BEYOND THE STANDARD MODEL

- All experimental observations in particle physics are consistent with the Standard Model, so far, provided neutrino masses are incorporated
- But, many unanswered questions
  - → Why the three generations? Are there more?
  - → Where do the masses of particles come from? We really don't know yet the mechanism of EW symmetry breaking
  - → Do the fundamental forces unify at a higher energy scale?
  - → Why is there so little antimatter in the universe?
  - → The parameters of SM unexplained and there is "Fine Tuning"
  - → What is dark matter?
  - → What is dark energy?
  - → Are there extra dimensions of space?
- So, Standard Model (SM) may be an approximate theory!
- New elements/concepts may be needed OR a more general theory that reduces to SM as an approximation.

There are a variety of theories of BSM. We will consider a few.

- Grand Unified Theories
- New Symmetries : Super Symmetry
- New forces : Technicolor
- Theory of Everything? String Theory
- Extra Dimensions
- .
- .
- .

GRAND UNIFICATION

- Electricity, Magnetism > Electromagnetism > Quantum Mechanics > QED

EM, weak > Electroweak. > QCD > ? GUT

Grand Unified Theory

But, at the energies now accessible,

$\alpha_s >> \alpha_w$

$\alpha_s(M_Z) = 0.118 \pm 0.002$

$\alpha_w = 0.0043 \pm 0.0002$

But, we know the α's are not really constants but vary with μ^2 (the energy-momentum transfer).

And, α_s decreases more rapidly with μ^2 as compared to α_w, and so extrapolating the behaviour from low energies, they should become equal at some large value of $\mu^2 = M_X^2$

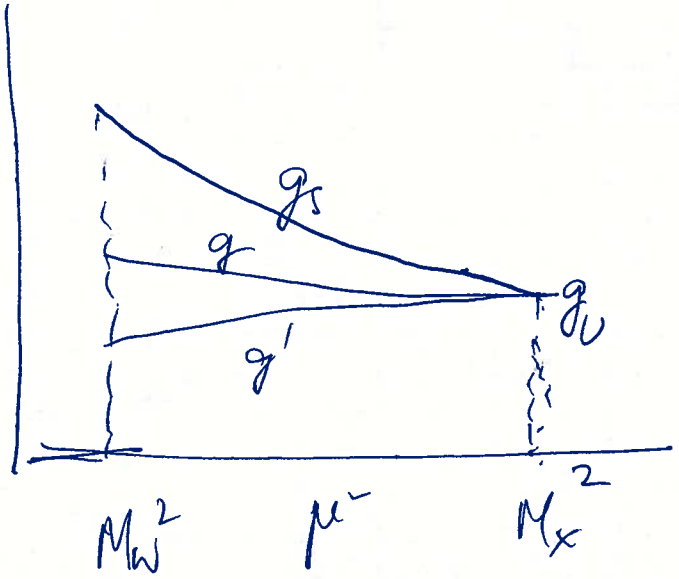
↑ Unification Scale or Unification Mass.

The plots of unification

$$g_s = \sqrt{\frac{\alpha_s}{4\pi}}$$

$$g = 2\sqrt{2}\, g_W$$

$$g' = 2\sqrt{2}\, g_Z$$



Naive extrapolation from M_W^2 i.e., from $\sim 10^2$ GeV to 10^{15} GeV

But something new can be going on in this range.

GUTs invoke extended families and gauge groups.

Simplest are Georgi-Glashow Model (1974)

$SU(5) \supset SU(3) \times SU(2) \times U(1)$

Puts ~~and~~ quarks and leptons to common families

Fermions in SU(5) GUT

Quintet : $e_L, \nu_L, \vec{d}_R^{\,r}, \vec{d}_R^{\,b}, \vec{d}_R^{\,g}$

Decuplet : $e_R, u_R^r, u_R^b, u_R^g, \vec{u}_L^{\,r}, \vec{u}_L^{\,b}, \vec{u}_L^{\,g}, \vec{d}_L^{\,r}, \vec{d}_L^{\,b}, \vec{d}_L^{\,g}$

SU(n) group has n^2-1 mediators

$\Rightarrow$ SU(5) has 24

8 gluons + 3 EW bosons + 1 photon

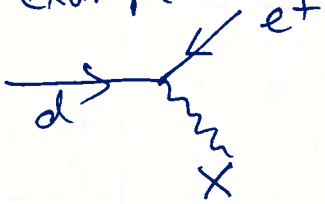
+ 12 new ones

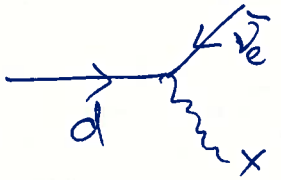
$\hookrightarrow$ 6 $X^{\pm}$ with ~~e~~ charge $\pm 4/3$ × 3 colors

6 $Y^{\pm}$ with charge $\pm 1/3$ × 3 colors

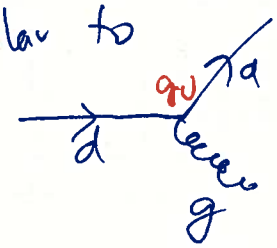
$M_X \sim 10^{15}$ GeV

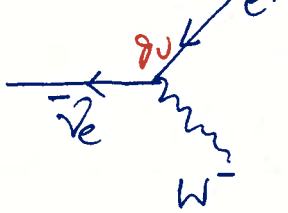
Then, we have for example





similar to





X and Y are Leptoquarks

$\Leftarrow$ we have searched for ~~these~~ LQ and set mass limits!

