Setup for the calculation of benchmark results

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1 Setup for benchmark results

Results are provided for the 8 TeV LHC for muons in the *bare* setup, i. e. when only applying acceptance cuts, and for electrons in the *calo* setup as defined in the setup for the tuned comparison (see Section 2).

We propose the follwing changes to the setup described in Section 2:

1) In the case of W production, in addition to the acceptance cuts we apply $M_T(l\nu) > 40$ GeV.

2) To account for the fact that we are using the constant width approach, we have to adjust the W, Z mass and width input parameters that have been measured in the s-dependent width approach accordingly, as follows [1, 2] ($\gamma_V = \Gamma_V/M_V$):

$$M_V \to \frac{M_V}{\sqrt{1+\gamma_V^2}} \;\; ; \;\; \Gamma_V \to \frac{\Gamma_V}{\sqrt{1+\gamma_V^2}}$$

Consequently, the input values for the W, Z masses and widths change to

$$\begin{aligned} M_Z &= 91.1535 \text{ GeV}, \qquad & \Gamma_Z &= 2.084 \text{ GeV} \\ M_W &= 80.358 \text{ GeV}, \qquad & \Gamma_W &= 2.4943 \text{ GeV} \end{aligned} \tag{1}$$

3) We use the following EW input scheme:
In the calculation of the tree-level couplings we replace $\alpha(0)$ by the effective coupling $\alpha_{G_\mu} = \sqrt{2} G_\mu M_W^2 (1 - M_W^2/M_Z^2)/\pi$. The relative $\mathcal{O}(\alpha)$ corrections are calculated with the fine structure constant $\alpha(0)$. At NLO EW this replacement implies an additional contribution of Δr to the relative $\mathcal{O}(\alpha)$ corrections. The one-loop result for Δr has been calculated in Refs. [3, 4] and can be decomposed as follows:

$$\Delta r(1-loop) = \Delta\alpha - \frac{c_w^2}{s_w^2}\Delta\rho + \Delta r_{rem}(M_H)$$

When using the input values of Eq. 2 and the values for M_W and M_Z given in item 2) $\Delta r(1-loop) = 0.0295633444$ (0.0296123554 for the unshifted masses).

We suggest to successively include higher-order corrections, i.e. we start with the NLO result using the changed setup as described above, and then assess the impact of multiple photon radiation, higher-order corrections to Δr, photon induced processes etc., compared to the NLO result.

Finally, for the case of Z boson production we suggest to add the distribution in Φ^*_η as defined, e.g., in Ref. [54] as follows:

$$\Phi^*_\eta = \tan(\frac{(\pi - \Delta\Phi)}{2}) \sin(\theta^*_\eta)$$

with $\Delta\Phi = \Phi^- - \Phi^+$ denoting the difference in the azimuthal angle of the two negatively/positively charged leptons in the laboratory frame and

$$\cos(\theta^*_\eta) = \tanh(\frac{\eta^- - \eta^+}{2})$$

$\eta^\pm$ denote the pseudo rapidity of the negatively/positively charged lepton. [Φ^*_η range (bin size): 0:0.4 (0.01)]

2 Setup for the tuned comparison

1.) For the numerical evaluation of the cross sections at the Tevatron ($\sqrt{s} = 1.96$ TeV) and the LHC ($\sqrt{s} = 8, 14$ TeV) we choose the following set of Standard Model input parameters [5]:

$$\begin{aligned}
G_\mu = 1.1663787 \times 10^{-5}\ \text{GeV}^{-2}, &\qquad \alpha = 1/137.035999074, \quad \alpha_s \equiv \alpha_s(M_Z^2) = 0.12018 \\
M_Z = 91.1876\ \text{GeV}, &\qquad \Gamma_Z = 2.4952\ \text{GeV} \\
M_W = 80.385\ \text{GeV}, &\qquad \Gamma_W = 2.085\ \text{GeV} \\
M_H = 125\ \text{GeV}, &\qquad \\
m_e = 0.510998928\ \text{MeV}, &\qquad m_\mu = 0.1056583715\ \text{GeV}, \quad m_\tau = 1.77682\ \text{GeV} \\
m_u = 0.06983\ \text{GeV}, &\qquad m_c = 1.2\ \text{GeV}, \quad m_t = 173.5\ \text{GeV} \\
m_d = 0.06984\ \text{GeV}, &\qquad m_s = 0.15\ \text{GeV}, \quad m_b = 4.6\ \text{GeV} \\
|V_{ud}| = 0.975, &\qquad |V_{us}| = 0.222 \\
|V_{cd}| = 0.222, &\qquad |V_{cs}| = 0.975 \\
|V_{cb}| = |V_{ts}| = |V_{ub}| &\quad = \quad |V_{td}| = |V_{tb}| = 0
\end{aligned} \tag{2}$$

