Monte Carlo tools for BSM Higgs

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Monte Carlo tools for the LHC

- The LHC needs accurate and automated predictions
  - Realistic fully differential simulations needed
  - Higher order corrections needed to reduce the theoretical uncertainties
  - Automation of NLO+PS (almost) fully achieved for the SM
- Need for precision also for BSM predictions
  - Progress towards fully automated simulation chain
  - NLOCT (Degrande, arXiv:1406.3030) allows us to create NLO UFO models starting from any Lagrangian

BSM in Monte Carlos

A well known chain:

Lagrangian → UFO model → MG5_aMC/Sherpa/
your favourite generator

FeynRules+NLOCT

↓ PYTHIA, HERWIG,
your favourite PS

https://feynrules.irmp.ucl.ac.be/wiki/ModelDatabaseMainPage

↓ Detector simulation
Delphes,PGS

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Models publicly available

- 2HDM
- Higgs effective Lagrangian
- Higgs characterisation
- many more

UFO models

FeynRules model database

This page contains a collection of models that are already implemented in FeynRules. For each model, a complete model-file is available, containing all the information that is needed, as well as the Lagrangian, as well as the references to the papers were this Lagrangian was taken from. All model-files can be freely downloaded and changed, serving like this as the starting point for building new models. A TeX-file for each model containing a summary of the Feynman Rules produced by FeynRules is also available.

The Standard model model-file is already included in the distribution of the FeynRules, but it can also be downloaded independently from the corresponding link below.

We encourage model builders writing a FeynRules implementation of their model to make their model file(s) public in the FeynRules model database, in order to make them useful to a community as wide as possible. For further information on how to make your model implementation public via the FeynRules model database, please send an email to

- neil@...
- celine.degrande@...
- claude.duhr@...
- benjamin.fuks@...

Available models

Standard Model	The SM implementation of FeynRules, included into the distribution of the FeynRules package.
Simple extensions of the SM	Several models based on the SM that include one or more additional particles, like a 4th generation, a second Higgs doublet or additional colored scalars.
Supersymmetric Models	Various supersymmetric extensions of the SM, including the MSSM, the NMSSM and many more.
Extra-dimensional Models	Extensions of the SM including KK excitations of the SM particles.
Strongly coupled and effective field theories	Including Technicolor, Little Higgs, as well as SM higher-dimensional op
Miscellaneous	
NLO	Models ready for NLO computations

NLO/Loop-Induced ready

https://feynrules.irmp.ucl.ac.be/wiki/ModelDatabaseMainPage

UFO models

Last modified 9 days ago

FeynRules models to be used for NLO calculations with aMC@NLO

This page contains a collection of models that have been implemented in FeynRules in the context of NLO calculations in the framework of aMC@NLO. It contains up to now simplified models inspired by the current searches undertaken by ATLAS and CMS, as well as a model developed to characterise the properties of the recently discovered Higgs boson. For each model:

- we include a brief description of the relevant signature,
- we provide the FeynRules model files as well as the UFO library to be used with MadGraph5_aMC@NLO,
- we indicate reference paper with the documentation on the model, together with the name of the contact person,
- validation figures generated in the framework of each model are provided, so that any user could try to reproduce them to verify their setup.

Available models

Description	Contact	Reference	FeynRules model files	UFO libraries	Validation material
Dark matter simplified models (more details)	K. Mawatari	arXiv:1508.00564 , arXiv: 1508.05327 , arXiv: 1509.05785	-	DMsimp_UFO.2.zip	-
Dark Matter Gauge invariant simplified model (scalar s-channel mediator) (more details)	G. Busoni	arXiv:1612.03475 , arXiv: 1710.10764 ,	-	-	-
Effective LR symmetric model (more details)	R. Ruiz	arXiv:1610.08985	effLRSM.fr	EffLRSM UFO	-
GM (more details)	A. Peterson	arXiv:1512.01243	-	GM_NLO UFO	-
Heavy Neutrino (more details)	R. Ruiz	arXiv:1602.06957	heavyN.fr	HeavyN NLO UFO	-
Higgs characterisation (more details)	K. Mawatari	arXiv:1311.1829 , arXiv:1407.5089 , arXiv: 1504.00611	-	HC_NLO_X0_UFO.zip	-
Inclusive sgluon pair production	B. Fuks	arXiv:1412.5589	sgluons.fr	sgluons_ufo.tgz	sgluons_validation.pdf ; sgluons_validation_root.tgz
Pseudoscalar top-philic resonance (more details)	D.B. Franzosi	http://arxiv.org/abs/1707.06760	-	AHttbar NLO UFO	-
Spin-2 (more details)	C. Degrande	http://arxiv.org/abs/1605.09359	dm_s_spin2.fr	SMspin2 NLO UFO	-
Stop pair -> t tbar + missing energy	B. Fuks	arXiv:1412.5589	stop_ttmet.fr	stop_ttmet_ufo.tgz	stop_ttmet_validation.pdf ; stop_ttmet_validation_root.tgz
SUSY-QCD	B. Fuks	arXiv:1510.00391	-	susyqcd_ufo.tgz	All figures available from the arxiv
Two-Higgs-Doublet Model (more details)	C. Degrande	arXiv:1406.3030	-	2HDM_NLO	-
Top FCNC Model (more details)	C. Zhang	arXiv:1412.5594	TopEFTFCNC.fr	TopFCNC UFO	-

https://feynrules.irmp.ucl.ac.be/wiki/ModelDatabaseMainPage

BSM models

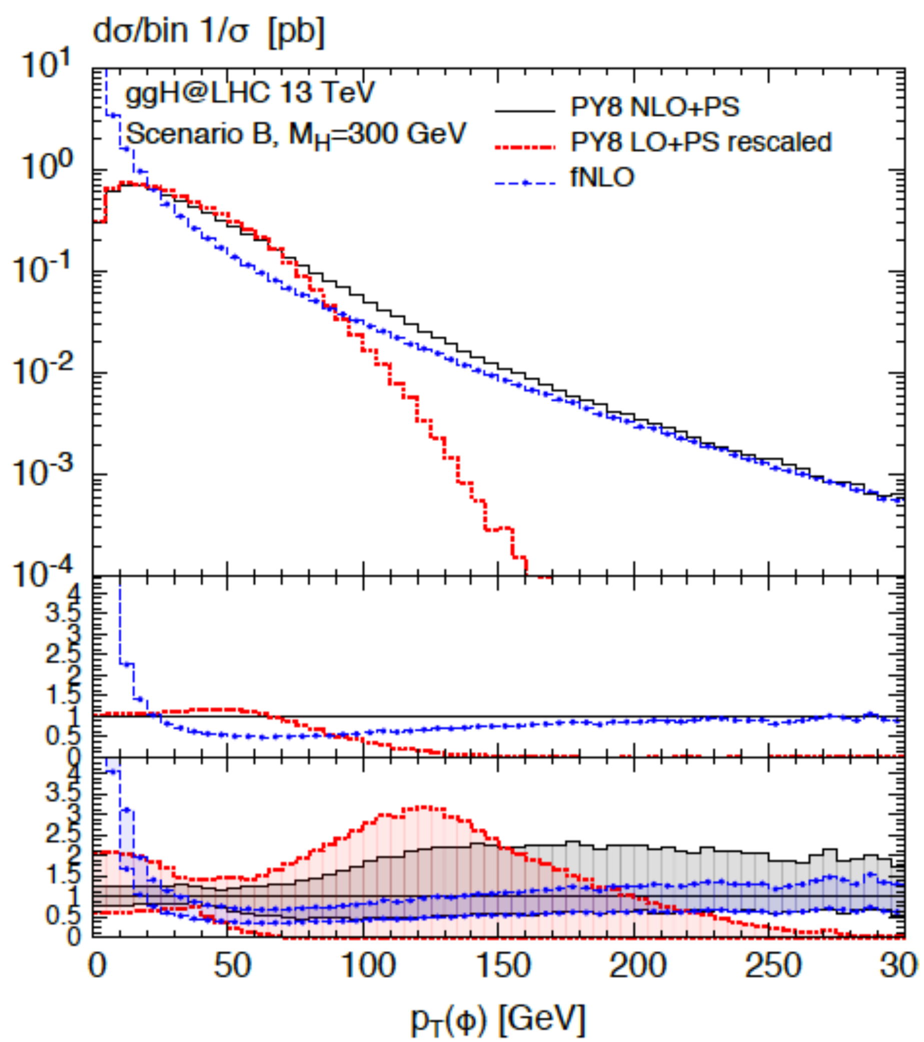
- SUSY/2HDM
- Georgi-Machacek model
- Simplified DM models

→

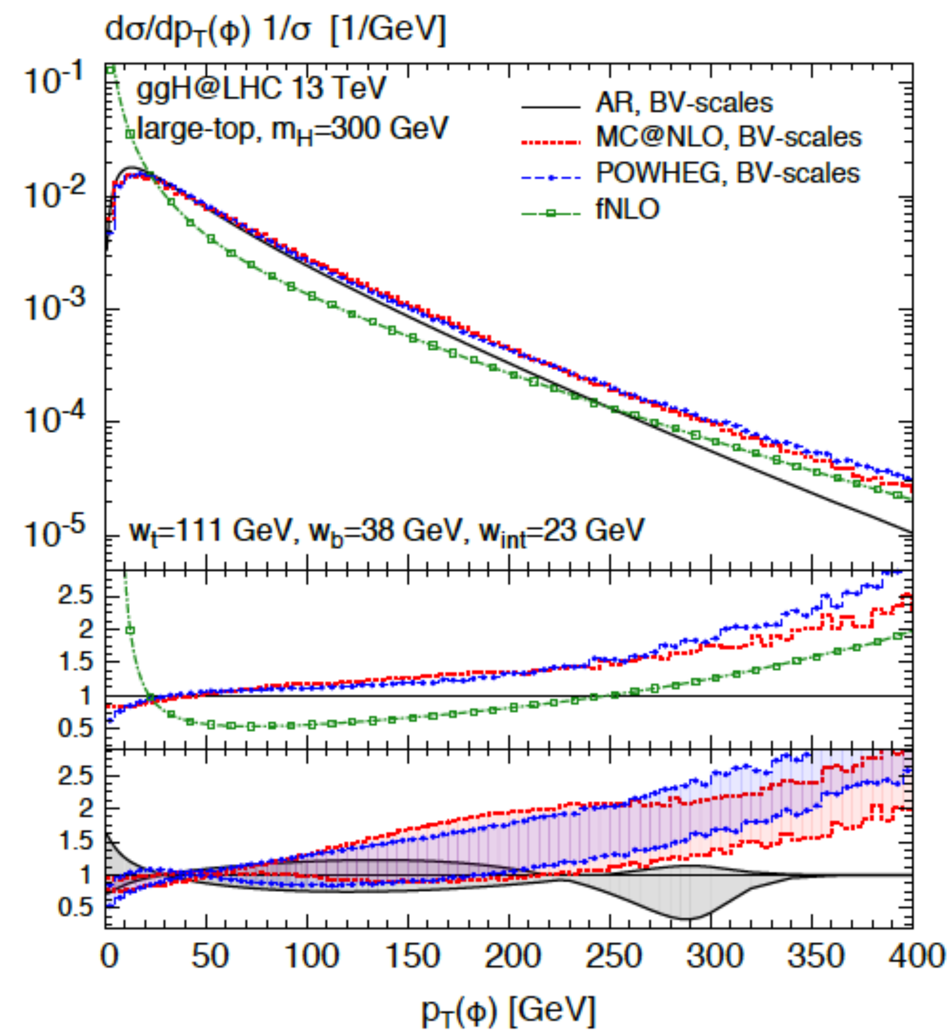
- Heavy Scalars
- Charged Higgs(es)
- VV, VH, HH, tt resonances
- Higgs+MET searches

Monte Carlo for BSM scalars

Gluon-fusion for SUSY/2HDM/NMSSM neutral scalars: Implemented in PowHeg and MG5_aMC (aMCSusHi)



Mantler et al arXiv:1504.06625



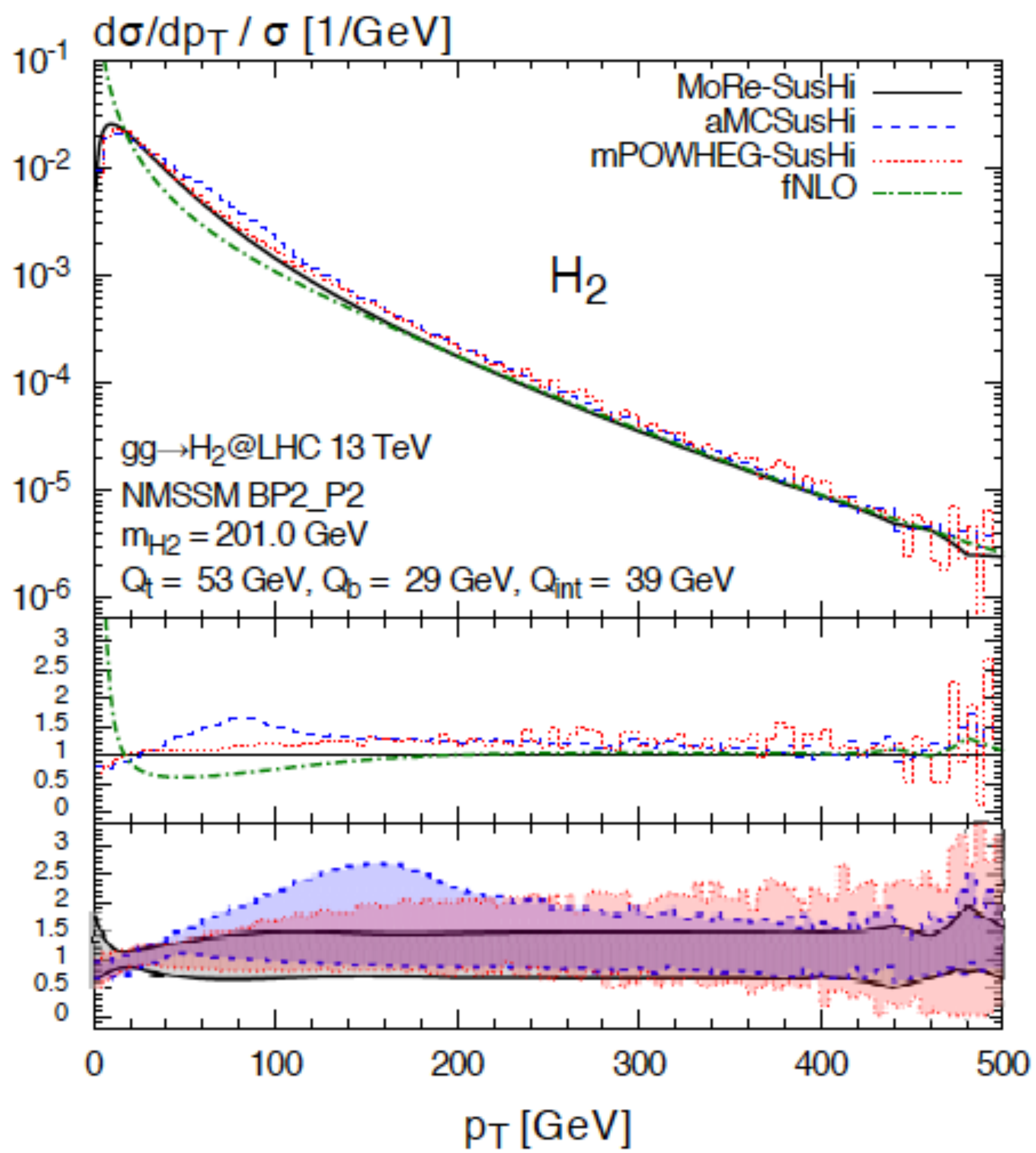
Bagnaschi et al arXiv:1510.08850

Detailed investigation of shower scale choice

https://cp3.irmp.ucl.ac.be/projects/madgraph/wiki/aMCSushi

Monte Carlo for BSM scalars

Gluon-fusion for SUSY/2HDM/NMSSM neutral scalars:
Implemented in PowHeg and MG5_aMC (aMCSusHi)



