HERWIRI1.0(31): New Approach to Parton Shower MC's in Precision QCD Theory

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Outline

- **Introduction**
- **Review of Exact Amplitude-Based Resummation for QED$\otimes$QCD**
- **IR-Improved DGLAP-CS Theory**
- **MC Realization: IR-Improved Kernels in HERWIG6.5 with Interface to MC@NLO**
- **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, S. Joseph *et al.*, PLB**685** (2010) 283, PRD**81** (2010) 076008

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., COLLINS ET AL.,BAUER ET AL....
  3. NO-GO THEOREMS–Di'Lieto et al.,Doria et al.,Catani et al.,Catani
  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., NPB* **662***(2003) 299, in "Proc. RADCOR07", for large (Sudakov log, etc.) EW effects in hadron-hadron scattering – at 1TeV, W's and Z's are almost massless!*
  4. *See also S. Dittmaier, in Proc. LP09, A. Denner et al., arXiv:1001.4462, and references therein for mixed EW X QCD corrections*

$\Rightarrow$ 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**05** (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 JHEP **09** (2008) 133), but no exclusive hard gluon/quark radiation phase space available – the latter are truly needed for realistic theoretical results. Our goal, at $\lesssim 1\%$.

  UPDATE: Adam et. al, arXiv:1006.3766, $Z \leftrightarrow 3.16 \pm 0.59\%$, $W^+ \leftrightarrow 3.88 \pm 0.75\%$, $W^- \leftrightarrow 4.01 \pm 0.66\%$

DEFINING 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, WITH SEAMLESS INTERFACE TO MC@NLO

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:

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

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

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

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 f rst 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 $2 \rightarrow n$ parton process [f] at hard scale Q,

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

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

$$\begin{aligned}\mathcal{M}^{[f]}_{\{r_i\}} &= \sum_{L}^{C} \mathcal{M}^{[f]}_{L}(c_L)_{\{r_i\}} \\ &= J^{[f]} \sum_{L}^{C} S_{LI} H^{[f]}_{I}(c_L)_{\{r_i\}},\end{aligned} \tag{5}$$

$J^{[f]}$ **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 coeff cient 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 def nition 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 def nition 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 def ned $\bar{J}^{[f]}=e^{-\alpha_s\Re B_{QCD}}J^{[f]}$, 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

$$d\hat{\sigma}^n=\frac{e^{2\alpha_s ReB_{QCD}}}{n!}\int\prod_{m=1}^{n}\frac{d^3k_m}{(k_m^2+\lambda^2)^{1/2}}\delta(p_1+q_1-p_2-q_2-\sum_{i=1}^{n}k_i)$$
$$\bar{\rho}^{(n)}(p_1,q_1,p_2,q_2,k_1,\cdots,k_n)\frac{d^3p_2d^3q_2}{p_2^0q_2^0}, \quad (7)$$

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

QED⊗QCD RESUMMATION

⇕

SCT RESUMMATION

⇕ (Lee & Sterman)

SCET RESUMMATION

IR-Improved DGLAP-CS Theory

Resummation of QCD higher order effects: Where to apply? I - Ann.Phys.323(2008)2147; II - Phys. Rev.D78(2008)056001; III - 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. $\Rightarrow$**

Unintegrable singularity at $z = 1$, usually regularized by

$$\frac{1}{(1-z)} \rightarrow \frac{1}{(1-z)_+} \tag{10}$$

with $\frac{1}{(1-z)_+}$ **such that**

$$\int_0^1 dz \frac{f(z)}{(1-z)_+} = \int_0^1 dz \frac{f(z)-f(1)}{(1-z)}. \tag{11}$$

$\Rightarrow$

$$\frac{1}{(1-z)_+} = \frac{1}{(1-z)}\theta(1-\epsilon-z) + \ln\epsilon\,\delta(1-z) \tag{12}$$

with the understanding that $\epsilon \downarrow 0$.

Require

$$\int_0^1 dz P_{qq}(z) = 0, \tag{13}$$

$\Rightarrow$ **add virtual corrections to get**

$$P_{qq}(z) = C_F\left(\frac{1+z^2}{(1-z)_+} + \frac{3}{2}\delta(1-z)\right). \tag{14}$$

Observations

- Smooth, divergent $1/(1-z)$ behavior as $z \to 1$ replaced with a mathematical artifact: the regime $1-\epsilon < z < 1$ now has no probability at all; at $z = 1$ we have a large negative integrable contribution $\Rightarrow$ a f nite (zero) value for the total integral of $P_{qq}(z)$

- LEP1,2 experience: such mathematical artifacts, while correct, impair precision.

Why set $P_{qq}(z)$ to 0 for $1-\epsilon < z < 1$ where it actually has its largest values?

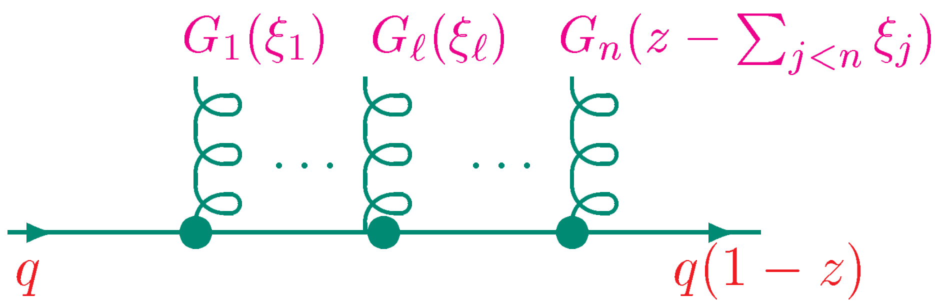
- USE EXPERIENCE FROM LEP1,2: $\frac{1}{(1-z)_+}$ SHOULD BE EXPONENTIATED –SEE CERN YELLOW-BOOKS, CERN-89-08., YIELDING FROM (1) THE REPLACEMENT (SEE I,III)

$$P_{BA} = \frac{1}{2} z(1-z) \overline{\sum_{spins}} \frac{|V_{A\to B+C}|^2}{p_\perp^2}$$

$$\Rightarrow \tag{15}$$

$$P_{BA} = \frac{1}{2} z(1-z) \overline{\sum_{spins}} \frac{|V_{A\to B+C}|^2}{p_\perp^2} z^{\gamma_q} F_{YFS}(\gamma_q) e^{\frac{1}{2}\delta_q}$$

WHERE $A = q$, $B = G$, $C = q$ AND $V_{A\to B+C}$ IS THE LOWEST ORDER AMPLITUDE FOR $q \to G(z) + q(1-z)$.



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

$\Rightarrow$

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

where

$$\gamma_q = C_F \frac{\alpha_s}{\pi} t = \frac{4C_F}{\beta_0} \tag{17}$$

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

and

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

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

is experimentally distinguishable from

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

- **NORMALIZATION CONDITION (13) $\Rightarrow$:**

$$P_{qq}(z) = C_F F_{YFS}(\gamma_q) e^{\frac{1}{2}\delta_q} \left[\frac{1+z^2}{1-z}(1-z)^{\gamma_q} - f_q(\gamma_q)\delta(1-z) \right] \tag{20}$$

where

$$f_q(\gamma_q) = \frac{2}{\gamma_q} - \frac{2}{\gamma_q+1} + \frac{1}{\gamma_q+2}. \tag{21}$$

- **THIS IS OUR IR-IMPROVED P_{qq} DGLAP-CS KERNEL.**

$\Rightarrow$ **USING STANDARD DGLAP-CS THEORY:**

for $z < 1$, we have

$$P_{Gq}(z) = P_{qq}(1-z) = C_F F_{YFS}(\gamma_q) e^{\frac{1}{2}\delta_q} \frac{1+(1-z)^2}{z} z^{\gamma_q}. \tag{22}$$

$\Rightarrow$ **TEST OF NEW THEORY – QUARK MOMENTUM SUM RULE:**

$$\int_0^1 dz z \left(P_{Gq}(z) + P_{qq}(z)\right) = 0. \tag{23}$$

⇒ **CHECK VANISHING OF**

$$I = \int_0^1 dzz\left(\frac{1+(1-z)^2}{z}z^{\gamma_q} + \frac{1+z^2}{1-z}(1-z)^{\gamma_q} - f_q(\gamma_q)\delta(1-z)\right). \quad (24)$$

NOTE,

$$\frac{z}{1-z} = \frac{z-1+1}{1-z} = -1 + \frac{1}{1-z}. \quad (25)$$

⇒

$$\begin{aligned} I &= \int_0^1 dz\{(1+(1-z)^2)z^{\gamma_q} - (1+z^2)(1-z)^{\gamma_q} \\ &\quad + \frac{1+z^2}{1-z}(1-z)^{\gamma_q} - f_q(\gamma_q)\delta(1-z)\} \\ &= 0 \end{aligned}$$

QUARK MOMENTUM SUM RULE IS SATISFIED.

