CERN HSSIP BG Project 7

Monte-Carlo modeling using CMSSW* - Drell-Yan process with two leptons ($\mu^+\mu^-$) in the final state. Analysis and Z boson mass reconstruction.

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Abstract

We present the results from analyzing Monte-Carlo data for Drell-Yan process with CMSSW[6]. The aim is to estimate Z boson mass.
For the mass and width of the Z boson we obtain $M_Z = 90.75 \pm 0.02 GeV$ with $\sigma = 2.994 \pm 0.022$.

Introduction

HSSIP BG 2017[1] is a first-of-its-kind programme giving Bulgarian high school students the opportunity to work with professional physicists, computer scientists and engineers at CERN, as well as to witness the collaboration of thousands of scientists.
During the two week period of the internship we visited most of the experiments at CERN and learned about their purpose and operation. Furthermore, much of our schedule was dedicated to project work. The list of projects for the internship is available *online*[2].
Hereby we present the results of our project and the methods used.

Using CMSSW to simulate Drell-Yan events

For the duration of the internship we had to learn and get used to the CMSSW and in particular the steps of simulating and analyzing events.

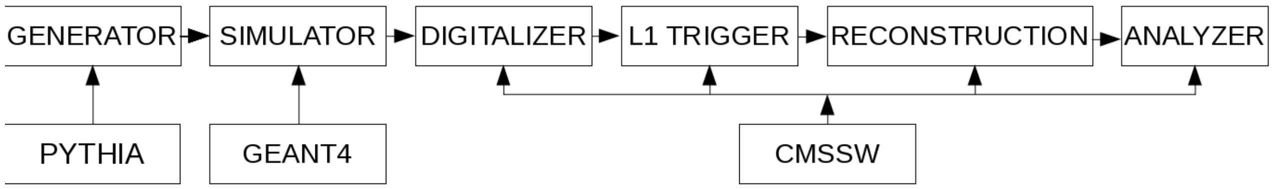

Figure 1: Modelling steps of the CMSSW to produce events

Figure 1 shows the order in which an event is simulated. For generating events PYTHIA[4] is used. Likewise GEANT4[5] is used for simulation. All of the steps are executed with CMSSW[6] on LXPLUS[8]. Event analyzers were written in C++ and Python within CMSSW Framework and then histograms of the data were obtained with ROOT[7].
Data from DAS[9] was analyzed in order to save computational time for the events needed. A total number of 309685 reconstructred events were analyzed.

Theory

Drell-Yan process

As we want to simulate events similar to these measured by CMS we should choose the process such that the outcome particles could be measured by CMS. Drell-Yan is a suitable process for measuring the Z boson mass because it is a mediator and could decay into μ^+ and μ^-.

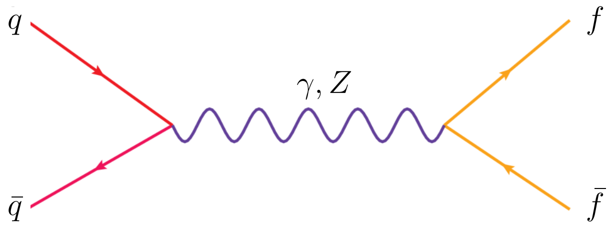

Figure 2: General form of the Drell-Yan process

$$q\bar{q} \xrightarrow{\gamma,Z} f\bar{f}$$

CMS collides proton beams and detects muons so the case of Drell-Yan we want to investigate is $q\bar{q} \xrightarrow{Z} \mu^+\mu^-$.

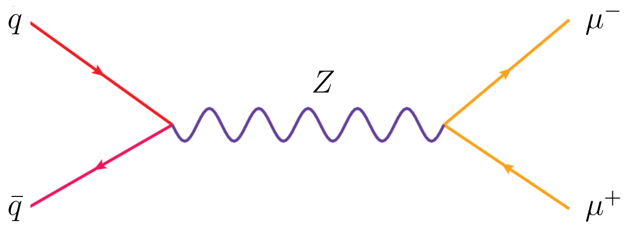

Figure 3: Simulated Drell-Yan process

A better description of the event of proton-proton interaction could be expressed as in figure 4.

