HERWIRI2.1:

Exponentiated Electroweak Corrections in a Hadronic Event Generator

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Supported in part by grants from The Citadel Foundation

QCD⊗QED Exponentiation

- Motivation: the successful application of YFS exponentiation to BHLUMI, BHWIDE, $\mathcal{KK}$ MC KORALZ, KORALW, and related programs to achieve high precision in LEP processes.
- These programs benefit from a very efficient representation of N-photon phase space with complete control over the soft and collinear singularities for arbitrary numbers of photons.
- Real and Virtual IR singularities cancel exactly to infinite order.
- The non-abelian extension should have the same advantages for N-gluon amplitudes The IR singularity cancelation is more complicated, but is still gauranteed at all orders.

The HERWIRI Project

- The class of programs based on this idea has been named HERWIRI, for High Energy Radiation With Infra-Red Improvements, a name acknowledging the fact that our present efforts build upon one of the leading shower generators, HERWIG.
- The structure is not tied to a particular shower, and our ultimate goal is a complete shower-generator based entirely on QCD$\otimes$QED nonabelian exponentiation with exact $\mathcal{O}(\alpha_s^2, \alpha_s\alpha, \alpha^2)$ residuals.
- The first program to be publicly released in this series was HERWIRI1, which applied the proposed exponentiation to the shower's splitting kernels.
- Work on incorporating $\mathcal{O}(\alpha)$ (or better) EWK corrections in the same exponentiation paradigm began in parallel, and is close to the point of producing results. This program is called HERWIRI2. It is independent of HERWIRI1, although the two will eventually be combined.

HERWIRI2

- The success of YFS exponentiation in the precision event generator $\mathcal{KK}$ MC (S. Jadach, B.F.L. Ward, and Z. Wąs) for $e^+e^- \to Z\gamma^* \to f\overline{f}$ provides a natural starting point for incorporating EWK corrections to the parton-level process.
- HERWIRI2 is a hybrid of $\mathcal{KK}$ MC with a with hadronic event generator, HERWIG6.5 in this talk, but an external generator can be used.
- HERWIRI2 provides a precise calculation of the hard process and generates multiple ISR and FSR photon emission. This can be showered internally or externally.
- The current version of HERWIRI2 is HERWIRI2.1.

$\mathcal{KK}$ 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: $\alpha, \alpha L, \alpha^2 L^2, \alpha^2 L$.
- Exact collinear bremsstrahlung for up to three γ's.
- $\mathcal{O}(\alpha)$ EWK corrections and more are included via DIZET 6.21.
- τ decay is simulated using TAUOLA.
- The current edition of KKMC, v. 4.22, supports quark initial states.

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 $k = 0$. (HERWIRI1 implements this for soft gluons.)

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 $q\overline{q} \to f\overline{f}$ has the form

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

where

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

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:

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

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

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

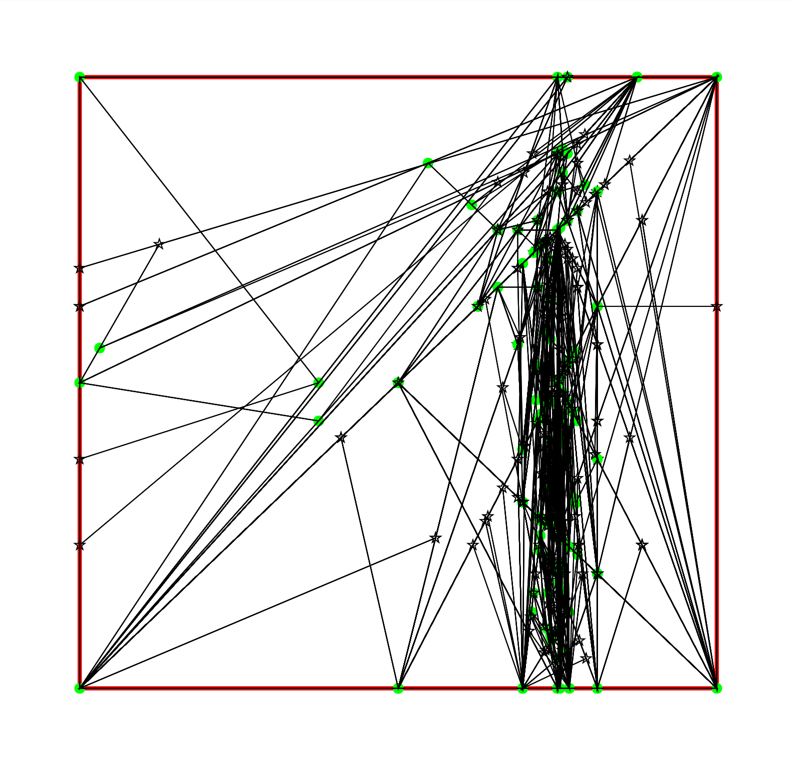
  where the final state phase space includes p_3, p_4 and k_i, $i = 1, \cdots, n$ and multiple gluon radiation + hadronization is included through a shower.

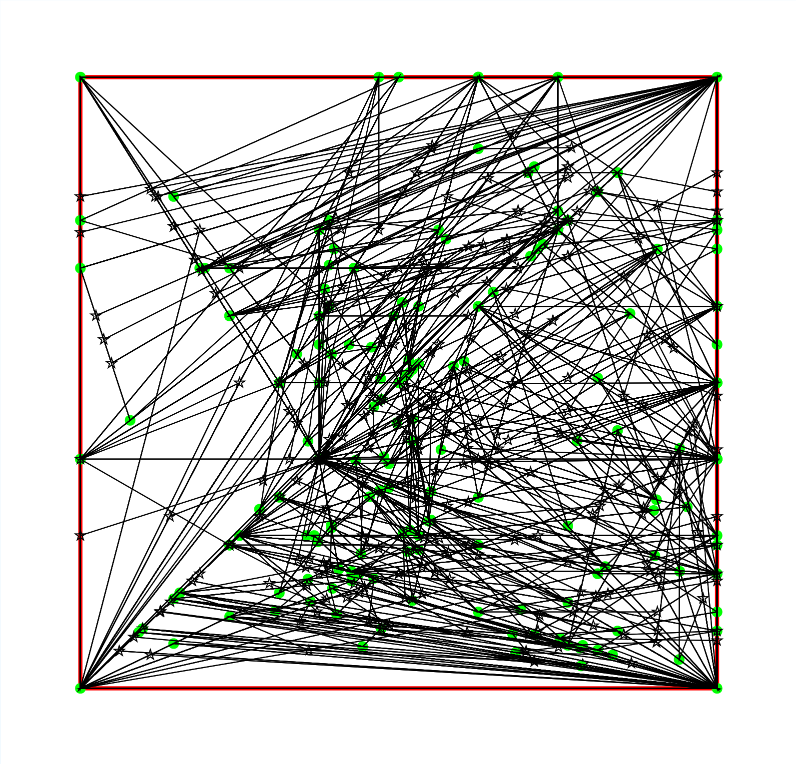
Event Generation

- 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.

Event Generation

- The figures below show the map for generating Q^2 and x_1 with ISR off, first with the simple mapping used in the program, and second with HERWIG's mapping which is included for comparison.



