Baryogenesis from the Decays of Exotic Vector-like Squarks

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Outline

- Determining the dynamical mechanism which generated the baryon asymmetry of the universe (BAU) is still an open question.
- The most accurate determination is given by WMAP5:

$$\eta \equiv \frac{n_B - n_{\overline{B}}}{s} = 6.225 \pm 0.170 \times 10^{-10}$$

- Any model for η must satisfy the Sakharov conditions:
  - Out-of-equilibrium
  - Baryon number violation
  - C and CP violation

- We will generate the BAU from the out-of-equilibrium decays of exotic vector-like squarks.
- Vector-like squarks are present in GUTs, string based models and gauge mediated SUSY breaking.
- Baryon-number and CP violation come from superpotential terms (i.e. we do not rely on SUSY breaking).

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- Previous related work includes the 1987 Dimopolous and Hall paper "Baryogenesis at the MeV Era."
- They use out-of-equilibrium decays of MSSM squarks to generate the BAU.
- Their universe could only reheat to $\mathcal{O}$(GeV) and they were constrained by electric dipole moment measurements.

This model can exhibit the following characteristics:

- Natural splittings for the TeV scale masses of the two lightest exotic squarks.
- Maximizes the reheat temperature of the universe, thereby requiring degenerate TeV scale squarks.
- Allow the TeV exotics to exhibit displaced vertices at the LHC.
- Allow the exotics to be the messengers of gauge mediated SUSY breaking.

Please see the paper for specific benchmark parameters.

Outline

- The relevant matter content is
  - the three generations of colored MSSM chiral superfields $(u_i^c,\, d_i^c,\, q_i)$, $i = 1 \ldots 3$,
  - 2 families of exotic vector-like quark superfields $(D_i, \overline{D}_i)$, $i = 1 \ldots 2$.
- There is an approximate $\mathbb{Z}_2$ "exotic-parity."
- If this parity were exact, the lightest exotic would be stable.

- The superpotential is

$$\mathcal{W} = \mathcal{W}_{\mathrm{MSSM}} + \mathcal{W}_{\mathrm{Exotic}}$$

with

$$\mathcal{W}_{\mathrm{Exotic}} = g'_{ijk}\, u_i^c\, D_j\, D_k + (\mu'_R)_{ij}\, d_i^c\, \overline{D}_j + \left(\frac{(\mu'_L)_{ij}}{v_d}\right) H_d\, q_i\, D_j + M_{ij}\, D_i\, \overline{D}_j$$

- In much of what follows $\mu'_L = \mu'_R = \mu'$.
- Note that μ' breaks exotic-parity so any interaction with an odd number of exotics is proportional to μ'.

- Rotate to a basis without μ' mass terms.
- This mixes d_L with $\overline{D}$ and d_R with D.
- There are new gauge interactions in this basis (including all SUSY counterparts):

$$\left(\frac{1}{2}\,\frac{g_w}{c_w}\,\frac{\mu'_L}{M}\right)(d_L)^{\dagger}\overline{\sigma}^{\mu}(\overline{D})\,Z^0_{\mu} + \mathrm{h.c.}$$

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- There are superpotential interactions:

$$g'\,u^c\,D\,D$$
$$g'\left(\frac{\mu'_R}{M}\right)u^c\,d^c\,D$$
$$g'\left(\frac{\mu'_R}{M}\right)^2 u^c\,d^c\,d^c$$

Typical values which lead to the correct value for the BAU and are consistent with the cosmological and phenomenological constraints are

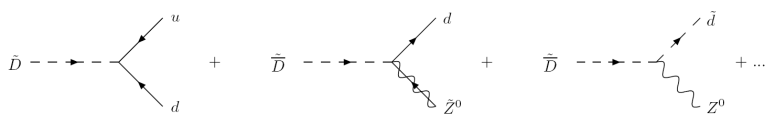
- $g' \lesssim 10^{-2}$
- $\frac{\mu'}{M} \lesssim 10^{-2}$
- $M \sim 100\,\mathrm{GeV} - 10^{6}\,\mathrm{GeV}$
- $\Delta M^2 \sim \mu'^2$
- $T_{\mathrm{RH}} \sim 10\,\mathrm{GeV}$ for TeV scale exotics

