QCD AND HIGH ENERGY INTERACTIONS: THEORY SUMMARY

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This article summarizes new theoretical developements, ideas and results that were presented at the 2014 Moriond "QCD and High Energy Interaction".

1 Introduction: Particle physics after the Higgs boson discovery

One year ago, at Moriond 2013, the ATLAS and CMS collaborations presented for the first time their results on the properties of a newly discovered boson [1]. A variety of different measurements shown then identified the boson to be the long-sought Higgs boson, the mediator of electroweak symmetry breaking. This discovery was crowned by the award of the 2013 Nobel Prize in Physics to François Englert and Peter Higgs.

During the past year, analysis of the LHC7 and LHC8 data continued, providing a wealth of new insights into the Higgs boson properties and many other observables. Particle physics is also eagerly preparing the next run of the LHC at higher collision energy, which will open up new mass ranges in searches for physics beyond the Standard Model. Planning for the next generation of high-energy particle colliders has gained a lot of momentum throughout the last year. Progress in particle physics relies on a fruitful interplay of experiment and theory, illustrated in a very lively manner throughout this conference.

A very prominent example for this interplay is the recent indirect measurement of the Higgs boson width, reported by the CMS collaboration [2]. The measurement is based on a comparison of the on-peak and off-peak cross sections for four-lepton production, which was suggested only very recently [3].

2 Hadronic physics and QCD at strong coupling

QCD has been established as theory of strong interactions though a multitude of experimental validations. In the high-energy regime, QCD is asymptotically free and can be handled with methods of perturbation theory, thereby allowing for highly precise theory predictions to be confronted with experimental data. In the low-energy regime, QCD becomes strongly coupled, and develops confinement. Quantitative predictions in this regime can be obtained only with non-perturbative methods, and are often restricted to model systems.

A commonly used model to study non-perturbative dynamics is N=4 Super-Yang-Mills theory, where symmetries and dualities can be used to obtain results at strong coupling [4,5]. In this framework, the pomeron intercept has been computed [6,7,8], and model results have been compared to HERA data from collisions at small x. It is observed that the qualitative behaviour of the intercept changes substantially between N=4 SYM and QCD.

An important application of QCD at strong coupling are exclusive decays of heavy quarks, which provide an excellent indirect probe of physics beyond the Standard Model at the highest energy scales [9]. New results on decays to tensor mesons have been derived [10], requiring an extension of the effective hamiltonian to include tensor modes. The physics of quarkonium bound states can be described perturbatively in non-relativistic QCD. Most recently, this theory has been applied successfully to describe the production and polarization of Y mesons [11].

Heavy-ion collisions probe the non-perturbative dynamics of strong interactions at high density. Their theory description must account for a multitude of effects from different areas of classical and quantum physics. Many collective effects can be described through models based on hydrodynamics [12]. To describe parton propagation in heavy-ion collisions, the interactions of partons with a surrounding plasma and its excitations have been computed [13,14]. The high-density regime probed in heavy-ion collisions may allow to study phenomena equally relevant to proton interactions at very high energies, such as saturation and geometrical scaling [15].

The non-perturbative bound state dynamics of quarks and gluons inside the proton enters into perturbative predictions of high-momentum transfer observables through the parton distribution functions. For most applications, these functions are considered inclusive in transverse momentum, described in the well-established framework of collinear factorization and DGLAP evolution equations [16,17]. Several new features appear if the dependence of parton distributions on transverse momentum is considered, as required for example for transverse momentum resummation. Owing to the helicity structure of the splitting process, gluons entering an unpolarized hadronic collision are linearly polarized in the direction of their transverse momentum. Consequently, unpolarized collisions at the LHC allow to probe certain spin observables, considered up to now only in polarized collisions for example at RHIC. The most promising probe of transverse gluon polarization at the LHC may be through asymmetries in $Y + \gamma$ production [18], and possible applications of transverse gluon polarization could be in probes of the spin and parity of the Higgs boson in decays other than the four-lepton channel [19].

3 Describing collisions at the LHC

The interpretation of data from particle colliders relies on a close interplay between theory and experiment. Precision calculations of collider observables are mandatory for the measurement of fundamental parameters, such as masses and coupling constants [20], for the determination of particle properties and for the extraction of auxiliary quantities such as parton distributions. Reliable predictions for anticipated signals and their Standard Model backgrounds are crucial in the design of searches for new physics effects, and in the interpretation of the search results in terms of exclusion limits or discovery evidence.

Theoretical predictions are obtained in perturbation theory, which is truncated at a certain order (LO, NLO, NNLO, ...). The conventional procedure to estimate the error on these predictions proceeds through the variation of renormalization and factorization scales around a predefined value related to the dominant kinematical properties of the process under consideration. The interpretation of this error, its combination with other sources of error and its propagation in an analysis of experimental data are however questionable. A new approach to the treatment of theoretical errors based on Bayesian statistics is currently under development [21].

The default standard for theoretical predictions in collider physics are multi-purpose simulation programs, usually based on LO calculations augmented by leading-logarithmic resummation in the form of a parton shower (PS). Owing to rapid developments in the automation of NLO calculations, a new standard is currently emerging in the form of simulation programs combining NLO+PS.

The description of multi-particle production processes often demands a complicated interplay of fixed-order descriptions and resummation. In the high-energy limit, the dominant dynamics of multi-particle production is described by the BFKL equation. Using this equation, one obtains

compact approximate forms for high-multiplicity matrix elements, which take proper account of multiple large-angle emission [23,24]. This approach is particularly relevant for observables that are poorly described by parton shower calculations, which are based on a resummation of small-angle emissions.

NLO calculations of high-multiplicity observables have seen an enormous progress during the past years, especially in view of their automation. This process has been catalyzed by the standardization of interfaces between different calculational ingredients (virtual and real contributions) in the Binoth Les Houches accord [22]. With this, new algorithmic developments for the evaluation of one-loop virtual amplitudes can be readily applied to physical processes by using established tools and infrastructures for the real radiation as well as for event-handling, final state reconstruction and comparison to data. The current frontier in multiplicity is set by the calculation of NLO corrections [25] to $W + 5j$ production using virtual corrections evaluated with the Blackhat package in the Sherpa event generator framework. A new development in this context is the dissemination of full event information resulting from NLO calculations in the form of n-tuples [26], which can be analyzed subsequently with appropriate final state definitions as used in the experimental analysis.

The combination of NLO calculations with parton showers is by now an established and widely used tool. To improve upon this, first steps are now being made to combine NNLO calculations with parton shower approximations. A first application in this context is to inclusive Higgs production [27], obtained by combining an NLO+PS description of Higgs+jet production with a dedicated scale setting, and a normalization to the inclusive NNLO result.

Resummation beyond leading logarithms becomes important for many precision observables in kinematical situations that receive comparable contributions from several different partonic multiplicities. The resulting uncertainties are difficult to quantify. The conventional determination of theory errors from scale variations on fixed-order calculations only regards a particular multiplicity, and may therefore miss out on the relevance of multiple emissions. A new approach towards quantifying theory uncertainties, the efficiency method, has been put forward to take proper account of kinematical situations prone to large resummation corrections [28], and has been applied to Higgs production with a jet veto.

4 Precision calculations at NNLO and beyond: results and methods

Corrections beyond NLO are needed for the interpretation of benchmark observables (usually low-multiplicity processes), which are measured experimentally to the per cent level as well as for observables with potentially large perturbative corrections. For hadron collider processes, a fully differential calculation of the higher order corrections, allowing to take into account experimental selection criteria and kinematical limitations and thus predicting fiducial cross sections, is very much demanded. This can be accomplished by a parton-level event generator, which supplies all partonic subprocess contributions with their full kinematical dependence. These calculations at NNLO accuracy face two major challenges: the derivation of the relevant two-loop matrix elements and the treatment of real radiation corrections. Major progress has been made on both aspects in the recent past, and has enabled NNLO calculations for several key processes at the LHC.

Transverse momentum distributions of colourless final states at hadron colliders display a universal behaviour at low q_T, which is well-understood from resummation. This feature is exploited in the q_T-subtraction technique to extract the singular real radiation contributions, and to construct parton-level event generator programs to NNLO accuracy. Recent applications of this technique are vector boson pair production [29] and associated VH production [30], including the full decay information and QCD corrections to the Higgs decay to bottom quarks.

The LHC experiments measure the top quark pair production cross section to very high precision. A similar level of accuracy is now obtained at the theory level with the recent calcu-

lation of NNLO corrections to the inclusive cross section [31], further improved by the inclusion of NNLL resummation terms. In the context of the calculation of the two-loop virtual corrections to top quark pair production, analytical results for the matching coefficients at NNLL [32] could be derived as a by-product, again illustrating the fruitful interplay of techniques for resummation and fixed order calculations at high perturbative orders.

Calculations multi-loop amplitudes in quantum field theory face major challenges due to the large number of amplitudes and Feynman integrals and due to the complicated analyticity structure of the individual multi-loop integrals. By systematically exploiting relations among integrals, one obtains a reduction to a minimal set of so-called master integrals. To compute these master integrals, various methods have been developed, often circumventing the direct integration over the loop momenta [33]. A particularly powerful technique exploits differential equations in masses and external invariants to compute master integrals. This technique has been recently systematized [34], and currently being applied to an increasing number of processes.

Gluon fusion is the dominant Higgs boson production process at the LHC. It receives large perturbative corrections at NLO and NNLO, and the determination of the Higgs boson properties could in the long run be limited by the theory precision on the NNLO calculation. The calculation of N^3LO corrections to Higgs production opens up a new era in complexity, with typically a hundred-fold increase in the number of diagrams and integrals. A first result in this endeavour is the threshold contribution to N^3LO, which is obtained analytically [35] using the soft-virtual approximation. This calculation makes extensive use of modern analytical developments, and establishes many of the technical tools that will pave the way towards the derivation of the full N^3LO coefficient function.

5 Going beyond the Standard Model

Although the Standard Model of particle physics is very successful in describing a wealth of experimental data that were taken at collider experiments during the past decades, it is not considered as ultimate theory of elementary particles, but rather as an effective theory describing dynamics at energy scales currently accessible, and possibly above. Searches for physics beyond the Standard Model [36] are a primary objective of particle physics, both theoretically and experimentally.

Direct searches for the production of new physics signatures have produced no evidence for new particles so far. They are constrained by the available collider energy, and expectations for next year's LHC run at highest-ever collision energy are consequently very high. Indirect searches [9] use precision observables, rare processes or the internal consistency of the Standard Model. They are not limited by the collider energy, but rather by experimental and theoretical precision, available luminosity, and last but not least, by the imagination and creativity of particle physicists.

Using the renormalization group equations, the parameters of the Standard Model Lagranigian can be extrapolated to very high energies. Of particular interest are the parameters related to the Higgs sector, since they determine the form of the effective Higgs potential. Depending on the form of the potential, the electroweak vaccum is either stable (absolute minimum of the potential), metastable (existence of a lower minimum at larger field values) or unstable (potential unbounded from below at large field values). The effective Higgs potential is particularly sensitive on the measured masses of the Higgs boson and the top quark, and current data point towards a metastable situation. In the case of metastability, tunnelling from the electroweak vacuum to the vacuum at large field values is possible. The tunnelling rate computed in the Standard Model (i.e. in absence of any physics beyond the Standard Model, even at the Planck scale) is however many orders of magnitude larger than the age of the universe. The tunnelling process is mediated by extended field configurations (instantons). Even in absence of physics beyond the Standard Model, it provides sensitivity to dynamics around the Planck scale, since

the typical instanton size is only about a factor ten larger than the Planck length. Following this observation, it has recently been demonstrated [37] that new physics at the Planck scale could lead to much smaller tunnelling times, thus invalidating the metastability condition. These new insights may provide very valuable input to model building for Planck scale physics.

One of the strongest motivations for physics beyond the Standard Model is the astrophysical evidence for dark matter in galaxies and in cosmological observations. Besides its gravitational effects, one expects dark matter to interact only weakly with known matter, and scenarios for dark matter production in the early universe favour masses of dark matter particles of the order of the weak scale. Direct searches for dark matter in recoil experiments have not produced conclusive evidence so far, and many realizations for weakly interacting massive particles are now constrained rather severely. An alternative scenario is provided by the so-called Higgs portal models, where dark matter and ordinary matter couple only through Higgs interactions, resulting in considerably lower rates for direct detection. A possible realization of the Higgs portal scenario is the inert doublet model [38,39], which will be probed at the next generation of direct detection experiments and which predicts small but detectable deviations in the Higgs boson properties.

Indirect searches for new physics in certain flavour observables are now reaching well beyond the energy scales probed in direct searches at the LHC. Visible, but not yet significant, discrepancies between experimental measurements and theoretical expectations are observed especially in $B \to K l^+ l^-$ final states [9] and in $B \to \tau\nu$ [40]. Both types of anomalies motivate theoretical speculation on possible new physics in the flavour sector, and further experimental validation is expected in due course.

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