Introduction to Higgs Physics

LECTURE III

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TIFR

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Veltman condition is not satisfied...

...hence SM is susceptible to a hierarchy problem...

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- must have verifiable predictions

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Even in broken SUSY, the quadratic divergence cancels

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Ross & Veltman 1975

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$$\boxed{M_W^2 = \frac{g^2 v^2}{2}\{t(t+1) - t_3^2\}} \qquad \boxed{\frac{1}{2}M_Z^2 = \frac{g^2 v^2}{2}\left(t_3^2 + \frac{y^2}{4}\tan^2\theta_W\right)}$$

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If there are several Higgs multiplets

$$M_W^2 = \frac{g^2}{8}\sum_i \{4t_i(t_i+1) - y_i^2\}\, v_i^2$$

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Experimentally $\rho = 1.0004^{+0.0003}_{-0.0004}$

Standard Model

$$\rho = \frac{4t(t+1) - y^2}{2y^2}$$

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$$\rho = \frac{4t(t+1) - y^2}{2y^2} = \frac{4 \times \frac{1}{2} \times \frac{3}{2} - 1}{2} = \frac{3-1}{2} = 1$$

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Standard Model + extra multiplets

$$\rho = \frac{2v^2 + \sum_j \left\{ 4t_j(t_j+1) - y_j^2 \right\} v_j^2}{2v^2 + \sum_j 2y_j^2 \, v_j^2}$$

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triplets $4t_j(t_j+1) - y_j^2 = 8 \qquad 2y_j^2 = 0$

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exotics

Standard Model

$$\rho = \frac{4t(t+1) - y^2}{2y^2} = \frac{4 \times \frac{1}{2} \times \frac{3}{2} - 1}{2} = \frac{3-1}{2} = 1$$

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doublets [illegible]

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exotics $t_j = 3, y_j = 4$

[illegible]

$$\rho = 1 + \left(\frac{\quad}{v} \right)$$

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$4t_j(t_j+1) = 3y_j^2$

One Extra Doublet (2HDM)

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- $\mathcal{L} = \mathcal{L}_1 + \mathcal{L}_2 + \mathcal{L}_3 + \mathcal{L}_4$
- $\mathcal{L}_1 = -\frac{1}{4} F^i_{\mu\nu} F^{i\mu\nu} - \frac{1}{4} G_{\mu\nu} G^{\mu\nu}, \quad i = 1, 2, 3.$
- $\mathcal{L}_2 = \overline{\psi} i \gamma^\mu D_\mu \psi, \qquad D_\mu = \left(\partial_\mu - ig\, T.A_\mu - i\frac{g'}{2} B_\mu\right)$
- $\mathcal{L}_3 = (D_\mu \phi_1)^\dagger (D_\mu \phi_1) + (D_\mu \phi_2)^\dagger (D_\mu \phi_2) - V(\phi_1, \phi_2)$
- $\mathcal{L}_4 = f^e_{1ij} \overline{l}'_{iL} \Phi_1 e'_{jR} + f^e_{2ij} \overline{l}'_{iL} \Phi_2 e'_{jR} + f^d_{1ij} \overline{q}'_{iL} \Phi_1 d'_{jR} + f^d_{2ij} \overline{q}'_{iL} \Phi_2 d'_{jR}$
  $+ f^u_{1ij} \overline{q}'_{iL} \Phi^c_1 u'_{jR} + f^u_{2ij} \overline{q}'_{iL} \Phi^c_2 u'_{jR}.$

$$
\begin{aligned}
V(\Phi_1, \Phi_2) \;=\; & \lambda_1 (\Phi_1^\dagger \Phi_1 - v_1^2)^2 + \lambda_2 (\Phi_2^\dagger \Phi_2 - v_2^2)^2 \\
& + \left[\lambda_3 (\Phi_1^\dagger \Phi_1 - v_1^2) + \lambda_2 (\Phi_2^\dagger \Phi_2 - v_2^2)\right]^2 \\
& + \lambda_4 \left[\left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) - \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right)\right] \\
& + \lambda_5 \mid \Phi_1^\dagger \Phi_2 - v_1 v_2 \mid^2
\end{aligned}
$$

