SANC system and its application for LHC

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on behalf of SANC group

ACAT 2013
16.05.2013, Beijing, China

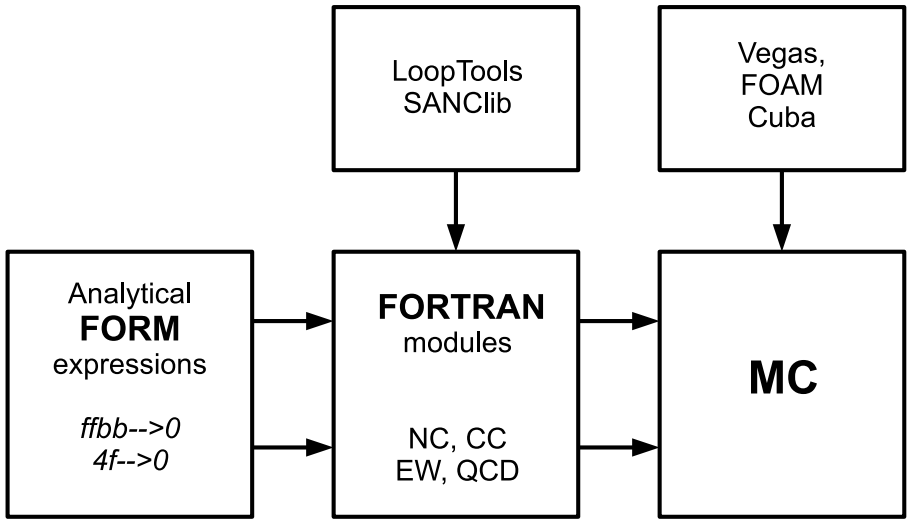
Outline

- SANC project
- Drell-Yan processes in SANC
- FSR QED in single W and Z production
- `mcsanc` integrator
- Summary

SANC project

- SANC: project to Support of Analytic and Numeric calculations for experiments at Colliders
- SANC web-page: http://sanc.jinr.ru. Stand-alone modules for differential cross-sections as well as Monte Carlo programs (integrators and generators) are available to download
- References:
  - A. Andonov et al., *SANCscope - v.1.00*, Comput. Phys. Commun. 174 (2006) 481
  - A. Andonov et al., *Standard SANC Modules*, Comput. Phys. Commun. 181 (2010) 305
  - D. Bardin et al., *Implementation of SANC EW corrections in WINHAC Monte Carlo generator*, Acta Phys. Pol. B40 (2009) 75
  - D. Bardin et al., *SANC integrator in the progress: QCD and EW contributions*, JETP Lett. 96 (2012) 285-289

SANC approach and features



- Calculation are performed with the on-mass-shell renormalization scheme in R_ξ gauge
- The total EW NLO cross section is divided into five terms:

$$\sigma^{\text{1-loop}} = \sigma^{\text{Born}} + \sigma^{\text{virt}}(\lambda) + \sigma^{\text{soft}}(\lambda, \bar{\omega}) + \sigma^{\text{hard}}(\bar{\omega}) + \sigma^{\text{subt}}$$

  The auxiliary parameters $\bar{\omega}$ and λ cancel out after summation
- The Passarino-Veltman reduction is applied
- For virtual corrections we use `SANC` and `LoopTools` libraries
- $\overline{\text{MS}}$ or **DIS** subtraction schemes are used

Drell-Yan processes in SANC

- Charged current Drell-Yan (CC): $pp \to \ell^+\nu_\ell + X$, $pp \to \ell^-\bar{\nu}_\ell + X$

  Subprocesses for W^+ production:

$$q + \bar{q}' \to W^+ \to \ell^+ + \nu_\ell$$
$$q + \gamma/g \to q' + W^+ \to q' + \ell^+ + \nu_\ell$$
$$\bar{q}' + \gamma/g \to \bar{q} + W^+ \to \bar{q} + \ell^+ + \nu_\ell$$

  Subprocesses for W^- production:

$$q' + \bar{q} \to W^- \to \ell^- + \bar{\nu}_\ell$$
$$q' + \gamma/g \to q + W^- \to q + \ell^- + \bar{\nu}_\ell$$
$$\bar{q} + \gamma/g \to \bar{q}' + W^- \to \bar{q}' + \ell^- + \bar{\nu}_\ell$$

  $qq' = \{ud, us, cd, cs\}, \quad \ell = \{e, \mu, \tau\}$

Drell-Yan processes in SANC

- Neutral current Drell-Yan (NC): $pp \to \ell^+\ell^- + X$

  Subprocesses for Z production:

$$
\begin{aligned}
& q + \bar{q} \to \gamma/Z \to \ell^+ + \ell^- \\
& q + \gamma/g \to q + \gamma/Z \to q + \ell^+ + \ell^- \\
& \bar{q} + \gamma/g \to \bar{q} + \gamma/Z \to \bar{q} + \ell^+ + \ell^- \\
& \gamma + \gamma \to \ell^+ + \ell^-
\end{aligned}
$$

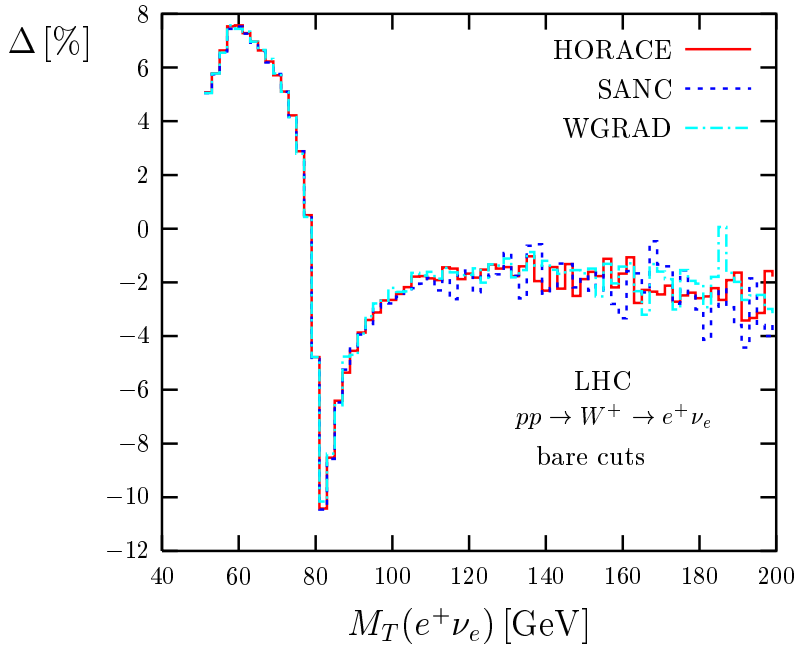
$q = \{u, d, s, c, b\}, \quad \ell = \{e, \mu, \tau\}$

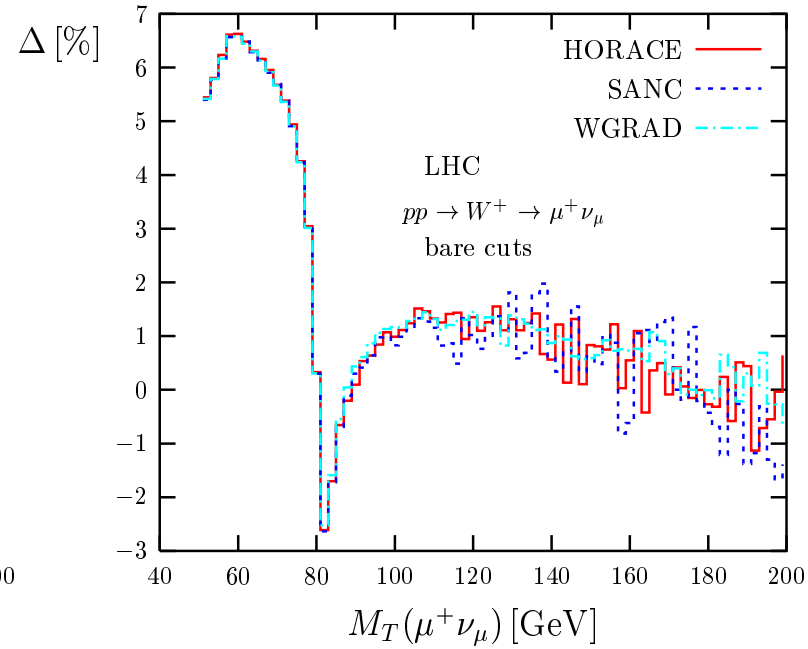
Tuned comparison of different codes

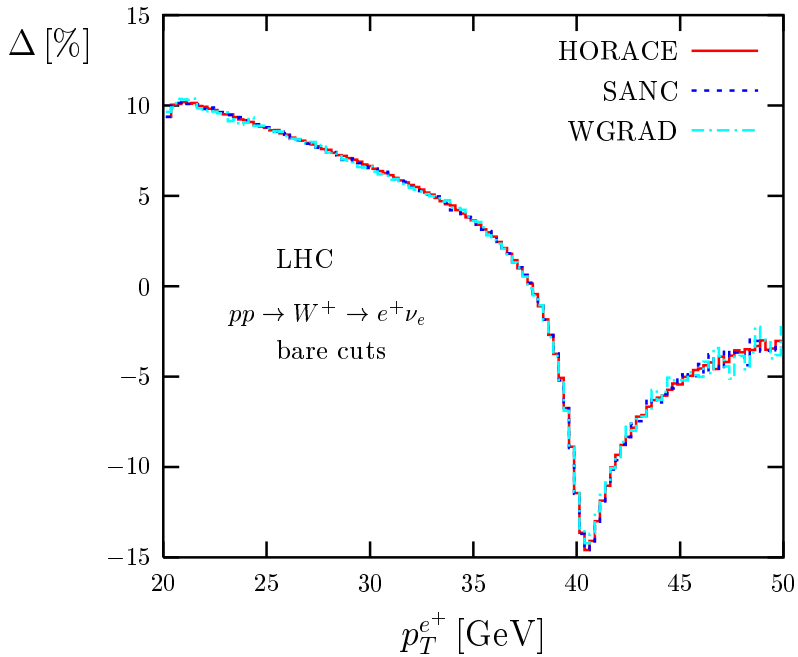
The tuned comparison between SANC and other codes for total cross-section and differential distributions of different observables for CC and NC DY processes was performed:

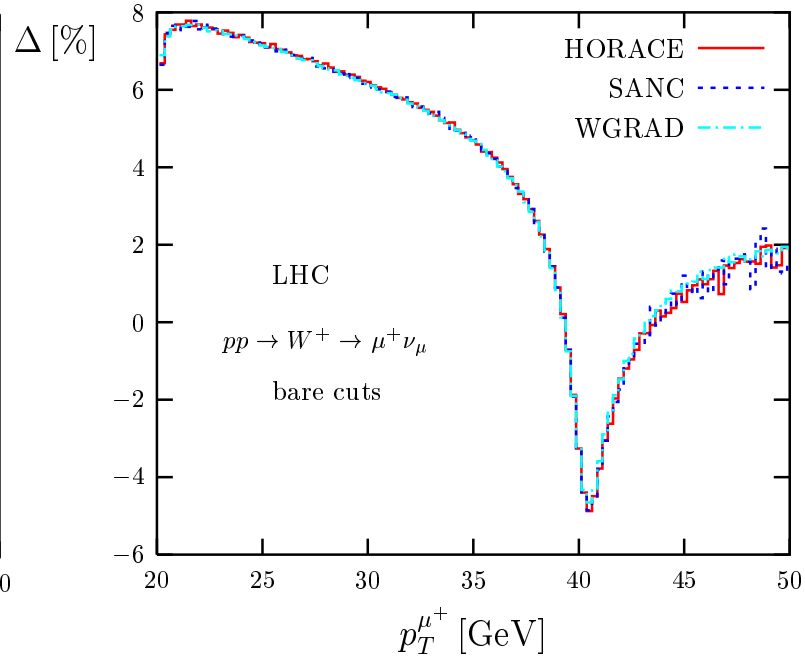
Processes	Codes	Ref.
CC DY (NLO EW)	SANC, HORACE, WGRAD2	arXiv:0705.3251
NC DY (NLO EW)	SANC, HORACE, ZGRAD2	arXiv:0803.0678
CC & NC DY (NLO QCD & EW)	SANC, HORACE, WZGRAD, RADY, FEWZ, DYNNLO, POWHEG-w, POWHEG-z	W-mass workshop (in progress)

CC. Tuned comparison

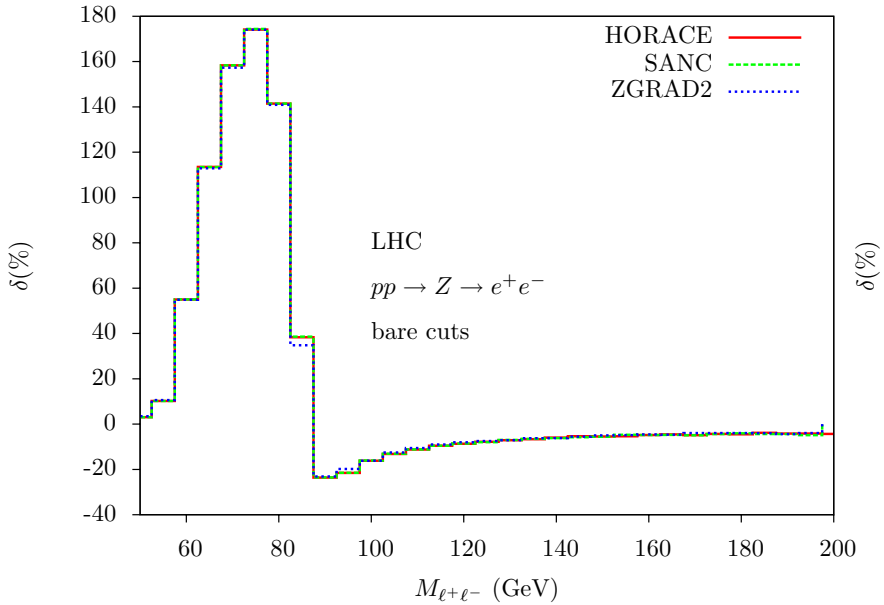


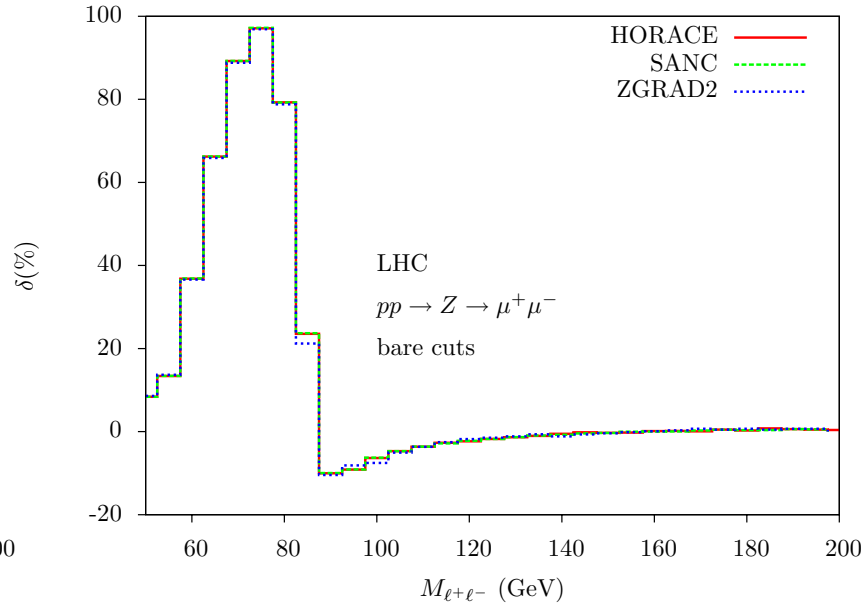


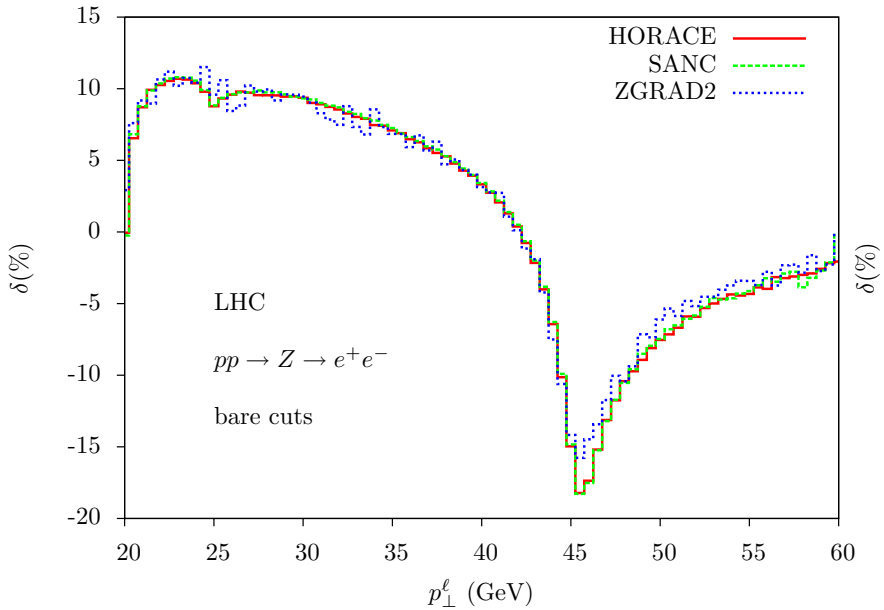


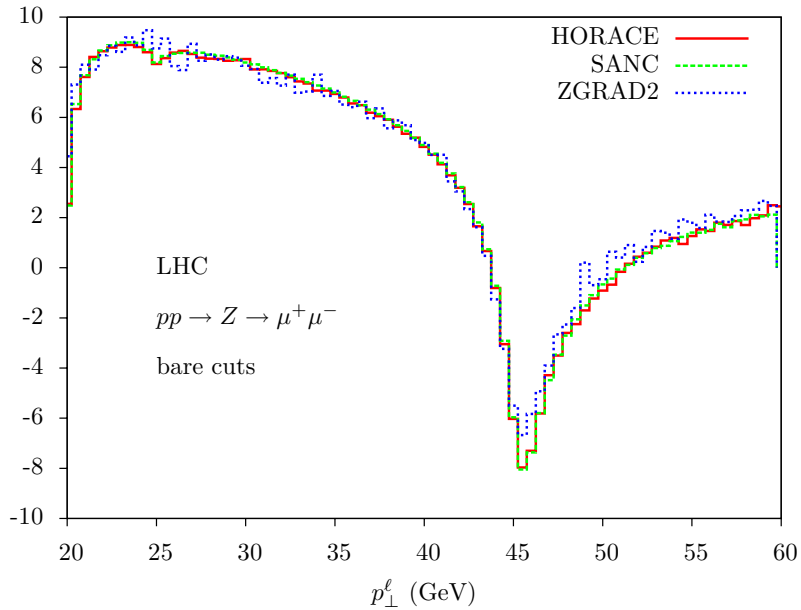


NC. Tuned comparison









FSR QED in W and Z production: motivation

- The effect of final-state QED radiation in Drell-Yan processes is large (up to 200% for invariant mass distribution in single Z production). The standard tool for simulation of QED FSR in ATLAS is PHOTOS program

Our goals are:

- to perform the comparison between SANC and PHOTOS in the single and multiple photon mode for FSR radiation in Drell-Yan like processes both for neutral (NC) and charged (CC) currents
- to check if QED FSR is properly installed in the two programs
- to tune a separation of the FSR QED corrections from a complete EW NLO corrections in CC case

Ref. arXiv:1212.6783

FSR QED: SANC and PHOTOS

- In PHOTOS the bremsstrahlung corrections to decays of W and Z bosons is calculated separately from other effects. PHOTOS is implemented to PYTHIA program in standard Monte-Carlo simulation through HepMC interface
- In SANC the complete EW corrections at one-loop is calculated for single W and Z production. The FSR QED corrections can be separated from the rest of EW corrections

SANC and PHOTOS: tuned comparison

Parton level cross-section was convoluted with CTEQ6L1 pdf set with running scale $Q^2 = s$. The C++ version of PHOTOS program was used together with Pythia8 program which provide the Born-level events in HEPevt format that subsequently passed to PHOTOS for addition of photon radiation off final leptons. PHOTOS was running in single and multiple photon mode with matrix-element corrections turned on.

Notations for QED corrections:

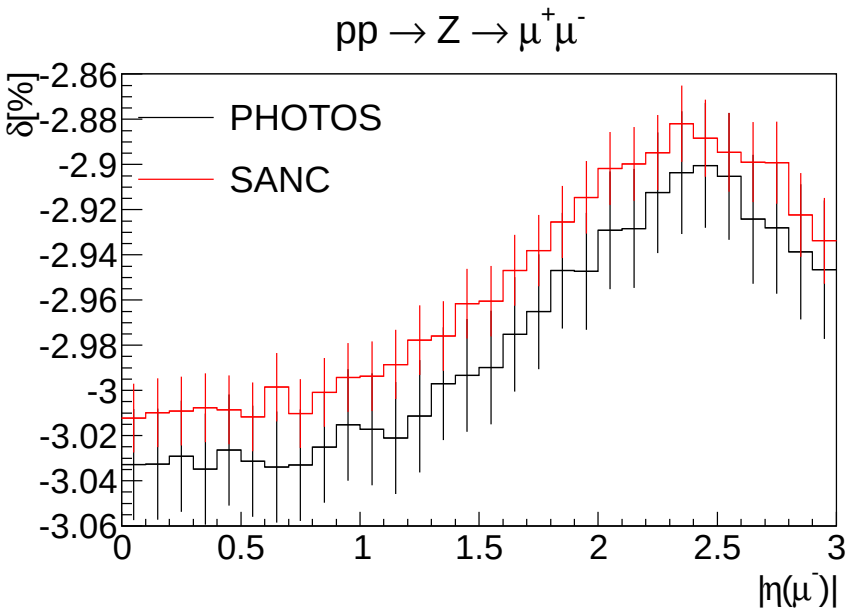
- effect of single-photon radiation:

