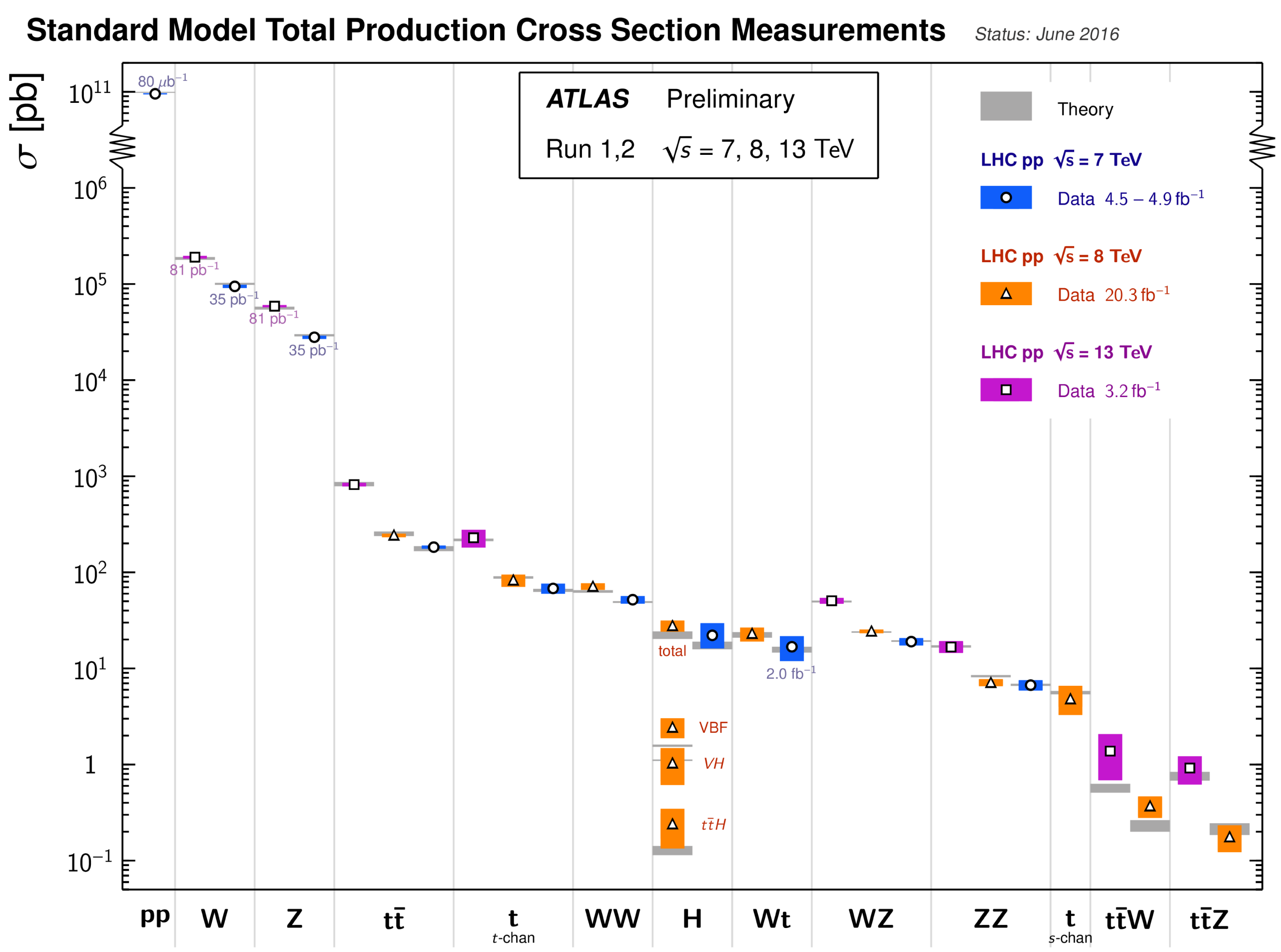
Progress in top quark physics

Eleni Vryonidou
Nikhef

LES RENCONTRES DE PHYSIQUE DE LA VALLEE D'AOSTE
La Thuile
9/3/2016

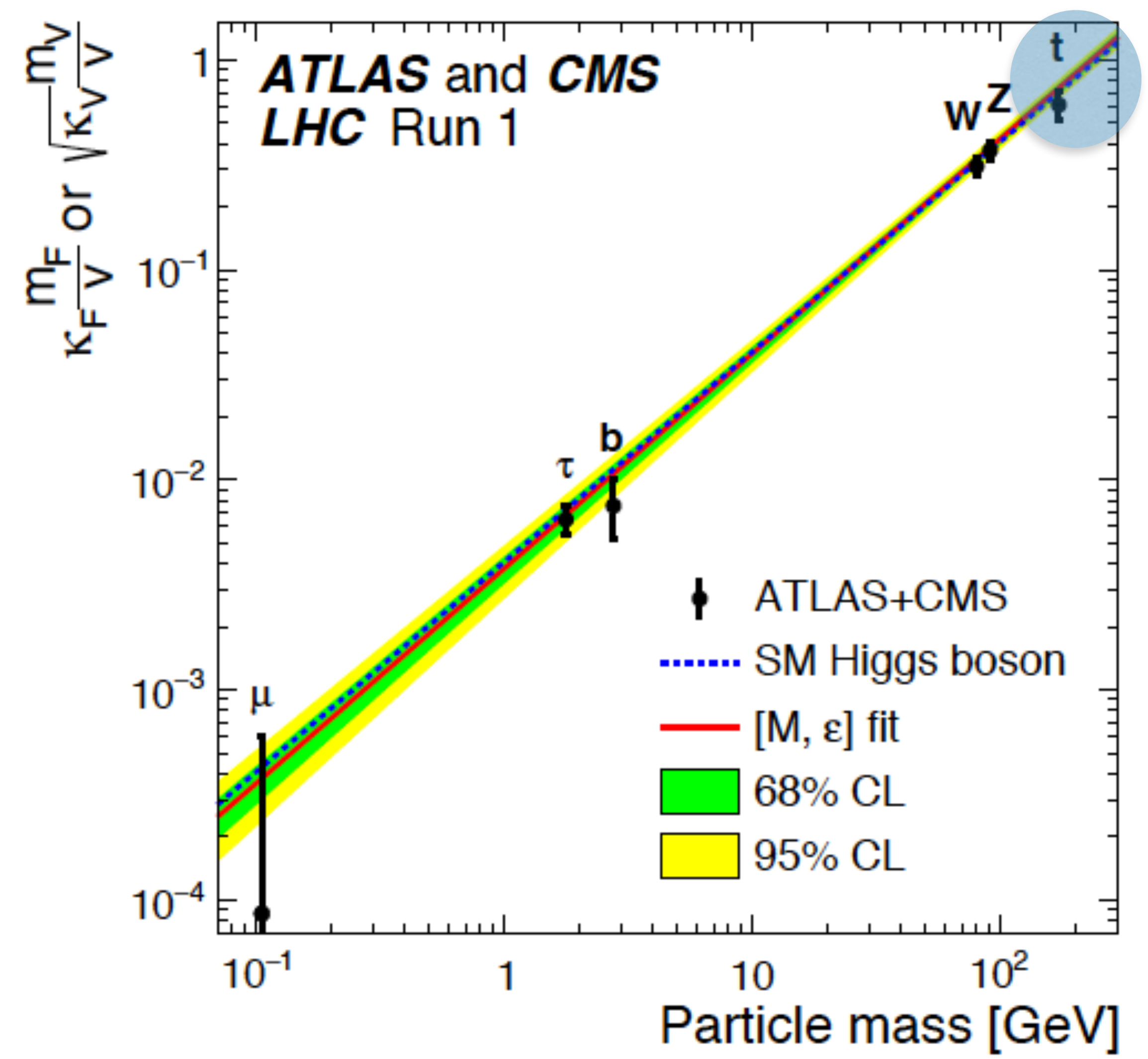
LHC: the story so far

Rediscovering the SM



Good agreement with the SM predictions

Higgs discovery



Search for New Physics continues

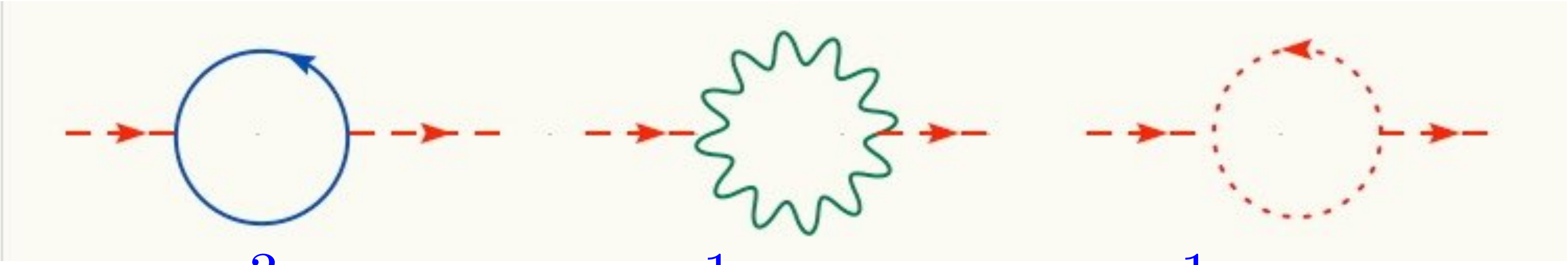
Top quark physics

Why is the top quark special-given the 125 GeV Higgs?

1. The heaviest SM quark ➡ Strong interaction with the Higgs: y_t=1

A special role in EWSB?

Important for stabilising the Higgs mass: top partners?



$$m_H^2 = m_{H0}^2 \quad - \frac{3}{8\pi^2} y_t \Lambda^2 \quad + \frac{1}{16\pi^2} g^2 \Lambda^2 \quad + \frac{1}{16\pi^2} \lambda^2 \Lambda^2$$

$$(125\,\mathrm{GeV})^2 = m_{H0}^2 + \left[-(2\,\mathrm{TeV})^2 + (700\,\mathrm{GeV})^2 + (500\,\mathrm{GeV})^2\right] \left(\frac{\Lambda}{10\mathrm{TeV}}\right)^2$$

