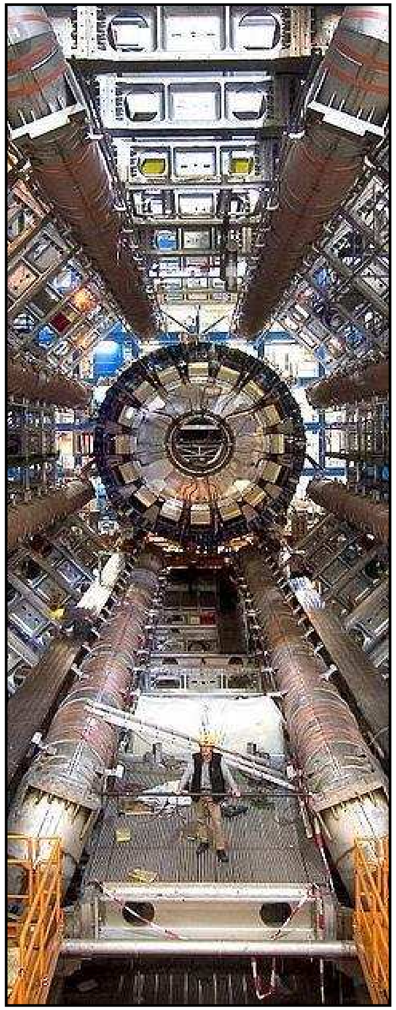
Beyond the Standard Model: **Supersymmetry**

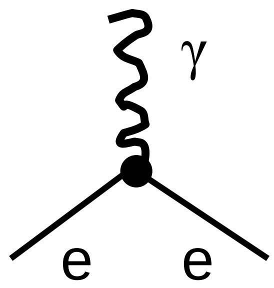
- **Outline**
  - **Why** the **Standard Model** is probably not the final word
  - One way it might be **fixed** up:
    - **Supersymmetry**
    - What it is
    - What is predicts
  - How can we **test** it?



A.J. Barr

Preface

- **Standard Model doing very well**
  - Measurements in **agreement** with predictions
  - Some very exact: electron dipole moment to **12 significant figures**
- However SM does **not** include:
  - **Dark matter**
    - **Weakly interacting massive particles?**
  - **Gravity**
    - **Not in SM at all**
  - **Grand Unification**
    - **Colour & Electroweak forces parts of one "Grand Unified" group?**
  - **Has a problem with Higgs boson mass**



All QED contributions to dipole moment with ≤ **four** loops calculated

Should expect to find new phenomena at high energy

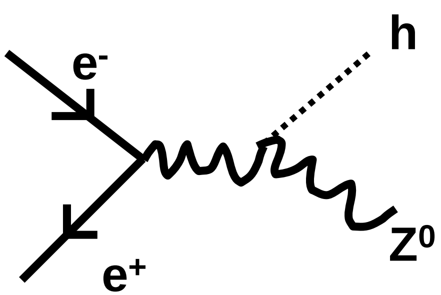
Higgs boson mass

- Standard Model Higgs boson mass:

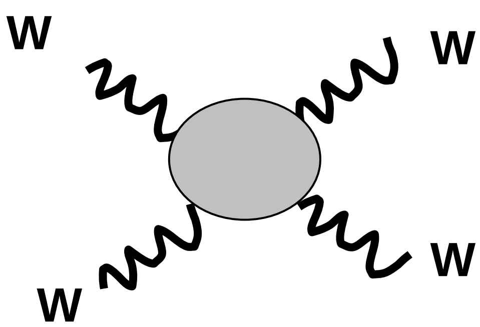
$$114 \text{ GeV} < m_H \lesssim 1 \text{ TeV}$$

Direct searches at "LEP" e^+e^- collider

WW boson scattering partial wave amplitudes > 1



Experimental search

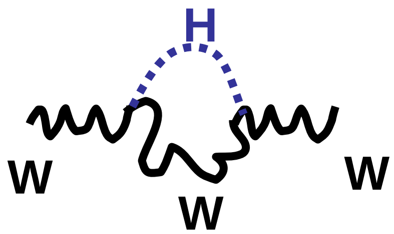


"Probabilities > 1"

(compare Fermi model of weak interaction)

