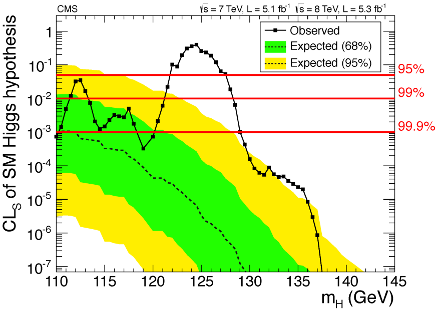
Maximal stop mixing and high-scale SUSY breaking

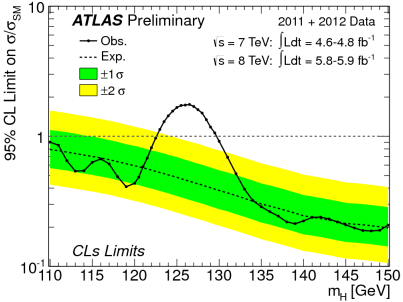
Felix Brümmer

arXiv:1204.5977, JHEP 1208 (2012) 089
Collaborators: S. Kraml, S. Kulkarni

4th of July: Discovery Day

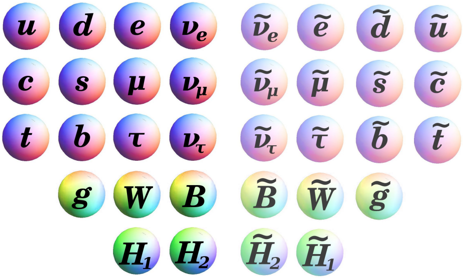
A new boson with $m = 126$ GeV





- Is this a Higgs?
- . . . a SUSY Higgs?
- . . . an MSSM Higgs?

Beyond the Standard Model: The MSSM



- minimal SUSY extension of Standard Model
- new states: superpartners, one more Higgs doublet
- $\langle H_2 \rangle = v_u, \quad \langle H_1 \rangle = v_d, \quad v_u^2 + v_d^2 = v^2 = (174\text{ GeV})^2, \quad \tan\beta \equiv v_u/v_d$
- physical Higgs bosons: 1 charged $H^\pm$, 1 pseudoscalar A^0, 2 scalar H^0, h^0
- for large range of parameters h^0 is SM-like...
- ...but its quartic coupling is not a free parameter

MSSM Higgs @ 126 GeV needs large loop corrections

$$m_{h^0}^2 = m_{h^0}^{2,\text{tree}} + \Delta m_{h^0}^{2,\text{1-loop}}$$
$$= m_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left(\log\frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12\,M_S^2}\right)\right)$$
$$(126\text{ GeV})^2 = (91\text{ GeV})^2 + (86\text{ GeV})^2$$

Here

$$M_S = \sqrt{m_{\tilde t_1} m_{\tilde t_2}}, \qquad X_t = A_t - \mu\cot\beta, \qquad \tan\beta = \frac{v_u}{v_d}$$

with A-term coupling top squarks to Higgs: $\mathcal{L} \supset -A_t\, y_t\, H_u \tilde t_L \tilde{\bar t}_R$

Want

- $\tan\beta \gtrsim 5$
- large $m_{\tilde t_i}$ (naturalness problem!)
- large $|X_t|$ (naturalness problem!)

In a little more detail

Stop/top loops give largest contribution to 1-loop eff. potential since y_t large

Stop mass matrix:

$$m_{\tilde{t}}^2 = \begin{pmatrix} m_{Q3}^2 + m_t^2 & m_t X_t \\ m_t X_t & m_{U_3}^2 + m_t^2 \end{pmatrix} + D\text{-terms}$$

$X_t = A_t - \mu \cot\beta =$ stop mass mixing parameter

$$\Delta m_{h^0}^2 = \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left(\log\frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12\, M_S^2}\right)\right)$$

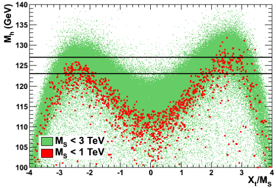
Maximal stop mixing:

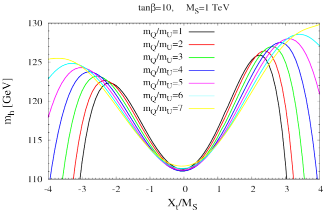
X_t such that radiative contribution to Higgs mass maximal

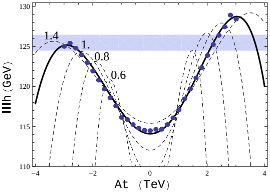
see e.g. → Carena/Haber/Heinemeyer/Hollik/Wagner/Weiglein ’00

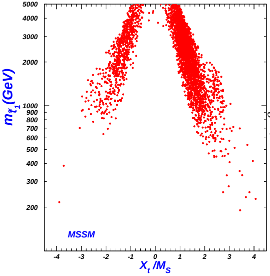
$$1.5 \lesssim \frac{|X_t|}{M_S} \lesssim 2.5$$

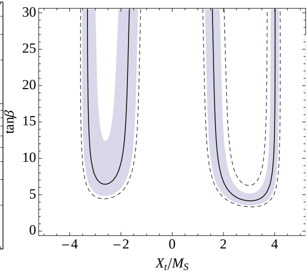
arXiv picture gallery on stop mixing

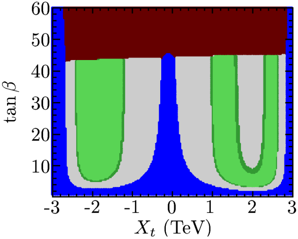












Credits: → Arbey et al.; Badziak/Dudas/Olechowski/Pokorski; Barger/Huang/Ishida/Keung; Cao et al.; Draper/Meade/Reece/Shih; Heinemeyer/Stål/Weiglein 2011/12

Why maximal mixing?