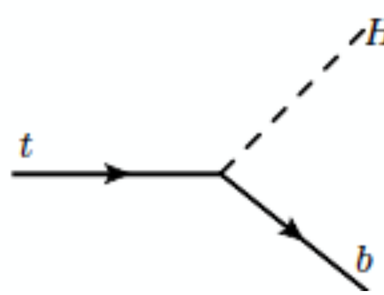
Liebler et al arXiv:1608.02949

For inclusive Higgs production:
SusHi: Provides also the Higgs pT distribution
Gluon fusion and bbH
Harlander, Liebler, Mantler arXiv:1605.03190
MoRe-SusHi: including resummation 1608.02949
Harlander, Mantler, Wiesemann arXiv:1409.0531
SusHiMi: CP-violation in MSSM
Liebler, Patel, Weiglein arXiv:1611.09308

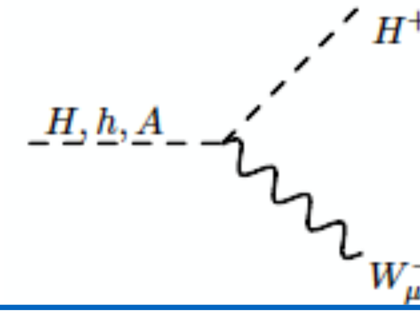
Higher order distributions typically used to reweight MC results

MC for charged Higgs in the 2HDM

Charged Higgs couplings in the 2HDM

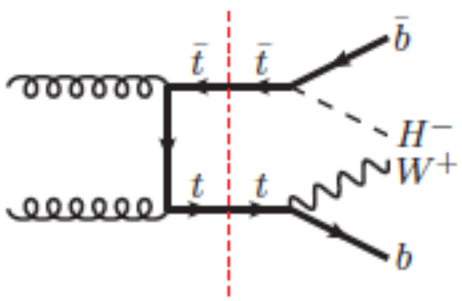


$$= -i\frac{1}{\tan\beta}(y_t P_R + y_b P_L) \quad \text{type I}$$
$$= -i\left(\frac{y_t}{\tan\beta}P_R + y_b \tan\beta P_L\right) \quad \text{type II}$$



$$= i\frac{g_W}{2}\cos(\beta-\alpha)p^\mu_W \quad (h)$$
$$= i\frac{g_W}{2}\sin(\beta-\alpha)p^\mu_W \quad (H)$$
$$= i\frac{g_W}{2}p^\mu_W \quad (A)$$

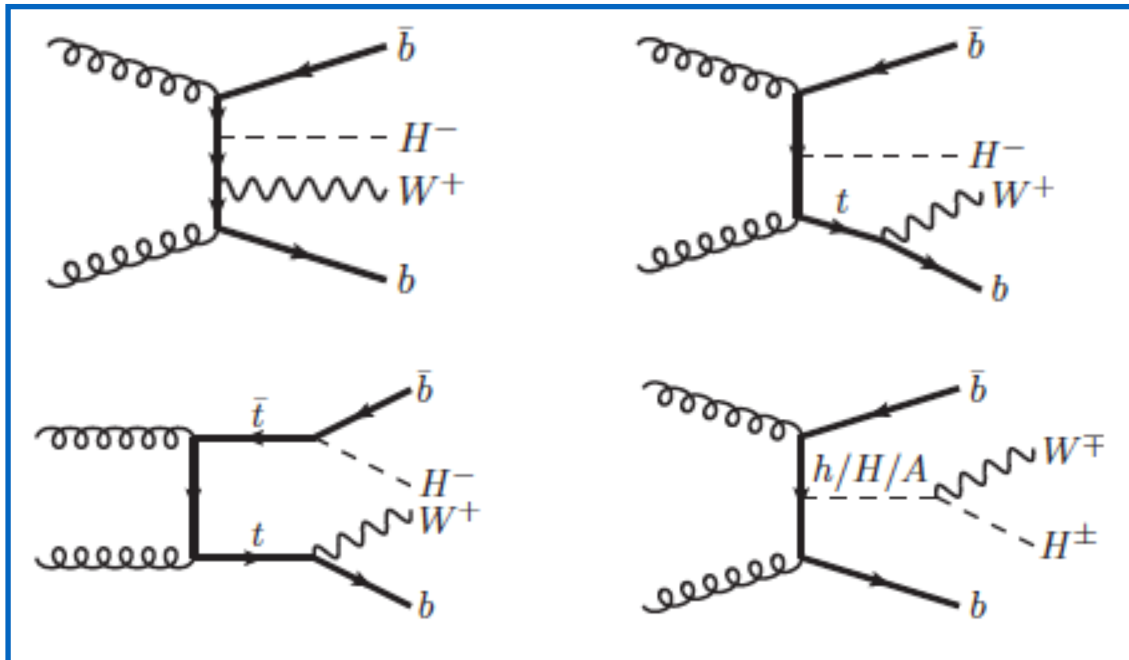
Charged Higgs production



Light Higgs

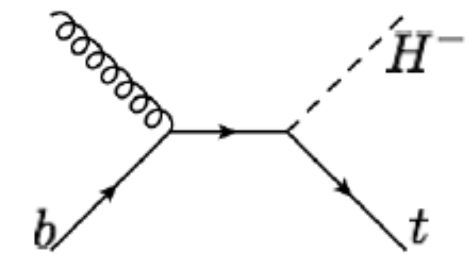
Use ttbar cross-section: Czakon et al, arXiv:1303.6254, arXiv:1511.00549

Light Higgs Branching ratio: Hollik et al., arXiv:0708.1697



Intermediate region

0, 1 and 2 resonant tops



Heavy Higgs

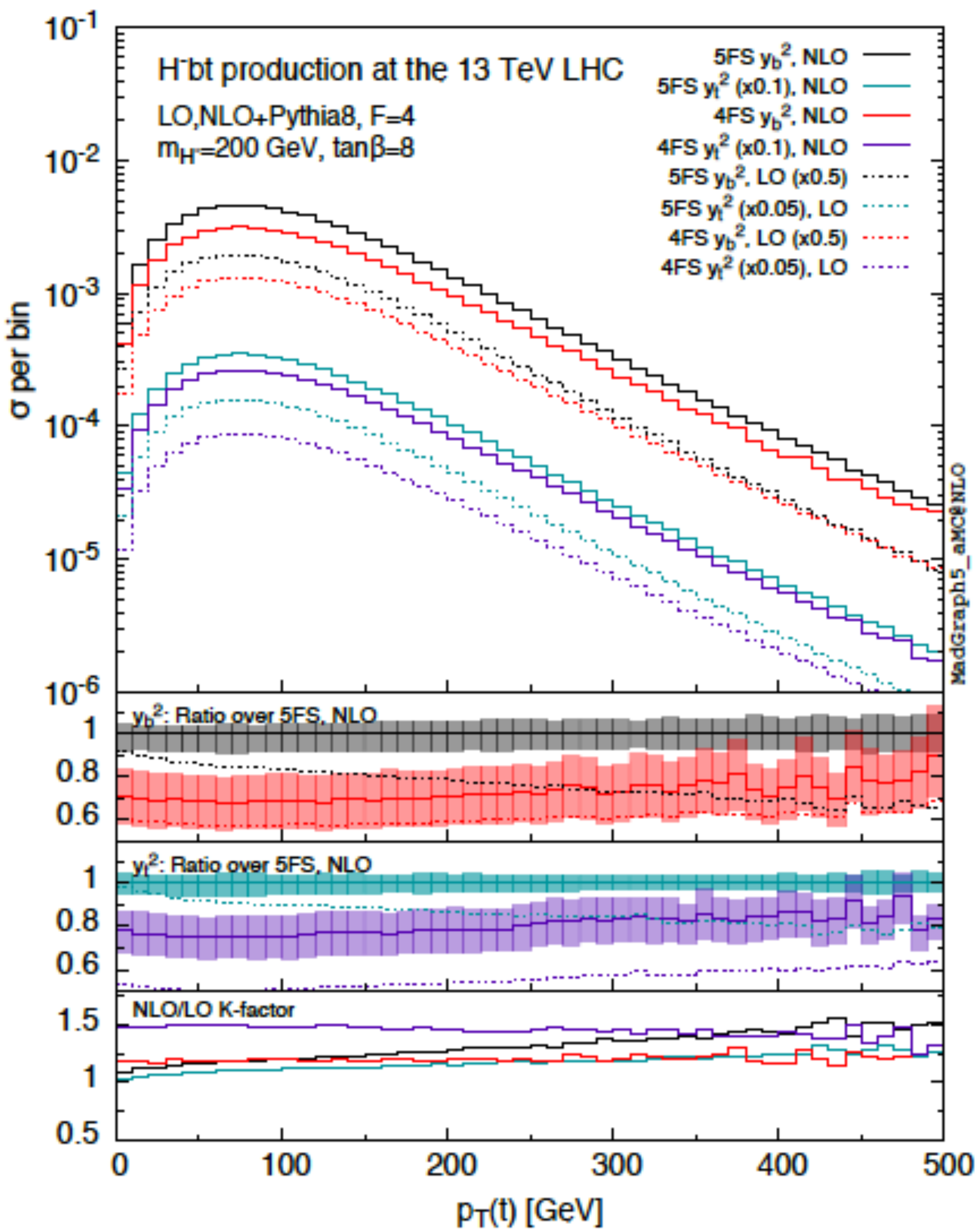
Fully differential NLO+PS Degrande et al, arXiv:1507.02549 [MG5_aMCatNLO]

4FS and 5FS schemes

NLO 2HDM UFO: http://feynrules.irmp.ucl.ac.be/wiki/2HDM

MC for charged Higgs

Heavy region



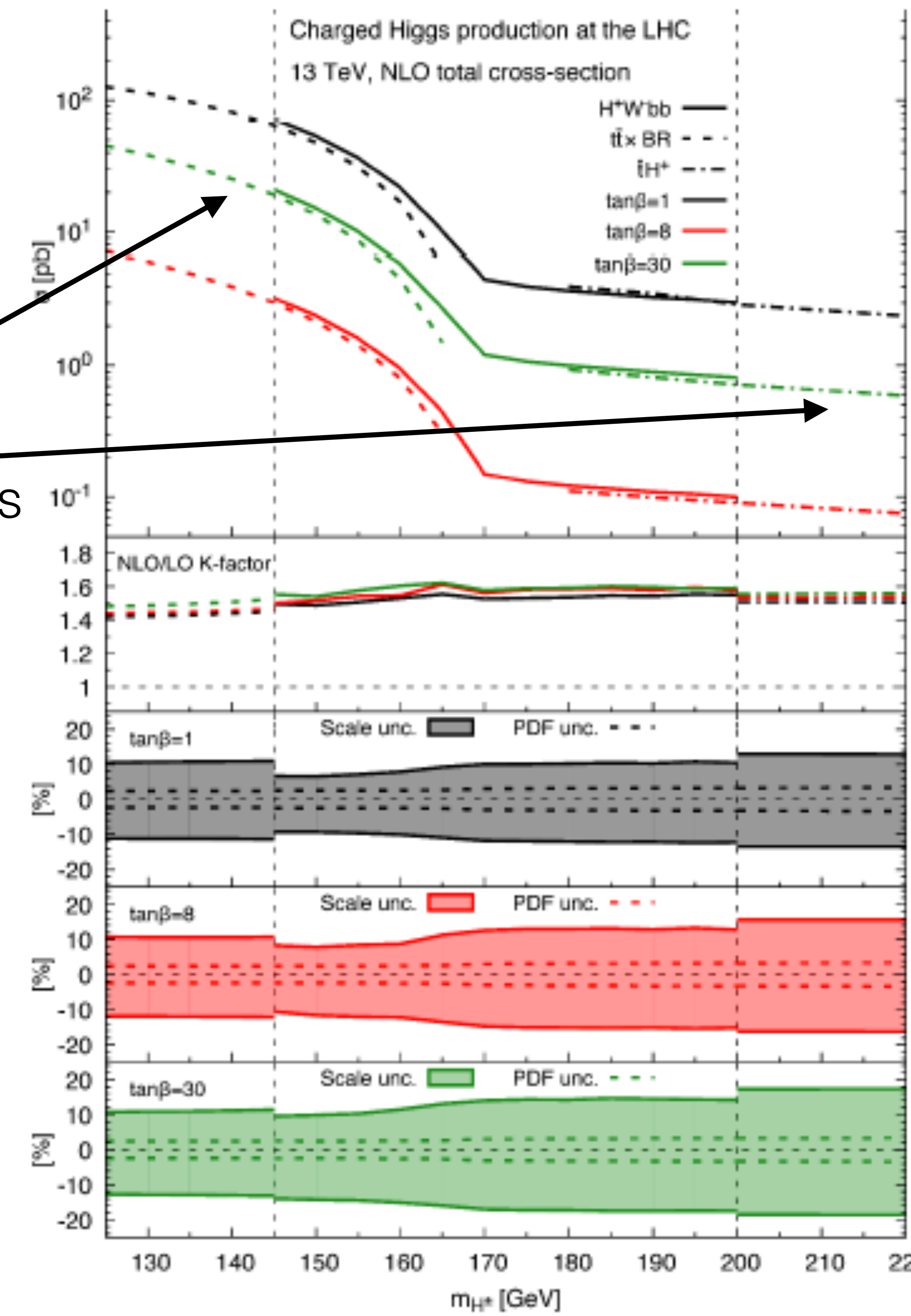
Degrande et al, arXiv:1507.02549

Code and instructions here:

https://cp3.irmp.ucl.ac.be/projects/madgraph/wiki/chargedHiggs#no1

Intermediate region

comparison to 2 and 0 resonant tops contributions

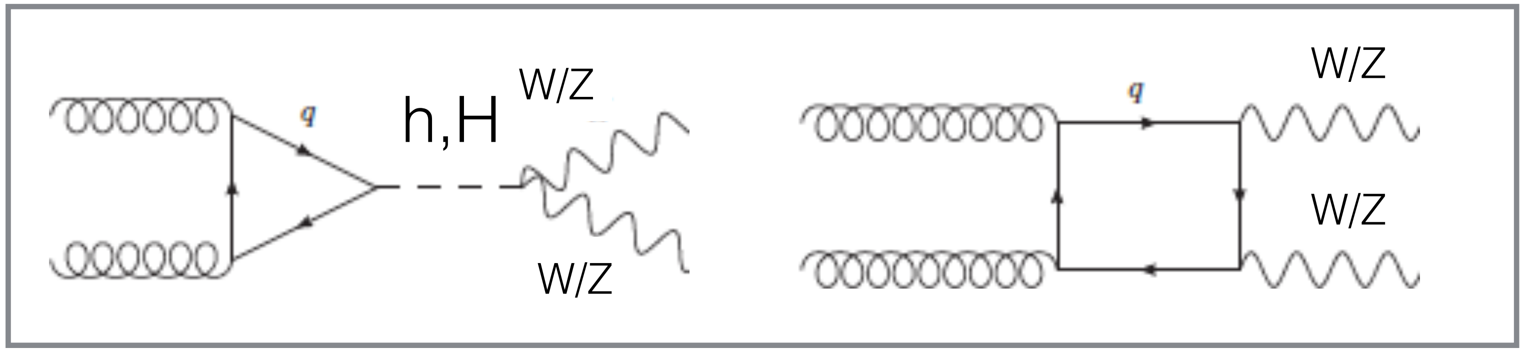


Degrande et al, arXiv:1607.05291

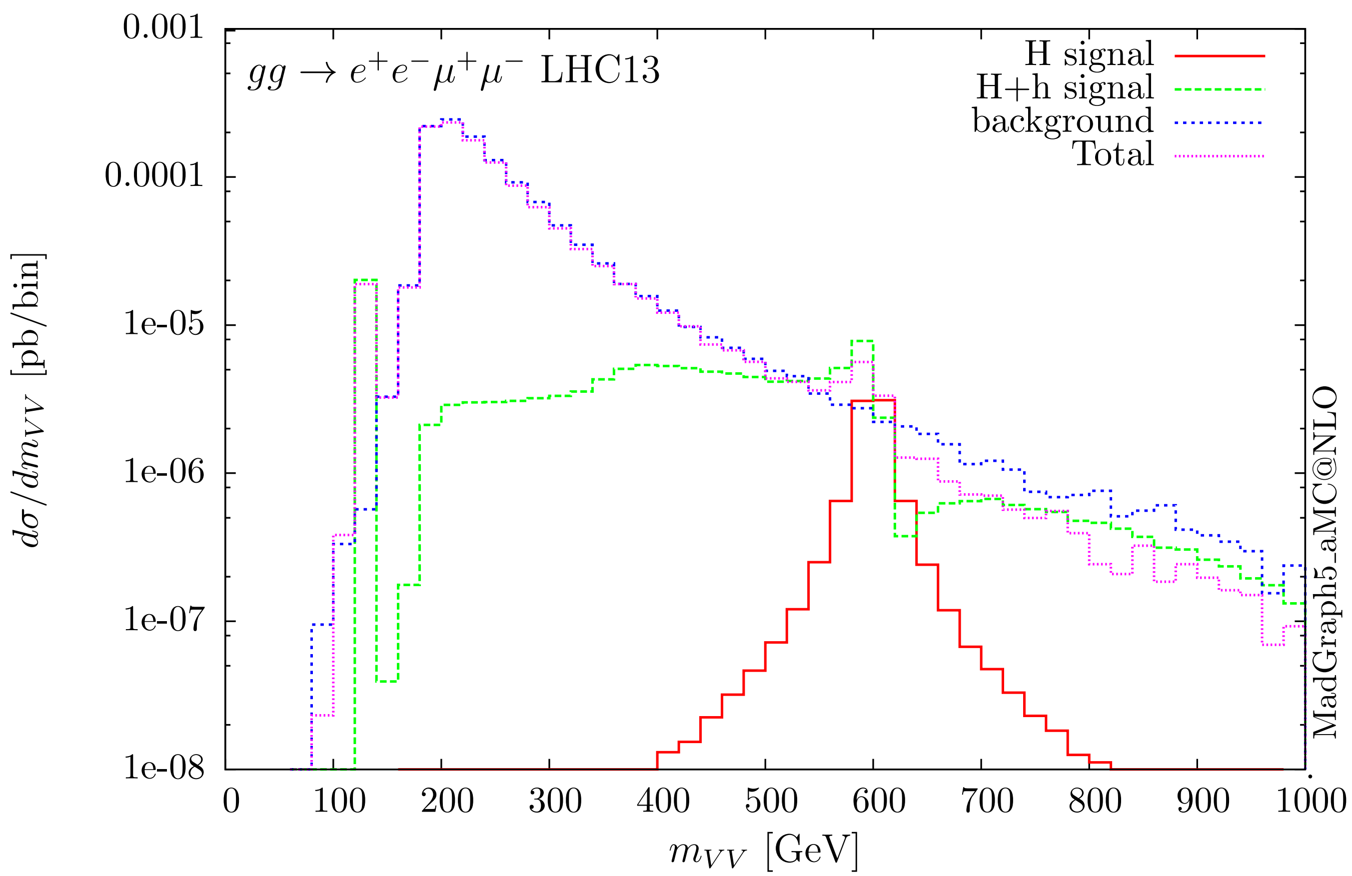
Cross-sections available here:

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGMSSMCharged#Intermediate_mass_145_200_GeV_ch

MC for scalar diboson resonances



e.g. 2HDM



2HDM parameters:

	$\tan\beta$	α/π	m_{H^0}	m_{A^0}	$m_{H^\pm}$	m_{12}^2
Z2	0.9	-0.775	600	700	700	120000

Couplings

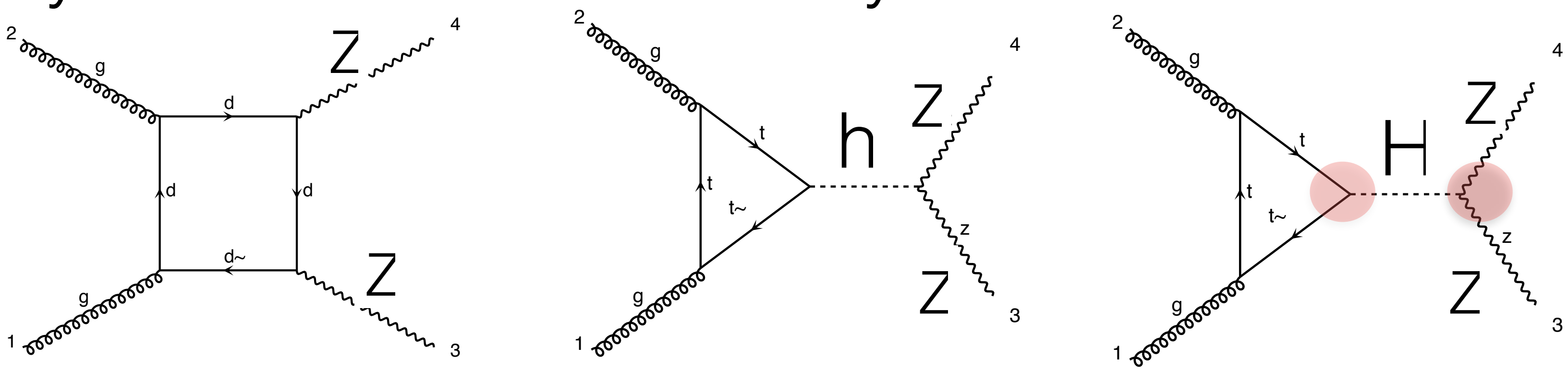
	$\hat{g}_{h^0tt}$	$\hat{g}_{h^0bb}$	$\hat{g}_{H^0tt}$	$\hat{g}_{H^0bb}$	$\hat{g}_{ZZh^0}$	$\hat{g}_{ZZH^0}$
Z2	1.07	0.94	-1.05	0.96	0.998	0.063

- Resonance peak suppressed by small HZZ coupling (cos(β-α))
- Peak-dip or dip-peak structures possible depending on the input

See also Greiner, Liebler and Weiglein arxiv:1512.07232

MC for signal-background Interference

Toy model: Additional heavy scalar



Free parameters

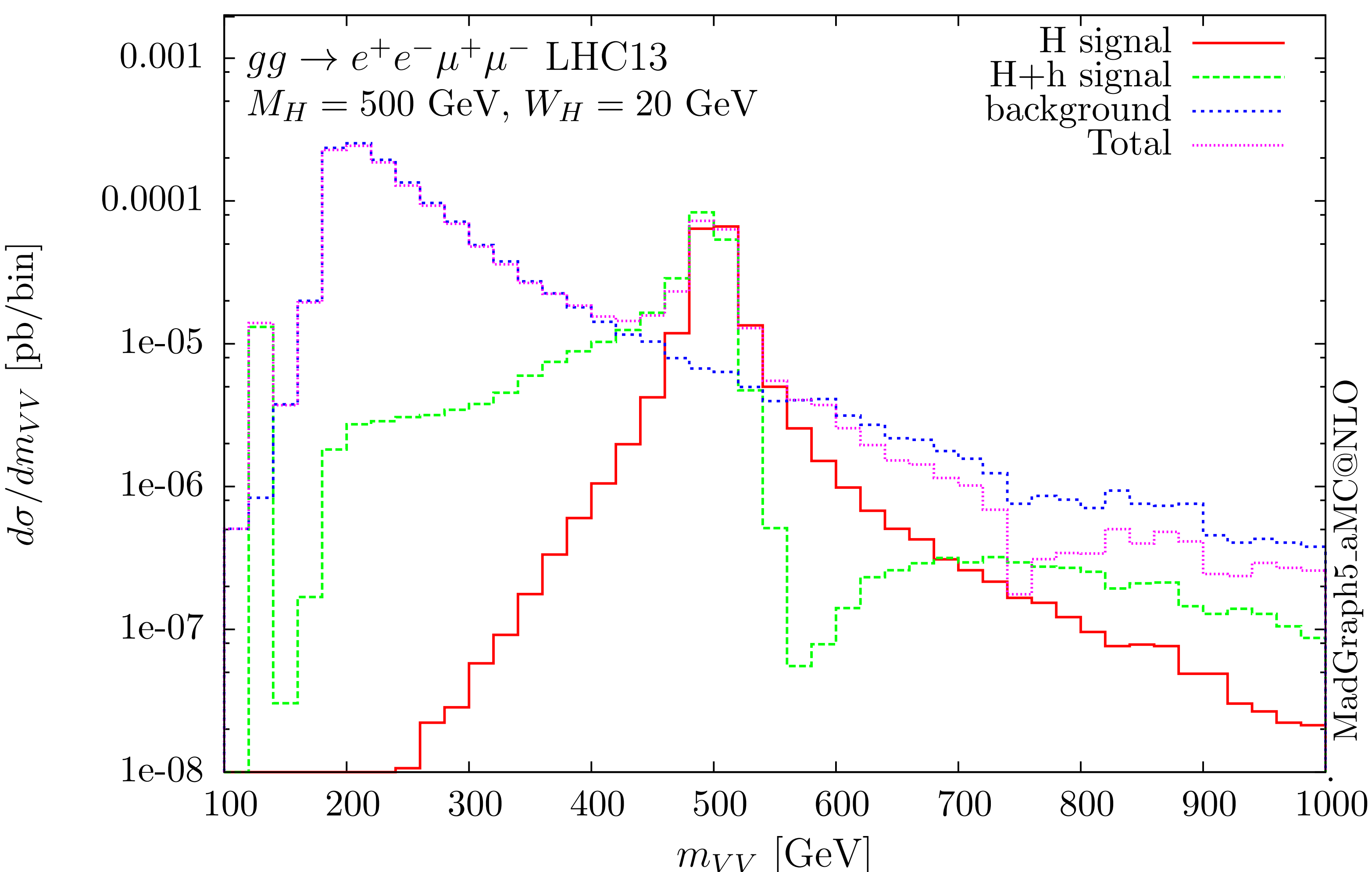
M_H

W_H

$Y_{t,b}$

$g_{w/Z}$

Parameters can be matched to one's favourite model



Signal+background+interference

All contributions can be generated separately using MG5 squared order functionality

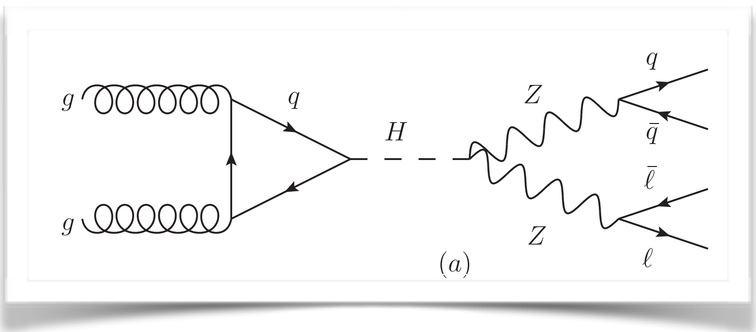
Signal:
>import model HC_NLO_X0_UFO
>generate g g > X0 > z z [QCD]
>output signalggZZ

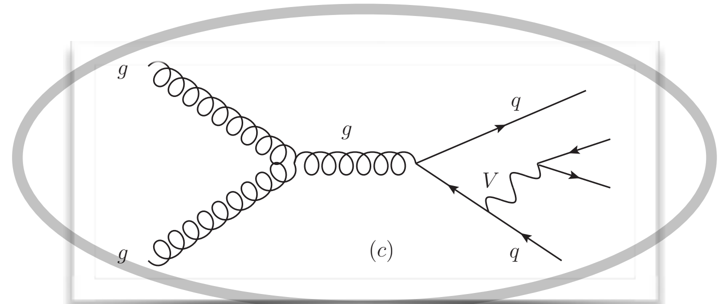
background:
>import model HC_NLO_X0_UFO
>generate g g > z z QNP=0 [QCD]
>output backggZZ

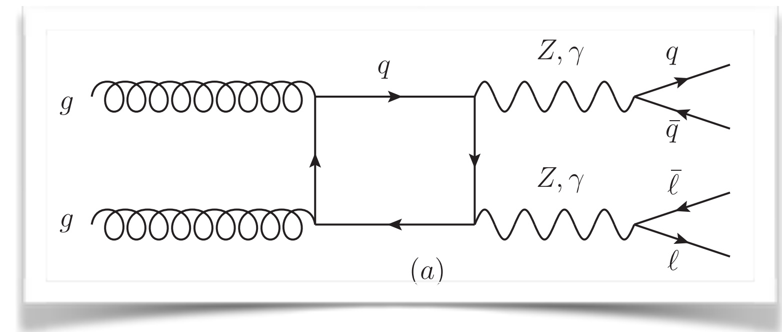
interference:
>import model HC_NLO_X0_UFO
>generate g g > z z QNP^2==1 [QCD]
>output interggZZ

MC for signal-background Interference

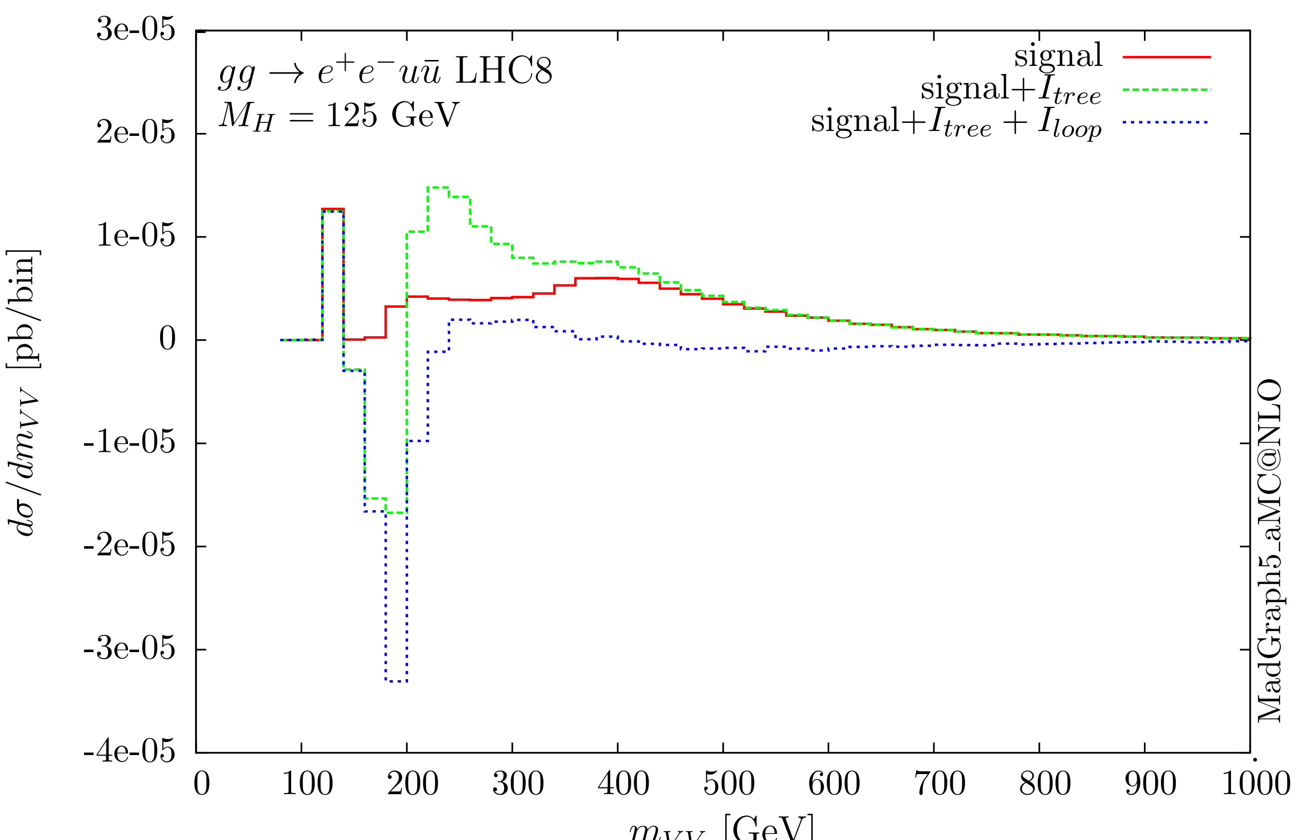
Semileptonic decay mode:

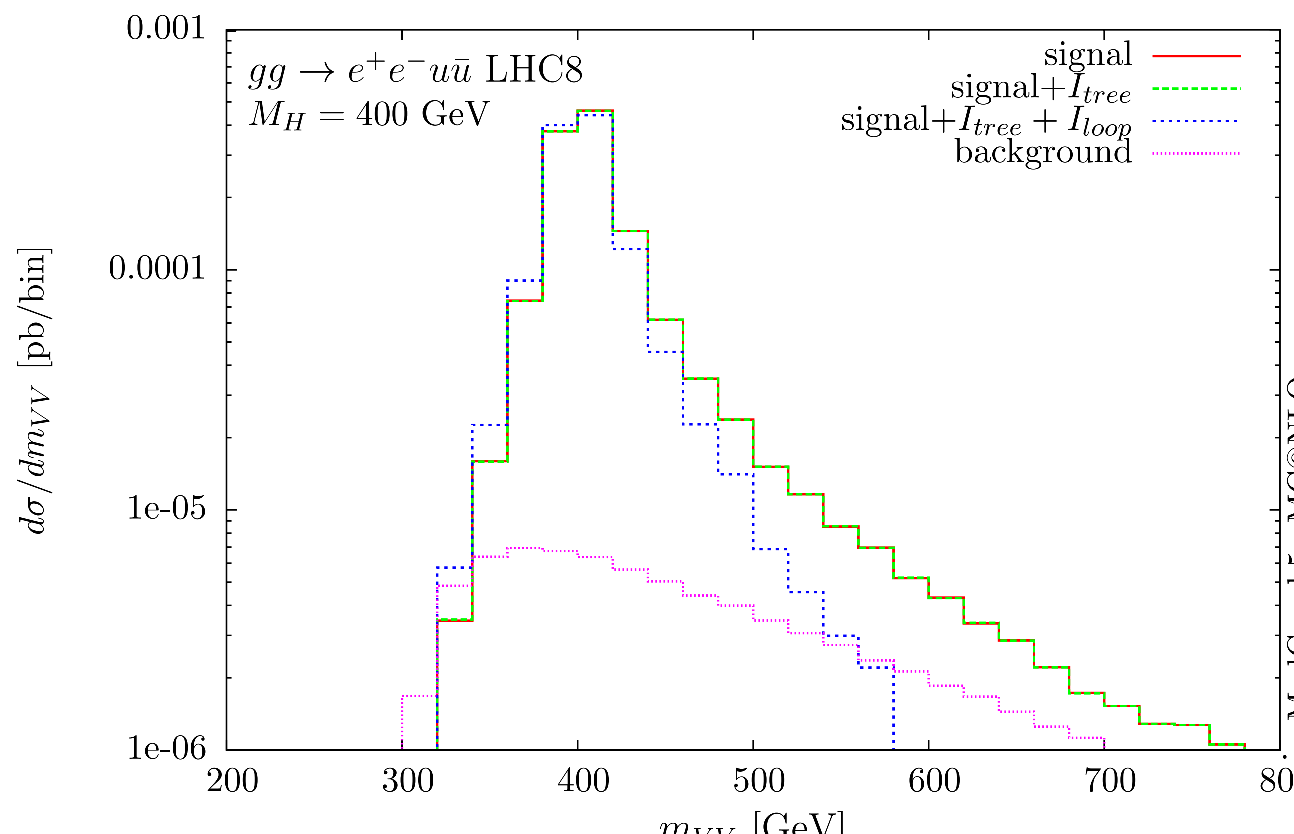






A new background $\mathcal{O}(g_s^2 e^2)$ $\mathcal{O}(g_s^2 e^4)$

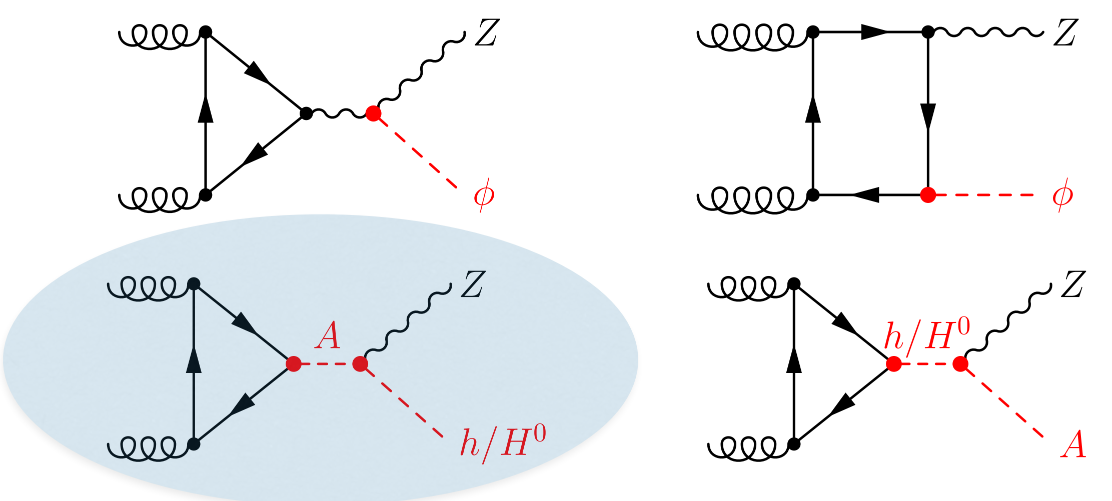




Kauer, O' Brien, EV arXiv:1506.01694

Formally Higher-order background is more important: MC available

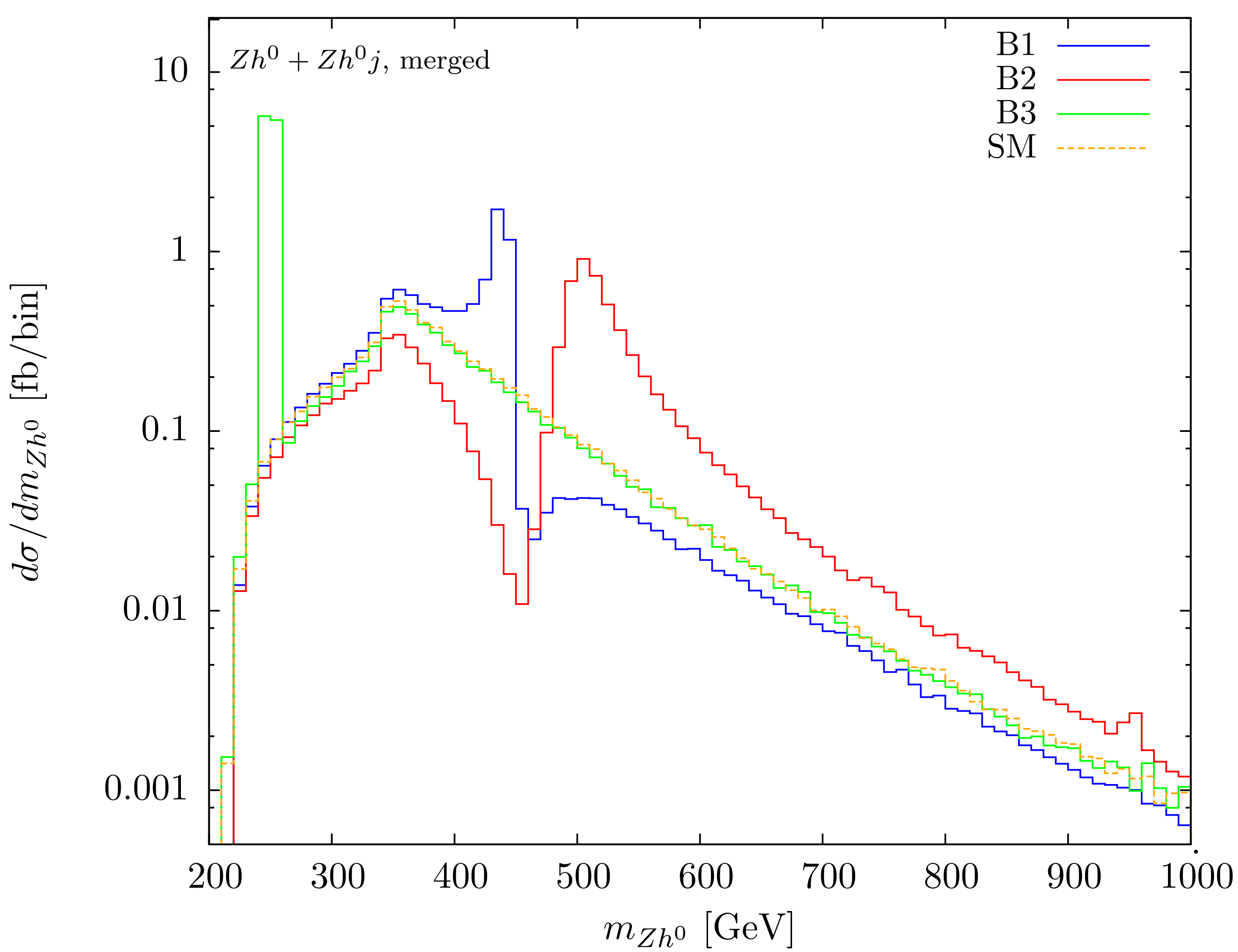
Resonant Zϕ production in 2HDM scenarios



2HDM parameters:

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

	$gg \to Zh^0$	$gg \to ZH^0$	$gg \to ZA^0$
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	$167\ ^{+31\%}_{-19\%}$	$0.891\ ^{+33\%}_{-21\%}$	$1325\ ^{+28\%}_{-21\%}$



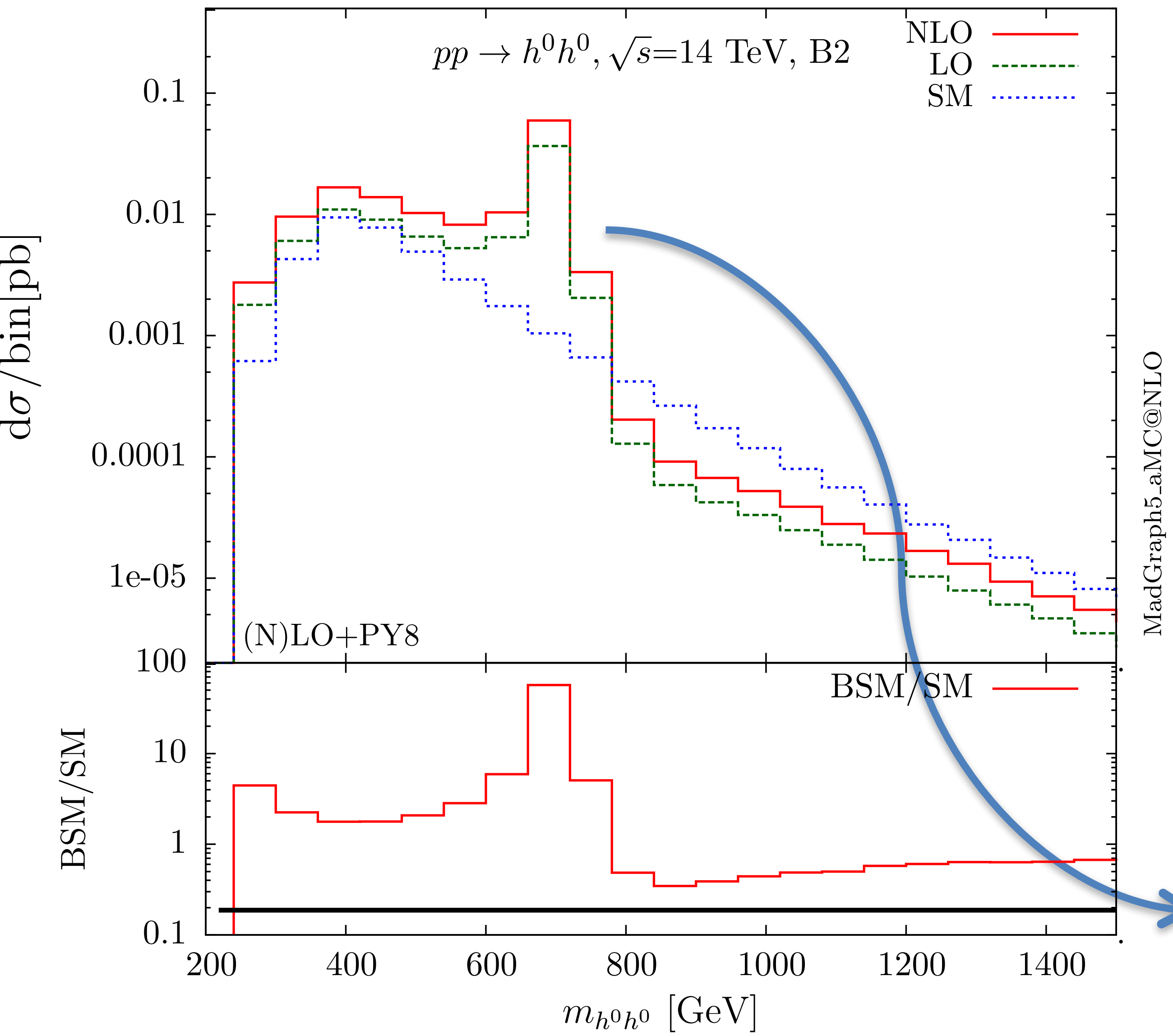
Hespel, Maltoni, EV arXiv:1503.01656

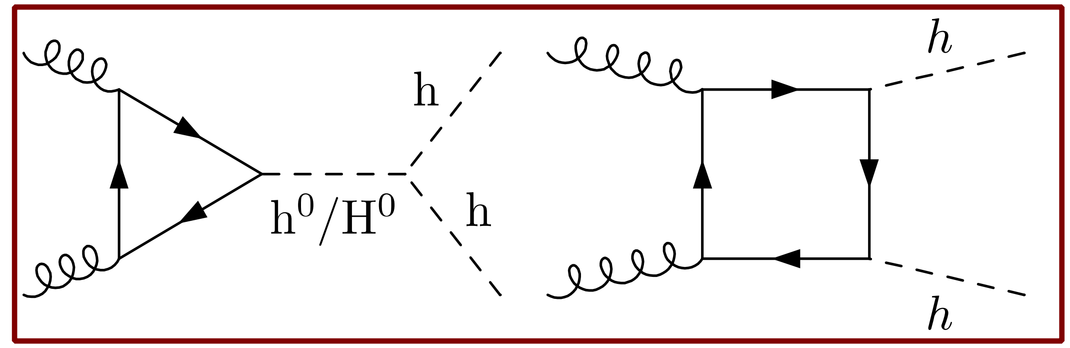
- Resonance peaks in ZH mass
- Interference with SM-like diagrams included
- Production of ZA and ZH at the picobarn level
- Merged samples also possible

also available in vh@nnlo
Harlander, Liebler, Zirke arXiv:1307.8122

MC for HH resonances

2HDM Heavy scalar decay





2HDM input: Type-ii

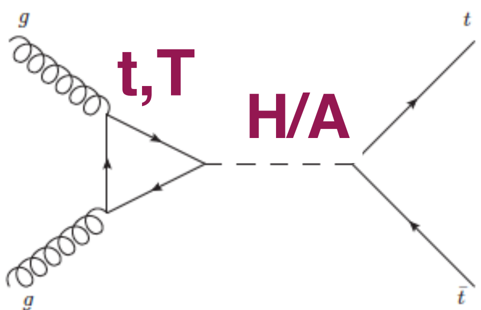
$\tan\beta$	α/π	m_{H^0}	m_{A^0}	$m_{H^\pm}$	m_{12}^2
1.50	-0.2162	700	701	670	180000

- Significant resonant enhancement from H➔hh
- Distinctive resonance peak, but also interference patterns before and after
- See also Baglio et al. arxiv:1403.1264

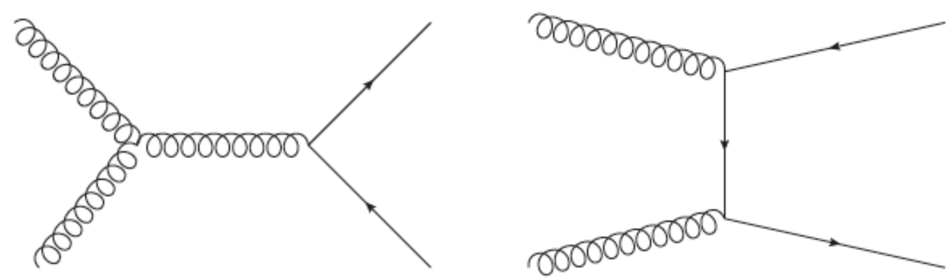
Hespel, Lopez-Val, EV arxiv:1407.0281
Using NLO 2HDM UFO model

