Exact $\mathcal{O}(\alpha^2 L)$ CEEX EW Calculations

Version 2: with corrected cuts in the plots without ISR

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$\mathcal{KK}$ MC-hh

- $\mathcal{KK}$ MC-hh is an event-generator for Z production and decay in hadronic collisions, which grew from the e^+e^- event generator $\mathcal{KK}$ MC created by S. Jadach, B.F.L. Ward, and Z. Wąs.

- The latest version of $\mathcal{KK}$ MC supports quark initial states, and provides a natural starting point for incorporating EWK corrections to the parton-level process.

- $\mathcal{KK}$ MC-hh adds an LHAPDF interface and an interface to a shower generator, presently HERWIG6.5, but an external generator can be used.

- This talk will present some results for cuts motivated by an ATLAS W mass analysis, and compare different levels of EW corrections within $\mathcal{KK}$ MC-hh.

- This version of the slides corrects a mistake in the application of the cuts to the plots without ISR, which made the ISR correction appear to be larger than it should have in the projected slides.

$\mathcal{KK}$ MC

- $\mathcal{KK}$ MC is a precision event generator for $e^+e^- \to f\overline{f} + n\gamma$, $f = \mu, \tau, d, u, s, c, b$ for CMS energies from $2m_\tau$ to 1 TeV. The precision tag for LEP2 was 0.2%.

- ISR and FSR γ emission is calculated up to $\mathcal{O}(\alpha^2)$, including interference.

- The MC structure is based on YFS exponentiation, including residuals calculated perturbatively to the relevant orders in $\alpha^k L^l$. ($L = \ln(s/m_e^2)$). CEEX mode: $\alpha, \alpha L, \alpha^2 L^2, \alpha^2 L$ with IFI.

- Exact collinear bremsstrahlung for up to three γ's in EEX mode.

- $\mathcal{O}(\alpha)$ EWK corrections and more are included via DIZET 6.21.

- τ decay is simulated using TAUOLA.

- Version 4.22 of $\mathcal{KK}$ MC supports quark initial states, and a modified version of this is incorporated into $\mathcal{KK}$ MC-hh.

Coherent Exclusive Exponentiation

- CEEX was introduced for pragmatic reasons, the traditional exponentiation (EEX) of spin-summed cross sections suffered from a proliferation of interference terms, limiting its ability to reach the desired 0.2% precision tag for LEP2.

- CEEX works at the level of spinor helicity amplitudes, greatly facilitating the calculation of effects such as ISR-FSR interference, which are included in $\mathcal{KK}$ MC, and therefore HERWIRI2.

- CEEX is maximally exclusive: all real photons radiated are kept in the event record, no matter how soft or collinear. There is no need to "integrate out" a region of soft phase space because the exponentiated amplitudes are well-behaved at $k = 0$.

EEX and CEEX Formalism

Two exponentiation schemes are supported in KKMC: EEX and CEEX.

EEX refers to exclusive exponentiation, which is similar to the original YFS formulation, in which exponentiation is applied at the cross section level.

CEEX refers to coherent exclusive exponentiation, in which the exponentiation is applied at the amplitude level. This allows inclusion of additional effects such as initial-final interference (IFI).

The CEEX cross section for $q\bar{q} \to f\bar{f}$ has the form

$$\sigma = \frac{1}{\text{flux}} \sum_{n=0}^{\infty} \int d\text{PS} \; \rho_{\text{CEEX}}^{(n)}(\vec{p}, \vec{k})$$

where

$$\rho_{\text{CEEX}}^{(n)} = \frac{1}{n!} e^{Y(\vec{p}, E_{\min})} \frac{1}{4} \sum_{\text{hel.}} \left| \mathcal{M} \begin{pmatrix} \vec{p} & \vec{k} \\ \vec{\lambda} & \vec{\mu} \end{pmatrix} \right|^2$$

CEEX Formalism

The YFS form factor is

$$Y(\vec{p}, E_{\min}) = Q_i^2 Y(p_1, p_2, E_{\min}) + Q_f^2 Y(p_3, p_4, E_{\min}) + Q_i Q_f Y(p_1, p_3, E_{\min})$$

$$+ Q_i Q_f Y(p_2, p_4, E_{\min}) - Q_i Q_f Y(p_1, p_4, E_{\min}) - Q_i Q_f Y(p_2, p_3, E_{\min})$$

$$Y(p_i, p_j, E_{\min}) = 2\alpha \widetilde{B}(p_i, p_j, E_{\min}) + 2\alpha \mathrm{Re}\, B(p_i, p_j)$$

$$\widetilde{B} = -\int_{k^0 < E_{\min}} \frac{d^3\vec{k}}{8\pi^2 k^0} \left(\frac{p_i}{p_i \cdot k} - \frac{p_j}{p_j \cdot k} \right)^2,$$

$$B = \frac{i}{(2\pi)^3} \int \frac{d^4 k}{k^2} \left(\frac{2p_i + k}{2p_i \cdot k + k^2} - \frac{2p_j - k}{2p_j \cdot k - k^2} \right).$$

ElectroWeak Corrections

$\mathcal{KK}$ MC incorporates the DIZET library (version 6.2) from the semi-analytical program ZFITTER by A. Akhundov, A. Arbuzov, M. Awramik, D. Bardin, M. Bilenky, P. Christova, M. Czakon, A. Frietas, M. Gruenewald, L. Kalinovskaya, A. Olchevsky, S. Riemann, T. Riemann.

- The γ and Z propagators are multiplied by vacuum polarization factors:

$$H_\gamma = \frac{1}{2 - \Pi_\gamma}, \qquad H_Z = 4\sin^2(2\theta_\mathrm{W})\frac{\rho_\mathrm{EW} G_\mu M_Z^2}{8\pi\alpha\sqrt{2}}.$$

- Vertex corrections are incorporated into the coupling of Z to f via form factors in the vector coupling:

$$g_V^{(Z,f)} = \frac{T_3^{(f)}}{\sin(2\theta_W)} - Q_f F_\mathrm{v}^{(f)}(s)\tan\theta_W.$$

- Box diagrams contain these plus a new angle-dependent form-factor in the doubly-vector component:

$$g_V^{(Z,i)} g_V^{(Z,f)} = \frac{T_3^{(i)} T_3^{(f)} - 2T_3^{(i)} Q_f F_\mathrm{v}^{(f)}(s) - 2Q_i T_3^{(f)} F_\mathrm{v}^{(i)}(s) + 4Q_i Q_f F_\mathrm{box}^{(i,f)}(s,t)}{\sin^2(2\theta_W)}.$$

The correction factors are calculated at the beginning of a run and stored in tables.

