Imperial College London

SUSY Phenomenology & Experimental searches

Alex Tapper

Slides available at:

http://www.hep.ph.ic.ac.uk/~tapper/lecture.html

Objectives

- Know what Supersymmetry (SUSY) is
- Understand qualitatively the problems with the Standard Model that SUSY may be able to solve
- Know somewhat quantitatively the bounds that the different motives for SUSY impose on it's mass scale
- Be able to understand limits on SUSY presented in a variety of models
- Understand in general terms search strategy for direct detection at collider experiments
- Know where to find more detailed information

Outline

- What's wrong with the Standard Model?
- What's SUSY and why does it help?
- The usual models
- How do we search for SUSY (at colliders)?

Not included

- Nothing about the Higgs
  - See Gavin Davies's lectures on the Higgs
- Nothing about connection to dark matter experiments
  - Direct searches covered by Henrique et al.
- Combined fits to collider/cosmo/low energy data
  - See Rob Bainbridge's lectures

Reading list

- Vast literature on Supersymmetry

- Three of my favourites:
  - A Supersymmetry Primer (S. Martin)
    - http://arxiv.org/abs/hep-ph/9709356
  - Supersymmetry facing Experiment (Pape & Treille)
    - http://iopscience.iop.org/0034-4885/69/11/R01
  - SUSY and Such (S. Dawson)
    - http://arxiv.org/abs/hep-ph/9612229

- Check any day on hep-ph to see latest papers
    - http://arxiv.org/archive/hep-ph

First a poll…

- Who "believes" in supersymmetry?

  (even if you don't completely understand what it is)

- Why study this?

What's wrong with the SM?

- Why three generations?
- Neutrinos have mass
- Nineteen free parameters
- Doesn't include gravity or dark matter/energy
- Hierarchy problem
- ….

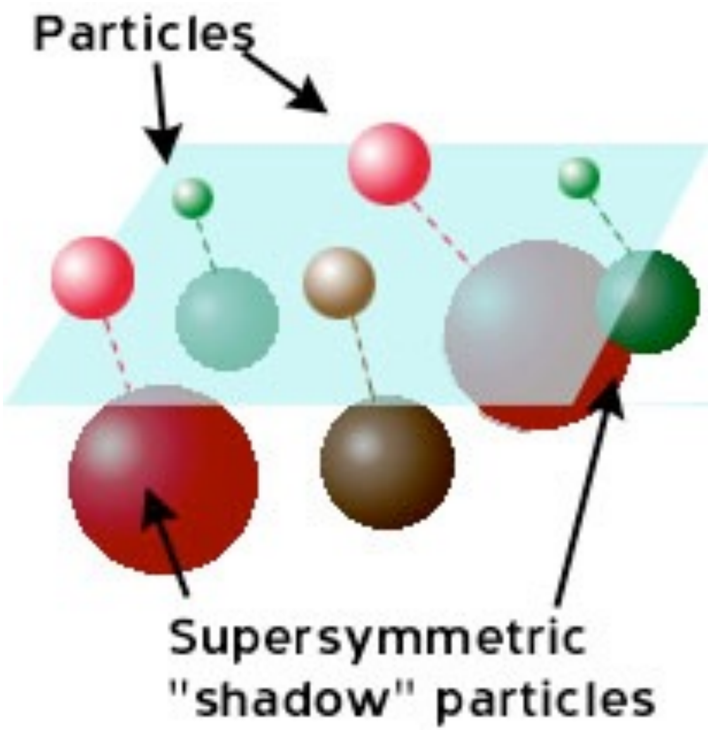
What is supersymmetry?

- If you want to add a symmetry to the Standard Model the Coleman-Mandula theorem says a symmetry connecting fermions and bosons is the only extra (not in the Poincare group) external symmetry you may add and preserve interactions

- Posit a symmetry such that:

$$\hat{O}|f\rangle = |b\rangle \quad \hat{O}|b\rangle = |f\rangle$$

- Where f (b) are fermions (bosons)
- Particle number is conserved



What is supersymmetry?

