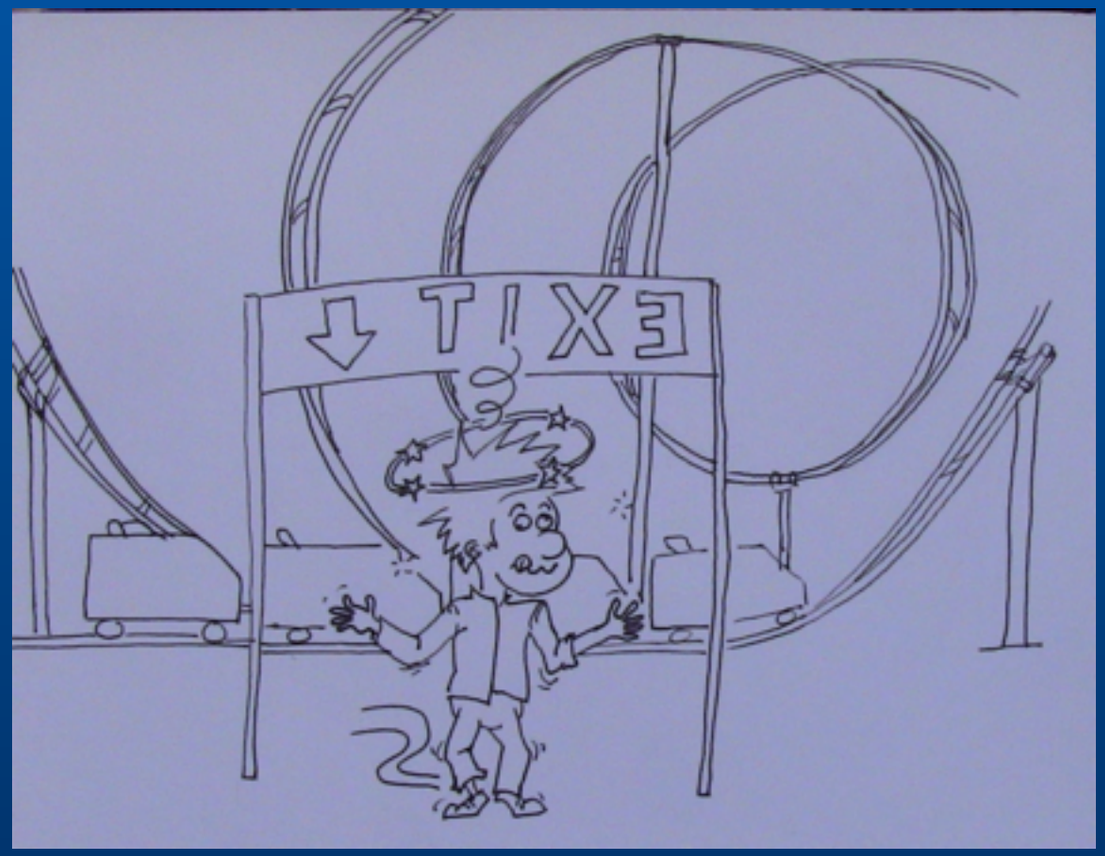
MG5_aMC@NLO
looping up to be mad!



Olivier Mattelaer
IPPP/Durham

work in progress with V. Hirschi

Type of generation

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

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Loop Induced

Why?

- Main production mechanism for Higgs & Higgs associated processes
- Contribution for NNLO computation
- Correction to shape of observables
- We have the tool available

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OLD Solution

- Use Effective Field Theory (=> Tree)
- And correct the mass effect

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

- Difficult control on numerical uncertainty
- Wrong Leading Color information/helicity
- Not generic

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

- Diffic… on n… certainty
- …g Leading Color …ormation/helicity
- Not generic

Not the method of choice for BSM
Not the method that we will choose

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

New Solution

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

parallelization

MadEvent

$$|M|^2 = \frac{|M_1|^2}{|M_1|^2 + |M_2|^2}|M|^2 + \frac{|M_2|^2}{|M_1|^2 + |M_2|^2}|M|^2$$

parallelization

MadEvent

$$\int |M|^2 = \int \frac{|M_1|^2}{|M_1|^2 + |M_2|^2} |M|^2 + \int \frac{|M_2|^2}{|M_1|^2 + |M_2|^2} |M|^2$$

parallelization

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- Grid Refinement
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parallelization

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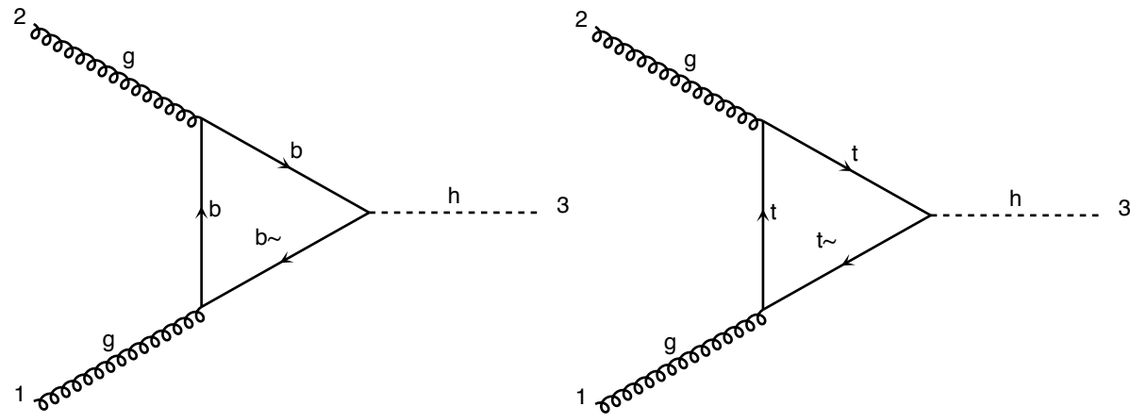
First Example: g g> h

User Input

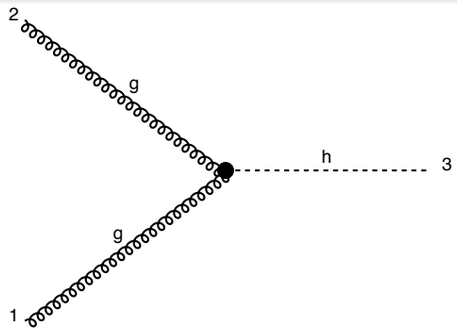
- generate g g > h [QCD]
- output
- launch

