Stefano Frixione

MadGraph5_aMC@NLO

ZPW2014

Zurich, 8/1/2014

From the current release (16/12/2013) *both* MadGraph *and* aMC@NLO are replaced by:

MadGraph5_aMC@NLO v2.0

This is a single framework, which inherits all the features of the two codes, has others which are new, and is poised to compute NLO corrections in and to any user-defined theory (thus lifting the current limitation of QCD NLO corrections to SM processes)

Developers of core code

Johan Alwall

Rikkert Frederix

Stefano Frixione

Valentin Hirschi

Fabio Maltoni

Olivier Mattelaer

Roberto Pittau

Tim Stelzer

Paolo Torrielli

Marco Zaro

One very important utility

MadSpin Pierre Artoisenet, Rikkert Frederix, Olivier Mattelaer,
Robbert Rietkerk

Current status of the code

- *Extremely* simple usage

- *Extremely* simple usage

```
> ./bin/mg5_aMC
```

- *Extremely* simple usage

```
> ./bin/mg5_aMC

MG5_aMC> generate p p > t t~ h [QCD]
```

♦ *Extremely* simple usage

```
> ./bin/mg5_aMC

MG5_aMC> generate p p > t t~ h [QCD]

MG5_aMC> output MY_TTH_DIR
```

♦ *Extremely* simple usage

```
> ./bin/mg5_aMC

MG5_aMC> generate p p > t t~ h [QCD]

MG5_aMC> output MY_TTH_DIR

MG5_aMC> launch
```

♦ *Extremely* simple usage

```
> ./bin/mg5_aMC

MG5_aMC> generate p p > t t~ h [QCD]

MG5_aMC> output MY_TTH_DIR

MG5_aMC> launch
```

Upon executing the `launch` command:

```
Terminal
File  Edit  View  Search  Terminal  Help
************************************************************
INFO: load configuration from /home/frixione/.mg5/mg5_configuration.txt
INFO: load configuration from /home/frixione/Work/aMCatNLO5/MG5_aMC_v2_0_0/PROCN
LO_loop_sm_3/Cards/amcatnlo_configuration.txt
INFO: load configuration from /home/frixione/Work/aMCatNLO5/MG5_aMC_v2_0_0/input
/mg5_configuration.txt
INFO: load configuration from /home/frixione/Work/aMCatNLO5/MG5_aMC_v2_0_0/PROCN
LO_loop_sm_3/Cards/amcatnlo_configuration.txt
set group_subprocesses Auto
set ignore_six_quark_processes False
set loop_optimized_output True
set gauge unitary
set complex_mass_scheme False
launch auto
The following switches determine which operations are executed:
 1 Perturbative order of the calculation:                            order=NLO
 2 Fixed order (no event generation and no MC@[N]LO matching):   fixed_order=OFF
 3 Shower the generated events:                                     shower=ON
 4 Decay particles with the MadSpin module:                        madspin=OFF
  Either type the switch number (1 to 4) to change its default setting,
  or set any switch explicitly (e.g. type 'order=LO' at the prompt)
  Type '0', 'auto', 'done' or just press enter when you are done.
 [0, 1, 2, 3, 4, auto, done, order=LO, order=NLO, ... ]
>
```

By toggling with the "1" and "2" switches one can:

- Perform NLO (QCD) or LO calculations
- With `(fixed_order=OFF)` or without `(fixed_order=ON)` parton showers

Note: the command

```
MG5_aMC> generate p p > t t~ h
```

(ie, without [QCD]) disables the NLO stuff, and the code behaves as "old" MG5 (up to new features wrt v1.5.xx) – in particular, all options for BSM simulations at the LO are still there

- `Models` for NLO computations require extra features wrt those used at the LO (more on this later)
- Only QCD corrections to SM are supported presently

- *Extremely* simple usage
- No external dependences (stripped FastJet included; LHAPDF optional)

- *Extremely* simple usage
- No external dependences (stripped FastJet included; LHAPDF optional)
- Very significant speed increase at the NLO

  (up to two orders of magnitude for difficult processes wrt previous β versions)

MadGraph5 2.0.0beta3

```
Summary:
Process p p > t t~ [QCD]
Run at p-p collider (4000 + 4000 GeV)
Total cross-section: 1.770e+02 +- 1.7e+00 pb
Ren. and fac. scale uncertainty: +13.5% -13.0%
Number of events generated: 10000
Parton shower to be used: HERWIG6
Fraction of negative weights: 0.16
Total running time : 12m 12s

DEBUG:
Number of loop ME evaluations: 168120
```

MadGraph5_aMC@NLO

```
Summary:
Process p p > t t~ [QCD]
Run at p-p collider (4000 + 4000 GeV)
Total cross-section: 1.765e+02 +- 9.2e-01 pb
Ren. and fac. scale uncertainty: +12.2% -12.3%
Number of events generated: 10000
Parton shower to be used: HERWIG6
Fraction of negative weights: 0.16
Total running time : 1m 35s

DEBUG:
Number of loop ME evaluations (by MadLoop): 6967
```

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MADGRAPH5 2.0.0BETA3

```
Summary:
Process p p > t t~ [QCD]
Run at p-p collider (4000 + 4000 GeV)
Total cross-section: 1.770e+02 +- 1.7e+00 pb
Ren. and fac. scale uncertainty: +13.5% -13.0%
Number of events generated: 10000
Parton shower to be used: HERWIG6
Fraction of negative weights: 0.16
Total running time : 12m 12s

DEBUG:
    Number of loop ME evaluations: 168120
```

N.A.

MADGRAPH5_AMC@NLO

```
Summary:
Process p p > t t~ [QCD]
Run at p-p collider (4000 + 4000 GeV)
Total cross-section: 1.765e+02 +- 9.2e-01 pb
Ren. and fac. scale uncertainty: +12.2% -12.3%
Number of events generated: 10000
Parton shower to be used: HERWIG6
Fraction of negative weights: 0.16
Total running time : 1m 35s

DEBUG:
    Number of loop ME evaluations (by MadLoop): 6967
```

```
Summary:
Process p p > t b t~ b~ [QCD]
Run at p-p collider (4000 + 4000 GeV)
Total cross-section: 2.671e+00 +- 1.2e-02 pb
Ren. and fac. scale uncertainty: +39.1% -27.8%
Number of events generated: 200000
Parton shower to be used: HERWIG6
Fraction of negative weights: 0.29
Total running time : 17h 0m
Sequential running time : ~ 6 days

DEBUG:
    Number of loop ME evaluations (by MadLoop): 367802
```

4 flavour, no cuts

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Mainly due to:

- More clever MC over helicities for virtuals
- Virtuals computed less often
- Virtuals are not an obvious bottleneck any longer (as they used to be)

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- More clever MC over helicities for virtuals
- Virtuals computed less often
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Which lead to:

Process		Syntax	Cross section (pb)	
Vector boson +jets			(LO) NLO 13 TeV	
a.1	$pp \to W^\pm$	`p p > wpm`	$(0000)\ 1.773 \pm 0.007 \cdot 10^5$	$^{+5.2\%}_{-9.4\%}$ $^{+1.9\%}_{-1.6\%}$
a.2	$pp \to W^\pm j$	`p p > wpm j`	$(0000)\ 2.843 \pm 0.010 \cdot 10^4$	$^{+5.9\%}_{-8.0\%}$ $^{+1.3\%}_{-1.1\%}$
a.3	$pp \to W^\pm jj$	`p p > wpm j j`	$(0000)\ 7.786 \pm 0.030 \cdot 10^3$	$^{+2.4\%}_{-6.0\%}$ $^{+0.9\%}_{-0.8\%}$
a.4*	$pp \to W^\pm jjj$	`p p > wpm j j j`	$(0000)\ 2.005 \pm 0.008 \cdot 10^3$	$^{+0.9\%}_{-6.7\%}$ $^{+0.6\%}_{-0.5\%}$
a.5	$pp \to Z$	`p p > z`	$(0000)\ 5.410 \pm 0.022 \cdot 10^4$	$^{+4.6\%}_{-8.6\%}$ $^{+1.9\%}_{-1.5\%}$
a.6	$pp \to Zj$	`p p > z j`	$(0000)\ 9.742 \pm 0.035 \cdot 10^3$	$^{+5.8\%}_{-7.8\%}$ $^{+1.2\%}_{-1.0\%}$
a.7	$pp \to Zjj$	`p p > z j j`	$(0000)\ 2.665 \pm 0.010 \cdot 10^3$	$^{+2.5\%}_{-6.0\%}$ $^{+0.7\%}_{-0.7\%}$
a.8*	$pp \to Zjjj$	`p p > z j j j`	$(0000)\ 6.996 \pm 0.028 \cdot 10^2$	$^{+1.1\%}_{-6.8\%}$ $^{+0.5\%}_{-0.5\%}$
a.9*	$pp \to \gamma j$	`p p > a j`	$(0000)\ 5.218 \pm 0.025 \cdot 10^4$	$^{+24.5\%}_{-21.4\%}$ $^{+1.4\%}_{-1.6\%}$
a.10*	$pp \to \gamma jj$	`p p > a j j`	$(0000)\ 1.004 \pm 0.004 \cdot 10^4$	$^{+5.9\%}_{-10.9\%}$ $^{+0.8\%}_{-1.2\%}$

