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Study of Higgs boson decay to muon-antimuon pairs at center of mass energy 14 TeV

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Abstract

This paper estimates the Higgs boson production and its decay into muon-antimuon pairs ($\mu+\mu-$) at 14 TeV center of mass energy of proton-proton collisions in the High Luminosity Large Hadron Collider (HL-LHC) era, assuming integrated luminosities of 0.3 ab^{-1} and 3 ab^{-1}. The events in this study were generated using Monte Carlo tools, MadGraph5_aMC@NLO. The simulation of hadronization, fragmentation, Initial State Radiation (ISR) and Final State Radiation (FSR) processes was performed using Pythia8. The simulation of the detector was done using DELPHES. According to the most recent ATLAS and CMS measurements, the mass of the Higgs boson was assumed to be 125.35 GeV. The expected number of collision events were calculated for the SM Higgs and all Standard Model processes that give two muons in the final state. An estimate for the size of data needed for observing the Higgs boson in the above channel is also calculated.

Keywords: SM, Higgs boson, HL- LHC, CMS, ATLAS.

1. Introduction

In particle physics all measurements of High Energy Physics (HEP) experiments are in consistency with the Standard Model (SM) at a very high degree of precision. The Higgs boson discovery in 2012 by CMS and ATLAS experiments at CERN, is a major milestone in elementary particle physics. It confirms the so-called Brout-Englert-Higgs (BEH) mechanism and provides evidence for the SM [1-3]. In the SM, the Electroweak (EW) symmetry could be broken via the BEH mechanism that generates masses for the W^-, W^+, and Z gauge bosons (the mediators of the weak force), while leaving the photon (the electromagnetic force carrier) massless. The BEH is the mechanism through which the SM matter particles get their observed masses [4-7]. According to the CMS and ATLAS latest mass measurements, the Higgs boson

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has a mass of 125.35 ± 0.1 (statistical) ± 0.15 (systematics) GeV and has properties as predicted by the SM [8-10].

The HL-LHC can measure the Higgs boson decays modes to fermion-antifermion, like top-antitop ($t\underline{t}$), bottom-antibottom ($b\underline{b}$), tau-antitau leptons ($\tau^-\tau^+$), and muon-antimuon ($\mu^-\mu^+$) with Branching Ratios (BR) that depend on the squares of the masses of the corresponding fermion. For a Higgs boson mass (m_H) of 125.35 GeV, the SM BR of the Higgs decay into a pair of muons is 2.172×10^{-4} [11, 12]. Despite this very small BR (due to the small coupling between Higgs and a light fermion like muon), the Higgs decay to two muons is a very clean channel [13]. It allows us to measure the coupling of the Higgs to second-generation fermions, and could be used as a tool to probe Physics Beyond Standard Model (BSM). Searches for heavy particles decaying into two heavy vector bosons (WW or ZZ) and for Higgs decays into two muons are among the most sensitive probes of BSM physics. The signal Feynman diagram is shown in Fig. 1, where the (H) boson is produced via the dominant production mechanism gluon-gluon fusion (ggF). The SM dimuon production via Z-boson or virtual photon (γ^*) (the so-called Drell-Yan, DY), $Z/\gamma^* \rightarrow \mu^+\mu^-$, is the dominant irreducible background that has production cross-section times BR approximately three orders of magnitude higher than that expected from the Higgs boson. For the above reasons, we explore the Higgs boson decay to $\mu^+\mu^-$.

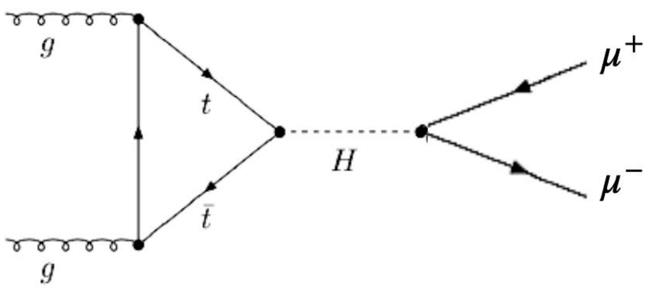

Fig.1.png. Feynman diagram of the Higgs boson produced via gg-Fusion and then decays into dimuons.

