Electroweak unification and the Higgs mechanism

- Outline:
  - Introduce Z
  - Show electroweak unification
  - Problem: W and Z are not massless
  - Vacuum is not empty
    - W and Z get mass by interactions with vacuum fields
    - Higgs particle is manifestation of this effect

Analogy with spin

- The double (ν, 0) and (0, e) is similar to the spinors (1, 0) and (0, 1)
- The bosons are similar to the spin matrices

Z boson gives an additional process!

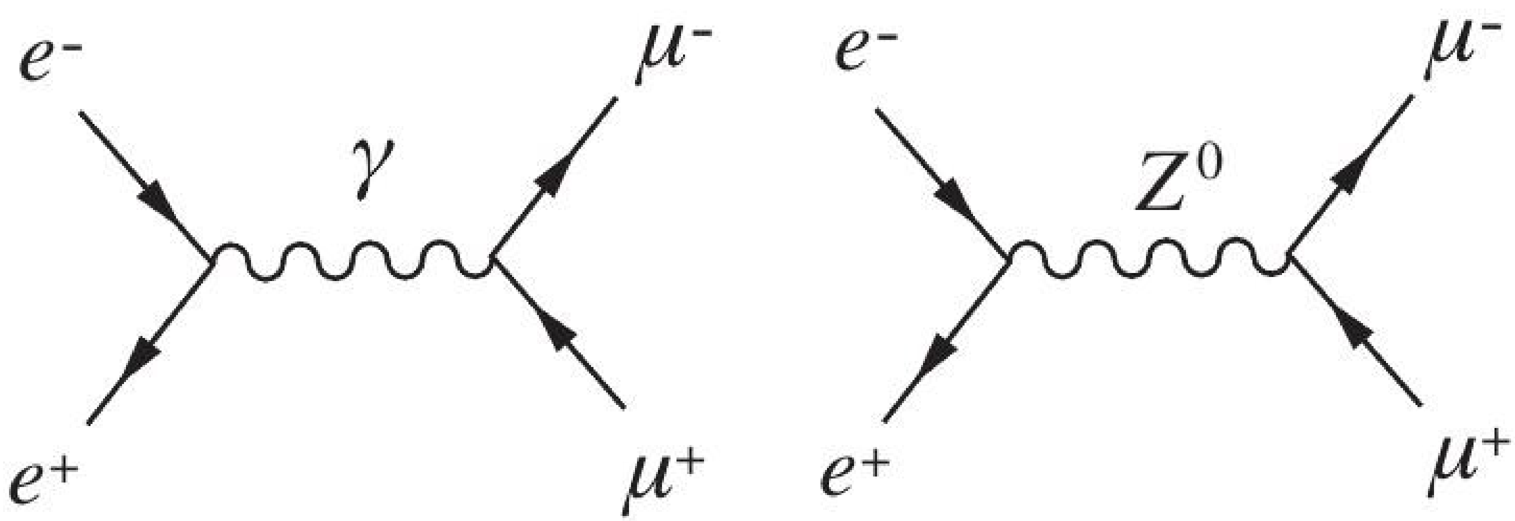


Figure 9.2 The two dominant contributions to the reaction $e^+ + e^- \rightarrow \mu^+ + \mu^-$ in the unified theory.

Calculation

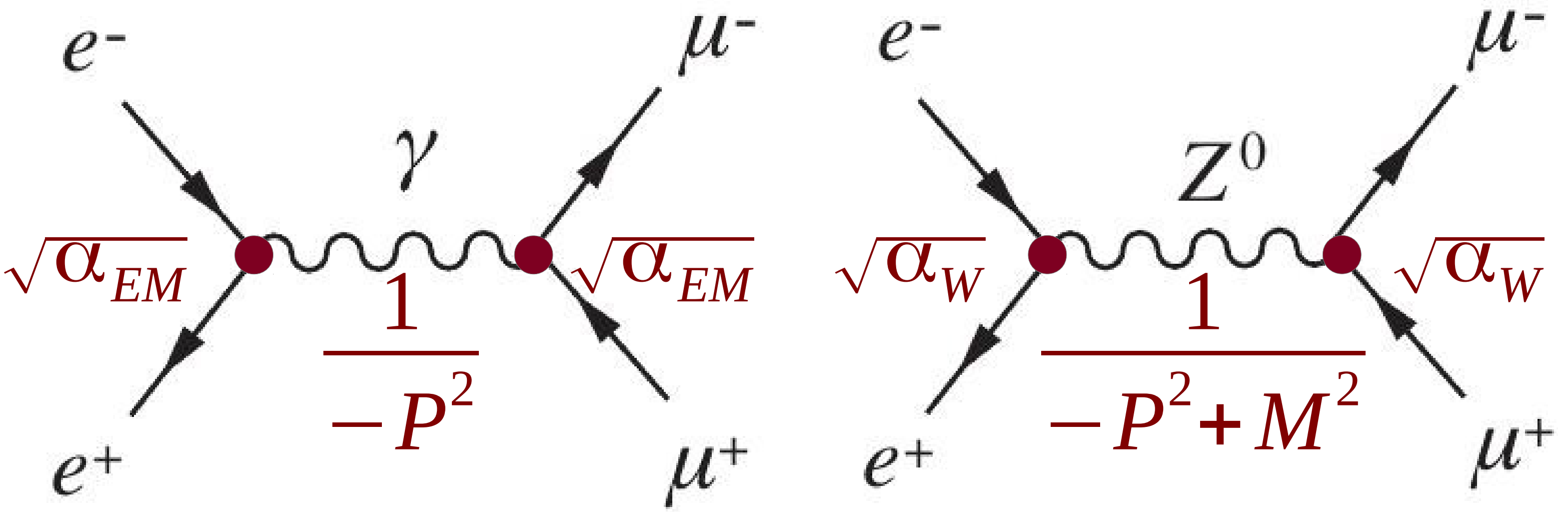


Figure 9.2 The two dominant contributions to the reaction $e^+ + e^- \rightarrow \mu^+ + \mu^-$ in the unified theory.

