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Lower Limit of the Higgs Mass from Neutrino Experiment

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Abstract

Theoretical predictions of Higgs production from the decay $\pi \rightarrow e\nu h$ and of the branching ratio $h \rightarrow e^+e^-$ are used to estimate the number of Higgs that would have been detected in the neutrino experiment RSC (BNL) for different Higgs masses. A lower limit for a light neutral Higgs boson is deduced.

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1. Introduction

The phenomenon of spontaneous symmetry breaking is one of the most important ingredients of the Standard Model of electroweak interactions. This mechanism gives mass to the W and Z bosons through their coupling to a scalar Higgs particle [1]. In the simplest model there is a single Higgs. Its mass is not predicted by the theory. Other more complicated models predict more Higgs, but none of them has been observed. In the case of a single Higgs, a theoretical lower limit on its mass exists ($> 7 \text{ GeV}/c^2$). But this limit disappears if the heaviest fermion in the Standard Model has a mass of the order of $80 \text{ GeV}/c^2$, or if there are more undiscovered heavy fermions. In more complicated models, in general, no lower limit can be derived [2].

Usually the extraction of mass limits from the data is rather delicate since hard theoretical calculations and experimental results must be combined. Recently a review on the limits on the light Higgs mass has appeared [2]. Experimental results are analysed and compared with theoretical expectations. It appears that in the mass region below $1 \text{ GeV}/c^2$ only two regions are excluded: $m_h \leq 14 \text{ MeV}/c^2$ and $2m_\mu \leq m_h < 700 \text{ MeV}/c^2$ for some values of the top mass.

2. Higgs production from pion decay

The branching ratio for Higgs boson production from charged pion decay, is given by the expression [2]

$$BR(\pi^+ \rightarrow e^+ \nu_e h) = 6.5 \cdot 10^{-9} \left[(1 - 8x + x^2)(1 - x^2) - 12x^2 \ln(x) \right] \quad (1)$$

where $x = m_h^2/m_\pi^2$.

For a Higgs with $m_h < 2m_\mu$, the only decay modes are: $h \rightarrow \gamma\gamma$ and $h \rightarrow e^+e^-$. The width of the first process is given by [3]

$$\Gamma(h \rightarrow \gamma\gamma) = \frac{G_F m_h^3}{8\pi\sqrt{2}} \left(\frac{\alpha}{4\pi} \right)^2 \left(7 - \frac{4}{3} \sum_f Q_f^2 \right)^2 \quad (2)$$

and the width for $h \rightarrow e^+e^-$ [5]

$$\Gamma(h \rightarrow e^+e^-) = \frac{G_F m_e^2}{4\pi\sqrt{2}} m_h \left(1 - \frac{4m_e^2}{m_h^2} \right)^{3/2} \quad (3)$$

The branching ratio $h \rightarrow e^+e^-$ for different values of the Higgs mass is presented in Figure 1.a. As can be seen, the di-electron decay is the predominant channel for $m_h < m_\pi$. Figure 1.b shows the Higgs life time for different mass values. τ ranges from 10 cm for $m_h \approx 20 \text{ MeV}/c^2$ to 1 cm for $m_h \approx 100 \text{ MeV}/c^2$.

The SINDRUM collaboration has searched for the decay of $\pi \rightarrow e^+ \nu \phi$, where ϕ is a neutral particle decaying into e^+e^- [4]. They obtain upper limits on the branching ratio $BR(\pi \rightarrow e^+ \nu \phi)$ ranging from 10^{-9} to 10^{-11} depending on the mass and lifetime of the ϕ particle. Those data seem to rule out

a Higgs boson with $2m_e \leq m_h \leq 80 \text{ MeV}/c^2$ but a definitive statement must await a detailed study of the effects of the acceptance of the SINDRUM detector [2].

3. Method

Neutrino beams at proton accelerators are produced by the decay in flight of secondary hadrons produced in a target which is irradiated by the primary proton beam. A large shield placed downstream the target is used to absorb hadrons by interaction and muons by ionization loss.

Several collaborations have searched for anomalous neutrinos sources or weakly interacting neutral particles [6,7,8,9,10,11]. These are beam-dump experiments, where the target is placed just in front of the shield in order to absorb the hadronic cascade as quickly as possible. The short decay path minimizes the background of conventional leptons from the decay of known long-lived particles (π , K , Λ , etc), thus facilitating the search for penetrating particles. Leptons produced in this way are referred to as prompt.

A massive detector placed after the dump is used to detect interactions or decays of weakly interacting particles that have been able to cross the dump. Because the interaction cross section of such particles is very small, a very large number of primary interactions is needed (typically 10^{18}). Detectors are usually placed far away from the target, typically hundreds of meters. Therefore only particles with a long life time ($> 10^{-8}$) can be detected.

In the present analysis we study the probability of detecting a Higgs from pion disintegration through its decay into e^+e^- in neutrino experiments. Since the Higgs is a weakly interacting particle, it will traverse the dump until its decay point. Moreover if the Higgs is energetic enough (few GeV) its mean free path may reach several meters. Therefore the probability that it decays inside the detector into e^+e^- , predominant decay channel (see Figure 1), may not be negligible.

