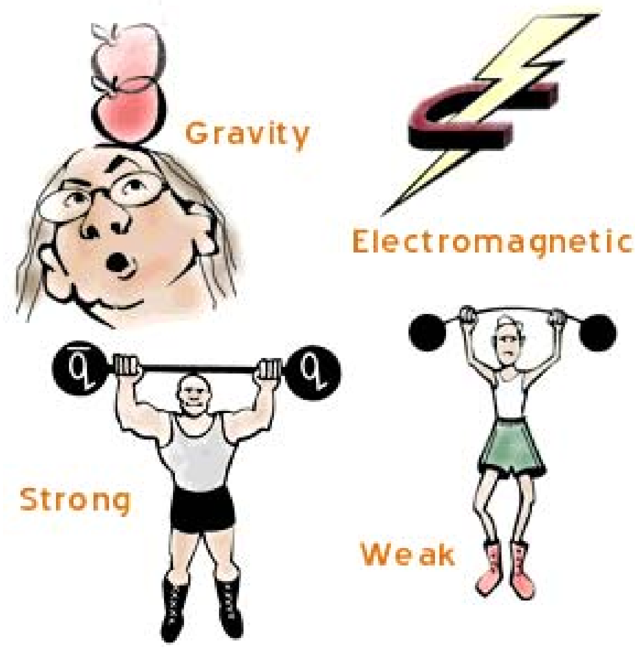
Fundamental Forces



Gravity Gravity governs the attraction between two massive objects. Negligible at the subatomic scale.

Electromagnetic Force Most of us are familiar with electric and magnetic phenomena.

Strong Force In the Standard Model, hadrons (like neutrons and protons) are considered to be made of quarks bound together by the strong force.

Weak Force The weak interaction is more subtle! It is responsible for the instability of some nuclei via β-decay (e.g. $n \to pe\nu$).

Interaction	Particle	Range (m)	Coupling
EM	γ	∞	10^{-2}
Strong	g	10^{-15}	1
Weak	W and Z	10^{-18}	10^{-6}

Elementary Particles

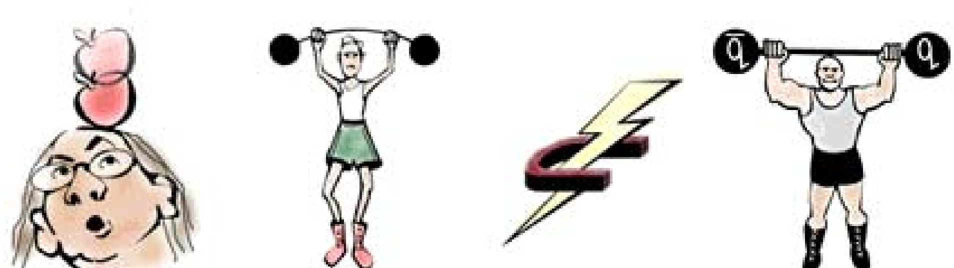
Fermions		Bosons	
Leptons and Quarks	Spin = $\frac{1}{2}$	Spin = 1*	Force Carrier Particles
Baryons (qqq)	Spin = $\frac{1}{2}, \frac{3}{2}, \frac{5}{2} \ldots$	Spin = 0, 1, 2...	Mesons ($q\bar{q}$)

