ElectroWeak Corrections in a Hadronic MC for Z Production

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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 comparisons to other programs and results for cuts motivated by an ATLAS W mass analysis. $\mathcal{KK}$ MC-hh.

$\mathcal{KK}$ 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 $\mathcal{KK}$ MC-hh.
- 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

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

where

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

CEEX Formalism

The YFS form factor is

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

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

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

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

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

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:

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

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

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

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

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

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 $q_i(p_1)\overline{q}_i(p_2) \rightarrow f(p_3)\overline{f}(p_4) + n\gamma(k)$, 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 $q^2 = x_1 x_2 s$:

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

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, $P_{\rm T}^{\ell\ell} < 30$ GeV, with both leptons having $P_{\rm T}^{\ell} > 25$ GeV, $|\eta_\ell| < 2.4$.

$\mathcal{KK}$ MC-hh Results

The test runs compare the best exact $\mathcal{O}(\alpha^2 L)$ CEEX implementation (labeled CEEX2) to several more limited models:

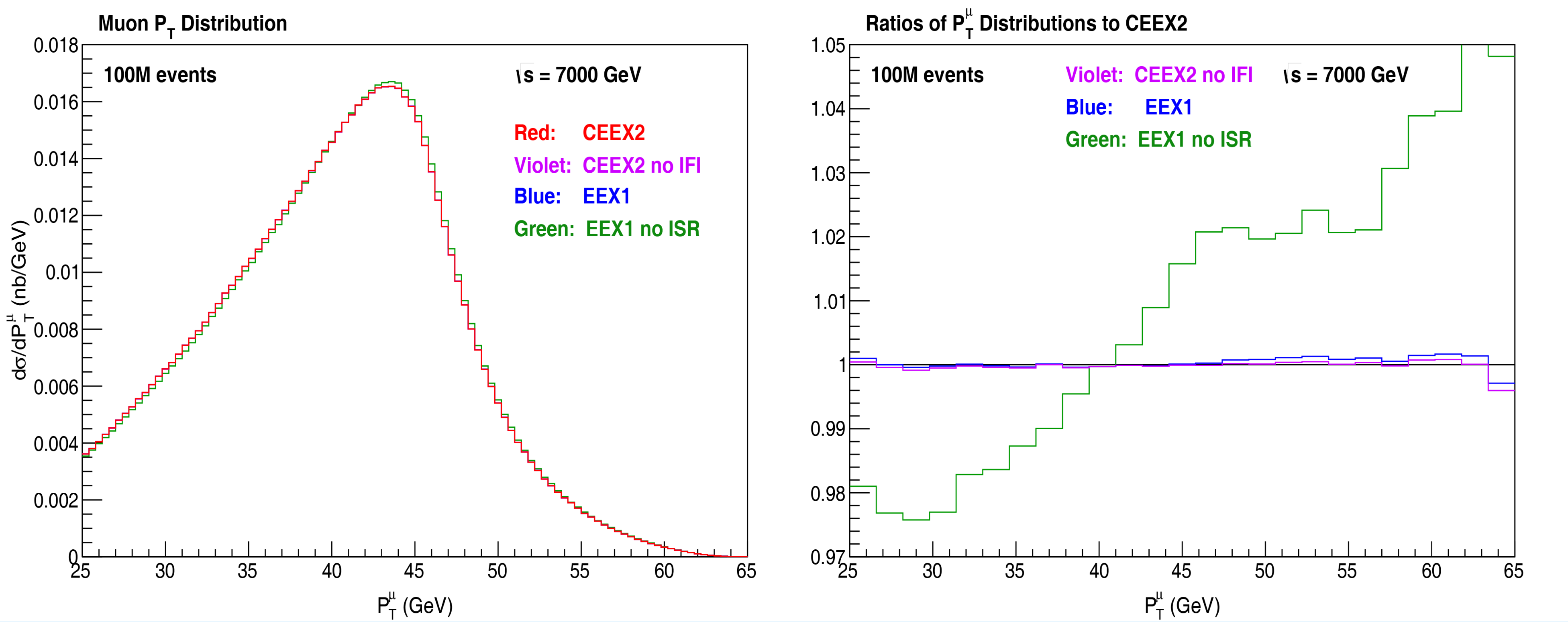
- $\mathcal{O}(\alpha^2 L)$ CEEX without IFI
- $\mathcal{O}(\alpha)$ EEX (labeled EEX1)
- $\mathcal{O}(\alpha)$ EEX without ISR

