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Highlights of the QCD and Hadronic Final States working group

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Highlights of the talks given during the "QCD and Hadronic Final States" working-group sessions are summarised. The contributions included the latest measurements on QCD and final states from colliders experiments at TeVatron, HERA and LHC and new results from the NA48/2, NA62, BaBar, PHENIX and Belle experiments. The most recent theoretical developments were also presented; the recent developments on fixed-order QCD, resummation and Monte Carlo models were discussed.

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1. Introduction

The "QCD and Hadronic Final States" working group received a large number of requests for presentations in its different sessions, which were categorised as "Hadron production", "Jet physics", "Photon and boson+jet production", "Theory of multi-jet events" and "Developments in Monte Carlo and resummations". The final agenda included 37 theoretical and experimental talks distributed in these sessions. Another 17 talks were included in joint sessions with the "Electroweak Physics and Beyond the Standard Model", "Heavy Flavours" and "Small-x, Diffraction and Vector Mesons" working groups. The contributions included the latest measurements on QCD and final states from colliders experiments at TeVatron, HERA and LHC and new results from the NA48/2, NA62, BaBar, PHENIX and Belle experiments. The most recent theoretical developments were also presented; the recent developments on fixed-order QCD, resummation and Monte Carlo models were discussed.

Tests of the theory of strong interactions is still one of the most active areas of research. Tests of perturbative QCD via jet and photon production in collider experiments, measurement of the parameters of the theory, study of non-perturbative effects and the constraints on the current models provided by the data and hadron production and spectroscopy are some of the experimental topics discussed during the sessions. Recent developments in Monte Carlo models and resummation as well as the theory of multijet events were also presented. A brief discussion of some selected topics is presented below. Further details can be found in the individual contributions to these proceedings.

2. Summary of the theory contributions

The theory talks in the session illustrated the enormous progress of the theoretical community in using and understanding hadronic jets. Knowledge of dynamics of jet formation is essential to develop effective strategies for New Physics searches at the LHC, especially those involving heavy resonances that decay hadronically [1]. One the other hand, with New Physics being elusive so far, precision calculations for jet cross sections become more and more important to have both signal and background under control. If one looks at events with high-p_T, well-separated jet, cross sections can be reliably computed as power series in the coupling α_S [2, 3]. On the other hand, looking inside jets requires modelling how jets are formed through the successive emissions of secondary partons from an ensamble of hard quarks and gluons. This is the aim of parton shower event generators [4, 5, 6]. Jet fragmentation can be also described analytically in QCD through the resummation of large logarithmic contributions appearing at all orders in the perturbative expansion [7, 8]. Not only is resummation needed to describe the dynamics of soft partons. It is also important to account for the presence of hard jets, widely separated in rapidity. This is the so-called BFKL regime, in which soft gluons are not emitted, but rather exchanged in the t-channel between hard partons [9, 10]. Our session hosted also more theoretical talks [11, 12]. In the following we will give a short overview of the above topics, referring to the corresponding contributions to these proceedings for more details.

We start with the use of jets for New Physics searches. J. Rojo illustrated a new method to tag heavy resonances decaying hadronically. He considered the production of a resonance X of mass

M_X decaying into two heavy resonances Y of mass M_Y, each decaying into two partons, giving a number of hard jets [1]. Then, according to the value of $r_X = M_X/(2M_Y)$, one expects different final states. For $r_X \gg 1$ the two resonances Y are boosted, so one expects the final state to contain two *fat* jets, each originated by the decay products of a Y resonance. On the contrary, at threshold $r_X \sim 1$, and one expects the signal to be characterised by four well-separated jets, i.e. we are in the so-called resolved regime. Different techniques are generally used for searches in the boosted and in the resolved regimes. J. Rojo illustrated a new technique, based on the number of mass-drop tags in each event, which makes it possible to obtain a tagging efficiency that is independent of the value of r_M, hence smoothly interpolating between resolved and boosted regimes [13].

