Motivation: Higgs and SUSY

Gauge extensions of MSSM

Chiral Higgses

Very large tan β limit

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A SUSY Higgs with Chiral D-terms

Andrey Katz

work in progress with N. Craig

Harvard University

GGI workshop, Firenze, November 13, 2012

Outline

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SUSY: summary of problems

1. We have no experimental evidence for NP, including superpartners. We already know that there are no gluinos below 1 TeV scale, and there are no squarks below TeV scale (with exceptions of Natural SUSY, RPV and some others)
2. MSSM predicts at the tree level $m_h < m_Z|\cos(2\beta)|$. If we believe that SUSY is a solution for naturalness, radiative corrections cannot be too large. In this sense $m_h \approx 125$ GeV is annoying
3. We do not see evidence for significant deviations from the SM in higgs BRs (at least in very early data). In general SUSY in $\tan\beta \gg 1$ limit (preferred if we would like to saturate the bound on the Higgs mass) is predicted to enhance BR($h \to b\bar{b}$). Some solutions to problem (2) prefer even bigger deviation from the SM.

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Higgs Mass in SUSY - a Problem of Quartic

The SM does not have a priori any prediction about the higgs mass. The quartic in the higgs potential is a free parameter, the mass is given by

$$m^2 \sim \lambda v^2$$

and depending on λ the higgs mass can be almost acquire any value.

MSSM predicts the Higgs quartic $\lambda \sim g^2$, because the only source of the of the quartic interactions are D-terms. Quartic is predicted $\Rightarrow$ mass is predicted. The bound is

$$m_h < m_Z|\cos(2\beta)|$$

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Radiative Corrections to the Higgs Mass

Gauge couplings are the Higgs quartic in exact SUSY. Since SUSY is broken we have radiative corrections to the Higgs quartic, $\propto$ SUSY-breaking:

$$\Delta m_h^2 \sim \frac{y_t^2}{4\pi^2} m_t^2 \ln\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right) + \dots$$

Assume $\tan\beta \gg 1$ (saturate the tree level bound). If we just rely on 1-loop expression, we need $m_{\tilde{t}} \sim 5 \dots 10$ TeV to get $m_h \approx 125$ GeV. Two loops make it even worse. We can get some help from trilinears to reduce the stops scale slightly, but it comes for a price of introducing additional fine-tuning.

Can we call this SUSY Natural? What about stabilization of the EW scale?

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SUSY and Higgs BRs

To saturate the tree level mass limit we need
$\cos 2\beta \to 1 \Rightarrow \tan\beta \to \infty$

Integrating out H_d *Blum & D'Agnolo, 2012*

In this limit we notice that the SM higgs is almost entirely H_u. We can integrate H_d (which is at the zeroth order the heavy higgs) out of the theory, systematically expanding in powers of $1/\tan\beta$

The results at the leading order:

- hVV and $ht\bar{t}$ couplings are unaffected
- $hb\bar{b}$ and $h\tau\tau$ couplings always grow $\Rightarrow h \to VV$ and $h \to \gamma\gamma$ BRs are suppressed.

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Higgs BR (Early) Measurements

- $h \to \gamma\gamma$: the central value is higher than in the SM, the deviation is not statistically significant, but $\mathrm{BR}_{exp} < \mathrm{BR}_{SM}$ is disfavored
- no significant deviations in $h \to VV$, agree pretty well with the SM
- $h \to \tau^+\tau^-$ was fluctuating downward at CMS, enhancement in this channel looks unlikely

Recall: SUSY wants enhanced $h \to \tau^+\tau^-$ and suppressed $h \to VV,\ \gamma\gamma$.

Does this mean that we have early hints that the data does not favor SUSY?

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Direct Searches for Superpartners

Current CMS and ATLAS bounds on SUSY partners are stringent. The generic bound on gluinos is around 1.1 TeV and the generic bound on squarks is 1 TeV. If we put squarks and gluinos on the same scale, we get the bound around 1.5 TeV. If this is the stop scale, SUSY already suffers from some degree of fine tuning. Should we already give up on naturalness?

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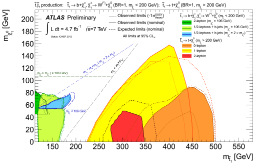
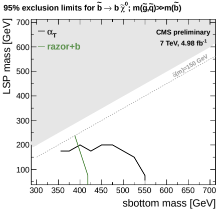
Not all the superpartners are responsible for naturalness, one only need stops, sbottoms and Higgsinos to be $\sim$ 400 GeV, other particles can be at TeV scale or higher.





