Phenomenology of supersymmetry

(and a bit of theory)

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Outline

Why we need BSM physics

Constructing the details of SUSY

Models of supersymmetry

What now?

Summary

Part I

Why we need BSM physics

Standard Model

Plenty of evidence in favour of the Standard Model:

- Predictions: Existence of W boson,Z boson, charm quark, top quark and the gluon.
- Electroweak precision measurements: Mass and width of W and Z bosons.

It is, as you know, not complete

What it doesn't include

- Neutrino masses (Dirac/Majorana): can add terms, but not a direct result [essential]
- Gravity
- Dark Matter ('orthogonal' measurement)

What does it get "wrong"?

- Anomalous Magnetic Moment of the Muon: $(g-2)_\mu$
- Natural solution to W-scattering cross-section
- Higgs mass [?]

There is also the problem of *naturalness*:

- Why do we need 19 parameters to describe the SM?
- Why do we have a hierarchy problem? (Fine tuned cancellations to Fermi's constant)

What is the hierarchy problem?

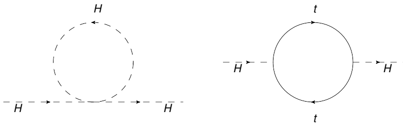
- Suppose SM valid up to GUT scale ($O(10^{15}\mathrm{GeV})$) or even the Planck scale ($O(10^{19}\mathrm{GeV})$)
- Weak interaction scale $\sim 100\mathrm{GeV}$
- If the inputs are chosen at these scales, the scalar mass terms in the Higgs sector must be chosen with an accuracy of 10^{-34} wrt the Planck mass.

W-scattering cross-section

One of the strongest indicators for something Higgs-like/BSM physics:

- Theory: the value explodes at some energy scale
- Violates perturbative unitarity
- Simplest solution: extra propagator = extra diagram $\rightarrow$ cancels divergences
- This propagator is a scalar $\rightarrow$ Higgs
- Good evidence for upper limit on Higgs mass

Divergent Higgs Mass



The one loop scalar(left) and fermion(right) corrections to the Higgs mass. When calculated we find the following contributions:

- dirac fermion $(-\lambda_f \bar{f} f)$: $\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2} \Lambda_{UV}^2 + \ldots$
- $\mathbb{C}$-scalar$(-\lambda_S |H|^2 |S|^2)$:
  $\Delta m_H^2 = \frac{\lambda_S}{16\pi^2} \left[\Lambda_{UV}^2 - 2 m_S^2 \ln \left(\Lambda_{UV} / m_S \right) \right]$

Here Λ_{UV} is known as the 'ultraviolet' cutoff - it regulates the loop integral, i.e $M = \int_0^{\Lambda_{UV}} \ldots$

Divergent Higgs Mass Part 2

These corrections imply two important things:

1. A quadratic dependence on Λ_{UV}
2. A quadratic dependence on m_S

This means it is both sensitive to the scale of 'new-physics', as well as the masses of the heaviest particles. Strangely enough the latter problem arises even if we have no direct coupling between the SM Higgs and the unknown "S".

We'll come back to this...

Why it could be SUSY

Phenomenologically While we haven't developed the details, yet, the extended particle spectrum gives hints at what it could provide,

- Corrections to $\Delta(g-2)_\mu$
- A candidate for dark matter.
- Cancellation terms for the Higgs mass
- A solution to the Hierarchy problem

Part II

Constructing the details of SUSY

Multiplets

In the standard model we arrange particles into the irreducible representations of the algebra called multiplets,

$$\begin{pmatrix} e_L \\ \nu_e \end{pmatrix}, \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

A similar approach is taken for SUSY; we form supermultiplets, simply an arrangement which contains both fermion and boson partner states

Multiplets Continued

If $|\Omega\rangle$ and $|\Omega'\rangle$ are both members of the same supermultiplet, then they are linear combinations of each other (with the SUSY operator $\hat{O}$ and $\hat{O}^\dagger$).
When constructing these multiplets we must ensure:

$$n_B = n_F$$

where n_B and n_F are the bosonic and fermionic degrees of freedom respectively (this can be shown).
The simplest arrangement: single weyl fermion (2 spin states, $n_F = 2$) and then 2 real scalars ($n_B = 1$ each)

More Multiplets

Note: $2 \times \mathbb{R}\text{-scalar} \equiv 1 \times \mathbb{C}\text{-scalar}$

The next simplest arrangement is a spin-1 vector boson ($n_B = 2$), with a massless Weyl fermion as its superpartner.

