GENERAL SEARCH FOR NEW PHENOMENA IN *pp COLLISIONS AT LHC USING DILEPTON FINAL STATES**

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Received February 20, 2013

The search for new physics is an objective of the experiments at future colliders, in particular at the LHC. This study is dedicated to dilepton (electrons or muons) final states resulting from proton-proton collisions at LHC at a centre of mass energy of 14 TeV. This paper investigates distributions for variables that are sensitive to new phenomena. Comparisons of two fast and generic ATLAS detector simulations are shown on selected physics processes.

Key words: particle physics, collisions, generators, new physics.

PACS: 07.05.Tp, 12.60.Cn.

1. INTRODUCTION

The Standard Model (SM) [1]- [3] of elementary particles and interactions is one of the best tested theories in physics. The SM includes the electromagnetic, strong and weak forces and all their carrier particles, and explains extremely well how these forces act on all the matter particles. It has been found to be in remarkable agreement with experiment, and its validity at the quantum level has been successfully probed in the electroweak sector. In spite of its experimental successes, the Standard Model suffers from a number of limitations, and is likely to be an incomplete theory.

There exist various theoretical models, which overcome the deficiencies of the SM by extending the physics Beyond the Standard Model (BSM). These extensions of the Standard Model predict new physics, which is favoured to occur at the TeV scale. A possible discovery of new physics would then be in the reach of current and future high-energy collider experiments.

The CERN Large Hadron Collider (LHC) is the highest energy physics experiment of our time. The LHC will accelerate two counter-rotating beams that will

*Paper presented at "The 8$^{\text{th}}$ Workshop on Quantum Field Theory and Hamiltonian Systems", September 19-22, 2012, Craiova, Romania.

collide head-on at a centre-of-mass energy of 14 TeV. The two beams are made to collide at four points where the main detectors are built. ATLAS (A Toroidal LHC Apparatus) [4] and CMS (Compact Muon Solenoid) [5] are general-purpose detectors to study proton-proton (pp) collisions. Although they share the same physics goals they involve different technical solutions and magnet system. ALICE (A Large Ion Collider Experiment) [6] is optimised to study the quark-gluon plasma in collision of heavy nuclei, while LHCb (LHC-beauty) [7] is designed to investigate CP violation in the b-quark sector. The ATLAS experiment has been designed as a detector for pp collisions with excellent measurement and identification of electrons and muons, good identification of jets with large transverse momentum, and a reliable measure of missing transverse energy. It will investigate a wide range of physics, including the search for the Higgs boson, extra dimensions, and particles that could make up dark matter.

This paper proposes obtaining as good as possible an estimate of the production of isolated dilepton final states that arise entirely from sources within the Standard Model itself from pp collisions at a centre of mass energy of 14 TeV. This paper studies the behaviour of the variables sensitive to new physics using the Standard Model prediction and the minimal B-L extension of the Standard Model [8].

This work is organised as follows. Section 2 describes physics processes and their simulation. Section 3 illustrates analysis strategy and event selection. The results are presented in sections 4. Finally, the conclusions are given in section 5.

2. PHYSICS PROCESSES AND MONTE CARLO SIMULATION

The process that we are interested in is dilepton production. The dominant Standard Model process for dilepton analysis is the Drell-Yan process, $pp \to \gamma, Z \to l^+l^-(l = e, \mu)$. No other sources, such $\mathrm{t\bar{t}}$ and diboson (WW, WZ and ZZ) production have been taken into account. The contribution of these processes is very small (0.6%), [9] [10]. The exotic process that is studied is $pp \to \gamma, Z, Z'_{B-L} \to l^+l^-(l = e, \mu)$ within the so-called ”pure” or ”minimal” B-L model.

