Introduction to Supersymmetry

Yu-Ting Shen

Outline

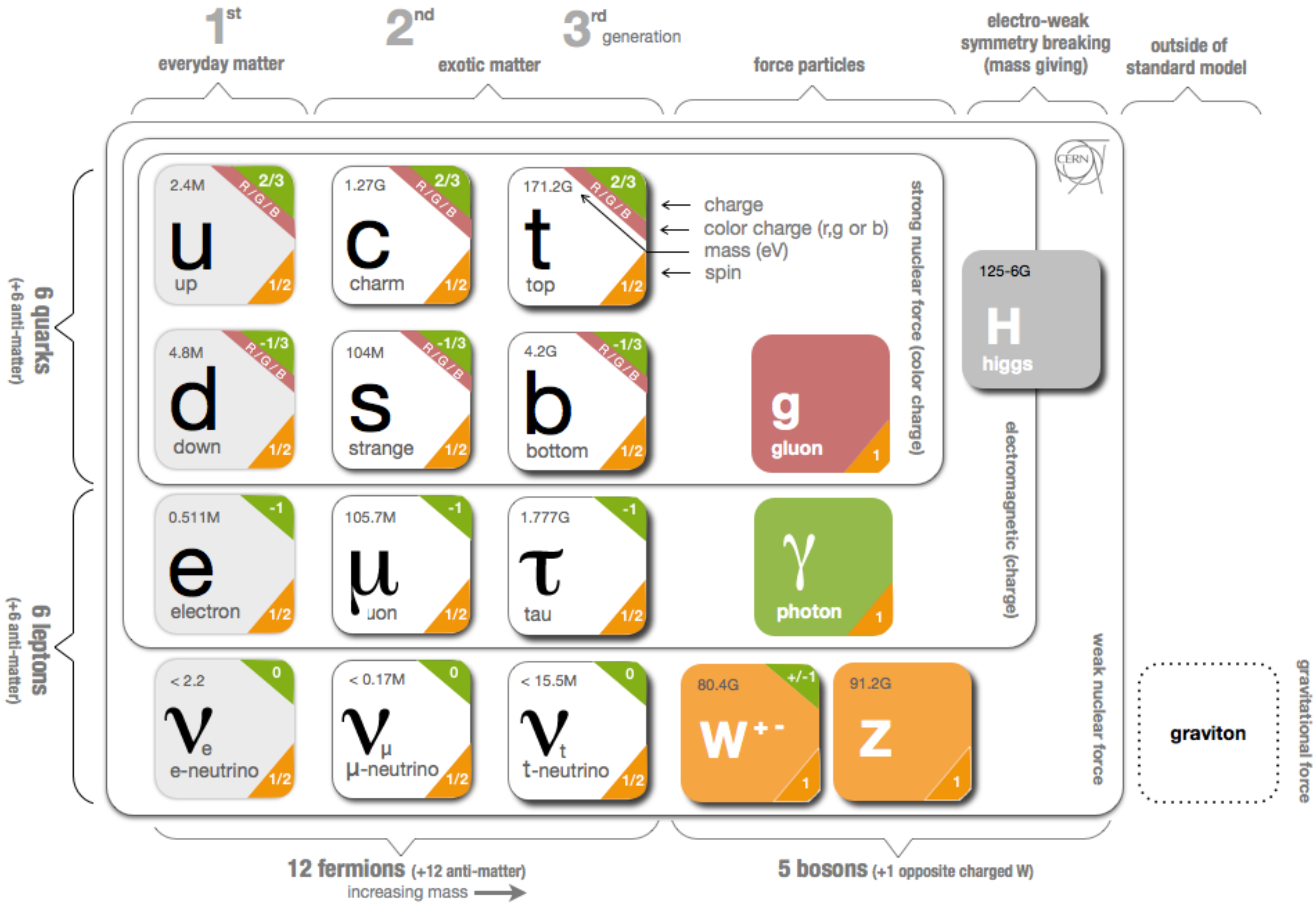
- Basic
  - ✓ Standard Model
  - ✓ Supersymmetry
- Supersymmetry Theory
  - ✓ The Wess-Zumino model
  - ✓ Superspace & superfields
  - ✓ Supersymmetry breaking
- Summary

Basic

Standard Model

- The Standard Model (SM)
  - ✓ was developed during 1970s.
  - ✓ is the most successful theory of particle physics.
  - ✓ explains elementary particles and the interactions.
  - ✓ cannot be the ultimate theory.

Standard Model



Standard Model

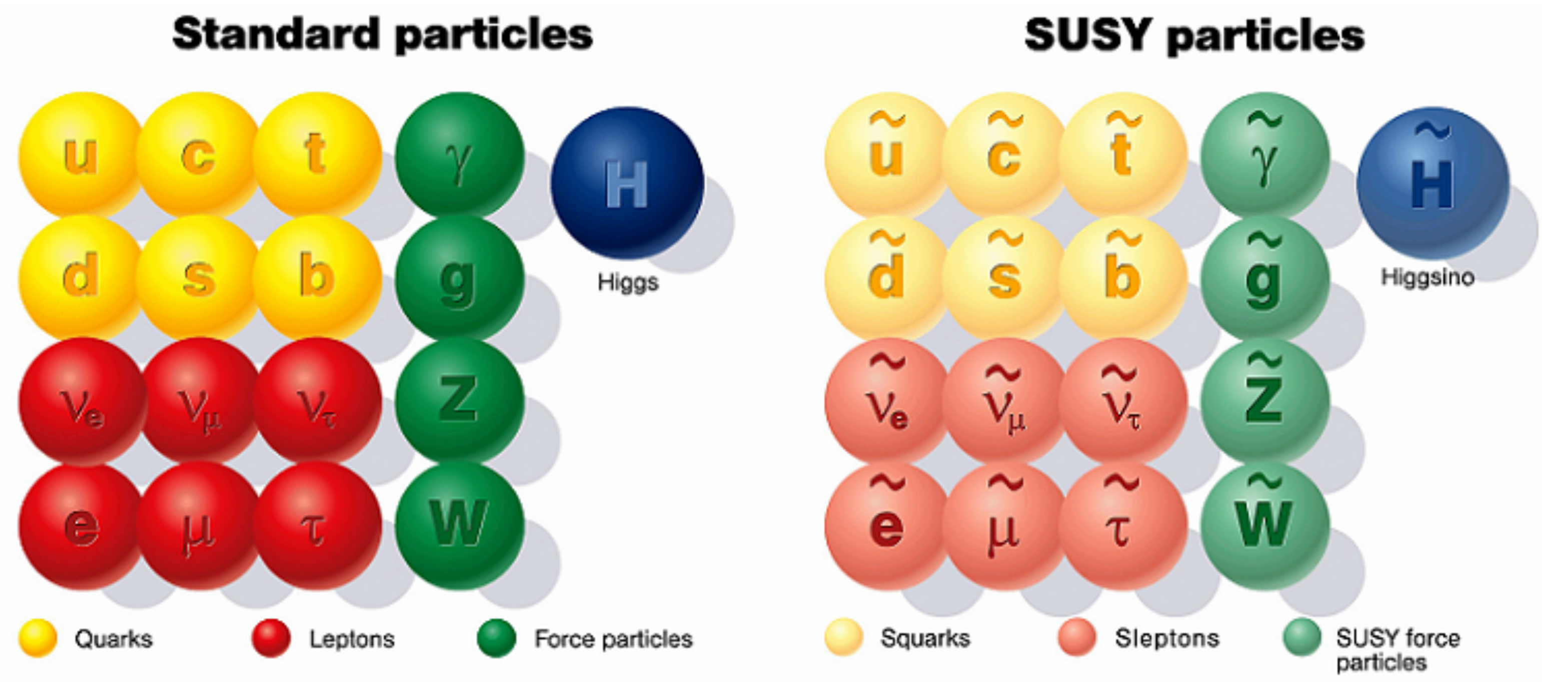
- Problems with the Standard Model:
    - ✓ Hierarchy problem
    - ✓ Why coupling constants do not converge?
    - ✓ Doesn’t include dark matters and dark energy.
    - ✓ …
- Standard Model needs to be extended.

Supersymmetry

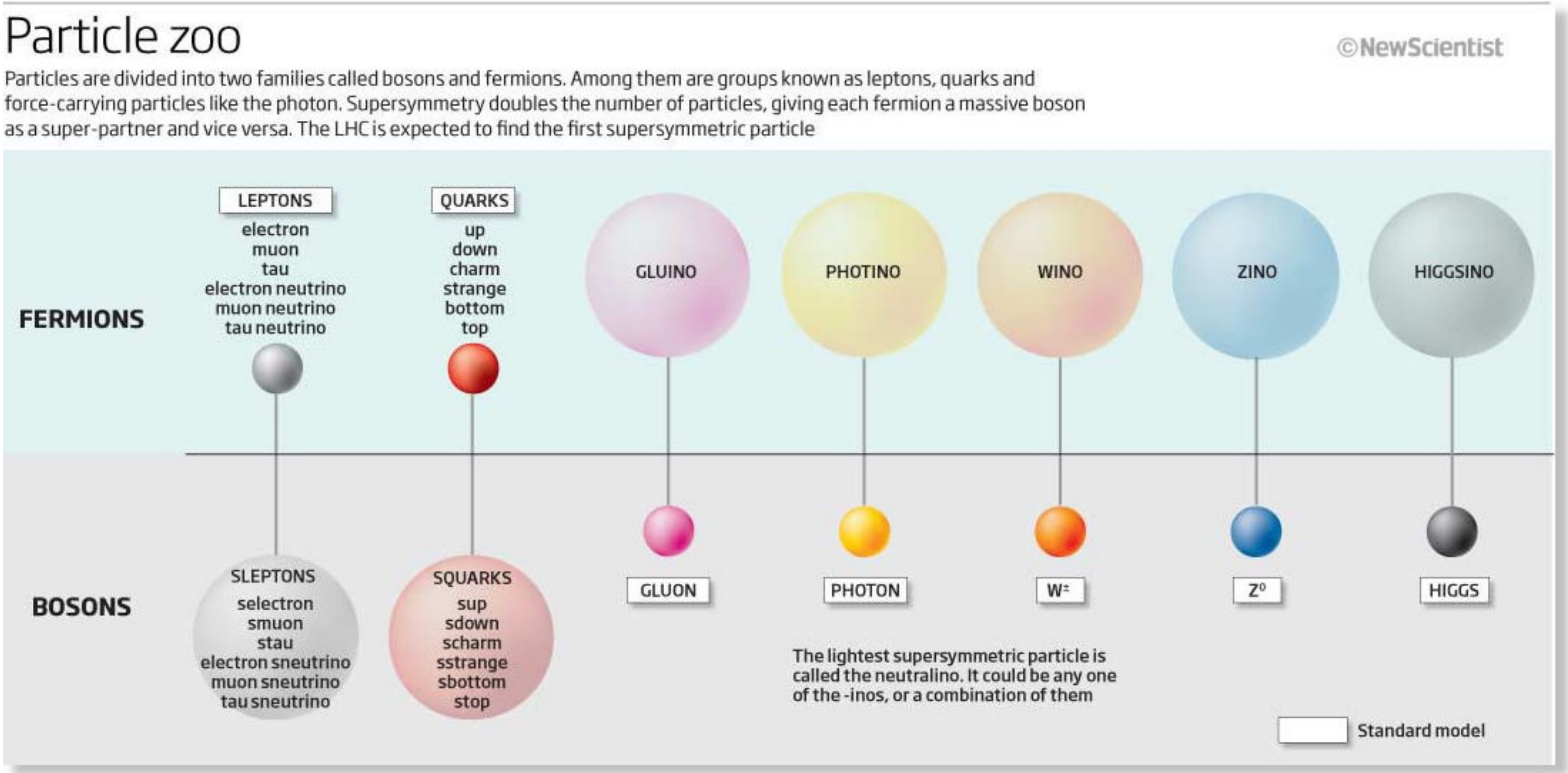
- Motivations for supersymmetry
  - ✓ SUSY solves the hierarchy problem.
  - ✓ The coupling constants converge.
  - ✓ SUSY provides dark matter candidate.
  - ✓ …