Some Simple Consequences

Quark and lepton charges in SU(5) GUT

One nice thing is that the sum of the electric charges in a multiplet should be zero.

So, for the quintuplet,

$$-3Q_d + e = 0$$

$$\Rightarrow \quad Q_d = -1/3$$

Similarly, one can see that $Q_u = +2/3$

The Weak Mixing Angle

From the GUT model, you can predict one of the 3 coupling strengths at low energy.

So, in SU(5), one predicts

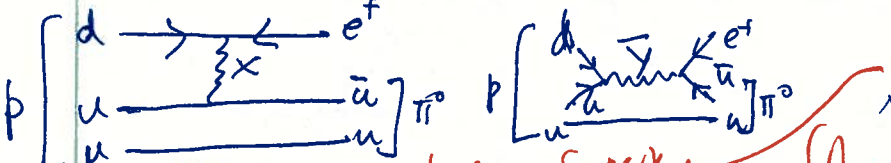
$$\sin^2\theta_W = 0.21$$

(not in bad agreement with $\sin^2\theta_W = .231$)

Proton Decay

Now that quarks and leptons are connected, protons can decay.

$$p \to \pi^0 + e^+ \quad ; \quad p \to \pi^+ + \bar{\nu}_e$$



$\tau \simeq 10^{29} - 10^{30}$ years sensitive to M_X

incompatible with { upper limit from Super-K $\tau_p > 1.5 \times 10^{32}$ years (Age of the Universe $\sim 10^{10}$ years)

SUPERSYMMETRY : A new Symmetry of Nature?

Every SM particle has a SUSY partner

Every fermion has a bosonic SUSY partner

Every Boson has a fermionic SUSY partner

Naming

Fermion → "s"fermion

Boson → Bos"ino" (Bosino isn't used, but why not?)

So, we will have

up squark, . . . , sbottom, stop,

Selectron, smuon, sneutrino, . .

And,

Wino, Zino, photino, Gluino

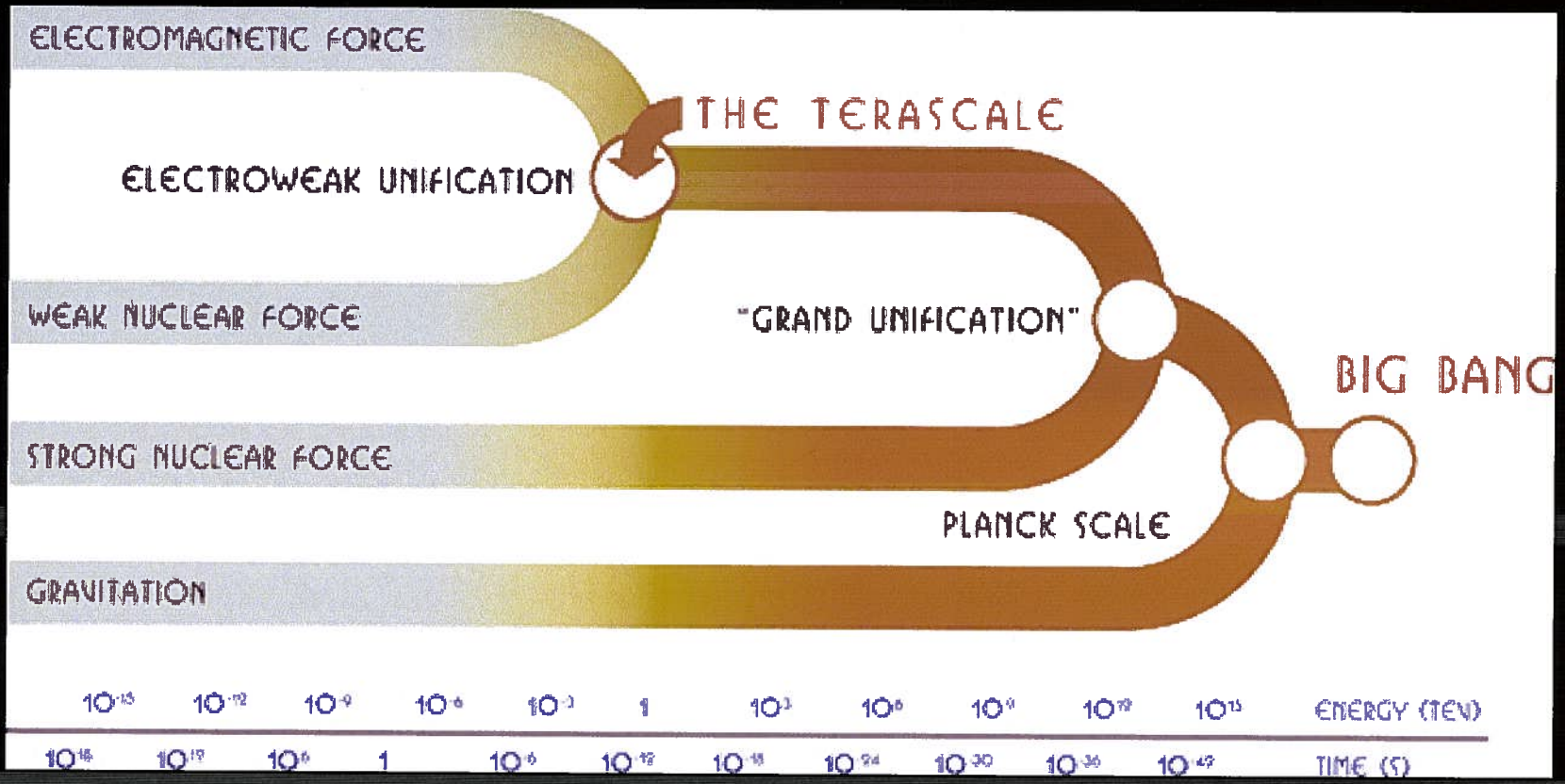
Also,

higgsino.