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- $\mathcal{L}_4 = f^e_{1ij} \overline{l}'_{iL} \Phi_1 e'_{jR} + \underline{f^e_{2ij} \overline{l}'_{iL} \Phi_2 e'_{jR}} + f^d_{1ij} \overline{q}'_{iL} \Phi_1 d'_{jR} + \underline{f^d_{2ij} \overline{q}'_{iL} \Phi_2 d'_{jR}}$
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$$
\begin{aligned}
V(\Phi_1, \Phi_2) \;=\; & \lambda_1 (\Phi_1^\dagger \Phi_1 - v_1^2)^2 + \underline{\lambda_2 (\Phi_2^\dagger \Phi_2 - v_2^2)^2} \\
& + \underline{\left[\lambda_3 (\Phi_1^\dagger \Phi_1 - v_1^2) + \lambda_2 (\Phi_2^\dagger \Phi_2 - v_2^2)\right]^2} \\
& + \underline{\lambda_4 \left[\left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) - \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right)\right]} \\
& + \underline{\lambda_5 \mid \Phi_1^\dagger \Phi_2 - v_1 v_2 \mid^2}
\end{aligned}
$$

$$\Phi_1(x) = \begin{bmatrix} \omega_1^+ \\ \frac{1}{\sqrt{2}}(\rho_1^0 + v_1 + i\eta_1^0) \end{bmatrix} \qquad \Phi_2(x) = \begin{bmatrix} \omega_2^+ \\ \frac{1}{\sqrt{2}}(\rho_2^0 + v_2 + i\eta_2^0) \end{bmatrix}$$

Total of 8 scalar fields = 3 Goldstone + 5 physical

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$$\mathrm{v}_1^2 + \mathrm{v}_2^2 = \mathrm{v}^2 \qquad \tan\beta = \frac{\mathrm{v}_1}{\mathrm{v}_2} \qquad \begin{aligned} \mathrm{v}_1 &= \mathrm{v}\sin\beta \\ \mathrm{v}_2 &= \mathrm{v}\cos\beta \end{aligned}$$

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$$\begin{aligned} G^+ &= \omega_1^+\cos\beta - \omega_2^+\sin\beta \\ H^+ &= \omega_1^+\sin\beta + \omega_2^+\cos\beta \end{aligned} \qquad \begin{aligned} M^2(G^+) &= 0 \\ M^2(H^+) &= \lambda_4\mathrm{v}^2 \end{aligned}$$

$$\Phi_1(x) = \begin{bmatrix} \omega_1^+ \\ \frac{1}{\sqrt{2}}(\rho_1^0 + v_1 + i\eta_1^0) \end{bmatrix} \qquad \Phi_2(x) = \begin{bmatrix} \omega_2^+ \\ \frac{1}{\sqrt{2}}(\rho_2^0 + v_2 + i\eta_2^0) \end{bmatrix}$$

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$$G^+ = \omega_1^+ \cos\beta - \omega_2^+ \sin\beta \qquad M^2(G^+) = 0$$

$$H^+ = \omega_1^+ \sin\beta + \omega_2^+ \cos\beta \qquad M^2(H^+) = \lambda_4 v^2$$

$$G^0 = \eta_1^0 \cos\beta - \eta_2^0 \sin\beta \qquad M^2(G^0) = 0$$

$$A^0 = \eta_1^0 \sin\beta + \eta_2^0 \cos\beta \qquad M^2(A^0) = \lambda_5$$

$$\Phi_1(x) = \begin{bmatrix} \omega_1^+ \\ \frac{1}{\sqrt{2}}(\rho_1^0 + v_1 + i\eta_1^0) \end{bmatrix} \qquad \Phi_2(x) = \begin{bmatrix} \omega_2^+ \\ \frac{1}{\sqrt{2}}(\rho_2^0 + v_2 + i\eta_2^0) \end{bmatrix}$$

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$$H^0 = \eta_1 \sin\beta + \eta_2 \cos\beta \qquad M^2(A^0) = \lambda_5$$

$$H^0 = -\rho_1^0 \cos\alpha + \rho_2^0 \sin\alpha$$

$$h^0 = -\rho_1^0 \sin\alpha + \rho_2^0 \cos\alpha \qquad \mathcal{M} = \begin{pmatrix} 4v_1^2(\lambda_1 + \lambda_3) + v_2^2\lambda_5 & (4\lambda_3 + \lambda_5)v_1 v_2 \\ (4\lambda_3 + \lambda_5)v_1 v_2 & 4v_2^2(\lambda_2 + \lambda_3) + v_1^2\lambda_5 \end{pmatrix}$$

