Supersymmetry and Exceptional New Physics

just beyond the Standard Model
Part 1

- Why go beyond the Standard Model?
- Supersymmetry
  - The Hierarchy Problem
- SUSY models: MSSM → E6SSM
- Further Motivation
  - Grand Unification, Dark matter...
- Radiative electroweak symmetry breaking
- Benchmark spectra

In this today’s talk I will mostly be pretending that the recent LHC constraints haven’t happened...
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Part 2

Next week I will focus on the LHC

- LHC phenomenology
- Impact of LHC search constraints
- Improved precision
Standard Model

- Standard Model (SM) of particle physics
  - Beautiful description of Electromagnetic, Weak and Strong forces
  - Tested to incredible precision, e.g. the anomalous magnetic moment of the electron,
    \[ a_e(\text{Exp}) = 11596521810 \pm 7 \times 10^{-13} \]
    \[ a_e(\text{SM}) = 11596521827.8(0.772)(0.011)(0.026) \times 10^{-13} \]
  - Electroweak (EW) symmetry is broken by the Higgs Mechanism.
  - Predicts the (as yet) unobserved Higgs boson.
  - The Higgs boson is sought at the Large Hadron collider.
Beyond the Standard Model

“If it ain’t broke, why fix it?”

- The SM has not been fully verified*
  - The SM Higgs boson has not been found yet.
- SM is incomplete
  - Neglects gravitation, very weak at low energies (large distances)
  - Expect New Physics at Planck Energy (mass) \( (\Lambda \sim 10^{19} \text{ GeV}) \)
- Neutrinos have mass
- Baryon/lepton asymmetry
- Expect New Physics at the TeV scale as well
  - Hierarchy Problem
  - No Gauge Coupling Unification in SM
  - Dark matter
  - ‘Ad hoc’ shape for Higgs potential.

*though there is an enormous body of experimental evidence to support it.
SUperSYmmetry (SUSY)

- A symmetry between fermions and bosons
  \[ Q |\text{Boson}\rangle = |\text{Fermion}\rangle \]
  \[ Q |\text{Fermion}\rangle = |\text{Boson}\rangle \]

- Extends special relativity, evading Coleman and Mandula “No-Go” theorem.

- The Super Poincare algebra:

  \[ P_\mu \quad \text{- translations} \]
  \[ M_{\mu\nu} \quad \text{- rotations and boosts} \]
  \[ Q_\alpha \quad \text{- SUSY transformation} \]

\[ \{Q^A_\alpha, \bar{Q}^B_\beta\} = 2\sigma^\mu_{\alpha\beta} P_\mu \delta^A_B \]
\[ \{Q^A_\alpha, Q^B_\beta\} = 0 \]
\[ [P_\mu, Q^A_\alpha] = [P_\mu, \bar{Q}^A_\alpha] = 0 \]

- SUSY = a translation in Superspace. \[ z = (x_\mu, \theta^a, \bar{\theta}_{\dot{a}}) \]
**Hierarchy Problem**

- Expect New Physics at Planck Energy (Mass) ($\Lambda \sim 10^{19}$ GeV)
- Higgs mass sensitive to this scale ($m_h \sim 100$ GeV)

\[
\text{physical mass} = \text{"bare mass" } + \text{"loops"}
\]

\[
m_h^2 = m_0^2 - \frac{\lambda f^2}{8\pi^2} (\Lambda^2 - \int_0^1 dx 2\Delta \ln \frac{\Lambda^2 + \Delta}{\Delta})
\]

\[
m_h^2 = m_0^2 - C\Lambda^2 + \ldots
\]

$\Rightarrow$ Huge Fine tuning!

- Cut off integral at Planck Scale ($\Lambda$) \(\leftarrow\) naive approach to renormalisation
In Supersymmetry

Bosonic degrees of freedom = Fermionic degrees of freedom.

⇒ Two scalar superpartners for each fermion

\[ m_H^2 = m_0^2 - \frac{\lambda^2_t}{8\pi^2} \left( \Lambda^2 - \int_0^1 dx 2\Delta \ln \frac{\Lambda^2 + \Delta}{\Delta} \right) \]

\[ + \frac{\lambda^2_t}{16\pi^2} \left( 2\Lambda^2 - m_{\tilde{t}_1}^2 \ln \frac{\Lambda^2 + m_{\tilde{t}_1}^2}{m_{s1}^2} - m_{\tilde{t}_2}^2 \ln \frac{\Lambda^2 + m_{\tilde{t}_2}^2}{m_{s2}^2} \right) \]

In SUSY \( \lambda_{\tilde{t}} = \lambda^2_t \)

 Quadratic divergences cancelled!

