Primeino Mediation

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

(Work in progress with Gil Paz, Liantao Wang, Itay Yavin)

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

Remnants Physics from the Top-Down

- Z' or other gauge (may couple to quasi-hidden sector)
- Extended Higgs/neutralino (doublet, singlet)
- Quasi-Chiral Exotics
- Non-standard ν mass (enhanced symmetries)
- Quasi-hidden (Strong coupling? SUSY breaking? Composite family?)
- Charge $1/2$ (Confinement?, Stable relic?)
- Time varying couplings
- LED (TeV black holes, stringy resonances)
- LIV, VEP (speeds, decays, (oscillations) of HE γ, e, gravity waves (ν's))

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: 850 (Z_{seq}), 740 (Z_χ), 725 (Z_ψ), 745 (Z_η))
- Discovery to $M_{Z'} \sim 5 - 8$ TeV at LHC, ILC, $(pp \to \mu^+\mu^-, e^+e^-, q\bar{q})$ (depends on couplings, exotics, sparticles)
- Diagnostics to 1-2 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 μ problem** $W \sim hSH_uH_d \rightarrow \mu_{eff} = h\langle S\rangle$
- **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
- Hidden valley effects if low scale (Strassler, Zurek)

- $\tilde{Z}'$ gaugino (primeino) mass 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 form of split supersymmetry (Arkani-Hamed, Dimopoulos), but may be some light scalars
  - FCNC, EDM suppression
  - Fine-tuning needed for electroweak scale, as in all split SUSY scenarios (anthropic motivation?)
  - Large μ_{eff}, Z' mass
  - Possible variant: $U(1)'$ breaking in hidden sector

$U(1)'$ Charges and Anomalies

- Most $U(1)'$ models require exotic chiral fermions (may be vector under SM) to cancel anomalies
- Impose dynamical μ: $W \sim \mu H_u H_d$ forbidden but $W \sim h S H_u H_d$ allowed
- Familiar E_6 charge assignments $E_6 \longrightarrow$ SM $\times U(1)_\chi \times U(1)_\psi$
  - Chiral spectrum

$$\mathbf{3}\times\mathbf{27} = \mathbf{3}\times\left[(u^c Q e^c) + (d^c L) + N^c + S + (D H_u) + (D^c H_d)\right]$$

  - (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

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 $\lambda S H_u H_d$, $h_D S D D^c$, $h_E S E E^c$ allowed (for effective μ 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), but we restrict to two simple special cases, $Q_Q = -Q_{H_d}/3$ or $(Q_{H_u} - Q_{H_d})/6$

- For $Q_{H_d} = 1,\ Q_{H_u} = x \neq -1,\ Q_Q = -1/3$:

$$
\begin{aligned}
Q_S &= -(1+x),\ Q_{u^c} = \frac{1}{3} - x,\ Q_{d^c} = -\frac{2}{3}, \\
Q_L &= \frac{2}{3} - \frac{1}{3}x,\ Q_{e^+} = -\frac{5}{3} + \frac{1}{3}x,\ Q_{N^c} = -\frac{2}{3}(1+x), \\
Q_D &= \frac{8}{9} + \frac{2}{9}x,\ Q_{D^c} = \frac{1}{9} + \frac{7}{9}x,\ Q_E = \frac{5}{3} - \frac{1}{3}x,\ Q_{E^c} = -\frac{2}{3} + \frac{4}{3}x
\end{aligned}
$$

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

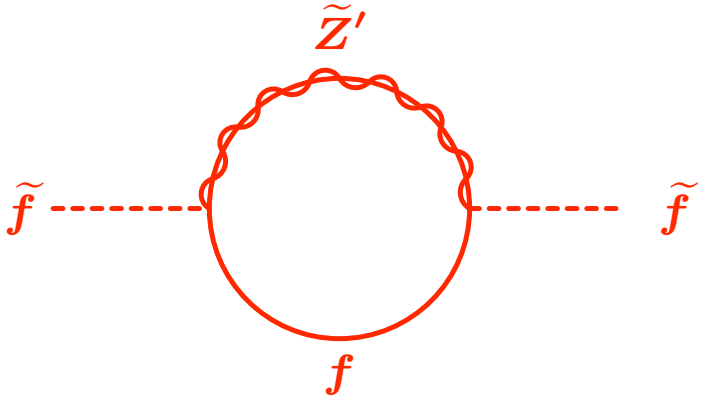
- $W = \lambda S H_u H_d + h_{D_i} S D_i D_i^c + h_{E_j} S E_j E_j^c$ + quark + lepton