Mz~90 GeV (~ 90 proton masses)

The effect (1/2)

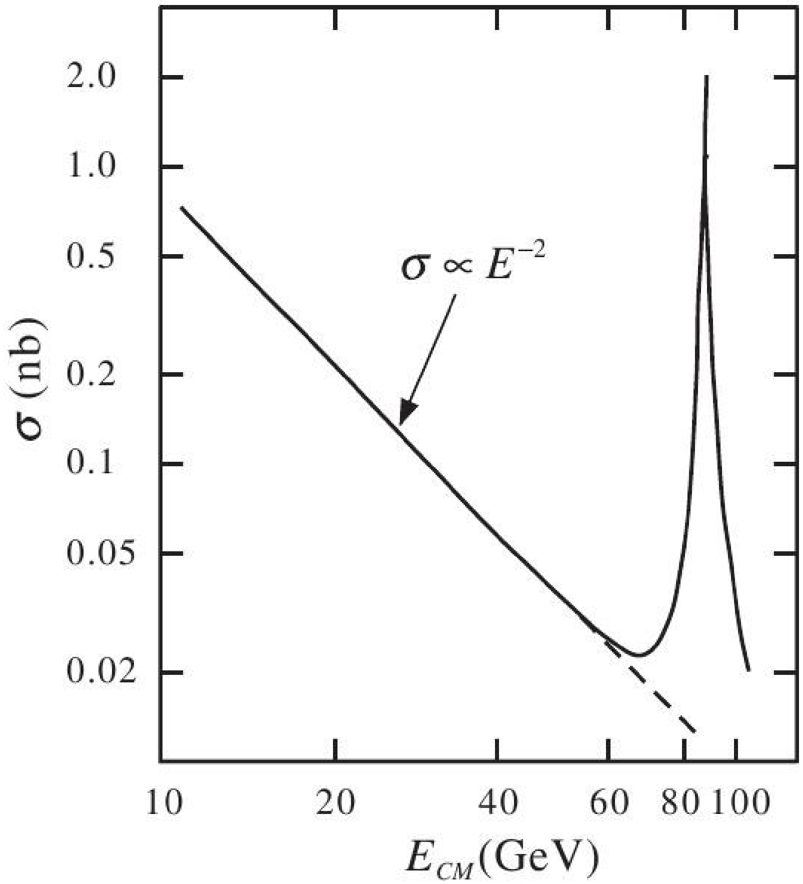


Figure 9.9 Total cross-section for the reaction $e^+ + e^- \to \mu^+ + \mu^-$ as a function of the total centre-of-mass energy (9.20). The dashed line shows the extrapolation of the low-energy behaviour (9.17) in the region of the Z^0 peak.

The effect (2/2)

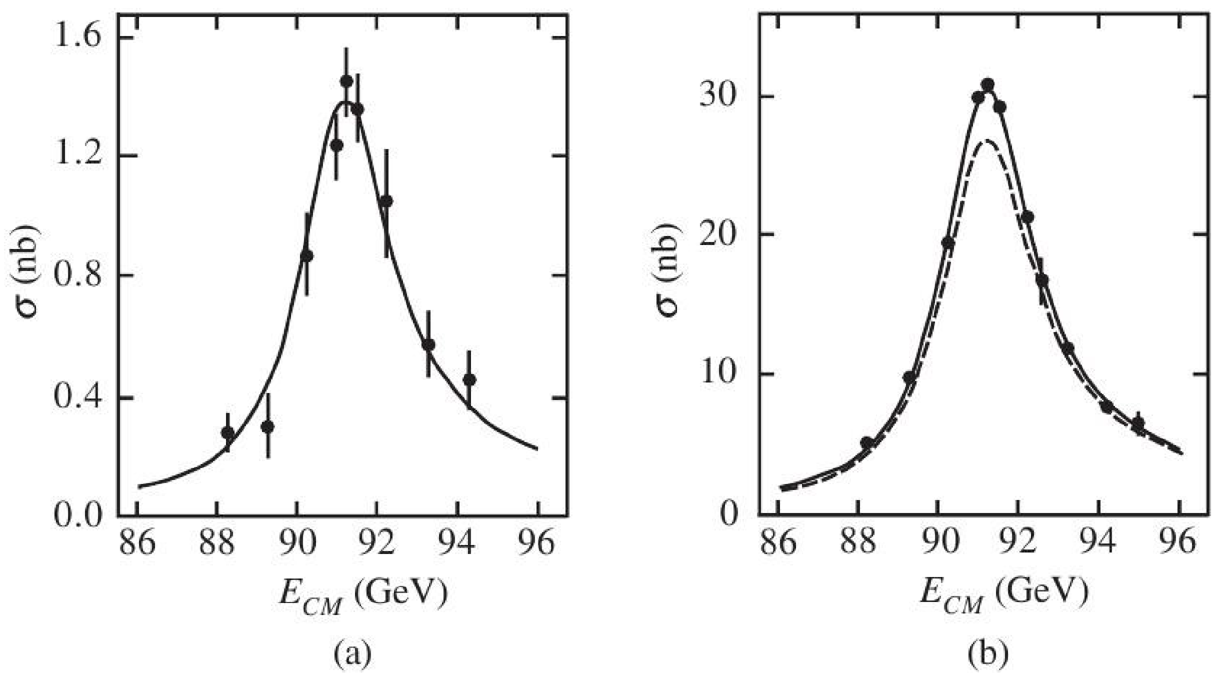
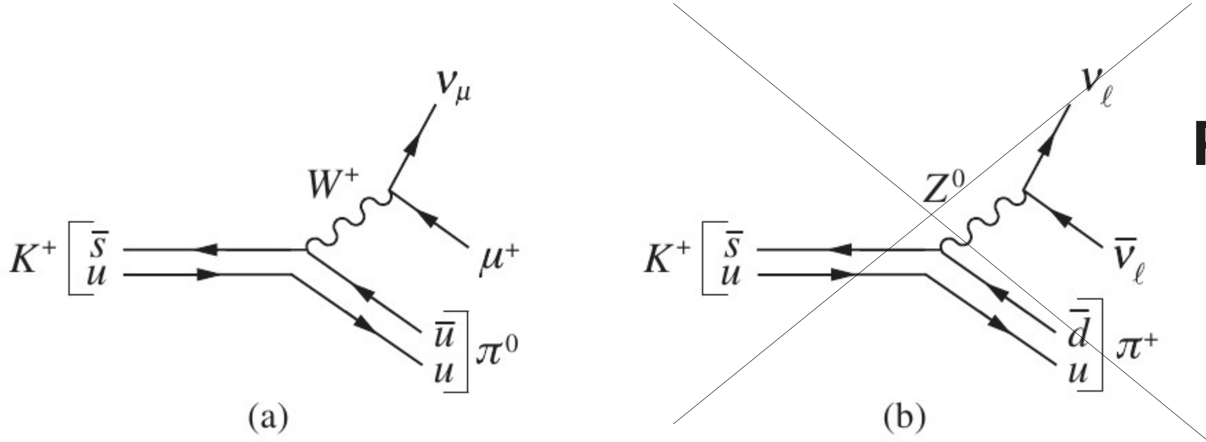


Figure 9.10 Measured cross-sections for (a) $e^+ + e^- \rightarrow \mu^+ + \mu^-$ and (b) $e^+ + e^- \rightarrow$ hadrons, in the region of the Z^0 peak. The solid and dashed lines show the predictions of the standard model on the assumptions that there are three and four types of light neutrinos, respectively. (Reprinted from Akrawy, M. Z., *et al.*, *Physics Letters B*, **240**, 497. Copyright 1990, with permission from Elsevier.)

The more states the Z can decay to the less likely it is to decay to a given state. If there were more neutrino states the lifetime would be shorter and the qq-bar would make out a smaller fraction of the total decay options.

Important to remember



Forbidden!

Figure 9.5 (a) The allowed decay $K^+ \to \pi^0 + \mu^+ + \nu_\mu$ and (b) the forbidden decay $K^+ \to \pi^+ + \nu_\ell + \bar{\nu}_\ell$.