It is still to early too give up on "natural SUSY", but the bounds become stronger

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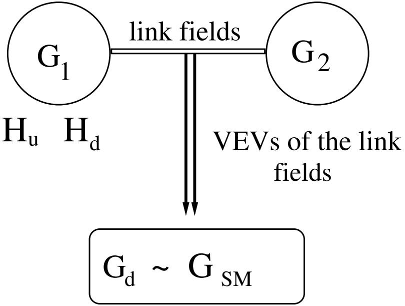
Gauge Extensions and the Higgs Mass

Batra, Delgado, D.E. Kaplan, Tait, '03; Maloney, Pierce, Wacker '04



Scale of the breaking to the diagonal: ~ 10 TeV. If this scale is much higher, the D-terms will decouple. If this scale is closer to TeV, the mixing between Z and Z' is not safe (EWPM). Higgs potential: MSSM D-terms + the D-terms of heavy W', Z'.

We have a new source of quartic $\Rightarrow$ we can get a tree-level enhancement to the higgs mass.

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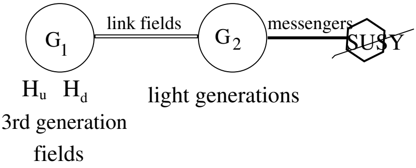
Gauge extensions, natural SUSY and flavor

Craig, Green, AK '11

We did not specify until now what are the charges of matter fields under $G_1 \times G_2$. The most obvious possibility is to charge them all under G_1, but in this case the spectrum will be (mostly) flavor universal and we should push it to the TeV scale.

More interesting possibility: try to explain the **flavor puzzle**



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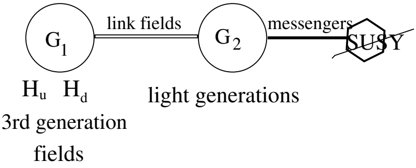

- We naturally explain why $Y_t \gg Y_{c,u}$
- 3rd generation superpartners feel gaugino mediation ⇒ light superpartners. 1st and 2nd generation superpartners feel gauge mediation ⇒ heavy superpartners

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Gauge Extension and Higgs potential

Corrections to the Higgs potential have now a simple form:

$$V = \frac{g^2(1+\Delta) + g'(1+\Delta')}{8}\left(|H_u^0|^2 - |H_d^0|^2\right)^2$$

All the contributions of the new D-terms can be parametrized by two new quantities, $\Delta > 0$ and $\Delta' > 0$. The structure of the quartic is precisely as in the SM.

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- No new contributions to custodial symmetry violation
- The bound on the higgs mass[2] goes up to $m_z^2 + (g^2\Delta + g'^2\Delta')(v^2/2)$

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- No new contributions to custodial symmetry violation
- The bound on the higgs mass^2 goes up to $m_z^2 + (g^2\Delta + g'^2\Delta')(v^2/2)$
- The problem of $h \to b\bar{b}$ is further exacerbated

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What Determines $hb\bar{b}$ Coupling?

SUSY is simply a constrained example of 2HDM.
What are the quartic couplings in 2HDM which govern the deviations of $hb\bar{b}$ from the SM in large $\tan\beta$ limit?

1. $V \sim \lambda_3 |H_u|^2 |H_d|^2$; the rate $\propto -\lambda_3$
2. $V \sim \lambda_7 H_u^3 H_d$; the rate is enhanced as $\lambda_7 \tan\beta$
3. $\mathcal{L} \sim \hat{y}_b H_u^\dagger Q \bar{b}$, the rate is again enhanced as $\hat{y}_b \tan\beta$

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3. $\mathcal{L} \sim \hat{y}_b H_u^\dagger Q \bar{b}$, the rate is again enhanced as $\hat{y}_b \tan\beta$

There are lots of other terms one can write down in a generic 2HDM, but only these term are relevant in large $\tan\beta$ limit. In SUSY model one can calculate all these couplings.

