Simulation of ttH (H->multileptons) in MadGraph5_aMC@NLO

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NLO event generation: TTV(V)

- All relevant processes can be computed at NLO accuracy using MadGraph5_aMC@NLO
- Unweighted (up to a sign) event generation possible
- FxFx merging available for ttV+0,1j at NLO accuracy
  - includes the leading order matrix elements for ttV+2j

LHC13 TeV			Leading order			Next-to-Leading order		
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`	$3.272 \pm 0.006 \cdot 10^{-3}$	$^{+28.4\%}_{-20.6\%}$	$^{+1.3\%}_{-1.1\%}$	$4.402 \pm 0.015 \cdot 10^{-3}$	$^{+7.8\%}_{-9.7\%}$	$^{+1.4\%}_{-1.4\%}$

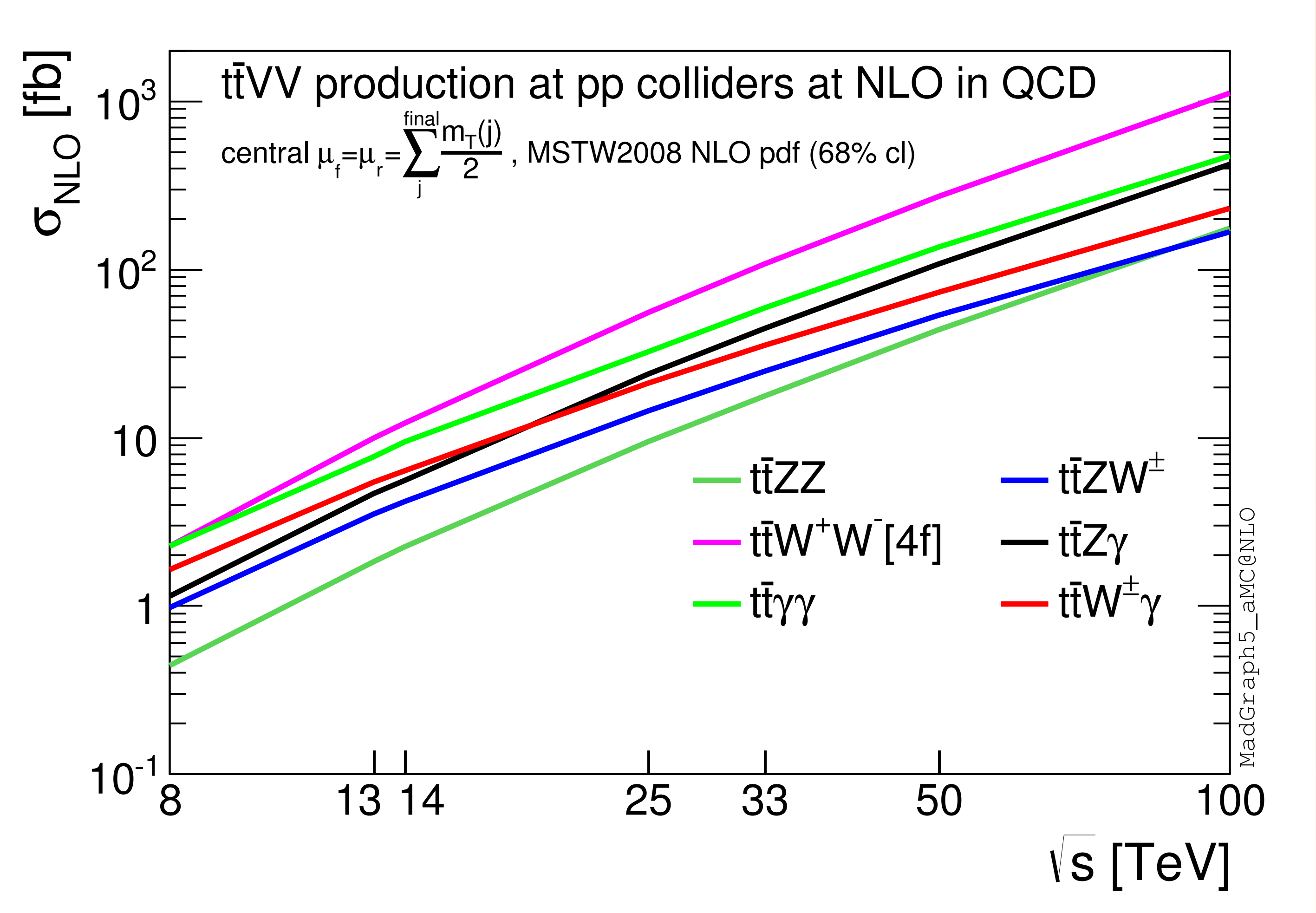
arXiv:1405.0301 [hep-ph]

NLO EVENT GENERATION: TTVV

✦ In MadGraph5_aMC@NLO, we have tried to make it as simple for you as possible. For example

- ./bin/mg5_aMC
- generate p p > t t~ w+ w- [QCD]
- output
- launch

F. Maltoni, D. Pagani & I. Tsinikos, *in preparation*



Decays

- Easiest is to use MadSpin to perform the decays. It is part of the commands on the previous slide, and a simple switch will turn it on
- MadSpin will
  - decay any massive particle using (chains of) on-shell 1->2 decays
  - use the complete matrix elements to **include spin correlations and (some) off-shell effects**
  - not include Z/γ^* interference
  - decays at (improved) leading order accuracy
- Therefore ideal for top and W-boson decays and on-shell Z decays
- Work in progress to go beyond 1->2 decays and LO accuracy

For example: 4 leptons in ttWW

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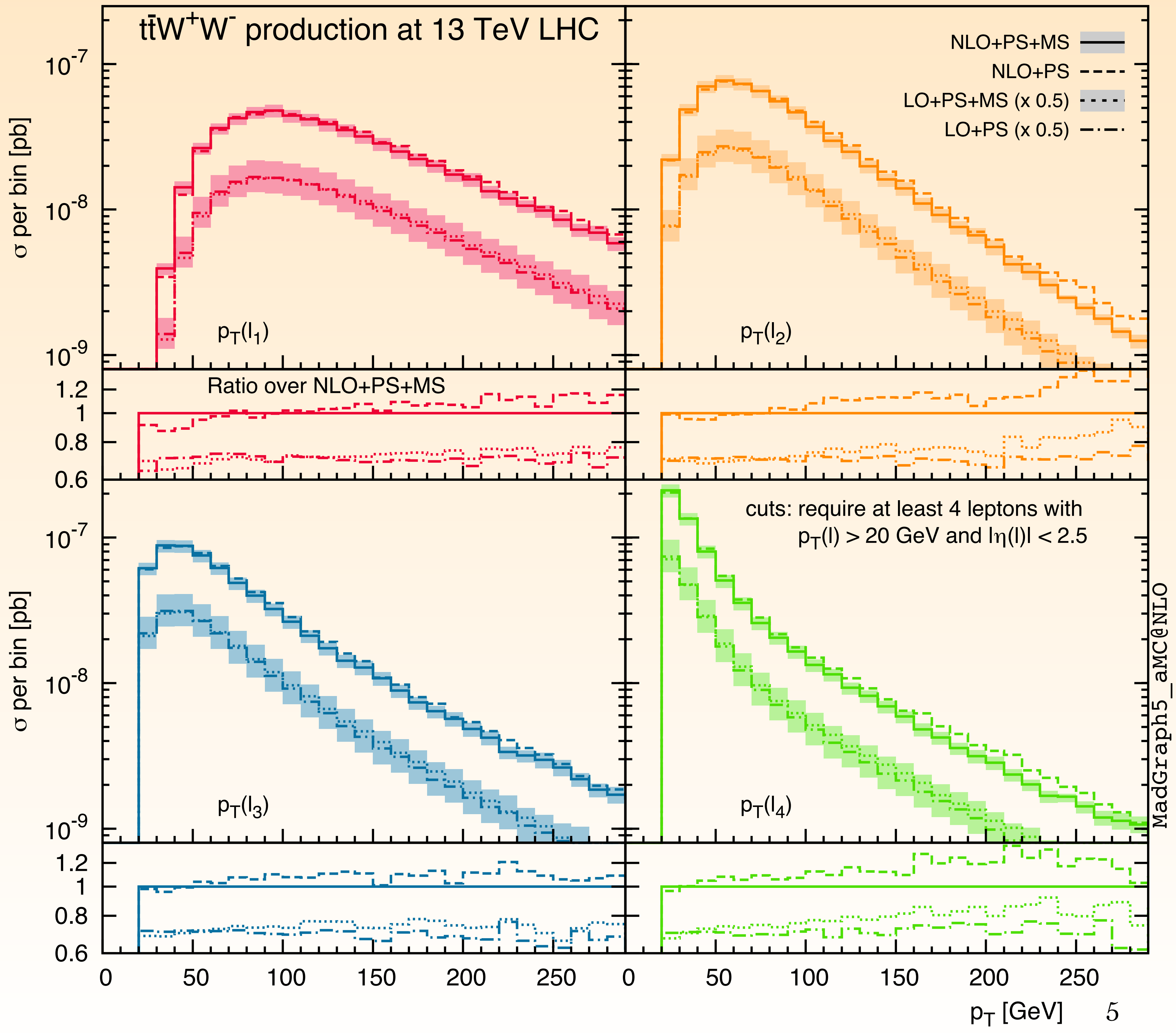
- Transverse momenta of the 4 leptons in fully leptonic ttWW decays
- Production spin correlations are important
  - not including them makes the predictions go outside the NLO uncertainty band!



Including interference

- To include the interference of *Z*-boson decays with the off-shell photon, include the decay at the level of generation, for example
  - generate p p > t t~ mu+ mu- [QCD]

- Note that ttZZ with decays, i.e. **pp -> tt e^+e^- $\mu^+\mu^-$**, is a complicated process for NLO event generation. Might be possible on a big cluster, though — I haven't tested it so you might want to give it a try if considered to be important

Multi-jet merging at NLO

- For multi-jet merging for, e.g., ttW^{+}+0,1j @NLO use
  - generate p p > t t~ w+ [QCD]
  - add process p p > t t~ w+ j [QCD]
  - output ; launch
  - In the run_card, set the ickkw parameter to
    - 3 to activate FxFx merging (tested with herwig6, herwig++ & pythia8) or see http://amcatnlo.web.cern.ch/amcatnlo/FxFx_merging.htm for more details
    - 4 to activate UNLOPS merging (pythia8)

NON-TTBAR BACKGROUNDS

- **VV+jets** backgrounds
  - Using FxFx merging, VV+0,1,2 jets can be consistently combined at NLO accuracy. At 3rd jet at NLO is currently beyond the capabilities of the MadGraph5_aMC@NLO code
  - Decays can be included using MadSpin
  - When requiring more than 3 jets in the analysis, there is no point in including NLO corrections. You are better of using VV+0,1,2,**3**,.. at LO
- **V+heavy flavour**
  - Use NLO Vbb in the 4 flavour scheme. FxFx merging not available for processes with b quarks. If requiring multi-jets, use LO merged predictions instead.
- **VVV+jets** backgrounds
  - Possible to use FxFx merging for VVV+0,1 jets @NLO. Otherwise use LO

Theory uncertainties

- Renormalisation and factorisation scale dependence (varied independently up and down by a factor 2) as well as PDF error sets can be included at no extra computational cost as a list of weights in the event file
- Matching NLO+PS possible to Pythia8 and Herwig++ (as well as the older fortran codes): allows for the study of PS systematics
- For FxFx merging:
  - Vary scale to cover so that both sides of the analyses' jet definition are covered
    - LHEF events are independent from the merging scale
    - Only shower needs to be rerun to estimate merging scale systematics
  - FxFx merging with Herwig++ and Pythia8 allows for study of the MC dependence
  - FxFx can be compared to UNLOPS merging for Pythia8

Default ren. and fac. scales

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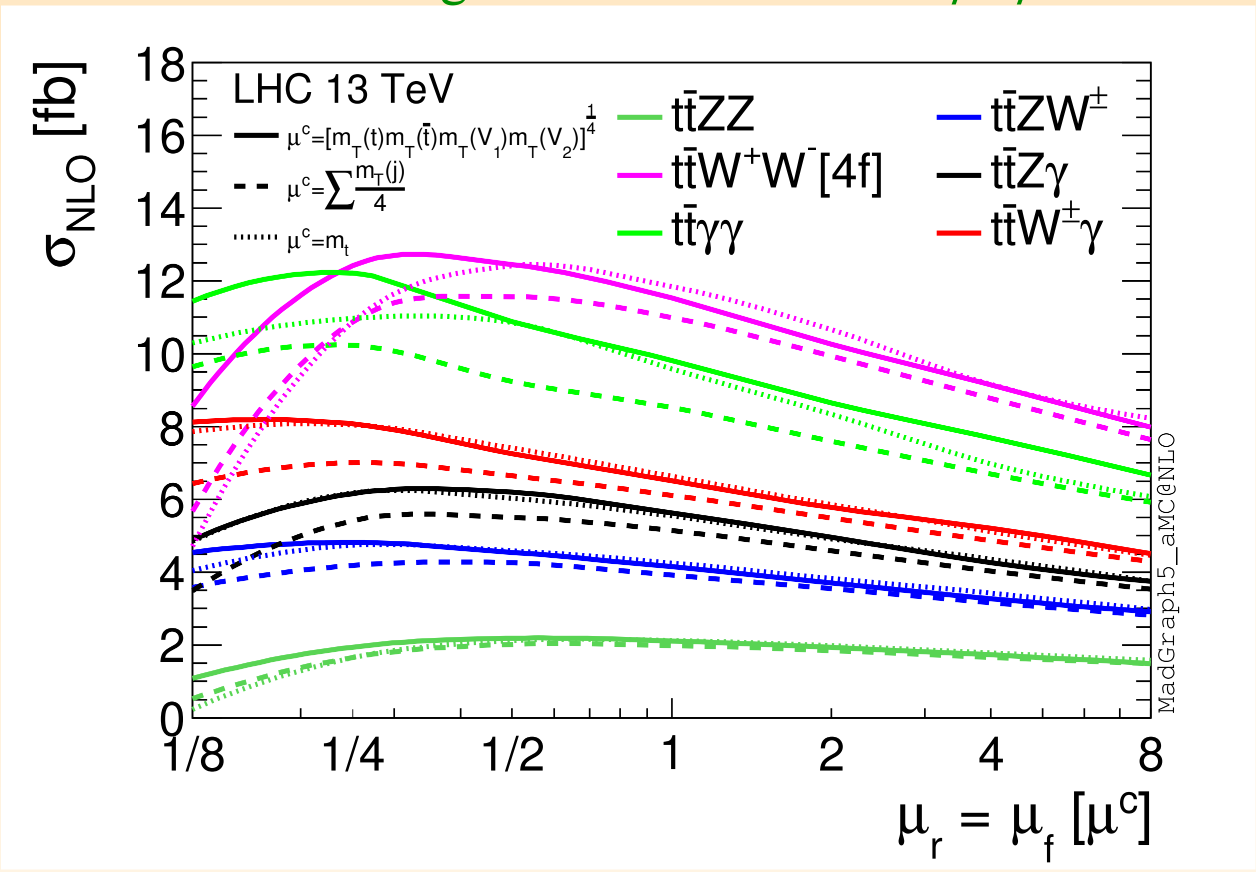

- The default renormalisation and factorisation scale in NLO event generation of MadGraph5_aMC@NLO are the sum of the transverse energies of the particles entering the matrix elements divided by 2
- Okay for ttV processes
- Not ideal for the ttVV processes: scale seems to be a bit too large
- "Plateau" in scale dependence appears at scales $\Sigma E_T/12 - \Sigma E_T/16$.
- Better to use $\Sigma m_T^2/4$ or $\Sigma m_T^2/8$ as a default central scale
  - similar to geometric mean
- Mild scale dependence at around ±10%-12% at 13 TeV (computed using an independent variation of factorisation and renormalisation scales by a factor 2 up and down)

Conclusions

- **tt+X available at NLO accuracy (X=H,W±,Z,γ,j)**
- **tt+XX also available at NLO accuracy (X=H,W±,Z,γ,j,b)**
- **FxFx merging** available for processes with jets: consistent combination of jet-multiplicities at NLO accuracy, **e.g. ttZ+0,1jets at NLO**
- **Decays** of W/Z can either be included
  - at the level of generation: (sometimes too) slow, but keeps all interferences/ off-shell effects and spin-correlations
  - using **MadSpin**: fast, keeps spin-correlations and most off-shell effects, but no interferences. Excellent for top and W decays and on-shell Z decays
- **VV(V)+jets** also possible with MadGraph5_aMC@NLO using FxFx multi-jet merging
- **V+ heavy flavour**: no FxFx merging available yet (work in progress), but can use NLO for Vbb in the four flavour scheme