Standard Model - Electroweak Interactions

Outline

Weak Neutral Interactions

- Neutral Currents (NC)

Electroweak Theory

- $W^{\pm}$ and Z^0 and γ
- Discovery of $W^{\pm}$ and Z^0 bosons

Experimental Tests

- LEP

Z^0 Boson

- Mass and Width
- Number of Neutrinos

$W^{\pm}$ Boson

- $W^{\pm}$ Pair Production
- Mass and Width

Higgs Boson

- Mass, LHC

Supersymmetry SUSY

- Unification

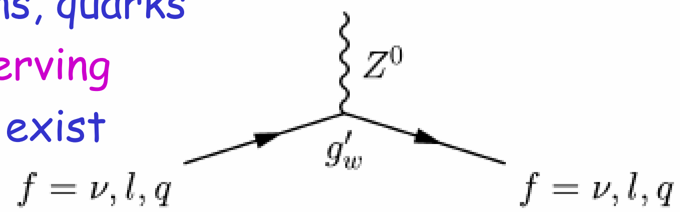
Standard Model

- Summary

Weak Neutral Interactions

Weak Neutral Current (NC)

Z^0 boson couples to all fermions:
neutrinos, charged leptons, quarks
Weak NC is flavour conserving
e.g $\mu\tau Z^0$ vertex does not exist



Coupling Strength

Proportional to weak neutral charge g'_W

➔ For each Z^0 vertex add factor g'_W to matrix element

How are g'_W and weak charge g_W related?

Z^0 Boson Propagator

Neutral Current mediated by exchange of virtual Z^0 boson

➔ Add propagator term $1/(q^2 - M_Z^2)$
to matrix element/amplitude

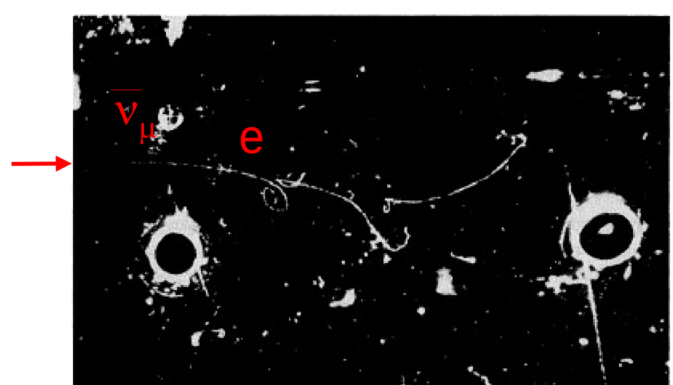
At small q^2 NC masked by electromagnetic interactions

Are weak and electromagnetic force related?

Discovery of Neutral Currents

1973 Bubble chamber
Gargamelle at CERN
3 events in elastic
neutrino scattering

$$\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$$



Anti-ν_μ beam
Very low background

Standard Model
Electroweak Interactions

Electroweak Unification

Developed in 1960s by Quantum Theory of weak charged (CC) and neutral currents (NC) and electromagnetic interactions (QED)

Glashow Weinberg Salam

Surprise - QED and weak interactions are a unified force

Electroweak Gauge Bosons

Initially four massless bosons W^+, W^0, W^- and B^0

Neutral bosons mix → **Physical bosons** $W^\pm$ and Z^0 and γ

$$\begin{pmatrix} Z^0 \\ \gamma \end{pmatrix} = \begin{pmatrix} \cos\theta_W & -\sin\theta_W \\ \sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} W^0 \\ B^0 \end{pmatrix}$$

θ_W weak mixing (Weinberg) angle

$W^\pm$ and Z^0 acquire mass via Higgs Mechanism

Electroweak Coupling Constants

g_W and g'_W are related to electric charge e

$$e = g_W \sin\theta_W = g'_W \cos\theta_W$$

Electroweak Theory

3 fundamental parameters, e.g. $\alpha_{em} = \frac{e^2}{4\pi}, \quad \frac{G_F}{\sqrt{2}} = \frac{g_W^2}{8M_W^2}, \quad \sin\theta_W$

