MC Realization of IR-Improved DGLAP-CS Parton Showers:HERWIRI1.0(2)

B.F.L. Ward[a], **S. Joseph**[a], **S. Majhi**[a] **and S. Yost**[b]

[a] Department of Physics, Baylor University, Waco, TX, USA

[b]Department of Physics, The Citadel, Charleston, SC, USA

Outline

- **Introduction**
- **Review of Exact Amplitude-Based Resummation for QED$\otimes$QCD**
- **IR-Improved DGLAP-CS Theory: Parton Distributions, Kernels, Reduced Cross Sections with Shower/ME Matching**
- **MC Realization: IR-Improved Kernels in HERWIG6.5**
- **Conclusions**

See B.F.L.W., S. Jadach and B.F.L. Ward, S. Jadach, *et al.*,B.F.L.W. and S. Yost, MPL A **14** (1999) 491, hep-ph/0205062; *ibid.* **12** (1997) 2425; *ibid.***19** (2004) 2113; hep-ph/0503189, 0508140,0509003, 0605054, 0607198, arxiv:0704.0294, 0707.2101, 0707:3424

Motivation

- FOR THE LHC/ILC, THE REQUIREMENTS ARE DEMANDING AND OUR $QED \otimes QCD$ SOFT n(G)-m(γ) MC RESUMMATION RESULTS WILL BE AN IMPORTANT PART OF THE NECESSARY THEORY – (YFS)RESUMMED $\mathcal{O}(\alpha_s^2)L^n, \mathcal{O}(\alpha_s\alpha)L^{n'}, \mathcal{O}(\alpha^2)L^{n''}, n = 0, 1, 2, n' = 0, 1, 2, n'' = 2, 1$, IN THE PRESENCE OF SHOWERS, ON AN EVENT-BY-EVENT BASIS, WITHOUT DOUBLE COUNTING AND WITH EXACT PHASE SPACE.

- HOW RELEVANT ARE QED HIGHER ORDER CORRECTIONS WHEN QCD IS CONTROLLED AT $\sim 1\%$ PRECISION?

- CROSS CHECK OF QCD LITERATURE:

  1. PHASE SPACE – CATANI, CATANI-SEYMOUR, ALL INITIAL PARTONS MASSLESS
  2. RESUMMATION – STERMAN, CATANI ET AL., BERGER ET AL., ...
  3. NO-GO THEOREMS–Di'Lieto et al.,Doria et al.,Catani et al.,Catani; PRD78(2008)056001
  4. IR QCD EFFECTS IN DGLAP-CS THEORY

- CROSS CHECK OF QED-EW LITERATURE:

  1. ESTIMATES BY SPIESBERGER, STIRLING, ROTH and WEINZIERL, BLUMLEIN and KAWAMURA – FEW PER MILLE EFFECTS FROM QED CORRECTIONS TO STR. FN. EVOLUTION.

  2. WELL-KNOWN POSSIBLE ENHANCEMENT OF QED CORRECTIONS AT THRESHOLD, ESPECIALLY IN RESONANCE PRODUCTION

  3. *See for example, A. Kulesza et al., A. Denner et al., in "Proc. RADCOR07", S. Dittmaier (LP09) for large (Sudakov log, etc.) EW effects in hadron-hadron scattering – at 1TeV, W's and Z's are almost massless!*

  $\Rightarrow$ HOW TO BEST REALIZE THESE EFFECTS AT THE LHC?

- TREAT QED AND QCD SIMULTANEOUSLY IN THE (YFS) RESUMMATION TO OBTAIN THE ROLE OF THE QED-EW AND TO REALIZE AN APPROACH TO SHOWER/ME MATCHING.

- CURRENT STATE OF AFFAIRS: see N. Adam et al., JHEP **0805** (2008) 062 – Using MC@NLO and FEWZ, HORACE, PHOTOS, etc., $(4.1 \pm 0.3)\% = (1.51 \pm 0.75)\%(QCD) \oplus 3.79(PDF) \oplus 0.38 \pm 0.26(EW)\%$ accuracy on single Z to leptons at LHC was found($\sim 5.7\%$ for W, see *ibid.* 0809, 133), but no exclusive hard gluon/quark radiation phase space available – the latter are truly needed for realistic theoretical results. They are our goal, at $\lesssim 1\%$.

PRELIMINARY STUDIES

- REPRESENTATIVE PROCESSES
  $pp \to V + m(\gamma) + n(G) + X \to \bar{\ell}\ell' + m'(\gamma) + n(G) + X$,
  where $V = W^{\pm}, Z$,and $\ell = e, \mu,\ \ell' = \nu_e, \nu_\mu(e, \mu)$
  respectively for $V = W^+(Z)$, and $\ell = \nu_e, \nu_\mu,\ \ell' = e, \mu$
  respectively for $V = W^-$.

- Realize IR-improved kernels in state-of-the-art MC environment:
  HERWIG-6.5 => HERWIRI1.0(2)

Recapitulation of QED⊗QCD Resummation

In hep-ph/0210357(ICHEP02), Acta Phys.Polon.B33,1543-1558,2002, Phys.Rev.D52(1995)108;ibid. 66 (2002) 019903(E);PLB342 (1995) 239; Ann.Phys.323(2008)2147;Phys. Rev.D78(2008)056001; Adv. High Energy Phys. 2008 (2008): 682312, we have extended the YFS theory to QCD:

$$\begin{aligned} d\hat\sigma_{\rm exp} &= \sum_n d\hat\sigma^n \\ &= e^{\rm SUM_{IR}(QCD)} \sum_{n=0}^{\infty} \int \prod_{j=1}^{n} \frac{d^3k_j}{k_j} \int \frac{d^4y}{(2\pi)^4} e^{iy\cdot(P_1+P_2-Q_1-Q_2-\sum k_j)+D_{\rm QCD}} \\ &\quad * \tilde{\bar\beta}_n(k_1,\ldots,k_n)\frac{d^3P_2}{P_2^{\,0}}\frac{d^3Q_2}{Q_2^{\,0}} \end{aligned} \tag{1}$$

where the new hard gluon residuals $\tilde{\bar\beta}_n(k_1,\ldots,k_n)$ defined by

$$\tilde{\bar\beta}_n(k_1,\ldots,k_n) = \sum_{\ell=0}^{\infty} \tilde{\bar\beta}_n^{(\ell)}(k_1,\ldots,k_n)$$

are free of all infrared divergences to all orders in $\alpha_s(Q)$. $\Rightarrow$

Simultaneous exponentiation of QED and QCD higher order effects,

hep-ph/0404087(MPLA19(2004)2119), arXiv:0704.0294(APPB38(2007)2395),

arXiv:0808.3133, 0810.0723 ,

gives

$$
\begin{aligned}
B^{nls}_{QCD} &\rightarrow B^{nls}_{QCD} + B^{nls}_{QED} \equiv B^{nls}_{QCED}, \\
\tilde{B}^{nls}_{QCD} &\rightarrow \tilde{B}^{nls}_{QCD} + \tilde{B}^{nls}_{QED} \equiv \tilde{B}^{nls}_{QCED}, \\
\tilde{S}^{nls}_{QCD} &\rightarrow \tilde{S}^{nls}_{QCD} + \tilde{S}^{nls}_{QED} \equiv \tilde{S}^{nls}_{QCED}
\end{aligned} \tag{2}
$$

which leads to

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

where the new YFS residuals

$\tilde{\bar{\beta}}_{n,m}(k_1,\ldots,k_n;k'_1,\ldots,k'_m)$, **with n hard gluons and m hard photons,** represent the successive application of the YFS expansion first for QCD and subsequently for QED.

The infrared functions are now

$$\mathrm{SUM_{IR}(QCED)} = 2\alpha_s \Re B^{nls}_{QCED} + 2\alpha_s \tilde{B}^{nls}_{QCED}$$
$$D_{\mathrm{QCED}} = \int \frac{dk}{k^0}\left(e^{-iky} - \theta(K_{max} - k^0)\right)\tilde{S}^{nls}_{QCED} \quad (4)$$

where K_{max} is a dummy parameter – here the same for QCD and QED.