The Soft Spectrum

- $M_{\widetilde{Z}'}$ generated below $\sqrt{F}$ in hidden sector; $\ln(\sqrt{F}/M_{\widetilde{Z}'}) \sim 10-1$, dependent on dynamics (will find $M_{\widetilde{Z}'} \sim 10^3 - 10^4$ TeV)

$$\frac{dm^2_{\phi_i}}{d\ln\mu} = \frac{-8g_1'^2 Q_i^2 M^2_{\widetilde{Z}'}}{16\pi^2} + \text{Yukawa}$$

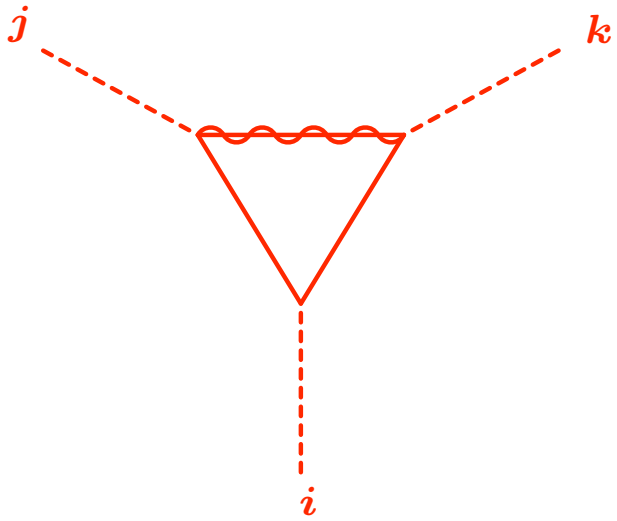
- Take $g_1' \sim \sqrt{\frac{5}{3}} g_Y$ (for similar charge normalization)

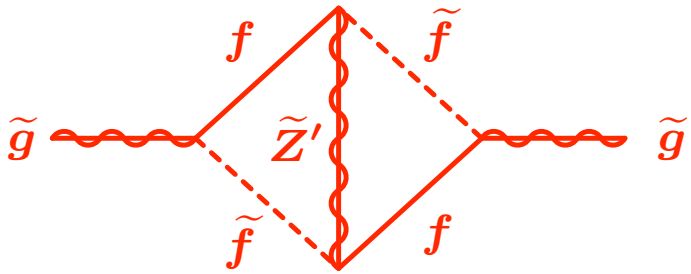


- **Similarly,**

$$\frac{dA}{d\ln\mu} = \frac{-4g_1'^2(Q_i^2+Q_j^2+Q_k^2)M_{\widetilde{Z}'}}{16\pi^2}$$

$$\frac{dM_{\tilde{q}_a}}{d\ln\mu} = -8\left(\frac{g_a^2}{16\pi^2}\right)\left(\frac{g_1'^2}{16\pi^2}\right)\mathrm{Tr}(Q^2T_a^2)M_{\widetilde{Z}'}$$





- **All scalar mass-squares positive. Negative contribution from large Yukawas $\lambda,\ h_t,\ h_b,\ h_{D_i},\ h_{E_j}$, e.g.,**

