NLO and off-shell effects in top quark mass determinations

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Abstract: Place for Abstract.

KEYWORDS: QCD, NLO Computations, LHC, Top Quark

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Contents

1 Experimental data

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1 Experimental data

Experiment	Ref.	Number of datapoints	Q_{min}^2	Q_{max}^2	
Lep L3 1998	[1]	24	1.9	5.0	0.0035
Lep L3 1999	[2]	11	10.8	23.1	0.055
Lep L3 2000	[3]	17	60.0	225.0	0.13
Lep L3 2005	[4]	10	12.5	12.5	0.013
Lep OPAL 1994	[5]	7	5.9	14.7	0.046
Lep OPAL 1997 1	[6]	10	7.5	135.0	0.046
Lep OPAL 1997 2	[7]	21	9.0	59	0.075
Lep OPAL 1997 3	[8]	8	1.86	3.76	0.004
Lep OPAL 2000	[9]	22	1.9	17.8	0.0012
Lep ALEPH 1999	[10]	11	9.9	284	0.039
Lep ALEPH 1999	[11]	16	17.3	67.2	0.065
Lep DELPHI 1996	[12]	7	12.0	12.0	0.0405
KEK-TRISTAN-AMY 1990	[13]	6	73.0	73.0	0.25
KEK-TRISTAN-AMY 1995	[14]	5	73.0	390	0.25
KEK-TRISTAN-AMY 1997	[15]	3	6.8	6.8	0.07
KEK-TRISTAN-TOPAZ 1994	[16]	8	5.1	80.0	0.043
DESY-PETRA-CELLO 1983	[17]	5	4.0	20.0	0.6
DESY-PETRA-TASSO 1986	[18]	5	23.0	23.0	0.11
DESY-PETRA-JADE 1983	[19]	5	24.0	100.0	0.05
DESY-PETRA-JADE 1984	Missing				
DESY-PETRA-PLUTO 1984	[19]	15	2.4	9.2	0.063
DESY-PETRA-PLUTO 1987	[19]	4	45.0	45.0 F2+charm	0.175
SLAC-PEP-TPC/2-GAMMA 1987 1	[?]	22	0.24	5.1	0.01
SLAC-PEP-TPC/2-GAMMA 1987 2	[?]	19	0.24	5.2	0.07

