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Lineshape of the Higgs boson in future lepton colliders ☆

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ABSTRACT

The effect of the photon emission (initial-state radiation) in the cross section of the process of direct production of the Higgs boson in future high luminosity electron and muon colliders is calculated. It was found that the cross section at the top of the Higgs boson resonance peak is reduced by a factor 0.348 for the electron collider and 0.548 for the muon collider. A centre-of-mass energy spread of the centre-of-mass energy of 4.2 MeV (equal to the Higgs width) would reduce peak cross section further, by a factor 0.170 and 0.256 (QED and energy spread) for electron and muon beams respectively. Possible uncertainties in the resummed QED calculations are discussed. Numerical results for the lineshape cross section including QED and many values of the centre-of-mass energy spread are provided.

1. Introduction

The recent Higgs boson discovery at the CERN LHC [1–3] has initiated a new era of precision measurements of its properties. The measured Higgs boson mass, allows the observation and perhaps the study of its resonant production to be seriously considered at future electron or a dedicated muon colliders, via the processes $e^-e^+ \to H$ and $\mu^-\mu^+ \to H$. Due to the extremely small coupling of the Higgs boson to the electron, it seems at first sight that its direct production in the electron collider is just hopeless. However, in the Future Circular Collider with $e^\pm$ beams (FCCee) considered at CERN featuring very high luminosity, this process would in principle be observable, provided one could eliminate copious background processes. On the other hand, the stronger coupling of the Higgs to muons gives a dedicated muon collider a definite advantage, provided a decent luminosity and small centre-of-mass energy spread are achieved. In either case, centre-of-mass energy spread and an additional smearing of the beam energy due to QED initial-state radiation (ISR) are major points in the feasibility studies of these projects. This is why the present study was undertaken. The influence of the centre-of-mass energy spread on direct Higgs observation in a FCCee collider was already discussed at the 8th FCC-ee Physics Workshop [4]. In this work we shall concentrate mainly on calculating effects due to ISR of multiple photons. It is done using past experience in calculating very precisely the similar QED effect for Z boson production at LEP experiments, for instance in Ref. [5]. Similar analysis of the initial state QED corrections, taking into account the centre-of-mass energy spread, for $\mu^-\mu^+ \to H$ process can be also found[1] in Refs. [6] and [7].

The paper is organized as follows: After defining the Born cross section for Higgs production in lepton annihilation, we will discuss the effect of ISR corrections. We shall discuss theoretical uncertainties in the evaluation of this QED effect, presenting numerical results for three different QED ISR formulas, of varying sophistication level. The effect of the centre-of-mass energy spread in the cross section will be included in the discussion, presenting numerical results for several values of such a spread. Finally, analogous effects in planned muon colliders will be discussed and numerical results will be presented.

2. QED initial state radiation formulas

The Born cross section for the Higgs particle production in $e^\pm$ collider is given by the (relativistic [8]) Breit–Wigner (B-W) formula [5]

$$\sigma_B(s) = \frac{4\pi B_{ee}\Gamma_H^2}{(s-M_H^2)^2 + \Gamma_H^2 M_H^2}, \tag{2.1}$$

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where $M_H = 125.09$ GeV and $\Gamma_H = 4.2$ MeV according to Refs. [9–11]. The branching ratio of $e^+e^- \to H$ is $B_{ee} = 5.3 \cdot 10^{-9}$. The electron and muon branching ratios are related by the factor m_μ^2/m_e^2, thus the above result can be obtained from $B_{\mu\mu} = 2.19 \cdot 10^{-4}$; see also Refs. [10,11]. There are variants of the B-W formulas with an s-dependent width, but for a narrow resonance like the Higgs they differ negligibly from the above; see more discussion in the Appendix A.

The initial state radiation correction to this process was calculated using formulas of Ref. [5] for Z boson production.[2] The entire initial-state $\mathcal{O}(\alpha^2)_{prag}$ formula of the Ref. [5] integrated cross section reads:

$$\sigma_I(s) = \int_0^1 dv\ \rho_I(v)\sigma_B(s(1-v)),$$
$$\rho_I(v) = e^{\delta_{YFS}}\, F(\gamma)\, \gamma\, v^{\gamma-1}\, \{d_s + \Delta_H(v)\}\,, \tag{2.2}$$

where

I	d_s	$\Delta_H(v)$
(a)	1	0
(b)	$1+\frac{\gamma}{2}+A\frac{\alpha}{\pi}$	$v\left(-1+\frac{1}{2}\right)$
(c)	$1+\frac{\gamma}{2}+\frac{\gamma^2}{8}+A\frac{\alpha}{\pi}$	$v\left(-1+\frac{1}{2}\right)+\gamma\left[-\frac{v}{2}-\frac{1+3(1-v)^2}{8}\ln(1-v)\right]$

(2.3)

and

$$\delta_{YFS} = \frac{\gamma}{4} + \frac{\alpha}{\pi}\left(-\frac{1}{2}+\frac{\pi^3}{3}\right),$$
$$\gamma = 2\frac{\alpha}{\pi}\left(\ln\frac{s}{m_e^2}-1\right), \quad F(\gamma) = \frac{\exp(-C\gamma)}{\Gamma(1+\gamma)}. \tag{2.4}$$

Here, α is the QED coupling constant, m_e the electron mass and C is the Euler–Mascheroni constant. In the case of muon beams m_e in γ is replaced by m_μ and B_{ee} by $B_{\mu\mu}$.