PRELIMINARY – to appear in the MadGraph5_aMC@NLO physics paper

Process		Syntax	Cross section (pb)		
Vector-boson pair +jets			(LO) NLO 13 TeV		
b.1	$pp \to W^+W^-$ (4f)	`p p > w+ w-`	(0000) $1.028 \pm 0.003 \cdot 10^{2}$	$^{+4.0\%}_{-4.5\%}$	$^{+1.9\%}_{-1.4\%}$
b.2	$pp \to ZZ$	`p p > z z`	(0000) $1.415 \pm 0.005 \cdot 10^{1}$	$^{+3.1\%}_{-3.7\%}$	$^{+1.8\%}_{-1.4\%}$
b.3	$pp \to ZW^\pm$	`p p > z wpm`	(0000) $4.487 \pm 0.013 \cdot 10^{1}$	$^{+4.4\%}_{-4.4\%}$	$^{+1.7\%}_{-1.3\%}$
b.4	$pp \to \gamma\gamma$	`p p > a a`	(0000) $6.593 \pm 0.021 \cdot 10^{1}$	$^{+17.6\%}_{-18.8\%}$	$^{+2.0\%}_{-1.9\%}$
b.5	$pp \to \gamma Z$	`p p > a z`	(0000) $3.695 \pm 0.013 \cdot 10^{1}$	$^{+5.4\%}_{-7.1\%}$	$^{+1.8\%}_{-1.4\%}$
b.6	$pp \to \gamma W^\pm$	`p p > a wpm`	(0000) $7.124 \pm 0.026 \cdot 10^{1}$	$^{+9.7\%}_{-9.9\%}$	$^{+1.5\%}_{-1.3\%}$
b.7	$pp \to W^+W^-j$ (4f)	`p p > w+ w- j`	(0000) $3.730 \pm 0.013 \cdot 10^{1}$	$^{+4.9\%}_{-4.9\%}$	$^{+1.1\%}_{-0.8\%}$
b.8	$pp \to ZZj$	`p p > z z j`	(0000) $4.830 \pm 0.016 \cdot 10^{0}$	$^{+5.0\%}_{-4.8\%}$	$^{+1.1\%}_{-0.9\%}$
b.9	$pp \to ZW^\pm j$	`p p > z wpm j`	(0000) $2.086 \pm 0.007 \cdot 10^{1}$	$^{+4.9\%}_{-4.8\%}$	$^{+0.9\%}_{-0.7\%}$
b.10*	$pp \to \gamma\gamma j$	`p p > a a j`	(0000) $2.292 \pm 0.010 \cdot 10^{1}$	$^{+17.2\%}_{-15.1\%}$	$^{+1.0\%}_{-1.4\%}$
b.11*	$pp \to \gamma Z j$	`p p > a z j`	(0000) $1.220 \pm 0.005 \cdot 10^{1}$	$^{+7.3\%}_{-7.4\%}$	$^{+0.9\%}_{-0.9\%}$
b.12*	$pp \to \gamma W^\pm j$	`p p > a wpm j`	(0000) $3.713 \pm 0.015 \cdot 10^{1}$	$^{+7.2\%}_{-7.1\%}$	$^{+0.9\%}_{-1.0\%}$
b.13	$pp \to W^+W^+jj$	`p p > w+ w+ j j`	(0000) $2.251 \pm 0.011 \cdot 10^{-1}$	$^{+10.5\%}_{-10.6\%}$	$^{+2.2\%}_{-1.6\%}$
b.14	$pp \to W^-W^-jj$	`p p > w- w- j j`	(0000) $1.003 \pm 0.003 \cdot 10^{-1}$	$^{+10.1\%}_{-10.4\%}$	$^{+2.5\%}_{-1.8\%}$
b.15*	$pp \to W^+W^-jj$ (4f)	`p p > w+ w- j j`	(0000) $1.396 \pm 0.005 \cdot 10^{1}$	$^{+5.0\%}_{-6.8\%}$	$^{+0.7\%}_{-0.6\%}$
b.16*	$pp \to ZZjj$	`p p > z z j j`	(0000) $1.706 \pm 0.011 \cdot 10^{0}$	$^{+5.8\%}_{-7.2\%}$	$^{+0.8\%}_{-0.6\%}$
b.17*	$pp \to ZW^\pm jj$	`p p > z wpm j j`	(0000) $9.139 \pm 0.031 \cdot 10^{0}$	$^{+3.1\%}_{-5.1\%}$	$^{+0.7\%}_{-0.5\%}$
b.18*	$pp \to \gamma\gamma jj$	`p p > a a j j`	(0000) $7.501 \pm 0.032 \cdot 10^{0}$	$^{+8.8\%}_{-10.1\%}$	$^{+0.6\%}_{-1.0\%}$
b.19*	$pp \to \gamma Z jj$	`p p > a z j j`	(0000) $4.242 \pm 0.016 \cdot 10^{0}$	$^{+6.5\%}_{-7.3\%}$	$^{+0.6\%}_{-0.6\%}$
b.20*	$pp \to \gamma W^\pm jj$	`p p > a wpm j j`	(0000) $1.448 \pm 0.005 \cdot 10^{1}$	$^{+3.6\%}_{-5.4\%}$	$^{+0.6\%}_{-0.7\%}$

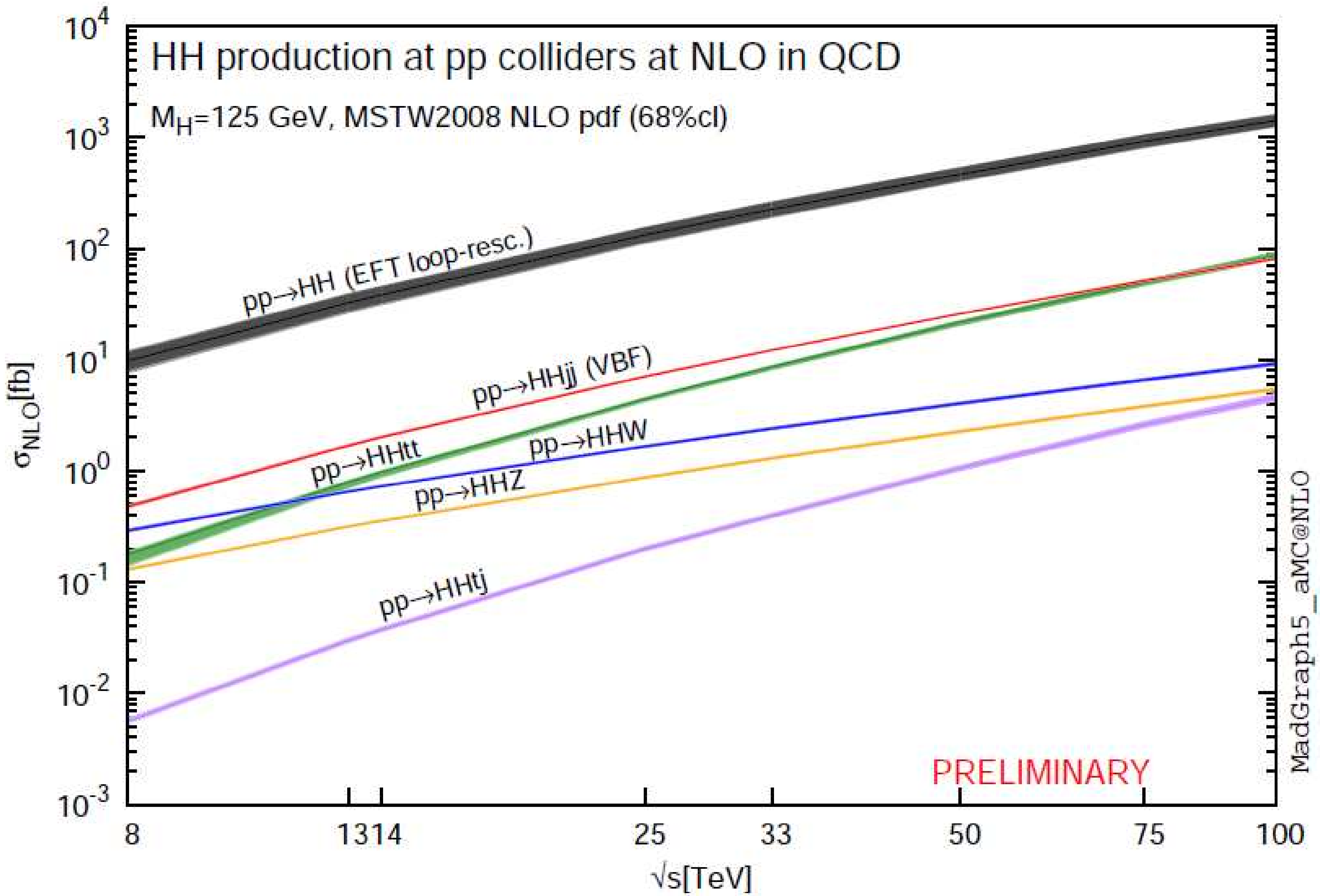
PRELIMINARY – to appear in the MadGraph5_aMC@NLO physics paper