- In the Standard Model particles are arranged into multiplets, e.g.

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

- Supersymmetry follows the same idea:
  – "Supermultiplets"
  – Same number of bosonic and fermionic degrees of freedom
  – Chiral supermultiplet: SM + SUSY fermions
  – Gauge supermultiplet: SM + SUSY bosons

R-Parity

- Supersymmetry introduces a new multiplicative quantum number named R-parity (R_P)
  - $R_P=(-1)^{3(B-L)+2S}$
  - B, L and S are Baryon no., Lepton no. and Spin
  - $R_P=1$ SM particles, $R_P=-1$ SUSY particles
- Think of R_P as "superness"
- SUSY theories can conserve or violate R_P
  - Big consequences in phenomenology

Motivations for supersymmetry

- Naturalness (the hierarchy problem)
- Unification of the EM, weak and strong forces (maybe…)
- Dark Matter candidate

Hierarchy problem

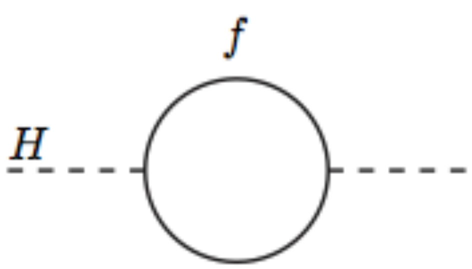
- In the Standard Model there's a Higgs boson
  - Weak scale set by vev of Higgs ~246 GeV
  - In principle sets scale for all masses in the theory including the Higgs (now know 125 GeV)

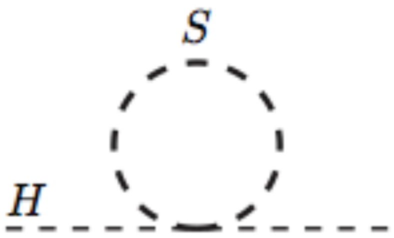
- Gravity scale set by the Planck mass 10^{19} GeV

- Why is the weak scale so different from the scale of gravity?

Hierarchy problem

- Looking in more detail at the Higgs Mass





- Receives corrections from all particles
  - From fermions: $\Delta m_H^2 = \frac{\lambda_f^2}{8\pi^2}[-\Lambda^2 + 6m_f^2 ln\frac{\Lambda}{m_f}]$
  - From scalars: $\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda^2 - 2m_S^2 ln\frac{\Lambda}{m_S}]$
  - Λ is cut-off scale to protect against infinite corrections
- Quadratic divergence
  - Natural scale for Higgs mass is cut-off scale
  - Can renormalise away the divergence if it has no physical meaning ➔ but what about gravity?

Hierarchy problem

- So the Higgs mass is extremely sensitive to the heaviest particle to which it couples and it's most natural value is close the the largest mass in the theory

- There was a hint to the solution on the previous page:
  - Fermions $\Delta m_H^2 = \frac{\lambda_f^2}{8\pi^2}[-\Lambda^2 + 6m_f^2 ln\,\frac{\Lambda}{m_f}]$
  - Scalars $\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda^2 - 2m_S^2 ln\,\frac{\Lambda}{m_S}]$
- So if every fermion is accompanied by two scalars with couplings $\lambda_S=\lambda_f^2$ the quadratic divergences cancel
- Relation between couplings by imposing a symmetry between fermions and bosons
  - Supersymmetry

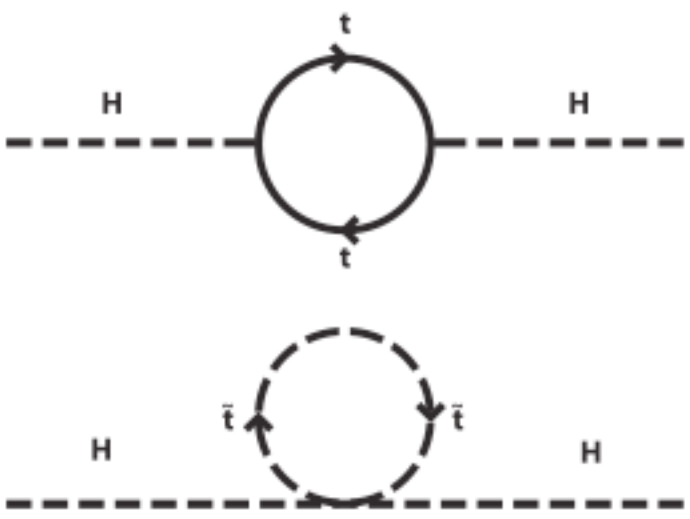
Hierarchy problem

- The correction then reduces to:

$$\Delta m_H^2 \approx \frac{\lambda_f^2}{4\pi^2}(m_S^2 - m_f^2) ln \frac{\Lambda}{m_S}$$

- Now divergence is logarithmic (normal in SM)
- Masses can be large but if almost degenerate correction is well behaved

- In Supersymmetry this is basically the top squark cancelling the effect of the top quark
- We'll come back to this when we talk about experimental searches



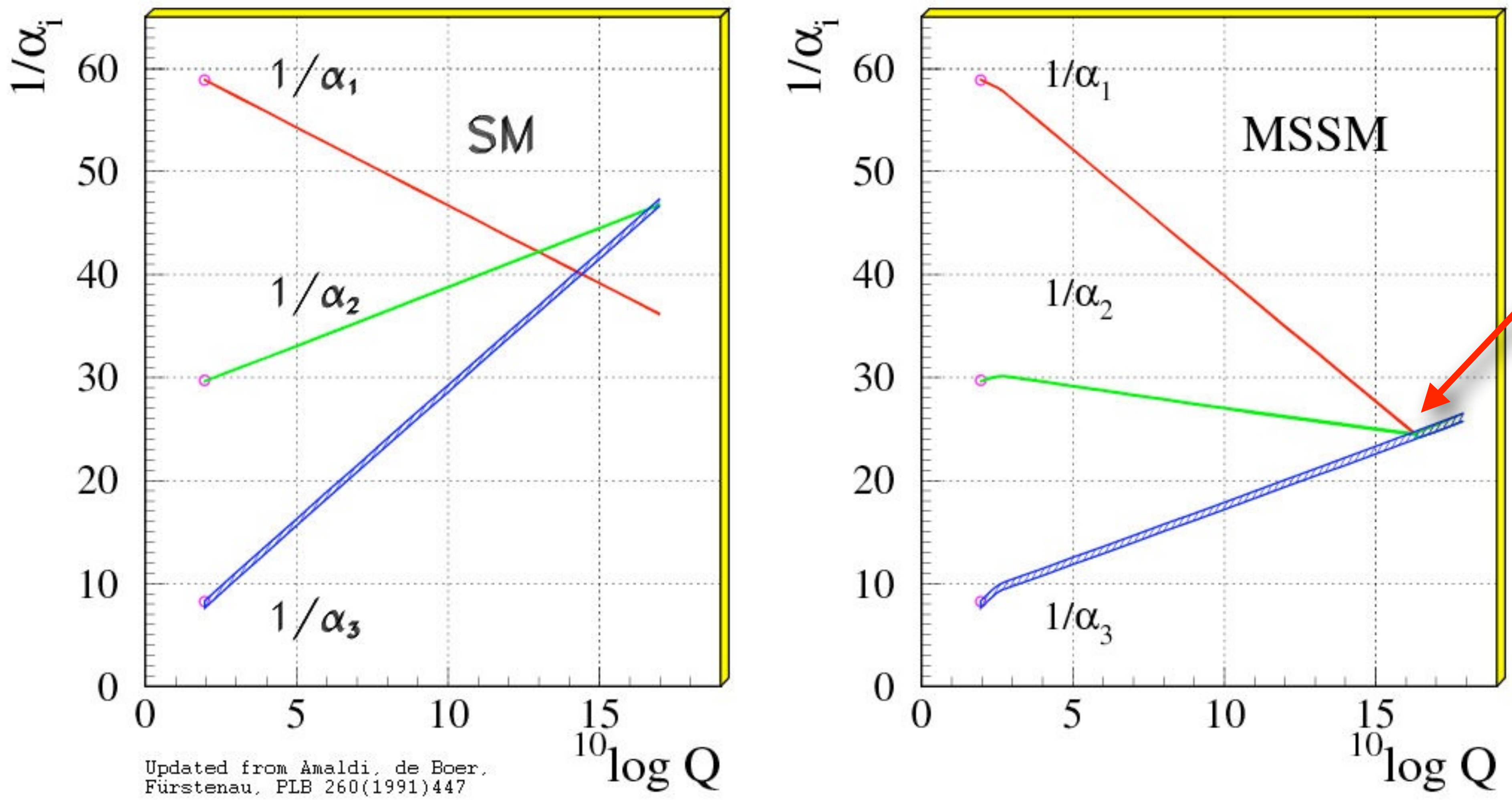
Unification

- A Grand Unified Theory (GUT) unifies the three gauge interactions of the Standard Model
  - Electromagnetic
  - Weak
  - Strong
- Unifies means they are characterised by one gauge symmetry and one coupling constant
