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DRELL–YAN PROCESSES WITH WINHAC* **

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We present the Monte Carlo event generator WINHAC for Drell–Yan processes in proton–proton, proton–antiproton, proton–ion and ion–ion collisions. It features multiphoton radiation within the Yennie–Frautschi–Suura exclusive exponentiation scheme with $\mathcal{O}(\alpha)$ electroweak corrections for the charged-current (W^+/W^-) processes and multiphoton radiation generated by PHOTOS for neutral-current ($Z+\gamma$) ones. For the initial-state QCD/QED parton shower and hadronisation, it is interfaced with PYTHIA. It includes several options, *e.g.* for the polarized W-boson production, generation of weighted/unweighted events, *etc.* WINHAC was cross-checked numerically at the per-mille level with independent Monte Carlo programs, such as HORACE and SANC. It has been used as a basic tool for developing and testing some new methods of precise measurements of the Standard Model parameters at the LHC, in particular the W-boson mass. Recently, it has been applied to simulations of the double Drell–Yan processes resulting from double-parton scattering, in order to assess their influence on the Higgs-boson detection at the LHC in its ZZ and W^+W^- decay channels.

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1. Introduction

The Drell–Yan (DY) process, *i.e.* lepton-pair production in hadronic collisions, played an important role in the past in testing the parton model as well as the quantum chromodynamics (QCD) as the theory of strong interactions. While at the low-energy hadron colliders the lepton pairs were produced through the virtual γ exchange, in the recent high-energy colliders (Tevatron, LHC) the collision energy is sufficient to produce $W^{\pm}$ and Z bosons. Moreover, the cross sections for these processes turn out to be relatively high. Therefore, they can be used to improve experimental precision of some Standard Model (SM) parameters values, in particular the W-boson mass M_W and width Γ_W, the weak-mixing angle $\sin^2\theta_W$ and the strong coupling constant $\alpha_{\rm s}$. According to PDG 2012 [1], the experimental errors on the W-boson mass and width are respectively: $\delta M_W = 15$ MeV, $\delta\Gamma_W = 42$ MeV, while the corresponding errors for the Z boson are $\delta M_Z = 2.1$ MeV, $\delta\Gamma_Z = 2.3$ MeV. A difference between the opposite-charge W masses is measured even worse: $\delta(M_{W^+} - M_{W^-}) = 600$ MeV. Smaller errors of the W-boson mass and width will allow for a better indirect determination of the SM Higgs-boson mass [2]. In the case of a direct Higgs discovery at the LHC, this will provide the important consistency test of the Standard Model [2]. In order to match the precision of other SM parameters in such fits/tests, M_W should be measured at the LHC with the accuracy of 10 MeV or better [3, 4].

In theoretical descriptions of the DY processes reaching a sufficiently high precision for the LHC experiments requires including besides the QCD effects also the electroweak (EW) corrections, in particular the QED final-state radiation (FSR) [5]. It is known that including $\mathcal{O}(\alpha)$ EW corrections is not sufficient for the W-mass precision target at the LHC, because the higher-order FSR effects can shift M_W by ~ 10 MeV, see *e.g.* [6]. Regions of a high transverse momentum of a charged lepton, a large W-boson transverse mass and a large Z-boson invariant mass are used at the LHC for various "new physics" searches. In these regions, the $\mathcal{O}(\alpha)$ EW corrections beyond FSR can be of the size of 20–30% [7, 8]. Because of high statistics of DY events expected at the LHC, these effects must be included in theoretical description of the SM background. However, as was argued in [9], for realistic predictions, the EW corrections should be combined in this case with the QCD parton-shower effects. High statistics of DY data at the LHC will be important to reduce uncertainties of parton distribution functions (PDFs) over a wide range of the (x, Q^2) domain, see *e.g.* [10]. The DY processes are also treated at the LHC as the so-called 'standard candle' processes (detector calibration, normalisation, *etc.*), see *e.g.* [11]. Last but not least, in addition to the standard single DY processes, the so-called double Drell–Yan processes (DDYP), being a product of double-parton scattering (DPS), may play an important role at the LHC, in particular for the Higgs-boson searches in the $4l$ and $2l2\nu$ channels, resulting from its decays into ZZ and W^+W^- pairs [12].