⇒ No Fine Tuning?
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Minimal Supersymmetric Standard Model (MSSM)

The MSSM = minimal particle content compatible with known physics, i.e Standard Model particles and properties.

Basic idea: take SM and supersymmetrise:

Warning: Image not entirely accurate.
Superfield content of the MSSM

Gauge group is that of SM: \( G_{SM} \equiv SU(3) \times SU(2) \times U(1)_Y \)

Vector superfields of the MSSM

<table>
<thead>
<tr>
<th>Supermultiplet</th>
<th>Gauge</th>
<th>spin 1/2</th>
<th>spin 1</th>
<th>( SU(3)_C )</th>
<th>( SU(2)_L )</th>
<th>( U(1)_Y )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \hat{G} )</td>
<td>( SU(3)_C )</td>
<td>( \tilde{g} )</td>
<td>( g )</td>
<td>8</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>( \hat{W} )</td>
<td>( SU(2)_W )</td>
<td>( \tilde{W}^\pm \tilde{W}^0 )</td>
<td>( W^\pm W^0 )</td>
<td>1</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>( \hat{B} )</td>
<td>( U(1)_Y )</td>
<td>( \tilde{B}^0 )</td>
<td>( B^0 )</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Gauge supermultiplets of the MSSM, and gauge group representations.
# MSSM Chiral Superfield Content

<table>
<thead>
<tr>
<th>Supermultiplet</th>
<th>spin 0</th>
<th>spin 1/2</th>
<th>( SU(3)_C )</th>
<th>( SU(2)_L )</th>
<th>( U(1)_Y )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \hat{Q}_i )</td>
<td>( (\tilde{u}_L ; \tilde{d}_L)_i )</td>
<td>( (u_L ; d_L)_i )</td>
<td>3</td>
<td>2</td>
<td>( \frac{1}{6} )</td>
</tr>
<tr>
<td>( \bar{u}_i )</td>
<td>( \tilde{u}_{R_i}^* )</td>
<td>( u_{R_i}^\dagger )</td>
<td>( \bar{3} )</td>
<td>1</td>
<td>( -\frac{2}{3} )</td>
</tr>
<tr>
<td>( \bar{d}_i )</td>
<td>( \tilde{d}_{R_i}^* )</td>
<td>( d_{R_i}^\dagger )</td>
<td>( \bar{3} )</td>
<td>1</td>
<td>( \frac{1}{3} )</td>
</tr>
<tr>
<td>( \hat{L}_i )</td>
<td>( (\tilde{\nu} ; \tilde{e}_L)_i )</td>
<td>( (\nu ; e_L)_i )</td>
<td>1</td>
<td>2</td>
<td>( -\frac{1}{2} )</td>
</tr>
<tr>
<td>( \bar{e}_i )</td>
<td>( \tilde{e}_{R_i}^* )</td>
<td>( e_{R_i}^\dagger )</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>( \hat{H}_u )</td>
<td>( (H_u^+ ; H_u^0) )</td>
<td>( (\tilde{H}_u^+ ; \tilde{H}_u^0) )</td>
<td>1</td>
<td>2</td>
<td>( +\frac{1}{2} )</td>
</tr>
<tr>
<td>( \hat{H}_d )</td>
<td>( (H_d^0 ; H_d^-) )</td>
<td>( (\tilde{H}_d^0 ; \tilde{H}_d^-) )</td>
<td>1</td>
<td>2</td>
<td>( -\frac{1}{2} )</td>
</tr>
</tbody>
</table>
Mass eigenstates of the MSSM (and SUSY jargon)

SUSY partners of SM particles are “sparticles”.

Scalar partners of SM fermions are “sfermions” → “squarks” and “sleptons”.

