

# Top and Higgs

## Recent theory developments

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TOP2017

Braga

21/9/17

# Why $t\bar{t}H$ ?

- $t\bar{t}H$  a probe of the top Yukawa coupling: window to NP
- Experimental results are being collected in all channels: see following ATLAS and CMS talks
- Precision needed from the theory side:
  - EW+QCD corrections
  - Physical final states
  - Background modelling
  - Predictions in the presence of new interactions

# Outline

- Overview of  $t\bar{t}H$  in the SM
  - higher order predictions for the signal
  - background modelling in  $t\bar{t}b\bar{b}$
- Top and Higgs beyond the SM
  - probe BSM top couplings using precise predictions

# Status of SM precision studies for ttH

## Top2016

QCD: NLO+PS

aMC@NLO: arXiv:1104.5613

PowHel: arXiv:1108.0387

Powheg Box: arXiv:1501.04498

Soft gluon resummation-beyond NLO:

Kulesza et al. arXiv:1509.02780

Broggio et al. arXiv:1510.01914

Off-shell:

Denner et al. arXiv:1506.07448

NLO EW:

Frixione et al. arXiv:1407.0823 &  
arXiv:1504.03446

Zhang et al. arXiv:1407.1110

## Top2017

NNLL resummation:

QCD: Kulesza et al. arXiv:1704.03363

SCET: Broggio et al. arXiv:  
1611.00049

EW corrections:

Sherpa+RECOLA:

Biedermann et al. 1704.05783

EW corrections including off-shell  
effects+combination with QCD  
corrections:

Denner et al arXiv:1612.07138

Progress in the background  
modelling: ttbb

Generator studies within LHCHSWG  
New POWHEG implementation of ttbb  
at NLO+PS (Jezo et al in preparation)

# NLO+NNLL resummation (1)

Threshold resummation:  $1 - \hat{\tau} = 1 - \frac{Q^2}{\hat{s}} \sim \frac{\text{energy of the emitted gluons}}{\text{total available energy}}$

$$\tilde{\sigma} \sim \tilde{\sigma}_{LO} \times \mathcal{C}(\alpha_s) \exp [Lg_1(\alpha_s L) + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + \dots]$$

LL

NLL

NNLL

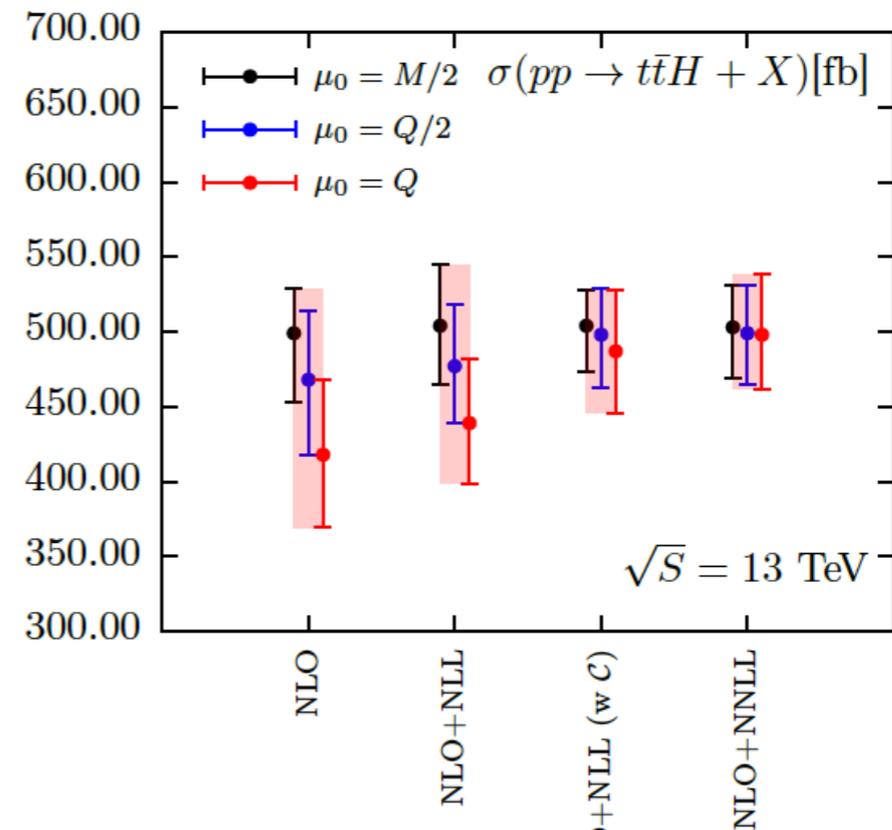
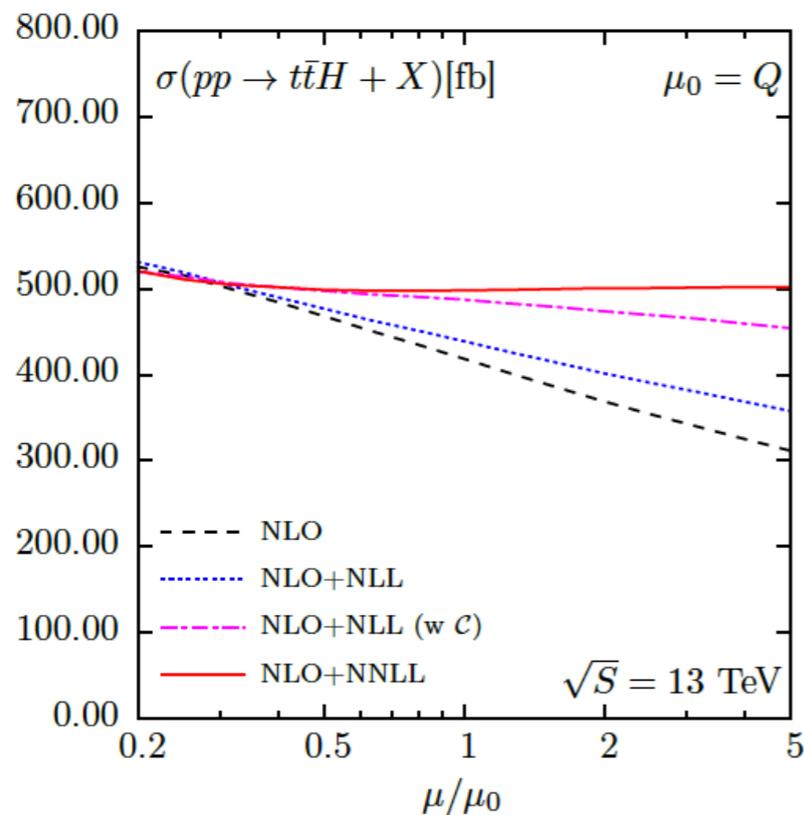
Kulesza et al. arXiv:1704.03363

Mellin space N

$$\alpha_s^n \log^{n+1}(N)$$

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$$\alpha_s^{n+1} \log^n(N)$$

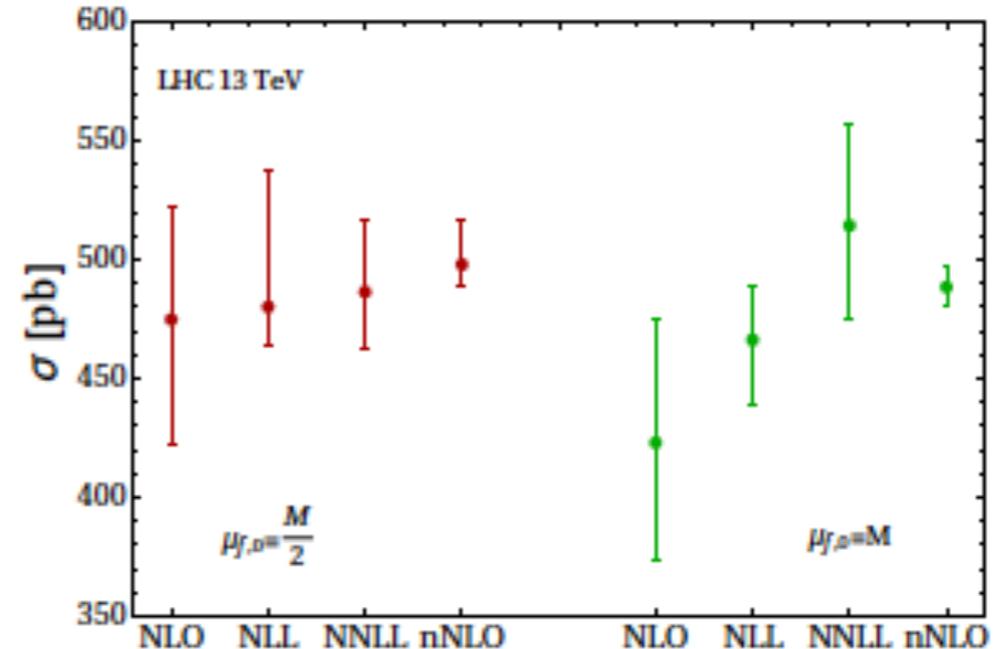
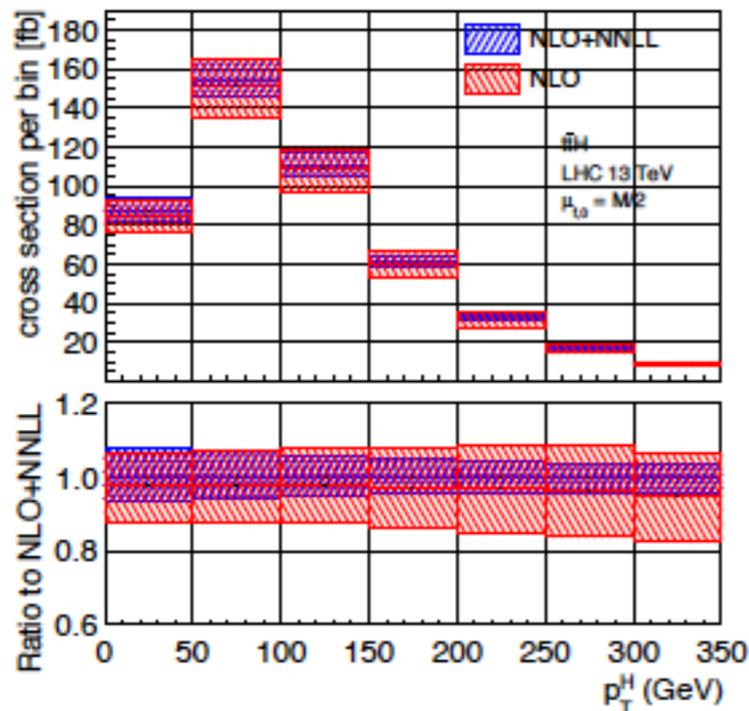
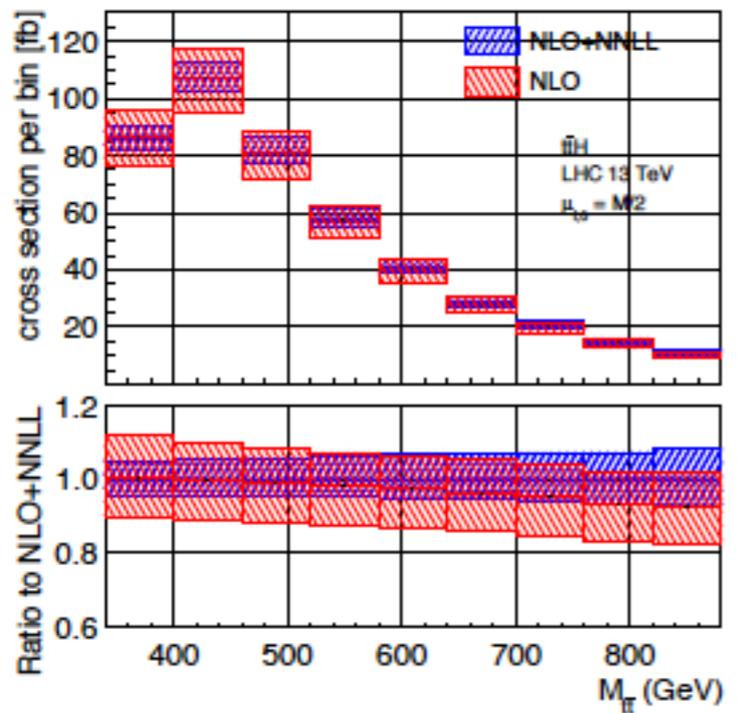


Significant reduction of scale uncertainty at NLO+NNLL

# NLO+NNLL resummation (2)

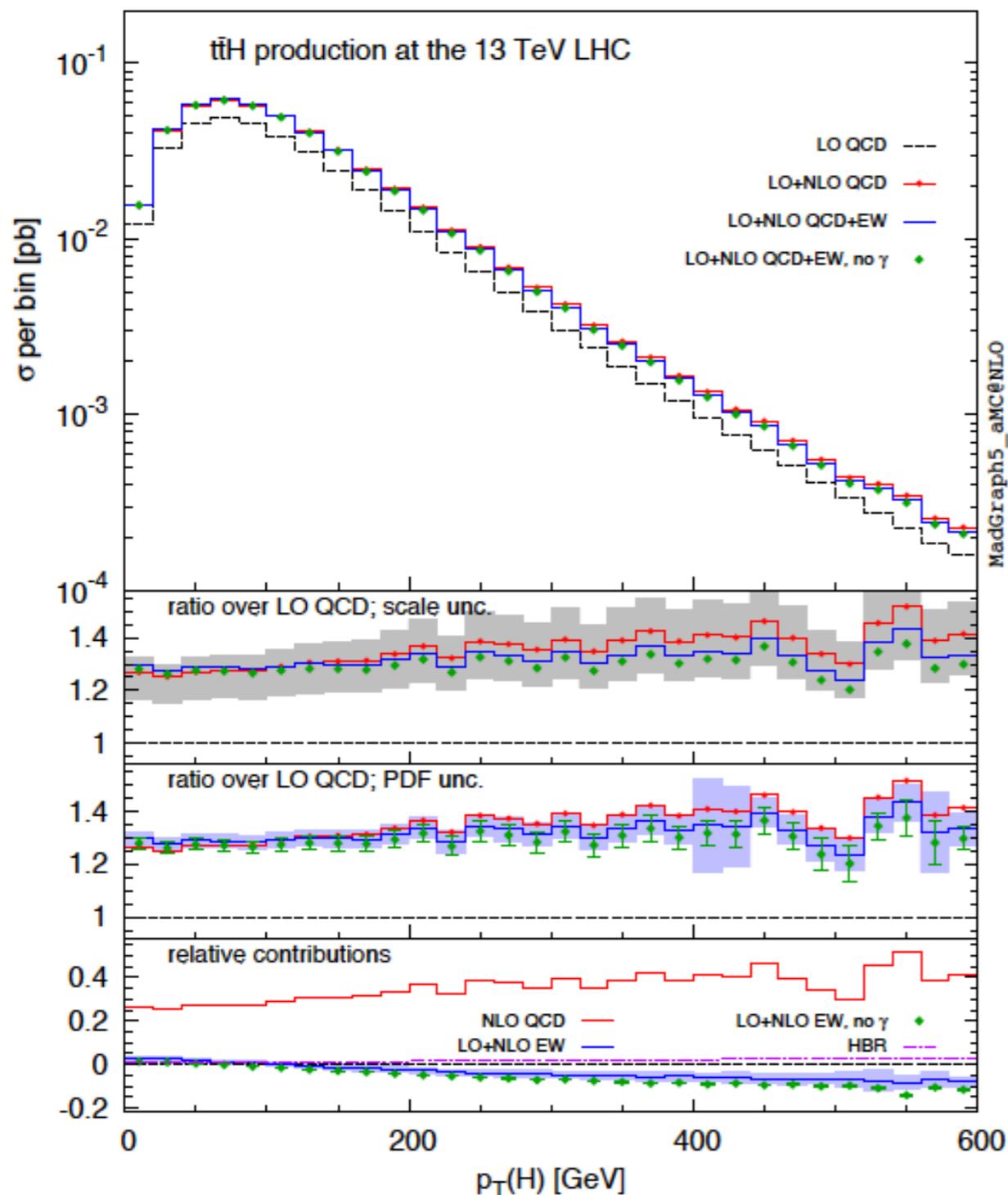
See Andrea's talk on resummation in top-pair(+H)

