HERWIRI: Progress on a Precision Event Generator for W and Z Production at the LHC

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W and Z Production at the LHC

Vector Boson Production will be an important process at the LHC:

- Precision luminosity measurement (1%).
- Precision EW parameter measurements
- Constraints on PDFs via Z/W rapidity.
- Important for detector calibration.
- New physics searches: Z' predicted by various SM extensions – few TeV range accessible.

Precision Event Generator

- An event generator is needed at 1% precision.
- The present best event generators incorporate NLO QCD with a parton shower:

MC@NLO (Frixione, Webber), POWHEG (Nason)

- NNLO QCD is available, but not interfaced to a shower: Vrap (Anastasiou, Dixon, Melnikov, Petriello) and FEWZ (Melnikov, Petriello).
- Electroweak corrections cannot be neglected.

  [≈ 0.3% to 4%, depending on cuts and process]
- Details: PHENO LHC2 (Pyle 121, 4:45 Tues.)

Existing Shower Generators

- Traditionally, W and Z production have been calculated using a tree-level matrix element for the hard process, coupled with a shower generator for multiple-gluon emission in the initial state. These are packaged with hadronization routines, PDFs, etc needed to generate a complete event.

  HERWIG, PYTHIA, ISAJET, SHERPA

- **MC@NLO** & **POWHEG** extend HERWIG with an NLO hard process, matched to the shower.

QCD $\otimes$ QED Exponentiation

- Our proposal is based on a simultaneous expontiation of QCD and QED radiative corrections
- Motivation: successful application of YFS exponentiation in BHLUMI, KKMC, …
  - DeLaney et al, Phys. Rev. D52, 108 (1995)
  - Glosser et al, Mod. Phys. Lett A19, 2113 (2004)
  - (many more – with references in the following)
  - Ward et al, ICHEP-2008 arXiv:0810.0723

Electroweak Corrections

- Electroweak corrections have been added in several ways:
- **PHOTOS** is an add-on generator which adds multi-photon emission to final state particles using exponentiation.
- **HORACE** combines exact $\mathcal{O}(\alpha)$ EWK corrections with a QED parton shower.
- PDFs are available (MRST2004) that include QED in the DGLAP evolution.

Electroweak Corrections

- Mixed $\mathcal{O}(\alpha_s \alpha)$ EWK corrections will be needed to reach the 1% level. These are not yet implemented, but we have calculated approximate mixed corrections using PHOTOS + MC@NLO and found EWK contributions can reach 2% or more for Z or W (typical cuts).

  Adams, Halyo, Yost, JHEP 05 (2008) 062, arXiv:0802.3251

  Adams, Halyo, Yost, Zhu, JHEP 09 (2008) 113, arXiv:0808.0758

- The EWK contribution becomes more important in TeV-scale new physics studies.

HERWIG + QED Exponentiation

- Proposal: Add QED radiation to HERWIG in the same manner as it is added in the KKMC, using YFS exponentiation.

  [Jadach, Ward, Was, PRD63, 113009 (2001), …]
- This builds on a set of radiative corrections developed to high precision for LEP physics over a course of at least 15 years.
- The YFS structure is conducive to building a multiplicative weight, good for stable calculations. Good soft/collinear behavior.

HERWIG + QED Exponentiation

- The program has been called **HERWIRI** –

High Energy Radiation With IR Improvement

The name is an umbrella covering several aspects of QCD $\otimes$ QED exponentiation combined with the HERWIG parton shower.

This particular subset of corrections (QED exponentiation only), is called **HERWIRI 2.0**.

Integration of the KKMC YFS3 module with HERWIG began last year, and should finish this summer. [Halyo, Hejna, Ward, Yost]

HERWIG + QED Exponentiation

- The programs have been merged, but some important details remain.
- The YFS3 routines were for e^+e^- scattering and must be modified for ISR with quarks (charge, mass parameters, color factor).
- The weights must be matched: both programs include a Born factor, and both generate an angle for the final state leptons in their CM frame. This can be handled with a multiplicative reweighting factor.

KKMC Radiative Corrections

- KKMC uses a combined expansion in powers of α and big logarithms ($L = \ln s/m_f^2$):

	LL	NLL	NNLL	N^{3}LL
LO	1			
NLO	αL	α		
NNLO	$\alpha^2 L^2$	$\alpha^2 L$	α^2	
N^{3}LO	$\alpha^3 L^3$	$\alpha^3 L^2$	$\alpha^3 L$	α^3

0.5 – 1 %   0.1 – 0.5%   0.01 – 0.05%

Errors shown are with exponentiation. Without it, they are 2-5 times more.

QED Exponentiation in KKMC

- The QED corrections in KKMC include YFS exponentiation. This is a re-ordering of the perturbation series in which certain terms are summed to all orders, and the residuals are calculated exactly to the order needed.
- The exponentiation is done exclusively, before integrating over phase space, for the cross-section (EEX) or amplitude (CEEX).
- We are adapting the YFS3 module, which implements EEX for ISR and FSR photons.

YFS-Exponentiated QED

For lepton pair production with FSR,

$$e^-(p_1)\,e^+(p_2) \to l(q_1)\,\bar{l}(q_2) + n\gamma(k_1,\ldots,k_n)$$

renormalization-group improved YFS theory organizes the cross section as follows:

$$d\sigma_{\exp} = \sum_{n=0}^{\infty}\frac{1}{n!}\int\frac{d^3q_1 d^3q_2}{q_1^0\; q_2^0}\prod_{j=1}^{n}\frac{d^3k_j}{k_j^0}\; e^{2\alpha Y(q_1,q_2,\kappa)}$$

YFS form factor.

