Constraints to EFT parameters from ttH production

6 May 2020

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Outline

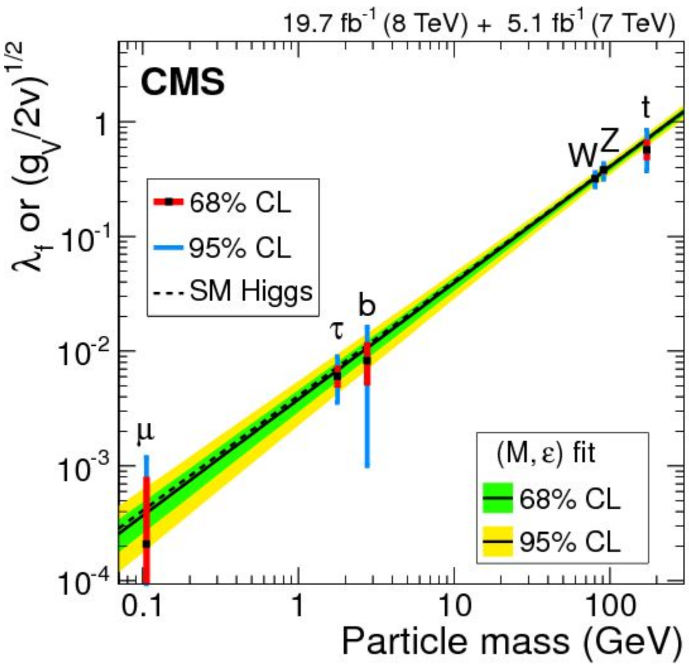
This seminar is based on the lectures given by F. Maltoni and A. Pich at the “Prefit20” school and on the article arXiv:1607.05330, and arXiv:1704.01953

- Motivation for a SM-EFT approach
- The case of ttH and single Higgs production
- Constraints to EFT parameters with CMS and ATLAS data
- Extended fit of all Higgs production processes

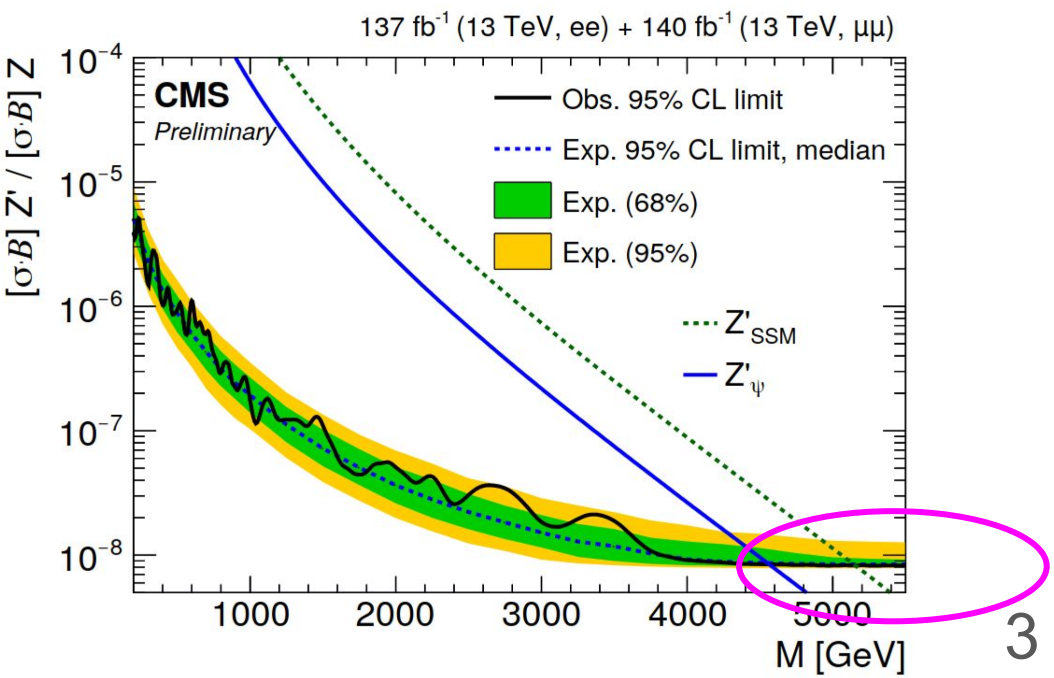
Standard Model matching with data

- All the measurements consistent with SM expectation
- No unexpected resonances observed
  - Too weak couplings → increase statistic or sensitivity
  - The energy scale of the new phenomena (***Λ***) is too large
  - ➢ Indirect probe at smaller accessible energies is possible

Couplings of the Higgs boson vs particle mass

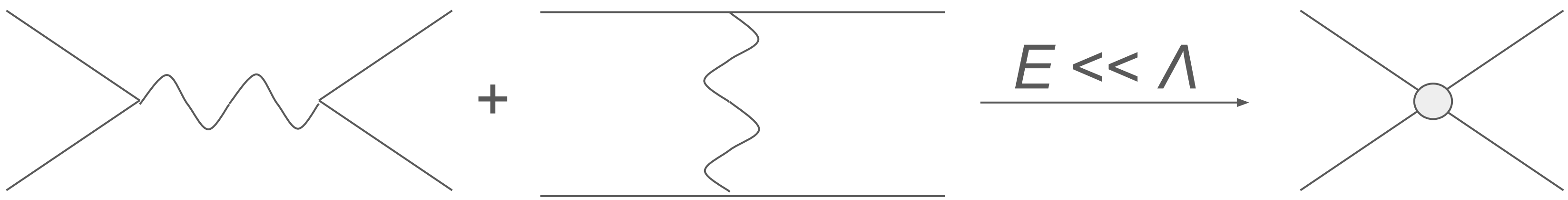


Search for Z’ particle in di-electron and di-muon final state



Standard Model Effective Field Theory

- PURPOSE: model independent description of the effects induced by the new phenomena at an energy scale $E<<\Lambda$



- Build most general lagrangian with the SM gauge symmetries using SM fields only:

Underlying dynamic is contained in C_i coeff.

dimension 6 operators

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

SM lagrangian

First order EFT lagrangian

4-fermions operators (dim=6)

Leptonic flavours mixing

Quark flavours mixing

Chirality mixing

Grzadkowski–Iskrzynski–Misiak–Rosiek

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$\mathcal{O}_{ll}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	$\mathcal{O}_{ee}$	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$	$\mathcal{O}_{le}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
$\mathcal{O}_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	$\mathcal{O}_{uu}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$	$\mathcal{O}_{lu}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
$\mathcal{O}_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	$\mathcal{O}_{dd}$	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$	$\mathcal{O}_{ld}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
$\mathcal{O}_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$	$\mathcal{O}_{eu}$	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$	$\mathcal{O}_{qe}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$\mathcal{O}_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	$\mathcal{O}_{ed}$	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
		$\mathcal{O}_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
		$\mathcal{O}_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$	$\mathcal{O}_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
				$\mathcal{O}_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

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

$q = q_L$, $l = l_L$, $u = u_R$, $d = d_R$, $e = e_R$, p, r, s, t = generation indices

0-fermions and 2-fermions operators (dim=6)

