A simulation study of a non-standard Z boson in the LHC Run 3 CMS experiment

The CMS (Compact Muon Solenoid) experiment at the Large Hadron Collider is designed to measure muons with high precision and plays a central role in studying electroweak interactions. In this study, we investigate a hypothetical Z boson that shares the same mass and decay properties as the Standard Model Z boson but features suppressed couplings to fermions. To explore its detectability, we perform a generator-level analysis of the $Z \to \mu\mu$ decay channel under LHC Run 3 conditions at a center-of-mass energy of $\sqrt{s} = 13.6$ TeV, with top quark pair ($t\bar{t}$) production as the dominant background process.

Events are selected using a realistic trigger, `HLT_DoubleIsoMu20_eta2p1`, which requires two muons each satisfying transverse momentum $p_{\mathrm{T}} > 20$ and pseudorapidity $|\eta| < 2.1$, along with an isolation requirement. Signal ($Z \to \mu\mu$) and background ($t\bar{t}$) events passing these criteria are generated using `PYTHIA8.313`. To emulate detector resolution effects, we apply Gaussian smearing to the muon momenta and angles. After implementing standard selection cuts, we reconstruct the dimuon invariant mass $M_{\mu\mu}$, where a pronounced peak at the Z boson mass is observed.

We fit the combined signal and background distribution to estimate the statistical significance of the Z peak and determine the integrated luminosity required for a 5σ discovery. This study serves as a baseline for evaluating the sensitivity of the CMS detector to non-standard Z boson scenarios under realistic LHC conditions.

1 Dataset generation

We create generator level datasets for $Z \to \mu\mu$ and $t\bar{t}$ events passing the trigger criteria. After experimenting with simulating the datasets in `PYTHIA`, to obtain good statistics for both the signal and background we decided to simulate $N_S^{\mathrm{sim}} = 10^6$ events for the signal and $N_B^{\mathrm{sim}} = 3 \cdot 10^6$ events for the background. These yield roughly an equivalent number of events passing the final selections for both the signal and the background.

All events are simulated using `PYTHIA` with a beam center-of-mass energy of $E_{\mathrm{CM}} = 13.6\,\mathrm{TeV}$. Protons (default) are used as the beam particles. We detail the used settings in `PYTHIA` for the simulations in the following two subsections, and describe the triggering in the third subsection.

1.1 Signal generation

Because our study emulates the LHC Run 3 we use `WeakSingleBoson:ffbar2gmZ = on` (fermion-antifermion annihilation to γ/Z) to generate events involving Z bosons. This includes the $q\bar{q}$ channel which is the dominant channel coming out of pp collisions at the LHC, with the $\ell\bar{\ell}$ channel being vanishingly small in pp collisions. We force Z decays to $\mu\mu$, so that computational resources are not wasted on $Z \to ee$ for instance. We also constrain the dimuon mass phase space to be between $15-500$ GeV, to avoid the very low mass Drell-Yan signals like J/ψ or $\Upsilon(nS)$, and to capture both of the sidebands.

1.2 Background generation

We simulate the $t\bar{t}$ background events using `Top:gg2ttbar = on` and `Top:qqbar2ttbar = on`, which represent the dominant gluon-gluon and quark-antiquark $t\bar{t}$ production channels coming out of the pp collisions at the LHC. We force the top quark mass to be $m_t = 172.5$ GeV/c^2. We do not impose phase space limitations on the $t\bar{t}$ mass, and we also do not force decays into a muon pair directly from the top quark pair, because we may have secondary decays into muons (e.g. $t \to Wb \to b\mu\nu_\mu$), rather than just direct semileptonic decays of the top quarks ($t \to b\mu\nu_\mu$). These may be meaningful decay channels which we want to keep for the most realistic simulation.