Therefore, a precise theoretical description of the DY processes is very important for the LHC. In order to be fully exploited by the experiments, such a description ought to be provided in form of a Monte Carlo event generator. In this paper, we briefly describe the Monte Carlo event generator WINHAC [13] dedicated to precise theoretical predictions for the DY processes. In Sec. 2 we describe the implementation of the EW corrections as well the QCD effects and discuss their interplay, while in Sec. 3 we briefly review some applications of WINHAC to the LHC physics. Finally, Sec. 4 contains summary and outlook.

2. Electroweak corrections and QCD effects

In the current version of WINHAC [13], the description of the charged-current Drell–Yan (CC DY) processes is more advanced. It features multiphoton radiation from all charged particles involved in the hard process, implemented within the Yennie–Frautschi–Suura (YFS) exclusive exponentiation scheme [14] including the $\mathcal{O}(\alpha)$ EW corrections. In order to avoid ambiguities related to photon radiation from light quarks, the QED initial-state radiation (ISR) is subtracted from the EW corrections, however not in $\overline{\mathrm{MS}}$ or DIS schemes, as they are not well suited for a Monte Carlo event generator. Instead, we include in the program three options of the ISR subtraction in a gauge-invariant way, with a default one called the YFS scheme, in which from virtual EW corrections for the full CC DY process one subtracts the YFS virtual form factor plus terms $\sim (1/2)Q_i^2[\ln(s/m_i^2) - 1]$, where Q_i is a quark electric charge in the units of the positron charge and m_i is its mass[1]. Generation of QED ISR effects is left to general-purpose parton shower generators, such as PYTHIA or HERWIG, to which WINHAC is, or will be, interfaced. In these generators, in addition to primary QCD effects, also QED ISR can be generated using the parton shower algorithm. In such an approach, QED radiation is intertwined with the dominant QCD radiation. This solution is, in our opinion, better than the one in which photon radiation from quarks is generated completely independently of the QCD effects. More details on the implementation of EW corrections for the CC DY processes in WINHAC can be found in Refs. [9, 16, 17].

WINHAC has been extensively tested numerically and cross-checked with independent Monte Carlo programs. For the $\mathcal{O}(\alpha)$ and higher-order QED FSR effects it was compared with HORACE [18], while for the $\mathcal{O}(\alpha)$ EW corrections it was compared with the SANC Monte Carlo integrator [17].

[1] A similar subtraction of QED corrections from the EW ones is done in Ref. [15], however our results differ by some constant terms.

In both cases, the agreement at the per-mille level or better between the results of the programs was found. Currently, there is an ongoing work within the LHC Electroweak Working Group on detailed comparisons of various theoretical calculation and Monte Carlo programs for DY processes — the results should be published soon.

For the NC DY process, in the current version of WINHAC, only QED FSR effects are included through the PHOTOS Monte Carlo generator. It implements multiphoton radiation in particle decays using a leading-log-type iterative algorithm where some important non-leading corrections are taken into account [19]. It was shown that in the case of Z-boson decays its predictions are in a very good agreement with the ones of the $\mathcal{O}(\alpha^2)$ YFS exponentiation.

The WINHAC program is a flexible Monte Carlo event generator. It includes several options allowing to choose between different collider types: proton–proton, proton–antiproton, ion–ion, between various EW parameter schemes, initial-state quark flavours, final-state lepton flavours, intermediate bosons, types of radiative corrections, weighted or unweighted events, *etc.* Important options are also possibilities to generate the CC DY processes with polarized W-bosons (transverse or longitudinal) in some predefined reference frames or in user-defined ones.

