Study of selection of dimuons in events with more than two muons in the CMS experiment

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Abstract. My work during CERN summer student program was with dimuon selection in events with more than two muons, in the analysis of search for narrow resonances in dimuon invariant mass spectra in the CMS experiment at the LHC. Most of the events selected for this analysis have two muons, but there are some events with more than two muons and we have to choose which pair of muons form the best dimuon candidate in these events. One of the problems of the search for new heavy resonances Z′ is the presence of background processes, for example diboson production WZ and ZZ, in which muons are produced. Dimuons formed from these muons can be misinterpreted as candidates for heavy resonances.

1 Introduction

The CMS physics research programme on the detection of new physics beyond the standard model (SM) is aimed at detecting deviations from SM predictions [1]. The CMS searches signals from new physical objects and phenomena predicted by models of the extended gauge sector [2], scenarios of extra-dimensions theories [3] and many others. The variety of new particles and phenomena predicted by these models requires the use of a wide range of experimental studies in various channels, including heavy resonance states and nonresonant signals in the spectrum of pairs of leptons, jets, photons, top quarks, gauge bosons to search for new heavy gauge bosons Z', Kaluza-Klein excited states of the graviton, etc.

Many physical scenarios outside the framework of the SM predict the existence of new resonance states in the spectra of the SM particles [4]. For example, heavy (with a mass of several TeV) resonances in the spectrum of pairs of leptons and jets appear in four-dimensional models with an extended gauge sector (extra gauge boson Z' beyond the SM with spin $S = 1$). In its characteristics, Z' is similar to the usual SM neutral gauge boson Z, the main differences are the larger expected mass and different coupling constants. Experimental signatures of these particles can be a pair of leptons (muons in this case) with large transverse momenta from the same vertex [1].

2 CMS detector

The search for new particles is carried out using the CMS detector (Compact Muon Solenoid), one of the four main LHC detectors [5–7]. The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid, in the pseudorapidity range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. Matching muons to tracks measured in the silicon tracker results in a relative transverse momentum resolution for muons with $20 < p_T < 100$ GeV of 1.3–2.0% in the barrel ($|\eta| < 1.2$) and better than 6% in the endcaps ($0.9 < |\eta| < 2.4$), the p_T resolution in the barrel is better than 10% for muons with p_T up to 1 TeV [6]. Events of interest are selected using a two-tiered trigger system. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a time interval of less than 4 μs. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage.

3 Dimuon resonances

In the CMS analysis the typical models [2] predicting extra Z-like bosons decaying to muon pairs have been considered. These models extend the gauge group of the SM by additional $U'(1)$ gauge groups. The $U'(1)$ gauge groups, or a linear combination of them, could be broken near the TeV scale giving rise to massive Z' gauge bosons. These models are generalized using an angle that continuously parametrizes the mixing of the respective $U'(1)$ generators. Specific choices of the mixing angle produce different models. One of them, the so-called Sequential Standard Model (SSM) in which heavy bosons Z'_{SSM} are assumed to have the same coupling constants as for Z bosons in the SM. Another one, ψ-model, is a special case of an extension of the SM to one of the gauge groups of the grand unification theory [2].

4 Event selection

The reconstruction algorithms and event selection employed are refined versions of those used for previous high-mass dilepton searches [8]. To reconstruct a muon candidate, hits from the inner tracker and the muon system are first fitted separately to have inner tracker and standalone muon tracks and then combined in a global muon track hypothesis.

Candidate muon pair events are required to have at least one muon with track segments reconstructed in the muon detectors and with transverse momentum p_T above 16 GeV at L1 trigger, and at least one muon with $p_T > 50$ GeV and $|\eta| < 2.4$ at the HLT. In order to extract the normalization factor in the control region ($60 < m_{ll} < 120$ GeV) around the Z peak, a prescaled HLT trigger with a p_T threshold of 27 GeV is used without changing other L1 requirements. The muon candidates are required to have $p_T > 53$ GeV and be within the sensitive region of $|\eta| < 2.4$.

The muon candidates are also required to pass a dedicated high-momentum muon identification selection [9]. Finally, isolated muon candidates are selected by requiring the p_T sum of tracks within a cone of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$ around the candidate direction to be less than 10% of the p_T of the candidate. The sums exclude the lepton candidate under consideration.

