MG5_aMC@NLO
looping up to be mad!

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based on 1401.7340 and 1405.0301
Work in progress with V. Hirschi

Plan

- What is MadGraph5_aMC@NLO
- Loop-Induced processes
  - ➡LO re-weighting
  - ➡ PS integration

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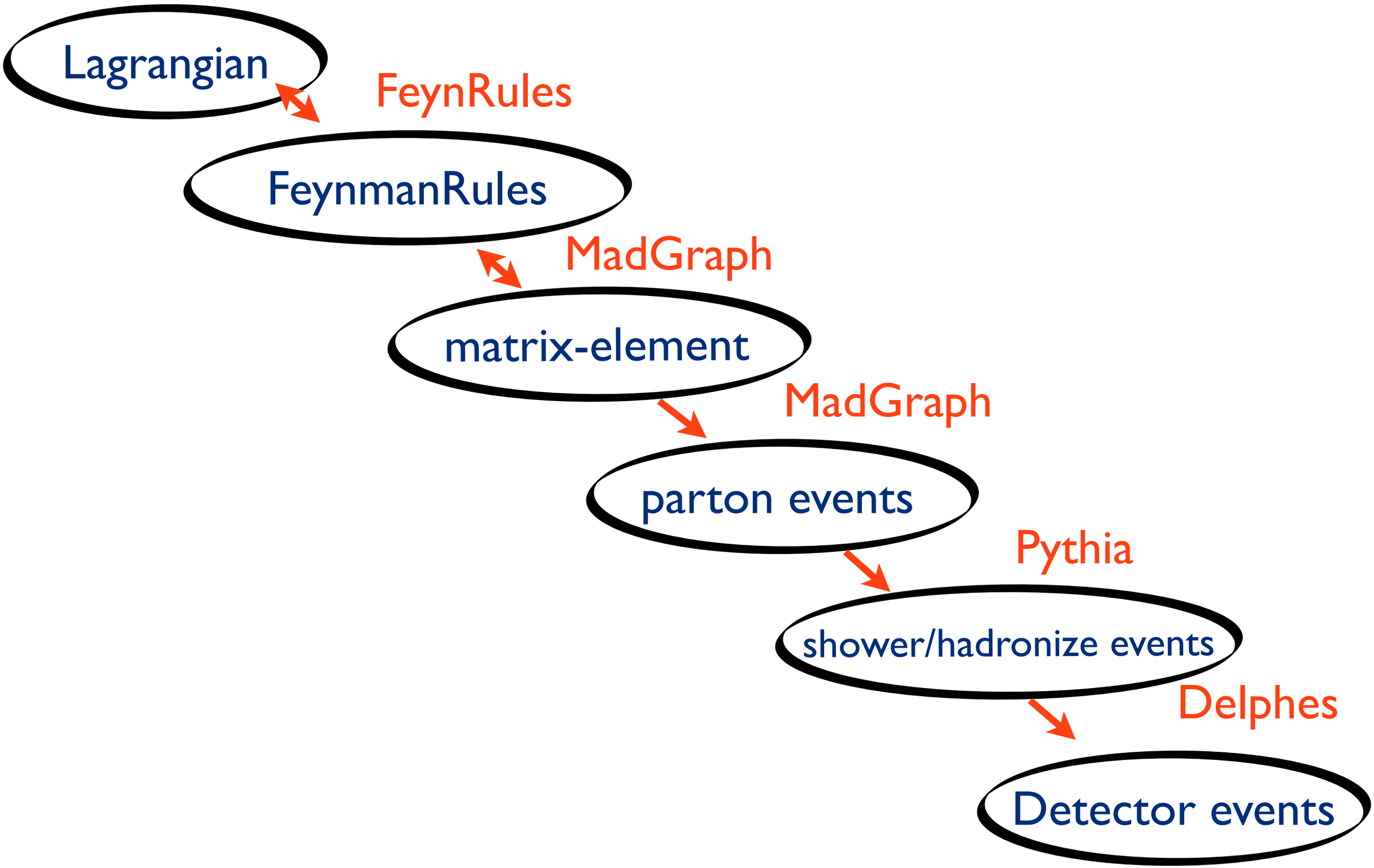
From Theory to Detector

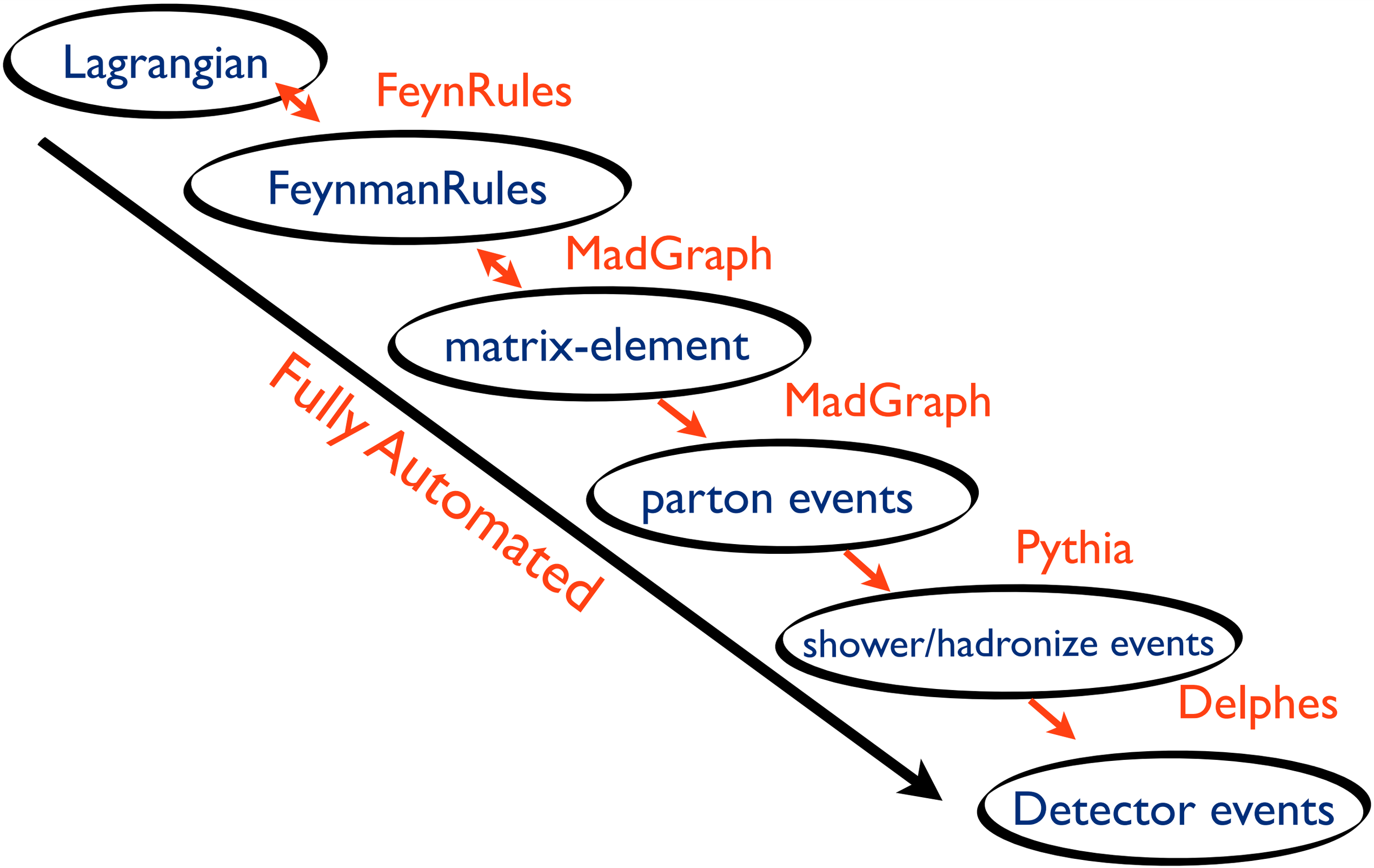
Lagrangian

Detector events

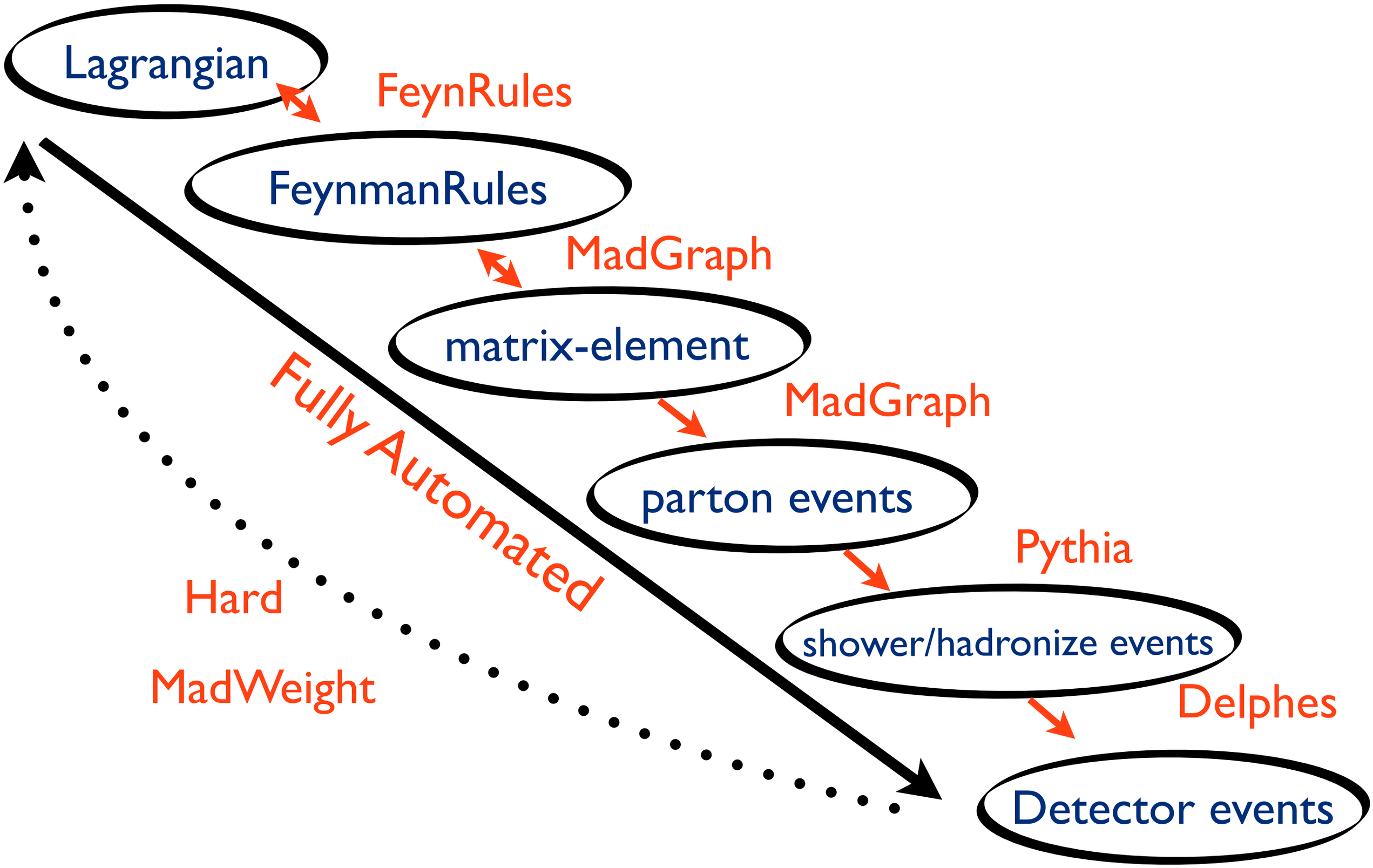
From Theory to Detector



From Theory to Detector



From Theory to Detector



Framework

MG Core	Functionalities	Tools
generate	Output	launch

Framework

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UFO / ALOHA

MadGraph StandAlone

MadLoop StandAlone

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LO

- MadEvent
- MadWeight
- To Pythia 8
- DarkMatter

NLO

- MadKFS
- aMC@NLO

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Generation

- MC@NLO
- MadSpin
- Tau-Decay
- MadWidth

NLO

- MadKFS
- aMC@NLO

Tools

- MadAnalysis5
- pythia-pgs
- Delphes

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`	$1.233 \pm 0.002 \cdot 10^1$	$^{+24.7\%}_{-18.6\%}$ $^{+0.6\%}_{-0.6\%}$	$1.448 \pm 0.005 \cdot 10^1$	$^{+3.6\%}_{-5.4\%}$ $^{+0.6\%}_{-0.7\%}$

	Process	Syntax	Cross section (pb) LO 13 TeV		NLO 13 TeV	
	Three vector bosons +jet					
c.1	$pp \to W^+W^-W^\pm$ (4f)	`p p > w+ w- wpm`	$1.307 \pm 0.003 \cdot 10^{-1}$	$^{+0.0\%}_{-9.8\%}$ $^{+9.0\%}_{-1.4\%}$	$2.109 \pm 0.006 \cdot 10^{-1}$	$^{+5.1\%}_{-4.1\%}$ $^{+1.6\%}_{-1.2\%}$
c.2	$pp \to ZW^+W^-$ (4f)	`p p > z w+ w-`	$9.658 \pm 0.065 \cdot 10^{-2}$	$^{+0.8\%}_{-1.1\%}$ $^{+3.1\%}_{-1.6\%}$	$1.679 \pm 0.005 \cdot 10^{-1}$	$^{+6.3\%}_{-4.1\%}$ $^{+1.6\%}_{-1.2\%}$
c.3	$pp \to ZZW^\pm$	`p p > z z wpm`	$2.996 \pm 0.016 \cdot 10^{-2}$	$^{+1.0\%}_{-1.4\%}$ $^{+9.0\%}_{-1.6\%}$	$5.350 \pm 0.020 \cdot 10^{-2}$	$^{+6.8\%}_{-5.5\%}$ $^{+1.5\%}_{-1.1\%}$
c.4	$pp \to ZZZ$	`p p > z z z`	$1.085 \pm 0.002 \cdot 10^{-2}$	$^{+0.0\%}_{-9.5\%}$ $^{+1.9\%}_{-1.4\%}$	$1.417 \pm 0.005 \cdot 10^{-2}$	$^{+3.7\%}_{-2.1\%}$ $^{+1.9\%}_{-1.5\%}$
c.5	$pp \to \gamma W^+W^-$ (4f)	`p p > a w+ w-`	$1.427 \pm 0.011 \cdot 10^{-1}$	$^{+1.9\%}_{-2.6\%}$ $^{+3.0\%}_{-1.4\%}$	$2.581 \pm 0.008 \cdot 10^{-1}$	$^{+5.1\%}_{-4.3\%}$ $^{+1.4\%}_{-1.1\%}$
c.6	$pp \to \gamma W^\pm$	`p p > a a wpm`	$2.681 \pm 0.007 \cdot 10^{-2}$	$^{+4.4\%}_{-5.6\%}$ $^{+1.9\%}_{-1.8\%}$	$8.251 \pm 0.032 \cdot 10^{-2}$	$^{+7.6\%}_{-7.0\%}$ $^{+1.0\%}_{-1.0\%}$
c.7	$pp \to \gamma ZW^\pm$	`p p > a z wpm`	$4.994 \pm 0.011 \cdot 10^{-2}$	$^{+9.8\%}_{-1.4\%}$ $^{+1.9\%}_{-1.4\%}$	$1.117 \pm 0.004 \cdot 10^{-1}$	$^{+7.2\%}_{-5.9\%}$ $^{+1.2\%}_{-0.9\%}$
c.8	$pp \to \gamma ZZ$	`p p > a z z`	$2.320 \pm 0.005 \cdot 10^{-2}$	$^{+2.0\%}_{-2.8\%}$ $^{+1.9\%}_{-1.5\%}$	$3.118 \pm 0.012 \cdot 10^{-2}$	$^{+2.8\%}_{-2.7\%}$ $^{+1.6\%}_{-1.4\%}$
c.9	$pp \to \gamma\gamma Z$	`p p > a a z`	$3.078 + 0.007 \cdot 10^{-2}$	$^{+9.6\%}_{-6.8\%}$ $^{+1.9\%}_{-1.6\%}$	$4.634 + 0.020 \cdot 10^{-2}$	$^{+4.4\%}_{-5.0\%}$ $^{+1.7\%}_{-1.3\%}$
c.10	$pp \to \gamma\gamma\gamma$	`p p > a a a`	$1.269 + 0.003 \cdot 10^{-2}$	$^{+19.8\%}_{+51.5\%}$ $^{+2.0\%}_{+1.8\%}$	$3.441 + 0.012 \cdot 10^{-2}$	$^{+11.8\%}_{+11.6\%}$ $^{+1.4\%}_{+1.5\%}$
c.11	$pp \to W^+W^-W^\pm j$ (4f)	`p p > w+ w- wpm j`	$9.167 \pm 0.010 \cdot 10^{-2}$	$^{+15.0\%}_{-12.2\%}$ $^{+1.0\%}_{-0.7\%}$	$1.197 \pm 0.004 \cdot 10^{-1}$	$^{+3.7\%}_{-5.6\%}$ $^{+1.0\%}_{-0.8\%}$
c.12*	$pp \to ZW^+W^-j$ (4f)	`p p > z w+ w- j`	$8.340 \pm 0.010 \cdot 10^{-2}$	$^{+15.0\%}_{-12.6\%}$ $^{+1.0\%}_{-0.7\%}$	$1.066 \pm 0.003 \cdot 10^{-1}$	$^{+4.3\%}_{-5.3\%}$ $^{+1.0\%}_{-0.7\%}$
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`	$4.823 \pm 0.011 \cdot 10^{-3}$	$^{+14.8\%}_{-11.8\%}$ $^{+1.4\%}_{-1.0\%}$	$6.341 \pm 0.025 \cdot 10^{-3}$	$^{+4.9\%}_{-5.4\%}$ $^{+1.4\%}_{-1.0\%}$
c.15*	$pp \to \gamma W^+W^-j$ (4f)	`p p > a w+ w- j`	$1.182 \pm 0.004 \cdot 10^{-1}$	$^{+12.6\%}_{-11.2\%}$ $^{+0.8\%}_{-0.7\%}$	$1.233 \pm 0.004 \cdot 10^{0}$	$^{+10.9\%}_{-10.9\%}$ $^{+1.0\%}_{-1.5\%}$
c.16	$pp \to \gamma\gamma W^\pm j$	`p p > a a wpm j`	$4.107 \pm 0.015 \cdot 10^{-2}$	$^{+11.8\%}_{-10.2\%}$ $^{+0.6\%}_{-0.6\%}$	$5.807 \pm 0.023 \cdot 10^{-2}$	$^{+9.8\%}_{-8.5\%}$ $^{+0.7\%}_{-0.7\%}$
c.17*	$pp \to \gamma ZW^\pm j$	`p p > a z wpm j`	$5.833 + 0.023 \cdot 10^{-2}$	$^{+14.4\%}_{-12.0\%}$ $^{+0.7\%}_{-0.6\%}$	$7.764 + 0.025 \cdot 10^{-2}$	$^{+8.1\%}_{-6.5\%}$ $^{+0.6\%}_{-0.6\%}$
c.18*	$pp \to \gamma ZZj$	`p p > a z z j`	$9.995 + 0.013 \cdot 10^{-3}$	$^{+12.5\%}_{-10.6\%}$ $^{+1.2\%}_{-0.9\%}$	$1.371 + 0.005 \cdot 10^{-2}$	$^{+5.6\%}_{-5.5\%}$ $^{+1.2\%}_{-0.9\%}$
c.19*	$pp \to \gamma\gamma Zj$	`p p > a a z j`	$1.372 + 0.003 \cdot 10^{-2}$	$^{+10.9\%}_{-9.6\%}$ $^{+1.0\%}_{-0.9\%}$	$2.051 + 0.011 \cdot 10^{-2}$	$^{+7.0\%}_{-6.3\%}$ $^{+1.0\%}_{-0.9\%}$
c.20*	$pp \to \gamma\gamma\gamma j$	`p p > a a a j`	$1.031 + 0.006 \cdot 10^{-2}$	$^{+14.3\%}_{-12.6\%}$ $^{+0.9\%}_{-1.2\%}$	$2.020 + 0.008 \cdot 10^{-2}$	$^{+12.8\%}_{-11.0\%}$ $^{+0.8\%}_{-1.2\%}$

	Process	Syntax	Cross section (pb) LO 13 TeV		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`	$1.594 \pm 0.004 \cdot 10^{-5}$	$^{+4.7\%}_{-5.7\%}$ $^{+1.9\%}_{-1.7\%}$	$3.389 \pm 0.012 \cdot 10^{-5}$	$^{+7.0\%}_{-6.7\%}$ $^{+1.3\%}_{-1.3\%}$

	Process	Syntax	Cross section (pb) LO 13 TeV		NLO 13 TeV	
	Heavy quarks and jets					
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`	$8.940 \pm 0.021 \cdot 10^{4}$	$^{+43.8\%}_{-38.4\%}$ $^{+1.2\%}_{-1.4\%}$	$7.791 \pm 0.037 \cdot 10^{4}$	$^{+2.1\%}_{-33.9\%}$ $^{+1.1\%}_{-1.3\%}$
d.3	$pp \to b\bar{b}$ (4f)	`p p > b b~`	$3.743 \pm 0.004 \cdot 10^{3}$	$^{+26.2\%}_{-18.9\%}$ $^{+1.5\%}_{-1.8\%}$	$6.438 \pm 0.028 \cdot 10^{3}$	$^{+15.9\%}_{-13.3\%}$ $^{+1.5\%}_{-1.7\%}$
d.4*	$pp \to b\bar{b}j$ (4f)	`p p > b b~ j`	$1.050 + 0.002 \cdot 10^{3}$	$^{+44.1\%}_{-28.5\%}$ $^{+1.6\%}_{-1.8\%}$	$1.327 + 0.007 \cdot 10^{3}$	$^{+9.8\%}_{-11.6\%}$ $^{+1.5\%}_{-1.8\%}$
d.5*	$pp \to b\bar{b}jj$ (4f)	`p p > b b~ j j`	$1.852 + 0.006 \cdot 10^{2}$	$^{+61.8\%}_{-35.6\%}$ $^{+2.1\%}_{-2.4\%}$	$2.471 + 0.012 \cdot 10^{2}$	$^{+8.2\%}_{-16.4\%}$ $^{+2.0\%}_{-2.3\%}$
d.6	$pp \to b\bar{b}b\bar{b}$ (4f)	`p p > b b~ b b~`	$5.050 + 0.007 \cdot 10^{-1}$	$^{+81.7\%}_{-35.6\%}$ $^{+2.9\%}_{-3.4\%}$	$8.736 + 0.034 \cdot 10^{-1}$	$^{+20.9\%}_{-22.0\%}$ $^{+2.9\%}_{-3.4\%}$
d.7	$pp \to t\bar{t}$	`p p > t t~`	$4.584 \pm 0.003 \cdot 10^{2}$	$^{+39.0\%}_{-21.1\%}$ $^{+1.8\%}_{-2.0\%}$	$6.741 \pm 0.023 \cdot 10^{2}$	$^{+9.8\%}_{-10.5\%}$ $^{+1.8\%}_{-2.1\%}$
d.8	$pp \to t\bar{t}j$	`p p > t t~ j`	$3.135 \pm 0.002 \cdot 10^{2}$	$^{+45.1\%}_{-29.0\%}$ $^{+2.3\%}_{-2.5\%}$	$4.106 \pm 0.015 \cdot 10^{2}$	$^{+8.1\%}_{-12.2\%}$ $^{+1.7\%}_{-2.5\%}$
d.9	$pp \to t\bar{t}jj$	`p p > t t~ j j`	$1.361 \pm 0.001 \cdot 10^{2}$	$^{+61.4\%}_{-39.6\%}$ $^{+2.6\%}_{-3.0\%}$	$1.795 \pm 0.006 \cdot 10^{2}$	$^{+9.8\%}_{-16.1\%}$ $^{+2.4\%}_{-2.9\%}$
d.10	$pp \to t\bar{t}t\bar{t}$	`p p > t t~ t t~`	$4.505 \pm 0.005 \cdot 10^{-3}$	$^{+68.8\%}_{-36.5\%}$ $^{+0.4\%}_{-5.7\%}$	$9.201 \pm 0.028 \cdot 10^{-3}$	$^{+30.8\%}_{-25.6\%}$ $^{+0.5\%}_{-5.9\%}$
d.11	$pp \to t\bar{t}b\bar{b}$ (4f)	`p p > t t~ b b~`	$6.119 \pm 0.004 \cdot 10^{0}$	$^{+62.1\%}_{-30.7\%}$ $^{+2.9\%}_{-3.0\%}$	$1.452 \pm 0.005 \cdot 10^{1}$	$^{+37.6\%}_{-27.6\%}$ $^{+2.9\%}_{-3.0\%}$

	Process	Syntax	Cross section (pb) LO 13 TeV		NLO 13 TeV	
	Heavy quarks+vector bosons					
e.1	$pp \to W^\pm b\bar{b}$ (4f)	`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	$pp \to Z b\bar{b}$ (4f)	`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	$pp \to \gamma b\bar{b}$ (4f)	`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*	$pp \to W^\pm b\bar{b}j$ (4f)	`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*	$pp \to Z b\bar{b}j$ (4f)	`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*	$pp \to \gamma b\bar{b}j$ (4f)	`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*	$pp \to t\bar{t}Zj$	`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*	$pp \to t\bar{t}ZZ$	`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`	$3.272 \pm 0.006 \cdot 10^{-3}$	$^{+28.4\%}_{-20.6\%}$ $^{+1.3\%}_{-1.1\%}$	$4.402 \pm 0.015 \cdot 10^{-3}$	$^{+7.8\%}_{-9.7\%}$ $^{+1.4\%}_{-1.4\%}$

