PHYS 5326 – Lecture #24

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- Issues with SM picture
- Introduction to SUSY
- Construction of SUSY Lagrangian
- Super-potential
- R-parity conservation

Issues with Higgs

- Haven't been observed yet.
- Potential is not well known.
- Does not explain why fermion masses are what they are.
- Minimal SM loop corrections give quadratic divergences to the mass of Higgs.
- Other Symmetry breaking models…
- How many Higgs?
- What are the couplings (Yukawa?)? How strong are they?

Issues With SM Picture

- M_h with one loop correction is

$$M_h^2 \approx M_{h0}^2 + \frac{g_F^2}{4p^2}\left(\Lambda^2 + m_F^2\right) - \frac{g_S^2}{4p^2}\left(\Lambda^2 + m_S^2\right)$$

- If $g_S=g_F$, we obtain

$$M_h^2 \approx M_{h0}^2 + \frac{g_F^2}{4p^2}\left(m_F^2 - m_S^2\right)$$

•It is acceptable if the difference between mF and mS are at the natural level (<1TeV)

•Requires a symmetry in order for this cancellation to persists in all orders of perturbation theory

Introduction of SUSY

- An alternate solution to resolve mass hierarchy issue caused by the quadratic divergences in SM.
- Avoiding the divergences require a tuning at the precision of 10^{16}GeV
  - SM EW scale of ~ 10^{3}GeV
  - No other physics from EW scale to Planck scale of ~10^{19}GeV
  - Leading to the adjustment of 10^{16} level
  - This is unacceptable

SUSY Lagrangian

- The simplest form of *L*$_{SUSY}$ contains a complex scalar, S, and two-component Majorana Fermion, ψ, where $\psi^c=\psi$.

$$L=-\partial_m S^*\partial^m S-i\overline{y}\,\overline{s}^m\partial_m y-\frac{1}{2}m\left(y\,y+\overline{y}\,\overline{y}\right)$$

$$-cSy\,y-c^2S^2\overline{y}\,\overline{y}-\left|mS+cS^2\right|^2$$

- The *L*$_{SUSY}$ is invariant under the transformation between Scalar and Fermions
- Lagrangian contains both a scalar and fermion of equal mass

What is SUSY?

- A symmetry that relates particles of differing spins.
- Particles are combined in superfields which contain fields differing by spin ½.
- Scalars and fermions in superfields have the same coupling to gauge bosons and cause the quadratic divergence to cancel
- The L_{SUSY} contains scalar and fermion pairs of equal mass
  - SUSY connects particles of different spins but all other characteristics the same

SUSY is a Broken Symmetry

- Since there are no observed candidate of scalar partners of fermions of the same mass vice verse in nature.
- Non-zero mass splitting of the superfields is necessary.
- SUSY is a broken symmetry.

Construction of SUSY

- Start from the supersymmetric version of SM.
- Pick the particles in superfields.
- Two types of superfields relevant for this are:

Chiral Superfields: A complex scalar field, S, and a 2 component Majorana Fermion Field, y

Massless Vector Superfields: a massless gauge field with field strength $F^{A}_{\mu\nu}$ and a 2-component Majorana Fermion fields, λ_A, termed a gaugino.

The Particles of the MSSM

Uses the same SU(3)xSU$_L$(2)xU$_Y$(1) gauge symmetry as the Standard Model and yields the following list of particles

Chiral Superfields

Superfield	SU(3)	$SU(2)_L$	$U(1)_Y$	Particle Content
$\hat{Q}$	3	2	$\frac{1}{6}$	(u_L, d_L), $(\tilde{u}_L, \tilde{d}_L)$
$\hat{U}^c$	$\overline{3}$	1	$-\frac{2}{3}$	$\overline{u}_R$, $\tilde{u}_R^*$
$\hat{D}^c$	$\overline{3}$	1	$\frac{1}{3}$	$\overline{d}_R$, $\tilde{d}_R^*$
$\hat{L}$	1	2	$-\frac{1}{2}$	(ν_L, e_L), $(\tilde{\nu}_L, \tilde{e}_L)$
$\hat{E}^c$	1	1	1	$\overline{e}_R$, $\tilde{e}_R^*$
$\hat{H}_1$	1	2	$-\frac{1}{2}$	$(H_1, \tilde{h}_1)$
$\hat{H}_2$	1	2	$\frac{1}{2}$	$(H_2, \tilde{h}_2)$

Vector Superfield

Superfield	SU(3)	$SU(2)_L$	$U(1)_Y$	Particle Content
$\hat{G}^a$	8	1	0	g, $\tilde{g}$
$\hat{W}^i$	1	3	0	W_i, $\tilde{\omega}_i$
$\hat{B}$	1	1	0	B, $\tilde{b}$

Majorana fermion partners

Scalar and vector particle names have suffix –inos.

Higgs Doublets in the MSSM

- In SM contains a single $SU(2)_L$ scalar doublet, the Higgs Doublet.
- In MSSM this doublet acquires a SUSY partner which is a SU(2)L double of Majorana Fermion fields, $\tilde{h}_1$, the higgsinos
- These Higgsinos contribute to the triangle SU(2) and U(1) gauge anomalies
  - The SM fermions have exactly the right QN to cancel these anomalies
  - The SUSY fermionic partners contribute to the anomaly
- Simplest solution of adding a second doublet, H2, with precisely the opposite QN to the first doublet and its fermionic partner
- Theory becomes anomaly free and sensible

SUSY Higgs Mechanism

Before the EW symmetry was broken, the two complex $SU(2)_L$ Higgs doublets had 8 DoF of which three have been are observed to give masses to W and Z gauge bosons,leaving five physical DoF.

