ELEMENTARY PARTICLES AND FIELDS

Experiment

Electroweak Physics from the CMS Experiment at the LHC

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Abstract—The results obtained in the CMS experiment at the Large Hadron Collider (LHC) by studying electroweak interaction are surveyed.

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Precision measurements of various features of electroweak processes at the record particle-interaction energies accessible at the Large Hadron Collider (LHC) is an indispensable part of the research program of experiments at CERN. Such investigations would become a test of paramount importance for the Standard Model in the new energy region and would set the stage for performing experiments aimed at searches for new physics beyond the Standard Model.

In the present article, we give an account of the results obtained by studying electroweak interactions in the Compact Muon Solenoid (CMS) experiment [1], which is one of the two multipurpose experiments at the LHC, during the first (RUN1) and second (RUN2) stages of LHC operation. The center-of-mass (c.m.) proton–proton interaction energy was $\sqrt{s} = 7$ and 8 TeV during RUN1, and its value of $\sqrt{s} = 13$ TeV came very close to the rated LHC energy in the course of RUN2. It is expected that the rated energy of $\sqrt{s} = 14$ TeV will be reached at the LHC toward the implementation of RUN3.

Study of the properties of the Z and W gauge bosons, which are interaction carriers, is one of the most important lines of research into electroweak processes—specifically, we mean measurement of the total and differential cross sections, decay branching ratios, masses, and other features of various electroweak particle-production processes. The results of the measurements performed during RUN1 and RUN2 agree perfectly with each other and with the respective Standard Model predictions in the next-to-leading order (NLO) of perturbation theory and, in a number of cases, in the next-to-next-to-leading order (NNLO). In particular, the energy dependence of the total production cross sections for Z and W bosons exhibits the expected growth

(see Fig. 1a), whereas the cross-section values themselves taken with allowance for the respective branching ratios do not go beyond the theoretical expectations (see Fig. 1b) and are compatible with the principle of lepton universality in the new energy region [2].

In studying electroweak processes, much attention is given to measuring properties of the Drell–Yan process [3] (cross sections, their energy dependences, angular distributions, and spatial asymmetry of final-state particles). Not only is this process a sensitive tool for searches of signals from physics beyond the Standard Model, but it is also one of the sources of backgrounds in studying the double production of top quarks and gauge bosons and in searching for the Higgs boson and measuring its properties in the channel of decay to four leptons. At the present time, the results obtained by measuring the double differential cross section $d^2\sigma/dmdy^Z$ (where m and y^Z are the dilepton invariant mass and rapidity, respectively) during RUN1 and RUN2 cover values of the Bjorken variable in the range of $3 \times 10^{-4} < x < 1.0$ and values of the square of the 4-momentum transfer in the range $6 \times 10^2 < Q^2 < 7.5 \times 10^5 \text{ GeV}^2/c^4$ [4]. The differential cross section $d\sigma/dm$ was measured over a wider range, $3 \times 10^2 < Q^2 < 3 \times 10^6 \text{ GeV}^2/c^4$. Measurement of the dependence of cross sections on the gauge-boson transverse momentum p_T^Z and rapidity y^Z is of importance for constraining the proton structure functions and for testing the predictions of various event generators (see, for example, Fig. 2) [8]. In addition, an analysis of angular distributions of leptons originating from the Drell–Yan process permits determining the square of the sine of the effective weak mixing angle, $\sin^2\theta_{\text{eff}}^l$. The respective CMS result obtained for the $(e^+e^- + \mu^+\mu^-)$ combined channel is $\sin^2\theta_{\text{eff}}^l = 0.23101 \pm 0.00036(\text{stat.}) \pm 0.00018(\text{syst.}) \pm 0.00016(\text{theor.}) \pm$

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Fig. 1. (a) Total cross sections for gauge-boson production versus $\sqrt{s}$ according to the results of the CMS experiment and experiments at Tevatron and Super Proton Cyclotron (SPS) [2]; (b) values of the gauge-boson cross sections in various channels and ratios of the measured values to those predicted within the Standard Model [2].

Fig. 2. Ratio of theoretical predictions and experimental data for the differential cross section for the Drell–Yan process with respect to the dilepton ($e^+ e^- + \mu^+ \mu^-$) (a) rapidity $|y^Z|$ and (b) transverse momentum p_T^Z . The FEWZ [5], MadGraph [6], and POWHEG [7] generators were used in respective theoretical calculations.

0.00031(PDF) [9], which agrees well with the results of the ATLAS [10] and LHCb [11] experiments.