	Process	Syntax	Cross section (pb)		
	Multiple vector bosons		(LO) NLO 13 TeV		
c.1	$pp \to W^+W^-W^\pm$ (4f)	p p > w+ w- wpm	(0000) $2.109 \pm 0.006 \cdot 10^{-1}$	$^{+5.1\%}_{-4.1\%}$	$^{+1.6\%}_{-1.2\%}$
c.2	$pp \to ZW^+W^-$ (4f)	p p > z w+ w-	(0000) $1.679 \pm 0.005 \cdot 10^{-1}$	$^{+6.3\%}_{-5.1\%}$	$^{+1.6\%}_{-1.2\%}$
c.3	$pp \to ZZW^\pm$	p p > z z wpm	(0000) $5.550 \pm 0.020 \cdot 10^{-2}$	$^{+6.8\%}_{-5.5\%}$	$^{+1.5\%}_{-1.1\%}$
c.4	$pp \to ZZZ$	p p > z z z	(0000) $1.417 \pm 0.005 \cdot 10^{-2}$	$^{+2.7\%}_{-2.1\%}$	$^{+1.9\%}_{-1.5\%}$
c.5*	$pp \to \gamma W^+W^-$ (4f)	p p > a w+ w-	(0000) $2.581 \pm 0.008 \cdot 10^{-1}$	$^{+5.4\%}_{-4.3\%}$	$^{+1.4\%}_{-1.1\%}$
c.6*	$pp \to \gamma\gamma W^\pm$	p p > a a wpm	(0000) $8.251 \pm 0.032 \cdot 10^{-2}$	$^{+7.6\%}_{-7.0\%}$	$^{+1.0\%}_{-1.0\%}$
c.7*	$pp \to \gamma ZW^\pm$	p p > a z wpm	(0000) $1.117 \pm 0.004 \cdot 10^{-1}$	$^{+7.2\%}_{-5.9\%}$	$^{+1.2\%}_{-0.9\%}$
c.8*	$pp \to \gamma ZZ$	p p > a z z	(0000) $3.177 \pm 0.015 \cdot 10^{-2}$	$^{+3.1\%}_{-2.9\%}$	$^{+1.8\%}_{-1.4\%}$
c.9*	$pp \to \gamma\gamma Z$	p p > a a z	(0000) $4.571 \pm 0.017 \cdot 10^{-2}$	$^{+4.2\%}_{-4.8\%}$	$^{+1.7\%}_{-1.4\%}$
c.10*	$pp \to \gamma\gamma\gamma$	p p > a a a	(0000) $3.441 \pm 0.012 \cdot 10^{-2}$	$^{+11.8\%}_{-11.6\%}$	$^{+1.4\%}_{-1.5\%}$
c.11	$pp \to W^+W^-W^\pm j$ (4f)	p p > w+ w- wpm j	(0000) $1.197 \pm 0.004 \cdot 10^{-1}$	$^{+5.2\%}_{-5.6\%}$	$^{+1.0\%}_{-0.8\%}$
c.12	$pp \to ZW^+W^-j$ (4f)	p p > z w+ w- j	(0000) $1.066 \pm 0.003 \cdot 10^{-1}$	$^{+4.5\%}_{-5.3\%}$	$^{+1.0\%}_{-0.7\%}$
c.13	$pp \to ZZW^\pm j$	p p > z z wpm j	(0000) $3.660 \pm 0.013 \cdot 10^{-2}$	$^{+4.8\%}_{-5.6\%}$	$^{+1.0\%}_{-0.7\%}$
c.14	$pp \to ZZZj$	p p > z z z j	(0000) $6.341 \pm 0.025 \cdot 10^{-3}$	$^{+4.9\%}_{-5.4\%}$	$^{+1.4\%}_{-1.0\%}$
c.15*	$pp \to \gamma W^+W^-j$ (4f)	p p > a w+ w- j	(0000) $1.233 \pm 0.004 \cdot 10^{3}$	$^{+18.9\%}_{-19.9\%}$	$^{+1.0\%}_{-1.5\%}$
c.16*	$pp \to \gamma\gamma W^\pm j$	p p > a a wpm j	(0000) $5.807 \pm 0.023 \cdot 10^{-2}$	$^{+5.8\%}_{-5.5\%}$	$^{+0.7\%}_{-0.7\%}$
c.17*	$pp \to \gamma ZW^\pm j$	p p > a z wpm j	(0000) $7.764 \pm 0.025 \cdot 10^{-2}$	$^{+5.1\%}_{-5.5\%}$	$^{+0.8\%}_{-0.6\%}$
c.18*	$pp \to \gamma ZZj$	p p > a z z j	(0000) $1.371 \pm 0.005 \cdot 10^{-2}$	$^{+5.6\%}_{-5.5\%}$	$^{+1.2\%}_{-0.9\%}$
c.19*	$pp \to \gamma\gamma Zj$	p p > a a z j	(0000) $2.051 \pm 0.011 \cdot 10^{-2}$	$^{+7.0\%}_{-6.3\%}$	$^{+1.0\%}_{-0.9\%}$
c.20*	$pp \to \gamma\gamma\gamma j$	p p > a a a j	(0000) $2.020 \pm 0.008 \cdot 10^{-2}$	$^{+12.8\%}_{-11.0\%}$	$^{+0.8\%}_{-1.2\%}$
c.21*	$pp \to W^+W^-W^+W^-$ (4f)	p p > w+ w- w+ w-	(0000) $9.959 \pm 0.035 \cdot 10^{-4}$	$^{+7.4\%}_{-6.0\%}$	$^{+1.7\%}_{-1.2\%}$
c.22*	$pp \to W^+W^-W^\pm Z$ (4f)	p p > w+ w- wpm z	(0000) $1.188 \pm 0.004 \cdot 10^{-3}$	$^{+8.4\%}_{-6.8\%}$	$^{+1.7\%}_{-1.2\%}$
c.23*	$pp \to W^+W^-W^\pm\gamma$ (4f)	p p > w+ w- wpm a	(0000) $1.546 \pm 0.005 \cdot 10^{-3}$	$^{+7.9\%}_{-6.3\%}$	$^{+1.5\%}_{-1.1\%}$
c.24*	$pp \to W^+W^-ZZ$ (4f)	p p > w+ w- z z	(0000) $7.107 \pm 0.020 \cdot 10^{-4}$	$^{+7.0\%}_{-5.7\%}$	$^{+1.8\%}_{-1.3\%}$
c.25*	$pp \to W^+W^-Z\gamma$ (4f)	p p > w+ w- z a	(0000) $1.483 \pm 0.004 \cdot 10^{-3}$	$^{+7.2\%}_{-5.8\%}$	$^{+1.6\%}_{-1.2\%}$
c.26*	$pp \to W^+W^-\gamma\gamma$ (4f)	p p > w+ w- a a	(0000) $9.381 \pm 0.032 \cdot 10^{-4}$	$^{+6.7\%}_{-5.3\%}$	$^{+1.4\%}_{-1.1\%}$
c.27*	$pp \to W^\pm ZZZ$	p p > wpm z z z	(0000) $1.240 \pm 0.004 \cdot 10^{-4}$	$^{+9.9\%}_{-8.0\%}$	$^{+1.7\%}_{-1.2\%}$
c.28*	$pp \to W^\pm ZZ\gamma$	p p > wpm z z a	(0000) $2.945 \pm 0.008 \cdot 10^{-4}$	$^{+10.8\%}_{-8.7\%}$	$^{+1.3\%}_{-1.0\%}$
c.29*	$pp \to W^\pm Z\gamma\gamma$	p p > wpm z a a	(0000) $3.033 \pm 0.010 \cdot 10^{-4}$	$^{+10.6\%}_{-8.6\%}$	$^{+1.1\%}_{-0.8\%}$
c.30*	$pp \to W^\pm\gamma\gamma\gamma$	p p > wpm a a a	(0000) $1.246 \pm 0.005 \cdot 10^{-4}$	$^{+9.8\%}_{-8.1\%}$	$^{+0.9\%}_{-0.8\%}$
c.31*	$pp \to ZZZZ$	p p > z z z z	(0000) $2.629 \pm 0.008 \cdot 10^{-5}$	$^{+3.5\%}_{-3.0\%}$	$^{+2.2\%}_{-1.7\%}$
c.32*	$pp \to ZZZ\gamma$	p p > z z z a	(0000) $5.224 \pm 0.016 \cdot 10^{-5}$	$^{+3.3\%}_{-2.7\%}$	$^{+2.1\%}_{-1.6\%}$
c.33*	$pp \to ZZ\gamma\gamma$	p p > z z a a	(0000) $7.518 \pm 0.032 \cdot 10^{-5}$	$^{+3.4\%}_{-2.6\%}$	$^{+2.0\%}_{-1.5\%}$
c.34*	$pp \to Z\gamma\gamma\gamma$	p p > z a a a	(0000) $7.103 \pm 0.026 \cdot 10^{-5}$	$^{+3.4\%}_{-3.2\%}$	$^{+1.6\%}_{-1.5\%}$
c.35*	$pp \to \gamma\gamma\gamma\gamma$	p p > a a a a	(0000) $3.389 \pm 0.012 \cdot 10^{-5}$	$^{+7.0\%}_{-6.7\%}$	$^{+1.3\%}_{-1.3\%}$

PRELIMINARY – to appear in the MadGraph5_aMC@NLO physics paper

Process		Syntax	Cross section (pb)		
Heavy quarks+vector bosons			(LO) NLO 13 TeV		
e.1	$pp \to W^{\pm} b\bar{b}$	`p p > wpm b b~`	(0000) $8.162 \pm 0.034 \cdot 10^{2}$	$^{+29.8\%}_{-23.6\%}$	$^{+1.5\%}_{-1.2\%}$
e.2	$pp \to Z\, b\bar{b}$	`p p > z b b~`	(0000) $1.235 \pm 0.004 \cdot 10^{3}$	$^{+19.9\%}_{-17.4\%}$	$^{+1.0\%}_{-1.4\%}$
e.3	$pp \to \gamma\, b\bar{b}$	`p p > a b b~`	(0000) $4.171 \pm 0.015 \cdot 10^{3}$	$^{+33.7\%}_{-27.1\%}$	$^{+1.4\%}_{-1.9\%}$
e.4	$pp \to W^{\pm} b\bar{b}\, j$	`p p > wpm b b~ j`	(0000) $3.957 \pm 0.013 \cdot 10^{2}$	$^{+27.0\%}_{-21.0\%}$	$^{+0.7\%}_{-0.6\%}$
e.5*	$pp \to Z\, b\bar{b}\, j$	`p p > z b b~ j`	(0000) $2.805 \pm 0.009 \cdot 10^{2}$	$^{+21.0\%}_{-17.6\%}$	$^{+0.8\%}_{-1.0\%}$
e.6*	$pp \to \gamma\, b\bar{b}\, j$	`p p > a b b~ j`	(0000) $1.233 \pm 0.004 \cdot 10^{3}$	$^{+18.9\%}_{-19.9\%}$	$^{+1.0\%}_{-1.5\%}$
e.7	$pp \to t\bar{t}\, W^{\pm}$	`p p > t t~ wpm`	(0000) $5.616 \pm 0.019 \cdot 10^{-1}$	$^{+11.0\%}_{-10.5\%}$	$^{+1.8\%}_{-1.3\%}$
e.8	$pp \to t\bar{t}\, Z$	`p p > t t~ z`	(0000) $7.598 \pm 0.026 \cdot 10^{-1}$	$^{+9.7\%}_{-11.1\%}$	$^{+1.9\%}_{-2.2\%}$
e.9	$pp \to t\bar{t}\, \gamma$	`p p > t t~ a`	(0000) $1.744 \pm 0.005 \cdot 10^{0}$	$^{+9.8\%}_{-11.0\%}$	$^{+1.7\%}_{-2.0\%}$
e.10	$pp \to t\bar{t}\, W^{\pm} j$	`p p > t t~ wpm j`	(0000) $3.404 \pm 0.011 \cdot 10^{-1}$	$^{+11.2\%}_{-14.0\%}$	$^{+1.2\%}_{-0.9\%}$
e.11*	$pp \to t\bar{t}\, Z j$	`p p > t t~ z j`	(0000) $5.074 \pm 0.016 \cdot 10^{-1}$	$^{+7.0\%}_{-12.3\%}$	$^{+2.5\%}_{-2.9\%}$
e.12*	$pp \to t\bar{t}\, \gamma j$	`p p > t t~ a j`	(0000) $1.135 \pm 0.004 \cdot 10^{0}$	$^{+7.5\%}_{-12.2\%}$	$^{+2.2\%}_{-2.5\%}$
e.13	$pp \to t\bar{t}\, W^{-} W^{+}$ (4f)	`p p > t t~ w+ w-`	(0000) $9.904 \pm 0.026 \cdot 10^{-3}$	$^{+10.9\%}_{-11.8\%}$	$^{+2.1\%}_{-2.1\%}$
e.14	$pp \to t\bar{t}\, W^{\pm} Z$	`p p > t t~ wpm z`	(0000) $3.525 \pm 0.010 \cdot 10^{-3}$	$^{+10.6\%}_{-10.8\%}$	$^{+2.3\%}_{-1.6\%}$
e.15	$pp \to t\bar{t}\, W^{\pm} \gamma$	`p p > t t~ wpm a`	(0000) $3.927 \pm 0.013 \cdot 10^{-3}$	$^{+10.3\%}_{-10.4\%}$	$^{+2.0\%}_{-1.5\%}$
e.16*	$pp \to t\bar{t}\, ZZ$	`p p > t t~ z z`	(0000) $1.840 \pm 0.007 \cdot 10^{-3}$	$^{+7.9\%}_{-9.9\%}$	$^{+1.7\%}_{-1.5\%}$
e.17*	$pp \to t\bar{t}\, Z\gamma$	`p p > t t~ z a`	(0000) $3.656 \pm 0.012 \cdot 10^{-3}$	$^{+9.7\%}_{-11.0\%}$	$^{+1.8\%}_{-1.9\%}$
e.18*	$pp \to t\bar{t}\, \gamma\gamma$	`p p > t t~ a a`	(0000) $4.402 \pm 0.015 \cdot 10^{-3}$	$^{+7.8\%}_{-9.7\%}$	$^{+1.4\%}_{-1.4\%}$

