Theoretical Uncertainties in Electroweak Boson Production Cross Sections at 7, 10, and 14 TeV at the LHC

N. Adam, V. Halyo,

Princeton University, Princeton, NJ 08544, USA

S.A. Yost

The Citadel, 171 Moultrie St., Charleston, SC 29409, USA

ABSTRACT: We present an updated study of the systematic errors in the measurements of the electroweak boson cross-sections at the LHC for various experimental cuts for a center of mass energy of 7, 10 and 14 TeV. The size of both electroweak and NNLO QCD contributions are estimated, together with the systematic error from the parton distributions. The effects of new versions of the MSTW, CTEQ-TEA, and NNPDF PDFs are considered.

KEYWORDS: Hadron-Hadron Scattering, NLO Computations.
1. Introduction

A precise measurement of electroweak gauge boson production for $pp$ scattering will be essential in LHC physics. These processes are important as standard candles in the luminosity measurement, as well as precision electroweak parameter measurements, constraints on the PDFs, and as backgrounds to new physics. The high luminosity at the LHC ensures that systematic errors will play a dominant role in determining the accuracy of the cross-section. Previously, [1, 2] we studied these systematic errors at 14 TeV, focusing on missing electroweak corrections, NNLO QCD, and PDF uncertainties. In this update, we calculate the same effects for the initial LHC start-up energy of 7 TeV, and also an intermediate scale of 10 TeV. We also specialize the calculation to various experimental cuts which better reflect cuts similar to the one considered by the CMS and ATLAS collaborations.

We also revisit the PDF errors, because updated PDFs have since been released which permit a significant reduction in the PDF errors quoted in our previous studies. Finally, HORACE has been updated since the study of Ref. [2], requiring the missing electroweak contribution to be recalculated in the $W$ case.\footnote{We thank P. Harris, K. Sung, P. Everaerts, and K. Hahn for bringing this to our attention.} This study compares the MSTW2008\cite{4} (an update of MRST\cite{5}), NNPDF\cite{3}, and the CTEQ-TEA family of PDF sets\cite{7, 8}.\footnote{We thank C.-P. Yuan for helpful discussions and for providing us with the CT10, CT10W PDF sets.}
2. Theoretical Calculations and Monte Carlo Generators

The processes of interest in this paper are electroweak boson production, predominantly via the Drell-Yan process, in which a quark and antiquark annihilate, producing a vector boson which decays into a lepton pair. The cross section mediated by a gauge boson $B$ may be inferred from the number $N_B^{\text{obs}}$ of observed events via the relation

$$N_B^{\text{obs}} = \sigma_{\text{tot}}(pp \to B \to \ell\ell') A_B \int L dt,$$

where $A_B$ is the acceptance obtained after applying the experimental selection criteria. For example, if the cuts require $p_T^\ell > p_T^\text{min}$, $0 < \eta^\ell < \eta_{\text{max}}$ for both leptons, then

$$A_B(p_T^\text{min}, \eta_{\text{max}}) = \frac{1}{\sigma_{\text{tot}}(pp \to B \to \ell\ell')} \int_{p_T^\text{min}}^{\sqrt{s}/2} dp_T^\ell \int_{p_T^\text{min}}^{\sqrt{s}/2} dp_{T'\ell'} \int_0^{\eta_{\text{max}}} d\eta^\ell \int_0^{\eta_{\text{max}}} d\eta^{\ell'} \frac{d^4\sigma}{dp_T^\ell dp_{T'\ell'} d\eta^\ell d\eta^{\ell'}}(B \to \ell\ell').$$

The neutral bosons $\gamma, Z$ are normally combined, and both $\sigma_{\text{tot}}$ and the acceptance may also include further cuts on the invariant mass $M_{\ell\ell'}$ of the lepton pair, to prevent the cross section from being dominated by photons, which give a divergent contribution at low energies.

The corrected $Z$ or $W$ yield can be used as a standard candle for a luminosity monitor by calculating the cross section and solving for $\int L dt$. The cross section may be calculated by convoluting a parton-level cross section $\hat{\sigma}_{ab}$ for partons $a,b$ with their parton density functions $f_a, f_b$, giving a cross section

$$\sigma = \sum_{a,b} \int_0^1 dx_1 dx_2 f_a(x_1) f_b(x_2) \hat{\sigma}_{ab}(x_1, x_2),$$

where the integral is over momentum fractions $x_1, x_2$. Theoretical uncertainties arise from limitations in the order of the calculation of $\sigma_{ab}$, on its completeness (for example, on whether it electroweak corrections or $\gamma^* / Z$ interference, and on whether any phase space variables or spins have been averaged), and on errors in the PDFs.

The simulation of hadronic processes requires an event generator incorporating a parton shower and hadronization. HERWIG, Pythia, and Sherpa are examples. At present, event generators are available which incorporate NLO QCD, including MC@NLO and POWHEG. Differential NNLO corrections are available in vrap FEWZ, and DYNNLO, but not yet interfaced to a shower. The Resbos family of MC programs calculates resummed cross-sections which improve the results in certain parts of phase space where large logarithms render a fixed-order calculation unreliable. Resbos is based on a resummed NLO calculation with the addition of approximate NNLO corrections to the Drell-Yan process. As in Refs. [1, 2], we take MC@NLO as our basic generator, and calculate NNLO corrections using FEWZ, since it provides a complete calculation at NNLO, and the perturbative series converges well for the cuts of interest here.
POWHEG could be used as an alternative to MC@NLO, or DYNNLO as an alternative to FEWZ, at the same order in QCD.

It has been stressed that to achieve 1% accuracy in the Drell-Yan process, electroweak corrections must be added as well, including mixed QCD and QED corrections, and included coherently in a single event generator. [19, 20, 21, 22, 23] Electroweak corrections have been calculated at order $\alpha$ and combined with a hadronic shower in HORACE. [24] Another program incorporating electroweak corrections into a hadronic generator which has appeared recently is WINHAC[25], for $W$ production, with a companion ZINHAC for $Z$ production under development. Earlier programs calculating parton-level electroweak corrections at order $\alpha$ include ZGRAD and WGRAD. [19] Partial electroweak corrections, specifically final-state photon radiation (FSR), can also be added to an existing shower via the program PHOTOS. [26] In our previous analyses [1, 2], we used HORACE to estimate the effects of electroweak corrections on the systematic error in calculations done using MC@NLO and PHOTOS. We continue this approach in the present study, using HORACE to estimate the electroweak corrections beyond photon FSR.