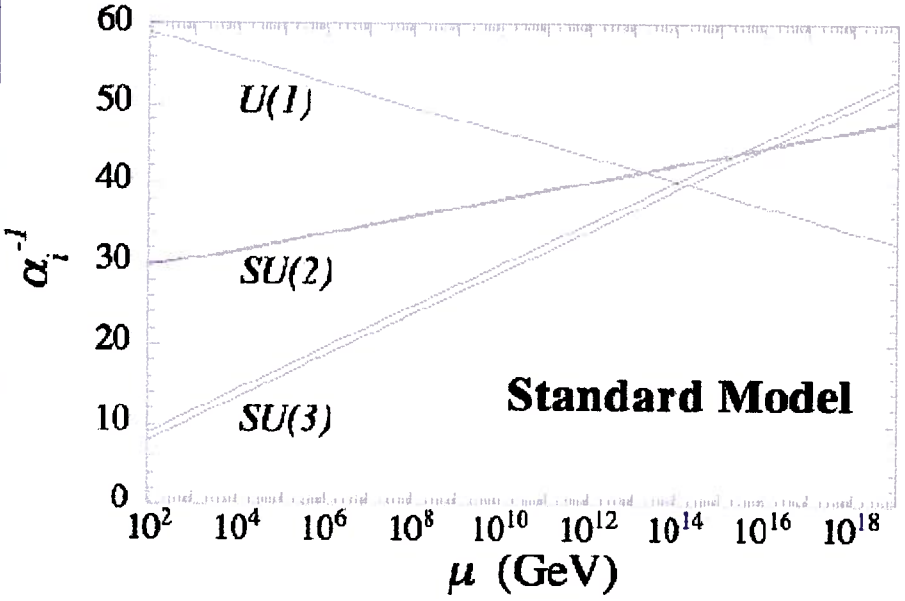
- If SUSY were exact, SM particles and superpartners would have exactly the same masses. But, we know that is not the case.
  So SUSY is approximate and BROKEN!
- But, the masses cannot be too different, so that contribution from particles and superpartners cancel each other the radiative corrections loops
- If the masses are $\sim M_{W,Z}$, then the unification of forces occur at $\sim 10^{16}$ GeV ($\sim M_X$) and so proton lifetime $\sim 10^{32} - 10^{33}$ years

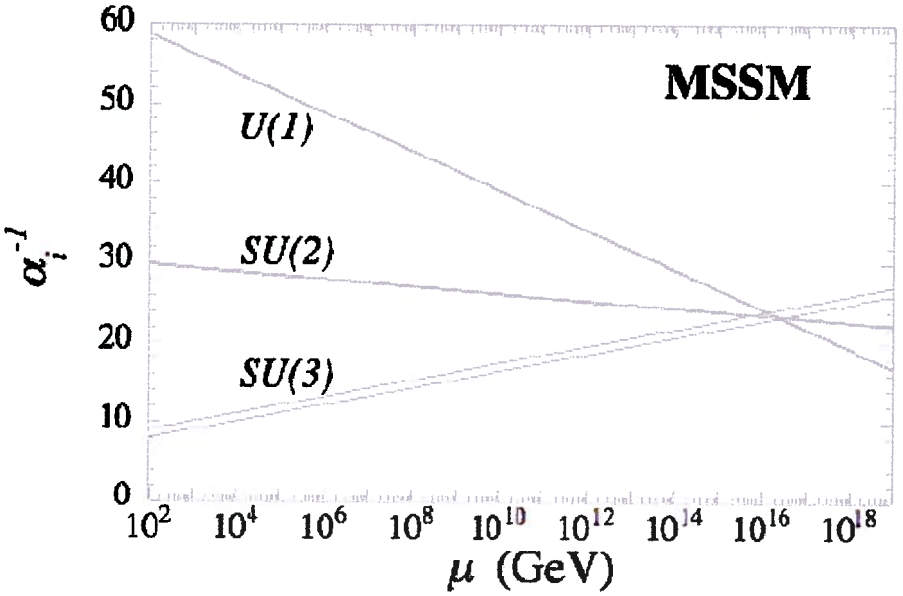
⇐ agrees with expt.

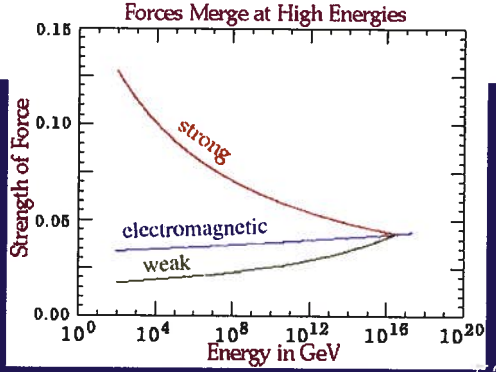
More on Unification



Gauge Coupling Unification



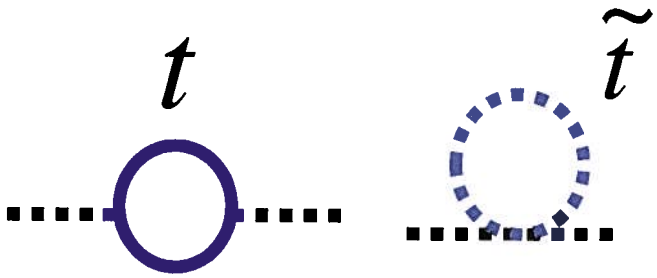




The MSSM – 124-parameter theory!

