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W^+W^- production at LHC at NLO in extra dimension models

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NLO QCD corrections to production of two W bosons at the LHC in the ADD model are presented. Invariant mass and rapidity distributions are obtained to order α_s in QCD by taking into account all the parton level subprocesses. We estimate the impact of the QCD corrections on various observables and find that they are significant. We present some results for a 10 TeV LHC but most of the results presented here are for 14 TeV LHC. We also show the reduction in factorization scale uncertainty when $\mathcal{O}(\alpha_s)$ effects are included.

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The Large Hadron Collider (LHC) offers to shed light on new physics beyond the Standard Model (SM). The most popular new physics models are based on the ideas of supersymmetry and extra spatial dimensions. Proposals to address the hierarchy problem using extra dimensions were introduced in [1, 2]. Here we will consider the ADD model [1]. In this model SM fields are confined to a (3+1) dimensional manifold and the extra d spatial dimensions are compactified, with same radius of compactification R, on a d-torii. Extra dimensions manifest as Kaluza Klein (KK) gravitons on the 3-brane. These gravitons couple to SM fields through energy momentum tensor with a strength κ [3].

$$\kappa^2 R^d = 8\pi(4\pi)^{d/2}\Gamma(d/2)M_s^{-(d+2)}. \tag{1}$$

Here M_s is fundamental scale in $4+d$ dimensions. Although the coupling κ is M_{Pl} suppressed, the fact that there are large number of KK modes that couple to the SM fields makes the cumulative effect significant and leads to observable effects. We will consider here $d=3$ and above since one extra dimension ie. $d=1$ is ruled out [4] and $d=2$ is severely constrained. Here we will consider only the effects of virtual spin-2 KK states.

The precise measurement of hadronic production of gauge boson pairs is one of the important endeavors at the LHC both in the context of SM and new physics studies. Studies in other channels have been reported in [5] in extra dimension models. Here we will consider production of W pair at the LHC. This channel has attracted a lot of attention in the literature in the SM. A study in the context of anomalous triple gauge boson vertices was carried out in [6]. Leading order (LO) studies in the SM can be found in [7]. Next-to-leading-order (NLO) studies in the SM are reported in [8, 9]. It has also been studied via gluon fusion through a quark box loop or triangle quark loop with γ or Z boson exchange [10] and at one and two loop levels in high energy limit in SM [11].

LO results are highly sensitive to the renormalization and factorization scales. Inclusion of higher order terms reduces this dependence . In addition the NLO results are usually significantly enhanced as compared to the LO results. It is thus important to carry out a full NLO calculation.

The significance of NLO computations in the extra dimension models for Drell-Yan [12], diphoton [13], ZZ [14], graviton+photon [15], graviton+jet [16] production has already been demonstrated. These studies show that not only the predictions at NLO are enhanced but are also less sensitive to the factorization scale.

Here we have used the two cutoff phase space slicing [17] to carry out the NLO calculation for production of W^+W^- pairs in the ADD model. We use dimensional regularization and $\overline{MS}$ scheme throughout this paper to regulate and subtract the divergences. The details of the calculations and matrix elements at LO and NLO are presented in [18].

In the following we present the results using our monte carlo code. This code can easily accommodate any cuts on the final state bosons and can evaluate various kinematical distributions. The LHC with a center of mass energy of 14 TeV will be our default choice. However we will also present some results for a center of mass energy of 10 TeV for the LHC. For numerical evaluation, the following SM parameters [19] are used

$$m_W = 80.398\ GeV, \quad m_Z = 91.1876\ GeV, \quad \Gamma_Z = 2.4952\ GeV, \quad \sin^2\theta_W = 0.231 \tag{2}$$

where θ_W is the weak mixing angle. For the electromagnetic coupling constant α we use $\alpha^{-1} = 128.89$. CTEQ6 [20] density sets are used for parton distribution functions. 2-loop running for the strong coupling constant is used . The number of active massless-quark flavors is taken to be 5 and the value of Λ_{QCD} is chosen as prescribed by the CTEQ6 density sets. At leading order, that is at order α_s^0, we use CTEQ6L1 density set . At NLO we use CTEQ6M density set. We will set renormalization and factorization scales equal to the invariant mass of the W boson pair ie., $\mu_F = \mu_R = Q$ and implement rapidity cut on W bosons, $|y_W| < 2.5$.