	Process	Syntax	Cross section (pb) LO 13 TeV		NLO 13 TeV	
	Single-top					
f.1	$pp \to tj$ (t-channel)	`p p > tt j $$ w+ w-`	$1.520 \pm 0.001 \cdot 10^{2}$	$^{+0.4\%}_{-11.5\%}$ $^{+0.4\%}_{-0.6\%}$	$1.563 \pm 0.005 \cdot 10^{2}$	$^{+1.4\%}_{-1.4\%}$ $^{+0.4\%}_{-0.6\%}$
f.2	$pp \to t\gamma j$ (t-channel)	`p p > tt a j $$ 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 $$ w+ w-`	$6.967 \pm 0.007 \cdot 10^{-1}$	$^{+12.0\%}_{-5.5\%}$ $^{+0.9\%}_{-1.0\%}$	$6.993 \pm 0.021 \cdot 10^{-1}$	$^{+1.6\%}_{-1.1\%}$ $^{+0.9\%}_{-1.0\%}$
f.4	$pp \to tbj$ (t-channel, 4f)	`p p > tt bb j $$ w+ w-`	$1.003 \pm 0.000 \cdot 10^{2}$	$^{+18.8\%}_{-11.8\%}$ $^{+0.4\%}_{-0.6\%}$	$1.319 \pm 0.003 \cdot 10^{2}$	$^{+9.8\%}_{-8.2\%}$ $^{+0.4\%}_{-0.6\%}$
f.5*	$pp \to tbj\gamma$ (t-channel, 4f)	`p p > tt bb j a $$ w+ w-`	$6.293 \pm 0.006 \cdot 10^{-1}$	$^{+16.8\%}_{-13.5\%}$ $^{+0.8\%}_{-0.9\%}$	$8.612 \pm 0.025 \cdot 10^{-1}$	$^{+9.2\%}_{-6.6\%}$ $^{+0.8\%}_{-0.9\%}$
f.6*	$pp \to tbjZ$ (t-channel, 4f)	`p p > tt bb j z $$ w+ w-`	$3.934 + 0.002 \cdot 10^{-1}$	$^{+18.7\%}_{-14.7\%}$ $^{+1.0\%}_{-0.9\%}$	$5.657 + 0.014 \cdot 10^{-1}$	$^{+7.7\%}_{-7.9\%}$ $^{+0.9\%}_{-0.9\%}$
f.7	$pp \to tb$ (s-channel, 4f)	`p p > w+ > t b~, p p > w- > t~ b`	$7.489 \pm 0.007 \cdot 10^{0}$	$^{+3.5\%}_{-4.4\%}$ $^{+1.9\%}_{-1.4\%}$	$1.001 \pm 0.004 \cdot 10^{1}$	$^{+3.7\%}_{-3.9\%}$ $^{+1.9\%}_{-1.4\%}$
f.8*	$pp \to tb\gamma$ (s-channel, 4f)	`p p > w+ > t b~ a, p p > w- > t~ b a`	$1.490 \pm 0.001 \cdot 10^{-2}$	$^{+1.5\%}_{-1.8\%}$ $^{+1.9\%}_{-1.5\%}$	$1.952 \pm 0.007 \cdot 10^{-2}$	$^{+3.6\%}_{-2.3\%}$ $^{+1.7\%}_{-1.4\%}$
f.9*	$pp \to tbZ$ (s-channel, 4f)	`p p > w+ > t b~ z, p p > w- > t~ b z`	$1.072 \pm 0.001 \cdot 10^{-2}$	$^{+1.5\%}_{-1.5\%}$ $^{+1.9\%}_{-1.6\%}$	$1.539 \pm 0.005 \cdot 10^{-2}$	$^{+3.6\%}_{-3.2\%}$ $^{+1.6\%}_{-1.8\%}$

	Process	Syntax	Cross section (pb) LO 13 TeV		NLO 13 TeV	
Single Higgs production						
g.1	$pp \to H$ (HEFT)	`p p > h`	$1.593 + 0.003 \cdot 10^{1}$	$^{+34.8\%}_{-26.0\%}$ $^{+1.2\%}_{-1.7\%}$	$3.261 + 0.010 \cdot 10^{1}$	$^{+20.2\%}_{-17.9\%}$ $^{+1.1\%}_{-1.6\%}$
g.2	$pp \to Hj$ (HEFT)	`p p > h j`	$8.367 + 0.003 \cdot 10^{0}$	$^{+39.4\%}_{-26.4\%}$ $^{+1.2\%}_{-1.4\%}$	$1.422 + 0.006 \cdot 10^{1}$	$^{+18.5\%}_{-16.0\%}$ $^{+1.3\%}_{-1.4\%}$
g.3	$pp \to Hjj$ (HEFT)	`p p > h j j`	$3.020 + 0.002 \cdot 10^{0}$	$^{+89.1\%}_{-34.7\%}$ $^{+1.4\%}_{-1.7\%}$	$5.124 + 0.020 \cdot 10^{0}$	$^{+20.7\%}_{-31.0\%}$ $^{+1.3\%}_{-1.5\%}$
g.4	$pp \to Hjj$ (VBF)	`p p > h j j $$ w+ w- z`	$1.987 \pm 0.002 \cdot 10^{0}$	$^{+1.7\%}_{-2.0\%}$ $^{+1.0\%}_{-1.4\%}$	$1.900 \pm 0.006 \cdot 10^{0}$	$^{+0.8\%}_{-0.9\%}$ $^{+3.0\%}_{-1.8\%}$
g.5	$pp \to Hjjj$ (VBF)	`p p > h j j j $$ w+ w- z`	$2.824 \pm 0.005 \cdot 10^{-1}$	$^{+16.7\%}_{-12.7\%}$ $^{+1.0\%}_{-1.0\%}$	$3.085 \pm 0.010 \cdot 10^{-1}$	$^{+2.0\%}_{-3.0\%}$ $^{+1.0\%}_{-1.1\%}$
g.6	$pp \to HW^{\pm}$	`p p > h wpm`	$1.195 \pm 0.002 \cdot 10^{0}$	$^{+3.5\%}_{-4.0\%}$ $^{+1.9\%}_{-1.6\%}$	$1.419 \pm 0.005 \cdot 10^{0}$	$^{+2.1\%}_{-2.6\%}$ $^{+1.9\%}_{-1.4\%}$
g.7	$pp \to HW^{\pm} j$	`p p > h wpm j`	$4.018 \pm 0.003 \cdot 10^{-1}$	$^{+10.7\%}_{-9.9\%}$ $^{+1.3\%}_{-0.9\%}$	$4.842 \pm 0.017 \cdot 10^{-1}$	$^{+3.6\%}_{-8.7\%}$ $^{+1.3\%}_{-1.0\%}$
g.8*	$pp \to HW^{\pm} jj$	`p p > h wpm j j`	$1.198 \pm 0.016 \cdot 10^{-1}$	$^{+56.1\%}_{-19.4\%}$ $^{+0.8\%}_{-0.6\%}$	$1.574 \pm 0.014 \cdot 10^{-1}$	$^{+5.0\%}_{-6.5\%}$ $^{+0.9\%}_{-0.6\%}$
g.9	$pp \to HZ$	`p p > h z`	$6.468 + 0.008 \cdot 10^{-1}$	$^{+3.8\%}_{-4.5\%}$ $^{+1.9\%}_{-1.6\%}$	$7.674 + 0.027 \cdot 10^{-1}$	$^{+2.0\%}_{-2.5\%}$ $^{+1.9\%}_{-1.4\%}$
g.10	$pp \to HZ j$	`p p > h z j`	$2.225 + 0.001 \cdot 10^{-1}$	$^{+10.6\%}_{-9.9\%}$ $^{+1.1\%}_{-0.8\%}$	$2.667 + 0.010 \cdot 10^{-1}$	$^{+3.5\%}_{-3.6\%}$ $^{+1.1\%}_{-0.9\%}$
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-`	$8.325 \pm 0.139 \cdot 10^{-3}$	$^{+0.0\%}_{-0.3\%}$ $^{+2.0\%}_{-1.8\%}$	$1.065 \pm 0.003 \cdot 10^{-2}$	$^{+2.5\%}_{-1.9\%}$ $^{+2.0\%}_{-1.5\%}$
g.13*	$pp \to HW^{\pm}\gamma$	`p p > h wpm a`	$2.518 + 0.006 \cdot 10^{-3}$	$^{+0.7\%}_{-1.4\%}$ $^{+1.9\%}_{-1.5\%}$	$3.309 + 0.011 \cdot 10^{-3}$	$^{+2.7\%}_{-2.0\%}$ $^{+1.7\%}_{-1.4\%}$
g.14*	$pp \to HZW^{\pm}$	`p p > h z wpm`	$3.763 + 0.007 \cdot 10^{-3}$	$^{+1.5\%}_{-1.5\%}$ $^{+2.0\%}_{-1.6\%}$	$5.292 + 0.015 \cdot 10^{-3}$	$^{+3.9\%}_{-3.1\%}$ $^{+1.8\%}_{-1.4\%}$
g.15*	$pp \to HZZ$	`p p > h z z`	$2.093 + 0.003 \cdot 10^{-3}$	$^{+0.1\%}_{-0.6\%}$ $^{+1.9\%}_{-1.5\%}$	$2.538 + 0.007 \cdot 10^{-3}$	$^{+1.9\%}_{-1.4\%}$ $^{+2.0\%}_{-1.5\%}$
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`	$4.994 \pm 0.005 \cdot 10^{-2}$	$^{+5.4\%}_{-4.2\%}$ $^{+1.7\%}_{-1.3\%}$	$6.328 \pm 0.022 \cdot 10^{-2}$	$^{+0.9\%}_{-1.8\%}$ $^{+1.7\%}_{-1.6\%}$
g.18	$pp \to Hb\bar{b}$ (4f)	`p p > h b b~`	$4.983 \pm 0.002 \cdot 10^{-1}$	$^{+28.1\%}_{-21.0\%}$ $^{+1.0\%}_{-1.6\%}$	$6.085 \pm 0.026 \cdot 10^{-1}$	$^{+7.3\%}_{-9.6\%}$ $^{+1.0\%}_{-2.0\%}$
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`	$7.367 \pm 0.002 \cdot 10^{-2}$	$^{+45.6\%}_{-29.1\%}$ $^{+1.8\%}_{-2.1\%}$	$9.034 \pm 0.032 \cdot 10^{-2}$	$^{+7.3\%}_{-11.0\%}$ $^{+1.8\%}_{-2.2\%}$

	Process	Syntax	Cross section (pb) LO 13 TeV		NLO 13 TeV	
Higgs pair production						
h.1	$pp \to HH$ (Loop improved)	`p p > h h`	$1.772 \pm 0.006 \cdot 10^{-2}$	$^{+39.5\%}_{-21.4\%}$ $^{+2.1\%}_{-2.6\%}$	$2.763 \pm 0.008 \cdot 10^{-2}$	$^{+11.4\%}_{-11.8\%}$ $^{+2.1\%}_{-2.6\%}$
h.2	$pp \to HHjj$ (VBF)	`p p > h h j j $$ w+ w- z`	$6.503 \pm 0.019 \cdot 10^{-4}$	$^{+7.9\%}_{-6.4\%}$ $^{+9.3\%}_{-1.6\%}$	$6.820 \pm 0.026 \cdot 10^{-4}$	$^{+0.4\%}_{-1.0\%}$ $^{+9.4\%}_{-1.7\%}$
h.3	$pp \to HHW^{\pm}$	`p p > h h wpm`	$4.303 \pm 0.005 \cdot 10^{-4}$	$^{+0.9\%}_{-1.3\%}$ $^{+9.0\%}_{-1.8\%}$	$5.002 \pm 0.014 \cdot 10^{-4}$	$^{+1.5\%}_{-1.2\%}$ $^{+9.0\%}_{-1.8\%}$
h.4*	$pp \to HHW^{\pm} j$	`p p > h h wpm j`	$1.922 \pm 0.002 \cdot 10^{-4}$	$^{+14.2\%}_{-11.7\%}$ $^{+1.6\%}_{-1.1\%}$	$2.218 \pm 0.009 \cdot 10^{-4}$	$^{+2.7\%}_{-3.3\%}$ $^{+1.6\%}_{-1.1\%}$
h.5*	$pp \to HHW^{\pm}\gamma$	`p p > h h wpm a`	$1.952 \pm 0.004 \cdot 10^{-6}$	$^{+8.0\%}_{-3.0\%}$ $^{+2.2\%}_{-1.6\%}$	$2.347 \pm 0.007 \cdot 10^{-6}$	$^{+2.4\%}_{-2.0\%}$ $^{+2.1\%}_{-1.6\%}$
h.6	$pp \to HHZ$	`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.7*	$pp \to HHZj$	`p p > h h z j`	$1.211 + 0.001 \cdot 10^{-4}$	$^{+14.1\%}_{-11.7\%}$ $^{+1.4\%}_{-1.1\%}$	$1.394 + 0.006 \cdot 10^{-4}$	$^{+2.7\%}_{-3.2\%}$ $^{+1.5\%}_{-1.1\%}$
h.8*	$pp \to HHZ\gamma$	`p p > h h z a`	$1.397 + 0.003 \cdot 10^{-6}$	$^{+2.4\%}_{-2.5\%}$ $^{+2.2\%}_{-1.7\%}$	$1.604 + 0.005 \cdot 10^{-6}$	$^{+1.7\%}_{-1.4\%}$ $^{+2.3\%}_{-1.7\%}$
h.9*	$pp \to HHZZ$	`p p > h h z z`	$2.309 + 0.005 \cdot 10^{-6}$	$^{+3.9\%}_{-3.8\%}$ $^{+2.2\%}_{-1.7\%}$	$2.754 + 0.009 \cdot 10^{-6}$	$^{+2.3\%}_{-2.0\%}$ $^{+2.3\%}_{-1.7\%}$
h.10*	$pp \to HHZW^{\pm}$	`p p > h h z wpm`	$3.708 + 0.013 \cdot 10^{-6}$	$^{+4.8\%}_{-4.7\%}$ $^{+2.3\%}_{-1.7\%}$	$4.904 + 0.029 \cdot 10^{-6}$	$^{+3.7\%}_{-3.9\%}$ $^{+2.2\%}_{-1.6\%}$
h.11*	$pp \to HHW^{+}W^{-}$ (4f)	`p p > h h w+ w-`	$7.524 + 0.070 \cdot 10^{-6}$	$^{+3.5\%}_{-3.4\%}$ $^{+2.3\%}_{-1.7\%}$	$9.268 + 0.030 \cdot 10^{-6}$	$^{+2.3\%}_{-3.1\%}$ $^{+2.3\%}_{-1.7\%}$
h.12	$pp \to HHt\bar{t}$	`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.13	$pp \to HHtj$	`p p > h h tt j`	$1.844 \pm 0.008 \cdot 10^{-5}$	$^{+0.0\%}_{-0.6\%}$ $^{+1.8\%}_{-1.8\%}$	$2.444 \pm 0.009 \cdot 10^{-5}$	$^{+4.5\%}_{-3.1\%}$ $^{+2.8\%}_{-3.0\%}$
h.14*	$pp \to HHb\bar{b}$	`p p > h h b b~`	$7.849 \pm 0.022 \cdot 10^{-8}$	$^{+34.3\%}_{-33.9\%}$ $^{+3.1\%}_{-3.7\%}$	$1.084 \pm 0.012 \cdot 10^{-7}$	$^{+7.4\%}_{-10.8\%}$ $^{+3.1\%}_{-3.7\%}$

	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`	$4.045 \pm 0.011 \cdot 10^{-5}$	$^{+30.5\%}_{-21.6\%}$	$7.049 \pm 0.052 \cdot 10^{-5}$	$^{+13.7\%}_{-13.1\%}$

	Process	Syntax	Cross section (pb) LO 1 TeV		NLO 1 TeV	
Top quarks +bosons						
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-`	$1.372 \pm 0.003 \cdot 10^{-4}$	$^{+0.0\%}_{-0.0\%}$	$1.540 \pm 0.006 \cdot 10^{-4}$	$^{+1.0\%}_{-0.9\%}$

Type of generation

Type of generation

Fix Order

+Parton Shower

Merged Sample

Type of generation

	Tree (SM)
Fix Order	✓
+Parton Shower	✓
Merged Sample	✓

Type of generation

	Tree (SM)	Tree (BSM)
Fix Order	✓	✓
+Parton Shower	✓	✓
Merged Sample	✓	✓

Type of generation

	Tree (SM)	Tree (BSM)	NLO (QCD) (SM)
Fix Order	✓	✓	✓
+Parton Shower	✓	✓	✓
Merged Sample	✓	✓	✓

Type of generation

	Tree (SM)	Tree (BSM)	NLO (QCD) (SM)	NLO (QCD) (BSM)
Fix Order	✓	✓	✓	✓
+Parton Shower	✓	✓	✓	✓
Merged Sample	✓	✓	✓	✓

Type of generation

	Tree (SM)	Tree (BSM)	NLO (QCD) (SM)	NLO (QCD) (BSM)	NLO (EW) (SM)
Fix Order	✓	✓	✓	✓	✓
+Parton Shower	✓	✓	✓	✓	✓
Merged Sample	✓	✓	✓	✓	✓

Type of generation

	Tree (SM)	Tree (BSM)	NLO (QCD) (SM)	NLO (QCD) (BSM)	NLO (EW) (SM)	NLO (EW) (BSM)
Fix Order	✓	✓	✓	✓	✓	
+Parton Shower	✓	✓	✓	✓	✓	
Merged Sample	✓	✓	✓	✓	✓	

Type of generation

	Tree (SM)	Tree (BSM)	NLO (QCD) (SM)	NLO (QCD) (BSM)	NLO (EW) (SM)	NLO (EW) (BSM)	Loop Induced
Fix Order	✓	✓	✓	✓	✓		✓
+Parton Shower	✓	✓	✓	✓	✓		✓
Merged Sample	✓	✓	✓	✓	✓		✓

Plan

- What is MadGraph5_aMC@NLO
- Loop-Induced processes
  - ➡ LO re-weighting
  - ➡ PS integration

Loop Induced

Why?

- Main production mechanism for Higgs & Higgs associated processes
- Contribution for NNLO computation
- Correction to shape of observables

Difficulties?

- The phase-space integration is based on the born diagram
- Loop evaluation are extremely slow
- Need Leading Color information for writing Events associated to the loop

ME-Reweighting

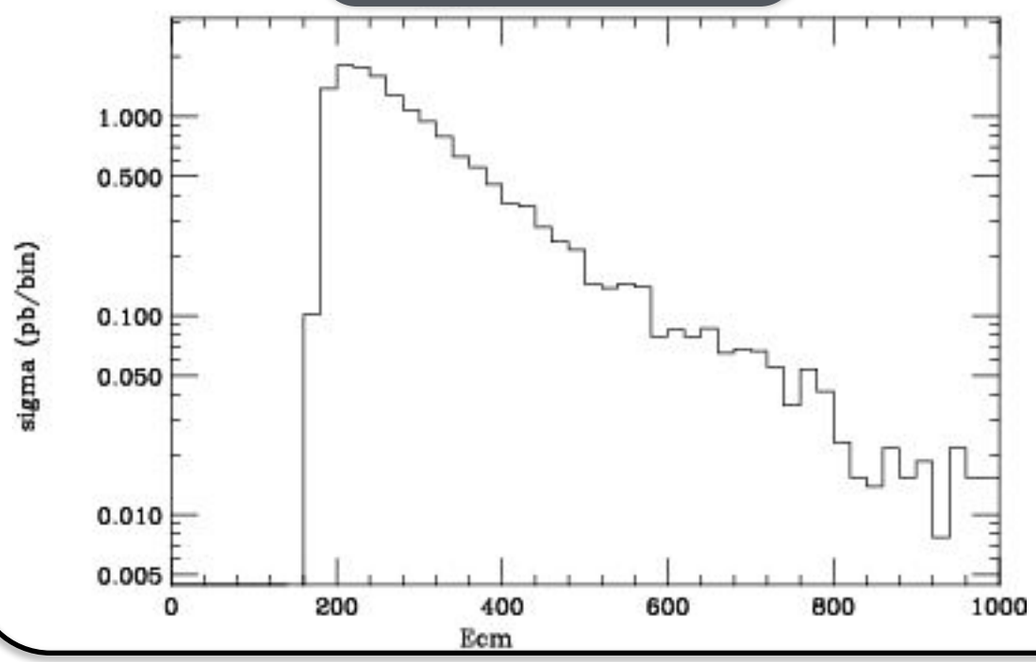
- Idea: use one (un)weighted generations and associate additional weights from different hypothesis.

$$W_{new} = \frac{|M_{new}|^2}{|M_{old}|^2} * W_{old}$$

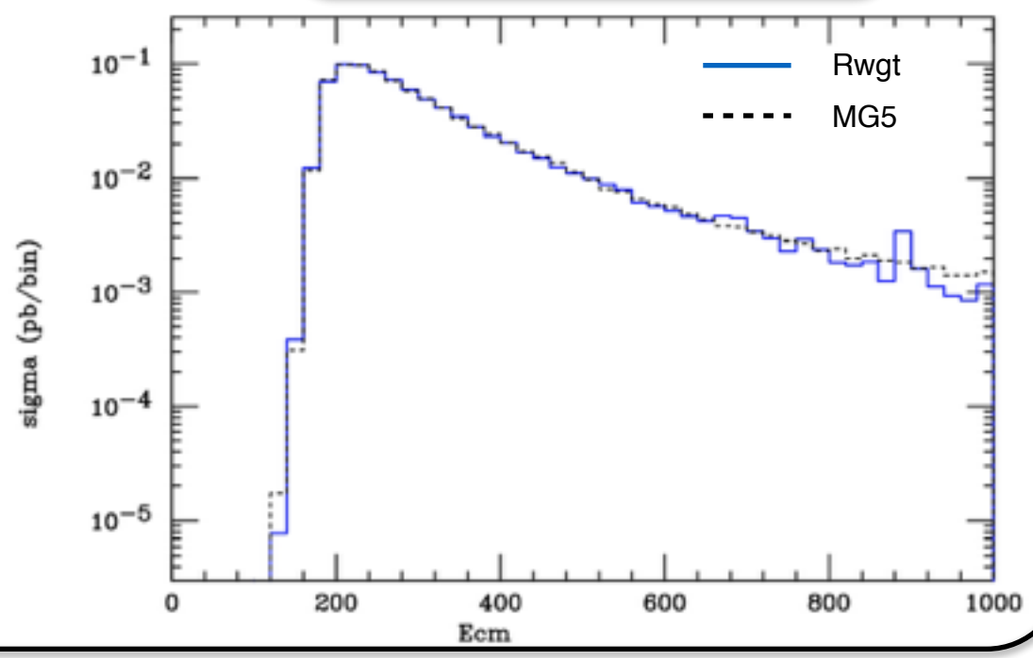
LO Example (p p > Z W)

[1405.0301/1404.7129]

Original



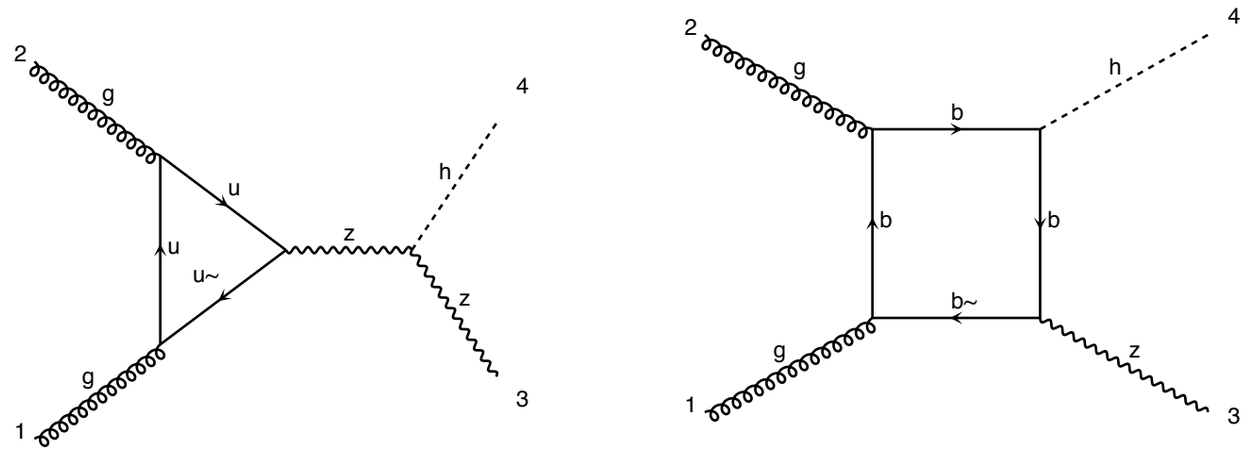
Reweighted

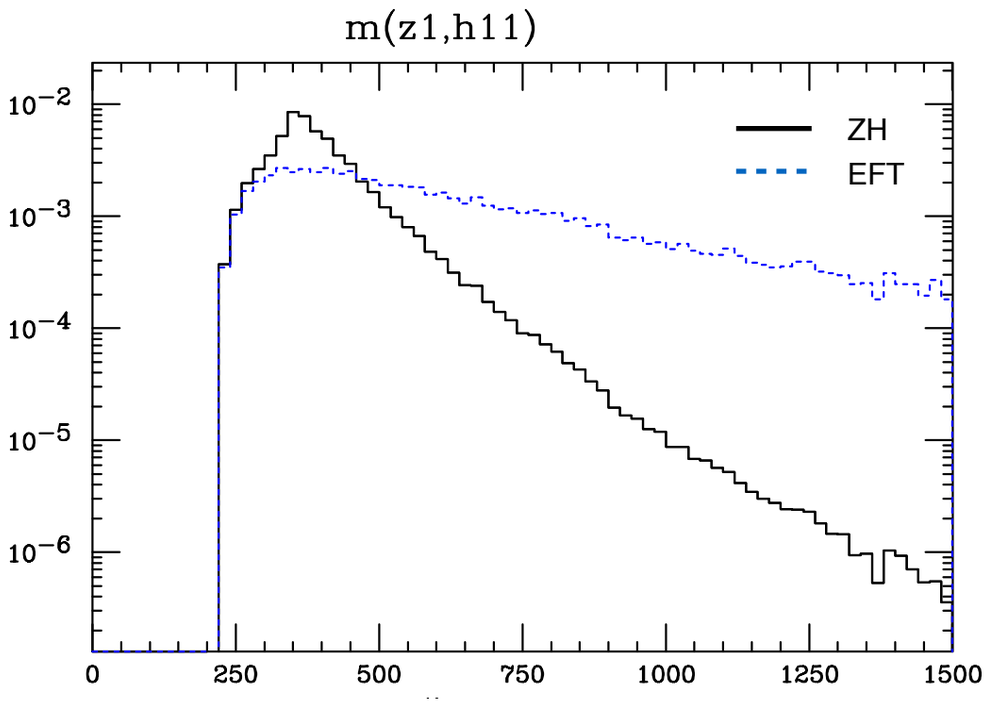


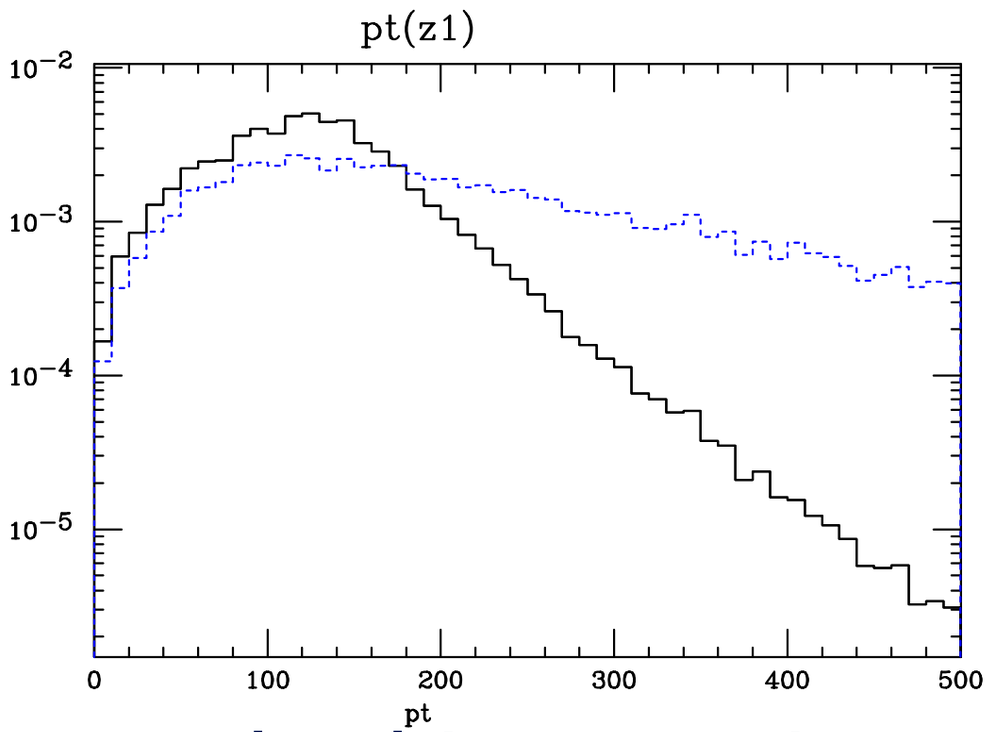
g g > ZH

Loop Induced Example

$$\sigma_{rwgt} = 0.0584pb$$







- Result identical to the standard integration method $\sigma_{true} = 0.0575(5)pb$

Loop Induced

Why?