M. Acciarri et~al.~ [L3 Collaboration], Phys. Lett. B ${\bf 436},~403~(1998).~$ doi:10.1016/S0370-2693(98)01025-9

M. Acciarriet~al. [L3 Collaboration], Phys. Lett. B $\bf 447,~147~(1999).~doi:10.1016/S0370-2693(98)01552-4$

- M. Acciarri *et al.* [L3 Collaboration], Phys. Lett. B **483**, 373 (2000) doi:10.1016/S0370-2693(00)00587-6 [hep-ex/0004005].
- P. Achard *et al.* [L3 Collaboration], Phys. Lett. B **622**, 249 (2005) doi:10.1016/j.physletb.2005.07.028 [hep-ex/0507042].
- R. Akers et al. [OPAL Collaboration], Z. Phys. C 61, 199 (1994). doi:10.1007/BF01413097
- K. Ackerstaff $et\ al.\ [{\rm OPAL\ Collaboration}], {\rm Z.\ Phys.\ C\ 74}, 33\ (1997).\ doi:10.1007/s002880050368$
- K. Ackerstaff *et al.* [OPAL Collaboration], Phys. Lett. B **411**, 387 (1997) doi:10.1016/S0370-2693(97)01023-X [hep-ex/9708019].
- K. Ackerstaff *et al.* [OPAL Collaboration], Phys. Lett. B **412**, 225 (1997) doi:10.1016/S0370-2693(97)01022-8 [hep-ex/9708028].
- G. Abbiendi *et al.* [OPAL Collaboration], Eur. Phys. J. C 18, 15 (2000) doi:10.1007/s100520000523 [hep-ex/0007018].
- R. Barate *et al.* [ALEPH Collaboration], Phys. Lett. B **458**, 152 (1999). doi:10.1016/S0370-2693(99)00559-6
- A. Heister et~al.~ [ALEPH Collaboration], Eur. Phys. J. C ${\bf 30},\,145~(2003).~$ doi:10.1140/epjc/s2003-01291-4
- P. Abreu et al. [DELPHI Collaboration], Z. Phys. C 69, 223 (1996). doi:10.1007/s002880050022
- T. Sasaki et al. [AMY Collaboration], Phys. Lett. B 252, 491 (1990). doi:10.1016/0370-2693(90)90577-S
- S. K. Sahu et al. [AMY Collaboration], Phys. Lett. B $\bf 346$, 208 (1995). doi:10.1016/0370-2693(95)00092-Y
- T. Kojima et al. [AMY Collaboration], Phys. Lett. B $\bf 400$, 395 (1997). doi:10.1016/S0370-2693(97)00349-3
- K. Muramatsu et al. [TOPAZ Collaboration], Phys. Lett. B $\bf 332$, 477 (1994). doi:10.1016/0370-2693(94)91284-X
- H. J. Behrend *et al.* [CELLO Collaboration], Phys. Lett. $\bf 126B$, 391 (1983). doi:10.1016/0370-2693(83)90187-9
- M. Althoff et al. [TASSO Collaboration], Z. Phys. C 31, 527 (1986). doi:10.1007/BF01551073
- W. Bartel *et al.* [JADE Collaboration], Phys. Lett. **121B**, 203 (1983). doi:10.1016/0370-2693(83)90915-2
- H. Aihara et al. [TPC/Two Gamma Collaboration], Z. Phys. C 34, 1 (1987). doi:10.1007/BF01561108
- H. Aihara *et al.* [TPC/Two Gamma Collaboration], Phys. Rev. Lett. **58**, 97 (1987). doi:10.1103/PhysRevLett.58.97

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References

- [1] M. Czakon, M. L. Mangano, A. Mitov and J. Rojo, Constraints on the gluon PDF from top quark pair production at hadron colliders, JHEP 07 (2013) 167, [1303.7215].
- M. Guzzi, K. Lipka and S.-O. Moch, Top-quark pair production at hadron colliders: differential cross section and phenomenological applications with DiffTop, JHEP 1501 (2015) 082, [1406.0386].
- [3] V. del Duca and E. Laenen, Top physics at the LHC, Int. J. Mod. Phys. A30 (2015) 1530063, [1510.06690].
- [4] M. Czakon, N. P. Hartland, A. Mitov, E. R. Nocera and J. Rojo, Pinning down the large-x gluon with NNLO top-quark pair differential distributions, JHEP 04 (2017) 044, [1611.08609].
- [5] CDF Collaboration, T. Aaltonen et al., Final combination of the CDF results on top-quark mass, CDF note 11080 (2014).
- [6] D0 collaboration, D0 Collaboration, V.M. Abazov et al., Combination of D0 measurements of the top quark mass, Phys. Rev. D 95 (2017) 112004, [1703.06994].
- [7] ATLAS Collaboration, "Measurement of the top quark mass in the $t\bar{t} \to \text{lepton+jets}$ channel from $\sqrt{s} = 8$ TeV ATLAS data." ATLAS-CONF-2017-071, 2017.
- [8] CMS collaboration, V. Khachatryan et al., Measurement of the top quark mass using proton-proton data at $\sqrt{(s)} = 7$ and 8 TeV, Phys. Rev. **D93** (2016) 072004, [1509.04044].
- [9] ATLAS collaboration, M. Aaboud et al., Measurement of the top quark mass in the $t\bar{t} \rightarrow dilepton\ channel\ from\ \sqrt{s} = 8\ TeV\ ATLAS\ data,\ Phys.\ Lett.\ B761\ (2016)\ 350-371,$ [1606.02179].
- [10] S. Frixione and A. Mitov, Determination of the top quark mass from leptonic observables, JHEP 09 (2014) 012, [1407.2763].
- [11] M. Beneke, P. Marquard, P. Nason and M. Steinhauser, On the ultimate uncertainty of the top quark pole mass, Phys. Lett. B775 (2017) 63–70, [1605.03609].
- [12] M. Butenschoen, B. Dehnadi, A. H. Hoang, V. Mateu, M. Preisser and I. W. Stewart, Top Quark Mass Calibration for Monte Carlo Event Generators, Phys. Rev. Lett. 117 (2016) 232001, [1608.01318].
- [13] S. Kawabata and H. Yokoya, Top-quark mass from the diphoton mass spectrum, Eur. Phys. J. C77 (2017) 323, [1607.00990].
- [14] A. H. Hoang, A. Jain, C. Lepenik, V. Mateu, M. Preisser, I. Scimemi et al., The MSR Mass and the $\mathcal{O}(\Lambda_{\rm QCD})$ Renormalon Sum Rule, 1704.01580.
- [15] A. H. Hoang, C. Lepenik and M. Preisser, On the Light Massive Flavor Dependence of the Large Order Asymptotic Behavior and the Ambiguity of the Pole Mass, JHEP 09 (2017) 099, [1706.08526].
- [16] A. H. Hoang, S. Mantry, A. Pathak and I. W. Stewart, Extracting a Short Distance Top Mass with Light Grooming, 1708.02586.
- [17] G. Bevilacqua, H. B. Hartanto, M. Kraus, M. Schulze and M. Worek, Top quark mass studies with $t\bar{t}j$ at the LHC, 1710.07515.