The background to hadronically decaying resonances is of course multi-jet events, whose rates needs to be reliably predicted in QCD. D. Maitre presented the main features of the latest version of the next-to-leading-order (NLO) QCD program BLACKHAT+SHERPA [2]. Here BLACKHAT is responsible for the calculation of virtual corrections using unitarity methods, whereas SHERPA deals with efficient generation of real radiation. These techniques make it possible nowadays to compute $2 \to 6$ processes at NLO, specifically W production with five additional jets [14]. One interesting feature of the phenomenology of W plus jets, is that cross sections for different jet multiplicities exhibit a so-called "staircase" scaling, i.e. $\sigma[W+(n+1)\,\text{jets}]/\sigma[W+n\,\text{jets}] \sim$ constant. This makes it possible to obtain an extrapolated estimate for the cross section for $W+6$-jet events. Another characteristics of events with vector boson plus jets is the presence of large K-factors (NLO/LO) in certain kinematical distributions. This is due to the opening of new partonic channels in which the vector boson is radiated softly from a hard quark. F. Campanario explained how to account for these corrections in WZ production [3, 15] using the program LOOPSIM [16]. With the LOOPSIM method it is possible to exploit recent NLO calculations for di- and tri-boson (plus jet) cross sections (see [17, 18, 19] and references therein) implemented in VBFNLO [20] to reliably simulate NNLO corrections to di- and tri- boson production for high-p_T observables.

A general question that arises in multi-jet studies is how to merge different jet multiplicities. This is important for instance in order to describe the distribution in H_T, the total transverse energy in the event, which gets contributions from higher and higher jet multiplicities. One way to predict such distribution is through the sum of the contribution of exclusive n-jet samples at NLO. In fact, the natural tool to investigate the merging of different jet multiplicities is parton shower event generators. M. Ritzmann presented the new version of the VINCIA event generator [4], in which for the first time hadronic collisions are simulated [21]. In [22, 23], a new procedure to merge LO matrix elements and parton shower has been demonstrated in VINCIA for colourless resonance decays. It greatly reduces the growth of the running time with jet multiplicity compared to existing approaches. At present, algorithms for merging of different jet multiplicities do exist at NLO. A relevant question is whether it is possible to extend these procedures to account for NNLO corrections, when these are available. S. Plätzer answered this question, providing a general procedure for merging jet multiplicities at any desired order in perturbation theory. In his method, the requirement that the inclusive cross section produced by the parton shower is equal to the fixed-order one, gives automatically the counterterms to be added to the parton shower [5, 24]. Although the procedure is general, we have to remark that a merging to NNLO accuracy requires an improvement of the parton shower evolution kernels to the next logarithmic accuracy. We conclude the overview of parton shower Monte Carlo's with the contribution of S. Dooling, who discussed how they should be consistently used to estimate non-perturbative (NP) corrections to inclusive cross sections, for instance the inclusive-jet p_T distribution [6]. First, when using NLO calculations, NP contributions should be evaluated using a NLO matched Monte Carlo. This is because NLO hard corrections change significantly the transverse momentum of partons, hence changing the corresponding pattern of multi-parton interactions. Second, one should also take into account that, especially at large rapidities (small x), the parton shower induces a reshuffling in the longitudinal momentum fractions of incoming partons. She proposes to take this reshuffling into account by adding an extra "parton-shower" correction on top of the NP one [25].

One of the limitations of both NLO calculations and parton shower event generators is that only a pre-determined number of hard jets can be produced. Extra jets beyond the maximum available multiplicity are eventually produced by the parton shower, which is reliable only in the collinear limit. Production of an arbitrary number of hard jets is the aim of BFKL-inspired Monte Carlo event generators. H. Jung reported on recent progress in CASCADE [26], an event generator based on CCFM equation. CASCADE is at present able to satisfactorily describe various distributions in events with a W plus jets, even at high jet multiplicity where traditional parton showers fail [9]. Another approach to multi-jet production is provided by the program High Energy Jets (HEJ), in which approximate matrix elements derived from the high-energy limit are used together with all-order leading $\ln(-t/s)$-enchanced virtual corrections [27]. Such approximation is expectly to be appropriate when considering jets with a large rapidity gap between them. J. Andersen presented recent improvements in HEJ, including the implementation of production of Higgs and W bosons, accompanied by an arbitrary number of hard jets [10]. In particular, he showed how HEJ describes better than other programs the average number of jets as a function of the rapidity difference between the two hardest jets [28].