We will present invariant mass distribution, $d\sigma/dQ$, where Q is the invariant mass of the final state W boson pair, rapidity distribution $d\sigma/dY$ where $Y = 1/2 \ \ln(P_1 \cdot q)/(P_2 \cdot q)$, where P_1 and P_2 are incoming proton momenta and q is the sum of the W boson 4-momenta.

Fig. 1 presents the invariant mass distribution both for the SM and the signal, in the range 300 GeV to 1300 GeV. Here results are displayed for three extra dimensions and for $M_s = 2\ TeV$. To highlight the importance of QCD corrections we have also displayed the LO results of SM and the signal, and we observe that the K factors are significantly large. We note that for the signal K factor varies between 1.55 to 1.98 in the invariant mass range of 300 to 1300 GeV. This also shows that the LO results can be only treated as first approximations and to have more precise estimates we should go beyond the leading order. We note here that present computation does not take into account decay of W bosons to leptons which is observed experimentally, but as QCD corrections are independent of these decays, the K factors obtained here would not change when decays are taken into account.

To estimate the effect of the number of extra dimensions we plot in Fig. 2 the signal for three different values of d (3,4,5) with M_s fixed at 2 TeV. We note that the lower the value of d, higher is the strength of the signal. Next in Fig. 3 we have plotted $d\sigma/dQ$ for three different values of M_s (2.0, 2.5, 3.0) at a fixed value 3 for the number of extra dimensions. As expected, with increase in the fundamental scale the deviations from SM predictions become less, and significant deviations from SM are observed at higher energies still.

Fig. 4 shows rapidity distribution $d\sigma/dY$ at LO and NLO both for SM and the signal for $d = 3$ and M_s fixed at 2 TeV in the interval $-2.0 < Y < 2.0$. An integration over the invariant mass interval $900 < Q < 1100$ has been done to increase the signal over the SM background. As expected the distribution is symmetric about $Y = 0$.

As was noted before, the NLO QCD corrections reduce the sensitivity of the cross sections to the factorization scale μ_F; this we now show in the Fig. 5. We have plotted SM and the signal both at LO and NLO, and have varied the factorization scale μ_F in the range $Q/2 < \mu_F < 2Q$. The central curve in a given band (shown by the dotted curves) correspond to $\mu_F = Q$. In all these the renormalization scale is fixed at $\mu_R = Q$. We notice that the factorization scale uncertainties in SM are less compared to the signal. This is because of the dominant role of the gluon gluon initiated process in the signal. We see in this figure that a significant reduction in theoretical uncertainty, arising from the factorization scale, is achieved by our NLO computation. At $Q = 1300\ GeV$ the $d\sigma/dQ$ for the signal varies by 18.8 % at LO as μ_F is varied between $Q/2$ to $2Q$ and it varies by 7.6 % at NLO. At the end we present in Fig. 6, $d\sigma/dQ$ for LHC with a centre of mass energy of 10 TeV at NLO both for SM and signal. For comparison we have also plotted the 14 TeV results in the same figure.

