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Status of MadGraph5_aMC@NLO

I shall mention a few things relevant
to the general organisation of the code,
so as to facilitate discussions.
I shall mostly repeat what has been said
in the ATLAS+CMS MC meeting

The current public version is (since Jul 1st 2015):

MadGraph5_aMC@NLO v2.3.3

Main reference (and many physics applications): 1405.0301

Yes, we know about the name... You have our blessing to shorten it (as we also do: MG5_aMC@NLO, MG5_aMC, MG5aMC,...) but please refrain from using the names of obsolete codes (MadGraph5 and aMC@NLO)

Speaking of which...

Plan for azimuthal correlations

- We can plan an analysis based on these results.

- Extend the work also to 3 and 4 jet topologies.

- Compare to various MC generators
  - Pythia8 CUETM1
  - Herwig++
  - MadGraph + Pythia8 CUETM1
  - Powheg + Pythia8 CUETM1
  - Herwig7
  - MadGraph_MC@NLO
  - Blackhat+Sherpa, NLOJet etc.

Six different types of computations in the same framework

▶ fLO Fixed order, tree level

▶ fNLO Fixed order, NLO

▶ LO+PS Hard tree-level events, showered

▶ NLO+PS Hard "NLO" events, showered (MC@NLO)

▶ MLM-merged Multijet tree-level merging (k_T-jet and shower-k_T schemes)

▶ FxFx- or UNLOPS-merged Multijet NLO merging

The sameness of framework facilitates cross checks. A more systematic use of f(N)LO results by experiments would be worthwhile

The basic philosophy, common to LO and NLO:

Given a Lagrangian, transform it in a set of rules (eg with `FeynRules`): this is what is called a (UFO) `model`. MadGraph5_aMC@NLO imports the model, and carries out computations according to its rules

- ♦ Models that underpin NLO computations have more information than those restricted to LO (chiefly, the type of corrections: QCD, QED, ...). This is what is meant by "NLO models" or "LO models"; one can obviously perform a LO calculation using an NLO model

- ♦ Thanks to the steady development of NLOCT (UV and R_2 cnts), NLO models are almost on the same footing as LO ones (more later)

$\implies$ crucial for BSM applications

Main activities in 2015

♦ Phenomenology validations and SM studies

♦ Mixed-coupling expansion (e.g. α_s, α)

♦ New integral-reduction methods and OLPs

♦ Loop-induced processes

♦ BSM features and applications

♦ ...

Before going into that: about PDF4LHC

MadGraph5_aMC@NLO associates with each event $N_{\text{scales}}^2 + N_{\text{PDF}}$ weights that allow one to compute the corresponding theoretical uncertainties at no extra CPU cost

These weights are stored in hard-event files in a way compliant with the Les Houches Accord 3 in (N)LO+PS simulations, and dealt with internally in f(N)LO runs

As of 2015, PDF4LHCs are "just" another PDF set with errors, bar for the presence of two extra members associated with α_S variation

This is fully compatible with the structure already in place from v2.3.0 for (N)LO+PS runs. α_S-variation sets in f(N)LO runs will be added in v2.3.4