- The Z boson does not violate flavor!
- The quark mixing “cancels” for Z0, see book

The Z basic diagrams

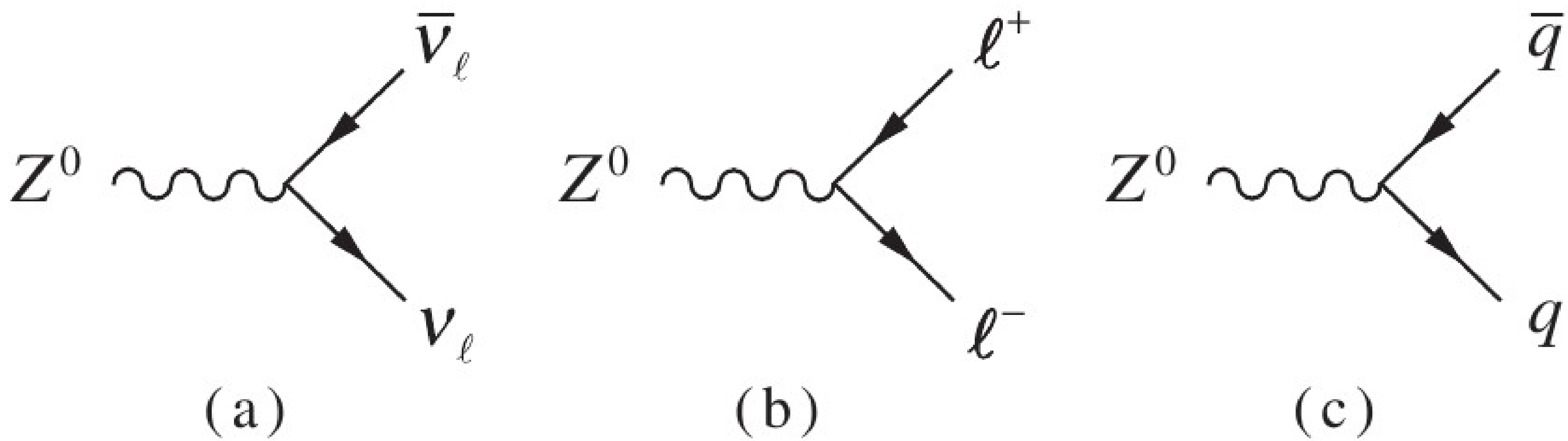


Figure 9.12 Feynman diagrams for the Z^0 decays (9.30a), (9.30b) and (9.30c), respectively.

Why electro weak unification?

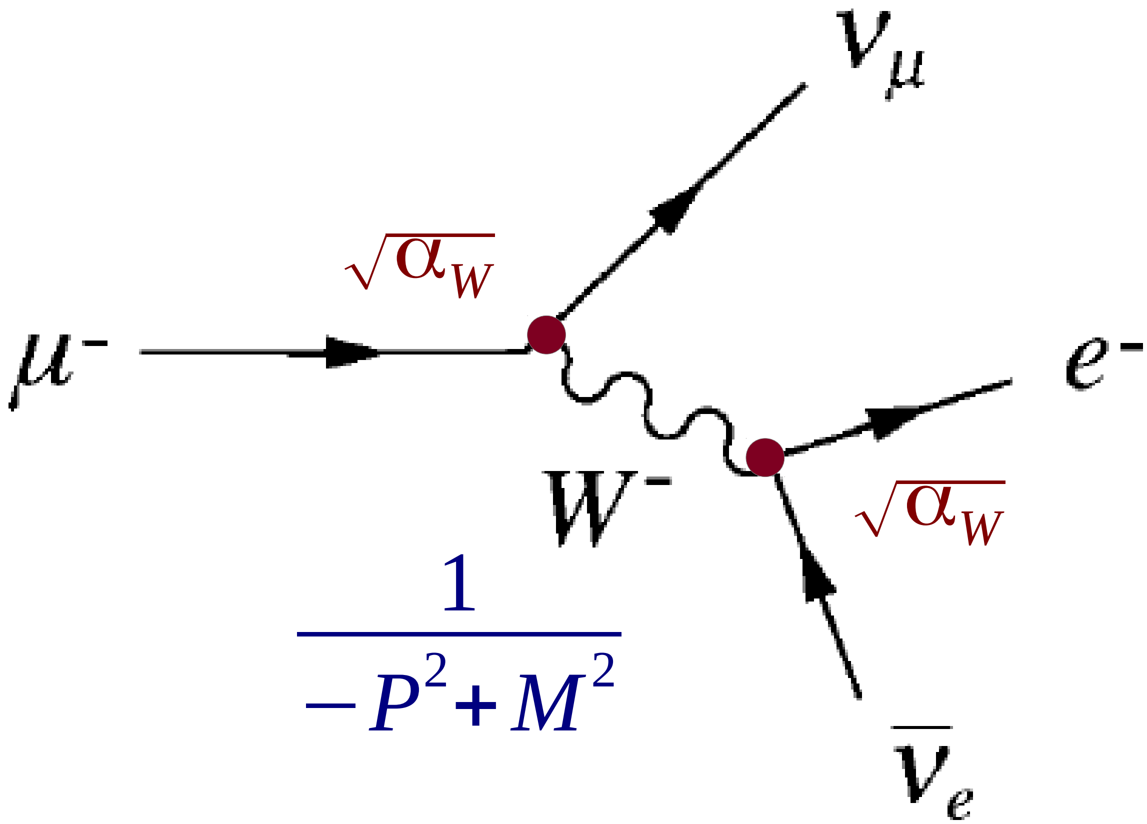


Figure 2.5 Dominant Feynman diagram for muon decay.

Estimate α_W from G_F

- $G_F = 1.166 \times 10^{-5}\ GeV^{-2}$
- Relation:

$$\frac{G_F}{\sqrt{2}} = \frac{g_W^2}{M_W^2} = \frac{4\pi\alpha_W}{M_W^2} \qquad (2.17)$$

- So $\alpha_W \sim 0.0042$, so that $\alpha_W \sim 0.58*\alpha$
- Couplings are very similar
  - Points to same origin!