Also in Hpair:Plehn, Spira, Zerwas hep-ph/9603205;
Dawson, Dittmaier, Spira hep-ph/9805244
Grober, Muhlleitner, Spira, Streicher 1504.06577
Grober, Muhlleitner, Spira arXiv:1705.05314: C2HDM

Scalar resonances in $t\bar{t}$



signal

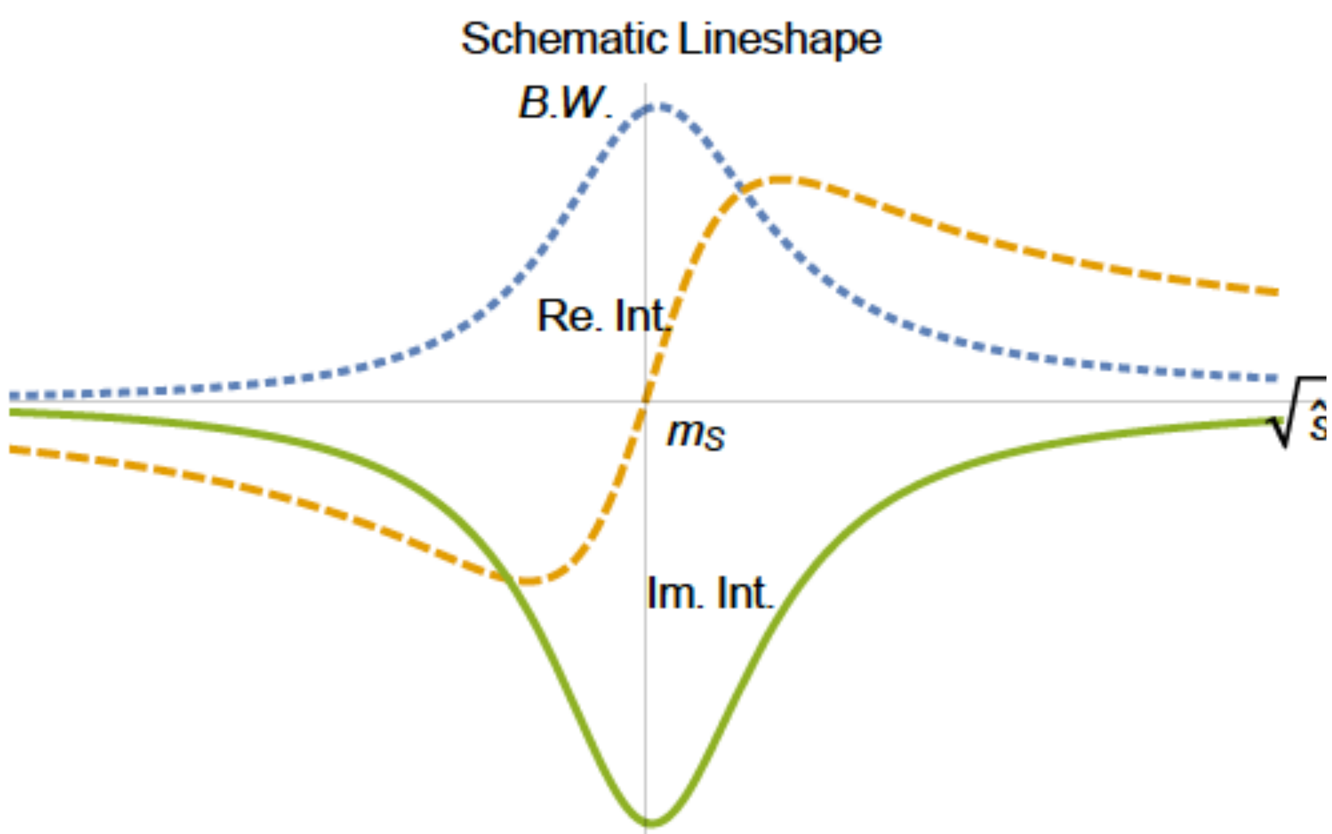


QCD continuum

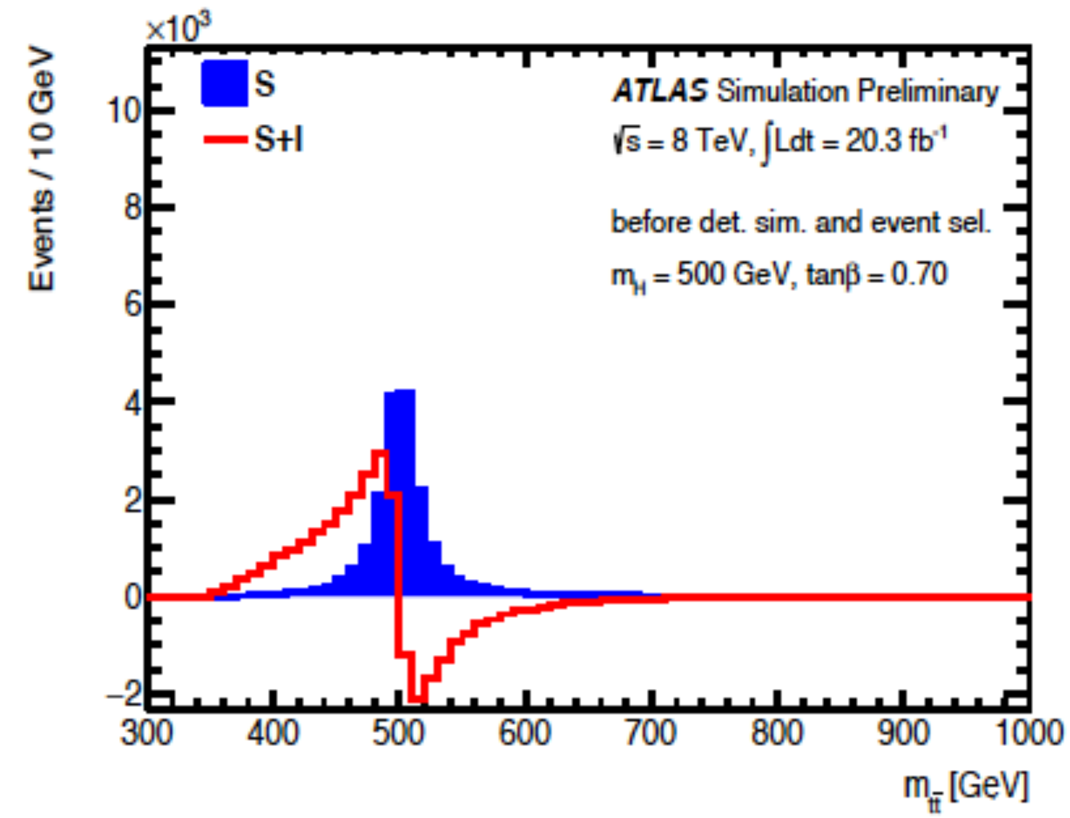
Interference important for the line shape for widths~0.01M

Peak-dip structures

Scalar or pseudoscalar resonance
Top-loop, heavy quark (VLQ) loop

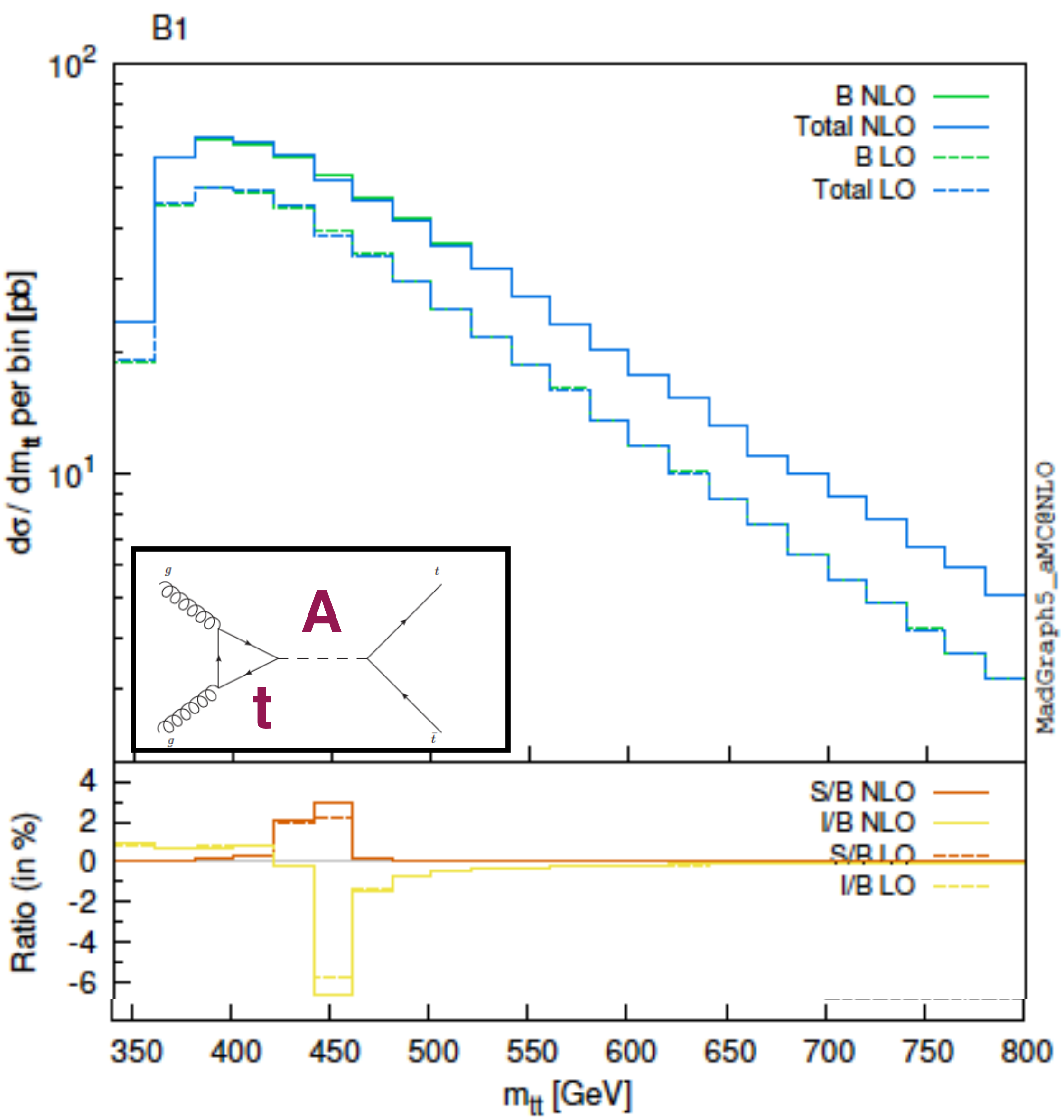


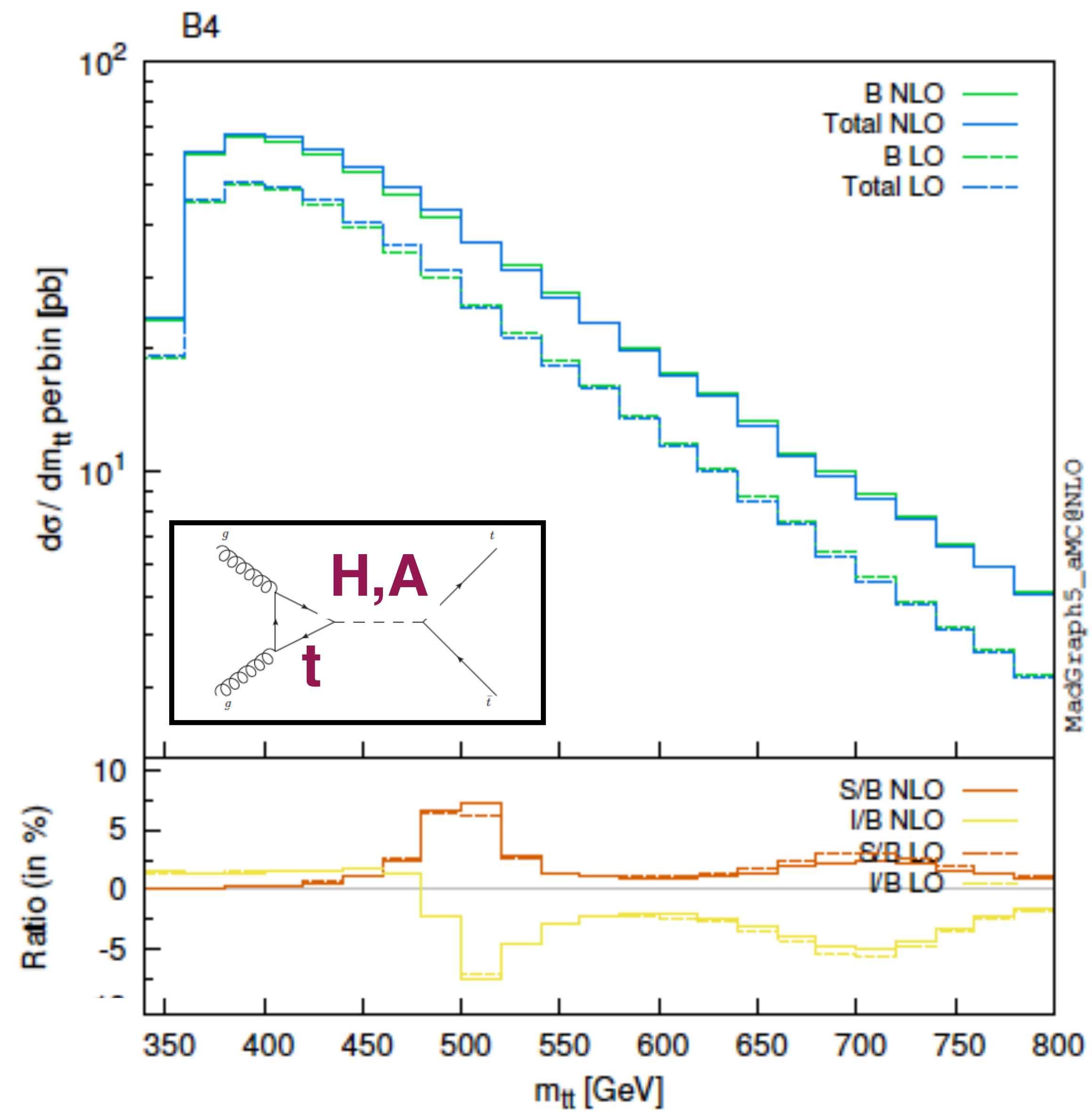
Carena, Liu arXiv: 1608.07282



ATLAS-CONF-2016-073
First experimental study modelling the interference

2HDM top resonances





	$\tan\beta$	α/π	m_{H^0}	m_{A^0}	$m_{H^\pm}$	m_{12}^2
B1	1.75	-0.1872	300	441	442	38300
B4	0.6	-0.328	500	710	720	10000

Hespel, Maltoni, EV arXiv:1606.04149

Approximate NLO for the interference

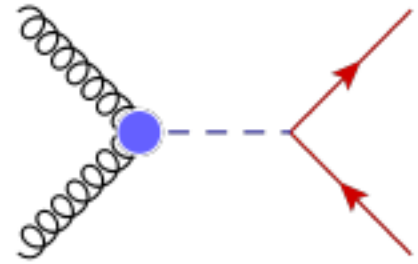
$$\boxed{\sigma_{\rm NLO} = \sigma_{\rm NLO}^{\rm back} + \sigma_{\rm NLO}^{\rm signal} + \sigma_{\rm LO}^{\rm inter}\sqrt{K_S K_B}}$$