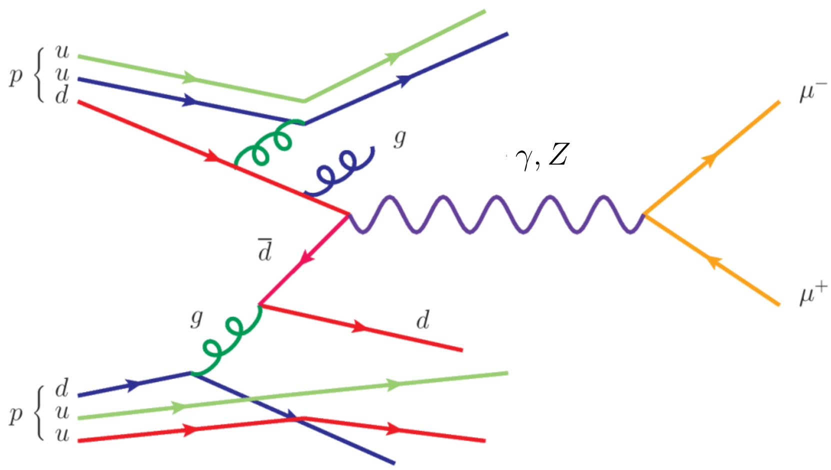

Figure 4: Drell-Yan process occuring after proton bunch interaction

PYTHIA configuration was set such that Drell-Yan process could occur from any $q\bar{q}$ from the same type ($u\bar{u}$, $d\bar{d}$, $b\bar{b}$, $s\bar{s}$, $c\bar{c}$, $t\bar{t}$). We might say $t\bar{t}$ is an exception because the probability of such a process is extremely low.

Coordinate system

It is useful to define coordinates of reconstructed particles with φ and η as shown in figure 5, where $\eta = -\ln\tan\left(\frac{\theta}{2}\right)$.

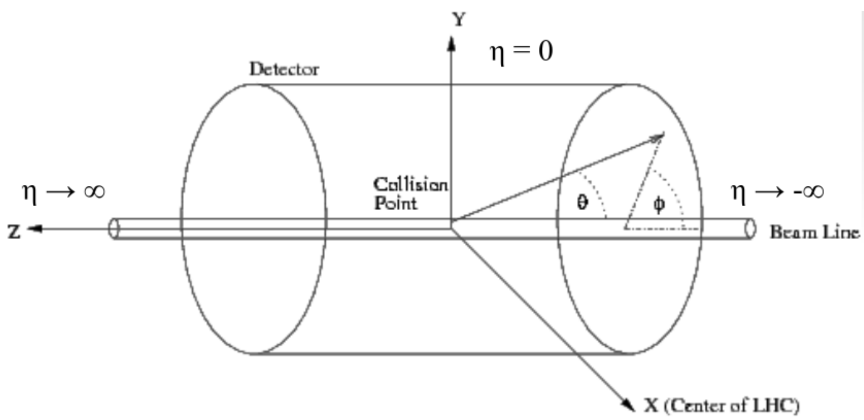

Figure 5: Coordinate System of CMS

Z boson mass

The particle's energy and momentum are represented as the four-momentum Lorentz vector in the Minkowski space.

Having data from the detector of the E and p_x, p_y, p_z of each reconstructed particle and using the Minkowski space metric tensor $g = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$, we define the four-momentum of each particle as

$$\widetilde{P}_\mu = \begin{pmatrix} E \\ -p_x \\ -p_y \\ -p_z \end{pmatrix} \tag{1}$$

The quantity which is conserved under the transformations of four-vectors in the Minkowski space is the scalar product of two four-vectors and in particular the square of the four-vector:

$$\widetilde{P}_\mu^2 = \begin{pmatrix} E \\ -p_x \\ -p_y \\ -p_z \end{pmatrix} \cdot \begin{pmatrix} E \\ -p_x \\ -p_y \\ -p_z \end{pmatrix}^T$$

Let us write the conservation of momentum and energy in terms of the four-momentum in the Drell-Yan process we simulate.

$$M^2 = \left(\sum_i \widetilde{P}_{\mu_i}\right)^2 = \left(\sum_f \widetilde{P}_{\mu_f}\right)^2 = \left(\sum_i E_i\right)^2 - \left(\sum_i |\vec{p}_i|\right)^2 \tag{2}$$

where μ runs for all space-time coordinates, i runs for all particles in the initial state, and f runs for all particles in the final state.
The above means the invariant quantity is the invariant mass of all the particles in the final state of the process, which should be the same as the invariant mass of the particles of the initial state.

Analysis

As explained in the Theory section we should look in our data for reconstructed events with outcome of two or more muons and check for combinations of muons with opposite charges that could have been produced by the decay of Z in the Drell-Yan.
As expected there should be two muons in each event that came as a result from the Drell-Yan. However, figure 6 shows that in our analysis many events had more or less than two muons reconstructed by the detector. In fact, most of the events had 3 muons reconstructed. This is due to the large number of primary interactions because of the large number of protons in the bunches collided($\sim 10^{11}$ each) and also the intervention of other events nearby.