Infrared Algebra(QCED):

$x_{avg}(QED) \cong \gamma(QED)/(1+\gamma(QED))$

$x_{avg}(QCD) \cong \gamma(QCD)/(1+\gamma(QCD))$

$\gamma(A) = \frac{2\alpha_A \mathcal{C}_A}{\pi}(L_s - 1)$, $A = QED, QCD$

$\mathcal{C}_A = Q_f^2, C_F$, respectively, for $A = QED, QCD$

$\Rightarrow$ QCD dominant corrections happen an order of magnitude earlier than those for QED.

$\Rightarrow$ Leading $\tilde{\bar{\beta}}^{(0,0)}_{0,0}$-level gives a good estimate of the size of the effects we study: see arxiv.org: 0808.3133, and references therein.

Relationship to Sterman-Catani-Trentadue Soft Gluon Resummation

In Phys. Rev. D74 (2006) 074004[MADG], Abayat et al. apply the more familiar resummation for soft gluons to a general $2 \to n$ parton process [f] at hard scale Q,

$f_1(p_1, r_1) + f_2(p_2, r_2) \to f_3(p_3, r_3) + f_4(p_4, r_4) + \cdots + f_{n+2}(p_{n+2}, r_{n+2})$**,**

where the p_i, r_i label 4-momenta and color indices respectively, with all parton masses set to zero to get

$$\mathcal{M}^{[f]}_{\{r_i\}} = \sum_L^C \mathcal{M}^{[f]}_L(c_L)_{\{r_i\}} \\ = J^{[f]} \sum_L^C S_{LI} H^{[f]}_I (c_L)_{\{r_i\}}, \tag{5}$$

$J^{[f]}$ is the jet function

S_{LI} is the soft function which describes the exchange of soft gluons between the external lines

$H_I^{[f]}$ **is the hard coefficient function**

infrared and collinear poles calculated to 2-loop order.

To make contact with our approach, identify in $\bar{Q}'Q \rightarrow \bar{Q}'''Q'' + m(G)$ **in (1)**
$f_1 = Q, \bar{Q}', f_2 = \bar{Q}', f_3 = Q'', f_4 = \bar{Q}''', \{f_5, \cdots, f_{n+2}\} = \{G_1, \cdots, G_m\}$
$\Rightarrow n = m + 2$ **here.**

Observe the following:

- **By its definition in eq.(2.23) of [MADG], the anomalous dimension of the matrix** S_{LI} **does not contain any of the diagonal effects described by our infrared functions** $\Sigma_{IR}(QCD)$ **and** D_{QCD}**.**
- **By its definition in eqs.(2.5) and (2.7) of [MADG], the jet function** $J^{[f]}$ **contains the exponential of the virtual infrared function** $\alpha_s \Re B_{QCD}$**, so that we have to take care that we do not double count when we use (5) in (1) and the equations that lead thereto.**

$\Rightarrow$

We identify $\bar{\rho}^{(m)}$ in our theory as

$$\bar{\rho}^{(m)}(p_1,q_1,p_2,q_2,k_1,\cdots,k_m) = \overline{\sum}_{colors,spin} |\mathcal{M}'^{[f]}_{\{r_i\}}|^2$$

$$\equiv \sum_{spins,\{r_i\},\{r'_i\}} \mathfrak{h}^{cs}_{\{r_i\}\{r'_i\}} |\bar{J}^{[f]}|^2 \sum_{L=1}^{C}\sum_{L'=1}^{C} S^{[f]}_{LI} H^{[f]}_{I}(c_L)_{\{r_i\}} \left(S^{[f]}_{L'I'} H^{[f]}_{I'}(c_{L'})_{\{r'_i\}}\right)^{\dagger}, \quad (6)$$

where here we defined $\bar{J}^{[f]} = e^{-\alpha_s \Re B_{QCD}} J^{[f]}$, and we introduced the color-spin density matrix for the initial state, $\mathfrak{h}^{cs}$.

Here, we recall (see Ann.Phys.323(2008)2147;Phys. Rev.D78(2008)056001; Adv. High Energy Phys. 2008 (2008): 682312, for example) that in our theory, we have

$$d\hat{\sigma}^n = \frac{e^{2\alpha_s ReB_{QCD}}}{n!} \int \prod_{m=1}^{n} \frac{d^3k_m}{(k_m^2+\lambda^2)^{1/2}} \delta(p_1+q_1-p_2-q_2-\sum_{i=1}^{n} k_i)$$
$$\bar{\rho}^{(n)}(p_1,q_1,p_2,q_2,k_1,\cdots,k_n) \frac{d^3p_2 d^3q_2}{p_2^0 q_2^0}, \quad (7)$$

for n-gluon emission. $\Rightarrow$ Repeat usual steps to get our formula (1), no double counting of effects - in progress. Today, we show platform for this progress.

QED$\otimes$QCD RESUMMATION

$\Updownarrow$

SCT RESUMMATION

$\Updownarrow$ (Lee & Sterman)

SCET RESUMMATION

IR-Improved DGLAP-CS Theory: Parton Distributions, Kernels, Reduced Cross Sections with Shower/ME Matching

IR-Improved DGLAP-CS Theory

Exponentiation of QCD higher order effects: Where to apply?

Ann.Phys.323(2008)2147;Phys. Rev.D78(2008)056001; Adv. High Energy Phys. 2008 (2008): 682312,

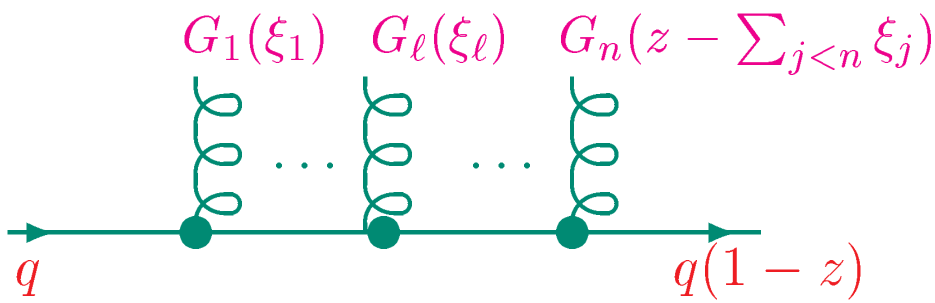
consider

$$\frac{dq^{NS}(x,t)}{dt} = \frac{\alpha_s(t)}{2\pi}\int_x^1 \frac{dy}{y} q^{NS}(y,t)P_{qq}(x/y) \tag{8}$$

where the well-known result for the kernel $P_{qq}(z)$ is, for $z < 1$,

$$P_{qq}(z) = C_F\frac{1+z^2}{1-z}, \tag{9}$$

$t = \ln \mu^2/\mu_0^2$ for some reference scale μ_0. $\Rightarrow$



$$q \rightarrow q(1-z) + G_1 + \cdots + G_n$$

$\Rightarrow$

$$P_{qq}(z) = C_F F_{YFS}(\gamma_q) e^{\frac{1}{2}\delta_q} \frac{1+z^2}{1-z} (1-z)^{\gamma_q} \tag{16}$$

where

$$\gamma_q = C_F \frac{\alpha_s}{\pi} t = \frac{4C_F}{\beta_0} \quad (17)$$

$$\delta_q = \frac{\gamma_q}{2} + \frac{\alpha_s C_F}{\pi}(\frac{\pi^2}{3} - \frac{1}{2}) \quad (18)$$

and

$$F_{YFS}(\gamma_q) = \frac{e^{-C_E \gamma_q}}{\Gamma(1+\gamma_q)}. \quad (19)$$

Note: $\int_{k_0} dz/z = C_0 - \ln k_0$

is experimentally distinguishable from

$\int_{k_0} dz/z^{1-\gamma} = C'_0 - k_0^{\gamma}/\gamma$.