Mass of $W^\pm$ and Z^0 related $M_{Z^0}^2 = M_W^2 / \cos^2\theta_W$

Predicts coupling strengths of $W^\pm$ and Z^0 to quarks and leptons, self interaction couplings of $W^\pm$ and Z^0 and γ

W and Z Bosons

Virtual W± and Z0 Bosons

Mediate weak interaction in scattering and decay of weakly interacting fermions

e.g. muon or meson decay, $\mu^- \to e^- \bar{\nu}_e \nu_\mu$ $\quad D^0 \to K^- \mu^+ \nu_\mu$

ν-e scattering $\nu_e + e^- \to \nu_e + e^-$ $\quad \bar{\nu}_\mu + e^- \to \bar{\nu}_\mu + e^-$

Real W± and Z0 Bosons

Produced in collisions if sufficient energy available

$$u + \bar{d} \to W^+ \to e^+ \nu_e, \mu^+ \nu_\mu$$

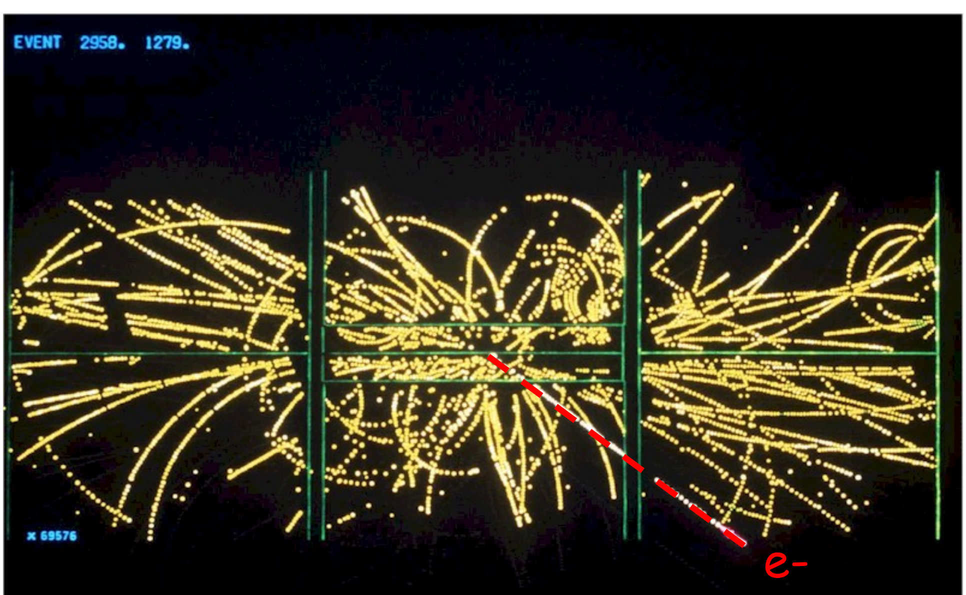
$$\bar{u} + d \to W^- \to e^- \bar{\nu}_e, \mu^- \bar{\nu}_\mu$$

$$\left.\begin{matrix} u + \bar{u} \\ d + \bar{d} \end{matrix}\right\} \to Z^0 \to e^+ e^-, \mu^+ \mu^-$$