Leptons

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$$

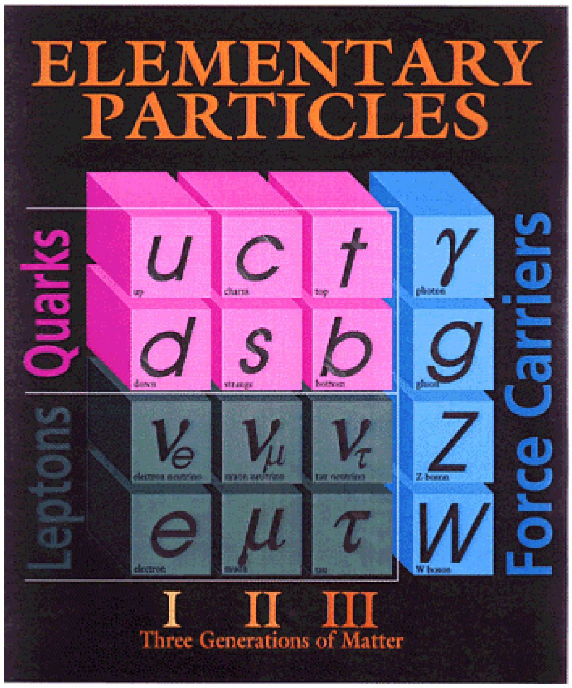
Quarks

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$



	Gravity	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong
Carried By	Graviton (not yet observed)	$W^+ W^- Z^0$	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and $W^+ W^-$	Quarks and Gluons

The Standard Model



The SM provides a general description of the physics physics currently accessible with modern particle accelerators. The minimal SM postulates that matter is composed of fundamental spin-$\frac{1}{2}$ **quarks** and spin-$\frac{1}{2}$ **leptons** interacting via spin one **gauge bosons**.

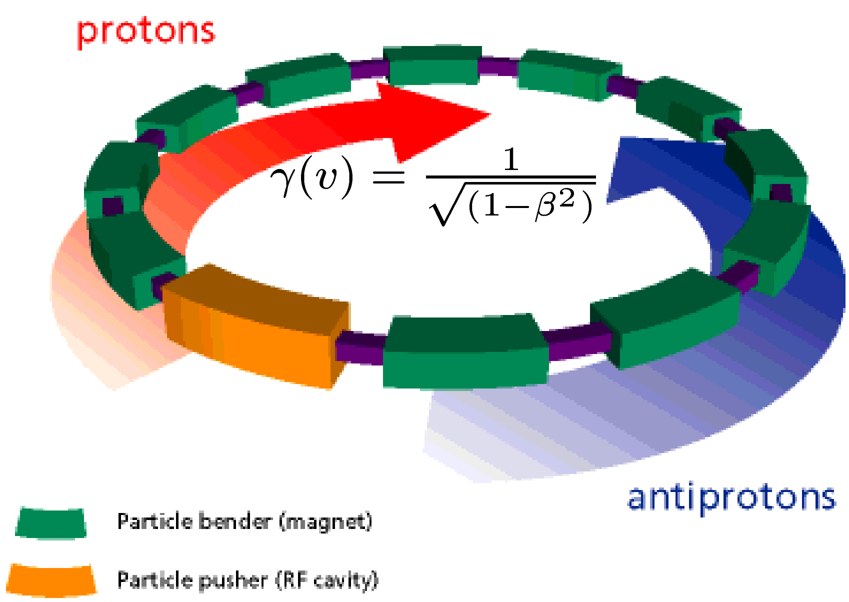
Electroweak Lagrangian:

$$\begin{aligned}
\mathcal{L} &= \mathcal{L}(\text{weak CC}) + \mathcal{L}(\text{weak NC}) + \mathcal{L}(\text{em NC}) \\
\mathcal{L}(\text{weak CC}) &= \frac{g}{\sqrt{2}}\,(J_\mu^-\,W_\mu^+ + J_\mu^+\,W_\mu^-) \\
\mathcal{L}(\text{weak NC}) &= \frac{g}{\cos\theta_W}\,(J_\mu^0 - \sin^2\theta_W\,J_\mu^{\text{em}})\,Z_\mu \\
\mathcal{L}(\text{em NC}) &= e\,J_\mu^{\text{em}}\,A_\mu
\end{aligned}$$

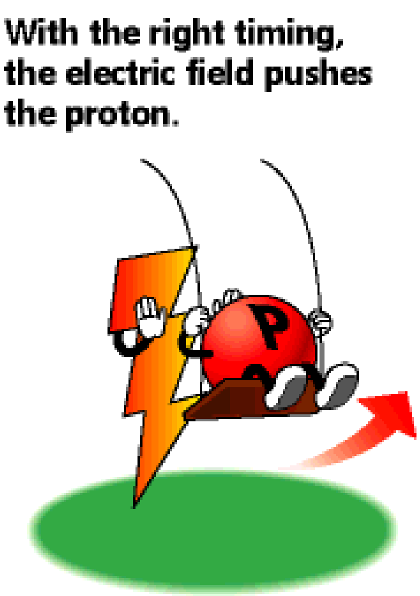
Higgs Field:

Physicists have theorized the existence of the so-called Higgs field, which in theory interacts with other particles to give them **mass**. The Higgs field requires a particle, the Higgs boson. The Higgs boson has not been observed, but physicists are looking for it with great enthusiasm.