Supersymmetry

- New symmetry between fermions and bosons
  - ✓ Every SM particle has a superpartner differing by half of spin.
  - ✓ $\mathbf{Q}\,|\text{boson}\rangle = |\text{fermion}\rangle$, $\mathbf{Q}\,|\text{fermion}\rangle = |\text{boson}\rangle$



Supersymmetry



Supersymmetry

- Supermultiplets
  - ✓ contain bosons and fermions.
    - ‣ have the same number of degrees of freedom.
  - ✓ all particles in the same supermultiplet have the same mass.
  - ✓ two kinds of supermultiplets
    - ‣ Chiral supermultiplet: s = 0 bosons (Higgs) & s = 1/2 fermions (quarks & leptons)
    - ‣ Vector supermultiplet: s = 1 gauge bosons

Supersymmetry

- R-Parity
  - ✓ is a new quantum number introduced by SUSY.
  - ✓ $R = (-1)^{3(B-L)+2s}$
    - ‣ B, L and s are Baryon number, Lepton number and spin
  - ✓ R = +1: SM particles, R = -1: SUSY particles
- If R-parity is conserved
  - ✓ there is no mixing between sparticles and Standard Model particles.
  - ✓ SUSY predicts the sparticles produced in pairs.

Supersymmetry

- Higgs mass $m_H^2\,(\text{phys}) = m_H^2(\text{bare}) + \delta m_H^2$

✓ Radiative corrections: there are quadratically divergent contributions to the mass.

✓ From fermions: $\delta m_H^2 = \frac{|\lambda_f|^2}{8\pi^2}[-\Lambda^2 + 6m_f^2 \ln \frac{\Lambda}{m_f}]$

✓ From scalars: $\delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda^2 - 2m_S^2 \ln \frac{\Lambda}{m_S}]$

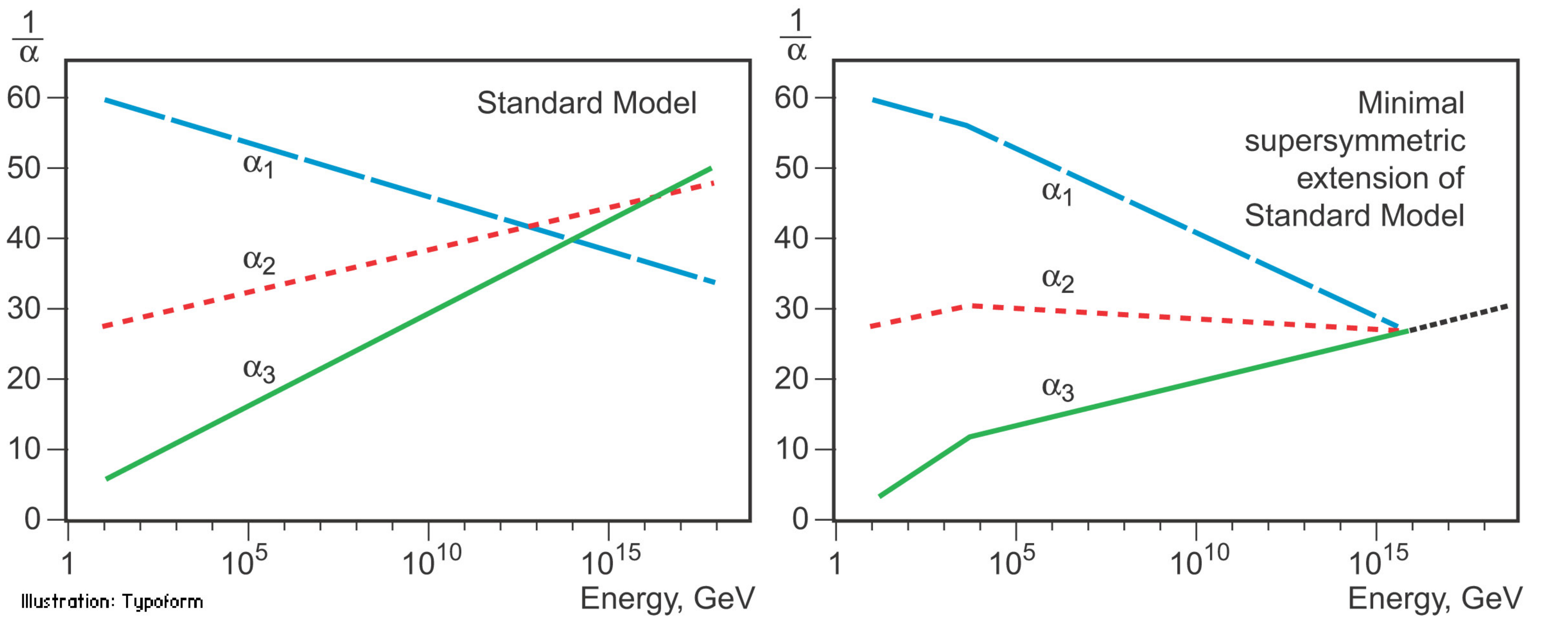
✓ If Λ goes to infinity ➜ δm_H^2 quadratically divergent.

Supersymmetry

- Higgs mass $m_H^2\text{ (phys)} = m_H^2\text{(bare)} + \delta m_H^2$
  - ✓ m_H^2(phys) is finite (m_H~125 GeV).
    ➜ We need to fine tune parameters to get a finite Higgs mass.
  - ✓ This is called the hierarchy problem.
- In SUSY
  - ✓ If every fermion is accompanied by two scalars with couplings $\lambda_S = \lambda_f^2$ the quadratic divergences cancel.
  - ✓ Fermions: $$\delta m_H^2 = \frac{|\lambda_f|^2}{8\pi^2}[-\Lambda^2 + 6m_f^2 \ln \frac{\Lambda}{m_f}]$$
  - ✓ Scalars: $$\delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda^2 - 2m_S^2 \ln \frac{\Lambda}{m_S}]$$
  - ✓ The correction reduces to $\delta m_H^2 \approx \frac{\lambda_f^2}{4\pi^2}(m_S^2 - m_f^2) \ln \frac{\Lambda}{m_S}$

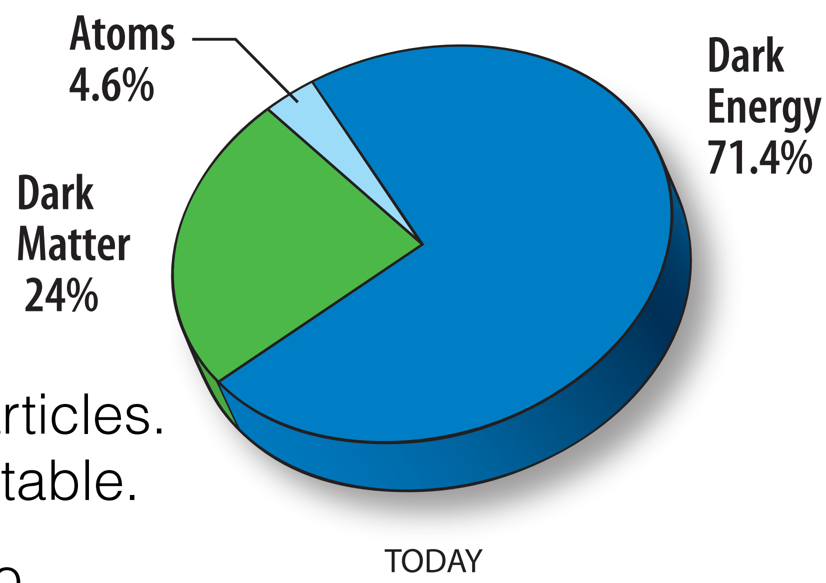
Supersymmetry

- The running coupling constants
  - ✓ **α_1**: the electromagnetic coupling
  - ✓ **α_2**: the weak coupling
  - ✓ **α_3**: the strong coupling
  - ✓ are functions of energy.
  - ✓ are identical in strength at grand unification scale (~10^{16} GeV).