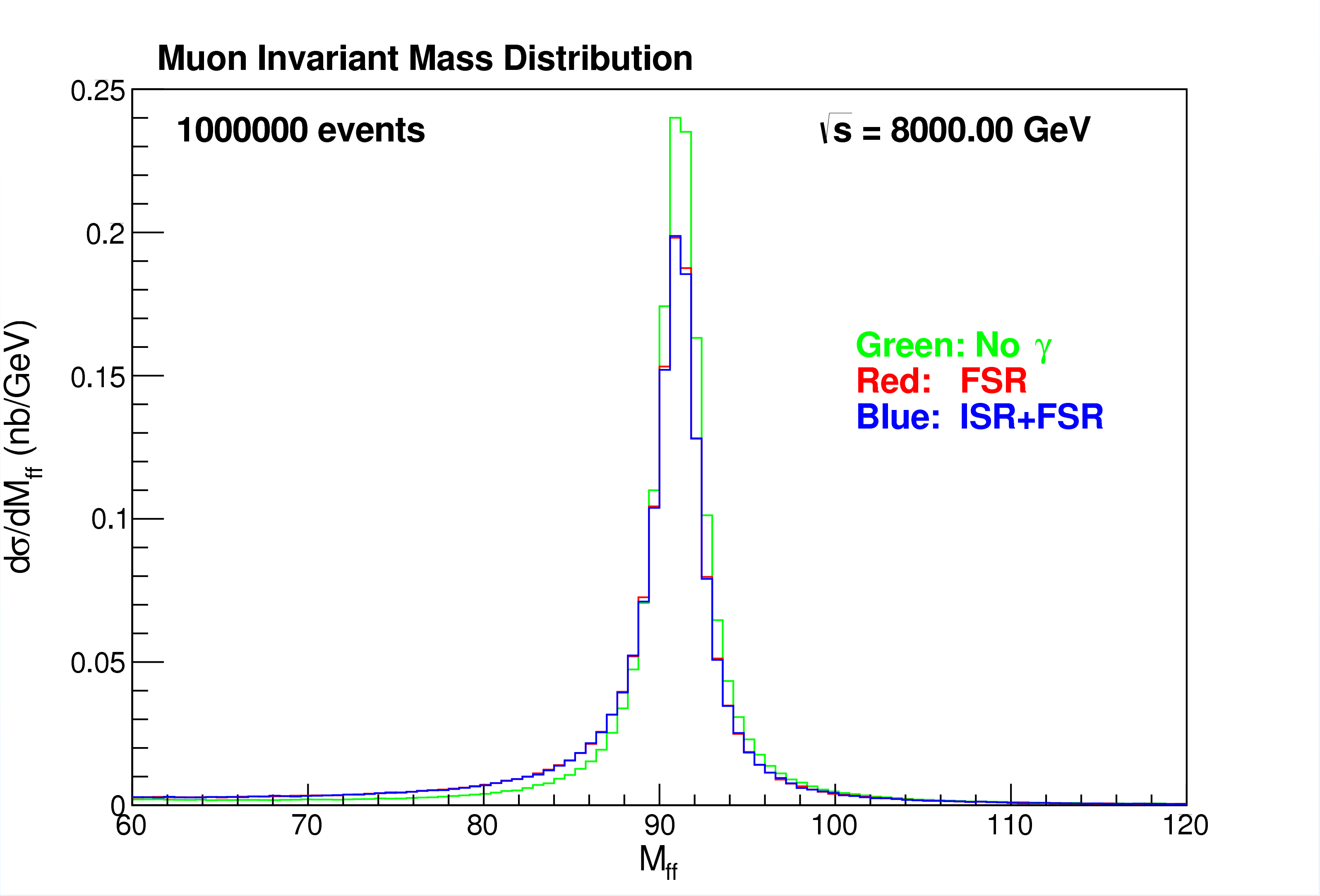


HERWIRI2 Results: Showered

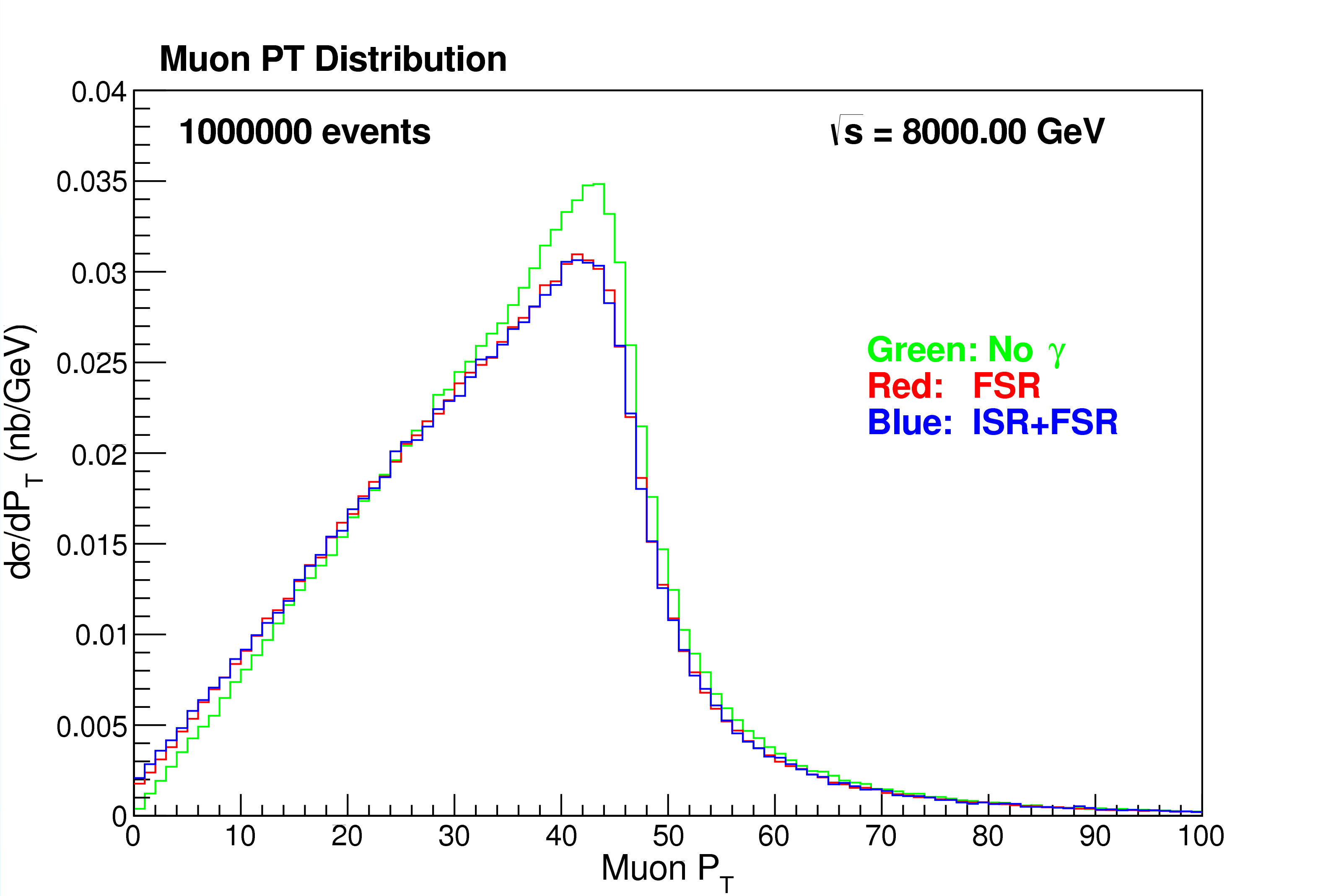
- Herwiri2 can be run without electroweak corrections and photons, in which case it simply replaces the hard process generation mechanism, without essentially changing the physics. Corrections can be added incrementally to test their effect.
- Test runs: 10^6 events, MSTW2008 PDFs, Generator cut 50 GeV < $M_q q$ < 200 GeV.
- Showered tests: HERWIG6.521

HERWIG		1041 ± 1 pb	
HERWIRI2	No Photons	1036 ± 1 pb	(-0.5%)
HERWIRI2	FSR+EWK	992 ± 1 pb	(-5.3%)
HERWIRI2	ISR+FSR+EWK	991 ± 1 pb	(-5.0%)

