Supersymmetry

A phenomenological Introduction

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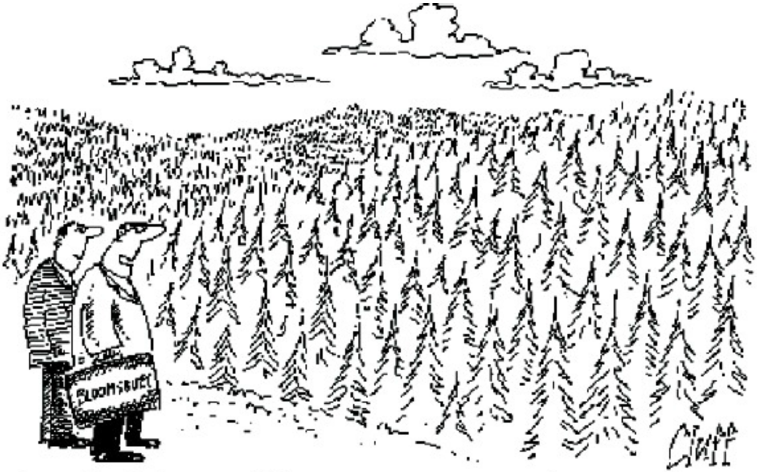


"One day, all of these will be supersymmetric phenomenology papers."

Some words about Renormalization

Renormalization

- eliminate things which act on a scale irrelevant to the question (fast degrees of freedom)

  $\Rightarrow$ effective description
- e.g. in molecular physics: no physics of quarks

Dimensional Analysis

- Three important parameters in P.P.: Energy, Length, Time
- By setting $\hbar = c = 1$ we get:

  $[m] = [E] = [P] = \frac{1}{[l]} = \frac{1}{[m]} = \frac{1}{[length]}$

Scalar Quantum Field Theory

A scalar Field Φ

$\mathscr{L} = (\partial_\mu \Phi)^2 + V(\Phi)$, Dimension of Φ?

Quantity of interest: action $S = \int \mathscr{L} \, \mathrm{d}^4 x$

$[S] = 1 \Rightarrow [\mathscr{L}] = [l]^{-4} \Rightarrow [\Phi] = [l]^{-1}$

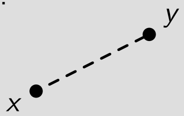
Concept of Propagators

Create a particle at x and detect it at y:

$\langle 0 | \Phi(y)\Phi(x) | 0 \rangle$, [Propagator]$= [l]^{-2}$

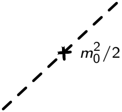
only reasonable scale: $|x - y|$

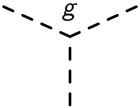
$\Rightarrow \langle 0 | \Phi(y)\Phi(x) | 0 \rangle \propto \frac{1}{|x-y|^2}$

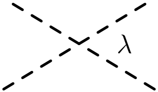


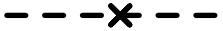
Renormalization of mass

$$V(\Phi) = \frac{m_0^2}{2}\Phi^2 + g\Phi^3 + \lambda\Phi^4$$

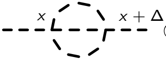






Other processes that contribute to  :


$$\propto \frac{\lambda}{|x-y|^2} \propto \frac{\lambda}{\delta^2}$$



$$\propto \int_\delta \frac{\lambda^2}{\Delta^6}\mathrm{d}^4\Delta \propto \frac{\lambda^2}{\delta^2}$$

Renormalization of mass

$$\Rightarrow m_{exp}^2 \propto m_0^2 + \frac{\lambda}{\delta^2} + \frac{\lambda^2}{\delta^2} + \cdots$$

- In SM: Higgs-Boson parameter m_{exp} is of order 100 GeV
- Scale at which SM breaks (probably) down: Plank length l_P

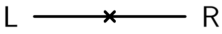
  $l_P = \sqrt{\frac{\hbar G}{c^3}} \simeq 1.6 \times 10^{-35}$m; often used as Cut-off parameter Λ

- unpleasant Fine-Tuning necessary (over 34 digits):

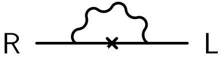
  bare mass m_0 has to compensate the radiative corrections
- Hierarchy problem of the contributions to the Higgs mass

Renormalization of mass for Fermions and Bosons

Mass term for Fermions: $\mathscr{L} \propto m\bar{\Psi}\Psi$



further contributions have also to flip Helicity



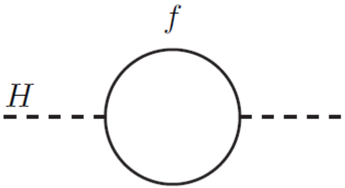
$$\Rightarrow m_{exp} = m_0 + e^2 m_0 + e^4 m_0 + \cdots$$

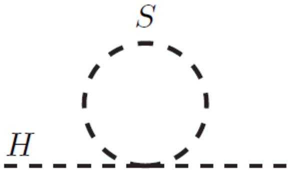
Corrections are small and not dependent on a scale

same observation holds for Bosons

$\Rightarrow$ Chiral Symmetry acts as protection mechanism

Similar for (scalar) Higgs-Boson possible?