Supersymmetry

- Dark Matter (DM)
  - ✓ The strong evidence of DM was discovered in 1960s - 1970s.
  - ✓ Dark matter and dark energy consist ~95% of the universe
  - ✓ doesn't join strong or electromagnetic interactions.
  - ✓ is not included in Standard Model.
- SUSY
  - ✓ can provide a dark matter candidate.
  - ✓ R-parity must be conserved (RPC).
  - ✓ SUSY particles cannot decay to SM particles.
    ➜ The lightest SUSY particle (LSP) is stable.
  - ✓ LSP can be lightest neutralino, gravitino…



Supersymmetry Theory

The Wess-Zumino Model

- Symmetry transformation:
  - ✓ Equation of motion is invariant under a transformation.
- Action S = $\int d^4x\, \mathcal{L}$ is invariant under symmetry transformation.
  - ✓ Lagrangian $\mathcal{L}$ is invariant
  - ✓ Lagrangian changes by total derivative

$$\mathcal{L} \to \mathcal{L}' = \mathcal{L} + \partial_\mu \Lambda^\mu$$

Λ^μ vanishes at the boundary

The Wess-Zumino Model

- The simplest SUSY Lagrangian: the free Wess-Zumino model
- Particle content:
  - ✓ a massless complex scalar field Φ
  - ✓ a massless left-handed two-component Weyl fermion Ψ
  - ✓ without interaction between Φ and Ψ
- The simplest action

$$S = \int d^4x \, (\mathcal{L}_{\text{scalar}} + \mathcal{L}_{\text{fermion}})$$

$$\mathcal{L}_{\text{scalar}} = \partial^\mu \phi^* \partial_\mu \phi, \quad \mathcal{L}_{\text{fermion}} = i\psi^\dagger \overline{\sigma}^\mu \partial_\mu \psi$$

$$\overline{\sigma}^\mu = (1, -\vec{\sigma})$$

Pauli matrix

The Wess-Zumino Model

- SUSY changes bosons into fermions and vice versa.

$$\delta\phi = \epsilon\psi \qquad\qquad \delta\phi^* = \epsilon^\dagger\psi^\dagger$$

$$\delta\psi_\alpha = -i(\sigma^\mu\epsilon^\dagger)_\alpha\partial_\mu\phi \qquad\qquad \delta\psi^\dagger_{\dot\alpha} = i(\epsilon\sigma^\mu)_{\dot\alpha}\partial_\mu\phi^*$$

- The variations of the Lagrangian are

$$\begin{aligned}
\delta\mathcal{L}_{\text{scalar}} &= \partial^\mu(\delta\phi^*)\partial_\mu\phi + \partial^\mu\phi^*\partial_\mu(\delta\phi) \\
&= \epsilon\partial^\mu\psi\partial_\mu\phi^* + \epsilon^\dagger\partial^\mu\psi^\dagger\partial_\mu\phi \\
\delta\mathcal{L}_{\text{fermion}} &= i(\delta\psi^\dagger)\overline{\sigma}^\mu\partial_\mu\psi + i\psi^\dagger\overline{\sigma}^\mu\partial_\mu(\delta\psi) \\
&= -\epsilon\sigma^\nu\partial_\nu\phi^*\overline{\sigma}^\mu\partial_\mu\psi + \psi^\dagger\overline{\sigma}^\mu\sigma^\nu\epsilon^\dagger\partial_\mu\partial_\nu\phi \\
&= -\epsilon\partial^\mu\psi\partial_\mu\phi^* - \epsilon^\dagger\partial^\mu\psi^\dagger\partial_\mu\phi \\
&\quad + \boxed{\partial_\mu(\epsilon\sigma^\mu\overline{\sigma}^\nu\psi\partial_\nu\phi^* - \epsilon\psi\partial^\mu\phi^* + \epsilon^\dagger\psi^\dagger\partial^\mu\phi)}
\end{aligned}$$

total derivative term

- The action S is invariant.

The Wess-Zumino Model

- Closure: the commutator of two SUSY transformations must itself be a symmetry transformation

$$(\delta_{\epsilon 2}\delta_{\epsilon 1} - \delta_{\epsilon 1}\delta_{\epsilon 2})\phi = -i(\epsilon_1\sigma^\mu\epsilon_2^\dagger - \epsilon_2\sigma^\mu\epsilon_1^\dagger)\partial_\mu\phi$$

$$(\delta_{\epsilon 2}\delta_{\epsilon 1} - \delta_{\epsilon 1}\delta_{\epsilon 2})\psi_\alpha = -i(\epsilon_1\sigma^\mu\epsilon_2^\dagger - \epsilon_2\sigma^\mu\epsilon_1^\dagger)\partial_\mu\psi_\alpha$$

$$\boxed{+\, i(\epsilon_{1\alpha}\epsilon_2^\dagger\overline{\sigma}^\mu\partial_\mu\psi - \epsilon_{2\alpha}\epsilon_1^\dagger\overline{\sigma}^\mu\partial_\mu\psi)}$$

unwanted term

✓ on-shell

$$\overline{\sigma}^\mu\partial_\mu\psi = 0$$

✓ off-shell

- introduce a scalar auxiliary field $\mathcal{F}$

$$\delta\mathcal{F} = -i\epsilon^\dagger\overline{\sigma}^\mu\partial_\mu\psi, \quad \delta\mathcal{F}^* = i\partial_\mu\psi^\dagger\overline{\sigma}^\mu\epsilon$$

- The Lagrangian $\mathcal{L}_{\text{auxiliary}} = \mathcal{F}^*\mathcal{F}$

- fermionic field

$$\delta\psi_\alpha = -i(\sigma^\mu\epsilon^\dagger)_\alpha\partial_\mu\phi + \epsilon_\alpha\mathcal{F}, \quad \delta\psi^\dagger_{\dot\alpha} = i(\epsilon\sigma^\mu)_{\dot\alpha}\partial_\mu\phi^* + \epsilon^\dagger_{\dot\alpha}\mathcal{F}^*$$

The Wess-Zumino Model

- The variations of Lagrangians are

$$\delta\mathcal{L}_{\text{auxiliary}} = i\partial_\mu\psi^\dagger\overline{\sigma}^\mu\epsilon\mathcal{F} - i\epsilon^\dagger\overline{\sigma}^\mu\partial_\mu\psi\mathcal{F}^*$$

$$\begin{aligned}\delta\mathcal{L}_{\text{fermion}} &= -\epsilon\sigma^\nu\partial_\nu\phi^*\overline{\sigma}^\mu\partial_\mu\psi + \psi^\dagger\overline{\sigma}^\mu\sigma^\nu\epsilon^\dagger\partial_\mu\partial_\nu\phi + i\epsilon^\dagger\overline{\sigma}^\mu\partial_\mu\psi\mathcal{F}^* + i\psi^\dagger\overline{\sigma}^\mu\partial_\mu(\epsilon\mathcal{F}) \\ &= \delta^{\text{old}}\mathcal{L}_{\text{fermion}} + i\epsilon^\dagger\overline{\sigma}^\mu\partial_\mu\psi\mathcal{F}^* - i(\partial_\mu\psi^\dagger)\overline{\sigma}^\mu\epsilon\mathcal{F} + \boxed{\partial_\mu(i\psi^\dagger\overline{\sigma}^\mu\epsilon\mathcal{F})}\end{aligned}$$

total derivative term

- S = ∫ $d^4x\ \mathcal{L}$ = ∫ $d^4x\ (\mathcal{L}_{\text{scalar}} + \mathcal{L}_{\text{fermion}} + \mathcal{L}_{\text{auxiliary}})$ is invariant under SUSY transformations.
  ➜ δS = 0

- Field X = Φ, Φ*, Ψ, $\Psi^\dagger$, $\mathcal{F}$, $\mathcal{F}^*$

  ✓ SUSY algebra closes $\quad (\delta_{\epsilon 2}\delta_{\epsilon 1} - \delta_{\epsilon 1}\delta_{\epsilon 2})X = i(-\epsilon_1\sigma^\mu\epsilon_2^\dagger + \epsilon_2\sigma^\mu\epsilon_1^\dagger)\partial_\mu X$

The Wess-Zumino Model

- The multi-fields free Lagrangian

$$\mathcal{L}_{\text{free}} = \partial^\mu \phi^{*i} \partial_\mu \phi_i + i\psi^{\dagger i} \overline{\sigma}^\mu \partial_\mu \psi_i + \mathcal{F}^{*i} \mathcal{F}_i$$

✓ i = 1 ~ N, N is number of particle

- On-shell/Off-shell SUSY transformation for muticomponents

$$\begin{aligned} \delta\phi_i &= \epsilon\psi_i \\ \delta\psi_{i\alpha} &= -i(\sigma^\mu \epsilon^\dagger)_\alpha \partial_\mu \phi_i + \epsilon_\alpha \mathcal{F}_i \\ \delta\mathcal{F}_i &= -i\epsilon^\dagger \overline{\sigma}^\mu \partial_\mu \psi_i \end{aligned}$$

$$\begin{aligned} \delta\phi^{*i} &= \epsilon^\dagger \psi^{\dagger i} \\ \delta\psi^{\dagger i}_{\dot{\alpha}} &= i(\epsilon\sigma^\mu)_{\dot{\alpha}} \partial_\mu \phi^{*i} + \epsilon^\dagger_{\dot{\alpha}} \mathcal{F}^{*i} \\ \delta\mathcal{F}^{*i} &= i\partial_\mu \psi^{\dagger i} \overline{\sigma}^\mu \epsilon \end{aligned}$$

The Wess-Zumino Model

- Consider interactions
  - ✓ General form of the interaction Lagrangian

$$\mathcal{L}_{\rm int} = \Big(-\frac{1}{2} W^{ij}\psi_i\psi_j + W^i\mathcal{F}_i \Big) + \text{c.c.}$$

  - ✓ Superpotential W
    - function of Φ_i only

$$W^i \equiv \frac{\partial W}{\partial \phi_i}, \quad W^{ij} \equiv \frac{\partial^2 W}{\partial\phi_i\partial\phi_j}$$

  - ✓ The Lagrangian

$$\mathcal{L}_{\rm free} + \mathcal{L}_{\rm int} = \partial^\mu\phi^{*i}\partial_\mu\phi_i + i\psi^{\dagger i}\overline{\sigma}^\mu\partial_\mu\psi_i + \mathcal{F}^{*i}\mathcal{F}_i$$
$$+ \Big(-\frac{1}{2} W^{ij}\psi_i\psi_j + W^i\mathcal{F}_i - \frac{1}{2} W^*_{ij}\psi^\dagger_i\psi^\dagger_j + W^*_i\mathcal{F}^{*i} \Big)$$

The Wess-Zumino Model

- Consider interactions
  - ✓ The auxiliary fields
    - ‣ can be replaced by superpotential W using equations of motion.

$$\frac{\partial \mathcal{L}}{\partial \mathcal{F}^{i*}} = 0 \Longrightarrow \mathcal{F}_i = -W_i^*$$
$$\frac{\partial \mathcal{L}}{\partial \mathcal{F}_i} = 0 \Longrightarrow \mathcal{F}^{*i} = -W^i$$

  - ✓ The Lagrangian

$$\mathcal{L} = \mathcal{L}_{\text{free}} + \mathcal{L}_{\text{int}}$$
$$= \partial^\mu \phi^{*i} \partial_\mu \phi_i + i\psi^{\dagger i} \overline{\sigma}^\mu \partial_\mu \psi_i - \frac{1}{2}\Big(W^{ij}\psi_i\psi_j + W_{ij}^* \psi^{\dagger i}\psi^{\dagger j}\Big) - W^i W_i^*$$

  - ✓ Scalar potential

$$V(\phi, \phi^*) = W^i W_i^* = \mathcal{F}^{*i}\mathcal{F}_i \geq 0$$

Superspace & Superfields

- Supersymmetry is a symmetry in superspace.
- Superspace coordinate $(x^\mu, \theta_\alpha, \overline{\theta}_{\dot{\alpha}})$

✓ $\theta_\alpha, \ \overline{\theta}_{\dot{\alpha}}$ are fermionic coordinates

  - two-component spinors.
  - Anticommute

$$\{\theta_\alpha, \theta_\beta\} = \{\overline{\theta}_{\dot{\alpha}}, \overline{\theta}_{\dot{\beta}}\} = \{\theta_\alpha, \overline{\theta}_{\dot{\beta}}\} = 0$$

  - the spinor indices $\alpha, \beta, \dot{\alpha}, \dot{\beta}$ go from 1 to 2.

