Beyond the Standard Model

M. Cobal

Grand Unified Theories

In this section we will cover the following topics:

- Standard Model Summary
- Unanswered Questions
- Beyond the Standard Model
- Grand Unified Theories (GUTs)
- Leptoquarks
- Proton Decay
- Successes and Failures of GUTs

- The Planck Scale
- Quantum Gravity
- Supergravity
- String Theories
- Extra Dimensions
- Superstring Theory

Standard Model Summary

Particles

1. Spin $\frac{1}{2}$ fermions and antifermions
   (a) 3 generations of quarks (u, d) (c, s) (t, b)
   (b) 3 generations of leptons (e^-, ν_e) (μ^-, ν_μ) (τ^-, ν_τ)
   + their antiparticles
2. Spin 1 gauge bosons
   (a) 1 massless electroweak boson γ
   (b) 3 massive electroweak bosons W^+, W^-, Z^0
   (c) 8 massless gluons g
3. Spin 0 Higgs boson H^0

Interactions

1. The electromagnetic with coupling e
2. The weak interaction with coupling G_F

} unified electroweak with coupling g and g'

3. The strong interaction with coupling α_s

Unanswered Questions

The Standard Model makes many predications - most of which have been tested to very high precision e.g. at LEP such as the branching rations of the Z^0 into various quarks and leptons.

The Standard Model does not predict:

- The values of the coupling constants e, g, g', α_s
- The masses of the quarks and leptons

Other questions:

- Why there are 3 generations not 1?
- Is there a relationship between the strong and electroweak forces?
- Is there a relationship between quarks and leptons? i.e. why do the proton and electron have exactly opposite electric charges but are so different in their properties.
- What is the origin of CP violation?
- What about Gravity?

UNIVERSITÀ DEGLI STUDI DI UDINE
hic sunt futura

Increasingly General Theories

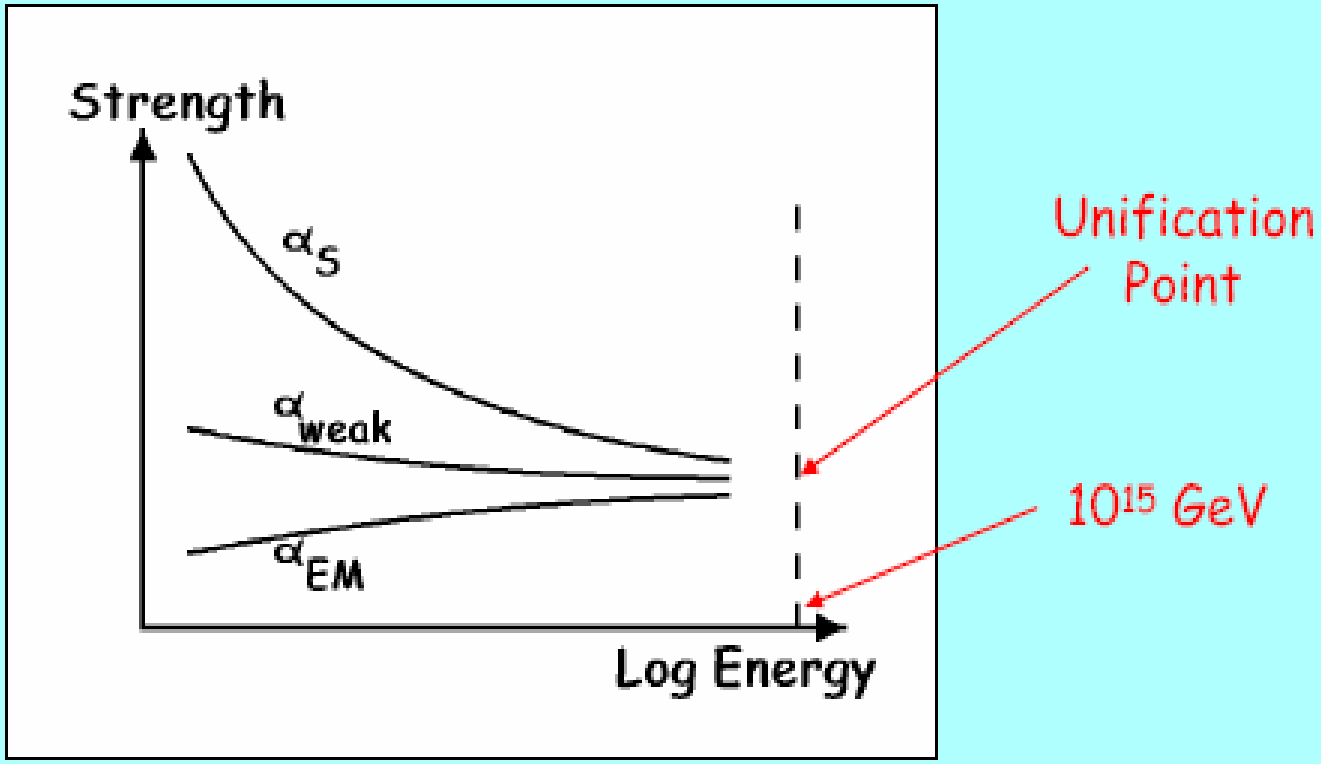
- Grand Unified Theories of electroweak and strong interactions
- Supersymmetry
- Superstring Theories – 10 dimensions with gravity
- Superstring Unification to M Theory

Running Coupling Constants

- Charged particles have virtual quantum allowed clouds around them of photons and electron-positron pairs.
- Colored particles have virtual gluons and q-anti-q pairs.
- So the total coupling at long distance or "charge", is different from the coupling at short distance, where the the cloud is penetrated.
- Electromagnetic coupling α_{em} increases with energy from 1/137 to 1/40 at 10^{17} GeV Unification Scale
- Strong coupling α_s decreases from ~1 to 1/40
- So **couplings come together at unification scale**

Grand Unified Theories (GUTs)

The running coupling constant for electromagnetism α_{EM} increases while that for the strong interaction α_S decreases with energy.



