Higgs+X: Warped Supersymmetry and Chiral Extensions

Theory Seminar, DESY

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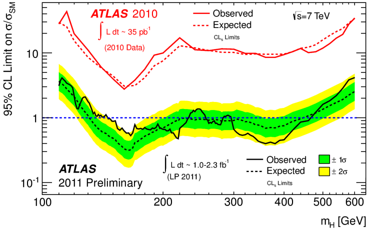
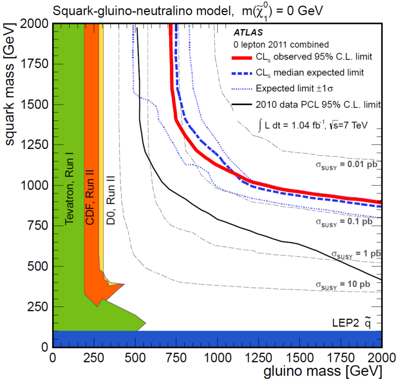
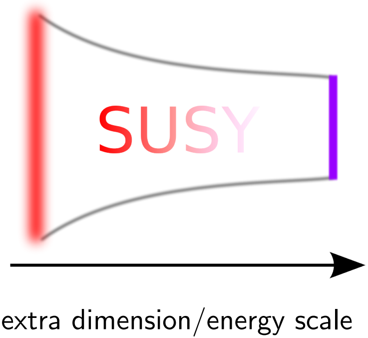
The LHC era has begun

- 5 fb^{-1} recorded, 1-2 fb^{-1} publ.
- Decision about the existence of the SM Higgs boson at horizon.
- No LHC hints for SUSY or any BSM physics
- Problems addressed by BSM models still there...
  - EWSB/Unitarity
  - Dark Matter/Dark Energy
  - Gauge hierarchy problem
  - Little hierarchy problem
  - Unification? Gravity?







[Randall, Sundrum '99]

- Background metric:
  $g_{\mu\nu} \sim \eta_{\mu\nu} e^{-2Rky}$, $y \in [0, \pi]$
- Induced by brane/bulk cosmological constants
- AdS/CFT
- $M_{pl} e^{-Rk\pi} = \text{TeV if } Rk \sim 11.8$.
  Planck size parameters (m_H,μ,...) redshifted to TeV at $y = \pi$.

Why does it make sense to consider rigid SUSY in a curved background?

[Gherghetta, Pomarol '00-'03][Hall, Nomura, Okui, Oliver '04]

- No Weyl spinor in 5D! No chirality, $\mathcal{N} = 2$ SUSY/Sugra
- Symmetries of the RS background (slice of AdS) $\leftrightarrow$ SUSY generators:

4D translations $\rightarrow$ Killing vectors $\rightarrow$ Killing spinors ξ $\rightarrow$ rigid $\mathcal{N} = 1$!

5D translations/scaling $\rightarrow$ Killing vectors $\rightarrow$ conformal SUSY, broken

- While we assume Sugra to be there, this is a great simplification!

Can use $\mathcal{N} = 1$ Superfield formalism!

[Siegel][Arkani-Hamed, Gregoire, Wacker '01][Marti, Pomarol '01]

- 5D Lorentz/SUSY not manifest, but broken anyways...
- 5D Vector multiplet $\longrightarrow$ 4D Vector + Chiral

$$(V, \Omega) \sim (A_\mu, \lambda_1, \lambda_2, \Sigma + iA_5, D, F)$$

- 5D Hypermultiplet $\longrightarrow$ 4D Chiral + $\overline{\text{Chiral}}$

$$(\Phi, \overline{\Phi}^{--}) \sim (\psi_1, \overline{\psi}_2, \phi_1, \overline{\phi}_2, F_1, \overline{F}_2)$$