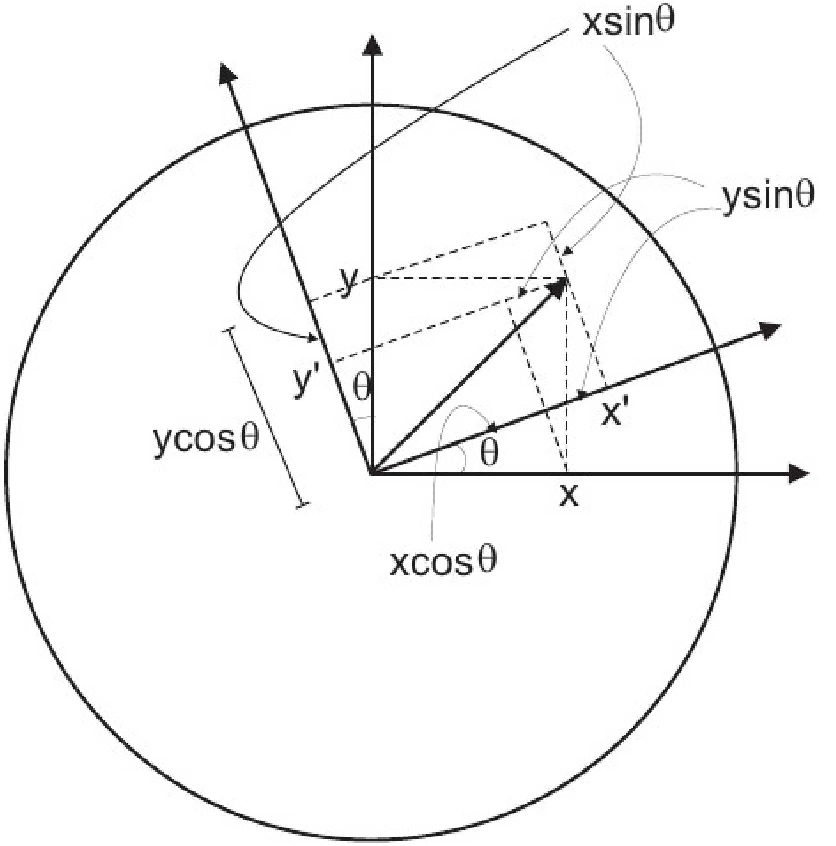
Electro weak unification

- The 3 bosons associated with weak interactions are W+, W-, and W0 (not Z0)!

  The process e → e + Z0 has similar partner:

  - The process e → e + gamma
- The neutrino does not have this but the claim is that also not photon is the basic boson:
  - Rather there is e → e + B and ν → ν + B!

~~Neutrino oscillations~~
~~Quark mixing~~
Gauge boson mixing!



$$x' = x\cos\theta + y\sin\theta$$

$$y' = y\cos\theta - x\sin\theta$$

The gauge bosons are mixed

- The weak interaction couples to “rotated” states:

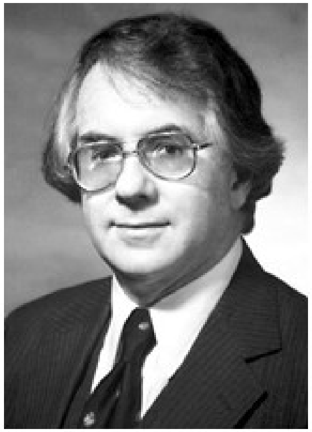
  $|\gamma> = |B> * \cos \theta w + |W0> * \sin \theta w$

  $|Z0> = - |B> * \sin \theta w + |W0> * \cos \theta w$

- The angle $\theta w \sim 30$ degrees is called the weak mixing angle (or the Weinberg angle)
- We follow Leif's notes here

The Nobel Prize in Physics 1979

Sheldon Glashow, Abdus Salam, Steven Weinberg



Sheldon Lee Glashow

Abdus Salam

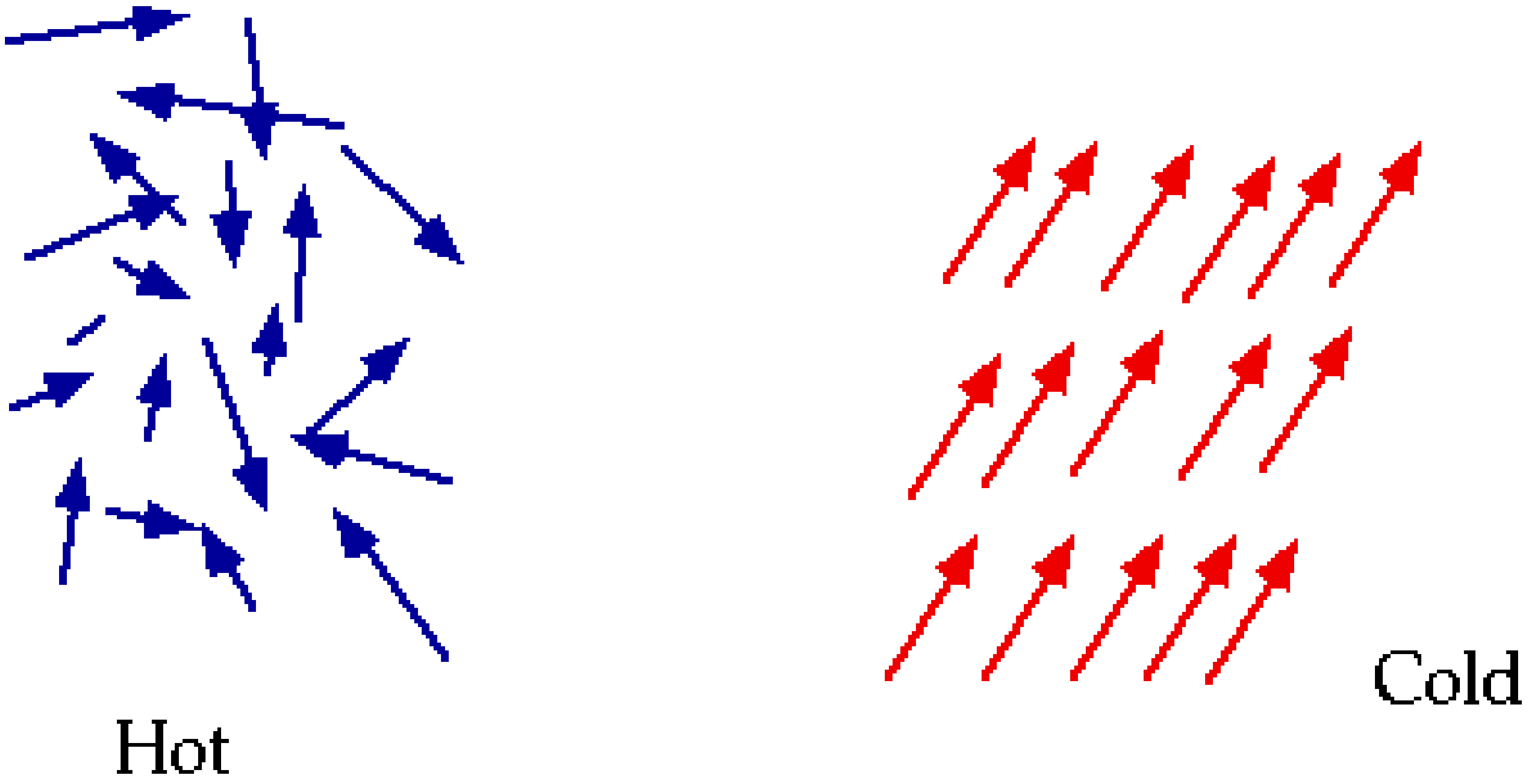
Steven Weinberg

The Nobel Prize in Physics 1979 was awarded jointly to Sheldon Lee Glashow, Abdus Salam and Steven Weinberg *"for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current"*.