Glashow-Weinberg theorem

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$$\mathcal{L}_{\text{mass}} = \sum_{i,j=1}^{3} \left(h_{ij}^{\ell} \bar{L}_{Li} \langle \Phi_1 \rangle e_{Rj} + h_{ij}^{d} \bar{Q}_{Li} \langle \Phi_1 \rangle d_{Rj} + h_{ij}^{u} \bar{Q}_{Li} \langle \widetilde{\Phi}_1 \rangle u_{Rj} \right) + \text{H.c.}$$

$$+ \sum_{i,j=1}^{3} \left(\tilde{h}_{ij}^{\ell} \bar{L}_{Li} \langle \Phi_2 \rangle e_{Rj} + \tilde{h}_{ij}^{d} \bar{Q}_{Li} \langle \Phi_2 \rangle d_{Rj} + \tilde{h}_{ij}^{u} \bar{Q}_{Li} \langle \widetilde{\Phi}_2 \rangle u_{Rj} \right) + \text{H.c.}$$

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not seen!

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Just like Standard Model

SUSY Higgs sector

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Variant of a Type-I 2HDM

But there is more....

General 2HDM

$$
\begin{aligned}
V(\phi_1, \phi_2) = \lambda_1 (\phi_1^\dagger \phi_1 - v_1^2)^2 + \lambda_2 (\phi_2^\dagger \phi_2 - v_2^2)^2 \\
+ \lambda_3 \left[(\phi_1^\dagger \phi_1 - v_1^2) + (\phi_2^\dagger \phi_2 - v_2^2) \right]^2 \\
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\lambda_2 &= \lambda_1 \\
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General 2HDM

6 free parameters: λ's and tan β

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2 free parameters: λ_1 and tan β

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2 free parameters: λ_1 and tan β

$\Downarrow$

Common choice: M_A and tan β

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$$m_{A^0}^2 = m_{H^\pm}^2 - m_W^2$$

$$m_{H^0,h^0}^2 = \frac{1}{2}\left[m_{A^0}^2 + m_Z^2 \pm \sqrt{(m_{A^0}^2 + m_Z^2)^2 - 4m_Z^2 m_{A^0}^2 \cos^2 2\beta}\right]$$

$$\cos 2\alpha = -\cos 2\beta \left(\frac{m_{A^0}^2 - m_Z^2}{m_{H^0}^2 - m_{h^0}^2}\right)$$

$$\sin 2\alpha = -\sin 2\beta \left(\frac{m_{H^0}^2 + m_{h^0}^2}{m_{H^0}^2 - m_{h^0}^2}\right)$$

$$m_{A^0}^2 = m_{H^\pm}^2 - m_W^2$$

$$m_{H^0,h^0}^2 = \frac{1}{2}\left[m_{A^0}^2 + m_Z^2 \pm \sqrt{(m_{A^0}^2 + m_Z^2)^2 - 4m_Z^2 m_{A^0}^2 \cos^2 2\beta}\right]$$

$$\cos 2\alpha = -\cos 2\beta \left(\frac{m_{A^0}^2 - m_Z^2}{m_{H^0}^2 - m_{h^0}^2}\right)$$

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$m_{H^\pm} \geq m_W$ $\qquad$ $m_{H^0} \geq m_Z$ $\qquad$ $m_{A^0} \geq m_{h^0}$

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$$\boxed{\begin{gathered} m_{h^0} \leq m|\cos 2\beta| \leq m_Z, \\ m \equiv \min\{m_Z, m_{A^0}\}. \end{gathered}}$$

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A light Higgs!

Discovered Higgs has mass 125.5 GeV > mass of Z, i.e. 91.2 GeV

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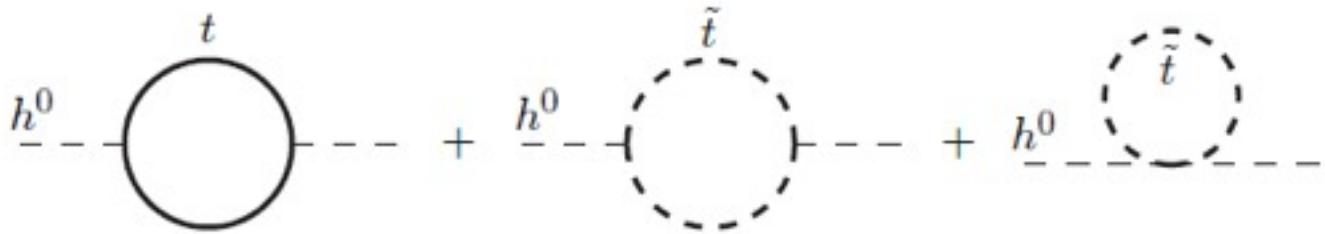
Include radiative corrections

$\Delta(m^2_{h^0}) =$



$$m^2_{h^0} = m^2_Z \cos^2(2\beta) + \frac{3}{4\pi^2} \sin^2\beta \, y_t^2 \Big[m_t^2 \ln\left(m_{\tilde{t}_1} m_{\tilde{t}_2}/m_t^2\right) + c_{\tilde{t}}^2 s_{\tilde{t}}^2 (m^2_{\tilde{t}_2} - m^2_{\tilde{t}_1}) \ln(m^2_{\tilde{t}_2}/m^2_{\tilde{t}_1})$$
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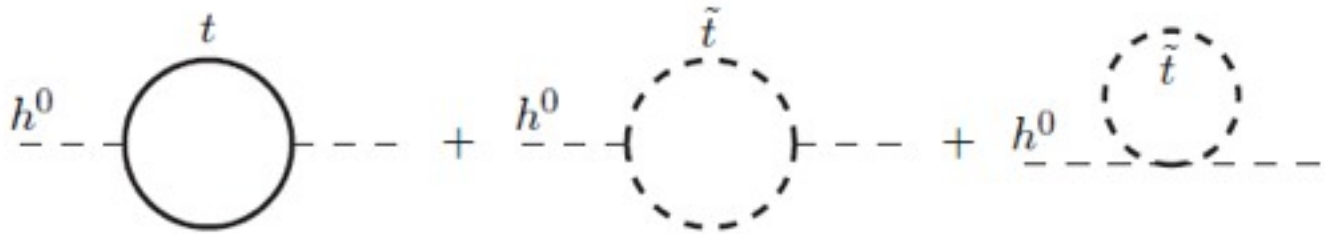

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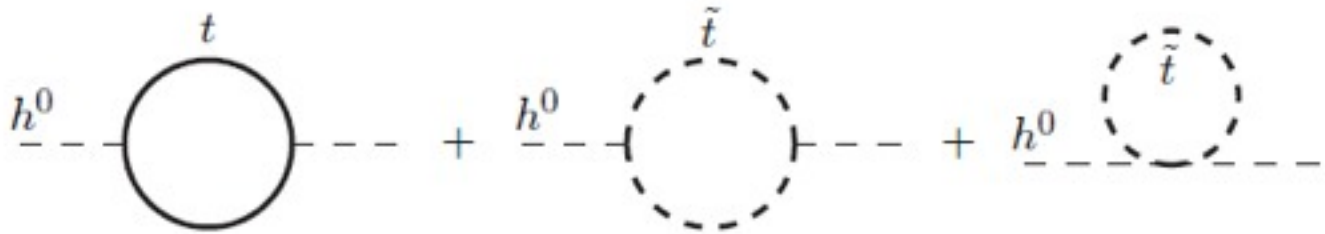

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91.2 GeV 118 GeV

Discovered Higgs has mass 125.5 GeV > mass of Z, i.e. 91.2 GeV

Include radiative corrections

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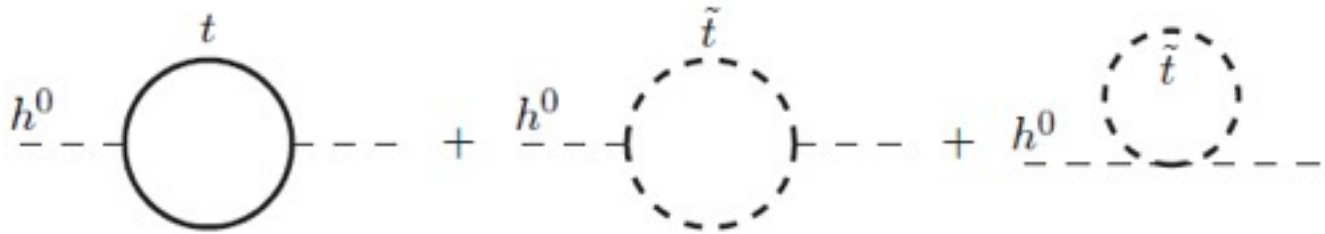

