Beyond the MSSM

- Heavy $Z'$
- Higgs
- Neutralinos
- Exotics
References

• S. Eidelman et al. [Particle Data Group],

• J. Kang and P. Langacker,
  “$Z'$ discovery limits for supersymmetric $E(6)$ models”,

• J. Erler, P. Langacker and T. j. Li,
  “The $Z - Z'$ mass hierarchy in a supersymmetric model with a
  secluded $U(1)'$-breaking sector,”

• V. Barger, C. W. Chiang, J. Jiang and P. Langacker,
  “$B_s - \bar{B}_s$ mixing in $Z'$ models with flavor-changing neutral
  currents,”
• T. Han, P. Langacker and B. McElrath,
  “The Higgs sector in a $U(1)'$ extension of the MSSM,”

• V. Barger, P. Langacker and H. S. Lee,
  “Lightest neutralino in extensions of the MSSM,”

• Work in preparation with J. Kang, B. Nelson; V. Barger, G.
  Shaughnessy, H.S. Lee; T. Han, B. McElrath.
Motivations for (TeV-Scale) Supersymmetry

- Incorporation of gravity \((But \ MSUSY \ could \ be \ very \ large)\)

- Stabilization of electroweak scale
  - But landscape ideas (anthropically-motivated fine tuning); variants (e.g., split supersymmetry)
  - Alternatives: LED, DSB, Little Higgs

- Gauge unification (many variations, compensations possible)

- Cold dark matter (LSP) if \(R_P\) conserved (strongly constrained in MSSM)

- \(Z\)-pole: any new physics decouples

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Minimal Supergravity

- MSSM (minimal supersymmetric extension of standard model): SM gauge group/spectrum \textit{plus} second Higgs doublet, sparticles, \(\lesssim 105\) new parameters

- Minimal supergravity: SUGRA mediation + five (real) parameters (at \(M_P\))
  \[
  m_0, \ M_{1/2}, \ A_0, \ B, \ \mu \quad \text{universal soft breaking} \quad \text{Why small?}
  \]
  \[\rightarrow m_0, \ M_{1/2}, \ A_0, \ tan\beta, \ M_Z, \ signs(\mu)\]

- Specific models (e.g., dilaton) \(\rightarrow\) further relations

- RGE to electroweak scale

- Usually assume \(R_P\) conservation \(\rightarrow\) LSP candidate \(\chi_1^0\) for CDM
Signatures of Minimal SUGRA with $R_P$ at the LHC

- Squarks, gluinos pair-produced at large rate by QCD

- Sleptons, charginos, neutralinos: smaller direct rate (Drell-Yan and $t$-channel squark), but occur in squark decay chains

- Missing transverse energy: decay chains end in LSP

- Cascade decays $\rightarrow$ multiple jets and leptons (same/opposite sign dileptons, trileptons); kinematic edges (mass eigenstates); some spin information

- Same sign leptons $\leftrightarrow$ Majorana fermions

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Minimal SUGRA is simple, but

- Poorly motivated theoretically
- FCNC, diagonal $CP$ violation (EDM’s)
- Tightly constrained by $M_H$, $m_{\chi^\pm}$, cold dark matter, $b \rightarrow s \gamma$, $g_\mu - 2$
Alternatives

- Minimal SUGRA unlikely to be full story, but many alternatives

- Universal gaugino and universal scalar within each sector \((Q, U, D, L, E, N)\)

- Non-universal gaugino masses (e.g., anomaly mediation (slepton problem))

- Phases

- Expanded parameter space, e.g., non-bino LSP
Gauge mediation

- FCNC better, but $\mu$?
- LSP $\leftrightarrow$ Goldstino $g_{3/2}$
- NLSP may decay promptly, in detector, or outside detector
  (Goldstino CDM prefers fast decays)
- NLSP decay: $\chi_1^0 \rightarrow \gamma g_{3/2}$ or $\tilde{l}_R \rightarrow l g_{3/2}$

$R_P$ violation

- $L$ violating: $W \sim LH_u, LL\bar{E}, LQ\bar{D}$
- $B$ violating: $W \sim \bar{U}\bar{U}\bar{D}$
- No missing energy signature
- Multi jets or leptons
- No CDM candidate (axion?)
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)

μ 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, extended Higgs sectors

Important to explore alternatives/extensions to MSSM
Remnants Physics from the Top-Down

