Measurements of $\alpha_s$ in $pp$ Collisions at the LHC

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The coupling of the strong force, $\alpha_s$, is deemed to be a fundamental parameter of Nature, and, beyond the quark masses, constitutes the only free parameter in the QCD Lagrangian. Provided is an overview of CERN Large Hadron Collider (LHC) measurements of $\alpha_s(M_Z)$ evaluated at the $Z$-boson mass and of the running of $\alpha_s(Q)$ as a function of energy-momentum transfer $Q$. The measurements were performed by the ATLAS and CMS Collaborations using proton-proton ($pp$) collisions with centre-of-mass energies of 7 TeV and data samples with time-integrated luminosities up to 5 fb$^{-1}$. Four different categories of observable were used in the described extractions of $\alpha_s$: inclusive jet cross sections, 3-jet to 2-jet inclusive cross-section ratios, 3-jet mass cross sections, and top-quark pair production cross sections. These results, which include the first NNLO measurement of $\alpha_s$ at a hadron collider and the first determinations of $\alpha_s$ at energy scales above 1 TeV, are consistent with each other, with the world-average value, and with QCD predictions of their running with $Q$.

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1 Introduction

Due to the dominance of quantum chromodynamics (QCD) processes in its collisions, the Large Hadron Collider (LHC) [1] is foremost a factory of jet production. Measurements of final states with jets at the LHC are important to the testing of both the Standard Model (SM) at high energies and perturbative QCD in hitherto-unexplored kinematic regimes. Jets are frequently used in characterizations of the principal backgrounds to searches for new physics, as well as in the provision of constraints on parton distribution functions (PDFs).

The coupling of the strong force, $\alpha_s$, is deemed to be a fundamental parameter of Nature, and, beyond the quark masses, constitutes the only free parameter in the QCD Lagrangian [2]. Experimentally testing the running of the $\alpha_s$ coupling with $Q$, the energy-momentum-transfer scale, is important at frontier high energies, which have not yet been studied. Moreover, investigations into $\alpha_s$ can probe for new physics by revealing deviations from the renormalization group equation (RGE) calculation of the running of $\alpha_s$ with $Q$ [2]. For example, the existence of new coloured matter near TeV energies could modify the three-jet rate, resulting in significant departures from expectations in the apparent running of $\alpha_s$ [3].

Leading-order dijet and inclusive jet production processes have interaction rates proportional to $\alpha_s^2$, whereas three-jet production rates have $\alpha_s^3$ dependencies. A prominent strategy in the experimental extraction of $\alpha_s(Q)$ is to examine inclusive jet cross-section ratios so as to eliminate or reduce the effects of integrated-luminosity, PDF, and other systematic uncertainties. Determinations of $\alpha_s$ in LHC data can be compared with the current world-average value of $\alpha_s(M_Z) = 0.1185 \pm 0.0006$ [2], which was computed without inputs from hadron-collider measurements. These proceedings constitute a review of LHC Run 1 $\alpha_s$ measurements using the ATLAS [4] and CMS [5] experiments in studies of proton-proton ($pp$) collisions at centre-of-mass energies of 7 TeV. Four different approaches to obtaining $\alpha_s$ measurements will be discussed: inclusive jet cross sections, 3-jet to 2-jet inclusive cross-section ratios, 3-jet mass cross sections, and top-quark pair production cross sections.

