KKMChh: Matching CEEX Photonic ISR to a QED-Corrected Parton Shower

S.A. Yost

The Citadel

July 7, 2022

KKMC-hh is a collaboration with S. Jadach, B.F.L. Ward, Z. Wąs, and A. Siodmok

Computational resources provided by IFJ-PAN, Kraków and The Citadel.

KKMChh for Precision EW Phenomenology

- KKMC was developed for precision Z **boson** phenomenology in e^+e^- collisions, $e^+e^- \to Z/\gamma^* \to f\bar{f} + n\gamma$ including exact $O(\alpha), O(\alpha^2 L)$ ISR, FSR, and IFI photonic corrections with soft photon exponentiation implemented at the amplitude level (CEEX).
- $O(\alpha)$EW corrections were included via an independent DIZET6.45 module, whose form factors must be tabulated before running KKMC.
- Collision energies up to 1TeV are supported, with a LEP2 precision tag of 0.2%
- The original KKMC has been upgraded and transcoded to C++ and relabeled KKMCee 5.00.00. See arXiv:2204.11949.
- This talk focuses on the hadronic branch, KKMChh for $pp \to Z/\gamma^* \to l\bar{l} + n\gamma$ based on the same physics adapted to $q\bar{q}$ initial states.
- For now, the parton shower is HERWIG6.5, but a major upgrade to HERWIG7 is in progress. Today's examples will be without the shower.

Effect of ISR on the Parton Luminosity

To understand the effect of ISR more simply, we can set $\sigma_{q\bar{q}}^{\mathrm{Born}}(z\hat{x}s)\langle W_{\mathrm{MC}}\rangle$ to 1 for now and look at the QED-corrected joint parton luminosity function for each quark individually ,

$$xL_{q\bar{q}}^{\mathrm{QED}}(xs) \equiv \int d\hat{x}dz_\gamma \int dx_q dx_{\bar{q}}\, \delta\left(\hat{x} - x_q x_{\bar{q}}\right) f_q\left(x_q, \hat{x}s\right) f_{\bar{q}}\left(x_{\bar{q}}, \hat{x}s\right) \rho_{\mathrm{ISR}}(1 - z,\, \hat{x}s)$$

$$= \int_0^{1-x} dv \int_x^1 d\hat{x}\, \delta\left(\hat{x} - \frac{x}{1-v}\right) \left[\hat{x}L_{q\bar{q}}(\hat{x}s)\right] \left[(1-v)\rho_{\mathrm{ISR}}^{(0)}(v, \hat{x}s)\right]$$

in terms of the luminosity function $L_{q\bar{q}}(\hat{x}s)$ at $\hat{x} = x(1-v)$ and with YFS ISR radiator

$$\rho_{ISR}^{(0)}(v,\, \hat{x}s) = F_{\mathrm{YFS}}(\gamma)\gamma v^{\gamma-1}, \quad F_{\mathrm{YFS}}(\gamma) = \frac{e^{-C_E\gamma}}{\Gamma(1+\gamma)}\ , \quad \gamma = \gamma_{\mathrm{ISR}}\left(\hat{x}s, Q_q, m_q\right) = \frac{2\alpha}{\pi} Q_q^2 \left[\ln\left(\frac{\hat{x}s}{m_q^2}\right) - 1\right]$$

We use current quark masses:

$m_u = 4.7$ MeV, $m_d = 2.2$ MeV, $m_s = 150$ MeV, $m_c = 1.2$ GeV, $m_b = 4.6$ GeV.

