PROCEEDINGS OF SCIENCE

Electroweak corrections

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I review the last progresses in the computation of electroweak corrections in the Standard Model (SM) for LHC physics. I present the last developed tools for the automatization of the calculations of elementary scattering amplitudes, together with their implementation in parton-level generators to make predictions for important LHC processes. A first attempt to insert EW corrections in a multijet merging framework is also presented.

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1. Electroweak (and QCD) Tools at NLO

In the past years, many groups have concentrated their efforts on the development of several codes to produce theoretical prediction with next-to-leading-order (NLO) accuracy. Most of them have been created to deal with QCD corrections, but recently a lot of interest have been devoted to the electroweak (EW) sector of the Standard Model (SM). The core programs are the libraries for the computation of one-loop integrals like FF [1], LoopTools [2], CutTools [3], QCDLoop [4], Samurai [5], OneLOop [6], PJFry [7], Golem95C [8], Package-X [9]. The last published package is Collier [10], a fast and stable library for the calculation of tensor integrals[1]. These libraries are usually included in matrix elements generators, to compute one-loop QCD and EW amplitudes for elementary processes. Some examples are FeynArts/FormCalc [11, 12, 13], Blackhat [14], Helac-1loop [15], NGluon [16], Madloop [17], GoSam [18] and OpenLoops [19]. Most of them were developed with a focus on QCD corrections, but recently EW corrections have been included also in OpenLoops [20, 21] and Madloop [22, 23]. The last published code is Recola [24], designed for the automated calculation of both EW and QCD corrections[2]. The production of theoretical predictions is then achieved by parton-level Monte Carlo event generators, like MCFM [25], ALPGEN [26], VbfNlo [27], MadGraph5_aMC@NLO [28], which rely on the above-listed programs or on internal matrix element generators. The matching to parton shower is performed through matching programs (as MC@NLO [29] and Powheg-Box [30]) and general-purpose event generators like Pythia [31, 32], Herwig [33] and Sherpa [34, 35].

In order to give an idea of the efficiency of the codes for the computation of matrix elements, in Table 1 we present the CPU time needed by the Recola+Collier package for the computation of some processes of physical interest at the LHC. The amount of memory for executables, object files and libraries is usually negligible, while the RAM needed does not exceed 2 Gbyte even for complicated processes.

NLO	Process	Computation of 1 PS point		
		Recola	+	Collier
QCD	$u\bar{d} \to l^+\nu_l\, g\, g$	1.6 ms	+	3.2 ms
	$u\,\bar{d} \to l^+\nu_l\, g\, g\, g$	49 ms	+	61 ms
	$u\bar{u} \to l^+\nu_l\, l'^-\bar{\nu}_{l'}\, g\, g$	26 ms	+	48 ms
QCD + EW	$u\bar{u} \to l^+l^-\, g\, g$	28 ms	+	17 ms
	$u\bar{u} \to l^+l^-\, u\bar{u}$	38 ms	+	70 ms
	$u\bar{u} \to l^+l^-\, t\bar{t}$	47 ms	+	36 ms
	$u\bar{u} \to l^+l^-\, u\bar{u}\, g$	713 ms	+	565 ms

Table 1: Performances of Recola+Collier for the computation of QCD corrections (second row) and QCD+EW corrections (third row) for some sample processes, on a personal computer with processor Intel(R) Core(TM) i5-2450M CPU@2.50GHza. The given CPU time refers to the computation of the matrix elements for one phase-space (PS) point, i.e. for one configuration of external momenta.

[1] Collier can be downloaded from http://collier.hepforge.org.

[2] Recola is available from http://recola.hepforge.org.

2. Drell-Yan

The importance of the Drell-Yan process to determine the W-Mass and the effective weak mixing angle at LHC and the exceptional experimental precision of the measurements have driven a considerable effort for the computation of theoretical predictions. The current state of the art of higher-order corrections includes QCD NNLO corrections in a parton-shower framework supplemented by higher-order effects [36, 37]. Concerning EW effects, the NLO corrections, supplemented by leading higher-order effects from multiple photon emission and universal weak effects, are also known [38, 39, 40]. The NLO EW and QCD corrections have been combined in a parton shower framework in [41, 42].

