Phenomenology and Naturalness in Gauge Extensions of the MSSM after the Higgs discovery

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Outline Part A

In the first part of this talk we will:

- briefly review the main observations on natural scenarios of the MSSM.
- study the fine tuning measure Δ_z in the MSSM and impose constraints from Higgs data and collider searches on SUSY particles.
- present regions of the parameter space in which the natural MSSM scenarios are not yet ruled out by currently available searches.

Outline-Part B

In the second part of this talk we will:

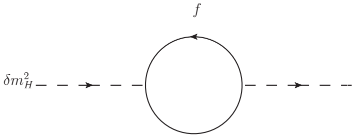
- motivate the gauge extensions of the MSSM and introduce a version of the phenomenological UMSSM model with generic charges.
- impose constraints from Higgs data and SUSY searches, study the fine tuning in pUMSSM and identify regions with low Δ_z.

The Hierarchy problem in the SM

- The masses of the SM particles are proportional to the VEV of the Higgs field $\langle H \rangle$ which in turn depends on the quadratic scalar mass of the Higgs boson

$$\langle H \rangle = \sqrt{\frac{-m_H^2}{2\lambda}}$$

- The problem arises from the fact that the squared mass m_H^2 of the Higgs boson receives quadratic corrections with respect to the UV cutoff scale Λ_{UV} from loop diagrams involving heavy particles. The largest contribution is given by the top quark loop.



The Hierarchy problem in the SM

- The corrected squared mass of the higgs scalar depends on the UV cut-off scale Λ

$$m_H^2 = 2v^2\lambda + \kappa\Lambda^2$$

where $v = \langle H \rangle \approx 174$GeV.

  - if $\Lambda \sim M_W$ then m_H is of the order $\mathcal{O}(M_W)$ and the SM corrections then pose no problem.
  - but if $\Lambda \gg M_W$ then $m_H \sim \Lambda \gg M_W$.

- in order to avoid the higgs mass from becoming too large we have to fine tune the parameter κ

$$\text{if} \quad \Lambda \sim M_P \Longrightarrow \qquad \kappa \sim \frac{M_w^2}{M_P^2} \sim 10^{-34}$$

$$\text{if} \quad \Lambda \sim M_{GUT} \Longrightarrow \qquad \kappa \sim \frac{M_w^2}{M_{GUT}^2} \sim 10^{-26}$$

Susy gives an elegant solution to the hierarchy problem

- The Naturalness criterion attributes this quadratic divergence of the Higgs mass to the lack of a symmetry that would protect the mass from diverging.
- Susy provides such a symmetry between fermions and bosons by ensuring that each supermultiplet contains the same number of fermionic and bosonic degrees of freedom i.e every known SM particle has its own superpartner with a spin that differs by $1/2$ unit.
- Every Weyl spinor has 2 fermionic d.o.f due to the two possible spin states. In order to equate these fermionic dof with bosonic dof we need to associate 2 real scalar fields (1 bosonic dof each) to every Weyl spinor (left-handed or right-handed). The simplest way to do this is by accomodating these dof into a complex scalar field.

μ problem in MSSM and fine tuning

The superpotential of the MSSM reads

$$\begin{aligned} W_{MSSM} &= \bar{u}^i y_{u_{ij}} Q_\alpha^{T^j} \epsilon^{\alpha\beta} H_{u_\beta} - \bar{d}^i y_{d_{ij}} Q_\alpha^{T^j} \epsilon^{\alpha\beta} H_{d_\beta} - \bar{e}^i y_{e_{ij}} L_\alpha^{T^j} \epsilon^{\alpha\beta} H_{d_\beta} \\ &+ \mu H_{u_\alpha}^T \epsilon^{\alpha\beta} H_{d_\beta} \end{aligned}$$

$Q, L, \bar{u}, \bar{d}, \bar{e}, H_u, H_d$: chiral superfields

- $\mu H_u H_d \overset{\text{equivalent}}{\Longleftrightarrow} m_H^2 |H|^2$ in the SM.
- The dimensionful parameter μ gives the Higgsino mass terms and the Higgs squared mass terms in the scalar potential V_{scalar}

$$\begin{aligned} -\mathcal{L}_{\tilde{H}} &= \mu(\tilde{H}_u^+ \tilde{H}_d^- - \tilde{H}_u^0 \tilde{H}_d^0) + c.c, \\ -\mathcal{L}_{\text{Higgs mass}} &= |\mu|^2 \Big(|H_u^0|^2 + |H_u^+|^2 + |H_d^0|^2 + |H_d^-|^2 \Big). \end{aligned}$$

- To break SUSY we have to add soft terms $\mathcal{L}_{soft} \supset m_{H_d}^2, m_{H_u}^2$

μ problem in MSSM and fine tuning

V_{Higgs} consists of:
$|\mu|^2$: SUSY respecting term, $m^2_{H_d}, m^2_{H_u}$: soft SUSY breaking terms
$\rightarrow$ both have to be $\mathcal{O}(m^2_{soft})$ so that $H \xrightarrow[VEV]{gets} \langle H \rangle$ (μ problem)

At the minimum of the potential (in the large $\tan\beta$ limit):

$$\frac{M_Z^2}{2} = -m^2_{H_u} - |\mu|^2$$

- if $|m^2_{H_u}|, |\mu|^2 \gg M_Z^2 \Rightarrow$ large cancellation is needed to get M_Z.
- $m^2_{H_u}$ is very sensitive to radiative corrections

$$\begin{aligned}\beta^{(1)}_{m^2_{H_u}} &= 6|y_t|^2(m^2_{H_u} + m^2_{Q_3} + m^2_{T^c} + |A_t|^2) - 6g_2^2|M_2|^2 \\ &- \frac{6}{5}g_1^2|M_1^2| + \frac{3}{5}g_1^2 S\end{aligned}$$

Fine Tuning in the MSSM

- beta function of $m_{H_u}^2$ depends on the soft SUSY breaking masses of the top squarks m_{Q_3}, m_{T^c} and the soft trilinear coupling A_t which induces mixing in the stop sector.
- The stop masses control the radiative corrections to the lightest Higgs mass. Approximate relation for 1-loop corrections

$$m_{h_0}^2 = M_Z^2 \cos 2\beta^2 + \frac{3g_2^2}{8\pi^2}\frac{m_t^4}{M_W^2}\left[\ln\frac{m_{\tilde{t}_1}m_{\tilde{t}_2}}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}_1}m_{\tilde{t}_2}}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}_1}m_{\tilde{t}_2}}\right)\right]$$

$X_t = A_t - \mu \cot\beta$ and one can make the approximation $M_{susy}^2 \equiv m_{\tilde{t}_1}m_{\tilde{t}_2} \approx m_{Q_3}m_{T^c}$.