SUSY….Our favorite model

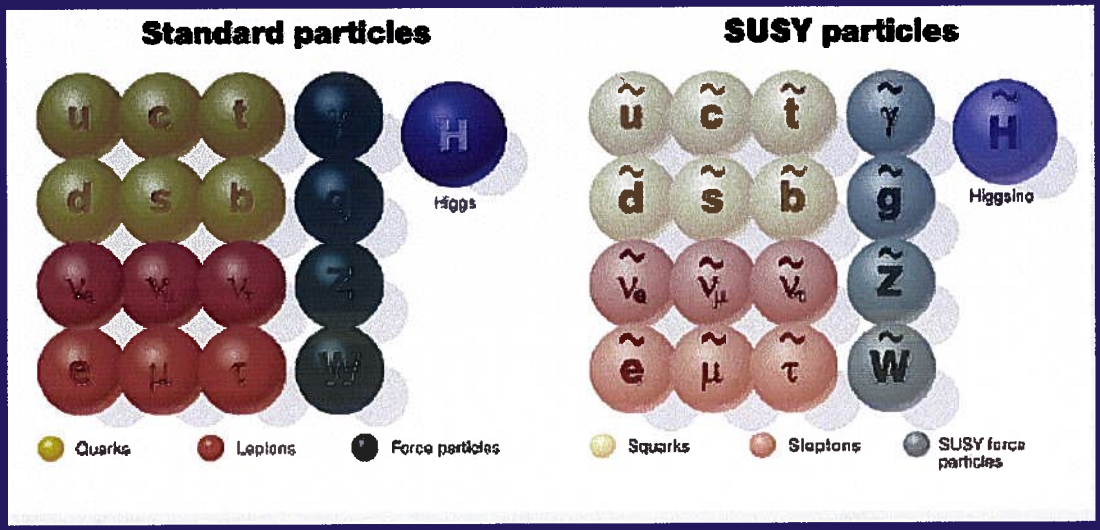
- Quadratic divergences cancelled automatically if SUSY particles at TeV scale
- Cancellation result of ***supersymmetry***, so happens at every order



$$\delta M_h^{\,2} \approx (....) G_F \Lambda^2 (M_t^{\,2} - M_{\tilde{t}}^{\,2})$$

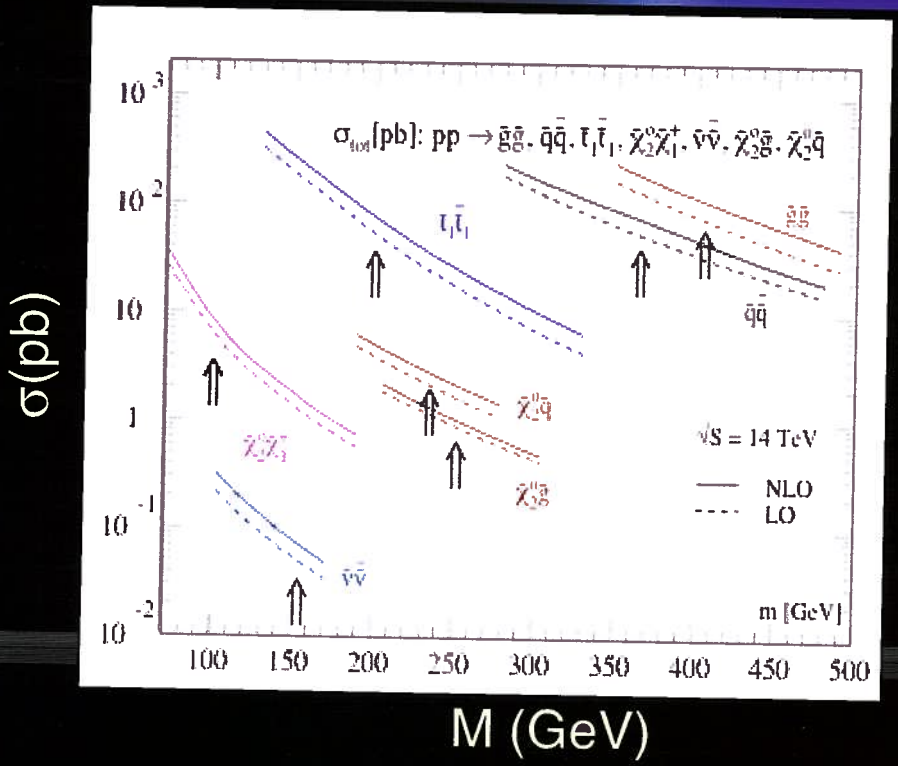
- Stop mass should be TeV scale

Supersymmetry



SM Particles	SUSY Particles			
quarks: q	q	squarks: $\tilde{q}$		
leptons: l	l	sleptons: $\tilde{l}$		
gluons: g	g	gluino: $\tilde{g}$		
charged weak boson: $W^{\pm}$	$W^{\pm}$	Wino: $\tilde{W}^{\pm}$	$\tilde{\chi}^{\pm}_{1,2}$	chargino
Higgs: H^0	$H^{\pm}$	charged higgsino: $\tilde{H}^{\pm}$		
	h^0, A^0, H^0	neutral higgsino: $\tilde{h}^0, \tilde{A}^0, \tilde{H}^0$		higgsino
neutral weak boson: Z^0	Z^0	Zino: $\tilde{Z}^0$	$\tilde{\chi}^0_{1,2,3,4}$	neutralino
photon: γ	γ	photino: $\tilde{\gamma}$		