More on m_H …

Measured **W** mass depends on m_H



W emits & absorbs virtual **Higgs boson**

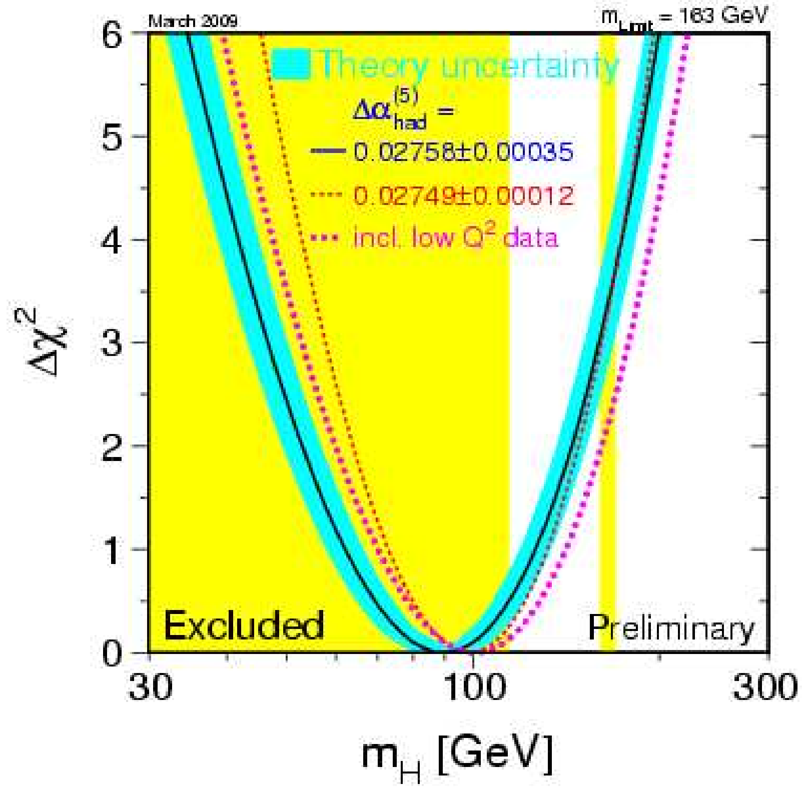
➔ changes **propagator**

➔ changes measured $\mathbf{m_W}$:

$$\Delta_H m_W \propto m_W \ln \frac{m_H^2}{m_W^2}$$

➔ log dependence on m_H

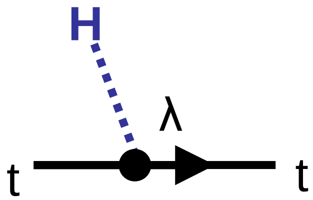
Fit to lots of data (including m_W)…



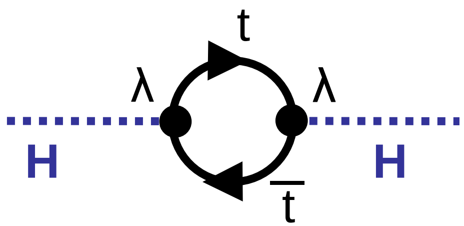
… m_H lighter than about 200 GeV

Higgs mass is same order as W, Z bosons

Corrections to Higgs Mass?



The **top quark** gets its **mass** by coupling to Higgs bosons



Similar diagram leads to a change in the Higgs propagator

➔ **change in m_H**

Integrate (2) up to loop momentum ~ $\boldsymbol{\Lambda_{UV}}$

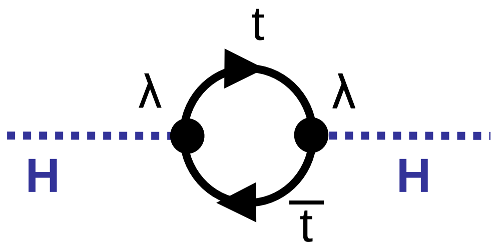
$$\Delta m_H^2 = -\frac{\lambda^2}{8\pi^2}\Lambda_{\mathrm{UV}}^2$$

Changes of order $\boldsymbol{\Lambda_{UV}}$

Maximum energy at which we think existing theory (SM) is valid

Fixing the Higgs mass

Problem:



$\Delta m_H \sim \boldsymbol{\Lambda_{UV}}$

$$\begin{cases} m_{\text{GUT}} \sim 10^{16}\,\text{GeV} \\ m_{\text{Pl}} = \sqrt{\dfrac{\hbar c}{G}} \sim 10^{19}\,\text{GeV} \end{cases}$$

m_H (true) = m_H (bare) + Δm_H

➔ needs **extraordinary** cancellation

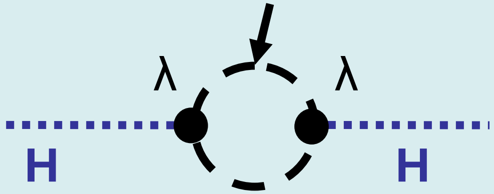
➔ **"Fine tuning"** of m_H (bare)

Fermion loop

$$\Delta m_H^2 = -\frac{\lambda^2}{8\pi^2}\Lambda_{\text{UV}}^2$$

Fix:

Spin-0 particle



Need **new** partner **Δs = ½** to cancel **each** SM particle

Cancel this correction?

Boson loop ➔ **opposite** correction:

$$\Delta m_H^2 = +\frac{\lambda^2}{8\pi^2}\Lambda_{\text{UV}}^2$$

Same coupling as top

➔ **New** spin-0 particle

Supersymmetry

- Nature permits only particular types of symmetry:

(1) Space & time

- Lorentz transforms
- Rotations and translations

(2) Gauge symmetry

- Such as Standard Model force symmetries
- $SU(3)_c \times SU(2)_L \times U(1)$

(3) Supersymmetry

- Anti-commuting generators:

$$\{Q_r, \overline{Q}_s\} = 2\gamma^{\mu}_{rs} P_{\mu}$$

$$\{A,B\} \equiv AB + BA$$

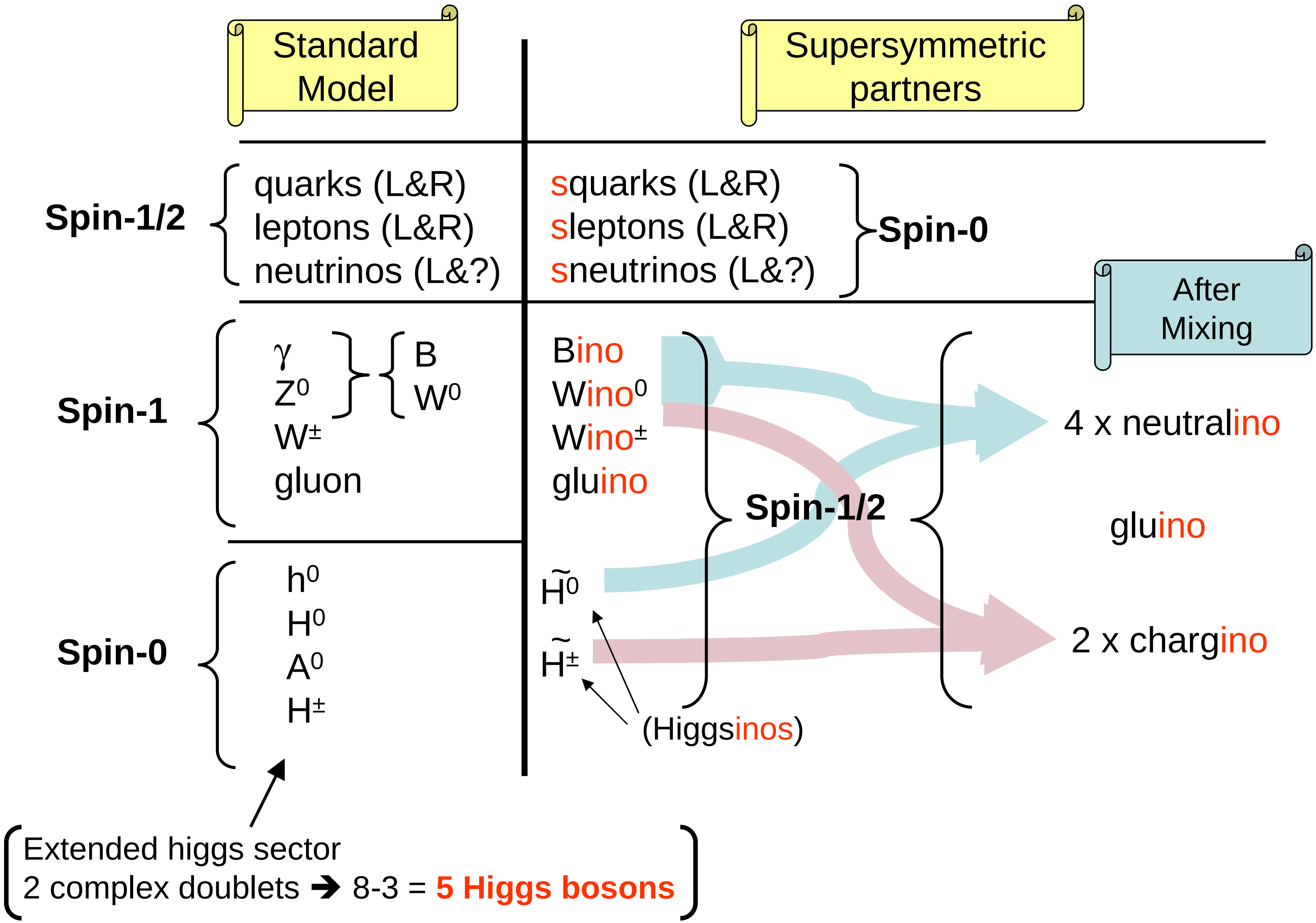
- Q changes Fermion into Boson and vice-versa:

Symbolically:
Q fermion → boson
Q boson → fermion

Equal numbers of **bosonic** & **fermionic** degrees of freedom

Precisely what is needed to **fix** Higgs mass problem

(S)Particles



Standard Model
Supersymmetric partners
Spin-1/2
quarks (L&R)
leptons (L&R)
neutrinos (L&?)
squarks (L&R)
sleptons (L&R)
sneutrinos (L&?)
Spin-0
After Mixing
Spin-1
γ
Z^0
$W^\pm$
gluon
B
W^0
Bino
Wino^0
$\mathrm{Wino}^\pm$
gluino
Spin-1/2
4 x neutralino
gluino
2 x chargino
Spin-0
h^0
H^0
A^0
$H^\pm$
$\tilde{H}^0$
$\tilde{H}^\pm$
(Higgsinos)
Extended higgs sector
2 complex doublets ➔ 8-3 = **5 Higgs bosons**

Two complications

Supersymmetry is a **broken** symmetry

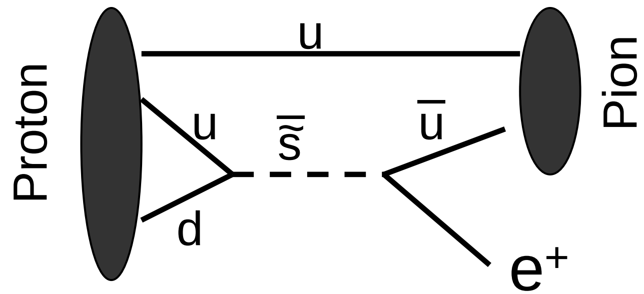
If exact would have

$$m(\tilde{e}) = m(e)$$

No partners **yet observed** up to *m* ~ 100 GeV

Expect masses **~ TeV**
➔ fine tuning problem

Unrestricted supersymmetry
➔ fast **proton decay**



For **stable protons** need conservation of:

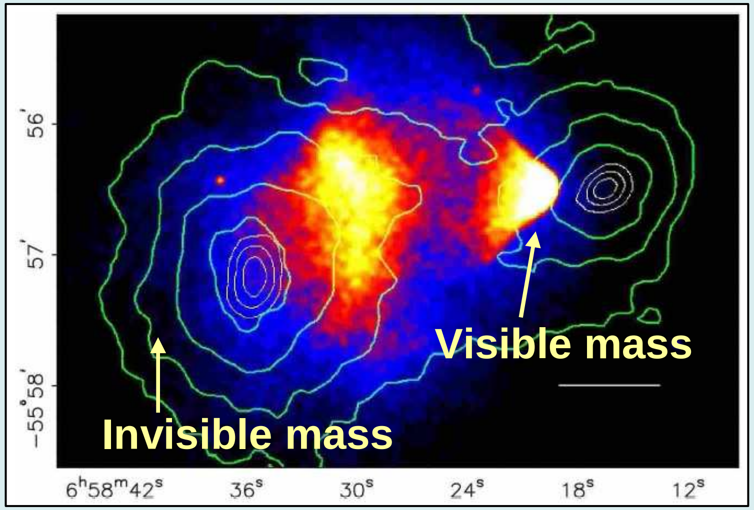
$$\mathbf{R_P} = (-1)^{3B+L+2S}$$

$$\mathbf{R_P} = \begin{cases} \mathbf{+1} & \textbf{SM}\text{ particles} \\ \mathbf{-1} & \textbf{SUSY}\text{ particles} \end{cases}$$

Do we really need to double the particles?

