The Standard Model and Beyond

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The status of particle physics

Lecture 1

1. The Standard Model (SM) is the best theory of describing the nature of particle physics, which is in excellent agreement with almost all current experiments.

2. However, there are some theoretical problems & recent experimental results, which strongly suggest New Physics beyond the SM.

Lecture 2

3. Many well-motivated New Physics models have been proposed.

4. Many planned and on-going (collider) experiments may reveal New Physics in the near future.
Lecture 2

Beyond the Standard Model

---- Supersymmetric Models ----
TeV scale New Physics

(1) motivated to solve the hierarchy problem
(2) suitable for WIMP Dark Matter

TeV scale

→ Accessible at future collider experiments!

Large Hadron Collider (LHC)

International Linear Collider (ILC)
Large Hadron Collider (LHC) in operation!
LHC: hadron collider

Initial state: **pp** (not elementary particles)

\[ \sqrt{s} = 10 - 14 \text{ TeV} \]

Initial states: \( gg, gq(\bar{q}), q\bar{q}, qq' \)
Parton distribution function (pdf)

A parton distribution function is defined as the probability density for finding a particle with a certain longitudinal momentum fraction $x$ at momentum transfer $Q^2$.

Parton: $u, d, g, \bar{u}, \bar{d}, \ldots$ in proton

\[
\int_0^1 dx \left[ f_u(x) - f_\bar{u}(x) \right] = 2, \quad \int_0^1 dx \left[ f_d(x) - f_\bar{d}(x) \right] = 1.
\]
Fundamental process

Colliding parton energy is not fixed
PDF has a peak at $x << 1 \rightarrow$ full 14 TeV cannot be used
Lots of QCD background

$LHC$: high energy machine
$\rightarrow$ high New Particle discovery potential
**International Linear Collider (ILC)** from 20XX?

Lepton collider

**Initial states:** \( e^+ e^- \) **elementary particle**

Colliding particle energy is fixed and tunable

\[ \sqrt{s} = 500 \text{ GeV} - 1 \text{ TeV} \]

Polarized beam option

**ILC:** more precise measurements

\[ \rightarrow \text{ discriminate New Physics Models} \]
Many TeV scale New Physics Models have been proposed

Examples:

**Supersymmetric** models: MSSM, GUT, SUSY breaking,

**Extra-dimension** models: large Xdim, Warped Xdim, Universal Xdm,

  - gauge-Higgs model, Higgs-less model,

**non-SUSY models in 4D**: Technicolor, Little Higgs models,

**Unexpected**: unparticle, hidden valley, quirk models,

**Common feature of New Physics Models**

\[
\begin{align*}
\text{New Particles} & \rightarrow \text{``partners’’ of SM particles} \\
\text{New interactions between New & SM particles}
\end{align*}
\]
Supersymmetric models: one of promising candidate of BSM

Supersymmetry $\rightarrow$ symmetry between bosons and fermions

Supersymmetry trans.: \( \phi \leftrightarrow \psi \) \quad \text{``superpartner''}

\( V_\mu \leftrightarrow \lambda \)

No quadratic divergence for scalar self energy corrections

\[
\Delta m_f \sim m_f \log(\Lambda_{new})
\]

\[
\Delta m_s^2 \sim \Lambda_{new}^2 + m^2 \log(\Lambda_{new}) + \cdots
\]

Scalar self energy corrections are UV insensitive!
More technically,

No quadratic divergence

$$\Delta m_H^2 = -\Lambda^2$$

Cancellation by New Particle (superpartner) contributions
SUSY algebra

\[ \{ Q_\alpha, \overline{Q}_{\dot{\alpha}} \} = -2 (\sigma^\mu)_{\alpha \dot{\alpha}} P_\mu, \]

\[ \{ Q_\alpha, Q_\beta \} = \{ \overline{Q}_{\dot{\alpha}}, \overline{Q}_{\dot{\beta}} \} = 0, \]

\[ [P_\mu, Q_\alpha] = [P_\mu, \overline{Q}_{\dot{\alpha}}] = 0, \]

\[ [P_\mu, P_\nu] = 0, \]