- for $m_{h_1^0} \simeq 125$GeV $\rightarrow$ need large radiative corrections and thus relatively heavy stop masses m_{Q_3}, m_{T^c} with large mixing $X_t \rightarrow$ radiative corrections $\delta m_{H_u}^2$ become large and the electroweak scale becomes unstable. Large cancellations at 1-loop are needed to get M_Z

Definition of Fine Tuning

One can define a low scale fine tuning measure with the input parameters at the weak scale (Kitano-Nomura 2006)

$$\Delta_Z = \max_i \frac{|B_i|}{(M_Z^2/2)}$$

where $B_i = \delta m_{H_u}^2,\, \delta\mu^2,\, m_{H_u}^2|_{tree},\, \mu^2|_{tree}$.

- Higgsino mass is constrained at tree level $\Rightarrow$ $105\mathrm{GeV} \lesssim \mu \lesssim 200\mathrm{GeV}$ for $\Delta_Z \lesssim 10$. Lower bound comes from LEP chargino searches.

- Lightest 3rd generation squarks $\tilde{t}_1, \tilde{b}_1$:

$$\sqrt{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2} \lesssim 450\mathrm{GeV} \frac{\sin\beta}{(1+X_t^2)^{1/2}} \left(\frac{3}{\ln \frac{\Lambda}{M_{susy}}} \right)^{1/2} \frac{M_Z}{91.2\mathrm{GeV}} \left(\frac{\Delta_Z}{5} \right)^{1/2}$$

for $\Delta_Z \lesssim 10$ and $\Lambda \sim 10^{15} - 10^{16}$GeV $\Rightarrow \tilde{t}_1, \tilde{b}_1 \lesssim 200$GeV

- Large Logs are responsible for the large coefficients when we solve the RGE's and thus increase FT
- Past solutions: make Logs smaller by choosing a low mediation scale $\Lambda \sim 10 - 100$TeV [Papucci 2011]
- Recent solutions: heavy gaugino masses $M_1, M_2 > M_3 \rightarrow$ cause cancellations within the beta function $\beta_{m^2_{H_u}}$ [Baer 2013] $\rightarrow$ points of low FT of $\Delta_Z \sim \mathcal{O}(10)$ are possible.

In this study:

- for the calculation of FT we consider light gaugino masses M_1, M_2 to avoid cancellations $\rightarrow$ results coincide with broad scans from other studies.
- in order to impose constraints from SUSY searches using the program `Fastlim` and achieve highest possible coverage we use as input heavy gauginos $M_1, M_2 > M_3$.

Computational Framework

program SARAH [Staub 2013]:

-implementation of SUSY (and non-SUSY) models by defining the gauge structure, particle content and the superpotential of the theory.

-calculates 1-loop corrections to the masses of all scalars

-calculates 2-loop corrections to the masses of real scalars using two methods. (a) Effective potential (b) Fully diagrammatic calculation. No 2-loop electroweak corrections. For MSSM and NMSSM: results reproduce exactly calculations with other public routines.

-creates SPheno code for your favourite model $\rightarrow$ heavy numerics and more

program SPheno [Porod 2004]:

-Spectrum generator. Decays and branching ratios. Flavour and precision observables and more. Written in Fortran.

Computational Framework

program `Fastlim` [Papucci et al 2014]:

-calculates conservative limits for BSM models from LHC searches without running Monte Carlo event generation. Reconstructs the visible cross section from contributions of the relevant simplified topologies. The number of events falling inside a specific signal region α is calculated by

$$N^{(\alpha)} = \sum_{i}^{\text{all top}} \epsilon_i^{(a)} \cdot \sigma_i \cdot \mathcal{L}_{\text{int}}$$

$\epsilon_i^{(a)}$ (# of events falling in α)/N_{total} (efficiency)

σ_i: for topology $i \rightarrow \sigma_i = \sigma_{\text{prod}} \times BR(\ldots)$. The production cross section is interpolated from pre-calculated tables which depend on the masses of the particles involved and BR()s are taken from SUSY spectrum generator output file (`SPheno`).

Computational Framework

Additional Routines created in `Mathematica`:

- SLHA I/O routine which reads and writes the `SPheno` input/output file.
- routine which interfaces `SPheno` and `Fastlim`. The routine modifies the `SPheno` ouput files to be used as input by `Fastlim`
- routine which reads the `Fastlim` output files and creates the exclusion points for each available experimental searches. The points are interpolated in `Mathematica` to obtain exclusion regions

✎ HPC parallelization scripts $\Rightarrow$ speed up processing time by a factor of 5 for the full calculation chain
one plot: # points $\sim (6-8) \times 10^3 \rightarrow T \sim (3.5-5)$h