Recently the enhanced contributions in pole approximation to the mixed NNLO QCD-EW corrections have been addressed in [43, 44]. In pole approximation the Feynman diagrams that are enhanced by the resonant propagator of the W or Z boson can be classified according to Figure 1. The initial-initial O($\alpha_s\alpha$) corrections are only partially known (a consistent computation would also

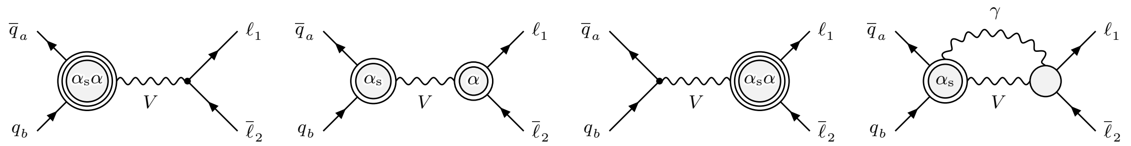

Figure 1: The leading contributions in pole approximation for the Drell-Yan process (from left to right): factorizable initial-initial corrections, factorizable initial-final corrections, factorizable final-final corrections and non-factorizable corrections.

need a PDF set including O($\alpha_s\alpha$) corrections, not available yet); in any case they are expected to be much smaller than the huge QCD corrections. The final-final corrections and the non-factorizable corrections are negligible. The dominant contributions come from the factorizable initial-final corrections. An example of the impact of these corrections can be inferred from Figure 2. The

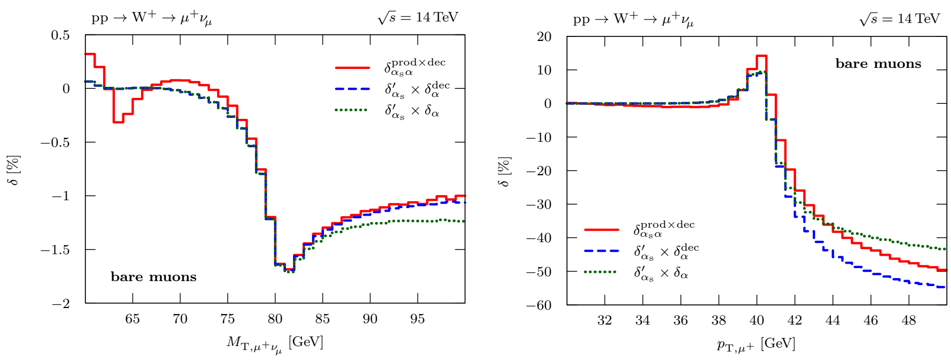

Figure 2: Initial-final factorizable corrections to the transverse-mass (left) and transverse-lepton-momentum (right) distributions for W^+ production, compared with the naive $\delta'_{\alpha_s} \times \delta_\alpha$ approximation.

corrections in the transverse-mass distribution turn out to be small and well approximated by the naive QCD×EW approximation. This does not hold anymore in the transverse-lepton-momentum distribution, where the naive product $\delta'_{\alpha_s} \times \delta_\alpha$ fails to describe the large corrections for $p_{T,\mu^+} \geq M_W/2$. From the analysis of the Drell-Yan process with and without lepton recombination, the authors of [44] have estimated the impact of the factorizable mixed NNLO QCD-EW corrections on the determination of the W mass, to be respectively of around $-4\,\text{MeV}$ and $-14\,\text{MeV}$.

3. $\text{pp} \to \text{V}+\text{jets}$

The production of a vector boson in association with jets is an important process at the LHC, as background of Higgs production and in the search of new physics. The detailed study of QCD and EW NLO corrections of $\text{pp} \to \text{V}+1$ jet done in [45] reveals large EW corrections of Sudakov origin in high-energy regions, which need to be combined in a multijet approach with the known huge QCD corrections in TeV regions.

The computation of NLO QCD corrections of order $\mathscr{O}(\alpha_s^3\alpha^2)$ to $\text{pp} \to \text{V}+2$ jets have been addressed in [46], while a subset of $\mathscr{O}(\alpha_s\alpha^4)$ corrections have been computed in [47]. The dominant EW corrections of order $\alpha_s^2\alpha^3$ have been considered by two groups [48, 20, 21] finding good agreement [49]. Figure 3 gives an example of the size of the EW corrections for $\text{pp} \to l^+l^-jj$ and $\text{pp} \to \nu\bar{\nu}jj$ and shows again the large effects of Sudakov logarithms in the high p_T regions. For the second process, which is the SM irreducible background for the search of new physics in the production of two jets with missing transverse energy, the analysis based on the selection cuts of [50] shows overall EW corrections of -10% for the total cross section.

