Exploring the LHC Landscape with Dileptons

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Abstract

The dilepton decay channels provide clean signatures and are an ideal hunting ground for high mass resonant, like Z', or non-resonant, like contact interactions or extra dimensions, searches at the LHC. The production of high invariant mass opposite sign lepton pairs in proton-proton collisions in the Standard Model is dominated by the Drell-Yan process. In addition to this photon or Z exchange mediated mechanism, photons radiated by the incoming protons can collide and produce lepton pairs. In this paper detailed calculations of the Drell-Yan process at next-to-next-to-leading order in QCD and next-to-leading order in the electroweak corrections, augmented with the photon-induced effects, are presented in the typical acceptance of a multi-purpose LHC detector at center of mass energy 13 TeV. Estimates of the expected backgrounds for new physics searches are provided for dilepton invariant masses up to the LHC kinematic limit.

1 Introduction

The Standard Model (SM) of particle physics has ruled the collider scene for decades. Varied and very detailed tests of the SM have confirmed its validity at the available energies. Searches for new physics phenomena beyond the SM in dilepton (electron or muon) final states provide clean signatures and have been a mainstay of the quest strategy. Resonant or non-resonant effects have been searched for extensively at hadron colliders like the LHC, see e.g. [1, 2, 3, 4, 5, 6, 7, 8], and in the cleaner environment of lepton colliders at lower energies, see e.g. [9, 10].

The backgrounds for new high mass resonant (like Z') or non-resonant (like contact interactions or extra dimensions) effects are dominated by the Drell-Yan (DY) process of opposite sign lepton pair production, mediated through photon or Z exchange from the initial partons in the incoming protons. With the rapidly increasing accumulated luminosity at the LHC precise estimations of the background are a key ingredient of the dilepton searches, especially of the non-resonant variety. To reach the required precision, calculations at next-to-leading order (NLO) and next-to-next-to-leading order (NNLO) in Quantum Chromodynamics (QCD) are needed. NNLO cross section calculations reduce the dependence of the results on the renormalization and factorization scale choices to the couple of percent level, as expected when enough orders are included in the calculation.

The QCD calculations depend on the parton density functions (PDF) of the protons. The following modern PDFs [11, 12, 13] are used in this study. The PDF uncertainties are estimated using the latest PDF4LHC [14] prescriptions. In most cases the CT14 PDF set or the PDF4LHC15 set (which is an average of the CT14, MMHT14 and NNPDF3.0 PDF
sets) are used. Additional PDF sets are utilized for special purposes. The reweighting technique \cite{15} for PDF uncertainties is used.

Beside the QCD effects, electroweak (EWK) effects become very important at LHC energies. Technically (and as implemented in various calculation or simulation tools), they fall in two classes:

1. Quantum Electrodynamics (QED) only effects: Final State Radiation (FSR), Initial State Radiation (ISR) and their interference

2. Pure Weak corrections: vertex, WW and ZZ box, and self-energy contributions.

In addition to the DY process, lepton pairs can be produced in gamma-gamma collisions, where photons radiated by the incoming protons collide. To calculate this process, usually labeled photon-initiated (PI) background in various searches, we need parton density functions including the photon component. Quantum Electrodynamics introduces corrections to the parton evolution: photon parton distributions $\gamma(x,Q^2)$ are present for the proton (neutron), and part of the proton (or neutron) momentum is carried by the photons. The PDF depends on the parton momentum fraction - Bjorken $x$, and the momentum transfer $Q^2$. In this study the modern photon PDF \cite{16} is used. In Drell-Yan, W and Z production at the LHC the photon contribution is suppressed by a factor $\mathcal{O}(\alpha/\alpha_s)$ compared to the canonical quark-antiquark contribution.

For an up-to-date paper on the issues involved in precision studies of the DY process, see e.g. \cite{17}, which concentrates on W and Z boson production. In contrast, the focus of this paper is on the high mass search region up to the LHC kinematic limit - a not so well explored area of phase space.

\section{Setup}

The calculations for the Drell-Yan process and the photon-induced background are carried out with the program \textsc{FEWZ} \cite{18}. The $G_{\mu}$ scheme with the W mass, the Z mass and the Fermi constant $G_{\mu}$ (measured in muon decay) as input parameters besides the fermion masses is used. The PDFs considered in this study are CT14, NNPDF30 and PDF4LHC15, as provided by the LHAPDF libraries version 5 or 6 \cite{19 20 21}.

