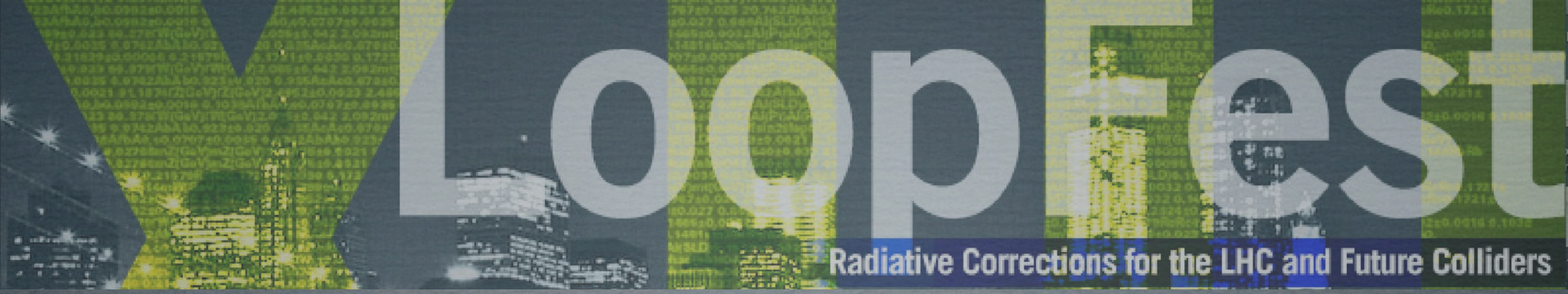


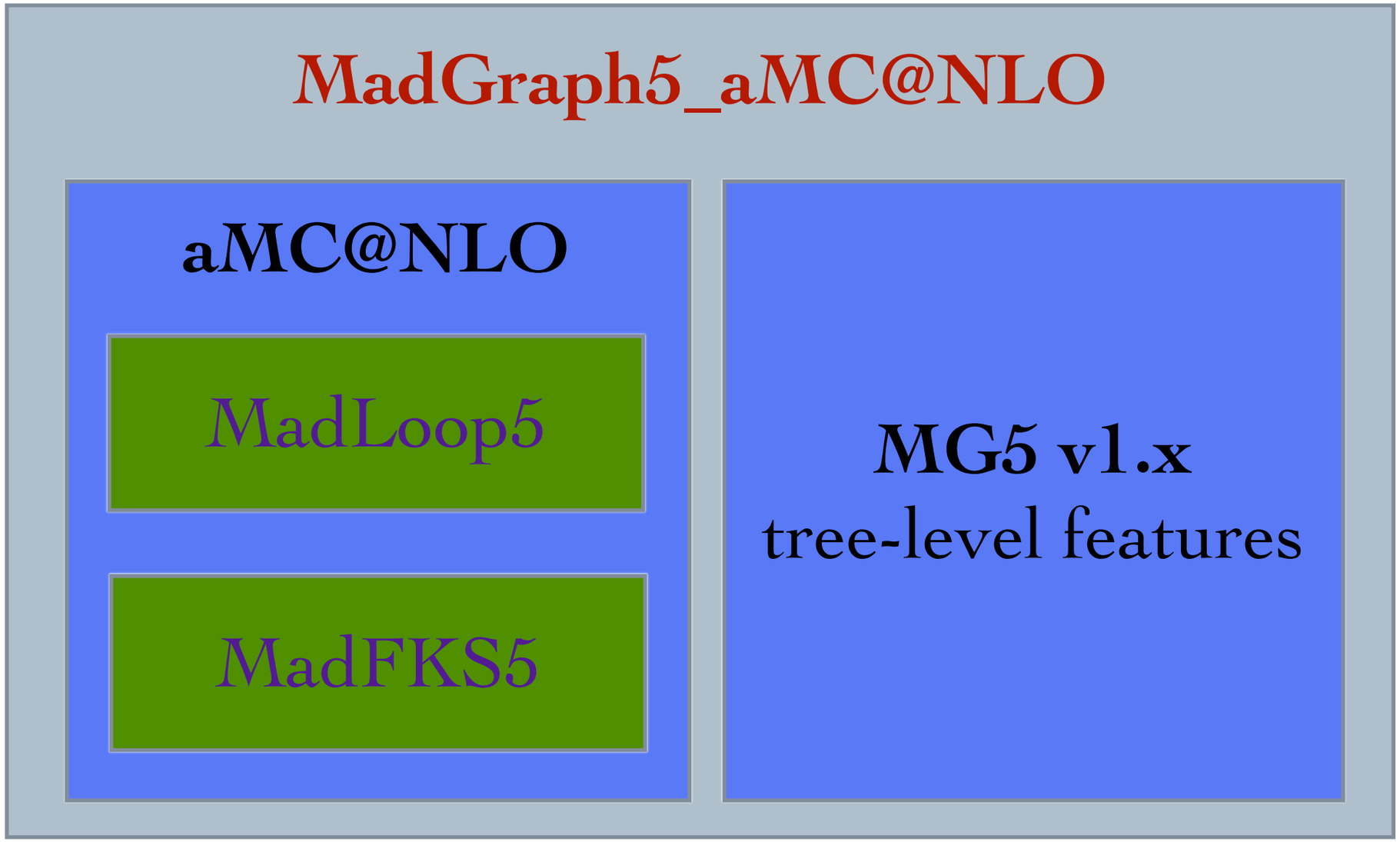

# MadLoop status

Valentin Hirschi, SLAC

LoopFest XIII 2014, NYCCT

June 18th, 2014

# A QUICK OVERVIEW




[ J. Alwall, R. Frederix, S. Frixione, V. H, F. Maltoni, O. Mattelaer, H.-S. Shao, T. Stelzer, P. Torrielli, M. Zaro ]

This separation is transparent to the users.

Publicly available since 8th Nov. 2012

(Reference paper came out recently, [hep-ph/1405.0301] )

# MADGRAPH5_AMC@NLO

## FRIEND OF USERS

- Process generation
  - `import model <model_name>-<restrictions>`
  - `generate <process> <amp_orders_and_option> [<mode>=<pert_orders>] <squared_orders>`
  - `output <format> <folder_name>`
  - `launch <options>`
- Examples, starting from a blank MG5 interface.
  - Very simple one:

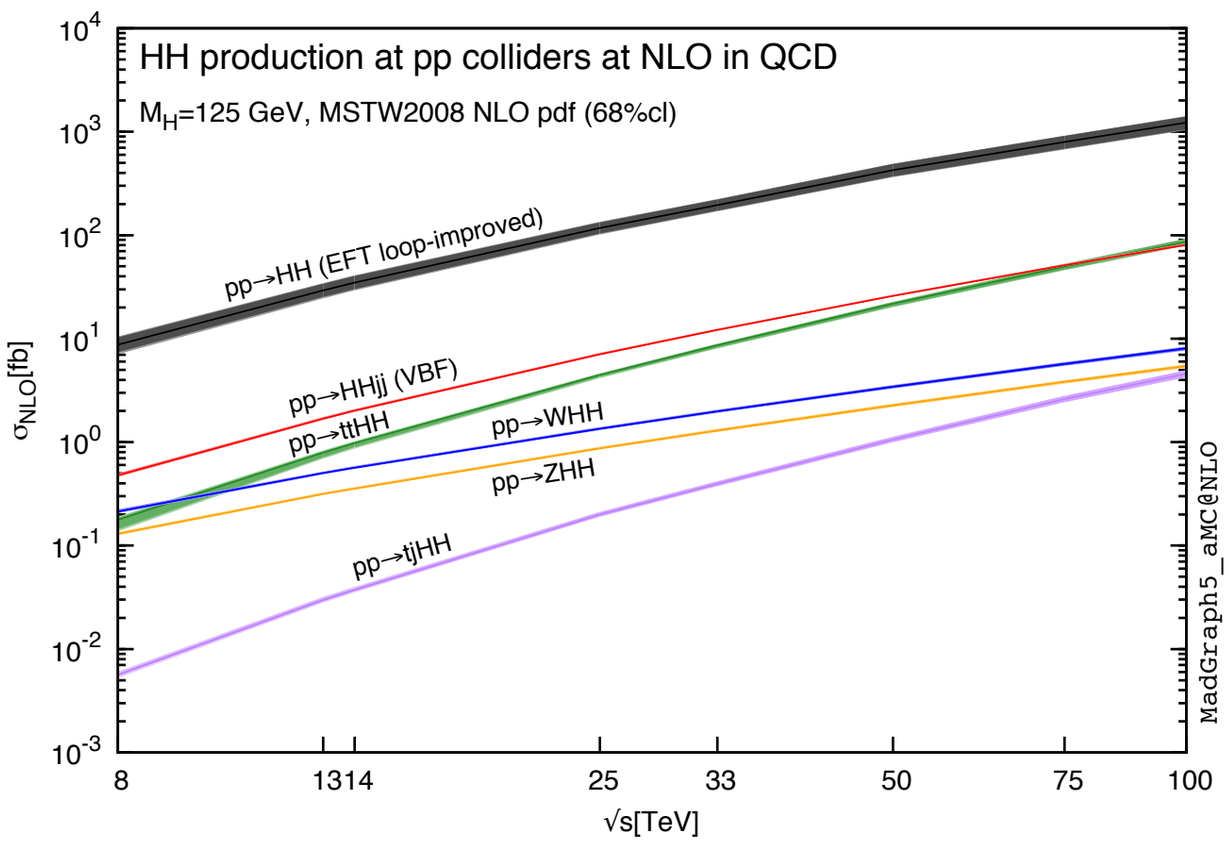
```
> generate p p > t t~ [QCD]
> output
> launch
```

  - With options specified:

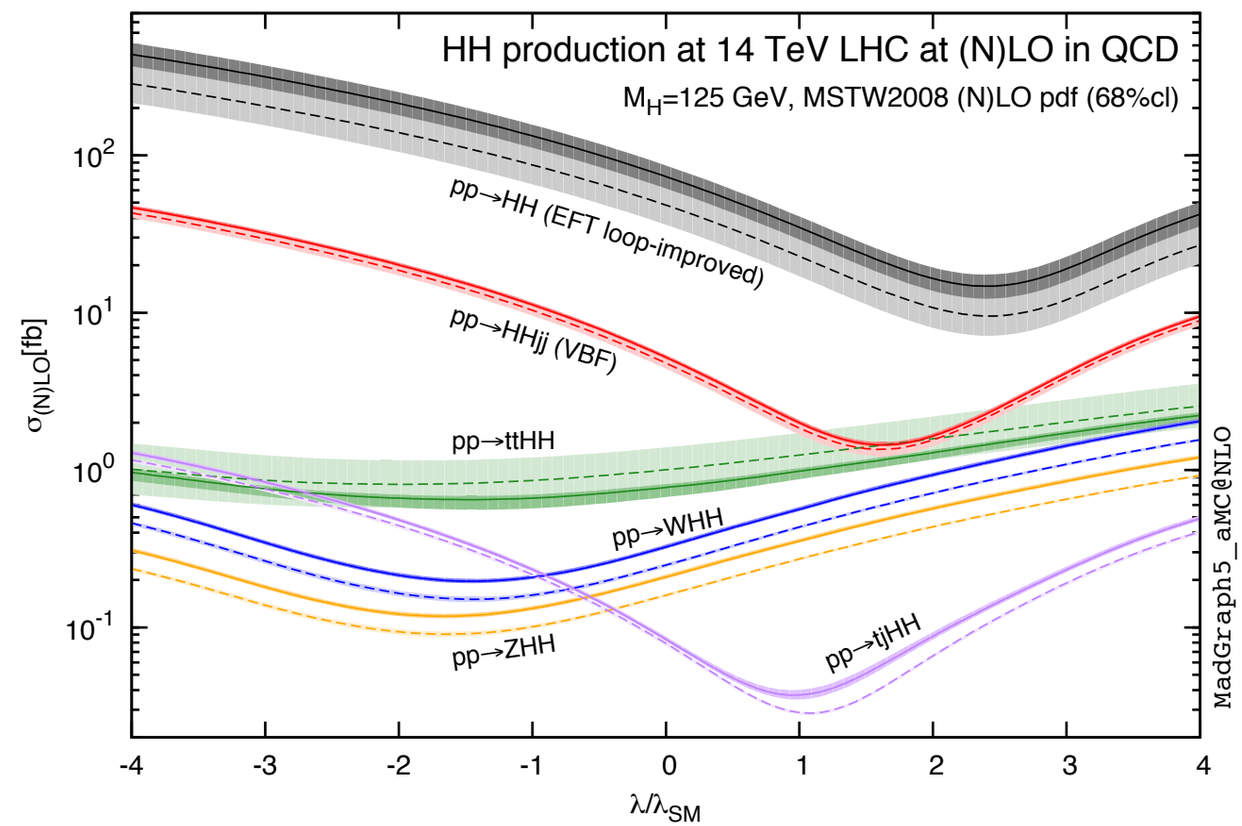
```
> import model loop_sm-no_hwidth
> set complex_mass_scheme
> generate p p  > e+ ve mu- vm~ b b~ / h QED=2 [QCD]
> output MyProc
> launch -f
```

[Frederix et al. 1401.7340]

# HH production at PP colliders




Total cross sections at NLO for the various channels



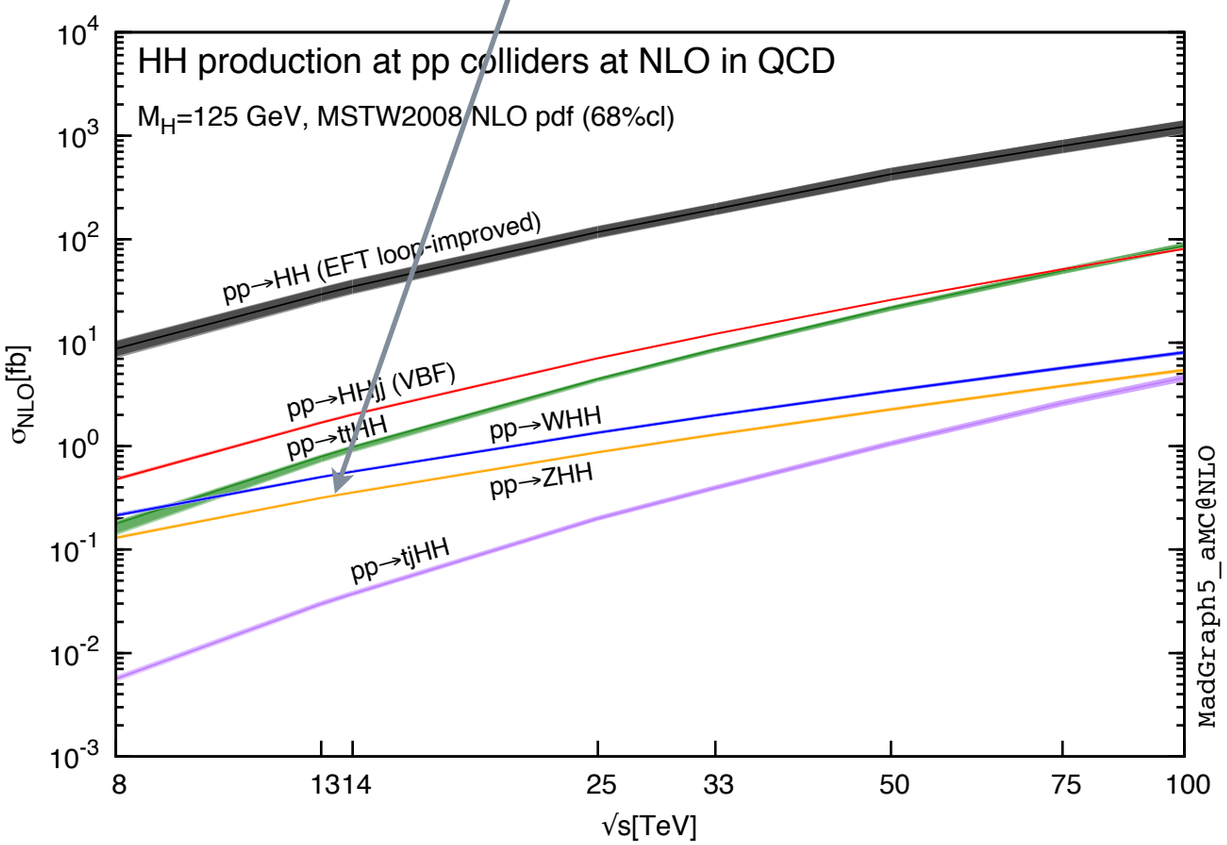

Trilinear coupling sensitivity

[Frederix et al. 1401.7340]

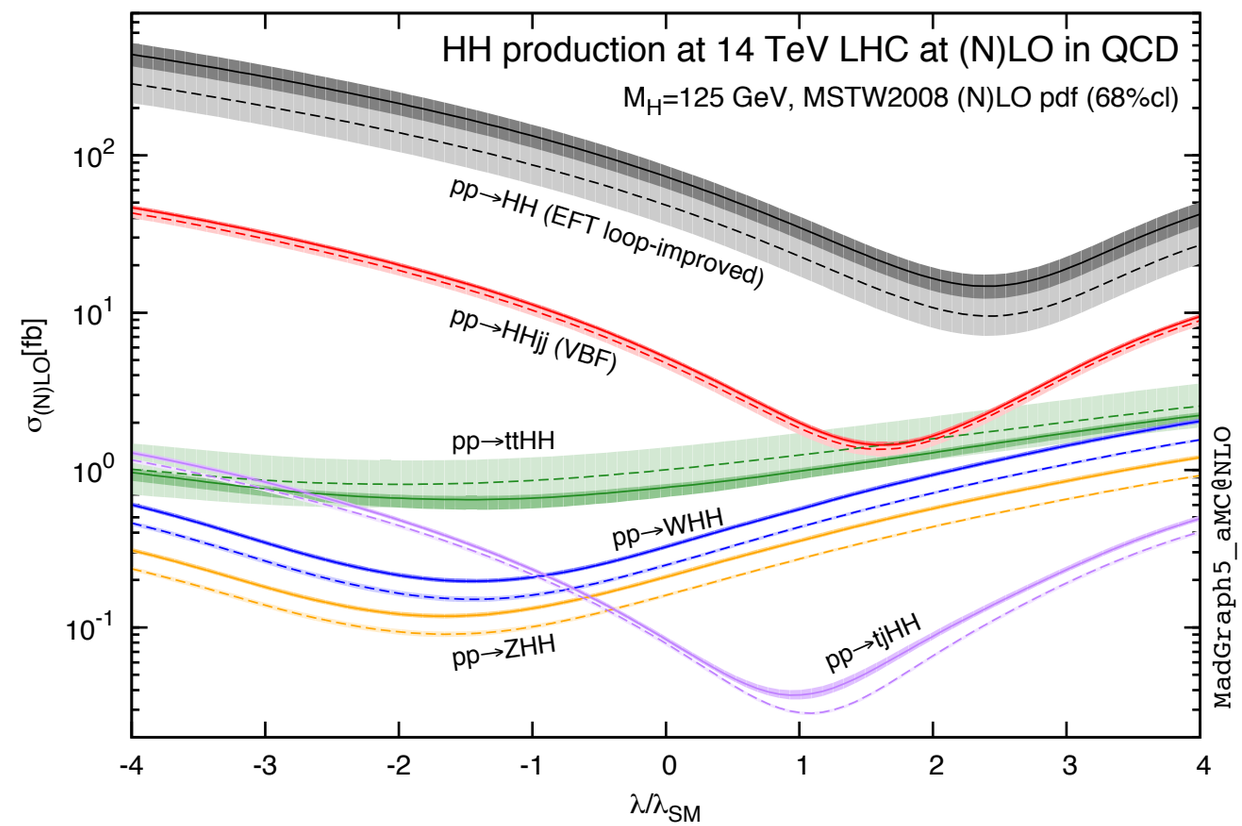
# HH production at pp colliders

You don't believe this particular data point? Then just type:

```
> generate p p > z h h [QCD]
> output
> launch
```




Total cross sections at NLO for the various channels



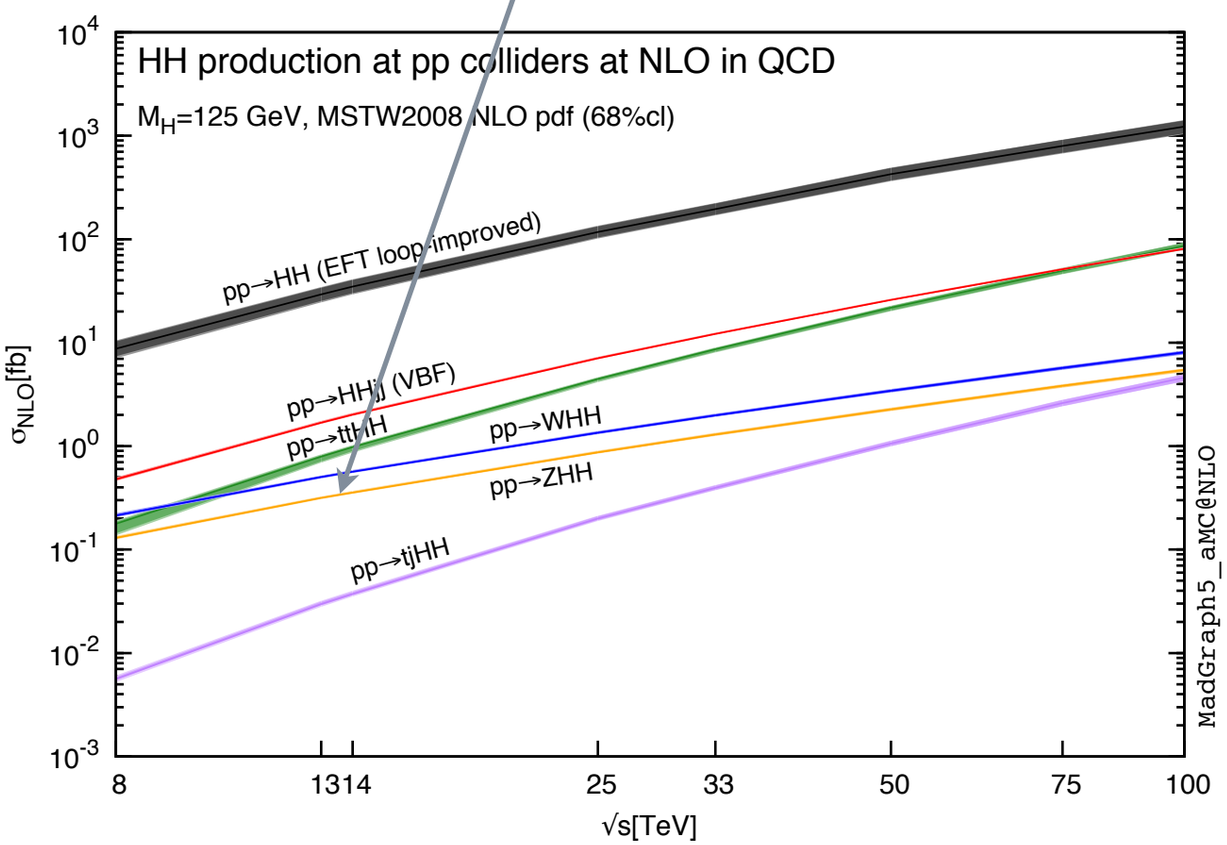

Trilinear coupling sensitivity

[Frederix et al. 1401.7340]

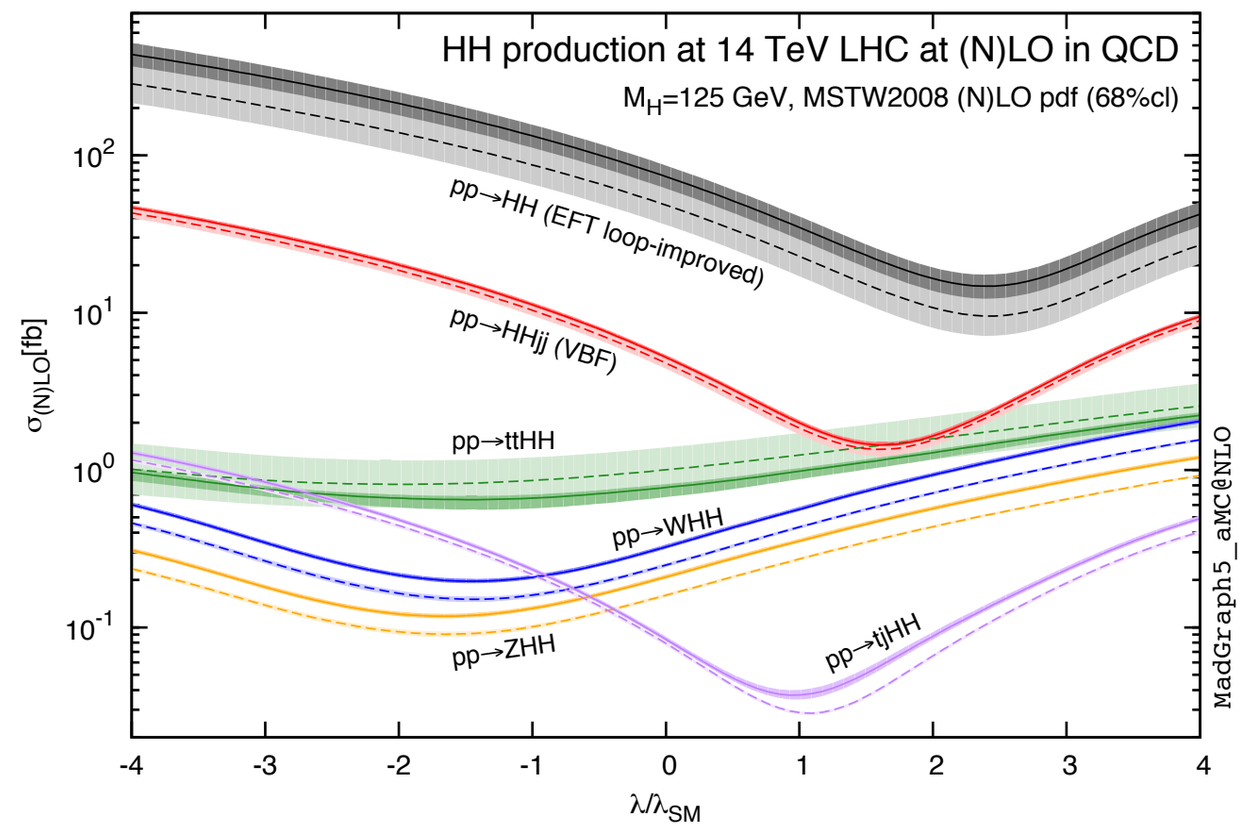
# HH production at pp colliders

Or just the evaluation of the loop matrix element for a given PS point ?

```
> generate p p > z h h [virt=QCD]
> output
> launch
```

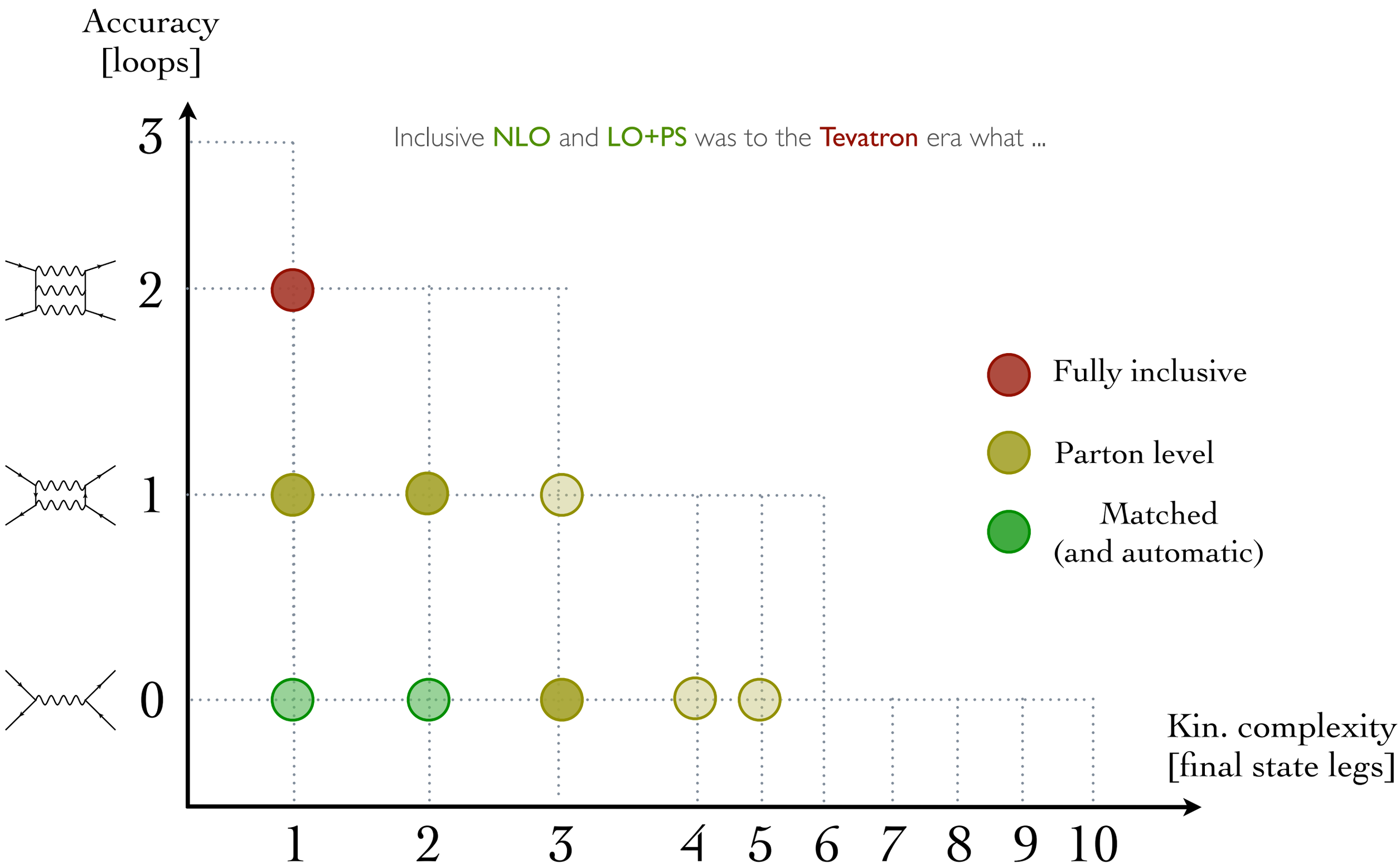



Total cross sections at NLO for the various channels

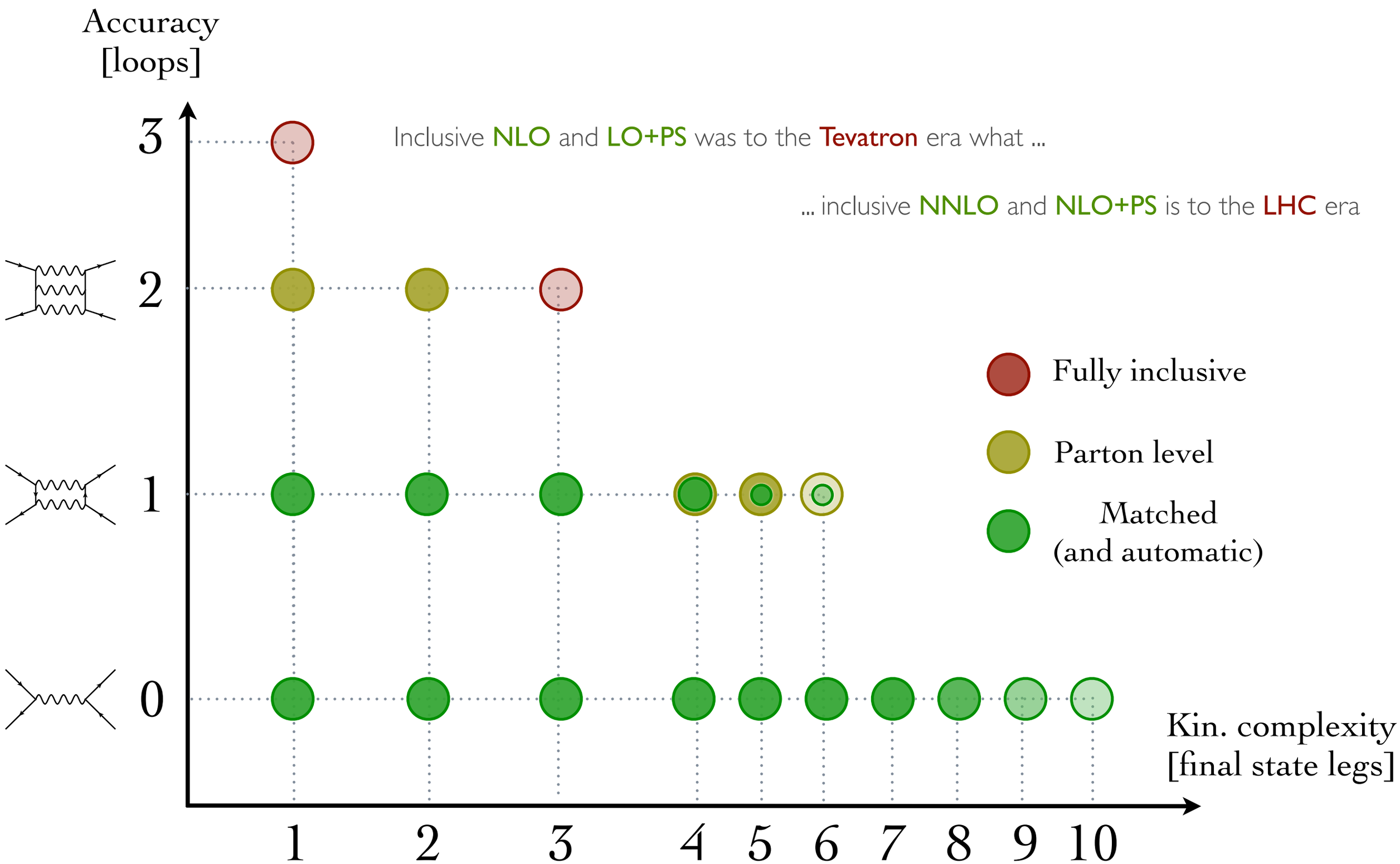



Trilinear coupling sensitivity

# State of the art in 2000



# State of the art in 2014



[J. Alwall et al. 1405.0301]

# Automatic NLO in the SM (2014)

| Process | | Syntax | Cross section (pb) | | | | | |
|---|---|---|---|---|---|---|---|---|
| Vector boson +jets | | | LO 13 TeV | | | NLO 13 TeV | | |
| a.1 | $pp \to W^{\pm}$ | `p p > wpm` | $1.375 \pm 0.002 \cdot 10^5$ | $^{+15.4\%}_{-16.6\%}$ | $^{+2.0\%}_{-1.6\%}$ | $1.773 \pm 0.007 \cdot 10^5$ | $^{+5.2\%}_{-9.4\%}$ | $^{+1.9\%}_{-1.6\%}$ |
| a.2 | $pp \to W^{\pm} j$ | `p p > wpm j` | $2.045 \pm 0.001 \cdot 10^4$ | $^{+19.7\%}_{-17.2\%}$ | $^{+1.4\%}_{-1.1\%}$ | $2.843 \pm 0.010 \cdot 10^4$ | $^{+5.9\%}_{-8.0\%}$ | $^{+1.3\%}_{-1.1\%}$ |
| a.3 | $pp \to W^{\pm} jj$ | `p p > wpm j j` | $6.805 \pm 0.015 \cdot 10^3$ | $^{+24.5\%}_{-18.6\%}$ | $^{+0.8\%}_{-0.7\%}$ | $7.786 \pm 0.030 \cdot 10^3$ | $^{+2.4\%}_{-6.0\%}$ | $^{+0.9\%}_{-0.8\%}$ |
| a.4 | $pp \to W^{\pm} jjj$ | `p p > wpm j j j` | $1.821 \pm 0.002 \cdot 10^3$ | $^{+41.0\%}_{-27.1\%}$ | $^{+0.5\%}_{-0.5\%}$ | $2.005 \pm 0.008 \cdot 10^3$ | $^{+0.9\%}_{-6.7\%}$ | $^{+0.6\%}_{-0.5\%}$ |
| a.5 | $pp \to Z$ | `p p > z` | $4.248 \pm 0.005 \cdot 10^4$ | $^{+14.6\%}_{-15.8\%}$ | $^{+2.0\%}_{-1.6\%}$ | $5.410 \pm 0.022 \cdot 10^4$ | $^{+4.6\%}_{-8.6\%}$ | $^{+1.9\%}_{-1.5\%}$ |
| a.6 | $pp \to Zj$ | `p p > z j` | $7.209 \pm 0.005 \cdot 10^3$ | $^{+19.3\%}_{-17.0\%}$ | $^{+1.2\%}_{-1.0\%}$ | $9.742 \pm 0.035 \cdot 10^3$ | $^{+5.8\%}_{-7.8\%}$ | $^{+1.2\%}_{-1.0\%}$ |
| a.7 | $pp \to Zjj$ | `p p > z j j` | $2.348 \pm 0.006 \cdot 10^3$ | $^{+24.3\%}_{-18.5\%}$ | $^{+0.6\%}_{-0.6\%}$ | $2.665 \pm 0.010 \cdot 10^3$ | $^{+2.5\%}_{-6.0\%}$ | $^{+0.7\%}_{-0.7\%}$ |
| a.8 | $pp \to Zjjj$ | `p p > z j j j` | $6.314 \pm 0.008 \cdot 10^2$ | $^{+40.8\%}_{-27.0\%}$ | $^{+0.5\%}_{-0.5\%}$ | $6.996 \pm 0.028 \cdot 10^2$ | $^{+1.1\%}_{-6.8\%}$ | $^{+0.5\%}_{-0.5\%}$ |
| a.9 | $pp \to \gamma j$ | `p p > a j` | $1.964 \pm 0.001 \cdot 10^4$ | $^{+31.2\%}_{-26.0\%}$ | $^{+1.7\%}_{-1.8\%}$ | $5.218 \pm 0.025 \cdot 10^4$ | $^{+24.5\%}_{-21.4\%}$ | $^{+1.4\%}_{-1.6\%}$ |
| a.10 | $pp \to \gamma jj$ | `p p > a j j` | $7.815 \pm 0.008 \cdot 10^3$ | $^{+32.8\%}_{-24.2\%}$ | $^{+0.9\%}_{-1.2\%}$ | $1.004 \pm 0.004 \cdot 10^4$ | $^{+5.9\%}_{-10.9\%}$ | $^{+0.8\%}_{-1.2\%}$ |

[J. Alwall et al. 1405.0301]

# Automatic NLO in the SM (2014)

| Process | | Syntax | Cross section (pb) | | | |
|---|---|---|---|---|---|---|
| Vector-boson pair +jets | | | LO 13 TeV | | NLO 13 TeV | |
| b.1 | $pp \to W^+W^-$ (4f) | `p p > w+ w-` | $7.355 \pm 0.005 \cdot 10^1$ | $^{+5.0\%}_{-6.1\%}$ $^{+2.0\%}_{-1.5\%}$ | $1.028 \pm 0.003 \cdot 10^2$ | $^{+4.0\%}_{-4.5\%}$ $^{+1.9\%}_{-1.4\%}$ |
| b.2 | $pp \to ZZ$ | `p p > z z` | $1.097 \pm 0.002 \cdot 10^1$ | $^{+4.5\%}_{-5.6\%}$ $^{+1.9\%}_{-1.5\%}$ | $1.415 \pm 0.005 \cdot 10^1$ | $^{+3.1\%}_{-3.7\%}$ $^{+1.8\%}_{-1.4\%}$ |
| b.3 | $pp \to ZW^\pm$ | `p p > z wpm` | $2.777 \pm 0.003 \cdot 10^1$ | $^{+3.6\%}_{-4.7\%}$ $^{+2.0\%}_{-1.5\%}$ | $4.487 \pm 0.013 \cdot 10^1$ | $^{+4.4\%}_{-4.4\%}$ $^{+1.7\%}_{-1.3\%}$ |
| b.4 | $pp \to \gamma\gamma$ | `p p > a a` | $2.510 \pm 0.002 \cdot 10^1$ | $^{+22.1\%}_{-22.4\%}$ $^{+2.4\%}_{-2.1\%}$ | $6.593 \pm 0.021 \cdot 10^1$ | $^{+17.6\%}_{-18.8\%}$ $^{+2.0\%}_{-1.9\%}$ |
| b.5 | $pp \to \gamma Z$ | `p p > a z` | $2.523 \pm 0.004 \cdot 10^1$ | $^{+9.9\%}_{-11.2\%}$ $^{+2.0\%}_{-1.6\%}$ | $3.695 \pm 0.013 \cdot 10^1$ | $^{+5.4\%}_{-7.1\%}$ $^{+1.8\%}_{-1.4\%}$ |
| b.6 | $pp \to \gamma W^\pm$ | `p p > a wpm` | $2.954 \pm 0.005 \cdot 10^1$ | $^{+9.5\%}_{-11.0\%}$ $^{+2.0\%}_{-1.7\%}$ | $7.124 \pm 0.026 \cdot 10^1$ | $^{+9.7\%}_{-9.9\%}$ $^{+1.5\%}_{-1.3\%}$ |
| b.7 | $pp \to W^+W^-j$ (4f) | `p p > w+ w- j` | $2.865 \pm 0.003 \cdot 10^1$ | $^{+11.6\%}_{-10.0\%}$ $^{+1.0\%}_{-0.8\%}$ | $3.730 \pm 0.013 \cdot 10^1$ | $^{+4.9\%}_{-4.9\%}$ $^{+1.1\%}_{-0.8\%}$ |
| b.8 | $pp \to ZZj$ | `p p > z z j` | $3.662 \pm 0.003 \cdot 10^0$ | $^{+10.9\%}_{-9.3\%}$ $^{+1.0\%}_{-0.8\%}$ | $4.830 \pm 0.016 \cdot 10^0$ | $^{+5.0\%}_{-4.8\%}$ $^{+1.1\%}_{-0.9\%}$ |
| b.9 | $pp \to ZW^\pm j$ | `p p > z wpm j` | $1.605 \pm 0.005 \cdot 10^1$ | $^{+11.6\%}_{-10.0\%}$ $^{+0.9\%}_{-0.7\%}$ | $2.086 \pm 0.007 \cdot 10^1$ | $^{+4.9\%}_{-4.8\%}$ $^{+0.9\%}_{-0.7\%}$ |
| b.10 | $pp \to \gamma\gamma j$ | `p p > a a j` | $1.022 \pm 0.001 \cdot 10^1$ | $^{+20.3\%}_{-17.7\%}$ $^{+1.2\%}_{-1.5\%}$ | $2.292 \pm 0.010 \cdot 10^1$ | $^{+17.2\%}_{-15.1\%}$ $^{+1.0\%}_{-1.4\%}$ |
| b.11* | $pp \to \gamma Zj$ | `p p > a z j` | $8.310 \pm 0.017 \cdot 10^0$ | $^{+14.5\%}_{-12.8\%}$ $^{+1.0\%}_{-1.0\%}$ | $1.220 \pm 0.005 \cdot 10^1$ | $^{+7.3\%}_{-7.4\%}$ $^{+0.9\%}_{-0.9\%}$ |
| b.12* | $pp \to \gamma W^\pm j$ | `p p > a wpm j` | $2.546 \pm 0.010 \cdot 10^1$ | $^{+13.7\%}_{-12.1\%}$ $^{+0.9\%}_{-1.0\%}$ | $3.713 \pm 0.015 \cdot 10^1$ | $^{+7.2\%}_{-7.1\%}$ $^{+0.9\%}_{-1.0\%}$ |
| b.13 | $pp \to W^+W^+jj$ | `p p > w+ w+ j j` | $1.484 \pm 0.006 \cdot 10^{-1}$ | $^{+25.4\%}_{-18.9\%}$ $^{+2.1\%}_{-1.5\%}$ | $2.251 \pm 0.011 \cdot 10^{-1}$ | $^{+10.5\%}_{-10.6\%}$ $^{+2.2\%}_{-1.6\%}$ |
| b.14 | $pp \to W^-W^-jj$ | `p p > w- w- j j` | $6.752 \pm 0.007 \cdot 10^{-2}$ | $^{+25.4\%}_{-18.9\%}$ $^{+2.4\%}_{-1.7\%}$ | $1.003 \pm 0.003 \cdot 10^{-1}$ | $^{+10.1\%}_{-10.4\%}$ $^{+2.5\%}_{-1.8\%}$ |
| b.15 | $pp \to W^+W^-jj$ (4f) | `p p > w+ w- j j` | $1.144 \pm 0.002 \cdot 10^1$ | $^{+27.2\%}_{-19.9\%}$ $^{+0.7\%}_{-0.5\%}$ | $1.396 \pm 0.005 \cdot 10^1$ | $^{+5.0\%}_{-6.8\%}$ $^{+0.7\%}_{-0.6\%}$ |
| b.16 | $pp \to ZZjj$ | `p p > z z j j` | $1.344 \pm 0.002 \cdot 10^0$ | $^{+26.6\%}_{-19.6\%}$ $^{+0.7\%}_{-0.6\%}$ | $1.706 \pm 0.011 \cdot 10^0$ | $^{+5.8\%}_{-7.2\%}$ $^{+0.8\%}_{-0.6\%}$ |
| b.17 | $pp \to ZW^\pm jj$ | `p p > z wpm j j` | $8.038 \pm 0.009 \cdot 10^0$ | $^{+26.7\%}_{-19.7\%}$ $^{+0.7\%}_{-0.5\%}$ | $9.139 \pm 0.031 \cdot 10^0$ | $^{+3.1\%}_{-5.1\%}$ $^{+0.7\%}_{-0.5\%}$ |
| b.18 | $pp \to \gamma\gamma jj$ | `p p > a a j j` | $5.377 \pm 0.029 \cdot 10^0$ | $^{+26.2\%}_{-19.8\%}$ $^{+0.6\%}_{-1.0\%}$ | $7.501 \pm 0.032 \cdot 10^0$ | $^{+8.8\%}_{-10.1\%}$ $^{+0.6\%}_{-1.0\%}$ |
| b.19* | $pp \to \gamma Zjj$ | `p p > a z j j` | $3.260 \pm 0.009 \cdot 10^0$ | $^{+24.3\%}_{-18.4\%}$ $^{+0.6\%}_{-0.6\%}$ | $4.242 \pm 0.016 \cdot 10^0$ | $^{+6.5\%}_{-7.3\%}$ $^{+0.6\%}_{-0.6\%}$ |
| b.20* | $pp \to \gamma W^\pm jj$ | `p p > a wpm j j` | $1.233 \pm 0.002 \cdot 10^1$ | $^{+24.7\%}_{-18.6\%}$ $^{+0.6\%}_{-0.6\%}$ | $1.448 \pm 0.005 \cdot 10^1$ | $^{+3.6\%}_{-5.4\%}$ $^{+0.6\%}_{-0.7\%}$ |

[J. Alwall et al. 1405.0301]

# Automatic NLO in the SM (2014)

| | Process | Syntax | Cross section (pb) | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Three vector bosons +jet | | LO 13 TeV | | | NLO 13 TeV | | |
| c.1 | $pp \to W^+W^-W^\pm$ (4f) | `p p > w+ w- wpm` | $1.307 \pm 0.003 \cdot 10^{-1}$ | $^{+0.0\%}_{-0.3\%}$ | $^{+2.0\%}_{-1.5\%}$ | $2.109 \pm 0.006 \cdot 10^{-1}$ | $^{+5.1\%}_{-4.1\%}$ | $^{+1.6\%}_{-1.2\%}$ |
| c.2 | $pp \to ZW^+W^-$ (4f) | `p p > z w+ w-` | $9.658 \pm 0.065 \cdot 10^{-2}$ | $^{+0.8\%}_{-1.1\%}$ | $^{+2.1\%}_{-1.6\%}$ | $1.679 \pm 0.005 \cdot 10^{-1}$ | $^{+6.3\%}_{-5.1\%}$ | $^{+1.6\%}_{-1.2\%}$ |
| c.3 | $pp \to ZZW^\pm$ | `p p > z z wpm` | $2.996 \pm 0.016 \cdot 10^{-2}$ | $^{+1.0\%}_{-1.4\%}$ | $^{+2.0\%}_{-1.6\%}$ | $5.550 \pm 0.020 \cdot 10^{-2}$ | $^{+6.8\%}_{-5.5\%}$ | $^{+1.5\%}_{-1.1\%}$ |
| c.4 | $pp \to ZZZ$ | `p p > z z z` | $1.085 \pm 0.002 \cdot 10^{-2}$ | $^{+0.0\%}_{-0.5\%}$ | $^{+1.9\%}_{-1.5\%}$ | $1.417 \pm 0.005 \cdot 10^{-2}$ | $^{+2.7\%}_{-2.1\%}$ | $^{+1.9\%}_{-1.5\%}$ |
| c.5 | $pp \to \gamma W^+W^-$ (4f) | `p p > a w+ w-` | $1.427 \pm 0.011 \cdot 10^{-1}$ | $^{+1.9\%}_{-2.6\%}$ | $^{+2.0\%}_{-1.5\%}$ | $2.581 \pm 0.008 \cdot 10^{-1}$ | $^{+5.4\%}_{-4.3\%}$ | $^{+1.4\%}_{-1.1\%}$ |
| c.6 | $pp \to \gamma\gamma W^\pm$ | `p p > a a wpm` | $2.681 \pm 0.007 \cdot 10^{-2}$ | $^{+4.4\%}_{-5.6\%}$ | $^{+1.9\%}_{-1.6\%}$ | $8.251 \pm 0.032 \cdot 10^{-2}$ | $^{+7.6\%}_{-7.0\%}$ | $^{+1.0\%}_{-1.0\%}$ |
| c.7 | $pp \to \gamma ZW^\pm$ | `p p > a z wpm` | $4.994 \pm 0.011 \cdot 10^{-2}$ | $^{+0.8\%}_{-1.4\%}$ | $^{+1.9\%}_{-1.6\%}$ | $1.117 \pm 0.004 \cdot 10^{-1}$ | $^{+7.2\%}_{-5.9\%}$ | $^{+1.2\%}_{-0.9\%}$ |
| c.8 | $pp \to \gamma ZZ$ | `p p > a z z` | $2.318 \pm 0.004 \cdot 10^{-2}$ | $^{+2.0\%}_{-2.8\%}$ | $^{+1.9\%}_{-1.5\%}$ | $3.177 \pm 0.015 \cdot 10^{-2}$ | $^{+3.1\%}_{-2.9\%}$ | $^{+1.8\%}_{-1.4\%}$ |
| c.9 | $pp \to \gamma\gamma Z$ | `p p > a a z` | $3.077 \pm 0.008 \cdot 10^{-2}$ | $^{+5.7\%}_{-6.8\%}$ | $^{+1.9\%}_{-1.6\%}$ | $4.571 \pm 0.017 \cdot 10^{-2}$ | $^{+4.2\%}_{-4.8\%}$ | $^{+1.7\%}_{-1.4\%}$ |
| c.10 | $pp \to \gamma\gamma\gamma$ | `p p > a a a` | $1.269 \pm 0.003 \cdot 10^{-2}$ | $^{+9.8\%}_{-11.0\%}$ | $^{+2.0\%}_{-1.8\%}$ | $3.441 \pm 0.012 \cdot 10^{-2}$ | $^{+11.8\%}_{-11.6\%}$ | $^{+1.4\%}_{-1.5\%}$ |
| c.11* | $pp \to W^+W^-W^\pm j$ (4f) | `p p > w+ w- wpm j` | $9.167 \pm 0.010 \cdot 10^{-2}$ | $^{+15.0\%}_{-12.2\%}$ | $^{+1.0\%}_{-0.7\%}$ | $1.197 \pm 0.004 \cdot 10^{-1}$ | $^{+5.2\%}_{-5.6\%}$ | $^{+1.0\%}_{-0.8\%}$ |
| c.12* | $pp \to ZW^+W^-j$ (4f) | `p p > z w+ w- j` | $8.340 \pm 0.010 \cdot 10^{-2}$ | $^{+15.6\%}_{-12.6\%}$ | $^{+1.0\%}_{-0.7\%}$ | $1.066 \pm 0.003 \cdot 10^{-1}$ | $^{+4.5\%}_{-5.3\%}$ | $^{+1.0\%}_{-0.7\%}$ |
| c.13* | $pp \to ZZW^\pm j$ | `p p > z z wpm j` | $2.810 \pm 0.004 \cdot 10^{-2}$ | $^{+16.1\%}_{-13.0\%}$ | $^{+1.0\%}_{-0.7\%}$ | $3.660 \pm 0.013 \cdot 10^{-2}$ | $^{+4.8\%}_{-5.6\%}$ | $^{+1.0\%}_{-0.7\%}$ |
| c.14* | $pp \to ZZZj$ | `p p > z z z j` | $4.823 \pm 0.011 \cdot 10^{-3}$ | $^{+14.3\%}_{-11.8\%}$ | $^{+1.4\%}_{-1.0\%}$ | $6.341 \pm 0.025 \cdot 10^{-3}$ | $^{+4.9\%}_{-5.4\%}$ | $^{+1.4\%}_{-1.0\%}$ |
| c.15* | $pp \to \gamma W^+W^-j$ (4f) | `p p > a w+ w- j` | $1.182 \pm 0.004 \cdot 10^{-1}$ | $^{+13.4\%}_{-11.2\%}$ | $^{+0.8\%}_{-0.7\%}$ | $1.233 \pm 0.004 \cdot 10^{3}$ | $^{+18.9\%}_{-19.9\%}$ | $^{+1.0\%}_{-1.5\%}$ |
| c.16 | $pp \to \gamma\gamma W^\pm j$ | `p p > a a wpm j` | $4.107 \pm 0.015 \cdot 10^{-2}$ | $^{+11.8\%}_{-10.2\%}$ | $^{+0.6\%}_{-0.8\%}$ | $5.807 \pm 0.023 \cdot 10^{-2}$ | $^{+5.8\%}_{-5.5\%}$ | $^{+0.7\%}_{-0.7\%}$ |
| c.17* | $pp \to \gamma ZW^\pm j$ | `p p > a z wpm j` | $5.833 \pm 0.023 \cdot 10^{-2}$ | $^{+14.4\%}_{-12.0\%}$ | $^{+0.7\%}_{-0.6\%}$ | $7.764 \pm 0.025 \cdot 10^{-2}$ | $^{+5.1\%}_{-5.5\%}$ | $^{+0.8\%}_{-0.6\%}$ |
| c.18* | $pp \to \gamma ZZj$ | `p p > a z z j` | $9.995 \pm 0.013 \cdot 10^{-3}$ | $^{+12.5\%}_{-10.6\%}$ | $^{+1.2\%}_{-0.9\%}$ | $1.371 \pm 0.005 \cdot 10^{-2}$ | $^{+5.6\%}_{-5.5\%}$ | $^{+1.2\%}_{-0.9\%}$ |
| c.19* | $pp \to \gamma\gamma Zj$ | `p p > a a z j` | $1.372 \pm 0.003 \cdot 10^{-2}$ | $^{+10.9\%}_{-9.4\%}$ | $^{+1.0\%}_{-0.9\%}$ | $2.051 \pm 0.011 \cdot 10^{-2}$ | $^{+7.0\%}_{-6.3\%}$ | $^{+1.0\%}_{-0.9\%}$ |
| c.20* | $pp \to \gamma\gamma\gamma j$ | `p p > a a a j` | $1.031 \pm 0.006 \cdot 10^{-2}$ | $^{+14.3\%}_{-12.6\%}$ | $^{+0.9\%}_{-1.2\%}$ | $2.020 \pm 0.008 \cdot 10^{-2}$ | $^{+12.8\%}_{-11.0\%}$ | $^{+0.8\%}_{-1.2\%}$ |

[J. Alwall et al. 1405.0301]

# Automatic NLO in the SM (2014)

| Process | | Syntax | Cross section (pb) LO 13 TeV | | | Cross section (pb) NLO 13 TeV | | |
|---|---|---|---|---|---|---|---|---|
| Four vector bosons | | | | | | | | |
| c.21* | $pp \to W^+W^-W^+W^-$ (4f) | `p p > w+ w- w+ w-` | $5.721 \pm 0.014 \cdot 10^{-4}$ | $^{+3.7\%}_{-3.5\%}$ | $^{+2.3\%}_{-1.7\%}$ | $9.959 \pm 0.035 \cdot 10^{-4}$ | $^{+7.4\%}_{-6.0\%}$ | $^{+1.7\%}_{-1.2\%}$ |
| c.22* | $pp \to W^+W^-W^\pm Z$ (4f) | `p p > w+ w- wpm z` | $6.391 \pm 0.076 \cdot 10^{-4}$ | $^{+4.4\%}_{-4.1\%}$ | $^{+2.4\%}_{-1.8\%}$ | $1.188 \pm 0.004 \cdot 10^{-3}$ | $^{+8.4\%}_{-6.8\%}$ | $^{+1.7\%}_{-1.2\%}$ |
| c.23* | $pp \to W^+W^-W^\pm\gamma$ (4f) | `p p > w+ w- wpm a` | $8.115 \pm 0.064 \cdot 10^{-4}$ | $^{+2.5\%}_{-2.5\%}$ | $^{+2.2\%}_{-1.7\%}$ | $1.546 \pm 0.005 \cdot 10^{-3}$ | $^{+7.9\%}_{-6.3\%}$ | $^{+1.5\%}_{-1.1\%}$ |
| c.24* | $pp \to W^+W^-ZZ$ (4f) | `p p > w+ w- z z` | $4.320 \pm 0.013 \cdot 10^{-4}$ | $^{+4.4\%}_{-4.1\%}$ | $^{+2.4\%}_{-1.7\%}$ | $7.107 \pm 0.020 \cdot 10^{-4}$ | $^{+7.0\%}_{-5.7\%}$ | $^{+1.8\%}_{-1.3\%}$ |
| c.25* | $pp \to W^+W^-Z\gamma$ (4f) | `p p > w+ w- z a` | $8.403 \pm 0.016 \cdot 10^{-4}$ | $^{+3.0\%}_{-2.9\%}$ | $^{+2.3\%}_{-1.7\%}$ | $1.483 \pm 0.004 \cdot 10^{-3}$ | $^{+7.2\%}_{-5.8\%}$ | $^{+1.6\%}_{-1.2\%}$ |
| c.26* | $pp \to W^+W^-\gamma\gamma$ (4f) | `p p > w+ w- a a` | $5.198 \pm 0.012 \cdot 10^{-4}$ | $^{+0.6\%}_{-0.9\%}$ | $^{+2.1\%}_{-1.6\%}$ | $9.381 \pm 0.032 \cdot 10^{-4}$ | $^{+6.7\%}_{-5.3\%}$ | $^{+1.4\%}_{-1.1\%}$ |
| c.27* | $pp \to W^\pm ZZZ$ | `p p > wpm z z z` | $5.862 \pm 0.010 \cdot 10^{-5}$ | $^{+5.1\%}_{-4.7\%}$ | $^{+2.4\%}_{-1.8\%}$ | $1.240 \pm 0.004 \cdot 10^{-4}$ | $^{+9.9\%}_{-8.0\%}$ | $^{+1.7\%}_{-1.2\%}$ |
| c.28* | $pp \to W^\pm ZZ\gamma$ | `p p > wpm z z a` | $1.148 \pm 0.003 \cdot 10^{-4}$ | $^{+3.6\%}_{-3.5\%}$ | $^{+2.2\%}_{-1.7\%}$ | $2.945 \pm 0.008 \cdot 10^{-4}$ | $^{+10.8\%}_{-8.7\%}$ | $^{+1.3\%}_{-1.0\%}$ |
| c.29* | $pp \to W^\pm Z\gamma\gamma$ | `p p > wpm z a a` | $1.054 \pm 0.004 \cdot 10^{-4}$ | $^{+1.7\%}_{-1.9\%}$ | $^{+2.1\%}_{-1.7\%}$ | $3.033 \pm 0.010 \cdot 10^{-4}$ | $^{+10.6\%}_{-8.6\%}$ | $^{+1.1\%}_{-0.8\%}$ |
| c.30* | $pp \to W^\pm\gamma\gamma\gamma$ | `p p > wpm a a a` | $3.600 \pm 0.013 \cdot 10^{-5}$ | $^{+0.4\%}_{-1.0\%}$ | $^{+2.0\%}_{-1.6\%}$ | $1.246 \pm 0.005 \cdot 10^{-4}$ | $^{+9.8\%}_{-8.1\%}$ | $^{+0.9\%}_{-0.8\%}$ |
| c.31* | $pp \to ZZZZ$ | `p p > z z z z` | $1.989 \pm 0.002 \cdot 10^{-5}$ | $^{+3.8\%}_{-3.6\%}$ | $^{+2.2\%}_{-1.7\%}$ | $2.629 \pm 0.008 \cdot 10^{-5}$ | $^{+3.5\%}_{-3.0\%}$ | $^{+2.2\%}_{-1.7\%}$ |
| c.32* | $pp \to ZZZ\gamma$ | `p p > z z z a` | $3.945 \pm 0.007 \cdot 10^{-5}$ | $^{+1.9\%}_{-2.1\%}$ | $^{+2.1\%}_{-1.6\%}$ | $5.224 \pm 0.016 \cdot 10^{-5}$ | $^{+3.3\%}_{-2.7\%}$ | $^{+2.1\%}_{-1.6\%}$ |
| c.33* | $pp \to ZZ\gamma\gamma$ | `p p > z z a a` | $5.513 \pm 0.017 \cdot 10^{-5}$ | $^{+0.0\%}_{-0.3\%}$ | $^{+2.1\%}_{-1.6\%}$ | $7.518 \pm 0.032 \cdot 10^{-5}$ | $^{+3.4\%}_{-2.6\%}$ | $^{+2.0\%}_{-1.5\%}$ |
| c.34* | $pp \to Z\gamma\gamma\gamma$ | `p p > z a a a` | $4.790 \pm 0.012 \cdot 10^{-5}$ | $^{+2.3\%}_{-3.1\%}$ | $^{+2.0\%}_{-1.6\%}$ | $7.103 \pm 0.026 \cdot 10^{-5}$ | $^{+3.4\%}_{-3.2\%}$ | $^{+1.6\%}_{-1.5\%}$ |
| c.35* | $pp \to \gamma\gamma\gamma\gamma$ | `p p > a a a a` | $1.594 \pm 0.004 \cdot 10^{-5}$ | $^{+4.7\%}_{-5.7\%}$ | $^{+1.9\%}_{-1.7\%}$ | $3.389 \pm 0.012 \cdot 10^{-5}$ | $^{+7.0\%}_{-6.7\%}$ | $^{+1.3\%}_{-1.3\%}$ |

[J. Alwall et al. 1405.0301]

# Automatic NLO in the SM (2014)

| Process | | Syntax | Cross section (pb) | | | | | |
|---|---|---|---|---|---|---|---|---|
| Heavy quarks and jets | | | LO 13 TeV | | | NLO 13 TeV | | |
| d.1 | $pp \to jj$ | `p p > j j` | $1.162 \pm 0.001 \cdot 10^{6}$ | $^{+24.9\%}_{-18.8\%}$ | $^{+0.8\%}_{-0.9\%}$ | $1.580 \pm 0.007 \cdot 10^{6}$ | $^{+8.4\%}_{-9.0\%}$ | $^{+0.7\%}_{-0.9\%}$ |
| d.2 | $pp \to jjj$ | `p p > j j j` | $8.940 \pm 0.021 \cdot 10^{4}$ | $^{+43.8\%}_{-28.4\%}$ | $^{+1.2\%}_{-1.4\%}$ | $7.791 \pm 0.037 \cdot 10^{4}$ | $^{+2.1\%}_{-23.2\%}$ | $^{+1.1\%}_{-1.3\%}$ |
| d.3 | $pp \to b\bar{b}$ | `p p > b b~` | $3.743 \pm 0.004 \cdot 10^{3}$ | $^{+25.2\%}_{-18.9\%}$ | $^{+1.5\%}_{-1.8\%}$ | $6.438 \pm 0.028 \cdot 10^{3}$ | $^{+15.9\%}_{-13.3\%}$ | $^{+1.5\%}_{-1.7\%}$ |
| d.4* | $pp \to b\bar{b}j$ | `p p > b b~ j` | $1.050 \pm 0.002 \cdot 10^{3}$ | $^{+44.1\%}_{-28.5\%}$ | $^{+1.6\%}_{-1.8\%}$ | $1.327 \pm 0.007 \cdot 10^{3}$ | $^{+6.8\%}_{-11.6\%}$ | $^{+1.5\%}_{-1.8\%}$ |
| d.5* | $pp \to b\bar{b}jj$ | `p p > b b~ j j` | $1.852 \pm 0.006 \cdot 10^{2}$ | $^{+61.8\%}_{-35.6\%}$ | $^{+2.1\%}_{-2.4\%}$ | $2.471 \pm 0.012 \cdot 10^{2}$ | $^{+8.2\%}_{-16.4\%}$ | $^{+2.0\%}_{-2.3\%}$ |
| d.6 | $pp \to b\bar{b}b\bar{b}$ | `p p > b b~ b b~` | $5.050 \pm 0.007 \cdot 10^{-1}$ | $^{+61.7\%}_{-35.6\%}$ | $^{+2.9\%}_{-3.4\%}$ | $8.736 \pm 0.034 \cdot 10^{-1}$ | $^{+20.9\%}_{-22.0\%}$ | $^{+2.9\%}_{-3.4\%}$ |
| d.7 | $pp \to t\bar{t}$ | `p p > t t~` | $4.584 \pm 0.003 \cdot 10^{2}$ | $^{+29.0\%}_{-21.1\%}$ | $^{+1.8\%}_{-2.0\%}$ | $6.741 \pm 0.023 \cdot 10^{2}$ | $^{+9.8\%}_{-10.9\%}$ | $^{+1.8\%}_{-2.1\%}$ |
| d.8 | $pp \to t\bar{t}j$ | `p p > t t~ j` | $3.135 \pm 0.002 \cdot 10^{2}$ | $^{+45.1\%}_{-29.0\%}$ | $^{+2.2\%}_{-2.5\%}$ | $4.106 \pm 0.015 \cdot 10^{2}$ | $^{+8.1\%}_{-12.2\%}$ | $^{+2.1\%}_{-2.5\%}$ |
| d.9 | $pp \to t\bar{t}jj$ | `p p > t t~ j j` | $1.361 \pm 0.001 \cdot 10^{2}$ | $^{+61.4\%}_{-35.6\%}$ | $^{+2.6\%}_{-3.0\%}$ | $1.795 \pm 0.006 \cdot 10^{2}$ | $^{+9.3\%}_{-16.1\%}$ | $^{+2.4\%}_{-2.9\%}$ |
| d.10 | $pp \to t\bar{t}t\bar{t}$ | `p p > t t~ t t~` | $4.505 \pm 0.005 \cdot 10^{-3}$ | $^{+63.8\%}_{-36.5\%}$ | $^{+5.4\%}_{-5.7\%}$ | $9.201 \pm 0.028 \cdot 10^{-3}$ | $^{+30.8\%}_{-25.6\%}$ | $^{+5.5\%}_{-5.9\%}$ |
| d.11 | $pp \to t\bar{t}b\bar{b}$ | `p p > t t~ b b~` | $6.119 \pm 0.004 \cdot 10^{0}$ | $^{+62.1\%}_{-35.7\%}$ | $^{+2.9\%}_{-3.5\%}$ | $1.452 \pm 0.005 \cdot 10^{1}$ | $^{+37.6\%}_{-27.5\%}$ | $^{+2.9\%}_{-3.5\%}$ |

[J. Alwall et al. 1405.0301]

# Automatic NLO in the SM (2014)

| Process | | Syntax | Cross section (pb) | | | | | |
|---|---|---|---|---|---|---|---|---|
| Heavy quarks+vector bosons | | | LO 13 TeV | | | NLO 13 TeV | | |
| e.1 | $pp \to W^{\pm} b\bar{b}$ | `p p > wpm b b~` | $3.074 \pm 0.002 \cdot 10^{2}$ | $^{+42.3\%}_{-29.2\%}$ | $^{+2.0\%}_{-1.6\%}$ | $8.162 \pm 0.034 \cdot 10^{2}$ | $^{+29.8\%}_{-23.6\%}$ | $^{+1.5\%}_{-1.2\%}$ |
| e.2 | $pp \to Z b\bar{b}$ | `p p > z b b~` | $6.993 \pm 0.003 \cdot 10^{2}$ | $^{+33.5\%}_{-24.4\%}$ | $^{+1.0\%}_{-1.4\%}$ | $1.235 \pm 0.004 \cdot 10^{3}$ | $^{+19.9\%}_{-17.4\%}$ | $^{+1.0\%}_{-1.4\%}$ |
| e.3 | $pp \to \gamma b\bar{b}$ | `p p > a b b~` | $1.731 \pm 0.001 \cdot 10^{3}$ | $^{+51.9\%}_{-34.8\%}$ | $^{+1.6\%}_{-2.1\%}$ | $4.171 \pm 0.015 \cdot 10^{3}$ | $^{+33.7\%}_{-27.1\%}$ | $^{+1.4\%}_{-1.9\%}$ |
| e.4* | $pp \to W^{\pm} b\bar{b} j$ | `p p > wpm b b~ j` | $1.861 \pm 0.003 \cdot 10^{2}$ | $^{+42.5\%}_{-27.7\%}$ | $^{+0.7\%}_{-0.7\%}$ | $3.957 \pm 0.013 \cdot 10^{2}$ | $^{+27.0\%}_{-21.0\%}$ | $^{+0.7\%}_{-0.6\%}$ |
| e.5* | $pp \to Z b\bar{b} j$ | `p p > z b b~ j` | $1.604 \pm 0.001 \cdot 10^{2}$ | $^{+42.4\%}_{-27.6\%}$ | $^{+0.9\%}_{-1.1\%}$ | $2.805 \pm 0.009 \cdot 10^{2}$ | $^{+21.0\%}_{-17.6\%}$ | $^{+0.8\%}_{-1.0\%}$ |
| e.6* | $pp \to \gamma b\bar{b} j$ | `p p > a b b~ j` | $7.812 \pm 0.017 \cdot 10^{2}$ | $^{+51.2\%}_{-32.0\%}$ | $^{+1.0\%}_{-1.5\%}$ | $1.233 \pm 0.004 \cdot 10^{3}$ | $^{+18.9\%}_{-19.9\%}$ | $^{+1.0\%}_{-1.5\%}$ |
| e.7 | $pp \to t\bar{t} W^{\pm}$ | `p p > t t~ wpm` | $3.777 \pm 0.003 \cdot 10^{-1}$ | $^{+23.9\%}_{-18.0\%}$ | $^{+2.1\%}_{-1.6\%}$ | $5.662 \pm 0.021 \cdot 10^{-1}$ | $^{+11.2\%}_{-10.6\%}$ | $^{+1.7\%}_{-1.3\%}$ |
| e.8 | $pp \to t\bar{t} Z$ | `p p > t t~ z` | $5.273 \pm 0.004 \cdot 10^{-1}$ | $^{+30.5\%}_{-21.8\%}$ | $^{+1.8\%}_{-2.1\%}$ | $7.598 \pm 0.026 \cdot 10^{-1}$ | $^{+9.7\%}_{-11.1\%}$ | $^{+1.9\%}_{-2.2\%}$ |
| e.9 | $pp \to t\bar{t} \gamma$ | `p p > t t~ a` | $1.204 \pm 0.001 \cdot 10^{0}$ | $^{+29.6\%}_{-21.3\%}$ | $^{+1.6\%}_{-1.8\%}$ | $1.744 \pm 0.005 \cdot 10^{0}$ | $^{+9.8\%}_{-11.0\%}$ | $^{+1.7\%}_{-2.0\%}$ |
| e.10* | $pp \to t\bar{t} W^{\pm} j$ | `p p > t t~ wpm j` | $2.352 \pm 0.002 \cdot 10^{-1}$ | $^{+40.9\%}_{-27.1\%}$ | $^{+1.3\%}_{-1.0\%}$ | $3.404 \pm 0.011 \cdot 10^{-1}$ | $^{+11.2\%}_{-14.0\%}$ | $^{+1.2\%}_{-0.9\%}$ |
| e.11* | $pp \to t\bar{t} Z j$ | `p p > t t~ z j` | $3.953 \pm 0.004 \cdot 10^{-1}$ | $^{+46.2\%}_{-29.5\%}$ | $^{+2.7\%}_{-3.0\%}$ | $5.074 \pm 0.016 \cdot 10^{-1}$ | $^{+7.0\%}_{-12.3\%}$ | $^{+2.5\%}_{-2.9\%}$ |
| e.12* | $pp \to t\bar{t} \gamma j$ | `p p > t t~ a j` | $8.726 \pm 0.010 \cdot 10^{-1}$ | $^{+45.4\%}_{-29.1\%}$ | $^{+2.3\%}_{-2.6\%}$ | $1.135 \pm 0.004 \cdot 10^{0}$ | $^{+7.5\%}_{-12.2\%}$ | $^{+2.2\%}_{-2.5\%}$ |
| e.13* | $pp \to t\bar{t} W^{-} W^{+}$ (4f) | `p p > t t~ w+ w-` | $6.675 \pm 0.006 \cdot 10^{-3}$ | $^{+30.9\%}_{-21.9\%}$ | $^{+2.1\%}_{-2.0\%}$ | $9.904 \pm 0.026 \cdot 10^{-3}$ | $^{+10.9\%}_{-11.8\%}$ | $^{+2.1\%}_{-2.1\%}$ |
| e.14* | $pp \to t\bar{t} W^{\pm} Z$ | `p p > t t~ wpm z` | $2.404 \pm 0.002 \cdot 10^{-3}$ | $^{+26.6\%}_{-19.6\%}$ | $^{+2.5\%}_{-1.8\%}$ | $3.525 \pm 0.010 \cdot 10^{-3}$ | $^{+10.6\%}_{-10.8\%}$ | $^{+2.3\%}_{-1.6\%}$ |
| e.15* | $pp \to t\bar{t} W^{\pm} \gamma$ | `p p > t t~ wpm a` | $2.718 \pm 0.003 \cdot 10^{-3}$ | $^{+25.4\%}_{-18.9\%}$ | $^{+2.3\%}_{-1.8\%}$ | $3.927 \pm 0.013 \cdot 10^{-3}$ | $^{+10.3\%}_{-10.4\%}$ | $^{+2.0\%}_{-1.5\%}$ |
| e.16* | $pp \to t\bar{t} Z Z$ | `p p > t t~ z z` | $1.349 \pm 0.014 \cdot 10^{-3}$ | $^{+29.3\%}_{-21.1\%}$ | $^{+1.7\%}_{-1.5\%}$ | $1.840 \pm 0.007 \cdot 10^{-3}$ | $^{+7.9\%}_{-9.9\%}$ | $^{+1.7\%}_{-1.5\%}$ |
| e.17* | $pp \to t\bar{t} Z \gamma$ | `p p > t t~ z a` | $2.548 \pm 0.003 \cdot 10^{-3}$ | $^{+30.1\%}_{-21.5\%}$ | $^{+1.7\%}_{-1.6\%}$ | $3.656 \pm 0.012 \cdot 10^{-3}$ | $^{+9.7\%}_{-11.0\%}$ | $^{+1.8\%}_{-1.9\%}$ |
| e.18* | $pp \to t\bar{t} \gamma\gamma$ | `p p > t t~ a a` | $3.272 \pm 0.006 \cdot 10^{-3}$ | $^{+28.4\%}_{-20.6\%}$ | $^{+1.3\%}_{-1.1\%}$ | $4.402 \pm 0.015 \cdot 10^{-3}$ | $^{+7.8\%}_{-9.7\%}$ | $^{+1.4\%}_{-1.4\%}$ |

[J. Alwall et al. 1405.0301]

# Automatic NLO in the SM (2014)

| | Process | Syntax | Cross section (pb) | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Single-top | | LO 13 TeV | | | NLO 13 TeV | | |
| f.1 | $pp \to tj$ (t-channel) | `p p > tt j $$ w+ w-` | $1.520 \pm 0.001 \cdot 10^{2}$ | $^{+9.4\%}_{-11.9\%}$ | $^{+0.4\%}_{-0.6\%}$ | $1.563 \pm 0.005 \cdot 10^{2}$ | $^{+1.4\%}_{-1.8\%}$ | $^{+0.4\%}_{-0.6\%}$ |
| f.2 | $pp \to t\gamma j$ (t-channel) | `p p > tt a j $$ w+ w-` | $9.956 \pm 0.014 \cdot 10^{-1}$ | $^{+6.4\%}_{-8.8\%}$ | $^{+0.9\%}_{-1.0\%}$ | $1.017 \pm 0.003 \cdot 10^{0}$ | $^{+1.3\%}_{-1.2\%}$ | $^{+0.8\%}_{-0.9\%}$ |
| f.3 | $pp \to tZj$ (t-channel) | `p p > tt z j $$ w+ w-` | $6.967 \pm 0.007 \cdot 10^{-1}$ | $^{+3.5\%}_{-5.5\%}$ | $^{+0.9\%}_{-1.0\%}$ | $6.993 \pm 0.021 \cdot 10^{-1}$ | $^{+1.6\%}_{-1.1\%}$ | $^{+0.9\%}_{-1.0\%}$ |
| f.4 | $pp \to tbj$ (t-channel) | `p p > tt bb j $$ w+ w-` | $1.003 \pm 0.000 \cdot 10^{2}$ | $^{+13.8\%}_{-11.5\%}$ | $^{+0.4\%}_{-0.5\%}$ | $1.319 \pm 0.003 \cdot 10^{2}$ | $^{+5.8\%}_{-5.2\%}$ | $^{+0.4\%}_{-0.5\%}$ |
| f.5* | $pp \to tbj\gamma$ (t-channel) | `p p > tt bb j a $$ w+ w-` | $6.293 \pm 0.006 \cdot 10^{-1}$ | $^{+16.8\%}_{-13.5\%}$ | $^{+0.8\%}_{-0.9\%}$ | $8.612 \pm 0.025 \cdot 10^{-1}$ | $^{+6.2\%}_{-6.6\%}$ | $^{+0.8\%}_{-0.9\%}$ |
| f.6* | $pp \to tbjZ$ (t-channel) | `p p > tt bb j z $$ w+ w-` | $3.934 \pm 0.002 \cdot 10^{-1}$ | $^{+18.7\%}_{-14.7\%}$ | $^{+1.0\%}_{-0.9\%}$ | $5.657 \pm 0.014 \cdot 10^{-1}$ | $^{+7.7\%}_{-7.9\%}$ | $^{+0.9\%}_{-0.9\%}$ |
| f.7 | $pp \to tb$ (s-channel) | `p p > w+ > t b~, p p > w- > t~ b` | $7.489 \pm 0.007 \cdot 10^{0}$ | $^{+3.5\%}_{-4.4\%}$ | $^{+1.9\%}_{-1.4\%}$ | $1.001 \pm 0.004 \cdot 10^{1}$ | $^{+3.7\%}_{-3.9\%}$ | $^{+1.9\%}_{-1.5\%}$ |
| f.8* | $pp \to tb\gamma$ (s-channel) | `p p > w+ > t b~ a, p p > w- > t~ b a` | $1.490 \pm 0.001 \cdot 10^{-2}$ | $^{+1.2\%}_{-1.8\%}$ | $^{+1.9\%}_{-1.5\%}$ | $1.952 \pm 0.007 \cdot 10^{-2}$ | $^{+2.6\%}_{-2.3\%}$ | $^{+1.7\%}_{-1.4\%}$ |
| f.9* | $pp \to tbZ$ (s-channel) | `p p > w+ > t b~ z, p p > w- > t~ b z` | $1.072 \pm 0.001 \cdot 10^{-2}$ | $^{+1.3\%}_{-1.5\%}$ | $^{+2.0\%}_{-1.6\%}$ | $1.539 \pm 0.005 \cdot 10^{-2}$ | $^{+3.9\%}_{-3.2\%}$ | $^{+1.9\%}_{-1.5\%}$ |

[J. Alwall et al. 1405.0301]

# Automatic NLO in the SM (2014)

| Process | | Syntax | Cross section (pb) LO 13 TeV | | Cross section (pb) NLO 13 TeV | |
|---|---|---|---|---|---|---|
| Single Higgs production | | | | | | |
| g.1 | $pp \to H$ (HEFT) | `p p > h` | $1.593 \pm 0.003 \cdot 10^{1}$ | $^{+34.8\%}_{-26.0\%}$ $^{+1.2\%}_{-1.7\%}$ | $3.261 \pm 0.010 \cdot 10^{1}$ | $^{+20.2\%}_{-17.9\%}$ $^{+1.1\%}_{-1.6\%}$ |
| g.2 | $pp \to Hj$ (HEFT) | `p p > h j` | $8.367 \pm 0.003 \cdot 10^{0}$ | $^{+39.4\%}_{-26.4\%}$ $^{+1.2\%}_{-1.4\%}$ | $1.422 \pm 0.006 \cdot 10^{1}$ | $^{+18.5\%}_{-16.6\%}$ $^{+1.1\%}_{-1.4\%}$ |
| g.3 | $pp \to Hjj$ (HEFT) | `p p > h j j` | $3.020 \pm 0.002 \cdot 10^{0}$ | $^{+59.1\%}_{-34.7\%}$ $^{+1.4\%}_{-1.7\%}$ | $5.124 \pm 0.020 \cdot 10^{0}$ | $^{+20.7\%}_{-21.0\%}$ $^{+1.3\%}_{-1.5\%}$ |
| g.4 | $pp \to Hjj$ (VBF) | `p p > h j j $$ w+ w- z` | $1.987 \pm 0.002 \cdot 10^{0}$ | $^{+1.7\%}_{-2.0\%}$ $^{+1.9\%}_{-1.4\%}$ | $1.900 \pm 0.006 \cdot 10^{0}$ | $^{+0.8\%}_{-0.9\%}$ $^{+2.0\%}_{-1.5\%}$ |
| g.5 | $pp \to Hjjj$ (VBF) | `p p > h j j j $$ w+ w- z` | $2.824 \pm 0.005 \cdot 10^{-1}$ | $^{+15.7\%}_{-12.7\%}$ $^{+1.5\%}_{-1.0\%}$ | $3.085 \pm 0.010 \cdot 10^{-1}$ | $^{+2.0\%}_{-3.0\%}$ $^{+1.5\%}_{-1.1\%}$ |
| g.6 | $pp \to HW^{\pm}$ | `p p > h wpm` | $1.195 \pm 0.002 \cdot 10^{0}$ | $^{+3.5\%}_{-4.5\%}$ $^{+1.9\%}_{-1.5\%}$ | $1.419 \pm 0.005 \cdot 10^{0}$ | $^{+2.1\%}_{-2.6\%}$ $^{+1.9\%}_{-1.4\%}$ |
| g.7 | $pp \to HW^{\pm} j$ | `p p > h wpm j` | $4.018 \pm 0.003 \cdot 10^{-1}$ | $^{+10.7\%}_{-9.3\%}$ $^{+1.2\%}_{-0.9\%}$ | $4.842 \pm 0.017 \cdot 10^{-1}$ | $^{+3.6\%}_{-3.7\%}$ $^{+1.2\%}_{-1.0\%}$ |
| g.8* | $pp \to HW^{\pm} jj$ | `p p > h wpm j j` | $1.198 \pm 0.016 \cdot 10^{-1}$ | $^{+26.1\%}_{-19.4\%}$ $^{+0.8\%}_{-0.6\%}$ | $1.574 \pm 0.014 \cdot 10^{-1}$ | $^{+5.0\%}_{-6.5\%}$ $^{+0.9\%}_{-0.6\%}$ |
| g.9 | $pp \to HZ$ | `p p > h z` | $6.468 \pm 0.008 \cdot 10^{-1}$ | $^{+3.5\%}_{-4.5\%}$ $^{+1.9\%}_{-1.4\%}$ | $7.674 \pm 0.027 \cdot 10^{-1}$ | $^{+2.0\%}_{-2.5\%}$ $^{+1.9\%}_{-1.4\%}$ |
| g.10 | $pp \to HZ j$ | `p p > h z j` | $2.225 \pm 0.001 \cdot 10^{-1}$ | $^{+10.6\%}_{-9.2\%}$ $^{+1.1\%}_{-0.8\%}$ | $2.667 \pm 0.010 \cdot 10^{-1}$ | $^{+3.5\%}_{-3.6\%}$ $^{+1.1\%}_{-0.9\%}$ |
| g.11* | $pp \to HZ jj$ | `p p > h z j j` | $7.262 \pm 0.012 \cdot 10^{-2}$ | $^{+26.2\%}_{-19.4\%}$ $^{+0.7\%}_{-0.6\%}$ | $8.753 \pm 0.037 \cdot 10^{-2}$ | $^{+4.8\%}_{-6.3\%}$ $^{+0.7\%}_{-0.6\%}$ |
| g.12* | $pp \to HW^{+}W^{-}$ (4f) | `p p > h w+ w-` | $8.325 \pm 0.139 \cdot 10^{-3}$ | $^{+0.0\%}_{-0.3\%}$ $^{+2.0\%}_{-1.6\%}$ | $1.065 \pm 0.003 \cdot 10^{-2}$ | $^{+2.5\%}_{-1.9\%}$ $^{+2.0\%}_{-1.5\%}$ |
| g.13* | $pp \to HW^{\pm}\gamma$ | `p p > h wpm a` | $2.518 \pm 0.006 \cdot 10^{-3}$ | $^{+0.7\%}_{-1.4\%}$ $^{+1.9\%}_{-1.5\%}$ | $3.309 \pm 0.011 \cdot 10^{-3}$ | $^{+2.7\%}_{-2.0\%}$ $^{+1.7\%}_{-1.4\%}$ |
| g.14* | $pp \to HZW^{\pm}$ | `p p > h z wpm` | $3.763 \pm 0.007 \cdot 10^{-3}$ | $^{+1.1\%}_{-1.5\%}$ $^{+2.0\%}_{-1.6\%}$ | $5.292 \pm 0.015 \cdot 10^{-3}$ | $^{+3.9\%}_{-3.1\%}$ $^{+1.8\%}_{-1.4\%}$ |
| g.15* | $pp \to HZZ$ | `p p > h z z` | $2.093 \pm 0.003 \cdot 10^{-3}$ | $^{+0.1\%}_{-0.6\%}$ $^{+1.9\%}_{-1.5\%}$ | $2.538 \pm 0.007 \cdot 10^{-3}$ | $^{+1.9\%}_{-1.4\%}$ $^{+2.0\%}_{-1.5\%}$ |
| g.16 | $pp \to Ht\bar{t}$ | `p p > h t t~` | $3.579 \pm 0.003 \cdot 10^{-1}$ | $^{+30.0\%}_{-21.5\%}$ $^{+1.7\%}_{-2.0\%}$ | $4.608 \pm 0.016 \cdot 10^{-1}$ | $^{+5.7\%}_{-9.0\%}$ $^{+2.0\%}_{-2.3\%}$ |
| g.17 | $pp \to Htj$ | `p p > h tt j` | $4.994 \pm 0.005 \cdot 10^{-2}$ | $^{+2.4\%}_{-4.2\%}$ $^{+1.2\%}_{-1.3\%}$ | $6.328 \pm 0.022 \cdot 10^{-2}$ | $^{+2.9\%}_{-1.8\%}$ $^{+1.5\%}_{-1.6\%}$ |
| g.18 | $pp \to Hb\bar{b}$ (4f) | `p p > h b b~` | $4.983 \pm 0.002 \cdot 10^{-1}$ | $^{+28.1\%}_{-21.0\%}$ $^{+1.5\%}_{-1.8\%}$ | $6.085 \pm 0.026 \cdot 10^{-1}$ | $^{+7.3\%}_{-9.6\%}$ $^{+1.6\%}_{-2.0\%}$ |
| g.19 | $pp \to Ht\bar{t}j$ | `p p > h t t~ j` | $2.674 \pm 0.041 \cdot 10^{-1}$ | $^{+45.6\%}_{-29.2\%}$ $^{+2.6\%}_{-2.9\%}$ | $3.244 \pm 0.025 \cdot 10^{-1}$ | $^{+3.5\%}_{-8.7\%}$ $^{+2.5\%}_{-2.9\%}$ |
| g.20* | $pp \to Hb\bar{b}j$ (4f) | `p p > h b b~ j` | $7.367 \pm 0.002 \cdot 10^{-2}$ | $^{+45.6\%}_{-29.1\%}$ $^{+1.8\%}_{-2.1\%}$ | $9.034 \pm 0.032 \cdot 10^{-2}$ | $^{+7.9\%}_{-11.0\%}$ $^{+1.8\%}_{-2.2\%}$ |

[J. Alwall et al. 1405.0301]

# Automatic NLO in the SM (2014)

| | Process | Syntax | Cross section (pb) | | | | | |
|---|---|---|---|---|---|---|---|---|
| Multiple Higgs production | | | LO 13 TeV | | | NLO 13 TeV | | |
| h.1 | $pp \to HH$ (Loop improved) | `p p > h h` | $1.772 \pm 0.006 \cdot 10^{-2}$ | $^{+29.5\%}_{-21.4\%}$ | $^{+2.1\%}_{-2.6\%}$ | $2.763 \pm 0.008 \cdot 10^{-2}$ | $^{+11.4\%}_{-11.8\%}$ | $^{+2.1\%}_{-2.6\%}$ |
| h.2 | $pp \to HHjj$ (VBF) | `p p > h h j j $$ w+ w- z` | $6.503 \pm 0.019 \cdot 10^{-4}$ | $^{+7.2\%}_{-6.4\%}$ | $^{+2.3\%}_{-1.6\%}$ | $6.820 \pm 0.026 \cdot 10^{-4}$ | $^{+0.8\%}_{-1.0\%}$ | $^{+2.4\%}_{-1.7\%}$ |
| h.3 | $pp \to HHW^{\pm}$ | `p p > h h wpm` | $4.303 \pm 0.005 \cdot 10^{-4}$ | $^{+0.9\%}_{-1.3\%}$ | $^{+2.0\%}_{-1.5\%}$ | $5.002 \pm 0.014 \cdot 10^{-4}$ | $^{+1.5\%}_{-1.2\%}$ | $^{+2.0\%}_{-1.6\%}$ |
| h.4* | $pp \to HHW^{\pm}j$ | `p p > h h wpm j` | $1.922 \pm 0.002 \cdot 10^{-4}$ | $^{+14.2\%}_{-11.7\%}$ | $^{+1.5\%}_{-1.1\%}$ | $2.218 \pm 0.009 \cdot 10^{-4}$ | $^{+2.7\%}_{-3.3\%}$ | $^{+1.6\%}_{-1.1\%}$ |
| h.5* | $pp \to HHW^{\pm}\gamma$ | `p p > h h wpm a` | $1.952 \pm 0.004 \cdot 10^{-6}$ | $^{+3.0\%}_{-3.0\%}$ | $^{+2.2\%}_{-1.6\%}$ | $2.347 \pm 0.007 \cdot 10^{-6}$ | $^{+2.4\%}_{-2.0\%}$ | $^{+2.1\%}_{-1.6\%}$ |
| h.6* | $pp \to HHHW^{\pm}$ | `p p > h h h wpm` | $3.989 \pm 0.009 \cdot 10^{-7}$ | $^{+3.9\%}_{-3.8\%}$ | $^{+2.2\%}_{-1.7\%}$ | $4.590 \pm 0.012 \cdot 10^{-7}$ | $^{+1.8\%}_{-1.7\%}$ | $^{+2.2\%}_{-1.7\%}$ |
| h.7 | $pp \to HHZ$ | `p p > h h z` | $2.701 \pm 0.007 \cdot 10^{-4}$ | $^{+0.9\%}_{-1.3\%}$ | $^{+2.0\%}_{-1.5\%}$ | $3.130 \pm 0.008 \cdot 10^{-4}$ | $^{+1.6\%}_{-1.2\%}$ | $^{+2.0\%}_{-1.5\%}$ |
| h.8* | $pp \to HHZj$ | `p p > h h z j` | $1.211 \pm 0.001 \cdot 10^{-4}$ | $^{+14.1\%}_{-11.7\%}$ | $^{+1.4\%}_{-1.1\%}$ | $1.394 \pm 0.006 \cdot 10^{-4}$ | $^{+2.7\%}_{-3.2\%}$ | $^{+1.5\%}_{-1.1\%}$ |
| h.9* | $pp \to HHZ\gamma$ | `p p > h h z a` | $1.397 \pm 0.003 \cdot 10^{-6}$ | $^{+2.4\%}_{-2.5\%}$ | $^{+2.2\%}_{-1.7\%}$ | $1.604 \pm 0.005 \cdot 10^{-6}$ | $^{+1.7\%}_{-1.4\%}$ | $^{+2.3\%}_{-1.7\%}$ |
| h.10* | $pp \to HHHZ$ | `p p > h h h z` | $2.735 \pm 0.006 \cdot 10^{-7}$ | $^{+3.9\%}_{-3.7\%}$ | $^{+2.2\%}_{-1.7\%}$ | $3.154 \pm 0.007 \cdot 10^{-7}$ | $^{+1.7\%}_{-1.6\%}$ | $^{+2.2\%}_{-1.7\%}$ |
| h.11* | $pp \to HHZZ$ | `p p > h h z z` | $2.309 \pm 0.005 \cdot 10^{-6}$ | $^{+3.9\%}_{-3.8\%}$ | $^{+2.2\%}_{-1.7\%}$ | $2.754 \pm 0.009 \cdot 10^{-6}$ | $^{+2.3\%}_{-2.0\%}$ | $^{+2.3\%}_{-1.7\%}$ |
| h.12* | $pp \to HHZW^{\pm}$ | `p p > h h z wpm` | $3.708 \pm 0.013 \cdot 10^{-6}$ | $^{+4.8\%}_{-4.5\%}$ | $^{+2.3\%}_{-1.7\%}$ | $4.904 \pm 0.029 \cdot 10^{-6}$ | $^{+3.7\%}_{-3.2\%}$ | $^{+2.2\%}_{-1.6\%}$ |
| h.13* | $pp \to HHW^{+}W^{-}$ (4f) | `p p > h h w+ w-` | $7.524 \pm 0.070 \cdot 10^{-6}$ | $^{+3.5\%}_{-3.4\%}$ | $^{+2.3\%}_{-1.7\%}$ | $9.268 \pm 0.030 \cdot 10^{-6}$ | $^{+2.3\%}_{-2.1\%}$ | $^{+2.3\%}_{-1.7\%}$ |
| h.14 | $pp \to HHt\bar{t}$ | `p p > h h t t~` | $6.756 \pm 0.007 \cdot 10^{-4}$ | $^{+30.2\%}_{-21.6\%}$ | $^{+1.8\%}_{-1.8\%}$ | $7.301 \pm 0.024 \cdot 10^{-4}$ | $^{+1.4\%}_{-5.7\%}$ | $^{+2.2\%}_{-2.3\%}$ |
| h.15 | $pp \to HHtj$ | `p p > h h tt j` | $1.844 \pm 0.008 \cdot 10^{-5}$ | $^{+0.0\%}_{-0.6\%}$ | $^{+1.8\%}_{-1.8\%}$ | $2.444 \pm 0.009 \cdot 10^{-5}$ | $^{+4.5\%}_{-3.1\%}$ | $^{+2.8\%}_{-3.0\%}$ |

[J. Alwall et al. 1405.0301]

# Automatic NLO in the SM (2014)

| Process | | Syntax | Cross section (pb) LO 1 TeV | | NLO 1 TeV | |
|---|---|---|---|---|---|---|
| Heavy quarks and jets | | | | | | |
| i.1 | $e^+e^- \to jj$ | `e+ e- > j j` | $6.223 \pm 0.005 \cdot 10^{-1}$ | $^{+0.0\%}_{-0.0\%}$ | $6.389 \pm 0.013 \cdot 10^{-1}$ | $^{+0.2\%}_{-0.2\%}$ |
| i.2 | $e^+e^- \to jjj$ | `e+ e- > j j j` | $3.401 \pm 0.002 \cdot 10^{-1}$ | $^{+9.6\%}_{-8.0\%}$ | $3.166 \pm 0.019 \cdot 10^{-1}$ | $^{+0.2\%}_{-2.1\%}$ |
| i.3 | $e^+e^- \to jjjj$ | `e+ e- > j j j j` | $1.047 \pm 0.001 \cdot 10^{-1}$ | $^{+20.0\%}_{-15.3\%}$ | $1.090 \pm 0.006 \cdot 10^{-1}$ | $^{+0.0\%}_{-2.8\%}$ |
| i.4 | $e^+e^- \to jjjjj$ | `e+ e- > j j j j j` | $2.211 \pm 0.006 \cdot 10^{-2}$ | $^{+31.4\%}_{-22.0\%}$ | $2.771 \pm 0.021 \cdot 10^{-2}$ | $^{+4.4\%}_{-8.6\%}$ |
| i.5 | $e^+e^- \to t\bar{t}$ | `e+ e- > t t~` | $1.662 \pm 0.002 \cdot 10^{-1}$ | $^{+0.0\%}_{-0.0\%}$ | $1.745 \pm 0.006 \cdot 10^{-1}$ | $^{+0.4\%}_{-0.4\%}$ |
| i.6 | $e^+e^- \to t\bar{t}j$ | `e+ e- > t t~ j` | $4.813 \pm 0.005 \cdot 10^{-2}$ | $^{+9.3\%}_{-7.8\%}$ | $5.276 \pm 0.022 \cdot 10^{-2}$ | $^{+1.3\%}_{-2.1\%}$ |
| i.7* | $e^+e^- \to t\bar{t}jj$ | `e+ e- > t t~ j j` | $8.614 \pm 0.009 \cdot 10^{-3}$ | $^{+19.4\%}_{-15.0\%}$ | $1.094 \pm 0.005 \cdot 10^{-2}$ | $^{+5.0\%}_{-6.3\%}$ |
| i.8* | $e^+e^- \to t\bar{t}jjj$ | `e+ e- > t t~ j j j` | $1.044 \pm 0.002 \cdot 10^{-3}$ | $^{+30.5\%}_{-21.6\%}$ | $1.546 \pm 0.010 \cdot 10^{-3}$ | $^{+10.6\%}_{-11.6\%}$ |
| i.9* | $e^+e^- \to t\bar{t}t\bar{t}$ | `e+ e- > t t~ t t~` | $6.456 \pm 0.016 \cdot 10^{-7}$ | $^{+19.1\%}_{-14.8\%}$ | $1.221 \pm 0.005 \cdot 10^{-6}$ | $^{+13.2\%}_{-11.2\%}$ |
| i.10* | $e^+e^- \to t\bar{t}t\bar{t}j$ | `e+ e- > t t~ t t~ j` | $2.719 \pm 0.005 \cdot 10^{-8}$ | $^{+29.9\%}_{-21.3\%}$ | $5.338 \pm 0.027 \cdot 10^{-8}$ | $^{+18.3\%}_{-15.4\%}$ |
| i.11 | $e^+e^- \to b\bar{b}$ (4f) | `e+ e- > b b~` | $9.198 \pm 0.004 \cdot 10^{-2}$ | $^{+0.0\%}_{-0.0\%}$ | $9.282 \pm 0.031 \cdot 10^{-2}$ | $^{+0.0\%}_{-0.0\%}$ |
| i.12 | $e^+e^- \to b\bar{b}j$ (4f) | `e+ e- > b b~ j` | $5.029 \pm 0.003 \cdot 10^{-2}$ | $^{+9.5\%}_{-8.0\%}$ | $4.826 \pm 0.026 \cdot 10^{-2}$ | $^{+0.5\%}_{-2.5\%}$ |
| i.13* | $e^+e^- \to b\bar{b}jj$ (4f) | `e+ e- > b b~ j j` | $1.621 \pm 0.001 \cdot 10^{-2}$ | $^{+20.0\%}_{-15.3\%}$ | $1.817 \pm 0.009 \cdot 10^{-2}$ | $^{+0.0\%}_{-3.1\%}$ |
| i.14* | $e^+e^- \to b\bar{b}jjj$ (4f) | `e+ e- > b b~ j j j` | $3.641 \pm 0.009 \cdot 10^{-3}$ | $^{+31.4\%}_{-22.1\%}$ | $4.936 \pm 0.038 \cdot 10^{-3}$ | $^{+4.8\%}_{-8.9\%}$ |
| i.15* | $e^+e^- \to b\bar{b}b\bar{b}$ (4f) | `e+ e- > b b~ b b~` | $1.644 \pm 0.003 \cdot 10^{-4}$ | $^{+19.9\%}_{-15.3\%}$ | $3.601 \pm 0.017 \cdot 10^{-4}$ | $^{+15.2\%}_{-12.5\%}$ |
| i.16* | $e^+e^- \to b\bar{b}b\bar{b}j$ (4f) | `e+ e- > b b~ b b~ j` | $7.660 \pm 0.022 \cdot 10^{-5}$ | $^{+31.3\%}_{-22.0\%}$ | $1.537 \pm 0.011 \cdot 10^{-4}$ | $^{+17.9\%}_{-15.3\%}$ |
| i.17* | $e^+e^- \to t\bar{t}b\bar{b}$ (4f) | `e+ e- > t t~ b b~` | $1.819 \pm 0.003 \cdot 10^{-4}$ | $^{+19.5\%}_{-15.0\%}$ | $2.923 \pm 0.011 \cdot 10^{-4}$ | $^{+9.2\%}_{-8.9\%}$ |
| i.18* | $e^+e^- \to t\bar{t}b\bar{b}j$ (4f) | `e+ e- > t t~ b b~ j` | $4.045 \pm 0.011 \cdot 10^{-5}$ | $^{+30.5\%}_{-21.6\%}$ | $7.049 \pm 0.052 \cdot 10^{-5}$ | $^{+13.7\%}_{-13.1\%}$ |

[J. Alwall et al. 1405.0301]

# Automatic NLO in the SM (2014)

| Process | | Syntax | Cross section (pb) | | | |
|---|---|---|---|---|---|---|
| Top quarks +bosons | | | LO 1 TeV | | NLO 1 TeV | |
| j.1 | $e^+e^- \to t\bar{t}H$ | `e+ e- > t t~ h` | $2.018 \pm 0.003 \cdot 10^{-3}$ | $^{+0.0\%}_{-0.0\%}$ | $1.911 \pm 0.006 \cdot 10^{-3}$ | $^{+0.4\%}_{-0.5\%}$ |
| j.2* | $e^+e^- \to t\bar{t}Hj$ | `e+ e- > t t~ h j` | $2.533 \pm 0.003 \cdot 10^{-4}$ | $^{+9.2\%}_{-7.8\%}$ | $2.658 \pm 0.009 \cdot 10^{-4}$ | $^{+0.5\%}_{-1.5\%}$ |
| j.3* | $e^+e^- \to t\bar{t}Hjj$ | `e+ e- > t t~ h j j` | $2.663 \pm 0.004 \cdot 10^{-5}$ | $^{+19.3\%}_{-14.9\%}$ | $3.278 \pm 0.017 \cdot 10^{-5}$ | $^{+4.0\%}_{-5.7\%}$ |
| j.4* | $e^+e^- \to t\bar{t}\gamma$ | `e+ e- > t t~ a` | $1.270 \pm 0.002 \cdot 10^{-2}$ | $^{+0.0\%}_{-0.0\%}$ | $1.335 \pm 0.004 \cdot 10^{-2}$ | $^{+0.5\%}_{-0.4\%}$ |
| j.5* | $e^+e^- \to t\bar{t}\gamma j$ | `e+ e- > t t~ a j` | $2.355 \pm 0.002 \cdot 10^{-3}$ | $^{+9.3\%}_{-7.9\%}$ | $2.617 \pm 0.010 \cdot 10^{-3}$ | $^{+1.6\%}_{-2.4\%}$ |
| j.6* | $e^+e^- \to t\bar{t}\gamma jj$ | `e+ e- > t t~ a j j` | $3.103 \pm 0.005 \cdot 10^{-4}$ | $^{+19.5\%}_{-15.0\%}$ | $4.002 \pm 0.021 \cdot 10^{-4}$ | $^{+5.4\%}_{-6.6\%}$ |
| j.7* | $e^+e^- \to t\bar{t}Z$ | `e+ e- > t t~ z` | $4.642 \pm 0.006 \cdot 10^{-3}$ | $^{+0.0\%}_{-0.0\%}$ | $4.949 \pm 0.014 \cdot 10^{-3}$ | $^{+0.6\%}_{-0.5\%}$ |
| j.8* | $e^+e^- \to t\bar{t}Zj$ | `e+ e- > t t~ z j` | $6.059 \pm 0.006 \cdot 10^{-4}$ | $^{+9.3\%}_{-7.8\%}$ | $6.940 \pm 0.028 \cdot 10^{-4}$ | $^{+2.0\%}_{-2.6\%}$ |
| j.9* | $e^+e^- \to t\bar{t}Zjj$ | `e+ e- > t t~ z j j` | $6.351 \pm 0.028 \cdot 10^{-5}$ | $^{+19.4\%}_{-15.0\%}$ | $8.439 \pm 0.051 \cdot 10^{-5}$ | $^{+5.8\%}_{-6.8\%}$ |
| j.10* | $e^+e^- \to t\bar{t}W^\pm jj$ | `e+ e- > t t~ wpm j j` | $2.400 \pm 0.004 \cdot 10^{-7}$ | $^{+19.3\%}_{-14.9\%}$ | $3.723 \pm 0.012 \cdot 10^{-7}$ | $^{+9.6\%}_{-9.1\%}$ |
| j.11* | $e^+e^- \to t\bar{t}HZ$ | `e+ e- > t t~ h z` | $3.600 \pm 0.006 \cdot 10^{-5}$ | $^{+0.0\%}_{-0.0\%}$ | $3.579 \pm 0.013 \cdot 10^{-5}$ | $^{+0.1\%}_{-0.0\%}$ |
| j.12* | $e^+e^- \to t\bar{t}\gamma Z$ | `e+ e- > t t~ a z` | $2.212 \pm 0.003 \cdot 10^{-4}$ | $^{+0.0\%}_{-0.0\%}$ | $2.364 \pm 0.006 \cdot 10^{-4}$ | $^{+0.6\%}_{-0.5\%}$ |
| j.13* | $e^+e^- \to t\bar{t}\gamma H$ | `e+ e- > t t~ a h` | $9.756 \pm 0.016 \cdot 10^{-5}$ | $^{+0.0\%}_{-0.0\%}$ | $9.423 \pm 0.032 \cdot 10^{-5}$ | $^{+0.3\%}_{-0.4\%}$ |
| j.14* | $e^+e^- \to t\bar{t}\gamma\gamma$ | `e+ e- > t t~ a a` | $3.650 \pm 0.008 \cdot 10^{-4}$ | $^{+0.0\%}_{-0.0\%}$ | $3.833 \pm 0.013 \cdot 10^{-4}$ | $^{+0.4\%}_{-0.4\%}$ |
| j.15* | $e^+e^- \to t\bar{t}ZZ$ | `e+ e- > t t~ z z` | $3.788 \pm 0.004 \cdot 10^{-5}$ | $^{+0.0\%}_{-0.0\%}$ | $4.007 \pm 0.013 \cdot 10^{-5}$ | $^{+0.5\%}_{-0.5\%}$ |
| j.16* | $e^+e^- \to t\bar{t}HH$ | `e+ e- > t t~ h h` | $1.358 \pm 0.001 \cdot 10^{-5}$ | $^{+0.0\%}_{-0.0\%}$ | $1.206 \pm 0.003 \cdot 10^{-5}$ | $^{+0.9\%}_{-1.1\%}$ |
| j.17* | $e^+e^- \to t\bar{t}W^+W^-$ | `e+ e- > t t~ w+ w-` | $1.372 \pm 0.003 \cdot 10^{-4}$ | $^{+0.0\%}_{-0.0\%}$ | $1.540 \pm 0.006 \cdot 10^{-4}$ | $^{+1.0\%}_{-0.9\%}$ |

# More complicated processes....

- More complicated one-loop matrix elements can be generated, and computed for a single phase space point.
  - Use MadLoop standalone mode, i.e. [virt= <>]
  - Can easily create a ML dynamic library to interface to other Monte-Carlo generator (as it is done in a still private plugin to Sherpa).
  - Being fully numerical, MadLoop generation time is not prohibitive.

| Process | $t_{generation}$ | $t_{run}$ / PS / hel. conf. | $n_{loops}$ \| $n_{loop_groups}$ |
|---|---|---|---|
| `g g → d d~ b b~ t t~ [virt=QCD]` | 15 h | 18.6 s | 5'4614 \| 8'190 |
| `u u~ → d d~ t t~ [virt=QCD QED]` | 28 min | 895 ms | 10'947 \| 811 |
| `u d~ → d d~ W+ Z H [virt=QCD QED]` | 25 h | 26.4 s | 187'138 \| 8'098 |

Details in 1405.0301

- No reason not to cross-check alternative computations of loop ME's vs MadLoop

# HOW IT **DOES** IT

# What does MadLoop really compute?

$$\mathcal{A}_{\mathrm{U}}^{(n,1)}\mathcal{A}^{(n,0)\star} = \sum_{\text{colour}}\sum_{h}\left(\sum_{l}\lambda_l^{(1)}\int d^d\bar{\ell}\,\frac{\mathcal{N}_{h,l}(\ell)}{\prod_{i=0}^{m_l-1}\bar{D}_{i,l}}\right)\left(\sum_{b}\lambda_b^{(0)}\mathcal{B}_{h,b}\right)^{\star}$$

# What does MadLoop really compute?

$$\mathcal{A}_{\mathrm{U}}^{(n,1)}\mathcal{A}^{(n,0)\star} = \sum_{\text{colour}}\sum_{h}\left(\sum_{l}\lambda_l^{(1)}\int d^d\bar{\ell}\,\frac{\mathcal{N}_{h,l}(\ell)}{\prod_{i=0}^{m_l-1}\bar{D}_{i,l}} + \sum_{l} R_{2,h,l}\right)\left(\sum_{b}\lambda_b^{(0)}\mathcal{B}_{h,b}\right)^{\star}$$

# What does MadLoop really compute?

$$\mathcal{A}_{\mathrm{U}}^{(n,1)}\mathcal{A}^{(n,0)\star}|_{\mathrm{non}-R_2} = \sum_{\mathrm{colour}}\sum_{h}\left(\sum_{l}\lambda_l^{(1)}\int d^d\bar{\ell}\,\frac{\mathcal{N}_{h,l}(\ell)}{\prod_{i=0}^{m_l-1}\bar{D}_{i,l}}\right)\left(\sum_{b}\lambda_b^{(0)}\mathcal{B}_{h,b}\right)^{\star}$$

# What does MadLoop really compute?

$$\mathcal{A}_{\mathrm{U}}^{(n,1)}\mathcal{A}^{(n,0)\star}|_{\mathrm{non}-R_2} = \sum_{\mathrm{colour}}\sum_{h}\left(\sum_{l}\lambda_l^{(1)}\int d^d\bar{\ell}\,\frac{\mathcal{N}_{h,l}(\ell)}{\prod_{i=0}^{m_l-1}\bar{D}_{i,l}}\right)\left(\sum_{b}\lambda_b^{(0)}\mathcal{B}_{h,b}\right)^{\star}$$

$$\Downarrow$$

$$\mathcal{A}_{\mathrm{U}}^{(n,1)}\mathcal{A}^{(n,0)\star}\Big|_{\mathrm{non}-R_2} = \sum_{h}\sum_{l}\sum_{b}\mathrm{Red}\left[\int d^d\bar{\ell}\,\frac{\mathcal{N}_{h,l}(\ell)}{\prod_{i=0}^{m_l-1}\bar{D}_{i,l}}\right]\Lambda_{lb}\,\mathcal{B}_{h,b}^{\star}\,,\;\;\Lambda_{lb} = \sum_{\mathrm{colour}}\lambda_l^{(1)}\lambda_b^{(0)\star}$$

# What does MadLoop really compute?

$$\mathcal{A}_{\mathrm{U}}^{(n,1)}\mathcal{A}^{(n,0)\star}|_{\mathrm{non}-R_2} = \sum_{\mathrm{colour}}\sum_{h}\left(\sum_{l}\lambda_l^{(1)}\int d^d\bar{\ell}\,\frac{\mathcal{N}_{h,l}(\ell)}{\prod_{i=0}^{m_l-1}\bar{D}_{i,l}}\right)\left(\sum_{b}\lambda_b^{(0)}\mathcal{B}_{h,b}\right)^{\star}$$

$$\Downarrow$$

$$\mathcal{A}_{\mathrm{U}}^{(n,1)}\mathcal{A}^{(n,0)\star}\Big|_{\mathrm{non}-R_2} = \sum_{h}\sum_{l}\sum_{b}\mathrm{Red}\left[\int d^d\bar{\ell}\,\frac{\mathcal{N}_{h,l}(\ell)}{\prod_{i=0}^{m_l-1}\bar{D}_{i,l}}\right]\Lambda_{lb}\,\mathcal{B}_{h,b}^{\star}\,,\;\;\Lambda_{lb} = \sum_{\mathrm{colour}}\lambda_l^{(1)}\lambda_b^{(0)\star}$$

$$\Downarrow$$

$$\mathcal{A}_{\mathrm{U}}^{(n,1)}\mathcal{A}^{(n,0)\star}\Big|_{\mathrm{non}-R_2} = \sum_{t}\mathrm{Red}\left[\int d^d\bar{\ell}\,\frac{\sum_h\sum_{l\in t}\sum_b\mathcal{N}_{h,l}(\ell)\,\Lambda_{lb}\,\mathcal{B}_{h,b}^{\star}}{\prod_{i=0}^{m_{l_t}-1}\bar{D}_{i,l_t}}\right]$$

# What does MadLoop really compute?

$$\mathcal{A}_{\mathrm{U}}^{(n,1)}\mathcal{A}^{(n,0)\star}|_{\mathrm{non}-R_2} = \sum_{\mathrm{colour}}\sum_{h}\left(\sum_{l}\lambda_l^{(1)}\int d^d\bar{\ell}\,\frac{\mathcal{N}_{h,l}(\ell)}{\prod_{i=0}^{m_l-1}\bar{D}_{i,l}}\right)\left(\sum_{b}\lambda_b^{(0)}\mathcal{B}_{h,b}\right)^{\star}$$

$$\Downarrow$$

$$\mathcal{A}_{\mathrm{U}}^{(n,1)}\mathcal{A}^{(n,0)\star}\Big|_{\mathrm{non}-R_2} = \sum_{h}\sum_{l}\sum_{b}\mathrm{Red}\left[\int d^d\bar{\ell}\,\frac{\mathcal{N}_{h,l}(\ell)}{\prod_{i=0}^{m_l-1}\bar{D}_{i,l}}\right]\Lambda_{lb}\,\mathcal{B}^{\star}_{h,b}\,,\;\;\Lambda_{lb} = \sum_{\mathrm{colour}}\lambda_l^{(1)}\lambda_b^{(0)\star}$$

$$\Downarrow$$

$$\mathcal{A}_{\mathrm{U}}^{(n,1)}\mathcal{A}^{(n,0)\star}\Big|_{\mathrm{non}-R_2} = \sum_{t}\mathrm{Red}\left[\int d^d\bar{\ell}\,\frac{\sum_h\sum_{l\in t}\sum_b\mathcal{N}_{h,l}(\ell)\,\Lambda_{lb}\,\mathcal{B}^{\star}_{h,b}}{\prod_{i=0}^{m_{l_t}-1}\bar{D}_{i,l_t}}\right]$$

$$\Downarrow$$

OpenLoops parametrization $\quad \mathcal{N}_{h,l}(\ell) = \sum_{r=0}^{r_{\max}} C^{(r)}_{\mu_1\ldots\mu_r;h,l}\,\ell^{\mu_1}\ldots\ell^{\mu_r}$

[1111.5206]
F. Cascioli, P. Maierhöfer, S. Pozzorini

# What does MadLoop really compute?

$$\mathcal{A}_{\mathrm{U}}^{(n,1)}\mathcal{A}^{(n,0)\star}|_{\mathrm{non}-R_2} = \sum_{\mathrm{colour}}\sum_{h}\left(\sum_{l}\lambda_l^{(1)}\int d^d\bar{\ell}\,\frac{\mathcal{N}_{h,l}(\ell)}{\prod_{i=0}^{m_l-1}\bar{D}_{i,l}}\right)\left(\sum_{b}\lambda_b^{(0)}\mathcal{B}_{h,b}\right)^{\star}$$

$$\Downarrow$$

$$\mathcal{A}_{\mathrm{U}}^{(n,1)}\mathcal{A}^{(n,0)\star}\Big|_{\mathrm{non}-R_2} = \sum_{h}\sum_{l}\sum_{b}\mathrm{Red}\left[\int d^d\bar{\ell}\,\frac{\mathcal{N}_{h,l}(\ell)}{\prod_{i=0}^{m_l-1}\bar{D}_{i,l}}\right]\Lambda_{lb}\,\mathcal{B}^{\star}_{h,b}\,,\quad \Lambda_{lb} = \sum_{\mathrm{colour}}\lambda_l^{(1)}\lambda_b^{(0)\star}$$

$$\Downarrow$$

$$\mathcal{A}_{\mathrm{U}}^{(n,1)}\mathcal{A}^{(n,0)\star}\Big|_{\mathrm{non}-R_2} = \sum_{t}\mathrm{Red}\left[\int d^d\bar{\ell}\,\frac{\sum_h\sum_{l\in t}\sum_b\mathcal{N}_{h,l}(\ell)\,\Lambda_{lb}\,\mathcal{B}^{\star}_{h,b}}{\prod_{i=0}^{m_{l_t}-1}\bar{D}_{i,l_t}}\right]$$

$$\Downarrow$$

OpenLoops parametrization $\quad \mathcal{N}_{h,l}(\ell) = \sum_{r=0}^{r_{\max}} C^{(r)}_{\mu_1\ldots\mu_r;h,l}\,\ell^{\mu_1}\ldots\ell^{\mu_r}$ [1111.5206]

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↳ Red[] inputs are $\left\{\int d^d\bar{\ell}\,\frac{\ell^{\mu_1}\ldots\ell^{\mu_r}}{\prod_{i=0}^{m_{l_t}-1}\bar{D}_{i,l_t}}\,,\ \sum_h\sum_{l\in t}\sum_b C^{(r)}_{\mu_1\ldots\mu_r;h,l}\,\Lambda_{lb}\,\mathcal{B}^{\star}_{h,b}\right\}_{r=0}^{r_{\max}}.$

# How does are the loops computed

$$\left\{ \int d^d\bar{\ell}\, \frac{\ell^{\mu_1} \ldots \ell^{\mu_r}}{\prod_{i=0}^{m_{l_t}-1} \bar{D}_{i,l_t}} \,,\; \sum_h \sum_{l\in t} \sum_b C^{(r)}_{\mu_1\ldots\mu_r;h,l}\, \Lambda_{lb}\, \mathcal{B}^\star_{h,b} \right\}_{r=0}^{r_{\max}} .$$

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OPP as implemented in

CutTools [0711.3596, G. Ossola, C.G.Papadopoulos, R.Pittau],

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TIR as implemented in

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| Reduction technique for g g > t t~ g | Reduction time ( % relative to total time, hel summed.) |
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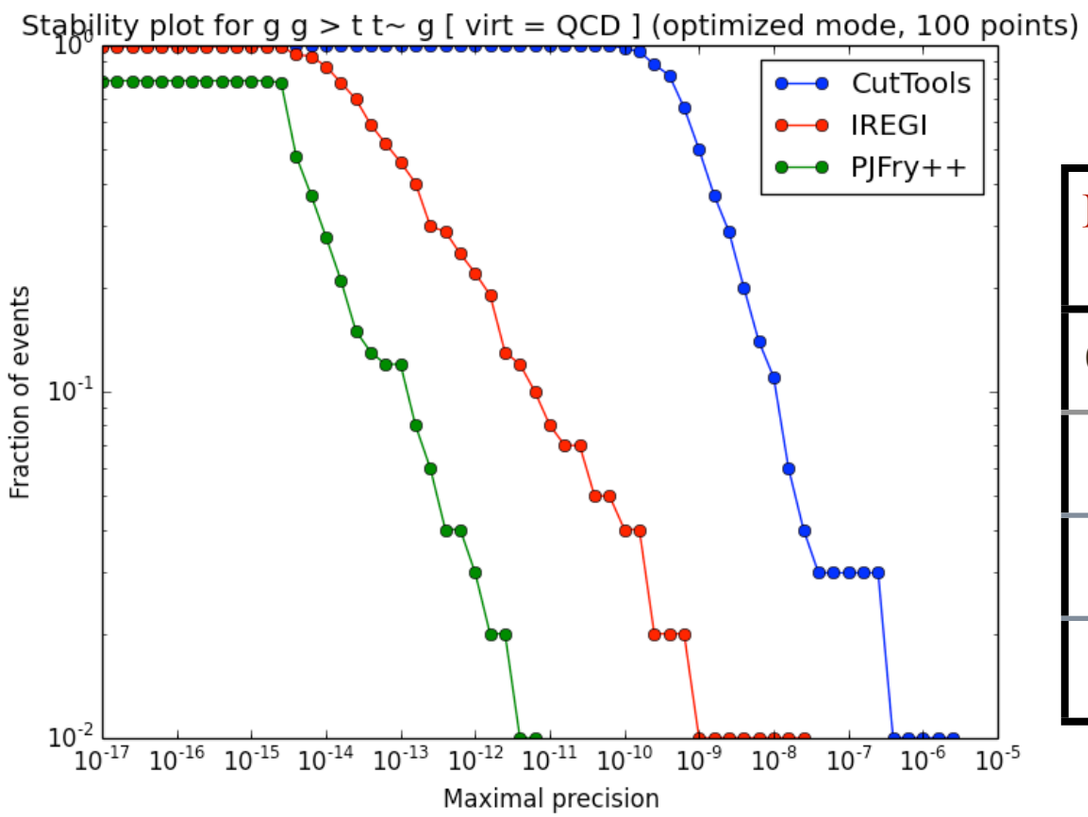


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# Open-loops

[S. Pozzorini & al. hep-ph/1111.5206]

- Lite-Motive: Be Numerical where you can and analytical where you should.

$$\mathcal{N}(l^\mu) = \sum_{r=0}^{r_{max}} C^{(r)}_{\mu_0\mu_1\cdots\mu_r} l^{\mu_0} l^{\mu_1} \cdots l^{\mu_r}$$

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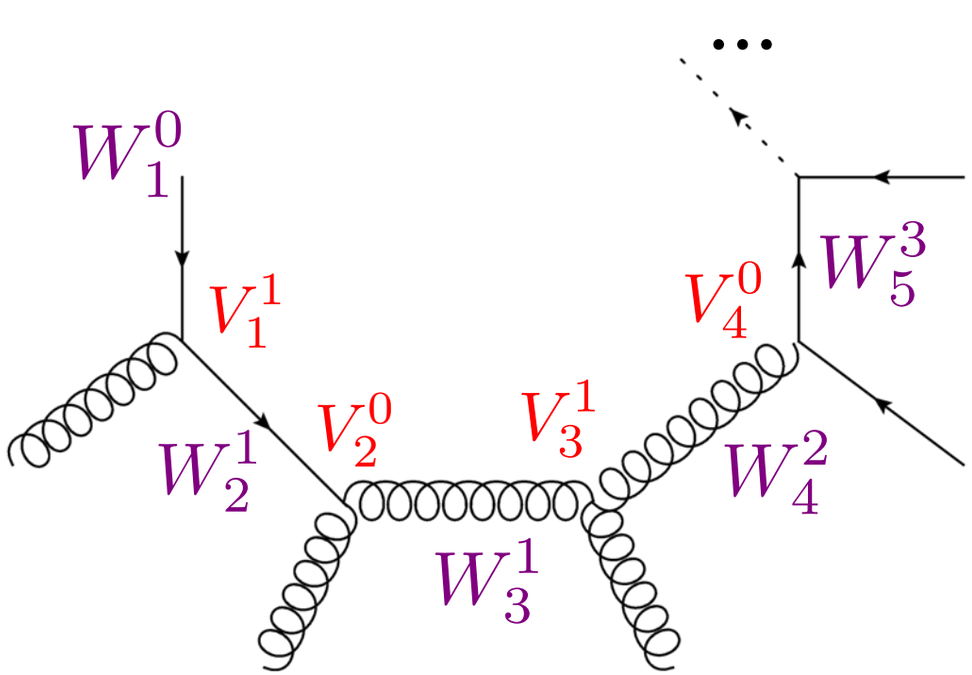

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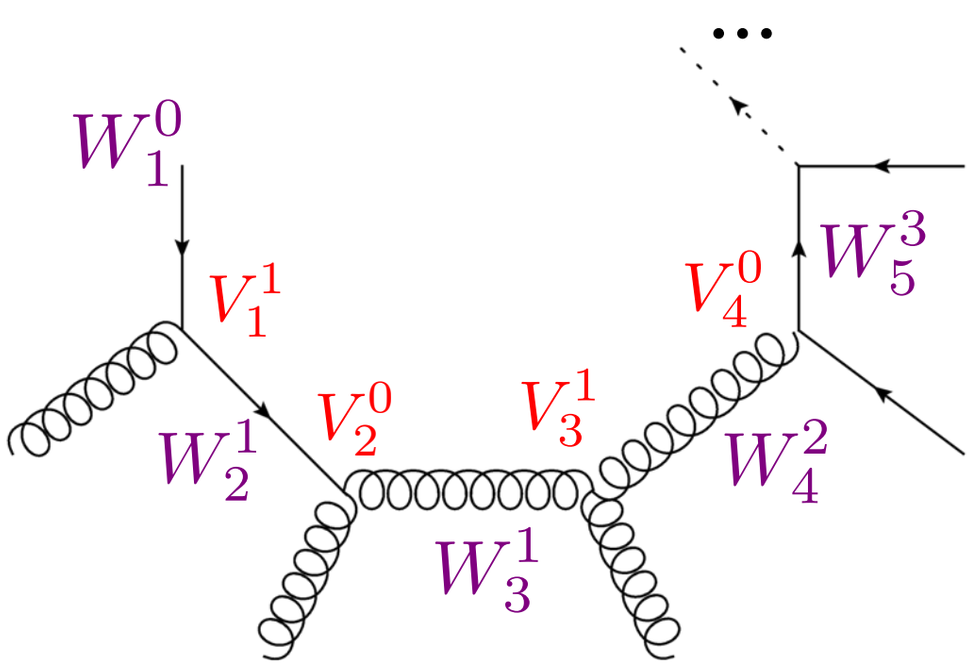


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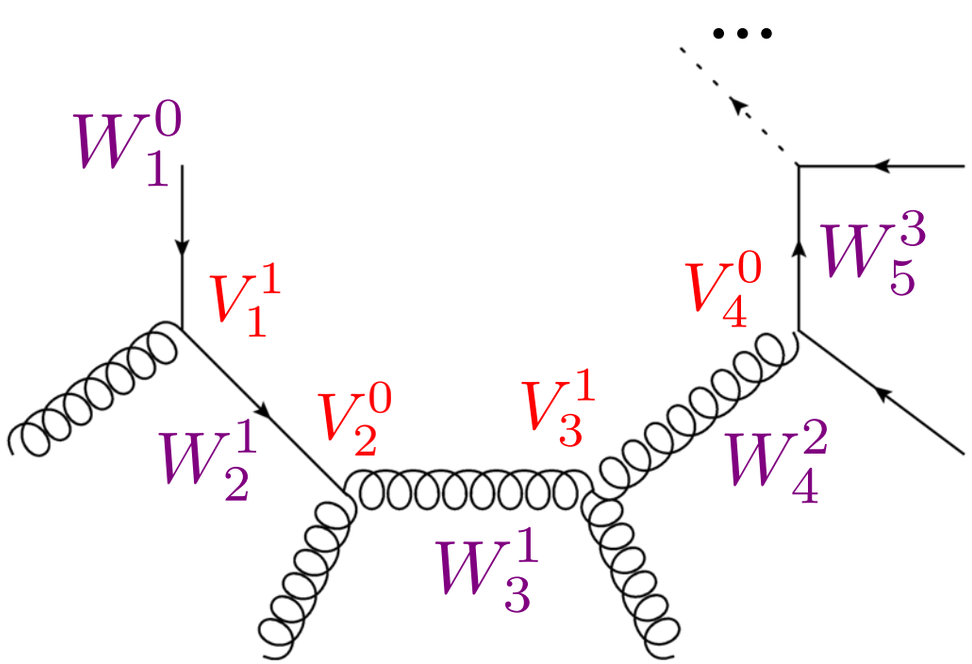


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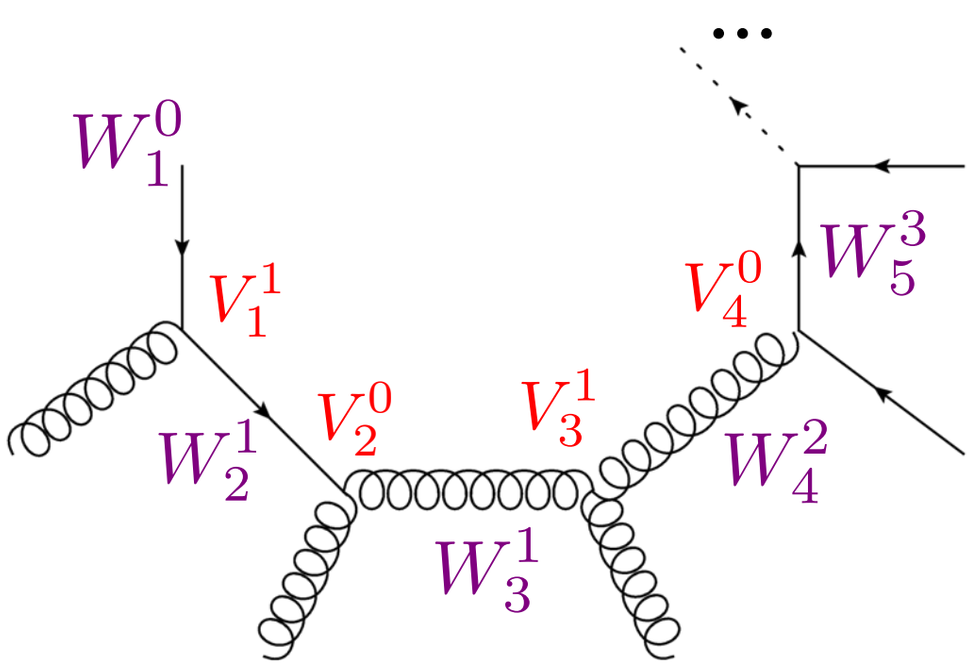


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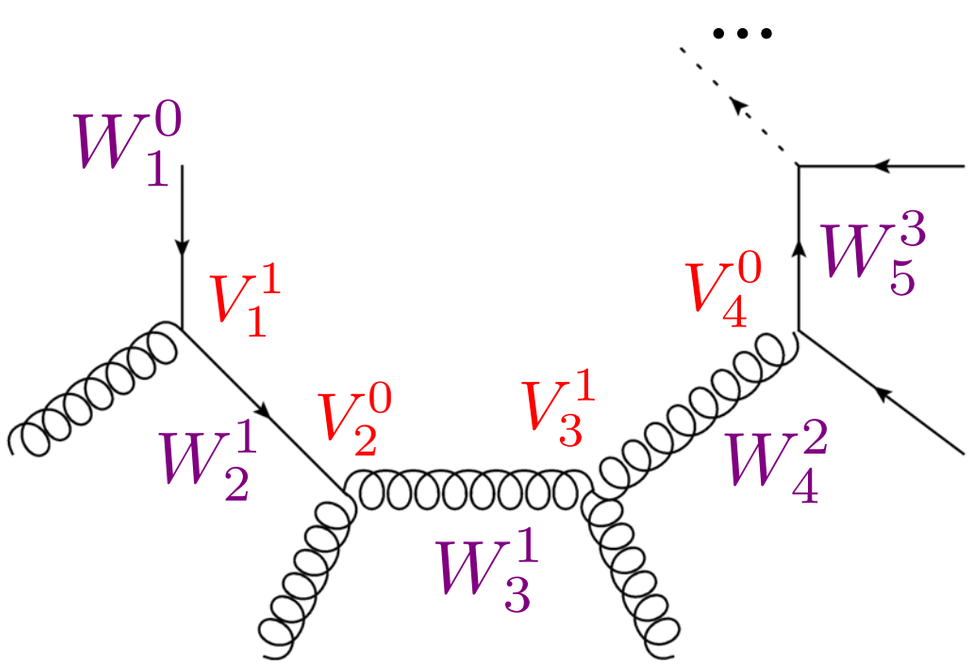


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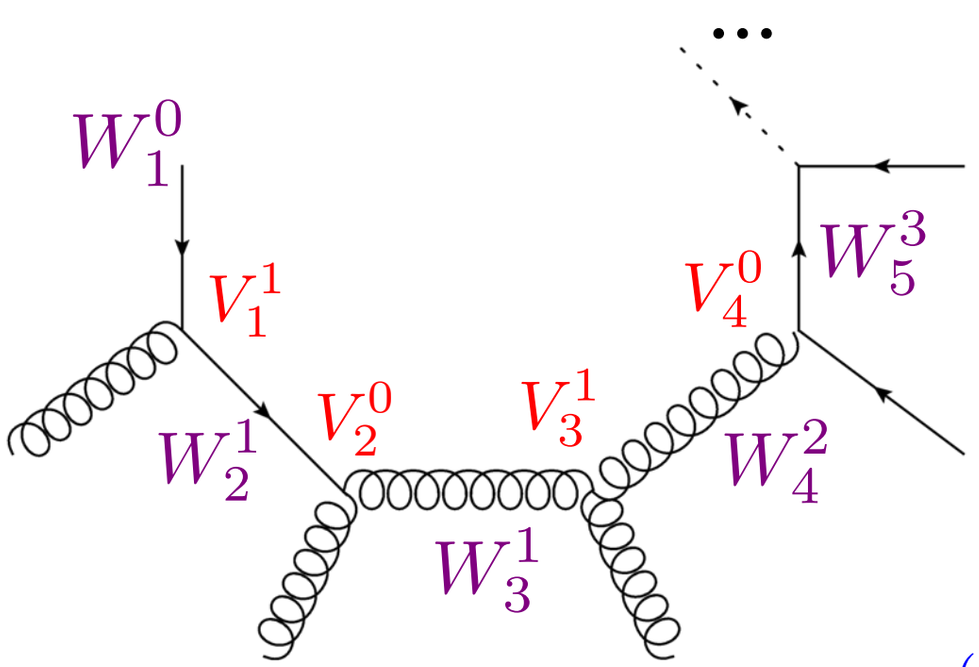


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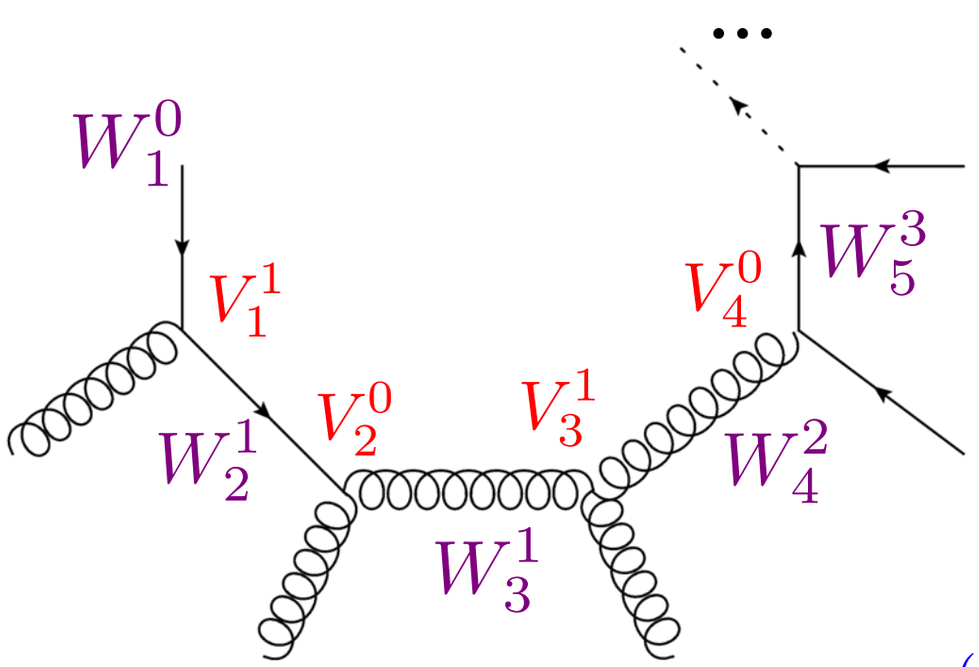


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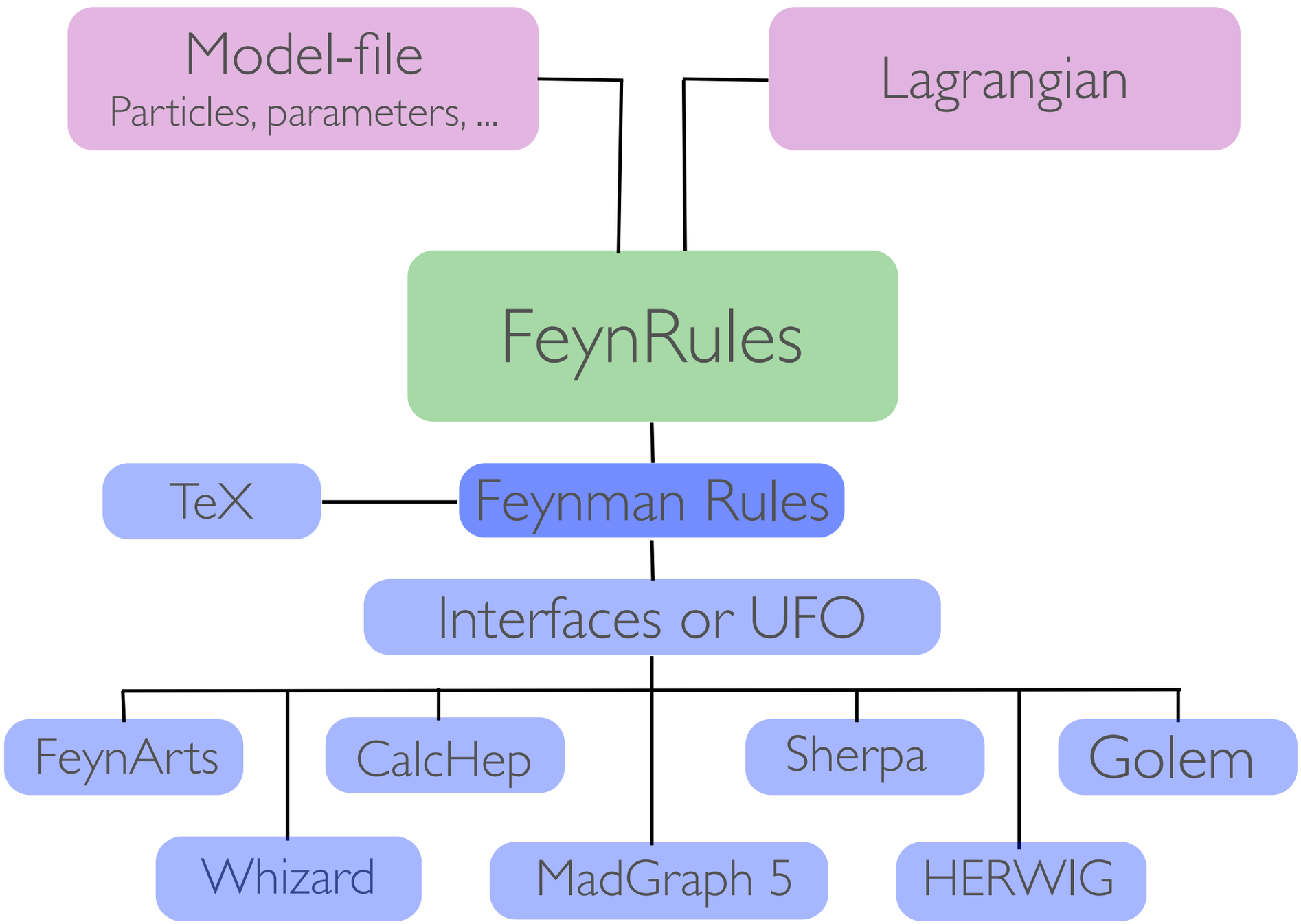
... or end of loop and $C^{(2)} = v_3^1 v_2^0 v_1^1 w_1^0, C^{(1)} = v_2^0 w_1^0 (v_3^1 v_0^1 + v_3^0 v_1^1), C^0 = \cdots$

# A NEW WEAPON FOR THE BSM CHASE.

# FeynRules @ NLO (version 2.1)

[Alloul, Christensen, Degrande, Duhr, Fuks]



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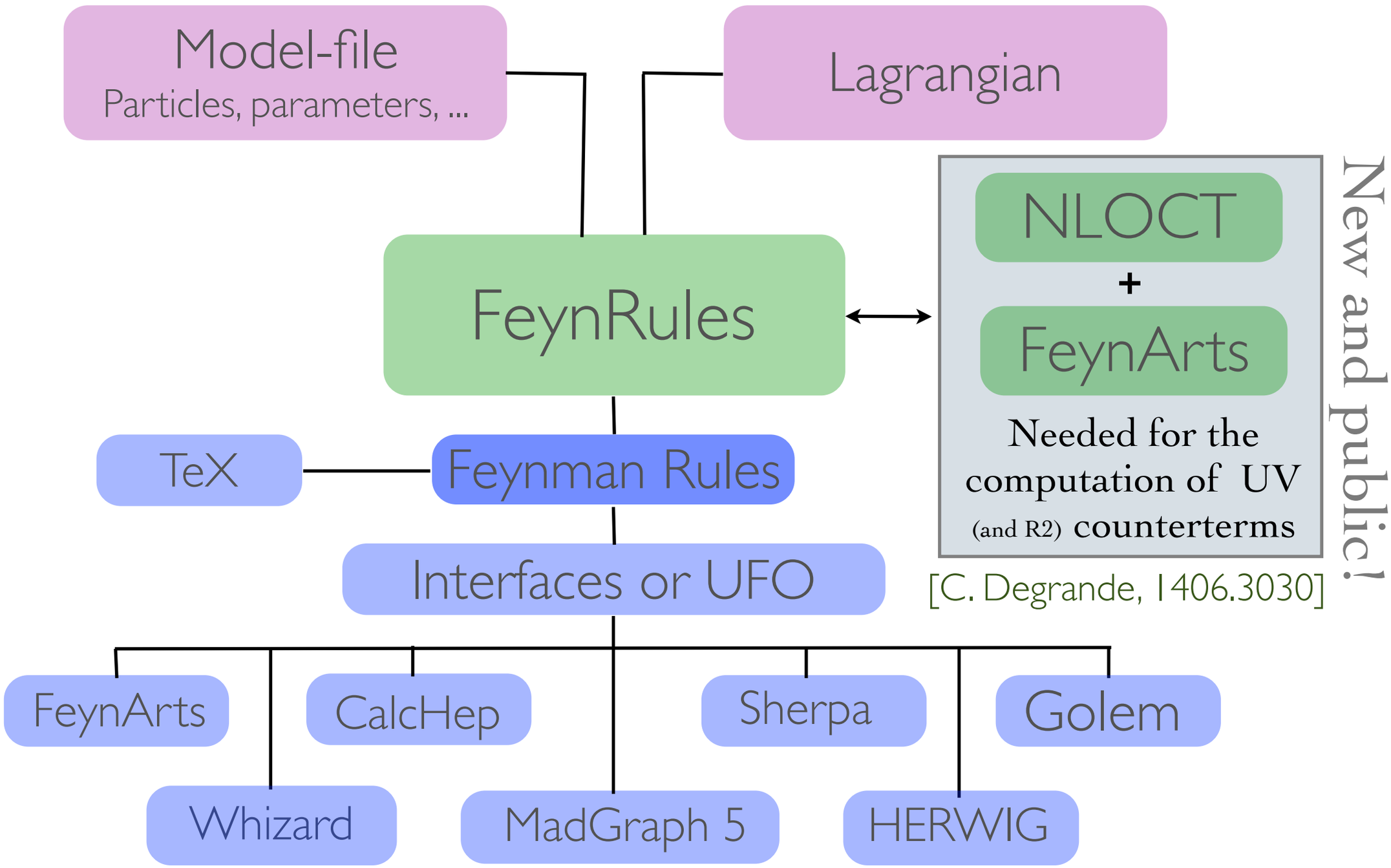

# Ex.: Renormalizing the Two Higgs Doublet Model

$$
\begin{aligned}
\delta Z_{H^+H^+} = \frac{1}{16\pi^2}\Bigg[ & -\frac{e^2 c_{2w}^2}{4c_w^2 s_w^2 m_{H^+}^4}\left(2m_{H^+}^4\left(\log\left(\frac{M_Z m_{H^+}}{\mu^2}\right)-\frac{1}{\bar{\epsilon}}\right)-m_{H^+}^2 M_Z^2\right. \\
& \left.+\left(m_{H^+}^2-M_Z^2\right)\left(\mathrm{l}\left(m_{H^+},M_Z,m_{H^+}\right)+\left(2m_{H^+}^2-M_Z^2\right)\log\left(\frac{M_Z}{m_{H^+}}\right)\right)\right) \\
& +\Bigg\{\frac{e^2 s_1^2}{4{s_w}^2 m_{H^+}^4}\Bigg(\frac{\mathrm{l}\left(M_W,m_{h_1},m_{H^+}\right)}{\left(\left(m_{h_1}-M_W\right)^2-m_{H^+}^2\right)\left(\left(m_{h_1}+M_W\right)^2-m_{H^+}^2\right)} \\
& \left(+M_W^2\left(m_{h_1}^2 m_{H^+}^2-2m_{H^+}^4+5m_{h_1}^4\right)-2\left(m_{h_1}^2-m_{H^+}^2\right)\left(m_{H^+}^4+m_{h_1}^4\right)+M_W^6\right. \\
& \left.-M_W^4\left(m_{H^+}^2+4m_{h_1}^2\right)\right)+m_{H^+}^2\left(2m_{H^+}^2\left(\frac{1}{\bar{\epsilon}}+1-\log\left(\frac{M_W m_{h_1}}{\mu^2}\right)\right)-2m_{h_1}^2+M_W^2\right) \\
& +\log\left(\frac{m_{h_1}}{M_W}\right)\left(M_W^4-3m_{h_1}^2 M_W^2+2m_{h_1}^4\right)\Bigg)+\frac{v^2\left(\lambda_4 s_1-2c_1\lambda_6\right)^2}{4m_{H^+}^4} \\
& \Bigg(\frac{M_W^4-m_{h_1}^2\left(m_{H^+}^2+2M_W^2\right)-M_W^2 m_{H^+}^2+m_{h_1}^4}{\left(m_{h_1}^4-2m_{h_1}^2\left(m_{H^+}^2+M_W^2\right)+\left(m_{H^+}^2-M_W^2\right)^2\right)}\mathrm{l}\left(M_W,m_{h_1},m_{H^+}\right) \\
& -\left(\left(m_{h_1}^2-M_W^2\right)\log\left(\frac{m_{h_1}}{M_W}\right)-m_{H^+}^2\right)\Bigg)+h_1\to h_2, c_1\to s_1, s_1\to -c_1 \\
& +h_1\to h_3, c_1\to 0, s_1\to 1\Bigg\}+\Bigg\{\frac{v^2\left(c_1\lambda_3-\lambda_7 s_1\right)^2}{m_{H^+}^4} \\
& \left(\left(\left(m_{H^+}^2-m_{h_1}^2\right)\log\left(\frac{m_{h_1}}{m_{H^+}}\right)-m_{H^+}^2\right)-\frac{\left(m_{h_1}^2-3m_{H^+}^2\right)}{4m_{H^+}^2-m_{h_1}^2}\mathrm{l}\left(m_{H^+},m_{h_1},m_{H^+}\right)\right) \\
& +h_1\to h_2, c_1\to s_1, s_1\to -c_1\Bigg\}-\sum_l G_l^2\left(-\log\left(\frac{m_{H^+}^2}{\mu^2}\right)+\frac{1}{\bar{\epsilon}}+i\pi+1\right) \\
& -3\sum_{light}\left(G_d^2+G_u^2\right)\left(-\log\left(\frac{m_{H^+}^2}{\mu^2}\right)+\frac{1}{\bar{\epsilon}}+i\pi+1\right) \\
& -\frac{12G_b G_t M_b M_t}{m_{H^+}^4}\Bigg(\frac{M_b^2\left(m_{H^+}^2+2M_t^2\right)+M_t^2 m_{H^+}^2-M_b^4-M_t^4}{-2M_b^2\left(m_{H^+}^2+M_t^2\right)+\left(m_{H^+}^2-M_t^2\right)^2+M_b^4}\mathrm{l}\left(M_t,M_b,m_{H^+}\right) \\
& -\left(m_{H^+}^2-\left(M_b^2-M_t^2\right)\left(\log\left(\frac{M_b}{M_t}\right)\right)\right)\Bigg)-\frac{3\left(G_b^2+G_t^2\right)}{m_{H^+}^4}\Bigg(\mathrm{l}\left(M_t,M_b,m_{H^+}\right) \\
& \frac{\left(M_b^2+M_t^2\right)\left(-M_b^2\left(m_{H^+}^2+2M_t^2\right)-M_t^2 m_{H^+}^2-m_{H^+}^4+M_b^4+M_t^4\right)+m_{H^+}^6}{-2M_b^2\left(m_{H^+}^2+M_t^2\right)+\left(m_{H^+}^2-M_t^2\right)^2+M_b^4} \\
& +\left(M_b^2+M_t^2\right)\left(m_{H^+}^2-\left(M_b^2-M_t^2\right)\log\left(\frac{M_b}{M_t}\right)\right)+m_{H^+}^4\left(\frac{1}{\bar{\epsilon}}+1-\log\left(\frac{M_b M_t}{\mu^2}\right)\right)\Bigg)\Bigg]
\end{aligned}
$$

$H^+$ wavefunction renormalization constant in 2HDM for QCD, QED and EW corrections...

... automation was much needed here

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& \left(\left(\left(m_{H^+}^2-m_{h_1}^2\right)\log\left(\frac{m_{h_1}}{m_{H^+}}\right)-m_{H^+}^2\right)-\frac{\left(m_{h_1}^2-3m_{H^+}^2\right)}{4m_{H^+}^2-m_{h_1}^2}\mathrm{l}\left(m_{H^+},m_{h_1},m_{H^+}\right)\right)\\
& +h_1\to h_2, c_1\to s_1, s_1\to -c_1\Bigg\}-\sum_l G_l^2\left(-\log\left(\frac{m_{H^+}^2}{\mu^2}\right)+\frac{1}{\bar\epsilon}+i\pi+1\right)\\
& -3\sum_{light}\left(G_d^2+G_u^2\right)\left(-\log\left(\frac{m_{H^+}^2}{\mu^2}\right)+\frac{1}{\bar\epsilon}+i\pi+1\right)\\
& -\frac{12G_b G_t M_b M_t}{m_{H^+}^4}\Bigg(\frac{M_b^2\left(m_{H^+}^2+2M_t^2\right)+M_t^2 m_{H^+}^2-M_b^4-M_t^4}{-2M_b^2\left(m_{H^+}^2+M_t^2\right)+\left(m_{H^+}^2-M_t^2\right)^2+M_b^4}\mathrm{l}\left(M_t,M_b,m_{H^+}\right)\\
& -\left(m_{H^+}^2-\left(M_b^2-M_t^2\right)\left(\log\left(\frac{M_b}{M_t}\right)\right)\right)\Bigg)-\frac{3\left(G_b^2+G_t^2\right)}{m_{H^+}^4}\Bigg(\mathrm{l}\left(M_t,M_b,m_{H^+}\right)\\
& \frac{\left(M_b^2+M_t^2\right)\left(-M_b^2\left(m_{H^+}^2+2M_t^2\right)-M_t^2 m_{H^+}^2-m_{H^+}^4+M_b^4+M_t^4\right)+m_{H^+}^6}{-2M_b^2\left(m_{H^+}^2+M_t^2\right)+\left(m_{H^+}^2-M_t^2\right)^2+M_b^4}\\
& +\left(M_b^2+M_t^2\right)\left(m_{H^+}^2-\left(M_b^2-M_t^2\right)\log\left(\frac{M_b}{M_t}\right)\right)+m_{H^+}^4\left(\frac{1}{\bar\epsilon}+1-\log\left(\frac{M_b M_t}{\mu^2}\right)\right)\Bigg)\Bigg]
\end{aligned}
$$

**with**

$$
\begin{aligned}
\mathrm{l}\left(m_1,m_2,m_3\right) &= \log\left(\frac{m_1^2+m_2^2-m_3^2+\sqrt{(m_1^4+(m_2^2-m_3^2)^2-2m_1^2(m_2^2+m_3^2))}}{2m_1 m_2}\right)\\
&\quad\times\sqrt{(m_1^4+(m_2^2-m_3^2)^2-2m_1^2(m_2^2+m_3^2))}.
\end{aligned}
$$

$H^+$ wavefunction renormalization constant in 2HDM for QCD, QED and EW corrections...

... automation was much needed here

# Handling BSM Models

## UFO models @ NLO

- Additional features in UFO@NLO: Specify UV and R2 vertices

### CTParameters

```
MyCTParam = CTParameter(name = 'MyCTParam',
                        type = 'real',
                        value = {-1 : 'A', 0 : 'B'}
                        texname = 'MadRules')
```

### CTVertices

```
V_GGZA = CTVertex(name = 'V_GGZA',
                  particles = [P.G, P.G, P.Z, P.A],
                  color = ['Tr(1, 2)'],
                  lorentz = [L.R2_GGVV],
                  loop_particles = [[[P.u], [P.c], [P.t]], [[P.d], [P.s], [P.b]]],
                  couplings = {(0, 0, 0) : C.R2_GGZAup, (0, 0, 1) : C.R2_GGZAdown},
                  type = 'R2')
```

BSM models under validation

- Higgs effective theory
- 2 Higgs doublet model
- SUSY
- EW/QED corrections
- Anomalous top FCNC eff. th.

### CouplingOrder

- `expansion_order`
- `perturbative_expansion`
- `hierarchy`

# A loop model database

**Available models**

| | |
|---|---|
| Standard Model | The SM implementation of FeynRules, included into the distribution of the FeynRules package. |
| Simple extensions of the SM (18) | Several models based on the SM that include one or more additional particles, like a 4th generation, a second Higgs doublet or additional colored scalars. |
| Supersymmetric Models (5) | Various supersymmetric extensions of the SM, including the MSSM, the NMSSM and many more. |
| Extra-dimensional Models (4) | Extensions of the SM including KK excitations of the SM particles. |
| Strongly coupled and effective field theories (8) | Including Technicolor, Little Higgs, as well as SM higher-dimensional operators, vector-like quarks. |
| Miscellaneous (0) | |

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| Strongly c theories ( | |
| Miscellane | |

| Model | Short Description | Contact | Status |
|---|---|---|---|
| Axigluon model | The SM plus a scalar gluon field. | S. Krastanov | **Available** |
| DY SM extension | The SM plus new spin-0, -1, and -2 bosons that contribute to Drell-Yan production of leptons at the LHC. | N. Christensen | **Available** |
| FCNC Higgs interactions | The SM plus higher-dimensional flavor changing Higgs interactions. | S. Krastanov | **Available** |
| Fourth generation model | A fourth generation model including a t' and a b' | C. Duhr | **Available** |
| General 2HDM | The most general 2HDM, including all flavor violation and mixing terms. | C. Duhr, M. Herquet | **Available** |
| Hidden Abelian Higgs Model | A Z' model where the Z' interacts with the SM through mixings, leading to very small non-SM like Z' couplings. | C. Duhr | **Available** |
| HiggsCharacterisation | The model file for the spin/parity characterisation of a 125 GeV resonance. | P. de Aquino, K. Mawatari | **Available** |
| Higgs effective theory | An add-on for the SM implementation containing the dimension 5 gluon fusion operator. | C. Duhr | **Available** |
| Higgs Effective Lagrangian | Higgs effective Lagrangian including operators up-to dimension 6. | A. Alloul, B. Fuks and V. Sanz | **Available** |
| Hill Model | A model with an unusual extension of the SM Higgs sector. | P. de Aquino, C. Duhr | **Available** |
| Inert Doublet Model | A model with an additional complex scalar SU(2)L doublet and an unbroken Z2 symmetry under which all SM particles are even while the extra doublet is odd. | A. Goudelis, B. Herrmann, O. Stal | **Available** |
| Minimal Zp models | The minimal Z' extension of the SM. | L. Basso | **Available** |
| Monotops | The SM plus monotop effective Lagrangian. | B. Fuks | **Available** |
| Sextet diquarks | The SM plus sextet diquark scalars. | J. Alwall, C. Duhr | **Available** |
| Standard model + Scalars | The SM, together with a set of singlet scalar particles coupling only to the SM Higgs, and allowing it to decay invisibly into this new scalar sector. | C. Duhr | **Available** |
| Triplet diquarks | The SM plus triplet diquark scalars. | J. Alwall, C. Duhr | **Available** |
| Type III See-Saw Model | The SM, including neutrino masses coming from a type III See-Saw mechanism. | C. Biggio, F. Bonnet | **Available** |

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| Miscellaneous (0) | |
| NLO models (100000) | SOON! |

# A look ahead...

- On-going developments :
  - Validation of automatically generated NLO UFO BSM models
  - Automated subtraction and matching for mixed corrections (loops are done)
  - More efficient MadLoop output for loop-induced processes and their automatic integration.
  - Systematic study of numerical stability with different TIR algos.
- On-going applications (just a taste)
  - Semi-automated study of EW corrections to p p → t t H
  - NLO QCD for SUSY processes with compressed spectra.

# THE END.

# Back Up slides

# MadLoop timings

| Process | $t_{pol}$ [ms] | $n_{hel}$ | $t_{unpol}$ [ms] |
|---|---|---|---|
| u u~ → t t~ | 0.52 | **3**/16 | 0.72 |
| u u~ → $w^+$ $w^-$ | 0.43 | **10**/36 | 1.00 |
| u d~ → $w^+$ g | 0.87 | **6**/24 | 1.51 |
| g g → t t~ | 2.51 | **6**/16 | 5.42 |
| u u~ → t t~ g | 7.44 | **16**/32 | 27.5 |
| u u~ → $w^+$ $w^-$ g | 9.3 | **36**/72 | 81.8 |
| u d~ → $w^+$ g g | 13.5 | **12**/48 | 36.9 |
| g g → t t~ g | 40.8 | **32**/32 | 381 |
| u u~ → t t~ g g | 142 | **32**/64 | 1010 |
| u u~ → $w^+$ $w^-$ g g | 166 | **72**/144 | 2820 |
| u d~ → $w^+$ g g g | 260 | **24**/96 | 1'310 |
| g g → t t~ g g | 826 | **64**/64 | 16'900 |
| u d~ → $w^+$ g g g g | 9400 | **48**/192 | 90'900 |

Polarized timing **competitive**

$t_{2\to2} : t_{2\to3} : t_{2\to4} \lesssim$ **1 : 40 : 800 ms**

Unpolarized timing
Good enough for **2 → 3**
and almost all **2 → 4**

Higher multiplicity
**2 → 5** generation feasible

But computation relatively slow, so only useful to cross-check other codes

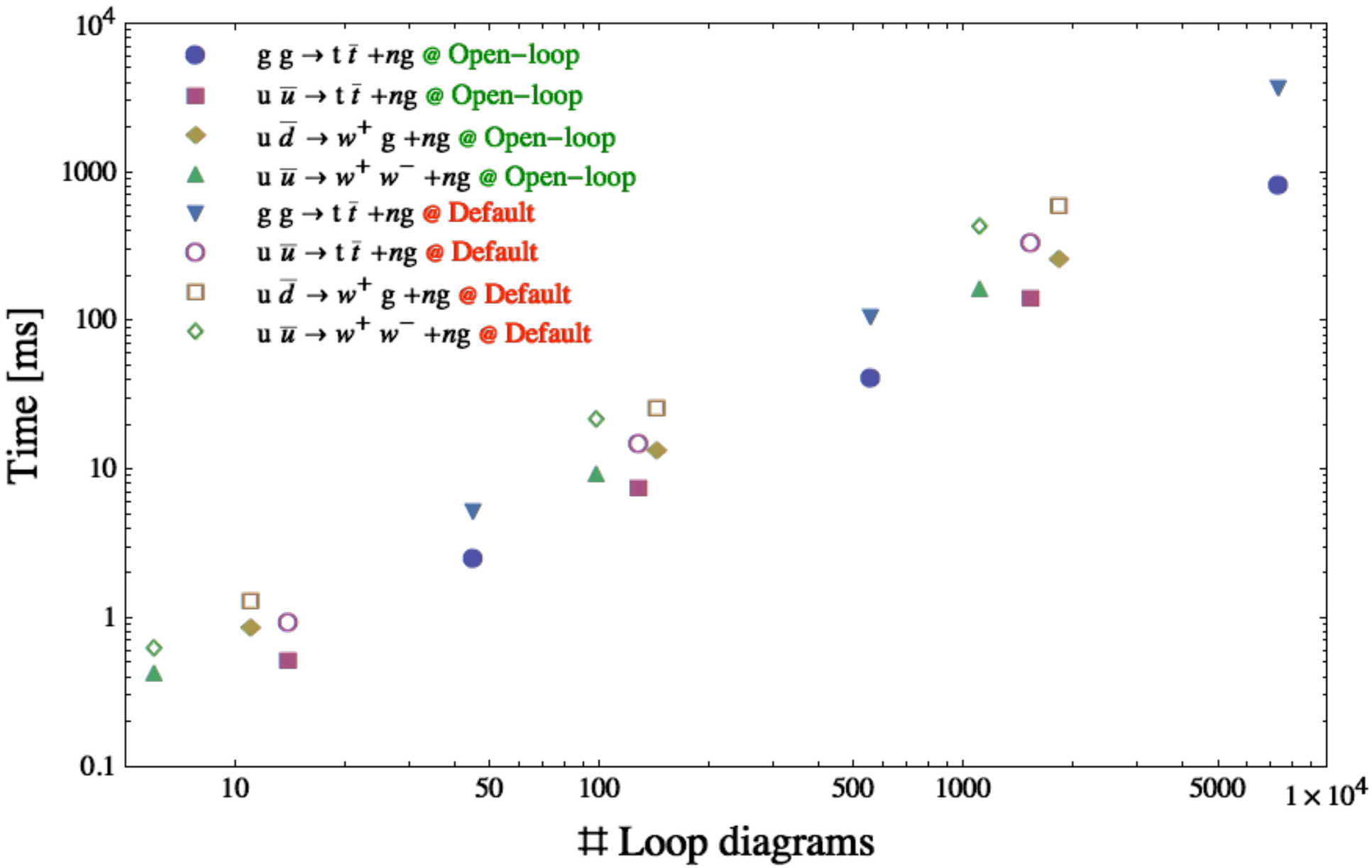
(Ex. gg→gggg successfully cross-checked vs NJet[S. Badger, V. Yundin])

# Timing of the OpenLoops coefficients computation

| Process | unpol $t_{coef}$ / $t_{tot}$ | pol $t_{coef}$ / $t_{tot}$ | $n_{loops}$ / $n_{loop_groups}$ |
|---|---|---|---|
| u u~ → t t~ | 42% | 20% | 8 / 14 |
| u u~ → $w^+$ $w^-$ | 69% | 21% | 5 / 6 |
| u d~ → $w^+$ g | 52% | 16% | 9 / 11 |
| g g → t t~ | 66% | 25% | 26 / 45 |
| u u~ → t t~ g | 78% | 18% | 54 / 128 |
| u u~ → $w^+$ $w^-$ g | 91% | 24% | 40 / 98 |
| u d~ → $w^+$ g g | 69% | 17% | 61 / 144 |
| g g → t t~ g | 92% | 29% | 164 / 556 |
| u u~ → t t~ g g | 88% | 22% | 374 / 1530 |
| u u~ → $w^+$ $w^-$ g g | 95% | 25% | 260 / 1108 |
| u d~ → $w^+$ g g g | 84% | 20% | 405 / 1827 |
| g g → t t~ g g | 97% | 35% | 1168 / 7356 |
| u d~ → $w^+$ g g g g | 94% | 21% | 3255 / 25666 |

# Default vs optimized timings

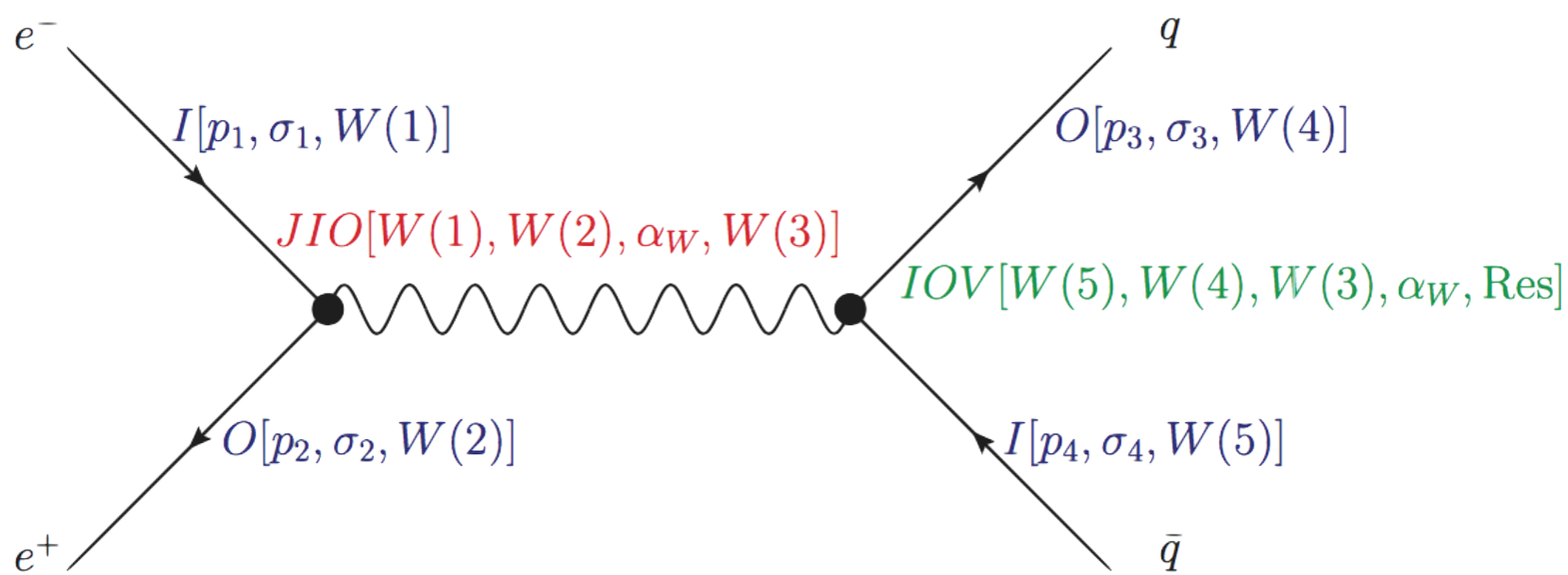
MadLoop5 opt vs default polarized eval. time per PS point



# A basic reminder

## The evolutive way of computing tree-diagrams

- First generates all tree-level Feynman Diagrams
- Compute the amplitude of each diagram using a chain of calls to HELAS subroutines

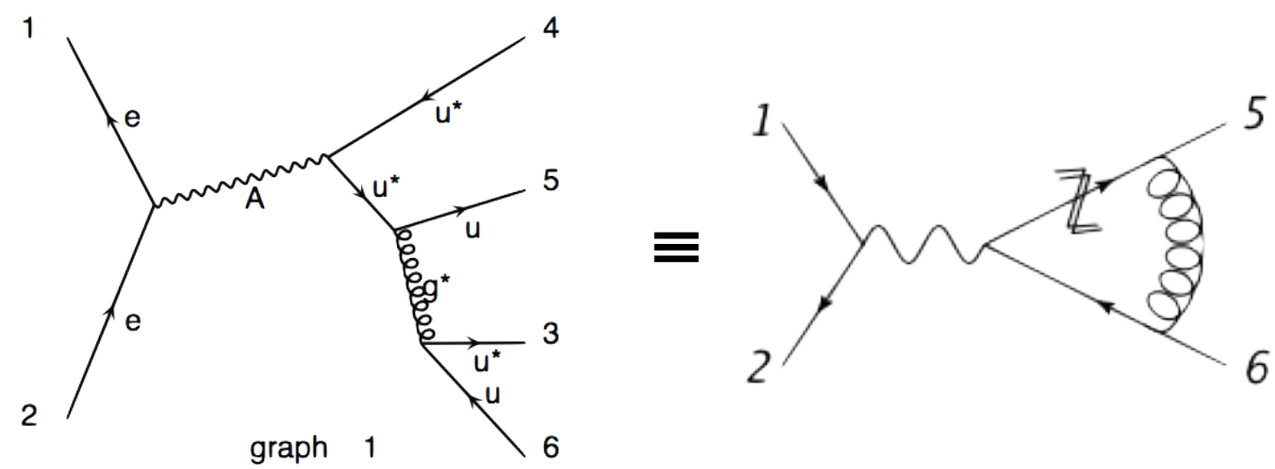



- Finally square all the related amplitude with their right color factors to construct the full LO amplitude

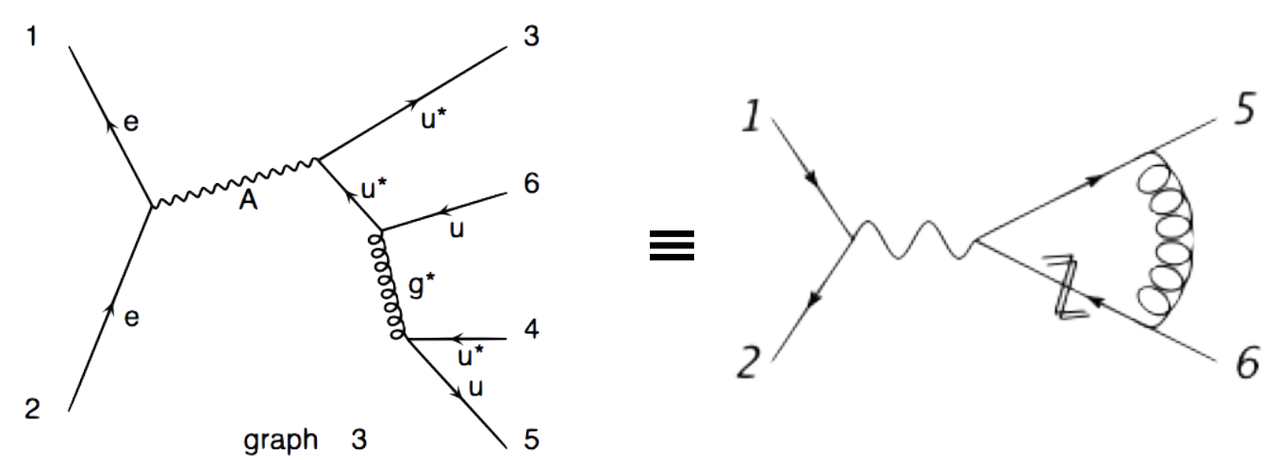
# Generating loop diagrams

- Instead of using an external tool for loop diagram generation, we recycle MadGraph5 algorithm for tree level diagram generation.
- A loop diagrams with the loop cut open has two extra external particles. Consider $e^+e^- \rightarrow u\ u\sim\ u\ u\sim$ (loop particles are in green). MadLoop will generate 8 L-cut diagrams. Here are two of them:

  - All diagrams with two extra particles are generated and the ones that are redundant need be filtered out
  - Each diagram gets an unique tag: any mirror and/or cyclic permutations of tags of diagrams already in the set are taken out
  - Additional filter to eliminate tadpoles and bubbles attached to external lines




$$\text{Diag}_1 = [u^*(6)g^*(5)u^*(A)]$$




$$\text{Diag}_3 = [u^*(A)u^*(6)g^*(5)]$$

# STABILITY TESTS AND RECOVERY

Stability probed via two methods:

- Loop reading direction : $D_0D_1...D_{n-1}D_n \rightarrow D_nD_{n-1}...D_1D_0$
  ➥ Advantage: The coefficients of N(q) need not be recomputed.
- Two PS point rotations : (E,x,y,z) → (E,z,-x,-y) and (E,x,y,z) → (E,-z,y,x)
- Accuracy estimation : These independent computations $E_i^{(DP)}$ of the same quantity provide an estimation $\xi^{(DP)}$ of the numerical accuracy of the result provided.

If unstable :

- Switch to other reduction methods if available (i.e various. TIR algos) and perform stability tests again.

If still unstable :

- Automatic switch to QP : MadLoop recomputes, on the flight, the loop ME for the unstable point, and its stability evaluation yields $\xi^{(QP)}$. If $\xi^{(QP)}$ is acceptable then point is UPS if not it is EPS
- EPS are inexistent from a practical point of view, but UPS can become a threat as their computation is 100 times slower.