# Higgs bosons: discovered and hidden, in extended supersymmetric standard models at the LHC

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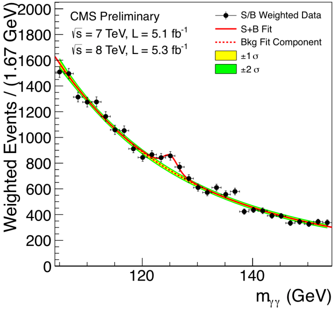
# Outline

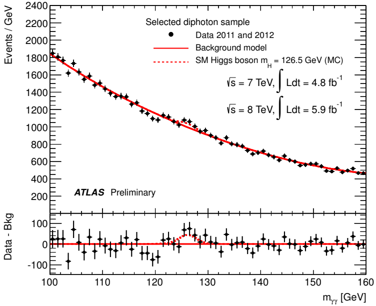
1. Plan
2. MSSM
3. TNSSM

# Plan

1. Observed Higgs boson
2. MSSM and its status
3. Triplet and singlet extended Supersymmetric scenarios
4. Possibility of Hidden scalar
5. Conclusion

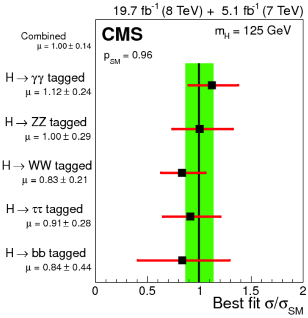
# Experimental constraints: LHC on $4^{th}$ July, 2012

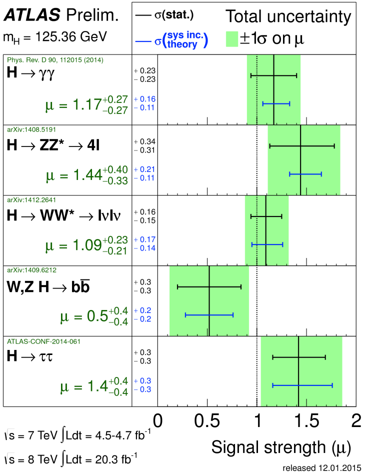



- Finally, on 4th of July 2012, we get evidence of a even-integer-spin particle similar to Higgs boson at the LHC.
- So far we have discovered Higgs boson around $\sim$ 125 GeV in $WW^*, ZZ^*, \gamma\gamma$ modes.

# Status of Higgs at the LHC

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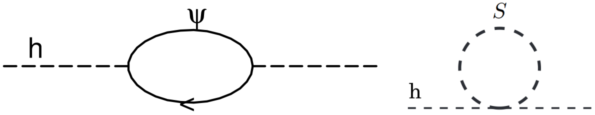
- CMS: $H \rightarrow ZZ \Rightarrow m_H = 125.5 \pm 0.2(\mathrm{stat})^{+0.5}_{-0.4}(\mathrm{sys})$
- ATLAS: $H \rightarrow ZZ \Rightarrow m_H = 125.7 \pm 0.3(\mathrm{stat}) \pm 0.3(\mathrm{sys})$

# Hierarchy problem and supersymmetry

- Higgs mass is not protected by any symmetry ⇒ Hierarchy problem.
- Supersymmetry protects the Higgs mass by giving possible cancellation.




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

# Outline

# Higgs sector in MSSM

- 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
- Including $R$-parity, $P_R = (-1)^{3(\mathrm{B-L})+2\mathrm{s}}$ conservation leads to the lightest supersymmetric particle as Dark matter candidate.

## Lightest Higgs in MSSM

- While in the SM the Higgs mass is essentially a free parameter the lightest CP–even Higgs particle in the MSSM is bounded from above.
- At tree level the lightest CP-even Higgs ($h$) mass, $m_h \leq M_Z$
- For desired Higgs mass around 125 GeV, one has to look for quantum correction.