- Yes, just add symmetry that links fermions to bosons and vv
- Cancellation of the loops due to their different statistics
- Assumption: except Spin, all quantum numbers are equal

$\Rightarrow$ Supersymmetry (SUSY)

Short Repetition of Symmetries in Physics

continuous Symmetries

- lead to a conserved quantity via the Noether theorem
- time invariance $\Leftrightarrow$ energy conservation
- spatial invariance $\Leftrightarrow$ momentum conservation
- rotation invariance $\Leftrightarrow$ angular momentum conservation
- gauge invariance $\Leftrightarrow$ conservation of electric charge

discrete Symmetries

- describe non continuous changes of a system
- time reversal
- spatial inversion (parity)
- charge conjugation

SUSY Basics

Lorentz and Poincare groups

- Lorentz group contains rotations and boosts:

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

- Poincare enlarges Lorentz group by adding translations:

$$[P_\mu, P_\nu] = 0,\ [J_i, P_j] = i\epsilon_{ijk} P_k,\ [J_i, P_0] = 0,\ [K_i, P_{j/0}] = -iP_{0/j},$$

Coleman-Mandula theorem

- How to extend space-time symmetries beyond Poincare group?
- Theorem: Symmetry group G $\simeq$ Poincare group $\times$ internal symmetries; think of a symmetry V then $[V, H] = 0$
- Loophole: Use of anticommutators

The Supersymmetry algebra (schematic)

Supercharges Q and $Q^\dagger$

- Relate boson- and fermionic states by a supersymmetry transformation:

$$Q\,|Fermion\rangle = |Boson\rangle, \quad Q\,|Boson\rangle = |Fermion\rangle$$

- That means Q shifts the spin of the particle by $1/2$:

$$Q\,|J\rangle = |J \pm 1/2\rangle$$

- Implementation by a set of (anti)commutators:
$\left\{Q_\alpha, Q^\dagger_{\dot\alpha}\right\} = -2\sigma^\mu_{\alpha\dot\alpha}P_\mu, \quad \{Q_\alpha, Q_\beta\} = \left\{Q^\dagger_{\dot\alpha}, Q^\dagger_{\dot\beta}\right\} = 0,$ and
$[P^\mu, Q_\alpha] = \left[P^\mu, Q^\dagger_{\dot\alpha}\right]$
- Now: Superspace $(x^\mu, \theta_\alpha, \bar\theta_{\dot\alpha})$, Superfields
- Grassmann coordinate θ: $x^2 = 0 \Leftrightarrow x = \theta$

The Supersymmetric Lagrangians

massless, non-interacting Wess-Zumino model

- Weyl fermion ψ, complex scalar field ϕ
- $\mathscr{L} = \partial_\mu \Phi^* \partial^\mu \Phi + i\psi^\dagger \overline{\tau}^\mu \partial_\mu \psi$
- implement infinitesimal transformation by

  $\delta\phi = \epsilon\psi \quad \delta\phi^* = \epsilon^\dagger \psi^\dagger \quad \delta\psi_\alpha = -i(\sigma^\mu \epsilon^\dagger)_\alpha \partial_\mu \phi \quad \delta\psi^\dagger_{\dot{\alpha}} = i(\epsilon\sigma^\mu)_{\dot{\alpha}} \partial_\mu \phi^*$
- this leads the action invariant under a transformation:

$$\delta S = \int d^4x (\delta\mathscr{L}_{fermion} + \delta\mathscr{L}_{scalar}) = 0$$

Interactions

- add interaction terms with auxiliary fields
- Choice of Superpotential W basically sets up the model of SUSY

The Minimal Supersymmetric Standard Model (MSSM)

Higgs doublets

- In order to give mass to all matter, 2 Higgs doublets with different hypercharge Y are needed
- doublets couple by a term $\mu \bar{H} H$ in W

  $\Rightarrow$ 2 vacuum expectation values v_u, v_d
- paramater $\tan\beta := \frac{v_u}{d}$, with $v^2 = v_u^2 + v_d^2 = \frac{1}{\sqrt{2} G_F} \approx (246\text{GeV})^2$

Supermultiplets

- Particles are arranged in 3 Supermultiplets:

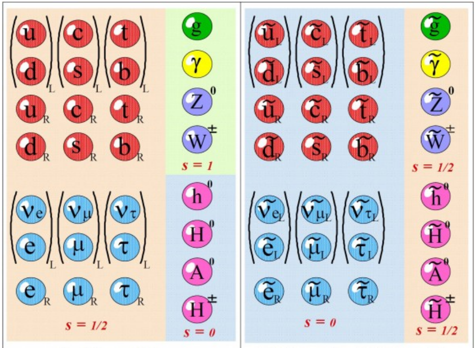
$$\text{chiral} \begin{pmatrix} \frac{1}{2} \\ 0 \end{pmatrix} \quad \text{gauge} \begin{pmatrix} 1 \\ \frac{1}{2} \end{pmatrix} \quad \text{gravitation} \begin{pmatrix} 2 \\ \frac{3}{2} \end{pmatrix}$$

- In unbroken SUSY the superpartners have same quantum numbers as their counterparts in the SM

Particle Content of the MSSM

General

- 2 scalar Higgs doublets: $8 - 3 = 5$ dof which result in $h^0, H^0, A^0, H^\pm$
- SUSY fermions mix to 2 chargino pairs $\chi_1^\pm$ $\chi_2^\pm$ and 4 neutralinos χ_1^0 χ_2^0 χ_3^0 χ_4^0



Existing particles

SUSY particles (MSSM model)

R-Parity

A New Quantum Number

- Superpotential of the MSSM is not unique
- could be extended by terms that violate baryon (B) or lepton number (L) conservation
- Decay of proton would be possible in theory (lifetime $> 2 \times 10^{29}$ years)

$$\Rightarrow \text{new quantum number: } R = (-)^{3B+L+2s} \quad \text{with spin } s$$

Consequences:

$R = 1$ for particles and $R = (-1)$ for sparticles

The lightest sparticle (LSP) is stable

$\Rightarrow$ if uncharged, candidate for Dark Matter

In accelerator experiments sparticles are produced in pairs

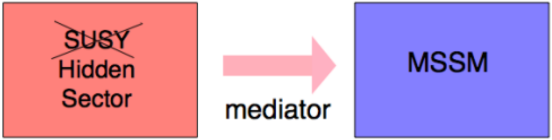
SUSY breaking

Need for a broken Symmetry

- No detection of superpartners with same mass : $m_f < m_{\tilde{f}}$
  $\Rightarrow$ Introduction of symmetry breaking: $\mathscr{L} = \mathscr{L}_{SUSY} + \mathscr{L}_{soft}$
- Additional 106 parameters (to the 18 of the SM)

Mechanism of SUSY breaking

- The mechanism is not known
- shifted to a hidden sector
- Weakness of the MSSM



Mechanisms for breaking

Gravity mediated (SUGRA)

- spontanous symmetrybreaking of a local SUSY
  $\Rightarrow$ emerging massles Goldstino is absorbed by Gravitino $\tilde{G}$
- very heavy $\tilde{G}$ sets the mass scale for sparticles
- Neutralino is the LSP

Gauge mediated (GMSB)

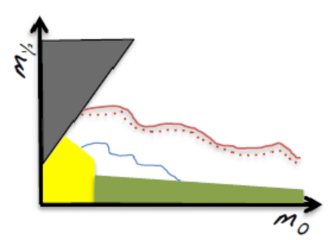
- mediation by gauge bosons and fields of the SM
  $\Rightarrow$ $\tilde{G}$ will get very light
- Gravitino is the LSP

$\Rightarrow$ Mass scale of SUSY particles depends on breaking mechanism

Experimental Search for SUSY — Approaches

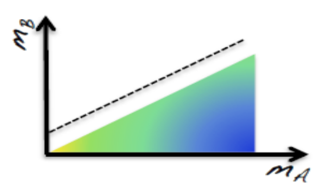
Top-down

- choose model of SUSY breaking
- Assume GUT scale parameters:
  - $m_0, m_{\frac{1}{2}}$: scalar & gaugino mass
  - A_0: trilinear Higgs-$\tilde{f}$-$\tilde{f}$ coupling
  - $\tan\beta$: ratio of Higgs vev
  - sign(μ): sign of Higgs parameter



Bottom-up

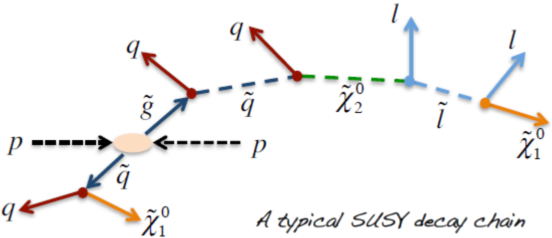
- Assume mass for SUSY particles
- Simplified models