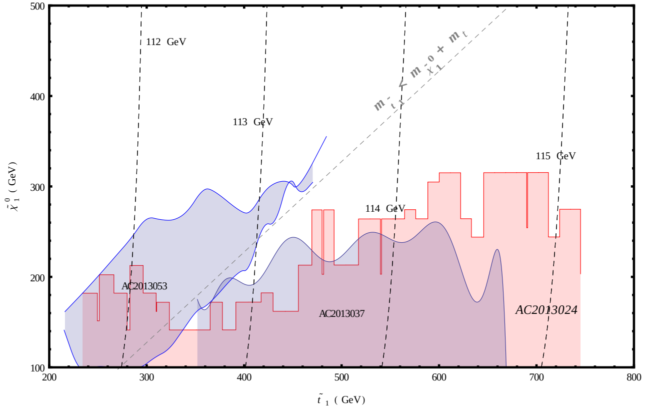


Figure : Exclusion regions on the $(\tilde{t}_1, \tilde{\chi}_1^0)$ mass plane for the three ATLAS searches: AC2013024 (red shaded area) AC2013053 (light blue shaded area on the left) AC2013037 (light blue shaded area on the right). Contributions from the other searches are small and have not been included in this plot. Higgs mass contours: black dotted lines. The coverage we get with `Fastlim` is nearly 100%

Comments:

- $A_t = 100$GeV to avoid getting tachyonic stops for light M_{Q_3}. Therefore $m_{h_1^0}^{\max} \sim 116$GeV for $m_{\tilde{t}_1^0} \simeq 800$GeV $\rightarrow$ not close to 125GeV.
- **AC2013053**: looks at production mechanism $pp \rightarrow \tilde{t_1}\tilde{t_1}$ where stops decay into $\tilde{t_1} \rightarrow t\tilde{\chi}_1^0$ or $\tilde{t_1} \rightarrow bW\tilde{\chi}_1^0 \rightarrow b(\bar{f}'f)\tilde{\chi}_1^0$. Strong assumptions have been made for $\mathrm{BR}(\tilde{t_1} \rightarrow t\tilde{\chi}_1^0) = 1$. To get strong constraints we need BR large $\rightarrow$ therefore Higgsinos and stops are often the lightest particles in a natural scenarios M_1, M_2 are taken to decouple enhancing the stop-top-neutralino coupling. Excludes mostly points for which $\tilde{t_1} \rightarrow t\tilde{\chi}_1^0$ is kinematically forbidden and $\mathrm{BR}(\tilde{t_1} \rightarrow b\tilde{\chi}^+) = 1$.
- **AC2013024, AC2013037** exclude mainly points for which $\tilde{t_1} \rightarrow t\tilde{\chi}_1^0$ is allowed.
- Higgs mass is below 125GeV, experimental searches exclude $m_{\tilde{t}_1^0} \lesssim 750$GeV for Higgsino LSP up to 300GeV.

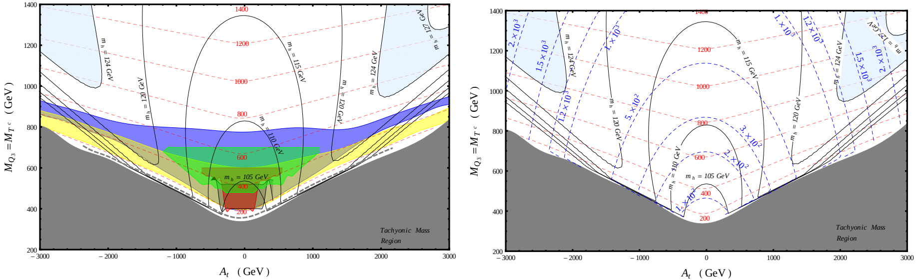


Figure : Lightest CP-even Higgs mass contours h_1^0 (solid black lines), lightest stop mass contours $\tilde{t}_1$ (red dashed lines) in the MSSM. Left: LHC constraints from various ATLAS searches using `Fastlim`. Right: Δ_Z contours. $\tan\beta = 20$, $\mu = 150$GeV. Shaded areas $\Rightarrow$ exclusion regions from ATLAS studies: AC2013024 (blue) AC2013053 (yellow) AC2013037 (green) AC2013048 (red) and AC2013093 (black).

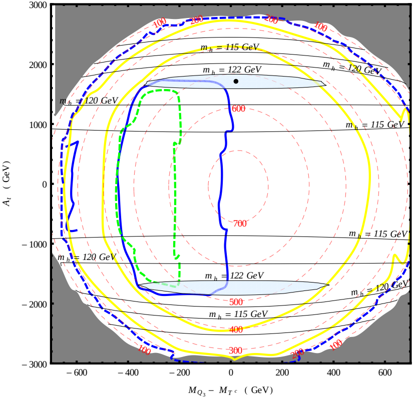
Comments:

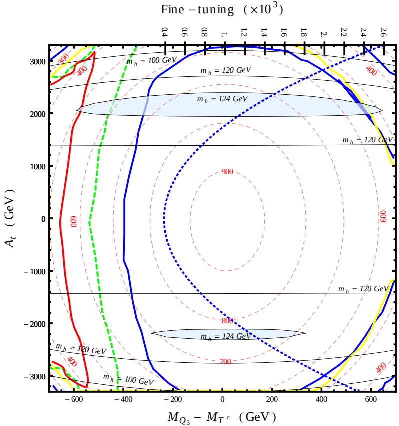
- For $A_t = 0$ stops with $m_{\tilde{t}_1} \lesssim 750$GeV are excluded. For $|A_t| \simeq 2$TeV stops with $m_{\tilde{t}_1} \lesssim 580$GeV are excluded.
- For lightest Higgs $m_{h_1^0} \sim 125$GeV $\Rightarrow M_{Q_3} = M_{T^c} \simeq 1$TeV and $|A_t| \sim 2$TeV with $m_{\tilde{t}_1} \gtrsim 800$GeV. FT is around $\Delta_Z \sim 1.2 \times 10^3$

What about $M_{Q_3} \neq M_{T^c}$?

- Fix the FT coming from $M_{Q_3}, M_{T^c} \stackrel{\text{set}}{\Longrightarrow} M_{Q_3}^2 + M_{T^c}^2 = C^2$, vary A_t and the difference $X = M_{Q_3} - M_{T^c}$.

- FT depends only on A_t, we show plots for $C = 800\sqrt{2}$GeV (left plot) and $C = 1000\sqrt{2}$GeV (right plot).





