Stefano Frixione

Status of MadGraph5_aMC@NLO

ATLAS-CMS MC meeting
CERN, 11/1/2016

Developers of the core code

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I am speaking on their behalf

Other very important contributors

MadSpin(spin corr) Pierre Artoisenet, Robbert Rietkerk

HW++, PY8, and NLO merging Andreas Papaefstathiou,
Stefan Prestel

aMCfast(fast NLO for PDFs) Valerio Bertone, Juan Rojo

w/SusHi($gg \to H$ 2HDM/MSSM) Marius Wiesemann

EW corrections Davide Pagani, Stefano Carrazza

Others(EFT, BSM, loop-induced, ...) Benjamin Fuks, Eleni Vryonidou,
Andrew Papanastasiou, Kentarou Mawatari, Cen Zhang

Many thanks to our experimental colleagues for their feedback

Outside of the code, but with bearing on it

FeynRules(models) Adam Alloul, Neil Christensen, Celine Degrande, Claude Duhr, Benjamin Fuks

NLOCT(models) Celine Degrande

Rosetta(EFTs) Adam Falkowski, Benjamin Fuks, Kentarou Mawatari, Ken Mimasu, Francesco Riva, Veronica Sanz

MadDM(DM) Mihailo Backovic, Kyoungchul Kong, Antony Martini, Olivier Mattelaer, Gopolang Mohlabeng

MadAnalysis Eric Conte, Beranger Dumont, Benjamin Fuks, Chris Wymant

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)

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)

$\Longrightarrow$ crucial for BSM applications

This is not a thorough review: I shall only sketch a few activities which have been prominent in 2015 and/or will lead to significant developments in the near future

- 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 $N_{\rm scales}^2 + N_{\rm PDF}$ 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

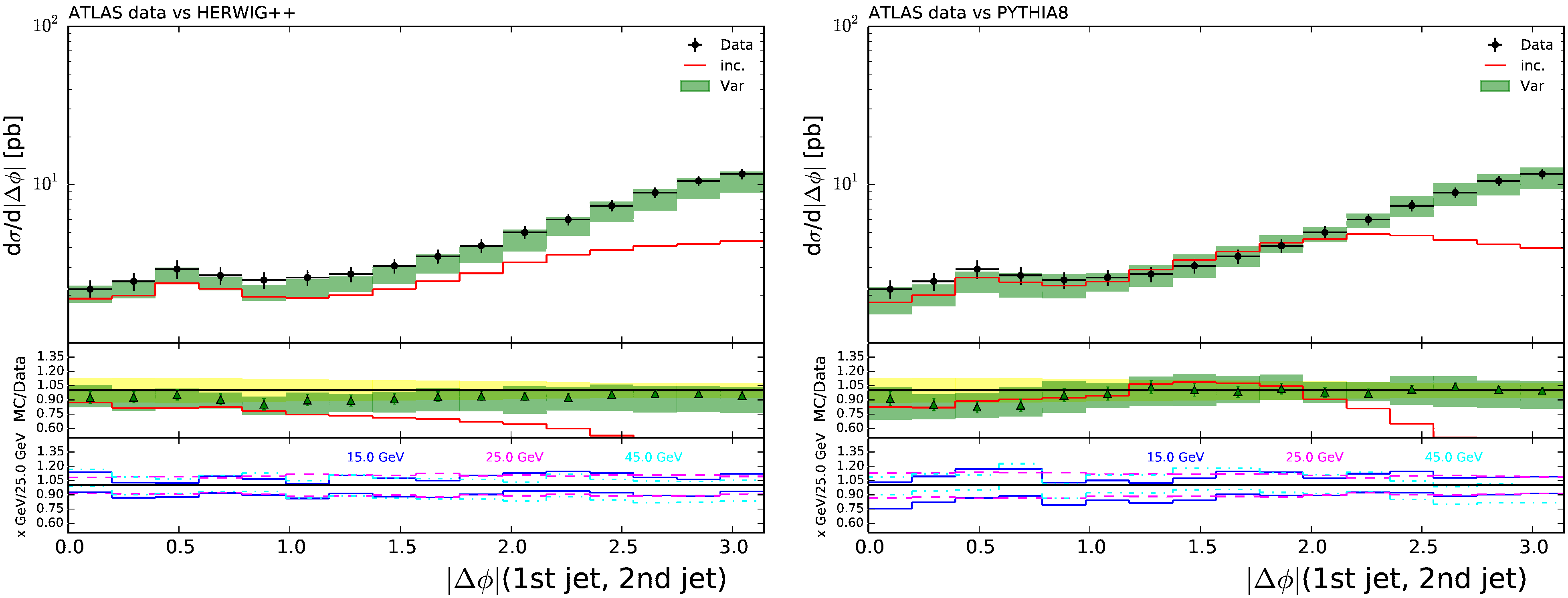
This is fully compatible with the structure already in place from v2.3.0 for (N)LO+PS runs. α_S-variation sets in f(N)LO runs will be added in v2.3.4

Usual recommendations

- Try and make a systematic use of these weights in experiments
- Make Rivet fully compatible with LHA3

Phenomenology validations and SM studies

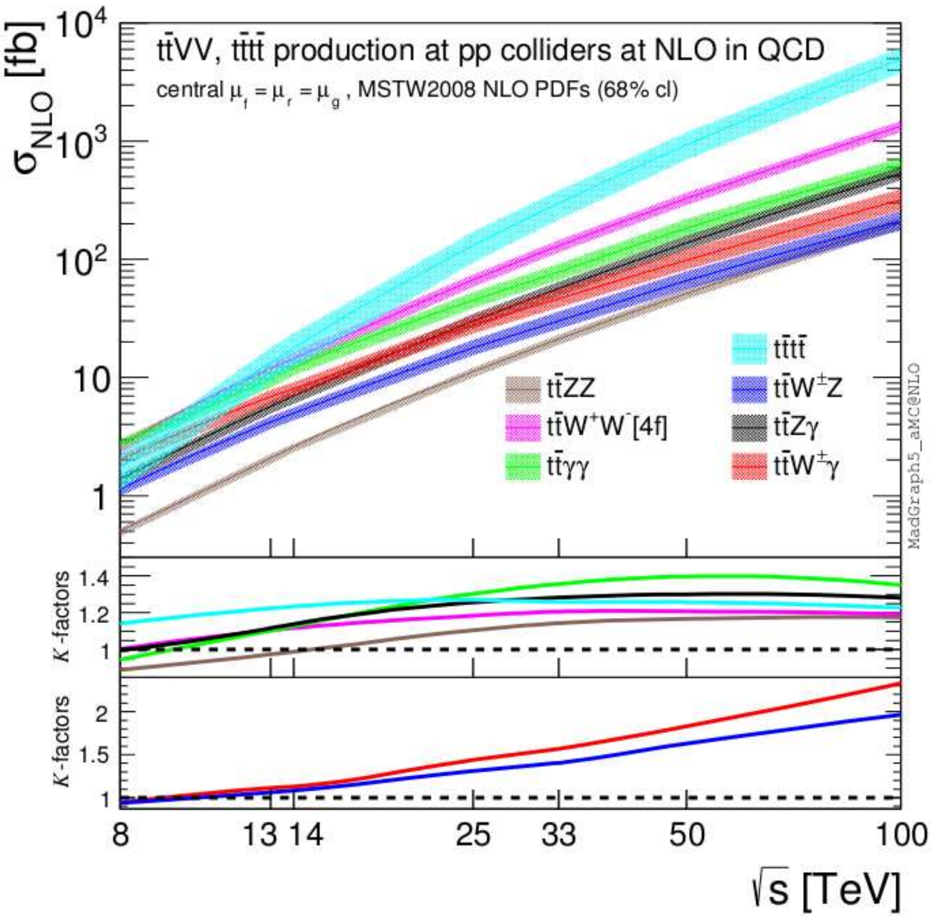
- The code is mature and very reliable
- A lot of work done within experiments
- We tend to study "involved" process
- Recent emphasis has been on NLO-merging validation against data: very thorough for $W/Z+$jets, ongoing for $t\bar{t}+$jets