Higgs mechanism

- Important ingredient for explaining why the gauge bosons can be massless which is normally not allowed!

Vacuum does not have to be empty



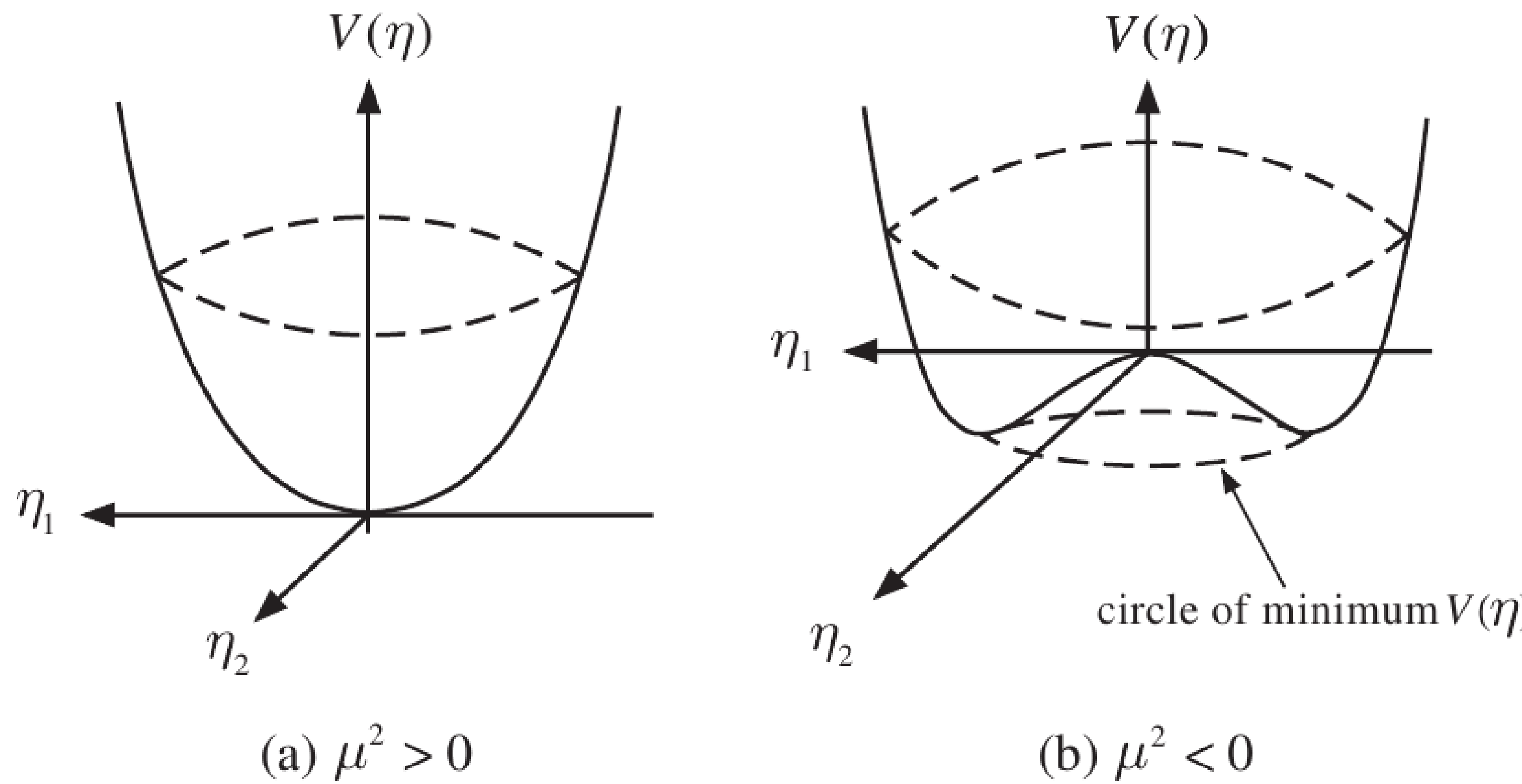


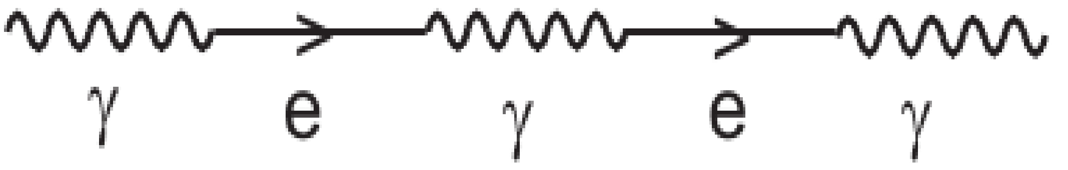
Figure 9.14 The potential energy density $V(\eta)$, as given by Equation (9.39), for $\lambda > 0$.

The ground state is not necessarily empty

- Due to interactions the ground state with large vacuum fluctuations can have lower energy than the empty state
- Vacuum = ground state (not empty state!)
- Particles can interact with vacuum particles and be modified i.e. gain mass
- The vacuum condensate is assumed to be neutrino like

From Leif's notes

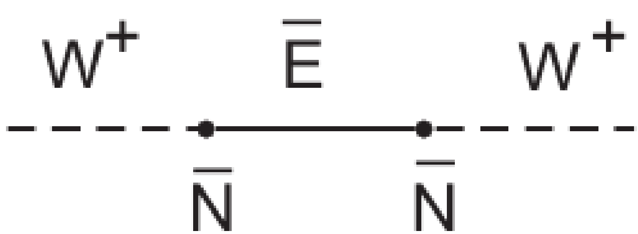
Basic idea:

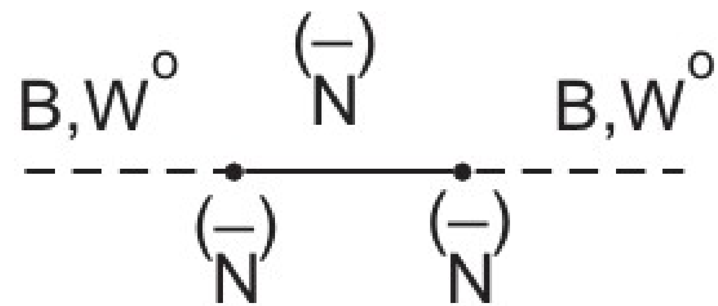


From Leif's notes

Basic idea:

Interactions with vacuum particles N and N-bar:





N ($\bar{N}$) is neutrino like and E ($\bar{E}$) are electron like.
In particular the couplings are exactly the same.
This guarantees that the photon remains massless.

Important Higgs result

- The weak mixing angle can be related to the ratio between the masses:

$$\cos\theta_W = \frac{M_W}{M_Z}$$

The number of states is constant

Degrees of freedom:

1) In the electroweak theory

Massless $W^+, W^-, W^o, B \otimes$ 2 polarization states	$4 \otimes 2 = 8$
$N, \overline{N}, E, \overline{E}$	4
Σ	12

2) Experimentally

Massive $W^+, W^-, Z^o \otimes$ 3 polarization states	$3 \otimes 3 = 9$
Massless $\gamma, \otimes 2$ polarization states	$1 \otimes 2 = 2$
Σ	11

The remaining degree of freedom corresponds to the Higgs particle.

