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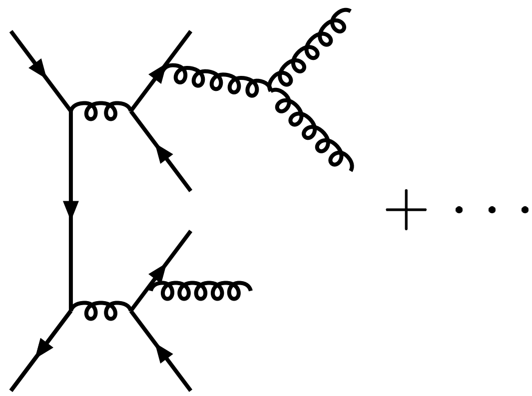
PRODUCTION OF GAUGE BOSONS PLUS JETS IN HADRONIC COLLISIONS

1) Introduction
2) The strategy
3) The **ALPGEN** project
4) An example: $\mathbf{W}b\bar{b}+n$ jets
5) Some results
6) Conclusions

INTRODUCTION

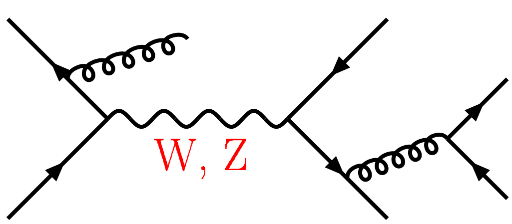
Multijet final states are characteristic of a large class of important phenomena present in high-energy hadronic collisions.

- QCD interactions generate multijet final states via radiative processes at high orders of perturbation theory (pure QCD processes):



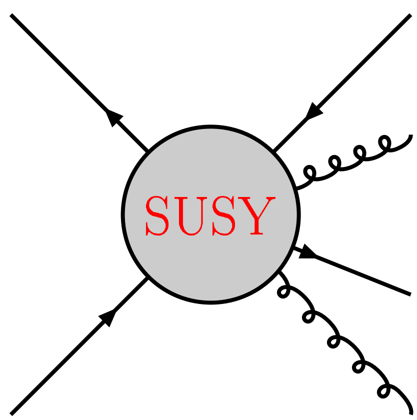
- Heavy particles in the Standard Model (SM), such as W and Z bosons or the top quark, t, decay to multiquark configurations (eventually leading to jets) via electroweak (EW) interactions

(mixed EW-QCD processes):



•In addition to the above SM sources, particles possibly present in theories beyond the SM (BSM) are expected to decay to multiparton final states, and therefore to lead to multijets. Typical examples are the cascade decays to quarks and gluons of supersymmetric strongly interacting particles, such as squarks and gluinos

(mixed SUSY-QCD processes):



In addition to fully hadronic multijet final states, a special interest exists in final states where the jets are accompanied by gauge bosons.

• For example

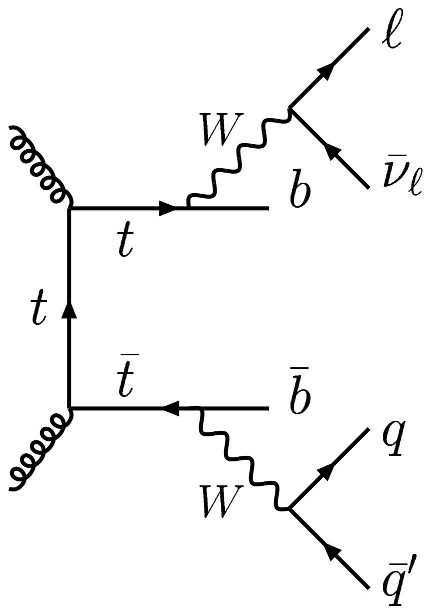
$$p \overset{(-)}{p} \to Z + \ jets \to \nu\bar{\nu} + jets$$

is an important background to SUSY searches.

• Likewise,

$$p\overset{(-)}{p} \to W + \ 4\ jets \to \ell\ \bar{\nu}_\ell + 4\ jets$$

provides the leading source of backgrounds to the identification and study of top quark pairs in hadronic collisions:



Typical $t\bar{t}$ production diagram

Several parton-level Monte Carlo (MC) event generators exist in the literature:

PAPAGENO	VECBOS	NJETS
MADGRAPH	CompHEP	GRACE
HELAC-PHEGAS		

• Studies can be performed by assuming that hard partons can be identified with jets, and that the jets' momenta are equal to those of the parent partons.