(a) $C = 800\sqrt{2}$GeV, $\mu = 105$GeV (b) $C = 1000\sqrt{2}$GeV, $\mu = 105$GeV

- Blue dashed: FT measure Δ_Z (read values on top), Red dashed: $m_{\tilde{t}_1}$, Black solid: $m_{h_1^0}$. Gray area: tachyonic mass region.

- exclusion curves: AC2013024 (Blue), AC2013053 (Yellow), AC2013037 (Green), AC2013048 (Red)

- For both plots $M_{B^c} = 3$TeV $\xrightarrow{\text{thus}}$ lightest bottom squark is mostly left-handed $\tilde{b}_1 \sim \tilde{b}_L$. Moving from left to right M_{Q_3} increases and thus $m_{\tilde{b}_1}$ increases. The sbottom mass $m_{\tilde{b}_1} = 1043$GeV for $X \simeq 600$GeV.

- For $C = 800\sqrt{2}$GeV the max Higgs mass (black dot) achieved is $m^{\max}_{h^0_1} = 122.31$ and $\Delta_Z \simeq 800$ at this point.

- For $C = 1000\sqrt{2}$GeV the blue shaded area achieves $124\text{GeV} \lesssim m_{h^0_1} \lesssim 124.6$GeV with $10^3 \lesssim \Delta_z \lesssim 1.5 \times 10^3$ for relatively large mass splitting $X = M_{Q_3} - M_{T^c}$. For $X = 700$GeV, $m_{\tilde{b}_1} = 1275.86$GeV.

- larger mass splitting $X > 0$ is favourable and can pass experimental constraints.

Part B: Gauge Extensions

Why gauge extensions of MSSM ?

- solution to μ problem in MSSM: $\mu \sim \mathcal{O}(TeV) \sim m_{soft}$ but μ is supersymmetry respecting parameter.

  UMSSM/NMSSM: generates μ-term effectively

$$W = W_{MSSM}(\mu = 0) + \lambda S H_u H_d$$

  after EWSB: $\mu_{eff} = \lambda \langle S \rangle H_u H_d$
  Now μ_{eff} is supersymmetry breaking parameter

- NMSSM $\mu H_u H_d \xrightarrow{replaced} \lambda S H_u H_d$: W_{NSSM} PQ-symmetry

$$\phi_i \to \phi_i' = e^{iQ_{PQ}}\phi$$

  PQ=continuous symmetry $\to$ SSB produces massless Goldstone mode (not observed)

- UMSSM Solution: PQ global $\xrightarrow{promote}$ $U(1)'$ local massless axion eaten by new $U(1)'$ gauge boson B' $\rightarrow$ massive extra Z' at the TeV scale.
- no cubic term $\frac{1}{3}\kappa S^3$ (NMSSM)$\rightarrow$ no domain problems (spoil CMB radiation)
- Extra $U(1)'$ also emerge from GUT's and string theories. Larger groups: $SU(5), SO(10)$ and $E_6 \xrightarrow{break} G_{SM} \times U(1)'^{\,n},\ n \geq 1$.
  - Breaking mechanism imposes charge constraints.

Phenomenological implications of extra $U(1)$ symmetries:

- new F-term and $U(1)'$ D-term contributions to the Higgs scalar potential $\Rightarrow$ can raise the Higgs mass at tree level
- extra $U(1)'$ D-terms present in the squared mass matrices of the sfermions
- extra Z' boson $\rightarrow$ rich phenomenology
- extended neutralino sector.

UMSSM: minimal extension of MSSM, one extra $U(1)$ gauge symmetry + one gauge singlet S which receives a VEV and breaks $U(1)$.

- Exotic sector is assumed to decouple $\rightarrow$ no relevant terms enter the superpotential of the low scale effective theory [Barger 2006, Barger 2007]

- in principle once the high scale d.o.f have been integrated out the $U(1)'$ charges can be free parameters [Cvetic 1997, Keith & Ma 1997]
$\dashrightarrow$ Construct a complete UV model: cancel anomalies, FCNC (and perhaps gauge unification). This is outside the scope of our study.

pUMSSM:
+ effective bottom-up approach $\Rightarrow$ takes advantage of rapidly increasing LHC data.

+ parametrize $U(1)'$ charges most pertinent to indirect constraints $\Rightarrow$ charges entering Higgs and stop/sbottom sector. + impose constraints on charges: 1) Perurbativity 2) gauge invariance 3) W mass constraint.

Constraints:

➡ $U(1)'$ gauge invariance gives 3 constraints:

$$
\begin{array}{rcl}
\lambda S H_u H_d & \rightarrow & \underbrace{Q_{H_u}} + Q_{H_d} + \underbrace{Q_s} = 0 \\
y_u \bar{u} Q H_u & \rightarrow & Q_{H_u} + \underbrace{Q_{q3}} + Q_{T^c} = 0 \\
y_d \bar{d} Q H_d & \rightarrow & Q_{H_d} + Q_{q_3} + Q_{B^c} = 0 \\
y_e \bar{e} L H_d & \rightarrow & Q_{H_d} + Q_{L_3} + Q_{\tau^c} = 0
\end{array}
$$

(last two eq. relevant for large $\tan\beta$)

➡ Define $\tilde{Q}_i = g_1' Q_i$. Perturbativity of g_1' up to $\Lambda = 2 \times 10^{16}$GeV:

$$\sum m_i Q_i(\mu_0)^2 < 2.22$$

$\mu_0 = 1$TeV and m_i multiplicity of the multiplet ϕ_i (e.g 6 for Q_{q3}, 2 for H_u)

W mass constraint:

- $Z - Z'$ mixing angle is constrained by EWPD to be typically less than $\mathcal{O}(10^{-3})$. The limits are model dependent. $\rightarrow$ use W mass to apply limits for models with generic charges (pUMSSM).

- W mass is sensitive to quantum corrections and can be used to constrain BSM scenarios [Heinemeyer et al 2013].

  - Improved W mass measurement + improved top quark measurement $\Rightarrow$ reduces theoretical uncertainty.

  - Using M_W data and known SM corrections $\Rightarrow \delta M_W \sim 54(95)$MeV at $1\sigma(2\sigma)$.