- For $P_{qG}(z),\ P_{GG}(z)$, we get, with the replacement $C_F \rightarrow C_G$ in the IR algebra, that the usual results

$$P_{GG}(z) = 2C_G(\frac{1-z}{z} + \frac{z}{1-z} + z(1-z))$$
$$P_{qG}(z) = \frac{1}{2}(z^2 + (1-z)^2) \tag{26}$$

become

$$P_{GG}(z) = 2C_G F_{YFS}(\gamma_G) e^{\frac{1}{2}\delta_G}\{\frac{1-z}{z} z^{\gamma_G} + \frac{z}{1-z}(1-z)^{\gamma_G}$$
$$+ \frac{1}{2}(z^{1+\gamma_G}(1-z) + z(1-z)^{1+\gamma_G}) - f_G(\gamma_G)\delta(1-z)\}, \tag{27}$$

$$P_{qG}(z) = F_{YFS}(\gamma_G) e^{\frac{1}{2}\delta_G}\frac{1}{2}\{z^2(1-z)^{\gamma_G} + (1-z)^2 z^{\gamma_G}\}, \tag{28}$$

where

$$\gamma_G = C_G \frac{\alpha_s}{\pi} t = \frac{4C_G}{\beta_0} \tag{29}$$

$$\delta_G = \frac{\gamma_G}{2} + \frac{\alpha_s C_G}{\pi}\left(\frac{\pi^2}{3} - \frac{1}{2}\right), \tag{30}$$

$$f_G(\gamma_G) = \frac{n_f}{C_G} \frac{1}{(1+\gamma_G)(2+\gamma_G)(3+\gamma_G)} + \frac{2}{\gamma_G(1+\gamma_G)(2+\gamma_G)} \tag{31}$$

$$+ \frac{1}{(1+\gamma_G)(2+\gamma_G)} + \frac{1}{2(3+\gamma_G)(4+\gamma_G)} \tag{32}$$

$$+ \frac{1}{(2+\gamma_G)(3+\gamma_G)(4+\gamma_G)}. \tag{33}$$

THE GLUON MOMENTUM SUM RULE HAS BEEN USED.

- **THIS DEFINES THE NEW IR-IMPROVED DGLAP-CS THEORY.**

IR-IMPROVED DGLAP-CS KERNELS

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

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

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

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

Higher Order DGLAP-CS Kernels

Connection with the exact $\mathcal{O}(\alpha_s^2),\ \mathcal{O}(\alpha_s^3)$ kernel results of Curci, Furmanski and Petronzio, Floratos et al., Moch et al., etc., is immediate:

For example, non-singlet case, using standard notation,

$$P_{ns}^{+} = P_{qq}^{v} + P_{q\bar{q}}^{v} \equiv \sum_{n=0}^{\infty} (\frac{\alpha_s}{4\pi})^{n+1} P_{ns}^{(n)+} \tag{38}$$

where at order $\mathcal{O}(\alpha_s)$ we have

$$P_{ns}^{(0)+}(z) = 2C_F\{\frac{1+z^2}{(1-z)_+} + \frac{3}{2}\delta(1-z)\} \tag{39}$$

$\Rightarrow P_{ns}^{(0)+}(z)$ agrees with the unexponentiated result for P_{qq} except for an overall factor of 2. Floratos et al., etc., have exact result for $P_{ns}^{(1)+}(z)$, and Moch et al. have

exact results for $P_{ns}^{(2)+}(z)$. Applying (1) to $q \rightarrow q + X$, $\bar{q} \rightarrow q + X'$, we get

$$P_{ns}^{+,exp}(z) = (\frac{\alpha_s}{4\pi})2P_{qq}^{exp}(z) + F_{YFS}(\gamma_q)e^{\frac{1}{2}\delta_q}\Big[(\frac{\alpha_s}{4\pi})^2\{(1-z)^{\gamma_q}\bar{P}_{ns}^{(1)+}(z) + \bar{B}_2\delta(1-z)\} + (\frac{\alpha_s}{4\pi})^3\{(1-z)^{\gamma_q}\bar{P}_{ns}^{(2)+}(z) + \bar{B}_3\delta(1-z)\}\Big] \quad (40)$$

where $P_{qq}^{exp}(z)$ is given above and the resummed residuals $\bar{P}_{ns}^{(i)+}$, $i = 1, 2$ are related to the exact results for $P_{ns}^{(i)+}$, $i = 1, 2$, as follows:

$$\bar{P}_{ns}^{(i)+}(z) = P_{ns}^{(i)+}(z) - B_{1+i}\delta(1-z) + \Delta_{ns}^{(i)+}(z) \quad (41)$$

where

$$\Delta_{ns}^{(1)+}(z) = -4C_F\pi\delta_1\{\frac{1+z^2}{1-z} - f_q\delta(1-z)\}$$
$$\Delta_{ns}^{(2)+}(z) = -4C_F(\pi\delta_1)^2\{\frac{1+z^2}{1-z} - f_q\delta(1-z)\} - 2\pi\delta_1\bar{P}_{ns}^{(1)+}(z) \quad (42)$$

and

$$\bar{B}_2 = B_2 + 4C_F\pi\delta_1 f_q$$
$$\bar{B}_3 = B_3 + 4C_F(\pi\delta_1)^2 f_q - 2\pi\delta_1\bar{B}_2. \tag{43}$$

The constants $B_i,\ i=2,3$ are given by

$$B_2 = 4C_GC_F(\frac{17}{24}+\frac{11}{3}\zeta_2-3\zeta_3)-4C_Fn_f(\frac{1}{12}+\frac{2}{3}\zeta_2)+4C_F^2(\frac{3}{8}-3\zeta_2+6\zeta_3)$$
$$B_3 = 16C_GC_Fn_f(\frac{5}{4}-\frac{167}{54}\zeta_2+\frac{1}{20}\zeta_2^2+\frac{25}{18}\zeta_3)$$
$$+16C_GC_F^2(\frac{151}{64}+\zeta_2\zeta_3-\frac{205}{24}\zeta_2-\frac{247}{60}\zeta_2^2+\frac{211}{12}\zeta_3+\frac{15}{2}\zeta_5)$$
$$+16C_G^2C_F(-\frac{1657}{576}+\frac{281}{27}\zeta_2-\frac{1}{8}\zeta_2^2-\frac{97}{9}\zeta_3+\frac{5}{2}\zeta_5)$$
$$+16C_Fn_F^2(-\frac{17}{144}+\frac{5}{27}\zeta_2-\frac{1}{9}\zeta_3)$$
$$+16C_F^2n_F(-\frac{23}{16}+\frac{5}{12}\zeta_2+\frac{29}{30}\zeta_2^2-\frac{17}{6}\zeta_3)$$
$$+16C_F^3(\frac{29}{32}-2\zeta_2\zeta_3+\frac{9}{8}\zeta_2+\frac{18}{5}\zeta_2^2+\frac{17}{4}\zeta_3-15\zeta_5). \tag{44}$$

Contact with Wilson Expansion

N-th moment of the invariants $T_{i,\ell},\ i = L, 2, 3,\ \ell = q, G,$ of the forward Compton amplitude in DIS:(Gorishni et al.)

$$\mathcal{P}_N \equiv \left[\frac{q^{\{\mu_1} \cdots q^{\mu_N\}}}{N!} \frac{\partial^N}{\partial p^{\mu_1} \cdots \partial p^{\mu_N}} \right] \Big|_{p=0}, \tag{45}$$

$x_{Bj} = Q^2/(2qp)$ in the standard DIS notation – Projects the coeff cient of $1/(2x_{Bj})^N$. Terms which we resum here $\Leftrightarrow$ Formally γ_q-dependent anomalous dimensions associated with the respective coeff cient, not in Wilson's expansion by usual def nition.:

LARGE λ NOT ALL ON TIP OF LIGHTCONE.

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:

$$\sigma = \sum_{i,j} \int dx_1 dx_2 F_i(x_1) F_j(x_2) \hat{\sigma}(x_1 x_2 s)$$
$$= \sum_{i,j} \int dx_1 dx_2 F'_i(x_1) F'_j(x_2) \hat{\sigma}'(x_1 x_2 s) \qquad (46)$$

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: Quaranteed by fundamental quantum f eld theoretic principles: Global Gauge Invariance, Unitarity – Everybody may use these principles.