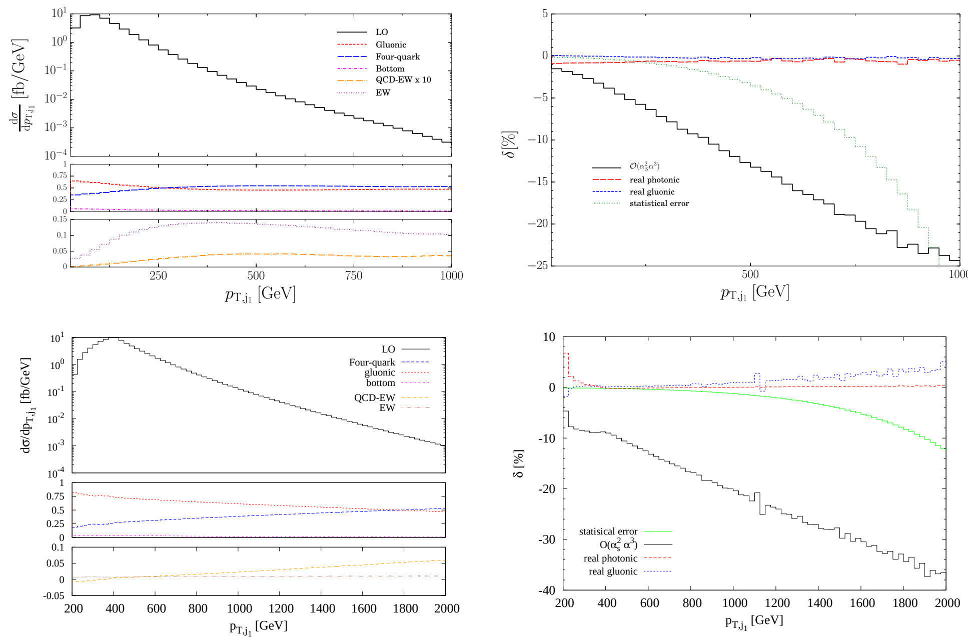

Figure 3: EW corrections of order $\mathscr{O}(\alpha_s^2\alpha^3)$ of the p_T distribution of the hardest jet for $\text{pp} \to l^+l^-jj$ with basic cuts (first row) and for $\text{pp} \to \nu\bar{\nu}jj$ with cuts inspired by [50] (second row).

The production of a vector boson with more than two jets is known at NLO QCD for $\text{pp} \to \text{W}+\leq 5\text{j}$ [51] and $\text{pp} \to \text{Z}+\leq 4\text{j}$ [52] and at NLO EW only for $\text{pp} \to \text{W}+\leq 3\text{j}$ with on-shell W [20]. Jet multiplicity can be also successfully studied by matching NLO predictions with parton shower and by merging all of the underlying matrix elements with up to two light partons at the

Born level. This procedure is well understood in QCD and has been applied in [53] for pp $\rightarrow$ V + jets, reproducing present LHC data also at high jet multiplicities.

Less simple is the extension of this procedure to cover the combination of QCD and EW corrections. The problem has been recently addressed in [21]. In the first two plots of Figure 4 are shown the p_T distribution of the hardest jet for pp $\rightarrow$ V + 1, 2 jets with NLO QCD and EW corrections with fixed jet multiplicities. The tail of the distribution is for kinematic reasons populated by pp $\rightarrow$ V + 2 jets, giving rise to huge QCD corrections for pp $\rightarrow$ V + 1 jet (where the second jet is present just at LO in the computation) and hiding the large negative EW corrections. In order to combine QCD and EW corrections, a merging procedure is therefore necessary. A first rough merg-