Superspace & Superfields

- Superfield $S(x^\mu, \theta_\alpha, \overline{\theta}_{\dot{\alpha}})$
  - ✓ is a function of superspace coordinate.
  - ✓ is the representation of supermultiplet in superspace.
  - ✓ general form:

$$S(x, \theta, \overline{\theta}) = a + \theta\xi + \overline{\theta}\overline{\chi} + \theta^2 b + \overline{\theta}^2 c + \theta\sigma^\mu\overline{\theta} v_\mu + \theta^2\overline{\theta}\,\overline{\zeta} + \overline{\theta}^2\theta\eta + \theta^2\overline{\theta}^2 d$$

bosonic fields

fermionic fields

$$\theta^2 = \theta\theta = \theta^\alpha\theta_\alpha$$

$$\overline{\theta}^2 = \overline{\theta}\,\overline{\theta} = \overline{\theta}_{\dot{\alpha}}\overline{\theta}^{\dot{\alpha}}$$

Superspace & Superfields

- SUSY generators

$$Q_\alpha = -i\frac{\partial}{\partial\theta^\alpha} - \sigma^\mu_{\alpha\dot{\beta}}\overline{\theta}^{\dot{\beta}}\partial_\mu \qquad \overline{Q}_{\dot{\alpha}} = i\frac{\partial}{\partial\overline{\theta}^{\dot{\alpha}}} + \theta^\beta\sigma^\mu_{\beta\dot{\alpha}}\partial_\mu$$

$$Q^\alpha = i\frac{\partial}{\partial\theta_\alpha} + (\overline{\theta}\overline{\sigma}^\mu)^\alpha\partial_\mu \qquad \overline{Q}^{\dot{\alpha}} = -i\frac{\partial}{\partial\overline{\theta}_{\dot{\alpha}}} - (\overline{\sigma}^\mu\theta)^{\dot{\alpha}}\partial_\mu$$

✓ anticommutation relations

$$\{Q_\alpha, \overline{Q}_{\dot{\beta}}\} = 2\sigma^\mu_{\alpha\dot{\beta}}P_\mu = -2i\sigma^\mu_{\alpha\dot{\beta}}\partial_\mu$$

$$\{Q_\alpha, Q_\beta\} = 0$$

$$\{\overline{Q}_{\dot{\alpha}}, \overline{Q}_{\dot{\beta}}\} = 0$$

Superspace & Superfields

- SUSY transformation

$$
\begin{aligned}
\delta_\epsilon S(x,\theta,\overline{\theta}) &= S(x^\mu + i\epsilon\sigma^\mu\overline{\theta} + i\overline{\epsilon\sigma}^\mu\theta, \theta+\epsilon, \overline{\theta}+\overline{\epsilon}) - S(x,\theta,\overline{\theta}) \\
&= (i\epsilon Q + i\overline{\epsilon Q})S(x,\theta,\overline{\theta}) \\
&= \left[\epsilon^\alpha \frac{\partial}{\partial\theta^\alpha} + \overline{\epsilon}_{\dot{\alpha}} \frac{\partial}{\partial\overline{\theta}_{\dot{\alpha}}} - i\Big(\epsilon\sigma^\mu\overline{\theta} + \overline{\epsilon\sigma}^\mu\theta\Big)\right] S(x,\theta,\overline{\theta})
\end{aligned}
$$

Superspace & Superfields

- SUSY covariant derivatives

$$D_\alpha = \frac{\partial}{\partial\theta^\alpha} + i\sigma^\mu_{\alpha\dot\beta}\overline{\theta}^{\dot\beta}\partial_\mu$$

$$\overline{D}_{\dot\alpha} = (D_\alpha)^\dagger = \frac{\partial}{\partial\overline{\theta}^{\dot\alpha}} + i\theta^\beta\sigma^\mu_{\beta\dot\alpha}\partial_\mu$$

✓ anticommutation relations

$$\{D_\alpha, \overline{D}_{\dot\beta}\} = 2i\sigma^\mu_{\alpha\dot\beta}\partial_\mu$$

$$\{D_\alpha, D_\beta\} = \{\overline{D}_{\dot\alpha}, \overline{D}_{\dot\beta}\} = 0$$

$$\{D_\alpha, Q_\beta\} = \{D_\alpha, \overline{Q}_{\dot\beta}\} = 0$$

$$\{\overline{D}_{\dot\alpha}, Q_\beta\} = \{\overline{D}_{\dot\alpha}, \overline{Q}_{\dot\beta}\} = 0$$

✓ SUSY transformation

$$\delta_\epsilon(D_\alpha S) = D_\alpha(\delta_\epsilon S)$$

$$\delta_\epsilon(\overline{D}_{\dot\alpha} S) = \overline{D}_{\dot\alpha}(\delta_\epsilon S)$$

Superspace & Superfields

- Chiral superfields
  - ✓ describe spin 0 bosons and spin 1/2 fermions
    - ‣ Higgs bosons, quarks, and leptons
  - ✓ Superfield $\Phi(x, \theta, \overline{\theta})$
    - ‣ chiral (left-chiral) superfield

$$\overline{D}_{\dot{\alpha}} \Phi = 0$$

    - ‣ antichiral (right-chiral) superfield

$$D_{\alpha} \Phi^* = 0$$

Superspace & Superfields

- Chiral superfields
  - ✓ Change coordinate $(x^\mu, \theta, \overline{\theta}) \to (y^\mu, \theta)$
    - chiral coordinate

$$(y^\mu, \theta) \qquad y^\mu = x^\mu + i\theta\sigma^\mu\overline{\theta}$$

    - antichiral coordinate

$$(\overline{y}^\mu, \overline{\theta}) \qquad \overline{y}^\mu = x^\mu - i\theta\sigma^\mu\overline{\theta}$$

    - Covariant derivative

$$D_\alpha = \frac{\partial}{\partial\theta^\alpha} + 2i\sigma^\mu_{\alpha\dot{\beta}}\overline{\theta}^{\dot{\beta}}\frac{\partial}{\partial y^\mu} \qquad \overline{D}_{\dot{\alpha}} = \frac{\partial}{\partial\overline{\theta}^{\dot{\alpha}}}$$

Superspace & Superfields

- Chiral superfields
  - ✓ The general form in chiral coordinate

$$\Phi(y,\theta) = \phi(y) + \sqrt{2}\theta\phi(y) + \theta\theta\mathcal{F}(y)$$

    - function of (y^μ, θ)
    - SUSY transformation $\delta_\epsilon\Phi = (i\epsilon Q + i\overline{\epsilon}\overline{Q})\Phi$

      component fields

$$\delta_\epsilon\phi = \sqrt{2}\epsilon\psi$$

$$\delta_\epsilon\psi_\alpha = i\sqrt{2}\partial_\mu\phi(\sigma^\mu\overline{\epsilon})_\alpha - \sqrt{2}\epsilon_\alpha\mathcal{F}$$

$$\delta_\epsilon\mathcal{F} = i\sqrt{2}\partial_\mu\psi\sigma^\mu\overline{\epsilon}$$

Superspace & Superfields

- Vector superfields
  - ✓ describe spin 1 gauge bosons.
  - ✓ are real superfields $V(x,\theta,\bar\theta) = V^\dagger(x,\theta,\bar\theta)$
  - ✓ The general form

real scalar fields

Weyl spinor fields

vector field

$$
\begin{aligned}
V(x,\theta,\bar\theta) = {} & C + i\theta\chi - i\bar\theta\bar\chi + \theta\sigma^\mu\bar\theta v_\mu \\
& + \frac{i}{2}\theta^2(M+iN) - \frac{i}{2}\bar\theta^2(M-iN) \\
& + i\theta^2\bar\theta(\bar\lambda + \frac{i}{2}\bar\sigma^\mu\partial_\mu\chi) - i\bar\theta^2\theta(\lambda - \frac{i}{2}\sigma^\mu\partial_\mu\bar\chi) \\
& + \frac{1}{2}\theta^2\bar\theta^2(D - \frac{1}{2}\partial^2 C)
\end{aligned}
$$

Superspace & Superfields

- Vector superfields
  - ✓ a chiral superfield $\mathbf{\Phi}$ can construct a vector field.
    - ‣ example

$$\begin{aligned}\Phi + \Phi^\dagger = &(\phi + \phi^*) + \sqrt{2}\theta\psi + \sqrt{2}\overline{\theta}\ \overline{\psi} \\ &- i\theta\sigma^\mu\overline{\theta}\partial_\mu(\phi - \phi^*) + \theta^2\mathcal{F} + \overline{\theta}^2\mathcal{F}^* \\ &+ \frac{i}{\sqrt{2}}\theta^2\overline{\theta}\overline{\sigma}^\mu\partial_\mu\psi - \frac{i}{\sqrt{2}}\overline{\theta}^2\theta\sigma^\mu\partial_\mu\overline{\psi} \\ &- \frac{1}{4}\theta^2\overline{\theta}^2\partial^2(\phi + \phi^*)\end{aligned}$$

Superspace & Superfields

- Vector superfields
  - ✓ SUSY gauge transformation $V \to V + i(\Phi - \Phi^\dagger)$
  - ✓ Wess-Zumino gauge
    - C(x) = M(x) = N(x) = χ(x) = $\chi^\dagger$(x) = 0
    - reduces the number of the components
    - vector superfield under WZ gauge

$$V_{WZ} = \theta\sigma^\mu\overline{\theta}v_\mu(x) + i\theta^2\overline{\theta}\ \overline{\lambda}(x) - i\overline{\theta}^2\theta\lambda(x) + \frac{1}{2}\theta^2\overline{\theta}^2 D(x)$$

$$V_{WZ}^2 = [\theta\sigma^\mu\overline{\theta}v_\mu(x)][\theta\sigma^\nu\overline{\theta}v_\nu(x)] = \frac{1}{2}\theta^2\overline{\theta}^2 v_\mu v^\mu$$

$$V_{WZ}^n = 0, n \geq 3$$

Supersymmetry Breaking

- What is symmetry breaking?

