# Summary of the Hadronic Final States Working Group

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**DOI:** http://dx.doi.org/10.3204/DESY-PROC-2012-02/361

In this summary we give a short overview of the experimental and theoretical results, which were presented during the sessions of the QCD and Hadronic Final States Working Group [1] at the DIS 2012 conference.

## 1 Experimental contributions

In the Hadronic Final States Working Group a large number of experimental collaborations presented their most recent updates from a broad range of QCD measurements. The covered topics include the physics of jets, prompt photons, identified particles, the underlying event as well as tuning and model development. Here, only some highlights of the talks given during the working group sessions are presented, for details please refer to the individual contributions in the workshop proceedings.

### 1.1 Jet production

The ZEUS collaboration has presented a new inclusive jet production measurement at the photoproduction limit [2], which is well described by NLO QCD. From these data, the strong coupling could be determined to be $\alpha_s(M_Z) = 0.1206^{+0.0023}_{-0.0022}(\text{exp})^{+0.0042}_{-0.0035}(\text{th})$, which is in agreement with the HERA and world averages. A range of further studies has been performed: the choice of the jet algorithm, the potential to restrict the proton and photon PDFs, and the sensitivity to multi-parton interaction effects.

The H1 collaboration has developed and applied a new, sophisticated unfolding method for jet measurements at high $Q^2$ [3]. The neutral-current DIS (deep inelastic scattering), inclusive jet, dijet and tri-jet cross sections are unfolded simultaneously preserving all the statistical and experimental correlations between them, which subsequently can be used in a fit of $\alpha_s(M_Z)$ as well as in PDF fitting programs. In addition, the unfolding procedure takes into account migrations into and out of the investigated phase space. The neutral current DIS cross sections serve to normalize the jet cross sections, which significantly reduces experimental and theoretical uncertainties. Jet cross sections are theoretically calculated up to next-to-leading order (NLO) with the help of NLOJet++ [4] and fastNLO [5, 6]. Extracting the strong coupling constant from these data yields $\alpha_s(M_Z) = 0.1163 \pm 0.0008(\text{exp}) \pm 0.0011(\text{had}) \pm 0.0014(\text{pdf})^{+0.0044}_{-0.0035}(\text{th})$ in agreement with previous H1 measurements.

Because of their potential for constraining the proton PDFs, the results on inclusive jet production by the ATLAS and CMS collaborations have been presented in the joint session of the Hadronic Final States and Structure Functions working groups, and are summarized elsewhere [7]. Additional jet measurements on dijets and multi-jets presented in [8] are reasonably well described by theory predictions or Monte Carlo (MC) event generators.

Jets in the forward pseudorapidity region $3.2 < |\eta| < 4.7$ were studied by CMS [9]. Events with activity in the forward region are populated by more asymmetric final-state configurations in terms of momentum fractions of the interacting partons, thus allowing studies to be extended to smaller $x$ values. Also, the forward region is expected to be most sensitive to deviations from the DGLAP parton evolution. Both reported forward jet cross sections as well as a cross section for forward-central jet pair production have been shown, within errors, to be reasonably well described by theory predictions.

The ratio of inclusive to exclusive dijet production as a function of the rapidity separation has been studied by CMS [9]. Here, all possible jet pairings are counted within the inclusive sample, while only events with exactly one jet pair passing the selection criteria are considered in the exclusive selection. The ratio is well described by Pythia [10], while Herwig [11], HEJ [12], and Cascade [13] predictions deviate significantly.

Jets reconstructed from tracks allow a meaningful comparison to MC simulations in the soft region of very low $p_T$; this study was undertaken by ATLAS for jet transverse momenta down to 4 GeV [8], where events recorded with a minimum-bias trigger were used for the study. All employed MC event generators fail to describe this measurement demonstrating the need for improvements in modelling the transition region between soft and perturbative physics.

A set of measurements aiming to explore jet shapes has been presented by ATLAS [14]. The internal structure of a jet is influenced primarily by fragmentation and hadronization effects but also by hard physics, colour reconnections, the underlying event and pile-up as well as heavy particle production. Some discrepancies to the MC models have been observed for jet shapes and jet fragmentation. Nevertheless all studied models provide a reasonable description of the data. For the jet mass distributions, it was found that the "splitting and filtering" technique [15] has the potential to reduce the sensitivity to soft physics.

## 1.2 Weak boson plus jets production

The production of jets in association with a $Z$ boson has been studied by the CDF collaboration combining the two channels $Z/\gamma^* \to \mu^+\mu^-$ and $Z/\gamma^* \to e^+e^-$ using the full CDF data set [16]. The results were compared to several predictions at different perturbative orders (at NLO: MCFM, BlackHat+Sherpa, at $\bar{n}$NLO: LoopSim+MCFM) and are in a very good agreement with each other. In addition, the cross section of $Z$+$b$-jet is found to be in agreement with NLO predictions from MCFM, which, however, show a large uncertainty due to the choice of the renormalization scale.

