

Rare Higgs, top, and vector-boson production processes at 100 TeV

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Outline

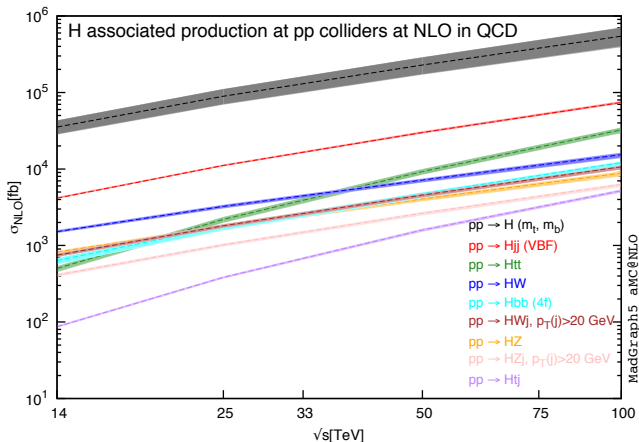
- ▶ Multi Higgs production at the LHC and at 100 TeV.
- ▶ Multi vector-boson production at the LHC at 100 TeV.
- ▶ Multi top production at the LHC at 100 TeV.

Framework

- ▶ I use [MadGraph5_aMC@NLO](#) (hep-ph/1405-0301). It makes **extremely easy** the task of simulating very complicated processes with NLO+PS accuracy, as it used to be for MadGraph5 at LO+PS.
- ▶ Renormalisation and factorisation scale: $\mu_R = \mu_F = \frac{1}{2} \sum_j m_T^{(j)}$, $j = \text{final}$.
- ▶ Parton distributions: MSTW2008 NLO (68% c.l.), 4 flavours or 5 flavours.
- ▶ $M_H = 125 \text{ GeV}$, $M_t = 173 \text{ GeV}$.
- ▶ Diagonal CKM matrix.
- ▶ Jets clustered with anti- k_T , $R = 0.7$.
- ▶ Frixione photon isolation with $p_T(\gamma) > 20 \text{ GeV}$, $R_0(\gamma) = 0.4$, $\epsilon_\gamma = n = 1$.

Multi Higgs production

Higgs associated production



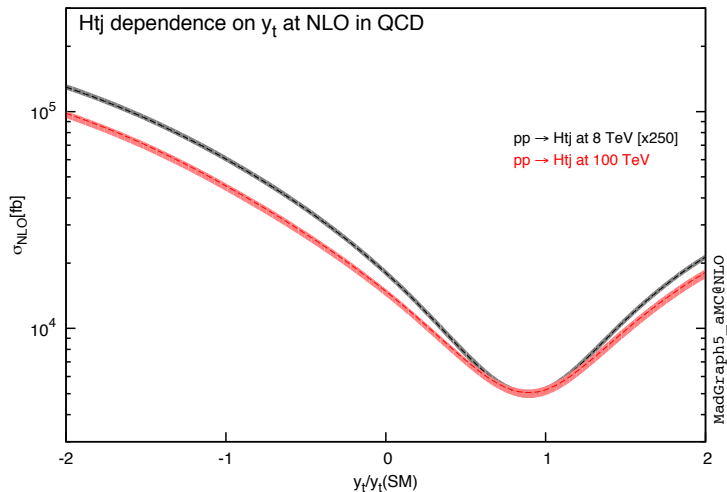
| Channel | $\frac{\sigma_{100}}{\sigma_{14}}$ | $\frac{\sigma_{100}}{\sigma_8}$ |
|-------------------------------|------------------------------------|---------------------------------|
| <i>H</i> | 20 | 40 |
| <i>Hjj</i> VBF | 20 | 45 |
| <i>Ht\bar{t}</i> | 60 | 270 |
| <i>HW</i> | 10 | 20 |
| <i>HWj</i> | 15 | 35 |
| <i>Hb\bar{b}</i> | 20 | 50 |
| <i>HZ</i> | 10 | 20 |
| <i>HZj</i> | 15 | 35 |
| <i>Htj</i> | 60 | 250 |

- The big growth in *Ht \bar{t}* and *Htj* makes them optimal channels for measuring the magnitude and the sign of y_t .