Grzadkowski–Iskrzynski–Misiak–Rosiek

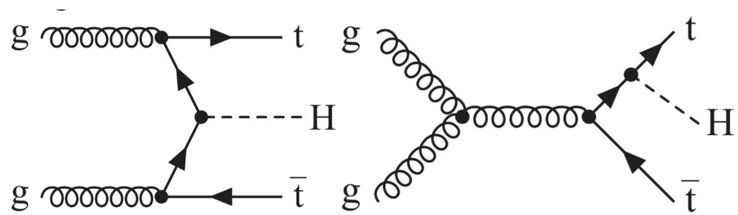
X^3		Φ^6 and $\Phi^4 D^2$		$\psi^2\Phi^3$	
$\mathcal{O}_G$	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$\mathcal{O}_\Phi$	$(\Phi^\dagger\Phi)^3$	$\mathcal{O}_{e\Phi}$	$(\Phi^\dagger\Phi)(\bar{l}_p e_r \Phi)$
$\mathcal{O}_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$\mathcal{O}_{\Phi\Box}$	$(\Phi^\dagger\Phi)\Box(\Phi^\dagger\Phi)$	$\mathcal{O}_{u\Phi}$	$(\Phi^\dagger\Phi)(\bar{q}_p u_r \widetilde{\Phi})$
$\mathcal{O}_W$	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$\mathcal{O}_{\Phi D}$	$(\Phi^\dagger D^\mu \Phi)^\star (\Phi^\dagger D_\mu \Phi)$	$\mathcal{O}_{d\Phi}$	$(\Phi^\dagger\Phi)(\bar{q}_p d_r \Phi)$
$\mathcal{O}_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\Phi^2$		$\psi^2 X \Phi$		$\psi^2\Phi^2 D$	
$\mathcal{O}_{\Phi G}$	$\Phi^\dagger\Phi\, G_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{eW}$	$(\bar{l}_p \sigma^{\mu\nu} e_r)\, \tau^I \Phi\, W_{\mu\nu}^I$	$\mathcal{O}_{\Phi l}^{(1)}$	$(\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{l}_p \gamma^\mu l_r)$
$\mathcal{O}_{\Phi\widetilde{G}}$	$\Phi^\dagger\Phi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{eB}$	$(\bar{l}_p \sigma^{\mu\nu} e_r)\, \Phi\, B_{\mu\nu}$	$\mathcal{O}_{\Phi l}^{(3)}$	$(\Phi^\dagger i \overleftrightarrow{D}_\mu^I \Phi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$\mathcal{O}_{\Phi W}$	$\Phi^\dagger\Phi\, W_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{uG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\, \widetilde{\Phi}\, G_{\mu\nu}^A$	$\mathcal{O}_{\Phi e}$	$(\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{e}_p \gamma^\mu e_r)$
$\mathcal{O}_{\Phi\widetilde{W}}$	$\Phi^\dagger\Phi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{uW}$	$(\bar{q}_p \sigma^{\mu\nu} u_r)\, \tau^I \widetilde{\Phi}\, W_{\mu\nu}^I$	$\mathcal{O}_{\Phi q}^{(1)}$	$(\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{q}_p \gamma^\mu q_r)$
$\mathcal{O}_{\Phi B}$	$\Phi^\dagger\Phi\, B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{uB}$	$(\bar{q}_p \sigma^{\mu\nu} u_r)\, \widetilde{\Phi}\, B_{\mu\nu}$	$\mathcal{O}_{\Phi q}^{(3)}$	$(\Phi^\dagger i \overleftrightarrow{D}_\mu^I \Phi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$\mathcal{O}_{\Phi\widetilde{B}}$	$\Phi^\dagger\Phi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{dG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r)\, \Phi\, G_{\mu\nu}^A$	$\mathcal{O}_{\Phi u}$	$(\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{u}_p \gamma^\mu u_r)$
$\mathcal{O}_{\Phi WB}$	$\Phi^\dagger \tau^I \Phi\, W_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{dW}$	$(\bar{q}_p \sigma^{\mu\nu} d_r)\, \tau^I \Phi\, W_{\mu\nu}^I$	$\mathcal{O}_{\Phi d}$	$(\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{d}_p \gamma^\mu d_r)$
$\mathcal{O}_{\Phi\widetilde{W}B}$	$\Phi^\dagger \tau^I \Phi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{dB}$	$(\bar{q}_p \sigma^{\mu\nu} d_r)\, \Phi\, B_{\mu\nu}$	$\mathcal{O}_{\Phi ud}$	$i(\widetilde{\Phi}^\dagger D_\mu \Phi)(\bar{u}_p \gamma^\mu d_r)$

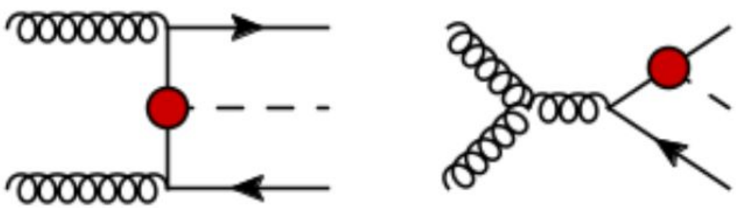
$q = q_L\ ,\ l = l_L\ ,\ u = u_R\ ,\ d = d_R\ ,\ e = e_R$, $\overleftrightarrow{D}_\mu^I \equiv \tau^I \overrightarrow{D}_\mu - \overleftarrow{D}_\mu \tau^I$, $p, r =$ generation indices

SMEFT operators relevant for ttH production

SM production

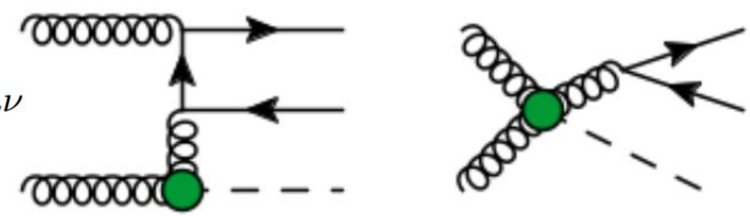


$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) \left(\bar{Q}t\right) \tilde{\phi}$



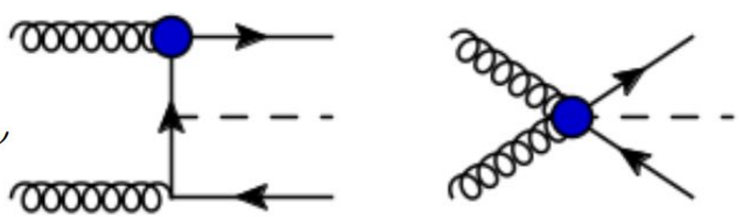
- Modification of top Yukawa coupling

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



- New ggH and gggH couplings

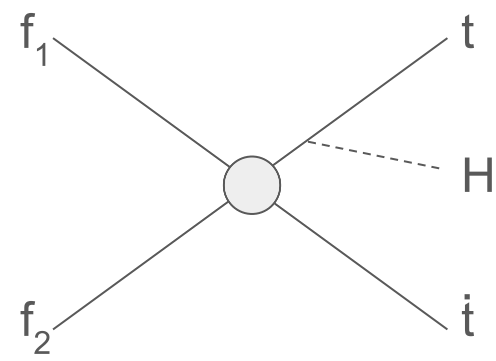
$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\phi} G^A_{\mu\nu}$



- Modification of ttg coupling and new ttggH coupling

Other SMEFT operators in ttH production

- Significant contribution from 4-fermions operators
  - Assumption: their contribution can be constrained using ttbar production process
  - Better approach would be a simultaneous fit of σ_{ttH} and σ_{ttbar} or take the ratio $\sigma_{ttH}/\sigma_{ttbar}$



Additional processes to gain sensitivity

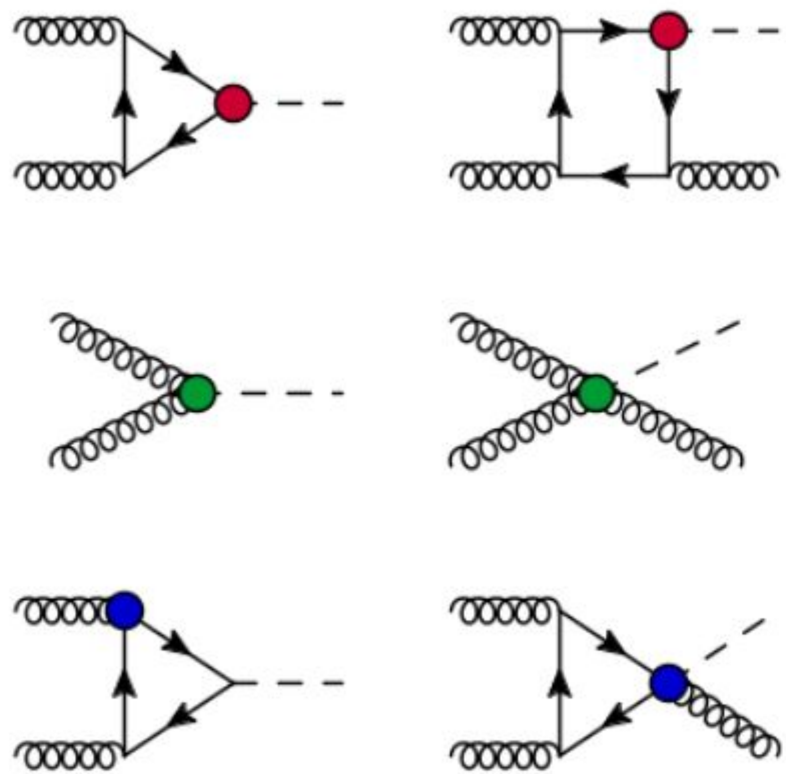
- ttH production is statistically limited
- Break degeneracy between operators

Gluon-gluon fusion Higgs production | Gluon-gluon fusion Higgs+jet production

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

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

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



Procedure

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

Interference
SM-EFT diagrams

$|\text{EFT diagrams}|^2$

1 `MG5_aMC` framework to compute total σ_{SM}, σ_i, and σ_{ij}
   - Also differentially in $p_T(H)$, rapidity, ...

