

Dark matter

Experimental evidence for the **Big Bang** model is:

- A nearly uniform distribution of matter in the universe.
- The universe expands.
- The cosmic background radiation which has a temperature of 2.7 K (0.0002 eV).
- An abundance of light elements (He, D, Li)

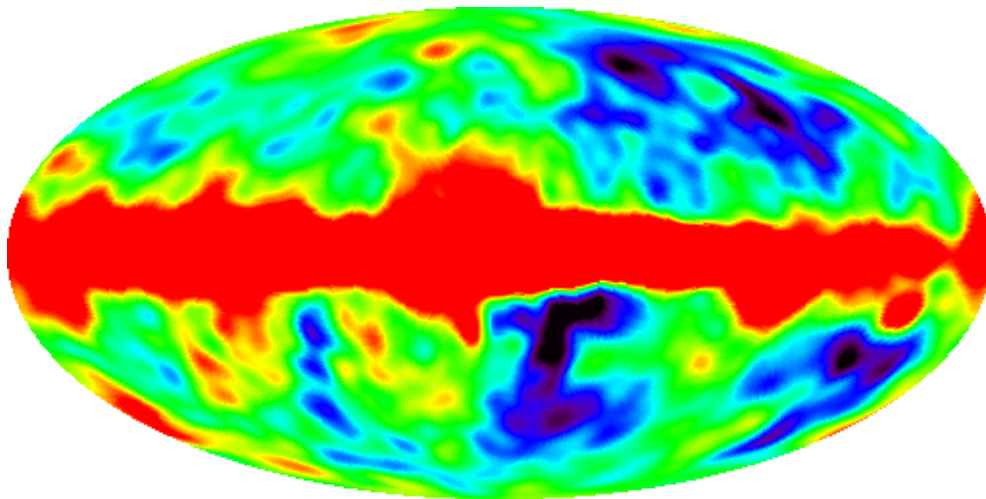


Figure 141: Sky as seen at microwave frequencies by the COBE satellite. Red (hottest) and blue (coldest) regions differ by only 0.0002 K while the overall temperature is 2.7 K

- If the density of the universe is smaller than the critical density, the expansion of the universe will continue for ever.

The critical density: $\rho_c = \frac{3H_0^2}{8\pi G} = O(10^{-26}) \text{ kg m}^3$

Where H_0 is the **Hubble constant** and G is the gravitational constant.

In the **inflationary Big Bang model**, the density of the universe is estimated to be close to the critical density:

$$\Omega \equiv \rho / \rho_c = 1$$

Where Ω is called the **relative density**. However, the observable (i.e. emitting electromagnetic radiation) matter in the Universe give only $\Omega_L \approx 0.01$

→ The rest is called “**dark matter**”

Possible components of the dark matter:

- a) *Baryonic matter* that emit little or no e.m. radiation: brown dwarfs, small black holes – **MACHO's** (for MAAssive Compact Halo Object). There is evidence that $\Omega_B \approx 0.06$ only.
- b) If **neutrinos** have a mass $> 1\text{eV}$ they would make a significant contribution to the density of the universe (“*hot dark matter*”). It is, however, difficult to explain how the galaxies have formed if neutrinos are the dark matter.
- c) “*Cold dark matter*”: **WIMP's** (Weakly Interacting Massive Particles), non-baryonic objects, non-relativistic at the early stages of the evolution of the universe.

The search for WIMPs

- ❖ **Interactions** between WIMPs and matter are very **rare**. About one WIMP per day is expected to interact in each kg of matter.
- ❖ To minimize the background, the WIMP detectors are installed **deep underground** and surrounded with shielding.
- ❖ The **Boulby experiment** uses a NaI detector which produces scintillation light if a WIMP interacts with an atom. 200 tons of ultra pure water is used as shielding.

