Effective Field Theory: Top and Higgs

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CERN TH

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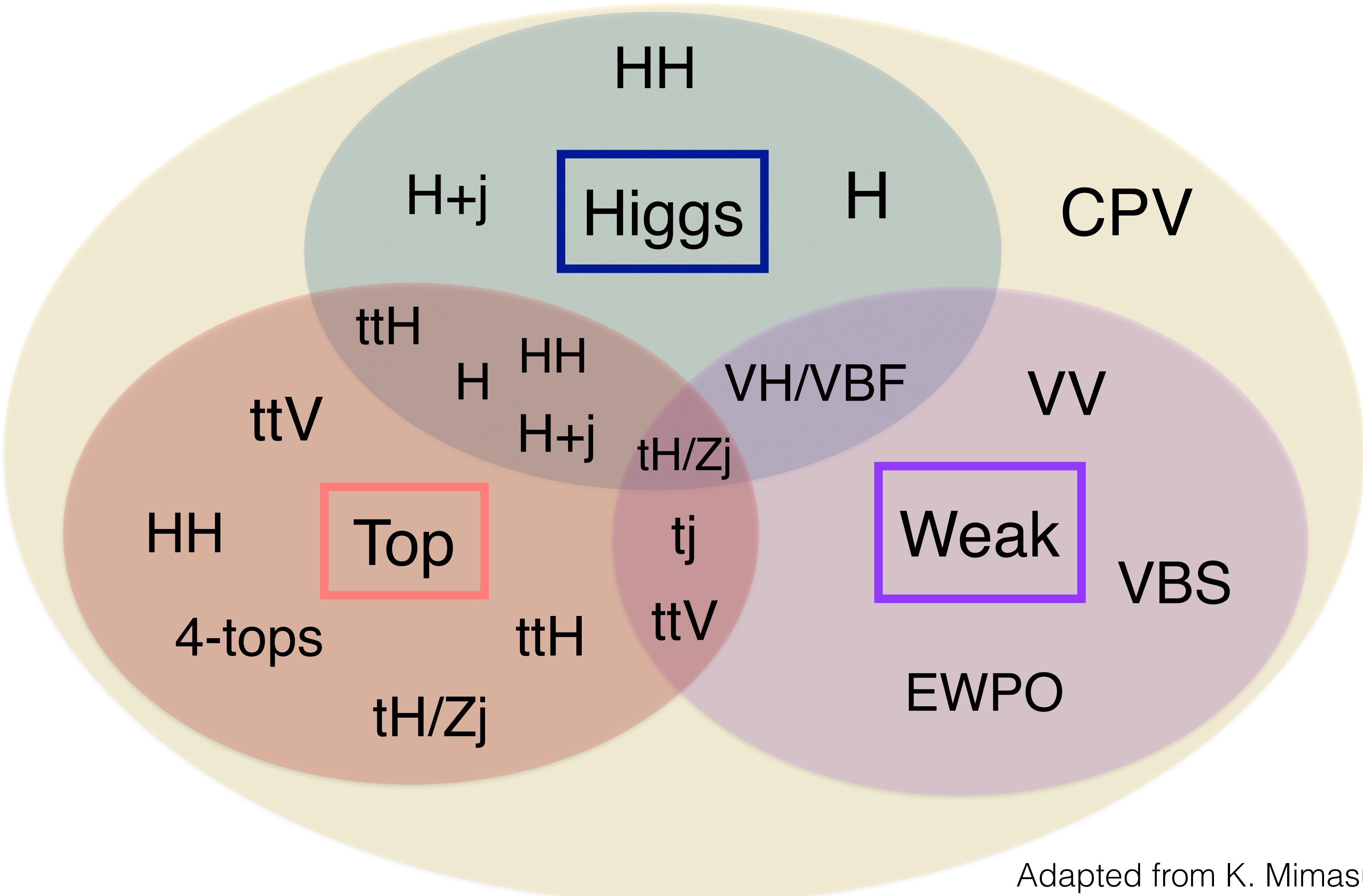
13/01/20