So what is the Higgs

- The Higgs mechanism (E, E-bar, N, N-bar) provides mass to the Z and W
  - And it is assumed that in fact all free masses of quarks and leptons are generated in a similar way
- The remaining field is the Higgs particle
- <u>It couples to mass</u> (not EM charge, weak charge or color)!
  - (That is also how/why it gives mass)

Higgs production (remember g_{HX} proportionl to mass)

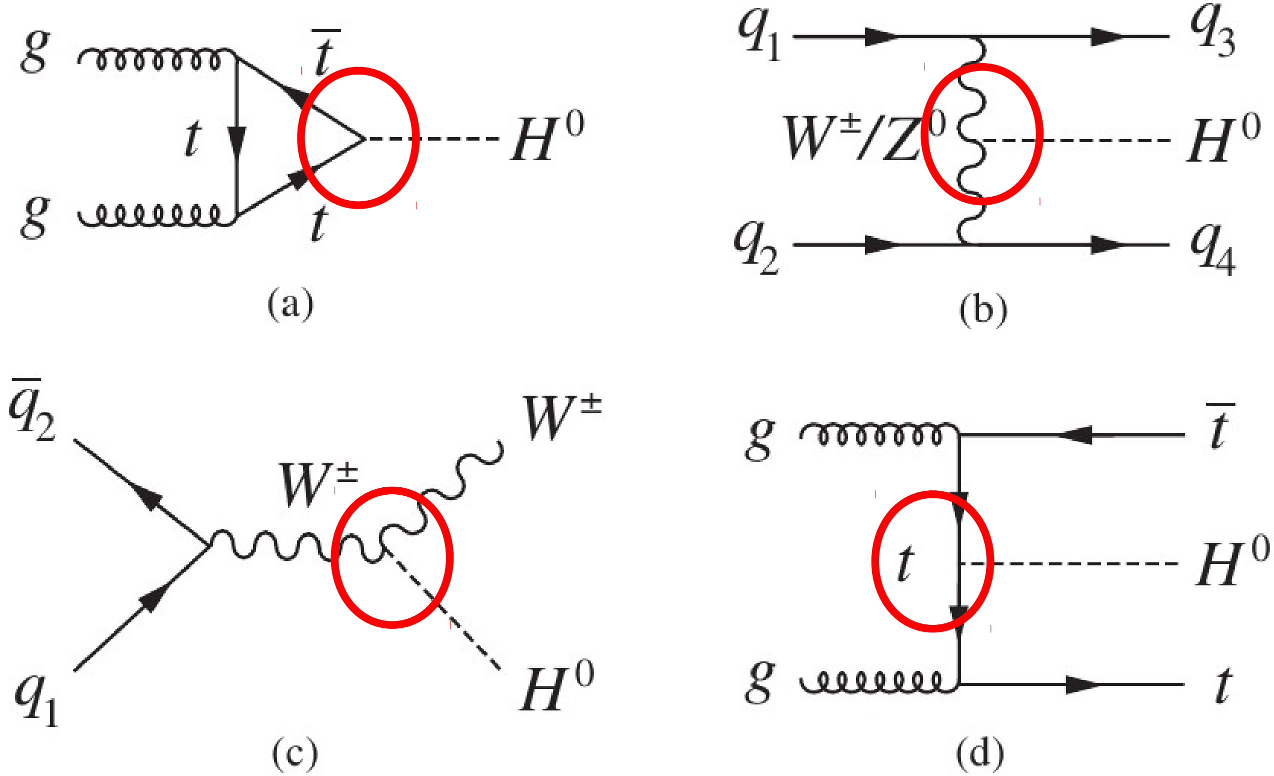


Figure 9.23 Production mechanisms for a standard model Higgs boson at the LHC.

