Outline

Brief overview of supersymmetry and its phenomenology

Components of the Standard Model

fermions

$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} c_L \\ s_L \end{pmatrix}, \begin{pmatrix} t_L \\ b_L \end{pmatrix},$

$u_R, d_R, c_R, s_R, t_R, b_R$

$\begin{pmatrix} \nu_e \\ e^-_L \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu^-_L \end{pmatrix}, \begin{pmatrix} \nu_\tau \\ \tau^-_L \end{pmatrix},$

e^-_R, μ^-_R, τ^-_R

gauge bosons

$SU(3)_c \times SU(2)_L \times U(1)_Y$

elm.: γ

weak: $W^\pm, Z^0$

strong: gluons

Higgs

additional scalar weak-isospin doublet with weak hypercharge $Y_H = \frac{1}{2}$:

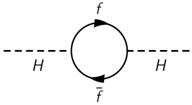
$$SU(2)_L \times U(1)_Y \xrightarrow{SSB} U(1)_{\mathrm{elm}} \qquad \Phi(x) = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}\rho(x) \end{pmatrix}$$

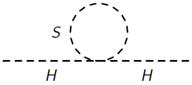
Problems of the Standard Model

- many parameters
- SM describes about 4 % of the matter in the universe only
- hierarchy problem

$$M_{\mathrm{SM}} \sim 10^2 \mathrm{GeV} \qquad M_{\mathrm{Planck}} \sim 10^{19} \mathrm{GeV}$$

- Higgs mass corrections





$$-\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{\mathrm{UV}}^2 + \ldots \qquad +\frac{\lambda_s}{16\pi^2}\Lambda_{\mathrm{UV}}^2 \tag{1}$$

- mass-less neutrinos in contradiction to observed neutrino oscillations
- no underlying symmetry for baryon number conservation

Grand unification - SU(5)

- 3 gauge groups in SM
  $\Rightarrow$ 3 couplings as "free" parameters
- running couplings approach each other for $M \sim 10^{14}$ GeV
- unification into 1 group containing the SM gauge groups possible?
  $\Rightarrow$ only 1 parameter
- smallest such group (Georgi, Glashow, 19??):

$$SU(5) \supset SU(3) \times SU(2) \times U(1)$$

- fermion decomposition into $SU(3), SU(2)$:

$$\bar{5} = (1,2) + (\bar{3},1) = (\nu_{\mathrm{e}}, \mathrm{e}^-) + \bar{\mathrm{d}}_L \quad (2)$$

$$10 = (1,1) + \bar{3},1) + (3,2) = \mathrm{e_L}^+ + \mathrm{u_L} + (\mathrm{u_L}, \mathrm{d_L}) \quad (3)$$

- gauge bosons ($N^2 - 1 = 24$):

$$24 = (8,1) + (1,3) + (1,1) + (3,2) + (\bar{3},2) \quad (4)$$

Predictions from SU(5) unification

- weak mixing angle: $\sin^2\theta_W \sim 0.2$
- quark charges:

$$Q_\mathrm{d} = \frac{1}{3} Q_{\mathrm{e}^-} \qquad Q_\mathrm{u} = -2 Q_\mathrm{u} \tag{5}$$

- proton decay:
  consider $\mathrm{p} \to \pi^0 \mathrm{e}^+$ in analogy to weak interaction

$$\frac{G_G}{\sqrt{2}} = \frac{g_G^2}{8 M_X^2} \tag{6}$$

$$\Rightarrow \Gamma(\mathrm{p} \to \pi^0 \mathrm{e}^+) \propto G_G^2 m_\mathrm{p}^5 \propto \frac{m_\mathrm{p}^5}{M_X^4} \tag{7}$$

$$\Rightarrow \tau_\mathrm{p} \sim 10^{30} \mathrm{y} \tag{8}$$

  but experimental limit $\tau_{\mathrm{p} \to \pi^0 \mathrm{e}^+} > 10^{34} \mathrm{y}$