We work in the constant width scheme and fix the weak mixing angle by $c_w = M_W/M_Z$, $s_w^2 = 1 - c_w^2$. The Z and W-boson decay widths given above are used in the LO, NLO and NNLO evaluations of the cross sections. The fermion masses only enter through loop contributions to the vector boson self energies and as regulators of the collinear singularities which arise in the calculation of the QED contribution. The light quark masses are chosen in such a way, that the value for the hadronic five-flavour contribution to the photon vacuum polarization, $\Delta\alpha^{(5)}_{had}(M_Z^2) = 0.027572$ [6], is recovered, which is derived from low-energy e^+e^- data with the help of dispersion relations.

2.) To compute the hadronic cross section we use the MSTW2008 [36] set of parton distribution functions and take the renormalization scale, μ_r, and the QCD factorization scale, $\mu_{\rm QCD}$, to be $\mu_r = \mu_{\rm QCD} = M_{l\nu}$ in the W boson case and $\mu_r = \mu_{\rm QCD} = M_{l^+l^-}$ in the Z boson case.

All numerical evaluations of EW corrections require the subtraction of QED initial state collinear divergences, which is performed using the QED DIS scheme. It is defined analogously to the usual DIS [8] scheme used in QCD calculations, i.e. by requiring the same expression for the leading and next-to-leading order structure function F_2 in deep inelastic scattering, which is given by the sum of the quark distributions. Since F_2 data are an important ingredient in extracting PDFs, the effect of the $\mathcal{O}(\alpha)$ QED corrections on the PDFs should be reduced in the QED DIS scheme [1]. The QED factorization scale is chosen to be equal to the QCD factorization scale, $\mu_{QED} = \mu_{QCD}$. The QCD factorization is performed in the $\overline{\rm MS}$ scheme.

3) For NLO EW predictions, we work in the on-shell renormalization scheme and use the following Z and W mass renormalization constants:

$$\delta M_Z^2 = \mathcal{R}e\Sigma^Z(M_Z^2), \quad \delta M_W^2 = \mathcal{R}e\Sigma^W(M_W^2) \tag{3}$$

where Σ^V denotes the transverse parts of unrenormalized vector boson self energy.

For the sake of simplicity and to avoid additional sources of discrepancies in the tuned comparison we suggest to use the fine structure constant $\alpha(0)$ throughout in both the calculation of CC and NC cross sections.

In the course of the calculation of the W observables the Kobayashi-Maskawa-mixing has been neglected, but the final result for each parton level process has been multiplied with the square of the corresponding physical matrix element V_{ij}. From a numerical point of view, this procedure does not significantly differ from a consideration of the Kobayashi-Maskawa-matrix in the renormalisation procedure as it has been pointed out in [11].

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[1] The subtraction of the QED initial state collinear divergences is a necessary step to obtain a finite partonic cross section. The absence of a QED evolution in the PDF set CTEQ6.6 has little phenomenological impact on the distributions, much smaller than the change from the massless-charm parametrizations like MRST2004QED to the massive charm sets CTEQ6.6 or MSTW2008

Table 1: Two-loop and three-loop running of $\alpha_s(\mu_r^2)$.

