Physics Beyond the MSSM

- Beyond the MSSM
- From the top-down
- Possible new TeV-scale physics
- A heavy $Z'$?
Beyond the MSSM

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

Most of the problems of standard model remain (hierarchy of electroweak and Planck scales is stabilized but not explained)

$\mu$ problem introduced

Could be that all new physics is at GUT/Planck scale, but there could be remnants surviving to TeV scale

Specific string constructions often have extended gauge groups, exotics

Important to explore alternatives/extensions to MSSM
Unification: from the Top Down

Bottom up: usually motivated by SM problems

Top down:

- Ambitious/promising string/M theory paradigm. However:
  - many realms of perturbative and non-perturbative M theory
  - compactification
  - dilaton/moduli
  - SUSY breaking, $\Lambda_{\text{cosm}}$
• Detailed study of specific constructions:

  – develop techniques
  – suggest new TeV-scale physics
  – suggest promising new directions

• Unlikely to find fully realistic theory soon. Studies emphasize specific features:

  – fundamental scale $M_{\text{fund}} \ll M_{\text{pl}}$ (LED)
  – SUSY breaking, $\Lambda_{\text{cosm}}$
  – dilaton/moduli stabilization
  – semi-realistic 4D gauge theories containing MSSM ($M_{\text{fund}} \sim M_{\text{pl}}$) (M. Cvetič, PL; G. Cleaver, J.R. Espinosa, J. Wang, G. Shiu)
Implications of semi-realistic models

Flat Directions: G. Cleaver, M. Cvetič, J. R. Espinosa, L. L. Everett, and PL, hep-th/9711178, 9805133

Heterotic Constructions: (Chaudhury, Hockney, Lykken models)
  • G. Cleaver, M. Cvetič, J. R. Espinosa, L. L. Everett, PL, and J. Wang, hep-ph/9807479, 9811355

Intersecting Brane constructions: (Cvetič, Shiu, Uranga models)
  • M. Cvetič, PL, and J. Wang, hep-th/0303208
Possible features

- Direct compactification: String $\rightarrow$ MSSM (+ extended?) in 4D without intermediate GUT phase
  - Avoids doublet-triplet problem, and need for large representations for GUT breaking and fermion/neutrino masses/mixings

- Non-standard gauge unification (higher Kač-Moody, exotics, moduli boundary conditions)
  - Cancellations or search for canonical?

- Selection rules from string dynamics, not 4d symmetries
• Exotic chiral supermultiplets
  – Quarks/leptons w. non-standard $SU(2) \times U(1)$
  – Extra Higgs doublets
  – Standard model singlets
  – Fractional charges
  – Lepton-Higgs mixing ($R_P$)

• Quasi-hidden sector
  – Fractional charges if not asymptotically free (AF)
  – Charge confinement, light composites, SUSY breaking, dilaton/moduli stabilization if AF
• Yukawa sector very model dependent
  – Different embeddings for different families
  – Stringy selection rules, textures
  – Non-GUT relations
  – Majorana masses? Seesaw scales?

• Extended gauge sectors
  – Extra $U(1)'$ (non-anomalous), often family-nonuniversal; standard model singlets
A TeV scale $Z'$?

Review

- M. Cvetič and PL, hep-ph/9707451

Electroweak $Z'$

- M. Cvetič and PL, hep-ph/9511378, 9602424
- M. Cvetic, D. A. Demir, J. R. Espinosa, L. L. Everett and PL, hep-ph/9703317
- PL and J. Wang, hep-ph/9804428

Intermediate scale

- G. Cleaver, M. Cvetic, J. R. Espinosa, L. L. Everett and PL, hep-ph/9705391
- PL, hep-ph/9805281 ($\nu$ implications)
Secluded sector model

- J. Erler, PL, and T. J. Li, hep-ph/0205001

Implications

- L. L. Everett, PL, M. Plümmacher and J. Wang, hep-ph/0001073 (sparticle spectrum)
- PL and M. Plümmacher, hep-ph/0001204 (FCNC)
- D. Demir and L. Everett, tbp (CP phases)
- J. Kang, T. Li, T. Liu, and PL, tbp (electroweak baryogenesis)
- J. Kang, T. Li, and PL, tbp (TeV seesaw)
- V. Barger, PL and H. S. Lee, hep-ph/0302066 (BBN constraints)
- PL, hep-ph/0304053 ($\nu_R$ decoupling)
- T. Han, B. McElrath, tbp (implications of Higgs sector)
- V. Barger, PL and H. S. Lee, tbp (rare $B$ decays)
Motivations