Full electroweak corrections at next-to-leading order (NLO) are computed (the flag \texttt{EW control = 0} is used). QCD effects are computed at next-to-leading order (NLO) and next-to-next-to-leading order (NNLO). When the PI background is added to the Drell-Yan cross section we label the results DY+PI.

Calculations for dielectrons or dimuons in the acceptance of a generic general purpose LHC experiment are presented: both outgoing leptons are required to have pseudorapidity $|\eta| < 2.4$. Relatively hard cuts suitable for searches at high invariant masses extending to the multi-TeV region are used - the transverse momenta for both leptons have to satisfy $p_T > 50$ GeV.

An important difference between the two channels is the treatment of photons located close in space to the leptons. They can originate from Final State Radiation, or from unrelated sources, e.g. the copious decays of $\pi^0$ in a hadron collider environment. The variable $\Delta R$ is used to measure “closeness”:

\[
\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2},
\]
where \( \eta \) and \( \varphi \) are the pseudorapidities and azimuthal angles of the lepton and the photon.

In the case of electrons the electromagnetic calorimeters of the experiments provide a natural “integration” of the energies of close-by photons with the electron energies. As a result the invariant mass reconstructed from the electron energies is closer to the electron pair mass before FSR. In the case of muons where the transverse momenta can be measured both in the central trackers, and in the outer muon detectors after the photons are absorbed, there is no such effect. Two lepton definitions as available in \texttt{FEWZ} are used in the calculations:

1. “Dressed” electrons: photons within \( \Delta R < 0.1 \), and with \(|\eta| < 2.5\) and transverse momentum \( p_T > 0.5 \text{ GeV} \) are included in the electron energies

2. “Bare” muons: photon energy is not included.

In [16] \texttt{CT14qed} sets are produced. The initial photon distribution is defined by the initial photon momentum fraction

\[
p_0^\gamma = \int_0^1 x f_{\gamma/p}(x,Q_0) dx
\]

at scale \( Q_0 = 1.295 \text{ GeV} \).

From the ZEUS data on deep inelastic scattering with isolated photons [22] the photon PDF is constrained to \( p_0^\gamma \leq 0.14\% \). The constraint can be improved in measurements where the photon contribution is enhanced by selecting exclusive dimuon pair production in elastic, single dissociative and double dissociative pp collisions [23, 24]. These CMS measurements are used in [25] to update the \texttt{CT14qed} analysis:

\[
p_0^\gamma \leq 0.09\% \text{ at } 68\% \text{ CL} \quad (3)
\]

\[
p_0^\gamma \leq 0.13\% \text{ at } 90\% \text{ CL} \quad (4)
\]

consistent with the ZEUS data analysis.

3 Cross Section Calculations

**EWK corrections**

In Figure 1 the cross section ratios at NLO in QCD and electroweak corrections are shown. We compare three sets of calculations:

1. QCD at NLO, no EWK corrections

2. QCD at NLO and QED corrections: FSR, ISR and their interference; Weak corrections off

3. QCD at NLO and full EWK corrections.

As can be seen the pure QED corrections are bigger in the dimuon channel due to the use of “bare” muons. The full EWK corrections are very important at high invariant masses: they reduce the cross section by more than 20% in the dielectron channel and by
up to 30 % in the dimuon channel. In some Monte-Carlo simulations only QED effects are taken into account. Clearly the inclusion of full EWK effects is key for successful comparisons to data. The importance of complete EWK corrections for LHC at 14 TeV was recognized early [26]. The results presented here agree well with calculations in this exploratory study. Higher order corrections of mixed QCD-EWK type $\mathcal{O}(\alpha_s\alpha)$ are ignored in FEWZ. They are generally less important [27] except for high precision studies.

PDF uncertainties
In Figure 2 the PDF uncertainties for the NLO cross sections (QCD and full EWK), using the CT14nlo PDF, are shown as a function of mass. They become sizable above 2 TeV and approach $\sim \pm 40\%$ for masses above 5 TeV. As discussed later, the PDF uncertainties are dominant at high mass.

PDF choice
The dependence of the cross sections on the choice of PDF is displayed in Figure 3A for the CT14nlo and PDF4LHC nlo_100 sets. For masses below 5 TeV the variation is below 5%, reaching $\sim 15\%$ for the highest masses. The variation from one is covered by the PDF uncertainties, and could become important only for very high integrated luminosities - as shown in the next section even for 100 fb$^{-1}$ no events from SM sources are expected above 5 TeV.