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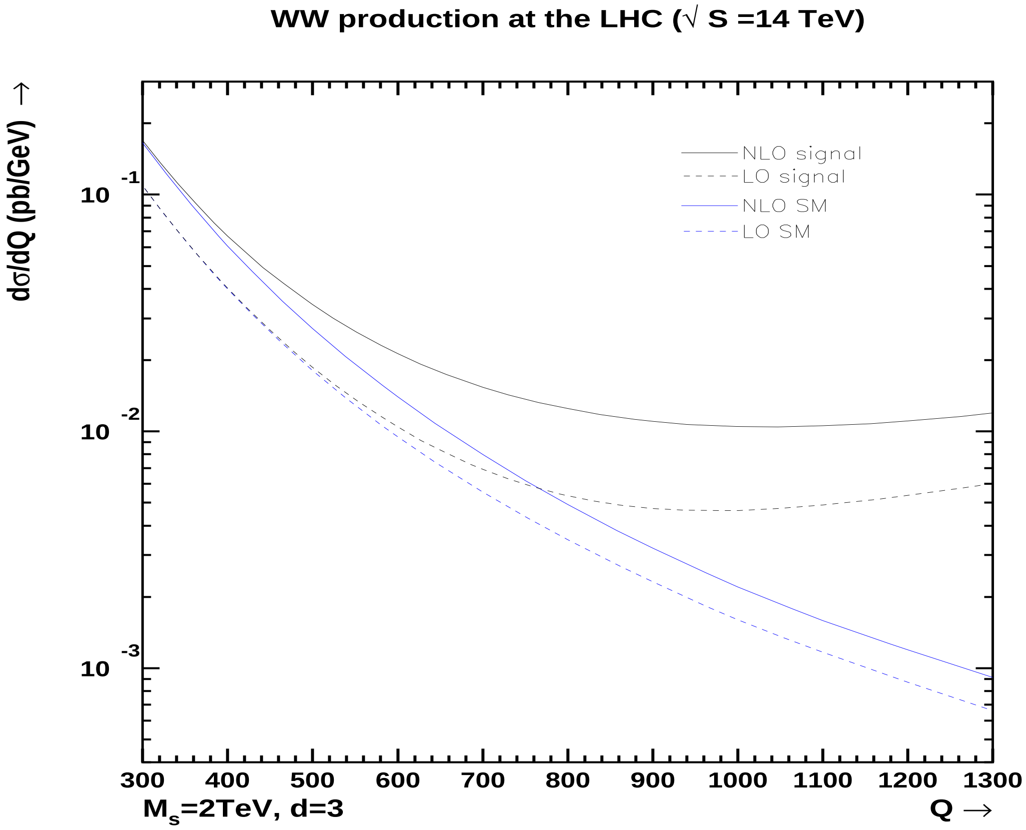

Figure 1: Invariant mass distribution at LO and NLO in SM and for the signal at $M_s = 2TeV$ and 3 extra dimensions.

