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Mixed QCD-EW corrections to the Drell-Yan process

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Precise predictions of hard scattering processes at the LHC usually require the inclusion of NNLO corrections in QCD and NLO in EW. For some specific cases, this might not be sufficient to match the experimental accuracy, and higher-order radiative contributions must be taken into account too. In such situations, effects due the interplay among strong and electroweak interactions may be relevant. The Drell-Yan process provides a promiment example of ultra precision physics at the LHC. We recently completed the first calculation of the mixed QCD-EW corrections to the neutral current Drell-Yan process for massive leptons. In this proceeding, we elaborate on the comparison of the exact two-loop virtual amplitude with its approximation by a pole expansion and show phenomelogical results in the region of high invariant masses of the lepton pair system.

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The hadroproduction of a dilepton pair via the Drell-Yan (DY) mechanism is a cornerstone process for the precision physics programme at the LHC. The bulk of the DY cross section is peaked in the region around the resonant production of a single EW weak boson. Given the rather clean signature, characterised by the presence of two leptons with high transverse momentum, and the relatively large production rates, the DY process is an ideal proxy for very accurate determinations of fundamental electro-weak (EW) parameters and for PDFs extraction. Measurements of the W mass [1] and of the electro-weak mixing angle [2] start to compete with previous results from LEP and Tevatron and a remarkable sub per-mille precision target is expected by the end of the high-luminosity phase.

Off-shell production, especially in the region at high invariant masses of the lepton pair system, is of great importance too. Beyond the Standard Model searches carried on at the LHC largely constraint the parameter space associated, directly, to new heavy resonances decaying leptonically, or, indirectly, to higher-dimensional operators inducing shape distortions through virtual loop corrections, usually enhanced at high scales. CMS has recently reported on a measurement of the backward-forward asymmetry for invariant masses of the produced lepton pair system up to about 1 TeV [3] using the Run II dataset and setting stringent limits on the mass of a possible Z' model. Together with other analyses, see for example [4], this confirm the potential of the LHC experiments to probe the TeV region with an accuracy of order $O(1\%)$.

Hence, the effort of the theoretical community in producing the most accurate possible predictions for the DY process, including higher-order corrections both in the context of fixed order and resummed calculations, is well justified. At the LHC, the strong interaction is certainly the lead actor. Concerning QCD radiative corrections, DY is one of the most studied and advanced process thanks also to its simplicity: N^{3}LO QCD corrections to fiducial cross sections have been recently computed [5, 6] and matched to the N^{3}LL resummation of the vector boson transverse momentum [7, 8]. Turning to the EW corrections, we adopt the so-called "physical" counting, $\alpha \approx \alpha_s^2$, so that they are parametrically of the same order as NNLO QCD ones. Furthermore, EW effects may get enhanced in some relevant region of the phase space. For example, it is well known that they induce large negative corrections in the high-energy tail of the invariant mass distribution of the produced lepton pair system because of large Sudakov logarithms.

Considering the most general expansion of the differential hadronic cross section for the Drell-Yan process with respect to two coupling constants

$$d\sigma = \sum_{i,j} d\sigma^{(i,j)}, \tag{1}$$

where $d\sigma^{(0,0)} \equiv d\sigma_{\rm LO}$ is the Born contribution and the general term $d\sigma^{(i,j)}$ corresponds to the $O(\alpha_s^i \alpha^j)$ correction. In this way, mixed strong and EW effects naturally arise, with the leading contribution given by the term $d\sigma^{(1,1)}$. Assuming the "physical" counting, the latter competes with the N^{3}LO QCD correction. From now on we refer to it as the mixed QCD-EW correction.

In terms of Feynman diagrams, the computation of the mixed correction $d\sigma^{(1,1)}$ involves double real diagrams associated to the emission of a photon and a gluon (and all possible crossing), real-virtual diagrams associated to one real emission of a photon/gluon and one virtual QCD/EW loop, and mixed two-loop diagrams. The complexity is that of a NNLO computation for a multi-scale $2 \to 2$ process. The major bottleneck is represented by the evaluation of the two-loop virtual amplitude. In passing by, we mention that such ingredient is still not available for the charged current Drell-Yan (CC-DY) process. This highlights the relevance of some approximate results, valid in particular limits, that, on one hand, allow to produce an estimate of the physical cross section and, on the other, are useful for cross-checks of the exact result once available.