As the amount of accumulated data grows, it becomes possible to study the processes of double and triple gauge-boson production and to measure accordingly the constant of Triple and Quartic Gauge boson Couplings (TGC and QGC). Some new-physics scenarios described within effective field theory predict an anomalous increase in the interaction strength owing to the presence of higher dimensionality terms in the Lagrangian. Thus, the above processes are an important probe of physics

beyond the Standard Model. In the CMS experiment, double gauge-boson production was studied in the charged-current ($WW\gamma$ and WWZ TGC vertices) and neutral-current ($Z\gamma\gamma$ $ZZ\gamma$ TGC vertices) channels [12]. At the present time, the cross sections measured for multiparticle gauge-boson production are in good agreement with the Standard Model predictions in the NNLO approximation (see Fig. 3), so that the coupling constants have not shown any signature of anomalous behavior. In the absence of significant deviations from the Standard Model predictions, limits at a 95% confidence level (C.L.)

Fig. 3. Ratio of experimental data and theoretical predictions [in the next-to-next-to-leading order (NNLO)] for the total cross section for double gauge-boson production.

were set on the parameters of the TGC vertices (see Fig. 4). The QGC vertices were studied in channels featuring three gauge bosons in the final state ($W^\pm W^\pm W^\mp$, $W\gamma\gamma$, and $Z\gamma\gamma$) and in the channels of associated production of a gauge-boson pair and jets in the gauge-boson fusion process ($W^\pm W^\pm jj$ and $ZW^\pm jj$) [13]. At the present level of accuracy, the results have not shown anomalous behavior of QGC either.

Experiments at the LHC provide a unique possibility of coming ever closer to measurement of rare decays. For example, the leptonic decays $B_s^0 \rightarrow \mu^+ \mu^-$ and $B^0 \rightarrow \mu^+ \mu^-$ proceeding in the Standard Model via Flavor-Changing Neutral Currents (FCNC) are strongly suppressed and are characterized by extremely small branching-ratio values of $(3.66 \pm 0.14) \times 10^{-9}$ and $(1.03 \pm 0.05) \times 10^{-10}$, respectively. Any deviation of experimental data from the predictions may be indicative of a manifestation of new physics. Owing to a high dimuon-detection efficiency and a record luminosity provided by the LHC accelerator complex, it turned out to be possible in the CMS experiment [14] to record the decay $B_s^0 \rightarrow \mu^+ \mu^-$ at a statistical-significance level of 5.6σ and to estimate its branching ratio at $(2.9 \pm 0.27) \times 10^{-9}$ (Fig. 5) [14]. At the same time, the decay process $B^0 \rightarrow \mu^+ \mu^-$ could not be seen on the basis of existing data—only the branching ratio for this process was

constrained at a 95% C.L. as $\text{Br}(B^0 \rightarrow \mu^+ \mu^-) < 3.6 \times 10^{-9}$ (see Fig. 5b) [14]. The above results are compatible with the Standard Model predictions.

Particular interest in single-particle t -quark production processes is caused by their sensitivity to new-physics contributions changing values of coupling constants in the tWb vertex function. Indirect measurements of the Cabibbo–Kobayashi–Maskawa (CKM) matrix element V_{tb} have been repeatedly performed in experiments with t quarks [15] and B hadrons [16] under the assumption that the CKM matrix is unitary and the assumption that the number of quark generations in the Standard Model is fixed (equal to three). On the other hand, a direct estimation of this matrix element on the basis of measurement of the cross sections for single-particle t -quark production processes is free from these assumptions. Figure 6 shows the results obtained by measuring $|V_{tb}|$ in various channels of t -quark production [17]. Data from the CMS and ATLAS experiments agree fully with each other and with the theoretical predictions of the Standard Model.

In conclusion, we would like to note that, at the present time, all results of investigations into electroweak processes in experiments at the LHC are in perfect agreement with the respective Standard Model predictions. Moreover, rare processes predicted theoretically but not observed earlier (for example, the associated production of t and W and

Fig. 4. Allowed (at a 95% C.L.) interval of parameters of the anomalous WWZ Triple Gauge boson Coupling (TGC).

Fig. 5. (a) Distribution of dimuon invariant masses in detected events (closed circles). Also shown in this panel are the fitted results for signal (shaded regions) and background (dotted curves) events [14]. (b) Decay branching ratios $\text{Br}(B_s^0 \rightarrow \mu^+ \mu^-)$ and $\text{Br}(B^0 \rightarrow \mu^+ \mu^-)$ measured in the CMS experiment (cross) along with five regions (contours) corresponding to 1–5 root-mean-square deviations [14]. The Standard Model prediction is also presented here (box).

the decay $B_s^0 \rightarrow \mu^+ \mu^-$ were discovered and studied. A further accumulation of experimental data would contribute to the improvement of the accuracy of

measurements and to the creation of preconditions for observing rare processes expected within the Standard Model.

Fig. 6. Results of the ATLAS and CMS experiments for the matrix element V_{tb} according to measurements in single-particle t -quark production processes [17].

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