2. Decay before hadronisation

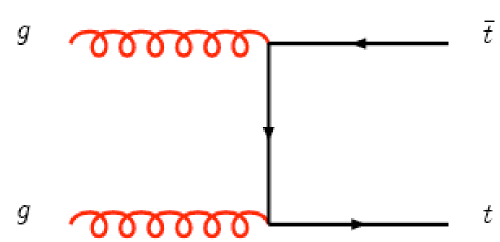
$\tau_{top} \approx h/\,\Gamma_{top} = 1/(G_F\, m_t^3\, |V_{tb}|^2/8\pi\sqrt{2}) \approx 5 \bullet 10^{-25}$ s

spin correlations

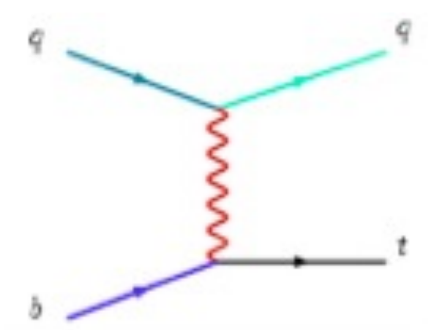
Top quark physics at the LHC

3. Rich phenomenology at the LHC:

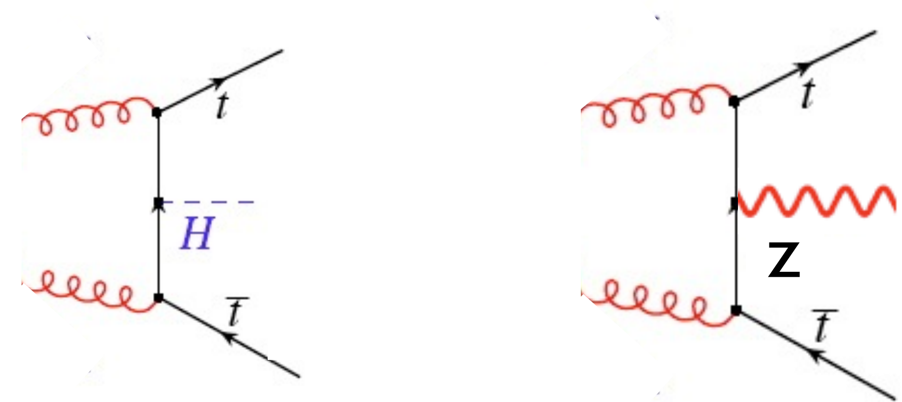
pair production



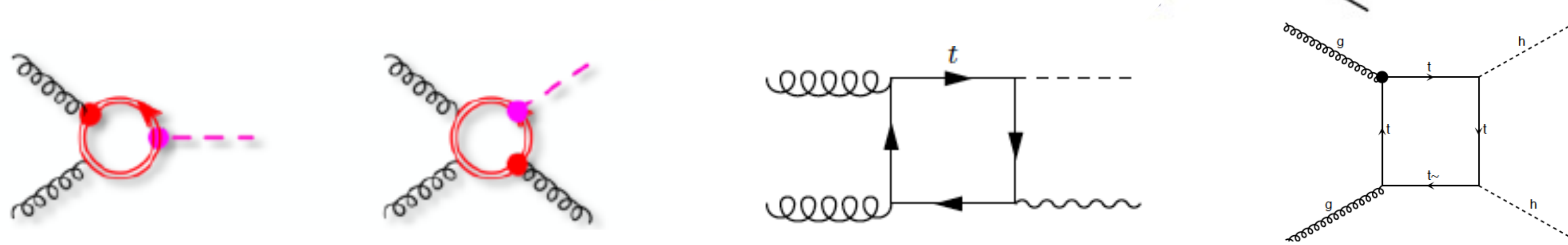
single



associated production



top loops



Millions of top quarks at the LHC: precise measurements

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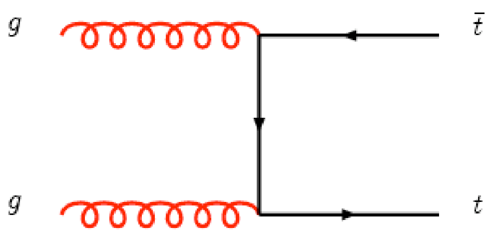
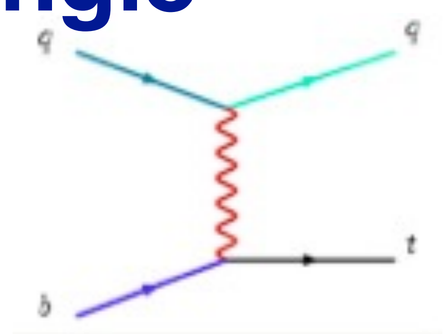
Precision top calculations

pair production



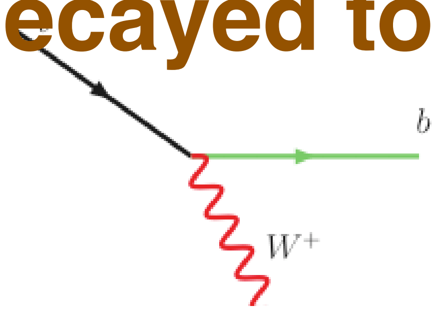
NNLO QCD: inclusive and differential
Czakon, Mitov et al arXiv: 1204.5201,1303.6254,1601.05375,1606.03350
NNLL resummation (also for boosted): Ferroglia et al arXiv:1601.07020
Precision allows constraints set on PDFs using tt measurements: Czakon et al. arXiv:1611.08609

single



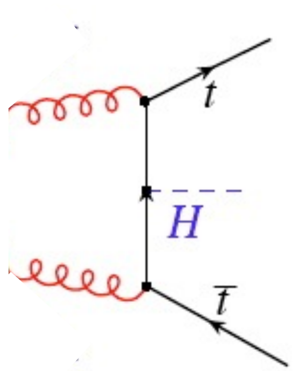
NNLO fully differential: Berger et al arXiv:1606.08463 (decays in NWA)
NLO+PS including off-shell, interference effects Frederix et al arXiv:1603.01178 (MG5@MC) Jezo et al arXiv:1607.04538 (Powheg)

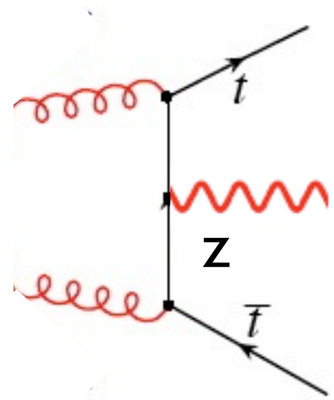
decayed tops



Physical final states: $t\bar{t}$ is $e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$
QCD and EW corrections for physical final states
Denner et al arXiv:1012.3975,1607.05571
Bevilacqua et al arXiv:1012.4230,1609.01659

Associated production





t(t)+X with X=H,Z,photon,W
actively studied and searched for

Why?

- $t(\bar{t})V$: Direct probe of top couplings to the EW gauge bosons
- $t(\bar{t})H$: Direct probe of top Yukawa coupling
- $t\bar{t}V(V)$: main background for $t\bar{t}H$ searches
- tops+V(s): Important as a signal as well as a background for BSM scenarios with high multiplicity signatures
- High threshold processes: accessible for the first time at the LHC, important for LHC13

Precision: NLO+PS (+NNLL)

Status of precision studies for t(t)V(V)

tH	tZ	tWH
QCD: NLO+PS MG5_aMC@NLO: Demartin et al. arXiv:1504.00611	QCD: NLO+PS MG5_aMC@NLO:arXiv:1405.0301 MCFM: arXiv:1302.3856	QCD: NLO+PS MG5_aMC@NLO: Demartin et al arXiv:1607.05862
$t\bar{t}H$ 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	$t\bar{t}Z/W$ QCD: NLO+PS aMC@NLO: arXiv:1103.0621 PowHel: arXiv:1111.1444, 1208.2665 Soft gluon resummation for ttW: Broggio et al. arXiv:1607.05303 NLO EW: Frixione et al. arXiv:1504.03446	$t\bar{t}ZZ$, $t\bar{t}WW$, $t\bar{t}WZ$ $t\bar{t}Z\gamma$, $t\bar{t}W\gamma$ QCD: NLO+PS MG5_aMC@NLO: Maltoni et al. arXiv:1507.05640
	$t\bar{t}\gamma$ QCD: NLO+PS aMC@NLO: arXiv:1103.0621 PowHel: arXiv:1406.2324	$t\bar{t}\gamma\gamma$ NLO+PS PowHel: Kardos et al. arXiv: 1408.0278 aMC@NLO: Maltoni et al. arXiv: 1507.05640 van Deurzen et al. arXiv: 1509.02077

What’s next?

SM: precision for top processes

- QCD, EW corrections
- Resummation
- Off-shell and interference effects
- Monte Carlo tools

Needed to realistically describe top quark processes at the LHC

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→

SM precision allows us to use top production and decay as a probe of new physics

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→ SM precision allows us to use top production and decay as a probe of new physics

↓ Look for deviations from SM predictions in LHC measurements

What's next?

SM: precision for top processes

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Needed to realistically describe top quark processes at the LHC

SM precision allows us to use top production and decay as a probe of new physics

Look for deviations from SM predictions in LHC measurements

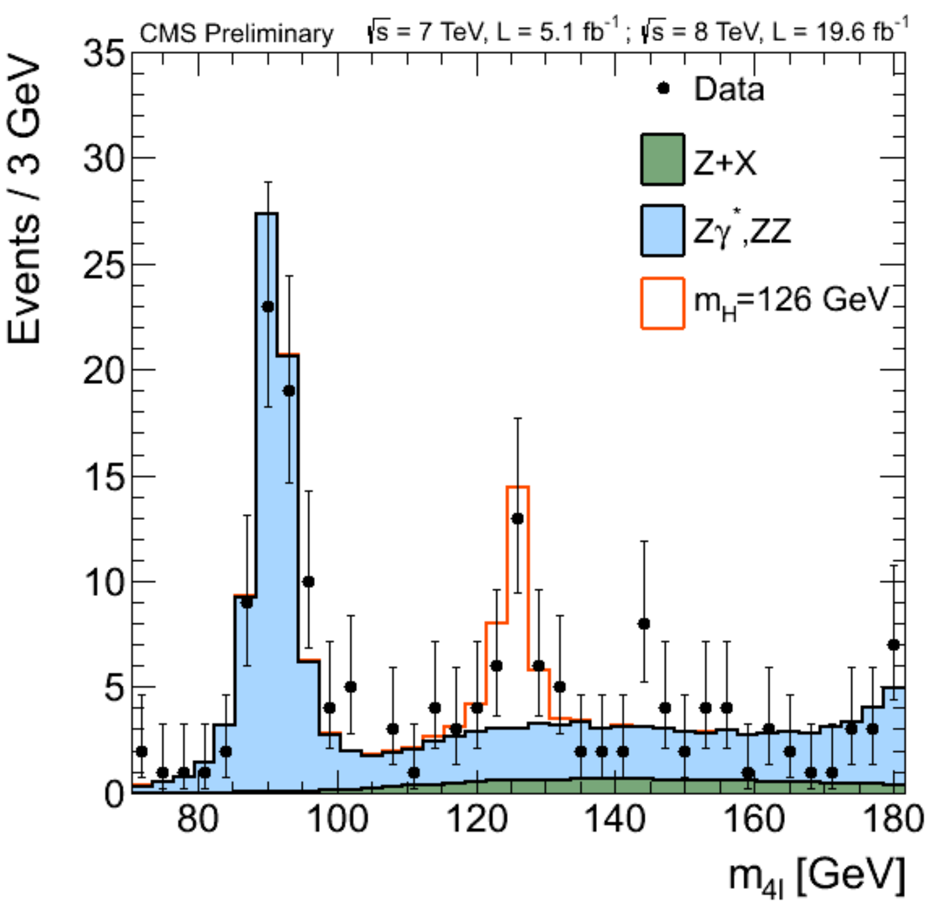
How do we look for new physics?
A BSM strategy needed

How to look for new physics?