Loop Induced

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



HEFT



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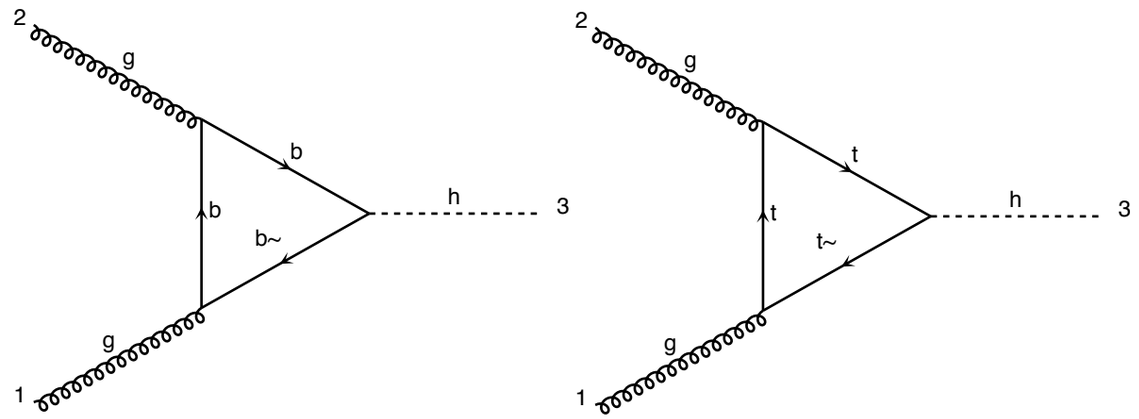

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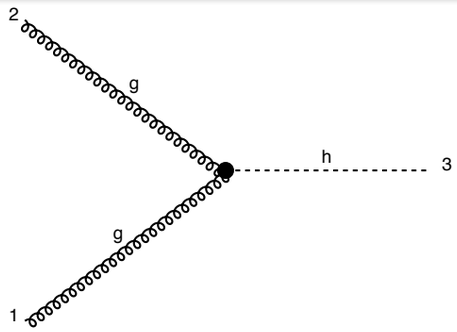
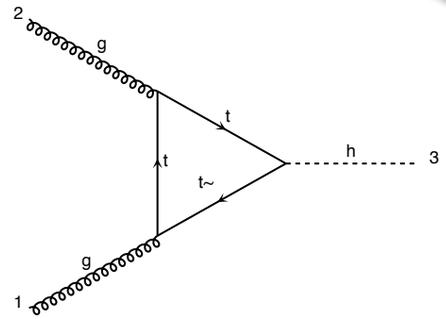


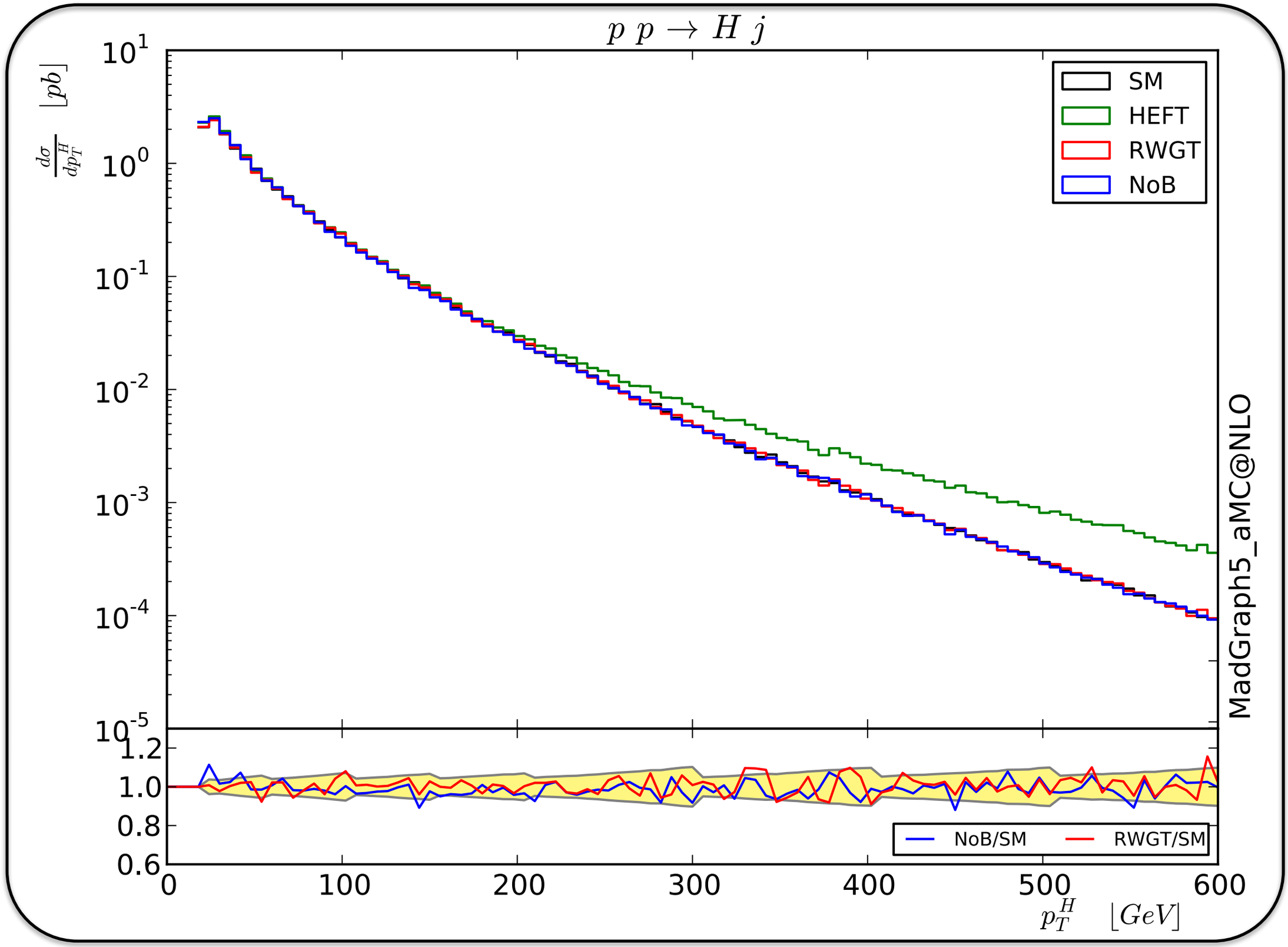
$$\sigma_{heft} = 17.63(2)pb$$

No bottom loop



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

Validation p p > h j



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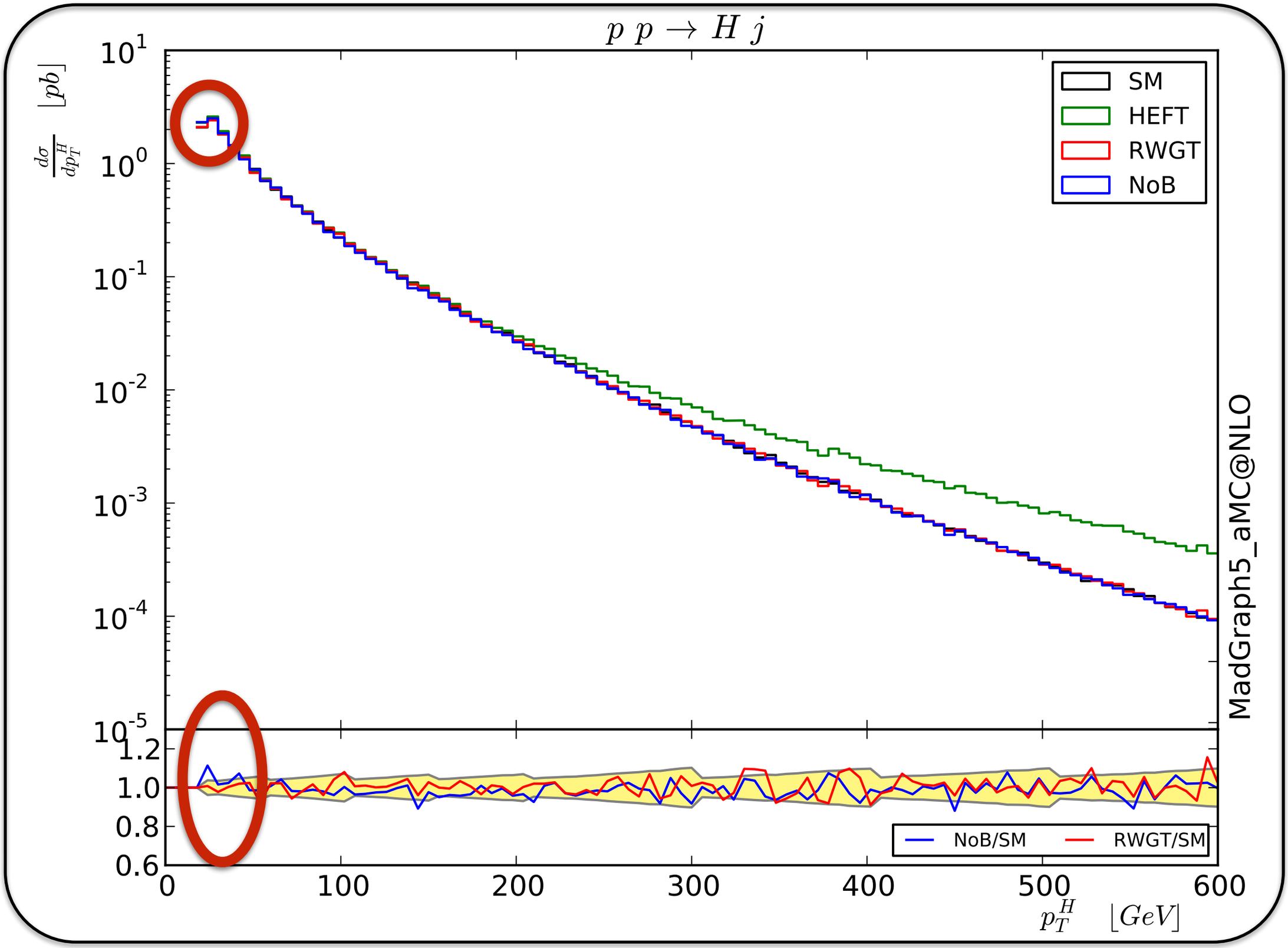

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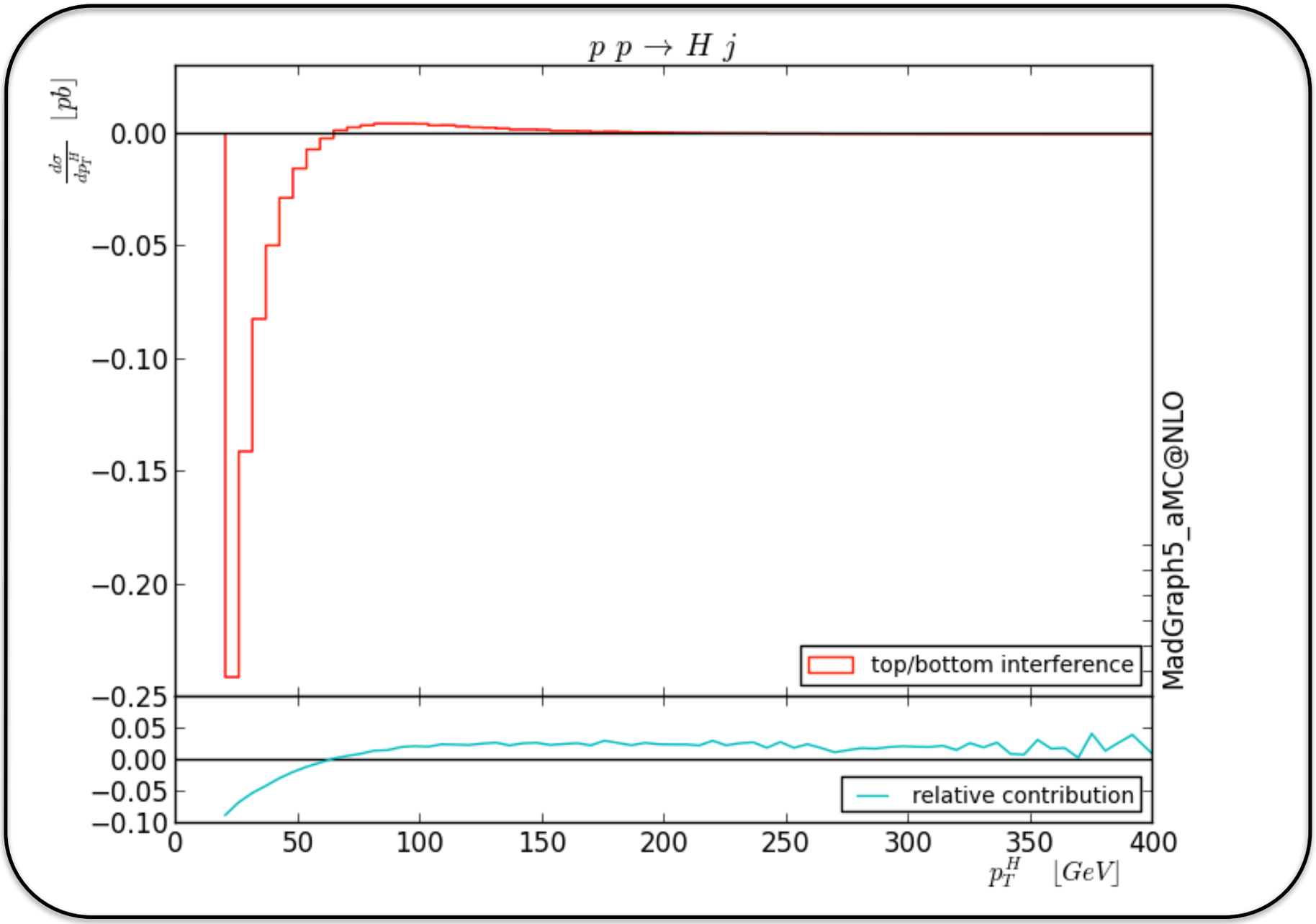
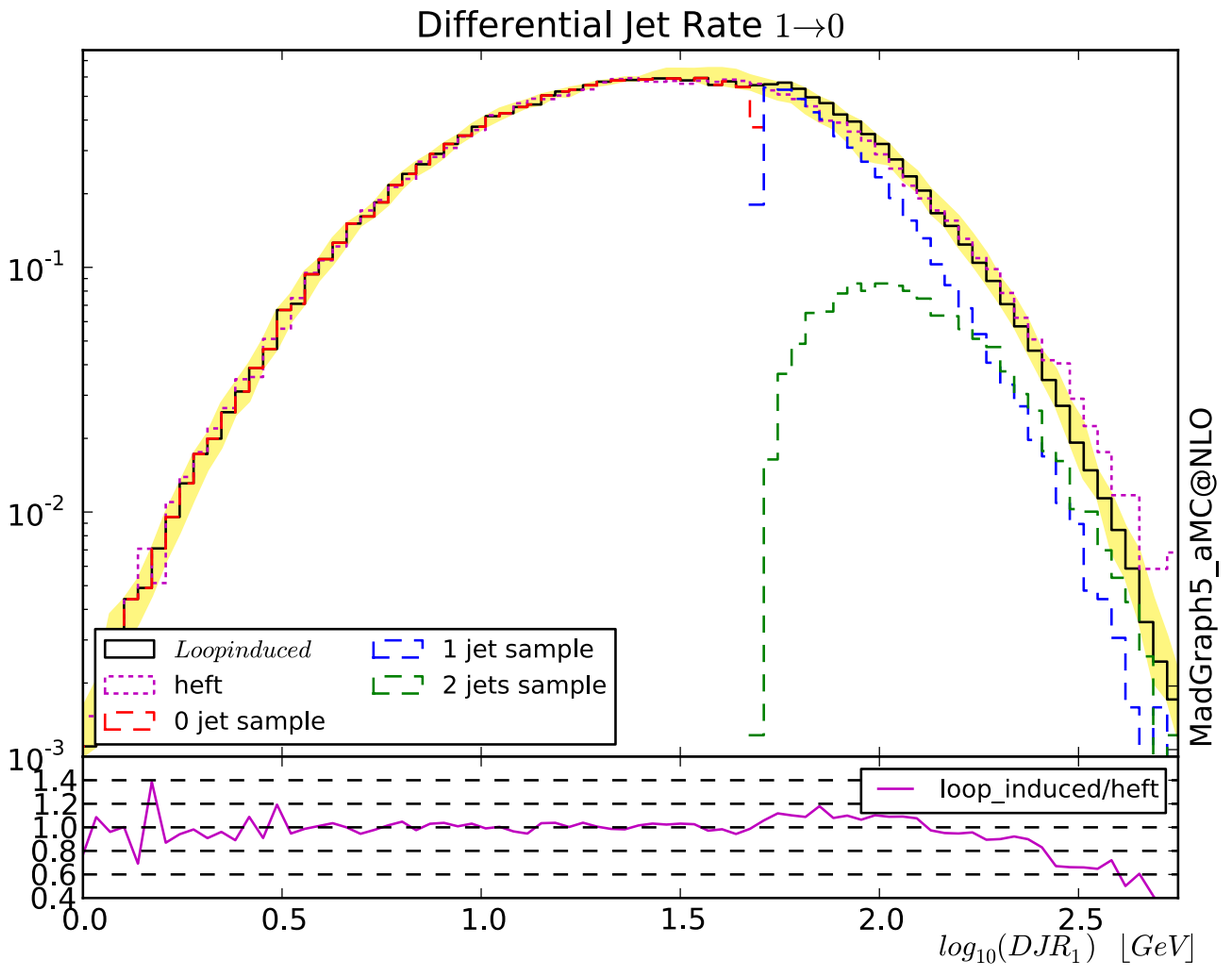
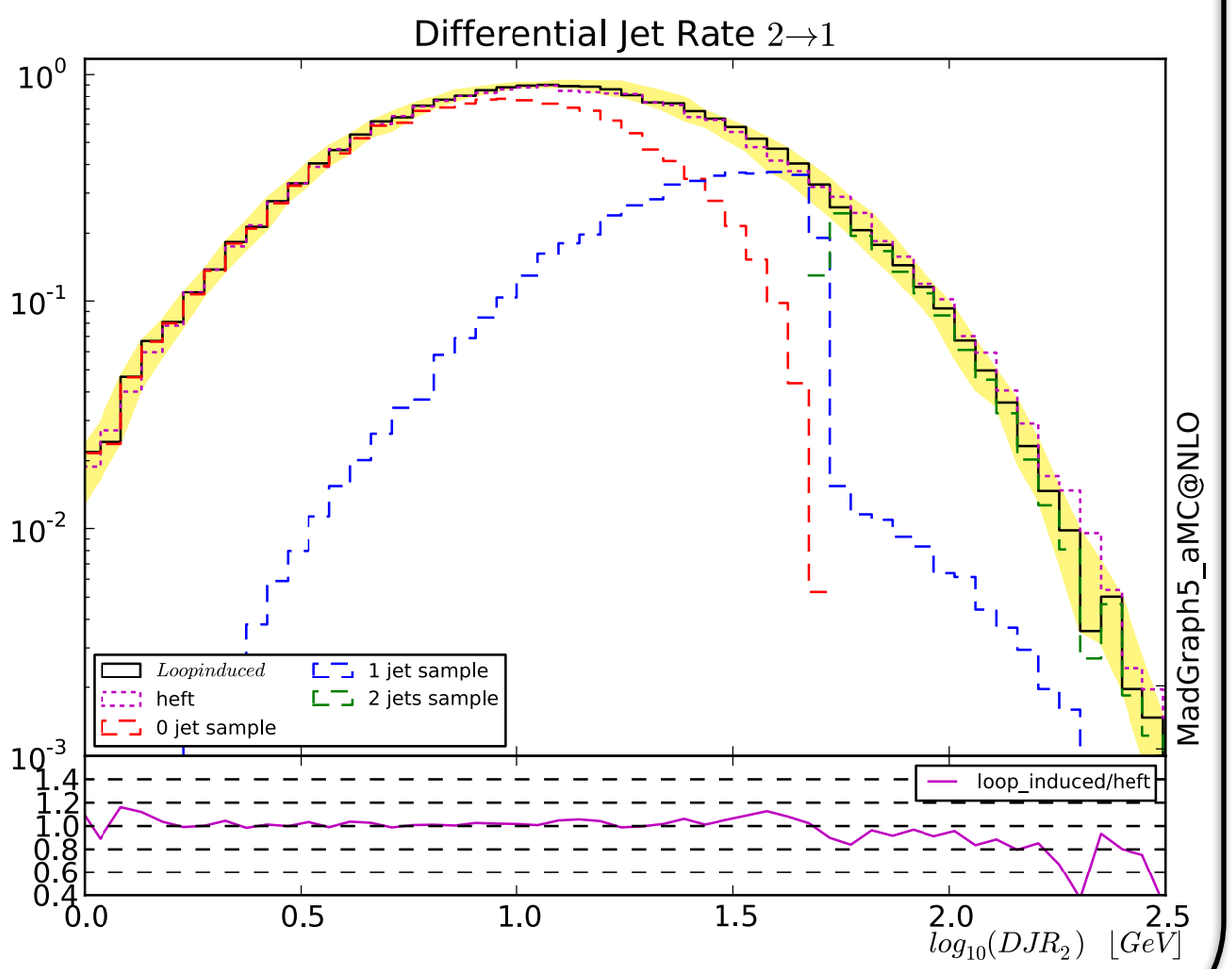


- b effect only important at low pt
- at large pt, this is just a re-scaling

Matching/Merging

KT MLM





$$Q_{match} = 50GeV$$

BSM Example: 2HDM

BSM technicalities

- Our code is fully ready for (all) BSM
- We (only) need NLO-UFO model

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Benchmark Point

	$\tan\beta$	α/π	m_{h^0}	m_{H^0}	m_{A^0}	$m_{H^\pm}$	m_{12}^2
B1	1.75	-0.1872	125	300	441	442	38300
B2	1.20	-0.1760	125	200	500	500	-60000
B3	1.70	-0.1757	125	350	250	350	12000

Z+Scalar Processes

Exact Phase-Space integration

	$gg \to Zh^0$	$gg \to ZH^0$	$gg \to ZA^0$
B1	$113.6\ ^{+28.9\%\ +1.0\%}_{-21.2\%\ -1.2\%}$	$682.4\ ^{+29.6\%\ +1.2\%}_{-21.5\%\ -1.2\%}$	$0.6203\ ^{+32.5\%\ +1.9\%}_{-23.0\%\ -1.9\%}$
B2	$85.59\ ^{+29.9\%\ +1.4\%}_{-21.4\%\ -1.1\%}$	$1545\ ^{+30.1\%\ +1.3\%}_{-21.8\%\ -1.3\%}$	$0.8614\ ^{+33.0\%\ +2.0\%}_{-23.3\%\ -2.0\%}$
B3	$169.9\ ^{+28.1\%\ +1.4\%}_{-19.9\%\ -0.5\%}$	$0.8968\ ^{+31.2\%\ +1.5\%}_{-22.3\%\ -1.6\%}$	$1317\ ^{+28.4\%\ +1.0\%}_{-20.8\%\ -1.0\%}$

Reweighting (1503.01656)

	$gg \to Zh^0$	$gg \to ZH^0$	$gg \to ZA^0$
B1	$113\ ^{+30\%}_{-21\%}$	$686\ ^{+30\%}_{-22\%}$	$0.622\ ^{+32\%}_{-23\%}$
B2	$85.8\ ^{+30.1\%}_{-21\%}$	$1544\ ^{+30\%}_{-22\%}$	$0.869\ ^{+34\%}_{-23\%}$
B3	$167\ ^{+31\%}_{-19\%}$	$0.891\ ^{+33\%}_{-21\%}$	$1325\ ^{+28\%}_{-21\%}$

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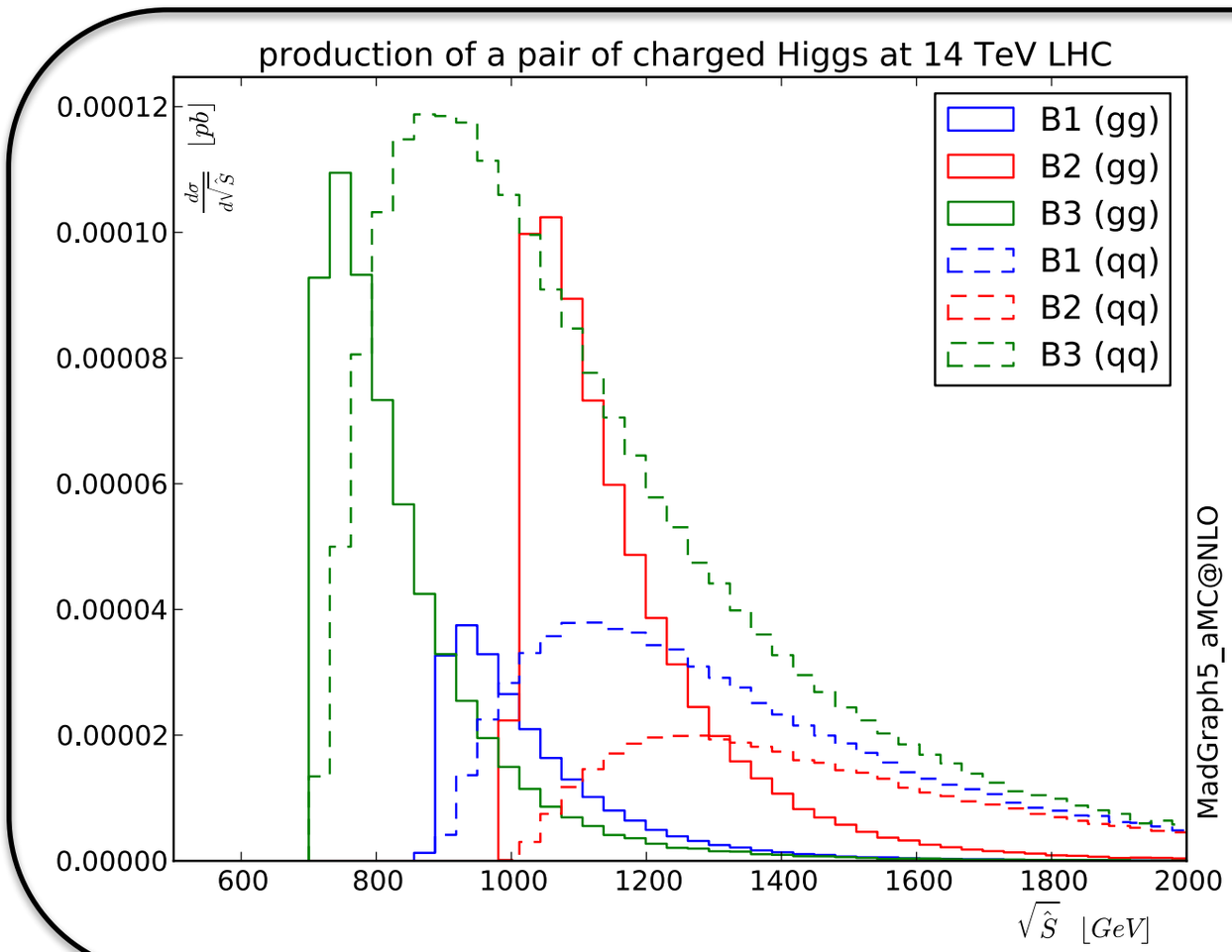
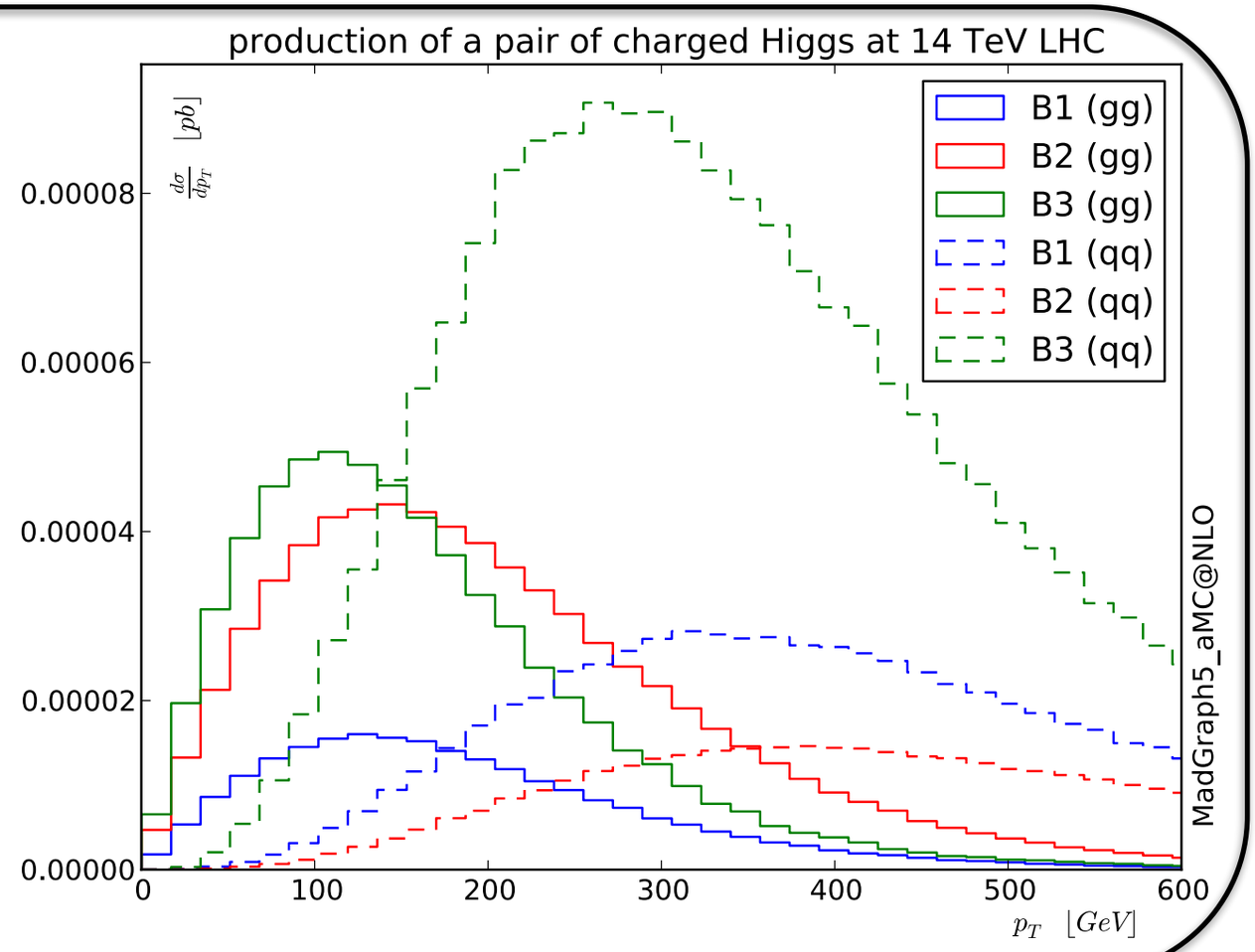
Charged Higgs

Exact Phase-Space integration

	$gg \to H^+H^-$			$q\bar{q} \to H^+H^-$		
B1	0.2334	$^{+34.0\%}_{-23.8\%}$	$^{+2.2\%}_{-2.2\%}$	0.7669	$^{+5.9\%}_{-5.4\%}$	$^{+1.1\%}_{-1.0\%}$
B2	0.7011	$^{+34.6\%}_{-24.1\%}$	$^{+2.4\%}_{-2.4\%}$	0.4406	$^{+6.5\%}_{-5.9\%}$	$^{+1.4\%}_{-1.0\%}$
B3	0.618	$^{+32.8\%}_{-23.2\%}$	$^{+1.9\%}_{-1.9\%}$	2.072	$^{+4.6\%}_{-4.3\%}$	$^{+0.9\%}_{-0.8\%}$

Charged Higgs





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Merged Sample	✓	✓	✓	?	✗	✗	✓	✓

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Merged Sample	✓	✓	✓	?	✗	✗	✓	✓

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

SM Tables

	Process	Syntax	Cross section (pb)	$\Delta_{\hat{\mu}}$	Δ_{PDF}
Single boson + jets			13 TeV		
a.1	$pp \to H$	`p p > h [noborn=QCD]`	17.79 ± 0.060	$^{+31.3\%}_{-23.1\%}$	$^{+0.7\%}_{-1.0\%}$
a.2	$pp \to Hj$	`p p > h j [noborn=QCD]`	12.86 ± 0.030	$^{+42.3\%}_{-27.7\%}$	$^{+0.6\%}_{-0.9\%}$
a.3	$pp \to Hjj$	`p p > h j j QED=1 [noborn=QCD]`	6.175 ± 0.020	$^{+61.8\%}_{-35.6\%}$	$^{+0.9\%}_{-0.9\%}$
a.4	$gg \to Zg$	`g g > z g [noborn=QCD]`	43.05 ± 0.060	$^{+43.7\%}_{-28.4\%}$	$^{+0.7\%}_{-1.0\%}$
a.5	$gg \to Zgg$	`g g > z g g [noborn=QCD]`	20.85 ± 0.030	$^{+64.5\%}_{-36.5\%}$	$^{+1.2\%}_{-1.2\%}$
a.6	$gg \to \gamma g$	`g g > a g [noborn=QCD]`	75.61 ± 0.200	$^{+73.8\%}_{-41.6\%}$	$^{+0.8\%}_{-1.1\%}$
a.7	$gg \to \gamma gg$	`g g > a g g [noborn=QCD]`	14.50 ± 0.030	$^{+76.2\%}_{-40.7\%}$	$^{+0.8\%}_{-1.1\%}$

	Process	Syntax	Cross section (pb)	$\Delta_{\hat{\mu}}$	Δ_{PDF}
Double bosons + jet			13 TeV		
b.1	$pp \to HH$	`p p > h h [noborn=QCD]`	$1.641 \pm 0.002 \cdot 10^{-2}$	$^{+30.2\%}_{-21.7\%}$	$^{+1.3\%}_{-1.3\%}$
b.2	$pp \to HHj$	`p p > h h j [noborn=QCD]`	$1.758 \pm 0.003 \cdot 10^{-2}$	$^{+45.7\%}_{-29.2\%}$	$^{+1.4\%}_{-1.4\%}$
b.3	$pp \to H\gamma j$	`p p > h a j [noborn=QCD]`	$4.225 \pm 0.006 \cdot 10^{-3}$	$^{+38.6\%}_{-25.9\%}$	$^{+0.5\%}_{-0.8\%}$
b.4	$gg \to HZ$	`g g > h z [noborn=QCD]`	$6.537 \pm 0.030 \cdot 10^{-2}$	$^{+29.4\%}_{-21.3\%}$	$^{+1.2\%}_{-1.2\%}$
b.5	$gg \to HZg$	`g g > h z g [noborn=QCD]`	$5.465 \pm 0.020 \cdot 10^{-2}$	$^{+46.0\%}_{-29.4\%}$	$^{+1.5\%}_{-1.6\%}$
b.6	$gg \to ZZ$	`g g > z z [noborn=QCD]`	1.313 ± 0.004	$^{+27.1\%}_{-20.1\%}$	$^{+0.8\%}_{-1.0\%}$
b.7	$gg \to ZZg$	`g g > z z g [noborn=QCD]`	0.6361 ± 0.002	$^{+45.4\%}_{-29.1\%}$	$^{+1.2\%}_{-1.2\%}$
b.8	$gg \to Z\gamma$	`g g > z a [noborn=QCD]`	1.265 ± 0.0007	$^{+30.2\%}_{-22.2\%}$	$^{+0.9\%}_{-1.1\%}$
b.9	$gg \to Z\gamma g$	`g g > z a g [noborn=QCD]`	0.4604 ± 0.001	$^{+43.7\%}_{-28.4\%}$	$^{+0.7\%}_{-1.0\%}$
b.10	$gg \to \gamma\gamma$	`g g > a a [noborn=QCD]`	$5.182 \pm 0.010 \cdot 10^{+2}$	$^{+72.3\%}_{-43.4\%}$	$^{+1.2\%}_{-1.5\%}$
b.11	$gg \to \gamma\gamma g$	`g g > a a g [noborn=QCD]`	19.22 ± 0.030	$^{+59.7\%}_{-35.7\%}$	$^{+0.9\%}_{-1.2\%}$
b.12	$gg \to W^+W^+$	`g g > w+ w- [noborn=QCD]`	4.099 ± 0.010	$^{+26.5\%}_{-19.7\%}$	$^{+0.7\%}_{-1.0\%}$
b.13	$gg \to W^+W^-g$	`g g > w+ w- g [noborn=QCD]`	1.837 ± 0.004	$^{+45.2\%}_{-29.0\%}$	$^{+1.1\%}_{-1.1\%}$

SM Tables

Process		Syntax	Cross section (pb)	$\Delta_{\hat{\mu}}$	Δ_{PDF}
Triple bosons			13 TeV		
c.1	$pp \to HHH$	`p p > h h h [noborn=QCD]`	$3.968 \pm 0.010 \cdot 10^{-5}$	$^{+31.8\%}_{-22.6\%}$	$^{+1.7\%}_{-1.7\%}$
c.2	$gg \to HHZ$	`g g > h h z [noborn=QCD]`	$5.260 \pm 0.009 \cdot 10^{-5}$	$^{+31.2\%}_{-22.2\%}$	$^{+1.6\%}_{-1.6\%}$
c.3	$gg \to HZZ$	`g g > h z z [noborn=QCD]`	$1.144 \pm 0.004 \cdot 10^{-4}$	$^{+31.1\%}_{-22.2\%}$	$^{+1.6\%}_{-1.5\%}$
c.4	$gg \to HZ\gamma$	`g g > h z a [noborn=QCD]`	$6.190 \pm 0.020 \cdot 10^{-6}$	$^{+29.3\%}_{-21.2\%}$	$^{+1.1\%}_{-1.2\%}$
c.5	$pp \to H\gamma\gamma$	`p p > h a a [noborn=QCD]`	$6.058 \pm 0.004 \cdot 10^{-6}$	$^{+30.3\%}_{-21.8\%}$	$^{+1.3\%}_{-1.3\%}$
c.6	$pp \to HW^+W^-$	`g g > h w+ w- [noborn=QCD]`	$2.670 \pm 0.007 \cdot 10^{-4}$	$^{+31.0\%}_{-22.2\%}$	$^{+1.5\%}_{-1.6\%}$
c.7	$gg \to ZZZ$	`g g > z z z [noborn=QCD]`	$6.964 \pm 0.009 \cdot 10^{-5}$	$^{+30.9\%}_{-22.1\%}$	$^{+1.5\%}_{-1.5\%}$
c.8	$gg \to ZZ\gamma$	`g g > z z a [noborn=QCD]`	$3.454 \pm 0.010 \cdot 10^{-6}$	$^{+28.7\%}_{-20.9\%}$	$^{+1.0\%}_{-1.1\%}$
c.9	$gg \to Z\gamma\gamma$	`g g > z a a [noborn=QCD]`	$3.079 \pm 0.005 \cdot 10^{-4}$	$^{+28.0\%}_{-20.9\%}$	$^{+0.9\%}_{-1.2\%}$
c.10	$gg \to ZW^+W^-$	`g g > z w+ w- [noborn=QCD]`	$8.595 \pm 0.020 \cdot 10^{-3}$	$^{+26.9\%}_{-19.5\%}$	$^{+0.7\%}_{-0.7\%}$
c.12	$gg \to \gamma W^+W^-$	`g g > a w+ w- [noborn=QCD]`	$1.822 \pm 0.005 \cdot 10^{-2}$	$^{+28.7\%}_{-20.9\%}$	$^{+0.9\%}_{-1.1\%}$

Process		Syntax	Decay width (GeV)
Bosonic decays			
g.1	$H \to jj$	`h > j j [noborn=QCD]`	$1.646 \pm 0.003 \cdot 10^{-4}$
g.2	$H \to jjj$	`h > j j j [noborn=QCD]`	$4.630 \pm 0.030 \cdot 10^{-5}$
g.3	$H \to jjjj$	`h > j j j j QED=1 [noborn=QCD]`	$2.549 \pm 0.020 \cdot 10^{-6}$
g.4	$H \to \gamma\gamma$	`h > a a [noborn=QED]`	$9.743 \pm 0.004 \cdot 10^{-6}$
g.5	$Z \to ggg$	`z > g g g [noborn=QCD]`	$3.921 \pm 0.010 \cdot 10^{-7}$

SM Tables

Process		Syntax	Cross section (pb)	$\Delta_{\hat{\mu}}$	Δ_{PDF}
Selected $2 \to 4$			13 TeV		
d.1	$pp \to Hjjj$	`p p > h j j j QED=1 [noborn=QCD]`	2.519 ± 0.005	0% 0%	
d.2	$pp \to HHjj$	`p p > h h j j QED=1 [noborn=QCD]`	$1.085 \pm 0.002 \cdot 10^{-2}$	0% 0%	
d.3	$pp \to HHHj$	`p p > h h h j [noborn=QCD]`	$4.981 \pm 0.008 \cdot 10^{-5}$	$^{+62.1\%}_{-35.8\%}$	$^{+1.5\%}_{-1.6\%}$
d.3	$pp \to HHHH$	`p p > h h h h [noborn=QCD]`	$1.080 \pm 0.003 \cdot 10^{-7}$	$^{+46.3\%}_{-29.6\%}$	$^{+1.8\%}_{-1.8\%}$
d.4	$gg \to e^+e^-\mu^+\mu^-$	`g g > e+ e- mu+ mu- [noborn=QCD]`	$2.022 \pm 0.003 \cdot 10^{-3}$	$^{+33.3\%}_{-23.4\%}$	$^{+2.2\%}_{-2.1\%}$
d.5	$pp \to HZ\gamma j$	`g g > h z a g [noborn=QCD]`	$4.950 \pm 0.008 \cdot 10^{-6}$	$^{+26.4\%}_{-19.4\%}$	$^{+1.0\%}_{-1.3\%}$
				$^{+45.8\%}_{-29.3\%}$	$^{+1.5\%}_{-1.6\%}$
e^+e^- processes			$\hat{s} = 500$ GeV		
e.1	$e^+e^- \to ggg$	`e+ e- > g g g [noborn=QED]`	$2.526 \pm 0.004 \cdot 10^{-6}$	$^{+31.2\%}_{-22.0\%}$	
e.2	$e^+e^- \to HH$	`e+ e- > h h [noborn=QED]`	$1.567 \pm 0.003 \cdot 10^{-5}$	$^{+0.0\%}_{-0.0\%}$	
e.3	$e^+e^- \to HHgg$	`e+ e- > h h g g [noborn=QED]`	$6.629 \pm 0.010 \cdot 10^{-11}$	$^{+19.2\%}_{-14.8\%}$	
Miscellaneous			13 TeV		
f.1	$pp \to tt$	`p p > t t [noborn=QED]`	$4.045 \pm 0.007 \cdot 10^{-15}$	$^{+0.2\%}_{-0.8\%}$	$^{+1.1\%}_{-1.1\%}$

Conclusion

- MadGraph5_aMC@NLO
  - ➡ Framework for LO and NLO computation
  - ➡ Fixed order or matched to the shower
  - ➡ Merging possible
  - ➡ SM and BSM on the same level
- Loop-Induced
  - ➡ Code in public beta
  - ➡ Fine tuning in progress
  - ➡ Officially release in ~ weeks