SCET framework calculation  
 Significant reduction of scale uncertainties  
 Small change of shapes compared to NLO



Broggio et al. arXiv:1611.00049

# EW corrections in $t\bar{t}H$



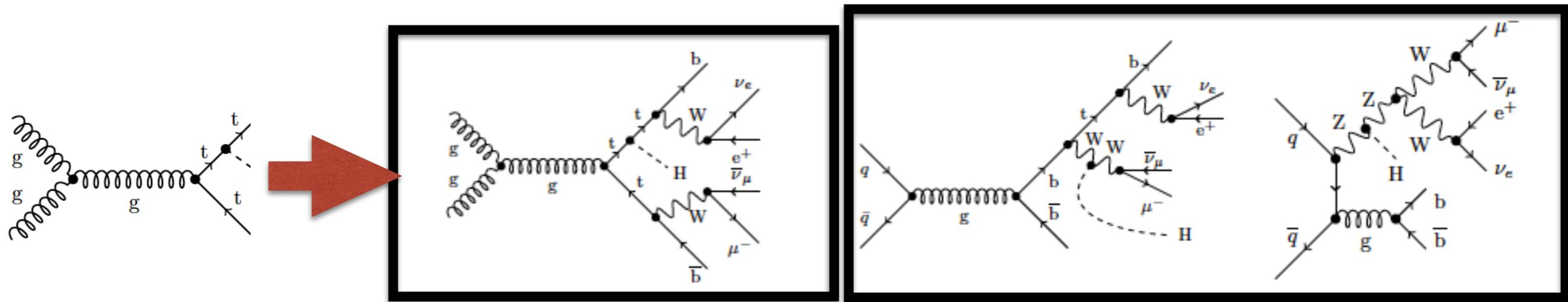
Frixione et al arXiv:1504.03446

$t\bar{t}H : \delta(\%)$	8 TeV		13 TeV
NLO QCD	$25.9^{+5.4}_{-11.1} \pm 3.5$	$29.7^{+6.8}_{-11.1} \pm 2.8$	$(24.2^{+4.8}_{-10.6} \pm 4.5)$
LO EW	$1.8 \pm 1.3$	$1.2 \pm 0.9$	$(2.8 \pm 2.0)$
LO EW no $\gamma$	$-0.3 \pm 0.0$	$-0.4 \pm 0.0$	$(-0.2 \pm 0.0)$
NLO EW	$-0.6 \pm 0.1$	$-1.2 \pm 0.1$	$(-8.2 \pm 0.3)$
NLO EW no $\gamma$	$-0.7 \pm 0.0$	$-1.4 \pm 0.0$	$(-8.5 \pm 0.2)$
HBR	0.88	0.89	$(1.87)$

- Small corrections at the total cross-section level
- Important and negative for high  $p_T$  tails - Sudakov logs
- Vector boson radiation only partially cancelling Sudakov logs

See Steffen's Talk  
arXiv:1704.05783 for Sherpa+RECOLA  
implementation at NLO QCD+EW

# EW corrections for off-shell top quarks



Off-shell and interference effects taken into account

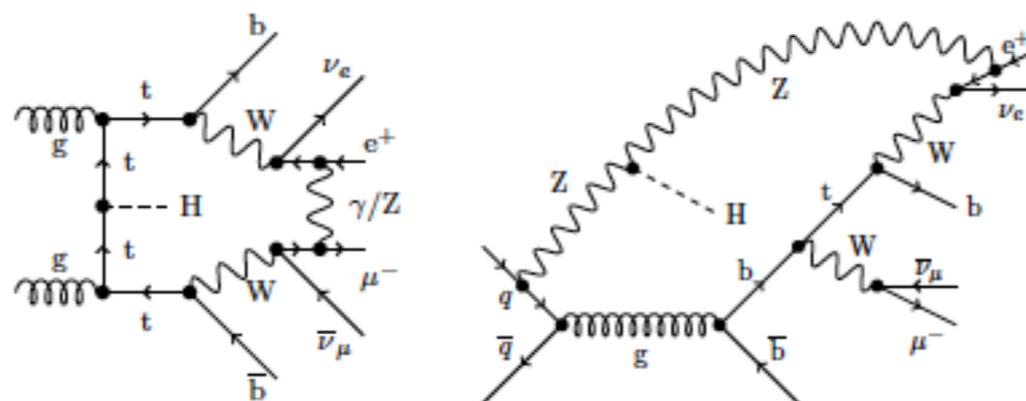
Final state

$$pp \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu b \bar{b} H \quad \mathcal{O}(\alpha_s^2 \alpha^5) \quad \text{Denner et al arXiv:1612.07138}$$

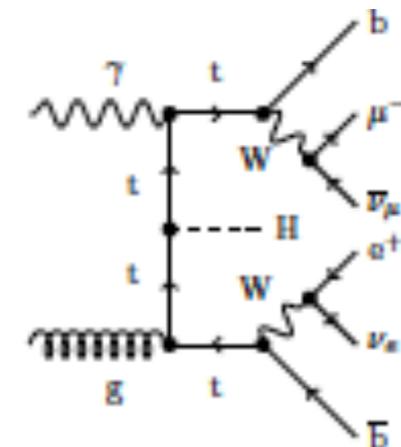
Virtual corrections

NLO EW

$$\mathcal{O}(\alpha_s^2 \alpha^6)$$



Photon-induced contributions



# EW corrections for off-shell top quarks

Ch.	$\sigma_{\text{LO}}$ [fb]	$\sigma_{\text{NLO EW}}$ [fb]	$\delta$ [%]
gg	2.0116(1)	2.020(1)	+0.42
$q\bar{q}$	0.84860(5)	0.8454(6)	-0.38
$gq(/\bar{q})$		0.00007(2)	
$\gamma g$	0.02178(1)		
pp	2.8602(1)	2.866(1)	+0.20

Small effects at the total cross-section level

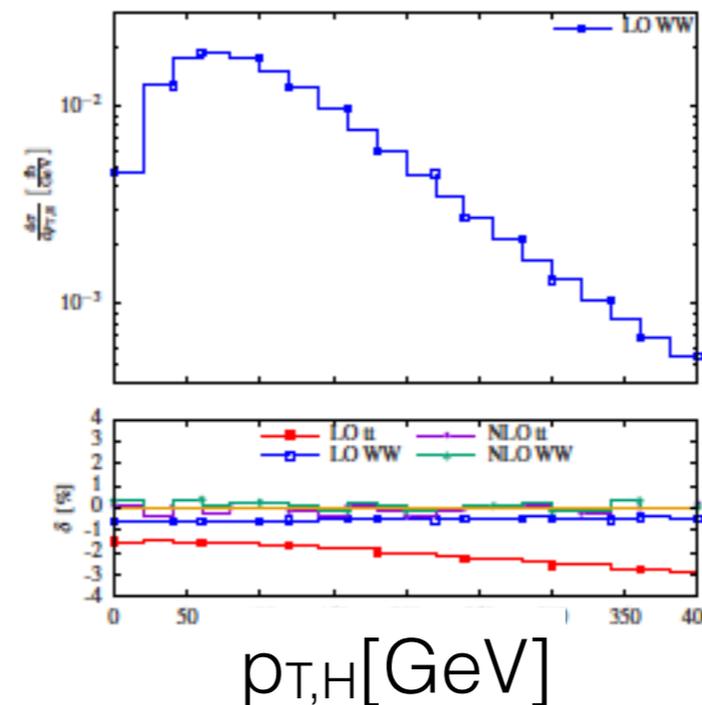
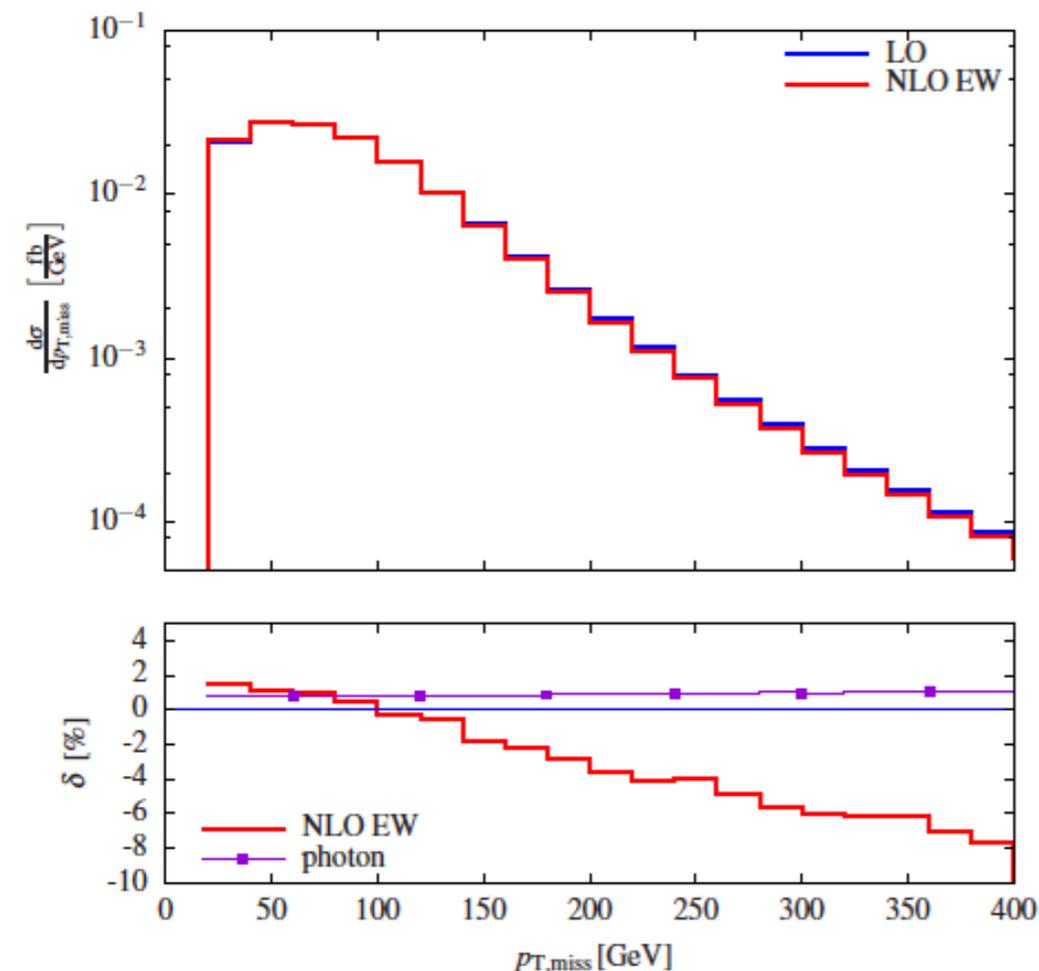
Combination with QCD corrections:

$$\sigma_{\text{QCD+EW}}^{\text{NLO}} = \sigma^{\text{Born}} + \delta\sigma_{\text{QCD}}^{\text{NLO}} + \delta\sigma_{\text{EW}}^{\text{NLO}}$$

and

$$\sigma_{\text{QCD}\times\text{EW}}^{\text{NLO}} = \sigma_{\text{QCD}}^{\text{NLO}} \left( 1 + \frac{\delta\sigma_{\text{EW}}^{\text{NLO}}}{\sigma^{\text{Born}}} \right) = \sigma_{\text{EW}}^{\text{NLO}} \left( 1 + \frac{\delta\sigma_{\text{QCD}}^{\text{NLO}}}{\sigma^{\text{Born}}} \right)$$

$\sigma_{\text{QCD}}^{\text{NLO}}$	$\sigma_{\text{EW}}^{\text{NLO}}$	$\sigma_{\text{QCD+EW}}^{\text{NLO}}$	$\sigma_{\text{QCD}\times\text{EW}}^{\text{NLO}}$
2.866(1)	2.721(3)	2.806	2.804