The couplings come together at the so called Unification mass $\sim 10^{15}$ GeV/c^2 → one constant α_{GUT}.

UNIVERSITÀ DEGLI STUDI DI UDINE

hic sunt futura

Fundamental Particles

- Unification: @ GUT scale, where masses can be ignored, all fundamental particles appear in the same multiplet.

- This allows their charges to be the same or given fractions of each other, and accounts for the proton and electron charge being equal.

- The particles from the SM to include for the first generation are **16** (left handed):

  u_r u_g u_b d_r d_g d_b, ν_e , e^- , and their anti-particles

- In the GUT, there are vector bosons that take fundamental particles into another in the multiplet.

Grand Unified Theories

At this energy everything would be highly symmetric.

All masses and couplings would be the same.

This symmetry is broken at lower energies to give the different masses and couplings we see.

A liquid (high energy) is symmetric and looks the same from all directions - as it freezes (low energy) it loses that symmetry and crystals form with preferred directions.

Current theories are associated with certain 'groups' which obey the mathematics of group theory.

The EM group U(1) has 1 electric charge → 1 gauge boson (γ).

The QCD group SU(3) has 3 colour charges → 8 gauge bosons (gluons)

The simplest GUT is labelled SU(5) and has 24 gauge bosons.

Grand Unified Theories

We have 12 so far:

$$\gamma,\ W^+,\ W^-,\ Z^0 + 8 \text{ gluons}$$

Add 3 with electric charge $-\frac{1}{3}$ in 3 colours red, green and blue:

$$Y_R,\ Y_G,\ Y_B$$

and 3 with electric charge $-\frac{4}{3}$:

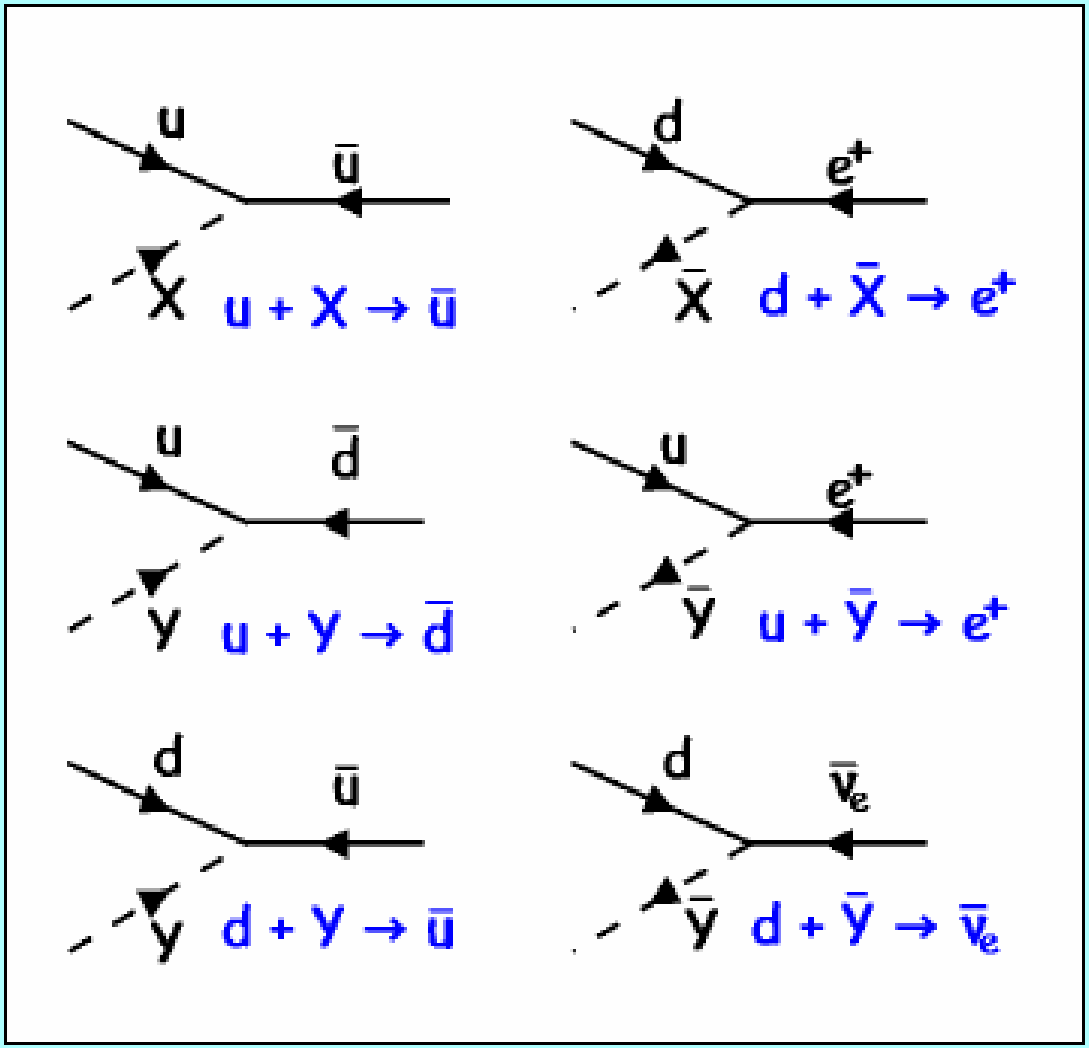
$$X_R,\ X_G,\ X_B$$

plus 6 antiparticles.

These are called leptoquarks and can change quarks into leptons and quarks into antiquarks and vice-versa.

