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CMS Results on Dimuon Physics

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Abstract

We review the recent results obtained by the CMS collaboration in the physics of dimuon production in pp collisions, primarily the measurement of the Drell-Yan differential cross section and the search for narrow high-mass resonances in the dimuon channel.

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Keywords: Dilepton production, Drell-Yan process, new heavy dimuon resonances, extra gauge models, Randall-Sundrum graviton, collider measurements

1 Introduction

Dimuon studies have led to a number of important discoveries in the particle physics, such as discoveries of J/ψ and Υ mesons, Z bosons and precision measurements of their characteristics. Muons, due to their large penetrating power in the matter, can provide signature of clean measurements filtering out large background from the high-luminosity pp interactions at the Large Hadron Collider (LHC). The Compact Muon Solenoid (CMS) detector at the LHC has a dedicated muon system enabling efficient triggering and detection of muons with a high accuracy [1, 2, 3]. Recently, a discovery of $B_s^0 \to \mu^+\mu^-$ rare decay has confirmed the Standard model (SM) with $6\,\sigma$ and an evidence of $B_s^0 \to \mu^+\mu^-$ decay with $3\,\sigma$ has been obtained by the combined analysis of CMS and LHCb data [4]. A search for the $\mu^+\mu^-$ decay channel of the standard model-like Higgs boson is going on [5, 6].

The production of lepton pairs in hadron-hadron collisions via the Drell–Yan (DY) process is described in the SM by the s-channel exchange of γ^*/Z produced in the parton interactions. The theoretical calculations of the differential cross section are well established up to next-to-next-to-leading order (NNLO) of quantum chromodynamics (QCD) [7, 8, 9]. Therefore, comparisons between calculations and precise experimental measurements provide stringent tests of perturbative QCD and significant constraints on the evaluation of the parton distribution functions (PDFs).

Many models of new physics predict the existence of narrow resonances at the TeV mass scale decaying to a pair of charged leptons [10, 11], in particular, Sequential Standard Model Z_{SSM} with SM-like couplings, the Z_ψ predicted by grand unified theories [12], and Kaluza–Klein graviton excitations arising in the Randall–Sundrum (RS) model of extra dimensions [13, 14].

In the present paper we review the recent CMS results of measurements of the differential DY cross section $d\sigma/dM$ [15] and the search for narrow heavy dimuon resonances [16, 17].

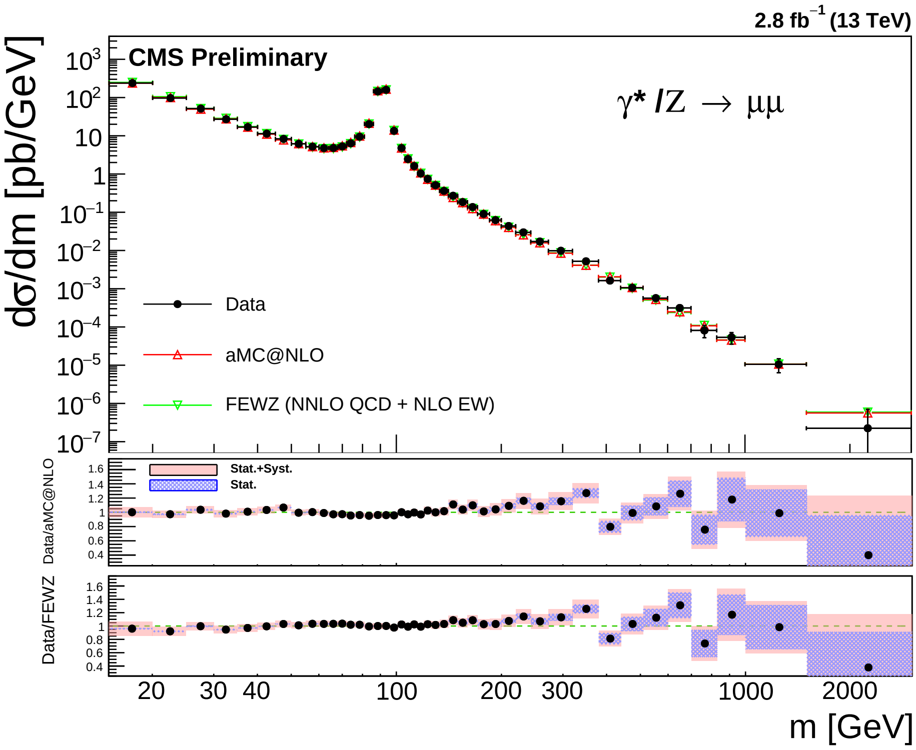

Figure 1: Result of the DY differential cross section measurement for full phase space with FSR correction as a function of the dimuon invariant mass compared to the NLO prediction of MadGraph5_aMC@NLO (red) and the NNLO theoretical prediction of FEWZ (green) [15]. NNPDF3.0 PDF set is used for the theoretical calculation.