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)



13 TeV σ[fb]		SR1	SR2	SR3
	NLO+PS	$1.54^{+5.1\%}_{-9.0\%}{}^{+2.2\%}_{-2.6\%} \pm 0.02$	$1.47^{+5.2\%}_{-9.0\%}{}^{+2.0\%}_{-2.4\%} \pm 0.02$	$0.095^{+7.4\%}_{-9.7\%}{}^{+2.0\%}_{-2.4\%} \pm 0.002$
$t\bar{t}H(H \to WW^*)$	LO+PS	$1.401^{+35.6\%}_{-24.4\%}{}^{+2.1\%}_{-2.2\%} \pm 0.008$	$1.355^{+35.2\%}_{-24.1\%}{}^{+2.0\%}_{-2.2\%} \pm 0.008$	$0.0855^{+34.9\%}_{-24.0\%}{}^{+2.0\%}_{-2.2\%} \pm 0.0007$
$K = 1.10$	K^{PS}	1.10 ± 0.02	1.09 ± 0.02	1.11 ± 0.02
	NLO+PS	$0.0437^{+5.5\%}_{-9.2\%}{}^{+2.3\%}_{-2.8\%} \pm 0.0004$	$0.119^{+6.3\%}_{-9.6\%}{}^{+2.1\%}_{-2.5\%} \pm 0.002$	$0.0170^{+5.0\%}_{-8.5\%}{}^{+2.0\%}_{-2.4\%} \pm 0.0003$
$t\bar{t}H(H \to ZZ^*)$	LO+PS	$0.0404^{+36.1\%}_{-24.6\%}{}^{+2.2\%}_{-2.3\%} \pm 0.0002$	$0.1092^{+35.3\%}_{-24.2\%}{}^{+2.0\%}_{-2.2\%} \pm 0.0008$	$0.0152^{+34.7\%}_{-23.9\%}{}^{+1.9\%}_{-2.1\%} \pm 0.0001$
$K = 1.10$	K^{PS}	1.08 ± 0.01	1.09 ± 0.02	1.12 ± 0.02
	NLO+PS	$0.563^{+4.6\%}_{-8.8\%}{}^{+2.2\%}_{-2.7\%} \pm 0.007$	$0.669^{+6.0\%}_{-9.4\%}{}^{+2.1\%}_{-2.6\%} \pm 0.008$	$0.0494^{+7.1\%}_{-9.9\%}{}^{+2.1\%}_{-2.5\%} \pm 0.0007$
$t\bar{t}H(H \to \tau^+\tau^-)$	LO+PS	$0.513^{+35.9\%}_{-24.5\%}{}^{+2.2\%}_{-2.3\%} \pm 0.003$	$0.611^{+35.4\%}_{-24.2\%}{}^{+2.1\%}_{-2.2\%} \pm 0.003$	$0.0438^{+35.1\%}_{-24.1\%}{}^{+2.0\%}_{-2.2\%} \pm 0.0003$
$K = 1.10$	K^{PS}	1.10 ± 0.02	1.10 ± 0.01	1.13 ± 0.02
	NLO+PS	$5.77^{+15.1\%}_{-12.7\%}{}^{+1.6\%}_{-1.2\%} \pm 0.07$	$2.44^{+13.1\%}_{-11.6\%}{}^{+1.7\%}_{-1.4\%} \pm 0.01$	-
$t\bar{t}W^{\pm}$	LO+PS	$4.57^{+27.7\%}_{-20.2\%}{}^{+1.8\%}_{-1.9\%} \pm 0.03$	$1.989^{+27.5\%}_{-20.0\%}{}^{+1.8\%}_{-1.9\%} \pm 0.007$	-
$K = 1.22$	K^{PS}	1.26 ± 0.02	1.23 ± 0.01	-
	NLO+PS	$1.61^{+7.7\%}_{-10.5\%}{}^{+2.0\%}_{-2.5\%} \pm 0.02$	$2.70^{+9.0\%}_{-11.2\%}{}^{+2.0\%}_{-2.5\%} \pm 0.03$	$0.280^{+9.8\%}_{-11.0\%}{}^{+1.9\%}_{-2.3\%} \pm 0.003$
$t\bar{t}Z/\gamma^*$	LO+PS	$1.422^{+36.8\%}_{-24.9\%}{}^{+2.2\%}_{-2.3\%} \pm 0.008$	$2.21^{+36.4\%}_{-24.7\%}{}^{+2.1\%}_{-2.2\%} \pm 0.01$	$0.221^{+35.8\%}_{-24.4\%}{}^{+2.0\%}_{-2.2\%} \pm 0.001$
$K = 1.23$	K^{PS}	1.13 ± 0.02	1.23 ± 0.01	1.27 ± 0.01
	NLO+PS	$0.288^{+8.0\%}_{-11.1\%}{}^{+2.3\%}_{-2.6\%} \pm 0.003$	$0.201^{+7.4\%}_{-10.7\%}{}^{+2.1\%}_{-2.3\%} \pm 0.003$	$0.0116^{+6.9\%}_{-10.2\%}{}^{+2.2\%}_{-2.3\%} \pm 0.0002$
$t\bar{t}W^+W^-$	LO+PS	$0.260^{+38.4\%}_{-25.5\%}{}^{+2.3\%}_{-2.3\%} \pm 0.001$	$0.181^{+38.0\%}_{-25.3\%}{}^{+2.2\%}_{-2.2\%} \pm 0.001$	$0.01073^{+37.7\%}_{-25.1\%}{}^{+2.2\%}_{-2.2\%} \pm 0.00008$
$K = 1.10$	K^{PS}	1.11 ± 0.01	1.11 ± 0.01	1.08 ± 0.02
	NLO+PS	$0.340^{+27.5\%}_{-25.8\%}{}^{+5.5\%}_{-6.4\%} \pm 0.004$	$0.211^{+27.4\%}_{-25.6\%}{}^{+5.2\%}_{-6.1\%} \pm 0.003$	$0.0110^{+27.0\%}_{-25.5\%}{}^{+5.0\%}_{-5.9\%} \pm 0.0002$
$t\bar{t}t\bar{t}$	LO+PS	$0.271^{+80.9\%}_{-41.5\%}{}^{+4.6\%}_{-4.6\%} \pm 0.001$	$0.166^{+80.3\%}_{-41.4\%}{}^{+4.4\%}_{-4.4\%} \pm 0.001$	$0.00871^{+79.8\%}_{-41.2\%}{}^{+4.2\%}_{-4.2\%} \pm 0.00007$
$K = 1.22$	K^{PS}	1.26 ± 0.02	1.27 ± 0.02	1.26 ± 0.03
13 TeV σ[ab]		SR1	SR2	SR3
	NLO+PS	$9.60^{+3.5\%}_{-8.4\%}{}^{+1.8\%}_{-1.8\%} \pm 0.06$	$5.02^{+3.7\%}_{-8.3\%}{}^{+1.8\%}_{-1.7\%} \pm 0.04$	$0.249^{+7.2\%}_{-9.6\%}{}^{+1.9\%}_{-1.8\%} \pm 0.009$
$t\bar{t}ZZ$	LO+PS	$9.71^{+36.3\%}_{-24.5\%}{}^{+1.9\%}_{-1.9\%} \pm 0.02$	$5.08^{+35.9\%}_{-24.3\%}{}^{+1.9\%}_{-1.9\%} \pm 0.02$	$0.250^{+35.5\%}_{-24.2\%}{}^{+1.9\%}_{-1.9\%} \pm 0.004$
$K = 0.99$	K^{PS}	0.99 ± 0.01	0.99 ± 0.01	1.00 ± 0.04
	NLO+PS	$62.0^{+9.0\%}_{-10.2\%}{}^{+2.2\%}_{-1.6\%} \pm 0.7$	$27.9^{+9.2\%}_{-10.3\%}{}^{+2.3\%}_{-1.7\%} \pm 0.5$	$0.91^{+7.2\%}_{-9.2\%}{}^{+2.4\%}_{-1.7\%} \pm 0.02$
$t\bar{t}W^{\pm}Z$	LO+PS	$60.2^{+32.2\%}_{-22.6\%}{}^{+2.4\%}_{-2.3\%} \pm 0.3$	$26.4^{+32.0\%}_{-22.5\%}{}^{+2.4\%}_{-2.2\%} \pm 0.2$	$0.893^{+31.9\%}_{-22.4\%}{}^{+2.4\%}_{-2.2\%} \pm 0.009$
$K = 1.06$	K^{PS}	1.03 ± 0.01	1.06 ± 0.02	1.02 ± 0.02