PRELIMINARY – to appear in the MadGraph5_aMC@NLO physics paper



SM at NLO: thickness of lines is scale+PDF uncertainties

PRELIMINARY – to appear in a dedicated paper

- Reproducing all but a handful of known NLO QCD results, and significantly extending them
- Can compute all processes (bar QCD jets) that have up to $2 \to 4$ Born contributions
- Need a medium-size cluster only for the most involved processes; the others are doable on a single multi-core machine
- Note the ubiquitous scale and PDF uncertainties

- *Extremely* simple usage
- No external dependences (stripped FastJet included; LHAPDF optional)
- Very significant speed increase at the NLO
  (up to two orders of magnitude for difficult processes wrt previous β versions)
- Scale and PDF uncertainties without recomputation

Scale and PDF uncertainties

These are done by reweighting, and hence are essentially "free" (see arXiv:1110.4738). In

./PROCDIR/Cards/run_card.dat

one sets

```
.true.  = reweight_scale !  reweight to get scale dependence
.true.  = reweight_PDF ! reweight to get PDF uncertainty
```

for the relevant weights to be computed during the cross section integration, and stored in the hard-event file (for NLO+PS runs)

./PROCDIR/Events/run_nn/events.lhe.gz

In there, one will find the following information $\longrightarrow$

Note: the format has changed wrt to that of v2.0.0β_3, and is now the new LHA

```
<header>
 ...

 <initrwgt>
  <weight id='1'> This is the original event weight </weight>
  <weightgroup type='scale_variation' combine='envelope'>
     <weight id='2'> muR=2.0 </weight>
     <weight id='3'> muR=0.5 </weight>
  </weightgroup>
   <weightgroup type="mrst2008e40" combine="hessian">
     <weight id='4'> set01 </weight>
     <weight id='5'> set02 </weight>
     ...
   </weightgroup>
  <weightgroup type='Qmatch_variation' combine='envelope'>
     <weight id='44'> Qmatch=20 </weight>
     <weight id='45'> Qmatch=40 </weight>
  </weightgroup>
  <weight id='46'> BSM benchmark point number 42B, see arXiv XXXX.XXXX </weigh
 </initrwgt>
...
</header>
```

The header will contain detailed information on the meaning of the various weights, to be found in each event $\longrightarrow$

```
<event id='evtid'>
7 100  0.10000000E+01  0.20000000E+00  0.00000000E+00  0.00000000E+00
 -2 -1  0  0 0 0  0.12699952E+01  0.55429630E+01  0.57634577E+02  0.57914435E+
  2 -1  0  0 0 0 -0.91353745E+00  0.13160013E+01 -0.34965448E+02  0.35002128E+
 23  2  1  1 0 0  0.35645919E+00  0.68589662E+01  0.22669189E+02  0.92916566E+
-13  2  3  3 0 0  0.51612833E+01  0.21143065E+02  0.53960893E+02  0.58184682E+
 13  2  3  3 0 0 -0.48048241E+01 -0.14284099E+02 -0.31291705E+02  0.34731884E+
-13  1  0  0 0 0  0.51612833E+01  0.21143065E+02  0.53960893E+02  0.58184682E+
 13  1  0  0 0 0 -0.48048241E+01 -0.14284099E+02 -0.31291705E+02  0.34731884E+
 <rwgt>
  <wgt id='1'> 1.001e+00 </wgt>
  <wgt id='2'> 0.204e+00 </wgt>
  <wgt id='3'> 1.564e+00 </wgt>
  <wgt id='4'> 2.248e+00 </wgt>
  <wgt id='5'> 1.486e+00 </wgt>
  ...
  <wgt id='46'> -0.899e+00 </wgt>
 </rwgt>
</event>
```

Note: fixed-order runs do not feature hard-event files. Reweight information are given on the fly (as extra weights) and event-by-event

- *Extremely* simple usage
- No external dependences (stripped FastJet included; LHAPDF optional)
- Very significant speed increase at the NLO
  (up to two orders of magnitude for difficult processes wrt previous β versions)
- Scale and PDF uncertainties without recomputation
- Rather flexible fixed-order user interface

Terminal

File Edit View Search Terminal Help

```
[pcthxfrixione]~ > cat FO_analyse_card.dat
#######################################################################
#
# This file contains the settings for analyses to be linked to aMC@NLO
# fixed order runs. Analyse files are meant to be put (or linked)
# inside <PROCDIR>/FixedOrderAnalysis/ (<PROCDIR> is the name of the
# exported process directory). See the
# <PROCDIR>/FixedOrderAnalysis/analysis_template.f file for details on
# how to write your own analysis.
#
#######################################################################
#
# Analysis format. Can either be 'topdrawer', 'root', or 'none'.
# Topdrawer is human-readable text format, which allows for easy
# conversion to other formats. When choosing topdrawer, the
# histogramming package 'dbook.f' is included in the code, while when
# choosing root the 'rbook_fe8.f' and 'rbook_be8.cc' are included. If
# 'none' is chosen, all the other entries below have to be set empty.
FO_ANALYSIS_FORMAT = topdrawer
#
# Needed extra-libraries (FastJet is already linked):
FO_EXTRALIBS =
#
# (Absolute) path to the extra libraries. Directory names should be
# separated by white spaces.
FO_EXTRAPATHS =
#
# (Absolute) path to the dirs containing header files needed by the
# libraries (e.g. C++ header files):
FO_INCLUDEPATHS =
#
# User's analysis (to be put in the <PROCDIR>/FixedOrderAnalysis/
# directory). Please use .o as extension and white spaces to separate
# files.
FO_ANALYSE = analysis_td_template.o
#
#
## When linking with root, the following settings are a working
## example on lxplus (CERN). When using this, comment out the lines
## above and replace <PATH_TO_ROOT> with the physical path to root,
## e.g. /afs/cern.ch/sw/lcg/app/releases/ROOT/5.34.11/x86_64-slc6-gcc46-dbg/root/
#FO_ANALYSIS_FORMAT = root
#FO_EXTRALIBS = Core Cint Hist Matrix MathCore RIO dl Thread
#FO_EXTRAPATHS = <PATH_TO_ROOT>/lib
#FO_INCLUDEPATHS = <PATH_TO_ROOT>/include
#FO_ANALYSE = analysis_root_template.o
[pcthxfrixione]~ >
```

- Fixed-order analyses are trivial; however, templates are provided
- Root and topdrawer (which is human-readable) formats are supported
- User-defined formats require the user to write routines that sum the results of individual integration channels

  (trivial if one wants n-tuples rather than histograms)

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- Rather flexible fixed-order user interface
- NLO matching to Pythia8* – Herwig$++$, Pythia6(Q^2), Herwig6, Pythia6(p_T, ISR only) were already there

