gg > h in MG5_aMC@NLO

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based on 1401.7340 and 1405.0301 Work in progress with V. Hirschi, E. Vryonidou, B. Hestel



Plan





- Loop-Induced processes
 - → PS integration (gg > h)
 - LO re-weighting (g g > z h)
 - NLO re-weighting (g g > h h)



Plan





- Loop-Induced processes
 - PS integration (gg > h)
 - LO re-weighting (g g > z h)
 - NLO re-weighting (g g > h h)

- Simulation for discovery



Background directly measured from **data**. Theory needed only for parameter extraction

Background **SHAPE** needed. Flexible MC for both signal and background validated and tuned to data Relies on prediction for both shape and normalization. Complicated interplay of best simulations and data













MadGraph StandAlone

MadLoop StandAlone















Higgs+Jets



Process		Syntax	$ \begin{array}{c} \text{Cross section (pb)} \\ \hline \text{LO 13 TeV} & \text{NLO 13 TeV} \\ \hline 7.355 \pm 0.005 \cdot 10^1 & +5.0\% & +2.0\% \\ 1.097 \pm 0.002 \cdot 10^1 & +4.5\% & +1.9\% \\ -5.6\% & -1.5\% \\ 2.777 \pm 0.003 \cdot 10^1 & +3.6\% & +2.0\% \\ \hline 4.487 \pm 0.013 \cdot 10^1 & +4.4\% & +1.7\% \\ \hline 4.487 \pm 0.013 \cdot 10^1 & +4.4\% & +1.7\% \\ \hline \end{array} $			
Vector-bo	oson pair +jets		LO 13 T	eV.	NLO 13 7	ΓeV
b.1 p	$p \rightarrow W^+ W^-$ (4f)	p p > w+ w-	$7.355 \pm 0.005 \cdot 10^{1}$	+5.0% +2.0% -6.1% -1.5%	$1.028 \pm 0.003 \cdot 10^2$	+4.0% +1.9% -4.5% -1.4%
b.2 <i>p</i>	$p \rightarrow ZZ$	p p > z z	$1.097 \pm 0.002 \cdot 10^{1}$	+4.5% +1.9% -5.6% -1.5%	$1.415 \pm 0.005 \cdot 10^{1}$	+3.1% +1.8% -3.7% -1.4%
b.3 <i>p</i>	$p \rightarrow ZW^{\pm}$	p p > z wpm	$2.777 \pm 0.003 \cdot 10^{1}$	+3.6% +2.0% -4.7% -1.5%	$4.487 \pm 0.013 \cdot 10^{1}$	+4.4% +1.7% -4.4% -1.3%
b.4 p_1	$p \rightarrow \gamma \gamma$	pp>aa	$2.510 \pm 0.002 \cdot 10^{1}$	+22.1% +2.4% -22.4% -2.1%	$6.593 \pm 0.021 \cdot 10^{1}$	+17.6% +2.0% -18.8% -1.9%
b.5 p_{1}	$p \rightarrow \gamma Z$	pp>az	$2.523 \pm 0.004 \cdot 10^{1}$	+9.9% $+2.0%-11.2%$ $-1.6%$	$3.695 \pm 0.013 \cdot 10^{1}$	+5.4% $+1.8%-7.1%$ $-1.4%$
b.6 p	$p \rightarrow \gamma W^{\pm}$	p p > a wpm	$2.954 \pm 0.005 \cdot 10^{1}$	+9.5% $+2.0%-11.0%$ $-1.7%$	$7.124 \pm 0.026 \cdot 10^{1}$	+9.7% $+1.5%-9.9%$ $-1.3%$
b.7 <i>p</i>	$p \rightarrow W^+ W^- j$ (4f)	p p > w+ w- j	$2.865 \pm 0.003 \cdot 10^{1}$	+11.6% +1.0% -10.0% -0.8%	$3.730 \pm 0.013 \cdot 10^{1}$	+4.9% +1.1% -4.9% -0.8%
b.8 p	$p \rightarrow ZZj$	p p > z z j	$3.662 \pm 0.003 \cdot 10^{0}$	+10.9% +1.0% -9.3% -0.8%	$4.830 \pm 0.016 \cdot 10^{0}$	+5.0% $+1.1%-4.8%$ $-0.9%$
b.9 p	$p \rightarrow ZW^{\pm}j$	p p > z wpm j	$1.605 \pm 0.005 \cdot 10^{1}$	+11.6% +0.9% -10.0% -0.7%	$2.086 \pm 0.007 \cdot 10^{1}$	+4.9% +0.9% -4.8% -0.7%
b.10 p	$p \rightarrow \gamma \gamma j$	pp>aaj	$1.022 \pm 0.001 \cdot 10^{1}$	+20.3% $+1.2%-17.7%$ $-1.5%$	$2.292 \pm 0.010 \cdot 10^{1}$	+17.2% +1.0% -15.1% -1.4%
b.11* p	$p \rightarrow \gamma Z j$	pp>azj	$8.310 \pm 0.017 \cdot 10^{0}$	+14.5% +1.0% -12.8% -1.0%	$1.220 \pm 0.005 \cdot 10^{1}$	+7.3% +0.9% -7.4% -0.9%
b.12* p	$p\! ightarrow\!\gamma W^{\pm} j$	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 p	$p \rightarrow W^+W^+jj$	p p > w+ w+ j j	$1.484 \pm 0.006 \cdot 10^{-1}$	+25.4% +2.1% -18.9% -1.5%	$2.251 \pm 0.011 \cdot 10^{-1}$	$^{+10.5\%}_{-10.6\%}$ $^{+2.2\%}_{-1.6\%}$
b.14 p	$p \rightarrow W^-W^-jj$	p p > w- w- j j	$6.752 \pm 0.007 \cdot 10^{-2}$	+25.4% +2.4% -18.9% -1.7%	$1.003 \pm 0.003 \cdot 10^{-1}$	$^{+10.1\%}_{-10.4\%}$ $^{+2.5\%}_{-1.8\%}$
b.15 p_1	$p \rightarrow W^+ W^- jj$ (4f)	p p > w+ w- j j	$1.144 \pm 0.002 \cdot 10^{1}$	+27.2% +0.7% -19.9% -0.5%	$1.396 \pm 0.005 \cdot 10^{1}$	+5.0% +0.7% -6.8% -0.6%
b.16 p	$p \rightarrow ZZjj$	pp>zzjj	$1.344 \pm 0.002 \cdot 10^{0}$	+26.6% +0.7% -19.6% -0.6%	$1.706 \pm 0.011 \cdot 10^{0}$	+5.8% +0.8% -7.2% -0.6%