Usual recommendations

▶ Try and make a systematic use of these weights in experiments

▶ Make Rivet fully compatible with LHA3

Phenomenology validations and SM studies

▶ The code is mature and very reliable

▶ A lot of work done within experiments

▶ We tend to study "involved" process

▶ Recent emphasis has been on NLO-merging validation against data: very thorough for W/Z+jets, ongoing for $t\bar{t}$+jets
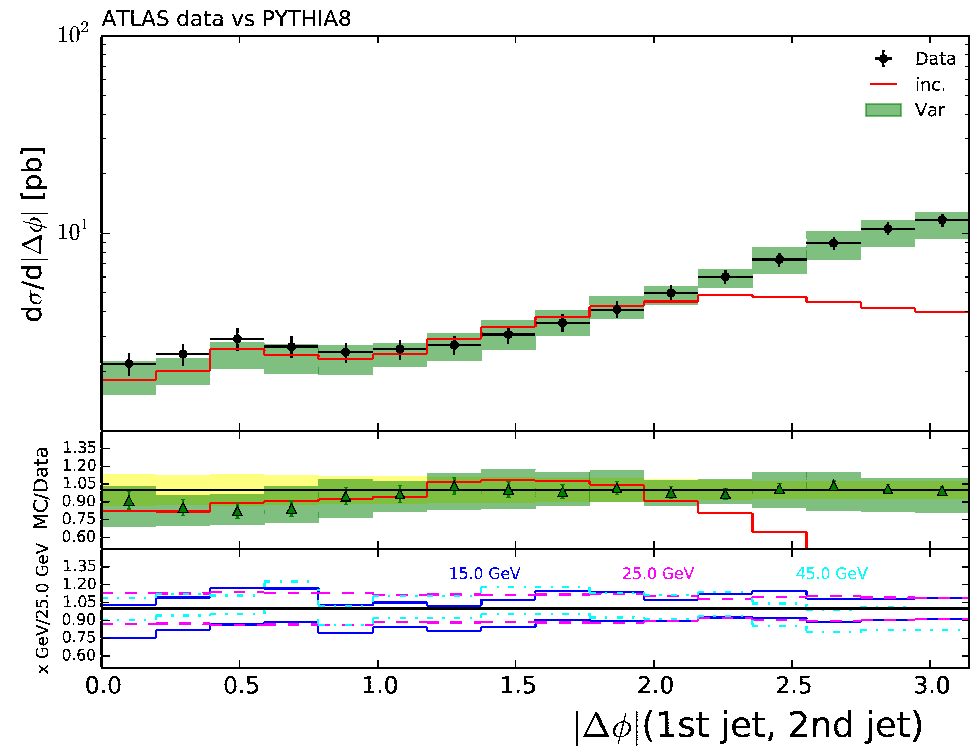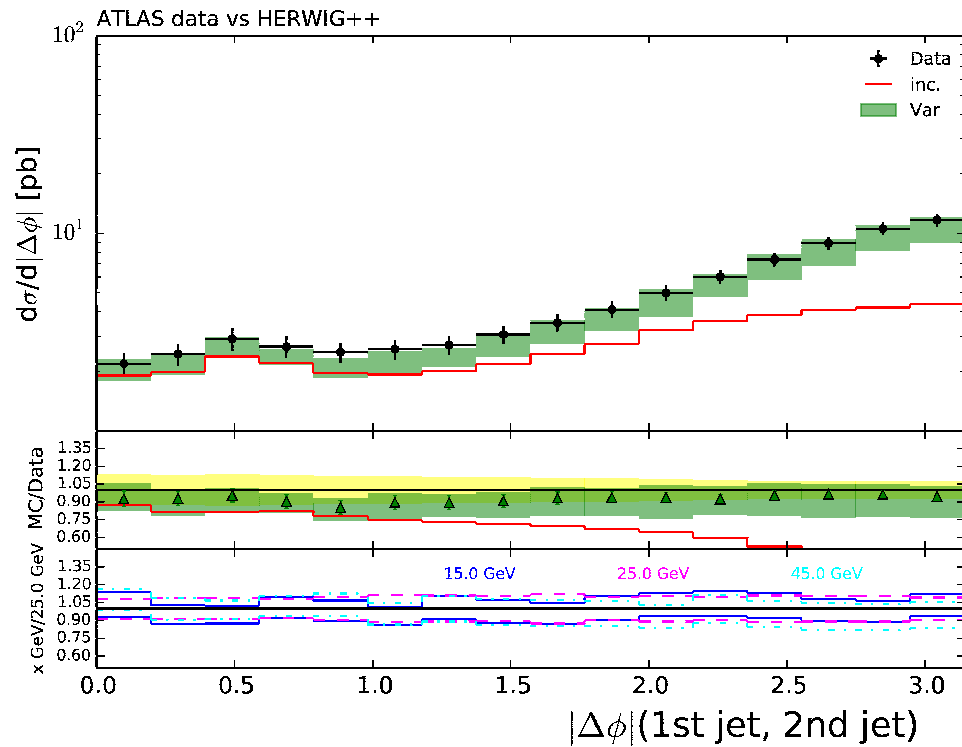
We considered all observables of the 5 fb^{-1} 7-TeV ATLAS and CMS analyses

arXiv:1511.00847 [hep-ph]

(Frederix, Papaefstathiou, Prestel, Torrielli, SF)

On merging schemes

♦ k_T-jet (LO), shower-k_T (LO), and FxFx (NLO) all feature an MLM-type rejection

♦ FxFx fully automated with both PY8 and HW++

♦ LO mergings fully automated for PY6 and PY8, but the latter not yet public. Not done for HW++ (got *very* few requests)
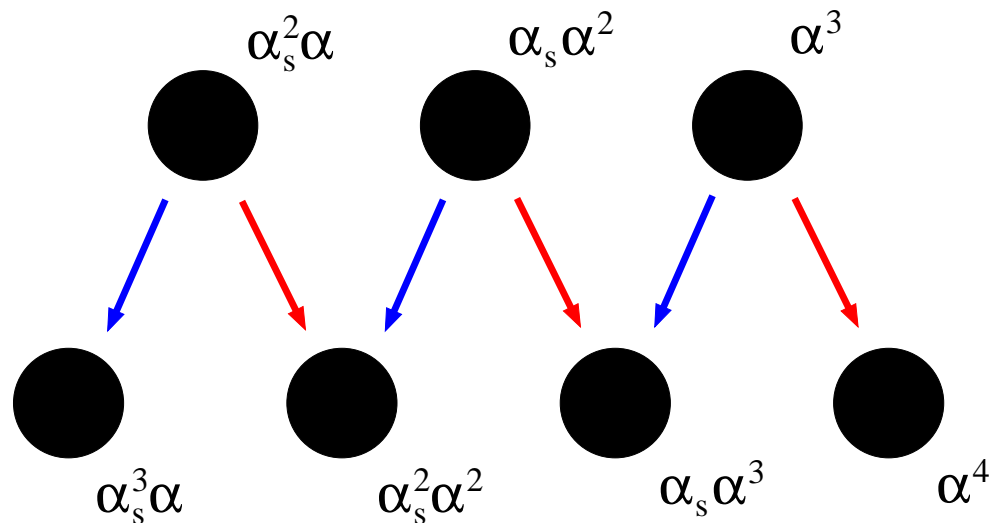
♦ CKKW(-L) handled directly by PY8

