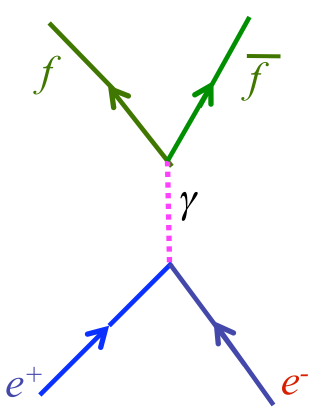
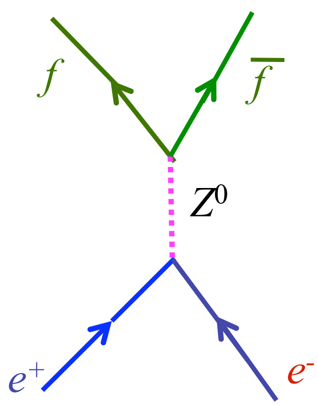
Properties of the Z^0

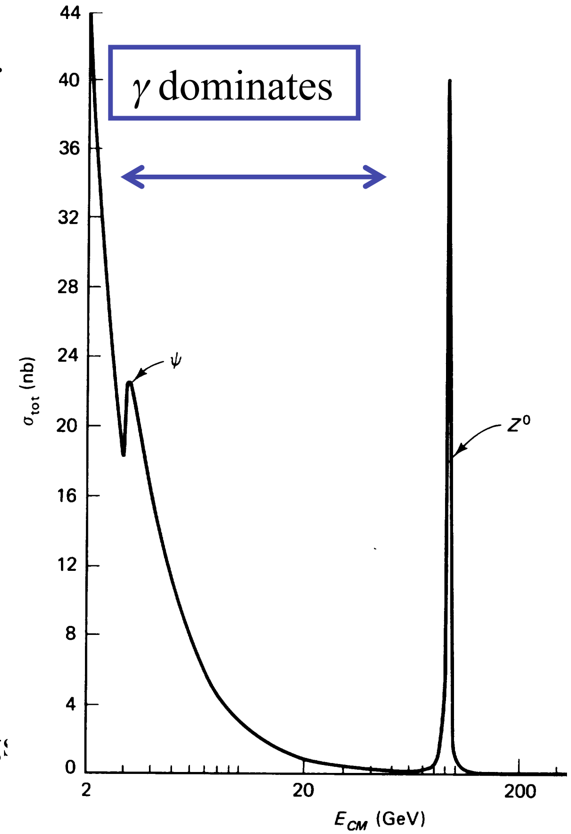
- For about ten years the Z^0 was studied in great detail at two accelerator complexes:
  - LEP at CERN and SLC at SLAC
  - Both of these accelerators were able to produce millions of Z^0's using the reaction:

    $$e^+e^- \to Z^0 \to f\,\bar{f}$$
  - The fermions could be charged leptons, neutrinos, and quarks.
  - The mass the fermion has to be $< M_Z/2$:

    $$M_Z = 91.1882 \pm 0.0022 \text{ GeV}$$
  - Both accelerators collided e^+e^- beams with energy $\approx M_Z/2$.
  - The Standard Model makes many predictions about the decay modes of the Z.
  - At center of mass energies close to M_Z:
    - the reaction with Z dominates over the reaction with γ.





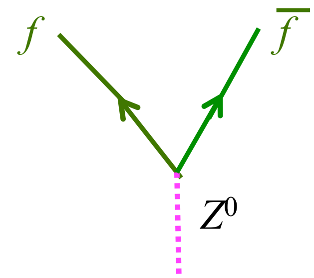


Decay of the Z^0

- The Standard Model predicts that the decay rate into fermion anti-fermion pairs:

$$\Gamma(Z^0 \to f + \bar{f}) = K \frac{g_Z^2 M_Z c^2}{48\pi\hbar}\left[\left|c_V^f\right|^2 + \left|c_A^f\right|^2\right]$$

See Griffiths p.327



  - With $K = 1$ for leptons and $K = 3$ (color factor) for quarks.
  - C_A^f and C_A^f are the vertex factors listed in lecture 11.
  - Standard Model prediction for the Z decay widths (first order):

Fermion	Γ (MeV)
e, μ, τ	84
ν_e, ν_μ, ν_τ	167
u, c	300
d, s, b	380

Z cannot decay into the top quark since $M_t > M_Z$.