2 Differential Drell-Yan cross section

A new measurement of the differential Drell-Yan cross section $d\sigma/dM$ is based on the full 2015 dataset corresponding to an integrated luminosity of 2.8 fb^{-1} of proton-proton collision data at the center-of-mass energy $\sqrt{s} = 13$ TeV collected by the CMS detector in proton-proton collisions. The measured differential cross section has been determined using the following formula:

$$\sigma = \frac{N_u}{A \cdot \varepsilon \cdot \rho \cdot \mathcal{L}_{int}}, \tag{1}$$

where N_u denotes the signal yield after subtracting backgrounds obtained using an unfolding technique to correct for the effect of the migration due to the detector resolution and the final-state QED radiation (FSR) effect; A and ε are the acceptance and efficiency for signal events obtained from the MC simulation; ρ is the scale factor to account for the difference in the efficiency between data and MC; $\mathcal{L}_{int}$ is the integrated luminosity of the 2015 dataset. The FSR effect has been also corrected using the unfolding technique.

The DY differential cross section in the full phase space has been measured after full corrections. The results are presented in Fig. 1 as a function of the dimuon invariant mass. They are compared to the NNLO theoretical predictions which have been calculated using FEWZ 3.1 with NNPDF3.0 and NLO EW correction, as well as MadGraph5_aMC@NLO predictions with NNPDF3.0 (NLO). The results of the measurement are in good agreement with both theoretical predictions within uncertainties, see details in the recent CMS physics analysis summary [15].

In addition to the fully corrected DY differential cross section measurement, the result of the fiducial cross section has been produced, within the detector acceptance and without FSR correction. The results are in good agreement with the theoretical prediction.

Other recent CMS results in electroweak physics in dimuon channel include the following. A new measurement of Z production cross section at $\sqrt{s} = 13$ TeV has been made which agrees well with the NNLO QCD expectation and complements the previous measurements at $\sqrt{s} = 7$ and 8 TeV [18]. Measurement of the transverse momentum and rapidity distributions of DY pairs in the Z mass region $60 < M_{\ell\ell} < 120\,\mathrm{GeV}$ has been made [19, 20]. The measurement of the forward-backward asymmetry has been performed for the dilepton masses between 40 GeV and 2 TeV and for the dimuon rapidity up to 2.4, as a function of the dilepton mass and rapidity, the results which are sensitive to the new physics are consistent with the SM predictions [21]. A recent CMS analysis has measured the five most significant angular coefficients, A_0 through A_4, for Z bosons produced in pp collisions at $\sqrt{s} = 8$ TeV as a function of the transverse momentum and rapidity of the Z boson. These measurements provide comprehensive information about the Z boson production mechanisms, and are compared to the QCD NNLO predictions. The violation of the Lam-Tung relation ($A_0 = A_2$) is observed predicted by the QCD calculations beyond leading order [22].

3 Search for narrow heavy dimuon resonances

Search for narrow heavy dimuon resonances has been performed with the data recorded in 2016, corresponding to an integrated luminosity of 13 fb^{-1} at $\sqrt{s} = 13$ TeV [16]. The dimuon invariant mass spectrum is shown in Fig. 2a. The event with the largest dimuon mass was 2.2 TeV, and an event with dielectron of 2.9 TeV was found in 2015 data sample.