- Main production mechanism for Higgs & Higgs associated processes
- Contribution for NNLO computation
- Correction to Shape of observables

Difficulties?

- The phase-space integration is based on the born diagram
- Loop evaluation are extremely slow
- Need Leading Color information for writing Events associated to the loop

Exact Integration

Difficulties?

- The phase-space integration is based on the born diagram
- Loop evaluation are extremely slow
- Need Leading Color information for writing Events associated to the loop

Solution

- Contract the loop to have tree-level diagrams which drive the integration multi-channel
- Use Monte-Carlo over helicity
- Increase parallelization
- Compute the loop with the color flow algebra

Exact Integration

Difficulties?

- The phase-space integration is based on the born diagram
- Loop evaluation are extremely slow
- Need Leading Color information for writing Events associated to the loop

Solution

- Contract the loop to have tree-level diagrams which drive the integration m… channel
- Use Mo… hel… …over …e parallelization
- …ompute the loop with the color flow algebra

WARNING: WORK IN PROGRESS
Temporary Result

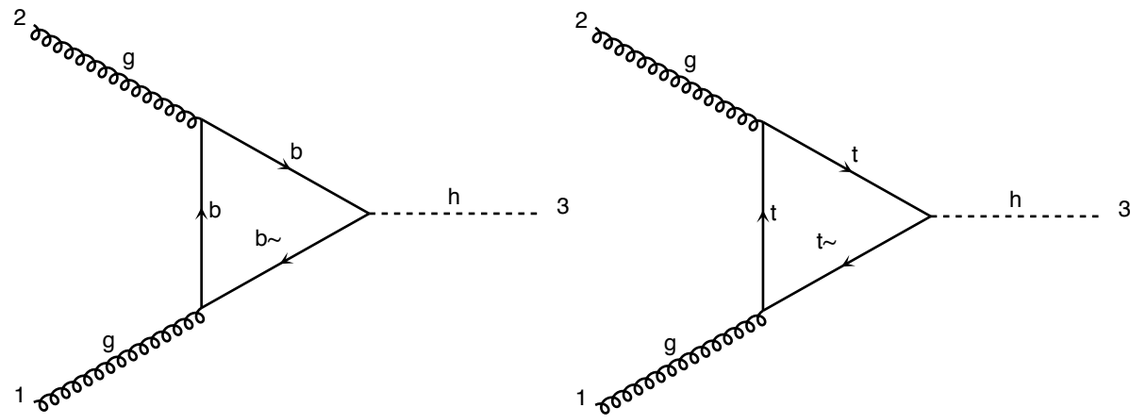
First Example: g g> h

User Input

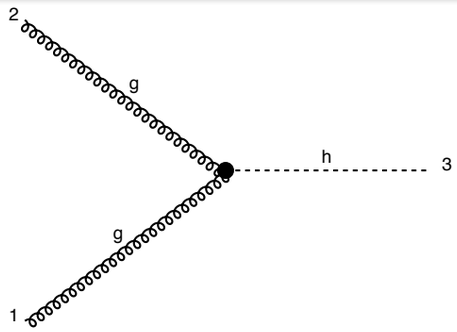
- generate g g > h [QCD]
- output
- launch

Loop Induced

$$\sigma_{loop} = 15.74(2)pb$$



HEFT



$$\sigma_{heft} = 17.63(2)pb$$

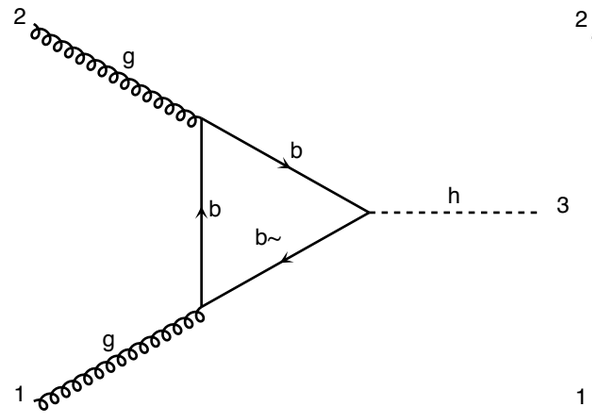
First Example: g g> h

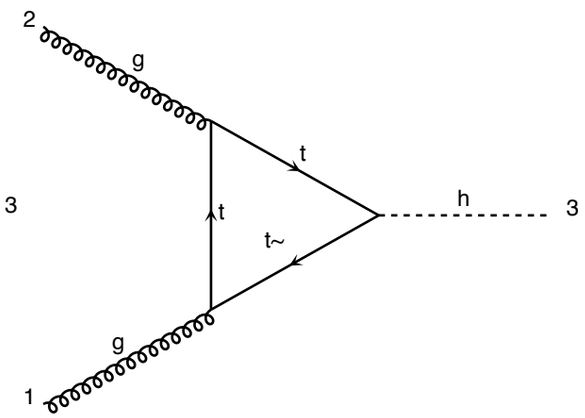
User Input

- generate g g > h [QCD]
- output
- launch

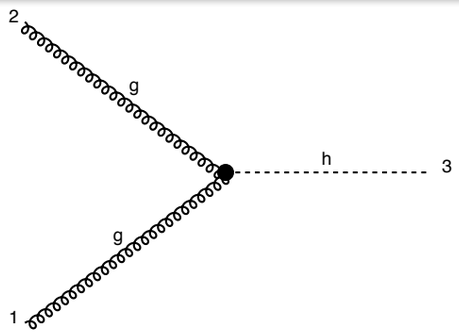
Loop Induced

$$\sigma_{loop} = 15.74(2)pb$$



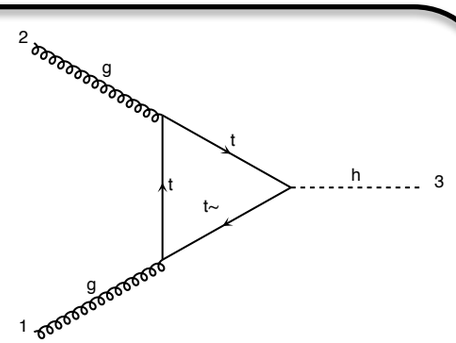


HEFT



$$\sigma_{heft} = 17.63(2)pb$$

No bottom loop

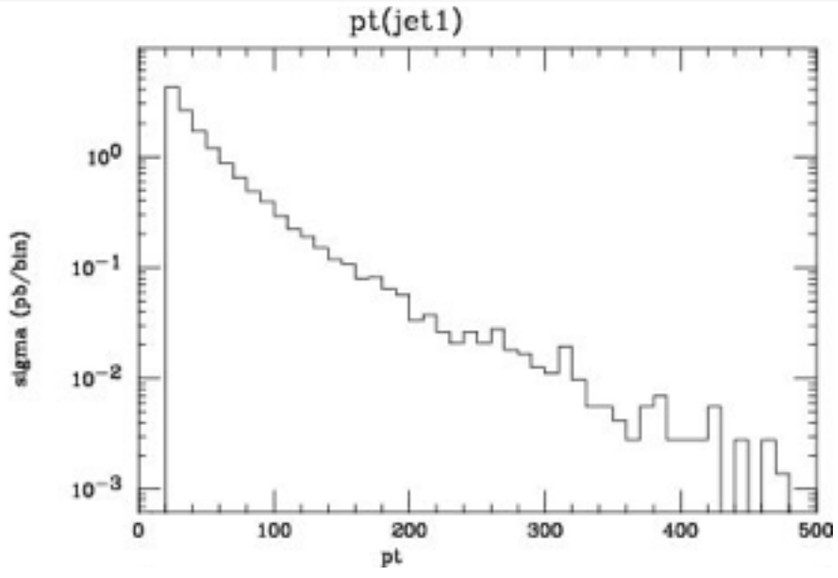


$$\sigma_{toploop} = 17.65(2)pb$$

p p > h j

HEFT

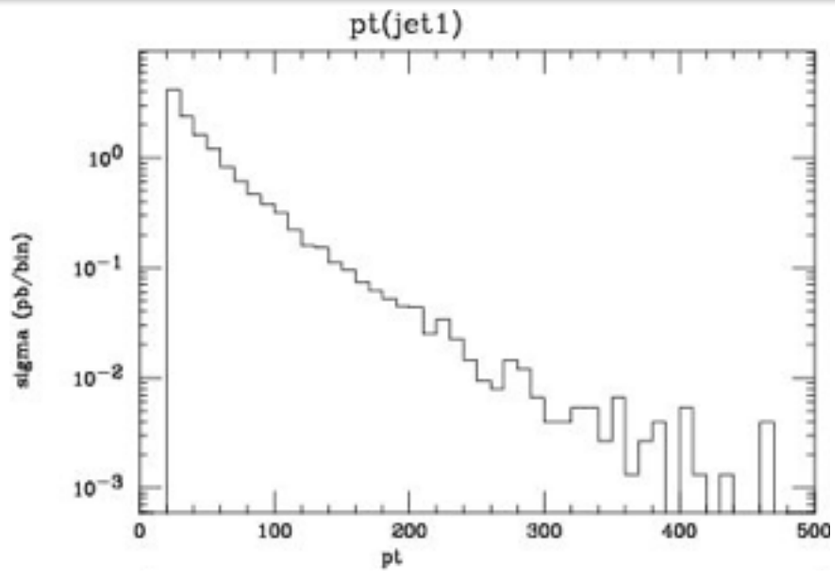
$$\sigma_{heft} = 13.87(3)pb$$



Loop Induced

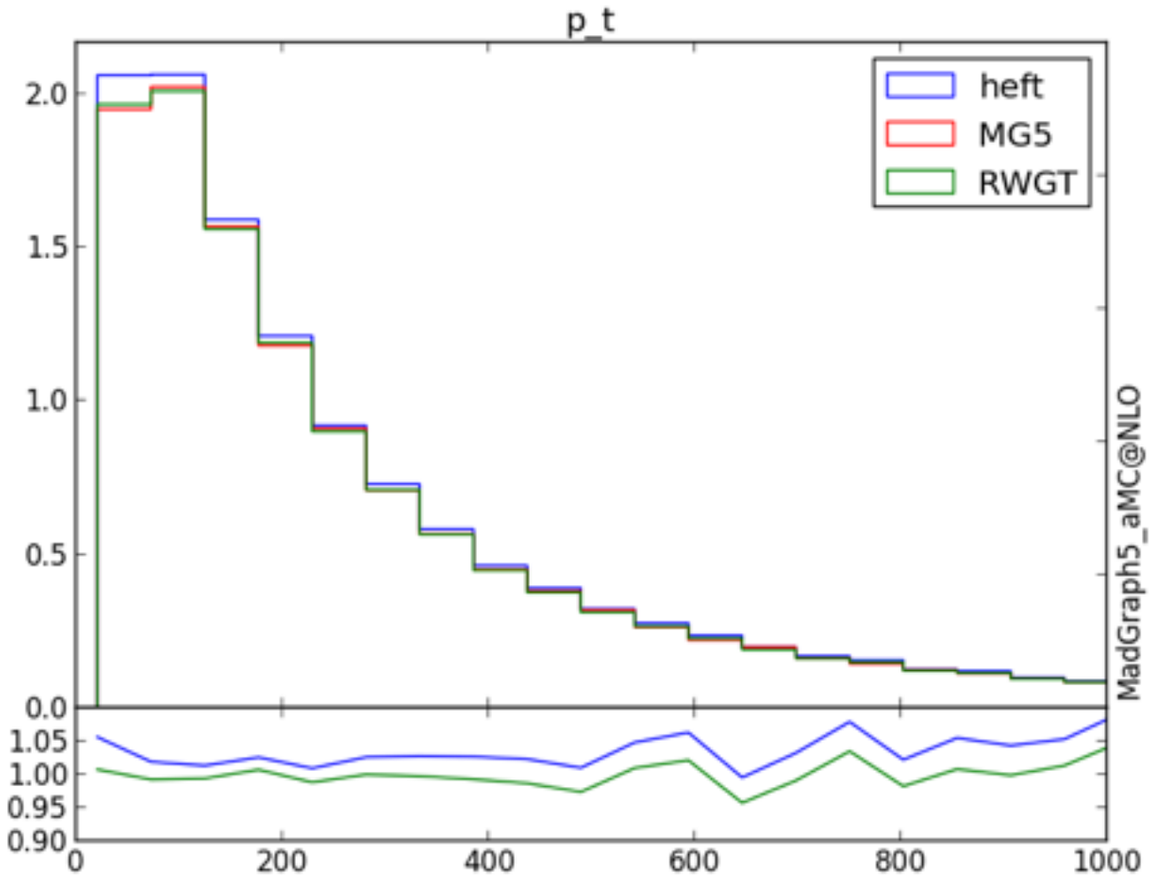
$$\sigma_{loop} = 13.24(2)pb$$

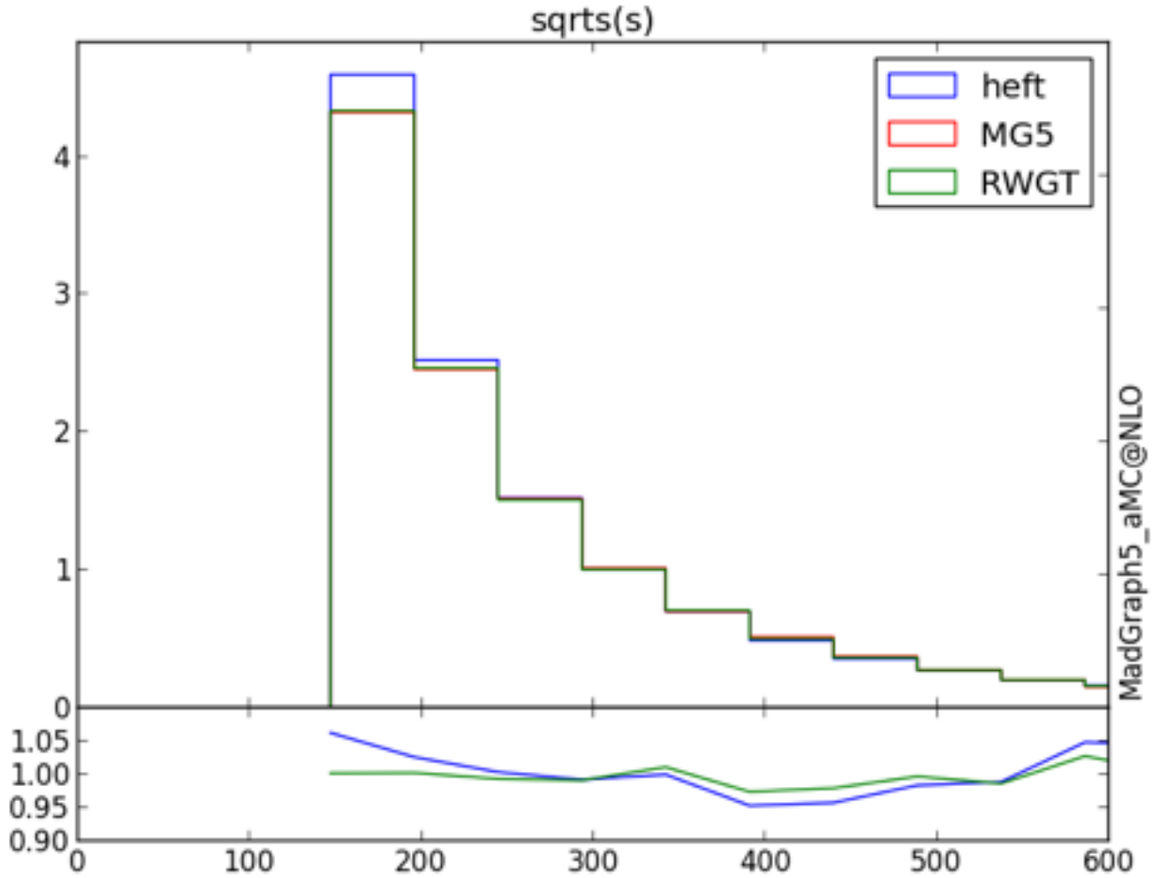
$$\sigma_{toploop} = 13.56(2)pb$$



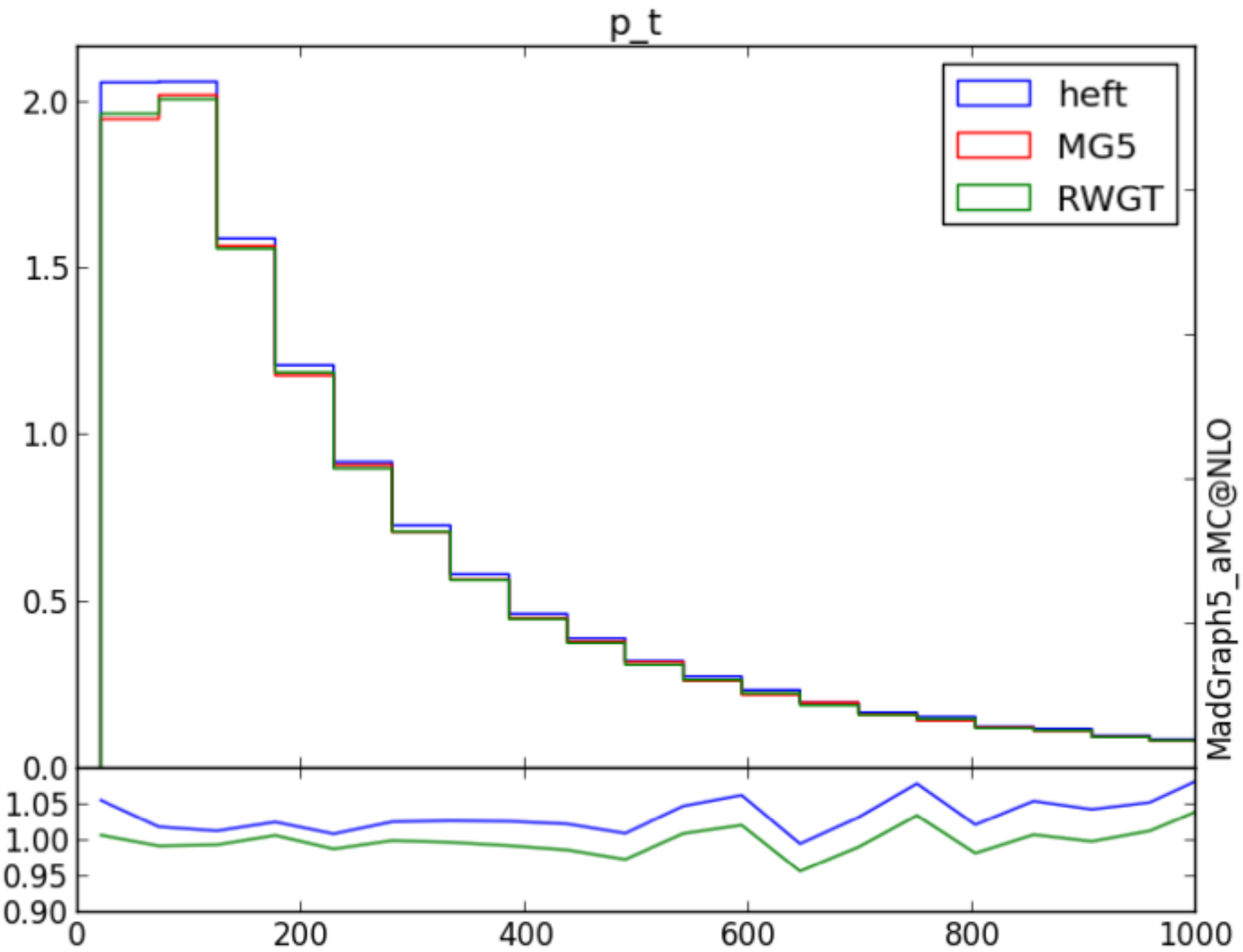
Validation

- Comparison of g g > h g between
  - ➡ heft
  - ➡ loop induced
  - ➡ re-weighting

