_0| \lesssim 0.3m_0$ is excluded for m_0 up to 20 TeV

Conclusion: High m_0 and A_0 are required!. PRD85(2012)075010





Situation of the MSSM

Conclusion Either large mixing or large stop masses are required for a $\sim$ 125 GeV Higgs.

$\Rightarrow$ Very large SUSY mass scale and large mixings result in fine tuning. MSSM looses its motivation to solve the hierarchy problem.

Solution: Extended MSSM models can give additional contributions to the lightest Higgs mass so no large mixing and/or heavy sfermions needed.

Bonus:

- Extended theory may solve the μ problem (in case of singlet extension)
- Possibility of spontaneous CP-violation.
- New triplet(s) can generate small neutrino masses through the seesaw mechanism.

Outline

Triplet extended MSSM

- In addition to the MSSM an $SU(2)$ complex Higgs triplet with zero hypercharge is introduced:

$$\mathbf{\Sigma} = \begin{pmatrix} \sqrt{\frac{1}{2}}\xi^0 & \xi_2^+ \\ \xi_1^- & -\sqrt{\frac{1}{2}}\xi^0 \end{pmatrix}.$$

Here ξ^0 is a complex neutral field, while ξ_1^- and ξ_2^+ are the charged Higgs fields. Note that $(\xi_1^-)^* \neq -\xi_2^+$.

Higgs sector of superpotential

$$W = \lambda H_d.\Sigma H_u + \mu_D H_d.H_u + \mu_T Tr(\Sigma^2),$$

μ_D: mixing parameter of the two MSSM Higgses doublets , μ_T: Triplet Mass parameter

λ: Triplet-Doublet coupling

- No interaction term between triplet and fermion superfields.

Triplet extended MSSM

- The Higgs potential can be calculated as

$$V = V_F + V_D + V_S,$$

where V_F, V_D and V_S are contributions from the F-terms D-terms and the soft-supersymmetry breaking terms respectively.

$$\begin{aligned} V_S &= m_1^2|H_d|^2 + m_2^2|H_u|^2 + m_3^2\mathrm{Tr}(\Sigma^\dagger\Sigma) \\ &+ [A_\lambda \lambda H_d \Sigma H_u + B_D \mu_D H_d H_u + B_T \mu_T \mathrm{Tr}(\Sigma^2) + \mathrm{H.c.}]. \end{aligned}$$

Here A_λ is the soft trilinear parameter,
B_D and B_T are the soft bilinear parameters
while m_i $(i = 1, 2, 3)$ represent the soft SUSY breaking masses.

TESSM constraint from EWSB

- When these neutral fields acquire non-zero vevs, the electro-weak symmetry (EWS) is spontaneously broken and all fermions and gauge bosons gain masses.
- The non-zero VEVs are denoted by

$$\langle H_u^0 \rangle = v_u, \;\; \langle H_d^0 \rangle = v_d, \;\; \langle \xi^0 \rangle = v_T,$$

  where $\tan\beta = v_u/v_d$.
- However, the W boson mass expression is altered by the triplet vev as
  $m_W^2 = g_2^2(v^2 + 4v_T^2)/2$, where $v^2 = v_u^2 + v_d^2$;
  whereas the Z boson mass expression remains unaffected.

TESSM constraint from EWSB

- The constraint is defined as ρ parameter,

$$\rho = 1 + 4v_T^2/v^2.$$

- Current experimental measured value of which is,

$$\rho = 1.0004 \begin{array}{l} +0.0003 \\ -0.0004 \end{array}$$

- Thus the triplet vev is strongly constrained
  and implies $v_T \leqslant 3$ GeV.
  We have used $v_T = 3$ GeV in our numerical analysis.

Higgs Sector Of the TESSM

- There are three CP-even neutral Higgs bosons: h, H_1, H_2
  two CP odd Higgs bosons: A_1 and A_2
  and three Charged Higgs bosons: $H_1^{\pm}$, $H_2^{\pm}$ and $H_3^{\pm}$
- Any of these CP-even neutral Higgs could be a candidate $\sim$ 125 GeV Higgs,
  where the other two remains somehow unobserved till now.
  $\Rightarrow$ Buried or decoupled Higgs bosons.
- Possibility of light charged Higgs can affect the indirect observables, e.g., the flavour observables.

Possibility of $\sim$ 125 GeV Higgs @ Tree-level

Tree-level light Higgs mass

- At tree-level the lightest mass-squared eigenvalue is bounded by,

$$m_h^2 \leq M_Z^2 \left(\cos 2\beta + \frac{2\lambda^2}{g_2^2 + g_1^2} \sin 2\beta \right) .$$

- It is possible to obtain the lightest Higgs boson with a mass up to 120 GeV at tree level
- But for a 125 GeV Higgs one also needs to consider the radiative corrections to the neutral Higgs sector.