Standard Model and exotic samples have been produced especially for this study. There were generated 1,000,000 events for SM signal and 100,000 events in the case of the BSM process using a combination of `MadGraph/MadEvent` [11] and `PYTHIA` [12] at a centre of mass energy of 14 TeV. The newest version of `MadGraph` Monte Carlo event generator (`MadGraph5`) that is open source software written in `Python` creates the matrix elements for a specified process. `MadEvent` generates events on a statistical basis at parton level and the cross sections are computed. Thanks to an interface between `MadGraph/MadEvent` and `PYTHIA`, the generated events are used in `PYTHIA`, where the events at parton level are showered according to a specific shower scheme. `PYTHIA` decays the final particles and simulates the subsequent hadronisation process. Two independent detector simulatios modified to match ATLAS geometries, efficiencies, and detailed reconstruction procedures were executed. The generation of the event samples was thus held independent of the detector simulation and the same data could be made available to both simulations.

For this study two fast detector simulations, `PGS` [13] and `Delphes` [14] were used. Fast detector simulations do not attempt to simulate the physical detector response but emulate the detector performance by calculating key values like particle momenta and missing energy within a simple detector model. The `PGS` – Pretty Good Simulation – detector simulation was designed for the Tevatron Run II Higgs/Susy Workshop and was formerly called SHW. PGS is written in `Fortran` and it is used in principle by theorists. `Delphes`, being written in `C++` is a "modern version" of `PGS` and is used by experimentalists as well as by theorists.

`Delphes` and `PGS` both use strongly simplified models of the calorimeter system and simulate the energy deposition in cells of η and ϕ. Both simulate an electromagnetic and a hadronic calorimeter, where no longitudinal segmentation is simulated. The bending of charged particles in the magnetic field of the tracking devices is taken into account in `Delphes` to estimate the impact points of tracks in the calorimeter system. Constant track reconstruction efficiencies are assumed for charged particles. The energy deposits in the calorimeter cells of individual particles are smeared according to parametrised energy resolutions with stochastic, noise and constant terms. However, an energy sharing between neighbouring calorimeter cells is not simulated. The types of particles (e/γ *versus* hadrons) are used to determine to which kind of calorimeter (EM, hadronic) the energy is accounted for.

Jets are reconstructed by running jet algorithms on the simulated energy accumulation of the calorimeter cells. The cell energies are also taken to calculate the expected missing transverse energy E_T^{miss}. For the simulation of electrons, muons and photons simply the corresponding final state particles from the event generator are used, where the energy resolution of the calorimeter may be taken into account for electrons and photons.

The event samples are analysed using `ROOT` [15] to get the results that are used to draw conclusions. `ROOT` is an object-oriented data analysis framework designed for large scale data analysis, written in `C++`. It contains several tools designed for statistical data exploration, fitting, and reporting.

3. ANALYSIS STRATEGY AND EVENT SELECTION

In this analysis, the distributions of the invariant mass M_{all} and the scalar sum of transverse momenta ΣP_T of the final states will be discussed. Both kinematic quantities are chosen since they are sensitive to new physics signals as well as easy to measure: $M_{all} = \sqrt{(\Sigma_i p_i)^2}$ and $\Sigma P_T \equiv \Sigma_i P_{T,i} = \Sigma_i \sqrt{P_{x,i}^2 + P_{y,i}^2}$, where the sum runs over all high-P_T leptons belonging to the final state and p_i, $P_{T,i}$ and $P_{x,i}$, $P_{y,i}$ denote the four-momentum, the transverse momentum and the x and y momentum components of each lepton.

The dilepton final states will be also evaluated in terms of angular distributions, which are sensitive to spin and decay properties of hypothetical high mass particles. The variable used to study the decomposition of the final states, inspired by topological analyses of multi-jet events, is defined in the following (more in reference [16]). In each final state, a leading lepton will be selected according to its energy. The variable $\cos\theta^*_{lead}$ is defined as the cosine of the polar angle of the leading lepton relative to the incident proton (0z axis) in the centre-of-mass frame defined by all leptons. For events with two leptons, the $\cos\theta^*_{lead}$ distribution is related to the underlying $2 \to 2$ matrix element. Therefore, the angular distribution of a particle coming from the decay of a new resonance may be markedly different from that of particles produced in SM processes.

