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Bounds on a Light Higgs produced through a Bremsstrahlung process

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Abstract

Theoretical expectations on the production of a light Higgs through a bremsstrahlung process in hadronic interactions, combined with data from a search for neutral heavy leptons, are used to establish limits on the mass of a neutral light Higgs boson.

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1. Introduction

In the Standard Model the spontaneous symmetry breaking mechanism gives mass to the W and Z particles through their coupling to a scalar boson, the Higgs [1]. The mass of such a particle is not predicted by the theory, and at present no Higgs has been observed experimentally. In the minimal Standard Model, there is a theoretical lower limit on its mass given by [2]:

$$M_H^2 > (7.2 \text{ GeV})^2 [1 - (m_t / 80 \text{ GeV})^4] \quad (1)$$

where m_t is the mass of the top quark. If m_t turns out to be greater than 80 GeV a re-examination of the limit will be necessary. There are more elaborate models with more Higgses, but in general no lower limit can be derived in such models [3].

Experimentally several Higgs mass regions have been excluded. A first lower limit ($M_H > 14 \text{ MeV}/c^2$) was obtained by observing the decay of an excited state of He^4 [4]. A study of neutrino experiment data led to the limit $M_H > 40 \text{ MeV}/c^2$ [5]. The mass window $10 \leq M_H \leq 110 \text{ MeV}/c^2$ was ruled out by the SINDRUM collaboration from an analysis of pion decay [6]. The study of K, B and Y decay excluded $2 m_\mu \leq M_H < 700 \text{ MeV}/c^2$ for some values of the top mass [3]. To summarize an allowed Higgs mass window exists in the region $110 < M_H < 210 \text{ MeV}/c^2$.

Since the Higgs boson plays a very important role in the Standard Model, it is of great interest to study the low mass regions still allowed for such a particle.

2. Higgs production by bremsstrahlung

In proton-nucleus reactions a light Higgs boson ($M_H \approx 30\text{-}200 \text{ MeV}/c^2$), with a Compton wavelength comparable to the nuclear size, could couple to the proton the same way it couples to an elementary fermion, namely proportional to the proton mass squared. The cross section for Higgs production through such a mechanism by an incoming proton with a momentum in the laboratory system, $p_{lab} \gg 1 \text{ GeV}/c$ is [7]

$$\sigma \approx 0.6 G_F m_p^2 \frac{\sigma_0^2}{B} \ln\left(\frac{\gamma}{B M_H}\right) \quad (2)$$

where $G_F = 1.2 \cdot 10^{-5} \text{ GeV}^{-2}$ is the Fermi constant, m_p is the proton mass, σ_0 is the total proton-nucleus cross section, $B/2$ is the slope of the forward elastic peak and γ is the relativistic factor of the incident proton in the laboratory system.

Figure 1.a presents the Higgs lifetime dependence on M_H . It ranges from 10 cm/c for $M_H \approx 10 \text{ MeV}/c^2$ to 0.1 cm/c for $M_H \approx 200 \text{ MeV}/c^2$. A Higgs with a mass smaller than twice the mass of a muon has two possible decay channels: $H \rightarrow \gamma\gamma$ and $H \rightarrow e^+e^-$. The branching ratio $H \rightarrow e^+e^-$ is shown in Figure 1.b versus the Higgs mass M_H calculated according to the formulae given in reference [3].

3. Heavy lepton search data

A search for long-lived neutral heavy leptons in 400 GeV/c proton interactions was carried out in the M2 neutral-hyperon beam line at Fermilab [8]. Figure 2 shows the set-up of the experiment. A beam of 400 GeV/c protons was incident upon a 4.9-m-long sweeping magnet which was used as a hadron absorber: the collimated channel of the magnet was plugged with stainless steel rods. A 1.3-m-thick wall of concrete followed the magnet, two walls of scintillation counters in coincidence were erected to veto charged particles. After the counters there was a vacuum decay volume of length 9.2 m and radius 18 cm, followed by a multiwire proportional chamber (MWPC), a scintillation counter TC, two more MWPC's, a superconducting analyzing magnet and then three more MWPC'S [8].

The experiment triggered on events with some signal in the spectrometer behind the vacuum decay volume in coincidence with no signal in the veto counters behind the magnet. In an analysis of charge-balanced two-track events where both particles passed through the analyzing magnet, no evidence of new neutral long-lived particles was found. That fact was used to put limits on the long-lived neutral heavy lepton production.