Chiara et al. PRD78(055016)2008

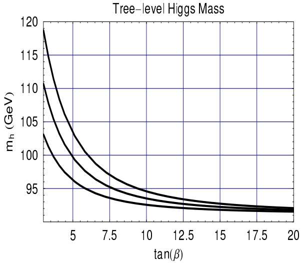


Figure : Tree-level upper bound on the mass of the lightest CP-even Higgs boson as a function of $\tan\beta$ for $\lambda = 0.7$ (lowest line), 0.8 (middle line), and 0.9 (top line)

Possibility of $\sim$ 125 GeV Higgs @ One-loop

- The weak sector contributions could be enough to achieve $\sim$ 125 GeV Higgs unlike MSSM.
  Chiara et al. PRD78(055016)2008
- We saw in pMSSM and other constrain MSSM scenarios one needs either $M_{SUSY} \gtrsim$ few TeV or with large stop mass splittings.
- We will see that for TESSM neither of these two are needed to attend $\sim$ 125 GeV Higgs.
- For the neutral Higgs boson masses at one loop where we consider (s)top,(s)bottom contributions as well as the weak sector contributions (chargino-Higgs-Neutralino loops).

Possibility of $\sim$ 125 GeV Higgs @ One-loop

- For one-loop neutral Higgs mass spectrum we follow the effective-potential approach by Coleman-Weinberg
- The one-loop radiative corrections to the Higgs potential can be calculated using the effective potential approach

$$\Delta V = \frac{1}{64\pi^2} Str \left[\mathcal{M}^4 \left(ln \frac{\mathcal{M}^2}{\Lambda^2} - \frac{3}{2} \right) \right].$$

where $\mathcal{M}$ represents the field dependent mass matrices of the particles and Λ is the renormalization scale.

Numerical Analysis for ~ 125 GeV Higgs @ one-loop

The triplet-Higgs doublet interaction term:

$$\lambda H_d \Sigma H_u$$

- Highly coupled triplet theory: λ is large i.e. $\lambda \sim 0.8 - 0.9$
- Weakly coupled triplet theory: λ is small i.e. $\lambda \sim 0.1$

Scenario	$m_{\tilde{t}_1,\tilde{b}_1}$ (GeV)	$m_{\tilde{t}_2,\tilde{b}_2}$ (GeV)	μ_T (GeV)
Sc1	500	550	500
Sc2	500	550	1200
Sc3	1000	1050	500
Sc4	1000	1050	1200

Table : Scenarios for the allowed parameter space.

We scan the parameter space for $\tan\beta = 5,\ 10,\ 15,\ 30$ and 50 for each scenario. We take the points that satisfy the 125 ± 2 GeV range.

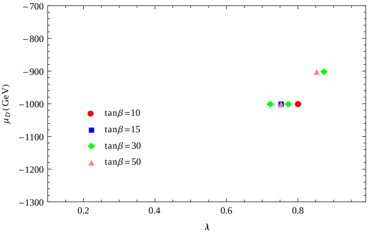
$\sim$ 125 GeV Higgs boson in the TESSM

$\sim$ 125 GeV light Higgs with EW one-loop correction

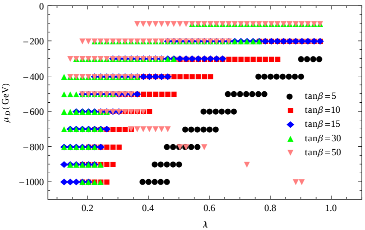
- Fig.(a) describe the parameter space where even with only electro-weak quantum correction one can have $\sim$ 125 GeV Higgs for Sc1.
- We can see that the weak contributions are important and enough to get $\sim$ 125 GeV Higgs for when $\lambda \sim 0.8 - 0.9$
- $\mu_T \sim 500$ GeV was enough to achieve $\sim$ 125 GeV Higgs.

$\sim$ 125 GeV light Higgs with Strong one-loop correction

- Fig.(b) shows when only strong-sector quantum corrections have been considered for Sc1.
- Which is the case with $m_{\tilde{t}_1,\tilde{b}_1} = 500$ GeV and $m_{\tilde{t}_2,\tilde{b}_2} = 550$ GeV.
- $\Rightarrow$ without much splitting in the third generation squark sector and also $M_{SUSY} \sim 500 GeV$ much less than that required for most of the MSSM scenarios..
- Finally Fig(c) shows the parameter space where both the strong and electro-weak sector contributes.