As theoretical benchmarks, we have used three different models: the Sequential Standard Model Z_{SSM} with SM-like couplings, the Z_ψ predicted by grand unified theories [12], and Kaluza–Klein graviton excitations arising in the Randall–Sundrum (RS) model of extra dimensions [13, 14]. The RS model has two free parameters: the mass of the first graviton excitation and the coupling $k/\overline{M}_{\mathrm{Pl}}$, where k is the curvature of the extra dimension and $\overline{M}_{\mathrm{Pl}}$ is the reduced effective Planck scale. For a resonance mass of 1 TeV, the widths are 30, 6 and 14 GeV for the Z_{SSM}, Z_ψ, and G_{KK} with $k/\overline{M}_{\mathrm{Pl}} = 0.1$, respectively. To impose the mass limits, we normalize to $\sigma(Z)$:

$$R_\sigma = \frac{\sigma(Z' \to \mu^+\mu^-)}{\sigma(Z \to \mu^+\mu^-)} = \frac{N(Z')}{N(Z)} \times \frac{A(Z)}{A(Z')} \times \frac{\varepsilon(Z)}{\varepsilon(Z')}$$

In this way the luminosity uncertainty is removed and other systematic effects reduced. The search for resonances is based on a shape analysis of dilepton mass spectra, in order to be robust against uncertainties in the absolute background level. Existence (or lack) of a signal is established by performing unbinned maximum likelihood fits to the observed spectrum. No significant deviations from the SM expectation have been observed, therefore lower bounds are set on the masses of hypothetical particles that arise in new-physics scenarios. The obtained upper limits on the cross section ratio R_σ at 95% confidence level (C.L.) are shown in Fig. 2b for the dimuon channel. Using the dimuon analysis, we could exclude at 95% C.L. the following Z' masses: the Z_{SSM} can be excluded below 3.75 TeV, the Z_ψ below 3.20 TeV. Combining the measurements from both dimuon and electron channels (Fig. 2c), the following 95% C.L. lower limits on the mass of a Z' resonance have been obtained: 4.00 TeV for the Z_{SSM}, and 3.50 TeV for the Z_ψ. The procedure and the results are described in detail in the CMS public analysis summary [16].

