Phenomenology at collider experiments [Part 4: BSM physics]

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HEP Summer School 31.8.-12.9.2008, RAL

Outline

Looking for physics beyond the Standard Model

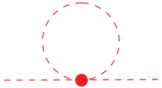
Motivation

- SM is a model with 18(+1) parameters, can this be reduced?
- Somewhat related: Can a GUT be constructed -
  a theory with only one interaction rather than three?
- If there is a GUT, it presumably lives at scales $\mathcal{O}(10^{16}\mathrm{GeV})$.
  A big desert from μ_{EWSB} to μ_{GUT}?
  (The "philosophical" hierarchy problem)
- How can gravity be incorporated at all?
  Gauge constructions of gravity are tricky.
- If dark matter is fundamental, where is it?
  The SM has no viable candidates.
- Let's not even start with dark energy/cosmological constant.

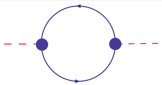
Looking for physics beyond the Standard Model

Another nasty feature: The technical hierarchy problem

- Consider two corrections to the mass of the Higgs boson:



$\propto \lambda_H \Lambda^2$



$\propto -\lambda_t^2 \Lambda^2$

- Each of them is quadratically divergent, with a brute-force cutoff Λ.

  (Think of it as limit of validity of SM, $\mu_{\rm GUT}$, or scale of new physics kicking in)

  Remark: In QED, the fermion self-energy is only log-divergent due to gauge symmetry. Not a help here.

- Huge finetuning of renormalization mandatory to keep $m_H \approx vev$.

  (One-loop correction terms alone $\propto \mu^2_{\rm GUT}$)

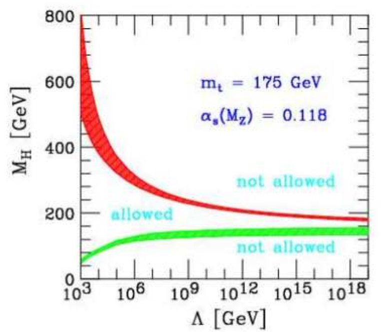
- Two solutions: Lower Λ (idea behind extra dimensions)
  or introduce a symmetry, e.g. $\lambda_H = \lambda_t^2$ (SUSY)

Looking for physics beyond the Standard Model

Aside: Could the Standard Model survive up to $\mu_{\rm Planck}$?

- Remember: $m_H^2 = \lambda v^2$

  (v = vev = 246 GeV)
- Two constraints on mass:
  1. Keep perturbativity: $\lambda \to \infty$ forbidden.
  2. Keep vacuum structure: $\lambda \to 0$ forbidden.
- Therefore: "Stable island" in the middle



The idea behind supersymmetry

What is supersymmetry?

- Remember quantization through operators:
  - Have creation and annihilation operators $\hat{a}^{(\dagger)}$: $\hat{a}^\dagger|n\rangle \propto |n+1\rangle$, $\hat{a}|n\rangle \propto |n-1\rangle$, and $\hat{a}|0\rangle = 0$.
  - Quantization achieved through fixing their relation Commutator: $[\hat{a},\,\hat{a}^\dagger] \propto i$, $[\hat{a},\,\hat{a}] = [\hat{a}^\dagger,\,\hat{a}^\dagger] = 0$
- Commutator for bosonic degrees of freedom.
- Anticommutator $\{f_1,\,f_2\} = f_1 f_2 + f_2 f_1$ for fermionic d.o.f..
- Supersymmetry:
  - Construct operation $\hat{Q}$ linking bosonic and fermionic states: $\hat{Q}|b\rangle = |f\rangle$ & $\hat{Q}^\dagger|f\rangle = |b\rangle$.
  - Demand invariance under this operation
  - Therefore: For each bosonic d.o.f. in your model a fermionic one is mandatory and vice versa $\Longrightarrow b, f \in$ one "superfield"

(This is the symmetry from above: Scalar and fermion belong to same superfield, therefore same coupling)

The benefits of supersymmetry

A collection of reasons why this is a good model

Two “philosophical” in principle reasons:

1. The Coleman-Mandula Theorem states
   that the construction of a quantum theory of graviation in form of a local gauge theory is feasible only in the framework of supersymmetric theories.
2. The Haag-Sohnius-Lopuszanski Theorem states
   that the maximal symmetry of the S-matrix of a consistent QFT is given by the direct product of Lorentz-invariance, gauge symmetry and supersymmetry.