Mixed-coupling expansion

Consider e.g. $t\bar{t}V$ production (V is an SM boson); Σ is a generic observable

$$\Sigma_{t\bar{t}V}^{(\mathrm{LO})}(\alpha_s, \alpha) = \alpha_s^2 \alpha \, \Sigma_{3,0} + \alpha_s \alpha^2 \, \Sigma_{3,1} + \alpha^3 \, \Sigma_{3,2}$$

$$\equiv \Sigma_{\mathrm{LO},1} + \Sigma_{\mathrm{LO},2} + \Sigma_{\mathrm{LO},3}$$

$$\Sigma_{t\bar{t}V}^{(\mathrm{NLO})}(\alpha_s, \alpha) = \alpha_s^3 \alpha \, \Sigma_{4,0} + \alpha_s^2 \alpha^2 \, \Sigma_{4,1} + \alpha_s \alpha^3 \, \Sigma_{4,2} + \alpha^4 \, \Sigma_{4,3}$$

$$\equiv \Sigma_{\mathrm{NLO},1} + \Sigma_{\mathrm{NLO},2} + \Sigma_{\mathrm{NLO},3} + \Sigma_{\mathrm{NLO},4}$$

Usually, $\Sigma_{\mathrm{NLO},1}$=QCD corrections, $\Sigma_{\mathrm{NLO},2}$=EW corrections

Current syntax (leading terms, e.g. for $t\bar{t}W^+$ production):

```
MG5_aMC> generate p p > t t~ w+ [QCD]
```