See also: Bernreuther et al. arXiv:1511.0558

Signal background interference at NLO

$$gg \to H(A) \to t\bar{t}$$

Direct coupling of gluons to the Heavy scalar



=

$$\boxed{O_{HG} = g_s^2 G^A_{\mu\nu} G^{A\mu\nu} H}$$

$$\boxed{O_{A\tilde{G}} = g_s^2 G^A_{\mu\nu} \tilde{G}^{A\mu\nu} A}$$

For a VLQ coupling to a scalar

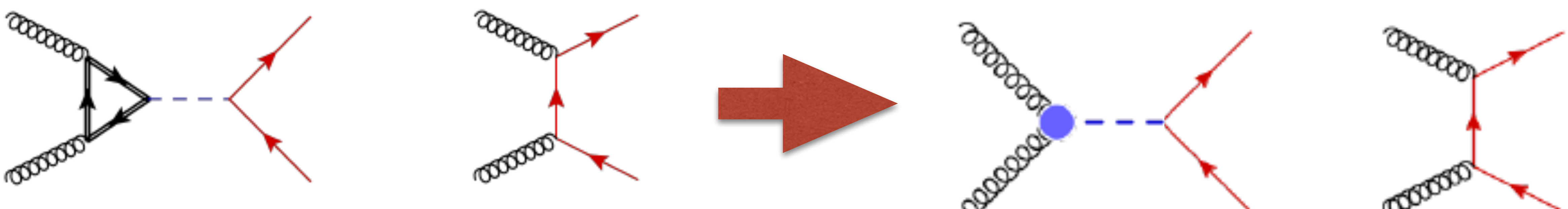
$$L_{Yuk} = y_F \bar{F} F H + \tilde{y}_F F i\gamma^5 F A$$

m_F>>

Matching

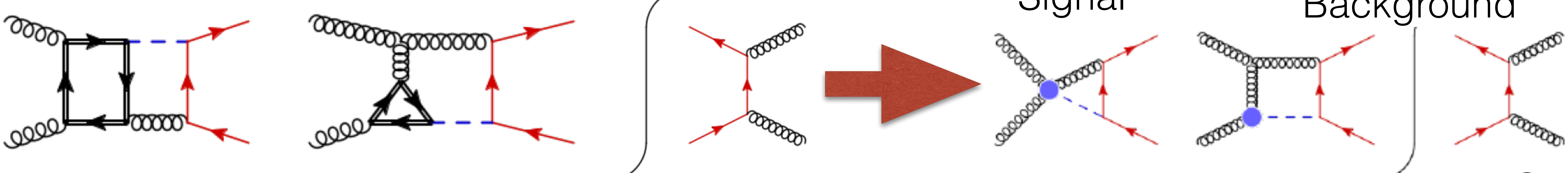
$$\frac{C_{HG}(m_F)}{\Lambda} = -\frac{y_F}{48\pi^2 m_F}$$

$$\frac{C_{A\tilde{G}}(m_F)}{\Lambda} = -\frac{\tilde{y}_F}{32\pi^2 m_F}$$



Signal

Background



2-loop becomes 1-loop: NLO computation possible

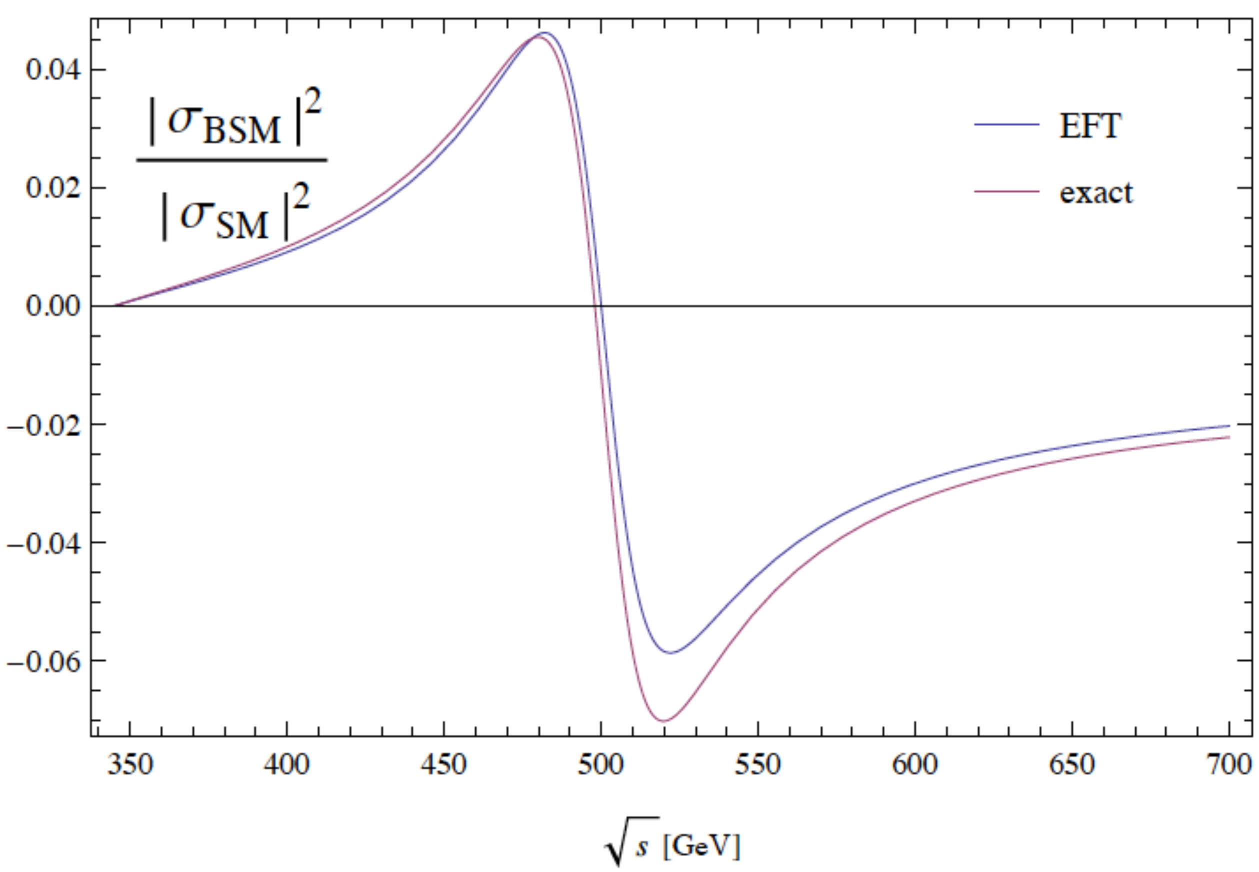
Scalar resonances in $t\bar{t}$

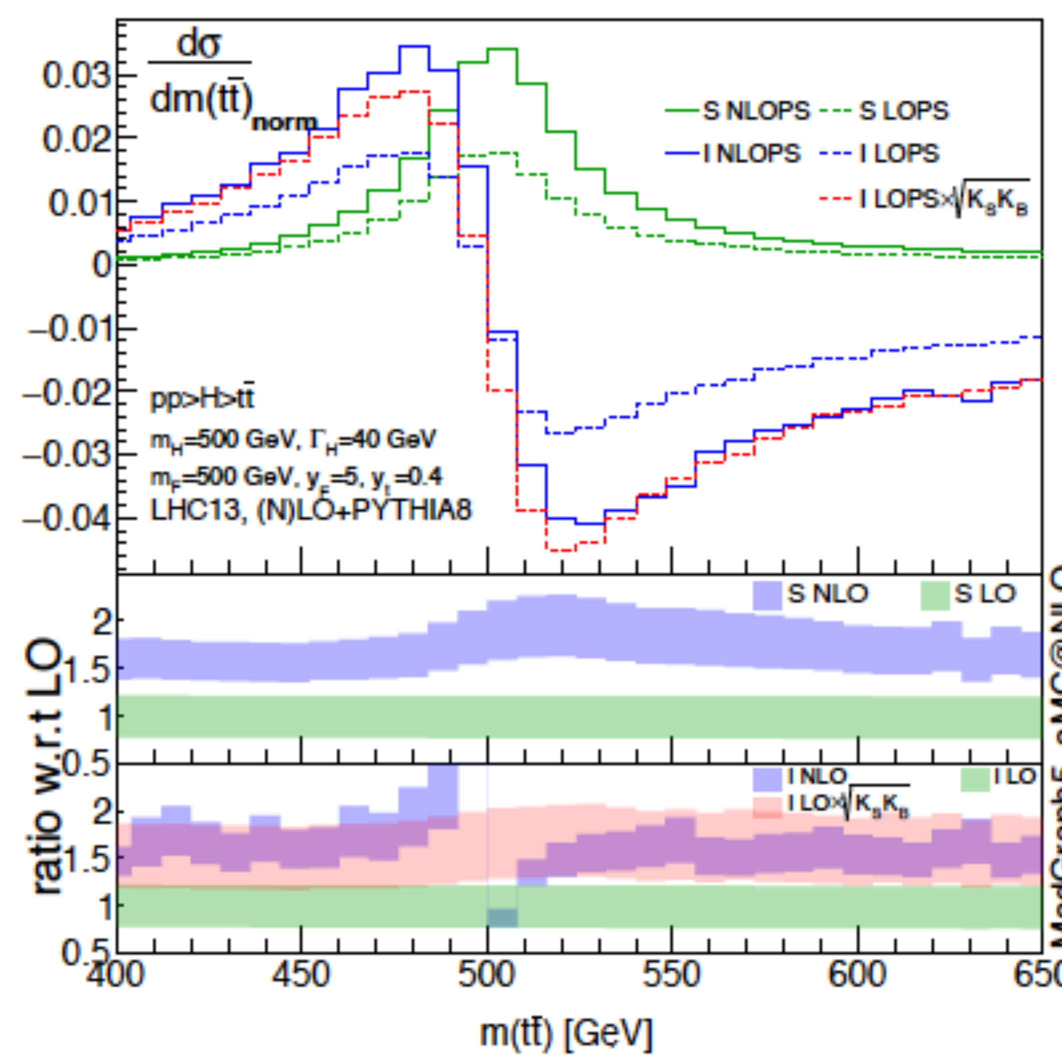
Scenario A: Heavy VLQ

m_H=500 GeV, Γ_H=40 GeV

m_F=500 GeV, y_F=5, y_t=0.4

$$\frac{C_{HG}}{\Lambda} = -5.11 \times 10^{-5}\ \text{GeV}^{-1}\,,$$
$$\frac{C_{tG}}{\Lambda} = -1.40 \times 10^{-6}\ \text{GeV}^{-1}\,.$$