In this study events passing the following filter requirements were analysed: isolated electrons with $P_T > 30$ GeV and $|\eta| < 2.47$, reconstructed photons with $P_T > 50$ GeV and $|\eta| < 2.37$, reconstructed jets with $P_T > 100$ GeV and $|\eta| < 2.8$ and isolated muons within $|\eta| < 2.4$ and $P_T > 30$ GeV. After this selection it is required to have exactly two leptons (electrons or muons) in the final state. So, this analysis is based on exclusive final states.

4. RESULTS

Comparing the results obtained with the `PGS` simulation to those of the `Delphes` simulation it is found that `PGS` and `Delphes` simulations differ in the reconstruction efficiency for leptons. `PGS` has a better reconstruction performance for electrons and `Delphes` for muons (see Table 1). A different behaviour is seen in Fig. 1 where the number of events with two reconstructed electrons is higher in case of the `Delphes` simulation.

Good agreement is achieved for the reconstructed muons which is visible in the P_T spectra of the muons in Fig. 2(right). The P_T spectra of electrons (Fig. 2 - left) is in a good agreement for `PGS` and `Delphes`, even if there are too many electrons simulated in case of `PGS`.

The pseudorapidity distributions for leading and sub-leading electron after applying the criteria for event selection are different for `PGS` and `Delphes`, whereas one can find a good agreement in case of muons (see Fig. 3).

The exclusive final states used in this analysis have two electrons and, respectively, two muons. We observed that 22.5% of the total number of the SM events have two electrons in case of `PGS` and only 18.2% in case of `Delphes`. For dimuon final states, survive 22% of the total number of the SM events for `PGS` simulation and

Type of leptons	Requirement	Number of leptons (SM PGS)	Number of leptons (SM Delphes)
Electrons	no cut	926204	840182
	$P_T > 30$ GeV	561872	519861
	$\|eta\| < 2.47$	560975	519043
Muons	no cut	795197	839283
	$P_T > 30$ GeV	552491	526395
	$\|eta\| < 2.4$	552467	522680

Table 1

Number of leptons before and after applying the requirements for the event selection.

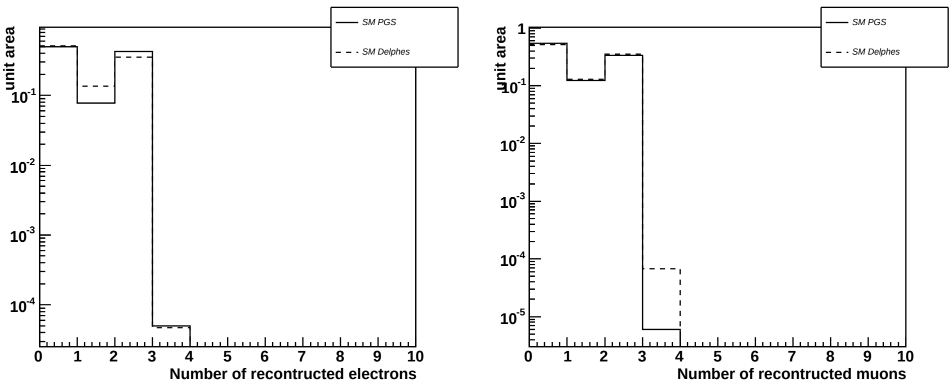

Fig. 1 – Multiplicity of leptons for the SM prediction in the ee (left) and $\mu\mu$ (right) final states before event selection.

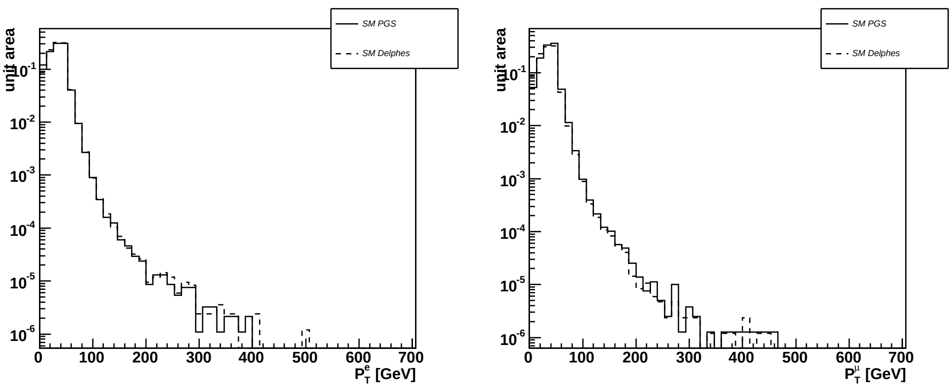

Fig. 2 – Transverse momentum P_T of electrons (left) and muons (right) before event selection.