3. Analysis of Electro-Weak Corrections

As suggested in Refs. [1, 2], our best estimates of the cross-sections are obtained using MC@NLO with final state radiation added via PHOTOS. We will begin our analysis of theoretical errors by examining the electro-weak corrections. The choices of cuts for this study are shown in Table 1. The results are shown in Table 2. For the $W$, acceptances in this table are defined relative to the total cross section, while for the $Z$, they are defined relative to the total cross section with an invariant mass cut $40 \text{ GeV} < M_{ZZ} c^2 < 1000 \text{ GeV}$ to avoid energies dominated by soft photons.

| Process               | Cut                                                                 |
|-----------------------|----------------------------------------------------------------------|
| $Z$ Production        | $E_T^\ell > 20 \text{ GeV, } |\eta_\ell| < 2.5, \ 70 < M_{\ell\ell} < 110 \text{ GeV/}c^2$ |
| $W$ Production        | $E_T^\ell > 30 \text{ GeV, } |\eta_\ell| < 2.5$                                                                 |

Table 1: Acceptance regions for the Electroweak vector bosons.

As in Refs. [1, 2], we used HORACE [24] to study the error arising from missing $O(\alpha)$ electroweak (EWK) corrections. This program includes initial and final-state QED radiation in a photon shower approximation and exact $O(\alpha)$ EWK corrections matched to a leading-log QED shower. Specifically, the missing EWK contribution was calculated by generating events for $pp \to Z/\gamma^* \to \ell^+\ell^-$ and $pp \to W^\pm \to \ell^\pm\nu$ using HORACE with its full $O(\alpha)$ corrections and parton-showered with HERWIG. These were compared to events generated again by HORACE, but without EWK corrections (Born-level), also showered with HERWIG, and HERWIG plus PHOTOS. MSTW2008 PDFs were used in the calculations.

The results are shown in Table 3. The acceptance is the ratio of the cut to total cross section. In the $Z$ case, each total cross section entry includes an invariant mass cut 40
Cross Sections

| Energy | \( \sigma_{\text{tot}} \) (pb) | \( \sigma_{\text{cut}} \) (pb) | \( A \) | \( \sigma_{\text{cut}} \) (pb) | \( \sigma_{\text{cut}} \) (pb) | \( A \) | \( \sigma_{\text{cut}} \) (pb) | \( \sigma_{\text{cut}} \) (pb) | \( A \) | \( \sigma_{\text{cut}} \) (pb) | \( \sigma_{\text{cut}} \) (pb) | \( A \) |
|--------|----------------|----------------|------|----------------|----------------|------|----------------|----------------|------|----------------|----------------|------|
| 7 TeV  | 1071^{+16}_{-18} ± 2 | 446.6^{+13.4}_{-8.9} ± 1.4 | 0.417^{+0.0008}_{-0.0003} ± 0 | 1590^{+14}_{-30} ± 3 | 619.4^{+5.4}_{-22.0} ± 2.0 | 0.389^{+0.002}_{-0.008} ± 0 | 2279^{+18}_{-51} ± 5 | 832.9^{+13.5}_{-21.0} ± 2.8 | 0.366^{+0.007}_{-0.003} ± 0 | 12019^{+165}_{-222} ± 24 | 4179^{+46}_{-115} ± 14 | 0.348^{+0.003}_{-0.007} ± 0 |
| 10 TeV | 5947^{+99}_{-80} ± 12 | 2440^{+22}_{-63} ± 8 | 0.410^{+0.001}_{-0.0007} ± 0 | 8590^{+135}_{-144} ± 17 | 3219^{+48}_{-71} ± 11 | 0.375^{+0.003}_{-0.004} ± 0 | 12019^{+165}_{-222} ± 24 | 4179^{+46}_{-115} ± 14 | 0.348^{+0.003}_{-0.007} ± 0 | 9047^{+83}_{-247} ± 18 | 3455^{+39}_{-115} ± 11 | 0.382^{+0.003}_{-0.005} ± 0 |

Table 2: Total and cut cross sections \( \sigma_{\text{tot}}, \sigma_{\text{cut}} \) and acceptances \( A \) for the cuts in Table 1 using MC@NLO and PHOTOS. The errors are separated into PDF uncertainties (MSTW2008), with upper and lower bounds, and MC uncertainties.

GeV < \( M_{Zc}^2 < 1000 \) GeV, as noted above. Final state radiation should dominate for both \( W \) and \( Z \) production,[19] so there is good justification for passing the Born-level events through PHOTOS to add final-state photons, as is verified in previous LHC studies.[27, 1].

Figs. 1, 2 and the the \( W^\pm \) acceptance results in Table 3 show the improvement to the kinematic distributions obtained by using PHOTOS. Table 3 shows that the error introduced by using PHOTOS in place of the more complete electroweak corrections of HORACE is typically less than 1%, both in the cross sections and acceptances. Larger errors found in Ref. [2] were due to a technical problem in the earlier version of HORACE, which has been corrected in the current version 3.1 used in the present study.

4. QCD Errors: NNLO Corrections and Scale Dependence

The QCD error is divided into two categories, the error due to stopping at NLO order, and the dependence on residual dependence on the factorization and renormalization scales, due to truncating the calculation at finite order. For an estimate of the missing higher-order corrections, we take the NNLO calculation obtained using the current state-of-the-art program, FEWZ [16]. The residual scale dependence is estimated by calculating the NNLO result and varying the factorization and renormalization scales. The NNLO scale dependence is relevant here, since we may consider the NNLO result to be known, but neglected.

To obtain the results shown, we ran FEWZ [16] using using MSTW2008[4] PDFs at the appropriate QCD order, and calculated the difference between the NLO and NNLO result, choosing the renormalization and factorization scales at \( M_Z \) or \( M_W \), as appropriate. The estimates of residual scale dependence at NNLO was found by repeating the calculations...
with the renormalization and factorization scales multiplied by 2 or 1/2. Both scales are
taken to be equal.

The size of the NNLO contribution, as well as the residual scale dependence at order
NNLO, is shown in table 4. The scale dependence is calculated by dividing the standard
deviation of the results at the three scales by their average. If the NLO result at the center
scale is taken as the result, an estimate of the combined error is shown in the final column,
adding the two errors in quadrature as in Refs. [1, 2].

5. Parton Distribution Function Errors

Since our previous studies,[1, 2], new PDF sets have been released incorporating the latest
data. We consider the most recent PDF sets from three groups: MSTW [4], NNPDF[3],
and CTEQ-TEA [8]. PDF errors for MSTW and CT10 were calculated as in Refs. [1, 2]
using the asymmetric Hessian method, where the cross-section results from the various
eigenvector PDF sets have been combined according to the prescriptions found in Refs. [7, 5,
4]. NNPDF is based on an entirely different neural-network based approach, which provides
a collection of replica PDFs, for which the standard deviation provides a symmetric error
estimate.