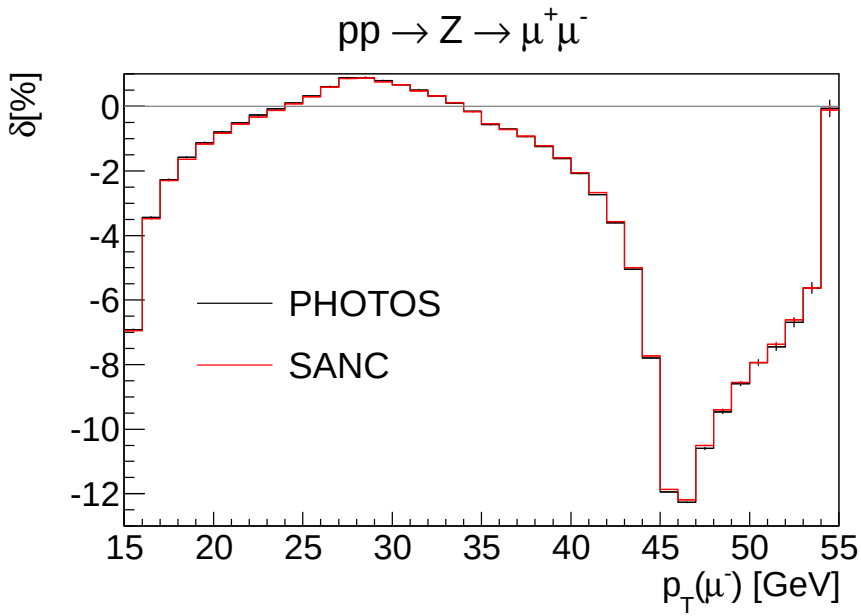
$$\delta = \frac{\mathcal{O}(\alpha)FSR - Born}{Born}$$

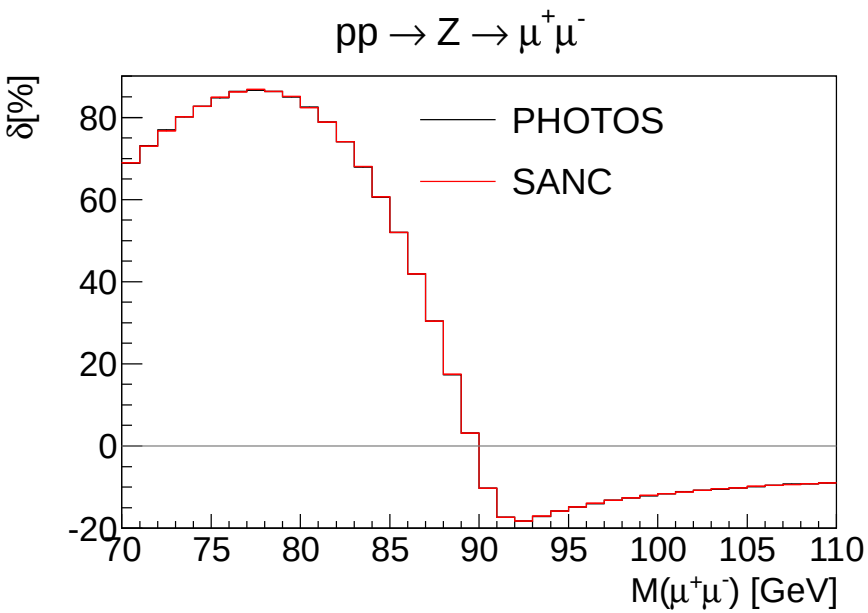
- effect of multi-photon radiation:

$$\delta_{h.o.} = \frac{h.o.FSR - \mathcal{O}(\alpha)FSR}{Born}$$

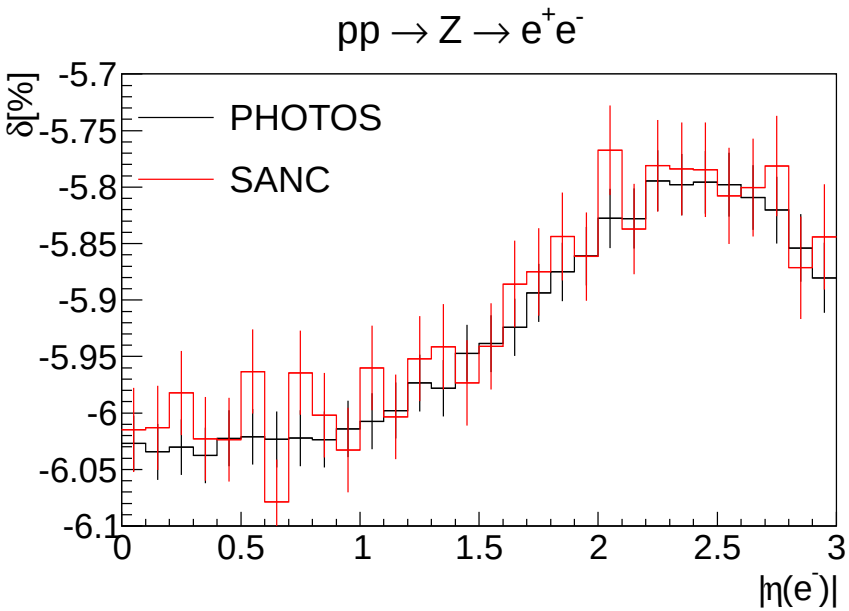
NC. Single-photon mode. Muons

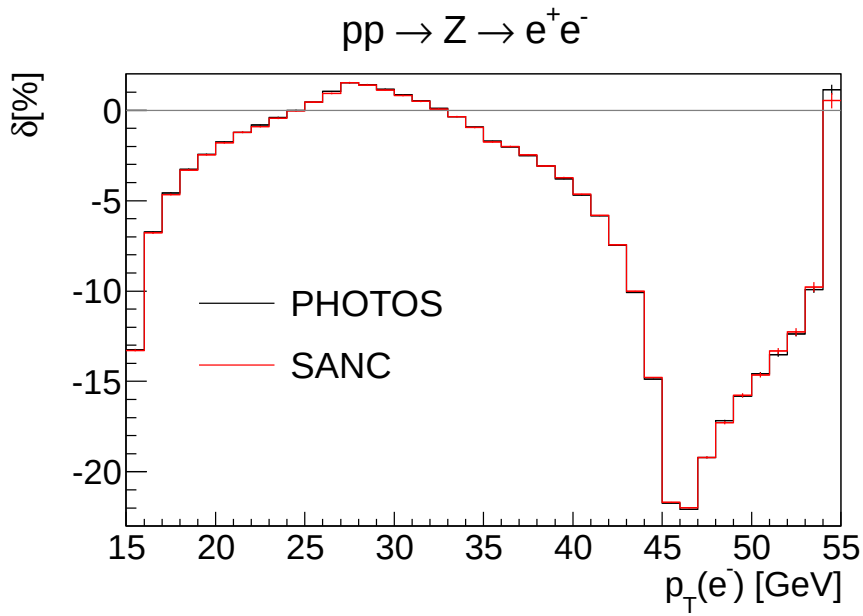


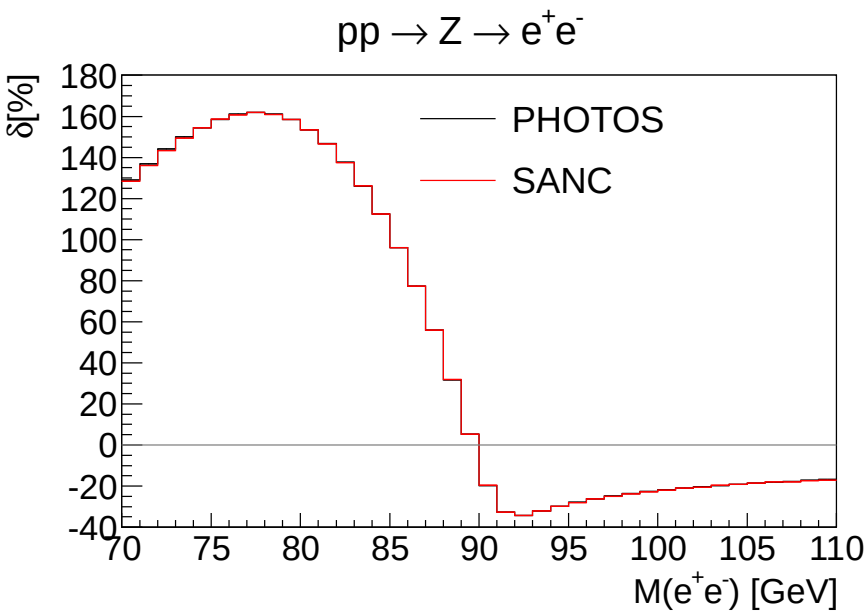




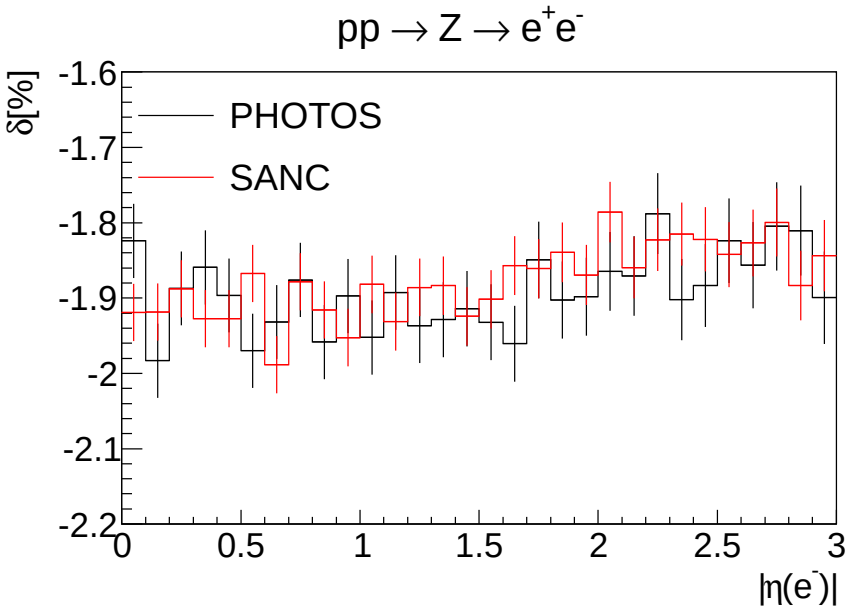
NC. Single-photon mode. Bare electrons

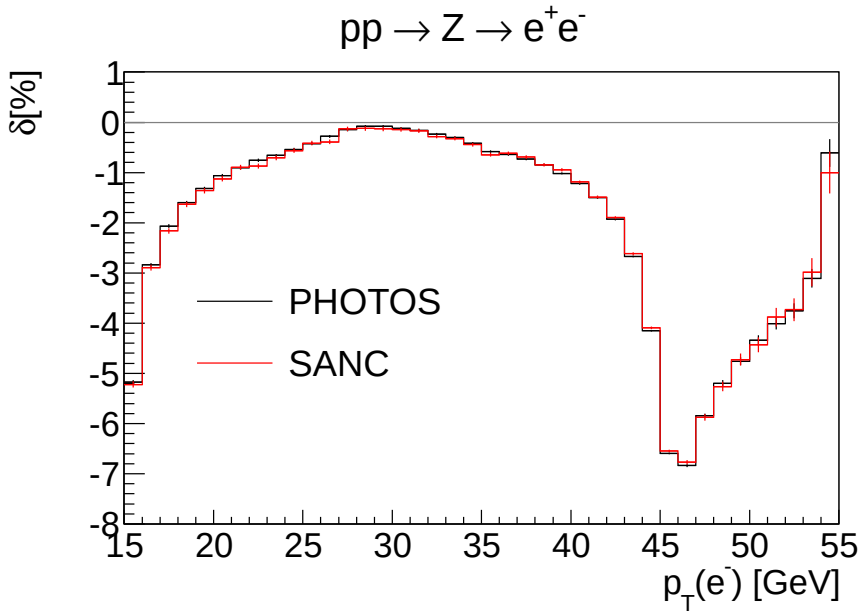


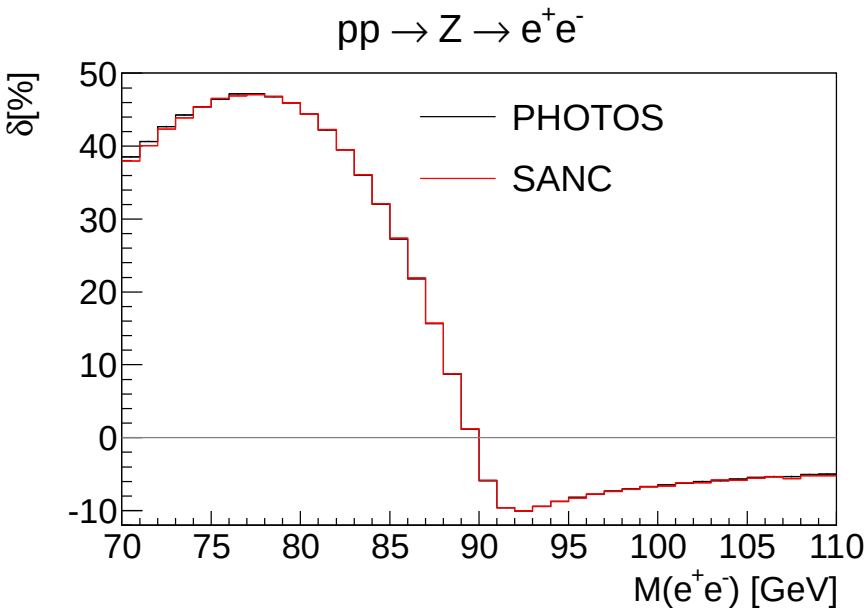




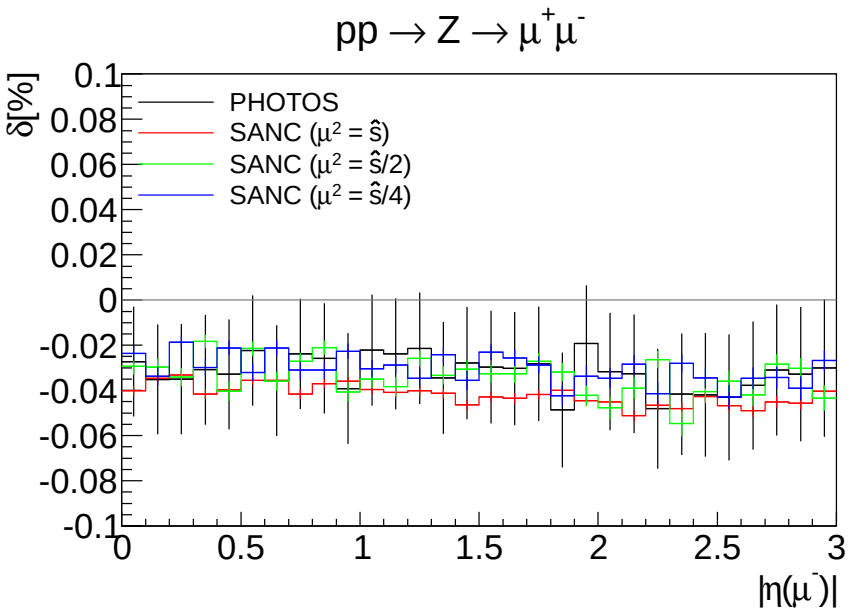
NC. Single-photon mode. Dressed electrons