$$m_{h^0}^2 = \underline{m_Z^2 \cos^2(2\beta)} + \frac{3}{4\pi^2} \sin^2\beta \, y_t^2 \Big[\underline{m_t^2 \ln\left(m_{\tilde{t}_1} m_{\tilde{t}_2}/m_t^2\right)} + \underline{c_{\tilde{t}}^2 s_{\tilde{t}}^2 (m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2) \ln(m_{\tilde{t}_2}^2/m_{\tilde{t}_1}^2)}$$
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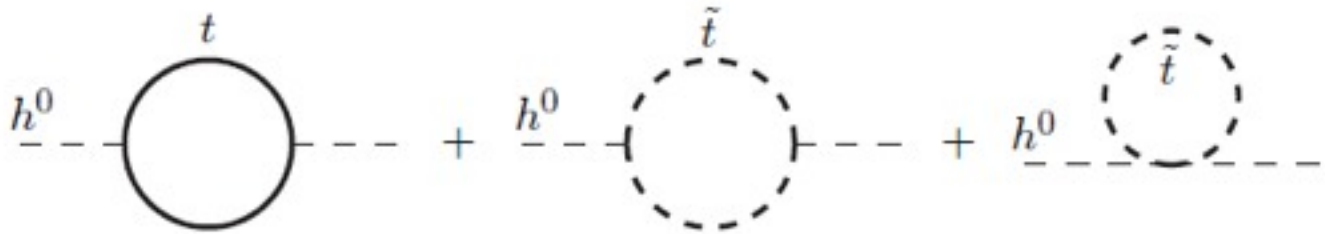

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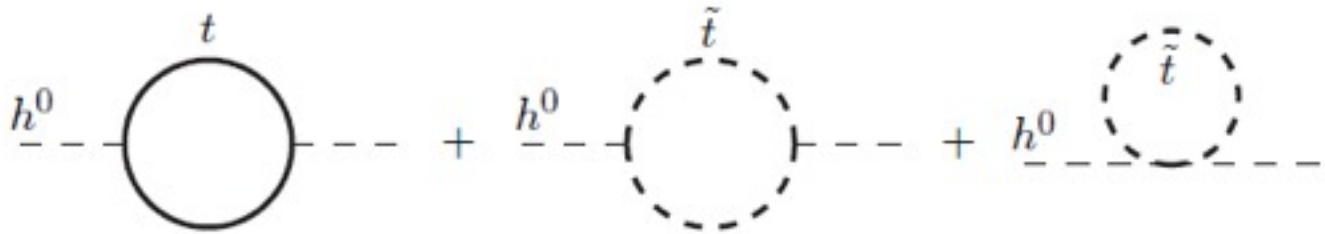
91.2 GeV 118 GeV 125.5 GeV

Predict a large splitting between the two stops ⇒ a light stop?

Discovered Higgs has mass 125.5 GeV > mass of Z, i.e. 91.2 GeV

Include radiative corrections

$\Delta(m_{h^0}^2) =$



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91.2 GeV 118 GeV 125.5 GeV

Predict a large splitting between the two stops ⇒ a light stop?

Is this consistent with all other data?

Testing Times for Supersymmetry: Looking Under the Lamp Post

Amol Dighe,[1] Diptimoy Ghosh,[2] Ketan M. Patel,[1] and Sreerup Raychaudhuri[1]

[1] *Department of Theoretical Physics, Tata Institute of Fundamental Research, Mumbai 400 005, India.*
[2] *INFN, Sezione di Roma, Piazzale A. Moro 2, I-00185 Roma, Italy.*

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light stop

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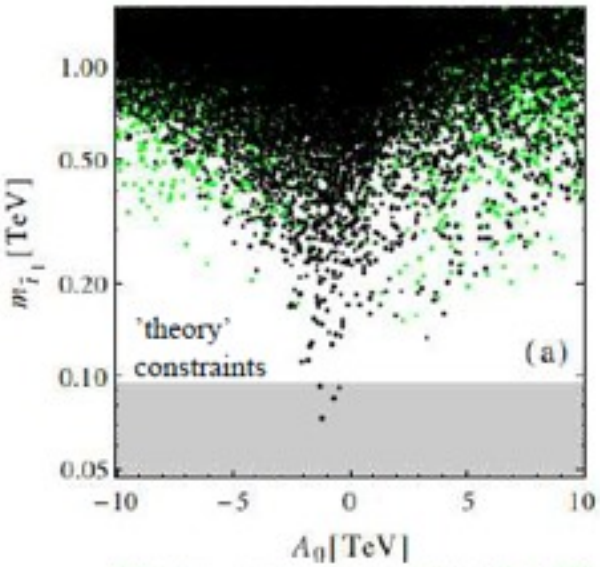