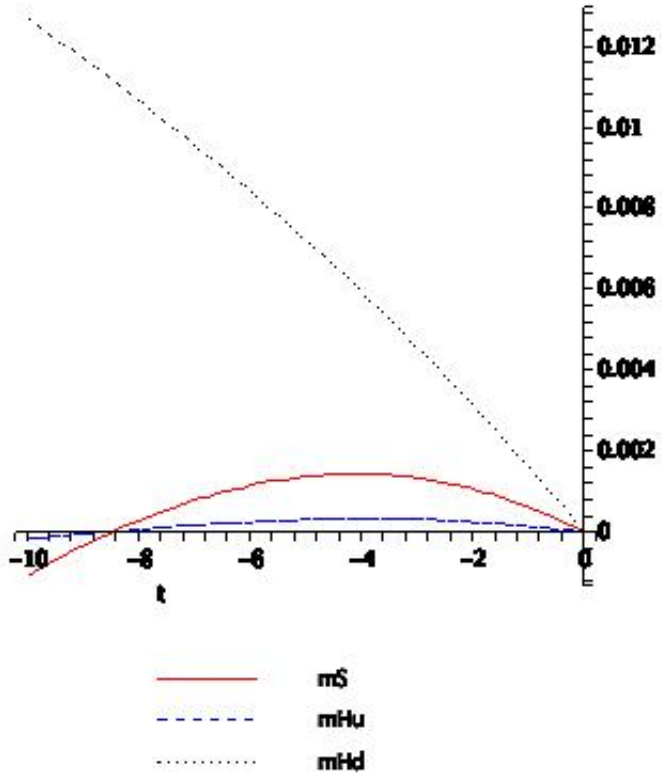
$$\frac{dm_S^2}{d\ln\mu} = \frac{-8g_1'^2 Q_S^2 M_{\widetilde{Z}'}^2 + 4\lambda^2\Sigma_\lambda + 6h_{D_i}^2\Sigma_{D_i} + 2h_{E_j}^2\Sigma_{E_j}}{16\pi^2}$$

$$\begin{aligned}
\Sigma_\lambda &\equiv m_S^2 + m_{H_u}^2 + m_{H_d}^2 \\
\Sigma_{D_i} &\equiv m_S^2 + m_{D_i}^2 + m_{D_i^c}^2 \\
\Sigma_{E_j} &\equiv m_S^2 + m_{E_j}^2 + m_{E_j^c}^2
\end{aligned}$$

- **Integrate RGE**

- **Can easily drive m_S^2 negative and $m_{H_u}^2$ small** (and possibly negative)

- **Find large** $s \equiv \langle S \rangle = \sqrt{-m_S^2/g_1'^2 Q_S^2} \sim M_{\tilde{Z}'}$, $M_{Z'} = \sqrt{-2m_S^2}$



- **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 $v_{u,d} \equiv \langle H^0_{u,d} \rangle$** (only small shift due to $v_{u,d}$)
  - **Need one negative eigenvalue of $H^0_{u,d}$ mass matrix M^2_H near electroweak scale**

$$M^2_H = \begin{pmatrix} m^2_{H_u} + (\lambda^2 + g'^2_1 Q_S Q_{H_u}) s^2 & -\lambda s A_\lambda \\ -\lambda s A_\lambda & m^2_{H_d} + (\lambda^2 + g'^2_1 Q_S Q_{H_d}) s^2 \end{pmatrix}$$

  - $\mu_{eff} = \lambda s > 100$ GeV; $A_\lambda \sim 10$ TeV $\Rightarrow \lambda s A_\lambda >$ (1 TeV)^2
  - $\tan\beta \equiv \frac{v_u}{v_d} \sim \frac{m^2_{H_d} + (\lambda^2 + g'^2_1 Q_S Q_{H_d}) s^2}{\lambda s A_\lambda}$ (large)

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

- **Example:** $Q_{H_u}/Q_{H_d} = -1/3,\ h_{D_i} = 0.4,\ h_{E_i} = 0.8,\ \lambda = 0.07$
  $M_{\widetilde{Z}'} = 10^3$ **TeV,** $\ln(\sqrt{F}/M_{\widetilde{Z}'}) = 10$**; all results in TeV**
  (results preliminary; RGE below $M_{\widetilde{Z}'}$ **only estimated)**