Model-dependent

SUSY, 2HDM…

New particles



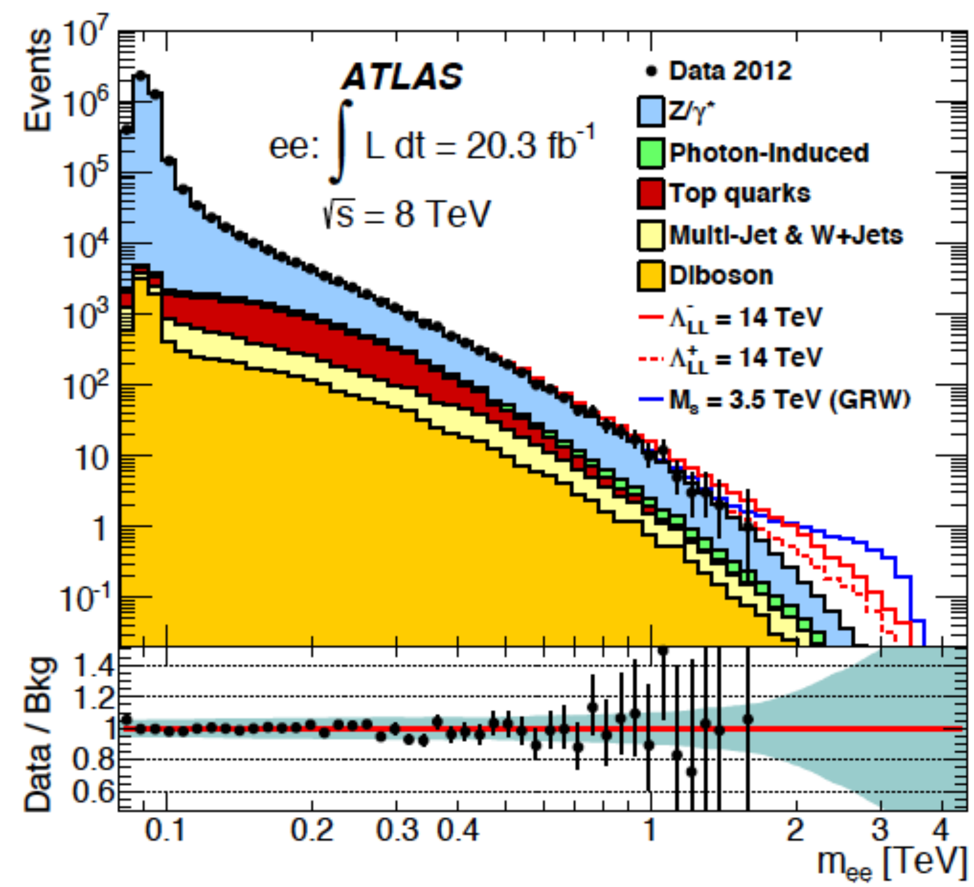
Resonance peaks

Model-Independent

simplified models,EFT

New Interactions of SM particles

anomalous couplings, EFT



Typically deviations in tails

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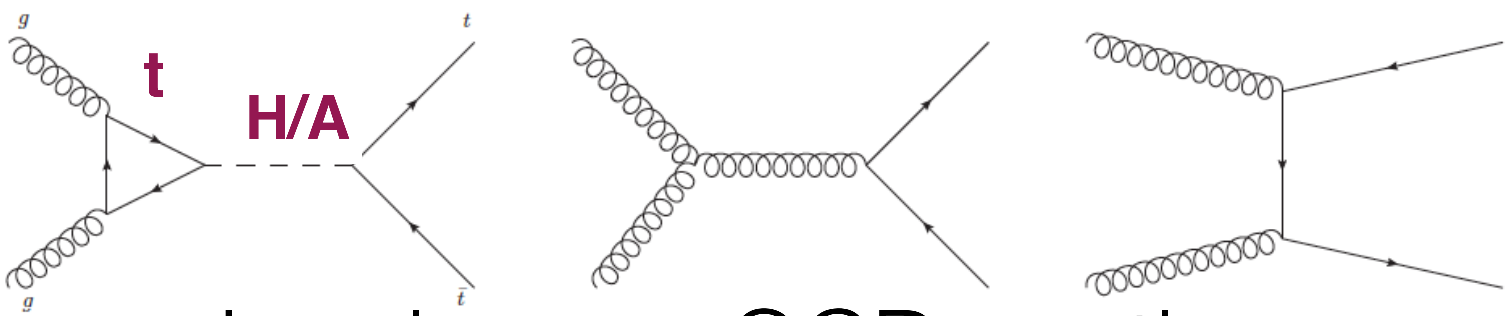
Model dependent
An example: Resonances in ttbar

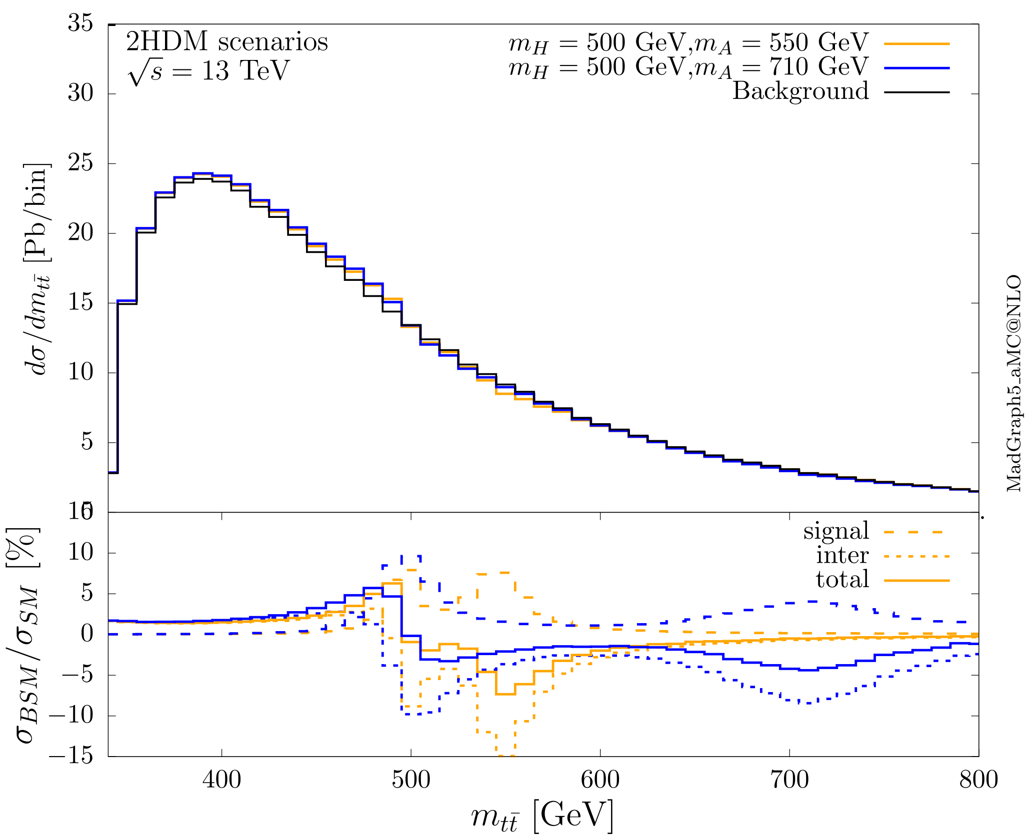


signal QCD continuum

Scalar or pseudoscalar resonance
Interference important for the line shape for widths~0.01M

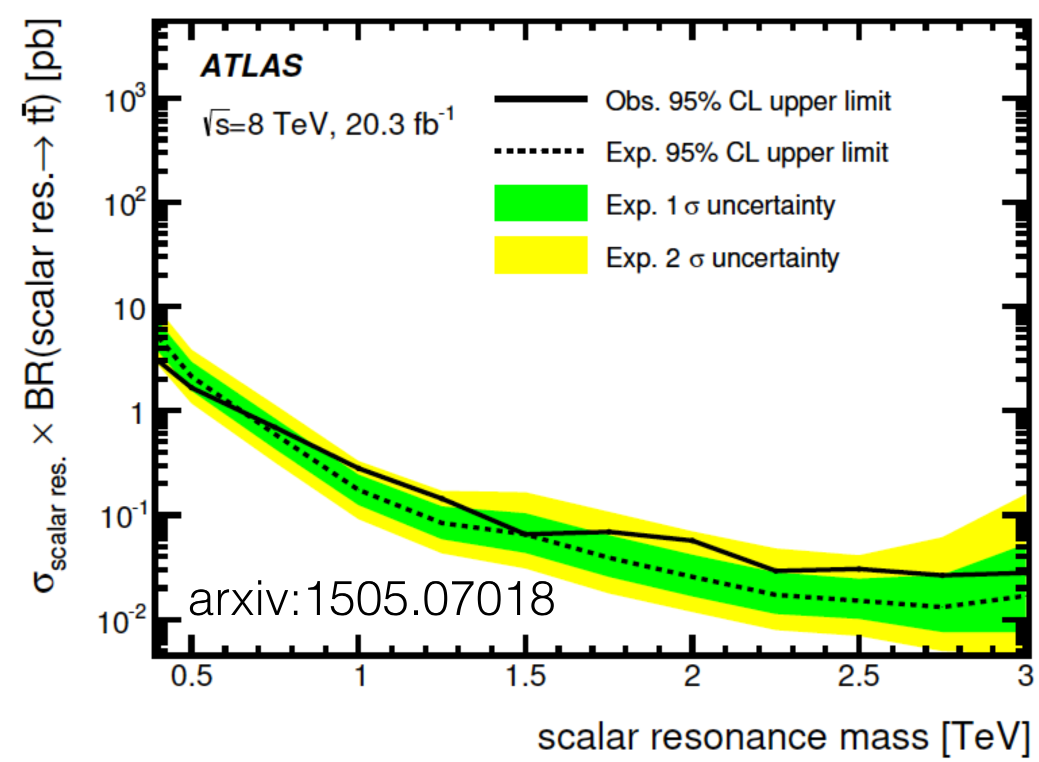
Peak-dip structures

2HDM: H and A states



Hespel, Maltoni, EV arXiv:1606.04149

ATLAS Searches



See also Ellis, Djouadi, Quevillon arXiv:1605.00542 Carena, Liu arXiv: 1608.07282, Bernreuther et al. arXiv:1511.0558

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New physics without new light particles

- No new light states

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

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
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}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

Top-quark operators and how to look for them

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

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

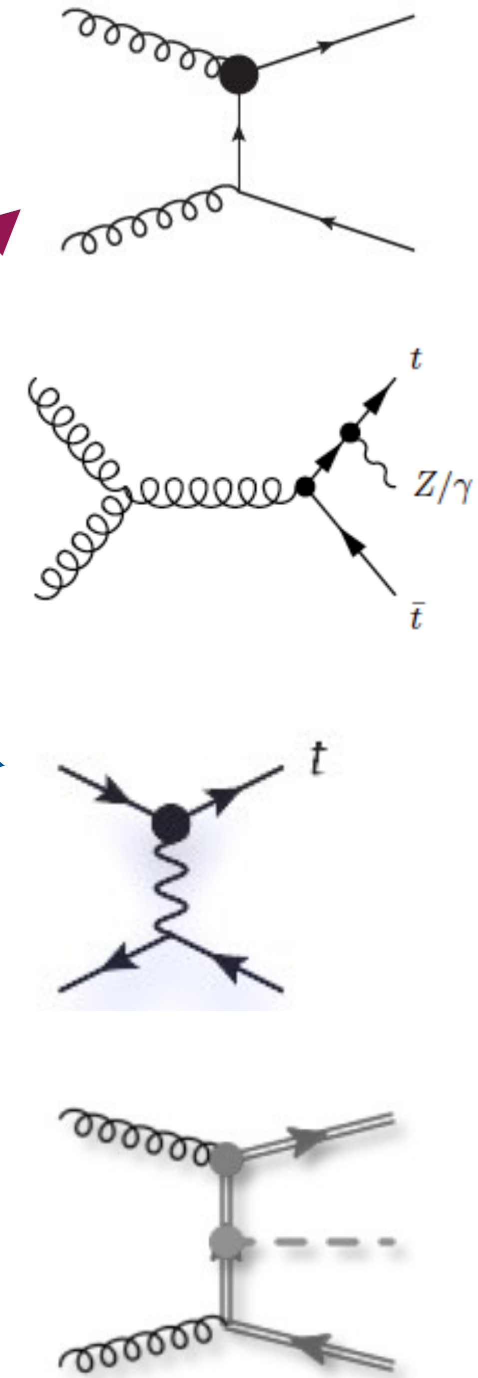
$$O_{\varphi t} = i\frac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right) (\bar{t}\gamma^\mu t)$$