Discovery of W± and Z0 Bosons

at p-pbar collider at CERN in 1983

Energy E(p) =E(pbar) = 270 GeV



W event
UA1 experiment
CERN

$W^- \to e^- \bar{\nu}_e$

Experimental Tests - LEP

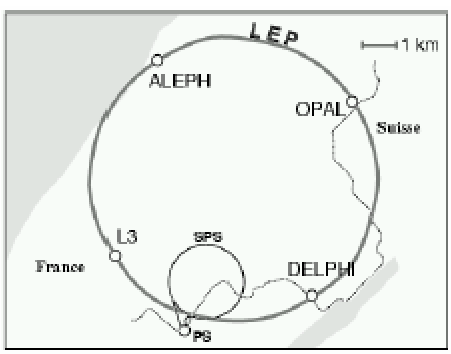
LEP - Large Electron Positron Collider

Largest e+e- collider, 27 km circumference

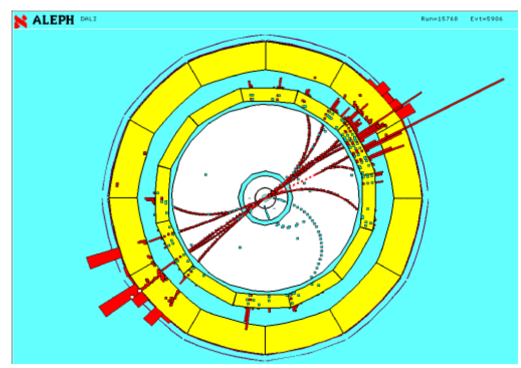
Centre-of-mass energy $\sqrt{s}$ = 90 – 200 GeV

Operational from 1989 to 2000

Four experiments: Aleph, Delphi, L3, OPAL



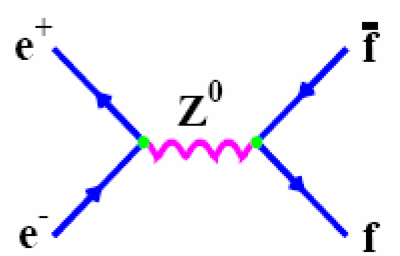
$e^+e^- \to Z^0 \to q\bar{q} \to$ hadrons



Z^0 Bosons at LEP

Resonance production at $\sqrt{s} = M_Z$

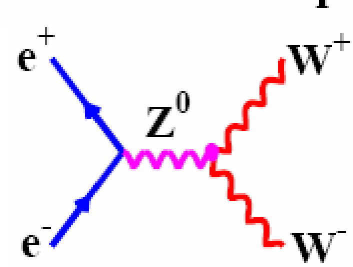
~4 million $e^+e^- \longrightarrow Z^0$ events/expt