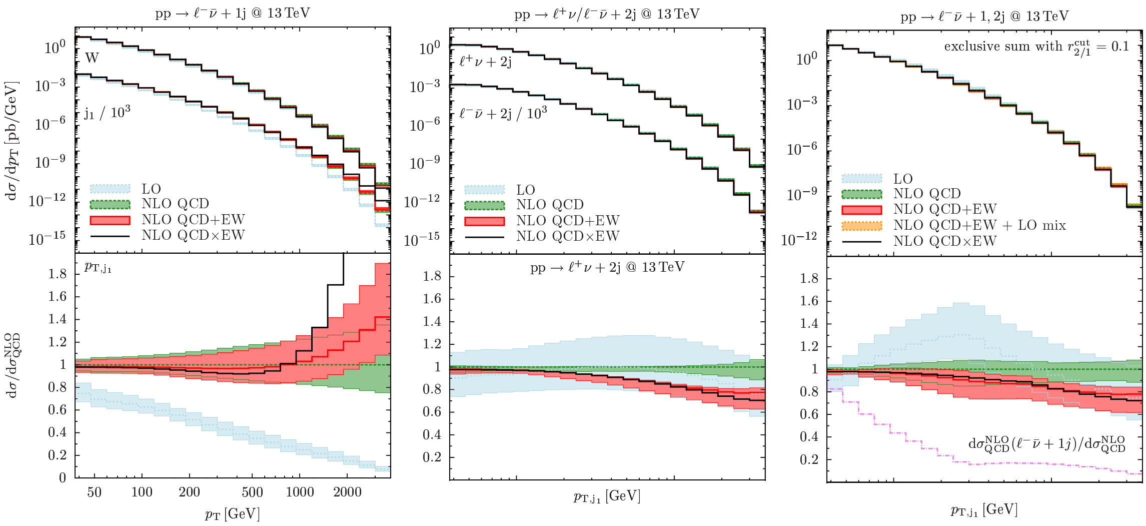

Figure 4: NLO QCD and EW corrections for the p_T distribution of the hardest jet for pp $\rightarrow$ V + 1 jet (left), pp $\rightarrow$ V + 2 jets (center) and for the merging of pp $\rightarrow$ V + 1, 2 jets via exclusive sums.

ing of pp $\rightarrow$ V + 1, 2 jets has been done in [21] using exclusive sums, i.e. dividing the phase-space in two regions according to the value assumed by the ratio

$$r_{2/1} = \frac{p_{\mathrm{T}j_2}}{p_{\mathrm{T}j_1}}. \tag{3.1}$$

For $r_{2/1}$ below some $r_{2/1}^{\mathrm{cut}}$ just pp $\rightarrow$ V + 1 jet contributes to the cross section, while the region defined by $r_{2/1} > r_{2/1}^{\mathrm{cut}}$ is only populated by pp $\rightarrow$ V + 2 jets. As shown in Figure 4, this stabilizes QCD corrections and the typical negative EW effects appear. In order to proceed in a more precise framework and take advantage of the QCD merging procedure, the author of [21] propose to approximate the one-loop EW corrections with their virtual part (where the IR divergences have been properly regularized with the inclusion of the counterterms described in [54]) and insert these approximated EW corrections in the MEPS@NLO merging framework. The approximation well describes the behavior of EW corrections in many observables[3], allowing a well defined combination of QCD and EW in the merging procedure. The results for the p_T distribution of the hardest jet and of the W boson are shown in Figure 5. In both cases the enhanced QCD corrections have

[3]The most striking exceptions are the invariant mass distributions involving charged leptons, where the neglected real QED radiation can lead to corrections of a few tens of percent in the off-shell region below the Breit-Wigner peak.

