Two Approaches to the SUSY Little Hierarchy Problem

LHC phenomenology of motivated scenarios

James Younkin
Advisor: Dr. Stephen P. Martin

Northern Illinois University

2010 LHC-TI Fellows Meeting
Brookhaven National Laboratory
October 8, 2010

The SUSY Little Hierarchy Problem

- At the minimum of the MSSM scalar potential that breaks Electroweak symmetry, a typically large cancellation occurs between the supersymmetry-breaking Higgs mass terms H_u,H_d and the supersymmetry-respecting Higgs mass term μ

$$m_Z^2 = 2(-m_{H_u}^2 - |\mu|^2) + \mathcal{O}\left(\frac{1}{\tan^2\beta}\right) + \text{loop corrections}$$

- Since $|\mu|$ can easily reach 1 TeV, it seems unnatural for the supersymmetry-breaking sector to be finely tuned to one part in 100
- We may take this unnaturalness in the MSSM as a motivation for exploring models that require less cancellation in the electroweak sector

Two Paths to More Natural Models

In light of the fine-tuning in the MSSM, I will take two approaches to finding more natural models

- Abandon universality condition, vary input-scale gaugino masses by mixing GUT representations (Non-universal gaugino mass models)
- Add additional supermultiplets within current experiemental constraints that can reduce fine-tuning (Models with additional vectorlike matter)

In the rest of this talk, I will give a brief summary of these scenarios and some interesting aspects of their phenomenology

Non-universal gaugino masses

- Renormalization group running up to input scale shows that μ as a function of the input scale parameters takes the approximate form

$$|\mu|^2 = C_1\hat{M}_3^2 - C_2\hat{M}_2^2 + C_3\hat{M}_2\hat{M}_3 - C_4\hat{M}_3\hat{A}_t$$
$$-C_5\hat{m}_0 + \text{terms with small coefficients}$$

  where the hats indicate an input scale value and the coefficients $C_i > 0$ will depend on $\tan\beta$.
- Important features:
  - Decreasing M_3 will lower μ: C_1 tends to be very large and C_3 is usually small
  - Increasing M_2 will lower μ
  - M_1 has a minimal influence on mu
  - Increasing the scalar mass parameter decreases mu

Non-universal gaugino masses

- Motivated by SU(5) and SO(10) gauge unification, I will consider mSUGRA models in which the F-term that breaks supersymmetry can transform as anything in the symmetric product of the adjoint representation of SU(5) with itself:

$$(\mathbf{24} \times \mathbf{24})_S = \mathbf{1} + \mathbf{24} + \mathbf{75} + \mathbf{200}$$

- It has been shown that the ratio of the gaugino mass parameters $M_1 : M_2 : M_3$ in these representations are

1	$1:1:1$	**75**	$5:-3:-1$
24	$1:3:-2$	**200**	$10:2:1$

- The **24** representation is well-suited to alleviate the mu problem, since increasing the contribution from this representation lowers the gaugino mass parameter and increases the wino mass parameter, thereby lowering $|\mu|$.

Non-universal gaugino masses

- In my parametrization, the relative contribution of the singlet and **24** representation to the gaugino masses is given by θ_{24}, where $\sin\theta_{24} = 0$ is mSUGRA and $\sin\theta_{24} = 1$ has a pure **24** F-term. Then M_1 and θ_{24} determine M_2 and M_3:

$\sin\theta_{24}$ parametrization, fixed M_1

$$
\begin{aligned}
M_2 &= M_1 \left(\frac{1 + 3\tan\theta_{24}}{1 + \tan\theta_{24}}\right) \\
M_3 &= M_1 \left(\frac{1 - 2\tan\theta_{24}}{1 + \tan\theta_{24}}\right)
\end{aligned}
$$

- Covers entire space for given M_1; $-\pi/4 < \theta_{24} < 3\pi/4$ for $\mu > 0$ solutions, with the rest of the domain covering negative μ solutions.

Non-universal gaugino masses

- Using micromegas and softsusy, the m_0 v. θ_{24} parameter space can be mapped to find low-μ regions where relic density of thermal dark matter within observed limit $0.09 < \Omega h^2 < 0.13$
- Assuming minimal flavor violation, the important flavor constraints are $b \to s\gamma$, $B_S \to \mu^+\mu^-$, and $B \to \tau\nu$ through contributions from decays through the charged Higgs boson.

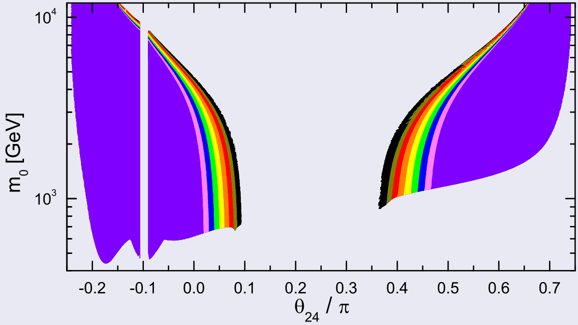
$$
\begin{aligned}
B_S \to \mu^+\mu^- &< 4.3 \times 10^{-8} \quad \text{[CDF note 9892]} \\
b \to s\gamma &> 2 \times 10^{-4} \\
\tan\beta &< 7.4 \frac{m_{H^+}}{100\ \text{GeV}} \quad \text{[UTfit, 2009]}
\end{aligned}
$$

- We also require $m_{h^0} > 113$ GeV and exclude all model points where charged particles are the LSP or violate the approximately 100 GeV LEP bound.

Non-universal gaugino masses

Map of mu parameter

$M_1 = -A_0 = 900$ GeV, $\tan\beta = 45$, $\mu > 0$



Legend

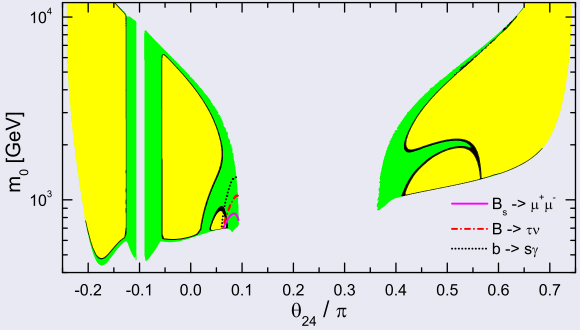
- $\mu < 300$ GeV
- $300 < \mu < 400$
- $400 < \mu < 500$
- $500 < \mu < 600$
- $600 < \mu < 700$
- $700 < \mu < 800$
- $800 < \mu < 900$
- $900 < \mu < 1000$
- $\mu > 1000$ GeV

- Value of mu decreases near $M_3 = 0$ line at $\theta_{24}/\pi = 1/\pi\ \tan^{-1}(1/2) \approx 0.15$ and with increasing scalar mass

Non-universal gaugino masses

Relic density map

$M_1 = -A_0 = 900$ GeV, $\tan\beta = 45$, $\mu > 0$



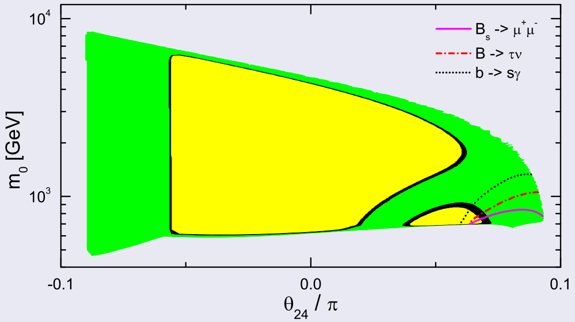
Relic Density

- $\Omega h^2 < 0.09$
- $0.09 < \Omega h^2 < 0.13$
- $\Omega h^2 > 0.13$

- Higher $\tan\beta$ and M_1 regions have much less problematic flavor constraints
- A_0 funnel contains several interesting regions, including "confluence islands", which contain a mixture of several annihilation mechanisms

Non-universal gaugino masses

Relic density map, zoomed
$M_1 = -A_0 = 900$ GeV, $\tan\beta = 45$, $\mu > 0$



Relic Density

- $\Omega h^2 < 0.09$
- $0.09 < \Omega h^2 < 0.13$
- $\Omega h^2 > 0.13$

- Much of the confluence island lies outside flavor constraints, and has the thickest region in agreement with observed dark matter density.
- The part of the $\Omega h^2 < 0.09$ region in the A^0 funnel outside constraints is large and has a relatively small μ and $\tan\beta$ compared to typical mSUGRA A^0 funnel points.

