Loop-Induced Processes: Status in MG5_aMC@NLO

Eleni Vryonidou
Centre for Cosmology, Particle Physics and Phenomenology
Université catholique de Louvain

ERC Miniworkshop
CERN
4/7/16

Outline

- Status of Loop-Induced processes in MG5_aMC
- Physics applications
- Future directions

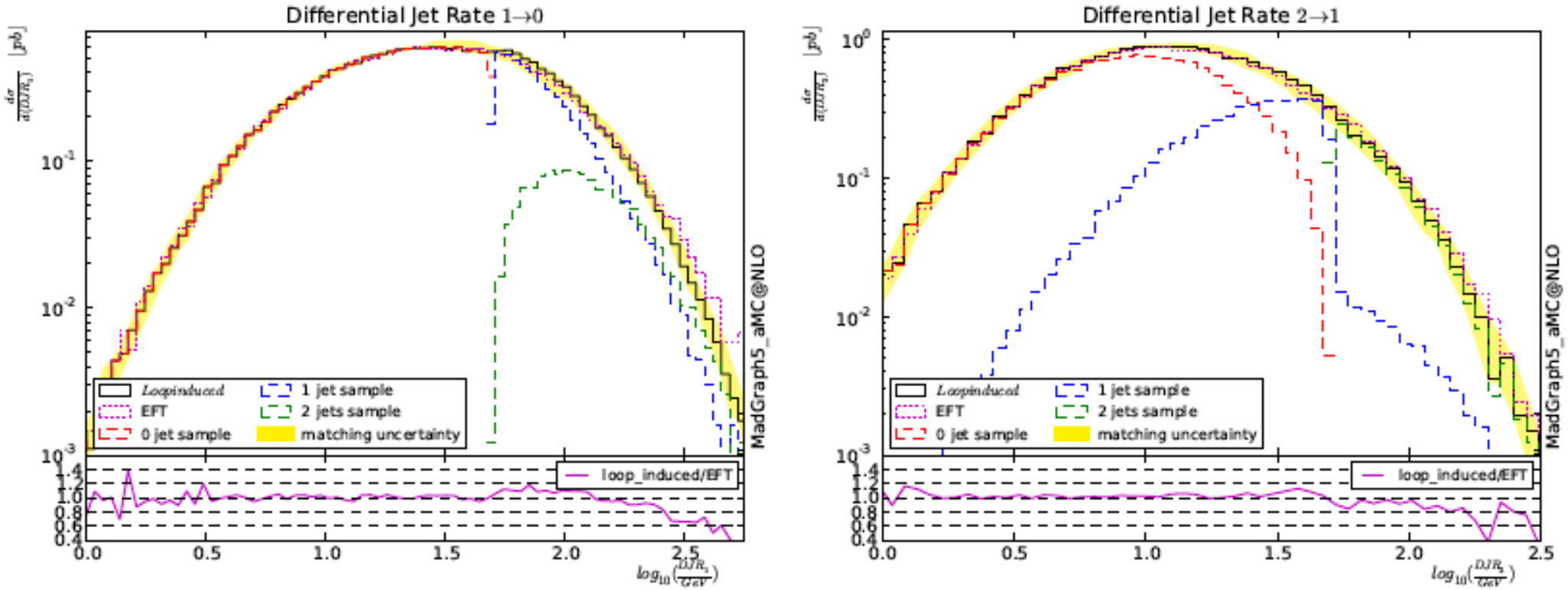
Automation of event generation

Hirschi and Mattelaer: arXiv:1507.00020
Part of the official release since 2.3

Process		Syntax	Cross section (pb) $\sqrt{s} = 13$ TeV	$\Delta_{\hat{\mu}}$	Δ_{PDF}	Ref.
Triple bosons						
*c.1	$pp \to HHH$	`p p > h h h [QCD]`	$3.968 \pm 0.010 \cdot 10^{-5}$	$^{+31.8\%}_{-22.6\%}$	$^{+1.4\%}_{-1.4\%}$	[59]
†c.2	$gg \to HHZ$	`g g > h h z [QCD]`	$5.260 \pm 0.009 \cdot 10^{-5}$	$^{+31.2\%}_{-22.2\%}$	$^{+1.3\%}_{-1.3\%}$	[–]
†c.3	$gg \to HZZ$	`g g > h z z [QCD]`	$1.144 \pm 0.004 \cdot 10^{-4}$	$^{+31.1\%}_{-22.2\%}$	$^{+1.2\%}_{-1.3\%}$	[–]
†c.4	$gg \to HZ\gamma$	`g g > h z a [QCD]`	$6.190 \pm 0.020 \cdot 10^{-6}$	$^{+29.3\%}_{-21.2\%}$	$^{+1.0\%}_{-1.2\%}$	[–]
†c.5	$pp \to H\gamma\gamma$	`p p > h a a [QCD]`	$6.058 \pm 0.004 \cdot 10^{-6}$	$^{+30.3\%}_{-21.8\%}$	$^{+1.1\%}_{-1.3\%}$	[–]
*c.6	$gg \to HW^+W^-$	`g g > h w+ w- [QCD]`	$2.670 \pm 0.007 \cdot 10^{-4}$	$^{+31.0\%}_{-22.2\%}$	$^{+1.2\%}_{-1.3\%}$	[60]
†c.7	$gg \to ZZZ$	`g g > z z z [QCD]`	$6.964 \pm 0.009 \cdot 10^{-5}$	$^{+30.9\%}_{-22.1\%}$	$^{+1.2\%}_{-1.3\%}$	[–]
†c.8	$gg \to ZZ\gamma$	`g g > z z a [QCD]`	$3.454 \pm 0.010 \cdot 10^{-6}$	$^{+28.7\%}_{-20.9\%}$	$^{+0.9\%}_{-1.1\%}$	[–]
*c.9	$gg \to Z\gamma\gamma$	`g g > z a a [QCD]`	$3.079 \pm 0.005 \cdot 10^{-4}$	$^{+28.0\%}_{-20.9\%}$	$^{+0.7\%}_{-1.0\%}$	[61]
†c.10	$gg \to ZW^+W^-$	`g g > z w+ w- [QCD]`	$8.595 \pm 0.020 \cdot 10^{-3}$	$^{+26.9\%}_{-19.5\%}$	$^{+0.6\%}_{-0.6\%}$	[–]
†c.12	$gg \to \gamma W^+W^-$	`g g > a w+ w- [QCD]`	$1.822 \pm 0.005 \cdot 10^{-2}$	$^{+28.7\%}_{-20.9\%}$	$^{+0.9\%}_{-1.1\%}$	[–]

\+ A lot more examples
\+ Up to 2⟶4

Merging-Matching at LO



H+jets arXiv:1507.00020

Automated for MLM-merging with PYTHIA6

(PYTHIA8 merging also possible but not automated)

NLO-status

- NLO+PS event generation not automated for loop-induced
- Direct integration of loop matrix elements: aMCSusHi for single Higgs
- NLO reweighting applied to several cases: HH, H+jets, H > tt (through customised code adjustments - 2-loop amplitudes approximated or external codes)
- NLO reweighting automation (work by Olivier):
  - Start with NLO+PS event generation
  - Generate new amplitudes through a reweight card
  - Different weights stored in the event file

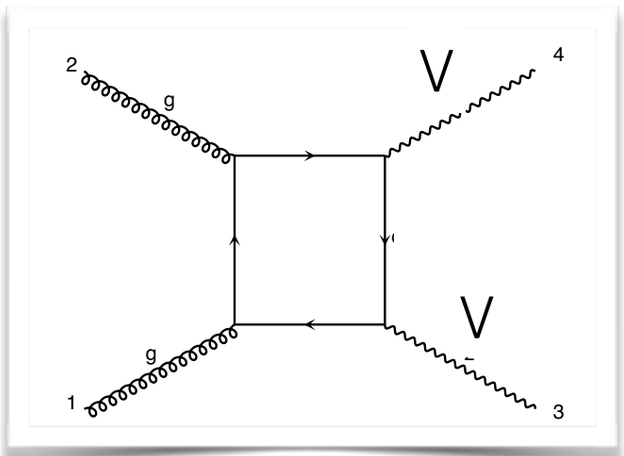
Physics applications

- Higgs studies
  - Off-shell -Interference effects in gg > VV
  - Higgs+Jets with FxFx
- Dark Matter
- EFT in loop-induced processes

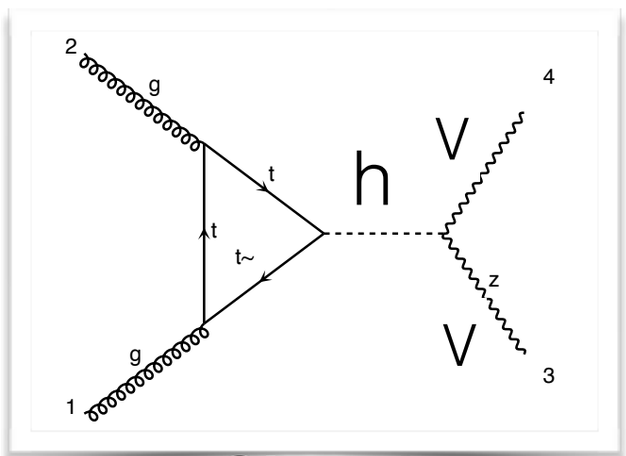
Physics applications

- Higgs studies
  - Off-shell -Interference effects in gg > VV
  - Higgs+Jets with FxFx
- Dark Matter
- EFT in loop-induced processes

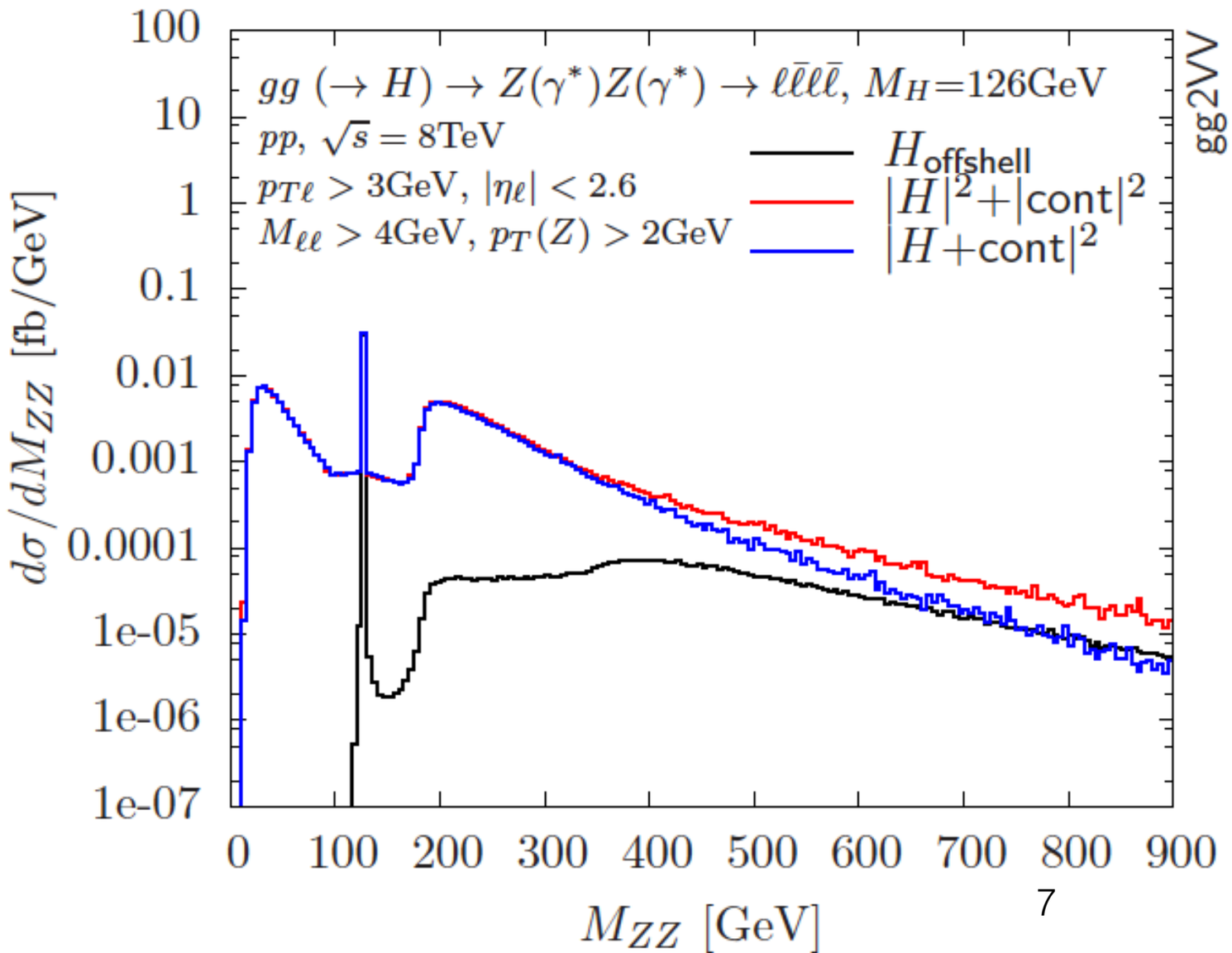
Off-shell and interference effects in gg(>H)>VV