$W^\pm$ Bosons at LEP

Production at $\sqrt{s} \geq 2\ M_W$

~8000 $e^+e^- \longrightarrow W^+W^-$ events/expt



LEP Measurements

Mass and width of Z^0 and $W^\pm$ bosons

Z^0 and $W^\pm$ boson couplings to quarks and leptons

Weak decays of heavy mesons

QCD measurements

Precision tests of **Standard Model of Particle Physics**

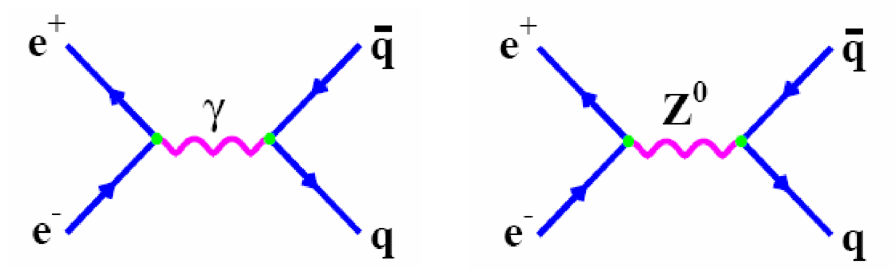
Z^0 Resonance

$e^+ e^-$ Annihilations → Hadrons at High Energies

$\sqrt{s}$ < 50 GeV   exchange of γ dominates

At larger energies $\sqrt{s} \geq 50$ GeV

Z^0 and γ exchange diagram,   also Z^0/γ interference



Z^0 Boson Production

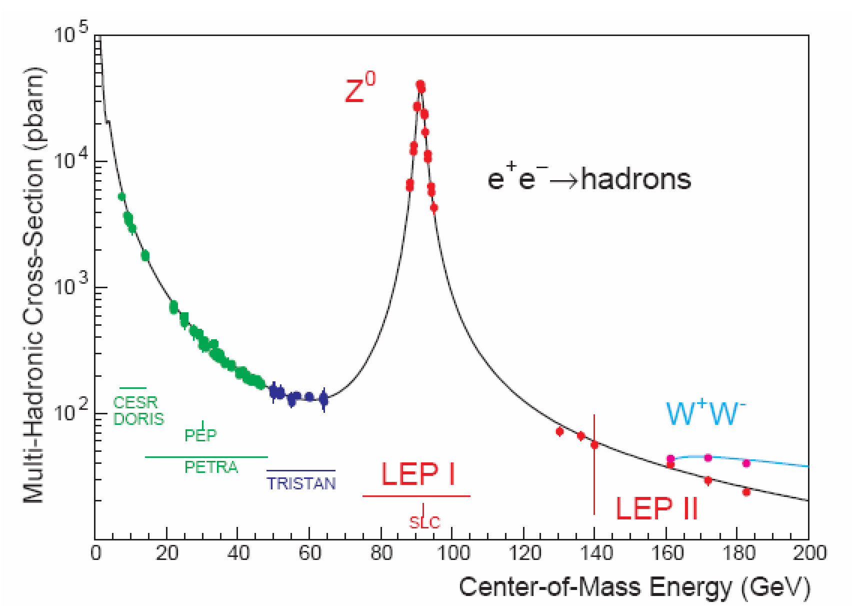
at energies $\sqrt{s} \approx M_Z$ production of real Z^0 boson

diagram with Z^0 boson dominates

Z^0 boson is Breit-Wigner Resonance

Z^0 boson decays very fast, lifetime $\tau \sim 10^{-25}$ s

Measure energy width of Z^0 resonance $\Gamma_Z = \hbar/\tau$



Z^0 Mass and Width

Breit-Wigner Resonance

Cross section for relativistic initial and final states

$$\sigma\left(e^+e^- \to Z^0 \to f\,\bar{f}\right) = g\,\frac{4\pi}{s}\,\frac{\Gamma_{e\bar{e}}\Gamma_{f\bar{f}}}{\left[\left(\sqrt{s}-M_Z\right)^2+\Gamma_Z^2/4\right]}$$

Partial decay widths $\Gamma_{f\bar{f}} = \Gamma\left(Z^0 \to f\,\bar{f}\right)$

Spin: average initial states

& sum final states

$$g = \frac{2J_Z+1}{\left(2s_{e^-}+1\right)\left(2s_{e^+}+1\right)}$$

Total Decay Width Γ_Z

Sum over all partial decay widths Γ_{ff}

$$\Gamma_Z = \Gamma_{q\bar{q}} + \Gamma_{e\bar{e}} + \Gamma_{\mu\bar{\mu}} + \Gamma_{\tau\bar{\tau}} + \Gamma_{\nu_e\bar{\nu}_e} + \Gamma_{\nu_\mu\bar{\nu}_\mu} + \Gamma_{\nu_\tau\bar{\nu}_\tau}$$

Cross section at peak of resonance $\sqrt{s} = M_Z$

$$\sigma^0_{f\bar{f}} = \sigma\left(e^+e^- \to Z^0 \to f\,\bar{f}\right) = \frac{12\pi}{M_Z^2}\,\frac{\Gamma_{e\bar{e}}\Gamma_{f\bar{f}}}{\Gamma_Z^2}$$

