Supersymmetry

Physics Colloquium

University of Virginia

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- The Standard Model of particle physics
- The “Hierarchy Problem”: why is the Higgs mass so small?
- Supersymmetry as a solution
- New particles predicted by supersymmetry
- Supersymmetry is spontaneously broken
- How to find supersymmetry

The Standard Model of Particle Physics

Quarks (spin=$1/2$):

Name:	down	up	strange	charm	bottom	top
Charge:	$-\frac{1}{3}$	$\frac{2}{3}$	$-\frac{1}{3}$	$\frac{2}{3}$	$-\frac{1}{3}$	$\frac{2}{3}$
Mass:	0.005	0.002	0.1	1.5	5	173.1

Leptons (spin=$1/2$):

Name:	e^-	ν_e	μ^-	ν_μ	τ^-	ν_τ
Charge:	-1	0	-1	0	-1	0
Mass:	0.000511	~ 0	0.106	~ 0	1.777	~ 0

Gauge bosons (spin=1):

Name:	photon (γ)	$W^\pm$	Z^0	gluon (g)
Charge:	0	± 1	0	0
Mass:	0	80.4	91.2	0

All masses in GeV. (Proton mass = 0.938 GeV.) Not shown: antiparticles of quarks, leptons.

There is a last remaining undiscovered fundamental particle in the Standard Model: the **Higgs boson**.

What we know about it:

Charge: 0

Spin: 0

Mass: Greater than 114 GeV, and not between 158 and 175 GeV

( in most simple versions)

Less than about 215 GeV (  indirect, very fuzzy, simplest model only)

Fine print: There might be more than one Higgs boson. Or, it might be a composite particle, made of other more basic objects. Or, it might be an "effective" phenomenon, described more fundamentally by other unknown physics. But it must exist in some form, because. . .

The Higgs boson is the source of all mass.

The Higgs boson is ∧ the source of all mass.

NOT!

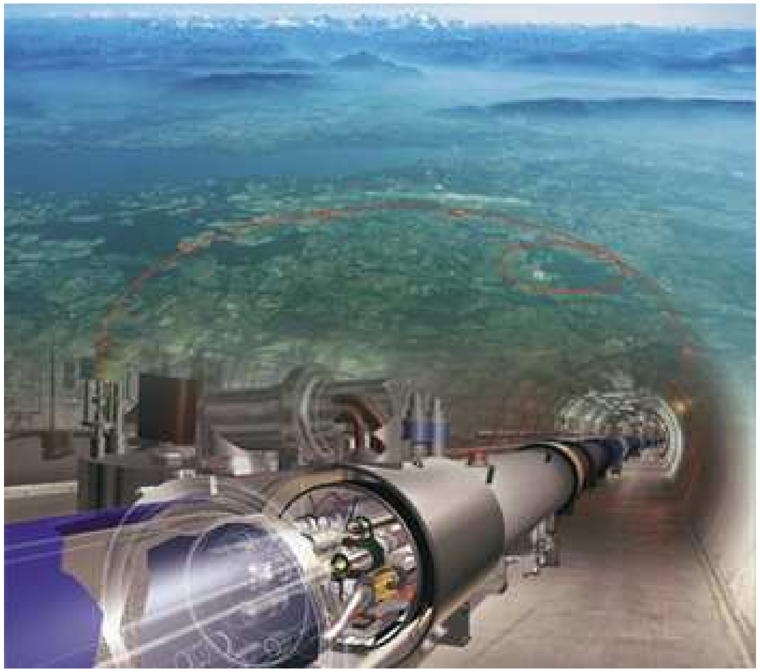
Most of the mass of protons and neutrons comes from the strong nuclear force, by a well-understood mechanism involving gluons called “chiral symmetry breaking”.

Cosmologists tell us that most of the matter in the universe is some exotic stuff called Dark Matter; this also does not get its mass from the Higgs boson.

The Higgs is still crucial, because it is the main source of mass for the heaviest known particles, the top quark and the W, Z force carrier bosons, and for the charged leptons.

The search for the Higgs boson is the main goal of experimental elementary particle physics today.

Assuming it indeed exists, it will (eventually) be found in proton-proton collisions by the CMS and ATLAS detector collaborations at the Large Hadron Collider, at CERN, on the border of Switzerland and France.



The Higgs boson vs. the Higgs field

The Higgs field is a nearly uniform physical quantity, filling all space.

The Higgs boson is a particle, consisting of local disturbances of the Higgs field.

An analogy (David Miller, University College London, cartoons courtesy of CERN):

Consider a cocktail party filled with minor political operatives (the Higgs field).

A rumor in the room results in a mobile cluster of discussion (the Higgs boson).

Now, a celebrity (a particle) enters the room. She is immediately surrounded by a knot of admirers, effectively giving her inertia, and therefore mass.

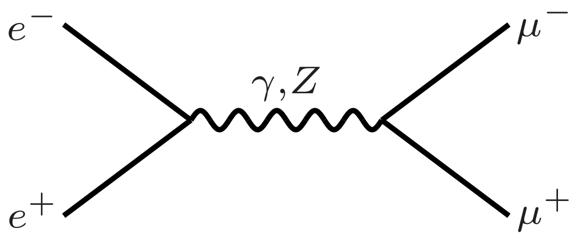
Major celebrities (Margaret Thatcher = top quark) get large masses.

Minor celebrities (dogcatcher of Newcastle = electron) get smaller masses.