Background



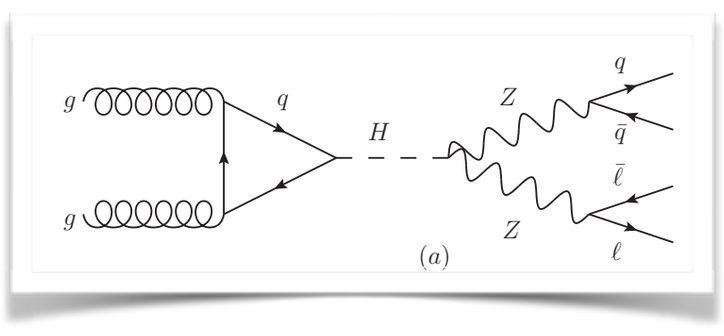
Signal

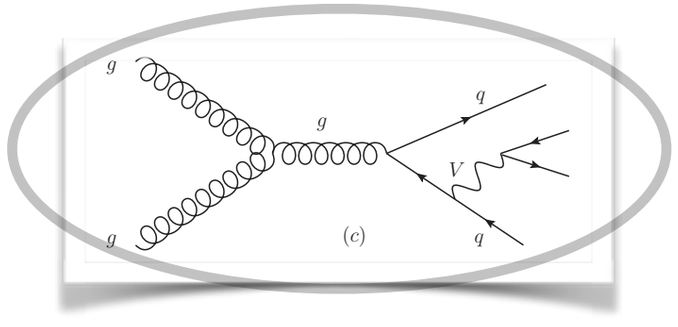


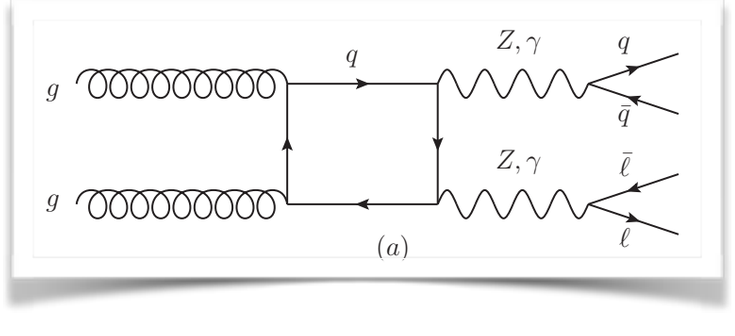
Significant off-shell contribution
Interference: important for M_{VV}>350GeV
destructive

gg2VV, N. Kauer et al.

Semileptonic decay modes







A new background

$gg \to H \to ZZ \to \ell\bar{\ell}q_u\bar{q}_u$ σ [fb], pp, $\sqrt{s} = 13$ TeV			interference			ratio		
M_H [GeV]	cuts	S	I_{tree}	I_{loop}	I_{full}	R_{tree}	R_{loop}	R_{full}
125.5	min.	4.79(4)	-0.45(3)	-1.088(2)	-1.54(3)	0.91(2)	0.773(9)	0.68(1)
125.5	LHC	0.375(2)	0.063(7)	-0.612(1)	-0.552(6)	1.17(2)	-0.633(6)	-0.47(2)
400	bkg.	4.043(4)	-0.0027(3)	-0.3569(9)	-0.359(3)	0.999(2)	0.912(2)	0.911(2)

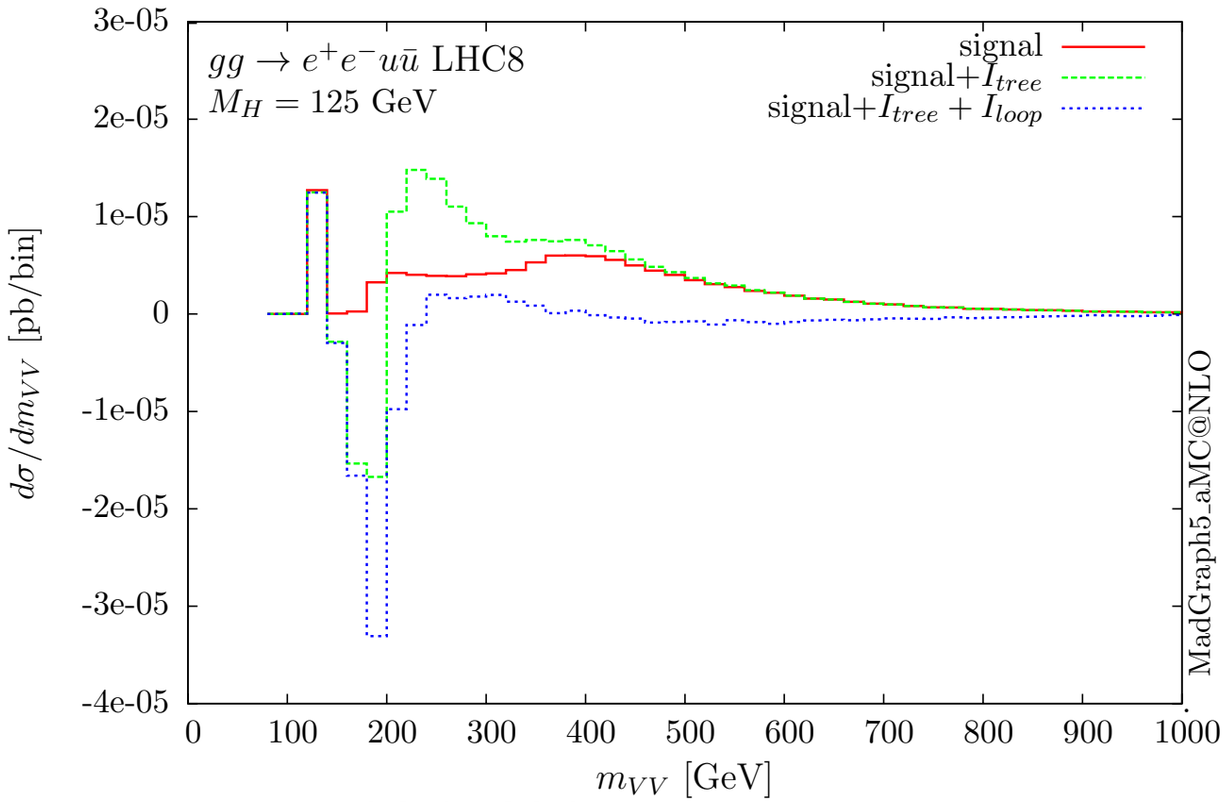
N. Kauer, C. O'Brien, EV
arXiv:1506.01694
Computed with gg2VV and MG5@MC

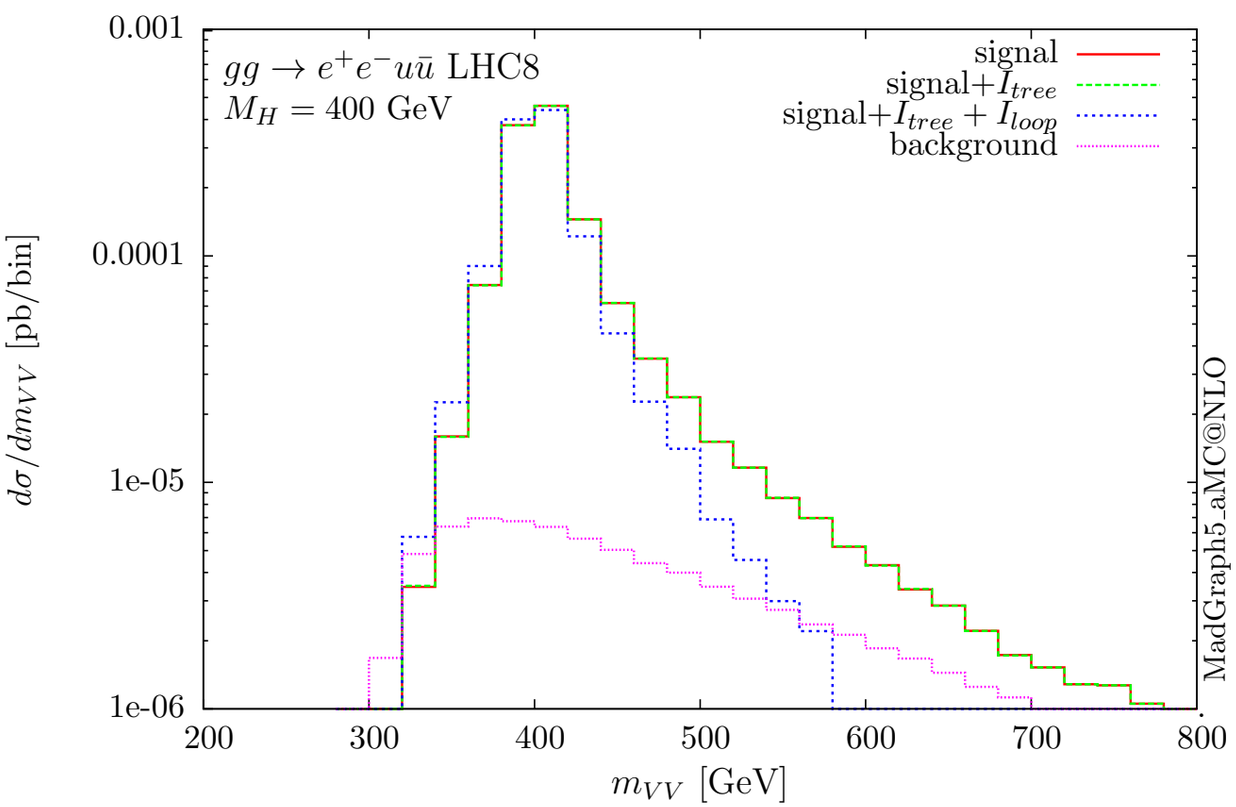
Tree and loop interference contributions depend on the selection cuts