IR-IMPROVED DGLAP-CS KERNELS

$$P_{qq}(z) = C_F F_{YFS}(\gamma_q) e^{\frac{1}{2}\delta_q} \left[\frac{1+z^2}{1-z}(1-z)^{\gamma_q} - f_q(\gamma_q)\delta(1-z) \right], \quad (34)$$

$$P_{Gq}(z) = C_F F_{YFS}(\gamma_q) e^{\frac{1}{2}\delta_q} \frac{1+(1-z)^2}{z} z^{\gamma_q}, \quad (35)$$

$$P_{GG}(z) = 2C_G F_{YFS}(\gamma_G) e^{\frac{1}{2}\delta_G} \{ \frac{1-z}{z} z^{\gamma_G} + \frac{z}{1-z}(1-z)^{\gamma_G}$$
$$+ \frac{1}{2}(z^{1+\gamma_G}(1-z) + z(1-z)^{1+\gamma_G}) - f_G(\gamma_G)\delta(1-z)\}, \quad (36)$$

$$P_{qG}(z) = F_{YFS}(\gamma_G) e^{\frac{1}{2}\delta_G} \frac{1}{2} \{ z^2(1-z)^{\gamma_G} + (1-z)^2 z^{\gamma_G} \}. \quad (37)$$

COMMENTS

$(*)$ IRI-DGLAP-CS RESUMS IR SINGULAR ISR;BY FACTORIZATION THIS IS NOT CONTAINED IN ANY RESUMMATION OF HARD SHORT-DISTANCE COEFFICIENT FN CORRECTIONS AS IN THE STERMAN, CATANI-TRENTADUE, COLLINS ET AL. FORMULAS

$(**)$ WE DO NOT CHANGE THE PREDICTED HADRON CROSS SECTION:

$$\begin{aligned}\sigma &= \sum_{i,j}\int dx_1 dx_2 F_i(x_1)F_j(x_2)\hat{\sigma}(x_1x_2s)\\ &= \sum_{i,j}\int dx_1 dx_2 {F'}_i(x_1){F'}_j(x_2)\hat{\sigma}'(x_1x_2s)\end{aligned} \tag{46}$$

ORDER BY ORDER IN PERTURBATION THEORY.

$\{P^{exp}\}$ factorize $\hat{\sigma}_{\text{unfactorized}} \Rightarrow \hat{\sigma}'$ – NEW SCHEME

$\{P\}$ factorize $\hat{\sigma}_{\text{unfactorized}} \Rightarrow \hat{\sigma}$

$(***)$ QUARK NUMBER CONSERVATION AND CANCELLATION OF IR SINGULARITIES IN XSECTS: Guaranteed by fundamental quantum field theoretic principles: Global Gauge Invariance, Unitarity – Everybody may use these principles.

QUARK MASSES and RESUMMATION in PRECISION QCD THEORY

* D'iLieto et al. (NPB**183**(1981)223), Doria et al. (ibid.**168**(1980)93), Catani et al. (*ibid*.**264(**1986)588; Catani (ZPC**37**(1988)357): IN ISR, BLOCH-NORDSIECK CANCELLATION FAILS AT $O(\alpha_s^2)$ for $m_q \neq 0$

* BFLW: PRD**78**(2008) 056001, RESUMMATION VIA (1) CAUSES UNCANCELLED IR DIVERGENCE TO VANISH

⇒ CAN USE REALISTIC QUARK MASSES IN (1) AND (3) TO ALL ORDERS IN α_s.

MC Realization: IR-Improved Kernels in HERWIG6.5

- Approach:
  - Modify the kernels in the HWBRAN and Related Modules - (BW,MS)

$$\text{DGLAP-CS } P_{AB} \Rightarrow \text{IR-I DGLAP-CS } P^{exp}_{AB} \tag{68}$$

  - Leave Hard Processes Alone for the Moment:
    In progress (SY,BFLW,VH,MH,SM,SJ)– include YFS synthesized EW modules from Jadach et al. MC's for HERWIG6.5,++ hard processes.
  - ISSUE: CTEQ and MRST BEST(after 2007) P.Dstrbn. Fns DO NOT INCLUDE PRECISION EW HO CORR.

Implementation Illustration

Probability that no branching occurs above virtuality cutoff Q_0^2 is $\Delta_a(Q^2, Q_0^2)$

$\Rightarrow$

$$d\Delta_a(t, Q_0^2) = \frac{-dt}{t}\Delta(t, Q_o^2)\sum_b \int dz \frac{\alpha_s}{2\pi} P_{ba}(z), \tag{69}$$

$\Rightarrow$

$$\Delta_a(Q^2, Q_0^2) = \exp\left[-\int_{Q_0^2}^{Q^2} \frac{dt}{t}\sum_b \int dz \frac{\alpha_s}{2\pi} P_{ba}(z)\right]. \tag{70}$$

Non-branching probability appearing in the evolution equation is

$$\Delta(Q^2, t) = \frac{\Delta_a(Q^2, Q_o^2)}{\Delta_a(t, Q_o^2)}, \quad t = k_a^2 \text{ the virtuality of gluon } a. \tag{71}$$

Virtuality of parton a is generated with

$$\Delta_a(Q^2, t) = R, \tag{72}$$

where R is a random number uniformly distributed in $[0, 1]$.

With

$$\alpha_s(Q) = \frac{2\pi}{b_0 \log\left(\frac{Q}{\Lambda}\right)}, \tag{73}$$

we get

$$\begin{aligned} \int_0^1 dz \frac{\alpha_s(Q^2)}{2\pi} P_{qG}(z) &= \frac{4\pi}{2\pi b_0 \ln\left(\frac{Q^2}{\Lambda^2}\right)} \int_0^1 dz \frac{1}{2}\left[z^2 + (1-z)^2\right] \\ &= \frac{2}{3} \frac{1}{b_0 \ln\left(\frac{Q^2}{\Lambda^2}\right)}. \end{aligned} \tag{74}$$

$\Rightarrow$

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

$$\begin{aligned} I = & \quad \frac{2}{3b_0} \ln\ln\frac{t}{\Lambda^2}\Big|_{Q_0^2}^{Q^2} \\ = & \quad \frac{2}{3b_0}\left[\ln\left(\frac{\ln\left(\frac{Q^2}{\Lambda^2}\right)}{\ln\left(\frac{Q_0^2}{\Lambda^2}\right)}\right)\right]. \end{aligned} \tag{75}$$

Finally

$$\begin{aligned} \Delta_a(Q^2, Q_0^2) & = \exp\left[-\frac{2}{3b_0}\ln\left(\frac{\ln\left(\frac{Q^2}{\Lambda^2}\right)}{\ln\left(\frac{Q_0^2}{\Lambda^2}\right)}\right)\right] \\ & = \left[\frac{\ln\left(\frac{Q^2}{\Lambda^2}\right)}{\ln\left(\frac{Q_0^2}{\Lambda^2}\right)}\right]^{-\frac{2}{3b_0}}. \end{aligned} \tag{76}$$

Let $\Delta_a(Q^2,t)=R$, then

$$\left[\frac{\ln\left(\frac{t}{\Lambda^2}\right)}{\ln\left(\frac{Q^2}{\Lambda^2}\right)}\right]^{\frac{2}{3b_0}}=R \tag{77}$$

$\Rightarrow$

$$t=\Lambda^2\left(\frac{Q^2}{\Lambda^2}\right)^{R^{\frac{3b_0}{2}}}. \tag{78}$$

Recall

$$\begin{aligned} b_0 &= \left(\frac{11}{3}n_c-\frac{2}{3}n_f\right) \\ &= \frac{1}{3}\left(11n_c-10\right), \quad n_f=5 \\ &= \frac{2}{3}\mathbf{BETAF}. \end{aligned} \tag{79}$$