symmetry

symmetry is broken

Supersymmetry Breaking

- Symmetry breaking
  - ✓ spontaneous symmetry breaking: $E_{\text{ground state}} \neq 0$ ✓
  - ✓ soft symmetry breaking: non-symmetric term in E.O.M
- SUSY theory
  - ✓ In the same supermultiplet: $M_{\text{particle}} = M_{\text{sparticle}}$
    - ‣ No selectrons m = 0.51 MeV are found.
    - ‣ No massless ferminoic partner of photon.
  - ✓ Nature is not exactly supersymmetry ➜ SUSY is broken.
    - ‣ $E_{\text{ground state}} > 0$

Supersymmetry Breaking

- Energy
  - ✓ is the expectation of the Hamiltonian H.
    - $E_{\psi} = \langle \psi | H | \psi \rangle$ for an arbitrary state $|\psi\rangle$.
  - ✓ $|\Omega\rangle$: vacuum state (ground state)
    - vacuum expectation value (VEV)

      $E_{\text{ground state}} = \langle \Omega | H | \Omega \rangle$

Supersymmetry Breaking

- Superalgebra

$$H = \frac{1}{4}(\{Q_1, \overline{Q}_1\} + \{Q_2, \overline{Q}_2\})$$

- Energy

$$\begin{aligned} E_\Psi &= \langle \Psi | H | \Psi \rangle \\ &= \frac{1}{4} \sum_{\alpha, \dot{\alpha}} (\| Q_\alpha | \Psi \rangle \|^2 + \| \overline{Q}_{\dot{\alpha}} | \Psi \rangle \|^2) \end{aligned}$$

✓ non-negative

✓ VEV

‣ E = 0: $Q_\alpha | \Omega \rangle = \overline{Q}_{\dot{\alpha}} | \Omega \rangle = 0$

‣ E ≠ 0: $Q_\alpha | \Omega \rangle \neq 0$ or $Q_\alpha | \Omega \rangle \neq 0$

Supersymmetry Breaking

- The scalar potential V

$$V(\phi, \phi^*) = \mathcal{F}^{*i}\mathcal{F}_i + \frac{1}{2}\sum_a \mathcal{D}^a\mathcal{D}_a$$

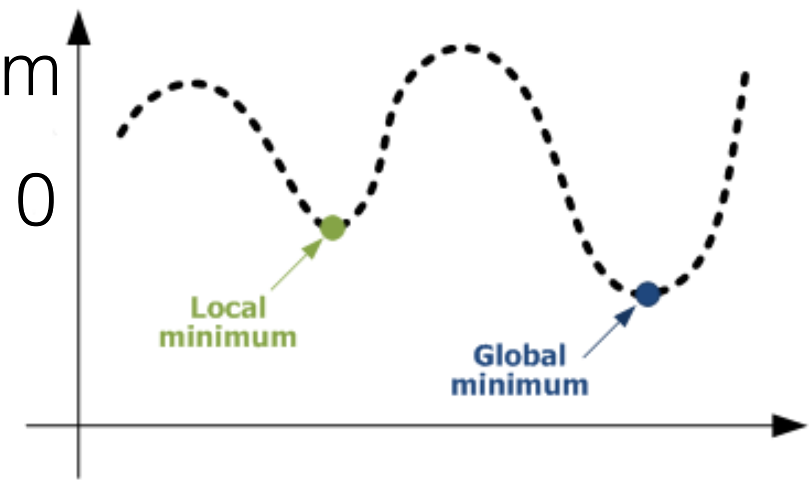
✓ Minimum of V and vacuum state $|\Omega\rangle$

- true vacuum: global minimum

  example: $\mathcal{F}_i = \mathcal{D}_a = 0 \rightarrow V = 0$

- false vacuum: local minimum

  example: $\langle\mathcal{F}_i\rangle \neq 0$ or $\langle\mathcal{D}_a\rangle \neq 0$



Supersymmetry Breaking

- O'Raifeartaigh model ($\mathcal{F}$-term breaking)
  - ✓ 3 chiral supermultiplets: Φ_1, Φ_2, Φ_3
  - ✓ superpotential W

$$W = g\,\Phi_1\,(\Phi_3^2 - m^2) + M\,\Phi_2\,\Phi_3,\ M \gg m$$

  - ✓ The auxiliary field $\mathcal{F}^{*i} = -W^i$

$$\mathcal{F}^{*1} = -W^1 = \frac{\partial W}{\partial \phi_1} = g(\phi_3^2 - m^2)$$

$$\mathcal{F}^{*2} = -W^2 = \frac{\partial W}{\partial \phi_2} = M\phi_3$$

$$\mathcal{F}^{*3} = -W^3 = \frac{\partial W}{\partial \phi_3} = 2g\phi_1\phi_3 + M\phi_2$$

$$\mathcal{F}^{*1} = 0 \Longleftrightarrow \mathcal{F}^{*2} = 0$$

$\mathcal{F}^{*i} = 0$ for i=1, 2, 3

Summary

- SUSY
    - ✓ expects the supersymmetric particles exist.
        - R= -1 for superparticles
    - ✓ two supermultiplets
        - chiral supermultiplet: s=0 bosons and s=1/2 fermions.
        - vector supermultiplet: gauge bosons
    - ✓ must be broken.

Summary

- SUSY
  - ✓ superspace & superfields
  - ✓ supermultiplets ➜ superfields
  - ✓ transformation $(i\epsilon Q + i\overline{\epsilon}\overline{Q})S(x,\theta,\overline{\theta})$
    - $S(x,\theta,\overline{\theta})$ is a general superfield
    - ϵ is an anticommuting constant spinor
    - Q is a generator

$$\{Q_\alpha, \overline{Q}_{\dot{\beta}}\} = 2\sigma^\mu_{\alpha\dot{\beta}} P_\mu, \quad \{Q_\alpha, Q_\beta\} = 0 \quad \{\overline{Q}_{\dot{\alpha}}, \overline{Q}_{\dot{\beta}}\} = 0$$

References

- Stephen Martin. "A Supersymmetry Primer".
  arXiv:hep-ph/9709356v6
- Michael Peskin. "Supersymmetry in Elementary Particle Physics".
  arXiv:0801.1928
- Adel Bilal. "Introduction to Supersymmetry".
  arXiv:hep-th/0101055v1
- Manuel Dress. "An Introduction to Supersymmetry".
  arXiv:hep-ph/9611409v1
- Lecture notes from Alex Tapper.
  http:www.hep.ph.ic.ac.uk/~tapper/lecture.html
- Howard Baer & Xerxes Tata. "Weak Scale Supersymmetry".

Backup

Lorentz Group

- Lorentz transformation = rotation + boost
- The infinitesimal Lorentz transformation

$$U(\vec{\theta},\vec{\phi}) \simeq 1 + i\vec{\theta}\cdot\vec{J} + i\vec{\phi}\cdot\vec{K}$$

J rotation generator, ***K*** boost generator

- Commutation relations

$[J_i, J_j] = i\,\epsilon_{ijk}\,J_k$

$[K_i, K_j] = -i\,\epsilon_{ijk}\,J_k$

$[J_i, K_j] = i\,\epsilon_{ijk}\,K_k$

$i, j, k = 1, 2, 3$

If we define new generators as

$$J_i^{\pm} = \frac{1}{2}(J_i \pm iK_i)$$

the commutation relations become

$$[J_i^+, J_j^+] = i\epsilon_{ijk}J_k^+$$

$$[J_i^-, J_j^-] = i\epsilon_{ijk}J_k^-$$

$$[J_i^+, J_j^-] = 0$$

➡ Two independent *SU(2)* groups!

Poincaré Group

- Poincaré group = Lorentz group ⊗ translation group (in space-time)
  - ✓ is the underly symmetry group of particle physics.
- Commutation relations

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

  $[M_{\mu\nu}, P_\lambda] = i\,(g_{\nu\lambda} P_\mu - g_{\mu\lambda} P_\nu)$

  $[M_{\mu\nu}, M_{\rho\sigma}] = -i\,(g_{\mu\rho} M_{\nu\sigma} - g_{\mu\sigma} M_{\nu\rho} - g_{\nu\rho} M_{\mu\sigma} + g_{\nu\sigma} M_{\mu\rho})$

  where $M_{\mu\nu}$ is an antisymmetric tensor with rank 2.

  - ✓ The six components are the six Lorentz group generators.
  - ✓ $M_{ij} = \epsilon_{ijk} J_k$
  - ✓ $M_{0i} = -M_{i0} = -K_i$
  - ✓ The metric $g_{\mu\nu} = diag\,(1, -1, -1, -1)$.

Spinors

- Spinors
  - ✓ The general state of a spin-1/2 particle can be expressed as a two component column matrix.

$$\chi = c_+ \chi_+ + c_- \chi_- = \begin{pmatrix} c_+ \\ c_- \end{pmatrix} \qquad \chi_+ = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \qquad \chi_- = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

- Bi-spinors
  - ✓ consist of two spinors which belong to two different *SU(2)* group.
  - ✓ Ψ_D is a solution of the Dirac equation $(i\, \gamma^\mu \partial_\mu - m)\Psi = 0$
    - is a 4-component field

$$\psi_D = \boxed{\begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \\ \psi_4 \end{pmatrix}} = \boxed{\begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}}$$

4-component form

bi-spinor form

Spinors

- Weyl spinors (Weyl fermion fields)
  - ✓ are the building blocks for any fermion field.
  - ✓ Ψ_L and Ψ_R are Weyl spinors.
- Majorana spinors
  - ✓ Majorana condition: $\psi = C\overline{\psi}^T$
  - ✓ bi-spinor form

$$\psi = \begin{pmatrix} \xi_\alpha \\ \overline{\xi}^{\dot{\alpha}} \end{pmatrix}$$

Hermitian conjugate

- Identities
  - ✓ Spinors Ψ and χ are anticommute objects.