Loop interference always more important

Semileptonic decay modes

- Comparison with implementation in **gg2VV** for a SM (125GeV) Higgs and a heavy (400GeV) Higgs for different selection cuts





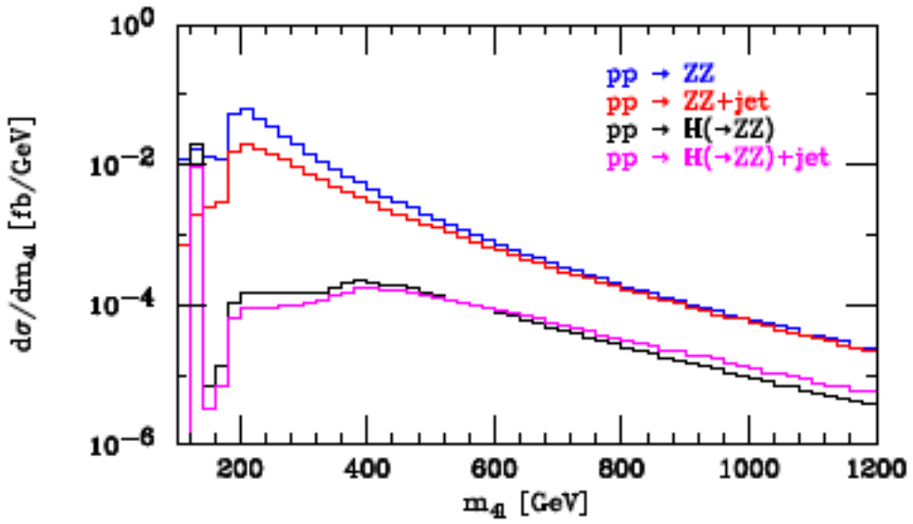
arXiv:1506.01694

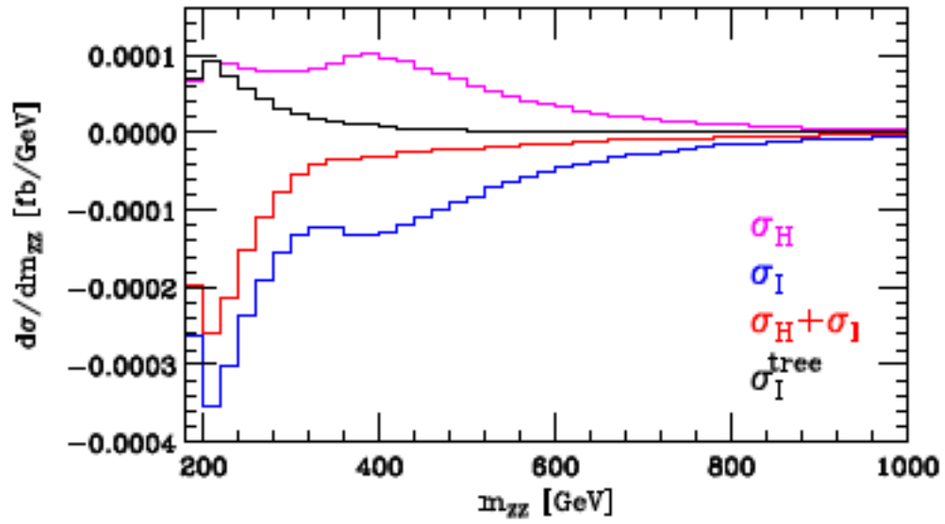
$$\mathcal{M}_{background} = \mathcal{M}_{tree} + \mathcal{M}_{loop}$$

$$\mathcal{O}(g_s^2 e^2) \quad \mathcal{O}(g_s^2 e^4)$$

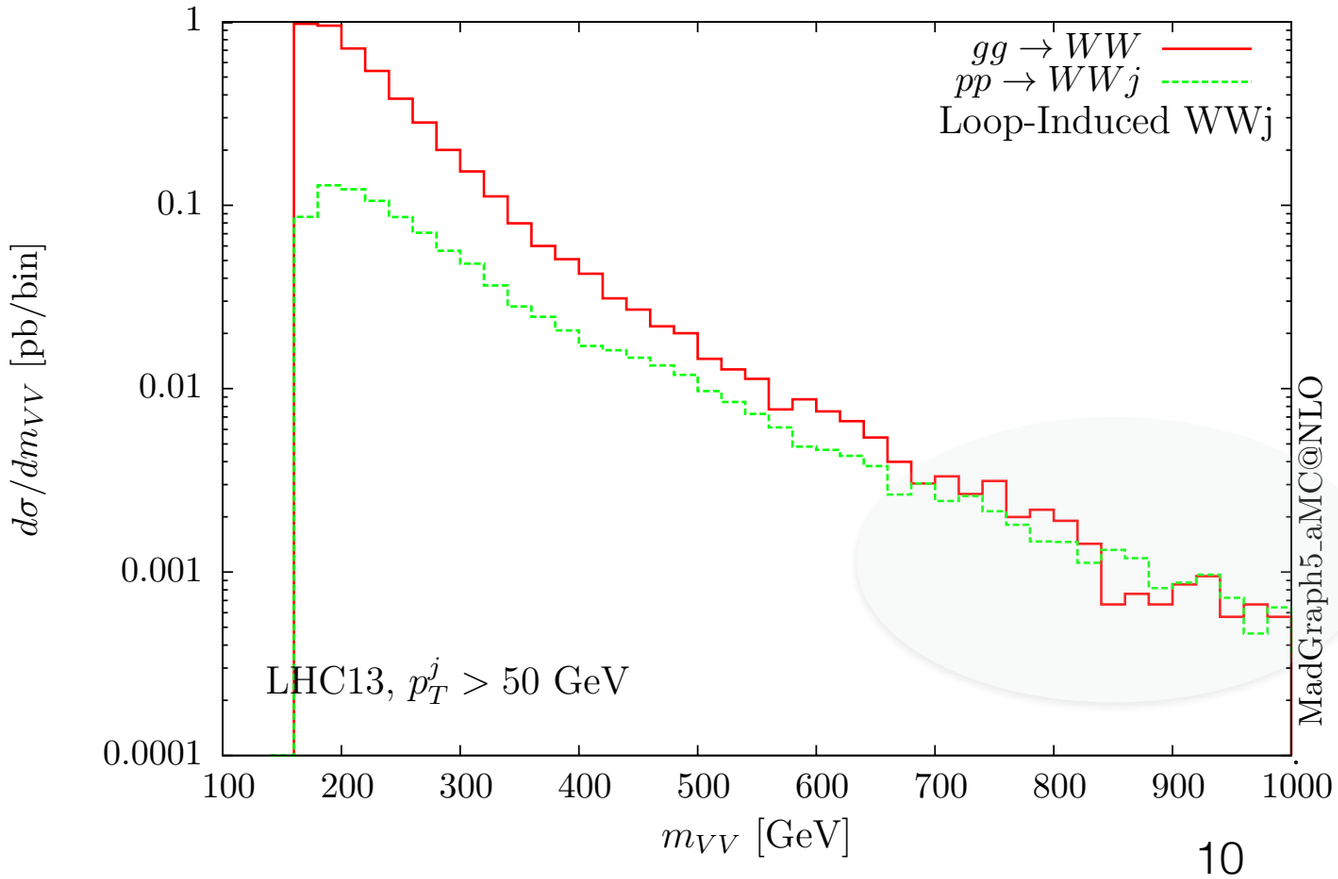
Formally Higher-order background is more important

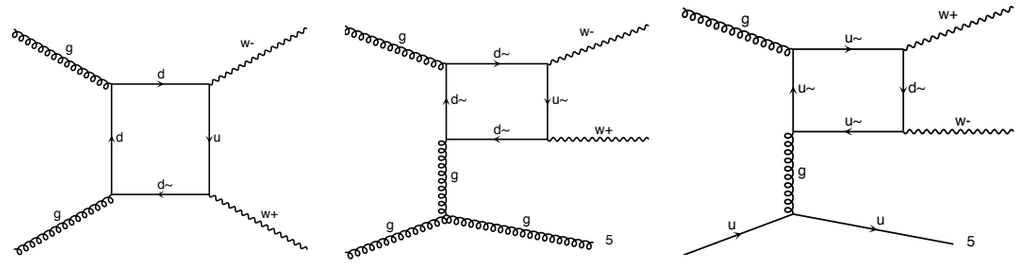
Additional QCD jets in loop-induced VV





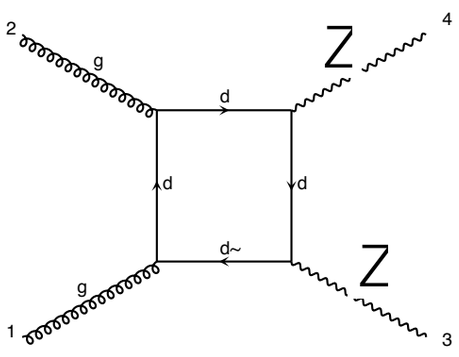
Campbell, Ellis, Furlan, Rontsch: arXiv:1409.1897