Comparison with double pole approximations shows good agreement with full result

larger impact on distributions

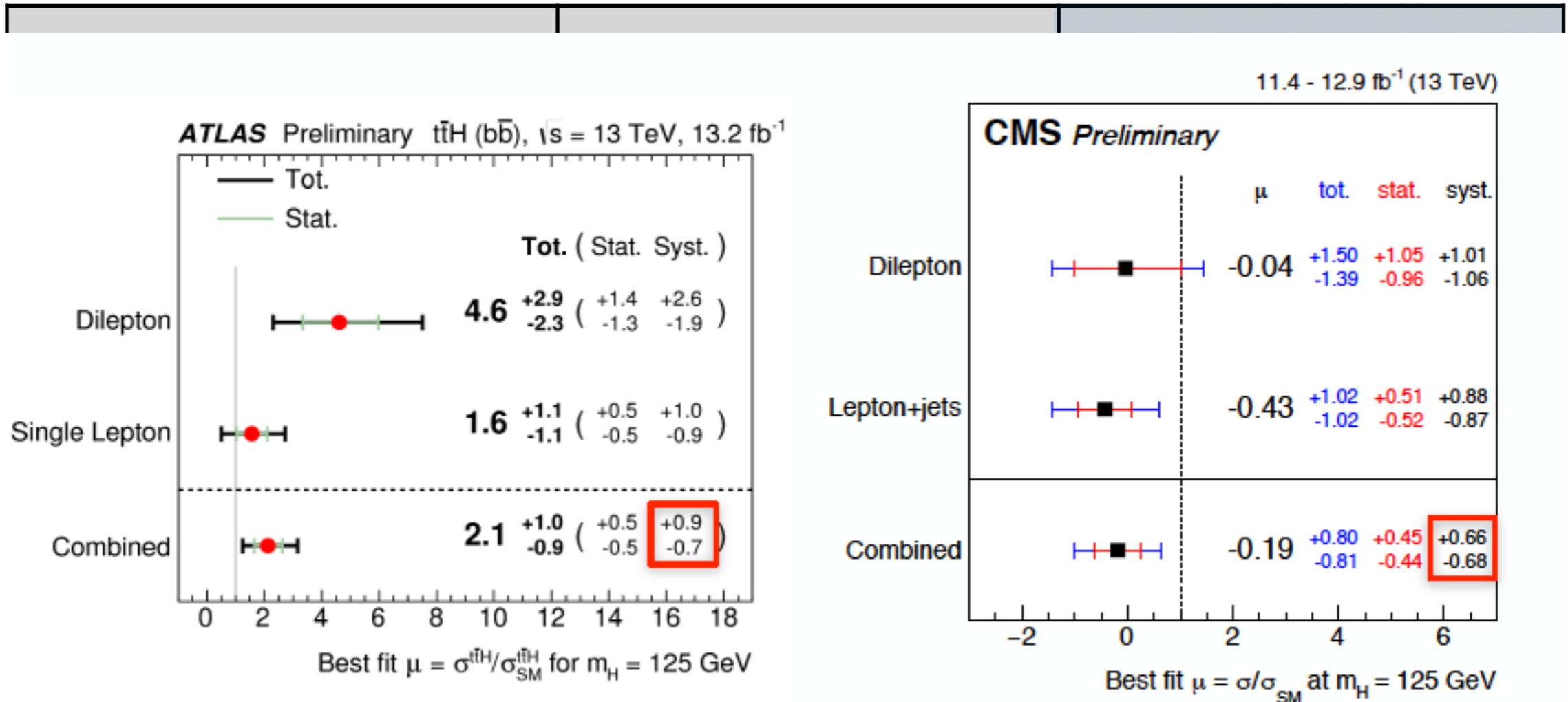
E. Vryonidou

Denner et al arXiv:1612.07138

# ttH background modelling

<p>ttZ/W            QCD: NLO+PS            aMC@NLO: arXiv:1103.0621            PowHel: arXiv:1111.1444,            1208.2665            Soft gluon resummation:            Broggio et al. arXiv:            1607.05303, 1702.00800            NLO EW:            Frixione et al. arXiv:1504.03446</p>	<p>ttZZ, ttWW, ttWZ            ttZ<math>\gamma</math>, ttW<math>\gamma</math>            QCD: NLO+PS            MG5_aMC@NLO:            Maltoni et al. arXiv:1507.05640</p>	<p>ttbb            NLO:            Bredenstein et al. arXiv:            0905.0110 &amp; arXiv:            1001.4006            Bevilacqua et al. arXiv:            0907.4723            NLO+PS:            Powhel:Kardos et al.            1303.6201            Sherpa+OpenLoops:            Cascioli et al. 1309.5912</p>
<p>tty            QCD: NLO+PS            aMC@NLO: arXiv:1103.0621            PowHel: arXiv:1406.2324</p>	<p>tty<math>\gamma\gamma</math>            NLO+PS            PowHel: Kardos et al. arXiv:            1408.0278            aMC@NLO: Maltoni et al. arXiv:            1507.05640            van Deurzen et al. arXiv:            1509.02077</p>	

# ttH background modelling

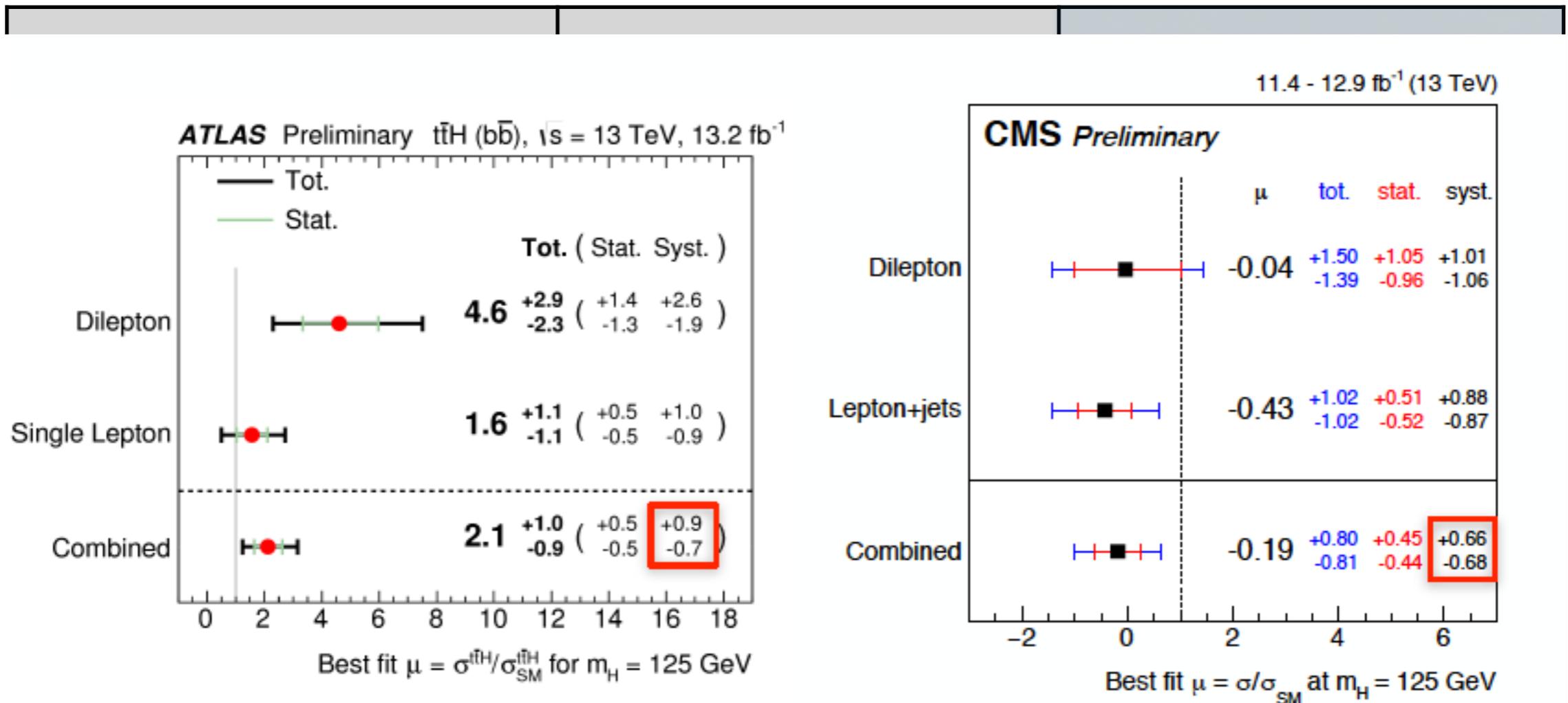


aMC@NLO: arXiv:1103.0621  
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Sherpa+OpenLoops:  
Cascioli et al. 1309.5912

# ttH background modelling



aMC@NLO: arXiv:1103.0621

PowHel: arXiv:1406.2324

1408.0278

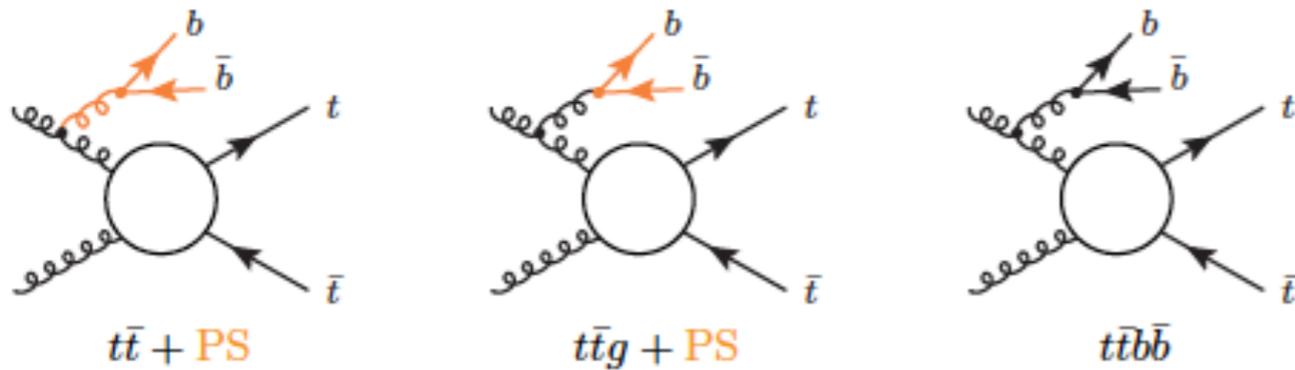
Sherpa+OpenLoops:

Cascioli et al. 1309.5912

Large systematic uncertainties  
Dominated by background modelling

1509.02077

# Background modelling: $t\bar{t}b\bar{b}$



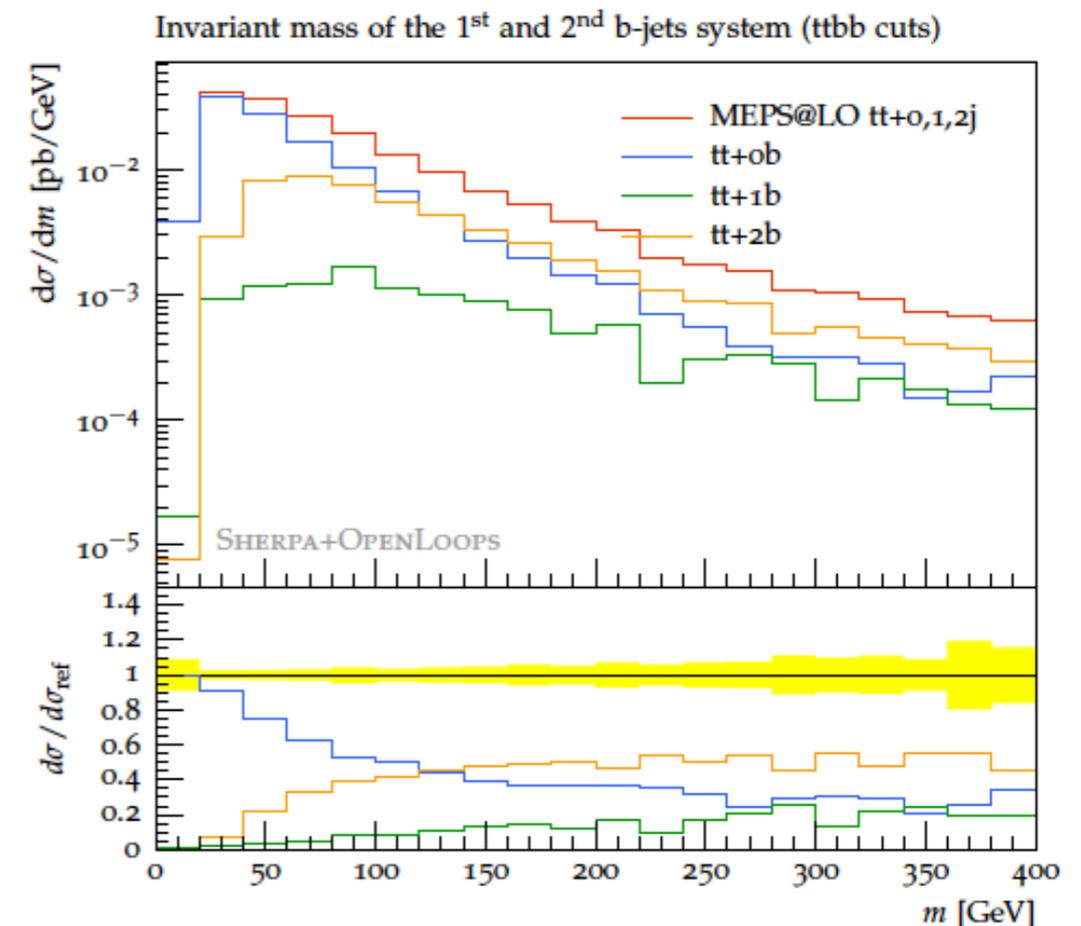
- Relevant aspects:
- 5F/4F scheme
  - NLO+PS matching
  - PS effects

Options:

- ◆ NLO+PS  $t\bar{t}$  5F:
  - ◆  $g \rightarrow b\bar{b}$  in shower: not precise
- ◆  $t\bar{t} + 0, 1, 2$  jets merging 5F
  - ◆ ME+ $g \rightarrow b\bar{b}$  shower splittings
  - ◆ Dominance of light quark MEs

**Need for  $t\bar{t}b\bar{b}$  MEs**

$m_{bb}$  with  $t\bar{t}b\bar{b}$  cuts

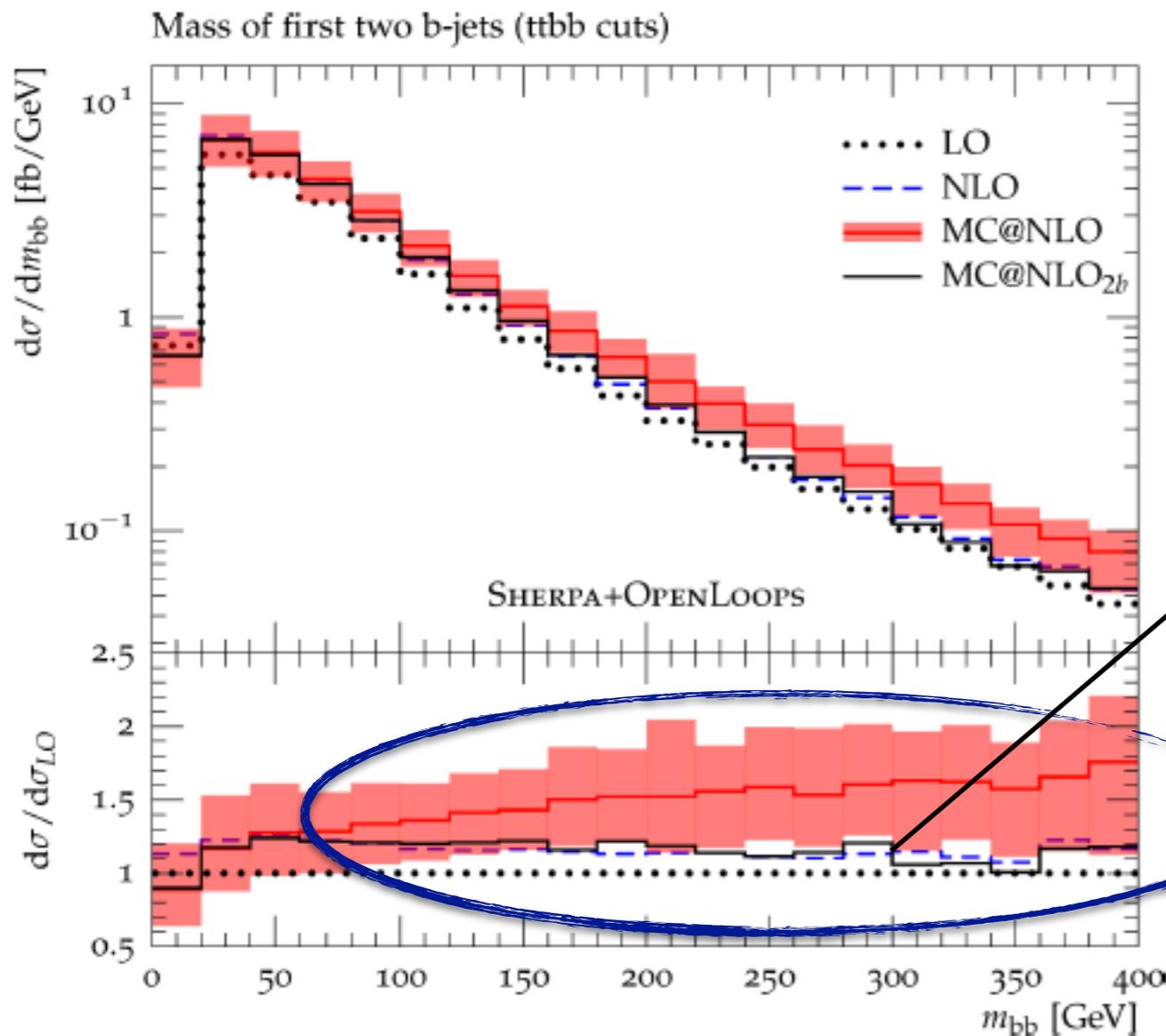


S. Pozzorini, July 2017 LHCHXSWG

# $t\bar{t}b\bar{b}$ at NLO+PS

NLO+PS for  $t\bar{t}b\bar{b}$  (4F, massive b's)