Tables 5 – 7 compare the cross sections, acceptances, and their attendant uncertainties
for four sets of PDFs: MSTW2008[4] NNPDF2.0[3], and both CT10 and CT10W[8] from
the latest CTEQ-TEA analysis. The two CT10 sets differ in their treatment of the Tevatron
D0 Run-2 W lepton asymmetry data.[28] Since this data creates tension with existing
constraints on d(x)/u(x), two approaches were taken: CT10 omits this data, while CT10W
includes it with an extra weight.[8] All of the PDF sets in this comparison are NLO versions
with 90% CL. The cuts are as in Table 1, and the upper and lower limits of the asymmetric
errors are shown. (Symmetric errors are given for NNPDF.) The results for 7 TeV are also
shown in Figs. 3 – 5.

In addition we studied the sensitivity of the kinematic acceptance calculations to the
uncertainties affecting the PDF sets. The errors considered here are due to the experimental
inputs used to obtain the PDFs, not to the QCD order of the calculation, which should be
matched to the order of the hard matrix element used. Figs. 6 – 8 show the systematic error
on the production cross-sections as a function of the |η| cut, minimum lepton p_T cut and
(where appropriate) M_T cut for the values given in Table 1. The fractional uncertainties,
shown in in the same figures, demonstrate that the relative uncertainty in the cross-section
is very flat as a function of the kinematic cuts, until the region of extreme cuts and low
statistics in the MC are reached. The corresponding uncertainty on the acceptance as a
function of the kinematic cuts is shown in Figs 9 – 11. These show a similar dependence
to the cross-section uncertainties, though the fractional errors are smaller.

The new PDF sets have improved the error estimates relative to our previous studies.[1, 2].
Uncertainties in the cross-sections contributed by the PDFs are typically in the range
of 1 – 2% for MSTW2008 and NNPDF2.0, and 2 – 3% for CT10(W). The acceptances have
smaller errors in all cases, typically close to 1%, with less dependence on the choice of PDF.

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The error bands of CT10(W) typically encompass those of MSTW2008 and NNPDF2.0, and appear to be a more conservative error estimate.

6. Summary

Tables 8 and 9 show the combined errors in the cross sections and acceptances, respectively. These tables separate the errors into three classes, and calculate the total errors under the assumption that they are independent. Since the missing NNLO and missing electroweak corrections are known, including the sign, these can be combined to give a total error for missing higher-order effects, labeled “Higher Order” in the table.\(^3\) The QCD scale uncertainty remaining at NNLO is included as a separate random error. The NNLO scale dependence is relevant since the calculation has been done at this order, although we may choose not to implement the resulting \(K\)-factor. Symmetric errors are used for the PDFs. The CT10 errors are shown in these tables, since these are more conservative than for the other PDF sets, and typically encompass the PDF differences. The cross section error is much more sensitive to the choice of PDFs than the acceptance error. For acceptances, we have verified that CT10 and MSTW2008 give very similar acceptance errors, in spite of significant differences in the cross section errors.

The total uncertainties are typically in the range of 4–5% for the cut cross sections, and 1–3% for the acceptances. The QCD errors are comparable to those seen in the earlier studies at 14 TeV.\(^1, 2\) There is a significant improvement in the PDF errors (see Tables 5, 6, 7), especially for acceptances, though they still dominate the errors in the cross sections. The higher-order electroweak contribution has been reduced significantly in the \(W\) case, due to a correction to the HORACE program. Although the electroweak and NNLO QCD corrections are not yet available in an event generator, they can be calculated using HORACE and FEWZ, respectively, and used to improve the calculation via \(K\)-factors, reducing the quoted errors to the sum (in quadrature) of the PDF and NNLO QCD scale uncertainties.\(^4\) An implementation of the next level of electroweak and QCD corrections in an event generator would have the potential for a significant improvement.

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\(^3\)In previous studies \([1, 2]\), the missing EWK and QCD errors were treated as independent random errors, but the present treatment is more accurate, since these are systematic errors of known sign.

\(^4\)However, in the case of NNLO QCD, some care is needed because the shower already incorporates some NNLO effects, which would partially duplicate those calculated by FEWZ or DYNNOLO.
References

[1] N.E. Adam, V. Halyo, and S.A. Yost, *JHEP* **05** (2008) 062.

[2] N.E. Adam, V. Halyo, S.A. Yost, and W.-H. Zhu, *JHEP* **09** (2008) 133.

[3] L. Del Debbio *et al.*, *JHEP* **0503** (2005) 080; *ibid.* **0703** (2007) 039; R.D. Ball *et al.*, *Nucl. Phys.* **B809** (2009) 1; *ibid.* **B823** (2009) 195; J.I. Latorre, J. Rojo, and M. Ubiali, *JHEP* **1005** (2010) 075; *ibid.* arXiv:1002.4407.

[4] A.D. Martin, W.J. Stirling, R.S. Thorne, and G. Watt, *Eur. Phy. J.* **C63** (2009) 189 [arXiv:0901.0002].

[5] A.D. Martin, R.G. Roberts, W.J. Stirling, and R.S. Thorne, *Phys. Lett.* **B652** (2007) 292; *ibid.* **B636** (2006) 259; *Eur. Phys. J.* **C28** (2003) 455; *ibid.* **C23** (2002) 73; *ibid.* **C18** (2000) 117.

[6] S.D. Drell and T.M. Yan, *Phys. Rev. Lett.* **25** (1970) 316.

[7] W.K. Tung, H.L. Lai, A. Belyaev, J. Pumpkin, D. Stump, C.-P. Yuan, *JHEP* **0702** (2007) 053; D. Stump, J. Huston, J. Pumpkin, W.-K. Tung, H.L. Lai, S. Kuhlmann, and J.F. Owens, *JHEP* **0310** (2003) 046; J. Pumpkin, D. Stump, J. Huston, H.L. Lai, P. Nadolsky and W.-K. Tung, *JHEP* **07** (2002) 012.

[8] H.-L. Lai *et al.*, *New Parton Distributions for Collider Physics*, MSUHEP-100707, SMU-HEP-10-10 (July, 2010), arXiv:1007.2241.

[9] M.W. Krasny, F. Fayette, W. Placzek, and A. Siodmok, *Eur. Phys. J.* **C51** (2007) 607; S. Frixione and M.L. Mangano, *JHEP* **05** (2004) 056.

[10] G. Marchesini, B.R. Webber, G. Abbiendi, I.G. Knowles, M.H. Seymour and L. Stanco, *Comp. Phys. Commun.* **67** (1992) 465; G. Corella, I.G. Knowles, G. Marchesini, S. Moretti, K. Odagiri, P. Richardson, M.H. Seymour and B.R. Webber, *JHEP* **0101** (2001) 010 [arXiv:hep-ph/0011363]; arXiv:hep-ph/0210213; S. Gieseke, A. Ribon, M.H. Seymour, P. Stephens and B. Webber, *JHEP* **0402** (2004) 005.

[11] M. Bertini, L. Lönnblad, and T. Sjöstrand, *Comput. Phys. Commun.* **134** (2001) 365; T. Sjöstrand, P. Eden, C. Friberg, L. Lönnblad, G. Miu, S. Mrenna and E. Norrbin, *Comput. Phys. Commun.* **135** (2001) 238; T. Sjöstrand, L. Lönnblad, S. Mrenna, and P. Skands, arXiv:hep-ph/0308153; T. Sjöstrand, S. Mrenna, and P. Skands, arXiv:hep-ph/0603175.

[12] T. Gleisberg, S. Höche, F. Krauss, A. Schälicke, S. Schumann, and J.C. Winter, *JHEP* **0402** (2004) 056; A. Schaelicke and F. Krauss, *JHEP* **0507** (2005) 018; F. Krauss, A. Schaelicke, S. Schumann, G. Soff, *Phys. Rev.* **D72** (2004) 114009; *ibid.* (2005) 054017.

[13] S. Frixione and B.R. Webber, *JHEP* **0206** (2002) 029 [arXiv:hep-ph/0204244]; S. Frixione, P. Nason and B.R. Webber, *JHEP* **0308** (2003) 007 [arXiv:hep-ph/0305252].

[14] P. Nason, *JHEP* **11** (2004) 040; P. Nason and G. Ridolfi, *JHEP* **08** (2006) 077; S. Alioli, P. Nason, C. Oleari, and E. Re, *JHEP* **07** (2008) 060.

[15] C. Anastasiou, L. Dixon, K. Melnikov, and F. Petriello, *Phys. Rev. Lett.* **91** (2003) 182002; *Phys. Rev.* **D69** (2004) 094008.

[16] K. Melnikov and F. Petriello, *Phys. Rev. Lett.* **96** (2006) 231803; *Phys. Rev.* **D74** (2006) 114017.
[17] S. Catani, L. Cieri, G. Ferrera, D. de Florian, and M. Grazzini, Phys. Rev. Lett. 103 (2009) 082001; S. Catani and M. Grazzini, Phys. Rev. Lett. 98 (2007) 222002.

[18] G.A. Ladinsky and C.-P. Yuan, Phys. Rev. D50 (1994) 4239; C. Balazs, J.-W. Qiu, and C.-P. Yuan, Phys. Lett. B355 (1995) 335; C. Balazs and C.-P. Yuan, Phys. Rev. D56 (1997) 5558; F. Landry, R. Brock, P.M. Nadolsky, and C.-P. Yuan, Phys. Rev. D67 (2003) 073016; A.V. Konychev and P.M. Nadolsky, Phys. Lett. B633 (2006) 710.

[19] U. Baur, S. Keller, and W.K. Sakumoto, Phys. Rev. D57 (1998) 199; U. Baur, S. Keller, and D. Wackeroth, Phys. Rev. D59 (1999) 013002; U. Baur, O. Brein, W. Hollik, C. Schappacher, and D. Wackeroth, Phys. Rev. D65 (2002) 033007.

[20] V.A. Zykunov, Eur. Phys. J. C3 (2001) 9; ibid., Phys. Rev. D75 (2007) 073019.

[21] C. Glosser, S. Jadach, B.F.L. Ward, and S.A. Yost, Mod. Phys. Lett. A19 (2004) 2113; B.F.L. Ward and S.A. Yost, in Alekhin et al., QED $\otimes$ QCD Exponentiation and Shower/ME Matching at the LHC, in HERA and the LHC, CERN-2005-014 (2005) 304 [hep-ph/0509003]; ibid., QED$\otimes$QCD Exponentiation: Shower/ME Matching and IR-Improved DGLAP Theory at the LHC, in Proc. ICHEP-2006, Moscow (World Scientific, 2007) 505 [hep-ph/0610230]; ibid., Acta Phys. Polon. B38 (2007) 2395; B.F.L. Ward, S. Joseph, S. Majhi, and S.A. Yost, Precision QED$\otimes$QCD Resummation Theory for LHC Physics: IR-Improved Scheme for Parton Distributions, Kernels, Reduced Cross Sections with Shower/ME Matching (2008), arXiv:0808.3133, to appear in Proc. ICHEP-2008, Philadelphia.

[22] G. Balossini, et al., Acta Phys. Polon. B38 (2007) 3407; ibid., Acta Phys. Polon. B39 (2008) 1675; ibid., JHEP 1001 (2010) 013 [arXiv:0907.0276].

[23] S. Dittmaier and M. Krämer, Phys. Rev. D65 (2002) 073007; S. Dittmaier and M. Huber, Radiative corrections to the neutral-current Drell-Yan process in the Standard Model and its minimal supersymmetric extension, arXiv:0911.2329.

[24] C.M. Carloni Calame, G. Montagna, O. Nicrosini and M. Treccani, Phys. Rev. D69 (2004) 037301; JHEP 0505 (2005) 019; C.M. Carloni Calame, G. Montagna, O. Nicrosini and A. Vicini, JHEP 0612 (2006) 016; JHEP 10 (2007) 109.

[25] W. Placzek and S. Jadach, Eur. Phys. J. C29 (2003) 325; W. Placzek, WINHAC - the Monte Carlo event generator for single W-boson production in hadronic collisions, in Proc. European Physical Society Europhysics Conference on High Energy Physics, 2009, Krakow, Poland, PoS EPS-HEP2009 (2009) 340 [arXiv:0911.0572].

[26] E. Barberio, B. van Eijk, and Z. Was, Comput. Phys. Commun. 66 (1991) 115; E. Barberio and Z. Was, Comput. Phys. Commun. 79 (1994) 291; P. Golonka and Z. Was, Eur. Phys. J. C45 (2006) 97.

[27] N.E. Adam, C.M. Carloni Calame, V. Halyo and C. Shepherd-Themistocleous “Comparison of HORACE and PHOTOS in the $Z \rightarrow \ell^+\ell^-$ Peak Region” in Summary Report of the Tools and Jets part of the SMHC Working Group of the Les Houches 2007 workshop Physics at TeV Colliders, arXiv:0803.0678.

[28] V.M. Abazov et al. [D0 Collaboration], Phys. Rev. Lett. 101 (2008) 211801; Phys. Rev. D77 (2008) 011106.
Figure 1: $W^+$: FSR photon $p_T$ and electron–neutrino invariant mass distributions. The addition of PHOTOS to the HERWIG showering improves the shape of the kinematic distributions.

Figure 2: $W^-$: FSR photon $p_T$ and electron–neutrino invariant mass distributions. The addition of PHOTOS to the HERWIG showering improves the shape of the kinematic distributions.
Figure 3: Comparison of $Z/\gamma^* \to \ell^+\ell^-$ cross-sections for $M_{\ell\ell} > 40$ GeV/$c^2$ for several recent PDF calculations.

Figure 4: Comparison of $W^+ \to \ell^+\nu$ total cross-sections for several recent PDF calculations.

Figure 5: Comparison of $W^- \to \ell^-\bar{\nu}$ total cross-sections for several recent PDF calculations.
### Electro-Weak Corrections

#### Z Production

| Energy | $\sigma_{\text{tot}}$ (Born) | $\sigma_{\text{tot}}$ (Born+FSR) | $\sigma_{\text{tot}}$ (Electro-Weak) | Difference |
|--------|-------------------------------|---------------------------------|--------------------------------------|------------|
| 7 TeV  | 906.47 ± 0.40                 | 906.47 ± 0.40                   | 922.14 ± 1.04                       | +1.70 ± 0.12% |
|        | $\sigma_{\text{cut}}$         | 356.72 ± 0.46                   | 333.60 ± 0.48                       | −0.23 ± 0.21% |
|        | $A$                            | 0.3935 ± 0.0005                 | 0.3680 ± 0.0006                     | +1.96 ± 0.24% |
| 10 TeV | 1359.25 ± 0.80                | 1359.25 ± 0.80                  | 1387.67 ± 1.09                      | +2.05 ± 0.10% |
|        | $\sigma_{\text{cut}}$         | 494.58 ± 0.63                   | 462.65 ± 0.66                       | −0.06 ± 0.20% |
|        | $A$                            | 0.3639 ± 0.0005                 | 0.3404 ± 0.0005                     | +2.15 ± 0.23% |
| 14 TeV | 1964.76 ± 1.13                | 1964.76 ± 1.13                  | 2001.20 ± 1.79                      | +1.82 ± 0.10% |
|        | $\sigma_{\text{cut}}$         | 669.09 ± 0.86                   | 625.66 ± 0.89                       | +0.05 ± 0.20% |
|        | $A$                            | 0.3405 ± 0.0005                 | 0.3184 ± 0.0005                     | +1.81 ± 0.23% |

#### W$^+$ Production

| Energy | $\sigma_{\text{tot}}$ (Born) | $\sigma_{\text{tot}}$ (Born+FSR) | $\sigma_{\text{tot}}$ (Electro-Weak) | Difference |
|--------|-------------------------------|---------------------------------|--------------------------------------|------------|
| 7 TeV  | 4993.2 ± 0.4                  | 4993.2 ± 0.4                    | 4948.5 ± 0.3                         | −0.904 ± 0.009% |
|        | $\sigma_{\text{cut}}$         | 2065 ± 5                        | 1940 ± 5                             | −0.41 ± 0.36% |
|        | $A$                            | 0.4136 ± 0.0010                 | 0.3885 ± 0.0010                      | +0.49 ± 0.36% |
| 10 TeV | 7271.1 ± 0.7                  | 7271.1 ± 0.7                    | 7205.6 ± 0.5                         | −0.899 ± 0.014% |
|        | $\sigma_{\text{cut}}$         | 2748 ± 7                        | 2579 ± 7                             | −0.60 ± 0.45% |
|        | $A$                            | 0.3780 ± 0.0010                 | 0.3547 ± 0.0010                      | +0.30 ± 0.37% |
| 14 TeV | 10384 ± 1                     | 10384 ± 1                       | 10350 ± 1                            | −0.322 ± 0.014% |
|        | $\sigma_{\text{cut}}$         | 3575 ± 10                       | 3372 ± 10                            | −0.68 ± 0.41% |
|        | $A$                            | 0.3443 ± 0.0010                 | 0.3248 ± 0.0009                      | −0.36 ± 0.41% |

#### W$^-$ Production

| Energy | $\sigma_{\text{tot}}$ (Born) | $\sigma_{\text{tot}}$ (Born+FSR) | $\sigma_{\text{tot}}$ (Electro-Weak) | Difference |
|--------|-------------------------------|---------------------------------|--------------------------------------|------------|
| 7 TeV  | 3555.2 ± 0.2                  | 3555.2 ± 0.2                    | 3504.0 ± 0.2                         | −0.890 ± 0.008% |
|        | $\sigma_{\text{cut}}$         | 1489 ± 4                        | 1412 ± 3                             | −1.03 ± 0.35% |
|        | $A$                            | 0.4213 ± 0.0010                 | 0.3993 ± 0.0010                      | −0.14 ± 0.35% |
| 10 TeV | 5355.6 ± 0.7                  | 5355.6 ± 0.7                    | 5307.9 ± 0.3                         | −0.908 ± 0.012% |
|        | $\sigma_{\text{cut}}$         | 2114 ± 5                        | 2001 ± 5                             | −0.51 ± 0.39% |
|        | $A$                            | 0.3948 ± 0.0010                 | 0.3735 ± 0.0010                      | +0.39 ± 0.39% |
| 14 TeV | 7899.2 ± 0.8                  | 7899.2 ± 0.8                    | 7875.7 ± 0.6                         | −0.297 ± 0.013% |
|        | $\sigma_{\text{cut}}$         | 2919 ± 8                        | 2747 ± 8                             | +0.03 ± 0.39% |
|        | $A$                            | 0.3695 ± 0.0010                 | 0.3477 ± 0.0010                      | +0.32 ± 0.39% |

**Table 3:** Electro-Weak corrections to the $pp \rightarrow Z \rightarrow \ell^+\ell^-$, $pp \rightarrow W^+ \rightarrow \ell^+\nu_\ell$, and $pp \rightarrow W^- \rightarrow \ell^-\bar{\nu}_\ell$ total and cut cross-sections $\sigma_{\text{tot}}, \sigma_{\text{cut}}$ and acceptance $A$. The Born + FSR column shows corrections obtained using PHOTOS, and the Electro-Weak column shows corrections generated using HORACE 3.1, for $\ell = e$ or $\mu$. The difference is the missing electroweak correction if PHOTOS is used instead of HORACE, with the correct sign.
NNLO QCD Corrections and Scale Dependence