  - This size can be attributed to $Z - Z'$ mixing.

$$\frac{\Delta_Z^2}{2M_Z} \cdot \tan 2\theta_{ZZ'} < 110(190)\text{MeV}$$

where $\Delta_Z^2 = \frac{1}{2} g_Z (Q_{H_d} v_d^2 - Q_{H_u} v_u^2)$

Stop/Sbottom Sector

Squared mass matrices for stops and sbottoms:

$$\mathcal{M}_{\tilde{t}}^2 = \begin{pmatrix} m_{Q_3}^2 + m_t^2 + \Delta_{\tilde{u}_L} + Q_{q_3} d' & m_t^2 (A_t^* - \mu_{eff} \cot\beta) \\ m_t^2 (A_t - \mu_{eff}^* \cot\beta) & m_{T^c}^2 + m_t^2 + \Delta_{\tilde{u}_R} + Q_{T^c} d' \end{pmatrix} \quad \mathcal{M}_{\tilde{b}}^2 = \begin{pmatrix} m_{Q_3}^2 + m_b^2 + \Delta_{\tilde{d}_L} + Q_{q_3} d' & m_b^2 (A_d^* - \mu_{eff} \tan\beta) \\ m_b^2 (A_b - \mu_{eff}^* \tan\beta) & m_{B^c}^2 + m_b^2 + \Delta_{\tilde{d}_R} + Q_{B^c} d' \end{pmatrix}$$

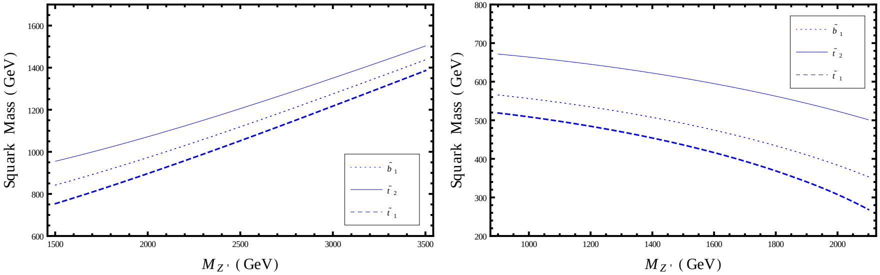
Δ_{ϕ_i}: ordinary $U(1)_Y, SU(2)_L$ gauge terms present in the MSSM and

$$d' = \frac{1}{2}\left(Q_{H_d} v_u^2 + Q_{H_u} v_u^2 + Q_S v_s^2\right)$$

$U(1)'$ D-terms $D_a = \sum_{a,i} g_a (\phi_i^\star T^a \phi) \xrightarrow{U(1)'} d' = \sum_i Q_i |\phi|^2$

- Heavy $Z' \Rightarrow d' \simeq \frac{1}{2} M_{Z'}^2 / Q_S$ diagonal terms can be dominated by the extra D-terms.
- Depending on the sign of $(Q_{q_3} \cdot Q_s)$, $(Q_{T^c} \cdot Q_s)$, $(Q_{B^c} \cdot Q_s)$, stop and sbottom mass can be enhanced or suppressed $\Rightarrow$ gauge invariance: $Q_{H_u} + Q_{q_3} + Q_{T^c} = 0$ dictates $Q_{H_u} \cdot Q_S < 0$ or equiv. $r = Q_{H_u}/Q_S < 0$.
- we consider $Q_{q_3} = Q_{T^c}$: boost $\tilde{t}_L$ and $\tilde{t}_R$ stops by the same amount here.

Stop/Sbottom Sector



(c) $(-0.5, -0.5)$ (d) $(0.2, -0.3)$

Figure : Masses of the 3rd generation $\tilde{t}_1, \tilde{t}_2, \tilde{b}_1$ squarks with respect to the Z' mass for different $U(1)'$ charge assignments $(r = Q_{H_u}/Q_S, Qs)$. $M_{Q_3} = M_{T^c} = 0.7$TeV and stop trilinear coupling $T_t = y_t A_t = 1$TeV, $M_{B^c} = 3$TeV.

➡Boosted lightest 3rd generation squark masses can evade current and future experimental searches ✓

Tree level Higgs mass

How can we get the most out of the tree level Higgs mass?

☞ approximate upper bound on h_1^0 mass in UMSSM is often given:

$$m_{h^0}^2 \lesssim m_z^2 \cos^2(2\beta) + \lambda^2 v^2 \sin^2(2\beta) + v^2(Q_{H_d}\cos^2(\beta) + Q_{H_u}\sin^2(\beta))^2 + \Delta m_{h^0}^2$$

- **second term**: comes from λ-term in W (F-term) also present in NMSSM: vanishes for large $\tan\beta$.

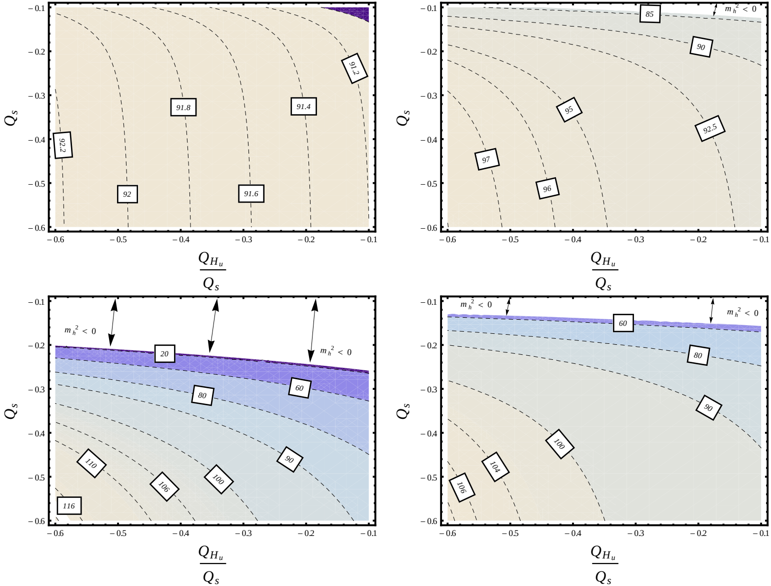
- **third term**: $U(1)'$ D-term contributions present only in UMSSM. For $\tan\beta \gg 1$ this term becomes $\sim Q_{H_u}^2 v^2 \Rightarrow$ boost tree level Higgs by increasing Q_{H_u}

Is this the best we can do? **No**

☞ Numerical analysis shows a strong dependence on the effective Higgsino mass μ_{eff}. Effect not present in MSSM.