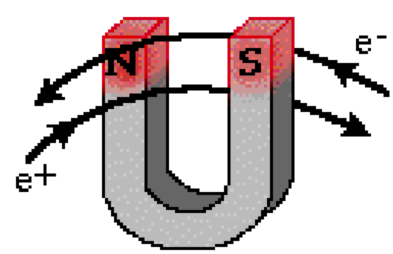
Particle Accelerator



$$\gamma(v) = \frac{1}{\sqrt{(1-\beta^2)}}$$



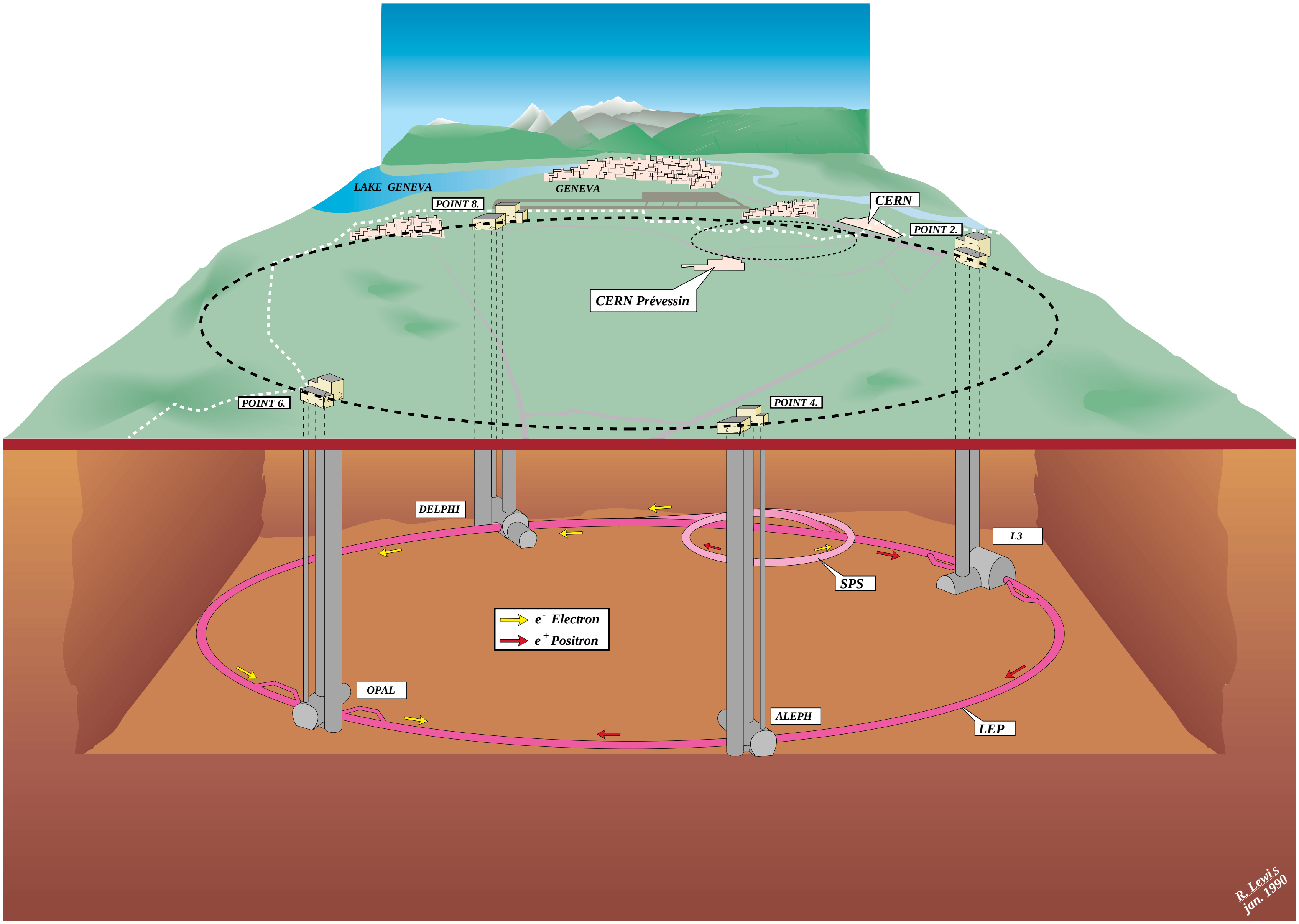
The presence of a magnetic field does not add or subtract energy from the particles. It only bends the particles paths along the arc of the accelerator.