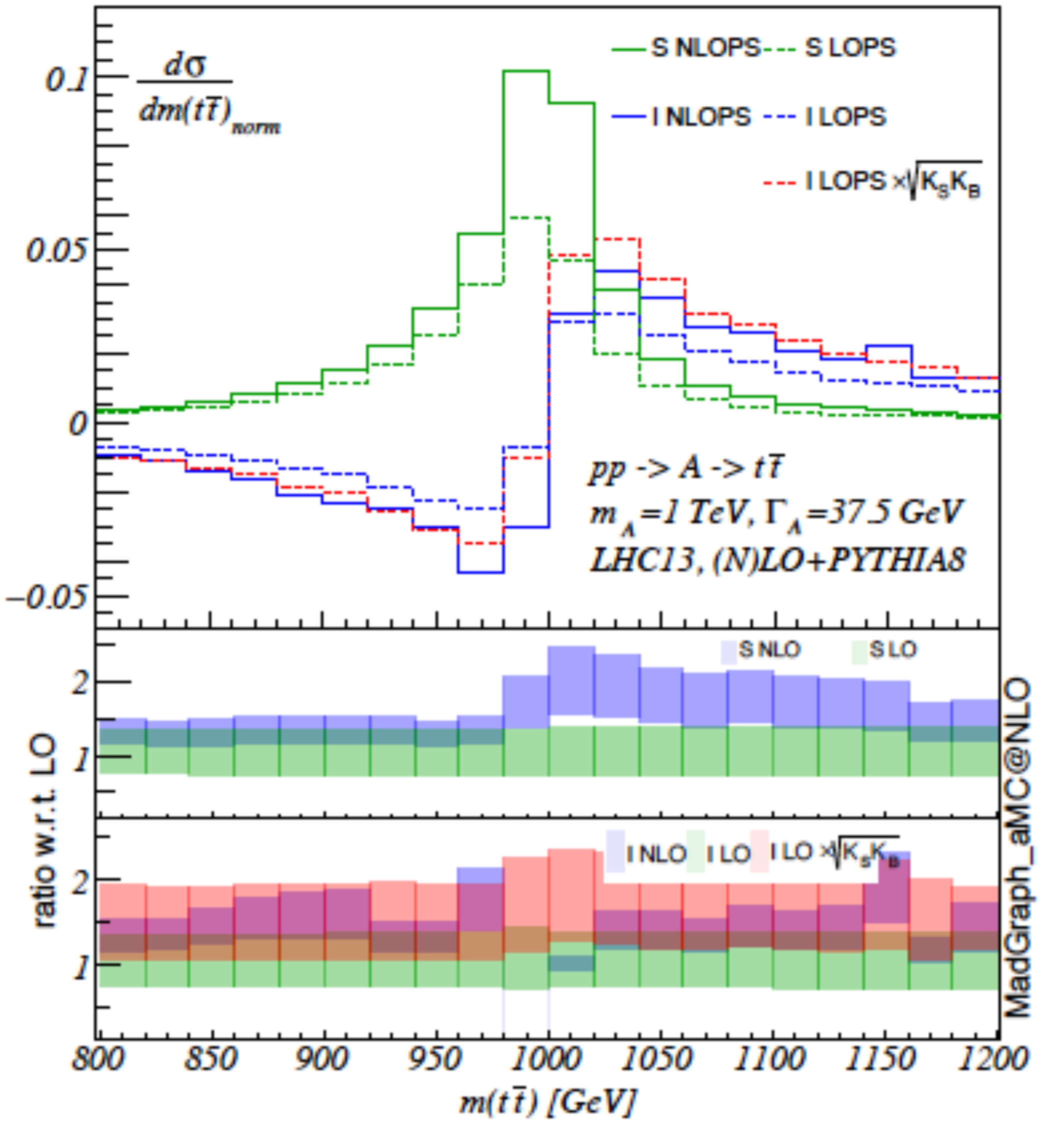


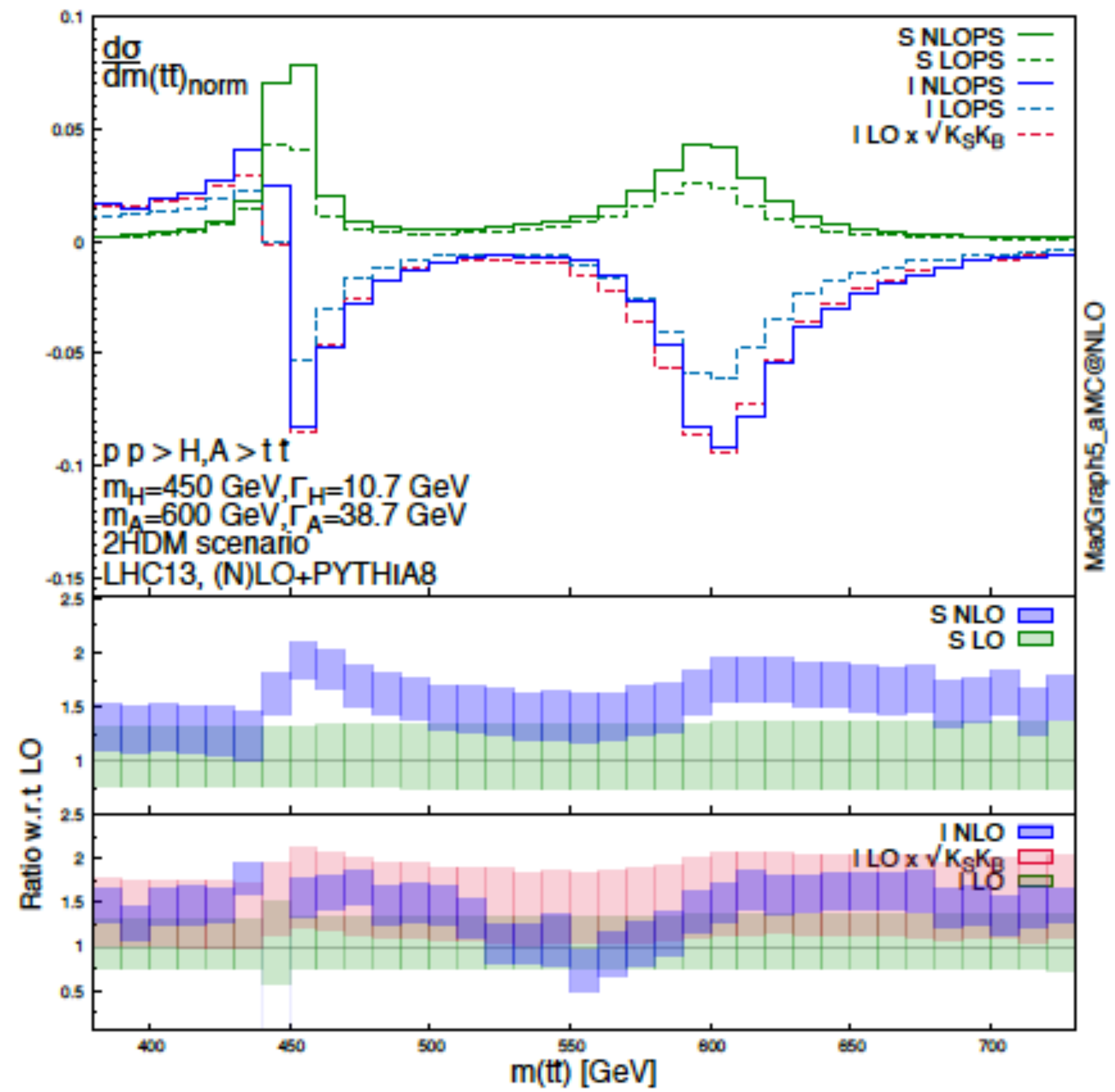
EFT: a good approximation in this case

Dominated by VLQ loop

Franzosi, EV, Zhang arXiv:1707.06760

More examples for top resonances





Franzosi, EV, Zhang arXiv:1707.06760

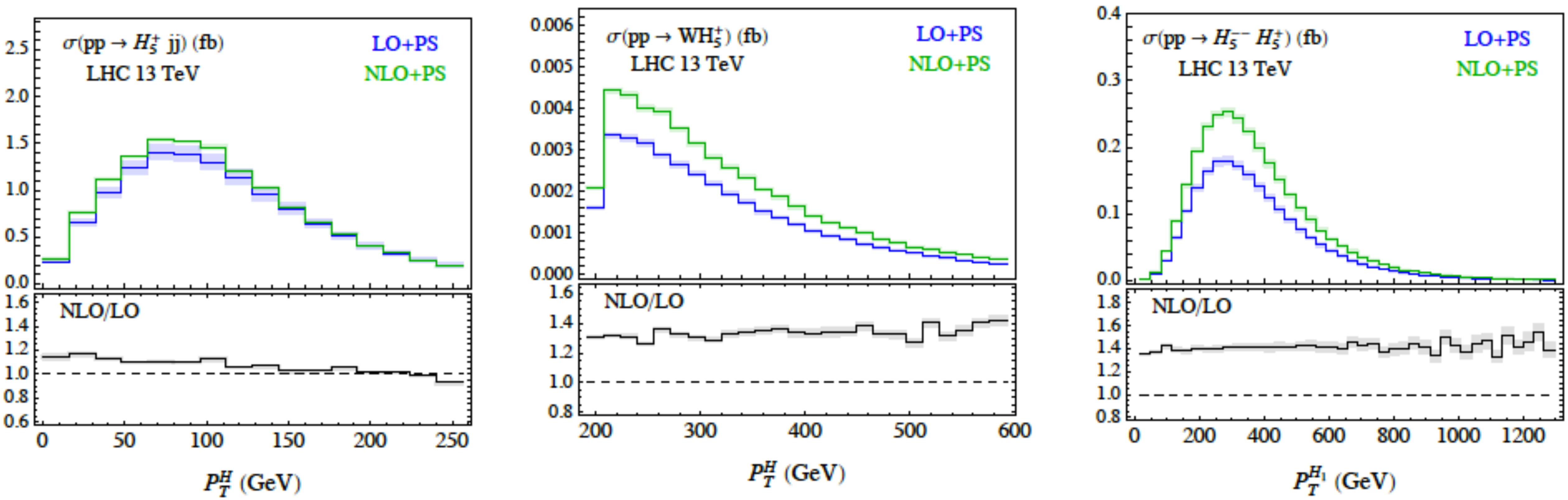
```
mg5> import model AHttbar
mg5>set complex_mass_scheme
mg5>generate p p > t t~ QCD=2 QED=1 EFT=1 [QCD]
mg5>output PROC_pp-tt
```

http://feynrules.irmp.ucl.ac.be/wiki/AHttbarNLO

Georgi-Machacek model phenomenology at NLO

- Two custodial singlets $\rightarrow h^0, H^0$ m_h, m_H
- Custodial triplet $\rightarrow (H_3^+, H_3^0, H_3^-)$ m_3
- Custodial fiveplet $(H_5^{++}, H_5^+, H_5^0, H_5^-, H_5^{--})$ m_5

Heavy Higgs searches




```
> import model GM_UFO
> generate p p > H5p j j $$ w+ w- z [QCD]
> output VBF_h5p_NLO
> launch
```

Degrande et al arXiv:1512.01243

http://feynrules.irmp.ucl.ac.be/wiki/GeorgiMachacekModel

Higgs plus MET in simplified DM models

Simplified DM model with spin-0 or spin-1 mediator

$$\mathcal{L}_{SM}^{Y_0} = \bar{t}\frac{y^t}{\sqrt{2}}(g_t^S + i g_t^P \gamma^5) t\, Y_0$$

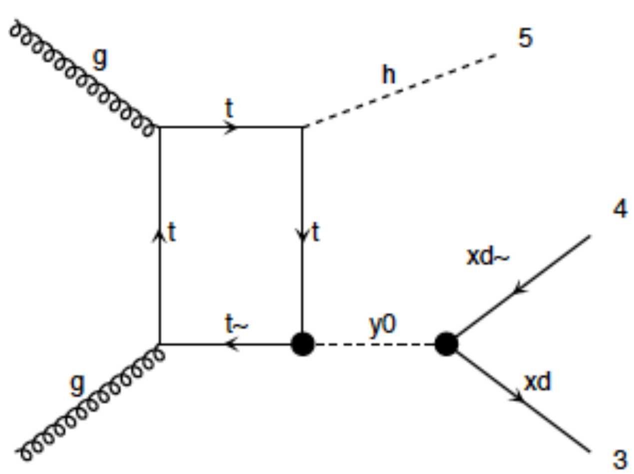
$$\mathcal{L}_{SM}^{Y_1} = \bar{t}\gamma_\mu (g_t^V + g_t^A \gamma^5) t\, Y_1^\mu + \bar{b}\gamma_\mu(-g_t^A \gamma^5) b\, Y_1^\mu$$

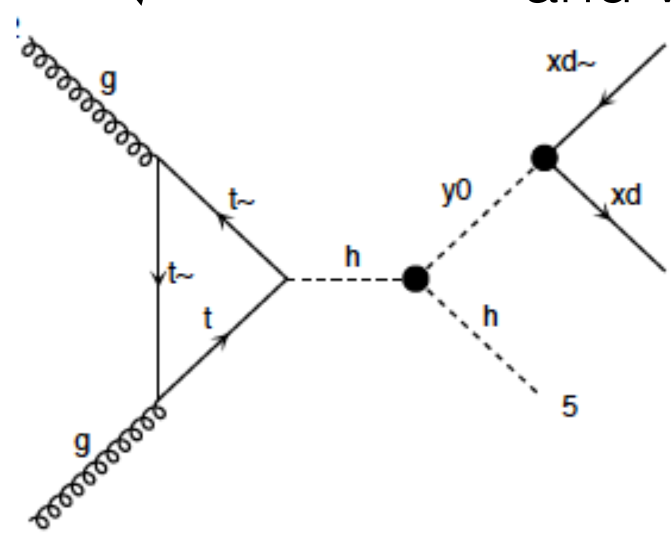
Mediator couples only to the top

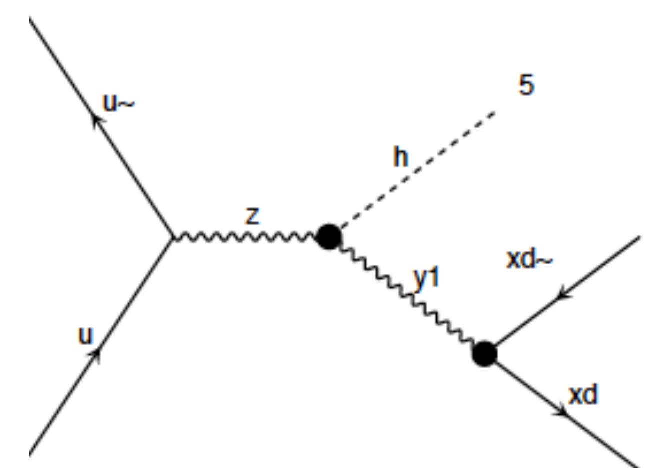
$$\mathcal{L}_{SM\ EW}^{Y_0} = \frac{1}{\Lambda}\Big[g_{h1}^S (D^\mu \phi)^\dagger (D_\mu \phi)\, Y_0 + g_{h2}^S m_H^2 \left(|\phi|^2 - v^2/2\right) Y_0\Big]$$

$$\mathcal{L}_{SM\ EW}^{Y_1} = g_h^V \frac{i}{2}\left(\phi^\dagger D_\mu \phi - D_\mu \phi^\dagger \phi\right) Y_1^\mu$$

Mediator couples also to Higgs and vector bosons







Missing E_T processes:

Loop-Induced or tree-level: mono-Higgs signals

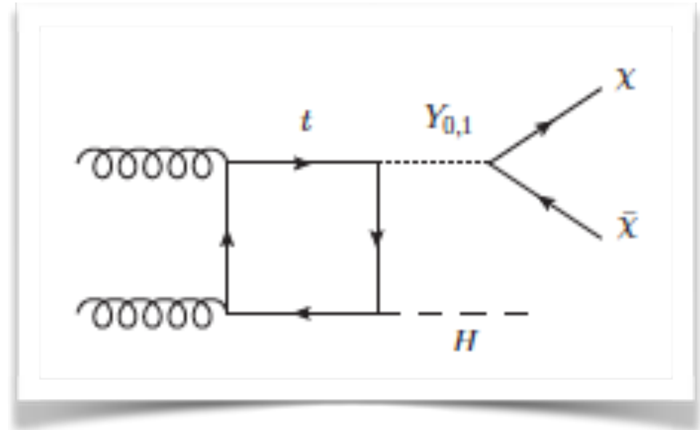
Mono-Higgs studies (1)

Top-Philic model

$$\boxed{\mathcal{L}_{SM}^{Y_0} = \bar{t}\frac{y^t}{\sqrt{2}}(g_t^S + i g_t^P \gamma^5)t\, Y_0}$$

$$\boxed{\mathcal{L}_{SM}^{Y_1} = \bar{t}\gamma_\mu(g_t^V + g_t^A \gamma^5)t\, Y_1^\mu + \bar{b}\gamma_\mu(-g_t^A \gamma^5)b\, Y_1^\mu}$$

Process	S	P	V	A
mono-Z	✓	✓	✓	✓
mono-photon	✗	✗	✓	✗
mono-Higgs	✓	✓	✗	✓

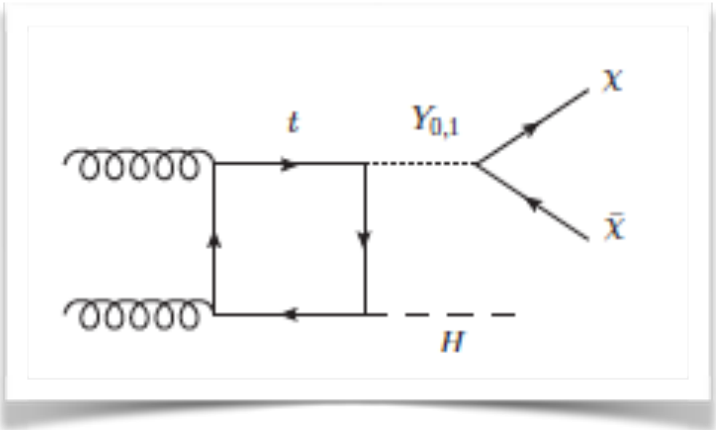


Top-Philic simplified model **Selection Rules**: charge conjugation invariance forbids certain processes

Pheno studies:
Mattelaer, EV arXiv:1508.00564: Mono-X loop-induced processes in top-philic model
M. Backovic et al arXiv:1508.05327: jets+met, top pair+met
Neubert, Wang, Zhang arXiv:1509.05785: mono-Z with EW interactions
Arina et al arXiv:1605.09242: spin-0 top-philic mediator

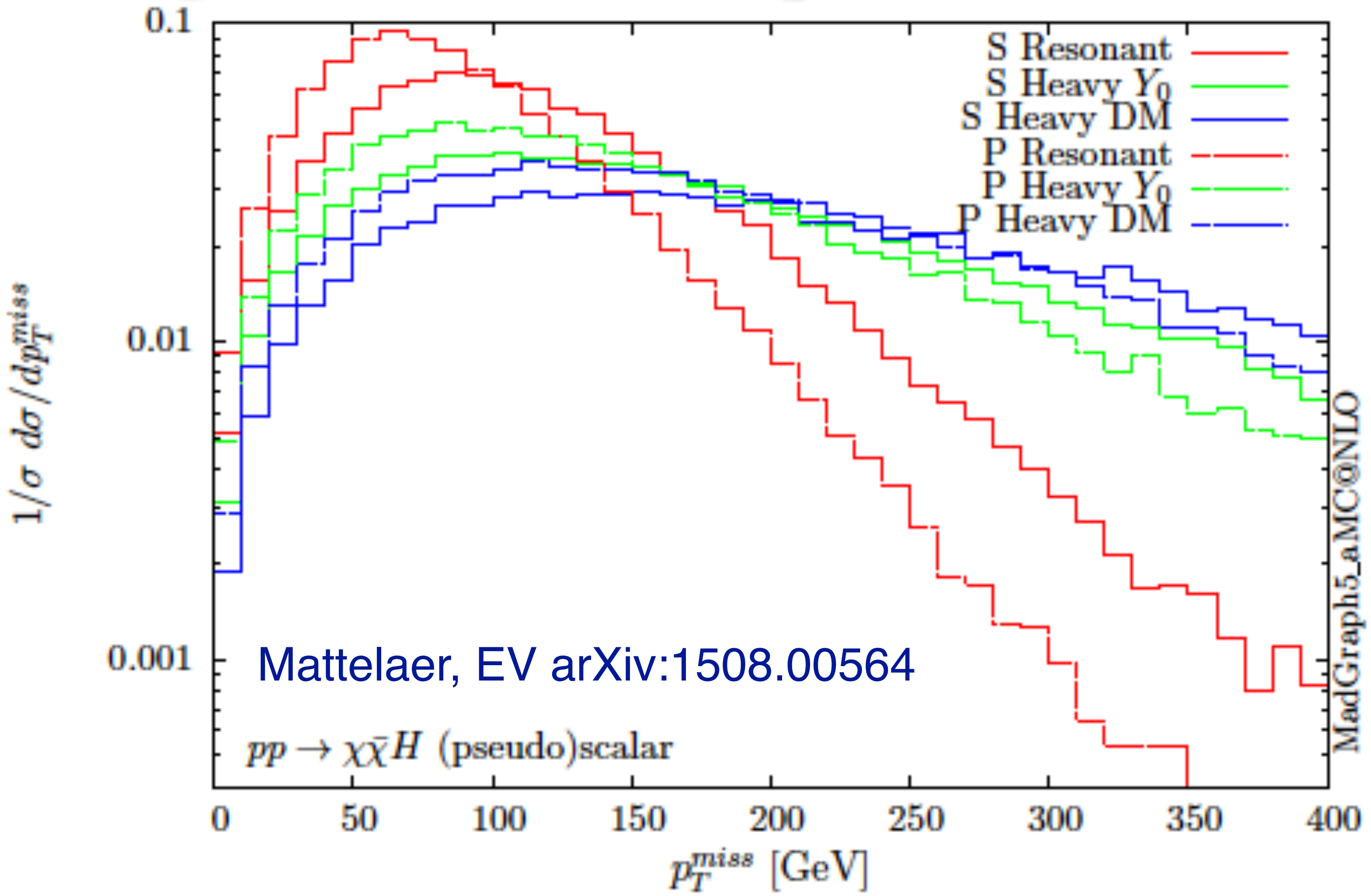
http://feynrules.irmp.ucl.ac.be/wiki/DMsimp

Mono-Higgs studies (2)