(a)

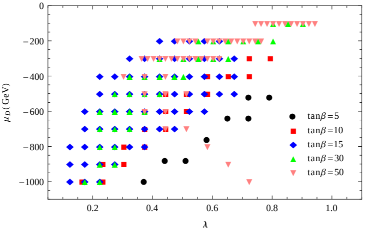


(b)

∼ 125 GeV Higgs boson in the TESSM

∼ 125 GeV light Higgs with total one-loop correction

- Finally Fig(c) shows the parameter space where both the strong and electro-weak sector contributes.
- We can see solution exist for almost all $\tan\beta$ values 5-50.
- The tri-linear parameter $A_t, A_b = 500$ GeV are taken.



(c)

Possibility of ∼ 125 GeV Higgs in TESSM

Triplet extended supersymmetry

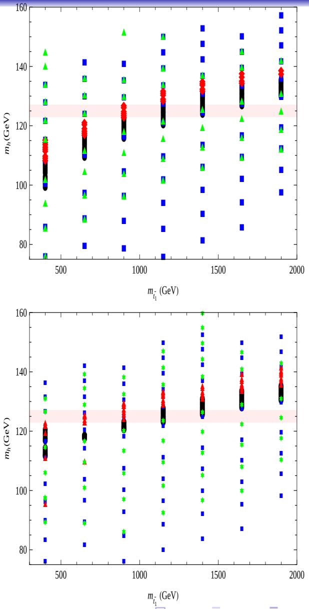
⋆ The stop mass matrix in TESSM:

$$M^2_{\tilde{t}} = \begin{pmatrix} m^2_{\tilde{t}_L} + m^2_t + D_L & X^2_t \\ X^2_t & m^2_{\tilde{t}_R} + m^2_t + D_R \end{pmatrix}$$

where $X^2_t = m_t(A_t + \mu \cot\beta - \frac{\lambda}{\sqrt{2}} v_T \cot\beta)$

- The minimal mixing scenario: $A_t = -\mu \cot\beta$, so only mixing term comes from triplet.
- The maximal mixing scenario: keep X^2_t as it is.
- Lower bounds on the third generation squark masses coming from 125 GeV Higgs are rather week, e.g. a 200 GeV squark mass is still possible.

⋆ $m_{\tilde{t}_1}$ versus m_h for the minimal (up panel) and maximal scenario (down). Black and Red Points : Weakly coupled theory i.e. $\lambda = 0.1$ for $tan\beta = 5$ and $\tan\beta = 50$. Green and Blue Points: Highly coupled theory i.e. $\lambda = 0.9$ for $tan\beta = 5$ and $\tan\beta = 50$.



Outline

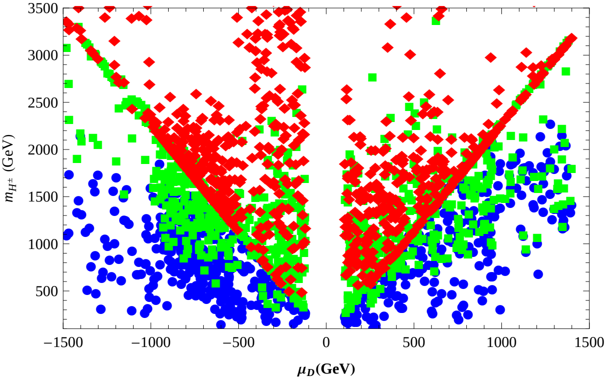
Charged Higgses in TESSM

- There are three Charged Higgs bosons: $H_1^\pm$, $H_2^\pm$ and $H_3^\pm$
- In principle all of them would a mixture of doublet and triplet, i.e.,

$$H^+_{i=1,2,3} = c_{iu} H^+_u + c_{id} H^{-*}_d + c_{T_2} T^+_2 + c_{T_1} T^{-*}_1$$

- We calculate the tree-level charged Higgs masses consistent with a $\sim$ 125 GeV light neutral Higgs.

Charged Higgses in TESSM



- The heaviest charged Higgs ($H_3^\pm$) remains decoupled with mass $\gtrsim$ 500 GeV.
- The 2nd heavier charged Higgs ($H_2^\pm$) stays at $m_{H_2^\pm} \gtrsim 200$ GeV.