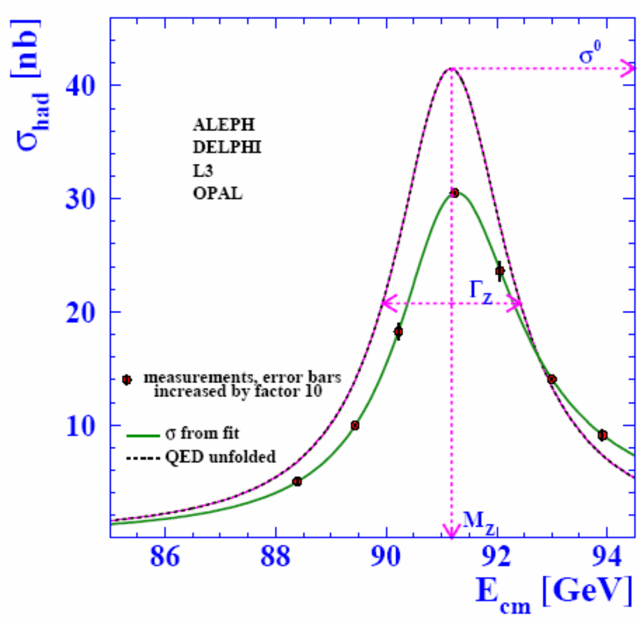
Z^0 Resonance

Measure $e^+e^- \longrightarrow$ Hadrons

at energies close to M_Z

QED corrections

Shift: $e^+e^- \longrightarrow \gamma$ hadrons



Mass and Width of Z^0

M_Z = 91.1876(21) GeV

Γ_Z = 2.49529(23) GeV

Peak cross section

σ^0_{qq} = 41.5409(37) nb

Z^0 Partial Decay Widths

Cross Sections

$$\sigma\left(e^+e^- \to Z^0 \to f\ \bar{f}\right)$$

Measurements for all visible fermions

Obtain partial decay widths using

peak cross section σ^0_{qq} and M_Z, Γ_Z

Note --- all resonance curves have width Γ_Z

$$\Gamma_Z = 2495.2 \pm 2.3\ \mathrm{MeV}$$

$$\Gamma_{q\bar{q}} = 1744.4 \pm 2.0\ \mathrm{MeV}$$

Evidence for $N_{colour} = 3$

$$\Gamma_{l\bar{l}} = \Gamma_{e\bar{e}} = \Gamma_{\mu\bar{\mu}} = \Gamma_{\tau\bar{\tau}} = 83.984 \pm 0.086\ \mathrm{MeV}$$

Invisible Z^0 Width

Decays $Z^0 \to \nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau$

Comparison of total and partial decay widths

$$\Gamma_Z = \Gamma_{q\bar{q}} + \Gamma_{e\bar{e}} + \Gamma_{\mu\bar{\mu}} + \Gamma_{\tau\bar{\tau}} + N_\nu \Gamma_{\nu\bar{\nu}}$$
$$\Gamma_{\nu\bar{\nu}} = \Gamma_{\nu_e\bar{\nu}_e} = \Gamma_{\nu_\mu\bar{\nu}_\mu} = \Gamma_{\nu_\tau\bar{\nu}_\tau}$$

N_ν - number of neutrino flavours

Number of Neutrino Flavours

Prediction $\Gamma_{\nu\nu}$ = 167 MeV

Measurement

$N_\nu\Gamma_{\nu\nu} = 499.0 \pm 1.5$ MeV

Number of light neutrinos

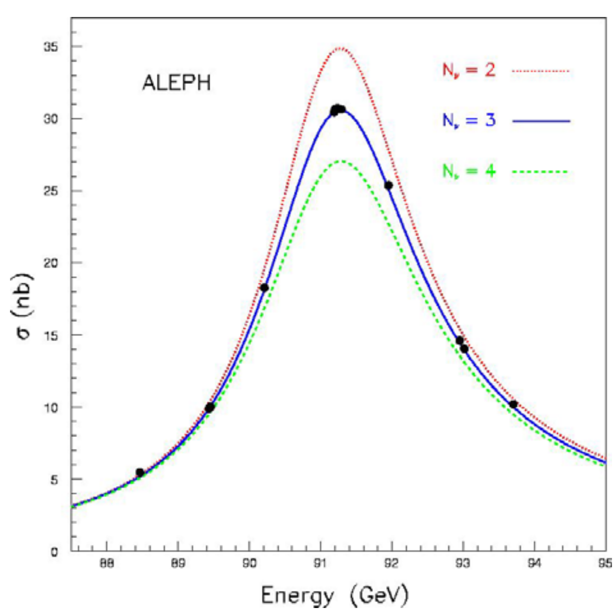
$N_\nu = 2.994 \pm 0.012$

(with mass $m_\nu < M_Z/2$)