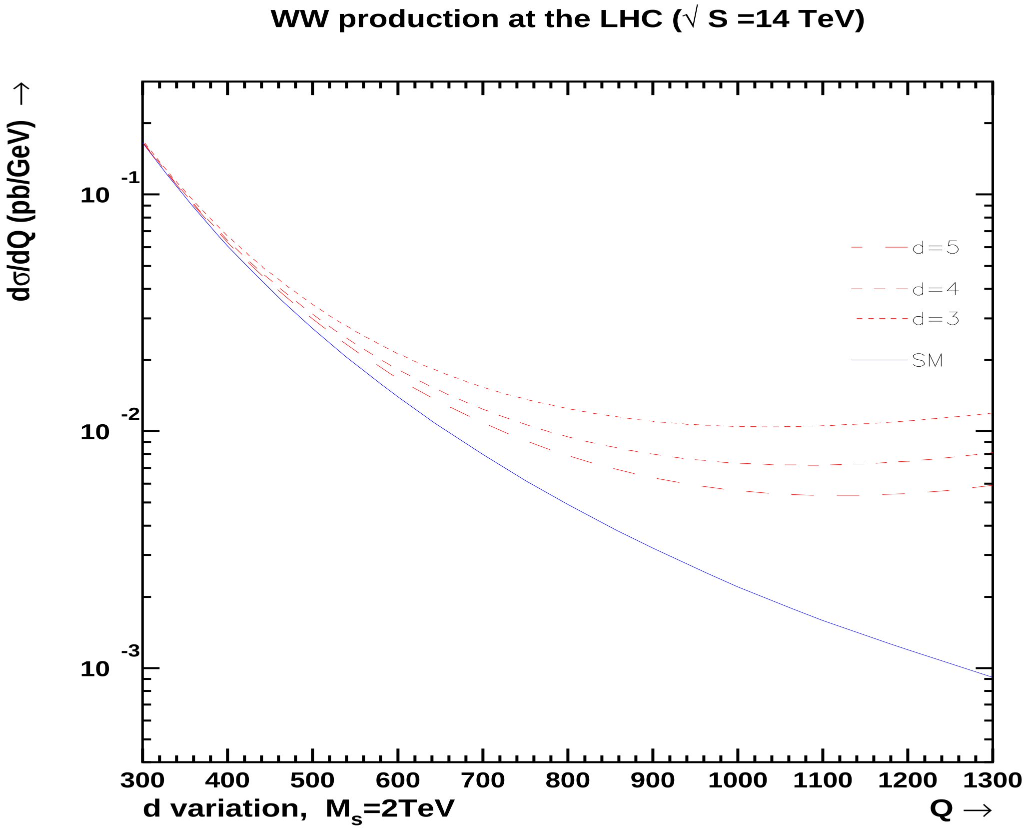

Figure 2: Effect of variation of number of extra dimensions in invariant mass distribution. The fundamental scale M_s has been fixed at 2 TeV. The curves correspond to NLO results.

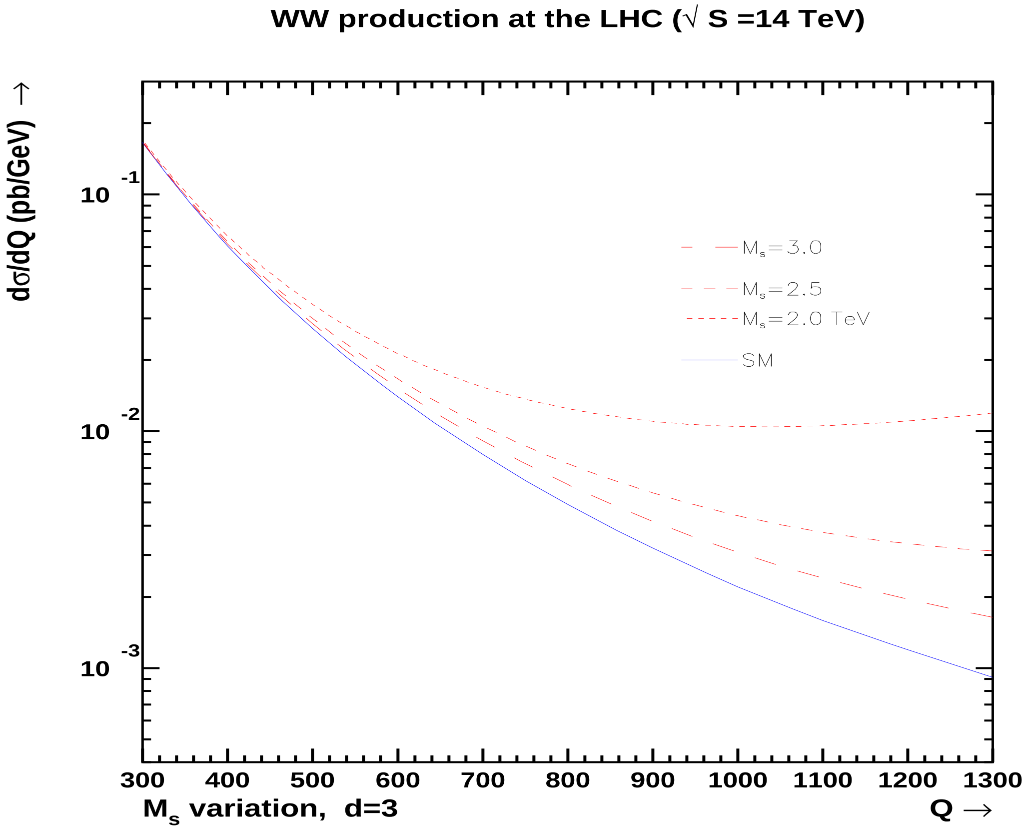

Figure 3: Effect of variation of the fundamental scale M_s in the invariant mass distribution. The number of extra dimensions has been fixed at 3. The curves correspond to NLO results.