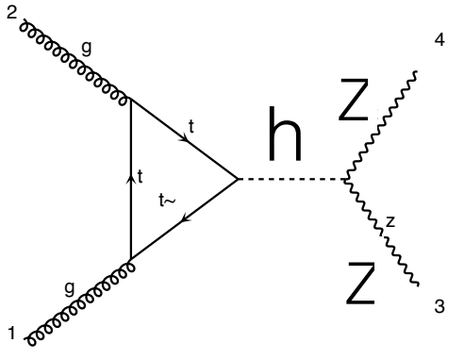


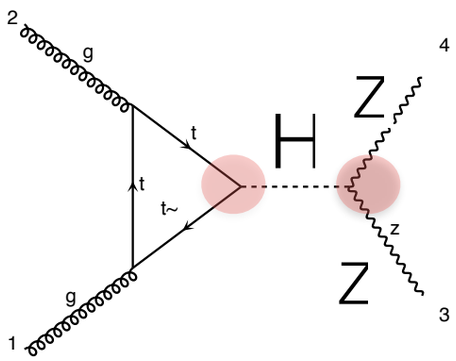


Additional jet contribution important at large m_{VV}
Merging also possible

Heavy Higgs-light Higgs-continuum







Free parameters

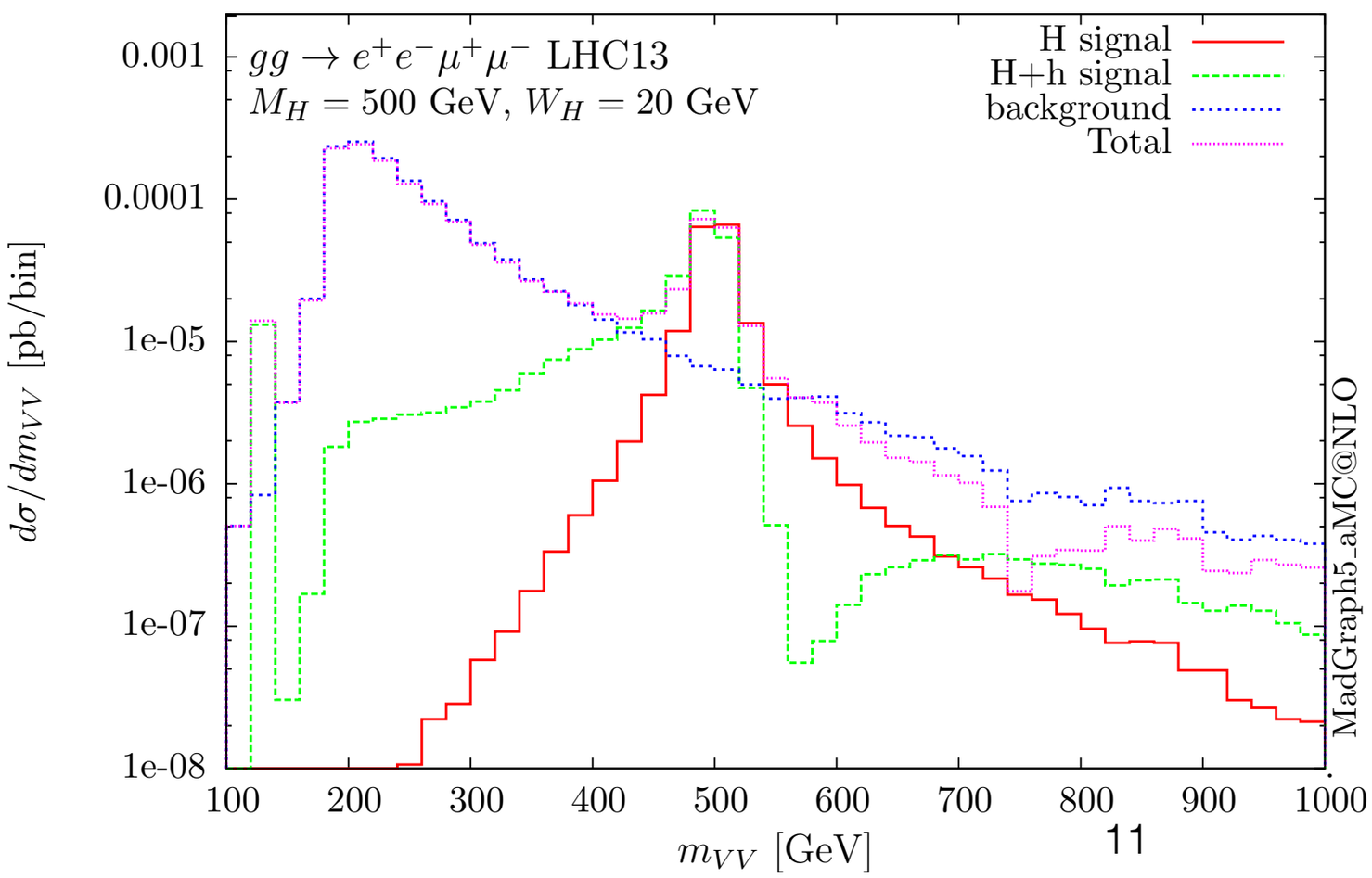
M_H

W_H

$Y_{t,b}$

$g_{w/Z}$

Parameters can be matched to one's favourite model



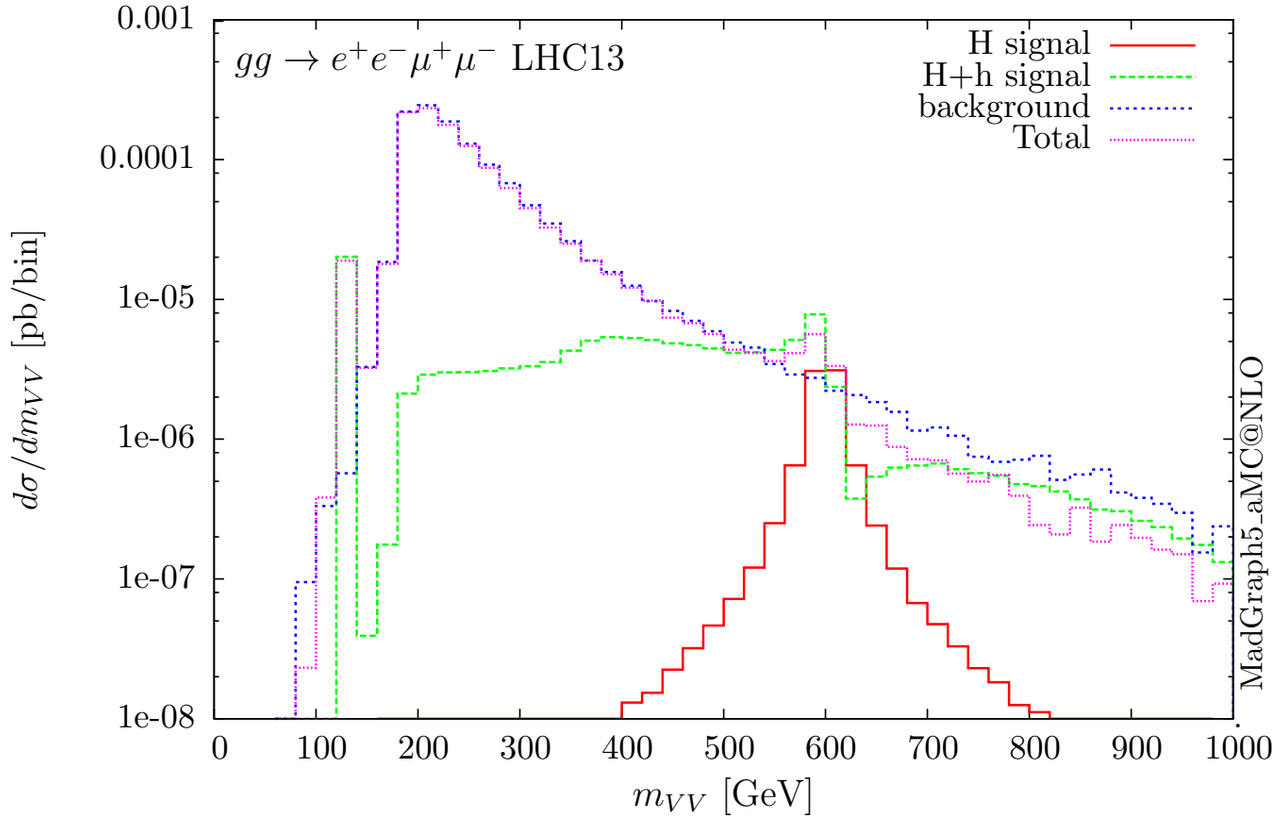
Signal+background +interference

All loop-induced contributions can be generated separately

A 2HDM example

NLO 2HDM model available through NLOCT [Degrande arxiv:1406.3030]

2HDM Benchmarks can be imported in MG5_aMC@NLO



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

Non-excluded scenario

See also Greiner, Liebler and Weiglein arxiv:1512.07232

Physics applications

- SM Higgs studies
  - Off-shell -Interference effects in gg > VV
  - Higgs+Jets with FxFx
- Dark Matter
- EFT in loop-induced processes

Physics applications

- SM Higgs studies
  - Off-shell -Interference effects in gg > VV
  - Higgs+Jets with FxFx
- Dark Matter
- EFT in loop-induced processes

Higgs plus jets at NLO

- H+0jet contribution computed exactly at NLO and matched to the parton shower with aMCSushi (arxiv:1504.06625)
- H+1,2… jets available at NLO in the HEFT (HC model: arxiv:1306.6464)
- Merging possible at NLO in MG5_aMC@NLO with FxFx (arxiv:1209.6215)
- Possibility to compute 1-loop amplitudes for H+1,2,3 jets with MadLoop

Combine 1) the exact 0j NLO result: top and bottom included (aMCSusHi)
2) higher multiplicities at NLO in HEFT

Include the **exact top mass dependence in the real corrections** of H+1,2 jets
2-loop amplitudes only available for H+0j:
Born-normalised HEFT virtual corrections for all higher multiplicities

(similar to what we did for HH arxiv:1408.6542,1407.0281,1401.7340)

Technical details (1)

Reweighting currently the only viable option:
i.e. generate all the events in HEFT and adjust weights afterwards

- Use weights stored internally for scale and pdf reweighting

- New intermediate event format in version 2.3 allows easier identification of various weights:

$$d\sigma^{(\mathbb{H})} = d\phi_{n+1}\left(\mathcal{R} - \mathcal{C}_{MC}\right),$$
$$d\sigma^{(\mathbb{S})} = d\phi_{n+1}\left[\left(\mathcal{B} + \mathcal{V} + \mathcal{C}^{int}\right)\frac{d\phi_n}{d\phi_{n+1}} + \left(\mathcal{C}_{MC} - \mathcal{C}\right)\right]$$

MC@NLO formalism

i.e. Born, real, virtual, counterterms

$$\begin{aligned} \mathcal{B}, \mathcal{V}, \mathcal{C}^{(int)}, \mathcal{C}_{MC} &\times \mathcal{B}_{FT}/\mathcal{B}_{HEFT} \\ \mathcal{R} &\times \mathcal{R}_{FT}/\mathcal{R}_{HEFT} \end{aligned}$$

→ **New event weight**

NLO reweighting automated by Olivier (upcoming paper)

Technical details (2)

1) Loop Amplitude library

Provides results for all 1-loop matrix elements (Born and real)

- Created and compiled beforehand using a script
- Input: all the processes (in PDG codes) that will be needed for H+1,2,3 jets
- Similar to the usual MadLoop standalone output but now all combined in a dynamic library (only tops in the loops)
- Library wrapper takes PDG codes as inputs, checks for permutations of PDG codes/ momenta to call the right amplitude