The benefits of supersymmetry

Some more "technological" remarks

- Quadratic divergences are cancelled.
  For each loop with bosonic d.o.f. (sign $= +$), there is one with fermionic d.o.f. (sign $=$ -) with exactly the same coupling, mass etc.: only difference is the sign!
  $\Longrightarrow$ Perfect cancellation of quadratic divergences.
- Extra particles may help in enforcing unification of couplings.
- The vacuum energy arising in second quatization (zero-mode energy of harmonic oscillator) is exactly cancelled by fermions
  $\Longrightarrow$ Vacuum energy is exactly 0

  (Compare: Cosmological constant)
- Typically, SUSY models have a natural dark matter candidate (a stable WIMP=LSP) with reasonable mass for CDM.

  (Caveat: Only after SUSY-breaking)

Field content before EWS/SUSY breaking: all massless

Matter fields: left-handed doublets right-handed singlets Weyl-spinors/complex scalars generations $J = 1, 2, 3$	$\begin{pmatrix} u^J \\ d^J \end{pmatrix}_L, \; u^J_R, \; d^J_R$ $\begin{pmatrix} \nu^J \\ \ell^J \end{pmatrix}_L, \quad \ell^J_R$	$\begin{pmatrix} \tilde{u}^J \\ \tilde{d}^J \end{pmatrix}_L, \; \tilde{u}^J_R, \; \tilde{d}^J_R$ $\begin{pmatrix} \tilde{\nu}^J \\ \tilde{\ell}^J \end{pmatrix}_L, \quad \tilde{\ell}^J_R$
Gauge fields: spin-1 bosons/Weyl-spinors generators $a = 1 \dots n_g$	$G^a_\mu, \; W^{\pm,0}_\mu, \; B_\mu$	$\tilde{\psi}^a_G, \; \tilde{\psi}^{\pm,0}_W, \; \tilde{\psi}_B$
Higgs fields: 2 doublets (i=1,2) of Complex scalars/Weyl-spinors	$\begin{pmatrix} H^1_i \\ H^2_i \end{pmatrix}_L$	$\begin{pmatrix} \tilde{\psi}^1_{H_i} \\ \tilde{\psi}^2_{H_i} \end{pmatrix}_L$

Breaking SUSY . . .

. . . is unfortunately necessary

- Pattern: SUSY partners with quantum numbers as SM particles, differing just in spin by a half unit
- SUSY must be broken: no superpartner (with identical mass) found
- Various mechanisms advocated, barely tractable
- Way out: Breaking by hand through "soft term"

  (Terms that do not spoil the nice features, like absence of quadratic divergences)
- This introduces ≈ 100 new parameters in MSSM:
  mostly boiling down to all possible mixings.
- Typically imposed: R-parity
  Pictorial: SUSY particles always pairwise in vertex!
  Consequence: A lightest stable SUSY particle (LSP).

The MSSM spectrum after EWS/SUSY breaking

- The SM matter content (apart from Higgs sector) remains.
- In the Higgs sector, the 8 scalar real Higgs fields are reduced to 5:
  - 2 neutral scalars: h_0 & H_0, 1 neutral pseudoscalar: A_0,
  - 2 charged scalars $H^{\pm}$
  - the three other fields are "eaten" by gauge bosons (Higgs-mechanism a la SM)
- The up-type and down type sfermions mix (6×6 matrix), typically only $L - R$ mixing in third generation important, inter-generations still by CKM (helps with flavour constraints)
- Neutral Weyl spinors (ψ_B, ψ_{W^0}, $\psi_{H_1^0}$, & $\psi_{H_2^0}$) $\to$ 4 neutralinos
- Charged Weyl spinors ($\psi_{W^\pm}$ & $\psi_{H^\pm}$) $\to$ 2 charginos

Order from chaos

. . . or: the striking power of (over-)simplification

- Prospect of measuring $\mathcal{O}(100)$ new parameters a nightmare
- Maybe better to cook up theory-inspired "SUSY-breaking scenarios"
- Various such scenarios on the market:
  gauge-mediation, anomaly-mediation, mSUGRa
- Common feature:
  Have an extra sector of the theory, potentially "GUTty",
  will not respect SUSY and mediates information in some way.
- Benefit: Few parameters ($\mathcal{O}(5)$) to describe spectrum + interaction.
- In mSUGRA/CMSSM:
  - m_A, $\tan\beta$ for Higgs sector - we've been there
  - $m_{1.2}$, m_0, A for soft breaking terms (mass+trilinear couplings)