- A Theory Of Everything (TOE) would also include gravity

Unification

- Standard Model
  - $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$
- Theory to unify gauge interactions should include these groups
  - SU(5), SO(10)….
- Predictions
  - Proton decay, magnetic monopoles….

Unification



Consistent with proton decay limits

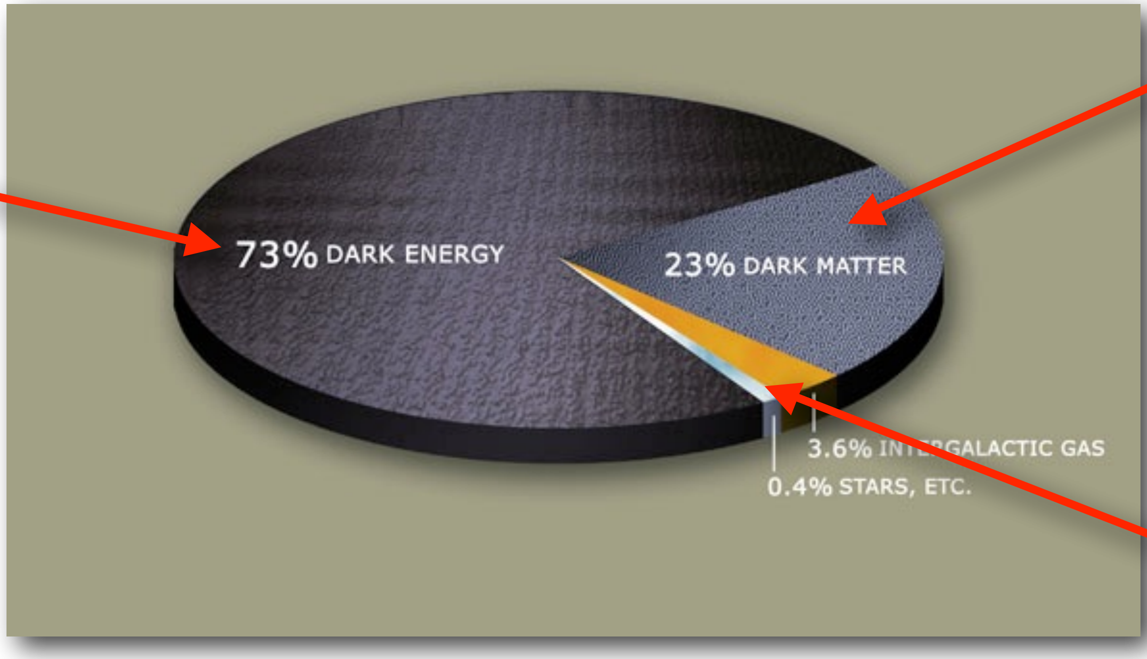
- Couplings run like: $\frac{d}{d(lnQ)}(\alpha_i^{-1}) = \frac{b_i}{2\pi}$
- Take measured couplings at Z pole and b_i from MSSM
- Unification at 1% level at $\Lambda_{GUT} \approx 10^{16}$ GeV for masses < 10 TeV

Dark Matter

- 23% of Universe!