κ = IR cutoff

$$\times \quad \int\frac{d4y}{(2\pi)^4}\, e^{iy\cdot\left(p_1+p_2-q_1-q_2-\sum_j k_j\right)+D(y;q_1,q_2,\kappa)}\quad \bar{\beta}\left(k_1,\ldots,k_n\right)$$

YFS residuals: Calculate to desired order (IR-finite)

YFS Exponentiation for QED

- YFS IR functions:

Soft Photons

Virtual Photons

$$Y(q_1,q_2,\kappa) = -\frac{Q_f^2}{8\pi^2}\int_{k^0>\kappa}\frac{d^3k}{k^0}\left(\frac{q_1}{q_1\cdot k}-\frac{q_2}{q_2\cdot k}\right)^2$$

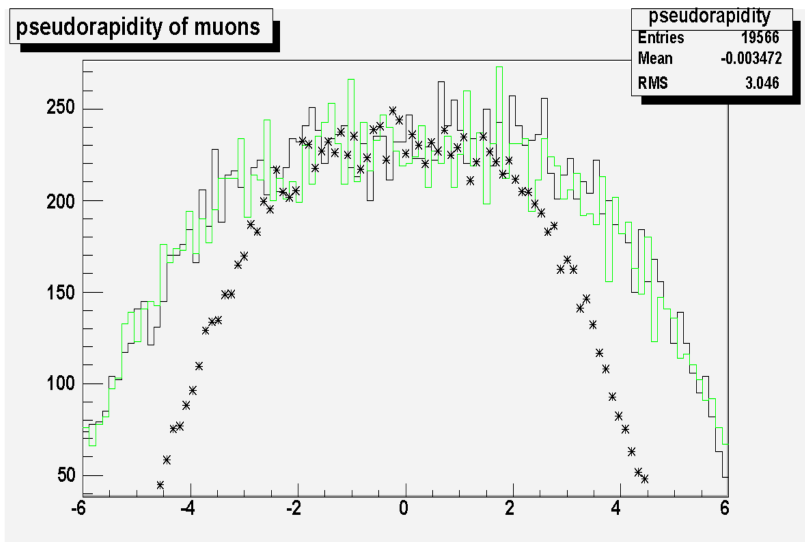
$$+\frac{Q_f^2}{8\pi^2}\mathrm{Re}\int\frac{d^4k}{k^2}\frac{i}{\pi}\left(\frac{2q_1-k}{(2q_1-k)\cdot k}-\frac{2q_2-k}{(2q_2-k)\cdot k}\right)^2$$

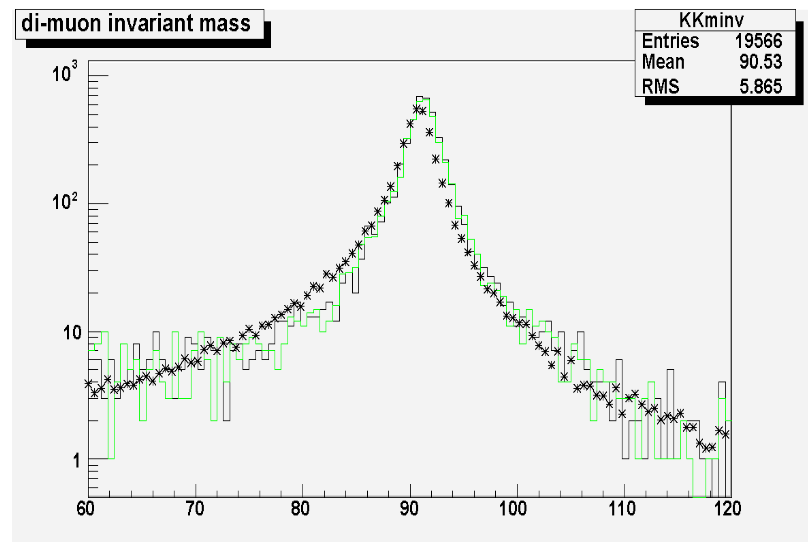
$$D(y;q_1,q_2,\kappa) = \frac{\alpha Q_f^2}{4\pi^2}\int\frac{d^3k}{k^0}\left(\frac{q_1}{q_1\cdot k}-\frac{q_2}{q_2\cdot k}\right)^2\left[e^{-iy\cdot k}-\theta(\kappa-k^0)\right]$$

The result is independent of the soft-photon cutoff κ.