* Special thanks to Stefan Prestel for his help

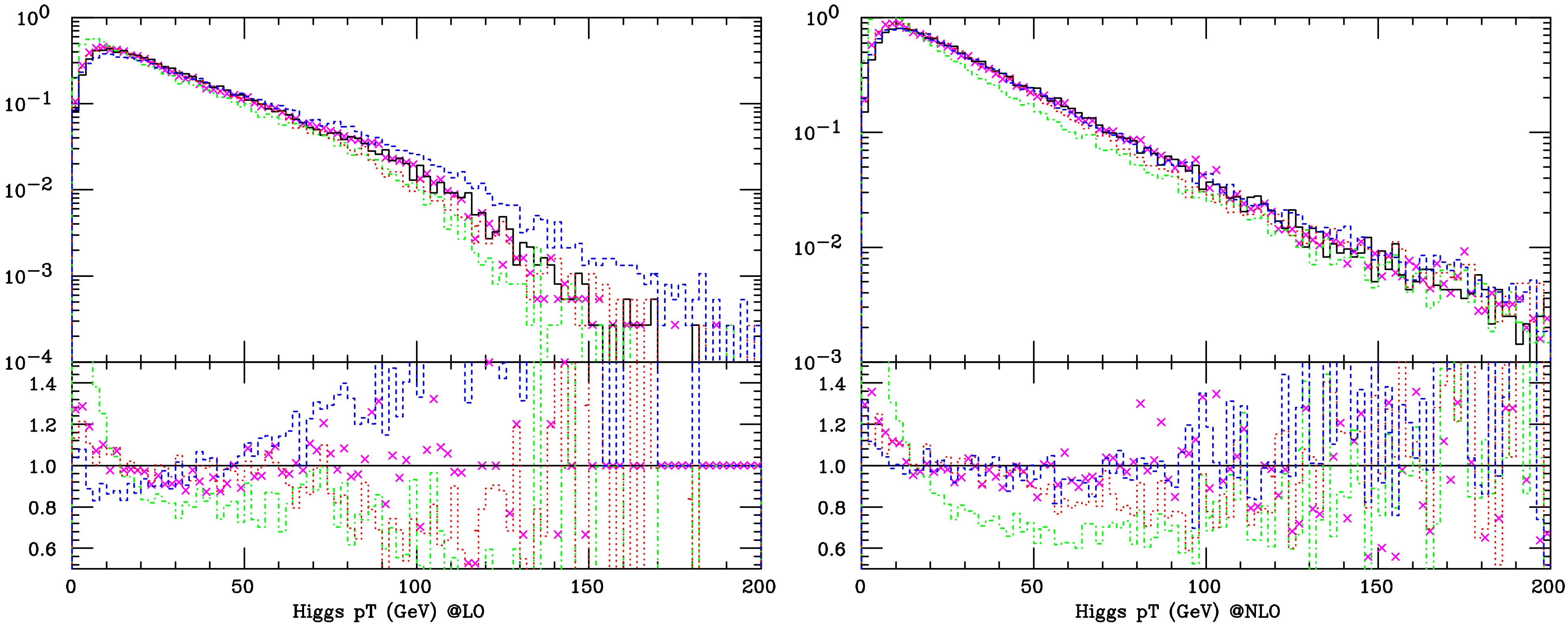
Example: $gg \to H$

- Left plots: LO+PS; right plots: NLO+PS
- Black solid: Herwig6; blue dashed: Pythia8; crosses: Herwig++; red dotted: Pythia6(p_T); green dot-dashed: Pythia6(Q^2)

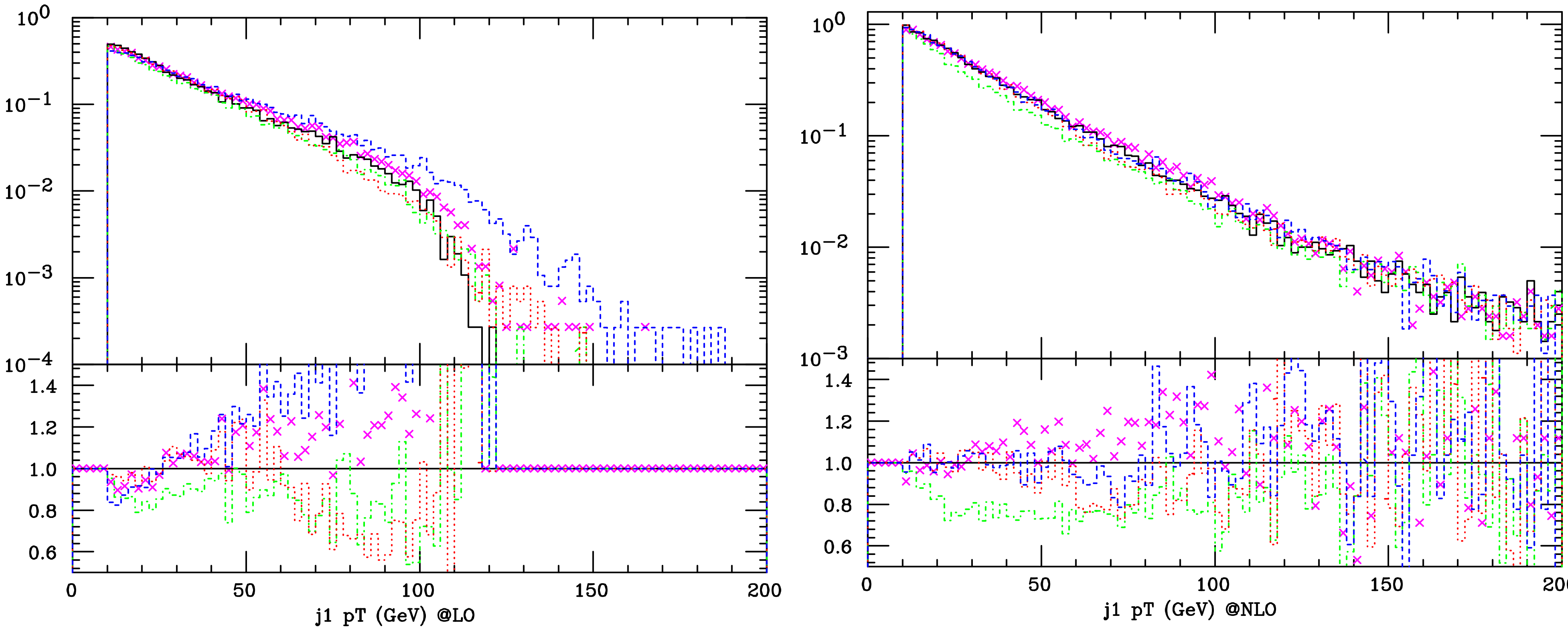
No tuning or consistency for input MC parameters