Evidence from galactic rotation

Evidence from CMB



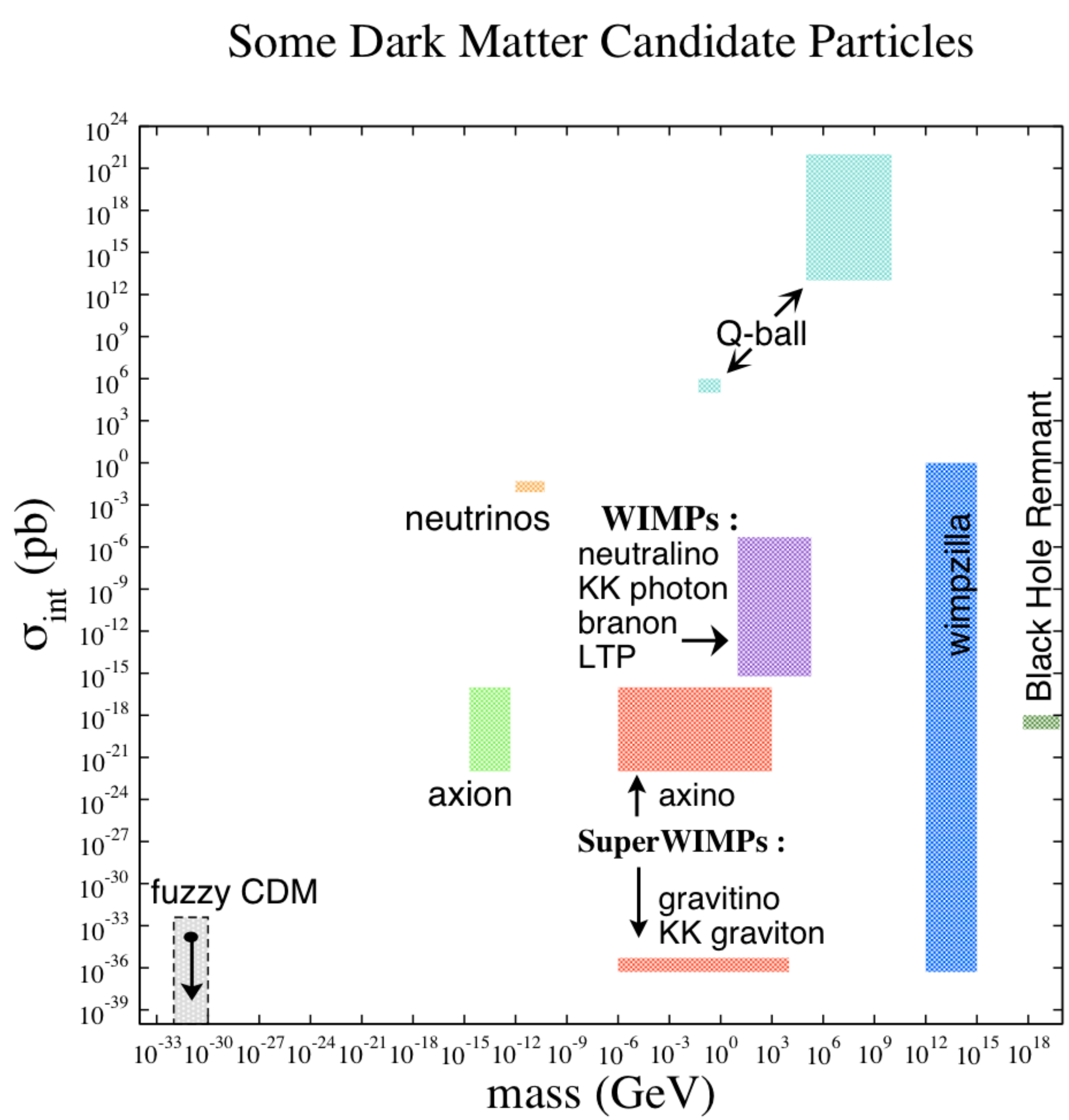
Evidence from observation with telescopes