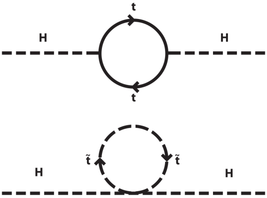
# Higgs sector in MSSM

## Lightest Higgs in MSSM

- Depending on the SUSY parameters that enter the radiative corrections, it is restricted to values

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

- SUSY particles mass and other parameters enter in the radiative correction to the Higgs sector.
- $\Rightarrow$ "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.




$$\mathbf{M}^2_{\tilde{t}} = \begin{pmatrix} M_L^2 & m_t X_t \\ m_t X_t & M_R^2 \end{pmatrix} .$$

- With the radiative correction at one-loop the lightest Higgs mass becomes,

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

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: $X_t^{max} = \sqrt{6} M_S$.

# Higgs sector in MSSM

## Lightest Higgs in MSSM

- Lightest CP-even Higgs boson is the candidate $\sim$ 125 GeV Higgs boson.
- In MSSM, the main loop contributions come from the third generation strong sectors,
- push the mass scale $\gtrsim$ 1 TeV to up to 10 TeV depending on the models.
- In most constrained SUSY scenarios viz mSUGRA , the required SUSY mass scale is $\gtrsim$ 10 TeV.
- In pMSSM, $\lesssim$ TeV SUSY scale still a possibility but with large mixing in the stop mass matrix.
- Fine tuning is necessary for MSSM to have lightest Higgs boson mass around $\sim$ 125 GeV.

▸ more

## Heavy Higgs bosons

- The other CP-even and CP-odd Higgs search is still on.
- So far both CMS and ATLAS have not found any evidence of heavier Higgs bosons.

## Charged Higgs bosons

- MSSM has one charged Higgs boson.
- The charged Higgs dominantly decays to $\tau\nu$
- So far no evidence has been found.

$\sim$ 125 GeV Higgs $\Rightarrow$ very large SUSY mass scale or/and large mixings $\Rightarrow$ fine tuning.

# Solution!

Extended Higgs sector!

- New scalars give additional contributions to the lightest Higgs mass
- so no large mixing and/or heavy sfermions needed
- Extended theory may solve the $\mu$ problem
- Possibility of spontaneous CP-violation.

Options ?

Triplet and/or singlet extensions.

# Outline

# Triplet-Singlet extended Supersymmetric scenarios

- The $\mu_D$ term in the superpotenial can be generated spontaneously by the introduction of a gauge singlet superfield $S$.
- The scale invariant superpotential with the $Y = 0$ triplet T and singlet S is given by,

$$W_S = \lambda_T H_d.TH_u + \lambda_S SH_d \cdot H_u + \lambda_{TS} STr[T^2] + \frac{\kappa}{3}S^3.$$

- The complete Lagrangian with the soft SUSY breaking terms has an accidental $Z_3$ symmetry; $\phi_i \to e^{2\pi i/3}\phi_i$ ▸ more
- When the neutral parts get vev,

$$< H^0_{u,d} >= \frac{v_{u,d}}{\sqrt{2}}, \quad < S >= \frac{v_S}{\sqrt{2}} \quad < T^0 >= \frac{v_T}{\sqrt{2}}$$

generate the the doublet mixing term $\mu_D = \frac{\lambda_S}{\sqrt{2}} v_S + \frac{\lambda_T}{2} v_T$

- Singlet does not couple to fermions and gauge bosons, whereas $Y = 0$ triplet only couples to $W^{\pm}$
- Experimental $\rho$ parameter gives strong bounds, $v_T \lesssim 5$ GeV.

# TNSSM: Higgs bosons and mass spectrum at tree-level

- Enhanced Higgs particle spectrum

$$\begin{array}{ccc} \mathrm{CP-even} & \mathrm{CP-odd} & \mathrm{charged} \\ h_1, h_2, h_3, h_4 & a_1, a_2, a_3 & h_1^\pm, h_2^\pm, h_3^\pm. \end{array}$$

- The extra interaction terms also enhances the Higgs mass contribution at the tree-level thus reduces required SUSY the fine-tuning further.