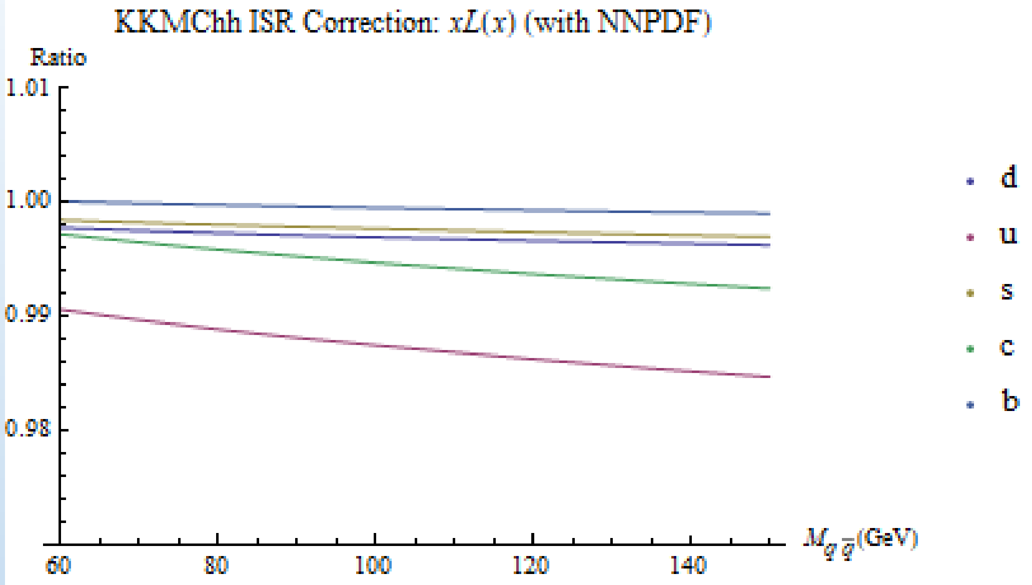
The following pages show the ratios of the QED-corrected joint luminosity to the original one.

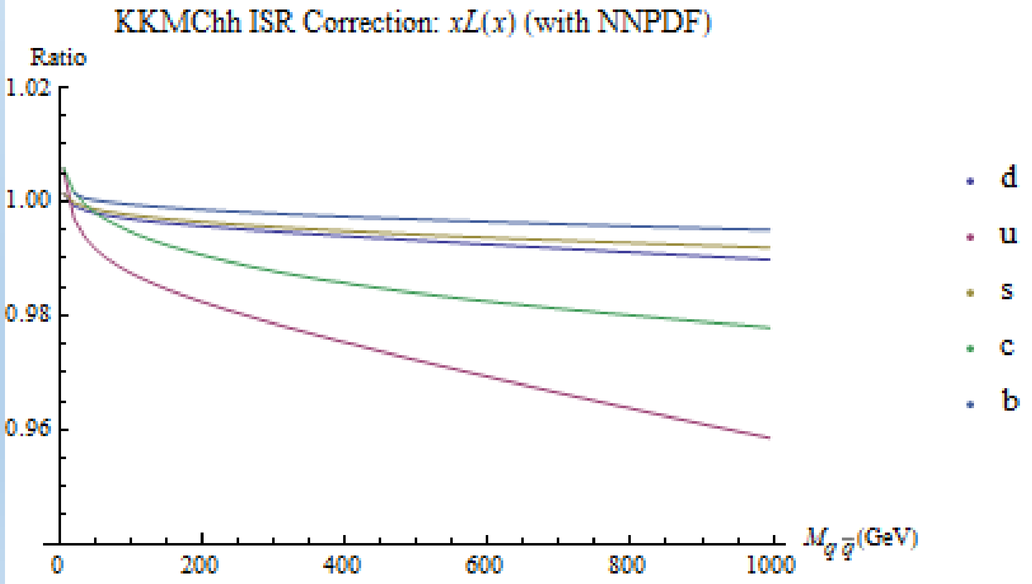
Effect of ISR on the Quark Luminosity Function

These graphs show the ratio of NNPDF $xL(xs)$ with QED corrections to without in a region around the Z pole used in many applications, and on a wider scale from 5 GeV to 1 TeV.

At $M_{q\bar{q}} = M_Z$, QED ISR reduces xL by -1.2% for the up quark and -0.29% for the down quark. The correction factor varies slowly over this range, mostly affecting normalization. (The inclusive Drell-Yan invariant mass distribution is reduced by a nearly flat $\sim 0.5\%$ in this range.)

The up quark correction varies from $+0.61\%$ to -4.2% over the wider range, while the down quark correction varies much less, from $+0.15\%$ to -1.0%.





Using KKMChh with a QED-Corrected PDF set

"Ordinary" PDF sets that fit data containing QED contamination to pure QCD evolution may not be an ideal starting point for precision EW calculations – it is hard to know the effect the residual QED unless some consistency checks can be done.

In cases where the ratio of L_{qq}^{QED} to L_{qq} matches the ratio of QED to regular PDFs, using KKMChh's ab-initio ISR with the regular PDF may still be a good approach: this is the case for NNPDF and MMHT, both of which have ratios matching ours within 0.1% from 60 to 150 GeV.

To allow us to work with QED-corrected PDF sets, a procedure we call "Negative ISR", or **NISR**, was introduced, backing out the QED from the PDF starting at a scale Q_0 and then generating ISR via KKMC's algorithm, ending up at the starting point, but with a set of photons.