$$\psi\chi = \chi\psi \qquad \chi\sigma^\mu\overline{\psi} = -\overline{\psi}\overline{\sigma}^\mu\chi \qquad \chi\sigma^\mu\overline{\sigma}^\nu\psi = \psi\sigma^\nu\overline{\sigma}^\mu\chi$$

$$\overline{\psi}\overline{\chi} = \overline{\chi}\overline{\psi} \qquad (\chi\sigma^\mu\overline{\psi})^\dagger = \psi\sigma^\mu\overline{\chi} \qquad (\chi\sigma^\mu\overline{\sigma}^\nu\psi)^\dagger = \overline{\psi}\overline{\sigma}^\nu\sigma^\mu\overline{\chi}$$

$$(\psi\chi)^\dagger = \overline{\psi}\overline{\chi}$$

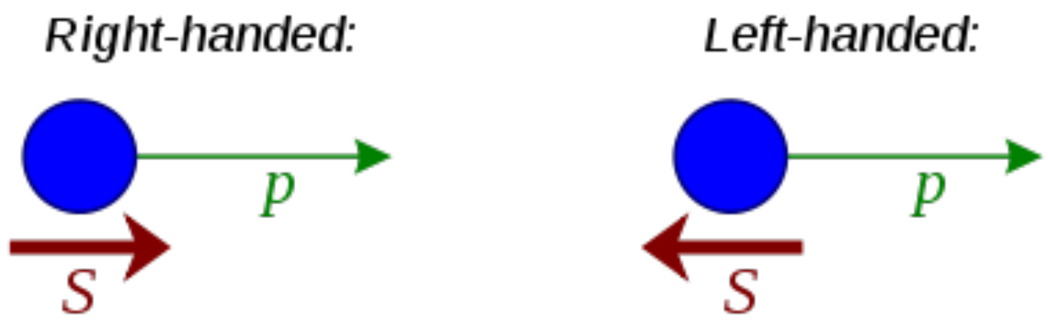
Helicity

- the projection of angular momentum ***J*** onto the direction of momentum ***P***.

$$h = \vec{J} \cdot \hat{p} = (\vec{L} + \vec{S}) \cdot \hat{p} = \vec{S} \cdot \hat{p}, \quad \hat{p} = \frac{\vec{p}}{|\vec{p}|}$$

✓ eigenvalues of ***h*** are *±1*

h = +1: right-handed, *h = -1*: left-handed



- is invariant under rotations but not invariant under boost.

✓ For a massless particle, the helicity is Lorentz invariant.

Chirality

- Chirality ≠ Helicity
  - ✓ For a mass less particle, chirality = helicity
- Chirality operators $P_L = \frac{1-\gamma_5}{2}$ $P_R = \frac{1+\gamma_5}{2}$
- Bi-spinor Ψ
  - ✓ $\Psi = \Psi_L + \Psi_R$
  - ✓ $\Psi_L = P_L\,\Psi$, $\Psi_R = P_R\,\Psi$
  - ✓ $P_L\,\Psi_R = 0$, $P_R\,\Psi_L = 0$
- Chirality is preserved under Lorentz transformation.

Grassmann Numbers

- Anticommute $\{\theta_\alpha, \theta_\beta\} = \{\overline{\theta}_{\dot\alpha}, \overline{\theta}_{\dot\beta}\} = \{\theta_\alpha, \overline{\theta}_{\dot\beta}\} = 0$
- Identities

$$\theta_\alpha\theta_\beta = \frac{1}{2}\epsilon_{\alpha\beta}\theta\theta \qquad (\theta\psi)(\theta\chi) = -\frac{1}{2}\theta\theta\psi\chi \qquad (\theta\sigma^\mu\overline{\theta})(\theta\sigma^\nu\overline{\theta}) = \frac{1}{2}\theta\theta\overline{\theta\theta}g^{\mu\nu}$$

$$\overline{\theta}_{\dot\alpha}\overline{\theta}_{\dot\beta} = -\frac{1}{2}\epsilon_{\dot\alpha\dot\beta}\overline{\theta\theta} \qquad (\overline{\theta\psi})(\overline{\theta}\overline{\chi}) = -\frac{1}{2}\overline{\theta\theta\psi}\overline{\chi}$$

$$\theta_\alpha\overline{\theta}_{\dot\beta} = \frac{1}{2}\sigma^\mu_{\alpha\dot\beta}(\overline{\theta}\overline{\sigma}_\mu\theta) \qquad (\theta\psi)(\overline{\theta}\overline{\chi}) = \frac{1}{2}(\overline{\theta}\overline{\sigma}^\mu\theta)(\psi\sigma_\mu\overline{\chi})$$

- Derivatives $\frac{\partial}{\partial\theta^\alpha}(\theta^\beta) = \delta^\beta_\alpha, \quad \frac{\partial}{\partial\overline{\theta}_{\dot\alpha}}(\overline{\theta}_{\dot\beta}) = \delta^{\dot\alpha}_{\dot\beta}, \quad \frac{\partial}{\partial\theta^\alpha}(\overline{\theta}_{\dot\beta}) = 0, \quad \frac{\partial}{\partial\overline{\theta}_{\dot\alpha}}(\theta^\beta) = 0$
- Integrations $\int d\theta_\alpha = 0, \quad \int d\theta_\alpha\ \theta_\alpha = 1$

$$\int d^2\theta\ \theta\theta = \int d^2\overline{\theta}\ \overline{\theta\theta} = 1 \quad \text{where} \quad d^2\theta = \frac{1}{2}d\theta^1 d\theta^2, \quad d^2\overline{\theta} = \frac{1}{2}d\overline{\theta}^2 d\overline{\theta}^1 = (d^2\theta)^\dagger$$

Super-Poincaré Group

- Commutation relations

$$[P_\mu, Q^I_\alpha] = 0 \qquad [M_{\mu\nu}, Q^I_\alpha] = i(\sigma_{\mu\nu})_\alpha{}^\beta Q^I_\beta \qquad \{Q^I_\alpha, \overline{Q}^J_{\dot\beta}\} = 2\sigma^\mu_{\alpha\dot\beta} P_\mu \delta^{IJ}$$

$$[P_\mu, \overline{Q}^I_{\dot\alpha}] = 0 \qquad [M_{\mu\nu}, \overline{Q}^{I\dot\alpha}] = i(\overline{\sigma}_{\mu\nu})^{\dot\alpha}{}_{\dot\beta} \overline{Q}^{I\dot\beta} \qquad \{Q^I_\alpha, Q^J_\beta\} = \epsilon_{\alpha\beta} Z^{IJ}$$

$$\{\overline{Q}^I_{\dot\alpha}, \overline{Q}^J_{\dot\beta}\} = \epsilon_{\dot\alpha\dot\beta} (Z^{IJ})^*$$

✓ $Z^{IJ} = -Z^{JI}$ central charge (≠ 0 for N > 1).

- commutes with all generators

✓ I, J = 1, 2, …, N

- N ≤ 8 physical meaning
- N = 1 SUSY
- N > 1 extended SUSY

Supermultiplets

- Supermultipletes
  - ✓ are SUSY single particle states $\Longleftrightarrow$ irreducible representations of super-Poincaré alrgbra
  - ✓ contain bosons and fermions.
    - ‣ equal number of degree of freedom.
  - ✓ all particles in the same supermultiplet have the same mass.
    - ‣ $P^2 = m^2$, commutes with all generators
- chiral supermultiplet: a complex scalar and a Weyl fermion

  vector supermultiplet: a gauge boson and a Weyl fermion

Standard Model

- Extensions:
  - ✓ Technicolor
    - ‣ The role of Higgs boson is replaced by a composite state of tightly bound fermions which is called technifermions.
  - ✓ Little Higgs models
    - ‣ use global symmetries to stabilize the mass of the Higgs bosons.
  - ✓ Supersymmetry (SUSY)
  - ✓ …

The Wess-Zumino Model

- Noether's theorem
  - ✓ symmetry ⇔ conserved current
  - ✓ symmetry transformation $\Phi(x) \to \Phi'(x) + \boldsymbol{\alpha}\Delta\Phi(x)$
    - ‣ Equation of motion $\partial_\mu\Big(\frac{\partial\mathcal{L}}{\partial(\partial_\mu\phi)}\Big) - \frac{\partial\mathcal{L}}{\partial\phi} = 0$ is invariant.
    - ‣ The Lagrangian $\mathcal{L}(x) \to \mathcal{L}(x) + \boldsymbol{\alpha}\, \partial_\mu \mathcal{J}^\mu(x)$ is invariant.
  - ✓ conserved current
    - ‣ $\partial_\mu \mathcal{J}^\mu(x) = 0$, for $\mathcal{J}^\mu = \frac{\partial\mathcal{L}}{\partial(\partial_\mu\phi)}\Delta\phi - \mathcal{J}^\mu$
  - ✓ conserved charge

$$Q \equiv \int_{\mathrm{all\ space}} j^0 d^3x$$

The Wess-Zumino Model

- SUSY is a symmetry in superspace.
  - ✓ Noether's theorem
    - conserved currents (supercurrents)

$$J^{\mu}_{\alpha} = (\sigma^{\nu}\overline{\sigma}^{\mu}\psi)_{\alpha}\partial_{\nu}\phi^{*}$$

$$J^{\dagger\mu}_{\dot{\alpha}} = (\psi^{\dagger}\overline{\sigma}^{\mu}\sigma^{\nu})_{\dot{\alpha}}\partial_{\nu}\phi$$

    - conserved charges (supercharges)

$$Q_{\alpha} = \sqrt{2}\int d^{3}x\ J^{0}_{\alpha}$$

$$Q^{\dagger}_{\dot{\alpha}} = \sqrt{2}\int d^{3}x J^{\dagger 0}_{\dot{\alpha}}$$