The selected opposite-charge muons are combined to form dimuon candidates. To ensure that the two muons originate from the same vertex a fit is performed to a common vertex. This vertex fit is required to have $\chi^2/\mathrm{dof} < 20$. To suppress background from cosmic ray muons that pass near the interaction point, the three-dimensional angle between the two track momentum vectors is required to be less than $\pi - 0.02$.

5 Analysis

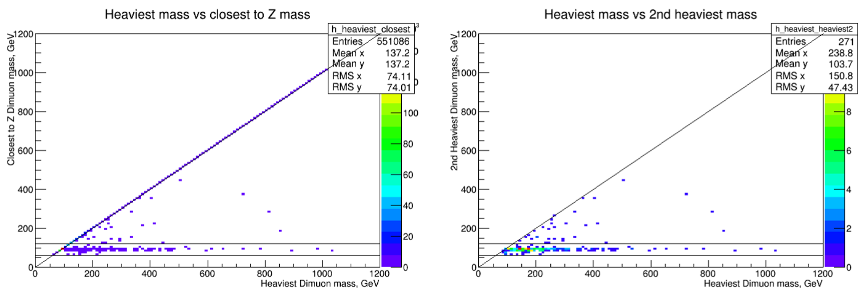
Several dimuon pairs can be found in some events. In the current analysis in CMS, only the one dimuon with the two largest sum of transverse momenta p_T of the muons is considered for further analysis. In the CMS data obtained in 2016 there were found events with 3 and more muons which can be combined into a number of possible dimuons. Due to this reason, there is a problem of choosing the real dimuon candidate in event. So, it is important to make a decision whether dimuon can come from a usual Z_{SM} boson or a possible candidate for Z′ analysis. We should always ensure that we look at all combinations of muons. Also in this way we can reduce the physical backgrounds of the diboson production in the channels ZZ and WZ.

Due to the events with 3 and more muons it is important to study them and modify the current algorithm of the dimuon selection. For this reason the modification was made by selecting a pair of muons that has mass within 30 GeV of the Z boson ($60 < M_Z < 120$ GeV), otherwise the highest p_T pair is taken. Pairs from Z should be excluded from Z′ analysis.

6 Results

For analysis we used 2016 datasets which were reconstructed with the improved offline calibration and alignment constants. Statistics corresponds to 36.3 fb^{-1}.

Now, in Run 2, there is enough statistics accumulated to start seeing multiple lepton pairs with high masses, therefore there is a need to consider the problem of dealing with them and discuss the selection we want to use. I studied the algorithm before and after modification (working titles are "option 1" and "option 3", respectively). A proposal was made to modify dimuon selection in the analysis for the search for narrow heavy dimuon resonances: a muon of a dimuon with a mass close to Z mass can not be produced from a heavy additional Z′ boson, and it should be excluded from usage for heavy dimuon candidates (using modification). This modification will help to reduce the physical backgrounds of dibosons production in the ZZ and WZ channels.



(a) (b)

Figure 1. 2-dimensional distributions of dimuon masses. a) The distribution of the heaviest dimuons in the event relatively to the mass of the dimuon closest to $m_Z = 91$ GeV. b) The distribution of the mass of the second heaviest dimuon in event.

It is seen Fig.1(a) that in those cases when there are more than two muons in an event, one of these muons is produced, most of the time, from the Z boson. Therefore, this muon can not be produced from a heavy additional Z′ boson candidate. To avoid bias there was made another plot Fig.1(b) of the second heaviest dimuon in event. As can be seen from the distribution, the mass of the second heaviest dimuon in event is also mainly concentrated near $m_Z = 91$ GeV.