Effects on Parton Distributions

Moments of kernels ⇔ Logarithmic exponents for evolution

$$\frac{dM_n^{NS}(t)}{dt} = \frac{\alpha_s(t)}{2\pi} A_n^{NS} M_n^{NS}(t) \qquad (47)$$

where

$$M_n^{NS}(t) = \int_0^1 dz z^{n-1} q^{NS}(z,t) \qquad (48)$$

and the quantity A_n^{NS} is given by

$$\begin{aligned} A_n^{NS} &= \int_0^1 dz z^{n-1} P_{qq}(z), \\ &= C_F F_{YFS}(\gamma_q) e^{\frac{1}{2}\delta_q} [B(n,\gamma_q) + B(n+2,\gamma_q) - f_q(\gamma_q)] \end{aligned} \qquad (49)$$

where $B(x,y)$ is the beta function given by

$$B(x,y) = \Gamma(x)\Gamma(y)/\Gamma(x+y)$$

.

Compare the usual result

$$A_n^{NS^o} \equiv C_F\left[-\frac{1}{2}+\frac{1}{n(n+1)}-2\sum_{j=2}^{n}\frac{1}{j}\right]. \qquad (50)$$

- **ASYMPTOTIC BEHAVIOR: IR-improved goes to a multiple of $-f_q$, consistent with** $\lim_{n\to\infty} z^{n-1}=0$ **for** $0\le z<1$**; usual result diverges as** $-2C_F \ln n$**.**
- **Different for f nite n as well: for $n=2$ we get, for example, for $\alpha_s \cong .118$,**

$$A_2^{NS} = \begin{cases} C_F(-1.33) & , \text{ un-IR-improved} \\ C_F(-0.966) & , \text{ IR-improved} \end{cases} \qquad (51)$$

- **For completeness we note**

$$
\begin{aligned}
M_n^{NS}(t) &= M_n^{NS}(t_0) e^{\int_{t_0}^{t} dt' \frac{\alpha_s(t')}{2\pi} A_n^{NS}(t')} \\
&= M_n^{NS}(t_0) e^{\bar{a}_n [Ei(\frac{1}{2}\delta_1 \alpha_s(t_0)) - Ei(\frac{1}{2}\delta_1 \alpha_s(t))]} \\
&\underset{t,t_0 \text{ large with } t>>t_0}{\Longrightarrow} M_n^{NS}(t_0) \left(\frac{\alpha_s(t_0)}{\alpha_s(t)}\right)^{\bar{a'}_n}
\end{aligned} \qquad (52)
$$

where $Ei(x) = \int_{-\infty}^{x} dr e^r/r$ **is the exponential integral function,**

$$
\begin{aligned}
\bar{a}_n &= \frac{2C_F}{\beta_0} F_{YFS}(\gamma_q) e^{\frac{\gamma_q}{4}} [B(n,\gamma_q) + B(n+2,\gamma_q) - f_q(\gamma_q)] \\
\bar{a'}_n &= \bar{a}_n \left(1 + \frac{\delta_1}{2} \frac{(\alpha_s(t_0) - \alpha_s(t))}{\ln(\alpha_s(t_0)/\alpha_s(t))}\right)
\end{aligned} \qquad (53)
$$

with

$\delta_1 = \frac{C_F}{\pi}\left(\frac{\pi^2}{3} - \frac{1}{2}\right)$.

Compare with un-IR-improved result where last line in eq.(52) holds exactly with $\bar{a'}_n = 2A_n^{NS^o}/\beta_0$**.**

- For $n = 2$, taking $Q_0 = 2$GeV and evolving to $Q = 100$GeV, with $\Lambda_{QCD} \cong .2GeV$ and $n_f = 5$ for illustration, (52,53) $\Rightarrow$ a shift of evolved NS moment by $\sim\ 5\%$, of some interest in view of the expected HERA precision (see for example, T. Carli et al., Proc. HERA-LHC Wkshp, 2005).

ANOTHER EXAMPLE: THRESHOLD CORRECTIONS

We have applied the new simultaneous QED$\otimes$QCD exponentiation calculus to the single Z production with leptonic decay at the LHC (and at FNAL) to focus on the ISR alone, for def niteness. See also the work of Baur *et al.*, Dittmaier and Kramer, Zykunov for exact $\mathcal{O}(\alpha)$ results and Hamberg *et al.*, van Neerven and Matsuura and Anastasiou *et al.* for exact $\mathcal{O}(\alpha_s^2)$ results.

For the basic formula

$$d\sigma_{exp}(pp \to V+X \to \bar{\ell}\ell'+X') = \sum_{i,j}\int dx_i dx_j F_i(x_i)F_j(x_j)d\hat{\sigma}_{exp}(x_i x_j s), \tag{54}$$

we use the result in (3) f rst here with semi-analytical methods and structure functions from Martin *et al.* and then in a new MC – see below.

SHOWER/ME MATCHING

- Note the following: In (54) WE DO NOT ATTEMPT *HERE* TO REPLACE HERWIG and/or PYTHIA – WE INTEND *HERE* TO COMBINE OUR EXACT YFS CALCULUS, $d\hat{\sigma}_{exp}(x_i x_j s)$, WITH HERWIG and/or PYTHIA BY USING THEM/IT TO GENERATE A PARTON SHOWER STARTING FROM (x_1, x_2) AT FACTORIZATION SCALE μ AFTER THIS POINT IS PROVIDED BY $\{F_i\}$: THERE ARE TWO APPROACHES TO THE MATCHING UNDER STUDY, ONE BASED ON p_T-MATCHING AND ONE BASED ON SHOWER-SUBTRACTED RESIDUALS $\{\hat{\bar{\bar{\beta}}}_{n,m}(k_1, \ldots, k_n; k'_1, \ldots, k'_m)\}$, WHEREIN THE SHOWER FORMULA AND THE $QED \otimes QCD$ EXPONENTIATION FORMULA CAN BE EXPANDED IN PRODUCT AND REQUIRED TO MATCH THE GIVEN EXACT RESULT TO THE SPECIFIED ORDER – SEE hep-ph/0509003.
- THIS COMBINATION OF THEORETICAL CONSTRUCTS CAN BE SYSTEMATICALLY IMPROVED WITH EXACT RESULTS ORDER-BY-ORDER IN α_s, α, WITH EXACT PHASE SPACE.
- THE RECENT ALTERNATIVE PARTON EVOLUTION ALGORITHM BY JADACH and SKRZYPEK,Acta. Phys. Pol.B35, 745 (2004), CAN ALSO BE USED.
- LACK OF COLOR COHERENCE $\Rightarrow$ ISAJET NOT CONSIDERED HERE.

With this said, we compute , with and without QED, the ratio

$r_{exp} = \sigma_{exp}/\sigma_{Born}$

to get the results (We stress that we *do not* use the narrow resonance approximation here.)

$$r_{exp} = \begin{cases} 1.1901 & ,\text{QCED} \equiv \text{QCD+QED, LHC} \\ 1.1872 & ,\text{QCD, LHC} \\ 1.1911 & ,\text{QCED} \equiv \text{QCD+QED, Tevatron} \\ 1.1879 & ,\text{QCD, Tevatron} \end{cases} \quad (55)$$

$\Rightarrow$

QED IS AT .3% AT BOTH LHC and FNAL.

THIS IS STABLE UNDER SCALE VARIATIONS.

WE AGREE WITH BAUR ET AL., HAMBERG ET AL., van NEERVEN and ZIJLSTRA–NOTE THAT AS WE HAVE AN EXPONENTITED FORMULA, IT MAKES SENSE TO COMPARE WITH THE LATTER.

QED EFFECT SIMILAR IN SIZE TO STR. FN. RESULTS.

DGLAP-CS SYNTHESIZATION HAS NOT COMPROMISED THE NORMALIZATION.

QUARK MASSES and RESUMMATION in PRECISION QCD THEORY

(PHYS. REV.D78(2008)056001)

- Di'Lieto et al.(NPB183(1981)223), Doria et al.(*ibid.*168(1980)93), Catani et al.(*ibid.*264(1986)588;Catani(ZPC37(1988)357): IN ISR, BLOCH-NORDSIECK CANCELLATION FAILS AT $\mathcal{O}(\alpha_s^2)$ for $m_q \neq 0$.
- FOR $q + q' \to q'' + q''' + V + X$, THEY GET

$$\text{flux}\ \frac{d\sigma}{d^3Q} = \frac{-g^4\bar{H}}{(d-4)32\pi^2}\left(\frac{1-\beta}{\beta}\right)\left(\frac{1}{\beta}\ln(\frac{1+\beta}{1-\beta}) - 2\right) \tag{56}$$

- HERE, $\bar{H}$ IS THE HARD PROCESS DRESSED AS

$$F_1 = C_2(G) H_{ab}^{\alpha\beta} (T_i)^{\beta\alpha} (T_i)_b a \tag{57}$$

FOR

$$f_{ijk} f_{ijl} = C_2(G)\delta_{kl}$$

$$(T_i T_i)_{ab} = C_2(F) I_{ab}.$$

THEY EVALUATE THE GRAPHS IN FIG.1 USING MUELLER'S THM.