2. Samples Preparation and Simulations

The Signal and the SM backgrounds samples were generated using the matrix element generator, MadGraph5. Because quark confinement [14, 15] the hadronization process is necessary, it was done using Pythia8 [16]. Also, the so-called the Final and the Initial State Radiations (FSR and ISR) resulting from Electroweak (EW) and Quantum Chromodynamics

(QCD) processes, were simulated using Pythia8. The DELPHES fast detector simulator [17] was used to simulate the detector response. In our simulation, a detector configuration similar to that of the Compact Muon Solenoid detector (CMS) at the High Luminosity Large Hadron Collider (HL-LHC) was assumed.

In this paper, the term "signal" refers to the Higgs boson that decay to a pair of muons, while the term "background" refers to other standard model processes; DY, diboson (VV) production (WW, WZ, and ZZ), and top-antitop ($t\underline{t}$). Here under Tab.1 displays the full process cross-section in pico-barn (pb) for both signal and that of backgrounds, as well as their BRs in the dimuon channel.

Table 1. Production cross-sections and BR for signal and backgrounds at 14 TeV.

	Signal	DY	VV			tt^-
			WW	WZ	ZZ	
Cross-section (pb)	$4.786\text{x}10^{-3}$	895.5	895.5	0.09742	0.01156	7.561
Branching ratios	$9.7\text{x}10^{-5}$	$5001\ \text{x}10^{-8}$	0.012	$3.65\text{x}10^{-3}$	0.0011	0.0123

3. Muons and Cutflow to Select Events

For the baseline selection; all events have to have two isolated muons in the final state. Both muons should pass the tight working point criteria. Moreover, each muon has a transverse momentum, $p_T > 10$ GeV and has to be in the fiducial range of the muon system that's $|\eta| < 2.5$ and $|\eta| < 2.8$, for Run III and Run IV, respectively. Here (η) represents the pseudorapidity coverage and is given by the relation ($\eta = \ln \tan\theta/2$) with (θ) being the polar angle in yz-plane of the CMS coordinate system. Since the signal is a very rare process, this necessitates a careful selection of the events and needs a relatively large dataset to have enough statistics in order to be sensitive to new physics. Therefore, events are required to have two oppositely charged muons at least. This requirement is important to kill backgrounds from the same leptons charge processes. Then events are selected if the p_T-leading and p_T-subleading muon has $p_T > 25$ GeV and $p_T > 15$ GeV, respectively. Moreover, each event has to have transverse missing energy ($E_T^{miss} < 70$ GeV), in order to suppress backgrounds from two vector bosons (WW, WZ, and ZZ), and top-antitop (tt^-) processes.

4. Results and Discussions

The expected number of weighted events to be seen at the end of the current Run III of the LHC with a dataset size of 0.3 ab^{-1} is shown in Tab. 2 before (initial) and after applying all the selection cuts that were described in Sec. 3. The expected signal yield obtained is almost 745 events. The same investigation is performed at the foreseen Run IV of the high luminosity LHC (HL-LHC) in 2026 with an integrated luminosity (L_{int}) of 3 ab^{-1}. Tab. 3 lists the expected number of weighted events in this case with an expected signal yield of 10182 events. The signal significance (S) is computed for both Runs III and IV.

Table 2. Cut-flow table demonstrating the event yields for the signal ($H \rightarrow \mu^+\mu^-$) versus total backgrounds after each selection cut at 14 TeV and L_{int}= 0.3 $ab^{-1.}$ The significance is also presented in the last column.

	Signal (S)	DY	VV			$t\bar{t}$	Total Background (B)	S/√B
			WW	WZ	ZZ			
Initial (no cut)	1437.56	2.68 x 10^8	257755.5	27076.14	2.35 x 10^8	2.26 x 10^6	505546269.2	0.064
Nb. of muons > 1	829.2	1.26 x 10^8	133117.86	22203.31	2.22 x 10^8	1132904	347289054.4	0.0445
Two oppositely charged muons	829.04	1.26 x 10^8	133117.86	15175.4	1.34 x 10^8	1132224.36	261281346.7	0.0513
MET < 70 GeV	745.66	1.13 x 10^8	90152.6	9380.7	1.18 x 10^8	490104.72	231590383.7	0.049

Table 3. Cut-flow table demonstrating the event yields for the signal ($H \rightarrow \mu^+\mu^-$) versus total backgrounds after each selection cut at 14 TeV and L_{int}= 3 $ab^{-1.}$ The significance is also presented in the last column.