The goal is to have a PDF that represents the full data, modeled with QCD and QED together, below the scale Q_0 but "prunes out" the QED component from $Q > Q_0$, where KKMChh will model the QED evolution.

Basic Description of the NISR Implementation

For a process at a hard scale sx, we take $Q_0^2 = sx$ so that KKMChh starts with a pruned PDF at a higher scale before radiating its ISR.

The "pruning" can be done on the fly, and the net effect is to make a convolution of each quark PDF with a "half-radiator" $\rho_{\rm ISR}\left(-\frac{1}{2}\gamma_{\rm ISR}(xs), u_1\right)$ and $\rho_{\rm ISR}\left(-\frac{1}{2}\gamma_{\rm ISR}(xs), u_1\right)$, the convolution of which makes a full reverse radiator function. This introduces two more variables u_1, u_2 in the primary distribution, with the constraints $x = \hat{x}(1-u_1)(1-u_2)$.

The modified ISR energy fraction used in the MC generation becomes v' satisfying

$$(1-v') = (1-v)(1-u_1)(1-u_2)$$

and the quark energy fractions become

$$x_1(1-u_1)\ , \qquad x_2(1-u_2).$$

There are now 6 variables in the initial state primary MC distribution to generate the quark flavor and the variables $\hat{x}$, x_1, v, u_1, and u_2.

Simple Cross-Check of NISR Implementation

The implementation of NISR can be checked by comparing the cross section obtained with a given PDF set alone to the cross section obtained using the PDF set with KKMChh's ISR and NISR together.

We can also check the independence on the quark mass, since the logarithmic dependence should cancel through second order.

We calculated the quark-level sections for muons with $60\ \mathrm{GeV} < M_{\mu\mu} < 150\ \mathrm{GeV}$ with NNPDF3.1 alone and using KKMChh ISR with NISR turned on. We find that the original PDF result is recovered to within 0.3% for charge $\frac{2}{3}e$ quarks and 0.08% for charge $-\frac{1}{3}e$ quarks.

This is explained by a non-logarithmic NLO correction $\delta_Q = Q^2\frac{\alpha}{\pi}\left(-\frac{1}{2}+\frac{\pi^2}{3}\right)$ which is not included in the NISR evolution, and 0.3% for up-type quarks and 0.08% for down-type quarks.

Examples of Distributions with Cuts: $M_{\mu^+\mu^-}$

For differential distributions, cuts on the photons, or away from the Z pole, the way of treating ISR becomes more important.