Bulk Superfield Action

$$\mathcal{S}_{gauge} = \frac{1}{4}\int d^5x \int d^2\theta \;\; (W^\alpha W_\alpha + h.c.) + \int d^5x \int d^4\theta \;\; e^{-2\sigma(y)} \left(\partial_y V - \frac{1}{\sqrt{2}}(\Omega + \overline{\Omega})\right)^2$$

$$\mathcal{S}_{matter} = \int d^5x \int d^4\theta \;\; e^{-2\sigma(y)} \left(\overline{\Phi}_L e^{-2gq_L V} \Phi_L + \Phi_L^{--} e^{2gq_L V} \overline{\Phi}_L^{--}\right)$$
$$+ \int d^5x \int d^2\theta \;\; e^{-3\sigma(y)} \left(\Phi_L^{--} [D_5 - \sqrt{2} g q_L \Omega] \Phi_L + h.c.\right)$$

Branes: 4D subspaces with explicitely $\mathcal{N} = 1$ SUSY $\rightarrow$ Superpotential

$$\mathcal{L} \rightarrow \mathcal{L} + \delta(y - \pi) \int d^2\theta \, \mathcal{W}_{brane} + c.c.$$

Assume e.g. all fields living in the bulk, with a superpotential coupling on the brane $\mathcal{W}_{brane} = \mathcal{Y} \, HQd^c$

$$\delta(y - \pi) \int d^2\theta \, \mathcal{Y} \, HQd^c \sim \mathcal{Y} \, \delta(y - \pi) \left[h\psi_Q \psi_d^c + h\tilde{Q} F_d^c + hF_Q \tilde{d}^c + .. \right]$$

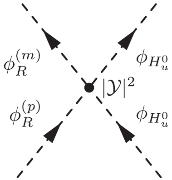
Solving for the auxiliary fields F_d^c yields the F term

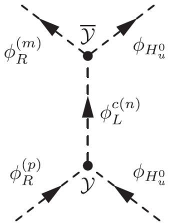
$$F_d^{c\dagger} F_d^c \rightarrow \delta(y - \pi)^2 h^2 \tilde{Q}^2 + \cdots \xrightarrow{4D} \infty \cdot h_0^2 \tilde{Q}_0^2$$

Something seems wrong!
Is bulk SUSY + brane superpotentials inconsistent in low energy limit w/o supergravity?

No (flat): [*Peskin, Mirabelli '98*]
Detailed treatment in warped space: [*Bouchart, Moreau, AK '11*]

- What is the problem?
  Compare to D-term couplings from the $SU(5)$ 'broken' auxiliary fields
  They decouple after cancellation with GUT Higgs exchange graphs!
- Error: we have taken into account F-terms from infinite tower of KK modes without integrating out the corresponding particles properly!





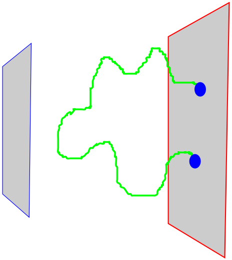
- triple couplings $\propto m\mathcal{Y}$.
  Heavy contributions alone **do not decouple**
- Can define finite low energy scalar coupling by taking both into account

$$\frac{\delta^4 i\mathcal{L}_{4D}}{\delta\phi_{H_u^0}\bar{\phi}_{H_u^0}\phi_R^{(n)}\bar{\phi}_R^{(m)}} = -i|\mathcal{Y}|^2\delta(0)\bar{f}_m^{++}(c_R;\pi R_c)f_n^{++}(c_R;\pi R_c) \quad (1)$$

$$\left.\frac{\delta^4 i\mathcal{L}_{4D}}{\delta\phi_{H_u^0}\bar{\phi}_{H_u^0}\phi_R^{(p)}\bar{\phi}_R^{(m)}}\right|_{indirect} = -|\mathcal{Y}|^2\sum_{n\geq 1}\frac{i\, m_L^{(n)2}}{k^2-m_L^{(n)2}}f_p^{++}(c_R;\pi R_c)f_m^{++}(c_R;\pi R_c)\left(f_n^{++}(c_L;\pi R_c)\right)^2$$

The resulting 4D expression has a nice 5D interpretation:

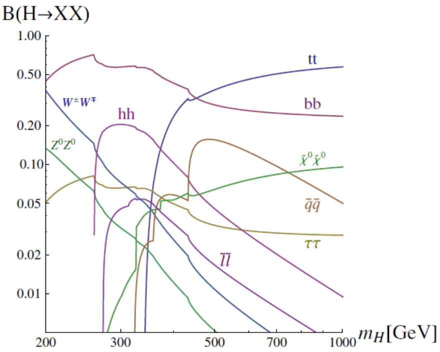
$$\left.\frac{\delta^4 i\mathcal{L}_{4D}}{\delta\phi_{H_u^0}\bar{\phi}_{H_u^0}\phi_R^{(p)}\bar{\phi}_R^{(m)}}\right|_{total} = -i|\mathcal{Y}|^2 f_p^{++}(c_R;\pi R_c)f_m^{++}(c_R;\pi R_c)k^2 G_5^{f^{++}(c_L)}(k^2;\pi R_c,\pi R_c). \quad (2)$$

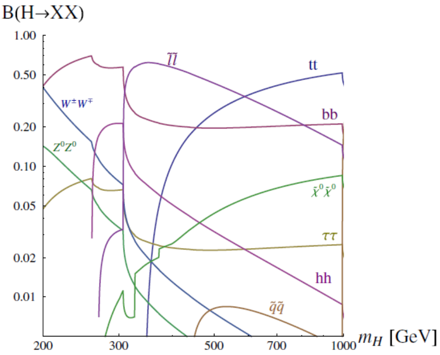


Similar arguments for absence of scalar Λ^2 divergences (→ paper).

Pheno example: Heavy Higgs decays

$$
\begin{aligned}
i\mathcal{C}_{H\tilde{t}\tilde{t}} \equiv |\mathcal{Y}|^2 \sin\alpha v_u \times & \begin{pmatrix} (f_L^0)^2 k^2 G_5^{f^{++}(c_{\tilde{t}_R})}(k^2;\pi R_c,\pi R_c) & 0 & f_L^0 f_L^1 (f_R^0)^2 & 0 \\ 0 & (f_R^0)^2 k^2 G_5^{f^{++}(c_{\tilde{t}_L})}(k^2;\pi R_c,\pi R_c) & 0 & f_R^0 f_R^1 (f_L^0)^2 \\ f_L^0 f_L^1 (f_R^0)^2 & 0 & (f_L^1 f_R^0)^2 & 0 \\ 0 & f_R^0 f_R^1 (f_L^0)^2 & 0 & (f_L^0 f_R^1)^2 \end{pmatrix} \\
& - \frac{\mathcal{Y}\cos\alpha \mu_{\text{eff}}}{\sqrt{2}} \begin{pmatrix} 0 & f_L^0 f_R^0 & 0 & f_L^0 f_R^1 \\ f_L^0 f_R^0 & 0 & f_L^1 f_R^0 & 0 \\ 0 & f_L^1 f_R^0 & 0 & f_L^1 f_R^1 \\ f_L^0 f_R^1 & 0 & f_L^1 f_R^1 & 0 \end{pmatrix} + g_Z^2 \pi R_c \cos(\alpha+\beta) v \\
& \times \begin{pmatrix} Q_Z^{t_L} \int dy f_L^0(y)^2 k^2 G_5^{g^{++}}(k^2;y,\pi R_c) & 0 & 0 & 0 \\ 0 & -Q_Z^{t_R} \int dy f_R^0(y)^2 k^2 G_5^{g^{++}}(k^2;y,\pi R_c) & 0 & 0 \\ 0 & 0 & Q_Z^{t_L}/2\pi R_c & 0 \\ 0 & 0 & 0 & -Q_Z^{t_R}/2\pi R_c \end{pmatrix} \\
& + \frac{A e^{-k\pi R_c}\sin\alpha}{\sqrt{2}} \begin{pmatrix} 0 & f_L^0 f_R^0 & 0 & f_L^0 f_R^1 \\ f_L^0 f_R^0 & 0 & f_L^1 f_R^0 & 0 \\ 0 & f_L^1 f_R^0 & 0 & f_L^1 f_R^1 \\ f_L^0 f_R^1 & 0 & f_L^1 f_R^1 & 0 \end{pmatrix},
\end{aligned}
$$





For more details, see [PRD **84**, 015016 (2011)]

