Update on NLO EWK effects in POWHEG-BOX-V2

Fulvio Piccinini

INFN, Sezione di Pavia

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based on

L. Barzè, G. Montagna, P. Nason, O. Nicrosini, F.P.

JHEP 1204 (2012) 037 arXiv:1202.0465[hep-ph]

and

L. Barzè, G. Montagna, P. Nason, O. Nicrosini, F.P. and A. Vicini

Eur. Phys. J.C73 (2013) 2474 arXiv:1302.4606[hep-ph]

and

with the collaboration of V. Prosperi and H. Martinez

Master formula and its extension to EW

P. Nason 2004 / S. Frixione, P. Nason and C. Oleari 2007

POWHEG idea: **hardest radiation at NLO followed by p_T-ordered shower**

$$d\sigma = \sum_{f_b} \bar{B}^{f_b}(\mathbf{\Phi}_n)\, d\mathbf{\Phi}_n \left\{ \Delta^{f_b}\left(\mathbf{\Phi}_n, p_\mathrm{T}^\mathrm{min}\right) + \sum_{\alpha_\mathrm{r}} \frac{d\Phi_\mathrm{rad}\ \theta\left(k_\mathrm{T} - p_\mathrm{T}^\mathrm{min}\right) \Delta^{f_b}(\mathbf{\Phi}_n, k_\mathrm{T})\ R(\mathbf{\Phi}_{n+1})}{B^{f_b}(\mathbf{\Phi}_n)} \right\}$$

- $\bar{B}^{f_b}(\mathbf{\Phi}_n)$: **NLO normalization**

$$\bar{B}^{f_b}(\mathbf{\Phi}_n) = \left[B(\mathbf{\Phi}_n) + V(\mathbf{\Phi}_n)\right]_{f_b} + \sum_{\alpha_\mathrm{r}} \int d\Phi_\mathrm{rad} \left[R(\mathbf{\Phi}_{n+1}) - C(\mathbf{\Phi}_{n+1})\right]$$
$$+ \sum_{\alpha_\oplus} \int \frac{dz}{z} G_\oplus^{\alpha_\oplus}(\mathbf{\Phi}_{n,\oplus}) + \sum_{\alpha_\ominus} \int \frac{dz}{z} G_\ominus^{\alpha_\ominus}(\mathbf{\Phi}_{n,\ominus})$$

- $\Delta^{f_b}(\mathbf{\Phi}_n, p_\mathrm{T})$: **(modified) Sudakov form factor**

$$\Delta^{f_b}(\mathbf{\Phi}_n, p_\mathrm{T}) = \exp\left\{ -\sum_{\alpha_\mathrm{r}} \int \frac{d\Phi_\mathrm{rad}\, R(\mathbf{\Phi}_{n+1})\ \theta\left(k_\mathrm{T}(\mathbf{\Phi}_{n+1}) - p_\mathrm{T}\right)}{B^{f_b}(\mathbf{\Phi}_n)} \right\}.$$

- **QCD $\longrightarrow$ QCD$\otimes$EW combination**

L. Barzè *et al.* 2012, 2013

POWHEG-BOX/W_ew-BMNNP and POWHEG-BOX/Z-BMNNPV

$$V = \text{virtual} + \text{soft/coll.} = V_\mathrm{QCD} + V_\mathrm{EW} \qquad R = \text{real radiation m.e.} = R_\mathrm{QCD} + R_\mathrm{EW}$$
$$C = \text{coll. counterterms} = C_\mathrm{QCD} + C_\mathrm{QED} \qquad G_{\oplus/\ominus} = \text{coll. remnants} = G_\mathrm{QCD} + G_\mathrm{QED}$$
$$\alpha_\mathrm{r} = \text{singular regions of } R = \alpha_\mathrm{r}{}^\mathrm{QCD} + \alpha_\mathrm{r}{}^\mathrm{QED}$$

