backgrounds to ttH with MadGraph5_aMC@NLO

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Backgrounds for Higgs in association with top pairs

- ttH with Higgs to bbbar
  - main backgrounds: ttbar+bbbar, ttbar+jets
- ttH with Higgs to leptons (via VV* or directly to taus)
  - main backgrounds (depending on the flavour of the required leptons): ttbar+V, V(V)+HF, VV(V)+jets, ttbar+VV
- ttH with Higgs to di-photon
  - non-reducible background: ttbar+di-photon. I will not discuss this in this talk

Overview of ttbar + 2 jets simulation

- NLO+PS matched for pp > ttbar
  - Only shower accuracy for ttbar+2jets
  - Mass effects in jets at shower accuracy
- LO+PS merged for pp > ttbar +0,1,2,… jets
  - ttbar+2jets at LO accuracy
  - Mass effects can easily be included in the matrix elements
- NLO+PS matched & merged for pp > ttbar +0,1,2,… jets ("FxFx merging")
  - NLO accuracy for ttbar+2jets (with some caveats!)
  - Inclusive for HF, but no mass effects in matrix elements
- NLO+PS matched for pp > ttbar bbbar
  - 4 FS calculation: mass effects included
  - No need for generation cuts
  - Possibly large logs of Log[m_b/p_T]

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FxFx merging at NLO

- In MadGraph5_aMC@NLO, we have tried to make it as simple as possible
  - ./bin/mg5_aMC
  - generate p p > t t~ [QCD] @0
  - add process p p > t t~ j [QCD] @1
  - add process p p > t t~ j j [QCD] @2
  - 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)