The momentum available after a $q\bar{q}$ split in HERWIG is given by

$$QQBAR = QCDL3\left(\frac{QLST}{QCDL3}\right)^{R^{BETAF}}. \tag{80}$$

Let us now repeat the above calculation for the IR-Improved kernels.

$$P_{qG}(z)^{exp} = F_{YFS}(\gamma_G)e^{\frac{1}{2}\delta_G}\frac{1}{2}\left[z^2(1-z)^{\gamma_G} + (1-z)^2 z^{\gamma_G}\right] \tag{81}$$

so

$$\int_0^1 dz \frac{\alpha_s\left(Q^2\right)}{2\pi} P_{qG}(z)^{exp} = \frac{4F_{YFS}(\gamma_G)e^{\frac{1}{2}\delta_G}}{b_0 \ln\left(\frac{Q^2}{\Lambda^2}\right)\left(\gamma_G+1\right)\left(\gamma_G+2\right)\left(\gamma_G+3\right)}. \tag{82}$$

⇒

$$I = \int_{Q_0^2}^{Q^2} \frac{dt}{t} \frac{4F_{YFS}(\gamma_G) e^{\frac{1}{2}\delta_G}}{b_0 \ln\left(\frac{t}{\Lambda^2}\right)(\gamma_G+1)(\gamma_G+2)(\gamma_G+3)},$$

$$I = \frac{4F_{YFS}(\gamma_G) e^{0.25\gamma_G}}{b_0(\gamma_G+1)(\gamma_G+2)(\gamma_G+3)} Ei\left(1, \frac{8.369604402}{b_0 \ln\left(\frac{t}{\Lambda^2}\right)}\right)\Bigg|_{Q_0^2}^{Q^2} \quad (83)$$

Where we have used

$$\delta_G = \frac{\gamma_G}{2} + \frac{\alpha_s C_G}{\pi}\left(\frac{\pi^2}{3} - \frac{1}{2}\right), \quad (84)$$

with $C_G = 3$ the gluon quadratic Casimir invariant. So finally

$$\Delta_a(Q^2, t) = \exp\left[-\left(F\left(Q^2\right) - F\left(t\right)\right)\right], \quad (85)$$

where

$$F(Q^2) = \frac{4F_{YFS}(\gamma_G) e^{0.25\gamma_G}}{b_0(\gamma_G+1)(\gamma_G+2)(\gamma_G+3)} Ei\left(1, \frac{8.369604402}{b_0 \ln\left(\frac{Q^2}{\Lambda^2}\right)}\right), \quad (86)$$

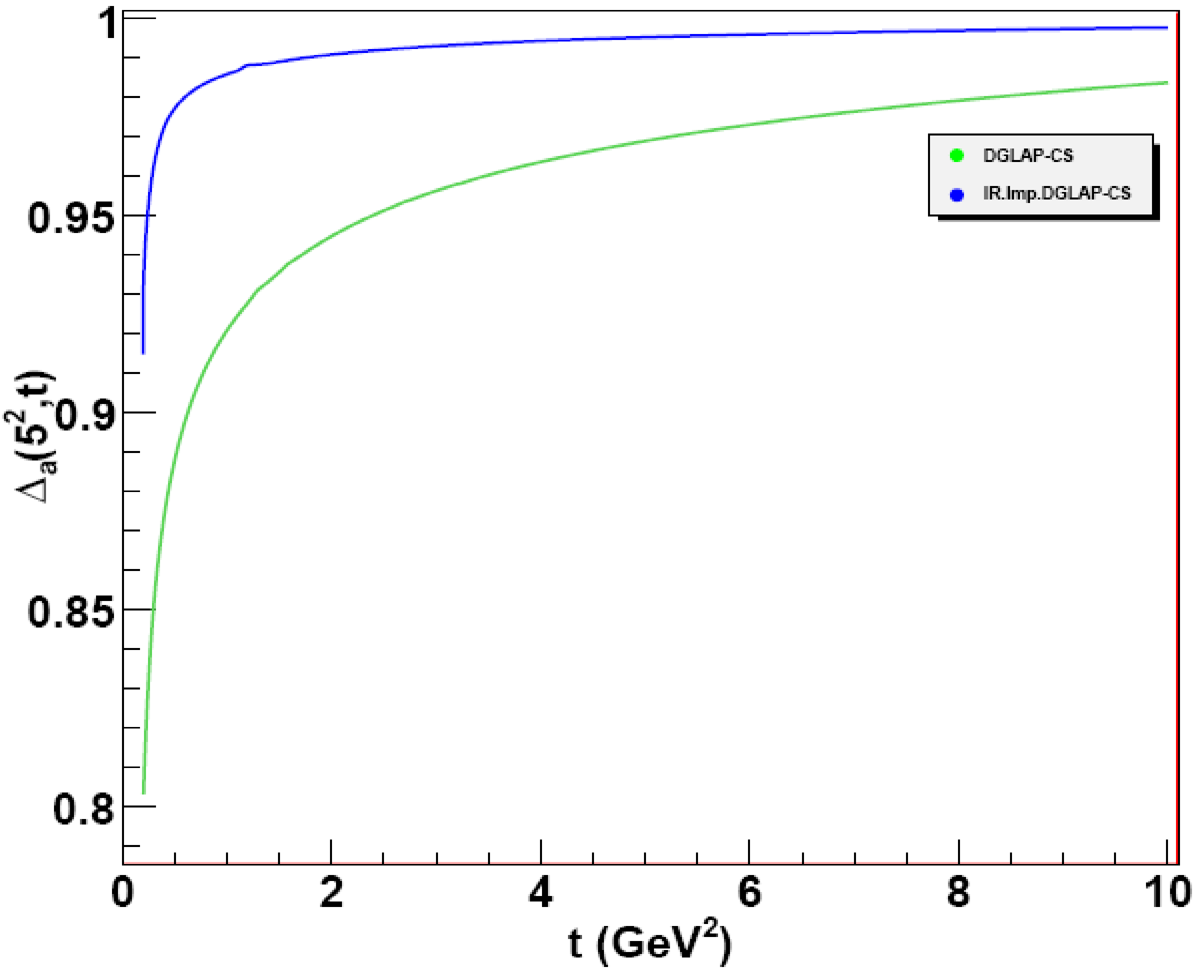


Figure 1. Graph of $\Delta_a(Q^2,t)$for the DGLAP-CS and IR-Imp. DGLAP-CS kernels (76,85)

RESULTS

We have illustrative results on IR-Improved Showers in HERWIG6.5: we compare the z-distributions, p_T-dist. etc., of the IR-Improved and usual DGLAP-CS showers in the following figs.

NOTE: SIMILAR RESULTS FOR PYTHIA and MC@NLO IN PROGRESS.

- **First, 2$\longrightarrow$2 hard processes at LHC**

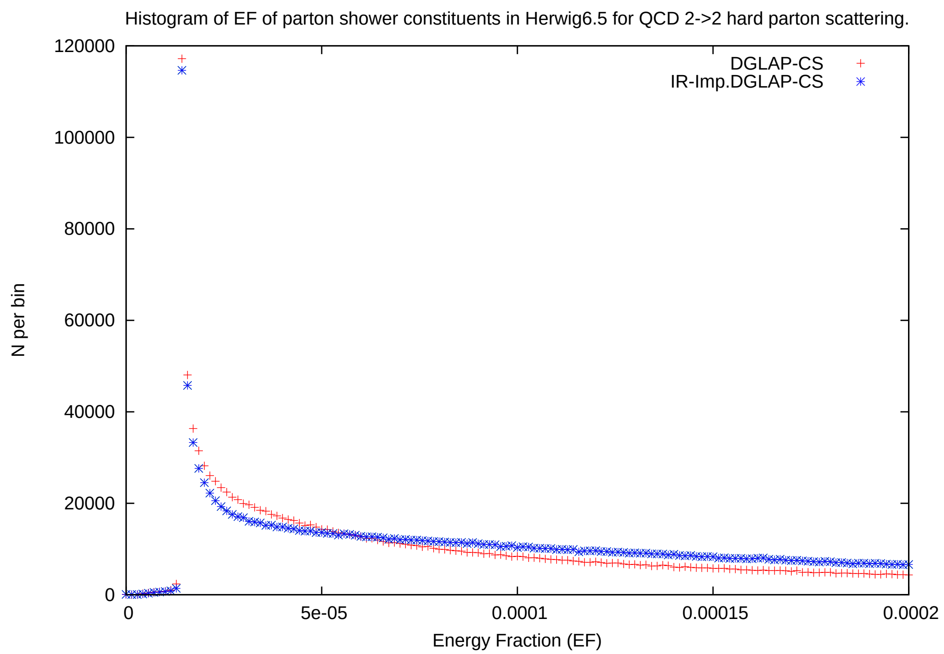


Figure 2: The z-distribution(ISR parton energy fraction) shower comparison in HERWIG6.5.