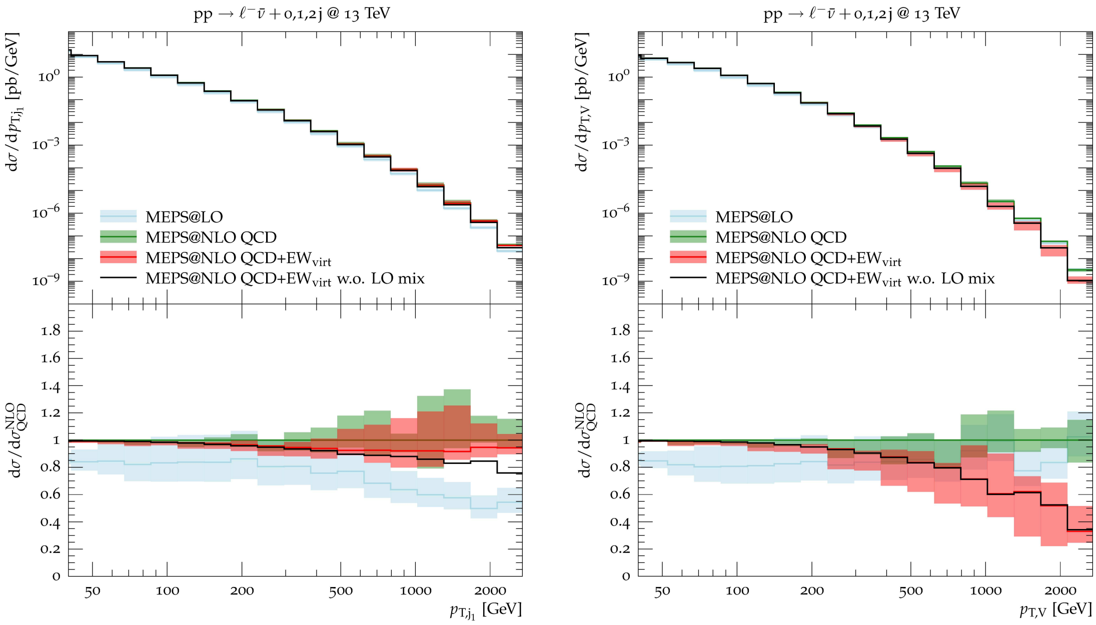

Figure 5: Combination of QCD and EW corrections for the p_T distributions of the hardest jet (left) and of the W boson (right), after the merging procedure in the MEPS@NLO framework.

disappeared, revealing an accidental cancellation between one-loop EW corrections and LO interference effects in the tail of p_{T,j_1} and the expected large EW Sudakov effects for high $p_{T,\mathrm{W}}$. For this latter distribution the result of the merging is quantitatively consistent with the factorized QCD$\times$EW prescription for the combination of QCD and EW corrections.

4. pp $\to t\bar{t} + \mathrm{H}, \mathrm{V}$

Another recent development in the computation of EW corrections concerns the production of a $t\bar{t}$ pair in association with a Higgs or a vector boson. The NLO QCD corrections to pp $\to t\bar{t} + \mathrm{H}$ matched with parton shower are known for on-shell t, $\bar{t}$, H [55, 56, 57], while results with all off-shell $t\bar{t}$ effects are available only at fixed order [58]. The EW corrections have been computed in [22, 59], again with on-shell top, antitop and Higgs boson. The computation of NLO QCD and EW corrections to pp $\to t\bar{t} + \mathrm{V}$ have been carried out in [23] (for oh-shell t, $\bar{t}$, V).

The results for the total cross section, as given in [23], are shown in Table 2. When the selection cut requiring high p_T external particles is applied, large EW corrections appear, but remain inside the QCD uncertainties, which represent the dominant contribution to the theoretical error for this process. It is important to notice that the real radiation of an additional heavy boson (HBR)[4] gives a non negligible contribution for $t\bar{t}$W production.

[4] This contribution usually ignored in literature, because its final states are supposed to be distinguishable from $t\bar{t} + \mathrm{H}, \mathrm{V}$. The authors of [23] argue that such an argument is not physical without a detailed study on the decay products of the vector bosons.

		$\sigma_{\mathrm{LO}}(\mathrm{pb})$	$\delta_{\mathrm{QCD}}[\%]$	$\delta_{\mathrm{EW}}[\%]$	$\delta_{\mathrm{HBR}}[\%]$
$t\bar{t}H$	13 TeV	$3.617\cdot10^{-1}$	$29.7^{+6.8}_{-11.1}\pm2.8$	-1.4 ± 0.0	0.89
	13 TeV*	$1.338\cdot10^{-2}$	$24.2^{+4.8}_{-10.6}\pm4.5$	-8.5 ± 0.2	1.87
	100 TeV	23.57	$40.8^{+9.3}_{-9.1}\pm1.0$	-2.7 ± 0.0	0.91
$t\bar{t}Z$	13 TeV	$5.282\cdot10^{-1}$	$45.9^{+13.2}_{-15.5}\pm2.9$	-4.1 ± 0.1	0.96
	13 TeV*	$1.955\cdot10^{-2}$	$40.2^{+11.1}_{-15.0}\pm4.7$	-11.5 ± 0.3	2.13
	100 TeV	37.69	$50.4^{+11.4}_{-10.9}\pm1.1$	-5.4 ± 0.0	0.85
$t\bar{t}W^+$	13 TeV	$2.496\cdot10^{-1}$	$50.1^{+14.2}_{-13.5}\pm2.4$	-8.0 ± 0.2	3.88
	13 TeV*	$7.749\cdot10^{-3}$	$59.7^{+18.9}_{-17.7}\pm3.1$	-20.0 ± 0.5	7.41
	100 TeV	3.908	$156.4^{+38.3}_{-35.0}\pm2.4$	-9.6 ± 0.1	21.52
$t\bar{t}W^-$	13 TeV	$1.265\cdot10^{-1}$	$51.5^{+14.8}_{-13.8}\pm2.8$	-7.0 ± 0.2	6.50
	13 TeV*	$3.186\cdot10^{-3}$	$66.3^{+21.7}_{-19.6}\pm3.9$	-19.1 ± 0.6	15.01
	100 TeV	2.833	$153.6^{+37.7}_{-34.9}\pm2.2$	-8.8 ± 0.1	28.91