Objective: Additional fermion content beyond the SM which

- is in a non-real representation of $SU(3)_c \times SU(2)_L \times U(1)_Y$
- can become massive via the standard Higgs
- can only become massive via the standard Higgs
- is anomaly free

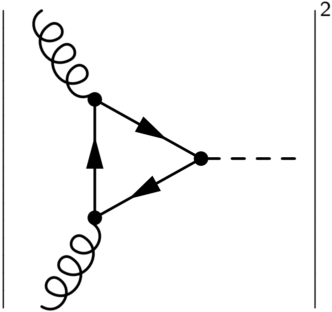
Standard example: Fourth generation

e.g. [Kribs, Plehn, Spannowsky, Tait '07]

Constraints on such scenarios:

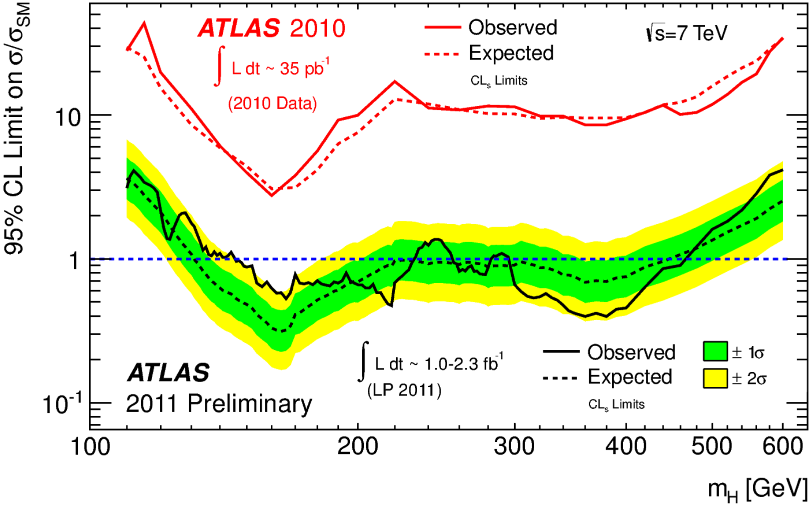
- (ex) Direct searches
- (ex) Flavor (unitariy of CKM...)
- (ex) Higgs production rates
- (ex) EWPTs
- (th) RG running (perturbativity, vacuum)

Most severe bound on 4th generation today: Higgs searches!
Chiral fermions do not decouple as $m \to \infty$.

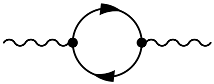


$$\left| \cdots \right|^2 \propto \left(N_{\text{heavy color triplet fermions}}\right)^2$$

in the limit $m_f \gg m_h$, less enhancement for $m_h \sim m_f$.

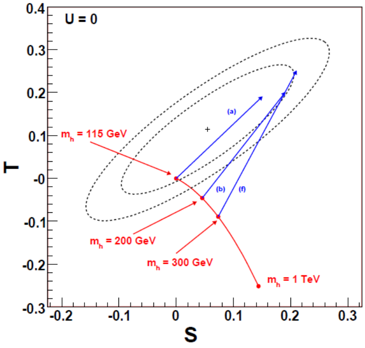

ATLAS 2010
∫ L dt ~ 35 pb-1
(2010 Data)
Observed
Expected
CLs Limits
√s=7 TeV
95% CL Limit on σ/σSM
10
1
10-1
ATLAS
2011 Preliminary
∫ L dt ~ 1.0-2.3 fb-1
(LP 2011)
Observed
Expected
CLs Limits
± 1σ
± 2σ
100
200
300
400
500
600
mH [GeV]

Chiral fermions are visible in electroweak SE [Kennedy,Lynn][Peskin, Takeuchi]
For contributions of new fermions e.g. [Kniehl '91]