Combining $\mathcal{KK}$ MC with a Shower

- The Drell-Yan cross section with multiple-photon emission can be expressed as an integral over the parton-level process $q_i(p_1)\bar{q}_i(p_2) \to f(p_3)\bar{f}(p_4) + n\gamma(k)$, integrated over phase space and summed over photons.

- The parton momenta p_1, p_2 are generated using parton distribution functions giving a process at CMS energy q and momentum fractions x_1, x_2 such that $q^2 = x_1 x_2 s$:

$$\sigma_{\text{DY}} = \int \frac{dx_1}{x_1} \frac{dx_2}{x_2} \sum_i f_i(q, x_1) f_{\bar{i}}(q, x_2) \sigma_i(q^2) \delta(q^2 - x_1 x_2 s),$$

where the final state phase space includes p_3, p_4 and $k_i, i = 1, \cdots, n$ and multiple gluon radiation + hadronization is included through a shower.

Event Generation

- An adaptive MC, S. Jadach's FOAM (C++ version) calculates the primary distribution of quarks and ISR photons. The distribution grid is set up during an exploratory phase at the beginning of the run.

- A four-dimensional distribution generates the quark flavor, the hard process scale Q, one of the momentum fractions x, and the amount of ISR photon radiation.

- A set of 4 random numbers in [0,1] are generated. The first of these is uniformly distributed between u, d, c, s, and b quarks and anti-quark flavor indices. The remaining three are in a 3-dimensional volume which is mapped into simplicial cells to optimize the MC integration.

- There is no need for sophisticated mapping before calling FOAM, though some minimal mapping is done, since an exponential map for x_1 improves performance.

$\mathcal{KK}$ MC-hh Tests Motivated by W Mass Measurement

- For a precise measurement of the W mass, Z boson events are used to calibrate the detector response and test the modelling of vector-boson production.

- A recent ATLAS analysis (arXiv:1701.0740) used PHOTOS to model the dominant EW correction: QED FSR. Pure weak and IFI corrections were not included, nor was FSR pair production, but these were estimated using WINHAC, SANC, *etc*.

- The following slides show Z boson distributions generated at 7 TeV CMS energy with $\mathcal{KK}$ MC-hh using MSTW2008 PDFs and a HERWIG6.5 shower, with 10^7 weighted events (before cuts).

- Cuts: 80 GeV $< M_{\ell\ell} <$ 100 GeV, $P_{\mathrm{T}}^{\ell\ell} < 30$ GeV, with both leptons having $P_{\mathrm{T}}^{\ell} > 25$ GeV, $|\eta_\ell| < 2.5$.

- Correction: In the version of these slides projected, the $P_{\mathrm{T}}^{\ell\ell}$ cut was not applied to the plots without ISR. This has been fixed in the present version.

$\mathcal{KK}$ MC-hh Results

The test runs compare the best exact $\mathcal{O}(\alpha^2 L)$ CEEX implementation (labeled CEEX2) to several more limited models:
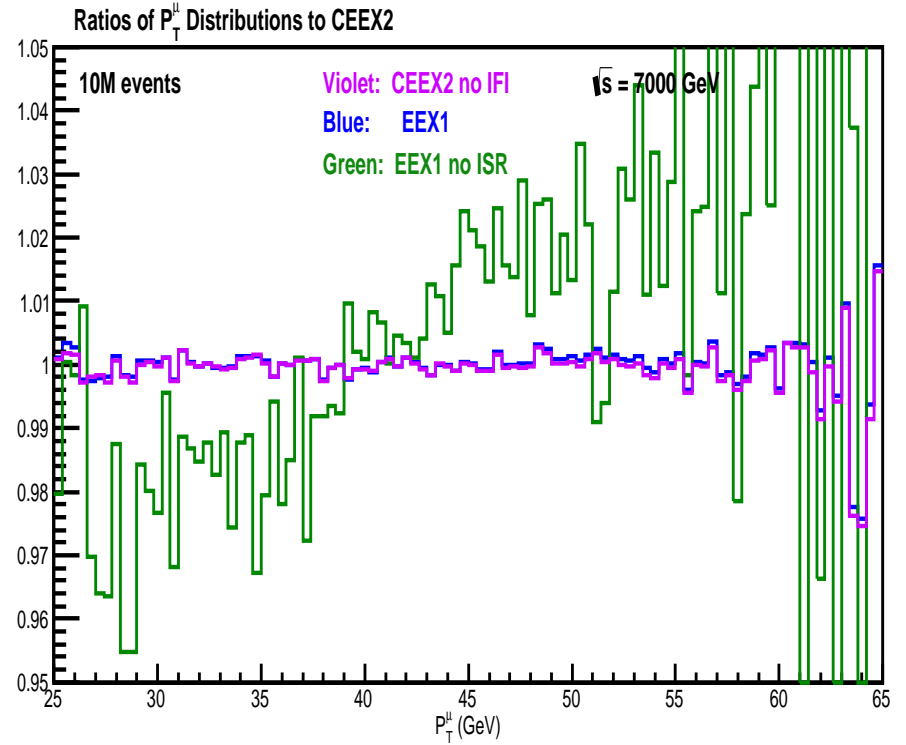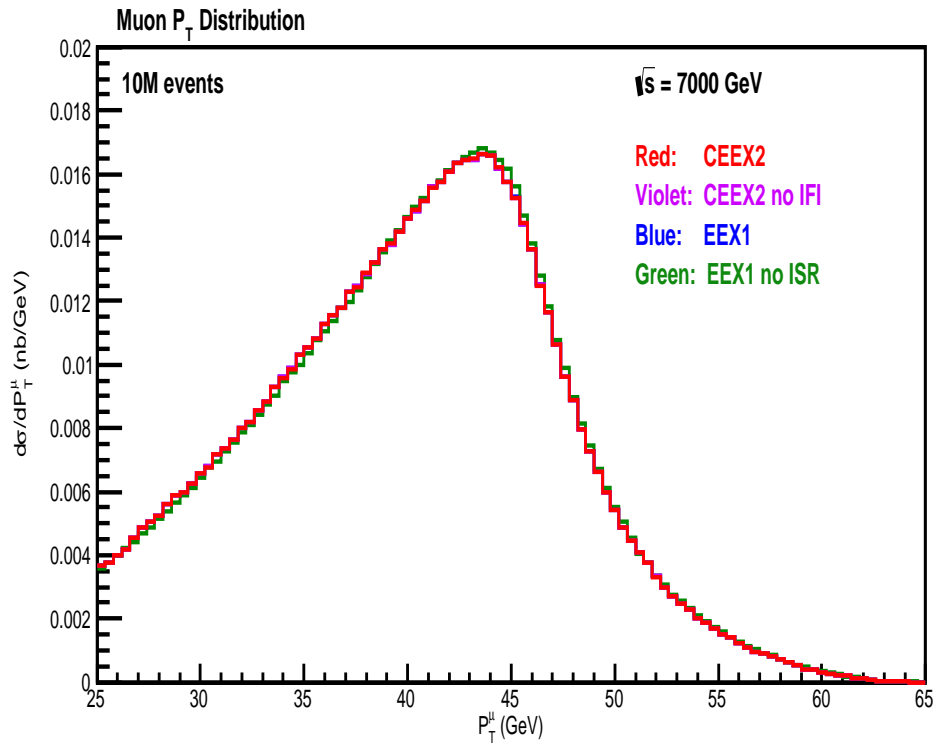
- $\mathcal{O}(\alpha^2 L)$ CEEX without IFI