Outline

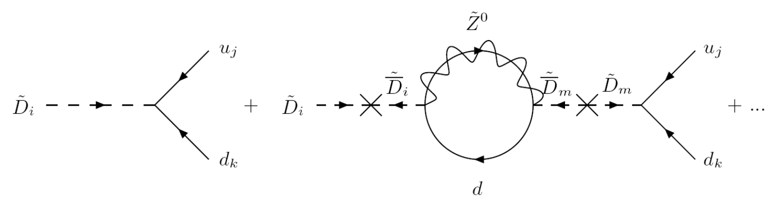
- We concentrate on representative contributions to the BAU, from g' and weak interactions.
- Need to interfere 1-loop with tree diagram.
- BAU will be generated without CP violation in soft terms.
- Define

$$\epsilon \equiv \sum_{i=1}^{n} \frac{\Gamma((\tilde{D}_\ell)_i \to u + d) - \Gamma((\tilde{D}^*_\ell)_i \to u^\dagger + d^\dagger)}{\Gamma_{\text{total}}((\tilde{D}_\ell)_i)}$$

- The dominant contributions to the total width are given by



- Then ϵ is given by

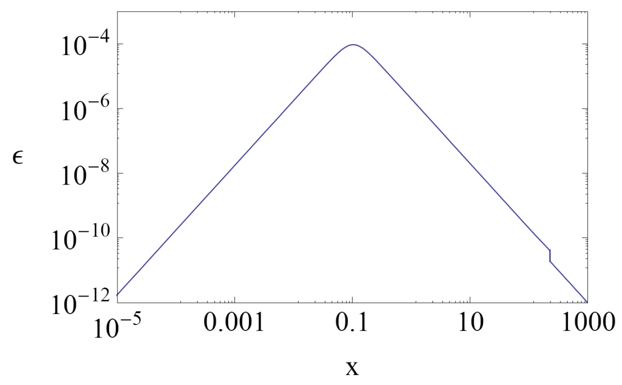


- Only the lightest exotic squarks make non-trivial contributions to ϵ.
- We can estimate

$$\epsilon \approx \frac{1}{16\,\pi}\,\frac{g'^2\,\left(\frac{g_w}{c_w}\right)^2}{\left(\frac{g_w}{c_w}\right)^2}\left(\frac{\mu'^2}{\Delta M^2}\right)$$

where we have assumed a phase of $\pi/2$ in one of the $(g'\,\mu'_R)$ couplings and $g' < g_w$.

- Define mass splitting parameter, x, by $(x\,\mu')^2 \equiv \Delta M^2$.
- Then the μ' suppression of ϵ drops out.
- If $\Delta M^2 \sim \mu'^2 \Leftrightarrow x \sim 1$, then degenerate squarks compensate for small μ'.



- This is a plot of ϵ (please see paper for parameter choices).
- We have properly regulated the resonance via the width of $\tilde{D}$.
- The full expression for ϵ is given in the paper.

Outline

- Introduce a "inflaton" field ϕ.
- Our cosmology begins in a ϕ dominated phase.
- Then ϕ decays to exotic squarks providing an out-of-equilibrium population given by

$$Y_D \equiv \frac{n_D}{s} \approx \mathrm{BR}\left(\frac{T_{\mathrm{RH}}}{m_\phi}\right),$$

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$$Y_D \equiv \frac{n_D}{s} \approx \mathrm{BR}\left(\frac{T_{\mathrm{RH}}}{m_\phi}\right),$$

- It is important that the squarks decay before they annihilate back to equilibrium.

$$\Gamma_{\mathrm{decay}} > \Gamma_{\mathrm{ann}}(T_{\mathrm{RH}}).$$

where the dominant annihilation rate is $\tilde{D}\,\tilde{D} \leftrightarrow g\,g$

- Then the BAU is given by

$$\eta \equiv \frac{n_B - n_{\overline{B}}}{s} = \epsilon \left(\frac{Y_D}{s}\right) = \epsilon\,\mathrm{BR}\left(\frac{T_{\mathrm{RH}}}{m_\phi}\right)$$

- Note that

$$\Gamma_{\mathrm{decay}} > H(T_{\mathrm{RH}})$$

  for all models considered.
- This means that the squarks decay instantaneously, i.e. at a temperature T_{RH}.

- We must be sure that the BAU is not erased.
- There are three dominant washout processes.
- We must check that the following conditions are satisfied

$$\begin{aligned} H(T_{\rm RH}) &> \Gamma_{\rm ID}(T_{\rm RH}) \\ H(T_{\rm RH}) &> \Gamma^{\rm heavy}_{\rm washout}(T_{\rm RH}) \\ H(T_{\rm RH}) &> \Gamma^{\rm light}_{\rm washout}(T_{\rm RH}) \end{aligned}$$