Preliminary Distributions

- Comparisons with Horace





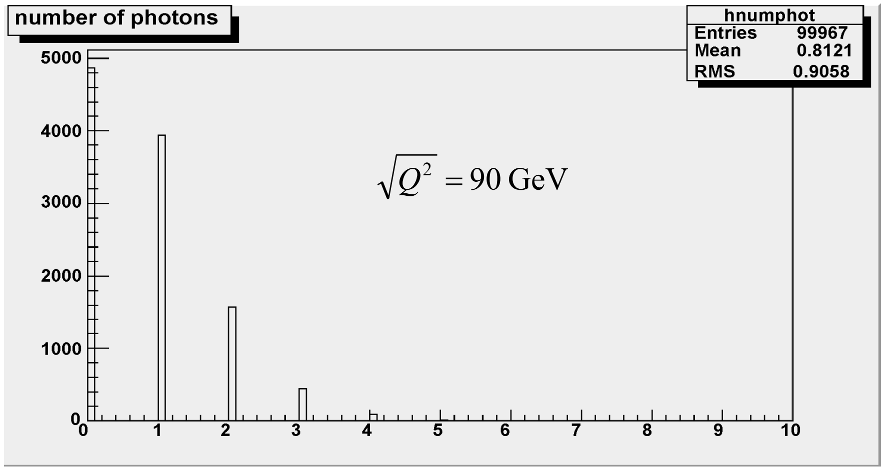
— HERWIRI2.0 — Horace 3.1 * HERWIG6.5

FSR only. Uncorrected weights

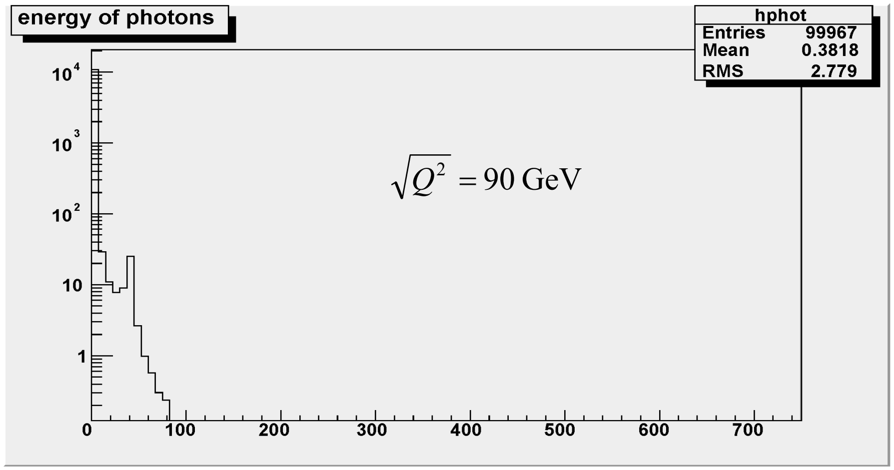
Generated Photons: Test Runs

Generated Photons in a fixed-Q^2 test run

Number of photons:



Total photon energy:



Next Steps

- HERWIRI 2.0 is partly a warm-up project for extending the MC implementation of simultaneous QCD $\otimes$ QED exponentiation to the case of mixed gluons and photons.
- The first real test of this will be merging the KKMC exponentiated QED radiation with MC@NLO.
- The extension to W processes is less straight-forward, since KKMC assumes a neutral boson. The same principles still apply.

QCD Exponentiation

- So far, we have discussed the beginnings of the construction of a much larger project, in which the QCD perturbative series is re-organized analogously to the QED series in YFS exponentiation.
- This is made possible by the fact that soft and virtual corrections still cancel, and can be represented by a QCD analog of the YFS form factor Y.

QCD Exponentiation

- Specifically, the gluon analog of the YFS Form factor is

$$Y_{\mathrm{QCD}}(q_1, q_2, \kappa) = -\frac{1}{8\pi^2}\int_{k^0<\kappa}\frac{d^3k}{k^0}\left\{C_F\left(\frac{q_1}{q_1\cdot k}-\frac{q_2}{q_2\cdot k}\right)^2 - \Delta C_S\frac{2p_1\cdot p_2}{(p_1\cdot k)(p_2\cdot k)}\right\}$$

$$+\frac{1}{8\pi^2}\mathrm{Re}\int\frac{d^4k}{k^2}\frac{i}{\pi}\left\{\left(\frac{2q_1-k}{(2q_1-k)\cdot k}-\frac{2q_2-k}{(2q_2-k)\cdot k}\right)^2\right.$$

$$\left.-\Delta C_S\frac{2(2q_1-k)\cdot(2q_2-k)}{[(2q_1-k)\cdot k][(2q_2-k)\cdot k]}\right\}$$

with $C_F = 4/3$, $\Delta C_S = -1$ (qq') or $-1/6$ ($q\bar{q}'$)

QCD Exponentiation

- The residuals are not automatically IR finite, because of non-abelian terms missed in the exponentiation. However, they still cancel in pairs, permitting an IR-finite definition of the β's at each order.
- The IR-finite β's can then be calculated to the desired order in perturbation theory.
- This re-organized perturbative series is completely equivalent to the standard one. Nothing has been added or taken away.

IR-Improved DGLAP Evolution

- As an application of the proposed QCD exponentiation, Ward has applied it to the DGLAP kernels, obtaining "IR-Improved" kernels.

[Ann. Phys. 323 (2008) 2147, PRD78 (2008) 056001]

- Standard evolution of NS structure function:

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

$$P_{qq}(z) = C_F\frac{1+z^2}{1-z}, \quad t = \log\left(\frac{\mu^2}{\mu_0^2}\right)$$

IR-Improved DGLAP Kernels

- But $1/(1-z)$ is requires regularization. The usual choice is a "+ distribution"

$$\left(\frac{1}{1-z}\right)_{+}=\frac{1}{1-z}\theta(1-z-\varepsilon)+\delta(z-1)\log\varepsilon$$

with $\varepsilon\to 0$. After adding virtual corrections,

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

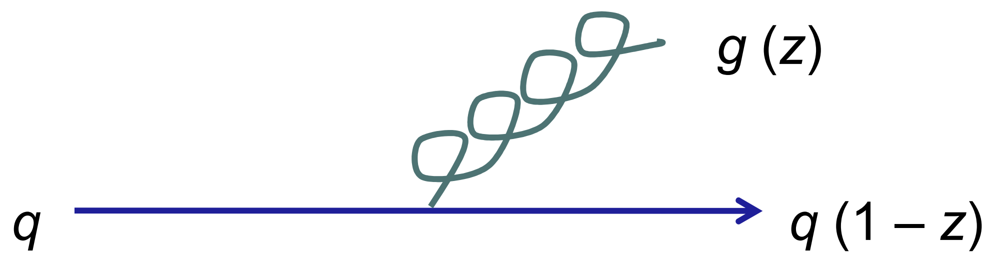
Mathematically, this is fine, but … how well does it represent real data? Can it be improved?