These remaining DoF are two charged Higgs bosons ($H^{+/-}$), a CP-odd neutral Higgs boson, A^0, and 2 CP-even neutral higgs bosons, h^0 and H^0.

It is a general prediction of supersymmetric models to expand physical Higgs sectors.

The MSSM

- SUSY's predictive power comes from the limited ways of interaction between ordinary particles and their super-partners
- However, there is nothing that can stop us from adding more particles to the list of particles given previously, as long as any additional contributions to gauge anomalies cancel among themselves.
- Some models add an additional gauge singlet superfield to the spectrum
- But we stick with the simplest case here

Construction of MSSM *L*

- The SUSY associates each 2-component Majorana fermion with a complex scalar, while the massive fermions in SM are Dirac fermions with four components
- The canonical kinetic energy of the field of MSSM is

$$L_{KE} = \sum_i \left\{ \left(D_m S_i^*\right)\left(D^m S_i\right) + i\overline{y}_i D y_i \right\}$$

$$+ \sum_A \left\{ -\frac{1}{4} F_{mn}^A F^{mn A} + \frac{i}{2} \overline{l}_A D l_A \right\}$$

Where D is the $SU(3)xSU(2)_L xU(1)_Y$ gauge invariant derivative.

Σ_i is for all fermion fields of the SM, ψ_i, and their scalar partners, Σ_i.

Σ_A is over the $SU(3)$, $SU(2)_L$ and $U(1)_Y$ gauge fields with their fermion partners, the gauginos.

L for Interactions between Chiral superfields and gauginos

L is completely specified by the gauge symmetries and by supersymmetry as follows:

$$L_{int} = -\sqrt{2}\sum_{i,A} g_A \left[S_i^* T^A \overline{\psi}_{iL} \lambda_A + h.c. \right] - \frac{1}{2}\sum_A \left(\sum_i g_A T^A S_i \right)$$

Where $\psi_L \equiv \frac{1}{2}(1-\gamma_5)\psi$

- g_A is the relevant gauge coupling constant.
- The interaction strengths are fixed in terms of these constants.
  - E.g., the interaction between a quark, the squark and the gluino is governed by the strong coupling constant, g_s

The Super-potential

- The only freedom left in constructing the SUSY *L* is in a function called super-potential, W.
- W is a function of the chiral superfields only
  - Terms in W with more than 3 chiral superfields would yield non-renomalizable interactions in L.
  - W is not allowed to contain derivative interactions.
- Corresponding lagrangian that contains W with scalar potential and the Yukawa interactions of fermions and scalars is

$$L_W = -\sum_i \left| \frac{\partial W}{\partial z_i} \right|^2 - \frac{1}{2}\sum_{i,j}\left[\bar{y}_{iL} \frac{\partial^2 W}{\partial z_i \partial z_j} y_j + h.c. \right]$$

Where z is a chiral superfield.

This form of *L* is dictated by SUSY and by the renomalizability.

Form of the Super-potential

- The most general $SU(3)xSU(2)_L xU(1)_Y$ invariant superpotential with arbitrary coefficients for interactions is

$$W = e_{i,j} m \hat{H}_1^i \hat{H}_2^j + e_{i,j}\left[l_L \hat{H}_1^i \hat{L}^{cj} \hat{E}^c + l_D \hat{H}_1^i \hat{Q}^j \hat{D}^c + l_U \hat{H}_2^j \hat{Q}^i \hat{U}^c \right]$$

$$+ e_{i,j}\left[l_1 \hat{L}^i \hat{L}^j \hat{E}^c + l_2 \hat{L}^i \hat{Q}^j \hat{D}^c \right] + l_3 \hat{U}^c \hat{D}^c \hat{D}^c$$

M_H term

Terms violating baryon number and mediate proton decay

Yukawa interactions between fermions and Higgs bosons

- The coefficients are determined in terms of fermion masses and vacuum expectation vaues of the neutral members of the scalar components of the Higgs double and are not free parameters
- *L* so far does not provide masses to all the particles, fermions, scalars and gauge fields yet.

R-Parity

- To eliminate the undesirable lepton and baryon number violation terms, a symmetry require these to be forbidden.
- If they are forbidden, they will not reappear in higher order perturbation theory.
- The symmetry to do this is called R-Parity
- R-parity can be defined as a multiplicative quantum number such that all SM particles have R-parity +1 (even) while their super partners are –1 (odd).
- For particle of spin s, it can also be defined as:

$$R \equiv (-1)^{3(B-L)+2s}$$

R-Parity Conservation

•Requiring R-parity to conserve has consequences

•Since R-parity is a multiplicative QN, the number of SUSY partners in a given interaction is always conserved modulo 2.

➔SUSY Partners can only be pair produced from SM particles

•SUSY particles will decay in a chain until the lightest SUSY particle, LSP, which must be absolutely stable to conserve R-parity, is produced

➔ A theory with R parity conservation will have a lightest SUSY particle which is stable

•LSP must be stable and neutral (not detectable) since it only interacts only by the exchange of a heavy virtual SUSY particle

➔LSP will interact very weakly w/ ordinary matter

➔Direct signature of R-parity conserving SUSY is missing E_T

•There is no LSP for R-parity violating SUSY theories

Suggested Readings

- S. Dawson, "SUSY and Such," hep-ph/9612229
- H. Murayama, " Supersymmetry," hep-ph/9410285