  - Comparison of experiment and Standard Model (from PDG)

Γ	Experiment (MeV)	SM (MeV)
Hadrons	1743.9 ± 2.0	1742.2 ± 1.5
Neutrinos	498.8 ± 1.5	501.65 ± 0.15
Lepton	83.96 ± 0.09	84.00 ± 0.03

excellent agreement

Z^0 Decay and the Number of Neutrinos

- The Standard Model predicts the following cross section:

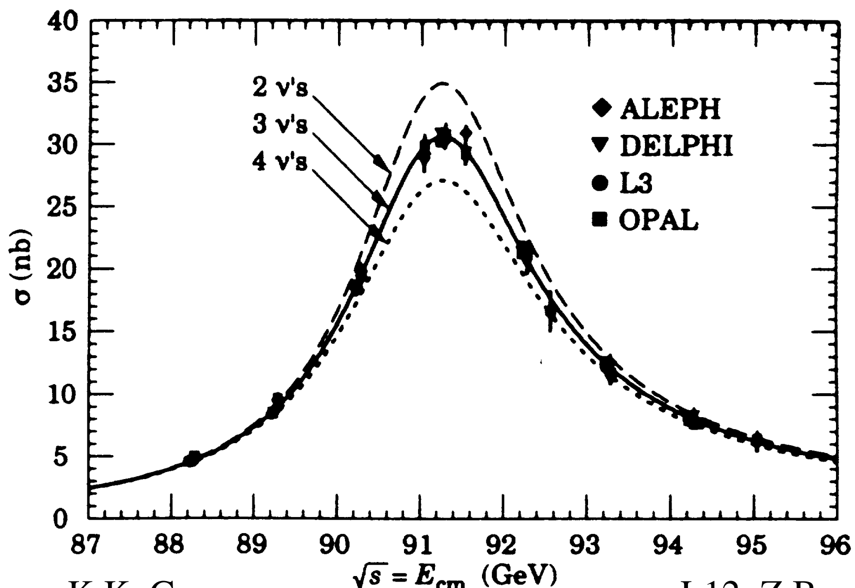
$$\sigma(e^+e^- \to Z^0 \to X) = \frac{12\pi M_Z^2}{E_{cm}^2} \frac{\Gamma(Z^0 \to e^+e^-)\Gamma(Z^0 \to X)}{(E_{cm}^2 - M_Z^2)^2 + M_Z^2\Gamma_Z^2}$$

M&S 9.1.4

  - Γ_Z is the "total width" of the Z:
    - sum of all the partial widths listed on the previous page.
  - "X" refers to the final state and is usually the sum of all measured hadronic (quark) final states.
  - The height of the curve depends on Γ_X.
  - The shape of the curve depends on the full width, Γ_Z:
    - This depends on the number of neutrino species:

$$\Gamma_Z = 3\Gamma(Z^0 \to l^+l^-) + 3\Gamma(Z^0 \to d\bar{d}) + 2\Gamma(Z^0 \to u\bar{u}) + n\Gamma(Z^0 \to \nu\bar{\nu})$$

      - Each neutrino species contributes 167 MeV to Γ_Z.
  - By varying the energy of the beams $\sigma(e^+e^- \to Z \to X)$ can be mapped out and determine Γ_Z.



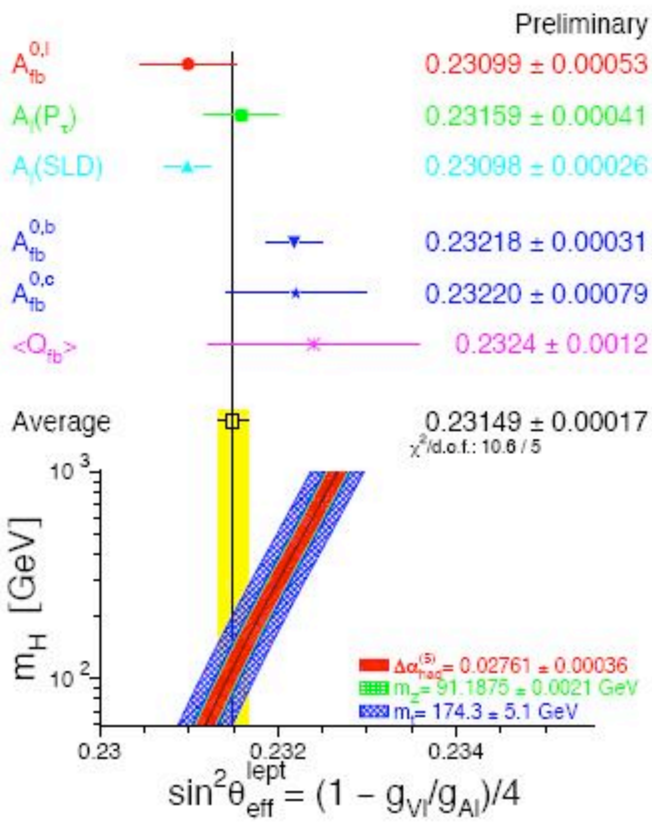
Data from the four LEP experiments.
All experiments measure the cross section for $e^+e^- \to$ hadrons ("X") as a function of center of mass energy.