Will become something like (e.g. for $\Sigma_{\mathrm{LO},1}$ and $\Sigma_{\mathrm{NLO},2}$):

```
MG5_aMC> generate p p > t t~ w+ QCD=2 QED=1 [QED]
```
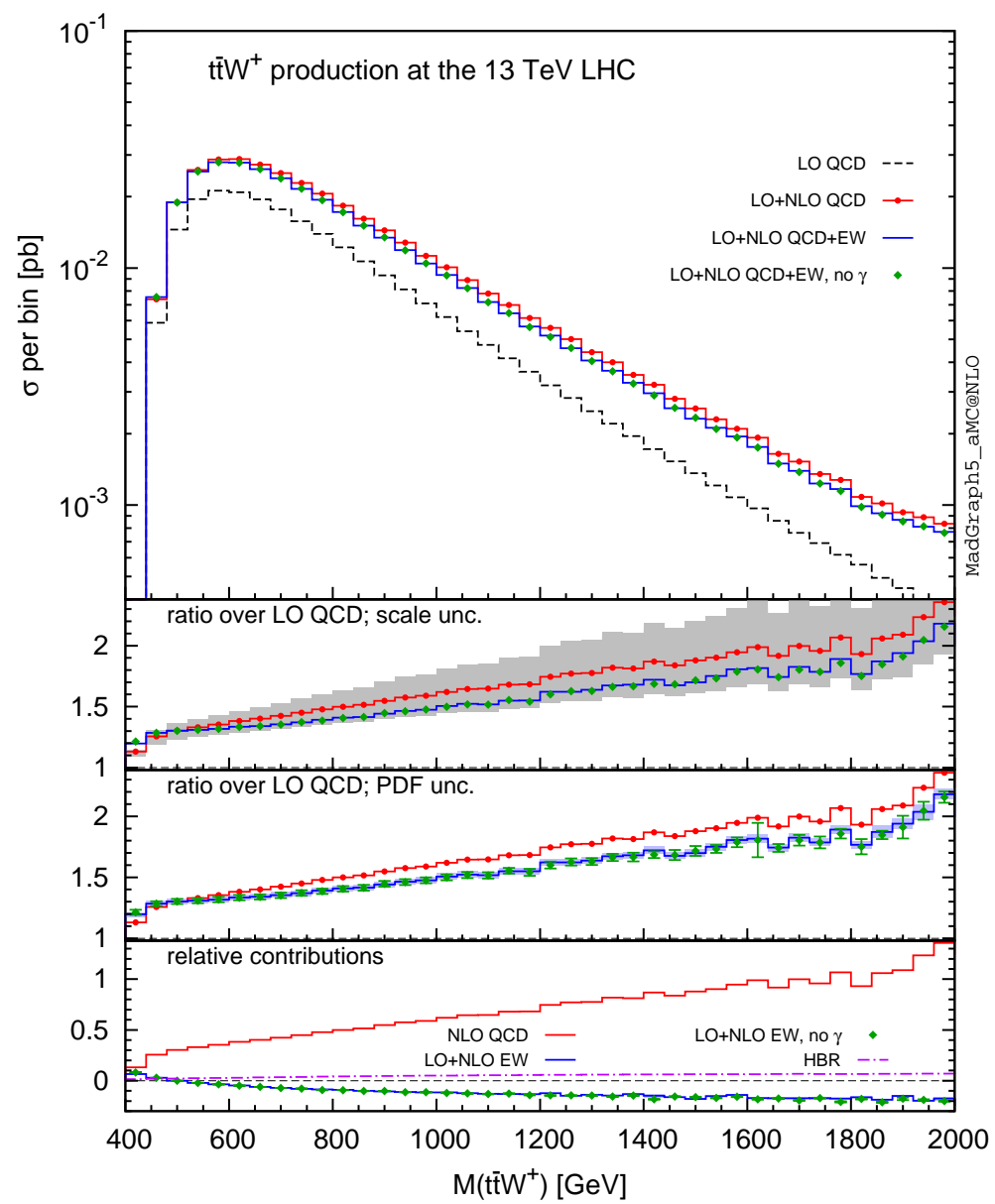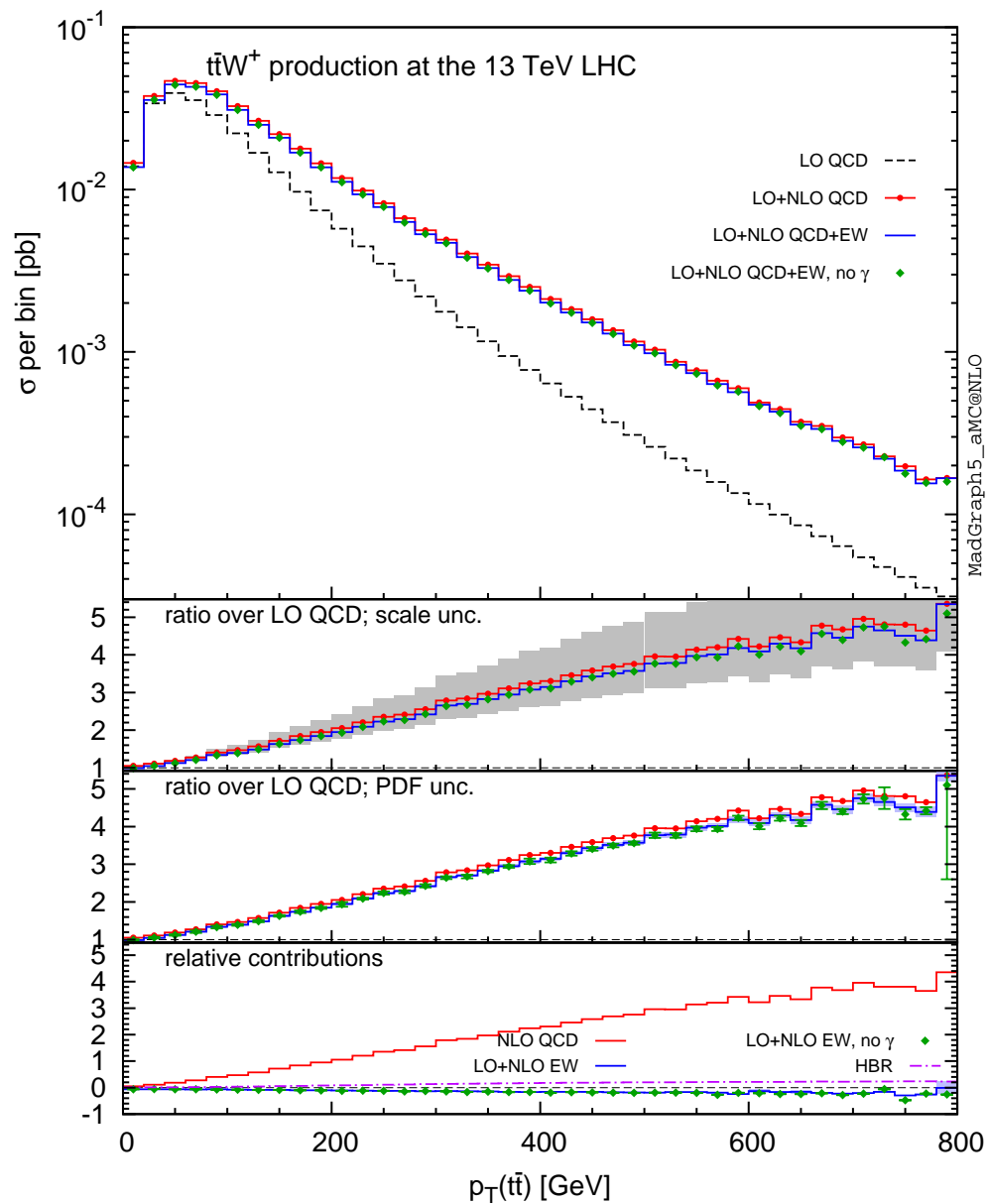
In general:

```
MG5_aMC> generate a b > c d e f QCD=n QED=m [QCD QED]
```