For all processes, our (N)LO+PS events are unweighted

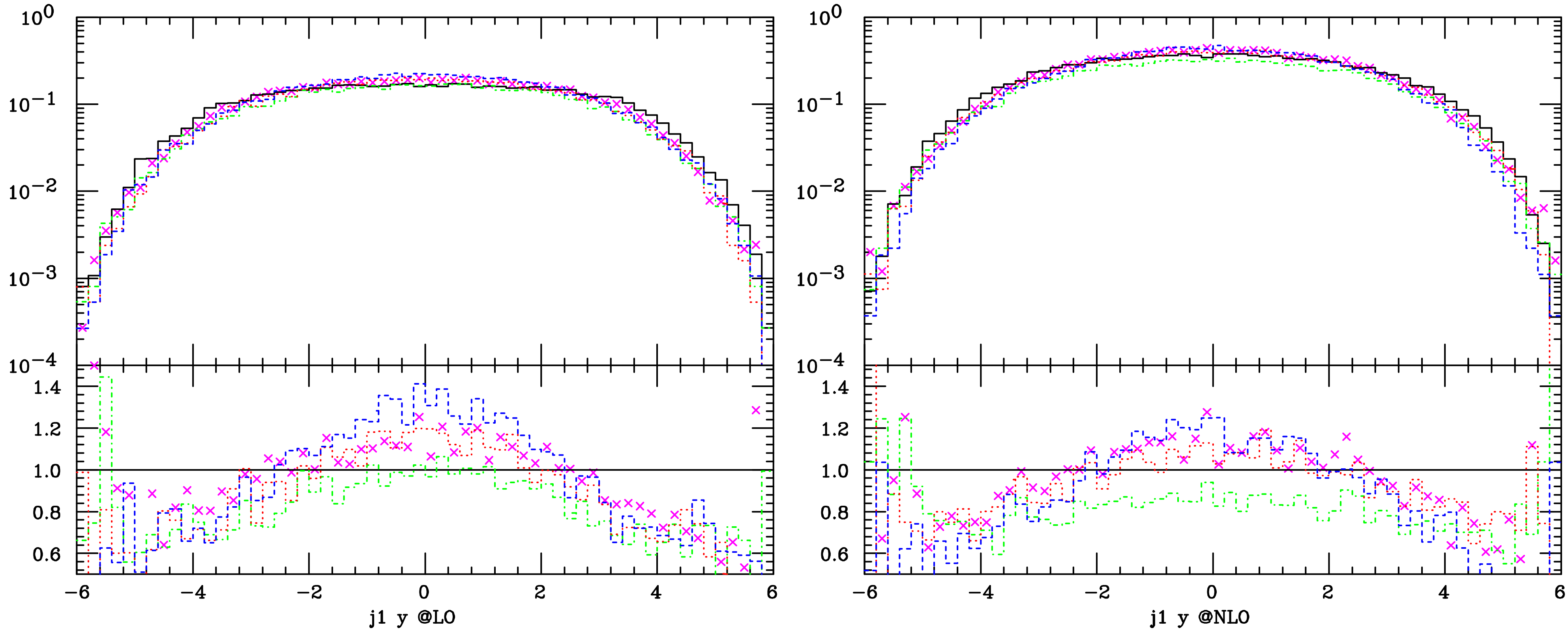
$p_T(H)$



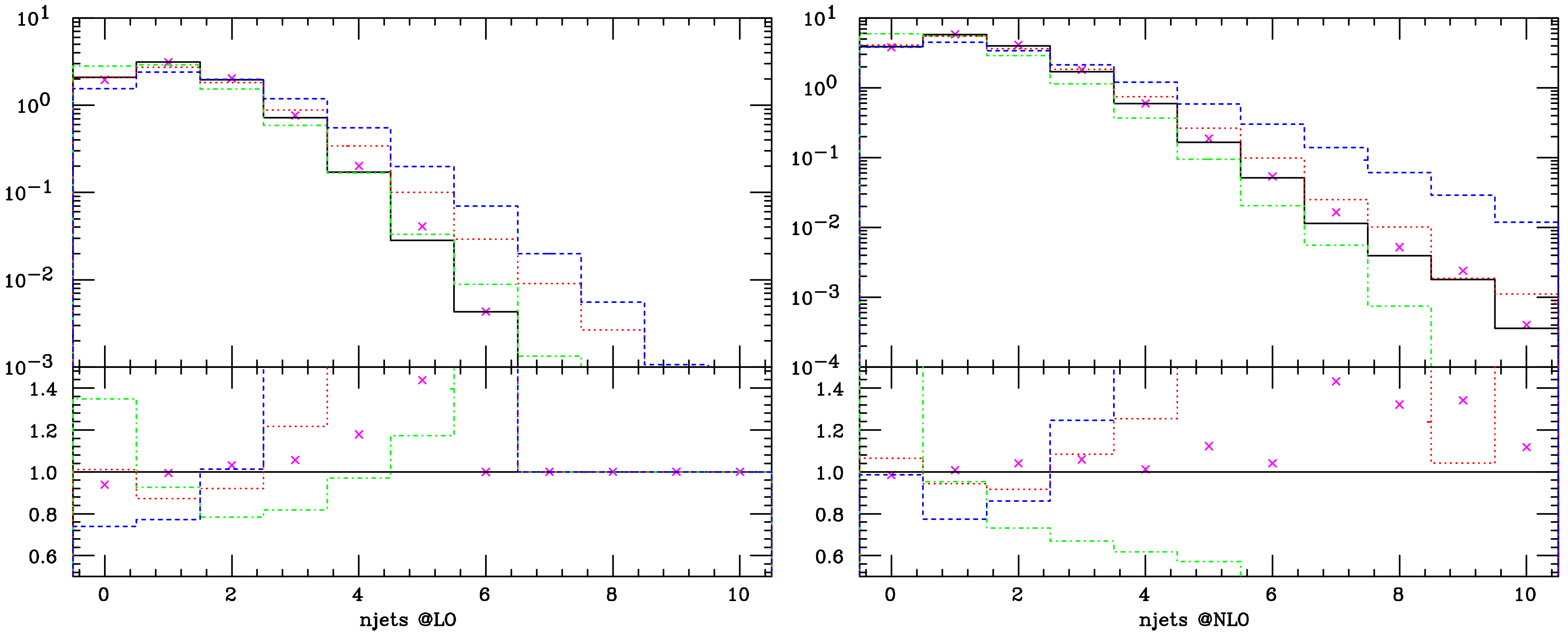
$p_T(j_1)$



$y(j_1)$



jets



10^1
10^0
10^-1
10^-2
10^-3
1.4
1.2
1.0
0.8
0.6
0
2
4
6
8
10
njets @LO
10^1
10^0
10^-1
10^-2
10^-3
10^-4
njets @NLO

- Results at the NLO much closer to each other than at the LO
- NLO p_T spectra all rather similar bar for PY6(Q^2)
- jets of PY8 more central than PY6(p_T)$\simeq$ HW$++$,
  in turn more central than HW6
- More jets in PY8 than in PY6(p_T);
  both more jetty than HW6$\simeq$ HW$++$

Main message: no two MCs behave the same for all observables
(so it's very important to be able to switch among them)

- *Extremely* simple usage
- No external dependences (stripped FastJet included; LHAPDF optional)
- Very significant speed increase at the NLO
  (up to two orders of magnitude for difficult processes wrt previous β versions)
- Scale and PDF uncertainties without recomputation
- Rather flexible fixed-order user interface
- NLO matching to Pythia8 – Herwig++, Pythia6(Q^2), Herwig6, Pythia6(p_T, ISR only) were already there
- Very significant speed increase in MadSpin

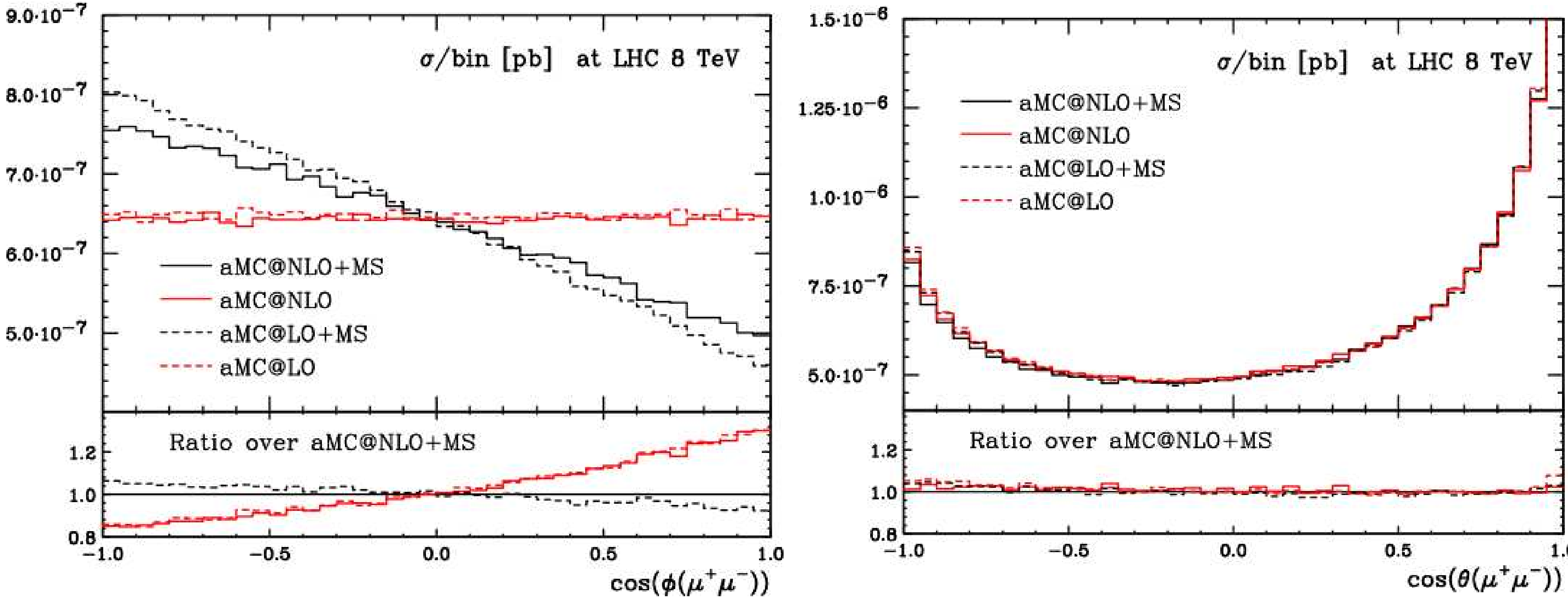
- MadSpin allows one to recover *production* spin correlations in (N)LO+PS unweighted events, for processes too complicated to be computed directly (eg $be^+\nu_e\bar{b}e^-\bar{\nu}_e jj$ vs $t\bar{t}jj$)

- It is based on tree-level matrix elements, but gives an *extremely good* approximation to full NLO results (eg, approximate off-shell effects in MS are much more important than exact NLO decay on-shell results)

- Presently supports all decays that are $1 \to 2$ sequences

- Increase in speed mainly due to a vastly more efficient phase-space generation, and to some recycling

Note: spin correlations are sometimes more important than NLO corrections or differences among MC's $\longrightarrow$



Angular correlation variables in $W^+(\to \mu^+\nu_\mu)W^-(\to \mu^-\bar{\nu}_\mu)Z(\to e^+e^-)$ production

From V. Hirschi's thesis

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- Very significant speed increase in MadSpin
- FxFx merging semi-automated (HW6)

FxFx merging (1209.6215)

- The i-parton sample receives contributions from the same matrix elements that enter the i-jet cross section at the NLO
- The i-parton cross section is basically the MC@NLO one, times a suitable combination of damping factors defined with a (smooth) function $D(\mu)$, which allow one to distinguish ME-dominated, MC-dominated, and intermediate regions
- $D(\mu)$ can also be chosen to be sharp, in which case

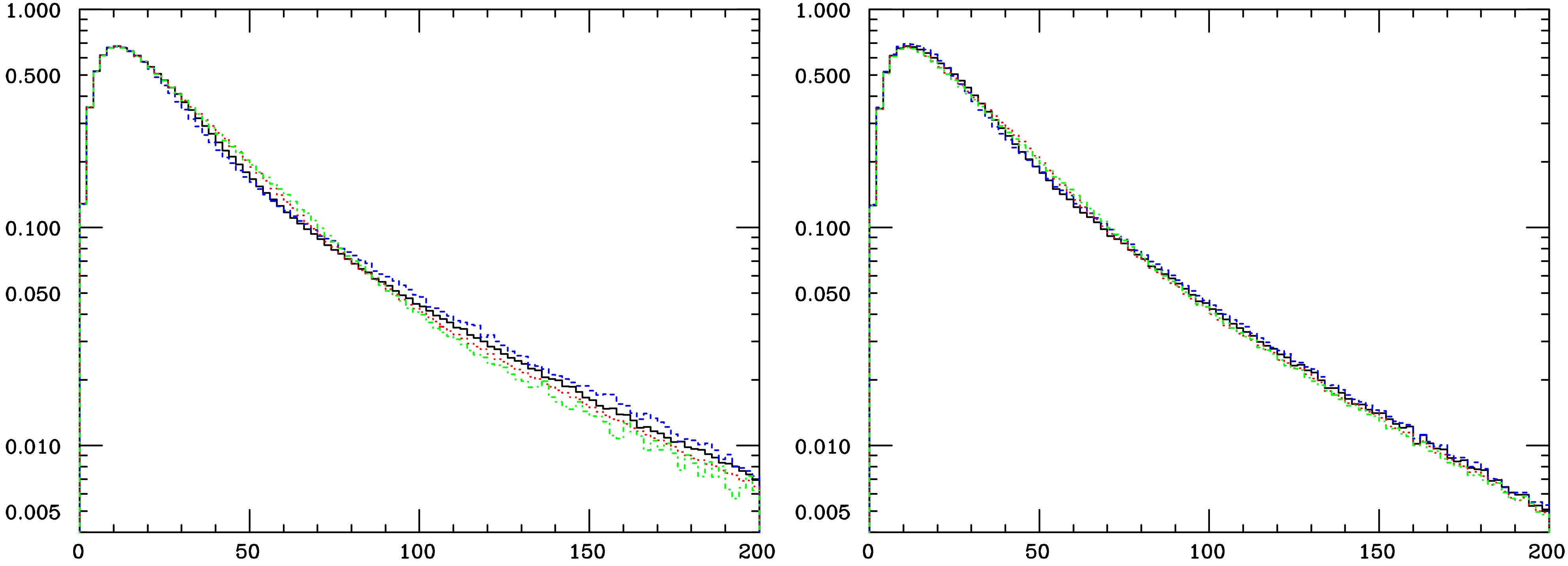
$$D(\mu) = \Theta\left(\mu_Q - \mu\right)$$

  with μ_Q the merging scale
- The above is further supplemented by a CKKW-like procedure