Mass dim. Q = 1/2

\[ Q_\alpha \phi \sim \psi_\alpha \quad \overline{Q}_{\dot{\alpha}} Q_\alpha \phi \sim \overline{Q}_{\dot{\alpha}} \psi_\alpha \]

Weyl spinor index

Left-handed: \[ \alpha = 1, 2 \]

Right-handed: \[ \dot{\alpha} = \dot{1}, \dot{2} \]

Dim: \[ \frac{1}{2} \quad 1 \quad 3/2 \]

"aQ^2" \[ \phi(x^\mu) \sim \phi(x^\mu + a^\mu) \]
Superfield formalism

4D spacetime → “superspace”

\[ \{ x^\mu \} \longrightarrow \{ x^\mu , \theta_\alpha, \bar{\theta}_{\dot{\alpha}} \} \]

fermionic coordinate (dim: -1/2)

\[ \{ \theta_\alpha, \theta_\beta \} = \{ \bar{\theta}_{\dot{\alpha}}, \bar{\theta}_{\dot{\alpha}} \} = \{ \bar{\theta}_{\dot{\alpha}}, \theta_\alpha \} = 0 \]

Define SUSY trans as translation on superspace

\[ e^{i(x^\mu P_\mu + \epsilon Q + \bar{\epsilon} \bar{Q})} \Phi(y^\mu, \theta, \bar{\theta}) = \Phi(x^\mu + y^\mu + i\theta \sigma \bar{\epsilon} - i\epsilon \sigma \theta, \epsilon + \theta, \bar{\epsilon} + \bar{\theta}) \]

Superfield: \[ \Phi(x^\mu, \theta, \bar{\theta}) \]
Expression as differential operators

\[
\begin{aligned}
  iQ_\alpha &= \frac{\partial}{\partial \theta^\alpha} - i(\sigma^\mu)_{\alpha \dot{\alpha}} \bar{\theta} \dot{\alpha} \partial_\mu \\
  i\bar{Q}_{\dot{\alpha}} &= -\frac{\partial}{\partial \theta^{\dot{\alpha}}} + i\theta^\alpha (\sigma^\mu)_{\alpha \dot{\alpha}} \partial_\mu
\end{aligned}
\]

\[\{Q_\alpha, \bar{Q}_{\dot{\alpha}}\} = -2i(\sigma^\mu)_{\alpha \dot{\alpha}} \partial_\mu\]

\[\{Q_\alpha, Q_\beta\} = \{\bar{Q}_{\dot{\alpha}}, \bar{Q}_{\dot{\beta}}\} = 0\]

General superfield: \(\Phi(x^\mu, \theta, \bar{\theta})\)

\[
\phi(x, \theta, \bar{\theta}) = C(x) + \theta \chi(x) + \bar{\theta} \chi'(x) + \theta \partial M(x) + \bar{\theta} \partial N(x) \\
+ \theta \sigma^\mu \bar{\theta} V_\mu(x) + \theta \partial \bar{\theta} \lambda(x) + \bar{\theta} \partial \theta \psi(x) + \theta \partial \theta \partial \bar{\theta} D(x)
\]

Many bosons and fermions are included
This is reducible in fact.
Chiral superfield

SUSY covariant derivative

\[ D_\alpha = \frac{\partial}{\partial \theta^\alpha} + i (\sigma^\mu)^{\alpha \dot{\alpha}} \bar{\theta}^{\dot{\alpha}} \partial_\mu, \]
\[ \bar{D}_{\dot{\alpha}} = -\frac{\partial}{\partial \bar{\theta}^{\dot{\alpha}}} - i \theta^\alpha (\sigma^\mu)^{\alpha \dot{\alpha}} \theta_\mu. \]

\[ \{ Q_\alpha, D_\beta \} = \{ \bar{Q}_{\dot{\alpha}}, D_\alpha \} = \{ Q_\alpha, \bar{D}_{\dot{\alpha}} \} = \{ \bar{Q}_{\dot{\alpha}}, \bar{D}_{\dot{\beta}} \} = 0 \]