From the bottom-up perspective, $1.5 \lesssim |X_t|/M_S \lesssim 2.5$ just a parameter choice

But: SUSY breaking soft terms generated at high scale in realistic models, e.g. M_{GUT}

Questions:

- Can get maximal stop mixing from "reasonable" high-scale soft terms?
- What constraints does this pose on the underlying model?
- Are there classes of models which are thus preferred/disfavoured?

RG evolution of A-terms

MSSM renormalization group equations:

$$\frac{\mathrm{d}}{\mathrm{d}\log Q} A_t = \frac{3}{4\pi^2}|y_t|^2 A_t + \frac{2}{3\pi^2} g_3^2\, M_3 + \ldots$$

For $M_{\mathrm{GUT}} = 2 \cdot 10^{16}$ GeV, $M_S = 1$ TeV, $\tan\beta = 20$:

$$X_t^4 = \left(9.4\, M_{1/2}^4 - 7.5\, A_t\, M_{1/2}^3 + 2.2\, A_t^2\, M_{1/2}^2 - 0.3\, A_t^3\, M_{1/2}\right)\Big|_{M_{\mathrm{GUT}}} + \ldots$$

$$M_S^4 = m_{U3}^2 m_{Q3}^2\big|_{M_S}$$
$$= \left(8.7\, M_{1/2}^4 + 2.5\, M_{1/2}^2\, m_{U3}^2 + 1.7\, M_{1/2}^2\, m_{Q3}^2 + 1.2\, A_t\, M_{1/2}^3\right)\Big|_{M_{\mathrm{GUT}}} + \ldots$$

Want $5 \lesssim \frac{X_t^4}{M_S^4} \lesssim 40$: need $A_t|_{M_{\mathrm{GUT}}}$ large and negative

or $m_{U3}^2 < 0$, $m_{Q3}^2 < 0$ at M_{GUT} $\rightarrow$ Dermisek/Kim '06

Disfavoured scenarios

- **Minimal gauge mediation**: predicts $A_t = 0$ at messenger scale
  Messenger scale generally $< M_{\text{GUT}}$, but this doesn't help

Disfavoured scenarios

- **Minimal gauge mediation**: predicts $A_t = 0$ at messenger scale
  Messenger scale generally $< M_{\text{GUT}}$, but this doesn't help

Disfavoured scenarios

- **Minimal gauge mediation**: predicts $A_t = 0$ at messenger scale
  Messenger scale generally $< M_{\rm GUT}$, but this doesn't help
  

- **Minimal gaugino mediation**: only gaugino masses $\neq 0$ at high scale
  

Disfavoured scenarios

- **Minimal gauge mediation**: predicts $A_t = 0$ at messenger scale
  Messenger scale generally $< M_{\mathrm{GUT}}$, but this doesn't help

- **Minimal gaugino mediation**: only gaugino masses $\neq 0$ at high scale

- **"Radion mediation"**/Scherk-Schwarz ~~SUSY~~ in extra dimensions:
  in some simple models $A_t = -M_{1/2}$ at mediation scale
  (see e.g. $\rightarrow$ FB/Fichet/Hebecker/Kraml '09)
  A_t negative, but not large enough

Disfavoured scenarios

- **Minimal gauge mediation**: predicts $A_t = 0$ at messenger scale
  Messenger scale generally $< M_{\text{GUT}}$, but this doesn't help

- **Minimal gaugino mediation**: only gaugino masses $\neq 0$ at high scale

- **"Radion mediation"**/Scherk-Schwarz ~~SUSY~~ in extra dimensions:
  in some simple models $A_t = -M_{1/2}$ at mediation scale
  (see e.g. → FB/Fichet/Hebecker/Kraml '09)
  A_t negative, but not large enough

These models are not "ruled out", but become significantly more ugly if they are to accommodate a 126 GeV Higgs.

