

Four Generations, Higgs Physics and the MSSM

Prerit Jaiswal

YITP, Stony Brook University
and
Brookhaven National Lab

May 10, 2011

Pheno 2011

S. Dawson and P. Jaiswal, Four Generations, Higgs Physics and the MSSM, Phys. Rev. D 81, 073017 (2010) [arXiv-1009.1099]

Four generations and the MSSM

Four Generations

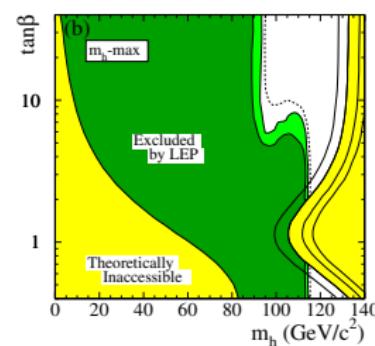
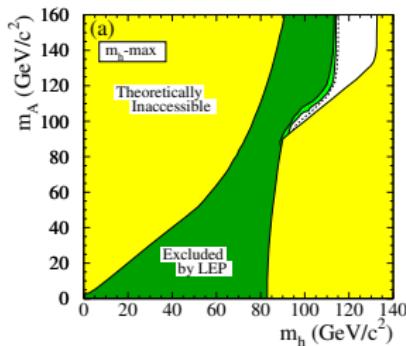
- Why 3? 4 generations viable and simplest extension of SM:
 - Anomaly cancellation possible
 - QCD (Asymptotic freedom) : $N_f < 9$
- Baryon asymmetry in the universe
- EWSB/composite Higgs, DM and more.

MSSM

- Solves hierarchy problem
 - Cancellation of quadratic divergences to the Higgs mass
- Gauge coupling unification
- Induces EWSB radiatively
- Local SUSY \rightarrow quantum gravity
- Baryon asymmetry, DM and more

The MSSM Higgs Sector

- Independent parameters in MSSM Higgs sector : $\tan\beta$ and m_{A0}
- Tree level mass : $m_h^2 = \frac{1}{2} \left[(m_{A0}^2 + m_Z^2) - \sqrt{(m_{A0}^2 + m_Z^2)^2 - 4m_{A0}^2 m_Z^2 \cos^2 2\beta} \right]$
- $m_{h0} \leq m_Z |\cos 2\beta|$. At 2-Loop, $m_h < \sim 130$ GeV

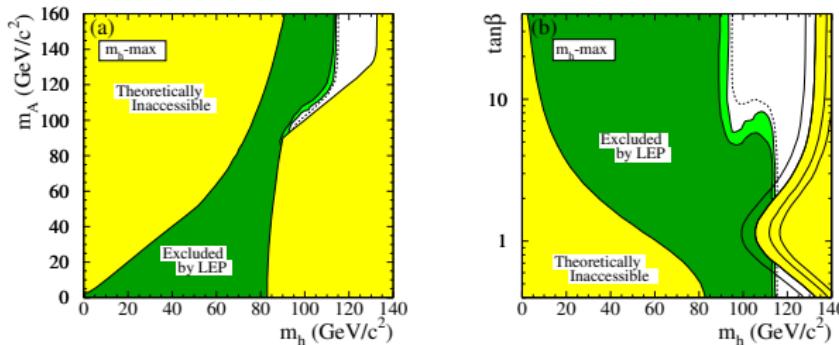


Motivation for 4G-MSSM

- The upper bound in 4G-MSSM is relaxed.

The MSSM Higgs Sector

- Independent parameters in MSSM Higgs sector : $\tan\beta$ and m_{A0}
- Tree level mass : $m_h^2 = \frac{1}{2} \left[(m_{A0}^2 + m_Z^2) - \sqrt{(m_{A0}^2 + m_Z^2)^2 - 4m_{A0}^2 m_Z^2 \cos^2 2\beta} \right]$
- $m_{h0} \leq m_Z |\cos 2\beta|$. At 2-Loop, $m_h < \sim 130$ GeV



Motivation for 4G-MSSM

- The upper bound in 4G-MSSM is relaxed.