Following this strategy, we have provided results for the transverse momentum distribution of the charged lepton produced in the CC-DY process [9], approximating the virtual contribution by its expansion around the resonant peak, i.e. relying on the Pole Approximation (PA) [10, 11]. Recently, thanks to the progress in multi-loop techniques, the two-loop virtual amplitude for the neutral current Drell-Yan (NC-DY) process with massive leptons have been computed [12, 13]. This was the missing ingredient needed for the exact calculation of the mixed correction for this process, that we reported in [14] for the case of (bare) massive muons. A second and independent calculation has appeared for dressed electrons [15] which makes use of a different calculation of the two-loop virtual amplitude [16]. For the reasons explained above, it is quite interesting to analyse in some details the quality of the Pole approximation by its direct comparison with the exact result. After briefly presenting the main aspects of our calculation in Sec. 1, we will address these aspects in Sec. 2. In Sec. 3, we move on presenting preliminary new results for the high-energy tail of the invariant mass distribution in NC-DY, before giving our conclusions.

1. Mixed corrections to the NC-DY process: q_T subtraction formalism and power corrections

We make use of the q_T subtraction formalism [17] to handle the infrared singularities stemming from the various $O(\alpha_s\alpha)$ contributions (double real, real-virt, virtual) entering the physical mixed correction $d\sigma^{(1,1)}$. Then, we evaluate $d\sigma^{(1,1)}$ according to the master formula

$$d\sigma^{(1,1)} = \mathcal{H}^{(1,1)} \otimes d\sigma_{\mathrm{LO}} + \left[d\sigma_{\mathrm{R}}^{(1,1)} - d\sigma_{\mathrm{CT}}^{(1,1)} \right]_{q_T/m_{\ell\ell} > r_{\mathrm{cut}}} + O(r_{cut}^k) \,. \tag{2}$$

The first term in Eq. (2) is obtained through a convolution (denoted by the symbol $\otimes$), with respect to the longitudinal-momentum fractions z_1 and z_2 of the colliding partons, of the perturbatively computable function $\mathcal{H}^{(1,1)}$ with the LO cross section $d\sigma_{\mathrm{LO}}$. The second term is the *real* contribution $d\sigma_{\mathrm{R}}^{(1,1)}$, where the lepton pair system is accompanied by additional QCD and QED radiation that produces a recoil with finite transverse momentum q_T. For a non-vanishing transverse momentum q_T, only one radiation at time can become unresolved. The content in the square bracket is integrated with a constraint on the smallest possible q_T value introducing a dimensionless cut-off r_{cut} on the quantity $q_T/m_{\ell\ell}$. Therefore, $d\sigma_{\mathrm{R}}^{(1,1)}$ can be obtained as the sum of two separate NLO calculations: NLO EW corrections to the associated production of an Z/γ^* (decaying leptonically) and an hard jet and the NLO QCD corrections to the associated production of an Z/γ^* (decaying leptonically) and an hard photon [1]. Both calculations can be performed using a suitable NLO subtraction scheme as the dipole subtraction formalism [18, 19]. In the limit $q_T \to 0$, the real contribution $d\sigma_{\mathrm{R}}^{(1,1)}$ is divergent, since the recoiling radiation becomes soft and/or collinear to the initial-state partons. The last term, the so-called counterterm $d\sigma_{\mathrm{CT}}^{(1,1)}$, cancels the singular behaviour in the limit $q_T \to 0$, thereby rendering the cross section in Eq. (2) finite.

[1] This includes the evaluation of NLO QCD corrections to the photon induced subprocess, $\gamma q \to \ell^+\ell^- q$.

