

Gerwick, Erik; Schumann, Steffen; Höche, Stefan; Marzani, Simone

Soft evolution of multi-jet final states. (English) [Zbl 1388.81105](#)

J. High Energy Phys. 2015, No. 2, Paper No. 106, 37 p. (2015).

Summary: We present a new framework for computing resummed and matched distributions in processes with many hard QCD jets. The intricate color structure of soft gluon emission at large angles renders resummed calculations highly non-trivial in this case. We automate all ingredients necessary for the color evolution of the soft function at next-to-leading-logarithmic accuracy, namely the selection of the color bases and the projections of color operators and Born amplitudes onto those bases. Explicit results for all QCD processes with up to 2 5 partons are given. We also devise a new tree-level matching scheme for resummed calculations which exploits a quasi-local subtraction based on the Catani-Seymour dipole formalism. We implement both resummation and matching in the Sherpa event generator. As a proof of concept, we compute the resummed and matched transverse-thrust distribution for hadronic collisions.

MSC:

81Q05 Closed and approximate solutions to the Schrödinger, Dirac, Klein-Gordon and other equations of quantum mechanics

Keywords:

QCD phenomenology; jets

Software:

BlackHat; Golem95; PHEGAS; GoSam; CutTools; HELAC-1LOOP; ALPGEN; Comix; SHERPA; MC@NLO; ColorMath

Full Text: [DOI](#)

References:

- [1] ATLAS collaboration, Measurement of multi-jet cross sections in proton-proton collisions at a 7 TeV center-of-mass energy, *Eur. Phys. J., C* 71, 1763, (2011)
- [2] ATLAS collaboration, Measurement of the production cross section of jets in association with a Z boson in pp collisions at $\sqrt{s}=7$ TeV with the ATLAS detector, *JHEP*, 07, 032, (2013)
- [3] CMS collaboration, *Measurements of jet multiplicity and differential production cross sections of Z+jets events in proton-proton collisions at $\sqrt{s}=7$ TeV*, arXiv:1408.3104 [INSPIRE].
- [4] Mangano, ML; Moretti, M.; Piccinini, F.; Pittau, R.; Polosa, AD, ALPGEN, a generator for hard multiparton processes in hadronic collisions, *JHEP*, 07, 001, (2003)
- [5] Cafarella, A.; Papadopoulos, CG; Worek, M., Helac-phegas: a generator for all parton level processes, *Comput. Phys. Commun.*, 180, 1941, (2009)
- [6] Gleisberg, T.; Höche, S., Comix, a new matrix element generator, *JHEP*, 12, 039, (2008)
- [7] Denner, A.; Dittmaier, S., Reduction schemes for one-loop tensor integrals, *Nucl. Phys., B* 734, 62, (2006) · [Zbl 1192.81158](#)
- [8] Ossola, G.; Papadopoulos, CG; Pittau, R., Reducing full one-loop amplitudes to scalar integrals at the integrand level, *Nucl. Phys., B* 763, 147, (2007) · [Zbl 1116.81067](#)
- [9] Ellis, RK; Giele, WT; Kunszt, Z., A numerical unitarity formalism for evaluating one-loop amplitudes, *JHEP*, 03, 003, (2008)
- [10] Binoth, T.; Guillet, J-P; Heinrich, G.; Pilon, E.; Reiter, T., Golem95: a numerical program to calculate one-loop tensor integrals with up to six external legs, *Comput. Phys. Commun.*, 180, 2317, (2009) · [Zbl 1197.81004](#)
- [11] Berger, CF; et al., An automated implementation of on-shell methods for one-loop amplitudes, *Phys. Rev., D* 78, 036003, (2008)
- [12] Bevilacqua, G.; et al., Helac-nlo, *Comput. Phys. Commun.*, 184, 986, (2013)
- [13] Cullen, G.; et al., Automated one-loop calculations with gosam, *Eur. Phys. J., C* 72, 1889, (2012)
- [14] Cascioli, F.; Maierhöfer, P.; Pozzorini, S., Scattering amplitudes with open loops, *Phys. Rev. Lett.*, 108, 111601, (2012)
- [15] Hirschi, V.; et al., Automation of one-loop QCD corrections, *JHEP*, 05, 044, (2011) · [Zbl 1296.81138](#)
- [16] Badger, S.; Biedermann, B.; Uwer, P.; Yundin, V., Numerical evaluation of virtual corrections to multi-jet production in massless QCD, *Comput. Phys. Commun.*, 184, 1981, (2013)