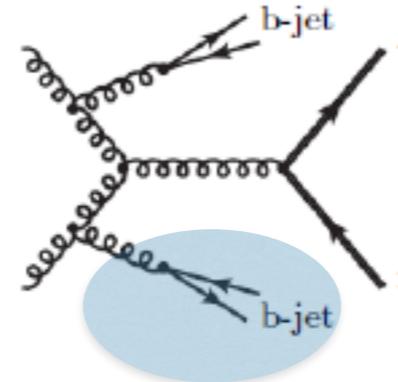
1- and 2b-jet observables NLO accurate



Cascioli et al: arXiv:1309.5912

NLO+PS findings:

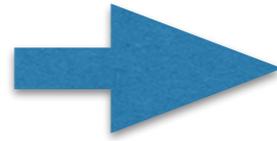
- Large enhancement wrt fixed-order in the Higgs region ( $\sim 30\%$ )
- Due to secondary  $g \rightarrow b\bar{b}$  splittings in the shower (eliminated when turning off  $g$  to  $b\bar{b}$  in the shower)



- Need to carefully assess matching & shower uncertainties for the **sensitive** b-observables

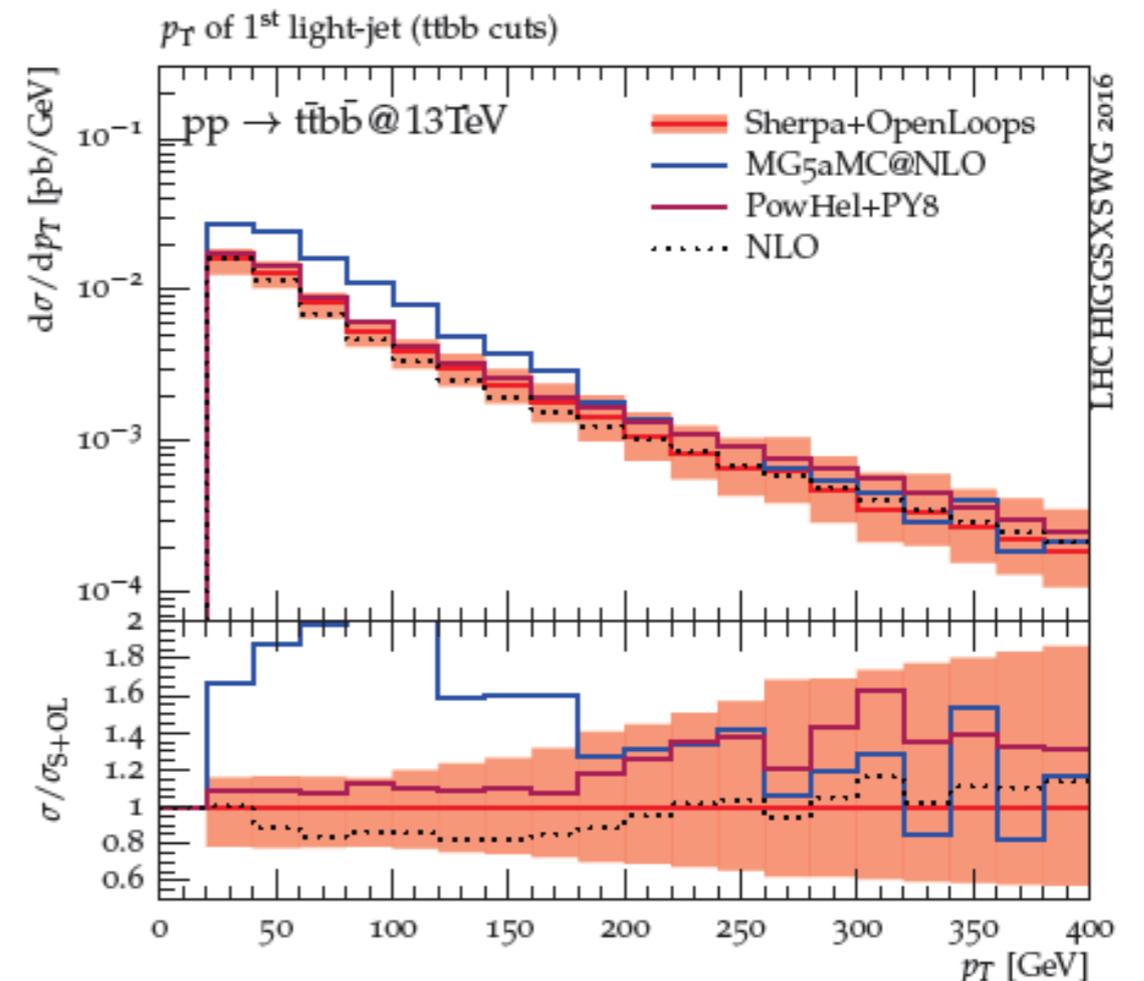
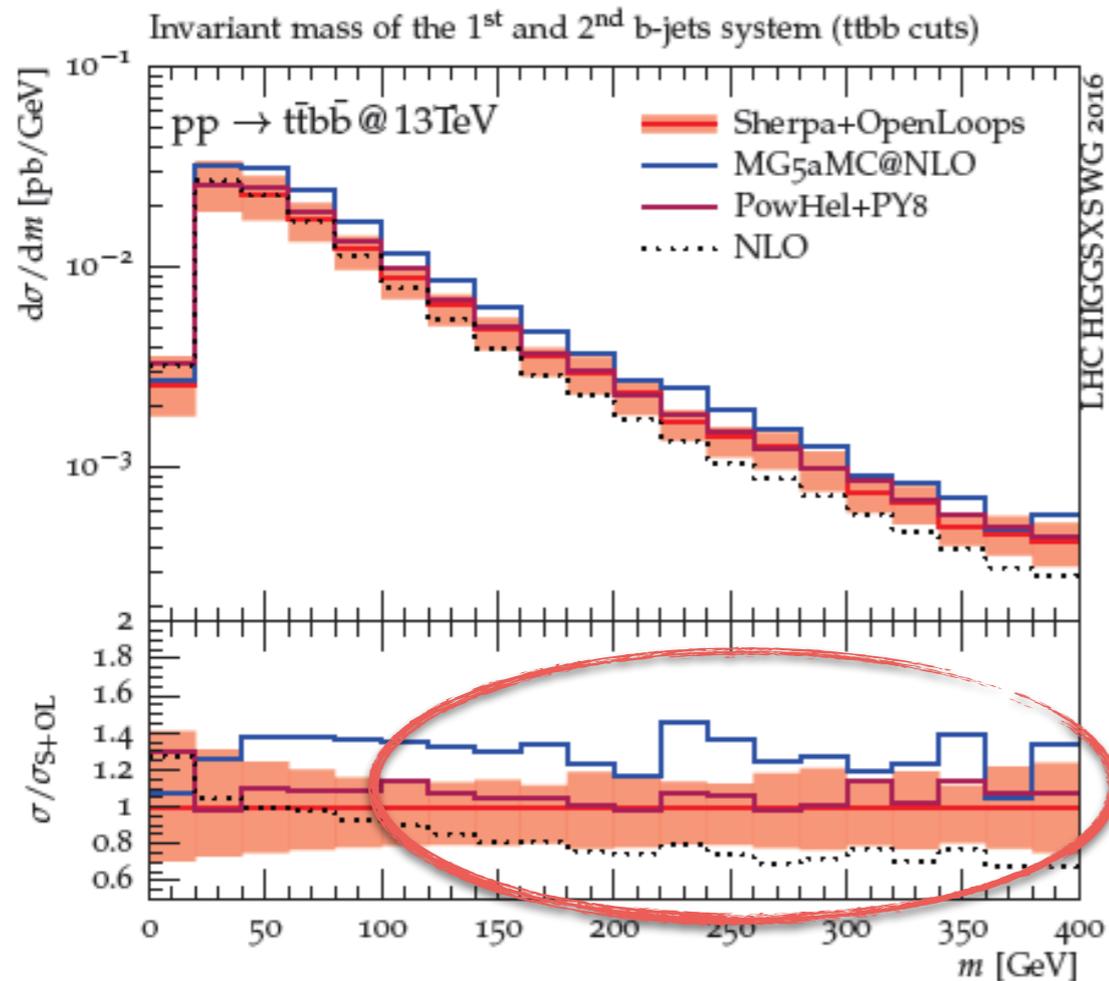
# $t\bar{t}b\bar{b}$ at NLO+PS

NLO+PS studies



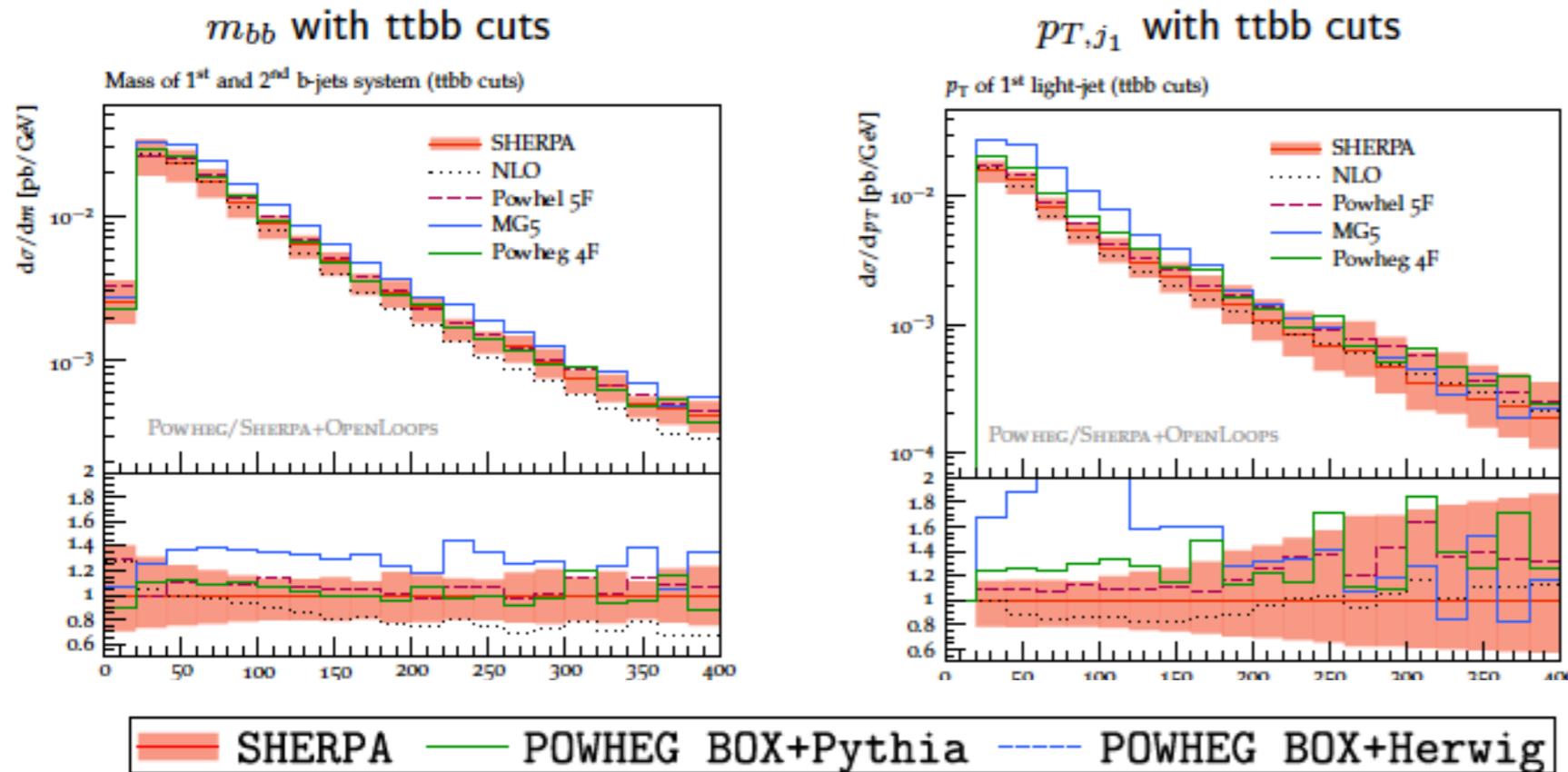
b-observables relevant for ttH searches e.g.  $m_{bb}$  extremely sensitive to matching and shower

Shower and matching uncertainties studies within the LHCHXSWG  
Generator comparisons: Stable tops, no hadronisation

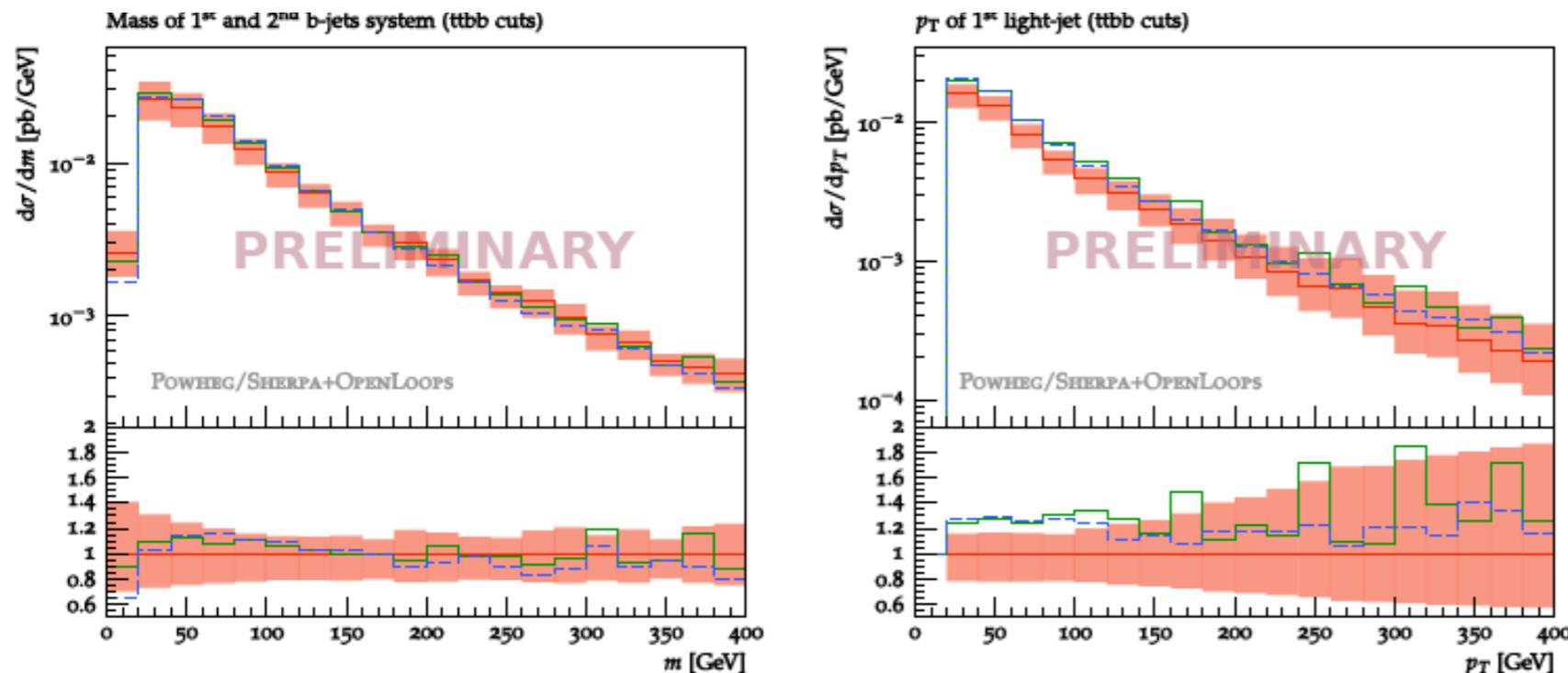


Enhancement wrt to the fixed-order due to secondary g to bb splittings in the shower: confirming Cascioli et al: arXiv:1309.5912

