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MC@NLO

MC4LHC, CERN, 17/7/2006

SF & B. Webber, JHEP 0206(2002)029 [hep-ph/0204244]

SF, P. Nason & B. Webber, JHEP 0308(2003)007 [hep-ph/0305252]

SF, E. Laenen, P. Motylinski & B. Webber, JHEP 0603(2006)092 [hep-ph/0512250]

Basic facts

- Inclusive rates accurate to NLO (in α_S)
- More predictive than LO-based MC's (as usual when LO $\longrightarrow$ NLO) for shapes *and* rates
- The above true only for small numbers of extra jets – prefer CKKW-like procedures for many jets
- Tuning is the same as for the MC used for showering (presently only HERWIG) $\Longrightarrow$ smoother version upgrades

MC@NLO 3.2 [hep-ph/0601192]

IPROC	IV	IL_1	IL_2	Spin	Process
–1350–IL				✓	$H_1H_2 \to (Z/\gamma^* \to) l_{IL}\bar{l}_{IL} + X$
–1360–IL				✓	$H_1H_2 \to (Z \to) l_{IL}\bar{l}_{IL} + X$
–1370–IL				✓	$H_1H_2 \to (\gamma^* \to) l_{IL}\bar{l}_{IL} + X$
–1460–IL				✓	$H_1H_2 \to (W^+ \to) l^+_{IL}\nu_{IL} + X$
–1470–IL				✓	$H_1H_2 \to (W^- \to) l^-_{IL}\bar{\nu}_{IL} + X$
–1396				×	$H_1H_2 \to \gamma^*(\to \sum_i f_i \bar{f}_i) + X$
–1397				×	$H_1H_2 \to Z^0 + X$
–1497				×	$H_1H_2 \to W^+ + X$
–1498				×	$H_1H_2 \to W^- + X$
–1600–ID					$H_1H_2 \to H^0 + X$
–1705					$H_1H_2 \to b\bar{b} + X$
–1706				×	$H_1H_2 \to t\bar{t} + X$
–2000–IC				×	$H_1H_2 \to t/\bar{t} + X$
–2001–IC				×	$H_1H_2 \to \bar{t} + X$
–2004–IC				×	$H_1H_2 \to t + X$
–2600–ID	1	7		×	$H_1H_2 \to H^0W^+ + X$
–2600–ID	1	i		✓	$H_1H_2 \to H^0(W^+ \to) l^+_i\nu_i + X$
–2600–ID	-1	7		×	$H_1H_2 \to H^0W^- + X$
–2600–ID	-1	i		✓	$H_1H_2 \to H^0(W^- \to) l^-_i\bar{\nu}_i + X$
–2700–ID	0	7		×	$H_1H_2 \to H^0Z + X$
–2700–ID	0	i		✓	$H_1H_2 \to H^0(Z \to) l_i\bar{l}_i + X$
–2850		7	7	×	$H_1H_2 \to W^+W^- + X$
–2850		i	j	✓	$H_1H_2 \to (W^+ \to) l^+_i\nu_i(W^- \to) l^-_j\bar{\nu}_j + X$
–2860		7	7	×	$H_1H_2 \to Z^0Z^0 + X$
–2870		7	7	×	$H_1H_2 \to W^+Z^0 + X$
–2880		7	7	×	$H_1H_2 \to W^-Z^0 + X$

Most recent work:

- Single-top production (s- and t-channels)
- Interface to LHAPDF

http://www.hep.phy.cam.ac.uk/theory/webber/MCatNLO

MC@NLO: formalism

Double counting $\Longleftrightarrow$ MC evolution results in spurious NLO terms

$\longrightarrow$ *Eliminate the spurious NLO terms "by hand"*

- The generating functional is

$$\mathcal{F}_{\text{MC@NLO}} = \sum_{ab} \int dx_1\, dx_2\, d\phi_{n+1}\, f_a(x_1) f_b(x_2) \times \left[\mathcal{F}_{\text{MC}}^{(2\to n+1)} \left(\mathcal{M}_{ab}^{(r)} - \mathcal{M}_{ab}^{(\text{MC})}\right) + \mathcal{F}_{\text{MC}}^{(2\to n)} \left(\mathcal{M}_{ab}^{(b,v,c)} - \mathcal{M}_{ab}^{(c.t.)} + \mathcal{M}_{ab}^{(\text{MC})}\right)\right]$$

$$\mathcal{M}_{\mathcal{F}(ab)}^{(\text{MC})} = \mathcal{F}_{\text{MC}}^{(2\to n)} \mathcal{M}_{ab}^{(b)} + \mathcal{O}(\alpha_S^2 \alpha_S^b)$$

There are *two* MC-induced contributions: they eliminate the spurious NLO terms due to the branching of a final-state parton, and to the non-branching probability

MC@NLO in a nutshell

1. Choose your favourite MC (HERWIG, PYTHIA), and compute analytically the "NLO cross section", i.e., the first emission. This is an observable-independent, process-independent procedure, which is done once and for all

2. Implement the NLO matrix elements of your favourite process according to the universal, observable-independent, subtraction-based formalism of SF, Kunszt, Signer (Nucl.Phys.B467(1996)399) for cancelling IR divergences

   This is the only non-trivial step necessary in order to add new processes

3. Add and subtract the MC counterterms, computed in step 1, to what computed in step 2. The resulting expression allows one to generate the hard kinematic configurations, which are eventually fed into the MC showers as initial conditions

On step 1: MC counterterms

- An analytic computation is needed for each type of MC branching from a massless leg: there are only two cases!

- Initial-state branchings have been studied in JHEP0206(2002)029 (SF, Webber) and JHEP0308(2003)007 (SF, Nason, Webber)

- Final-state branchings have been studied in JHEP0603(2006)092 (SF, Laenen, Motylinski, Webber)

For each new process, just assemble these pieces into a computer code. No new computation is now required for matching with fortran HERWIG

On MC@NLO code

Time for the inclusion of a new process is spent:

- 80% for the pure-NLO computation
- 15% for MC counterterms and LHI-related code
- 5% debugging

The structure of the MC counterterms is modular

$$\mathcal{M}^{(\mathrm{MC})} = \mathcal{K}^{(\mathrm{MC})}\mathcal{M}^{(b)}$$

Kernels $\mathcal{K}^{(\mathrm{MC})}$ now fully worked out for HERWIG

- Work in progress (Seyi Latunde-Dada) on the computation of $\mathcal{K}^{(\mathrm{MC})}$ for HERWIG++

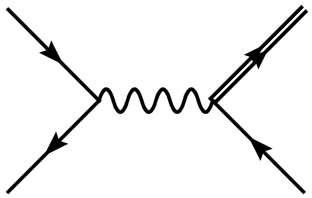
Activities on MC@NLO mainstream

- Wt-mode in single-top production (Laenen, Motylinski)
- Dijet production (Laenen, Motylinski)
- Top spin correlations (Laenen, Motylinski)
- Anomalous couplings in WZ production (Oh)*
- Higgs in VBF (Del Duca, Oleari)**

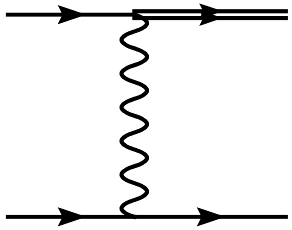
* Up and running. Being debugged

** Early stages

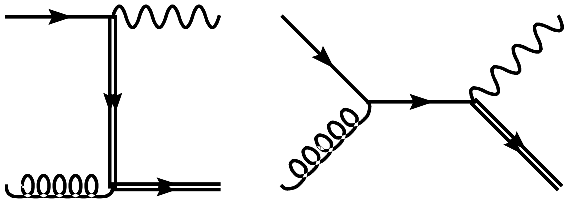
Single-top production



s channel IPROC=2010/2011/2014



t channel IPROC=2020/2021/2024



Wt mode

Do not forget: channels mix beyond LO

- Status of Wt mode: all NLO matrix elements computed, being assembled. Ready by the end of 2006?

Dijet production

- NLO code up and running, fully debugged
- MC counterterms ready, those for ISR also tested
- Need to compute leading-$1/N_c$ matrix elements for $2 \to 3$ processes

- Preliminary version of the code ready by the end of the summer. Expect more debugging than usual due to bookkeeping complexity

Spin correlations

The standard way: compute the matrix elements for

$$a + b \longrightarrow (P \longrightarrow) d_1 + \cdots + d_n + X \qquad \text{Full ME}$$

This full-ME strategy is implemented in MC@NLO for:

- Single-V production ($V = W, Z, \gamma, Z/\gamma$)
- VH production ($V = W, Z$)

For large-multiplicity final states this may not be convenient, since

- ME must be integrated and unweighted
- The integration time increases and the unweighting efficiency decreases (for MC@NLO, typically ε=10–40%) by increasing the number of final-state particles

For W^+W^- production we have implemented an alternative strategy: hit-and-miss

Hit-and-miss

Whatever the behaviours of the decay products, the momenta of the decaying particles will not change

$\Longrightarrow$ The full ME's must be bounded from above by the undecayed ME's, times a suitable constant. Find this bound and do hit-and-miss

Advantages

- Only the undecayed ME's will be integrated: no further loss of time
- Unweighting is a two-step procedure: first get the P's momenta, then the d's momenta with hit-and-miss

Vector bosons (tested and running)

$$\frac{d\sigma_{l_1\bar{l}_1\ldots l_n\bar{l}_n}}{d\Phi_{2n+k}} \leq \left(\prod_{i=1}^{n} \frac{2\,F_{V_i}^2\,(V_{V_il_i}+A_{V_il_i})^2}{\Gamma_i^2}\right)\frac{d\sigma_{V_1\ldots V_n}}{d\Phi_{n+k}}$$

Top (being tested)

$$\frac{d\sigma_{b_1l_1\nu_1\ldots b_nl_n\nu_n}}{d\Phi_{3n+k}} \leq \left(\prod_{i=1}^{n} \frac{4G_F^4 E_{l_i} k_{b_i}\cdot k_{\nu_i}}{m_t\Gamma_i^2}\right)\frac{d\sigma_{t_1\ldots t_n}}{d\Phi_{n+k}}$$

Theory-oriented activity

We (Nason, Oleari, SF) are writing a paper with all the details on:

MC@NLO: the implementation of a new process requires skills similar to those necessary for NLO computations

POWHEG: a new formalism proposed by Nason (2004), with no negative weights

- Proof-of-concept for ZZ hadroproduction (Nason, Ridolfi)
- Full agreement with MC@NLO for inclusive observables
- Lacks "soft" showers – currently not available in MC's. Need them to treat correctly exclusive observables

We'll study the possibility of implementing soft showers in a package which can be interfaced to an MC via Les Houches interface

Outlook

- A few more processes in MC@NLO, e.g. full-ME approach for all spin correlations
- MC@NLO with HERWIG++ “easy”. No attempts with PYTHIA so far
- CKKW-type matching at NLO is doable. Bottleneck: NLO multi-leg computations
- Progress with POWHEG

Most serious problem: lack of manpower