1.3 Triggering on dimuon events

In the dataset generation we ignore the isolation requirement and simply trigger on events which have at least two muons present in the final state, with the leading two muons satisfying $p_\mathrm{T} > 20$ GeV/c and $|\eta| < 2.1$. The isolation requirement imposed by `HLT_DoubleIsoMu20_eta2p1` will be treated when we apply selection criteria. This is a realistic order of cuts to be made, because the isolation cut requires the reconstruction of tracks to determine the proximity of pions to the muon. In a realistic situation the isolation cut would be made later offline.[1] Thus the trigger efficiencies ignoring the isolation requirement are

$$\eta^{\mathrm{S}}_{\mathrm{trig.}} \approx 0.203, \quad \text{and} \quad \eta^{\mathrm{B}}_{\mathrm{trig.}} \approx 0.0080. \tag{1}$$

The trigger efficiencies are as hoped. We trigger more on the signal than on the background. Note however that we simulated $Z \to \mu\mu$ in the $15\,\mathrm{GeV}/c^2 < M_{\mu\mu} < 500\,\mathrm{GeV}/c^2$ phase space. For an earlier simulation of ours done only in the peak region with the phase space $60\,\mathrm{GeV}/c^2 < M_{\mu\mu} < 120\,\mathrm{GeV}/c^2$, we were able to obtain $\eta^{\mathrm{S}}_{\mathrm{trig.}} \approx 0.430$. Triggered events are stored to ROOT TTrees for further treatment.

2 Emulating detector effects

We simulate detector effects when measuring muons by applying a 1% Gaussian smearing to the transverse momentum p_T and 2 mrad Gaussian smearing to the angles θ and φ defining the four momentum vector, i.e.

$$\tilde{p}_\mathrm{T} = p_\mathrm{T} \cdot \mathcal{N}(1, 0.01), \quad \tilde{\theta} = \theta \cdot \mathcal{N}(0, 0.002), \quad \text{and} \quad \tilde{\varphi} = \varphi \cdot \mathcal{N}(0, 0.002), \tag{2}$$

[1] True, false? The HLT has some track reconstruction but it isn't as accurate as the offline one, so this might not be true. Is the real reason that we want the smearing done first and then isolation?

so that the four momentum has the components

$$p_x = \tilde{p}_T \cos\tilde{\varphi}, \tag{3}$$

$$p_y = \tilde{p}_T \sin\tilde{\varphi}, \tag{4}$$

$$p_z = \tilde{p}_T / \cos\tilde{\theta}, \tag{5}$$

$$E = \sqrt{p_x^2 + p_y^2 + p_z^2 + m_\mu^2}. \tag{6}$$

This Gaussian smearing models the limited momentum and angular resolution of the CMS detector. Although the smearing is simplified and applies only to muons, it captures the dominant effects relevant to our analysis. Importantly, the smearing is applied before any isolation criteria, in order to reflect the fact that isolation cuts are typically computed using reconstructed quantities, not generator-level values. While the High-Level Trigger (HLT) performs partial tracking and isolation estimations, its resolution is inferior to the offline reconstruction. Therefore, our approach mirrors the realistic order of operations in CMS data processing, where isolation is applied after full track reconstruction.

3 Final selection criteria

We apply two standard selections to the muon candidates. Firstly, we require that $p_{\mathrm{T}} > 30$ GeV/c for each of the muon candidates. Secondly, we require isolation, meaning that the sum of the momenta of charged pions within $\Delta R < 0.3$ of a muon candidate is smaller than 1.5 GeV/c in p_{T}. Note that because we triggered on events purely in terms of the muons, the pions may in truth be unresolvable at the CMS, e.g. with $|\eta| > 2.5$ or with p_{T} very small. At least two muon candidates satisfying the p_{T} and isolation criteria must exist in the event for it to be accepted. After applying both the p_T and isolation cuts, approximately 144000 signal events and 150000 background events out of the initial $N_S^{\mathrm{sim}} = 10^6$ signal and $N_B^{\mathrm{sim}} = 3 \cdot 10^6$ background events remain.