- $Z'$ or other gauge
- Extended Higgs/neutralino (doublet, singlet)
- Quasi-Chiral Exotics
- Charge $1/2$ (Confinement?, Stable relic?)
- Quasi-hidden (Strong coupling? SUSY breaking? Composite family?)
- Time varying couplings
- LED (TeV black holes, stringy resonances)
- LIV, VEP (e.g., maximum speeds, decays, (oscillations) of HE $\gamma$, $e$, gravity waves ($\nu$'s))
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: 845 ($Z_{\text{seq}}$), 720 ($Z_\chi$), 690 ($Z_\psi$), 715 ($Z_\eta$)

Discovery to $M_{Z'} \sim 5-8$ TeV at LHC, LC, ($pp \rightarrow e^+e^-, \mu^+\mu^-, q\bar{q}$)

(Depends on couplings, exotics, sparticles)

Diagnostics to 1-2 TeV (asymmetries, $y$ distributions, associated production, rare decays)
Implications of a TeV-scale $U(1)'$

- **Natural Solution to $\mu$ problem** $W \sim hS H_u H_d \rightarrow \mu_{\text{eff}} = h\langle S \rangle$ ("stringy version" of NMSSM)

- **Extended Higgs sector**
  - Relaxed upper limits, couplings, parameter ranges (e.g., $\tan \beta$ can be close to 1)
  - Higgs singlets needed to break $U(1)'$
  - Doublet-singlet mixing $\rightarrow$ highly non-standard collider signatures

- **Large $A$ term and possible tree-level $CP$ violation** (no new EDM constraints) $\rightarrow$ electroweak baryogenesis

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Paul Langacker (FNAL/Penn/IAS)
• **Extended neutralino sector**
  
  – Additional neutralinos, non-standard couplings, e.g., light singlino-dominated, extended cascades
  – Enhanced possibilities for cold dark matter, $g_\mu - 2$ (even small $\tan \beta$)

• **Exotics (anomaly-cancellation)**
  
  – May decay by mixing; by diquark or leptoquark coupling; or be quasi-stable

• **Constraints on neutrino mass generation**

• **Flavor changing neutral currents (for non-universal $U(1)'$ charges)**
  
  – Tree-level effects in $B$ decay competing with SM loops (or with enhanced loops in MSSM with large $\tan \beta$)
**FCNC and rare $B$ decays**

- $U(1)'$ couplings often family-nonuniversal in string constructions
  $\Rightarrow$ FCNC ($Z'$ and $Z$ from $Z - Z'$ mixing) after family mixing (GIM breaking) (also from exotic mixing)

- Depends on $V_{\psi L}$ and $V_{\psi R}$, $\psi = u, d, e, \nu$, but only $V_{\text{CKM}} = V_{uL}^c V_{dL}^\dagger$ and $V_{\text{MNS}} = V_{\nu L}^c V_{eL}^\dagger$ known from exp

- $K$ and $\mu$ decays $\Rightarrow$ first two families are universal (PL, Plüümacher)

- Third family could be nonuniversal
  - $A_{FB}^{0b}$ (Erler, PL)
  - $B_s - \bar{B}_s$ mixing and rare $B$ decays, especially in competition with SM (or SUSY) loops, e.g. $B \to \phi K, \eta'K, \pi K$ or $B_s \to \mu^+\mu^-$ (Leroux, London; Barger, Chiang, Jiang, PL, Lee)
Interaction $\mathcal{L}^{Z'} = -g' J'_\mu Z'^\mu$, where

$$J'_\mu = \sum_{i,j} \bar{\psi}_i^I \gamma_\mu \left[ (\epsilon_{\psi_L})_{ij} P_L + (\epsilon_{\psi_R})_{ij} P_R \right] \psi_j^I$$

Can pick basis with $\epsilon_{\psi_L,R}$ real and diagonal, but non-universal. In mass basis, couplings are

$$B^L_d \equiv V_{dL} \epsilon_{dL} V_{dL}^\dagger, \quad B^R_d \equiv V_{dR} \epsilon_{dR} V_{dR}^\dagger,$$

which is Hermitian but non-diagonal.
$B_s - \bar{B}_s$ mixing

- $x_s = \Delta M_s / \Gamma_s > 20.8$ (new HFAG, $x_s > 21.1$ (\(\Delta M_s > 14.4 \text{ ps}^{-1}\)); CDF: $\Delta M_s > 7.9 \text{ ps}^{-1}$)

- SM box: $x_s^{SM} = 26.3 \pm 5.5$

- $\phi_s^{SM} = 2 \arg(\mathcal{V}_{tb} \mathcal{V}_{ts}^*) = -2\lambda^2 \eta \simeq -2^\circ$

