**$Z'$- mediated Supersymmetry Breaking**

Visible Sector

- **MSSM + S + Exotics**

Hidden Sector

- **DSB**

- **Beyond the MSSM?**
- **A TeV-Scale $Z'$**
- **$Z'$ mediation**
- **The spectrum**
- **Implications**

(With Gil Paz, Liantao Wang, and Itay Yavin, 0710.1632 and in progress)
P. G. Langacker, G. Paz, L. T. Wang and I. Yavin, 

H. Verlinde, L. T. Wang, M. Wijnholt and I. Yavin, 

R. Dermisek, H. Verlinde and L. T. Wang, 

Y. Nakayama, 
Stable SUSY Breaking Model with O(10) eV Gravitino from Combined D-term 

Beyond the MSSM

Even if supersymmetry holds, MSSM may not be the full story

Most of the problems of standard model remain, new ones introduced
(FCNC, EDM)

µ problem introduced: \( W_\mu = \mu \hat{H}_u \cdot \hat{H}_d, \quad \mu = O(\text{electroweak}) \)

Ingredients of 4d GUTs hard to embed in string, especially large Higgs representations, Yukawa relations

Remnants of GUT/Planck scale physics may survive to TeV scale

Specific string constructions often have extended gauge groups, exotics, extended Higgs/neutralino sectors (Defect or hint?)

Important to explore alternatives/extensions to MSSM

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A TeV-Scale $Z'$

- Strings, GUTs, DSB, little Higgs, LED often involve extra $Z'$

- Typically $M_{Z'} > 600 - 900$ GeV (Tevatron, LEP 2, WNC);
  $|\theta_{Z-Z'}| < \text{few} \times 10^{-3}$ ($Z$-pole)
  (CDF di-electron: 923 ($Z_{\text{seq}}$), 822 ($Z_\chi$), 822 ($Z_\psi$), 891 ($Z_\eta$))

- Discovery to $M_{Z'} \sim 5 - 6$ TeV at LHC, ILC,
  $(pp \rightarrow \mu^+\mu^-, e^+e^-, q\bar{q})$ (depends on couplings, exotics, sparticles)

- Diagnostics to 2 – 2.5 TeV (asymmetries, $y$ distributions,
  associated production, rare decays)

- SUSY $Z'$ generally at SUSY-breaking scale (unless along flat direction)
Implications of a TeV-scale $U(1)'$

- **Natural Solution to $\mu$ problem** $W \sim hS H_u H_d \rightarrow \mu_{eff} = h\langle S \rangle$

- **Extended Higgs sector** ($\langle S \rangle$ needed to break $U(1)'$)

- **Large $A$ term, tree-level $CP$ violation** (electroweak baryogenesis)

- **Extended neutralino sector** (collider, CDM)

- **Exotics** (anomaly-cancellation)

- **Constraints on neutrino mass generation**

- $Z'$ decays into sparticles/exotics

- **Possible flavor changing neutral currents** (rare $B$ decays)
Coupling of a $U(1)'$ to a Quasi-Hidden Sector

- $U(1)'$ may couple to both ordinary and (quasi)-hidden sectors
- $Z' - \tilde{Z}'$ mass difference may communicate supersymmetry breaking

- **Unusual spectrum:** scalar masses and $A$ terms at 1 loop; standard model gauginos at two loops
- Predictive, but details depend on $U(1)'$ charges and Yukawas
- Motivated mini-version of split supersymmetry
- FCNC, EDM suppression
- Fine-tuning needed for electroweak scale, as in all split SUSY scenarios *(anthropic motivation?)*
- Large $\mu_{\text{eff}}$, $Z'$ mass; lighter singlino
- **Variants:** $U(1)'$ breaking in hidden sector; hybrid scenarios
**U(1)' Charges and Anomalies**

- Most $U(1)'$ models require exotic chiral fermions (may be vector under SM) to cancel anomalies

- Impose dynamical $\mu$: $W \sim \mu H_u H_d$ forbidden but $W \sim h S H_u H_d$ allowed

- Familiar $E_6$ charge assignments $E_6 \rightarrow \text{SM} \times U(1)_\chi \times U(1)_\psi$
  - Chiral spectrum

\[
3 \times 27 = 3 \times [(u^c Q e^c) + (d^c L) + N^c + S + (D H_u) + (D^c H_d)]
\]

- $(N^c, S) =$SM singlets; $D =$ exotic quark with $Q_{elm} = -1/3$
- Non-minimal Higgs $(S, H_u, H_d)$ sector; will have bino LSP

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A Minimal Model

- Chiral spectrum: 3 families (with $N^c$); single $(S, H_u, H_d)$; $n_D$ color triplets $D, D^c$; $n_E$ color singlets $E, E^c$ (no exotic doublets)

- Allow ordinary Yukawa interactions plus $\lambda S H_u H_d$, $y_D S D D^c$, $y_E S E E^c$ allowed (for effective $\mu$ and exotic masses)

- Allow $H_u L N^c$ (or $S H_u L N^c / M_{Pl}$ in variant)