Besides Monte Carlo event generators, it is possible to describe jet fragmentation analytically through the resummation of logarithmically enhanced contributions appearing at all orders in perturbation theory. In particular, two contributions dealt specifically with the description of dijets events with a gap between the jets. There one considers two hard jets of average transverse momentum $p_{\mathrm{T,jet}}$ and vetoes all jets between them with a transverse momentum above a veto-scale Q_0. This generates large single logarithms $\alpha_S^n \ln^n(p_{\mathrm{T,jet}}/Q_0)$, originating from the suppression of soft large-angle gluon emissions above the scale Q_0. These logarithms are not simply described by a Sudakov form factor, but one needs to consider also non-global logarithms, arising from soft gluons close to the gap boundary, that emit softer gluons inside. C. Marquet explained how, using the non-linear BMS equation that resums specifically non-global logarithms, one can obtain predictions for the dijet cross section with a rapidity gap. Remarkably, predictions are in good agreement with data, especially if the considered dijet pair is made up of the two jets that are most separated in rapidity [29]. Another improvement in the description of dijet events with a gap was presented by Y. Delenda. He recalled that, if the algorithm used to select jets is not the anti-k_T, one has to resum a new class of single-logarithmic contributions, the so-called clustering logarithms. He showed through an explicit calculation that, up to four loops, clustering logarithms exponentiate [30]. Whilst in resummation for gaps between jets many open issues still remain, our theoretical understanding is much better for global observables, such as the one-jettiness in DIS, presented by D. Kang [8]. The one-jettiness is a shape variable that is small when one has a single highly collimated jet in DIS. It is close to the invariant mass of the jet, but is defined in such a way that it is global. Three variants of the one-jettiness were presented, together with resummation of large logarithms at the next-to-next-to-leading (NNLL) accuracy, in the framework of soft-collinear effective theory (SCET) [31]. Such accurate calculation makes it possible to clearly disentangle perturbative and non-perturbative effects. We remark that one of the proposed variants is just one minus the thrust of the current hemisphere, normalised to the photon virtuality. This variable could be recovered from already existing experimental analyses.

We conclude this overview by presenting two more theoretical contributions, whose phenomenological applications are yet to come. The first, presented by G. Chachamis, deals with the problem of obtaining a solution of the BKP equation (in a conformal theory like $\mathcal{N} = 4$ Super Yang-Mills), governing the Odderon Regge trajectory, via a Monte Carlo procedure [11]. Since the BKP kernel consists of reggeised gluons in the symmetric octet representation interacting in pais through ordinary gluons, it then makes sense to try and solve numerically the non-forward colour-octet BFKL equation. The Green's function of this equation is not infrared finite. However, its singular part factorises analytically, leaving a finite remainder which can be computed with a Monte-Carlo procedure [32, 33]. In particular, the Green's function for the octet case requires emission of less gluons than the singlet case, thus giving hope that a Monte Carlo solution of the BKP equation might be available in the near future. The last contribution [12] deals with a general problem in any QCD calculation involving many partons, the decomposition of an amplitude in a basis of orthogonal colour structures. M. Sjodahl illustrated an algorithm to construct minimal bases of orthogonal colour tensors, into which any amplitude can be decomposed [34]. The decomposition of arbitrary colour structures into colour bases can be performed using the Mathematica package ColorMath [35].

3. Experimental summary

A large number of experimental talks were presented in the "QCD and Hadronic Final States" session. They covered numerous results from B factories at low energies and DIS experiments as well as from the hadron colliders at the energy frontier. Both QCD precision measurements and studies of QCD processes as a background for other measurements and new-physics searches were discussed.

3.1 QCD at work

Precision measurements of numerous channels contributing to the cross section $e^+e^- \to$ hadrons have been presented by the BaBar collaboration [36]. They are performed using the ISR method, where events with a hard photon emitted from the initial state are considered. This method, exploitable due to the large luminosity available at B factories, allows for a simultaneous measurement of the spectra from the threshold to high masses, under the same detector and collider conditions. It allows to obtain smaller systematic uncertainties comparing to measurements performed through collider energy scans. The measured spectra are exploited to compute the hadronic contribution to the theoretical prediction of the $g-2$ of the muon, dominated by the low energy contributions which can not be computed directly from QCD. A deviation of about 3.6 standard deviations is observed between the theoretical prediction and the experimental measurement of the $g-2$ of the

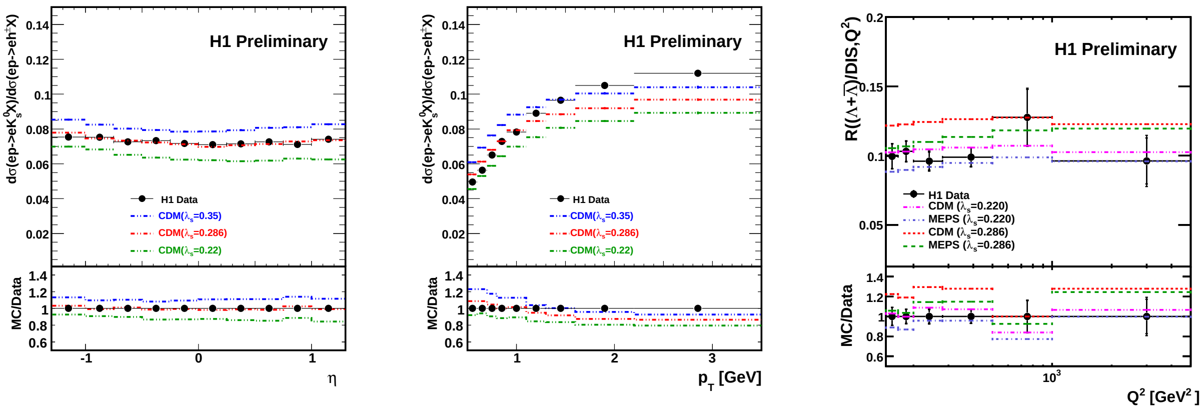

Figure 1: K^0_S production cross section as a function of η (left) and p_T (middle). Right: $\Lambda\bar{\Lambda}$ production cross section as a function of Q^2.

muon, which could be an indication of new physics. A large difference is also observed between the measured charge kaon form-factor and the prediction of asymptotic QCD.

Several spectroscopy measurements have been presented by the Belle collaboration [37], both for the charmonium and the bottomium mass regions. There are still open questions concerning the statistical significance of the potential observation of a new resonance in the charmonium region, towards 4 GeV.

Strangeness production in DIS can occur through the hard process, boson gluon fusion, heavy quark decays or hadronisation. Measurements of the K^0_S and $\Lambda\bar{\Lambda}$ production cross sections, normalized to the total DIS one, were presented [38] by the H1 collaboration (see Fig. 1). They are compared with the predictions of various Monte Carlo (MC) generators, for several values of their tunning parameters. While good agreement can be achieved for the pseudorapidity and Q^2 distributions, the shape of the p_T distribution is not well described.

3.2 QCD at the energy frontier

At hadron colliders, which allow the highest energies accessible nowadays, QCD interactions have the largest cross section. This can be exploited in order to perform precision tests of the corresponding theoretical predictions. However, QCD also represents the dominant background contribution for many new physics searches.

3.2.1 QCD as background

The complex environment at hadron colliders involves, in addition to the interesting hard scattering, several other contributions from initial- and final-state radiation, multiple-parton interactions and beam remnants. In addition, at the LHC, the number of multiple proton-proton collisions in the same bunch-crossing has reached high levels at the end of the first run, and further enhancements are foreseen for the next data-taking periods. This makes the searches for new phenomena very challenging.

A typical example is provided by the SUSY searches [39]. For models with R-parity conservation, the typical signature is provided by jets with $E_T^{\rm miss}$ from the lightest SUSY particles, plus eventually other leptons in the event. The types of background encountered in these searches are classified in reducible and irreducible. For the latter, MC or semi data-driven estimates are used. The reducible background has various sources like fake E_T^{miss}, fake leptons or charge mis-identification. Fake E_T^{miss} can be produced by a mis-measured jet energy. This is studied using a MC and/or in-situ jet response function, applying a smearing for the low E_T^{miss} in data and validating the effect in a control region. If good agreement is observed between data and MC in the signal region, limits are set on the contributions from new physics.

A measurement of the k_T splitting scale in $W(\to l\nu)+$jets events has been reported by the ATLAS collaboration [40], allowing the probing of the QCD evolution and the test of MC generators. In this study, the W is used to tag a pure sample of events. A distance between two jet constituents is defined as:

$$d_{ij} = \min(p_{Ti}^2; p_{Tj}^2) \times \frac{\Delta R_{ij}^2}{R^2},$$

where p_{Ti} is the transverse momentum of the i^{th} constituent, ΔR_{ij} is the distance between the two constituents in the $(\eta;\phi)$ plane, and R is the size parameter of the jet algorithm. A distance d_k is defined as being the minimal distance between two constituents at step number k. Results have been presented for measurements of several of these distances, as well as their ratios. They are compared with predictions obtained using several MC generators. While a good agreement is observed for ALPGEN+HERWIG, in the case of the $\sqrt{d_0}$ and $\sqrt{d_3/d_2}$ distances, tensions are observed when comparing with other generators.

Measurements of event shapes and transverse energy flow have also been presented by the ATLAS collaboration [41] (see Fig. 2, left). They are complementary to the minimum bias and underlying event results, representing an important input for MC tuning.

Jet shapes and substructure studies at the LHC have been discussed. In a study presented by the ATLAS collaboration [42], a $t\bar{t} \to (Wb)(Wb) \to (\mu\nu b)(q\bar{q}b)$ sample is used. A hadronic top candidate is found using the anti $-\,k_T$ jet algorithm, with a size parameter $R = 1$. A trimming algorithm is used in order to remove the low p_T constituents of the jet. It significantly improves the jet mass resolution, which allows a clear evidence of the top mass peak (see Fig. 2, right). The CMS collaboration reported a double-differential jet mass cross section measurement, via the jet substructure resolution [43]. It is performed as a function of the jet mass and transverse momentum. The measurement has a precision which suffices to distinguish between various PYTHIA and HERWIG++ tunes.

3.2.2 Precision measurements at the highest energies

Precision measurements at the energy frontier are particularly interesting, because they allow the testing of various predictions, probing of the QCD running at the highest accessible scales and the improvement of the constraints on proton PDFs.

Inclusive photon cross section measurements have been presented by the ATLAS [44] and ZEUS [45] collaborations. ATLAS has performed measurements both as a function of the transverse photon energy and of the angle between the photon and the leading jet (see Fig. 3, left and middle). Good agreement is found when comparing with the HERWIG and PYTHIA generators, as well as with the NLO predictions for various PDF sets. The ZEUS measurement as a function

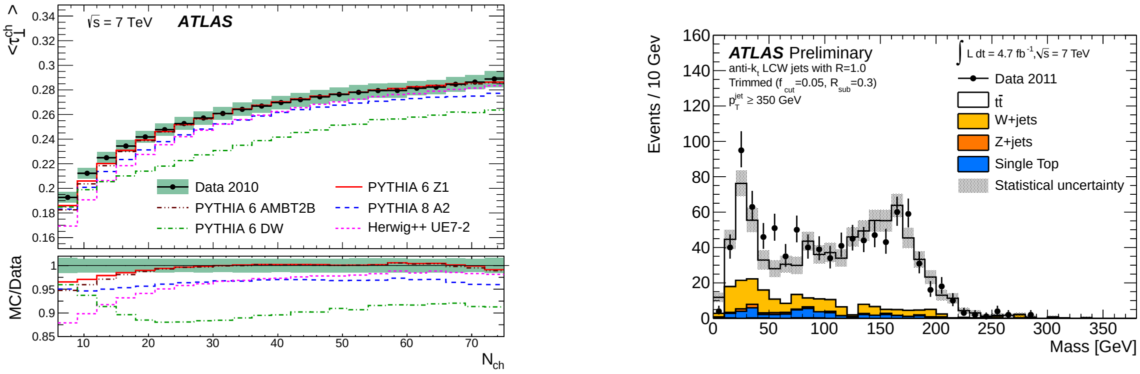

Figure 2: Left: transverse thrust measurement as a function of the number of charged tracks. Right: trimmed jet mass distribution.

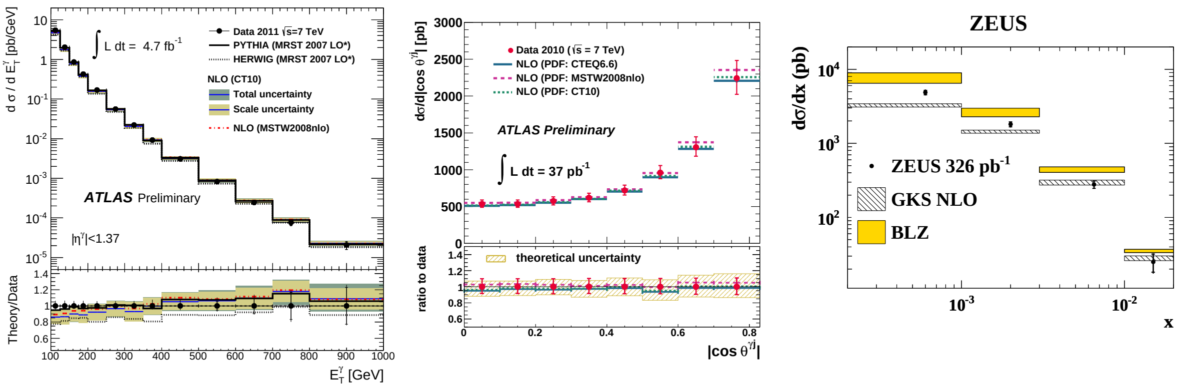

Figure 3: ATLAS photon cross section measurement as a function of the transverse photon energy (left) and the angle between the photon and the jet (middle). Right: photon cross section measurement by ZEUS, as a function of x.

of x shows a tension with respect to both the GSK NLO and BLZ generators, which is especially large at x values of about 10^{-3} (see Fig. 3, right).

The CDF experiment presented the differential photon cross section measurement, in association with heavy flavor [46]. Surprisingly, the systematic differences between the measurement and the prediction of the PYTHIA generator increase with the transverse photon energy.

The ATLAS and CMS experiments presented a series of jet measurements. The ratio between the three-jet and two-jet cross section measurement from ATLAS [47], and the double differential jet cross section measurement from CMS [43] were presented at centre-of-mass energy of 7 TeV. Good agreement is observed between these measurements and the corresponding theoretical predictions. Together with other jet measurements presented during the session, they offer the possibility to constraint the PDFs at high x. However, the full information on the correlations of their uncertainties must be provided to exploit these data in PDF fits and other phenomenological

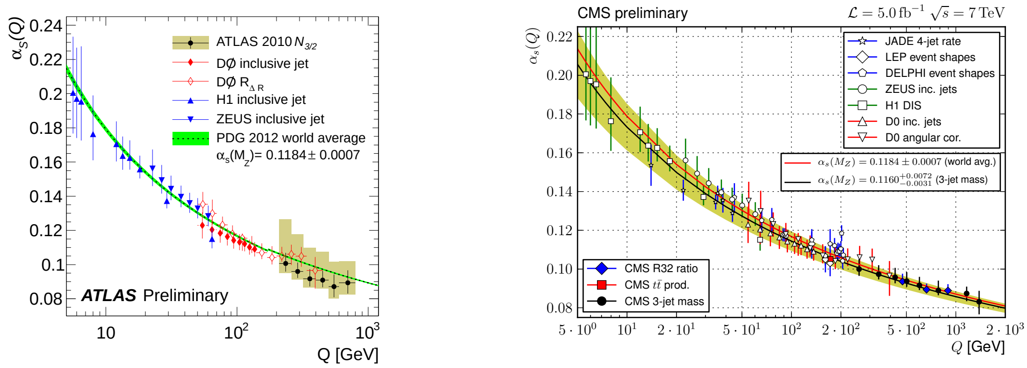

Figure 4: α_S values determined by the ATLAS (left) and CMS (right) experiments, compared with results from previous experiments. The bands indicate the running of the strong coupling by the renormalization group equation.

studies.

The ratios between the three-jet and two-jet cross section measurements have been exploited by both the ATLAS and CMS experiments to extract the value of the strong coupling constant α_S (see Fig. 4). Actually, these studies allow the extension of the tests of the running of α_S by the renormalisation group equation up to the TeV scale. The theoretical predictions for these cross section ratios benefit from an important cancelation of the PDF uncertainties. However, the scale uncertainties are relatively large for the ratios and the NNLO predictions would help to improve the precision of the phenomenological studies. It would also be desirable to unify the procedures used for evaluating the scale uncertainties in the ATLAS and CMS studies, as important differences are observed between the two results. The uncertainty due to the choice of the jet algorithm should also be taken into account when evaluating the precision of the α_S determination.

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