2 Fit of data to extract the C_i coefficients
   - Inclusive cross section (+ distributions)

➢ Theoretical uncertainties
   - pdf, **factoriz. and renormaliz. scales** as in SM calculations
   - EFT scale uncertainty: missing higher orders in the α_s expansion of the cross sections
   - dimension-8 operators → neglected

SMEFT calculation at QCD NLO

- Calculation up to O(α_s^3 α)
- More precise prediction and smaller theoretical uncertainties
- NLO corrections might change differential cross sections
- Loop induced effects under control

➢ Renormalization to re-absorb UV divergences
  - Dependence on an ‘arbitrary’ scale μ
  - QCD-induced mixing of the C_i parameters

$$\frac{dC_i(\mu)}{d\log\mu} = \frac{\alpha_s}{\pi}\gamma_{ij}C_j(\mu), \quad \gamma = \begin{pmatrix} -2 & 16 & 8 \\ 0 & -7/2 & 1/2 \\ 0 & 0 & 1/3 \end{pmatrix}$$

with (C_1 , C_2 , C_3) = ($C_{t\Phi}$, $C_{\Phi G}$, C_{tG})

Inclusive cross sections for ttH production

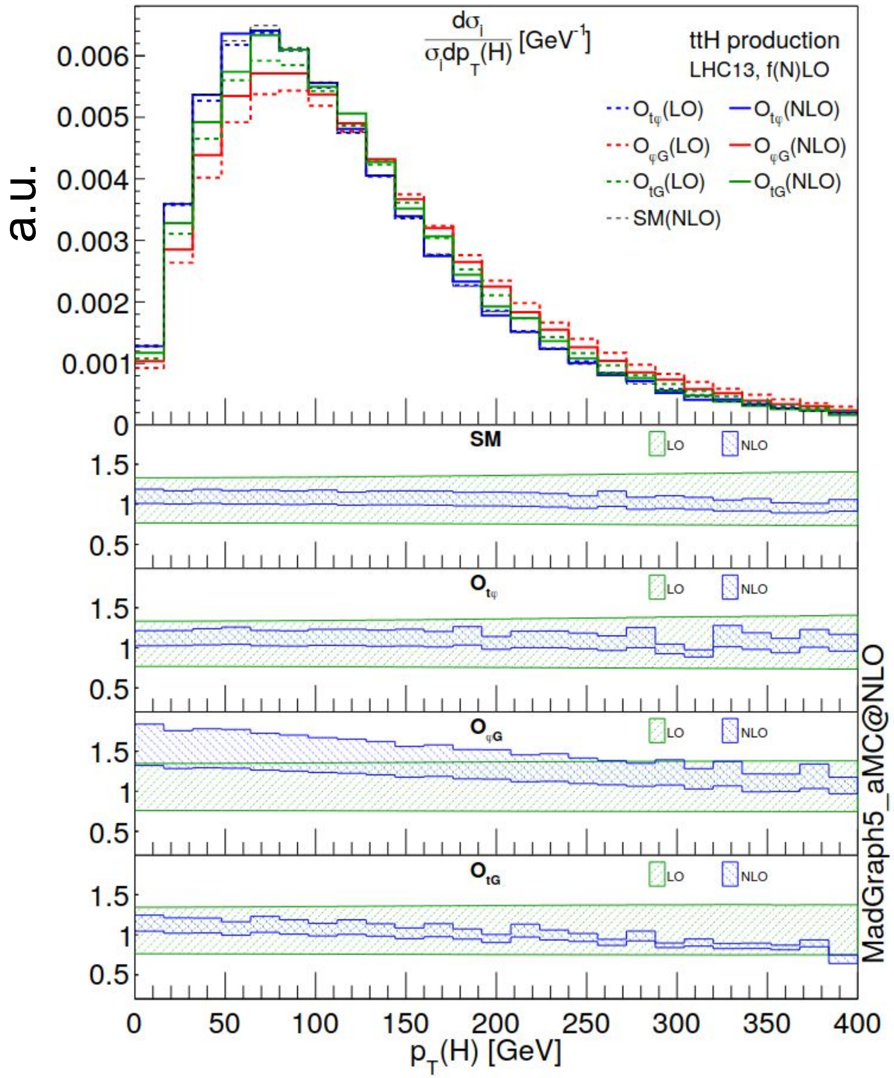
13 TeV	σ LO	σ/σ_{SM} LO	σ NLO	σ/σ_{SM} NLO	K
σ_{SM}	$0.464^{+0.161+0.000+0.005}_{-0.111-0.000-0.004}$	$1.000^{+0.000+0.000+0.000}_{-0.000-0.000-0.000}$	$0.507^{+0.030+0.000+0.007}_{-0.048-0.000-0.008}$	$1.000^{+0.000+0.000+0.000}_{-0.000-0.000-0.000}$	1.09
$\sigma_{t\phi}$	$-0.055^{+0.013+0.002+0.000}_{-0.019-0.003-0.001}$	$-0.119^{+0.000+0.005+0.000}_{-0.000-0.006-0.000}$	$-0.062^{+0.006+0.001+0.001}_{-0.004-0.001-0.001}$	$-0.123^{+0.001+0.001+0.000}_{-0.001-0.002-0.000}$	1.13
$\sigma_{\phi G}$	$0.627^{+0.225+0.081+0.007}_{-0.153-0.067-0.005}$	$1.351^{+0.011+0.175+0.002}_{-0.011-0.145-0.001}$	$0.872^{+0.131+0.037+0.013}_{-0.123-0.035-0.016}$	$1.722^{+0.146+0.073+0.004}_{-0.089-0.068-0.005}$	1.39
σ_{tG}	$0.470^{+0.167+0.000+0.005}_{-0.114-0.002-0.004}$	$1.014^{+0.006+0.000+0.001}_{-0.006-0.004-0.001}$	$0.503^{+0.025+0.001+0.007}_{-0.046-0.003-0.008}$	$0.991^{+0.004+0.003+0.000}_{-0.010-0.006-0.001}$	1.07
$\sigma_{t\phi,t\phi}$	$0.0016^{+0.0005+0.0002+0.0000}_{-0.0004-0.0001-0.0000}$	$0.0035^{+0.0000+0.0004+0.0000}_{-0.0000-0.0003-0.0000}$	$0.0019^{+0.0001+0.0001+0.0000}_{-0.0002-0.0000-0.0000}$	$0.0037^{+0.0001+0.0002+0.0000}_{-0.0000-0.0001-0.0000}$	1.17
$\sigma_{\phi G,\phi G}$	$0.646^{+0.274+0.141+0.018}_{-0.178-0.107-0.010}$	$1.392^{+0.079+0.304+0.025}_{-0.066-0.231-0.014}$	$1.021^{+0.204+0.096+0.024}_{-0.178-0.085-0.029}$	$2.016^{+0.267+0.190+0.021}_{-0.178-0.167-0.027}$	1.58
$\sigma_{tG,tG}$	$0.645^{+0.276+0.011+0.020}_{-0.178-0.015-0.010}$	$1.390^{+0.082+0.023+0.028}_{-0.069-0.031-0.016}$	$0.674^{+0.036+0.004+0.016}_{-0.067-0.007-0.019}$	$1.328^{+0.011+0.008+0.014}_{-0.038-0.014-0.018}$	1.04
$\sigma_{t\phi,\phi G}$	$-0.037^{+0.009+0.006+0.000}_{-0.013-0.007-0.000}$	$-0.081^{+0.001+0.012+0.000}_{-0.001-0.015-0.000}$	$-0.053^{+0.008+0.003+0.001}_{-0.008-0.004-0.001}$	$-0.105^{+0.006+0.006+0.000}_{-0.009-0.007-0.000}$	1.42
$\sigma_{t\phi,tG}$	$-0.028^{+0.007+0.001+0.000}_{-0.010-0.001-0.000}$	$-0.060^{+0.000+0.002+0.000}_{-0.000-0.003-0.000}$	$-0.031^{+0.003+0.000+0.000}_{-0.002-0.000-0.000}$	$-0.061^{+0.000+0.000+0.000}_{-0.000-0.001-0.000}$	1.10
$\sigma_{\phi G,tG}$	$0.627^{+0.252+0.053+0.014}_{-0.166-0.047-0.008}$	$1.349^{+0.054+0.114+0.016}_{-0.046-0.100-0.009}$	$0.859^{+0.127+0.021+0.017}_{-0.126-0.020-0.022}$	$1.691^{+0.137+0.042+0.013}_{-0.097-0.039-0.017}$	1.37

value ± scale unc. ± EFT scale unc. ± pdf unc.