Sensitivity to the top Yukawa at 8 and 100 TeV

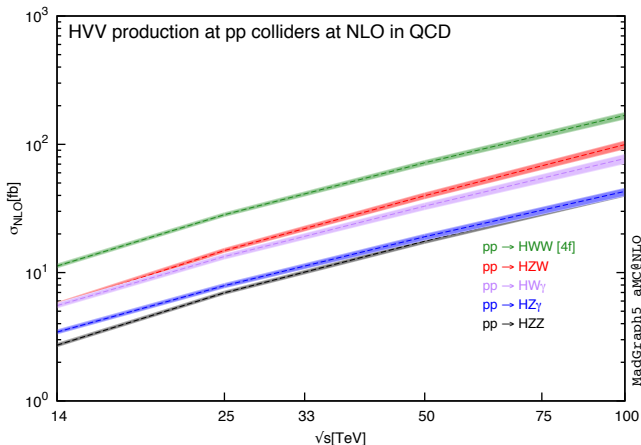
- ▶ Htj a golden channel to determine the sign of y_t (see hep-ph/1211.3736): strong suppression in the SM, while with anomalous Yukawa the amplitude grows as \sqrt{s} .
- ▶ Some sensitivity already at the LHC14 with 300 fb^{-1} (see hep-ph/1403.2053) for semileptonic t , mainly for $H \rightarrow b\bar{b}$ and $H \rightarrow \gamma\gamma$ (but only $O(15)$ SM $H(\rightarrow \gamma\gamma)tj$ events expected without cuts).
- ▶ At 100 TeV with 10 ab^{-1} $O(30000)$ SM $H(\rightarrow \gamma\gamma)tj$ events expected without cuts.
- ▶ $tj\gamma\gamma$, the main background to the $H(\rightarrow \gamma\gamma)tj$ channel, does not grow more than the signal (200 vs 250 times with this photon-isolation setup and $p_T(j) > 20 \text{ GeV}$).
- ▶ Potential to measure precisely sign (and magnitude) of the top Yukawa if the σ dependence upon y_t at 100 TeV is similar to the dependence at the LHC.

Sensitivity to the top Yukawa at 8 and 100 TeV



- $\sigma(-1) \sim 10 \sigma(1)$ both at 8 TeV and at 100 TeV.

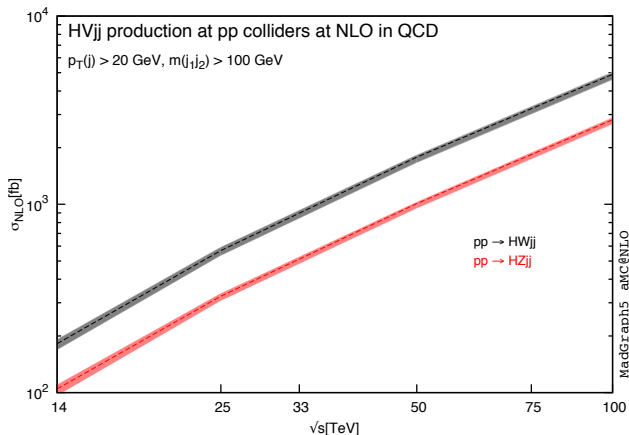
Higgs-diboson associated production



| Channel | $\frac{\sigma_{100}}{\sigma_{14}}$ | $\frac{\sigma_{100}}{\sigma_8}$ |
|------------|------------------------------------|---------------------------------|
| HWW | 20 | 35 |
| HZW | 20 | 45 |
| $HW\gamma$ | 15 | 35 |
| $HZ\gamma$ | 10 | 30 |
| HZZ | 15 | 40 |

- ▶ Direct probes of the structure of the Higgs couplings to gauge bosons.
- ▶ At 100 TeV with 10 ab^{-1} $O(15000)$ events expected without cuts for $H(\rightarrow b\bar{b})Z(\rightarrow \text{lep})Z(\rightarrow \text{had})$, compared to $O(30)$ events at 300 fb^{-1} LHC14.