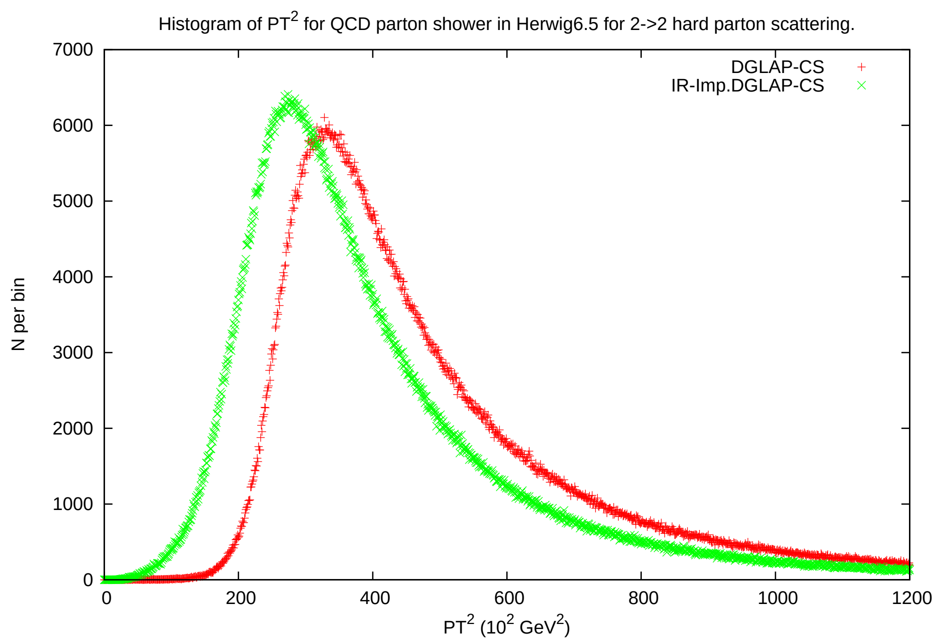


Figure 3: The P_T^2-distribution (ISR parton) shower comparison in HERWIG6.5.

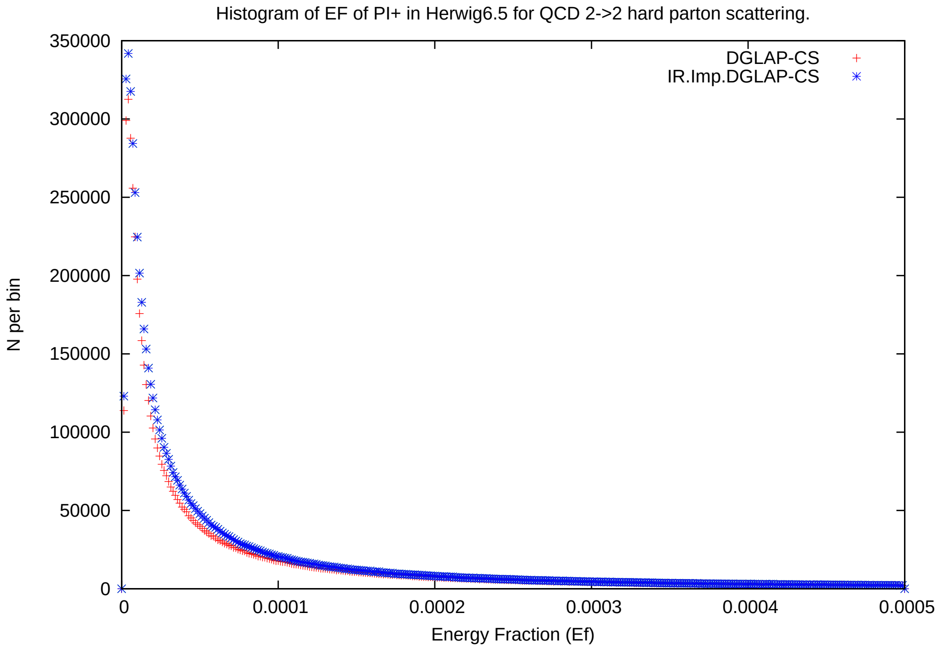


Figure 4: The π^+ energy fraction distribution shower comparison in HERWIG6.5.

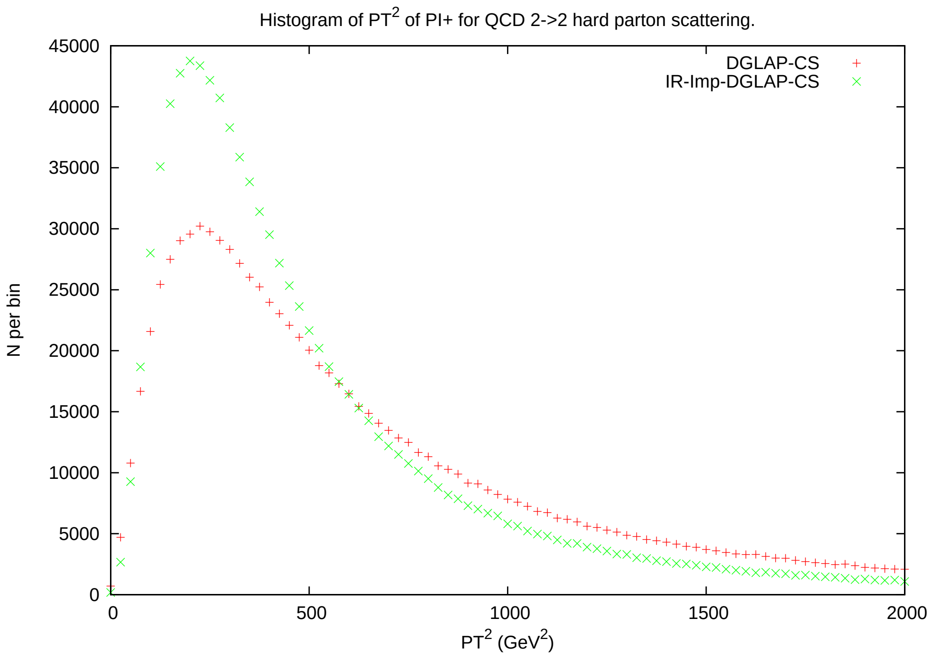


Figure 5: The π^+ P_T^2-distribution shower comparison in HERWIG6.5.