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

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

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

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



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

+four-fermion operators
+FCNC

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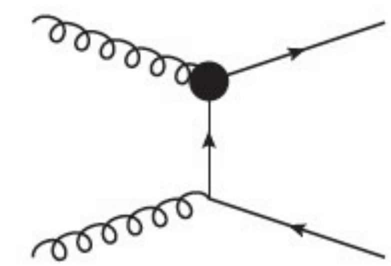
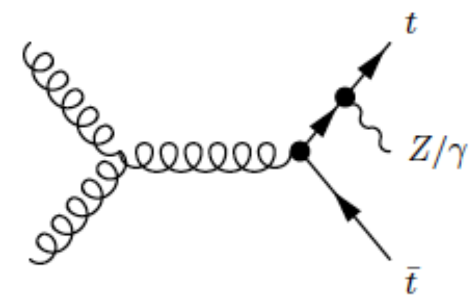
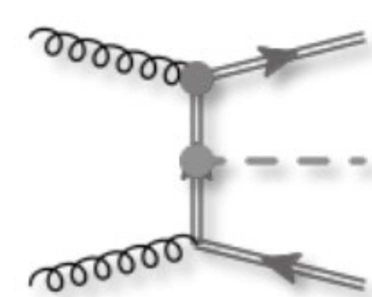
$$O_{tG} = y_t g_s(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}\,,$$

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







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+four-fermion operators
+FCNC

Operators entering various processes: Global approach needed

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Towards global fits

EFT only makes sense if we follow a global approach

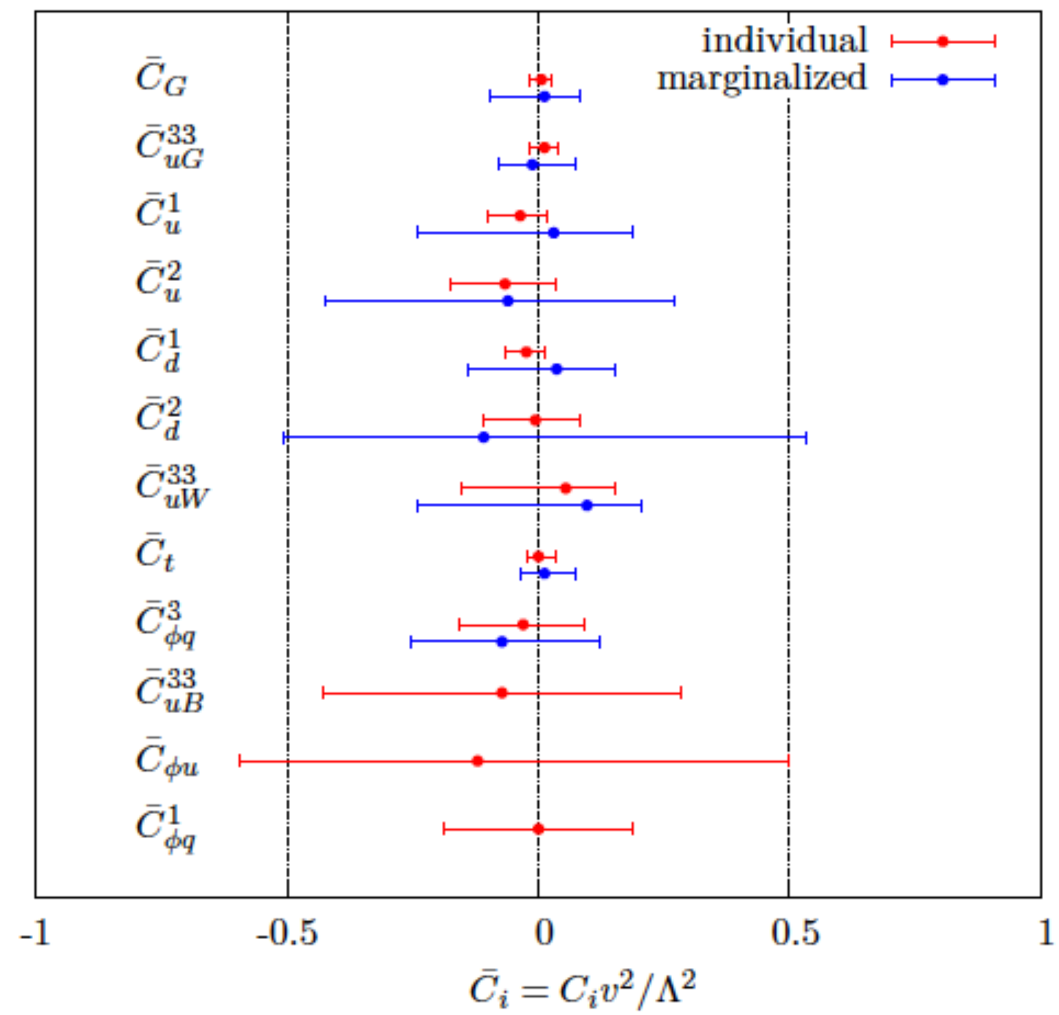
First work towards global fits:

TopFitter: Buckley et al arxiv:1506.08845 and 1512.03360

Dataset	$\sqrt{s}$ (TeV)	Measurements	arXiv ref.	Dataset	$\sqrt{s}$ (TeV)	Measurements	arXiv ref.
Top pair production							
Total cross-sections:				Differential cross-sections:			
ATLAS	7	lepton+jets	1406.5375	ATLAS	7	$p_T(t)$, $M_{t\bar{t}}$, $\|y_{t\bar{t}}\|$	1407.0371
ATLAS	7	dilepton	1202.4892	CDF	1.96	$M_{t\bar{t}}$	0903.2850
ATLAS	7	lepton+tau	1205.3067	CMS	7	$p_T(t)$, $M_{t\bar{t}}$, y_t, $y_{t\bar{t}}$	1211.2220
ATLAS	7	lepton w/o b jets	1201.1889	CMS	8	$p_T(t)$, $M_{t\bar{t}}$, y_t, $y_{t\bar{t}}$	1505.04480
ATLAS	7	lepton w/ b jets	1406.5375	DØ	1.96	$M_{t\bar{t}}$, $p_T(t)$, $\|y_t\|$	1401.5785
ATLAS	7	tau+jets	1211.7205				
ATLAS	7	$t\bar{t}$, $Z\gamma$, WW	1407.0573	Charge asymmetries:			
ATLAS	8	dilepton	1202.4892	ATLAS	7	A_C (inclusive+$M_{t\bar{t}}$, $y_{t\bar{t}}$)	1311.6742
CMS	7	all hadronic	1302.0508	CMS	7	A_C (inclusive+$M_{t\bar{t}}$, $y_{t\bar{t}}$)	1402.3803
CMS	7	dilepton	1208.2761	CDF	1.96	A_{FB} (inclusive+$M_{t\bar{t}}$, $y_{t\bar{t}}$)	1211.1003
CMS	7	lepton+jets	1212.6682	DØ	1.96	A_{FB} (inclusive+$M_{t\bar{t}}$, $y_{t\bar{t}}$)	1405.0421
CMS	7	lepton+tau	1203.6810				
CMS	7	tau+jets	1301.5755	Top widths:			
CMS	8	dilepton	1312.7582	DØ	1.96	Γ_{top}	1308.4050
CDF + DØ	1.96	Combined world average	1309.7570	CDF	1.96	Γ_{top}	1201.4156
Single top production				W-boson helicity fractions:			
ATLAS	7	t-channel (differential)	1406.7844	ATLAS	7		1205.2484
CDF	1.96	s-channel (total)	1402.0484	CDF	1.96		1211.4523
CMS	7	t-channel (total)	1406.7844	CMS	7		1308.3879
CMS	8	t-channel (total)	1406.7844	DØ	1.96		1011.6549
DØ	1.96	s-channel (total)	0907.4259				
DØ	1.96	t-channel (total)	1105.2788				
Associated production				*Run II data*			
ATLAS	7	$t\bar{t}\gamma$	1502.00586	CMS	13	$t\bar{t}$ (dilepton)	1510.05302
ATLAS	8	$t\bar{t}Z$	1509.05276				
CMS	8	$t\bar{t}Z$	1406.7830				

Tevatron and LHC data

Cross-sections and distributions



Limits on Wilson coefficients

How can we improve the fits?

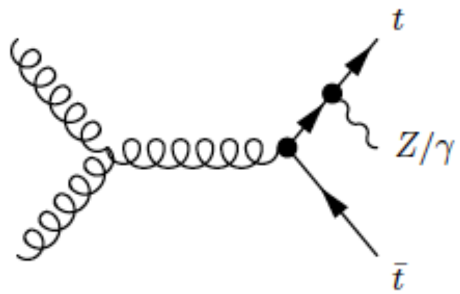
- Need at least NLO in QCD to match the SM precision and experimental accuracy: SMEFT@NLO

Recent progress:

- top pair production: Franzosi and Zhang (arxiv:1503.08841)
- single top production: C. Zhang (arxiv:1601.06163)
- ttZ/γ: O. Bylund, F. Maltoni, I. Tsinikos, EV, C. Zhang (arXiv:1601.08193)
- ttH: F. Maltoni, EV, C. Zhang (arXiv:1607.05330)

All automated within MadGraph5_aMC@NLO
NLO+PS: realistic simulations
R2+UV counterterms: NLOCT Degrande (arxiv:1406.3030)

Top pair + Z/γ



probe of top neutral couplings: ttZ,ttγ,ttg

SM σ(ttZ)=0.88 pb at 13TeV
LHC (ATLAS): σ(ttZ) =0.92±0.29(stat)±0.10(syst) pb

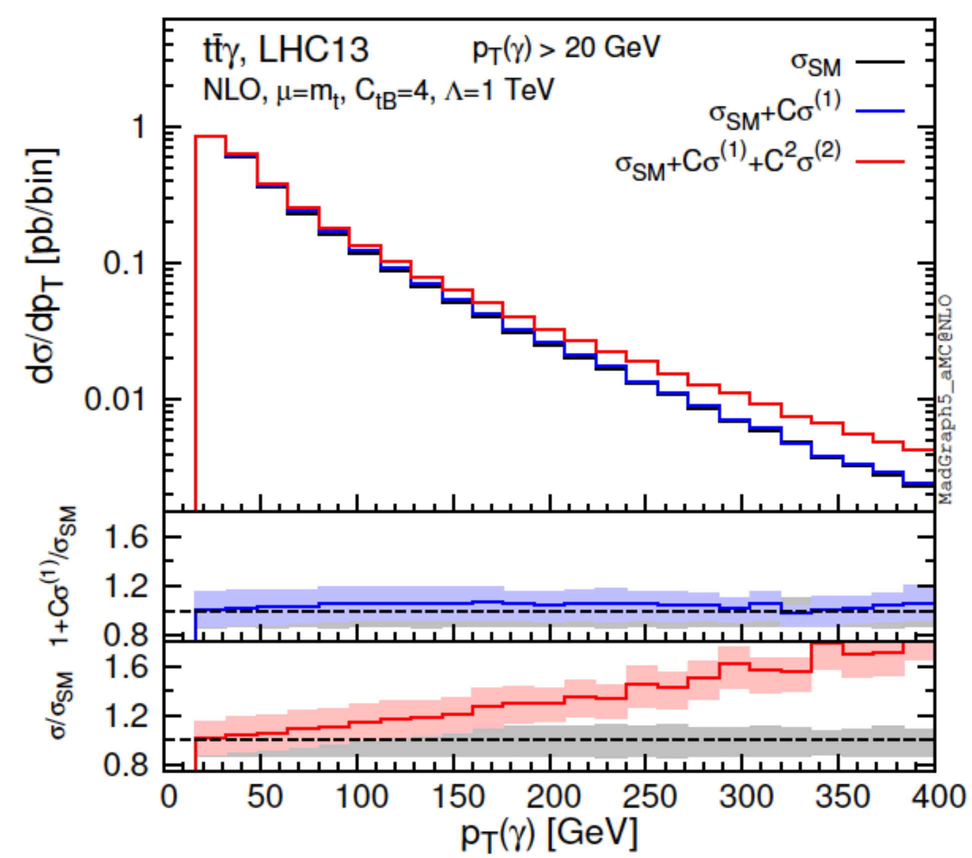
operators

$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu \tau^I Q)$$
$$O_{\varphi Q}^{(1)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{Q}\gamma^\mu Q)$$
$$O_{\varphi t} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$
$$O_{tW} = y_t g_w(\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}$$
$$O_{tB} = y_t g_Y(\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu}$$
$$O_{tG} = y_t g_s(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}\,,$$

$$\sigma = \sigma_{SM} + \sum_i \frac{C_i}{(\Lambda/1\text{TeV})^2}\sigma_i^{(1)} + \sum_{i\le j}\frac{C_i C_j}{(\Lambda/1\text{TeV})^4}\sigma_{ij}^{(2)}$$