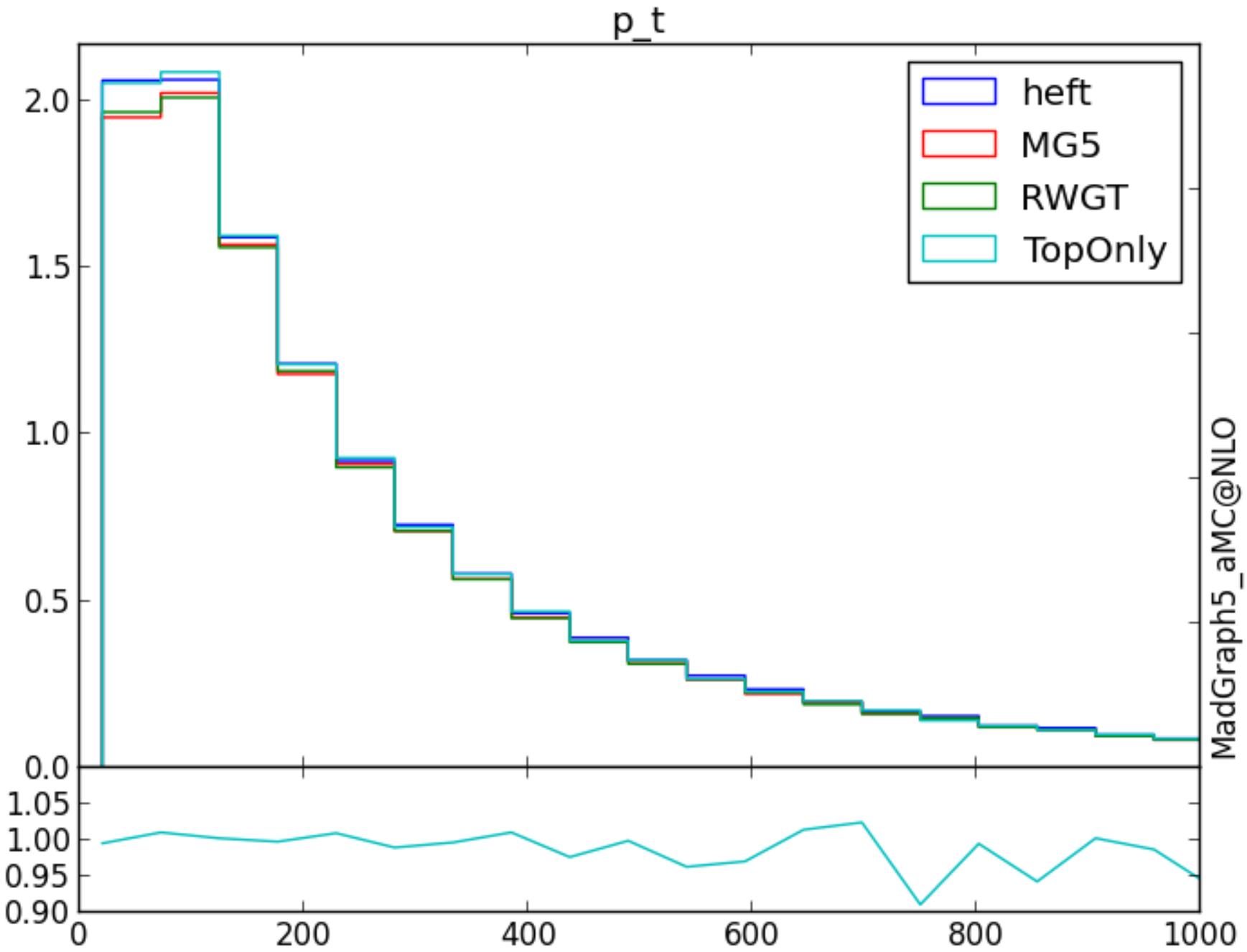




Validation

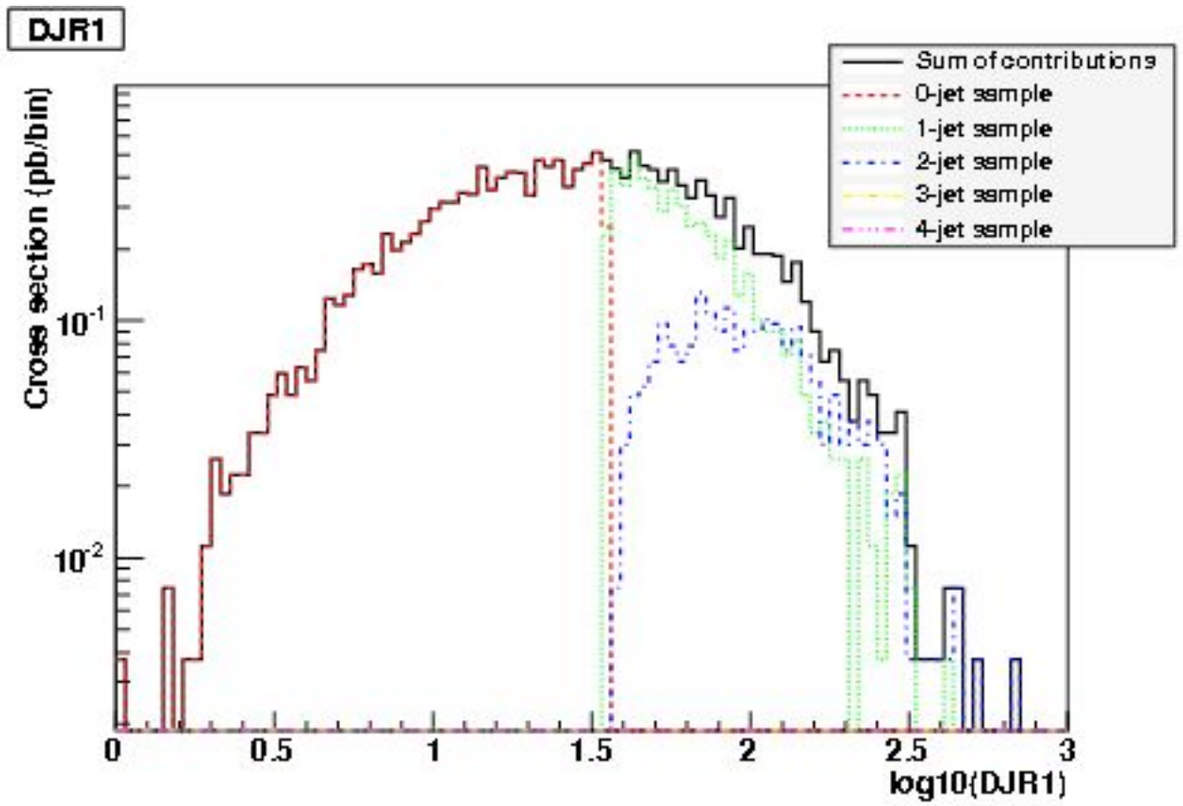

p_t
heft
MG5
RWGT
2.0
1.5
1.0
0.5
0.0
1.05
1.00
0.95
0.90
0
200
400
600
800
1000
MadGraph5_aMC@NLO

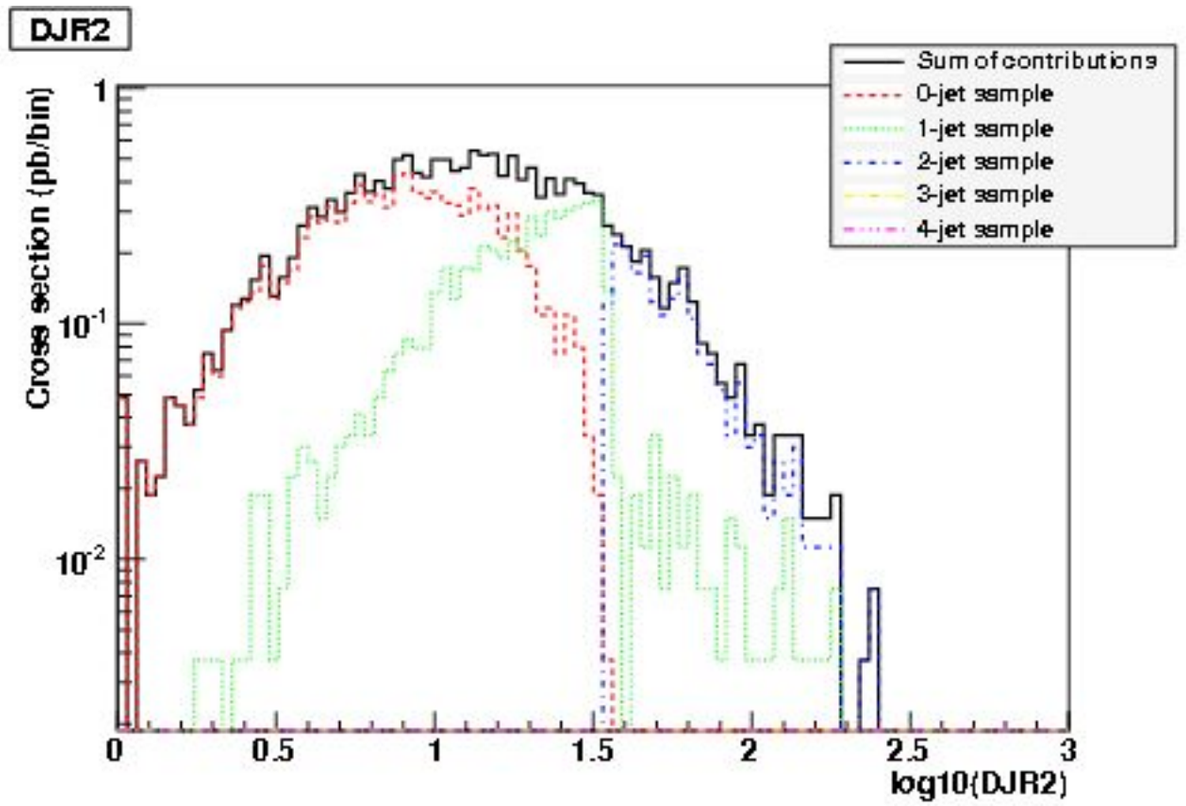
Validation


p_t
heft
MG5
RWGT
TopOnly
2.0
1.5
1.0
0.5
0.0
1.05
1.00
0.95
0.90
0
200
400
600
800
1000
MadGraph5_aMC@NLO

Matched/Merged

- Higgs Production up to two loop
  - ➡ not considering the VBS production

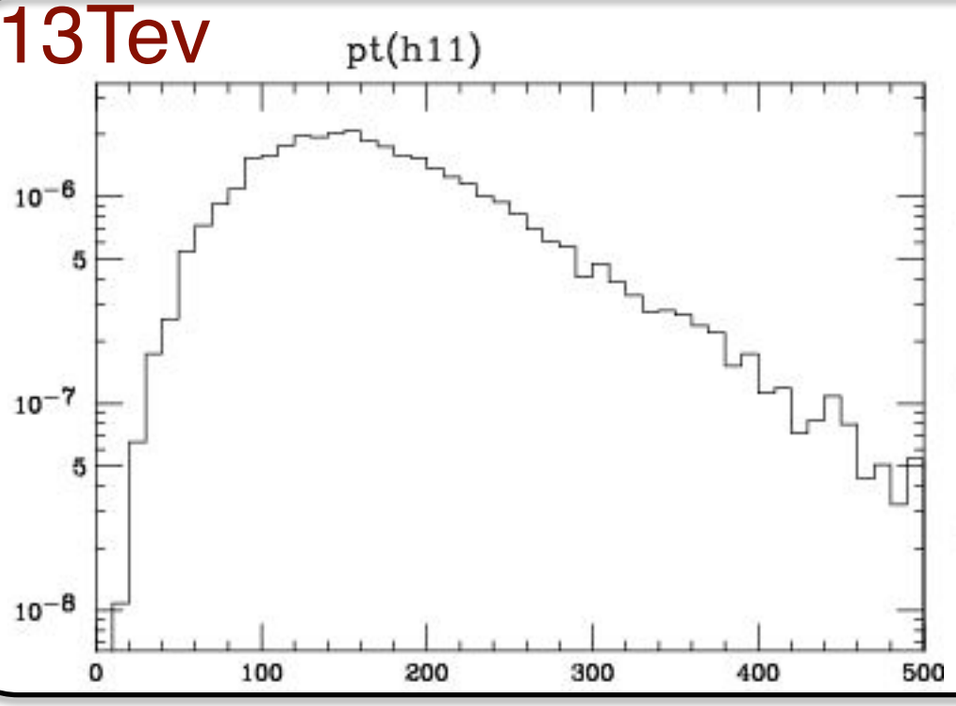


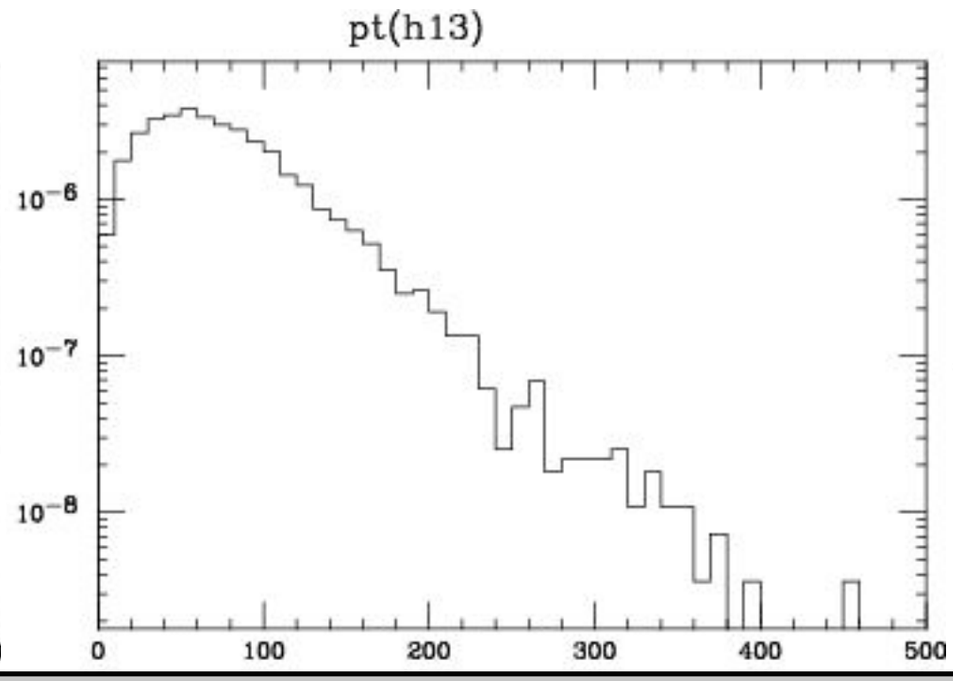


Three Higgs

- Important for the quartic term

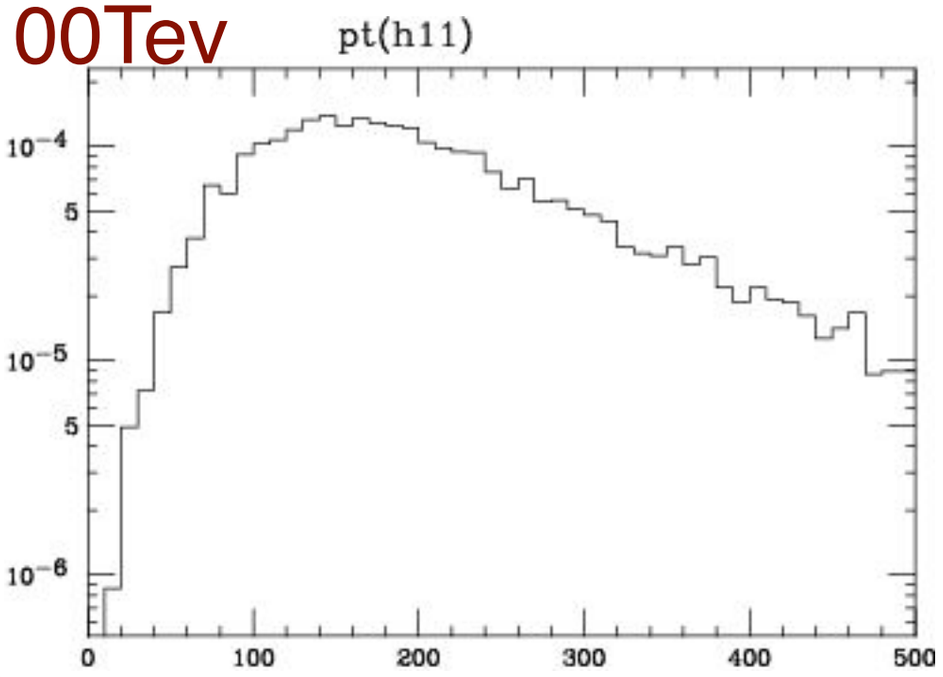
13Tev

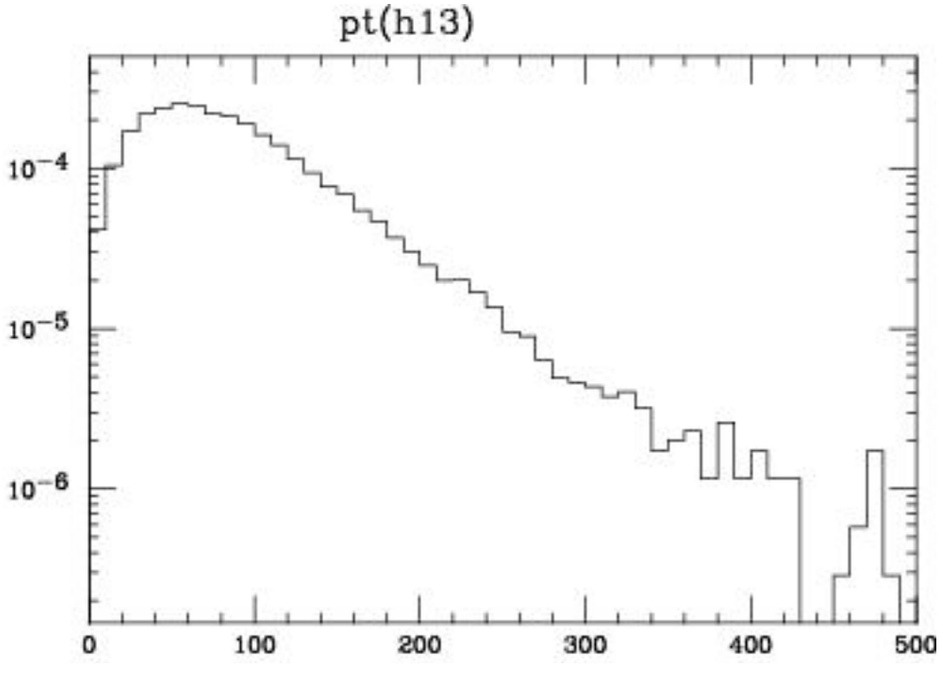




$3.6\,10^{-5} pb$

100Tev

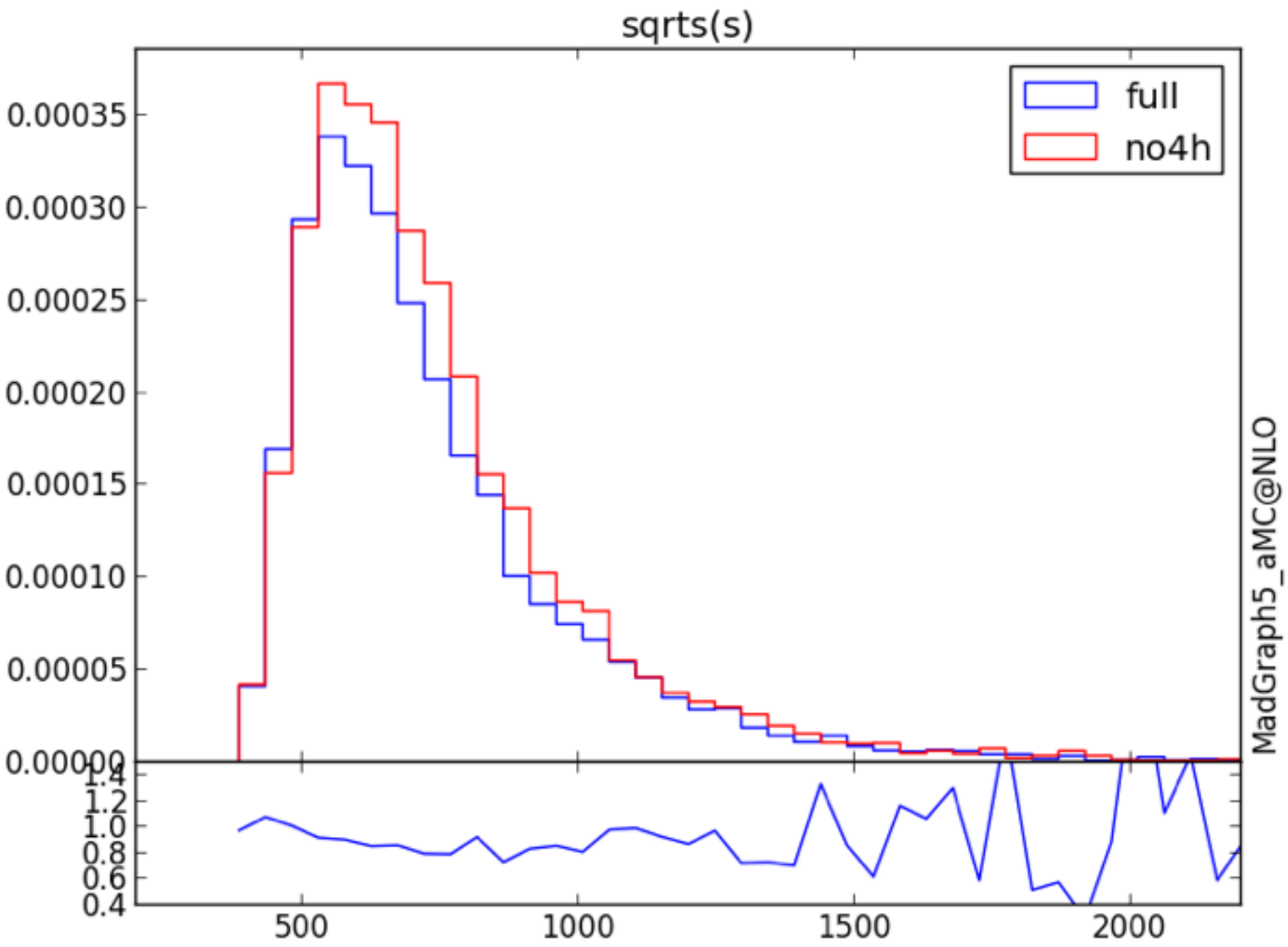




$2.8\,10^{-3} pb$

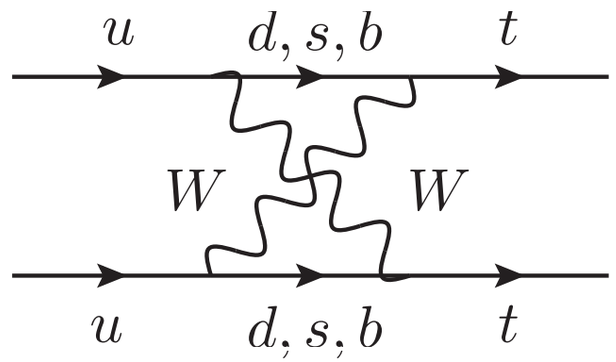
Three Higgs

- What is the sensitivity in the 4 Higgs coupling:



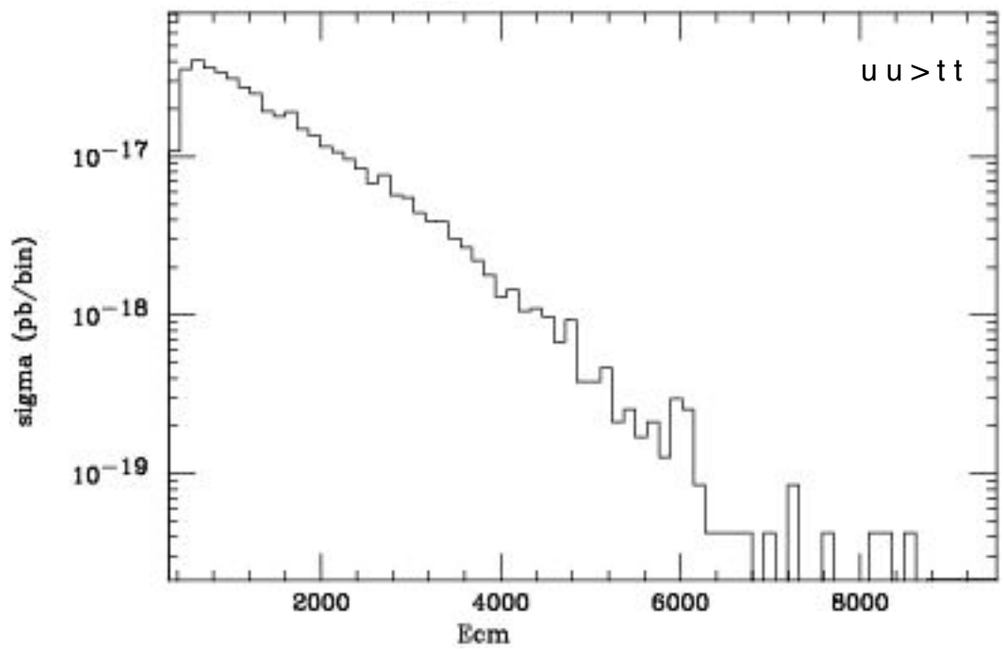
p p > t t

- Same sign top discovery will be the proof of New Physics but this process exists in the SM
- QED Loop
- suppressed by CKM/bottom mass