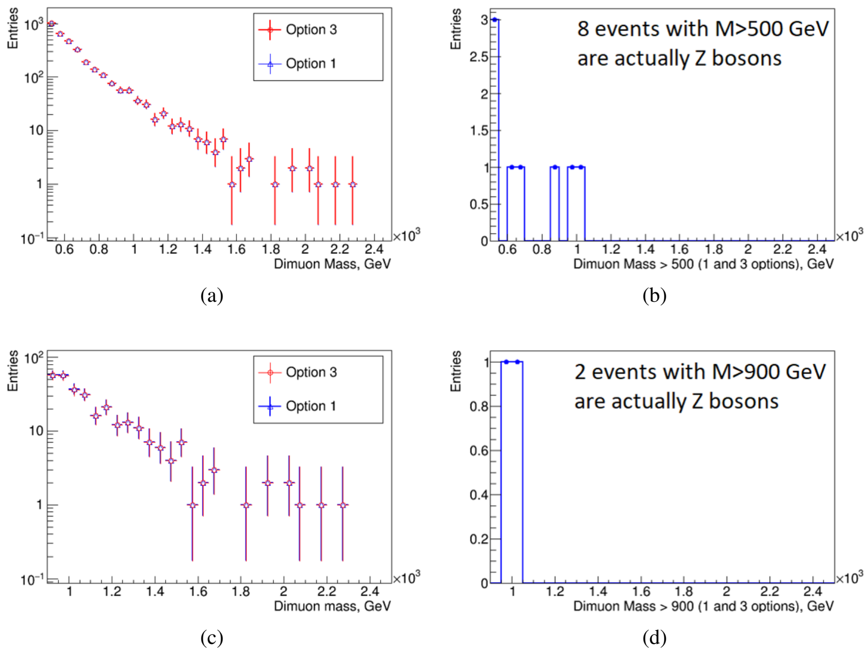


Figure 2. Comparison of the spectra of the invariant dimuon mass (current and new algorithms) and their difference.

Mass distributions for $M > 500$ GeV (Fig.2(a–b)) and $M > 900$ GeV (Fig.2(c–d)). The number of events with 3 or more muons in the considered data set is 3310 for $M > 500$ GeV, and 293 for $M > 900$ GeV.

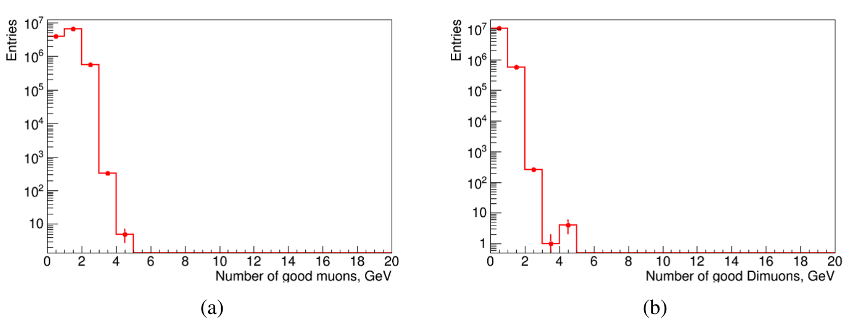


Figure 3. Distributions of the number of "good" (a) muons and (b) dimuons in events, i.e. muons and dimuons satisfying the selection criteria.

It is important to have distributions like number of good muons and dimuons. For Fig.3(a) we used only muon cuts. One can see that there are 3 and 4 "good" muons. Number of dimuons per event can reach 4.

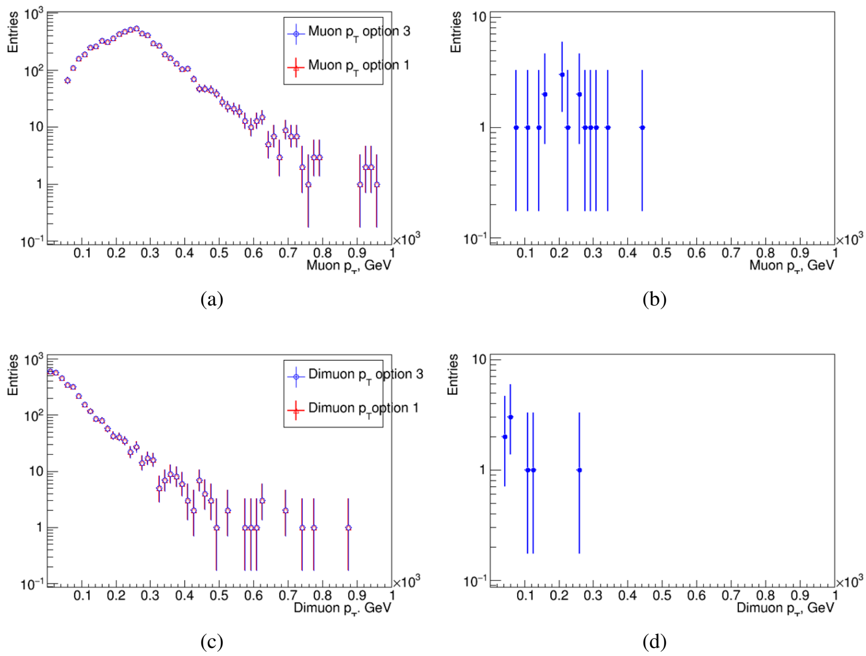


Figure 4. Comparison of the spectra of the invariant dimuon mass and transverse momentum p_T (current and new algorithms) and their difference.