b.17 p	$p \rightarrow ZW^{\pm}jj$	p p > z wpm j j	$8.038 \pm 0.009 \cdot 10^{0}$	+26.7% +0.7% -19.7% -0.5%	$9.139 \pm 0.031 \cdot 10^{0}$	+3.1% +0.7% -5.1% -0.5%
b.18 p	$p \rightarrow \gamma \gamma j j$	pp>aajj	$5.377 \pm 0.029 \cdot 10^{0}$	+26.2% +0.6% -19.8% -1.0%	$7.501 \pm 0.032 \cdot 10^{0}$	+8.8% +0.6% -10.1% -1.0%
b.19* p	$p \rightarrow \gamma Z j j$	pp>azjj	$3.260 \pm 0.009 \cdot 10^{0}$	+24.3% +0.6% -18.4% -0.6%	$4.242 \pm 0.016 \cdot 10^{0}$	+6.5% +0.6% -7.3% -0.6%
b.20* p	$p\! ightarrow\!\gamma W^{\pm}jj$	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 sec	ction (pb)
Three vector bosons +jet		LO 13 TeV NLO 13 TeV		NLO 13 TeV
c.1 $pp \rightarrow W^+W^-W^{\pm}$ (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 $pp \rightarrow ZW^+W^-$ (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 $pp \rightarrow ZZW^{\pm}$	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 $pp \rightarrow ZZZ$	p p > z z z	$1.085\pm0.002\cdot10^{-2}$	$^{+0.0\%}_{-0.5\%}$ $^{+1.9\%}_{-1.5\%}$	$1.417 \pm 0.005 \cdot 10^{-2}$ $^{+2.7\%}_{-2.1\%}$ $^{+1.9\%}_{-1.5\%}$
c.5 $pp \rightarrow \gamma W^+W^-$ (4f)	pp>aw+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 $pp \rightarrow \gamma \gamma W^{\pm}$	pp>aawpm	$2.681 \pm 0.007 \cdot 10^{-2}$	+4.4% +1.9% -5.6% -1.6%	$8.251 \pm 0.032 \cdot 10^{-2}$ $^{+7.6\%}_{-7.0\%}$ $^{+1.0\%}_{-1.0\%}$
c.7 $pp \rightarrow \gamma ZW^{\pm}$	pp>az wpm	$4.994 \pm 0.011 \cdot 10^{-2}$	+0.8% +1.9% -1.4% -1.6%	$1.117 \pm 0.004 \cdot 10^{-1}$ $^{+7.2\%}_{-5.9\%}$ $^{+1.2\%}_{-0.9\%}$
c.8 $pp \rightarrow \gamma ZZ$	pp>azz	$2.320 \pm 0.005 \cdot 10^{-2}$	+2.0% +1.9% -2.9% -1.5%	$3.118 \pm 0.012 \cdot 10^{-2}$ $^{+2.8\%}_{-2.7\%}$ $^{+1.8\%}_{-1.4\%}$
c.9 $pp \rightarrow \gamma \gamma Z$	pp>aaz	$3.078 \pm 0.007 \cdot 10^{-2}$	+5.6% +1.9% -6.8% -1.6%	$4.634 \pm 0.020 \cdot 10^{-2}$ $^{+4.5\%}_{-5.0\%}$ $^{+1.7\%}_{-1.3\%}$
c.10 $pp \rightarrow \gamma \gamma \gamma$	pp>aaa	$1.269 \pm 0.003 \cdot 10^{-2}$	$+9.8\% +2.0\% \\ -11.0\% -1.8\%$	$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$
c.11 $pp \rightarrow W^+W^-W^{\pm}j$ (4f)	pp>w+w-wpmj	$9.167 \pm 0.010 \cdot 10^{-2}$	$^{+15.0\%}_{-12.2\%}$ $^{+1.0\%}_{-0.7\%}$	$1.197 \pm 0.004 \cdot 10^{-1}$ $^{+5.2\%}_{-5.6\%}$ $^{+1.0\%}_{-0.8\%}$
c.12* $pp \rightarrow ZW^+W^-j$ (4f)	p p > z w+ w- j	$8.340 \pm 0.010 \cdot 10^{-2}$	+15.6% +1.0% -12.6% -0.7%	$1.066 \pm 0.003 \cdot 10^{-1}$ $^{+4.5\%}_{-5.3\%}$ $^{+1.0\%}_{-0.7\%}$
c.13* $pp \rightarrow ZZW^{\pm}j$	pp>zzwpm j	$2.810 \pm 0.004 \cdot 10^{-2}$	+16.1% +1.0% -13.0% -0.7%	$3.660 \pm 0.013 \cdot 10^{-2} \ {}^{+4.8\%}_{-5.6\%} \ {}^{+1.0\%}_{-0.7\%}$
c.14* $pp \rightarrow ZZZj$	p p > z z z j	$4.823 \pm 0.011 \cdot 10^{-3}$	+14.3% +1.4% -11.8% -1.0%	$6.341 \pm 0.025 \cdot 10^{-3} {}^{+4.9\%}_{-5.4\%} {}^{+1.4\%}_{-1.0\%}$
c.15* $pp \rightarrow \gamma W^+W^-j$ (4f)	pp>aw+w-j	$1.182 \pm 0.004 \cdot 10^{-1}$	+13.4% +0.8% -11.2% -0.7%	$1.233 \pm 0.004 \cdot 10^3 \ ^{+18.9\%}_{-19.9\%} \ ^{+1.0\%}_{-1.5\%}$
c.16 $pp \rightarrow \gamma \gamma W^{\pm} j$	pp>aawpm j	$4.107 \pm 0.015 \cdot 10^{-2}$	+11.8% +0.6% -10.2% -0.8%	$5.807 \pm 0.023 \cdot 10^{-2}$ $^{+5.8\%}_{-5.5\%}$ $^{+0.7\%}_{-0.7\%}$
c.17* $pp \rightarrow \gamma ZW^{\pm}j$	pp>az wpm j	$5.833 \pm 0.023 \cdot 10^{-2}$	+14.4% +0.7% -12.0% -0.6%	$7.764 \pm 0.025 \cdot 10^{-2}$ $^{+5.1\%}_{-5.5\%}$ $^{+0.8\%}_{-0.6\%}$
c.18* $pp \rightarrow \gamma ZZj$	pp>azzj	$9.995 \pm 0.013 \cdot 10^{-3}$	+12.5% +1.2% -10.6% -0.9%	$1.371 \pm 0.005 \cdot 10^{-2}$ $^{+5.6\%}_{-5.5\%}$ $^{+1.2\%}_{-0.9\%}$
c.19* $pp \rightarrow \gamma \gamma Z j$	pp>aazj	$1.372 \pm 0.003 \cdot 10^{-2}$	+10.9% +1.0% -9.4% -0.9%	$2.051 \pm 0.011 \cdot 10^{-2}$ $^{+7.0\%}_{-6.3\%}$ $^{+1.0\%}_{-0.9\%}$
c.20* $pp \rightarrow \gamma \gamma \gamma j$	pp>aaaj	$1.031 \pm 0.006 \cdot 10^{-2}$	$^{+14.3\%}_{-12.6\%}$ $^{+0.9\%}_{-1.2\%}$	$2.020 \pm 0.008 \cdot 10^{-2} {}^{+ 12.8 \% }_{- 11.0 \% } {}^{+ 0.8 \% }_{- 1.2 \% }$



Process		Syntax	Cross section (pb)			
Fo	ur vector bosons		LO 13 Te	V	NLO 13 Te	eV
c.21*	$pp \rightarrow W^+W^-W^+W^-$ (4f)	p p > w+ w- w+ w-	$5.721 \pm 0.014 \cdot 10^{-4}$	+3.7% +2.3% -3.5% -1.7%	$9.959 \pm 0.035 \cdot 10^{-4}$	+7.4% +1.7% -6.0% -1.2%
c.22* 1	$pp \rightarrow W^+W^-W^\pm Z$ (4f)	pp>w+w-wpmz	$6.391 \pm 0.076 \cdot 10^{-4}$	+4.4% +2.4% -4.1% -1.8%	$1.188 \pm 0.004 \cdot 10^{-3}$	+8.4% +1.7% -6.8% -1.2%
c.23* 1	$pp \rightarrow W^+W^-W^\pm \gamma$ (4f)	pp>w+w-wpma	$8.115 \pm 0.064 \cdot 10^{-4}$	$^{+2.5\%}_{-2.5\%}$ $^{+2.2\%}_{-1.7\%}$	$1.546 \pm 0.005 \cdot 10^{-3}$	$+7.9\% +1.5\% \\ -6.3\% -1.1\%$
c.24* 1	$pp \rightarrow W^+W^-ZZ$ (4f)	p p > w+ w- z z	$4.320 \pm 0.013 \cdot 10^{-4}$	+4.4% +2.4% -4.1% -1.7%	$7.107 \pm 0.020 \cdot 10^{-4}$	+7.0% +1.8% -5.7% -1.3%
c.25* 1	$pp \rightarrow W^+W^-Z\gamma$ (4f)	pp>w+w-za	$8.403 \pm 0.016 \cdot 10^{-4}$	+3.0% +2.3% -2.9% -1.7%	$1.483 \pm 0.004 \cdot 10^{-3}$	+7.2% +1.6% -5.8% -1.2%
c.26* 1	$pp \rightarrow W^+W^-\gamma\gamma$ (4f)	pp>w+w-aa	$5.198 \pm 0.012 \cdot 10^{-4}$	+0.6% +2.1% -0.9% -1.6%	$9.381 \pm 0.032 \cdot 10^{-4}$	+6.7% +1.4% -5.3% -1.1%
c.27* 1	$pp \rightarrow W^{\pm}ZZZ$	p p > wpm z z z	$5.862 \pm 0.010 \cdot 10^{-5}$	+5.1% +2.4% -4.7% -1.8%	$1.240 \pm 0.004 \cdot 10^{-4}$	$^{+9.9\%}_{-8.0\%}$ $^{+1.7\%}_{-1.2\%}$
c.28* 1	$pp \rightarrow W^{\pm}ZZ\gamma$	pp>wpmzza	$1.148 \pm 0.003 \cdot 10^{-4}$	$^{+3.6\%}_{-3.5\%}$ $^{+2.2\%}_{-1.7\%}$	$2.945 \pm 0.008 \cdot 10^{-4}$	$^{+10.8\%}_{-8.7\%}$ $^{+1.3\%}_{-1.0\%}$
c.29* 1	$pp \rightarrow W^{\pm} Z \gamma \gamma$	pp>wpmzaa	$1.054 \pm 0.004 \cdot 10^{-4}$	$^{+1.7\%}_{-1.9\%}$ $^{+2.1\%}_{-1.7\%}$	$3.033 \pm 0.010 \cdot 10^{-4}$	$^{+10.6\%}_{-8.6\%}$ $^{+1.1\%}_{-0.8\%}$
c.30* 1	$pp \rightarrow W^{\pm} \gamma \gamma \gamma$	pp>wpmaaa	$3.600 \pm 0.013 \cdot 10^{-5}$	+0.4% +2.0% -1.0% -1.6%	$1.246 \pm 0.005 \cdot 10^{-4}$	+9.8% +0.9% -8.1% -0.8%
c.31* 1	$pp \rightarrow ZZZZ$	p p > z z z z	$1.989 \pm 0.002 \cdot 10^{-5}$	$+3.8\% +2.2\% \\ -3.6\% -1.7\%$	$2.629 \pm 0.008 \cdot 10^{-5}$	$+3.5\% +2.2\% \\ -3.0\% -1.7\%$
c.32* 1	$pp \rightarrow ZZZ\gamma$	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* 1	$pp \rightarrow ZZ\gamma\gamma$	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* 1	$pp \rightarrow Z \gamma \gamma \gamma$	pp>zaaa	$4.790 \pm 0.012 \cdot 10^{-5}$	$^{+2.3\%}_{-3.1\%}$ $^{+2.0\%}_{-1.6\%}$	$7.103 \pm 0.026 \cdot 10^{-5}$	$^{+3.4\%}_{-3.2\%}$ $^{+1.6\%}_{-1.5\%}$
c.35* 1	$pp \rightarrow \gamma \gamma \gamma \gamma$	pp>aaaa	$1.594 \pm 0.004 \cdot 10^{-5}$	$^{+4.7\%}_{-5.7\%}$ $^{+1.9\%}_{-1.7\%}$	$3.389 \pm 0.012 \cdot 10^{-5}$	$^{+7.0\%}_{-6.7\%}$ $^{+1.3\%}_{-1.3\%}$



Process	Syntax	Cross section (pb)			
Heavy quarks and jets		LO 13 TeV	NLO 13 TeV		
$\begin{array}{ll} \mathrm{d.1} & pp \rightarrow jj \\ \mathrm{d.2} & pp \rightarrow jjj \end{array}$	p p > j j p p > j j j	$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$	$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$		
$\begin{array}{ll} \mathrm{d.3} & pp \rightarrow b\bar{b} \ (\mathrm{4f}) \\ \mathrm{d.4^*} & pp \rightarrow b\bar{b}j \ (\mathrm{4f}) \\ \mathrm{d.5^*} & pp \rightarrow b\bar{b}jj \ (\mathrm{4f}) \\ \mathrm{d.6} & pp \rightarrow b\bar{b}b\bar{b} \ (\mathrm{4f}) \end{array}$	p p > b b~ p p > b b~ j p p > b b~ j j p p > b b~ b b~	$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$	$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$		
$\begin{array}{lll} \mathrm{d.7} & pp \rightarrow t\bar{t} \\ \mathrm{d.8} & pp \rightarrow t\bar{t}j \\ \mathrm{d.9} & pp \rightarrow t\bar{t}jj \\ \mathrm{d.10} & pp \rightarrow t\bar{t}t\bar{t} \end{array}$	p p > t t~ p p > t t~ j p p > t t~ j j p p > t t~ t t~	$\begin{array}{ccccccc} 4.584\pm 0.003\cdot10^2 & +29.0\% & +1.8\% \\ -21.1\% & -2.0\% \\ 3.135\pm 0.002\cdot10^2 & +45.1\% & +2.2\% \\ -29.0\% & -2.5\% \\ 1.361\pm 0.001\cdot10^2 & +61.4\% & +2.6\% \\ -35.6\% & -3.0\% \\ 4.505\pm 0.005\cdot10^{-3} & +63.8\% & +5.4\% \\ -36.5\% & -5.7\% \end{array}$	$\begin{array}{cccccccccccccccccccccccccccccccccccc$		
d.11 $pp \rightarrow t\bar{t}b\bar{b}$ (4f)	p p > t t \sim b b \sim	$6.119 \pm 0.004 \cdot 10^{0} {}^{+ 62.1 \% }_{- 35.7 \% } {}^{+ 2.9 \% }_{- 3.5 \% }$	$1.452 \pm 0.005 \cdot 10^{1} {}^{+ 37.6 \% }_{- 27.5 \% } {}^{+ 2.9 \% }_{- 3.5 \% }$		



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Process	Syntax	Cross section (pb)			
Heavy quarks+vector bosons		LO 13 TeV	NLO 13 TeV		
e.1 $pp \rightarrow W^{\pm} b\bar{b}$ (4f)	p p > wpm b b \sim	$3.074 \pm 0.002 \cdot 10^{2} {}^{+ 42.3 \% }_{- 29.2 \% } {}^{+ 2.0 \% }_{- 1.6 \% }$	$8.162 \pm 0.034 \cdot 10^{2} {}^{+ 29.8 \% }_{- 23.6 \% } {}^{+ 1.5 \% }_{- 1.2 \% }$		
e.2 $pp \rightarrow Z b\bar{b}$ (4f)	pp>zbb \sim	$6.993 \pm 0.003 \cdot 10^2 {}^{+ 33.5 \% }_{- 24.4 \% } {}^{+ 1.0 \% }_{- 1.4 \% }$	$1.235 \pm 0.004 \cdot 10^{3} {}^{+ 19.9 \% }_{- 17.4 \% } {}^{+ 1.0 \% }_{- 1.4 \% }$		
e.3 $pp \rightarrow \gamma b\bar{b}$ (4f)	pp>abb \sim	$1.731 \pm 0.001 \cdot 10^{3} {}^{+ 51.9 \% }_{- 34.8 \% } {}^{+ 1.6 \% }_{- 2.1 \% }$	$4.171 \pm 0.015 \cdot 10^{3} {}^{+ 33.7 \% }_{- 27.1 \% } {}^{+ 1.4 \% }_{- 1.9 \% }$		
e.4* $pp \rightarrow W^{\pm} b\bar{b} j$ (4f)	p p > wpm b b \sim 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* $pp \rightarrow Z b\bar{b} j$ (4f)	pp>zbb∼ 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* $pp \rightarrow \gamma b\bar{b} j$ (4f)	pp>abb~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 $pp \rightarrow t\bar{t} W^{\pm}$	p p > t t \sim 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 $pp \rightarrow t\bar{t} Z$	pp>tt \sim 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 $pp \rightarrow t\bar{t}\gamma$	p p > t t \sim 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* $pp \rightarrow t\bar{t} W^{\pm} j$	p p > t t \sim 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* $pp \rightarrow t\bar{t} Zj$	pp>tt \sim zj	$3.953 \pm 0.004 \cdot 10^{-1} {}^{+ 46.2 \% }_{- 29.5 \% } {}^{+ 2.7 \% }_{- 3.0 \% }$	$5.074 \pm 0.016 \cdot 10^{-1} {}^{+ 7.0 \% }_{- 12.3 \% } {}^{+ 2.5 \% }_{- 2.9 \% }$		
${\rm e.12^*} pp \mathop{\rightarrow} t \bar{t} \gamma j$	pp>tt \sim aj	$8.726 \pm 0.010 \cdot 10^{-1} {}^{+ 45.4 \% }_{- 29.1 \% } {}^{+ 2.3 \% }_{- 2.6 \% }$	$1.135 \pm 0.004 \cdot 10^{0} {}^{+ 7.5 \% }_{- 12.2 \% } {}^{+ 2.2 \% }_{- 2.5 \% }$		
e.13* $pp \rightarrow t\bar{t} W^-W^+$ (4f)	p p > t t \sim 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* $pp \rightarrow t\bar{t} W^{\pm} Z$	p p > t t \sim 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* $pp \rightarrow t\bar{t} W^{\pm} \gamma$	p p > t t \sim 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* $pp \rightarrow t\bar{t} ZZ$	p p > t t \sim 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* $pp \rightarrow t\bar{t} Z\gamma$	pp>tt~za	$2.548 \pm 0.003 \cdot 10^{-3}$ $^{+30.1\%}_{-21.5\%}$ $^{+1.7\%}_{-1.6\%}$	$3.656 \pm 0.012 \cdot 10^{-3} {}^{+ 9.7 \% }_{- 11.0 \% } {}^{+ 1.8 \% }_{- 1.9 \% }$		
${\rm e.18}^* pp \mathop{\rightarrow} t \bar{t} \gamma \gamma$	pp>tt \sim aa	$3.272 \pm 0.006 \cdot 10^{-3} {}^{+28.4\%}_{-20.6\%} {}^{+1.3\%}_{-1.1\%}$	$4.402 \pm 0.015 \cdot 10^{-3} {}^{+ 7.8 \% }_{- 9.7 \% } {}^{+ 1.4 \% }_{- 1.4 \% }$		



	Process	Syntax	Cross sect	tion (pb)
	Single-top		LO 13 TeV	NLO 13 TeV
f.1	$pp \rightarrow tj$ (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	$pp \rightarrow t\gamma j$ (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	$pp \rightarrow tZj$ (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	$pp \! \rightarrow \! tbj$ (t-channel, 4f)	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*	$pp \rightarrow tbj\gamma$ (t-channel, 4f)	p p > tt bb j a \$\$ w+ w-	$6.293 \pm 0.006 \cdot 10^{-1}$ $^{+16.8\%}_{-13.5\%}$ $^{+0.8\%}_{-0.9\%}$	$8.612 \pm 0.025 \cdot 10^{-1} {}^{+ 6.2 \% }_{- 6.6 \% } {}^{+ 0.8 \% }_{- 0.9 \% }$
f.6*	$pp \! \rightarrow \! tbjZ$ (t-channel, 4f)	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	$pp \rightarrow tb$ (s-channel, 4f)	p p > w+ > t b~, p p > w- > t~ b	$7.489 \pm 0.007 \cdot 10^{0} {}^{+ 3.5 \% }_{- 4.4 \% } {}^{+ 1.9 \% }_{- 1.4 \% }$	$1.001 \pm 0.004 \cdot 10^{1} {}^{+ 3.7 \% }_{- 3.9 \% } {}^{+ 1.9 \% }_{- 1.5 \% }$
f.8*	$pp \rightarrow tb\gamma$ (s-channel, 4f)	p p > w+ > t b~ a, p p > w- > t~ b a	$1.490 \pm 0.001 \cdot 10^{-2}$ $^{+1.2\%}_{-1.8\%}$ $^{+1.9\%}_{-1.5\%}$	$1.952 \pm 0.007 \cdot 10^{-2}$ $^{+2.6\%}_{-2.3\%}$ $^{+1.7\%}_{-1.4\%}$
f.9*	$pp \! \rightarrow \! tbZ$ (s-channel, 4f)	p p > w+ > t b~ z, p p > w- > t~ b z	$1.072 \pm 0.001 \cdot 10^{-2} {}^{+ 1.3 \% }_{- 1.5 \% } {}^{+ 2.0 \% }_{- 1.6 \% }$	$1.539 \pm 0.005 \cdot 10^{-2} {}^{+ 3.9 \% }_{- 3.2 \% } {}^{+ 1.9 \% }_{- 1.5 \% }$



Process	Syntax	Cross section (pb)			
Single Higgs production		LO 13 TeV	NLO 13 TeV		
g.1 $pp \rightarrow H$ (HEFT)	p	$1.593 \pm 0.003 \cdot 10^{1}$ $^{+34.8\%}_{-26.0\%}$ $^{+1.2\%}_{-1.7\%}$	$3.261 \pm 0.010 \cdot 10^{1} {}^{+ 20.2 \% }_{- 17.9 \% } {}^{+ 1.1 \% }_{- 1.6 \% }$		
g.2 $pp \rightarrow Hj$ (HEFT)	pp>hj	$8.367 \pm 0.003 \cdot 10^{0}$ $^{+39.4\%}_{-26.4\%}$ $^{+1.2\%}_{-1.4\%}$	$1.422 \pm 0.006 \cdot 10^{1}$ $^{+18.5\%}_{-16.6\%}$ $^{+1.1\%}_{-1.4\%}$		
g.3 $pp \rightarrow Hjj$ (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 $pp \rightarrow Hjj$ (VBF)	pp>hjj\$\$ 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 $pp \rightarrow Hjjj$ (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 $pp \rightarrow HW^{\pm}$	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 $pp \rightarrow HW^{\pm} j$	p p > h wpm j	$4.018 \pm 0.003 \cdot 10^{-1}$ $^{+10.7\%}_{-9.3\%}$ $^{+1.2\%}_{-0.9\%}$	$4.842 \pm 0.017 \cdot 10^{-1}$ $^{+3.6\%}_{-3.7\%}$ $^{+1.2\%}_{-1.0\%}$		
${\rm g.8^*} \qquad pp \mathop{\rightarrow} HW^{\pm} jj$	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 $pp \rightarrow HZ$	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 $pp \rightarrow HZ j$	pp>hzj	$2.225 \pm 0.001 \cdot 10^{-1}$ $^{+10.6\%}_{-9.2\%}$ $^{+1.1\%}_{-0.8\%}$	$2.667 \pm 0.010 \cdot 10^{-1}$ $^{+3.5\%}_{-3.6\%}$ $^{+1.1\%}_{-0.9\%}$		
g.11* $pp \rightarrow HZ jj$	pp>hzjj	$7.262 \pm 0.012 \cdot 10^{-2} {}^{+ 26.2 \% }_{- 19.4 \% } {}^{+ 0.7 \% }_{- 0.6 \% }$	$8.753 \pm 0.037 \cdot 10^{-2} {}^{+ 4.8 \% }_{- 6.3 \% } {}^{+ 0.7 \% }_{- 0.6 \% }$		
g.12* $pp \rightarrow HW^+W^-$ (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* $pp \rightarrow HW^{\pm}\gamma$	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* $pp \rightarrow HZW^{\pm}$	p p > h z wpm	$3.763 \pm 0.007 \cdot 10^{-3} {}^{+1.1\%}_{-1.5\%} {}^{+2.0\%}_{-1.6\%}$	$5.292 \pm 0.015 \cdot 10^{-3}$ $^{+3.9\%}_{-3.1\%}$ $^{+1.8\%}_{-1.4\%}$		
${\rm g.15^*} pp {\rightarrow} HZZ$	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 $pp \rightarrow Ht\bar{t}$	p p > h t t \sim	$3.579 \pm 0.003 \cdot 10^{-1} {}^{+ 30.0 \% }_{- 21.5 \% } {}^{+ 1.7 \% }_{- 2.0 \% }$	$4.608 \pm 0.016 \cdot 10^{-1} {}^{+ 5.7 \% }_{- 9.0 \% } {}^{+ 2.0 \% }_{- 2.3 \% }$		
g.17 $pp \rightarrow Htj$	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 $pp \rightarrow Hb\bar{b}$ (4f)	p p > h b b \sim	$4.983 \pm 0.002 \cdot 10^{-1} {}^{+ 28.1 \% }_{- 21.0 \% } {}^{+ 1.5 \% }_{- 1.8 \% }$	$6.085 \pm 0.026 \cdot 10^{-1} {}^{+ 7.3 \% }_{- 9.6 \% } {}^{+ 1.6 \% }_{- 2.0 \% }$		
g.19 $pp \rightarrow H t \bar{t} j$	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* $pp \rightarrow Hb\bar{b}j$ (4f)	p p > h b b~ j	$\begin{array}{rrrr} 7.367 \pm 0.002 \cdot 10^{-2} & {}^{+ 45.6 \% }_{- 29.1 \% } +1.8 \% \\ & -29.1 \% & -2.1 \% \end{array}$	$9.034 \pm 0.032 \cdot 10^{-2} {}^{+ 7.9 \% }_{- 11.0 \% } {}^{+ 1.8 \% }_{- 2.2 \% }$		



Process	Syntax	Cross section (pb)		
Higgs pair production		LO 13 TeV	NLO 13 TeV	
h.1 $pp \rightarrow HH$ (Loop improved) pp>hh	$1.772 \pm 0.006 \cdot 10^{-2} {}^{+ 29.5 \% }_{- 21.4 \% } {}^{+ 29.5 \% }_{- 2.6 \% }$	$2.763 \pm 0.008 \cdot 10^{-2} {}^{+ 11.4 \% }_{- 11.8 \% } {}^{+ 2.1 \% }_{- 2.6 \% }$	
h.2 $pp \rightarrow HHjj$ (VBF)	pp>hhjj\$\$ w+ w- z		$6.820 \pm 0.026 \cdot 10^{-4}$ $^{+0.8\%}_{-1.0\%}$ $^{+2.4\%}_{-1.7\%}$	
h.3 $pp \rightarrow HHW^{\pm}$	p p > h h wpm	$ \begin{array}{rrrr} 4.303 \pm 0.005 \cdot 10^{-4} & {}^{+0.9\%}_{-1.3\%} & {}^{+2.0\%}_{-1.5\%} \end{array} $	$5.002 \pm 0.014 \cdot 10^{-4}$ $^{+1.5\%}_{-1.2\%}$ $^{+2.0\%}_{-1.6\%}$	
h.4* $pp \rightarrow HHW^{\pm}j$	p p > h h wpm j	$1.922 \pm 0.002 \cdot 10^{-4}$ $^{+14.2\%}_{-11.7\%}$ $^{+15\%}_{-1.1\%}$	$2.218 \pm 0.009 \cdot 10^{-4} {}^{+ 2.7 \% }_{- 3.3 \% } {}^{+ 1.6 \% }_{- 1.1 \% }$	
h.5* $pp \rightarrow HHW^{\pm}\gamma$	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 $pp \rightarrow HHZ$	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* $pp \rightarrow HHZj$	pp>hhzj	$1.211 \pm 0.001 \cdot 10^{-4}$ $^{+14.1\%}_{-11.7\%}$ $^{+1.4\%}_{-1.1\%}$	$1.394 \pm 0.006 \cdot 10^{-4}$ $^{+2.7\%}_{-3.2\%}$ $^{+1.5\%}_{-1.1\%}$	
h.8* $pp \rightarrow HHZ\gamma$	p p > h h z a	$1.397 \pm 0.003 \cdot 10^{-6}$ $^{+2.4\%}_{-2.5\%}$ $^{+2.2\%}_{-1.7\%}$	$1.604 \pm 0.005 \cdot 10^{-6}$ $^{+1.7\%}_{-1.4\%}$ $^{+2.3\%}_{-1.7\%}$	
${\rm h.9^*} \qquad pp {\rightarrow} HHZZ$	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.10* $pp \rightarrow HHZW^{\pm}$	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.11* $pp \rightarrow HHW^+W^-$ (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.12 $pp \rightarrow HHt\bar{t}$	pp > h h t t \sim	$6.756 \pm 0.007 \cdot 10^{-4}$ $^{+30.2\%}_{-21.6\%}$ $^{+1.8\%}_{-1.8\%}$	$7.301 \pm 0.024 \cdot 10^{-4}$ $^{+1.4\%}_{-5.7\%}$ $^{+2.2\%}_{-2.3\%}$	
h.13 $pp \rightarrow HHtj$	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* $pp \rightarrow HHb\bar{b}$	p p > h h b b \sim	$7.849 \pm 0.022 \cdot 10^{-8} {}^{+ 34.3 \% }_{- 23.9 \% } {}^{+ 3.1 \% }_{- 3.7 \% }$	$1.084 \pm 0.012 \cdot 10^{-7} {}^{+ 7.4 \% }_{- 10.8 \% } {}^{+ 3.1 \% }_{- 3.7 \% }$	



Process	Syntax	Cross section (pb)		
Heavy quarks and jets		LO 1 TeV	NLO 1 TeV	
i.1 $e^+e^- \rightarrow jj$	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 $e^+e^- \rightarrow jjj$	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 $e^+e^- \rightarrow jjjjj$	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 $e^+e^- \rightarrow jjjjjj$	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 $e^+e^- \rightarrow t\bar{t}$	e+ e- > t t \sim	$1.662 \pm 0.002 \cdot 10^{-1} {}^{+ 0.0 \% }_{- 0.0 \% }$	$1.745 \pm 0.006 \cdot 10^{-1} {}^{+ 0.4 \% }_{- 0.4 \% }$	
i.6 $e^+e^- \rightarrow t\bar{t}j$	e+ e- > t t \sim 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* $e^+e^- \rightarrow t\bar{t}jj$	e+ e- > t t \sim 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* $e^+e^- \rightarrow t\bar{t}jjj$	e+ e- > t t \sim 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* $e^+e^- \rightarrow t\bar{t}t\bar{t}$	e+ e- > t t \sim t t \sim	$6.456 \pm 0.016 \cdot 10^{-7} {}^{+ 19.1 \% }_{- 14.8 \% }$	$1.221 \pm 0.005 \cdot 10^{-6} \ {}^{+ 13.2 \% }_{- 11.2 \% }$	
i.10* $e^+e^- \rightarrow t\bar{t}t\bar{t}j$	e+ e- > t t \sim t t \sim 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 $e^+e^- \rightarrow b\bar{b}$ (4f)	e+ e- > b b \sim	$9.198 \pm 0.004 \cdot 10^{-2} {}^{+ 0.0 \% }_{- 0.0 \% }$	$9.282 \pm 0.031 \cdot 10^{-2} {}^{+ 0.0 \% }_{- 0.0 \% }$	
i.12 $e^+e^- \rightarrow b\bar{b}j$ (4f)	e+ e- > b b \sim 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* $e^+e^- \rightarrow b\bar{b}jj$ (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 [*] $e^+e^- \rightarrow b\bar{b}jjj$ (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 [*] $e^+e^- \rightarrow b\bar{b}b\bar{b}$ (4f)	e+ e- > b b \sim b b \sim	$1.644 \pm 0.003 \cdot 10^{-4} \ ^{+19.9\%}_{-15.3\%}$	$3.601 \pm 0.017 \cdot 10^{-4} \ {}^{+ 15.2 \% }_{- 12.5 \% }$	
i.16* $e^+e^- \rightarrow b\bar{b}b\bar{b}j$ (4f)	e+ e- > b b \sim b b \sim 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* $e^+e^- \rightarrow t\bar{t}b\bar{b}$ (4f)	e+ e- > t t \sim b b \sim	$1.819 \pm 0.003 \cdot 10^{-4} {}^{+ 19.5 \% }_{- 15.0 \% }$	$2.923 \pm 0.011 \cdot 10^{-4} {}^{+ 9.2 \% }_{- 8.9 \% }$	
i.18 [*] $e^+e^- \rightarrow t\bar{t}b\bar{b}j$ (4f)	e+ e- > t t \sim b b \sim 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	Cı	ross section (pb)
Top quarks +bosons	1	LO 1 TeV	NLO 1 TeV
j.1 $e^+e^- \rightarrow t\bar{t}H$	e+ e- > t t \sim h	$2.018 \pm 0.003 \cdot 10^{-3}$	$^{+0.0\%}_{-0.0\%}$ 1.911 ± 0.006 · 10 ⁻³ $^{+0.4\%}_{-0.5\%}$
j.2* $e^+e^- \rightarrow t\bar{t}Hj$	e+ e- > t t \sim 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* $e^+e^- \rightarrow t\bar{t}Hjj$	<i>j</i> 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* $e^+e^- \rightarrow t\bar{t}\gamma$	e+ e- > t t \sim a	$1.270 \pm 0.002 \cdot 10^{-2}$	$^{+0.0\%}_{-0.0\%}$ 1.335 ± 0.004 · 10 ⁻² $^{+0.5\%}_{-0.4\%}$
j.5* $e^+e^- \rightarrow t\bar{t}\gamma j$	e+ e- > t t \sim 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* $e^+e^- \rightarrow t\bar{t}\gamma jj$	e+ e- > t t \sim 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* $e^+e^- \rightarrow t\bar{t}Z$	e+ e- > t t \sim z	$4.642 \pm 0.006 \cdot 10^{-3}$	$^{+0.0\%}_{-0.0\%}$ 4.949 ± 0.014 · 10 ⁻³ $^{+0.6\%}_{-0.5\%}$
j.8* $e^+e^- \rightarrow t\bar{t}Zj$	e+ e- > t t \sim 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* $e^+e^- \rightarrow t\bar{t}Zjj$	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* $e^+e^- \rightarrow t\bar{t}W^{\pm}$	jj e+ e- > t t \sim 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* $e^+e^- \rightarrow t\bar{t}HZ$	e+ e- > t t \sim 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* $e^+e^- \rightarrow t\bar{t}\gamma Z$	e+ e- > t t \sim 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* $e^+e^- \rightarrow t\bar{t}\gamma H$	e+ e- > t t \sim 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* $e^+e^- \rightarrow t\bar{t}\gamma\gamma$	e+ e- > t t \sim 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* $e^+e^- \rightarrow t\bar{t}ZZ$	e+ e- > t t \sim z z	$3.788 \pm 0.004 \cdot 10^{-5}$	$^{+0.0\%}_{-0.0\%}$ 4.007 ± 0.013 · 10 ⁻⁵ $^{+0.5\%}_{-0.5\%}$
j.16* $e^+e^- \rightarrow t\bar{t}HH$	e+ e- > t t \sim 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* $e^+e^- \rightarrow t\bar{t}W^+$	W^- e+ e- > t t \sim w+ w-	$1.372 \pm 0.003 \cdot 10^{-4}$	$^{+0.0\%}_{-0.0\%}$ 1.540 ± 0.006 · 10 ⁻⁴ $^{+1.0\%}_{-0.9\%}$



Plan





- NLO re-weighting (g g > h h)



Loop Induced



Why?

- Main production mechanism for Higgs & Higgs associated processes
- Effective Theory are not always relevant



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



Implementation



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 multichannel
- •Use Monte-Carlo over helicity
- Increase parallelization
- •Compute the loop with the color flow algebra

First Example: g g> h



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9/12/2014

First Example: g g> h

















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





ME-Reweighting



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

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





g g > ZH







gg>HH beyond LO



Full NLO

- real emission: HHg (one loop) : doable
- virtual corrections: two-loop



Currently not available!



Use Effective Theory

$$\mathcal{L}_{\text{eff}} = \frac{1}{4} \frac{\alpha_s}{3\pi} G^a_{\mu\nu} G^{a\,\mu\nu} \log(1 + h/v)$$

$$\mathcal{L} \supset + \frac{1}{4} \frac{\alpha_s}{3\pi v} G^a_{\mu\nu} G^{a\,\mu\nu} h - \frac{1}{4} \frac{\alpha_s}{6\pi v^2} G^a_{\mu\nu} G^{a\,\mu\nu} h^2.$$





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:

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

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

[1401.7340 and 1408.6542]

















Conclusion