Chiral superfield is defined as \( \bar{D}_{\dot{\alpha}} \phi = 0 \)

“y-basis” \( y^\mu \equiv x^\mu + i (\theta \sigma^\mu \bar{\theta}) \)

\[ \phi(y, \theta) = A(y) + \sqrt{2} \theta \psi(y) + \theta \theta F(y) \]
\[ = A(x) + i (\theta \sigma^\mu \bar{\theta}) \partial_\mu A(x) - \frac{1}{4} \theta \theta \bar{\theta} \square A(x) + \sqrt{2} \theta \psi(x) \]
\[ - \frac{i}{\sqrt{2}} \theta \theta (\partial_\mu \psi) \sigma^\mu \bar{\theta} + \theta \theta F(x), \]
\[ \phi(y, \theta) = A(y) + \sqrt{2} \theta \psi(y) + \theta \theta F(y) \]

\[ \begin{array}{ccccccc}
\text{dim:} & 1 & 1 & -1/2 & 3/2 & -1 & 2 \\
\text{spin:} & 0 & 0 & 1/2 & 0
\end{array} \]

**Transformation law**

\[ \delta A = \sqrt{2} \epsilon \psi, \]

\[ \delta \psi = \sqrt{2i} \sigma^\mu \bar{\epsilon} \partial_\mu A + \sqrt{2} \epsilon F, \]

\[ \delta F = -\sqrt{2i} \bar{\epsilon} \sigma^\mu \partial_\mu \psi. \]

The highest component transforms to total derivative of a lower component field

\[ F \rightarrow \partial_\mu \psi \]
For general superfield

\[ \phi(x, \theta, \bar{\theta}) = C(x) + \theta \chi(x) + \bar{\theta} \chi'(x) + \theta \theta M(x) + \bar{\theta} \theta N(x) \]

\[ + \quad \theta \sigma^\mu \bar{\theta} V_\mu(x) + \theta \theta \bar{\theta} \lambda(x) + \bar{\theta} \theta \theta \psi(x) + \theta \theta \bar{\theta} \bar{\theta} D(x) \]

highest comp.

Transformation law

\[ \delta D = \frac{i}{2} (\sigma^\mu)_{\alpha \dot{\alpha}} (\epsilon^\alpha \partial_\mu \lambda^{\dot{\alpha}} - (\partial_\mu \psi^a) \bar{\epsilon}^{\dot{\alpha}}). \]

The highest component transforms to total derivative of lower component fields
SUSY invariant action

\[ S_{SUSY} = \int d^4 x \mathcal{L}_{SUSY} \]

\[ \mathcal{L}_{SUSY} = \int d^4 \theta \left[ X + X^\dagger \right] + \left[ \int d^2 \theta W + \int d^2 \bar{\theta} W^\dagger \right] \]

\[ d^2 \theta = d\theta^\alpha d\theta_\alpha \]
\[ d^2 \bar{\theta} = d\bar{\theta}^\dot{\alpha} d\bar{\theta}_{\dot{\alpha}} \]
\[ d^4 \theta = d^2 \theta d^2 \bar{\theta} \]

\[ \int d^2 \theta \theta \theta = \int d^2 \bar{\theta} \bar{\theta} \bar{\theta} = 1 \]
\[ \int d^4 \theta \theta \theta \bar{\theta} \bar{\theta} = 1 \]

Others are zero

\[ \int d^4 \theta X = D_X \]
\[ \int d^2 \theta W = F_W \]