- [17] Actis, S.; Denner, A.; Hofer, L.; Scharf, A.; Uccirati, S., Recursive generation of one-loop amplitudes in the standard model, *JHEP*, 04, 037, (2013)
- [18] Ita, H.; et al., Precise predictions for $Z + 4$ jets at hadron colliders, *Phys. Rev., D* 85, 031501, (2012)
- [19] Bern, Z.; et al., Next-to-leading order $W + 5$ -jet production at the LHC, *Phys. Rev., D* 88, 014025, (2013)
- [20] Badger, S.; Biedermann, B.; Uwer, P.; Yundin, V., Next-to-leading order QCD corrections to five jet production at the LHC, *Phys. Rev., D* 89, 034019, (2014)
- [21] Cullen, G.; et al., Next-to-leading-order QCD corrections to Higgs boson production plus three jets in gluon fusion, *Phys. Rev. Lett.*, 111, 131801, (2013)
- [22] Marchesini, G.; Webber, BR, Simulation of QCD jets including soft gluon interference, *Nucl. Phys., B* 238, 1, (1984)
- [23] Sjöstrand, T., A model for initial state parton showers, *Phys. Lett., B* 157, 321, (1985)
- [24] Marchesini, G.; Webber, BR, Monte Carlo simulation of general hard processes with coherent QCD radiation, *Nucl. Phys., B* 310, 461, (1988)
- [25] Z. Nagy and D.E. Soper, `\textit{A new parton shower algorithm: shower evolution, matching at leading and next-to-leading order level}`, hep-ph/0601021 [INSPIRE].
- [26] Giele, WT; Kosower, DA; Skands, PZ, A simple shower and matching algorithm, *Phys. Rev., D* 78, 014026, (2008)
- [27] Schumann, S.; Krauss, F., A parton shower algorithm based on catani-seymour dipole factorisation, *JHEP*, 03, 038, (2008)
- [28] Plätzer, S.; Gieseke, S., Coherent parton showers with local recoils, *JHEP*, 01, 024, (2011) · [Zbl 1214.81306](#)
- [29] Plätzer, S.; Sjödhahl, M., Subleading N_{c^2} improved parton showers, *JHEP*, 07, 042, (2012)
- [30] Nagy, Z.; Soper, DE, Parton shower evolution with subleading color, *JHEP*, 06, 044, (2012)
- [31] Catani, S.; Krauss, F.; Kuhn, R.; Webber, BR, QCD matrix elements + parton showers, *JHEP*, 11, 063, (2001)
- [32] Mangano, ML; Moretti, M.; Pittau, R., Multijet matrix elements and shower evolution in hadronic collisions: $\overline{b} + n$ jets as a case study, *Nucl. Phys., B* 632, 343, (2002)
- [33] Lönnblad, L., Correcting the color dipole cascade model with fixed order matrix elements, *JHEP*, 05, 046, (2002)
- [34] Krauss, F., Matrix elements and parton showers in hadronic interactions, *JHEP*, 08, 015, (2002)
- [35] Frixione, S.; Webber, BR, Matching NLO QCD computations and parton shower simulations, *JHEP*, 06, 029, (2002)
- [36] Nason, P., A new method for combining NLO QCD with shower Monte Carlo algorithms, *JHEP*, 11, 040, (2004)