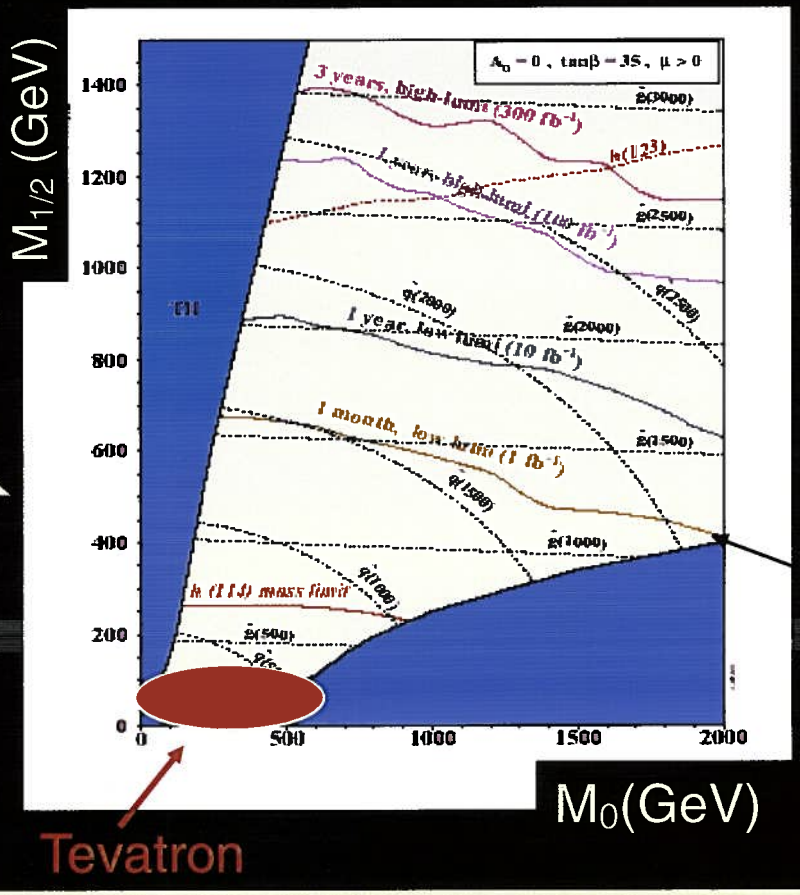
Supersymmetry at the LHC



- Huge rates; well defined signatures
  - M(gluino, squark) ~ 1 TeV gives 100 events with 100 pb^{-1} at LHC

Supersymmetry at the LHC

- LHC will find SUSY if it is at 1 TeV



2009

Tevatron

Immediate improvements over Tevatron limits

mSUGRA – LM8

- Final States

	BF(%)
$pp \to \tilde{g}\ \tilde{q}$	47.6
$pp \to \tilde{q}\ \tilde{q}$	18.9
$pp \to \tilde{g}\ \tilde{g}$	14.7
$pp \to \tilde{C}\ \tilde{N}$	6.1
$pp \to \tilde{C}\ \tilde{C}$	3.0
$pp \to \tilde{t}\ \tilde{t}$	2.9

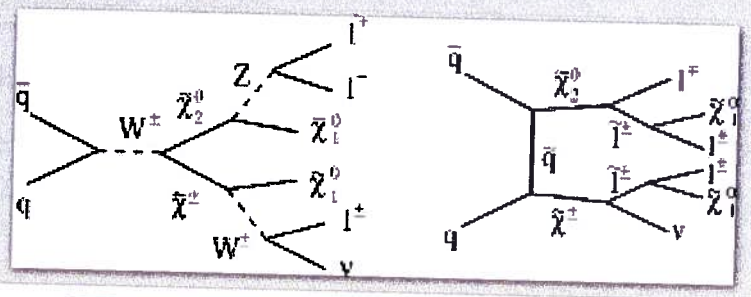
Total cross section:

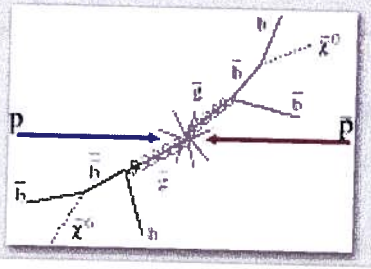
8800 fb

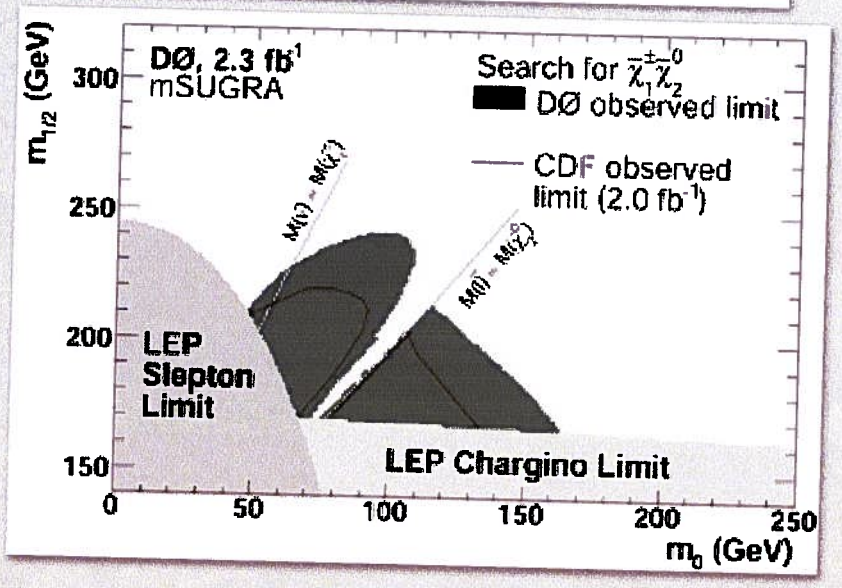
- Signatures
  - Multiple jets
  - Multiple leptons
  - Large missing transverse energy