2) 0-jet contribution

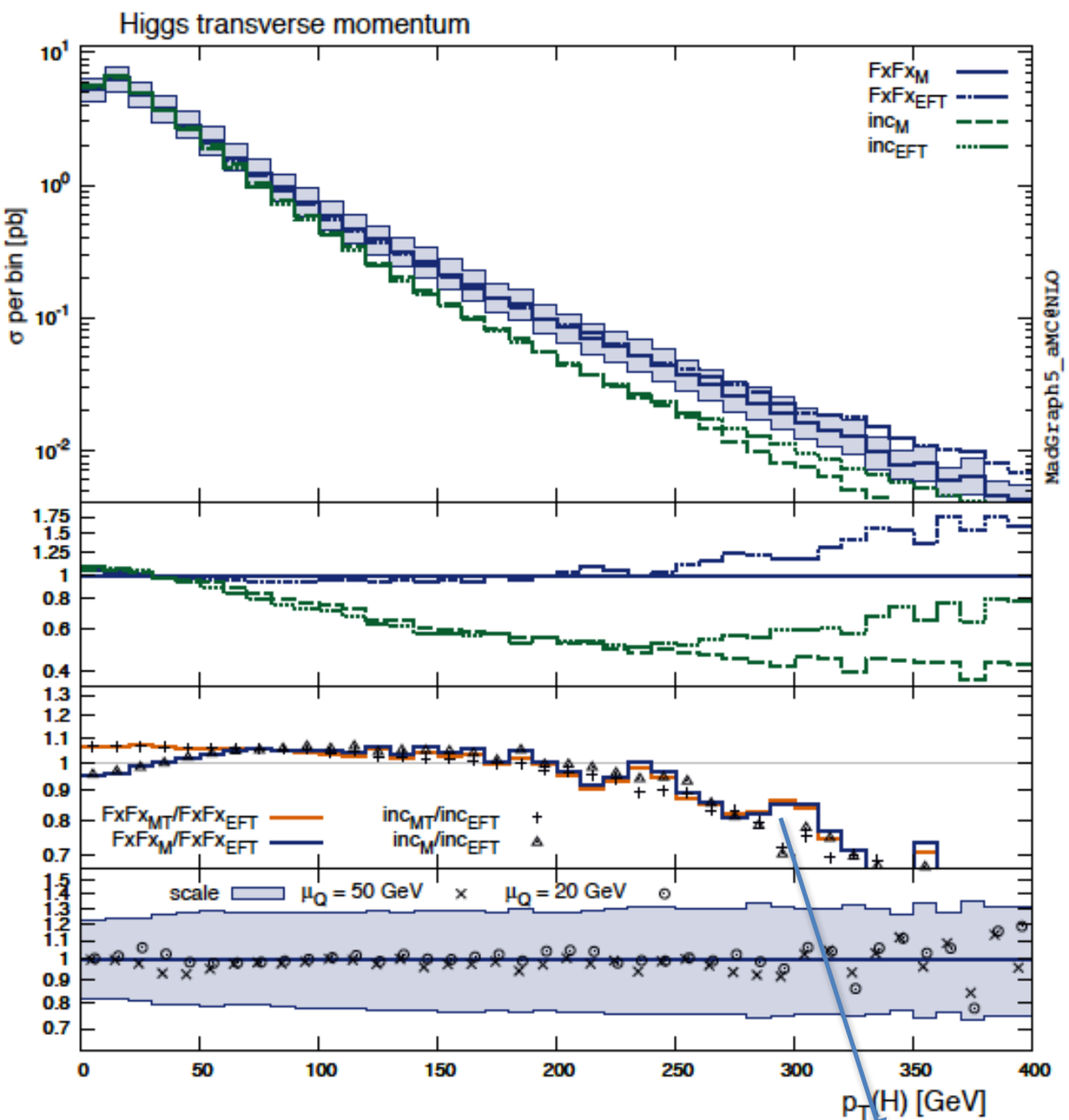
- Not reweighted, obtained by linking the exact matrix elements (1-loop and 2-loop) from aMCSusHi
- Top x bottom contribution and bottom^2 included
- Events generated separately, showered with the appropriate/different scales (1409.0531)
- Results added at the end at the plot level

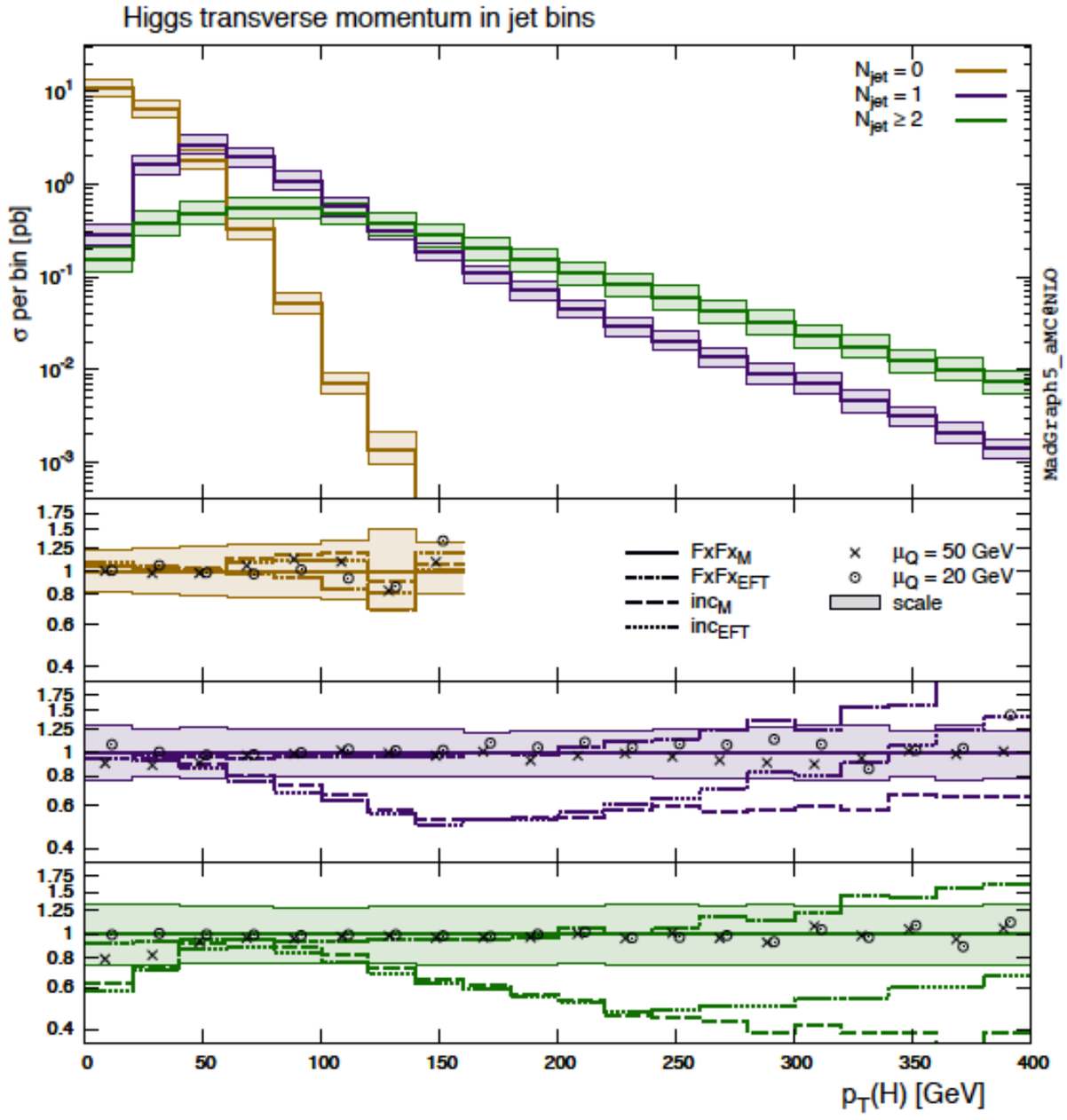
Results can be compared with inclusive NLO results

Merging scale dependence also studied

Frederix, Frixione, EV, Wiesemann arXiv:1604.03017

Results for H+jets





High p_T tail top mass effect

Merged results harder than inclusive one in the tails

Merging scale uncertainty always within the hard scale ($\mu_{R,F}$) variations

Physics applications

- SM Higgs studies
  - Off-shell -Interference effects in gg > VV
  - Higgs+Jets with FxFx
- Dark Matter at the LHC
- EFT in loop-induced processes

Physics applications

- SM Higgs studies
  - Off-shell -Interference effects in gg > VV
  - Higgs+Jets with FxFx
- Dark Matter at the LHC
- EFT in loop-induced processes

Top-phili simplified DM model

$$\mathcal{L}_{DM}^{Y_0} = \bar{\chi}(g_{DM}^S + ig_{DM}^P\gamma^5)\chi\, Y_0$$

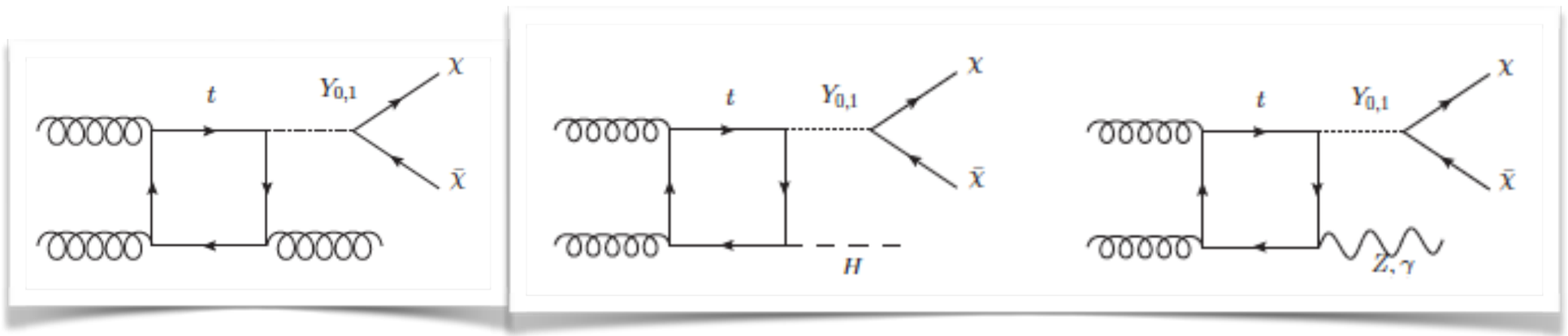
$$\mathcal{L}_{SM}^{Y_0} = \bar{t}\frac{y^t}{\sqrt{2}}(g_t^S + ig_t^P\gamma^5)t\, Y_0$$

Mediator couples only to the top
(scalar/pseudoscalar and vector/axial-vector)

Missing E_T processes:

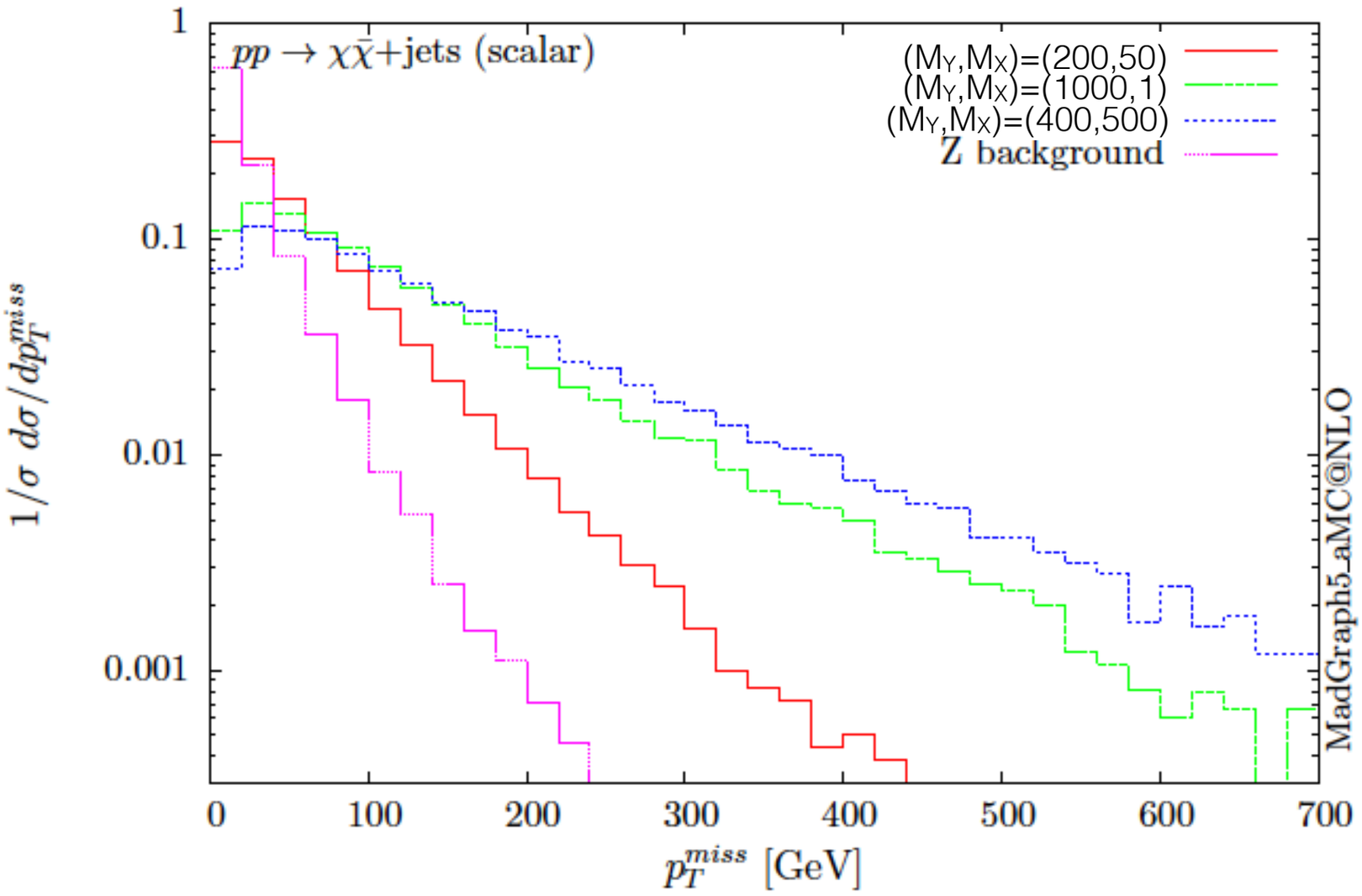
Tree-level: top-pair associated production