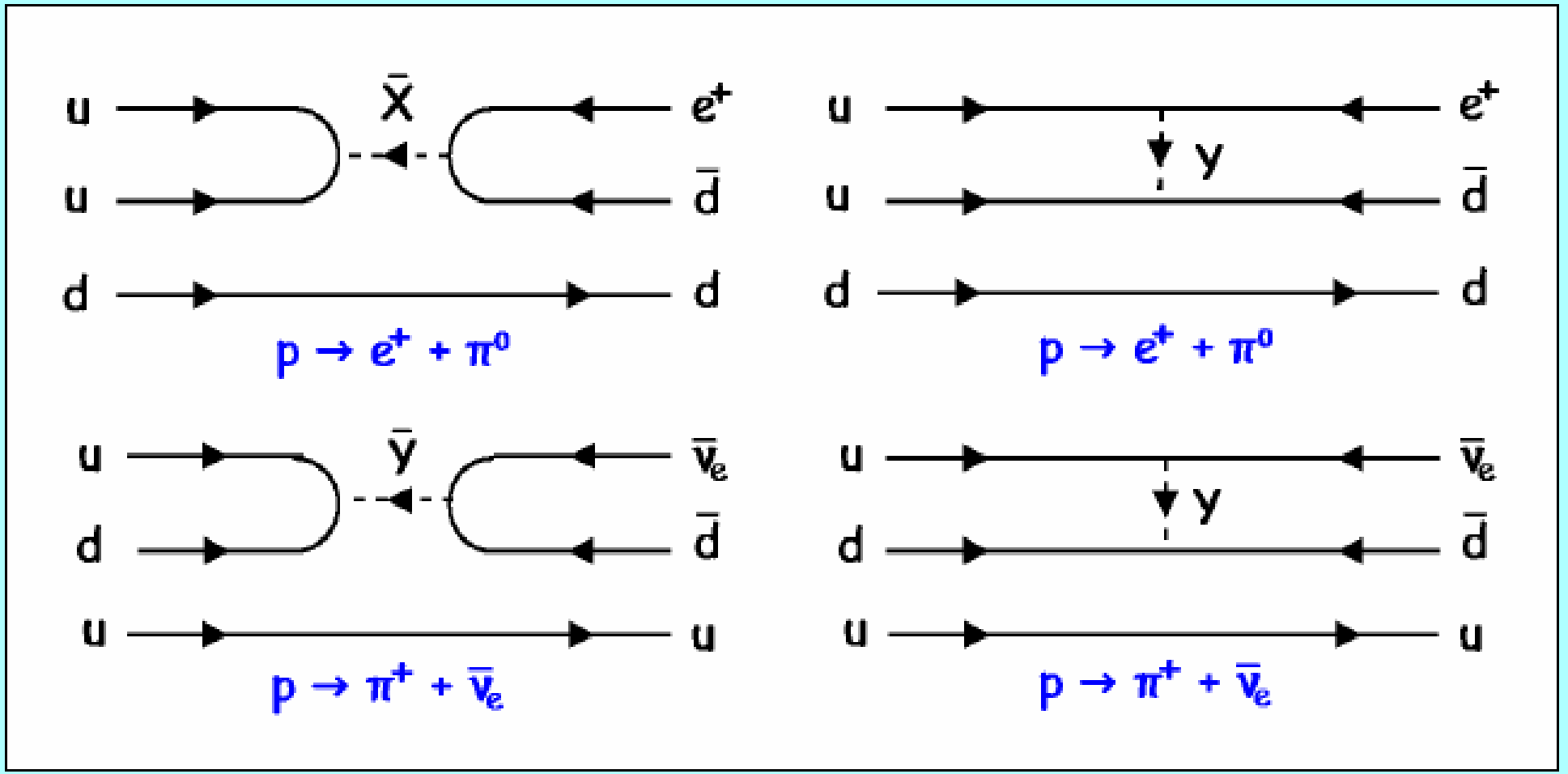
They violate lepton and baryon number conservation but B - L is still conserved.

Leptoquarks



These would lead to proton decay to mesons and leptons.

Proton Decay



The 'π' can be other mesons by adding quark lines.

Proton Decay

One can calculate the proton lifetime in the GUT Model.

The coupling α_{GUT} is the value at which the 3 running coupling constants meet.

The masses of the X and Y particles is assumed to be around the energy at which they meet → $M_{X,Y} \sim 10^{15}$ GeV/c^2.

This gives a proton lifetime between 2×10^{28} and 6×10^{30} years.

Current measurements give > 10^{31} to 10^{32} years depending on the decay mode.

Prediction is clearly wrong.

Successes & Failures

Successes of SU(5) GUTs

- Unifies EM, Weak and Strong Interaction.
- Explains relationships between quarks and leptons and their charges.
- Predicts the correct value for the weak mixing angle θ_W.

Failures

- Does not explain number of generations.
- Predicted proton decay not seen!
- Also predicts Magnetic Monopoles which carry magnetic but not electric charge – long predicted but never seen

GUTs are not a strong contender these days.

Depressing part – no new physics between 100 GeV and 10^{15} GeV.

UNIVERSITÀ DEGLI STUDI DI UDINE
hic sunt futura

A Bit of History of Unification

- Electricity unified with magnetism (M. Faraday and J. C. Maxwell).
- Relativity and General Relativity (A. Einstein).

- Quantum Mechanics (Planck, Bohr, Schrodinger and Heisenberg).
- Relativistic quantum mechanics (P. Dirac).
- Quantum Electrodynamics (R. Feynman, Tomonaga, Schwinger).
- Quarks and Quantum Chromodynamics (Nemann, M. Gell-Mann and G. Zweig).
- Unification of Electromagnetism with Weak Interactions to form Electroweak theory (S. Weinberg, A. Salam).