Outline

1 4G Quark Masses

- Direct Search Bounds
- Unitarity Constraints

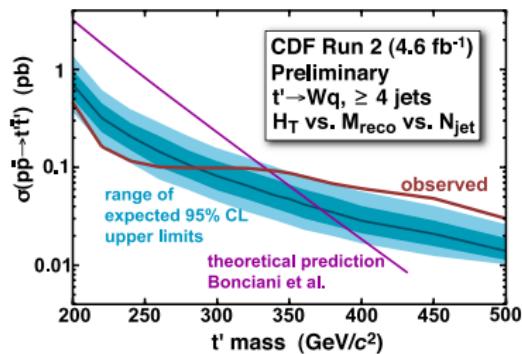
2 Higgs Physics

3 Electroweak Constraints

4 Parameter Scans

Direct Search Bounds

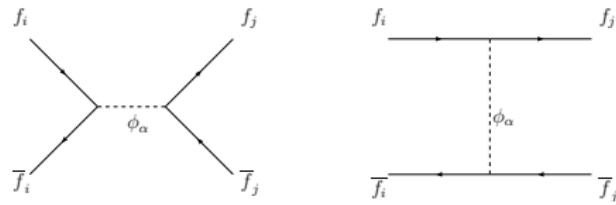
- LEP I bounds : $m_{\nu_4} > m_Z/2$ (invisible Z width)
- LEP II bounds : $m_{l_4}, m_{\nu_4} > \sim 101$ GeV
- CDF (2010) search for t' ... looked for $t't' \rightarrow q\bar{q} W^+ W^-$
 - Assumptions : BR ($t' \rightarrow Wq$) ~ 1



- $m_{t'} < 335$ GeV excluded at 95% CL
- CDF (2010) search for b' assuming BR ($b' \rightarrow Wt$) ~ 1 gives $m_{b'} < 372$ GeV excluded at 95% CL

Unitarity Constraints

- Partial wave analysis for $f_i \bar{f}_i \rightarrow f_j \bar{f}_j$
- Use optical theorem elastic scattering in 4GMSSM
- 4G-MSSM : Scalars, pseudoscalars and Goldstone bosons h^0 , H^0 , A^0 , G^0 , H^+ and G^+ contribute



Unitarity Constraints

- Unitarity constraints on 4th generation leptons

4G-MSSM :

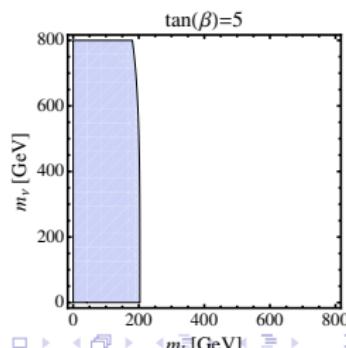
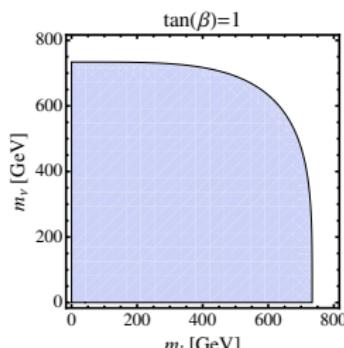
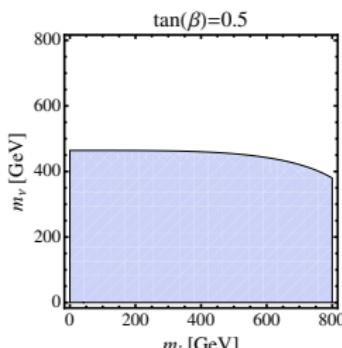
$$\frac{m_\nu^2}{s_\beta^2} < \frac{4\sqrt{2}\pi}{G_F}$$

$$\frac{m_l^2}{c_\beta^2} < \frac{4\sqrt{2}\pi}{G_F}$$

$$\sqrt{\left(\frac{m_\nu^2}{s_\beta^2}\right)^2 + \left(\frac{m_l^2}{c_\beta^2}\right)^2} < \frac{4\pi}{G_F}$$

4G-SM :

$$m_{l_4}^2, m_{\nu_4}^2 < \frac{4\sqrt{2}\pi}{G_F}$$



Unitarity Constraints

Similar analysis for quarks

4G-MSSM :

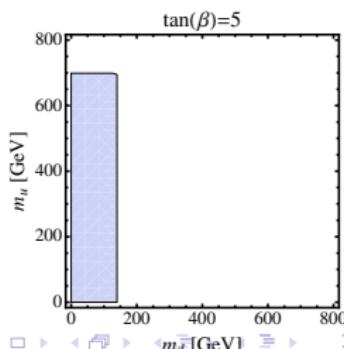
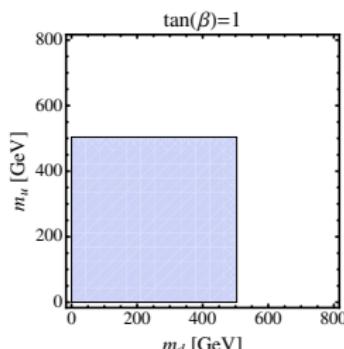
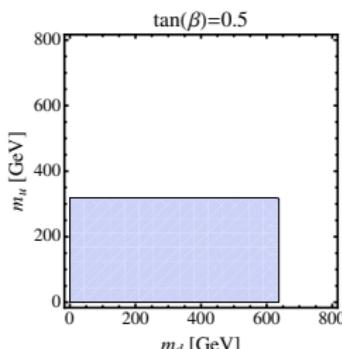
$$\frac{m_{u_4}^2}{s_\beta^2} < \frac{4\sqrt{2}\pi}{3G_F}$$