- Never computed before

$$\sigma_{loop} = 2.23(1)10^{-15} pb$$



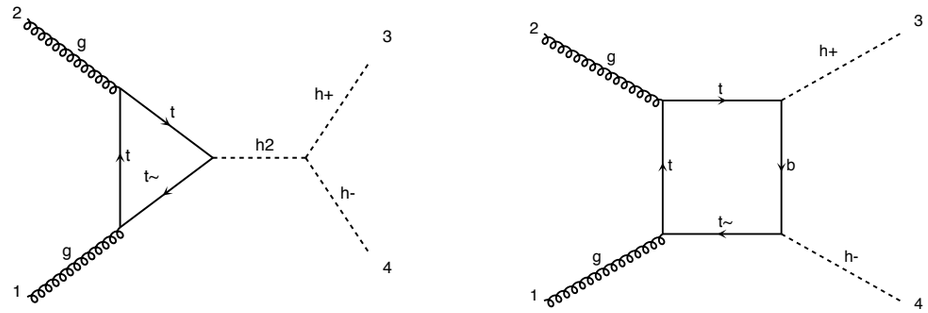
p p > h+ h-

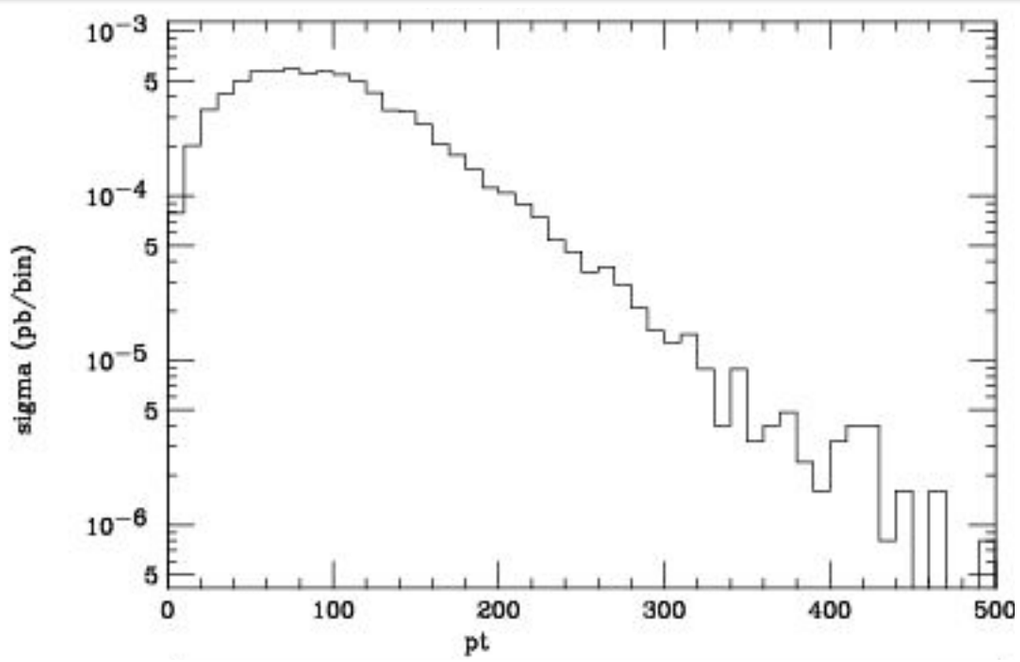
Model

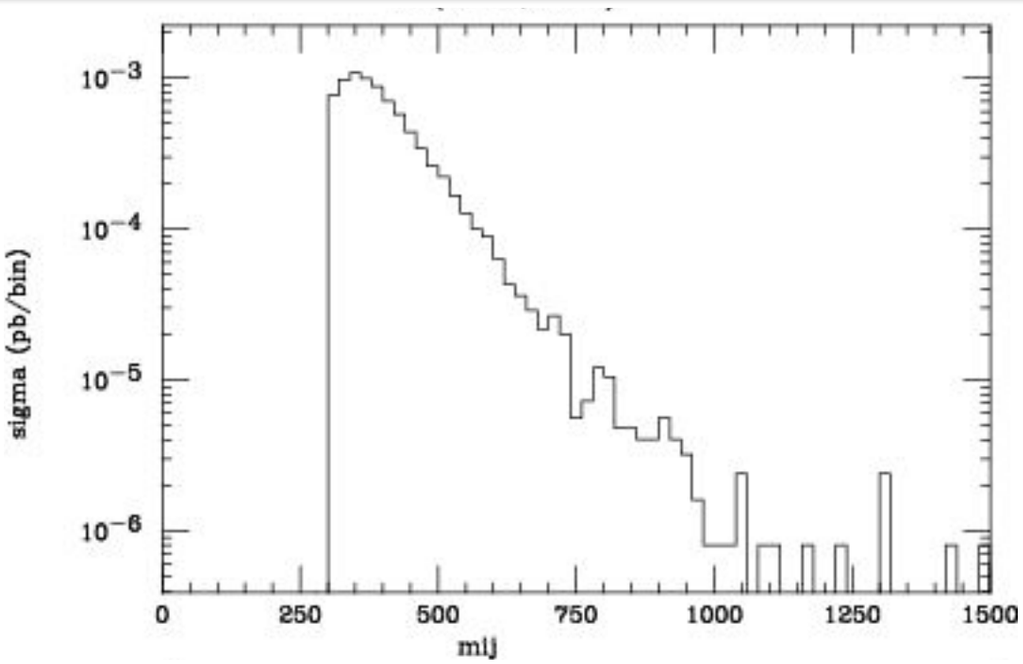
- 2HDM type II (generate via NLOCT)
- massive b

Loop

$$\sigma_{loop} = 0.00803(1)pb$$







Status

- 2 to 2 processes: OK on a laptop
- 2 to 3 processes: OK on a small size cluster
- 2 to 4 processes: Specific case

Process		Syntax	Cross section (pb) 13 TeV	
Single boson + jets				
a.1	$pp \to H$	`p p > h [noborn=QCD]`	17.77 ± 0.060	$^{+31.3\%}_{-23.1\%}$ $^{+0.7\%}_{-1.0\%}$
a.2	$pp \to Hj$	`p p > h j [noborn=QCD]`	14.82 ± 0.010	$^{+43.9\%}_{-28.4\%}$ $^{+0.6\%}_{-0.9\%}$
a.3	$pp \to Hjj$	`p p > h j j [noborn=QCD]`	8.807 ± 0.010	$^{+65.3\%}_{-36.9\%}$ $^{+0.8\%}_{-1.0\%}$
a.4	$gg \to Zg$	`g g > z g [noborn=QCD]`	51.80 ± 0.050	$^{+46.3\%}_{-29.4\%}$ $^{+0.7\%}_{-1.1\%}$
a.5	$gg \to Zgg$	`g g > z g g [noborn=QCD]`	0.0	0% 0% 0% 0%
a.6	$gg \to \gamma g$	`g g > a g [noborn=QCD]`	0.0	0% 0% 0% 0%
a.7	$gg \to \gamma gg$	`g g > a g g [noborn=QCD]`	0.0	0% 0% 0% 0%

Process		Syntax	Cross section (pb) 13 TeV	
Double bosons + jet				
b.1	$pp \to HH$	`p p > h h [noborn=QCD]`	$1.547 \pm 0.002 \cdot 10^{-2}$	$^{+29.5\%}_{-21.4\%}$ $^{+1.3\%}_{-1.3\%}$
b.2	$pp \to HHj$	`p p > h h j [noborn=QCD]`	0.0	0% 0% 0% 0%
b.3	$pp \to H\gamma j$	`p p > h a j [noborn=QCD]`	0.0	0% 0% 0% 0%
b.4	$gg \to HZ$	`g g > h z [noborn=QCD]`	$6.180 \pm 0.010 \cdot 10^{-2}$	$^{+28.7\%}_{-20.9\%}$ $^{+1.1\%}_{-1.2\%}$
b.5	$gg \to HZg$	`g g > h z g [noborn=QCD]`	0.0	0% 0% 0% 0%
b.6	$gg \to ZZ$	`g g > z z [noborn=QCD]`	1.182 ± 0.003	$^{+26.5\%}_{-19.8\%}$ $^{+0.7\%}_{-1.0\%}$
b.7	$gg \to ZZg$	`g g > z z g [noborn=QCD]`	0.0	0% 0% 0% 0%
b.8	$gg \to Z\gamma$	`g g > z a [noborn=QCD]`	1.211 ± 0.006	$^{+29.2\%}_{-21.7\%}$ $^{+0.8\%}_{-1.1\%}$
b.9	$gg \to Z\gamma g$	`g g > z a g [noborn=QCD]`	0.0	0% 0% 0% 0%
b.10	$gg \to \gamma\gamma$	`g g > a a [noborn=QCD]`	$5.119 \pm 0.007 \cdot 10^{+2}$	$^{+68.8\%}_{-42.0\%}$ $^{+1.1\%}_{-1.5\%}$
b.11	$gg \to \gamma\gamma g$	`g g > a a g [noborn=QCD]`	0.0	0% 0% 0% 0%
b.12	$gg \to W^+W^+$	`g g > w+ w- [noborn=QCD]`	3.698 ± 0.010	$^{+26.0\%}_{-19.4\%}$ $^{+0.7\%}_{-1.0\%}$
b.13	$gg \to W^+W^-g$	`g g > w+ w- g [noborn=QCD]`	0.0	0% 0% 0% 0%

Process		Syntax	Cross section (pb) 13 TeV	
Triple bosons				
c.1	$pp \to HHH$	`p p > h h h [noborn=QCD]`	0.0	0% 0% 0% 0%
c.2	$gg \to HHZ$	`g g > h h z [noborn=QCD]`	0.0	0% 0% 0% 0%
c.3	$gg \to HZZ$	`g g > h z z [noborn=QCD]`	0.0	0% 0% 0% 0%
c.4	$gg \to HZ\gamma$	`g g > h z a [noborn=QCD]`	0.0	0% 0% 0% 0%
c.5	$pp \to H\gamma\gamma$	`p p > h a a [noborn=QCD]`	0.0	0% 0% 0% 0%
c.6	$pp \to HW^+W^-$	`g g > h w+ w- [noborn=QCD]`	0.0	0% 0% 0% 0%
c.7	$gg \to ZZZ$	`g g > z z z [noborn=QCD]`	0.0	0% 0% 0% 0%
c.8	$gg \to ZZ\gamma$	`g g > z z a [noborn=QCD]`	0.0	0% 0% 0% 0%
c.9	$gg \to Z\gamma\gamma$	`g g > z a a [noborn=QCD]`	0.0	0% 0% 0% 0%
c.10	$gg \to ZW^+W^-$	`g g > z w+ w- [noborn=QCD]`	0.0	0% 0% 0% 0%
c.11	$gg \to \gamma\gamma\gamma$	`g g > a a a [noborn=QCD]`	0.0	0% 0% 0% 0%
c.12	$gg \to \gamma W^+W^-$	`g g > a w+ w- [noborn=QCD]`	0.0	0% 0% 0% 0%

Process		Syntax	Cross section (pb) 13 TeV	
Selected $2 \to 4$				
d.1	$pp \to Hjjj$	`p p > h j j j [noborn=QCD]`	0.0	0% 0% 0% 0%
d.2	$pp \to HHjj$	`p p > h h j j [noborn=QCD]`	0.0	0% 0% 0% 0%
d.3	$gg \to e^+e^-\mu^+\mu^-$	`g g > e+ e- mu+ mu- [noborn=QCD]`	0.0	0% 0% 0% 0%
d.4	$pp \to HZ\gamma j$	`g g > h z a g [noborn=QCD]`	0.0	0% 0% 0% 0%
d.5	$gg \to W^+W^-W^+W^-$	`g g > w+ w- w+ w- [noborn=QCD]`	0.0	0% 0% 0% 0%
	e^+e^- processes			$\hat{s} = 500$ GeV
e.1	$e^+e^- \to ggg$	`e+ e- > g g g [noborn=QED]`	0.0	0% 0% 0% 0%
e.2	$e^+e^- \to HH$	`e+ e- > h h [noborn=QED]`	0.0	0% 0% 0% 0%
e.3	$e^+e^- \to HHgg$	`e+ e- > h h g g [noborn=QED]`	0.0	0% 0% 0% 0%

Conclusion

- MadGraph5_aMC@NLO
  - ➡ Framework for LO and NLO computation
  - ➡ Fixed order or matched to the shower
  - ➡ Merging possible
- Loop-Induced
  - ➡ Re-weighting
  - ➡ Phase-Space Integration
  - ➡ Both will be released soon

Demo

Olivier Mattelaer
IPPP/Durham

Demo Plan

Example I: HEFT

- Model Description
- Width Computation
- Decay Chain

Example II: MSSM

- Fermion Flow
- Model support
- Systematics

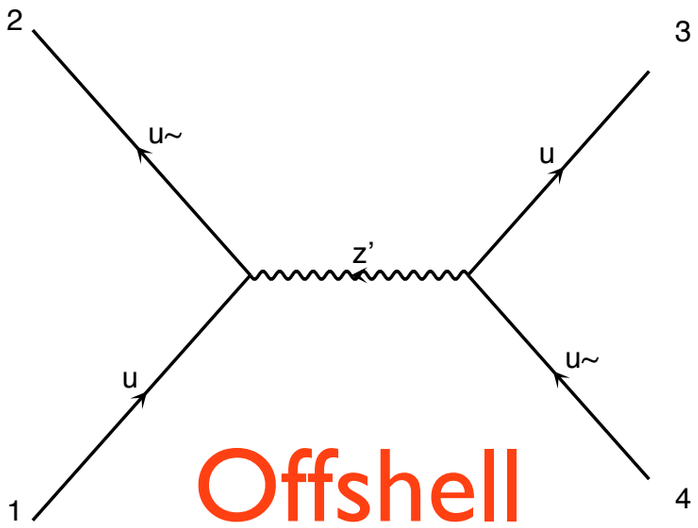
Example III: NLO

Effective Operator

- New Physics at (too?) High Energy

Effective Operator

- New Physics at (too?) High Energy

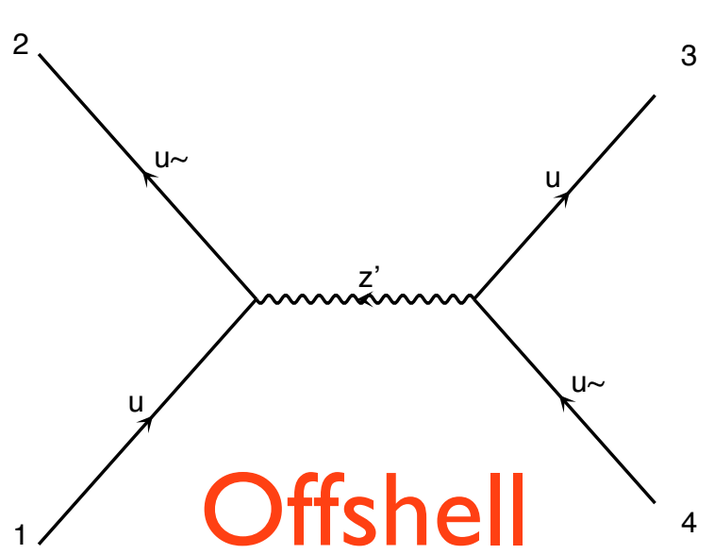


Offshell

$$M_{Z'} \gg \sqrt{\hat{S}}$$

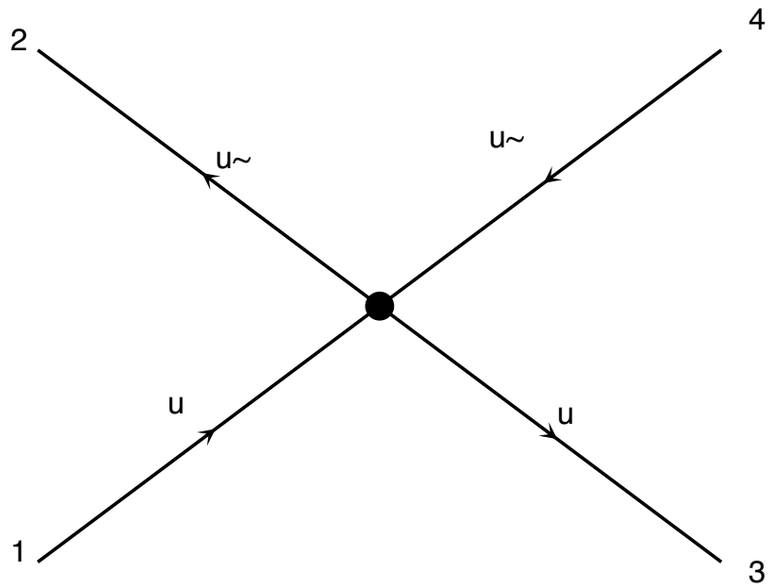
Effective Operator

- New Physics at (too?) High Energy



Offshell

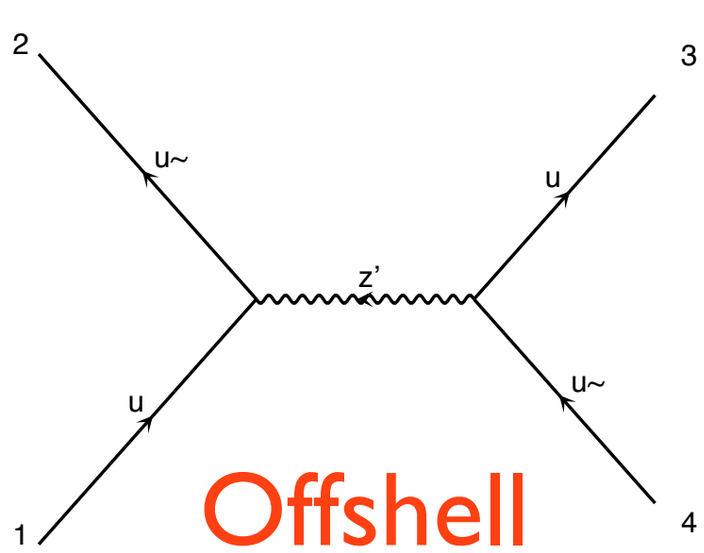
$$M_{Z'} \gg \sqrt{\hat{S}}$$



Effective Vertex

Effective Operator

- New Physics at (too?) High Energy



Offshell

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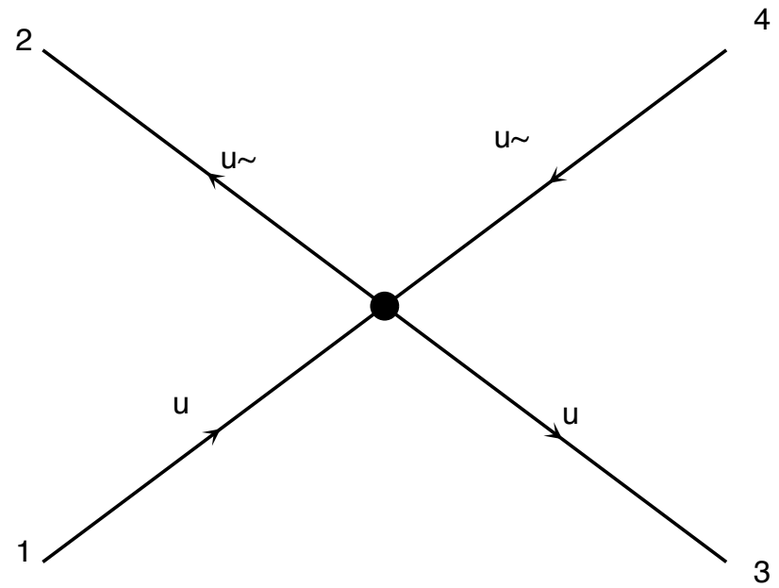


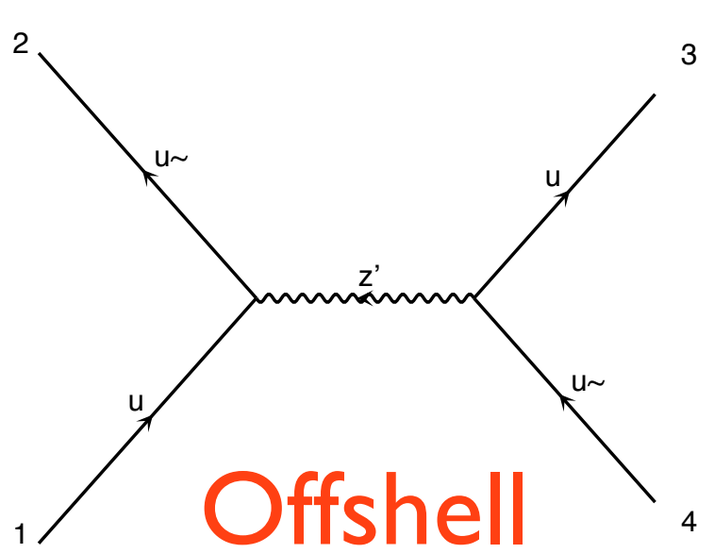
Effective Vertex

☞ Additional terms in the Lagrangian

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \dots$$

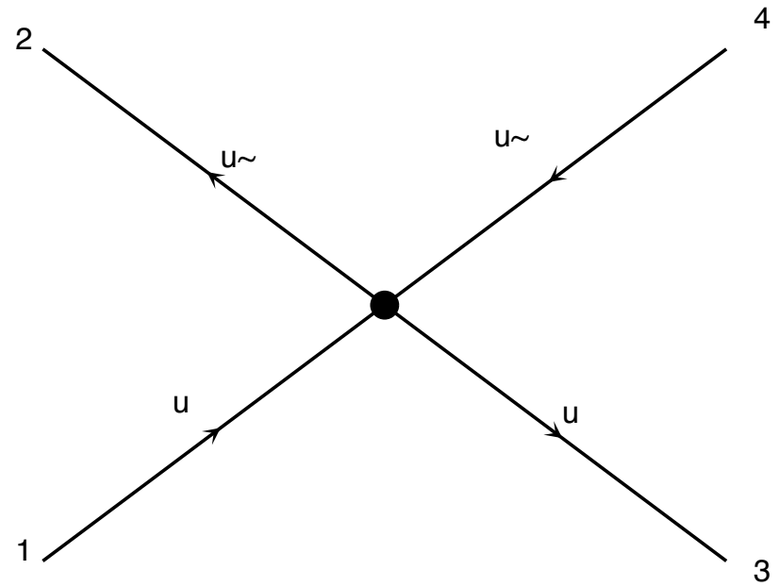
Effective Operator

- New Physics at (too?) High Energy



Offshell

$$M_{Z'} \gg \sqrt{\hat{S}}$$



Effective Vertex

☞ Additional terms in the Lagrangian

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cancel{\frac{1}{\Lambda^4}\mathcal{L}_8} + \dots$$

Effective Field Theory

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^2} \mathcal{O}_i$$

The number of possible Operators are huge

- 59 Dimension 6 Operators If
  - ☞ Preserve the SM gauge symmetries
  - ☞ Preserve B-L accidental symmetries
  - ☞ We consider only one flavor

Effective Field Theory

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^2} \mathcal{O}_i$$

The number of possible Operators are huge

- 59 Dimension 6 Operators If
  - ☞ Preserve the SM gauge symmetries
  - ☞ Preserve B-L accidental symmetries
  - ☞ We consider only one flavor

- Only One Dimension 5 Operator:

$$\mathcal{O} = LHLH$$

Give a mass to the neutrino

Effective Field Theory

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^2} \mathcal{O}_i$$

- Only few Operators for one process and different effects

Weak Boson production

Conserving CP

$$\mathcal{O}_{WWW} = \mathrm{Tr}[W_{\mu\nu} W^{\nu\rho} W^{\mu}_{\rho}]$$
$$\mathcal{O}_{W} = (D_\mu \Phi)^\dagger W^{\mu\nu} (D_\nu \Phi)$$
$$\mathcal{O}_{B} = (D_\mu \Phi)^\dagger B^{\mu\nu} (D_\nu \Phi)$$

Not Conserving CP

$$\mathcal{O}_{\tilde{W}WW} = \mathrm{Tr}[\tilde{W}_{\mu\nu} W^{\nu\rho} W^{\mu}_{\rho}]$$
$$\mathcal{O}_{\tilde{W}} = (D_\mu \Phi)^\dagger \tilde{W}^{\mu\nu} (D_\nu \Phi)$$

Demo 1

BASIC COMMAND

- import model EWDim6
- generate p p > w- z
- output
- launch

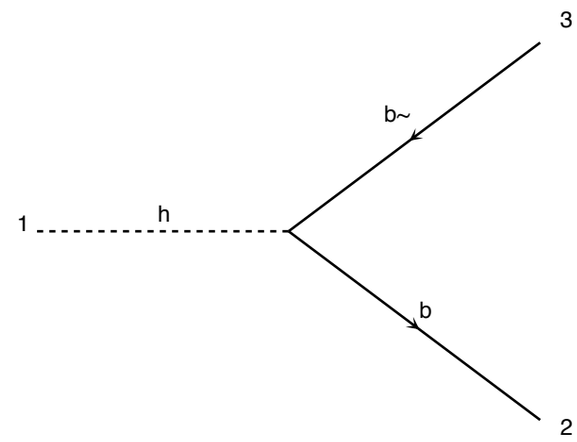
SM + Interference

- import model EWDim6
- generate p p > w- z NP^2<=2
- output
- launch

2-body decay

2 body decay

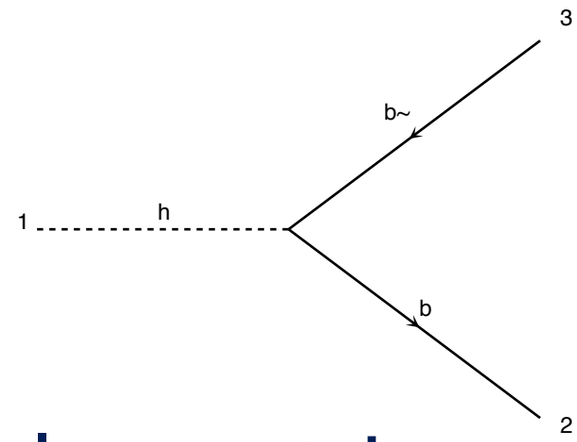
$$\Gamma = \frac{1}{2MS} \int d\Phi_2 |\mathcal{M}|^2$$



2-body decay

2 body decay

$$\Gamma = \frac{1}{2MS} \int d\Phi_2 |\mathcal{M}|^2$$



- By Lorentz Invariance the matrix element is constant over the phase-space.