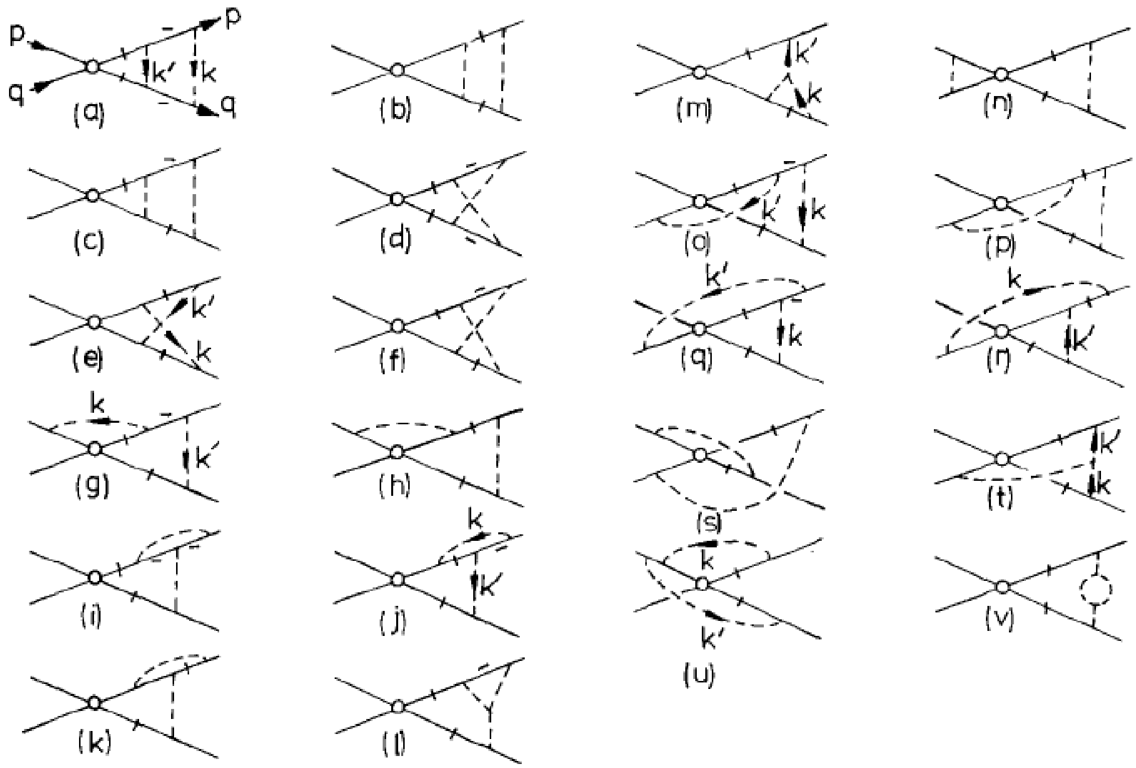


Figure 1. Graphs evaluated in Ref. [2] (see the first paper therein especially) in arriving at the result in (3) using Mueller's theorem for the respective cross section. The usual Landau-Bjorken-Cutkosky (LBC) [10] rules obtain so that a slash puts the line on-shell and a dash changes the iε-prescription; and, graphs that have cancelled or whose contributions are implied by those in the figure are not shown explicitly.

- SINCE BN VIOLATION VANISHES FOR $m_q \rightarrow 0$, MUST SET $m_q = 0$ IN ISR for $\mathcal{O}(\alpha_s^n),\ n \geq 2$: NOTE, $m_b \cong 5$GeV.

- SOURCE OF BN-VIOLATION: LOOK AT CONTRIBUTION OF DIAGRAMS (q-o) IN FIG.1:

$$A_{q-o} = \frac{1}{\beta^2}\int \frac{d^3k d^3k' 2k_z}{(k_z + k'_z + i\epsilon)(\beta^2 k_z^2 - \mathbf{k}^2)(\beta^2 k_z^2 - \mathbf{k'}^2 + i\epsilon)(k_z^2 + \epsilon^2)} \quad (58)$$

UV-REGULATED RESULT: USE THE REGULATOR $e^{-\mathbf{k}^2/\Lambda^2}$,

$\Rightarrow$

$$A_{q-o}|_{UV-reg} = \frac{4\pi^{n+1}(\Lambda^2)^{n-3}}{\beta^2}\left\{\frac{1}{(n-3)^2} + \frac{1}{2(n-3)}\ln\left(\frac{1+\beta}{1-\beta}\right)\right\}. \quad (59)$$

$\Rightarrow$

$$F_{nbn} = \frac{(1-\beta)(\ln\left(\frac{1+\beta}{1-\beta}\right) - 2\beta)}{\ln\left(\frac{1+\beta}{1-\beta}\right)} \quad (60)$$

IS FRACTION OF SINGLE-POLE TERM UN-CANCELLED.

- ANALYSIS IN PRD 78 (2008) 056001 $\Rightarrow$ REAL EMISSION IN A_{q-o} SATURATES SINGLE IR POLE.

- THUS, WE WRITE

$$\text{flux}\ \frac{d\sigma}{d^3Q} = \frac{-g^4\bar{H}}{64\pi^6} F_{nbn} A_{q-o}\Big|_{\mathfrak{R},\text{real rad., IR pole part}}, \quad (61)$$

WHERE FROM PRD78(2008)056001 WE HAVE

$$A_{q-o}\Big|_{\mathfrak{R},\text{real rad., IR pole part}} = \frac{4\pi^4}{\beta^2}\left(\frac{1}{2(n-3)}\ln\left(\frac{1+\beta}{1-\beta}\right)\right). \quad (62)$$

- APPLY QCD RESUMMATION TO REAL EMISSION IN $A_{q-o}\Big|_{\mathfrak{R}}$: APPLY IT TO THE FRACTION F_{nbn}; REMAINING $1-F_{nbn}$ CANCELLED BY VIRTUAL CORRECTIONS

- USING

$$d\hat{\sigma}_{\rm exp} = e^{\rm SUM_{IR}(QCD)} \sum_{n=0}^{\infty} \int \prod_{j=1}^{n} \frac{d^3 k_j}{k_j} \int \frac{d^4 y}{(2\pi)^4} e^{iy\cdot(p_1+q_1-p_2-q_2-p_X-\sum k_j)}$$

$$* \, e^{D_{\rm QCD}} \tilde{\bar{\beta}}_n(k_1,\ldots,k_n) \frac{d^3 p_2}{p_2^{\,0}} \frac{d^3 q_2}{q_2^{\,0}} \frac{d^3 p_X}{p_X^{\,0}}$$

(63)

WE GET

$$F_{nbn} A_{q-o}\big|_{\Re,\text{real rad., resummed}} = F_{nbn} \Re \frac{-i\pi^2}{\beta^2} \int d^2 k_\perp \int_0^{\sqrt{\epsilon}} dk_z F_{YFS}(\bar{\gamma}_q) e^{\bar{\delta}_q/2}$$

$$(\beta k_z)^{\bar{\gamma}_q} \left(-\ln(k_z + i\epsilon - \beta k_z) + \ln(k_z + i\epsilon + \beta k_z)\right)$$

$$\frac{1}{\beta^2 k_z^2 - \mathbf{k}^2} \frac{2k_z}{k_z^2 + \epsilon^2},$$

(64)

WHERE WE HAVE DEFINED

$$\bar{\gamma}_q = 2C_F \frac{\alpha_s(Q^2)}{\pi}(\ln(s/m^2) - 1) \quad (65)$$

$$\bar{\delta}_q = \frac{\bar{\gamma}_q}{2} + \frac{2\alpha_s C_F}{\pi}(\frac{\pi^2}{3} - \frac{1}{2}). \quad (66)$$

- USING THE SUBSTITUTION $k_z = \sqrt{\epsilon}\bar{k}_z$, WE HAVE

$$F_{nbn}A_{q-o}|_{\Re,\text{real rad., resummed}} = F_{nbn}\Re\frac{-i\pi^2\epsilon^{\frac{\bar{\gamma}_q}{2}}}{\beta^2}\int d^2k_\perp \int_0^1 d\bar{k}_z F_{YFS}(\bar{\gamma}_q)e^{\bar{\delta}_q/2}$$
$$(\beta\bar{k}_z)^{\gamma_q}\left(-\ln(\bar{k}_z + i\sqrt{\epsilon} - \beta\bar{k}_z) + \ln(\bar{k}_z + i\sqrt{\epsilon} + \beta\bar{k}_z)\right)$$
$$\frac{1}{-(1-\beta^2)\epsilon\bar{k}_z^2 - \mathbf{k}_\perp{}^2}\frac{2\bar{k}_z}{\bar{k}_z^2 + \epsilon}. \quad (67)$$

THE RHS OF THIS LAST EQUATION VANISHES AS $\epsilon \longrightarrow 0$, REMOVING THE VIOLATION OF BLOCH-NORDSIECK CANCELLATION IN (56).