☞ Surprisingly Cvetic 1997 $\Rightarrow$ formula which accommodates this effect, seems to have been overlooked.

$$m_{h_1^0}^2 \lesssim M_Z^2 \cos^2(2\beta) + \frac{1}{2}(\lambda v)^2 \sin^2(2\beta) + 4\mu_{eff}^2 \left(\frac{v}{v_S}\right)^2 \left[\left|\frac{Q_{H_u}}{Q_S}\right| - \left(\frac{\mu_{eff}}{M_{Z'}}\right)^2\right]$$



Tree level $m_{h_1^0}$ on (r, Q_s) plane for different values of the effective Higgsino mass μ_{eff}. Top left: $\mu_{eff} = 150$GeV Right: $\mu_{eff} = 350$GeV. BL: $\mu_{eff} = 800$GeV BR: $\mu_{eff} = 800$GeV $v_s = 5.0$TeV. All other $v_s = 3.5$TeV and $\tan\beta = 20$.

Fine Tuning in pUMSSM

Using the tadpole equations $\xRightarrow[\text{write}]{\text{we can}}$ eq. for the stability of EW scale

- for large $\tan\beta$

$$\boxed{\frac{1}{2}M_z^2 \underbrace{\left[1 - 4\frac{\lambda^2}{g_z^2}\left(2\frac{Q_{H_u}}{Q_S} + \frac{\lambda^2}{Q_S^2}\right)\right]}_{=\xi} = -m_{H_u}^2 + m_s^2 \underbrace{\left(\frac{Q_{H_u}}{Q_S} + \frac{\lambda^2}{Q_S^2}\right)}_{=\alpha}}$$

- μ_{eff} does not directly enter the eq. like in MSSM $\Rightarrow$ not constrained from Δ_Z at tree level as in MSSM.

1-loop corrections to the RHS:

$$\delta(-m_{H_u}^2 + \alpha m_s^2) = \frac{1}{16\pi^2}\ln\frac{\Lambda}{\mu_0}\left(-\beta^{(1)}_{m_{H_u}^2} + \alpha\beta^{(1)}_{m_s^2} + m_s^2\beta^{(1)}_{\alpha}\right)$$

we calculate the 1-loop beta functions using SARAH.

- Define FT measure:

$$\Delta_Z = \max_i \frac{|B_i/\xi|}{(M_Z^2/2)}$$

where $B_i = m^2_{H_u},\ \delta m^2_{H_u}, \alpha m_s^2, \delta(\alpha m_s^2)$.

- one loop beta functions:

$$\begin{aligned}\beta^{(1)}_{m^2_{H_u}} &= 6|y_t|^2\left(m^2_{H_u} + m^2_{Q_3} + m^2_{T^c} + |A_t|^2\right) + -\frac{6}{5}g_1^2|M_1|^2 - 6g_2^2|M_2|^2 + \frac{3}{5}g_1^2 S \\ &+ 2|\lambda|^2\left(m^2_{H_u} + m^2_{H_d} + m_s^2 + |A_s|^2\right) + 2Q_{H_u}S_1 - 8Q^2_{H_u}|M_1'|^2\end{aligned}$$

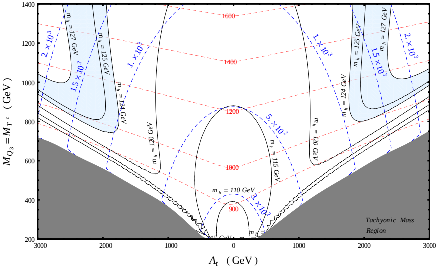
$$\beta^{(1)}_{m_s^2} = 4|\lambda|^2\left(m^2_{H_d} + m^2_{H_u} + m_s^2 + |A_\lambda|^2\right) + 2Q_s S_1 - 8Q_s^2|M_1'|^2$$

- tree level tadpole conditions:

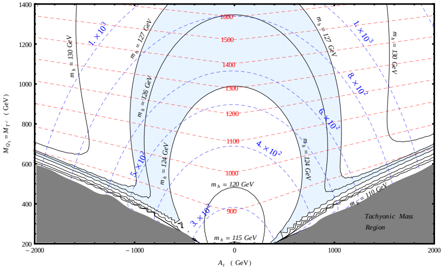
$$\begin{aligned}&m^2_{H_u} - M_z^2/2\cos 2\beta - \frac{\lambda A_\lambda v_s \cot\beta}{\sqrt{2}} + \frac{\lambda^2}{2}(v_s^2 + v^2\cos^2\beta) + Q_{H_u}d' = 0 \\ &m_s^2 - \frac{v^2}{v_s}\frac{\sin\beta\cos\beta}{\sqrt{2}}\lambda A_\lambda + \lambda^2\frac{v^2}{2} + Q_S d' = 0\end{aligned}$$

