HERWIRI1.0: MC Realization of IR-Improved DGLAP-CS Parton Showers†

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Abstract

We present Monte Carlo data showing the comparison between the parton shower generated by the standard Dokshitzer-Gribov-Lipatov-Altarelli-Parisi-Callan-Symanzik (DGLAP-CS) kernels and that generated with the new IR-improved DGLAP-CS kernels recently developed by one of us. We do this in the context of HERWIG6.5 by implementing the new kernels therein to generate a new MC, HERWIRI1.0, for hadron-hadron interactions at high energies. We discuss possible phenomenological implications for precision LHC theory. We also present comparisons with FNAL data.

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1 Introduction

With the advent of the LHC, we enter the era of precision QCD, which is characterized by predictions for QCD processes at the total precision \[1\] tag \[1\] of \(1\%\) or better. At such a precision as we have as our goal, issues such as the role of QED \[2,3\] are an integral part of the discussion and we deal with this by the simultaneous resummation of QED and QCD large infrared (IR) effects, \(QED \otimes QCD\) resummation \[4\] in the presence of parton showers, to be realized on an event-by-event basis by MC methods. We stress that, as shown in Refs. \[3\], no precision prediction for a hard LHC process at the \(1\%\) level can be complete without taking the large EW corrections into account.

In proceeding with our discussion, we first review our approach to resummation and its relationship to those in Refs. \[5,6\]; this review is followed by a summary of the attendant new IR-improved \[7,8\] DGLAP-CS theory \[9,10\] with some discussion of its implications. We then present the implementation of the new IR-improved kernels in the framework of HERWIG6.5 \[11\] to arrive at the new, IR-improved parton shower MC HERWIRI1.0. We illustrate the effects of the IR-improvement first with the generic \(2 \rightarrow 2\) processes at LHC energies and then with the specific single \(Z\) production process at LHC energies. The IR-improved showers are generally softer as expected and we discuss possible implications for precision LHC physics. We compare with recent data from FNAL to make direct contact with observation. Section 5 contains our summary remarks.

To put the discussion in the proper perspective, we note that the authors in Ref. \[12,13\] have argued that the current state-of-the-art theoretical precision tag on single \(Z\) production at the LHC is \((4.1 \pm 0.3\%) = (1.51 \pm 0.75\%)\) (QCD) \(\oplus 3.79\%\) (PDF) \(\oplus 0.38 \pm 0.26\%\) (EW) and that the analogous estimate for single \(W\) production is \(\sim 5.7\%\). These estimates, which can be considered as lower bounds, show how much work is still needed to achieve the desired \(1.0\%\) total precision tag on these two processes, for example. This point cannot be over-emphasized.

2 QED\(\otimes\)QCD Resummation

In Refs. \[4,7,8\], we have derived the following expression for the hard cross sections in the SM \(SU_{2L} \times U_1 \times SU_3^c\) EW-QCD theory

\[
\begin{align*}
\hat{d}\sigma_{\text{exp}} &= e^{\text{SUMIR(QCED)}} \sum_{n,m=0}^{\infty} \frac{1}{n!m!} \int \frac{d^3p_2}{p_2^0} \frac{d^3q_2}{q_2^0} \prod_{j=1}^{n} \frac{d^3k_{j1}}{k_{j1}} \prod_{j=2}^{m} \frac{d^3k'_{j2}}{k'_{j2}} \\
& \times \int \frac{d^4y}{(2\pi)^4} e^{iy \cdot (p_1 + q_1 - p_2 - q_2 - \sum k_{j1} - \sum k'_{j2}) + D_{\text{QCED}} \bar{\beta}_{n,m}(k_1, \ldots, k_n; k'_1, \ldots, k'_{m})},
\end{align*}
\]