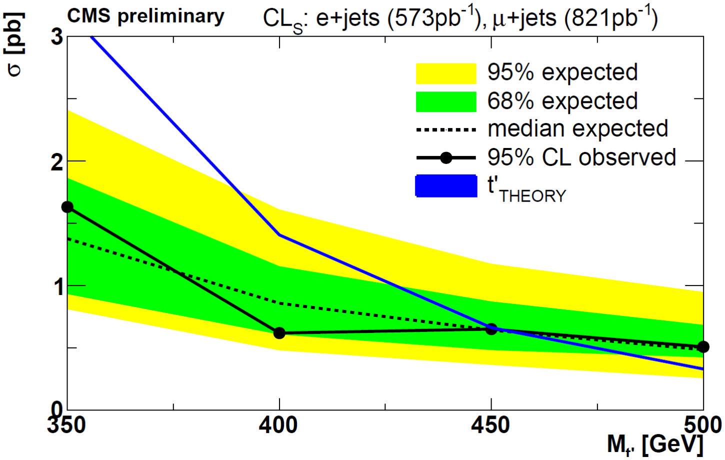


$$\Delta T = \frac{N_c}{6\pi s_w^2 m_W^2}\left(m_U^2 + m_D^2 - \frac{m_U^2 m_D^2}{m_U^2 - m_D^2}\log\frac{m_U^2}{m_D^2}\right)$$
$$\Delta S = \frac{N_c}{6\pi}\left(1 - 2Y\log\frac{m_U^2}{m_D^2}\right)$$

S roughly counts degrees of freedom, T sees isospin violation.



[Plehn et al.]


CMS preliminary
CLS: e+jets (573pb-1), μ+jets (821pb-1)
σ [pb]
3
2
1
0
350
400
450
500
Mt' [GeV]
95% expected
68% expected
median expected
95% CL observed
t'THEORY

The standard Higgs: $H \sim (\mathbf{1},\mathbf{2})_{1/2}$, $\tilde{H} = \epsilon H^* \sim (\mathbf{1},\mathbf{2})_{-1/2}$.

- $\langle H \rangle$ can give a Dirac mass to $\mathbf{1} \otimes \mathbf{2}$, $\mathbf{2} \otimes \mathbf{3}$, $\mathbf{3} \otimes \mathbf{4}$, ...

General scheme for $\mathbf{1} \otimes \mathbf{2}$ case:

$$
\begin{array}{ccccc}
(\alpha,\mathbf{2})_{Y1} & + & (\overline{\alpha},\mathbf{1})_{-Y1+1/2} & + & (\overline{\alpha},\mathbf{1})_{-Y1-1/2} \\
(\beta,\mathbf{2})_{Y2} & + & (\overline{\beta},\mathbf{1})_{-Y2+1/2} & + & (\overline{\beta},\mathbf{1})_{-Y2-1/2} \\
 & & & & \ldots
\end{array}
$$

- Have studied chiral triplets, but for now concentrate on standard case

General fermion content destroys quantum gauge theory

$$\int \mathcal{D}\psi\mathcal{D}\overline{\psi}e^{iS} \quad \xrightarrow{\psi \to e^{i\alpha\gamma_5}\psi} \quad \int \mathcal{D}\psi\mathcal{D}\overline{\psi}e^{iS+i\int d^4x\,\mathcal{A}}$$

where $\mathcal{A} \propto Tr[\gamma^5 \otimes T^a\{T^b, T^c\}]$.

Consistency conditions from $\mathcal{A} = 0$

$$SU(2)^2U(1): \quad \sum_{i(SU(2)\text{ doublets})} N_{ci}Y_i = 0$$

$$SU(3)^2U(1): \quad \sum_{i(SU(3)\text{ triplets})} Y_i = 0$$

$$U(1)^3: \quad \sum_{i(\text{all})} N_{ci}Y_i^3 = 0$$

$$G^2U(1): \quad \sum_{i(\text{all})} N_{ci}Y_i = 0$$

Simplification from Yukawa condition:

$$\begin{aligned} 2Y(X_L)^3 + Y(u_R^c)^3 + Y(d_R^c)^3 &= -\frac{3}{2}Y(X_L) \\ 2Y(X_L) + Y(u_R^c) + Y(d_R^c) &= 0\,. \end{aligned}$$

$SU(3)^3$ condition is trivial.