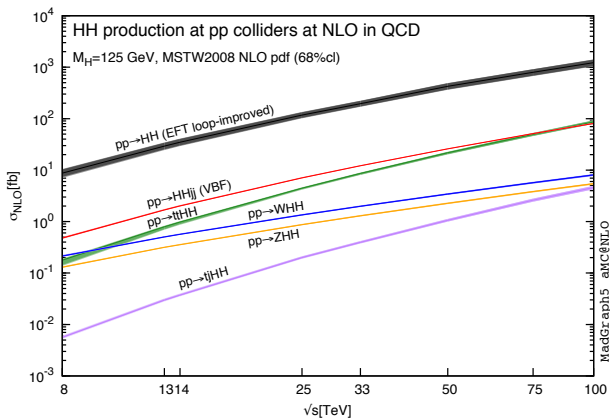
Higgs-vector-dijet associated production



| Channel | $\frac{\sigma_{100}}{\sigma_{14}}$ | $\frac{\sigma_{100}}{\sigma_8}$ |
|---------|------------------------------------|---------------------------------|
| HWjj | 20 | 35 |
| HZjj | 20 | 45 |

- ▶ Probe of the structure of the Higgs couplings to gauge bosons.
- ▶ A background to HVV : cut on the invariant mass.
- ▶ At 100 TeV with 10 ab^{-1} $O(5000)$ events expected without cuts for $H(\rightarrow \gamma\gamma)Z(\rightarrow \text{lep})jj$, compared to $O(10)$ events at 300 fb^{-1} LHC14.

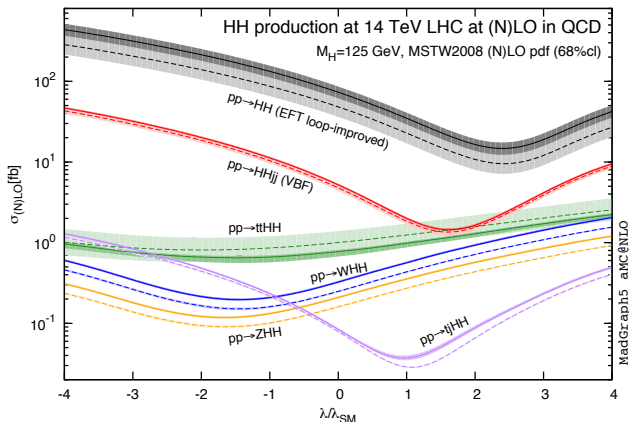
Higgs-pair associated production



| Channel | $\frac{\sigma_{100}}{\sigma_{14}}$ | $\frac{\sigma_{100}}{\sigma_8}$ |
|--------------|------------------------------------|---------------------------------|
| HH | 35 | 150 |
| HHj VBF | 45 | 180 |
| $HHt\bar{t}$ | 100 | 600 |
| HHW | 15 | 40 |
| HHZ | 15 | 40 |
| $HHtj$ | 130 | 800 |

- ▶ A way to constrain the Higgs trilinear coupling.
- ▶ $gg \rightarrow HH$ not fully automated in MadGraph5_aMC@NLO. Born and real diagrams in EFT reweighted by ones with t loops. Possibility to include b effects as well.
- ▶ At 100 TeV with 10 ab^{-1} $O(10000)$ $H(\rightarrow b\bar{b})H(\rightarrow \gamma\gamma)$ events expected without cuts, against $O(10)$ at 300 fb^{-1} LHC14 (plot from hep-ph/1401-7340).

Higgs-pair sensitivity to the trilinear Higgs coupling



- ▶ $\sigma_{HH}(-1) \sim 4 \sigma_{HH}(1)$ at the LHC14 (plot from hep-ph/1401.7340).
- ▶ The dominant channel HH is also very sensitive to λ variations.

Triple-Higgs associated production

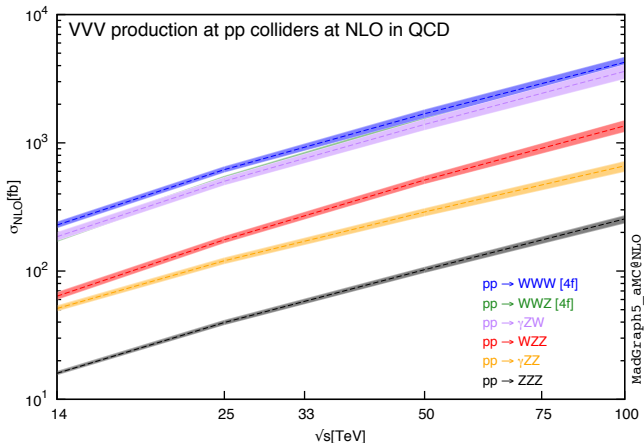
- ▶ A way to measure the Higgs quartic coupling.
- ▶ Very challenging processes, many subleading channels are difficult to see (assuming SM couplings) even at the FCC: at NLO in QCD $\sigma_{HHHW}(100 \text{ TeV}) = 10 \text{ ab}$ and $\sigma_{HHHZ}(100 \text{ TeV}) = 7.5 \text{ ab}$, thus few events after BRs even at 10 ab^{-1} .
- ▶ But: at (almost) NLO in QCD $\sigma_{HHH}(100 \text{ TeV}) \sim 5 \text{ fb}$ against $\sim 0.08 \text{ fb}$ at the LHC14, thus $O(10000)$ events expected in the $H \rightarrow b\bar{b}$ channel at 100 TeV with 10 ab^{-1} , against $O(5)$ at the LHC14 with 300 fb^{-1} .
- ▶ It would be interesting to study its dependence on the Higgs self-couplings.