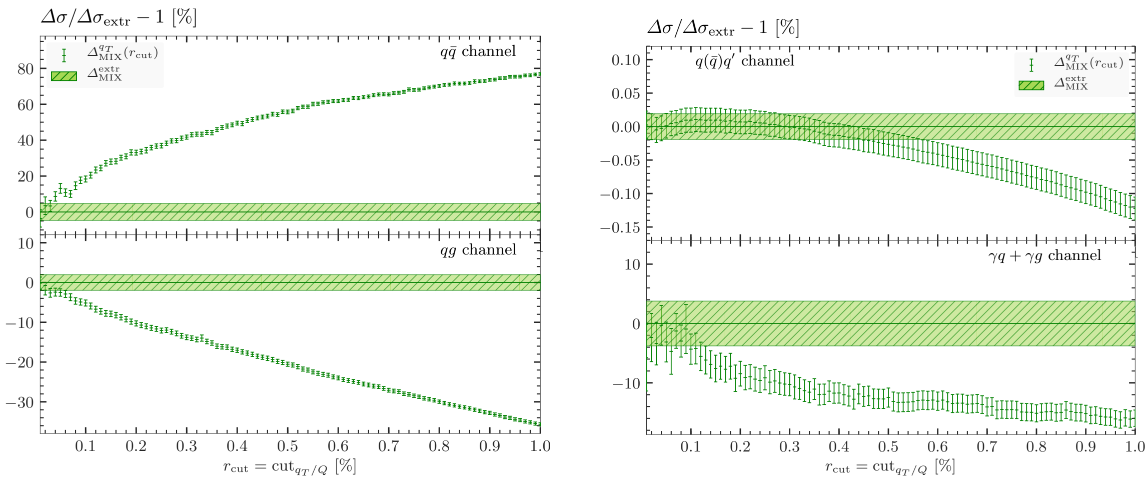

Figure 1: Dependence on the slicing parameter $r_{\rm cut}$ of the mixed QCD-EW correction to the production of a massive muon pair (NC-DY) in $\sqrt{s} = 14$ TeV proton-proton collisions [14]. The results, split into 4 different partonic channels as explained in the main text, are normalised to the $r_{\rm cut} \to 0$ limiting value obtained according to the extrapolation procedure implemented in MATRIX [21].

The interference of the two-loop virtual amplitude with the tree-level one enters the coefficient $\mathcal{H}^{(1,1)}$. In order to expose its contribution in a more clear way, we further decompose $\mathcal{H}^{(1,1)}$ as

$$\mathcal{H}^{(m,n)} = H^{(1,1)}\delta(1-z_1)\delta(1-z_2) + \delta\mathcal{H}^{(1,1)}, \tag{3}$$

where the hard contribution $H^{(1,1)}$ contains the renormalised mixed two-loop virtual corrections after the subtraction of the infrared poles. More precisely, we define

$$H^{(1,1)} = \frac{2{\rm Re}\left(\mathcal{M}^{(1,1)}_{\rm fin}\mathcal{M}^{(0,0)*}\right)}{|\mathcal{M}^{(0,0)}|^2}\,. \tag{4}$$

where $\mathcal{M}^{(0,0)}$ is the Born amplitude and $\mathcal{M}^{(1,1)}_{\rm fin}$ is the finite part of the renormalised virtual amplitudes entering the mixed QCD–EW calculations as defined in Refs [9, 14]. The mass of the lepton acts as the physical regulator of the final-state collinear divergence and must be kept finite in our calculation. For this reason, we make use of the amplitude of Ref. [12, 13]. For an efficient integration, we interpolate a pre-computed numerical grid. We refer to [20] for an overview on the computation of the amplitude.

