Diffractive Higgs: CMS/TOTEM Level-1 Trigger Studies

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Abstract

Retaining events containing a Higgs Boson with mass around 120 GeV poses a special challenge to triggering at the LHC due to the relatively low transverse momenta of the decay products. We discuss the potential of including into the CMS trigger the TOTEM forward detectors and possible additional detectors at a distance of 420 m from the CMS interaction point. We find that the output rate of a 2-jet Level-1 trigger condition with thresholds sufficiently low for the decay products of a 120 GeV Higgs Boson can be limited to $\mathcal{O}(1)$ kHz for luminosities of up to $2 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ by including the TOTEM forward detectors in the Level-1 trigger.

1 Introduction

A Higgs Boson with mass close to the current exclusion limit poses a special challenge to triggering at the LHC. The dominant decay of a Standard Model Higgs Boson of mass $\sim$120 GeV is into two b-quarks and generates 2 jets with at most 60 GeV transverse momentum, p_T, each. The so far considered Level-1 (L1) trigger tables of CMS [1] are optimized for events with high p_T; the necessity of keeping the overall L1 rate at acceptable levels requires thresholds in two-jet events above p_T =100 GeV per jet. Conversely, triggering is not a problem should the mass of the Higgs Boson be sufficiently high so that its final states are rich in high p_T leptons, as is the case for $H \to WW^\star$.

In order to retain a potential Higgs signal with mass close to the current exclusion limit, information beyond that from the central CMS detector needs to be included in the L1 trigger. A proton that scatters diffractively at the CMS interaction point (IP) may be detected by Roman Pot (RP) detectors further downstream. Roman Pot detectors up to 220 m downstream of CMS will be part of the TOTEM experiment [2]. Information from TOTEM will be available to the CMS L1 trigger. Furthermore, detectors at up to 420 m distance from the IP are currently discussed as part of the FP420 project [3]. Including information from them into the CMS L1 trigger is however not possible without an increase in the trigger latency.

This article discusses the effect of including the TOTEM forward detectors and/or those planned at 420 m distance on rate and selection efficiency of the CMS L1 trigger. All results reported in the following are preliminary; further studies are still on-going at the time of writing.

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2 Experimental apparatus

The CMS trigger system is designed to reduce the input rate of 10^9 interactions per second at the nominal LHC luminosity of $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ to an output rate of not more than 100 Hz. This reduction of 10^7 is achieved in two steps, by the CMS L1 trigger (output rate 100 kHz) and the CMS Higher-Level Trigger (HLT). The L1 trigger carries out its data selection algorithms with the help of three principal components: the Calorimeter Trigger, the Muon Trigger and the Global Trigger. The decision of the Calorimeter Trigger is based on the transverse energy, E_T, information of the CMS calorimeters (pseudorapidity coverage $|\eta| < 5$). A L1 jet consists of 3×3 regions, each with 4×4 trigger towers, where the E_T in the central region is above the E_T in any of the outer regions. A typical L1 jet has dimensions $\Delta\eta \times \Delta\phi = 1 \times 1$, where ϕ is the azimuthal angle. The E_T reconstructed by the L1 trigger for a given jet corresponds on the average only to 60% of its true E_T. All studies in this article use calibrated jet E_T values, obtained from the reconstructed value by means of an η and E_T dependent correction.

The TOTEM experiment [2] will have two identical arms, one at each side of the CMS IP. Each arm will comprise two forward tracker telescopes, T1 (Cathode Strip Chambers) and T2 (Gas Electron Multipliers), as well as Silicon detectors housed in RP stations along the LHC beam-line. The TOTEM detectors will provide input data to the Global Trigger of the CMS L1 trigger. Track finding in T1 and T2 (combined coverage $3.2 < |\eta| < 6.6$) for triggering purposes is optimized with respect to differentiating between beam-beam events that point back to the IP and beam-gas and beam-halo events that do not. The TOTEM RP stations will be placed at a distance of ± 147 m and ± 220 m from the CMS IP. Each station will consist of two units, 2.5 m and 4 m apart, each with one horizontally and two vertically movable pots equipped with Silicon strip detectors. The possibility of implementing a cut on ξ in the L1 trigger is currently under investigation.

The fractional momentum loss, ξ, of diffractively scattered protons peaks at $\xi = 0$ ("diffractive peak"). The combination of CMS and TOTEM will permit to measure protons that have undergone a fractional momentum loss $0.2 > \xi > 0.02$. Detectors at a distance of 420 m, in the cryogenic region of the LHC ring, are currently being considered by the FP420 project [3]. They would provide a coverage of $0.02 > \xi > 0.002$, complementary to that of the TOTEM detectors, but cannot be included in the L1 trigger without an increase in the L1 latency of 3.2 μs. A special, long latency running mode might be feasible at lower luminosities. This option is currently under investigation. Using detectors at 420 m in the L1 trigger is included as an option in the studies discussed in this article.