- Many direct searches
- Many different particles proposed →

Dark Matter

- SUSY can provide a dark matter candidate
- No strong or electromagnetic interactions
- WIMP
- Non-baryonic Cold Dark Matter (CDM)

L. Roszkowski, Pramama, 62 (2004) 389



Dark Matter

- Relies on R-Parity conservation (RPC)
- Remember if R_P is conserved then SUSY particles can only be produced in pairs of a SUSY particle and it's antiparticle
- SUSY particles cannot decay directly to SM particles so the lightest SUSY particle has nothing to decay to ➔ stable, weakly interacting Dark Matter candidate
- Can be lightest neutralino, sneutrino, Gravitino….
  – Mass depends on details but for Wino $M_{LSP} < 3$ TeV

The MSSM

- Minimal Supersymmetric Standard Model
- The least number of particles you can add to the Standard Model to make a viable SUSY model (N=1 supersymmetry)
- Assume R-Parity is conserved (stable proton)
- Each SM particle has a SUSY partner
  - In total O(120) free parameters mostly to do with symmetry breaking ➔

MSSM Higgs

- Supersymmetry requires two Higgs doublets
  - To cancel gauge anomalies and provide mass to both up and down-type particles
- Since we are not swamped in SUSY particles we assume SUSY is a broken symmetry
  - Aside: could any of the particles we know of be super-partners?
- Many different theories for SUSY breaking
  - Generally spontaneous symmetry breaking in a hidden sector is communicated to the visible sector through corrections to the masses
  - Radiative electroweak symmetry breaking ➔ "more natural"

MSSM particles

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	−1	$\widetilde{u}_L\ \widetilde{u}_R\ \widetilde{d}_L\ \widetilde{d}_R$ $\widetilde{s}_L\ \widetilde{s}_R\ \widetilde{c}_L\ \widetilde{c}_R$ $\widetilde{t}_L\ \widetilde{t}_R\ \widetilde{b}_L\ \widetilde{b}_R$	(same) (same) $\widetilde{t}_1\ \widetilde{t}_2\ \widetilde{b}_1\ \widetilde{b}_2$
sleptons	0	−1	$\widetilde{e}_L\ \widetilde{e}_R\ \widetilde{\nu}_e$ $\widetilde{\mu}_L\ \widetilde{\mu}_R\ \widetilde{\nu}_\mu$ $\widetilde{\tau}_L\ \widetilde{\tau}_R\ \widetilde{\nu}_\tau$	(same) (same) $\widetilde{\tau}_1\ \widetilde{\tau}_2\ \widetilde{\nu}_\tau$
neutralinos	1/2	−1	$\widetilde{B}^0\ \widetilde{W}^0\ \widetilde{H}_u^0\ \widetilde{H}_d^0$	$\widetilde{N}_1\ \widetilde{N}_2\ \widetilde{N}_3\ \widetilde{N}_4$
charginos	1/2	−1	$\widetilde{W}^\pm\ \widetilde{H}_u^+\ \widetilde{H}_d^-$	$\widetilde{C}_1^\pm\ \widetilde{C}_2^\pm$
gluino	1/2	−1	$\widetilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\widetilde{G}$	(same)