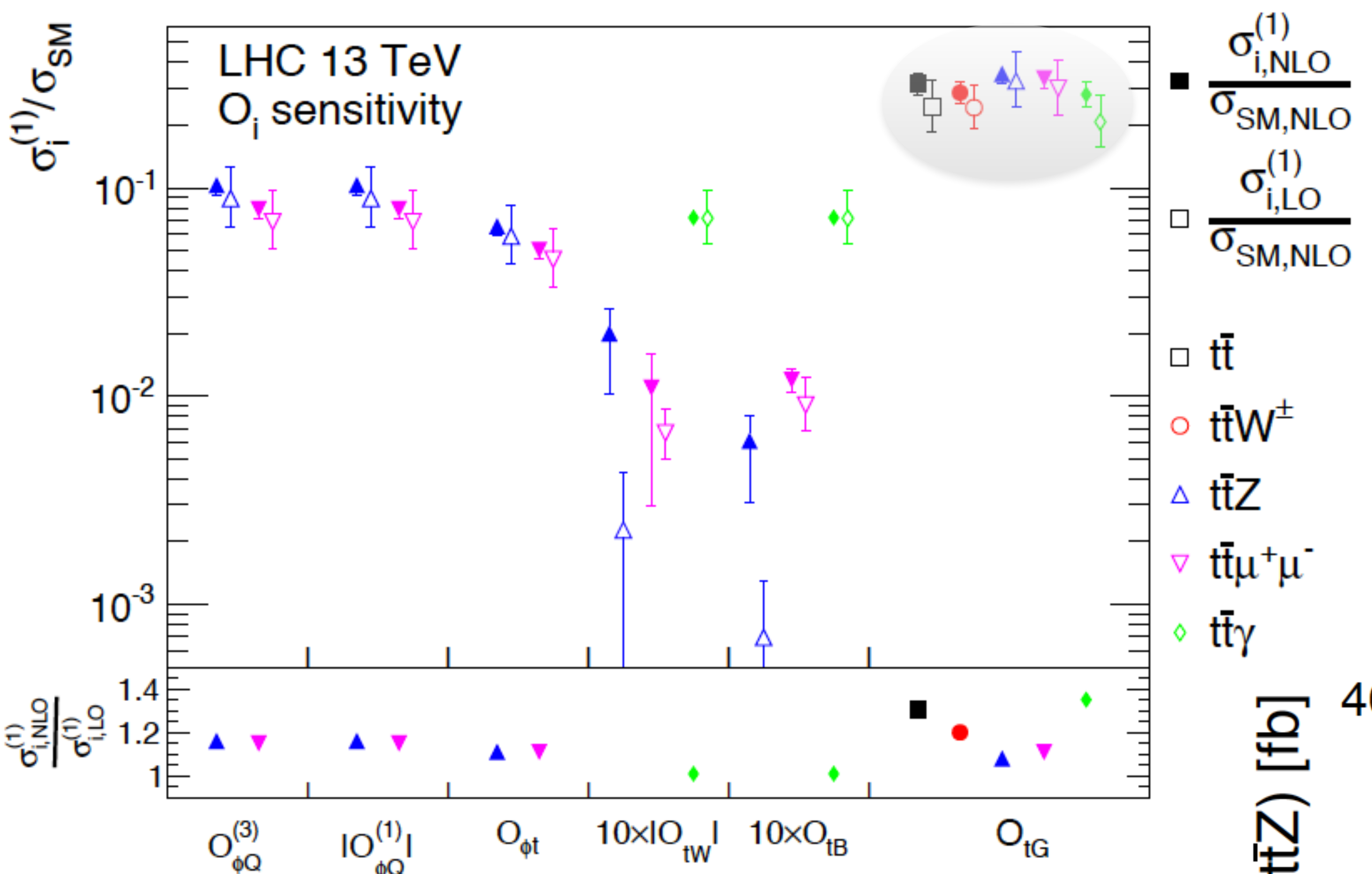
13TeV	$\mathcal{O}_{tG}$	$\mathcal{O}_{\phi Q}^{(3)}$	$\mathcal{O}_{\phi t}$	$\mathcal{O}_{tW}$
$\sigma_{i,LO}^{(1)}$	$286.7^{+38.2\%}_{-25.5\%}$	$78.3^{+40.4\%}_{-26.6\%}$	$51.6^{+40.1\%}_{-26.4\%}$	$-0.20(3)^{+88.0\%}_{-230.0\%}$
$\sigma_{i,NLO}^{(1)}$	$310.5^{+5.4\%}_{-9.7\%}$	$90.6^{+7.1\%}_{-11.0\%}$	$57.5^{+5.8\%}_{-10.3\%}$	$-1.7(2)^{+31.3\%}_{-49.1\%}$
K-factor	1.08	1.16	1.11	8.5
$\sigma_{ii,LO}^{(2)}$	$258.5^{+49.7\%}_{-30.4\%}$	$2.8(1)^{+39.7\%}_{-26.9\%}$	$2.9(1)^{+39.7\%}_{-26.7\%}$	$20.9^{+44.3\%}_{-28.3\%}$
$\sigma_{ii,NLO}^{(2)}$	$244.5^{+4.2\%}_{-8.1\%}$	$3.8(3)^{+13.2\%}_{-14.4\%}$	$3.9(3)^{+13.8\%}_{-14.6\%}$	$24.2^{+6.2\%}_{-11.2\%}$

Bylund et al arXiv:1601.08193

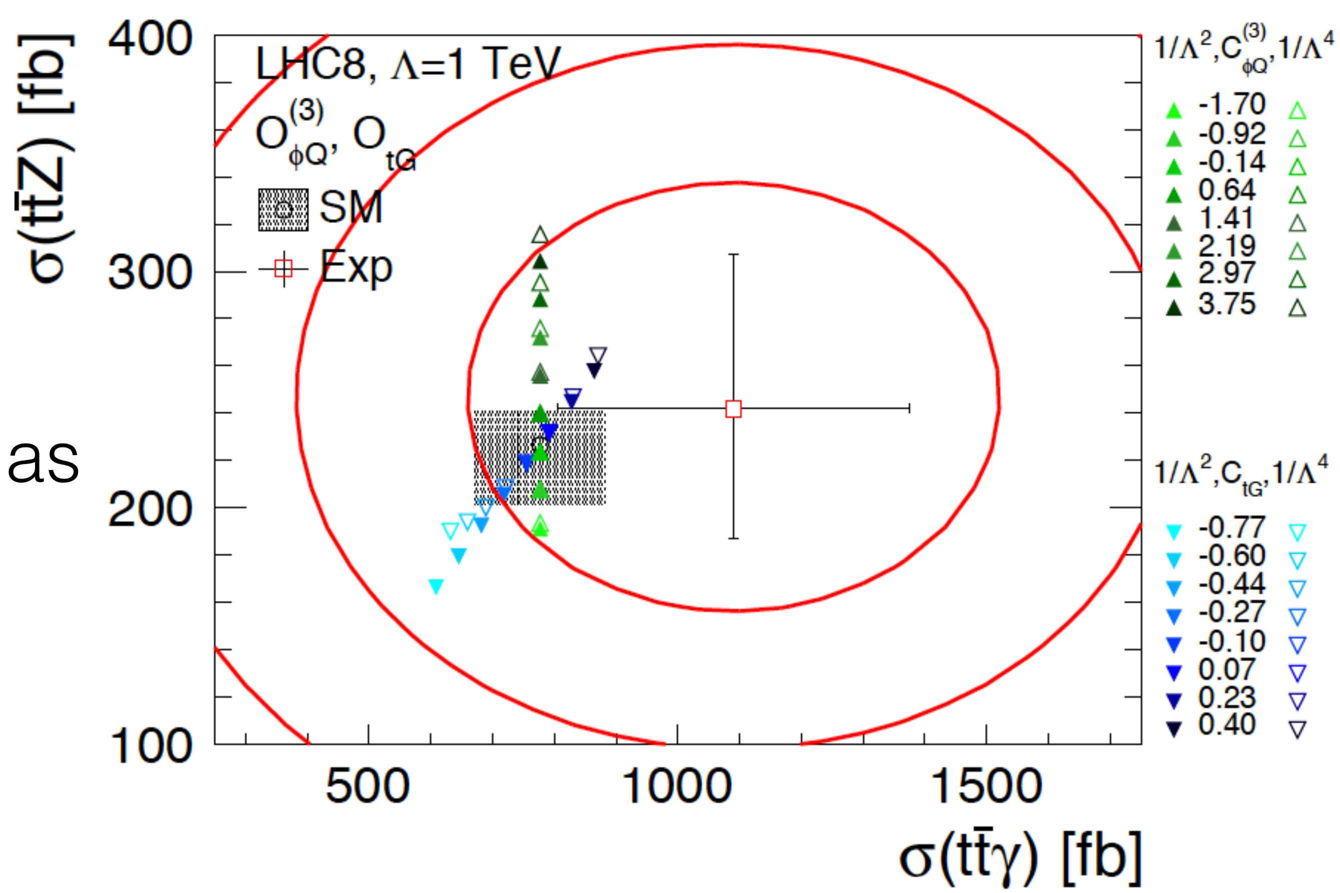


E.Vryonidou

A sensitivity study



For a given (c,Λ) impact of operators varies
Chromomagnetic operator affecting all processes in the same way