The ATLAS collaboration has presented a range of weak boson plus jet measurements based on 2010 LHC data [17]. The $Z$+jet and $W$+jet cross sections are in agreement with predictions by BlackHat [18] or Alpgen [19]. Pythia and Sherpa [20] on the other hand fail in some details, in particular for the $W$+jet measurement. In addition, the $W$+jet to $Z$+jet cross section ratio, which benefits from at least partial cancellations in the experimental uncertainties, was studied as a function of the jet $p_T$ threshold. The MCFM prediction describes the data well in the full range of investigated $p_T$ threshold values. Lastly, the $W$ and $Z$ production in association with a $b$-jet has been discussed. Again, the data are reasonably well described by the theory.

## 1.3 Photon production

Prompt photon production is another example of an environment suitable for testing the understanding of the underlying QCD process. Photons, contrary to jets, do not undergo a hadronization process leading to a direct sensitivity to the partonic hard process. Non-prompt photons coming from decays of secondary particles such as $\pi^0$ are removed to a large extent by requiring the photon to be isolated from the rest of the hadronic final state.

The ZEUS collaboration reported on the production of isolated photons with an associated jet in the range $10 < Q^2/\mathrm{GeV}^2 < 350$ [21]. The remaining background from hadronic decays is estimated by exploring differences in size and shape of the calorimetric shower. The experimental results are compared to the theory prediction at NLO assuming collinear factorization, as well as to a calculation based on the $k_T$-factorization approach. Both predictions do not give a satisfactory description of the data, in particular in terms of the overall normalization. The NLO result underestimates while the one based on the $k_T$-factorization overestimates the production rate of isolated photons.

The CDF collaboration presented a new measurement of di-photon production compared to a set of theoretical predictions, ranging from that of the LO parton shower PYTHIA to that of RESBOS, where an analytically resummed calculation at low-$p_T$ is matched to NLO high-$p_T$ matrix elements [22]. A pure NLO calculation cannot describe the measurements in the limit $p_T \to 0$ since resummation effects become important. Hence, RESBOS provides the best description. The LO event generator SHERPA incorporating matrix element plus parton shower merging provides the best overall description in the explored phase-space region. Both collaborations, CDF [22] and DØ [23], presented their recent studies on $\gamma$ plus heavy flavour production. While the $\gamma$ plus beauty production is relatively well described by theory, particularly when the gluon splitting rate is increased, the $\gamma$ plus charm production is underestimated.

Finally, ATLAS has reported on inclusive photon, photon plus jet and di-photon production studied with data collected in 2010 at a centre-of-mass energy of 7 TeV [24]. The understanding of photon production at the LHC is of particular importance in view of the Higgs boson search, where the background for its photonic decay needs to be well modelled. All measurements are in agreement with the studied calculations. The NLO prediction from JETPHOX slightly overestimates the photon production rate for low transverse momenta.

## 1.4 Particle production

New results on the production of identified particles, important for testing and tuning hadronization and fragmentation models, were presented based on HERA and LHC data. The ZEUS collaboration has measured the scaled momentum distributions for $K^0_S$ and $\Lambda/\bar{\Lambda}$ hadrons [25]. The scaled momentum is defined as $x_p = 2P_{\mathrm{Breit}}/\sqrt{Q^2}$ where $P_{\mathrm{Breit}}$ is the particle momentum in the Breit frame of reference. Measured cross sections were compared to MC predictions based on two approaches, which are the colour dipole model and matrix element plus parton shower merging. Both of which reproduce the shape of the studied distributions but fail to give the correct normalization, in particular for the $K^0_S$ production. The results were also compared to NLO calculations using fragmentation functions (FF) tuned to previously available data. These, in turn, do not provide a satisfactory description of the presented measurement demonstrating the potential to better constrain future FF tunes.

LHCb has measured the multiplicity of primary charged particles [26], i.e. those produced in $pp$ collisions or from short-lived resonances. The measurement has been made in the forward region as covered by the LHCb detector. All the studied MC predictions underestimate the primary charged particle multiplicities. A better agreement can be achieved by excluding diffractive processes in PYTHIA. Also, hard events with at least one track of $p_T > 1$ GeV are better described. Furthermore, the collaboration has measured the production ratios of $\frac{\bar{p}}{p}$, $\frac{K^-}{K^+}$, $\frac{\pi^-}{\pi^+}$, $\frac{\bar{p}+p}{K^-+K^+}$, $\frac{\bar{p}+p}{\pi^-+\pi^+}$ and $\frac{K^-+K^+}{\pi^-+\pi^+}$. The best description of these ratios are provided by the NOCR (no-colour-reconnection) and LHCb PYTHIA tunes.

The spectra of charged pions, kaons and protons were measured by the CMS collaboration [27]. They are shown to be well described by fits using the Tsallis–Pareto formula [28]. In addition, studies of the multiplicity dependence of various observables have been performed, motivated by recently published CMS results showing intriguing hadron correlations at high track multiplicities [29]. Here, pion distributions are in practice independent of the collision energy $\sqrt{s}$ and average transverse momenta $\langle p_T \rangle$. Also the ratios between production rates of pions, kaons, and protons as well as $\langle p_T \rangle$ are independent of the multiplicity and $\sqrt{s}$.

The COMPASS collaboration presented pion and kaon multiplicities from deep inelastic scattering of 160 GeV muons off the deuteron target [30]. The $\pi$ multiplicities as a function of the Bjørken-$x$ and $z = E_h/E_\gamma$ are well described by existing FFs up to $z = 0.65$, the maximal $z$ value used in the FF fit. In the case of $K$ multiplicities on the other hand, significant discrepancies are observed over the entire kinematic region, indicating that particularly kaon measurements have the prospect of leading to significant improvements in future fits of FFs.

