name: **group:**

Exercise Sheet 13 – Particle Physics – SS 2016

hand in: Tue 19th July (after the lecture or at INF 226, 3.104 by 4 pm)

13.1 Polarized Beams (6 points)

Electrons and positrons are collided at two different center-of-mass energies $\sqrt{s_1} = 20$ GeV and $\sqrt{s_2} = 91$ GeV. The process $e^+e^- \to \mu^+\mu^-$ is observed.

a) For both center-of-mass energies compute the relative production rates for the following running conditions:

- Both beams are unpolarized.
- The electron beam has left-handed polarization, the positron beam is unpolarized.
- The electron has left-handed and the positron beam has right-handed polarization.

b) What is the fraction of left- to right-handed outgoing μ^- particles in each of the above 2×3 cases?

Hints: Consider only the dominant process at each center-of-mass energy. Neglect the masses of the leptons.

13.2 Number of neutrinos (6 points)

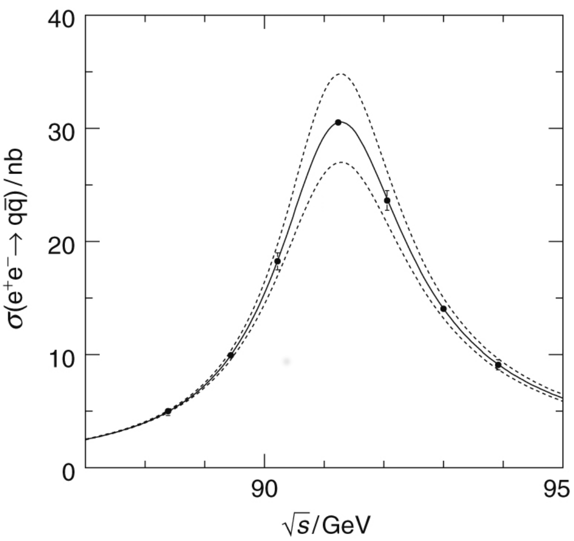

Figure 1: The measurement of the $e^+e^- \to q\bar{q}$ cross section from LEP close to the Z resonance compared to the Standard Model expectation for two, three and four light neutrino generations. Taken from Thomson.

Precision measurements of Z-boson decays are corner stones of the standard model. The partial decay width for the Z-decay into a fermion anti-fermion-pair is given by

$$\Gamma_f = \frac{g_Z^2 m_Z}{48\pi} g \left(\left(c_V^f\right)^2 + \left(c_A^f\right)^2 \right) \tag{1}$$

where $g = 3$ for quarks and $g = 1$ for leptons and $g_Z^2 = g_W^2/\cos^2\theta_W$. The couplings c_V^f and c_A^f depend on the weak mixing angle and the particle type involved and are given in Table 15.1 on page 423 of Thomson (available electronically via the UB).

a) Compute the partial decay widths for the decay to

- charged leptons
- hadrons
- neutrinos

using $\sin^2\theta_W = 0.23$.

b) Assume that, in addition to the known decay products, the Z boson can also decay into pairs of massless neutrinos and anti-neutrinos of a fourth generation. Compute the change in the total decay width due to these additional particles (assuming the values of c_V^f and c_A^f do not change).

c) Figure 1 shows the measurement of the $e^+e^- \to q\bar{q}$ cross section from LEP close to the Z resonance compared to the Standard Model expectation for two, three and four light neutrino generations. Label *correctly* the dashed and solids lines according to the number of light neutrinos used for the calculation of the expectation.
Hint: The cross section at the peak of the Z resonance is given by $\sigma(e^+e^- \to Z \to f\bar{f}) = \frac{12\pi}{m_Z^2}\frac{\Gamma_{ee}\Gamma_{ff}}{\Gamma_Z^2}$.

d) Under what conditions could additional neutrinos exist and be compatible with the measurements?

13.3 Rediscovery of the Standard Model (4 points)

One of the first tasks to be carried out at the LHC experiments after the succesful start of operation in 2010 was the "Rediscovery of the Standard Model". The measurement of well known resonances

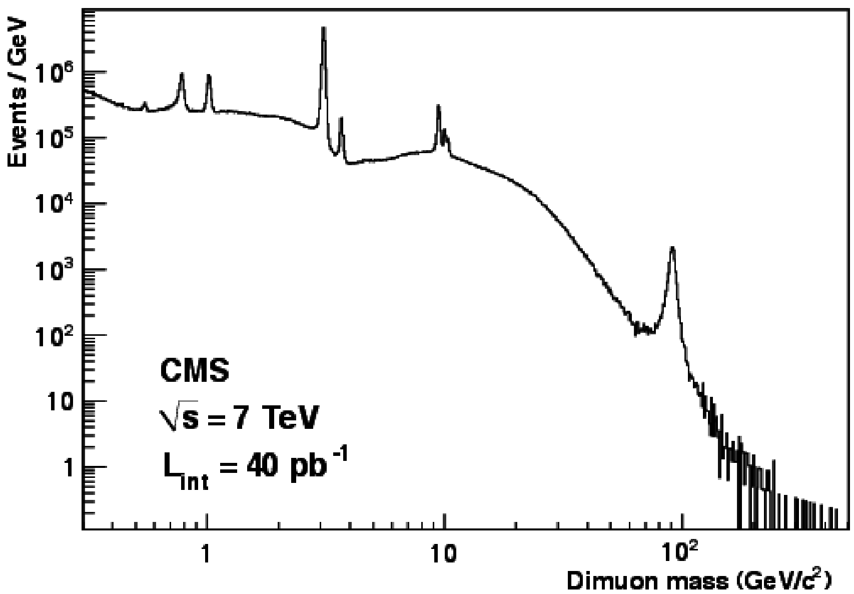

Figure 2: Number of events with two muons as a function of the dimuon mass recorded by the CMS detector.

provides important information about the performance of the detectors. The number of events containing two opposite-sign muons recorded at the CMS detector in 2010 is shown in Figure 2 as function of their invariant mass.

a) Label the seven resonances visible in Figure 2 and write down the quark content for the mesons.
Hint: Consider the following resonances: J/ψ, ϕ, η, Z, ρ, ω, Y, ψ'.

b) Explain the continuum between the resonances and draw the relevant Feynman diagram(s).

c) Consider a hypothetical resonance, X, at 20 GeV with a width of 2 GeV. Calculate how many additional events would be needed to claim a discovery.
Hint: To claim a discovery 5 times more events than the uncertainty of the continuum need to be detected.

d) In your spare time you decided to extend the Standard Model and your new theory now includes the aforementioned hypothetical resonance. You calculated the predicted cross section of the new resonance to be $\sigma_{pp \to X \to \mu^+\mu^-} = 16.5\,\text{pb}$. Assuming an efficiency of $\varepsilon = 70\,\%$ for events from the decay of X, would you be able to claim discovery and win the Nobel prize?

13.4 Observation of neutrino-like interactions without muon or electron in the Gargamelle neutrino experiment (4 points)

Read the paper ”Observation of neutrino-like interactions without muon or electron in the Gargamelle neutrino experiment” (Physics Letters B, Vol. 46, 138 (1973)) and answer the following questions:

a) What beam was used in the experiment?
b) How is the bubble chamber read out?
c) How are hadrons separated from muons?
d) What is the most important source of background? How is its size estimated?
e) What did the experiment discover? How many events of this type were observed?
f) How did they measure $\sin^2\theta_W$?