Table 2: Total cross section for pp $\to t\bar{t}+$ H, V (on-shell t, $\bar{t}$, H, V) for different center of mass energy with basic selection cuts. The blue numbers refer to the cross section with the additional cut $p_T > 200\,\mathrm{GeV}$ for the outgoing particles. The LO cross section is given in the third column, while the forth and fifth columns contain QCD and EW correction respectively. The correction from undetected radiation of real heavy bosons is given in the sixth column.

5. pp $\to$ VV

The EW corrections to the production of a heavy vector boson in association with a photon has been recently computed in [60, 61], including the leptonic decay of the vector boson. The state of the art for this process also includes NLO QCD corrections matched with parton shower for pp $\to l^+\nu\gamma, l^-\bar{\nu}\gamma$ [62] and NNLO corrections to pp $\to l^+l^-\gamma, \nu\bar{\nu}\gamma$ [63]. The impact of EW corrections can be seen in Figure 6. Besides the expected large EW effects at high $p_{T,\gamma}$, the photon-

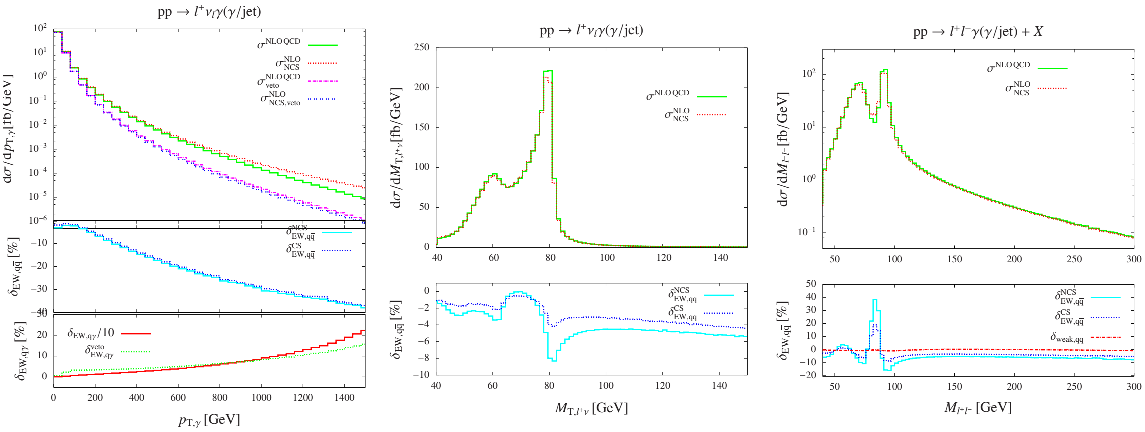

Figure 6: Impact of EW corrections on $p_{T,\gamma}$ (left), $M_{l^+\nu}$ (center) and $M_{l^+l^-}$ (right) distributions. CS and NCS refer respectively to the collinear-safe and non-collinear-safe situations, corresponding to the cases where photon-lepton recombination is performed or not. $q\gamma$ and $q\bar{q}$ refer to photon-induced and quark-induced contributions respectively.

induced corrections $\delta_{\mathrm{EW},q\gamma}$ are huge in this region; they are however plagued by the uncertainties of photon PDF of up to 100% and can be reduced to $10-15\%$ by a jet veto. The $M_{l^+\nu}$ distribution receives EW corrections of the order of few percent around the W-mass peak, essentially due to photonic emission (usually well described by parton shower). The same photonic corrections are responsible of the large EW corrections in the $M_{l^+l^-}$ distribution around the Z-mass peak.