- $\mathcal{O}(\alpha)$ EEX (labeled EEX1)

- $\mathcal{O}(\alpha)$ EEX without ISR

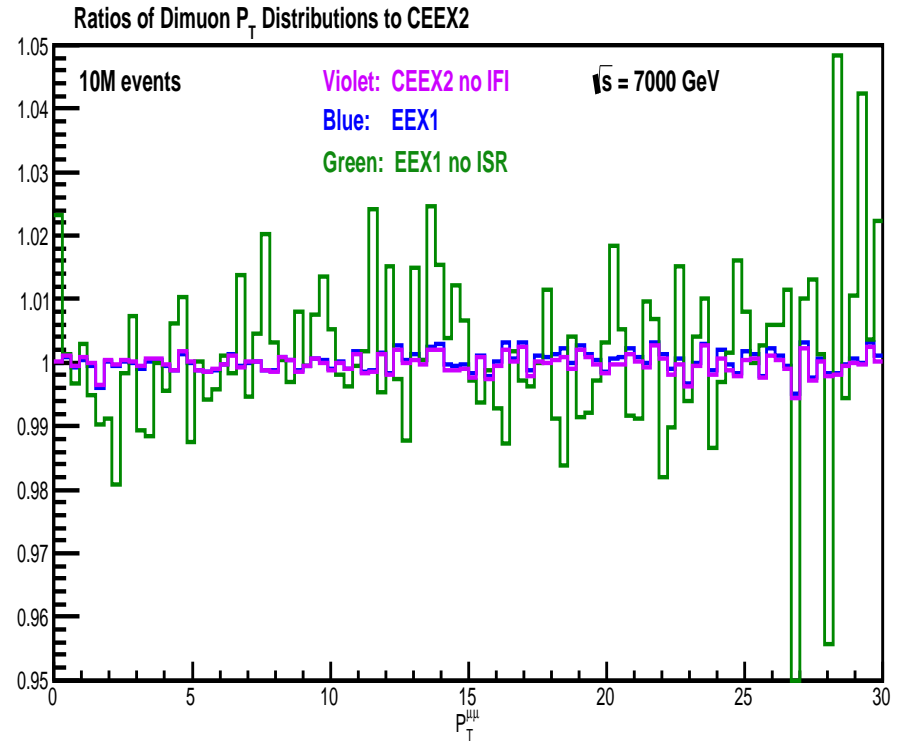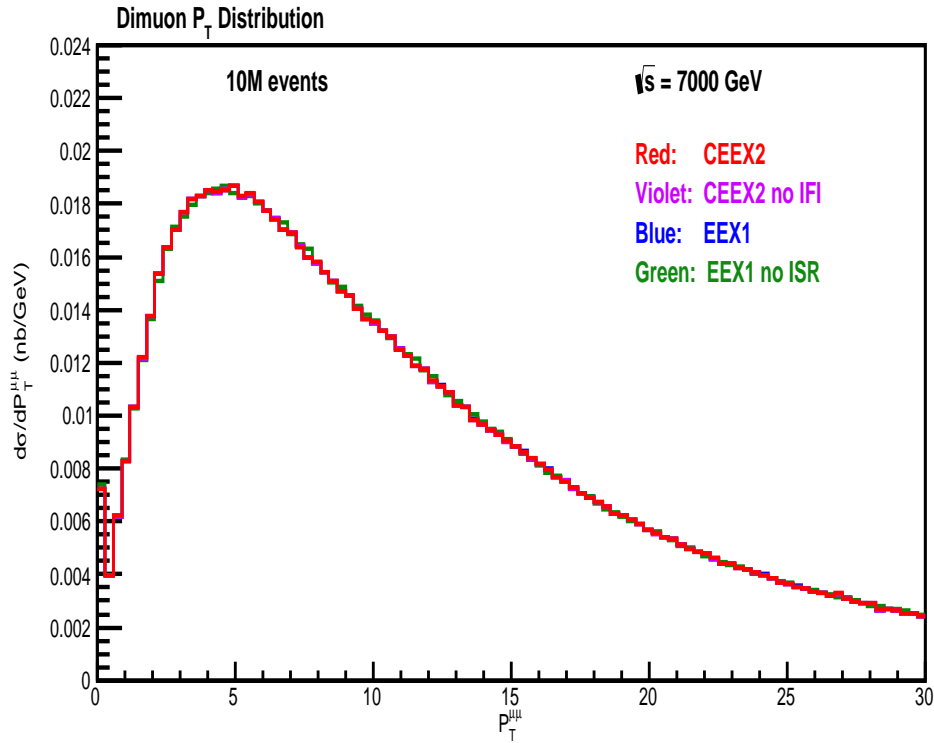The table shows the cut cross-sections with and without these cases:

	uncut (pb)	cut (pb)
CEEX2	844.74	280.36
CEEX2 (no IFI)	844.97	280.31
EEX1	844.45	280.38
EEX1 (no ISR)	844.97	280.64