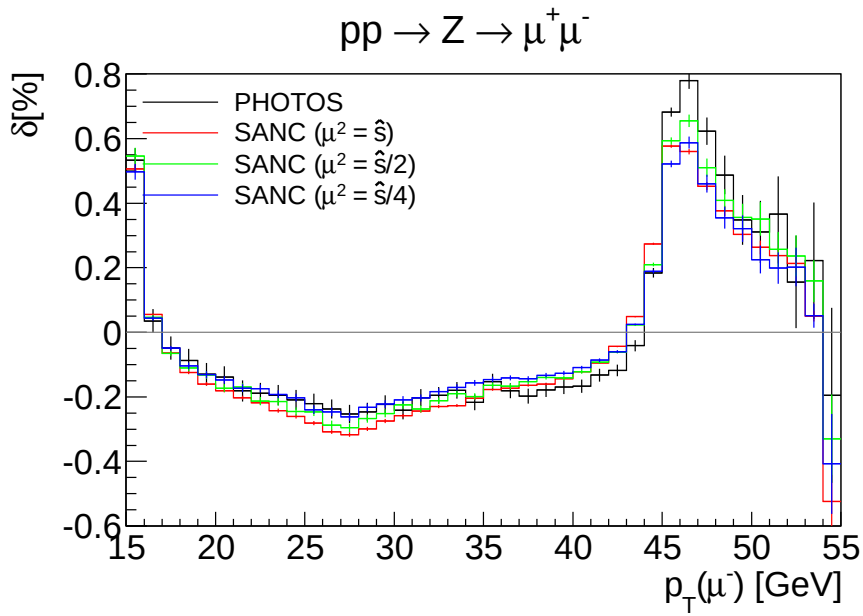


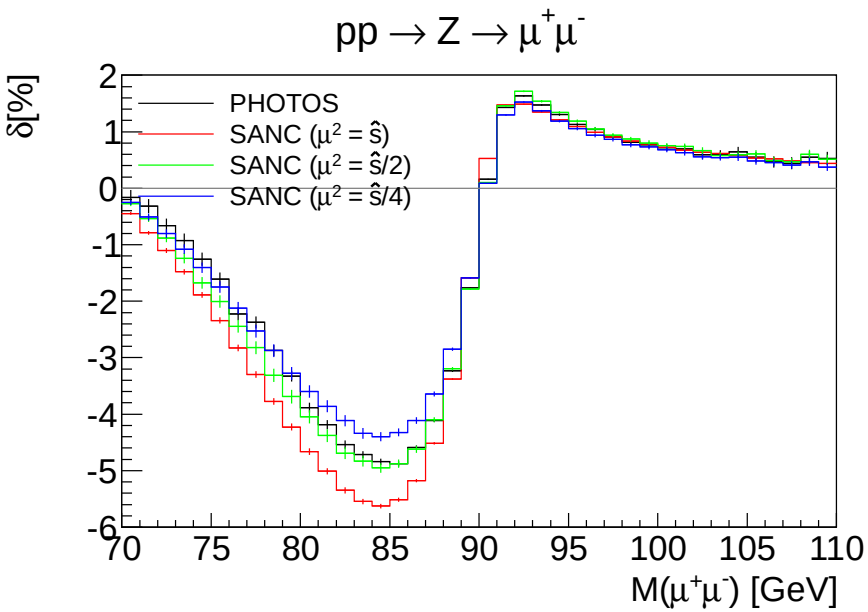




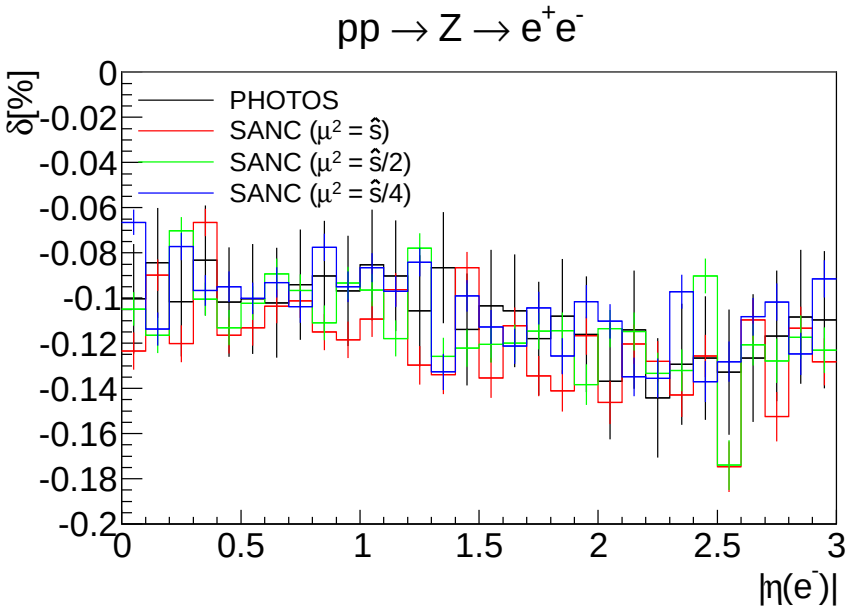
NC. Multi-photon mode. Muons

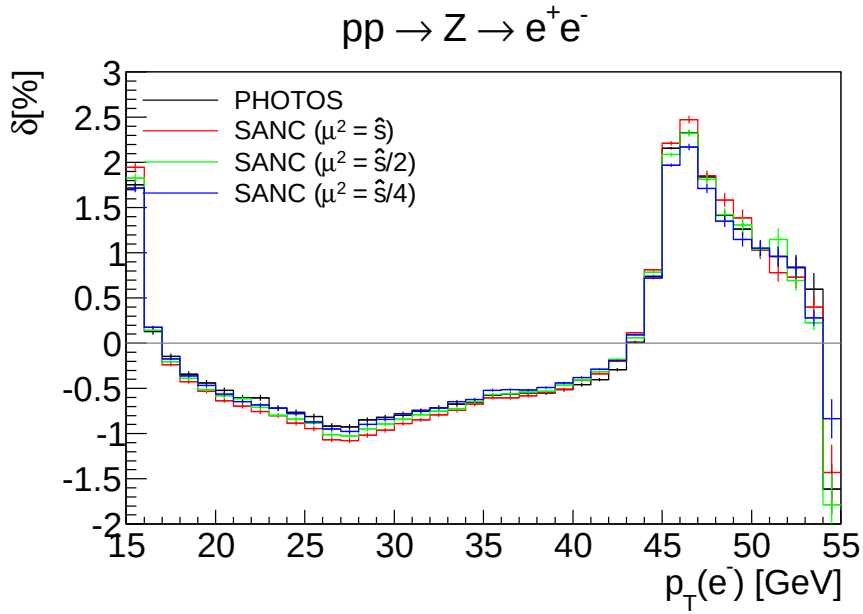


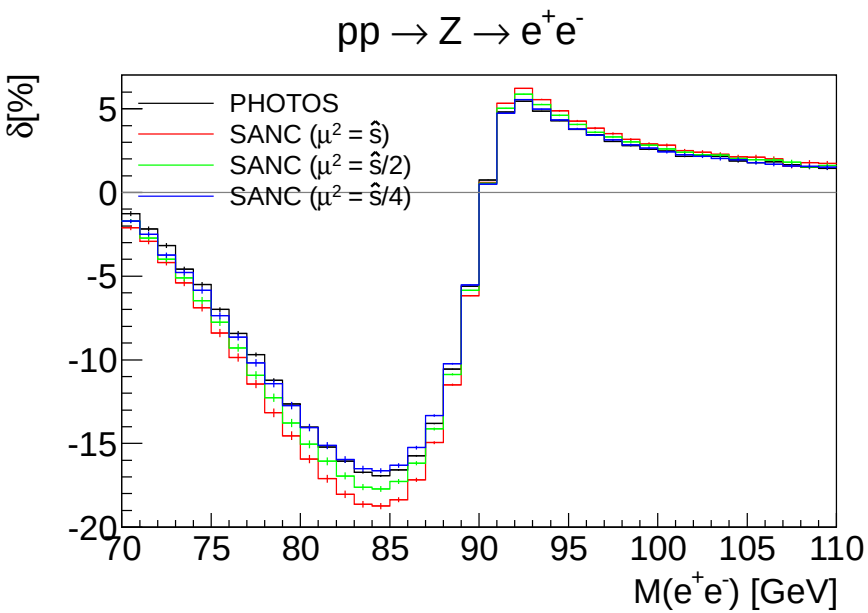




NC. Multi-photon mode. Bare electrons







Tuning of SANC FSR scale in CC case

The total $W \to u + d$ decay width

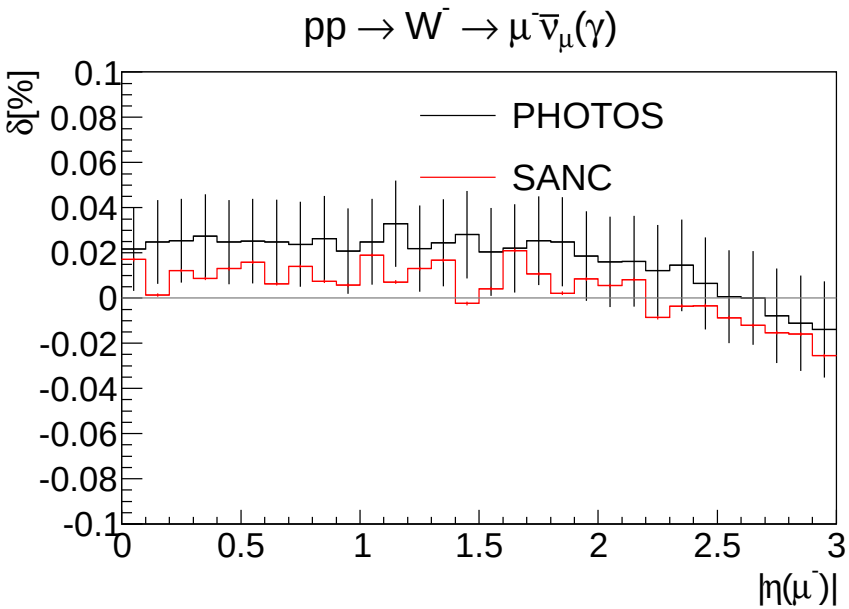
$$\Gamma_W^{\mathrm{PW+QED}} = \Gamma^{\mathrm{LO}}(\delta^{\mathrm{PW}} + \delta^{\mathrm{QED}}).$$

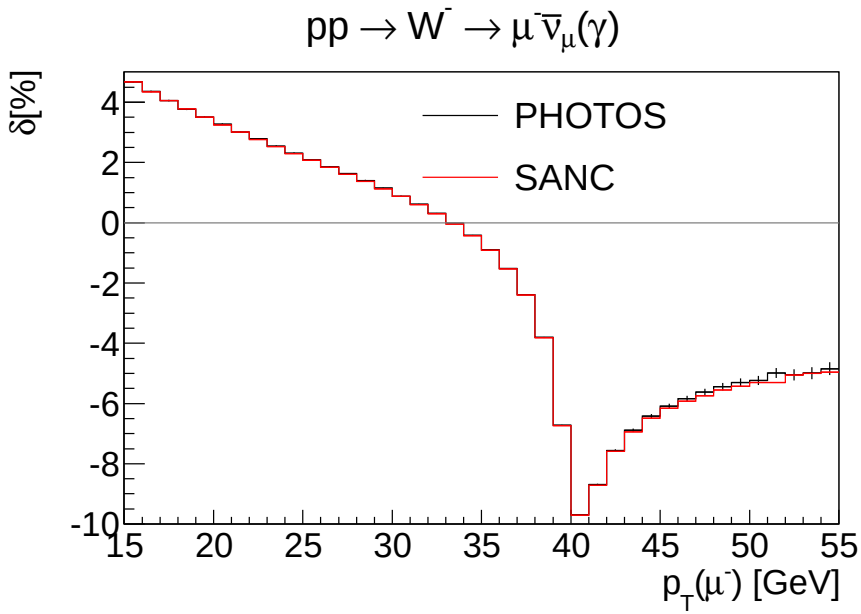
- QED/EW separation is not gauge-invariant
- 6 QED diagrams with virtual photons and 3 — with real photons:

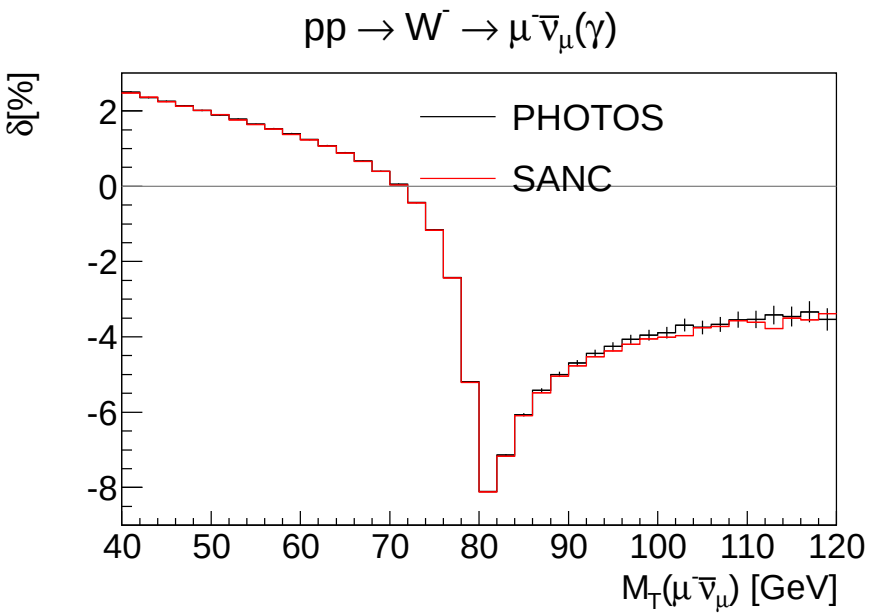
$$\delta^{\mathrm{QED}} = \frac{\alpha}{\pi}\left[Q_W^2\left(\frac{11}{6} - \frac{\pi^2}{3}\right) + (Q_u^2 + Q_d^2)\left(\frac{11}{8} - \frac{3}{4}\log\frac{M_W^2}{\mu^2}\right)\right]$$

- Why ud-channel? δ^{QED} contains only charges squared
- Natural and u, d symmetric expression. Clear ISR/FSR separation
- Setting $\mu^2 = M_W^2 \exp(-\frac{11}{6})$ annulates the FSR in δ^{QED} as PHOTOS does