$$\frac{m_{d_4}^2}{c_\beta^2} < \frac{4\sqrt{2}\pi}{3G_F}$$

$$\sqrt{\left(\frac{m_{u_4}^2}{s_\beta^2}\right)^2 + \left(\frac{m_{d_4}^2}{c_\beta^2}\right)^2} < \frac{4\pi}{G_F}$$

4G-SM :

$$m_{u_4}^2, m_{d_4}^2 < \frac{4\sqrt{2}\pi}{5G_F}$$

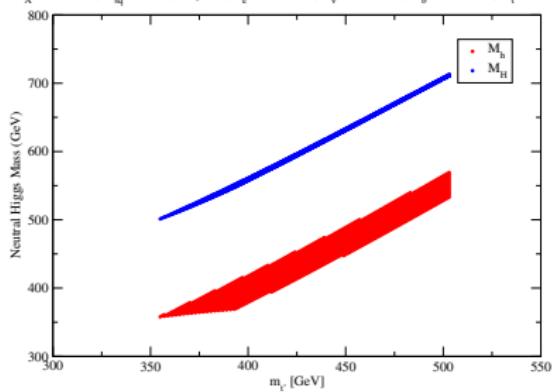


Higgs in 4G-MSSM

- Dominant radiative corrections from heavy quarks

$$\Delta m_{h^0}^2 \propto \frac{m_t^4}{m_W^2} \ln \left(\frac{\tilde{M}_{t_1}^2 \tilde{M}_{t_2}^2}{m_t^4} \right)$$

Higgs Masses Allowed by Unitarity and S,T,U
 $M_A = 300 \text{ GeV}$, $M_{\tilde{q}_1} = 1 \text{ TeV}$, $\tan\beta = 1$, $m_{\tilde{e}} = 200 \text{ GeV}$, $m_{\tilde{\chi}^0} = 150 \text{ GeV}$, $m_{\tilde{g}} > 300 \text{ GeV}$, $m_{\tilde{l}} > 300 \text{ GeV}$



- $m_{t'}$, $m_{e'}$ fixed. $m_{\nu'}$ and $m_{b'}$ allowed to vary.
- Lightest Higgs in 4G-MSSM has mass $350 - 550$ GeV.
- Decays mostly to $W^+ W^-$, ZZ and $t\bar{t}$.

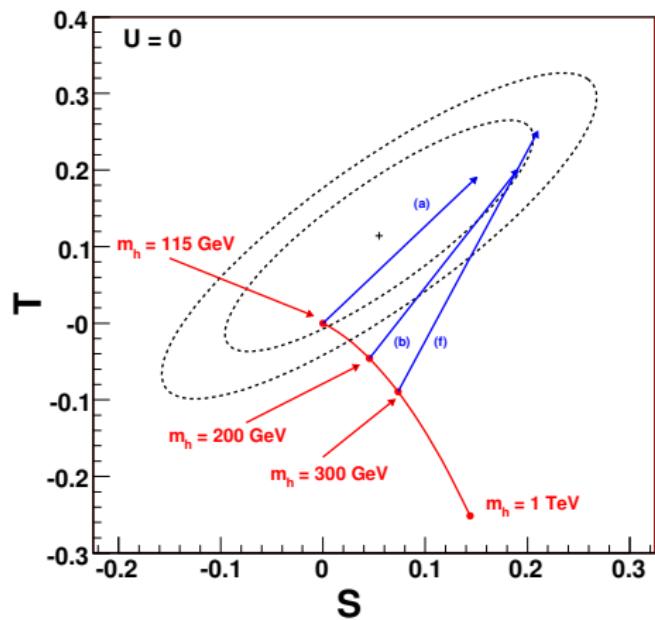
EW Constraints in 4G-SM

- $\Delta T \geq 0 \Rightarrow m_{u_4} \approx m_{d_4}$
- $\Delta S > 0$ for $m_{u_4} \approx m_{d_4}$

$$m_{l_4} = 155 \text{ GeV}, m_{\nu_4} = 100 \text{ GeV}$$

(a) $m_{u_4} = 310 \text{ GeV}$,
 $m_{d_4} = 260 \text{ GeV}$,
 $m_h = 115 \text{ GeV}$