- [37] Frixione, S.; Nason, P.; Oleari, C., Matching NLO QCD computations with parton shower simulations: the POWHEG method, *JHEP*, 11, 070, (2007)
- [38] Höche, S.; Krauss, F.; Schönherr, M.; Siegert, F., QCD matrix elements + parton showers: the NLO case, *JHEP*, 04, 027, (2013)
- [39] Frederix, R.; Frixione, S., Merging meets matching in MC@NLO, *JHEP*, 12, 061, (2012)
- [40] Lönnblad, L.; Prestel, S., Merging multi-leg NLO matrix elements with parton showers, *JHEP*, 03, 166, (2013)
- [41] Hamilton, K.; Nason, P.; Oleari, C.; Zanderighi, G., Merging H/W/Z + 0 and 1 jet at NLO with no merging scale: a path to parton shower + NNLO matching, *JHEP*, 05, 082, (2013)
- [42] Hamilton, K.; Nason, P.; Re, E.; Zanderighi, G., NNLOPS simulation of Higgs boson production, *JHEP*, 10, 222, (2013)
- [43] S. Höche, Y. Li and S. Prestel, `\textit{Drell-Yan lepton pair production at NNLO QCD with parton showers}`, arXiv:1405.3607 [INSPIRE].
- [44] Andersen, JR; Smillie, JM, Multiple jets at the LHC with high energy jets, *JHEP*, 06, 010, (2011)
- [45] Dasgupta, M.; Salam, GP, Event shapes in e^+e^- annihilation and deep inelastic scattering, *J. Phys., G* 30, r143, (2004)
- [46] Banfi, A.; Salam, GP; Zanderighi, G., Phenomenology of event shapes at hadron colliders, *JHEP*, 06, 038, (2010) · [Zbl 1290.81159](#)
- [47] Banfi, A.; Salam, GP; Zanderighi, G., Semi-numerical resummation of event shapes, *JHEP*, 01, 018, (2002)
- [48] Banfi, A.; Salam, GP; Zanderighi, G., Generalized resummation of QCD final state observables, *Phys. Lett., B* 584, 298, (2004)
- [49] Banfi, A.; Salam, GP; Zanderighi, G., Resummed event shapes at hadron-hadron colliders, *JHEP*, 08, 062, (2004)
- [50] Banfi, A.; Salam, GP; Zanderighi, G., Principles of general final-state resummation and automated implementation, *JHEP*, 03, 073, (2005)
- [51] Abbate, R.; Fickinger, M.; Hoang, AH; Mateu, V.; Stewart, IW, Thrust at N^3 LL with power corrections and a precision global fit for $\alpha_s(m_Z)$, *Phys. Rev., D* 83, 074021, (2011)
- [52] A.H. Hoang, D.W. Kolodrubetz, V. Mateu and I.W. Stewart, `\textit{C-parameter distribution at N^3 LL with power corrections}`, arXiv:1411.6633 [INSPIRE].
- [53] Oderda, G.; Sterman, GF, Energy and color flow in dijet rapidity gaps, *Phys. Rev. Lett.*, 81, 3591, (1998)
- [54] Appleby, RB; Seymour, MH, The resummation of interjet energy flow for gaps between jets processes at HERA, *JHEP*, 09, 056, (2003)
- [55] Forshaw, JR; Kyrieleis, A.; Seymour, MH, Super-leading logarithms in non-global observables in QCD, *JHEP*, 08, 059, (2006)