Loop-Induced: mono-jet, mono-Z, mono-photon, mono-Higgs



Mattelaer, EV
1508.00564

Jets+Missing E_T:Scalar mediator

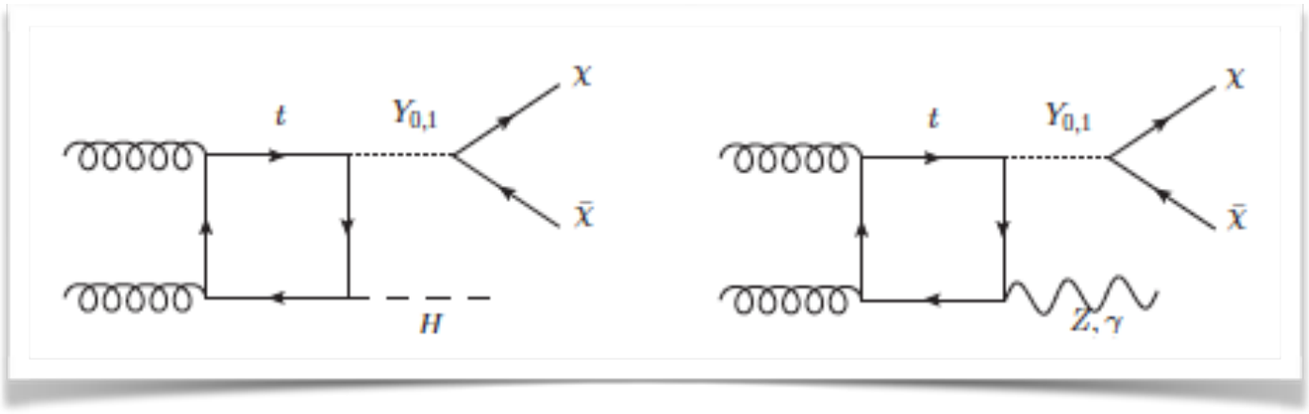


Benchmark	Resonant	Heavy mediator	Heavy DM
Mediator mass	200	1000	400
Dark matter mass	50	1	500

- MLM merged samples of 0,1,2jets
- All scenarios harder than the Z background
- Resonant scenario gives fastest falling distributions
- Used also in arXiv: 1605.09242 (more in Antony's talk)

$$g_{DM}^S = g_t^S = 1$$

Mono-X processes

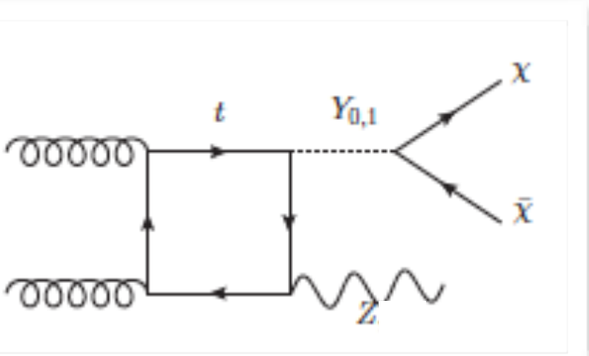


Selection Rules: charge conjugation invariance forbids certain processes

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

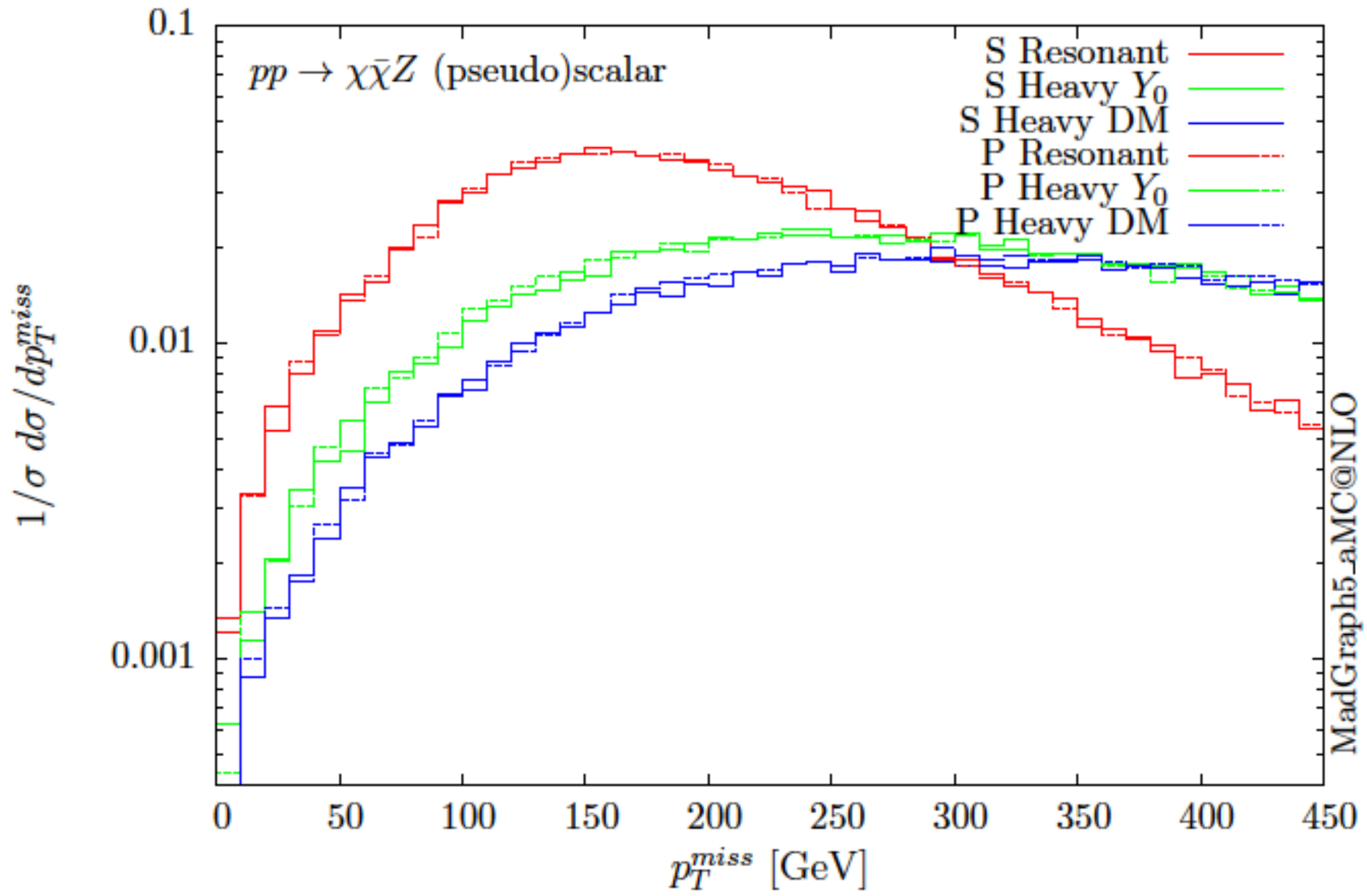
Signal or absence of signal can be used to identify the nature of the propagator

Mono-Z



Benchmark	scalar	pseudoscalar
Resonant	$2.99 \cdot 10^{-2}\ ^{+36\%\ +1.3\%}_{-25\%\ -1.4\%}$	$3.28 \cdot 10^{-2}\ ^{+36\%\ +1.3\%}_{-25\%\ -1.4\%}$
Heavy mediator	$2.20 \cdot 10^{-4}\ ^{+43\%\ +2.5\%}_{-28\%\ -2.5\%}$	$2.08 \cdot 10^{-4}\ ^{+43\%\ +2.6\%}_{-28\%\ -2.5\%}$
Heavy DM	$4.75 \cdot 10^{-7}\ ^{+45\%\ +3.5\%}_{-29\%\ -3.4\%}$	$1.40 \cdot 10^{-6}\ ^{+44\%\ +3.2\%}_{-28\%\ -3.1\%}$