The q_T subtraction method is challenged by the presence of spurious power corrections in the slicing parameter $r_{\rm cut}$, while the physical cross section is formally recovered in the limit $r_{\rm cut} \to 0$. Since the calculation can only be carried out for a finite $r_{\rm cut}$, such a limit procedure must be carefully taken through a numerical extrapolation. We have implemented our calculation in the MATRIX [21] framework and we rely on the extrapolation procedure defined therein. Phenomenological results for the hadroproduction of a muon pair via the NC-DY process in proton-proton collisions at $\sqrt{s} = 14$ TeV have been presented in Ref. [14]. We briefly report here on the size of the power corrections, considering the same setup as in Ref. [14]. In particular, we remind that symmetric cuts on the transverse momenta of the charged leptons, $p^T_{\mu^+,\mu^-} > 25$ GeV, are enforced. In Fig. 1, we

σ [pb]	$q\bar{q}$	qg	$q(\bar{q})q'$	$\gamma q + \gamma g$
σ_{LO}	809.56(1)	–	–	–
$\sigma^{(1,1)}$	−4.8(2)	8.6(1)	0.19069(4)	0.084(3)

Table 1: Breakdown of the mixed correction into the different partonic channels (see text) and comparison with the LO cross section in the dominant $q\bar{q}$ channel.

show the dependence of the mixed correction, normalised to the extrapolated result, on the slicing parameter r_{cut} in the nominal range $[0.01, 1]\%$ for individual partonic channels: flavour diagonal quark-antiquark ($q\bar{q}$), quark-gluon (qg), all remaining flavour non-diagonal (anti)quark-(anti)quark combinations ($q(\bar{q})q'$) and the sum of photon induced contributions photon-quark and photon-gluon ($\gamma q + \gamma g$). The results can be summarised as follows

- the r_{cut} dependence observed in the $q\bar{q}$ and qg channels is compatible with the hypothesis of linear power corrections ($k = 1$ in Eq. 2) as expected in the case of the emission of a soft particle from a massive final-state emitter [22, 23] and in the presence of symmetric cuts [21, 24–27];

- also the photon induced channel $\gamma q + \gamma g$ displays a behavior compatible with linear power corrections due to the presence of symmetric cuts;

- the power corrections are much milder in the $q(\bar{q})q'$ channel.

Finally, we observe that, despite the fact that the power corrections are relatively large in the considered nominal range, the systematics of the method are under control thanks to the extrapolation procedure and, being at the sub per-mille level compared to the total cross section as shown in Tab. 1, negligible for phenomenology.

2. Virtual corrections and pole approximation

In the following, we focus on the hard-virtual coefficient $H^{(1,1)}$ in Eq. (4). We consider its hadronic contribution obtained by performing the convolution with the Born differential hadronic cross section, $d\sigma_H^{(1,1)} = H^{(1,1)} \otimes d\sigma_{\mathrm{LO}}$. We can then study the quality of the PA directly on a quantity that is more closely related to the physical mixed correction. We focus on two key observables, the invariant mass of the lepton pair system $m_{\mu\mu}$ and the transverse momentum of the charged lepton $p^T_{\mu^+}$. Our main results are summarised in Fig. 2. We show the comparison between the predictions obtained with the exact virtual amplitude (blue curve) and with the approximate one (orange curve) for the contribution $d\sigma_H^{(1,1)}$ in the top panel, and its ratio to the exact result in the middle panel. In addition, we display the relative importance of $d\sigma_H^{(1,1)}$ with respect to the full mixed correction $d\sigma^{(1,1)}$ in the bottom panel. We observe that the PA captures the bulk of the exact result, with deviations of $O(10 - 20)\%$ in the resonant region for both distributions. Remarkably, the PA provides a reasonable description of the virtual corrections also in off-shell regions. In particular, it undershoots the exact result by roughly 40% in the high energy tail of the invariant mass of the lepton pair and transverse momentum of the charged lepton. The "improved" description away from

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the resonance region is due to the fact that we are adopting the reweighting procedure introduced in Ref. [9], namely

$$H^{(1,1)}_{\mathrm{PA,rwg_B}} = H^{(1,1)}_{\mathrm{PA}} \times \frac{|\mathcal{M}^{(0,0)}|^2}{|\mathcal{M}^{(0,0)}_{\mathrm{PA}}|^2} = \frac{2\mathrm{Re}\left(\mathcal{M}^{(1,1)}_{\mathrm{fin}}\mathcal{M}^{(0,0)*}\right)_{\mathrm{PA}}}{|\mathcal{M}^{(0,0)}_{\mathrm{PA}}|^2}\,. \tag{5}$$

In the pure PA, the $H^{(1,1)}_{\mathrm{PA}}$ coefficient is simply computed by evaluating the interference of the tree-level and the two-loop amplitude in the PA. Since the $H^{(1,1)}$ coefficient is eventually multiplied with the Born cross section $d\sigma_{\mathrm{LO}}$, the above procedure effectively reweights the virtual–tree interference in PA with the full squared Born amplitude.