The uncut cases are all consistent to 0.06% while the cut cases are consistent 0.02% with ISR, or 0.09% if the no-ISR case is included.
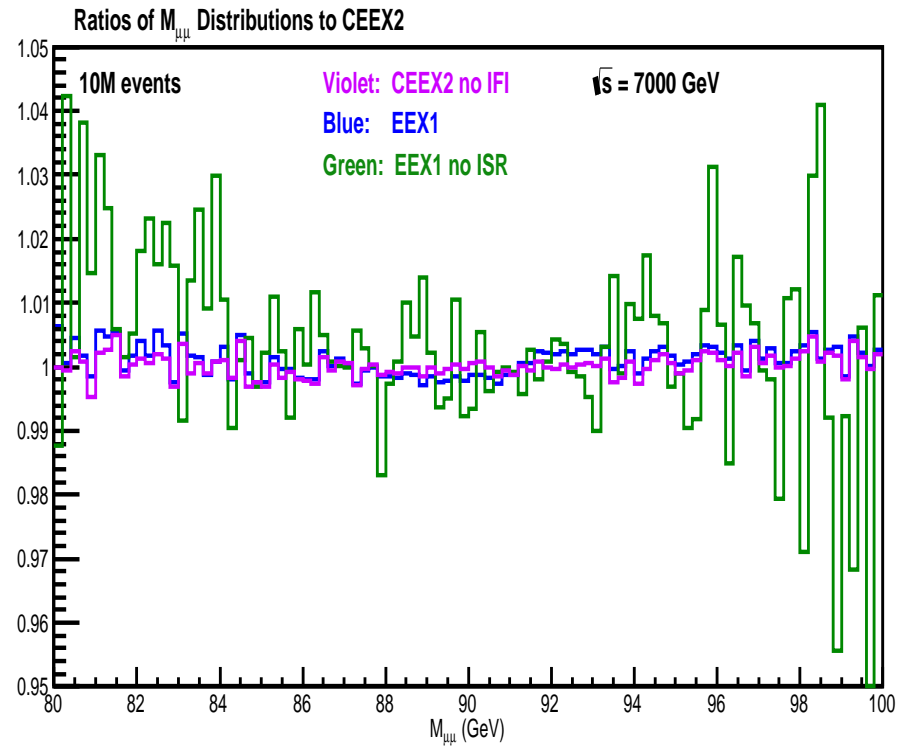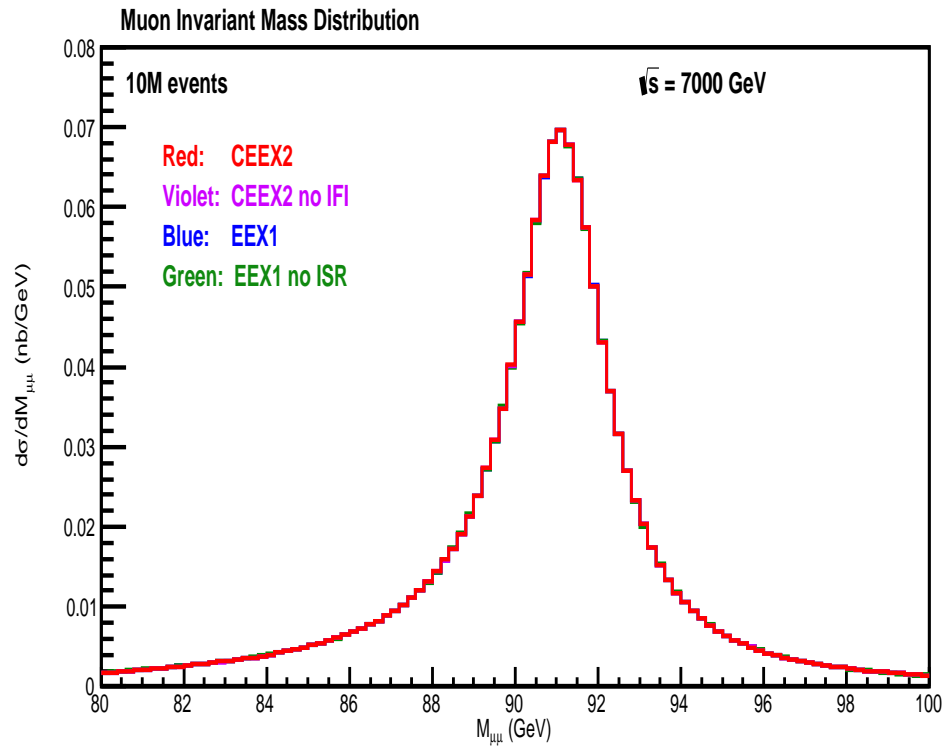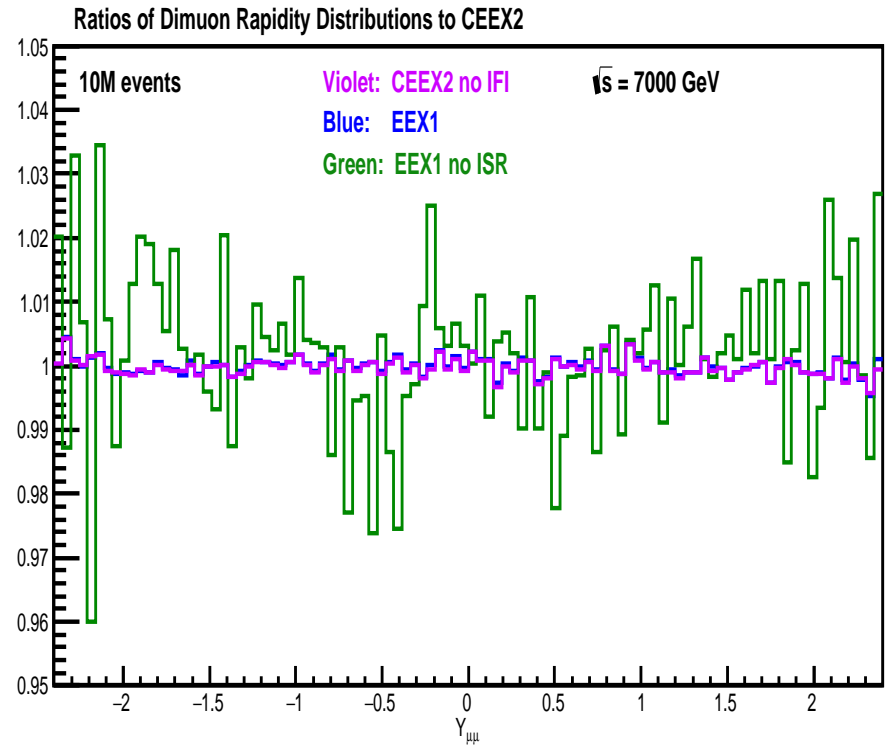
Muon Transverse Momentum