$\alpha_s$ dependence
In Figure 3B the dependence of the cross sections on variations in the value of the strong coupling constant $\alpha_s$ is examined. For variations larger then the current error from the world average [28]:

$$\alpha_s(M_Z) = 0.1185 \pm 0.0006,$$

the effects are below 1% for the whole mass range under study.

PI background
The effect of photon-initiated lepton pair production on the cross sections is shown in Figure 4 where the ratios (DY+PI)/DY are displayed. The CT14qed proton PDF is used. It includes the photon contribution. The initial photon momentum fraction $p_0^\gamma$, which is a free parameter, is varied between 0.00% and 0.09% as discussed earlier, and the two limiting cases are displayed. Their difference is used conservatively as one standard deviation in the estimate of event rates.

The photon-initiated effects are generally small, well below the 5% level for masses of up to 2 TeV, and can reach $\sim 15\%$ above 5 TeV if the photon momentum fraction is taken to be 0.09%. The results presented here agree well with the results from [29] based on the MRST2004qed [30] PDF set (member one). The predictions from another photon PDF [31], also analyzed in [29], have large PDF uncertainties in the most interesting search region.

NNLO/NLO K functions and NNLO PDF uncertainties
In Figure 5 the cross section ratios for calculations at NNLO or NLO in QCD, the so called K functions, are shown for dielectrons and dimuons. In all cases full EWK corrections are included. The K functions are below 1.04 for the whole mass range under study, so the NNLO QCD effects are quite small. The K functions exhibit a complex
behavior as a function of mass.

Figure 6 compares the PDF uncertainties for NLO and NNLO cross sections (QCD and full EWK), using the order-matched CT14nlo and CT14nnlo PDFs. The good news is that the uncertainties are reduced at NNLO.

**Scale dependence**

If enough orders are included in the perturbative expansion, the results should not depend on the choice of renormalization and factorization scales. Traditionally this effect is estimated by varying the scales by a factor of two around the nominal scale, which for Drell-Yan is taken to be the mass of the outgoing dilepton system. An example of such variation for NNLO calculations is shown in Figure 7. The cross sections change by less than 3% below masses of 5 TeV. For the highest masses the variation reaches 3.6%. At NNLO in QCD the calculations are precise enough to serve the needs of searches for new phenomena.

**All combined**

In Figure 8 the K functions and photon-induced effects are combined. The ratios of NNLO cross sections including PI contributions to NLO cross sections (QCD and full EWK) are shown. Results with all effects taken into account will be discussed in the rest of this paper.

## 4 Differential Cross Sections and Event Yields

The differential cross sections as function of mass are shown in Figure 9 for the dielectron and dimuon channels. As explained in the previous section, a conservative estimate is used for the uncertainty of the photon-induced background, and it shows on the plots. As this background as much smaller than the Drell-Yan contribution, the impact on the combined cross section is minor.

Ad–hoc fits to the differential cross sections as function of mass are shown in Figure 10. The following function is used:

\[
\frac{d\sigma}{dm} = p_0 \cdot m^{(p_1 + p_2 \cdot \ln m + p_3 \cdot (\ln m)^2 + p_4 \cdot (\ln m)^3)},
\]

where \( p_0 \) to \( p_4 \) are free parameters, \( m \) is the invariant mass of the dilepton system in TeV, and \( \sigma \) is the cross section in fb. The fits, inspired by the “not-too-far from linear” behavior of the curves on a double logarithmic plot, perform well if five parameters are used. The \( \chi^2/\text{d.o.f.} \) is good, and the fit parameters are shown on the plots for the two channels. The shapes of the two distributions are identical within the statistical errors, while the yield (compare the values of the \( p_0 \) parameter) is higher in the electron channel, as discussed in the next paragraph.

The cumulative number of events expected in one experiment above a given mass for integrated luminosity of 100 fb\(^{-1}\) at 13 TeV are given in Figure 11 for the two channels. The apparent “kink” in the distributions at 1 TeV is just an artifact of the change of binning from 0.1 to 0.5 TeV bins at this point. The expected numbers of events are summarized in Table 1. The yield is slightly higher in the dielectron channel due to the recovery of FSR radiation by the electromagnetic calorimeters. As a result fewer events...
migrate to lower masses. In practice, this channel has an additional advantage due to the favorable energy dependence of the mass resolution. In the dimuon channels the mass resolution relies on tracking and deteriorates at high mass. All things being equal the dielectron channel might be first in a discovery. Additional search options are provided by measuring the forward-backward asymmetry. Here the muon channel may have an advantage, as the charge determination for electrons relies on the central trackers with much shorter lever arm, so it becomes increasingly difficult at high energies. Around one event with mass exceeding 3 TeV per channel is expected for luminosity of 100 fb$^{-1}$. Given the luminosities being collected by ATLAS and CMS in 2016, with a bit of luck we may expect to see first event(s) at these high masses this year.

