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QUANTUM CHROMODYNAMICS AT THE LHC

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Abstract

The LHC physics program aims to both perform some of the most precise measurements of Standard Model processes and search for physics beyond the Standard Model in phase space that has never been accessible before. This ambitious program requires a deep understanding of a broad array of phenomena. Central to all of this is our understanding of quantum chromodynamics (QCD), which affects everything from precision calculations of hard processes to the modeling of jets. I summarize a selection of measurements which further our understanding of parton distribution functions, the strong coupling constant, and jet modeling, and discuss the implications of such measurements for the high-luminosity LHC physics program.

1 Introduction

Our understanding of QCD directly impacts the quality of the entire physics program at the LHC. Jet-related systematics are frequently the limiting experimental systematic uncertainty, both searches and measurements struggle to estimate multijet backgrounds accurately, and precision measurements Higgs processes are becoming more sensitive to the uncertainty on the strong coupling constant α_s as the statistical precision improves. Even analyses without jets still rely on our understanding of perturbative QCD through our ability to model parton distribution functions (PDFs). In many cases, searches are limited by the PDF uncertainties as they probe challenging phase space. Despite its importance, precision understanding of QCD has remained elusive due to its complexity; high-order calculations are difficult to produce, meaningful observables are not always apparent, and accurate models do not exist for all relevant scales.

There are three specific ways in which QCD is relevant to a broad set of analyses at the LHC: parton distribution functions, the strong coupling constant, and jet modeling. Each of these topics poses unique challenges and provides specific opportunities for extending the reach of the LHC physics program. The high-luminosity LHC is expected to produce around 3000 fb^{-1} of data, around 20 times the existing dataset. In studies of the expected sensitivity to various phenomena [1], ATLAS and CMS provide a few different scenarios for expected reduction in uncertainties at the HL-LHC, Most of these studies assume the scenario where all three of these uncertainties improve by approximately a factor of two. Some of these improvements are fairly concrete, such as increased statistical accuracy and the inclusion of more recent measurements in PDF fits, while others are more speculative, such as assumptions about improved methodology and improvements in jet modeling. These assumptions are only feasible through measurements that improve our understanding of QCD across all scales. I highlight a few representative examples of innovative measurements which are being used to further our understanding of QCD.

2 Parton Distribution Functions

Cross-section calculations at the LHC are factorized into two parts: the calculation of a hard process and the probability of the incoming partons existing at a given momentum within the colliding protons. While hard processes may often be calculated from first principles, the internal structure of a proton cannot be calculated due to the non-perturbative interactions of its partons. Instead, these are determined experimentally using PDFs, which describe the probability of finding a particular parton which carries a fraction x of a proton with energy Q. As searches push the mass limits for new particles higher, they become increasingly sensitive to high-x PDFs. Since these PDFs tend to be poorly constrained, the PDF uncertainties are becoming increasingly relevant to enabling us to find physics beyond the Standard Model. This is particularly relevant for searches for physics beyond the Standard Model. While the HL-LHC will provide more data for rare parameter space, its usefulness will be limited by the ability to predict the cross-sections for these distributions using PDFs.

PDFs are determined from a combination of perturbative QCD calculations and analytical parameterizations using measurements from experiments across a wide range of energy scales to fit the functional forms of different partons. Much of this is best-constrained by measurements of deep inelastic scattering, but particularly for the high-x regions, LHC data is crucial for constraining PDFs. Fig. 1b demonstrates this with the example of a measurement of the dijet cross-section at $\sqrt{s} = 8$ TeV, where this measurement is able to provide significant constraints on the high-x gluon PDF compared to a PDF produced using only measurements from HERA. This is further demonstrated in Fig. 1, which shows that dijet measurements from ATLAS and CMS are the most constraining measurements for the high-x gluon PDF for the CT18 NNLO fits. These fits only consider measurements from $\sqrt{s} = 7$ and 8 TeV, and with the large dataset that has already been produced at 13 TeV, further improvements can be expected both from the increased statistics and higher energy.

3 The Strong Coupling Constant

The strong coupling constant α_s has long been a challenging parameter to measure. Currently, α_s is only known with a precision around 1%, and significant tensions exist among the values extracted from different measurements, as seen in Fig. 2. While this could be explained, at least in part, by the underestimation of uncertainties for some of these measurements, this motivates the development of other uncorrelated measurements to be included in the world average while also improving our understanding of existing measurement techniques. This is challenging for a couple reasons. It is difficult to find observables which are both sensitive to α_s but fairly insensitive to various non-perturbative effects. In addition, at

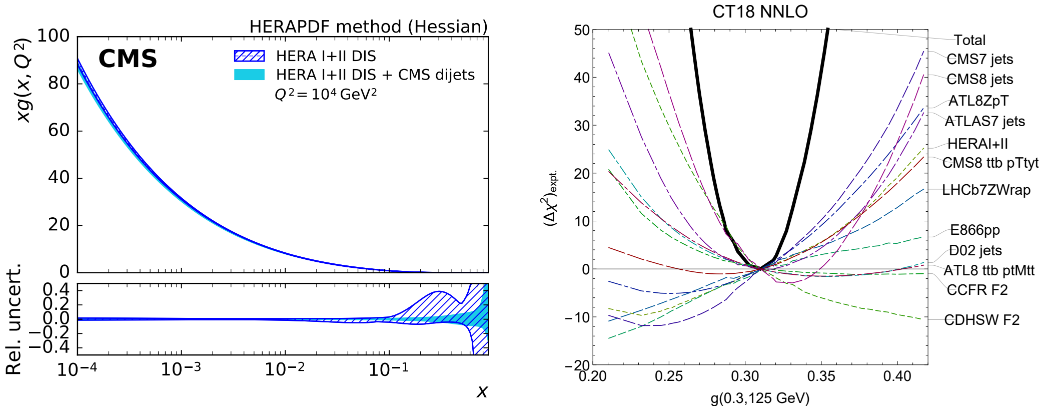

Figure 1: *a) The gluon PDF at $Q^2 = 10^4$ GeV^2 as a function of x as derived from HERA inclusive DIS data alone, and in combination with CMS dijet data* [3]*, and b) The Lagrange Multiplier scan of gluon PDF at Q=125 GeV and x = 0.3, for the CT18 NNLO fits.* [2].

a hadron collider, calculations must be available at NNLO in order for them to be included in the world average. Currently, the only measurement from a hadron collider which has been used to extract α_s using NNLO predictions is the measurement of the $t\bar{t}$ cross-section. Even so, there are many observables at the LHC sensitive to α_s, and since there has been significant theoretical progress towards creating predictions, there is strong motivation to perform measurements of sensitive observables. The precision of such measurements is still unknown, but extractions of α_s at NLO at the LHC demonstrate precision which is competitive with other methods which are already being used [7, 8, 9].

Measurements of α_s at the LHC are not only useful for understanding the world average; they uniquely provide access to high scales, and also enable measurements across a wide range of scales within a single measurement. Measurements of the running of α_s can be used to provide indirect constraints on physics beyond the SM in a model-independent way [5, 6]. While the $t\bar{t}$ measurement does provide an important insight into α_s at high scales, it is currently not possible to probe the running of the coupling using this measurement. However, several other observables that have been calculated at NLO accuracy have been measured at the LHC. These observables include the inclusive jet cross section, the ratio of the 3-jet to 2-jet cross sections, transverse energy-energy correlations, the 3-jet mass, and angular correlations. Several of these measurements are shown in Fig. 3, which shows the broad range of scales which can be accessed by any single one of these measurements. As theoretical predictions become available at higher order, these types of measurements will test the limits of our understanding of QCD by accessing scales that have not yet been carefully explored.

4 Jet Modeling

Most analyses at the LHC – both searches and measurements – rely on accurate modeling of jets, either by using them directly, or through a jet veto. Jets are notoriously difficult to model, since jet observables are affected not only by perturbative effects such as the parton shower, but also nonperturbative effects like hadronization. First principle calculations of jets across all relevant scales are difficult, and Monte Carlo generators are necessary for providing predictions for these effects. Several Monte Carlo generators exist using different models for the parton shower and hadronization, and their parameters are tuned to

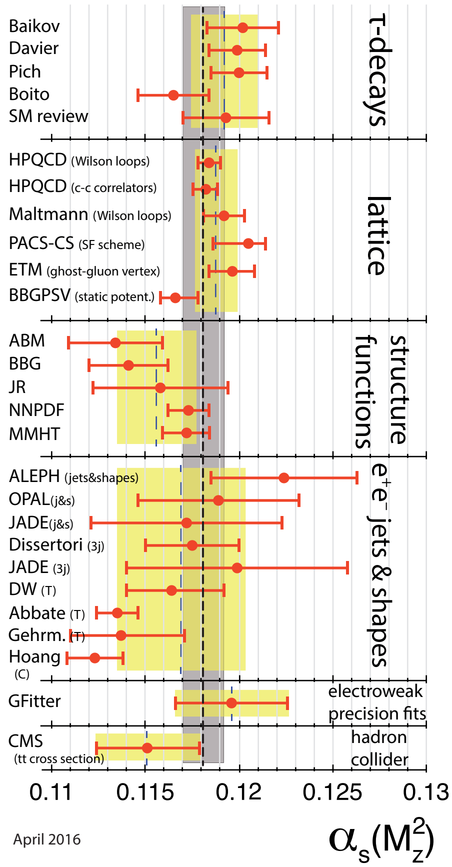

Figure 2: *Summary of determinations of $\alpha_s(M_Z^2)$ from different sub-fields. The yellow (light shaded) bands and dotted lines indicate the pre-average values of each sub-field. The dashed line and blue (dark shaded) band represent the final world average value of $\alpha_s(M_Z^2)$* [4].

measured data in order to provide accurate descriptions of jets.

ATLAS and CMS both produce their own individual Monte Carlo tunes using their own measurements, using a variety of measurements of jet substructure observables, multijet observables, and distributions of individual jet properties. These measurements are sometimes sensitive to multiple effects, and since not all tunable parameters have a clear physical meaning, it can be challenging to select the optimal observables for tuning. These challenges may be visualized in looking at several Monte Carlo predictions for jet substructure observables, which demonstrate clear differences between the predictions [11, 12, 13, 14].

This can be improved by providing more and better inputs to the tuning procedure, which would better constrain the tuned parameters. Ideally, to reduce the complexity of the fitting procedure, measurements would be sensitive to a single effect or parameter, though in practice such observables are hard to find. Recently, a new jet observable was proposed, which builds upon years of understanding of how to describe jets. This observable is called the Lund jet plane [15], and it approximates the emissions of a parton as a series of emissions from the core of a jet, parameterized by the fraction of momentum carried by the emission z and the angle of the emission ΔR. This simple characterization of a jet is extremely

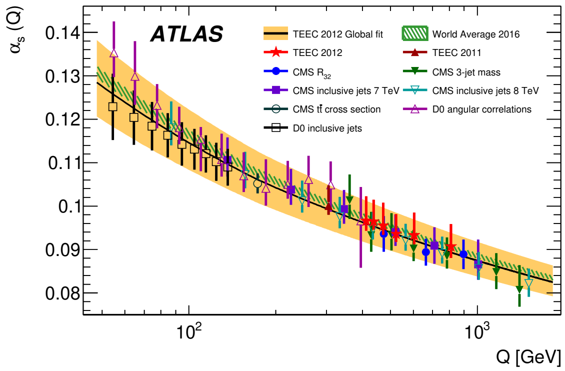

Figure 3: *Comparison of the values $\alpha_s(Q)$ obtained from fits from several experiments with the uncertainty band from the global fit (orange full band) and the 2016 world average (green hatched band). Determinations from other experiments are also shown as data points. The errorbars, as well as the orange full band, include all experimental and theoretical sources of uncertainty. The strong coupling constant is assumed to run according to the two-loop solution of the RGE* [7].

powerful, as it factorizes different effects into different regions of this two-dimensional space, which is represented in Fig. 4a.

The Lund Jet plane was measured in dijet events by the ATLAS experiment. Fig. 4b shows a single slice of the plane, where the left side of the distribution is sensitive to effects from the parton shower, while the right side of the distribution is sensitive to hadronization effect. It demonstrates the factorization predicted, since differences between similar generators are only seen in the regions predicted. While it remains to be seen how this will impact Monte Carlo tuning, the demonstration of the factorization of effects indicates that this could be a powerful tool.

5 Summary

Continuing to measure observables sensitive to various QCD effects will enable us to study rare processes, perform precision measurements, and searches for physics beyond the Standard Model. Analyses frequently probe processes where the relevant PDFs are poorly constrained, making LHC measurements relevant. Measurements of processes such as the dijet cross section are already being used to constrain PDFs and will continue to be important in preparation for the HL-LHC. ATLAS and CMS have laid the foundations for measuring α_s using a variety of observables, and theoretical progress will enable these to be used to study QCD at high scales, testing the limits of our understanding. Even analyses that are not limited by PDFs or α_s are often reliant on jet modeling, which impacts the multijet background modeling and jet energy scale uncertainties. Only by studying QCD will we be able to use the full power of the data that will be collected by the HL-LHC.

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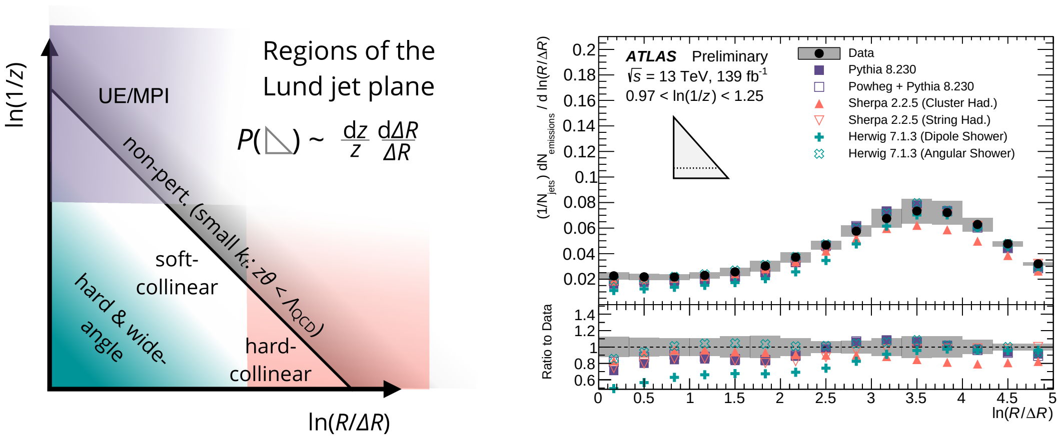

Figure 4: *a) Diagram of the Lund jet plane, highlighting regions where different effects are dominant. b) Representative horizontal slice through the Lund jet plane. Unfolded data are compared to particle-level simulation from several Monte Carlo generators. The uncertainty band includes all sources of systematicand statistical uncertainty. The inset triangle illustrates which slice of the plane is depicted* [14].

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