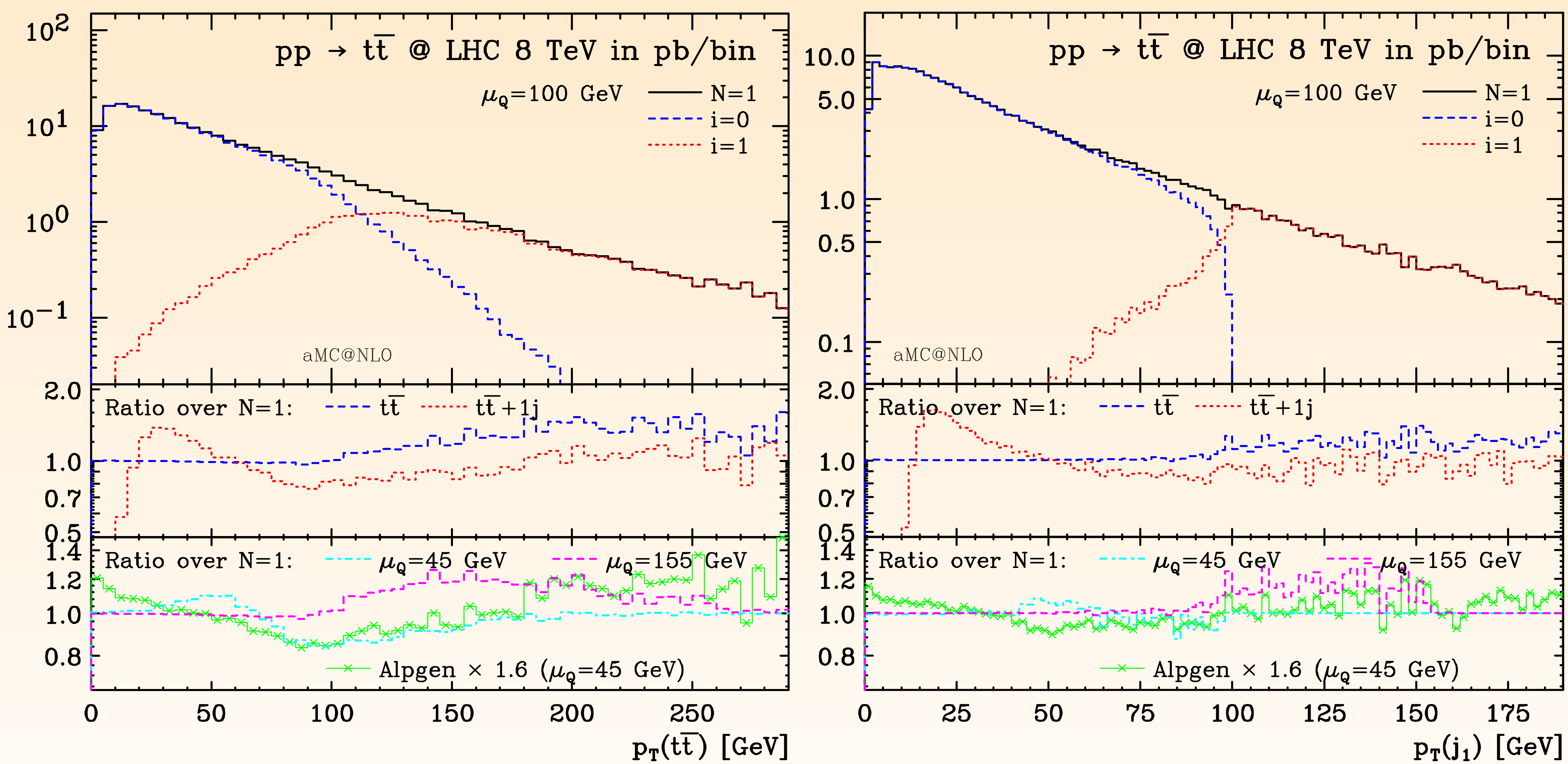
MG5_aMC advertisement

- MadGraph5_aMC@NLO features
  - Event weights to include scale & PDF uncertainties event-by-event at no extra cost
  - Decays with MadSpin: spin correlations included
  - 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

Merging scale

- Check that your results are "independent" from the merging scale

RF & Frixione: JHEP 1212 (2012) 061



- These plots are for ttbar+0/1j @ NLO; ttbar+2j @NLO is a tough calculation but can be included to improve the description of 2-jet observables

NLO accuracy

- Even though one is merging NLO samples together, this does not necessarily mean that the combined sample is also NLO accurate
  - The introduction of the merging scale introduces logarithms dependent on the merging scale
  - Leading dependence is cancelled among the various samples
  - When these logarithms are too large (i.e. a very small merging scale), they introduce terms that are of similar order as the NLO corrections.
    - See also Nason's talk (yesterday) on the details
  - Also applies for LO CKKW(-L)/MLM merging techniques (but less of issue, because aiming at lower accuracy)
- Always vary it at least so that both sides of the analyses' jet definition are covered
  - e.g. if jets are defined with 40 GeV p_T, vary the merging scale from below to above 40 GeV to cover uncertainties

Heavy flavour

- When using a 5FS calculation, b quarks are included in the matrix elements (but as massless quarks only)
- So, FxFx merging for ttbar+0,1,2jets gives you an inclusive sample in all parton flavours
- Alternatively, when computing explicitly pp > ttbar bbbar (in the 4FS) allows one to generate NLO+PS samples including the b quark mass effects
  - Particularly needed when b quark are close to each other or at not very high p_T
  - Sample can be used for ttbar+2 b-jets and ttbar+1 b-jet or ttbar+bbjet
  - Used to be a complicated calculation, but with MG5_aMC it is possible to setup the process and generate 100k unweighted events at NLO+PS accuracy overnight on my desktop computer

Inclusive sample using both 5FS and 4FS

- Can one combine a
  - 5FS calculation (ttbar+FxFx merging) for all light jets and hard, well-separated b-jets, with a
  - 4FS calculation for other b-quark contributions?
- No theoretically sound method known…
  - Intricate interplay between matrix elements and parton shower
- Related to this is the fact that FxFx merging does not work for processes with massive b quarks

Summary for ttbar+jets

- MadGraph5_aMC@NLO can be used for the simulation of ttbar+jets and ttbb
  - For ttbar+jets, FxFx merging can be used
    - Use a large variation of the merging scale: in general from below to above the jet definition
  - For ttbar+HF, use the ttbb process (4 flavour scheme)
    - Not known how to add it into the ttbar+jets sample without double counting contributions
    - Not known to combine it with the FxFx merged ttbar +jets sample

NLO event generation: TTV(V)

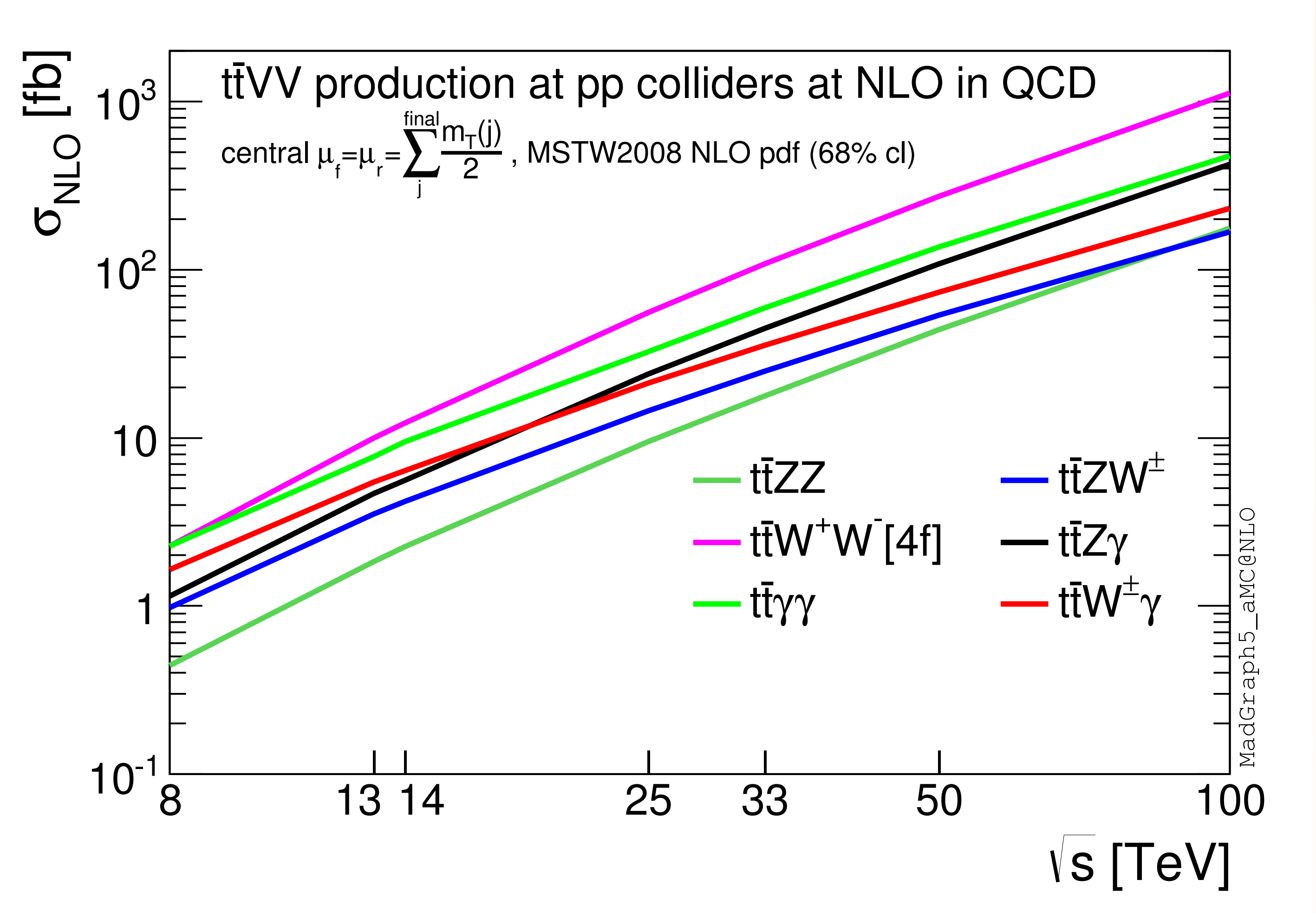
- All relevant processes can be computed at NLO accuracy using MadGraph5_aMC@NLO
- Unweighted (up to a sign) event generation + matching to the parton shower
- FxFx merging available for ttV+0,1j at NLO accuracy
  - includes the leading order matrix elements for ttV+2j

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

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



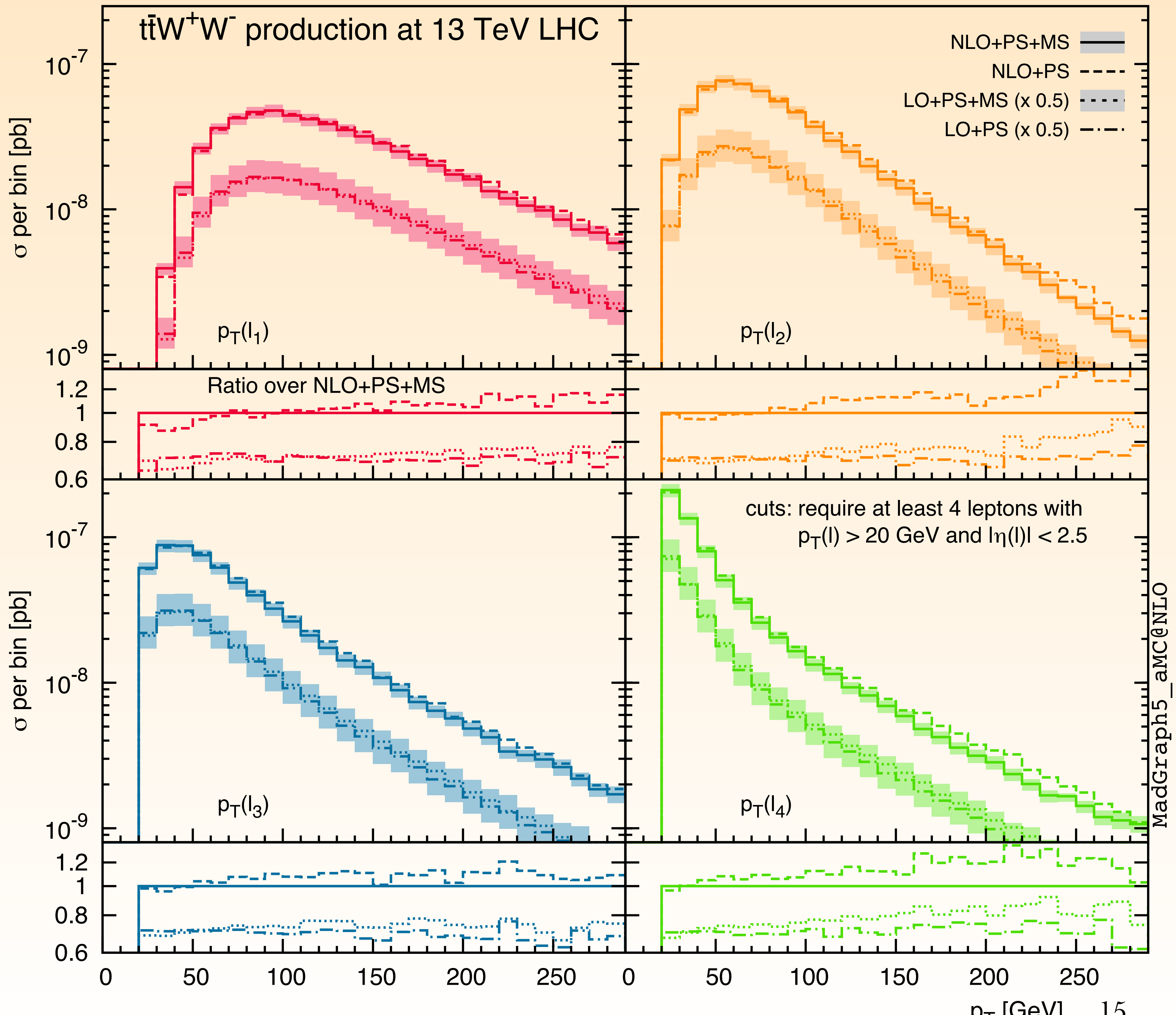
- In MadGraph5_aMC@NLO, we have tried to make it as simple for you as possible. For example
  - ./bin/mg5_aMC
  - generate p p > t t~ w+ w- [QCD]
  - output
  - launch

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

arXiv:1405.0301 [hep-ph]



- ✦ 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!