in order to include in the computation all the terms that factorise:

$$\begin{array}{llll} \text{LO} & \alpha_S^k \alpha^p \,, & k \leq n \,, & p \leq m \,, & k+p = b \\ \text{NLO} & \alpha_S^k \alpha^p \,, & k \leq n{+}1 \,, & p \leq m{+}1 \,, & k+p = b{+}1 \end{array}$$

$t\bar{t}W^+$ production at the 13 TeV LHC

LO QCD
LO+NLO QCD
LO+NLO QCD+EW
LO+NLO QCD+EW, no γ

MadGraph5_aMC@NLO

ratio over LO QCD; scale unc.

ratio over LO QCD; PDF unc.

relative contributions

NLO QCD
LO+NLO EW
LO+NLO EW, no γ
HBR

$p_T(t\bar{t})$ [GeV]

$t\bar{t}W^+$ production at the 13 TeV LHC

LO QCD
LO+NLO QCD
LO+NLO QCD+EW
LO+NLO QCD+EW, no γ

MadGraph5_aMC@NLO

ratio over LO QCD; scale unc.

ratio over LO QCD; PDF unc.

relative contributions

NLO QCD
LO+NLO EW
LO+NLO EW, no γ
HBR

$M(t\bar{t}W^+)$ [GeV]

arXiv:1504.03446 [hep-ph]

(Hirschi, Pagani, Shao, Zaro, SF)

♦ A fully generic implementation of the complex-mass scheme

♦ Mixed-coupling fixed-order capabilities public $\sim$ summer

♦ Matching to (QED) showers later

New integral-reduction methods and OLPs

MG5_aMC@NLO features an internal OLP (MadLoop), which is responsible for the computation of the virtual matrix elements

A crucial component of such a computation is the integral-reduction procedure (which, given a *single* one-loop integral, returns its value)

MadLoop is able to switch dynamically among different reductions (with user's pre-defined ordering); new options are being added to allow more flexibility (improved numerical stability, treatment of higher-rank integrals)
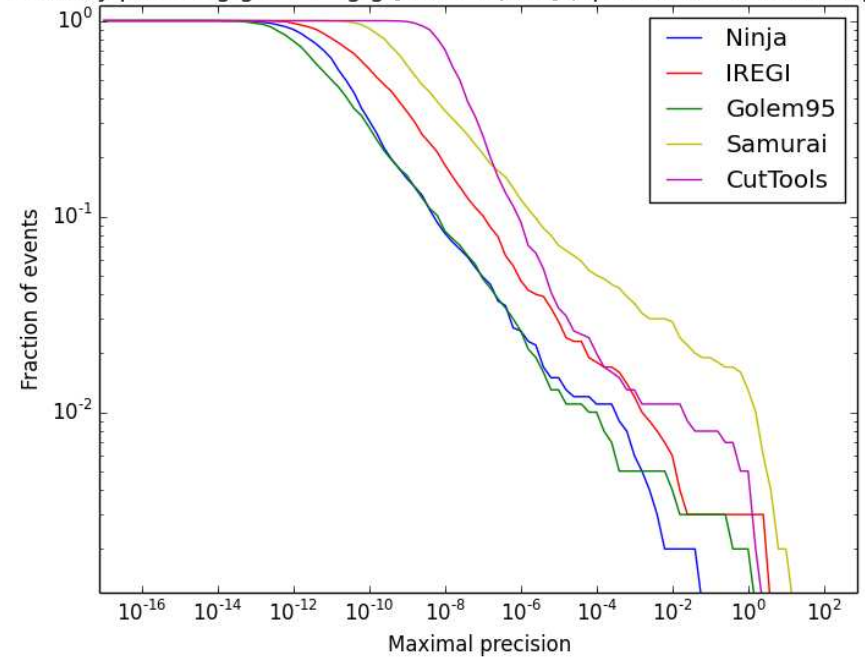
Also, an independent OLP (GoSam) can now be used (simply from configuration card: not available for loop-induced)

$$gg \rightarrow t\bar{t}gg$$

CutTools	230 ms
IREGI	13295 ms
Golem95	6226 ms
Samurai	580 ms
Ninja	90 ms

Averages over a few points

Stability plot for g g > t t~ g g [virt = QCD] (optimized mode, 1000 points)