How we do calculations in high-energy physics: Feynman diagrams

$$e^- e^+ \to \mu^- \mu^+$$

INITIAL STATE



FINAL STATE

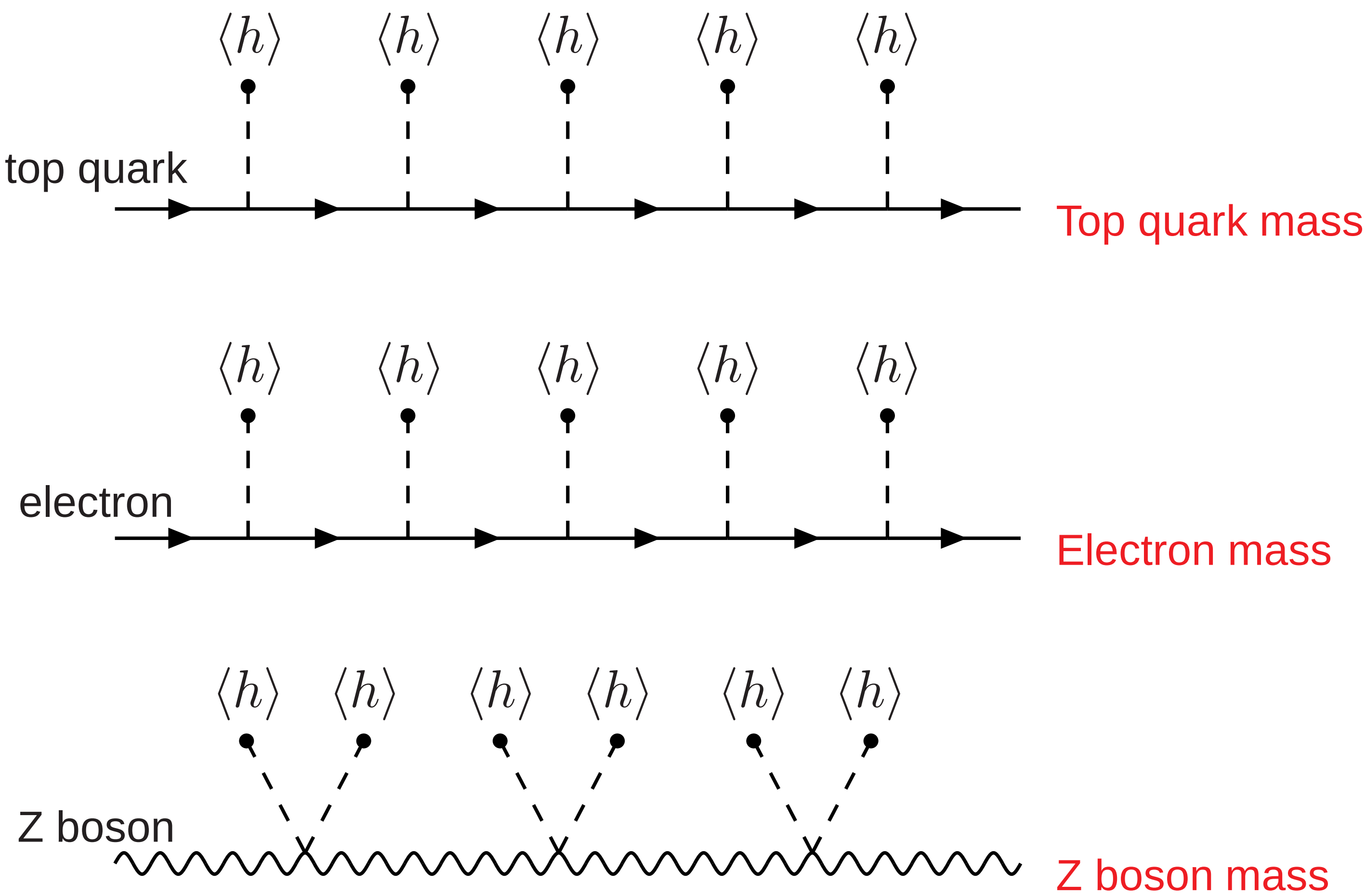
Lines represent free propagation of particles:

- wavy = spin 1
- solid = spin 1/2
- dashed = spin 0

Vertices represent interactions of particles

Each Feynman diagram is both a picture of what happened, AND a “code” for the formula for the probability amplitude of the quantum process.

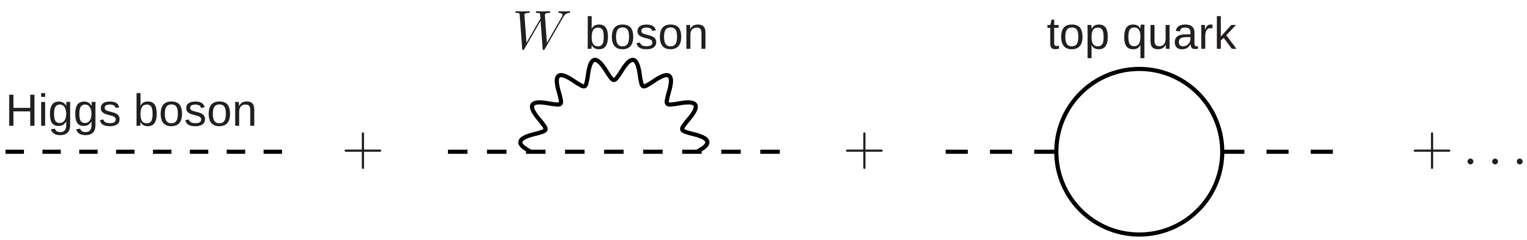
Translating the Higgs analogy above into Feynman diagram language:



etc. The $\langle h \rangle$ is the expectation value of the Higgs field in the vacuum.

The Hierarchy Problem

Compute quantum corrections to the Higgs mass in perturbation theory, by doing a sum of Feynman diagrams. Schematically:



$m^2 \qquad +g^2 M_{UV}^2 \qquad -y_t^2 M_{UV}^2$

Here M_{UV} is the “ultraviolet cutoff”, the maximum allowed value of the energies of the virtual particles. If provided by the unknown physics of quantum gravity:

$$M_{UV} \sim M_{\text{Planck}} = \sqrt{\hbar c / G_{\text{Newton}}} = 1.2 \times 10^{19} \text{GeV}/c^2$$

We know the Higgs mass squared is $\lesssim$ (few$\times 100$ GeV)^2, but without miraculous cancellation, expect it to be about 32 orders of magnitude larger!

Key Observation: Fermions and Bosons contribute with opposite signs to m_h^2. Maybe they can be arranged to cancel?

This requires a conspiracy!

In physics, “conspiracies” are known as “symmetries”. . .

Symmetries can explain what would appear, otherwise, to be extreme fine-tunings, for example:

$$\frac{\text{(Electron charge)} + \text{(Positron charge)}}{\text{(Electron charge)}} \quad < \quad 4 \times 10^{-8}$$

$$\frac{\text{(Electron mass)} - \text{(Positron mass)}}{\text{(Electron mass)}} \quad < \quad 3 \times 10^{-9}$$

These very small numbers are explained by the symmetries of Special Relativity (Lorentz invariance), which says they should be exactly 0.

Even symmetries that are broken, or only approximate, are predictive.

If you see only part of a snowflake, you can still predict what the other part looks like, if you know the symmetry group.

There are also approximate symmetries for elementary particles, as for the snowflake. The near equality of the proton and neutron masses is a consequence of an approximate symmetry between the up quark and the down quark, known by the technical term Isospin.

Example: flavor $SU(3)$ symmetry, an **approximate** invariance under rotations in an abstract 3-d space, combining isospin and "strangeness", was noticed by Gell-Mann and Ne'eman in 1962.

Isospin →

"Strangeness" ↓

$$\Delta^{-}_{1232} \quad \Delta^{0}_{1232} \quad \Delta^{+}_{1234} \quad \Delta^{++}_{1234}$$

$$\Sigma^{-}_{1387} \quad \Sigma^{0}_{1384} \quad \Sigma^{+}_{1383}$$

$$\Xi^{-}_{1535} \quad \Xi^{0}_{1532}$$

$$\Omega^{-}_{1672}$$

Prediction: Nine known spin-3/2 baryons (made out of Up, Down and Strange quarks) should have a tenth "partner", Ω^-. Charge, mass, and decay rate predicted.

Result: Ω^- discovered in 1964!

Supersymmetry is a symmetry that relates bosons (integer spin) and fermions (half-integer spin) particles.

In other words, there is an operator Q in the quantum theory, called the supersymmetry charge, such that:

$$Q\big|\text{Fermion}\big\rangle = \big|\text{Boson}\big\rangle \qquad\qquad Q\big|\text{Boson}\big\rangle = \big|\text{Fermion}\big\rangle$$

The Fermion and Boson so related are called **superpartners**.

To be a physical symmetry, the operator Q must be conserved, or commute with the Hamiltonian:

$$[Q, H] = 0.$$

A theorem says that this can only happen if. . .

General Predictions of Supersymmetry:

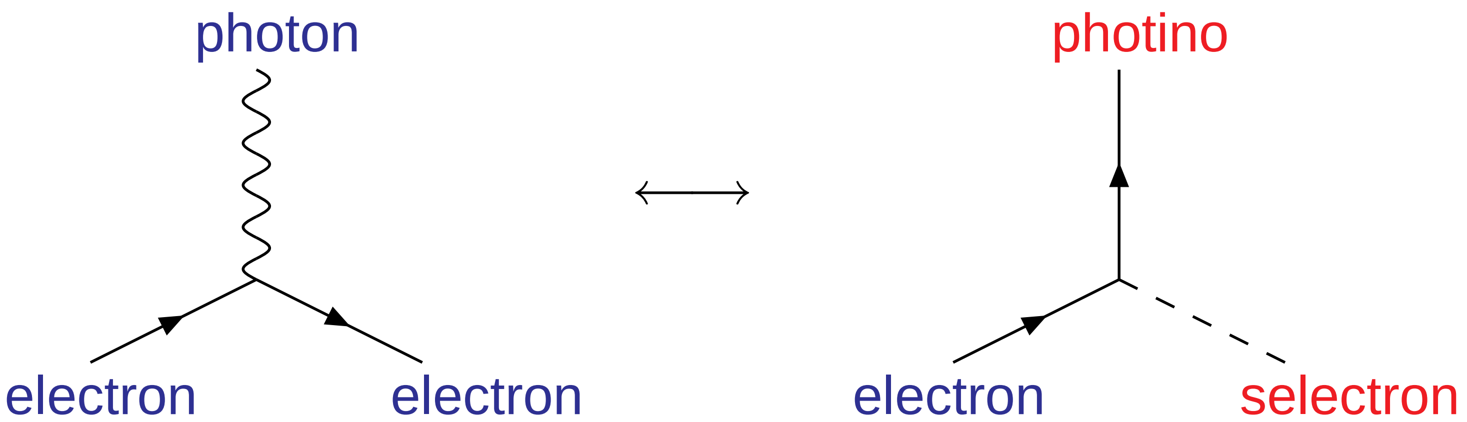
- For every known spin-1/2 particle type, there must be a spin 0 “superpartner” with the same charge and color and interactions.
- For every known spin-1 particle (gauge boson), there should be a spin 1/2 superpartner (gaugino fermion).
- The spin-0 Higgs boson has a spin-1/2 superpartner called the Higgsino.
- The spin-2 graviton (the carrier of the gravitational force) has a superpartner with spin-3/2 called the gravitino.

Particles of the Supersymmetric Standard Model

Known	Superpartners
Quarks: u, d, s, c, b, t **(Spin 1/2)**	**Squarks:** $\tilde{u}, \tilde{d}, \tilde{s}, \tilde{c}, \tilde{b}, \tilde{t}$ **(Spin 0)**
Leptons: e, μ, τ, ν_e, ν_μ, ν_τ **(Spin 1/2)**	**Sleptons:** $\tilde{e}$, $\tilde{\mu}$, $\tilde{\tau}$, $\tilde{\nu}_e$, $\tilde{\nu}_\mu$, $\tilde{\nu}_\tau$ **(Spin 0)**
Gauge bosons: **gluon (g), photon (γ),** $W^\pm$, Z **(Spin 1)**	**Gauginos:** **gluino ($\tilde{g}$), photino ($\tilde{\gamma}$),** **Wino ($\tilde{W}^\pm$), Zino ($\tilde{Z}$)** **(Spin 1/2)**
Higgs: h^0, $h^\pm$ **(Spin 0)**	**Higgsinos:** $\tilde{h}^0$, $\tilde{h}^\pm$ **(Spin 1/2)**
Graviton: G **(Spin 2)**	**Gravitino:** $\tilde{G}$ **(Spin 3/2)**