Fermion partners of SM bosons are “gauginos/higgsinos”

<table>
<thead>
<tr>
<th>SUSY partners</th>
<th>Mass eigenstates</th>
</tr>
</thead>
<tbody>
<tr>
<td>up squarks</td>
<td>$\tilde{u}_L$, $\tilde{u}_R$, $\tilde{s}_L$, $\tilde{s}_R$, $\tilde{t}_L$, $\tilde{t}_R$</td>
</tr>
<tr>
<td>down squarks</td>
<td>$\tilde{d}_L$, $\tilde{d}_R$, $\tilde{c}_L$, $\tilde{c}_R$, $\tilde{b}_L$, $\tilde{b}_R$</td>
</tr>
<tr>
<td>charged sleptons</td>
<td>$\tilde{e}_L$, $\tilde{e}_R$, $\tilde{\mu}_L$, $\tilde{\mu}_R$, $\tilde{\tau}_L$, $\tilde{\tau}_R$</td>
</tr>
<tr>
<td>sneutrinos</td>
<td>$\tilde{\nu}<em>e$, $\tilde{\nu}</em>\mu$, $\tilde{\nu}_\tau$</td>
</tr>
<tr>
<td>Higgs bosons</td>
<td>$H_u^0$, $H_d^0$, $H_u^+$, $H_d^-$</td>
</tr>
<tr>
<td>neutralinos</td>
<td>$\tilde{B}_u^0$, $\tilde{W}_u^0$, $\tilde{H}_u^0$, $\tilde{H}_d^0$</td>
</tr>
<tr>
<td>charginos</td>
<td>$\tilde{W}_u^\pm$, $\tilde{H}_u^+$, $\tilde{H}_d^-$</td>
</tr>
<tr>
<td>gluino</td>
<td>$\tilde{g}$</td>
</tr>
</tbody>
</table>
SUSY Theory space

Gauge group (vector superfields)

$G_{SM} \times U(1)_N$

USSM

$G_{SM}$

MSSM

NMSSM

Minimal superfields

Complete E6 multiplets

Chiral superfields

E6SSM
The $\mu$ problem

- The MSSM superpotential is written down before EWSB or SUSY breaking:
  - it should know nothing about the EW scale.

\[ W_{MSSM} = Y_u \tilde{Q}_L H_u u_R - Y_d \tilde{Q}_L \cdot H_d d_R - Y_e \tilde{E} \cdot H_d d_R - \mu H_u H_d \]

- The superpotential contains a mass scale!

- What mass should we use?
  - The natural choices would be 0 or $M_{\text{Planck}}$ (or $M_{\text{GUT}}$)

- Phenomenological Constraints $\Rightarrow \mu \approx 0.1 - 1$ TeV
Supersymmetric Models

- **Minimal Supersymmetric Standard Model (MSSM)**

\[ W_{MSSM} = Y_u \bar{Q}_L H_u u_R - Y_d \bar{Q}_L H_d d_R - Y_e \bar{E} H_d d_R - \mu H_u H_d \]

- **Next to Minimal Supersymmetric Standard Model (NMSSM)**

[Dine, Fischler and Srednicki]
[Ellis, Gunion, Haber, Roszkowski, Zwirner]

\[ W_{NMSSM} = Y_u \bar{Q}_L H_u u_R - Y_d \bar{Q}_L H_d d_R - Y_e \bar{E} H_d d_R - \lambda S H_u H_d + \frac{1}{3} \kappa S^3 \]

Other variants: nmMSSM, PQSNMSSM.

\[ \mu_{eff} = \lambda \langle S \rangle \]

- **U(1) extended Supersymmetric Standard Model (USSM)**

- **Exceptional Supersymmetric Standard Model (E_6SSM)**

Exceptional New Physics

just beyond the Standard Model

E_8 \times E_8' Heterotic String Theory

Grand Unified Theory, e.g. SU(5), SO(10), E_6

Desert

Exceptional New Physics (exotic matter, e.g. Leptoquarks)

Supersymmetry, e.g. MSSM, E_6SSM

Electroweak physics

Exotic matter from complete E_6 multiplets survives to low energies!
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Exceptional Supersymmetric Standard Model


- E$_6$ inspired model with an extra gauged U(1) symmetry

\[ SU(3) \times SU(2) \times U(1)_Y \times U(1)_N \]

“Inspired” by:

\[ U(1)_N = \cos \theta U(1)_\chi + \sin \theta U(1)_\psi \]

\[ E_6 \rightarrow SO(10) \times U(1)_\psi \]

\[ \downarrow \]

\[ SU(5) \times U(1)_\chi \]

\[ \downarrow \]

\[ SU(3)_C \times SU(2)_W \times U(1)_Y \]

Solves the $\mu$-problem!