Towards supersymmetry

- trivial cancellation of Higgs mass corrections
  if we postulate pairs of fermions and bosons
  $\rightarrow$ supersymmetry
- introduce operator Q, s.t.

$$Q\,|\text{fermion}\rangle = |\text{boson}\rangle \qquad Q\,|\text{boson}\rangle = |\text{fermion}\rangle \tag{9}$$

Observations:

- $Q^\dagger$ also a symmetry generator
- Q, $Q^\dagger$ fermionic operators with $S = \frac{1}{2}$
- decomposition into supermultiplets:

$$\left|\Omega'\right\rangle = \alpha Q\,|\Omega\rangle + \beta Q^\dagger\,|\Omega\rangle \tag{10}$$

Supermultiplets

consider members of a given supermultiplets

- $[Q, P^2] = [Q^\dagger, P^2] = 0 \Rightarrow$ equal masses
- $[Q, G] = [Q^\dagger, G] = 0$ for G any generator of a gauge group
  $\Rightarrow$ same elm. charge, weak isospin, colour
- $N_{\mathrm{bosons}} = N_{\mathrm{fermions}}$

we get

- scalar supermultiplet:

$$\text{Weyl fermion } (S = \frac{1}{2}) \leftrightarrow \text{complex scalar } (S = 0) \tag{11}$$

- vector supermultiplet:

$$\text{Weyl fermion } (S = \frac{1}{2}) \leftrightarrow \text{boson } (S = 1) \tag{12}$$

  implies identical gauge transf. for left-/right-handed components
- (gravitational supermultiplet)

Minimal Supersymmetric Standard Model (MSSM)

fermions

- construct a minimal SUSY model which contains the SM particles
- SM fermions must be in scalar supermultiplets
- scalar quarks → squarks:
  $\begin{pmatrix}\widetilde{\mathrm{u}}_\mathrm{L}\\ \widetilde{\mathrm{d}}_\mathrm{L}\end{pmatrix}, \begin{pmatrix}\widetilde{\mathrm{c}}_\mathrm{L}\\ \widetilde{\mathrm{s}}_\mathrm{L}\end{pmatrix}, \begin{pmatrix}\widetilde{\mathrm{t}}_\mathrm{L}\\ \widetilde{\mathrm{b}}_\mathrm{L}\end{pmatrix},$
  $\widetilde{\mathrm{u}}_\mathrm{R}, \widetilde{\mathrm{d}}_\mathrm{R}, \widetilde{\mathrm{c}}_\mathrm{R}, \widetilde{\mathrm{s}}_\mathrm{R}, \widetilde{\mathrm{t}}_\mathrm{R}, \widetilde{\mathrm{b}}_\mathrm{R}$
- scalar leptons → sleptons:
  $\begin{pmatrix}\nu_\mathrm{e}\\ \mathrm{e}^-_\mathrm{L}\end{pmatrix}, \begin{pmatrix}\nu_\mu\\ \mu^-_\mathrm{L}\end{pmatrix}, \begin{pmatrix}\nu_\tau\\ \tau^-_\mathrm{L}\end{pmatrix},$
  $\mathrm{e}^-_\mathrm{R}, \mu^-_\mathrm{R}, \tau^-_\mathrm{R}$
- chiral index refers to handedness of the fermionic parter, e.g. only $(\widetilde{\mathrm{u}}_\mathrm{L}, \widetilde{\mathrm{d}}_\mathrm{L})$ couple to W

Minimal Supersymmetric Standard Model (MSSM)

Higgs

- $S = 0 \Rightarrow$ scalar supermultiplet
- two supermultiplets needed to avoid anomalies
  $\Rightarrow$ extend SM Higgs sector
- introduce two weak isospin doublets with $Y = \pm\frac{1}{2}$:

$$(\mathrm{H}_u^+, \mathrm{H}_u^0) \qquad (\mathrm{H}_d^0, \mathrm{H}_d^-) \tag{13}$$

- then supersymmetric higgsinos:

$$(\widetilde{\mathrm{H}}_u^+, \widetilde{\mathrm{H}}_u^0) \qquad (\widetilde{\mathrm{H}}_d^0, \widetilde{\mathrm{H}}_d^-) \tag{14}$$

- el. weak symmetry breaking more complicated because of two Higss doublets ...