Charginos in TESSM

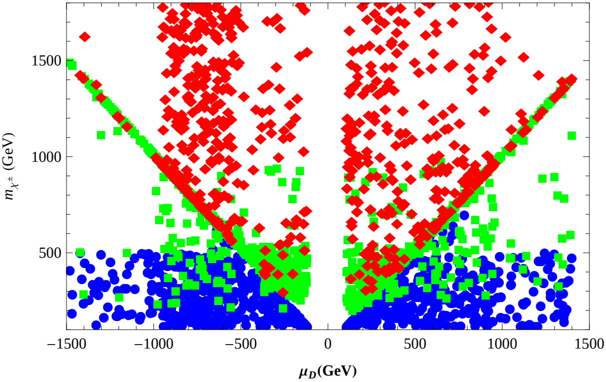
- There are three Charginos : $\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_2^{\pm}$ and $\tilde{\chi}_3^{\pm}$
- In principle all of them would a mixture of doublet and triplet, i.e.,

$$\tilde{\chi}^{+}_{i=1,2,3} = V_{1i}\tilde{W}^{+} + V_{2i}\tilde{H}^{+}_{u} + V_{3i}\tilde{T}^{+}_{2}$$

$$\tilde{\chi}^{-}_{i=1,2,3} = U_{1i}\tilde{W}^{-} + U_{2i}\tilde{H}^{-}_{d} + U_{3i}\tilde{T}^{-}_{1}$$

- We calculate the tree-level chargino masses consistent with a ~ 125 GeV light neutral Higgs.

Charginos in TESSM



- The heaviest chargino ($\tilde{\chi}_3^\pm$) have mass $\gtrsim$ 300 GeV.
- The lightest chargino ($\tilde{\chi}_1^\pm$) mostly have mass $\lesssim$ 500 GeV.

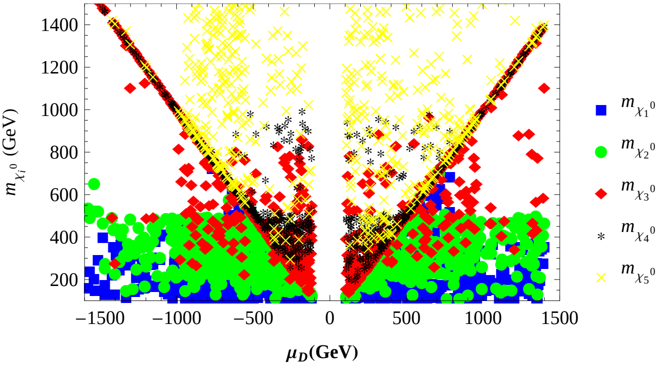
Neutralinos in TESSM

- There are five Neutralinos : $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$, $\tilde{\chi}_4^0$ and $\tilde{\chi}_5^0$
- In principle all of them would a mixture of Bino, Wino, Higgsino and triplino, i.e.,

$$\tilde{\chi}^0_{i=1-5} = N_{1i}\tilde{B}^0 + N_{2i}\tilde{W}^0 + N_{3i}\tilde{H}^0_d + N_{4i}\tilde{H}^0_u + N_{5i}\tilde{T}^0$$

- We calculate the tree-level chargino masses consistent with a ~ 125 GeV light neutral Higgs.

Neutralinos in TESSM



- The heaviest neutralio ($\tilde{\chi}_5^0$) have mass $\gtrsim$ 300 GeV.
- The lightest neutralino ($\tilde{\chi}_1^0$) mostly have mass $\lesssim$ 500 GeV.

Constraints from $B_s \to X_s\gamma$

- Rare B-meson decay analysis provides stringent constraints on new physics beyond the Standard Model.
- In particular, MSSM like models with minimal or general flavor mixings in the sfermion sector get strong bounds from the B-physics observables.
- He we consider the constraints coming from Br$(B_s \to X_s\gamma)$ along with a light neutral Higgs boson ~ 125 GeV.
- In MSSM the significant contributions to $\mathcal{B}r(B_s \to X_s\gamma)$ come from the top-charged Higgs boson and stop-chargino loop contributions in addition to the SM contributions.

Constraints from $B_s \to X_s\gamma$

- Compared to SM, in the case of 2HDM, the only extra contribution to $\mathcal{B}r(B_s \to X_s\gamma)$ comes from the top-charged Higgs loop
  which gives a conservative lower bound to charged Higgs mass $\gtrsim$ 230 GeV. Gambino *et al.*.
- In MSSM this lower bound can go down further due to the cancellation between top-charged Higgs and stop-chargino loops.
- Similarly, in TESSM there are possibilities for such cancellations.