13TeV
σ in pb

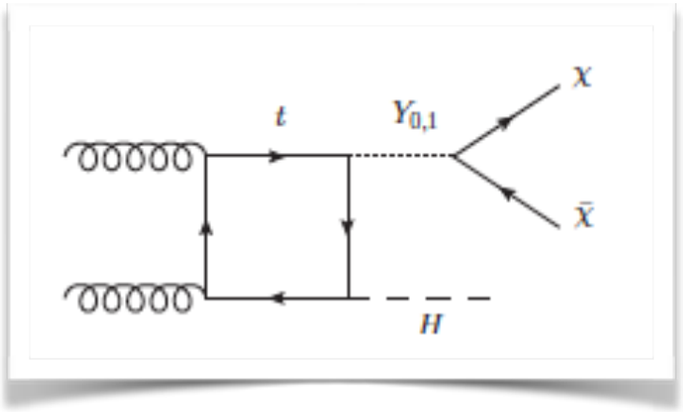


Small cross-sections for loop-induced
See:1509.05785 for tree level production

Similar shapes for scalar and pseudoscalar

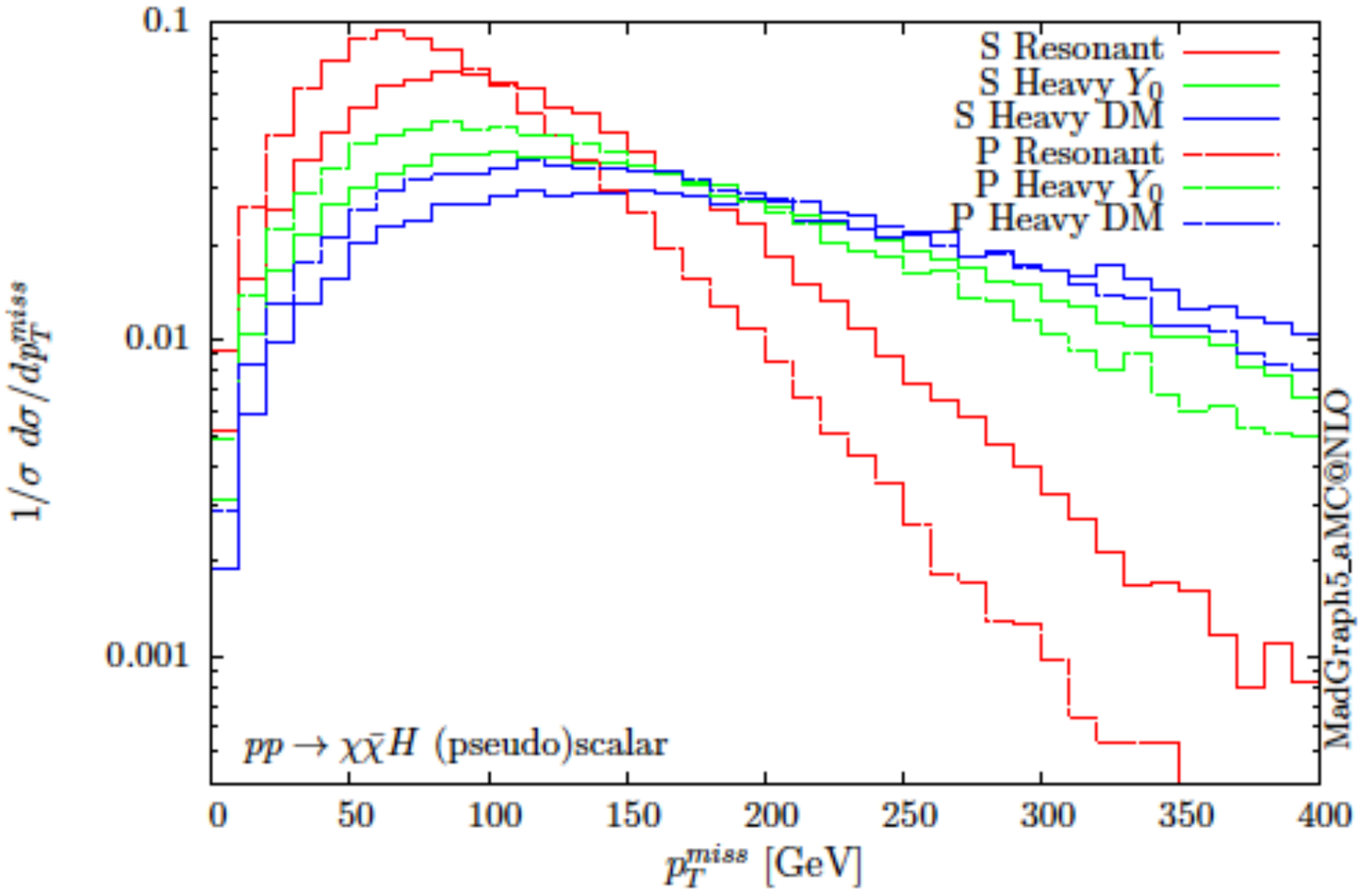
ATLAS searches 1309.4017,1404.0051

Mono-Higgs



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

ATLAS search:1506.01081

Physics applications

- SM Higgs studies
  - Off-shell -Interference effects in gg > VV
  - Higgs+Jets with FxFx
- Dark Matter at the LHC
- EFT in loop-induced processes

Physics applications

- SM Higgs studies
  - Off-shell -Interference effects in gg > VV
  - Higgs+Jets with FxFx
- Dark Matter at the LHC
- EFT in loop-induced processes

Top-quark operators and how to look for them

$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu \tau^I Q)$$

$$O_{\varphi Q}^{(1)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{Q}\gamma^\mu Q)$$

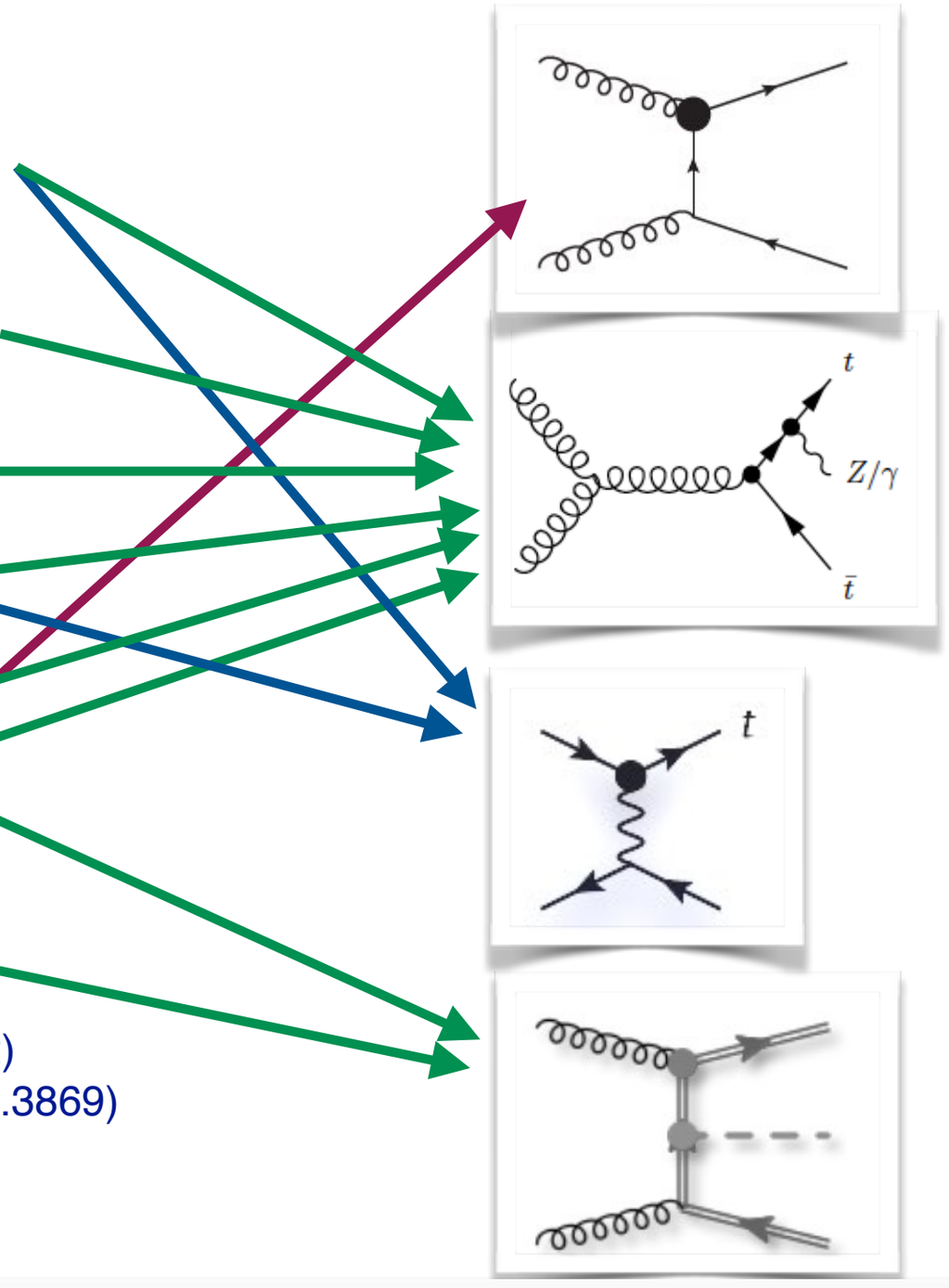
$$O_{\varphi t} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$

$$O_{tW} = y_t g_w(\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}$$

$$O_{tB} = y_t g_Y(\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu}$$

$$O_{tG} = y_t g_s(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}\,,$$

$$O_{t\phi} = y_t^3\left(\phi^\dagger\phi\right)(\bar{Q}t)\,\tilde{\phi}$$

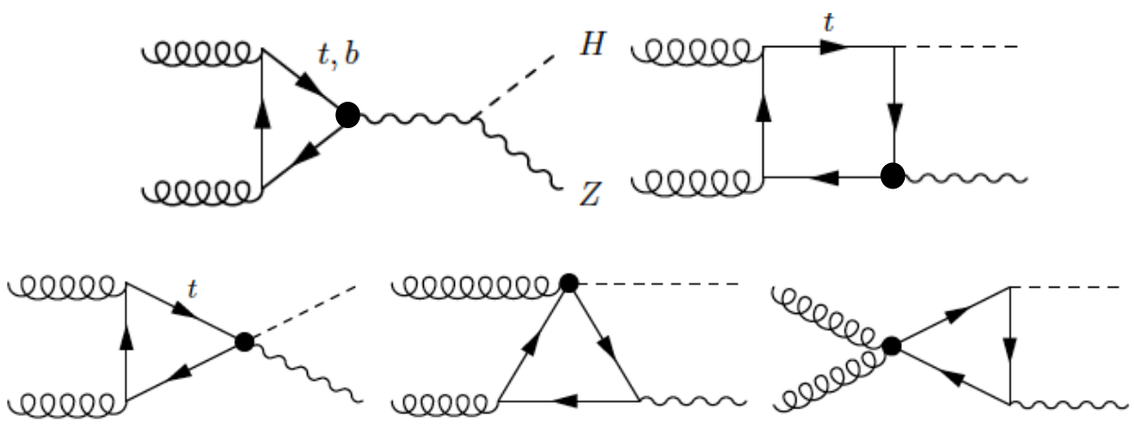


see for example: Aguilar-Saavedra (arXiv:0811.3842)
Zhang and Willenbrock (arXiv:1008.3869)

+four-fermion operators

Operators entering various processes: Global approach needed
Towards computing all these at NLO in QCD (more tomorrow)