- $Z'$ (tree)

$$\mathcal{H}_{\text{eff}}^{Z'} = \frac{G_F}{\sqrt{2}} \left( \frac{g_2 M_Z}{g_1 M_{Z'}} B_{sb} \right)^2 O^{LL}(m_b) + LR + RR + RL$$

$$\equiv \frac{G_F}{\sqrt{2}} \rho_L^2 e^{2i\phi_L} O^{LL}(m_b) + LR + RR + RL$$
$\sin 2\phi_s = 0.5$

Consistent with SM

$1\sigma$ range of $x_s$

Exp. excluded

$\sigma$ range of $x_s$ -0.07

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\[ B_{s} \to \mu^{+}\mu^{-} \]

- **CDF:** \( B(B_{s} \to \mu^{+}\mu^{-}) < 2.0 \times 10^{-7} \) (95%)

- **Standard model:** \( \sim 3.8 \times 10^{-9} \)

- **SUSY loops (especially large \( \tan \beta \))**: \( \sim 5 \times 10^{-7} \)

- **TeV -scale \( Z' \) with family non-universal:** \( \sim 10^{-7} - 10^{-8} \)
The $\mu$ problem

Superpotential: $W = \mu \hat{H}_u \hat{H}_d + h_t \hat{Q} \hat{H}_u \hat{d}^c \Rightarrow$

$L_{\text{fermion}} = \mu \hat{H}_u \hat{H}_d + h_t (\hat{Q} \hat{H}_u \hat{d}^c + \hat{Q} \hat{H}_u \hat{d}^c + \hat{Q} \hat{H}_u \hat{d}^c)$

$-L^W_{\text{scalar}} = \sum_\phi \left| \frac{\delta W}{\delta \phi} \right|^2 = \mu^2 (|H_u|^2 + |H_d|^2) + h_t \text{ terms}$

$-L^D = \frac{g^2 + g'^2}{8} (|H_u|^2 - |H_d|^2)^2 + \text{charged Higgs, squark, slepton}$

$-L^\text{soft} = m_u^2 |H_u|^2 + m_d^2 |H_d|^2 + (m_3^2 H_u H_d + \text{h.c.})$

$+ \text{squark/slepton} + M_3 \tilde{g} \tilde{g} \text{ gluino} + M_2 \tilde{w} \tilde{w} \text{ wino} + M_1 \tilde{b} \tilde{b} \text{ bino}$
• Soft terms set EW scale, e.g., $m_{\text{soft}} \sim F^2/M_{\text{pl}}$, $F \sim 10^{11}$ GeV, $M_{\text{pl}} \sim 10^{19}$ GeV

• $\mu$ problem: $\mu$ is supersymmetric $\Rightarrow$ could be very large (or exactly zero in string theory), but need $\mu \sim m_{\text{soft}} \lesssim 1$ TeV

• Two classes of solutions
  – Dynamical: $\mu \equiv 0$ by symmetry or string, but $W = h_s \hat{S} \hat{H}_u \hat{H}_d \Rightarrow \mu_{\text{eff}} = h_s \langle S \rangle$, $\langle S \rangle \sim m_{\text{soft}}$ (Examples: $Z'$ models, NMSSM, nMSSM)
  – Generate $\mu$ in hidden sector along with $m_{\text{soft}}$
Extended Higgs Sector

- Standard model singlets $S_i$ and additional doublet pairs $H_{u,d}$ very common.

- Additional doublet pairs
  - Richer spectrum, decay possibilities
  - May be needed (or expand possibilities for) quark/lepton masses/mixings (e.g., stringy symmetries may restrict single Higgs couplings to one or two families)
  - Extra neutral Higgs $\rightarrow$ FCNC (suppressed by Yukawas)
  - Significantly modify gauge unification
Higgs singlets $S_i$

- Standard model singlets extremely common in string constructions
- Needed to break extra $U(1)'$ gauge symmetries
- Solution to $\mu$ problem ($U(1)'$, NMSSM, nMSSM)

$$W \sim h S H_u H_d \rightarrow \mu_{\text{eff}} = h \langle S \rangle$$

- Relaxed upper limits, couplings, parameter ranges (e.g., $\tan \beta$ can be close to 1), singlet-doublet mixing
- Large $A$ term and possible tree-level $CP$ violation $\rightarrow$ electroweak baryogenesis
A Secluded Sector $U(1)'$ Model

(Erler, PL, Li, hep-ph/0205001)

- 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 $H_{1,2}$
- Off-diagonal Yukawas
- Can be consistent with minimal gauge unification
- Complex Higgs, neutralino spectrum and decays, very different from MSSM and NMSSM because of small $\tan\beta$, mixing, and $D$ terms (T. Han, PL, B. McElrath. hep-ph/0405244)
6 Higgs scalars and 4 pseudoscalars

