PROCEEDINGS OF SCIENCE

Measurements of the top-quark mass using the ATLAS detector at the LHC

Thomas McLachlan[a,1,*]

[a] *Deutsches Elektronen–Synchrotron (DESY), Hamburg, Germany*

E-mail: thomas.mclachlan@desy.de

The top-quark mass is one of the key fundamental parameters of the Standard Model that must be determined experimentally. Its value has an important effect on many precision measurements and tests of the Standard Model. The Tevatron and LHC experiments have developed an extensive program to determine the top quark mass using a variety of methods. In this contribution, recent top quark mass measurements by the ATLAS experiment are reviewed. These include measurements in two broad categories, the direct measurements, where the mass is determined from a comparison with Monte Carlo templates, and determinations that compare differential cross-section measurements to first-principle calculations.

12th Edition of the Large Hadron Collider Physics Conference (LHCP2024)
3-7 June 2024
Boston, USA

---

[1] For the ATLAS collaboration.

[*] Speaker

https://pos.sissa.it/

PoS(LHCP2024)318

1. Introduction

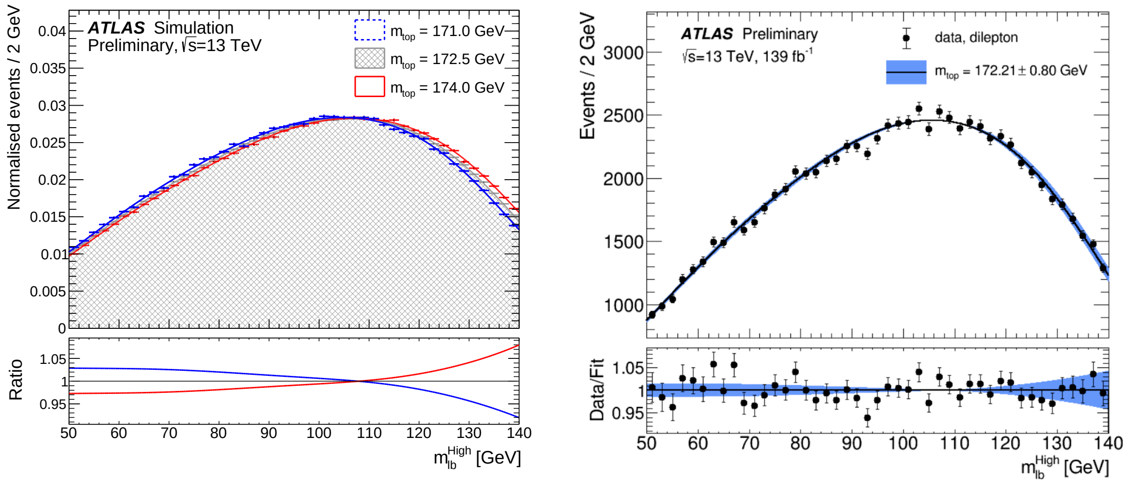
The mass of the top quark, the heaviest known elementary particle, is a fundamental parameter of the Standard Model (SM) of particle physics and must be determined experimentally. Its substantial mass plays a unique role in the SM, significantly influencing radiative corrections to the masses of both the Higgs boson and the W boson. Consequently, precise measurements of the top-quark mass are essential for testing the internal consistency of the SM [1]. Moreover, accurate determination of the top-quark mass is crucial for predicting the behavior of the Higgs quartic coupling at high energy scales, which in turn shapes the Higgs potential. This relationship is linked in the SM to the stability of the quantum vacuum [2].

Measurements of the top-quark mass are generally divided into two types: direct measurements and indirect measurements. The direct approach relies on reconstructing the decay products of the top quark, where m_{top} is extracted by fitting detector-level distributions to templates generated with Monte Carlo simulations. This typically yields the mass $m_{\text{top}}^{\text{MC}}$. Although associating these measurements with a precise renormalisation scheme is challenging, it is commonly assumed that the resulting mass closely approximates the theoretical pole mass [3, 4]. However, the most accurate direct measurements are subject to relatively large uncertainties, primarily due to the calibration of hadronic jet energies [5, 6].