SUSY trans: \[ \mathcal{L}_{SUSY} \rightarrow \mathcal{L}_{SUSY} + \partial_\mu \mathcal{O} \]

\[ \Rightarrow \text{This action is SUSY invariant} \]
Wess-Zumino model

\[
\begin{align*}
\text{Kahler potential: } K &= \sum_i \phi_i^\dagger \phi_i \\
\text{Superpotential: } W(\phi) &= \lambda_i \phi_i + \frac{1}{2} m_{i,j} \phi_i \phi_j + \frac{1}{3} g_{i,j,k} \phi_i \phi_j \phi_k
\end{align*}
\]

\[
\mathcal{L}_{SUSY} = \int d^4 \theta K + \left[ \int d^2 \theta W + \int d^2 \bar{\theta} W^\dagger \right]
\]

Canonical kinetic terms

\[
\begin{align*}
\int d^4 \theta K &= (\partial_\mu A_i^*)(\partial^\mu A_i) - i \bar{\psi}_i \bar{\sigma}^\mu \partial_\mu \psi_i + F_i^* F_i \\
\int d^2 \theta W &= \frac{\partial W(A)}{\partial A_i} F_i - \frac{1}{2} \frac{\partial^2 W(A)}{\partial A_i \partial A_j} \psi_i \psi_j.
\end{align*}
\]

Mass, interaction terms

\(F\) has no kinetic term \(\Rightarrow\) auxiliary field
Scalar potential

\[ V = \sum_i F_i^* F_i \]

where \( F_i \) are solutions of E.O.M.:

\[ F_i^* = \frac{\partial W(A)}{\partial A_i} \]

Potential energy in SUSY model is semi-positive definite

\[ V = \sum_i F_i^* F_i = \sum_i \left| \frac{\partial W(A)}{\partial A_i} \right|^2 \geq 0 \]

SUSY vacuum \( \Rightarrow \) \( V_{min} = 0 \)

\[ \Rightarrow F_i^* = \frac{\partial W(A)}{\partial A_i} = 0 \]

SUSY vacuum condition

(F-flat condition)
Vector superfield: \[ V = V^\dagger \]

\[
V = -\theta \sigma^\mu \bar{\theta} V_\mu + i(\bar{\theta} \bar{\theta} \lambda - \bar{\theta} \theta \lambda) + \frac{1}{2} \bar{\theta} \bar{\theta} \bar{\theta} \theta D.
\]

in Wess-Zumino gauge

dim: 0 1 3/2 3/2 2
spin: 0 1 1/2 1/2 0

gauge boson  gaugino

Field strength (chiral) superfield (U(1) gauge theory)

\[
W_\alpha = -\frac{1}{4} D D \bar{D} D_\alpha V.
\]

\[
\mathcal{L}_{\text{gauge-kin}} = \frac{1}{4} \int d^2 \theta W_\alpha W_\alpha + h.c.
\]

\[
= -\frac{1}{4} F^{\mu \nu} F_{\mu \nu} - i \lambda^\alpha (\sigma^\mu)_{\alpha \dot{\alpha}} \partial_\mu \bar{\lambda}^\dot{\alpha} + \frac{1}{2} D^2
\]
**SUSY QED**

\[ \text{U(1)} \]

Chiral superfield: \( \phi_i \quad Q_i \)

**Gauge invariant matter kinetic term**

\[
\mathcal{L} = \int d^4 \theta \, \phi_i^\dagger e^{2eQ_i} V \phi_i \\
= (D_\mu A_i)^* (D^\mu A_i) - i \bar{\psi}_i \sigma^\mu D_\mu \psi_i + |F_i|^2 \\
- \sqrt{2}ieQ_i (A_i \bar{\lambda} \bar{\psi}_i - A_i^* \lambda \psi_i) + eQ_i D |A_i|^2
\]

\[ V = \sum_i F_i^* F_i + \frac{1}{2} D^2 \]

where \( D \) is determined by E.O.M of \( D \),

\[ D + eQ_i |A_i|^2 \]

\[ V_{min} = 0 \rightarrow D + eQ_i |A_i|^2 = 0 \]