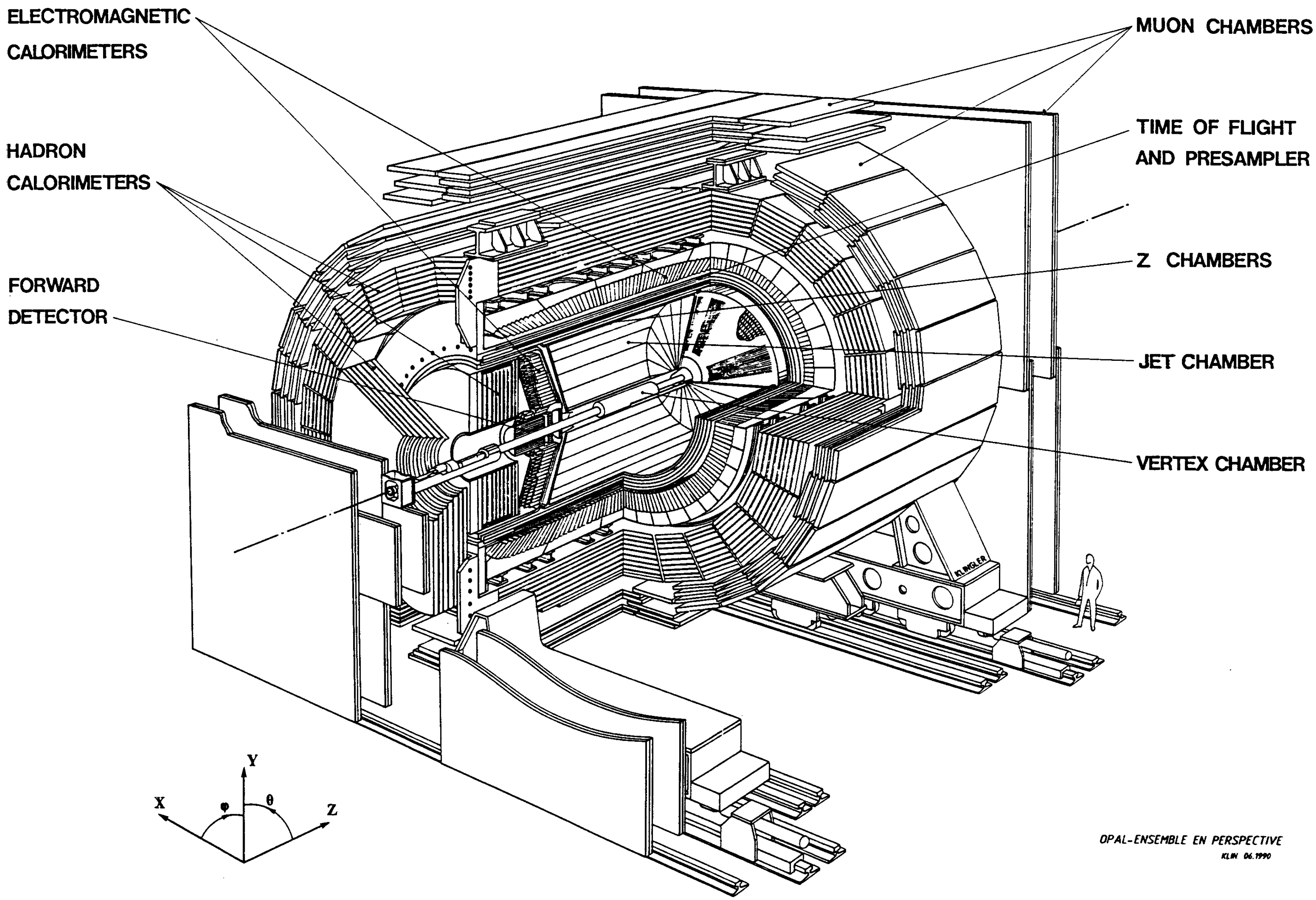
Collider

Circulate the particle in one direction and its anti-matter partner in the other.
RF cavities: Electric field.
Dipole Magnet: B-field.

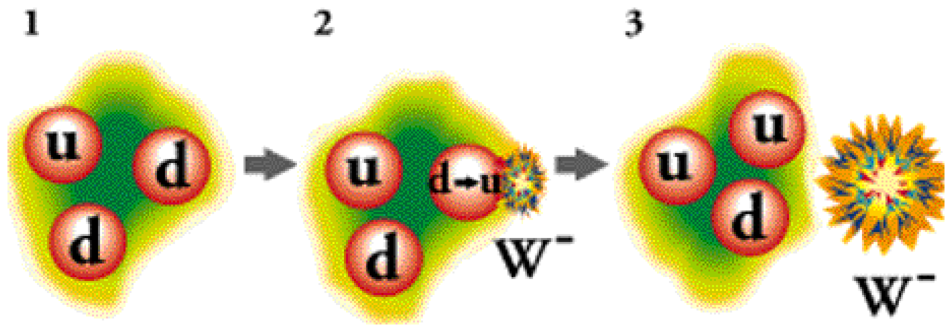
Experimental Apparatus: LEP



Experimental Apparatus: OPAL



Electroweak Reaction



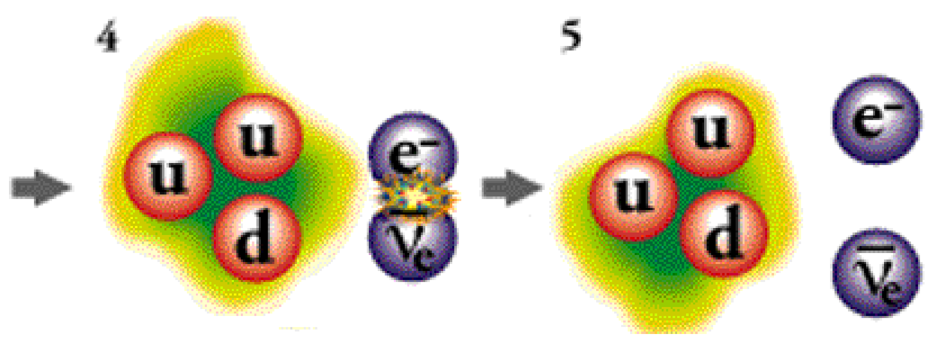
Frame 1 The neutron (charge = 0) made of up, down, down quarks.

Frame 2 One of the the down quarks is transformed into an up quark. Since the down quark has a charge of -1/3 and and the up quark has a charge of 2/3, it follows that this process is mediated by a virtual W particle, which carries away a unit (-1) of charge. Thus charge is conserved!

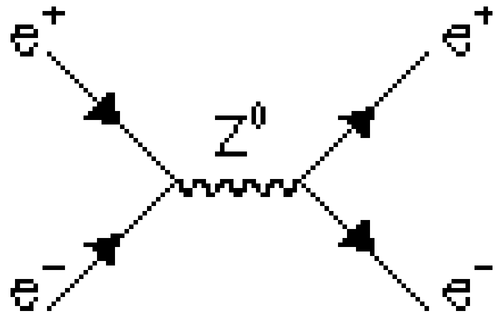
Frame 3 The new up quark rebounds away from the emitted W boson. The neutron now has become a proton.

