Campagne 2020 Contrats Doctoraux Instituts/Initiatives

Proposition de Projet de Recherche Doctoral (PRD)

Appel à projet 2020

Intitulé du Projet de Recherche Doctoral :
Pushing the precision frontier of LHC physics: Automating QCD resummation for new physics

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Code : UMR 7589

Ecole Doctorale de rattachement de l'équipe & d'inscription du doctorant :
EDPIF (École Doctorale Physique en Île-de-France)

Doctorants actuellement encadrés par le directeur de thèse :
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Ecole Doctorale de rattachement :
EDPIF (École Doctorale Physique en Île-de-France)

Doctorants actuellement encadrés par le co-directeur de thèse : aucun

Cotutelle internationale : Non

Description du projet de recherche doctoral *(en français ou en anglais)*

Context

The Standard Model of particle physics is an extremely successful theory, with (almost) all observations performed so far perfectly matching the predictions. However, the present experimental status also reveals several of the conceptual issues and practical limitations of the Standard Model, like the absence of a candidate for dark matter, the hierarchy problem or the problematics of the neutrino masses. The Standard Model is therefore acknowledged as an effective theory that should originate from a more fundamental one yet to be discovered, and new phenomena are expected at energies well below the Planck scale. Whilst there are currently numerous intriguing features that provide hints that new physics could be accessible at energies that are already probed, none of these are yet significant enough to exclude the standard paradigm. However, as more data will be collected, we have reasons to be optimistic towards the close future.

One interesting avenue in the searches for new physics relies on probes in which precision theoretical predictions are confronted to accurate experimental measurements. With the steady increase of the statistics accumulated by the LHC experiments, and the absence of positive results in the searches for new physics, it becomes hence necessary to improve the accuracy not only of description of the new physics signals, but also of the Standard Model backgrounds. By far and large, this currently means making use of matrix elements computed at the next-to-leading-order accuracy in quantum chromodynamics (QCD) and matched with parton showers. The corresponding Monte Carlo simulations, *i.e.* in which matrix elements including next-to-leading order corrections driven by QCD are matched with parton showers, consists in the state-of-the-art for new physics predictions at the LHC [1].

However, the accuracy of the parton showers is quite limited, several approximation being inherent to the formalism. It is therefore desirable to calculate specific observables, like the total production rate of a given system or its invariant-mass spectrum, at a higher accuracy. This can be achieved by recalling that the next-to-leading-order QCD corrections include contributions that are enhanced when the system under consideration is produced in association with soft and/or collinear extra radiation. The impact of such QCD radiation is indeed known to enhance the production rate when the initial partons have just enough energy to produce the final-state system. In practice, there is a mismatch between the virtual corrections and the phase-space suppressed real emission contributions, which leads to the appearance of large threshold logarithmic terms. In the limit of the invariant mass of the final-state system M tending towards the partonic centre-of-mass energy $\sqrt{s}$, these threshold logarithms can be resummed to all orders in the strong coupling α_s [2,3].

Although these logarithms are manifest in the partonic cross section, they do not generally leads to divergences in the physical cross sections since they are smoothed by a convolution with the steeply falling parton distribution functions. Threshold resummation is then not really a summation of kinematic logarithms in the physical cross section, but rather an attempt to quantify the effect of a well-defined set of quantum corrections to all orders. This can be significant even if the hadronic threshold is far from being reached, and leads to a reduction of the theoretical uncertainties on the predictions. This resummation procedure therefore provides a systematic way to improve the predictions in a regime in which the perturbative series feature large logarithmic terms, *i.e.* where the whole perturbative expansion is not justified. As said above, such a resummation can be handled through the parton showers, although their accuracy is limited. In this thesis, we propose to improve upon this scheme, in order to provide **a better description at the hard-scattering level of any process of any theory**.

Technicalities

This thesis fits within this context of aiming at the best precision for the theoretical predictions associated with a given process at particle colliders, and for a given model. All-order resummation is achieved through the exponentiation of the soft QCD radiation, the latter usual leading to logarithms of the log(*1-z*) form, where $z = M^2/s$. Those logarithms are the so-called threshold logarithms and are thus large close to threshold, *i.e.* for $z \rightarrow 1$. Their resummation does however not take place in the *z*-space directly, but in a Mellin *N*-space, where *N* is the Mellin variable conjugate to *z*. The threshold region therefore $z \rightarrow 1$ corresponds to the $N \rightarrow \infty$ limit. In such a space, the parton cross section takes a form featuring important factorisation properties, that are necessary for achieving the resummation of the threshold logarithms to all orders. Whilst parton showers achieve the resummation of the logarithms at the leading logarithmic accuracy, *i.e.* the contributions featuring the highest powers in the logarithms are resummed to all orders, analytical resummation can be achieved at the next-to-leading, or even at the next-to-next-to-leading and next-to-next-to-next-to-leading accuracy in Mellin space. In this last case, lower powers of the logarithms are also systematically included and more accurate predictions can therefore be achieved. One must finally perform an inverse Mellin transform to obtain a resummed cross section in the physical *z*-space.

Close to threshold, $z \sim 1$, log(*1-z*) is large so that resummation is essential. On the other hand, in a kinematical regime where the *z* variable is small, the perturbative series in the strong coupling is well behaved so that fixed-order calculations are totally valid. These two ways of computing the predictions are complementary and can be combined, so that the resummation dominates close to threshold and the fixed-order results do far from threshold. In the intermediate regime, both pieces of the calculation are combined following a prescription avoid the double-counting.

During the last decade, we have developed the high-energy physics package RESUMMINO that consists in a computer code targeting resummed predictions, at the next-to-leading-logarithmic accuracy, matched with fixed-order calculations at the next-to-leading-order [4]. The programme can be used to achieve such precision predictions in the weak scale supersymmetry framework [5,6], for slepton pair production [7], electroweakino pair-production [8] and the associated production of a gluino and an electroweakino [9].

In this thesis, we plan to generalise this work so that **QCD resummation calculations for various observables relevant for the LHC could be performed for any process in any model**, *i.e.* both in the framework of the Standard Model and for new physics. This goal is today reachable thanks to the development of highly automated computations for next-to-leading-order calculations, as well as for their matching with parton showers, and thus for a large class of models and processes through the MADGRAPH5_aMC@NLO [1,10]. The first technical part of the thesis project will then consist in understanding how next-to-leading order calculations in QCD work and in devising an efficient method to extract the components allowing for all-order QCD resummation from the code generated by the MADGRAPH5_aMC@NLO framework.

Working plans

We plan to begin with studying standard candles (total rates and invariant mass distributions) for processes in the Standard Model and in supersymmetric models, for which a vast literature exists. This will allow the student for a better understanding of how perturbative QCD works, and to analytically validate the results to be obtained automatically through a plugin linking MADGRAPH5_aMC@NLO and RESUMMINO to be developed during the thesis. The corresponding software will be open access for both theoretical and experimental physicists who are working on collider (in particular LHC) physics.

In a second step, novel phenomenological applications to new physics will be conducted, in particular in the framework of well-motivated and widely studied UV-complete models (such as models featuring a strong dynamics at a high-energy scale or supersymmetric models), simplified models (including *e.g.* a dark matter candidate and a mediator connecting it to the Standard Model), and effective field theories extending the Standard Model by higher-dimensional operators. Several signatures of these models being actively searched for at the LHC, our calculations will allow to revisit the existing limits and update them by accounting for more precise predictions plagued with smaller theoretical systematic uncertainties. Moreover, tables of total and differential cross sections relevant for LHC and future collider physics will be provided, as this is known as relevant inputs for the high-energy physics community.

Expertise and skills to be developed

Within this thesis project, the candidate is expected to develop a deep knowledge of new physics models and phenomenology, as well as to acquire strong computing skills in particular in QCD. Achieving the predefined goals will allow the candidate to obtain a strong expertise both in the development and in the usage of various tools widely used in our community, which is a valuable expertise for most research groups in the world and therefore opens the door to a long carrier in academia. On the other hand, the technical skills to be acquired in programming and computing, as well as the way of thinking in solving long and hard problems typical of high-energy particle physics, are also in high demand into the wider scientific area (including the private sector). Numerous career choices will then be available to the candidate after the thesis.

References

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