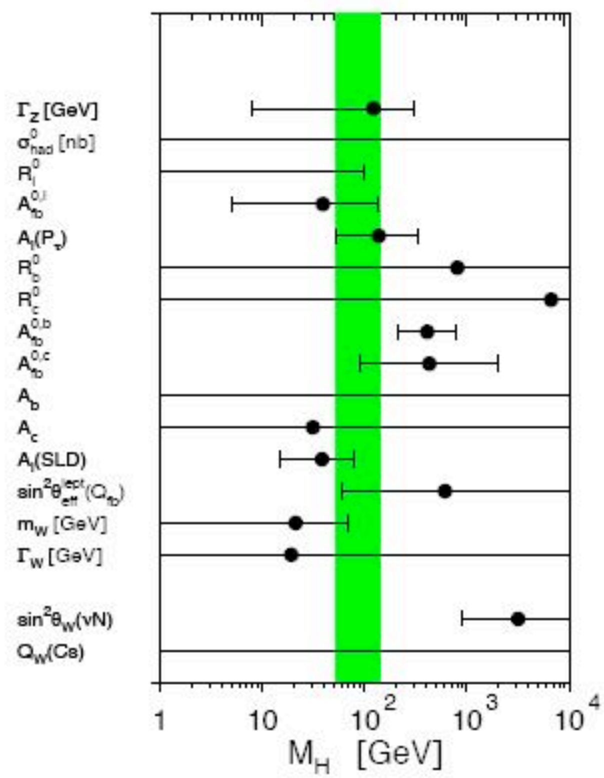
Excellent agreement with only 3 (light) neutrino families!

How Good is the Standard Model?

Summary of Standard Model measurements compared with predictions.
Talk given by Prof. Kevin McFarland (U of Rochester and member of NuTeV).

The Standard Model of particle physics (Glashow, Weinberg, Salam) is very successful in explaining electro-weak phenomena. But we may be seeing some cracks in the model!





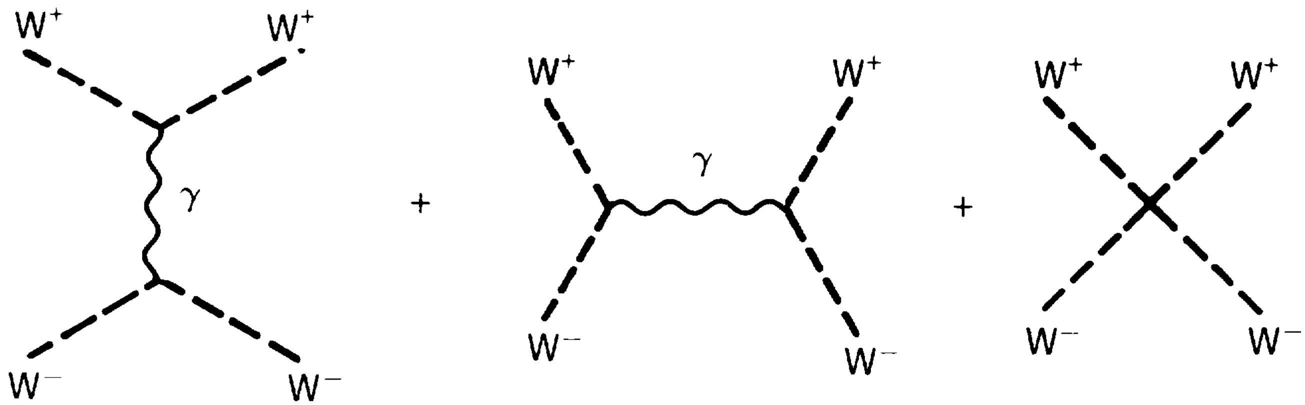
Limits of Standard Model

- What's in the Standard Model?
  - Quantum field theory based on SU(3)xSU(2)xU(1) symmetry containing:
    a) spin ½ point-like objects: quarks and leptons
    b) spin 1 objects: force carriers (W, Z, γ, gluons)
    c) spin 0 (scaler) object(s): Higgs Boson(s) (M&S 9.2.2)
  - The minimal Standard Model has been very successful in describing known phenomena.
  - The minimal Standard Model has a), b), massless neutrinos, and one massive neutral Higgs boson.
- What's wrong with the Standard Model?
  - There are (at least) 18 parameters that must be put into the Standard Model:
    - masses of quarks (6)
    - masses of charged leptons (3)
    - CKM matrix (4)
    - coupling constants, α_{EM}, α_{strong}, α_{weak} (3)
    - Fermi constant (G_F) or vacuum expectation value of Higgs field (1)
    - mass of Higgs (or masses if more than one Higgs boson)
  - The three coupling constants are not unified at the Planck scale.
  - How to include gravity in the unification?