- Grand Unified Theories
- Supersymmetry
- Superstring Theory of Everything including gravity.

Particle Supersymmetry

- In a Grand Unified Theory, all quarks and leptons are in a generation are united into one family.
- The GUT gauge bosons transform one quark or lepton to another, such a gluon changing one color quark into another.
- Another symmetry would be to transform all gauge bosons to fermions with the same charges, and vice versa.
- Thus for every spin $\frac{1}{2}$ fermion there would be a spin 0 boson with the same charges and flavor, and to every gauge boson, there would be a like charged and coupled spin $\frac{1}{2}$ fermion.
- These look-alikes, except for spin, are called sparticles.

UNIVERSITÀ DEGLI STUDI DI UDINE

hic sunt futura

Conserved Supersymmetry

- If supersymmetryness is conserved, sparticles can only be created or destroyed in pairs
- Sparticles would then decay to the ordinary particles plus another sparticle, until they reach the lightest supersymmetric particle (LSP)
- The LSP should be neutral and is a leading dark matter candidate
- They should have masses about 1 TeV
- They should be produced in pairs at the LHC

Sparticle Names

- Thus with quarks there would be spin 0 squarks. Leptons would have spin 0 sleptons (selectron and sneutrino)
- The photon also would have a spin $\frac{1}{2}$ photino
- The W's and Z's would have spin $\frac{1}{2}$ Winos and Zinos (after Wess and Zumino)
- Spin 0 Higgs would have spin $\frac{1}{2}$ Higgsinos
- In a supergravity theory, spin 2 gravitons have spin 3/2 gravitino look-alikes.

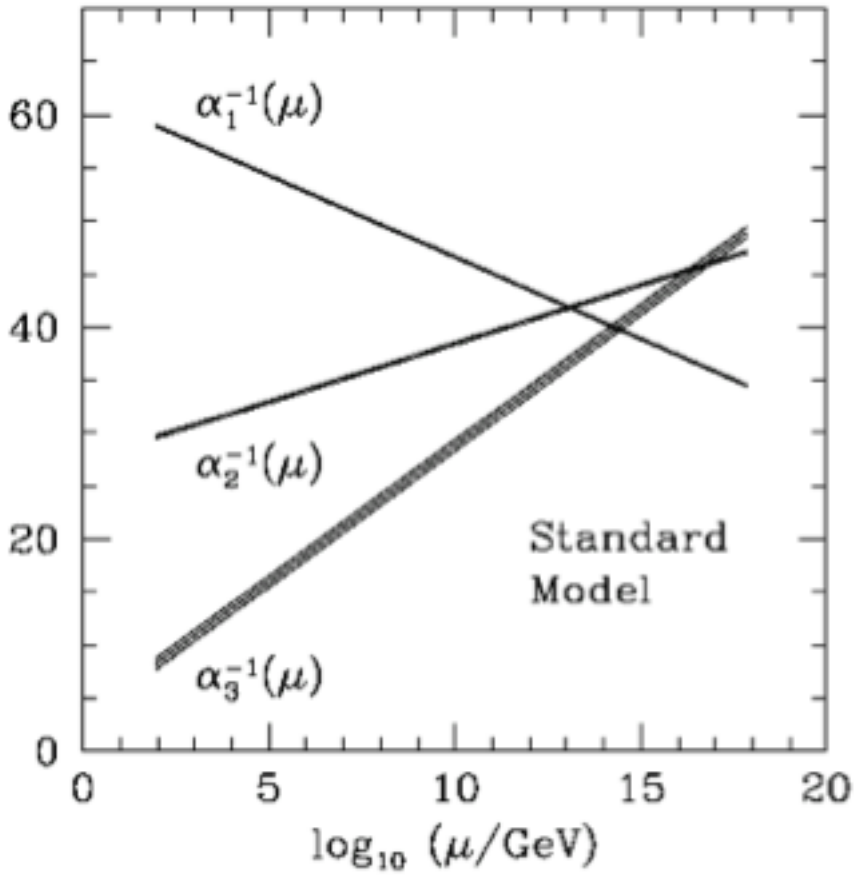
UNIVERSITÀ DEGLI STUDI DI UDINE
hic sunt futura

Why Supersymmetry (SUSY)?

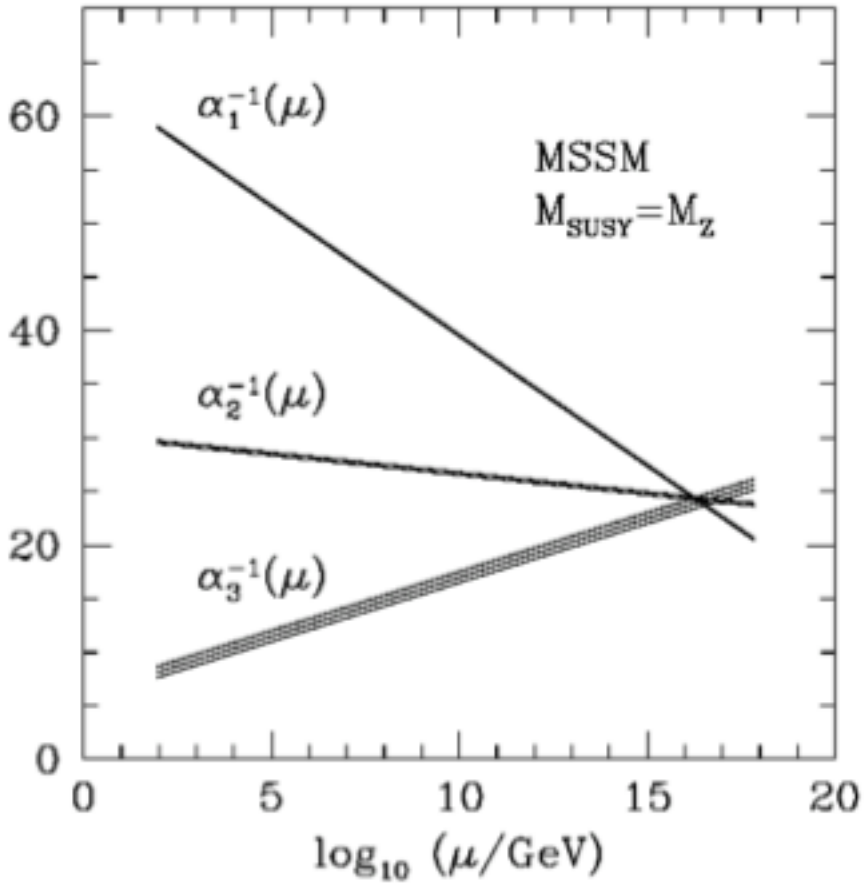
- It's believers think it is a beautiful symmetry between fermions and bosons, and should be a part of nature.
- If the sparticles are at about 1 TeV, then the running coupling constants actually do meet at a GUT scale of 10^{17} GeV.
- GUT scale (mass) Higgs's would normally couple to the light SM Higgs and bring its mass up to the GUT scale.
- Adding sparticles to particles cancel this coupling to leave the SM Higgs light, solving the so-called Heirarchy problem.
- String Theory requires SUSY, again for similar cancellations.