**D-flat condition**
Scalar potential of SUSY QED

\[ V = \sum_i F_i^* F_i + \frac{1}{2} D^2 = \sum_i \left| \frac{\partial W(A)}{\partial A_i} \right|^2 + \frac{e^2}{2} \left( \sum_i Q_i |A_i|^2 \right)^2 \]

F-term potential \hspace{1cm} D-term potential

If W doesn’t include triple terms of As, quartic scalar coupling is nothing but the gauge coupling

New SUSY interactions

\[ - \sqrt{2} ie Q_i (A_i \bar{\lambda} \bar{\psi}_i - A^*_i \lambda \psi_i) \]

← SUSY generalization of gauge interaction
Construction of non-Abelian SUSY gauge theory is analogous to SUSY QED

Matter multiplet: chiral superfield of a representation

\[ A & \psi \] : sfermion & fermion

Gauge multiplet: vector superfield

\[ V_\mu & \lambda \] : gauge boson & gaugino
**Minimal Supersymmetric Standard Model (MSSM)**

<table>
<thead>
<tr>
<th>CSF</th>
<th>$SU(3)$</th>
<th>$SU(2)$</th>
<th>$U(1)$</th>
<th>$B$</th>
<th>$L$</th>
<th>Particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_i$</td>
<td>1</td>
<td>2</td>
<td>$-\frac{1}{2}$</td>
<td>0</td>
<td>1</td>
<td>leptons $(\nu, e)$ and sleptons $(\tilde{\nu}, \tilde{e})$</td>
</tr>
<tr>
<td>$E^c_i$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>$-1$</td>
<td>electron $e^c$ and selectron $\tilde{e}^c$</td>
</tr>
<tr>
<td>$Q_i$</td>
<td>3</td>
<td>2</td>
<td>$+\frac{1}{6}$</td>
<td>$\frac{1}{3}$</td>
<td>0</td>
<td>quarks $(u, d)$ and squarks $(\tilde{u}, \tilde{d})$</td>
</tr>
<tr>
<td>$U^c_i$</td>
<td>3</td>
<td>1</td>
<td>$-\frac{2}{3}$</td>
<td>$-\frac{1}{3}$</td>
<td>0</td>
<td>quarks $u^c$ and squarks $\tilde{u}^c$</td>
</tr>
<tr>
<td>$D^c_i$</td>
<td>3</td>
<td>1</td>
<td>$\frac{1}{3}$</td>
<td>$-\frac{1}{3}$</td>
<td>0</td>
<td>quarks $d^c$ and squarks $\tilde{d}^c$</td>
</tr>
<tr>
<td>$H_u$</td>
<td>1</td>
<td>2</td>
<td>$\frac{1}{2}$</td>
<td>0</td>
<td>0</td>
<td>Higgs $h_u$ and Higgsinos $\tilde{h}_u$</td>
</tr>
<tr>
<td>$H_d$</td>
<td>1</td>
<td>2</td>
<td>$-\frac{1}{2}$</td>
<td>0</td>
<td>0</td>
<td>Higgs $h_d$ and Higgsinos $\tilde{h}_d$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>VSF</th>
<th>$SU(3)$</th>
<th>$SU(2)$</th>
<th>$U(1)$</th>
<th>$B$</th>
<th>$L$</th>
<th>Particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V^a$</td>
<td>8</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>gluons $g$ and gluinos $\tilde{g}$</td>
</tr>
<tr>
<td>$V^i$</td>
<td>1</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>$W$'s and winos $\tilde{W}$</td>
</tr>
<tr>
<td>$V$</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>$B$ and bino $\tilde{B}$</td>
</tr>
</tbody>
</table>
Extended interactions

SUSY gauge int.:

SM-SM-SM
→ SM-SP-SP

Example:
General gauge invariant MSSM superpotential

\[ \mathcal{W} = Y_u^{ij} Q^i H_u \bar{U}^j + Y_d^{ij} Q^i H_d \bar{D}^j + Y_e^{ij} L^i H_d \bar{E}^j + \mu H_d H_u + \mathcal{W}_{R_{\mu}} \]

Yukawa couplings \quad mu-term

\[ \mathcal{W}_{R_{\mu}} = a_1^{ijk} Q^i L^j \bar{D}^k + a_2^{ijk} L^i L^j \bar{E}^k + a_3 L^i H_u + a_4^{ijk} \bar{D}^i \bar{D}^j \bar{U}^k \]

B/L number violating terms
SUSY (top) Yukawa int.