$t\bar{t}VV$, $t\bar{t}t\bar{t}$ production, f(N)LO and (N)LO+PS

arXiv:1507.05640 [hep-ph]

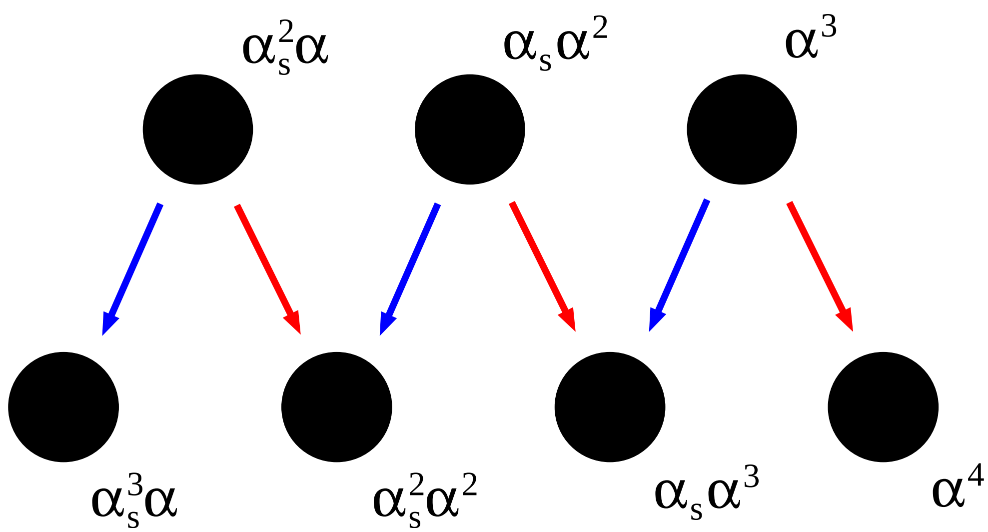
(Maltoni, Pagani, Tsinikos)

Mixed-coupling expansion

Consider e.g. ttV production (V is an SM boson); Σ is a generic observable

$$\begin{aligned}
\Sigma^{(\mathrm{LO})}_{t\bar{t}V}(\alpha_S,\alpha) &= \alpha_S^2\alpha\,\Sigma_{3,0}+\alpha_S\alpha^2\,\Sigma_{3,1}+\alpha^3\,\Sigma_{3,2}\\
&\equiv \Sigma_{\mathrm{LO},1}+\Sigma_{\mathrm{LO},2}+\Sigma_{\mathrm{LO},3}\\
\Sigma^{(\mathrm{NLO})}_{t\bar{t}V}(\alpha_S,\alpha) &= \alpha_S^3\alpha\,\Sigma_{4,0}+\alpha_S^2\alpha^2\,\Sigma_{4,1}+\alpha_S\alpha^3\,\Sigma_{4,2}+\alpha^4\,\Sigma_{4,3}\\
&\equiv \Sigma_{\mathrm{NLO},1}+\Sigma_{\mathrm{NLO},2}+\Sigma_{\mathrm{NLO},3}+\Sigma_{\mathrm{NLO},4}
\end{aligned}$$

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 $\Sigma_{\mathrm{NLO},2}$):

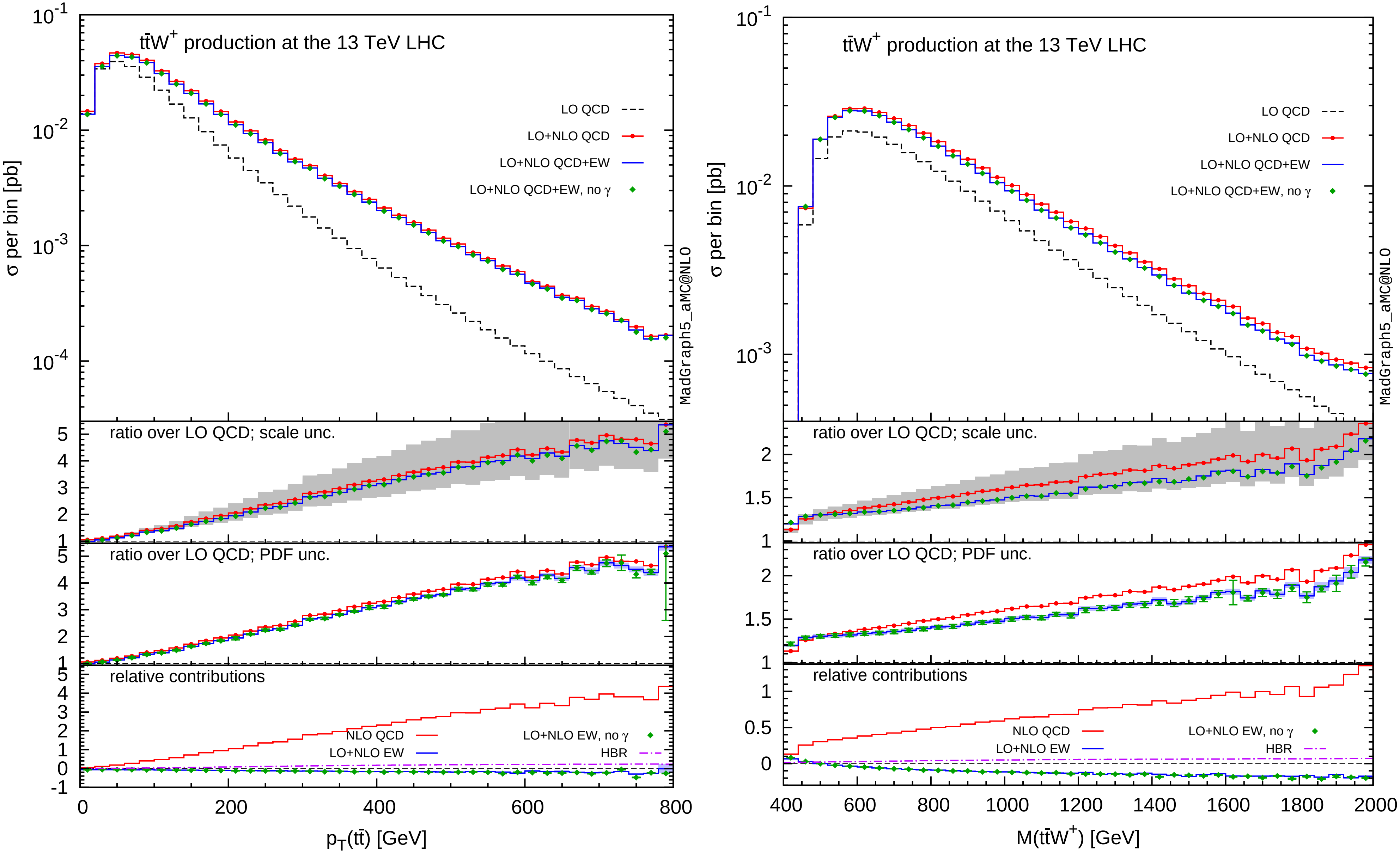
```
MG5_aMC> generate p p > t t~ w+ QCD=2 QED=1 [QED]
```