- Strings, GUTs, LED, DSB often involve extra $U(1)'$

- String models
  - Extra $U(1)'$ and SM singlets extremely common
  - Radiative breaking of electroweak (SUGRA or gauge mediated) often yield EW/TeV scale $Z'$ (unless breaking along flat direction $\rightarrow$ intermediate scale)
Solution to $\mu$ problem

$$W \sim hS H_u H_d,$$

- $S =$ standard model singlet, charged under $U(1)'$
- $\langle S \rangle$ breaks $U(1)'$, $\mu_{eff} = h\langle S \rangle$
- Like NMSSM, but no domain walls
- SM-singlets usually have $U(1)'$ charges in constructions studied
• Current limits (precision and collider) model dependent, but typically \( M_{Z'} > (500 - 800) \text{ GeV} \) and \( Z - Z' \) mixing \(|\delta| < \text{ few} \times 10^{-3}\)

• Discovery to \( M_{Z'} \sim 5 - 8 \text{ TeV} \) at LHC, LC

• Diagnostics to 1-2 TeV (asymmetries, \( y \) distributions, associated production, rare decays)
Flat directions

- Two SM singlets charged under $U(1)'$. If no $F$ terms,

$$V(S_1, S_2) = m_1^2|S_1|^2 + m_2^2|S_2|^2 + \frac{g'^2Q'^2}{2}(|S_1|^2 - |S_2|^2)^2$$

Break at EW scale for $m_1^2 + m_2^2 > 0$, at intermediate scale for $m_1^2 + m_2^2 < 0$ (stabilized by loops or HDO)

- Small Dirac (or other fermion) masses from

$$W \sim \hat{H}_2 \hat{L}_L \hat{\nu}^c_L \left( \frac{\hat{S}}{\hat{M}} \right)^{P_D}$$

- Secluded sector: lift $F$-flatness by small ($\sim 0.05$) singlet Yukawa
• **SUSY-breaking scale models** (Demir et al)
  
  – $M_{Z'} \sim M_Z$, leptophobic
  – $M_{Z'} \gtrsim 10M_Z$ by modest tuning

• **Secluded sector models** (Erler, PL, Li)
  
  – Approximately flat direction, broken by small ($\sim 0.05$) Yukawa
  – $Z'$ breaking decoupled from effective $\mu$ term
  – Four SM singlets: $S, S_{1,2,3}$, doublets $H_{1,2}$
Superpotential

\[ W = h S H_1 H_2 + \lambda S_1 S_2 S_3 \]

Potential

\[ V = V_F + V_D + V_{soft} \]

\[ V_F = h^2 (|H_1|^2|H_2|^2 + |S|^2|H_1|^2 + |S|^2|H_2|^2) \]
\[ + \lambda^2 (|S_1|^2|S_2|^2 + |S_2|^2|S_3|^2 + |S_3|^2|S_1|^2) \]

\[ V_D = \frac{G^2}{8} (|H_2|^2 - |H_1|^2)^2 \]
\[ + \frac{1}{2} g_Z^2 \left( Q_S |S|^2 + Q_{H_1} |H_1|^2 + Q_{H_2} |H_2|^2 + \sum_{i=1}^{3} Q_{S_i} |S_i|^2 \right)^2 \]
where $G^2 = g_1^2 + g_2^2$.

$$V_{soft} = m_{H_1}^2 |H_1|^2 + m_{H_2}^2 |H_2|^2 + m_S^2 |S|^2 + \sum_{i=1}^{3} m_{S_i}^2 |S_i|^2$$

$$- (A_h h S H_1 H_2 + A_\lambda \lambda S_1 S_2 S_3 + \text{H.C.})$$

$$+ (m_{SS_1}^2 S S_1 + m_{SS_2}^2 S S_2 + m_{S_1 S_2}^2 S_1^\dagger S_2 + \text{H.C.})$$