UNIVERSITÀ DEGLI STUDI DI UDINE
hic sunt futura

Evolution of Gauge Couplings



Standard Model



Supersymmetry

UNIVERSITÀ DEGLI STUDI DI UDINE
hic sunt futura

Minimal SUSY Standard Model

- The MSSM has two Higgs doublets, as opposed to the one in the standard model.
- The doublets also have distinct anti-Higgs.
- Thus there are 8 Higgs particles.
- Three are "eaten" to make the $W^{\pm}$ and Z massive.
- One makes the neutral mass generating Higgs.
- Four more are observable, of which two are charged.

The Planck Scale

The Gravitational Constant $G = 6.7 \times 10^{-11}\ m^3 kg^{-1} s^{-2}$ (SI).

Other fundamental constants are:

$$\hbar = 1.05 \times 10^{-34}\ Js\ (kg\ m^2 s^{-1})$$

$$c = 3 \times 10^{8}\ m\ s^{-1}$$

so $G\hbar = 7.04 \times 10^{-45}\ m^5 s^{-3}$ ← Divide by c^3 to get rid of the seconds

$$\therefore G\hbar/c^3 = 2.61 \times 10^{-70}\ m^2$$

$$\therefore (G\hbar/c^3)^{\frac{1}{2}} = 1.6 \times 10^{-35}\ m$$

This is the only combination of fundamental constants involving G that gives a length.

→ 'Planck length'

Quantum Gravity

How do we make a quantum theory of gravity?

In analogy with other interactions:

field $\rightleftharpoons$ exchange of quanta

Postulate that gravitational field arises through exchange of 'gravitons' between masses (energy).

Because gravity has a $1/r^2$ dependence and infinite range like electromagnetism:

→ graviton must be massless

Quantum Gravity

Spin of exchanged particle has significant effect on force.

Spin 2 gives an attractive force.

The field equations of a massless spin 2 particle ≡ components of 4 dimensional curved space-time.

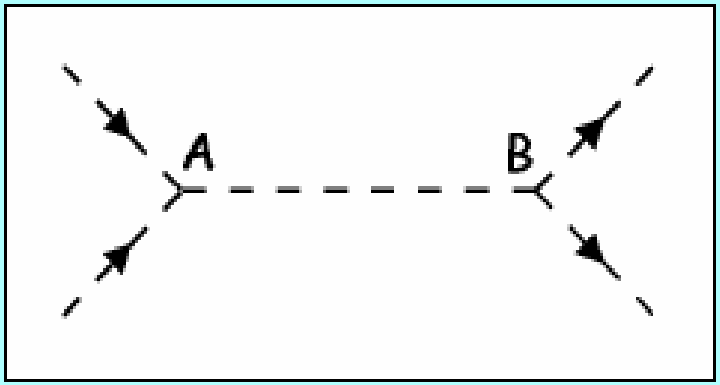
Assume graviton is spin 2.

Since gravitons have energy they can interact and scatter off each other as well as on ordinary matter.

Unfortunately attempts to calculate scattering cross sections lead to problems.

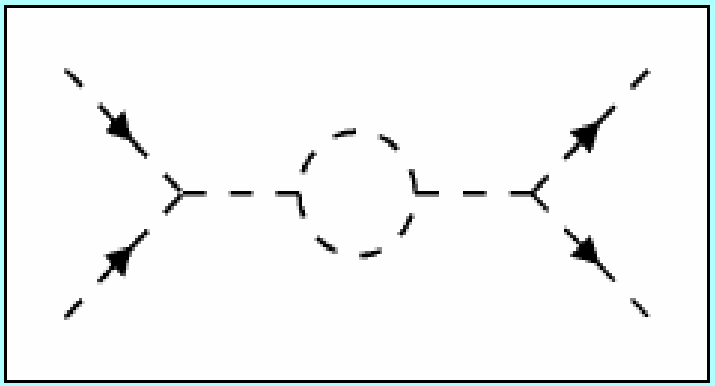
Quantum Gravity

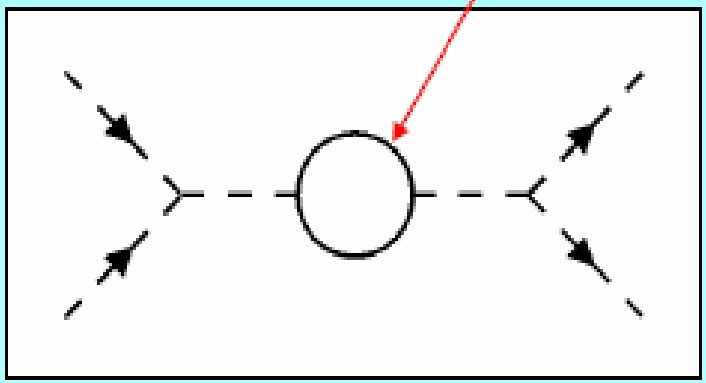
2 incoming gravitons combine at A to give a third that travels to B before splitting into a pair