Constraints from $B_s \to X_s\gamma$ in TESSM

- TESSM has two more charged Higgses and one more chargino than in the MSSM.
- The difference compared to the MSSM is that the triplet part of the charged Higgses and charginos does not couple to quarks

Higgs sector of superpotential

$$W = \lambda H_d.\Sigma H_u + \mu_D H_d.H_u + \mu_T Tr(\Sigma^2),$$

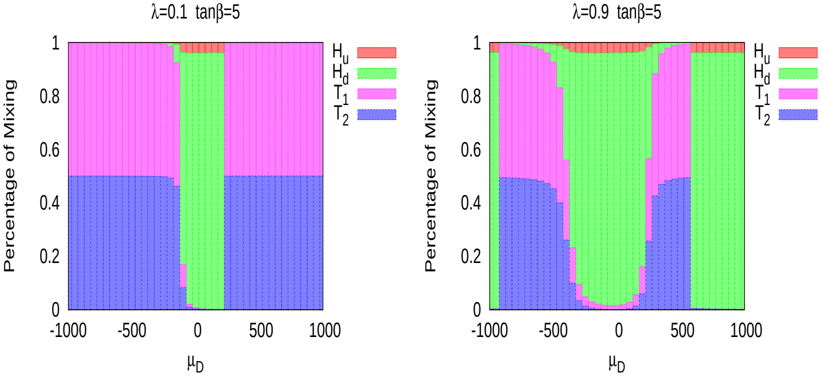
μ_D: mixing parameter of the two MSSM Higgses doublets , μ_T: Triplet Mass parameter

λ: Triplet-Doublet coupling

Constraints from $B_s \to X_s \gamma$ in TESSM

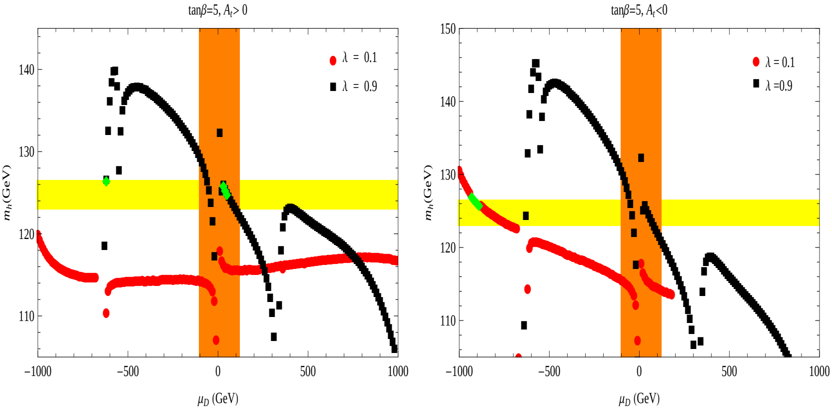
- In TESSM we see that only one Charged Higgs can be light ($\lesssim$ 200 GeV).
- Other charged Higgs are decoupled $\gtrsim$ TeV at the Tree-level.
- Similar in the case for Higgsino like charginos the lighter one is $\sim \mu_D$ and the heavier is $\sim \mu_T$.
- Thus for the practical purpose only the lightest charged Higgs and lightest chargino contributes $B_s \to X_s \gamma$ decay.
- For this purpose we check the doublet content in Both the lightest Charged Higgs and lightest chargino.

Percentage mixing lightest charged Higgs in TESSM



- For $\lambda = 0.1$, low $|\mu_D| \lesssim 200$ GeV, the lightest charged Higgs is mostly doublet.
- For $\lambda = 0.9$ some more regions become doublet like.

Allowed parameter space in TESSM

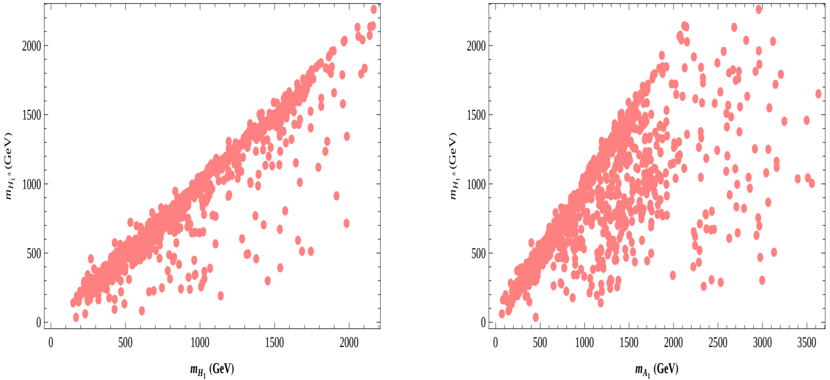


- The variation of the lightest Higgs mass with μ_D for $\tan\beta = 5$ and $m_{\tilde{t}_1} = 500$ GeV.
- The yellow band represents $m_h = 125 \pm 2$ GeV and the orange band shows the LEP-excluded chargino mass region.
- The green points satisfy the allowed experimental value of $\mathcal{B}r(B_s \to X_s\gamma)$ within $\pm 2\sigma$.