IR-Improved DGLAP Kernels

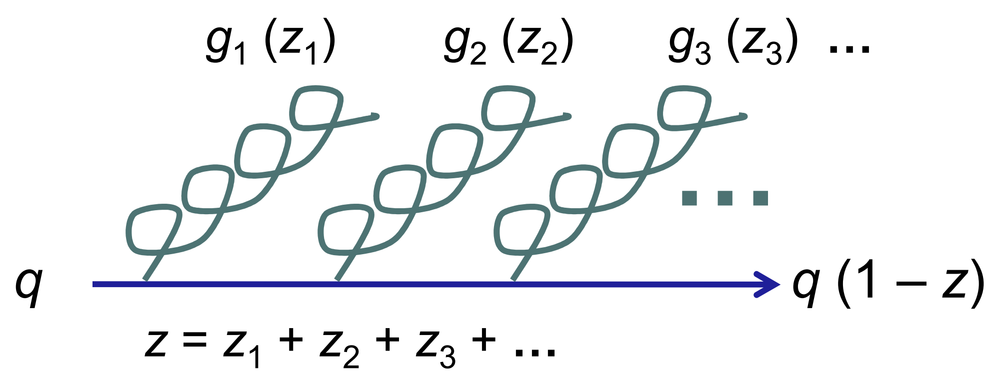
- In practice, ε has to be set to a finite value, giving a bizarre mathematical artifact:
  - The region where the distribution is most strongly peaked, $1 - \varepsilon < z < 1$, now has no contribution at all!
- This is compensated by a large negative integrable contribution from $z = 1$.
- Experience from LEP shows that such perturbative artifacts impair the precision, but this can be cured by exponentiation...

IR-Improved DGLAP Kernels

- A more reasonable behavior at $z \to 1$ can be obtained by exponentiation, replacing the standard



by a sum



IR-Improved DGLAP Kernels

- The modification can be calculated using YFS-style exponentiation, leading to [Ward]

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

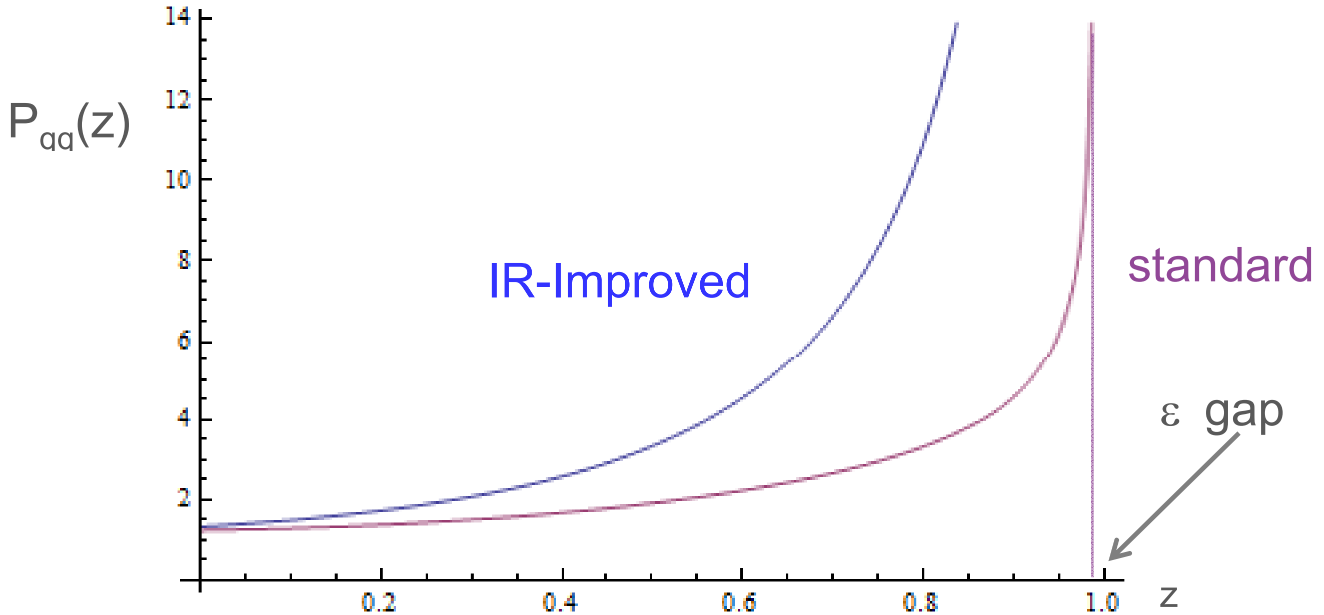
with

$$\gamma_q = \frac{C_F\alpha_s}{\pi}t = \frac{4C_F}{\beta_0}, \quad \beta_0 = 11 - \tfrac{2}{3}n_f\,, \quad \delta_q = \frac{\gamma_q}{2} + \frac{C_F\alpha_s}{\pi}\left(\frac{\pi^2}{3} - \frac{1}{2}\right)$$

$$f_q(\gamma_q) = \frac{2}{\gamma_q} - \frac{2}{\gamma_q+1} + \frac{1}{\gamma_q+2}\,, \quad F_{YFS}(\gamma_q) = \frac{e^{-0.5772\ldots\gamma_q}}{\Gamma(\gamma_q+1)}$$

IR-Improved DGLAP Kernels

- Both kernels agree at $z = 0$ and become large at $z \to 1$, but the exponentiated one has an integrable IR limit. This gives more realistic behavior for $z \to 1$ than the + function.