The studies discussed in the following assume that the RP detectors are 100% efficient in detecting all particles that emerge at a distance of at least $10\sigma_{beam} + 0.5$ mm from the beam axis. Their acceptance was calculated by way of a simulation program that tracks particles through the accelerator lattice [4]. This has been done for the nominal LHC optics, the so-called low-β^* optics, version V6.5. Further details can be found in [5]. All Monte Carlo samples used in the following assume LHC bunches with 25 ns spacing.

3 Level-1 trigger rates and signal efficiencies

We consider here perhaps the most challenging case, that of a low-mass (120 GeV) Standard Model Higgs Boson, decaying into two b-jets. There, the jets have transverse energies of at most 60 GeV. In order to retain as large a signal fraction as possible, as low an E_T threshold as possible is desirable. In practice, the threshold value cannot be chosen much lower than 40 GeV per jet. The L1 trigger applies cuts on the calibrated E_T value of the jet. Thus, a threshold of 40 GeV corresponds to 20 to 25 GeV in reconstructed E_T, i.e. to values where noise effects start becoming sizable.

In the trigger tables forseen for the first LHC running period, a L1 2-jet rate of $\mathcal{O}(1)$ kHz is planned. For luminosities of $10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and above, the rate from standard QCD processes for events with at least 2 central jets ($|\eta| < 2.5$) with $E_T > 40$ GeV is above this. Thus additional conditions need to be employed in the L1 trigger to reduce the rate from QCD processes. The efficiency of several conditions was investigated and, in the following, the corresponding rate reduction factors are always quoted with respect to the rate of QCD events that contain at least 2 central jets with $E_T > 40$ GeV per jet. These conditions are:

1) Condition based on additional central detector quantities available to the Calorimeter Trigger.
2) Condition based on T1 and T2 as vetoes.
3) Condition based on the RP detectors at ± 220 m and ± 420 m distance from the CMS IP.
4) Condition based on the Muon Trigger.

The QCD background events were generated with the Pythia Monte Carlo generator.

At higher luminosities more than one interaction takes place per bunch crossing; the central exclusive production of a Higgs boson is overlaid with additional, typically soft events, the so-called pile-up. In order to assess the effect when the signal is overlaid with pile-up, a sample of 500,000 pile-up events was generated with Pythia. This sample includes inelastic as well as elastic and diffractive events. Pythia underestimates the number of final state protons in this sample. The correction to the Pythia leading proton spectrum described in [6] was used to obtain the results discussed in the following.

The effect from beam-halo and beam-gas events on the L1 rate is not yet included in the studies discussed here. Preliminary estimates suggest that the size of their contribution is such that the conclusions of this article are not invalidated.

Table 1 summarizes the situation for luminosities between $10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Given a target rate for events with 2 central L1 jets of $\mathcal{O}(1)$ kHz, a total rate reduction between a factor 20 at $1 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and 200 at $1 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ is necessary.

Table 1: Reduction of the rate from standard QCD processes for events with at least 2 central L1 jets with $E_T >$ 40 GeV, achievable with requirements on the tracks seen in the RP detectors. Additional rate reductions can be achieved with the H_T condition and with a topological condition (see text). Each of them yields, for all luminosities listed, an additional reduction by about a factor 2.

Luminosity $[\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	# Pile-up events per bunch crossing	L1 2-jet rate [kHz] for $E_T > 40$GeV per jet	Total reduction needed	Reduction when requiring track in RP detectors				
				at 220 m		at 420 m	at 220 m & 420 m (asymmetric)	
					$\xi < 0.1$			$\xi < 0.1$
1×10^{32}	0	2.6	2	370				
1×10^{33}	3.5	26	20	7	15	27	160	380
2×10^{33}	7	52	40	4	10	14	80	190
5×10^{33}	17.5	130	100	3	5	6	32	75
1×10^{34}	35	260	200	2	3	4	17	39

3.1 Condition based on central CMS detector quantities

In addition to the E_T values of individual L1 jets, the CMS Calorimeter Trigger has at its disposal the scalar sum, H_T, of the E_T values of all jets. Requiring that essentially all the E_T be concentrated in the two central L1 jets with highest E_T, i.e. $[E_T^1 + E_T^2]/H_T > 0.9$ (H_T condition), corresponds to imposing a rapidity gap of at least 2.5 units with respect to the beam direction. This condition reduces the rate of QCD events by approximately a factor 2, independent of the presence of pile-up and with only a small effect on the signal efficiency.