General solution:

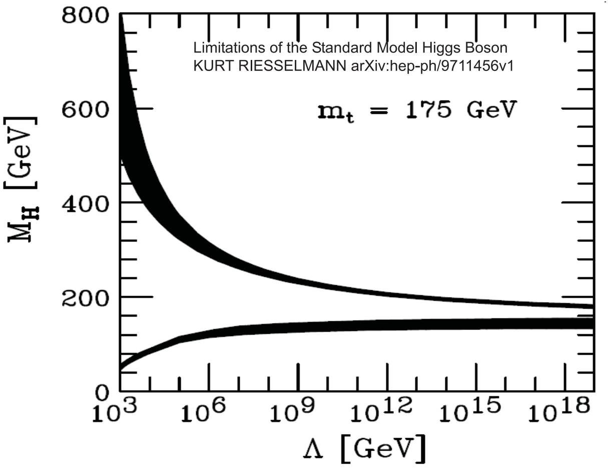
$$\begin{array}{ccc} (\alpha_1, 2)_{Y_1} & (\overline{\alpha}_1, 1)_{-Y_1-\frac{1}{2}} & (\overline{\alpha}_1, 1)_{-Y_1+\frac{1}{2}} \\ & \vdots & \\ (\alpha_{n_D}, 2)_{Y_{n_D}} & (\overline{\alpha}_{n_D}, 1)_{-Y_{n_D}-\frac{1}{2}} & (\overline{\alpha}_{n_D}, 1)_{-Y_{n_D}+\frac{1}{2}} \end{array}$$

$$\sum_{i=1}^{n_D} |\alpha_i| Y_i = 0$$

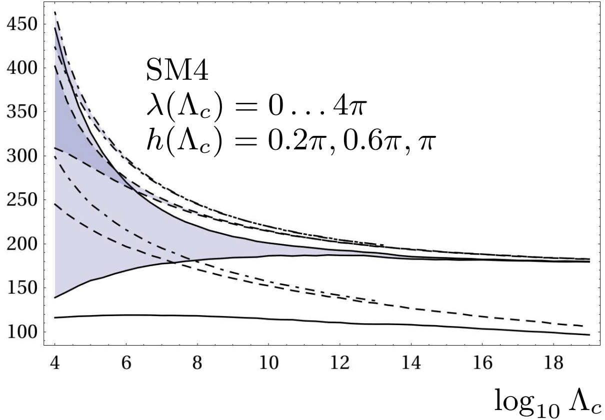
Simplest general solutions

SM4$_Y$	$(3,2)_Y$	$(\overline{3},1)_{-Y-\frac{1}{2}}$	$(\overline{3},1)_{-Y+\frac{1}{2}}$
	$(1,2)_{-3Y}$	$(1,1)_{3Y-\frac{1}{2}}$	$(1,1)_{3Y+\frac{1}{2}}$
SM4Q$_Y$	$(3,2)_Y$	$(\overline{3},1)_{-Y-\frac{1}{2}}$	$(\overline{3},1)_{-Y+\frac{1}{2}}$
	$(3,2)_{-Y}$	$(\overline{3},1)_{+Y-\frac{1}{2}}$	$(\overline{3},1)_{+Y+\frac{1}{2}}$
SM4L$_{\vec{Y}}$	$(1,2)_A$	$(1,1)_{-A-\frac{1}{2}}$	$(1,1)_{-A+\frac{1}{2}}$
	$(1,2)_B$	$(1,1)_{-B-\frac{1}{2}}$	$(1,1)_{-B+\frac{1}{2}}$
	$(1,2)_C$	$(1,1)_{-C-\frac{1}{2}}$	$(1,1)_{-C+\frac{1}{2}}$
	$(1,2)_D$	$(1,1)_{-D-\frac{1}{2}}$	$(1,1)_{-D+\frac{1}{2}}$
	$A+B+C+D=0$		
SM4Q'$_{\vec{Y}}$	$(3,2)_A$	$(\overline{3},1)_{-A-\frac{1}{2}}$	$(\overline{3},1)_{-A+\frac{1}{2}}$
	$(3,2)_B$	$(\overline{3},1)_{-B-\frac{1}{2}}$	$(\overline{3},1)_{-B+\frac{1}{2}}$
	$(3,2)_C$	$(\overline{3},1)_{-C-\frac{1}{2}}$	$(\overline{3},1)_{-C+\frac{1}{2}}$
	$A+B+C=0$		