The probability per proton on target of observing a Higgs di-electron decay inside the detector may be expressed as

$$P_h = \eta D_\pi BR(\pi \rightarrow e \nu h) D_h BR(h \rightarrow e^+ e^-) \quad (4)$$

η is the detector acceptance, D_π is the probability that a pion decays before interacting; for beam-dump experiments a typical value is 10^{-3} . D_h is the probability that the Higgs disintegrates inside the fiducial volume of the detector. Its value is given by

$$D_h = e^{-\frac{L_1}{\alpha h \gamma_h}} \left[1 - e^{-\frac{(L_2 - L_1)}{\alpha h \gamma_h}} \right] \quad (5)$$

where $L_{1(2)}$ is the front(back) edge of the detector fiducial volume along the Higgs trajectory. The second term in parenthesis reflects the finite length of the detector. As can be observed, D_h has an exponential dependence on the target to detector distance. The expected number of Higgs decaying inside the detector is $N_h = P_h N_{col}$, where N_{col} is the number of protons on target.

A neutrino experiment must fulfil two requirements to be able to apply this method to its data: a target close enough to the detector and that a search for uncorrelated e^+e^- pairs in the detector has been performed.

The RSC collaboration [9] fulfills those requirements. The experiment was carried out with a proton beam of 28 GeV/c on a copper target, placed in front of a 30 meter iron dump. The detector, the 7-feet bubble chamber, was placed 13 meters behind the dump. The number of protons on target was $N_{col} = 1.3 \cdot 10^{18}$. They searched for uncorrelated e^+e^- pairs, produced by the decay of neutral weakly interacting particles. No events were found with such characteristics. This fact was used to put limits on axion production relative to pion production.

Data from a Gargamelle neutrino experiment has also been considered in this analysis [12]. Statistics are larger than the RSC collaboration but the target-detector distance is longer. We do not present limits on the Higgs mass from their data, since a simulation of the beam line used in the experiment is needed. Nevertheless, it has been estimated that the limits that could be deduced from the Gargamelle experiment would be equivalent to those from the RSC data within few per cent.

A Monte Carlo simulation is used to determine the probability, P_h , of detecting a Higgs decay ($h \rightarrow e^+e^-$) inside the detector. The interaction of the 28 GeV protons on the Cu target is simulated with the FRITIOF Monte Carlo [13]. Figure 2 shows the pseudorapidity distribution of charged particles for several hadron-Cu reactions at energies close to 28 GeV. Points represent the experimental data [14] and lines the Monte Carlo predictions. FRITIOF reproduces the shape of the distributions rather well, but it tends to shift the spectra towards higher values of rapidity. The fact that FRITIOF overestimates the forward production will increase the prediction on the number of observed Higgs, N_h . This effect, even though its influence is small, is taken into account to derive a lower limit for the Higgs mass.

The pions produced by the Monte Carlo decay ($\pi \rightarrow evh$) with a phase space prescription. The geometrical acceptance is estimated considering a detector fiducial volume 210 cm along the beam axis and a $110 \times 110 \text{ cm}^2$ cross section [9].

4. Results

In order to check the Monte Carlo performance the number of expected charged current neutrino interactions in the RSC detector has been calculated with the program and confronted with the experimental data. The Monte Carlo predicts 17, to be compared with 16 ± 5 found events. The agreement is rather good.

Figure 3 shows the number of expected Higgs decays inside the detector, N_h , versus the Higgs mass. As can be observed the dependence is very strong. N_h ranges from 10^4 for $m_h = 15 \text{ MeV}/c^2$ to 10^{-2} for $m_h = 60 \text{ MeV}/c^2$. This effect is mainly due to the strong D_h dependence on the Higgs gamma factor γ_h . (See (4), (5)). The lighter the Higgs, the larger γ_h and the longer its mean path.

An upper limit on the branching ratio $\text{BR}(\pi \rightarrow evh)$ is deduced from the absence of uncorrelated pairs in the RSC data. Figure 4 shows the upper limit obtained, at 90% CL, versus the Higgs mass along with the theoretical value of the branching ratio $\text{BR}(\pi \rightarrow evh)$. The region where the theoretical expectation exceeds the experimental upper limit is excluded by the present analysis. A limit $m \geq 40 \text{ MeV}/c^2$ at 90% CL is deduced. It is to be noted that an error of 50% on the calculations would change the lower limit by less than 2%.

5. Summary

Data from the neutrino experiment RSC and theoretical estimations for Higgs production in pion decay are used to get a lower limit on the neutral Higgs mass. $m_h \geq 40 \text{ MeV}/c^2$ at 90% CL is obtained.

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Figure captions

1. (a)Higgs life time versus Higgs mass, (b)Branching ratio $h \rightarrow e^+ e^-$ versus Higgs mass.
2. Pseudorapidity distribution of charged particles for several hadron-Cu reactions. Points represent experimental data [14] and curves are FRITIOF predictions [13].
3. Number of Higgs that would have been expected to decay into $e^+ e^-$ pairs in the RSC bubble chamber versus the Higgs mass. Line is drawn to guide the eye.
4. Experimental upper limit of the decay $\pi \rightarrow e \nu h$ (solid line) and theoretical expected value (dashed line) versus the Higgs mass. The allowed and excluded regions deduced from the data are also shown.

Figure 1

Figure 2

Figure 3

Figure 4