Focusing on the bottom panels, we notice that the relative importance of $d\sigma^{(1,1)}_{H}$ for the case of the invariant mass distribution has a different trend compared to that for the transverse momentum one. For the case of the invariant mass spectrum, $d\sigma^{(1,1)}_{H}$ represents 10% of the full mixed corrections $d\sigma^{(1,1)}$ around $m_{\mu\mu} \simeq 70$ GeV , about 50% in the region around the peak $m_{\mu\mu} \simeq 90$ GeV (with the exception of the bin right next to the peak, corresponding to the region in which the correction reaches the steepest slope), and about 80% at 1 TeV. We notice that, instead, the contribution due to $d\sigma^{(1,1)}_{H}$ quickly drops right after the jacobian peak at $p^{T}_{\mu^+} \simeq 45$ GeV and represents a very small fraction (about 2%) of the full mixed correction at high transverse momenta of the charged lepton. Hence, the difference between the PA and the exact result in that region is negligible. This is not unexpected as the dominant contributions to large transverse momenta of the charged lepton come from configurations in which an on-shell Z recoils against an hard jet. To summarise, we find that the pole approximation provides a decent description of the virtual corrections and, therefore, represents a powerful tool to analyse their impact. This is extremely valuable in the absence of the exact calculation, as for the case of the CC-DY process. Beyond the case of the distribution of transverse momentum of the charged lepton, this motivates the study of other relevant observables, as the transverse mass, which we leave to future work.

3. Results at high invariant masses

Virtual EW corrections are enhanced in the region of high invariant masses of the lepton pair system by large Sudakov logarithms. Assuming a complete factorisation of QCD and EW corrections, one would expect non-negligible mixed effects in the high energy tail of the invariant mass distribution. It is therefore of great interest to assess the impact of the mixed QCD-EW corrections and to what extent the factorised ansatz reproduces the exact result. To this aim, we consider the following factorised approximation of the mixed corrections

$$\frac{d\sigma^{(1,1),fact}}{dm_{\mu\mu}} = \frac{d\sigma^{(1,0)}}{dm_{\mu\mu}} \times \frac{d\sigma^{(0,1)}_{qq}}{dm_{\mu\mu}} \times \left(\frac{d\sigma_{\mathrm{LO}}}{dm_{\mu\mu}}\right)^{-1} \tag{6}$$

given by the product of differential NLO QCD and NLO EW K-factors[2]. In Fig. 3 we show preliminary results for di-muon invariant masses up to the TeV region. The backward (left) and forward (right) directions are defined according to the Collin-Soper angle, and the bands correspond

[2]The EW K-factor does not include photon induced processes [9].