• This simplification gives rough estimates, but *cannot be used in the context of realistic detector simulations, for which a representation of the full structure of the final state (in terms of hadrons) is required.*

• This full description can be obtained by merging the partonic final states with shower MC programs such as

`HERWIG PYTHIA ISAJET`

where partons are perturbatively evolved through emission of gluons, and subsequently hadronized.

• However, this merging is not always possible, since common parton-level MC's sum and average over flavours and colours, and do not usually provide sufficient information on the flavour and colour content of the events

$$\Rightarrow$$

1) We review a strategy for the construction of event generators for multijet final states, based on the exact leading-order evaluation of the matrix elements for assigned flavour and colour configurations, and the subsequent shower development and transition into a fully hadronized final state.

2) We present `ALPGEN`, a collection of codes realized within the framework of the presented approach.

3) As a case study, we focus on the production of $WQ\bar{Q}+n$ jet final states (with Q being a massive quark, and $n \leq 4$).

4) We present results, in the case of $Q = b$, for several production rates and distributions of interest at the LHC and at the Tevatron.

Work done in collaboration with M. Mangano, M. Moretti, F. Piccinini and A. Polosa:

- `hep-ph/0206293;`
- `Nucl.Phys.B632:343-362,2002, hep-ph/0108069;`
- `Nucl.Phys.B539:215-232,1999, hep-ph/9807570.`

THE STRATEGY

There are two main problems:

a) The Matrix-element evaluation

b) The reconstruction of the colour flow

We discuss for simplicity the case of multigluon processes, as the extensions to cases with quarks and electroweak particles follow the same pattern.

a)

• The process $gg \to 10\ g$ has 5×10^9 contributing Feynman diagrams $\Rightarrow$

The algorithm **`ALPHA`** is the best possible tool to carry out the computation.

• This algorithm determines the matrix elements from a (numerical) Legendre transform of the effective action, using a recursive procedure *which does not make explicit use of Feynman diagrams.*

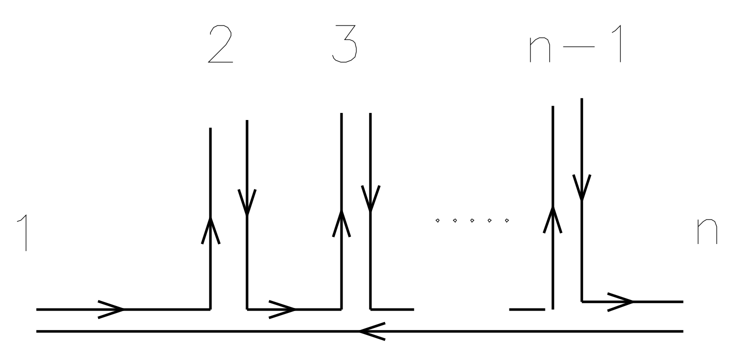
b)

The scattering amplitude for n gluons with momenta p_i^μ, helicities ϵ_i^μ and colours a_i (with $i = 1, \ldots, n$), can be written as

$$M\left(\{p_i\}, \{\epsilon_i\}, \{a_i\}\right) = \sum_{P(2,3,\ldots,n)} \mathrm{tr}(\lambda^{a_{i_1}} \lambda^{a_{i_2}} \ldots \lambda^{a_{i_n}})\, A(\{p_{i_1}\}, \{\epsilon_{i_1}\}; \ldots \{p_{i_n}\}, \{\epsilon_{i_n}\})$$

The sum extends over all permutations P_i of indices $(2, 3, \ldots, n)$, and the functions $A(\{P_i\})$ (known as *dual* or *colour-ordered* amplitudes) are gauge invariant, cyclically-symmetric functions of the gluons' momenta and helicities.

• Each dual amplitude $A(\{P_i\})$ corresponds to colour flows from one gluon to the next, according to the ordering specified by the permutation of indices:



• Any event generator should keep track, event by event, of the colour flow (and flavour content) for a realistic simulation of the subsequent evolution into fully hadronized final states.