### Z Production

| Energy | $\sigma_{\text{tot}}$ (NNLO QCD) | QCD Scale (%) |
|--------|----------------------------------|----------------|
| 7 TeV  | +2.86 ± 0.10                    | 0.42 ± 0.02%   |
|        | +2.74 ± 0.62                    | 0.21 ± 0.08%   |
|        | -0.12 ± 0.61                    | 0.54 ± 0.21%   |
| 10 TeV | +2.62 ± 0.10                    | 0.53 ± 0.03%   |
|        | +2.01 ± 0.73                    | 0.59 ± 0.26%   |
|        | -0.60 ± 0.71                    | 1.05 ± 0.46%   |
| 14 TeV | +2.24 ± 0.11                    | 0.57 ± 0.03%   |
|        | +2.40 ± 0.71                    | 1.10 ± 0.44%   |
|        | +0.16 ± 0.70                    | 0.54 ± 0.22%   |

### W$^+$ Production

| Energy | $\sigma_{\text{tot}}$ (NNLO QCD) | QCD Scale (%) |
|--------|----------------------------------|----------------|
| 7 TeV  | +3.09 ± 0.25                     | 0.41 ± 0.08%   |
|        | +3.35 ± 0.70                     | 0.47 ± 0.19%   |
|        | +0.25 ± 0.72                     | 0.75 ± 0.34%   |
| 10 TeV | +2.80 ± 0.35                     | 0.70 ± 0.13%   |
|        | +3.47 ± 0.64                     | 0.35 ± 0.14%   |
|        | +0.65 ± 0.71                     | 0.40 ± 0.18%   |
| 14 TeV | +2.11 ± 0.39                     | 0.047 ± 0.020% |
|        | +3.86 ± 0.77                     | 1.41 ± 0.58%   |
|        | +1.71 ± 0.85                     | 1.45 ± 0.88%   |

### W$^-$ Production

| Energy | $\sigma_{\text{tot}}$ (NNLO QCD) | QCD Scale (%) |
|--------|----------------------------------|----------------|
| 7 TeV  | +2.69 ± 0.18                     | 0.54 ± 0.09%   |
|        | +2.80 ± 0.66                     | 0.59 ± 0.23%   |
|        | +0.11 ± 0.67                     | 0.84 ± 0.35%   |
| 10 TeV | +2.31 ± 0.51                     | 0.88 ± 0.23%   |
|        | +3.83 ± 0.62                     | 0.24 ± 0.08%   |
|        | +1.48 ± 0.79                     | 1.08 ± 0.45%   |
| 14 TeV | +2.20 ± 0.38                     | 0.87 ± 0.18%   |
|        | +3.52 ± 0.63                     | 0.86 ± 0.30%   |
|        | +1.30 ± 0.72                     | 0.093 ± 0.038% |

**Table 4:** QCD errors for the total cross and cut cross sections $\sigma_{\text{tot}}$, $\sigma_{\text{cut}}$ and acceptance $A$ using the cuts from Table 1. The NNLO contribution obtained using FEWZ[16] includes the correct sign, and could be added as a $K$-factor if desired. The scale dependence is calculated at three scales, $M_B$, $2M_B$, and $M_B/2$, for the appropriate boson mass $M_B$. The standard deviation of the three results is divided by their average to obtain the scale dependence shown.
PDF Errors in $Z$ Production

### 7 TeV

| PDF Set   | $\sigma_{\text{tot}}$ | $\Delta \sigma^+_{\text{tot}}$ | $\Delta \sigma^-_{\text{tot}}$ | $\sigma_{\text{cut}}$ | $\Delta \sigma^+_{\text{cut}}$ | $\Delta \sigma^-_{\text{cut}}$ | $A$ | $\Delta A^+$ | $\Delta A^-$ |
|-----------|----------------------|---------------------------------|-------------------------------|----------------------|---------------------------------|-------------------------------|-----|----------------|----------------|
| MSTW2008  | 1071 ± 2             | 16                              | 18                            | 447 ± 1              | 13                              | 9                             | 0.417 | 0.008          | 0.003          |
| NNPDF     | 1032 ± 2             | 22                              | 22                            | 429 ± 1              | 7                               | 7                             | 0.415 | 0.005          | 0.005          |
| CT10      | 1068 ± 2             | 32                              | 35                            | 447 ± 1              | 20                              | 15                            | 0.418 | 0.009          | 0.003          |
| CT10W     | 1072 ± 2             | 27                              | 39                            | 449 ± 1              | 13                              | 20                            | 0.418 | 0.006          | 0.006          |

### 10 TeV

| PDF Set   | $\sigma_{\text{tot}}$ | $\Delta \sigma^+_{\text{tot}}$ | $\Delta \sigma^-_{\text{tot}}$ | $\sigma_{\text{cut}}$ | $\Delta \sigma^+_{\text{cut}}$ | $\Delta \sigma^-_{\text{cut}}$ | $A$ | $\Delta A^+$ | $\Delta A^-$ |
|-----------|----------------------|---------------------------------|-------------------------------|----------------------|---------------------------------|-------------------------------|-----|----------------|----------------|
| MSTW2008  | 1590 ± 3             | 15                              | 30                            | 619 ± 2              | 5                               | 22                            | 0.389 | 0.002          | 0.008          |
| NNPDF     | 1524 ± 3             | 30                              | 30                            | 619 ± 2              | 10                              | 10                            | 0.387 | 0.005          | 0.005          |
| CT10      | 1585 ± 3             | 61                              | 44                            | 620 ± 2              | 27                              | 22                            | 0.391 | 0.006          | 0.009          |
| CT10W     | 1589 ± 3             | 55                              | 51                            | 618 ± 2              | 30                              | 20                            | 0.389 | 0.009          | 0.004          |

### 14 TeV

| PDF Set   | $\sigma_{\text{tot}}$ | $\Delta \sigma^+_{\text{tot}}$ | $\Delta \sigma^-_{\text{tot}}$ | $\sigma_{\text{cut}}$ | $\Delta \sigma^+_{\text{cut}}$ | $\Delta \sigma^-_{\text{cut}}$ | $A$ | $\Delta A^+$ | $\Delta A^-$ |
|-----------|----------------------|---------------------------------|-------------------------------|----------------------|---------------------------------|-------------------------------|-----|----------------|----------------|
| MSTW2008  | 2279 ± 5             | 18                              | 51                            | 833 ± 3              | 14                              | 21                            | 0.366 | 0.007          | 0.003          |
| NNPDF     | 2174 ± 4             | 40                              | 40                            | 796 ± 3              | 16                              | 16                            | 0.366 | 0.005          | 0.005          |
| CT10      | 2286 ± 5             | 68                              | 97                            | 844 ± 3              | 25                              | 50                            | 0.369 | 0.004          | 0.009          |
| CT10W     | 2287 ± 5             | 73                              | 96                            | 836 ± 3              | 43                              | 29                            | 0.366 | 0.012          | 0.002          |