- $\langle S_i \rangle \sim m_{S_i}/\lambda$ large for small $\lambda$
- Breaking along $D(U(1)') \sim 0$
- Smaller $\langle S \rangle$, $\langle H_i \rangle$, dominated by $h A_h \rightarrow \tan \beta \sim 1, \langle S \rangle \sim \langle H_i \rangle$
- Large doublet-singlet mixing
- Two sectors nearly decoupled
Implications of $U(1)'$

- Solution to $\mu$ problem
- CP phase correlations possible (Demir, Everett)
- Exotics
- FCNC (especially in string models); rare $B$ decays
- Non-standard sparticle spectrum
- Neutrino implications: Dirac, natural $\nu_R$ decoupling, TeV seesaw
- Non-standard Higgs masses, couplings (doublet-singlet mixing) (Han, PL, McElrath)
- Enhanced possibility of EW baryogenesis (Kang, Liu, PL, Li)
- Dirac neutrinos and BBN (Barger, PL, Lee)
Nonstandard Higgs
(T. Han, PL, B. McElrath)

- Complex Higgs, neutralino spectrum and decays, very different from MSSM and NMSSM because of mixing and $D$ terms

- 6 scalars and 4 pseudoscalars
  - Can have tree level CP breaking $\Rightarrow$ mixing
  - Separate into two sectors, one decoupled
  - Often light scalars with significant doublet admixture, but reduced coupling due to singlet admixture ($M_A < 65$ GeV)
  - Can have lightest Higgs up to 168 GeV with all couplings perturbative to $M_P$ because of $D$ terms

$$m_h^2 \leq m_h^2 (MSSM) + h^2 (v_1^2 + v_2^2) \sin^2 2\beta + 2g_{Z'}^2 \frac{(Q_{H_1} v_1^2 + Q_{H_2} v_2^2)^2}{(v_1^2 + v_2^2)}$$
Linear Collider (500 GeV) Higgsstrahlung Cross Section

\[ \sigma(e^+e^- \rightarrow ZH) \text{ (fb)} \]

- \( H_1 \)
- \( H_2 \)
- \( H_3 \)
- Standard Model

\( M_H \)
$M_A$ vs. MSSM $A$ mass

$M_{A,MSSM} = \sqrt{2 A_h h s / \sin(2\beta)}$ (GeV)
Baryon asymmetry $n_B/n_\gamma \sim 6 \times 10^{-10}$

Possible mechanisms
- Affleck-Dine baryogenesis
- GUT baryogenesis (wiped out by sphalerons for $B - L = 0$)
- Leptogenesis
- Electroweak baryogenesis
Electroweak baryogenesis requires strong first order transition, \( v(T_c)/T_c \gtrsim 1 - 1.3 \) and adequate CP violation in expanding bubble wall

(W. Bernreuther, hep-ph/0205279)
• Standard model: no strong first order for $M_h > 114.4 \text{ GeV}$; CP violation too small

• MSSM: small parameter space for light Higgs and stop

• NMSSM: can have strong first order for large $h A_h S H_1 H_2$

• Secluded sector $U(1)'$
  - Symmetry breaking driven by large $h A_h S H_1 H_2$
  - Tree level CP breaking in Higgs sector associated with soft SM singlet terms
  - New contributions to electric dipole moments very small
  - First phase transition breaks $U(1)'$, second breaks $SU(2) \times U(1)$
Transition at $T_c = 122$ GeV, $\nu(T_c)/T_c = 2.02$
• If we only consider the $\tau$ lepton and thin wall approximation,

$$n_B = \frac{45}{2\pi^2 g_* T^3} \frac{9\gamma^2 (v_W + v) m^2 n_f \Gamma_{SDL} \theta_{CP}}{2\pi^2 \delta v_W T^3}$$

where $\theta_{CP} = (\theta_1)_t - (\theta_1)_f$.