(b) $m_{u_4} = 320 \text{ GeV}$,
 $m_{d_4} = 260 \text{ GeV}$,
 $m_h = 200 \text{ GeV}$

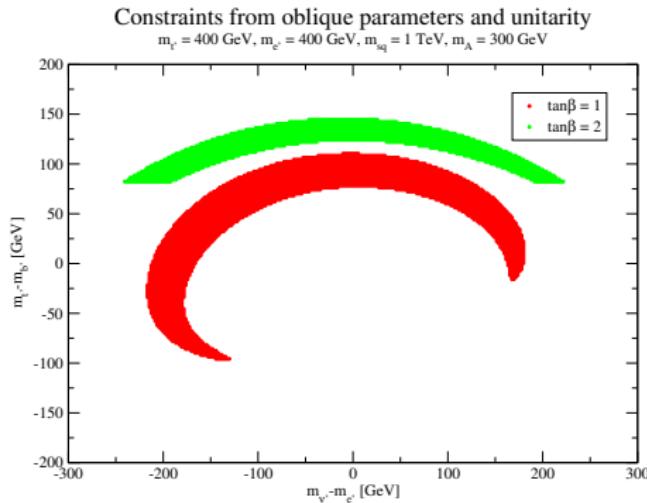
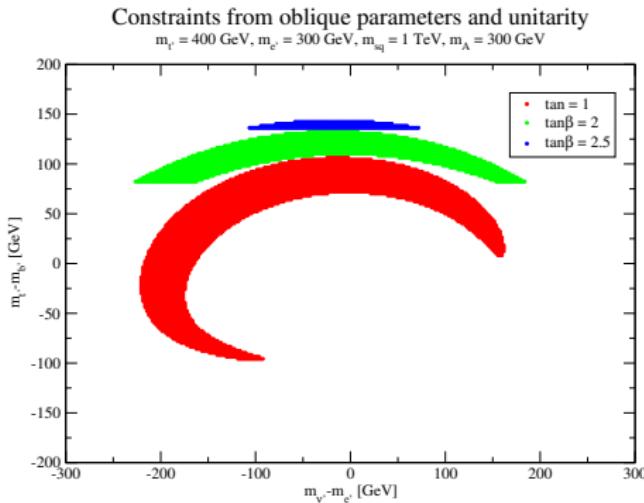


Kribs, Plehn, Spannowsky, Tait [Phys. Rev. D 76, 075016 (2007)]

EW constraints in 4G-MSSM

- S,T,U receive contributions from sfermions and 4th generation fermions.
- $\Delta T_{sf} > 0$
⇒ Assume degenerate sfermions in further analysis.
 - ΔS and ΔT contributions from sfermions are negligible for degenerate squarks.
- S,T,U also receive contributions from all the MSSM Higgs bosons which receive large radiative corrections.

Parameter Scans

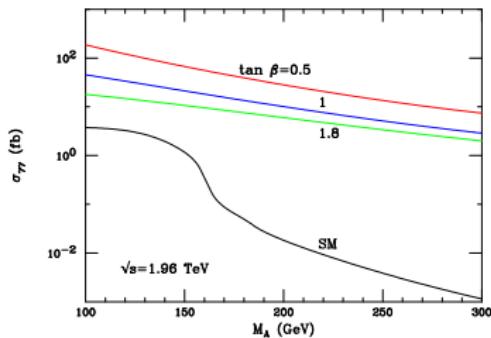
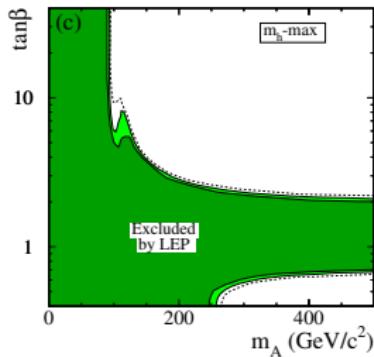
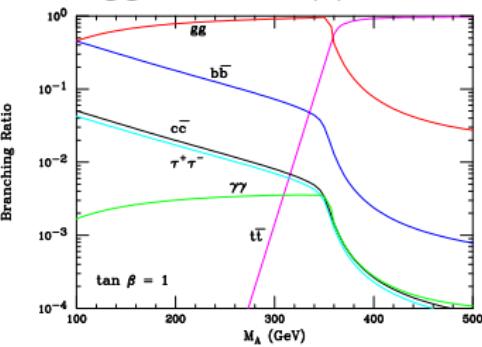


- Fine-tuning of 4th generation fermion masses required
- Parameter space shrinks as $\tan\beta$ increases. $\tan\beta \sim 1$ preferred due to unitarity.
- For higher lepton masses, $\tan\beta \sim 1$ is strongly preferred. Lepton masses enter S,T,U through the Higgs masses.