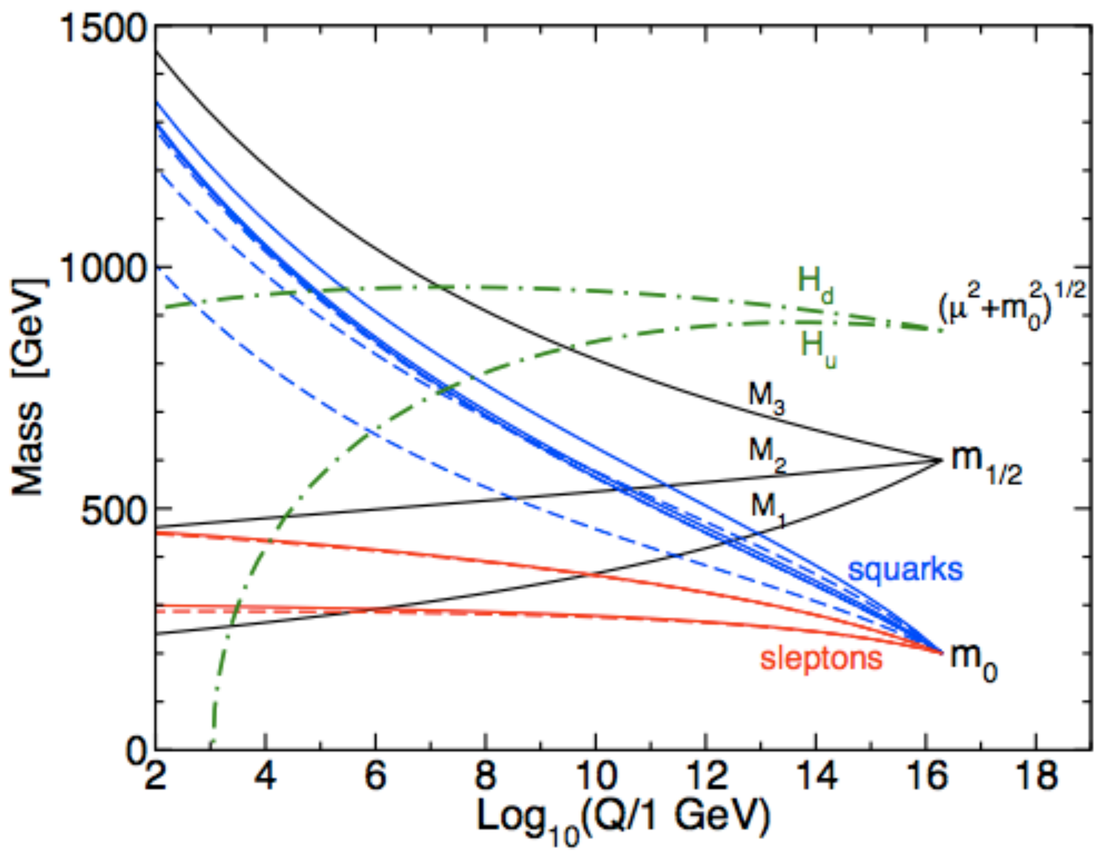
Neutralinos and charginos are often denoted as $X^{0,\pm}$ χ

The CMSSM

- Take a step further in simplification
  - Constrained MSSM (sometimes mSUGRA)
- Impose GUT scale (M_{Pl}) relations on the MSSM
  - Set all scalar masses to one value m_0
  - Set all gaugino masses to one value $m_{1/2}$
  - Set trilinear couplings to one value A_0
  - Set ratio of Higgs doublet VeVs to $\tan\beta$
- Gravity-Mediated Supersymmetry Breaking