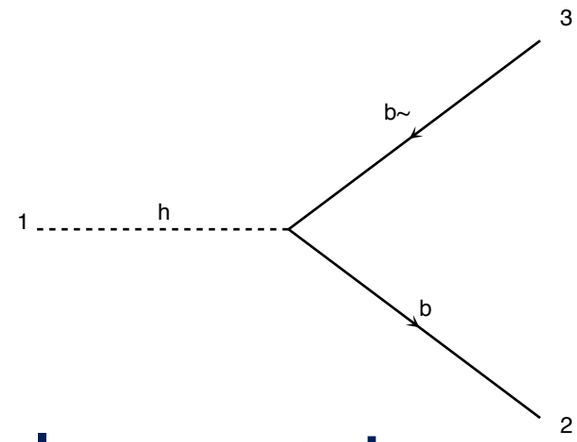
$$\Gamma = \frac{\sqrt{\lambda(M^2, m_1^2, m_2^2)}|\mathcal{M}|^2}{16\pi S M^3}$$

$$\lambda(M^2, m_1^2, m_2^2) = \left(M^2 - m_1^2 - m_2^2\right)^2 - 4m_1^2 m_2^2$$

2-body decay

2 body decay

$$\Gamma = \frac{1}{2MS} \int d\Phi_2 |\mathcal{M}|^2$$



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$$\Gamma = \frac{\sqrt{\lambda(M^2, m_1^2, m_2^2)}|\mathcal{M}|^2}{16\pi S M^3}$$

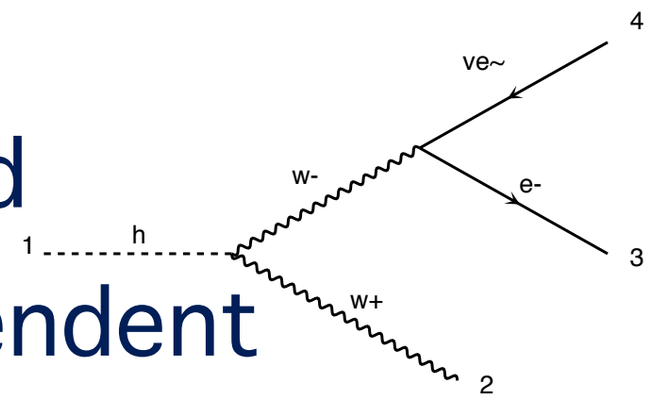
$$\lambda(M^2, m_1^2, m_2^2) = \left(M^2 - m_1^2 - m_2^2\right)^2 - 4m_1^2 m_2^2$$

- Calculable analytically by FeynRules

```
Decay_t = Decay(name = 'Decay_t',
                particle = P.t,
                partial_widths = {(P.W__plus__,P.d):'((MT**2 - MW**2)*((3*CKM3x1*ee**2*MT**2*complexconjugate(CKM3x1))/(2.*
                                  (P.W__plus__,P.s):'((MT**2 - MW**2)*((3*CKM3x2*ee**2*MT**2*complexconjugate(CKM3x2))/(2.*
                                  (P.W__plus__,P.b):'(((3*CKM3x3*ee**2*MB**2*complexconjugate(CKM3x3))/(2.*sw**2) + (3*CKM3
```

N Body Decay

3(and more)-body Decay



- Analytical Formula too complicated
  - ➡ Especially in a spectrum independent way
  - Numerical integration
- Need to remove double counting with 2-body
- Typically LO computation
  - Remove radiation diagram

Example of code

- Herwig / Bridge / MadWidth

MadWidth

hep-ph/1402.1178

2-body

- Use FeynRules formula (instantaneous)

MadWidth

hep-ph/1402.1178

2-body

- Use FeynRules formula (instantaneous)

Fast-Estimation of 3-body

- Only use 2-body decay and PS factor

MadWidth

hep-ph/1402.1178

2-body

- Use FeynRules formula (instantaneous)

Fast-Estimation of 3-body

- Only use 2-body decay and PS factor

Relevant?

MadWidth

hep-ph/1402.1178

2-body

- Use FeynRules formula (instantaneous)

Fast-Estimation of 3-body

- Only use 2-body decay and PS factor

Relevant?

No

DONE

MadWidth

hep-ph/1402.1178

2-body

- Use FeynRules formula (instantaneous)

Fast-Estimation of 3-body

- Only use 2-body decay and PS factor

Relevant?

Maybe

No

DONE

Channel Generation

- Remove Sequence of 2-body/radiation diagram

MadWidth

hep-ph/1402.1178

2-body

- Use FeynRules formula (instantaneous)

Fast-Estimation of 3-body

- Only use 2-body decay and PS factor

Relevant?

Maybe

No

DONE

Channel Generation

- Remove Sequence of 2-body/radiation diagram

Estimation of 3-body

- Based on the diagram. Approx. PS/Matrix-Element

Relevant?

MadWidth

hep-ph/1402.1178

2-body

- Use FeynRules formula (instantaneous)

Fast-Estimation of 3-body

- Only use 2-body decay and PS factor

Relevant?

Maybe

No

Channel Generation

- Remove Sequence of 2-body/radiation diagram

DONE

Estimation of 3-body

- Based on the diagram. Approx. PS/Matrix-Element

Relevant?

No

MadWidth

hep-ph/1402.1178

2-body

- Use FeynRules formula (instantaneous)

Fast-Estimation of 3-body

- Only use 2-body decay and PS factor

Relevant?

Maybe

No

Channel Generation

- Remove Sequence of 2-body/radiation diagram

DONE

Estimation of 3-body

- Based on the diagram. Approx. PS/Matrix-Element

No

Relevant?

Yes?

Numerical Integration

MadWidth

hep-ph/1402.1178

2-body

- Use FeynRules formula (instantaneous)

Fast-Estimation of 4 body

- Only use 2-body decay and PS factor

Relevant?

No

Maybe

Channel Generation

- Remove Sequence of 2-body/radiation diagram

DONE

No

Estimation of 4 body

- Based on the diagram. Approx. PS/Matrix-Element

Relevant?

Yes?

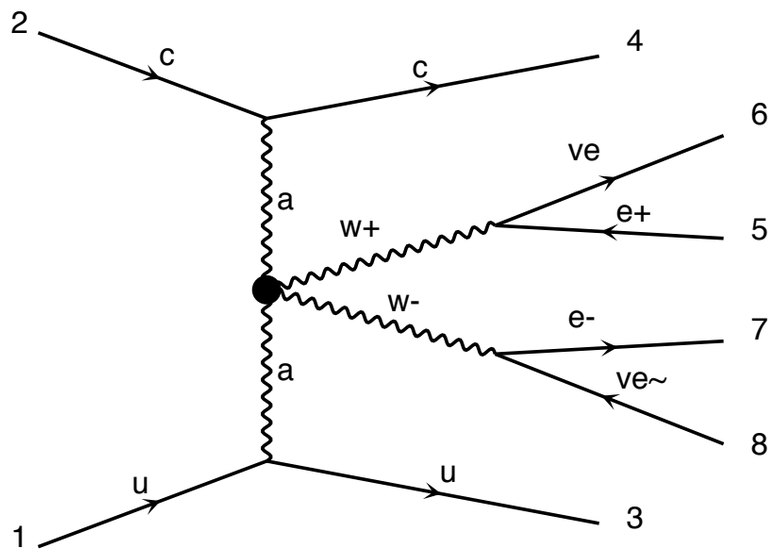
Numerical Integration

Demo 2

- MadWidth
- Run_card

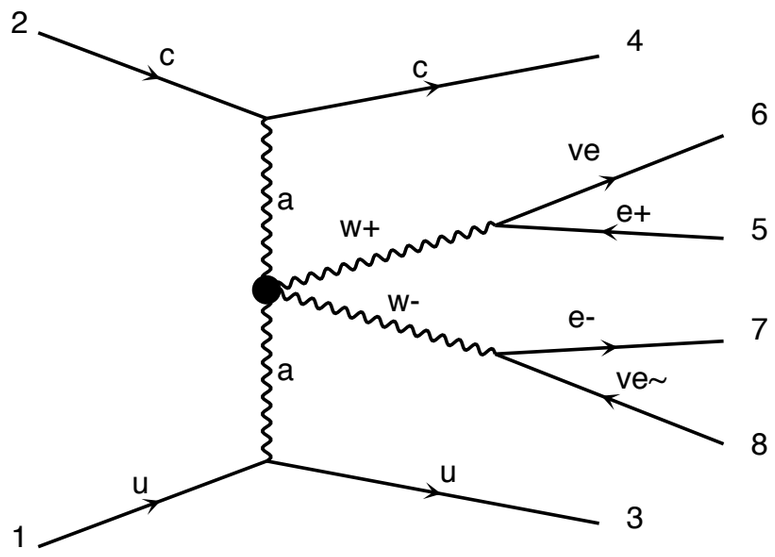
Decay

Resonant Diagram

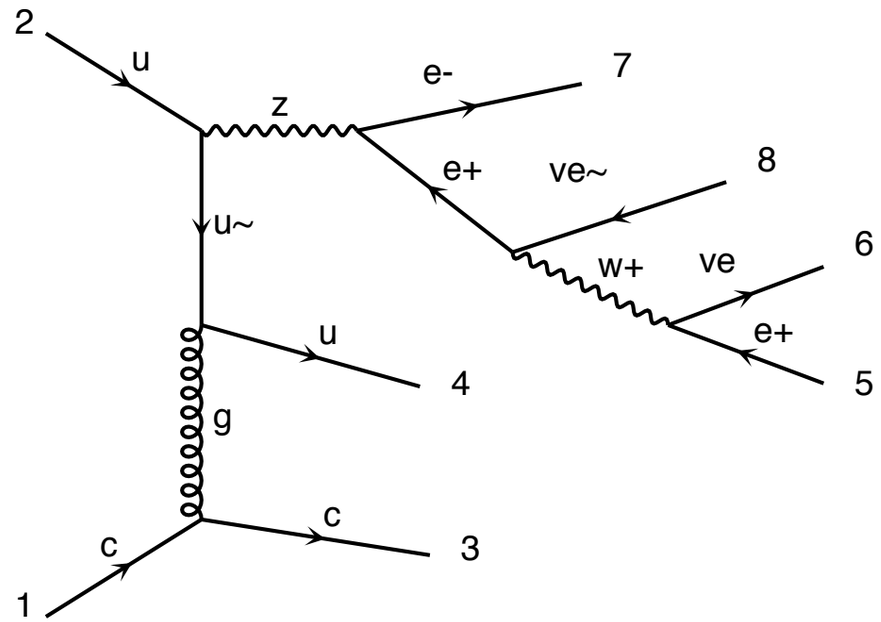


Decay

Resonant Diagram



Non Resonant Diagram



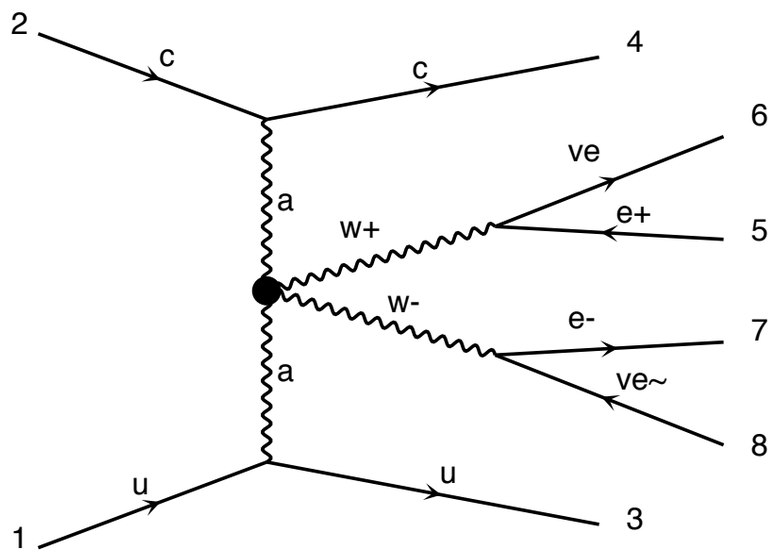
Problem

- Process complicated to have the full process

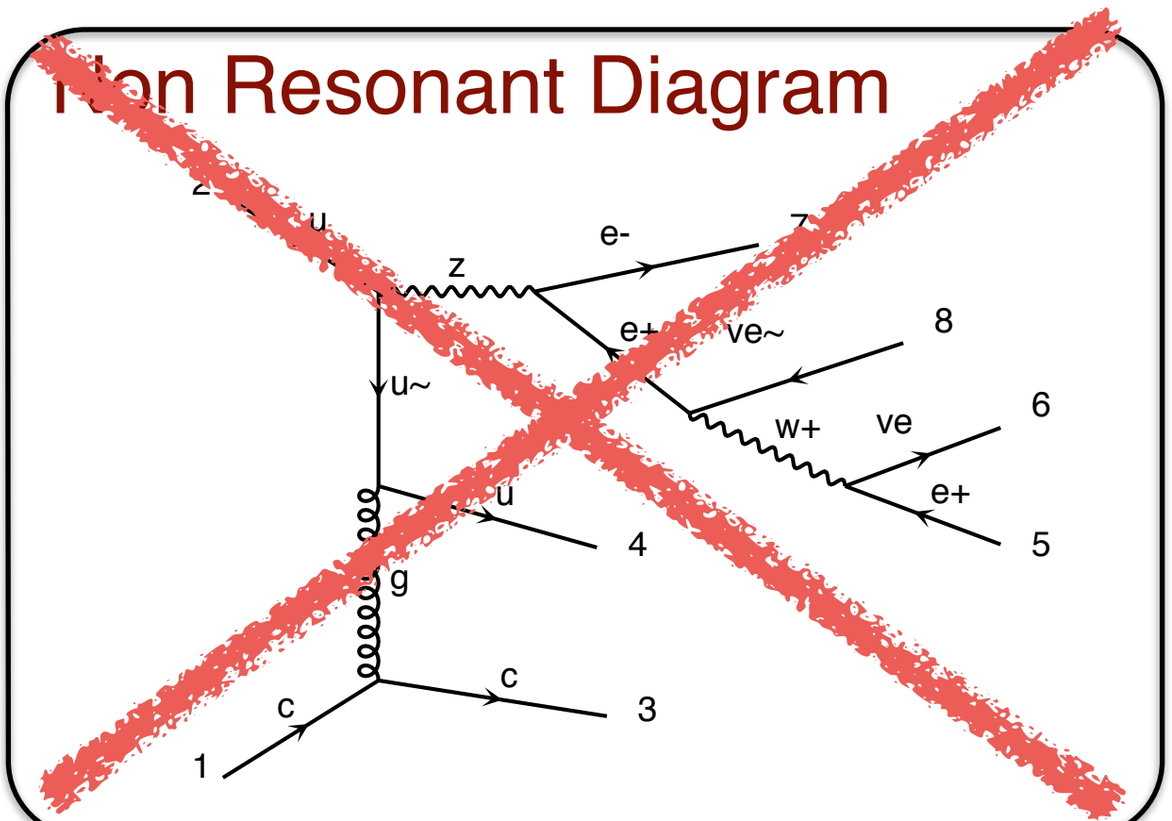
➡Including off-shell contribution

Decay

Resonant Diagram



Non Resonant Diagram



Problem

- Process complicated to have the full process

➡Including off-shell contribution

Solution

- Only keep on-shell contribution

Narrow-Width Approx.

Theory

$$\int dq^2 \left| \frac{1}{q^2 - M^2 - iM\Gamma} \right|^2 \approx \frac{\pi}{M\Gamma}\, \delta(q^2 - M^2)$$

$$\sigma_{full} = \sigma_{prod} * (BR + \mathcal{O}(\frac{\Gamma}{M}))$$

Comment

Narrow-Width Approx.

Theory

$$\int dq^2 \left| \frac{1}{q^2 - M^2 - iM\Gamma} \right|^2 \approx \frac{\pi}{M\Gamma}\, \delta(q^2 - M^2)$$

- This is an Approximation!
- This force the particle to be on-shell!

$$\sigma_{full} = \sigma_{prod} * (BR + \mathcal{O}(\frac{\Gamma}{M}))$$

Comment

- Recover by re-introducing the Breit-wigner up-to a cut-off

Decay chains

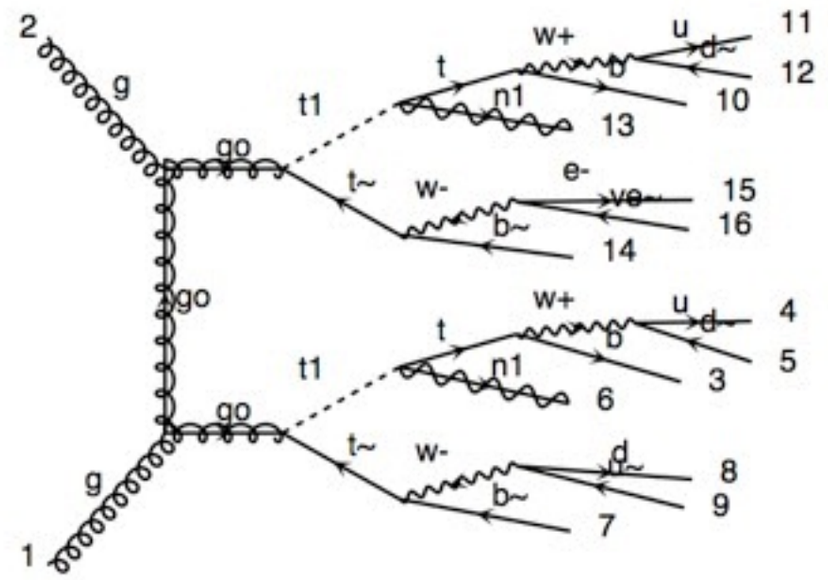
- p p > t t~ w+, (t > w+ b, w+ > l+ vl), \
  (t~ > w- b~, w- > j j), \
  w+ > l+ vl

- Separately generate core process and each decay
  - Decays generated with the decaying particle as resulting wavefunction
- Iteratively combine decays and core processes
- Difficulty: Multiple diagrams in decays

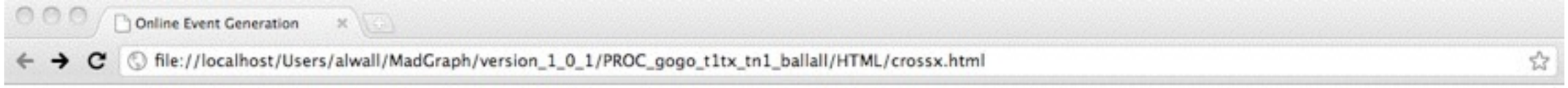
Decay chains

- Decay chains retain full matrix element for the diagrams compatible with the decay
- Full spin correlations (within and between decays)
- Full width effects
- However, no interference with non-resonant diagrams
  - ➡ Description only valid close to pole mass
  - ➡ Cutoff at $|m \pm n\Gamma|$ where n is set in run_card.

Decay chains



- 16-particle



Results for g g > go go , (go > t1 t~ , t~ > b~ all all / h+ , (t1 > t n1 , t > b all all / h+)) in the mssm

Available Results

Links	Events	Tag	Run	Collider	Cross section (pb)	Events
results banner	Parton-level LHE	fermi	test	p p 7000 x 7000 GeV	.33857E-03	10000

Main Page

Thanks to developments in MadEvent, also (very) long decay chains possible to simulate directly in MadGraph!

MadSpin

Read Event

generate a virtual mass

generate a decay

[Frixione, Leanen, Motylinski,Webber (2007)]

MadSpin

Read Event

generate a virtual mass

generate a decay

- Finite width

{

- Spin correlation
- unweighted events

[Frixione, Leanen, Motylinski, Webber (2007)]

MadSpin

Read Event

generate a virtual mass

generate a decay

{

- Finite width
- Spin correlation

$$|M^{P}_{LO}|^2 \longrightarrow |M^{P+D}_{LO}|^2$$

- unweighted events

[Frixione, Leanen, Motylinski, Webber (2007)]

MadSpin

Read Event

generate a virtual mass

generate a decay

{

Finite width

$$|M^P_{LO}|^2 \longrightarrow |M^{P+D}_{LO}|^2$$

Spin correlation

associate a weight to the event

$$|M^{P+D}_{LO}|^2 / |M^{P_{LO}}|^2$$

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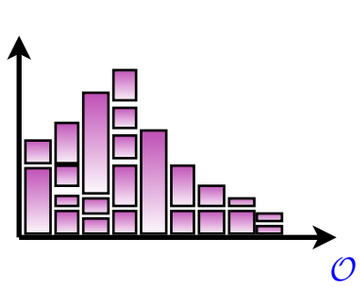

- Finite width
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- unweighted events

[Frixione, Leanen, Motylinski, Webber (2007)]

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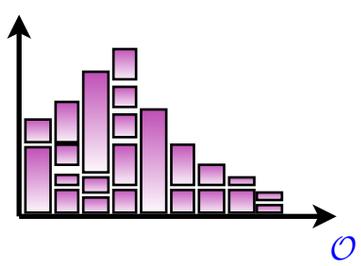
- Spin correlation

associate a weight to the event

$$|M^{P+D}_{LO}|^2 / |M^{P_{LO}}|^2 \quad \frac{d\sigma}{d\mathcal{O}}$$



unweighting

- Finite width
- Spin correlation
- unweighted events

[Frixione, Leanen, Motylinski, Webber (2007)]

MadSpin

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generate a virtual mass

generate a decay

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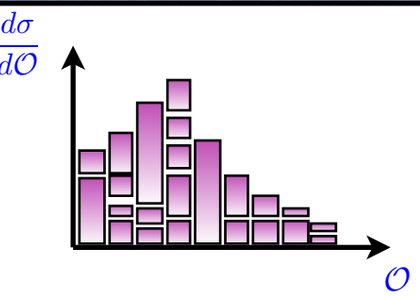
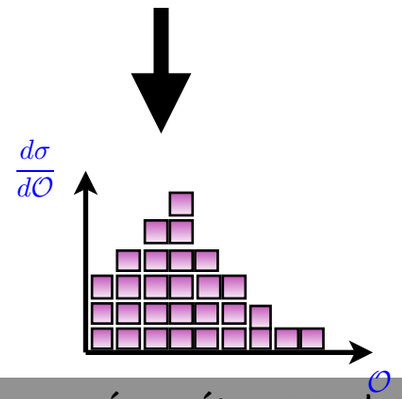
unweighting





- Finite width
- Spin correlation
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[Frixione, Leanen, Motylinski, Webber (2007)]

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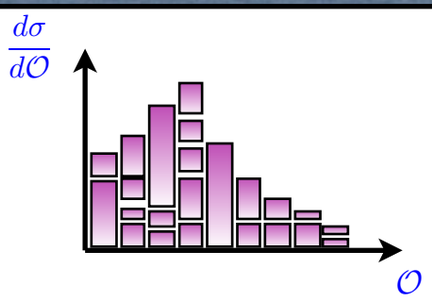
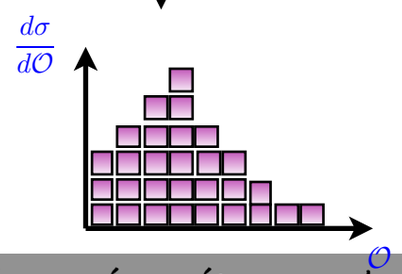


unweighting



PASS

- Finite width
- Spin correlation
- unweighted events

[Frixione, Leanen, Motylinski, Webber (2007)]

MadSpin

Read Event

generate a virtual mass

generate a decay

- Finite width

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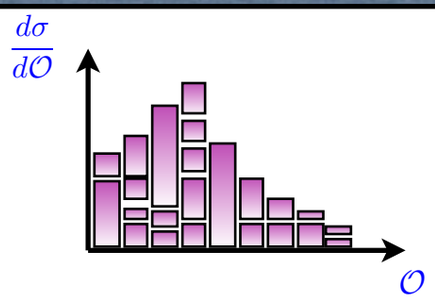
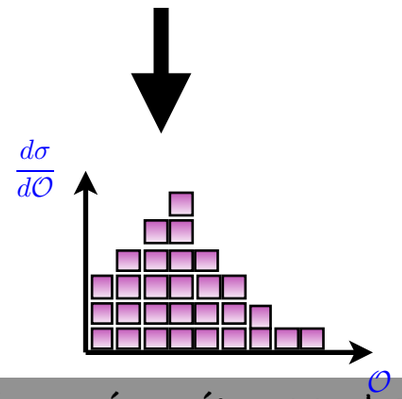


unweighting

FAIL

PASS



- Finite width
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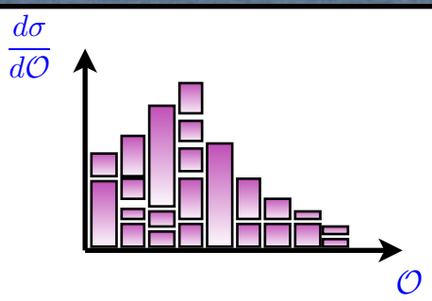
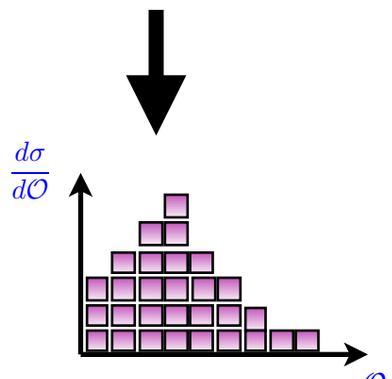


unweighting

FAIL

PASS



- Finite width
- Spin correlation
- unweighted events

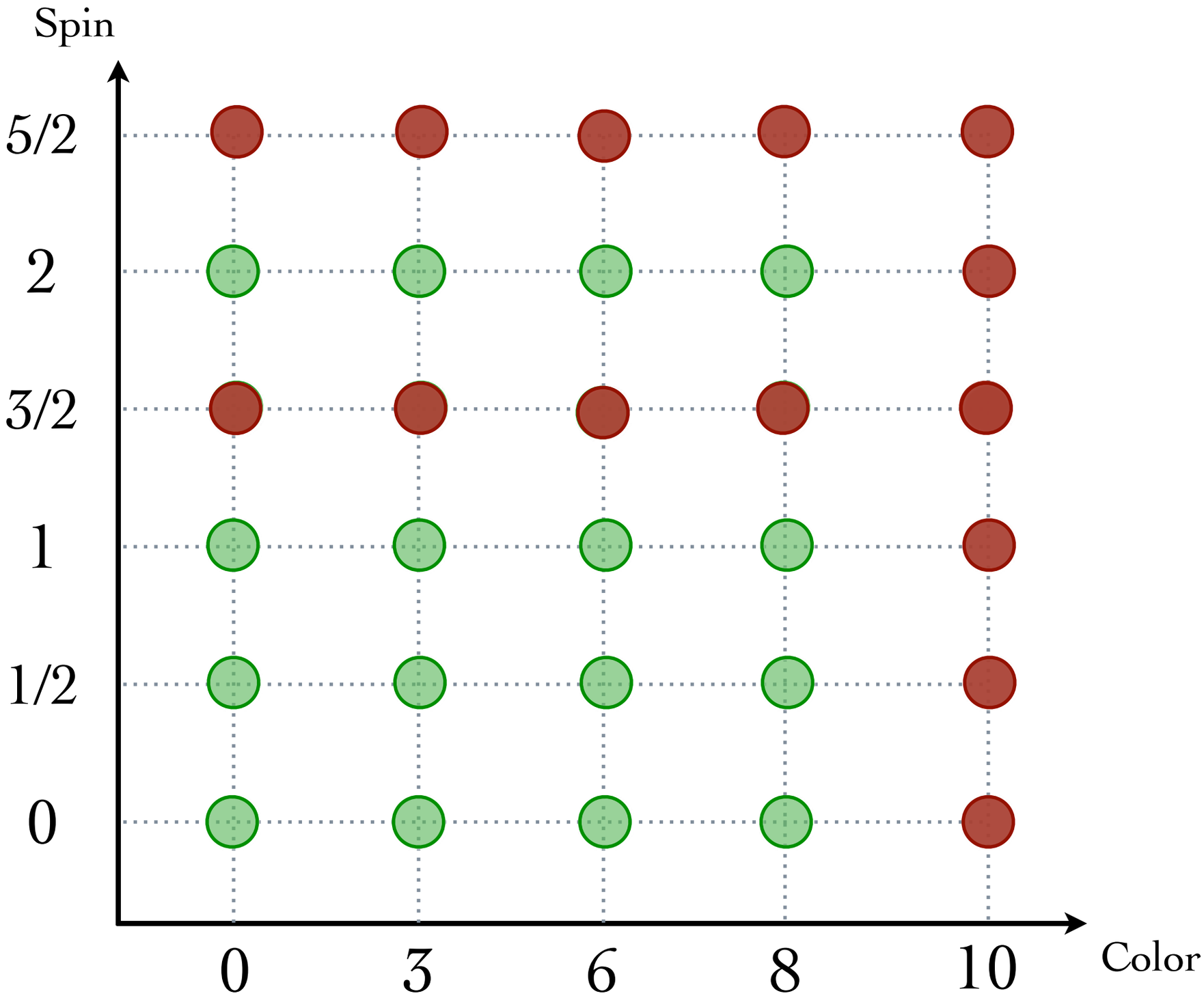
- Finite width
- Spin correlation
- unweighted events