# $t\bar{t}b\bar{b}$ NLO+PS in Powheg+OpenLoops



Enhancement in the same direction as MG5\_aMC but sizeable differences remain

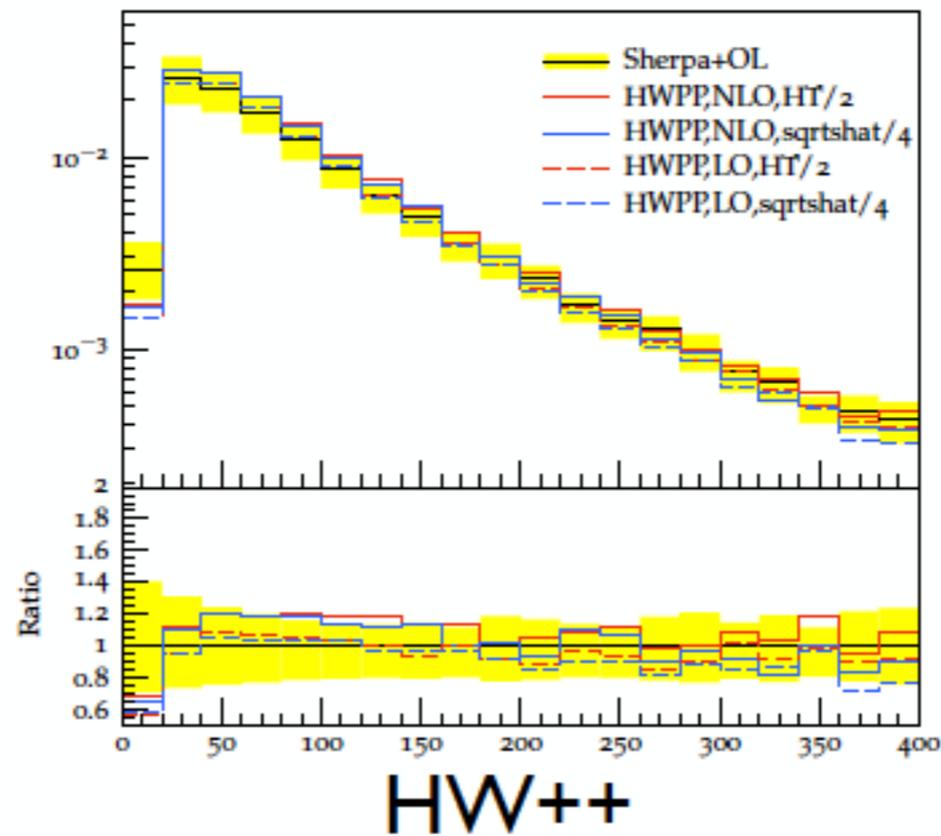
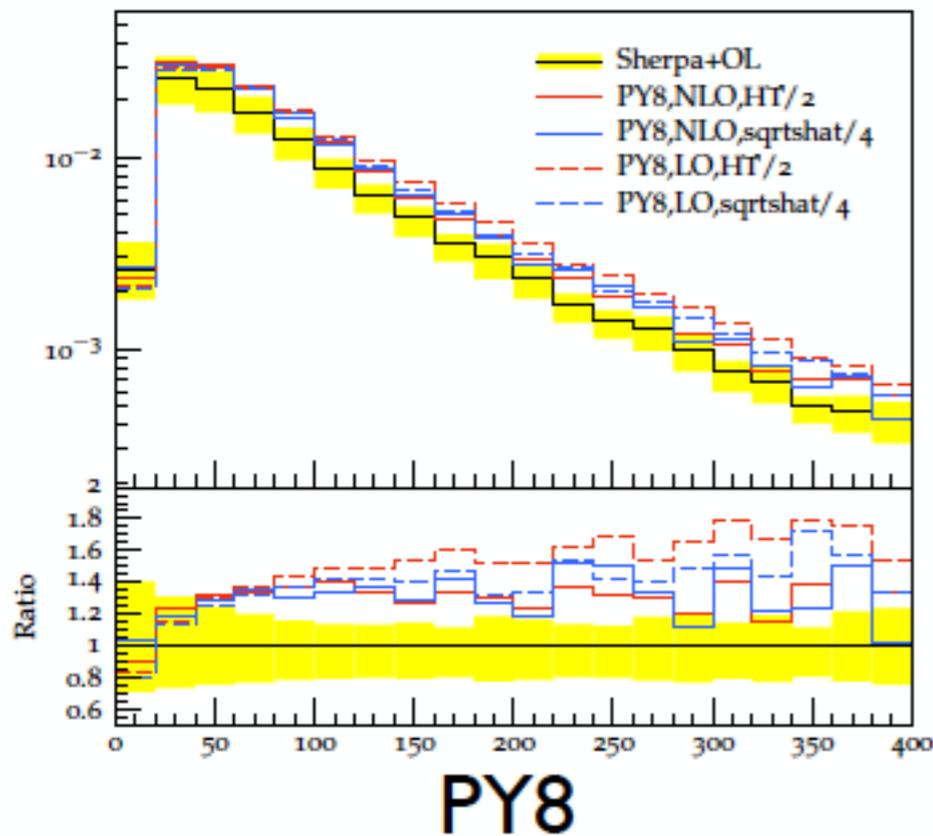


No significant differences between showers

hdamp comparisons: ongoing  
Jezo et al

# $t\bar{t}b\bar{b}$ revisited in mg5\_aMG

$m_{b_1 b_2}$



- HWPP radiates much less than PY8
- Small differences between shower scale HT/4 and sqrt(s)/4

M. Zaro, LHCHSWG meeting July 2017

Further comparisons in progress: Frixione, Maltoni, Zaro

Towards a more thorough understanding of the features and modelling uncertainties for  $t\bar{t}b\bar{b}$

# What's next?

## SM: precision for ttH

- QCD corrections-resummation
- Progress in EW and off-shell effects
- Realistic description of the signal distributions
- Progress in assessing modelling uncertainties of the relevant backgrounds

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ttH as a probe of  
new physics

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ttH as a probe of  
new physics



New top  
interactions

# New physics in ttH?

## New Interactions of SM particles

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

- Operators at dim-6:

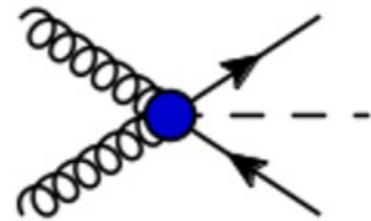
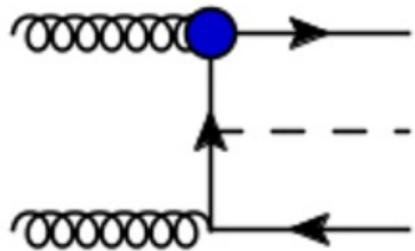
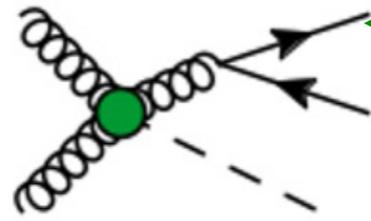
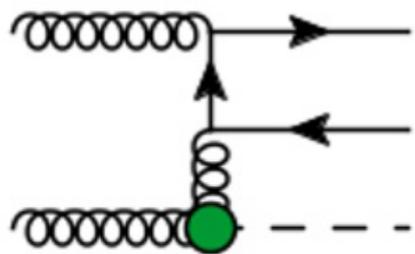
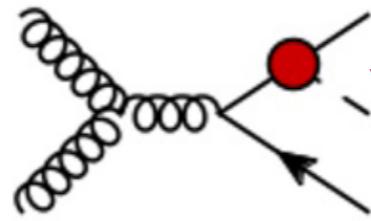
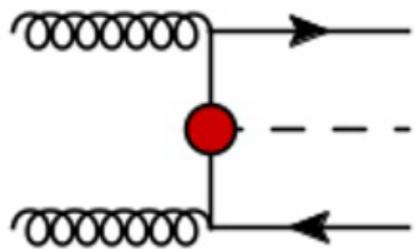
Buchmuller, Wyler Nucl.Phys. B268 (1986) 621-653

Grzadkowski et al arxiv:1008.4884

$X^3$		$\varphi^6$ and $\varphi^4 D^2$		$\psi^2 \varphi^3$	
$Q_G$	$f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	$Q_\varphi$	$(\varphi^\dagger \varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger \varphi)(\bar{l}_p e_r \varphi)$
$Q_{\tilde{G}}$	$f^{ABC} \tilde{G}_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$	$Q_{\varphi\Box}$	$(\varphi^\dagger \varphi)\Box(\varphi^\dagger \varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p u_r \tilde{\varphi})$
$Q_W$	$\varepsilon^{IJK} W_{\mu\nu}^I W_{\nu\rho}^J W_{\rho\mu}^K$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D_\mu \varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p d_r \varphi)$
$Q_{\tilde{W}}$	$\varepsilon^{IJK} \tilde{W}_{\mu\nu}^I W_{\nu\rho}^J W_{\rho\mu}^K$				
$X^2 \varphi^2$		$\psi^2 X \varphi$		$\psi^2 \varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger \varphi G_{\mu\nu}^A G^{A\mu\nu}$	$Q_{eW}$	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$Q_{\varphi \tilde{G}}$	$\varphi^\dagger \varphi \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$	$Q_{eB}$	$(\bar{l}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger \varphi W_{\mu\nu}^I W^{I\mu\nu}$	$Q_{uG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \tilde{\varphi} G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$Q_{\varphi \tilde{W}}$	$\varphi^\dagger \varphi \tilde{W}_{\mu\nu}^I W^{I\mu\nu}$	$Q_{uW}$	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \tilde{\varphi} W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$	$Q_{uB}$	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tilde{\varphi} B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi \tilde{B}}$	$\varphi^\dagger \varphi \tilde{B}_{\mu\nu} B^{\mu\nu}$	$Q_{dG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) \varphi G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi W_{\mu\nu}^I B^{\mu\nu}$	$Q_{dW}$	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
$Q_{\varphi \tilde{W}B}$	$\varphi^\dagger \tau^I \varphi \tilde{W}_{\mu\nu}^I B^{\mu\nu}$	$Q_{dB}$	$(\bar{q}_p \sigma^{\mu\nu} d_r) \varphi B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\tilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$Q_{ll}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	$Q_{ee}$	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$	$Q_{le}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	$Q_{uu}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$	$Q_{lu}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	$Q_{dd}$	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{ld}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$	$Q_{eu}$	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$	$Q_{qe}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	$Q_{ed}$	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
		$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		$B$ -violating			
$Q_{ledq}$	$(\bar{l}_p e_r)(\bar{d}_s q_t^i)$	$Q_{duq}$	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{ijk} [(d_p^\alpha)^T C u_r^\beta] [(q_s^\gamma)^T C l_t^k]$		
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r) \varepsilon_{jk} (\bar{q}_s^k d_t)$	$Q_{ququ}$	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{ijk} [(q_p^{\alpha j})^T C q_r^{\beta k}] [(u_s^\gamma)^T C e_t]$		
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r) \varepsilon_{jk} (\bar{q}_s^k T^A d_t)$	$Q_{qqqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{ijk} \varepsilon_{mnn} [(q_p^{\alpha j})^T C q_r^{\beta k}] [(q_s^m)^T C l_t^n]$		
$Q_{lequ}^{(1)}$	$(\bar{l}_p e_r) \varepsilon_{jk} (\bar{q}_s^k u_t)$	$Q_{qqqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma} (\tau^I \varepsilon)_{jk} (\tau^I \varepsilon)_{mn} [(q_p^{\alpha j})^T C q_r^{\beta k}] [(q_s^m)^T C l_t^n]$		
$Q_{lequ}^{(3)}$	$(\bar{l}_p e_r) \varepsilon_{jk} (\bar{q}_s^k \sigma^{\mu\nu} u_t)$	$Q_{duuu}$	$\varepsilon^{\alpha\beta\gamma} [(d_p^\alpha)^T C u_r^\beta] [(u_s^\gamma)^T C e_t]$		

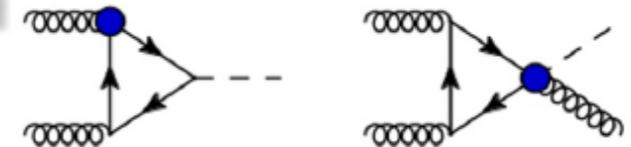
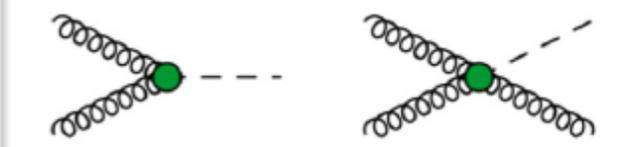
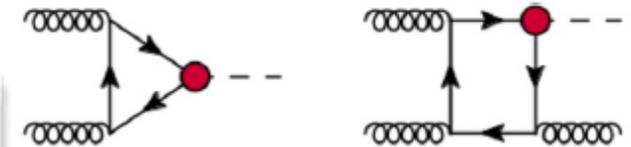
# ttH in the EFT



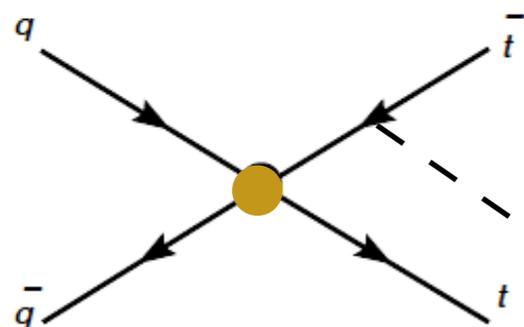
$$O_{t\phi} = y_t^3 (\phi^\dagger \phi) (\bar{Q}t) \tilde{\phi}$$