Example: $gg \to H$

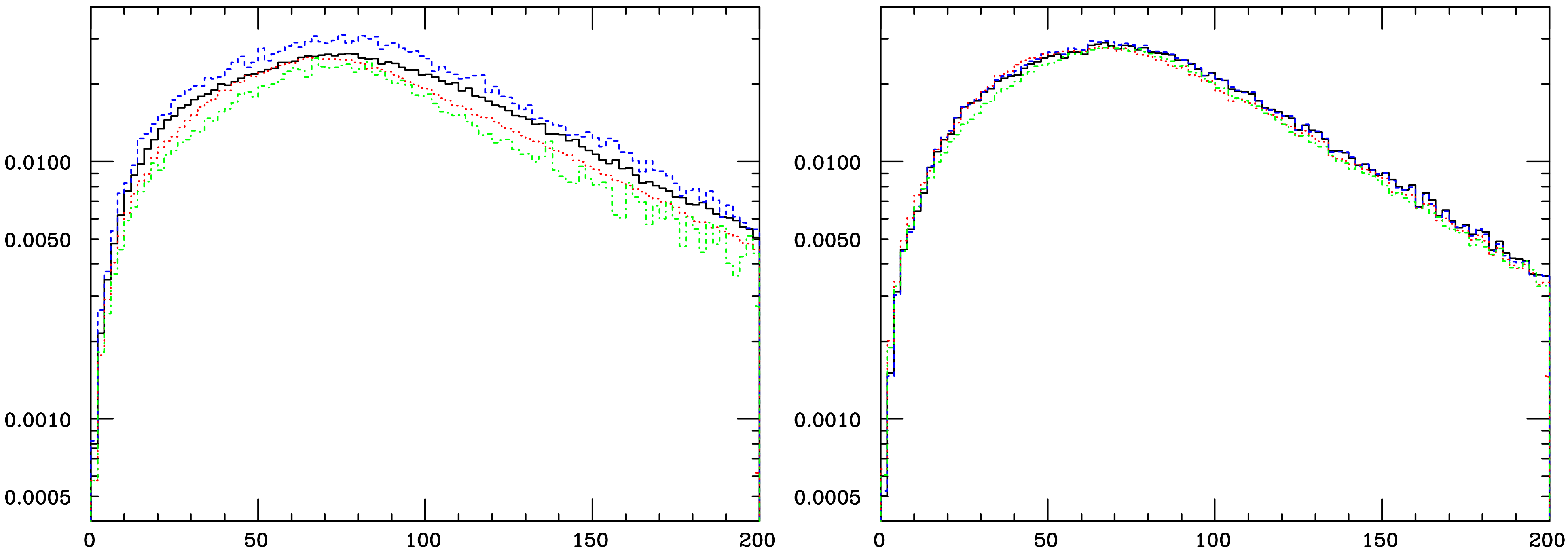
- Left plots: Alpgen (LO); right plots: MadGraph5_aMC@NLO (NLO)
- Alpgen: up to 3 partons;
  MadGraph5_aMC@NLO: up to 2 partons@NLO
- Black solid: $\mu_Q = 30$ GeV; blue dashed: $\mu_Q = 20$ GeV;
  red dotted: $\mu_Q = 50$ GeV; green dot-dashed: $\mu_Q = 70$ GeV
- Some differences in the inputs to the two codes

$p_T(H)$



Fully inclusive

$p_T(H)$



Require at least two jets (anti-k_T, $R = 0.4$, $p_T > 25$ GeV, $|\eta| < 5$)

- Significant reduction of merging-scale dependence wrt LO
- It is crucial to investigate the behaviour in a large range in μ_Q, which must contain the jet minimum p_T
- FxFx in Pythia8 will be fully automated, and ready very soon
- Hopefully the same level of automation will be achieved with Herwig$++$, but for this we need the authors' active help

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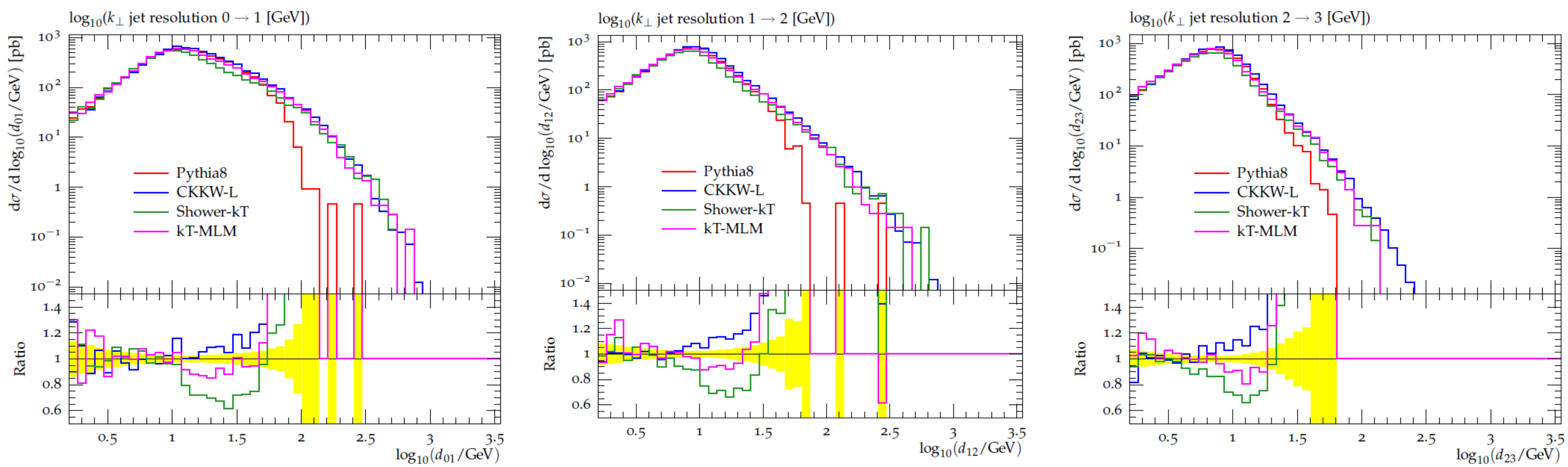
- Very significant speed increase in MadSpin
- FxFx merging semi-automated (HW6)
- Several new things at the LO

I don't have time to review the novelties on the LO side: here's an incomplete list

- Groundwork: a new version of FeynRules (1310.1921: Alloul, Christensen, Degrande, Duhr, Fuks), especially useful for SUSY theories
- MadDM (1308.4955: Backovic, Kong, McCaskey), computes dark matter relic abundance
- TauDecay (1212.6247: Hagiwara, Li, Mawatari, Nakamura) simulates polarized τ decays
- MadWidth: computations of LO widths for n-body decays
- Reweighting/MEM tools: SysCalc, MadWeight, MadMax (Alwall, Kalegoroupoulos, Mattelaer; : 1007.3300: Artoisenet, Lemaitre, Maltoni, Mattelaer; 1311.2591: Plehn, Schichtel, Wiegand)
- Automatic LO merging in Pythia8 with different schemes (Alwall, de Visscher, Mrenna, Prestel) $\longrightarrow$

$Z+\leq 3$ jets



Systematic comparisons with FxFx will be straightforward

What’s behind all this

Owing to the increasing complexity of the simulations necessary for LHC analyses, the strategic assumption has been made that automation is the *only* viable long-term solution

- Automation must be in the strictest sense: no human intervention whatsoever, bar inputs

- No process-by-process optimisation: solutions are blind and general

- The structure must work for any user-defined theory
  (renormalisable if NLO is computed)

Basics: from the Lagrangian to the matrix elements

This is done via the `FeynRules` $\longrightarrow$ `UFO` $\longrightarrow$ `ALOHA` chain

- An overkill for the SM, but a necessity for anything beyond that
- Very exciting news: being extended to NLO (Degrande), which entails the automated computation of UV and R_2 counterterms
  - R_2: done; tested against the analytical expressions available for the SM (QCD+QED, Papadopoulos, Pittau *etal*) and the MSSM (Shao, Zhang)
  - UV: done; tested against the analytical expressions available for QCD, and for the 2-point vertices in EW

This is it! At the NLO, one just needs trees, UV, and R_2

Subtraction of IR singularities

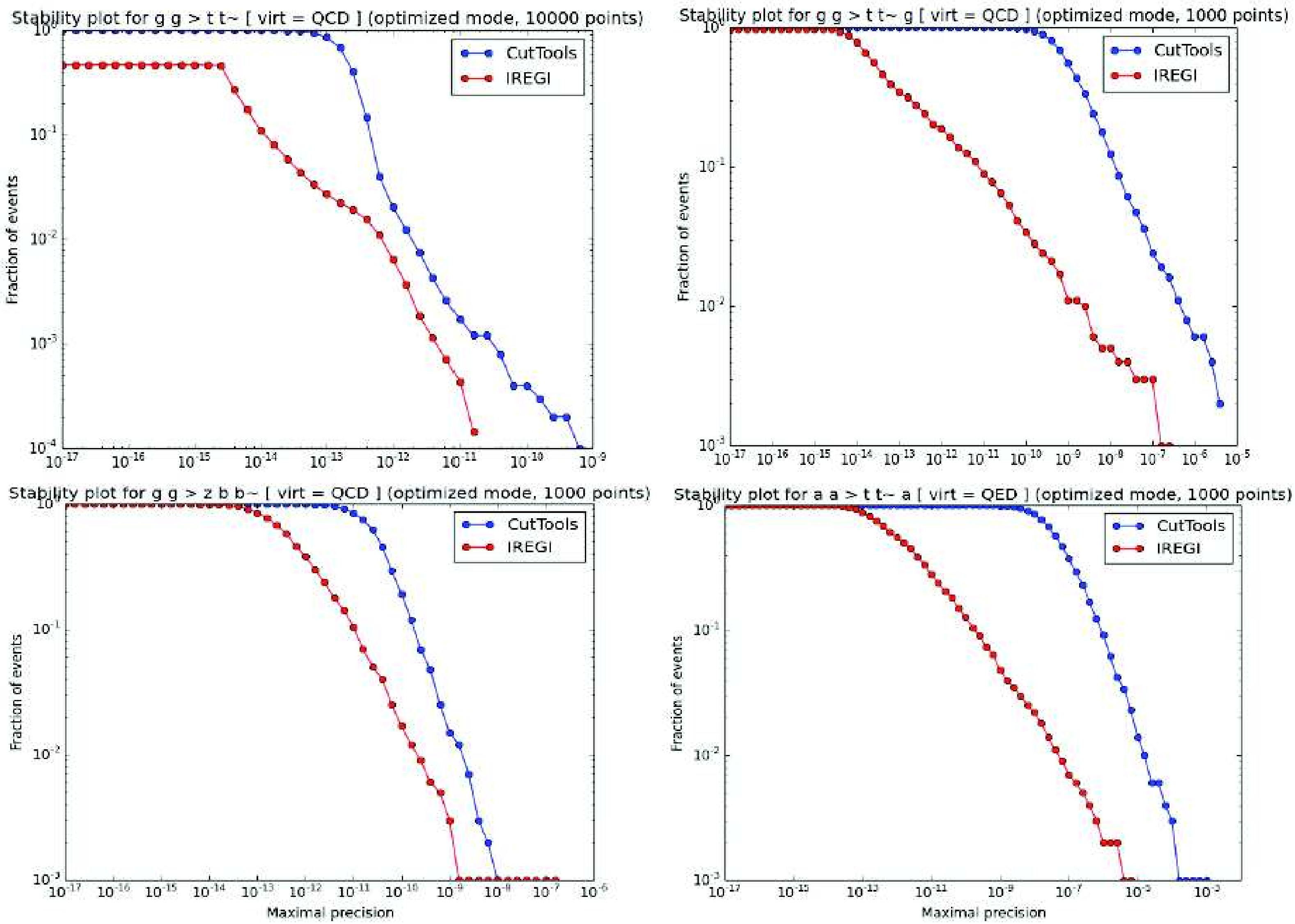
This is done with FKS subtraction, automated in the module `MadFKS`

- Very limited number of subtractions
- Highly parallelizable: each integration channel has three subtractions at most
- Done for QCD, which is the worst-case scenario. Being extended to the general case of mixed expansion (QCD+QED)

One-loop matrix elements

This is done with OPP or TI reduction, automated in the module MadLoop

- MadLoop handles the filtering and L-cutting of one-loop diagrams, computes the R_2 contribution, and UV-renormalises
- MadLoop performs the reduction with either CutTools, or with a TIR module
- MadLoop has its own implementation of the OpenLoops technique (1111.5206: Cascioli, Maierhofer, Pozzorini)
- Significant amount of work lately (still not public), by V. Hirschi and H-S. Shao, to allow MadLoop to be compatible with mixed expansion, and to perform TIR
- TIR has been tested with PJFry to some extent, and with the new TIR package IREGI by H-S. Shao $\longrightarrow$



PRELIMINARY – H-S. Shao and V. Hirschi

Matching to showers

This is done by means of the `MC@NLO` formalism

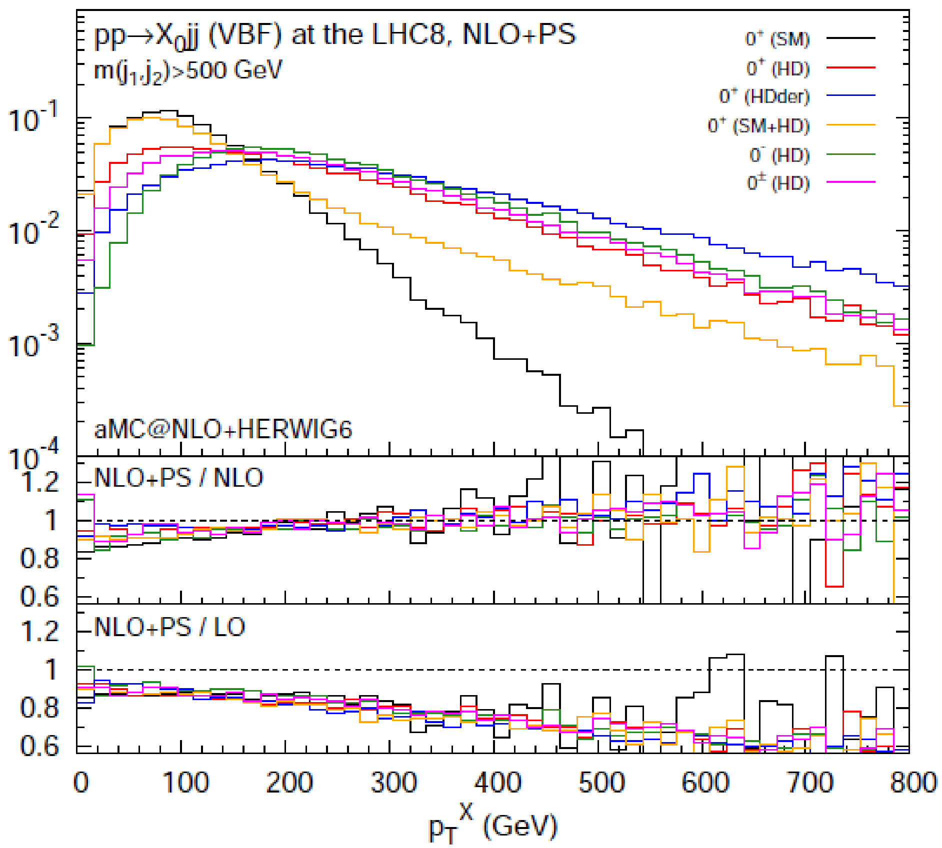
- MC@NLO perturbs minimally the underlying matrix element computations (no terms of $\mathcal{O}(\alpha_S^{b+2})$ and beyond) and MC simulations (the MC is the sole responsible for Sudakov suppressions), which fits nicely into the automation strategy

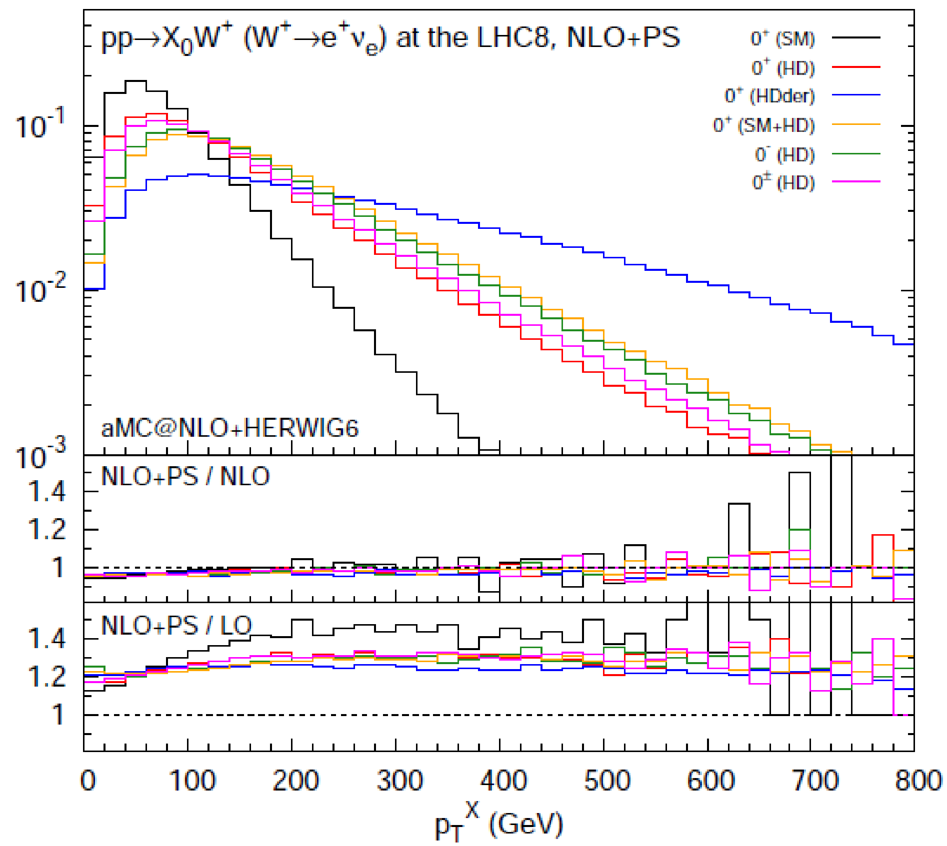
- The structure of the MC counterterms is very modular – any new MC might be interfaced without changing the existing structure

The code has been tested very extensively for many different theories at the LO, and for QCD corrections to SM at the NLO

As it should be clear from the previous slides, we have all pieces in place to perform NLO computations in arbitrary theories as well – we are in the debugging/testing phase

Actually, in simplified cases results have already been published that exploit the machinery in theories other than the SM – eg the Higgs Characterization model (1306.6464, Artoisenet *etal*) $\longrightarrow$





p_T of a spin-0 state in VBF and W-associated production modes

1311.1829: Maltoni, Mawatari, Zaro

Conclusion I

MadGraph5_aMC@NLO is public, out of β, and replaces both MadGraph and aMC@NLO

- NLO (in BSM) and LO strictly on the same footing in $\mathcal{O}(1)$ year
- Emphasis will gradually shift on the development of (analysis) tools, and on phenomenology
- As for MadGraph, MadGraph5_aMC@NLO should be seen as a framework that can be used for one's projects – we'll be happy to help

Conclusions II

The significant progress made in the past few years by several groups has not only led to remarkable physics results, but also to two (unintended) sociological consequences:

- NLO computations will not require any expertise
- Hiring PhD's or young postdocs as (highly-skilled) human computers is not justified any longer

Conclusions II

The significant progress made in the past few years by several groups has not only led to remarkable physics results, but also to two (unintended) sociological consequences:

NLO computations will not require any expertise

Hiring PhD's or young postdocs as (highly-skilled) human computers is not justified any longer

So while it is not true that QCD has become "easy" by magic, it is true that one entire class of difficult problems has been fully solved, thus paving the way for precision hadron phenomenology and, for theorists, putting back the emphasis on more conceptual problems