- Anomaly conditions $\Rightarrow n_D = 3$, $n_E = 2$, $Y_D = -Y_{D^c} = -1/3$, $Y_E = -Y_{E^c} = -1$

- If no additional chiral SM singlets, two solutions for $Q_D$ in terms of $(Q_{H_d}, Q_{H_u}, Q_Q)$; two simple special cases, $Q_Q = -Q_{H_d}/3$ or $(Q_{H_u} - Q_{H_d})/6$
• For \( Q_{H_d} = 1, \ Q_{H_u} = x \neq -1, \ Q_Q = -1/3: \)

| \( H_d \) | \( 1 \) | \( 2/3 - \frac{1}{3}x \) |
| \( H_u \) | \( x \) | \( -\frac{5}{3} + \frac{1}{3}x \) |
| \( S \) | \(- (1 + x) \) | \(-\frac{2}{3}(1 + x) \) |
| \( Q \) | \(-\frac{1}{3} \) | \( \frac{8}{9} + \frac{2}{9}x \) |
| \( u^c \) | \( \frac{1}{3} - x \) | \( \frac{1}{9} + \frac{7}{9}x \) |
| \( d^c \) | \(-\frac{2}{3} \) | \( \frac{5}{3} - \frac{1}{3}x \) |

• Can have additional non-chiral (hidden sector, gauge unification, exotic decay)

• More general two parameter solutions possible

• \( W = \lambda S H_u H_d + y_{D_i} S D_i D^c_i + y_{E_j} S E_j E^c_j + \text{quark} + \text{lepton} \)
The Soft Spectrum

- $M_{\tilde{Z}'}$, generated below $\Lambda_S \sim 10^7 - 10^{11}$ GeV in hidden sector (dependent on dynamics) (will take $M_{\tilde{Z}'} = 10^3$ TeV (gauginos))

$$\frac{dm_{\tilde{f}_i}^2}{d \ln \mu} = \frac{-8g_{\tilde{z}'}^2Q_i^2M_{\tilde{Z}'}^2}{16\pi^2} + \text{Yukawa}$$

- Take $g_{\tilde{z}'}^2 = N^2g_Y^2 \frac{Tr}{Tr} \frac{Y^2}{Q^2}$
Similarly,

\[
\frac{dA}{d \ln \mu} = -\frac{4g_z^2(Q_i^2 + Q_j^2 + Q_k^2)M_{\tilde{Z}'}}{16\pi^2}
\]

\[
\frac{dM_\alpha}{d \ln \mu} = -8 \left( \frac{g_\alpha^2}{16\pi^2} \right) \left( \frac{g_{z'}^2}{16\pi^2} \right) \text{Tr}(Q^2T_\alpha^2)M_{\tilde{Z}'}
\]
• All scalar mass-squares positive. Negative contribution from large Yukawas $\lambda$, $y_t$, $y_b$, $y_{D_i}$, $y_{E_j}$, e.g.,

$$\frac{d m^2_S}{d \ln \mu} = \frac{-8 g^2 z Q^2 S M^2_Z + 4 \lambda^2 \Sigma \lambda + 6 y_{D_i}^2 \Sigma_{D_i} + 2 y_{E_j}^2 \Sigma_{E_j}}{16 \pi^2}$$

\[\Sigma \lambda \equiv m^2_S + m^2_{H_u} + m^2_{H_d}\]

\[\Sigma_{D_i} \equiv m^2_S + m^2_{D_i} + m^2_{D_i^c}\]

\[\Sigma_{E_j} \equiv m^2_S + m^2_{E_j} + m^2_{E_j^c}\]
• Integrate RGE

• Can easily drive $m_S^2$ negative and $m_{Hu}^2$ small (and possibly negative)

• Find large $s \equiv \langle S \rangle = \sqrt{-m_S^2/g_z^2}Q_S^2 \sim M_{Z'}/4\pi$, $M_{Z'} = \sqrt{-2m_S^2}$
Electroweak scale $v \ll s$ (and one light Higgs) by one fine tuning (typical of split SUSY: Arkani-Hamed, Dimopoulos). Anthropic motivation?

- Regard $s$ as fixed, minimize potential for $v_{u,d} \equiv \langle H_{u,d}^0 \rangle$ (only small shift due to $v_{u,d}$)

- Need one electroweak scale eigenvalue of $H_{u,d}^0$ mass matrix $M_H^2$

$$M_H^2 = \begin{pmatrix}
    m_{H_u}^2 + (\lambda^2 + g_z^2 Q_S Q_{H_u}) s^2 & -\lambda s A_{\lambda} \\
    -\lambda s A_{\lambda} & m_{H_d}^2 + (\lambda^2 + g_z^2 Q_S Q_{H_d}) s^2
\end{pmatrix}$$

- $\mu_{eff} = \lambda s = O(10\text{–}100 \text{ TeV}); A_{\lambda} \sim 10 \text{ TeV}$

- $\tan \beta \equiv \frac{v_u}{v_d} \sim \frac{m_{H_d}^2 + (\lambda^2 + g_1^2 Q_S Q_{H_d}) s^2}{\lambda s A_{\lambda}} \sim 10 - 100$

- Further running of SM quartic $\lambda_H$ down to EW scale

- Require other scalar mass-squares positive after including $F$ terms, $U(1)'$ $D$ terms and $A$ term mixing (charges constrained)
Parameter scan

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Gluino (Red), wino (Black), singlino (Green) and $Z'$ gauge-boson (Blue)

$Q_Q = -1/3$ and $Q_2 = -1/4$. 
Gluino (Red), wino (Black), singlino (Green) and $Z'$ gauge-boson (Blue)

$Q_Q = -2$ and $Q_2 = -1/2$.  