For QCD effects, the current version of WINHAC is interfaced with the parton shower generator PYTHIA 6.4. It generates QCD/QED ISR using parton shower algorithm, performs proton-remnant treatment, hadronisation and particle decays. Two kinds of interfaces are available now: the first one is the internal interface in which the PYTHIA routines are called directly from the WINHAC code and the second one is based on the Les Houches Accord in which events from WINHAC are transmitted to PYTHIA through special LHA-format files [20]. The former interface is less universal — it allows to use only some limited set-up of the PYTHIA parameters, but is faster and more flexible for some dedicated studies, and also includes corrections to PYTHIA 6 for its improper predictions of lepton transverse momenta [21]. The second interface is more universal — it allows for any set-up of the PYTHIA parameters, including PYTHIA tunes. In this case, Monte Carlo events from WINHAC are written in the LHA format into disk files and read in by PYTHIA, which performs further processing of events. We have also added a possibility to transmit the hard-process event from PYTHIA back to WINHAC, through another LHA file, for some data analysis. Instead of ordinary disk files we prefer to use the UNIX named (FIFO) pipes, for which the input/output operations are identical as for ordinary files, but the data transmission goes through RAM, not disk, and thus is much faster. Moreover, one does not need to care about overloading a disk space with huge data files when high event statistics are generated.

As was argued in Ref. [9], in order to provide realistic predictions of the EW effects in DY processes at the LHC and other hadron colliders, the QCD parton shower effects must be taken into account. The QCD initial-state parton shower in DY processes modifies considerably the transverse momenta of the final-state leptons. Since a lower cut on the charged-lepton transverse momentum $p_{\rm T}^{l}$ is one of the primary cuts used by the LHC experiments for the DY processes, this affects all the DY observables. In Table I, we present the results for the Born cross sections as well as the EW and 'weak' corrections for the $W^+ \to \mu^+\nu_\mu$ channel of the CC DY process at the LHC collision energy of 14 TeV for the increasing lower cut on $p_{\rm T}^{l}$. In the upper part of the table, we show the results without the QCD parton-shower effects, while in the lower part the ones in which these effects, as generated by PYTHIA, are included. In Table II, we present similar results for the $W^- \to \mu^-\bar{\nu}_\mu$ channel. The so-called 'weak' corrections correspond to the difference of the EW corrections and a dominant gauge-invariant part of the QED corrections, as defined in Ref. [9]. One can see by comparing the upper and lower parts of the tables that the QCD parton-shower corrections affect considerably not only the total cross sections but also both EW and 'weak' corrections. These changes depend strongly on the $p_{\rm T}^{l}$ cuts and are different for W^+ than for W^-. In particular, the 'weak' corrections can be up to a factor ~ 7 smaller in the presence of the QCD effects than without them. Therefore, any theoretical predictions of the EW corrections for the DY observables at the LHC without inclusion of the QCD parton-shower effects are not realistic. On the other hand, the EW corrections can be quite sizeable, up to $\sim 20\%$, thus they also have to be taken into account. One can con-

TABLE I

Born cross sections as well as electroweak and 'weak' corrections without (upper part) and with QCD effects from PYTHIA (lower part) for the $W^+ \to \mu^+\nu_\mu$ channel at the LHC collision energy of 14 TeV corresponding to the increasing lower cut on the muon transverse momentum.

$p_{\rm T}^{\mu}$ [GeV]	> 25	> 50	> 100	> 200	> 500	> 1000
No QCD						
σ_0 [pb]	4779.0 (2)	30.34 (1)	1.944 (3)	0.178 (1)	0.0051 (1)	0.00015 (1)
$\delta_{\rm EW}$ [%]	−2.748 (3)	−6.10 (3)	−8.7 (1)	−12.8 (4)	−21.4 (1.3)	−28 (5)
$\delta_{\rm weak}$ [%]	−0.108 (0)	−1.193 (1)	−3.88 (1)	−7.36 (4)	−15.7 (3)	−23 (2)
With QCD PS (PYTHIA)						
σ_0 [pb]	4096.1 (2)	254.86 (4)	10.025 (8)	0.683 (2)	0.0114 (2)	0.00024 (2)
$\delta_{\rm EW}$ [%]	−2.548 (3)	−4.99 (1)	−4.98 (6)	−7.1 (2)	−13.2 (1.8)	−20 (11)
$\delta_{\rm weak}$ [%]	−0.113 (0)	−0.250 (0)	−0.91 (0)	−2.16 (1)	−7.0 (2)	−15 (2)

TABLE II

Born cross sections as well as electroweak and 'weak' corrections without (upper part) and with QCD effects from PYTHIA (lower part) for the $W^- \to \mu^- \bar{\nu}_\mu$ channel at the LHC collision energy of 14 TeV corresponding to the increasing lower cut on the muon transverse momentum.