Constraints from RG running

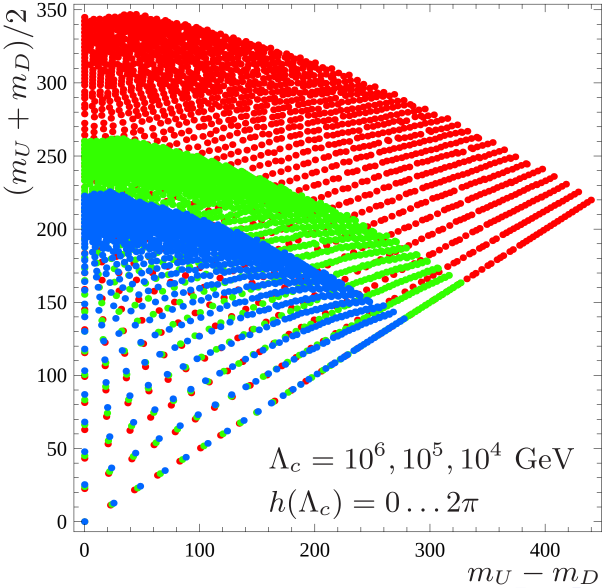


$$\kappa^{-1}\beta_\lambda = 12\lambda^2 + 4\Sigma\lambda - 4X, \quad \kappa^{-1}\beta_U = \tfrac{3}{2}(UU^\dagger - DD^\dagger) + \Sigma, \quad \ldots$$

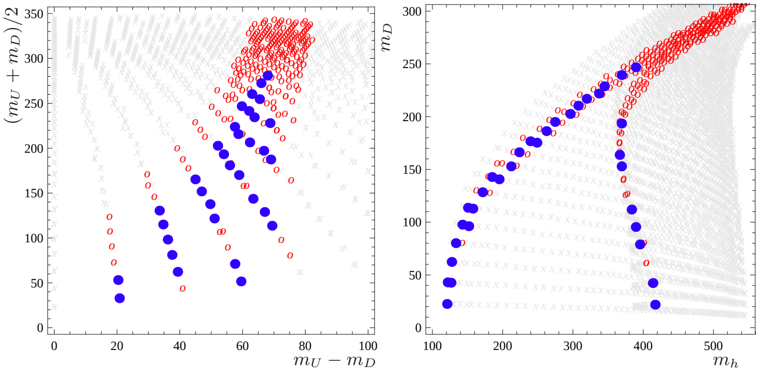


- Higgs masses strongly constrained from both sides
- Fermion masses have upper bound!
- Large fermion masses lead to strong fixpoint behavior of Higgs

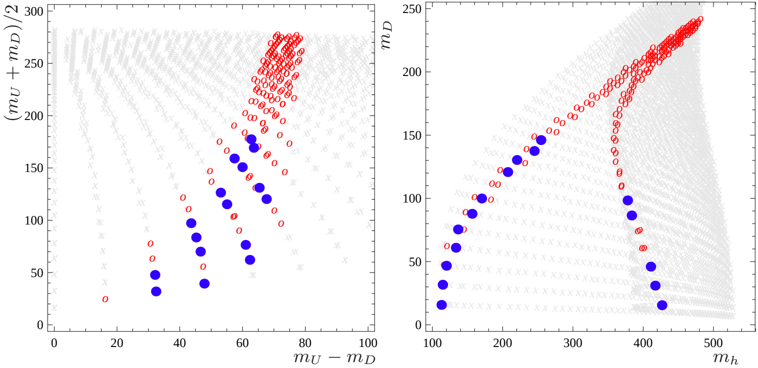
Constraints from RG running



- Severe theoretical upper bounds
- Higgs must be super-heavy
- SM-like hypercharges:



- $\Lambda \sim 10^{12}$ GeV possible
- almost allows gauge unification!
- SM-like hypercharges:



For more details, see [AK, C. Wetterich '11]

Thank you for your Attention!