[Frixione, Leanen, Motylinski, Webber (2007)]

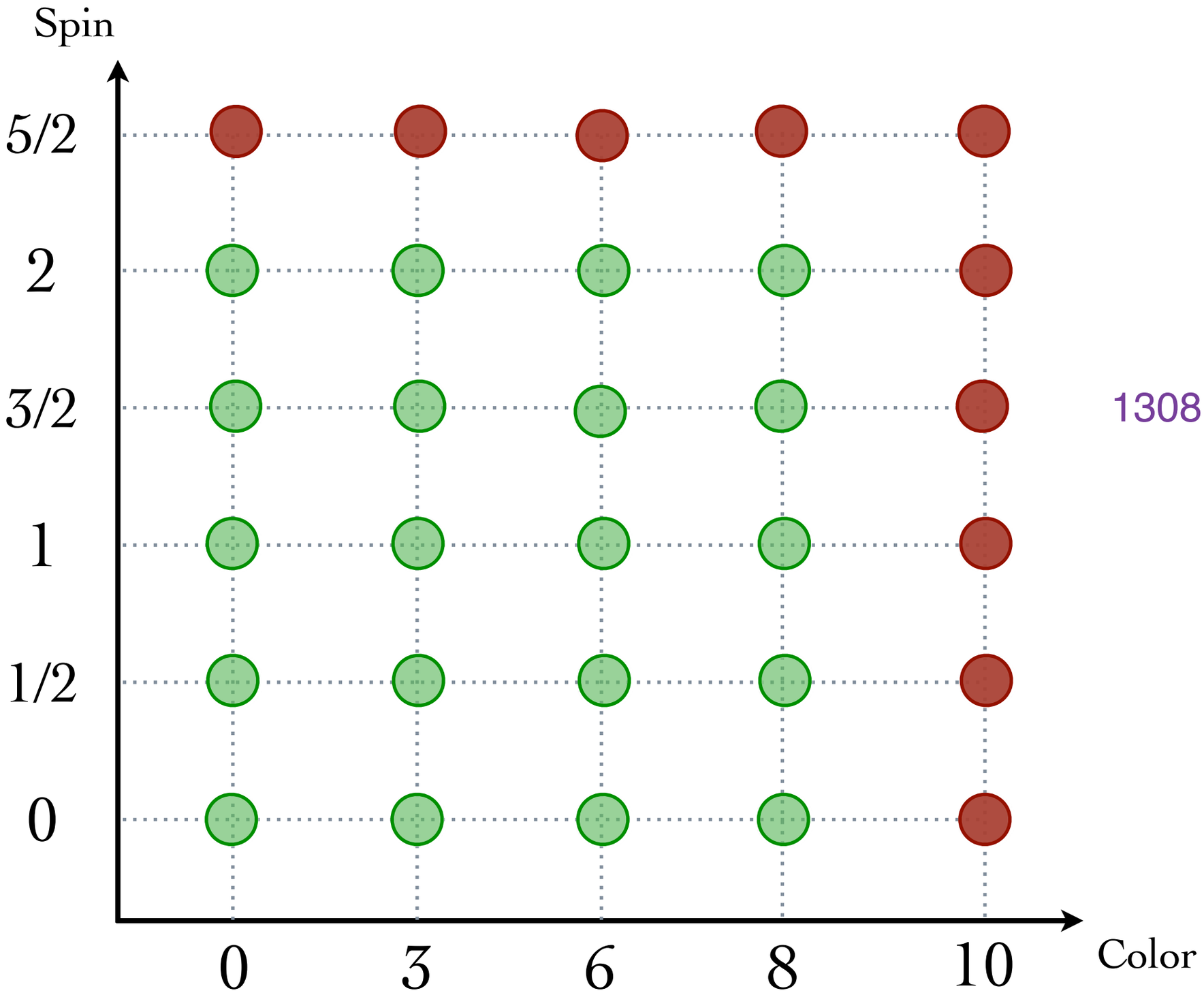
Demo 3

- Decay Chain
- MadSpin

Spin/Color

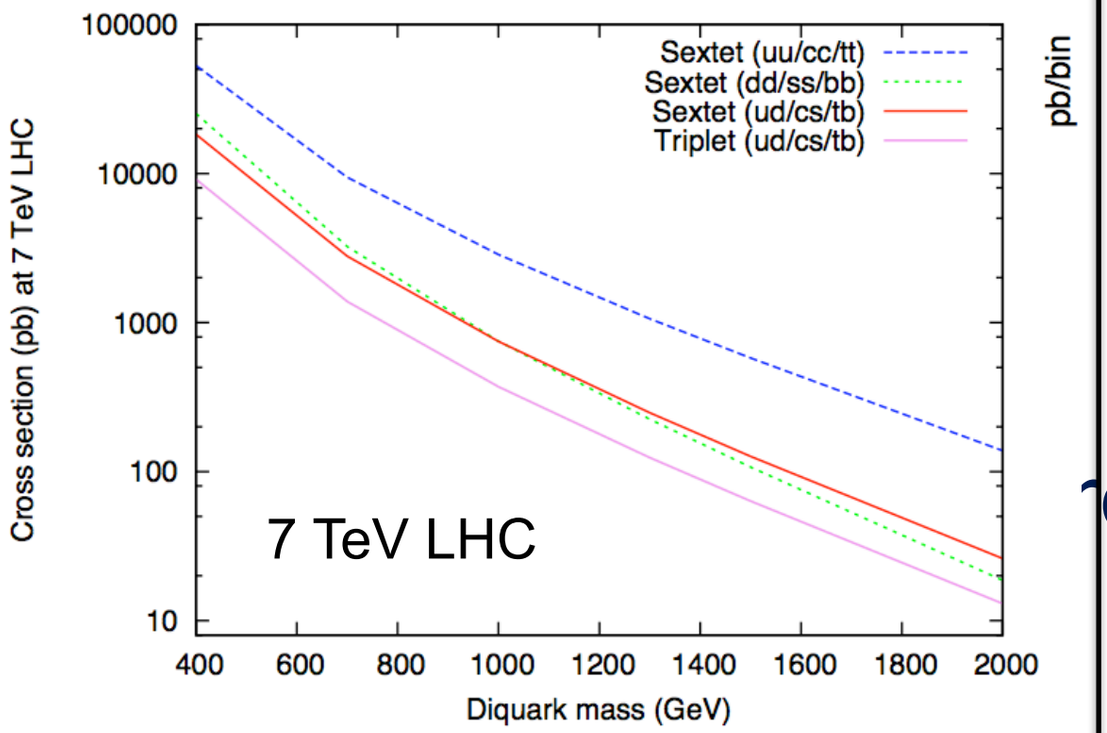


Spin/Color



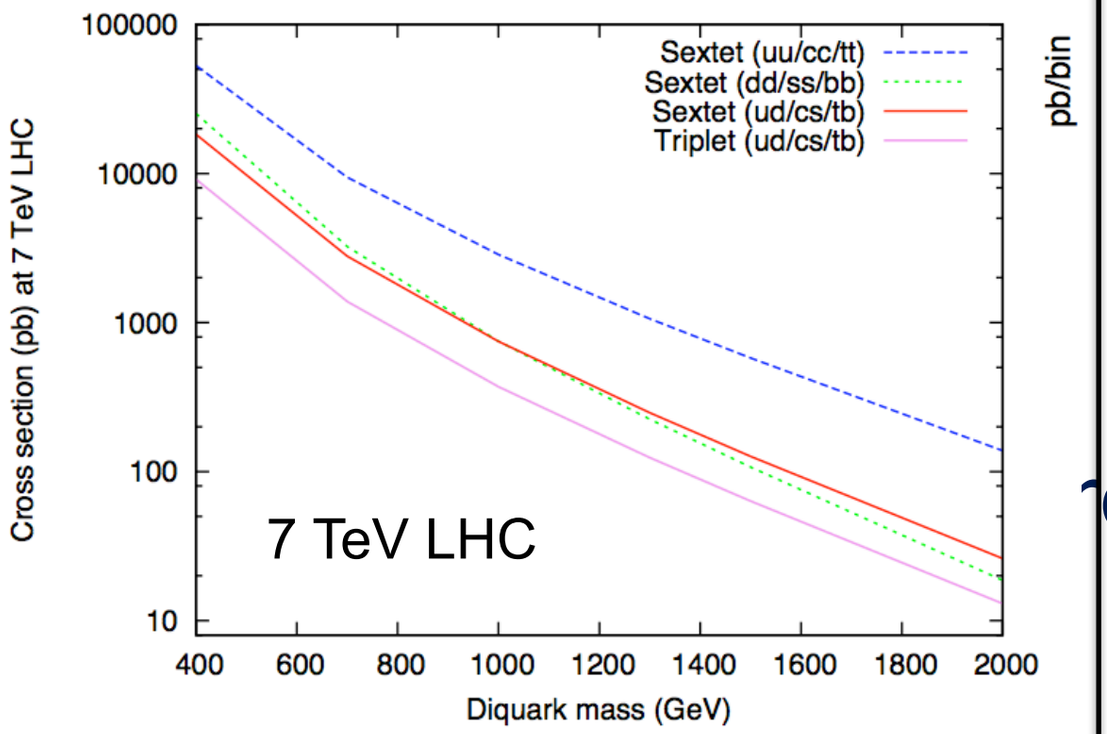
1308.1668

Diquark

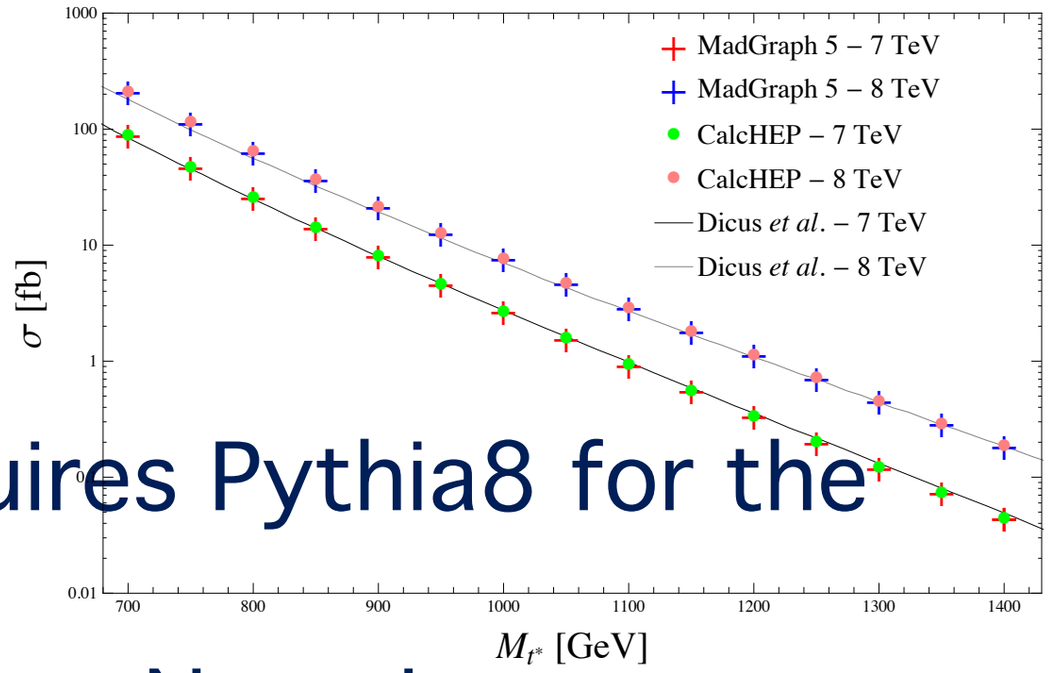


equires Pythia8 for the

Diquark



Spin 3/2



requires Pythia8 for the

- No unique convention for spin 3/2 and 2

➡Define your own propagator if needed

Systematics

$$\sum_{a,b} \int dx_1 dx_2 d\Phi_{\mathrm{FS}}\, f_a(x_1,\mu_F) f_b(x_2,\mu_F)\, \hat{\sigma}_{ab\to X}(\hat{s},\mu_F,\mu_R)$$

Phase-space integral

Parton density functions

Parton-level cross section

- Which scale to choose?
- Which PDF?

Scale

- No clear choice
- Typical recipe change your scale by a factor of Two

PDF

- Take the envelop

Demo

- Demo
  - ➡ SysCalc

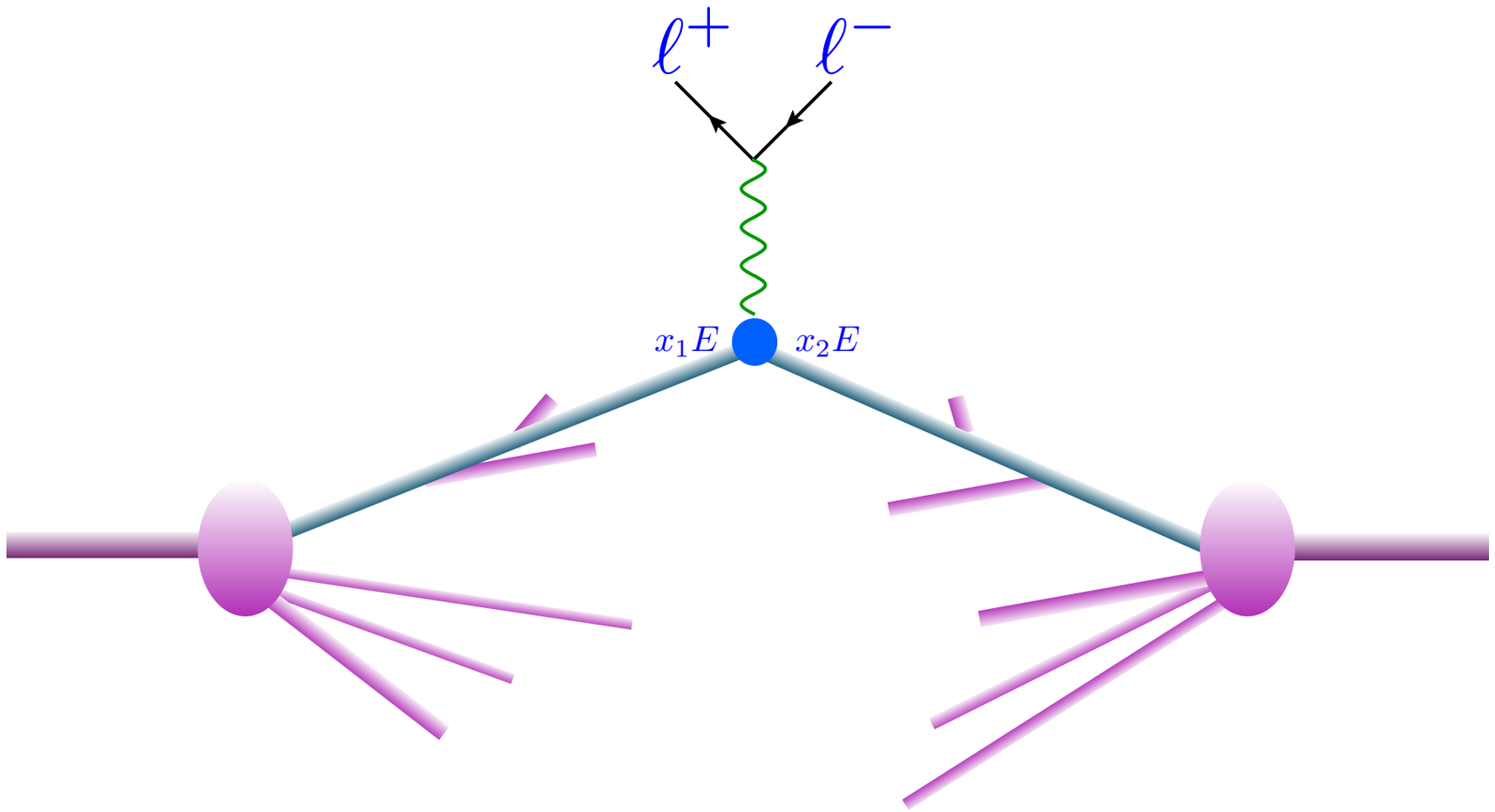
NLO corrections

- NLO corrections have three parts:
  - ➡The Born contribution, i.e. the Leading order.
  - ➡Virtual (or Loop) corrections: a closed loop of particles interfered with the Born amplitudes
  - ➡Real emission corrections: one extra parton compared to the Born process
- Both Virtual and Real emission have one power of α_s extra compared to the Born process

$$\sigma^{\mathrm{NLO}} = \int_m d\sigma^B + \int_m d\sigma^V + \int_{m+1} d\sigma^R$$

NLO predictions

- As an example, consider Drell-Yan Z/γ* production



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$$\hat{\sigma} = \sigma^{\text{Born}} \left(1 + \frac{\alpha_s}{2\pi} \sigma^{(1)} + \dots \right)$$

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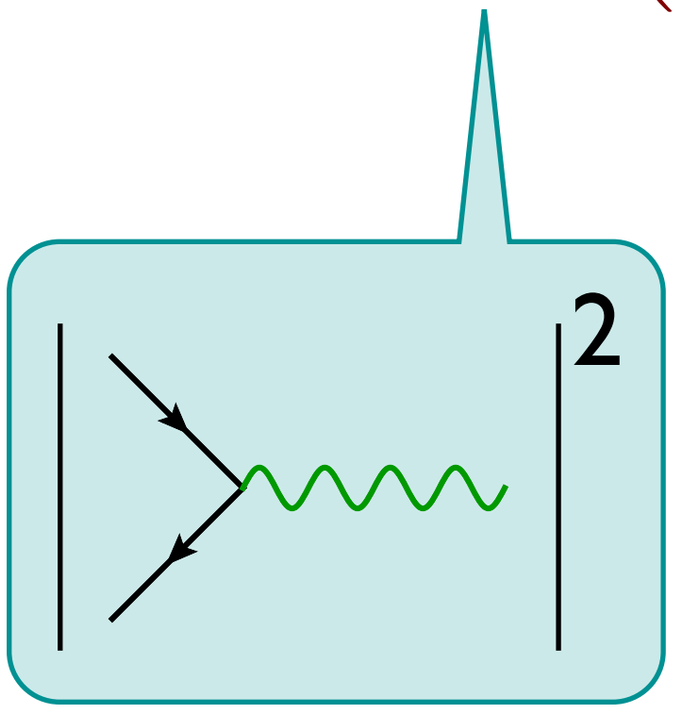

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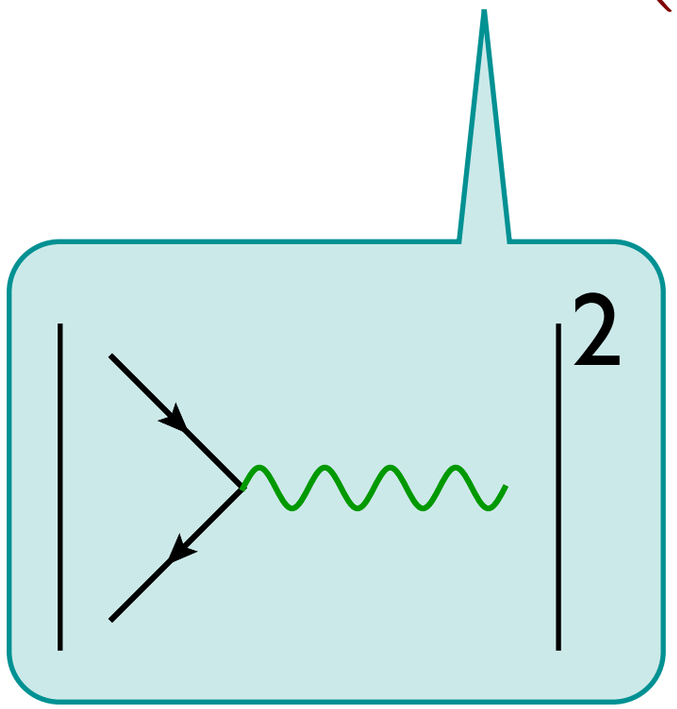

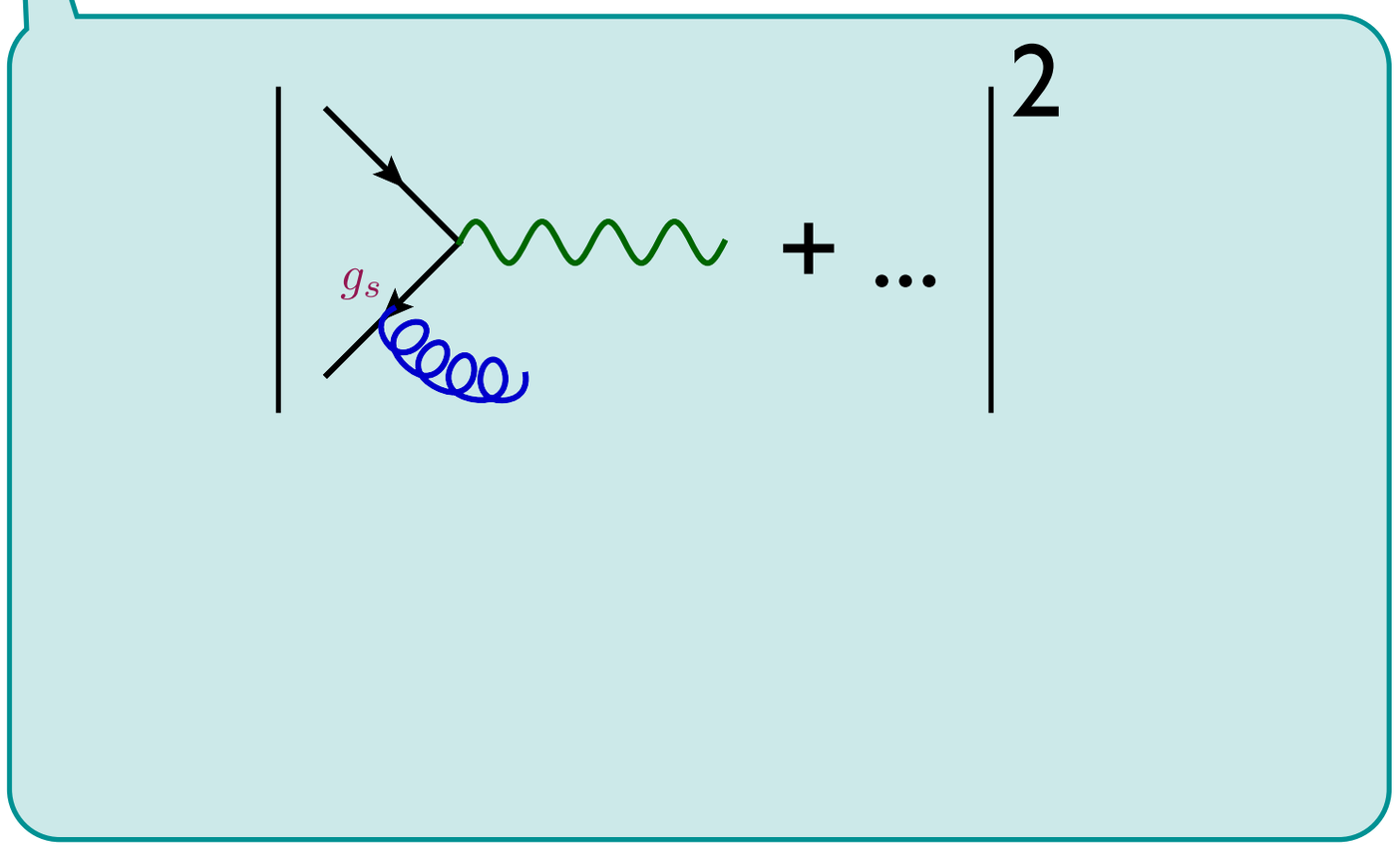

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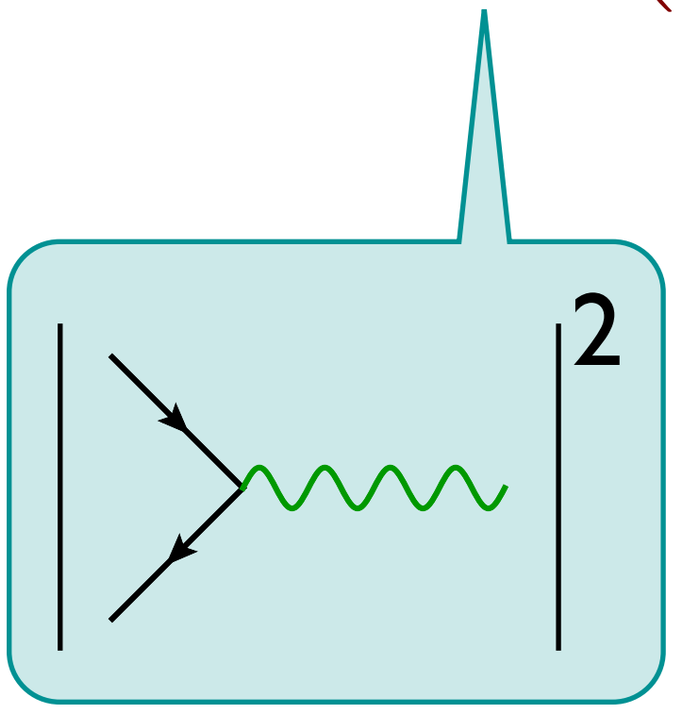