Superspace & Superfields

- Superfield $S(x^\mu, \theta_\alpha, \overline{\theta}_{\dot{\alpha}})$
  - ✓ is a function of superspace coordinate.
  - ✓ is the representation of supermultiplet in superspace.
  - ✓ general form:

$$
\begin{aligned}
S(x, \theta, \overline{\theta}) = & \; a + \theta\xi + \overline{\theta}\overline{\chi} + \theta\theta b + \overline{\theta}\overline{\theta} c \\
& + \overline{\theta}\overline{\sigma}^\mu \theta v_\mu + \theta\theta\overline{\theta}\overline{\zeta} + \overline{\theta}\overline{\theta}\theta\eta + \theta\theta\overline{\theta}\overline{\theta} d
\end{aligned}
$$

bosonic fields
fermionic fields

Superspace & Superfields

- Vector superfields
  - ✓ describe spin 1 gauge bosons.
  - ✓ are real superfields $V(x,\theta,\overline{\theta}) = V^\dagger(x,\theta,\overline{\theta})$
  - ✓ The general form

$$
\begin{aligned}
V(x,\theta,\overline{\theta}) = {} & C + i\theta\chi - i\overline{\theta}\overline{\chi} + \theta\sigma^\mu\overline{\theta}v_\mu \\
& + \frac{i}{2}\theta\theta(M + iN) - \frac{i}{2}\overline{\theta\theta}(M - iN) \\
& + i\theta\theta\overline{\theta}\left(\overline{\lambda} + \frac{i}{2}\overline{\sigma}^\mu\partial_\mu\chi\right) - i\overline{\theta\theta}\theta\left(\lambda - \frac{i}{2}\sigma^\mu\partial_\mu\overline{\chi}\right) \\
& + \frac{1}{2}\theta\theta\overline{\theta\theta}\left(D - \frac{1}{2}\partial^2 C\right)
\end{aligned}
$$

real scalar fiel

Weyl spinor fi

vector field

Superspace & Superfields

- Vector superfields
  - ✓ a chiral superfield $\mathbf{\Phi}$ can construct a vector field.
    - ‣ example

$$
\begin{aligned}
\Phi + \Phi^\dagger = & (\phi + \phi^*) + \sqrt{2}\theta\psi + \sqrt{2}\overline{\theta\psi} \\
& - i\theta\sigma^\mu\overline{\theta}\partial_\mu(\phi - \phi^*) + \theta\theta\mathcal{F} + \overline{\theta\theta}\mathcal{F}^* \\
& + \frac{i}{\sqrt{2}}\theta\theta\overline{\theta}\overline{\sigma}^\mu\partial_\mu\psi - \frac{i}{\sqrt{2}}\overline{\theta\theta}\theta\sigma^\mu\partial_\mu\overline{\psi} \\
& - \frac{1}{4}\theta\theta\overline{\theta\theta}\partial^2(\phi + \phi^*)
\end{aligned}
$$

Superspace & Superfields

- Vector superfields
  - ✓ SUSY gauge transformation $V \to V + i(\Phi - \Phi^\dagger)$
  - ✓ Wess-Zumino gauge
    - C(x) = M(x) = N(x) = χ(x) = $\chi^\dagger$(x) = 0
    - reduces the number of the components
    - vector superfield under WZ gauge

$$V_{WZ} = \theta\sigma^\mu\overline{\theta}v_\mu(x) + i\theta\theta\overline{\theta\lambda}(x) - i\overline{\theta\theta}\theta\lambda(x) + \frac{1}{2}\theta\theta\overline{\theta\theta}D(x)$$

$$V_{WZ}^2 = [\theta\sigma^\mu\overline{\theta}v_\mu(x)][\theta\sigma^\nu\overline{\theta}v_\nu(x)] = \frac{1}{2}\theta\theta\overline{\theta\theta}v_\mu v^\mu$$

$$V_{WZ}^n = 0, n \geq 3$$

Supersymmetry Breaking

- Superalgebra
  - anticommutation relation $\{Q_\alpha, \overline{Q}_{\dot{\beta}}\} = 2\sigma^\mu_{\alpha\dot{\beta}} P_\mu$
    - Pauli matrices

$$\sigma^0 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \quad \sigma^1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad \sigma^2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \quad \sigma^3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\{Q_1, \overline{Q}_1\} = 2(\sigma^0_{11} P_0 + \sigma^1_{11} P_1 + \sigma^2_{11} P_2 + \sigma^3_{11} P_3) = 2(P_0 + P_3)$$

$$\{Q_2, \overline{Q}_2\} = 2(\sigma^0_{22} P_0 + \sigma^1_{22} P_1 + \sigma^2_{22} P_2 + \sigma^3_{22} P_3) = 2(P_0 - P_3)$$

- Hamiltonian

$$H \equiv P^0 = g^{00} P_0 = P_0$$
$$= \frac{1}{4}(\{Q_1 + \overline{Q}_1\} + \{Q_2, \overline{Q}_2\})$$

$$g^{\mu\nu} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

Supersymmetry Breaking

- $\mathcal{F}$-term breaking and $\mathcal{D}$-term breaking

MSSM

- The **m**inimal **s**upersymmetry **s**tandard **m**odel
- vector fields ➜ vector supermultiplets

Names	spin 1/2	spin 1	$SU(3)_C, SU(2)_L, U(1)_Y$
gluino, gluon	$\widetilde{g}$	g	$(\mathbf{8}, \quad , \mathbf{1}, \quad 0)$
winos, W bosons	$\widetilde{W}^{\pm}, \widetilde{W}^0$	$W^{\pm}, W^0$	$(\mathbf{1}, \quad \mathbf{3}, \quad 0)$
bino, B boson	$\widetilde{B}^0$	B^0	$(\mathbf{1}, \quad \mathbf{1}, \quad 0)$

MSSM

- matter fields ➜ chiral supermultiplets
- 5 left-chiral supermultiplets for fermions
- 2 Higgs supermultiplets $Q = T_3 + Y$

Names		spin 0	spin 1/2	$SU(3)_C, SU(2)_L, U(1)_Y$
squarks, quarks (×3 families)	Q	$(\widetilde{u}_L \quad \widetilde{d}_L)$	$(u_L \quad d_L)$	$(\mathbf{3}, \quad \mathbf{2}, \quad \frac{1}{6})$
	$\overline{u}$	$\widetilde{\overline{u}}_L = \widetilde{u}_R^*$	$\overline{u}_L = u_R^\dagger$	$(\overline{\mathbf{3}}, \quad \mathbf{1}, \quad -\frac{2}{3})$
	$\overline{d}$	$\widetilde{\overline{d}}_L = \widetilde{d}_R^*$	$\overline{d}_L = d_R^\dagger$	$(\overline{\mathbf{3}}, \quad \mathbf{1}, \quad \frac{1}{3})$
sleptons, leptons (×3 families)	L	$(\widetilde{\nu} \quad \widetilde{e}_L)$	$(\nu \quad e_L)$	$(\mathbf{1}, \quad \mathbf{2}, \quad -\frac{1}{2})$
	$\overline{e}$	$\widetilde{\overline{e}}_L = \widetilde{e}_R^*$	$\overline{e}_L = e_R^\dagger$	$(\mathbf{1}, \quad \mathbf{1}, \quad 1)$
Higgs, higgsinos	H_u	$(H_u^+ \quad H_u^0)$	$(\widetilde{H}_u^+ \quad \widetilde{H}_u^0)$	$(\mathbf{1}, \quad \mathbf{2}, \quad +\frac{1}{2})$
	H_d	$(H_d^0 \quad H_d^-)$	$(\widetilde{H}_d^0 \quad \widetilde{H}_d^-)$	$(\mathbf{1}, \quad \mathbf{2}, \quad -\frac{1}{2})$

Hypercharge (Y)

- Gell-Mann-Nishijima formula
  - ✓ $Q = I^3 + Y/2$
  - ✓ Q: electric charge (in units of e)
  - ✓ I^3: the 3rd component of isospin
- $Y = S + A$
  - ✓ S: strangeness
  - ✓ A: baryon number

Isospin

- Heisenberg
  - ✓ Neutron and proton are the two states of a single particle, the nucleon.
- I is a vector in isospin space
  - ✓ I_1, I_2, I_3 are three components
  - ✓ The nucleon carries isospin 1/2, and the 3rd component I_3 has eigenvalues +1/2 (the proton) and -1/2 (the neutron)

    $p = | 1/2, 1/2 \rangle$: isospin up

    $n = | 1/2, -1/2 \rangle$: isospin down
- The strong interactions are invariant under rotation in isospin space.

MSSM

- Superpotential

$$W_{\text{MSSM}} = \sum_{i,j=1}^{3} (\mathbf{y_u})_{ij} H_u Q_i \overline{u}_j - (\mathbf{y_d})_{ij} H_d Q_i \overline{d}_j$$
$$- (\mathbf{y_e})_{ij} H_d L_i \overline{e}_j + \mu H_u H_d$$

$$Q_i \overline{u}_j = Q_i^{\alpha} \overline{u}_{\alpha j}$$

α =1, 2,3

color indices

✓ y_u, y_d, y_e: Yukawa couplings

- 3x3 matrices
- masses (up quarks, down quarks, and leptons)

✓ μ-term $\mu H_u H_d = \mu (H_u)_\alpha (H_d)_\beta \epsilon^{\alpha\beta}$

MSSM

- Example

  ✓ top quark, bottom quark, $\boldsymbol{\tau}$ lepton

$$\mathbf{y_u} \approx \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_t \end{pmatrix}, \quad \mathbf{y_d} \approx \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_b \end{pmatrix}, \quad \mathbf{y_e} \approx \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_\tau \end{pmatrix}$$

$$\begin{aligned} W_{\mathrm{MSSM}} = {} & y_t(\widetilde{\bar{t}}_L \widetilde{t}_L H_u^0 - \widetilde{\bar{t}}_L \widetilde{b}_L H_u^+) - y_b(\widetilde{\bar{b}}_L \widetilde{t}_L H_d^- - \widetilde{\bar{b}}_L \widetilde{b}_L H_d^0) \\ & - y_\tau(\widetilde{\bar{\tau}}_L \widetilde{\nu}_{\tau L} H_d^- - \widetilde{\bar{\tau}}_L \widetilde{\tau}_L H_d^0) + \mu(H_u^+ H_d^- - H_u^0 H_d^0) \end{aligned}$$

  ✓ When $\langle\Omega|\, H_u^0\, |\Omega\rangle > 0$, $\langle\Omega|\, H_d^0\, |\Omega\rangle > 0$

    - Yukawa couplings become masses.

$$y_t \widetilde{\bar{t}}_L \widetilde{t}_L H_u^0, \quad y_b \widetilde{\bar{b}}_L \widetilde{b}_L H_d^0, \quad y_\tau \widetilde{\bar{\tau}}_L \widetilde{\tau}_L H_d^0$$

MSSM

- Superpotential

$$W_{\Delta L=1} = \frac{1}{2}\lambda_e^{ijk} L_i L_j \overline{e}_k + \lambda_L^{ijk} L_i Q_j \overline{d}_k + \mu_L L_i H_u$$

$$W_{\Delta B=1} = \frac{1}{2}\lambda_B^{ijk} \overline{u}_i \overline{d}_j \overline{d}_k$$

✓ SUSY

- baryon number and lepton number are conserved.
- $W_{\Delta L=1}$ and $W_{\Delta B=1}$ are not allowed
- introduce R-parity R = $(-1)^{3(B-L)+2s}$

