SUSY, the Third Generation and the LHC

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C. Brust, AK, S. Lawrence, and R. Sundrum; arXiv:1011.6670

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Outline

SUSY from the Weak Scale to the Planck Scale

Motivation:

- Solves the big hierarchy problem
- Suggests gauge coupling unification ($M_U \sim 10^{16}$ GeV)

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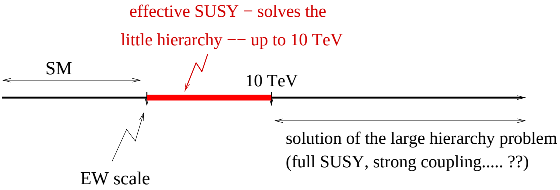
Drawbacks of this approach:

- Generic SUSY $\Rightarrow$ excessive FCNC's, usually resolved by scalar mass degeneracy
- LEP results suggest that MSSM suffers from (mild) fine tuning $\Rightarrow$ should give up on minimality to address the residual fine-tuning

SUSY and the Hierarchy Problem

In this work we take a following approach:



Important: a cutoff of the effective SUSY $\Lambda = 10$ TeV.

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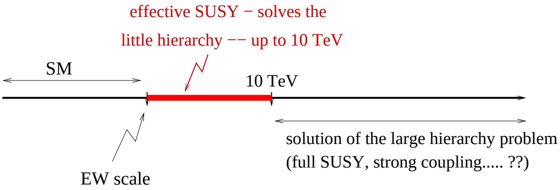

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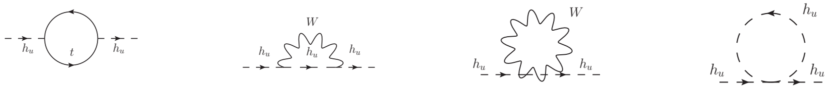
Little hierarchy approach *Dimopoulos, Giudice '95; Cohen, D. B. Kaplan, Nelson '96*

From the little hierarchy point of view most of the SUSY scalars are unimportant and we can get rid of them. Important for the little hierarchy: $\tilde{t}, \tilde{W}, \tilde{H}$...

Higgs naturalness

Should address the following (most important) divergences:

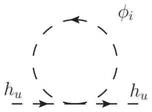


What masses does naturalness ($\Delta m^2 \sim m^2$) demand?

- $m_{\tilde{t}_R, \tilde{Q}_3} \lesssim 400$ GeV – two stops and one sbottom around 400 GeV
- wino, higgsino $\lesssim 1$ TeV
- bino $\lesssim 3$ TeV

$\tilde{b}_R$ and gluinos

After we introduced a new set of scalars, we have one more quadratically divergent diagram. It vanishes if $Tr\ Y = 0$, and to get this we should reintroduce $\tilde{b}_R$. However it is proportional to g'^2 and therefore we expect $m_{\tilde{b}_R} \sim m_{\tilde{B}} \lesssim 3$ TeV



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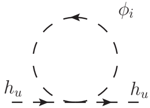
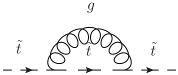
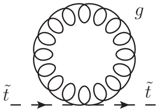


Gluino mass

New light scalars $(\tilde{t}, \tilde{b})$ have there own hierarchy problem:





to cancel these, should introduce gluino, in this mass range: $m_{\tilde{g}} \lesssim 2 m_{\tilde{t}}$

Higgsinos: heavy or light?

Higgsinos are light

Higgsino mass comes from the μ-term: $W \sim \mu H_u H_d$. Avoid unnatural cancellations in the Higgs mass $\Longrightarrow \mu \sim m_h$. We get: neutralino and chargino which are light. RP case – good LSP candidate.

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Observation:

- We can remove h_d and $\tilde{b}_R$ simultaneously. Tr $Y = 0$, no new div.
- Bottom quarks and leptons get non-SUSY masses from $\mathcal{L} \sim Y_d h_u^* Q \bar{d}$ – no threat for naturalness if $Y_d \ll 1$.

Higgsino gets its mass from a soft SUSY-breaking term $\mathcal{L} \sim m_{\tilde{h}} \tilde{H}_u \tilde{H}_d$

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Effective SUSY does not require two Higgses, small Yukawa couplings can be hard SUSY-breaking terms. Effective SUSY requires two Higgsinos though.

The Higgs mass and MSSM residual hierarchy problem

So far we completely disregarded MSSM constraints on the higgs mass. At the tree level MSSM predicts

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

Why?

$$V \sim -m^2|h|^2 + \lambda|h|^4$$

Effectively MSSM predicts the value of $\lambda \Rightarrow$ function of gauge couplings g, g'. Radiative corrections can raise the mass above the tree level bound, but $\Delta m_h^2 \propto \ln(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2})$. For $m_h \sim 115$ GeV we need almost TeV scale stops. This is the MSSM residual hierarchy problem.