IR-Improved DGLAP Kernels

- Also, $P_{Gq}(z) = P_{qq}(1 - z)$ for $z < 1$ as in standard DGLAP theory
- Quark momentum sum rule: can verify

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

- The remaining standard kernels are

$$P_{GG}(z) = 2C_G \left(\frac{1-z}{z} + \frac{z}{1-z} + z(1-z) \right)$$

$$P_{qG}(z) = \frac{1}{2}\left(z^2 + (1-z)^2 \right) \qquad C_G = N_c = 3$$

IR-Improved DGLAP Kernels

- The exponentiated forms are

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

$$P_{qG}(z) = 2C_G F_{YFS}(\gamma_G)\, e^{\delta_G/2} \Big\{ z^{\gamma_G}(1-z)^2 + z^2(1-z)^{\gamma_G} \Big\}$$

with

$$\gamma_G = \frac{C_G \alpha_s}{\pi} t = \frac{4C_G}{\beta_0}, \qquad \delta_G = \frac{\gamma_G}{2} + \frac{C_G \alpha_s}{\pi}\left(\frac{\pi^2}{3} - \frac{1}{2}\right)$$

$$f_G(\gamma_G) = \frac{1}{(\gamma_G + 1)(\gamma_G + 2)}\left(\frac{n_f}{C_G}\frac{1}{(\gamma_G + 3)} + \frac{2}{\gamma_q} + 1\right) + \frac{1}{(\gamma_G + 3)(\gamma_G + 4)}\left(\frac{1}{(\gamma_G + 2)} + \frac{1}{2}\right)$$

MC Implementation: HERWIRI 1

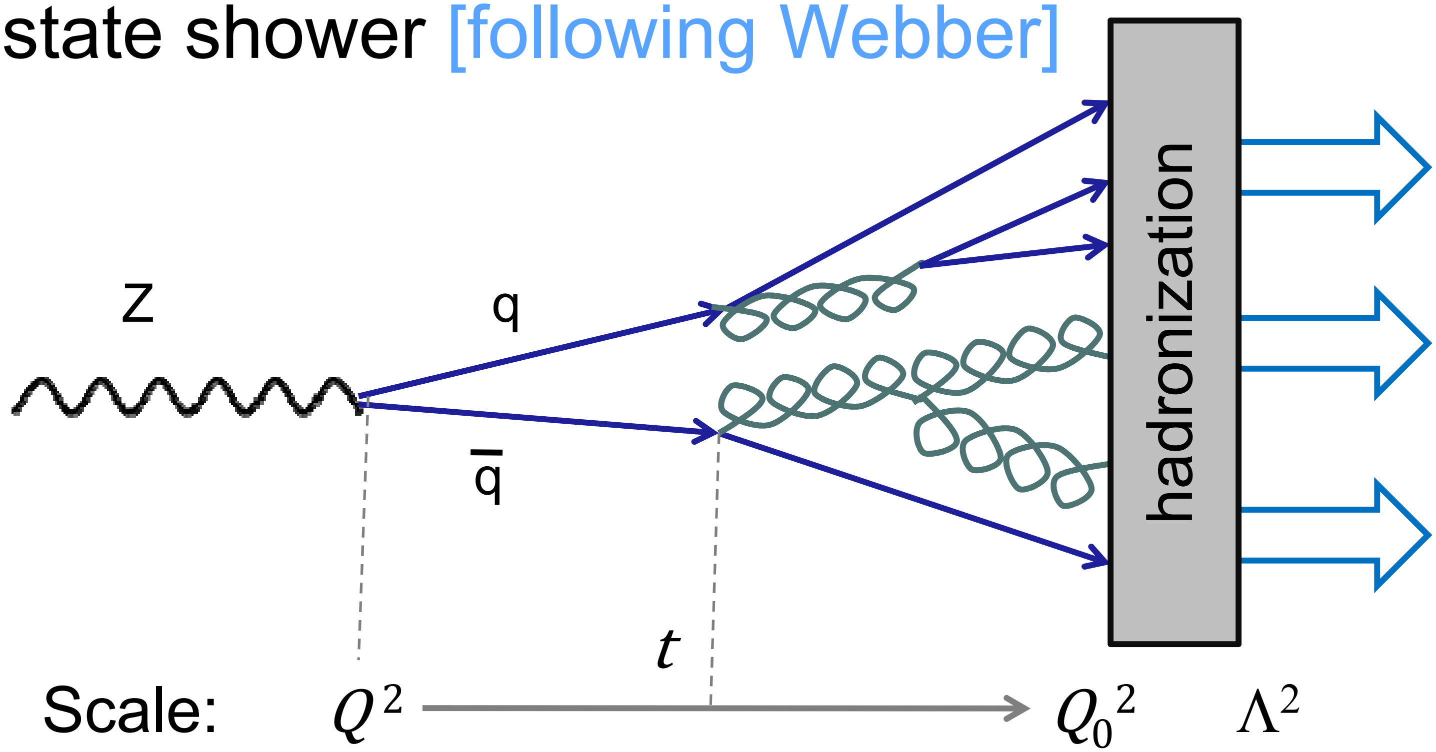
- **HERWIRI 1.0** implements the exponentiated Kernels in HERWIG6.5 without modifying the hard cross section. [Joseph, Majhi, Ward, Yost]
  - Download: http://thep03.baylor.edu/software
- Functions modified in HERWIG:

  HWBRAN, HWBSUD, HWBSU1

  HWBSU2, HWBSUG, HWIGIN
- We will take a quick look at the modified $q\bar{q}$ branching in HWBRAN.