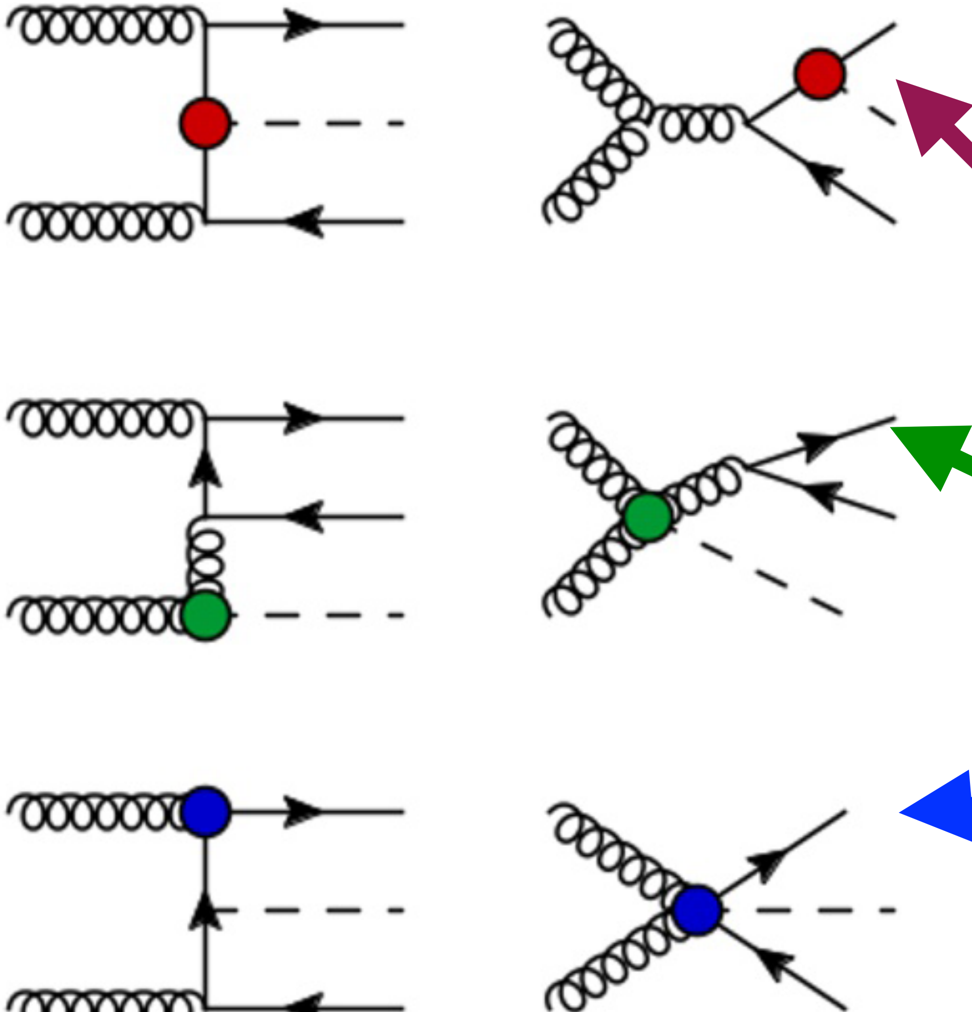


LHC measurements of ttV processes can set constraints on the Wilson coefficients as they become more precise

See also:
Schulze et al. arXiv:1404.1005,1501.05939, 1603.08911 (using ratios of cross-sections)
Dror et al. arXiv:1511.03674 for ttWj

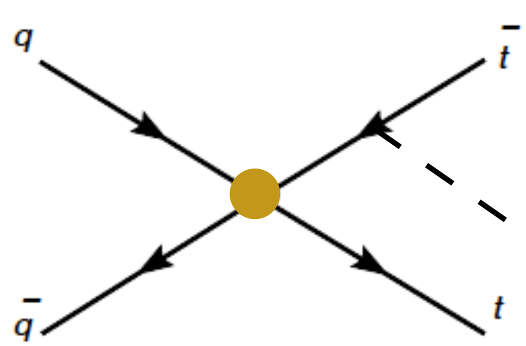
arXiv:1601.08193

ttH in the EFT

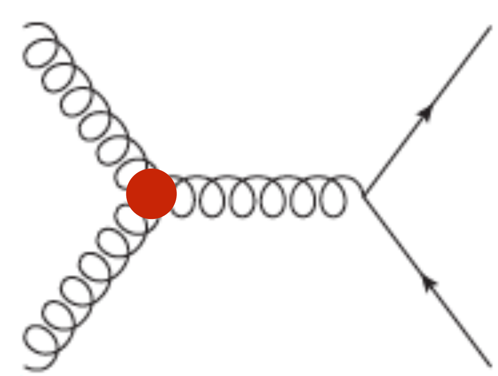


ttH signal strengths (leptons)**:**
ATLAS-CONF-2016-058: $\mu=2.5^{+1.3}_{-1.1}$
CMS PAS HIG-16-022: $\mu=2.0^{+0.8}_{-0.7}$
In agreement with SM but leave room for deviations

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



4-fermion operators



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

Not in this talk, work in progress

ttH@NLO

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

$$\frac{dC_i(\mu)}{d\log\mu} = \frac{\alpha_s}{\pi}\gamma_{ij}C_j(\mu)$$

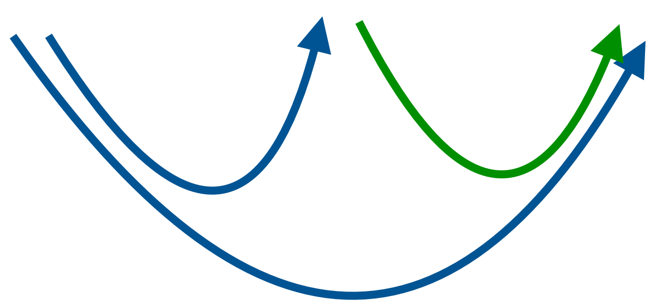
$(O_{t\phi}, O_{\phi G}, O_{tG})$

$$\gamma = \begin{pmatrix} -2 & 16 & 8 \\ 0 & -7/2 & 1/2 \\ 0 & 0 & 1/3 \end{pmatrix}$$

Running and mixing
Alonso et al. arxiv:1312.2014

dim-6 dim-5 dim-4

O_{tG} $O_{\phi G}$ $O_{t\phi}$



Higher-dimension operators mix into lower-dimension ones

Setup allows computation of:

$$\sigma = \sigma_{\rm SM} + \sum_i \frac{1\mathrm{TeV}^2}{\Lambda^2} C_i\sigma_i + \sum_{i\leq j}\frac{1\mathrm{TeV}^4}{\Lambda^4}C_iC_j\sigma_{ij}.$$

interference with SM

interference between operators, squared contributions

E.Vryonidou

ttH cross-section results

13 TeV	σ NLO	K
σ_{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
σ_{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

$$\sigma = \sigma_{\rm SM} + \sum_i \frac{1{\rm TeV}^2}{\Lambda^2} C_i \sigma_i + \sum_{i\leq j} \frac{1{\rm TeV}^4}{\Lambda^4} C_i C_j \sigma_{ij}.$$

- Different K-factors for different operators, different from the SM
- Large $1/\Lambda^4$ contribution for the chromomagnetic operator

How should we treat $O(1/\Lambda^4)$ terms?

EFT condition: $E<\Lambda$

EFT condition satisfied but $O(1/\Lambda^4)$ large for large operator coefficients

$$C_i^2 \frac{E^4}{\Lambda^4} > C_i \frac{E^2}{\Lambda^2} > 1 > \frac{E^2}{\Lambda^2}$$

To be checked on a case-by-case basis

- Constraints from top pair production: c_{tG}=[-0.42,0.30] Franzosi and Zhang arxiv:1503.08841

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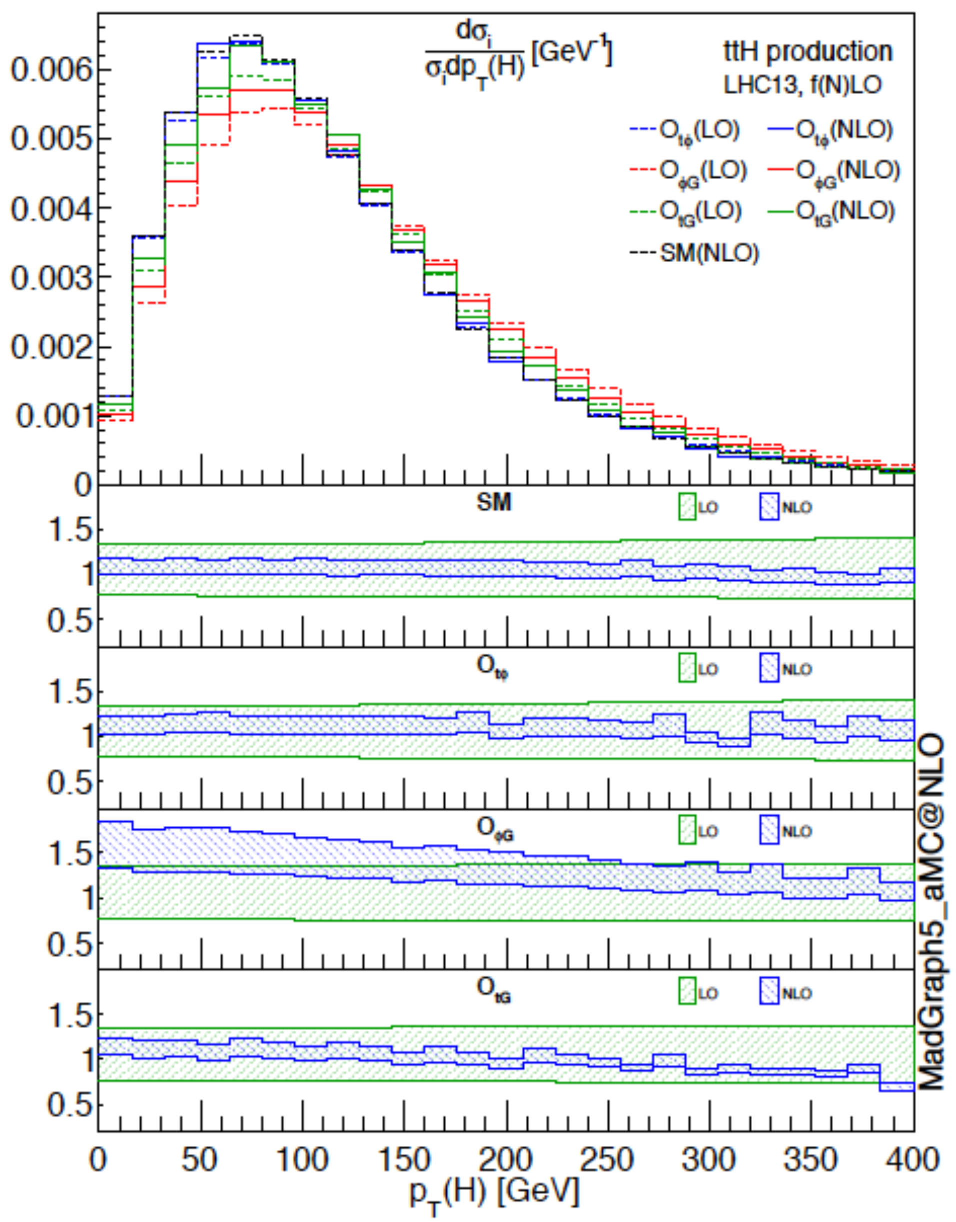
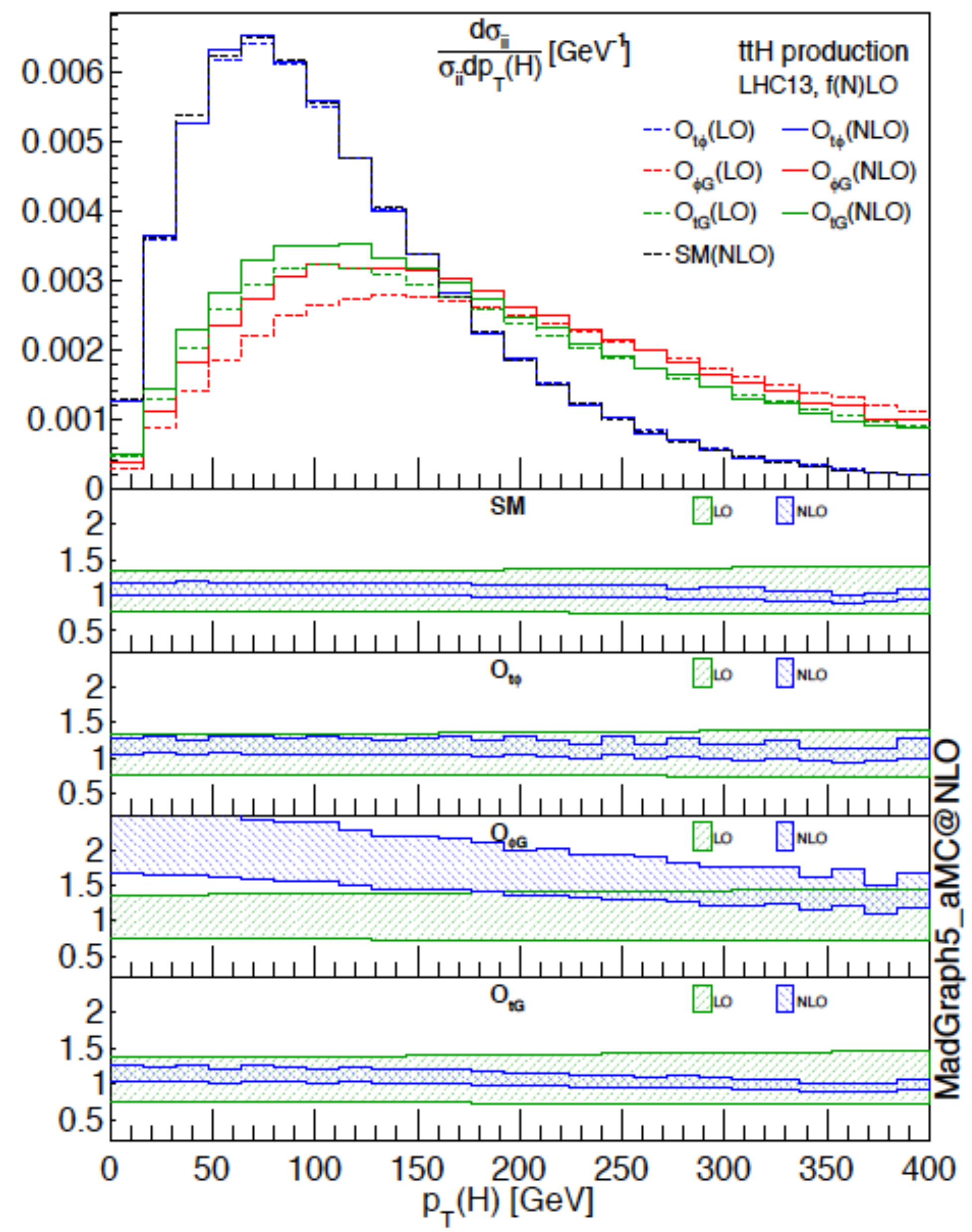
Differential distributions for ttH