NLO predictions and on/off switches

- in POWHEG theoretical precision at NLO in α_s and α
- in order to reliably estimate the size of the separate corrections within the same code, avoiding spurious effects due to parameter tunings, two input flags have been introduced
  - **no_ew**: setting it to 1 allows to switch off the NLO EWK corrections, obtaining pure NLO QCD predictions
  - **no_qcd**: setting it to 1 allows to switch off the NLO QCD corrections, obtaining pure EWK NLO predictions
    this flag is intended to be used only for NLO analysis
- **no_ew** can be set to 1 also at the event generation stage
- *technical remark:* for electron final states strong cancellations (due to $m_e/E \ll 1$) in collinear phase space regions can spoil the numerical convergence. This is handled by invoking extended 32-digits precision when $m_{e\gamma} < 10^{-5}$ GeV, supported by default by Intel compilers or gfortran (gcc versions $\geq$ 4.7)

Event generation

$$\Delta \equiv \Delta_{QCD} \times \Delta_{EW}$$

- generation of a radiation $p_\perp$ for each Sudakov form factor and choice of the largest one as maximum scale for gluon and γ radiation
- different lower radiation $p_\perp$ cutoff
  - $\sim \Lambda_{QCD}$ for g or γ radiation from quarks
    - input variable: **ptsqmin**, [default = $(0.8\text{GeV})^2$]
  - $\sim m_l$ for γ radiation off leptons
    - input variable: **kt2minqed**, [default = $(0.001\text{GeV})^2$]
- in the end, <u>three kinds</u> of events in the **file.lhe**:
  - elastic $2 \to 2$ events $(q\bar{q} \to l\bar{l}^{(\prime)})$
  - QCD radiative events $2 \to 3$ $(q\bar{q} \to l\bar{l}^{(\prime)}g)$, $(gq \to l\bar{l}^{(\prime)}q)$
  - QED radiative events $2 \to 3$ $(q\bar{q} \to l\bar{l}^{(\prime)}\gamma)$
  - contribution from events of the kind $\gamma q \to l\bar{l}^{(\prime)}q$ not yet available
- the LH events already contain part of higher order corrections, to be completed by the subsequent shower evolution

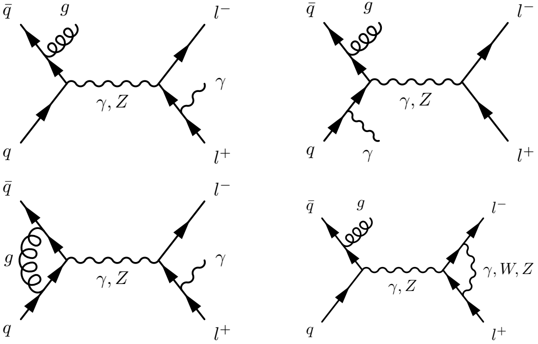
Interface to Parton Shower, both for QCD and QED

- in order to keep the NLO normalization, the LH events have to be showered with the requirement that the matrix element radiated parton/photon (when present) is the hardest one ($\rightarrow$ **scalup**)
- relevant files for the user:
  - **main-PYTHIA.f**, **setup-PYTHIA-lhef.f** and **photos.f**
  - **main-PYTHIA8.f**, **pythia8F77.cc** and **PHOTOS++** source files
- in principle, if the shower is $p_\perp$ ordered, it is enough to give `scalup` as the starting scale for the shower (only possibility in our PYTHIA6 interface)
- as a matter of fact different $p_\perp$ definitions are used in PYTHIA and in POWHEG $\Longrightarrow$ some double counting or dead zone can arise
- safest solution (available and default in our PYTHIA8 interface):

  allow shower emissions up to the kinematical limit (**SpaceShower:pTmaxMatch=2**, **TimeShower:pTmaxMatch=2**) and then veto emissions harder than POWHEG emission, according to the POWHEG $p_\perp$ definition, using the provided **class PowhegHooks**
- the same philosophy applies to QED radiation from resonance

$\mathcal{O}(\alpha\alpha_s)$ and $\mathcal{O}(\alpha\alpha_s)$ content of POWHEG

- The full machinery of QCD and EWK corrections in POWHEG gives rise to $\mathcal{O}(\alpha_s^2)$ and mixed $\mathcal{O}(\alpha\alpha_s)$ contributions
- correctly taken into account the NLO contribution with one additional radiation in the soft/collinear limit



- irreducible $\mathcal{O}(\alpha\alpha_s)$ contributions need a full two-loop calculation