- Can have tree level CP breaking ⇒ mixing
- Often light scalars with significant singlet/doublet admixture → reduced coupling; often light pseudoscalar
- Can have lightest Higgs up to \( \sim 168 \) GeV with all couplings perturbative to \( M_P \) because of \( D \) terms

\[
M_h^2 \leq h^2 v^2 + (M_Z^2 - h^2 v^2) \cos^2 2\beta \\
+ 2g_Z^2 v^2 (Q_{H_2} \cos^2 \beta + Q_{H_1} \sin^2 \beta)^2 \\
+ \frac{3}{4} \frac{m_t^4}{v^2 \pi^2} \log \frac{m_{t_1} m_{t_2}}{m_t^2}.
\]

- Typically, \( \tan \beta \sim 1 - 3 \)
One of the most important parameters in the SUSY Higgs sector is $\tan \beta$. In the model
LEP2 (209 GeV) Higgsstrahlung Cross Section

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LEP2 H A Cross Section

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

\[ M_A \text{ (GeV)} \]

- \( H_1 A_1 \)
- \( H_1 A_2 \)
- \( H_2 A_1 \)
- MSSM NLO (\( \tan \beta = 5 \))
• Wide range of spectra, including light or heavy $H_1, A_1$; usually light $\chi_1^0$

• Many possible decay channels for light and heavy, including MSSM-like, Higgs, neutralino (invisible), cascade (heavier neutralinos)
  – Usually $H_1 \to \chi_1^0 \chi_1^0$ or $A_1 A_1$ when kinematically possible
  – Also, $H \to b\bar{b}, \tau^+ \tau^-, c\bar{c}; H_i \to H_j H_k, A_j A_k$
Typical allowed light CP-even and odd masses are shown in Fig. 2(a) for various ranges of MSSM fractions. We see...
A ... is lighter than the b¯b pair mass. Charm and tau decays can also be significant, depending on the value of tan β.
### Neutralinos

<table>
<thead>
<tr>
<th>Model</th>
<th>Symmetry</th>
<th>Superpotential</th>
<th>Higgses (CP even, CP odd, charged)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSSM</td>
<td>–</td>
<td>$\mu H_1 H_2$</td>
<td>$H_1^0, H_2^0, A^0, H^\pm$</td>
</tr>
<tr>
<td>NMSSM</td>
<td>$Z_3$</td>
<td>$h_s S H_1 H_2 + \frac{\kappa}{3} S^3$</td>
<td>+ $H_3^0, A_2^0$</td>
</tr>
<tr>
<td>nMSSM</td>
<td>$Z_5^R, Z_7^R$</td>
<td>$h_s S H_1 H_2 + \alpha S$</td>
<td>+ $H_3^0, A_2^0$</td>
</tr>
<tr>
<td>UMSSM</td>
<td>$U(1)'$</td>
<td>$h_s S H_1 H_2$</td>
<td>+ $H_3^0$</td>
</tr>
<tr>
<td>SMSSM</td>
<td>$U(1)'$</td>
<td>$h_s S H_1 H_2 + \lambda_S S_1 S_2 S_3$</td>
<td>+ $H_3^0, H_4^0, H_5^0, H_6^0, A_2^0, A_3^0, A_4^0$</td>
</tr>
</tbody>
</table>

- **MSSM**: gaugino unification but general $\mu$
- **NMSSM**: domain wall problems
- **nMSSM**: avoids domain walls
- **UMSSM**: additional $Z'$
- **SMSSM**: stringy NMSSM w. decoupled $\mu_{eff}, M_{Z'}$ (lighter neutralinos similar to nMSSM)
Mass matrix ($M_{\chi^0}$) in basis \{\tilde{B}, \tilde{W}_3, \tilde{H}_1^0, \tilde{H}_2^0, \tilde{S}, \tilde{Z}'\}:

$$
\begin{pmatrix}
M_1 & 0 & -g_1 v_1/2 & g_1 v_2/2 & 0 & 0 \\
0 & M_2 & g_2 v_1/2 & -g_2 v_2/2 & 0 & 0 \\
-g_1 v_1/2 & g_2 v_1/2 & 0 & -\mu_{\text{eff}} & -\mu_{\text{eff}} v_2/s & g_{Z'} Q_{H_1} v_1 \\
g_1 v_2/2 & -g_2 v_2/2 & -\mu_{\text{eff}} & 0 & -\mu_{\text{eff}} v_1/s & g_{Z'} Q_{H_2} v_2 \\
0 & 0 & -\mu_{\text{eff}} v_2/s & -\mu_{\text{eff}} v_1/s & \sqrt{2} \kappa s & g_{Z'} Q_{S} v_2 \\
0 & 0 & g_{Z'} Q_{H_1} v_1 & g_{Z'} Q_{H_2} v_2 & g_{Z'} Q_{S} v_2 & M_{1}'
\end{pmatrix}
$$