Additional Vectorlike Supermultiplets

- If we can construct a radiative method for increasing the Higgs mass, we can decrease the size of the μ and H_u without running into LEP II constraint $m_{h^0} > 114$ GeV
- In the MSSM, loop corrections ΔV to the Higgs scalar potential effectively increases H_U^2 and H_D^2 at the minimum of the scalar potential:

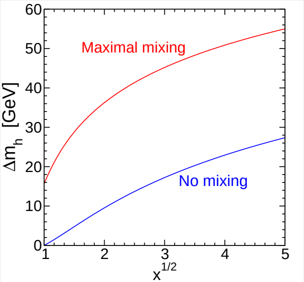
$$
\begin{aligned}
m_{H_u}^2 &\rightarrow m_{H_u}^2 + \frac{1}{2v_u}\frac{\partial(\Delta V)}{\partial v_u} \\
m_{H_d}^2 &\rightarrow m_{H_d}^2 + \frac{1}{2v_d}\frac{\partial(\Delta V)}{\partial v_d}
\end{aligned}
$$

- Primary source of MSSM loop corrections are top quark and stop squark loops

Additional Vectorlike Supermultiplets

- Chiral fourth generation needs large Yukawa couplings that would break perturbativity above electroweak scale, and fine tuning is required to evade precision electroweak observations
- A vectorlike fourth generation evades these problems, increases Higgs mass for $m_s > m_f$

Vectorlike corrections to m_{h^0}



arXiv:0910.2732 [hep-ph]

- Increase in Higgs mass depends on ratio x between scalar and fermion masses in vectorlike supermultiplet and the mixing between vectorlike SU(2) singlets and doublets

Additional Vectorlike Supermultiplets

- "Vectorlike" supermultiplets have the property that the left handed field and right handed field belong to the same gauge representation
- Gauge singlet mass terms for vectorlike fields can be written down independently of coupling to Higgs

Superpotential terms from vectorlike fields
SU(2) doublet Φ, SU(2) singlet ϕ

$$W = M_\Phi \Phi \bar{\Phi} + M_\phi \phi \bar{\phi} + k H_u \Phi \bar{\phi} - h H_d \bar{\Phi} \phi$$

- Yukawa terms can also be written for the mixings with MSSM fields

Additional Vectorlike Supermultiplets

- Possibilities for new supermultiplets restricted by requirement that they be able to mix with MSSM fields, preventing additional stable non-MSSM particles
- Some possible fields live in the representations of $SU(3)_C \times SU(2)_L \times U(1)_Y$ listed below

Vectorlike fields

$$Q = (\mathbf{3}, \mathbf{2}, 1/6) \quad \bar{Q} = (\bar{\mathbf{3}}, \mathbf{2}, -1/6) \quad U = (\mathbf{3}, \mathbf{1}, 2/3) \quad \bar{U} = (\bar{\mathbf{3}}, \mathbf{1}, -2/3)$$

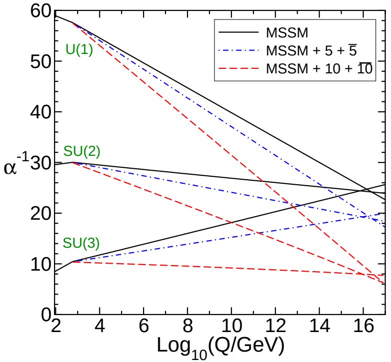
$$D = (\mathbf{3}, \mathbf{1}, -1/3) \quad \bar{D} = (\bar{\mathbf{3}}, \mathbf{1}, 1/3) \quad L = (\mathbf{1}, \mathbf{2}, -1/2) \quad \bar{L} = (\mathbf{1}, \mathbf{2}, 1/2)$$

$$E = (\mathbf{1}, \mathbf{1}, -1) \quad \bar{E} = (\mathbf{1}, \mathbf{1}, 1) \quad N = (\mathbf{1}, \mathbf{1}, 0) \quad \bar{N} = (\mathbf{1}, \mathbf{1}, 0)$$

- More exotic possibilites, such as a SU(2) triplet or a SU(3) octet, are also possible

Additional Vectorlike Supermultiplets

Gauge coupling unification



arXiv:0910.2732 [hep-ph]

- Only specific choices of new fields will maintain gauge coupling unification
- LND: Contains $L, \bar{L}, N, \bar{N}, D, \bar{D}$; a $\mathbf{5} + \bar{\mathbf{5}}$ of SU(5) plus two singlets
- QUE: Contains $Q, \bar{Q}, U, \bar{U}, E, \bar{E}$; a $\mathbf{10} + \overline{\mathbf{10}}$ of SU(5)
- QDEE: Contains $Q, \bar{Q}, D, \bar{D}, E_1, \bar{E}_1, E_2, \bar{E}_2$

Additional Vectorlike Supermultiplets

- Fourth families have not been ruled out by collider experiments; some chiral fourth family scenarios remain viable and constraints on vectorlike models typically much weaker
- Tevatron limits on masses of fourth family particles assume certain scenarios not necessarily true in all vectorlike scenarios

Limits on fourth family masses from CDF

$m_{t'} > 335$ GeV for $BR(t' \to Wq) = 1$, based on 4.65fb^{-1}

$m_{b'} > 385$ GeV for $BR(b' \to Wt) = 1$, based on 4.85fb^{-1}

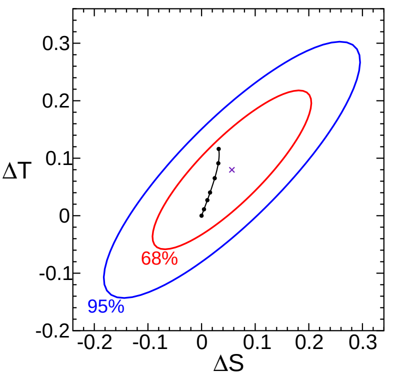
$m_{t'} > 268$ GeV for $BR(b' \to Zb) = 1$, based on 1.06fb^{-1}

$m_{t'} > 295$ GeV for $BR(t' \to Wq, Zb, h^0 b) = (0.5, 0.25, 0.25)$, based on 1.2fb^{-1}

- Additional, though less strict, limits exist on quasi-stable quarks

Additional Vectorlike Supermultiplets

Oblique electroweak parameters in an LND model



arXiv:0910.2732 [hep-ph]

- Vectorlike fourth family has fewer effects on precision electroweak measurements than chiral because it can be decoupled from the electroweak sector
- Corrections to oblique electroweak parameters decouple with larger vectorlike masses: ΔS and ΔT are proportional to M_F^{-2}
- On the left are LND corrections for fixed-point Yukawa coupling and $m_{\tau'} = \{100, 120, 150, 200, 250, 400, \infty\}$ from top to bottom

Promising Signals in Basic Models

- There are many interesting signatures for study, most of which have not been considered for chiral fourth family
- LND model:

$$
\begin{aligned}
b_1'\bar{b}_1' &\rightarrow bZ + X \rightarrow b(e^+e^-/\mu^+\mu^-) + X \\
b_1'\bar{b}_1' &\rightarrow W^+W^-t\bar{t} \rightarrow W^+W^+W^-W^-b\bar{b} \text{ (like sign dilepton)} \\
\nu_1'\bar{\nu}_1' &\rightarrow W^+W^-\tau^+\tau^- \\
\nu_1'\bar{\nu}_1' &\rightarrow h^0h^0 + E_T^{\text{miss}} \\
\nu_1'\bar{\nu}_1' &\rightarrow ZZ + E_T^{\text{miss}} \\
\nu_1'\bar{\nu}_1' &\rightarrow Wh^0 + E_T^{\text{miss}}
\end{aligned}
$$

- QUE model

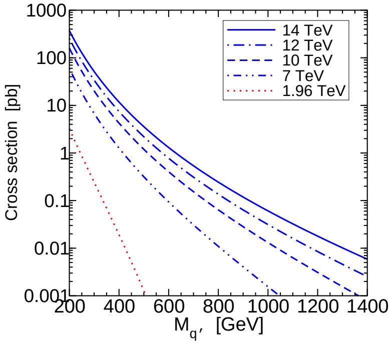
$$
t_1'\bar{t}_1' \rightarrow W^+W^-b\bar{b} \text{ (same as t, with higher invariant mass)}
$$

- QDEE model

$$
\begin{aligned}
b_1'\bar{b}_1' &\rightarrow W^+W^-t\bar{t} \rightarrow W^+W^+W^-W^-b\bar{b}\text{(like sign dilepton)} \\
b_1'\bar{b}_1' &\rightarrow h^0h^0b\bar{b} \rightarrow bbb\bar{b}\bar{b}\bar{b}\text{(6 b-jet events)}
\end{aligned}
$$

Vectorlike b' in an LND Scenario

Pair prodution for new quarks assuming $K = 1.5$

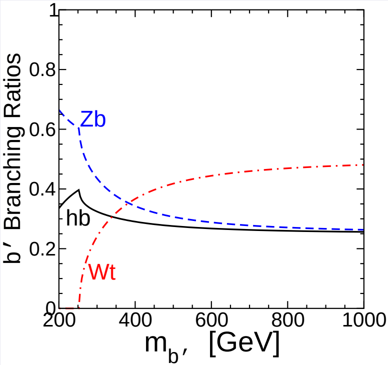


arXiv:0910.2732 [hep-ph]

- LHC cross sections are several orders of magnitude better than Tevatron; if new vectorlike matter exists, we should be able to see its collider signatures
- I will consider a signature arising from pair production of b' in the LND scenario, for which the LO cross section is approximately 8 pb

Vectorlike b' in an LND Scenario

Branching ratios for b' in LND model



arXiv:0910.2732 [hep-ph]

- Leading order branching ratios of b' in the LND model depend only on the b' mass
- Kinematic suppression of tW makes Zb and hb branching ratios relatively large at low b' mass

Reconstruction of b' from simulated collider data

- As an example of an interesting signal arising from these models, consider an LND model with the lightest new fermion, the b', having a mass of $400 GeV$

Scenario parameters

$m_{b'} = 400$ GeV

$BR(b' \to tW) = 0.35$

$BR(b' \to bZ) = 0.35$

$BR(b' \to bh) = 0.3$

Tree-level cross section: 8pb

- The $b' \to bZ$ process can result in a pair of same flavor, opposite sign light leptons that reconstruct a mass larger than the Standard Model backgrounds

Reconstruction of b' from simulated collider data

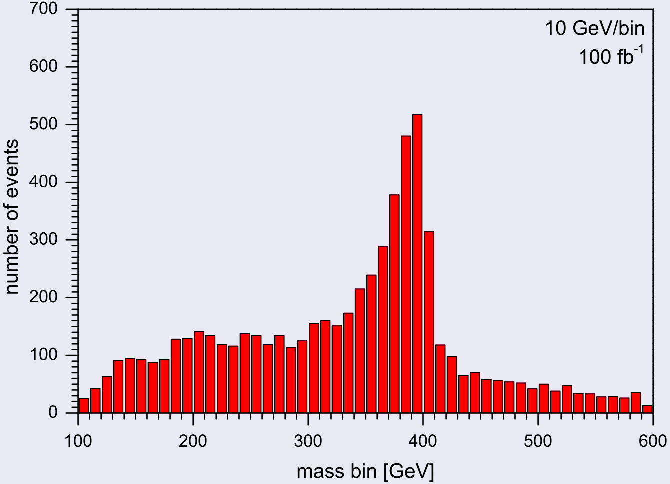
- Using Madgraph/Madevent, Pythia, and PGS, simulate 100 fb^{-1} of data at $\sqrt{s} = 14$ TeV from an "LHC" detector.
- Size of b' mass allows very strong p_T cuts

Cuts on data

- Events contain exactly one pair of oppositely charged, same flavor light leptons
- At least one of the leptons has $p_T > 50$ GeV
- Events contain at least one b-tagged jet with $p_T > 120$ GeV
- $\Delta R > 0.4$ between any lepton and any b-jet
- Reconstructed mass of light lepton pair is within 5 GeV of M_Z
- At least one occurance of $|M(\text{bjet,leptons}) - M(\text{3jet})| < 50$ GeV

Reconstruction of b' from simulated collider data

Reconstructed mass from b' pair production



Important backgrounds

Important background processes, $\sqrt{s} = 14\,TeV$

Process	Cross section
$pp \to bbZ$	873.8 pb
$pp \to bbZZ$	223.6 fb
$pp \to ttZ$	658.7 fb
$pp \to tbZ$	10.5 fb

- Use bbZ background to get an initial estimate of collider backgrounds

Important backgrounds

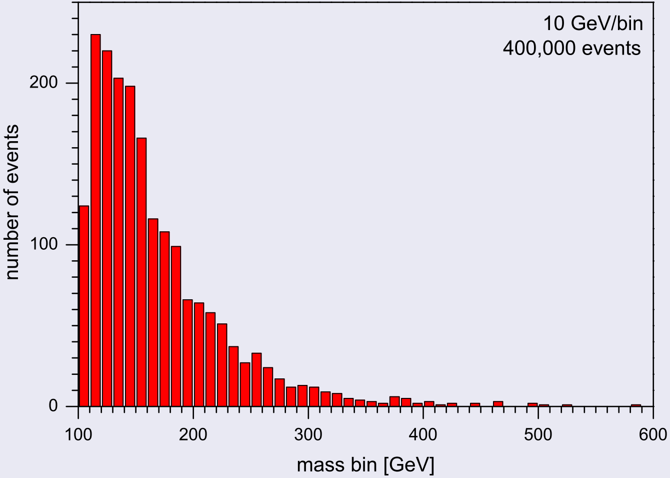
- To get a better understanding of standard model background, apply all cuts except for cuts on lepton and bjet p_T

Initial cuts on background

- Events contain exactly one pair of oppositely charged, same flavor light leptons
- Events contain at least one b-tagged jet
- $\Delta R > 0.4$ between any lepton and any b-jet
- Reconstructed mass of light lepton pair is within 5 GeV of M_Z

Important backgrounds

Reconstructed mass from bbZ background



Important backgrounds

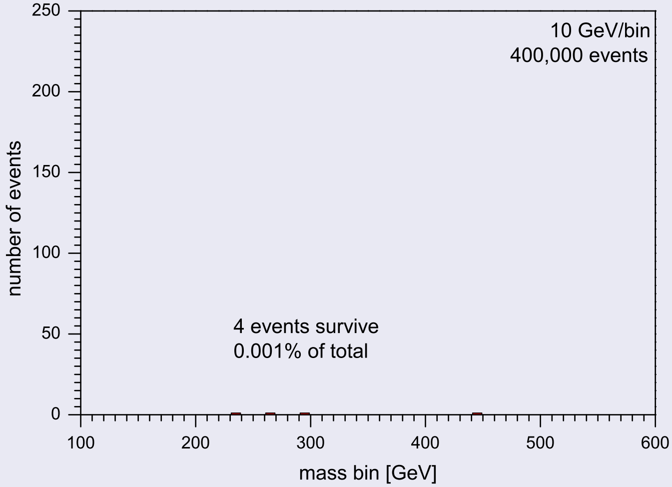
- Very difficult for Standard Model background to reconstruct a mass greater than m_t
- Appropriate cuts on transverse momentum can eliminate virtually all of remaining background

Additional cuts on background

- At least one of the leptons has $p_T > 50$ GeV
- Events contain at least one b-tagged jet with $p_T > 120$ GeV
- At least one occurance of $|M(bjet, leptons) - M(3jet)| < 50$ GeV

Important backgrounds

Reconstructed mass from bbZ background



Important backgrounds

- Study of bbZ background demonstrates that Standard Model background (in principle) not problematic for important signatures of vectorlike particles above current mass limits
- More serious analysis of background needed for actual analysis of vectorlike signals
- Most important challenges may be b-jet misidentification, detector resolution, and detector noise

Vectorlike frontend for MadEvent

- To assist in more thorough study of vectorlike additions to the MSSM, I will develop a frontend for MadEvent that will assist in phenomenological studies
- Expected features:
  - Implementation of LND, QUE, QDEE models
  - Ability to add vectorlike fields to MSSM in a general way
  - Computation of corrections to oblique electroweak parameters
  - Automatic multi-loop running of gauge couplings
  - Python wrapper for Fortran code, allowing implementation of GUI and other complex routines
- I will then use this new analysis tool to explore more complex models with extra vectorlike matter

Future Work

- Complete analysis of high $\tan\beta$ parameter space
- Complete initial analyses of important LND, QUE, QDEE signals
- Create vectorlike supermultiplet frontend for Madgraph / Madevent
- Model building / analysis for more complex vectorlike models