In order to extract an upper limit on the production cross section, the heavy lepton acceptance was calculated with a Monte Carlo program for different values of the lifetime, mass, Feymann-x (x_F) and transverse momentum (p_T) of the particle. The program took into account the decay volume as well as the apertures of the first three MWPC's and the analyzing magnet. For a given heavy lepton decay channel with branching ratio BR, the 90% CL limit on the production cross section per nucleon is given by the expression

$$\sigma < 11.2 \sigma_{pp} / (N_p A BR) \quad (3)$$

where σ_{pp} is the total pp cross section, A is the particle acceptance and $N_p = 2.8 \cdot 10^{13}$ is the integrated proton luminosity of the experiment. The numerical factor in the expression (3) is deduced from Figure 2 of reference [8], using a proton-proton cross section $\sigma_{pp} = 40 \text{ mbarns}$.

The authors concluded that the upper limit on the cross section for the production of neutral heavy leptons with $x_F \geq 0.2$ and $\theta_{lab} < 10 \text{ mrad}$ and their subsequent decay with branching ratio BR into two charged particles is $\sigma BR < 2.8 \cdot 10^{-35} \text{ cm}^2/\text{nucleon}$ at the 90% CL for the mass region less than 1.0 GeV/c² and the lifetime range between 10^{-10} and 10^{-8} sec.

4. Application to the Higgs case

A Higgs produced in a pFe collision and disintegrating inside the decay volume would satisfy the trigger of the heavy lepton search experiment [8]. In the present analysis the same data are used to put limits on the production of a light Higgs through a bremsstrahlung process. A Monte Carlo program is used to generate a Higgs produced by a 400 GeV/c projectile according to the expressions given in reference [7]. A total pFe cross section $\sigma_{pFe} = 1.120 \text{ barns}$ is considered [9]. Taken into account that the slope of the forward elastic peak is of the order of the proton radius [10], we consider $B/2 = 12.8 (\text{GeV}/c)^{-2}$. Figure 3 shows the x_F distributions of the Higgs produced for different values of the Higgs mass. The peak of the distribution shifts towards higher values as the mass of the Higgs boson increases.

A calculation of the Higgs acceptance is needed to deduce a limit on its production from the Heavy Lepton Search data. A computer program is used to simulate the spectrometer [8] taking into account the geometry of the experiment. In addition two adjustable parameters are considered to account for the detector efficiency and the analyzing magnet effect. Those parameters are tuned to obtain acceptances for neutral heavy (mass $< 2.5 \text{ GeV}/c^2$) leptons equal to or smaller than the ones reported by the authors in reference [8].

Once the Monte Carlo is tuned, the acceptance of a Higgs produced through a bremsstrahlung process is calculated. It ranges from $6.7 \cdot 10^{-3}$ for $M_H = 10 \text{ MeV}/c^2$ to $1.9 \cdot 10^{-5}$ for $M_H = 200 \text{ MeV}/c^2$. An experimental upper limit on the Higgs production is deduced using the expression (3). In our case BR is the $H \rightarrow e^+e^-$ branching ratio. In addition, since we are considering pFe collisions, the pp total cross section σ_{pp} must be replaced by σ_{pFe} . The limits obtained on the total production cross section are shown in Figure 4 along with the theoretical expectations from the expression (2). As can be observed, the uncertainty on the theoretical calculation is rather large [11], but in spite of this large uncertainty, the theoretical expectations are several orders of magnitude above the experimental upper limit. Therefore a light neutral Higgs with $M_H \leq 200 \text{ MeV}/c^2$ produced in hadronic collisions is excluded by the present analysis.

5. Conclusions

The use of data from a search of a heavy neutral lepton with mass smaller than $1 \text{ GeV}/c^2$ allow to exclude a neutral Higgs with $M_H < 200 \text{ MeV}/c^2$ produced through a bremsstrahlung mechanism in hadronic reactions.

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Figure captions

1. (a) Higgs lifetime versus its mass, (b) $BR(H \rightarrow e^+ e^-)$ versus the Higgs mass.
2. Experimental set-up of the Heavy Lepton Search at Fermilab [8]. C1 through C6 are MWPC's and TC is a scintillation counter used in the trigger. The veto consists of two planes of scintillation counters in coincidence. A possible Higgs decay into $e^+ e^-$ is indicated.
3. Feymann-x distribution of a Higgs particle generated in pFe collisions at 400 GeV/c, for different values of the Higgs mass.
4. Higgs production cross section by 400 GeV/c proton beam on Fe versus the Higgs mass: (a) theoretical prediction (b) 90% CL experimental upper limit obtained from the analysis

Figure 1

Figure 2

Figure 3

Figure 4