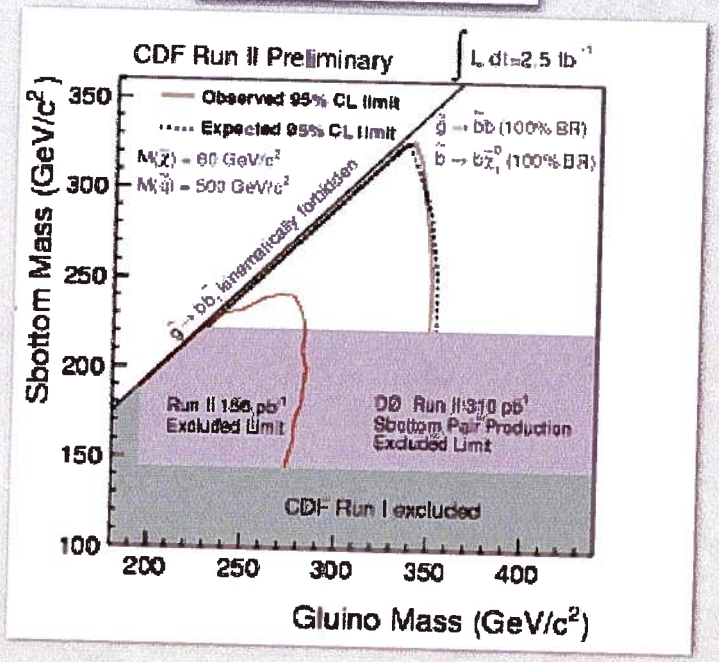
Cornering Supersymmetry

And many other theories for physics beyond the Standard Model





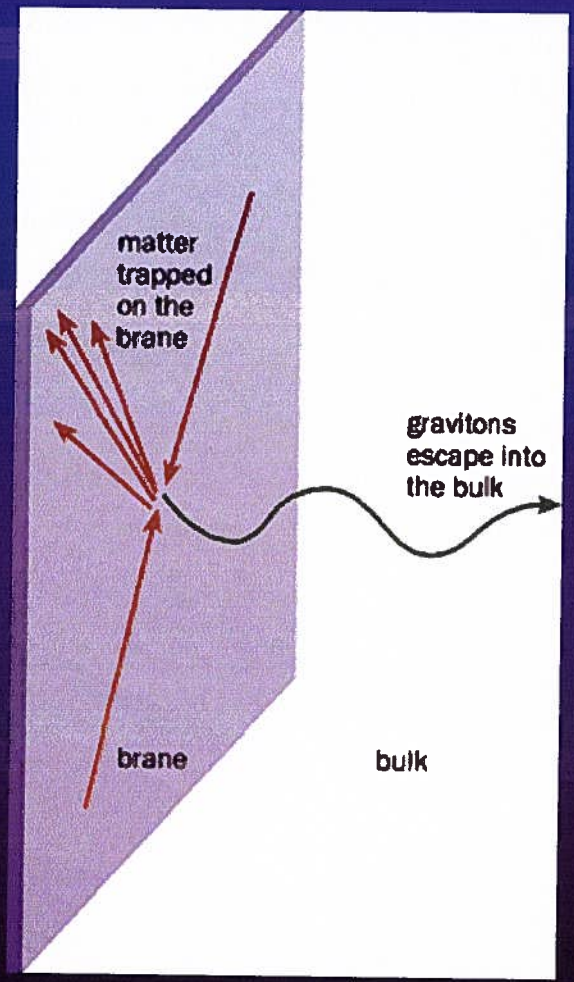




Exclude regions of SUSY masses

Are there Extra Spatial Dimensions?

- Why do we think there might be extra dimensions?
  - String theory needs them
  - They can be used to explain why gravity seems weak to us
  - They would also solve other mysteries of particle physics.
- The extra dimensions are hard to see, for some reason. They might be compact and small. If an extra spatial dimension is compact, coiled up with size R, we would see new massive "Kaluza-Klein" particles m=1/R, 2/R, ...
  - We can produce these at colliders if there is enough energy.
- The extra dimensions could be large, but we are trapped on a 3-dimensional membrane in a higher-dimensional space-time.
  - Only gravity acts in the extra dimensions, which can be of macroscopic size.

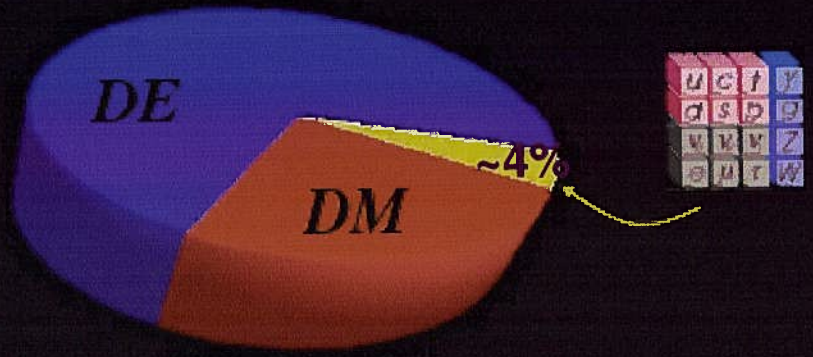


Technicolor (TC)

- New strong interactions of fermions and bosons at ~1 TeV scale
- Causes breaking of electroweak symmetry dynamically
- In its simplest form, TC is a scaled-up version of QCD
- Requires new technicolor particles
  - Technipions, technirho, techniomega, etc.
  - Masses in the range 100 – 200 GeV.
  - None seen yet at the Tevatron.