These two arrangements have names:

- spin-1/2 Weyl Fermion + $\mathbb{C}$-scalar: Chiral supermultiplet
- spin-1 Vector boson + massless Weyl fermion: Gauge supermultiplet

Breaking SUSY

If SUSY were an exact symmetry of the Lagrangian, then we would have,

$$M_{\mathrm{SM}} = M_{\mathrm{SUSY}}$$

for all particles. If this were true, SUSY would be evident in experiments already. We therefore expect SUSY to be broken to some degree, i.e. the mass scale of the particles is not completely restricted. There is a much better reason than this...

What is a gauge anomaly

Definition

A gauge anomaly is any effect that breaks the gauge symmetry of the system, in our case the quantum field theory.

The Higgs Sector

Naively one would expect the following:

$$\text{Higgs } H \leftrightarrow \tilde{H} \text{ Higgsino}$$

There is a (two) problem(s) with this,

- Introduction of a gauge anomaly, namely Higgsino ($S = \pm 1/2$) has hypercharge $\mathrm{Y} = \frac{1}{2}$, so we no longer have $\sum \mathrm{Y} = 0$ (our $U(1)$ gauge symmetry has been broken)

The Higgs Sector Continued

Can remedy this gauge anomaly by introducing a second higgs doublet, labelling the two (unsuggestively) H_u and H_d.

- Opposite hypercharge (fixes the anomaly)
- H_u now couples to up-type fermions (u, c, t, ℓ)
- H_d couples to down-type fermions (d, s, b, ν_ℓ)

Supersymmetry is...

A symmetry that generates a second set of particles matching those in the SM but with masses at a higher scale.

- Each boson(fermion) has a corresponding (fermion)boson superpartner
- A second Higgs doublet is included, resulting in 5 physical Higgs bosons

Part III

Models of supersymmetry

Minimal Supersymmetric Standard Model

So far we have constructed what is known as the Minimal Supersymmetric Standard Model (MSSM)

- super-partners for each SM particle
- softly-broken (mass differences, but no quadratic divergences)

This was motivated by the SM seeming “unnatural”,

- Number of parameters (19)
- Energy scale (M_{pl} vs. M_W)

Not so natural...

Unfortunately we have only really solved one of these problems,

- ✓ Energy scale [almost]
- ✗ Parameters

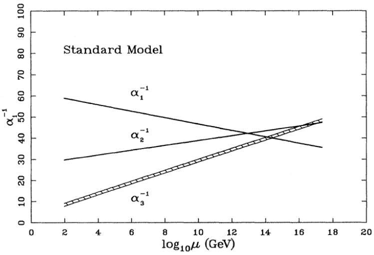
To fully specify all the masses and couplings in the MSSM we need 108 free parameters.

Solution: Choose some 'natural' boundary condition to alleviate this problem.

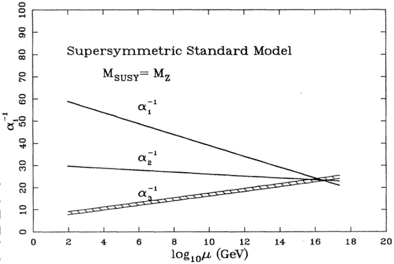
Constrained MSSM

Motivating unification,

Standard model



MSSM



CMSSM: A gut scale condition

We now impose another GUT scale constraint

- Scalar masses unify $= m_0$
- Gaugino masses unify $= m_{1/2}$
- Trilinear couplings unify $= A_0$

This almost gives us a complete description of the physics, just need to describe the Higgs sector,

- Two higgs fields - $\phi_{H_u}/\phi_{H_d} = \tan\beta$

cMSSM: Dragging it out...

While phenomenologically not the most interesting:

- Simple unification collapses parameter space
- Forces ration between the gauge couplings

This last point is important for the phenomenology. Consider the following decay:

$$\tilde{g} \to \tilde{q} \to \tilde{\chi}_1^0$$

If the couplings are fixed, then the mass ratios are also fixed

$$6 : 4 : 1$$

NUHM

While there is *some* motivation for models like the cMSSM, the phenomenology is not wide ranging NUHM models are an attempt to remedy that via the introduction of a new degree(s) of freedom,

- NUHM1 $m_{H_u} = m_{H_d} \neq m_0$
- NUHM2 $m_{H_u} \neq m_{H_d} \neq m_0$

Some common confusion

SUSY adds a new set of partner particles to the SM

- Commonly talk about neutralinos and charginos
- No obvious SM partner for these particles
- Actually combinations of the photino ($\tilde{\gamma}$), bino ($\tilde{B}$), wino ($\tilde{W}$) and higgsino ($\tilde{H}$) fields.