CONCLUSION:

- RESUMMATION CURES LACK OF BN CANCELLATION IN MASSIVE QCD

MC Realization: IR-Improved Kernels in HERWIG6.5 $\Rightarrow$ HERWIRI1.0(31)

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

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

HERWIG6.5 $\Rightarrow$ HERWIRI1.0(31)

MC@NLO/HERWIG6.5 $\Rightarrow$ MC@NLO/HERWIRI1.0(31)–(SF,BW)

  - Leave Hard Processes Alone for the Moment:

    In progress (SY,BFLW,MH,SM,SJ)– include YFS synthesized EW modules from Jadach et al. MC's for HERWIG6.5,++ hard processes $\Rightarrow$ HERWIRI2.0.

  - ISSUE: CTEQ and MRST BEST(after 2007) Str. 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

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

⇒

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

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

Finally

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

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

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

$\Rightarrow$

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

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

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

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

and Ei is the exponential integral fn.

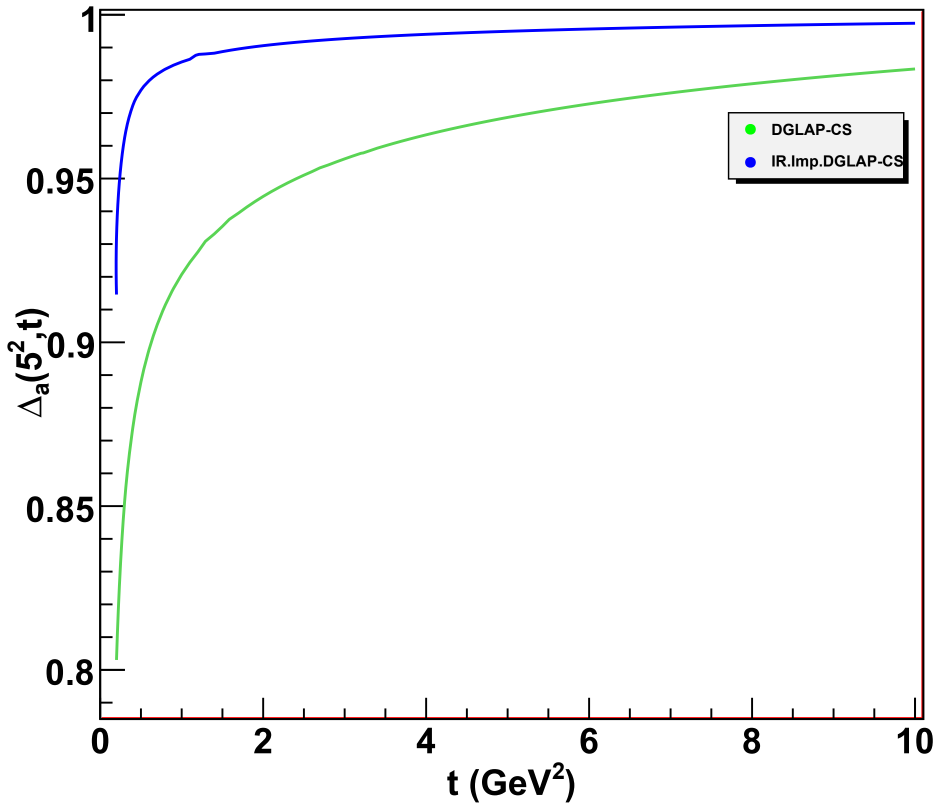


Figure 1: Graph of $\Delta_a(Q^2,t)$ for the DGLAP-CS and IR.Imp.DGLAP-CS kernels (76, 85)

RESULTS

We have new results for IR-Improved Showers in HERWIG6.5 $\equiv$ HERWIRI1.031:

we compare the z-distributions, p_T-dist. etc., of the IR-Improved and usual DGLAP-CS showers in the following f gs., and show MC@NLO interface

NOTE: SIMILAR RESULTS FOR PYTHIA and HERWIG++ IN PROGRESS.

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

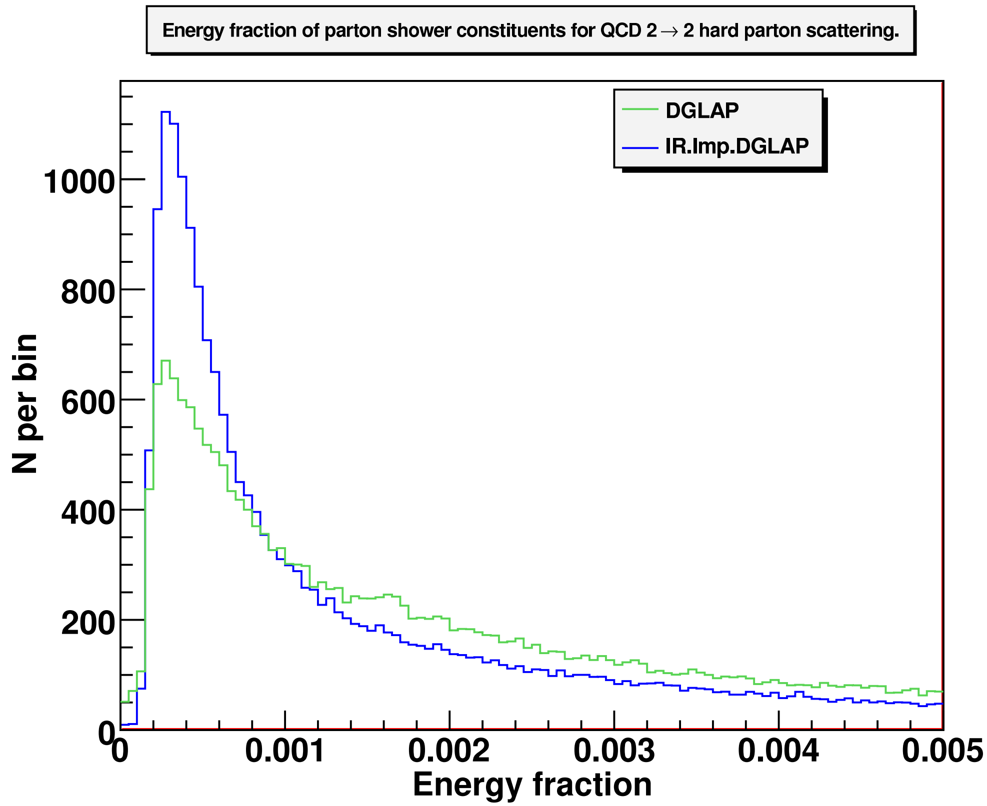


Figure 2: The z-distribution(ISR parton energy fraction) shower comparison in HERWIG6.5.

