NLO predictions for many-particle production

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Abstract

1. INTRODUCTION

At the LHC, most of the background processes to interesting signatures will involve multi-particle final states, either through the decay of resonances or from direct multi-particle production. However, only a few theoretical predictions beyond leading order are available up to now for processes with more than two particles in the final state. A lot of activity is going on at the moment to improve this situation. The following sections should serve to summarize the current situation and to assess the needs and prospects for the near future.

2. STATUS

In the following we list the $2 \to 3$ processes in hadronic collisions that have been calculated so far, and summarize the current status concerning the calculation of $2 \to 4$ processes.

pp→ 3 particles		
process $(V = Z, W^{\pm})$	references	comments
$pp \to 3$ jets	[?, ?, ?, ?, ?, ?]	public MC available [?]
$pp \to V +$ 2 jets	[?, ?, ?, ?]	public MC available
$pp \to \gamma\gamma$ jet	[?, ?]	
$pp \to Zb\bar{b}$	[?]	
$pp \to t\bar{t}H, b\bar{b}H, b\bar{b}A$	[?, ?, ?, ?]	
$pp \to t\bar{t}$ jet	[?]	still under construction

2→ 4 (5)		
process	references	comments
$e^+e^- \to 4$ fermions	[?, ?]	cross sections
$e^+e^- \to HH\nu\bar{\nu}$	[?]	status report
6- and 7 - gluon amplitudes for Super–Yang–Mills $\mathcal{N} = 4$	[?, ?]	only selected helicity configurations
6-scalar amplitudes in the Yukawa model	[?]	
2-photon 4-scalar amplitudes in the Yukawa model	[?]	
N-photon helicity amplitudes	[?]	MHV only

3. A realistic NLO wishlist for multi-particle final states

The "experimenter's wishlist" which has been set up at the Tevatron Run II Monte Carlo workshop in April 2001 has been shown at many conferences and workshops since, but both experimentalists and theorists agree that it is time for an update where the list items are "weighted" by experimental priorities and some less important and/or theoretically barely feasible processes are eliminated. The list below is realistic in the sense that those processes have a good chance to be calculated by the start of LHC or during the first year of data taking with present technologies. For this reason, the list only contains $2 \to 3$ and $2 \to 4$ processes. An overview over the theoretical tools which have been developed recently, indicating also for which types of processes they are most suitable, will be given in section 4.

process ($V \in \{Z, W, \gamma\}$)	background to
1. $pp \to V\,V$ jet	$t\bar{t}H$, new physics
2. $pp \to H + 2$ jets	H production by vector boson fusion (VBF)
3. $pp \to t\bar{t}\,b\bar{b}$	$t\bar{t}H$
4. $pp \to t\bar{t} + 2$ jets	$t\bar{t}H$
5. $pp \to V\,V\,b\bar{b}$	VBF$\to H \to VV$, $t\bar{t}H$, new physics
6. $pp \to V\,V + 2$ jets	VBF$\to H \to VV$
7. $pp \to V + 3$ jets	various new physics signatures
8. $pp \to V\,V\,V$	SUSY trilepton

Work on (at least) the processes 1. to 4. is already in progress by several groups, and clearly all of them aim at a setup which allows for a straightforward application to other processes.

4. REVIEW OF THEORETICAL APPROACHES

In this section, Ţrst a brief overview of the existing methods to tackle one-loop multi-leg amplitudes will be given. In the following subsections, the individual methods will be presented in more detail.

In general, the NLO calculation of a $2 \to N$ particle process at partonic level involves the following steps:

1. diagram generation
2. calculation of the real radiation corrections (requires $2 \to N+1$ amplitudes at tree level and subtraction of poles due to soft/collinear massless particles)
3. calculation of the one-loop amplitude (involves $(N+2)$–point integrals)
4. combination of real and virtual contributions, integration over the phase space

For multi-particle processes, step 3. above is the bottleneck, so we will concentrate on this one in the following. It must be mentioned at this point that there is also an approach [**?**, **?**, **?**] which avoids the splitting into real and virtual parts by Ţrst performing the sum over cuts for a given graph and then integrating over all momenta, including the loop momenta, numerically. In this way unitarity is exploited to cancel soft and collinear divergences before they show up as explicit poles. However, this method has not been applied to hadronic initial states yet.