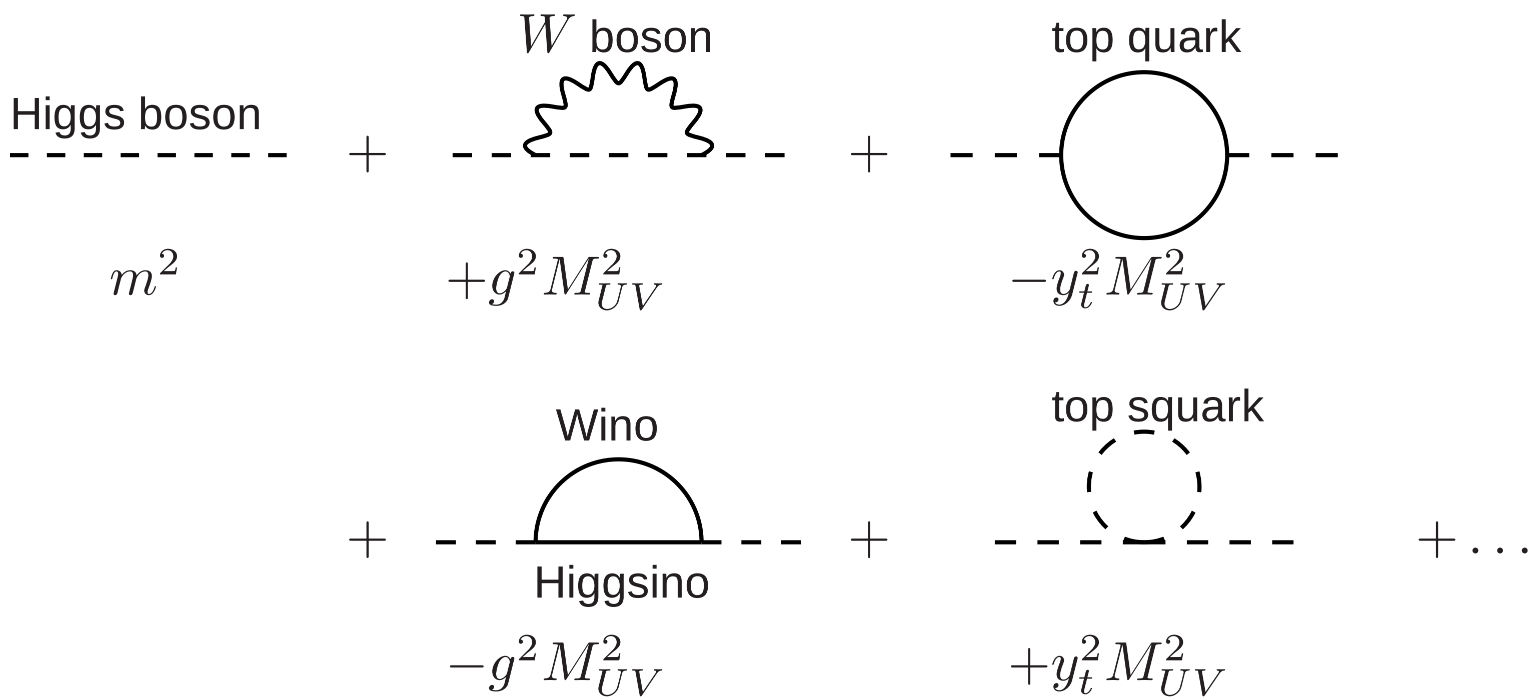
Another General Prediction of Supersymmetry

- Interactions of superpartners are related to those of known particles, for example:



q_e $\qquad\qquad$ $\sqrt{2}q_e$

Supersymmetry **automatically** provides exactly the cancellation needed to solve the hierarchy problem:



This cancellation has been proved to all orders in perturbation theory.

Yet Another General Prediction of Supersymmetry:

- **If** supersymmetry were also a symmetry of the vacuum state, then each pair of superpartners would be exactly degenerate in mass!

Experiment says this definitely isn't true. It is an experimental fact that:

$$\begin{array}{ccc} \text{(spin 1/2)} & & \text{(spin 0)} \\ m_{\text{electron}} & \neq & m_{\text{selectron}} \\ (0.511\ \text{MeV}) & & (> 100\ \text{GeV}) \end{array}$$

So. . .

Supersymmetry must be a **spontaneously broken** symmetry.

The idea is that the supersymmetry charge still commutes with the Hamiltonian:

$$[Q, H] = 0,$$

but does not leave the vacuum (no particle) state invariant:

$$Q|0\rangle \neq 0.$$

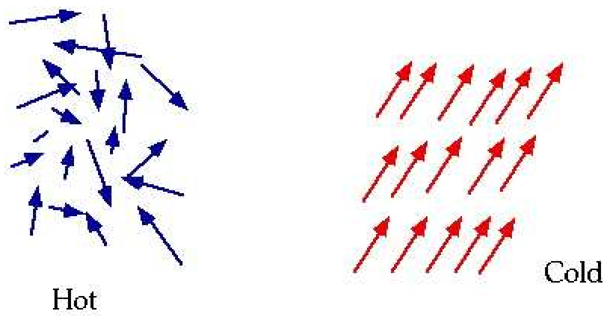
The symmetry is still there, but “hidden” in the state the Universe happens to be in.

This gives mass to all of the superpartners, without raising any of the known particle masses!

Analogy: a ferromagnet below critical temperature

The laws of electromagnetism are exactly invariant under rotations.

However, the ground state of a ferromagnet always locally picks out a special direction, spontaneously breaking the rotational symmetry:



Spontaneous breaking really means that the symmetry is “hidden”, or not manifest in the ground state. It is still an exact symmetry of the Laws of Nature!

That’s what is believed to happen to supersymmetry, too. In the hot early universe, manifest supersymmetry was restored.

The central theoretical question for supersymmetry is:

"How is supersymmetry broken?"

The masses of the superpartners arise (mostly) from supersymmetry breaking.

All other parameters of the Supersymmetric Standard Model are already known and measured, from experiments with ordinary particles!