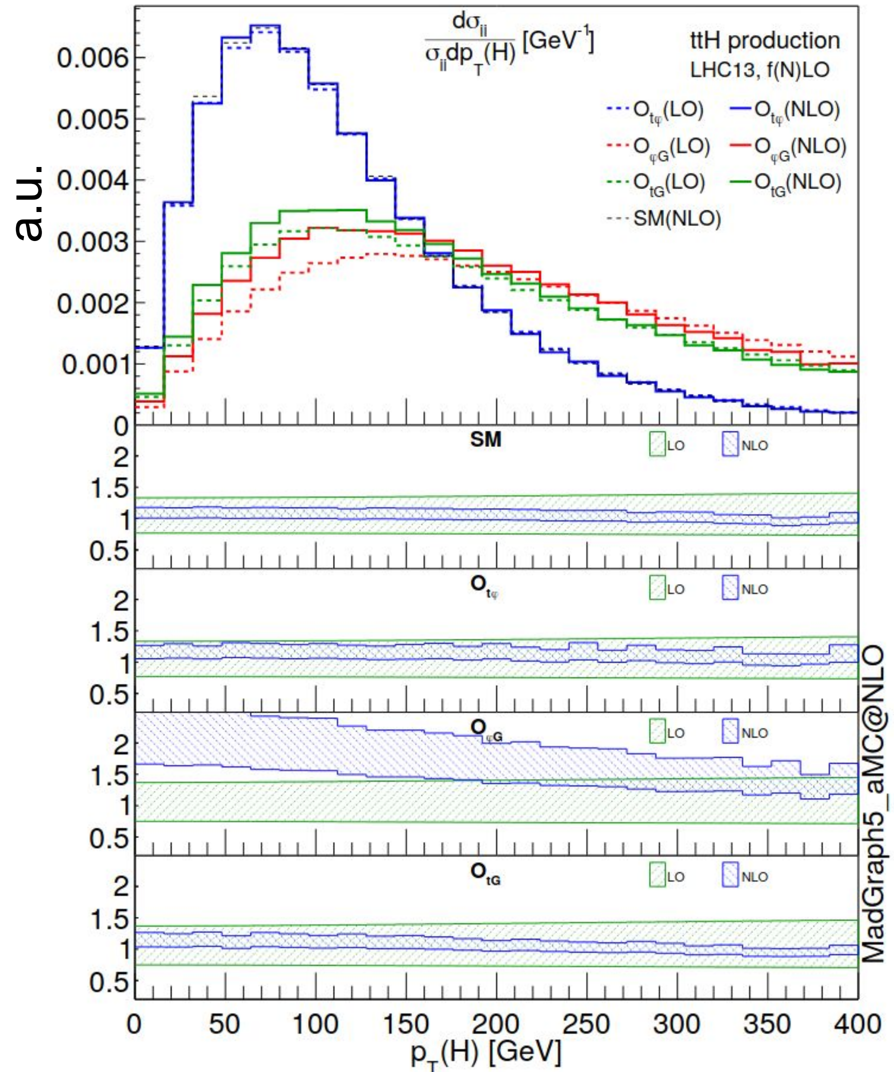
- Scale unc. reduced taking the ratios σ/σ_{SM}
- k-factors (σ_{NLO}/σ_{LO}) up to 1.58

Differential cross sections for ttH production

Interference EFT-SM terms

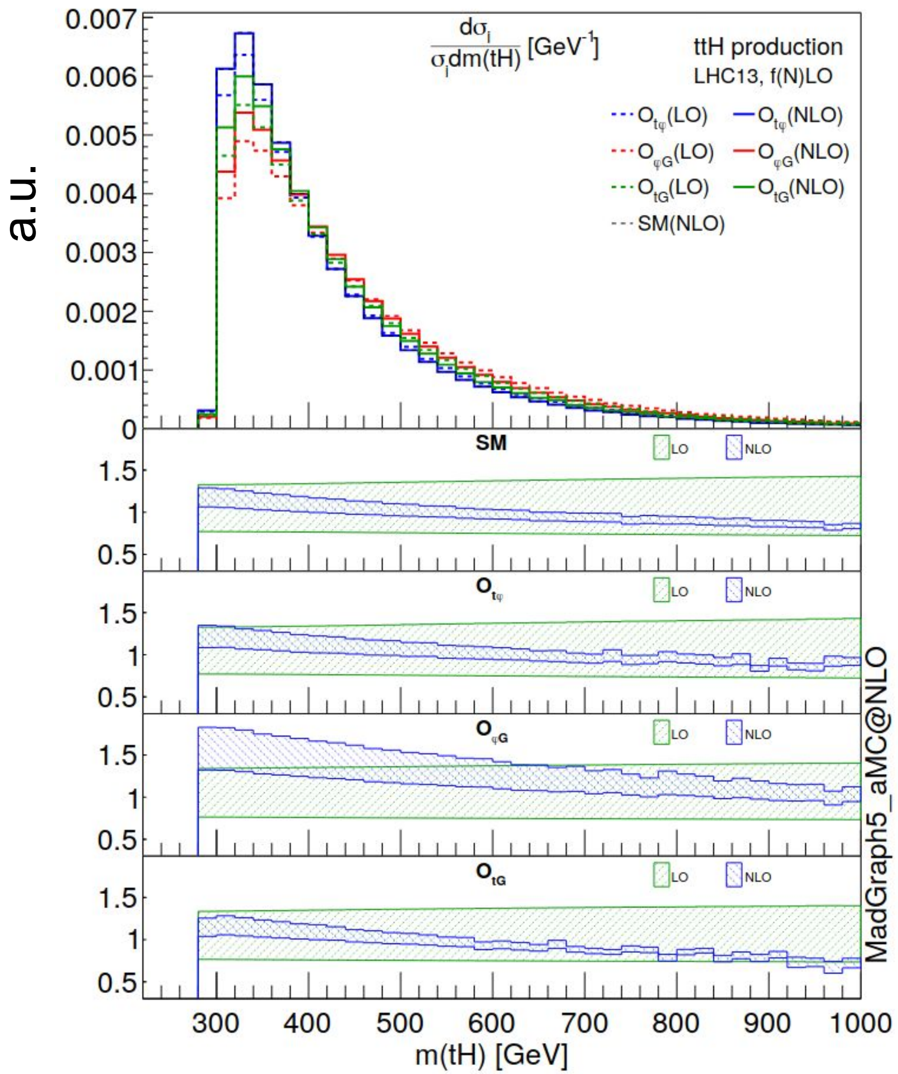


|EFT|^2 terms

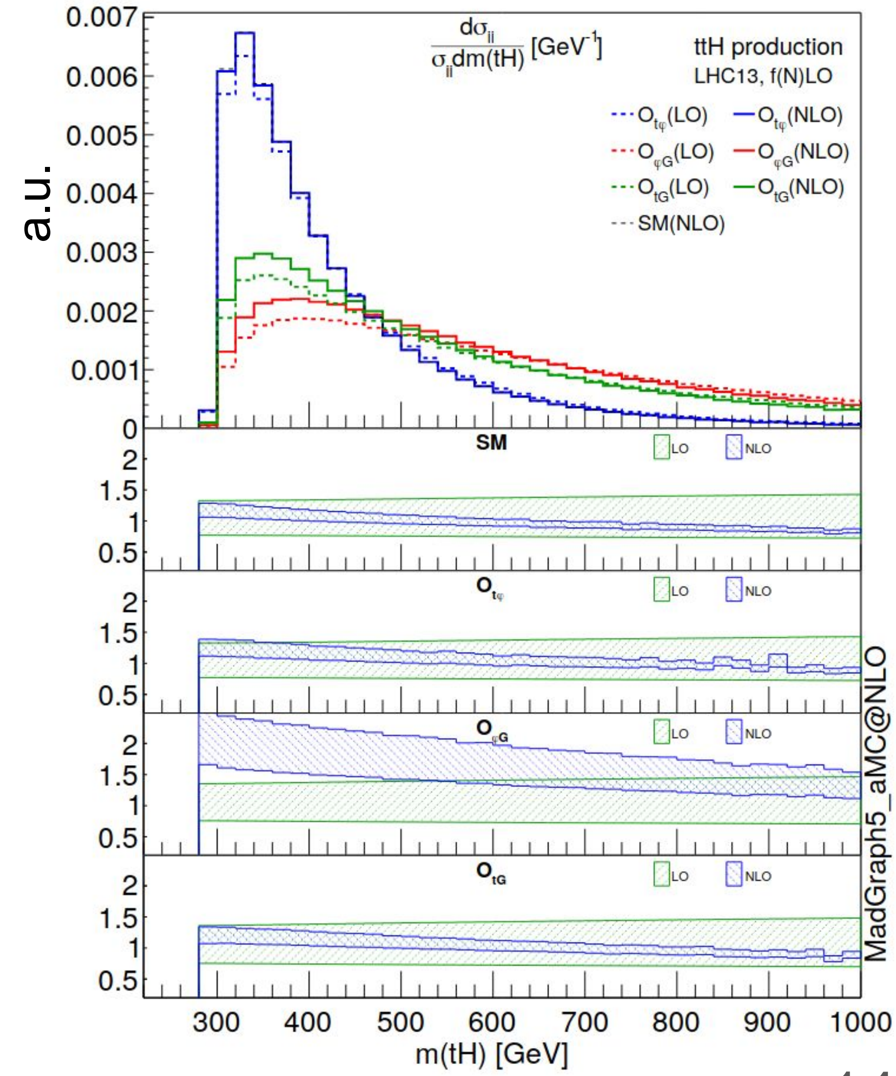


Differential cross sections for ttH production

Interference EFT-SM terms



$|EFT|^2$ terms



Fit to Run1 and Run2(2015) data

- H production measurement (gluon-fusion) at ATLAS and CMS in the exclusive decay channels H→WW, H→ZZ, H→ττ, H→γγ
- ttH production measurement at ATLAS and CMS in the exclusive decay channels H-multilepton, H→bb, H→γγ