Table 1: Cumulative expected numbers of events in one experiment above a given mass for integrated luminosity of 100 fb$^{-1}$ at 13 TeV. The “From Fit” columns are obtained by integrating the fits to the differential cross sections, as explained in the text.

| Mass (TeV) | Dielectrons | Dimuons |
|-----------|-------------|---------|
|           | Events   | Error$^+$ | Error$^-$ | From Fit | Events   | Error$^+$ | Error$^-$ | From Fit |
| 0.4       | 17500   | 215       | 282     | 17600   | 16950   | 210       | 274     | 17050   |
| 0.5       | 8100    | 99        | 131     | 8090    | 7820    | 97        | 127     | 7800    |
| 0.6       | 4180    | 53        | 69      | 4200    | 4030    | 51        | 67      | 4040    |
| 0.7       | 2340    | 32        | 42      | 2370    | 2240    | 31        | 40      | 2280    |
| 0.8       | 1380    | 22        | 28      | 1420    | 1320    | 21        | 27      | 1360    |
| 0.9       | 850     | 17        | 22      | 890     | 810     | 16        | 21      | 850     |
| 1.0       | 540     | 15        | 19      | 570     | 520     | 14        | 18      | 550     |
| 1.5       | 81.0    | 2.7       | 3.2     | 87.5    | 76.7    | 2.6       | 3.1     | 82.9    |
| 2.0       | 16.8    | 0.68      | 0.78    | 17.9    | 15.8    | 0.64      | 0.74    | 16.8    |
| 2.5       | 4.1     | 0.21      | 0.23    | 4.3     | 3.8     | 0.20      | 0.22    | 4.0     |
| 3.0       | 1.1     | 0.073     | 0.077   | 1.1     | 1.0     | 0.062     | 0.064   | 1.0     |
| 3.5       | 0.33    | 0.027     | 0.027   | 0.32    | 0.30    | 0.023     | 0.023   | 0.29    |
| 4.0       | 0.097   | 0.0091    | 0.0091  | 0.094   | 0.088   | 0.0084    | 0.0083  | 0.086   |
| 4.5       | 0.029   | 0.0034    | 0.0034  | 0.029   | 0.026   | 0.0029    | 0.0029  | 0.026   |
| 5.0       | 0.0086  | 0.0012    | 0.0012  | 0.0085  | 0.0078  | 0.0011    | 0.0011  | 0.0078  |
| 5.5       | 0.0024  | 0.0005    | 0.0005  | 0.0021  | 0.0022  | 0.0005    | 0.0005  | 0.0019  |

The event yields are reproduced well by integrating the fits to the differential cross sections, shown in Figure 10. The “From Fit” columns in the Table, obtained this way, agree with the yields produced by calculating directly from the cross sections (the “Events” columns). All that is needed for predictions in different binnings is a new integration of the fit functions.

The total number of expected events above 0.4 TeV for the two channels in one experiment for 100 fb$^{-1}$ is 34450. It is interesting to compare this number to the early study [26] from 1999. The center-of-mass energy is 14 TeV, and the selection is not exactly the same: $|\eta| < 2.5$ and $p_T > 20$ GeV for both leptons. The simulation is done at leading order with
PYTHIA 5.7 and the then available PDFs. Given all these caveats, the 1999 prediction: 33000 expected events, is surprisingly close to the new result \[1\].

The most important test for the expected yields is the comparison to the data from the LHC experiments. The ATLAS collaboration observes \[7\] 26 events above 0.9 TeV for integrated luminosity 3.2 fb\(^{-1}\). Corrections have to be applied to this number to account for background contamination and detection efficiency, which work in opposite directions. The ATLAS acceptance extends to \(|\eta| < 2.5\), but excludes the transition region \(1.37 < |\eta| < 1.52\) between the central and forward calorimeters. The prediction from the numbers in Table 1 rescaled by luminosity and pseudorapidity acceptance, is 26.6 events, in excellent agreement with the data. The comparison in the muon channel is not so straightforward due to the lower detection efficiency and higher backgrounds. The updated preliminary ATLAS dielectron numbers \[8\] for 13.3 fb\(^{-1}\) are 99 observed events. From the results presented here the expectation is 111 events, in good agreement with the data.