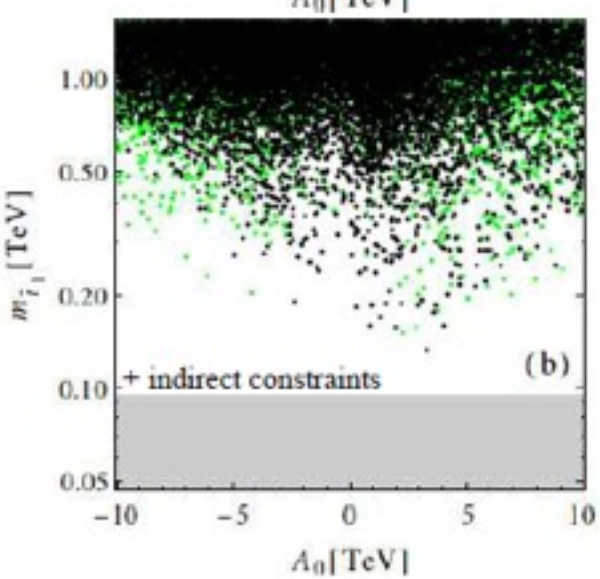

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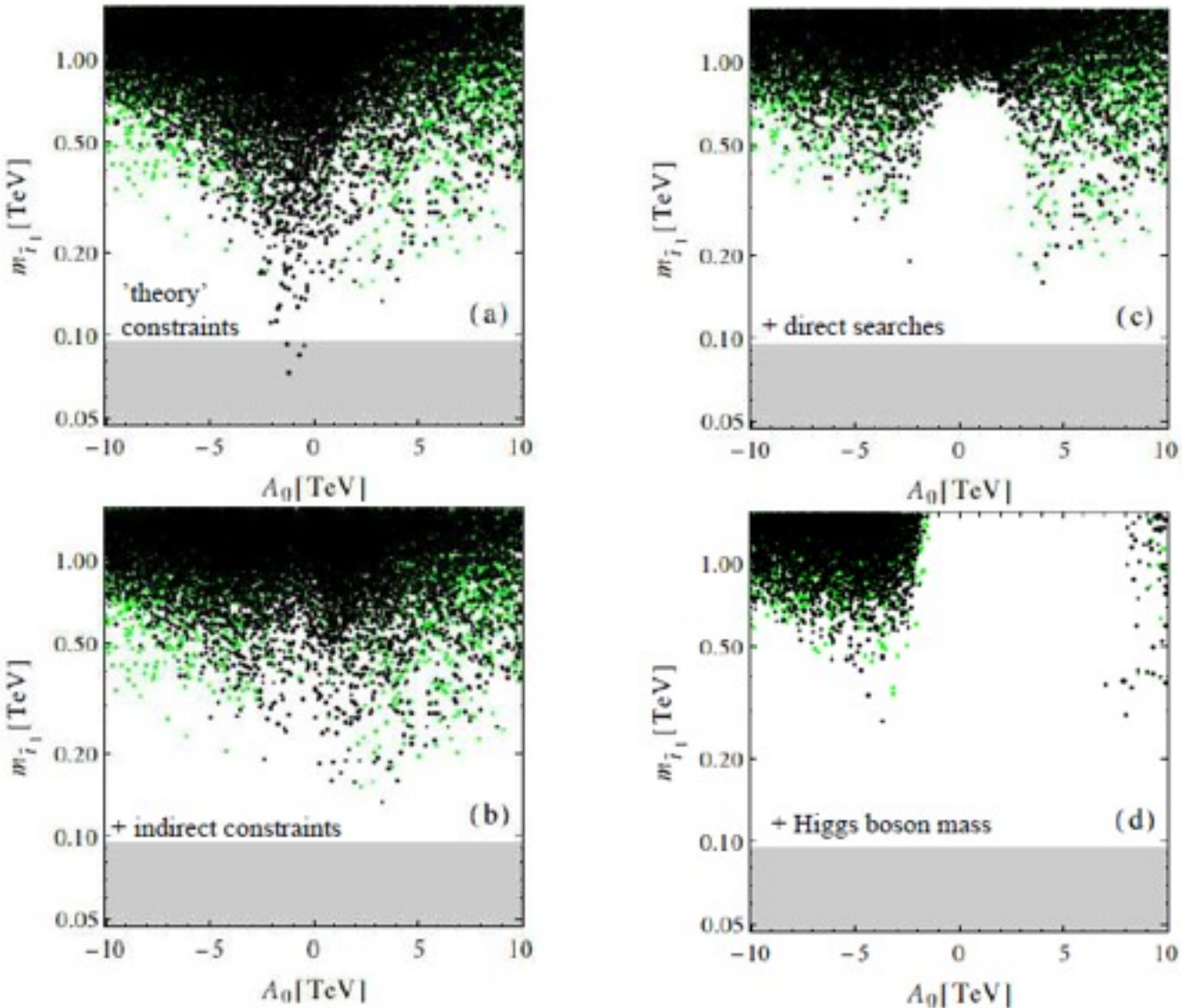
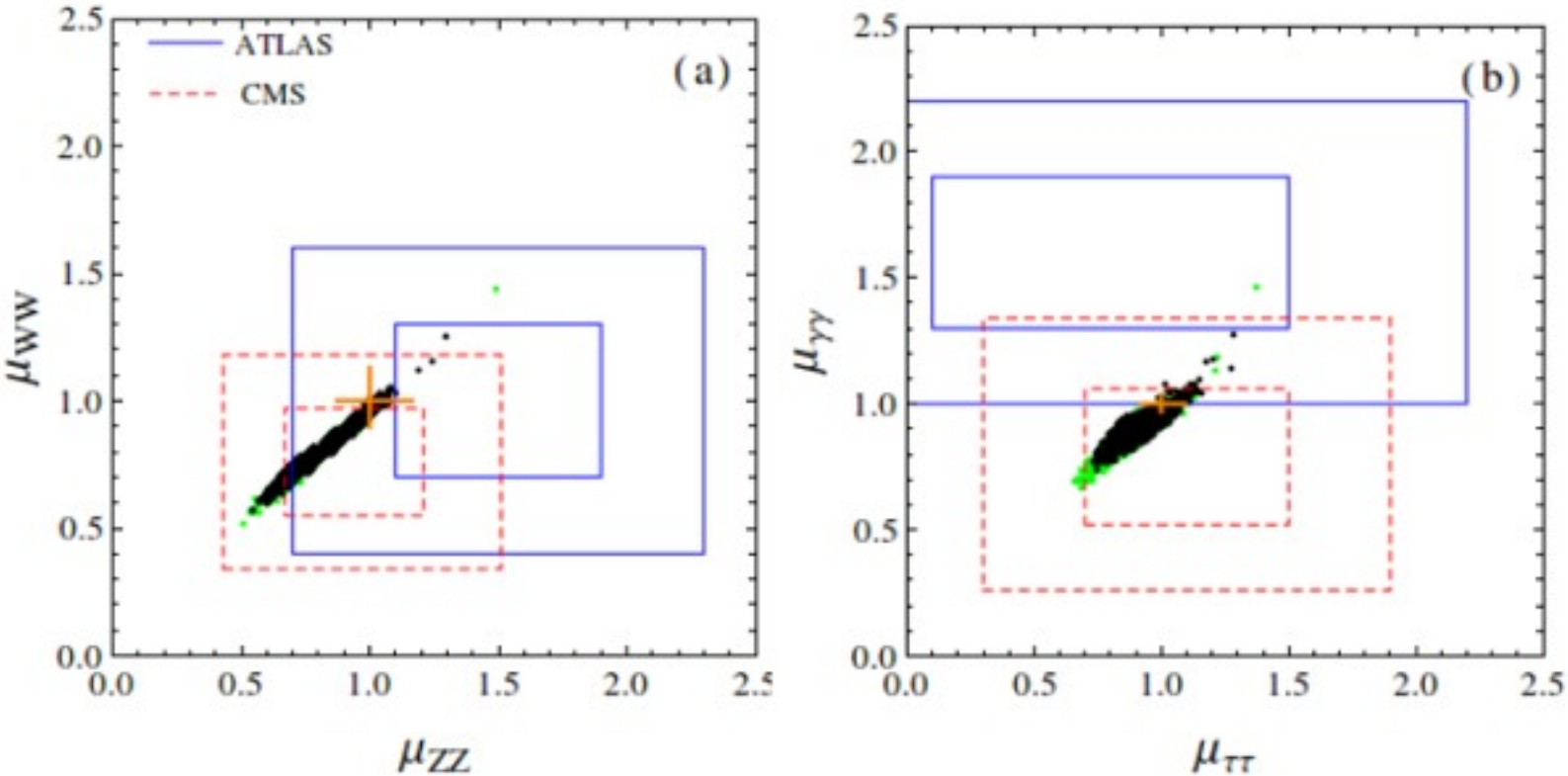