- **Single Z-production at LHC**

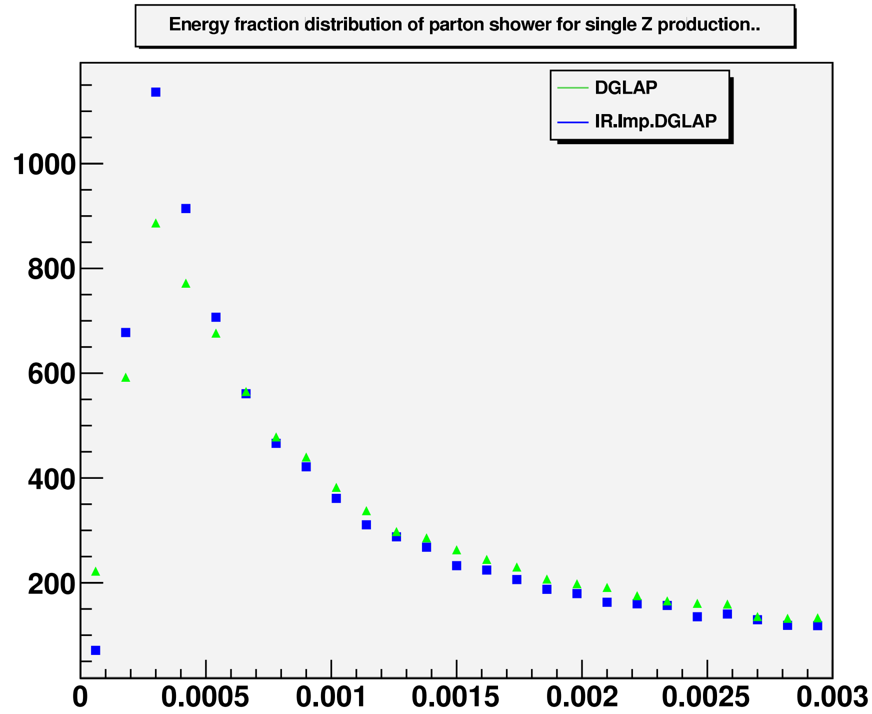


Figure 6: The z-distribution(ISR parton energy fraction) shower comparison in HERWIG6.5.

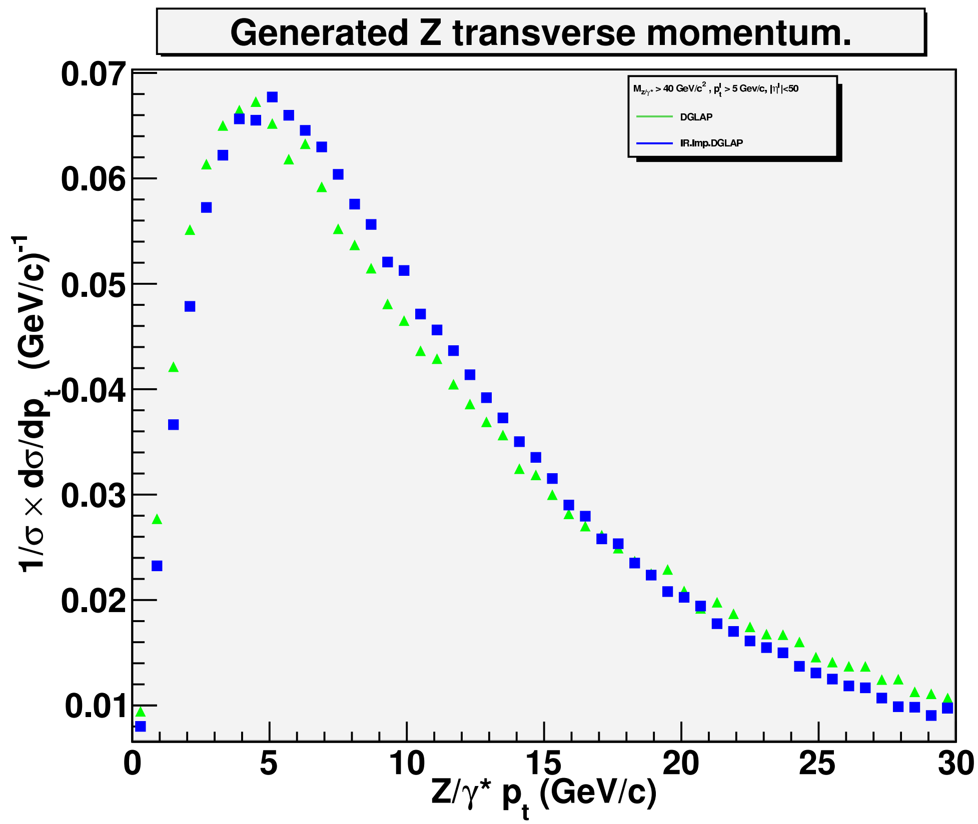


Figure 7: The Z p_T-distribution(ISR parton shower effect) comparison in HERWIG6.5.

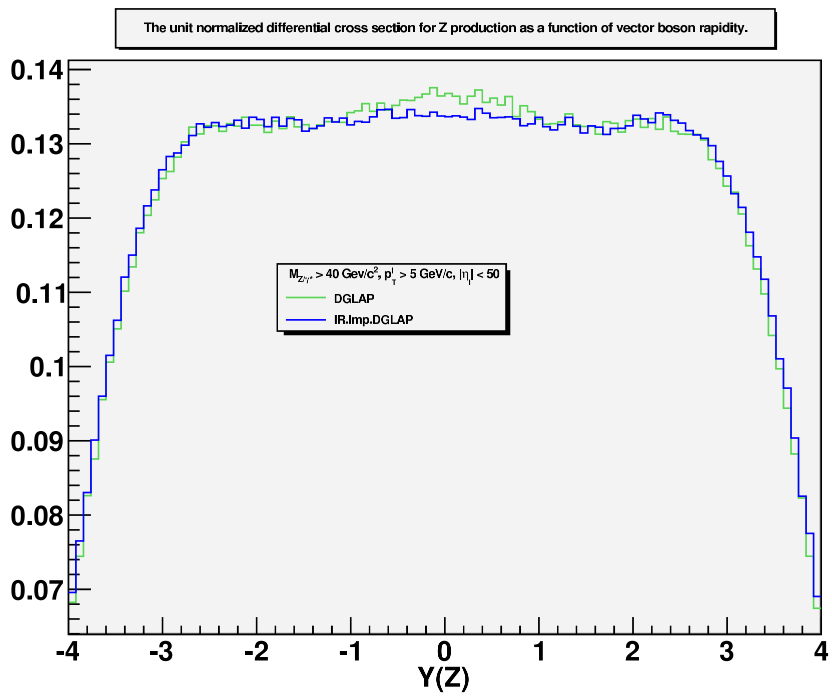
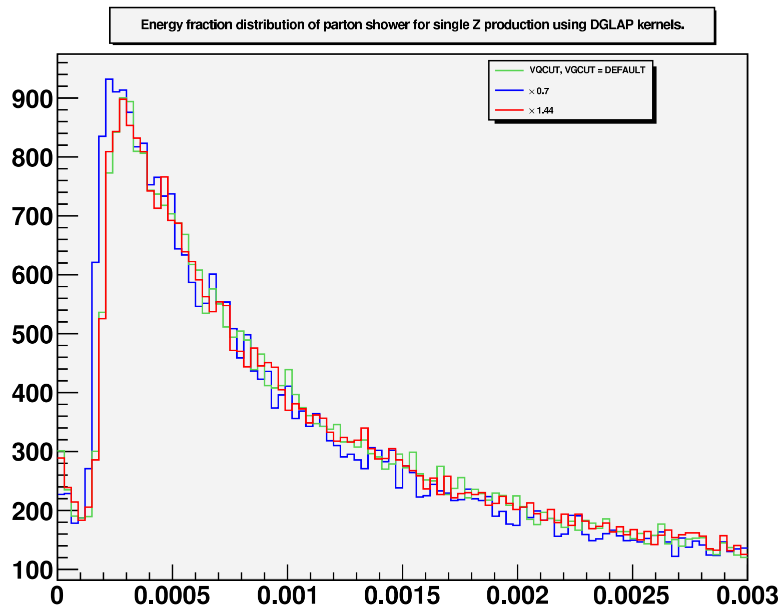


Figure 8: The Z rapidity-distribution(ISR parton shower) comparison in HERWIG6.5.