\[1\] By total precision of a theoretical prediction, we mean the technical and physical precisions combined in quadrature or otherwise, as appropriate.
where the new YFS-style \cite{14} residuals $\tilde{\beta}_{n,m}(k_1, \ldots, k_n; k'_1, \ldots, k'_m)$ have $n$ hard gluons and $m$ hard photons and we show the final state with two hard final partons with momenta $p_2, q_2$ specified for a generic 2f final state for definiteness. The infrared functions $\text{SUM}_{\text{IR}}(\text{QCED}), \ D_{\text{QCED}}$ are defined in Refs. \cite{4, 7, 8}. This is the simultaneous resummation of QED and QCD large IR effects. Eq. \cite{11} is an exact implementation of amplitude-based resummation of the latter effects valid to all orders in $\alpha$ and in $\alpha_s$.

Our approach to QCD resummation is fully consistent with that of Refs. \cite{5, 6} as follows. First, Ref. \cite{15} has shown that the latter two approaches are equivalent. We show in Refs. \cite{7, 8} that our approach is consistent with that of Refs. \cite{5} by exhibiting the transformation prescription from the resummation formula for the theory in Refs. \cite{5} for the generic $2 \rightarrow n$ parton process as given in Ref. \cite{16} to our theory as given for QCD by restricting Eq.\cite{11} to its QCD component, where a key point is to use the color-spin density matrix formulation of our residuals to capture the respective full quantum mechanical color-spin correlations in the results in Ref. \cite{10} – see Refs. \cite{7, 8} for details.

We show in Refs. \cite{7, 8} that the result Eq.\cite{11} allows us to improve in the IR regime\footnote{This should be distinguished from the also important resummation in parton density evolution for the “$z \rightarrow 0$” regime, where Regge asymptotics obtain – see for example Ref. \cite{17, 18}. This improvement must also be taken into account for precision LHC predictions.} the kernels in DGLAP-CS [9, 10] theory as follows, using a standard notation:

\begin{align*}
P_{qq}^{\text{exp}}(z) &= C_F F_{\text{YFS}}(\gamma_q) e^{\frac{1}{2} \delta g} \left[ \frac{1 + z^2}{1 - z} (1 - z)^{\gamma_q} - f_q(\gamma_q) \delta(1 - z) \right], \\
P_{Gq}^{\text{exp}}(z) &= C_F F_{\text{YFS}}(\gamma_q) e^{\frac{1}{2} \delta g} \frac{1 + (1 - z)^2}{z} z^{\gamma_q}, \\
P_{GG}^{\text{exp}}(z) &= 2 C_G F_{\text{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} ight. \\
&\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}^{\text{exp}}(z) &= F_{\text{YFS}}(\gamma_G) e^{\frac{1}{2} \delta g} \frac{1}{2} \left\{ z^2 (1 - z)^{\gamma_G} + (1 - z)^2 z^{\gamma_G} \right\},
\end{align*}

(2)
\begin{equation}
\gamma_q = C_F \alpha_s t = \frac{4C_F}{\beta_0}, \quad \delta_q = \frac{\gamma_q}{2} + \frac{\alpha_s C_F}{\pi} \left(\frac{C^2}{3} - \frac{1}{2}\right),
\end{equation}

\begin{equation}
f_q(\gamma_q) = \frac{2}{\gamma_q} - \frac{2}{\gamma_q + 1} + \frac{1}{\gamma_q + 2},
\end{equation}

\begin{equation}
\gamma_G = C_G \alpha_s t = \frac{4C_G}{\beta_0}, \quad \delta_G = \frac{\gamma_G}{2} + \frac{\alpha_s C_G}{\pi} \left(\frac{C^2}{3} - \frac{1}{2}\right),
\end{equation}

\begin{equation}
f_G(\gamma_G) = \frac{n_f}{6C_G F_{YFS}(\gamma_G)} e^{-\frac{1}{2} \delta_G} + \frac{2}{\gamma_G (1 + \gamma_G) (2 + \gamma_G)} + \frac{1}{(1 + \gamma_G) (2 + \gamma_G)},
\end{equation}