$p_{\rm T}^{\mu}$ [GeV]	> 25	> 50	> 100	> 200	> 500	> 1000
No QCD						
σ_0 [pb]	3720.1 (1)	22.45 (1)	1.211 (2)	0.0971 (4)	0.00211 (3)	0.000052 (2)
$\delta_{\rm EW}$ [%]	−2.612 (3)	−6.16 (3)	−8.9 (1)	−12.9 (4)	−21.6 (1.5)	−32 (5)
$\delta_{\rm weak}$ [%]	−0.106 (0)	−1.094 (1)	−3.72 (1)	−7.13 (4)	−14.4 (3)	−22 (2)
With QCD PS (PYTHIA)						
σ_0 [pb]	3234.3 (1)	247.49 (4)	10.931 (8)	0.832 (2)	0.0133 (3)	0.00027 (4)
$\delta_{\rm EW}$ [%]	−2.406 (3)	−4.85 (1)	−4.47 (5)	−5.5 (2)	−8.7 (1.3)	−15 (8)
$\delta_{\rm weak}$ [%]	−0.110 (0)	−0.210 (0)	−0.59 (0)	−1.10 (1)	−2.8 (1)	−5 (1)

clude that any Monte Carlo event generator for precision physics at the LHC involving the DY processes should include both these effects. This is particularly important for the W-boson mass measurement with the precision target below 10 MeV. In this case, even more important than the change of the size of the EW corrections after including the QCD effects is the change of their shape for the $p_{\rm T}^{l}$ distribution, which is the main observable for the M_W measurements at the LHC [22].

3. Applications

We have already applied WINHAC to several dedicated physics studies of possible measurements at the LHC where the DY processes may play an important role. Our first study was devoted to a possibility of the experimental investigation of the electroweak symmetry breaking mechanism in proton–ion collisions at the LHC by exploiting the effective beams of polarized W-bosons and their interactions with spectator quarks [23]. Then, we proposed a way to use the NC DY process, *i.e.* single-Z production, at the LHC as a 'standard candle' for precision measurements of the SM parameters, particularly the ones related to the W-boson physics [11].

Our main focus was on investigating the possibility of measuring the W-boson mass M_W as well as the difference $\Delta M_{W^\pm} = M_{W^+} - M_{W^-}$ at the LHC with the precision of 10 MeV or better. This was the subject of a series of papers [24, 25]. We discussed important differences between the DY processes at the Tevatron and at the LHC, and showed that the M_W measurements procedures used at the Tevatron cannot be applied at the LHC. We proposed four bias-reducing observables to be used by the LHC experiments in such measurements and argued that a dedicated fix-target "LHC-support" experiment with a high-intensity muon beam is needed to achieve the aimed M_W precision target [25].

Recently, using WINHAC, we have performed studies of the double Drell–Yan processes (DDYP), resulting from double-parton scattering (DPS), and their possible influence on the Higgs-boson searches in its ZZ and WW decay channels. We have found that DDYP can produce an excess of events in the Higgs-signal region corresponding to the Higgs mass of ~ 125 GeV. This excess can contribute to the background to the Higgs signal, and even explain under certain conditions, the four-lepton event shapes observed by the ATLAS and CMS experiments [12].

4. Summary and outlook

We have briefly described the program WINHAC and its applications to some physics studies at the LHC. WINHAC is an efficient and flexible Monte Carlo event generator for Drell–Yan processes at the LHC and other hadron colliders. It features higher-order QED radiative corrections and is interfaced with the PYTHIA parton shower generator for QCD effects. For the charged-current Drell–Yan processes it includes also the $\mathcal{O}(\alpha)$ electroweak corrections within the YFS exclusive exponentiation scheme.

The original WINHAC program is written in the Fortran programming language. Currently, its object-oriented versions in C++ are under development: for the charge-current DY processes called WINHAC++ [26] and for the neutral-current ones called ZINHAC [27]. In the future, we would like to interface these programs with our own QCD parton shower generator, see Refs. [28–30].

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