LHC Signatures of Natural SUSY

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Andrey Katz

Z. Han, AK, D. Krohn, M. Reece, 1205.5808

C. Brust, AK, R. Sundrum, 1206.2353

Harvard University

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Outline

Motivation and overview of Natural SUSY

Very light stop in R-parity conserving scenario
- Spin correlation
- Rapidity gap

Light 3rd generation squarks and baryon number violation

Conclusions

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)

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
- No sign of SUSY from the LHC so far $\Rightarrow$ already pushes "conventional" SUSY spectra to the TeV scale (and even higher)

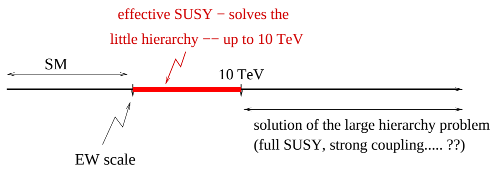
Effective (Natural) SUSY

How can we hide "SUSY"?

Supersoft SUSY (Dirac gaugino masses), RPV (with baryon number violation) – can all relax the LHC bounds.

Here we concentrate on "Effective SUSY" - light 3rd generation superpartners, heavy 1st and 2nd generation scalars. This scenario addresses the hierarchy problem of the LHC and "hides" from the LHC.

Bottom up approach to the Natural SUSY:



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

More on spectrum of Natural SUSY

- Stops should not be too heavy to cancel the top-divergence in the Higgs mass. Perfect naturalness $\Rightarrow$ the average mass is around 400 GeV.
- There is at least one sbottom (part of the LH multiplet) which is light $m_{\tilde{b}_L} \approx m_{\tilde{t}_L}$
- Wino and Higgsino should not be arbitrarily heavy, to cancel Higgs mass divergences $m_{\tilde{W}} \lesssim 1$ TeV, $m_{\tilde{B}} \lesssim 3$ TeV
- RH sbottom should be in the spectrum to cancel $U(1)_Y$ D-term divergence (1-3 TeV)
- Higgsinos should not be too heavy to avoid tree-level fine tuning between the μ-term and the soft masses
- Gluinos should cancel the leading divergence in the stop-sbottom mass. If gluinos are Majorana $m_{\tilde{g}} \sim 2m_{\tilde{t}}$, but it can be heavier by factor of 2 or 3 if the gluinos are Dirac.
- All other particles can be of order 10 TeV, and we effectively integrate them out of the theory

R parity: conserving or violating?

We assumed that the cutoff of the theory is 10 TeV. Even if the R-parity is conserved, operators like $QQQL$ will cause rapid proton decay. Therefore we should either consider UV completions which are supersymmetric with R-parity or assume that the proton is protected by some other symmetry (lepton or baryon number). In this talk we will consider both RPC and RPV scenarios. The latter is well-motivated from bottom-up approach.

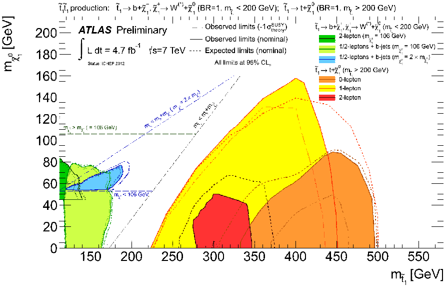
Assume heavy gluinos

Right now the bounds on gluinos are pretty stringent, in the RPC case gluinos are constrained to be 800-900 GeV. However SUSY can be natural even if $m_{\tilde{g}} \gtrsim 1$ TeV. Focus on heavy gluinos.

What are the current bounds?

Assume that we have one stop and one sbottom which are bit to heavy to be probed directly, (e.g. $\gtrsim$ 600 GeV). The second stop is light, very close to the top mass, and the neutralino is nearly massless.

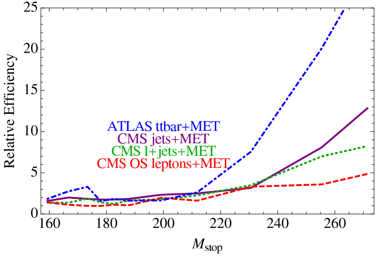
Can we see this light stop? What are the current bounds?