3.2 Condition based on TOTEM detectors T1 and T2

Using T1 and T2 as vetoes in events with 2 central L1 jets imposes the presence of a rapidity gap of at least 4 units. This condition suppresses QCD background events by several orders of magnitude. At luminosities low enough so that not more than one interaction takes place per bunch crossing, the signal efficiency is very high ($> 90\%$). In the presence of pile-up, the signal efficiency falls rapidly. The non-diffractive component in pile-up events tends quickly to fill in the rapidity gap in the Higgs production process. Only about 20 (5) % of signal events survive in the presence of 1 (2) pile-up event(s).

3.3 Condition based on Roman Pot detectors

Demanding that a proton be seen in the RP detectors at 220 m results in excellent suppression of QCD background events in the absence of pile-up. This is demonstrated in Figure 1 for a luminosity of $10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. There, the rate of QCD background events with at least 2 central L1 jets with E_T above a threshold is shown as function of the threshold value. The two histograms reflect the rate without and with the requirement that a proton be seen in the RP detectors at 220 m. The rate of QCD background events containing at least 2 central L1 jets with $E_T > 40$ GeV each is reduced by a factor $\sim$ 370. At $2 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, where on the average 7 pile-up events overlay the signal event, the diffractive component in the pile-up causes the reduction to decrease to a factor ~ 4, and at $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, to a factor $\sim$ 2, as can be seen from table 1.

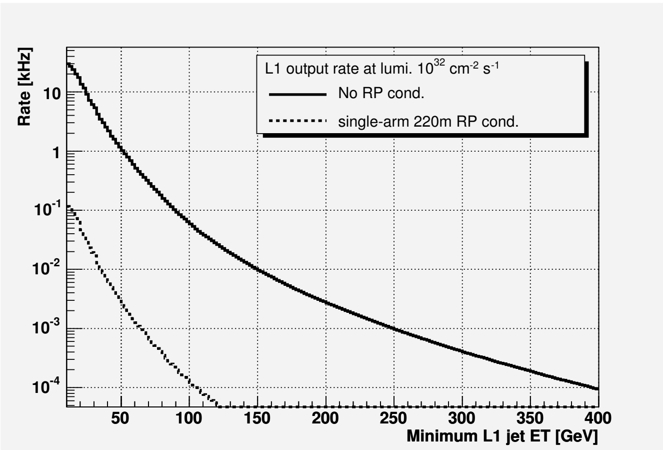
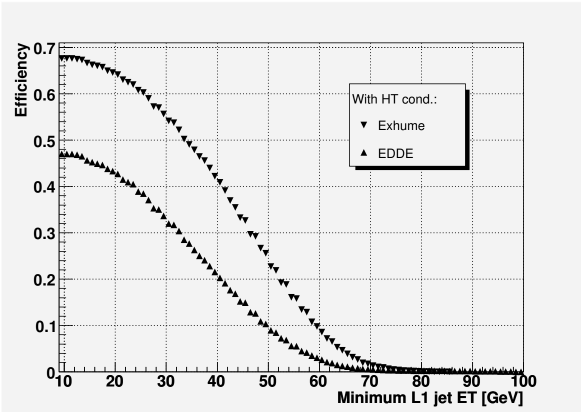


Fig. 1: L1 rate for the QCD background at a luminosity of $10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ as function of the L1 threshold value when requiring at least 2 central L1 jets with E_T above threshold.

Table 1 summarizes the reduction factors achieved with different conditions for tracks in the RP detectors: a track in the RP detectors at 220 m distance on one side of the IP (single-arm 220 m), without and with a cut on ξ, a track in the RP detectors at 420 m distance on one side of the IP (single-arm 420 m), a track in the RP detectors at 220 m and 420 m distance (asymmetric). Because the detectors at 220 m and 420 m have complementary coverage in ξ, the last condition in effect selects events with two tracks of very different ξ value, in which one track is seen at 220 m distance on one side of the IP and a second track is seen on the other side at 420 m. If not by the L1 trigger, these asymmetric events can be selected by the HLT and are thus of highest interest. The effect on the acceptance of the RP detectors of a collimator located in front of the LHC magnet Q5, which will be operative at higher luminosities, has not been taken into account in table 1.