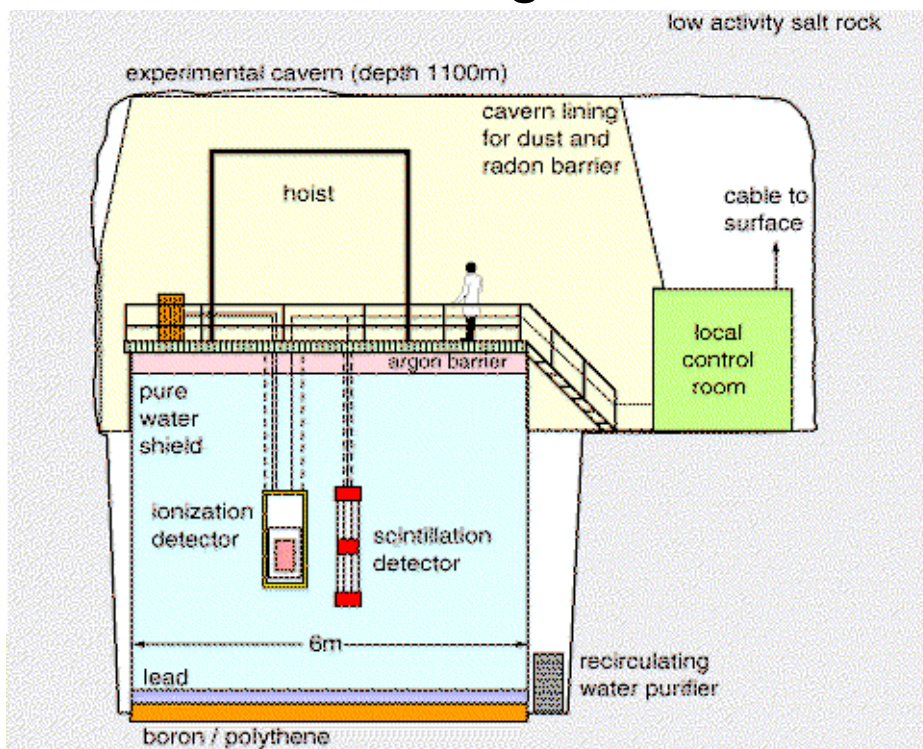


Figure 142: Layout of the Boulby experiment in the UK.

Grand Unified Theories (GUTs)

- Weak and electromagnetic interactions are unified, why not to add the strong one?
- At some very high “unification mass” electroweak and strong couplings might become equal