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:

$$\begin{array}{lllll} \mathrm{LO} & \alpha_S^k \alpha^p\,, & k \le n\,, & p \le m\,, & k+p=b \\ \mathrm{NLO} & \alpha_S^k \alpha^p\,, & k \le n+1\,, & p \le m+1\,, & k+p=b+1 \end{array}$$



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)

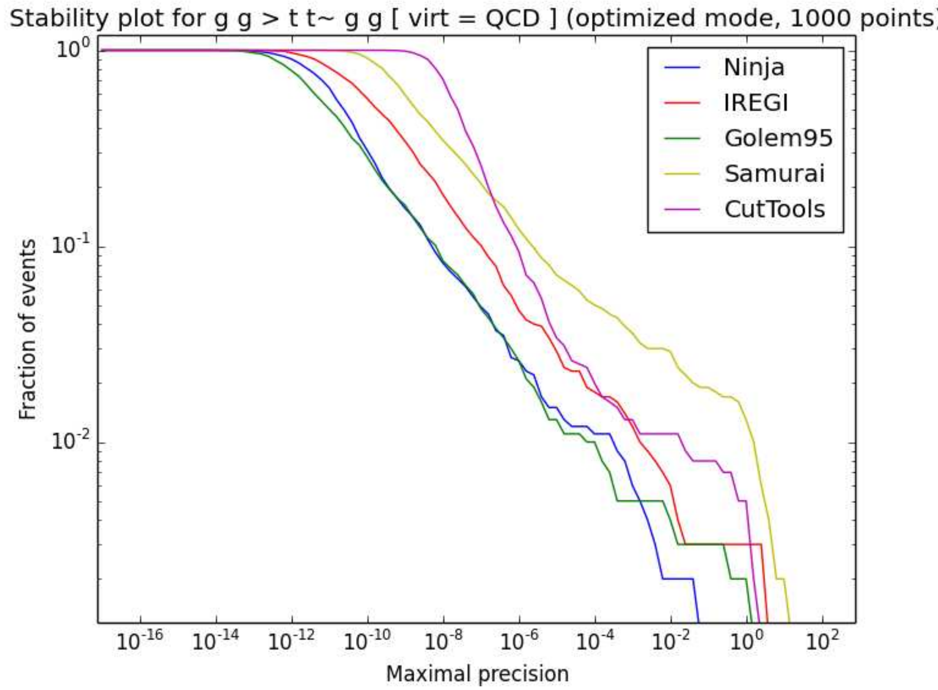
MadLoop is able to switch dynamically among different reductions (with user's pre-defined ordering); new options are being added to allow more flexibility (improved numerical stability, treatment of higher-rank integrals)

Also, an independent OLP (GoSam) can now be used (simply from configuration card: not available for loop-induced)

$$gg \to t\bar{t}gg$$

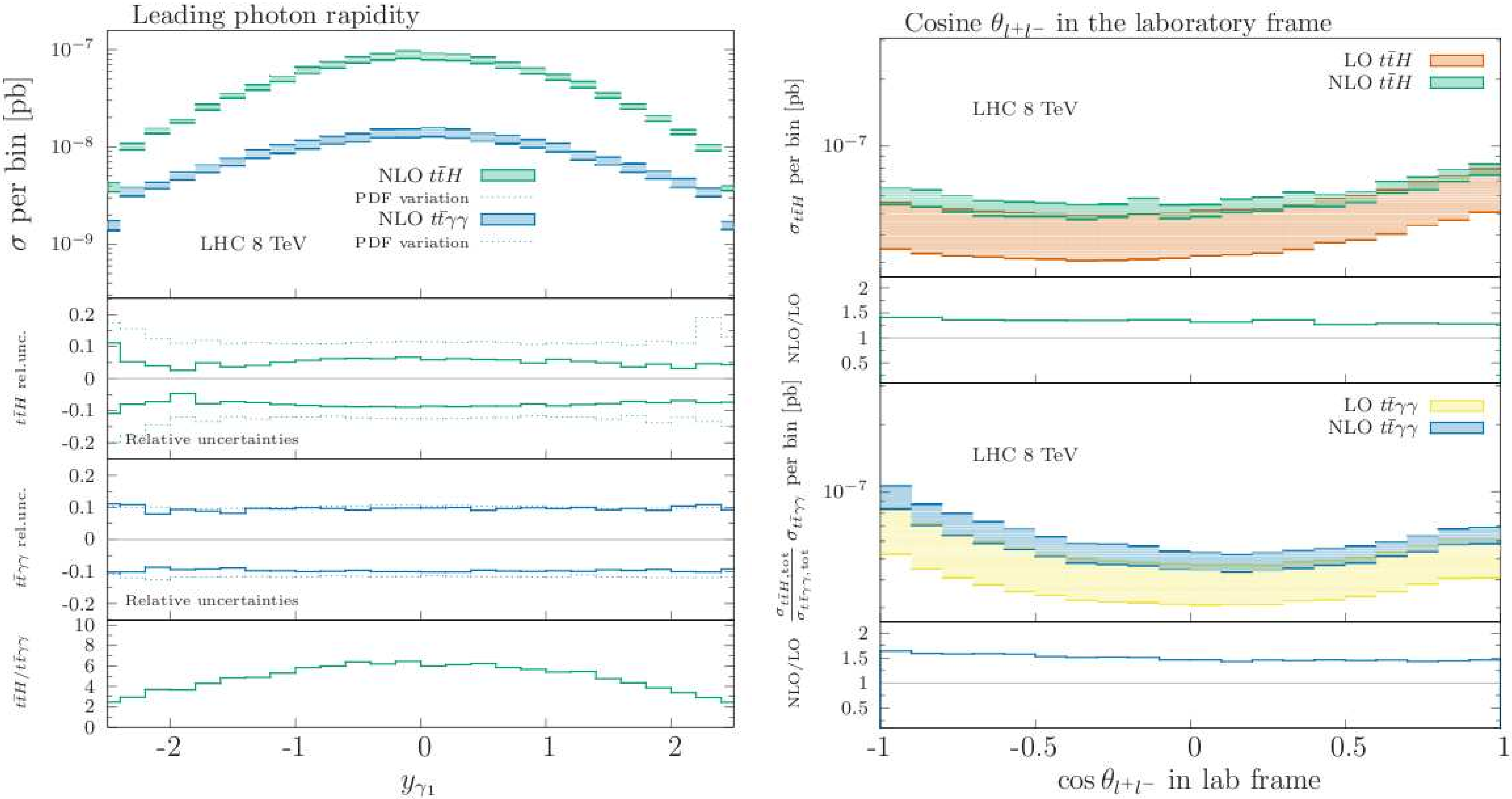
CutTools	230 ms
IREGI	13295 ms
Golem95	6226 ms
Samurai	580 ms
Ninja	90 ms

Averages over a few points



Dozens of SM amplitudes tested

Not yet public



$t\bar{t}H$ and $t\bar{t}\gamma\gamma$: first application with OLP=GoSam

arXiv1509.02077 [hep-ph]

(van Deurzen, Frederix, Hirschi, Luisoni, Mastrolia, Ossola)