2 Jet Measurements

Both the ATLAS [4] and CMS [5] experiments use the infrared- and collinear-safe anti-$k_t$ jet algorithm [6]. ATLAS identifies jets by clustering electromagnetic and hadronic calorimeter cells and using the values 0.4 and 0.6 for the anti-$k_t$ clustering parameter $R$. CMS forms jets (with $R$ values of 0.5 and 0.7) by clustering particle-flow candidates constructed by combining information from all the detector subsystems. Several PDFs are considered by the experiments; for citations and discussions of the latest PDF sets, the reader is referred to Ref. [2].
A dominant experimental uncertainty is the degree of knowledge about the jet energy scale (JES). The ATLAS JES has been measured to have uncertainties in the range $0.5 - 6\%$ using *in situ* techniques that correct for multiple $pp$ interactions \cite{7} and depending on the jet transverse momentum ($p_T$), the pseudorapidity, and the event topology. The CMS JES has been determined using various Monte Carlo and data techniques to have uncertainties extrapolating from below 1% in the vicinity of jet $p_T \sim 150$ GeV to 1.2% near 2 TeV \cite{8,9}.

### 3 Inclusive Jet Cross Sections

An early analysis \cite{10} of inclusive jet cross sections \cite{11} measured by ATLAS in 37 pb$^{-1}$ of 7 TeV $pp$ collisions examined the running of $\alpha_s(Q)$ up to $p_T = 600$ GeV and made a measurement of $\alpha_s(M_Z)$, the strong coupling evaluated at the $Z$-boson mass. No deviations from the RGE running in QCD and the world-average value of $\alpha_s(M_Z)$, respectively, were observed. It is important to point out that the obtained uncertainty on $\alpha_s(M_Z)$ of 8% was dominated by differences between the results obtained using $R = 0.4$ and $R = 0.6$ clustering parameters \cite{10}. Understanding the sensitivities of jet clustering sizes to nonperturbative QCD corrections in contexts of NNLO (next-to-next-to-leading-order) QCD is a critical prerequisite to enabling more precise extractions of $\alpha_s(M_Z)$ from inclusive jet cross sections at the LHC.

Inclusive jet cross sections have also been measured in five rapidity ($y$) bins in 5.0 fb$^{-1}$ of 7 TeV LHC data by the CMS experiment \cite{12}. Refer to Fig. 1 (Left). More recently, the CMS collaboration has used these jet cross sections to constrain PDFs and extract $\alpha_s$ \cite{13}. The inclusive jet cross section, $d^2\sigma/dp_Tdy$, doubly differential in $p_T$ and rapidity $y$, is proportional to $\alpha_s^2$. Perturbative QCD and reliable parton-shower Monte Carlo programs can be used to calculate this observable to next-to-leading order (NLO), but the extraction of $\alpha_s$ first requires an estimate of the true theoretical differential cross section, taking into account nonperturbative corrections including multiple parton interactions and hadronization effects. Fig. 1 (Right) depicts the results of Monte Carlo calculations of these multiplicative nonperturbative corrections, as a function of jet $p_T$, for determinations based on both leading-order (LO) and NLO matrix elements.

The extraction of $\alpha_s$ from inclusive jet cross-section data is achieved by forming ratios of the data cross-section observations, corrected for nonperturbative (NP) and electroweak (EW) effects, with theoretical predictions computed using different input values of $\alpha_s$ and various PDF sets. An example of a set of predictions with $\alpha_s$ ranging from 0.112 to 0.126 in steps of 0.001 and using the CT10-NLO PDF set is provided in Fig. 2 (Left). A $\chi^2$ is formed between the measurements and the theoretical predictions (refer to Fig. 2 (Right)), where the covariance matrix entering into the $\chi^2$ definition includes terms that are statistical (with correlations), uncorrelated
systematics, JES, unfolding, luminosity, and PDF related. The $\chi^2$ is minimized and the extracted result, with all rapidity bins $|y| < 2.5$ combined, is $^{13}$

$$\alpha_s(M_Z) = 0.1185 \pm 0.0019 \text{(exp)} \pm 0.0028 \text{(PDF)} \pm 0.0004 \text{(scale)}.$$  \hfill (1)

where the uncertainties are experimental, PDF, nonperturbative, and scale-related, respectively. The total uncertainty varies between 3.5% and 5.5%, and is dominated by the renormalization ($\mu_r$) and factorization ($\mu_f$) scales, the uncertainties for which are computed by the standard method of varying the default values, chosen in this instance to be $\mu_r = \mu_f = p_T$, by factors of 0.5 and 2. The $\chi^2$ minimization fit is also performed in separate $p_T$ bins in order to test the running of $\alpha_s$ as a function of $Q$.  

4  3-Jet to 2-Jet Inclusive Cross-Section Ratios

The observable $R_{32}$, defined as the ratio of the inclusive 3-jet cross section to the inclusive 2-jet cross section, is proportional to $\alpha_s(Q)$. Here, $Q$ is defined as the average transverse momentum of the two highest-$p_T$ (leading) jets in a selected event:

$$Q \equiv \langle p_{T_{1,2}} \rangle = \frac{p_{T_1} + p_{T_2}}{2}.$$  \hfill (3)

Figure 3 (Left) depicts a CMS measurement of $R_{32}$ versus
Figure 2: **Left:** CMS ratio of inclusive jet cross section, corrected for nonperturbative (NP) and electroweak (EW) effects, to theoretical predictions using the CT10-NLO PDF set for the central rapidity bin, where the \( \alpha_s(M_Z) \) value is varied in the range \( 0.112 - 0.126 \) in steps of 0.001. The error bars correspond to the total uncertainty [13].

**Right:** CMS \( \chi^2 \) minimization with respect to \( \alpha_s(M_Z) \) using the CT10-NLO PDF set and data from all rapidity bins. The experimental uncertainty is obtained from the \( \alpha_s(M_Z) \) values for which \( \chi^2 \) is increased by one with respect to the minimum value, indicated by the dashed line. The curve corresponds to a second-degree polynomial fit through the available \( \chi^2 \) points. [13].

\( \langle p_{T,1,2} \rangle \) for selected events with two or more jets having \( p_T > 150 \) GeV and rapidities \( |y_{1,2}| < 2.5 \) [14].

Figure 3 (Right) represents a comparison of the CMS observed \( R_{32} \) distribution with numerous NLO predictions in which the assumed values of \( \alpha_s(M_Z) \) were varied in steps of 0.001 from 0.106 to 0.124. Using techniques similar to those described in Section 3, fits were performed to identify the value of \( \alpha_s \) most favoured in the data [14]:

\[
\alpha_s(M_Z) = 0.1148 \pm 0.0014(\text{exp}) \pm 0.0018(\text{PDF}) \pm 0.0050(\text{theory}),
\]

with a total uncertainty of 4.7% that was again dominated by sensitivity to knowledge about the impact of the \( \mu_r \) and \( \mu_f \) scales, defined identically to those discussed in Section 3. The analysis was also done splitting the sample into three different \( p_T \) ranges, thereby providing running values of \( \alpha_s(Q) \) of 0.0936\( \pm 0.0041 \), 0.0894\( \pm 0.0031 \), and 0.0889\( \pm 0.0034 \) for \( Q = 474, 664, \) and 896 GeV, respectively [14].

In 37 pb\(^{-1}\) of early 7 TeV data, the ATLAS collaboration also performed a preliminary study of \( R_{32} \), but as a function of the \( p_T \) of the leading jet [15]. In addition, an observable \( N_{3/2} \), defined as the ratio of the jet \( p_T \) distribution for events with at least three jets to that for events with at least two jets, was used as a function of jet \( p_T \). In contrast to \( R_{32} \), for which the numerator and denominator received a single value
Figure 3: **Left:** CMS measurement of $R_{32}$ and next-to-leading-order predictions using the NNPDF2.1 PDF set. **Right:** Next-to-leading-order predictions using the NNPDF2.1 PDF set and compared with the CMS $R_{32}$ measurements for several assumed values of $\alpha_s(M_Z)$. Results using other PDF sets are also provided in Ref. [14].

per event, the numerator and denominator used to determine $N_{3/2}$ contained one entry per jet. The $N_{3/2}$ approach was found by the ATLAS collaboration to have less sensitivity to the JES and to event pile-up effects. The $\alpha_s$ values from this study [15] were consistent with the world average [2] and possessed total uncertainties ranging from 6% to 15%, dominated by the effects of uncertainties due to the renormalization and factorization scale parameters, $\mu_r = \mu_f = p_T$.

## 5 3-Jet Mass Cross Sections

The doubly differential 3-jet mass cross section, expressed as a function of the invariant mass $m_3$ (where $m_3^2 \equiv (p_1 + p_2 + p_3)^2$) and maximum rapidity ($y_{\text{max}}$) of the 3-jet system, is proportional to $\alpha_s^3$. Both the ATLAS [16] and CMS [17] collaborations have measured this observable. Figure 4 (Left) depicts the CMS measured differential cross section, which is described well by NLO perturbative QCD (with nonperturbative corrections) over five orders of magnitude and for 3-jet masses up to 3 TeV. In Fig. 4 (Right), a ratio of the data, corrected for nonperturbative effects, to the NLO theory prediction using a nominal value of $\alpha_s(M_Z) = 0.118$, is presented. In addition, theoretical predictions involving $\alpha_s(M_Z)$ values ranging from 0.112 to 0.127...
in steps of 0.001 are shown. The extracted fitted result was found to be \[ \alpha_s(M_Z) = 0.1171 \pm 0.0013(\text{exp}) \pm 0.0024(\text{PDF}) \pm 0.0008(\text{NP}) \pm 0.0069(\text{scale}), \] (3)

with a total uncertainty ranging between 4% and 6%, again dominated by $\mu_r = \mu_f \equiv m_3/2$. To examine the running of $\alpha_s$ with $Q$, this analysis was broken down into seven sub-datasets, providing $\alpha_s(Q)$ quantities at seven different values of momentum transfer, including a highest value of 1402 GeV, which constitutes the highest $Q$ value of $\alpha_s$ measurements performed to date [17].

6 Top-Quark Pair Production Cross Section

A first measurement of $\alpha_s$ in a study of top-quark production has been achieved by the CMS collaboration [18]. The inclusive top-antitop ($t\bar{t}$) production cross section, $\sigma_{t\bar{t}}$, in 2.3 fb$^{-1}$ of $pp$ collisions at a centre-of-mass energy of $\sqrt{s} = 7$ TeV [19] is used for the measurement. To accomplish this, a theoretical prediction involving QCD production at next-to-next-to-leading-order (NNLO) precision combined with soft-gluon resummation at next-to-next-to-leading-log (NNLL) precision [20] was compared with the experimental $\sigma_{t\bar{t}}$ for the assumed scales $\mu_r$ and $\mu_f$ set to the top-quark pole mass, $m_t^\text{pole}$. In $\sigma_{t\bar{t}}$ cross-section calculations, $\alpha_s$ appears both in the expression for the parton-parton interactions and in the QCD evolution of the proton PDFs. Figure 5
Figure 5: Predicted $t\bar{t}$ cross section at NNLO+NNLL as a function of the top-quark pole mass (Left) and of the strong coupling constant $\alpha_s(M_Z)$ (Right), using five different NNLO PDF sets, compared to the cross section measured by CMS [19] assuming $m_t = m_t^{\text{pole}}$ [18].

(Left) shows the predicted $\sigma_{t\bar{t}}$ for several NNLO PDF sets as a function of $m_t^{\text{pole}}$ and with $\alpha_s$ constrained to a value of $0.1184 \pm 0.0007$ [21]. Figure 5 (Right) depicts the predicted $\sigma_{t\bar{t}}$ as a function of $\alpha_s(M_Z)$, assuming $m_t^{\text{pole}} = 173.2 \pm 1.4$ GeV.

For a given NNLO PDF set, identifying the intersection of the $\sigma_{t\bar{t}}$ prediction with the CMS measured value in Fig. 5 (Right) yields a precise determination of $\alpha_s(M_Z)$. Using this technique for the centrally treated NNPDF2.3 PDF, the CMS collaboration obtained the most precise measurement of $\alpha_s$ at a hadron collider, with a total uncertainty of 2.4% [18]:

$$\alpha_s(M_Z) = 0.1151^{+0.0017\text{(exp)}}_{-0.0018\text{(PDF)}}^{+0.0013\text{(PDF)}}^{+0.0009\text{(scale)}}(M_t^{\text{pole}}) + 0.0008(E_{\text{LHC}}) \pm 0.0008.$$  \hspace{3cm} (4)

Unlike for the earlier described $\alpha_s$ measurements, the ±46 GeV uncertainty in the 7 TeV pp collision energy, $E_{\text{LHC}}$, manifests as a sizeable source of uncertainty on $\alpha_s(M_Z)$ using the $\sigma_{t\bar{t}}$ technique, tantamount to that due to scale-related sources.

Figure 6 depicts results for $\alpha_s(M_Z)$ determined using various different NNLO PDF sets. The NNPDF2.3, CT10, MSTW2008, and HERAPDF1.5 PDF sets are somewhat lower than the world average [21], though generally still compatible. While the ABM11 result for $\alpha_s$ is compatible with the world average, its default natively assumed value is seen to be markedly different.

7 Conclusion

Figure 7 [22] places the discussed CMS $\alpha_s(Q)$ results alongside some select measurements from electron-proton and proton-antiproton colliders, visually demonstrating
Figure 6: CMS results [18] obtained for $\alpha_s(M_Z)$ from the measured $t\bar{t}$ cross section [19] together with the prediction at NNLO+NNLL using different NNLO PDF sets. The inner error bars include the uncertainties on the measured cross section and on the LHC beam energy as well as the PDF and scale uncertainties on the predicted cross section. The outer error bars additionally account for the uncertainty on $m_t^{\text{pole}}$. For comparison, the $\alpha_s(M_Z)$ world average [21] with its uncertainty is shown as a hatched band. For each PDF set, the default $\alpha_s(M_Z)$ value, used natively by that PDF set, and its uncertainty are indicated using a dotted line and a shaded band.

The mutual consistency in the running of the $\alpha_s$ coupling with scale $Q$, as well as consistency with the QCD RGE prediction described in Ref. [13]. Note the comparatively small uncertainty on the (red square) point showing the $\alpha_s$ value derived using the $\sigma_{tt}$ technique [18], the first NNLO measurement of $\alpha_s$ performed at a hadron collider. To date, no significant deviations from the QCD RGE running have been observed, and first explorations of $\alpha_s$ running into the TeV regime have commenced.

Figure 8 [22] provides an overview of the $\alpha_s(M_Z)$ measurements described here, as well as some earlier results from colliders involving hadrons. The indicated measurements agree with each other and with the current world average [2]. New 7 TeV [28] and 8 TeV results are on the way from the LHC, with others anticipated at 13 TeV and 14 TeV. In the interim, theoretical improvements at the NNLO level will need to be provided to enable significant further precision increases in the future.

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Figure 7: The strong coupling $\alpha_s(Q)$ (solid line) and its total uncertainty (band) as determined in the Ref. [13] analysis using a 2-loop solution to the RGE as a function of the momentum transfer $Q = p_T$ and 7 TeV inclusive jet cross section measurements described in Ref. [12]. Extractions of $\alpha_s(Q)$ in six separate ranges of $Q$ are shown together with results from the H1 [23, 24], ZEUS [25], and D0 [26, 27] experiments at the HERA and Tevatron colliders. Additional recent CMS measurements are also included [14, 18, 17].

Figure 8: An overview of recent $\alpha_s(M_Z)$ measurements made in hadron collisions (with citations), and the current world-average value [2].
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