NLO: smaller uncertainties, non-flat K-factors

Different shapes for different operators for the squared terms

Maltoni, EV, Zhang arXiv:1607.05330

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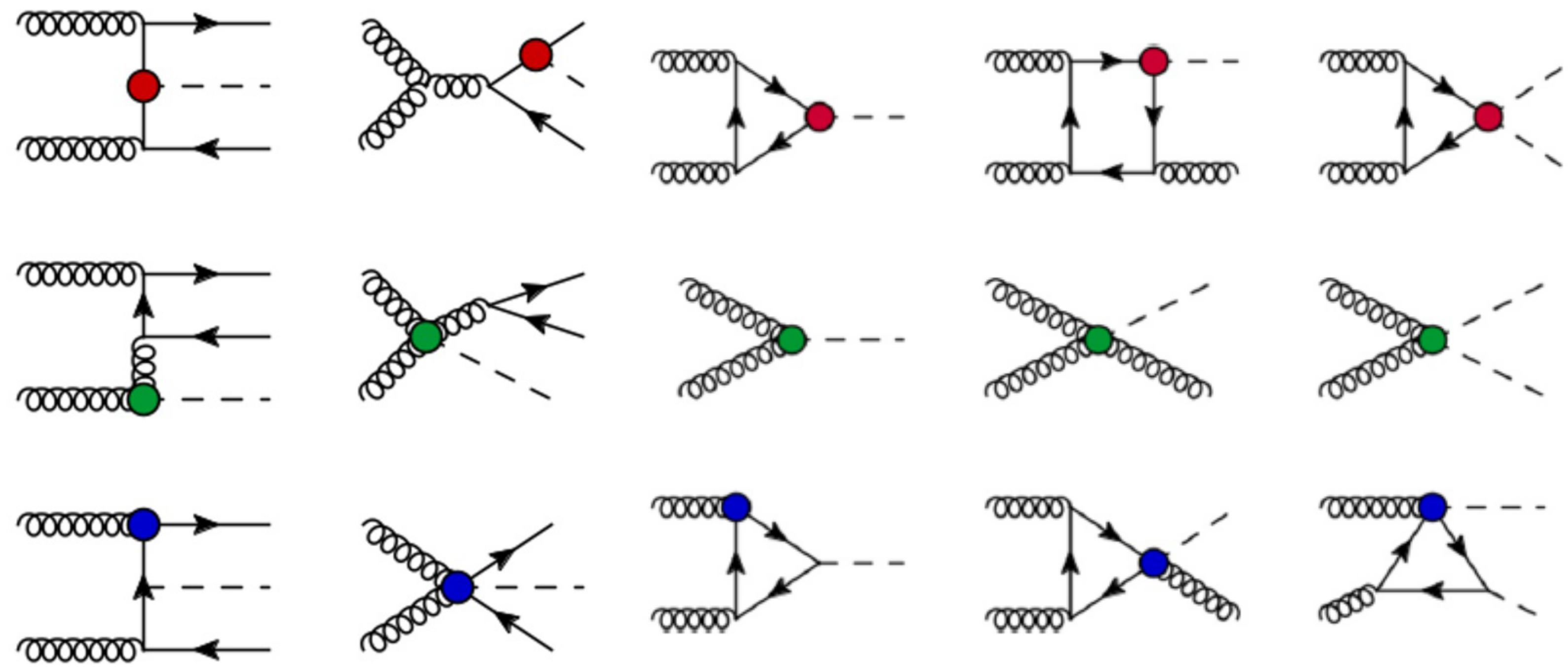
Top and Higgs

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



ttH

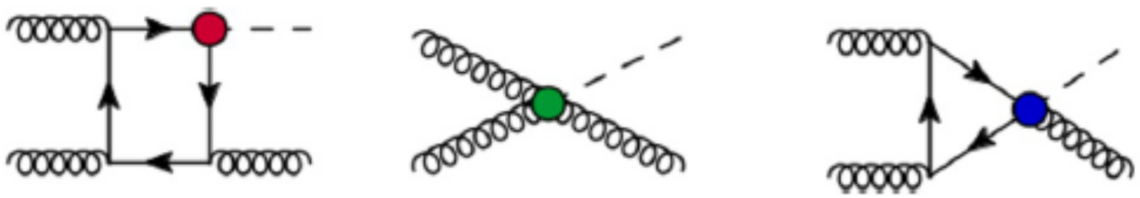
H, H+j, HH

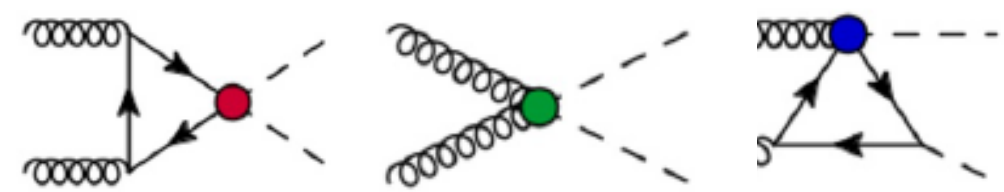
See also
Degrande et al. arXiv:1205.1065
Grojean et al. arXiv:1312.3317
Azatov et al arXiv:1608.00977

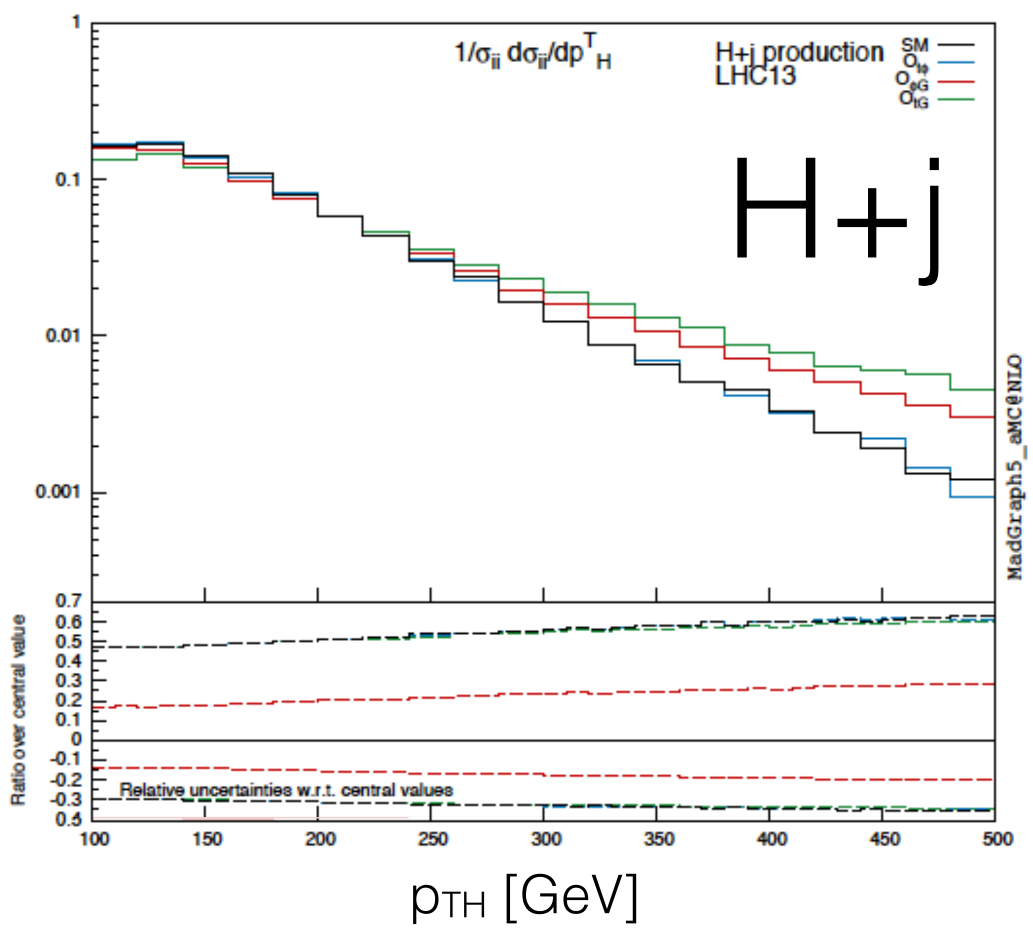
Use with 1) ttH and 2) H, H+j to break degeneracy between operators and extract maximal information on these operators