- [18] G. Corcella, R. Franceschini and D. Kim, Fragmentation Uncertainties in Hadronic Observables for Top-quark Mass Measurements, 1712.05801.
- [19] S. Ferrario Ravasio, T. Jezo, P. Nason and C. Oleari, A Theoretical Study of Top-Mass Measurements at the LHC Using NLO+PS Generators of Increasing Accuracy, 1801.03944.
- [20] M. Czakon, D. Heymes and A. Mitov, *High-precision differential predictions for top-quark pairs at the LHC*, *Phys. Rev. Lett.* **116** (2016) 082003, [1511.00549].
- [21] M. Czakon, D. Heymes and A. Mitov, Dynamical scales for multi-TeV top-pair production at the LHC, JHEP 04 (2017) 071, [1606.03350].
- [22] M. Czakon, D. Heymes and A. Mitov, fastNLO tables for NNLO top-quark pair differential distributions, 1704.08551.
- [23] M. Czakon, D. Heymes, A. Mitov, D. Pagani, I. Tsinikos and M. Zaro, Top-pair production at the LHC through NNLO QCD and NLO EW, JHEP 10 (2017) 186, [1705.04105].
- [24] W. Hollik and D. Pagani, The electroweak contribution to the top quark forward-backward asymmetry at the Tevatron, Phys. Rev. D84 (2011) 093003, [1107.2606].
- [25] J. H. Kühn, A. Scharf and P. Uwer, Weak Interactions in Top-Quark Pair Production at Hadron Colliders: An Update, Phys. Rev. **D91** (2015) 014020, [1305.5773].
- [26] D. Pagani, I. Tsinikos and M. Zaro, The impact of the photon PDF and electroweak corrections on $t\bar{t}$ distributions, Eur. Phys. J. C76 (2016) 479, [1606.01915].
- [27] A. Denner and M. Pellen, NLO electroweak corrections to off-shell top-antitop production with leptonic decays at the LHC, JHEP 08 (2016) 155, [1607.05571].
- [28] C. Gütschow, J. M. Lindert and M. Schönherr, Multi-jet merged top-pair production including electroweak corrections, 1803.00950.
- [29] W. Bernreuther, A. Brandenburg, Z. G. Si and P. Uwer, Top quark pair production and decay at hadron colliders, Nucl. Phys. B690 (2004) 81–137, [hep-ph/0403035].
- [30] K. Melnikov and M. Schulze, NLO QCD corrections to top quark pair production and decay at hadron colliders, JHEP 0908 (2009) 049, [0907.3090].
- [31] J. M. Campbell and R. K. Ellis, Top-quark processes at NLO in production and decay, J. Phys. G42 (2015) 015005, [1204.1513].
- [32] M. Brucherseifer, F. Caola and K. Melnikov, $\mathcal{O}(\alpha_s^2)$ corrections to fully-differential top quark decays, JHEP **04** (2013) 059, [1301.7133].
- [33] J. Gao and A. S. Papanastasiou, Top-quark pair-production and decay at high precision, Phys. Rev. D96 (2017) 051501, [1705.08903].
- [34] M. Beneke, P. Falgari, S. Klein and C. Schwinn, *Hadronic top-quark pair production with NNLL threshold resummation*, *Nucl. Phys.* **B855** (2012) 695–741, [1109.1536].
- [35] M. Cacciari, M. Czakon, M. Mangano, A. Mitov and P. Nason, Top-pair production at hadron colliders with next-to-next-to-leading logarithmic soft-gluon resummation, Phys. Lett. B710 (2012) 612–622, [1111.5869].
- [36] A. Ferroglia, S. Marzani, B. D. Pecjak and L. L. Yang, Boosted top production: factorization and resummation for single-particle inclusive distributions, JHEP 01 (2014) 028, [1310.3836].

- [37] A. Broggio, A. S. Papanastasiou and A. Signer, Renormalization-group improved fully differential cross sections for top pair production, JHEP 10 (2014) 98, [1407.2532].
- [38] N. Kidonakis, High-order threshold corrections for top-pair and single-top production, in Proceedings, Meeting of the APS Division of Particles and Fields (DPF 2015): Ann Arbor, Michigan, USA, 4-8 Aug 2015, 2015. 1509.07848.
- [39] B. D. Pecjak, D. J. Scott, X. Wang and L. L. Yang, Resummed differential cross sections for top-quark pairs at the LHC, Phys. Rev. Lett. 116 (2016) 202001, [1601.07020].
- [40] A. Denner, S. Dittmaier, S. Kallweit and S. Pozzorini, NLO QCD corrections to WWbb production at hadron colliders, Phys. Rev. Lett. 106 (2011) 052001, [1012.3975].
- [41] A. Denner, S. Dittmaier, S. Kallweit and S. Pozzorini, NLO QCD corrections to off-shell top-antitop production with leptonic decays at hadron colliders, JHEP 10 (2012) 110, [1207.5018].
- [42] G. Bevilacqua, M. Czakon, A. van Hameren, C. G. Papadopoulos and M. Worek, Complete off-shell effects in top quark pair hadroproduction with leptonic decay at next-to-leading order, JHEP 02 (2011) 083, [1012.4230].
- [43] G. Heinrich, A. Maier, R. Nisius, J. Schlenk and J. Winter, NLO QCD corrections to W⁺W⁻b\(\bar{b}\) production with leptonic decays in the light of top quark mass and asymmetry measurements, JHEP 1406 (2014) 158, [1312.6659].
- [44] A. Denner and M. Pellen, Off-shell production of top-antitop pairs in the lepton+jets channel at NLO QCD, JHEP **02** (2018) 013, [1711.10359].
- [45] R. Frederix, Top Quark Induced Backgrounds to Higgs Production in the WW^(*) → llνν Decay Channel at Next-to-Leading-Order in QCD, Phys. Rev. Lett. 112 (2014) 082002, [1311.4893].
- [46] F. Cascioli, S. Kallweit, P. Maierhöfer and S. Pozzorini, A unified NLO description of top-pair and associated Wt production, Eur. Phys. J. C74 (2014) 2783, [1312.0546].
- [47] J. M. Campbell, R. K. Ellis, P. Nason and E. Re, Top-pair production and decay at NLO matched with parton showers, JHEP **04** (2015) 114, [1412.1828].
- [48] S. Frixione, P. Nason and C. Oleari, Matching NLO QCD computations with Parton Shower simulations: the POWHEG method, JHEP 11 (2007) 070, [0709.2092].
- [49] S. Alioli, P. Nason, C. Oleari and E. Re, A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX, JHEP 06 (2010) 043, [1002.2581].
- [50] S. Höche, F. Krauss, P. Maierhöfer, S. Pozzorini, M. Schönherr and F. Siegert, Next-to-leading order QCD predictions for top-quark pair production with up to two jets merged with a parton shower, Phys. Lett. B748 (2015) 74-78, [1402.6293].
- [51] S. Höche, P. Maierhöfer, N. Moretti, S. Pozzorini and F. Siegert, Next-to-leading order QCD predictions for top-quark pair production with up to three jets, Eur. Phys. J. C77 (2017) 145, [1607.06934].
- [52] J. Bellm, K. Cormier, S. Gieseke, S. Pltzer, C. Reuschle, P. Richardson et al., Top Quark Production and Decay in Herwig 7.1, 1711.11570.
- [53] M. V. Garzelli, A. Kardos and Z. Trocsanyi, Hadroproduction of $W^+W^-b\bar{b}$ at NLO accuracy matched with shower Monte Carlo programs, JHEP **08** (2014) 069, [1405.5859].