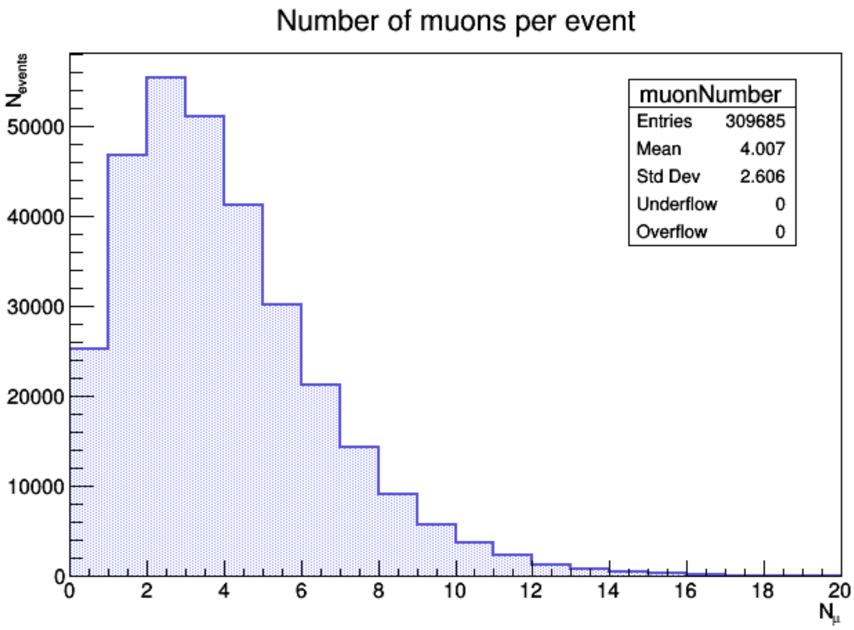

Figure 6: Number of reconstructed muons per event

As might be seen from figure 7 the distribution is uniform so there is no tendency for the direction of muons coming from Drell-Yan in the φ plane and figure 8 shows a symmetrical distribution of η relative to $\eta = 0$ again meaning there is no preferable direction in the z axis.

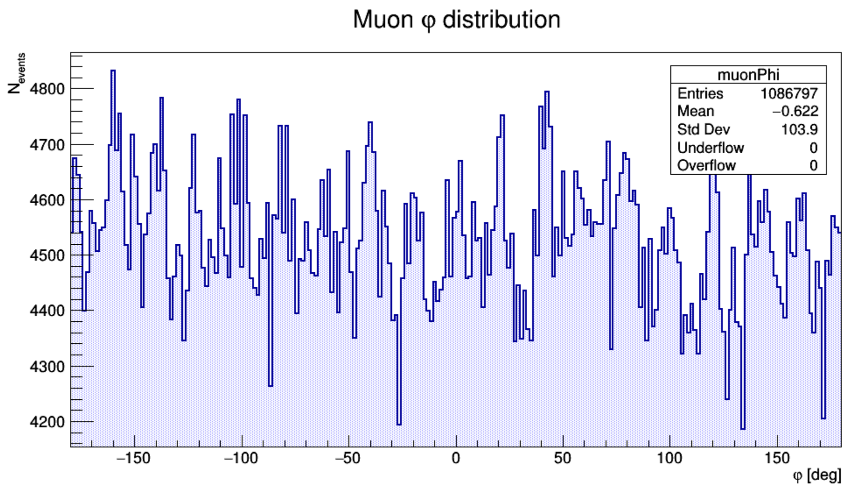

Figure 7: φ distribution of muons

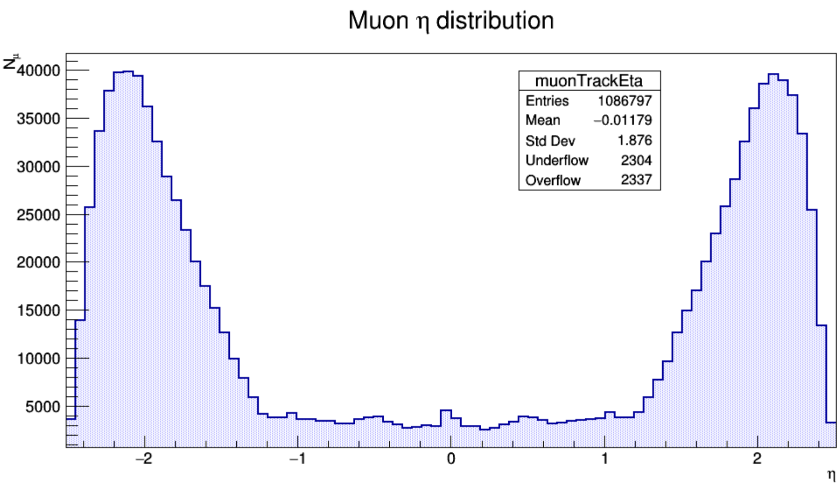

Figure 8: η distribution of muons

Using equation 2 we calculated the dimuon mass for our data in figure 9.