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

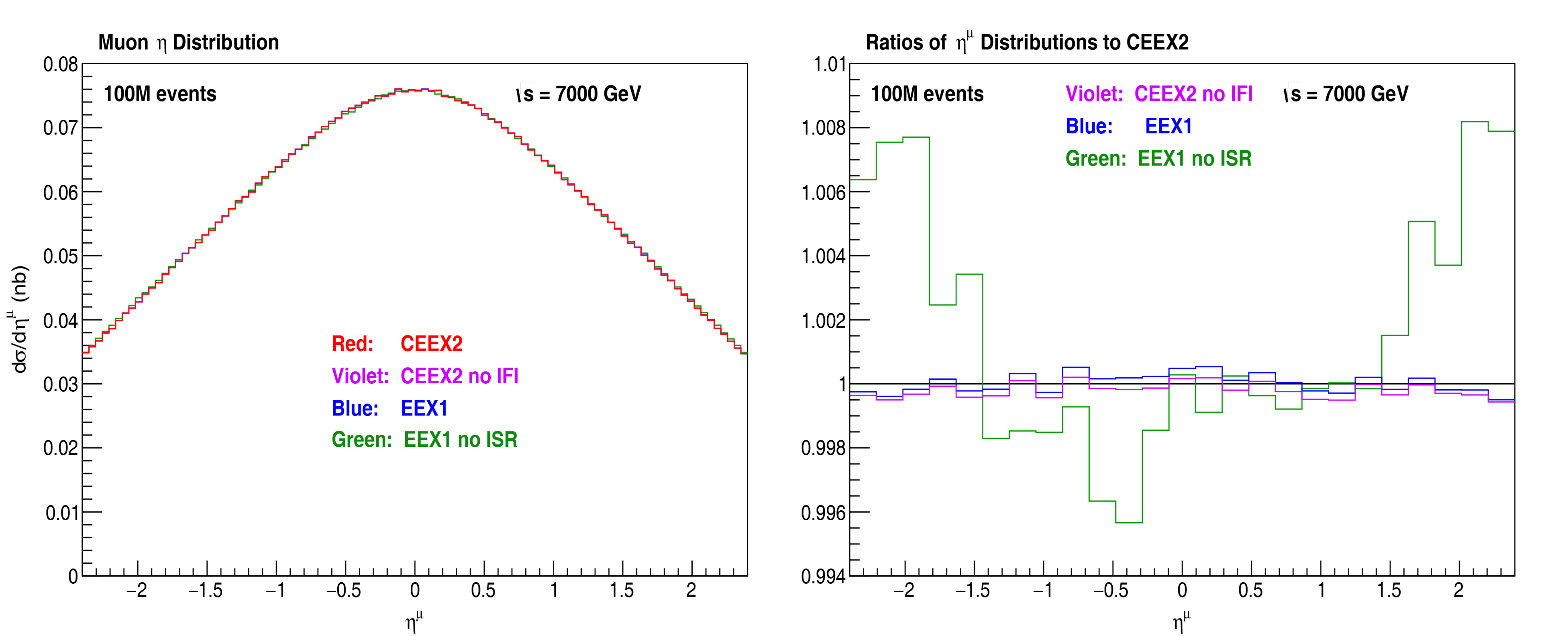
	uncut (pb)	cut (pb)
CEEX2	844.74	280.36
CEEX2 (no IFI)	844.97	280.31
EEX1	844.45	280.38
EEX1 (no ISR)	844.97	280.64

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.