Loop-induced processes

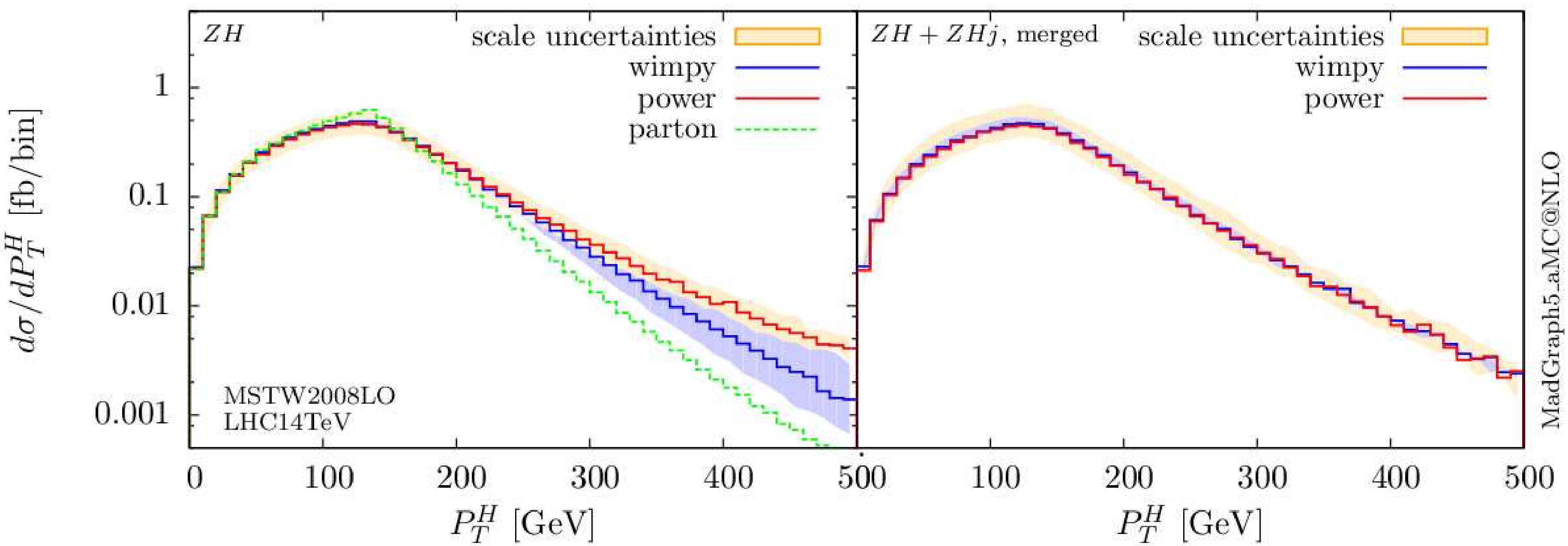
LI processes were previously treated only through reweighting

(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?



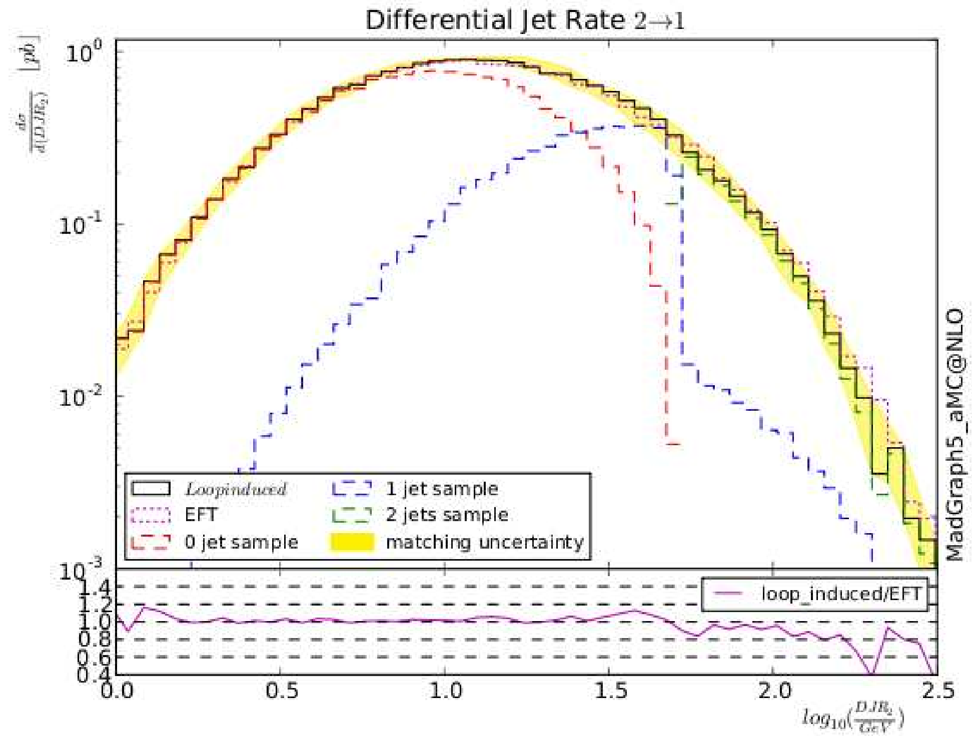
Loop induced, reweighted

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

arXiv:1503.01656 [hep-ph]

(Hespel, Maltoni, Vryonidou)

Process		Syntax	Cross section (pb)	$\Delta_{\hat{\mu}}$	Δ_{PDF}	Ref.
Selected $2 \to 4$			$\sqrt{s} = 13$ TeV			
†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:

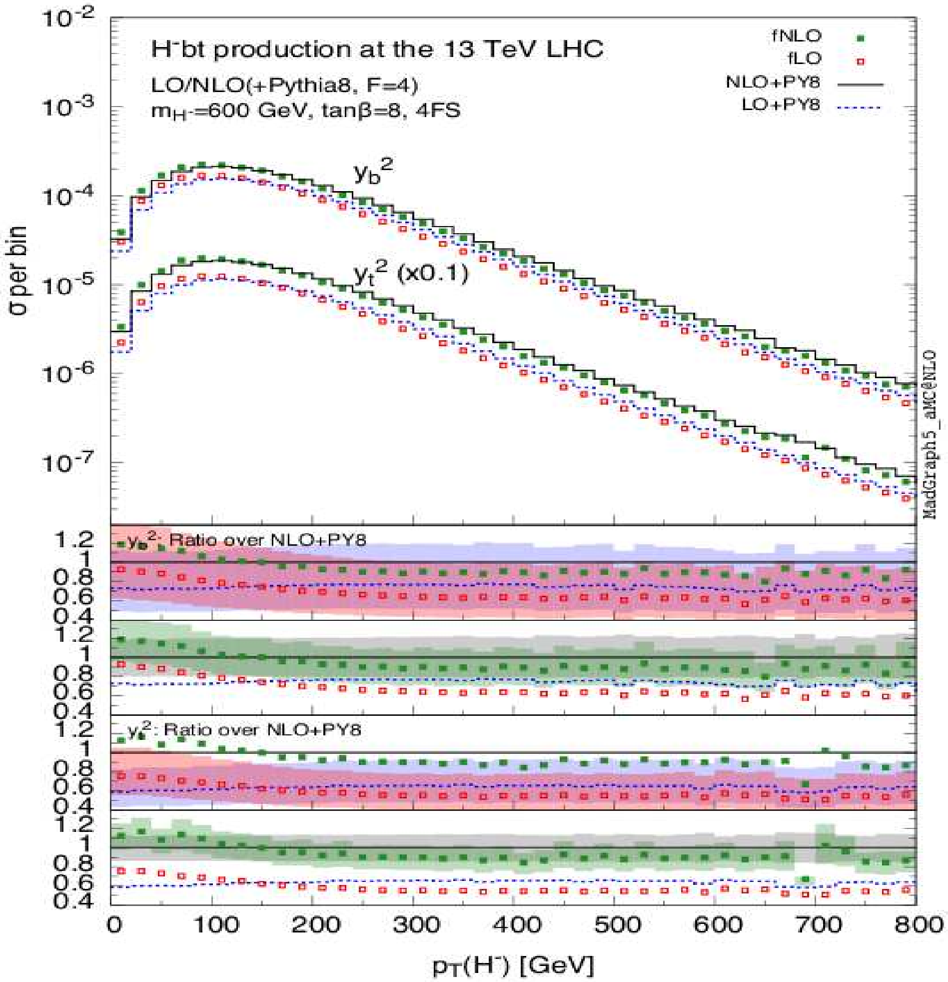
FeynRules - NLOCT - MadGraph5_aMC@NLO

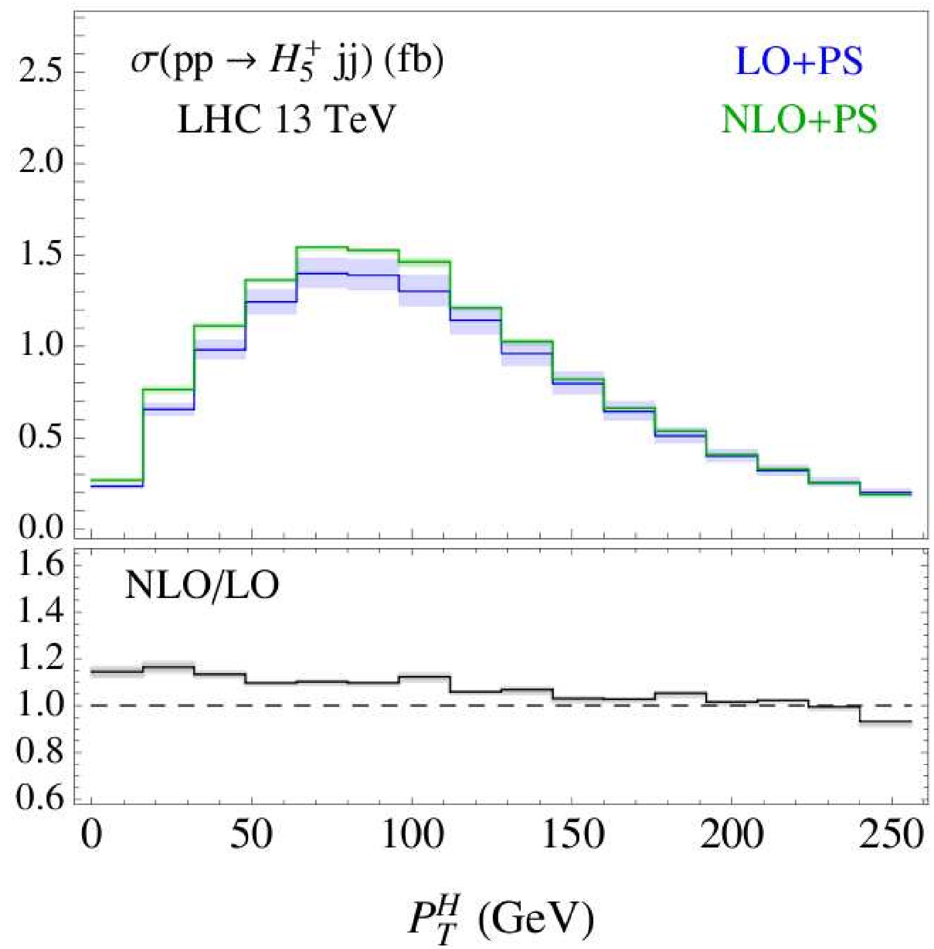
A. Full and simplified renormalisable theories

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`



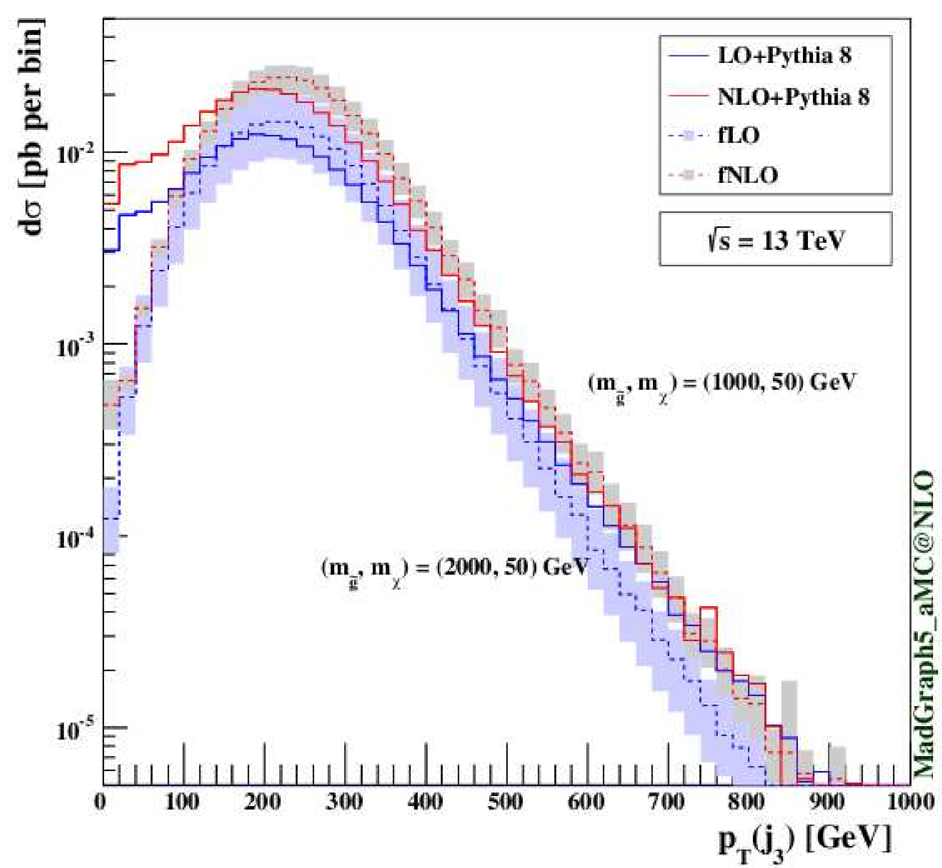


(Heavy) charged Higgs production, 2HDM and Georgi-Machacek, f(N)LO, (N)LO+PS

arXiv:1507.02549 [hep-ph] (Degrande, Ubiali, Wiesemann, Zaro)

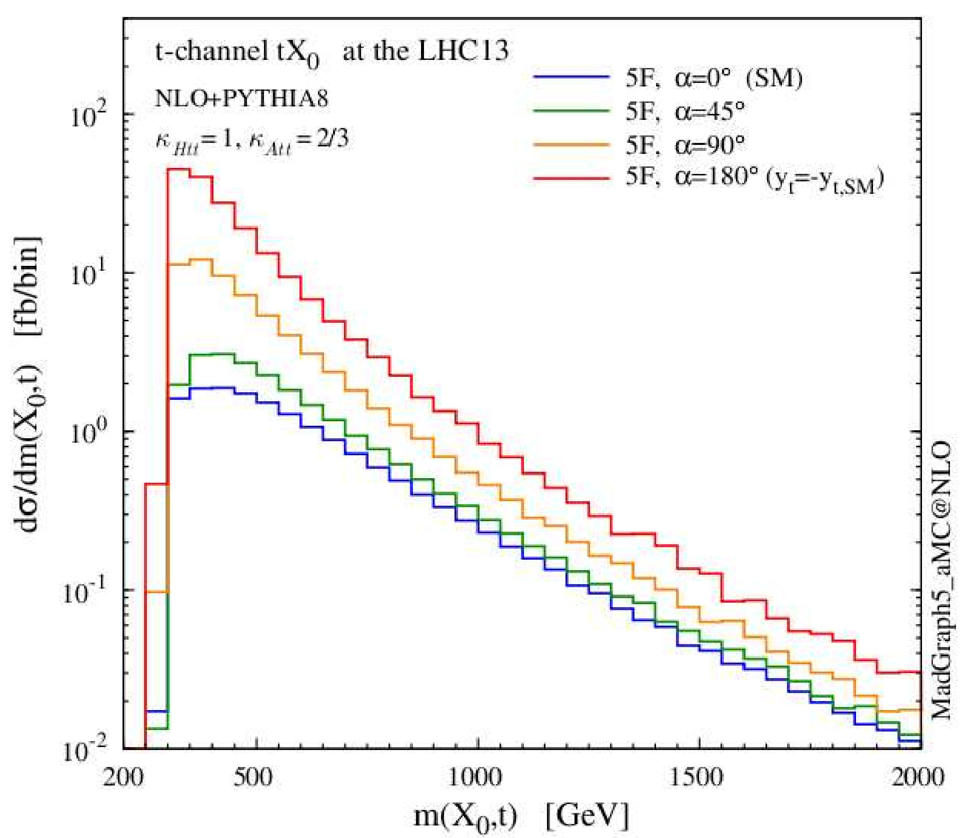
arXiv:1512.01243 [hep-ph] (Degrande, Hartling, Logan,Peterson, Zaro)