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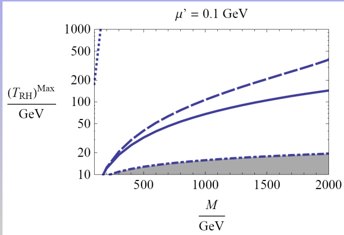
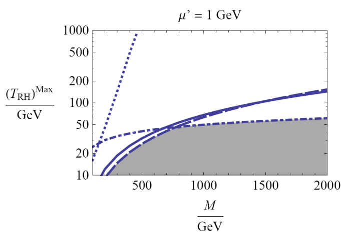
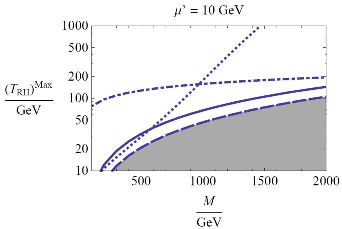
- The processes $\Gamma^{\rm light}_{\rm washout}$ and $\Gamma^{\rm heavy}_{\rm washout}$ are given by







$H(T_{\rm RH}) > \Gamma^{\rm heavy}_{\rm washout}(T_{\rm RH})$	solid	$H(T_{\rm RH}) > \Gamma^{\rm light}_{\rm washout}(T_{\rm RH})$	dotted
$H(T_{\rm RH}) > \Gamma_{\rm ID}(T_{\rm RH})$	dashed	$\Gamma_{\rm decay} > \Gamma_{\rm ann}(T_{\rm RH})$	dash-dotted

Outline

For the scenario where the exotic squarks are the messengers of gauge mediation:

- There are new flavor violating contributions to the MSSM up-squark masses proportional to g'.
- There is the possibility of proton decay via $p^+ \rightarrow K^+ + \tilde{G}$.

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In general

- There are constraints from unitarity of the CKM matrix.
- There are constraints from $D^0 - \overline{D}^0$ mixing.
- Electric dipole moments vanish at 1-loop and the 2-loop effect is smaller then from the standard model.
- There is the spectacular LHC signal of long-lived tracks with baryon number violating decays.

Outline

Conclusions

- We have realized the BAU via the out-of-equilibrium decays of exotic vector-like squarks.
- We explored a variety of tests and predictions for this class of models.
- The exotic squarks can be the messengers of gauge mediation.

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Future Work

- Do a detailed calculation with specific g' and μ' matrices.
- Work out details when quarks are the lightest exotic states.
- Find family symmetry when degenerate squarks are required.
- Build a DM sector.
- Do a full collider simulation to determine the viability of discovering Baryon-number violation at the LHC.

Thank You

Are there any questions?

Backup Slides

Large $\tilde{D}$ mass splittings					
scenario	g'	$\frac{M}{(\mathrm{GeV})}$	$\frac{\mu'}{(\mathrm{GeV})}$	$\frac{\Delta M^2}{(\mathrm{GeV})^2}$	ϵ
large splittings	0.4	500	4	$(57\,\mu')^2$	2×10^{-6}
Degenerate $\tilde{D}$ masses					
scenario	g'	$\frac{M}{(\mathrm{GeV})}$	$\frac{\mu'}{(\mathrm{GeV})}$	$\frac{\Delta M^2}{(\mathrm{GeV})^2}$	ϵ
high T_{RH}	0.005	1000	2	$(0.5\,\mu')^2$	8×10^{-6}
displaced vertices	0.06	500	10^{-5}	$(0.2\,\mu')^2$	6×10^{-3}
gauge mediation	0.01	10^6	1	$(0.4\,\mu')^2$	6×10^{-5}

Large $\tilde{D}$ mass splittings								
scenario	$\frac{T_{\mathrm{RH}}}{\mathrm{GeV}}$	$\frac{H}{\mathrm{GeV}}$	$\frac{\Gamma_{\mathrm{decay}}}{\mathrm{GeV}}$	$\frac{\Gamma_{\mathrm{ann}}}{\mathrm{GeV}}$	$\frac{\Gamma_{\mathrm{ID}}}{\mathrm{GeV}}$	$\frac{\Gamma^{\mathrm{heavy}}_{\mathrm{washout}}}{\mathrm{GeV}}$	$\frac{\Gamma^{\mathrm{light}}_{\mathrm{washout}}}{\mathrm{GeV}}$	$\frac{m_\phi}{\mathrm{GeV}}$
large splittings	18	4×10^{-16}	8×10^{-4}	3×10^{-6}	8×10^{-17}	2×10^{-24}	1×10^{-17}	5000
Degenerate $\tilde{D}$ masses								
scenario	$\frac{T_{\mathrm{RH}}}{\mathrm{GeV}}$	$\frac{H}{\mathrm{GeV}}$	$\frac{\Gamma_{\mathrm{decay}}}{\mathrm{GeV}}$	$\frac{\Gamma_{\mathrm{ann}}}{\mathrm{GeV}}$	$\frac{\Gamma_{\mathrm{ID}}}{\mathrm{GeV}}$	$\frac{\Gamma^{\mathrm{heavy}}_{\mathrm{washout}}}{\mathrm{GeV}}$	$\frac{\Gamma^{\mathrm{light}}_{\mathrm{washout}}}{\mathrm{GeV}}$	$\frac{m_\phi}{\mathrm{GeV}}$
high T_{RH}	75	8×10^{-15}	4×10^{-5}	1×10^{-5}	1×10^{-15}	4×10^{-16}	6×10^{-20}	10^5
displaced vertices	0.1	1×10^{-20}	2×10^{-15}	2×10^{-16}	~ 0	~ 0	~ 0	10^5
gauge mediation	1000	1×10^{-12}	1×10^{-8}	1×10^{-9}	~ 0	~ 0	~ 0	10^7