For example, we already know that the selectron has charge -1, and the squarks and the gluino have strong nuclear interactions.

An important clue/constraint: the overall scale of supersymmetry breaking

The hierarchy problem returns when you spontaneously break supersymmetry, if you break it “too much”.

To avoid miraculous fine-tuning for the Higgs, W, and Z boson masses, need:

$$m^2_{\text{top squark}} - m^2_{\text{top quark}} \lesssim \text{(few hundred GeV)}^2.$$

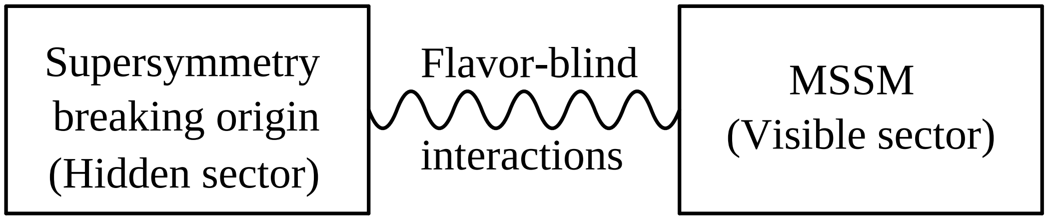
Similar arguments say that, more generally:

$$m_{\text{superpartners}} \lesssim 1000 \text{ GeV}.$$

This implies that supersymmetric particles should be detected at the Large Hadron Collider (collision energy 7000 GeV now, up to 14000 GeV in the future).

The Structure of Supersymmetry Breaking

Spontaneous supersymmetry breaking occurs in a “hidden sector” of particles that have only indirect or quantum-suppressed couplings to us:



(MSSM = Minimal Supersymmetric Standard Model = us)

The interactions connecting the two parts of the theory must be “flavor-blind”; don’t violate the flavor symmetries of the Standard Model. Two main candidates:

- gravity
- gauge forces (electromagnetism, weak nuclear, strong nuclear)

There are many competing sub-proposals, but they generally fall into those two camps.

A complication: superpartners mix

Neutral fermion superpartners are: photino $(\tilde{\gamma})$, Zino $(\tilde{Z})$, Higgsinos $(\tilde{h}_1^0, \tilde{h}_2^0)$.

These are eigenstates of the interaction Hamiltonian.

The **mass eigenstates** are called neutralinos ($\tilde{N}_1$), related by a unitary matrix:

$$\begin{pmatrix} \tilde{N}_1 \\ \tilde{N}_2 \\ \tilde{N}_3 \\ \tilde{N}_4 \end{pmatrix} = \begin{pmatrix} * & * & * & * \\ * & * & * & * \\ * & * & * & * \\ * & * & * & * \end{pmatrix} \begin{pmatrix} \tilde{\gamma} \\ \tilde{Z} \\ \tilde{h}_1^0 \\ \tilde{h}_2^0 \end{pmatrix}$$

The objects that will actually be created at colliders are the mass eigenstates.

Similarly, the charged fermion superpartner **interaction eigenstates** are the Wino $\tilde{W}^+$ and the charged Higgsino $\tilde{h}^+$.

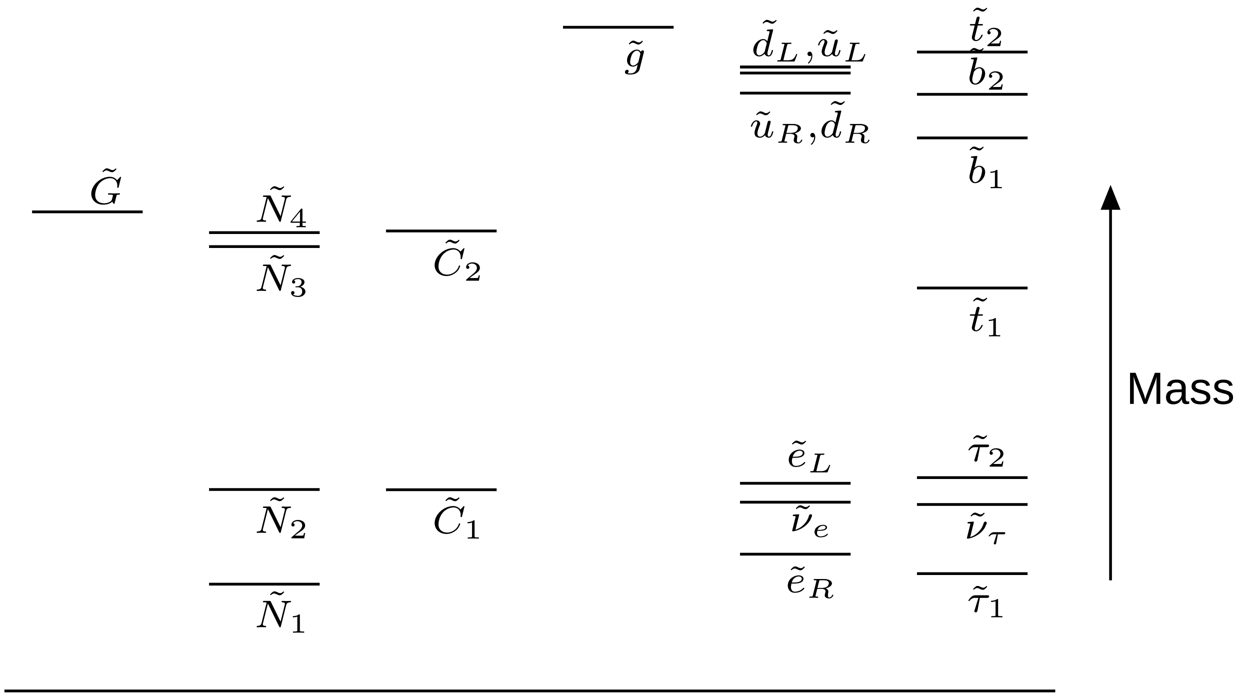
The **mass eigenstates** are related by a 2×2 unitary rotation matrix:

$$\begin{pmatrix} \tilde{C}_1^+ \\ \tilde{C}_2^+ \end{pmatrix} = \begin{pmatrix} * & * \\ * & * \end{pmatrix} \begin{pmatrix} \tilde{W}^+ \\ \tilde{h}^+ \end{pmatrix}$$

These are called Charginos.

