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# Extra dimension searches at hadron colliders to next-to-leading order-QCD

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**Abstract.** The quantitative impact of NLO-QCD corrections for searches of large and warped extra dimensions at hadron colliders are investigated for the Drell-Yan process. The K-factor for various observables at hadron colliders are presented. Factorisation, renormalisation scale dependence and uncertainties due to various parton distribution functions are studied. Uncertainties arising from the error on experimental data are estimated using the MRST parton distribution functions.

**Keywords.** Parton distribution function and scale uncertainties; large and warped extra dimensions.

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## 1. Introduction

The gauge hierarchy problem has been one of the main motivations for physics beyond the standard model (SM). The apparent weakness of gravity can be accounted for by the existence of either large extra spatial dimensions ADD model [1] or warped extra dimension RS model [2]. In either case the fundamental Planck scale could be of the order of a few TeV and hence a possible explanation of the hierarchy. In both these models only gravity is allowed to propagate the extra dimensions while the SM particles are constrained on a 3-brane. Due to different methods of compactification of the extra dimensions in ADD and RS models, their Kaluza–Klein (KK) spectrum and their effective interactions with the SM model particles are distinct. Experimental signature of extra dimensions would correspond to deviation from SM predictions due to the virtual exchange of KK modes or direct production of KK modes at a collider.

At hadron colliders, it is important to have a precise knowledge of the parton distribution functions (PDFs) to predict production cross-sections of both signals and backgrounds. These universal PDFs are non-perturbative inputs that are extracted from global fits to available data on DIS, DY and other hadronic processes.

Parametrisation of PDFs to a particular order in QCD would involve various theoretical and experimental uncertainties. Recently there has been a series of papers [3–5] which for the first time have calculated the next-to-leading order (NLO) QCD corrections to various distributions of the DY process for both ADD and RS model. These NLO results would certainly reduce one aspect of the theoretical uncertainties as results prior to this calculation were only to leading order (LO) in QCD for process involving gravity.

## 2. Theoretical uncertainties

In the QCD improved parton model the hadronic cross-section can be expressed in terms of the partonic cross-section convoluted with appropriate parton distribution function. The subprocess cross-section is a perturbative expansion in the strong coupling constant $\alpha_s(\mu_R)$. The partonic flux is non-perturbative and is given in terms of the parton distribution function $f_a(z, \mu_F)$. In perturbative QCD, the unknown higher-order corrections and the scale uncertainties are strongly correlated. The factorisation of mass singularities from the perturbatively calculable partonic cross-sections leads to the introduction of factorisation scale $\mu_F$ in both non-perturbative parton densities $f_a(x, \mu_F)$ as well as the finite partonic cross-sections $d\hat{\sigma}_{ab}(x, \mu_F)$. The value of the scale is arbitrary and one demands that the physical cross-sections be independent of them. In addition to the factorisation scale, the partonic cross-sections are dependent on the renormalisation scale $\mu_R$. This is the scale at which the bare parameters of the theory become finite renormalised ones. The choice of the scale is again arbitrary. Gravity couples to the SM fields via its energy momentum tensor, and the calculations are done in the high energy limits where masses of the SM particles are ignored. The only parameter that requires UV renormalisation is the strong coupling constant. The scale uncertainties come about from the truncation of the perturbative series.

### 2.1 *PDF uncertainty*

Unlike the perturbatively calculable partonic cross-sections, the PDFs being non-perturbative in nature are extracted from various experiments. These are fitted at a scale of the experiments and then evolved according to the Altarelli–Parisi evolution equations to any other relevant scale. They are not only sensitive to experimental errors but also to theoretical uncertainties that enter through the partonic cross-section calculations and the splitting functions that are known only to certain orders in strong coupling constant in perturbative QCD. There are various groups that are involved in parametrising these PDFs taking the uncertainties into account. These groups use not only different experiments but also different methods to parametrise these PDFs. Here, we mainly concentrate on the uncertainties coming from the various PDFs, viz. Alekhin [6], CTEQ [7] and MRST [8], in detail and quantify their impact on the new physics searches in extra dimensional models. Differences among the various PDFs would translate as uncertainties on the physical observables. To

