New physics with MadGraph5_aMC@NLO

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NLO computations and matching with parton showers

- Why NLO (+PS)?
  - Reliable predictions of rates and shapes
  - Reliable estimate of uncertainties (scale & PDF)
  - Better theoretical accuracy, less need of fine tuning
  - Realistic description of the final state
  - Better understanding of data
  - Steep increase in complexity (in particular for higher multiplicities)

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Ask a computer to do the hard job
Automation!

NLO: how to?

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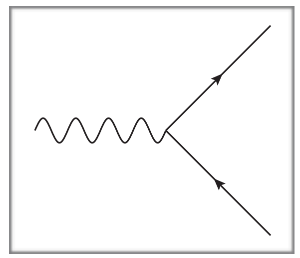
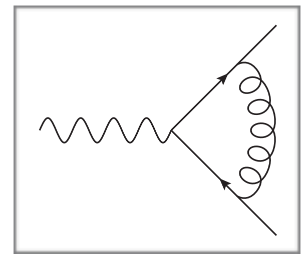
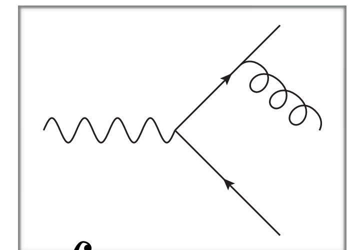
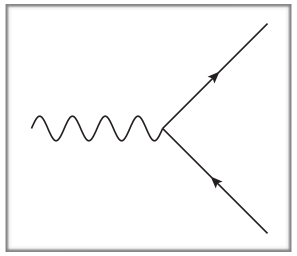
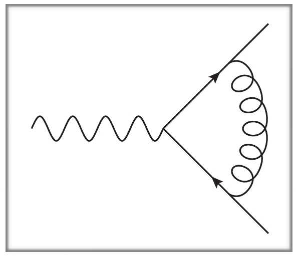
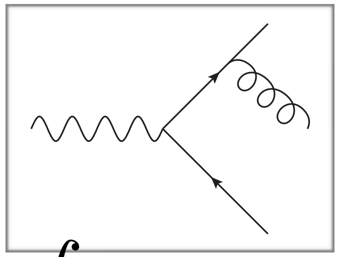
  

$$d\sigma^n_{NLO} = d\sigma^n_{LO} + d\sigma^n_V + \int d\Phi_1 \, d\sigma^{n+1}_R$$

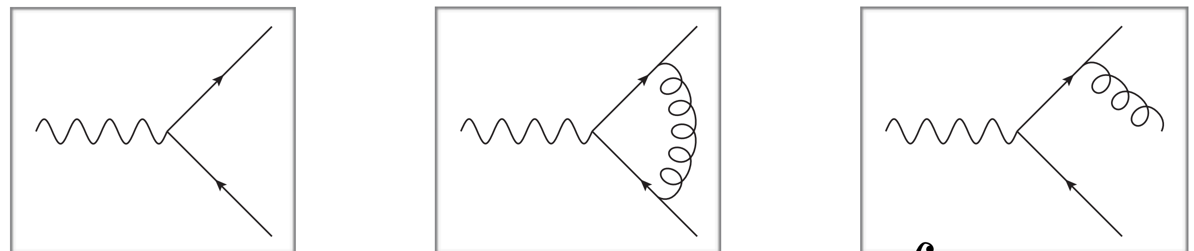
NLO: how to?

$$d\sigma^n_{NLO} = d\sigma^n_{LO} + d\sigma^n_V + \int d\Phi_1 \, d\sigma^{n+1}_R$$

- Warning! Real emission ME is divergent!
  - Divergences cancel with those from virtuals (in D=4-2eps)
  - Need to cancel them before numerical integration (in D=4)

NLO: how to?

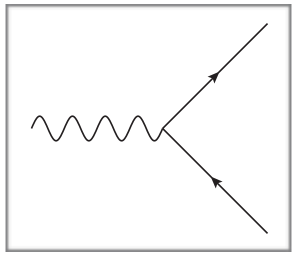
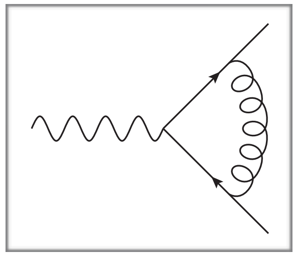
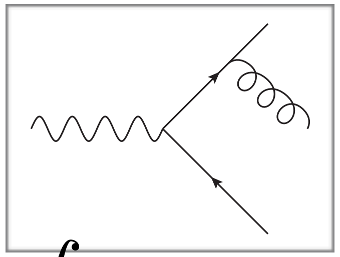


$$d\sigma^n_{NLO} = d\sigma^n_{LO} + d\sigma^n_V + \int d\Phi_1 \, d\sigma^{n+1}_R$$

$$d\sigma^n_{NLO} = d\sigma^n_{LO} + d\sigma^n_V - \int d\Phi_1 \, C + \int d\Phi_1 \, \left(C + d\sigma^{n+1}_R\right)$$

- Add local counterterms in the singular regions and subtract its integrated finite part (poles will cancels against the virtuals)
- The *n* and *n+1* body integral now are finite in 4 dimension
  - Can be integrated numerically

NLO: how to?

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  - Can be integrated numerically

How to do this in an efficient way?

The FKS subtraction

Frixione, Kunszt, Signer, arXiv:hep-ph/9512328

- Soft/collinear singularities arise in many PS regions
- Find parton pairs *i*, *j* that can give collinear singularities
- Split the phase space into regions with one collinear sing
  - Soft singularities are split into the collinear ones

$$|M|^2 = \sum_{ij} S_{ij} |M|^2 = \sum_{ij} |M|^2_{ij} \qquad \sum S_{ij} = 1$$

$$S_{ij} \to 1 \text{ if } k_i \cdot k_j \to 0 \qquad S_{ij} \to 0 \text{ if } k_{m \neq i} \cdot k_{n \neq j} \to 0$$

- Integrate them independently
  - Parallelize integration
  - Choose ad-hoc phase space parameterization
- Advantages:
  - # of contributions ~ n^2
  - Exploit symmetries: 3 contributions for `X Y > ng`

Loop ME evaluation: MadLoop

Hirschi et al. arXiv:1103.0621

- Load the NLO UFO model
- Generate Feynman diagrams to evaluate the loop ME
- Add R_2/UV renormalisation counter terms
- Interface to CutTools or to TIR programs (Ossola, Papadopoulos, Pittau, arXiv:hep-ph/0609007 & arXiv:0711.3596)
- Improved with the OpenLoops method (Cascioli, Maierhofer, Pozzorini arXiv:1111.5206)
- Check PS point stability (and switch to QP if needed)
- And much more (can be used as standalone or external OLP via the BLHA, handle loop-induced processes, …)

Automatic UV/R_2 counterterms: NLOCT

Degrande arXiv:1406.3030

- Start with your favourite Lagrangian
- Export tree-level Feynman rules with FeynRules
- Identify loop diagrams giving rise to UV divergences/R_2 counterterms and compute them with FeynArts
- Extract UV/R_2 counterterms
- NLO UFO model!

Automated for renormalizable models!

BSM at NLO: recent physics results

- SUSY

Degrande, Fuks, Hirschi, Proudom, Shao, arXiv:1412.5589

- Charged Higgs production in the 2HDM

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- Top FCNC

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- Top chromomagnetic dipole

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SUSY: automated NLO for colored scalar production

- Study stop and sgluon pair production at the LHC
- Use simplified models:
  - Stop

$$\mathcal{L}_3 = D_\mu \sigma_3^\dagger D^\mu \sigma_3 - m_3^2 \sigma_3^\dagger \sigma_3 + \frac{i}{2}\bar{\chi}\partial\!\!\!/\chi - \frac{1}{2} m_\chi \bar{\chi}\chi + \left[\sigma_3 \bar{t}\left(\tilde{g}_L P_L + \tilde{g}_R P_R\right)\chi + \text{h.c.}\right]$$

Majorana singlet

  - Sgluon

$$\mathcal{L}_8 = \frac{1}{2} D_\mu \sigma_8 D^\mu \sigma_8 - \frac{1}{2} m_8^2 \sigma_8 \sigma_8 + \frac{\hat{g}_g}{\Lambda}\sigma_8 G_{\mu\nu} G^{\mu\nu} + \sum_{q=u,d}\left[\sigma_8 \bar{q}\left(\hat{g}_q^L P_L + \hat{g}_q^R P_R\right) q + \text{h.c.}\right]$$

SUSY: automated NLO for colored scalar production

- Results:
  - Total rates (validated against Prospino and MadGolem)