Experimental Search for SUSY at LHC

General considerations

- SUSY phenomenology varies highly within parameter space
  $\Rightarrow$ search based on very general signatures
- proton-proton collisions produce gluinos and squarks
- decay cascades lead to high p_T jets and leptons
- If R-parity is conserved: stable LSP's
  $\Rightarrow$ high missing transverse Energy $\not{E}_T$

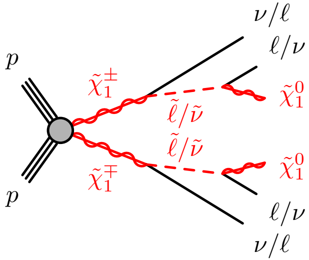


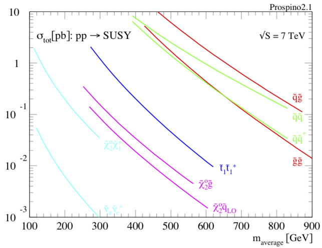
A typical SUSY decay chain

Dilepton Searches

Simplifying Assumptions

- Neutralino $\tilde{\chi}_1^0$ is the LSP
- SUSY particles decay promptly
- electroweak production of $\tilde{\chi}_1^+ \tilde{\chi}_1^-$
- only one s channel considered:
  $q\bar{q} \to Z/\gamma \to \tilde{\chi}_1^+ \tilde{\chi}_1^-$
- σ shrinks with increasing mass
- final-state leptons:
  same flavour(SF): e^+e^- or $\mu^+\mu^-$
  different flavour(DF): $e^\pm\mu^\mp$
- same BR for every generation





Dilepton Searches

Background

- Background: whole SM
- dominant BG processes: $t\bar{t}$, single top and diboson production
- estimated with Monte-Carlo Simulations

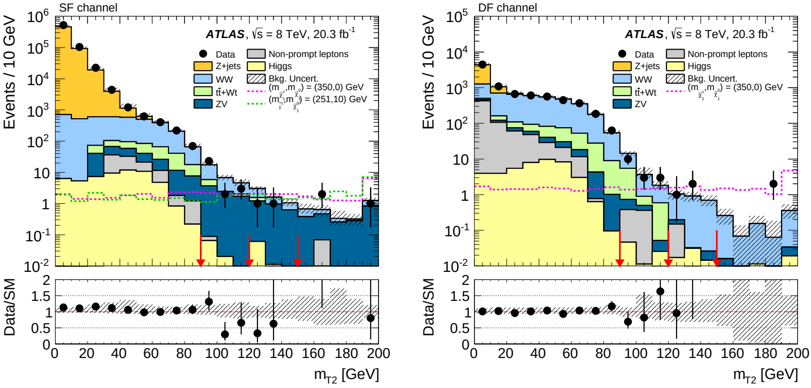
Signal

- Event selection: 2 OS signal leptons are required
- Signal region(SR): Require high m_{T2}-mass:

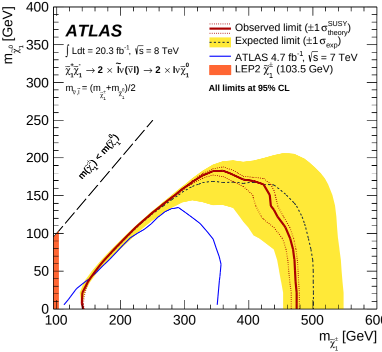
$$m_{T2} \equiv \min_{\not{p}_1 + \not{p}_2 = \not{p}_T} \left[\max\{ m_T^2(\mathbf{p}_{Tl^-}, \not{p}_1), m_T^2(\mathbf{p}_{Tl^+}, \not{p}_2) \} \right]$$

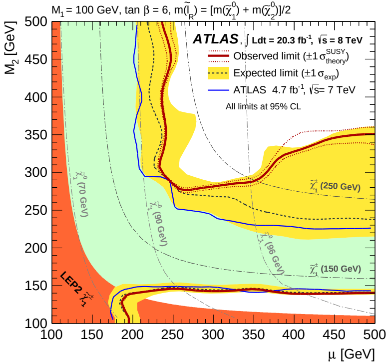
- 3 SR that require $m_{T2} > 90$ GeV, 120 GeV, 150 GeV, respectively
- in SF: invariant mass m_{ll} must be at least 10 GeV away from Z-mass

Results I — Comparison with SM



Results II — Exclusions





$\Rightarrow$ $\tilde{\chi}_1^\pm$-masses between 140 GeV and 465 GeV are excluded at 95% CL

Results III — Overall SUSY reach summary