There were no limits before ICHEP 2012. There is still no exclusion in the very light region and in the mass range $m_{\tilde{t}} < m_t + m_{\chi^0}$.

Three regimes of a stop NLSP

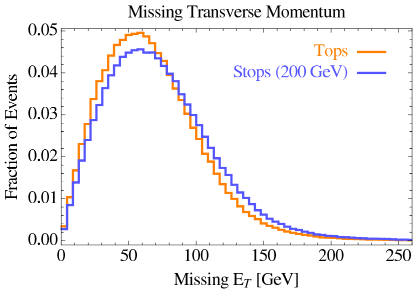
- $m_{\tilde{t}} < m_{\tilde{\chi}^0} + m_t \Rightarrow$ 3-body decays. m_{bl} distribution can be very different from $t\bar{t}$, but low signal acceptance can hurt.
- $m_{\tilde{t}} \gg m_t$ two body decays, searches for $t\bar{t} + \not{E}_T$ should start giving meaningful bounds (or maybe discovery?) at some point
- $m_{\tilde{t}} \gtrsim m_t$ stealthy ("one body") decay, neutralino carries very few momentum, searches for $t\bar{t} + \not{E}_T$ are probably not ideal.



Why the searches with $\not\!\!E_T$ fail?

Neutralino carries little $\not\!\!E_T$

In the stop's rest frame $p_{\chi^0} \sim \delta m = m_{\tilde{t}} - m_t$. In the lab frame $p_{\chi^0} \sim \gamma\delta m$, and it is still small for a typical stop event.



$\frac{\sigma_{\tilde{t}\tilde{t}^*}}{\sigma_{t\bar{t}}} \lesssim 0.1$, it is just few percent effect. And we still did not take into account systematic uncertainties for the $\not\!\!E_T$ distribution in tops, which is usually much bigger than this effect.

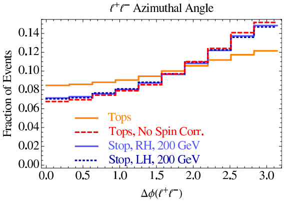
Spin correlation overview

Spins of the tops are correlated when they are pair produced, stops are spinless particles. Until now this fact was only used to probe spin-correlation in $t\bar{t}$ events.

Can we use this to see if there are "stealthy" stops in the top sample?

Which variables carry this information? *Mahlon, Parke, 2010*

1. $\Delta\phi$ between the leptons in 2l events. Almost no difference between the LH and the RH stops, very similar to spin-uncorrelated "tops".
2. Angle between the top and the lepton in zero-momentum frame



Others..

Full matrix element correlation

Based on Mahlon and Parke, 2010; Melnikov and Schulze, 2011

We can try to reconstruct leptonic events on event-by-event basis and ask what is the probability that the event is spin-correlated

$$\mathcal{R} = \frac{\sum_w |\mathcal{A}|^2_{corr}}{\sum_w |\mathcal{A}|^2_{corr} + \sum_w |\mathcal{A}|^2_{uncorr}}$$

Uncorrelated matrix element – matrix element of the decay which is spherical in the top rest frame.
Using this probability Melnikov-Schultze constructed a likelihood function for the spin-correlation hypothesis.

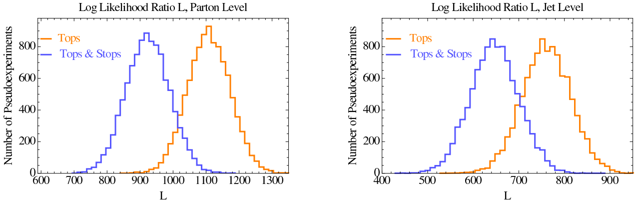
We never explicitly use stop matrix element

True power of this approach – stability with respect to NLO corrections

Likelihood

Using the distribution of $\mathcal{R}$ we can define log likelihood to discriminate between the hypothesis of tops vs. tops plus stops sample. The acceptance with our cuts and after full event reconstruction is 16.8% for tops and 15.6% for stops. The ratio between the σs is $\sim$1:12

Plot the log likelihood for 10K pseudo-experiments (32.8K events in each pseudo-experiment)



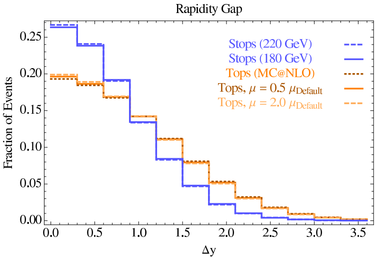
Can exclude stops w/ $m_{\tilde{t}} = 200$ GeV after 20/fb @ 95% CL.

t-channel singularity in $gg \to \tilde{t}\tilde{t}^*$

Why stop production is so small?

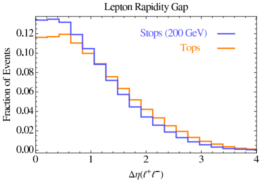
For $m_{\tilde{t}} = 200$ GeV $\sigma_{\tilde{t}\tilde{t}^*} < 0.1\sigma_{t\bar{t}}$. DY is small due to p-wave suppression, but gluon fusion is small due to t-channel singularity. There is no t-channel singularity for scalars.

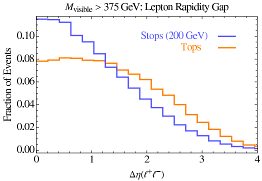
$$\Delta\eta^{av}_{t\bar{t}} > \Delta\eta^{av}_{\tilde{t}\tilde{t}^*}$$



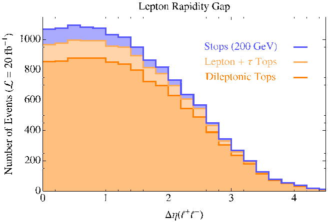
Practical realization

There is a simple way to use this variable, use rapidity gap between the lepton instead of tops. Moreover, in the limit of high mass events the effect becomes more pronounced ("massless tops limit").



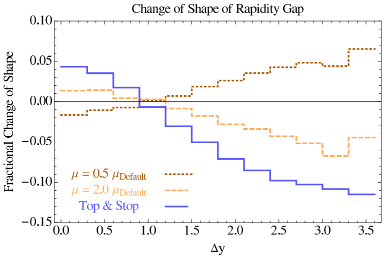


How big is the expected excess?



Can we trust this excess? (NLO corrections).

Bottleneck - we do not know who much does it change at the NLO. Here how the rapidity gap between the leptons can change at the NLO:



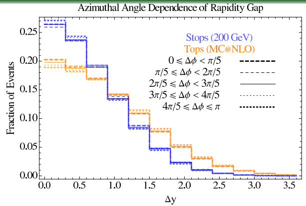
The uncertainties are dominated by systematics, tops with high renormalization scale can potentially mimic the effect. This variable might be useful when $t\bar{t}$ @ NNLO is known.

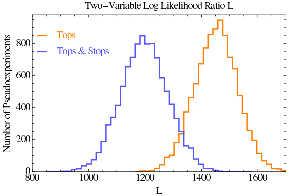
Multivariate analysis?

Can we try to combine two these approaches?

Combination of $\Delta\phi_{ll}$ with $\Delta\eta_{ll}$?

Are these variables correlated? Very weak, almost no correlation.





Assuming that these variables independent we can have $\sim 3\sigma$ significance @ 20/fb.

What is the spectrum? What are decay modes?

$$W \sim u^c d^c d^c$$

The LSP always decays either into jets or into a top and jets. Neutralino is not necessarily the LSP, it can be easily stop. Assume: A stop is LSP (mostly RH, w/ mixing), RPV is so small, that the resonant production is tiny, decays proceed through RPV only if it is the only available decay.

What decays can we look for?

- $\tilde{t}_1 \to jj \Rightarrow$ four or more jets, reconstructing two resonances - **challenging**
- $\tilde{b} \to W^{(*)}\tilde{t}_1$ the search for two resonances from four jets can be easier if we demand two additional leptons
- $\tilde{t}_2 \to Z^{(*)}\tilde{t}_1$ can give interesting signatures, but if $\tilde{t}_2$ is heavy we are just left with the system of stop and sbottom

$\tilde{b} \to \tilde{t} W^{(*)}$ transitions

Assume: the LH doublet soft mass is larger than $m_{\tilde{t}_R}$. The splitting inside the LH doublet mostly comes from $F_{\tilde{t}_R}$, SUSY contribution due to EWSB (thank you, Graham Kribs!). We end up w/ the spectrum $\tilde{t}_2 - \tilde{b} - \tilde{t}_1$.