Collider Phenomenology

[arXiv:1105.0039 : R.C. Cotta, J.L. Hewett, A. Ismail, M.-P. Le, T.G. Rizzo]

- LEP limits ($e^+e^- \rightarrow hZ$ and $e^+e^- \rightarrow hA$) do not apply in 4G-MSSM
- Light A allowed with $\tan\beta \sim 1$
- $gg \rightarrow A \rightarrow \tau^+\tau^-$ and $gg \rightarrow A \rightarrow \gamma\gamma$



Summary

- 4G-MSSM parameter space is highly constrained by
 - (a) Unitarity
 - (b) Electroweak Precision Measurement
 - (c) Direct search bounds on fourth generation fermion masses
- The fermion and squark masses require fine-tuning.
- $\tan \beta \sim 1$ is preferred mainly due to unitarity constraints.
- Upper bound on lightest Higgs mass in 4G-MSSM is relaxed. It can have mass of $350 - 550$ GeV as compared to ~ 135 GeV in 3G-MSSM
- LEP bounds not applicable. A might be the lightest particle in 4G-MSSM Higgs spectrum.

The MSSM Higgs Sector

- All Higgs sector parameters at tree level determined by $\tan \beta$ and m_{A^0} (and SM parameters)

- Example : $m_{H^\pm}^2 = m_A^2 + m_W^2$

- The mass of h^0 is bounded.

- Tree level mass :

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

$$m_{h^0} \leq m_Z |\cos 2\beta|$$

- One-loop and two loop corrections

- $m_{h^0}^{\max}$ scenario
- $m_{h^0} < \sim 135$ GeV

The MSSM Higgs Sector

- 2 Higgs doublets required H_u, H_d
- 8 DoF \rightarrow mass eigenstates : 3 Goldstone bosons (G^0, G^\pm) + 5 Higgs (h^0, H^0, A^0, H^\pm)
- $\tan \beta$ is the ratio of VEVs

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

- All Higgs sector parameters at tree level determined by $\tan \beta$ and m_{A^0} (and SM parameters)
 - Example : $m_{H^\pm}^2 = m_A^2 + m_W^2$
- No upper bounds on masses of H^0, A^0 and H^\pm

Higgs in 4G-MSSM

- m_h not a free parameter parameter is 4G-MSSM.
- Tree-level value depends on m_{A^0} and $\tan \beta$.

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

- Dominant radiative corrections from heavy quarks

$$\Delta m_{h^0}^2 \propto \frac{m_t^4}{m_W^2} \ln \left(\frac{\tilde{M}_{t_1}^2 \tilde{M}_{t_2}^2}{m_t^4} \right)$$

- These corrections are big and must be included in $m_{h/H}$.

Invisible Z width

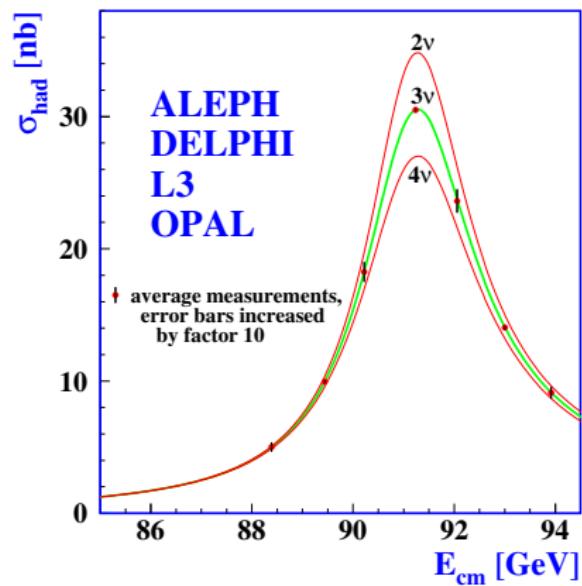
- Precise measurement of Z decay width

$$\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{\text{hadrons}} + \Gamma_{\text{invisible}}$$

- $\Gamma_{\text{invisible}} = \Gamma_{\nu\nu}$
- Conclusion : 3 generation of neutrinos
- or ?