Heavy Z' with $(r, Q_S) = (-0.6, -0.6)$

(a) $M_{Z'} = 2.1$TeV and $\mu_{eff} = 200$GeV

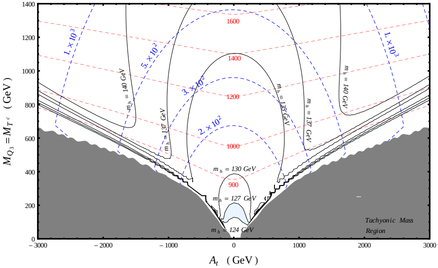


(b) $M_{Z'} = 2.1$TeV and $\mu_{eff} = 505$GeV

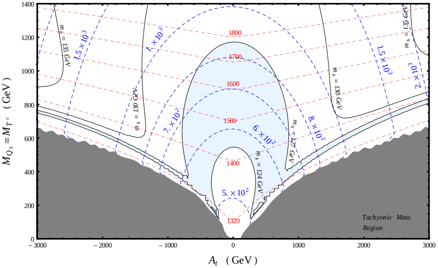


Plot (A_t, M_{Q_3}) for $M_{Z'} = 2.1$TeV and $(r, Q_S) = (-0.6, -0.6)$. All points in both plots pass the constrains from all the experimental searches included in `Fastlim`. **Left Plot:** The Higgs mass is enhanced at tree level $m^T_{h_1^0} = 93.29$GeV and lowest FT within the blue area: $\Delta_z \simeq 985$. **Right Plot:** $m^T_{h_1^0} = 104.62$GeV, lowest fine tuning is around $\Delta_z \sim 300$. $\theta_{ZZ'} = -1.8 \times 10^{-3}$, W mass within 2σ.

(c) $M_{Z'} = 2.1$TeV and $\mu_{eff} = 800$GeV



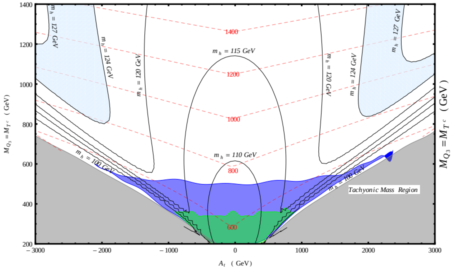
(d) $M_{Z'} = 3.3$TeV and $\mu_{eff} = 800$GeV



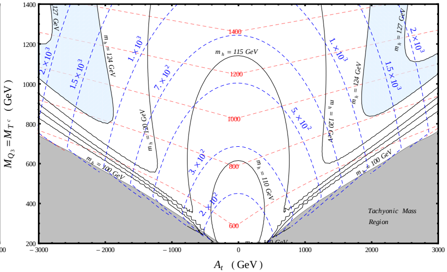
Plot (A_t, M_{Q_3}) for $M_{Z'} = 2.1$TeV, 3.3TeV and $(r, Q_S) = (-0.6, -0.6)$. All points in both plots pass the constrains from all the experimental searches included in `Fastlim`. **Left Plot:** The Higgs mass is enhanced at tree level $m^T_{h^0_1} = 118.27$GeV and lowest FT within the blue area: $\Delta_z \simeq 105$. Note that $\Delta_Z(m_{H_u^2}) \simeq 97.4$, $\theta_{ZZ'} = -1.8 \times 10^{-3}$, W mass within 2σ. **Right Plot:** $m^T_{h^0_1} = 104.96$GeV, lowest fine tuning is around $\Delta_Z \sim 500$. $\theta_{ZZ'} = -1.1 \times 10^{-3}$, W mass within 1σ.

Heavy Z' with $(r, Q_S) = (-0.1, -0.6)$

(e) $M_{Z'} = 3.6$TeV and $\mu_{eff} = 150$GeV

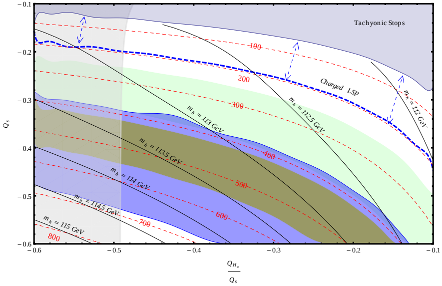


(f) Fine Tuning Contours

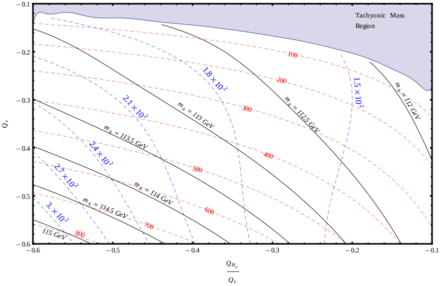


Plot $(, A_t, M_{Q3})$ for $M_{Z'} = 3.6$TeV and $(r, Q_S) = (-0.1, -0.6)$. All points in both plots pass the constrains from all the experimental searches included in `Fastlim`. **Left Plot:** The Higgs mass at tree level $m^T_{h^0_1} = 91.057$GeV and lowest FT within the blue area: $\Delta_z \simeq 10^3$. Note that $\Delta_Z(m_{H_u^2}) \simeq 10^{-3}$. Mixing angle $\theta_{ZZ'} = -1.01 \times 10^{-4}$. W mass within 1σ.

(g) Exclusion Regions



(h) Fine Tuning Contours

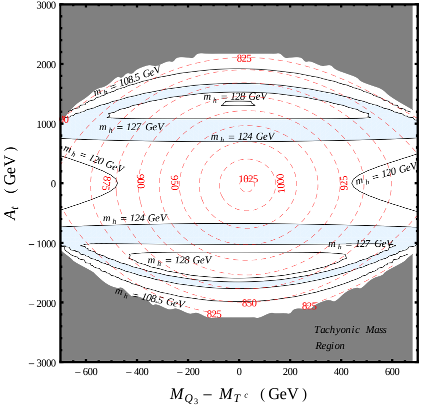


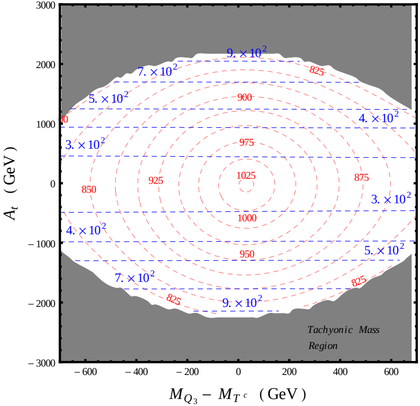
$M_{Q_3} = M_{T^c} = 400$GeV, $T_t = 500$GeV, $\mu_{eff} = 200$GeV. The mass of the Z' is varied with Q_S within the range $350\text{GeV} \leq M_{Z'} \leq 2.1\text{TeV}$. Exclusion regions: 1) AC2013024 (Blue) 2) AC2013037 (Yellow) 3)AC2013053 (light green). light Higgsino mass $\Rightarrow$ hence $m_{h_1^0}^{\max} \sim 115$GeV. Stop masses are excluded up to $m_{\tilde{t}_1} < 700$GeV. **Right**

- Δ_Z is increasing as Z' becomes heavier $|Q_S| \uparrow$ and is reduced as move to the right $|Q_{H_u}/Q_S| \downarrow$.