In contrast, indirect measurements are theoretically cleaner to interpret, yet they are often impacted by even greater uncertainties from both experimental and theoretical sources. Recent studies suggest that the value of $m_{\text{top}}^{\text{MC}}$ may differ from $m_{\text{top}}^{\text{pole}}$ by approximately 1 GeV [7, 8, 9]. Indirect measurements, on the other hand, can determine the top-quark mass using either the pole mass scheme or the modified minimal subtraction ($\overline{\text{MS}}$) running mass scheme. This approach involves comparing absolute or differential cross-section measurements to fixed-order theoretical predictions.

2. Direct measurements of the top-quark mass

The most precise single measurement of m_{top} by the ATLAS experiment is performed in $t\bar{t} \rightarrow$ dilepton events using 139 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV [10]. This analysis is optimised to reduce total uncertainty, with a particular focus on minimising signal modelling and jet-related uncertainties. Partial reconstruction of top-quark pair events utilises a deep neural network (DNN) to identify and score the pairings between the charged lepton and b-tagged jet (ℓb-pairing). To enhance the purity of the signal in the event selection, the output score of the best-matched pair must exceed 0.65. Given that there are only two possible pairings, the one with the largest transverse momentum is selected to construct the final observable. The top-quark mass is extracted using an unbinned maximum-likelihood fit to the data, employing top-quark mass templates as shown in fig. 1a. The observable sensitive to m_{top} is the invariant mass of the selected ℓb-pair as described above. The best fit to data is shown in fig. 1b, yielding a result of $m_{\text{top}} = 172.21 \pm 0.20\ (\text{stat}) \pm 0.67\ (\text{syst}) \pm 0.39\ (\text{recoil})$ GeV, where the third uncertainty represents the impact of the recoil scheme choice in the top-quark decay. The precision of this measurement is primarily limited by uncertainties in jet energy calibration and in modelling the matrix-element



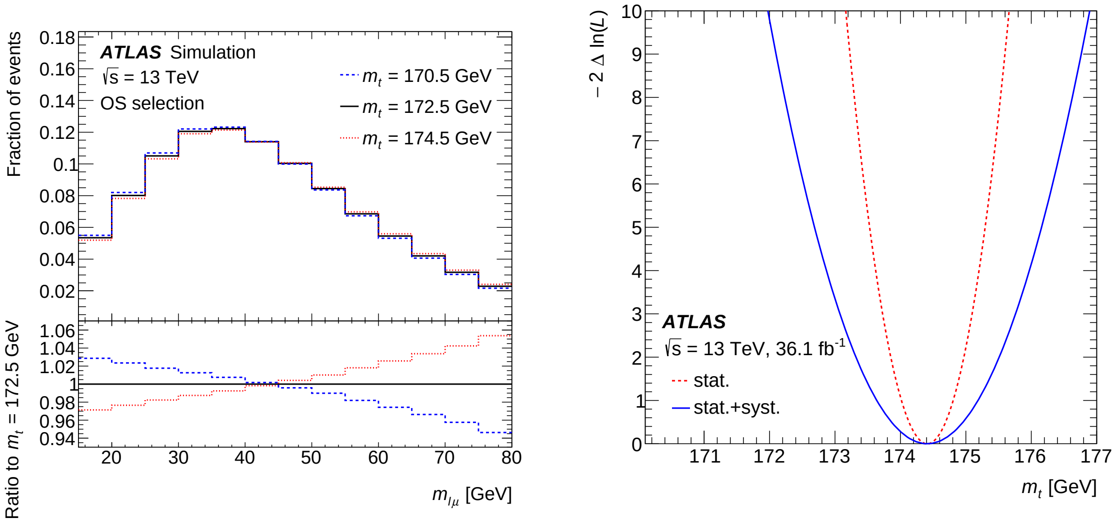
(a) **(b)**

Figure 1: Template fit functions using simulated signal samples for three different m_{top} values and compared to the histograms used in the parameterisation (left). The $m_{\ell b}^{\text{High}}$ distribution in data compared to the predicted distribution (right). Taken from [10].

to parton-shower matching in the $t\bar{t}$ production model. This measurement achieves precision comparable to the previous ATLAS result in the dilepton channel at 8 TeV [11].