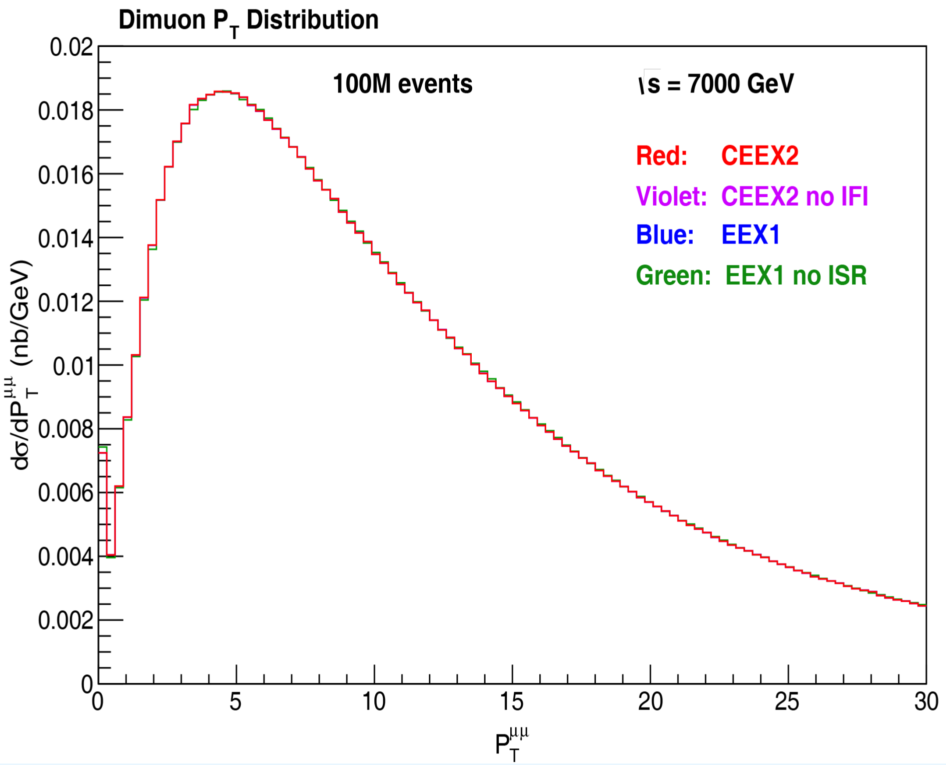
Muon Transverse Momentum

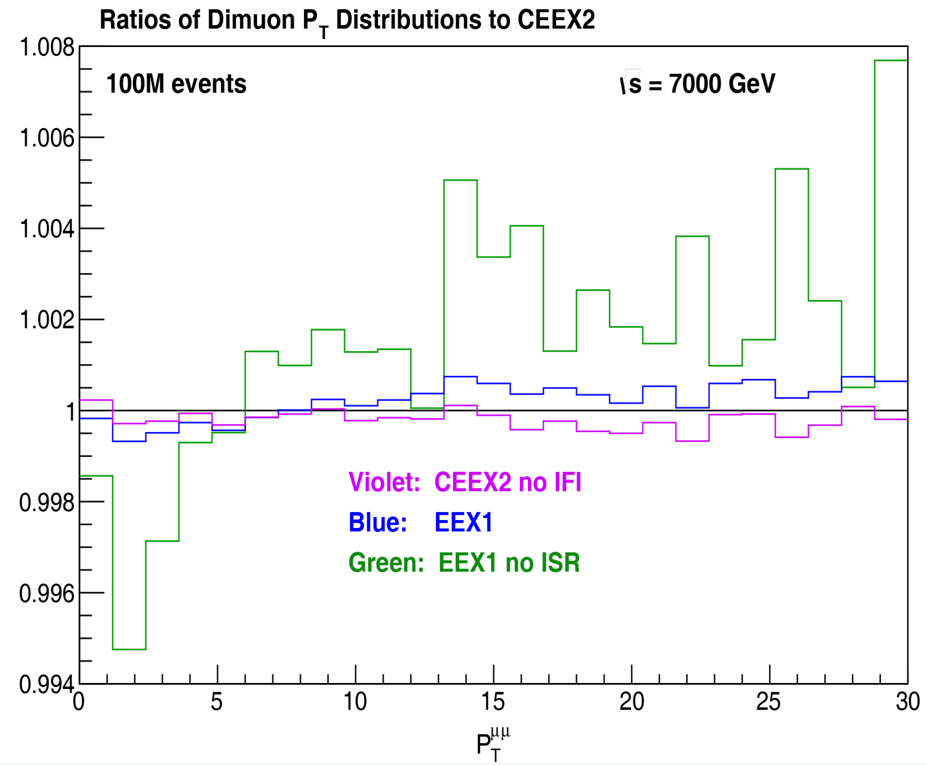


Muon Pseudorapidity

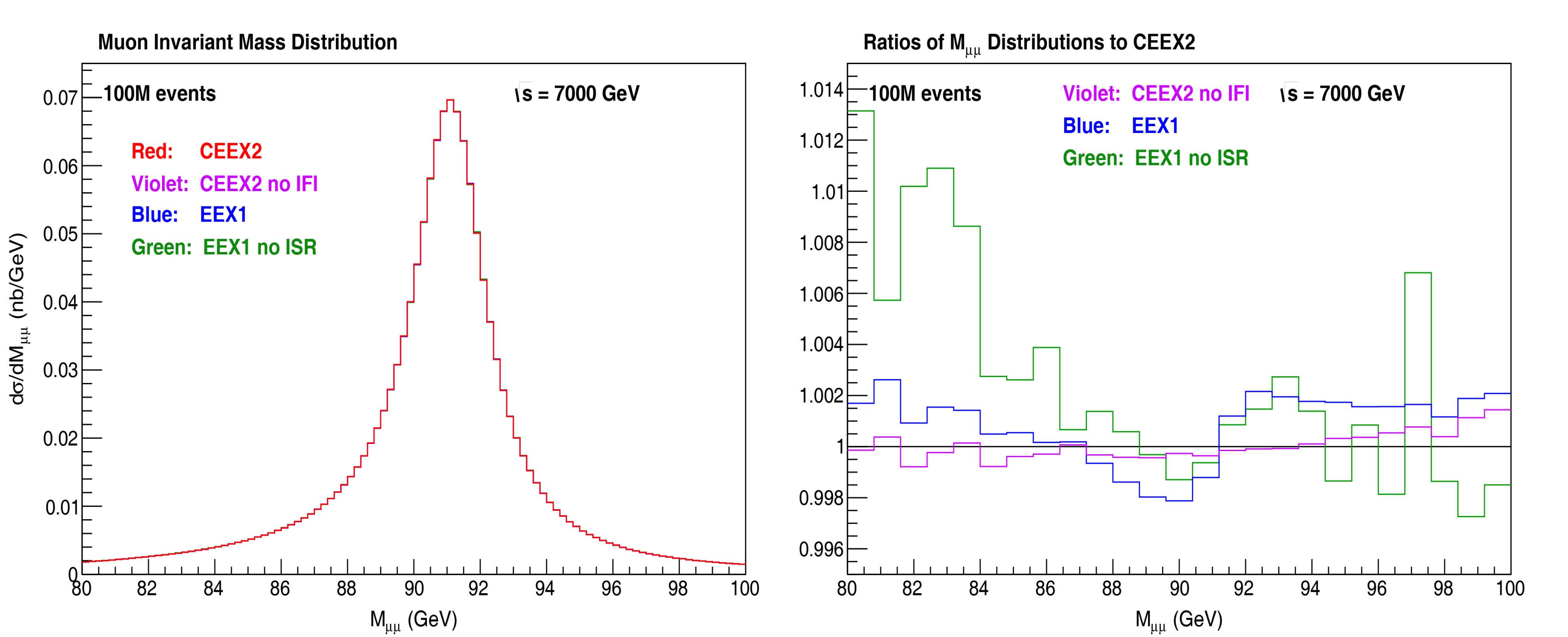


Dimuon Transverse Momentum

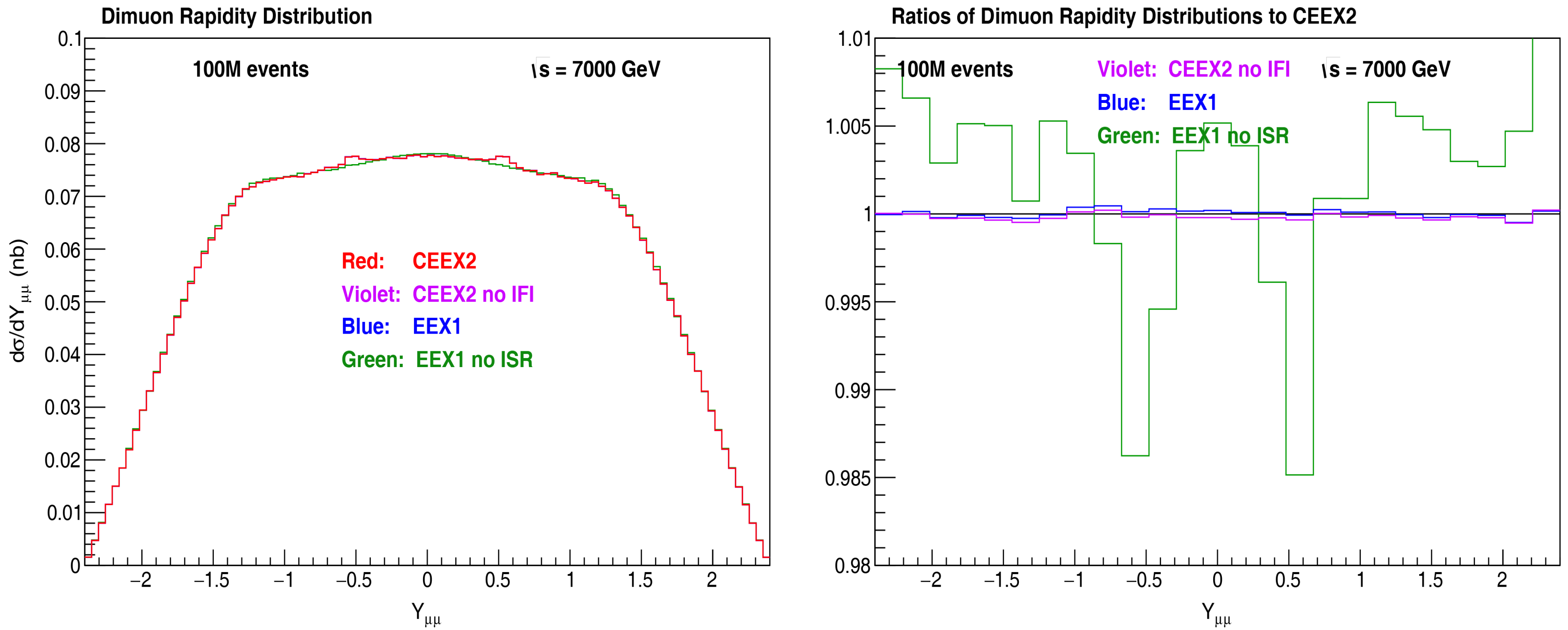




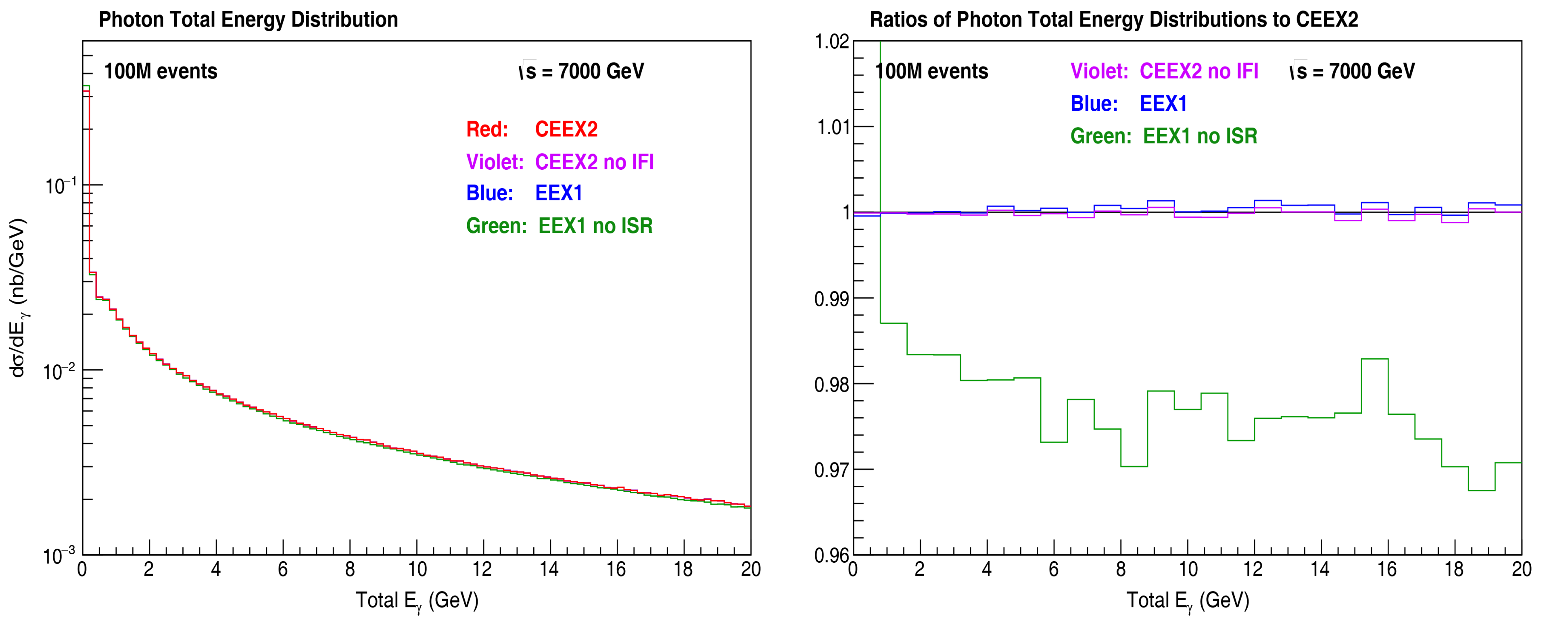
Dimuon Invariant Mass