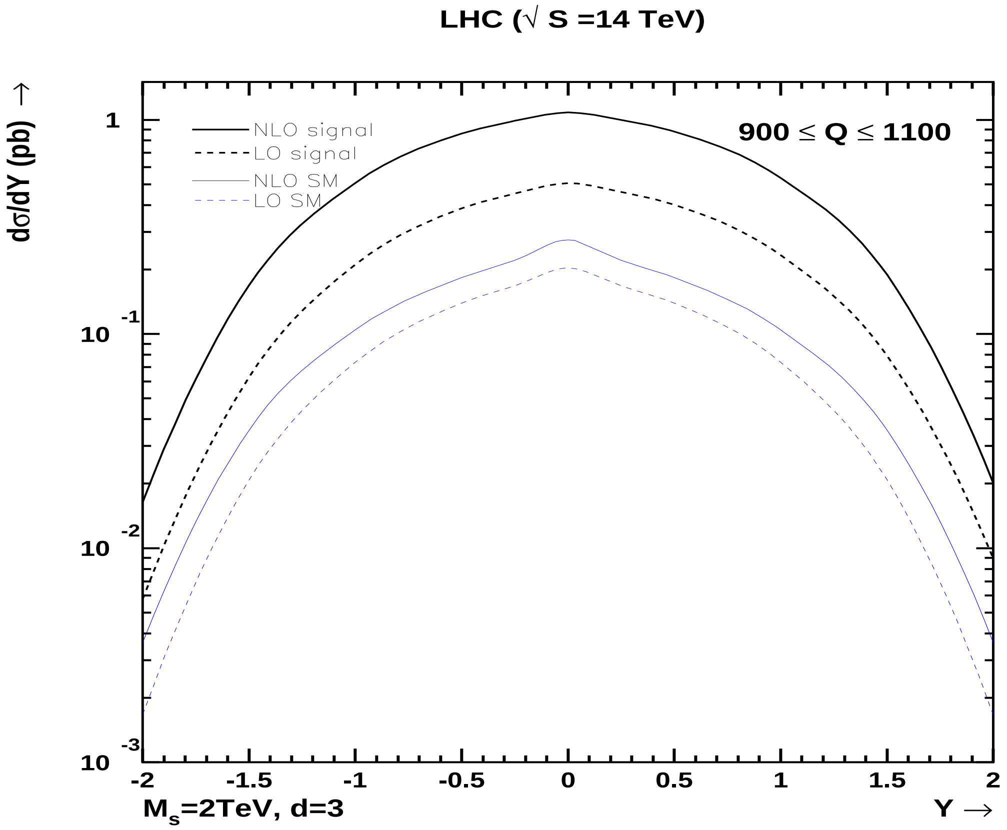

Figure 4: Rapidity distribution for $M_s = 2TeV$ for SM and signal for $d = 3$. We have integrated over the invariant mass range $900 < Q < 1100$ to enhance the signal.

