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Dimuons in LHC

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ABSTRACT

In a hadron collider like the Large Hadron Collider (LHC), the dimuon channel provides an ideal tool for the discovery of many predicted particles from Beyond Standard Model (BSM) theories such as high mass resonant, or non-resonant states. The high mass resonances like Z' and the high mass non-resonant like contact interactions or extra dimensions should appear in the high mass tail of dimuon distributions. The Drell-Yan process is the main source of high mass opposite sign muon pairs in the Standard Model (SM) which act as the irreducible background of signals of the above mentioned BSM models in proton-proton collisions. Therefore, it is important to study with the highest possible accuracy the Drell-Yan process.

In this paper, the expectations of the Drell-Yan process in the dimuon channel at next-to-next-to-leading order in QCD and next-to-leading order in the electroweak corrections are studied in detail. In the present study, a typical generic detector acceptance such as CMS or ATLAS at the LHC at center of mass energy 14 TeV is considered. At the end of this study, estimates of the expected backgrounds for new physics searches in the dimuon final states are given.

1- INTRODUCTION

The standard model (SM) of particle physics had been tested in detail in many experiments during the last half century. In all these experiments, the SM predictions coincide with the experimental results with very high precision and confirm the unprecedented success of the SM. In the SM, all the observed matter particles and the known forces between matter are described. These forces include the strong interactions which are invariant under the local $SU(3)$ color gauge group, and the electromagnetic and weak interactions which are invariant under local weak isospin and hypercharge gauge transformations, showing invariance under the $SU(2) \otimes U(1)$ group. The SM invariant Lagrangian can be written as:

$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \psi_i y_{ij}\psi_j\phi + h.c. + |D_\mu\phi|^2 - V(\phi) \quad \textbf{(1)}$$

The first term in equation (1) is the kinetic term for the gauge sector with a running over all the gauge fields. The second and the third terms in equation (1) describe the interactions between the matter fields ψ and the gauge fields with $h.c$ refers to their helicity conjugates. The fourth and fifth terms express the Yukawa sector and describe the interactions between the matter fields and the Higgs field, φ, which gives fermions their masses after electroweak symmetry breaking. The sixth term in equation (1) refers to the Higgs self-interaction while the last term is the Higgs potential, $V(\varphi)$, which takes the form

$$V(\varphi) = -\mu^2|\varphi|^2 + \lambda|\varphi|^4$$

Despite all the success of the SM, physicists still have cosmological observations and some questions that SM cannot predict or answer. The unanswered questions include the strong CP problem, neutrino mass, matter–antimatter asymmetry, and the nature of dark matter and dark energy. The presence of such unanswered questions and other unexplained observations in cosmology is the motivation for the BSM theories. Searches for new physics phenomena beyond the SM in dimuon final state provide a very clean signature and have been a mainstay

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of the quest strategy. Resonant or non-resonant effects have been searched for extensively at the LHC, see e.g [1, 2, 3, 4, 5, 6, 7, 8]. In order to do these searches in the dimuon final state, the Drell-Yan (DY) process of opposite sign muon pair must be studied with the highest possible precision. In the DY process, opposite sign muon pairs are produced from the initial partons from the incoming protons through a photon or Z vector boson mediation, (Figure 1).

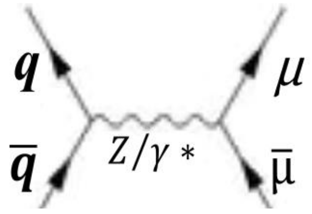

Fig (1): Drell-Yan process, in which a muon pair is produced from the incoming partons via virtual photon or *Z* boson

The DY process is the dominant background for many important Beyond Standard Model (BSM) predictions like new high mass resonant, Z', or non-resonant, like contact interactions or extra dimensions predictions, like Graviton. Therefore, it is essential to compute the DY expectations with the highest possible precision for any BSM dimuon searches at the LHC. The calculations must include the Quantum Chromodynamics (QCD) and Electroweak (EW) higher order corrections up to highest possible loop corrections. In this study, for QCD corrections, the Parton Distribution Function (PDF) sets used are the CT14 set, the PDF4LHC15 set or the LUXqed _plus PDF4LHC15 set. The PDFs are reweighted using the technique reported by Bourilkov et al. [9]. The EW corrections originate from two sources, the first is Quantum Electrodynamics (QED) and the second are pure weak effects. Processes such as Final State Radiation (FSR), and Initial State Radiation (ISR) are pure QED effects.

2- Monte-Carlo Simulation Tools

The DY process simulations were carried out using the FEWZ package [10]. The G_μ scheme with the W mass, the Z mass, the Fermi constant G_μ (measured in muon decay) and of course the fermion masses are used as input parameters. The strong coupling is set to $\alpha_s(M_Z) = 0.118$. For QCD, the PDFs considered are CT14, NNPDF30, PDF4LHC15 and LUXqed _plus PDF4LHC15 that are provided by the LHAPDF libraries version 6 [11, 12, 13]. Full electroweak corrections at next-to-leading order (NLO) are computed (the flag EW control = 0 is used). QCD effects are computed at next-to-leading order (NLO) and next-to-next-to-leading order (NNLO). DELPHES [14] was used to simulate detector responses to dimuons in the acceptance of a generic general purpose LHC experiment. In our analysis, both leading p_T muons are required to have pseudo-rapidity $|\eta| < 2.5$ and the transverse momenta for both muons have to be $p_T > 30$ GeV.