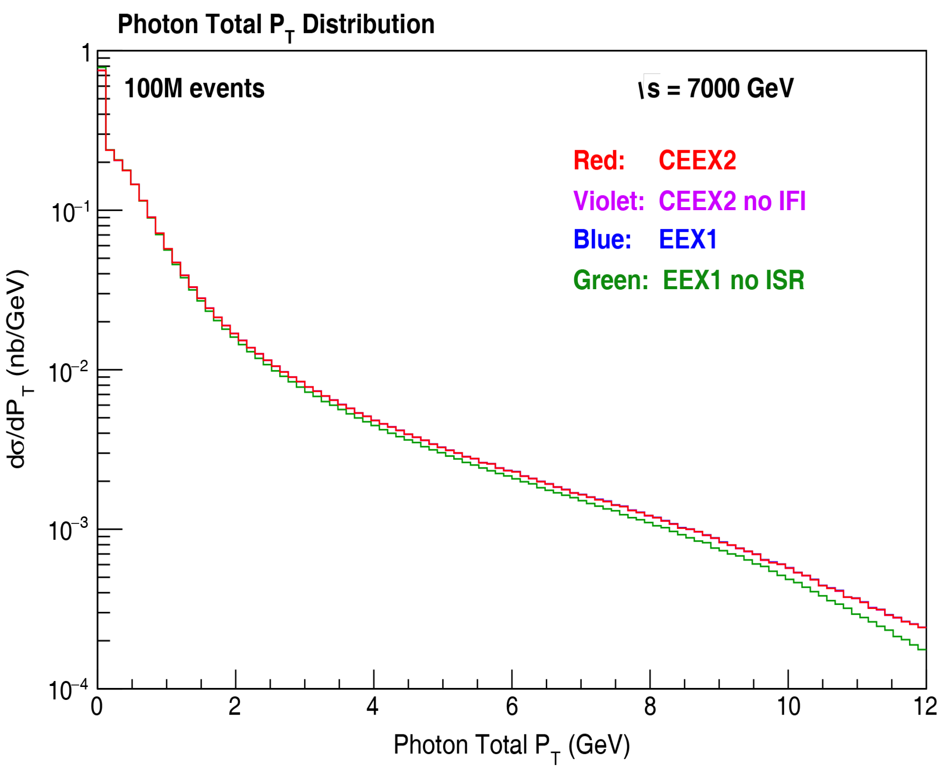
Dimuon Rapidity

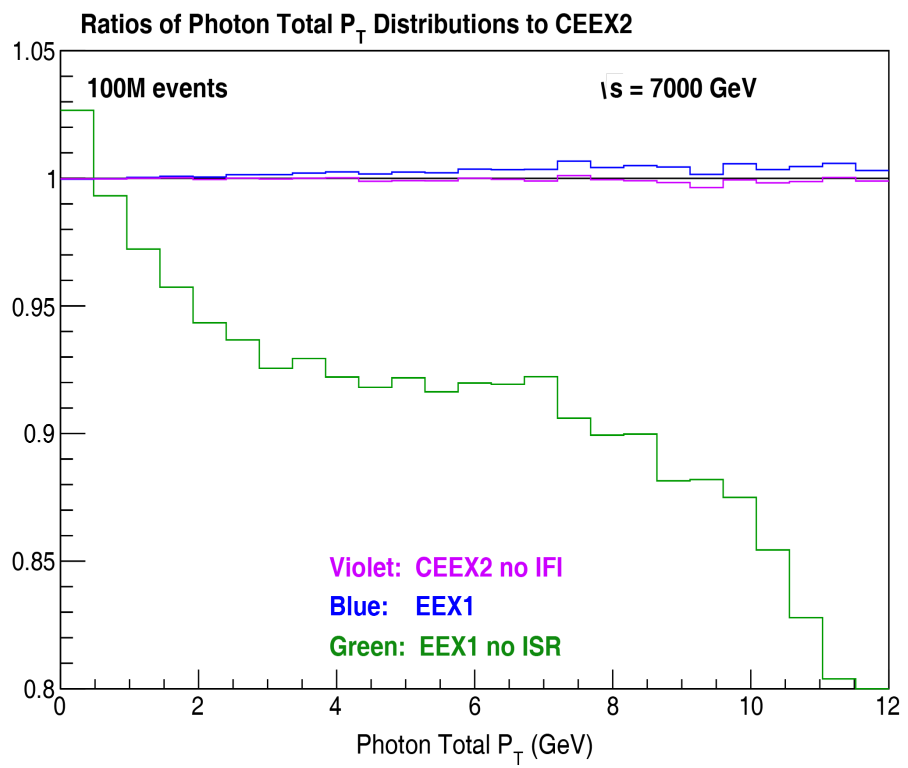


Total Energy of Photons

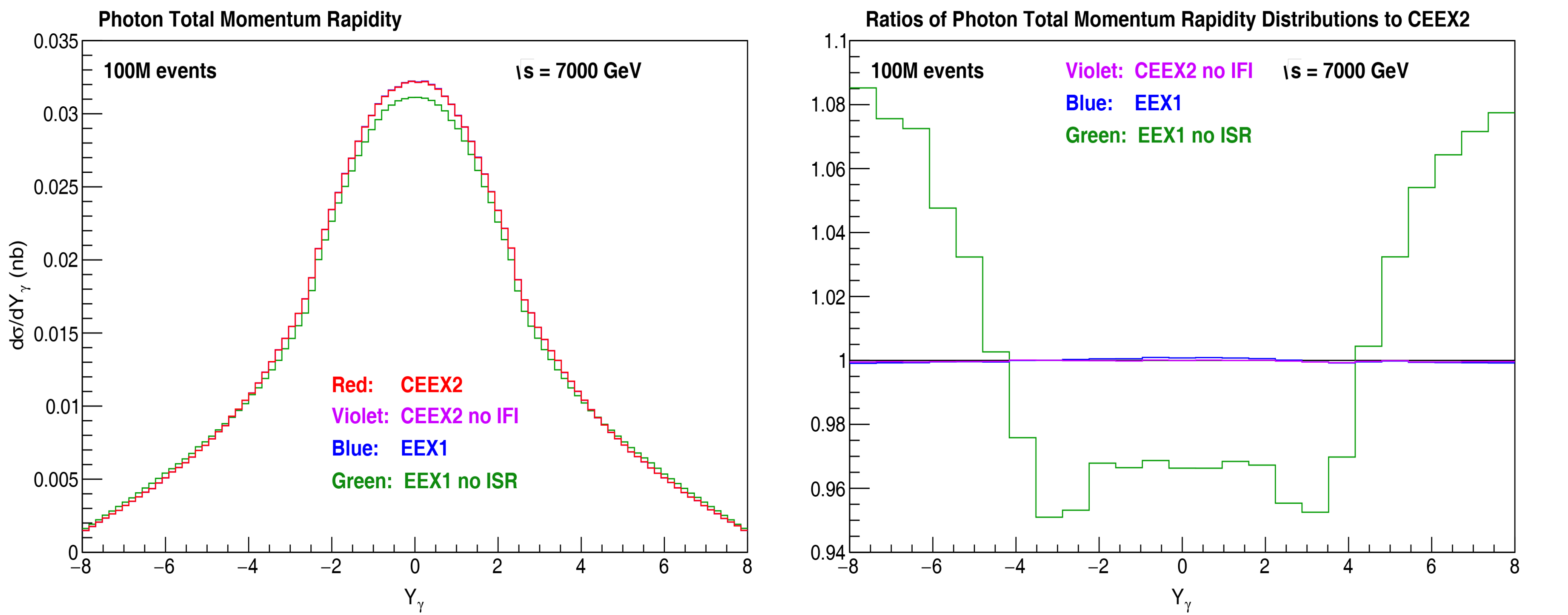


Total Transverse Momentum of Photons





Rapidity of Total Photon Momentum

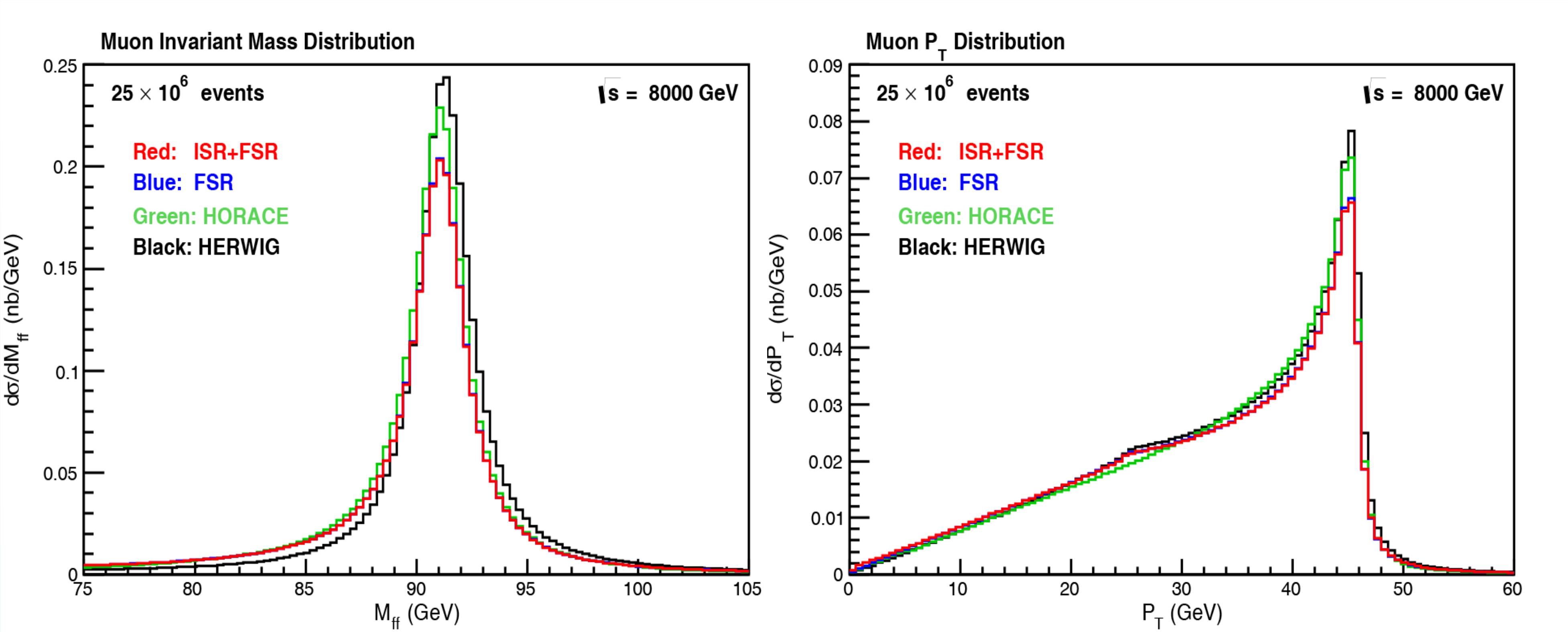


Comparisons of $\mathcal{KK}$ MC-hh and HORACE