MC Implementation

- The effect of the new kernels can be illustrated by looking at parton fragmentation in a final-state shower [following Webber]



MC Implementation

- Consider a parton splitting $a \to b + c$.

The probability $\Delta_a(t, Q_0^2)$ that the probability that parton a will not branch *below* virtuality t evolves according to the splitting function:

$$\frac{d\Delta_a(t,Q_0^2)}{dt} = -\frac{\Delta_a(t,Q_0^2)}{t}\sum_b \int_0^1 dz\,\frac{\alpha_s(t)}{2\pi}P_{ba}(z)$$

Solution:

$$\log\Delta_a\left(t,Q_0^2\right) = -\int_{Q_0^2}^{t}\frac{d\tau}{\tau}\sum_b \int_0^1 dz\,\frac{\alpha_s(\tau)}{2\pi}P_{ba}(z)$$

MC Implementation

- The probability of not branching at higher virtuality than t is can be determined from

$$\Delta_a\left(Q^2,t\right)\Delta_a\left(t,Q_0^2\right)=\Delta_a\left(Q^2,Q_0^2\right)$$

- The probability $\Delta_a(Q^2,t)$ takes values in [0,1], so the virtuality t can be generated with the correct distribution by generating a uniform random variable $R\in[0,1]$ and solving $R=\Delta_a(Q^2,t)$ for t…

MC IMPLEMENTATION

- Using $\alpha_s(t) = \dfrac{2\pi}{\beta_0 \log(t/\Lambda)}$ and the standard P_{qG} gives

$$\Delta_a\left(Q^2, t\right) = \left(\frac{\log(t/\Lambda^2)}{\log(Q^2/\Lambda^2)}\right)^{\frac{2}{3\beta_0}}, \qquad t = \Lambda^2\left(\frac{Q^2}{\Lambda^2}\right)^{R^{3\beta_0/2}}$$

- Repeating this with IR-Improved kernels gives

$$\log \Delta_a\left(Q^2, t\right) = F(t) - F(Q^2)$$

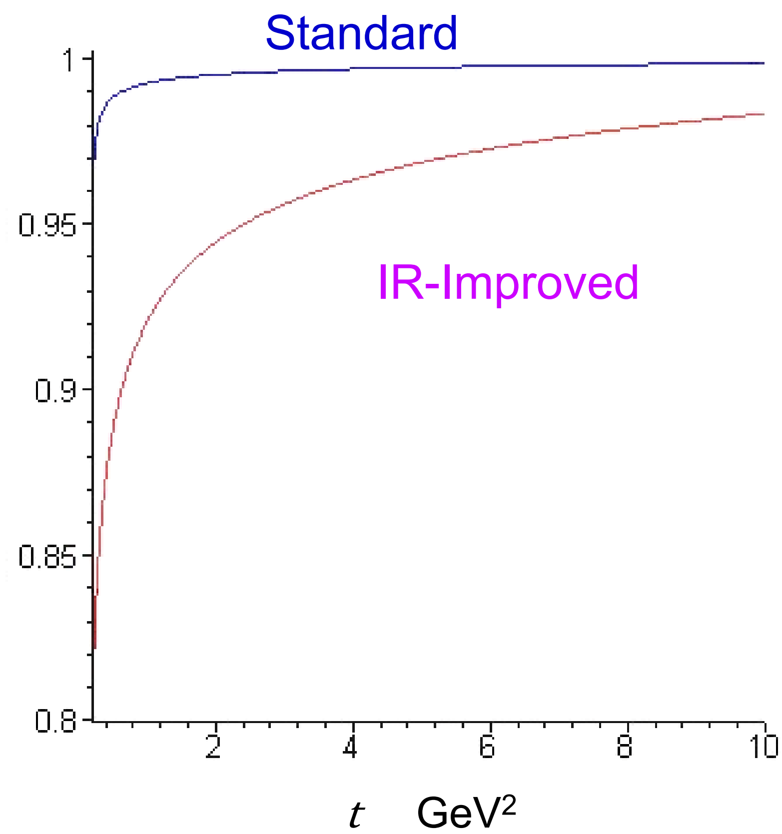
with

$$\mathrm{Ei}(x) = \int_{-\infty}^{x} \frac{e^t}{t} dt$$

$$F(Q^2) = \frac{4F_{YFS}(\gamma_G)\, e^{\gamma_G/4}}{\beta_0(\gamma_G+1)(\gamma_G+2)(\gamma_G+3)} \quad \mathrm{Ei}\left(1, \frac{8.369604402}{\beta_0 \log\left(Q^2/\Lambda^2\right)}\right)$$

MC Implementation

- Comparison of $\Delta_a(Q^2,t)$ at Q^2 = (25 GeV)^2 :

