aMC@NLO: status and new results

Marco Zaro, CP3-UCLouvain

in collaboration with

R. Frederix, S. Frixione, F. Maltoni, P. Torrielli, V. Hirschi

and the MadGraph5 team

May 14th, 2013, GDR@Montpellier

Motivations

- Why automation?
  - Time: trade time spent to code/debug with time to do physics
  - Trust: results from an automatic tool are “correct by definition”
  - Easy: automatic tools can be used as black-boxes: no need of highly skilled users

Motivations

- Why automation?
  - Time: trade time spent to code/debug with time to do physics
  - Trust: results from an automatic tool are "correct by definition"
  - Easy: automatic tools can be used as black-boxes: no need of highly skilled users
- Why NLO?
  - Reliable prediction of total rates
  - Reduction of theoretical uncertainties

Motivations

- Why automation?
  - Time: trade time spent to code/debug with time to do physics
  - Trust: results from an automatic tool are "correct by definition"
  - Easy: automatic tools can be used as black-boxes: no need of highly skilled users
- Why NLO?
  - Reliable prediction of total rates
  - Reduction of theoretical uncertainties
- Why matching with parton-showers?
  - Parton level is not the whole story
  - Matching with PS cures observables which are ill-behaved at fixed-order

NLO basics

$$d\sigma^{n}_{NLO} = \mathcal{B}^{n} + \mathcal{V}^{n} + \int d\Phi_1 \mathcal{R}^{n+1}$$

NLO basics

$$d\sigma^n_{NLO} = \mathcal{B}^n + \mathcal{V}^n + \int d\Phi_1 \mathcal{R}^{n+1}$$

$$d\sigma^n_{NLO} = \mathcal{B}^n + \mathcal{V}^n + \int d\Phi_1 \mathcal{C} + \int d\Phi_1 \left(\mathcal{R}^{n+1} - \mathcal{C}\right)$$

NLO basics

$$d\sigma^n_{NLO} = \mathcal{B}^n + \mathcal{V}^n + \int d\Phi_1 \mathcal{R}^{n+1}$$

$$d\sigma^n_{NLO} = \mathcal{B}^n + \mathcal{V}^n + \int d\Phi_1 \mathcal{C} + \int d\Phi_1 \left(\mathcal{R}^{n+1} - \mathcal{C}\right)$$

To do:

- Generate virtual matrix-element
- Generate real-emission matrix-element (and counterterms)
- Put everything together and integrate (possibly in an efficient way)

Virtual MEs:

Passarino & Veltman: every loop integral can be written as linear combination of 1- to 4-point scalar integrals:

$$\begin{aligned}\int \frac{d^D q}{2\pi^D} A(q) &= \sum_{i_0,i_1,i_2,i_3} d(i_0,i_1,i_2,i_3) D_0(i_0,i_1,i_2,i_3)\\ &+ \sum_{i_0,i_1,i_2} c(i_0,i_1,i_2) C_0(i_0,i_1,i_2)\\ &+ \sum_{i_0,i_1} b(i_0,i_1) B_0(i_0,i_1)\\ &+ \sum_{i_0} a(i_0) A_0(i_0)\\ &+ R\end{aligned}$$

Virtual MEs:

Passarino & Veltman: every loop integral can be written as linear combination of 1- to 4-point scalar integrals:

$$
\begin{aligned}
\int \frac{d^D q}{2\pi^D} A(q) &= \sum_{i_0,i_1,i_2,i_3} d(i_0,i_1,i_2,i_3) D_0(i_0,i_1,i_2,i_3) \\
&+ \sum_{i_0,i_1,i_2} c(i_0,i_1,i_2) C_0(i_0,i_1,i_2) \\
&+ \sum_{i_0,i_1} b(i_0,i_1) B_0(i_0,i_1) \\
&+ \sum_{i_0} a(i_0) A_0(i_0) \\
&+ R
\end{aligned}
$$

Do the same at the integrand level!