4 Analysis

We wish to reconstruct the invariant mass $M_{\mu\mu}$ spectrum for the dimuon events. To this end we need to scale our signal and background measurements so that they are comparable. It is standard to scale the histograms as

$$N = \frac{\sigma\mathcal{L}}{N_{\text{pass selections}}} \tag{7}$$

for each of the signal and background respectively, where $N_{\text{pass selections}}$ is the number of events which pass all the selections, including any domain restrictions. We assume a non-standard model Z boson with weaker couplings. We thus use the non-standard $\sigma_S = 62$ pb for the signal, and the standard $\sigma_B = 924$ pb for the background. The scaling by $\mathcal{L}$ will be omitted for now, and we will later determine the amount of integrated luminosity $\mathcal{L}$ required for us to declare a 5σ result. With this we obtain figure 1.

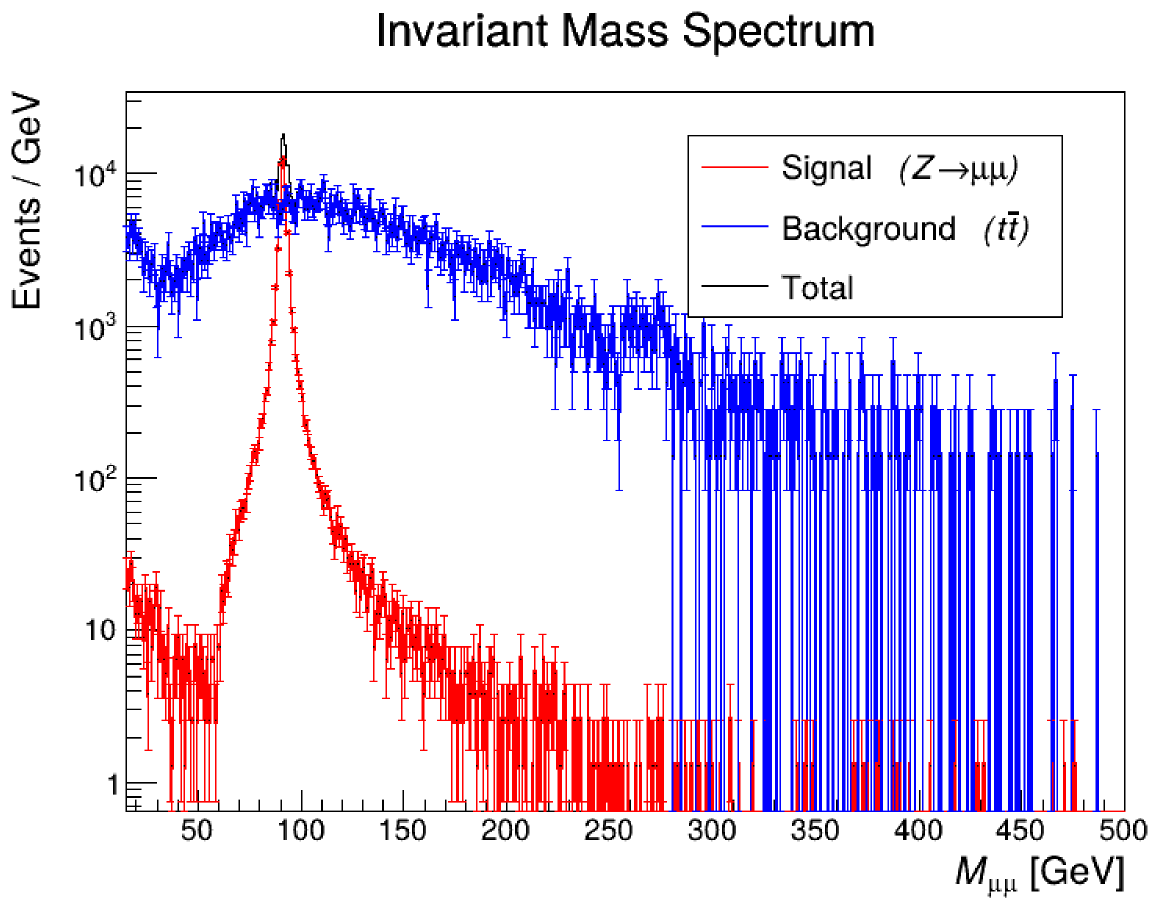

Figure 1: Full simulated dataset

We perform an overall fit of the form

$$\text{totalDistribution}(M_{\mu\mu}; \vec{\theta}_S, \vec{\theta}_B) = \text{signal}(M_{\mu\mu}; \vec{\theta}_S) + \text{background}(M_{\mu\mu}; \vec{\theta}_B) \tag{8}$$