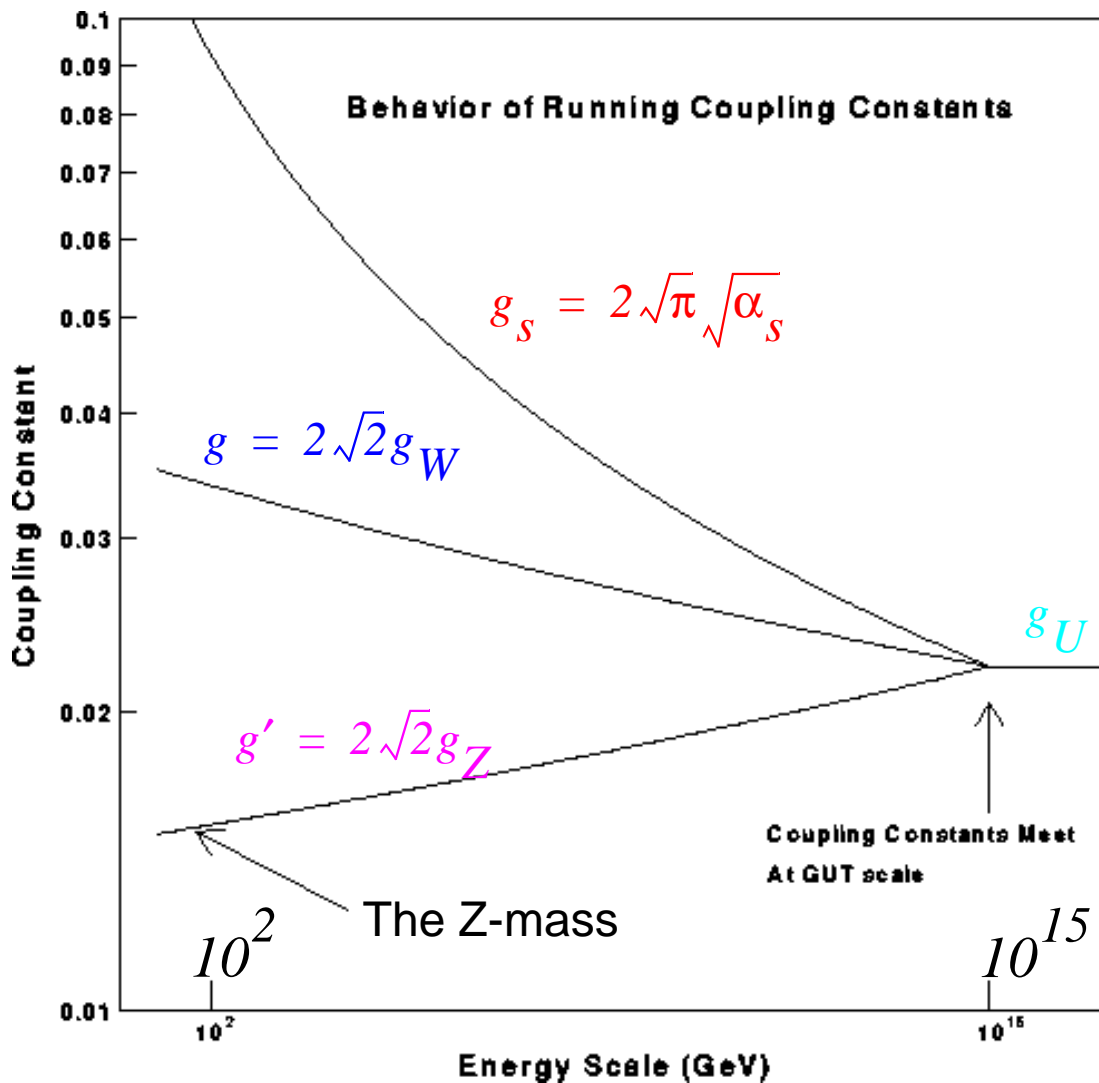


Figure 143: Behavior of the coupling constants in GUT

Grand unified theories can be constructed in many different ways.

❖ The **Georgi-Glashow model** combines coloured quarks and leptons in single families, like

$$(d_r, d_g, d_b, e^+, \bar{\nu}_e)$$

and hence new gauge bosons appear:

X with $Q=-4/3$ and **Y** with $Q=-1/3$, $M_X \approx 10^{15} \text{ GeV}/c^2$:

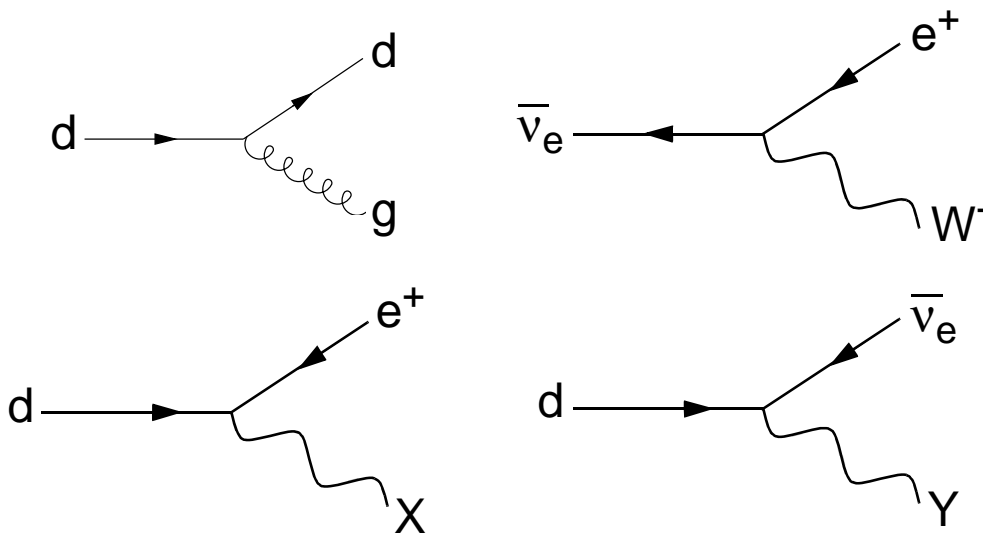


Figure 144: Standard processes together with new ones predicted by GUT

The single unified coupling constant is g_U , and

$$\alpha_U \equiv \frac{g_U^2}{4\pi} \approx \frac{1}{42} \tag{166}$$

→ The Georgi-Glashow model explains why the electron and the proton have the same charge

According to the model the sum of electric charges in any given family must be zero $\Rightarrow 3Q_d + e = 0 \Rightarrow$ the down-quark has charge $-e/3$.

❖ The factor of 3 arises simply from the number of colours

→ This model also predicts the weak mixing angle since it predicts the value of one of the three coupling constants:

$$\sin^2 \theta_W = 0,21 \quad (167)$$

This is close to the measured value of the weak mixing angle.

Proton decay

GUT predicts that the **proton** is **unstable** and that it can decay by a process involving X or Y bosons

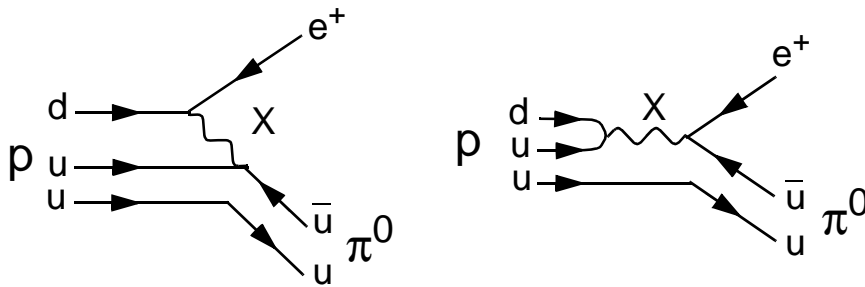


Figure 145: Proton decays in GUT

In processes like those above, baryon and lepton numbers are **not conserved**, but the combination

$$B - L \equiv B - \sum_{\alpha} L_{\alpha} \quad (\alpha = e, \mu, \tau) \quad (168)$$

is conserved.



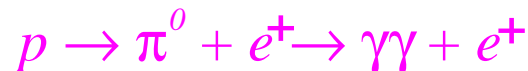
From a simple zero-range approximation, the lifetime of the proton can be estimated to be:

$$\tau_p = 10^{29} \div 10^{30} \text{ years} \quad (169)$$

while the age of the universe is only about 10^{10} years...

❖ Some detectors which are used in neutrino physics (IMB, Kamiokande) are also looking for the proton decays.

❖ The most looked for decay mode is



where the experiments look for one positron and two electron-photon pairs from photon conversions.

❖ No clear examples of proton decays have been observed and the upper limit on the proton lifetime is now:

$$\frac{\tau_p}{B(p \rightarrow \pi^0 e)} > 5 \times 10^{32} \text{ years}$$

❖ The **Georgi-Glashow model** predicts this ratio to be only $0.003 \times 10^{32} - 0.03 \times 10^{32}$ years **in disagreement** with the experiments. Other GUT models, however, predict longer lifetimes.

The cosmic baryon asymmetry

❖ Why are there more baryons than antibaryons in the universe ?

Answer:

1. There was always an excess of baryons (the **baryon number is conserved**).
2. At the time of the Big Bang the universe had zero baryon number. The baryons were produced later (the **baryon number is not conserved** as suggested by GUT).

In the second case it is also necessary that C and CP are not conserved so that more antiparticles can be transformed to particles than vice versa.

Supersymmetry (SUSY)

❖ The most popular GUTs incorporate **supersymmetry** (SUSY) in which the interactions are symmetric under the transformation of a fermion to a boson.