\begin{equation}
F_{YFS}(\gamma) = \frac{e^{-C \gamma}}{\Gamma(1 + \gamma)}, \quad C = 0.57721566..., \tag{4}
\end{equation}

where $\Gamma(w)$ is Euler’s gamma function and $C$ is Euler’s constant. We use a one-loop formula for $\alpha_s(Q)$, so that

\[ \beta_0 = 11 - \frac{2}{3} n_f, \]

where $n_f$ is the number of active quark flavors and $C_F = 4/3$ and $C_G = 3$ are the respective quadratic Casimir invariants for the quark and gluon color representations – see Refs. [7,8] for the corresponding details. The results in Eq.(2) have now been implemented by MC methods, as we exhibit in the following sections.

### 3 Illustrative Results/Implications

Firstly, we note that the connection to the higher order kernels in Refs. [19] has been made in Ref. [7]. This opens the way for the systematic improvement of the results presented herein. Secondly, in the NS case, we find [7] that the $n = 2$ moment is modified by $\sim 5\%$ when evolved with Eq.(2) from 2GeV to 100GeV with $n_f = 5$ and $\Lambda_{QCD} \approx 0.2GeV$, for illustration. This effect is thus relevant to the expected precision of the HERA final data analysis [20]. Thirdly, we have been able to use Eq.(1) to resolve the violation [21,22] of Bloch-Nordsieck cancellation in ISR(initial state radiation) at $O(\alpha_s^2)$ for massive quarks [23]. This opens the way to include realistic quark masses as we introduce the higher order EW corrections in the presence of higher order QCD corrections – note that the radiation probability in QED at the hard scale $Q$ involves the logarithm $\ln(Q^2/m^2)$, and it will not do to set $m_q = 0$ to analyze these effects in a fully exclusive, differential event-by-event calculation of the type that we are constructing. Fourthly, the threshold resummation implied by Eq.(1) for single $Z$ production at LHC shows a 0.3% QED effect and agrees with known exact results in QCD – see Refs. [4,24,25]. Fifthly,
we have a new scheme \[8\] for precision LHC theory: in an obvious notation,
\[
\sigma = \sum_{i,j} \int dx_1 dx_2 F_i(x_1) F_j(x_2) \hat{\sigma}(x_1 x_2 s) = \sum_{i,j} \int dx_1 dx_2 F'_i(x_1) F'_j(x_2) \hat{\sigma}'(x_1 x_2 s),
\]
where the primed quantities are associated with Eq.\((2)\) in the standard QCD factorization calculus. Sixthly, we have \[4\] an attendant shower/ME matching scheme, wherein, for example, in combining Eq.\((1)\) with HERWIG \[11\], PYTHIA \[26\], MC@NLO \[27\] or new shower MC’s \[28\], we may use either \(p_T\)-matching or shower-subtracted residuals \(\{\hat{\beta}_{n,m}(k_1, \ldots, k_n; k'_1, \ldots, k'_m)\}\) to create a paradigm without double counting that can be systematically improved order-by-order in perturbation theory – see Refs. \[4\].

The stage is set for the full MC implementation of our approach. We turn next to the initial stage of this implementation – that of the kernels in Eq.\((2)\).

### 4 MC Realization of IR-Improved DGLAP-CS Theory

In this section we describe the initial implementation of the new IR-improved kernels in the HERWIG6.5 environment, which then results in a new MC, which we denote by HERWIRI1.0, which stands for “high energy radiation with IR improvement.” \[3\]

Specifically, our approach can be summarized as follows. We modify the kernels in the HERWIG6.5 module HWBRAN and in the attendant related modules \[29\] with the following substitutions:

\[
\text{DGLAP-CS } P_{AB} \Rightarrow \text{IR-I DGLAP-CS } P^\text{exp}_{AB}\]

while leaving the hard processes alone for the moment. We have in progress \[30\] the inclusion of YFS synthesized electroweak modules from Refs. \[31\] for HERWIG6.5, HERWIG++ \[32\] hard processes. The fundamental issue is that CTEQ \[33\] and MRST (MSTW after 2007) \[34\] best parton densities do not include precision electroweak higher order corrections and such effects do enter in a 1% precision tag budget for processes such as single heavy gauge boson production in the LHC environment, as we have emphasized.