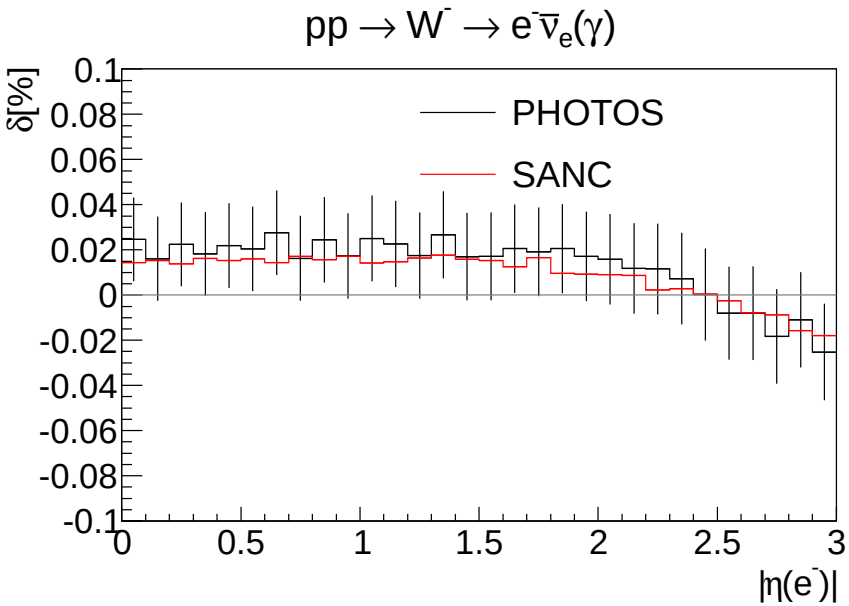
CC. Single-photon mode. Muons

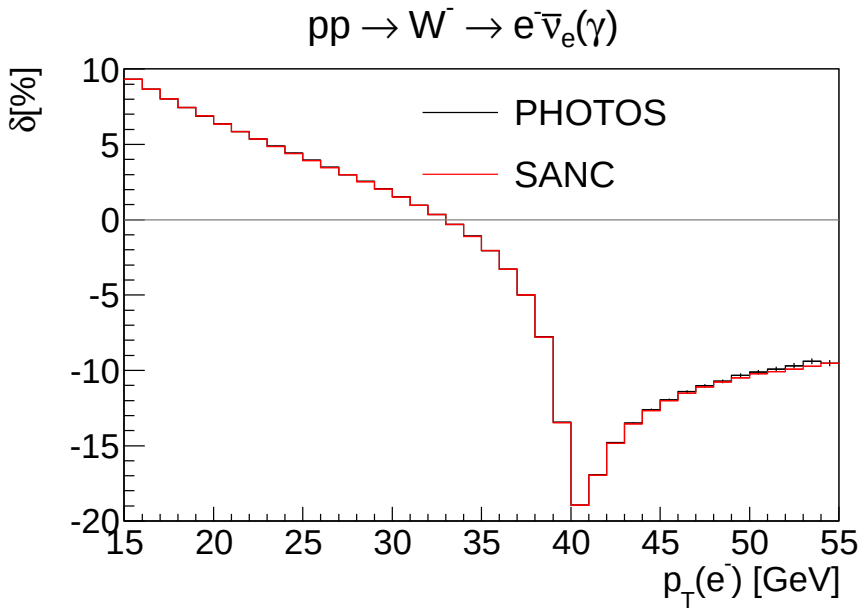


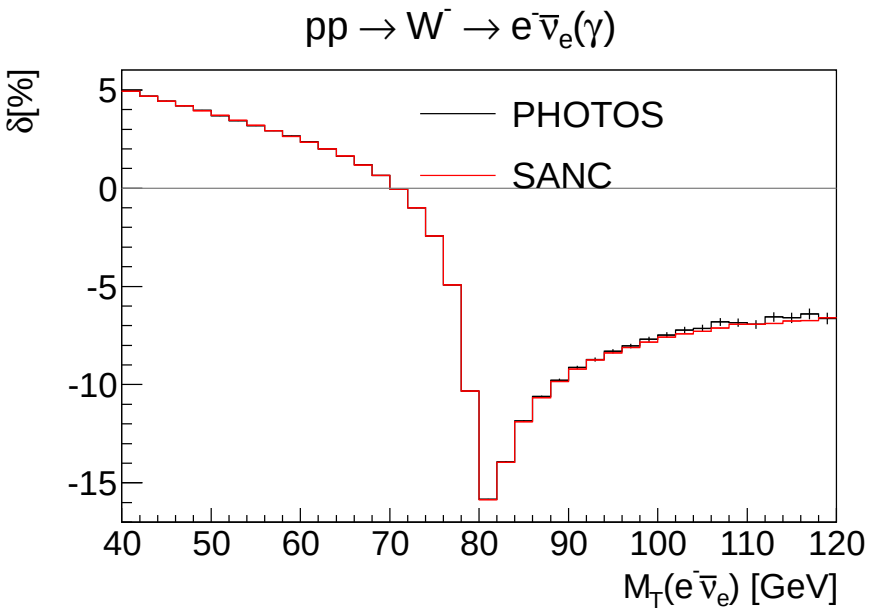




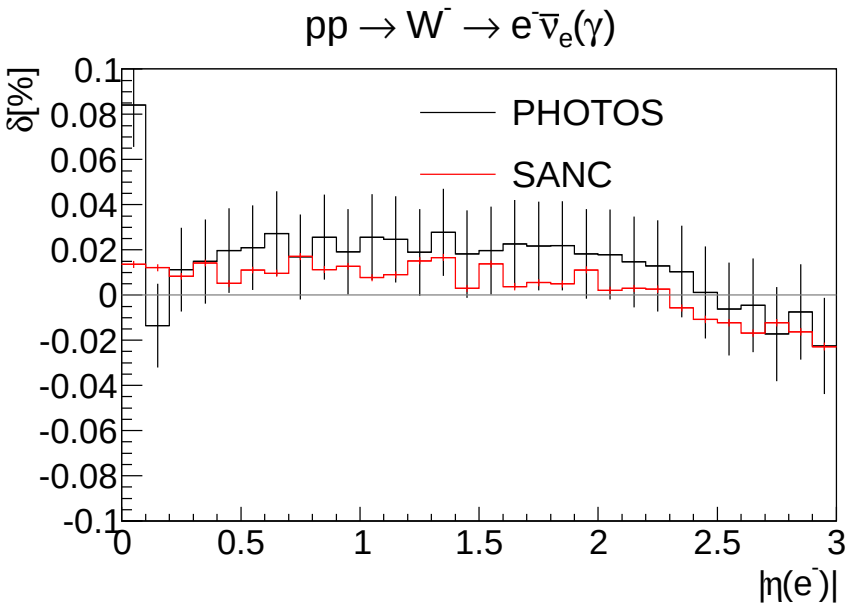
CC. Single-photon mode. Bare electrons

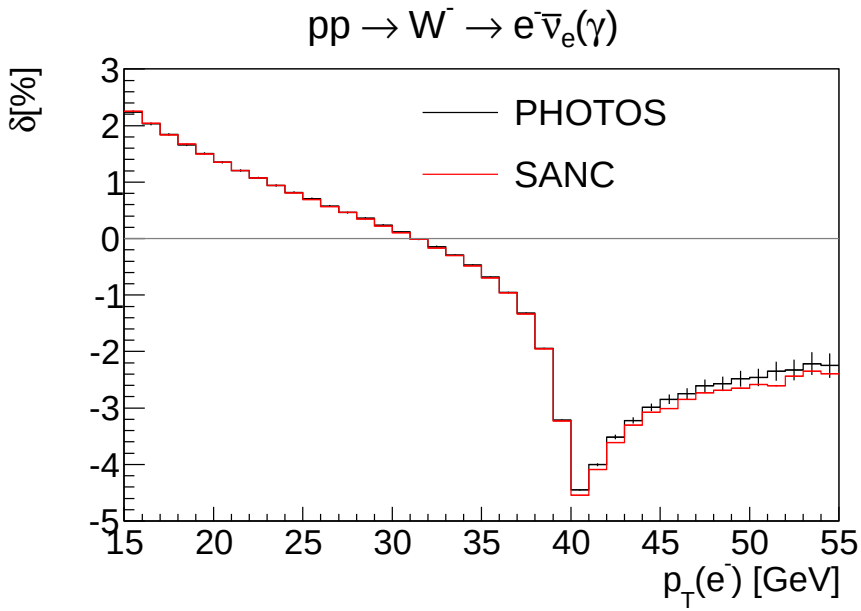


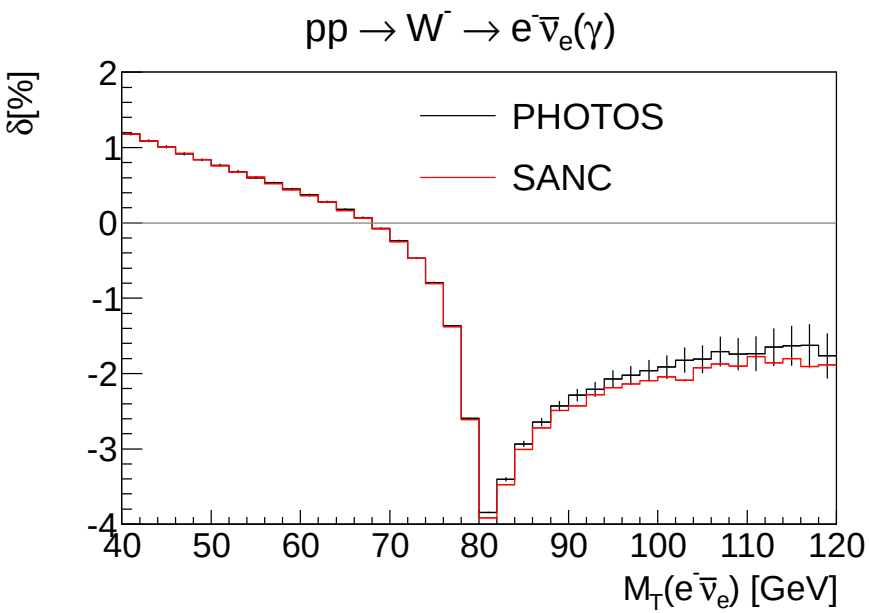




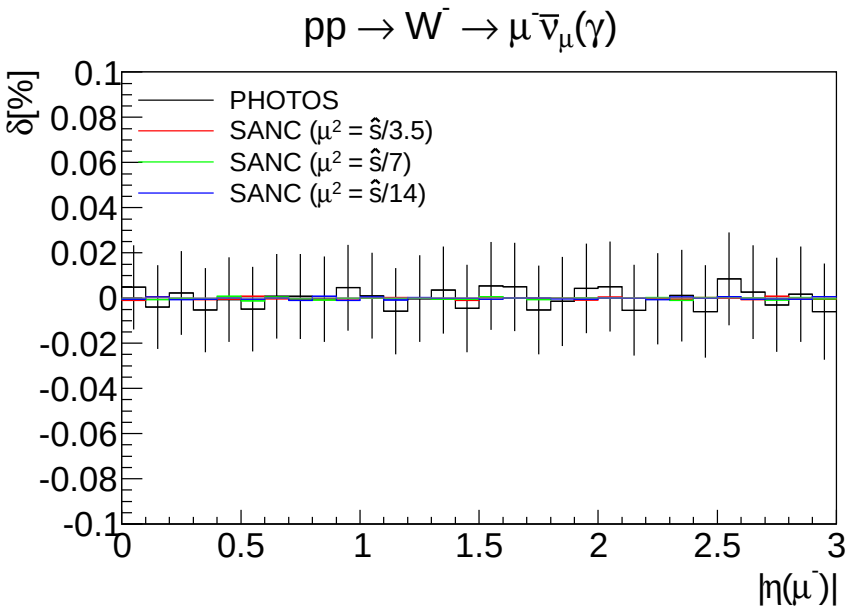
CC. Single-photon mode. Dressed electrons