The CMSSM

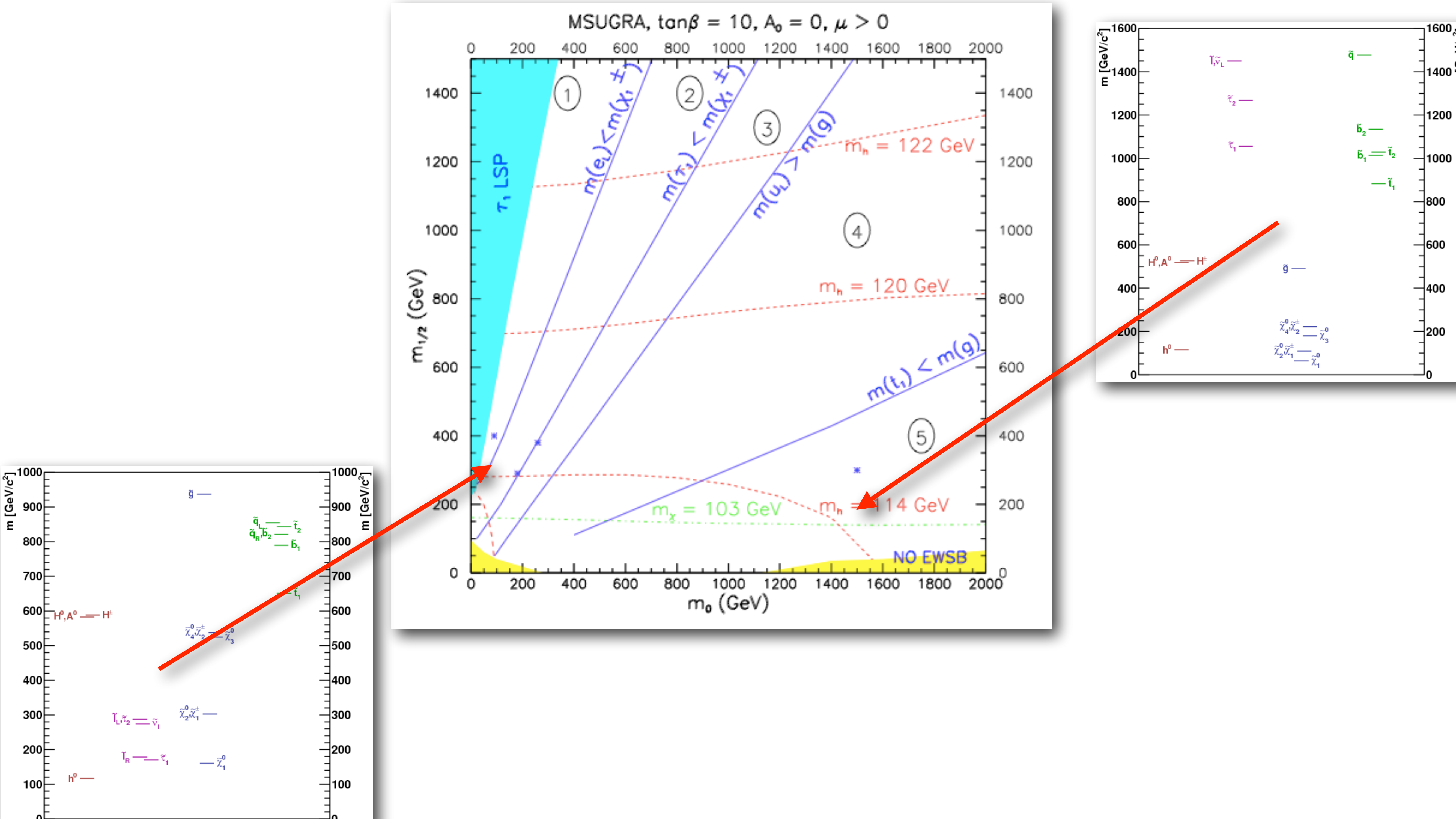
- A full viable SUSY theory in principle (nobody believes this is nature though)
- Very convenient way to simplify SUSY to just 4 parameters (and a sign)
- Widely used to quote results of experimental searches (next lecture)



The CMSSM

- Has a wide range of phenomenologies, but beware!
  - Unifications at the GUT scale lead to fixed ratios between couplings and therefore masses
  - $M_{gluino/squark} : M_{Chargino} : M_{Neutralino} \approx 6 : 4 : 1$
  - Large splittings between gluino, squarks and neutralinos ➔ easy signals to observe

The CMSSM


MSUGRA, tanβ = 10, A₀ = 0, μ > 0
m₀ (GeV)
m₁/₂ (GeV)
τ₁ LSP
m(e_L)<m(χ₁±)
m(τ₁) < m(χ₁±)
m(u_L) > m(g)
m(t₁) < m(g)
m_h = 122 GeV
m_h = 120 GeV
m_h = 114 GeV
m_χ = 103 GeV
NO EWSB
1
2
3
4
5
m [GeV/c²]

Summary

- Supersymmetry is a theory which postulates a new symmetry between fermions and bosons
- Best studied extension to the Standard Model with vast literature
- Has the potential to solve some of the most serious problems in the Standard Model quite naturally

- Next time: how we search for Supersymmetry at colliders