Taking these effects into account, here is a typical predicted superpartner mass spectrum:

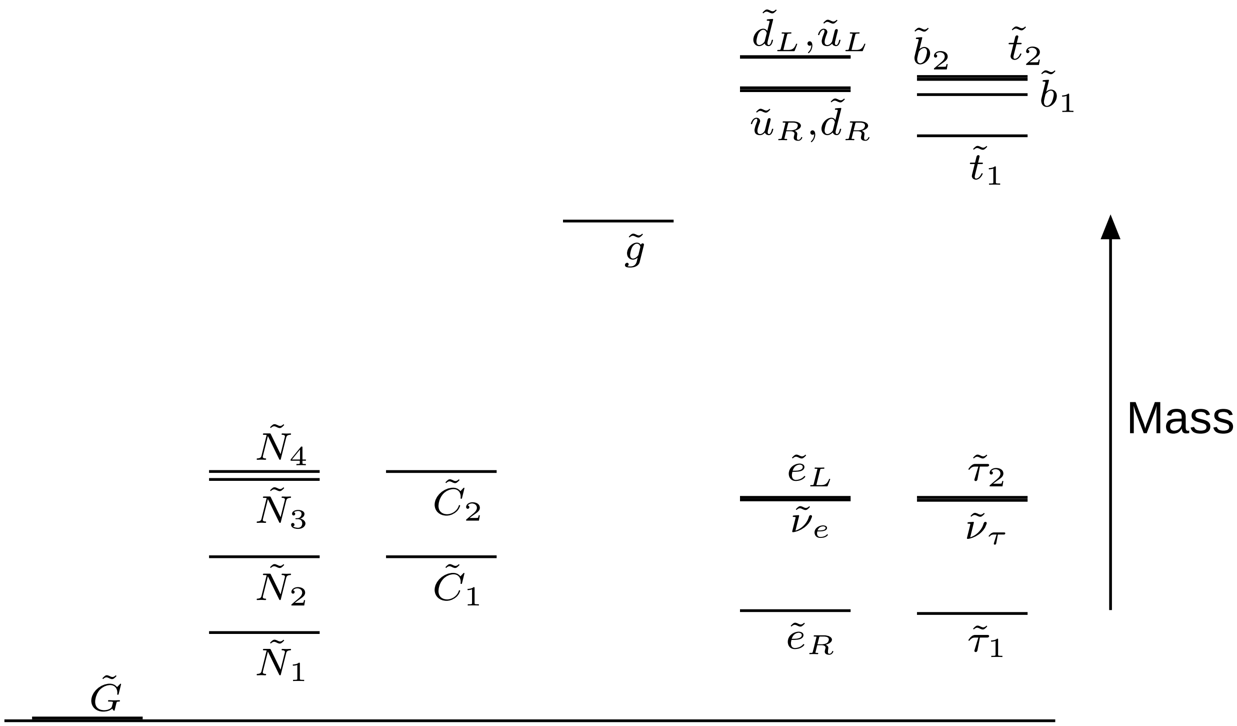
Superpartner masses; typical GRAVITY-mediated supersymmetry breaking model



Gravitino, Neutralinos, Charginos, gluino, squarks/sleptons

Compare to a typical GAUGE-mediated supersymmetry breaking case:

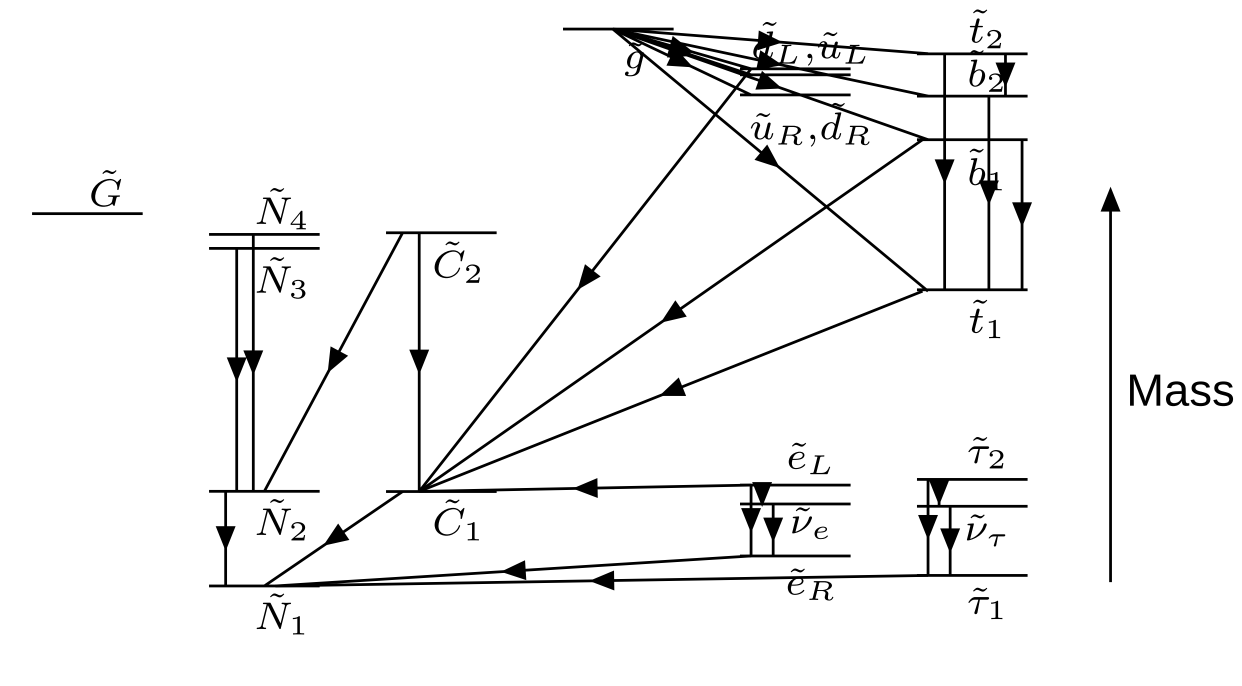
Superpartner masses; typical GAUGE-mediated supersymmetry breaking model



Gravitino, Neutralinos, Charginos, gluino, squarks/sleptons

Qualitative differences: squarks are heavier, Gravitino is nearly massless

Superpartners to other superpartners decay by “emitting” Standard Model particles (leptons, quark jets). The decay chains can be quite complicated:



Because of an additional symmetry called R-parity, the lightest supersymmetric particle, or LSP (usually a photino-like $\tilde{N}_1$), is absolutely stable.