Maltoni, EV, Zhang: arXiv:1607.05330

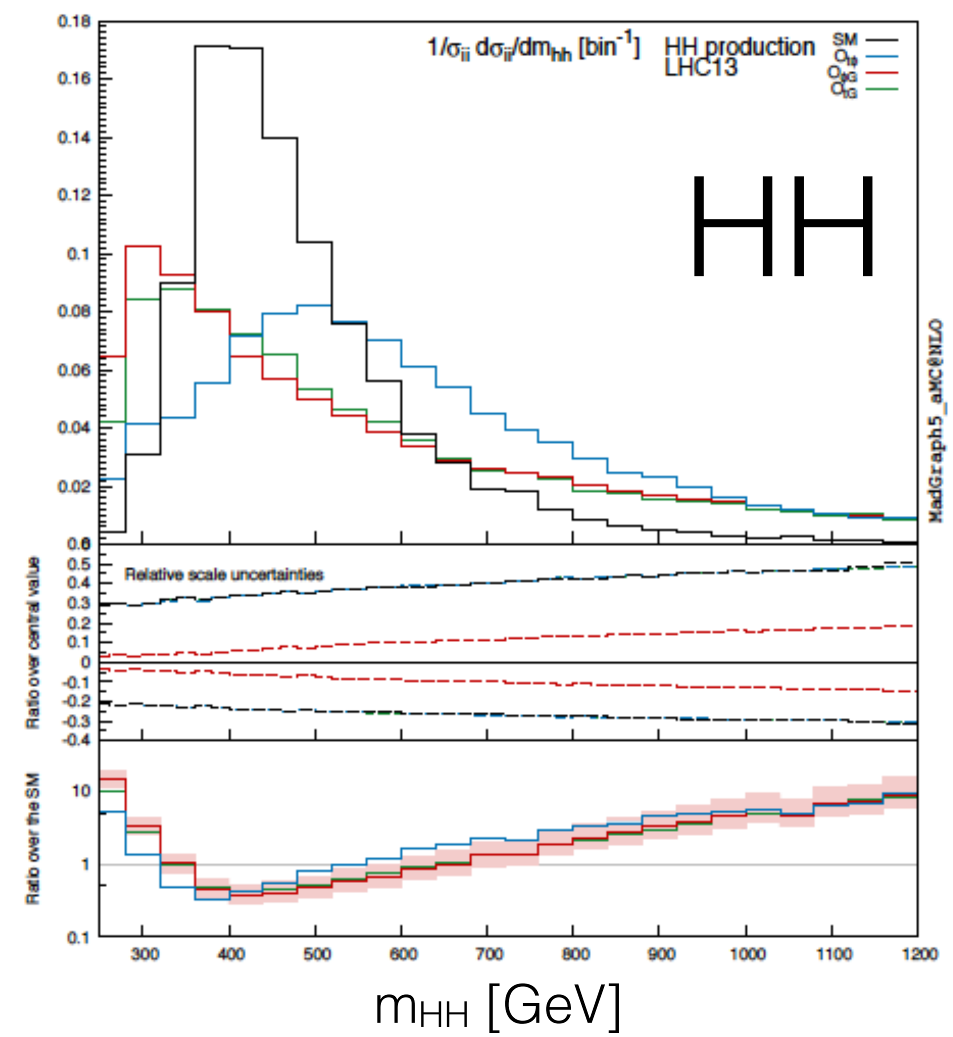
SMEFT in H+j and HH







Harder tails from dim-6 operators: Boosted analysis



Potential impact of the chromomagnetic operator in EFT analyses extracting the triple Higgs coupling λ from HH

E.Vryonidou

Maltoni, EV, Zhang: arXiv:1607.05330

Constraints on the Wilson coefficients

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

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

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

Toy χ^2 fit for illustrative purposes using: single H, ttH Run I and Run II results

Impact of the 3 operators also included in Higgs decays

	Individual	Marginalised	C_{tG} fixed
$C_{t\phi}/\Lambda^2$ [TeV^{-2}]	[-3.9,4.0]	[-14,31]	[-12,20]
$C_{\phi G}/\Lambda^2$ [TeV^{-2}]	[-0.0072,-0.0063]	[-0.021,0.054]	[-0.022,0.031]
C_{tG}/Λ^2 [TeV^{-2}]	[-0.68,0.62]	[-1.8,1.6]	

95% c.l.

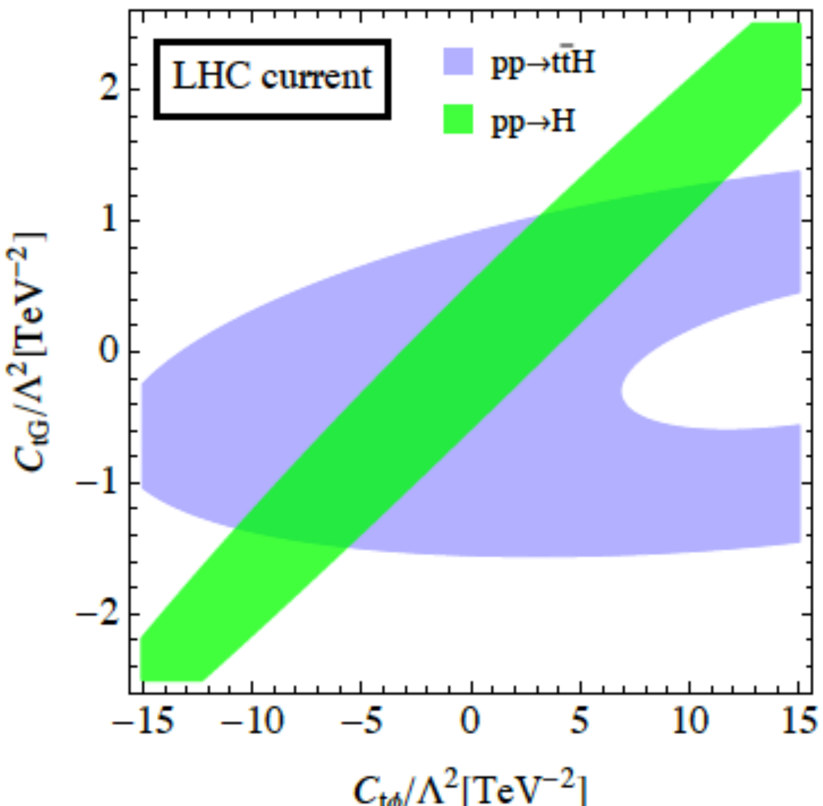
typically C_{tG}=0 in Higgs analyses

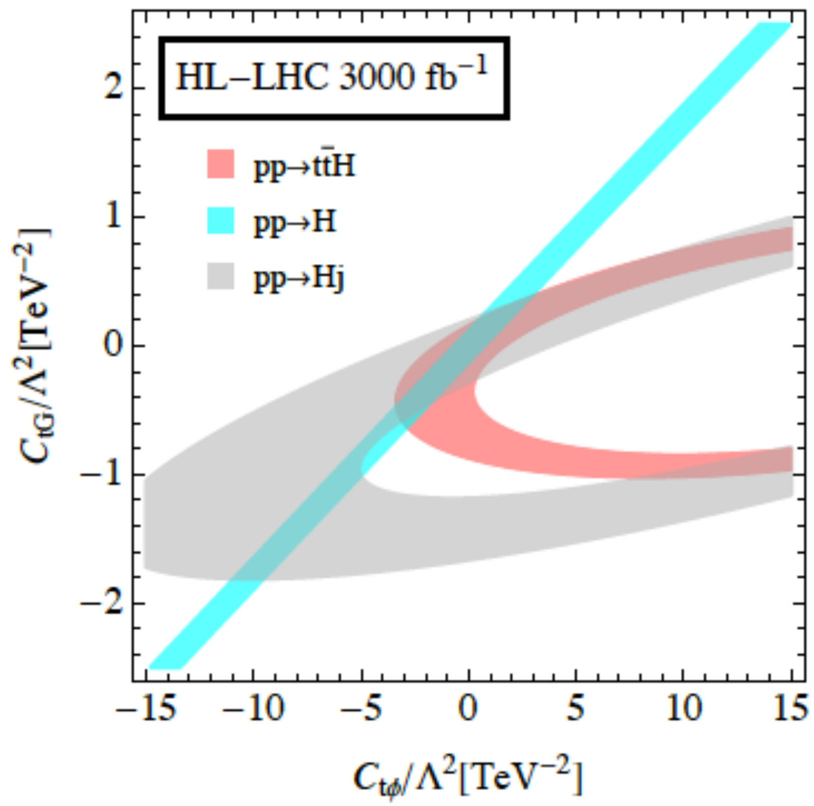
- Individual limit on C_{tG} comparable to the one from top pair production-room to improve with ttH measurement in run II
- Including the chromomagnetic operator leaves much more space to the other two operators

→ Need for global analysis

E.Vryonidou

Constraints from ttH and Higgs production





Current limits using LHC measurements

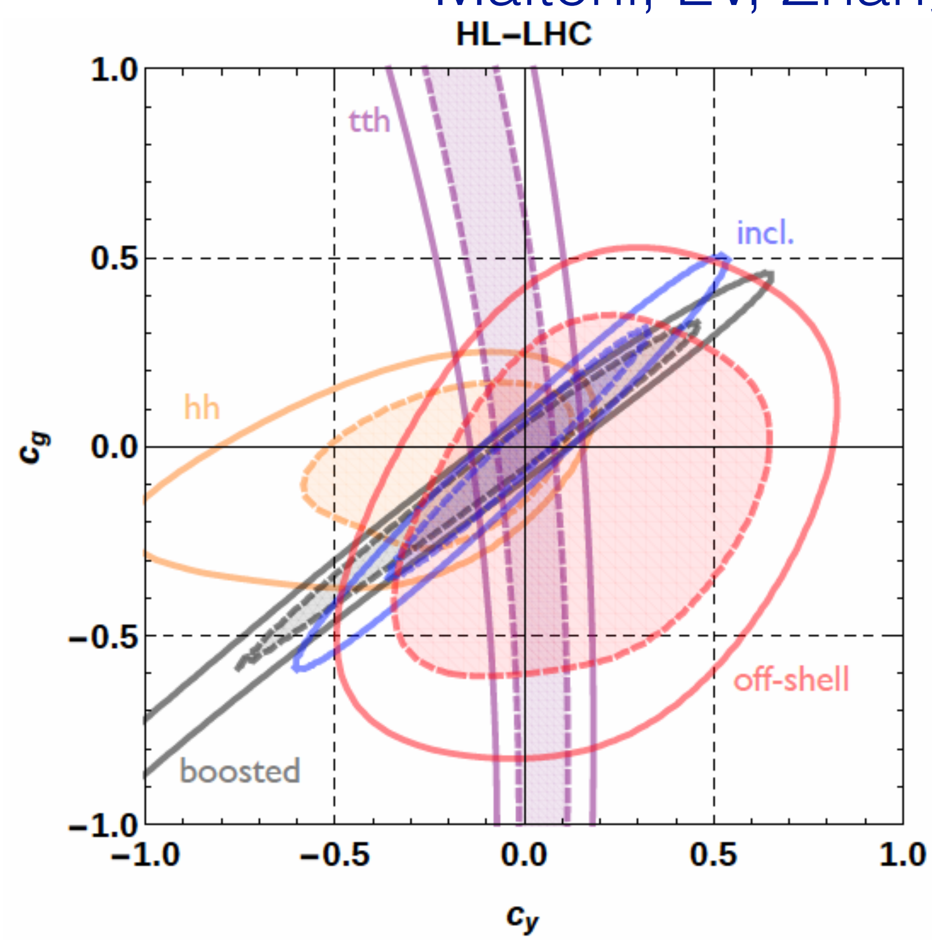
HL-LHC 14TeV projection 3000 fb^{-1}

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

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

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

Maltoni, EV, Zhang arXiv:1607.05330



Combination of:
- inclusive H
- boosted Higgs
- ttH
- HH
- off-shell Higgs

gives maximal information

Azatov et al arXiv:1608.00977

Summary

- Significant progress for precise predictions for top production in the SM: higher orders, resummation, Monte Carlo tools
- Higher-order corrections needed to match improving experimental accuracy
- Top processes a playground for new physics searches: new particles or new top interactions
- SMEFT a framework to look for new interactions
- Precision needed also for EFT predictions to obtain more reliable constraints
- QCD corrections important both for total cross-sections and distributions: SM k-factors are not enough
- Global fits results already available: important to include NLO predictions where available
- Input from Higgs and loop-processes is important in global fits

Thank you for your attention