Pion, kaon, proton, and anti-proton multiplicities in electron scattering on neon, krypton and xenon targets were studied by the HERMES collaboration [31]. Different nuclei were used in order to investigate the space-time development of the hadronization process. A suitable experimental variable is the nuclear attenuation ratio $R_A^h$ defined in [31]. The $R_A^h$ distribution is qualitatively different for the $K^+$ mesons as compared to $K^-$, $\pi^+$, or $\pi^-$ which might be the result of final-state interactions. The proton distributions are different to all the meson distributions and to anti-protons, which can be explained by the possibility of protons being knocked out of nuclei, while other hadrons are always produced in the hadronization process.

## 1.5 Minimum-bias studies and the underlying event

The CMS collaboration has determined the inelastic proton–proton cross section employing two different methods [32]. The first method with a single-sided trigger is based on counting events with as loose a selection as possible. The second method is based on the assumption that the number of inelastic $pp$ interactions in a given bunch crossing follows a Poisson distribution. Both methods rely on MC extrapolation in order to determine the total inelastic cross section. Within the relevant uncertainties both methods give consistent results which are in agreement with previously published results from the ATLAS, ALICE and TOTEM collaborations.

The ATLAS collaboration presented three separate correlation measurements in the minimum-bias data selection [33]. The description of forward-backward multiplicity correlations vary considerably depending on the MC tune chosen. The most recent LHC tunes best describe the data. The general features of two-particle angular correlations are relatively well reproduced by the employed MC tunes, but none of them provides a satisfactory quantitative description of the data. The presence of azimuthal ordering coming from the underlying QCD string structure is tested in a spectral analysis of correlations between longitudinal and transverse components of the momentum of charged hadrons. The measured spectra show features consistent with the fragmentation of a QCD string but the MC event generators typically produce a spectrum with more correlations than seen in data in a low-$p_T$ depleted sample. The spectra of low-$p_T$ particles is not well modelled.

The CMS collaboration presented three alternative approaches sensitive to the presence of the underlying event [34]. The experimentally clean Drell–Yan process has advantages of a clear separation between the hard interaction and soft components, the absence of final-state radiation, and a low probability of photon bremsstrahlung from the muons. The comparisons to theoretical models allow to conclude that MadGraph [35] provides an adequate description of the data while Pythia and Herwig++ do not. The second analysis calculates the median of all ratios of jet $p_T$ over the area covered by this jet in an event. This observable naturally isolates underlying event contributions by assuming that the majority of the event is dominated by soft contributions while the hard component of the interaction is well contained within the leading jets, which are treated as outliers via the median prescription. In contrast to the conventional approach, no explicit geometrical subdivision of an event is necessary. Similar to other studies it can be concluded that none of the examined MC event generator tunes provides a satisfactory description. The third analysis measures the underlying event activity by studying the energy densities at forward rapidities, where the phase space for sensitive observables is well separated from the hard interaction. The ratio of the number of events where the hard process is present to the number of events collected in minimum-bias selection is studied. In this case, the recent MC tunes to LHC data perform relatively well.

Lastly, the LHCb collaboration studies the underlying event in four distinctive classes in order to probe multiple parton interactions [36]: inclusive minimum-bias, hard scattering, diffractive, and non-diffractive enriched samples. The energy flow distributions were compared to various Pythia tunes and cosmic-ray models. None of the generated predictions describe all four studied samples simultaneously.

# 2 Theoretical contributions

There are many aspects to hadronic final states depending on the energy domains of the physics phenomena one is interested in. Accordingly we have grouped our summary of contributions into four parts reflecting jet physics at different scales: jet production and substructure, jet vetoes and intra-jet evolution. The working group covered a rich program of these topics, where we have seen a number of exciting results demonstrating progress on different frontiers, the tool-driven (progressing towards the inclusion of higher orders in MC tools), the phenomenology-driven (targetting enhanced signal from background separation) and the theory-driven frontier (aiming for better control of uncertainties). In all cases, however, thorough theory to jet-data comparisons are – and will keep – giving us feedback where models need to be refined.

## 2.1 Central & forward jet production

F. Siegert presented the predictions of a $W$+3-jet calculation at NLO matched with a parton shower (PS) using the MC@NLO technique as implemented in the Sherpa event generator [37]. This is the first application of NLO+PS matching to a final state of complexity higher than four outgoing legs. These remarkable results (using the virtual corrections as provided by BlackHat) were obtained in collaboration with S. Höche, F. Krauss and M. Schönherr [38], and were shown to be in good agreement with recent data taken by the ATLAS collaboration [39]. As a difference to the original MC@NLO approach, one should stress that Sherpa's technique of using an one-step parton shower based on the exact Catani–Seymour dipole subtraction terms allows them to maintain full NLO accuracy also for the subleading colour configurations [40].

S. Prestel discussed the Pythia 8 implementation of tree-level matrix element plus parton shower merging based on the CKKW-L method [41, 42]. This is work he did in collaboration with L. Lönnblad, the author of the CKKW-L(önnblad) approach [43, 44]. The talk addressed two issues of particular importance to this implementation: first, how to accomplish CKKW-L merging in the context of interleaved multiple parton interactions and spacelike parton showers by preserving Pythia's description of the underlying event; second, how to achieve a reliable estimate for the size of effects owing to matrix element configurations occurring outside the regime of strictly ordered parton shower phase space.