A 2.9 TeV event in the dielectron channel observed by CMS \[3\] is the highest mass event as of this writing. From the numbers in Table 1 and the luminosity reported in the Run 2 papers cited here, the expectation is for \(\sim 2\) events above 2.5 TeV to be observed when combining the ATLAS and CMS yields in the dielectron and dimuon channels.

5 Outlook

The production of high invariant mass opposite sign lepton pairs in proton-proton collisions at the LHC is an important search region for manifestations of new physics, and for tests of the Standard Model at highest momentum transfers. In this paper the Drell-Yan and photon-induced backgrounds for dilepton searches are examined in great detail. Electroweak corrections, PDF uncertainties and choice, \(\alpha_s\) and scale dependencies, and QCD effects at next-to-next-to-leading order are considered. The Drell-Yan background is dominating at high masses, and the major source of uncertainty comes from the limited knowledge of parton density functions in this kinematic area. The photon-induced background plays a supporting role. The backgrounds are low and well understood in the most promising search region, and the LHC accelerator and the experiments are delivering and recording record luminosities. The hunt is on.

\[1\] For the sake of full disclosure, the author of the present paper and the person who produced these numbers back then are identical.
Figure 1: Top: Electroweak corrections for the dielectron channel: QED only and full EWK corrections. Bottom: Electroweak corrections for the dimuon channel: QED only and full EWK corrections.
Dielectrons 13 TeV in LHC Acceptance CT14nlo

| Mass [TeV] | NLO PDF Uncertainties [%] |
|------------|---------------------------|
|            | + Uncertainty | − Uncertainty |
| 0.2        |              |               |
| 0.5        |              |               |
| 1.0        |              |               |
| 2.0        |              |               |
| 5.0        |              |               |

Dimuons 13 TeV in LHC Acceptance CT14nlo

| Mass [TeV] | NLO PDF Uncertainties [%] |
|------------|---------------------------|
|            | + Uncertainty | − Uncertainty |
| 0.2        |              |               |
| 0.5        |              |               |
| 1.0        |              |               |
| 2.0        |              |               |
| 5.0        |              |               |

Figure 2: Top: NLO PDF uncertainties for the dielectron channel. Bottom: NLO PDF uncertainties for the dimuon channel.
Figure 3: A: Dependence of the cross sections on the choice of PDFs for the dimuon channel. The CT14nlo and PDF4LHC_nlo_100 sets are compared. B: Dependence of the cross sections on variations in the value of the strong coupling constant $\alpha_s$ for the dimuon channel.
Figure 4: Top: Photon-induced background for the dielectron channel. Bottom: Photon-induced background for the dimuon channel. The cross section ratios (DY+PI)/DY are displayed.
Figure 5: Top: K function NNLO/NLO for the dielectron channel. Bottom: K function NNLO/NLO for the dimuon channel.
Figure 6: Top: NLO and NNLO PDF uncertainties for the dielectron channel. Bottom: NLO and NNLO PDF uncertainties for the dimuon channel.
Figure 7: Dependence of the cross sections on the choice of renormalization and factorization scales for the dimuon channel.
Figure 8: Top: Ratio of cross sections including all effects (NNLO and PI) to NLO cross sections for the dielectron channel. Bottom: Ratio of cross sections including all effects (NNLO and PI) to NLO cross sections for the dimuon channel.
Figure 9: Top: Differential cross section including all effects (NNLO and PI) for the dielectron channel. Bottom: Differential cross section including all effects (NNLO and PI) for the dimuon channel.
Figure 10: Top: Fit to the differential cross section including all effects (NNLO and PI) for the dielectron channel. Bottom: Fit to the differential cross section including all effects (NNLO and PI) for the dimuon channel.
Figure 11: Top: Cumulative number of events expected in one experiment above a given mass for integrated luminosity of 100 fb$^{-1}$ including all effects (NNLO and PI) for the dielectron channel. Bottom: Cumulative number of events expected in one experiment above a given mass for integrated luminosity of 100 fb$^{-1}$ including all effects (NNLO and PI) for the dimuon channel.
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