THE ALPGEN PROJECT

- Available codes and processes (within the SM):

1: $p\overset{(-)}{p} \to WQ\bar{Q} + n$ jets $(n \leq 4)$

2: $p\overset{(-)}{p} \to Z/\gamma^* Q\bar{Q} + n$ jets $(n \leq 4)$

3: $p\overset{(-)}{p} \to W + n$ jets $(n \leq 6)$

4: $p\overset{(-)}{p} \to Z/\gamma^* + n$ jets $(n \leq 6)$

5: $p\overset{(-)}{p} \to n_z\, Z + n_w\, W + n_h\, H + n$ jets
$(n_z + n_w + n_h + n \leq 8,\ n \leq 3)$

6: $p\overset{(-)}{p} \to Q\bar{Q} + n$ jets $(n \leq 6)$

7: $p\overset{(-)}{p} \to Q\bar{Q}Q'\bar{Q}' + n$ jets $(n \leq 4)$

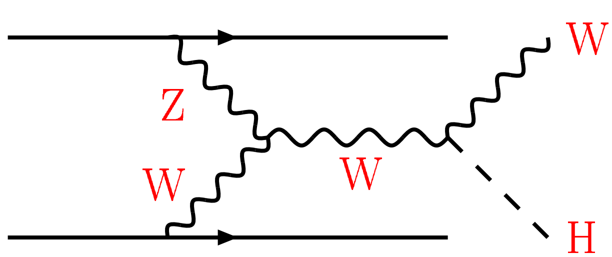
8: $p\overset{(-)}{p} \to HQ\bar{Q} + n$ jets $(n \leq 4)$.

- Where?

http://mlm.home.cern.ch/mlm/alpgen/

$\mathbf{W}b\bar{b} + n$ jets

- The associated production of W bosons and heavy quarks ($Q = b, t$) is an important background process to several searches for new physics, as well as to the detection of top quarks.
- The final state $Wb\bar{b}$ is also the leading irreducible background to the production of SM Higgs bosons via the process $p\overset{(-)}{p} \to W(H \to b\bar{b})$:



- As an application of our techniques, we focus on the process

$$p\overset{(-)}{p} \to (W \to \ell\nu_\ell) + Q\overline{Q} + n \text{ jets } (n \leq 4).$$

- The corresponding code, `WQQGEN`, is part of the `ALPGEN` package and includes an interface to `HERWIG`, allowing the events to be fully evolved through the coherent parton shower, and to be hadronized.

The partonic rates at the LHC ($m_b \neq 0$)

$$\text{Jets}: \ p_T^i > 20 \text{ GeV}, \quad |\eta_i| < 2.5, \quad \Delta R_{ij} > 0.4.$$

- The classes of processes (up to 2 light-quark pairs) are (additional final-state gluons understood):

$$
\begin{aligned}
PROC = 1: &\quad q\bar{q}' \to Wb\bar{b} \\
PROC = 2: &\quad qg \to Wb\bar{b}q' \\
PROC = 3: &\quad gg \to Wb\bar{b}q\bar{q}' \\
PROC = 4: &\quad (q\bar{q}' \to Wb\bar{b}q''\bar{q}'') + (q\bar{q}' \to Wb\bar{b}q\bar{q}) + (q\bar{q}'' \to Wb\bar{b}q'\bar{q}'') + \\
&\quad (q''\bar{q}'' \to Wb\bar{b}q\bar{q}') + (q\bar{q} \to Wb\bar{b}q\bar{q}') + (qq \to Wb\bar{b}qq') + \\
&\quad (qq' \to Wb\bar{b}qq) \\
PROC = 5: &\quad (qg \to Wb\bar{b}q'q''\bar{q}'') + (qg \to Wb\bar{b}q'q\bar{q}) + (qg \to Wb\bar{b}qq\bar{q}') \\
PROC = 6: &\quad (gg \to Wb\bar{b}q\bar{q}'q''\bar{q}'') + (gg \to Wb\bar{b}q\bar{q}'q\bar{q}) \ .
\end{aligned}
$$