• For reasonable parameters, can obtain adequate asymmetry, even for large $\tilde{t}$ mass.
• Suppose $U(1)'$ forbids large Majorana mass for $\nu_R$ needed for traditional seesaw $\Rightarrow$ need TeV seesaw or small Dirac masses

• $\nu_L\bar{\nu}_L, e^+e^- \rightarrow Z' \rightarrow \nu_R\bar{\nu}_R$ (or $W' \rightarrow e\nu_R$, etc) can produce $\nu_R$ efficiently prior to BBN (Olive, Schramm, Steigman, 1979)
- Rough estimate: $\sigma_{Z'}/\sigma_Z \sim (M_Z/M_{Z'})^4$
- $\nu_R$ decouples for reaction rate $\Gamma_{Z'}(T) = n\langle \sigma Z' v \rangle \sim G_W^2 (M_Z/M_{Z'})^4 T^5$ comparable to expansion rate $H \sim T^2/M_{Pl}$ at,

$$T_d(\nu_R) \sim \left( \frac{M_{Z'}}{M_Z} \right)^{4/3} T_d(\nu_L),$$

where $T_d(\nu_L) \sim$ few MeV.
- $\nu_R$ subsequently diluted by annihilations of heavy particles ($c, \tau, s, \mu, \pi$) and by the confinement of quarks and gluons at quark-hadron transition at $T_c \sim 150 - 400$ MeV (these reheat $e^\pm$, $\nu_L$, $\gamma$ but not $\nu_R$

- Full treatment requires detailed contributions of heavy particles to interactions, expansion rate, and entropy; and $Z - Z'$ mixing
$T_d$ (top) and $\Delta N_{\nu}$ (bottom) for the $\eta$ model, for $T_c = 150$ MeV (circles) and 400 MeV (crosses). Left: A0 and A3. Right: A1 and A2.
Results for the General $E_6$ Model

$T_d$ (left) and $\Delta N_\nu$ (middle) for $M_{Z_2} = 500, 1000, 1500, 2000, 2500, 3500, 4000,$ and $5000$ GeV, for $T_c = 150$ MeV and no mixing. Larger $M_{Z_2}$ corresponds to higher $T_d$ and smaller $\Delta N_\nu$. Right: $M_{Z_2}$ corresponding to $\Delta N_\nu = 0.3, 0.5, 1.0$ and $1.2$, with larger $\Delta N_\nu$ corresponding to smaller $M_{Z_2}$. $\chi, \psi,$ and $-\eta$ correspond to $\theta_{E_6} = 0, \pi/2, 0.71\pi$. The results including mixing are similar.
• Very sensitive to $\theta_{E6}$, $\delta$, and $T_c$

• $\eta$ model
  - $\Delta N_{\nu} < 0.3 \Rightarrow M_{Z'} > (2.5 - 3.2) \text{ TeV}$ for $T_c = 150 \text{ MeV}$
  - $\Delta N_{\nu} < 0.3 \Rightarrow M_{Z'} > (4.0 - 4.9) \text{ TeV}$ for $T_c = 400 \text{ MeV}$

• General $E_6$ case (all mixing assumptions)
  - $\Delta N_{\nu} < 0.3$ for all $\theta_{E6}$ for $M_{Z'} > 2.4 \text{ TeV}$ ($T_c = 150 \text{ MeV}$)
    (more stringent for $T_c = 400 \text{ MeV}$)
  - Limits disappear near $\nu_R$ decoupling angle $\theta_{E6} = 0.42\pi$ ($\chi = 0$, $\psi = \pi/2$, $-\eta = 0.71\pi$)

• Constraints often much more stringent than current direct/indirect; comparable to LHC range

• For $\Delta N_{\nu} < 0.3$, somewhat more stringent than supernova limits, but different uncertainties.
Implications

- $U(1)'$ may forbid traditional GUT-scale seesaw
- $Z'$ masses severely constrained for Dirac $\nu$ by BBN

Ways out
- TeV seesaw or other non-Dirac mechanism
- Large $\xi_e$ asymmetry (equilibration limits don’t apply because of $\Delta N_\nu$)
- $\nu_R$ decoupling from $Z'$ (can occur naturally in $U(1)' \times U(1)'$ model)
Conclusions

- Important to explore alternatives to MSSM
- Top-down string constructions very often contain extra $Z'$ and SM singlets $S$
- Elegant solution to $\mu$ problem
- Many implications, including nonstandard Higgs spectrum/couplings, efficient EW baryogenesis, neutrinos
- But, must observe $Z'$