OK gives a finite answer

But higher order diagrams have to be added which lead to infinite cross sections:



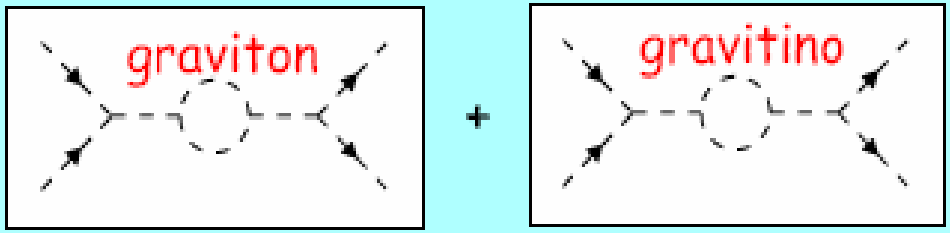


Not easy to construct a consistent, renormalizable (no infinities) quantum theory of gravity.

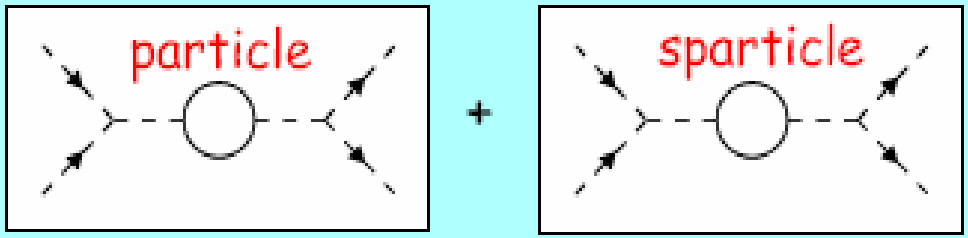
Supergravity

Supersymmetry helps.

The supersymmetric partner of the graviton, the gravitino with spin $\frac{3}{2}$ can form similar loops and cancel them out:



Similarly the SUSY partners can be used to cancel the matter loops:



→ Supergravity

Still problems so although supergravity may be a component of the final theory it is not the fundamental theory of physics.