Moving right: reduces Δ_Z but also suppresses $m_{h_1^0}$. The light gray region on the left shows the W mass constraint within 2σ. Gray area: points within 2σ W mass error.

what about $M_{Q_3} \neq M_{T^c}$





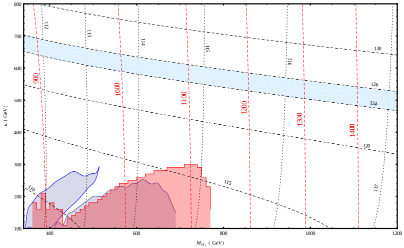
- $(r, Q_S) = (-0.6, -0.6)$, $\mu_{eff} = 500$GeV. Shaded area $124\text{GeV} \leq m_{h_1^0} \leq 127$GeV. Red dashed lines = $m_{\tilde{t}_1}$ contours. Right plot: Blue dashed: Δ_Z lines.
- Fix $M_{Q_3}^2 + M_{T^c}^2 = C^2$ and vary $X = M_{Q_3} - M_{T^c}$, A_t. $M_{Z'} = 2.1$TeV fixed.
- All points pass experimental searches in `Fastlim`
- Achieve $m_{h_1^0} \sim 125$GeV even for large X, lowest $\Delta_Z \sim 350$. $C = 600\sqrt{2}$GeV.

Conclusions

- In the MSSM $\Delta_Z \sim \mathcal{O}(10^3)$ if gaugino masses M_1, M_2 are relatively light and can be reduced to $\Delta_Z \sim \mathcal{O}(10-20)$ for heavy gauginos M_1, M_2
- Experimental searches favour scenarios where $M_{Q_3} > M_{T^c}$.
- For $M_{Q_3} = M_{T^c}$ stops are excluded up to $m_{\tilde{t}_1} < 750$GeV. This limit will be pushed up by future LHC searches.
- Gauge extensions are well motivated theoretically as well as phenomenologically.
- Lightest Higgs exhibits a strong dependence on μ_{eff} which can have a strong effect in reducing the FT.
- Interesting region for $(r, Q_s) = (-0.6, -0.6)$ for which $100 \lesssim \Delta_z \lesssim 500$ and Z' masses $2.1\text{TeV} \lesssim M_{Z'} \lesssim 3.3$TeV and heavy Higgsinos $\mu_{eff} = 800$GeV.

Conclusions

- Lightest squark masses can be $U(1)'$ D-term dominated well above the TeV scale evading currently available experimental searches and possibly future data.
- Bino and Wino in pUMSSM are preferably light in contrast to MSSM.



Plot μ Vs $M_{Q_3} = M_{Tc}$ for MSSM and pUMSSM with $(r, Q_S) = (-0.6, -0.6)$, $M_{Z'} = 2.1$TeV. The exclusion areas apply only to the MSSM. The "vertical" black dotted lines: MSSM Higgs mass, "horizontal" black dashed: $m_{h_1^0}$ in pUMSSM. Red dashed lines depict $m_{\tilde{t}_1}$ in pUMSSM. $A_t = 100$GeV.

Back up Slides/Extra Material

Name	Short description	$E_{\rm CM}$	$\mathcal{L}_{\rm int}$	# SRs
2013_024	0 lepton + (2 b-)jets + MET [Heavy stop]	8	20.5	3
2013_035	3 leptons + MET [EW production]	8	20.7	6
2013_037	1 lepton + 4(1 b-)jets + MET [Medium/heavy stop]	8	20.7	5
2013_047	0 leptons + 2-6 jets + MET [squarks & gluinos]	8	20.3	10
2013_048	2 leptons (+ jets) + MET [Medium stop]	8	20.3	4
2013_049	2 leptons + MET [EW production]	8	20.3	9
2013_053	0 leptons + 2 b-jets + MET [Sbottom/stop]	8	20.1	6
2013_054	0 leptons + $\geq$ 7-10 jets + MET [squarks & gluinos]	8	20.3	19
2013_061	0-1 leptons + $\geq$ 3 b-jets + MET [3rd gen. squarks]	8	20.1	9
2013_062	1-2 leptons + 3-6 jets + MET [squarks & gluinos]	8	20.3	13
2013_093	1 lepton + bb(H) + Etmiss [EW production]	8	20.3	2

Table : The analyses available in `Fastlim` version 1.0 (Papucci 2014). The units for the centre of mass energy, $E_{\rm CM}$, and the integrated luminosity, $\mathcal{L}_{\rm int}$, are TeV and fb^{-1}, respectively. The number of signal regions in each analysis and the references are also shown. For the name we use only the number of each ATLAS conference note.

$A_t = 0$, X (GeV) $=$	-600	-400	-200	0	200	400	600
$m_{\tilde{t}_1}$ (GeV)	845.93	898.38	960.78	1024.20	982.76	923.85	874.37
$m_{\tilde{t}_2}$ (GeV)	1189.14	1151.06	1101.12	1043.86	1084.31	1135.96	1175.21
$m_{\tilde{b}_1}$ (GeV)	835.97	888.98	951.97	1016.23	1076.43	1128.44	1167.94
$\sigma_{\rm tot}$ (fb)	3.95	2.44	1.47	1.02	0.935	1.15	1.59

The masses of $\tilde{t}_1$, $\tilde{b}_1$, $\tilde{t}_2$ and total cross sections at the points $(X, A_t = 0)$ (figure p36). The masses are calculated with `SARAH + SPheno` and the total cross sections with `Fastlim`.