Charged Higgs in TESSM

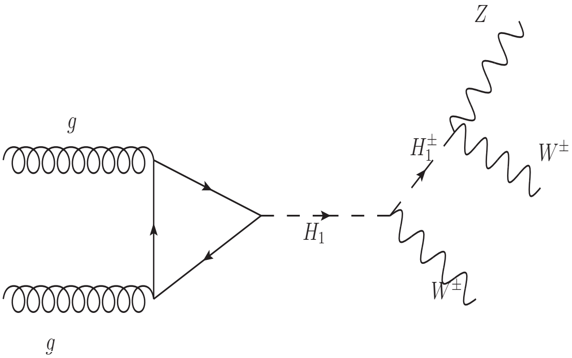
- With two more charged Higgs bosons, the model has a characteristic phenomenology at the LHC.
- Specially as the triplet component does not couples to fermions.
- As a result, a triplet like light charged Higgs can evade the recent bound on light charged Higgs by ATLAS, where $\mathrm{Br}(H^{\pm} \to \tau\nu_{\tau})$ has taken 100%.
- TESSM has $Z - H^{\pm} - W^{\mp}$ vertex unlike SM and MSSM, which could be probed at the LHC.
- A doublet-triplet mixture for both neutral and charged Higgs sector gives rise to interesting phenomenology.

Charged Higgs in TESSM



- Whenever $m_{H_1/A_1} \geq m_W + m_{H_1^\pm}$, $H_1/A_1 \to W^\pm, H_1^\mp$ decay is possible.
- Thus produced triplet type charged Higgs can give us interesting signature.

Charged Higgs in TESSM



- The doublet part of neutral Higgs couples to the fermion and so can be produced in gluon-gluon fusion.
- But it is the triplet part of the charged Higgs that couples to $Z - W^\pm$ and $H^\pm \to ZW^\pm$ is possible.

Charged Higgs in TESSM

- $W^{\pm} - W^{\mp} - Z$ final state can give us 4ℓ final state.
- At 14 TeV LHC it is possible to probe this vertex though this channel.
- We are analysing the final state with full background simulation.
  (work in progress with AS, KH)
- With one $W^{\pm}$ decaying hadronically, it is possible to reconstruct the charged Higgs mass from $2\ell + 2 - jet$ invariant mass distribution.

Multi-dimensional fit of TESSM

- We are analysing the best fit point of the model through a random scan of the model parameters.
- This includes the variation of the following parameters:

$$\tan\beta,\ \mu_D,\ \mu_T,\ A_\lambda,\ A_{t,b},$$

$$m_{\tilde{t}_{1,2}},\ m_{\tilde{b}_{1,2}},\ B_{D,T},\ M_{1,2}$$

- This includes the χ^2 minimization of total 17 observables from CMS, ATLAS and Tevatron.
- Constraints from $\mathrm{Br}(B_S \to X_s\gamma)$ has also been considered.

(Work in progress with SC, AS, KH)

Few Recent Studies

- The charged components of the triplet superfield enhances the diphoton Higgs decay rates by as much as 50% with respect to the Standard Model values.
  Antonio et al.,Phys.Rev. D86 (2012) 115010
- A benchmark scenario with low tan β has been discusses in the context of $\sim$ 125 GeV Higgs and SM like point.
  Antonio et al., JHEP 1307 (2013) 054

Outline

Conclusions

- We have studied the triplet extended supersymmetric model in the context of 125 GeV Higgs.
- Addition of two triplet parameters λ and μ_T, the lightest Higgs with $m_h \sim 125$ GeV, does not strongly constrain the third generation squark masses, the trilinear couplings A_q.
- For higher $\tan\beta$, even the weakly coupled theory ($\lambda \lesssim 0.2$) can have ~ 125 GeV Higgs with $M_{SUSY}, A \sim 500$ GeV.
- Both signs of μ_D can be allowed depending on the doublet-triplet mixing in the charged Higgses and charginos considering the constraints from $\text{Br}(B_s \to X_s\gamma)$.

Conclusions

- The charged Higgs phenomenology is very interesting because of the possible non-trivial decay mode to $W^{\pm}Z$ as this mode can evade the recent bounds on light charged Higgs.
- A multi-dimensional data fit would give us a direction about the parameter space and the acceptability.
- Dark matter constraints and many other phenomenological studies are in the process which will give us more inside to the model.

Thank you

Outline

Theoretical bounds on Standard Model Higgs boson

- Perturbative unitarity $\Rightarrow m_h < 870$ GeV.
- Triviality $\Rightarrow m_h < 160$ GeV.
- Stability $\Rightarrow m_h > 126$ GeV.