	Signal (S)	DY	VV			$t\bar{t}$	Total Background (B)	S/√B
			WW	WZ	ZZ			
Initial (no cut)	14375.64	2.69 x 10^9	2577555	270761.4	2.36 x 10^9	2.26 x 10^7	5071462692	0.202
Nb. of muons > 1	13507.34	2.44 x 10^9	2385752.7	269631.3	2.36 x 10^9	2.15 x 10^7	4824168891	0.2
Two oppositely charged muons	13490.1	2.44 x 10^9	2385295.2	185806.31	1.36 x 10^9	2.1 x 10^7	3823584592	0.22
MET < 70 GeV	10182.3	1.82 x 10^9	1338601.1	96589.23	1.0 x 10^{10}	7769100	1.193 x 10^{10}	0.1

The p_T distributions for the leading and subleading muons of the signal are shown in Fig. 2 and Fig. 3 at L_{int}= 0.3 ab^{-1} and L_{int}= 3 ab^{-1}, respectively. As depicted in Fig. 2 (a) and (b), the leading muon p_T is around 65 GeV for both L_{int} values, whereas that of the sub-leading muon is nearly 60 GeV, as shown in Fig. 3 (a) and (b). Fig. 4 (a) and (b) shows the dimuon invariant mass distributions after applying the full selections with almost 746 and 10182 total expected events at L_{int}= 0.3 ab^{-1} and L_{int}= 3 ab^{-1}, respectively. This is an important plot, as the di-muons events coming from the Higgs signal can be easily selected from other SM background events by the reconstructed Higgs mass (m_H = 125.35 GeV).

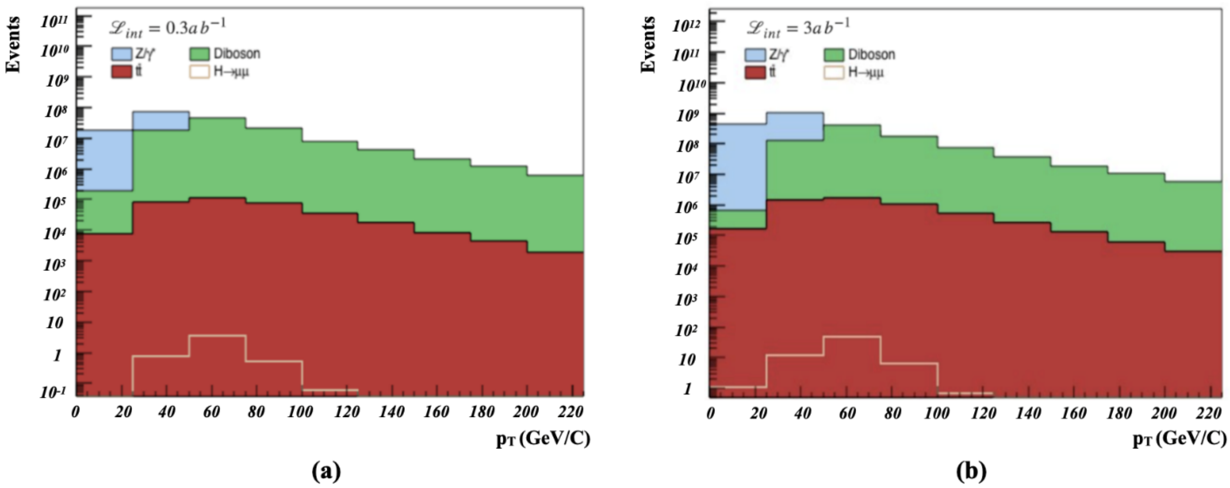

Fig.2.png. Transverse momentum p_T distributions for the leading muon of the ($H \to \mu^+\mu^-$) signal after the full selection at 14 TeV and L_{int}= 0.3 ab^{-1} (a) and L_{int}= 3 ab^{-1} (b).