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

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

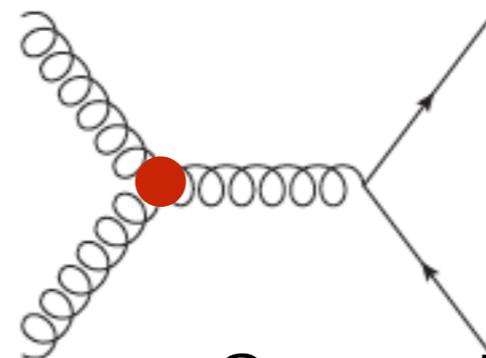


Also in H, H+j



4-fermion operators

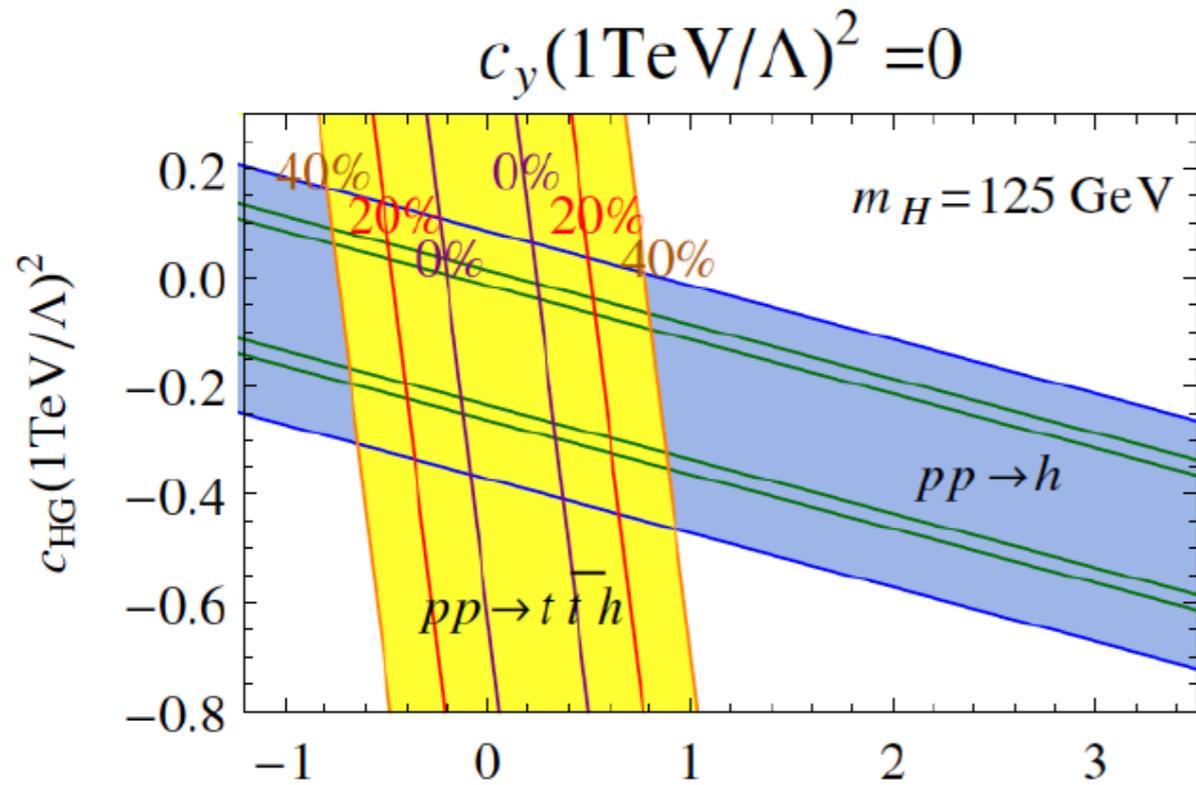
As in top pair



$$O_G = g_s f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$$

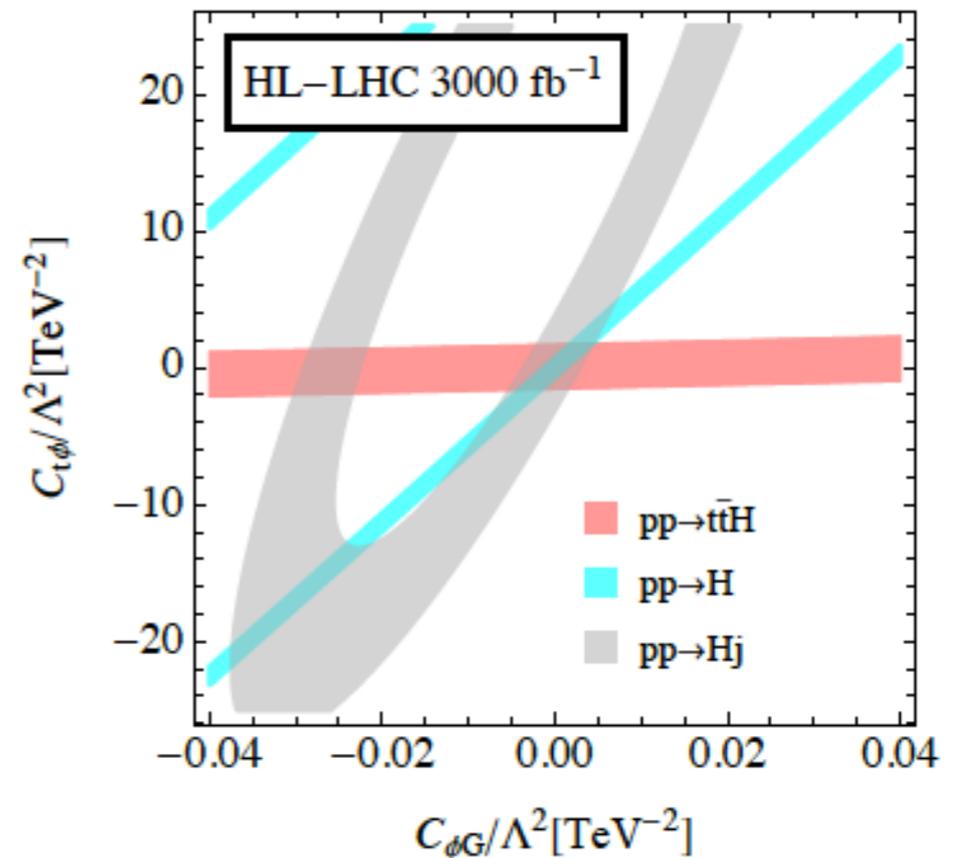
Constrained from multijets  
Krauss et al arXiv:1611.00767

# Impact of ttH on constraining dim-6



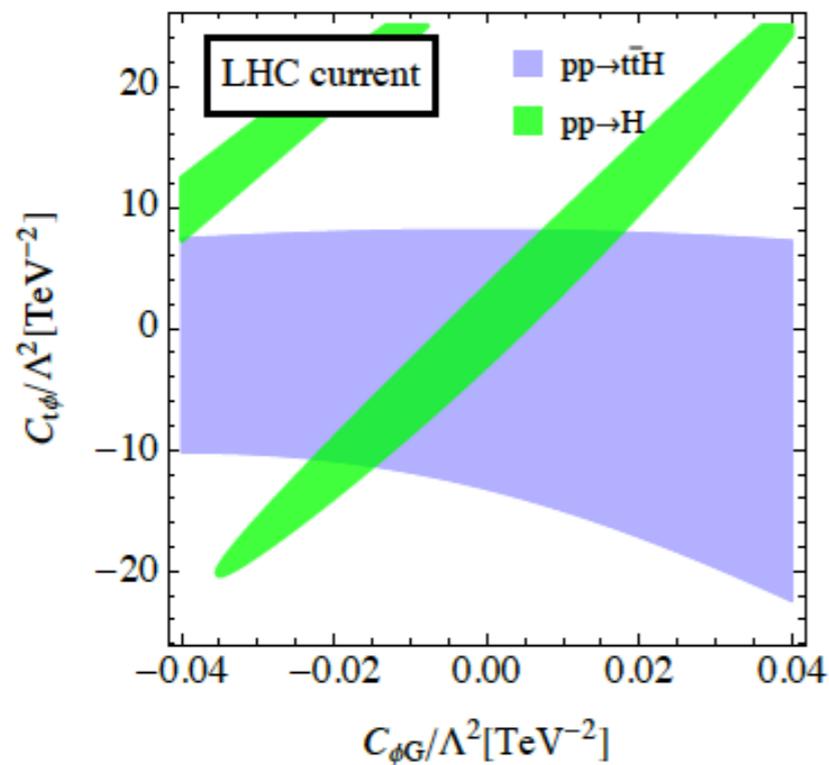
Use ttH

Degrande et al 1205.1065



Maltoni, EV, Zhang arXiv:1607.05330

Use boosted Higgs



Use inclusive H with 1) ttH and 2) boosted H production to break degeneracy between  $O_{t\phi}$  and  $O_{\phi G}$  operators

See also

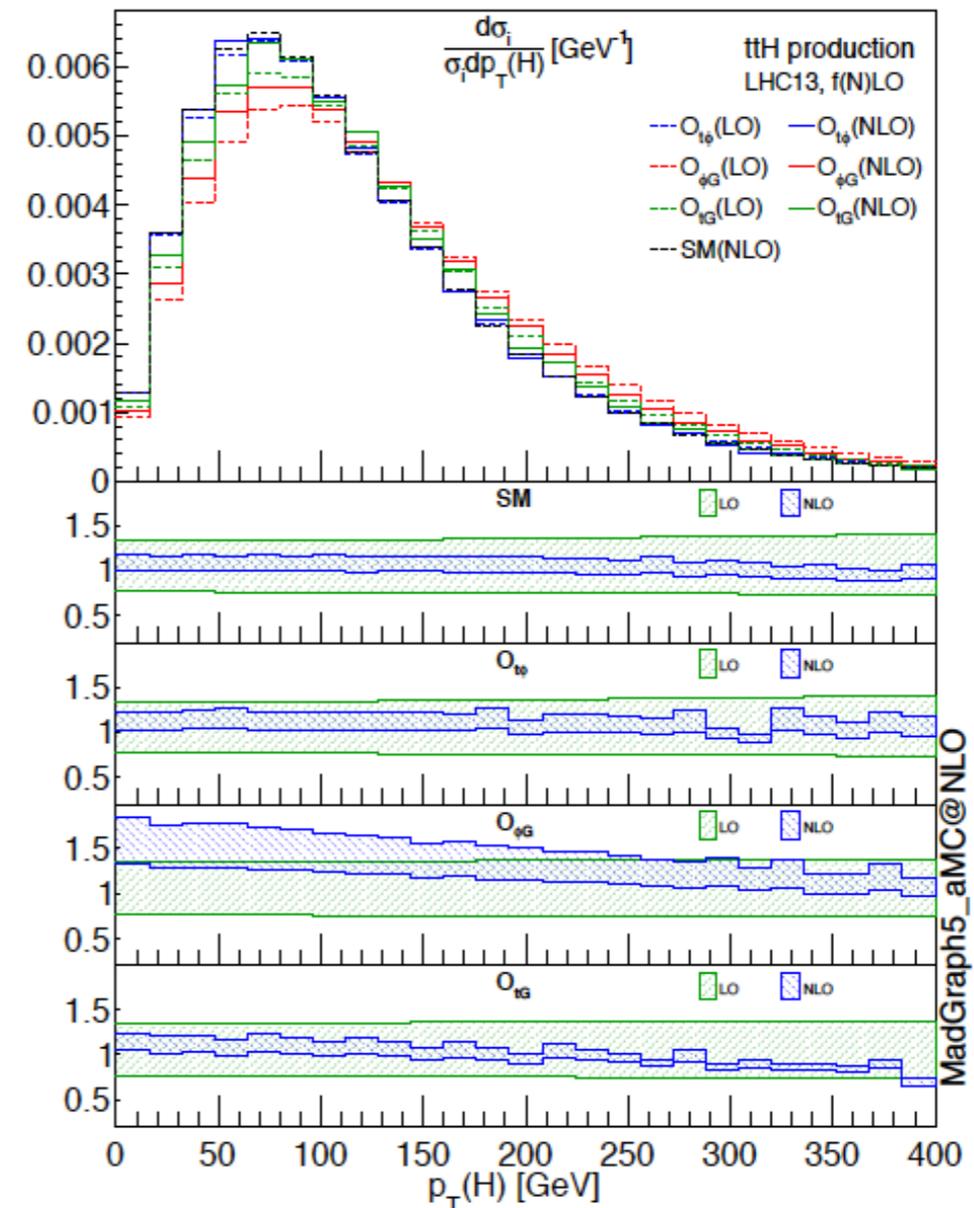
Grojean et al. arXiv:1312.3317

Azatov et al arXiv:1608.00977

# ttH@NLO in the EFT

NLO QCD corrections in the presence of dim-6 operators

13 TeV	$\sigma$ NLO	K
$\sigma_{SM}$	$0.507^{+0.030+0.000+0.007}_{-0.048-0.000-0.008}$	1.09
$\sigma_{t\phi}$	$-0.062^{+0.006+0.001+0.001}_{-0.004-0.001-0.001}$	1.13
$\sigma_{\phi G}$	$0.872^{+0.131+0.037+0.013}_{-0.123-0.035-0.016}$	1.39
$\sigma_{tG}$	$0.503^{+0.025+0.001+0.007}_{-0.046-0.003-0.008}$	1.07
$\sigma_{t\phi,t\phi}$	$0.0019^{+0.0001+0.0001+0.0000}_{-0.0002-0.0000-0.0000}$	1.17
$\sigma_{\phi G,\phi G}$	$1.021^{+0.204+0.096+0.024}_{-0.178-0.085-0.029}$	1.58
$\sigma_{tG,tG}$	$0.674^{+0.036+0.004+0.016}_{-0.067-0.007-0.019}$	1.04
$\sigma_{t\phi,\phi G}$	$-0.053^{+0.008+0.003+0.001}_{-0.008-0.004-0.001}$	1.42
$\sigma_{t\phi,tG}$	$-0.031^{+0.003+0.000+0.000}_{-0.002-0.000-0.000}$	1.10
$\sigma_{\phi G,tG}$	$0.859^{+0.127+0.021+0.017}_{-0.126-0.020-0.022}$	1.37



Different k-factors for the SM and dimension-6 contributions  
 Different k-factors for different operators