- We must assume a texture in the g' and μ' matrices for the "large splittings" benchmark.

- One could imagine that the exotic squarks are the messengers of gauge mediated SUSY breaking.
- There are new contributions to the MSSM up-squark masses at 1-loop and 2-loops which can lead to FCNCs:

$$(\delta\tilde{m}_{u_R}^{1-\mathrm{loop}})^2_{ij} = -\frac{1}{8\,\pi^2}\,g'_{ikm}\,g'^{*}_{jkm}\,\frac{F_X^4}{M_X^6}$$

$$(\delta\tilde{m}_{u_R}^{2-\mathrm{loop}})^2_{ij} \approx -\frac{1}{(16\,\pi^2)^2}\,g'_{ikm}\,g'^{*}_{jkm}\,g_s^2\,\frac{F_X^2}{M_X^2}$$

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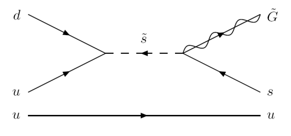
- There is also the possibility of proton decay via



There are a variety of phenomenological constraints one should consider:

- Unitarity of the CKM matrix:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 + N\left(\frac{\mu'}{M}\right)^2 = 0.9999 \pm 0.001 \Rightarrow \frac{\mu'}{M} \lesssim 0.03$$

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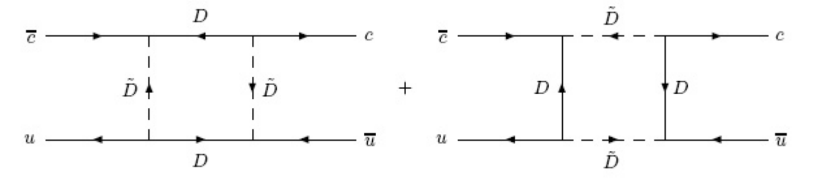
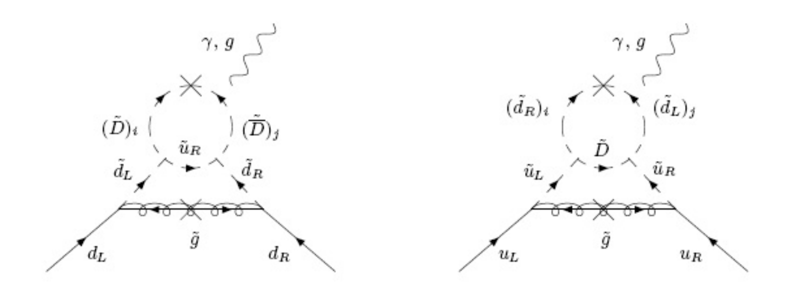
- $D^0 - \overline{D}^0$ mixing constrains g':



- EDMs are only generated at 2-loops and are $sim4$ orders smaller then the SM contribution:



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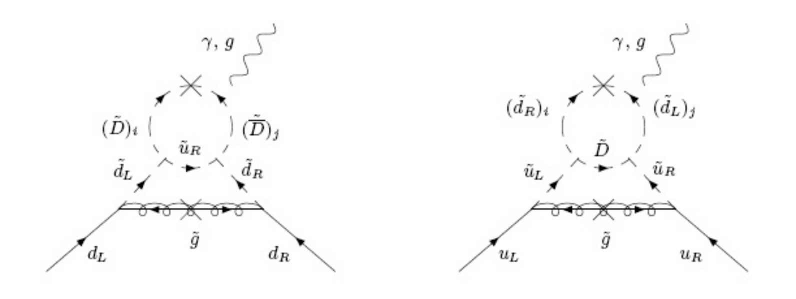

- There are potential LHC signals to determine Baryon-number violating decays.