($$\langle S \rangle \equiv \frac{s}{\sqrt{2}}$$, $$\langle H_{i}^0 \rangle \equiv \frac{v_i}{\sqrt{2}}$$, $$\sqrt{v_1^2 + v_2^2} \equiv v \simeq 246 \text{ GeV}$$, $$Q'_\phi = \phi U(1)'$$ charge)

(\text{black = MSSM; blue = extensions; cyan = NMSSM; magenta = UMSSM})

**Scan over plausible parameter ranges, requiring** $M_{\chi_1^\pm} > 104$ GeV, and $\Gamma_{Z \rightarrow \chi_1^0 \chi_1^0} < 2.3$ MeV (95\% C.L.) (V. Barger, PL, H.S. Lee, hep-ph/0508027)
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(Relic density and $g_\mu - 2$ in nMSSM, SMSSM)
Masses of $\chi_2^0 \text{ vs } \chi_1^0$

- Often $\chi_2^0 \cdots \chi_5^0$ are MSSM-like with light singlino-dominated $\chi_1^0$
- MSSM-like cascades with extra $\chi_2^0 \rightarrow \chi_1^0 + (l\bar{l}, q\bar{q}, Z, h)$
- Often $\chi_2^0 \rightarrow \chi_1^0 + (Z, h)$; $\chi_1^+ \rightarrow \chi_1^0 + (W^+, H^+)$ are open
  (e.g., $\chi_1^+ \chi_2^0 \rightarrow W^+ h + \not{E}_T \rightarrow l^+ b \bar{b} + \not{E}_T$)

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• Often $\chi_2^0 \rightarrow \chi_1^0 + (Z, h)$; $\chi_1^+ \rightarrow \chi_1^0 + (W^+, H^+)$ open w. fairly light $\chi_1^+$, $\chi_2^0$

(e.g., $\chi_1^+ \chi_2^0 \rightarrow W^+ h + E_T \rightarrow l^+ b \bar{b} + E_T$,
or $\chi_1^+ \chi_2^0 \rightarrow W^+ Z + E_T \rightarrow l^+ l^\prime \bar{l}^\prime + E_T$)

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Quasi-Chiral Exotics
(J. Kang, PL, B. Nelson, in progress)

- Often find exotic (wrt $SU(2) \times U(1)$) quarks or leptons at TeV scale
  
  - Assume non-chiral wrt SM gauge group (strong constraints from precision EW, especially on extra or mirror families)
  
  - Can be chiral wrt extra $U(1)$’s or other extended gauge
  
  - Usually needed for $U(1)$’ anomaly cancellation
  
  - Modify gauge unification unless in complete GUT multiplets
  
  - Can also be more extreme exotics (e.g., adjoints, symmetric, fractional charge, mixed quasi-hidden)
  
  - Experimental limits relatively weak
• Examples in 27-plet of $E_6$
  
  $D_L + D_R$ ($SU(2)$ singlets, chiral wrt $U(1)'$)

  $-(\begin{pmatrix} E^0 \\ E^- \end{pmatrix}_L + \begin{pmatrix} E^0 \\ E^- \end{pmatrix}_R)$ ($SU(2)$ doublets, chiral wrt $U(1)'$)

• Pair produce $D + \bar{D}$ by QCD processes (smaller rate for exotic leptons)

• Lightest $D$ or $\tilde{D}$ decays by

  $D \rightarrow u_i W^-, D \rightarrow d_i Z, D \rightarrow d_i H^0$ if driven by $D - \bar{d}$ mixing (not in minimal $E_6$; FCNC) $\rightarrow m_D \gtrsim 200$ GeV (future: $\sim 1$ TeV)

  Quark jets if driven by $R_P$ operator $\bar{u}\bar{u}\tilde{D}$ (diquark)

  Quark jet + lepton if driven by $R_P$ operator $l q \tilde{D}$ (leptoquark)

  May be stable at renormalizable level due to accidental symmetry (e.g., from extended gauge group) $\rightarrow$ escapes from detector as charged or neutral hadron (Quasi-stable from HDO $\rightarrow \tau \sim 1/10$ yr)
Conclusions

• Combination of theoretical ideas and new experimental facilities may allow testable theory to Planck scale

• From the bottom up: there may be more at TeV scale than (minimal SUGRA) MSSM

• From the top down: there may be more at TeV scale than (minimal SUGRA) MSSM