Scientific Report for the OTKA grant K 60432

The goal of the proposed research was to develop further some of the theoretical tools that were essential for exploiting the physics potential of present and future high-energy collider experiments. The most important experiments at present are installed on the Large Hadron Collider (LHC) that has been in operation since 2009 at CERN. In the LHC protons collide head-on at the total centre-of-mass energy of 7 TeV, which will later be increased to 14 TeV. At these energies the protons can be considered as a bunch of free-flying particles, quarks and gluons, or as commonly called partons — the constiutents of the proton. The physics of partons is described by Quantum Chromodynamics (QCD), therefore, the detection of new particles at the LHC and the detailed understanding of QCD are closely connected. In our research we made internationally recognized progress in two main areas of QCD: **(1) Exact higher order computations; (2) Shower Monte Carlo programs.**

1. Exact higher order computations

The frontline of research in exact higher order computations has two major fields: (a) computation of one-loop amplitudes to processes with high multiplicity in the final state; (b) computation of cross sections at the next-to-next-to-leading order (NNLO) accuracy to low multiplicity processes. In the research plan we outlined contribution to both of these fields.

a) *Computation of one-loop amplitudes to processes with high multiplicity in the final state*

In this field, *we have computed the six-photon amplitudes at one-loop, completely numerically* as planned [1]. In a second publication we have also computed *the eight-photon amplitudes at one-loop, completely numerically* [2]. Important specific applications of the fully numerical approach to computing radiative corrections is the computation of NLO corrections to the cross sections of the pp → $b\bar{b}\ t\bar{t}$ or $t\bar{t}\ \gamma\gamma$ processes (as discussed in the proposal, present analytic techniques and computer capacities are insufficient for computing these cross sections analytically). In the proposed research we planned to compute one of these cross sections in collaboration with prof. Kunszt. Unfortunately, this collaboration has not materialised. Therefore, we started to develop our own computer program for the computation of one-loop QCD amplitudes numerically [3]. In the meantime, publicly available programs have appeared that can be used for the same purpose, thus for the time being we put aside the development of our code. (However, we plan to continue this project in the future because we assume we can make further improvements in numerical stability and efficiency). Instead of computing one-loop amplitudes, we concentrated on utilising the available numerical codes for producing cross sections. In particular, we worked out the combination of two publicly available programs, the HELAC and POWHEG-box packages to generate unweighted Monte Carlo events at the parton level that can be interfaced with shower programs, such as PYTHIA. Using this method, we produced predictions for the hadron level cross section of $t\bar{t}$ [4] and $t\bar{t}$ + jet hadroproduction [5] which are correct up to NLO accuracy upon expansion in the strong coupling. Similar computations for the pp → $b\bar{b}\ t\bar{t}$ and $t\bar{t}$ + 2 jets processes are in progress. The advantage of such an approach as compared to the parton level NLO predictions is that we can provide unweighted events at the hadron level that can directly be compared with the experimental data. To illustrate our predictions, we show various distributions obtained at the hadron level (NLO+PS) as compared to parton-level predictions at next-to-leading order accuracy (NLO) in figure 1. for the pp → $t\bar{t}$ + jet process in the semileptonic decay mode of the $t\bar{t}$ pair: (a) transverse momentum distribution of the lepton; (b) rapiditiy distribution of the lepton; (d) transverse momentum distribution of the fifth jet (ordered by magnitude of the transverse momentum); (e)) rapiditiy distribution of the fifth jet. The differences indicate the importance of the parton-shower for the various distributions. More detailed discussion of these results will be presented in the research papers.

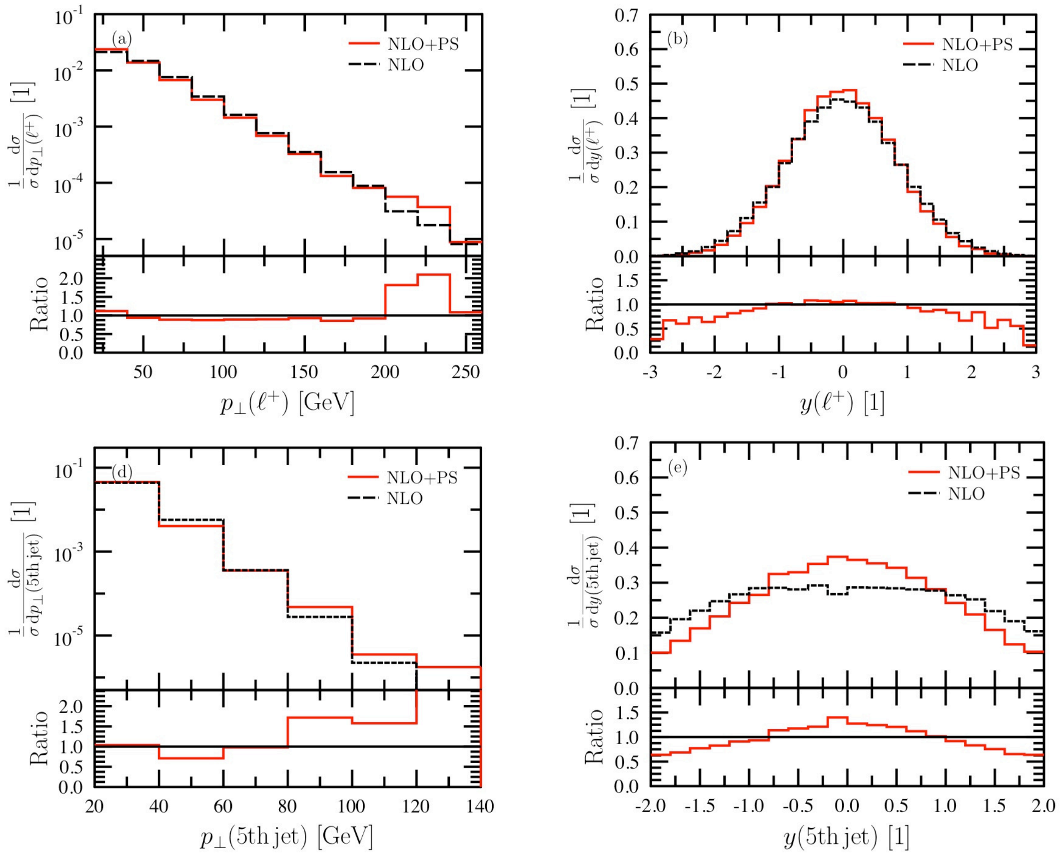

Figure 1. Lepton and jet distributions obtained at the hadron level (NLO+PS) as compared to parton-level predictions at next-to-leading order accuracy (NLO).

b) *Computation of cross sections at the next-to-next-to-leading order (NNLO) accuracy*

In some cases, it is desirable to compute QCD cross sections at NNLO accuracy. In the proposal we planned to develop *a general scheme of computing QCD cross sections at NNLO accuracy and apply the method to the Drell-Yan production with the spin-correlations of the leptonic decay products of the vector boson included.* The problem was more complex than we had envisaged. With the support of this grant, we published eight research papers [6-13] (almost 400 pages in total) and seven conference proceedings, but there are still missing integrals (the integral of the doubly-unresolved subtractions over the factorised phase space of the unresolved partons) for completion, thus we could not publish physical cross sections yet. This work is in progress and we plan to make predictions for 1 → 3 decays first.

2. Shower Monte Carlo programs

The exact higher order computations have the drawback that those can yield cross sections of processes with few number of final state particles as opposed to the experimentally observed large multiplicities. The usual approach to simulating events with large multiplicities and computing the relevant cross sections is the use of shower Monte Carlo programs. In recent years a lot of international effort has been invested to develop shower Monte Carlo programs for producing cross section predictions at the hadron level that are correct up to NLO accuracy when expanded in the strong coupling. During the grant period we also contributed to this line of research with a new approach. We specified recursive equations that can be used to generate a lowest order parton shower for hard scattering in hadron-hadron collisions. The formalism is based on the factorization soft and collinear interactions from relatively harder interactions in QCD amplitudes. The novelty of the approach is that *it incorporates quantum interference between different amplitudes in those cases in which the interference diagrams have leading soft or collinear singularities. It also incorporates the color and spin information carried by partons emerging from a hard interaction.* One motivation for this work is to have a method that can naturally cooperate with next-to-leading order calculations. We published four research papers [14-17] and seven conference proceedings (of which two are write-ups of plenary talks) about the relevant results.

During the grant period the student participant defended his thesis [18] in Debrecen and found post-doctoral employment first at the University of Zurich and than at DESY in Zeuthen. The post doctorand found tenured employment at DESY in Hamburg. Our results also helped us become a node in a successful joint Swiss-Hungarian-Serbian consortium proposal [19] and a FP7 network [20]. In summary, we made important contributions in all activities outlined in the proposal, not exactly as planned, but similar in scientific weight. The published papers are all known and frequently cited in the literature.

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