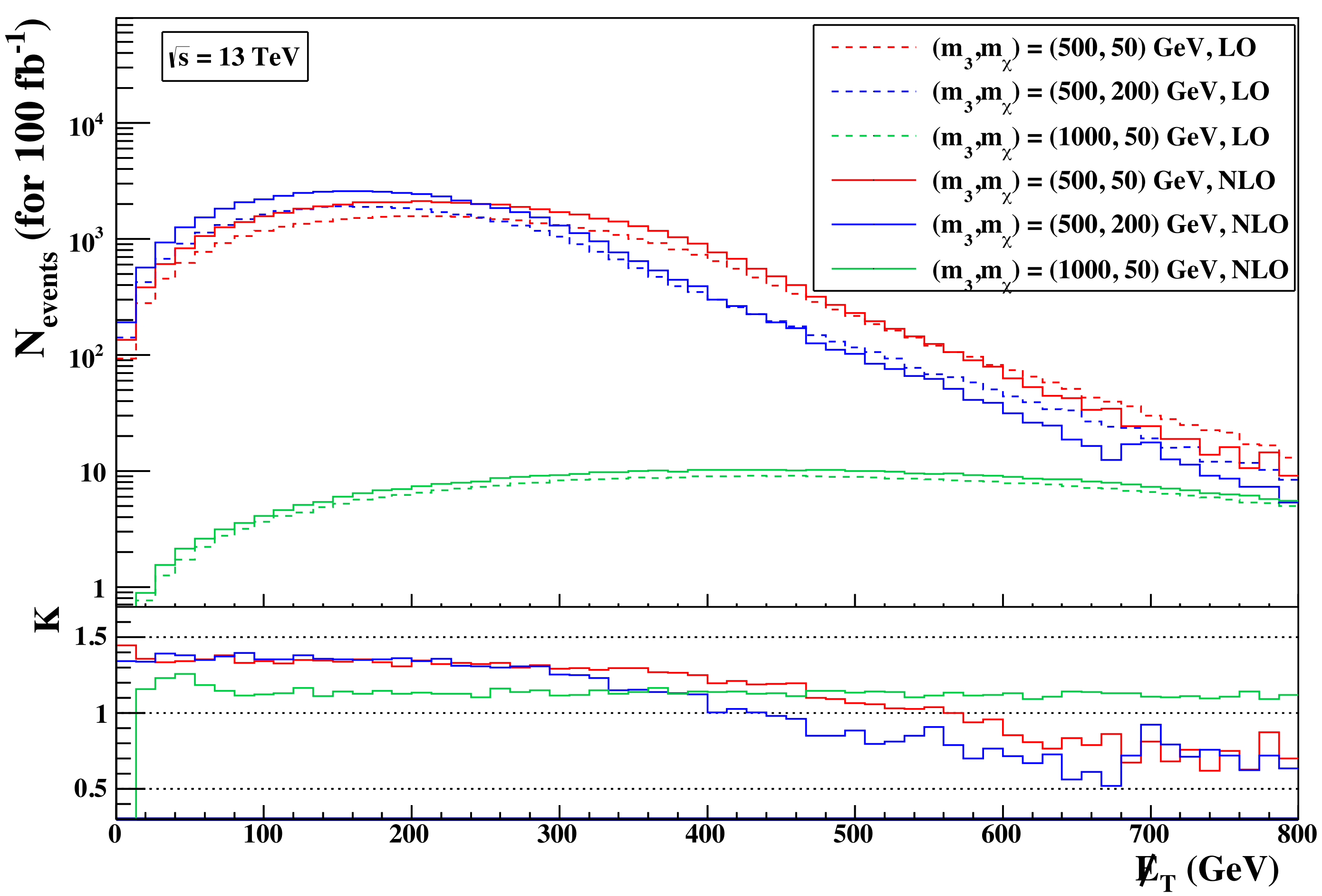
m_3 [GeV]	8 TeV $\sigma^{\rm LO}$ [pb]	8 TeV $\sigma^{\rm NLO}$ [pb]	13 TeV $\sigma^{\rm LO}$ [pb]	13 TeV $\sigma^{\rm NLO}$ [pb]
100	$389.3^{+34.2\%}_{-23.9\%}$	$554.8^{+14.9\%\,+1.6\%}_{-13.5\%\,-1.6\%}$	$1066^{+29.1\%}_{-21.4\%}$	$1497^{+14.1\%\,+1.2\%}_{-12.1\%\,-1.2\%}$
250	$4.118^{+40.4\%}_{-27.2\%}$	$5.503^{+13.1\%\,+3.7\%}_{-13.7\%\,-3.7\%}$	$15.53^{+35.2\%}_{-24.8\%}$	$21.56^{+12.1\%\,+2.4\%}_{-12.3\%\,-2.4\%}$
500	$(6.594\times10^{-2})^{+45.5\%}_{-29.1\%}$	$(7.764\times10^{-2})^{+12.1\%\,+6.7\%}_{-14.1\%\,-6.7\%}$	$0.3890^{+39.6\%}_{-26.4\%}$	$0.5062^{+11.2\%\,+4.4\%}_{-12.8\%\,-4.4\%}$
750	$(3.504\times10^{-3})^{+48.8\%}_{-30.5\%}$	$(3.699\times10^{-3})^{+12.3\%\,+10.2\%}_{-14.6\%\,-10.2\%}$	$(3.306\times10^{-2})^{+41.8\%}_{-27.5\%}$	$(4.001\times10^{-2})^{+10.8\%\,+6.1\%}_{-12.9\%\,-6.1\%}$
1000	$(2.875\times10^{-4})^{+51.5\%}_{-31.5\%}$	$(2.775\times10^{-4})^{+13.1\%\,+15.5\%}_{-15.2\%\,-15.5\%}$	$(4.614\times10^{-3})^{+43.6\%}_{-28.3\%}$	$(5.219\times10^{-3})^{+10.9\%\,+7.9\%}_{-13.2\%\,-7.9\%}$

m_8 [GeV]	8 TeV $\sigma^{\rm LO}$ [pb]	8 TeV $\sigma^{\rm NLO}$ [pb]	13 TeV $\sigma^{\rm LO}$ [pb]	13 TeV $\sigma^{\rm NLO}$ [pb]
100	$3854^{+34.4\%}_{-24.1\%}$	$5573^{+14.9\%\,+1.6\%}_{-13.6\%\,-1.6\%}$	$10560^{+29.2\%}_{-21.5\%}$	$14700^{+13.6\%\,+1.2\%}_{-11.9\%\,-1.2\%}$
250	$38.89^{+41.3\%}_{-27.7\%}$	$54.32^{+14.5\%\,+3.9\%}_{-14.6\%\,-3.9\%}$	$150.4^{+35.7\%}_{-25.1\%}$	$214.5^{+12.9\%\,+2.5\%}_{-12.9\%\,-2.5\%}$
500	$0.5878^{+47.6\%}_{-30.0\%}$	$0.7431^{+15.8\%\,+7.6\%}_{-16.2\%\,-7.6\%}$	$3.619^{+40.8\%}_{-27.0\%}$	$4.977^{+13.3\%\,+4.7\%}_{-14.1\%\,-4.7\%}$
750	$(2.977\times10^{-2})^{+52.0\%}_{-31.9\%}$	$(3.353\times10^{-2})^{+17.2\%\,+12.1\%}_{-17.3\%\,-12.1\%}$	$0.2951^{+43.6\%}_{-28.4\%}$	$0.3817^{+14.0\%\,+6.9\%}_{-14.8\%\,-6.9\%}$
1000	$(2.328\times10^{-3})^{+55.9\%}_{-33.4\%}$	$(2.398\times10^{-3})^{+19.0\%\,+19.1\%}_{-18.4\%\,-19.1\%}$	$(3.983\times10^{-2})^{+46.1\%}_{-29.5\%}$	$(4.822\times10^{-2})^{+15.1\%\,+9.3\%}_{-15.6\%\,-9.3\%}$

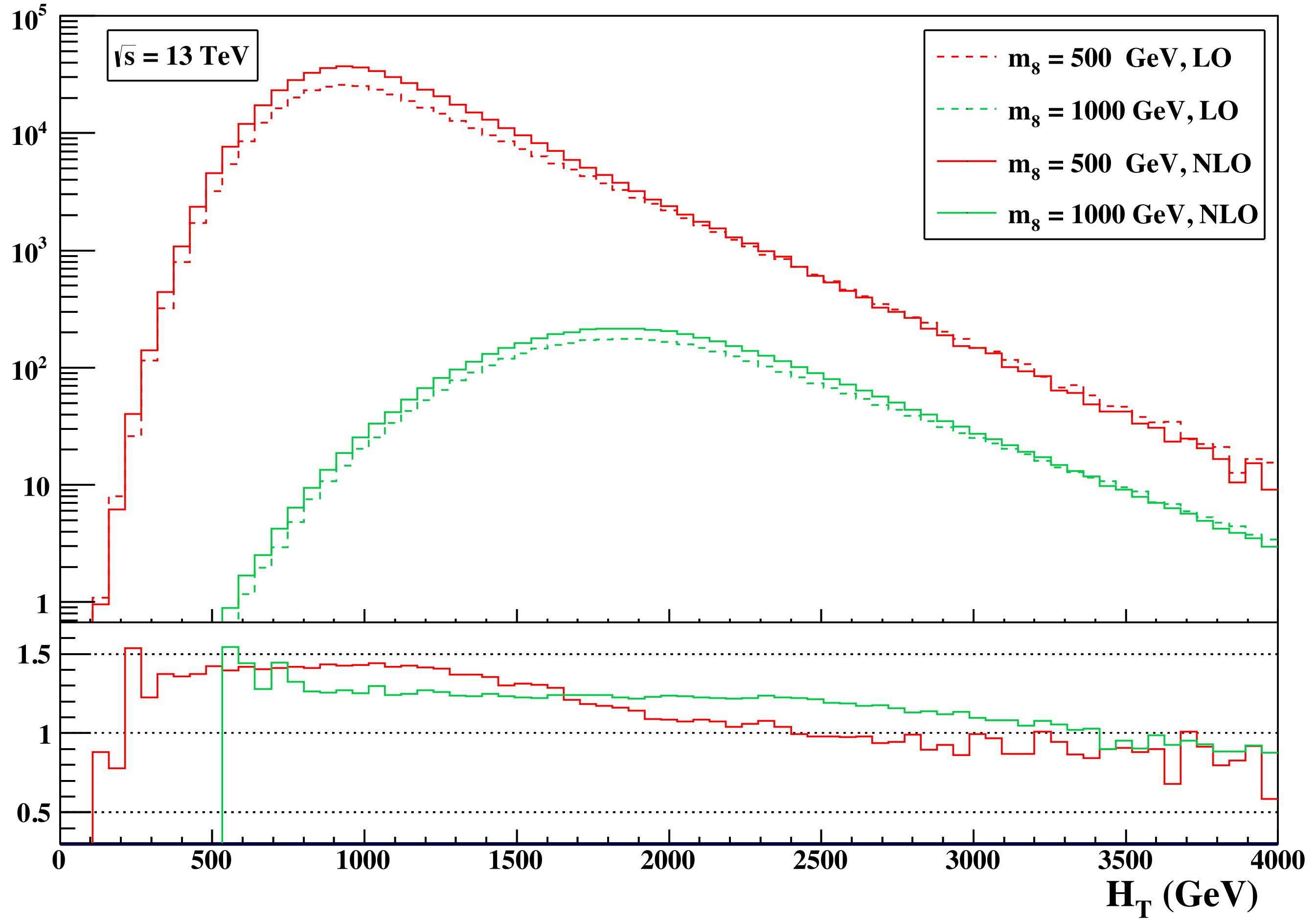
SUSY: automated NLO for colored scalar production

- Results:
  - Distribution at NLO (+Pythia8)

Stop pair



Sgluon pair



SUSY: automated NLO for colored scalar production

- As easy as:

```
./bin/mg5_aMC
> import model stop_ttmet_ufo
> generate p p > t1 t1~ [QCD]
> output
> launch
```

- Models available on the FeynRules website
  - https://feynrules.irmp.ucl.ac.be/wiki/NLOModels

Higgs Characterisation

- Aim: establish a framework to determine Higgs quantum numbers and couplings
- Build an EFT up to dim=6, keep operators compatible with SM gauge symmetries
- Study various Higgs production channels at NLO+PS accuracy

Higgs Characterisation: the effective Lagrangian

$$\mathcal{L}_0^V = \Big\{ c_\alpha \kappa_{\rm SM} \big[\tfrac{1}{2} g_{HZZ}\, Z_\mu Z^\mu + g_{HWW}\, W^+_\mu W^{-\mu}\big]$$

SM

$$- \frac{1}{4}\big[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma}\, A_{\mu\nu}A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma}\, A_{\mu\nu}\widetilde{A}^{\mu\nu}\big]$$
$$- \frac{1}{2}\big[c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma}\, Z_{\mu\nu}A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma}\, Z_{\mu\nu}\widetilde{A}^{\mu\nu}\big]$$
$$- \frac{1}{4}\big[c_\alpha \kappa_{Hgg} g_{Hgg}\, G^a_{\mu\nu}G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg}\, G^a_{\mu\nu}\widetilde{G}^{a,\mu\nu}\big]$$
$$- \frac{1}{4}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HZZ}\, Z_{\mu\nu}Z^{\mu\nu} + s_\alpha \kappa_{AZZ}\, Z_{\mu\nu}\widetilde{Z}^{\mu\nu}\big]$$
$$- \frac{1}{2}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HWW}\, W^+_{\mu\nu}W^{-\mu\nu} + s_\alpha \kappa_{AWW}\, W^+_{\mu\nu}\widetilde{W}^{-\mu\nu}\big]$$

0^+ 0^-

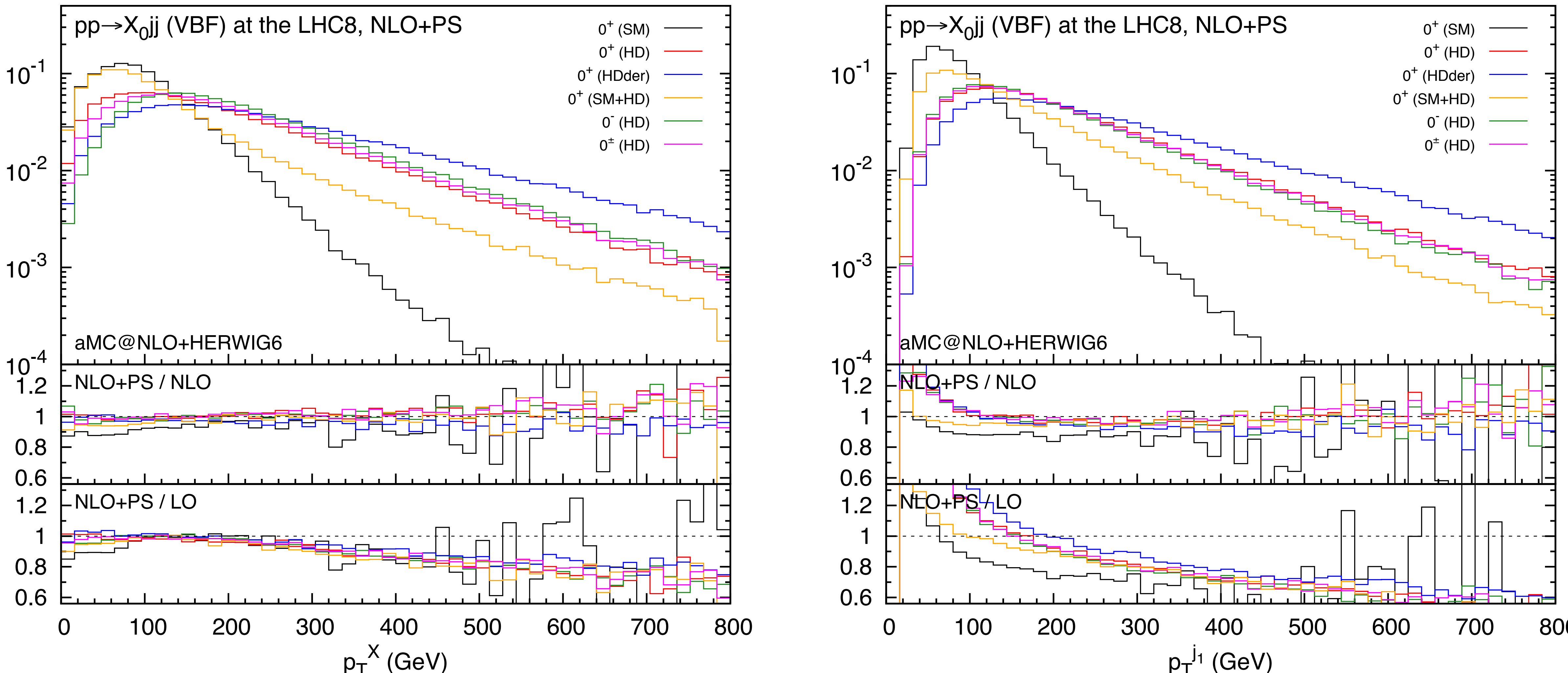
$$- \frac{1}{\Lambda} c_\alpha \big[\kappa_{H\partial\gamma}\, A_\nu \partial_\mu A^{\mu\nu} + \kappa_{H\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu}$$
$$+ \big(\kappa_{H\partial W} W^+_\nu \partial_\mu W^{-\mu\nu} + h.c.\big)\big]\Big\} X_0$$