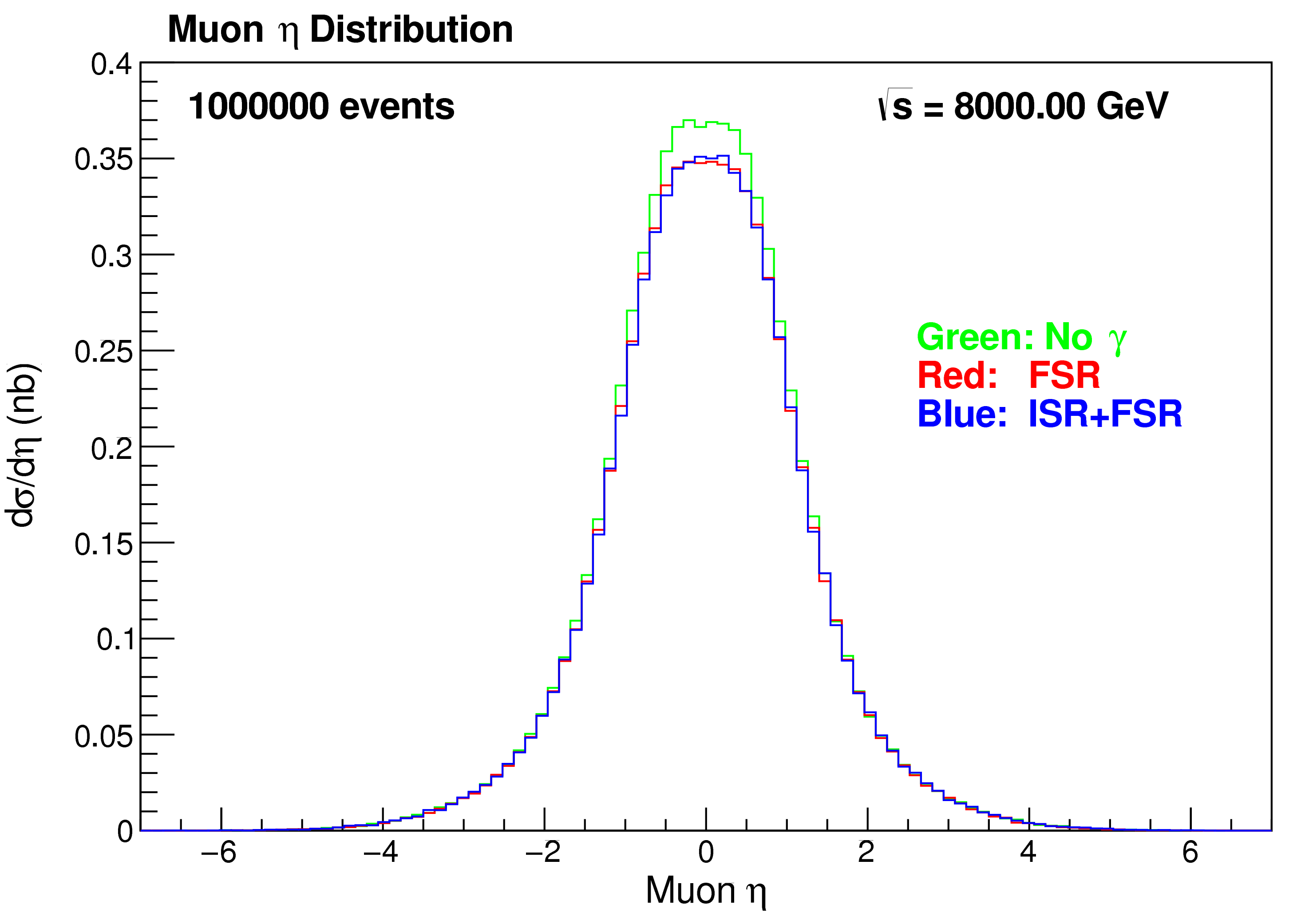
Muon Invariant Mass



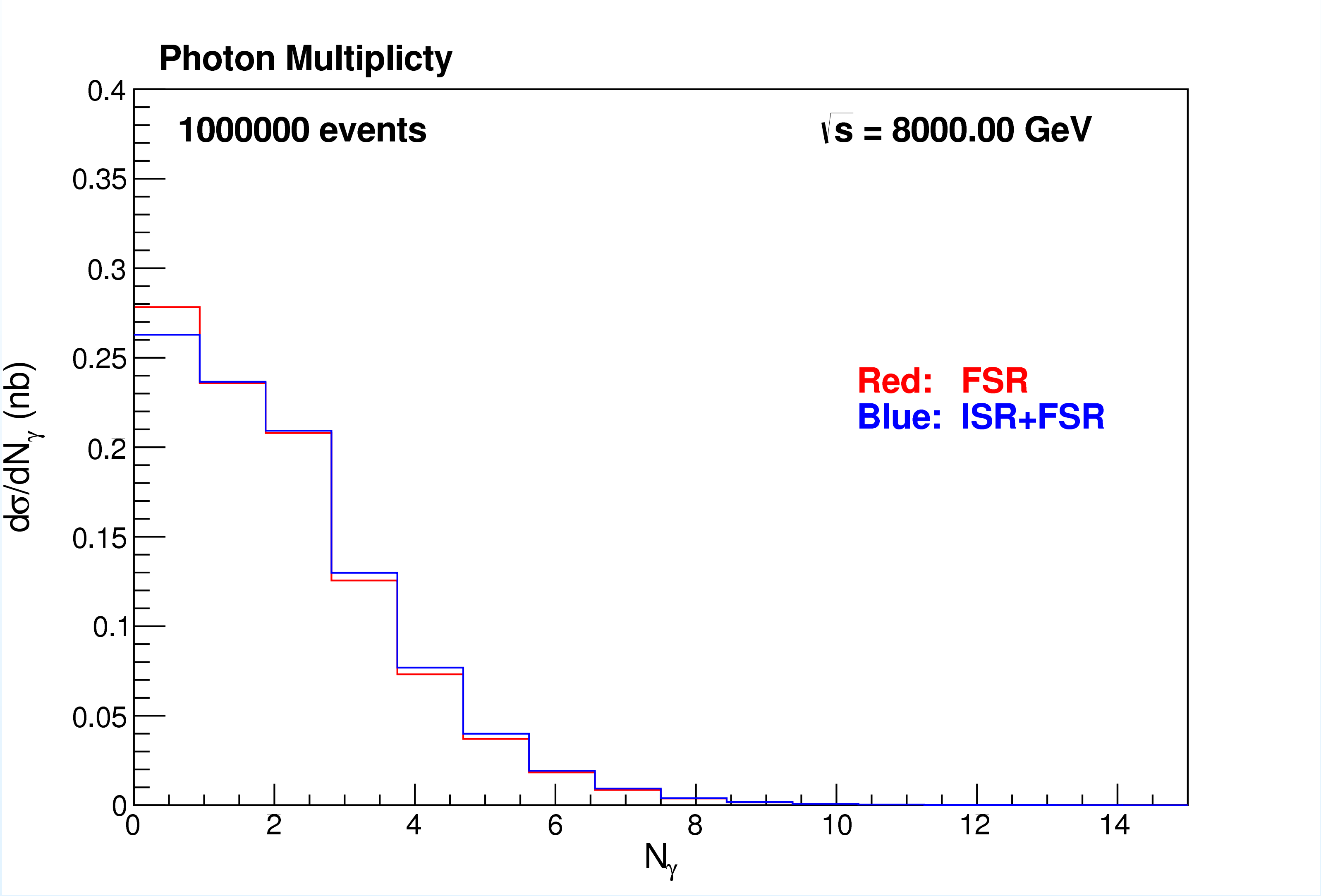
Muon Transverse Momentum



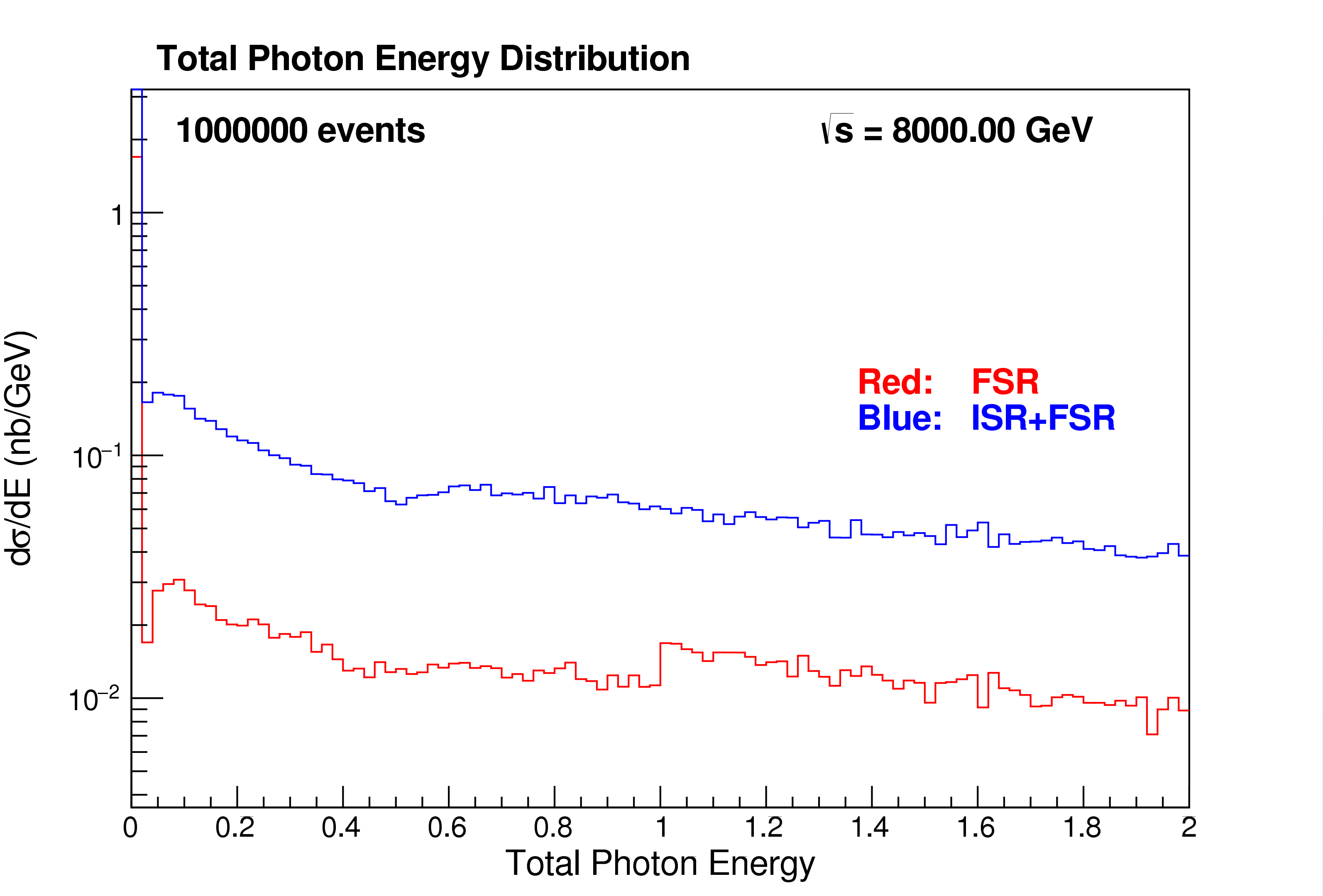
Muon PseudoRapidity



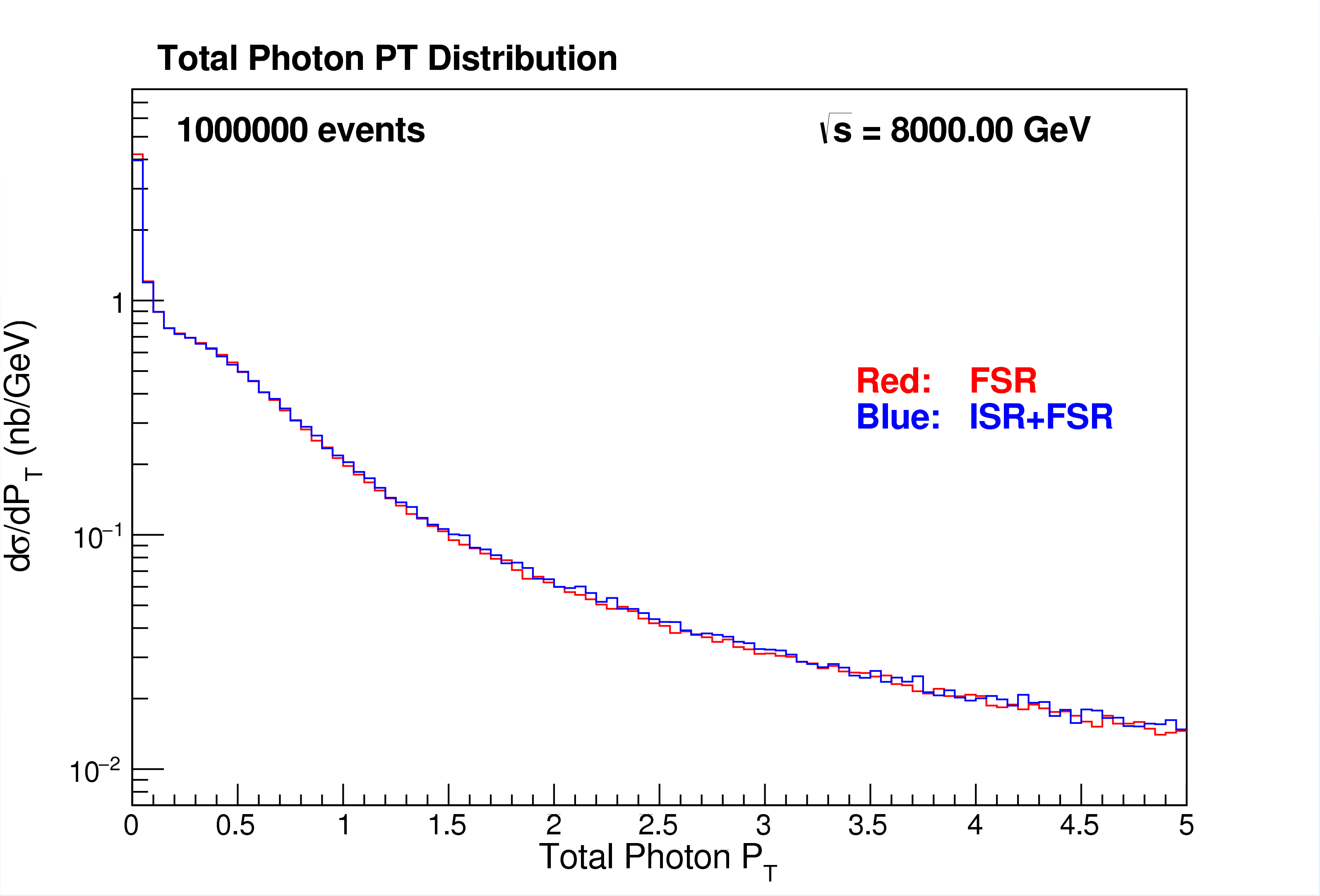
Photon Multiplicity



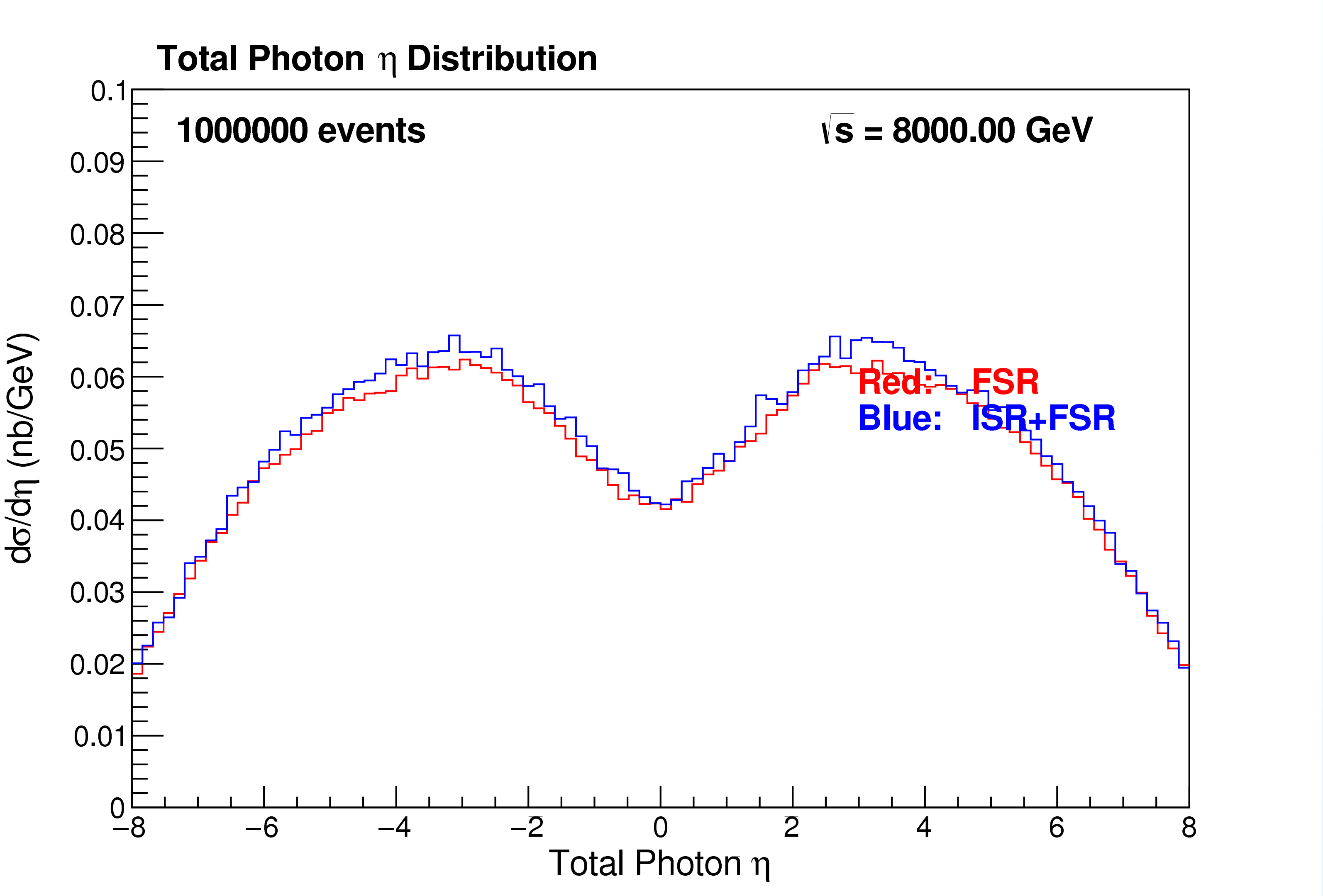
Total Energy of Photons