(a)



(b)

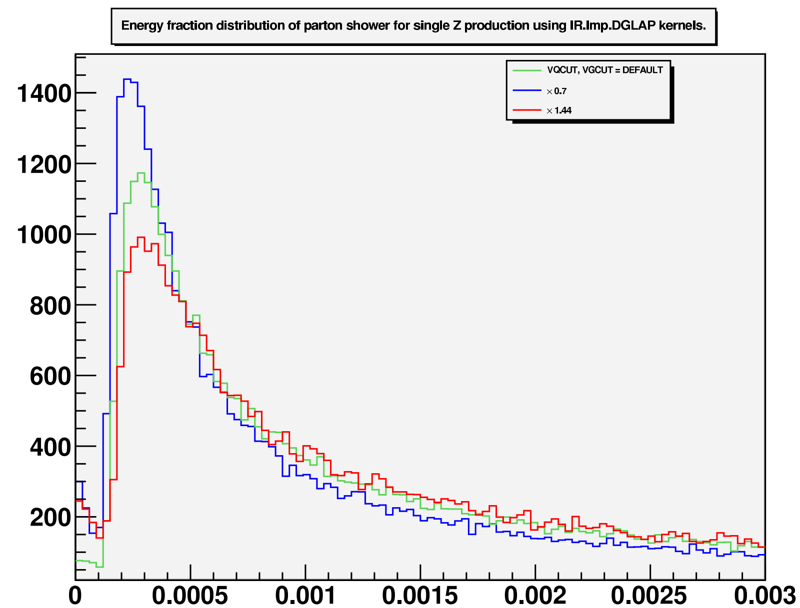
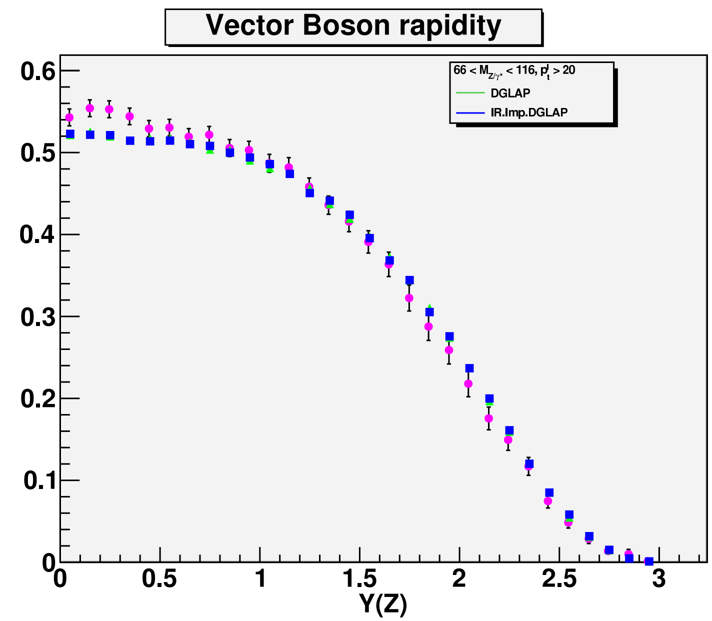


Figure 9: **IR-cut-off sensitivity in z-distributions of the ISR parton energy fraction: (a), DGLAP-CS (b), IR-I DGLAP-CS – for the single Z hard subprocess in HERWIG-6.5 environment.**

COMPARISON WITH DATA NOW FOLLOWS

(Galea, Proc. DIS 2008; Abasov et al., PRL100, 102002 (2008).)

