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MC REALIZATION OF IR-IMPROVED DGLAP-CS PARTON SHOWERS: HERWIRI1.031

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We introduce the new IR-improved Dokshitzer–Gribov–Lipatov–Altarelli–Parisi–Callan–Symanzik (DGLAP-CS) kernels recently developed by one of us into the HERWIG6.5 to generate a new MC, HERWIRI1.0(31), for hadron–hadron scattering at high energies. We use MC data to compare the parton shower generated by the standard DGLAP-CS kernels and that generated by the new IR-improved DGLAP-CS kernels. The seamless interface to MC@NLO, MC@NLO/HERWIRI, is illustrated. We show comparisons with FNAL data and discuss some possible LHC phenomenology implications.

Keywords: Amplitude-based resummation; precision QCD; IR-improved parton showers.

1. Introduction

For the era of precision LHC physics (1% or better total theoretical precision[1,2]), we need[3–15] resummed $\mathcal{O}(\alpha_s^2 L^n)$, $\mathcal{O}(\alpha_s \alpha L^{n'})$, $\mathcal{O}(\alpha^2 L^{n''})$ corrections for $n = 0, 1, 2$, $n' = 0, 1, 2$, $n'' = 1, 2$, in the presence of parton showers, on an event-by-event basis, without double counting and with exact phase space. We present the first step in realizing our new MC event generator approach to such precision LHC physics with amplitude-based QED $\otimes$ QCD resummation[16–24] by introducing the attendant new parton shower MC for QCD that follows from our approach. This will set the stage for the complete implementation of the QED $\otimes$ QCD resummed theory in which all IR singularities are canceled to all orders in α_s and α. This new parton shower MC, which is developed[25–27] in the HERWIG6.5 environment and which we have called HERWIRI1.0(31),[28,29] already shows improvement in comparison with the FNAL soft p_T data on single Z production as we quantify below. We also note that, while the explicit IR cutoffs in the HERWIG6.5 environment will not be removed here, HERWIRI only involves integrable distributions so that in principle these cutoffs could be removed.

This paper is organized as follows. We first review our approach to resummation and its relationship to those in Refs. 30–34. Section 3 contains a summary of the attendant new IR-improved DGLAP-CS[35–44] theory.[45,46] Section 4 presents the implementation of the new IR-improved kernels in the framework[25–27] of HERWIG6.5 to arrive at the new, IR-improved parton shower MC HERWIRI1.0(31). We illustrate the effects of the IR-improvement with the specific single Z production process at LHC energies. We compare with recent data from FNAL to make direct contact with observation.[a]

2. Review of QED ⊗ QCD Resummation

In Refs. 16–24, 45 and 46 we have derived the following expression for the hard cross-sections in the SM $\mathrm{SU}_{2L} \times \mathrm{U}_1 \times \mathrm{SU}_3^c$ EW-QCD theory

$$
\begin{aligned}
d\hat{\sigma}_{\rm exp} = e^{\mathrm{SUM_{IR}(QCED)}} \sum_{n,m=0}^{\infty} \frac{1}{n!m!} \int \frac{d^3p_2}{p_2^0}\frac{d^3q_2}{q_2^0} \prod_{j_1=1}^{n} \frac{d^3k_{j_1}}{k_{j_1}} \prod_{j_2=1}^{m} \frac{d^3k'_{j_2}}{k'_{j_2}} \\
\times \int \frac{d^4y}{(2\pi)^4} e^{iy\cdot(p_1+q_1-p_2-q_2-\sum k_{j_1}-\sum k'_{j_2})+D_{\rm QCED}} \\
\times \tilde{\bar{\beta}}_{n,m}(k_1,\ldots,k_n;k'_1,\ldots,k'_m)\,, \qquad (1)
\end{aligned}
$$

where the new YFS-style[49,50] residuals $\tilde{\bar{\beta}}_{n,m}(k_1,\ldots,k_n;k'_1,\ldots,k'_m)$ have n hard gluons and m hard photons and we illustrate the generic 2f final state with momenta p_2, q_2 specified for definiteness. The infrared functions $\mathrm{SUM_{IR}(QCED)}$, $D_{\rm QCED}$ are defined in Refs. 16–24, 45, 46. Equation (1) is exact to all orders in α and in α_s.

Given that the approaches in Refs. 30–34 to QCD resummation have been shown in Ref. 51 to be equivalent and given that we show in Refs. 45 and 46 that our approach is equivalent to that in Refs. 30–32, it follows that our approach is also equivalent to that of Refs. 33 and 34. See Refs. 45 and 46 for the attendant further details.