0^+Der

HD

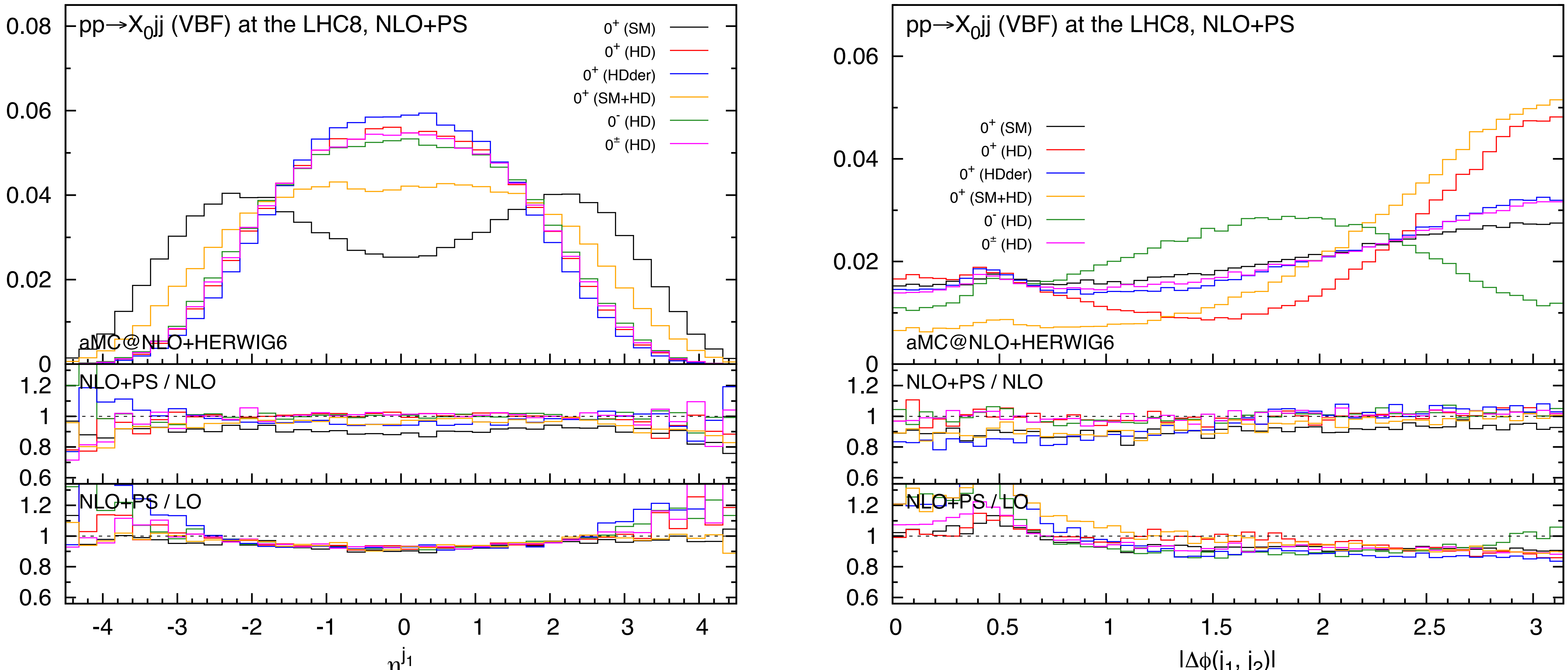
$$\mathcal{L}_0^t = -\bar{\psi}_t \big(c_\alpha \kappa_{Htt} g_{Htt} + i s_\alpha \kappa_{Att} g_{Att}\, \gamma_5\big) \psi_t\, X_0$$

Higgs Characterisation: VBF



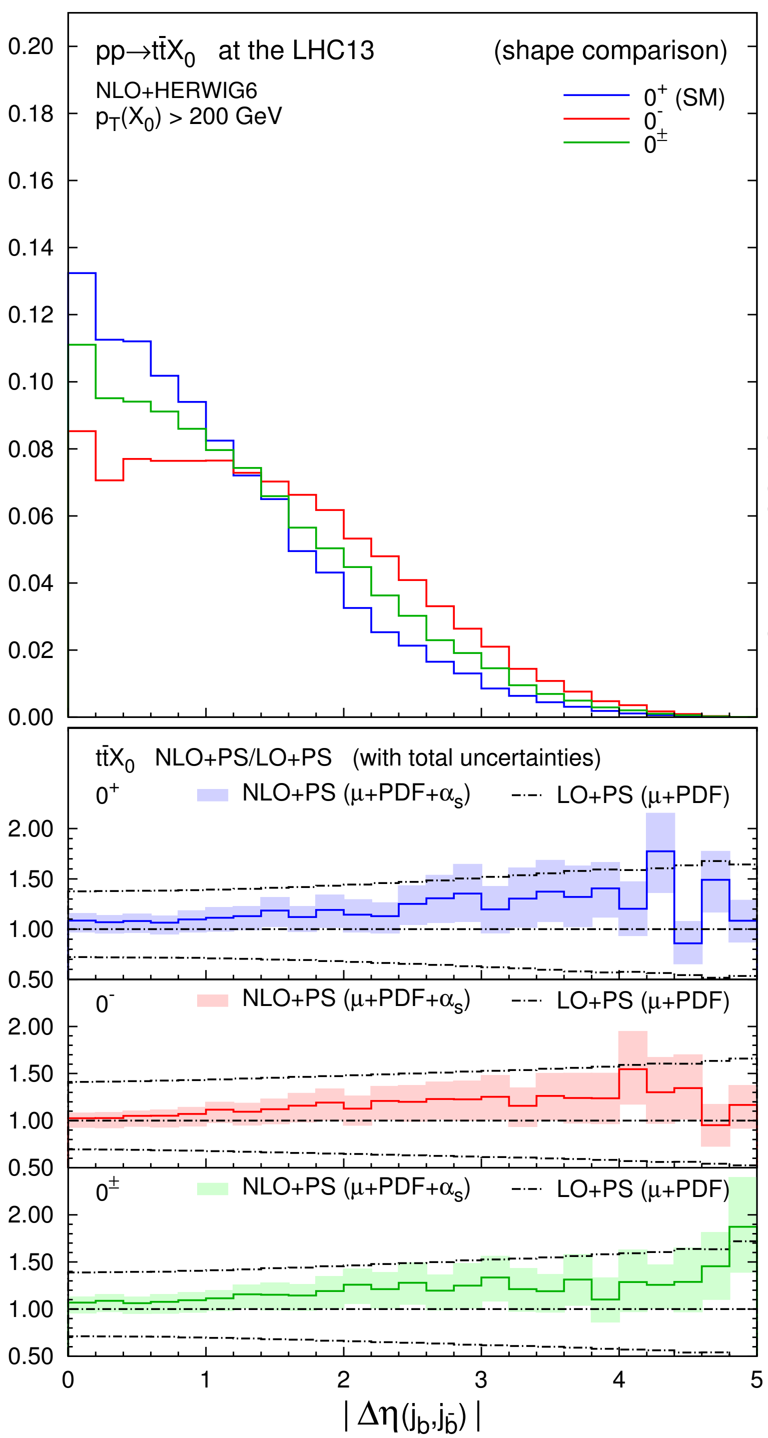
- SM case shows a softer behaviour (not for M_{jj})
- NLO and PS effects are important (in particular for jet-related observables)