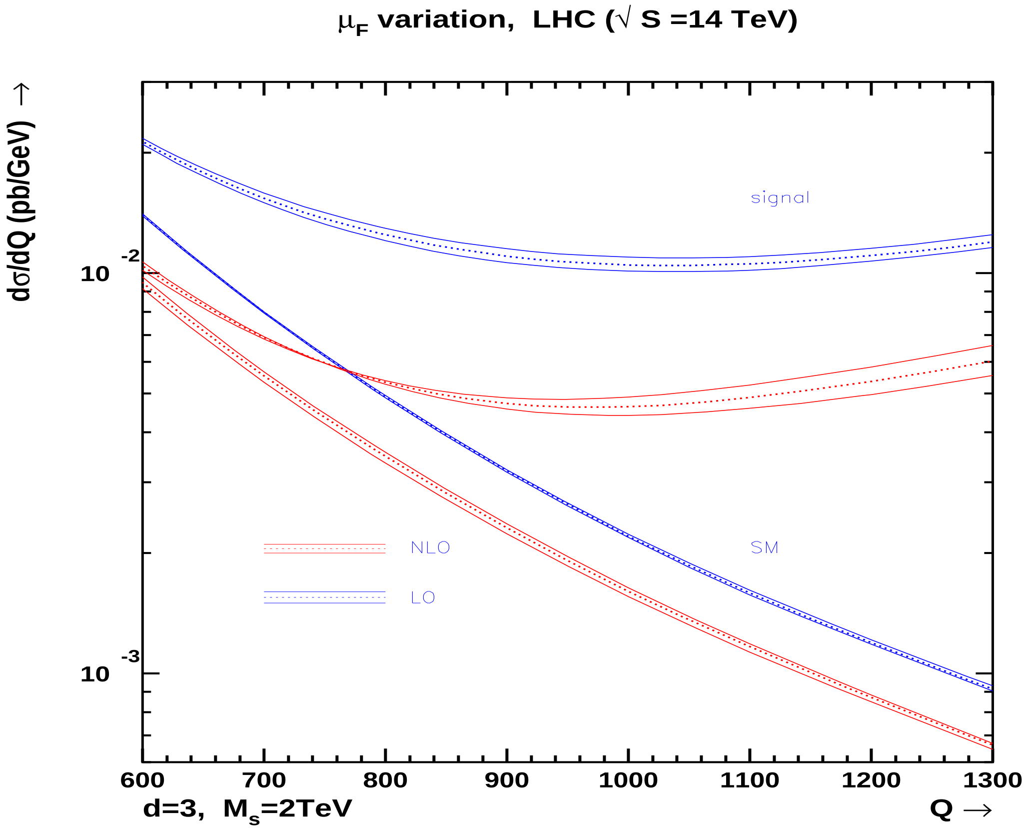

Figure 5: Factorization scale variation in the invariant mass distribution. The number of extra dimensions $d = 3$ and the fundamental scale $M_s = 2TeV$ have been chosen.

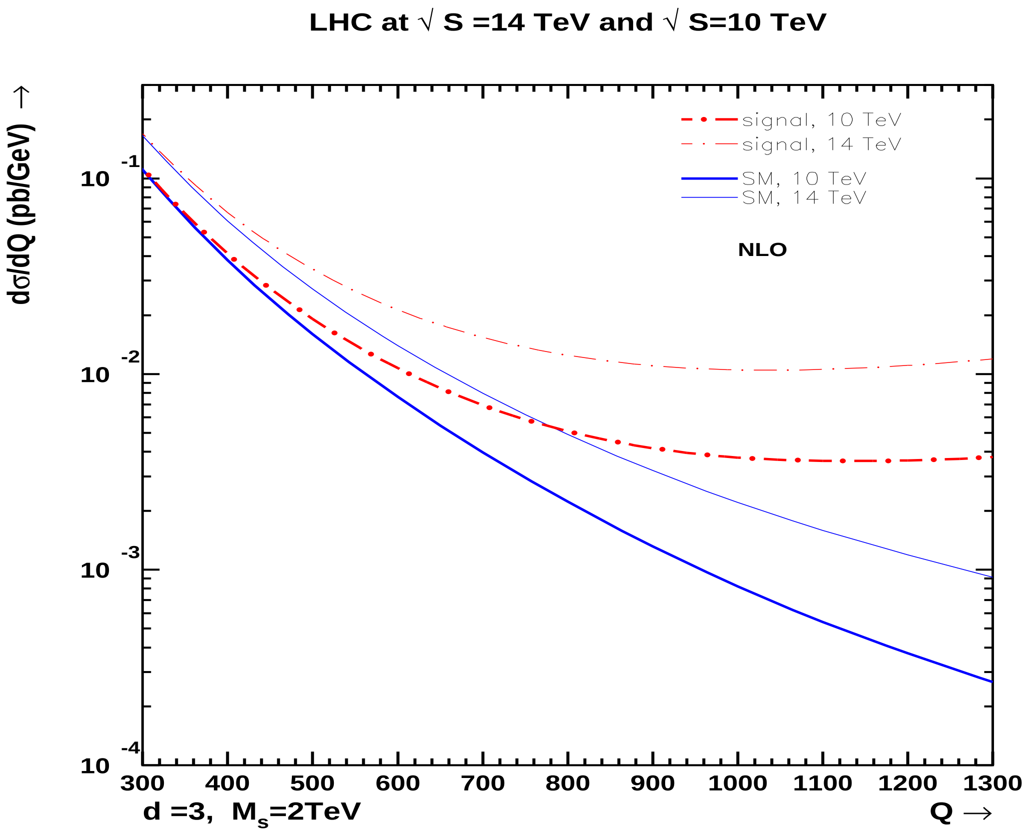

Figure 6: Invariant mass distribution at NLO for SM and the signal. Here the thicker curves correspond to $\sqrt{S} = 10TeV$ and lighter curves to $\sqrt{S} = 14TeV$ at the LHC.

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