**Table 5:** PDF Errors in the cross sections ($\sigma$) and acceptances ($A$) for the cuts in Table 1, calculated using the asymmetric Hessian method for MSTW and CT10(W), and the standard deviation for the NNPDF replica sets. All cross sections are in pb, while the acceptance is a ratio of cut to total cross sections. Statistical MC errors are shown for the $\sigma_{\text{tot}}$, $\sigma_{\text{cut}}$ entries, and are zero for the acceptances $A$, to the precision shown.
## PDF Errors in $W^+$ Production

### 7 TeV

| PDF Set    | $\sigma_{\text{tot}}$ | $\Delta \sigma_{\text{tot}}^+$ | $\Delta \sigma_{\text{tot}}^-$ | $\sigma_{\text{cut}}$ | $\Delta \sigma_{\text{cut}}^+$ | $\Delta \sigma_{\text{cut}}^-$ | $A$ | $\Delta A^+$ | $\Delta A^-$ |
|------------|------------------------|---------------------------------|---------------------------------|------------------------|---------------------------------|---------------------------------|-----|--------------|--------------|
| MSTW2008   | 5947 ± 12              | 99                              | 80                              | 2440 ± 8               | 22                              | 63                              | 0.410 | 0.001        | 0.007        |
| NNPDF      | 5794 ± 12              | 146                             | 146                             | 2376 ± 7               | 53                              | 53                              | 0.410 | 0.002        | 0.002        |
| CT10       | 5993 ± 12              | 178                             | 223                             | 2464 ± 8               | 58                              | 121                             | 0.411 | 0.002        | 0.008        |
| CT10W      | 5968 ± 12              | 209                             | 190                             | 2454 ± 8               | 100                             | 67                              | 0.411 | 0.004        | 0.003        |

### 10 TeV

| PDF Set    | $\sigma_{\text{tot}}$ | $\Delta \sigma_{\text{tot}}^+$ | $\Delta \sigma_{\text{tot}}^-$ | $\sigma_{\text{cut}}$ | $\Delta \sigma_{\text{cut}}^+$ | $\Delta \sigma_{\text{cut}}^-$ | $A$ | $\Delta A^+$ | $\Delta A^-$ |
|------------|------------------------|---------------------------------|---------------------------------|------------------------|---------------------------------|---------------------------------|-----|--------------|--------------|
| MSTW2008   | 8590 ± 17              | 135                             | 144                             | 3219 ± 11              | 48                              | 71                              | 0.375 | 0.003        | 0.004        |
| NNPDF      | 8311 ± 17              | 200                             | 200                             | 3124 ± 10              | 65                              | 65                              | 0.376 | 0.003        | 0.003        |
| CT10       | 8644 ± 17              | 348                             | 267                             | 3246 ± 11              | 137                             | 98                              | 0.376 | 0.004        | 0.003        |
| CT10W      | 8629 ± 17              | 304                             | 293                             | 3253 ± 11              | 149                             | 126                             | 0.377 | 0.007        | 0.006        |

### 14 TeV

| PDF Set    | $\sigma_{\text{tot}}$ | $\Delta \sigma_{\text{tot}}^+$ | $\Delta \sigma_{\text{tot}}^-$ | $\sigma_{\text{cut}}$ | $\Delta \sigma_{\text{cut}}^+$ | $\Delta \sigma_{\text{cut}}^-$ | $A$ | $\Delta A^+$ | $\Delta A^-$ |
|------------|------------------------|---------------------------------|---------------------------------|------------------------|---------------------------------|---------------------------------|-----|--------------|--------------|
| MSTW2008   | 12019 ± 24             | 165                             | 223                             | 4179 ± 14              | 46                              | 115                             | 0.348 | 0.003        | 0.007        |
| NNPDF      | 11559 ± 23             | 267                             | 267                             | 4032 ± 14              | 82                              | 82                              | 0.349 | 0.003        | 0.003        |
| CT10       | 12159 ± 24             | 366                             | 493                             | 4231 ± 14              | 159                             | 159                             | 0.348 | 0.006        | 0.003        |
| CT10W      | 12095 ± 24             | 453                             | 420                             | 4222 ± 14              | 190                             | 135                             | 0.349 | 0.006        | 0.003        |

**Table 6:** PDF Errors in the cross sections ($\sigma$) and acceptances ($A$) for the cuts in Table 1, calculated using the asymmetric Hessian method for MSTW and CT10(W), and the standard deviation for the NNPDF replica sets. All cross sections are in pb, while the acceptance is a ratio of cut to total cross sections. Statistical MC errors are shown for the $\sigma_{\text{tot}}, \sigma_{\text{cut}}$ entries, and are zero for the acceptances $A$, to the precision shown.
PDF Errors in $W^-$ Production

### 7 TeV

| PDF Set    | $\sigma_{\text{tot}}$ | $\Delta\sigma_{\text{tot}}^+$ | $\Delta\sigma_{\text{tot}}^-$ | $\sigma_{\text{cut}}$ | $\Delta\sigma_{\text{cut}}^+$ | $\Delta\sigma_{\text{cut}}^-$ | $A$ | $\Delta A^+$ | $\Delta A^-$ |
|------------|----------------------|--------------------------------|-------------------------------|----------------------|--------------------------------|-------------------------------|-----|--------------|--------------|
| MSTW2008   | 4166 ± 8             | 48                             | 98                            | 1763 ± 5             | 17                             | 50                            | 0.423 | 0.003        | 0.005        |
| NNPDF      | 3943 ± 8             | 89                             | 89                            | 1648 ± 5             | 30                             | 30                            | 0.418 | 0.004        | 0.004        |
| CT10       | 4084 ± 8             | 141                            | 147                           | 1723 ± 5             | 51                             | 76                            | 0.422 | 0.002        | 0.008        |
| CT10W      | 4117 ± 8             | 165                            | 121                           | 1702 ± 5             | 114                            | 14                            | 0.413 | 0.017        | 0.001        |

### 10 TeV

| PDF Set    | $\sigma_{\text{tot}}$ | $\Delta\sigma_{\text{tot}}^+$ | $\Delta\sigma_{\text{tot}}^-$ | $\sigma_{\text{cut}}$ | $\Delta\sigma_{\text{cut}}^+$ | $\Delta\sigma_{\text{cut}}^-$ | $A$ | $\Delta A^+$ | $\Delta A^-$ |
|------------|----------------------|--------------------------------|-------------------------------|----------------------|--------------------------------|-------------------------------|-----|--------------|--------------|
| MSTW2008   | 6255 ± 13            | 80                             | 148                           | 2503 ± 8             | 40                             | 68                            | 0.400 | 0.005        | 0.004        |
| NNPDF      | 5900 ± 12            | 123                            | 123                           | 2338 ± 7             | 40                             | 40                            | 0.396 | 0.004        | 0.004        |
| CT10       | 6164 ± 12            | 211                            | 248                           | 2460 ± 8             | 81                             | 105                           | 0.399 | 0.005        | 0.006        |
| CT10W      | 6214 ± 12            | 219                            | 241                           | 2456 ± 8             | 97                             | 92                            | 0.395 | 0.004        | 0.003        |