Benchmark	scalar	pseudoscalar
Resonant	$6.98 \cdot 10^{-2}\,{}^{+34\%}_{-24\%}\,{}^{+1.0\%}_{-1.2\%}$	$0.139\,{}^{+33\%}_{-23\%}\,{}^{+1.0\%}_{-1.2\%}$
Heavy mediator	$9.31 \cdot 10^{-5}\,{}^{+41\%}_{-27\%}\,{}^{+2.1\%}_{-2.1\%}$	$5.79 \cdot 10^{-5}\,{}^{+40\%}_{-27\%}\,{}^{+1.9\%}_{-1.9\%}$
Heavy DM	$1.28 \cdot 10^{-7}\,{}^{+43\%}_{-28\%}\,{}^{+3.0\%}_{-2.9\%}$	$2.44 \cdot 10^{-7}\,{}^{+42\%}_{-28\%}\,{}^{+2.6\%}_{-2.6\%}$

13TeV
σ in pb



Small cross-sections (similar to SM HH cross-section)

Different shapes for scalar and pseudoscalar mediators

http://feynrules.irmp.ucl.ac.be/wiki/DMsimp

Towards NLO+PS for SMEFT

$$\mathcal{L}_{\text{Eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})$$

Recent progress in automated NLO+PS:

Higgs:

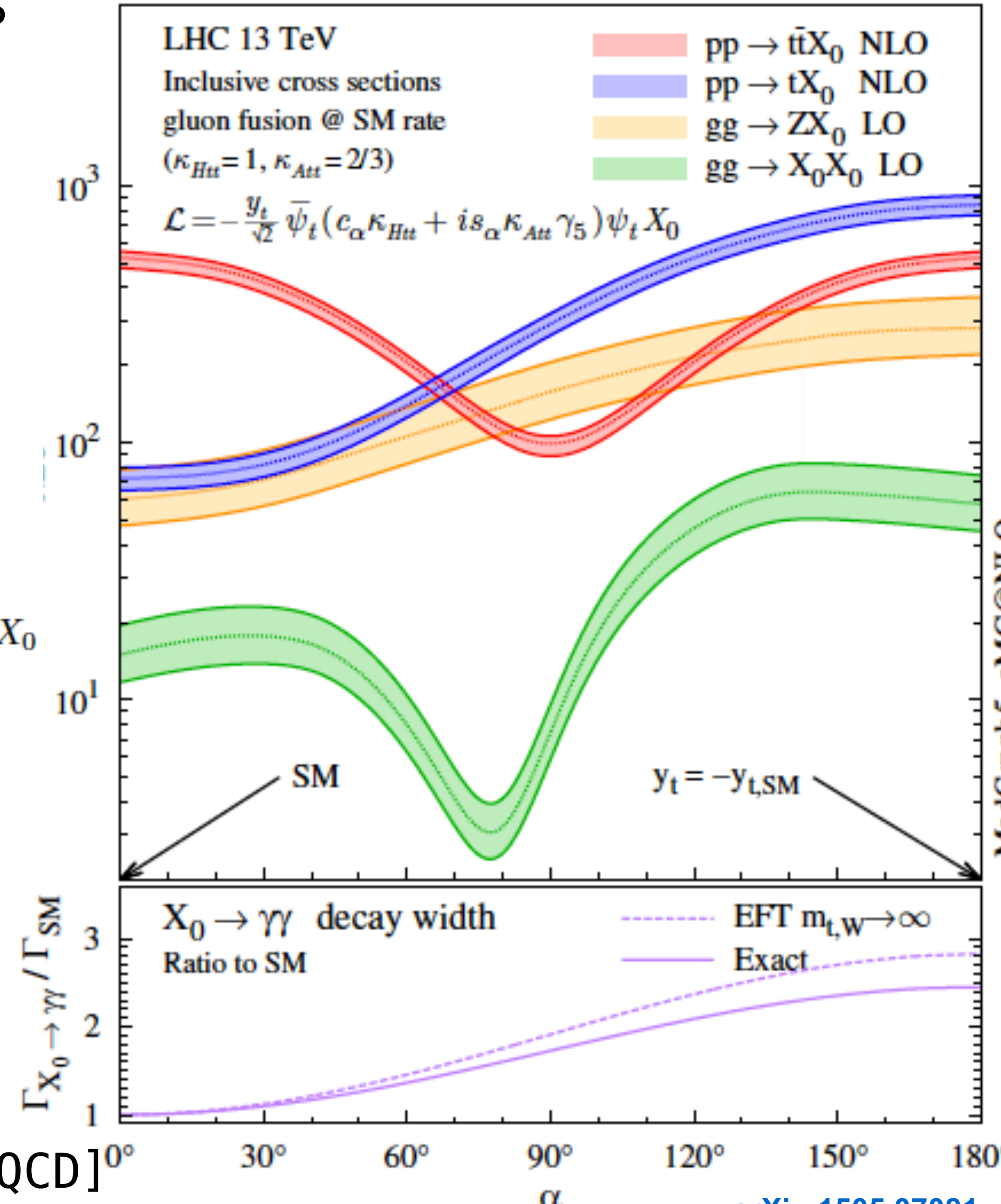
- Higgs characterisation arXiv:1306.6464
  - VBF, VH Maltoni et al arXiv:1311.1829
  - ttH Demartin et al arXiv:1407.5089, tH Demartin et al arXiv:1504.00611, tWH Demartin et al arXiv:1607.05862
- HELatNLO Degrande et al: arXiv:1609.04833
  - EW Higgs production
- Higgs production in gluon fusion Deutschmann, Duhr, Maltoni, EV (arXiv:1708.00460)
- ttH: F. Maltoni, EV, C. Zhang (arXiv:1607.05330)
- tHj: Degrande,Maltoni, Mimasu, EV, Zhang arXiv:1804.07773

Higgs characterisation

Higgs characterisation: CP properties

$$\mathcal{L}_0^V = \Big\{ c_\alpha \kappa_{\rm SM} \big[\tfrac{1}{2} g_{HZZ}\, Z_\mu Z^\mu + g_{HWW}\, W^+_\mu W^{-\mu}\big]$$
$$- \frac{1}{4}\big[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma}\, A_{\mu\nu}A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma}\, A_{\mu\nu}\widetilde{A}^{\mu\nu}\big]$$
$$- \frac{1}{2}\big[c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma}\, Z_{\mu\nu}A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma}\, Z_{\mu\nu}\widetilde{A}^{\mu\nu}\big]$$
$$- \frac{1}{4}\big[c_\alpha \kappa_{Hgg} g_{Hgg}\, G^a_{\mu\nu}G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg}\, G^a_{\mu\nu}\widetilde{G}^{a,\mu\nu}\big]$$
$$- \frac{1}{4}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HZZ}\, Z_{\mu\nu}Z^{\mu\nu} + s_\alpha \kappa_{AZZ}\, Z_{\mu\nu}\widetilde{Z}^{\mu\nu}\big]$$
$$- \frac{1}{2}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HWW}\, W^+_{\mu\nu}W^{-\mu\nu} + s_\alpha \kappa_{AWW}\, W^+_{\mu\nu}\widetilde{W}^{-\mu\nu}\big]$$
$$- \frac{1}{\Lambda} c_\alpha \big[\kappa_{H\partial\gamma}\, Z_\nu \partial_\mu A^{\mu\nu} + \kappa_{H\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} + \big(\kappa_{H\partial W}\, W^+_\nu \partial_\mu W^{-\mu\nu} + h.c.\big)\big]\Big\} X_0$$

$$\mathcal{L}_0^f = - \sum_{f=t,b,\tau} \bar\psi_f \big(c_\alpha \kappa_{Hff} g_{Hff} + i s_\alpha \kappa_{Aff} g_{Aff}\, \gamma_5\big)\psi_f X_0$$



arXiv:1505.07081

NLO+PS for Higgs production

Sample usage:

```
./bin/mg5_aMC
 > import model HC_NLO_X0
 > generate p p > x0 j j $$ w+ w- z QCD=0 [QCD]
 > output
 > launch
```

http://feynrules.irmp.ucl.ac.be/wiki/HiggsCharacterisation

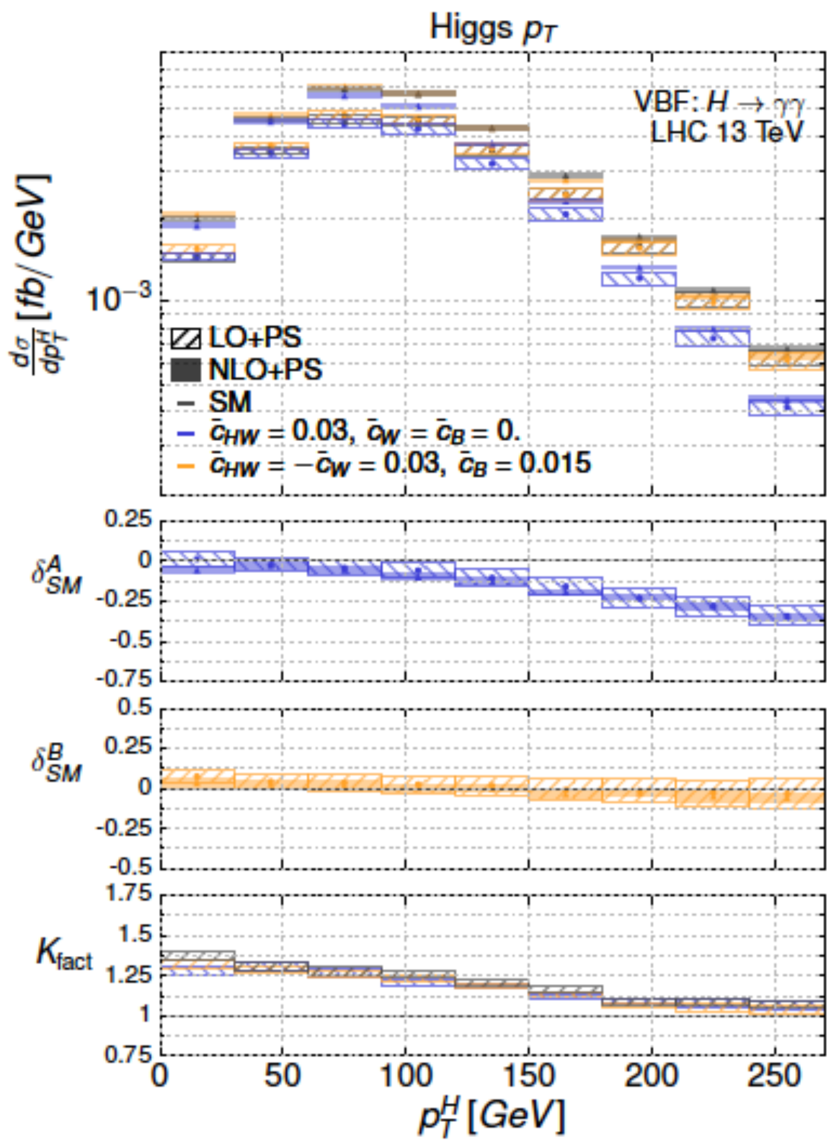
Higgs production in the SMEFT

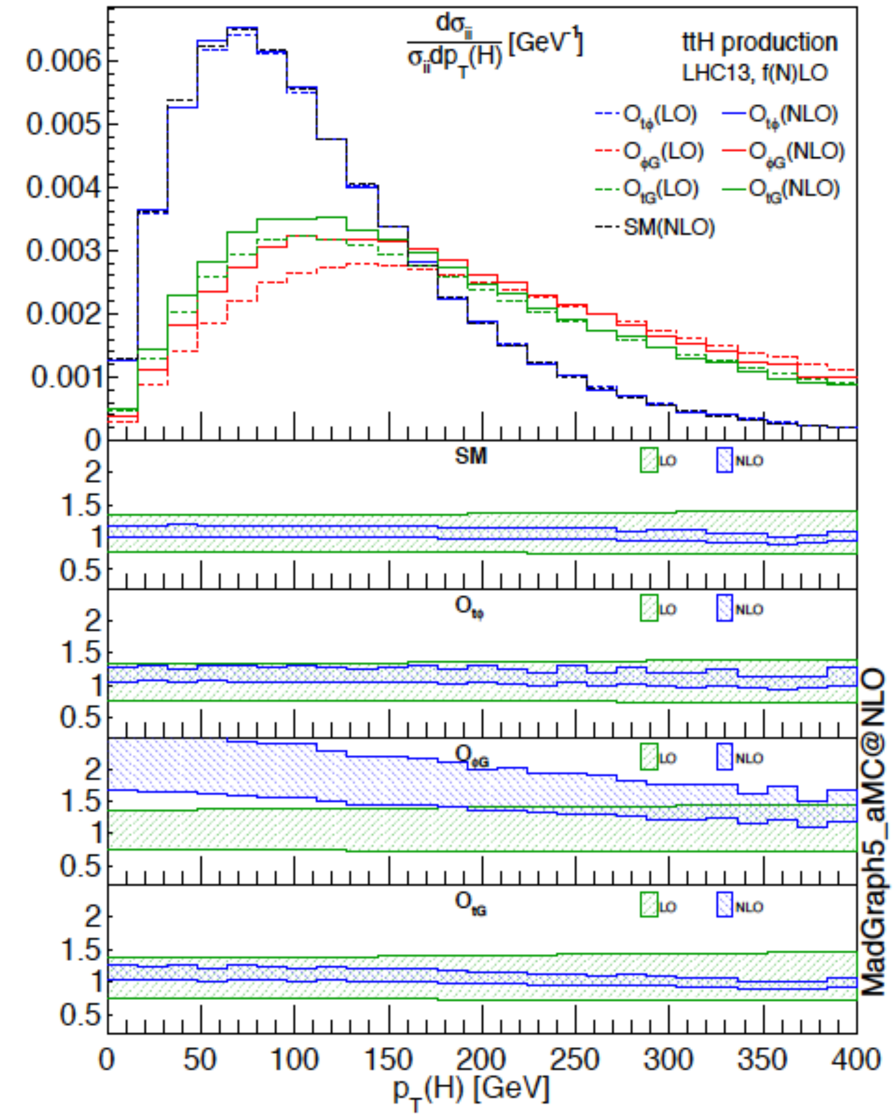
SILH operators:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{g'^2}{4\Lambda^2}\bar{c}_{BB}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu}$$
$$+ \frac{ig}{2\Lambda^2}\bar{c}_W\left[\Phi^\dagger T_{2k}\overleftrightarrow{D}_\mu\Phi\right]D_\nu W^{k,\mu\nu}$$
$$+ \frac{ig'}{2\Lambda^2}\bar{c}_B\left[\Phi^\dagger\overleftrightarrow{D}_\mu\Phi\right]\partial_\nu B^{\mu\nu}$$
$$+ \frac{ig}{\Lambda^2}\bar{c}_{HW}\left[D_\mu\Phi^\dagger T_{2k}D_\nu\Phi\right]W^{k,\mu\nu}$$
$$+ \frac{ig'}{\Lambda^2}\bar{c}_{HB}\left[D_\mu\Phi^\dagger D_\nu\Phi\right]B^{\mu\nu}\ .$$

Warsaw operators:

$$O_{t\phi} = y_t^3\left(\phi^\dagger\phi\right)\left(\bar{Q}t\right)\tilde{\phi}$$
$$O_{\phi G} = y_t^2\left(\phi^\dagger\phi\right)G^A_{\mu\nu}G^{A\mu\nu}$$
$$O_{tG} = y_t g_s(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\phi}G^A_{\mu\nu}$$





Degrande et al: arXiv:1609.04833 Maltoni, EV, Zhang: arXiv:1607.05330

http://feynrules.irmp.ucl.ac.be/wiki/HELatNLO

```
./bin/mg5_aMC
import model HELatNLO
generate p p > h j j $$ w+ w- z a  QCD=0 [QCD]
output VBFEFT
```

UFO available from authors

```
MG5_aMC>import model TEFT
MG5_aMC>generate p p > t t~ H EFT=1 [QCD]
MG5_aMC>output
MG5_aMC>launch
```

Summary

- Improved Monte Carlo tools: towards reaching SM precision and automation for BSM scenarios
- FeynRules/NLOCT/Monte Carlo generator chain automated - Plethora of physics processes can be studied at a precise fully differential level
- Better description of QCD effects for BSM Higgs, also for SMEFT