- In the E$_6$SSM $\tan \theta = \sqrt{15} \Rightarrow$ right-handed neutrino is a gauge singlet

$\Rightarrow$ super heavy right-handed neutrinos, generates lepton/baryon asymmetry of the universe [JHEP 0812, 042 (2008), S.F.King, R. Luo, R.Nevorov & D.J. Miller]

- Matter from 3 complete generations of E$_6$

$\Rightarrow$ automatic cancellation of gauge anomalies
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  - $a_\mu$: 3 $\sigma$ deviation
  - Hierarchy Problem / Naturalness
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Running modified at TeV scale! ⇒ TeV scale new physics

Minimal Supersymmetric Standard Model

\[
\frac{d \alpha_i^{-1}}{d (\log Q)} = \frac{b_i}{2\pi}
\]

SU(N) gauge theory

\[
b_N = \frac{11}{3} N - \frac{2}{3} N - \frac{1}{3} n_f - \frac{1}{6} n_s
\]

U(1) gauge

\[
b_1 = -\frac{1}{3} \sum_i Y_i^2
\]

(matter particles in fundamental representation)

Gauginos

Number of fermions

Number of scalars
GUT matter multiplets

\[ E_6 \rightarrow SO(10) \rightarrow SU(5) \]

\[ \begin{array}{c}
\{ 10 \}^i + \\
\{ 5^* \}^i + \\
\{ 1 \}^i \\
\end{array} \]

\[ Q_i, u_i^c, e_i^c \]

\[ L_i, d_i^c \]

\[ N_i^c \]

\[ \begin{array}{c}
\{ 5 \}^{(i)} + \\
\{ 5^* \}^{(i)} + \\
\{ 1 \}^{(i)} \\
\end{array} \]

\[ H_{u,(i)}, D_{(i)} \]

\[ H_{d,(i)}, \bar{D}_{(i)} \]

\[ S_i \]

SM singlets

Color triplets
Gauge Coupling Unification

Running modified at TeV scale!

$\Rightarrow$ TeV scale new physics

Minimal Supersymmetric Standard Model

$d\alpha_i^{-1} \over d(\log Q) = {b_i \over 2\pi}$

Complete GUT multiplets give equal $\Delta b_i$

Single step unification $\Rightarrow$ incomplete multiplets

Higgs $\not\in$ SU(5) matter multiplet.

$SU(N)$ gauge theory

$\frac{d\alpha_i^{-1}}{d(\log Q)} = \frac{b_i}{2\pi}$

$SU(N)$ gauge theory

$b_N = \frac{11}{3}N - \frac{2}{3}N - \frac{1}{3}n_f - \frac{1}{6}n_s$

Gauginos

$U(1)$ gauge

$b_1 = -\frac{1}{3} \sum_i Y_i^2$

(matter particles in fundamental representation)

Number of fermions

Number of scalars

$N = 1$

$N = 3$

$nf = 1$

$ns = 1$
Gauge Coupling Unification

Excepional Supersymmetric Standard Model

- Evolution changed dramatically!
- Strong gauge coupling beta vanishes at one loop!
- 2-loop and threshold effects important!
- Higgs $\in E_6$ 27plets $\Rightarrow$ relics of $27'$ and $\overline{27}'$ ($H'$ and $\overline{H}'$).
  (for 2 step unification without relics see R.Howl, S.F. King PLB 652, 331, JHEP 0801:030)

SU(N) gauge theory

$$b_N = \frac{11}{3} N - \frac{2}{3} N - \frac{1}{3} n_f - \frac{1}{6} n_s$$

New exotic matter!

$$b_1 = -\frac{1}{3} \sum_i Y_i^2$$

(matter particles in fundamental representation)
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Dark Matter

- No electromagnetic interaction $\Rightarrow$ ‘Dark’
- ‘Visable’ through gravitational interactions
- 85% of the matter in the universe is Dark
- So Dark matter exists, but what is it?

Neutrino Mass limits $\Rightarrow$ SM cannot account for observed Dark matter

Physics beyond the SM is required!
Particle physics explanation for Dark Matter required!

Both viewing the same thing: dark matter!

A particle theorist is interested in both. Fundamental theories should fit all data!
MSSM R-parity

Aim: build $\mathcal{L}_{SUSY}$ invariant under $G_{SM}$, with a chiral superfield for all SM fermions and gauge supermultiplet for each gauge boson of SM.

$$\mathcal{W}_{MSSM}^{RPV} = \epsilon_{\alpha\beta}(y^i_u \tilde{H}_u^\alpha \bar{u}_i \tilde{Q}_j^\beta - y^i_d \tilde{H}_d^\alpha \bar{d}_i \tilde{Q}_j^\beta - y^i_e \tilde{H}_e^\alpha \bar{e}_i \tilde{L}_j^\beta + \mu \tilde{H}_u^\alpha \tilde{H}_d^\beta)$$

$$+ \frac{1}{2} \lambda_{ijk} L_i L_j \bar{e}_k + \lambda'_{ijk} L_i Q_j \bar{d}_k + \mu' L_i H_u + \frac{1}{2} \lambda''_{ijk} \bar{u}_i \bar{d}_j \bar{d}_k$$

Strong constraints on L and B violating operators.