For definiteness, let us illustrate the implementation by an example \[35\] \[36\], which for pedagogical reasons we will take as a simple leading log shower component with a virtuality evolution variable, with the understanding that in HERWIG6.5 the shower development is angle ordered \[35\] so that the evolution variable is actually \(\sim E\theta\) where \(\theta\) is the opening angle of the shower as defined in Ref. \[35\] for a parton initial energy \(E\). In this pedagogical example, which we take from Ref. \[35\], the probability that no branching

\[^{3}\text{We thank M. Seymour and B. Webber for discussion on this point.}\]
occurs above virtuality cutoff \( Q_0^2 \) is \( \Delta_a(Q^2, Q_0^2) \) so that

\[
d\Delta_a(t, Q_0^2) = -\frac{dt}{t} \Delta(t, Q_0^2) \sum_b \int dz \frac{\alpha_s}{2\pi} P_{ba}(z),
\]

which implies

\[
\Delta_a(Q^2, Q_0^2) = \exp \left[ -\int_{Q_0^2}^{Q^2} \frac{dt}{t} \sum_b \int dz \frac{\alpha_s}{2\pi} P_{ba}(z) \right].
\]

The attendant non-branching probability appearing in the evolution equation is

\[
\Delta(Q^2, t) = \frac{\Delta_a(Q^2, Q_0^2)}{\Delta_a(t, Q_0^2)}, \quad t = k_a^2 \quad \text{the virtuality of gluon } a.
\]

The respective virtuality of parton \( a \) is then generated with

\[
\Delta_a(Q^2, t) = R,
\]

where \( R \) is a random number uniformly distributed in \([0, 1]\). With (note \( \beta_0 = b_0|_{n_c=3} \) here, where \( n_c \) is the number of colors)

\[
\alpha_s(Q) = \frac{2\pi}{b_0 \log \left( \frac{Q}{\Lambda} \right)},
\]

we get for example

\[
\int_0^1 dz \frac{\alpha_s(Q^2)}{2\pi} P_{qG}(z) = \frac{4\pi}{2\pi b_0 \log \left( \frac{Q^2}{\Lambda^2} \right)} \int_0^1 dz \frac{1}{2} \left[ z^2 + (1 - z)^2 \right]
\]

\[
= \frac{2}{3} \frac{1}{b_0 \ln \left( \frac{Q^2}{\Lambda^2} \right)}.
\]

so that the subsequent integration over \( dt \) yields

\[
I = \int_{Q_0^2}^{Q^2} \frac{1}{3} \frac{dt}{t} \frac{2}{b_0 \ln \left( \frac{Q}{\Lambda^2} \right)}
\]

\[
= \frac{2}{3b_0} \ln \ln \frac{t}{\Lambda^2 |Q_0^2|}
\]

\[
= \frac{2}{3b_0} \left[ \ln \left( \frac{\ln \left( \frac{Q^2}{\Lambda^2} \right)}{\ln \left( \frac{Q_0^2}{\Lambda^2} \right)} \right) \right].
\]
Finally, introducing $I$ into Eq. (8) yields

$$
\Delta_a(Q^2, Q_0^2) = \exp \left[ -\frac{2}{3b_0} \ln \left( \frac{\ln (\frac{Q^2}{\Lambda^2})}{\ln (\frac{Q_0^2}{\Lambda^2})} \right) \right]
$$

$$
= \left[ \frac{\ln (\frac{Q^2}{\Lambda^2})}{\ln (\frac{Q_0^2}{\Lambda^2})} \right]^{\frac{2}{3b_0}}. \quad (14)
$$

If we now let $\Delta_a(Q^2, t) = R$, then

$$
\left[ \frac{\ln (\frac{t}{\Lambda^2})}{\ln (\frac{Q^2}{\Lambda^2})} \right]^{\frac{2}{3b_0}} = R \quad (15)
$$

which implies

$$
t = \Lambda^2 \left( \frac{Q^2}{\Lambda^2} \right)^{R\frac{2}{3b_0}}. \quad (16)
$$

Recall in HERWIG6.5 [11] we have

$$
b_0 = \left( \frac{11}{3} n_c - \frac{2}{3} n_f \right)
$$

$$
= \frac{1}{3} (11n_c - 10), \quad n_f = 5
$$

$$
\equiv \frac{2}{3} \text{BETA}\text{F} \quad (17)
$$

where in the last line we used the notation in HERWIG6.5. The momentum available after a $q\bar{q}$ split in HERWIG6.5 [11] is given by

$$
Q\bar{Q} = \text{QCDL3} \left( \frac{\text{QLST}}{\text{QCDL3}} \right)^{R\text{BETA}} \quad (18)
$$

in complete agreement with Eq. (16) when we note the identifications $t = Q\bar{Q}^2$, $\Lambda \equiv \text{QCDL3}$, $Q \equiv \text{QLST}$.

The leading log exercise leads to the same algebraic relationship that HERWIG6.5 has between $Q\bar{Q}$ and $Q\bar{Q}$ but we stress that in HERWIG6.5 these quantities are the angle-ordered counterparts of the virtualities we used in our example, so that the shower is angle-ordered.

Let us now repeat the above calculation for the IR-Improved kernels in Eq. (2). We have

$$
P_{qG}^{\exp}(z) = F_{YFS}(\gamma_G) e^{\delta_G/2} \left[ z^2 (1 - z) \gamma_G + (1 - z)^2 z \gamma_G \right] \quad (19)
$$
so that
\[ \int_0^1 dz \frac{\alpha_s(Q^2)}{2\pi} P_q G(z) \exp \left( \frac{4F_{YFS}(\gamma G)e^{\delta G/2}}{b_0 \ln \left( \frac{Q^2}{\Lambda^2} \right) (\gamma G + 1)(\gamma G + 2)(\gamma G + 3)} \right). \] (20)

This leads to the following integral over \( dt \)
\[ I = \int_{Q_0^2}^{Q^2} \frac{dt}{t} \frac{4F_{YFS}(\gamma G)e^{\delta G/2}}{b_0 (\gamma G + 1)(\gamma G + 2)(\gamma G + 3)} \left. \exp \left( 1, \frac{8.369604402}{b_0 \ln \left( \frac{Q^2}{\Lambda^2} \right)} \right) \right|_{Q_0^2}^{Q^2}. \] (21)

Here we have used
\[ \delta_G = \frac{\gamma G}{2} + \frac{\alpha_s C_G}{\pi} \left( \frac{\pi^2}{3} - \frac{1}{2} \right), \] (22)

with \( C_G = 3 \) the gluon quadratic Casimir invariant. We finally get the IR-improved formula
\[ \Delta_a(Q^2, t) = \exp \left[ -(F(Q^2) - F(t)) \right], \] (23)

where
\[ F(Q^2) = \frac{4F_{YFS}(\gamma G)e^{\gamma G/4}}{b_0 (\gamma G + 1)(\gamma G + 2)(\gamma G + 3)} \left. \exp \left( 1, \frac{8.369604402}{b_0 \ln \left( \frac{Q^2}{\Lambda^2} \right)} \right) \right|_{Q_0^2}^{Q^2}, \] (24)

and \( \text{Ei} \) is the exponential integral function. In Fig. 1 we show the difference between the two results for \( \Delta_a(Q^2, t) \). We see that they agree within a few percent except for the softer values of \( t \), as expected. We look forward to determining definitively whether the experimental data prefer one over the other. This detailed study will appear elsewhere [37] but we begin the discussion below with a view on recent FNAL data. Again, we note that the comparison in Fig. 1 is carried out at the leading log virtuality level, but the subleading effects suppressed in this discussion will not change our general conclusions drawn therefrom.

For further illustration, we note that for the \( q \to q G \) branching process in HERWIG6.5 [11], we have therein the implementation of the usual DGLAP-CS kernel as follows:

\[ \text{WMIN} = \text{MIN}(\text{ZMIN*(1. -ZMIN), ZMAX*(1.-ZMAX)}) \]
\[ \text{ETEST} = (1. + \text{ZMAX**2}) * \text{HWUalf}(5-\text{SUDORD*2, QNOW*WMIN}) \]
\[ \text{ZRAT} = \text{ZMAX/ZMIN} \]
\[ 30 \quad \text{Z1} = \text{ZMIN} * \text{ZRAT**HWRGEN(0)} \]
\[ \text{Z2} = 1. - \text{Z1} \]
\[ \text{PGQW} = (1. + \text{Z2*Z2}) \]
\[ \text{ZTEST} = \text{PGQW} * \text{HWUalf}(5-\text{SUDORD*2, QNOW*Z1*Z2}) \]
\[ \text{IF (ZTEST .LT. ETEST*HWRGEN(1)) GOTO 30} \]

... (25)

where the branching of \( q \) to \( G \) at \( z = Z1 \) occurs in the interval from \( ZMIN \) to \( ZMAX \) set by
Figure 1: Graph of $\Delta_a(Q^2, t)$ for the DGLAP-CS and IR-Improved DGLAP-CS kernels Eqs. (14, 23). $Q^2$ is a typical virtuality close to the squared scale of the hard subprocess – here we use $Q^2 = 25\text{GeV}^2$ for illustration.

the inputs to the program and the current value of the virtuality $Q_{NOW}$, $\text{HWUALF}$ is the respective function for $\alpha_s$ in the program and $\text{HWRGEN(J)}$ are uniformly distributed random numbers on the interval from 0 to 1. It is seen that Eq.(25) is a standard MC realization of the unexponentiated DGLAP-CS kernel via

$$\alpha_s(Qz(1-z))P_{Gq}(z) = \alpha_s(Qz(1-z))\frac{1 + (1 - z)^2}{z}$$

(26)

where the normalization is set by the usual conservation of probability. To realize this with the IR-improved kernel, we make the replacement of the code in Eq.(25) with the lines
NUMFLAV = 5
B0 = 11. - 2./3.*NUMFLAV
L = 16./(3.*B0)
DELTAQ = L/2 + HWAULF(5-SUDORD*2, QNOW*WMIN)*1.184056810
ETEST = (1. + ZMAX**2) * HWAULF(5-SUDORD*2, QNOW*WMIN)
    * EXP(0.5*DELTAQ) * FYFSQ(NUMFLAV-1) * ZMAX**L
ZRAT = ZMAX/ZMIN
Z1 = ZMIN * ZRAT**HWRGEN(0)
Z2 = 1. - Z1
DELTAQ = L/2 + HWAULF(5-SUDORD*2, QNOW*Z1*Z2)*1.184056810
PGQW = (1. + Z2*Z2) * EXP(0.5*DELTAQ) * FYFSQ(NUMFLAV-1)
    * Z1**L
ZTEST = PGQW * HWAULF(5-SUDORD*2, QNOW*Z1*Z2)
IF (ZTEST .LT. ETEST*HWRGEN(1)) GOTO 30

so that with the identifications $\gamma_q \equiv L$, $\delta_q \equiv \text{DELTAQ}$, $F_{YFS}(\gamma_q) \equiv \text{FYFSQ(NUMFLAV-1)}$, we see that Eq.(27) realizes the IR-improved DGLAP-CS kernel $P_{Gq}^{\exp}(z)$ via $\alpha_s(Qz(1-z))P_{Gq}^{\exp}(z)$ with the normalization again set by probability conservation. Continuing in this way, we have carried out the corresponding changes for all of the kernels in Eq.(2) in the HERWIG6.5 environment, with its angle-ordered showers, resulting in the new MC, HERWIRI1.0(31), in which the ISR parton showers have IR-improvement as given by the kernels in Eq. (6). We now illustrate some of the results we have obtained in comparing ISR showers in HERWIG6.5 and with those in HERWIRI1.031 (see footnote 4) at LHC and at FNAL energies, where some comparison with real data is also featured at the FNAL energy. Specifically, we compare the $z$-distributions, $p_T$-distributions, etc., that result from the IR-improved and usual DGLAP-CS showers in what follows.\footnote{In the original release of the program, we stated that the time-like parton showers had been completely IR-improved in a way that suggested the space-like parton showers had not yet been IR-improved at all. We subsequently introduced release 1.02 in which the part of the space-like parton showers associated with HERWIG6.5’s space-like module HWSGQQ for the space-like branching process $G \rightarrow q\bar{q}$ was IR-improved. Recently, the remaining un-IR-improved aspect of the space-like branching process, that in HERWIG6.5’s space-like module HWSFBR, as also been IR-improved in release 1.031. All of the results in this paper were obtained using the latter release.}

First, for the generic $2 \rightarrow 2$ hard processes at LHC energies (14 TeV) we get the comparison shown Figs. 2, 3 for the respective ISR $z$-distribution and $p_T^2$ distribution at the parton level. Here, there are no cuts placed on the MC data and we define $z$ as $z = E_{\text{parton}}/E_{\text{beam}}$ where $E_{\text{beam}}$ is the cms beam energy and $E_{\text{parton}}$ is the respective parton energy in the cms system. The two quantities $z$ and $p_T^2$ for partons are of course not directly observable but their distributions show the softening of the IR divergence as we expect.\footnote{Similar comparisons for PYTHIA and MC@NLO are in progress and we show some results with MC@NLO below.}
Figure 2: The $z$-distribution (ISR parton energy fraction) shower comparison in HERWIG6.5.

Turning next to the similar quantities for the $\pi^+$ production in the generic $2\rightarrow 2$ hard processes at LHC, we see again in Figs. 4, 5 that the former spectra are very similar in the soft regime while the latter spectra are softer in the IR-improved case. These spectra of course would be subject to some “tuning” in a real experiment and we await with anticipation the outcome of such an effort in comparison to LHC data.

We turn next to the luminosity process of single $Z$ production at the LHC, where in Figs. 6 and 7 we show respectively the ISR parton energy fraction distribution and the $Z$ $p_T$ distribution with cuts on the acceptance as $40\text{GeV} < M_Z$, $p_T^\ell > 5\text{GeV}$ for $Z \rightarrow \mu\bar{\mu}$ – all lepton rapidities are included. For the energy fraction distribution we again see softer spectra in the IR-improved case whereas for the $p_T$ distributions we see very similar spectra. We look forward to the confrontation with experiment, where again we stress that in a real experiment, a certain amount of “tuning” will affect these results. We note for example that the difference between the spectra in Fig. 7 while it is interesting, is well within the range that could be tuned away by varying the amount of intrinsic transverse momentum of partons in the proton. The question will always be which set of distributions gives a better $\chi^2$ per degree of freedom.

Finally, we turn to the issue of the IR cut-off in HERWIG6.5. In HERWIG6.5, there
Figure 3: The $p_T^2$-distribution (ISR parton) shower comparison in HERWIG6.5.

are IR cut-off parameters used to separate real and virtual effects and necessitated by the +-function representation of the usual DGLAP-CS kernels. In HERWIRI, these parameters can be taken arbitrarily close to zero, as the IR-improved kernels are integrable [7,8].