➔ Every known elementary particle has a supersymmetric partner - "superparticle" - with different spin:

Particle	Symbol	Spin	Superparticle	Symbol	Spin
Quark	q	1/2	Squark	\tilde{q}	0
Electron	e	1/2	Selectron	\tilde{e}	0
Muon	μ	1/2	Smuon	$\tilde{\mu}$	0
Tauon	τ	1/2	Stauon	$\tilde{\tau}$	0
W	W	1	Wino	\tilde{W}	1/2
Z	Z	1	Zino	\tilde{Z}	1/2
Photon	γ	1	Photino	$\tilde{\gamma}$	1/2
Gluon	g	1	Gluino	\tilde{g}	1/2
Higgs	H	0	Higgsino	\tilde{H}	1/2

Supersymmetric particles have to be much heavier than their counterparts since they are not observed.

→ SUSY shifts the grand unification mass from 10^{15} to 10^{16} GeV/c², and hence the lifetime of the proton increases:

$$\tau_p = 10^{32} \div 10^{33} \text{ years} \quad (170)$$

which is more consistent with experimental (non)observations.

→ SUSY also predicts a value of the weak mixing angle which is closer to the experimental results.

→ SUSY models even attempts to unify ALL forces, including **gravity**, at the *Planck mass* of order 10^{19} GeV/c² by replacing particles with *superstrings*

→ The lightest superparticles can be candidates for the cold dark matter. Most models introduce a *neutralino* $\tilde{\chi}_0$, which is a mixture of photino, Higgsino and zino.

→ One possibility to look for SUSY at LEP is to search for **selectron production** followed by a decay to electrons and neutralinos:

$$e^+ + e^- \rightarrow \tilde{e}^+ + \tilde{e}^-$$

$$\tilde{e}^+ \rightarrow e^+ + \tilde{\chi}_0 \quad \tilde{e}^- \rightarrow e^- + \tilde{\chi}_0$$

- 1) The **cross section** for producing selectron pairs is comparable with that of producing ordinary charged particles of the same mass
- 2) The **selectrons decay** before they can reach a detector
- 3) **Neutralinos** are virtually **undetectable** due to very weak interaction

The events one is looking for has only final state electrons and these

- a) carry only about half of the collision energy
- b) are not emitted in the opposite directions in the centre-of-mass frame

- ➔ No events with a neutralino signature have been observed.
- ➔ A measurement by DELPHI, using many more searches than slepton searches, set a lower limit on the neutralino mass of 37 GeV:

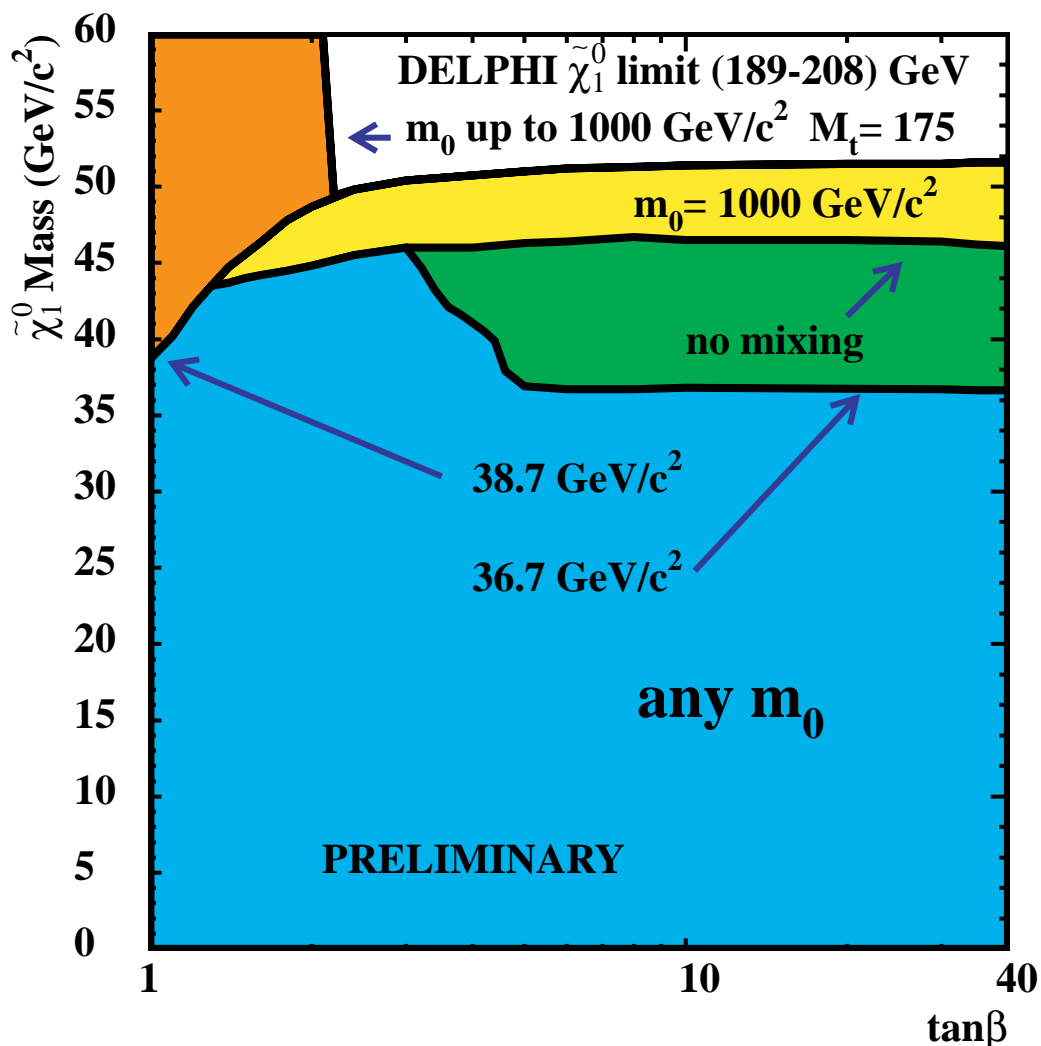


Figure 146: The lower limit on the mass of the lightest neutralino as a function of $\tan \beta$ (the ratio of the vacuum expectation values of the two SUSY Higgs doublets). m_0 is a universal SUSY mass parameter of the sfermions.

Gravitation and extra dimensions

❖ The **gravitational force** is much **weaker** than the electroweak and strong interactions and it has therefore not been studied in particle physics. One has, however, postulated that there exists gravitational force carriers (**Gravitons**) as for the other interactions.

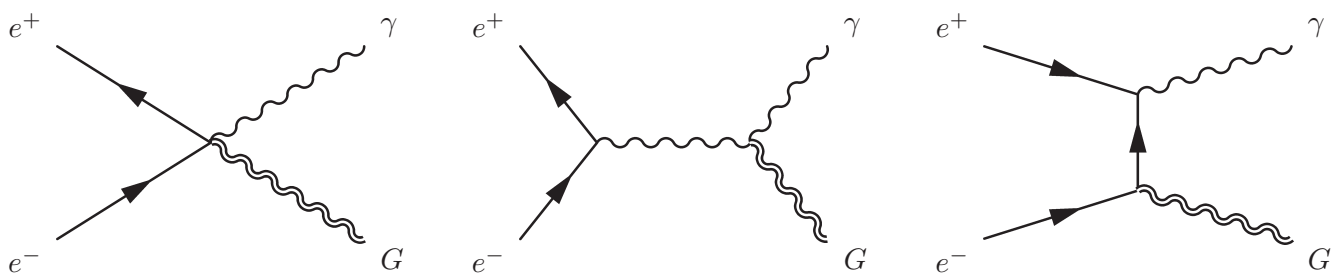
❖ Gravitation has only been studied at large distances (>1 mm) and it could be that it is **stronger at shorter distances**.

❖ In new theories it has been proposed that one can unify gravity with other interactions by introducing **new dimensions** of space (in addition to the normal 3 space + 1 time dimensions) in which **only gravity** can propagate.

❖ If our accelerators could reach the energy scale where gravity is unified with the other forces one could start to see **events** in which **gravitons** are **produced** that escape undetected into the extra dimensions.

