PROCEEDINGS OF SCIENCE

α_s determinations from CMS

K. Rabbertz (on behalf of the CMS Collaboration)*
KIT, Karlsruhe, Germany
E-mail: klaus.rabbertz@cern.ch

Significant progress in experimental and theoretical techniques allow a determination of the strong coupling constant α_s from proton-proton collisions with much improved precision. Results of the CMS experiment [1] at the LHC are reviewed, which are based on measurements of jet and of top-quark pair production.

α_s(2019): Workshop on precision measurements of the QCD coupling constant
11-15 February, 2019
Trento, Italy

*Speaker.

https://pos.sissa.it/

PoS(ALPHAS2019)012

In hadron-initiated collisions jets are produced abundantly and offer the opportunity to determine $\alpha_s(m_Z)$, where m_Z is the mass of the Z boson. Moreover, the dependence of $\alpha_s(\mu_R)$ on the renormalisation scale μ_R can be studied up to the TeV range by identifying μ_R with the jet momenta as relevant momentum or energy scale Q of the scattering process.

The CMS Collaboration has compared their measurements of the inclusive jet production cross section at 7 and 8 TeV centre-of-mass energy [2, 3], which reach up to 2.5 TeV of jet transverse momentum, to predictions of perturbative quantum chromodynamics (QCD) at next-to-leading order (NLO) accuracy from NLOJet++ [4]. Including corrections for nonperturbative and electroweak effects, $\alpha_s(m_Z)$ has been determined to lie in the range 0.1164–0.1192 with uncertainties of 1.3 to 3.0% from all sources other than the truncation of the perturbative expansion, cf. Table 1. The latter effect of missing higher orders is conventionally estimated by varying the renormalisation and factorisation scales μ_R and μ_F independently by factors of two avoiding the extreme cases of $\mu_R/\mu_F = 1/4$ and $\mu_R/\mu_F = 4$. At NLO this scale uncertainty amounts to 2–5% and clearly dominates the uncertainty of the extracted values of $\alpha_s(m_Z)$. Since next-to-next-to-leading order (NNLO) calculations for inclusive jet and dijet production have recently become available [5, 6], this uncertainty can be significantly reduced in the future.

The determination of $\alpha_s(m_Z)$ from jet cross sections in hadron-initiated collisions cannot be independent of assumptions on the hadron structure. For proton-proton collisions in particular the parton distribution function (PDF) of the gluon inside protons is correlated with the strong coupling constant. This effect has been considered by CMS through either an additional uncertainty (included in the column “other” in Table 1), or by performing a simultaneous fit of $\alpha_s(m_Z)$ and the proton PDFs using supplementary data on deep-inelastic scattering (DIS) from the H1 and ZEUS experiments. All four results from inclusive jet measurements are consistent among each other and with a simultaneous fit to triple-differential dijet production as reported by CMS in Ref. [7]. The “running” of the strong coupling constant, i.e. its scale dependence $\alpha_s(Q)$ as predicted by perturbative QCD, is found to be consistent with the jet measurements ranging up to 2 TeV.

Requiring additional partons, respectively jets, in the final state leads to 3-jet cross sections, which are sensitive to α_s^3 instead of α_s^2 as for the previous jet cross sections. Here, perturbative QCD is available only up to NLO and electroweak corrections, important at momentum scales in the TeV range, have been calculated only after the corresponding CMS publications on the 3-jet mass cross section [8] and the 3- to 2-jet ratio $R_{3/2}$ at 7 TeV [9] and 8 TeV [10] (preliminary). Compared to the 3-jet cross section the ratio $R_{3/2}$ has the advantage that numerous uncertainties cancel at least partially in the ratio. However, this comes at the price of an additional scale in the process, the p_T of the third jet, and a reduced sensitivity to α_s. The latter can be overcome by looking into multi-jet production ratios.

The results on $\alpha_s(m_Z)$ reported by CMS, cf. Table 1, suffer from somewhat enlarged scale uncertainties at NLO, but are compatible among each other and with the previous extractions, although the ratio $R_{3/2}$ exhibits a slight tendency towards smaller values of $\alpha_s(m_Z)$.

Exploiting the large centre-of-mass energy of 7 or even 13 TeV as compared to the top-quark

Table 1: Summary of $\alpha_s(m_Z)$ determinations from CMS. For each process the power in α_s of the leading order (LO), the centre-of-mass energy, the integrated luminosity, the accessed range of scale Q, and the number of fitted data points is given. H' signifies the sum of transverse masses of all final state partons. Theory is employed at NLO accuracy for all jet related observables and the $t\bar{t}$ differential distributions. In case of the $t\bar{t}$ production cross section theory is used at NNLO+NNLL precision at 7 TeV and at NNLO precision at 13 TeV centre-of-mass energy. The last two columns compare the scale uncertainty to the quadratic sum of all other uncertainties affecting the α_s determinations .

Observable	PDF fit?	LO α_s^n	$\sqrt{s}$ [TeV]	L_{int} [fb^{-1}]	Q [GeV]	N_p	$\alpha_s(m_Z)$	$\delta\alpha_s(m_Z)\cdot 1000$ other	scale	Ref.
incl. jets	–	2	7	5.0	114–2116	133	0.1185	35	$^{+53}_{-24}$	[2]
	✓						0.1192	$^{+23}_{-19}$	$^{+24}_{-39}$	
incl. jets	–	2	8	19.7	74–2500	185	0.1164	$^{+29}_{-33}$	$^{+53}_{-28}$	[3]
	✓						0.1185	$^{+19}_{-26}$	$^{+22}_{-18}$	
Dijet $p_{T,avg}$	✓	2	8	19.7	133-1784	122	0.1199	$^{+15}_{-16}$	$^{+31}_{-19}$	[7]
3-jet mass	–	3	7	5.0	332–1635	46	0.1171	28	$^{+69}_{-40}$	[8]
$R_{3/2}$	–	1	7	5.0	420–1390	21	0.1148	23	50	[9]
$R_{3/2}$	–	1	8	19.7	300–1680	29	0.1150	22	+50	[10]
$\sigma(t\bar{t})$	–	2	7	2.3	m_t	1	0.1151	$^{+27}_{-26}$	$^{+9}_{-8}$	[12]
$\sigma(t\bar{t})$	–	2	13	35.9	m_t	1	0.1139	23	$^{+14}_{-1}$	[13]
$N_{jet}^{0,1+}, M(t\bar{t}), y(t\bar{t})$	–	2–3	13	35.9	$H'/2$	24	0.1144	25	$^{+16}_{-20}$	[14]
	✓						0.1135	$^{+18}_{-17}$	$^{+11}_{-5}$	

mass m_t of around 172 GeV, the top-quark pair production has become a very good candidate for precision studies of QCD processes. Moreover, CMS could extract a value of $\alpha_s(m_Z)$ for the first time at NNLO from hadron-hadron collisions using the theory prediction from Ref. [11]. This first result [12] as well as a new one at 13 TeV [13] with many more data are reported in rows nine and ten of Table 1. The most obvious difference to the previous results with jets is a much reduced scale uncertainty at NNLO. Also, the general tendency of smaller $\alpha_s(m_Z)$ values at NNLO than at NLO is respected here.

One complication of the $\sigma(t\bar{t})$ observable is posed by its dependency on the top-quark mass m_t. Since there is only one measurement point, one can either assume m_t (and a PDF set) and extract $\alpha_s(m_Z)$ or do it the other way round. Both has been performed by CMS as reported in the quoted publications.

A strategy to remedy the m_t dependence in $t\bar{t}$ production consists in the exploitation of many data points of a multi-differential cross section. Concretely, CMS studied in total 24 data points of the normalised $t\bar{t}$ cross section as a function of the mass $M(t\bar{t})$ and rapidity $y(t\bar{t})$ of the top-quark pair, and of the additional jet multiplicity N_{jet} [14]. From these three quantities it could be shown that $M(t\bar{t})$ and $y(t\bar{t})$ are particularly sensitive to PDFs, $M(t\bar{t})$ to m_t, and N_{jet} to $\alpha_s(m_Z)$. As a consequence, $\alpha_s(m_Z)$ and m_t can be determined simultaneously, even together with PDFs provided the H1 and ZEUS DIS data are added to the fit as before with jet measurements. Unfortunately though, the theory for the multi-differential distributions was available only at NLO. The values for $\alpha_s(m_Z)$ with and without PDF fit are given in the last two rows of Table 1. The preliminary results [14] reported here have in the meantime been finalised and submitted to a journal [15].

To summarise, CMS has determined the strong coupling constant $\alpha_s(m_Z)$ at NLO from jet cross sections and for the first time at NNLO from $t\bar{t}$ production cross sections with a significantly reduced scale uncertainty as compared to around 3–5% at NLO. Including further experimental uncertainties of 1–2%, PDF uncertainties around 1–2% as well as nonperturbative effects, the extracted values of $\alpha_s(m_Z)$ are compatible among each other and with the last update of the world average as reported in Ref. [16], although small tensions are visible. Figure 1 presents an overview of the CMS results. The advent of theory predictions at NNLO and corresponding tools for fast fits promises a multitude of new results in the near future to be included in the $\alpha_s(m_Z)$ combination of the review of particle physics.

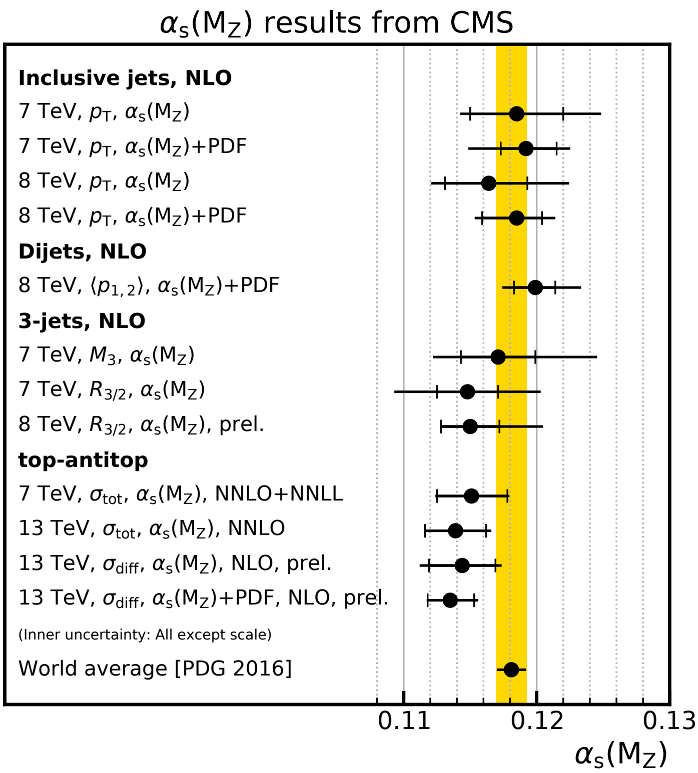

Figure 1: Summary of $\alpha_s(m_Z)$ determinations from CMS. The data points show the values of $\alpha_s(m_Z)$ for the various determinations as listed in Table 1 together with all uncertainties except the scale dependence (inner error bars) and the total uncertainty.

References

[1] S. Chatrchyan *et al.* [CMS Collab.], JINST 3 (2008) S08004.

[2] V. Khachatryan *et al.* [CMS Collab.], Eur. Phys. J. C **75** (2015) 288.

[3] V. Khachatryan *et al.* [CMS Collab.], JHEP **03** (2017) 156.

[4] Z Nagy, Phys. Rev. Lett. **88** (2002) 122003; Phys. Rev. D **68** (2003) 094002.

[5] J. Currie *et al.*, Phys. Rev. Lett. **118** (2017) 072002.

[6] J. Currie *et al.*, Phys. Rev. Lett. **119** (2017) 152001.

[7] A. M. Sirunyan *et al.* [CMS Collab.], Eur. Phys. J. C **77** (2017) 746.

[8] V. Khachatryan *et al.* [CMS Collab.], Eur. Phys. J. C **75** (2015) 186.

[9] S. Chatrchyan *et al.* [CMS Collab.], Eur. Phys. J. C **73** (2013) 2604.

[10] CMS Collaboration, CMS-PAS-SMP-16-008, https://cds.cern.ch/record/2253091.

[11] M. Czakon *et al.*, Phys. Rev. Lett. **110** (2013) 252004.

[12] S. Chatrchyan *et al.* [CMS Collab.], Phys. Lett. B **728** (2014) 496; Erratum *ibid.* **738** (2014) 526.

[13] A. M. Sirunyan *et al.* [CMS Collab.], Eur. Phys. J. C **79** (2019) 368.

[14] CMS Collaboration, CMS-PAS-TOP-18-004, https://cds.cern.ch/record/2647989.

[15] A. M. Sirunyan *et al.* [CMS Collab.], arXiv:1904.05237, submitted to: Eur. Phys. J. C.

[16] C. Patrignani *et al.* [PDG Collab.], Chin. Phys. C **40** (2016) 100001.