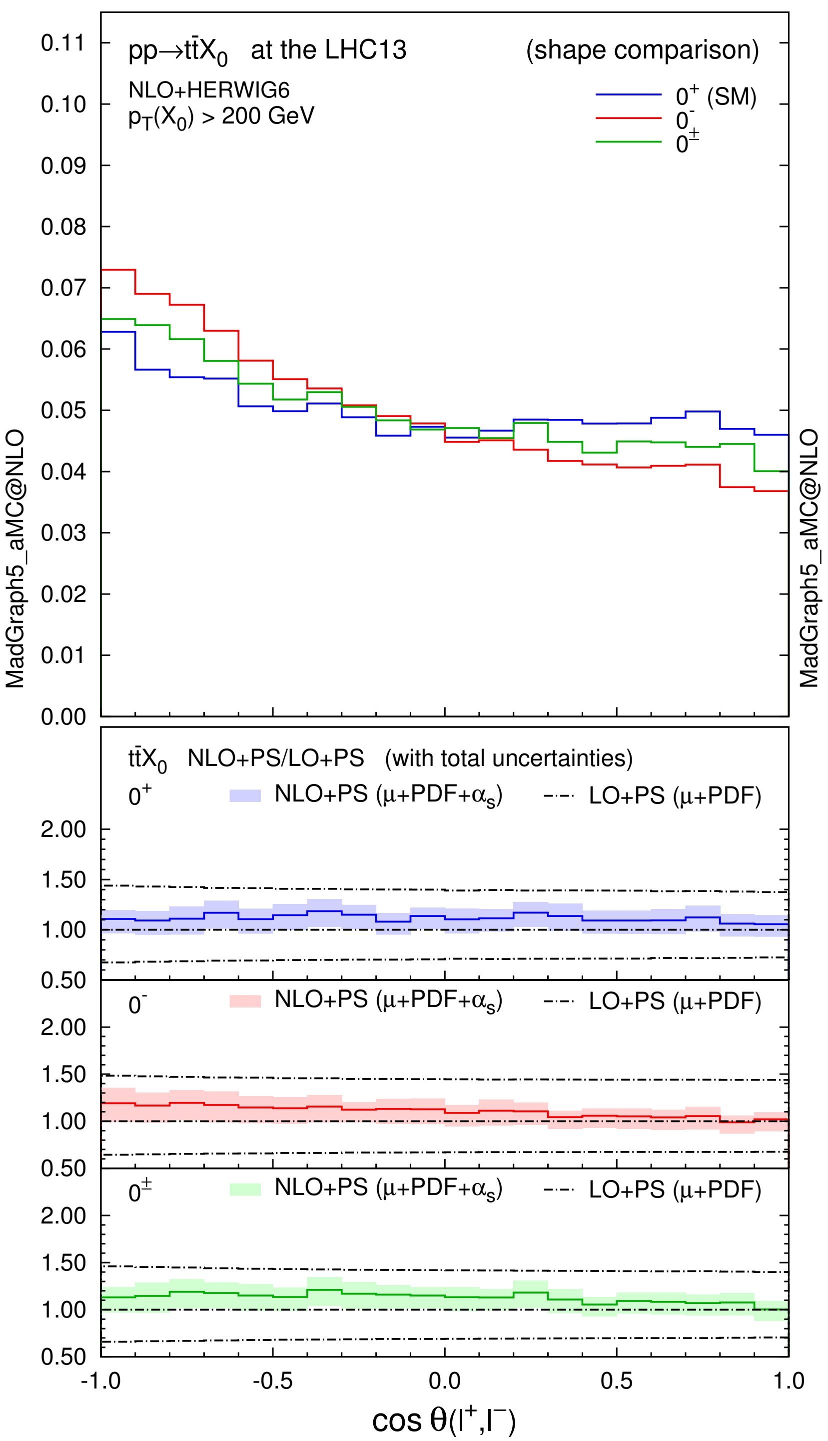
Higgs Characterisation: VBF



- In SM case jets are more forward: HD scenarios feature a different signature
- Jet correlations (Δϕ) are sensitive to the HVV structure

Higgs Characterisation: $t\bar{t}H$

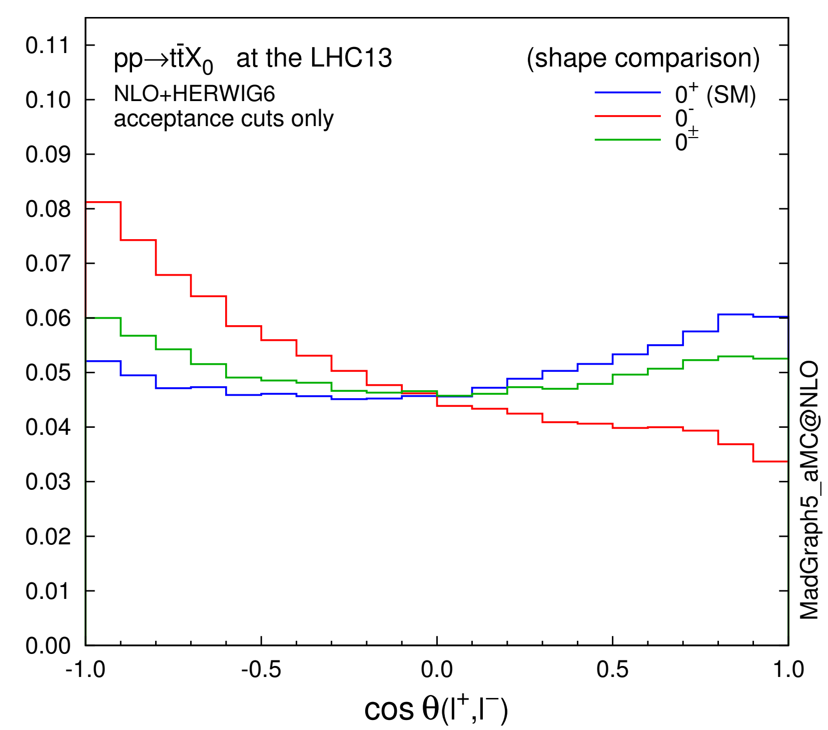




- Spin correlations of the top decay products kept with MadSpin

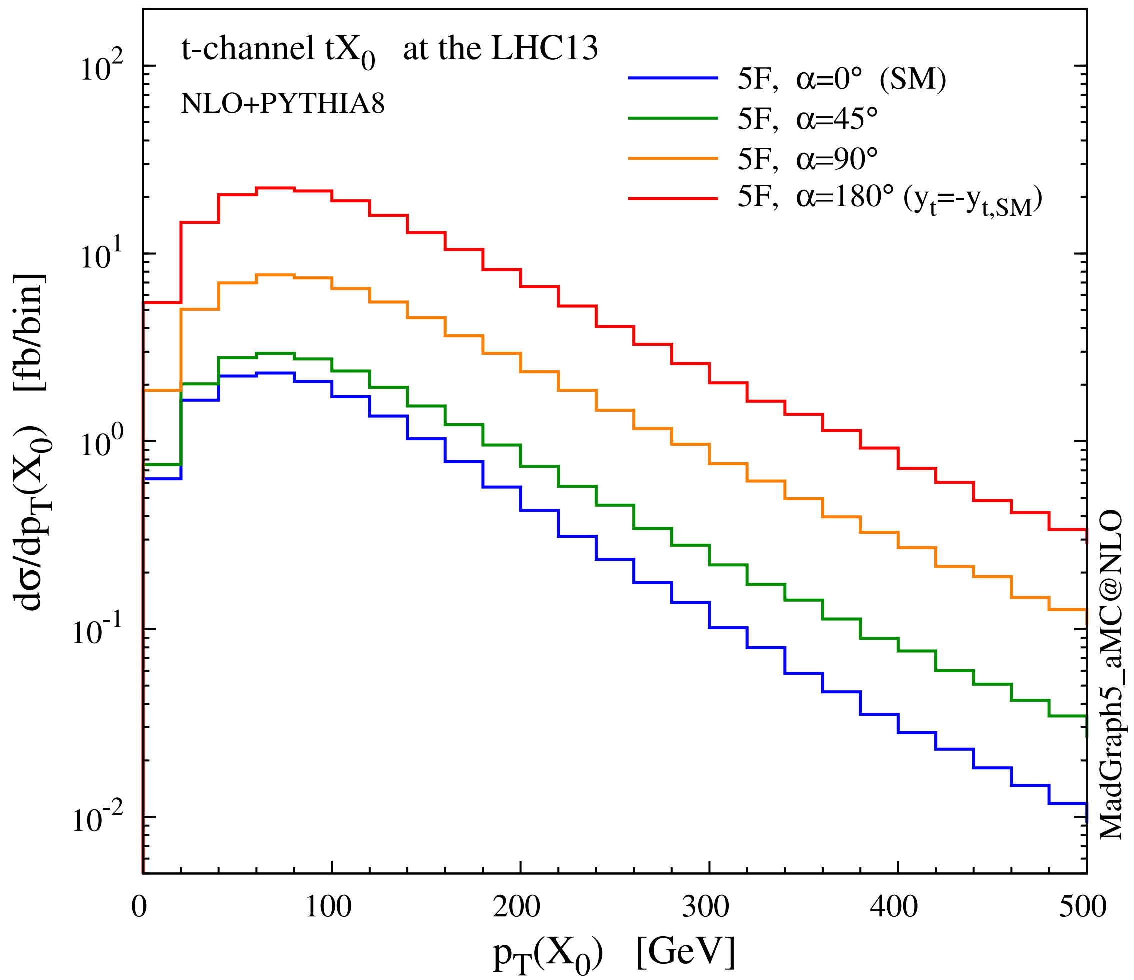
Artoisenet, Frederix, Mattelaer, Rietkerk, arXiv:1212.3460