μ_r [GeV]	α_s(NLO)	α_s(NNLO)
91.1876	0.1201789	0.1170699
50	0.1324396	0.1286845
100	0.1184991	0.1154741
200	0.1072627	0.1047716
500	0.0953625	0.0933828

4.) We choose to evaluate the running of the strong coupling constant at the two-loop level, with five flavours, for LO, NLO and NLO+PS predictions using as reference value $\alpha_s^{NLO}(M_Z) = 0.12018$, which is consistent with the choice made in the PDF set MSTW2008. NNLO QCD predictions use the NNLO PDF set and correspondingly the three-loop running of $\alpha_s(\mu_r)$, with reference value $\alpha_s^{NNLO}(M_Z) = 0.117$. In Table 1 we provide $\alpha_s(\mu_r^2)$ for several choices of the QCD renormalization scale μ_r, which are consistent with the results provided by the LHAPDF function `alphasPDF(`μ_r`)` when called in conjunction with MSTW2008.

5.) The detector acceptance is simulated by imposing the following transverse momentum (p_T) and pseudo-rapidity (η) cuts:

$$\begin{aligned} \text{Tevatron}: &\quad p_T(\ell) > 25 \text{ GeV}, \quad |\eta(\ell)| < 1, \quad \not{p}_T > 25 \text{ GeV}, \quad \ell = e,\, \mu, \\ \text{LHC}: &\quad p_T(\ell) > 25 \text{ GeV}, \quad |\eta(\ell)| < 2.5, \quad \not{p}_T > 25 \text{ GeV}, \quad \ell = e,\, \mu, \\ \text{LHCb}: &\quad p_T(\ell) > 20 \text{ GeV}, \quad 2 < \eta(\ell) < 4.5, \quad \not{p}_T > 20 \text{ GeV}, \quad \ell = e,\, \mu, \end{aligned} \tag{4}$$

where $\not{p}_T$ is the missing transverse momentum originating from the neutrino. These cuts approximately model the acceptance of the CDF II and DØdetectors at the Tevatron, and the ATLAS, CMS and LHCb detectors at the LHC. In addition to the separation cuts of Eq. 4 we apply a cut on the invariant mass of the final-state lepton pair of $M_{ll} > 50$ GeV and $M(l\nu) > 1$ GeV in the case of γ/Z production and W production respectively,

Results are provided for the *bare* setup, i. e. when only applying the acceptance cuts of Eq. 4, and the *calo* setup, which is defined as follows: In addition to the acceptance cuts, for muons we require that the energy of the photon is $E_\gamma < 2$ GeV for $\Delta R(\mu, \gamma) < 0.1$. For electrons we first recombine the four-momentum vectors of the electron and photon to an effective electron four-momentum vector when $\Delta R(e, \gamma) < 0.1$ and then apply the acceptance cuts to the recombined momenta. For both electrons and muons we reject the event for

Tevatron and LHC	
electrons	muons
combine e and γ momentum four vectors, if $\Delta R(e,\gamma) < 0.1$	reject events with $E_\gamma > 2$ GeV for $\Delta R(\mu,\gamma) < 0.1$
reject events with $E_\gamma > 0.1\ E_e$ for $0.1 < \Delta R(e,\gamma) < 0.4$	reject events with $E_\gamma > 0.1\ E_\mu$ for $0.1 < \Delta R(\mu,\gamma) < 0.4$

Table 2: Summary of lepton identification requirements in the *calo* setup.

$E_\gamma > 0.1\, E_{\mu,e}$ for $0.1 \leq \Delta R(e,\gamma) \leq 0.4$, where

$$\Delta R(l,\gamma) = \sqrt{(\Phi_l - \Phi_\gamma)^2 + (\eta_l - \eta_\gamma)^2}$$

We summarize the lepton identification requirements in the *calo* setup in Table 2.

6.) Since we consider predictions inclusive with respect to QCD radiation, we do not impose any jet definition.

3 W and Z boson observables

In the following we provide a list of observables which will be evaluated in the benchmarking of EW and QCD predictions. We consider the following charged (CC) and neutral current (NC) processes: $pp(p\bar{p}) \to W^\pm \to l^\pm \nu_l$ and $pp(p\bar{p}) \to \gamma, Z^0 \to l^+ l^-$ with $l = e, \mu$.

To facilitate a quick and easy comparison of histograms, please use the lower value of the bin range to label the bin (e.g., for a range of $0 - 100$ GeV and a bin size of 1 GeV the first bin is labeled 0 GeV, the second bin 1 GeV etc). Please provide the histograms in form of an ASCII file including a bin-by-bin Monte Carlo integration error.