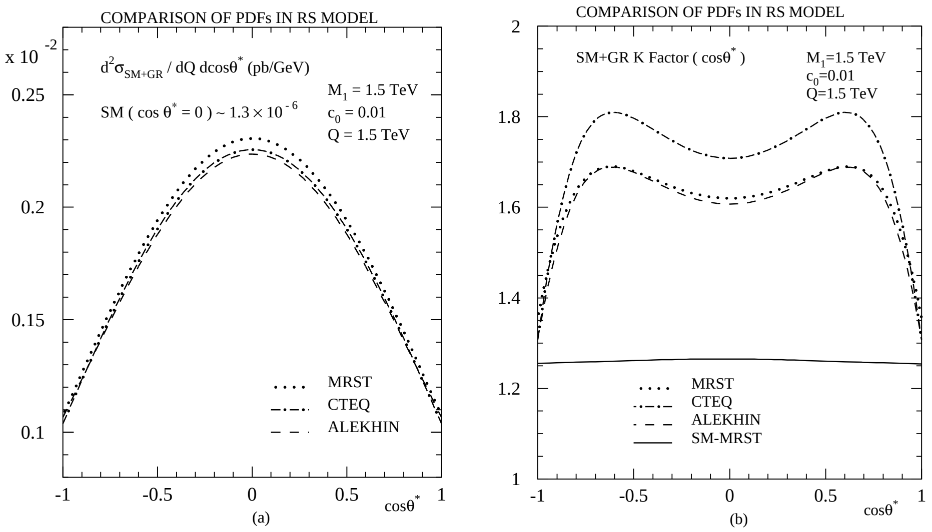


**Figure 1.** (**a**) In the region of first RS resonance, the double differential with respect to invariant mass and angular distribution of the lepton is plotted for various PDFs at LHC. (**b**) The corresponding K-factor for various PDFs.

NLO in QCD for various PDFs, we consider the following differential distributions [9]:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}Q}, \quad \frac{\mathrm{d}^2\sigma}{\mathrm{d}Q\ \mathrm{d}Y}, \quad \frac{\mathrm{d}^2\sigma}{\mathrm{d}Q\ \mathrm{d}\cos\theta^*}, \tag{1}$$

where $Q$ is the invariant mass, $Y$ is the rapidity and $\theta^*$ is the angle between the final-state lepton momenta and the initial state hadron momenta in the c.o.m frame of the lepton pair. The corresponding K-factor which is the ratio of NLO to LO of the above distributions are also plotted for various PDFs. The K-factor is as large as about 1.6. This clearly shows the need to go beyond LO in QCD in these models [3–5,9].

### 2.2 *Renormalisation/factorisation scale uncertainties*

The $\mu_\mathrm{F}$ variation is studied by varying $\mu_\mathrm{F}$ in the range $0.5Q \leq \mu_\mathrm{F} \leq 1.5Q$. We see that for both the ADD and RS models in going from LO to NLO in QCD, the uncertainties due to $\mu_\mathrm{F}$ variation considerably get reduced [9]. The spread of K-factor with $\mu_\mathrm{F}$ is much smaller for the SM as compared to SM+GR. This certainly indicates the need to go beyond NLO. In table 1 we tabulate the percentage spread of the factorisation scale $\mu_\mathrm{F}$ dependence of various distributions at LHC and Tevatron. On the average at LHC and Tevatron, the percentage spread of the scale variation gets reduced by about 2.88 times in going from LO to NLO. The dependence of cross-section on $\mu_\mathrm{R}$ comes from the strong coupling constant

**Table 1.** Percentage spread as a result of factorisation scale variation in the range $0.5Q \leq \mu_{\rm F} \leq 1.5Q$. For the ADD case $Q = 0.7$ TeV. For the RS, first resonance region $Q = 1.5$ TeV for LHC and $Q = 0.7$ TeV for Tevatron.

| | | Tevatron | | LHC | |
|---|---|---|---|---|---|
| | Distributions | LO | NLO | LO | NLO |
| ADD | $\mathrm{d}^2\sigma/\mathrm{d}Q\mathrm{d}Y$ | 22.8 | 7.4 | 9.5 | 3.5 |
| | $\mathrm{d}^2\sigma/\mathrm{d}Q\mathrm{d}\cos\theta$ | 24.2 | 8.2 | 10.9 | 3.8 |
| RS | $\mathrm{d}^2\sigma/\mathrm{d}Q\mathrm{d}Y$ | 23.2 | 7.7 | 18.7 | 6.9 |
| | $\mathrm{d}^2\sigma/\mathrm{d}Q\mathrm{d}\cos\theta$ | 24.2 | 8.0 | 18.4 | 6.8 |

at NLO and at LO there is no $\mu_{\rm R}$ dependence. At NLO $\mu_{\rm R}$ dependence for the $Y$ distribution is plotted for the $\mu_{\rm R}$ range $0.5Q \leq \mu_{\rm R} \leq 1.5Q$. The $\mu_{\rm R}$ spread is largest in the central rapidity region and would only reduce at the NNLO level when the $\mu_{\rm R}$ dependences would be compensated for by the dependence coming from the coefficient functions. We have studied the K-factor for SM and SM+GR and see its dependence on $\mu_{\rm R}$. The uncertainties due to $\mu_{\rm R}$ are much larger when the gravity is included. The percentage spread is of the order of 3.5% which is comparable to the $\mu_{\rm F}$ spread at NLO.