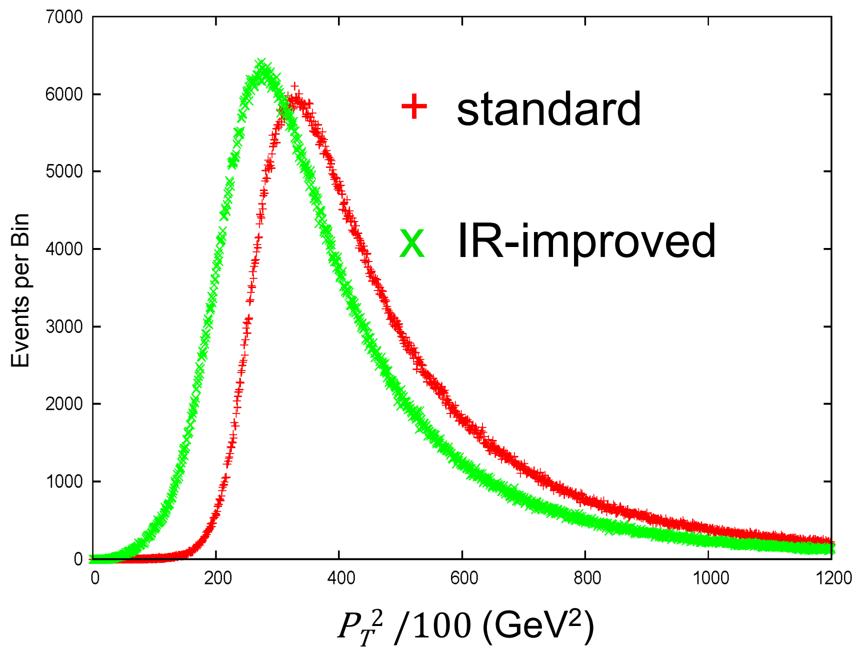


The two expressions agree to within a few percent over most of the range.

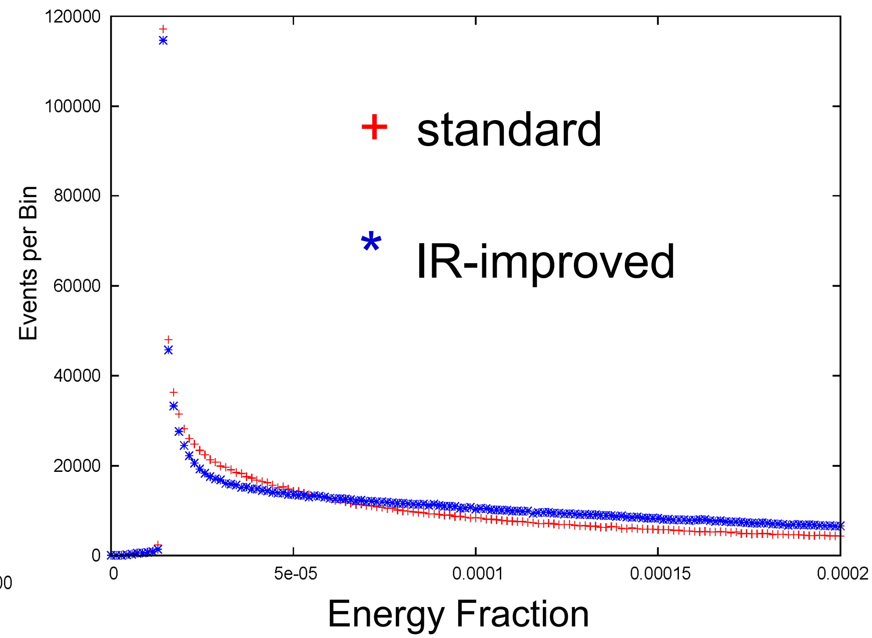
Experiment will decide which is better, when adequate precision is reached.

Effect on 2 → 2 Parton Scattering

Parton Transverse Momentum Distribution



Parton Energy Fraction Distribution



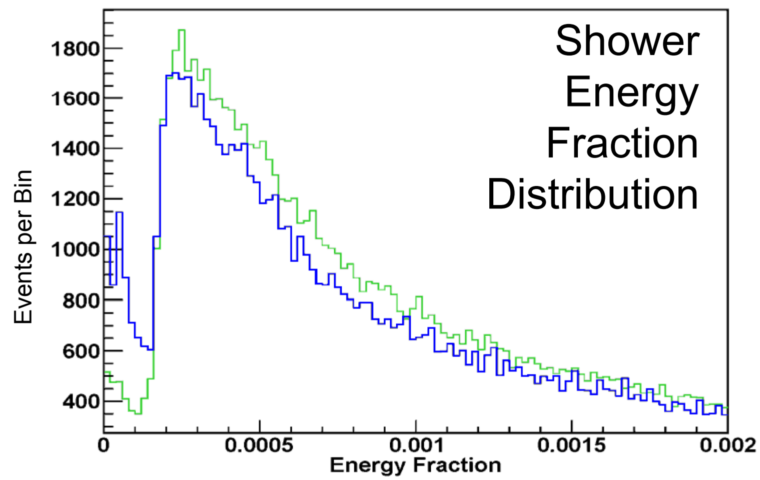
Generic 2 → 2 Parton Process at 14 TeV CMS Energy