Other puzzles

"Dark Matter and Dark Energy"

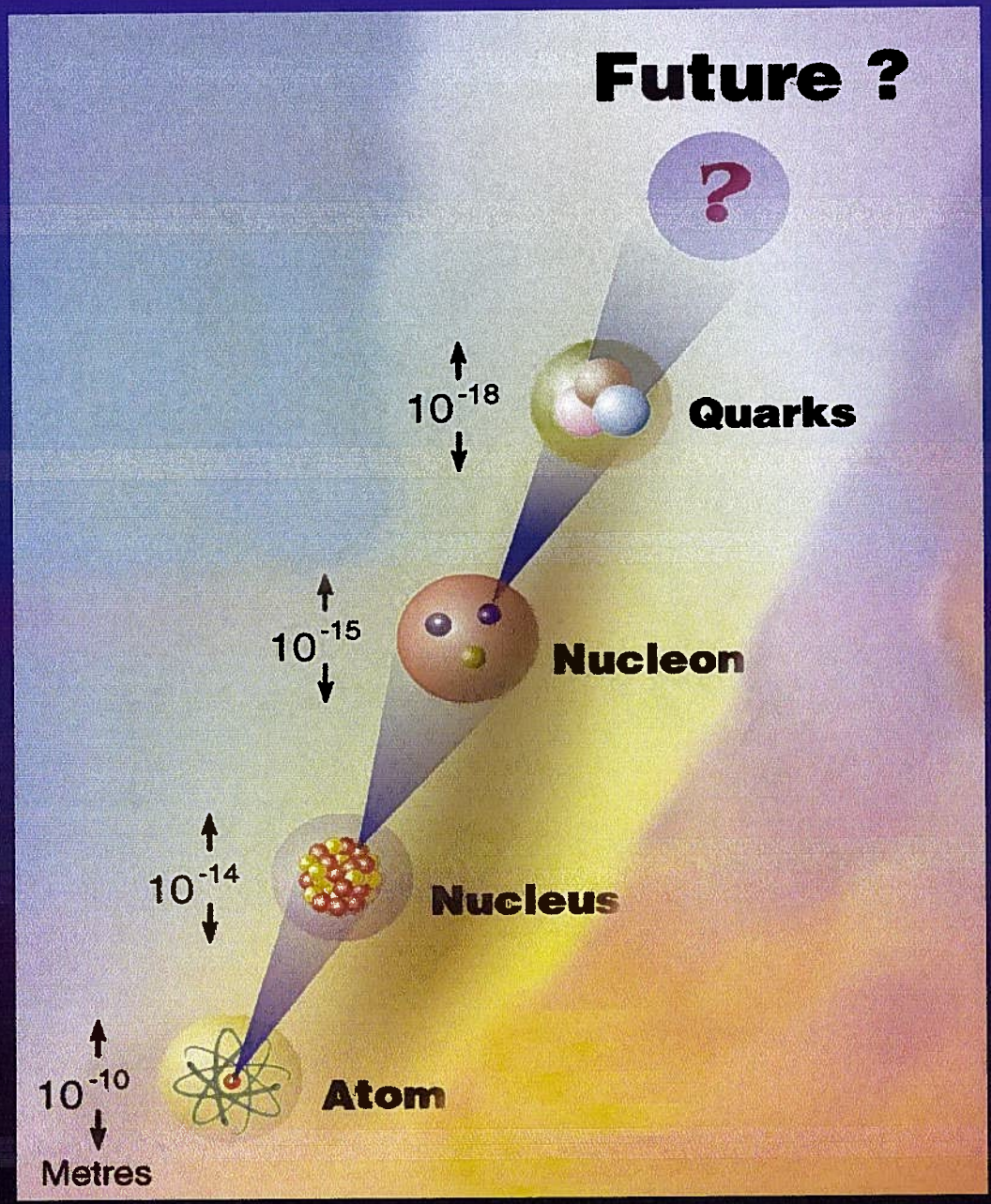


Dark Matter:
Galaxies rotation inconsistent with visible mass

Dark Energy:
The expansion of the Universe is accelerating

Physics [particles] beyond the Standard Model !

96% of the universe is unknown stuff!!!