3- Cross Section Calculations

EW corrections

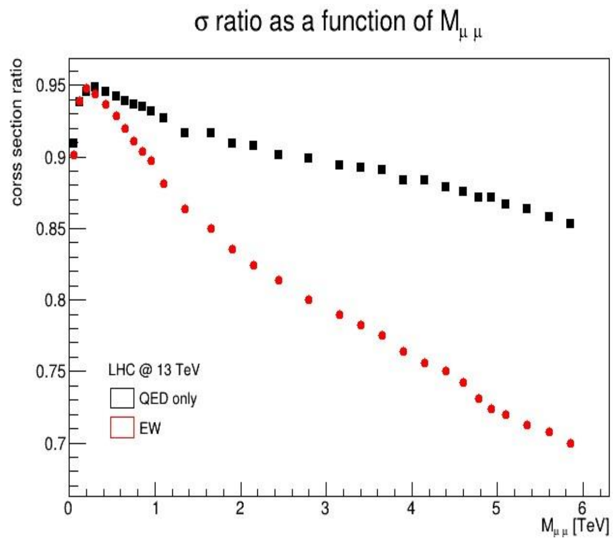

Fig. (2): Electroweak corrections for the dimuon channel: QED only and full EW corrections

In Figure (2), the cross section ratios at NLO in QCD and electroweak corrections are shown. two sets of calculations are compared:

1. QCD at NLO and QED corrections: FSR, ISR and their interference; Weak corrections off.
2. QCD at NLO and full EW corrections.

As shown in Figure (2), the pure QED corrections are bigger at high dimuon invariant mass and they reduce the cross-section by a factor of 10 %. In total the full EW effect reduces the cross section by more than 30 % at invariant mass around 5 TeV. It is clear that the full EW effects are important in order to compare simulations with data. This agrees with the conclusion of the earlier study [15] where it shows the necessity of including the full EW corrections at 14 TeV. Moreover higher order corrections of mixed QCD and EW type $O(\alpha_s\alpha)$ are also studied and we found that they are less important in agreement with [16] unless a very high precision is needed.

NNLO/NLO K functions

Figure 3 shows the so-called K-factor as a function of the invariant mass of the dimoun system. The K-factor is calculated the cross section ratios for calculations at NNLO and

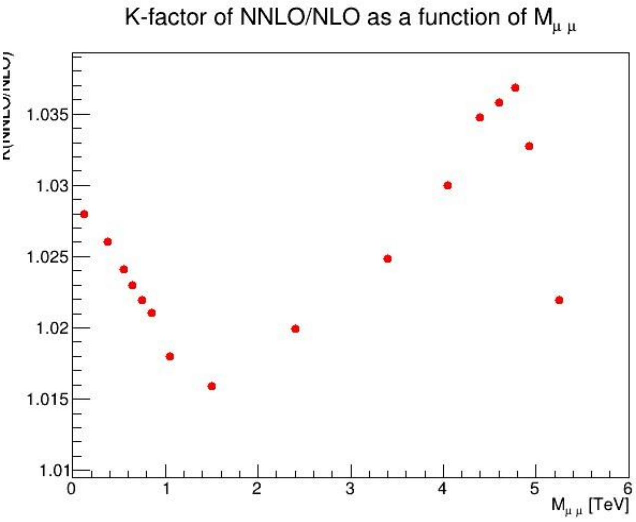

Fig. (3): K-factors for NNLO/NLO as a function of dimuon system invariant mass

NLO in QCD. In our calculation for the K-factor we included the full EW corrections. The K factor ranges from 1.015 up 1.04 for the dimuon invariant mass range from 0.1 TeV to 6 TeV. This shows that the NNLO QCD effects are quite small in SM dimoun production.

4- Differential Cross Sections Results

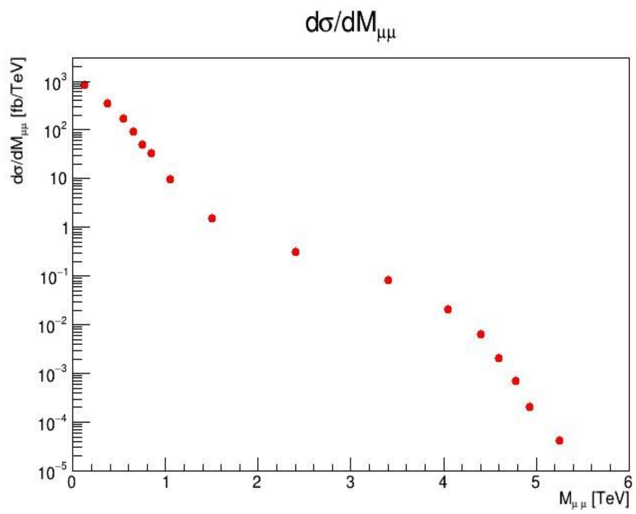

Fig. (4): Differential cross section (*dσ/dM$_{\mu\mu}$*) including all QCD and EW effects

The differential cross section, as a function of the dimuon invariant mass ($d\sigma/dM_{\mu\mu}$), is shown in Figure (4). In these calculations, the CT14 PDFs is used. The cross-section starts from about 850 *fb* at invariant mass equal to 0.15 TeV and decrease to a value of about 10^{-5}*fb* at invariant mass value of 6 TeV.

5- CONCLUSION

The study of the Drell-Yan process that gives dimoun out from the two interacting partons from the proton-proton collisions at the LHC is a very important one for new physics searches. Moreover, it tests the validity of the SM at LHC energy ranges. In this work, the dimuon production was studied in some detail and it gives values of the K-factors and differential cross-sections as functions of the dimoun system invariant mass. EW and QCD effects at next-to-next-to-leading order are considered. In conclusion, the backgrounds are quite low and almost well understood in the mass ranges for new physics searches, thanks to LHC run I and II.

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