Figs.4–5 show that the distribution of the studied events qualitatively coincides with the distributions of all events.

In Run 2016 data, in comparison between current and new algorithms, we found difference in 2 events with M>900 GeV and 8 events with M>500 GeV.

Study on Monte Carlo

It is necessary to study these effects in the dimuon selection using Monte Carlo (MC) simulation. For this we used ZZ and WZ datasets for CMSSW version 8.0.X.

One of the first thing is to estimate efficiency which can be defined as ratio of reconstructed and generated events.

$$\varepsilon = \frac{N_{\text{reco}}}{N_{\text{gen}}}$$

where N_{gen} is number of generated ZZ events using MC with cuts: at least 3 muons with $p_T^{\text{gen}} > 53$ GeV, $|\eta^{\text{gen}}| < 2.4$. N_{reco} is number of found reconstructed ZZ events which are the same events as in denominator, with an additional requirement of at least 3 reconstructed muons with $p_T^{\text{reco}} > 53$ GeV, $|\eta^{\text{reco}}| < 2.4$ and passing the analysis cuts for generated muons. The efficiency for ZZ MC dataset was found to be $\varepsilon_{ZZ} = 0.665 \pm 0.013$, and efficiency for WZ MC dataset is $\varepsilon_{WZ} = 0.61 \pm 0.08$.

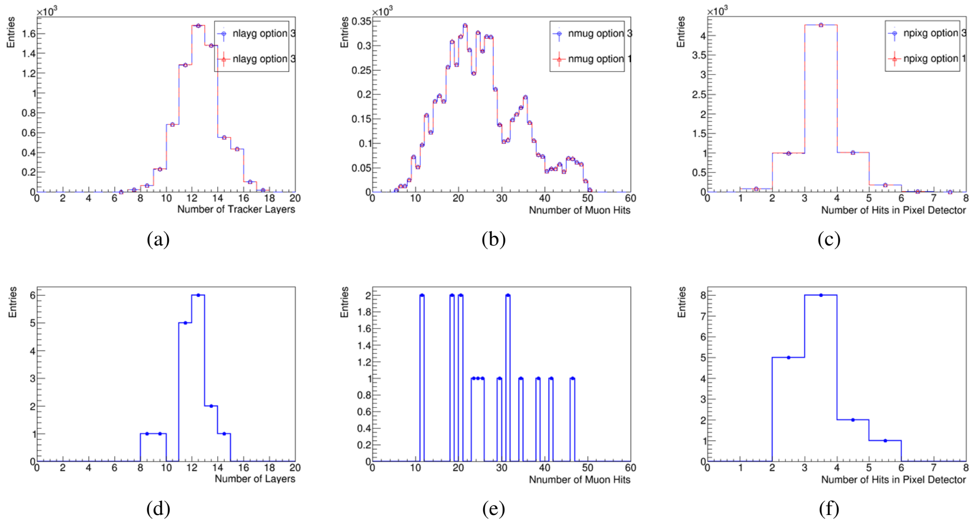


Figure 5. Comparison of the spectra of the invariant dimuon mass (current and new algorithms) and their difference for number of hits in detectors: the number of tracker layers (a,d), the number of muon hits (b,e) and hits in the pixel detector (c,f).

7 Conclusions

During the summer practice we raised the problem of dealing with multiple lepton pairs. At the moment, in Run 2, we have enough statistics accumulated and we see increase in the number of events with 3 or more muons, which actualizes the modification of current algorithm. We studied them and possible options of selection of this kind of events. We proposed to modify dimuon selection in the analysis for the search for narrow heavy dimuon resonances: a muon of a dimuon candidate with a mass close to Z mass can not be produced from a heavy additional Z′ boson and it should be excluded from usage for heavy dimuon candidates.

The results obtained on the data of 2016 and Monte Carlo confirmed the need for modification, which will become part of the Z′ analysis in the future.

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