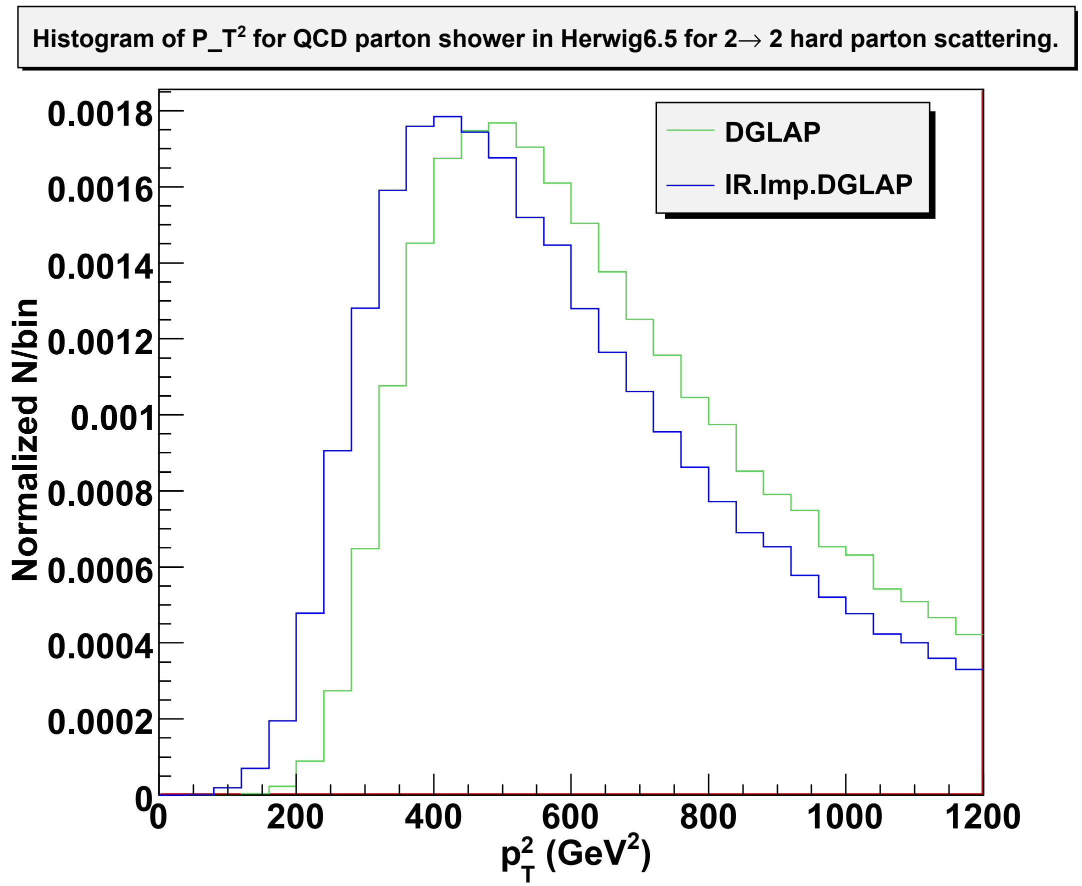


Figure 3: The P_T^2-distribution (ISR parton) shower comparison in HERWIG6.5.

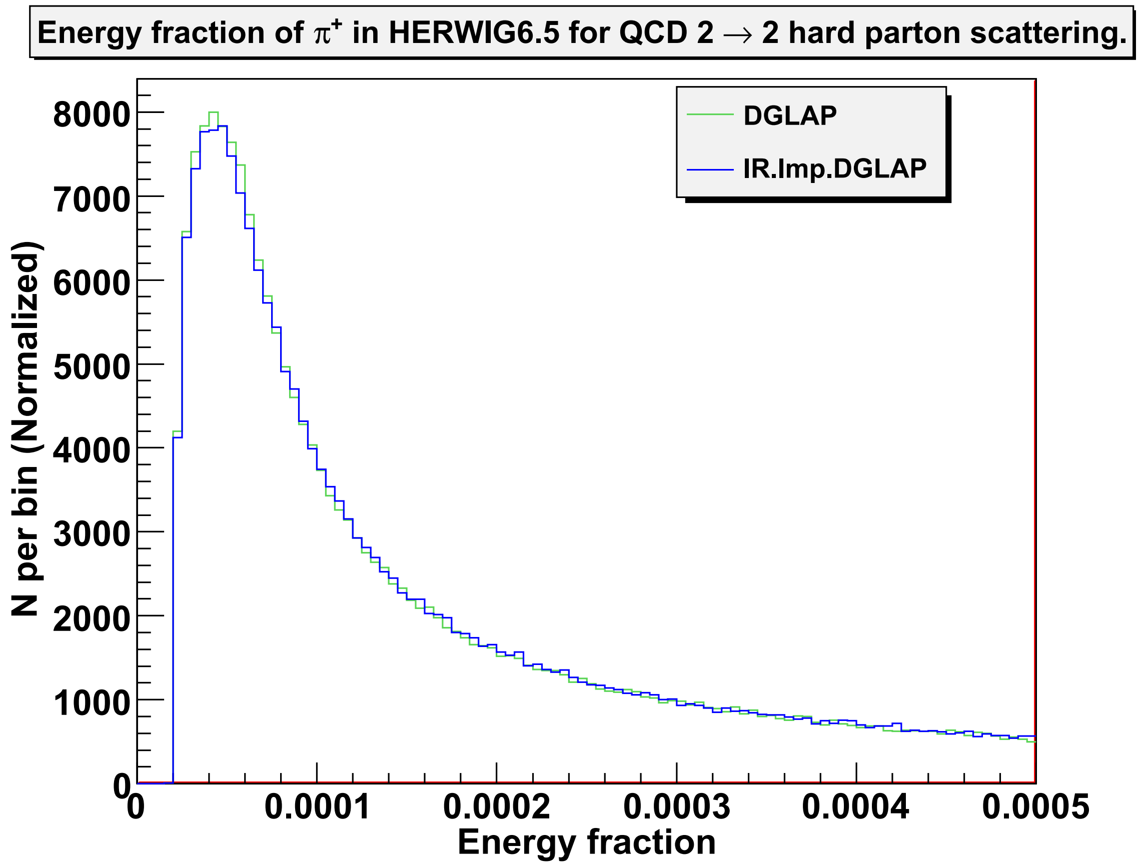


Figure 4: The π^+ energy fraction distribution shower comparison in HERWIG6.5.

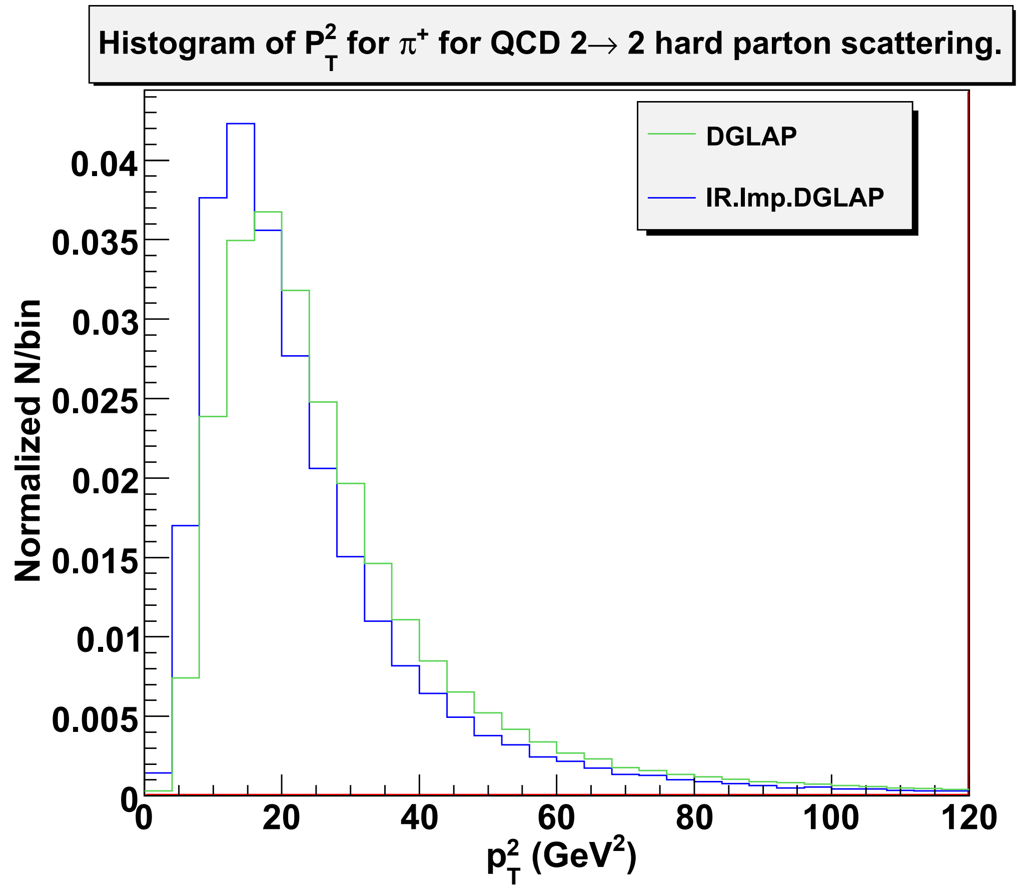


Figure 5: The π^+ P_T^2-distribution shower comparison in HERWIG6.5.