Tightest constraint comes from non-observation of proton decay

Solution: Impose R-parity.

$$P_R = (-1)^{3(B-L)+2s}$$

All SM particles + Higgs bosons: $P_R = +1$ ⇒ SUSY particles appear in even numbers

All SUSY particles: $P_R = -1$ ⇒ SUSY pair production

⇒ Lightest Supersymmetric Particle (LSP) is stable!

Gives rise to a Dark Matter candidate.
Dark Matter and R-parity

- Baryon and Lepton number violating interactions $\Rightarrow$ Proton decay
- Impose a $Z_2$ parity to forbid them.

- R-Parity: SM particles even
  SUSY partners odd
$\Rightarrow$ SUSY particles decay into an odd number of SUSY particles.

Lightest Supersymmetric Particle (LSP)
Stable, neutral, non-baryonic matter
$\Rightarrow$ Dark Matter Candidate

- Two independent phenomenological problems, same solution!
- Can the model correctly predict the relic abundance?
Generic $m_{1/2} - m_0$ plane

Slide stolen from: Keith Olive SUSY 2010
E₆SSM Discrete Symmetries

- $Z^B_2$ or $Z^L_2$ symmetries
  - To evade rapid proton decay.
  - Like R-parity but $D$ is odd while $\bar{D}$ is even.
  - $Z^B_2 \Rightarrow \text{leptoquarks}; \quad Z^L_2 \Rightarrow \text{diquarks}.$

- $Z^H_2$ symmetry (approximate)
  - To evade large Flavour Changing Neutral Currents.
  - $H_{1,3}, H_{2,3}$ and $S_3$ (superfields): even, all others: odd.
  - Exotic quarks and inert Higgs decay, violate $Z^H_2$
    $\Rightarrow Z^H_2$ only approximate!

For top down constructions see:
King and Howl, PLB 687, 355 (2010),

- In E₆SSM Relic density can be achieved entirely from the inert sector,
  or from a bino like neutralino with massless singlinos.
E$_6$SSM Superpotential

- Imposing $Z_2^{B/L}$ and $Z_2^H$

$$ W_{E_6SSM} \rightarrow \lambda_i \hat{S}(\hat{H}_{1i} \hat{H}_{2i}) + \kappa_i \hat{S}(\hat{D}_i \hat{D}_i) + f_{\alpha\beta} \hat{S}_\alpha(\hat{H}_d \hat{H}_{2\beta}) $$

$$ + \tilde{f}_{\alpha\beta} \hat{S}_\alpha(\hat{H}_{1\beta} \hat{H}_u) + \frac{1}{2} M_{ij} \hat{N}_i^c \hat{N}_j^c + \mu'(\hat{H'}^\dagger \hat{H'}) $$

$$ + h_{4j}^E(\hat{H}_d \hat{H'}) \hat{e}_j^c + h_{4j}^N(\hat{H}_u \hat{H'}) \hat{N}_j^c + W_{MSSM}(\mu = 0) $$

- To ensure only 3$^{rd}$ gen. gets vevs, we choose:

$$ \kappa_i \sim \lambda_3 \geq \lambda_{1,2} \Rightarrow f_{\alpha\beta}, \tilde{f}_{\alpha\beta}, h_{4j}^E, h_{4j}^N. $$

- Further integrating out super heavy, right handed neutrinos, and dropping $\mu'$, leaves:

$$ W_{E_6SSM} \approx \lambda_i S H_{1,i} H_{2,i} + \kappa_i S D_i \bar{D}_i $$

$$ + h_t H_u Q t^c + h_b H_d Q b^c + h_\tau H_d L \tau^c $$
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Next Week...

Focus on LHC:

- What we might see
- Current status
- How to interpret what it means for SUSY.

- Radiative electroweak symmetry breaking

- Benchmark spectra

- Closer Look at LHC phenomenology of E6SSM

- LHC search constraints

- Naturalness / fine tuning.