J. Smillie gave a brief overview of the physics implemented in the Monte Carlo program HEJ [12] and its capabilities in describing various jet data [45]. The HEJ (High Energy Jets) project is being developed by J. Andersen, T. Hapola and J. Smillie, and provides an interesting alternative in describing multi-jet production. The approach taken in HEJ is based on the amplitude factorization present in the high energy limit. In contrast to (matched) parton showers, HEJ resums contributions that originate from large $s_{ij} = (p_i + p_j)^2$ between well-separated pairs of partons with similar $p_T$ (i.e. soft and hard wide-angle radiation). These effects are important to consider at the LHC at high energies, as demonstrated by measurements of high $H_T$ in $W$+jets production [39]. To improve the description away from the high energy limit, HEJ is flexible to be merged with LO matrix elements (MadGraph) and parton showers (Ariadne) [47]. As a result HEJ's predictions agree well with measured $p_T$ spectra at the LHC in one forward plus one central jet production [48], and measured gap fractions as a function of the rapidity separation of tagged jets [49]. As expected, deviations occur in phase-space regions governed by jet $p_T$ hierarchy. Comparing different approaches to multi-jet emission, novel, very interesting ways to look at data have emerged. In Refs. [46, 50] it has been shown that one can distinguish predictions more clearly by plotting the average number of jets versus $\Delta y_{\mathrm{fb}}$ of the most forward and backward jet, or $H_T$, the scalar sum of all jet $p_T$ in the event. An example is shown in Figure 1.

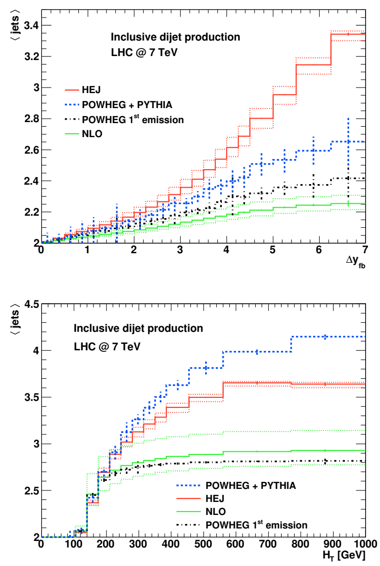


Figure 1: Average number of jets as a function of $\Delta y_{\mathrm{fb}}$ (top) and $H_T$, as predicted by HEJ, Powheg+Pythia and to (vanilla) NLO, cf. Ref. [46]. The impact of (factor-two) scale variations is indicated as well.

In their talks M. Deák and F. Hautmann presented results of studies related to the application of the Monte Carlo program Cascade to the interesting subject of forward high-$p_T$ production at the LHC [51, 52]. These studies were done in collaboration with H. Jung and K. Kutak. Cascade provides a framework for an initial-state $k_\perp$-dependent shower based on the CCFM evolution of gluon chains. A CCFM based parton shower coupled to high energy factorized matrix elements is in principle capable of describing arbitrarily large $p_T$, but the inclusion of (subleading) perturbative corrections as encoded in exact matrix elements is desirable to improve the precision of the description at high transverse momenta. To avoid double counting, subtractive procedures are necessary; one of which, a vetoing technique, was discussed in more detail by M. Deák as one element towards a complete merging procedure. To validate such an approach, a suitable experimental framework has to be defined. F. Hautmann discussed, in his talk, various scenarios of how to measure correlations in azimuthal angle, rapidity and $p_T$ in inclusive jet production with focus on forward jet hadroproduction. He emphasized the potential in measuring the rapidity and azimuthal dependence of transverse energy flows in one central plus one forward jet production [48] where CASCADE predicts, in the inter-jet region, enhanced particle and mini-jet energy flows [53, 54].

## 2.2 Jet substructure and jet shapes

S. Marzani, in collaboration with A. Banfi, M. Dasgupta, K. Khelifa-Kerfa and M. Spannowsky, presented their first analytical results on QCD jet mass distributions for jets produced in hadron–hadron collisions [55]. The results were obtained using traditional all-order resummation techniques, extending the application known for $e^+e^-$ scattering to the more complicated hadronic environment. An important ingredient to Marzani et al's calculation, almost accurate to NLL, is the inclusion of non-global logarithms in the large $N_\mathrm{C}$ limit (where $N_\mathrm{C}$ denotes the number of colours). Also, comparing different jet algorithms they find the anti-$k_T$ algorithm less prone to effects stemming from extra single logarithms, hence more robust than other algorithms like Cambridge/Aachen (C/A) or $k_T$. Marzani et al. applied their formalism to the phenomenologically interesting cases of $Z$+jet and dijet production. Although the NLL+NLO matched calculation was not quite completed at the time of the conference, they were already able to draw important conclusions using their preliminary NLL$^*$+LO matched resummation. They showed that the effect of the non-global logarithms is crucial in describing the peak region of the $(1/\sigma)\, d\sigma/d\rho$ distribution more accurately, $\rho = m^2_\mathrm{jet}/p^2_{T,\mathrm{jet}}$. Depending on the jet size these effects will reduce the peak height bringing them in better agreement with numerical results from tuned parton shower calculations. Given Marzani et al's result [56] we now understand that the large non-perturbative corrections introduced by other groups just make up for the missing contribution of non-global logarithms. Promising as is, as an outlook, they advocate a direction of application of their formalism to the comparison of jet grooming techniques like jet filtering, pruning and trimming on a more analytic level.