Consistency also for e, μ, τ

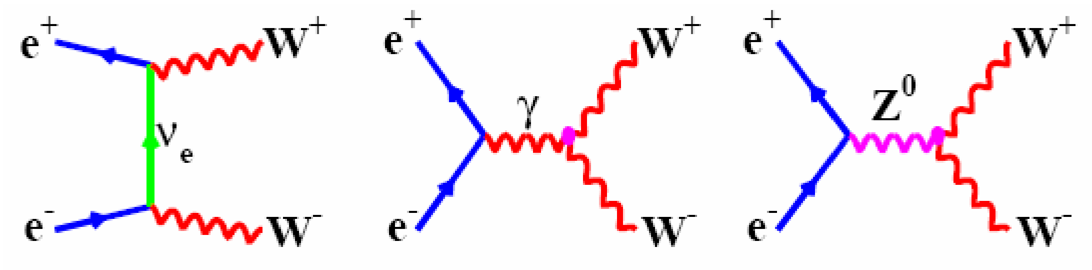
Lepton universality holds

for $Z^0 \to ee, \mu\mu, \tau\tau$ couplings



W^+W^- Pair Production

Standard Model Diagrams



W± Boson Decays

CC Universality for leptons and weak quark eigenstates

$$\Gamma(W^- \to e^-\bar{\nu}_e) = \Gamma(W^- \to \mu^-\bar{\nu}_\mu) = \Gamma(W^- \to \tau^-\bar{\nu}_\tau) = \tfrac{1}{3}\Gamma(W^\pm \to l\nu)$$

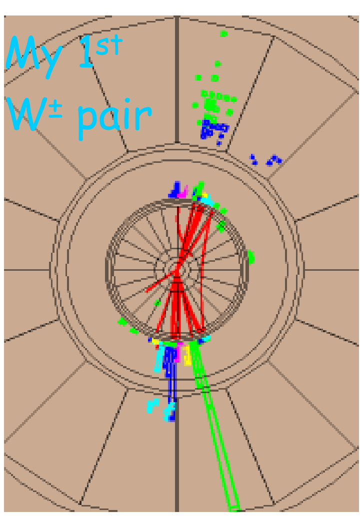
$$\Gamma(W^- \to d'\bar{u}) = \Gamma(W^- \to s'\bar{c}) = N_c\Gamma(W^- \to e^-\bar{\nu}_e) \qquad \Gamma(W^- \to b'\bar{t}) = 0$$

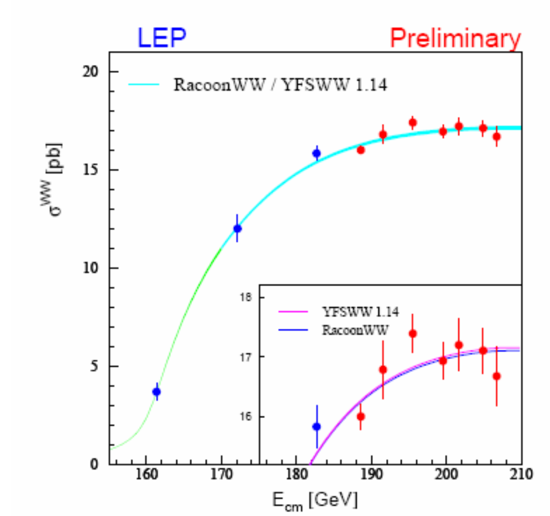
$$\Rightarrow \Gamma(W^\pm \to q'\bar{q}) = 2\Gamma(W^\pm \to l\nu)$$