Multi vector-boson production

Multiple vector-boson production

- ▶ Background to everything, accurate predictions important for disentangling signals.
- ▶ Important as signal themselves, to test the gauge structure of the SM against data.
- ▶ **Decays** in the MadGraph5_aMC@NLO simulations: either exact lepton NLO matrix elements (tried up to 6 leptons, probably 8 could still work), or with MadSpin, which works very accurately (see for example hep-ph/1405.0301).
- ▶ Future possibility to study **anomalous couplings** in MadGraph5_aMC@NLO, at least at LO, through reweighing.
- ▶ Impact of **loop-induced NNLO gg channels** increasingly important at high collider energy due to the gluon PDF: possibility to include these effects in MadGraph5_aMC@NLO, even if not yet automated.

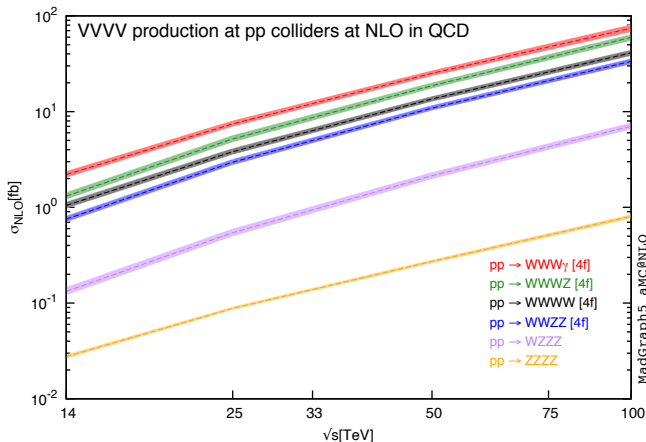
Triple vector-boson production



| Channel | $\frac{\sigma_{100}}{\sigma_{14}}$ | $\frac{\sigma_{100}}{\sigma_8}$ |
|-------------|------------------------------------|---------------------------------|
| WWW | 20 | 50 |
| WWZ | 20 | 60 |
| γ WZ | 20 | 50 |
| WZZ | 20 | 50 |
| γ ZZ | 10 | 30 |
| ZZZ | 15 | 40 |

- At 100 TeV with 10 ab^{-1} $O(20000)$ $Z(\rightarrow \text{had})Z(\rightarrow \text{lep})Z(\rightarrow \text{lep})$ events expected without cuts, $O(30)$ at the LHC14 with 300 fb^{-1} .

Quadruple-vector-boson production

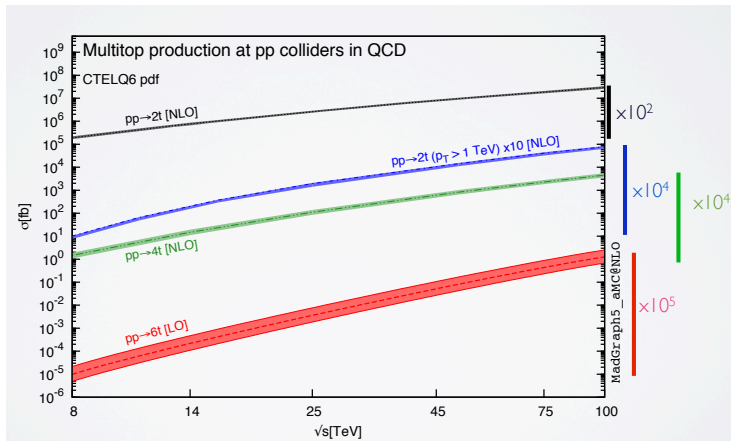


| Channel | $\frac{\sigma_{100}}{\sigma_{14}}$ | $\frac{\sigma_{100}}{\sigma_8}$ |
|-------------|------------------------------------|---------------------------------|
| $WWW\gamma$ | 40 | 110 |
| $WWWZ$ | 50 | 170 |
| $WWWW$ | 40 | 140 |
| $WWZZ$ | 45 | 170 |
| $WZZZ$ | 50 | 210 |
| $ZZZZ$ | 30 | 90 |

- At 100 TeV with 10 ab^{-1} $O(1500)$ $W(\rightarrow \text{had})W(\rightarrow \text{had})Z(\rightarrow \text{lep})Z(\rightarrow \text{lep})$ SM events expected without cuts, $O(1)$ at the LHC14 with 300 fb^{-1} .