Dozens of SM amplitudes tested
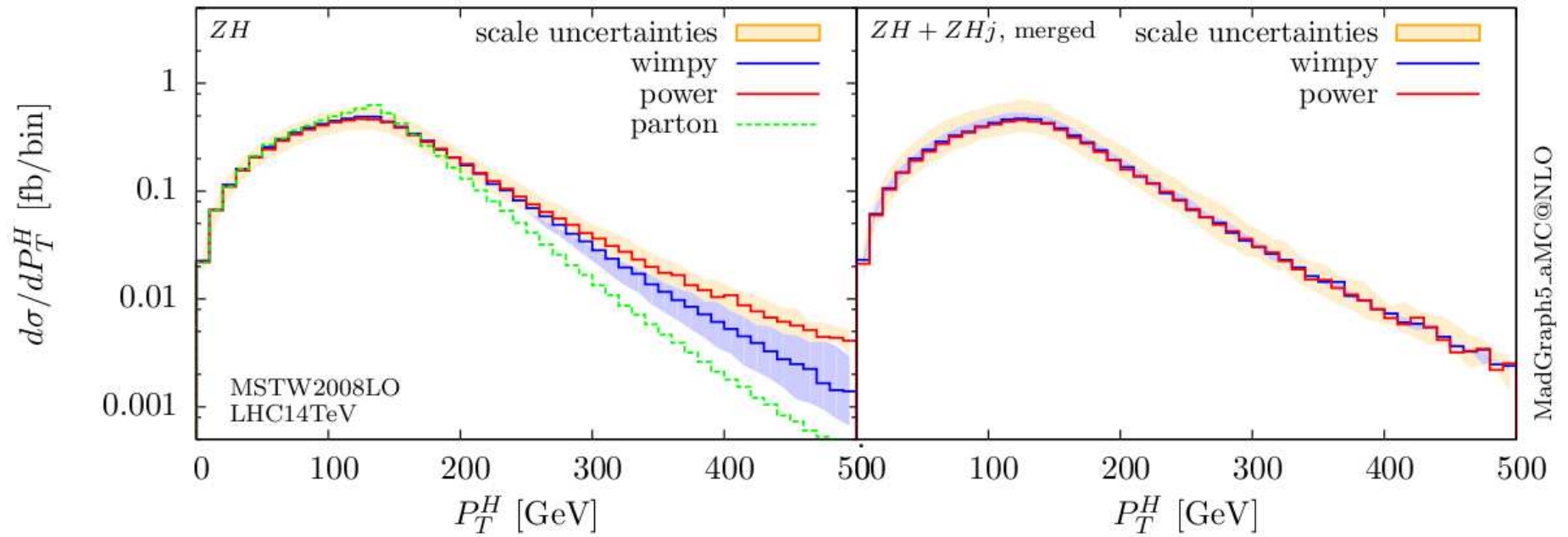Not yet public

Loop-induced processes

LI processes were previously treated only through reweighting

(one generates the process in a suitable EFT, then reweights events)

Relatively quick, but cumbersome and not ideal if full theory and EFT exhibit large differences

One can now integrate LI directly; tested for up to (some) $2 \to 4$

Usage in experiments?

Loop induced, reweighted

$gg \to ZH + 0, 1$ jets, shower-k_T merged

arXiv:1503.01656 [hep-ph]

(Hespel, Maltoni, Vryonidou)