$e^+ e^- \to W^+ W^-$ at LEP

Example L3 experiment

$$e^+e^- \to W^+W^- \to q\bar{q}e^-\bar{\nu}_e$$





Cross Section vs Energy

Agrees with SM prediction

Confirms existence of

$W^+ W^- Z^0$ vertex

Mass and Width of W± Boson

M_W = 80.425 ± 0.038 GeV

Γ_W = 2.124 ± 0.041 GeV

Higgs and Unification

Electroweak Theory

Precise measurements of α_{em}, G_F, M_Z, M_W and $\sin^2\theta_W$

Only 3 independent parameters

Powerful constraints, corrections: higher order diagrams

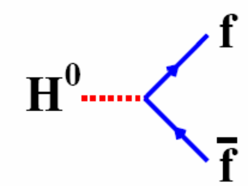
Higgs Mechanism

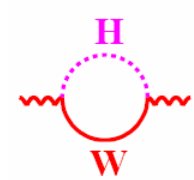
Only missing particle in Standard Model

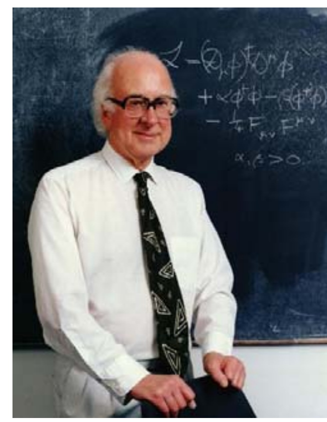
Scalar, i.e Spin 0,

Non-zero vacuum -> All particles

acquire mass by Higgs interaction







Peter Higgs

Prof emeritus

Univ of Edinburgh

Higgs coupling $\propto$ mass $g_{Hff} = \sqrt{(\sqrt{2}\, G_F)}\, m_f$

Direct Mass Limit $M_H > 114$ GeV

Require **Large Hadron Collider (LHC)** starts in 2007

Supersymmetry - SUSY

SUSY Partners: Fermion $\leftrightarrow$ Boson

fermion $\leftrightarrow$ sfermion

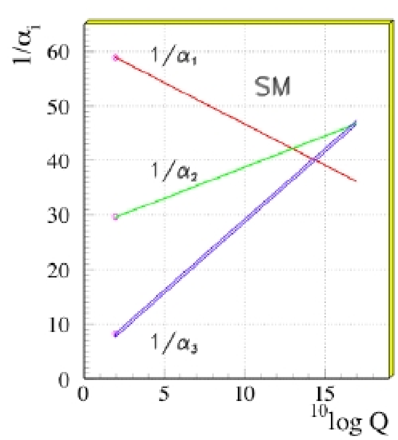
boson $\leftrightarrow$ ...ino

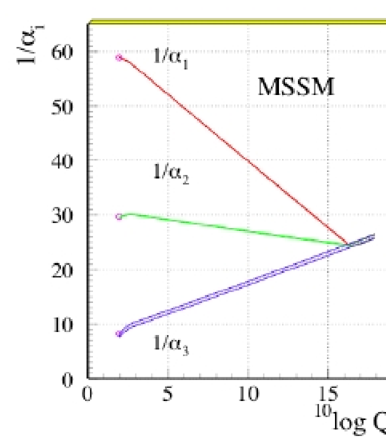
Unification of electroweak and strong interaction