Besides this fully numerical approach, there are semi-numerical methods, which do split into real and virtual corrections, but largely rely on the numerical evaluation of loop integrals, either by doing already the complex contour integration over the loop momenta numerically, or by evaluating the Feynman parameter representation of the integrals numerically. This requires the elaboration of a scheme to remove the poles from the integrals before the numerical integration. The following groups have worked in this direction recently: *(historical order)*

- Ferroglia, Passera, Passarino, Uccirati [**?**]
- Binoth, Heinrich, Kauer [**?**]
- Nagy, Soper [**?**, **?**]
- Kurihara, Kaneko [**?**]
- Anastasiou, Daleo [**?**]

The method to calculate one-loop amplitudes which was historically the Ţrst [**?**, **?**, **?**] and also has produced the largest number of physical results so far is the one where an algebraic reduction of the tensor integrals to a set of scalar ”basis integrals” is performed. As the basis integrals are known in analytic form, the virtual amplitude is expressed by analytic functions depending on the invariants of the given process, thus having maximal analytic control when proceeding to the phase space integration. On the other hand, it has become clear in recent years that, in order to avoid numerical instabilities upon phase space integration due to denominators tending to zero, the ”purely algebraic” approach for multi-leg amplitudes has to be supplemented by either Taylor expansions around the critical points or by numerical evaluation of some of the integrals, at least in the critical phase space regions[**?**, **?**, **?**]. Therefore, the borderline between ”algebraic” and ”semi-numerical” cannot be drawn in a clear way. As there are many variants of the ”algebraic/semi-numerical” approach, only the more recent ones will be listed below.

- Denner, Dittmaier
  massive and massless,
  applied to calculate the first cross section for a 6-point process [**?**, **?**, **?**, **?**, **?**]
- Ellis R.K., Giele, Glover, Zanderighi
  massless propagators only [**?**, **?**, **?**]
- Binoth, Guillet, Heinrich, Pilon, Schubert
  massless and massive [**?**, **?**]
- GRACE group
  applications so far massive, massless under development [**?**, **?**]

- Del Aguila, Pittau [**?**];
  Van Hameren, Vollinga, Weinzierl [**?**]
  based on spinor helicity
- Duplancic, Nizic
  massless propagators only [**?**]
- Fleischer, Jegerlehner, Tarasov
  massive only [**?**, **?**]
- Bern, Dixon, Kosower
  massless propagators only [**?**, **?**]
  This group now pursues a different approach based on the construction of loop integrals from unitarity cuts, factorisation properties and on-shell recursion relations, see below.

Very recently, a novel approach to the calculation of one-loop amplitudes has emerged, which is often referred to as ”twistor-space-inspired” methods []. Using these methods, compact expressions for very complex tree-level amplitudes could be achieved, and their extension to loop level has seen a very rapid development [**?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**]. In particular, the unitarity-based method of [**?**, **?**] has seen a successful revival due to the use of on-shell recursion relations [**?**, **?**, **?**]. However, this approach being very new, it is difŢcult to judge whether it will ever be useful for processes where several different mass scales are involved.

4.1 Public programs

The only NLO programs for $2 \to 3$ processes in hadronic collisions which are publicly available so far are

`NLOJET++`	$pp \to 3\,\mathrm{jets}$	Z. Nagy [**?**]
`MCFM`	$pp \to V + 2\,\mathrm{jets}$	J. Campbell, R.K. Ellis, D. Rainwater [**?**, **?**, **?**];
	$pp \to V + b\bar{b}$	J. Campbell, R.K. Ellis, F. Maltoni, S. Willenbrock [**?**].

4.2 Combination with parton showers

Ideally, the partonic calculation should be complemented by a parton shower and hadronisation for a maximally realistic comparison to data. Several groups have worked on the subject to consistently combine partonic NLO calculations with parton showers.

- Collins, Zu [**?**, **?**]
- Frixione, Nason, Webber (MC@NLO) [**?**, **?**, **?**]
- Kurihara, Fujimoto, Ishikawa, Kato, Kawabata, Munehisa, Tanaka [**?**]
- Krämer, Soper [**?**, **?**, **?**]
- Nagy, Soper [**?**]

will be treated extensively in other parts of the proceedings, I guess

4.3 More detailed descriptions of recent methods

put individual contributions here

CONCLUSIONS

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