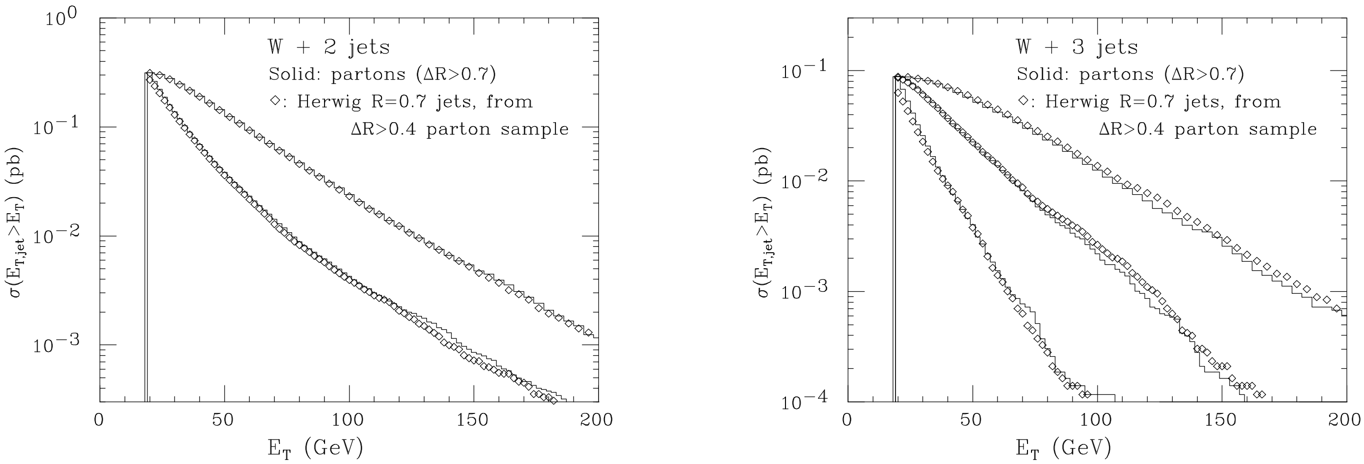
- Rates in pb, as a function of the total number of jets N_J (including b and $\bar{b}$):

Process	$N_J = 2$	$N_J = 3$	$N_J = 4$	$N_J = 5$	$N_J = 6$
1	2.60(1)	0.63(1)	0.144(3)	0.036(2)	0.008(1)
2	–	2.97(1)	2.11 (2)	1.08(2)	0.47(2)
3+4	–	–	0.288(1)	0.24(1)	0.13(2)
5	–	–	–	0.030(1)	0.031(4)
6	–	–	–	–	0.0010(3)
Total	2.60(1)	3.60(1)	2.54(2)	1.38(2)	0.64(3)

- The qualitatively new processes appearing when N_J increases are large.

Fully showered final states at the TEVATRON

A good matching of the jet spectra is achieved when using generation (parton level) cuts loser than jet-defining cuts:



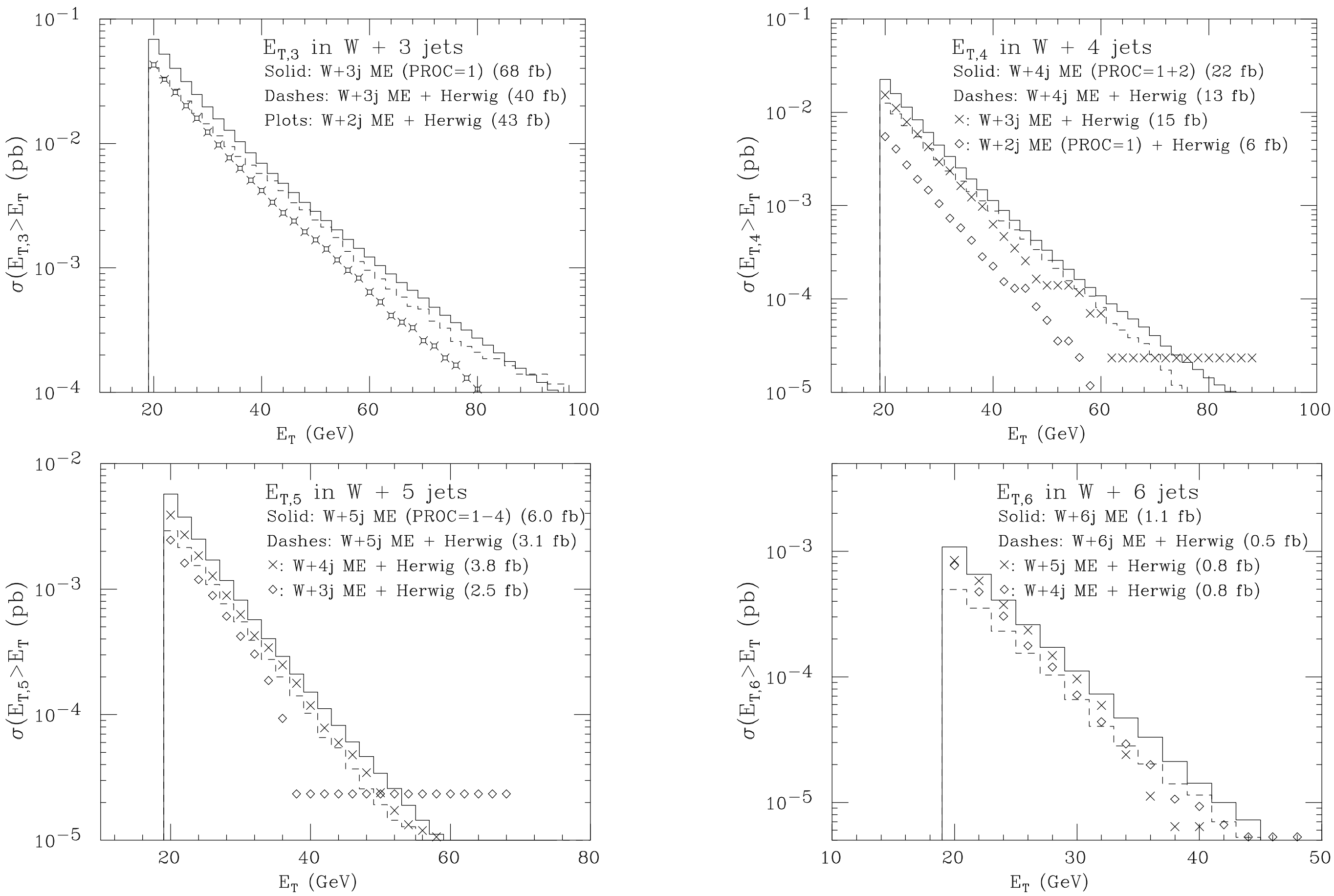
Inclusive p_T distributions of jets at the parton level, with separation cut $\Delta R > 0.7$ (solid curves), and of fully-showered $R_{jet} = 0.7$ jets (dashed curves). These last were obtained starting from the full sample of $\Delta R > 0.4$ partonic events.

• The message here is that when preparing parton-level samples to be used for the QCD evolution by a shower MC algorithm, it is important to set generation cuts looser than those used in the definition of the full jets, in order to cover the cases where two partons merge into a single jet, and extra jets are produced by the radiative processes.

• We also compared directions and momenta of the partons before and after the shower.

Jet radiation in HERWIG

We address the issue of the ability of the shower MC to correctly predict the rate for hard radiation leading to extra final-state jets:



Comparison of jet rates evaluated with matrix elements with those obtained from hard radiation during the shower evolution of lower-order parton-level processes.

- Large contributions, due to the appearance of new sub-processes, arise when higher-order parton level processes are considered. They are not included in the above plots.

CONCLUSIONS

• The formalism we have outlined, and the key use of **ALPHA** to enable the calculation of the matrix elements and the extraction of the colour information needed for the coherent shower evolution, allow us to compute several complex multiparton processes.

• **ALPGEN** is a collection of codes realized within the framework of the presented formalism. It can be used to perform realistic studies of multiparticle processes at **TEVATRON** and **LHC**.

• **ALPGEN** is ready-to-use and available at:

http://mlm.home.cern.ch/mlm/alpgen/

• The code is maintained and still in progress. We are working to include more and more processes (e.g. $p\overset{(-)}{p} \rightarrow n$ jets).