- [56] Forshaw, JR; Kyrieleis, A.; Seymour, MH, Super-leading logarithms in non-global observables in QCD: colour basis independent calculation, *JHEP*, 09, 128, (2008)
- [57] Forshaw, J.; Keates, J.; Marzani, S., Jet vetoing at the LHC, *JHEP*, 07, 023, (2009)
- [58] Duran Delgado, RM; Forshaw, JR; Marzani, S.; Seymour, MH, The dijet cross section with a jet veto, *JHEP*, 08, 157, (2011)
- [59] Liu, X.; Petriello, F., Resummation of jet-veto logarithms in hadronic processes containing jets, *Phys. Rev.*, D 87, 014018, (2013)
- [60] ATLAS collaboration, Measurement of dijet production with a veto on additional central jet activity in pp collisions at $\sqrt{s}=7$ TeV using the ATLAS detector, *JHEP*, 09, 053, (2011)
- [61] ATLAS collaboration, Measurement of $t\bar{t}$ production with a veto on additional central jet activity in pp collisions at $\sqrt{s}=7$ TeV using the ATLAS detector, *Eur. Phys. J.*, C 72, 2043, (2012)
- [62] ATLAS collaboration, Measurements of jet vetoes and azimuthal decorrelations in dijet events produced in pp collisions at $\sqrt{s}=7$ TeV using the ATLAS detector, *Eur. Phys. J.*, C 74, 3117, (2014)
- [63] CMS collaboration, Measurement of the inclusive production cross sections for forward jets and for dijet events with one forward and one central jet in pp collisions at $\sqrt{s}=7$ TeV, *JHEP*, 06, 036, (2012)
- [64] Banfi, A.; Salam, GP; Zanderighi, G., NLL+NNLO predictions for jet-veto efficiencies in Higgs-boson and Drell-Yan production, *JHEP*, 06, 159, (2012)
- [65] Banfi, A.; Monni, PF; Salam, GP; Zanderighi, G., Higgs and Z-boson production with a jet veto, *Phys. Rev. Lett.*, 109, 202001, (2012)
- [66] Banfi, A.; Monni, PF; Zanderighi, G., Quark masses in Higgs production with a jet veto, *JHEP*, 01, 097, (2014)
- [67] Becher, T.; Neubert, M., Factorization and NNLL resummation for Higgs production with a jet veto, *JHEP*, 07, 108, (2012)
- [68] Becher, T.; Neubert, M.; Rothen, L., Factorization and N^3LL_{p} + NNLO predictions for the Higgs cross section with a jet veto, *JHEP*, 10, 125, (2013)
- [69] Stewart, IW; Tackmann, FJ; Walsh, JR; Zuberi, S., Jet p_T resummation in Higgs production at $NNLL^{\text{p}}$ + NNLO, *Phys. Rev.*, D 89, 054001, (2014)
- [70] Boughezal, R.; Liu, X.; Petriello, F.; Tackmann, FJ; Walsh, JR, Combining resummed Higgs predictions across jet bins, *Phys. Rev.*, D 89, 074044, (2014)
- [71] Li, H-N; Li, Z.; Yuan, C-P, QCD resummation for light-particle jets, *Phys. Rev.*, D 87, 074025, (2013)
- [72] Dasgupta, M.; Khelifa-Kerfa, K.; Marzani, S.; Spannowsky, M., On jet mass distributions in Z+jet and dijet processes at the LHC, *JHEP*, 10, 126, (2012)
