Physics Beyond Standard Model

(mostly supersymmetry)

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Outline

1) Why BSM Physics?
2) Hierarchy Problem
3) Supersymmetry as a solution
4) The structure of MSSM
5) Soft terms in Different Mediation Schemes
why BSM Physics?

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neutrino masses

- Super K (atmospheric), SNO (solar), KamLAND, DAYA-BAY (reactor) etc. have put neutrino oscillations on a strong footing.

- Neutrino masses are tiny $\sim 10^{(-5-6)} m_e$

- There are three types of seesaw mechanisms all of which require additional particles at some high scale to generate tiny neutrino masses.

- We still do not know whether neutrinos have Dirac type or Majorana type masses. In either of the case, we expect new symmetries or new phenomena beyond SM.
dark matter

Clear and direct evidence for dark matter at all scales

no particle in SM can be the dark matter

new color and charge neutral, stable and perhaps weakly interacting particles are proposed to be the dark matter
**Matter Anti-Matter Asymmetry**

According to Big Bang theory, equal amount of matter and anti-matter was produced in the early universe. However the present universe is dominated by matter.

A tiny asymmetry in the early universe is sufficient to generate the large asymmetry observed today. 

\[ n_b - n_{\bar{b}} \sim 10^{-10} n_\gamma \]

Two of the three Sakharov conditions: (C violation, CP violation, B violation), in the Standard Model, B violation is very small. One needs a new source of B or L violation (leptogenesis).
Hierarchy problem

Consider QED:

\[ \mathcal{L}_{\text{QED}} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{\psi} \left[ i \gamma^\mu \partial_\mu - ie q_f A_\mu \right] - m_e \] \psi

\[ (\Delta m_e) \sim e^2 m_e^2 \ln \Lambda \]

The limit \( m_e \to 0 \) leads to an enhanced symmetry (chiral symmetry in the theory)

The electron mass is protected from large radiative corrections.

Furthermore there are no large corrections from muon, tau other heavy leptons to the electron mass. Heavy fermions are decoupled.

“natural theories “
Instead consider Yukawa theory:

\[
\frac{1}{2} \partial^\mu \phi \partial_\mu \phi - \frac{1}{2} m_S^2 \phi^2 + \bar{\psi} (i \gamma^\mu \partial_\mu - m_F) \psi + y \bar{\psi} \psi \phi
\]

The correction to the scalar mass term from one loop corrections is given by

\[
\delta m_S^2 = -y^2 \int \frac{d^4 k}{k^2 - m_F^2} \sim -y^2 m_F^2 \ln \left( \frac{m_F^2}{\mu^2} \right)
\]

In the limit \( m_F \gg m_S \) these corrections are very large.

Corrections to \( m_S \) are not proportional to itself.
they do not go to zero in the limit \( m_S \to 0 \)

there is no enhanced symmetry in that limit.

The effects of heavy fermions do not decouple!!

there is no symmetry which protects the scalar mass from large radiative corrections.

Theories with fundamental scalars are unnatural or fine-tuned.

The Standard Model is one such theory
Implications on the Higgs Mass in SM

\[\delta m_H^2 \sim \frac{1}{16\pi^2} M_{\text{GUT}}^2 \text{ or } M_{\text{Pl}}^2\]
If SM is an effective theory below Planck Scale with an elementary scalar, the mass of such a scalar would be unstable under radiative corrections.
GUTs and Quantum Gravity

Gauge couplings do not unify in SM

Hierarchy problem reappears as Doublet-Triplet splitting problem in GUTs.

The idea of Grand Unification are important after the discovery of neutrino masses
The scale of New Physics

- Neutrino masses can be accommodated with new mass scales to the SM from a few TeV to all the way up to GUT scale.

- Dark matter particle mass is not known, it crucially depends on its interaction strength with SM particles. Huge range in mass and other properties like spin etc. is allowed.

- Baryogenesis/leptogenesis can be accommodated by particles of TeV to GUT scale.

- A solution to Hierarchy problem however requires some new physics close to the electroweak scale.
Two Choices

(a) Either the cut-off is low (new physics scale (non-perturbative) like composite scale or extra dimensions etc)

(b) There is some symmetry protecting the Higgs Mass

Supersymmetry is a symmetry which protects the higgs mass but also introduces a new physics scale
How SUSY works

supermultiplets are formed with pairs of particles transforming by spin 1/2

(0,1/2): Chiral supermultiplet  (1/2,1): Vector supermultiplet

same masses and same couplings within the multiplet
The Structure of MSSM

Wess and Bagger, Text Book
Baer and Tata , Text Book
Drees, Godbole, Roy, Text Book
S. P. Martin, Primer hep-ph/9709356
Construction of MSSM

\[
\begin{align*}
(\nu_e e) & \rightarrow (\nu_e \tilde{\nu}_e) \\
\mathcal{W} & \rightarrow (\mathcal{W}, \tilde{\mathcal{W}})
\end{align*}
\]

every matter field with chiral multiplet

every vector field with vector multiplet
Supersymmetric Standard Model -1
Supersymmetric Standard Model Spectrum -2

- Gluons
- Photon
- $W^\pm$
- Higgs-up
- Higgs-down
Three functions of superfields

\[ L_{\text{kinetic, gauge}} = \int d^4 \theta \Phi^\dagger e^{g \Phi} \]

real fn of chiral and vector multiplets

\[ L_{\text{Yukawa}} = \int d^2 \theta W = \Phi_i \Phi_j \Phi_k \]

analytic fn of chiral multiplet

two Higgs doublets required to cancel anomalies
How SUSY works

susy qed as an example.