Preferred scenarios

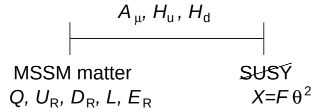
- Claim: Kähler moduli-dominated ~~SUSY~~ in type IIB/F-theory models
  $\Rightarrow$ maximal mixing $\rightarrow$ Aparicio/Cerdeño/Ibáñez '12

Preferred scenarios

- Claim: Kähler moduli-dominated $\not{SUSY}$ in type IIB/F-theory models
  $\Rightarrow$ maximal mixing $\rightarrow$ Aparicio/Cerdeño/Ibáñez '12
- Extreme hierarchies between soft terms can give maximal mixing
  E.g. 1st/2nd gen. squarks $\gtrsim$ 10 TeV (see also $\rightarrow$ Badziak/Dudas/Olechowski/Pokorski '12)

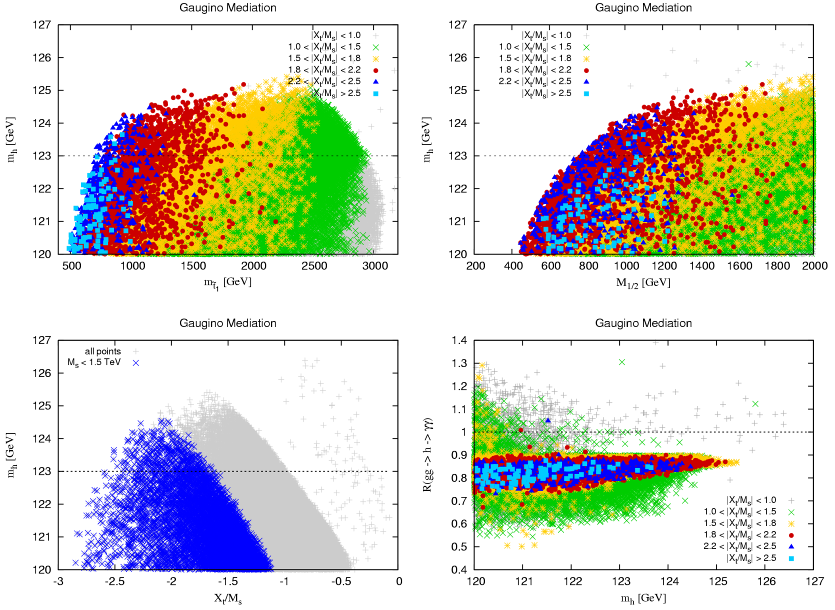
Preferred scenarios

- Claim: Kähler moduli-dominated ~~SUSY~~ in type IIB/F-theory models $\Rightarrow$ maximal mixing → Aparicio/Cerdeño/Ibáñez '12
- Extreme hierarchies between soft terms can give maximal mixing
  E.g. 1st/2nd gen. squarks $\gtrsim$ 10 TeV (see also → Badziak/Dudas/Olechowski/Pokorski '12)
- Any SUSY breaking model where A_t is a free parameter
  E.g. gaugino-Higgs mediation:



Free parameters: gaugino masses, Higgs soft masses, μ, B_μ, A-terms

Example: Gaugino mediation and maximal mixing



Fine-tuning

At $\tan\beta = 20$, $M_S = 1$ TeV:

$$m_Z^2 = 0.2\,A_0^2 + 0.7\,A_0\,M_{1/2} + 2.9\,M_{1/2}^2 - 2.1\,|\hat{\mu}|^2 - 1.3\,\widehat{m}_{H_u}^2 + 0.7\,\widehat{m}_{Q_3}^2 + 0.8\,\widehat{m}_{U_3}^2 + \ldots$$

(A_0, $M_{1/2}$, $\hat{\mu}$, $\widehat{m}_\phi$ = GUT-scale parameters)

$$\frac{1}{\text{fine-tuning}} = \max_a C_a \quad \text{where } C_a = \frac{\partial \log m_Z}{\partial \log a}$$

$$C_{M_{1/2}} = 2.9\frac{M_{1/2}^2}{m_Z^2} - 0.35\frac{A_0 M_{1/2}}{m_Z^2}, \qquad C_{A_0} = 0.2\frac{A_0^2}{m_Z^2} - 0.35\frac{A_0 M_{1/2}}{m_Z^2}$$

- For $|A_0| < 3\,M_{1/2}$: worst source of fine-tuning is gaugino mass
- Applies in particular to maximal mixing scenario
- Typical points in our scan have FT $\approx$ few permille

Conclusions

- The Higgs is uncomfortably heavy for the MSSM

Conclusions

- The Higgs is uncomfortably heavy for the MSSM
- Easy to get $m_h = 125$ GeV from maximal stop mixing

Conclusions

- The Higgs is uncomfortably heavy for the MSSM
- Easy to get $m_h = 125$ GeV from maximal stop mixing
- Less easy to get maximal stop mixing :
  - Mixing parameter X_t and soft scale M_S affected by large radiative corrections
  - Need large negative GUT-scale trilinears
    Points with positive X_t extremely unnatural
  - Few models known to predict maximal mixing
    Several models known to predict small mixing: disfavoured

Conclusions

- The Higgs is uncomfortably heavy for the MSSM
- Easy to get $m_h = 125$ GeV from maximal stop mixing
- Less easy to get maximal stop mixing :
  - Mixing parameter X_t and soft scale M_S affected by large radiative corrections
  - Need large negative GUT-scale trilinears
    Points with positive X_t extremely unnatural
  - Few models known to predict maximal mixing
    Several models known to predict small mixing: disfavoured
- In models allowing for maximal mixing: Fine-tuning still high