Higgs Xsection at LHC max energy as a function of its mass

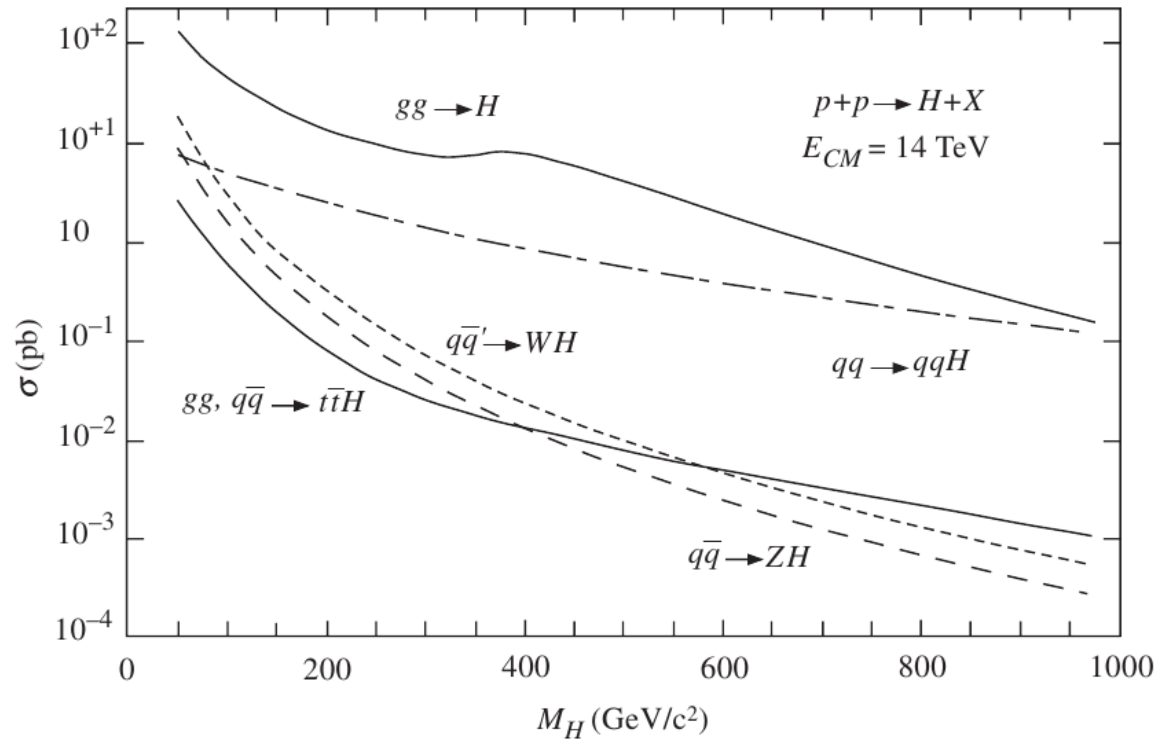
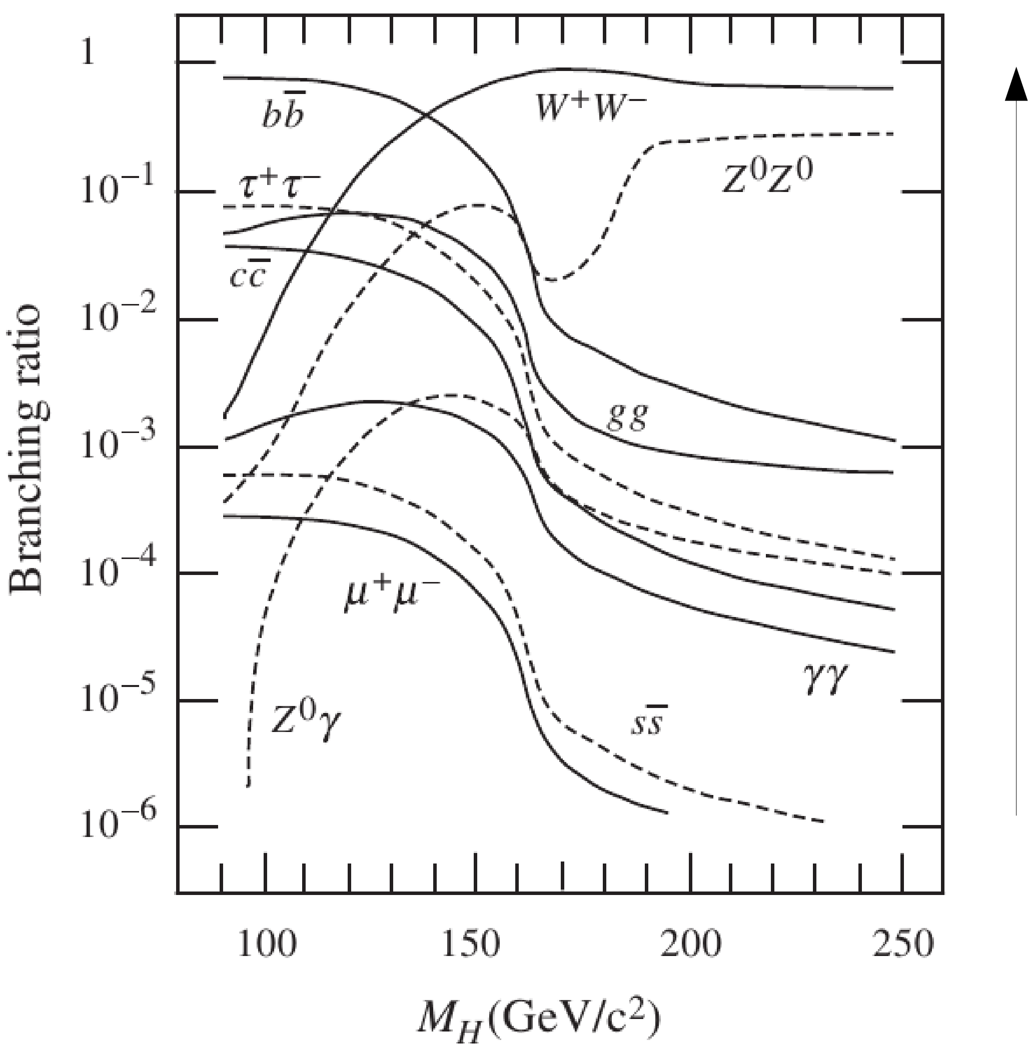


Figure 9.24 Production cross-sections of the standard model Higgs boson at the LHC at $E_{CM} = 14$ TeV. (With kind permission from Springer Science and Business Media, Kunszt *et al.*, *Zeitschrift für Physik C*, **74**, 1997, 479)

Possible Higgs decays (depending on mass)



Roughly Mass Ordering

Heavy Higgs decays

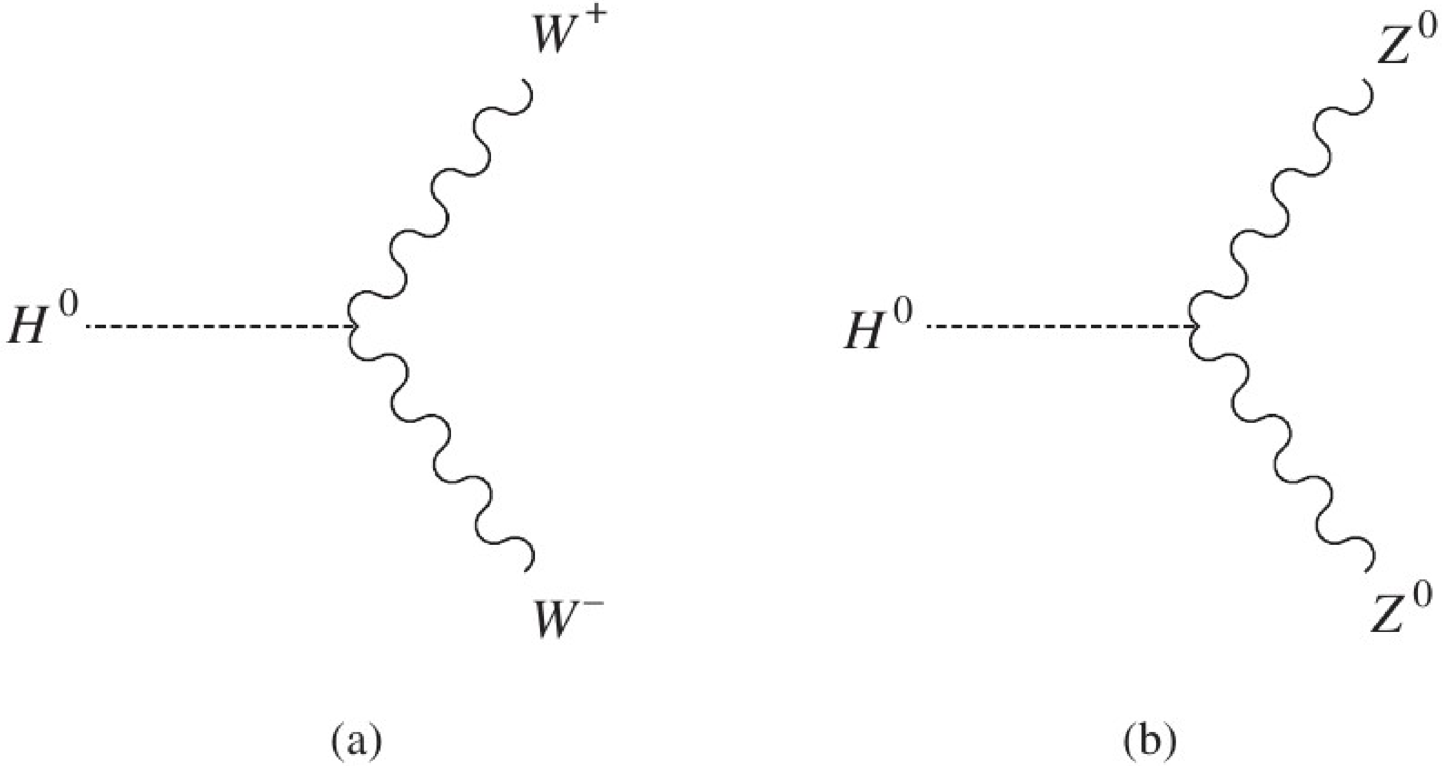


Figure 9.18 Decays of the Higgs boson to (a) W^+W^- and (b) Z^0Z^0 pairs.