SM-SM-SM

→ SM-SP-SP
B/L number violating terms $\rightarrow$ dangerous in phenomenology

$$\mathcal{W}_{B/L} = a_1^{ijk} Q^i L^j \bar{D}^k + a_2^{ijk} L^i L^j \bar{E}^k + a_3^i L^i H_u + a_4^{ijk} \bar{D}^i \bar{D}^j \bar{U}^k$$

Rapid proton decay

Introduction of ``R-parity'' $\rightarrow$ forbids $\mathcal{W}_{B/L}$

Under R-parity

<table>
<thead>
<tr>
<th>Even</th>
<th>Odd</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM fields</td>
<td>SUSY partners</td>
</tr>
</tbody>
</table>

Require L is R-parity even

$\rightarrow$ interactions between SM and SM partners

$$\mathcal{L}_{int} = (SM)^m(S\bar{M})^{2n}$$

$\rightarrow$ Lightest Superpartner is stable $\rightarrow$ if it is neutral, DM candidate
Minimal Supersymmetric Standard Model (MSSM)

SUSY version of SM

<table>
<thead>
<tr>
<th>SM particles</th>
<th>Superpartners</th>
</tr>
</thead>
<tbody>
<tr>
<td>quark, lepton (1/2)</td>
<td>squark, slepton (0)</td>
</tr>
<tr>
<td>gauge boson (1)</td>
<td>gaugino (1/2)</td>
</tr>
<tr>
<td>Higgs (0)</td>
<td>Higgsino (1/2)</td>
</tr>
</tbody>
</table>

But, SUSY should be broken, otherwise $m_{\tilde{e}} = m_e$

→ Superpartners have mass 100 GeV- 1 TeV

$\Lambda_{\text{New}} \rightarrow \tilde{m}$
Introducing SUSY breaking term in MSSM

Hidden sector scenario

SUSY is broken in the hidden sector (singlet) by $<F>$
$<F>$ is mediated to MSSM sector by some interactions

Effective interactions between hidden & MSSM
Spurion technique: $X = \theta^2 F_X$

Effective interaction between $X$ & MSSM fields

$$\int d^4 \theta \frac{X^\dagger X}{M^2} K \quad \int d^4 \theta \frac{X}{M} K + h.c. \quad \int d^2 \theta \frac{X}{M} W \quad \int d^2 \theta \frac{X}{M} W^\alpha W_\alpha$$

Ex) $\int d^4 \theta c \frac{X^\dagger X}{M^2} Q^\dagger Q \rightarrow c \frac{|F_X|^2}{M^2} \bar{Q}^\dagger \bar{Q}$ \hspace{1cm} sfermon mass

$$\int d^2 \theta c \frac{X}{M} Q H_u U^c \rightarrow c \frac{F_X}{M} \bar{Q} H_u \bar{U}^c$$ \hspace{1cm} A-term

$$\int d^2 \theta c \frac{X}{M} W^\alpha W_\alpha \rightarrow c \frac{F_X}{M} \lambda^\alpha \lambda_\alpha$$ \hspace{1cm} gaugino mass