$$m_{\nu_4} > \frac{M_Z}{2}$$

Assume mixing \Rightarrow No cosmological constraints



Unitarity Constraints

- Theoretical Limitations - Perturbation theory

Partial Wave Analysis

- 2 → 2 elastic scattering

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s} |\mathcal{M}|^2$$

- Partial wave decomposition

$$\mathcal{M} = 16\pi \sum_{j=0}^{\infty} (2j+1) P_j(\cos\theta) a_j$$

a_j = spin- j partial wave

Unitarity Constraints

- Total cross-section

$$\sigma = \frac{16\pi}{s} \sum_{j=0}^{\infty} (2j+1) |a_j|^2$$

Analysis of each partial wave amplitude possible

- Unitarity of S-matrix; $S = 1 + iT$; requires

$$-i(T - T^\dagger) = T^\dagger T$$

Apply to $2 \rightarrow 2$ elastic scattering

Unitarity Constraints

Optical Theorem

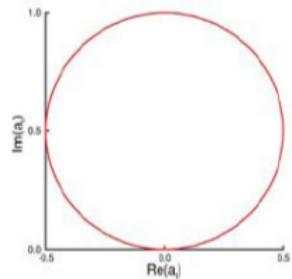
- Unitarity condition :

$$\begin{aligned} -i(T - T^\dagger) &= T^\dagger T \\ \Rightarrow \sigma &\leq \frac{1}{s} \text{Im}(\mathcal{M}(\theta = 0)) \end{aligned}$$

- Apply to partial wave amplitudes

$$\text{Im}(a_j) \leq |a_j|^2$$

$$\boxed{\text{Re}(a_j) < \frac{1}{2}}$$

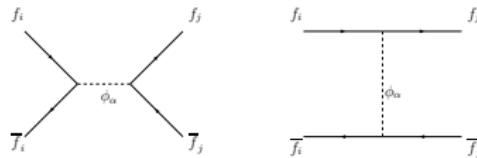


Unitarity Constraints

- Use optical theorem for $f_i \bar{f}_i \rightarrow f_j \bar{f}_j$ elastic scattering in 4GMSSM
- High energy limit $\sqrt{s} \gg m_i, m_\phi$
 - Independent helicity states
- Choose Feynman gauge ($\xi = 1$). Why?

$$\Delta_V^{\mu\nu} = \frac{-i}{k^2 - m_V^2} \left[g^{\mu\nu} - \frac{k^\mu k^\nu}{k^2 - \xi m_V^2} (1 - \xi) \right]$$

- Only scalars, pseudoscalars and Goldstone bosons contribute h^0 , H^0 , A^0 , G^0 , H^+ and G^+



Unitarity Constraints

$$a_0 = -\frac{G_F}{4\sqrt{2}\pi} \begin{pmatrix} \frac{m_\nu^2}{s_\beta^2} & 0 & 0 & 0 \\ 0 & \frac{m_l^2}{c_\beta^2} & 0 & 0 \\ 0 & 0 & \frac{m_\nu^2}{s_\beta^2} & 0 \\ 0 & 0 & 0 & \frac{m_l^2}{c_\beta^2} \end{pmatrix} \quad a_0^{ij} = a_0 (i \rightarrow j)$$

$i, j \in f_\nu^+ \bar{f}_\nu^+, f_l^+ \bar{f}_l^+, f_\nu^- \bar{f}_\nu^-, f_l^- \bar{f}_l^-$

$$a_0 = -\frac{G_F}{4\sqrt{2}\pi} \begin{pmatrix} 0 & \frac{m_u^2}{s_\beta^2} & 0 & \frac{m_d^2}{c_\beta^2} \\ \frac{m_u^2}{s_\beta^2} & 0 & \frac{m_u^2}{s_\beta^2} & 0 \\ 0 & \frac{m_u^2}{s_\beta^2} & 0 & \frac{m_d^2}{c_\beta^2} \\ \frac{m_d^2}{c_\beta^2} & 0 & \frac{m_d^2}{c_\beta^2} & 0 \end{pmatrix} \quad a_0^{ij} = a_0 (i \rightarrow j)$$

$i, j \in f_u^+ \bar{f}_u^-, f_u^- \bar{f}_u^+, f_d^+ \bar{f}_d^-, f_d^- \bar{f}_d^+$

- Impose unitarity on the largest eigenvalues : $\lambda < 1/2$.