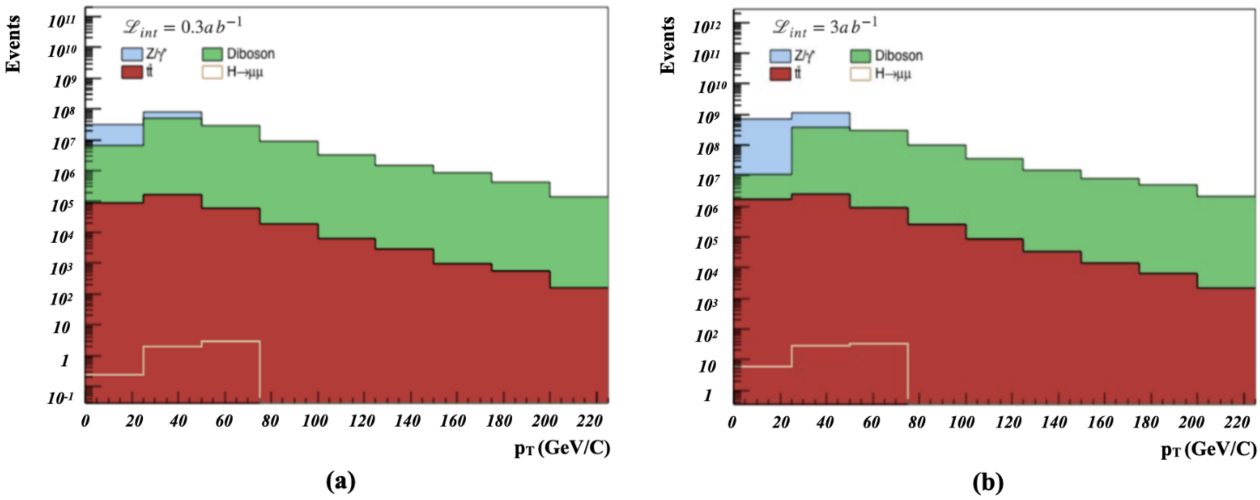

Fig.3.png Transverse momentum p_T distributions for the sub-leading muon of the ($H \to \mu^+\mu^-$) signal after the full selection at 14 TeV and L_{int}= 0.3 ab^{-1} (a) and L_{int}= 3 ab^{-1} (b).

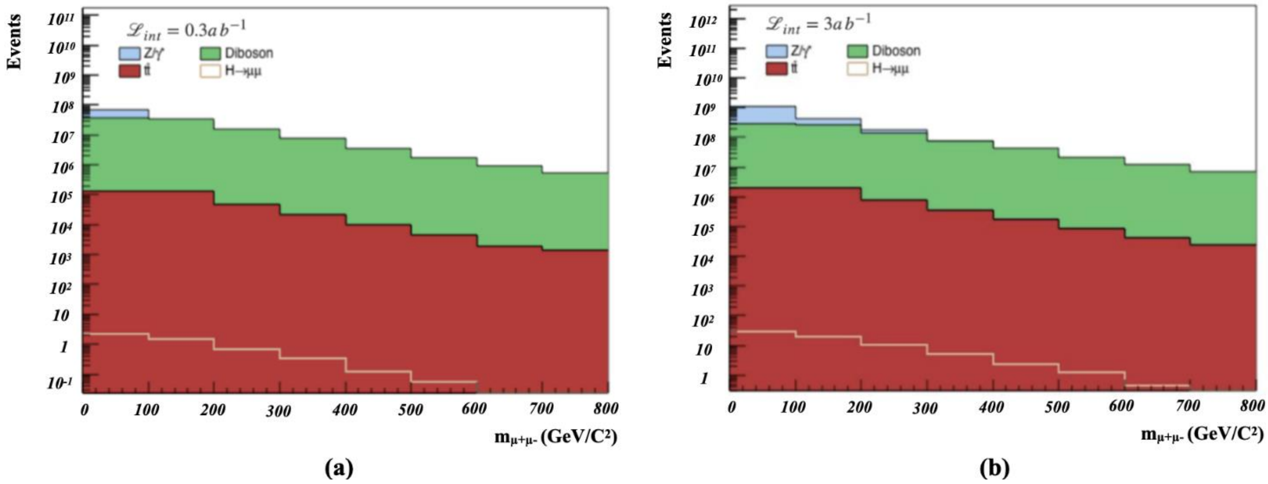

Fig.4.png. The two muons invariant mass spectrum after the full selection at 14 TeV and L_{int}= 0.3 ab^{-1} (a) and L_{int}= 3 ab^{-1}(b).