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$h \to b\bar{b}$ in MSSM and its Gauge Extension

- Both tree level MSSM and its gauge extension have no $H_u^\dagger Q\bar{b}$ and $H_u^3 H_d$ couplings. We get these terms at the one-loop level. As long as loop$\times \tan\beta \ll 1$ we can safely neglect them.
- We are left with one term $\lambda_3 |H_u|^2 |H_d|^2$
- MSSM: $\lambda_3 \propto -(g^2 + g'^2) \Rightarrow$ enhances couplings of the higgs to b's and τ's
- Gauge extension: λ_3 has the same sign as in the MSSM and bigger value, the rates $h \to b\bar{b}$ and $h \to \tau^+\tau^-$ are further enhanced and the enhancement is proportional to the higgs mass enhancement!

Short summary of the gauge extension: the improvement in the higgs mass is correlated with the enhancement of couplings to the down type quarks.

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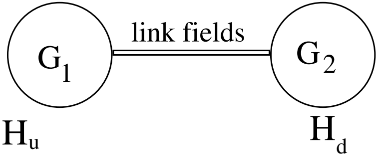
Charges of the Chiral Higgses



Several issues immediately arise with this charge assignment:

- What is a full and anomaly free charge assignment to the matter fields?
- What is the flavor structure?
- The construction does not explicitly preserve the custodial symmetry. Is the ρ-parameter safe?
- Even μ and $B\mu$ terms are not gauge invariant. How do we get them?

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Corrections to the Higgs Potential

It is possible to address all these worries one-by-one. The first question is: what do we gain from this charge assignment.

After we break $G_1 \times G_2$ through the VEVs of the gauge fields to the diagonal, we get a regular MSSM + contributions from the new D-terms:

$$\Delta V \propto \left(\#|H_u|^2 + \#|H_d|^2\right)^2$$

The plus sign is crucial. This is precisely the sign of the contributions to the λ_3, or equivalently to $h \to b\bar{b}$. The contribution to BR($h \to b\bar{b}$) is negative, namely this particular charge assignment undoes the "harm of the MSSM" and brings $h \to b\bar{b}/\tau^+\tau^-$ closer to the SM-predicted values.

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Spectrum of the Higgs Sector

- We have a new source for quartic, which is positive definite, therefore we have a new positive contribution to the Higgs mass
- It turns out that the correction to the higgs mass is not one-to-one correlated with the correction to $h \to b\bar{b}$ rate.
- The correction to $h \to b\bar{b}$ rate can not be arbitrarily big. The non-decoupling D-term is proportional to the soft masses of the link fields. In SUSY regime this correction decouples. Therefore for $\tan\beta \lesssim 50$ the negative contribution to $h \to b\bar{b}$ rate is either smaller or equal to the positive MSSM contribution.
- In MSSM we have $m_{H^+}^2 = m_A^2 + m_W^2$. If the Higgses are chiral we get a negative contribution to the $m_{H^+}^2$, which is of order m_W^2. ρ-parameter should agree better with the SM than MSSM.

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UV Completion - 4 Higgs Model

Now we know that the chiral Higgses can resolve the main problem of the standard gauge extension of the MSSM, we can see what are possible UV completions, full charge assignments and the flavor structure.

Simple possibility: assume a pair of vector-like Higgses charged under each of the quiver gauge groups. We write down all possible couplings for these Higgses:

- 2 μ-terms
- superpotential contact terms between the Higgses on different quiver sites and the link fields $W \sim \chi H_d^{left} H_u^{right}$

If one of the contact term couplings is bigger than μ's, the second contact term, we can integrate out two Higgses and get effectively chiral Higgses + WZ term for anomaly cancellation.

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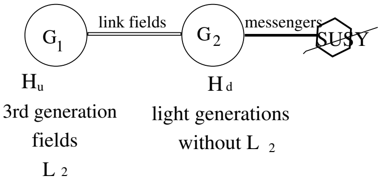
UV Completion with a Broken 5-plet

The basic idea here is that H_d and L have precisely the same quantum numbers in the MSSM. Therefore by moving L from one site to another we can get anomaly free structures. For example:



This charge assignment reproduces the correct flavor puzzle only in the regime $\tan\beta \sim \mathcal{O}(100)$. Because of the combination of gauge and gaugino mediation to different scalars the spectrum is still natural SUSY-like.

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What tan β do we expect?