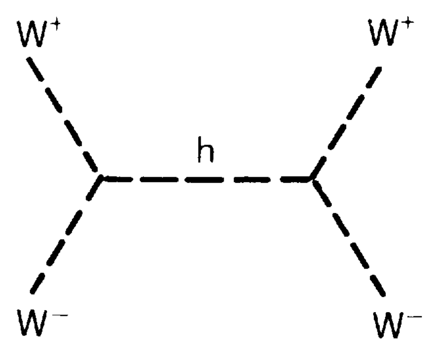
"The 18 Arbitrary Parameters of the Standard Model in Your Life", R. Cahn, RMP V68, No. 3, 1996

The Higgs Boson

- The Standard Model requires that at least one scalar particle exist.
  - This particle, known as the "Higgs" (after Peter Higgs) does two things:
    - "generates" the masses of the *W*, *Z*, and fermions
    - makes the theory renormalizable
      - Scattering amplitudes and cross sections will be finite at high energy.
      - Diagrams with the exchange of a virtual Higgs cancel other diagrams with virtual *W*'s and *Z*'s.



      - The cross section for $W^+W^- \rightarrow W^+W^-$ grows as E^2_{cm}!
        - At a few TeV the cross section grows so large that is violates unitarity (probability > 1)!
        - The cross section can be made to be finite by adding diagrams (amplitudes) of the form:



The Higgs Boson and Mass

- In the minimal Standard Model the Higgs field is a scalar in an SU(2) doublet.
  - Only one component of the doublet has to have mass.
    - There is only one massive Higgs particle in this model.
    - The mass of this particle is given by:

      $$m_H^2 = 2v^2\lambda$$

      - Both v and λ are constants.
      - Only one can be calculated from measured quantities!

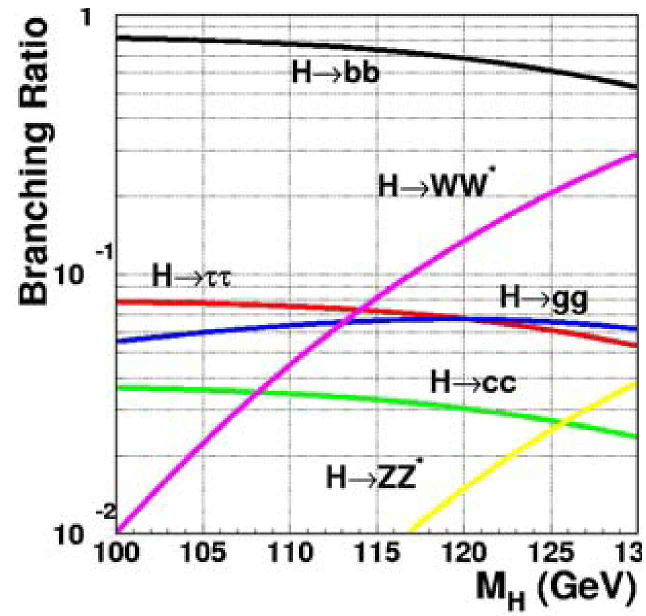
      $$v = \frac{M_W \sin\theta_W}{\sqrt{\alpha\pi}} \approx 246\,\mathrm{GeV/c^2}$$

  - The mass of the fermions are related to the Higgs field.
  - The Standard Model Lagrangian contains terms of the form:

    $$L_{\mathrm{int}} = m_f f\bar{f} + \frac{m_f}{v} f\bar{f}H$$

    - The strength of the Higgs coupling to a fermion anti-fermion pair depends on mass of the fermion.
      - Higgs decays preferentially to the fermion with mass closest to $M_H/2$.

        $$BR(H \to b\bar{b}) > BR(H \to \tau^+\tau^-) > BR(H \to c\bar{c}) \cdots > BR(H \to e^+e^-)$$



Where is the Higgs Boson?

- Present experimental limits on the Higgs suggest $M_H > 110$ GeV/c^2.
  - Constraints from theory predict a low mass Higgs ($M_H < 110$ GeV/c^2).
  - Mass of Higgs must be < 1 TeV otherwise higher order corrections cause problems with the model.
  - Higgs may be discovered at Fermilab in next 2 years.
  - Will definitely be discovered (or ruled out) at LHC/CERN in 5-7 years.