The p_T distribution of the reconstructed object from the two muons boson is depicted in Fig. 5. The events from the Higgs sample are accumulated in the low transverse momentum region (< 200 GeV) that is dominated by the SM backgrounds. This histogram is a good tool to be used to pick up events coming from the Higgs boson from that commencing from other heavy new particles predicted by new physics; like Z`-boson and B-meson [18].

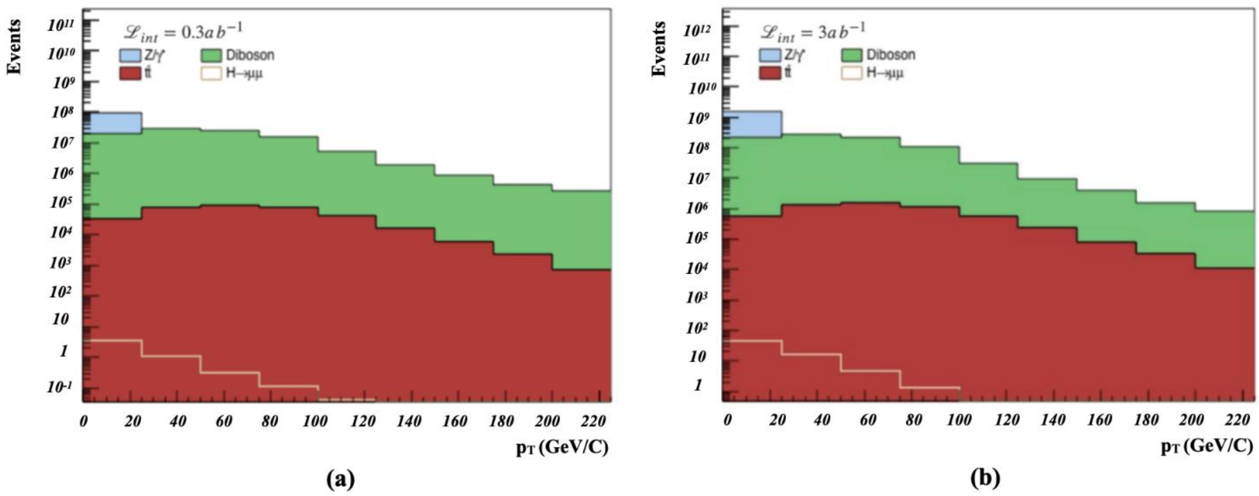

Fig.5.png. Transverse momentum p_T distributions of dimuons for the ($H \rightarrow \mu+\mu-$) signal at 14 TeV and L_{int}= 0.3 ab^{-1} (a) and L_{int}= 3 ab^{-1} (b).

Fig. 6 depicts the pseudorapidity flat distribution for the dimuons at both L_{int}. Through this distribution, the $H \rightarrow \mu^{+}\mu^{-}$ events could be distinguished as they are coming from the decay of a spin zero particle (like Higgs boson) from that coming from the decay of new heavy particle particles like Z`, which is a vector boson with spin = 1 that will give a different η-distribution.