New physics is expected around the 1 TeV energy scale

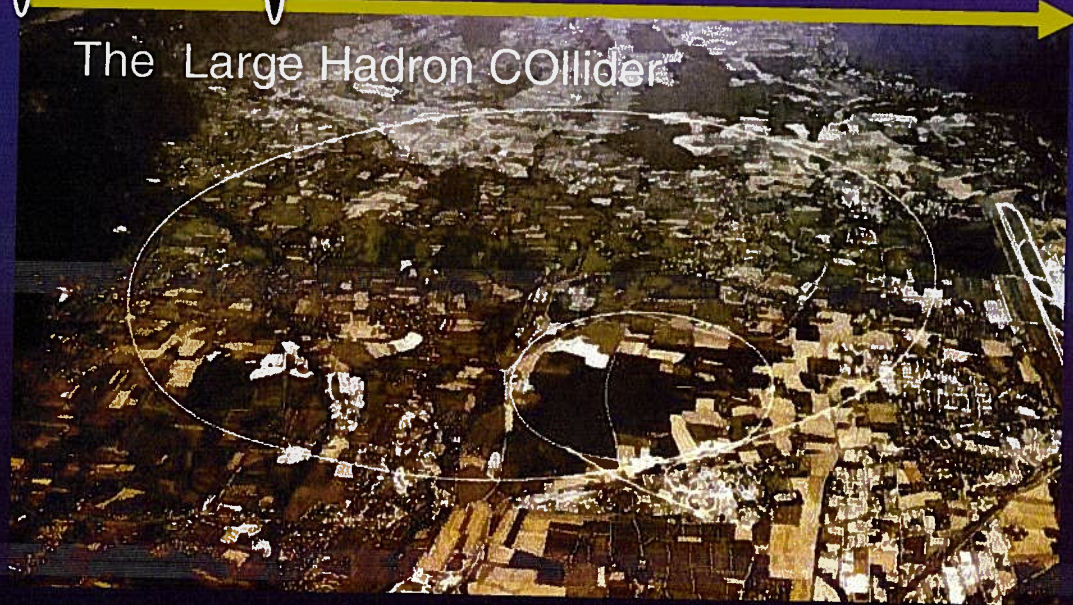
So the Tevatron or the Large Hadron Collider might show us the way

Or the clues may come from the Heavens!

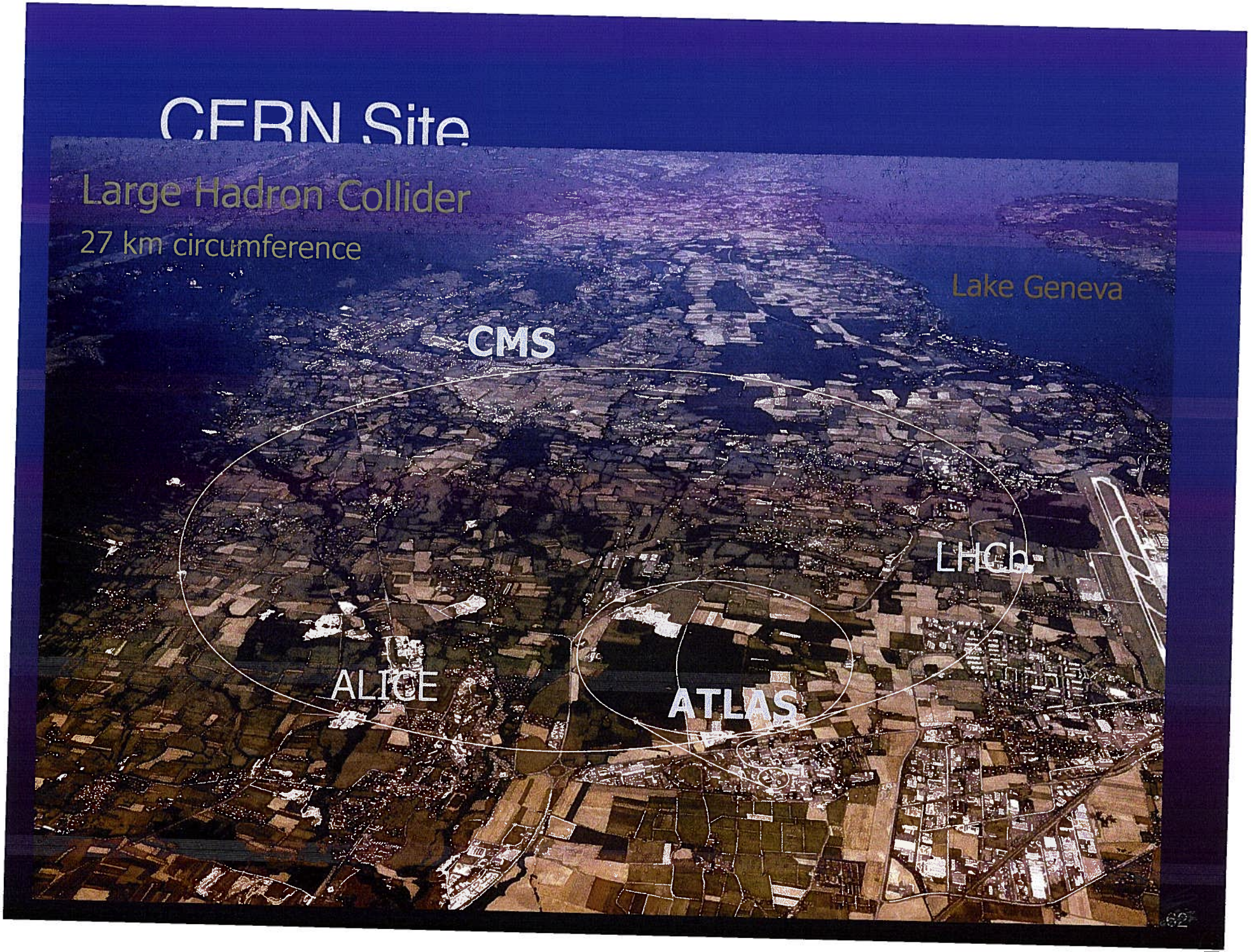
Passing the Torch

Sept '09

The Large Hadron COllider



March 2009


CERN Site
Large Hadron Collider
27 km circumference
Lake Geneva
CMS
LHCb
ALICE
ATLAS