The Lightest Supersymmetric Particle (LSP) is absolutely stable.

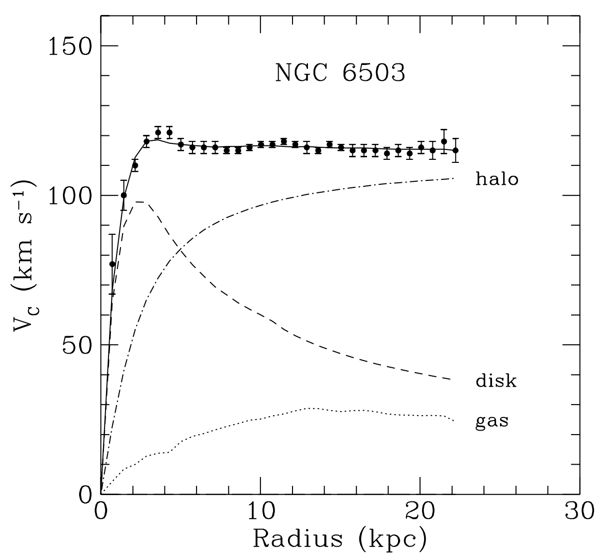
(In the most straightforward version of supersymmetry  .)

It is a “neutralino”, and feels no electromagnetic force, and no strong nuclear force.

This would be a great dark matter particle.

The mass density of the Universe is dominated by an invisible, very weakly interacting dark matter:

- Observed expansion rate of Universe
- Abundance of ordinary matter elements today
- Motion of large groups of galaxies
- Rotation speeds of stars around individual galaxies



Data vs. prediction for velocities of stars around the center of galaxy NGC6503.

“disk, gas” = ordinary matter

“halo” = dark matter

Cosmological and astrophysical evidence suggests the dark matter density today is about:

$$\rho_{\text{dark matter}} = 2 \times 10^{-27}\,\text{kg/meter}^3 \quad \text{(averaged over universe)}$$
$$\rho_{\text{dark matter}} = 5 \times 10^{-22}\,\text{kg/meter}^3 \quad \text{(in this room)}$$

Supersymmetry naturally predicts a comparable amount of dark matter left over from the Big Bang; a few thousand LSPs per cubic meter in this room.

LSPs interact extremely weakly, but there are ongoing searches using cryogenic solid-state, scintillator and noble gas underground detectors.

In collider experiments, this Lightest Supersymmetric Particle always escapes the detectors.

So the “Smoking Gun” of supersymmetry is large missing energy.

The Large Hadron Collider began searching for supersymmetry in very high energy proton-proton collisions last year, by looking for excess events with missing energy.

Only the component of missing energy found in momenta perpendicular to the beam, called $\not{E}_T$, is measurable.

Many "Jets" and $\not\!\!E_T$ at Large Hadron Collider

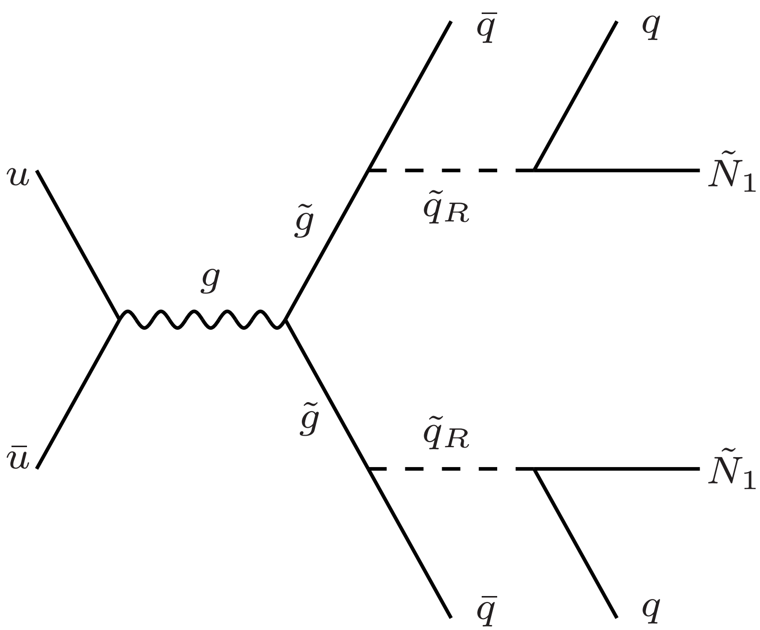
A strategy: look for events with gluino+gluino or gluino+squark or squark+squark production.

$$pp \longrightarrow \tilde{g}\tilde{g}$$

followed by decays **without** leptons:

$$\tilde{g} \longrightarrow q\bar{q}\tilde{N}_1 \quad \text{or} \quad \tilde{q} \longrightarrow q\tilde{N}_1.$$

A typical Feynman diagram for the whole event:



Each quark or antiquark in the final state turns into a bunch of strongly interacting particles, a "jet".

Signal here is 4 jets + $\not\!\!E_T$.

By vetoing events with isolated, energetic leptons, the Standard Model backgrounds with $\not\!\!E_T$ from $W \longrightarrow \ell\nu$ are reduced.