- **Single Z-production at LHC**

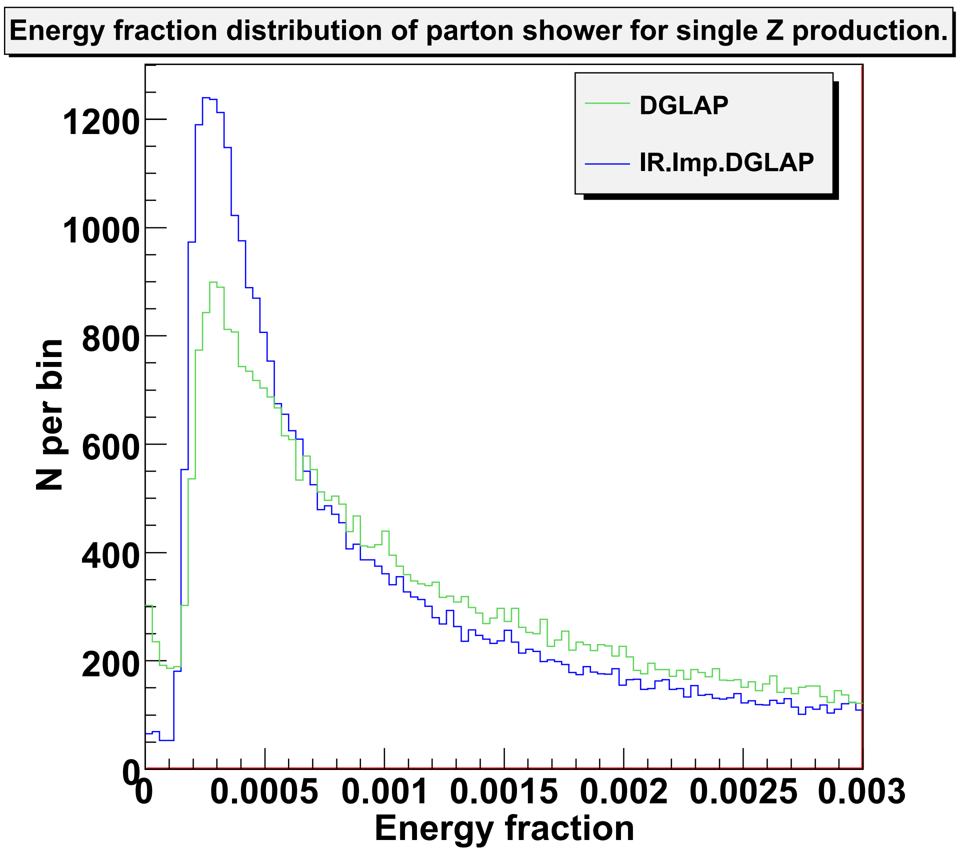


Figure 6: The z-distribution(ISR parton energy fraction) shower comparison in HERWIG6.5.

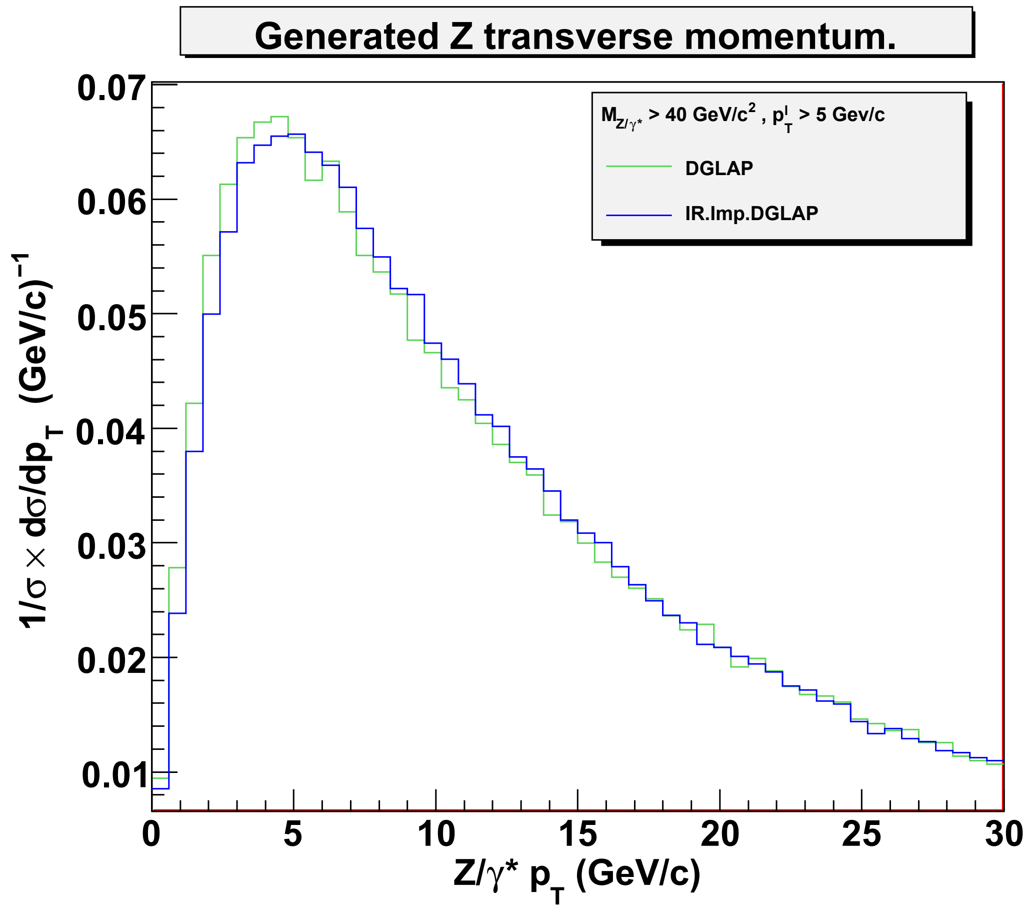


Figure 7: The Z p_T-distribution(ISR parton shower effect) comparison in HERWIG6.5.

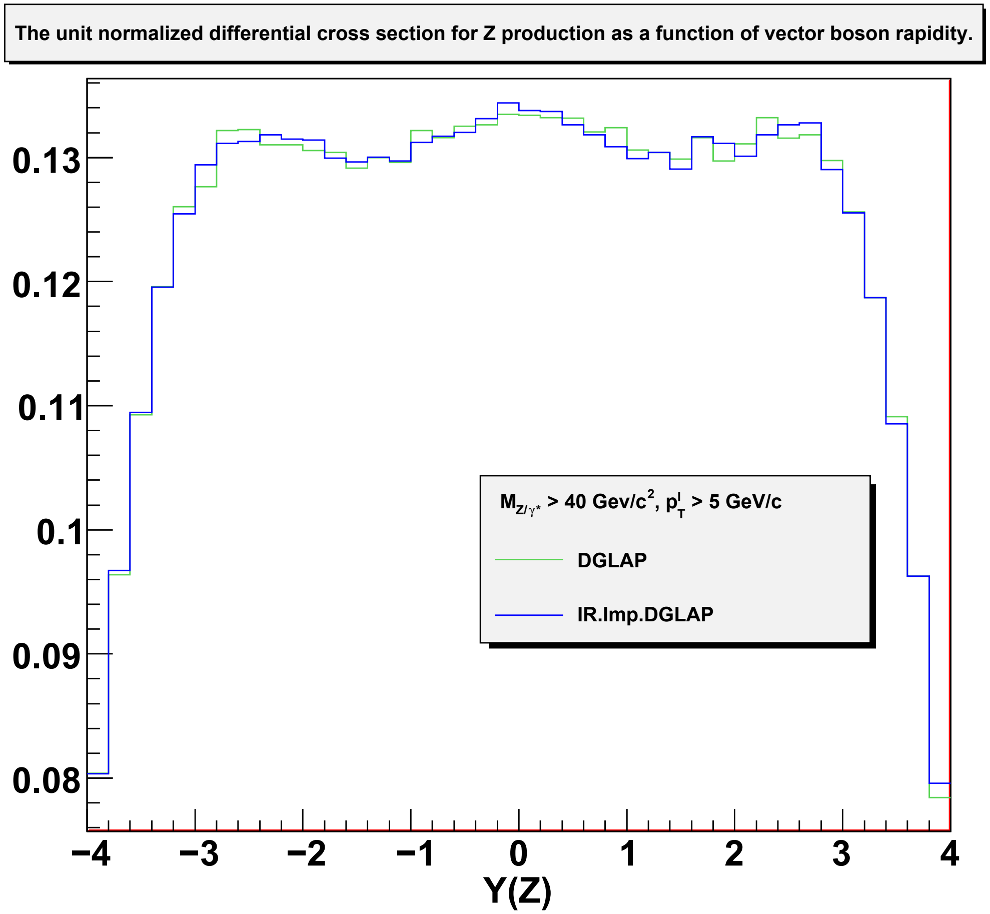


Figure 8: The Z rapidity-distribution(ISR parton shower) comparison in HERWIG6.5.