$s = 270$	$M_{Z'} = 46$	$M_S = M_{Z'}$	$\mu_{eff} = 19$	
$m_{H_1} \sim 0.13$	$m_{H_2} = 110$	$\tan\beta = 45$		
$A_\lambda = -13$	$A_D = -9$	$A_E = -41$	$A_{u_3^c} = -6$	$A_{d_3^c} = -13$
$m_{\widetilde{D}_1} = 110$	$m_{\widetilde{D}_2} = 150$	$m_D = 110$	$m_{D^c} = m_D$	
$m_{\widetilde{E}_1} = 250$	$m_{\widetilde{E}_2} = 310$	$m_E = 210$	$m_{E^c} = m_E$	
$m_{\widetilde{Q}_{1,2}} = 49$	$m_{\widetilde{u}^c_{1,2}} = 80$	$m_{\widetilde{d}^c_{1,2}} = 92$		
$m_{\widetilde{Q}_3} = 19$	$m_{\widetilde{u}^c_3} = 71$	$m_{\widetilde{d}^c_3} = 76$		
$m_{\widetilde{L}} = 94$	$m_{\widetilde{e}^+} = 24$	$m_{\widetilde{N}^c} = 63$		
$m_{\widetilde{g}_1} = 0.48$	$m_{\widetilde{g}_2} = 0.14$	$m_{\widetilde{g}_3} = 0.68$		

Typical results (may be modified in exceptional cases)

- SM gauginos in 100 GeV range; rapid cascades/decays
- Wino LSP (sets scale) (modified by supergravity)
- $m_{\widetilde{g}_2^+} - m_{\widetilde{g}_2^0} \sim$ 160 MeV (loop); $\widetilde{g}_2^+ \rightarrow \widetilde{g}_2^0 \pi^+$
- $M_{\widetilde{Z}'} \sim 10^3$ TeV
- $M_{Z'}$, scalars, second Higgs, exotic fermions $\sim 10^2$ TeV (some may be lighter)
- μ_{eff} (Higgsinos), $A-$ terms ~ 10 TeV
- Higgs $\sim 120 - 140$ GeV (prelim estimate); large $\tan\beta$

Gravitinos and Gauginos

- Wino LSP efficiently annihilates, $\Omega_{\tilde{g}_2} h^2 \sim 0.025 (m_{\tilde{g}_2}/\mathrm{TeV})^2$
- Experiment: $\Omega h^2 \sim 0.11$, i.e., must increase $m_{\tilde{g}_2}$, have enhanced production mechanism, or additional DM (e.g., axions)
- Have so-far ignored supergravity. Sugra contribution to soft parameters may be of order $m_{3/2} \gtrsim F/\sqrt{3} M_{Pl}$
- In example, $\sqrt{F} \sim 2 \times 10^7$ TeV (but could be lower or higher) $\Rightarrow$ $m_{3/2} = \mathcal{O}(100$ GeV), comparable to $m_{\tilde{g}}$

- **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, NLSP decays to gravitino upset BBN if hadron/electromagnetic (SuperWimp succeeds only for slepton NLSP)**
  - **Decay of unstable gravitino upsets BBN unless either $m_{3/2} > 10 - 100$ TeV *or* $T_R < 10^6 - 10^7$ GeV**

- **Compatible with primeino scenario for wino LSP with comparable two-loop and sugra contributions (may increase wino mass closer to CDM value), and low T_R**

- **Alternative: larger $m_{3/2}$ with reduced sugra contribution to soft (cf anomaly mediation)**

- **SM gaugino masses therefore very model dependent, but no significant sugra effect on other soft parameters**

Other Implications

- May be additional charged non-chiral matter (gauge unification, hidden sector)
- Some exotics stable at order-4 level $\Rightarrow$ either low reheating temperature or alternative $U(1)'$ charge assignment
- $U(1)'$ 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 $W \sim SH_u LN^c/M_{Pl}$ $\Rightarrow$ *Dirac* mass $\sim sv_u/M_{Pl} \sim 0.02$ eV (R_p still conserved)
- Nature of phase transitions, baryogenesis?

Conclusions

- Coupling of $U(1)'$ to quasi-hidden sector quite possible but little explored
- $\widetilde{Z}'$ (primeino) mediation implies a form of split SUSY, with one fine tuning
- Novel spectrum. Details dependent on $U(1)'$ charges, but usually squarks, sleptons, exotics, second Higgs, Z', μ_{eff}, A at 10 -100 TeV level.
- Usually only light SM gauginos at TeV scale, with comparable sugra contributions. May be wino LSP. Rapid cascades/decays
- Some versions imply light Dirac neutrino by HDO