THE PHYSICS OF THE STANDARD MODEL HIGGS BOSON AT THE LHC

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Abstract

Some topics related to Standard Model Higgs boson physics at the Large Hadron Collider are reviewed. Emphasis is put on an overview of QCD corrections to Higgs boson decay and production processes.

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1 Introduction

It is believed that the electroweak symmetry breaking $SU(2) \times U(1) \rightarrow U(1)_{em}$ and the generation of masses proceed via the Higgs mechanism. In the case of the electroweak Standard Model [1], the Higgs mechanism is implemented by a weak isodoublet scalar field φ with Lagrangian density (for a detailed review, see [2])

$$\mathcal{L}_{\text{Higgs}} = D\varphi^\dagger D\varphi + \mu^2\varphi^\dagger\varphi - \lambda\left(\varphi^\dagger\varphi\right)^2 . \tag{1}$$

For $\mu^2 > 0$, the field φ acquires a vacuum expectation value $v = \sqrt{\mu^2/2\lambda}$. The potential of the shifted field $\phi = \sqrt{2}(\varphi - v)$ has three flat directions and one direction corresponding to a massive mode for small fluctuations around the minimum. In the case of a global symmetry, the flat directions would correspond to three massless Goldstone bosons. Owing to the local nature of the gauge symmetry, however, these degrees of freedom become longitudinal components of the gauge fields, which thereby acquire a mass. The remaining massive mode is the physical Higgs boson.

The coupling of the Higgs boson to the electroweak gauge bosons Z^0 and $W^\pm$ is due to the minimal coupling via covariant derivatives. Fermions couple to the Higgs boson via Yukawa couplings, where the coupling is strongest to heavy particles like the τ lepton and the top and bottom quarks.

The vacuum expectation value of φ is known to be $v = 246$ GeV. Limits on the mass of the Higgs boson can be inferred from a possible triviality of the Higgs sector and from the requirement of vacuum stability up to a scale Λ [3, 4]. For a top quark mass of 175 GeV and for $\Lambda \approx 1$ TeV, the approximate bounds are 70 GeV $< m_H <$ 500 GeV. For $\Lambda \approx M_{\text{Planck}}$, the bounds 125 GeV $< m_H <$ 200 GeV are obtained.

In the next section, the two main search strategies for the Standard Model Higgs boson at pp colliders are reviewed. In Section 3 we give a brief overview of QCD corrections to decay and production processes of the Higgs boson, which have been calculated during the last few years.

2 The Search for the Higgs Boson

The LEP experiments have established a lower bound on the Higgs boson mass of $m_H \geq$ 63.8 GeV [5]. A lower bound of 85–90 GeV can be achieved at LEP2. Higgs particles with larger masses can be produced at hadron colliders (see [6], and for a recent review [7]).

We begin by reviewing the branching ratios of the Higgs boson, Fig. 1. For $m_H > 2m_Z$, the decay $H \rightarrow ZZ \rightarrow 4l$ provides a clean experimental signature. For 130 GeV $< m_H < 2m_Z$,

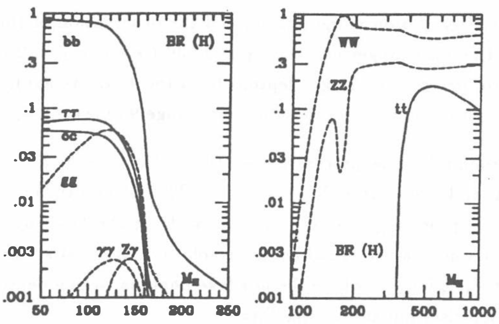

Figure 1: Branching ratios of the Standard Model Higgs boson

the decay H $\rightarrow$ ZZ* $\rightarrow$ 4l is still sizeable. For $m_H < 150$ GeV, the Higgs boson predominantly decays into $b\bar{b}$-pairs. The experimental signature for this process, however, is swamped by QCD background. The only reliable signature is the rare decay H $\rightarrow \gamma\gamma$, which is mediated by a loop of charged heavy particles ($W^{\pm}$-bosons and heavy quarks).

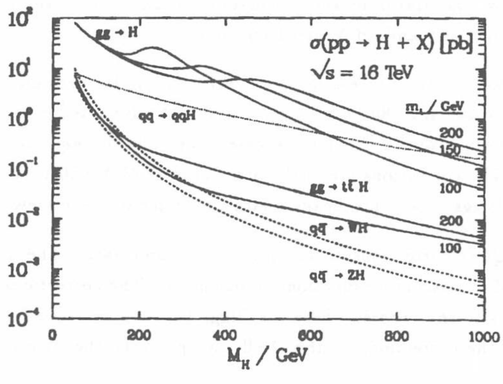

Figure 2: Production cross sections for the Standard Model Higgs boson in pp collisions

An overview of the production cross sections is given in Fig. 2 [8]. The main production mechanism of the Higgs boson at pp colliders is the gg fusion mechanism, which proceeds via a heavy-quark triangle loop. Other production mechanisms are WW and ZZ fusion, where the W and Z bosons have been radiated from the incoming quarks, $t\bar{t}$ fusion, where two $t\bar{t}$ pairs are produced by incoming gluons, and the radiation of a Higgs boson from a W or Z boson produced by $q\bar{q}$ fusion.