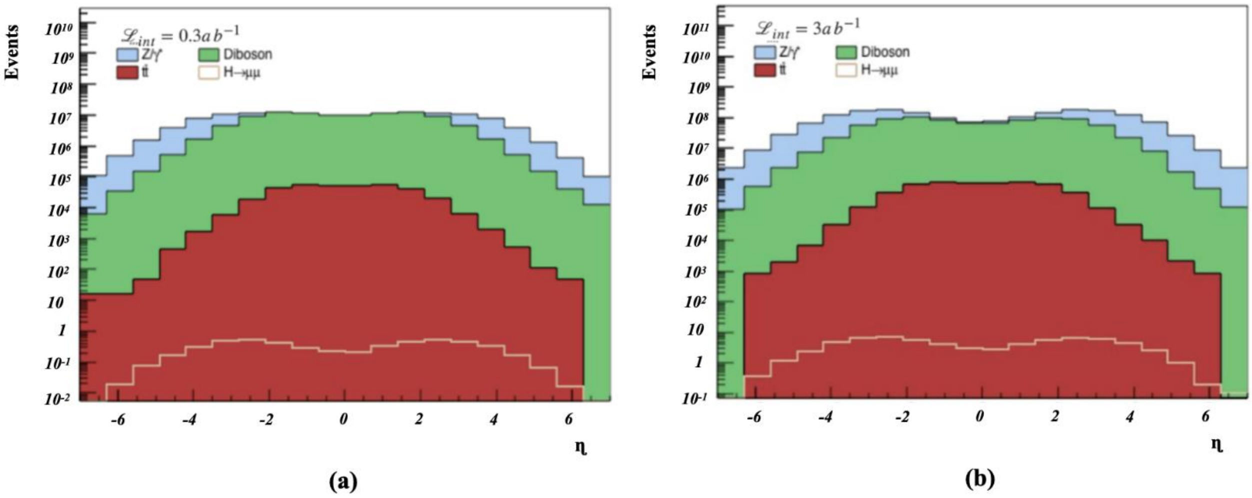

Fig.6.png. η-distributions of dimuons at 14 TeV and L_{int}= 0.3 ab^{-1} (a) and L_{int}= 3 ab^{-1} (b).

The angular separation (**Δ**R) between the leading and sub-leading muons of the signal are shown in Fig. 7 (a) and (b) for both L_{int}. It is obvious that the **Δ**R value at the peak region is almost 3.14, which corresponds to an angle of 180^0 indicating that the two muons emitted back-to-back due to the (H) boson decay.

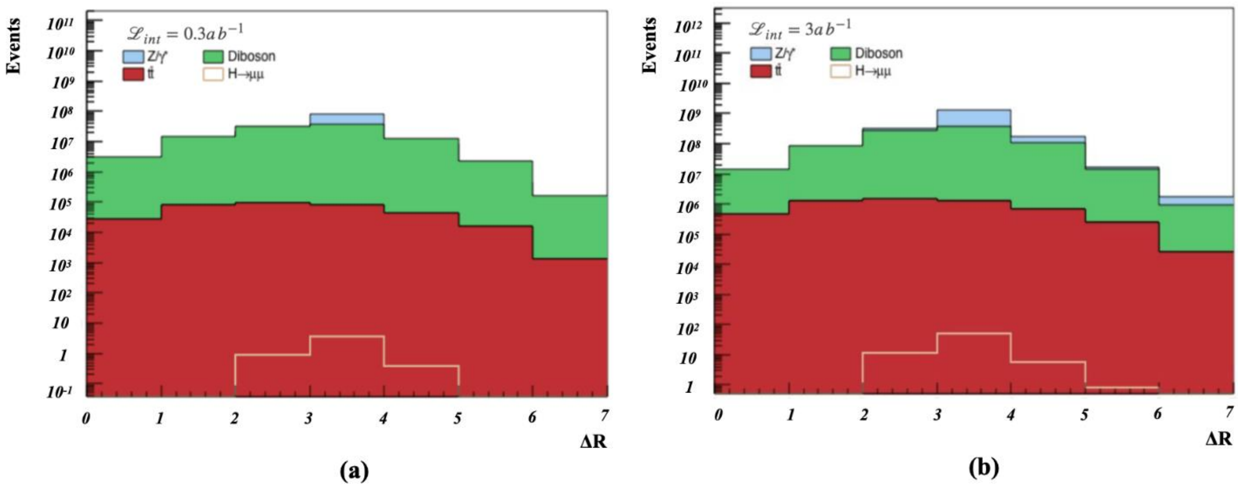

Fig.7.png. The angular separation (**Δ**R) between the leading and sub-leading muons at 14 TeV L_{int}= 0.3 ab^{-1} (a) and L_{int}= 3 ab^{-1} (b).

The statistical significance for the signal is estimated for Run III of the LHC (L_{int}= 0.3 ab^{-1}) and Run IV of HL-LHC (L_{int}= 3 ab^{-1}). As depicted in Fig. 8, it has been found that a datasets size of nearly 147185 ab^{-1} and 773608 ab^{-1} are required to to be collected during Run III and Run IV, respectively, to achieve a 5σ excess in the given channel at m_H = 125.35 GeV.