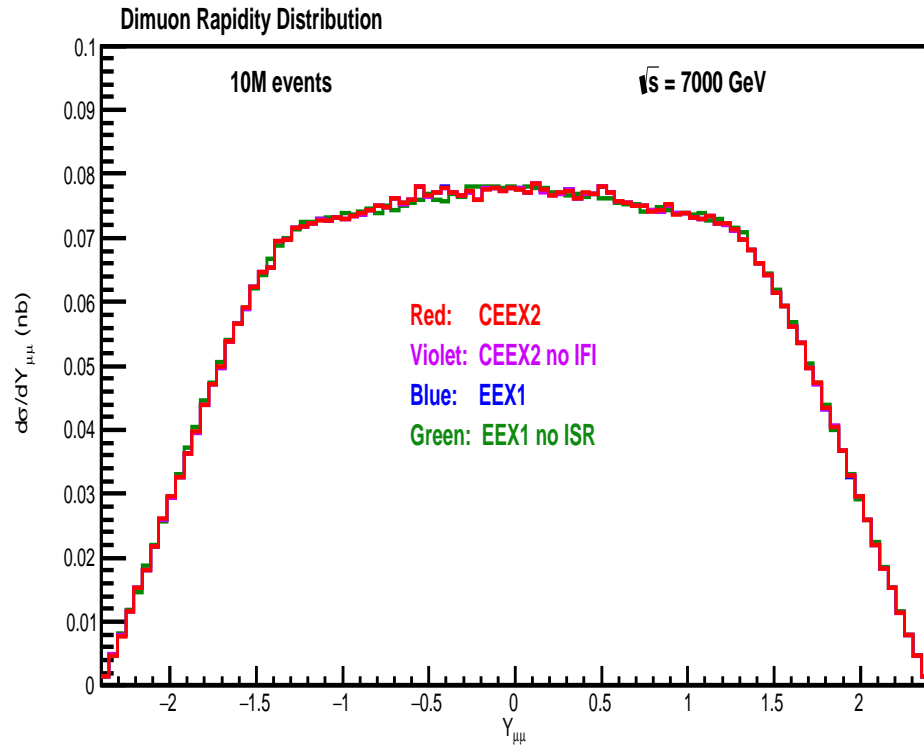**Muon P_T Distribution**

10M events

$\sqrt{s}$ = 7000 GeV

Red: CEEX2
Violet: CEEX2 no IFI
Blue: EEX1
Green: EEX1 no ISR

$d\sigma/dP_T^\mu$ (nb/GeV)

P_T^μ (GeV)

Ratios of P_T^μ Distributions to CEEX2

10M events

Violet: CEEX2 no IFI
Blue: EEX1
Green: EEX1 no ISR

$\sqrt{s}$ = 7000 GeV

P_T^μ (GeV)

Dimuon Transverse Momentum

Dimuon P_T Distribution

10M events $\sqrt{s}$ = 7000 GeV

Red: CEEX2
Violet: CEEX2 no IFI
Blue: EEX1
Green: EEX1 no ISR

$d\sigma/dP_T^{\mu\mu}$ (nb/GeV)

$P_T^{\mu\mu}$

Ratios of Dimuon P_T Distributions to CEEX2

10M events   Violet: CEEX2 no IFI $\sqrt{s}$ = 7000 GeV

Blue: EEX1

Green: EEX1 no ISR

$P_T^{\mu\mu}$

Dimuon Invariant Mass

Muon Invariant Mass Distribution

10M events $\sqrt{s} = 7000$ GeV

Red: CEEX2
Violet: CEEX2 no IFI
Blue: EEX1
Green: EEX1 no ISR

$d\sigma/dM_{\mu\mu}$ (nb/GeV)

$M_{\mu\mu}$ (GeV)

Ratios of $M_{\mu\mu}$ Distributions to CEEX2

10M events Violet: CEEX2 no IFI $\sqrt{s} = 7000$ GeV
Blue: EEX1
Green: EEX1 no ISR

$M_{\mu\mu}$ (GeV)

Dimuon Rapidity

Dimuon Rapidity Distribution

10M events $\sqrt{s}$ = 7000 GeV

Red: CEEX2
Violet: CEEX2 no IFI
Blue: EEX1
Green: EEX1 no ISR

$d\sigma/dY_{\mu\mu}$ (nb)