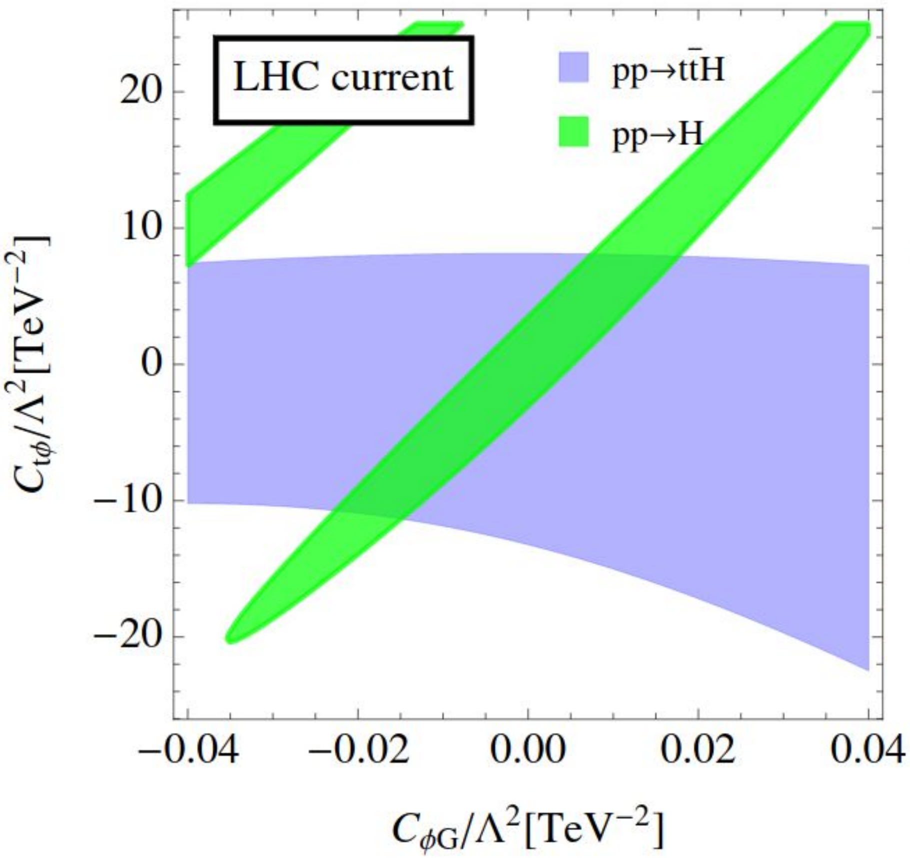
➢ EFT operators change Γ(H→γγ), Γ(H→gg), and Γ_{TOT}
  - considered in the fit

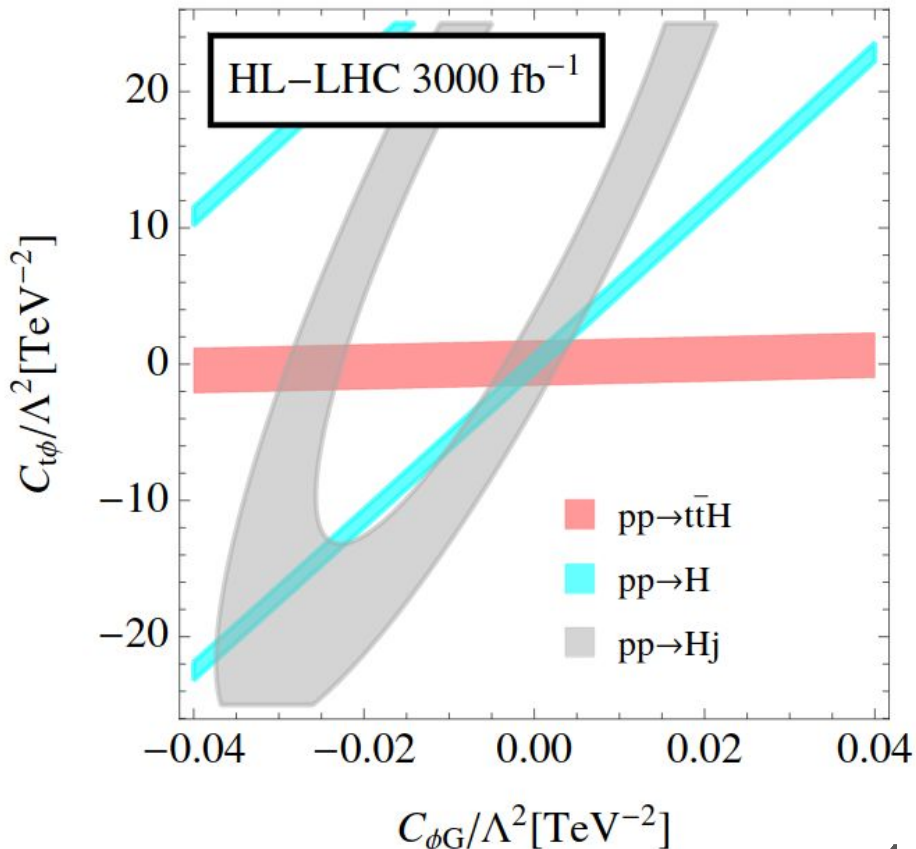
Negligible in many BSM scenarios ↓

	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]	

“current” and future prospects

- Assume C_{tG} fixed to zero
- Interesting to re-run with full Run2 dataset...





Extend fit to full EFT Higgs couplings

- Consider all Higgs production and decay modes
- Change operator basis→new coefficients
  - Higgs couplings to the SM gauge bosons: δc_z, c_{zz}, $c_{z\Box}$, $c_{z\gamma}$, $c_{\gamma\gamma}$, c_{gg}
  - Deformations of the fermion Yukawa's: δy_t, δy_b, δy_τ
  - Higgs trilinear self-coupling: κ_λ
- Linear expansion of XS and BR (SMEFT at LO)

$\kappa_\lambda = 1$

$\sigma/\sigma_{SM}(ZH) = 1 + 2\delta c_z + 8.3 c_{z\Box} + 3.5 c_{zz} - 0.67 c_{z\gamma} - 0.30 c_{\gamma\gamma}$

$\sigma/\sigma_{SM}(ggF) = 1 + 2c_{gg} + 2.06\delta y_t - 0.06\delta y_b$

$\sigma/\sigma_{SM}(ttH) = 1 - 2\delta y_t$

$\Gamma/\Gamma_{SM}(\gamma\gamma) = 1 + 2.56\delta c_z + 2.13 c_z + 0.98 c_{zz} - 0.066 c_{z\gamma} - 2.46 c_{\gamma\gamma} - 0.56\delta y_t$

➢ Coefficients computed also differentially in $p_T(H)$

Caveats for the Higgs global fit

- Neglected operators not directly related with Higgs couplings
- Many free parameters→prospects for HL-LHC

Expected uncertainties on signal strength at HL-LHC (3000 fb^{-1})

Process		Combination	Theory	Experimental
$H \to \gamma\gamma$	ggF	0.07	0.05	0.05
	VBF	0.22	0.16	0.15
	$t\bar{t}H$	0.17	0.12	0.12
	WH	0.19	0.08	0.17
	ZH	0.28	0.07	0.27
$H \to ZZ$	ggF	0.06	0.05	0.04
	VBF	0.17	0.10	0.14
	$t\bar{t}H$	0.20	0.12	0.16
	WH	0.16	0.06	0.15
	ZH	0.21	0.08	0.20
$H \to WW$	ggF	0.07	0.05	0.05
	VBF	0.15	0.12	0.09
$H \to Z\gamma$	incl.	0.30	0.13	0.27
$H \to b\bar{b}$	WH	0.37	0.09	0.36
	ZH	0.14	0.05	0.13
$H \to \tau^+\tau^-$	VBF	0.19	0.12	0.15

Results global fit with κ_λ = 1 at HL-LHC (3000 fb^{-1})