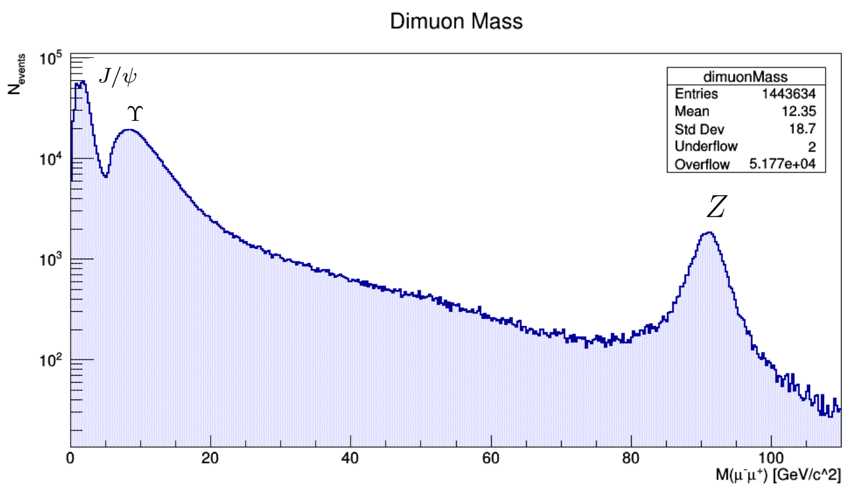

Figure 9: Dimuon mass of reconstructed events

Although the peak of Z boson is clearly seen, there are two other peaks at low energy. They correspond to the Υ and J/ψ mesons.
For a quick test of the results we fit a Gauss distribution to the data.

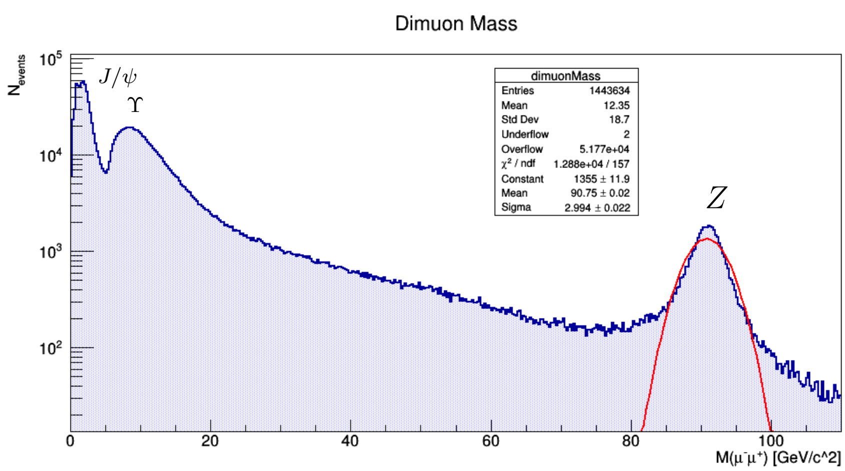

Figure 10: Dimuon mass of reconstructed events with Gauss fit for Z bozon peak

In figure 10 we show a Gauss fit for the Z that has a peak at $M_Z = 90.75 \pm 0.02 GeV$. Compared to the value from PDG[3] - $M_Z = 91.1876 \pm 0.0021 GeV$.

Discussion

We have obtained a value of $M_Z = 90.75 \pm 0.02 GeV$ with $\sigma = 2.994 \pm 0.022$ from DAS data. Compared to the reference data from PDG - $M_Z = 91.1876 \pm 0.0021 GeV$ with width $\Gamma = 2.4952 \pm 0.0023 GeV$, we could say it is a close result but a better fit should be obtained with a relativistic Breit-Wigner distribution convoluted with Gaussian.

References

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[10] `www.quantumdiaries.org/2015/05/18/dy-resummation`

[11] `pdg.lbl.gov/2017/reviews/rpp2016-rev-kinematics.pdf`