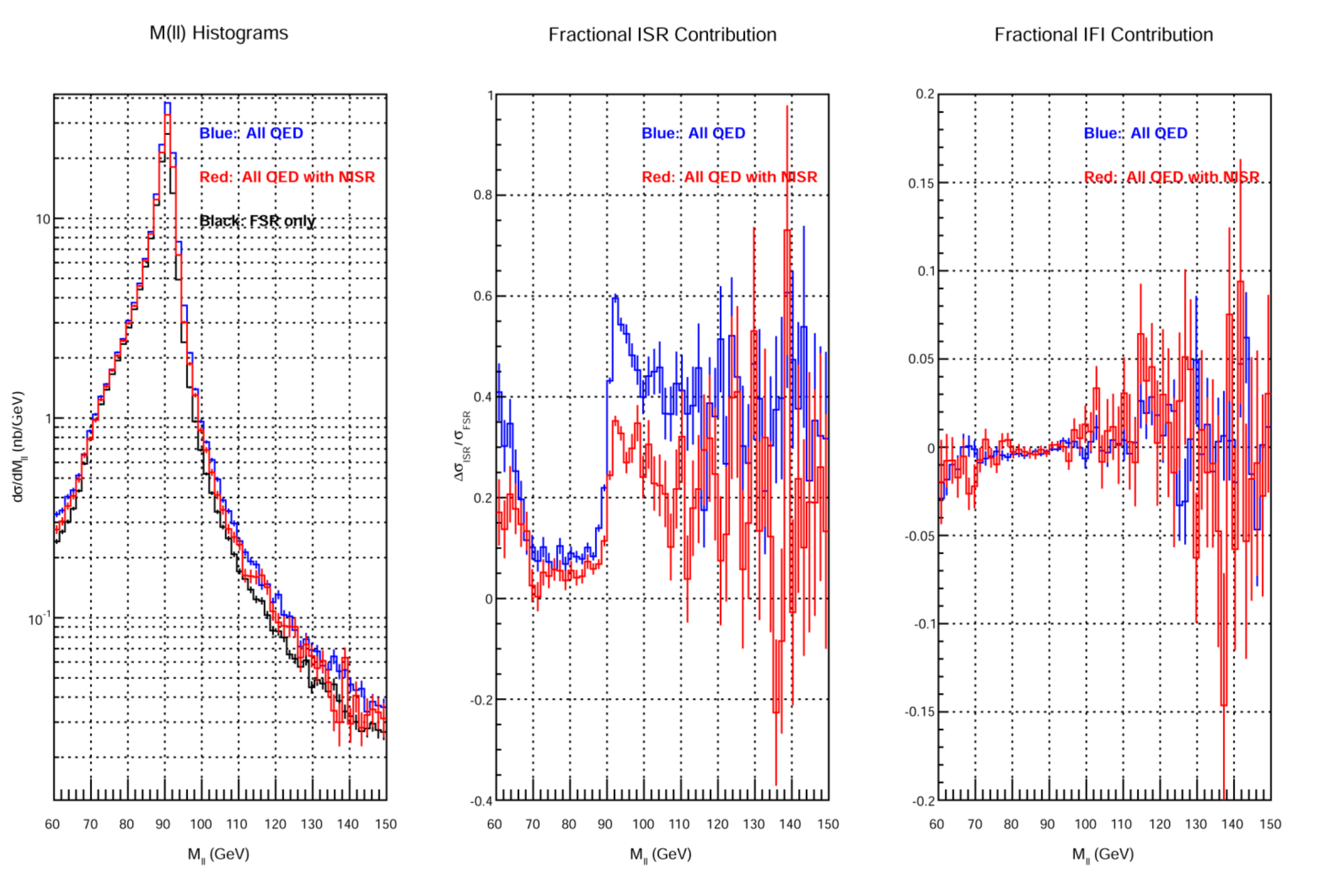
The following slides show some muon distributions with