$$m_{h_1}^2 \leq m_Z^2(\cos^2 2\beta + \frac{\lambda_T^2}{g_L^2 + g_Y^2}\sin^2 2\beta + \frac{2\lambda_S^2}{g_L^2 + g_Y^2}\sin^2 2\beta),$$

$$\tan\beta = \frac{v_u}{v_d}$$

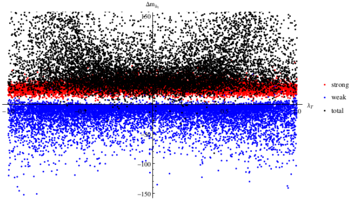
# TNSSM: Higgs mass spectrum at one-loop

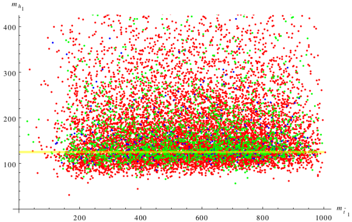
## Effective potential at one loop

- 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 $\Lambda$ is the renormalization scale.



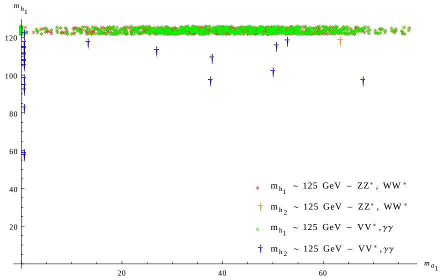

- The required stop mass is much lower and one should look for directed SUSY searches.

## In the limit of a continuous symmetry

- In the limit when the $A_i$ parameters go to zero, the discrete $Z_3$ symmetry of the Lagrangian is promoted to a continuos $U(1)$ symmetry

$$(\hat{H}_u, \hat{H}_d, \hat{T}, \hat{S}) \rightarrow e^{i\phi}(\hat{H}_u, \hat{H}_d, \hat{T}, \hat{S})$$

- If this symmetry is softly broken by very small parameters $A_i$ of $\mathcal{O}(1)$ GeV, we get a very light pseudoscalar as pseudo-Nambu-Goldstone boson of the symmetry.

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# TNSSM Phenomenology and studies going on

## Hidden Higgs phenomeology

- The possibility of very light hidden Higgs(es) is still viable in this scenario.
- Specially $h^{\pm} \to h_1 W^{\pm}$, $h_i \to a_j a_k$, $h_i \to Z a_j$ are very crucial in determining the Higgs sector.
- We are investigating $2b + 2\tau$, $2\tau + 2\mu$ and $2b + 2\mu$ final states to probe the hidden Higgs scenario taking care of the possible backgrounds.

## Charged Higgs phenomeology

- Triplet type charged Higgs does not couple to fermions.
- Tree-level $h_i^{\pm} - W^{\mp} - Z$ introduces new decay channel and production channels.

# Conclusions

- So far we have observed a CP-even Higgs boson around $\sim 125$ GeV.
- All possible Standard Model modes are yet to be discovered.
- Possibility of hidden Higgs is still a possibility.
- Observation of Charged Higgs would be a direct proof of extended Higgs sector.
- We have studied the triplet and triplet-singlet extended supersymmetric models in the context of 125 GeV Higgs.
- In the extended Higgs SUSY scenarios, lighter SUSY mass scale is still a possibility.
- $h_1^\pm \to ZW^\pm$ could be a smoking gun signature for the triplet scenario.
- A very light speudo-scalar is still a possibility with extended Higgs sector.

Thank you

# TNMSSM potential

$$
\begin{aligned}
V_{soft} \;=\;& m_{H_u}^2|H_u|^2 + m_{H_d}^2|H_d|^2 + m_S^2|S|^2 \\
& + m_T^2|T|^2 + m_Q^2|Q|^2 + m_U^2|U|^2 + m_D^2|D|^2 \\
& +(A_S S H_d.H_u + A_\kappa S^3 + A_T H_d.T.H_u + A_{TS} S Tr(T^2) \\
& + A_U U H_U.Q + A_D D H_D.Q + h.c),
\end{aligned}
$$

while the D-terms are given by

$$
V_D = \frac{1}{2}\sum_k g_k^2(\phi_i^\dagger t_{ij}^a \phi_j)^2.
$$

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