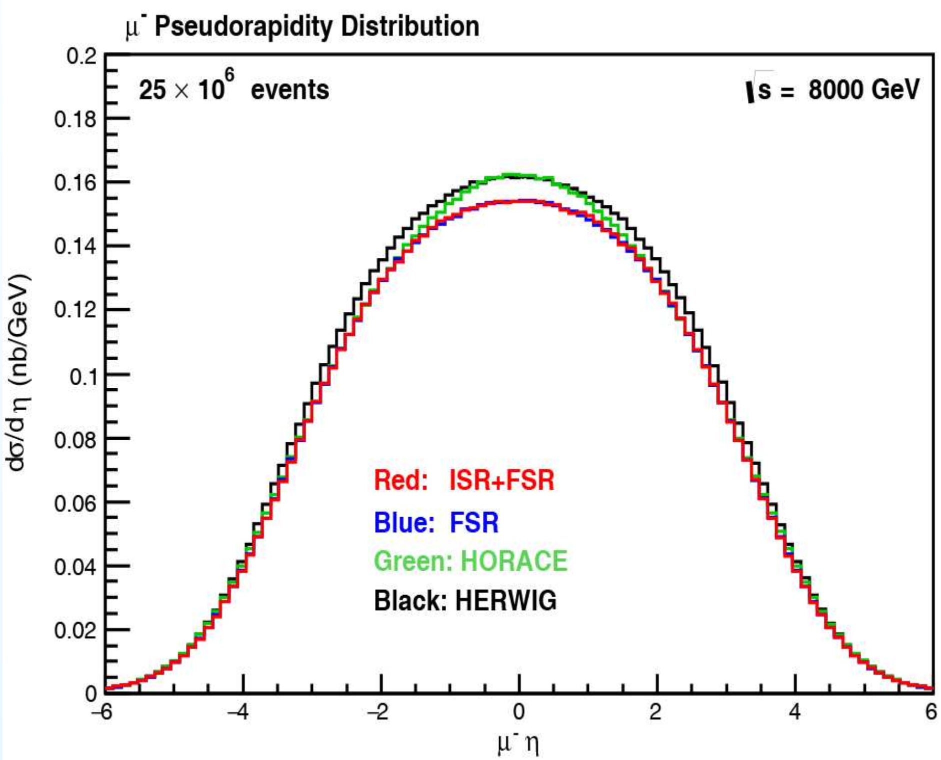
- The following are untuned comparison of muon production at 8 TeV with MSTW2008 PDFs and a cut 50 GeV $< M_{q\bar{q}} <$ 200 GeV.
- HORACE generated 10^8 events in its "best" EW scheme with exponentiated FSR.
- In this mode, HORACE should agree with $\mathcal{KK}$ MC-hh in its CEEX $\mathcal{O}(\alpha)$ exponentiated mode with ISR off. $\mathcal{KK}$ MC-hh generated 25×10^6 events.
- An unshowered HERWIG6.5 result for 10^8 events is also shown for a comparison without EW corrections. for HORACE.

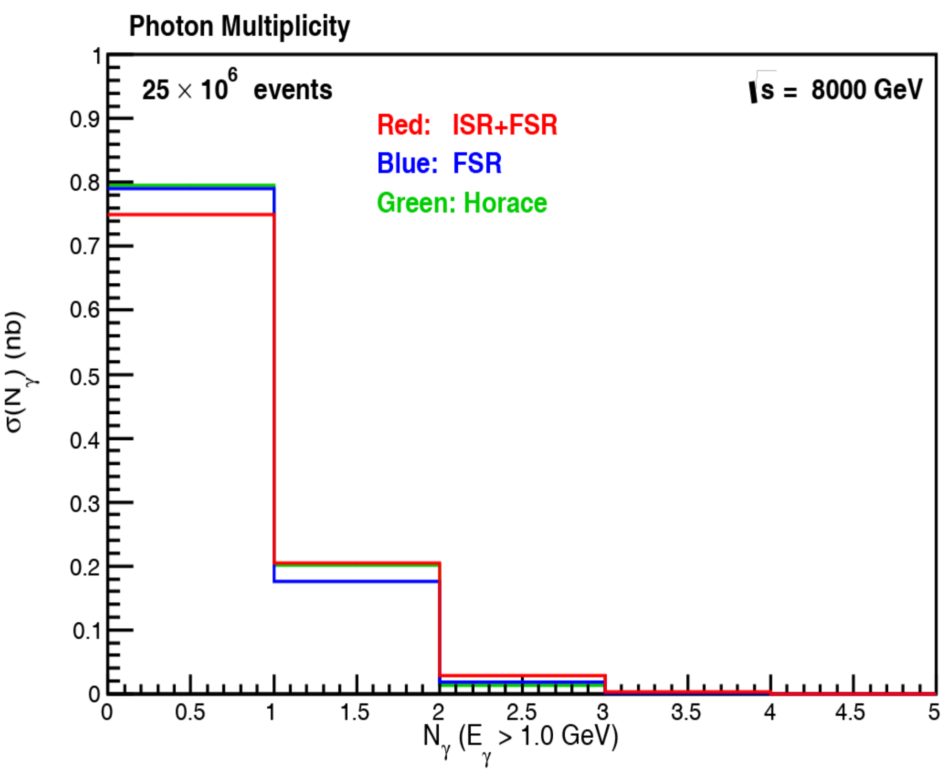
MC	EW Corrections	CS (pb)	Difference
$\mathcal{KK}$ MC-hh	$\mathcal{O}(\alpha^2 L)$ CEEX ISR + FSR + IFI	993 ± 1	$\times$
$\mathcal{KK}$ MC-hh	$\mathcal{O}(\alpha)$ CEEX FSR	991 ± 1	-0.20%
HORACE	$\mathcal{O}(\alpha)$ Exponentiated	1009.6 ± 0.4	$+1.7\%$
HORACE	Born level, no photons	1025.2 ± 0.4	$+3.2\%$
Herwig 6.5	Born level, no photons	1039.6 ± 0.2	$+4.7\%$