SUSY breaking model determines $M, \ F_X, \ c$

gravity mediation: $M = M_p$

gauge mediation: Messenger mass, $c$ given by gauge coupling
MSSM Lagrangian with soft SUSY breaking terms

\[ \mathcal{L}_{\text{total}} = \mathcal{L}_{\text{SUSY}}^{\text{MSSM}} + \mathcal{L}_{\text{soft}} \]

\[-\mathcal{L}_{\text{soft}} = \sum_{i=Q_1,\bar{U}_i,...} m_i^2 |\phi_i|^2 + \left( \sum_{i=1,2,3} M_i \lambda_i \lambda_i - B \mu H_1 H_2 + \right.\]

\[ + \sum_{ij} A_{ij}^u \lambda_{ij}^u Q_i H_2 \bar{U}_j + \sum_{ij} A_{ij}^d \lambda_{ij}^d Q_i H_1 \bar{D}_j + \sum_{ij} A_{ij}^e \lambda_{ij}^e L_i H_1 \bar{E}_j + h.c. \]
Interesting features of MSSM with soft SUSY breakings

Radiative EW symmetry breaking

mass^2 correction to Higgs doublets is negative!

$$\Delta m_h^2 \sim -\frac{3Y_t^2}{4\pi^2} m_t^2 \log \left( \frac{M_{UV}}{E_{EW}} \right) < 0$$
RGE running masses

In MSSM, EW symmetry breaking is triggered by interplay between the large top Yukawa & soft mass
Higgs potential is changing its shape according to energy

High Energy

$ m_{H_u}^2 > 0 $  
Symmetric

Low Energy

$ m_{H_u}^2 < 0 $  
EW symmetry breaking  
$ m_{H_u}^2 \sim -m_0^2 $  

Higgs VEV scale is $O$(sfermion mass)  
$\Rightarrow$ EW scale
Higgs mass prediction

Higgs self coupling = gauge coupling by SUSY

→ Higgs boson mass prediction

**SM:** \[ m_h^2 = \lambda v^2 \]

**MSSM:** gauge coupling via D-term potential

\[ m_h^2 \simeq m_Z^2 + \frac{3 Y_t^4 v^2}{4 \pi^2} \log \left( \frac{m_{\tilde{t}}^2}{m_t^2} \right) \]

tree level stop loop correction
Grand Unified Theories

Present measurement of gauge couplings + SUSY

→ successful gauge coupling unification

→ Evidence of GUTs?
Dark Matter $\rightarrow$ LSP Neutralino

$0.094 \leq \Omega_{DM} h^2 \leq 0.129$

Consistent with WMAP data

Figure 2: The strips display the regions of the $(m_{1/2}, m_0)$ plane that are compatible with $0.094 < \Omega_{\chi} h^2 < 0.129$ and the laboratory constraints for $\mu > 0$ and $\tan \beta = 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55$. The parts of the strips compatible with $g_\mu - 2$ at the 2-$\sigma$ level have darker shading.
Discover SUSY at LHC

Pair production of new particles: \( \text{SM} + \text{SM} \rightarrow \text{SP SP} \)
Discovery of superpartner & mass measurements

Neutralino (DM)

Collision point

\[ \tilde{q} \]

\[ \tilde{\chi} \]

[Image of particle interactions]

Jll invariant mass distribution

\[ M_{\tilde{\chi}^0}^{\max} = \left[ \frac{(M_{\tilde{q}L}^2 - m_{\tilde{\chi}^0}^2)(m_{\tilde{\chi}^0}^2 - M_{\tilde{\chi}^0}^2)}{M_{\tilde{\chi}^0}^2} \right]^{1/2} = 552.4 \text{ GeV}. \]
SUSY search at LHC (CMSSM parametrization)
SUSY: One of the most promising candidates for New Phys.

**MSSM**

1) SUSY breaking around 100GeV- 1TeV $\rightarrow$ No fine-tuning
2) Origin of EW symmetry breaking
3) Candidate of Dark Matter (LSP Neutralino)
4) Higgs boson mass prediction
5) GUT scenario

LHC is testing SUSY now!
Discovery of SUSY

→ clue to understand origin of SUSY breaking

SUSY breaking mediation

New concept of space-time???

As energy goes up…..

\[
\text{Time + space} \rightarrow \text{space-time} \rightarrow \text{superspace}???
\]

Newton’s theory \hspace{1cm} Theory of relativity \hspace{1cm} SUSY theory

\downarrow

local SUSY theory

= supergravity