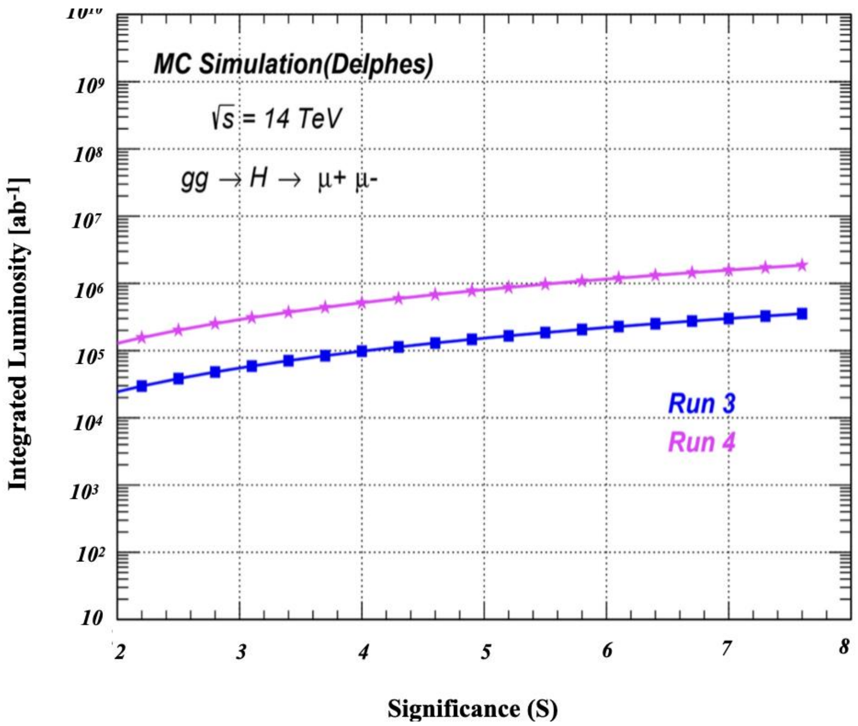

Fig.8.png. Integrated luminosity in ab^{-1} required to achieve a 5 σ excess in the $H \rightarrow \mu^+\mu^-$ events versus the statistical significance (σ) at Run III of the LHC and Run IV at 14 TeV.

5. Conclusion

An investigation of Higgs bosons that decay into a couple of muons is conducted assuming two scenarios Run III (0.3 ab^{-1}) and Run IV (3 ab^{-1}) of the CMS experiment. Based on this study, it has been found that a datasets of size much higher than targeted integrated luminosities for both Run III and RunIV are needed to have a 5σ excess in the ($H \rightarrow \mu^+\mu^-$) events at m_H = 125.35 GeV.

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الملخص العربى

دراسة اضمحلال بوزون هيجز لزوج من الميونات عند طاقة ١٤ تيرا إلكترون فولت

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ملخص

يتناول هذا البحث دراسة إمكانية إنتاج بوزون هيجز واضمحلاله إلى زوج من الميونات أثناء مرحلة تصادمات البروتونات الكثيفة في المصادم الهادروني الكبير (High Luminosity- Large Hadron Collider) عند مستوى طاقة ١٤ تيرا إلكترون فولت ومعدل تصادمات يساوي ٠،٣ ab^{-1} و ٣ ab^{-1}. تم إنتاج عينات عملية الاضمحلال الأساسية والعمليات المشابهة لها باستخدام احد برامج محاكاة مونت كارلو وهو MadGraph5_aMC@NLO. تمت محاكاة عمليات الهادرون والتجزئة بالإضافة إلى إشعاع الحالات الأولية والنهائية باستخدام برنامج Pythia٨. تم إجراء محاكاة الكاشف باستخدام DELPHES. وفقًا لأحدث قياسات تجارب ATLAS و CMS، تم افتراض كتلة بوزون هيجز كونها ١٢٥،٣٥جيجا إلكترون فولت. تم حساب عدد التصادمات المتوقعة لإنتاج بوزون هيجز وجميع العمليات المشابهة في النموذج القياسي (Standard Model) التي تعطي زوج من الميونات في الحالة النهائية للاضمحلال. تم أيضا حساب تقدير لحجم البيانات أو عدد التصادمات اللازمة لرصد بوزون هيجز في حالة الاضمحلال المذكورة أعلاه.