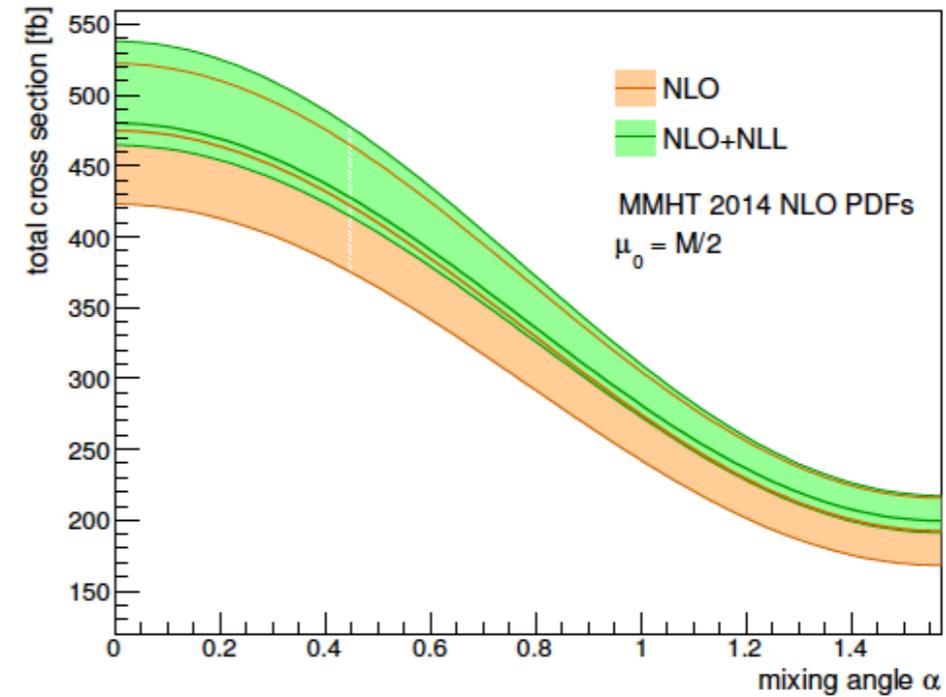
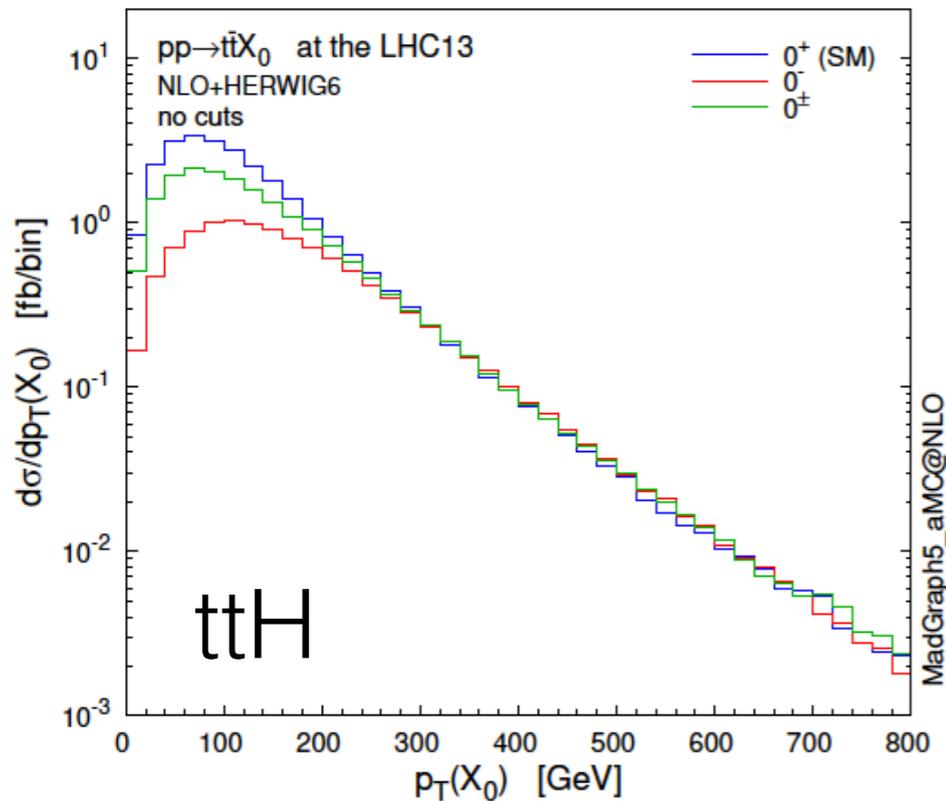


NLO is important when setting constraints

Maltoni, EV, Zhang: arXiv:1607.05330

# CP-violation in the top-Higgs sector

Yukawa  $-\bar{\psi}_t (c_\alpha \kappa_{Htt} g_{Htt} + i s_\alpha \kappa_{Att} g_{Att} \gamma_5) \psi_t X_0$

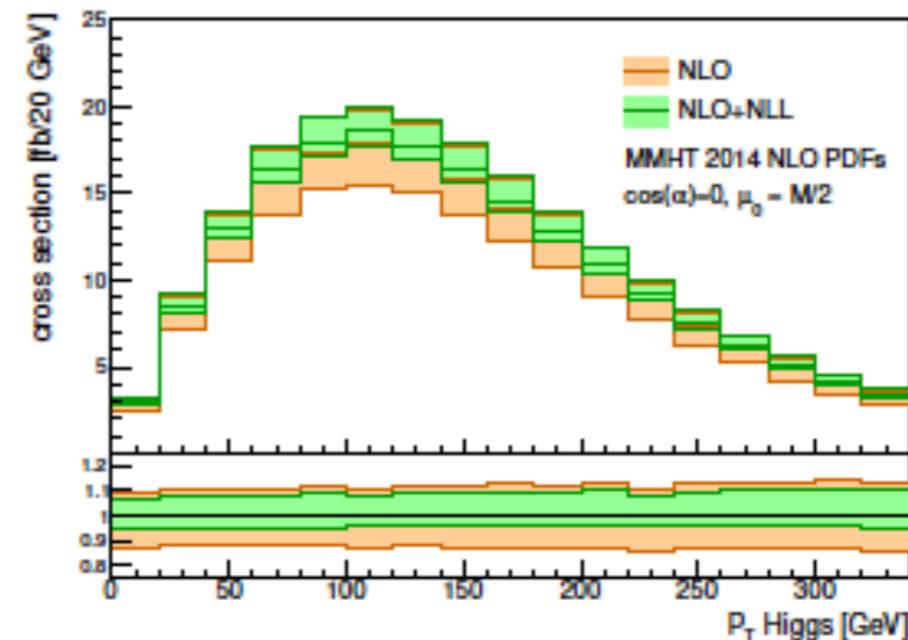


Broggio et al. arXiv:1707.01803

Studies within the HC model at NLO

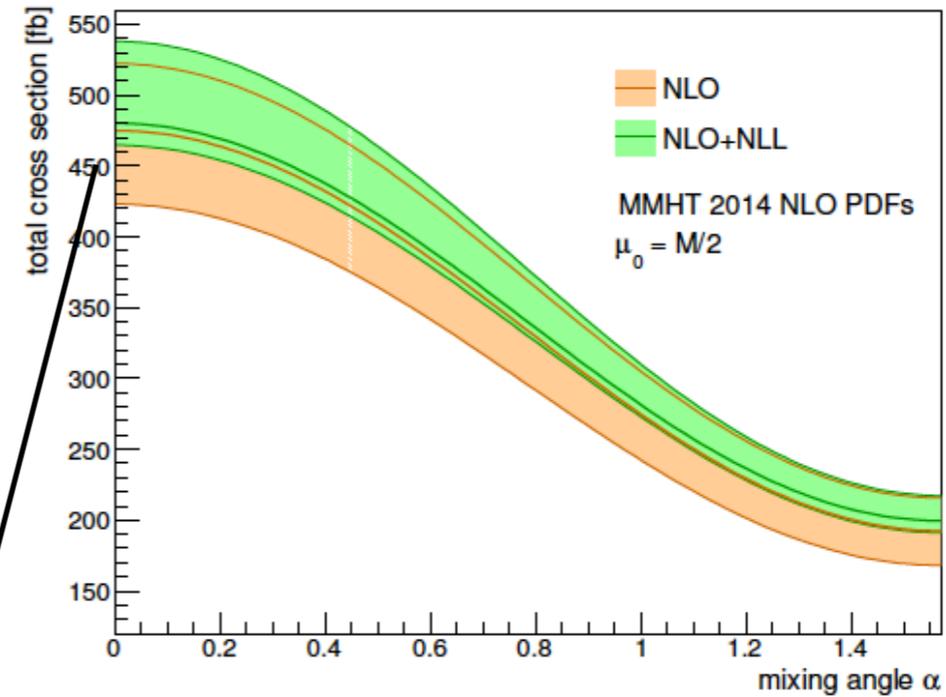
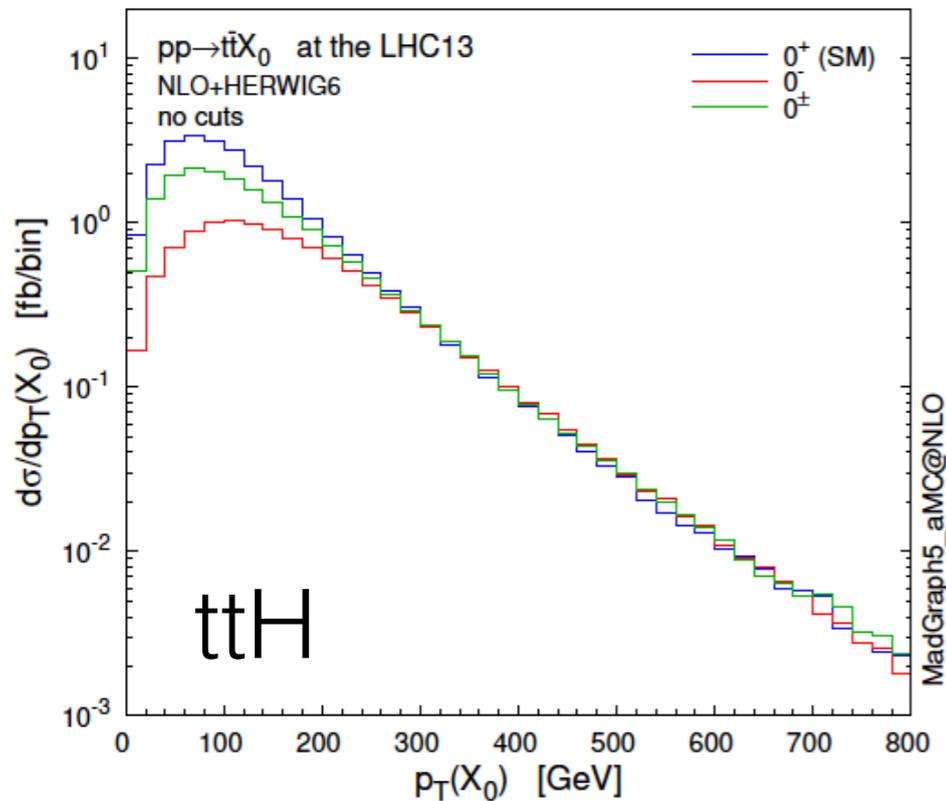
Demartin et al. arXiv:1504.00611,  
1407.5089

NLO+NLL	NLO	0	$480.3^{+57.8(12\%)}_{-15.6(3.2\%)}$
NLO+NLL	NLO	$\pi/2$	$199.6^{+17.7(8.9\%)}_{-8.4(4.2\%)}$



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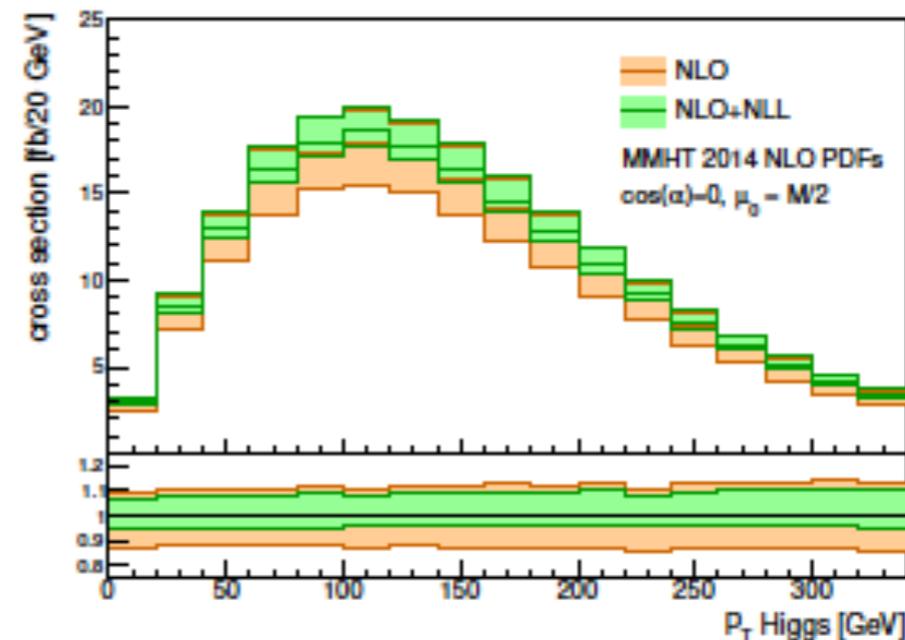


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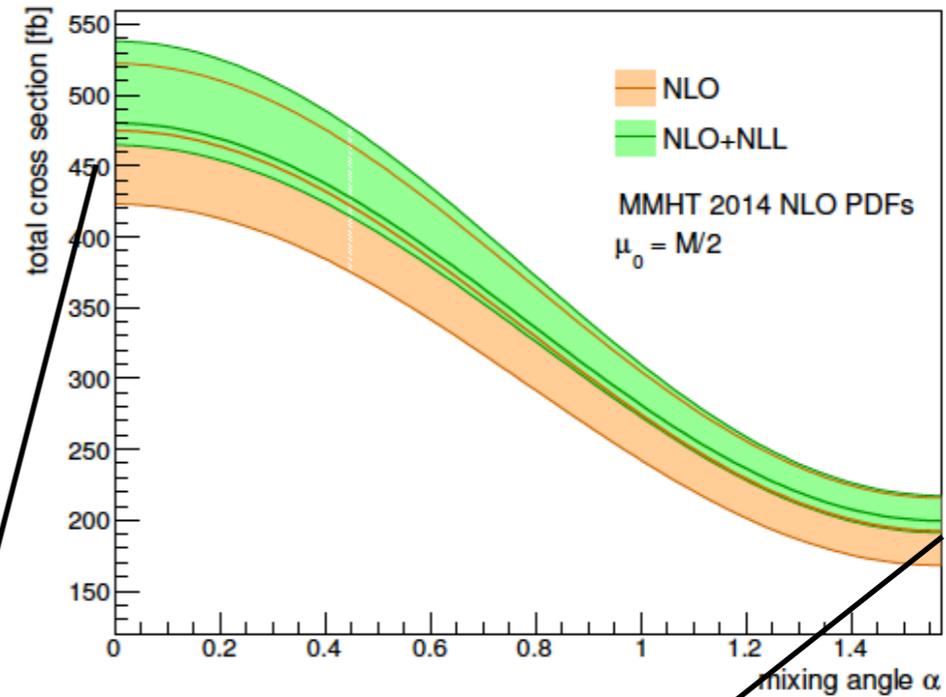
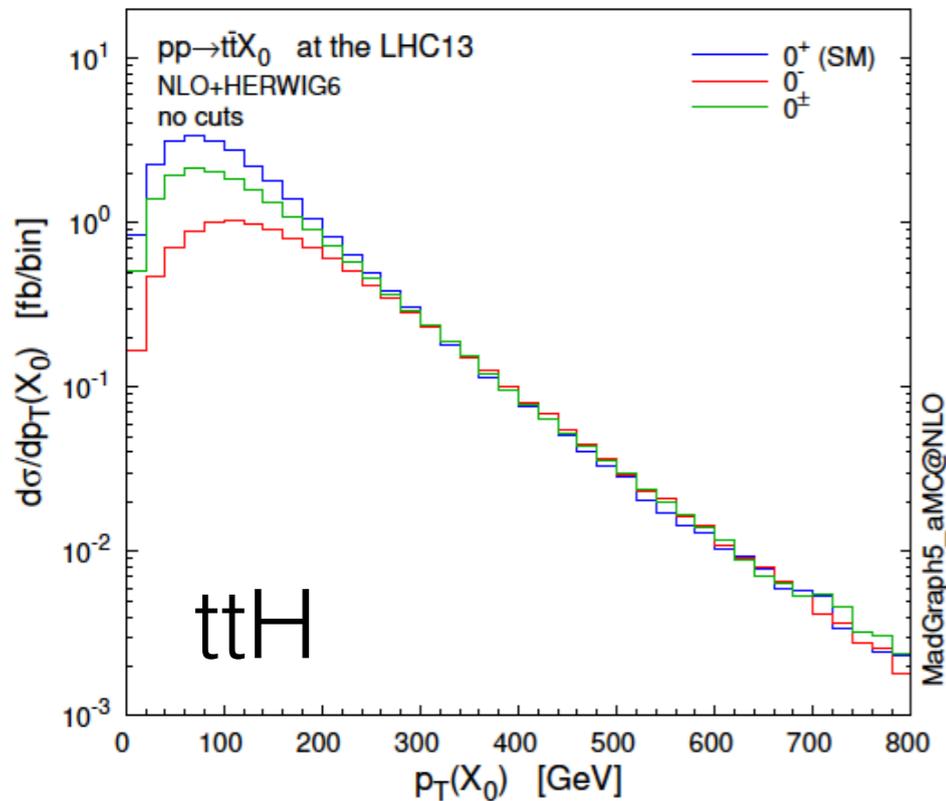
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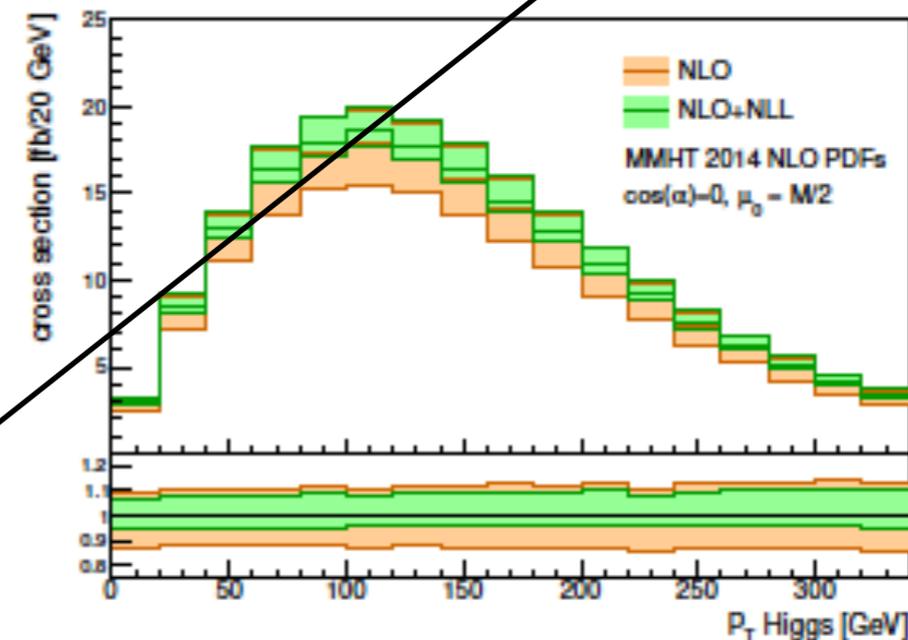