3. Review of IR-Improved DGLAP-CS Theory

The result Eq. (1) allows us to improve[45,46] in the IR regime the kernels in DGLAP-CS[35–44] theory as follows, using a standard notation:

$$
P_{qq}^{\rm exp}(z) = C_F F_{\rm YFS}(\gamma_q) e^{\frac{1}{2}\delta_q}\left[\frac{1+z^2}{1-z}(1-z)^{\gamma_q} - f_q(\gamma_q)\delta(1-z)\right],
$$

[a]From Refs. 47 and 48 the current state-of-the-art theoretical precision tag on single Z production at the LHC is $(4.1 \pm 0.3)\% = (1.51 \pm 0.75)\%(\mathrm{QCD}) \oplus 3.79(\mathrm{PDF}) \oplus 0.38 \pm 0.26(\mathrm{EW})\%$ and the analogous estimate for single W production is $\sim 5.7\%$.

$$P_{Gq}^{\exp}(z) = C_F F_{\rm YFS}(\gamma_q) e^{\frac{1}{2}\delta_q} \frac{1+(1-z)^2}{z} z^{\gamma_q}\,,$$

$$P_{GG}^{\exp}(z) = 2C_G F_{\rm YFS}(\gamma_G) e^{\frac{1}{2}\delta_G} \left\{ \frac{1-z}{z} z^{\gamma_G} + \frac{z}{1-z}(1-z)^{\gamma_G} \right.$$

$$\left. + \frac{1}{2}(z^{1+\gamma_G}(1-z) + z(1-z)^{1+\gamma_G}) - f_G(\gamma_G)\delta(1-z) \right\},$$

$$P_{qG}^{\exp}(z) = F_{\rm YFS}(\gamma_G) e^{\frac{1}{2}\delta_G} \frac{1}{2}\{z^2(1-z)^{\gamma_G} + (1-z)^2 z^{\gamma_G}\}\,, \tag{2}$$

where the superscript "exp" indicates that the kernel has been resummed as predicted by Eq. (1) when it is restricted to QCD alone and where we refer the reader to Refs. 45 and 46 for the detailed definitions of the respective resummation functions $F_{\rm YFS}$, γ_A, δ_A, f_G, $A = q, G$.[b]

We refer the reader to Refs. 45, 46, 23 and 24 for discussion of a number of illustrative results and implications of the new kernels and Eq. (1) that are beyond the scope we have here. The net effect of the results in Refs. 45, 46, 23 and 24 is that we have a consistent theoretical paradigm based on Eqs. (1) and (2) for precision LHC theory that can be systematically improved order-by-order in perturbation theory with no double counting. With an eye toward the full MC implementation of our approach, we turn next to the initial stage of that implementation — that of the new kernels.

4. Realization of IR-Improved DGLAP-CS Theory via MC Methods

We have implemented the new IR-improved kernels in the HERWIG6.5 environment to produce a new MC, HERWIRI1.0, which stands for "high energy radiation with IR improvement".[c]

Specifically, we modify the kernels in the HERWIG6.5 module HWBRAN and in the attendant related modules[d] with the following substitutions:

$$\text{DGLAP-CS}\, P_{AB} \Rightarrow \text{IR-IDGLAP-CS}\, P_{AB}^{\exp}$$

while leaving the hard processes alone for the moment. We have in progress[54] the inclusion in our framework of YFS synthesized electroweak modules from Refs. 55–63 for HERWIG6.5, HERWIG++,[64] and MC@NLO[65,66] hard processes,[e] as the CTEQ[70,71] and MRST(MSTW)[72,73] best (after 2007) parton densities do

[b]The improvement in Eq. (2) should be distinguished from the also-important resummation in parton density evolution for the "$z \to 0$" regime, where Regge asymptotics obtain — see for example Refs. 52 and 53. This latter improvement must also be taken into account for precision LHC predictions.

[c]We thank M. Seymour and B. Webber for helpful discussion on this point.

[d]We thank M. Seymour and B. Webber for helpful discussion.

[e]Similar results for PYTHIA[67] and for the new kernel evolution in Refs. 68 and 69 are under study.

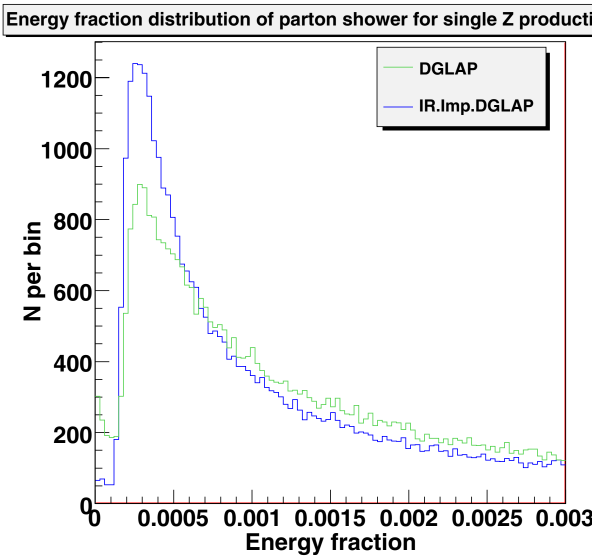
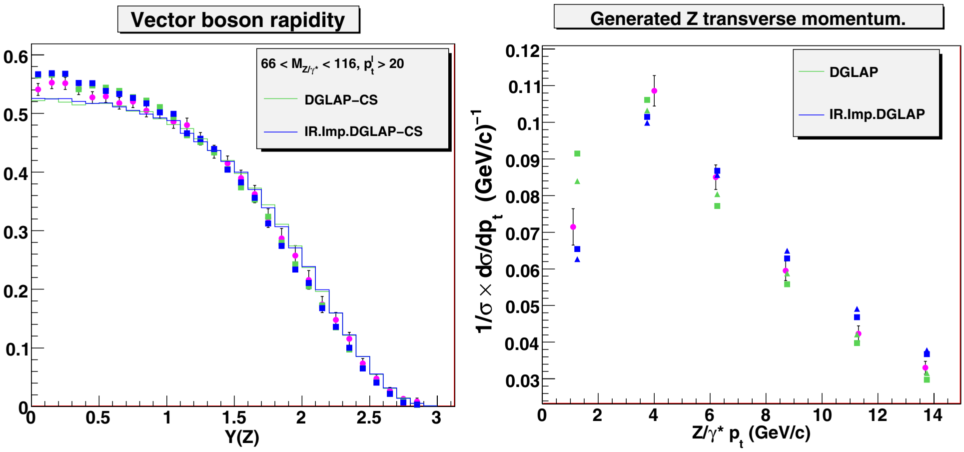