The OPP method

Ossola, Papadopoulos, Pittau, arXiv:hep-pt/0609007 and arXiv:0711.3596

$$A(q) = \frac{N(q)}{D_0 \ldots D_{m-1}}$$

$$\begin{aligned}
N(q) &= \sum_{i_0,i_1,i_2,i_3} [d(i_0,i_1,i_2,i_3) + \tilde{d}(i_0,i_1,i_2,i_3)] \prod_{i \neq i_0,i_1,i_2,i_3} D_i \\
&+ \sum_{i_0,i_1,i_2} [c(i_0,i_1,i_2) + \tilde{c}(i_0,i_1,i_2)] \prod_{i \neq i_0,i_1,i_2} D_i \\
&+ \sum_{i_0,i_1} [b(i_0,i_1) + \tilde{b}(i_0,i_1)] \prod_{i \neq i_0,i_1} D_i \\
&+ \sum_{i_0} [a(i_0) + \tilde{a}(i_0)] \prod_{i \neq i_0} D_i \\
&+ \tilde{P}(q) \prod_i D_i
\end{aligned}$$

- The determination of the loop coefficients can be done numerically (CutTools)
- UV renormalization /R2 terms can be added as new Feynman vertices

Real-emission MEs and integration: the FKS subtraction

Frixione, Kunszt, Signer, arXiv:hep-ph/9512328

- Soft/collinear singularities arise in many PS regions
- Find parton pairs i, j that give collinear singularities
- Split the PS into regions with only one collinear singularity:
  - Soft singularities are split into the collinear ones

$$|\mathcal{M}|^2 = \sum_{ij} S_{ij} \, |\mathcal{M}|^2 = \sum_{ij} |\mathcal{M}|^2_{ij} \qquad \sum_{ij} S_{ij} = 1$$

$$S_{ij} \to 1 \text{ if } k_i \cdot k_j \to 0 \qquad S_{ij} \to 0 \text{ if } k_{l \neq i} \cdot k_{m \neq j} \to 0$$

- Integrate each $\mathcal{M}_{ij}$ independently
- Number of contributions $\sim n^2$

MadLoop & MadFKS

- MadLoop (Hirschi et al, arXiv:1103.0621)
  - Computes the loop numerator for any given amplitude and feeds it to CutTools
  - Adds R2/UV counterterms (process-independent, coded as new vertices)
- MadFKS (Frederix et al, arXiv:0908.4272)
  - Generates realand born MEs and counterterms (color- and spin-linked borns)
  - Organizer the integration of the n and $n+1$ body cross-section
  - Generates events to be showered

MC@NLO basics: Matching NLO predictions with PS

- Problem: avoid double counting configurations generated by the real-emission ME and by the PS

MC@NLO basics: Matching NLO predictions with PS

- Problem: avoid double counting configurations generated by the real-emission ME and by the PS
- Solution: subtract the real-emission as it is generated by the shower, by means of suitable counterterms:

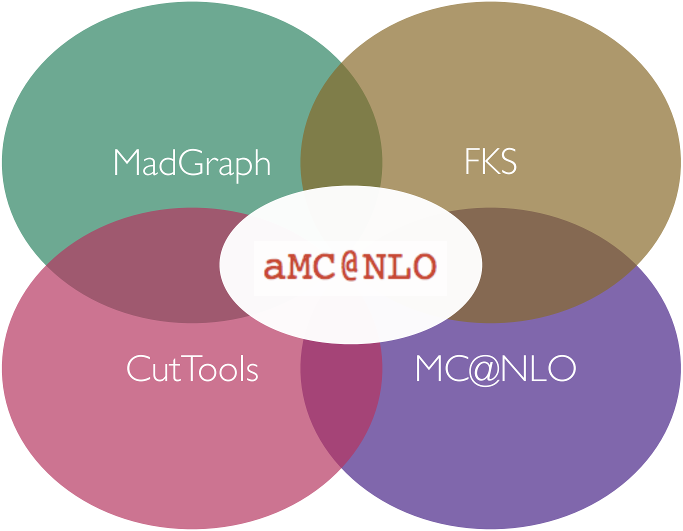
$$\frac{d\sigma_{MC@NLO}}{dO} = \left[d\Phi_n(\mathcal{B}+\mathcal{V}) + \int d\Phi_1 MC \right] I^n_{MC}(O) + \left[d\Phi_{n+1}(\mathcal{R} - MC) \right] I^{n+1}_{MC}(O)$$

