Comparisons of Exact Amplitude–Based Resummation Predictions and LHC Data

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Abstract

Using the MC Herwiri1.031, we present the current status of the comparisons with LHC data of the predictions of our approach of exact amplitude-based resummation for precision QCD calculations.

Keywords: QCD Resummation IR-Improved DGLAP-CS Theory NLO-PS MC

1. Introduction

The successful running of the LHC during 2010-2012 has resulted in large data samples on SM standard candle processes such as heavy gauge boson production and decay to lepton pairs (samples exceeding $10^7$ of such events for $Z/\gamma^*$ production) for ATLAS and CMS. Such data signal the arrival of the era of precision QCD, with predictions for QCD processes at the total precision tag of 1% or better, and make more manifest the need for exact, amplitude-based resummation of large higher order effects as discussed in Refs. [1]. Such precision allows one to distinguish new physics(NP) from higher order SM processes and to distinguish different models of new physics from one another as well. We present here comparisons of the attendant application of exact amplitude-based resummation theory to recent data from the LHC. We first review the elements our approach as formulated in Ref. [2] before we turn in the next section to comparisons with recent LHC data.

Our starting point is the well-known representation

$$d\sigma = \sum_{i,j} \int dx_1 dx_2 F_i(x_1) F_j(x_2) d\bar{\sigma}_{res}(x_1,x_2)$$

(1)

of a hard LHC scattering process, where $\{F_i\}$ and $d\bar{\sigma}_{res}$ are the respective parton densities (PDF’s) and reduced resummed hard differential cross section. The resummation includes all large EW and QCD higher order corrections as needed for achieving a total precision tag of 1% or better for the total theoretical precision of (1).

The total theoretical precision $\Delta\sigma_{th}$ of (1) as defined in Refs. [3, 4] is essential to the faithful application of any theoretical prediction to precision experimental data. Whenever $\Delta\sigma_{th} \leq f \Delta\sigma_{expt}$, where $\Delta\sigma_{expt}$ is the respective experimental error and $f \lesssim 1$, the theoretical uncertainty will not adversely affect the physics analysis of the data. With our eye on a provable theoretical precision tag we have developed the QCD $\otimes$ QED resummation theory in Refs. [2] for (1). The key exact master formula is

$$d\bar{\sigma}_{res} = e^{\text{SUM}_{IR(QCED)}} \sum_{n=0}^{\infty} \frac{1}{n!} \int \prod_{j=1}^{n} \frac{d^4p_j}{2\pi^2} e^{i(p_{1j} + q_1 - q_2 - q_3) \cdot x_1 + \Sigma x_j} e^{i(p_{1j} + q_1 - q_2 - q_3) \cdot x_1} D_{\text{QCED}}$$

$$\times \prod_{j=1}^{n} \frac{d^4p_j}{2\pi^2} e^{i(p_{1j} + q_1 - q_2 - q_3) \cdot x_1 + \Sigma x_j} D_{\text{QCED}}$$

(2)

Here $d\bar{\sigma}_{res}$ is either the reduced cross section $d\bar{\sigma}_{res}$ or the differential rate associated to a DGLAP-CS [5, 6] kernel involved in the PDF evolution and the new (YFS-style [7, 8]) non-Abelian residuals $\hat{\beta}_{n,m}(k_1, \ldots, k_n; k_1', \ldots, k_m')$ have $n$ hard gluons and $m$ hard photons and we show the generic $2f$ final state with momenta $p_2, q_2$ for definiteness. The infrared functions $\text{SUM}_{IR(QCED)}$, $D_{\text{QCED}}$ are given in...
Fig. 2 Left Panel: CMS rapidity data (magenta dots) vs Herwig6.5 (PTRMS = 2.2 GeV, green line), Herwiri1.031 (blue line), MC@NLO/Herwig6.5 (PTRMS = 2.2, green squares), MC@NLO/Herwiri1.031 (blue squares).

We first recall that, as we have discussed in Refs. [1], the methods we employ are fully consistent with the methods in Refs. [11, 12, 13, 14, 15, 16] but we do not have intrinsic physical barriers to sub-1 precision as do the approaches used in the latter references. They may used to give approximations to our new residuals $\hat{\beta}_{m,n}$ for studies of consistency [17].

With this understanding, we note that, if we apply (2) to the calculation of the kernels, $P_{AB}$, we arrive at an improved IR limit of these kernels, IR-improved DGLAP-CS theory. In this latter theory [9,10] large IR effects are resummed for the kernels themselves. From the resulting new resummed kernels, $P_{AB}^{\text{rep}}$ [9,10] we get a new resummed scheme for the PDF’s and the reduced cross section: $F_{j}, \hat{\sigma} \rightarrow F’_{j}, \hat{\sigma}’$ for $P_{\sigma}(z) \rightarrow F_{\sigma}^{\text{rep}}(z) = CF_{\text{FFS}}(\gamma_{q})e^{^\frac{1}{2}(1-\gamma_{q})z}$, etc. This new scheme gives $\sigma$ in [1] with improved MC stability [1]. Here, $CF$ is the quadratic Casimir invariant for the quark color representation. See Refs. [9,10] for the definitions of $F_{\text{FFS}}, \gamma_{q}, \hat{\sigma}$ as well as for the complete set of results for the new $P_{AB}^{\text{rep}}$.