- Strong correlation among some parameter

Uncertainties on the fitted parameters from simultaneous fit

Uncertainties fitting one single parameter

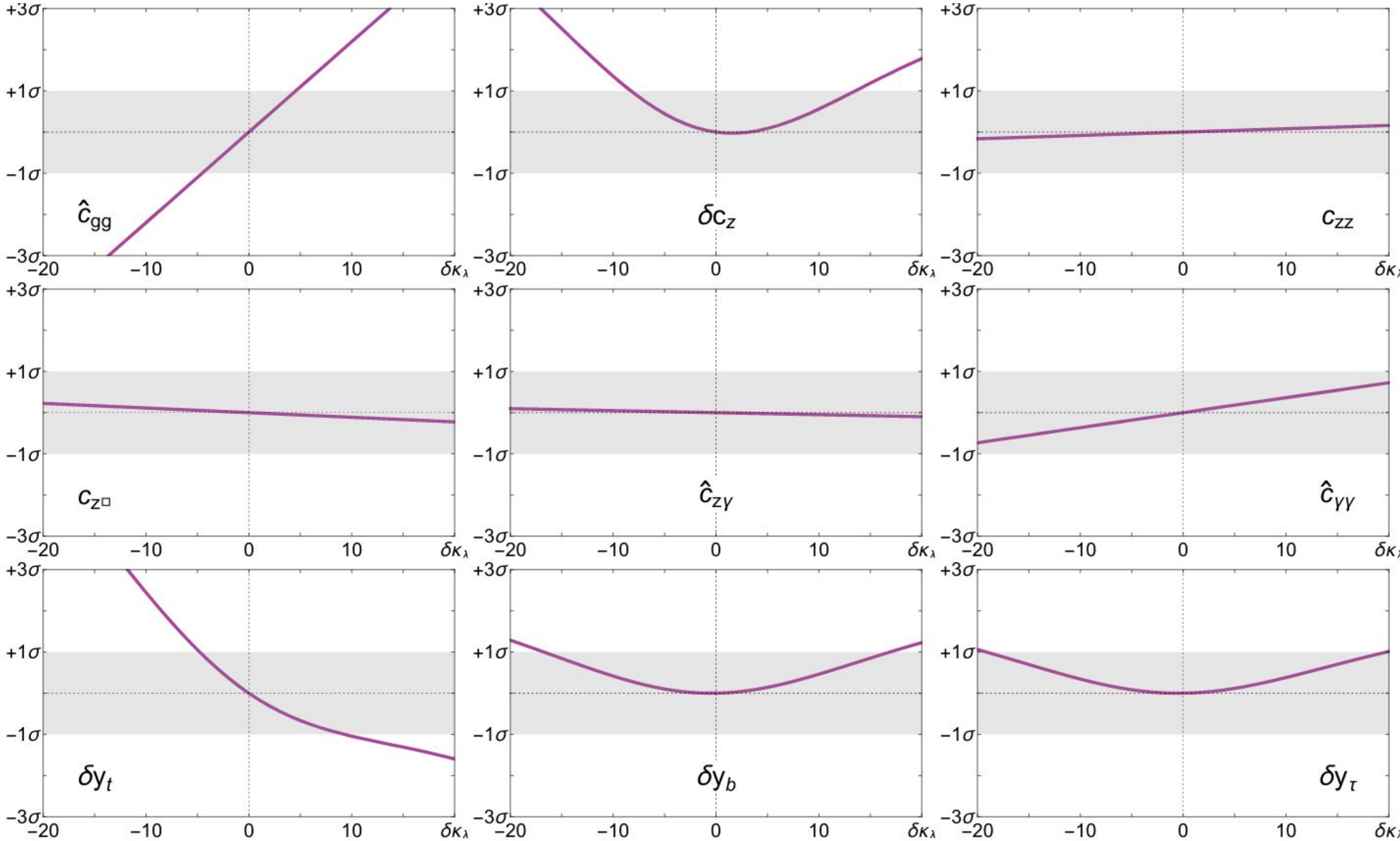
Correlation matrix

$$\begin{pmatrix} \hat{c}_{gg} \\ \delta c_z \\ c_{zz} \\ c_{z\Box} \\ \hat{c}_{z\gamma} \\ \hat{c}_{\gamma\gamma} \\ \delta y_t \\ \delta y_b \\ \delta y_\tau \end{pmatrix} = \pm \begin{pmatrix} 0.07 \ (0.02) \\ 0.05 \ (0.01) \\ 0.05 \ (0.02) \\ 0.02 \ (0.01) \\ 0.09 \ (0.09) \\ 0.03 \ (0.02) \\ 0.08 \ (0.02) \\ 0.12 \ (0.03) \\ 0.11 \ (0.09) \end{pmatrix}$$

$$\begin{bmatrix} 1 & 0.04 & -0.01 & -0.01 & 0.04 & 0.31 & \mathbf{-0.76} & 0.05 & 0.02 \\ & 1 & -0.07 & -0.26 & 0.01 & 0.01 & 0.36 & \mathbf{0.88} & 0.27 \\ & & 1 & \mathbf{-0.87} & 0.13 & 0.20 & 0.03 & -0.07 & -0.06 \\ & & & 1 & -0.09 & -0.09 & -0.09 & -0.17 & 0.08 \\ & & & & 1 & 0.05 & -0.02 & -0.02 & -0.03 \\ & & & & & 1 & -0.32 & -0.19 & -0.12 \\ & & & & & & 1 & 0.50 & 0.28 \\ & & & & & & & 1 & 0.36 \\ & & & & & & & & 1 \end{bmatrix}$$

Degeneracy when floating κ_λ

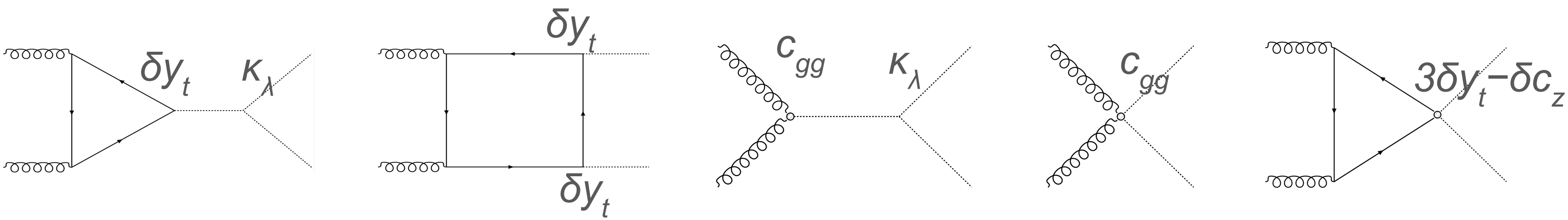
Couplings vs κ_λ along the χ^2 flat direction



Include Higgs pair production signal to remove degeneracy

Results global fit with floating κ_λ at HL-LHC (3000 fb^{-1})

- Include Higgs pair production to remove degeneracy
  - HH→bbɣɣ, bbbb, bbWW, bbττ
- Double Higgs production sensitive to other operators



$$\begin{pmatrix} \hat{c}_{gg} \\ \delta c_z \\ c_{zz} \\ c_{z\Box} \\ \hat{c}_{z\gamma} \\ \hat{c}_{\gamma\gamma} \\ \delta y_t \\ \delta y_b \\ \delta y_\tau \end{pmatrix} = \pm \begin{pmatrix} 0.07 \\ 0.05 \\ 0.05 \\ 0.02 \\ 0.09 \\ 0.03 \\ 0.08 \\ 0.12 \\ 0.11 \end{pmatrix}$$

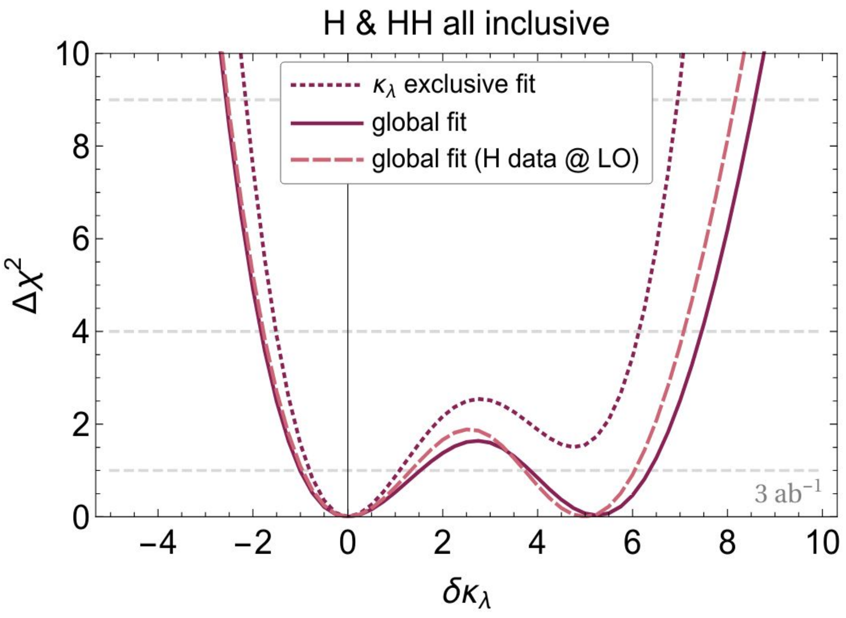
→ float κ_λ and include HH

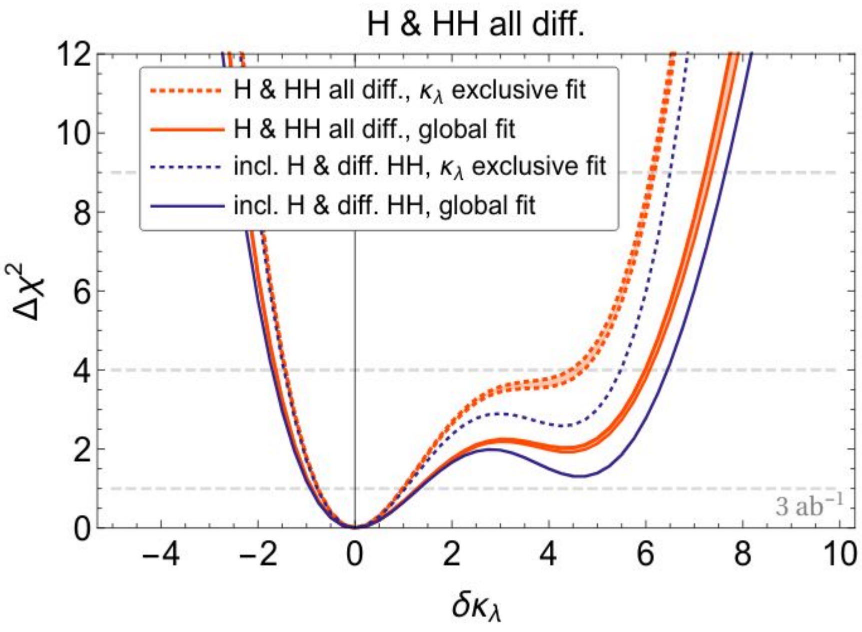
$$\begin{pmatrix} \hat{c}_{gg} \\ \delta c_z \\ c_{zz} \\ c_{z\Box} \\ \hat{c}_{z\gamma} \\ \hat{c}_{\gamma\gamma} \\ \delta y_t \\ \delta y_b \\ \delta y_\tau \\ \delta\kappa_\lambda \end{pmatrix} = \pm \begin{pmatrix} 0.06 \\ 0.04 \\ 0.04 \\ 0.02 \\ 0.09 \\ 0.03 \\ 0.06 \\ 0.07 \\ 0.11 \\ 1.0 \end{pmatrix}$$

Interesting to run with full Run2 dataset...