$\alpha_1 = \alpha_{em}$

$\alpha_2 = \alpha_W$

$\alpha_3 = \alpha_S$





Standard Model of Particle Physics

One-page Summary

Fermions

Quarks and Leptons

3 Generations of Leptons & Quarks			Charge [e]
ν_e	ν_μ	ν_τ	0
e-	μ-	τ-	-1
u	c	t	+2/3
d	s	b	-1/3

Gauge Bosons

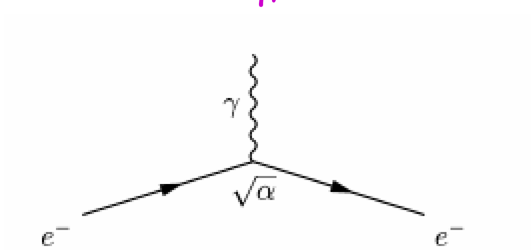
Mediate interactions

Inter-action	Gauge Goson	Charge [e]	Coupling Constant
Strong	g	0	$\alpha_S \approx 0.2$
Electro magnetic	γ	0	$\alpha_{em} \approx 0.008$
Weak	Z^0 $W^\pm$	0 ±1	$\alpha_W \approx 0.03$

Electromagnetic (QED)

γ couples to charge e

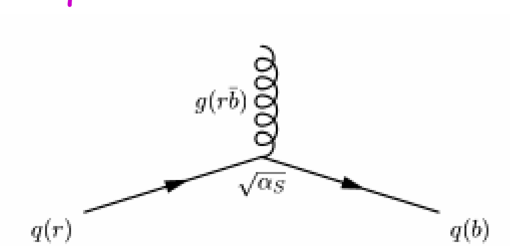
conserves q, l flavour



Strong (QCD)

g couple to colour

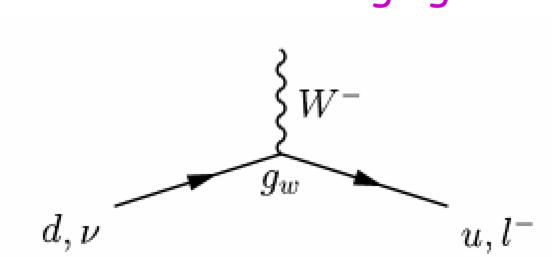
quark flavour conserved



Weak Charged Current (CC)

$W^\pm$ couples to weak charge g_W

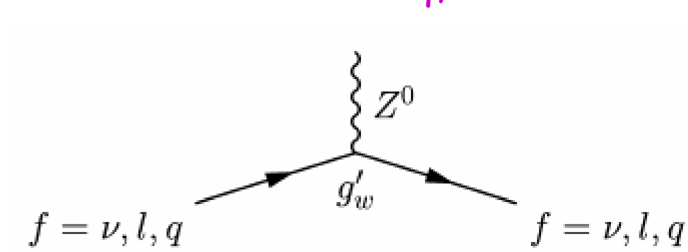
Flavour changing for quarks



Neutral Current (NC)

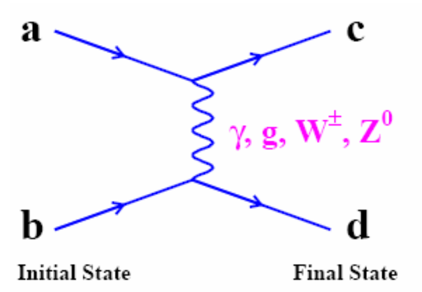
Z^0 couples to g'_W

conserves q, l flavour



Feynman Diagrams

One-page Tutorial



- Scattering, annihilation or decays
- Only Standard Model vertices

Initial and final states

- Write down quark/lepton/boson content for all initial and final state particles

Interactions

- Try to find out which exchange bosons are responsible for reaction by checking conservation laws

Conservation Laws

- For all interactions at each vertex
  - Energy-momentum
  - Electric charge, Baryon number
- For strong and electromagnetic interactions
  - Quark and Lepton flavour, Parity, Isospin, Strangeness
- For weak charged interactions (CC)
  - Quark flavour is not conserved, Lepton universality
- For weak neutral interaction (NC)
  - Quark and lepton flavour are conserved

Useful Hints

- Photon only interacts electromagnetically
- Neutrinos and Z^0 only interact weakly
- Only Quarks and Gluons interact strongly
- If more than 1 possibility, faster reaction wins
- Keep it as simple as possible