Total Transverse Momentum of Photons



PseudoRapidity of Total Photon Momentum

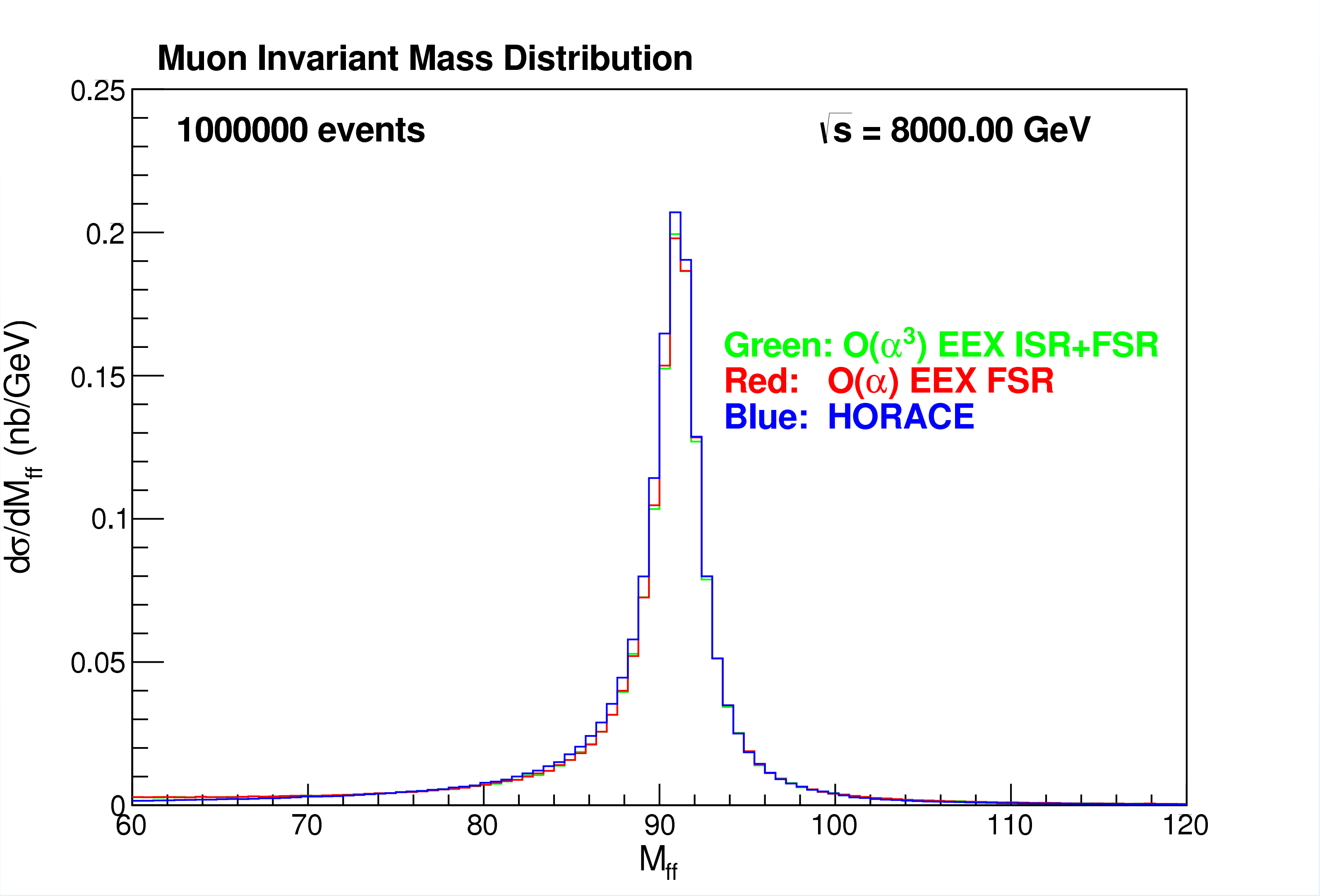


HERWIRI2 Results: Unshowered

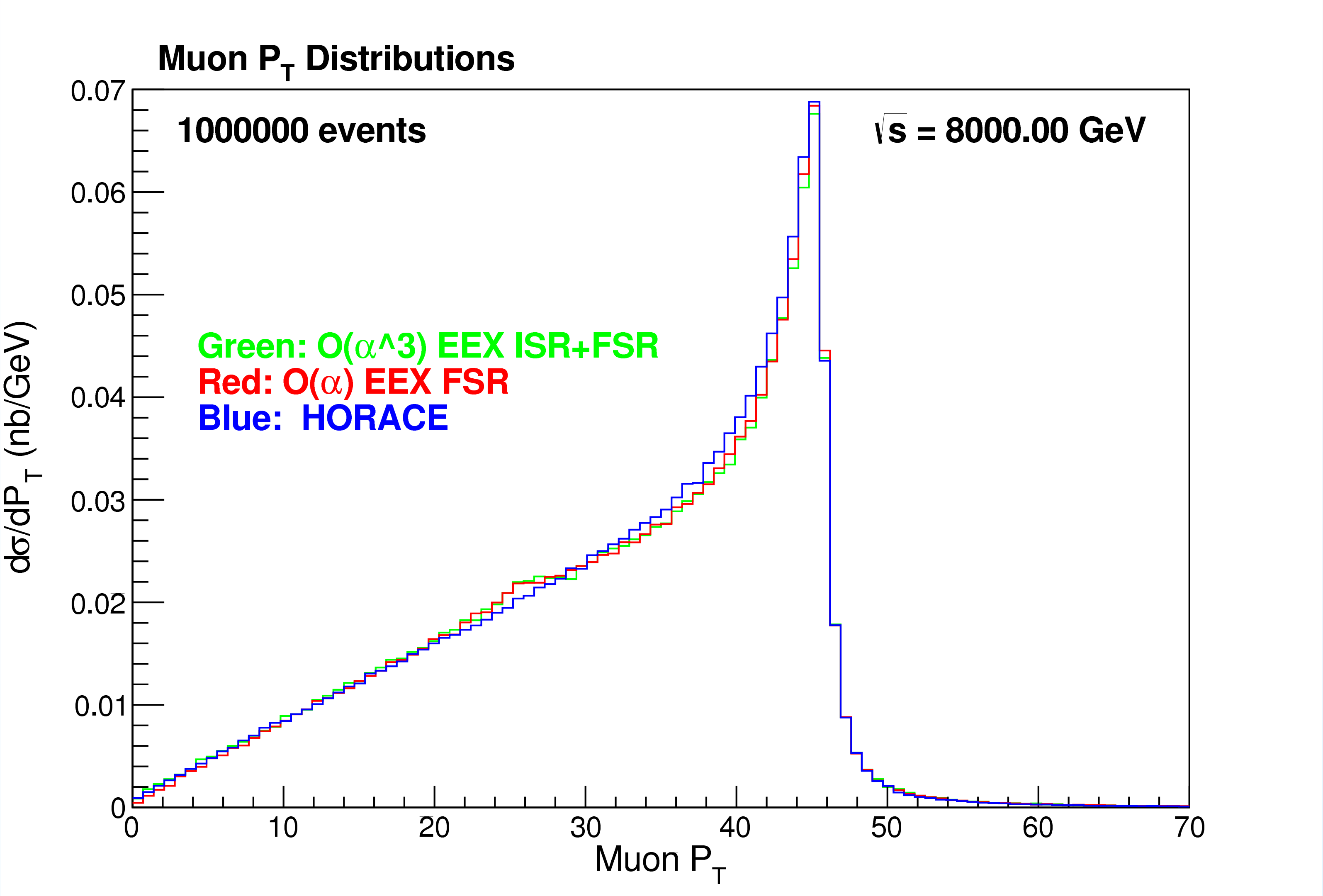
- Some comparisons have been made with HORACE with the shower off, and the same inputs: MSTW2008 PDFs, 50 GeV<$M_q q$«200 GeV.
- The Herwiri2 test runs KKMC at order α^3 pragmatic EEX, meaning a LL expansion is used, keeping corrections $\alpha^3 L^3$, $\alpha^2 L$, α beyond the Born level α^0, with exponentiation.
- Herwiri2 was also compared at order α^2 pragmatic EEX, meaning terms $\alpha^2 L^2$, α are kept beyond the Born level, with exponentiation, and α^1 exponentiated, but the differences are too small to be seen in a 10^6 event sample.
- Horace has order α Electroweak corrections and exponentiated FSR. Agreement, without detailed tuning, is to 1.8%.

HERWIRI2	$\mathcal{O}(\alpha^3)^{\rm prag}$ EEX ISR+FSR	993 ± 1 pb
HERWIRI2	$\mathcal{O}(\alpha)$ EEX FSR	991 ± 1 pb
HORACE	$\mathcal{O}(\alpha)$ exp FSR	1009 ± 4 pb