- [54] T. Jezo and P. Nason, On the Treatment of Resonances in Next-to-Leading Order Calculations Matched to a Parton Shower, JHEP 12 (2015) 065, [1509.09071].
- [55] F. Cascioli, P. Maierhöfer and S. Pozzorini, Scattering Amplitudes with Open Loops, Phys. Rev. Lett. 108 (2012) 111601, [1111.5206].
- [56] T. Jezo, J. M. Lindert, P. Nason, C. Oleari and S. Pozzorini, An NLO+PS generator for t\(\bar{t}\) and Wt production and decay including non-resonant and interference effects, Eur. Phys. J. C76 (2016) 691, [1607.04538].
- [57] L. Buonocore, P. Nason and F. Tramontano, Heavy quark radiation in NLO+PS POWHEG generators, Eur. Phys. J. C78 (2018) 151, [1711.06281].
- [58] R. Frederix, S. Frixione, A. S. Papanastasiou, S. Prestel and P. Torrielli, *Off-shell single-top production at NLO matched to parton showers*, *JHEP* **06** (2016) 027, [1603.01178].
- [59] B. Chokouf Nejad, W. Kilian, J. M. Lindert, S. Pozzorini, J. Reuter and C. Weiss, NLO QCD predictions for off-shell t\u00e4 and t\u00e4H production and decay at a linear collider, JHEP 12 (2016) 075, [1609.03390].
- [60] ATLAS collaboration, G. Aad et al., Measurement of the top quark mass in the $t\bar{t} \to lepton+jets$ and $t\bar{t} \to dilepton$ channels using $\sqrt{s} = 7$ TeV ATLAS data, Eur. Phys. J. C75 (2015) 330, [1503.05427].
- [61] T. Gleisberg, S. Höche, F. Krauss, M. Schönherr, S. Schumann, F. Siegert et al., Event generation with SHERPA 1.1, JHEP 02 (2009) 007, [0811.4622].
- [62] G. Cullen, N. Greiner, G. Heinrich, G. Luisoni, P. Mastrolia, G. Ossola et al., Automated One-Loop Calculations with GoSam, Eur. Phys. J. C72 (2012) 1889, [1111.2034].
- [63] G. Cullen et al., GOSAM-2.0: a tool for automated one-loop calculations within the Standard Model and beyond, Eur. Phys. J. C74 (2014) 3001, [1404.7096].
- [64] T. Binoth et al., A Proposal for a standard interface between Monte Carlo tools and one-loop programs, Comput. Phys. Commun. 181 (2010) 1612–1622, [1001.1307].
- [65] S. Alioli et al., Update of the Binoth Les Houches Accord for a standard interface between Monte Carlo tools and one-loop programs, Comput. Phys. Commun. 185 (2014) 560-571, [1308.3462].
- [66] A. Denner and S. Dittmaier, The Complex-mass scheme for perturbative calculations with unstable particles, Nucl. Phys. Proc. Suppl. 160 (2006) 22–26, [hep-ph/0605312].
- [67] S. Höche, F. Krauss, M. Schönherr and F. Siegert, A critical appraisal of NLO+PS matching methods, JHEP 09 (2012) 049, [1111.1220].
- [68] S. Höche, J. Huang, G. Luisoni, M. Schönherr and J. Winter, Zero and one jet combined next-to-leading order analysis of the top quark forward-backward asymmetry, Phys. Rev. D88 (2013) 014040, [1306.2703].
- [69] S. Höche, S. Kuttimalai, S. Schumann and F. Siegert, Beyond Standard Model calculations with Sherpa, Eur. Phys. J. C75 (2015) 135, [1412.6478].
- [70] K. Hamilton and P. Richardson, A Simulation of QCD radiation in top quark decays, JHEP 02 (2007) 069, [hep-ph/0612236].
- [71] C. G. Lester and D. J. Summers, Measuring masses of semiinvisibly decaying particles pair produced at hadron colliders, Phys. Lett. B463 (1999) 99–103, [hep-ph/9906349].

- [72] A. Barr, C. Lester and P. Stephens, m(T2): The Truth behind the glamour, J. Phys. G29 (2003) 2343–2363, [hep-ph/0304226].
- [73] ATLAS collaboration, Measurement of lepton differential distributions and the top quark mass in $t\bar{t}$ production in pp collisions at $\sqrt{s}=8$ TeV with the ATLAS detector, Tech. Rep. ATLAS-CONF-2017-044, CERN, Geneva, Jul, 2017.
- [74] J. Butterworth et al., PDF4LHC recommendations for LHC Run II, J. Phys. G43 (2016) 023001, [1510.03865].
- [75] S. Dulat, T.-J. Hou, J. Gao, M. Guzzi, J. Huston, P. Nadolsky et al., New parton distribution functions from a global analysis of quantum chromodynamics, Phys. Rev. D93 (2016) 033006, [1506.07443].
- [76] L. A. Harland-Lang, A. D. Martin, P. Motylinski and R. S. Thorne, Parton distributions in the LHC era: MMHT 2014 PDFs, Eur. Phys. J. C75 (2015) 204, [1412.3989].
- [77] NNPDF collaboration, R. D. Ball et al., Parton distributions for the LHC Run II, JHEP 04 (2015) 040, [1410.8849].
- [78] M. Jezabek and J. H. Kühn, Semileptonic Decays of Top Quarks, Phys. Lett. **B207** (1988) 91–96.
- [79] M. Cacciari, G. P. Salam and G. Soyez, The Anti-k(t) jet clustering algorithm, JHEP 04 (2008) 063, [0802.1189].
- [80] M. Cacciari, G. P. Salam and G. Soyez, FastJet User Manual, Eur. Phys. J. C72 (2012) 1896, [1111.6097].
- [81] A. A. Maier, Precision Measurements of the Top Quark Mass in the Dileptonic Top Quark Pair Decay Channel at ATLAS, PhD thesis, Max Planck Institute for Physics, Munich, Germany, https://publications.mppmu.mpg.de/2016/MPP-2016-76/FullText.pdf.