  - The MC counterterm is related to the Sudakov of the PS as

$$\Delta = \exp\left[- \int d\Phi_1 \frac{MC}{\mathcal{B}} \right]$$

  - NLO normalization is kept
  - MC are PS-dependent but process-independent
    Available for Herwig6, Pythia6, Herwig++

aMC@NLO



```
./bin/mg5
> generate p p > t t~ a [QCD]
> output my_tta
> launch
```

Physics!

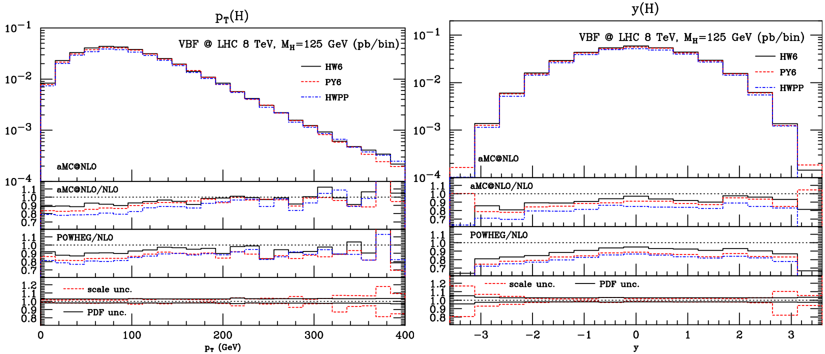
Latest results (soon in YR3):

- Study of matcihng systematics in VBF (also arXiv:1304.7927)
- Spin correlation in $t\bar{t}H$

Matching systematics in VBF

- Aim: ssess the effect of different PS and matching scheme in VBF
- Included in the Powheg box since some time (arXiv:0911.5299)
- VBF is a non-trivial process because of its peculiar topology
  - Possibly hidden matching systematics
  - Nice benchmark/validation for aMC@NLO

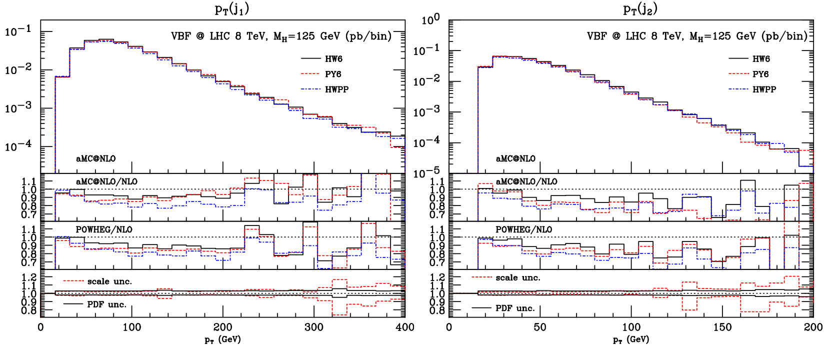
VBF: results (I)



$\geq$ 2 jets with $p_T > 20$GeV, $|y| < 4.5$, $|\Delta y| > 4$, $m_{j1,j2} > 600$GeV are required

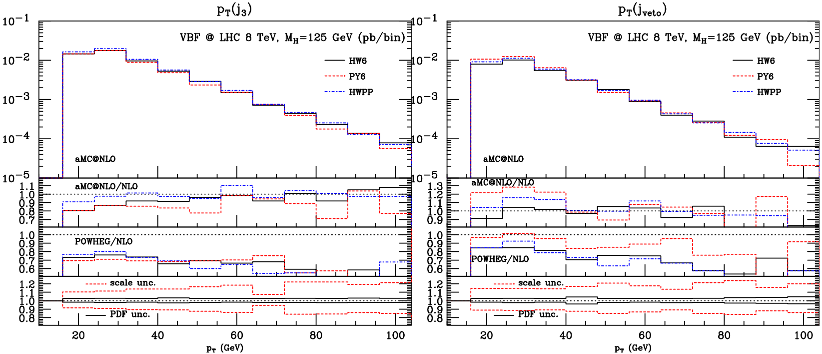
Both Powheg and aMC@NLO show HW6>PY6>HW++