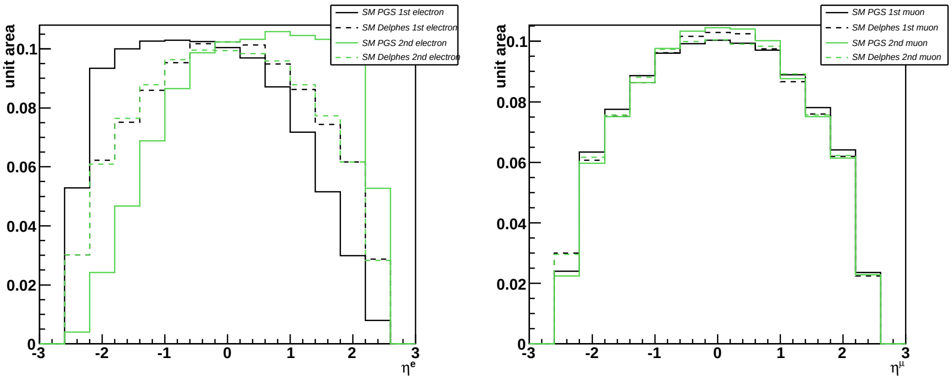

Fig. 3 – Pseudorapidity η of the leading and second electron (left) and leading and second muon (right) after event selection.

19.7% for Delphes simulation.

Fig. 4 and Fig. 5 represent the distributions for the invariant mass and the scalar sum of the transverse lepton momenta. For the Standard Model process, only in case of electrons there are some differences. They are more visible in case of the scalar sum of transverse momenta. Interestingly these differences occur at high values of momentum. A possible explanation is the parametrization of the electron identification efficiency implemented in PGS and Delphes.

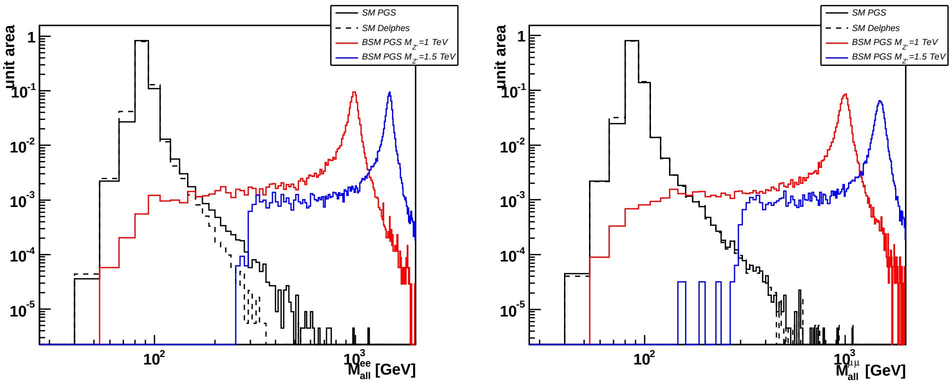

Fig. 4 – The invariant mass M_{all} for dilepton final state (left: electrons, right: muons) is shown for the SM prediction using PGS and Delphes fast detector simulation and for Z' signal for 2 masses: 1 TeV and 1.5 TeV using PGS.