Multi top production

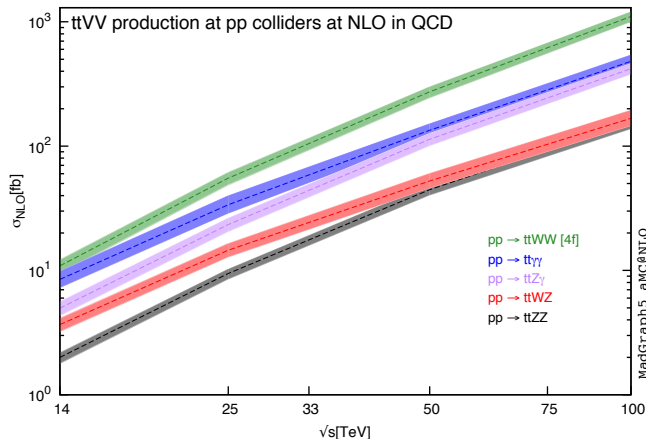
Multiple top production



Plot by N. Deutschmann.

- ▶ At 100 TeV with 10 ab^{-1} $O(400000)$ semileptonc $t\bar{t}t\bar{t}$ events expected without cuts, $O(5)$ at the LHC14 with 300 fb^{-1} .

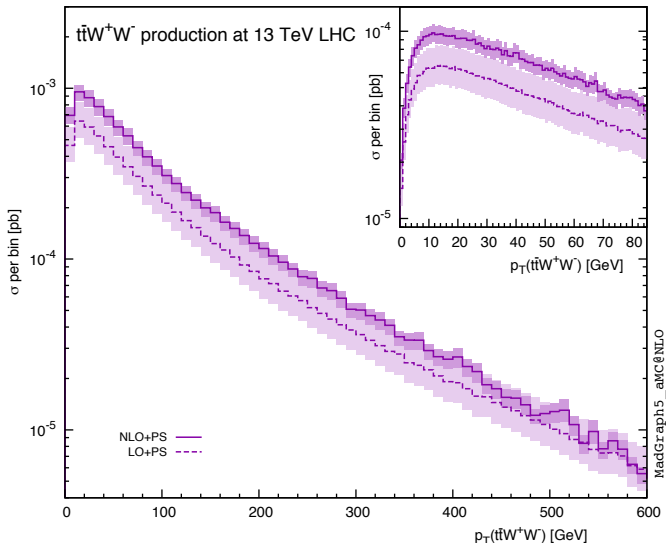
Top-antitop-diboson associated production



| Channel | $\frac{\sigma_{100}}{\sigma_{14}}$ | $\frac{\sigma_{100}}{\sigma_8}$ |
|-------------------|------------------------------------|---------------------------------|
| ttWW | 100 | 480 |
| tt $\gamma\gamma$ | 60 | 215 |
| ttZ γ | 80 | 370 |
| ttWZ | 50 | 170 |
| ttZZ | 70 | 350 |

- ▶ *ttWW* dominant and the most enhanced: at 100 TeV with 10 ab^{-1} $O(80000)$ semileptonic events expected without cuts, while only $O(20)$ at the LHC14 with 300 fb^{-1} .

Top-antitop-diboson associated production: a differential example



Plot from hep-ph/1405.0301.

Conclusions

- ▶ Many rare processes in the scope of the FCC: a factory for multi Higgs, multi boson and multi top processes.
- ▶ Precise determination of Higgs couplings to fermions (Htj), bosons (HVV), and itself (HH , HHH).
- ▶ Precision studies on the gauge structure of the SM (VVV , $VVVV$, $ttVV$).
- ▶ **MadGraph5_aMC@NLO** provides a flexible and robust tool to perform all these studies and many more in an extremely simple and consistent way, differentially, and up to level NLO+PS+merging. <http://amcatnlo.web.cern.ch/amcatnlo/>.

Thank you for your attention