The next most recent measurement of m_{top} is from the $t\bar{t} \to$ lepton+jets channel, using a technique exploiting semi-leptonic decays of b-hadrons produced in the top-quark decay chain. The analysis uses data corresponding to an integrated luminosity of 36.1 fb^{-1} of $\sqrt{s}$ = 13 TeV pp collisions and is based on the reconstruction of a purely leptonic invariant mass $m_{\ell\mu}$ [12], where ℓ (either an electron or a muon) originates from W-boson decay, and a relatively soft muon comes from the semileptonic decay of a b-hadron. When the prompt lepton and soft muon originate from the same leg of the $t\bar{t}$ decay process, the $m_{\ell\mu}$ value becomes strongly correlated with the top-quark mass, while having only a small dependence on jet reconstruction and energy calibration. The top-quark mass is then determined from a simultaneous binned profile-likelihood fit of the $m_{\ell\mu}$ distribution in two event categories: opposite sign (OS) and same sign (SS), where the fit distributio is shown for the OS events in fig. 2a. The measured value of the top-quark mass as shown in fig. 2b is m_{top} = 174.41 ± 0.39 (stat.) ± 0.66 (syst.) ± 0.25 (recoil) GeV, where the third uncertainty represents the impact of the choice of recoil scheme in the top-quark decay. The main sources of systematic uncertainty arise from the modelling of top-quark pair production, b-quark fragmentation and decay, with additional significant contributions from background uncertainties. Taking into account the correlations between uncertainties, the result is consistent with the current ATLAS combination of top-quark mass measurements from top-quark decay reconstruction at the level of approximately two standard deviations [13].

A combination of fifteen top-quark mass measurements from the ATLAS and CMS experiments at the LHC has been performed. The data sets used correspond to integrated luminosities of up to 5 and 20 fb^{-1} from pp collisions at $\sqrt{s}$ = 7 and 8 TeV, respectively [14]. The combination includes measurements from top-quark pair events, covering both semileptonic and hadronic top-



(a) **(b)**

Figure 2: Sensitivity of the $m_{\ell\mu}$ distribution to different input top-quark masses from simulated events, separately for the OS samples (left). Likelihood scan, showing the best-fit value and the statistical and total uncertainty profiles (excluding the recoil uncertainty) (right). Taken from [12]

quark decays, as well as a measurement from single top-quark production in the electroweak t-channel. All combinations employ the Best Linear Unbiased Estimate (BLUE) method [15, 16], with the implementation detailed in [17]. This method estimates the combined top-quark mass as $m_{\text{top}} = \sum w^i m^i_{\text{top}}$ for the input measurements m^i_{top}, where the weights w^i minimise the combined uncertainty, using covariance as a key input. The analyses are defined to be orthogonal, ensuring that each measurement is statistically uncorrelated, except for the CMS secondary vertex analysis [18], which overlaps statistically with the dilepton and lepton+jets measurements[6, 19]. The combination accounts for measurement correlations, achieving a 31% improvement in total uncertainty relative to the most precise individual measurement. The result of combining all fifteen measurements is $m_{\text{top}} = 172.52 \pm 0.14\ (\text{stat}) \pm 0.30\ (\text{syst})$ GeV, with a total uncertainty of 0.33 GeV. The largest systematic uncertainties arise from jet energy scale (JES), b-tagging, and $t\bar{t}$ modelling as shown in fig. 3a. As shown in fig. 3b the combination is consistent across measurements, with $\chi^2 = 7.5$ and a p-value of 91%.

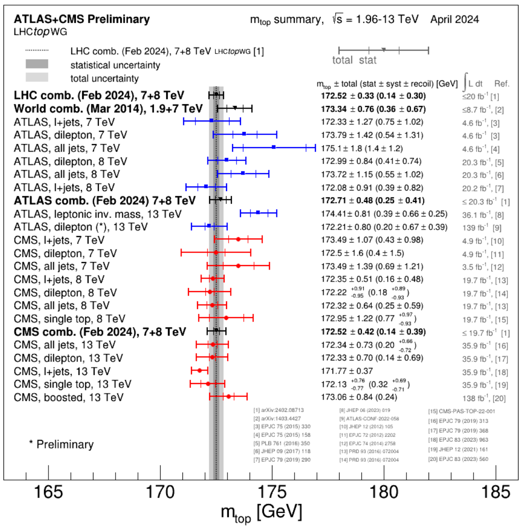
3. Indirect measurements of the top-quark mass

The study presents a determination of the top-quark mass in both the pole mass and $\overline{\text{MS}}$ schemes. This analysis uses data from $\sqrt{s} = 8$ TeV pp collisions, corresponding to an integrated luminosity of 20.2 fb^{-1} [20]. The measurement takes advantage of the sensitivity of the differential cross-section for $t\bar{t}$ production with at least one high-energy jet, which provides greater sensitivity to the top-quark mass compared to observables focused only on the $t\bar{t}$ system [21].

The top-quark mass is extracted using the observable $\mathcal{R}$, defined as the normalised differential

Uncertainty category	Uncertainty impact [GeV]		
	LHC	ATLAS	CMS
b-JES	0.18	0.17	0.25
b tagging	0.09	0.16	0.03
ME generator	0.08	0.13	0.14
JES 1	0.08	0.18	0.06
JES 2	0.08	0.11	0.10
Method	0.07	0.06	0.09
CMS b hadron $\mathcal{B}$	0.07	—	0.12
QCD radiation	0.06	0.07	0.10
Leptons	0.05	0.08	0.07
JER	0.05	0.09	0.02
CMS top quark p_T	0.05	—	0.07
Background (data)	0.05	0.04	0.06
Color reconnection	0.04	0.08	0.03
Underlying event	0.04	0.03	0.05
g-JES	0.03	0.02	0.04
Background (MC)	0.03	0.07	0.01
Other	0.03	0.06	0.01
l-JES	0.03	0.01	0.05
CMS JES 1	0.03	—	0.04
Pileup	0.03	0.07	0.03
JES 3	0.02	0.07	0.01
Hadronization	0.02	0.01	0.01
p_T^{miss}	0.02	0.04	0.01
PDF	0.02	0.06	<0.01
Trigger	0.01	0.01	0.01
Total systematic	0.30	0.41	0.39
Statistical	0.14	0.25	0.14
Total	0.33	0.48	0.42

(a)



(b)

Figure 3: Uncertainties on the m_t values extracted in the LHC, ATLAS, and CMS combinations arising from different categories (left). Comparison of the individual ATLAS and CMS measurements and the result of the combination (right). Taken from [14]

cross-section for $t\bar{t}$ + 1-jet production:

$$\mathcal{R}(m^{\text{pole}_t}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}} \cdot \frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s},$$

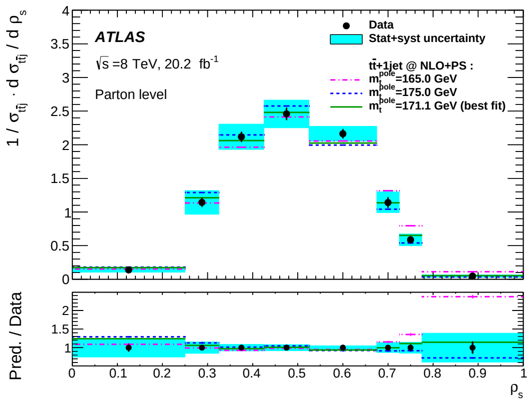
where $\rho_s = \frac{2m_0}{m_{t\bar{t}+1\text{-jet}}}$, with m_0 set to 170 GeV, and $m_{t\bar{t}+1\text{-jet}}$ representing the invariant mass of the $t\bar{t}$ + 1-jet system. After unfolding the data to parton level, both the pole mass and $\overline{\text{MS}}$ mass schemes are determined by fitting the $\mathcal{R}$ distribution with next-to-leading-order (NLO) QCD predictions as shown in fig. 4b.

In the pole-mass scheme, the extracted top-quark mass is $m_t^{\text{pole}} = 171.1 \pm 0.4\,(\text{stat}) \pm 0.9\,(\text{syst})\,^{+0.7}_{-0.3}\,(\text{theo})$ GeV, yielding a total uncertainty of $\Delta m_t^{\text{pole}} = ^{+1.2}_{-1.1}$ GeV. In the $\overline{\text{MS}}$ scheme, the extracted top-quark running mass is $m_t(m_t) = 162.9 \pm 0.5\,(\text{stat}) \pm 1.0\,(\text{syst})\,^{+2.1}_{-1.2}\,(\text{theo})$ GeV. When converting $m_t(m_t)$ to m_t^{pole}, the result is approximately $m_t^{\text{pole}} \approx 170.9$ GeV, which aligns well with the direct extraction of the pole mass. Therefore, the extracted masses m_t^{pole} and $m_t(m_t)$ are in good agreement [1] . The $\overline{\text{MS}}$ mass extraction has a larger theoretical uncertainty than the pole mass, stemming from a greater dependence on renormalisation and factorisation scales within the $\overline{\text{MS}}$ scheme, particularly in the region near the $t\bar{t}$ + 1-jet production threshold as seen in fig. 4a.

---

[1] The conversion of $\overline{\text{MS}}$ to pole-mass scheme uses the NLO QCD relation for top-quark masses in both scheme [22]. This relation is precise up to four loops but is truncated here at two loops to match the precision of the $t\bar{t}$ + 1-jet cross-section used in both extractions. The relation between masses in the two schemes is given by:

$$m_t^{\text{pole}} = m_t(m_t)\left(1 + \frac{4}{3}\frac{\alpha_s(\mu = m_t)}{\pi}\right) + O(\alpha_s^2) \tag{1}$$



(a)

Mass scheme	m_t^{pole} [GeV]	$m_t(m_t)$ [GeV]
Value	**171.1**	**162.9**
Statistical uncertainty	**0.4**	**0.5**
Simulation uncertainties		
Shower and hadronisation	0.4	0.3
Colour reconnection	0.4	0.4
Underlying event	0.3	0.2
Signal Monte Carlo generator	0.2	0.2
Proton PDF	0.2	0.2
Initial- and final-state radiation	0.2	0.2
Monte Carlo statistics	0.2	0.2
Background	<0.1	<0.1
Detector response uncertainties		
Jet energy scale (including *b*-jets)	0.4	0.4
Jet energy resolution	0.2	0.2
Missing transverse momentum	0.1	0.1
b-tagging efficiency and mistag	0.1	0.1
Jet reconstruction efficiency	<0.1	<0.1
Lepton	<0.1	<0.1
Method uncertainties		
Unfolding modelling	0.2	0.2
Fit parameterisation	0.2	0.2
Total experimental systematic	**0.9**	**1.0**
Scale variations	(+0.6, −0.2)	(+2.1, −1.2)
Theory PDF$\oplus\alpha_s$	0.2	0.4
Total theory uncertainty	**(+0.7, −0.3)**	**(+2.1, −1.2)**
Total uncertainty	**(+1.2, −1.1)**	**(+2.3, −1.6)**

(b)

Figure 4: Summary table of the uncertainties in the measurement of the pole mass, m_t^{pole}, and the running $\overline{\text{MS}}$ mass, $m_t(m_t)$ (left). Unfolded normalised differential cross section as a function of ρ_s compared to predictions of the NLO+PS calculation for a top-quark pole mass of 165 GeV, 175 GeV and 171.1 GeV (right). Taken from [20].

4. Summary

The top-quark mass is a fundamental parameter of the Standard Model (SM) and is known with remarkable precision. The most accurate measurement to date comes from the combination of data from the ATLAS and CMS experiments during LHC Run-1, achieving a precision of 0.33 GeV. In my presentation, I outlined several methods for determining the top-quark mass. One approach involves cross-section measurements, which serve as an indirect method for estimating the top-quark pole mass, yielding a precision of approximately $O(1)$. In contrast, direct measurements employing the template method in dilepton final states achieved a precision of 0.80 GeV, representing the best single measurement by ATLAS to date. Additionally, an experimental method utilising soft muons provided a similar precision of 0.81 GeV, while using only a partial dataset. Together, these methods provide consistent and precise measurements of the top-quark mass that are in good agreement with previous results.

References

[1] J. Haller, A. Hoecker, R. Kogler, K. Mönig, T. Peiffer, and J. Stelzer, *Update of the global electroweak fit and constraints on two-Higgs-doublet models*, *Eur. Phys. J. C* **78** (2018) 8.

[2] A. Andreassen, W. Frost, and M. D. Schwartz, *Scale-invariant instantons and the complete lifetime of the standard model*, *Phys. Rev. D* **97** (2018) 056006.

[3] A. H. Hoang, *What Is the Top Quark Mass?*, *Annu. Rev. Nucl. Part. Sci.* **70** (2020) 225–255.

[4] ATLAS Collaboration, *A precise interpretation for the top quark mass parameter in ATLAS Monte Carlo simulation*, *CERN Technical Report ATL-PHYS-PUB-2021-034*, https://cds.cern.ch/record/2777332 (2021).

[5] ATLAS Collaboration *Measurement of the top quark mass in the $t\bar{t} \rightarrow$ lepton + jets channel from $\sqrt{s} = 8$ TeV ATLAS data and combination with previous results*, *Eur. Phys. J. C* **79** (2019) 4.

[6] CMS Collaboration, *Measurement of the top quark mass using proton-proton data at $\sqrt{s} = 7$ and 8 TeV*, *Phys. Rev. D* **93** (2016) 072004.

[7] The ATLAS, CDF, CMS, and D0 Collaborations, *First combination of Tevatron and LHC measurements of the top-quark mass*, *arXiv:1403.4427* [hep-ex] (2014).

[8] 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.

[9] A. H. Hoang, *The Top Mass: Interpretation and Theoretical Uncertainties*, *arXiv:1412.3649* [hep-ph] (2014).

[10] ATLAS Collaboration, *Measurement of the top-quark mass in $t\bar{t} \rightarrow$ dilepton events with the ATLAS experiment using the template method in 13 TeV pp collision data*, *CERN Technical Report* **ATLAS-CONF-2022-058** (2022).

[11] ATLAS Collaboration, *Measurement of the top quark mass in the $t\bar{t} \rightarrow$ dilepton channel from $\sqrt{s} = 8$ TeV ATLAS data*, *Phys. Lett. B* **761** (2016) 350–371.

[12] ATLAS Collaboration, *Measurement of the top-quark mass using a leptonic invariant mass in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, *JHEP* **06** (2023) 019 [`arXiv:2209.00583`].

[13] ATLAS Collaboration, *Measurement of the top quark mass in the $t\bar{t} \rightarrow$ lepton+jets channel from $\sqrt{s} = 8$ TeV ATLAS data and combination with previous results*, *Eur. Phys. J. C* **79** (2019) 290 [`arXiv:1810.01772`].

[14] CMS Collaboration, *Combination of measurements of the top quark mass from data collected by the ATLAS and CMS experiments at $\sqrt{s} = 7$ and* 8 TeV, *CMS-PAS-TOP-22-001* (2023).

[15] L. Lyons, D. Gibaut, and P. Clifford, *How to Combine Correlated Estimates of a Single Physical Quantity*, *Nucl. Instrum. Meth. A* **270** (1988) 110.

[16] R. Nisius, *On the combination of correlated estimates of a physics observable*, *Eur. Phys. J. C* **74** (2014) 3004.

[17] R. Nisius, *BLUE: Combining correlated estimates of physics observables within ROOT using the Best Linear Unbiased Estimate method*, *SoftwareX* **11** (2020) 100468.

[18] CMS Collaboration, *Measurement of the top quark mass using charged particles in pp collisions at $\sqrt{s} = 8$ TeV*, *Phys. Rev. D* **93** (2016) 092006.

[19] CMS Collaboration, *Measurement of the top quark mass in the dileptonic $t\bar{t}$ decay channel using the mass observables $M_{b\ell}$, M_{T2}, and $M_{b\ell\nu}$ in pp collisions at $\sqrt{s} = 8$ TeV*, Phys. Rev. D **96** (2017) 032002.

[20] ATLAS Collaboration, *Measurement of the top-quark mass in $t\bar{t}+1$-jet events collected with the ATLAS detector in pp collisions at $\sqrt{s} = 8$ TeV*, *JHEP* **11** (2019) 150 [`arXiv:1905.02302`].

[21] S. Alioli, P. Fernandez, J. Fuster, A. Irles, S. Moch, P. Uwer, and M. Vos, *A new observable to measure the top-quark mass at hadron colliders*, *Eur. Phys. J. C* **73** (2013) 2438.

[22] P. Marquard, A. V. Smirnov, V. A. Smirnov, and M. Steinhauser, *Quark Mass Relations to Four-Loop Order in Perturbative QCD*, *Phys. Rev. Lett.* **114** (2015) 142002.