THE TOP QUARK MASS AT THE LHC

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Abstract

I briefly discuss some theoretical aspects of top mass measurements at the LHC. In particular, I illustrate recent theoretical studies performed using next-to-leading order (NLO) calculations interfaced to shower generators (NLO+PS) of increasing accuracy. I consider three generators: one that has NLO accuracy only at the production stage, and implements spin correlations in an approximate way; one that implements NLO corrections also in decay, and includes exact spin correlations in the narrow-width limit; and one that includes NLO corrections in production and decays, also taking care of finite width, non-resonant contributions and interference of radiation in production and decay.

An important goal of the LHC top-physics program is the measurement of its mass. Since the Higgs mass is known with high precision, improvements of both the $W$ and top mass measurements may lead to a refinement of the Electro-Weak precision tests 1, 2. The current precision of the $W$ mass measurement, of about 15 MeV, would match a precision on the top mass of about 2.4 GeV.

There is some tension at present between the value of the top mass obtained indirectly through electro-weak fits 1, 176.7 $\pm$ 2.1 GeV, and the direct determinations, with the value of 173.34 $\pm$ 0.76 GeV from the latest combination 3, and with later measurements yielding values smaller by about 1 GeV 4, 5, 6, 7, $^{1}$.

The value of the top mass is also relevant for the issue of vacuum stability in the Standard Model 10, 11, 12. Direct measurements are now well below the instability region, while the central value extracted from electro-weak fits is near its edge. The only conclusion that one can draw from these results is that no indication of new physics scales below the Plank scale arises from the vacuum

$^{1}$For recent reviews of top-mass measurements by the ATLAS and CMS collaborations see Refs. 8 and 9 from these proceedings.
metastability requirement. On the other hand, the very small value of the Higgs quartic coupling near
the Planck scale is an intriguing coincidence, even if at the moment we do not know how to interpret it.

The relatively small errors on top mass measurements quoted by the experimental collaborations has
been challenged in some theoretical works, that claimed that the mass extracted in direct measurements
is not related to a well defined field-theoretical mass parameter. This claim has appeared in different
forms, and with different meanings depending upon the authors. In ref. 13 it is argued in essence
that the difference between the pole mass and the Monte Carlo mass parameter is due to effects of non-
perturbative origin, and to effects of order \( \alpha_s \Gamma_t \). Other publications claim that since the Shower Monte
Carlos used to extract the top mass have only leading order accuracy, they cannot be possibly sensitive
to a well defined field theoretical mass like the \( \overline{\text{MS}} \) or the pole mass, since they start to differ at next-to-
leading order accuracy 14. Yet in other works it is argued that the use of jets should be avoided in top
mass measurements, since those are affected by hadronization errors 15. Several theoretical proposals of
alternative methods to measure the top mass have appeared in the literature, sometimes motivated by the
objections listed above 14, 15, 16, 17, 18, 19. Furthermore, experimental results are often separated
into “direct measurements” and “pole mass measurements”, where the latter are obtained by comparing
experimental measurements with calculations performed at least at the next-to-leading order level, and
no qualification is given to what kind of mass parameter is measured in direct measurements.

It has also been argued that the pole mass is not a viable mass parameter for top mass measurements,
because of the mass renormalon problem 13. Recent studies, however, have shown that the renormalon
ambiguity is safely below the current experimental errors, being equal to 110 MeV according to ref. 20,
and to 250 MeV according to ref. 21 (for a critical discussion of the larger uncertainty obtained there,
see ref. 22).

In ref. 22 I have argued that direct measurement should be considered pole mass measurements.
In short, it is easy to argue that this is the case as far as perturbation theory is concerned, and non-
perturbative effects can be estimated in the usual way using Monte Carlo hadronization models, with
special attention to their aspects that are particularly worrisome in top mass measurements (as for the
case of colour reconnection 23, 24). Furthermore, there are recent implementation of NLO calculations
interfaced to parton shower generators 25, 26 that are particularly relevant for studying whether subtle
perturbative effects can have important consequences in top mass measurements, and are typically
implemented in the (complex) pole mass scheme.

In ref. 27 we have performed a study using recent generators for top production, aimed at estimating theoretical errors in top mass measurements. We have considered three generators of increasing accuracy: the hvq generator 28, that implements NLO corrections only in production, and is widely
used by the experimental collaborations in top-mass analyses; the t\bar{t}dec 25 generator, that also implements
NLO corrections in top decay and exact spin correlations in the narrow width approximation,
and the b\bar{b}q\ell 26 generator, that also implements finite width and non-resonant contributions, including
interference effects of radiation in production and decay.

We have focused our study on a simplified observable, the mass of a “particle level top” defined as
the system made up of the hardest lepton, the hardest neutrino, and the jet containing the hardest B
meson, all with the appropriate flavour to match a top or an anti-top. The peak of this mass distribution,
that we call \( m_{Wj}^{\text{max}} \), is of course strongly correlated with the input top mass, that corresponds to the pole
mass scheme, since this is the scheme adopted in the NLO calculations of the three generators. Our
aim was then to examine the dependence of \( m_{Wj}^{\text{max}} \) on the generator being used (and also on parameters
settings, like the factorization and renormalization scale in each generator) for the same input top mass.
Since a difference in $m_{Wb_j}^{\text{max}}$ would result in a difference in the value of the extracted top mass of nearly the same magnitude and opposite sign when examining the same data set, we are in a position to determine intrinsic errors due to parameter settings, and errors due to the use of the less accurate generators.

The result of the comparison of the three generators interfaced to Pythia8.2 is reported in table 1. Besides reporting the “bare” $m_{Wb_j}^{\text{max}}$ value, we also report the $m_{Wb_j}^{\text{max}}$ value obtained after the application of a Gaussian smearing to the $m_{Wb_j}$ distribution, with a Gaussian width equal to 15 GeV (which is the typical experimental resolution of the reconstructed top mass) in order to mimic detector resolution effects. From the table we see that the shift in the peak position is very small for the bare distribution, while it is of the order of 100 MeV in the smeared case.

The very good agreement among the three generators may seem strange at first sight, since the hvq generator does not implement NLO correction to radiation in top decay, and this radiation may influence the peak position, since it controls how much energy is capture in the jet cone. It is however understandable if we remember that Pythia implements Matrix Element Corrections (MEC) in top decay, and in our case these are equivalent to NLO accuracy. If MEC are switched off we see a variation of $-61$ MeV in the bare $m_{Wb_j}^{\text{max}}$ for the hvq generator, while the variation becomes close to $-1$ GeV for the smeared distribution. This is understood as being due to the fact that the peak position is dominated by events where most radiation in decay is captured by the jet, while when smearing is performed, events that fall on the left side of $m_{Wb_j}^{\text{max}}$, associated to large angle radiation in decay, also contribute.

In ref. 27) several other sources of errors are considered, but none of them is disturbing, leading to the conclusion that the improvement brought by the new generators, and in particular the inclusion of off-shell, non-resonant contribution and the interference of radiation in production and decay, do not displace the peak of the reconstructed mass by more than about 150 MeV.

A very disturbing result is instead found if Herwig7 is used, as can be seen in table 2. In this case the hvq generator differs substantially from $bb4\ell$ and $t\bar{t}dec$ even for the bare $m_{Wb_j}$ distribution, where it exceeds $bb4\ell$ by more than 300 MeV, and even more for the smeared one, where the excess raises to almost 700 MeV. Furthermore, the difference between Pythia8 and Herwig7 for the smeared distribution when using the $bb4\ell$ and $t\bar{t}dec$ generators is larger than 1 GeV. In the hvq case the difference is of the order of 250 MeV and of opposite sign in the bare and smeared case. This signals that the relatively small 250 MeV difference in the smeared case is the accidental consequence of cancellation effects due to the very different description of the reconstructed mass peak in the two Monte Carlos.

In ref. 27) we also examined other observables, namely the peak of the b-jet energy 17) and the set of leptonic observables considered in ref. 18). Also in these cases we found large differences among

|          | PS only               | full               |
|----------|-----------------------|--------------------|
|          | No smearing          | smearing           |
|          | No smearing          | smearing           |
| $bb4\ell$| 172.522 GeV          | 171.403 GeV        |
| $t\bar{t}dec - bb4\ell$| $-18 \pm 2$ MeV   | $+191 \pm 2$ MeV  |
|          | $+21 \pm 6$ MeV      | $+140 \pm 2$ MeV  |
| $hvq - bb4\ell$| $-24 \pm 2$ MeV   | $-89 \pm 2$ MeV  |
|          | $+10 \pm 6$ MeV      | $-147 \pm 2$ MeV  |

Table 1: Differences in the $m_{Wb_j}^{\text{max}}$ for $m_t=172.5$ GeV for $t\bar{t}dec$ and hvq with respect to $bb4\ell$, showered with Pythia8.2, at the NLO+PS level and at the full hadron level. Results obtained after smearing the $m_{Wb_j}$ distribution with a Gaussian function with a 15 GeV width are also shown in order to mimic effects due to experimental uncertainties.
### Table 2: $m_{Wb_j}$ peak position for $m_t=172.5$ GeV obtained with the three different generators, showered with Herwig7.1 (He7.1). The differences with Pythia8.2 (Py8.2) are also shown.

|                  | No smearing | 15 GeV smearing |
|------------------|-------------|-----------------|
|                  | He7.1       | Py8.2 − He7.1   | He7.1       | Py8.2 − He7.1   |
| $bb\ell$         | 172.727 GeV | +66 ± 7 MeV     | 171.626 GeV | +1091 ± 2 MeV  |
| $t\bar{t}dec$    | 172.775 GeV | +39 ± 5 MeV     | 171.678 GeV | +1179 ± 2 MeV  |
| $hvq$            | 173.038 GeV | −235 ± 5 MeV    | 172.319 GeV | +251 ± 2 MeV   |

The Pythia and Herwig results. In the case of the leptonic observables, this finding contrasts with the naive expectation that leptonic observables should be insensitive to shower and hadronization effects.

It is unlikely that the 1 GeV difference found between Pythia and Herwig may translate directly into a corresponding top mass uncertainty in realistic analysis. It is, however, an important issue to be understood, since Pythia and Herwig differ considerably in the shower model (that is a dipole shower in the former, and an angular ordered parton shower in the latter). Assuming that no specific problems are found either in the two Monte Carlos or in their NLO+PS interfaces, and that both models may be tuned to fit fairly observables that are relevant for top mass measurements, we would be forced to consider remaining differences among the two Monte Carlos as sources of theoretical errors to be accounted for.

### References

1. Particle Data Group collaboration, C. Patrignani et al., *Electroweak model and constraints on new physics*, Review of Particle Physics, Chin. Phys. C40 (2016) 100001.

2. Gfitter Group collaboration, M. Baak, J. Cth, J. Haller, A. Hoecker, R. Kogler, K. Mnig et al., *The global electroweak fit at NNLO and prospects for the LHC and ILC*, Eur. Phys. J. C74 (2014) 3046, [1407.3792].

3. ATLAS, CDF, CMS, D0 collaboration, *First combination of Tevatron and LHC measurements of the top-quark mass*, arXiv:1403.4427.

4. ATLAS collaboration, M. Aaboud et al., *Measurement of the top quark mass in the $t\bar{t} \to \ell\ell$ channel from $\sqrt{s}=8$ TeV ATLAS data*, Phys. Lett. B761 (2016) 350–371, [1606.02179].

5. 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].

6. CMS collaboration, *Measurement of the top quark mass with lepton+jets final states in pp collisions at $\sqrt{s}=13$ TeV*, Tech. Rep. CMS-PAS-TOP-17-007, CERN, Geneva, 2017.

7. ATLAS collaboration, *Measurement of the top quark mass in the $t\bar{t} \to \ell\ell$ channel from $\sqrt{s}=8$ TeV ATLAS data*, Tech. Rep. ATLAS-CONF-2017-071, CERN, Geneva, Sep, 2017.

8. B. Pearson, *Top quark mass in ATLAS*, in 10th International Workshop on Top Quark Physics (TOP2017) Braga, Portugal, September 17-22, 2017. 2017. 1711.09763.

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In (27) it is also found that the dependence of $m_{Wb_j}^{\text{max}}$ as a function of the jet radius is different in the two Monte Carlos, and thus it is unlikely that both of them may represent the data fairly.
9. CMS collaboration, A. Castro, Recent Top Quark Mass Measurements from CMS, in 10th International Workshop on Top Quark Physics (TOP2017) Braga, Portugal, September 17-22, 2017, 2017. 1712.01027.

10. G. Degrassi, S. Di Vita, J. Elias-Miro, J. R. Espinosa, G. F. Giudice, G. Isidori et al., Higgs mass and vacuum stability in the Standard Model at NNLO, JHEP 08 (2012) 098, [1205.6497].

11. D. Buttazzo, G. Degrassi, P. P. Giardino, G. F. Giudice, F. Sala, A. Salvio et al., Investigating the near-criticality of the Higgs boson, JHEP 12 (2013) 089, [1307.3536].

12. A. Andreassen, W. Frost and M. D. Schwartz, Scale Invariant Instantons and the Complete Lifetime of the Standard Model, 1707.08124.

13. A. H. Hoang and I. W. Stewart, Top Mass Measurements from Jets and the Tevatron Top-Quark Mass, Nucl. Phys. Proc. Suppl. 185 (2008) 220–226, [0808.0222].

14. S. Alioli, P. Fernandez, J. Fuster, A. Irles, S.-O. Moch, P. Uwer et al., A new observable to measure the top-quark mass at hadron colliders, Eur. Phys. J. C73 (2013) 2438, [1307.6415].

15. S. Kawabata, Y. Shimizu, Y. Sumino and H. Yokoya, Weight function method for precise determination of top quark mass at Large Hadron Collider, Phys. Lett. B741 (2015) 232–238, [1405.2395].

16. A. H. Hoang, S. Mantry, A. Pathak and I. W. Stewart, Extracting a Short Distance Top Mass with Light Grooming, 1708.02586.

17. K. Agashe, R. Franceschini, D. Kim and M. Schulze, Top quark mass determination from the energy peaks of b-jets and B-hadrons at NLO QCD, Eur. Phys. J. C76 (2016) 636, [1603.03445].

18. S. Frixione and A. Mitov, Determination of the top quark mass from leptonic observables, JHEP 09 (2014) 012, [1407.2763].

19. S. Kawabata and H. Yokoya, Top-quark mass from the diphoton mass spectrum, Eur. Phys. J. C77 (2017) 323, [1607.00990].

20. 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].

21. 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].

22. P. Nason, The Top Mass in Hadronic Collisions, 1712.02796.

23. D. Wicke and P. Z. Skands, Non-perturbative QCD Effects and the Top Mass at the Tevatron, Nuovo Cim. B123 (2008) S1, [0807.3248].

24. T. Sjstrand, Colour reconnection and its effects on precise measurements at the LHC, 2013. 1310.8073.

25. 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].
26. T. Ježo, 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].

27. S. F. 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.

28. S. Frixione, P. Nason and G. Ridolfi, *A Positive-weight next-to-leading-order Monte Carlo for heavy flavour hadroproduction*, *JHEP* 09 (2007) 126, [0707.3088].

29. T. Sjstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten et al., *An Introduction to PYTHIA 8.2*, *Comput. Phys. Commun.* 191 (2015) 159–177, [1410.3012].

30. M. Bahr et al., *Herwig++ Physics and Manual*, *Eur. Phys. J.* C58 (2008) 639–707, [0803.0883].

31. J. Bellm et al., *Herwig 7.0/Herwig++ 3.0 release note*, *Eur. Phys. J.* C76 (2016) 196, [1512.01178].