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Gluino (Red), wino (Black), singlino (Green) and $Z'$ gauge-boson (Blue) $Q_Q = 1$ and $Q_2 = 7/8$. 
Typical results (may be modified in exceptional cases)

- SM gauginos in 100 GeV range; rapid cascades/decays
- Wino = lightest SM gaugino (sets scale) (modified by supergravity)
- $M_{\tilde{w}^+} - M_{\tilde{w}^0} \sim 160$ MeV (loop); $\tilde{w}^+ \rightarrow \tilde{w}^0 \pi^+$
- $M_{Z'} \sim 10^3$ TeV
- Scalars, second Higgs, exotic fermions $\sim 10^2$ TeV
- $\mu_{\text{eff}}$ (Higgsinos), $A$-terms $\sim 10 - 100$ TeV
- Higgs $\gtrsim 140$ GeV; large $\tan \beta \sim 10 - 100$
- $M_{Z'} \sim (\text{few} - 100) \text{ TeV}$ (may be observable)

- Singlino, $m_{\tilde{S}} \sim M_{Z'}^2 / M_{\tilde{Z}}', \sim \text{GeV-TeV}$

- $\tilde{S} \rightarrow h(\ast)\tilde{w}$ (from $Z'$) or $\tilde{w} \rightarrow h(\ast)\tilde{S}$ may have displaced vertex

- No displaced vertex for gluino cascade $\tilde{g} \rightarrow q\bar{q}\tilde{w}$

- $\tilde{g} \rightarrow g\tilde{S}$ may dominate
Gravitinos, Gauginos, and Singlinos

- Wino LSP efficiently annihilates, $\Omega h^2 \sim 0.025(M_2/\text{TeV})^2$

- Experiment: $\Omega h^2 \sim 0.11$, i.e., must increase $M_2$, have enhanced production mechanism, or additional DM (e.g., axions)

- Have so-far ignored supergravity. Sugra contribution to soft parameters may be of order $m_{3/2} \gtrsim F/\sqrt{3}M_{Pl}$

- For $\Lambda_S \sim \sqrt{F} \sim 2 \times 10^7$ TeV (but could be lower or higher) $\Rightarrow m_{3/2} = \mathcal{O}(100 \text{ GeV})$, comparable to $M_a$

- Exponential sensitivity: solutions for $m_{3/2} \sim (10^{-3} - 10^4)$ GeV
● **Constraints on $m_{3/2}$**

- Stable $m_{3/2} \gtrsim$ keV overcloses universe unless reheating temperature $T_R \lesssim 10^8 m_{3/2}$
- Even with lower $T_R$, wino NLSP decays to gravitino upset BBN
  $\rightarrow m_{3/2} < 100$ MeV (Singlino NLSP?)
- Decay of unstable gravitino upsets BBN unless either
  $m_{3/2} \gtrsim 10$ TeV or $T_R < 10^5 - 10^6$ GeV

● **Singlino may be LSP or NLSP** (not fully studied)

● **Sugra or anomaly mediation contributions to SM gauginos may be comparable to $Z'$ mediation, but no significant effect on other soft parameters**
Other Implications

- Additional non-chiral? (gauge unification, hidden sector, exotic decays)

- Some exotics stable at order-4 level ⇒ low $T_R$, alternative $U(1)'$ charge assignment, or unstable by non-chiral exotics

- $U(1)'$ ensures $R_p$ conservation

- $U(1)'$ prevents large Majorana masses for minimal seesaw. Dirac mass allowed at order-3 by assumption.
  - Alternative $U(1)'$ assignment only allows $W \sim SH_uLN^c/M_{Pl}$
    ⇒ Dirac mass $\sim s\nu_u/M_{Pl} \sim 0.02$ eV ($R_p$ still conserved)

- Nature of phase transitions, baryogenesis?

- Generalized/hybrid scenarios with lower $M_{\tilde{Z}}$?
Conclusions

- $U(1)'$ coupling to hidden sector quite possible but little explored
- $Z' - \tilde{Z}'$ mediation $\rightarrow$ form of split SUSY, with one fine tuning
- Novel spectrum. Details dependent on $U(1)'$ charges, but usually squarks, sleptons, exotics, second Higgs, $\mu_{eff}$, $A \sim 10^{-100}$ TeV
- $Z'$, singlino may be lighter
- $M_H \gtrsim 140$ GeV
- Usually only light SM gauginos at TeV scale, with comparable sugra or anomaly contributions.
  (May be wino LSP. Rapid cascades/decays. $\tilde{g} \rightarrow g\tilde{S}$ may dominate.)
- Some versions imply light Dirac neutrino by HDO

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