where we model the background by

$$\text{background}(M_{\mu\mu}, \vec{\theta}_B = (A_B, a_B, b_B)) = \frac{A_B}{1 + a_B M_{\mu\mu} + b_B M_{\mu\mu}^2}, \tag{9}$$

which is an empirical model which was observed to fit the background reasonably well. We model the signal distribution using the relativistic Breit-Wigner distribution available directly from ROOT,

$$\text{signal}(M_{\mu\mu}; \vec{\theta}_S = (A_S, M, \Gamma)) = \frac{A_S k}{(M_{\mu\mu}^2 - M^2)^2 + M^2\Gamma^2}, \tag{10}$$

where

$$k = \frac{2\sqrt{2} M\Gamma\sqrt{M^2(M^2+\Gamma^2)}}{\pi\sqrt{M^2 + \sqrt{M^2(M^2+\Gamma^2)}}}. \tag{11}$$

Fitting the total distribution we obtain figure 2. For fitting we chose to exclude a lot of the lower mass tail in our distribution because for $M_{\mu\mu} < 60$ GeV the signal no longer behaves as the same Breit-Wigner distribution. This part is likely an artefact of some lower mass Drell-Yan process. In theory the right hand tail could have been kept, but due to the relatively poor statistics in the high dimuon mass region it was decided to only fit until $M_{\mu\mu} = 250$ GeV.