### 14 TeV

| PDF Set    | $\sigma_{\text{tot}}$ | $\Delta\sigma_{\text{tot}}^+$ | $\Delta\sigma_{\text{tot}}^-$ | $\sigma_{\text{cut}}$ | $\Delta\sigma_{\text{cut}}^+$ | $\Delta\sigma_{\text{cut}}^-$ | $A$ | $\Delta A^+$ | $\Delta A^-$ |
|------------|----------------------|--------------------------------|-------------------------------|----------------------|--------------------------------|-------------------------------|-----|--------------|--------------|
| MSTW2008   | 9047 ± 18            | 83                             | 247                           | 3456 ± 11            | 39                             | 115                           | 0.382 | 0.003        | 0.005        |
| NNPDF      | 8490 ± 17            | 166                            | 166                           | 3218 ± 10            | 55                             | 55                            | 0.379 | 0.004        | 0.004        |
| CT10       | 8925 ± 18            | 362                            | 325                           | 3379 ± 11            | 201                            | 75                            | 0.379 | 0.013        | 0.001        |
| CT10W      | 8979 ± 18            | 369                            | 337                           | 3394 ± 11            | 139                            | 132                           | 0.378 | 0.004        | 0.003        |

**Table 7:** PDF Errors in the cross sections ($\sigma$) and acceptances ($A$) for the cuts in Table 1, calculated using the asymmetric Hessian method for MSTW and CT10(W), and the standard deviation for the NNPDF replica sets. All cross sections are in pb, while the acceptance is a ratio of cut to total cross sections. Statistical MC errors are shown for the $\sigma_{\text{tot}}, \sigma_{\text{cut}}$ entries, and are zero for the acceptances $A$, to the precision shown.
Summary of Cross Section Errors

### Z Production

| Energy   | 7 TeV       | 10 TeV     | 14 TeV    |
|----------|-------------|------------|-----------|
| Higher Order | $+2.50 \pm 0.65$ | $+1.95 \pm 0.75$ | $+2.45 \pm 0.73$ |
| QCD Scale  | $0.21 \pm 0.08$  | $0.59 \pm 0.26$  | $1.10 \pm 0.44$  |
| PDF       | $3.69 \pm 0.00$  | $4.14 \pm 0.00$  | $4.11 \pm 0.00$  |
| Total     | $4.46 \pm 0.48$  | $4.62 \pm 0.32$  | $4.91 \pm 0.38$  |

### W$^+$ Production

| Energy   | 7 TeV       | 10 TeV     | 14 TeV    |
|----------|-------------|------------|-----------|
| Higher Order | $+2.94 \pm 0.78$ | $+2.95 \pm 0.75$ | $+3.19 \pm 0.87$ |
| QCD Scale  | $0.47 \pm 0.19$  | $0.35 \pm 0.14$  | $1.41 \pm 0.58$  |
| PDF       | $3.33 \pm 0.00$  | $3.71 \pm 0.00$  | $3.65 \pm 0.00$  |
| Total     | $4.47 \pm 0.52$  | $4.75 \pm 0.47$  | $5.05 \pm 0.58$  |

### W$^-$ Production

| Energy   | 7 TeV       | 10 TeV     | 14 TeV    |
|----------|-------------|------------|-----------|
| Higher Order | $+1.78 \pm 0.75$ | $+3.23 \pm 0.72$ | $+3.55 \pm 0.74$ |
| QCD Scale  | $0.59 \pm 0.23$  | $0.24 \pm 0.08$  | $0.86 \pm 0.30$  |
| PDF       | $3.49 \pm 0.00$  | $3.48 \pm 0.00$  | $3.76 \pm 0.00$  |
| Total     | $3.96 \pm 0.34$  | $4.76 \pm 0.49$  | $5.24 \pm 0.0$   |

**Table 8:** Summary of systematic errors in the cross sections (σ_{cut}) for Z and W$^\pm$ production for the cuts of Table 1 at each of the three energy scales cross sections. The sign of the higher-order correction error shows the sign of the correction needed.
Table 9: Summary of systematic errors in the acceptance ($A$) for $Z$ and $W^\pm$ production for the cuts of Table 1 at each of the three energy scales. The sign of the higher-order correction error shows the sign of the correction needed.
Figure 6: The $Z/\gamma^* \rightarrow \ell^+\ell^-$ cross-section $\sigma$ at 7 TeV, as a function of the (a) $p_T$ cut and (b) $\eta$ cut for acceptance regions as defined in Table 1. We fix all cuts except the cut to be varied at their specified values. The figures on the right show the relative errors in the cross sections.
Figure 7: The $W^- \rightarrow l^- \nu$ cross-section $\sigma$ at 7 TeV, as a function of the (a) $p_T$ cut, (b) $\eta$ cut, and (c) $M_T$ cut for acceptance regions as defined in Table 1. We fix all cuts except the cut to be varied at their specified values. The figures on the right show the relative errors in the cross sections.
Figure 8: The $W^- \rightarrow l^- \bar{v}$ cross-section $\sigma$ at 7 TeV, as a function of the (a) $p_T$ cut, (b) $\eta$ cut, and (c) $M_T$ cut for acceptance regions as defined in Table 1. We fix all cuts except the cut to be varied at their specified values. The figures on the right show the relative errors in the cross sections.
Figure 9: The $Z/\gamma^* \rightarrow \ell^+\ell^-$ acceptances $A$ at 7TeV, as a function of the (a) $p_T$ cut and (b) $\eta$ cut for acceptance regions as defined in Table 1. We fix all cuts except the cut to be varied at their specified values. The figures on the right show the relative errors in the acceptances.
Figure 10: The $W^+ \rightarrow l^+\nu$ acceptances $A$ at 7TeV, as a function of the (a) $p_T$ cut, (b) $\eta$ cut, and (c) $M_T$ cut for acceptance regions as defined in Table 1. We fix all cuts except the cut to be varied at their specified values. The figures on the right show the relative errors in the acceptances.
Figure 11: The $W^{-} \rightarrow l^{-}\nu$ acceptances $A$ at 7TeV, as a function of the (a) $p_T$ cut, (b) $\eta$ cut, and (c) $M_T$ cut for acceptance regions as defined in Table 1. We fix all cuts except the cut to be varied at their specified values. The figures on the right show the relative errors in the acceptances.