Fig. 1. The z-distribution (ISR parton energy fraction) shower comparison in HERWIG6.5.

not include the precision electroweak higher order corrections that are needed in a 1% precision tag budget for processes such as single heavy gauge boson production in the LHC environment.[11–14]

The details of the implementation are given in Refs. 28, 29, 23, 24 and we do not reproduce them here due to space constraints. We have done many comparisons of the properties of the parton showers from HERWIG6.510 and HERWIRI1.031. In general, as we show here in Fig. 1, the IR-improved showers tend to be softer in the energy fraction variable $z = E/E_{\rm Beam}$ where $E\,(E_{\rm Beam})$ is the cms parton (beam) energy for hadron–hadron scattering respectively. See Refs. 28, 29, 23 and 24 for the complete discussion of such comparisons. We have also made comparison analyses with the data from FNAL on the Z rapidity and p_T spectra as reported in Refs. 74 and 75. We show these results, for 1.96 TeV cms energy, in Fig. 2. We see that HERWIRI1.0(31) and HERWIG6.5 both give a reasonable overall representation of the CDF rapidity data but that HERWIRI1.031 is somewhat closer to the data for small values of Y. The two χ^2/d.o.f. are 1.77 and 1.54 for HERWIG6.5 and HERWIRI1.0(31) respectively. The data errors in Fig. 2(a) do not include luminosity and PDF errors,[74] so that they can only be used conditionally at this point. We note as well that including the NLO contributions to the hard process via MC@NLO/HERWIG6.510 and MC@NLO/HERWIRI1.031[65,66,f] improves the agreement for both HERWIG6.510 and for HERWIRI1.031, where the χ^2/d.o.f. are changed to 1.40 and 1.42 respectively. That they are both consistent with one an-

[f] We thank S. Frixione for helpful discussions with this implementation.



(a) (b)

Fig. 2. (color online) Comparison with FNAL data: (a) CDF rapidity data on (Z/γ^*) production to e^+e^- pairs, the circular dots are the data, the green (blue) lines are HERWIG6.510 (HERWIRI1.031); (b) D0 p_T spectrum data on (Z/γ^*) production to e^+e^- pairs, the circular dots are the data, the blue triangles are HERWIRI1.031, the green triangles are HERWIG6.510 — in both (a) and (b) the blue squares are MC@NLO/HERWIRI1.031, and the green squares are MC@NLO/HERWIG6.510. These are untuned theoretical results.

other and within 10% of the data in the low Y region is fully consistent with what we expect given our comments about the errors and the generic accuracy of an NLO correction in QCD. A more precise discussion at the NNLO level with DGLAP-CS IR-improvement and a more complete discussion of the errors will appear.[76] These rapidity comparisons are then important cross-checks on our work. We also see that HERWIRI1.031 gives a better fit to the D0 p_T data compared to HERWIG6.510 for low p_T, (for $p_T < 12.5$ GeV, the χ^2/d.o.f. are ~ 2.5 and 3.3 respectively if we add the statistical and systematic errors), showing that the IR-improvement makes a better representation of QCD in the soft regime for a given fixed order in perturbation theory. We have also added the results of MC@NLO[65,66] for the two programs and we see that the $\mathcal{O}(\alpha_s)$ correction improves the χ^2/d.o.f. for the HERWIRI1.031 in both the soft and hard regimes and it improves the HERWIG6.510 χ^2/d.o.f. for p_T near 3.75 GeV where the distribution peaks. For $p_T < 7.5$ GeV the χ^2/d.o.f. for the MC@NLO/HERWIRI1.031 is 1.5 whereas that for MC@NLO/HERWIG6.510 is worse. These results are of course still subject to tuning as we indicated above. We await further tests of the new approach, both at FNAL and at LHC.

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