Impact of distribution shapes

- EFT couplings significantly change differential cross section of single Higgs (WH,ZH,ttH) and double Higgs production
  - Split WH,ZH,ttH in bins of $p_T(H)$
  - Split HH in bins of m_{HH}





Summary

- SMEFT is a powerful tool for BSM searches at $E \ll \Lambda$
- SMEFT predictions at NLO(QCD) for ttH, H, H+j processes
    - Focus on C_{tG}, $C_{t\phi G}$, and $C_{\phi G}$ operators
    - Results with Run1+Run2(2015) data of CMS and prospects for HL-LHC
    - Interesting combination with ttbar measurement
- Presented SMEFT predictions at LO for all single Higgs production processes
    - Full set of Higgs coupling operators
    - Higgs pair production process to remove degeneracy
    - Prospects for HL-LHC

➢ Interesting to run with full Run 2 dataset

BACKUP

HH process to gain sensitivity

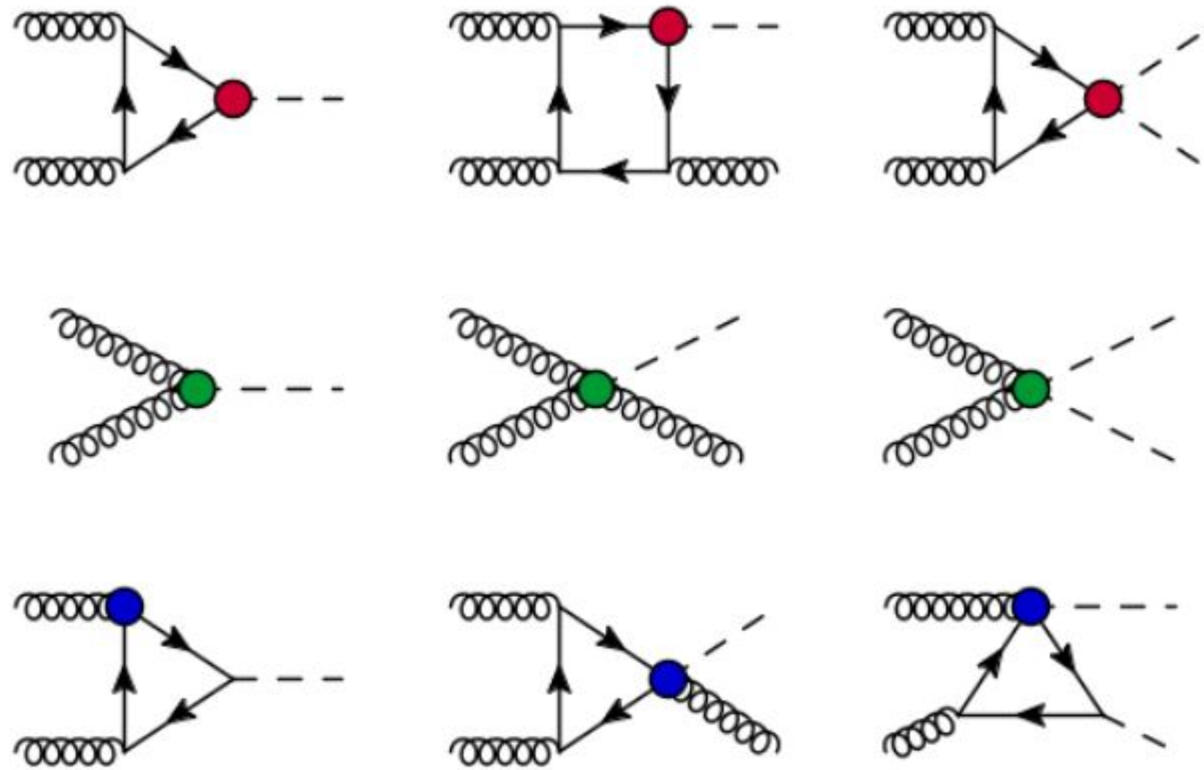
- ttH production is statistically limited
- Break degeneracy between operators

	Gluon-gluon fusion Higgs production	Gluon-gluon fusion Higgs+jet production	Double Higgs production

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

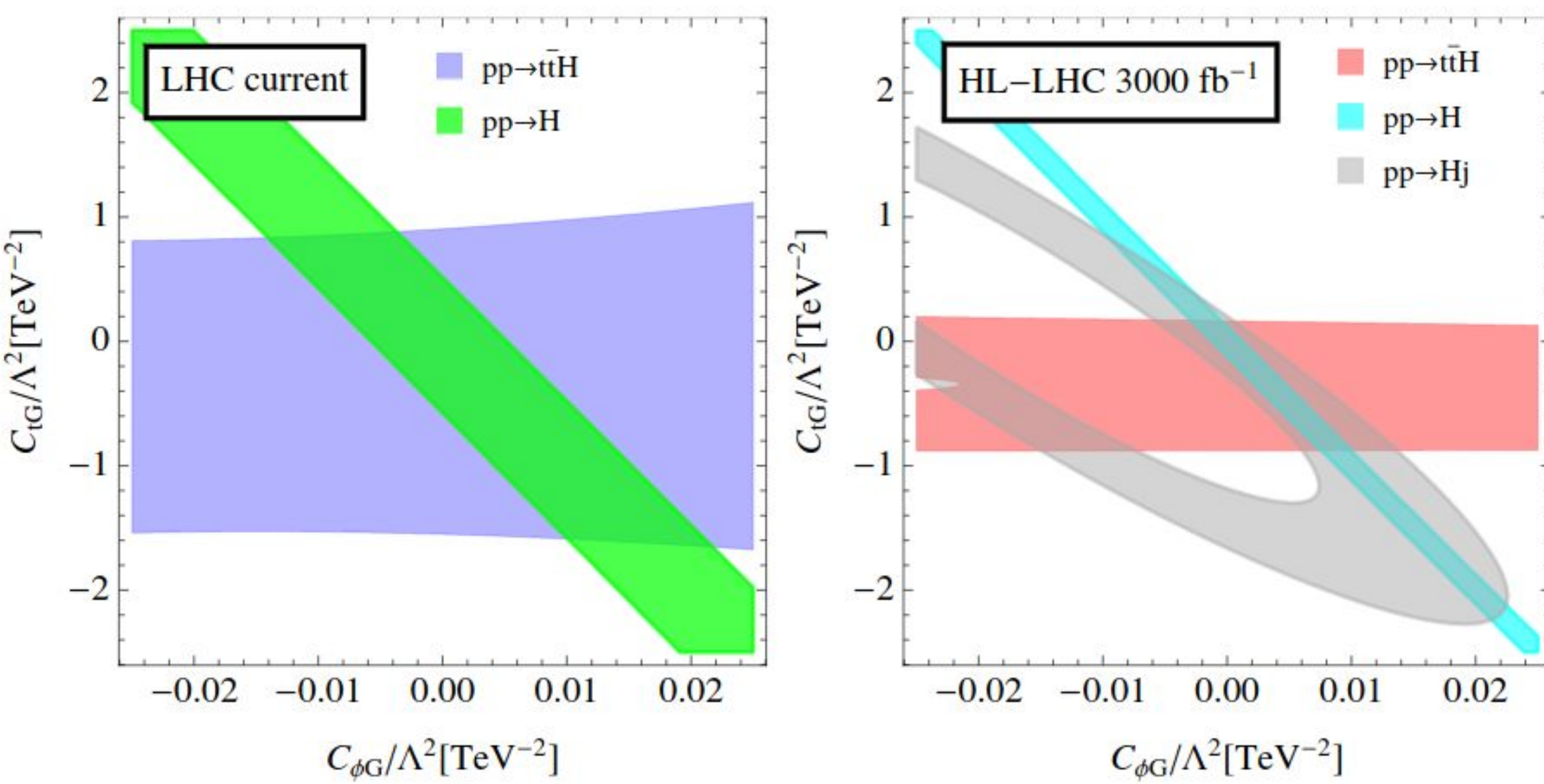
$$O_{\phi G} = y_t^2 \left(\phi^\dagger\phi\right) G^A_{\mu\nu}G^{A\mu\nu}$$