If $m_{\tilde{t}_1} < m_{\tilde{H}} < m_{\tilde{b}}$, the transition $\Gamma(\tilde{b} \to \tilde{H} b) \propto |y_b|^2$. $\tilde{b} \to \tilde{H} t$ transition is likely phase space suppressed, unless the mass splittings are not too large. We neglect all $\tilde{b}$ decays through Higgsinos.

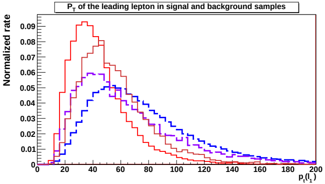
Needed search: 2 relatively soft leptons with 4 or more jets which reconstruct 2 resonance with the same mass

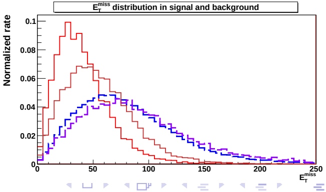
Search strategies and cuts

Dominant background: dileptonic $t\bar{t}$ with two additional hard jets

- Cluster the event with anti-k_T, clustering $R = 0.7$. Demand two isolated leptons, at least 4 jets with $p_T > 30$ GeV.
- Try all possible pairings between the 4 leading jets and pick up the combination which minimizes the invariant mass difference between the pairs. Discard the event if the minimal mass difference exceeds 10 GeV.
- $\not{E}_T > 35$ GeV, $S_T > 400$ GeV.

What else distinguished signal from background?

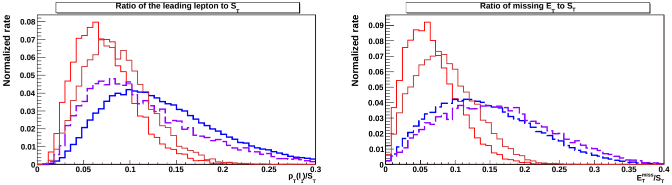




Search strategy - 2

$p_T(l)$ and $\not{E}_T$ distributions look so different for reason. The W in the signal events is either off shell or just marginally on shell (small splittings are motivated by naturalness). We can use a cut on dimensionless variables

$$r_{\not{E}_T} = \frac{\not{E}_T}{S_T}, \qquad r_l = \frac{p_T(l_1)}{S_T}$$



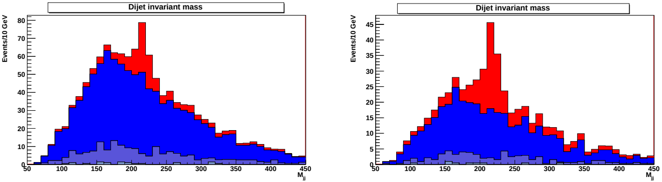
We use the cuts $r_{\not{E}_T} < 0.15$ and $r_l < 0.15$.

Results

How does stop decay?

Stop decays through $u^c d^c d^c$ operator into two jets, coming from two different down-type quarks. Possible combinations are ds, db, sb. A-priori we do not know the flavor structure of the RPV operator. It might have the dominant coupling to the b-quark, and in this case we have b-jets both in our signal and in our background. If it couples to ds, we can perform b-veto to reduce the background. Show two versions of the analysis.

Reference point: $m_{\tilde{b}} = 300$ GeV, $m_{\tilde{t}} = 217$ GeV



Conclusions

1. Natural SUSY is a very well motivated scenario, constraints are still relatively mild.
2. Stealthy regime for a stop in RPC case is very challenging, not impossible
3. Full matrix element correlation in 2l events gives a handle to the stealthy stops
4. Rapidity gap provides one more handle, can be used if and when NNLO tops are understood
5. RPV with natural SUSY is a well motivated scenario
6. Propose new search which should be sensitive to certain RPV spectra
7. Maybe new searches motivated by natural SUSY?