The distributions of $\cos\theta^*_{lead}$ are presented in Fig. 6 for final states with two electrons and two muons. In case of the SM a good agreement is observed between

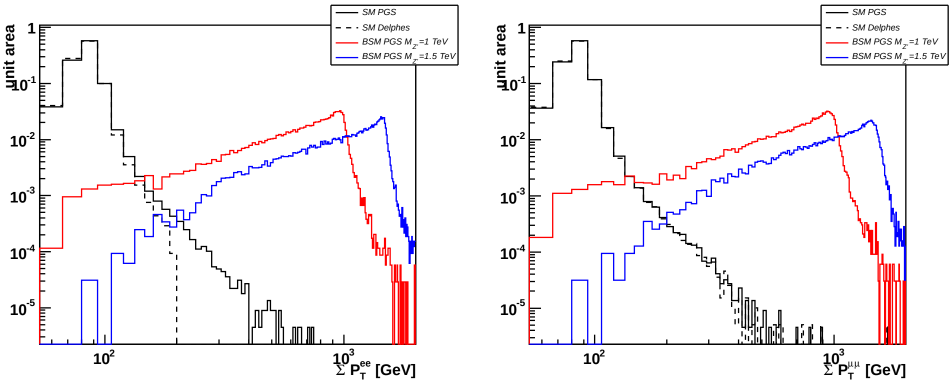

Fig. 5 – The scalar sum of transverse momenta P_T for dilepton final state (left: electrons, right: muons) is shown for the SM prediction using PGS and Delphes fast detector simulation and for Z' signal for 2 masses: 1 TeV and 1.5 TeV using PGS.

PGS and Delphes simulations.

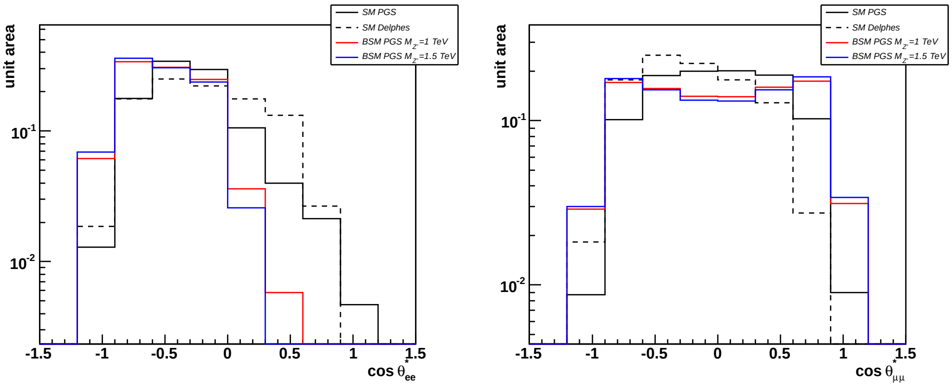

Fig. 6 – The variable $cos\theta^{\star}$ for dilepton final state (left: electrons, right: muons) is shown for the SM prediction using PGS and Delphes fast detector simulation and for Z' signal for 2 masses: 1 TeV and 1.5 TeV using PGS.

The sensitivity of the variables M_{all}, ΣP_T and $\cos\theta^{*}_{lead}$ to new physics is tested using Monte Carlo samples of exotic processes, for example in case of the minimal B-L model. It has been verified that SM and exotic events exhibit different spectra in these three variables using two PGS samples for Z' boson masses of 1 TeV and, respectively, 1.5 TeV in Fig. 4, Fig. 5 and Fig. 6.

5. CONCLUSIONS

Simulations of the detector are essential to compare predictions by Monte Carlo event generators to measured data. Event generators and detector simulations need to be tuned to give reliable predictions of Standard Model backgrounds as well as the signal processes one is interested in.

Generic detector simulations like `Delphes` and `PGS` are an option to estimate the detector response. They are much more simple than the full detector simulation, but may provide already a good overall picture, what may be expected in certain models. One finds that the main differences seen in this analysis come from the electron reconstruction methods used by `PGS` and `Delphes`.

In the next studies it is foreseen a comparison with data from the ATLAS experiment. Also the study will be extended to final states with more reconstructed objects.

Acknowledgments. The author would like to thank Dr. C. Alexa and O.A. Ducu for useful discussions. This work was presented at the 8th edition of the Workshop on Quantum Field Theory and Hamiltonian Systems, 19-22 September 2012, Craiova, Romania.

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