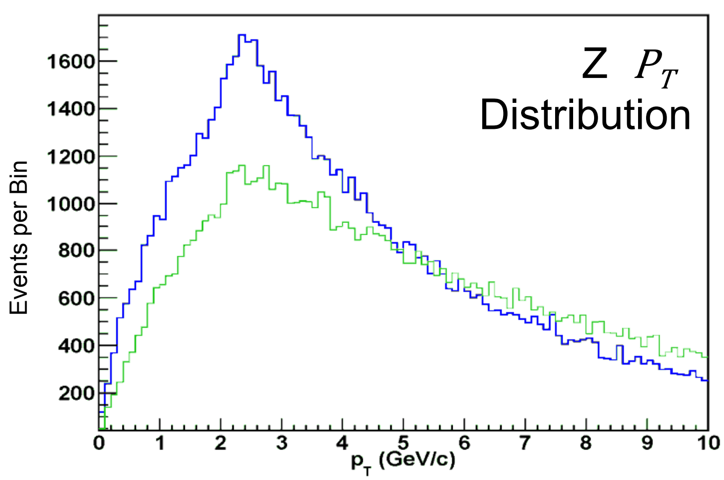
Effects in Z Production

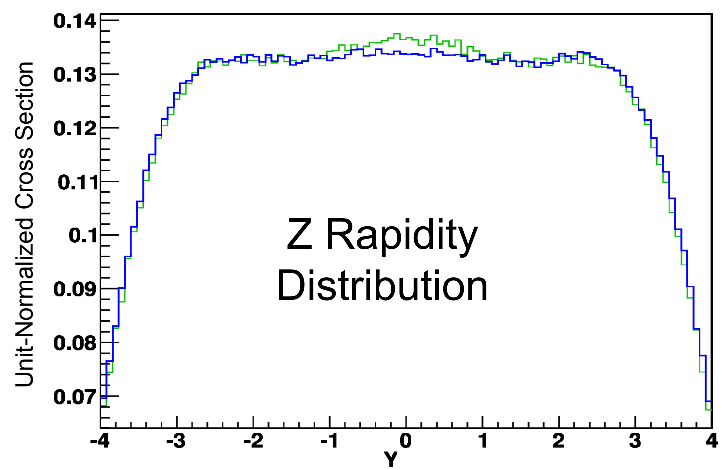
Standard

IR-Improved

Cuts: $M_{\mu\mu}$ > 40 GeV
$P_{T\mu}$ > 5 GeV
$|\eta_\mu|$ < 50





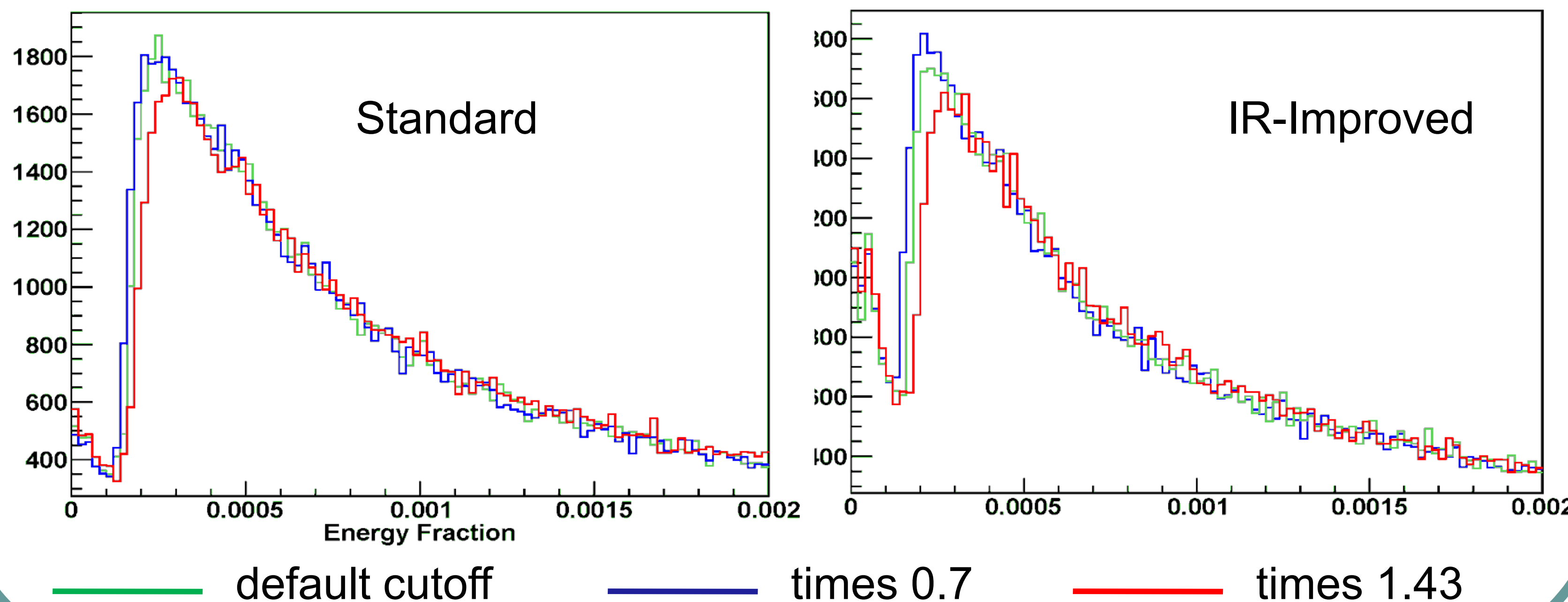


IR Cut-off Dependence

- HERWIG requires an IR cut-off to separate soft and virtual effects, and as required by the + functions in the DGLAP kernels.
- HERWIRI allows these parameters to be chosen arbitrarily close to zero in the kernels.
- We checked the cut-off dependence by multiplying the default values of quark and gluon virtual mass cutoffs `VQCUT` (= 0.48), `VGCUT` (= 0.1) by 0.7 and 1.43.

IR Cut-off Dependence

- We show the cutoff dependence of the parton energy fraction distribution for Z production for the standard and modified kernels.



Conclusions

- I have described two early stages in the construction of a fully exclusive MC program for vector boson production based on simultaneous QCD $\otimes$ QED exponentiation.
  - **HERWIRI 1.0**: HERWIG Shower + IR-improved DGLAP kernels (available now)
  - **HERWIRI 2.0**: HERWIG Shower + YFS-exponentiated QED / EWK corrections (soon)
- Beyond this, mixed QCD/EWK corrections will need to be incorporated. In the next stages, we anticipate continuing to build on existing successful structures, incorporating MC@NLO and KKMC structures into the QCD $\otimes$QED framework.