M. Takeuchi presented work done mainly in collaboration with T. Plehn and M. Spannowsky on boosted, hadronically decaying top quarks in searches for new physics [57]. Hadronically decaying tops ($t \to 3\,$jets) are in principle fully reconstructible. If the top quarks are boosted, they give a great handle for suppressing the large QCD and combinatorial backgrounds simply because they occur as “fat” (massive) jets with a distinct substructure. Various groups have built so-called top taggers around this idea with the aim to identify top-quark jets in a similar fashion as done for bottom-quark jets. Takeuchi et al. developed the HEPTOPTAGGER [58], which proceeds through the four steps of fat-jet finding (using the C/A algorithm for geometrically large sizes of jets: $2\,m_\mathrm{jet}/p_{T,\mathrm{jet}} \sim R \sim 1.5$), subjet identification invoking mass drop criteria, filter mass optimization for subjet triples and the implementation of constraints on 2-jet and 3-jet mass ratios. In doing so, emphasis was put on having a valid approach down to $p_{T,\text{fat-jet}} \sim 200$ GeV since the gain in cross section is huge. As one main application of the HEPTopTagger, M. Takeuchi discussed the prospects of scalar top reconstruction [59] highlighting a search strategy for the 8 TeV LHC and stop masses of $\sim 400$ GeV that reaches $\sim 3\,\sigma$ and $\mathcal{O}(1)$ discrimination with $\sim 10$ fb$^{-1}$ of data.

Z. Li reported on results of work with H. Li and C.-P. Yuan aiming at a better analytic understanding of jet substructure related quantities at hadron colliders [60]. They established a perturbative QCD framework based on the resummation formalism of Refs. [61, 62] to calculate jet energy profiles and jet mass distributions of light-quark and gluon jets. Their novel description improves NLO predictions for both of these observables significantly [63], leading to good agreement with CDF and CMS data on jet energy profiles $\Psi(r)$ for various $p_{T,\mathrm{jet}}$ intervals without application of any further corrections, see Figure 2. To describe the jet mass spectra in the low-mass region, they however introduce non-perturbative contributions to their resummation formalism, whose realm they plan to extend to heavy-quark/boosted jets. One interesting aspect pointed out by Z. Li regards the individual knowledge of $\Psi(r)$ for both, quark and gluon jets; e.g. the latter yield steeper $\Psi(r)$. This may help enhance the sensitivity to new-physics contributions when exploring ratios between quark and gluon initiated jets in more detail.

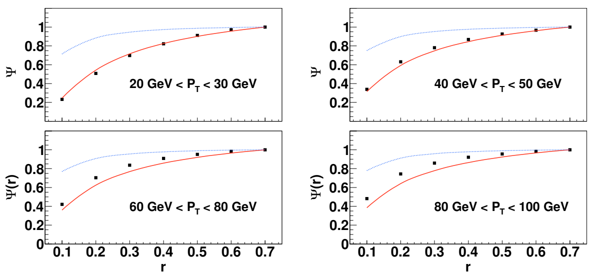


Figure 2: Examples of resummation (solid) and NLO (dashed) predictions [63] for jet energy profiles $\Psi(r)$ compared with CMS data [64].

## 2.3 Inclusive production versus jet vetoes

Work done in collaboration with A. Lipatov and N. Zotov was presented by M. Malyshev [65]. On the basis of the $k_T$-factorization approach (with its theoretical foundation given by the BFKL or CCFM equations) they calculated unpolarized Drell–Yan (DY) lepton pair production in $p\bar{p}$ and $pp$ collisions. In a field where collinear factorization is recognized as the standard,[1] it is worthwhile to investigate what an alternative based on non-collinear factorization can do for us. As a major difference one should note that the initial gluon emissions in the $k_T$-factorization formalism generate the finite dilepton transverse momentum already at the Born level. The ingredients to their calculation [66] are then given by the unintegrated parton densities following the KMR prescription, and the offshell production amplitudes for $Z/\gamma^*$ exchange including the $Z$-$\gamma^*$ interference and fully spin-correlated decays into leptons. They consider offshell amplitudes at $\mathcal{O}(\alpha)$ and $\mathcal{O}(\alpha\alpha_\mathrm{s})$. Using their calculational framework they show a broad comparison with data from the Tevatron and early LHC for differential cross sections with respect to variables such as $m_{\ell\ell}$, $y_{\ell\ell}$ and $p_{T,\ell\ell}$. Generally, the agreement is found to be very reasonable. Highlights to mention are the predicted distribution for $p_{T,\ell\ell}$ featuring the low-$p_T$ rise and turnover, and results obtained for the $p_T$-dependent coefficients $A_1$ through $A_4$ related to an angular analysis as recently done by the CDF collaboration [67].