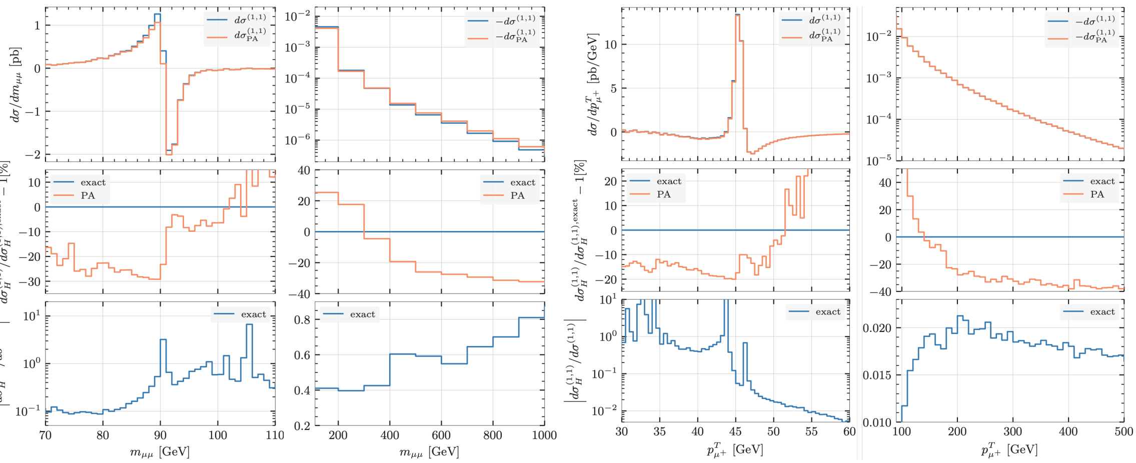

Figure 2: Invariant mass distribution of the di-muon system (left) and transverse momentum distribution of the positively charged muon (right) for $\sqrt{s}$ = 14 TeV proton-proton collisions [14]. The mixed correction is displayed in the top panel with the two-loop virtual amplitude computed exactly (blue) and approximated in PA (orange). The deviation from the exact result of the $d\sigma_H^{(1,1)}$ term approximated in PA is shown in the middle panel in percentage. In the bottom panel the relative importance of the $d\sigma_H^{(1,1)}$ with respect to the full mixed correction is reported.

to the customary 7-point scale variation. Focusing on the middle panel, in which the effects of the mixed corrections are shown relatively to the reference prediction given by the additive combination of NNLO QCD and NLO EW corrections (labelled NNLO QCD+EW), we observe, as expected, rather large $O(2-5\%)$ negative effects at few TeVs. Furthermore, our results show that the factorised approximation (gray curve) gives a good description of the exact correction (green curve). This points towards the fact that QCD corrections and Sudakov EW logarithms largely factorise, as also observed for the case of dressed electrons [15].

4. Conclusions

With the inclusion of N^{3}LO QCD radiative corrections, the theoretical description of the Drell-Yan process has reached a very mature status. Thanks to the recent progress in multi-loop calculations, also the computation of the mixed QCD-EW correction to the neutral current Drell-Yan process has been completed. In this proceeding, we have reported on the systematics associated to the power corrections entailed by the q_T subtraction formalism for this process, showing that they are under control and phenomenologically negligible. By a direct comparison with the exact two-loop virtual correction, we have shown that the Pole Approximation gives a good description of the full result in the resonance region, thus confirming previous results obtained for the charged current case using the same approximation. In addition, we have discussed the impact of the mixed corrections at high invariant masses of the lepton pair system. We find relatively large negative corrections which are in line with what expected on the basis of a factorisation of QCD corrections and large EW Sudakov logarithms. Further phenomenological studies to assess the implications of the mixed corrections to the Drell Yan process are ongoing.

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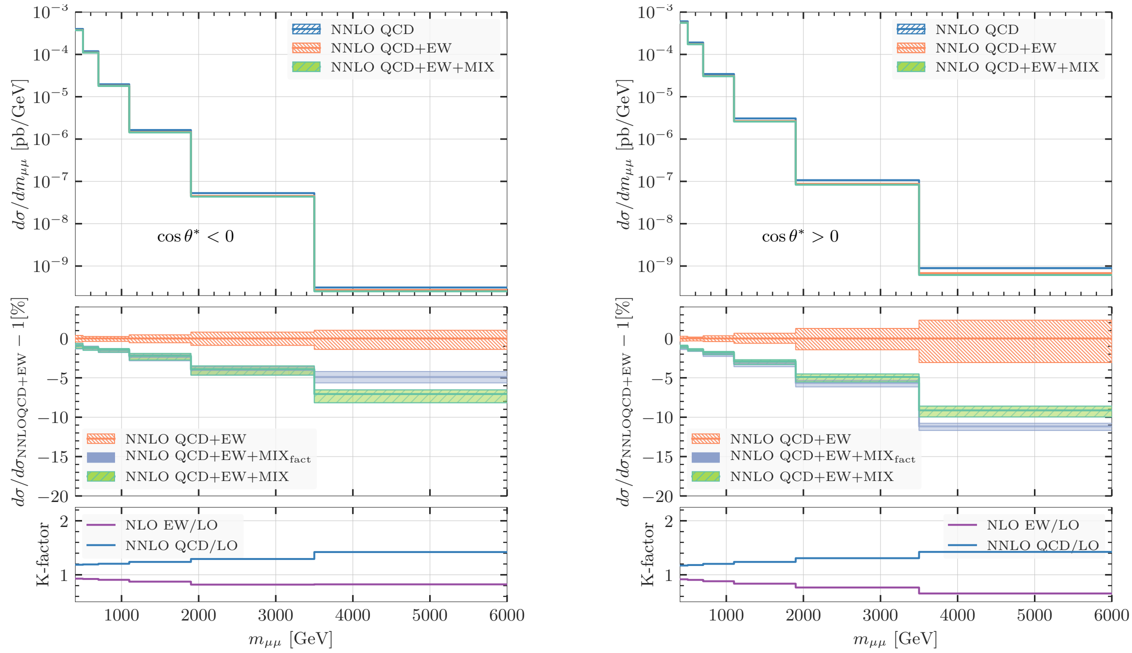