Searching for SUSY

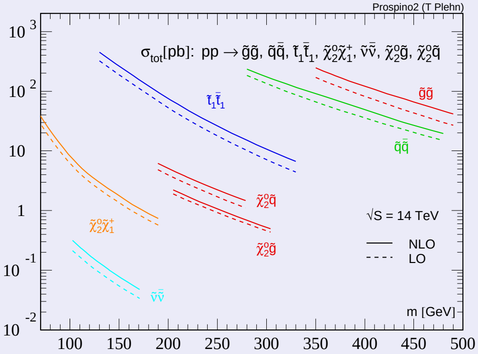
Some wild collection of signals

- With R-parity: Everything eventually decayss into LSP (χ_1^0) $\longrightarrow$ short or long decay chains
- Most prominent production: SQCD pair production ($\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, ...) will lead to signatures $\not{E}_\perp +$ jets, eventually with leptons

  (the latter from decays like $\chi_2^0 \to \chi_1^0 + \ell\bar{\ell}$ or $\chi_1^\pm \to \ell^\pm \nu \chi_1^0$ along the decay chain)
- Also well studied:
  - $\tilde{\ell}$-pair production: Kinematically like Drell-Yan of heavy lepton with (long) decay chain of $\tilde{\ell} \to \tilde{\chi}_i^0 \to \ldots$
  - $\chi_2^0\chi_1^\pm$, yielding a tri-lepton signal.

Searching for SUSY

Example cross sections



The idea behind extra dimensions

- Remember the hierarchy problem:
  Quadratic divergences pull m_H towards highest scale.
  $m_{\rm Planck}$ is the scale where the pure SM (no new physics) breaks down, since gravitation becomes quantum.
- So, the problem is maybe not the divergence structure, but $m_{\rm Planck}$.
- Connection with gravitational force: $G_N = \frac{1}{(16\pi m_{\rm Planck})^2}$
- Size of Planck scale maybe due to too weak gravitation?
- Could play with it by changing geometrical setup (more dims), dimensions are finite (size R), typically "curled up"
- Particles allowed to propagate in extra dimensions will show a pattern of Kaluza-Klein towers:
  Equidistant excitations with $\Delta M \propto 1/R$

The idea behind extra dimensions

Construction of large extra dimensions (ADD)

- Einstein-Hilbert action for true Planck scale M_*:
  $S = -\frac{1}{2}\int \mathrm{d}^4x\sqrt{|g|}M_*^2\Lambda \longrightarrow -\frac{1}{2}\int \mathrm{d}^{4+n}x\sqrt{|g|}M_*^{2+n}\Lambda$
- Compactify additional dimensions on torus R:
  $S \longrightarrow -\frac{1}{2}(2\pi R)^n\int \mathrm{d}^4x\sqrt{|g|}M_*^{2+n}\Lambda$
- Match to "measured" Planck scale:
  $S = -\frac{1}{2}\int \mathrm{d}^4x\sqrt{|g|}m_{\mathrm{Planck}}^2\Lambda$
- Therefore: $m_{\mathrm{Planck}} = M_*(2\pi RM_*)^{n/2}$
- Want $RM_* \gg 1$.
- Numbers for $M_* \approx 1$ TeV in table
- Check gravity at mm scales.

n	R
1	10^{12} m
2	10^{-3} m
3	10^{-8} m
⋮	⋮
6	10^{-11} m

Zoology of extra dimensions

- Large extra dimensions/ADD:
  - Have only gravity propagating in "bulk", SM on "brane"
  - KK towers of gravitons with small mass distance $1/R$
  - Gravitons couple weakly to SM particles with energy-momentum tensor $T^{\mu\nu}/M_{\rm planck}$
  - Look for spin-2 exchange with "continous mass" or graviton leaving detector.
- Universal extra dimensions/small extra dimensions:
  - All particles in "bulk", typically 1-2 ED
  - Every SM particle gains KK towers with sizable distance $1/R$

The idea behind technicolour

- Problem with Higgs boson self-energy, because it is an elementary scalar, and no gauge prevents quadratic divergences
- Make the Higgs boson composite!
- Analogy: Pions made off quarks (χSB)
- Add extra (techni-)fermions with new strong (techni-)interaction
- Main problems:
  - Strong coupling for bound states, make sure it does not run too fast. Solution: Use different representation for fermions.

    (Walking technicolour)
  - May have to add leptons to kill anomalies.
- Technifermions form technimesons, partially eaten by gauge bosons
- Survivors of the multiplets (techni-ρ's etc.) visible at the LHC similar to Z', W': resonances from $Z' \to f\bar{f}$ etc..