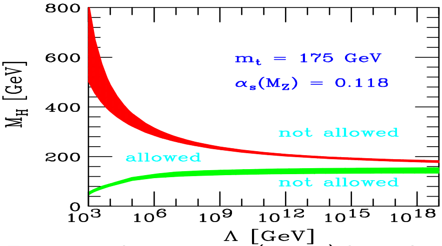
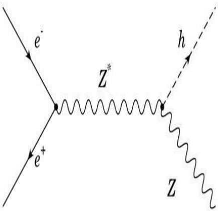
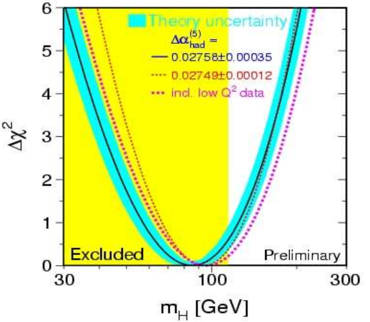


Figure : The triviality (upper) bound and the vacuum stability (lower) bound on the Higgs boson mass as a function of the New Physics or cut–off scale Λ for a top quark mass $m_t = 175 \pm 6$ GeV and $\alpha_s(M_Z) = 0.118 \pm 0.002$

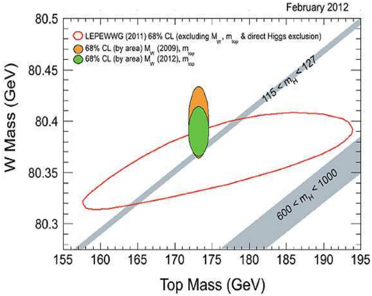
Experimental constraints:LEP





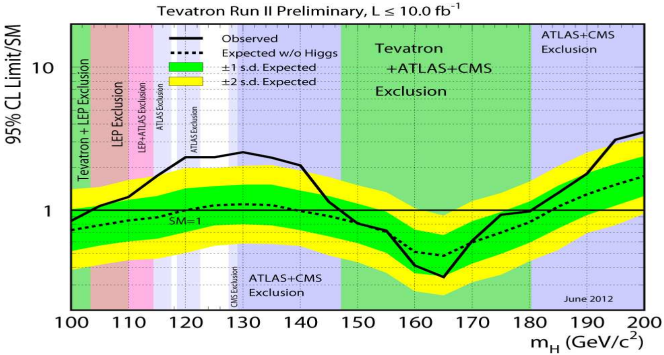
- The direct mass bound on SM Higgs is $m_H > 114.4$ GeV
- The blue band implies that the Higgs boson has a mass of 85^{+39}_{-28} GeV in the standard model at 1σ level.
- $\Rightarrow m_H \lesssim 124$ GeV.

Experimental constraints: CDF, Tevatron in February, 2012



- CDF has measured the mass of the W boson with a precision of 0.02 percent and $m_W = 80387 \pm 19$ MeV.
- The new W mass measurement and the latest the top quark mass triangulate the location of the Higgs particle and restrict $m_H < 145$ GeV @ 95% C.L. PRL 108, 151803 (2012)

Experimental constraints: Tevatron on 2^{th} July, 2012



- 95% C.L. exclusion for SM Higgs with mass $m_H = 147 - 180$ GeV, and $m_H = 100 - 103$ GeV.
- An excess with a significance of 2.5σ is seen that might be interpreted as coming from a Higgs boson with a mass in the region of 115 to 135 GeV.
- A significance of 2.9σ is seen in the combination of CDF and D's $H \to bb$ channels. arXiv:1207.0449[hep-ex]

Outline

A comparative study of different models, Djouadi et al.

mSUGRA:

50 GeV $\leq m_0 \leq$ 3 TeV, 50 GeV $\leq m_{1/2} \leq$ 3 TeV, $|A_0| \leq$ 9 TeV

GMSB:

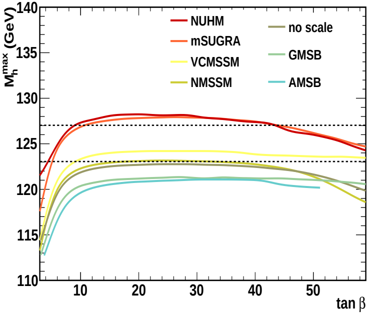
10 TeV $\leq \Lambda \leq$ 1000 TeV, $1 \leq M_{\rm mess}/\Lambda \leq 10^{11}$, $N_{\rm mess} = 1$

AMSB:

1 TeV $\leq m_{3/2} \leq$ 100 TeV, 50 GeV $\leq m_0 \leq$ 3 TeV.

Others

No scale: $m_0 \approx A_0 \approx 0$;
VCMSSM:$A_0 \approx -m_0$;
cNMSSM: $m_0 \approx 0$ and $A_0 \approx -\frac{1}{4} m_{1/2}$
NUHM: Universal Higgs mass term is different from sfermions.



model	AMSB	GMSB	mSUGRA	no-scale	cNMSSM	VCMSSM	NUHM
$M_h^{\rm max}$	121.0	121.5	128.0	123.0	123.5	124.5	128.5

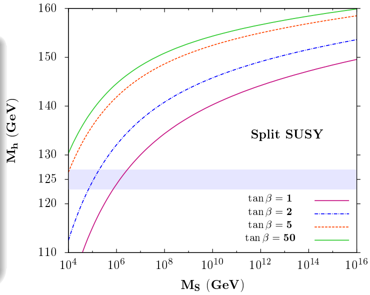
Slipt and High scale SUSY: Djouadi et al.