Hard SUSY breaking

To allow for low mass stops and sbottoms we need interactions beyond the MSSM in the Higgs sector. In low energy effective theory:

$$V \supset \frac{g^2 + g'^2 + \delta\lambda}{8} \left(|H_u|^2 - |H_d|^2\right)$$

$\delta\lambda$ is a hard SUSY breaking, it will reintroduce the hierarchy problem unless the new divergences are cut at the scale $\sim 2 - 3$ TeV (for $m_{\tilde{t}_1,\tilde{t}_2} \sim 300$ GeV). There are lots of physical scenarios which can yield such hard SUSY-breaking term at the low scale without reintroducing the hierarchy problem (e.g. a singlet which couples to the Higgses but does not get a VEV).

Flavor of effective SUSY – the logic

Even if the effective IR theory safe, one should worry about the operators at 10 TeV, e.g. $\mathcal{L} \sim \frac{\bar{s}d\bar{s}d}{10\ TeV}$ are still deadly. Such UV completions exist (*e.g. Sundrum '09; Craig, Green, AK '11, Jeong, Kim, Seo '11*), can have very different logic, but almost identical IR spectrum.

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Flavor structure in the IR theory

The choice is not unique, but it cannot be completely anarchical. Assume that the mixings (both in LH and RH sectors) are the same as in Wolfenstein's parametrization, namely w/ $\epsilon \approx 0.22$:

- mixing with the first-generation $\sim \epsilon^3$
- mixing with the second generation $\sim \epsilon^2$

Flavor/CPV constraints

Constraints - box diagrams, contributing to

- $B_s - \bar{B}_s\ \mathcal{O}(\epsilon^4)$
- $B_d - \bar{B}_d\ \mathcal{O}(\epsilon^4)$
- $K - \bar{K}\ \mathcal{O}(\epsilon^{10})$

The strongest constraint – $K - \bar{K}$, $\mathcal{L} = \kappa\ \bar{s}_L d_R \bar{s}_R d_L$,

$$\mathrm{Im}(\kappa) < \left(\frac{1}{3\times 10^5\ \mathrm{TeV}}\right)^2$$

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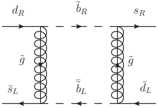
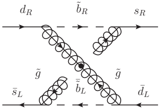
$K - \bar{K}$ - two insertions diagrams





All couplings and phases $= 1 \Longrightarrow m_{\tilde{b}_R} \gtrsim 17$ TeV. Reduce all the couplings by $1/2 \Longrightarrow m_{\tilde{b}_R} \gtrsim 3$ TeV

New fields at 1 TeV scale

What fields do we expect to detect?

- $\tilde{t}_L$, $\tilde{t}_R$, $\tilde{b}_L$ with masses 400 GeV or less
- $\tilde{g}$ with masses 800 GeV or less – is it allowed by current constraints?
- wino, bino higgsino - maybe , maybe not
- $\tilde{b}_R$ – maybe (in some sense, it's a bino-like particle)
- Heavy SUSY Higgses – possible, not necessary

Can we get rid of gluinos?

If gauginos are Majorana, we do not have too much room to play, but gluinos can be Dirac.

Dirac gauginos *Fox, Nelson, Weiner, 2002*

In minimal supersymmetric models gauginos get Majorana masses $m_\lambda \lambda^a \lambda^a$. However in non-minimal SUSY, one can introduce chiral fields in adjoint representation of the SM. Then gauginos can be paired with the fermions from these fields $m_D \lambda^a \psi^a$.

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Interesting properties of Dirac gauginos:

- Do not violate R-symmetry. If A-terms and SUSY μ-term vanish, the structure is fully R-symmetric
- Changes the radiative corrections to the scalars

Dirac vs Majorana

Majorana gluinos

$$\Delta m_{\tilde{t}}^2 = \frac{2g_s}{3\pi^2} m_{\tilde{g}}^2 \ln \frac{\Lambda}{m_{\tilde{g}}}$$

the correction is divergent, the log is of order ln 100.

expect $m_{\tilde{g}} \lesssim 2m_{\tilde{t}}$

Dirac gluinos

$$\Delta m_{\tilde{t}}^2 = \frac{2g_s}{3\pi^2} m_{\tilde{g}}^2 \ln \frac{\delta}{m_{\tilde{g}}}$$

this correction is finite, δ – SUSY breaking mass of the scalar partner in adjoint chiral s-field. The log can easily be e.g. ln 5, and $m_{\tilde{g}} \lesssim 4m_{\tilde{t}}$.

It can be just a difference of factor of 2 or even less in masses, but this difference might be crucial for $\sqrt{s} = 7$ TeV LHC.

CPV constraints (without FCNC)

Most severe constraints on SUSY come from CPV which has nothing to do with FCNCs – neutron EDM. The MSSM with all the "nice" assumptions has 2 irreducible phases:

$$\mathrm{Arg}(A^* m_{\tilde{g}}), \quad \mathrm{Arg}(B\mu^* \mu m_{\tilde{g}}) \ .$$

New phases from scalar mixing

We assumed that the "third generation" scalars have a small admixture of first and second generation squarks. These new admixtures come with phases (maps onto Weinberg operator $\mathcal{O} = f_{abc} G^a_{\mu\rho} G^{b\rho}_{\nu} G^c_{\sigma\lambda} \epsilon^{\mu\nu\sigma\lambda}$). New contributions are suppressed by powers of ϵ, the phases can be $\lesssim 1/3$ without any cancellation.

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One more interesting observation: in absence of μ-term and A-terms the R-symmetry is exact, and all the "regular phases" can be rotated out, leaving us only with scalar-mixing phases.

Very safe scenario compared to the MSSM

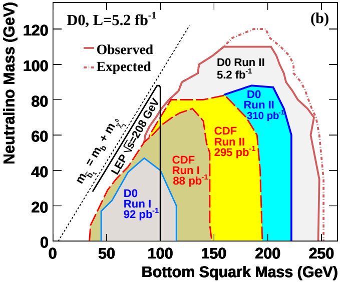
The most minimal natural model below 1 TeV

- includes $\tilde{t}_L$, $\tilde{t}_R$, $\tilde{b}_L$, all at masses 400 GeV or lower
- assume R-parity for simplicity (not as motivated as in a “regular” SUSY, but still a viable possibility)
- if $\tilde{t}$ or $\tilde{b}$ is the LSP (or more precisely long-living NLSP) – excluded by CMS search for R-hadrons (roughly up to masses 600 GeV)
- there should be a neutralino with the mass below the squarks mass (with or without chargino)

What are the constraints on this very minimal scenario? Is it excluded or not?

Tevatron searches

- D0 has a dedicated search for $\tilde{b}$ decaying $\tilde{b} \to b\tilde{\chi}^0$, which is just $jets + \not{E}_T$ with b-tag. The most updated bound on the sbottom mass - 245 GeV if the neutralino is massless

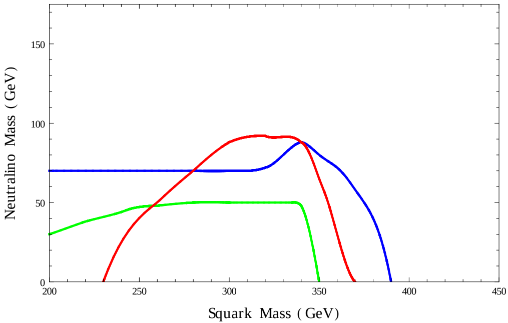


- CDF search for $t\bar{t} + \not{E}_T$ (both in monoleptonic and hadronic channels), do not put interesting bounds on a single stop.

Relevant SUSY searches and "accidental" bounds

- jets + $\not{E}_T \Rightarrow$ find bounds from α_T, simple $\not{H}_T$ search
- $l^+l^- + jets + \not{E}_T$ no bound
- $l + jets + \not{E}_T$ no bound
- $jets + b - tag + \not{E}_T$ no bound (the cuts on H_T, $\not{H}_T$ are too strong, very bad acceptance)
- $b - tag + l + jets + \not{E}_T$ – was designed to catch $\tilde{g} \to \tilde{t} \to \chi$, no bound
- $t\bar{t} + \not{E}_T$ (monoleptonic) – almost no bound on a single top, constrains our model with two tops
- Very recent – dedicated search for $\tilde{b}$ by Atlas

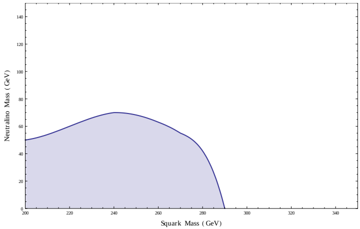
Relevant bounds



green line - α_T exclusion
red line - monoleptonic $t\bar{t} + \not{E}_T$ exclusion
blue line - simple $\not{H}_T$ search exclusion

$\tilde{b}$ vs $\tilde{t}$

Where do these bounds come from?



Mostly it is direct $\tilde{b}$ production. Even if we integrate out both $\tilde{t}$, we find a bound on a single $\tilde{b}$. On the other hand there is no analogous bound on $\tilde{t}$.

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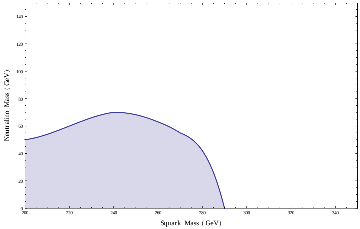

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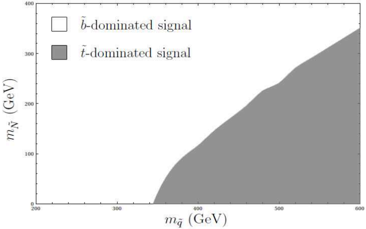
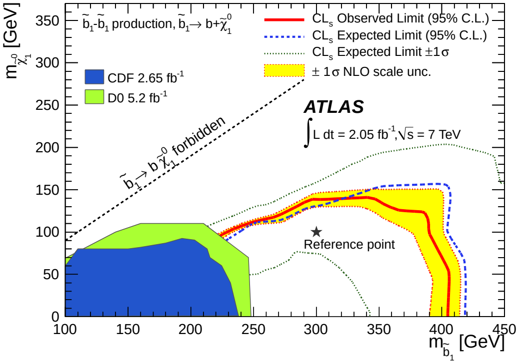
Where will two stops contribute more than one sbottom?



Atlas search for $\tilde{b}$

Very recently Atlas performed a dedicated search for a single sbottom. This search uses a variable of contransverse mass. The bound has been significantly improved:



Note that in the region $m_{\tilde{\chi}} > 100$ GeV the reach is still poor.

Why RPV is relevant

Motivations for R-parity:

- proton stability
- DM

Proton stability

Not easy to address in a model with 10 TeV cutoff (with R-parity only). The RP conserving operators

$$W \sim \frac{QQQL}{10\ \ TeV}, \quad W \sim \frac{u^c u^c d^c e^c}{10\ \ TeV}$$

cause very rapid proton decay.

Dark Matter

Can have a completely non-SUSY origin. Even in SUSY w/ RP need fine-tuning to get correct relic abundance.

In the SM model, there is no proton decay due to accidental symmetries (B and L). It is plausible that one of these symmetries survives also in the effective theory below 10 TeV.

Baryon number violation

$$W \sim u^c d^c d^c \Longrightarrow \mathcal{L} \sim \tilde{t}_R^c d_i^c d_j^c .$$

Constraints:

- $K - \bar{K}$ oscillations, constrain the couplings $\mathcal{O}(Y_B)$ (or bigger)
- $n - \bar{n}$ – mild

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- $n - \bar{n}$ – mild

Constraints on $n - \bar{n}$ completely disappear in the case Dirac gauginos. The baryon symmetry is restored and realized as an R-symmetry. Remove H_d and $\tilde{b}_R$ from the spectrum, form bottom-Yukawa from non-holomorphic couplings. Then the baryon number charges are :

- Q(quarks) $= 1/3$, $Q(\tilde{t}_L, \tilde{b}_L) = 4/3$
- $Q(\lambda) = 1, \quad Q(\psi) = -1$
- $Q(\tilde{h}_u) = -1, \quad Q(\tilde{h}_d) = +1$

Experimental signals

- $\tilde{t}$ just decays to 2 jets (maybe one of them is b-jet) – very challenging signature
- $\tilde{b}$ decays either to 2 jets or top and jet – also interesting and challenging channels
- even more interesting if the model is R(B)-symmetric. The LH particles do not mix and decay through gluinos off-shell ($\tilde{t}_L \to tjj$)

These signatures are very interesting, but probably also extremely challenging, will be very hard to distinguish them from $t\bar{t}$ and single top backgrounds. More promising avenue – gluino production, maybe at $\sqrt{s} = 14$ TeV.

BNV with gluinos

Signatures we can consider:

- $t\bar{t}$ + jets probably detectable in cut-and-count measurement of $\sigma(t\bar{t})$. Would be interesting to know what is the bound
- $t\bar{b} + jets$ (if one of the gluinos decays into through $\tilde{t}$, while the second through $\tilde{b}$)
- 6 jets from 2 different resonances, 2 of them b-tagged. This search (w/o b-tag) exists at CMS, was updated only at 35/pb and excludes gluions up to 280 GeV.

LFV and searches for leptoquarks

The usual MSSM has three LFV operators:

$$W \sim LQd^c, \quad LLe^c, \quad LH_u$$

In the context of effective SUSY only the first one is meaningful:

$$\mathcal{L} \propto \tilde{Q}_3 L_i d_j^c$$

A priori we do not what is the flavor structure of this operator, but we can assume that it is analogous to the SM. In this case dominant decay modes of the squarks are

- $\tilde{b} \to b\nu$, very similar to the RP case, jets (with b-tag) + $\not{E}_T$ should be sensitive to this mode
- $\tilde{t} \to b\tau$ – third generation leptoquark

Conclusions and Outlook

- analyzed effective SUSY bottom-up, this analysis favors very minimal particle content below 1 TeV scale
- the most interesting bounds one can put on these models come from jets plus $\not{E}_T$ searches, the possibility is far from being excluded
- RPV is extremely motivated, very few searches in this direction have been performed till now, lots of room for new ideas here...