❖ If this theory is correct + the unification energy is low then one should be able to produce **events with gravitons and photons** in e^+e^- collisions.

❖ The **cross section** for this process depends on the number of **extra dimensions (n)** and a **fundamental mass scale (M_D)**.



$e^+e^- \rightarrow \gamma G$
 $n = 2$
 $M_D = 0.75 \text{ TeV}$

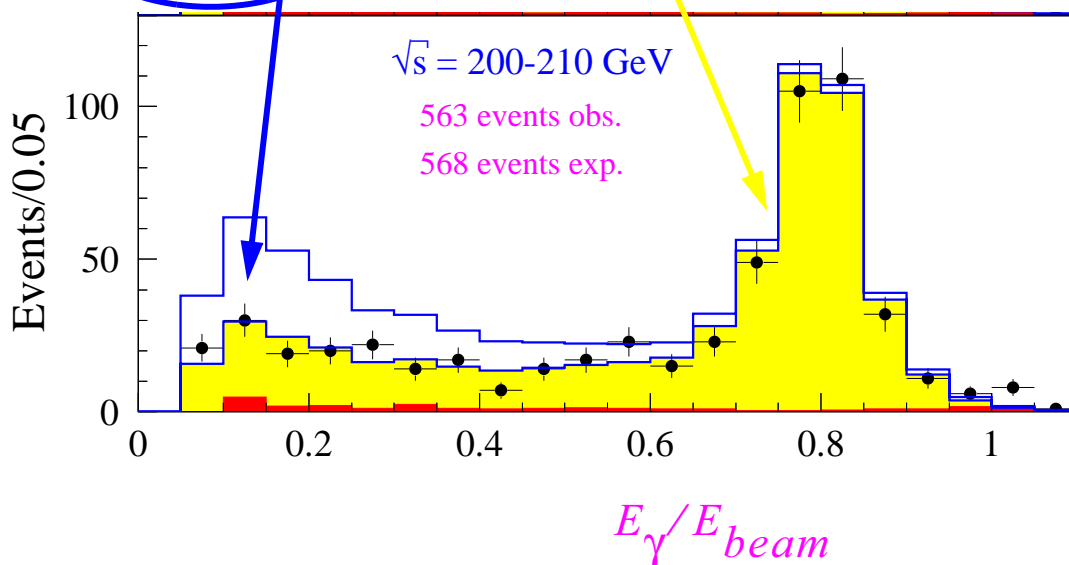
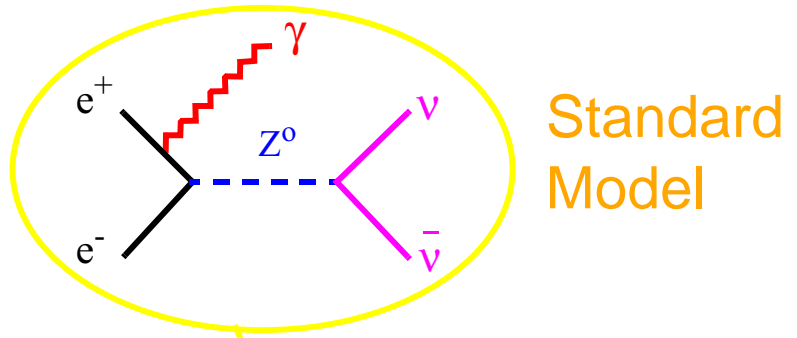


Figure 147: A search for graviton production at DELPHI.

❖ **No** single photon events have been found at LEP which could be interpreted as coming from **Graviton production**. This search for gravitons could, however, be used to set limits on the fundamental mass scale M_D .