Light Higgs decays

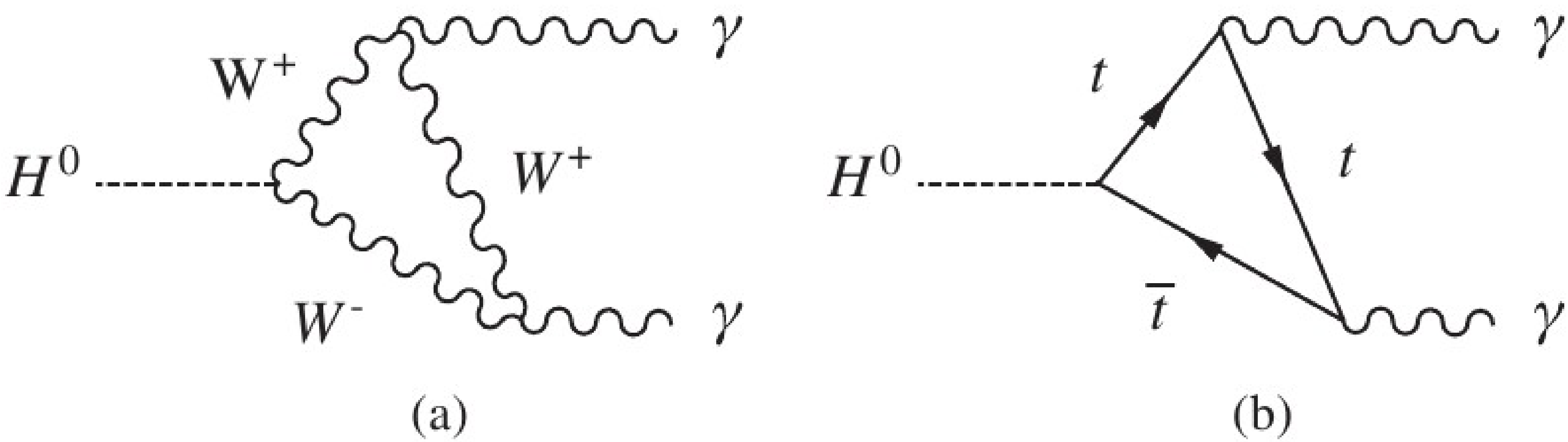
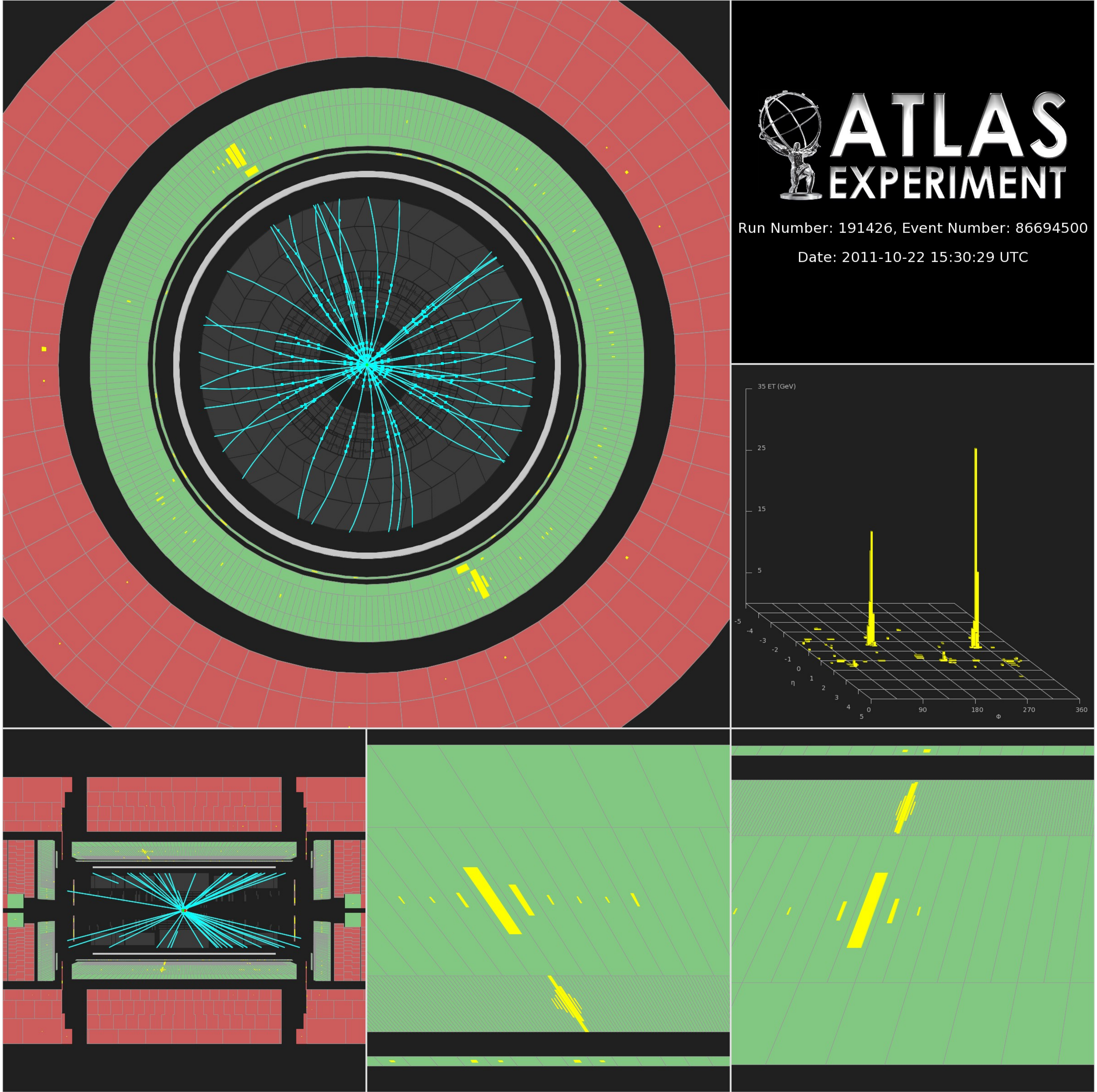


Figure 9.19 The dominant mechanisms for the decay $H^0 \to \gamma + \gamma$.


ATLAS
EXPERIMENT
Run Number: 191426, Event Number: 86694500
Date: 2011-10-22 15:30:29 UTC
35 ET (GeV)
25
15
5
η
Φ
0
90
180
270
360

Best Higgs signature: H → 2γ
2012 discovery