Broggio et al. arXiv:1707.01803

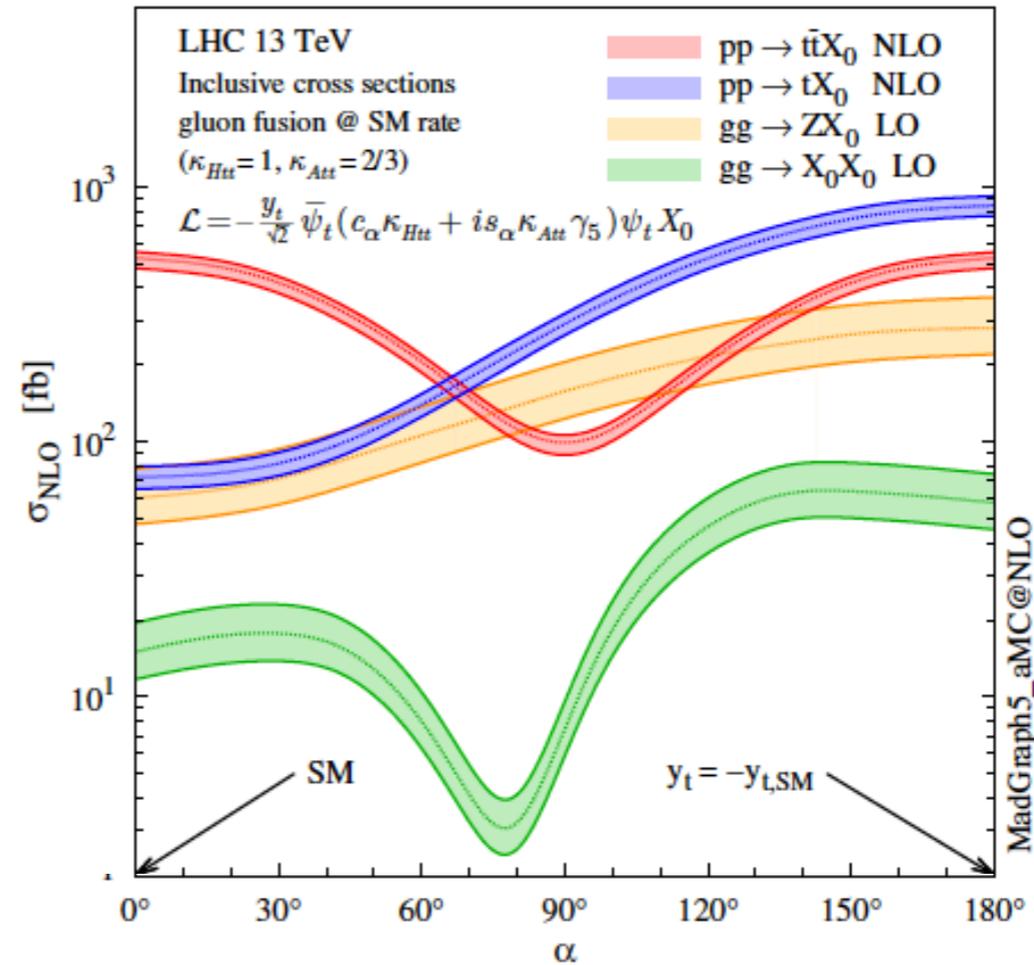
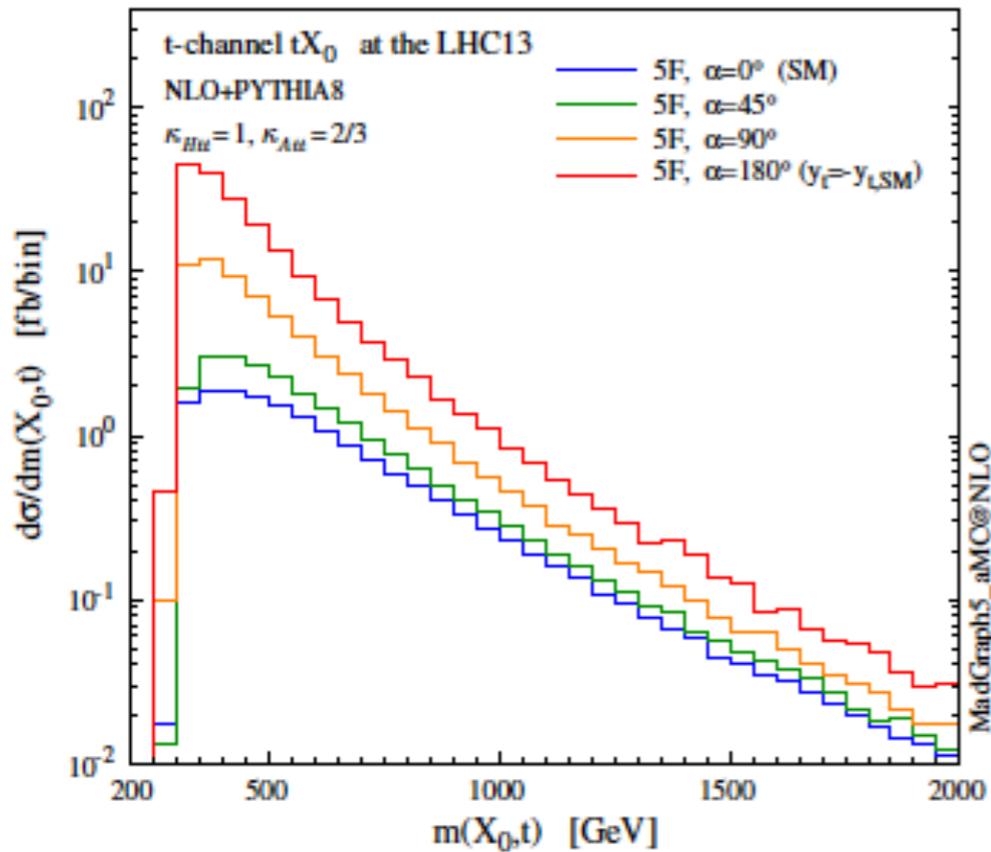
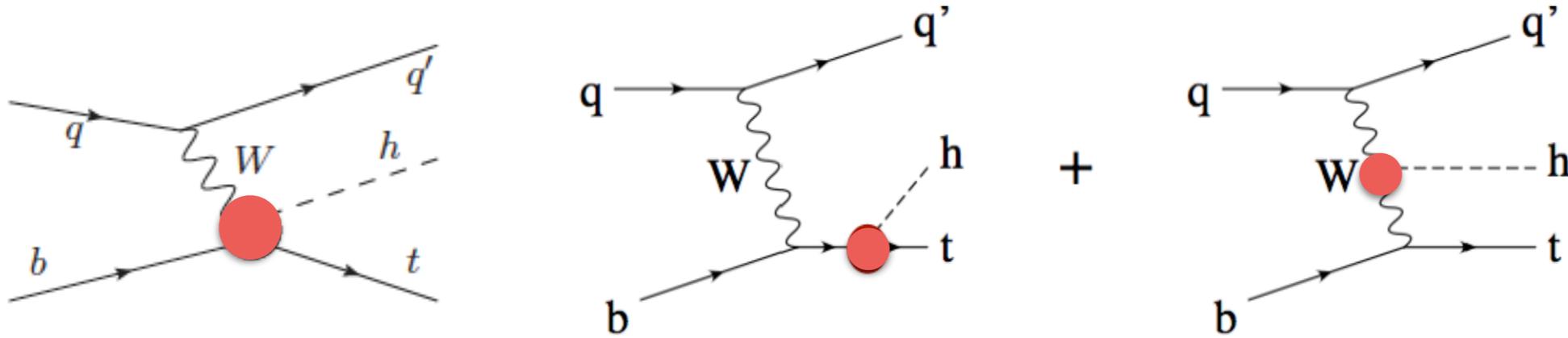
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# single top+Higgs



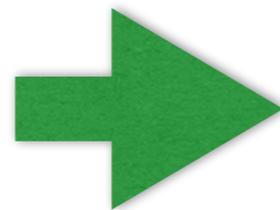
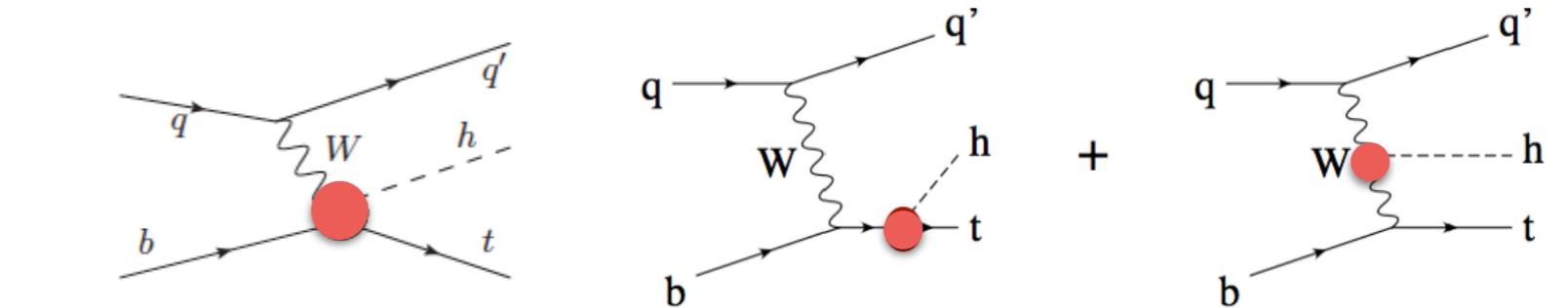
Higgs characterisation

Demartin et al. arXiv:1504.00611

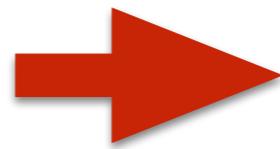
Single top Higgs: Unitarity violation in  $Wb \rightarrow th$  scattering

# single top+Higgs in the EFT

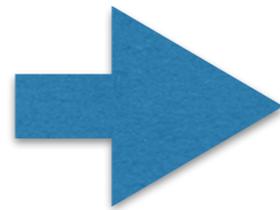
operator	$tHj$ inter	$tHj$ square
$\mathcal{O}_{\phi W}$	0.00693	0.00439
$\mathcal{O}_{\phi D}$	-0.0012	0.0000091
$\mathcal{O}_{\phi WB}$	0.00319	0.000150
$\mathcal{O}_{t\phi}$	-0.00105	0.000485
$\mathcal{O}_{tW}$	0.00872	0.0108
$\mathcal{O}_{\phi dQL}^{(3)}$	-0.000449	0.000552
$\mathcal{O}_{\phi dq}^{(3)}$	-0.00169	0.00233



Higgs weak boson couplings



Top Yukawa



Top weak couplings

$$\mathcal{O}_{\phi D} = (\phi^\dagger D_\mu \phi)^\dagger (\phi^\dagger D^\mu \phi)$$

$$\mathcal{O}_{\phi W} = \left(\phi^\dagger \phi - \frac{v^2}{2}\right) W_i^{\mu\nu} W_{\mu\nu}^i$$

$$\mathcal{O}_{\phi WB} = (\phi^\dagger W^{\mu\nu} \phi) B_{\mu\nu}$$

$$\mathcal{O}_{t\phi} = \left(\phi^\dagger \phi - \frac{v^2}{2}\right) \bar{Q}_L t_R \tilde{\phi}$$

$$\mathcal{O}_{tW} = Q_L \sigma_{\mu\nu} W^{\mu\nu} t_R \phi$$

$$\mathcal{O}_{\phi dq}^{(3)} = i \left(\phi^\dagger i \overleftrightarrow{D}_\mu^i \phi\right) \bar{q}_L \gamma^\mu \sigma^i q_L$$

$$\mathcal{O}_{\phi dQL}^{(3)} = i \left(\phi^\dagger i \overleftrightarrow{D}_\mu^i \phi\right) \bar{Q}_L \gamma^\mu \sigma^i Q_L$$

NLO QCD computation including all operators in progress:  
 Degrande, Maltoni, Mimasu, EV, Zhang

# Summary

- Significant progress for precise predictions for top Higgs associated production:
  - QCD corrections: NLO, NLO+PS, resummation
  - EW corrections
  - Physical states: decay and off-shell effects
- Higher-order corrections needed to match improving experimental accuracy and reliably describe distributions
- Progress in theoretical modelling of the background needed to quantify/reduce systematic uncertainties
  - detailed study and comparisons of MC generators
  - towards more realistic simulations of the  $t\bar{t}b\bar{b}$  state
- Phenomenological studies of  $t(t)H$  in the presence of new physics interactions, allow setting constraints on new physics effects

Thank you for your attention