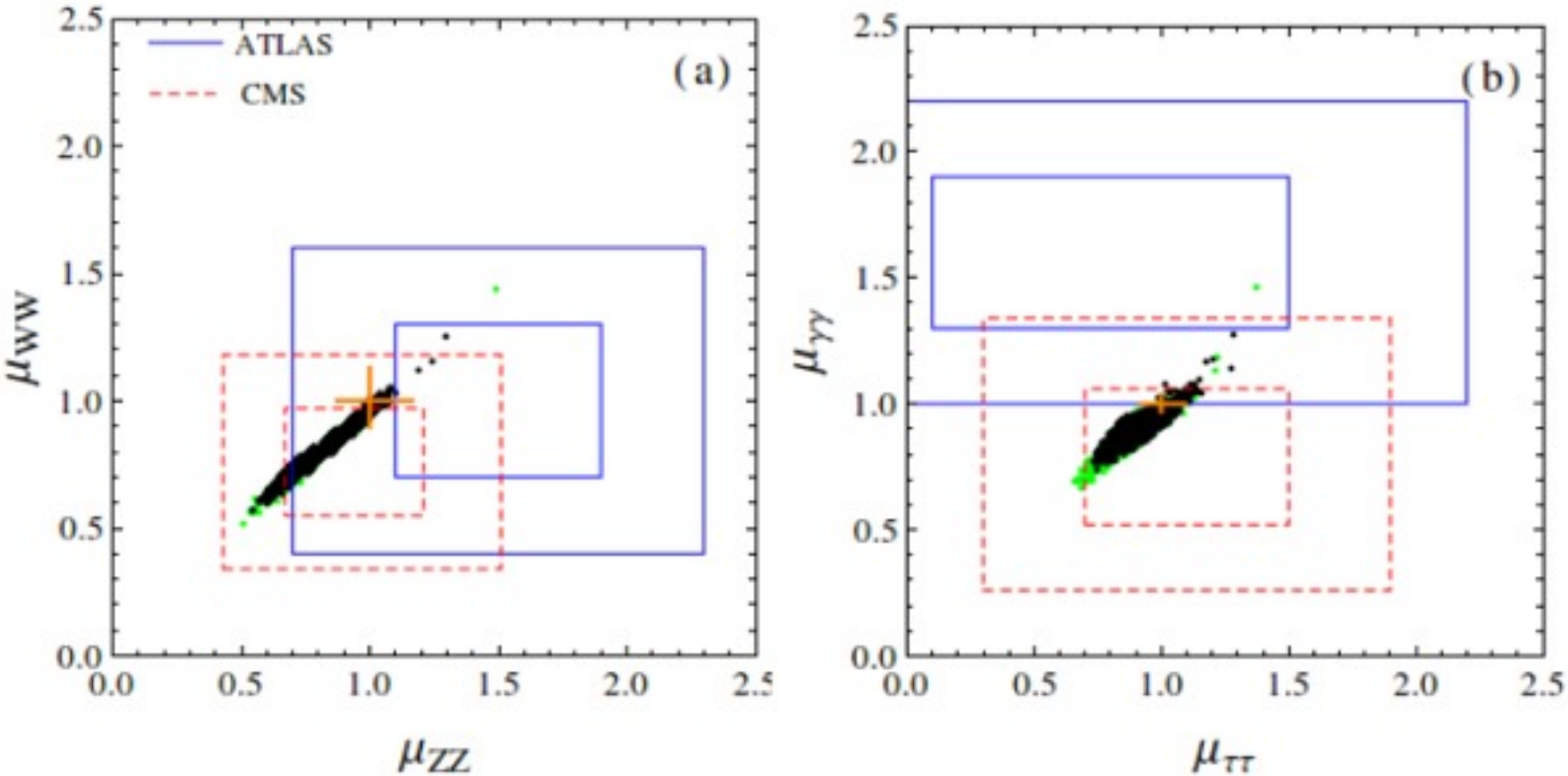



ATLAS
CMS
(a)
(b)
μ_{WW}
μ_{ZZ}
$\mu_{\gamma\gamma}$
$\mu_{\tau\tau}$
0.0
0.5
1.0
1.5
2.0
2.5



The possibility of seeing a light stop at the LHC-14 is very much there

"LOTS OF THINGS ARE INVISIBLE, BUT WE DON'T KNOW HOW MANY BECAUSE WE CAN'T **SEE** THEM."