$Y_{\mu\mu}$

Ratios of Dimuon Rapidity Distributions to CEEX2

10M events   Violet: CEEX2 no IFI $\sqrt{s}$ = 7000 GeV
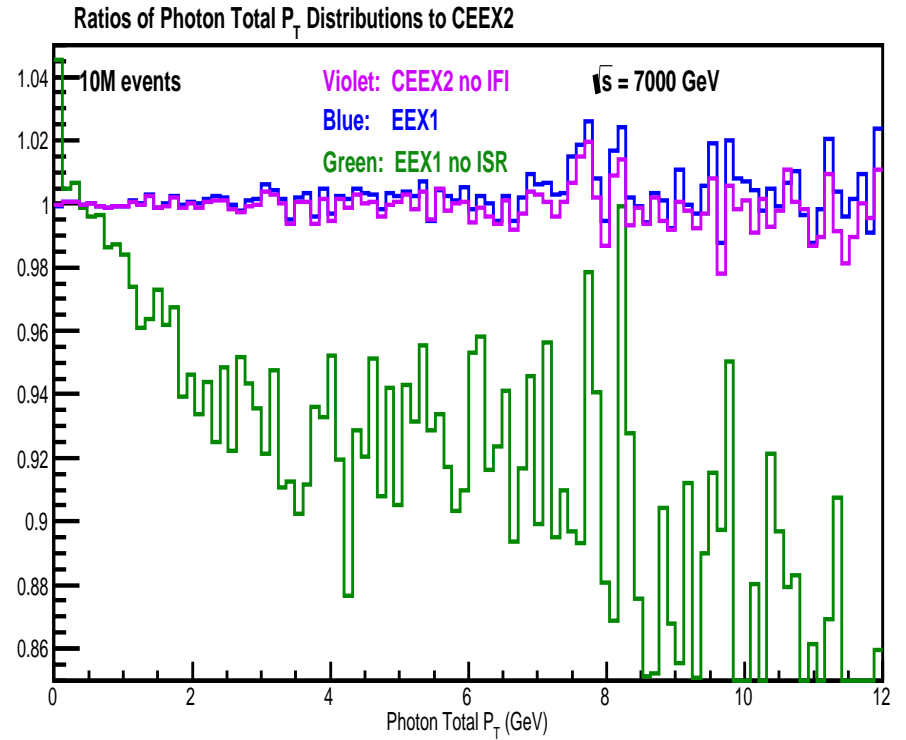
Blue: EEX1

Green: EEX1 no ISR

$Y_{\mu\mu}$

Photon Multiplicity (with Energy > 1 GeV)

Total Energy of Photons

Photon Total Energy Distribution

10M events $\sqrt{s} = 7000$ GeV

Red: CEEX2
Violet: CEEX2 no IFI
Blue: EEX1
Green: EEX1 no ISR

$d\sigma/dE_\gamma$ (nb/GeV)

Total E_γ (GeV)

Ratios of Photon Total Energy Distributions to CEEX2

10M events   Violet: CEEX2 no IFI $\sqrt{s} = 7000$ GeV
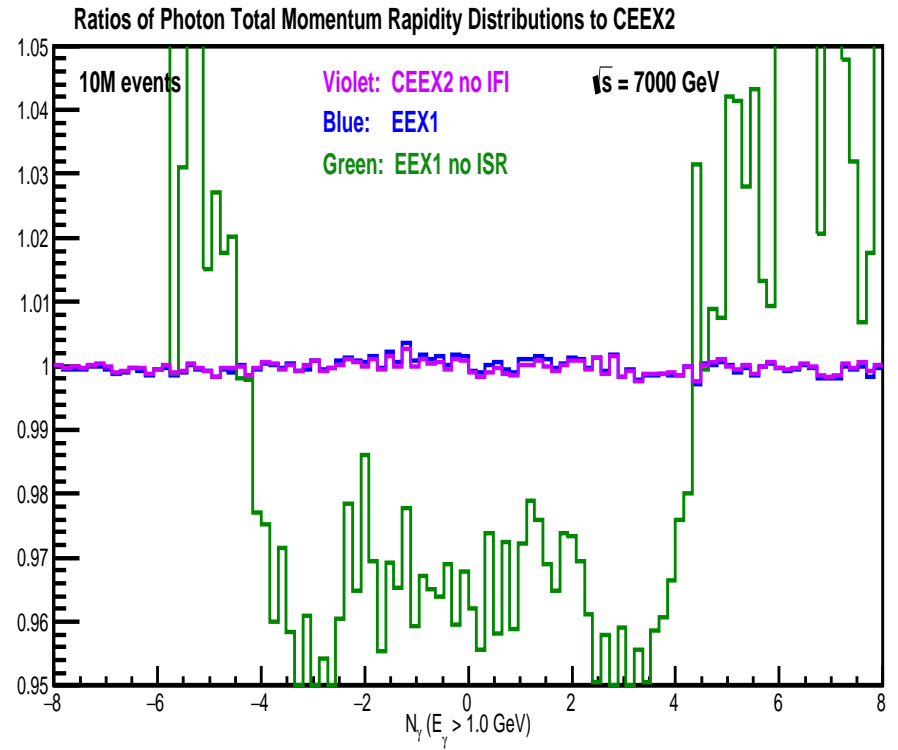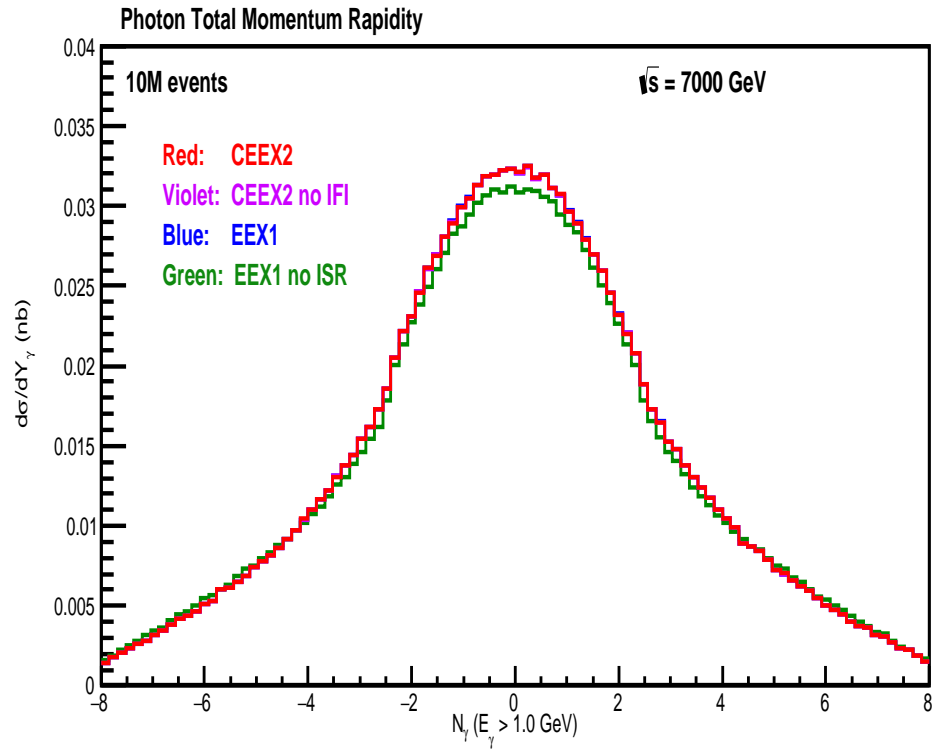Blue: EEX1
Green: EEX1 no ISR