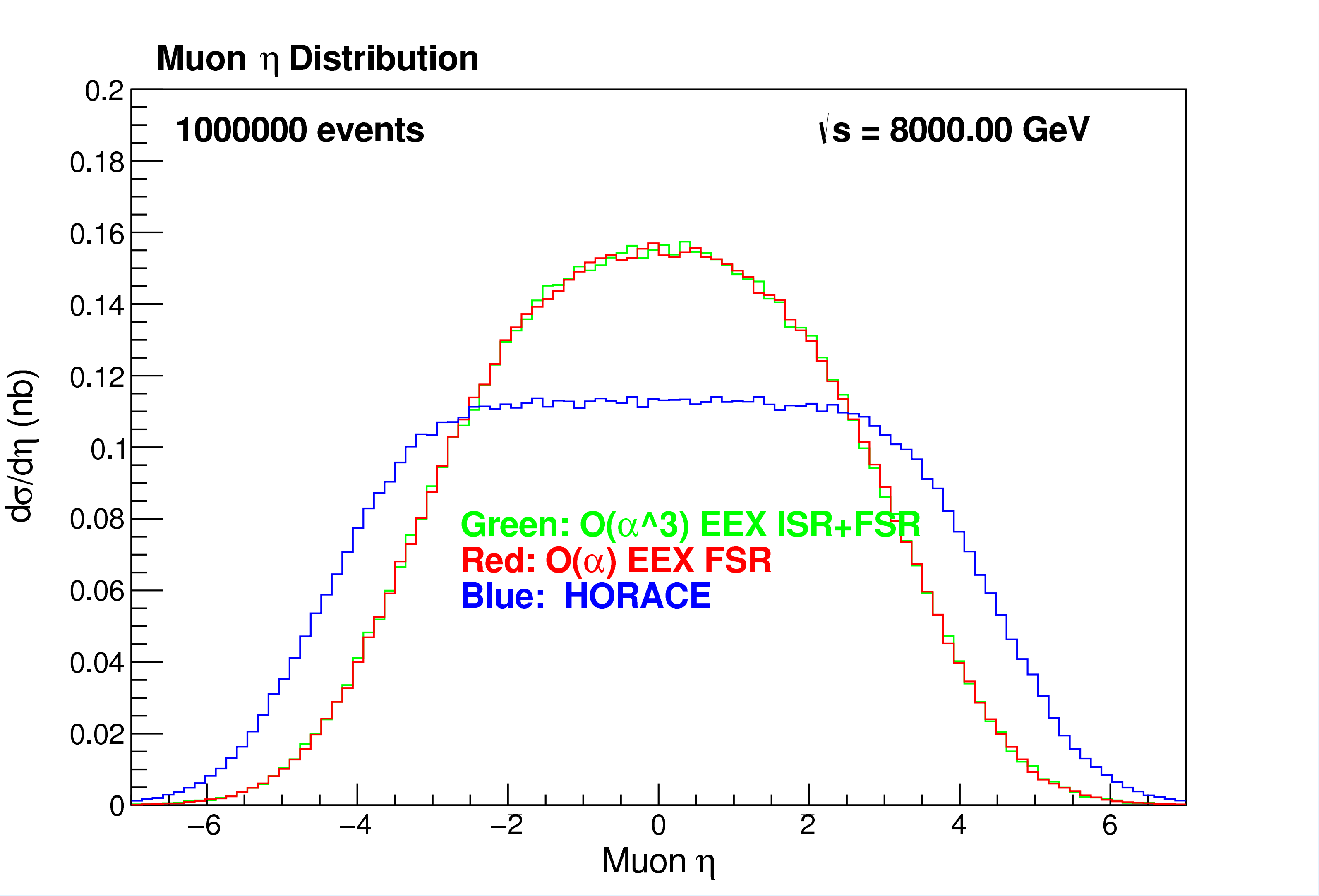
Muon Invariant Mass



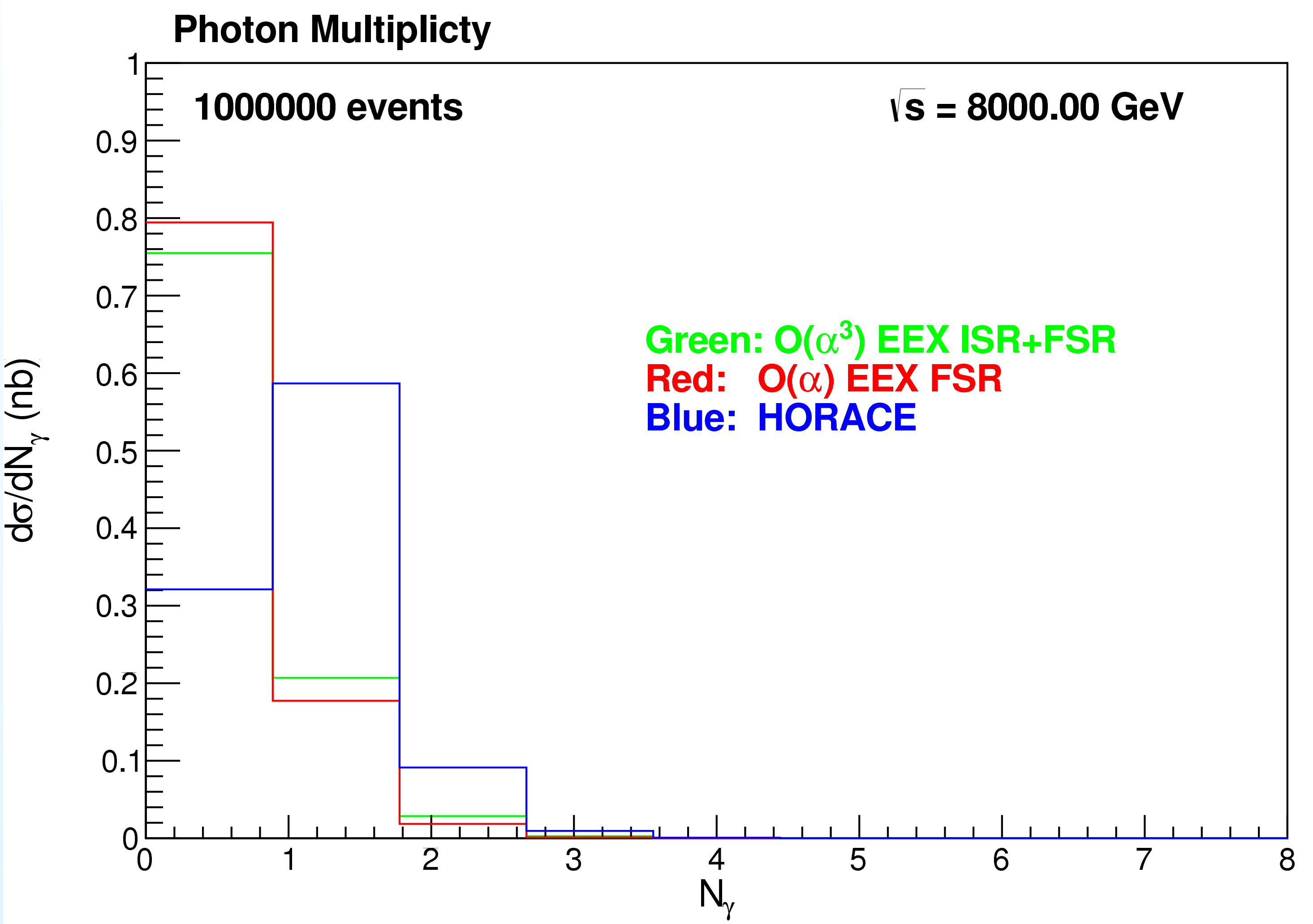
Muon Transverse Momentum



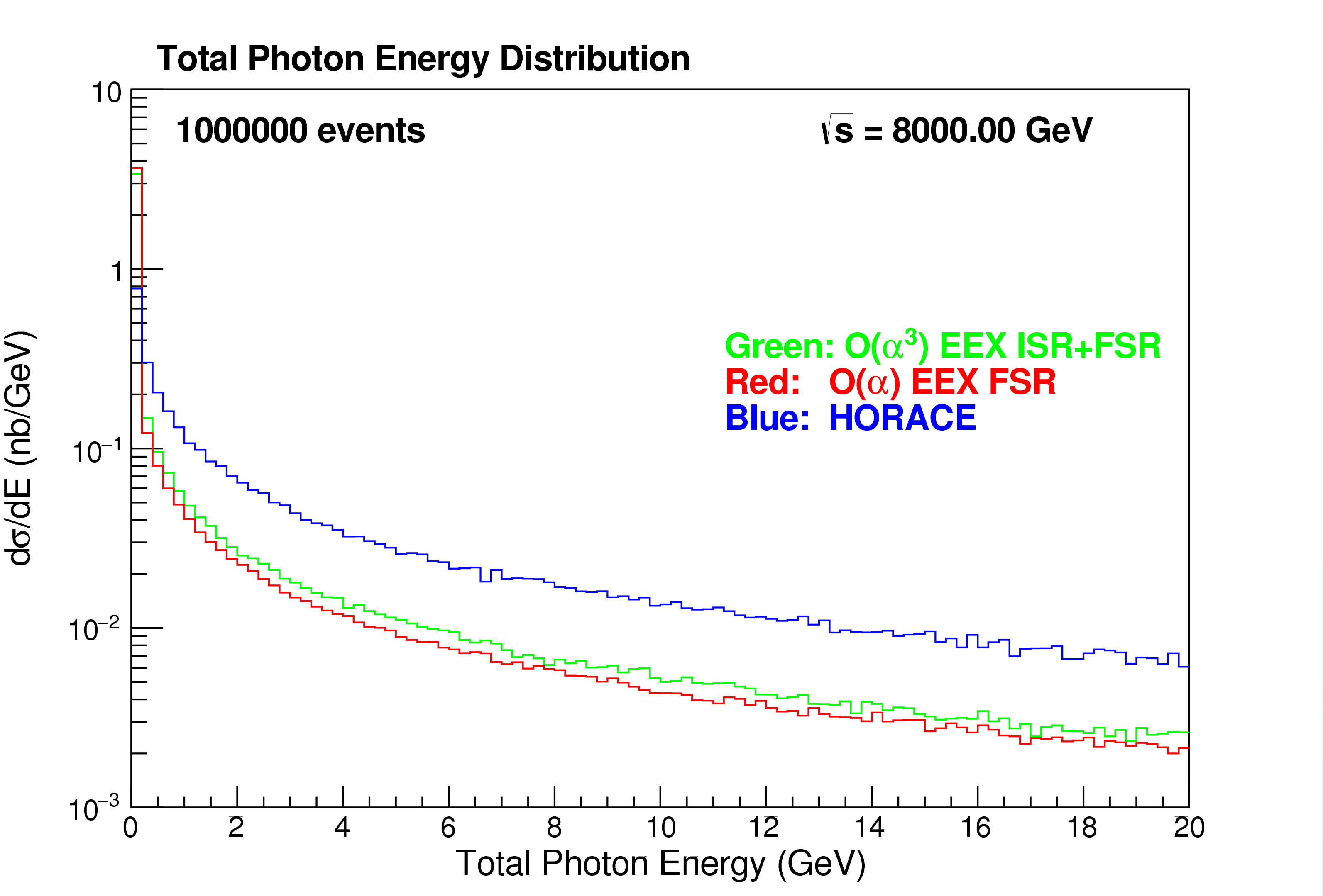
Muon PseudoRapidity



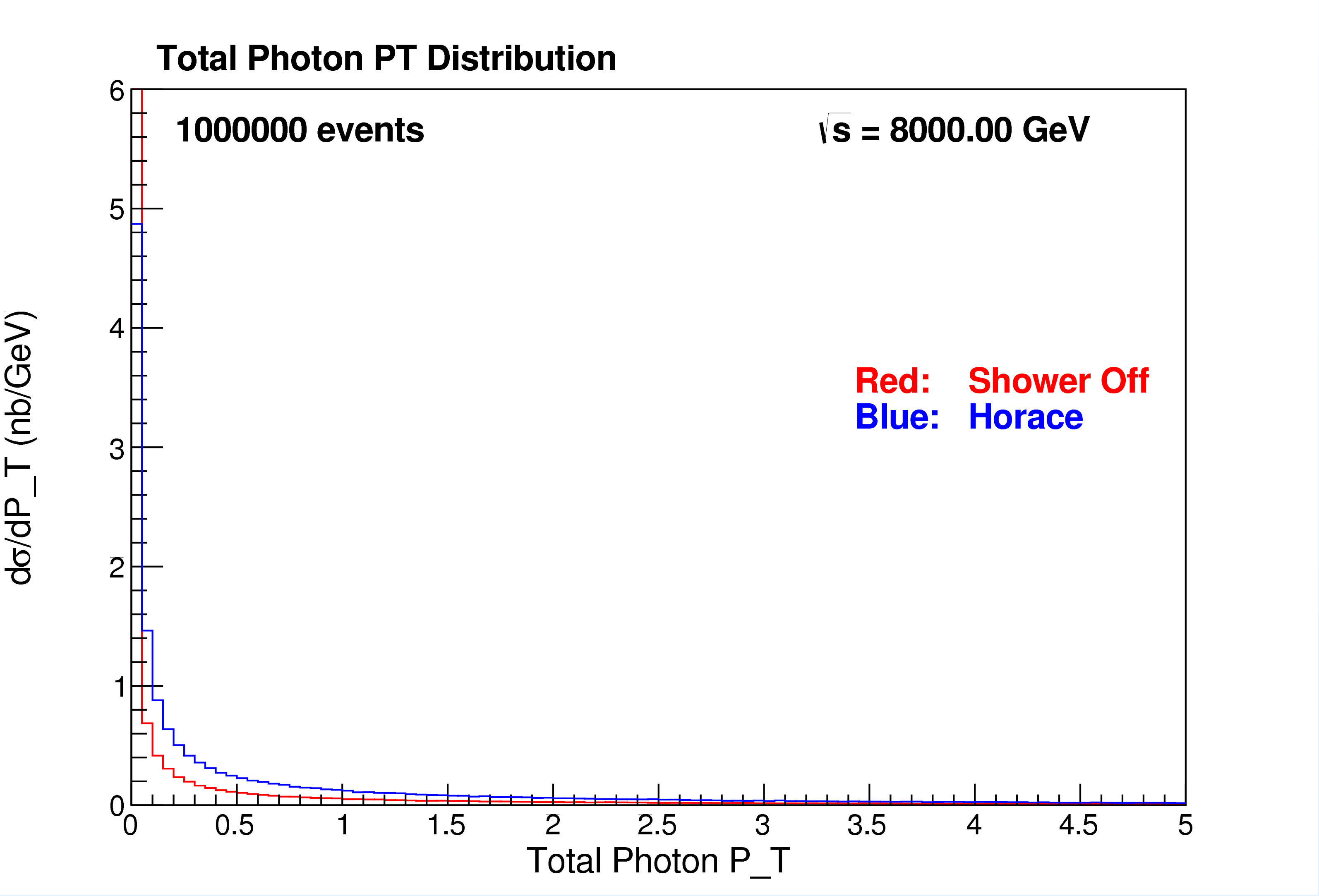
Photon Multiplicity



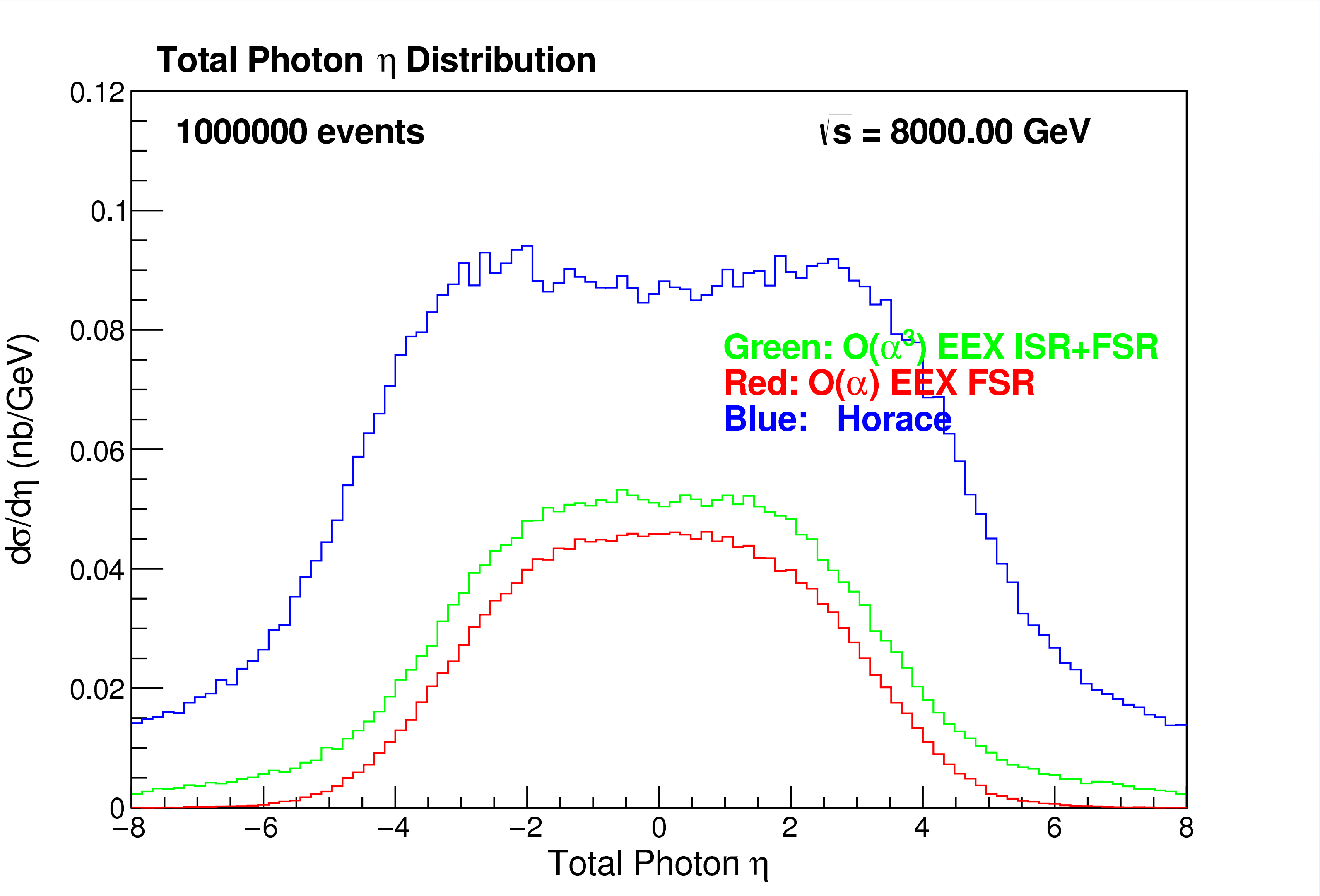
Total Energy of Photons



Total Transverse Momentum of Photons



PseudoRapidity of Total Photon Momentum



Summary

- HERWIRI2 includes multi-photon emission from both the initial and final states in Z production, with order α EW corrections.
- The EEX option is working now, CEEX is being tested.
- The program is still being refined to improve the weight distribution and efficiency.
- Further comparisons will be coming soon.
- HERWIRI2 is a step toward our goal of an event generator based on nonabelian QED$\otimes$QCD exponentiation and exact $\mathcal{O}(\alpha_s^2, \alpha_s\alpha, \alpha^2)$ residuals.