In the chiral Higgs model we do not have a tree level μ and $B\mu$ terms. We get them from the term in the superpotential which looks like $\lambda\chi H_u H_d$. Since χ is the link field which gets it VEV at the scale of ~ 10 TeV, we should have $\lambda \gtrsim 10^{-2}$. The $B\mu$ term comes from the F-term of the link field. If $F_\chi \sim \langle\chi\rangle$ we get $B\mu \sim \frac{\mu^2}{\lambda} \gg \mu^2$, and we get something very similar to $\mu/B\mu$ problem. Fortunately it is easy to think a UV completion with almost vanishing F_χ. In this case the $B\mu$ term is negligible and we get it only from loop contributions:

$$B\mu \sim \frac{\alpha_2}{4\pi}\mu\tilde{m}_W \ln\left(\frac{\langle\chi\rangle}{\tilde{m}_W}\right) \ll \mu^2,$$

$$B\mu \ll |m_{H_u}^2| \ll |m_{H_d}^2|$$

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Very large tan β

With this hierarchy of scales $\tan\beta \gg 1$ is inevitable. The running for B_μ is very small, and therefore $\tan\beta$ is very sensitive to the wino mass. It can vary from 50 to 5000 depending on the wino mass.

Quark masses, *Dobrescu & Fox; Altmanshofer & Straub*

For $\tan\beta \sim \mathcal{O}(100)$ we do not have sufficient bottom and tau mass from the holomorphic Yukawas and we should rely on $\mathcal{L} \supset \hat{y}_b H_u^\dagger Q b^c$. $\hat{y}_{b/\tau}$ arises from loops in softly broken SUSY. In order to get sufficient mass for b and τ we need tau and bottom yukawas of order 1, numerically larger than top Yukawa

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Higgs BRs in large tan β regime

In our previous calculations we neglected loop-suppressed but tan β enhanced terms $H_u^3 H_d$ and $\hat{y}_b H_u^\dagger Q b^c$. It is now time to put them back because $1/\tan\beta$ is of order one-loop and therefore $\hat{y}\tan\beta \sim \mathcal{O}(1)$, or even slightly bigger. In this regime:

- The contribution from the loop-induced terms easily overweights the tree-level MSSM contribution
- We get $\tan\beta \sim \mathcal{O}(100)$ regime when the soft mass of H_d is very big and the 2HDM is very well in decoupling regime, therefore we know that the corrections to $g_{hb\bar{b}}$ are small, of order several percents
- Unlike in the case of "λ_3", we can make no generic prediction about the sign of the radiatively induced corrections. The sign $\hat{y}$ depends on the interference between three different diagrams, the sign of $H_u^3 H_d$ is sensitive to the relative phase between the A-terms and μ and interference between 2 terms.

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Can we enhance $h \to \gamma\gamma$?

Right now the central value of $h \to \gamma\gamma$ is slightly too high. I will probably go down when more data is collected, probably premature to talk about now NP now. However, we can at least ask if the chiral Higgses model has ingredients to enhance this rate.

Note that the typical spectrum has the entire third generation superpartners light, including $\tilde{\tau}$. The mixing between the $\tilde{\tau}$s is $y_\tau \mu > \mu$, and this mixing is big, much bigger than one would get in a "regular" $\tan\beta$ regime. Therefore it is plausible that the lightest particle is indeed highly mixed $\tilde{\tau}$. In the (unlikely) situation that the enhancement survives it can be a sign that the lightest stau is very light, and in this model we get it naturally. Note also that in this case we should also find a highly mixed, not too heavy sbottom.

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Open questions about viability of very large tan β regime

- To get reasonable down type quark masses we need $y \gtrsim 1$. There is an especial problem with y_τ because of τ-bottleneck - no gluino mediated diagram for the soft mass. We get to the Landau pole in y_τ pretty quickly.
- Improved measurement of $B_s \to \mu^+\mu^-$
- The improved agreement with the SM of $B \to \tau\nu$
- Deviation from the SM of $B \to D\tau\nu$. May be this is the first indication?

Coclusions and Outlook

- Higgs at 125 GeV is a real problem for minimal SUSY, and some resolution for the quartic problem is needed
- Some well-motivated resolutions to the higgs mass problem already have some tension with the measured higgs BRs
- The Chiral Higgs model successfully resolves the Higgs mass problem and predicts the higgs BRs very similar to the SM (for a good reason)
- Maybe the chiral Higgs quiver can even naturally have light $\tilde{\tau}$
- Chiral Higgses motivate us to revisit the $\tan\beta \sim \mathcal{O}(100)$ regime, and to reconsider its viability in light of new LHC and flavor data

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