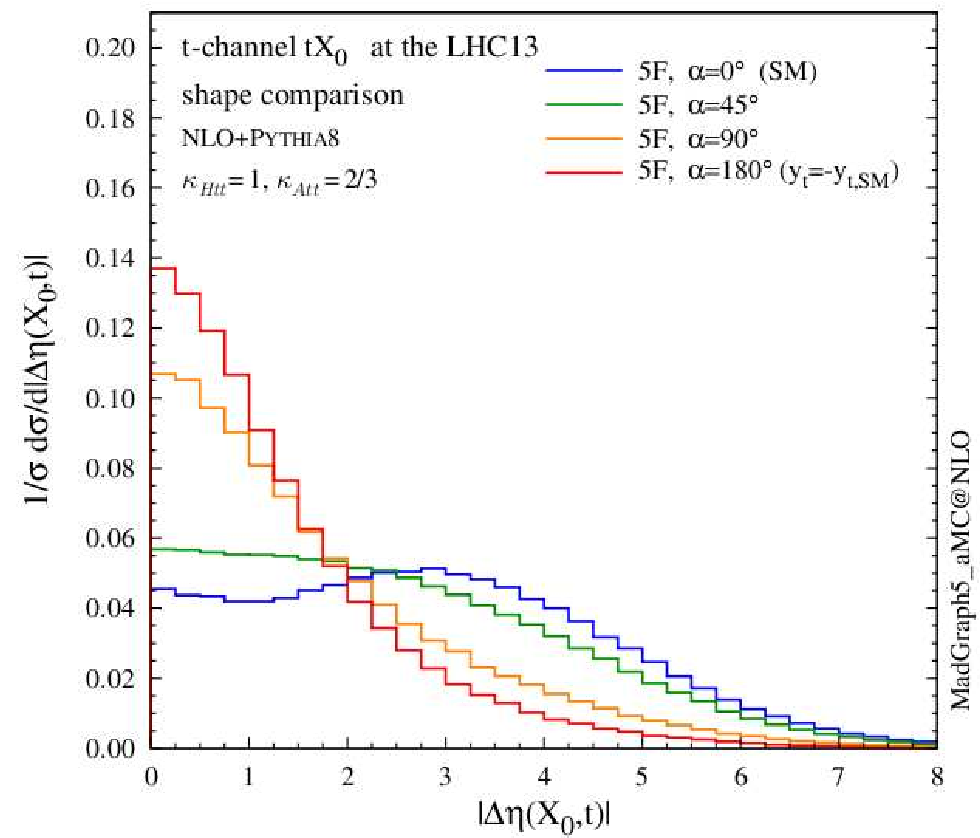
$$\mathcal{L}_{\rm SQCD} = D_\mu \tilde{q}_L^\dagger D^\mu \tilde{q}_L + D_\mu \tilde{q}_R^\dagger D^\mu \tilde{q}_R + \frac{i}{2}\bar{\tilde{g}} \not{D} \tilde{g}$$
$$- m_{\tilde{q}_L}^2 \tilde{q}_L^\dagger \tilde{q}_L - m_{\tilde{q}_R}^2 \tilde{q}_R^\dagger \tilde{q}_R - \frac{1}{2} m_{\tilde{g}} \bar{\tilde{g}} \tilde{g}$$
$$+ \sqrt{2} g_s \Big[- \tilde{q}_L^\dagger T \big(\bar{\tilde{g}} P_L q\big) + \big(\bar{q} P_L \tilde{g}\big) T \tilde{q}_R + \text{h.c.} \Big]$$
$$- \frac{g_s^2}{2} \Big[\tilde{q}_R^\dagger T \tilde{q}_R - \tilde{q}_L^\dagger T \tilde{q}_L \Big] \Big[\tilde{q}_R^\dagger T \tilde{q}_R - \tilde{q}_L^\dagger T \tilde{q}_L \Big] \ ,$$



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

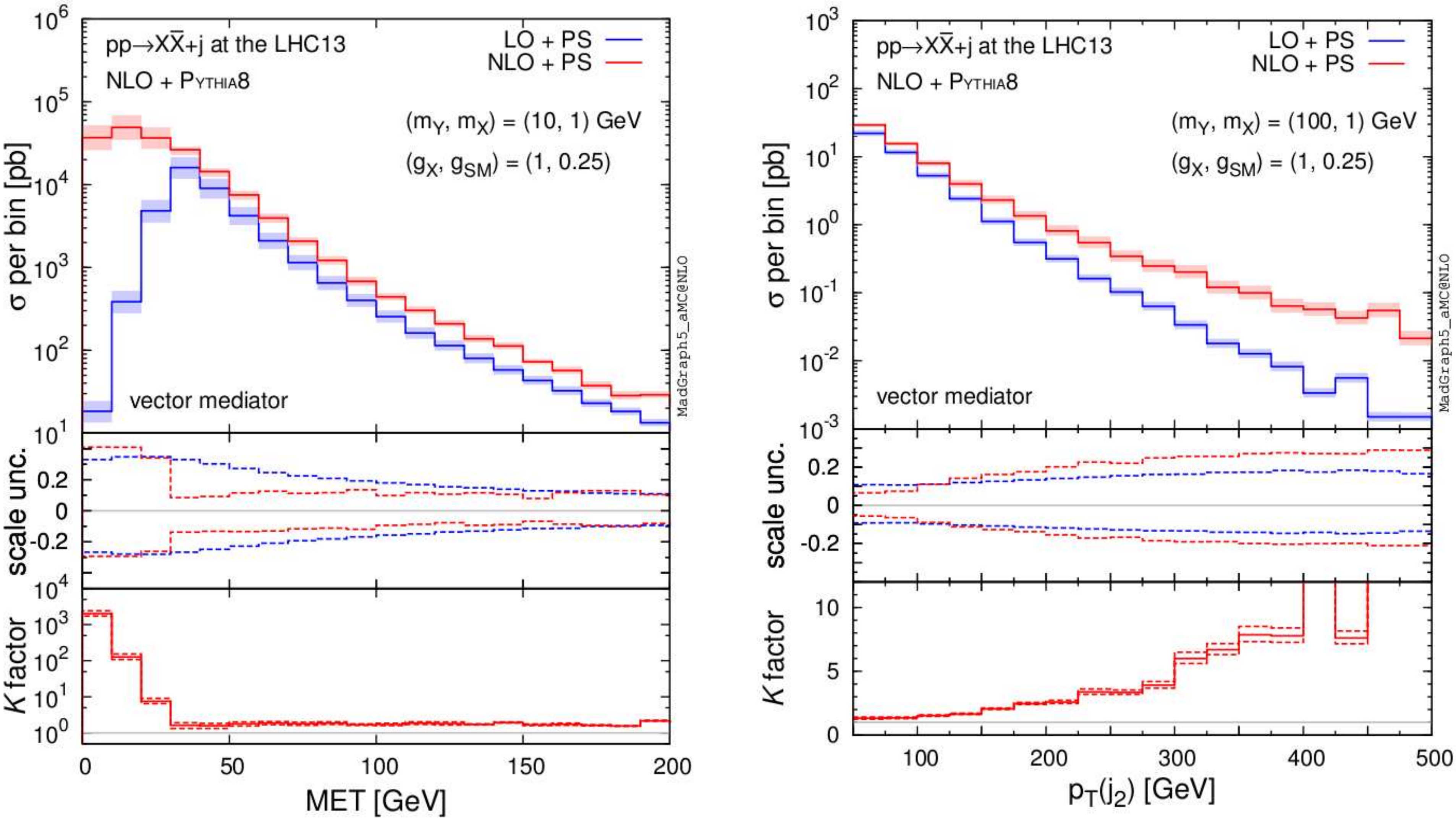
arXiv:1510.00391 [hep-ph] (Degrande, Fuks, Hirschi, Proudom, Shao)