VBF: results (II)



Overall agreement is found for NLO observables

VBF: results (III)



Larger differences (possibly matching systematics) are present for LO observables

Spin correlations in $t\bar{t}H$

- Spin correlation can be included in any aMC@NLO process with MadSpin, after the event generation
- For $t\bar{t}H$ spin effects are comparable with NLO corrections

MadSpin

Artoisenet et al, arXiv:12123460

Aim:

- For a given event sample include the decay of final state particles
- Keep spin correlation
- Generate decayed unweighted events

MadSpin

Artoisenet et al, arXiv:12123460

Aim:

- For a given event sample include the decay of final state particles
- Keep spin correlation
- Generate decayed unweighted events

Solution

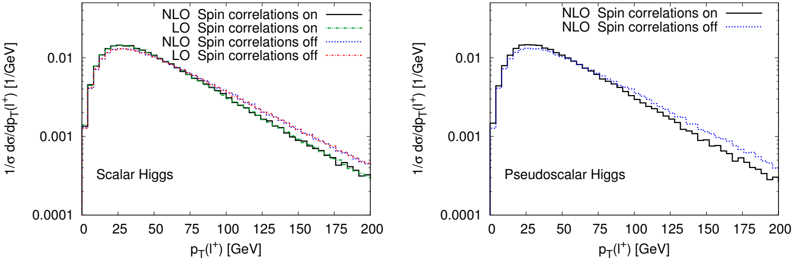
- MadGraph deals extremely well with decay chains
- Read the undecayed event
- Generate the ME including the desired decay
- Generate decay kinematic configuretions until

$$|\mathcal{M}_{P+D}|^2 / |\mathcal{M}_P|^2 > \mathrm{Rand}()\, \max\left(|\mathcal{M}_{P+D}|^2 / |\mathcal{M}_P|^2\right)$$

- Validated for $t\bar{t}$ and single-top production
  Frixione et al. arXiv:hep-ph/0702198

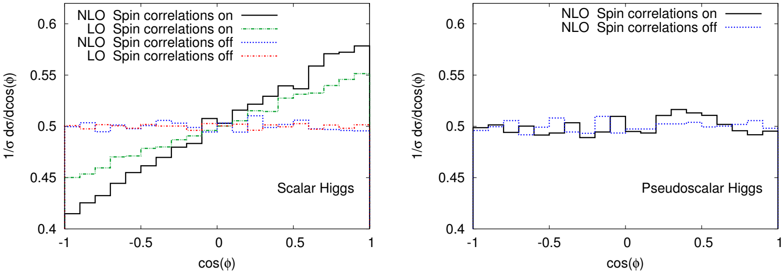
MadSpin with aMC@NLO events

- Spin correlation effects are typically small: include them only at tree level
- For $\mathbb{H}$ events ($n+1$ body), use decayed real-emission ME
- For $\mathbb{S}$ events (n body), use decayed born ME
- Production-related observables (e.g. $p_T(t)$ are described at NLO accuracy
- All spin correlations are included for observables related to production + decay



Spin effects can be larger than NLO corrections

$t\bar{t}H$



Interesting difference in the $\cos\phi$ shape (complementary information for Higgs characterization

Conclusion

- aMC@NLO allows to automatically generate events for any process, at NLO accuracy and matching with PS
- MadSpin allows to include spin-correlation effects at almost zero extra cost, starting from undecayed events
- aMC@NLO + MadSpin are included in MadGraph5 v2.0 (beta 3 version is available)
- More interesting results will come
- Stay tuned on `http://amcatnlo.web.cern.ch`