- [73] Chien, Y-T; Kelley, R.; Schwartz, MD; Zhu, HX, Resummation of jet mass at hadron colliders, *Phys. Rev.*, D 87, 014010, (2013)
- [74] Jouttenus, TT; Stewart, IW; Tackmann, FJ; Waalewijn, WJ, Jet mass spectra in Higgs boson plus one jet at next-to-next-to-leading logarithmic order, *Phys. Rev.*, D 88, 054031, (2013)
- [75] Larkoski, AJ; Salam, GP; Thaler, J., Energy correlation functions for jet substructure, *JHEP*, 06, 108, (2013) · [Zbl 1342.81689](#)
- [76] Larkoski, AJ; Thaler, J., Unsafe but calculable: ratios of angularities in perturbative QCD, *JHEP*, 09, 137, (2013)
- [77] Larkoski, AJ; Neill, D.; Thaler, J., Jet shapes with the broadening axis, *JHEP*, 04, 017, (2014)
- [78] Larkoski, AJ; Moul, I.; Neill, D., Toward multi-differential cross sections: measuring two angularities on a single jet, *JHEP*, 09, 046, (2014)
- [79] Larkoski, AJ; Moul, I.; Neill, D., Power counting to better jet observables, *JHEP*, 12, 009, (2014)
- [80] Gerwick, E.; Schumann, S.; Gripcios, B.; Webber, B., QCD jet rates with the inclusive generalized k_T algorithms, *JHEP*, 04, 089, (2013)
- [81] Dasgupta, M.; Fregoso, A.; Marzani, S.; Salam, GP, Towards an understanding of jet substructure, *JHEP*, 09, 029, (2013)
- [82] Dasgupta, M.; Fregoso, A.; Marzani, S.; Powling, A., Jet substructure with analytical methods, *Eur. Phys. J.*, C 73, 2623, (2013)
- [83] Larkoski, AJ; Marzani, S.; Soyez, G.; Thaler, J., Soft drop, *JHEP*, 05, 146, (2014)
- [84] Broggio, A.; Ferroglia, A.; Pecjak, BD; Zhang, Z., NNLO hard functions in massless QCD, *JHEP*, 12, 005, (2014)
- [85] Hinderer, P.; Ringer, F.; Sterman, GF; Vogelsang, W., Toward NNLL threshold resummation for hadron pair production in hadronic collisions, *Phys. Rev.*, D 91, 014016, (2015)
- [86] Dokshitzer, Y.; Marchesini, G., Hadron collisions and the fifth form-factor, *Phys. Lett.*, B 631, 118, (2005)
- [87] Dokshitzer, Y.; Marchesini, G., Soft gluons at large angles in hadron collisions, *JHEP*, 01, 007, (2006)
- [88] Kidonakis, N.; Oderda, G.; Sterman, GF, Evolution of color exchange in QCD hard scattering, *Nucl. Phys.*, B 531, 365, (1998)
- [89] Bonciani, R.; Catani, S.; Mangano, ML; Nason, P., Sudakov resummation of multiparton QCD cross-sections, *Phys. Lett.*, B 575, 268, (2003) · [Zbl 1094.81559](#)
- [90] Catani, S.; Ciafaloni, M.; Marchesini, G., Noncancelling infrared divergences in QCD coherent state, *Nucl. Phys.*, B 264, 588, (1986)
- [91] Catani, S.; Seymour, MH, The dipole formalism for the calculation of QCD jet cross-sections at next-to-leading order, *Phys. Lett.*, B 378, 287, (1996)