UNIVERSITÀ DEGLI STUDI DI UDINE

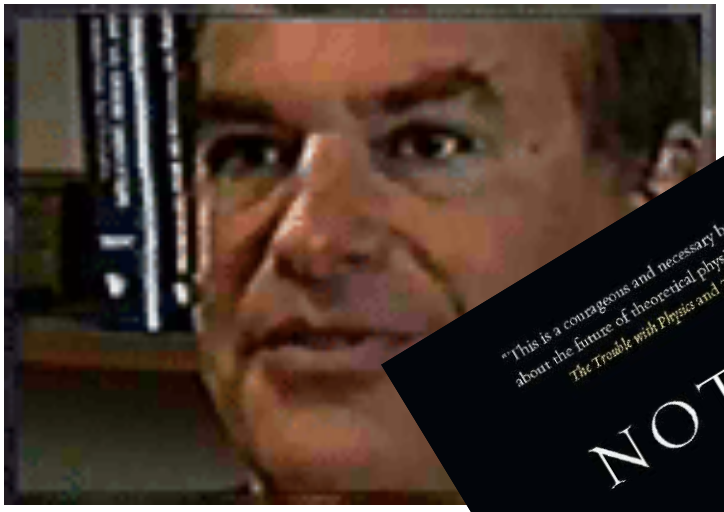
hic sunt futura

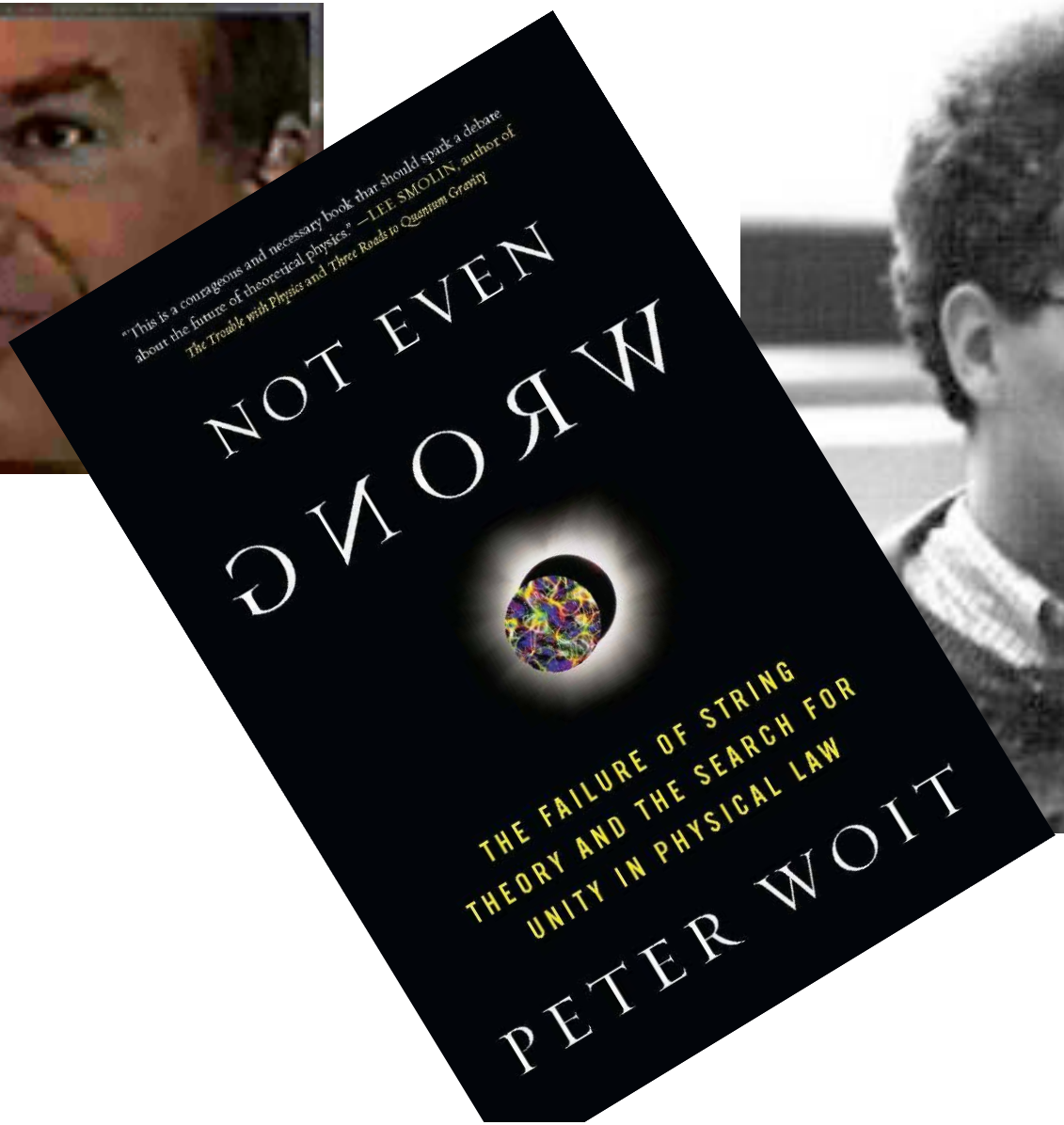
What is String Theory?

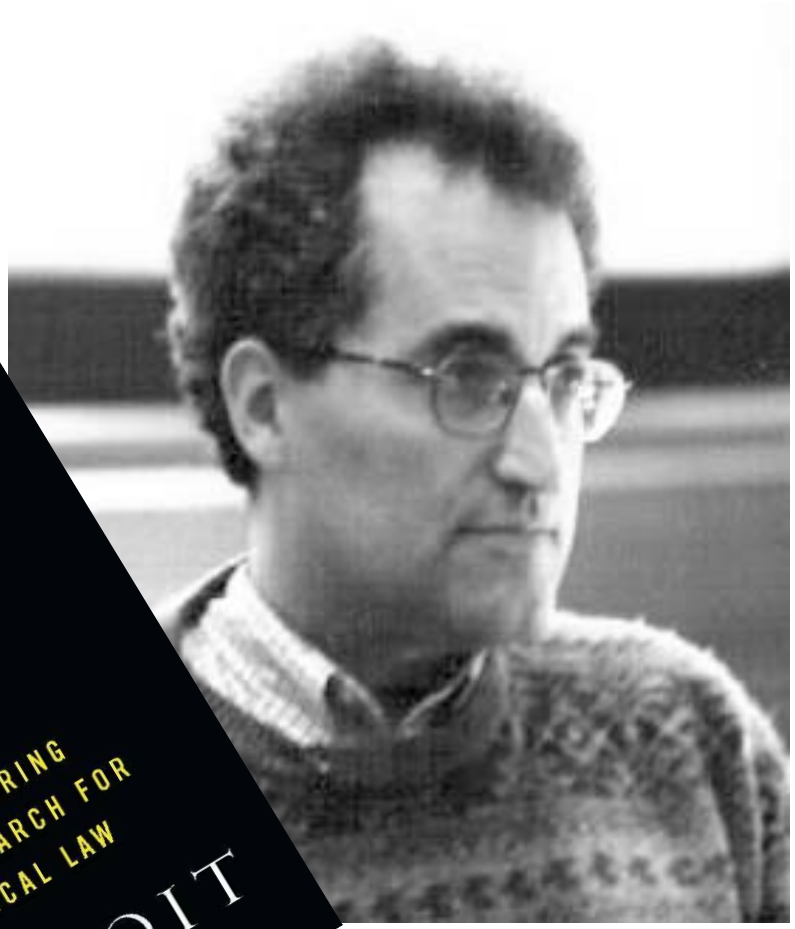
- It is the theory that elementary particles are really strings with tension, that obey relativity and quantum mechanics.
- By dispersing the particle away from a point, it avoids infinities in the treatment of gravity or gravitons by pointlike particles.
- The string size is close to the Planck size of 10^{-32} cm, which is the smallest size where gravity becomes strong.
- To avoid "anomaly" infinities requires supersymmetry and 10 dimensions (1 time and 9 space dimensions).
- String theory then provides a quantum theory of gravity.
- Andre Neveu, John Schwarz, Michael Green and Pierre Ramond were founders.