Total E_γ (GeV)
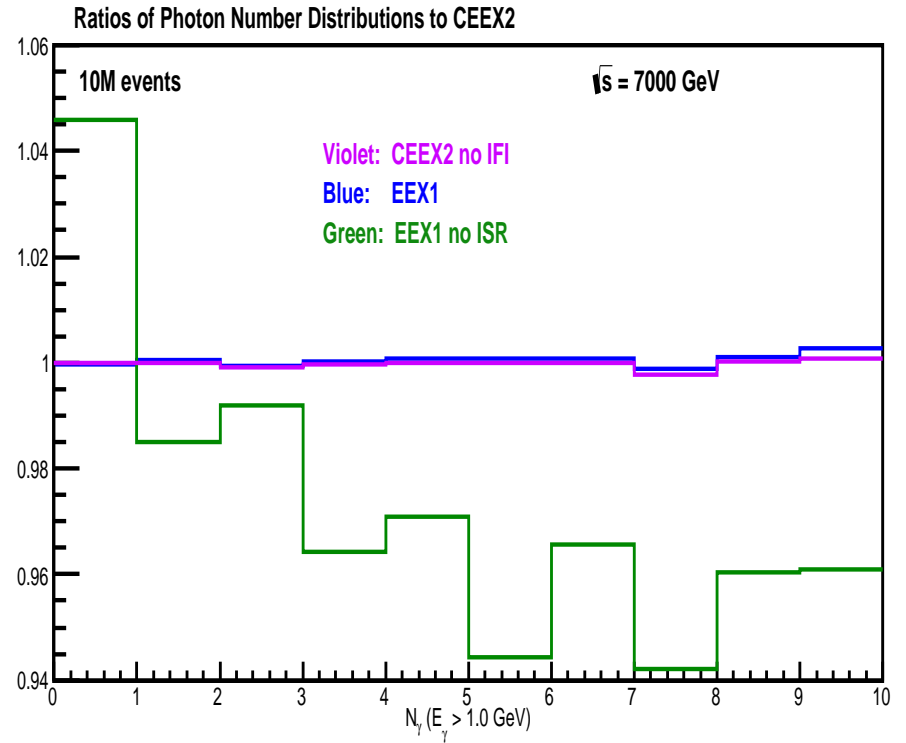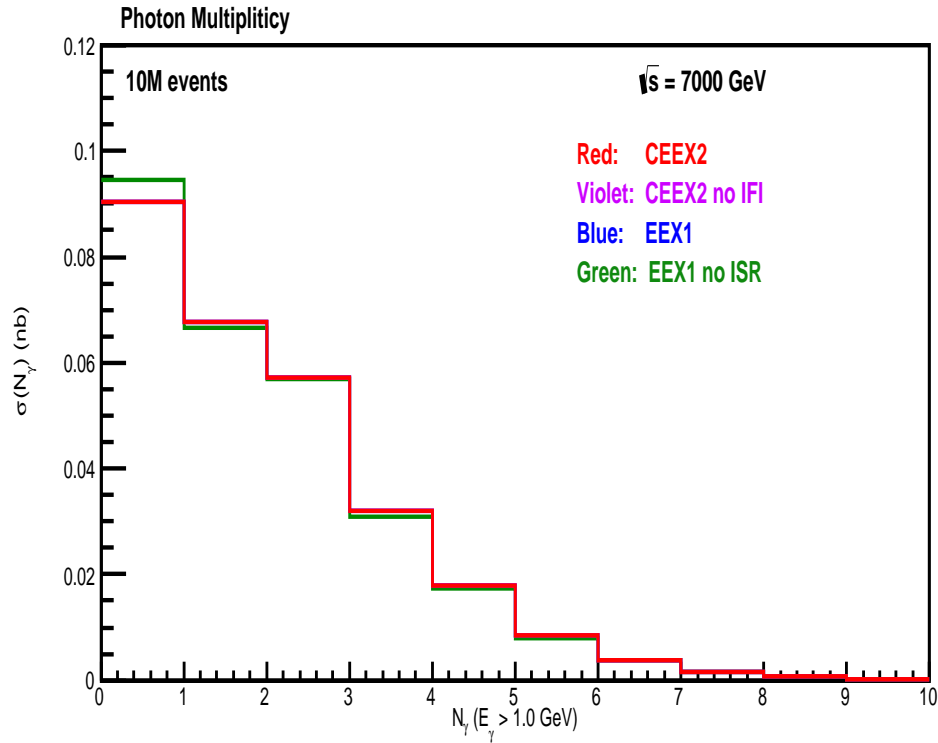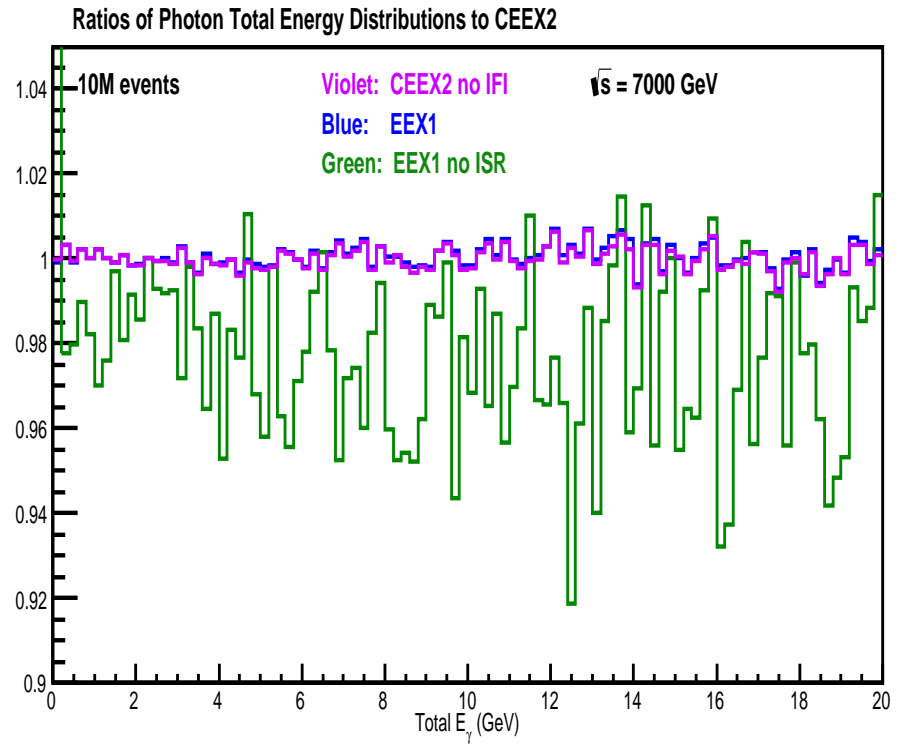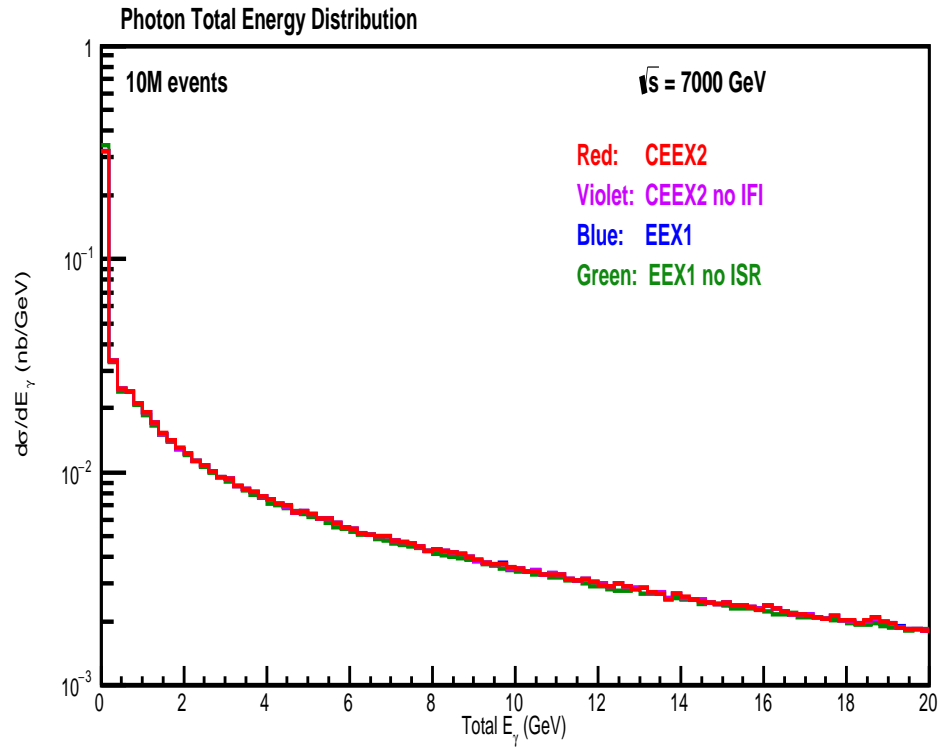
Total Transverse Momentum of Photons
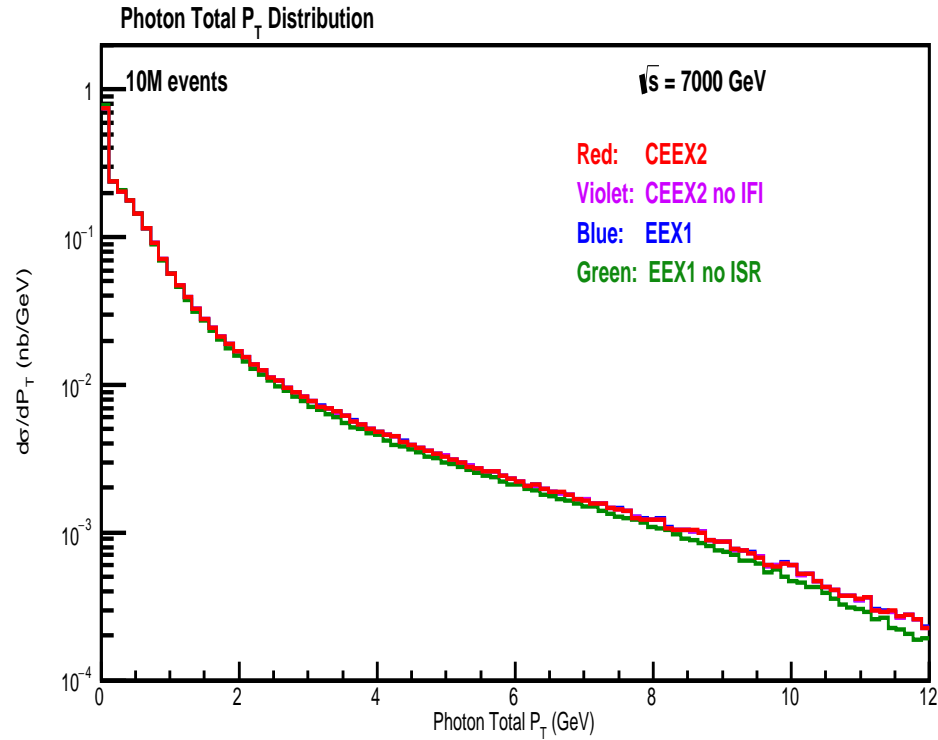
Rapidity of Total Photon Momentum

Summary

- $\mathcal{KK}$ MC-hh includes multi-photon emission from both the initial and final states in Z production, with order α EW matrix element corrections.

- $\mathcal{KK}$ MC-hh implements both EEX (cross-section level) and CEEX (amplitude level) exponentiation schemes. CEEX is exact to order $\alpha^2 L$.

- More details on $\mathcal{KK}$ MC-hh can be found in Phys. Rev. D94 (2016) 074006 (arXiv:1608.01260)

- Future developments include:
  - NLO QCD via the KrkNLO scheme of Jadach *et al.*
  - Updated EW matrix element corrections from a new version of SANC.
  - Fermion pairs (Wąs).

- We hope to have tuned tests against other programs (HORACE, ...) soon.