Process Selected $2 \to 4$	Syntax	Cross section (pb) $\sqrt{s} = 13$ TeV	$\Delta_{\hat{\mu}}$ Δ_{PDF}	Ref.
†d.1 $pp \to Hjjj$	p p > h j j j QED=1 [QCD]	2.519 ± 0.005	$^{+75.1\%}_{-39.8\%}$ $^{+0.6\%}_{-0.6\%}$	[62]
⋆d.2 $pp \to HHjj$	p p > h h j j QED=1 [QCD]	$1.085 \pm 0.002 \cdot 10^{-2}$	$^{+62.1\%}_{-35.8\%}$ $^{+1.2\%}_{-1.3\%}$	[63]
†d.3 $pp \to HHHj$	p p > h h h j [QCD]	$4.981 \pm 0.008 \cdot 10^{-5}$	$^{+46.3\%}_{-29.6\%}$ $^{+1.4\%}_{-1.4\%}$	[−]
†d.3 $pp \to HHHH$	p p > h h h h [QCD]	$1.080 \pm 0.003 \cdot 10^{-7}$	$^{+33.3\%}_{-23.4\%}$ $^{+1.7\%}_{-1.7\%}$	[−]
d.4 $gg \to e^+e^-\mu^+\mu^-$	g g > e+ e- mu+ mu- [QCD]	$2.022 \pm 0.003 \cdot 10^{-3}$	$^{+26.4\%}_{-19.4\%}$ $^{+0.7\%}_{-1.1\%}$	[64]
†d.5 $pp \to HZ\gamma j$	g g > h z a g [QCD]	$4.950 \pm 0.008 \cdot 10^{-6}$	$^{+45.8\%}_{-29.3\%}$ $^{+1.2\%}_{-1.3\%}$	[−]
Non-hadronic processes		$\sqrt{s} = 500$ GeV, no PDF		
⋆e.1 $e^+e^- \to ggg$	e+ e- > g g g [QED]	$2.526 \pm 0.004 \cdot 10^{-6}$	$^{+31.2\%}_{-22.0\%}$	[65]
†e.2 $e^+e^- \to HH$	e+ e- > h h [QED]	$1.567 \pm 0.003 \cdot 10^{-5}$		[−]
†e.3 $e^+e^- \to HHgg$	e+ e- > h h g g [QED]	$6.629 \pm 0.010 \cdot 10^{-11}$	$^{+19.2\%}_{-14.8\%}$	[−]
⋆e.4 $\gamma\gamma \to HH$	a a > h h [QED]	$3.198 \pm 0.005 \cdot 10^{-4}$		[66]
Miscellaneous		$\sqrt{s} = 13$ TeV		
†f.1 $pp \to tt$	p p > t t [QED]	$4.045 \pm 0.007 \cdot 10^{-15}$	$^{+0.2\%}_{-0.8\%}$ $^{+0.9\%}_{-1.0\%}$	[−]
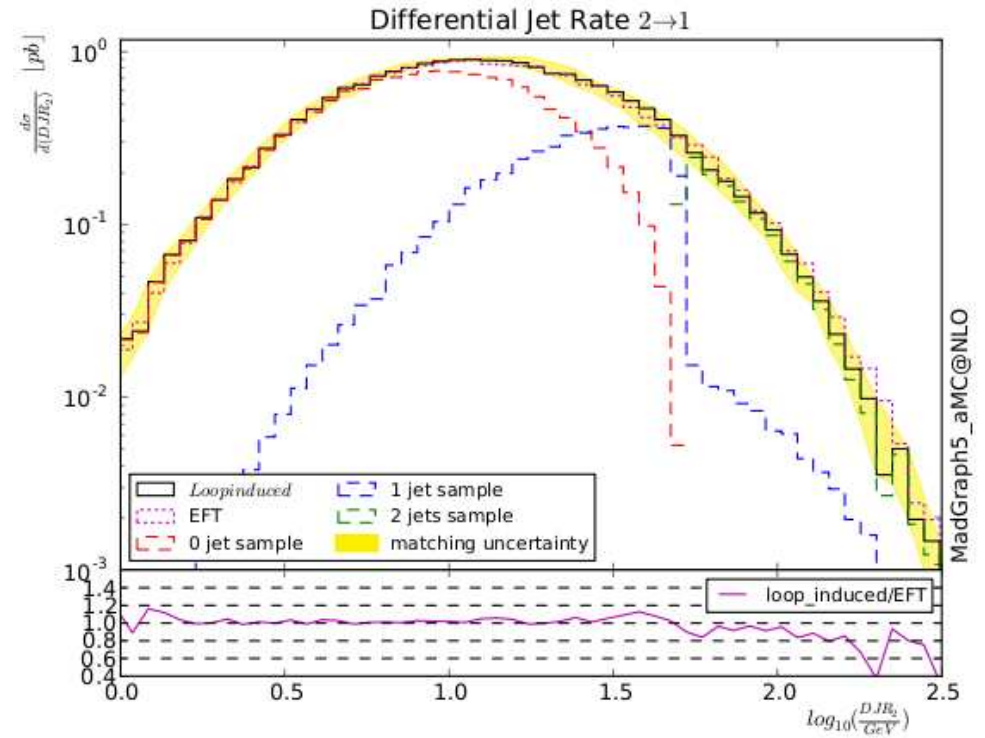
Loop induced, direct integration

Right panel: $gg \to H + 0, 1, 2$ jets, k_T-jet merged

arXiv:1507.00020 [hep-ph]

(Hirschi, Mattelaer)