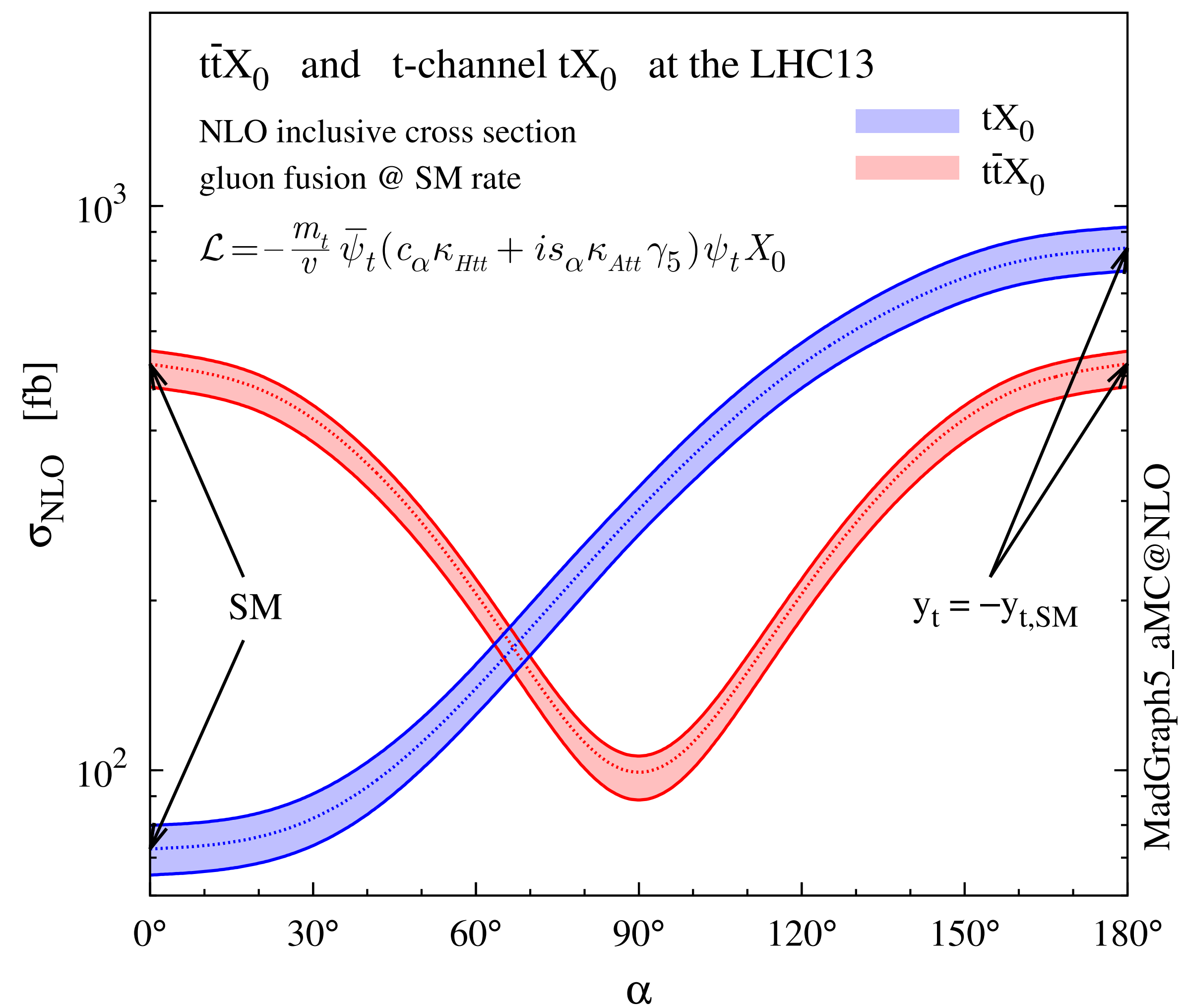
- Requiring a boosted Higgs reduces CP sensitivity for angular correlations
- NLO effects of ~20%, not flat



Higgs Characterisation: tH

- Sensitive to the sign of y_t
- To appear soon…





Conclusions

- The simulation of NLO processes within MadGraph5_aMC@NLO has become as easy as LO, both for SM and BSM
- "From-Lagrangian-to-events" chain automated in FeynRules for any renormalizable model
- Effective theories can be improved with NLO+PS effects
- FxFx/UNLOPS merging available also at NLO
- Lots of ongoing efforts for BSM pheno @NLO

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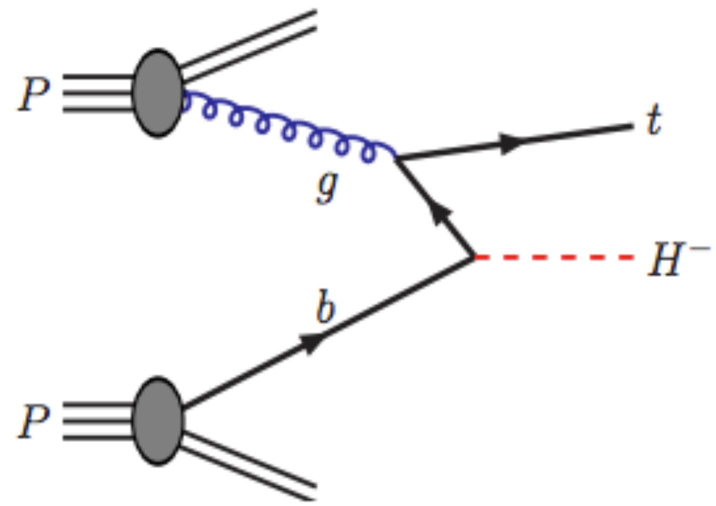
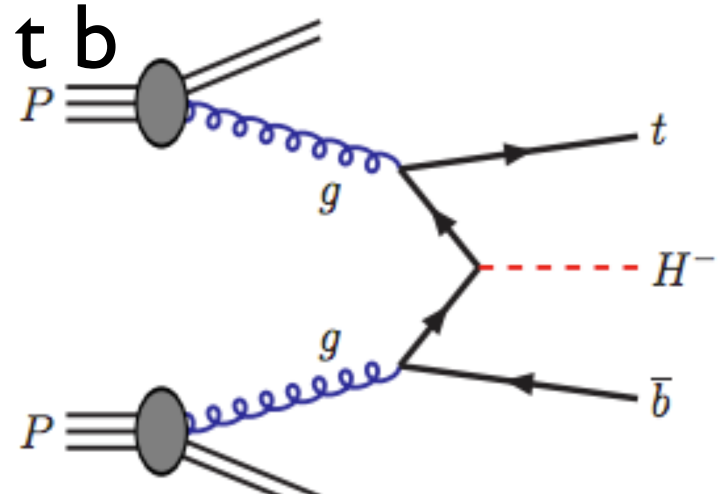
AAA discovery needed!

Charged Higgs production in the 2HDM (type II)

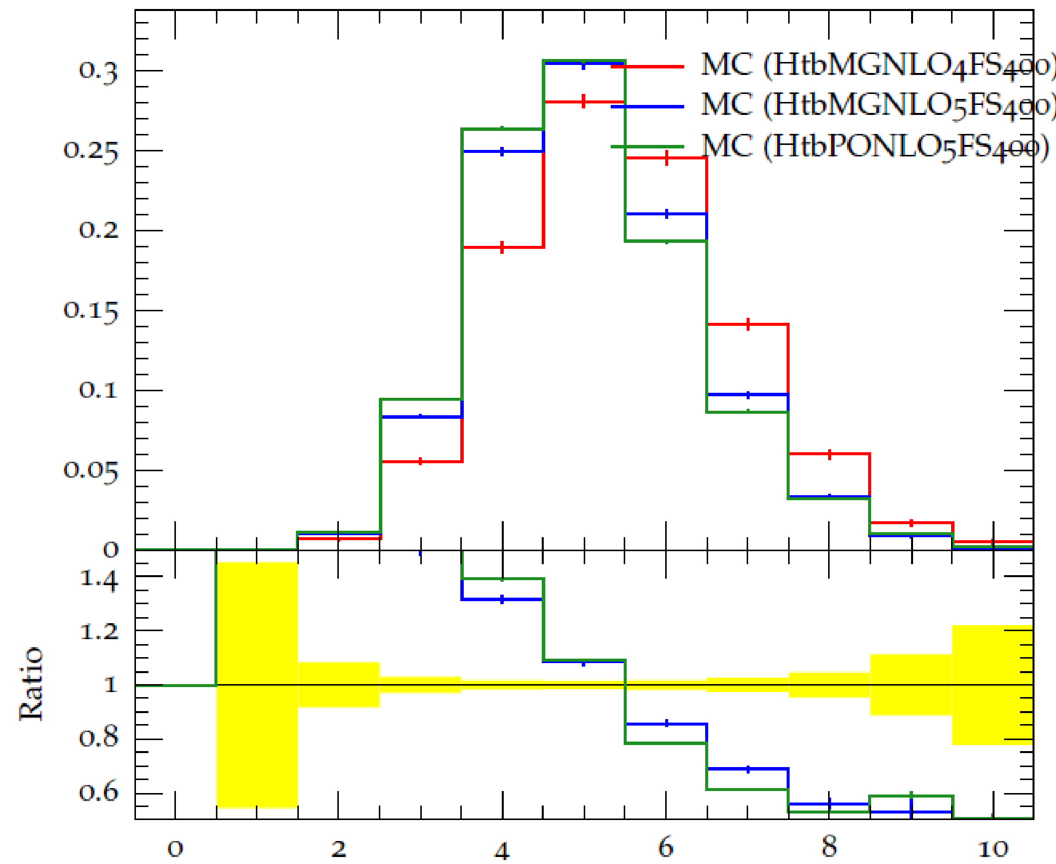
- Study the charged Higgs production in the 2HDM, for a heavy (m_H>200 GeV) Higgs boson $pp \to H^- t + X$
- Two possible schemes:
  - 5F (include b in proton, m_b=0): $gb \to H^- t$
    - Simpler process (lesser multiplicity)
    - No b mass effects
    - Worse description of b-related observables
    - Resum logs(m_b/Q)
  - 4F (keep mb≠0, no b in proton): $q\bar{q}/gg \to H^- t\, b$
    - b mass effects included in the matrix-element
    - Can be spoiled by large logs(m_b/Q)
    - Better description of b-related observables