The main search strategies [6] for the Higgs boson at the LHC are, depending on its mass, the production of the Higgs boson via gg fusion, and the observation of the subsequent decays into ZZ and ZZ*, for the mass ranges $m_H > 2m_Z$ and 130 GeV $< m_H < 2m_Z$, respectively (the experimental signature being four charged leptons from the Z, Z* decays), and the observation of the decay into two photons, $H \to \gamma\gamma$, for the mass range 90 GeV $< m_H <$ 130 GeV.

The main background for the process $gg \to H \to ZZ^{(*)} \to 4l$ are the processes $pp \to ZZ^{(*)} + X \to 4l + X$ and $pp \to t\bar{t} + X \to 4l + X'$. The latter can be reduced by requiring that $m^2_{l^+l^-} = m^2_Z$. The process $gg \to H \to \gamma\gamma$ suffers from the large irreducible background $pp \to \gamma\gamma + X$, which requires a very good energy resolution for γ pairs, and from the reducible background pp $\to$ jet + jet, jet + γ, where the jets fake photons, which demands a detector with an excellent photon/jet-discrimination capability.

More refined search strategies based on the observation of particles or jets produced in association with the Higgs boson are discussed in detail in [9].

3 QCD Corrections

Here we briefly review the status of the calculation of QCD corrections to the decay and production processes of the Standard Model Higgs boson.

The QCD corrections to the process $H \to \gamma\gamma$ decay width [10] turn out to be small, of the order of 1–2% in the mass range 80 GeV $< m_H <$ 160 GeV. Results for the corrections to the decay $H \to gg$ have been given in [11] for the case of an infinite loop-quark mass and in [12] for the general case. The corrections are of the order of 60–70% for 50 GeV $< m_H <$ 400 GeV. For the decay of the Higgs boson into heavy quarks, we refer to the review in [13].

Now we discuss QCD corrections to the production processes. The vector boson fusion process can be treated in a structure function approach [14]. The corrections are of the order of 6–8%. The corrections to the process where the Higgs boson is radiated from a W or Z boson can be inferred from the corrections to the Drell–Yan process: they are of the order of 10% [15].

We finally come to the corrections to the process $gg \to H$. The first approaches have been in the limit for an infinite loop-quark mass [11, 16] (see also [17]). The general case for arbitrary quark masses is treated in [18, 12]. The corrections are large, leading to a K-factor[1] of about 1.6, see Fig. 3. Thereby the dependence on the renormalization and factorization scales is reduced by about 50%.

[1]The K-factor is defined by σ_{NLO}/σ_{LO}, where all quantities are consistently evaluated in leading and next-to-leading order, respectively.

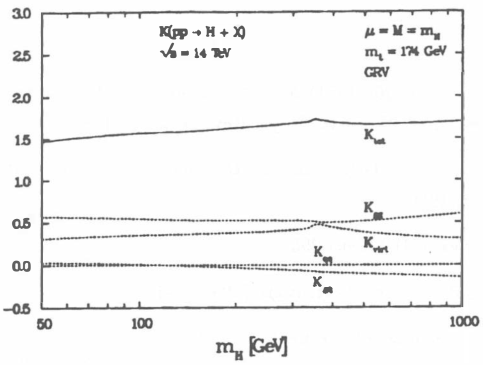

Figure 3: K-factors for the process gg → H+X

4 Summary and Conclusions

The study of the origin and nature of the electroweak symmetry-breaking mechanism is one of the most important tasks to be performed at the Large Hadron Collider. We have given a very brief overview of the physics of the Standard Model Higgs boson at this machine.

If $m_H > 2m_Z$, an elementary Higgs boson will certainly be found via the process gg → H → ZZ → 4l. For 130 GeV $< m_H < 2m_Z$, the search is more difficult, and proceeds via gg → H → ZZ* → 4l. In the mass range 90 GeV $< m_H <$ 130 GeV the search is very difficult. Here the rare decay H → $\gamma\gamma$ has to be exploited. In order to separate the signal from the background, a detector with a very good energy resolution for γ pairs and with an excellent γ/jet-discrimination is required [19].

The QCD corrections to the main decay and production processes of the Standard Model Higgs boson have been calculated during the last few years. Because of their possibly large size and of the large scale dependence of leading-order predictions, a solid study of the next-to-leading-order corrections had been necessary, in particular for the processes in the mass range where the search will turn out to be difficult. By now, the QCD corrections are well understood and the scale dependence is under proper control.

Acknowledgements

It is a great pleasure to thank my collaborators M. Spira and P.M. Zerwas for valuable discussions.

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