The zero spin nature of the Higgs boson instead of spin one of the Z counts negligibly in the QED ISR effects, simply because the deformation of the resonance curve is mainly due to soft photons. The constant A which is responsible for the above spin difference is of order $\frac{\alpha}{\pi} \simeq 1/400$ without any logarithmic enhancement. It influences mainly an overall normalization – hence at the precision level we are aiming at, it can be safely set to zero.[3]

On the other hand, soft photon exponentiation/resummation in eq. (2.2) is critical and mandatory. The formula of eq. (2.2) comes from standard diagrammatic perturbative QED calculations including Yennie–Frautschi–Suura (YFS) exponentiation, see Ref. [5] and was originally introduced for the purpose of the algebraic validation of the Monte Carlo program YFS2 of Ref. [12]. Later on it was discussed and used in many papers; see for instance Refs. [5, 13–16] and the references therein.

The three variants (for $I = (a), (b)$ or (c)) of the ISR formula in eq. (2.2) correspond to the increasing sophistication (perturbative order) of the non-soft collinear radiative corrections. Changing the type of ISR formula will be used to estimate uncertainty due to unknown/neglected QED higher orders.

3. Centre-of-mass energy spread

In real accelerator experiments, the beam is not monoenergetic, i.e., centre-of-mass energy $E = \sqrt{s}$ has a spread δ around the centre value $E_0 = \sqrt{s_0}$ of the beam energy. The distribution of E is usually well approximated by the following Gaussian distribution:

$$G(E-E_0;\delta) = \frac{1}{\delta\sqrt{2\pi}}e^{-\frac{(E-E_0)^2}{2\delta^2}}. \tag{3.1}$$

Without QED effects, the Born cross section (2.1) gets simply convoluted with the energy spectrum of eq. (3.1):

$$\sigma_B^{conv}(E;\delta) = \int dE'\ \sigma_B(E')\, G(E'-E;\delta). \tag{3.2}$$

Once QED ISR is switched on, the following double convolution provides realistic experimental cross section:

$$\sigma_I^{conv}(E;\delta) = \int dE'\ \sigma_I(E')G(E'-E;\delta)$$
$$= \int dE' \int_0^1 dv \frac{1}{\delta\sqrt{2\pi}}e^{-\frac{(E'-E)^2}{2\delta^2}}\rho_I(v)\sigma_B(E'^2(1-v)), \tag{3.3}$$

for three variants, $I = (a), (b), (c)$ of the radiative function (2.2).

Because of the rapid decrease of the Gaussian distribution for large arguments, the energy integration range will be restricted to $E - 10\delta \le E' \le E + 10\delta$ without any loss of the calculation reliability. The numerical integrations in one and two dimensions require a little bit of care, because of strongly singular integrands. The adaptive integration library functions of ROOT library [17] were used. All results were also cross-checked using the FOAM adaptive Monte-Carlo simulator/integrator of [18–20].[4]

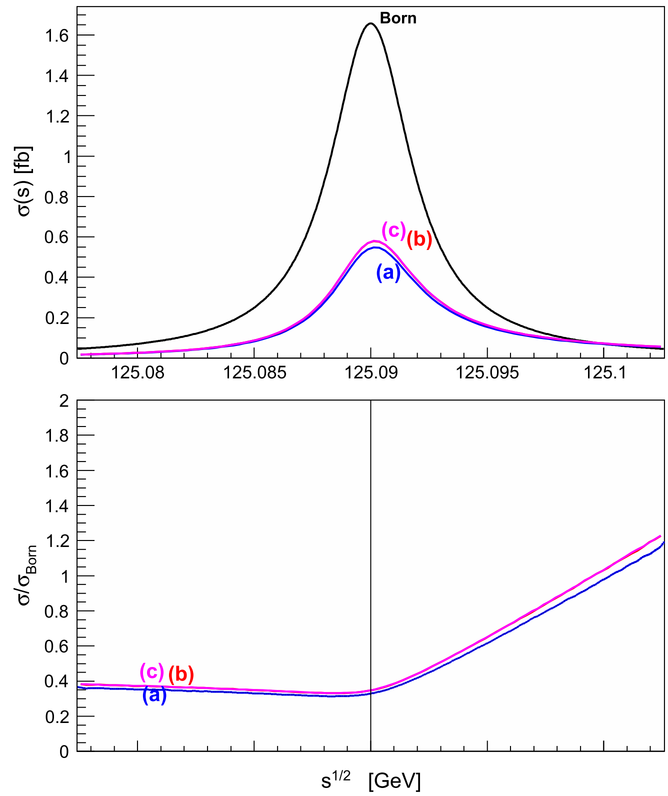

Fig. 1. Study of the pure QED effect in the Higgs line-shape for an electron collider. The plots show the Born cross section of eq. (2.1) and cross section affected by QED ISR, following eq. (2.2) for three types $I = a, b, c$ of the QED radiator functions defined in eq. (2.3). The ratios with respect to the Born cross section are also shown.

[2] See eq. (202) therein.

[3] Constant A is also set to zero in Ref. [7], while in Ref. [6] vertex and real-soft contributions are provided, but non-logarithmic constant A is explicitly obtained.

[4] Integration errors were also taken from FOAM, as they are more reliable.