For the production of two heavy vector bosons, NLO QCD corrections are available at the level of parton shower Monte Carlo generators [64, 65, 66, 67, 68, 69], with multijet merging [70], together with NNLO fixed order QCD computations [71, 72, 73, 74, 75]. Very recently the EW corrections to $\mathrm{pp} \to \mu^+\mu^-e^+e^-$ and $\mathrm{pp} \to \mu^+\nu_\mu e^-\bar{\nu}_e$ have been studied in [76, 77]. Some of their results are shown in Figure 7. The M_{4l} distribution of $\mathrm{pp} \to \mu^+\mu^-e^+e^-$ presents large photonic corrections around the $2M_Z$ peak (well approximated by parton showers) and moderate weak corrections. These ones change sign (from -3% to $+6\%$) rendering their inclusion via a global rescaling factor impossible. The p_{T,e^-} distribution of $\mathrm{pp} \to \mu^+\nu_\mu e^-\bar{\nu}_e$ shows large negative EW corrections ($\sim -20\%$ at $p_{T,e^-} \sim 400\,\mathrm{GeV}$) of Sudakov origin, partially compensated by the positive contribution of the $\gamma\gamma$-induced tree-level process.

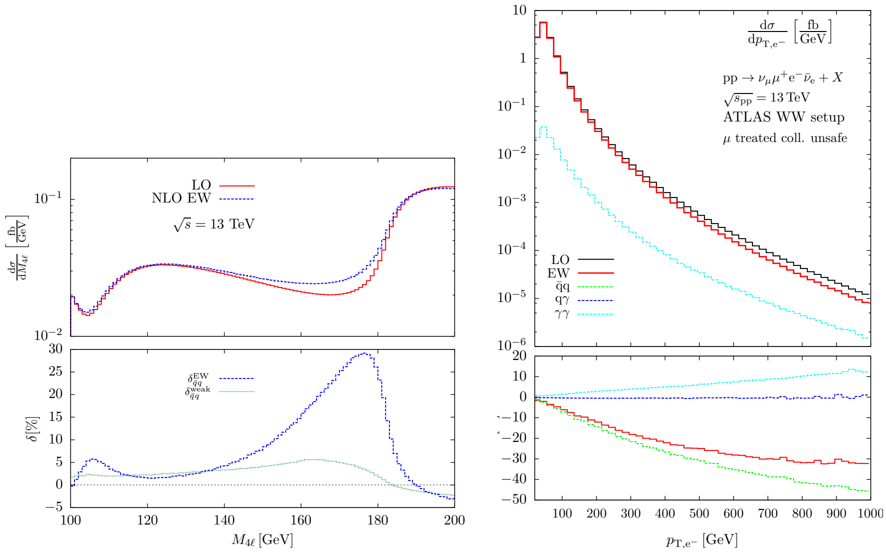

Figure 7: EW corrections to the M_{4l} distribution of the process $\mathrm{pp} \to \mu^+\mu^-e^+e^-$ (left) and to the p_{T,e^-} distribution of the process $\mathrm{pp} \to \mu^+\nu_\mu e^-\bar{\nu}_e$ (right). In the right upper panel, LO and $\gamma\gamma$ refers to $\bar{q}q$ and $\gamma\gamma$ initiated channels respectively, while EW stand for to the full NLO EW prediction. The right lower panel compares the relative corrections induced by the $\bar{q}q$, $q\gamma$, and $\gamma\gamma$ channels as well as their sum (EW).

6. Conclusions

I have presented the last developments in the theoretical computations of EW NLO corrections. A lot of effort has been devoted by several groups in the automatization of the calculations at the level of matrix elements and the available tools in the EW sector of the Standard Model have reached the same efficiency as the programs for NLO QCD. Such programs have been used in parton-level Monte Carlo (MC) generators to make predictions for non trivial LHC processes, whose results quantify the impact of EW corrections and show large negative corrections at the TeV scale. I have presented also the first implementations of EW calculations in general-purpose

MC generators and the first attempts to combine EW and QCD corrections in a multijet merging procedure.

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