Yet another approach to DY pair – or more generally gauge and Higgs boson – production was advocated by D. Wilhelm who reported on work accomplished in collaboration with

[1] Collinear factorization has been rigorously proven for DY pair production, which we nowadays control at NNLO in perturbative QCD matched to soft gluon analytic resummation at NNLL.

T. Becher and M. Neubert [68, 69]. Using methods from Soft-Collinear Effective field Theory, they developed a new, systematic framework for the evaluation of the cross section at small and very small transverse momentum of the boson, $\Lambda_{\rm QCD} \ll q_T \ll M_V$ [70]. In this framework large logarithms of the scale ratio $M_V/q_T$ are resummed to all orders by avoiding issues with Landau pole singularities as known from the conventional/traditional resummation approach [61]. In Becher et al's approach the cross section is written as a product of a $q^2$-dependent hard function with a convolution of two transverse-position dependent parton distribution functions. The form of the factorization theorem is affected by an anomaly of the effective Lagrangian at the quantum level, leading to the breakdown of the naive factorization of the two collinear sectors given at the classical level. Because of this anomaly, not only the hard function encoding the virtual effects associated with the electroweak boson production, but also the product of collinear functions has a dependence on $M_V$. As an interesting consequence one finds that the renormalization scale $\mu$ saturates to a non-perturbative value $q^* \sim M_V \exp\{-{\rm const}/\alpha_{\rm s}(M_V)\}$ for $q_T \to 0$. Numerically this amounts to $q^* \approx 1.88$ GeV for $Z$ production. They then find their (NNLO matched) results of NNLL accuracy – including some long-distance effects for $q_T \lesssim 3$ GeV – to be in nice agreement with data on low-$q_T$ spectra from the Tevatron and early LHC. It will be interesting to see how this approach performs in the scope of Higgs boson production where $q^* \approx 7.5$ GeV and long-distance power corrections shall be truly negligible.

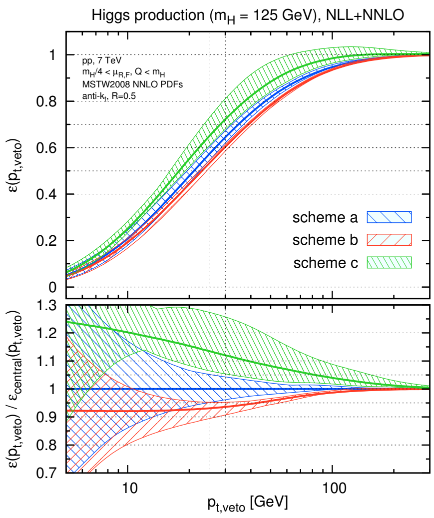


Figure 3: Jet-veto efficiency predictions at NLL+NNLO given in dependence on $p_{T,\rm veto}$ for Higgs boson production in 7 TeV $pp$ collisions. Results are shown for three different matching schemes; for more details, cf. [71].

One of the crucial channels to explore the nature of the low-mass Higgs-like boson discovered at the 7 and 8 TeV LHC is $H \to WW^*$. Good discrimination between signal and backgrounds can be guaranteed, in particular in the 0-jet bin where the $W$ boson contamination from the $t\bar{t}$ background is smallest. This implies a good understanding of the uncertainties related with the exclusive 0-jet cross section, $\sigma[0\,\rm jets]$. Obtaining a reliable error estimate, however, is a tricky task, because the scale variations of the jet-vetoed NNLO result for Higgs boson production are known to underestimate the uncertainty in the region of moderate $p_{T,\rm veto} \sim 30$ GeV; on the contrary assuming uncorrelated errors the estimate $\Delta\sigma^2[0\,\rm jets] = \Delta\sigma^2[\geq 0\,\rm jets] + \Delta\sigma^2[\geq 1\,\rm jet]$ is said to be too large. Results "fresh from the press" [71] regarding this subject were presented by A. Banfi during his talk at DIS 2012 [72]. Together with G. Salam and G. Zanderighi, they have been carefully studying an ansatz involving the jet-veto efficiency (i.e. the fraction of events with no jet of $p_T > p_{T,\rm veto}$): $\sigma[0\,\rm jets] = \sigma[\geq 0\,\rm jets] \times \varepsilon(p_{T,\rm veto})$. This allows them to discuss the uncertainties in determining the veto efficiency separately from the inclusive cross section, which has been intensely studied in the literature; for an up-to-date $H$ physics compendium, see Refs. [73, 74]. There are two sources of uncertainties to $\varepsilon(p_{T,\rm veto})$, those related to how one defines $\varepsilon$ at fixed order and those related to missing logarithms $\ln(M_h/p_{T,\rm veto})$ of Sudakov origin. For the former, they introduce three NNLO-equivalent schemes, which lead to very similar, precise results in their control scenario given by $Z$+jet production. Owing to the poorer convergence of the perturbative series in the $H$ case, they however see large deviations among the predictions of the different schemes. These deviations are tamed by including the logarithmic corrections to $\varepsilon$ occurring at all orders. Using the CAESAR program, they can resum these effects to NLL accuracy, and match them with the NNLO prediction where the freedom of choosing from three equivalent schemes can be used as an additional handle in estimating the uncertainties; the results are shown in Figure 3. Comparisons with other theoretical tools (HQT+MCFM, POWHEG+PYTHIA) confirm the consistency of their results for the veto efficiency.