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: ICHEP 2014

ATLAS Preliminary

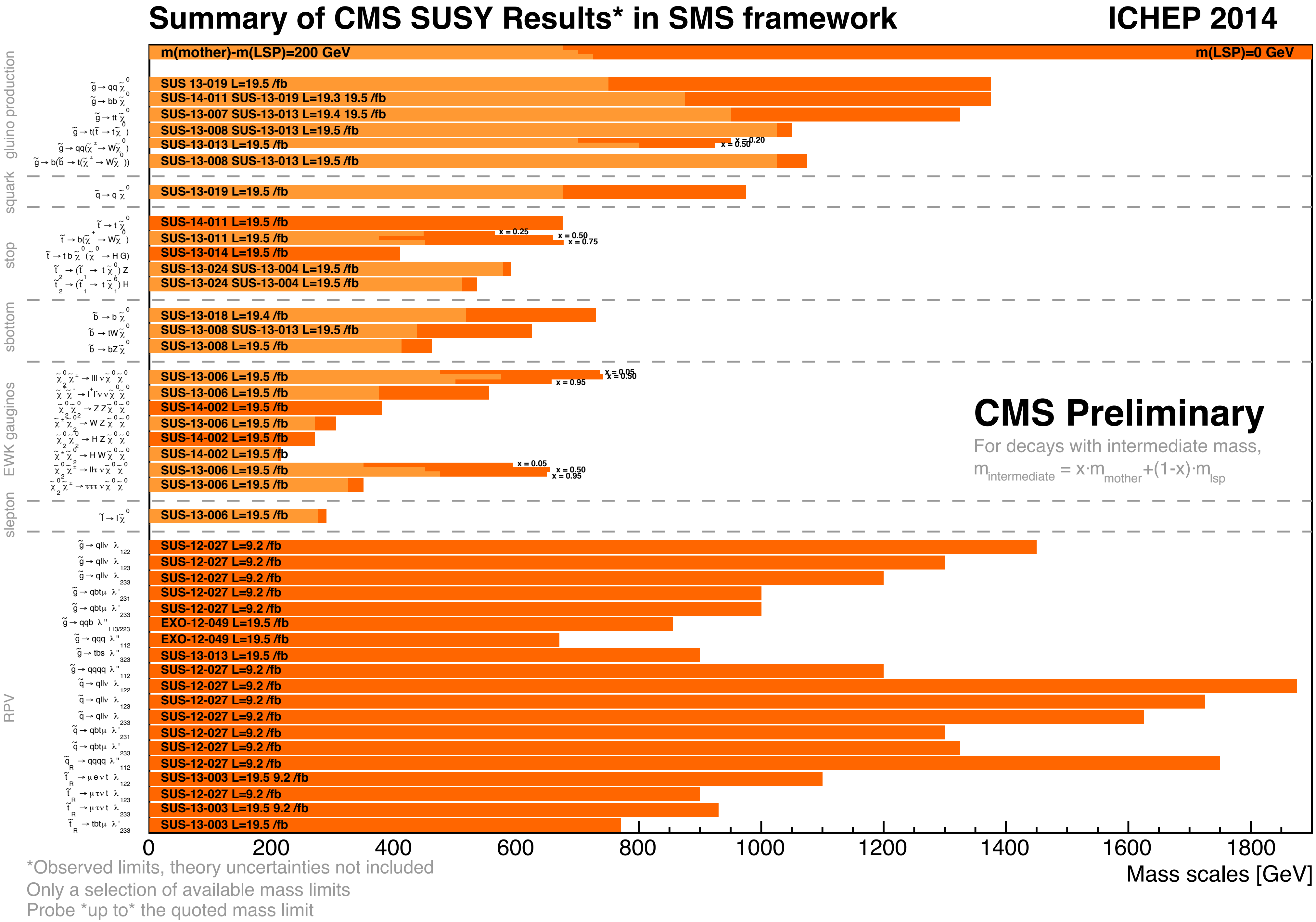
$\sqrt{s}$ = 7, 8 TeV

	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[fb^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q},\tilde{g}$ 1.7 TeV	m($\tilde{q}$)=m($\tilde{g}$)	1405.7875
	MSUGRA/CMSSM	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.2 TeV	any m($\tilde{q}$)	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	any m($\tilde{q}$)	1308.1841
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 850 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m(1^{st} gen. $\tilde{q}$)=m(2^{nd} gen. $\tilde{q}$)	1405.7875
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.33 TeV	m($\tilde{\chi}_1^0$)=0 GeV	1405.7875
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.18 TeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}^\pm$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$))	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20.3	$\tilde{g}$ 1.12 TeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e,μ	2-4 jets	Yes	4.7	$\tilde{g}$ 1.24 TeV	tanβ<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$ 1.6 TeV	tanβ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$ 1.28 TeV	m($\tilde{\chi}_1^0$)>50 GeV	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 $e,\mu+\gamma$	-	Yes	4.8	$\tilde{g}$ 619 GeV	m($\tilde{\chi}_1^0$)>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	m($\tilde{\chi}_1^0$)>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	m(NLSP)>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale 645 GeV	m($\tilde{G}$)>10^{-4} eV	ATLAS-CONF-2012-147
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.25 TeV	m($\tilde{\chi}_1^0$)<400 GeV	1407.0600
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	m($\tilde{\chi}_1^0$) <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	m($\tilde{\chi}_1^0$)<400 GeV	1407.0600
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	m($\tilde{\chi}_1^0$)<300 GeV	1407.0600
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-620 GeV	m($\tilde{\chi}_1^0$)<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$ 275-440 GeV	m($\tilde{\chi}_1^\pm$)=2 m($\tilde{\chi}_1^0$)	1404.2500
	$\tilde{t}_1\tilde{t}_1$ (light), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 110-167 GeV	m($\tilde{\chi}_1^0$)=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$ (light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 130-210 GeV	m($\tilde{\chi}_1^0$) =m($\tilde{t}_1$)-m(W)-50 GeV, m($\tilde{t}_1$)<<m($\tilde{\chi}_1^\pm$)	1403.4853
	$\tilde{t}_1\tilde{t}_1$ (medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e,μ	2 jets	Yes	20.3	$\tilde{t}_1$ 215-530 GeV	m($\tilde{\chi}_1^0$)=1 GeV	1403.4853
	$\tilde{t}_1\tilde{t}_1$ (medium), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	0	2 b	Yes	20.1	$\tilde{t}_1$ 150-580 GeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e,μ	1 b	Yes	20	$\tilde{t}_1$ 210-640 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1407.0583
	$\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{t}_1$ 260-640 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1406.1122
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-240 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 150-580 GeV	m($\tilde{\chi}_1^0$)>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$ 290-600 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$ 90-325 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$ 140-465 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 100-350 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1407.0350
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 700 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	2-3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 420 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0h\tilde{\chi}_1^0$	1 e,μ	2 b	Yes	20.3	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 285 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	ATLAS-CONF-2013-093
	$\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$ 620 GeV	m($\tilde{\chi}_2^0$)=m($\tilde{\chi}_3^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_2^0$)+m($\tilde{\chi}_1^0$))	1405.5086
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$ 270 GeV	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=160 MeV, τ($\tilde{\chi}_1^\pm$)=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 832 GeV	m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	1310.6584
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$ 475 GeV	10<tanβ<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$ 230 GeV	0.4<τ($\tilde{\chi}_1^0$)<2 ns	1304.6310
	$\tilde{q}\tilde{q}$, $\tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$ 1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, m($\tilde{\chi}_1^0$)=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e+\mu$	2 e,μ	-	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e(\mu)+\tau$	1 $e,\mu+\tau$	-	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q},\tilde{g}$ 1.35 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 750 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^\pm$), $\lambda_{121}\neq0$	1405.5086
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e,\mu+\tau$	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 450 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^\pm$), $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1t$, $\tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$ 850 GeV		1404.250
Other	Scalar gluon pair, sgluon$\to q\bar{q}$	0	4 jets	-	4.6	sgluon 100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\to t\bar{t}$	2 e,μ (SS)	2 b	Yes	14.3	sgluon 350-800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale 704 GeV	m(χ)<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

$\sqrt{s}$ = 7 TeV full data | $\sqrt{s}$ = 8 TeV partial data | $\sqrt{s}$ = 8 TeV full data

10^{-1} 1 Mass scale [TeV]

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.


Summary of CMS SUSY Results* in SMS framework
ICHEP 2014
m(mother)-m(LSP)=200 GeV
m(LSP)=0 GeV
gluino production
SUS 13-019 L=19.5 /fb
SUS-14-011 SUS-13-019 L=19.3 19.5 /fb
SUS-13-007 SUS-13-013 L=19.4 19.5 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-13-013 L=19.5 /fb
x = 0.20
x = 0.50
SUS-13-008 SUS-13-013 L=19.5 /fb
squark
SUS-13-019 L=19.5 /fb
stop
SUS-14-011 L=19.5 /fb
SUS-13-011 L=19.5 /fb
x = 0.25
x = 0.50
x = 0.75
SUS-13-014 L=19.5 /fb
SUS-13-024 SUS-13-004 L=19.5 /fb
SUS-13-024 SUS-13-004 L=19.5 /fb
sbottom
SUS-13-018 L=19.4 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-13-008 L=19.5 /fb
EWK gauginos
SUS-13-006 L=19.5 /fb
x = 0.05
x = 0.50
x = 0.95
SUS-13-006 L=19.5 /fb
SUS-14-002 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-14-002 L=19.5 /fb
SUS-14-002 L=19.5 /fb
SUS-13-006 L=19.5 /fb
x = 0.05
x = 0.50
x = 0.95
SUS-13-006 L=19.5 /fb
slepton
SUS-13-006 L=19.5 /fb
RPV
SUS-12-027 L=9.2 /fb
SUS-12-027 L=9.2 /fb
SUS-12-027 L=9.2 /fb
SUS-12-027 L=9.2 /fb
SUS-12-027 L=9.2 /fb
EXO-12-049 L=19.5 /fb
EXO-12-049 L=19.5 /fb
SUS-13-013 L=19.5 /fb
SUS-12-027 L=9.2 /fb
SUS-12-027 L=9.2 /fb
SUS-12-027 L=9.2 /fb
SUS-12-027 L=9.2 /fb
SUS-12-027 L=9.2 /fb
SUS-12-027 L=9.2 /fb
SUS-12-027 L=9.2 /fb
SUS-13-003 L=19.5 9.2 /fb
SUS-12-027 L=9.2 /fb
SUS-13-003 L=19.5 9.2 /fb
SUS-13-003 L=19.5 /fb
CMS Preliminary
For decays with intermediate mass,
m_intermediate = x·m_mother+(1-x)·m_lsp
0
200
400
600
800
1000
1200
1400
1600
1800
Mass scales [GeV]
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit