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Determination of the strong coupling and its running from measurements of inclusive jet production

The CMS Collaboration*

Abstract

The value of the strong coupling α_S is determined in a comprehensive analysis at next-to-next-to-leading order accuracy in quantum chromodynamics. The analysis uses double-differential cross section measurements from the CMS Collaboration at the CERN LHC of inclusive jet production in proton-proton collisions at centre-of-mass energies of 2.76, 7, 8, and 13 TeV, combined with inclusive deep-inelastic data from HERA. The value $\alpha_S(m_Z) = 0.1176\,^{+0.0014}_{-0.0016}$ is obtained at the scale of the Z boson mass. By using the measurements in different intervals of jet transverse momentum, the running of α_S is probed for energies between 100 and 1600 GeV.

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*See Appendix B for the list of collaboration members

1 Introduction

Collimated sprays of particles, conventionally called jets, are abundantly produced in high-energy proton-proton (pp) collisions at the CERN LHC. At sufficiently high transverse momenta (p_T), jet production is described by quantum chromodynamics (QCD) using perturbative techniques (pQCD), which have now reached next-to-next-to-leading order (NNLO) accuracy.

Predictions of jet production in hadronic collisions depend on the value of the strong coupling α_S and an accurate understanding of the proton structure, encoded in the parton distribution functions (PDFs). Precise measurements of jet production provide a means to determine the strong coupling constant at the mass of the Z boson, $\alpha_S(m_Z)$, and the PDFs up to high values of x, which is the proton momentum fraction carried by the struck parton.

Inclusive jet production, pp $\rightarrow$ jet + X, refers to events with at least one jet with p_T above a certain threshold in the final state and is a key process to test pQCD calculations up to the highest accessible energy scales.

In pp collisions at the LHC, inclusive jet production has been extensively studied by the CMS [1–6] and ATLAS [7–12] Collaborations at several centre-of-mass energies over a wide kinematic range.

This Letter presents a determination of $\alpha_S(m_Z)$ simultaneously obtained with the PDFs in a comprehensive QCD analysis at NNLO, where the CMS measurements of inclusive jet production in pp collisions at $\sqrt{s} = 2.76$ [1], 7 [2, 3], 8 [4], and 13 TeV [5] are used together with cross section measurements of inclusive deep-inelastic scattering (DIS) at the DESY HERA [13]. The simultaneous extraction of PDFs and $\alpha_S(m_Z)$ mitigates their correlation and avoids a potential bias in the determination of $\alpha_S(m_Z)$ [14]. Furthermore, the running of α_S as a function of the energy scale is demonstrated at NNLO up to 1.6 TeV.

2 The CMS detector

The CMS apparatus [15, 16] is a multipurpose, nearly hermetic detector, designed to trigger on [17–19] and identify electrons, muons, photons, and (charged and neutral) hadrons [20–22]. A particle-flow (PF) algorithm [23] aims to reconstruct all individual particles in an event, combining information provided by the all-silicon inner tracker, the crystal electromagnetic (ECAL) and the brass-scintillator hadron calorimeters (HCAL) that operate inside a 3.8 T superconducting solenoid, with data from the gas-ionization muon detectors embedded in the flux-return yoke outside the solenoid. The reconstructed PF particles are used to build τ leptons, jets, and missing transverse momentum [24–26].

3 Inclusive jet measurements

In this work, four CMS measurements of the double-differential inclusive jet cross section as functions of the individual jet p_T and absolute rapidity $|y|$ are included. These measurements use jets clustered with the anti-k_T [27] algorithm as implemented in the FASTJET [28] program with a distance parameter of $R = 0.7$. For each of the measurements, the corresponding integrated luminosity $\mathcal{L}$, the number of data points N_p, and the ranges in p_T and $|y|$ are listed in Table 1. Although the measurement at $\sqrt{s} = 8$ TeV extended up to 2.5 TeV in p_T, the range from 1784 to 2500 GeV was excluded from the fit in the original analysis [4] due to very large statistical correlations in these bins.

Table 1: The CMS inclusive jet measurements used in this analysis. The columns show the centre-of-mass energy, the integrated luminosity, the number of measured data points, the ranges of individual jet p_{T} and $|y|$, and the reference to the corresponding publication.

$\sqrt{s}$ [TeV]	$\mathcal{L}$ [fb^{-1}]	N_{p}	p_{T} [GeV]	$\|y\|$	Ref.
2.76	0.0054	80	74–592	0.0–3.0	[1]
7	5.0	130	114–2116	0.0–2.5	[2, 3]
8	20	165	74–1784	0.0–3.0	[4]
13	33.5	78	97–3103	0.0–2.0	[5]

The primary source of experimental systematic uncertainty in jet measurements comes from the calibration of the jet energy scale (JES) and the jet energy resolution (JER). These calibrations and their associated uncertainties are determined using test beam data, Monte Carlo (MC) simulations, and measurements of dijet, Z+jet, γ+jet, and multijet production [25, 29]. We estimate the correlations between these uncertainties across p_{T} and $|y|$ intervals within individual measurements and among the measurements at various $\sqrt{s}$, and include them in the QCD analysis. This analysis results in a recommendation for the use of these correlations in future global QCD analyses of CMS inclusive jet measurements.

The JES uncertainties are grouped into eight main categories. A detailed description of the JES calibration and the corresponding uncertainties is given in Refs. [25, 29]. The naming scheme of the uncertainty sources follows from previous publications [1–5] and is identical to the implementation in xFITTER [30, 31]. Additional uncertainties specific to each individual measurement are discussed in the original publications.

- Uncertainties related to the absolute scale are associated with the JES correction within the barrel region, corresponding to pseudorapidities $|\eta| < 1.3$. This correction (*AbsoluteScale*) is obtained from a global fit using Z+jet, γ+jet, and multijet data. It includes a correction for initial-state (ISR) and final-state radiation (FSR) (*AbsoluteMPFBias*). Extrapolations to high p_{T} beyond the reach of the measurements are performed by using MC simulations. Additional uncertainties are introduced to address response variations from different MC event generators (*Fragmentation*) and the single-particle response in the ECAL and HCAL (*SinglePionECAL*, *SinglePionHCAL*).
- Relative JER uncertainties represent the η-dependent uncertainty of the JES from the JER corrections (*RelativeJER*).
- The relative η correction of the JES calibration ensures a uniform detector response across different detector regions. In addition, it includes a log-linear p_{T} dependence. An uncertainty associated with the choice of the p_{T}-dependent shape is included. (*RelativePt*).
- The relative contribution *RelativeFSR* corresponds to an uncertainty in the η-dependent corrections for ISR and FSR.
- The statistical uncertainties in the determination of the relative corrections in various regions of η for multiple uncertainty sources are merged into one uncertainty (*RelativeStat*).
- Differences in the simulated detector response to jets from different quark flavours and gluons result in the *FlavourQCD* uncertainty. It is derived from differences between data and MC simulations when the corresponding corrections are applied to various mixtures of jet flavours. The uncertainty is based on response differences to

jets from uds/c/b quarks and gluons between PYTHIA [32] and HERWIG [33].

- Two time-dependent uncertainties address the JES variation over time during the data-taking periods (*TimePt* and *TimeEta*).
- Uncertainties associated with the corrections for additional pp interactions within the same or nearby bunch crossings (pileup) are included.

The correlation scheme for JES-related uncertainties across the different CMS measurements used in this analysis is described below and illustrated in Appendix A. The uncertainties in pileup, the relative statistical contribution *RelativeStat*, and the time-dependent sources *TimePt* and *TimeEta* are considered uncorrelated across the measurements. For the measurement at $\sqrt{s} = 7\,\text{TeV}$ [2], the correlation scheme for JES-related uncertainties is used as described in Ref. [3]. In particular, the *SinglePionECAL* and *SinglePionHCAL* sources are decorrelated as a function of η. The correlations in the remaining JES uncertainties between different data sets are implemented as follows.

- The *AbsoluteMPFBias* uncertainty is fully correlated between the 2.76, 8, and 13 TeV measurements. In the 7 TeV analysis, a combined source of uncertainty is used by including uncertainties from the *AbsoluteScale*, ISR and FSR, and a statistical component associated with the *AbsoluteScale* correction [3]. This combined source of uncertainty in the 7 TeV analysis is uncorrelated with uncertainties in the other measurements.
- The *AbsoluteScale*, *SinglePionECAL*, *SinglePionHCAL*, and *RelativeJER* uncertainties are fully correlated between the 2.76 and 8 TeV measurements, since the corresponding corrections were obtained using 8 TeV data and applied to both measurements. These uncertainties are uncorrelated with other data sets, for which the corrections were specifically derived.
- The *RelativeFSR* and *Fragmentation* uncertainties are fully correlated between the 2.76, 7, and 8 TeV measurements, but uncorrelated with the 13 TeV measurement, because of the use of different MC tunes and event generators.
- The *RelativePt* uncertainties are uncorrelated across the measurements, since these account for the differences between linear and logarithmic fits in the p_{T} extrapolation of the residual corrections, which vary across data-taking periods.
- The *FlavourQCD* uncertainty is treated as fully correlated between the 7 and 8 TeV measurements because these used identical uncertainties, but uncorrelated with the 2.76 and 13 TeV ones to account for differences in simulation setup, including centre-of-mass energy, pileup, and MC tunes.

The JER uncertainties are treated as uncorrelated across measurements at different energies. Furthermore, within each individual measurement, the JER uncertainties have been decorrelated across $|y|$ for the 2.76, 7, and 8 TeV measurements. This approach is motivated by the unaccounted residual $|y|$ dependence in these data sets. The JER uncertainty is considered correlated among $|y|$ and p_{T} for the 13 TeV measurement [5]. An additional uncorrelated component of 1.5% is assigned to the JER uncertainty in the 2.76 TeV measurement to take into account a statistical contribution to the JER uncertainty.

4 Theoretical predictions

The NNLO pQCD calculations used in this study are performed assuming five active massless quark flavours in the leading-colour (LC) and leading-flavour-number approximation using the NNLOJET program [34]. The subleading colour contributions for the NNLO corrections, neglected in Ref. [34], have been recently calculated [35] and have a very small impact on inclusive jet production with $R = 0.7$. The renormalization, μ_r, and factorization, μ_f, scales in the calculation are set to the individual jet p_T, following the studies of Ref. [36]. The cross section predictions for intervals in p_T and $|y|$ of the respective measurements are stored in the form of interpolation grids in the APPLFAST [37] format, allowing for a fast evaluation of the predictions under variations of α_S, PDFs, or the μ_r and μ_f scales. The numerical uncertainty in the grids is below 1% in most intervals and increases to about 5% in the forward region at high p_T, remaining significantly smaller than the statistical uncertainties in the measurements. However, in the forward region, predictions in a few intervals at the highest values of p_T have numerical grid uncertainties exceeding 10% and are, therefore, excluded from the QCD interpretation. When the interpolation grids for this analysis were produced, the recent improvements in the merging procedure of NNLOJET that aim to reject outliers without biasing the result in multidimensional MC integrations were not available. To account for the remaining point-to-point fluctuations, the numerical uncertainty has been increased by a factor of two. However, its impact on the fit is negligible.

The QCD predictions are modified with a multiplicative correction for contributions of the dominant electroweak (EW) effects. These arise from the virtual exchange of soft or collinear massive weak gauge bosons, calculated at next-to-leading-order precision [38]. The contribution of EW effects becomes important at large jet p_T, reaching 11% at the highest p_T probed in the 13 TeV measurement. Subleading EW effects from the emissions of real weak gauge bosons have been estimated in the 13 TeV measurement to be smaller than 1% at high p_T and are neglected. The EW corrections for the 13 TeV measurement are taken from the original publication [5]. For the 7 and 8 TeV measurements, these corrections have been updated using more recent PDF sets. The EW corrections are omitted for the 2.76 TeV measurement because of their negligible impact for p_T smaller than 600 GeV.

To compare the fixed-order predictions to the measured particle-level cross sections, these are corrected for the nonperturbative (NP) effects from hadronization and the underlying event. These NP corrections have been derived as cross section ratios from event generators with parton showers, in which NP effects are switched on and off. These corrections are applied through p_T- and $|y|$-dependent correction factors as provided in the original publications [1, 3–5] of the individual measurements. In each measurement, the generator tune used is the one providing the best match to the data. The NP corrections have a size between 5 and 20% at low p_T, with their effect decreasing with increasing p_T. The associated uncertainties range from 1 to 4% at low p_T, depending on $|y|$, and are negligible at high p_T. The uncertainties related to NP corrections are treated correlated in ranges of p_T and $|y|$ in each individual measurement and uncorrelated across the measurements. Despite slight differences in the way the NP corrections were obtained for each measurement, the impact of the NP corrections in the $\alpha_S(m_Z)$ and PDF determination is insignificant considering their uncertainties. In particular, the impact of the NP corrections in the QCD analysis was studied by performing individual fits with a subset of measurements with jet $p_T > 150$, 200, and 300 GeV. In this way, the kinematic ranges with decreasing importance of NP corrections are consecutively probed. The difference in the results is negligible. The main result is based on the full p_T spectra probed by the CMS jet data.

5 The QCD analysis

In the QCD analysis, the four CMS measurements of the double-differential cross sections of inclusive jet production are used together with the combined neutral current (NC) and charged current (CC) electron-proton DIS cross sections measured at HERA [13], following the general strategy of Refs. [13, 39].

Theoretical predictions for the DIS cross sections are calculated at fixed order in QCD at NNLO accuracy using the QCDNUM code [40], with μ_r and μ_f set to the squared four-momentum transfer Q^2. The contribution of massive c and b quarks to the DIS cross sections is treated in the Thorne–Roberts general-mass variable-flavour number scheme [41–43]. The masses of c and b quarks are set as $m_c = 1.47 \pm 0.06\,\text{GeV}$ and $m_b = 4.5 \pm 0.25\,\text{GeV}$, respectively. The fraction of the strange quark in the sea $f_s = x\bar{s}/(x\bar{d} + x\bar{s})$ is assumed to be 0.40, as in the HERAPDF2.0 analysis [13] and varied within $0.32 \le f_s \le 0.48$. The low-Q^2 region in DIS, where resummation effects from small-x logarithms become important, is removed from the fit by using only the DIS measurements with $Q^2 > 10\,\text{GeV}^2$. This cutoff is varied by $2.5\,\text{GeV}^2$ up and down. While the central values and the variations of m_c, m_b and f_s are set as in the QCD interpretation [5] of the CMS inclusive jet measurement at $\sqrt{s}$ =13 TeV, the minimum Q^2 cut for HERA data is increased from 7.5 to $10\,\text{GeV}^2$. This adjustment aligns with the original HERA publication [13], which features tensions between low-Q^2 ($< 15\,\text{GeV}^2$) and high-Q^2 ($> 150\,\text{GeV}^2$) data. The published DIS cross sections are already corrected for the dominant EW effects.

The PDFs for the gluon, valence u- and d-quark, and $\bar{u}$ and $\bar{d}$ quark densities are parametrized at a starting (evolution) scale of $Q_0^2 = 1.9\,\text{GeV}^2$, varied by $0.2\,\text{GeV}^2$ [5]. The Q^2 dependence of the PDFs and of α_S is obtained by solving the DGLAP evolution equations at NNLO in pQCD as implemented in QCDNUM. The functional form of the PDFs for each parton i at the starting scale is

$$xq_i(x) = A_i x^{B_i}(1-x)^{C_i} P_i(x), \tag{1}$$

where the A_i are normalization parameters and $P_i(x) = (1 + D_i x + E_i x^2)$ are polynomials that interpolate between the small- and large-x behaviour given by the B_i and C_i parameters. The D_i and E_i terms in the polynomial expansion are only included following the results of an optimization procedure. In such a "parametrization scan", all D_i and E_i parameters are set to zero and then included in the fit, one at a time. The process is monitored through the resulting change in χ^2 and the scan is terminated when no further improvement is observed. The parameters A_{u_v} and A_{d_v} are determined during the fit from the valence-quark number sum rule and the value of A_g is obtained from the momentum sum rule. In the present work, the parametrization scan led to the same parameters as the most recent NNLO QCD analysis [5] of the CMS measurement of inclusive jet production at 13 TeV, using the same assumptions for the PDF parameters. This parametrization includes 15 free parameters for the PDFs. Additional terms in the polynomial expansion proportional to D_i and E_i are added to estimate the parametrization uncertainty as discussed in Section 6.

The fit is performed using the XFITTER [30, 31] program. The values of the PDF parameters and of α_S are obtained in the minimization procedure using MINUIT [44] with a χ^2 goodness-of-fit function that includes experimental uncertainties as nuisance parameters $b_{i,\text{exp}}$. The χ^2 definition is the same as defined in XFITTER [30, 31] and used in most recent analyses [5],

$$\chi^2(\mathbf{T}, \mathbf{b}_{\text{exp}}) = \sum_{i=1}^{N_{\text{data}}} \frac{\left[M_i - T_i(1 - \sum_j \gamma_{ij}^{\text{exp}} b_{j,\text{exp}})\right]^2}{\delta_{i,\text{uncor}}^2 T_i^2 + \delta_{i,\text{stat}}^2 M_i T_i (1 - \sum_j \gamma_{ij}^{\text{exp}} b_{j,\text{exp}})} + \sum_{j=1}^{N_{\text{exp.sys}}} b_{j,\text{exp}}^2. \tag{2}$$

The index i runs over all $N_{\text{data}} = 1469$ data points of the inclusive jet and HERA measurements. Here, M_i and T_i are the measurements and theory predictions, respectively. Further, $\delta_{i,\text{uncor}}$ and $\delta_{i,\text{stat}}$ denote the statistical and uncorrelated systematic uncertainties of the measurement i. The experimental correlated uncertainty sources are included using the set of parameters

$b_{j,\text{exp}}$, with the impact of each source on the theory point T_i described by the matrices γ_{ij}^{exp}. Asymmetric uncertainties in the PDF parameters are obtained from a $\Delta\chi^2 = 1$ criterion using an iterative Hessian approach, following the prescription of Ref. [45]. The uncertainties quoted in the following correspond to 68% confidence level (CL).

6 Results

In Fig. 1, the measurements divided by the NNLO LC QCD predictions are shown, corrected for NP and EW effects. In general, a very good agreement between the theory predictions and the data is observed. The consistency of all the experimental data is quantified by the goodness of the fit χ^2 from Eq. (2). The values of χ^2 per N_p are reported for the individual data sets (partial χ^2/N_p) in Table 2, together with the total χ^2 per number of degrees of freedom N_dof, which is 1680/1453. A somewhat higher partial χ^2/N_p for the HERA DIS data is investigated in detail in the original work [13], where tensions between the measurements at low Q^2 ($<15\,\text{GeV}^2$) and high Q^2 ($>150\,\text{GeV}^2$) were identified. The sum of partial χ^2/N_p for all CMS jet measurements, including their correlation, is 496/453.

Table 2: The values of χ^2 per N_p for each individual data set as obtained in the fit to HERA and CMS jet data, together with the contribution to the χ^2 from correlated uncertainty sources. In the last line, the total χ^2 per number of degrees of freedom, N_dof, is reported.

Data set	Partial χ^2/N_p
HERA I+II neutral current	1036/935
HERA I+II charged current	112/81
CMS jets 2.76 TeV	63/80
CMS jets 7 TeV	81/130
CMS jets 8 TeV	206/165
CMS jets 13 TeV	77/78
Correlated χ^2 HERA	56
Correlated χ^2 Jets	69
Total χ^2/N_dof	1680/1453

In Fig. 2, the impact of the CMS jet data on the PDF determination (*HERA+CMS* fit) is illustrated, considering the Hessian fit uncertainties. The uncertainties in the PDFs resulting from the present QCD analysis are shown in comparison with the results of an alternative fit, which includes only HERA DIS data (*HERA-only* fit). In the HERA-only fit, due to poor sensitivity of the DIS data to $\alpha_\text{S}(m_\text{Z})$, its value is fixed to that of the HERA+CMS fit. The PDFs are shown at the factorization scale $Q^2 = m_\text{t}^2$, where m_t is the top quark mass. This particular scale is chosen for enabling comparisons with previous results [5]. Significant improvement in the uncertainties of all PDFs is observed once CMS jet measurements are included in the analysis. Whereas improvements in the precision of the gluon PDF have been reported in earlier QCD analyses using individual inclusive jet measurements, the inclusion of all available CMS inclusive jet measurements at different $\sqrt{s}$ provides additional constraints on the d_v distribution.

In Fig. 3, the PDFs obtained in the HERA+CMS fit are compared with those obtained by the global fitting groups HERAPDF20 [13], NNPDF40 [46], CT18NNLO [47], and MSHT20 [48]. These global PDFs are based on inclusive HERA DIS data and use some of the CMS jet measurements included in the present work, except for the HERAPDF20 PDF set. In general, the

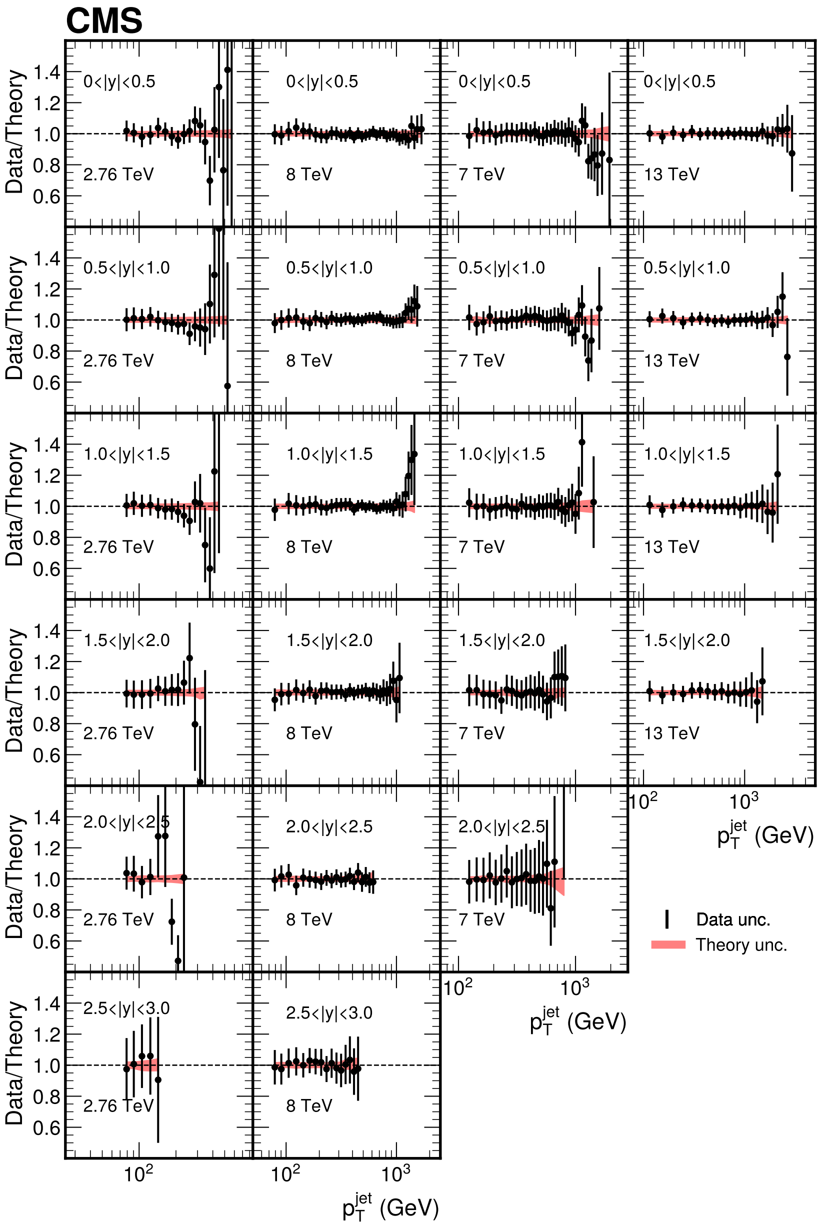

Figure 1: Cross section ratios between data and theory for inclusive jet production in pp collisions as measured by CMS at $\sqrt{s}$ of 2.76, 8, 7, and 13 TeV, using the anti-k_T clustering algorithm with $R = 0.7$, as functions of individual jet p_T in intervals of absolute rapidity $|y|$. Shown is the total uncertainty of every data point (vertical bar). Predictions correspond to the NNLO LC QCD calculations corrected for NP and EW effects. The PDFs obtained in this work are used. The total theory uncertainty (red shaded band) includes the PDF and scale variation uncertainties.

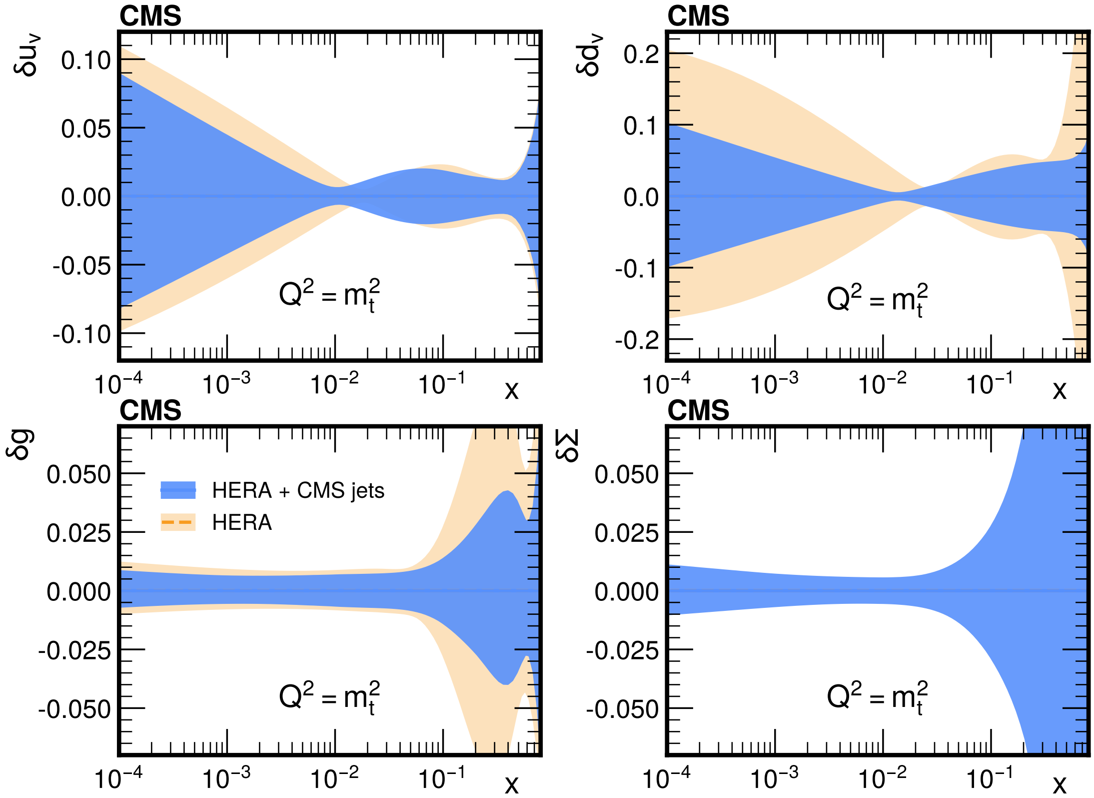

Figure 2: The fit uncertainties in the valence u quark (u_v) (upper left), valence d quark (d_v) (upper right), gluon g (lower left), and sea quark Σ (lower right) distributions, shown as a function of x at the factorization scale $Q^2 = m_t^2$. The results of the HERA+CMS fit (blue shaded area) are compared with the results of the HERA-only fit (orange shaded area). In the HERA-only fit, due to poor sensitivity of the DIS data to $\alpha_S(m_Z)$, its value is fixed to that of the HERA+CMS fit. The uncertainties are given at 68% CL.

PDFs determined in this analysis are in resonable agreement with the global PDF sets, particularly in the x range probed by the CMS jet data. By adding these data, the valence quark PDF, in particular the valence d quark (d_v) distribution, is observed to agree better with the global PDFs NNPDF40 and MSHT20 than HERAPDF20. In the HERA+CMS fit, the value of $\alpha_S(m_Z)$ is determined together with the PDFs, resulting in $\alpha_S(m_Z) = 0.1176 \pm 0.0009$, where the uncertainty denotes the Hessian fit uncertainties.

Additional uncertainties are included in the QCD analysis following the strategy of Ref. [5]. These uncertainties are the model uncertainty, obtained from variations of the fit input parameters, such as m_b, m_c, f_s, the minimum Q^2 for DIS data Q_0^2, the uncertainty originating from missing higher-order corrections, and the parametrization uncertainty, accounting for alternative PDF parametrizations. For each variation, an alternative fit is performed. The contributions to the model uncertainty are added in quadrature, resulting in $\delta\alpha_S(m_Z) = {}^{+0.0006}_{-0.0004}$ (model). The uncertainty from missing higher orders in the calculation of the jet cross sections is evaluated by varying the scales μ_r and μ_f (scale uncertainty) independently by a factor of two up and down, avoiding cases with $\mu_f/\mu_r = 4$ or $1/4$. For each scale choice, an individual fit is performed, and the maximum difference to the central result is included as an uncertainty of $\delta\alpha_S(m_Z) = {}^{+0.0009}_{-0.0012}$ (scale). The parametrization uncertainty is estimated by extending the functional form of the PDFs by additional parameters D and E, added one at a time. An uncertainty $\delta\alpha_S(m_Z) = {}^{+0}_{-0.00004}$ (param.) is obtained from an envelope of the results of the corresponding fits and is added linearly to the aforementioned uncertainties.

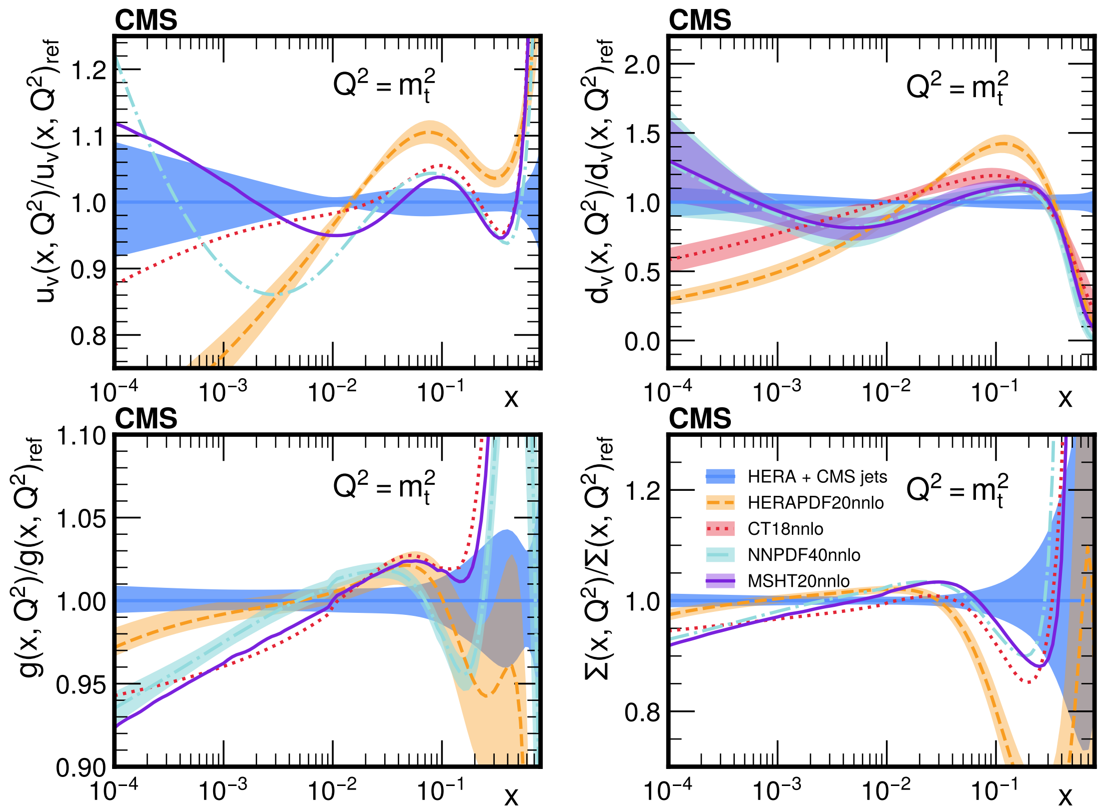

Figure 3: Ratios of different global PDF sets at NNLO, namely HERAPDF20 [13], CT18 [47], NNPDF4 [46], and MSHT20 [48], to the result of the present study. The valence u quark (u_v) (upper left), valence d quark (d_v) (upper right), gluon g (lower left), and sea quark Σ (lower right) distributions are shown as functions of x at the factorization scale $Q^2 = m_t^2$. The Hessian PDF uncertainties at 68% CL are shown, where the width of the band represents the uncertainty in the numerator by keeping the denominator constant.

Summarizing the findings above, the value of $\alpha_S(m_Z)$ is obtained as

$$\alpha_S(m_Z) = 0.1176\,^{+0.0009}_{-0.0009}\,(\text{fit})\,^{+0.0006}_{-0.0004}\,(\text{model})\,^{+0.0009}_{-0.0012}\,(\text{scale})\,^{+0.}_{<(-0.0001)}\,(\text{param.}), \tag{3}$$

corresponding to the total uncertainty of $^{+0.0014}_{-0.0016}$ (tot). This value is in good agreement with the PDG world average of $\alpha_S(m_Z) = 0.1180 \pm 0.0009$ [49] and with previous CMS results obtained at NNLO [5, 50–53], as shown in Fig. 4. The inclusion of data from multiple centre-of-mass energies improves the precision by significantly reducing the fit uncertainty. The dominant contribution to the uncertainty originates from missing higher order corrections.

The value of α_S in five different ranges of $\mu_r = p_T$ is determined, following the previous approach, which illustrates the running of the strong coupling, $\alpha_S(\mu_r)$ at NNLO. For this purpose, the CMS measurements of inclusive jet production are split into exclusive ranges of individual jet p_T. For each p_T range, a simultaneous fit of PDFs and $\alpha_S(m_Z)$ is performed individually. The values of $\alpha_S(m_Z)$ obtained in each individual fit are evolved as $\alpha_S(\mu_r)$ using the five-loop five-flavour renormalization group equation (RGE) encoded in CRUNDEC [54] version 0.5.2. The same RGE is used to obtain the corresponding uncertainties. The fit, model, scale, and parametrization uncertainties are computed as in the case of Eq. (3). In each p_T range, μ_r is calculated at NNLO QCD as a cross section-weighted average $\langle p_T \rangle$. Results are summarised in Table 3 and shown in Fig. 5, where the values of $\alpha_S(\mu_r)$ are compared with the evolution of the world average of $\alpha_S(m_Z)$ performed at five-loop order in QCD using CRUNDEC.

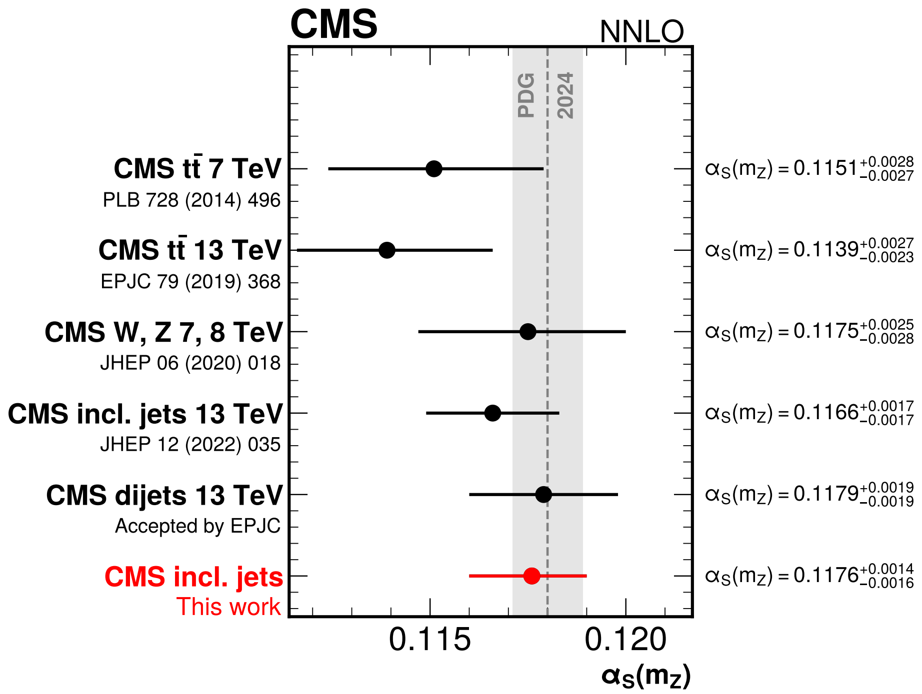

Figure 4: The value of $\alpha_S(m_Z)$ obtained in this analysis (red marker), compared with all CMS results obtained at NNLO by using different methods (black markers) with their total uncertainties (horizontal error bars). The PDG world average (dashed line) together with its uncertainty (shaded band) is also shown.

Table 3: The determined $\alpha_S(m_Z)$ and the corresponding $\alpha_S(Q)$ values for each p_T range with their total uncertainties. For $\alpha_S(Q)$, the individual uncertainty contributions (fit, scale, model, parametrization) are listed. Values reported as 0.0 indicate uncertainties smaller than 0.0001, while "–" indicates that the corresponding upper or lower uncertainty does not exist since it is one-sided.

p_T (GeV)	$\langle Q \rangle$	$\alpha_S(m_Z)$ (tot)	$\alpha_S(Q)$	(fit)	(scale)	(model)	(param.)	(tot)
74–220	103.06	$0.1182^{+0.0014}_{-0.0013}$	0.1160	$^{+0.0011}_{-0.0011}$	$^{+0.0007}_{-0.0005}$	$^{+0.0006}_{-0.0004}$	$^{+0.0}_{-}$	$^{+0.0014}_{-0.0012}$
220–395	266.63	$0.1184^{+0.0011}_{-0.0012}$	0.1019	$^{+0.0007}_{-0.0007}$	$^{+0.0}_{-0.0004}$	$^{+0.0004}_{-0.0003}$	$^{-}_{-0.0}$	$^{+0.0008}_{-0.0009}$
395–638	464.31	$0.1179^{+0.0013}_{-0.0012}$	0.0947	$^{+0.0007}_{-0.0007}$	$^{+0.0003}_{-0.0}$	$^{+0.0004}_{-0.0003}$	$^{-}_{-0.0}$	$^{+0.0009}_{-0.0008}$
638–1410	753.66	$0.1184^{+0.0014}_{-0.0012}$	0.0898	$^{+0.0006}_{-0.0006}$	$^{+0.0003}_{-0.0}$	$^{+0.0004}_{-0.0003}$	$^{+0.0}_{-}$	$^{+0.0008}_{-0.0007}$
1410–3103	1600.5	$0.1170^{+0.0021}_{-0.0016}$	0.0821	$^{+0.0007}_{-0.0007}$	$^{+0.0004}_{-}$	$^{+0.0005}_{-0.0003}$	$^{+0.0}_{-}$	$^{+0.0010}_{-0.0008}$

7 Summary

The value of the strong coupling constant at the scale of the mass of the Z boson, $\alpha_S(m_Z)$, is extracted together with the parton distribution functions (PDFs) of the proton in an analysis at next-to-next-to-leading order (NNLO) accuracy in quantum chromodynamics (QCD). The simultaneous extraction of $\alpha_S(m_Z)$ and PDFs mitigates a possible bias from their correlations. The analysis includes electroweak effects at next-to-leading order and nonperturbative corrections. The CMS measurements of inclusive jet production in proton-proton collisions at $\sqrt{s} = 2.76$, 7, 8, and 13 TeV, using the anti-k_T clustering algorithm with a distance parameter of 0.7, are used together with the inclusive deep inelastic scattering cross sections from HERA. The correlations among the systematic uncertainties of each individual jet cross section measurement, as well as across all centre-of-mass energies, are reevaluated. These correlations should be included in future global QCD analyses of these data. By using the CMS jet data in the fit, the value of $\alpha_S(m_Z) = 0.1176\,^{+0.0014}_{-0.0016}$ is obtained, in good agreement with the world average. It is the most precise result for $\alpha_S(m_Z)$ from jet cross sections to date. At the same time, this analysis demonstrates that improved PDFs can be extracted by using these data. Furthermore, by extracting the value of α_S in different intervals of jet p_T, the running of α_S is tested at NNLO in QCD up to energy scales of 1.6 TeV. The observed running of α_S is in agreement with the prediction of the QCD renormalization group equation.

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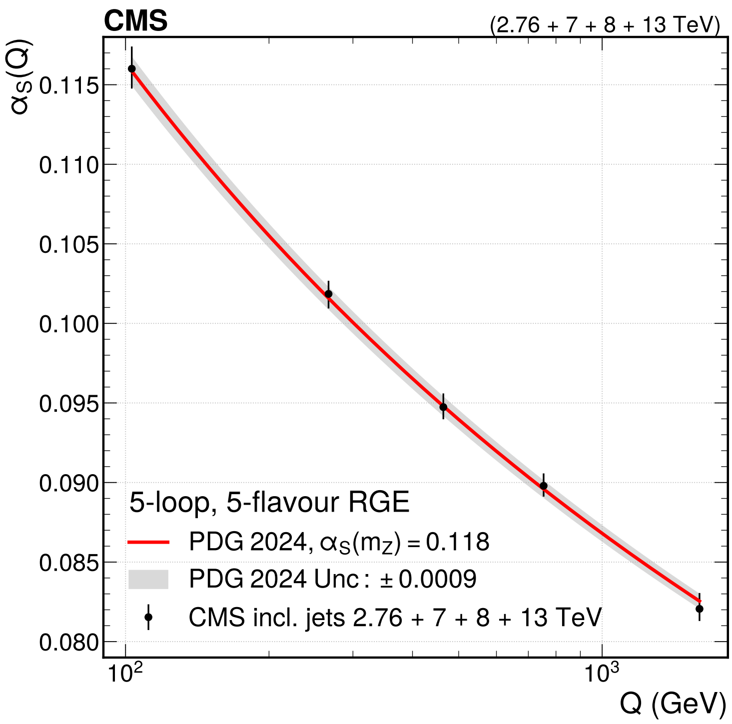

Figure 5: Values of α_S as extracted from different jet transverse momentum ranges in the present QCD analysis at NNLO, each translated to a single scale $\langle Q \rangle$, as indicated in Table 3. The results (black markers) are shown with their total uncertainties (vertical error bars). For comparison, the RGE at 5 loops is shown using the current world-average value $\alpha_S(m_Z) = 0.1180 \pm 0.0009$ [49] (red line) together with its associated total uncertainty (shaded band).

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A JES correlation of inclusive jet measurements

The JES correlation scheme as illustrated in Fig. A.1 has been applied in the QCD analysis of the CMS inclusive jet measurements at $\sqrt{s} = 2.76$, 7, 8, and 13 TeV. A filled black box indicates that the corresponding two measurements are treated as fully correlated for the specific source of uncertainty.

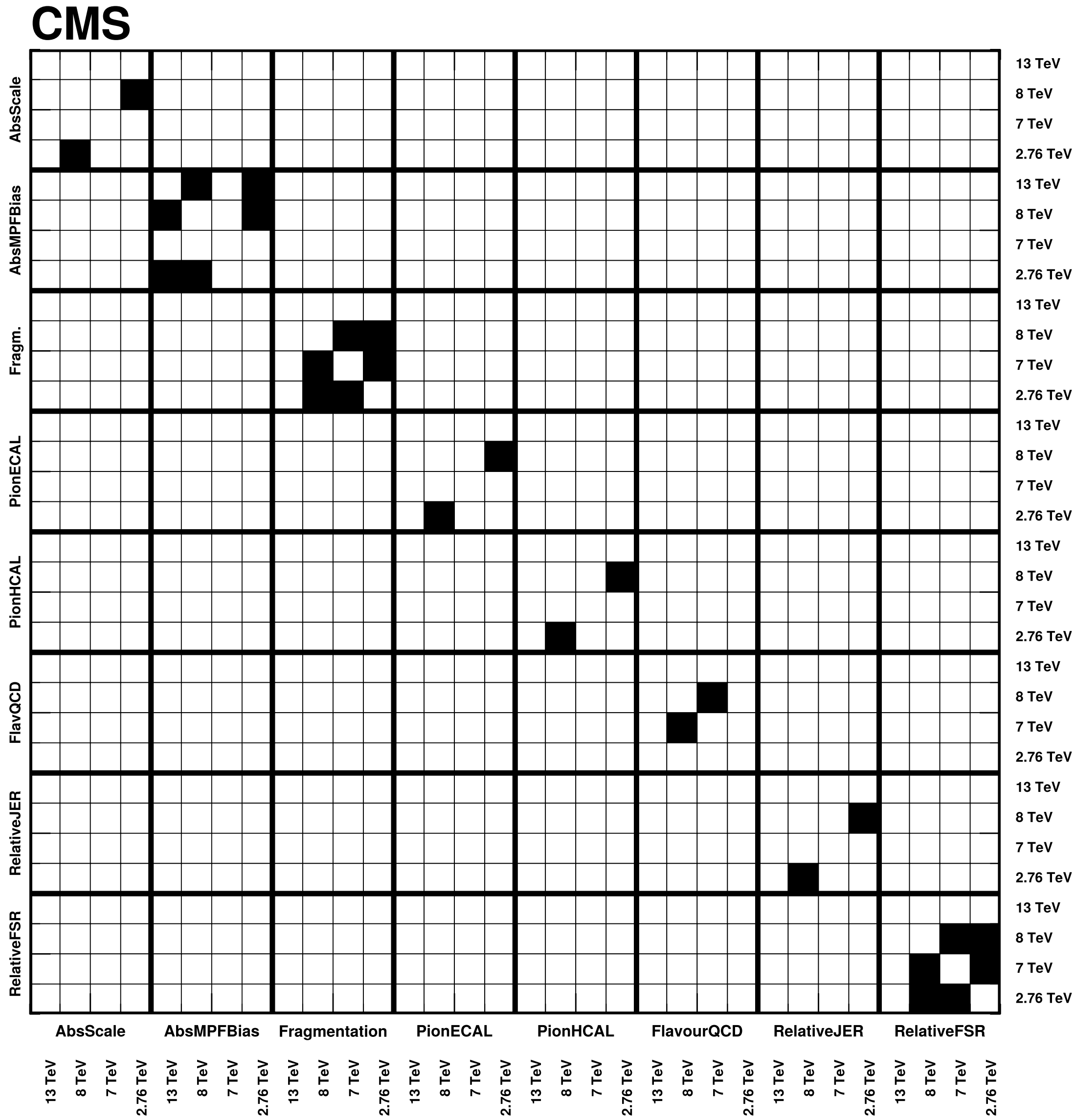

Figure A.1: Sketch of the treatment of JES sources of uncertainty among the measurements at different $\sqrt{s}$. A filled black box indicates that the corresponding two uncertainty sources are treated as correlated.

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