The physical idea underlying the new kernels was shown by Bloch and Nordsieck [18]: due to the coherent state of very soft massless gauge field quanta generated by an accelerated charge it impossible to know which of the infinity of possible states one has made in the splitting process $q(1) \rightarrow q(1-z) + G \otimes G_{1} \cdots \otimes G_{t}, \ell = 0, \cdots , \infty$. The new kernels take this effect into account by resumming the terms by resumming the terms $O((\alpha_{s} \ln q^{2}/\Lambda^{2}) \ln(1-z))^{\alpha}$ for the IR limit $z \rightarrow 1$. This resummation generates [11,10,9] the Gribov-Lipatov exponents $\gamma_{A}$ which start in $O(h)$ in the loop expansion [1].

The first realization of the new IR-improved kernels is given by new MC Herwiri1.031 [11] in the Herwig6.5 [20] environment. Realization of the new kernels in the Herwig++ [21], Pythia8 [22], Sherpa [23] and Powheg [24] environments is in progress as well.

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1 See Ref. [19] for the connection between the new kernels and the Wilson expansion.

In Fig. 1 we illustrate some of the recent comparisons we have made between Herwiri1.031 and Herwig6.510, both with and without the MC@NLO [25] exact $O(\alpha_{s})$ correction [26,27] in relation to the LHC data [26,27] on $Z/\gamma^{*}$ production with decay to lepton pairs. Just as we found in Refs. [11] for the FNAL data on single $Z/\gamma^{*}$ production, the unimproved MC requires the very hard value of PTRMS $\approx 2.2$ GeV to give a good fit to the $p_{T}$ spectra as well as the rapidity spectra whereas the IR-improved calculation gives very good fits to both of the spectra without the need of such a hard value of PTRMS, the rms value for an intrinsic Gaussian $p_{T}$ distribution, for the proton wave function: the $\chi^{2}/d.o.f$ are respectively (0.72, 0.72), (1.37, 0.70), (2.23, 0.70) for the $p_{T}$ and rapidity data for the MC@NLO/HIRWIR1.031, MC@NLO/HIRWIG6.510 (PTRMS = 2.2 GeV) and MC@NLO/HIRWIG6.510 (PTRMS = 0) results. Such a hard intrinsic value of PTRMS contradicts the results in Refs. [50,51], as we discuss in Refs. [1]. To illustrate the size of the exact $O(\alpha_{s})$ correction, we also show the results for both Herwig6.510 (green line) and Herwiri1.031 (blue line) without it in the plots in Fig. 1. As expected, the exact $O(\alpha_{s})$ correction is important for both the $p_{T}$ spectra and the rapidity spectra. The suggested accuracy at the 10% level shows the need for the NNLO extension of MC@NLO, in view of our goals for this process. We also note that, with the 1% precision

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2 See Refs. [11] for the connection between the $\hat{\beta}_{m,n}$ and the MC@NLO differential cross sections.

3 Similar comparisons were made in relation to such data [28,29] from FNAL in Refs. [1].
goal, one also needs per mille level control of the EW corrections. This issue is addressed in the new version of the KK MC [32], version 4.22, which now allows for incoming quark antiquark beams – see Ref. [32] for further discussion of the relevant effects in relation to other approaches [33].

We have also made comparisons with recent LHCb data [34] on single $Z/\gamma^*$ production and decay to lepton pairs. These results will be presented in detail elsewhere [17]. Here, we illustrate them with the results in Fig. 2 for the $\mu^+\mu^-$ pairs. These results will be presented in detail elsewhere [17]. Here, we illustrate them with the results in Fig. 2 for the $Z/\gamma^*$ rapidity as measured by LHCb for the $e^+e^-$ pairs and the $\mu^+\mu^-$ pairs. These are otherwise untuned theoretical results.

The data probe a different phase space regime: the lepton pseudorapidity $\eta$ satisfies $2.0 < \eta < 4.5$ to be compared with $|\eta_f| < 2.1(0.1 < |\eta_f| < 2.4)$ for the CMS/ATLAS data in Fig. 1. Here $\eta(\eta_f)$ is the respective pseudorapidity of $\ell$, $\ell' = \mu, \bar{\mu}(\ell', \ell' = e, \bar{e})$, respectively. Again, the agreement between the IR-improved MC@NLO/Herwiri1.031 without the need of an ad hocly hard value of PTRMS is shown for both the $e\bar{e}$ and $\mu\bar{\mu}$ data, where the $\chi^2/d.o.f.$ are 0.746, 0.773 respectively. The unimproved calculations with MC@NLO/Herwig6510 for PTRMS = 0 and PTRMS = 2.2 GeV respectively also give good fits, with the $\chi^2/d.o.f.$ of 0.814, 0.836 and 0.555, 0.537 respectively for the $e\bar{e}$ and $\mu\bar{\mu}$ data. In the phase space probed by the LHCb, it continues to hold that the more inclusive observables such as the normalized $Z/\gamma^*$ rapidity spectrum are not as sensitive to the IR-improvement as observables such as the $Z/\gamma^*$ $p_T$ spectrum.

As one has now more than $10^3$ $Z/\gamma^*$ decays to lepton pairs per experiment at ATLAS and CMS, we show in Refs. [1] that one may use the new precision data to distinguish between the fundamental description in Herwiri1.031 and the ad hocly hard intrinsic $p_T$ in Herwig6.5 by comparing the data to the predictions of the detailed line shape and of the more finely binned $p_T$ spectra – see Figs. 3 and 4 in the last two papers in Refs. [1]. We await the availability of the new precision data accordingly.

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*The discriminating power among the attendant theoretical predictions of $p_T$ spectra in single $Z/\gamma^*$ production at the LHC is manifest in Refs. [33] – the last paper in Refs. [1] provides more discussion on this point.*