W **boson observables:**

- σ_W: total inclusive cross section of W boson production.
- $\frac{d\sigma}{dM_T(l\nu)}$: transverse mass distribution of the lepton lepton-neutrino pair. The transverse mass is defined as

$$M_T = \sqrt{2 p_T(\ell) p_T(\nu)(1 - \cos\phi^{\ell\nu})}\ , \tag{5}$$

where $p_T(\nu)$ is the transverse momentum of the neutrino, and $\phi^{\ell\nu}$ is the angle between the charged lepton and the neutrino in the transverse plane. The neutrino transverse momentum is identified with the missing transverse momentum, $\not{p}_T$, in the event. M_T range (bin size): 50-100 GeV (0.5 GeV)

- $\frac{d\sigma}{dp_T^l}$: transverse lepton momentum distribution. p_T^l range (bin size): 25-55 GeV (0.25 GeV)
- $\frac{d\sigma}{d\not{E}_T^l}$: missing transverse energy distribution. $\not{E}_T$ range (bin size): 25-55 GeV (0.25 GeV)
- $d\sigma_W/dQ_T(W)$: W transverse momentum distributions. Q_T range (bin size): 0-25 (0.25 GeV) and 0-300 GeV (1 GeV)

Z **boson observables:**

- σ_Z: total inclusive cross section of Z boson production.
- $\frac{d\sigma}{dM_{ll}}$: invariant mass distribution of the lepton pair. M_{ll} range (bin size): 50-200 GeV (1 GeV)
- $\frac{d\sigma}{dp_T^l}$: transverse lepton momentum distribution (l is the positively charged lepton). p_T^l range (bin size): 25-65 GeV (0.25 GeV)
- $d\sigma_Z/dQ_T(Z)$: Z transverse momentum distributions. Q_T range (bin size): 0-25 (0.25 GeV) and 0-300 GeV (1 GeV)

W/Z **Ratios:**

- $\frac{\sigma_W}{\sigma_Z}$: ratio of the total inclusive cross sections of the W and Z boson.
- $\frac{d\sigma_W/dX_M(W)}{d\sigma_Z/dX_M(Z)}$: ratio of W and Z transverse mass distributions, with $X_M(V) = M_T^V/M_V, V = W, Z$. X_M range (bin size): 0.6-1.2 (0.006)
  The transverse mass of the lepton pair in Z boson events is defined in complete analogy to Eq. (5):

  $$M_T^Z = \sqrt{2p_T(\ell^+)p_T(\ell^-)(1-\cos\phi)}\ , \tag{6}$$

- $\frac{d\sigma_W/dX_p(W)}{d\sigma_Z/dX_p(Z)}$: ratio of the lepton transverse momentum distributions in W and Z boson production, with $X_p(V) = p_T^V(l)/M_V, V = W, Z$ (NC: l is the positively charged lepton). X_p range (bin size): 0.4-1.2 (0.008)

- $\frac{d\sigma_W/dQ_T(W)}{d\sigma_Z/dQ_T(Z)}$: ratio of the transverse momentum distributions of the W and Z bosons. Q_T range (bin size): 0-25 (0.25 GeV) and 0-300 GeV (1 GeV)

4 Benchmarks

For each observable (where applicable) listed in Section 3 we will compare predictions at NLO EW (RADY, HORACE, SANC, WZGRAD), NLO QCD (DYNNLO, Resbos, Powheg, FEWZ, Sherpa, Zanderighi-Re), NLO QCD+resummation (Resbos, Powheg (with Pythia),Sherpa), NNLO QCD (DYNNLO, FEWZ, Sherpa, Zanderighi-Re), NLO QCD+Pythia+NLO EW (POWHEG_BW and POWHEG_BMNNP), NLO QCD+Pythia+NLO EW+PHOTOS (POWHEG_BMNNP) and when including QED PS (PHOTOS).

We propose to use the Pythia version 6.4.26, Perugia tune (PYTUNE(320)). When producing NLO QCD+EW results with Pythia, the QED showering effects should be switched off by setting `MSTJ(41)=MSTP(61)=MSTP(71)=1`.

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