UNIVERSITÀ DEGLI STUDI DI UDINE
hic sunt futura

John Schwarz and Ed Witten



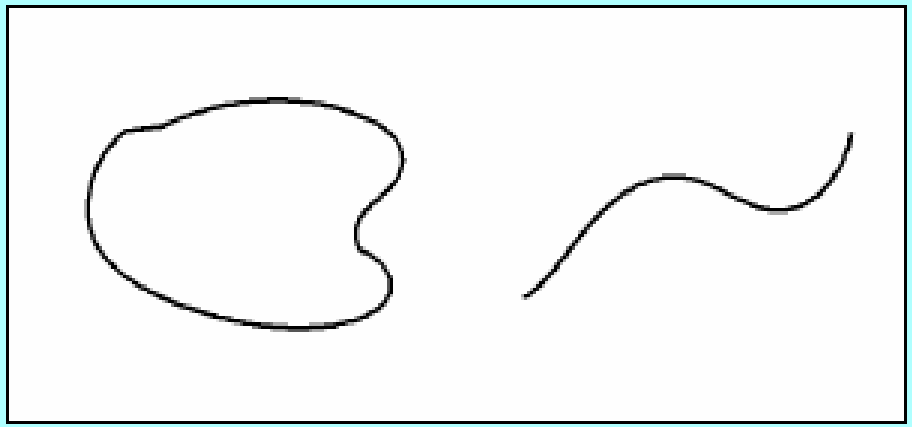




String Theories

String theory is based on the idea that the fundamental particles are not pointlike but string-like.

Particles can be closed or open strings:



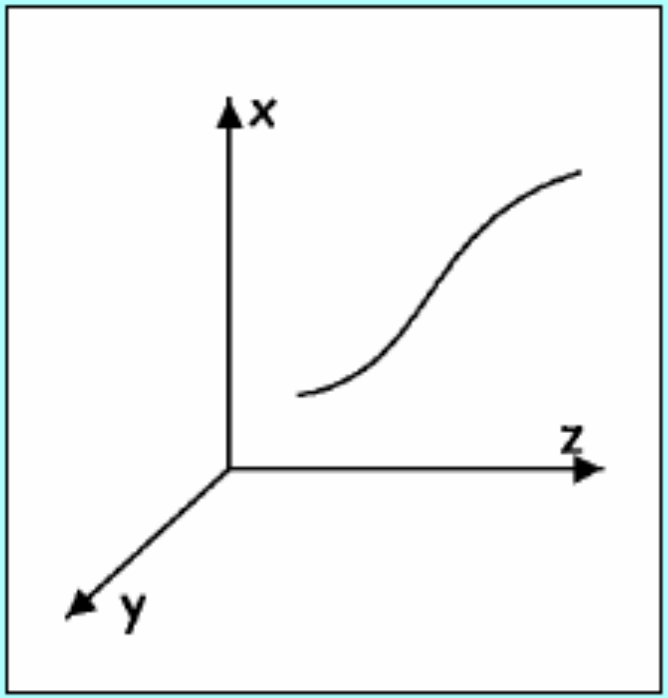
The theory is formulated in a space of ten or more dimensions!!

This idea is based on work by Kaluza and Klein in 1920s.

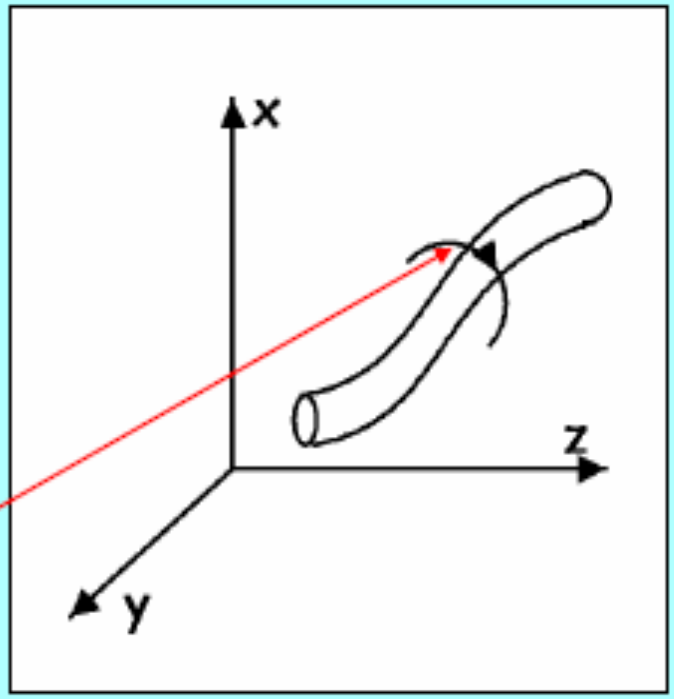
Extra Dimensions

They added a fifth dimension to the regular three space + one time dimensions.

This 5th dimension is 'curled up' and has no effect on normal physics.



look very much closer



Normally see a line with 3 space + 1 time dimensions.

At magnification of ~10^{29} see a pipe with 5th dimension.

Extra Dimensions

Can define a field in this 5 dimensional space which in 4 dimensions looks like:

(a) The field equations of General Relativity

(b) Maxwell's Equations of electromagnetism

This gives a connection between electromagnetism and general relativity (gravity).

There were some problems so this was not pursued at the time.

Interest now revived and extended to more dimensions.

UNIVERSITÀ DEGLI STUDI DI UDINE

hic sunt futura

Towards Verification of Superstring Theory

- Since superstring theory included the three unified forces of GUTS and gravity, it has been called the Theory of Everything.
- It has not been possible to "solve" superstring theory to find a unique physical model.
- There are a half-million ways to topologically "compactify" the extra six dimensions to very short distances, and leave the four dimensional world that we live in.
- So many GUTS and breakup paths of GUTS to the SM are still possible

UNIVERSITÀ DEGLI STUDI DI UDINE
hic sunt futura

Superstring Theory: verification

- The masses of sparticles are not well predicted.
  - If they are in the TeV range, they will appear in the LHC.
  - Once they are found, the NLC e+ e- collider will more precisely determine their properties.
- The convergence of the running coupling strengths at a GUT scale is more successful with SUSY particles than in SM.
- If SUSY is found, it will be considered a success of string theory. If not found, it could spell its demise.
- The lightest neutral SUSY particle (LSP) could be dark matter, and there are experiments to directly detect them, but they will take a while to reach large enough scale.