EW Constraints in 4G-SM

- New Physics : S, T, U parameters

$$\begin{aligned}\alpha S &= \frac{s_{2\theta}^2}{M_Z^2} \left[\Delta\Pi_{ZZ}(M_Z^2) - \Delta\Pi_{\gamma\gamma}(M_Z^2) - \frac{2c_{2\theta}}{s_{2\theta}} \Delta\Pi_{\gamma Z}(M_Z^2) \right] \\ \alpha T &= \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2} - \frac{2s_\theta}{c_\theta} \frac{\Pi_{\gamma Z}(0)}{M_Z^2} \\ \alpha U &= 4s_\theta^2 \left[\frac{\Delta\Pi_{WW}(M_W^2)}{M_W^2} - c_\theta^2 \frac{\Delta\Pi_{ZZ}(M_Z^2)}{M_Z^2} - s_{2\theta} \frac{\Delta\Pi_{\gamma Z}(M_Z^2)}{M_Z^2} - s_\theta^2 \frac{\Delta\Pi_{\gamma\gamma}(M_Z^2)}{M_Z^2} \right]\end{aligned}$$

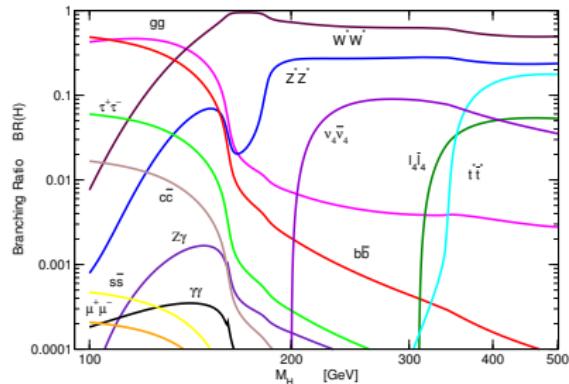
- 4G-SM :
 - Positive ΔS

$$\Delta S \approx \frac{N_C}{6\pi} \left[1 - 2Y \ln \frac{m_u^2}{m_d^2} \right]$$

- ΔT positive \Rightarrow Masses nearly degenerate

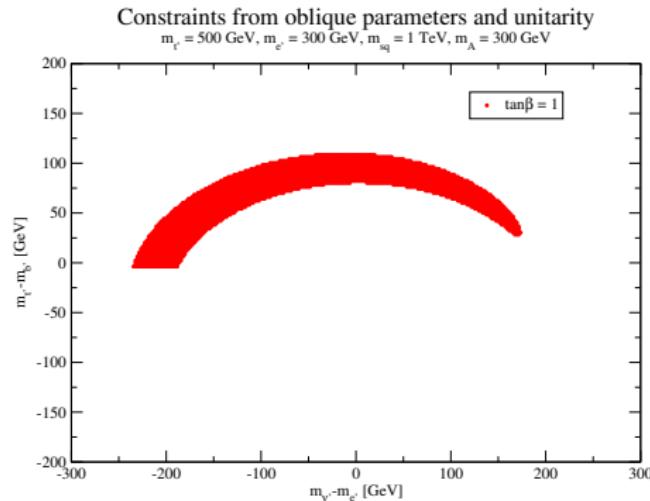
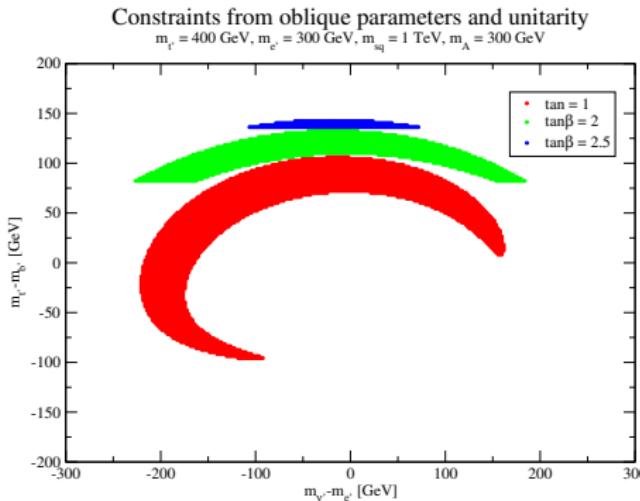
$$\Delta T = \frac{3}{8\pi s_\theta^2 M_W^2} \left[\frac{1}{2} (m_{u_4}^2 + m_{d_4}^2) - \frac{m_{u_4}^2 m_{d_4}^2}{m_{u_4}^2 - m_{d_4}^2} \ln \left(\frac{m_{u_4}^2}{m_{d_4}^2} \right) \right] \geq 0$$