(a) **(b)**



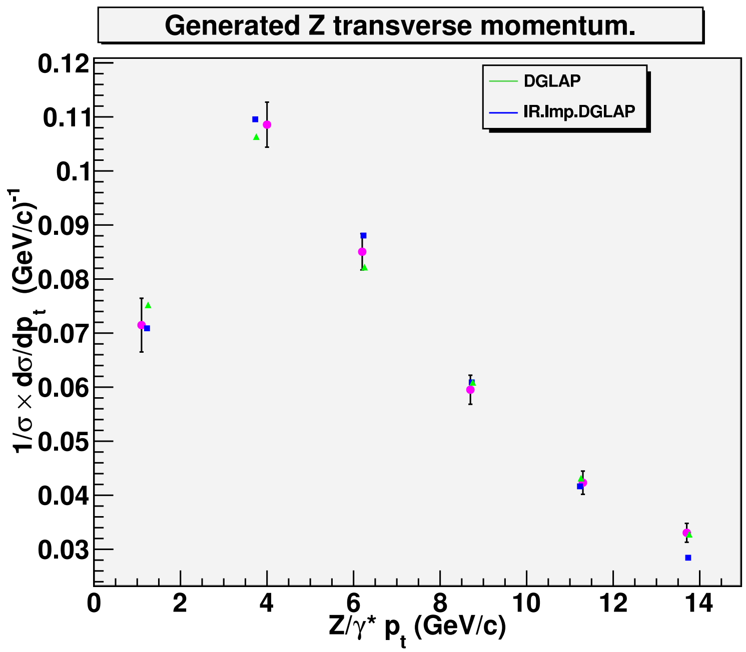
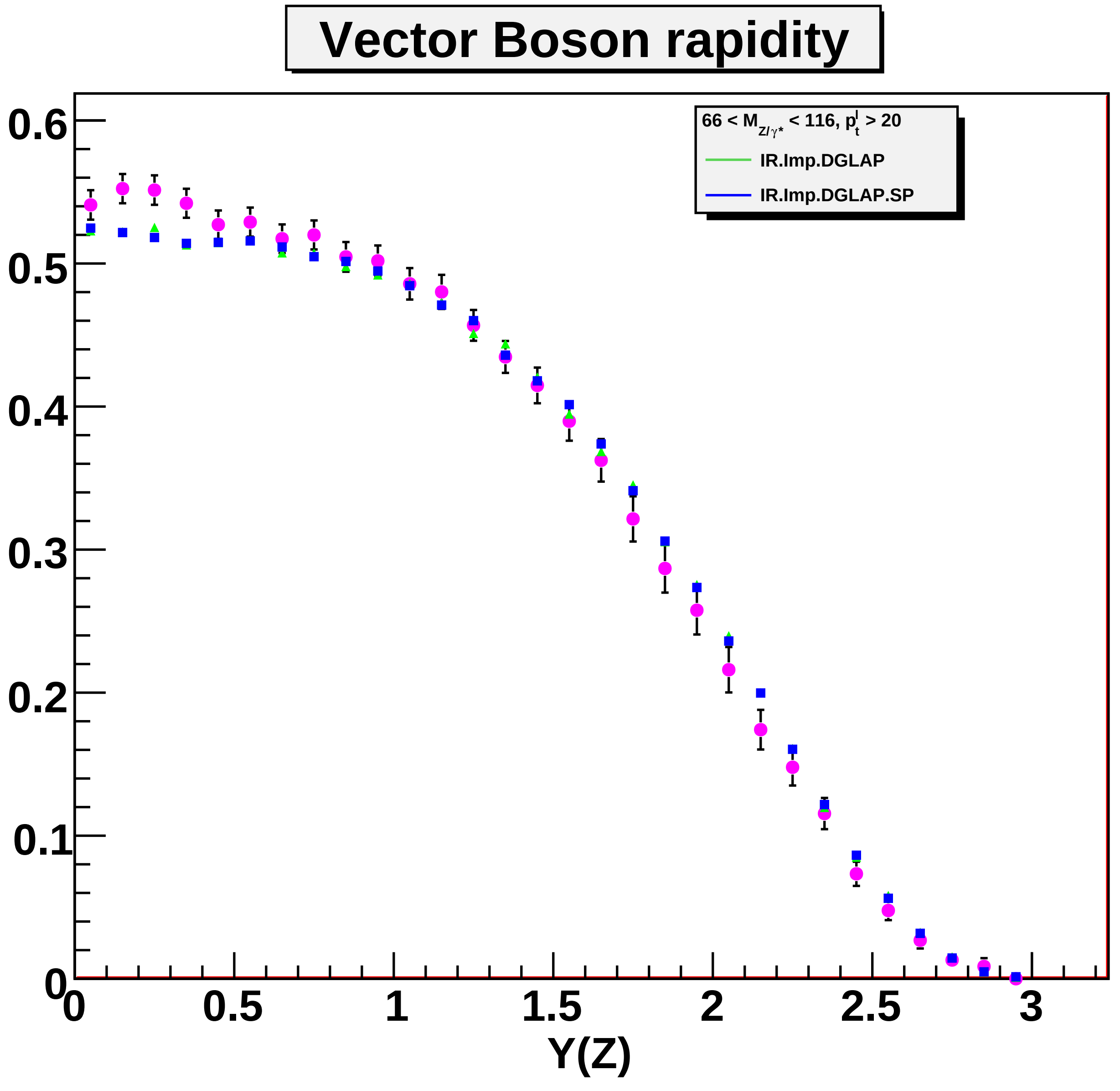
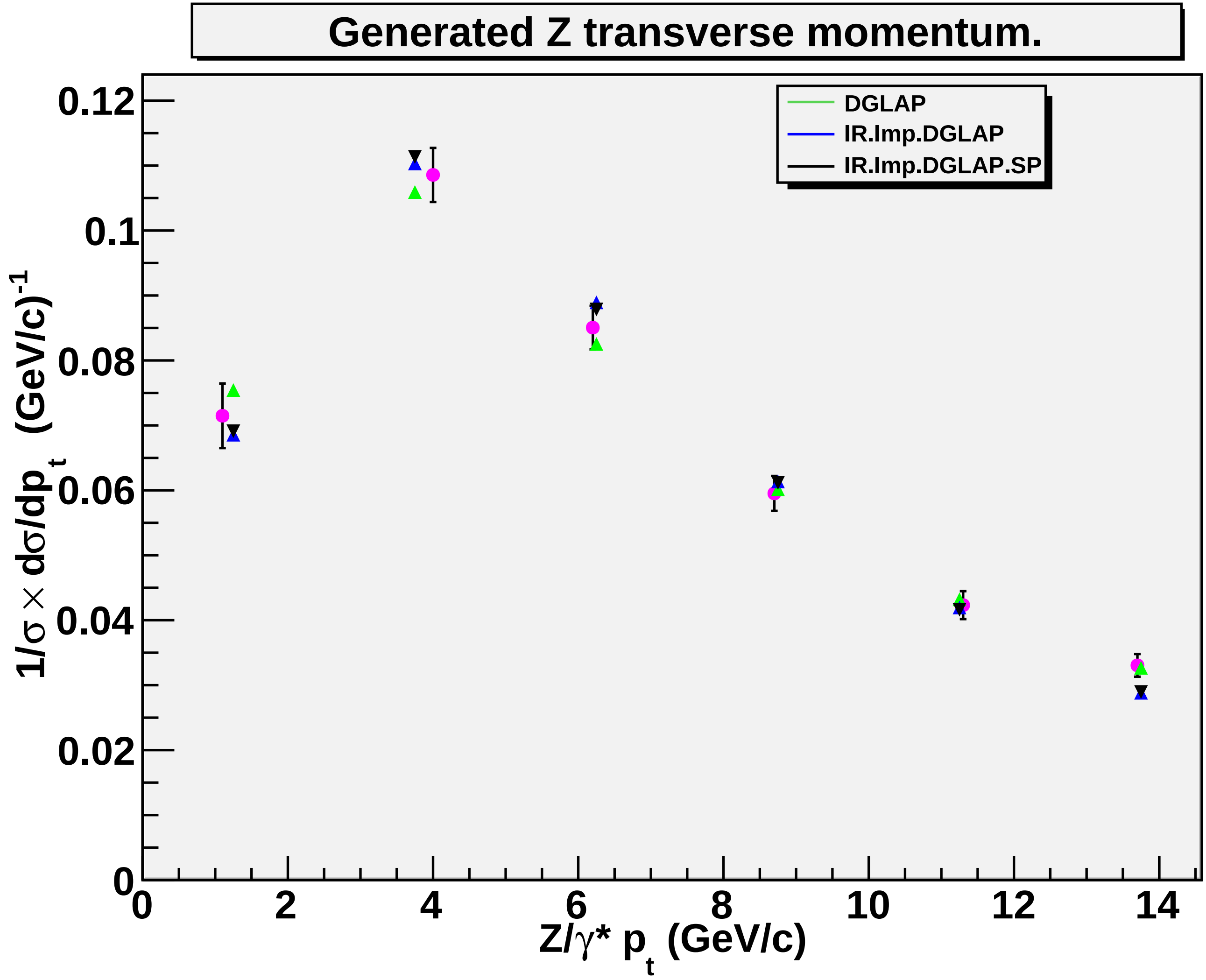


Figure 10: Comparison with FNAL data: (a), CDF rapidity data on (Z/γ^*) production to e^+e^- pairs, the circular dots are the data; (b), D0 p_T spectrum data on (Z/γ^*) production to e^+e^- pairs, the circular dots are the data.

For the D0 p_T data, we see that HERWIRI1.0(2) gives a better fit to the data compared to HERWIG6.5 for low p_T, (for $p_T < 12.5$GeV, the χ^2/d.o.f. are $\sim$ .29 and .40 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.



Vector Boson rapidity
66 < M_{Z/γ*} < 116, p_t^l > 20
IR.Imp.DGLAP
IR.Imp.DGLAP.SP
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.5
1
1.5
2
2.5
3
Y(Z)



Generated Z transverse momentum.
DGLAP
IR.Imp.DGLAP
IR.Imp.DGLAP.SP
0.12
0.1
0.08
0.06
0.04
0.02
0
0
2
4
6
8
10
12
14
Z/γ* p_t (GeV/c)
1/σ × dσ/dp_t (GeV/c)^-1

Conclusions

YFS-TYPE METHODS (EEX AND CEEX) EXTEND TO NON-ABELIAN GAUGE THEORY AND ALLOW SIMULTANEOUS RESMN OF QED AND QCD WITH PROPER SHOWER/ME MATCHING BUILT-IN.

FOR QED$\otimes$QCD

- **FULL MC EVENT GENERATOR REALIZATION OPEN.**
- **WE HAVE FIRST PHASE OF FULL MC REALIZATION: IR-IMPROVED HERWIG6.5 (HERWIRI1.0(2), arXiv:0906.0788, arXiv:0910.0491 at http://thep03.baylor.edu)**
- **COMPARISON WITH THEORY ENCOURAGING: SOFTER SPECTRA, MORE ROBUSTNESS TO CUTS, ETC. – $\Delta\sigma_{Shower}$ IN PLAY**
- **COMPARISON WITH DATA – INITIAL FNAL RESULTS GOOD**
- **IMPLEMENTATION IN PYTHIA, HERWIG++, MC@NLO IN PROGRESS**
- **IMPLEMENTATION OF PRECISION EW MODULES (FROM JADACH ET AL.) IN HERWIG ALSO IN PROGRESS -- HERWIRI2.0.**

- **A FIRM BASIS FOR THE COMPLETE $\mathcal{O}(\alpha_s^2, \alpha\alpha_s, \alpha^2)$ MC RESULTS NEEDED FOR THE PRECISION FNAL/LHC/RHIC/ILC PHYSICS HAS BEEN DEMONSTRATED AND ALL THE LATTER IS IN PROGRESS, WITH M. Kalmykov, S. Majhi, S. Yost and S. Joseph.– SEE JHEP0702(2007)040,arxiv:0707.3654,0708.0803, 0810.3238, 0901.4716, 0902.1352, NEW RESULTS FOR HO F-Int's,etc. –no time to discuss here**