Unshowered Fermion Distributions

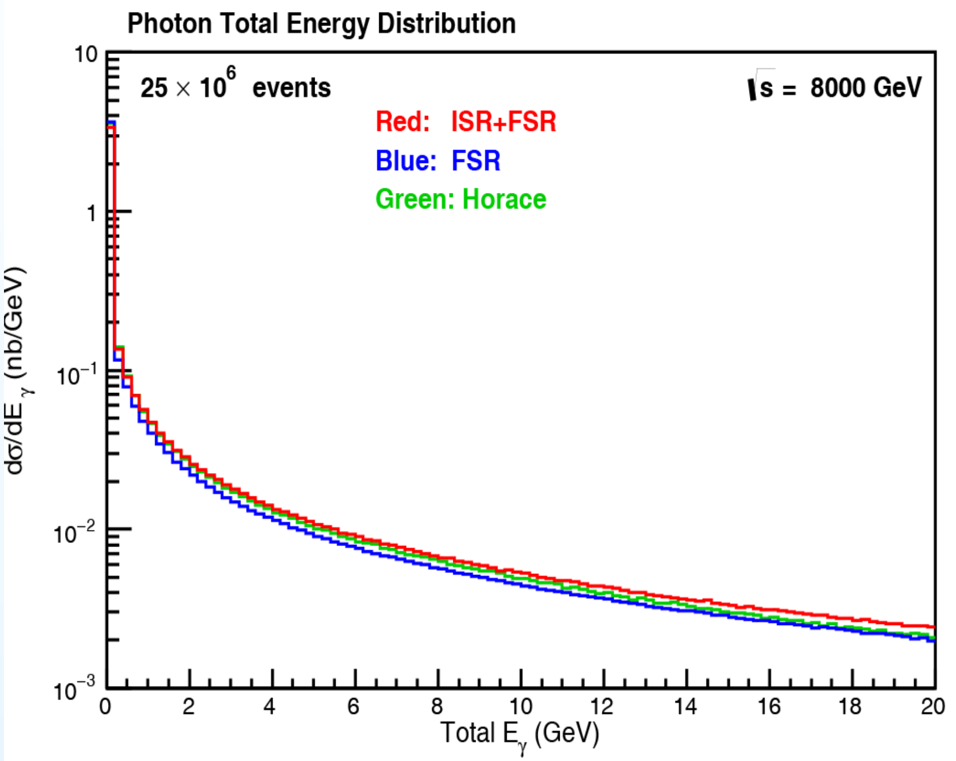


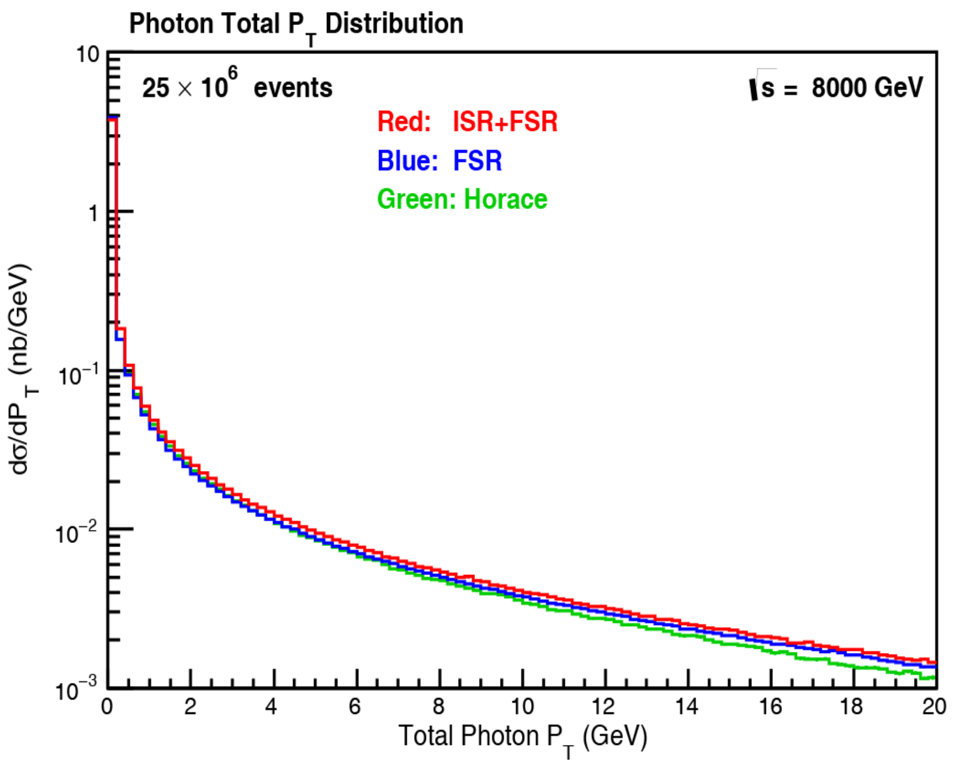
More Unshowered Distributions





Unshowered Photon Distributions





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)
- arXiv:1707.06502 (to appear in Phys. Rev. D)
- Future developments include:
- NLO QCD via the KrkNLO scheme of Jadach *et al.*
- Implementing a mode to add photons and EW corrections to previously generated events.
- 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.