## 3. Experimental uncertainties

In addition to the theoretical uncertainties that we have described in the previous section, there are uncertainties due to errors on the data. Various groups have studied the experimental errors and have estimated the uncertainties on the PDFs within NLO-QCD framework [10,11]. Now that NLO-QCD results are also available for extra dimension searches [3] for the dilepton production, we consider some of the distributions and estimate the uncertainties due to the experimental error. We have plotted the error band for the MRST 2001 PDF [11] in the ADD model for the dilepton invariant mass distribution at LHC. This error band is comparable to the spread associated with different sets of PDFs [9]. At $Q = 1$ TeV the percentage of experimental error is 7.5% for SM+GR while the pure SM error is about 3.3%. For the RS case at LHC in the first resonance region at $Q = 1.5$ TeV the experimental error is about 12.8%. At Tevatron the ADD model experimental error is 7.4% at $Q = 1$ TeV. In figure 2a we have plotted PDF comparison plots for the double differential distribution with respect to invariant mass and rapidity at a fixed value of $Q = 0.7$ TeV. The experimental error for this distribution for the central rapidity region is about 3.5% and is indicated in figure 2a by the thin line band.

## 4. Conclusions

We have studied the impact of various parton density sets at NLO in QCD on the Drell-Yan production of dileptons at hadron colliders such as LHC and Tevatron.

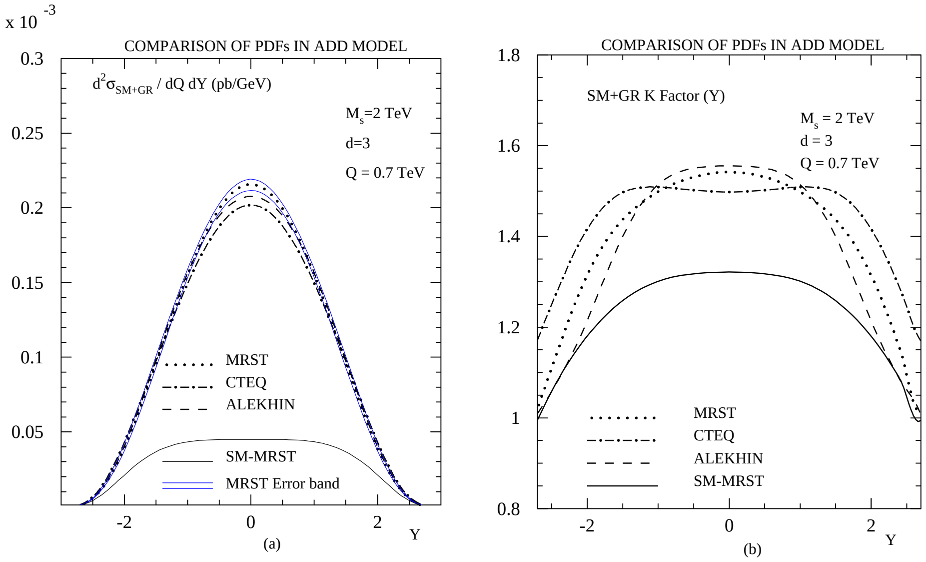


**Figure 2.** The comparison plots for the various PDF sets for $Q = 0.7$ TeV at LHC. (**a**) The double differential cross-section with respect to invariant mass and rapidity as a function of rapidity. The thin line band gives the range of experimental error on the MRST PDF. (**b**) The corresponding K-factor as a function of rapidity.

This process can probe the physics beyond the SM through exchange of new particles that these theories predict. At hadron colliders, the precise measurement of DY production cross-sections is possible. In this context, we have studied the theories of extra dimensions such as ADD and RS which attempt to explain gauge hierarchy problem in the SM. We have discussed various theoretical uncertainties that enter through renormalisation, factorisation scales and the parton density sets. We have quantified the uncertainties coming from various parton density sets using the recent results on NLO-QCD corrections to parton level cross-sections and recent PDF sets that take into account various theoretical and experimental errors. Our entire analysis is model-independent, thanks to the factorisation of QCD radiative corrections from the model-dependent contributions. We find that the K-factor for various observables depends on the choice of PDFs.

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