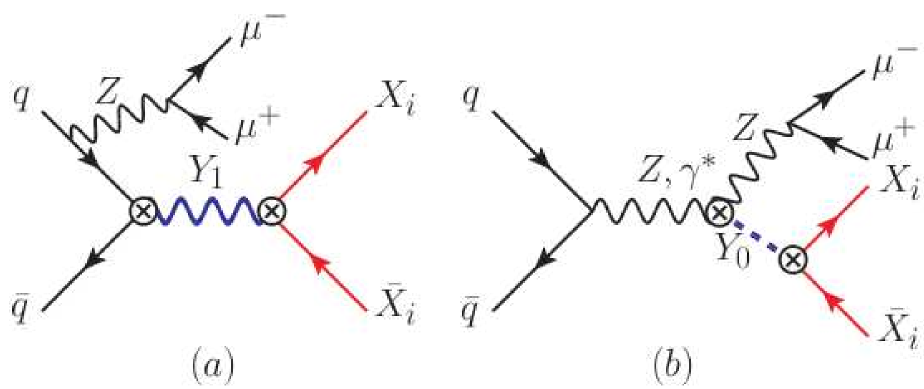
X_0t associated production, HC (EFT), (N)LO+PS

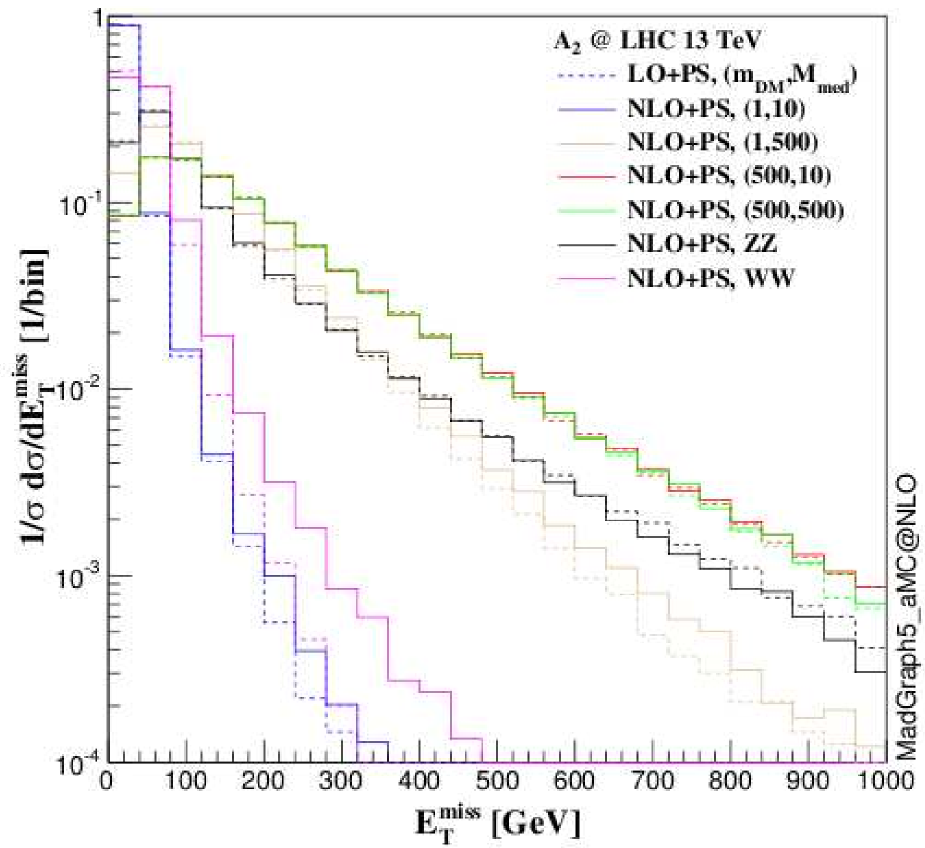
arXiv:1504.00611 [hep-ph] (Demartin, Maltoni, Mawatari, Zaro)



$\chi\chi$+jets or $t\bar{t}$, Dirac DM-simplified, spin-1 and spin-0 s-channel mediators
f(N)LO, (N)LO+PS, and FxFx-merged

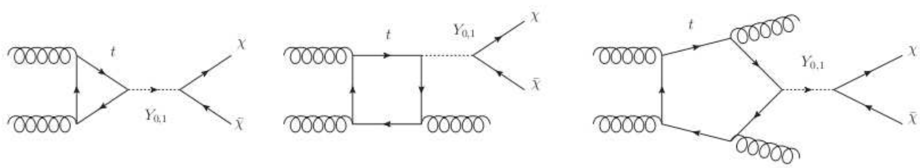
arXiv:1508.05327 [hep-ph] (Backovic, Krämer, Maltoni, Martini, Mawatari, Pellen)

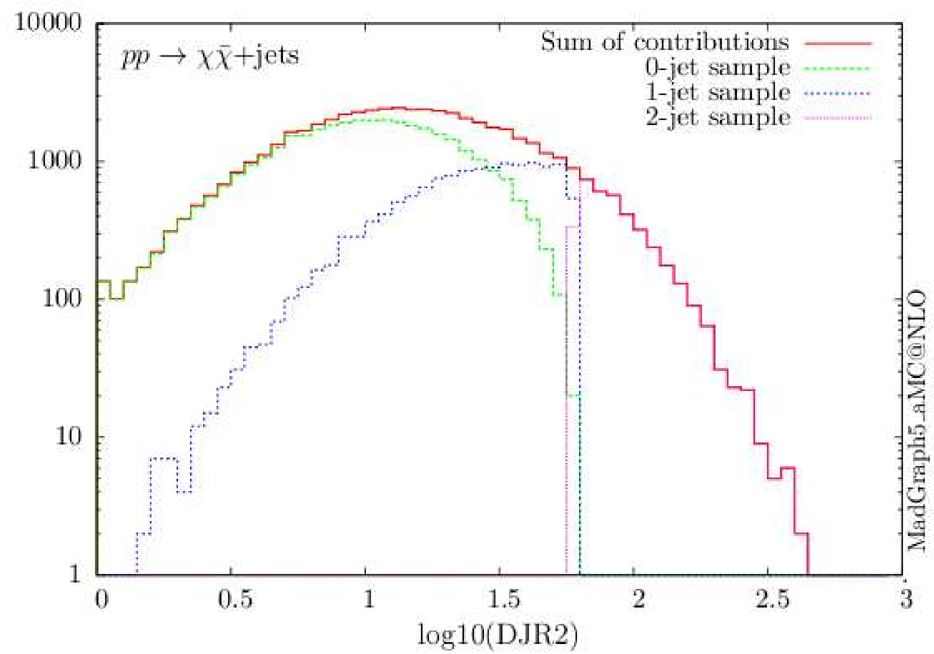




As before, plus dim-4 and dim-5 mediator-heavy boson couplings, (N)LO+PS

arXiv:1509.05785 [hep-ph] (Neubert, Wang, Zhang)





Dirac DM-simplified, top-philic, spin-1 and spin-0 s-channel mediators, k_T-jet merged

Note: this is loop-induced

arXiv:1508.00564 [hep-ph] (Mattelaer, Vryonidou)

An aside: MadDM

MadGraph5_aMC@NLO can serve as a host to MadDM (v2.0: relic density and direct detection) – the modules of the latter are copied under the main directory of the former

- Works with any UFO model with DM content
- Limited to LO so far
- Will exploit the features of MadGraph5_aMC@NLO to go beyond LO for relic density and to use loop-induced processes for direct detection

Conclusions

- MadGraph5_aMC@NLO is public and open-ended
- The code has grown and is growing in several directions
- Ongoing work:

  reweighting "theory $\longrightarrow$ 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

  ...