Parameter Scans



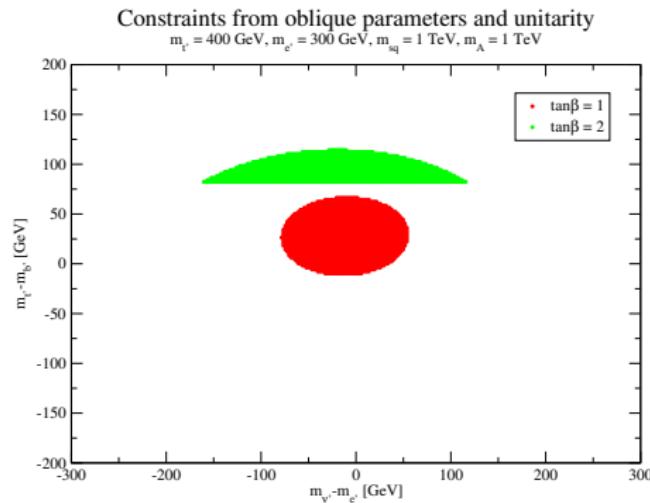
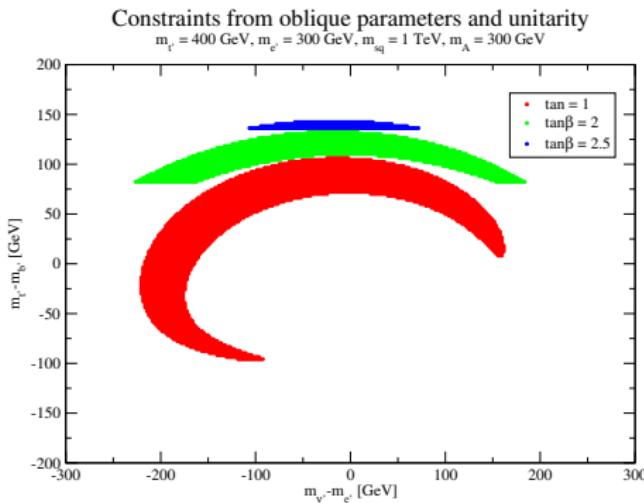
- h decays mostly to $W^+ W^-$ and $\bar{t}t$

Parameter Scans



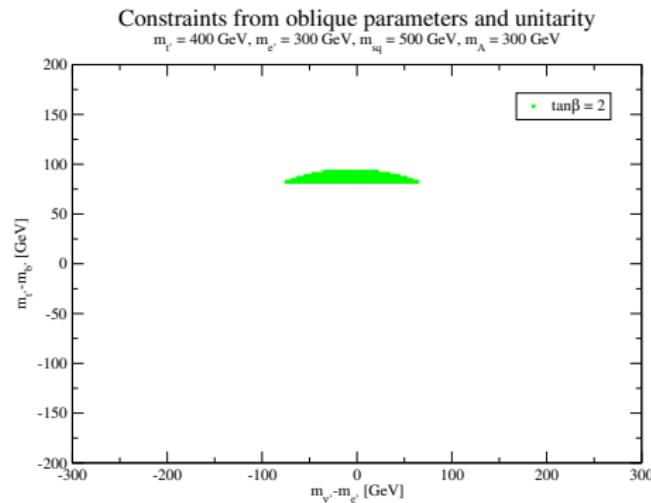
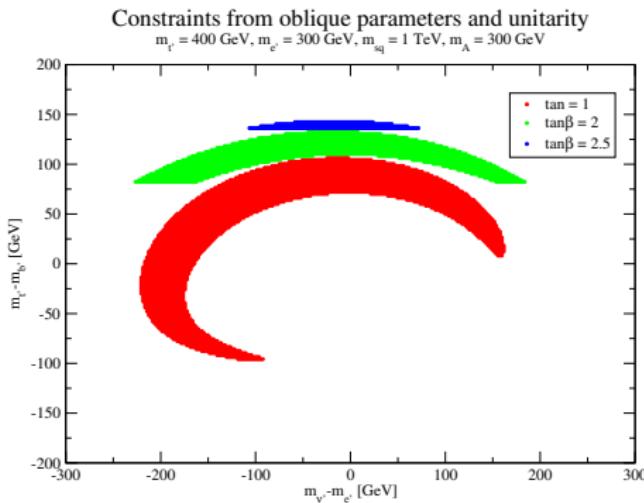
- For higher quark masses, $\tan\beta \sim 1$ is strongly preferred. Quark masses enter S,T,U through the Higgs masses.

Parameter Scans



- Large m_{A^0} shrinks parameter space

Parameter Scans



- Large squark masses strongly favoured.