Dittmaier, Huss and Scwhinn, Nucl. Phys. B885 (2014) 318

QED options: interface to **PYTHIA6**

- **default**: QED radiation from resonance handled by **PYTHIA**
  - IF NLO EWK corrections ON, veto needed to check transverse momentum of the γ w.r.t radiating lepton (provided with **subroutine scalupveto**)
- activating **use_photos 1** in `powheg.input`, QED radiation is handled by **PHOTOS**, fortran version
  - the provided routine **pass_veto** is used to veto photons from **PHOTOS** harder than scalup, when NLO EW corr. ON

QCD/QED options: interface to **PYTHIA8**

- QCD and QED-from-quark radiation
  - **default**: generated up to kinematical limit and vetoed through the **class PowhegHooks**
  - activating **veto1 1** in `powheg.input`, the starting scale is set to scalup and no veto is performed

- QED radiation from the resonance:
- handled within PYTHIA8
  - IF EWK corr. ON
    1. **default**: photons harder than scalup vetoed by the **subroutine scalupveto**
    2. activating **py8veto 1** in `powheg.input`
       a) photons harder than scalup are vetoed through the **class PowhegHooks** ;
       b) if(veto1 = 1) the scale is set to scalup through **canSetResonanceScale() = .true.** in the **class MyUserHooks**
- handled with PHOTOS++
  - IF EWK corr. ON: photons from **PHOTOS** harder than scalup are vetoed through the provided **subroutine pass_veto**

Additional flags for PYTHIA8 in `powheg.input`

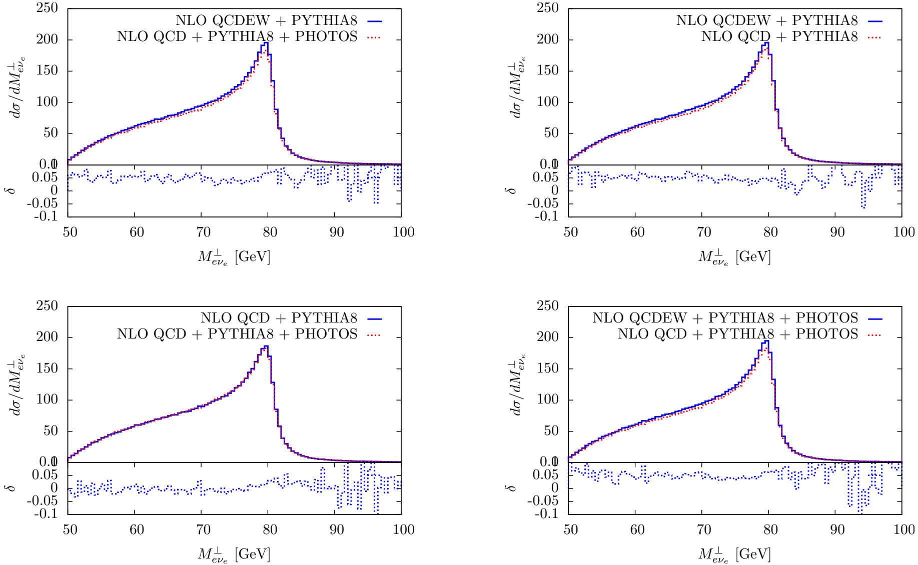
useful to study systematics in theoretical modelling

- **noQEDq 1**: switches off QED radiation from quarks
- **pytune #**: change default PYTHIA8 tuning
- **nohad 1**: switches off hadronization

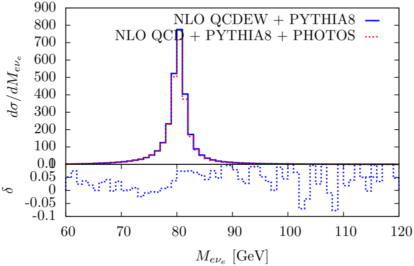
remark: in our default interface MPI are switched off

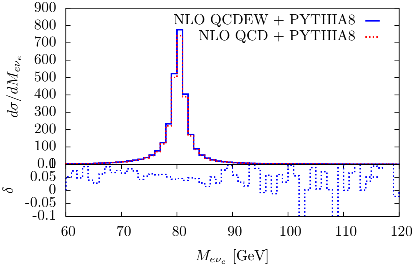
- in progress: additional input scheme choice with $\sin^2 \vartheta^l_{eff}$ as input