- Lightest SUSY particle can easily be:
  - **Uncharged**
  - **Stable**
  - **Massive**
- Good **dark matter** candidate

Why stable?



Bullet cluster

Adding **Supersymmetry** also helps with

- Grand Unification

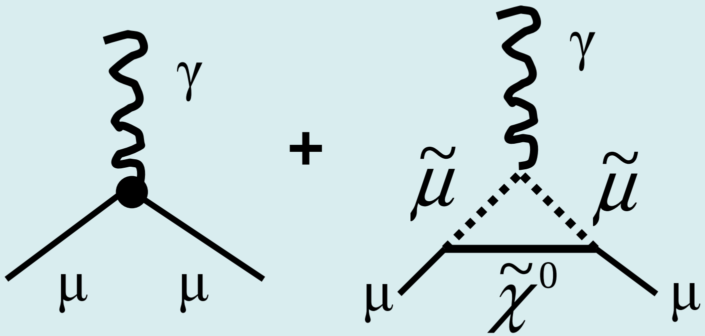
- Electroweak symmetry breaking

Supersymmetry solves a lot of problems

Finding Supersymmetry

- **Precision** experiments

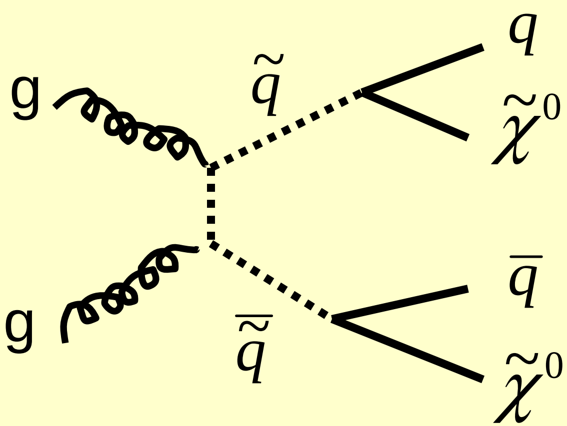
E.g. magnetic moment of the muon:



Currently expt not quite in agreement with **S.M.** prediction

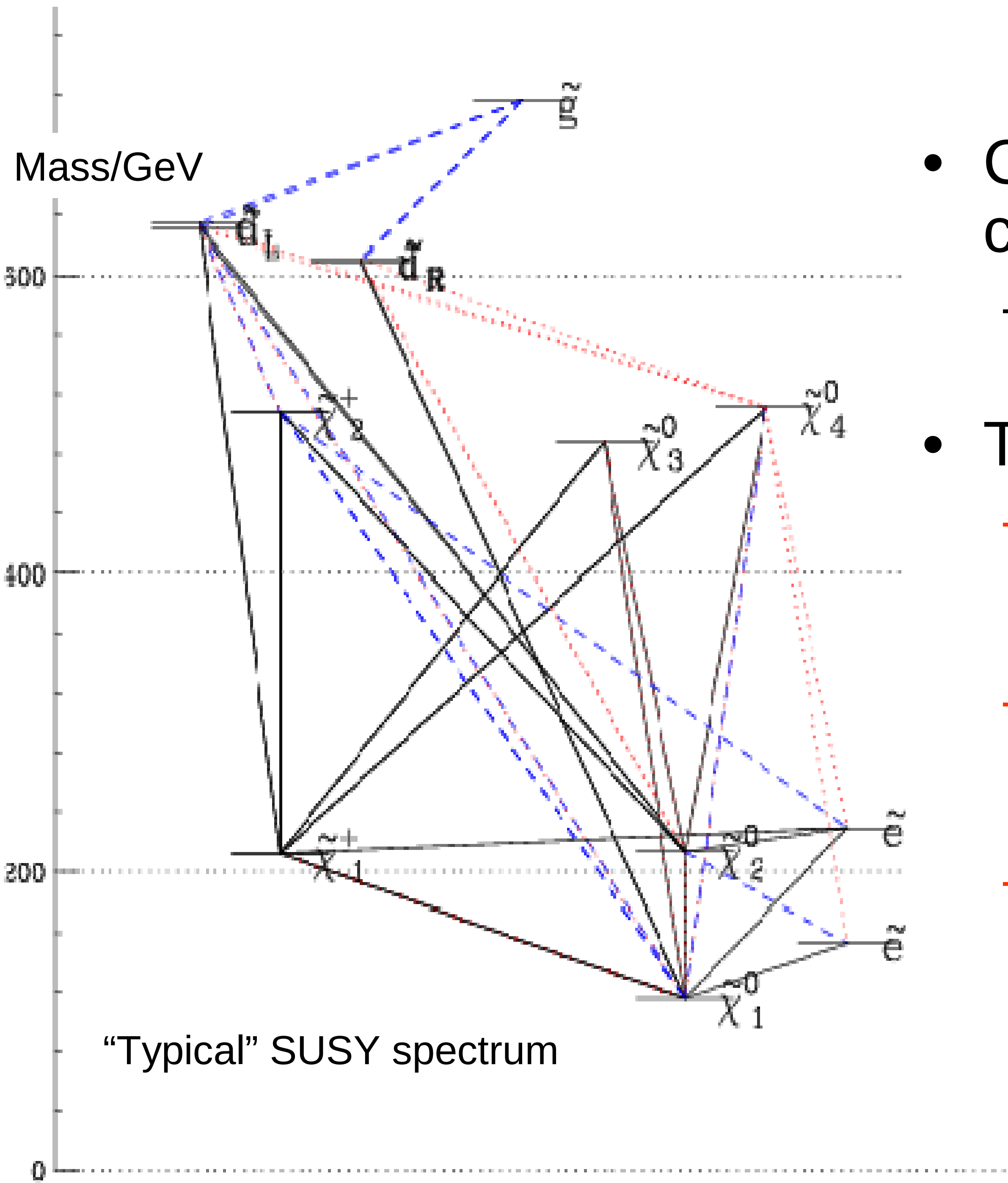
- **Direct search**

E.g. LEP, Tevatron, **LHC** colliders



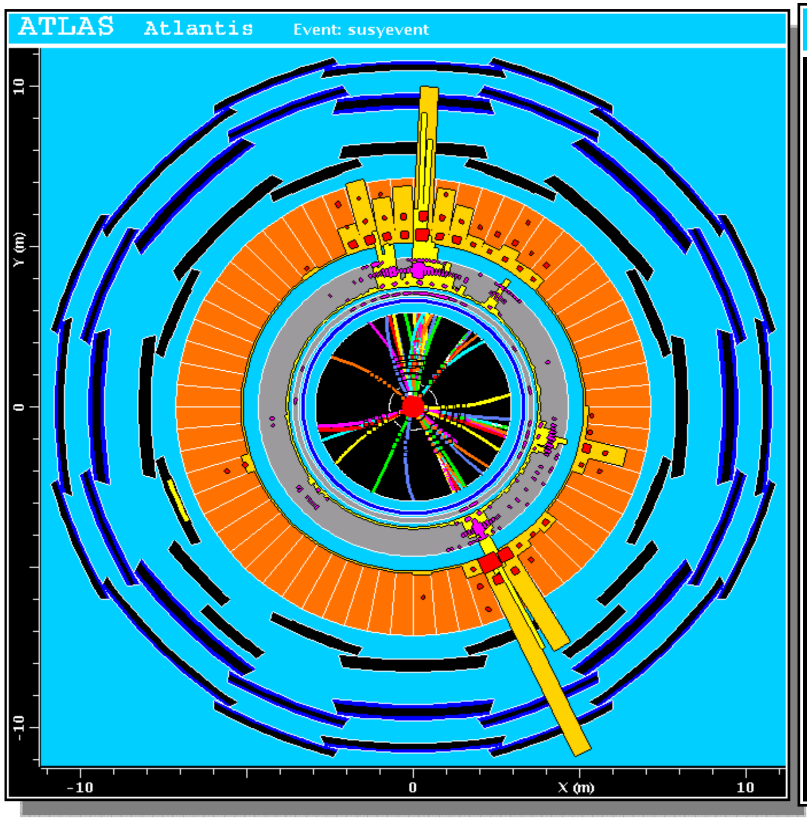
Produce heavy particles which then decay