The discussion of jet vetoes was of importance in two other contributions: S. Marzani's second presentation within this working group [75], and P. Schichtel's contribution where he presented work accomplished together with his collaborators C. Englert, T. Plehn and S. Schumann [76, 77, 78]. One can identify two limiting cases where the scaling properties of exclusive jet cross sections are governed by two simple patterns: Poisson scaling characterized by $\sigma_{n+1}/\sigma_n = \text{const}/(n+1)$, and staircase scaling expressed as $\sigma_{n+1}/\sigma_n = \text{const}$. Using this knowledge Schichtel et al. argue in favour of achieving better control over the theoretical errors associated with exclusive $n$-jet production. Since this occurs as a background to an overwhelming number of searches at the LHC, they present various cases where the application of jet scaling can have an impact. They discuss the experimental laboratory of $\gamma$+jets where one can interpolate between the two patterns imposing simple kinematic cuts [78]. Furthermore, in the context of Higgs boson searches in the vector boson fusion channel, they advertise the use of fitting the $n_{\text{jets}}$ distribution to determine the veto survival probability [79]. As an application to BSM searches, they discuss the idea of autofocus [77], a broad inclusive search that scans the parameter space using a missing transverse energy (MET) cut and two-dimensional log-likelihoods given in terms of $n_{\text{jets}}$ and $m_{\text{eff}} = p_{T,\text{MET}} + \sum_{\text{jets}} p_{T,i}$.

Jet vetoes have also been discussed as a means to probe the colour structure of hard processes. Taking the example of dijet production under a jet veto in the inter-jet region, S. Marzani, J. Forshaw and M. Seymour worked out analytical predictions [80] based on soft gluon resummation techniques for the observable gap fraction – defined by the cross section, and normalized to the inclusive rate, where a third jet with $p_T > Q_0$ is vetoed in the rapidity region between the two jets. Choosing $Q_0 \gg \Lambda_{\text{QCD}}$ reasonably small, the impact of the underlying event is kept small. Usually one uses Monte Carlo simulations in the form of (matched/merged) parton showers to conduct these or similar studies, but this way one, at least, neglects terms subleading in $N_{\text{C}}$. In fact, predictions obtained by these tools show a large spread. On the contrary Marzani et al. account for the full colour structure and the effects of non-global logarithms. To gain better control over the LL resummation, they also improve the pure eikonal treatment by incorporating energy-momentum conservation at least for the first/hardest emission. A matching to fixed order beyond the leading one is foreseen for future applications.

## 2.4 Intra-jet evolution and hadron production

Parton showers are vital ingredients to any event-generator based Monte Carlo simulation used in collider physics. For all practical purposes, these algorithms are formulated in the limit where QCD is treated as an SU($N_{\text{C}}$) gauge theory with arbitrarily large $N_{\text{C}}$, or $N_{\text{C}} \to \infty$.[2] S. Plätzer presented the results of a first successful attempt to include corrections to the parton shower that are beyond the large-$N_{\text{C}}$ limit [81]. This work has been done in collaboration with M. Sjö-

[2]There is one exception: $C_{\text{F}} < C_{\text{A}}/2$ is used as the colour factor associated with gluon emission off a quark.

dahl [82]. Using the dipole-like shower framework, they can extend its capabilities such that the full colour structure of the splitting is maintained as originally formulated in the dipole factorization according to Catani and Seymour [83]. They call this a colour matrix-element correction and explain the technicalities of implementing these corrections for subsequent emissions. As a proof-of-concept, results are shown from final-state showering LEP1-like collisions where up to 6 emissions have been colour-matrix-element corrected. An event shape observable like thrust receives only marginal corrections, however specifically designed variables such as the rapidity taken with respect to the thrust axis of the three hardest partons and averaged over these partons may show 5–10% deviations. More generally, this subject constitutes a very interesting direction of research, which – in the context of jet-veto based calculations as discussed in the previous subsection – can be understood as an effort from the Monte Carlo community to improve the accuracy of e.g. gap fraction predictions.

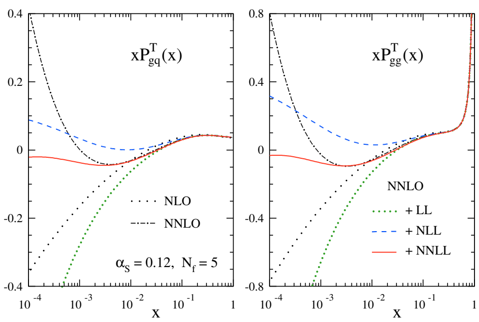


Figure 4: Timelike gluon–quark and gluon–gluon splitting functions (multiplied by $x$) in their NLO and NNLO approximation. Also shown is their stabilization through leading ($\alpha_s^{n-1} \ln^{2n} x$), next-to-leading and next-to-next-to-leading small-$x$ logarithmic corrections at all orders in $\alpha_s$; for more details, cf. [84].