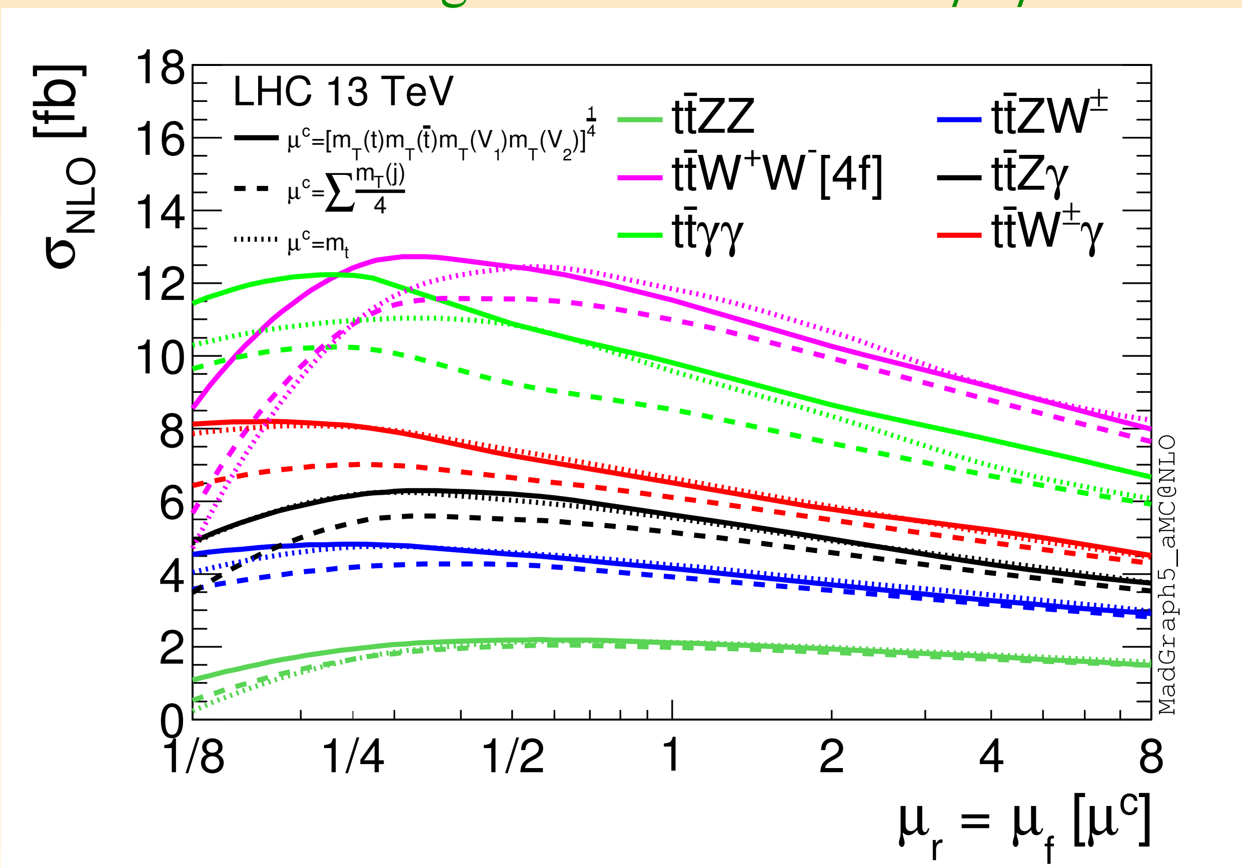
INCLUDING INTERFERENCE

- 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

Default ren. and fac. scales

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



- 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 around $\Sigma\, E_T/12 - \Sigma\, E_T/16$.
- 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)

Multi-jet merging at NLO

- For multi-jet merging for, e.g., ttW$^+$+0,1j @NLO use
  - generate p p > t t~ w+ [QCD] @0
  - add process p p > t t~ w+ j [QCD] @1
  - 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(V)+heavy flavour** (apart from W^+W^-bb which contains resonant tops)
  - 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

Conclusions

- **tt+X available at NLO accuracy (X=H,W$^{\pm}$,Z,γ,j)**
- **tt+XX also available at NLO accuracy (X=H,W$^{\pm}$,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(V)+ heavy flavour**: no FxFx merging available yet (work in progress), but can use NLO for V(V)bb in the four flavour scheme