Extending the physics scope of NLO simulations

The idea is to give the user complete flexibility in the choice of the Lagrangian whose predictions are to be explored, with the same ready-to-run approach of the SM. One exploits the chain:
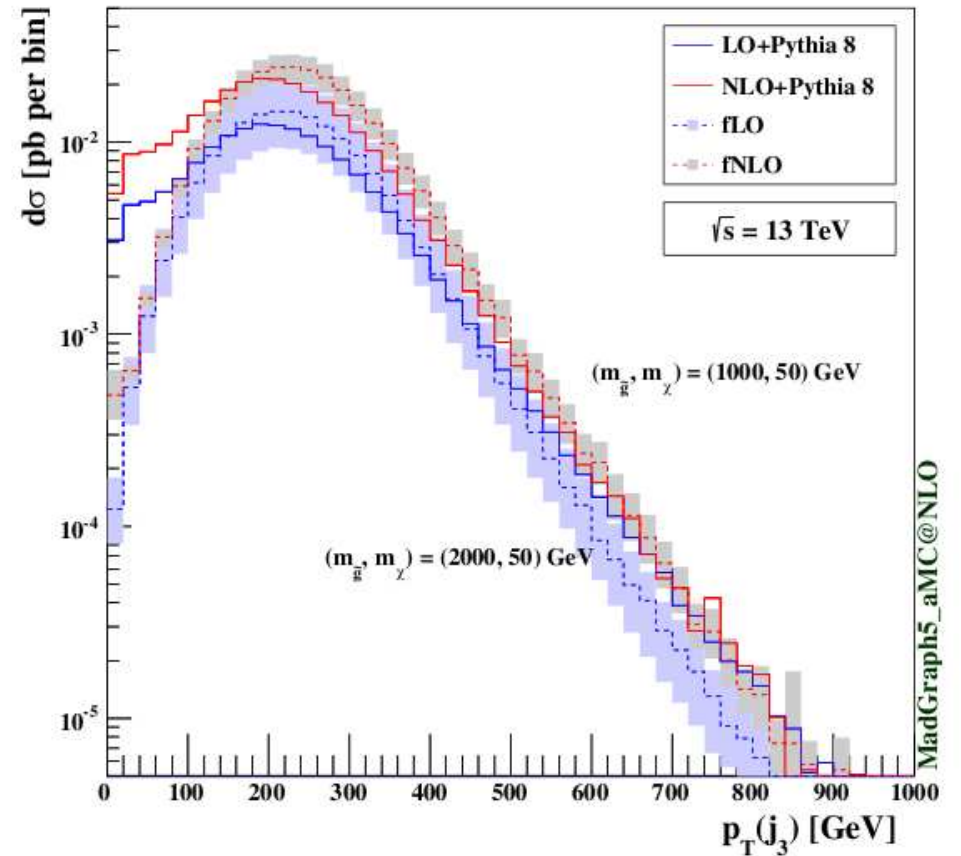
FeynRules - NLOCT - MadGraph5_aMC@NLO

A. Full and simplified renormalisable theories

B. EFTs

As for A., NLOCT is up and running; might require parallelisation for truly complicated cases. No general solution yet for B., but several ad-hoc applications are available. Check:

http://feynrules.irmp.ucl.ac.be/wiki/NLOModels

$$\mathcal{L}_{\mathrm{SQCD}} = D_\mu \tilde{q}_L^\dagger D^\mu \tilde{q}_L + D_\mu \tilde{q}_R^\dagger D^\mu \tilde{q}_R + \frac{i}{2}\bar{\tilde{g}}\slashed{D}\tilde{g}$$

$$- m_{\tilde{q}_L}^2 \tilde{q}_L^\dagger \tilde{q}_L - m_{\tilde{q}_R}^2 \tilde{q}_R^\dagger \tilde{q}_R - \frac{1}{2}m_{\tilde{g}}\bar{\tilde{g}}\tilde{g}$$

$$+ \sqrt{2}g_s \left[-\tilde{q}_L^\dagger T(\bar{\tilde{g}}P_L q) + (\bar{q}P_L\tilde{g})T\tilde{q}_R + \mathrm{h.c.} \right]$$

$$- \frac{g_s^2}{2}\left[\tilde{q}_R^\dagger T\tilde{q}_R - \tilde{q}_L^\dagger T\tilde{q}_L \right]\left[\tilde{q}_R^\dagger T\tilde{q}_R - \tilde{q}_L^\dagger T\tilde{q}_L \right],$$

Gluino-pair production, SUSY-QCD (non mixing squarks), f(N)LO, (N)LO+PS

arXiv:1510.00391 [hep-ph] (Degrande, Fuks, Hirschi, Proudom, Shao)

As far as QCD jets are concerned

Only very sporadic activity within our collaboration; CMS have more experience on LO+PS-merged than we do

At NLO+PS, I personally believe that, in order to accumulate statistics more effectively, we should extend the code to allow it to deal with: *a)* weighted events; *b)* phase-space enhancement factors

At the moment, FxFx cannot in any case handle QCD jets (needs a lowest multiplicity Born with no light final-state partons)

Conclusions

♦ MadGraph5_aMC@NLO is public and open-ended

♦ The code has grown and is growing in several directions

♦ Ongoing work:

reweighting "theory $\rightarrow$ theory" at the NLO

better treatment of resonances

threshold resummation *a la* SCET

aMCfast extended to NLO+PS

several phenomenology applications (SM and BSM)

contributions to YR4 and 100-TeV writeups

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