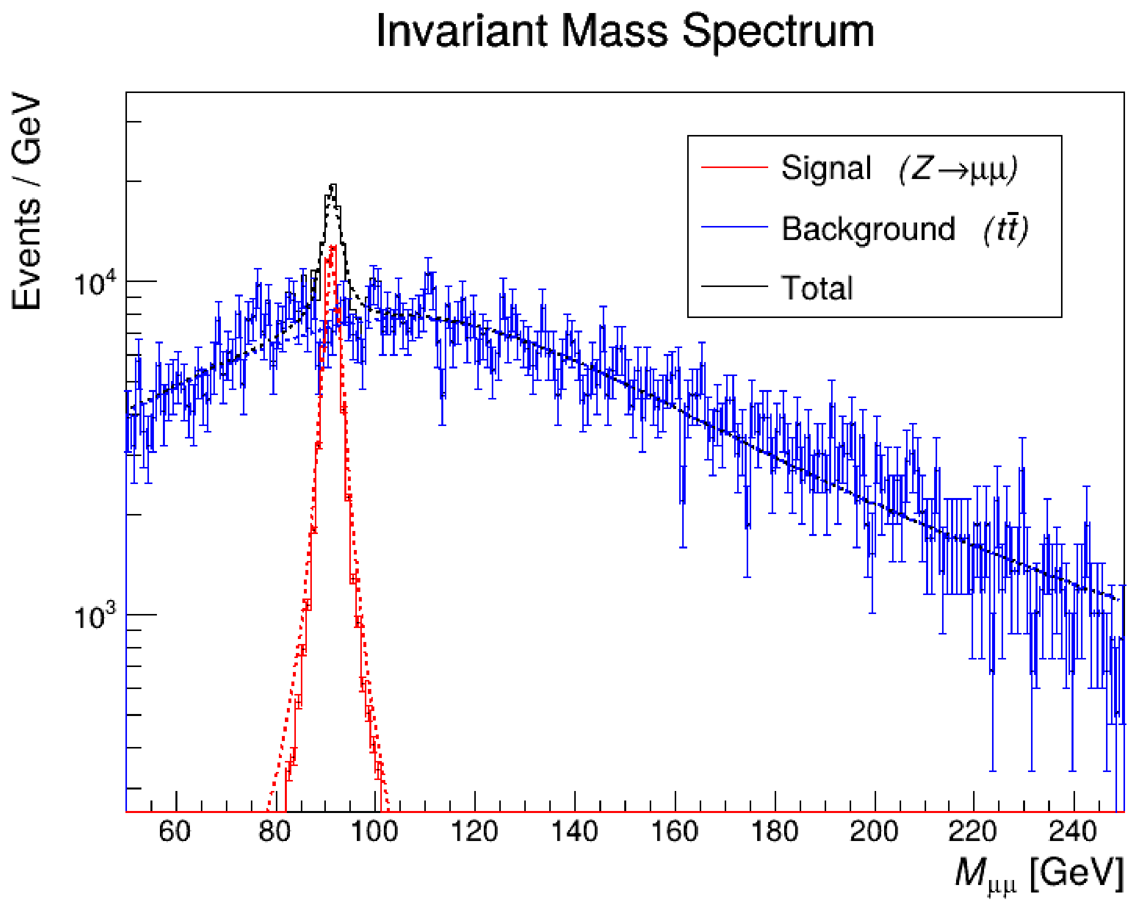

Figure 2: The total invariant mass spectrum which has been fit as equation 4 is shown in black (dashed black line for fit). The decomposition into signal (red dashed) and background (blue dashed) parts of the fit is also shown to demonstrate fit accuracy. The fit has a χ^2 value of $\chi^2 = 217.971$ with $N_{\mathrm{df}} = 197$ degrees of freedom, meaning $\chi^2/N_{\mathrm{df}} \sim 1.10$ so the fit is relatively good.

We integrate the total fit and background functions in the peak region $60 - 120$ GeV, in order to determine the number of background and signal events as in a real experimental analysis:

$$N_{\text{tot}} = \int_{60}^{120} dM_{\mu\mu}\, \text{totalDistribution}(M_{\mu\mu}; \vec{\theta}_S, \vec{\theta}_B), \tag{12}$$

$$N_B = \int_{60}^{120} dM_{\mu\mu}\, \text{background}(M_{\mu\mu}; \vec{\theta}_B), \tag{13}$$

$$N_S = N_{\text{tot}} - N_B. \tag{14}$$

This yields $N_S \approx 66900, N_B = 408400$, so approximately estimating, our Z peak has a statistical significance

$$\sigma = \frac{N_S}{\sqrt{N_B}} \approx 105. \tag{15}$$

From this we can work out the necessary integrated luminosity $\mathcal{L}$ to claim a 5σ discovery, by incorporating $\mathcal{L}$ into the scaling as it should have been:

$$5 = \frac{N_S \mathcal{L}}{\sqrt{N_B \mathcal{L}}} \Longrightarrow \mathcal{L} = \left(\frac{5}{N_S}\right)^2 N_B \approx 0.0023\,\text{fb}^{-1}. \tag{16}$$

The integrated luminosities obtained day-by-day in the 2024 LHC run are shown in figure 3.