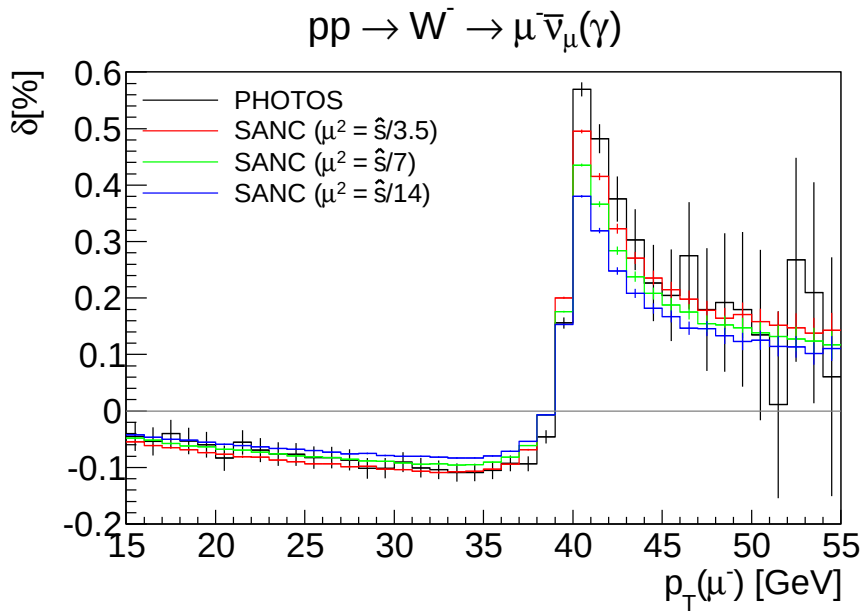


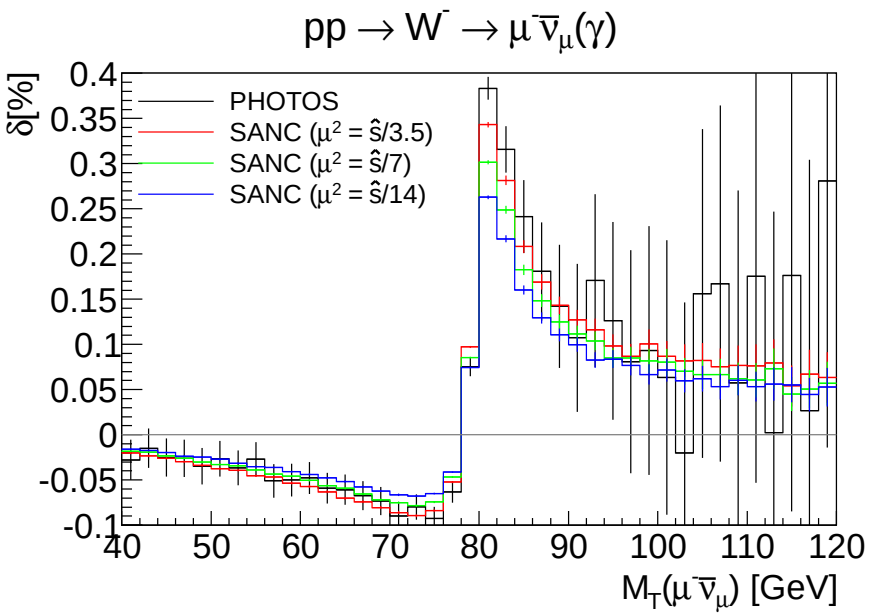




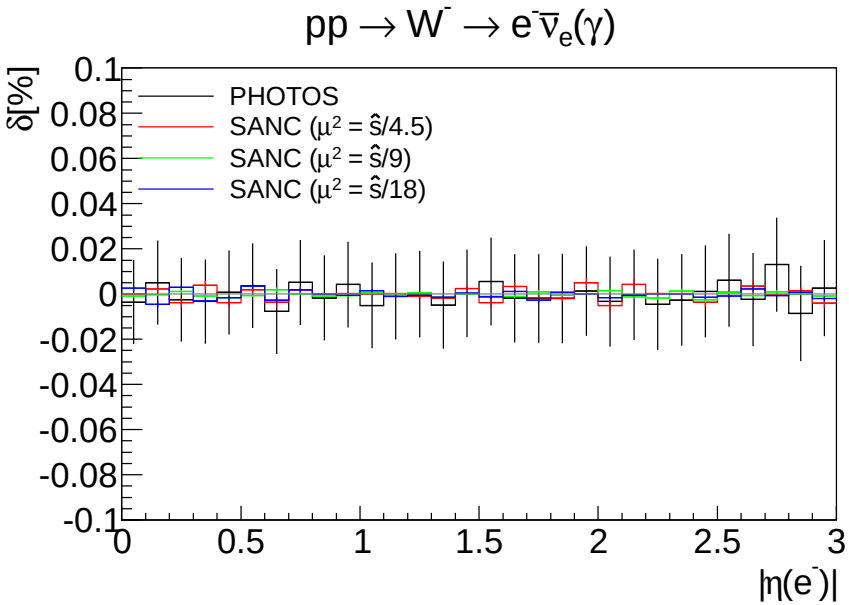
CC. Multi-photon mode. Muons

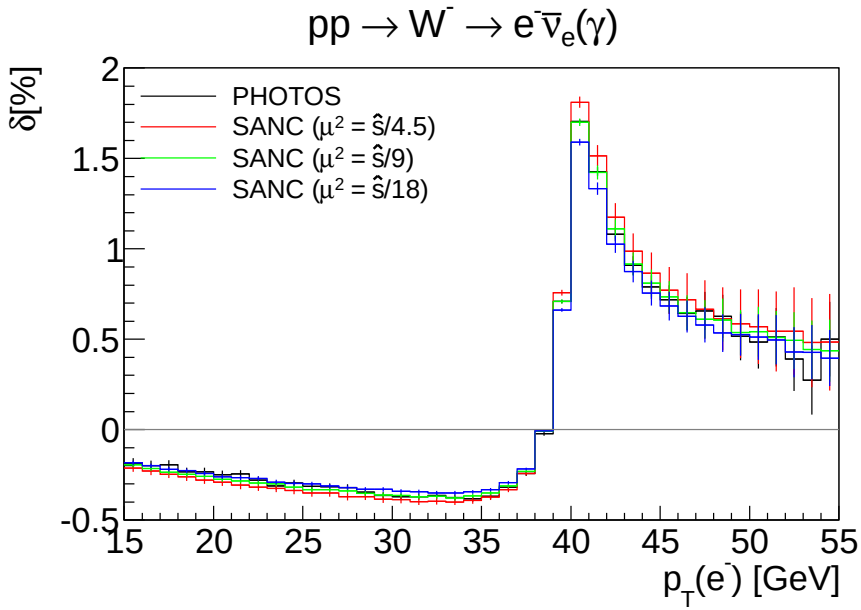


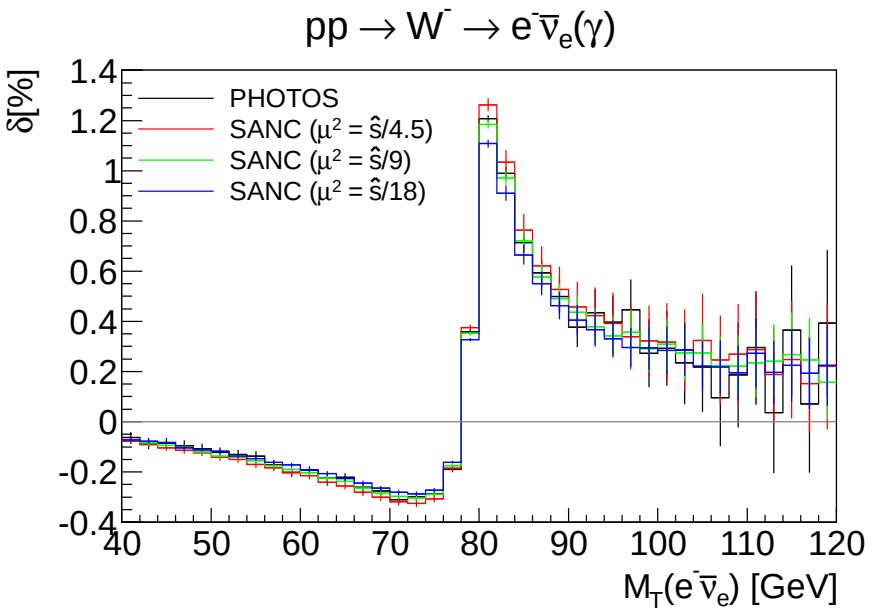




CC. Multi-photon mode. Bare electrons





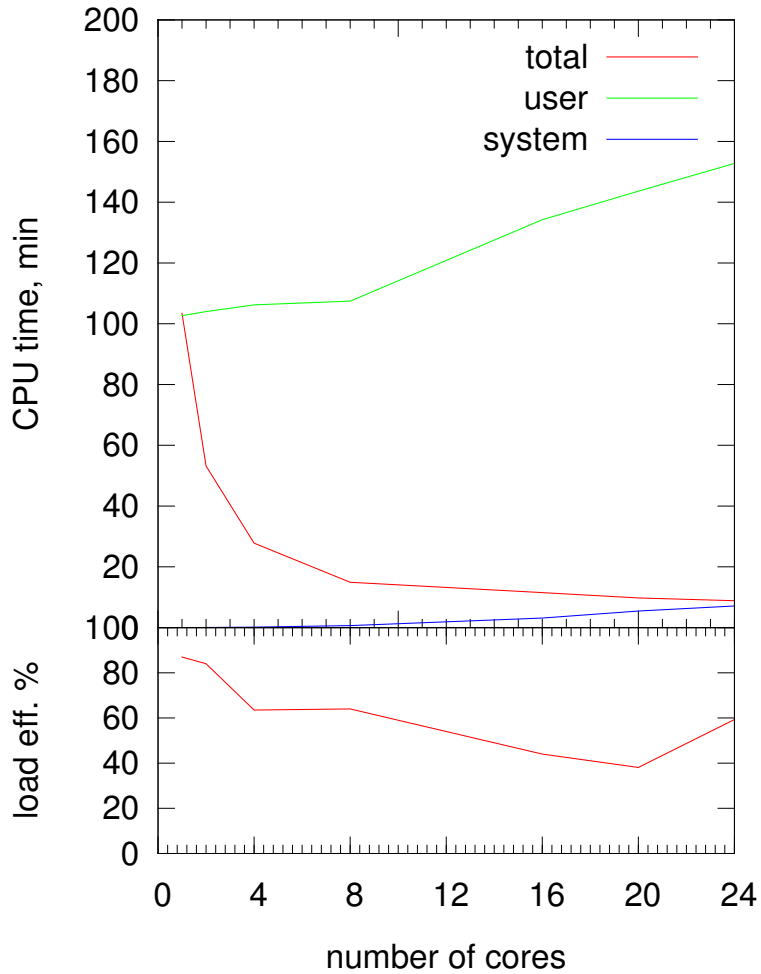


mcsanc integrator: features

- A Monte-Carlo integrator (weighted events) based on SANC modules
- Calculates fully differential cross section for DY and inclusive cross section for higgs-strahlung and single-top production
- Provides both NLO EW and QCD corrections
- Supports different EW-schemes: $\alpha(0), \alpha(M_Z), G_\mu$
- Fixed and running factorization and renormalization scale options
- Kinematic cuts, recombination
- Parallel calculation on multicore machines thanks to Cuba library (http://www.feynarts.de/cuba/)
- Easy installation and configuration (GNU autotools, LHAPDF, input configs for physics parameters, cuts, histogramming)

Persistency and parallelization

- Vegas integration statefile in Cuba and histograms are saved after every iteration and upon run completion. The files can be used to increase statistics or restore from interrupted run (e.g. batch time quota exceeded)
- When run on a multicore systems, the calculation is automatically split by the number of cores or by `$CUBACORES` environment variable.
- The parallelization efficiency is limited due to inter-process communications: the optimal number of cores is 8, after which the run time doesn't reduce and efficiency (CPU load) is below 50%



mcsanc integrator: supported processes

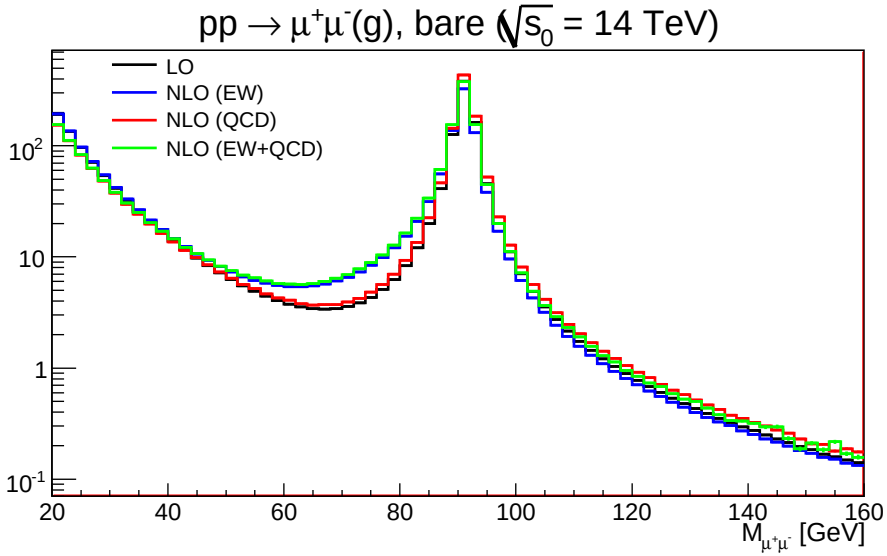
The process id notation is the following: first digit is a sign of EW-current, and the last two digits specify the final particle choice