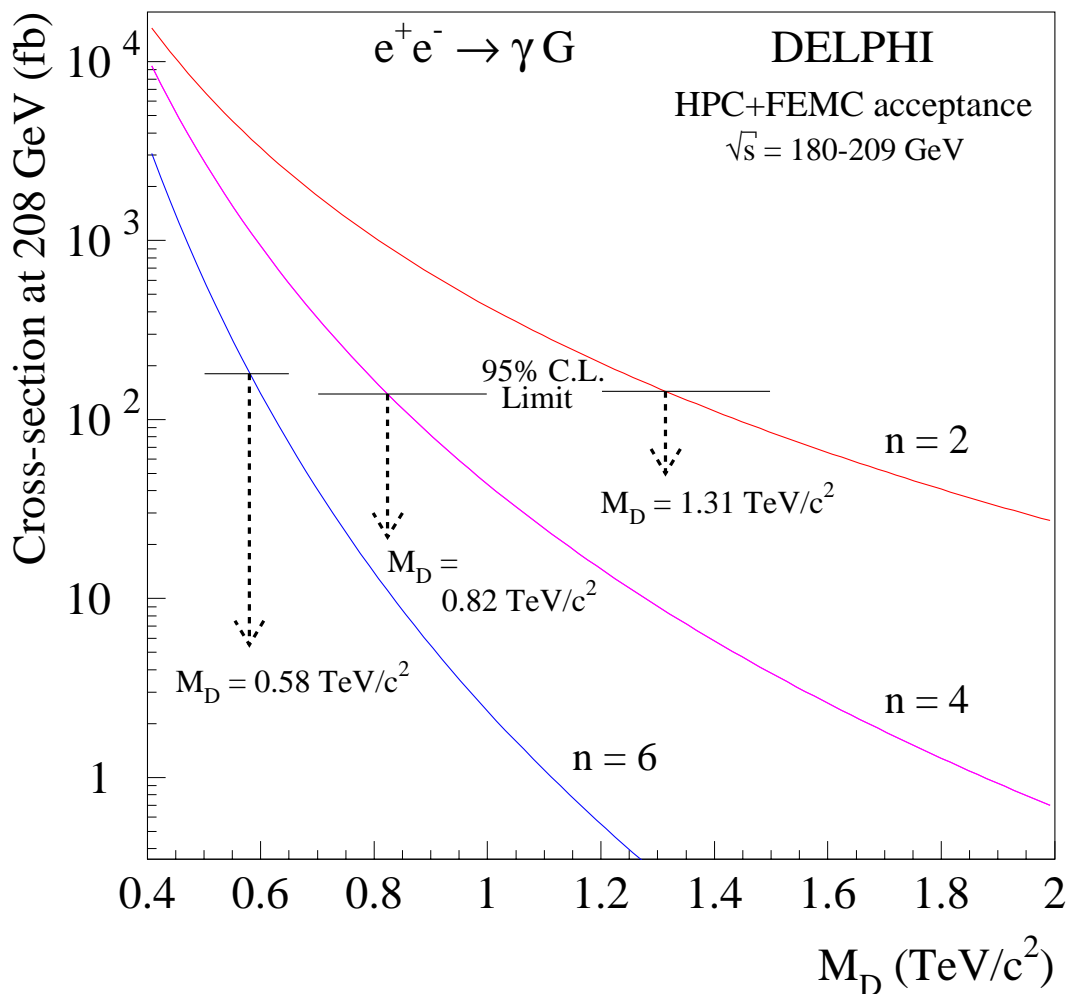


Figure 148: The expected cross section for graviton + photon production at LEP and the limits obtained by the DELPHI experiment.

➔ The result from DELPHI is that $M_D > 1.3 \text{ TeV}$ if there are two extra dimensions in nature.

Summary

• Neutrinos

- a) Neutrino mixing
- b) Neutrino oscillations
- c) Methods to detect neutrino oscillations
- d) The atmospheric neutrino anomaly
- e) The solar neutrino problem

• Dark matter

- f) What is dark matter ?
- g) Candidates for dark matter

• Grand Unified Theories

- h) All coupling constants equal
- i) The Georgi-Glashow model
- j) The importance of proton decay

- **Supersymmetry**

- k) Superparticles with different spin

- l) Unification of all forces including gravity

- m) The search for neutralinos

- **Gravitation and large extra dimensions**

- n) Predictions have been made that large extra dimensions exist in which only gravity can propagate.