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



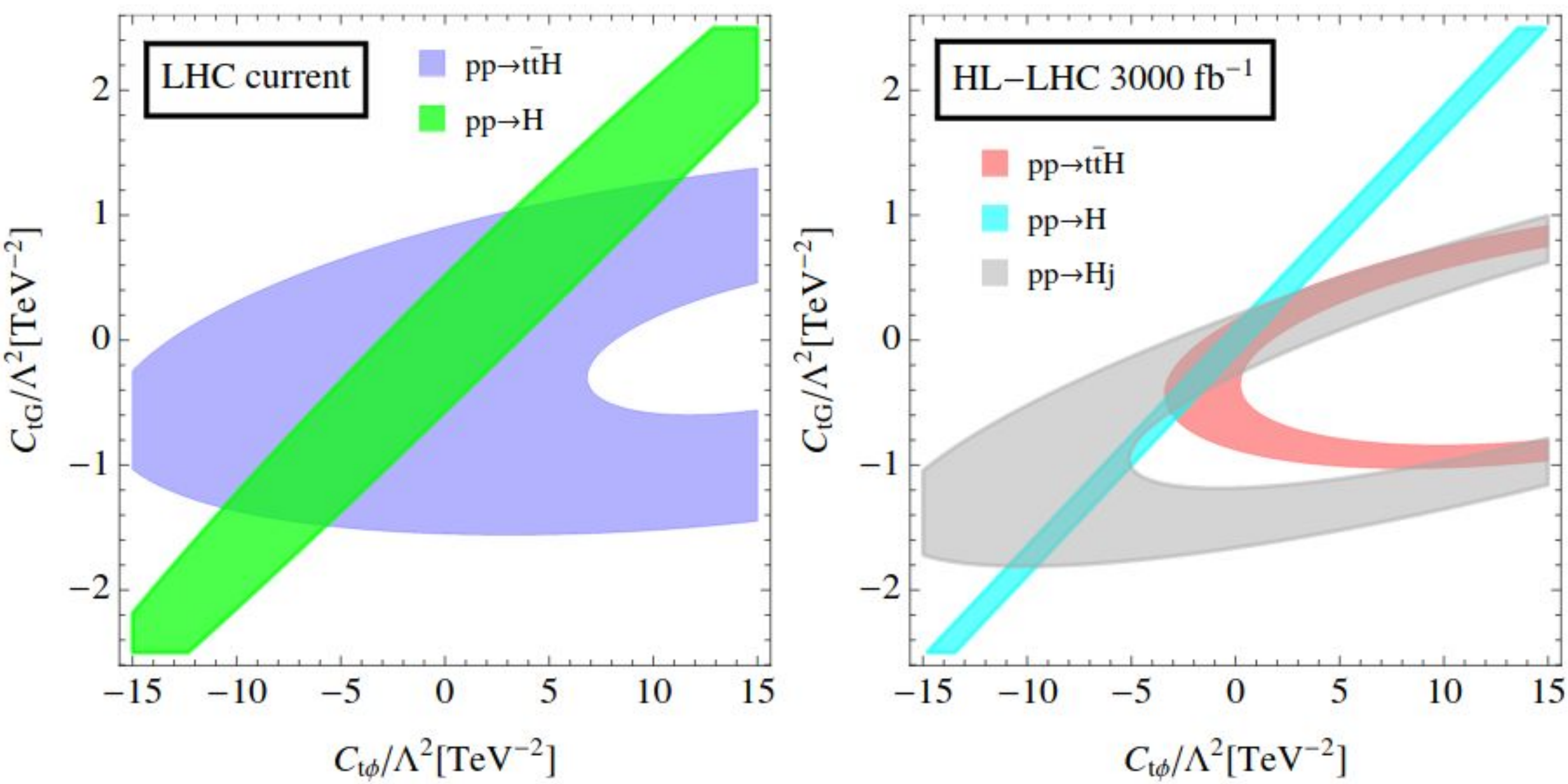
"current" and future prospects

- Assume $C_{t\phi}$ fixed to zero
- Interesting to re-run with full Run2 dataset...



“current” and future prospects

- Assume $C_{\phi G}$ fixed to zero
- Interesting to re-run with full Run2 dataset...



Lagrangian in the new operator basis

- Change operator basis
  - Higgs couplings to the SM gauge bosons: δc_z, c_{zz}, $c_{z\Box}$, $c_{z\gamma}$, $c_{\gamma\gamma}$, c_{gg}
  - Deformations of the fermion Yukawa's: δy_t, δy_b, δy_τ
  - Higgs trilinear self coupling: κ

$$
\begin{aligned}
\mathcal{L} \supset \frac{h}{v}\Bigg[& \delta c_w \frac{g^2 v^2}{2} W^+_\mu W^{-\mu} + \delta c_z \frac{(g^2+g'^2)v^2}{4} Z_\mu Z^\mu \\
& + c_{ww}\frac{g^2}{2} W^+_{\mu\nu} W^{-\mu\nu} + c_{w\Box} g^2 \left(W^-_\mu \partial_\nu W^{+\mu\nu} + \text{h.c.}\right) + \hat{c}_{\gamma\gamma}\frac{e^2}{4\pi^2} A_{\mu\nu}A^{\mu\nu} \\
& + c_{zz}\frac{g^2+g'^2}{4} Z_{\mu\nu}Z^{\mu\nu} + \hat{c}_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2\pi^2} Z_{\mu\nu}A^{\mu\nu} + c_{z\Box} g^2 Z_\mu \partial_\nu Z^{\mu\nu} + c_{\gamma\Box} g g' Z_\mu \partial_\nu A^{\mu\nu}\Bigg] \\
& + \frac{g_s^2}{48\pi^2}\left(\hat{c}_{gg}\frac{h}{v} + \hat{c}^{(2)}_{gg}\frac{h^2}{2v^2}\right) G_{\mu\nu}G^{\mu\nu} - \sum_f \left[m_f \left(\delta y_f \frac{h}{v} + \delta y_f^{(2)}\frac{h^2}{2v^2}\right)\bar{f}_R f_L + \text{h.c.}\right] \\
& - (\kappa_\lambda - 1)\lambda_3^{SM} v h^3 \,, \qquad (2.5)
\end{aligned}
$$

- The other coefficients appearing in the lagrangian can be expressed as a function of the operator basis

Results global fit with $\kappa_\lambda = 1$

- Strong correlation among some parameter
  - Reduced including WWɣ, WWZ, and H→Zɣ processes

$$
\begin{pmatrix} \hat{c}_{gg} \\ \delta c_z \\ c_{zz} \\ c_{z\Box} \\ \hat{c}_{z\gamma} \\ \hat{c}_{\gamma\gamma} \\ \delta y_t \\ \delta y_b \\ \delta y_\tau \end{pmatrix} = \pm \begin{pmatrix} 0.07\ (0.02) \\ 0.07\ (0.01) \\ 0.64\ (0.02) \\ 0.24\ (0.01) \\ 4.94\ (0.65) \\ 0.08\ (0.02) \\ 0.09\ (0.02) \\ 0.14\ (0.03) \\ 0.17\ (0.09) \end{pmatrix} \quad \begin{bmatrix} 1 & -0.01 & -0.02 & 0.03 & 0.08 & 0.01 & \mathbf{-0.71} & 0.03 & 0.01 \\ & 1 & -0.45 & 0.36 & -0.61 & -0.33 & 0.18 & \mathbf{0.89} & 0.53 \\ & & 1 & \mathbf{-0.99} & 0.69 & 0.11 & 0.38 & -0.47 & \mathbf{-0.74} \\ & & & 1 & -0.58 & -0.23 & -0.42 & 0.42 & \mathbf{0.71} \\ & & & & 1 & -0.58 & 0.09 & -0.46 & -0.63 \\ & & & & & 1 & 0.14 & 0.04 & 0.04 \\ & & & & & & 1 & 0.25 & -0.08 \\ & & & & & & & 1 & 0.57 \\ & & & & & & & & 1 \end{bmatrix} .
$$

$$
\begin{pmatrix} \hat{c}_{gg} \\ \delta c_z \\ c_{zz} \\ c_{z\Box} \\ \hat{c}_{z\gamma} \\ \hat{c}_{\gamma\gamma} \\ \delta y_t \\ \delta y_b \\ \delta y_\tau \end{pmatrix} = \pm \begin{pmatrix} 0.07\ (0.02) \\ 0.05\ (0.01) \\ 0.05\ (0.02) \\ 0.02\ (0.01) \\ 0.09\ (0.09) \\ 0.03\ (0.02) \\ 0.08\ (0.02) \\ 0.12\ (0.03) \\ 0.11\ (0.09) \end{pmatrix} \quad \begin{bmatrix} 1 & 0.04 & -0.01 & -0.01 & 0.04 & 0.31 & \mathbf{-0.76} & 0.05 & 0.02 \\ & 1 & -0.07 & -0.26 & 0.01 & 0.01 & 0.36 & \mathbf{0.88} & 0.27 \\ & & 1 & \mathbf{-0.87} & 0.13 & 0.20 & 0.03 & -0.07 & -0.06 \\ & & & 1 & -0.09 & -0.09 & -0.09 & -0.17 & 0.08 \\ & & & & 1 & 0.05 & -0.02 & -0.02 & -0.03 \\ & & & & & 1 & -0.32 & -0.19 & -0.12 \\ & & & & & & 1 & 0.50 & 0.28 \\ & & & & & & & 1 & 0.36 \\ & & & & & & & & 1 \end{bmatrix}
$$