- [92] S. Catani and M.H. Seymour, [A general algorithm for calculating jet cross-sections in NLO QCD](#), [Nucl. Phys.](#) **B 485** (1997) 291 [[Erratum ibid.](#)] **B 510** (1998) 503 [[hep-ph/9605323](#)] [[INSPIRE](#)].
- [93] Bassetto, A.; Ciafaloni, M.; Marchesini, G., Jet structure and infrared sensitive quantities in perturbative QCD, [Phys. Rept.](#), 100, 201, (1983)
- [94] Sjö Dahl, M., Color evolution of $2 \rightarrow 3$ processes, [JHEP](#), 12, 083, (2008)
- [95] Sjö Dahl, M., Color structure for soft gluon resummation: a general recipe, [JHEP](#), 09, 087, (2009)
- [96] Sjö Dahl, M., Colormath — a package for color summed calculations in $SU(N_c)$, [Eur. Phys. J., C](#) 73, 2310, (2013)
- [97] Keppeler, S.; Sjö Dahl, M., Orthogonal multiplet bases in $SU(N_c)$ color space, [JHEP](#), 09, 124, (2012) · [Zbl 1397.81452](#)
- [98] Duhr, C.; Höche, S.; Maltoni, F., Color-dressed recursive relations for multi-parton amplitudes, [JHEP](#), 08, 062, (2006)
- [99] Gleisberg, T.; et al., SHERPA 1.α: a proof of concept version, [JHEP](#), 02, 056, (2004)
- [100] Gleisberg, T.; et al., Event generation with SHERPA 1.1, [JHEP](#), 02, 007, (2009)
- [101] Mangano, ML; Parke, SJ, Multiparton amplitudes in gauge theories, [Phys. Rept.](#), 200, 301, (1991)
- [102] Duca, V.; Frizzo, A.; Maltoni, F., Factorization of tree QCD amplitudes in the high-energy limit and in the collinear limit, [Nucl. Phys., B](#) 568, 211, (2000)
- [103] Duca, V.; Dixon, LJ; Maltoni, F., New color decompositions for gauge amplitudes at tree and loop level, [Nucl. Phys., B](#) 571, 51, (2000)
- [104] Maltoni, F.; Paul, K.; Stelzer, T.; Willenbrock, S., Color flow decomposition of QCD amplitudes, [Phys. Rev., D](#) 67, 014026, (2003)
- [105] G. 't Hooft, [A planar diagram theory for strong interactions](#), [Nucl. Phys.](#) **B 72** (1974) 461 [[INSPIRE](#)].
- [106] Schofield, A.; Seymour, MH, Jet vetoing and HERWIG++, [JHEP](#), 01, 078, (2012)
- [107] Plätzer, S., Summing large-N towers in colour flow evolution, [Eur. Phys. J., C](#) 74, 2907, (2014)
- [108] A. Schofield, [Simulation of colour evolution in QCD scattering processes](#), Ph.D. thesis, University of Manchester, Manchester U.K. (2013).
- [109] Kleiss, R.; Kuijf, H., Multi-gluon cross-sections and five jet production at hadron colliders, [Nucl. Phys., B](#) 312, 616, (1989)
- [110] Höche, S.; Krauss, F.; Schönherr, M.; Siegert, F., Automating the POWHEG method in sherpa, [JHEP](#), 04, 024, (2011)
- [111] Dasgupta, M.; Salam, GP, Resummation of nonglobal QCD observables, [Phys. Lett., B](#) 512, 323, (2001) · [Zbl 0969.81646](#)
- [112] Dasgupta, M.; Salam, GP, Accounting for coherence in interjet $E_{\perp t}$ flow: a case study, [JHEP](#), 03, 017, (2002)
- [113] Cacciari, M.; Salam, GP; Soyez, G., The anti- $k_{\perp t}$ jet clustering algorithm, [JHEP](#), 04, 063, (2008)
- [114] Banfi, A.; Marchesini, G.; Smye, G., Away from jet energy flow, [JHEP](#), 08, 006, (2002)
- [115] Schwartz, MD; Zhu, HX, Nonglobal logarithms at three loops, four loops, five loops and beyond, [Phys. Rev., D](#) 90, 065004, (2014)
- [116] Hatta, Y.; Ueda, T., Resummation of non-global logarithms at finite N_c , [Nucl. Phys., B](#) 874, 808, (2013) · [Zbl 1282.81186](#)
- [117] Gleisberg, T.; Krauss, F., Automating dipole subtraction for QCD NLO calculations, [Eur. Phys. J., C](#) 53, 501, (2008)
- [118] D0 collaboration; Bertram, IA, Jet results at the D0 experiment, [Acta Phys. Polon., B](#) 33, 3141, (2002)
- [119] CDF collaboration; Aaltonen, T.; et al., Measurement of event shapes in proton-antiproton collisions at center-of-mass energy 1.96 TeV, [Phys. Rev., D](#) 83, 112007, (2011)
- [120] ATLAS collaboration, Measurement of event shapes at large momentum transfer with the ATLAS detector in pp collisions at $\sqrt{s}=7$ TeV, [Eur. Phys. J., C](#) 72, 2211, (2012)
- [121] CMS collaboration, Study of hadronic event-shape variables in multijet final states in pp collisions at $\sqrt{s}=7$ TeV, [JHEP](#), 10, 087, (2014)
- [122] Nagy, Z., Next-to-leading order calculation of three jet observables in hadron-hadron collision, [Phys. Rev., D](#) 68, 094002, (2003)

This reference list is based on information provided by the publisher or from digital mathematics libraries. Its items are heuristically matched to zbMATH identifiers and may contain data conversion errors. It attempts to reflect the references listed in the original paper as accurately as possible without claiming the completeness or perfect precision of the matching.