We now illustrate the difference in IR cut-off response by comparing it for HERWIG6.5 and HERWIRI: we change the default values of the parameters in HERWIG6.5 by factors of 0.7 and 1.44 as shown in the Fig. 3. We see that the harder cut-off reduces the phase space only significantly for the IR-improved kernels and that the softer cut-off has also a small effect on the usual kernels spectra whereas as expected the IR-improved kernels spectra move significantly toward softer values as a convergent integral would lead one to expect. This should lead to a better description of the soft radiation data at LHC. We

6We note that in the current version of HERWIRI, the formula for $\alpha_s(Q)$ is unchanged from that in HERWIG6.5 so that there is still a Landau pole therein and this would prevent our taking the attendant IR cut-off parameters arbitrarily close to zero; however, we also note that this Landau pole is spurious and a more realistic behavior for $\alpha_s(Q)$ as $Q \to 0$ from either the lattice approach [35] or from other approaches such as those in Refs. [39,40] could be introduced in the regime where the usual formula for $\alpha_s(Q)$ fails and this would allow us to approach zero with the IR cut-off parameters.

7One must note here that the spectra all stop at approximately the same value $z_0 \cong .00014 - .0016$ which is above some of the modulated IR-cut-off parameters, as the HERWIG environment has other
We finish this initial comparison discussion by turning to the data from FNAL on the $Z p_T$ spectra as reported in Refs. [41, 42]. We show these results, for 1.96 TeV cms energy, in Fig. 9. For these D0 $p_T$ data, we see that HERWIRI1.031 gives a better fit to the data compared to HERWIG6.510 for low $p_T$, (for $p_T < 8$ GeV, the $\chi^2$/d.o.f. are $\sim 2.5$ 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 [27] for the two programs and we see that the $\mathcal{O}(\alpha_s)$ correction improves the $\chi^2$/d.o.f for the HERWIRI1.031 in both the soft and hard regimes and it improves the HERWIG6.510 $\chi^2$/d.o.f for $p_T$ near 3.75 GeV where the distribution peaks. These results are of course still subject to tuning as we indicated above.

Figure 4: The $\pi^+$ energy fraction distribution shower comparison in HERWIG6.5.

We thank S. Frixione for helpful discussion on this implementation.

*We thank S. Frixione for helpful discussion on this implementation.
5 Conclusions

In this paper we have introduced the first QCD MC parton showers which do not need an IR cut-off to separate soft real and virtual corrections. We have shown that spectra at both the parton level and at the hadron level are softer in general. In the important process of single $Z$ production, these IR-improved spectra show the expected behavior of an integrable distribution. The comparison with the D0 $p_T$ spectrum in the soft regime shows that the IR-improvement does indeed improve the agreement with the data. Of course, this just sets the stage for the further implementation of the attendant new approach to precision QED×QCD predictions for LHC physics by the introduction of the respective resummed residuals needed to systematically improve the precision tag to the 1% regime for such processes as single heavy gauge boson production, for example. Already, however, we note that our new IR-improved MC, HERWIRI1.031, available at [http://thep03.baylor.edu](http://thep03.baylor.edu) is expected to allow for a better $\chi^2$ per degree of freedom in data analysis of high energy hadron-hadron scattering for soft radiative effects, thereby enabling.
a more precise comparison between theory and experiment. We have given evidence that this is indeed the case. Accordingly, we look forward to the further exploration and development of the results presented herein.

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Figure 7: The $Z$ $p_T$-distribution (ISR parton shower effect) comparison in HERWIG6.5.

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Figure 8: IR cut-off sensitivity in $z$-distributions of the ISR parton energy fraction: (a), DGLAP-CS (b), IR-I DGLAP-CS – for the single $Z$ hard subprocess in HERWIG-6.5 environment.

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Figure 9: Comparison with FNAL data: D0 $p_T$ spectrum data on $(Z/\gamma^*)$ production to $e^+e^-$ pairs, the circular dots are the data, the blue triangles are HERWIRI1.031, the green triangles are HERWIG6.510, the blue squares are MC@NLO/HERWIRI1.031, and the green squares are MC@NLO/HERWIG6.510.

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