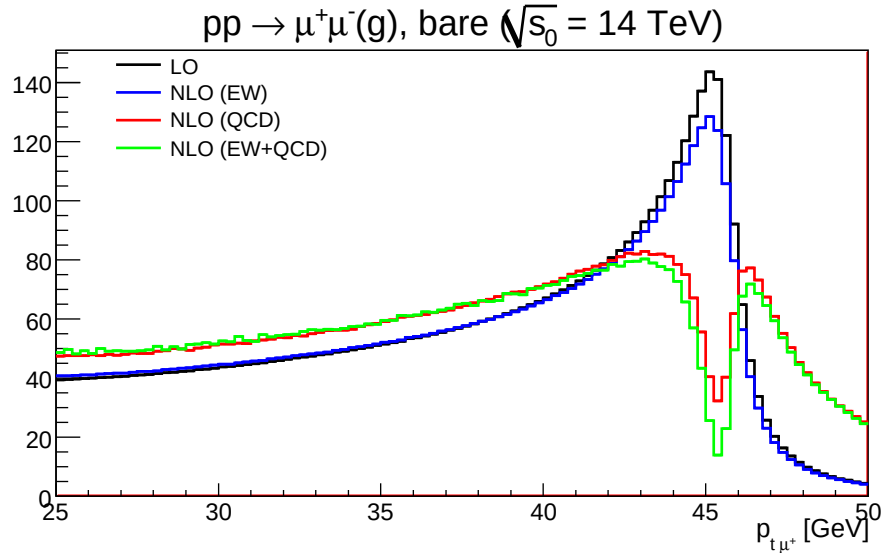
$0xx$ — neutral current, $xx = 01(e), 02(\mu), 03(\tau), 04(HZ)$

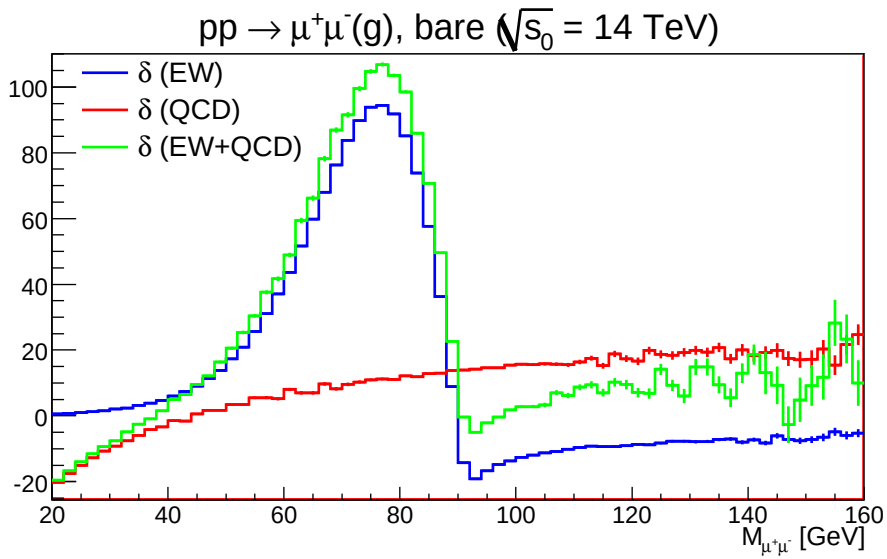
$\pm 1xx$ — charged current, $xx = 01(e), 02(\mu), 03(\tau), 04(HW)$, $05, 06(t\text{-production}, \text{s- and t-channels})$

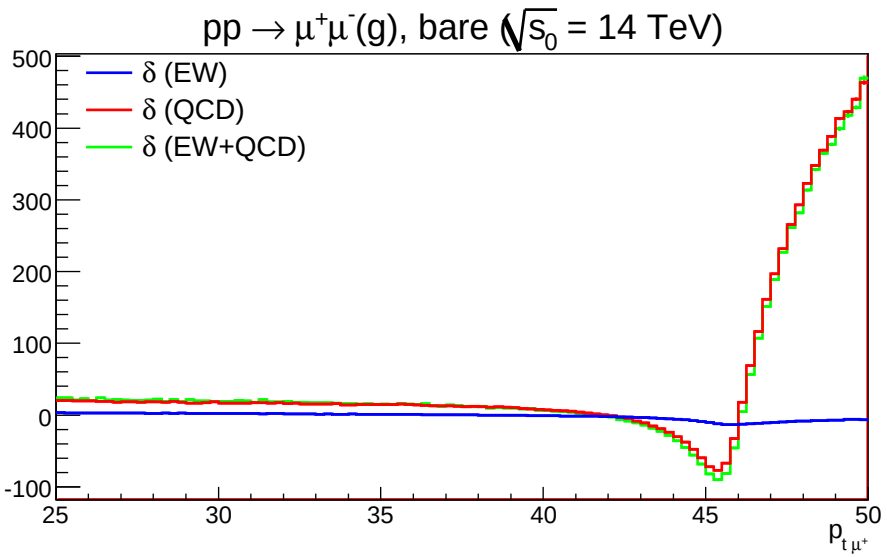
pid	$f + f \to$	SANC ref.
001:003	$\ell^+ + \ell^-(\ell = e, \mu, \tau)$	arXiv:0711.0625, 0901.2785
004	$Z^0 + H$	arXiv:hep-ph/0506120, 0812.4207
$\pm$ 101:103	$\ell^\pm + \nu_\ell$	arXiv:hep-ph/0506110
$\pm$ 104	$W^\pm + H$	-
105	$t + \bar{b}$ (s-channel)	arXiv:1110.3622,1207.4400
106	$t + q$ (t-channel)	-//-
-105	$\bar{t} + b$ (s-channel)	-//-
-106	$\bar{t} + q$ (t-channel)	-//-

QCD and EW NLO corrections



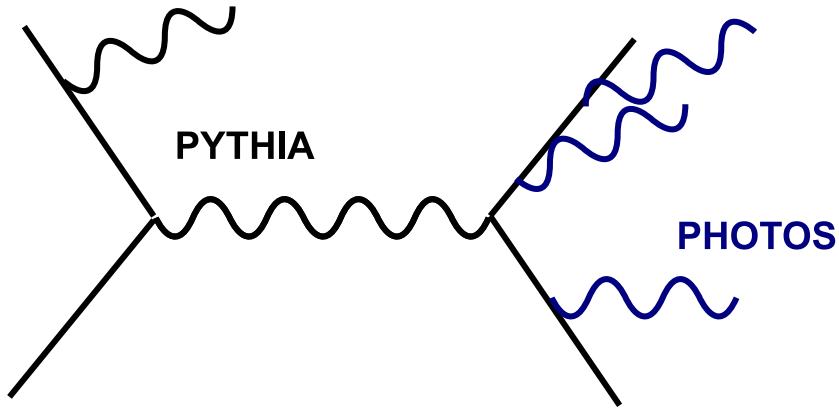






Estimating missing corrections

For example, standard ATLAS MC generation chain uses PYTHIA and PHOTOS for LO, initial and final state radiation (ISR, FSR), and partonic showers:



In addition SANC implements the following NLO EW corrections, which can be included separately by changing `iqed` flag:

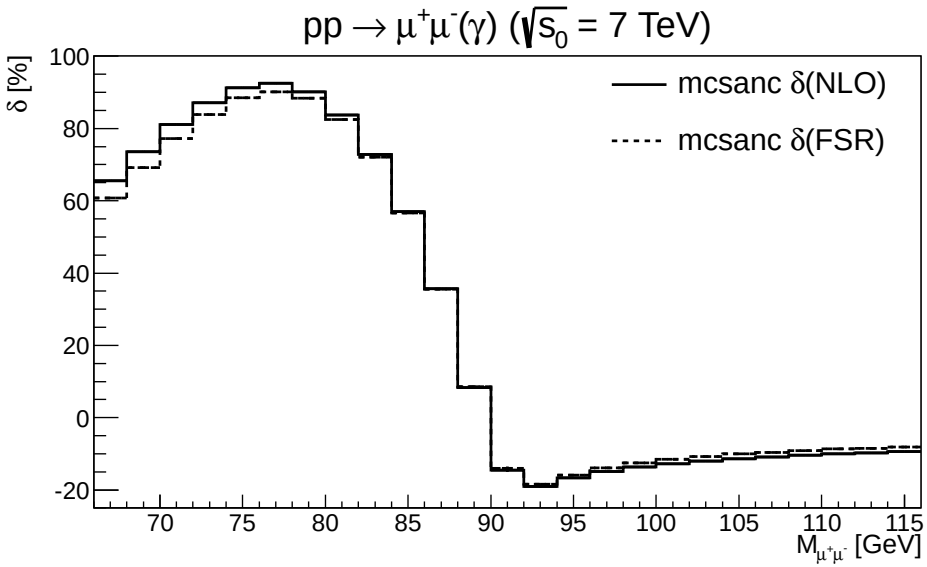
- pure weak (PW)
- initial–final QED interference (IFI)
- what remains of ISR after collinear divergences subtraction

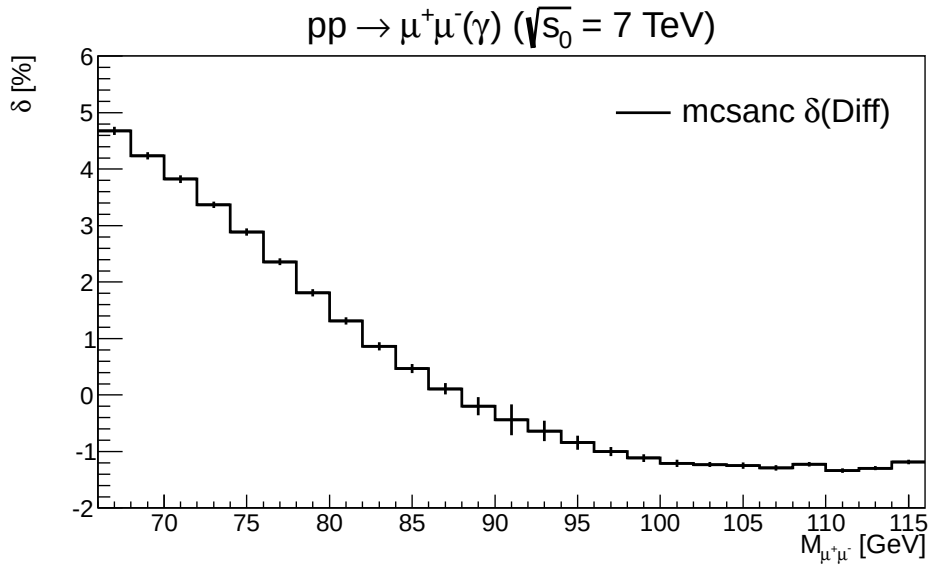
These missed corrections can be evaluated as a difference between the complete NLO EW corrections and the QED FSR ones.

Missed corrections

The missed corrections are cut-dependent for $M_{\mu^+\mu^-}$ distribution in the $pp \to Z \to \mu^+\mu^-$ process. Around Z-resonance they vary from -1% to 5%.

$$\delta_{M_{ll}}(\mathrm{MISS}) = \delta_{M_{ll}}(\mathrm{NLO} - \mathrm{FSR})$$





Therefore inclusion of these corrections in the analysis is mandatory.

Summary

- The overview of SANC project was presented. The results of tuned comparison between SANC and other codes for EW corrections to Drell-Yan production was shown
- The comparison of SANC and PHOTOS for single- and multiple-photon emission was performed for neutral and charged currents DY processes. The results agree within 0.1%
- New Monte-Carlo integrator mcsanc-v1.01 is available for download on http://sanc.jinr.ru. The tool is aimed for calculation of NLO EW and QCD corrections to DY, higgs-strahlung and single-top production processes in pp collisions