If $m_L \approx m_T$ quadratic divergences cancel from both the diagrams.

quantic coupling replaces by gauge coupling
\[ W = W_0 + W_1 \]

\[ W_0 = h_u Q_u^c H_u + h_d Q_d^c H_d + h_e L e^c H_d + \mu H_u H_d \]

\[ W_1 = \lambda_L L e^c + \lambda' L Q d^c + \lambda'' u^c d^c d^c + \epsilon L H_u \]

MSSM Superpotential

Baryon and Lepton Number Violating!

Imposing R-parity

\[ R_p = (-1)^{(3B+L+2S)} \]

LSP stable

Dark Matter Candidate
Supersymmetry breaking

E. Witten, Nucl. Phys B. 188(1981)513;
B. 202 (1982)253,
M. Luty, hep-ph/0509029
Y.Shirman, hep-ph/0907.0039
E. Dudas ,Pramana, 72,(2009) 131
soft susy breaking

Spontaneous Supersymmetry breaking leads to soft supersymmetry breaking terms.

Equal Couplings for particles and super-particles

Equal Masses for particles and super-particles

Super-particles have different couplings and different masses
soft susy breaking

gaugino masses $M_1 \tilde{B} \tilde{B}, M_2 \tilde{W}_I \tilde{W}_I, M_3 \tilde{G}_A \tilde{G}_A,$

scalar mass terms
$m_{Q,ij}^2 \tilde{Q}_i \tilde{Q}_j, m_{u,ij}^2 \tilde{u}_i^c \tilde{u}_j^c, m_{d,ij}^2 \tilde{d}_i^c \tilde{d}_j^c, m_{L,ij}^2 \tilde{L}_i^c \tilde{L}_j^c, m_{e,ij}^2 \tilde{e}_i^c \tilde{e}_j^c, m_{H_1}^2 H_1^c H_1, m_{H_2}^2 H_2^c H_2.$

trilinear couplings
$A_{ij}^u \tilde{Q}_i \tilde{u}_j^c H_2, A_{ij}^d \tilde{Q}_i \tilde{d}_j^c H_1, A_{ij}^e \tilde{L}_i \tilde{e}_j^c H_1$

bilinear couplings
$B H_1 H_2$

A total of about 105 parameters
SUSY FEYNMAN Rules: some examples.

FIG. 3: lepton-slepton-chargino and lepton-slepton-neutralino vertices.
BUT, SUSY cannot be broken spontaneously in any of the MSSM multiplets including Higgs

Constraints from Phenomenology

Hidden Sector Ideas

Consider a set of fields neutral (uncharged) under the Standard Model Gauge Group

Break supersymmetry spontaneously in that sector and propagate the breaking to the MSSM sector
Hidden and Visible sector fields need not be at the same space time points (non-traditional models)
Some traditional Models
\[ k = X_i^+ X_i + \Phi_i^+ \Phi_i + \ldots \]

\[ W = W_{\text{hidden}} + W_{\text{mssm}} \]

\[ V = e^G \left( G_i \cdot G_i - 3 \right) \]

\[ G_i = k + \ln |W|^2 \quad \quad G_i = \frac{\partial G}{\partial \Phi_i} \]
As long as Kahler potential is in canonical form:

\[
m_{f^2} = m^2_0 \]
\[
M_i = M_{1/2} \]
\[
A_{ijk} = A_0 \]
\[
B_{ij} = B \]

A small set of parameters describing the entire supersymmetric spectrum at weak scale.

Renormalisable theory after integrating out the gravity multiplet \((M_{Pl} \to \infty; m_{3/2} \text{ fixed})\)
Dynamical understanding of Electroweak Symmetry Breaking

$m_{H_u, H_d}^2 > 0$  \( q^2 \approx m_{\text{pe}}^2 \) or \( m_{\text{WU}}^2 \)

\[
\begin{align*}
\mathcal{R} & \mathcal{O} \\
\mu \frac{d m_{H_u}^2}{d \mu} & \propto h_t^2 m_{\tilde{\psi}}^2
\end{align*}
\]

@ weak scale

Ibanez, Lopez, Barbieri, Hall, Ross etc.
Gauge Mediation

Introduce a bunch of Matter Superfields which are Charged under gauge interactions but Couple to the hidden sector.

\[ W \supset \bar{z} \to \bar{z} \]

Hidden Sector \[\rightarrow\] Messenger Sector

Giudice and Rattazzi, Phys. Reports Review
SUSY broken spontaneously by $X$

Soft masses in MSSM through loops

$\tilde{\tilde{W}} \times \text{loop}$

$\tilde{\tilde{W}}$

$\text{bunch of two loop diagrams}$
Two loop diagrams contributing to soft masses
Trilinear Couplings

dimensional-full couplings

A-terms are essentially zero !!!
Non-Traditional Models

- Supergravity models without Singlets (roughly, Mediation through supergravity loops) : Anomaly Mediation Models and their variants
- Extra Dimensional Models : Gaugino Mediation Models, Randall-Sundrum Models, Strongly coupled models
- String Inspired Models : Moduli Mediation, KKLT, Hybrid Mediation models
- F-Theory Inspired Models (more gauge Mediation)

Luty, Shirman Reviews, Nomura et.al, Terning Text book + lecture notes, Nelson-Strassler etc.

Choi et.al, Nilles et.al

Maharana and Palti, 1212.0555, Heckman, 1001.4084
Other advantages of SUSY

• Its calculable and thus in principle, predictable.
• Dark Matter candidate if R-parity is conserved.
• Gauge coupling unification (GUTs with neutrino masses and mixing)
• Lightest Higgs boson can be SM-like in regions of parameter space.