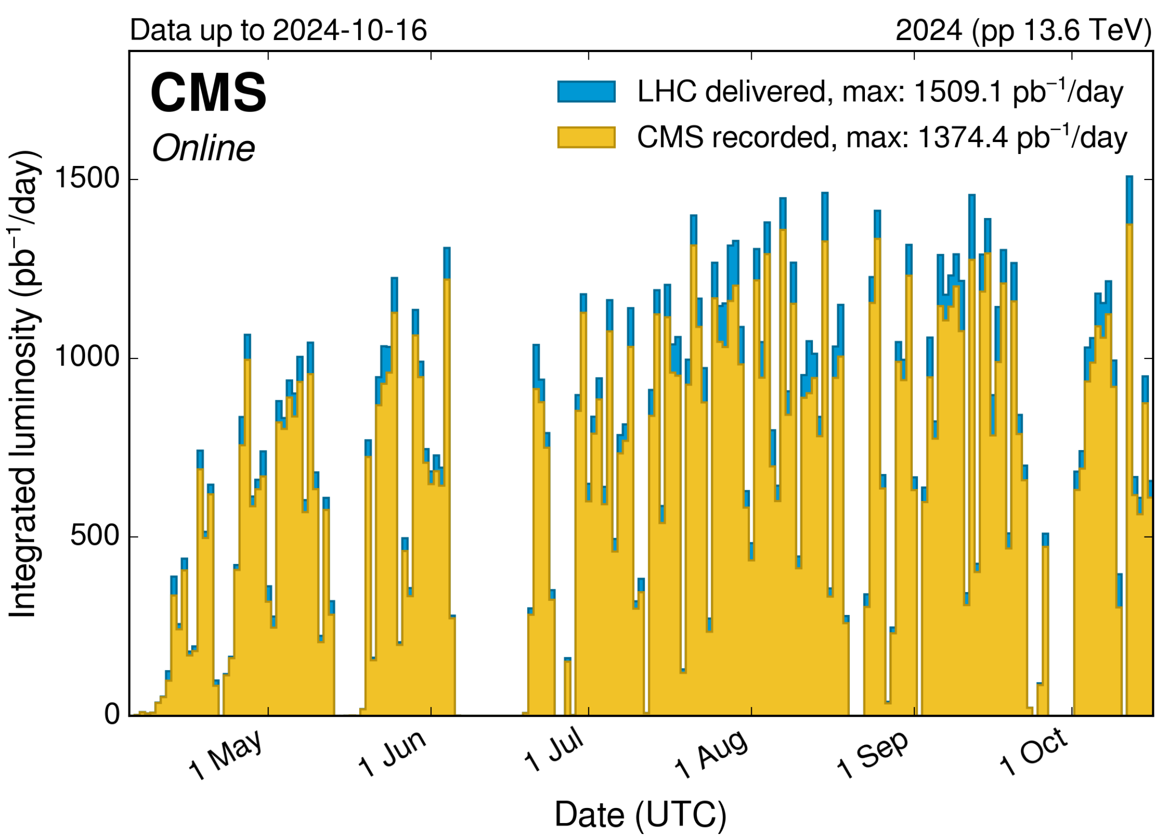

Figure 3: Integrated luminosity delivered by the LHC/recorded by the CMS day by day during the 2024 run of the LHC

From the above figure we have that the maximum integrated luminosity recorded in a single day was $1374.4\,\mathrm{pb}^{-1}/\mathrm{day} = 1.3744\,\mathrm{fb}^{-1}/\mathrm{day}$, suggesting that our signal could have been discovered by the LHC in

$$t_{\mathrm{disc}} = \frac{0.0023\,\mathrm{fb}^{-1}}{1.3744\,\mathrm{fb}^{-1}/\mathrm{day}} \approx 2.41\,\mathrm{minutes} \tag{17}$$

5 Discussion

To make the study more realistic one should consider the following:

(a) Using a full detector simulation, e.g. `GEANT4`, in order to better gauge detector effects. Our treatment of detector effects is very limited, and applied only to muons. The CMS ECAL is used to measure pions for instance, but we make no considerations in this regard. Similarly the Gaussian smearing which we apply is likely quite unrealistic.

(b) Using more detailed event generation. `PYTHIA8.313` uses only LO perturbative calculations from QCD, paired with parton showers. This was deemed accurate enough for our simple study, and did not demand large computational resources. For a more accurate simulation one should consider NLO/NNLO event generators, or perhaps even ones which are made specifically for simulating Z or top physics. Accurate jet simulations could also be considered beyond `PYTHIA`'s parton showers.

(c) Including a wider range of background processes besides $t\bar{t}$ production.

Despite these simplifications, the analysis remains credible as a baseline study. The scientific community can trust the results because the methodology is transparent and reproducible, using well-established tools such as Pythia 8 and ROOT. The application of realistic selection criteria, the inclusion of smearing to emulate detector resolution, and the clear reconstruction of the $Z \to \mu\mu$ signal contribute to the reliability of the findings. While the realism could be improved with full detector simulation and broader background modeling, this study demonstrates that even with basic assumptions, the Z boson peak is clearly observable under LHC Run 3 conditions.