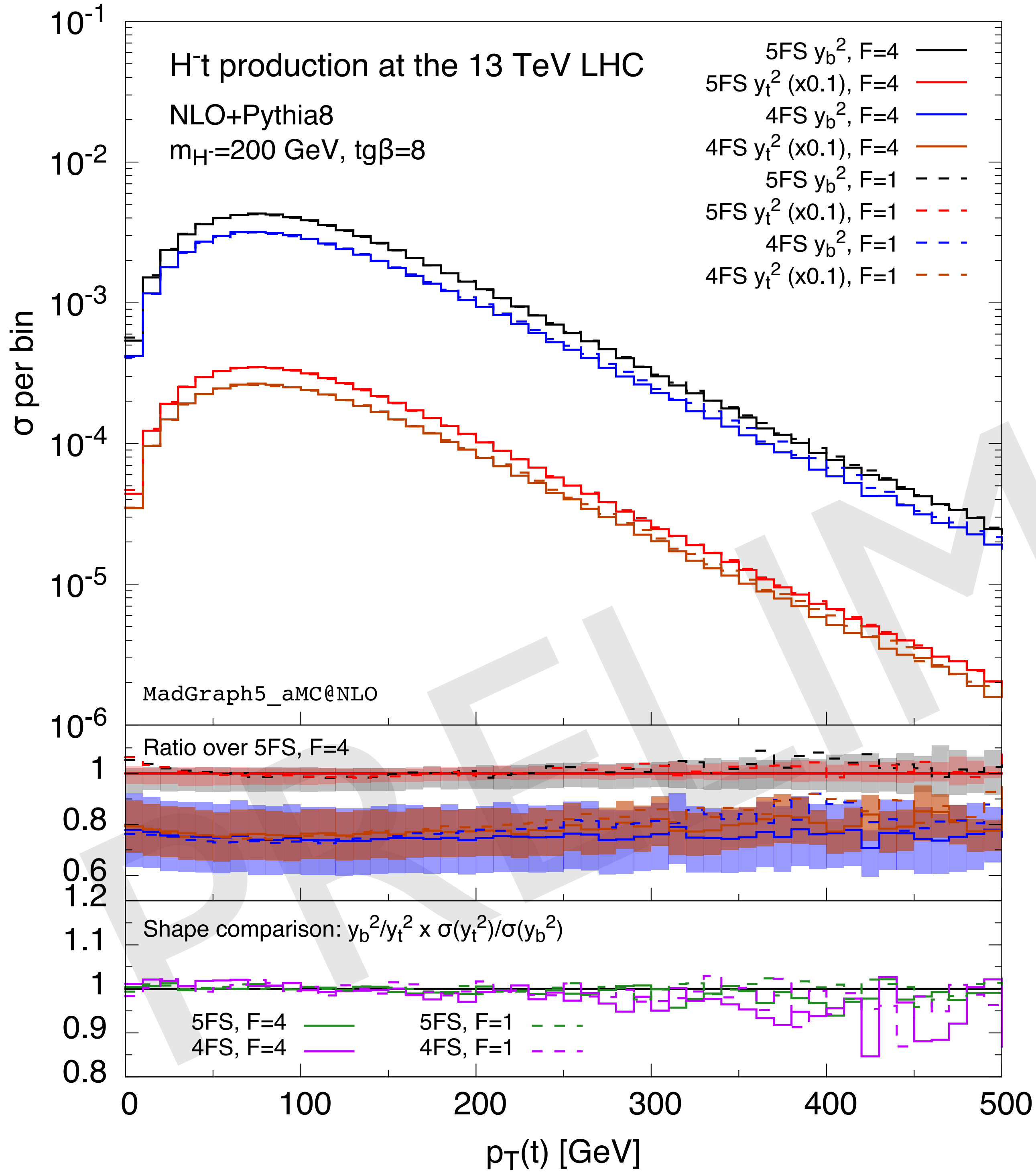
Charged Higgs production in the 2HDM (type II)

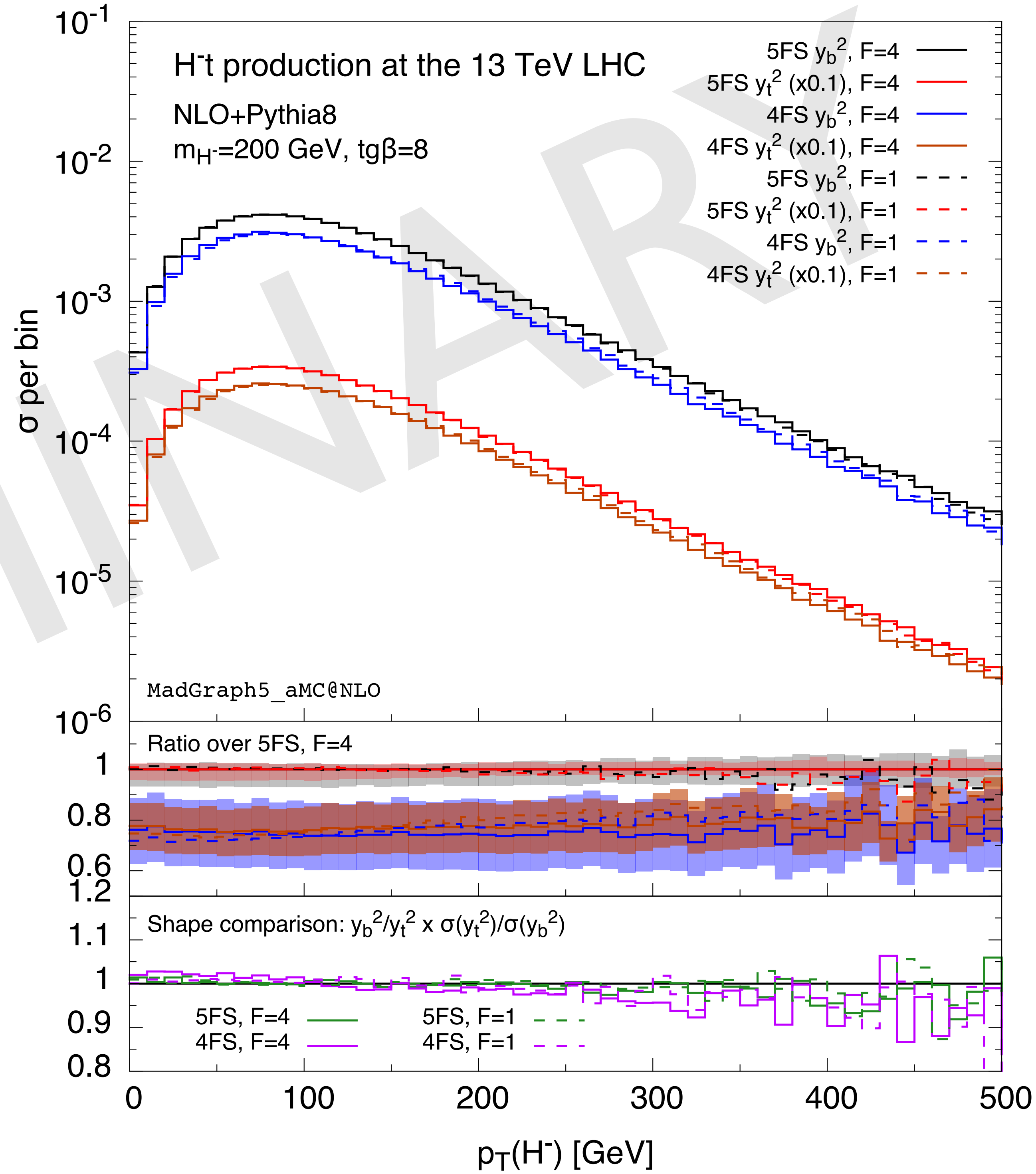
- Large discrepancies observed by ATLAS among the two schemes



- Discrepancies reduced by
  - Using MSbar bottom Yukawa: resum logs(m_H/m_b)
  - $\mu_{F/R}$ choice: $H_T/6$ in 5F and $H_T/3$ in 4F
  - Choose a reduced shower scale (factor F in the plots)

Charged Higgs production in the 2HDM (type II)





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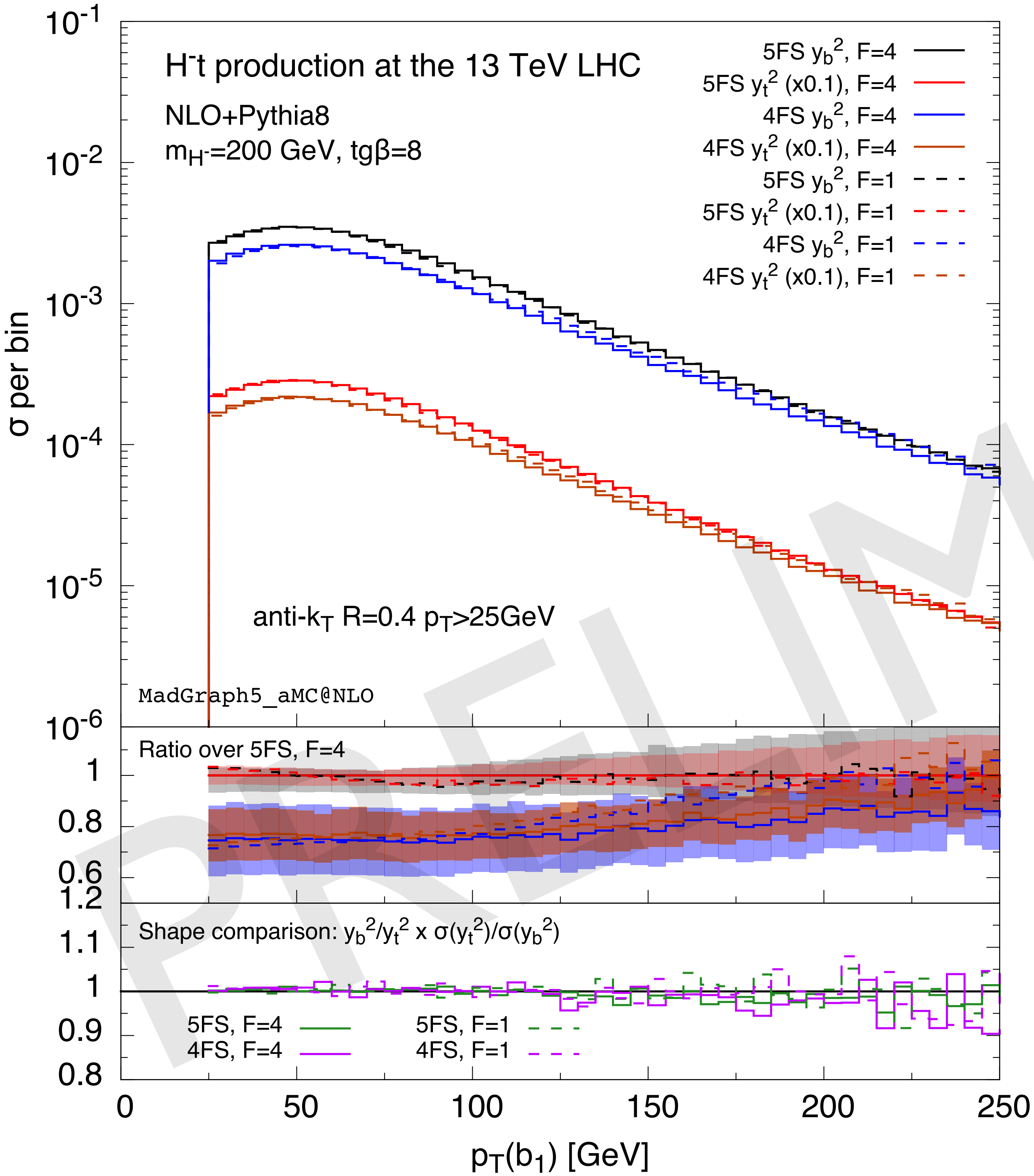

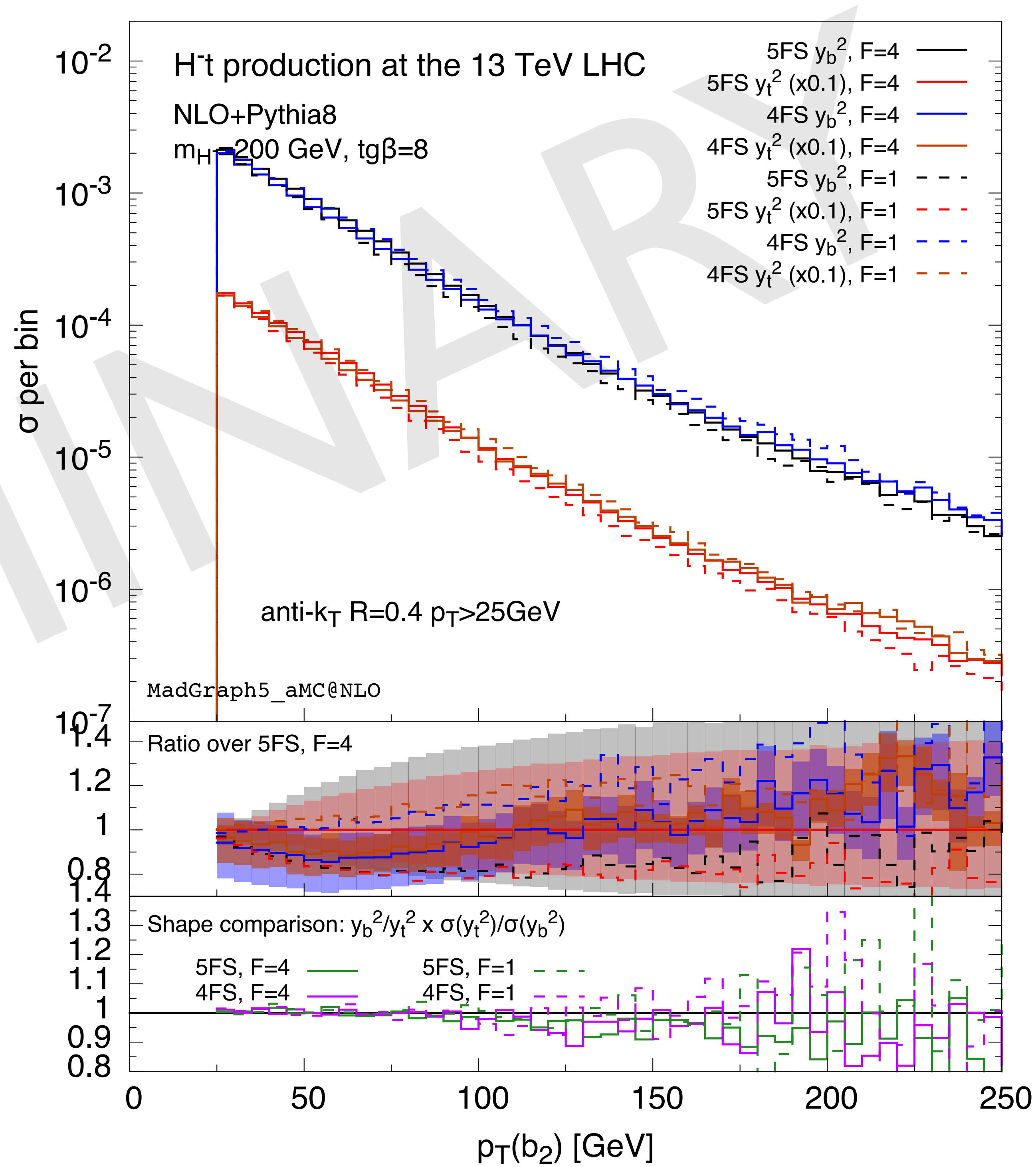

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