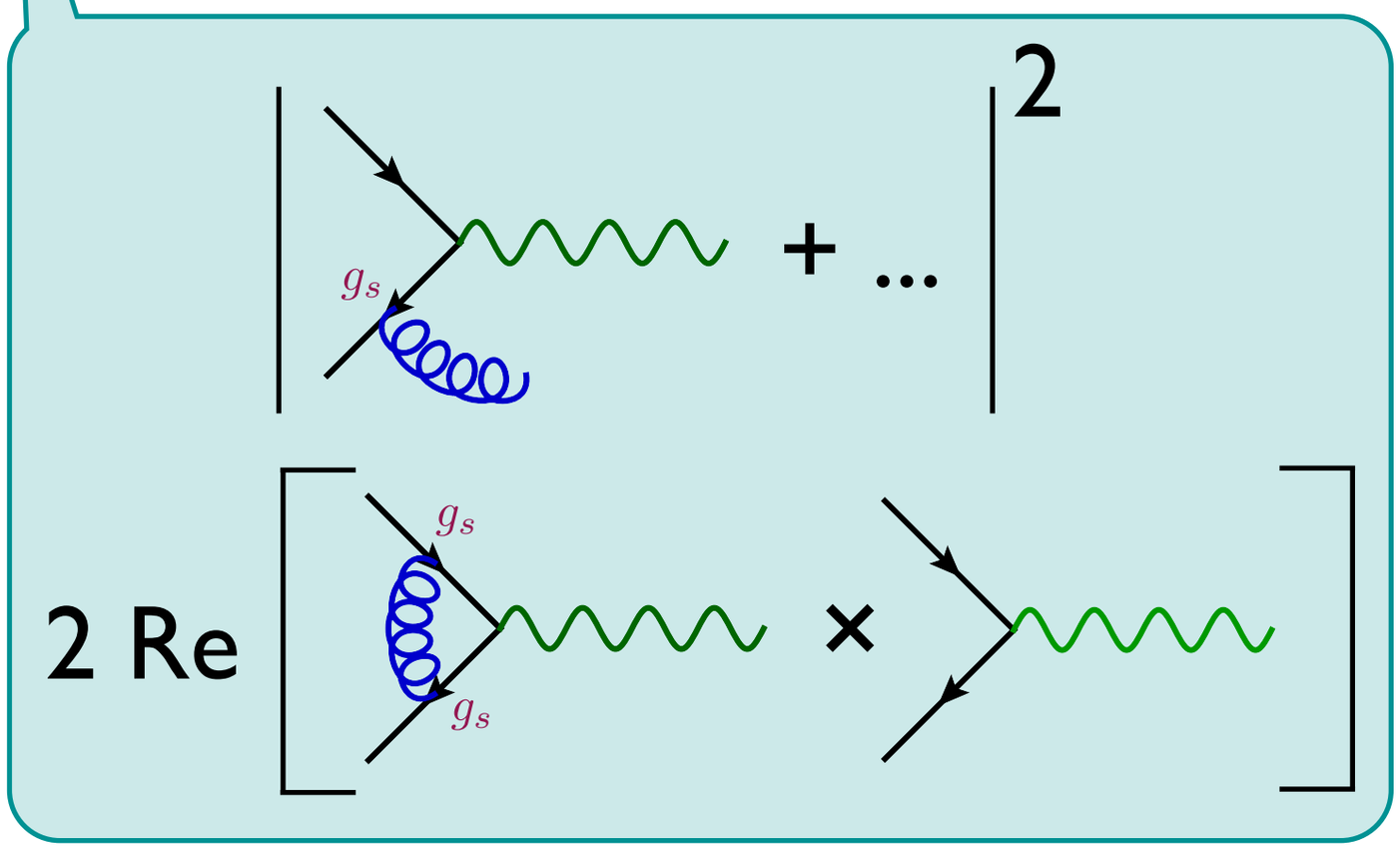

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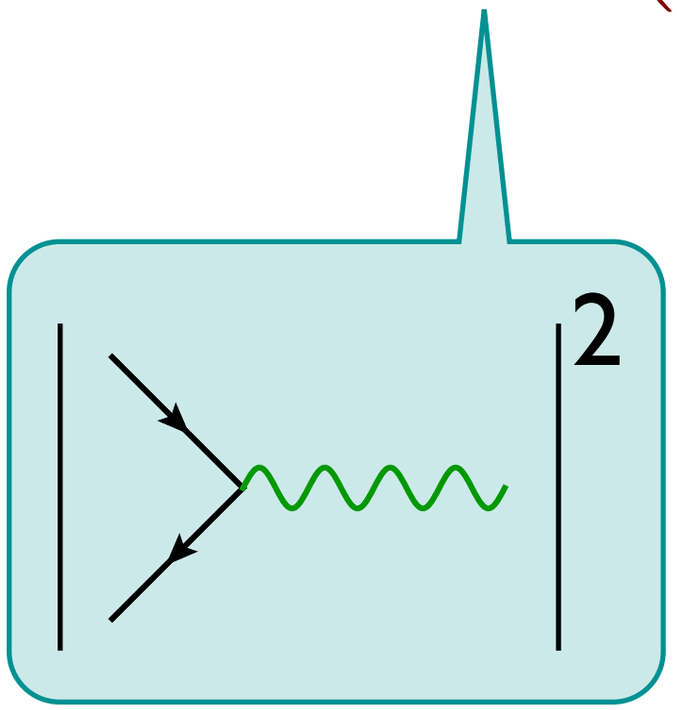
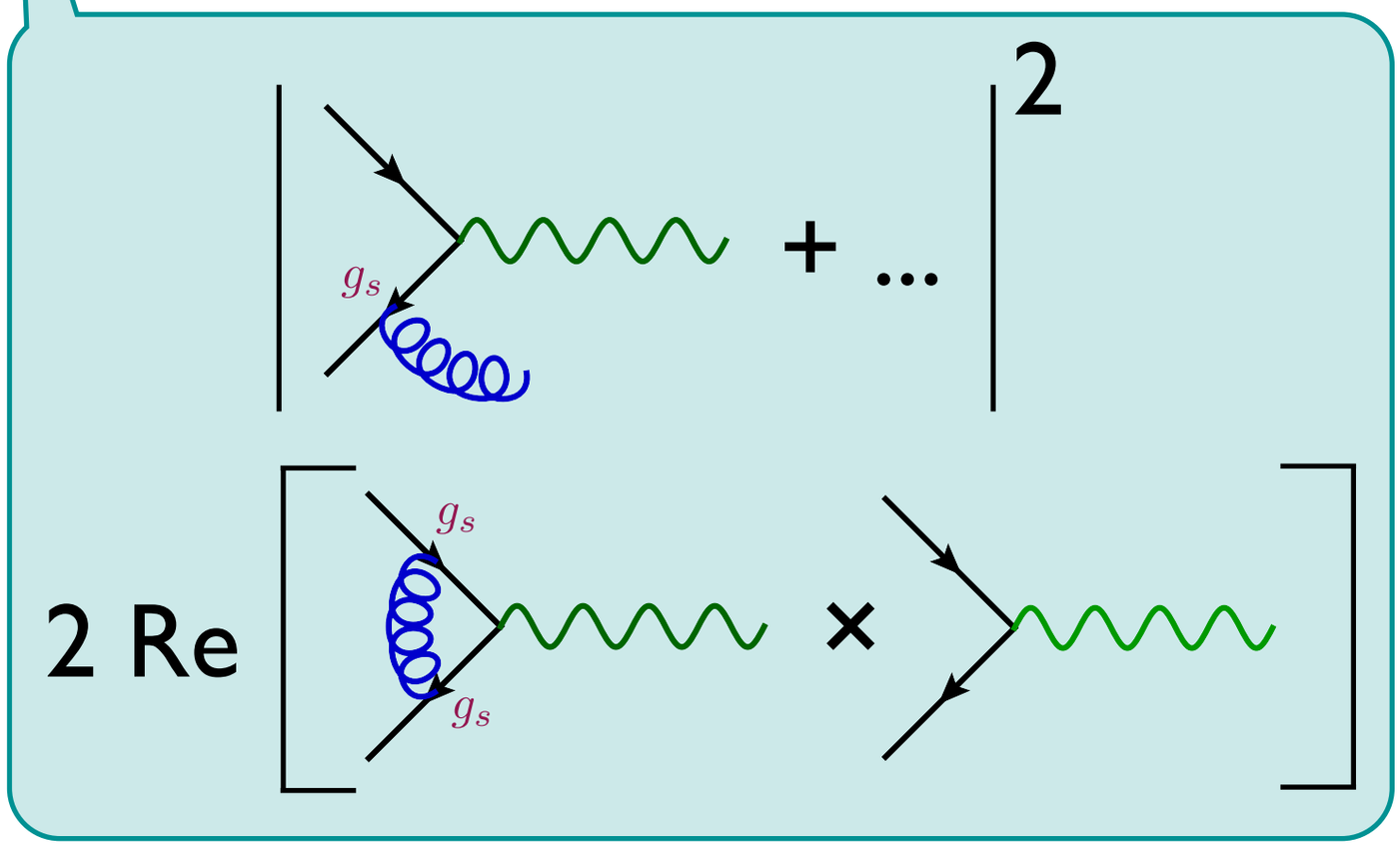
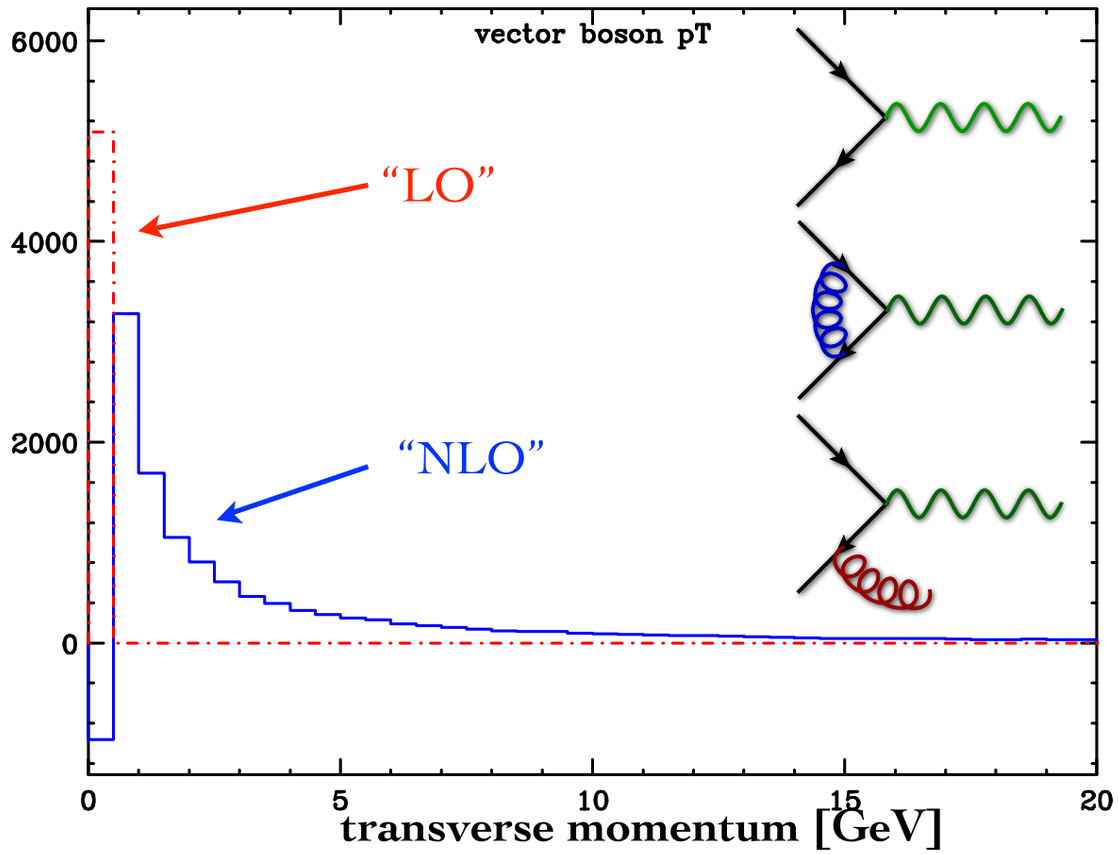


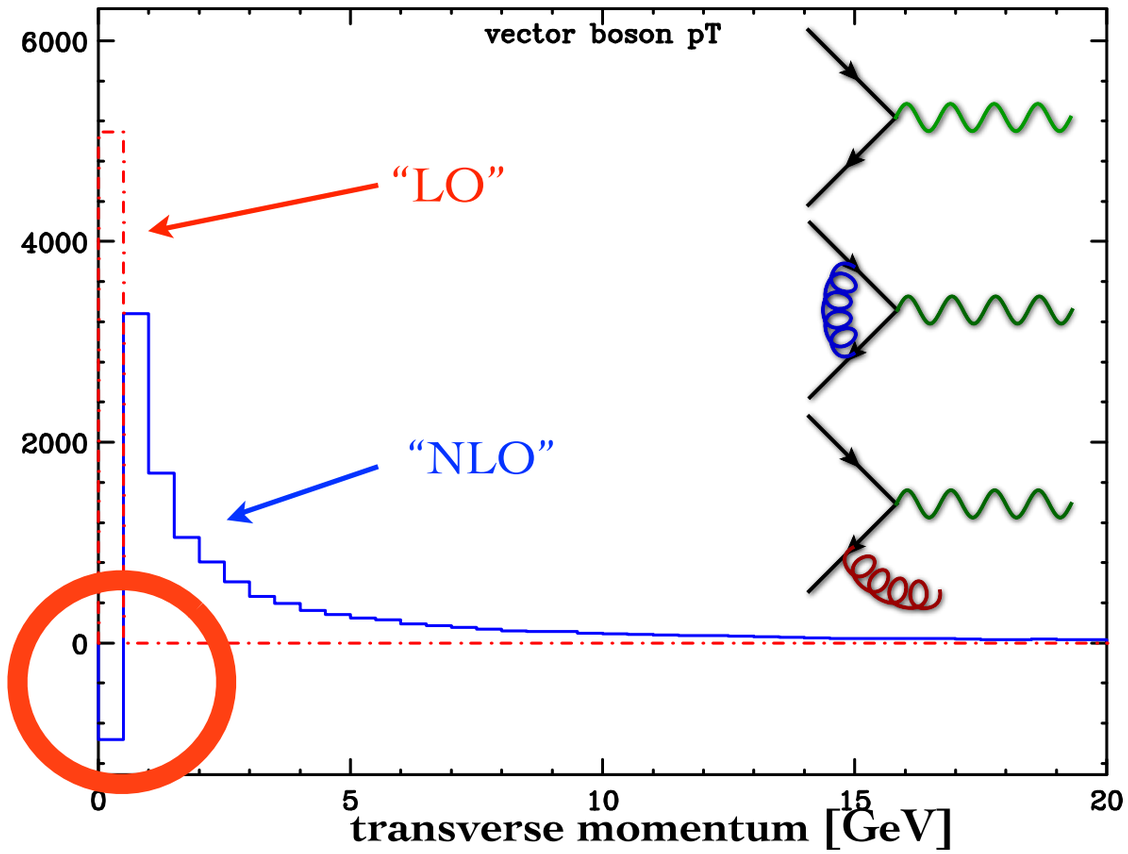


Not definite positive

Fixed Order calculations



Fixed Order calculations



Negative contribution of the 0-bin

Demo

- Demo NLO
  - Fix Order
  - Matched to the shower

Summary

- Presentation of MadGraph5
  - Support of BSM
  - Computation of the Width
  - Narrow width Approximation
    - Decay Chain
    - MadSpin
- Systematics
- NLO

A re-weighting approach for HH

- NLO HEFT event generation: MC@NLO method

$$d\sigma^{(\mathbb{H})} = d\phi_{n+1}\left(\mathcal{R} - \mathcal{C}_{MC}\right) ,$$
$$d\sigma^{(\mathbb{S})} = d\phi_{n+1}\left[\left(\mathcal{B} + \mathcal{V} + \mathcal{C}^{int}\right)\frac{d\phi_n}{d\phi_{n+1}} + \left(\mathcal{C}_{MC} - \mathcal{C}\right)\right]$$

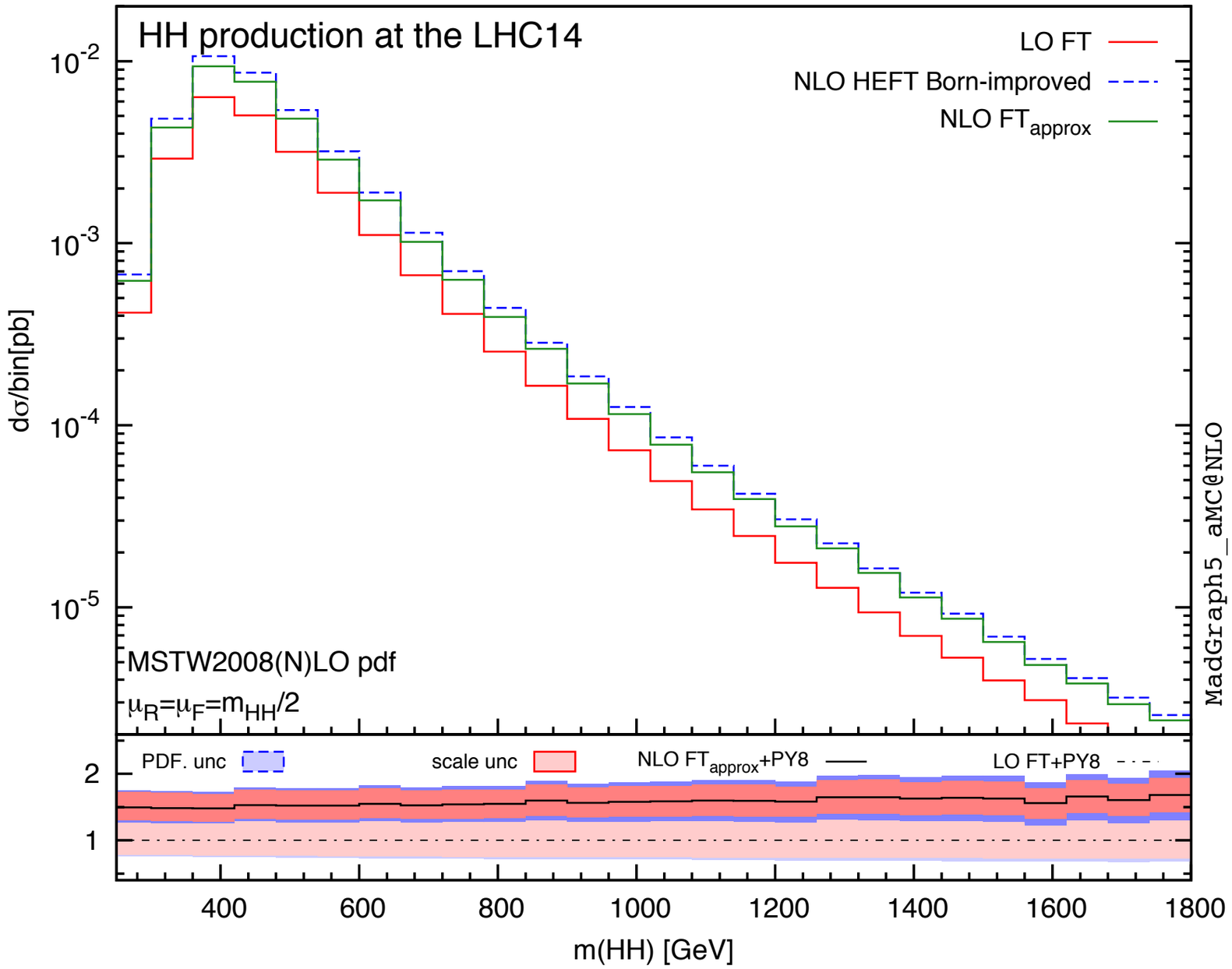
- Different weights stored internally: virtual, real and counter terms
- Reweight on an event-by-event basis using the results of the exact loop matrix elements. Schematically:

$$\begin{aligned} \mathcal{B}, \mathcal{V}, \mathcal{C}^{(int)}, \mathcal{C}_{MC} &\times \mathcal{B}_{FT}/\mathcal{B}_{HEFT} \\ \mathcal{R} &\times \mathcal{R}_{FT}/\mathcal{R}_{HEFT} \end{aligned}$$

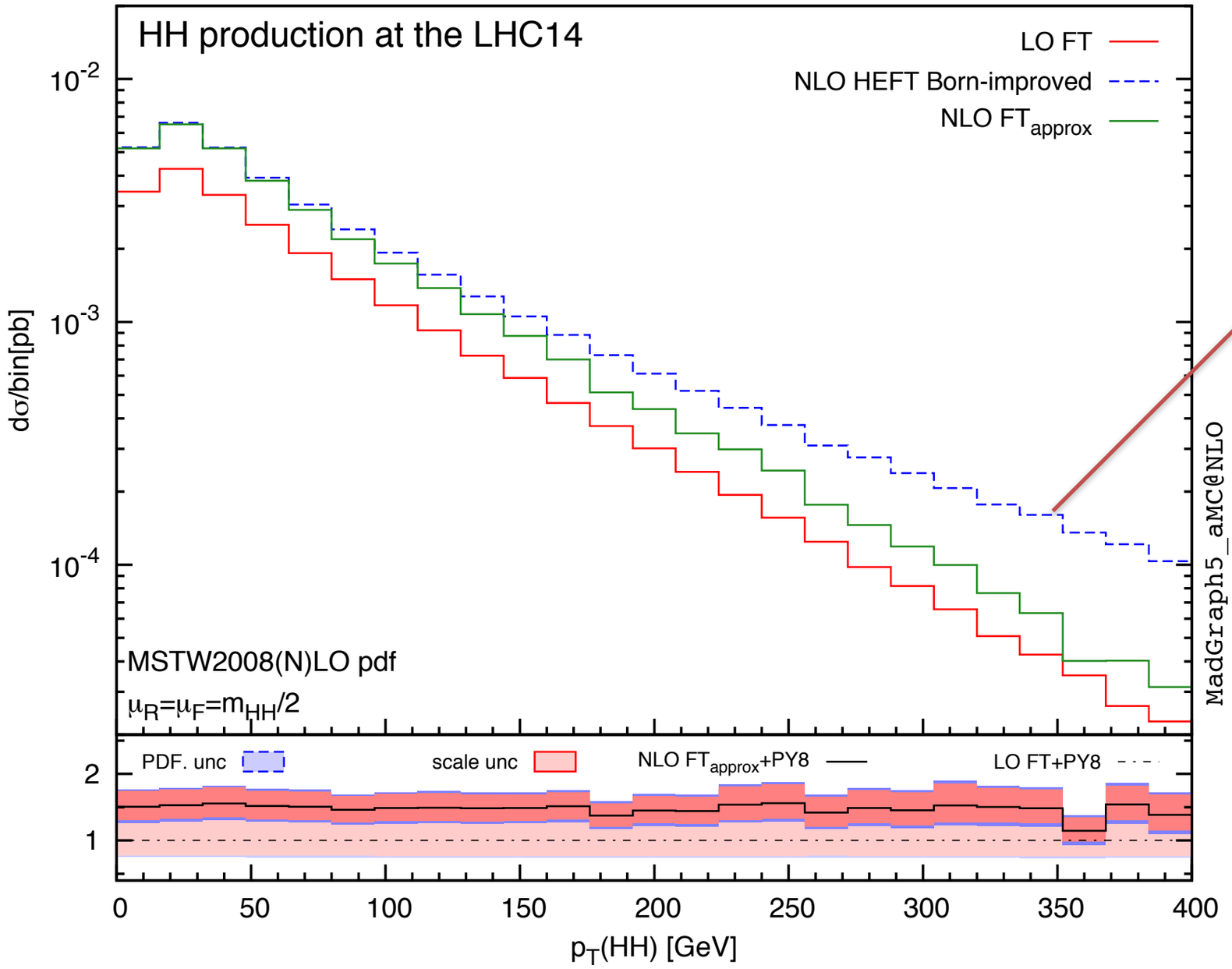
- Fully differential re-weighting
- Matching to parton showers with the MC@NLO method

[1401.7340 and 1408.6542]

Differential distributions for the LHC



Differential distributions for the LHC



Including the exact matrix elements has a bigger effect in the region of hard parton emission: tail of pT(HH) distribution

Exact matrix elements give a better description