Figure 3: Invariant mass distribution of the di-muon system in the backward (left) and forward (right) region for $\sqrt{s}$ = 13 TeV proton-proton collisions [4]. In the top panel, predictions including an increasing radiative content are shown: NNLO QCD (blue), NNLO QCD+EW (orange) and the "best" NNLO QCD+EW+MIX which includes the mixed correction. In the middle panel, the relative impact of the full mixed correction (green) and of the factorised ansatz (gray) with respect to the NNLO QCD+EW is reported. In the bottom panel NLO EW and NNLO QCD K-factor are shown.

References

[1] ATLAS collaboration, *Measurement of the W-boson mass in pp collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector*, Eur. Phys. J. C **78** (2018) 110 [1701.07240].

[2] CMS collaboration, *Measurement of the weak mixing angle using the forward-backward asymmetry of Drell-Yan events in pp collisions at 8 TeV*, Eur. Phys. J. C **78** (2018) 701 [1806.00863].

[3] CMS collaboration, *Measurement of the Drell-Yan forward-backward asymmetry at high dilepton masses in proton-proton collisions at $\sqrt{s}$ = 13 TeV*, 2202.12327.

[4] CMS collaboration, *Search for resonant and nonresonant new phenomena in high-mass dilepton final states at $\sqrt{s}$ = 13 TeV*, JHEP **07** (2021) 208 [2103.02708].

[5] X. Chen, T. Gehrmann, N. Glover, A. Huss, T.-Z. Yang and H.X. Zhu, *Di-lepton Rapidity Distribution in Drell-Yan Production to Third Order in QCD*, 2107.09085.

[6] X. Chen, T. Gehrmann, N. Glover, A. Huss, T.-Z. Yang and H.X. Zhu, *Transverse Mass Distribution and Charge Asymmetry in W Boson Production to Third Order in QCD*, 2205.11426.

[7] X. Chen, T. Gehrmann, E.W.N. Glover, A. Huss, P.F. Monni, E. Re et al., *Third-Order Fiducial Predictions for Drell-Yan Production at the LHC*, *Phys. Rev. Lett.* **128** (2022) 252001 [2203.01565].

[8] S. Camarda, L. Cieri and G. Ferrera, *Drell-Yan lepton-pair production: q_T resummation at N^3LL accuracy and fiducial cross sections at N^3LO*, 2103.04974.

[9] L. Buonocore, M. Grazzini, S. Kallweit, C. Savoini and F. Tramontano, *Mixed QCD-EW corrections to $pp \to \ell\nu_\ell + X$ at the LHC*, *Phys. Rev. D* **103** (2021) 114012 [2102.12539].

[10] S. Dittmaier, A. Huss and C. Schwinn, *Mixed QCD-electroweak $O(\alpha_s\alpha)$ corrections to Drell-Yan processes in the resonance region: pole approximation and non-factorizable corrections*, *Nucl. Phys. B* **885** (2014) 318 [1403.3216].