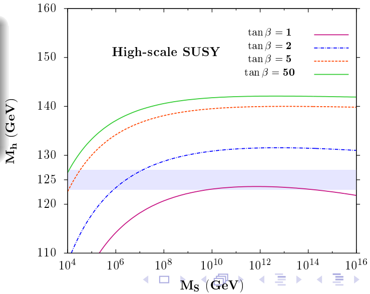
Slipt SUSY

- Except for the lightest h boson, no other scalar particle is accessible at the LHC or at any foreseen collider.
- Except for one Higgs doublet, other scalars have a common value; $M_S \gg 1$ TeV.
- The mass parameters for the spin$-\frac{1}{2}$ particles, the gauginos and the higgsinos, are left in the vicinity of the EWSB scale, allowing for a solution to the dark matter problem and a successful gauge coupling unification

High scale SUSY

- Gauginos and higgsinos are also very heavy, with a mass close to the scale M_S.
- Even if broken at very high scales, SUSY would still lead to a "light" Higgs boson whose mass will contain information on M_S and $\tan\beta$.



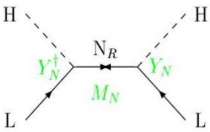


Outline

The 3 basic seesaw models

i.e. tree level ways to generate the dim 5 operator

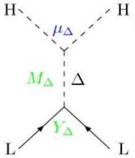
Right-handed singlet: (type-I seesaw)



$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

Minkowski; Gellman, Ramon, Slansky; Yanagida; Glashow; Mohapatra, Senjanovic

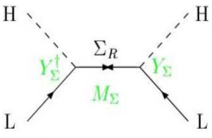
Scalar triplet: (type-II seesaw)



$$m_\nu = Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

Magg, Wetterich; Lazarides, Shafi; Mohapatra, Senjanovic; Schechter, Valle

Fermion triplet: (type-III seesaw)



$$m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$$

Foot, Lew, He, Joshi; Ma; Ma, Roy; T.H., Lin, Notari, Papucci, Strumia; Bajc, Nemevsek, Senjanovic; Dorsner, Fileviez-Perez;....

Higgs mechanism

- So we add a complex scalar $SU(2)_L$ doublet, Φ that coupled to the gauge fields,

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

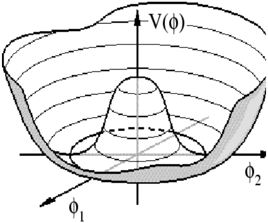
with a scalar potential given by

$$V(\Phi) = \mu^2 \mid \Phi^\dagger \Phi \mid + \lambda \left(\mid \Phi^\dagger \Phi \mid \right)^2$$

where, $\lambda \equiv \text{scalar self coupling},\ \lambda > 0$
and $\mu^2 \equiv \text{scalar mass parameter} \mu^2 < 0.$

- The minimum of the potential is given by $< v >= \sqrt{-\frac{\mu^2}{2\lambda}}$

Higgs mechanism



- The contribution of the scalar doublet to the Lagrangian is,

$$\mathcal{L}_s = (D^\mu \Phi)^\dagger (D_\mu \Phi) - V(\Phi)$$

where the covariant derivative involving the gauge-fields is given by,

$$D_\mu = \partial_\mu - i\frac{g}{2}\tau \cdot W_\mu - i\frac{g'}{2}B_\mu Y$$

Higgs mechanism

- Expanding around minimum, we have

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+h \end{pmatrix}$$

The mass-squared matrix for the gauge (vector) bosons looks like

$$M_V^2 \sim \frac{1}{2}(0,v)\left(\frac{1}{2}g\tau \cdot W_\mu + \frac{1}{2}g' B_\mu\right)^2 \begin{pmatrix} 0 \\ v \end{pmatrix}$$

Three of the degrees of freedom of the complex scalar doublet absorbed by the gauge bosons to show up as longitudinal polarizations for the W and Z bosons which thus become massive.

This is known as the Higgs mechanism of electroweak symmetry breaking.

- Fermion mass can be generated by the Yukawa coupling:

$$\mathcal{L}_d = -\lambda_d \overline{Q}_L \Phi d_R + h.c..$$