A further reduction of the QCD rate could be achieved with the help of a topological condition. The 2-jet system has to balance the total momentum component of the two protons along the beam axis. In signal events with asymmetric ξ values, the proton seen on one side in the RP detectors at 220 m distance is the one with the larger ξ and thus has lost more of its initial momentum component along the



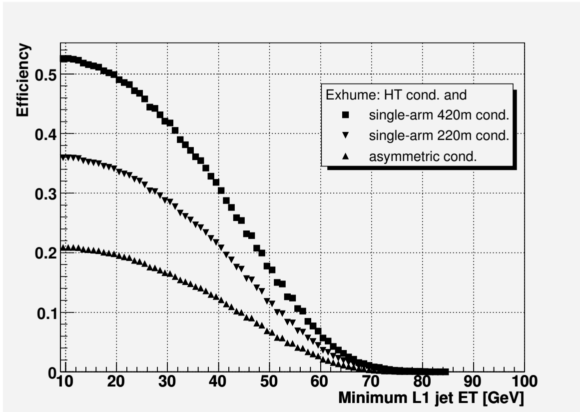


Fig. 2: L1 selection efficiency as function of the E_T threshold value when requiring at least 2 central L1 jets with E_T above threshold. All plots are for the non-pile-up case and the H_T condition (see text) has been applied. Left: Comparison between the EDDE and Exhume Monte Carlo generators, without applying any additional RP conditions. Right: Comparison of the effect of different RP conditions on the efficiency in the Exhume Monte Carlo sample.

beam axis. Hence the jets tend to be located in the same η-hemisphere as the RP detectors that detect this proton. A trigger condition requiring that $[\eta^{jet1} + \eta^{jet2}] \times \mathrm{sign}(\eta^{220m\ RP}) > 0$ would reduce the QCD background by a factor 2, independent of pile-up, and with no loss in signal efficiency.

A reduction of the QCD rate to levels compatible with the trigger bandwidth requirements by including RP detectors at a distance of 220 m from the CMS IP thus appears feasible for luminosities up to $2 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, as long as a ξ cut can be administered in the L1 trigger such that the accepted events can be restricted to the diffractive peak region around $\xi = 0$. Higher luminosities would necessitate inclusion of the RP detectors at 420 m distance in the L1 trigger.

In order to study the effect of the L1 trigger selection on the Higgs signal, signal samples of 20,000 events with central exclusive production of a Higgs Boson were generated with the Monte-Carlo programs EDDE [7] (version 1.1) and Exhume [8] (version 0.9). Figure 2 shows the L1 selection efficiency as a function of the E_T threshold values when requiring at least 2 central L1 jets with E_T above threshold. The histograms show the case when no pile-up is present. The presence of pile-up has only a small effect on the efficiency curves. The plot on the left-hand side compares the efficiency curves obtained for EDDE and Exhume. For a threshold of 40 GeV per jet, Exhume yields an efficiency of about 40%. As a consequence of its less central jet η distribution (see [9]), the efficiency for EDDE is about 20% lower than the one of Exhume. The plot on the right-hand side overlays the efficiency curves obtained with Exhume when including three different RP detector conditions in the L1 2-jet trigger: single-arm 220 m, single-arm 420 m and the asymmetric 220 & 420 m condition. At an E_T threshold of 40 GeV per jet, the single-arm 220 m (420 m) condition results in an efficiency of the order 20% (30%), the asymmetric condition in one of 15%. This also means that even without the possibility of including the RP detectors at 420 m distance from the CMS IP in the L1 trigger, 15% of the signal events can be triggered with the single-arm 220 m condition, but will have a track also in the 420 m detectors which can be used in the HLT.

3.4 Condition based on the Muon Trigger

An alternative trigger strategy may be to exploit the relatively muon-rich final state from B-decays. We estimate that up to 10% of the signal events could be retained using this technique. Further investigations are underway at the time of writing.

4 Conclusions

Retaining a Higgs Boson with mass around 120 GeV poses a special challenge to triggering at the LHC. The relatively low transverse momenta of its decay products necessitate L1 jet E_T thresholds as low as 40 GeV. Thresholds that low would result in a L1 trigger rate of more than 50 kHz, essentially saturating the available output bandwidth.

The results we presented in this article are preliminary and should be taken as a snapshot of our present understanding. They can be summarized as follows: The output rate of a 2-jet L1 trigger condition with thresholds of 40 GeV per jet can be kept at an acceptable $\mathcal{O}(1)$ kHz by including the TOTEM forward detectors in the CMS L1 trigger. In the absence of pile-up, either using the TOTEM T1 and T2 detectors as vetoes or requiring that a proton be seen in the TOTEM RP detectors at 220 m on one side of the CMS IP (single-sided 220 m condition) results in a sufficient reduction of the QCD event rate that dominates the L1 trigger output rate. At higher luminosities, up to $2 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, where pile-up is present, it is necessary to combine the single-sided 220 m condition with conditions based on event topology and on H_T, the scalar sum of all L1 jet E_T values. Going to even higher luminosities, up to $1 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, would necessitate additional L1 trigger conditions, such as inclusion of RP detectors at 420 m distance from the CMS IP, which, however, would require an increase in the L1 trigger latency. These L1 trigger conditions result in signal efficiencies between 15% and 20%.

We expect no trigger problems for final states rich in high p_T leptons, such as the WW decay modes of the Standard Model Higgs Boson.

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