[11] S. Dittmaier, A. Huss and C. Schwinn, *Dominant mixed QCD-electroweak $O(\alpha_s\alpha)$ corrections to Drell–Yan processes in the resonance region*, *Nucl. Phys. B* **904** (2016) 216 [1511.08016].

[12] T. Armadillo, R. Bonciani, S. Devoto, N. Rana and A. Vicini, *Two-loop mixed QCD-EW corrections to neutral current Drell-Yan*, *JHEP* **05** (2022) 072 [2201.01754].

[13] T. Armadillo, R. Bonciani, S. Devoto, N. Rana and A. Vicini, *Evaluation of Feynman integrals with arbitrary complex masses via series expansions*, 2205.03345.

[14] R. Bonciani, L. Buonocore, M. Grazzini, S. Kallweit, N. Rana, F. Tramontano et al., *Mixed Strong-Electroweak Corrections to the Drell-Yan Process*, *Phys. Rev. Lett.* **128** (2022) 012002 [2106.11953].

[15] F. Buccioni, F. Caola, H.A. Chawdhry, F. Devoto, M. Heller, A. von Manteuffel et al., *Mixed QCD-electroweak corrections to dilepton production at the LHC in the high invariant mass region*, 2203.11237.

[16] M. Heller, A. von Manteuffel, R.M. Schabinger and H. Spiesberger, *Mixed EW-QCD two-loop amplitudes for $q\bar{q} \to \ell^+\ell^-$ and γ_5 scheme independence of multi-loop corrections*, *JHEP* **05** (2021) 213 [2012.05918].

[17] S. Catani and M. Grazzini, *An NNLO subtraction formalism in hadron collisions and its application to Higgs boson production at the LHC*, *Phys. Rev. Lett.* **98** (2007) 222002 [hep-ph/0703012].

[18] S. Catani and M.H. Seymour, *A General algorithm for calculating jet cross-sections in NLO QCD*, *Nucl. Phys. B* **485** (1997) 291 [hep-ph/9605323].

[19] S. Catani, S. Dittmaier, M.H. Seymour and Z. Trocsanyi, *The Dipole formalism for next-to-leading order QCD calculations with massive partons*, *Nucl. Phys. B* **627** (2002) 189 [hep-ph/0201036].

[20] S. Devoto, *Two-loop mixed QCD-EW corrections to neutral current Drell-Yan*, in *16th DESY Workshop on Elementary Particle Physics: Loops and Legs in Quantum Field Theory 2022*, 8, 2022 [2208.03510].

[21] M. Grazzini, S. Kallweit and M. Wiesemann, *Fully differential NNLO computations with MATRIX*, *Eur. Phys. J. C* **78** (2018) 537 [1711.06631].

[22] S. Catani, S. Devoto, M. Grazzini, S. Kallweit, J. Mazzitelli and H. Sargsyan, *Top-quark pair hadroproduction at next-to-next-to-leading order in QCD*, *Phys. Rev. D* **99** (2019) 051501 [1901.04005].

[23] L. Buonocore, M. Grazzini and F. Tramontano, *The q_T subtraction method: electroweak corrections and power suppressed contributions*, *Eur. Phys. J. C* **80** (2020) 254 [1911.10166].

[24] S. Alekhin, A. Kardos, S. Moch and Z. Trócsányi, *Precision studies for Drell–Yan processes at NNLO*, *Eur. Phys. J. C* **81** (2021) 573 [2104.02400].

[25] G.P. Salam and E. Slade, *Cuts for two-body decays at colliders*, *JHEP* **11** (2021) 220 [2106.08329].

[26] L. Buonocore, S. Kallweit, L. Rottoli and M. Wiesemann, *Linear power corrections for two-body kinematics in the qT subtraction formalism*, *Phys. Lett. B* **829** (2022) 137118 [2111.13661].

[27] S. Camarda, L. Cieri and G. Ferrera, *Fiducial perturbative power corrections within the $\mathbf{q}_T$ subtraction formalism*, *Eur. Phys. J. C* **82** (2022) 575 [2111.14509].