In two thorough presentations [85], A. Vogt reviewed the status and spelled out the recent progress that has been achieved in calculating the timelike splitting functions, which govern the evolution of parton fragmentation functions in QCD. Using non-trivial relations to the spacelike DIS case and the supersymmetric limit, A. Almasy, S. Moch and A. Vogt were able to complete an indirect determination of the NNLO (i.e. third order) corrections to the timelike splitting functions, in particular the hitherto missing quark–gluon and gluon–quark quantities were derived [86]. These fixed-order results are adequate except for large ($1 - x \ll 1$) and small ($x \ll 1$) momentum fractions $x$ where higher-order corrections generally include double logarithms that can spoil the perturbative expansions. For $x \lesssim 10^{-3} \ldots 10^{-2}$, small-$x$ effects up to N$^n$LL need to be resummed and added to the N$^n$LO results ($n = 0, 1, 2$). A. Vogt then showed that this completely removes the huge small-$x$ instabilities present in the respective fixed-order results [84], see Figure 4 for an illustration. To accomplish the small-$x$ resummation at N(N)LL, Vogt, Soar, Lo Presti, Kom and Almasy studied the resummation of large-$x$ double logarithms beyond the scope of soft gluon exponentiation [87]. They realized that the same formalism can be applied to the dominant $x^{-1} \ln^{\ell} x$ terms occurring in semi-inclusive annihilation splitting and coefficient functions. Because of the importance in stabilizing the NNLO predictions, the talks also addressed the theoretical basics of these resummations.

Subject of P. Bolzoni's talk was the presentation of a new approach to the determination of the gluon to quark multiplicity ratio in dependence on the jet energy [88]. To get this ratio $r(Q^2)$, he uses the effective-$N$ approach where the ratio can be written as $r(Q^2) \equiv \hat{r}(N_{\text{eff}}, Q^2) = D_g(N_{\text{eff}}, Q^2)/D_s(N_{\text{eff}}, Q^2)$ employing the gluon and sea-quark densities $D_{g/s}$. As a prerequisite, one needs to evaluate the first Mellin moment which implies proper knowledge of the resummation corrections. These corrections can be incorporated by an appropriate choice of $N = N_{\text{eff}}$. P. Bolzoni extended the LO treatment of the effective-$N$ approach using the extensive theoretical input on the higher-order structure of QCD splitting functions that has become available over the last years (see e.g. above). This knowledge on splitting functions can be transferred over to the $D_{g/s}$ densities applying a specific diagonalization technique to the coupled gluon–singlet system whose scale evolution is given by the DGLAP equations. As a result the perturbative series he obtains shows good convergence and the global fit to data works fairly well.

Without any doubt there is huge desire to have a reliable and robust method at hand, which tells a light-quark from a gluon jet, in other words to design a jet flavour tagger going beyond heavy-quark or $b$-jet identification. The concept of jet flavour however is not well defined. Nevertheless in the context of LO Monte Carlo tools a working definition for jet flavour can be adopted by invoking the (geometrical) correspondence between the jet-initiating hard parton and the emerging jet, assigning the hard parton flavour to the jet. J. Gallicchio, who presented the talk, and his collaborator M. Schwartz conducted a thorough study to identify key handles that yield the largest discriminative power in separating gluon-like from quark-like jets [89]. To pursue this task they chose a Monte Carlo simulation based "laboratory" given by fully hadronized dijet and $\gamma$+jet events, which were classified according to jet $p_T$ windows defined at the hadron level. As for the observables, they divided them into two main classes: discrete and continuous ones where for the former, they found the number of charged particles (or, even better, all hadrons), and the latter, the linear radial moment (also known as girth) to be the strongest discriminators. The combination of these two variables into a bin-by-bin likelihood distribution led to additional, significant gain, which they also observed for other pairings of one discrete and one continuous observable. From an experimental point of view the specific ranking of the observables might differ from what Gallicchio and Schwartz established through their exhaustive search [90], but the direction and ideas they give are well testable and shall be scrutinized in an experimental environment.

On behalf of the Herwig collaboration, C. Röhr gave a short review of the multiple parton interactions (MPI) model implemented in the Herwig++ event generator [91]. He focused on explaining recent model refinements that were introduced as a consequence of the tuning efforts to LHC data, which can only be described if colour reconnections are properly taken into account. QCD properties such as local parton hadron duality and preconfinement disfavour the generation of massive clusters formed over large momentum distances. The core MPI model, however, enables the formation of too many heavy-mass clusters emerging during the hadronization phase of event generation. In particular those resulting from connections between beam remnants and partons of the evolving partonic interaction are problematic. C. Röhr discussed the physics and implications of two colour reconnection models implemented in newer Herwig++ versions. The basic idea in both the plain and the statistical model is to use alternative colour connections that overlap in momentum space and lead to a reduction in cluster masses [92]. He showed examples of underlying-event/min-bias observables where good agreement between model prediction and data was achieved once colour reconnections were employed.

V. Lyuboshitz investigated the phenomenological structure of inclusive cross sections for the pair production of neutral kaons taking strangeness conservation, effects of Bose statistics and $S$-wave strong final-state interactions into account [93]. Similar ideas may be applied to the systems of neutral mesons involving heavy quarks, however in this case one faces difficulties due to the similar lifetimes of the associated $CP$-even and $CP$-odd decay channels.

## Acknowledgements

We thank the presenters of the Hadronic Final States Session for their contributions. We also thank the conveners of *WG1: Structure Functions and Parton Densities* and *WG2: Diffraction and vector mesons* for coordinating joint sessions with our working group.


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