$$60\ \text{GeV} < M_{\mu^+\mu^-} < 150\ \text{GeV}$$

and both muons with

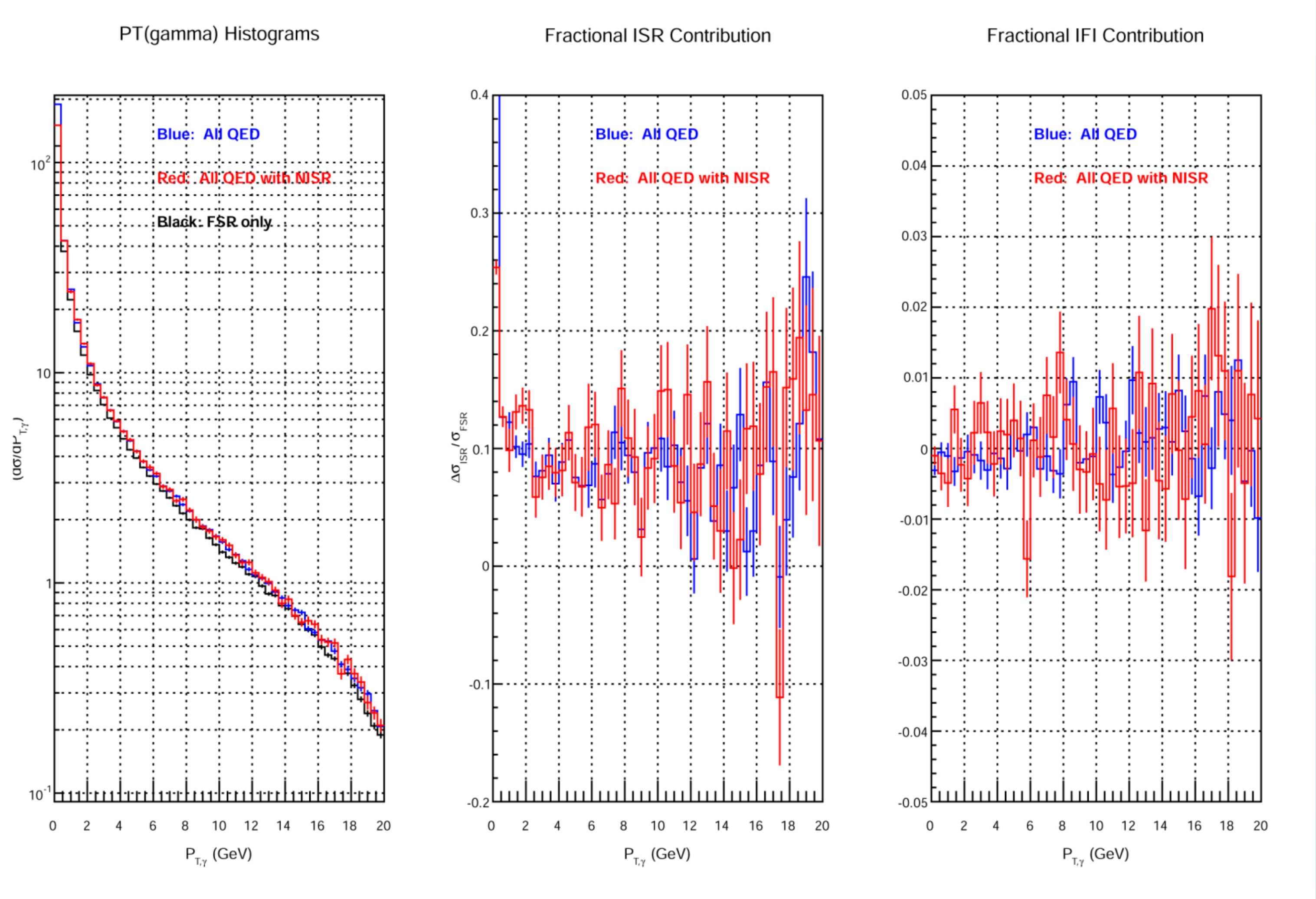
$$P_T > 25\ \text{GeV}/c, \eta < 2.5.$$

Here, NISR has little effect on ISR at the Z pole, but reduces it by about half in the tails.



Examples of Cut Distributions: Photon P_T

This is the distribution for the photon with greatest P_T. The regular and NISR results are similar within the errors and both ISR corrections are relatively small.



Summary

The NISR approach gives a better foundation for using KKMC-hh with QED-Corrected PDFs.

The additional 2 degrees of freedom in the primary distribution create a greater computational load that can be avoided by switching it off when it doesn't matter – such as when total ISR corrections are insignificant for the distribution of interest, or in studies focused near the Z pole where NISR makes little difference.

Pre-tabulating "pruned" PDFs would improve efficiency (and avoid negative weights).

Processes where IFI is the primary interest are independent of which way the ISR is treated – the full KKMChh ab-initio correction is adequate for studies involving forward backward asymmetry, for example, since this is affected mostly by IFI and very little by ISR when defined in terms of the Collins-Soper angle.

KKMChh is presently being used in some studies of high P_T photon events, along with Sherpa and POWHEG+PHOTOS, both of which also have YFS-exponentiated FSR. Soft photon exponentiation is essential for practically all precision EW calculations, since the higher order soft corrections are often more significant than the hard order α corrections.

Backup Slide: Table of NISR Comparisons

Quark-Level and Total Cross Sections for $60\ \mathrm{GeV} < M_{\mu\mu} < 150\ \mathrm{GeV}$, no FSR, NNPDF3.1.

Normal Masses	Born (No Photons)	QED: ISR + NISR (no FSR)	Fractional Difference
Down Quark	365.55 ± 0.00	365.86 ± 0.02	0.09 ± 0.01
Up Quark	420.68 ± 0.01	421.43 ± 0.05	0.18 ± 0.01
Strange Quark	120.66 ± 0.00	120.79 ± 0.01	0.11 ± 0.01
Charm Quark	43.12 ± 0.00	43.24 ± 0.01	0.27 ± 0.02
Bottom Quark	24.23 ± 0.00	24.23 ± 0.00	0.07 ± 0.02
Total: Five Quarks	974.23 ± 0.01	975.55 ± 0.05	0.14 ± 0.01

All Masses 500 MeV	Born (No Photons)	QED: ISR + NISR (no FSR)	Fractional Difference
Down Quark	365.55 ± 0.00	365.81 ± 0.02	0.07 ± 0.01
Up Quark	420.68 ± 0.01	421.43 ± 0.05	0.24 ± 0.00
Strange Quark	120.66 ± 0.00	120.79 ± 0.01	0.08 ± 0.00
Charm Quark	43.12 ± 0.00	43.24 ± 0.01	0.27 ± 0.01
Bottom Quark	24.23 ± 0.00	24.23 ± 0.00	0.08 ± 0.01
Total: Five Quarks	974.23 ± 0.01	975.55 ± 0.05	0.16 ± 0.0