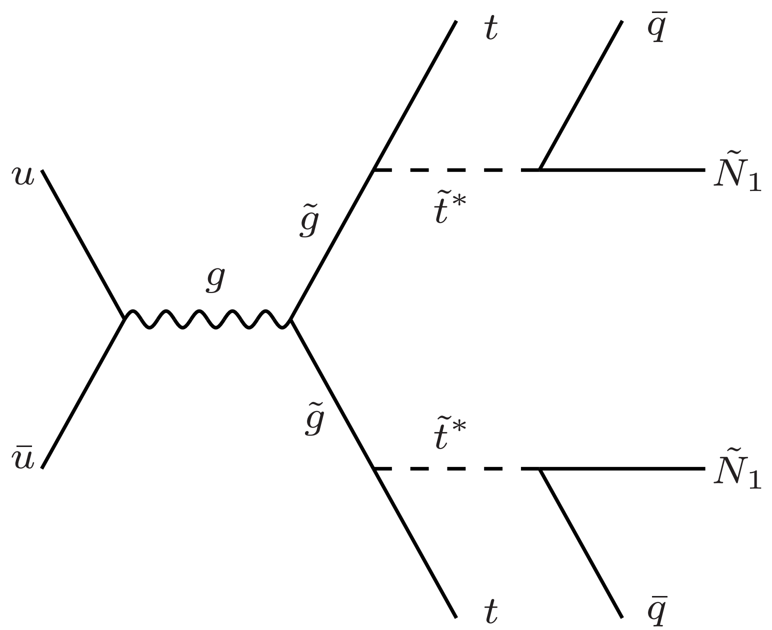
Same-charge leptons, jets and $\not\!\!E_T$ at Large Hadron Collider

Another strategy: look for events with gluino-gluino production,

$$pp \longrightarrow \tilde{g}\tilde{g}$$

but now followed by decays into a top quark and a top squark, which then also decay:

$$\tilde{g} \longrightarrow t\tilde{t}^*, \qquad \tilde{t}^* \longrightarrow q\tilde{N}_1, \qquad t \longrightarrow b\mu^+\nu$$



Signals here are:

$\mu^+\mu^+$ + jets + $\not\!\!E_T$,

$\mu^-\mu^-$ + jets + $\not\!\!E_T$,

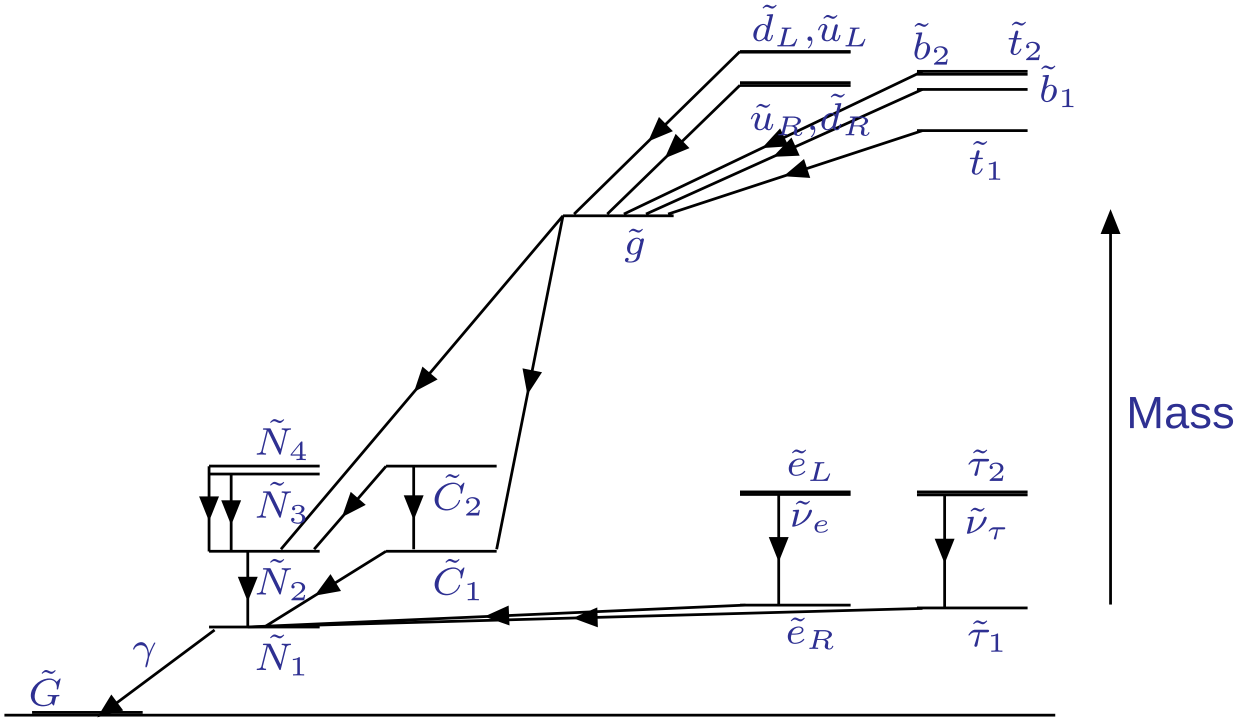
e^+e^+ + jets + $\not\!\!E_T$,

e^-e^- + jets + $\not\!\!E_T$.

Standard Model backgrounds are **very** small; hard to get two leptons with the same charge.

Two isolated, energetic photons and $\not\!\!E_T$ at Large Hadron Collider

In Gauge-Mediated Supersymmetry Breaking:



Each superpartner decays to the $\tilde{N}_1$ as before. BUT, the $\tilde{N}_1$ then decays to the gravitino ($\tilde{G}$) by emitting a very energetic photon.

The signatures are qualitatively the same as before, but with **2 extra energetic, isolated photons** in each event. Very distinctive!

Conclusion:

- Supersymmetry is a leading candidate for the next layer of fundamental physics
- It is a symmetry between particles of different spins (fermions and bosons)
- It solves an important theoretical puzzle, the “Hierarchy Problem” (Why is the Higgs mass so small?)
- It naturally provides a particle that could be the dark matter
- If Supersymmetry is correct, the CERN Large Hadron Collider should tell us within the next few years, perhaps even this year

But, particle physics is like a box of chocolates...

We never know what we're gonna get.