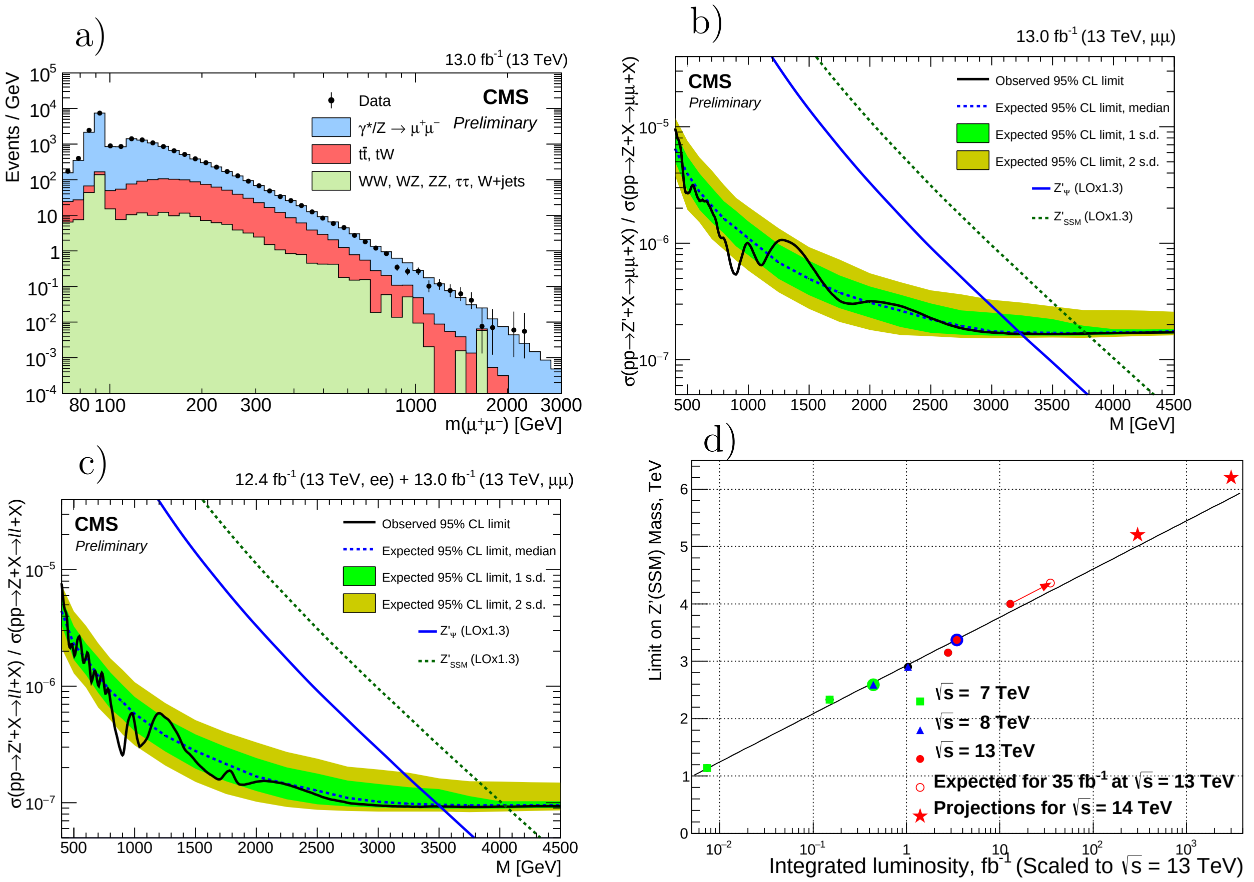

Figure 2: a) The invariant mass spectrum of dimuon events [16]. The MC simulated backgrounds are normalised to the data in the region of $60 < M_{\ell\ell} < 120$ GeV, with the muon channel using a prescaled lower threshold trigger. b), c) The 95% CL upper limits on the production cross section times branching fraction for a spin-1 resonance, relative to the production cross section times branching fraction for a Z boson, for (b) the dimuon channel, and (c) combined dimuon and dielectron channel [16]. The shaded bands correspond to the 68% and 95% quantiles for the expected limits. The theoretical predictions for the spin-1 $Z_{\rm SSM}$ and Z_ψ resonances are shown for comparison. d) History of the CMS mass lower limits for the $Z_{\rm SSM}$ model as a function of the integrated luminosities scaled to $\sqrt{s} = 13$ TeV.

Results for the RS model were presented in paper [17] based on analysis of the 2015 data corresponding to an integrated luminosity of 2.9 fb^{-1} at $\sqrt{s} = 13$ TeV giving the lower mass limits for RS Kaluza–Klein gravitons equal to 3.03 and 1.26 TeV in the dimuon channel, and for the combined dimuon and dielectron channels of 3.11 and 1.46 TeV, for couplings of 0.1 and 0.01, respectively.

Fig. 2d shows the history of the CMS mass lower limits for the $Z_{\rm SSM}$ model as a function integrated luminosities of the considered dilepton data samples at $\sqrt{s} = 7$, 8 and 13 TeV scaled to $\sqrt{s} = 13$ TeV using the ratios of LHC parton luminosities for different energies [23]. The results can be well fitted by the logarithmic curve which predicts a mass limit about 4.4 TeV for the data sample with an integrated luminosity of 35 fb^{-1} at $\sqrt{s} = 13$ TeV which is expected for the data of the full 2016 run. The figure also contains projections for possible discoveries at $5\,\sigma$ in the dimuon channel with an integrated luminosity of 300 and 3000 fb^{-1} at $\sqrt{s} = 14$ TeV [24].

4 Conclusions

The CMS collaboration has published the result on the DY differential cross section normalized to the cross section in the Z region $d\sigma/dM_{\ell\ell}$. Results are presented both inside the detector acceptance and in the full phase space. The measurements are in good agreement with the NNLO theoretical predictions, and can be used for further constraints of the SM parameters and PDFs.

Also, the CMS Collaboration has searched for narrow resonances in the invariant mass spectrum of dimuon and dielectron final states in the event samples corresponding to an integrated luminosity of 13 fb^{-1} at $\sqrt{s} = 13$ TeV. This search channel benefits from high signal selection efficiencies and relatively small, well-understood backgrounds. The spectra are consistent with expectations from the SM and the upper limits have been set on the cross section times branching fraction for Z' into lepton pairs relative to SM Z boson production. The mass limits have been set on neutral gauge bosons Z' and RS Kaluza–Klein gravitons G_{KK}. We will be able to extend the mass range for these analyses with new LHC data. Based on history of CMS results, prediction for the full 2016 run has been given.

The dimuon analysis is used also in other physics studies at CMS, e.g. search for low-mass resonances decaying into dimuons as a signal of new physics [25, 26], J/ψ, Υ and B meson physics, etc. [27]–[30].

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