Minimal Supersymmetric Standard Model (MSSM)

gauge bosons

- SM gauge bosons must be in vector supermultiplets:

$$\underbrace{\widetilde{W}^+, \widetilde{W}^0, \widetilde{W}^-}_{\text{winos}}, \underbrace{\widetilde{B}^0}_{\text{bino}} \text{ gauginos} \tag{15}$$

- mixing of $\widetilde{W}^0$, $\widetilde{B}^0$ to photino $\widetilde{\gamma}$ and zino $\widetilde{Z}^0$
- gluons: 8 gluinos
- because of el. weak symmetry breaking mixing:
  - neutralinos:

$$\widetilde{\mathrm{H}}_u^0, \widetilde{\mathrm{H}}_d^0, \widetilde{W}^0, \widetilde{B^0} \longrightarrow \widetilde{\chi_1^0}, \widetilde{\chi_2^0}, \widetilde{\chi_3^0}, \widetilde{\chi_4^0}$$

  - charginos

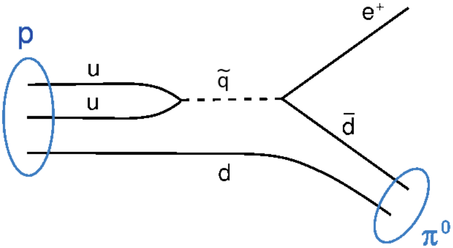
$$\widetilde{\mathrm{H}}_u^+, \widetilde{W}^+, \longrightarrow \widetilde{\chi_1^+}, \widetilde{\chi_2^+}$$
$$\widetilde{\mathrm{H}}_u^+, \widetilde{W}^+, \longrightarrow \widetilde{\chi_1^+}, \widetilde{\chi_2^+}$$

R-parity conservation

- introduce new quantum number

$$P_R = (-1)^{3(B-L)+2S} \tag{16}$$

  which is conserved
- no mixing between particles and sparticles
- lightest SUSY particle (lsp) must be stable
- proton decay, e.g.:



  forbidden

MSSM phenomenology

- if SUSY was exact ⇒ equal masses in supermultiplets
- contradicts lack of experimental evidence for SM states
- SUSY must be broken
  soft SUSY breaking, not unique

$$\mathcal{L}_{\mathrm{MSSM}} = \mathcal{L}_{\mathrm{SUSY}} + \mathcal{L}_{\mathrm{soft}} \tag{17}$$

- number of SUSY operators can be increased (here: 1)

⇒ many viable MSSM scenarios possible and proposed

MSSM scenarios

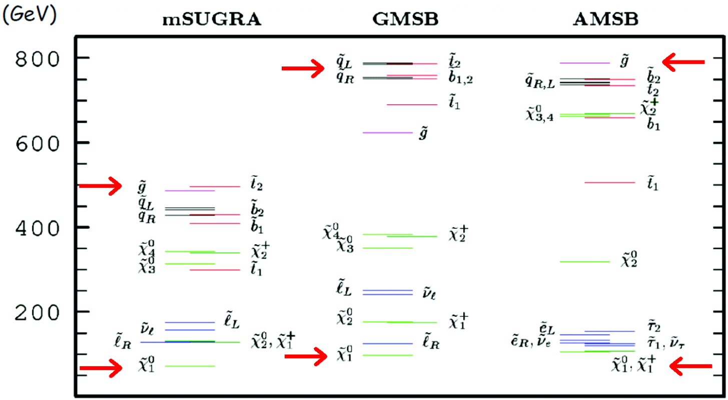


Figure: SUSY scenarios

Experimental SUSY searches

Problem Too many SUSY scenarios to check one specific prediction

Instead look for signatures which deviate from SM predictions and can be explaeined by SUSY,
e.g. jets and missing E_{T}

e.g. ATLAS: