Advancing Collider Physics: from Twistors to Monte Carlos

Scientific Program

The goal of this Workshop is to develop theoretical tools needed to explore spontaneous symmetry breaking in the Standard Model (SM) and uncover evidence for new physics at present and future high-energy colliders. We group the Workshop topics into the following areas,

– **Higgs production**

The primary goal of Higgs physics is to understand the dynamics of electroweak symmetry breaking. Beyond discovery of one or several Higgs resonances, this requires the measurement of couplings of these particles to gauge bosons, quarks and leptons. Distributions of final state particles give information of the CP properties of the produced Higgs boson, for example, the leptons in $H \to ZZ \to llll$ decays or azimuthal angle correlations of the quark jets in weak boson fusion. At the LHC or, later, at an ILC, coupling information is accessible by measuring the rates of various combinations of Higgs production and decay channels. A quantitative comparison with theoretical models requires the knowledge of cross sections at an accuracy that can only be achieved by including higher order QCD and/or electroweak corrections. Similarly an excellent understanding of the differential cross sections of a variety of background processes is needed for these coupling measurements, again requiring loop corrections. Other techniques suggested for Higgs coupling measurements require improved understanding of semi-soft jet emission in hard QCD events (central jet veto against b-quarks from top-decays and soft gluon jets from QCD backgrounds) or of forward jets in the LHC environment. Making progress on these fronts requires fruitful discussions between perturbative QCD experts, specialists on QCD parton shower programs and Higgs phenomenologists.

– **Higher-order computations**

The direct search for new physics signals at the LHC will almost always involve multiparticle final states. Top quarks are measured through their decay into a bottom quark and a subsequently decaying W-boson, yielding six-jet final states for top quark pair production. Searches for Higgs bosons in the vector boson fusion channel require them to be accompanied by two forward jets; including the Higgs boson decay products, four final state jets are formed. Searches for supersymmetric particles are somewhat analogous to top quark detection and often involve final states with six or more jets. Multiparticle tree-graphs give the leading order estimate of the size of new physics (mainly weak interaction) effects.

Meaningful searches for these signals require not only a very good anticipation of the expected signal, but also of all standard model backgrounds yielding identical final state signatures. Since leading-order calculations are affected by large uncertainties in their normalisation and their kinematical dependence, it appears almost mandatory to include strong NLO corrections.

At hadron colliders all processes are affected by sizeable effects of the strong interaction which are typically at the order of 20-50%. However, at high energies, the electroweak corrections also become important owing to the appearance of large logarithmic effects and can reach 20% or more at LHC energies. Therefore, we will discuss new tools to evaluate the large strong and electroweak corrections for the most important processes at the LHC such as those required for accurate measurements of the W mass. In particular, we will discuss the large electroweak logarithms relevant for both LHC and ILC processes.

In the cleaner environment of lepton colliders the accuracy of the experiments is much higher and theoretical predictions need to be more precise. At the ILC, high precision measurements of multiparticle final states provide a window on new physics effects at much higher energies - in much the same way as electroweak precision observables at LEP provided indirect evidence on the Higgs boson mass. This requires a more complete inclusion of higher-order electroweak corrections. In particular, for the GIGAZ and MEGAW options of the ILC the complete one-loop corrections to four-fermion production, two-loop corrections to fermion-pair production processes and Bhabha scattering are required.

NLO corrections

NLO corrections are becoming available for 2 → 3 processes where some of the particles are massive e.g. QCD corrections to $pp \to t\bar{t}H$, $pp \to W/Z + 2$ jets, and weak corrections to $H \to 4$ fermions. However, a major bottleneck is the analytic evaluation of the one-loop amplitudes and so far only very few one-loop amplitudes with more than five external legs have been computed. Nevertheless, substantial progress has been made very recently on both the numerical and algebraic computation of six point amplitudes, such as the QCD corrections to $gg \to gggg$ and the weak corrections to $e^+e^- \to 4$ fermions. We plan to foster discussions of both analytical and numerical techniques for evaluating multi-particle one-loop graphs with both internal and external massive particles that are necessary for the strong and electroweak corrections to the processes that give the best handle on new physics. By combining these techniques with efficient methods for the numerical computation of tree diagrams, it should be possible to develop programs for the fully-numerical computation of physical observables with many final-state partons. Bringing together the main players in this field during the Workshop, substantial progress is both possible and expected. In particular, we will discuss extensions of established techniques for automatically evaluating tree-graphs to determine the one-loop amplitudes for processes with more than four external legs such as four fermion production at the ILC and vector boson pair production at large transverse momentum at the LHC. A successful achievement of this program will open the way to a fully numerical hadron-level event generator with both strong and electroweak NLO corrections.

NNLO corrections

A (QCD) goal is to compute NNLO corrections to cross sections of basic QCD processes with very large NLO corrections, or when the dominant error of a measurement is due to unknown higher order corrections. These observables can therefore serve as very precise tests of QCD, or be used for an improved determination of the QCD coupling constant α_s and the parton density functions.

To compute an n-particle cross section to NNLO accuracy, one needs to know (i) the virtual two-loop corrections to the n-particle production process (ii) the virtual one-loop corrections to the $n+1$-particle process (iii) the tree level $n+2$-particle process. Moreover, one has to devise a method to extract the divergent parts due to real radiation from the $n+1$ and $n+2$ particle processes.

At NNLO, the current state of the art is predictions for the Higgs and Drell-Yan cross section (both inclusive, and via their rapidity distributions) in pp collisions and for 2 jet production in e^+e^- annihilation. No predictions exist at present for $2 \to 2$ scattering processes or $1 \to 3$ decay processes.

Thanks to a number of technical breakthroughs, the virtual two-loop corrections to all partonic $2 \to 2$ scattering and $1 \to 3$ decay matrix elements relevant to jet physics with massless quarks (as well as the QCD corrections to photon pair production $gg \to \gamma\gamma$ and $q\bar{q} \to \gamma\gamma$) have become available. These results were checked already very thoroughly, especially concerning their infrared pole structure, which was predicted from an infrared factorization formula. Topics for the Workshop will include extensions of these results to include more massive external particles as well as massive internal particles including both analytical and numerical techniques for evaluating massive two-loop vertex and two-loop box graphs that are vital for strong and weak interaction processes at the LHC and ILC.

The one-loop corrections to $2 \to 3$ scattering and $1 \to 4$ decay processes relevant to massless jet physics were computed in the context of multi-jet calculations at NLO some time ago. Similarly, the tree-level $2 \to 4$ scattering and $1 \to 5$ decay processes are also well known. Here the issue is to extract the infrared divergent parts arising from these configurations (which ultimately cancel against the two-loop divergences) leaving a finite remainder. Only after this separation has been performed, it is possible to implement the known finite remainder into NNLO calculation. The extraction of the divergent parts from these one-loop single unresolved and tree-level double unresolved configurations is however much more involved than at NLO. Several suggestions on how to achieve this have been made in the literature, however, and progress is expected on the timescale of this Workshop. In fact, there is the real possibility that the milestone of the first NNLO predictions for jet cross sections at both the LHC and ILC could be achieved at the Galileo Galilei Institute during this Workshop.

Resummations

In many cases the dominant logarithmic corrections to strong interaction processes are known to all orders in the strong coupling constant. In these cases, they can be resummed leading to improved perturbative predictions. The goals are: (a) to improve the accuracy of perturbative results by including resummation of effects enhanced in particular regions of phase space; (b) to extend the application of formalisms to match parton-shower event generators and NLO computations to as many physical processes as possible, and to improve their programming structure and interoperability.

– **Computer algebra**

The complexity of multi-particle multi-loop processes requires the use and development of algebraic programs. We will discuss refinements of these packages and applications to automatically generate and calculate amplitudes.

– **New Formal Developments**

In December 2003, Witten proposed a new kind of duality between gauge theories and a topological string theory with a novel target space, projective twistor space. This proposal generalized Nair's long-ago observation of a connection between twistors and the simplest gauge-theory amplitudes. The new duality is a weak coupling–weak coupling duality, so that perturbative methods can be applied on both sides. This also means that new insights emerging from the twistor-string theory can be applied directly to perturbative gauge theories, a subject of central importance in the run-up to the start of LHC operations.

The new insights emerging from twistor theory include sets of differential equations satisfied by gauge-theory amplitudes; a novel decomposition of tree-level amplitudes; a new connection with the so-called unitarity-based method for loop calculations, as well as enhancements to that method; and novel, on-shell recurrence relations for tree amplitudes. These new techniques and approaches have quickly led to vastly more efficient derivations of known amplitudes and more importantly have in the past year enabled the calculation of many new and general results which had previously proved intractable. These include N=1 supersymmetric and non-supersymmetric results, and amplitudes involving fermions, scalars, and massive particles. The latest developments in particular hold great promise for yielding new approaches to loop calculations, in turn promising new — and otherwise difficult-to-calculate — amplitudes of direct phenomenological relevance.

These developments have been greatly aided by interchanges between two previously-disconnected communities, namely that of experts in perturbative gauge-theory calculations (primarily QCD) and string theorists. It is one of the aims of the proposed Galileo Program to push forward the developments in this frontier area, with the active collaboration of members of both of these different communities. One of the virtues of the GGI is precisely that it will stimulate cross-area collaborations by researchers from these different areas over an extended period of time.

The proposed Galileo Program will also serve to disseminate these new techniques in the community of researchers most able to apply them to calculations of importance for LHC physics, namely that of physicists working in perturbative QCD and electroweak physics. The interaction amongst those working on new formal methods will also serve to clarify the most important open questions, and to further research to solve them. We believe that the current rapid pace of developments will continue, as there are numerous directions of phenomenological relevance where explorations are still at a relatively early stage. These include massive theories, and higher-loop results. The Workshop will also serve to encourage progress in these directions.