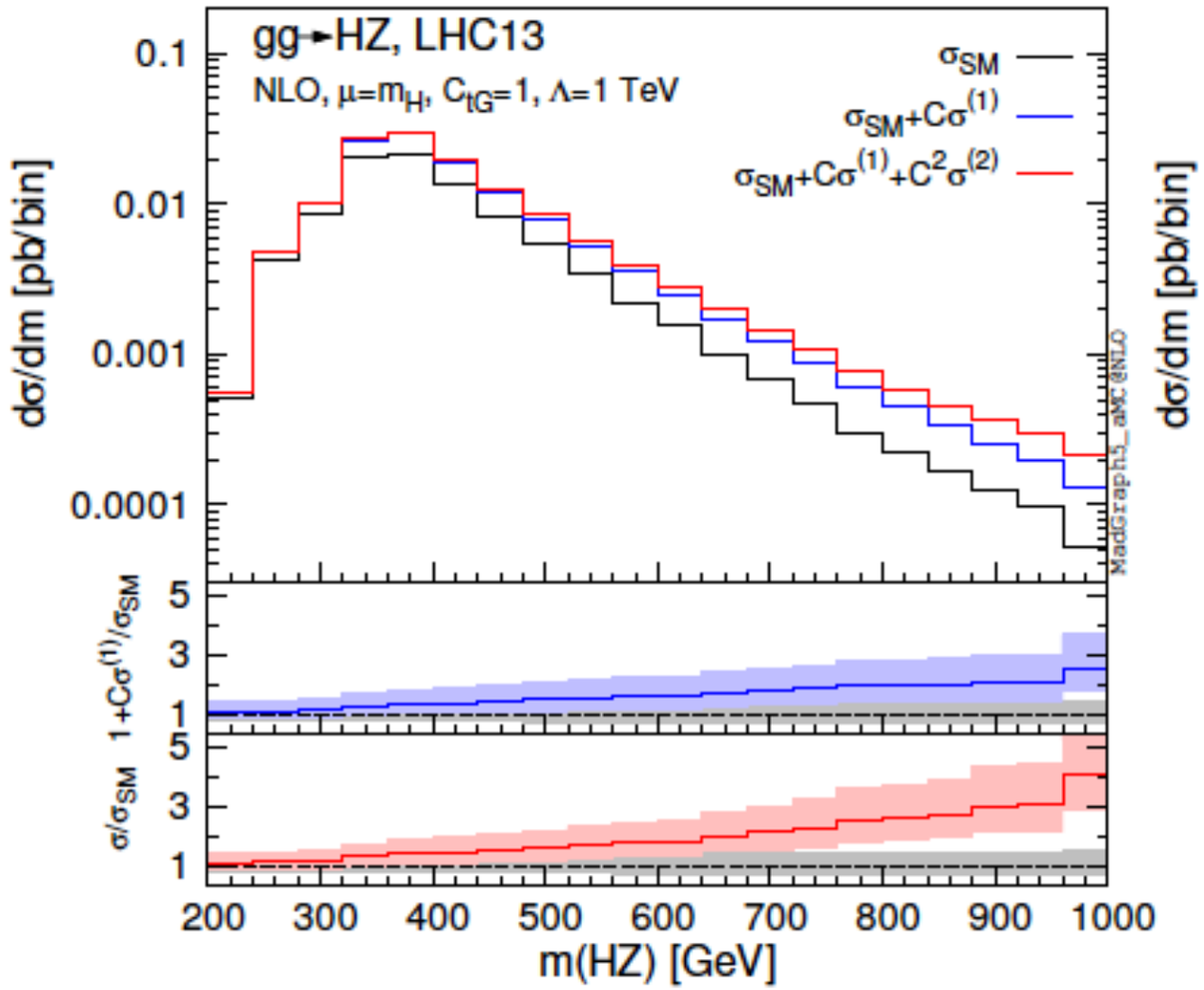
Top-operators in non-top final states



Gluon-fusion contribution to HZ production affected by the operators changing gtt, ttZ and ttH ➡ Additional information

[fb]	SM		$\mathcal{O}_{tG}$	$\mathcal{O}_{\phi Q}^{(1)}$
13TeV	$93.6^{+34.3\%}_{-23.8\%}$	$\sigma_i^{(1)}$	$34.6^{+35.2\%}_{-24.5\%}$	$5.91^{+36.4\%}_{-24.9\%}$
		$\sigma_{ii}^{(2)}$	$6.09^{+39.2\%}_{-26.1\%}$	$0.182^{+40.2\%}_{-26.6\%}$
		$\sigma_i^{(1)}/\sigma_{SM}$	$0.370^{+0.7\%}_{-0.9\%}$	$0.0631^{+1.6\%}_{-1.5\%}$
		$\sigma_{ii}^{(2)}/\sigma_i^{(1)}$	$0.176^{+2.9\%}_{-2.1\%}$	$0.0309^{+2.8\%}_{-2.2\%}$

No contributions from the electroweak dipole operators due to charge conjugation invariance



LO but loop-induced

arXiv:1601.08193

EFT in Higgs-top physics

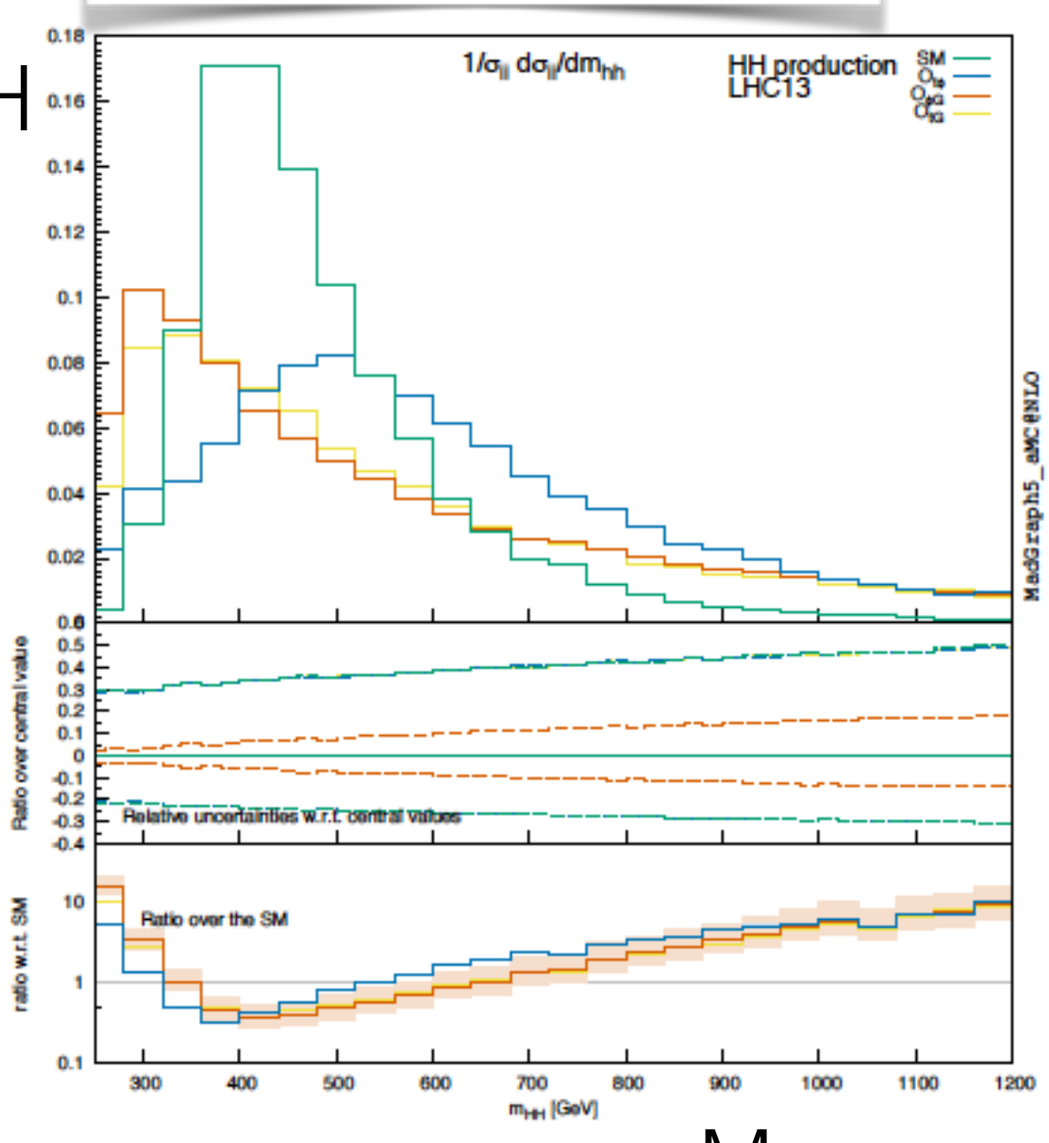
$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) (\bar{Q} t)\, \tilde{\phi}$$

$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu}$$

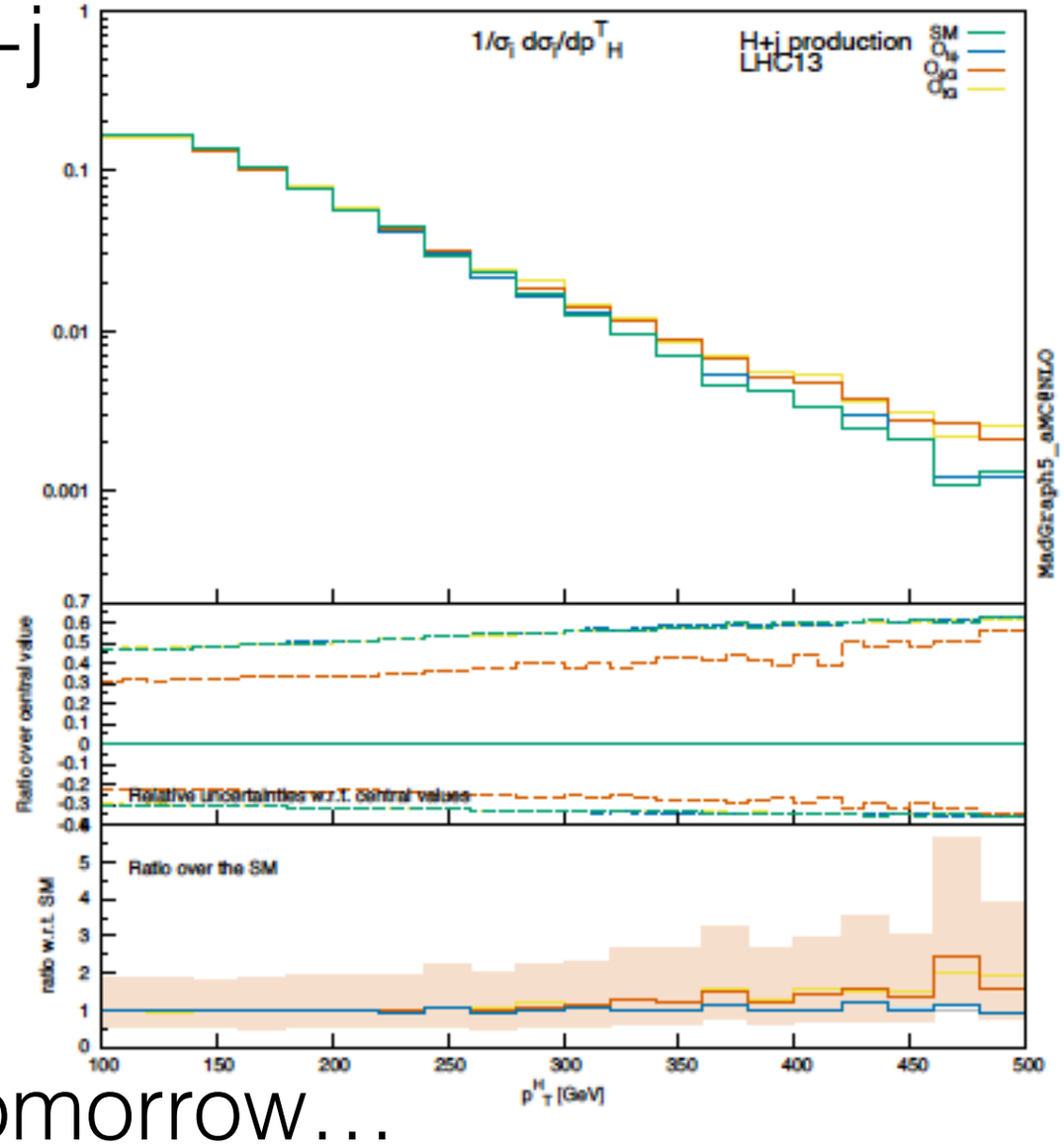
$$O_{tG} = y_t g_s (\bar{Q} \sigma^{\mu\nu} T^A t) \tilde{\phi} G^A_{\mu\nu}$$

Entering: ttH, H, H+jets, HH…

HH



H+j



More on this tomorrow…

Future directions

- Loop-Induced processes at NLO:
  - NLO+PS: currently not automated
  - Reweighting required
  - Limited by the availability of two-loop results
    - 2-loop amplitudes can be linked as a library
- gg > VV processes a good example to study

Thank you for your attention