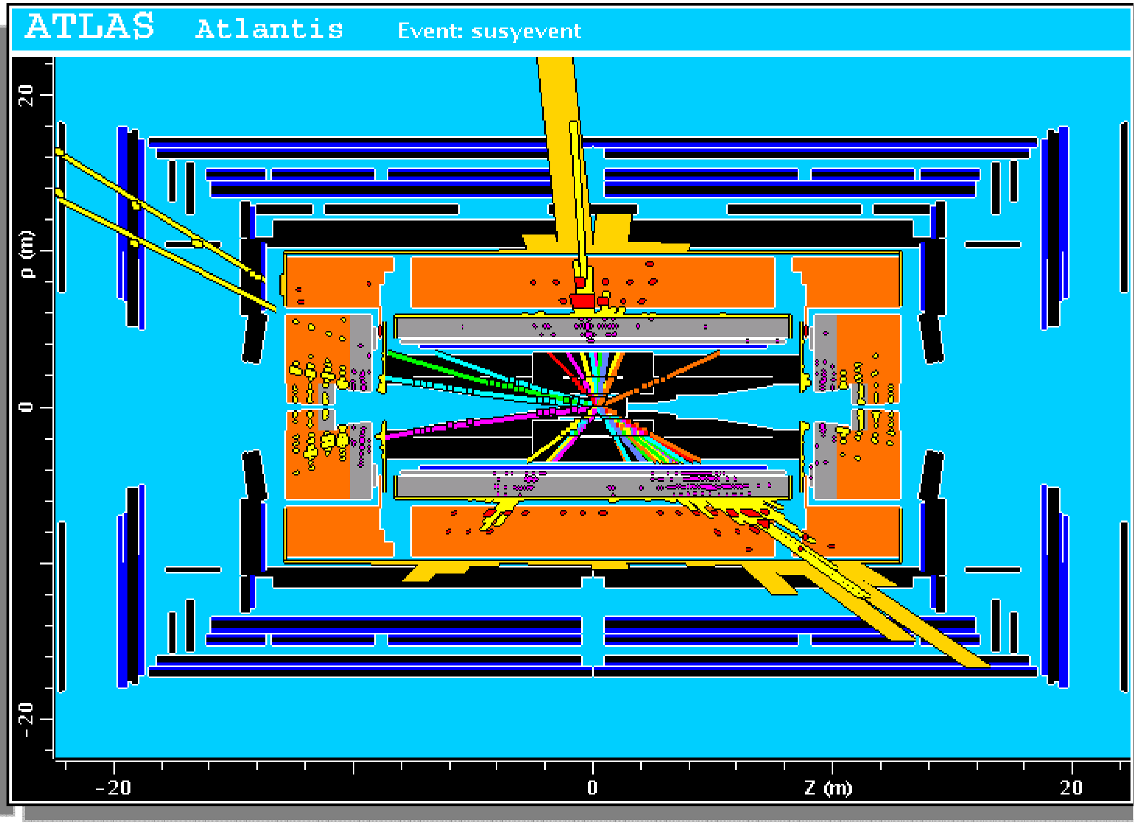
Why produced in pairs?



- Complicated cascade decays
  - Many intermediates
- Typical signal
  - **Jets**
    - Squarks and Gluinos
  - **Leptons**
    - Sleptons and weak gauginos
  - **Missing mmtm**
    - Undetected Lightest SUSY Particle

Simulated SUSY event





Missing transverse momentum

Jets

Heavy quarks

Leptons

After finding a Higgs boson…

- **Discover Supersymmetry**
  - Backgrounds?
- **Measure sparticle masses**
  - Probe SUSY **breaking** mechanism
- **Measure sparticle spins**
  - Show that they differ by ½ unit from SM
- **Find the other four Higgs bosons**
  - Supersymmetry requires **five**


Go hunting …

More…

- SUSY primer: S.P. Martin
  http://arxiv.org/abs/hep-ph/9709356