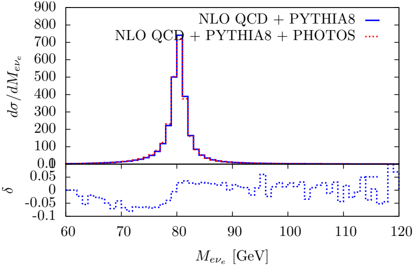
Effects of different switches: $M^{\perp}(e\nu_e)$

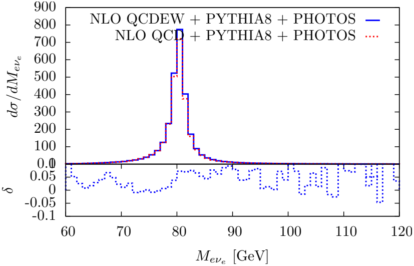


Effects of different switches: $M(e\nu_e)$

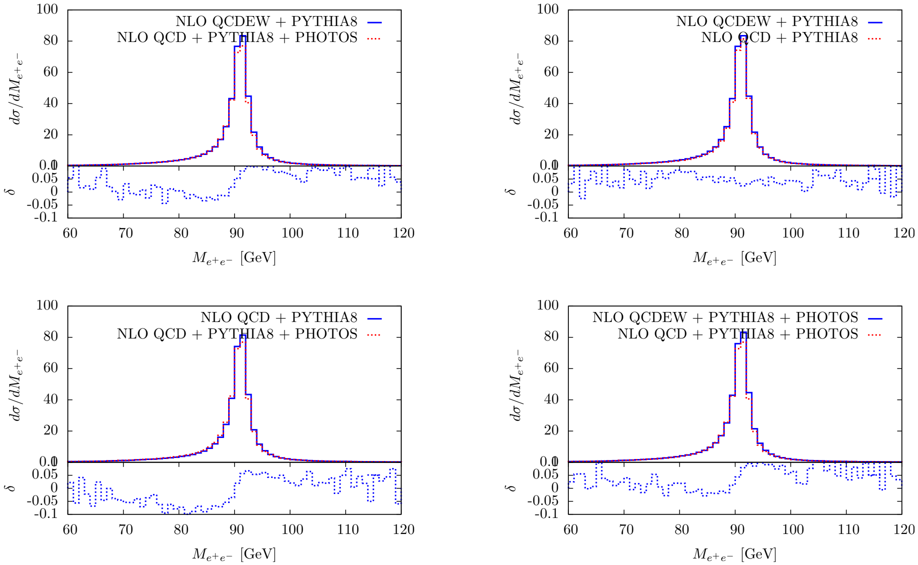




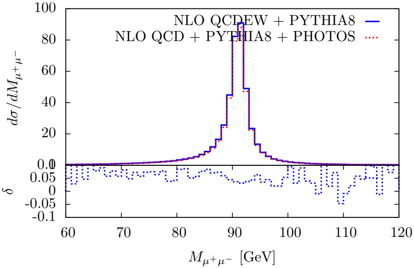


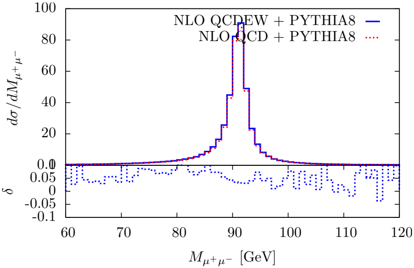


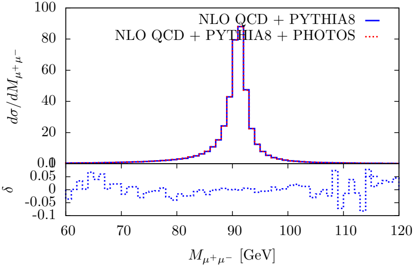
Effects of different switches: $M(e^+e^-)$

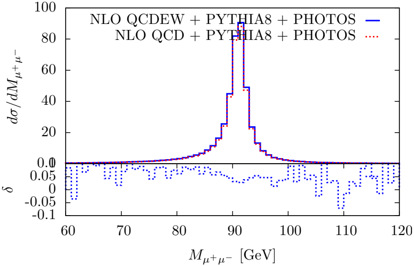


Effects of different switches: $M(\mu^+\mu^-)$









kt2minqed $\to 10^{-8}$ GeV^2 vs default (10^{-6} GeV^2)