Part IV

What now?

Understaning the models

- Nice to have models that are 'theoretically motivated'
- Do they match with Experiment?

There are 'indirect' tests of supersymmetry, can also act as constraints.

Constraints

There are, literally, thousands of measurements in physics. Can choose a handful that should be sensitive to supersymmetric effects

- Flavour physics
  - $R(b \to s\gamma)$
  - $BR(B_s \to \mu^+\mu^-)$
  - $R(b \to \tau\nu)$
- Higgs searches (LEP)
- Cosmological
  - Ωh^2
  - σ_p^{SI}
- Direct searches (TeVatron, CMS, ATLAS)

Attacking SUSY parameter space

While there aren't any true limits on SUSY-parameters,

- For each set of inputs $\{ m_0, m_{1/2}, A_0, \tan\beta, \ldots \}$ there is a uniquely defined spectrum of particles
- In fact for all $\{\ldots\}$ all other values are defined (as you'd expect)

Turning this into constraints

We know the phenomenology (through the masses and couplings) is well defined for any set of input parameters to any give model

- Calculate spectrum and couplings
- Calculate SUSY contribution to expectation value of various observables
- Compare to current experimental values and accuracy

In this way we can construct a method for determining the goodness-of-fit of any single point in any given model (so long as we can perform the first two steps).

Whole space approach

For some models it is possible to do this for a wide enough selection of points that we end up with well defined regions of best fit

This allows us to determine the most 'important' input parameters, and if they exist the observables that drive the sort of phenomenology we might expect to see

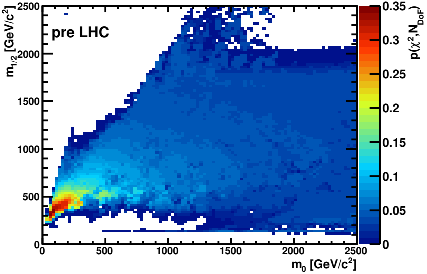
What do we get?

What might you execpt?

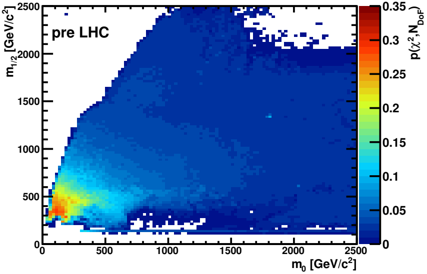
- Low/High masses?
- Low/High probability of fit?

What do we get?

CMSSM

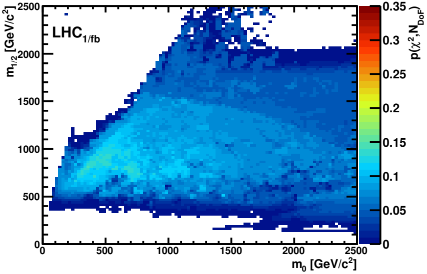


NUHM1

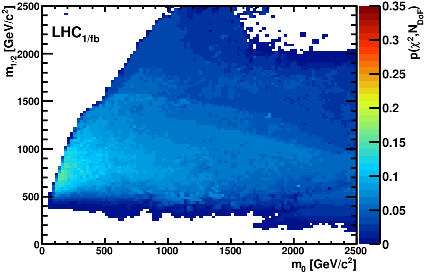


What do we get?

CMSSM



NUHM1

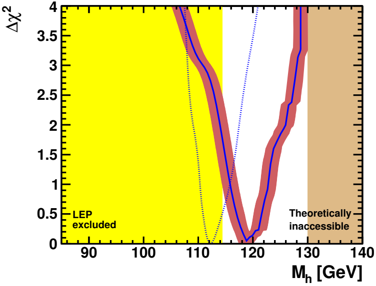


What else can we determine

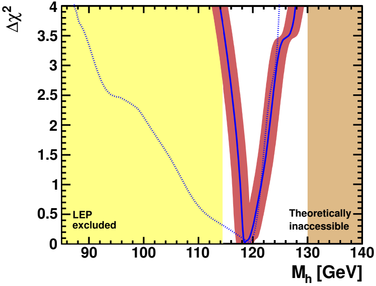
Parameter space plots are useful for discussions of the model directly, but we can determine the preferred region for phenomenologically interesting values, such as (s)particle masses

Higgs Mass

CMSSM



NUHM1



Summary

- SUSY seems to be a "cure-all" for problems with the SM
- Simple models can be constructed (CMSSM, NUHM1)
- These can be tested against experiment
- We still haven't seen any signals of SUSY
- Seems likely that more complicated / different models may yet be necessary