Frame 4 An electron and antineutrino emerge from the virtual W boson.

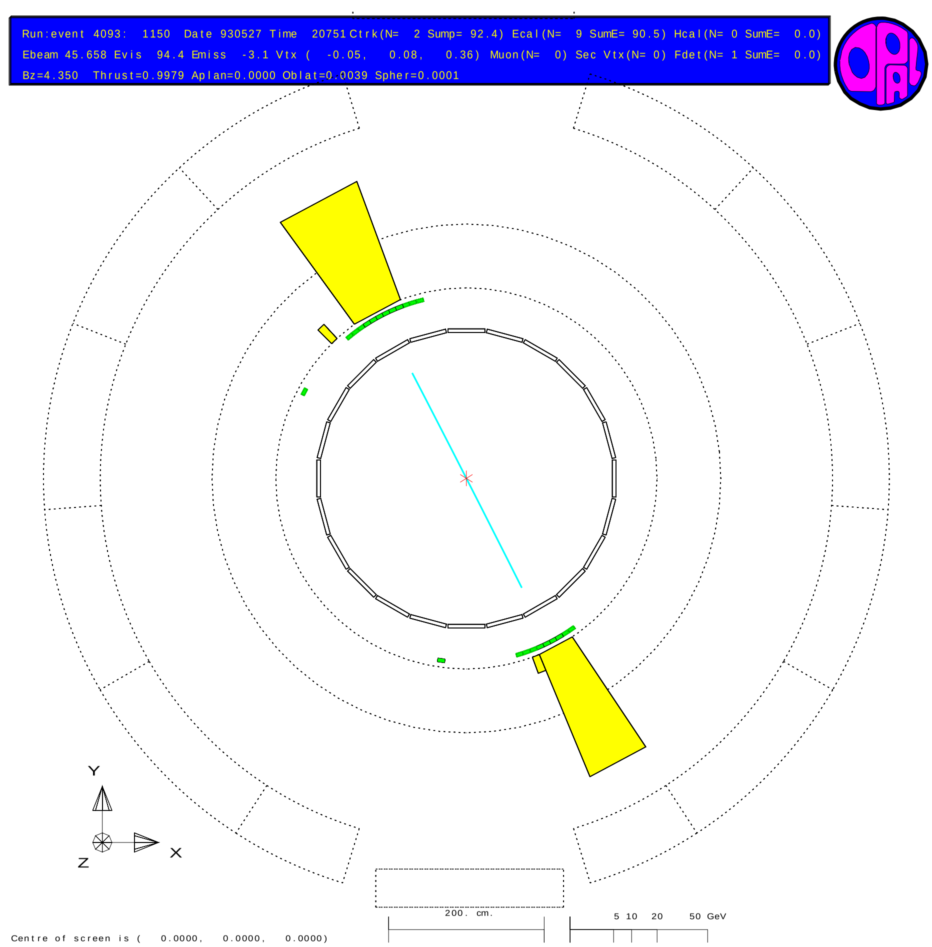
Frame 5 The proton, electron, and the antineutrino move away from one another.



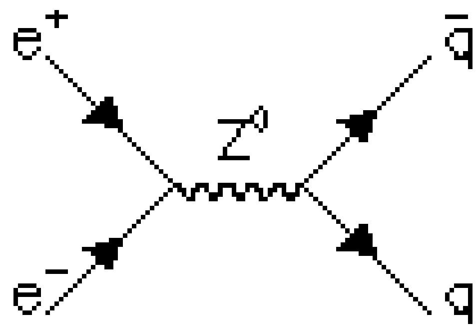
Leptonic Events at LEP1



$$E_{\mathrm{CM}} \simeq 91 GeV$$



Hadronic Events at LEP1



$$E_{\rm CM} \simeq 91 GeV$$