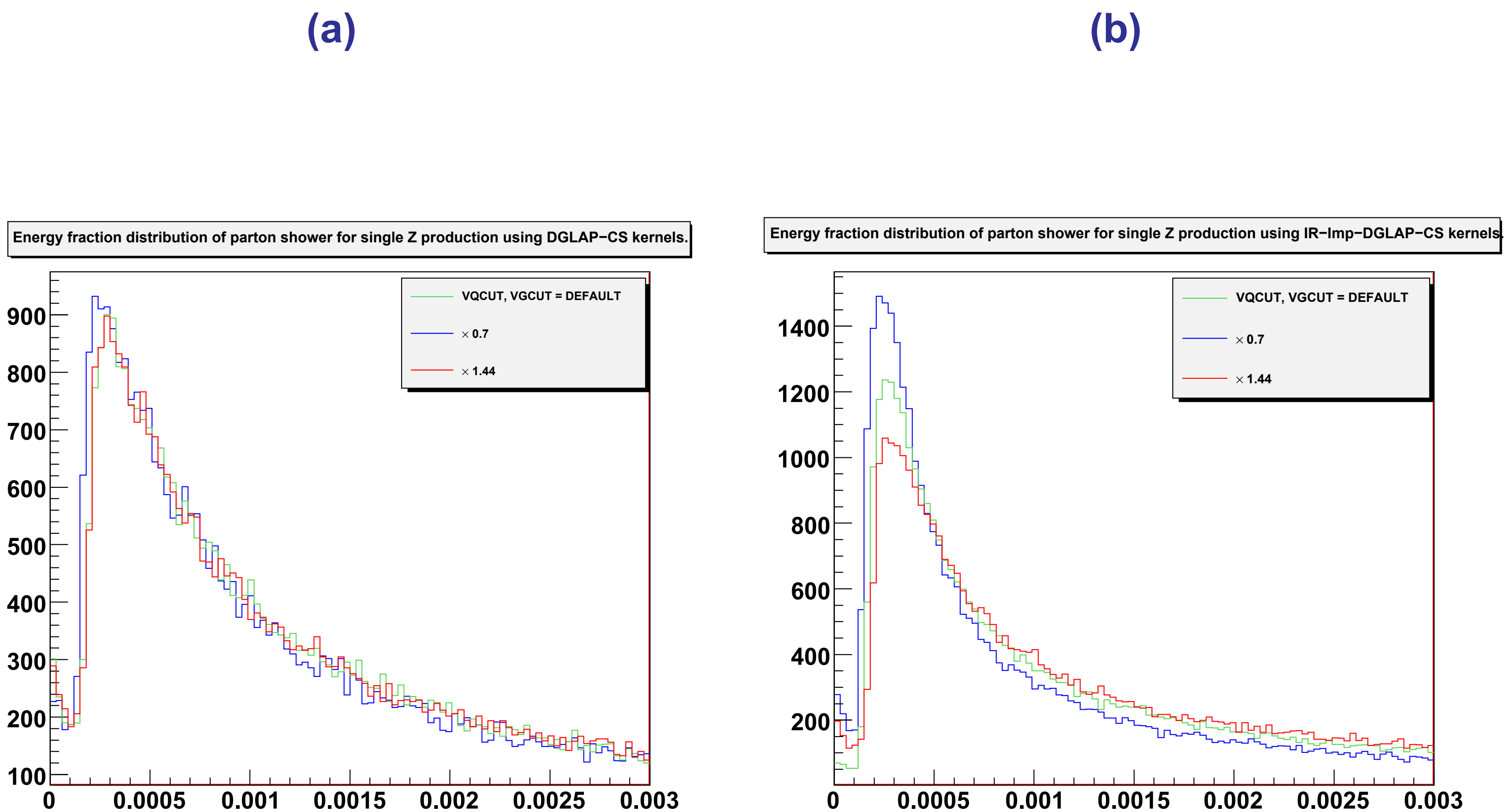
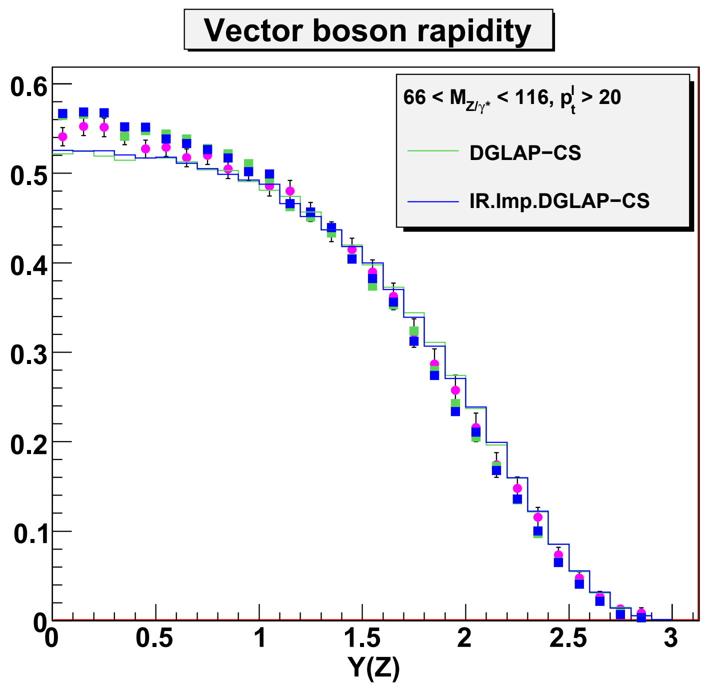


Figure 9: IR-cut-off sensitivity in z-distributions of the ISR parton energy fraction: (a), DGLAP-CS (b), IR-I DGLAP-CS – for the single Z hard subprocess in HERWIG-6.5 environment.

COMPARISON WITH DATA NOW FOLLOWS

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

(a) (b)



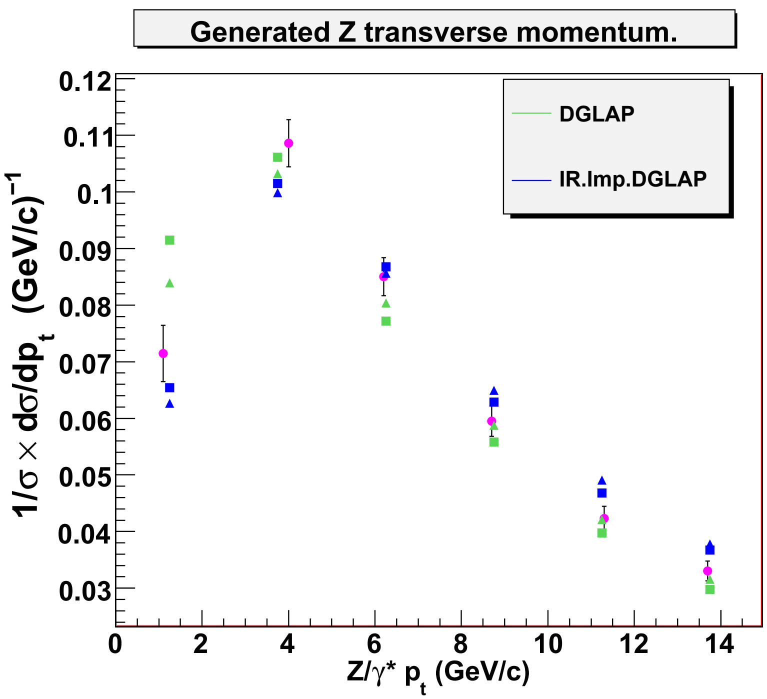


Figure 10: Comparison with FNAL data: (a), CDF rapidity data on (Z/γ^*) production to e^+e^- pairs, the circular dots are the data, the green(blue) lines are HERWIG6.510(HERWIRI1.031); (b), D0 p_T spectrum data on (Z/γ^*) production to e^+e^- pairs, the circular dots are the data, the blue triangles 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.

- For the CDF rapidity data, HERWIRI1.031 is closer to the data than is HERWIG6.510 (1.54 vs 1.77 for χ^2/d.o.f. resp.); for MC@NLO/HERWIRI1.031 and MC@NLO/HERWIG6.510 the χ^2/d.o.f are 1.42 and 1.40 resp., both are within 10% of the data $\Rightarrow$ Need NNLO level, in progress.
- For the D0 p_T data, HERWIRI1.031 gives a better f t to the data compared to HERWIG6.5 for low p_T, for $p_T < 12.5$GeV, the χ^2/d.o.f. are $\sim$ 2.5 and 3.3 respectively - 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 f xed order in perturbation theory. We see that the MC@NLO $\mathcal{O}(\alpha_s)$ corrections improves χ^2/d.o.f. – MC@NLO/HERWIRI1.031 has better agreement in soft regime.

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: HERWIRI1.0(31) (IR-IMPROVED HERWIG6.5)
- COMPARISON WITH THEORY ENCOURAGING: SOFTER SPECTRA, MORE ROBUSTNESS TO CUTS, ETC. – $\Delta\sigma_{Shower}$ IN PLAY
- COMPARISON WITH DATA IMMINENT – EXPERIMENTALISTS WELCOME
- IMPLEMENTATION IN PYTHIA, HERWIG++ IN PROGRESS
- IMPLEMENTAION 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