The global nature of the EFT



Adapted from K. Mimasu

Focussing on top-Higgs

Operators

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

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

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

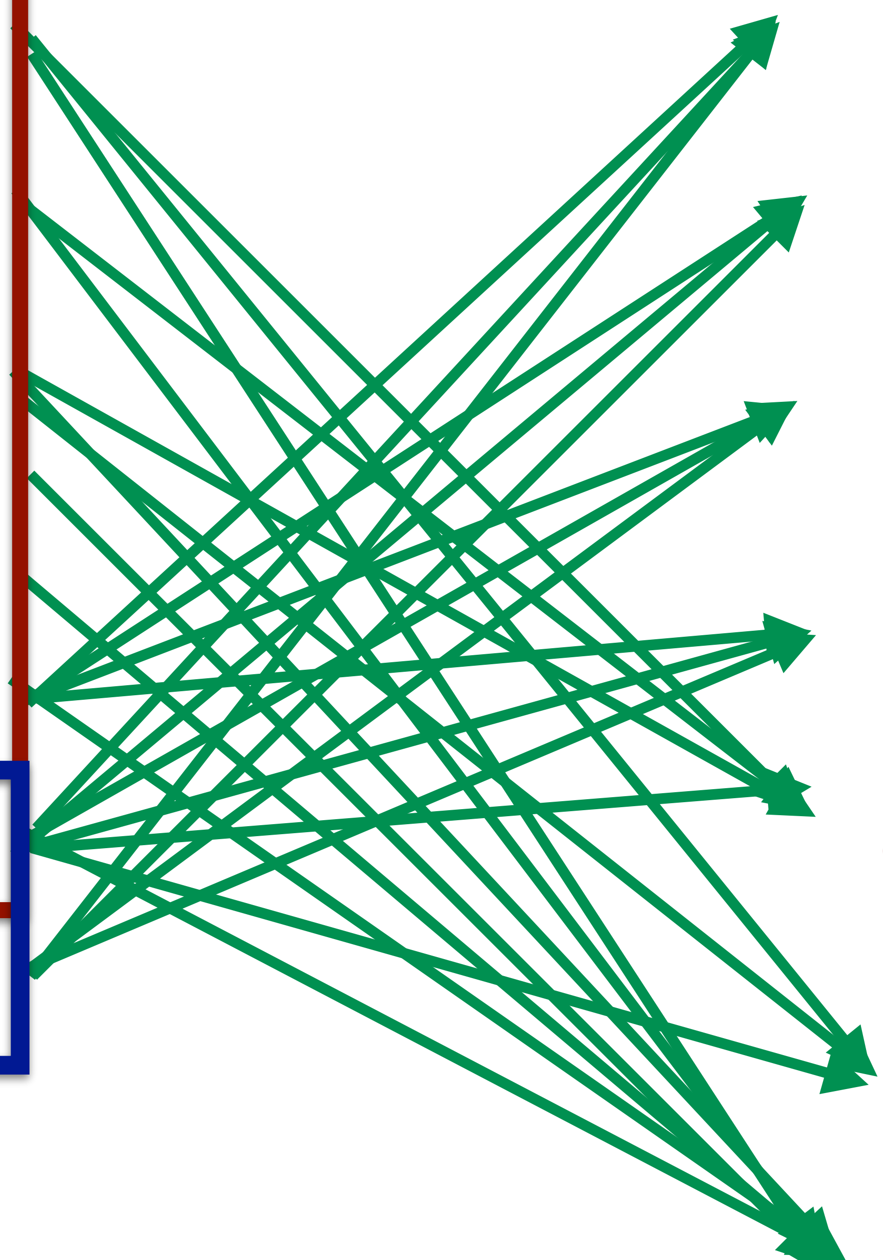
$$O_{tW} = y_t g_w(\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi} W^I_{\mu\nu}$$

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

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

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

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



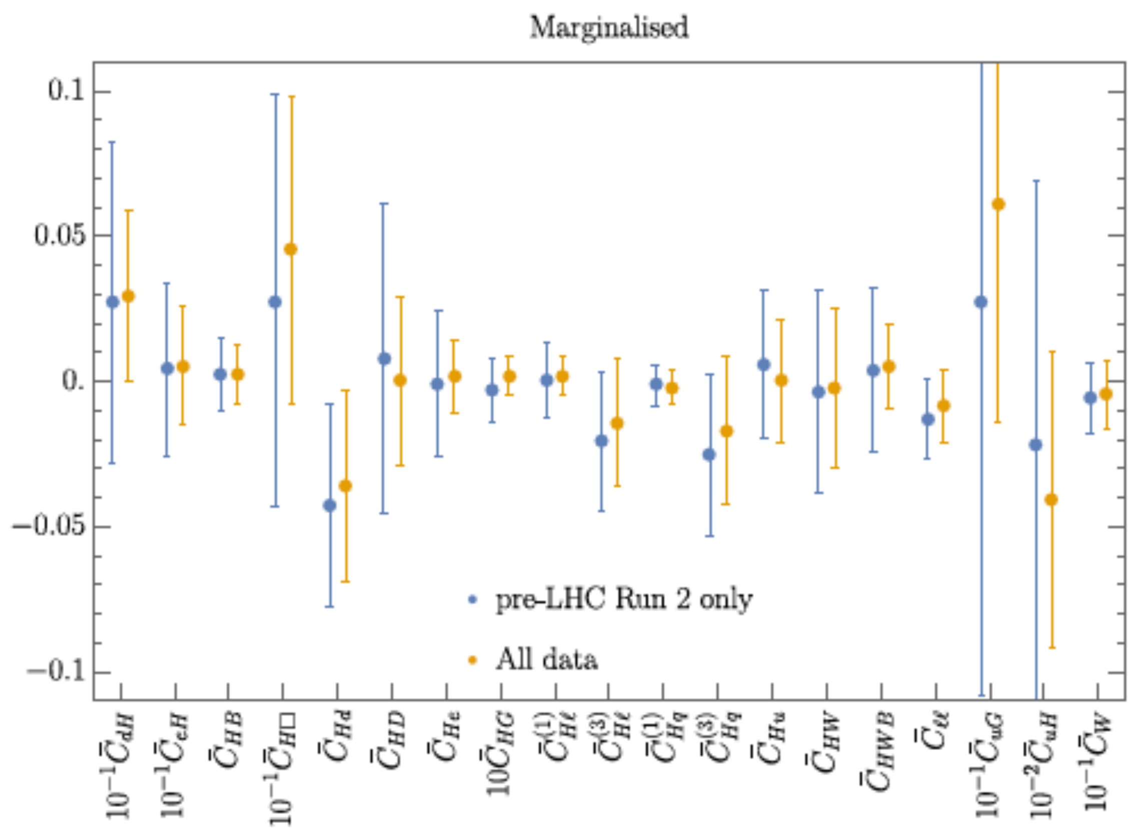
Production process

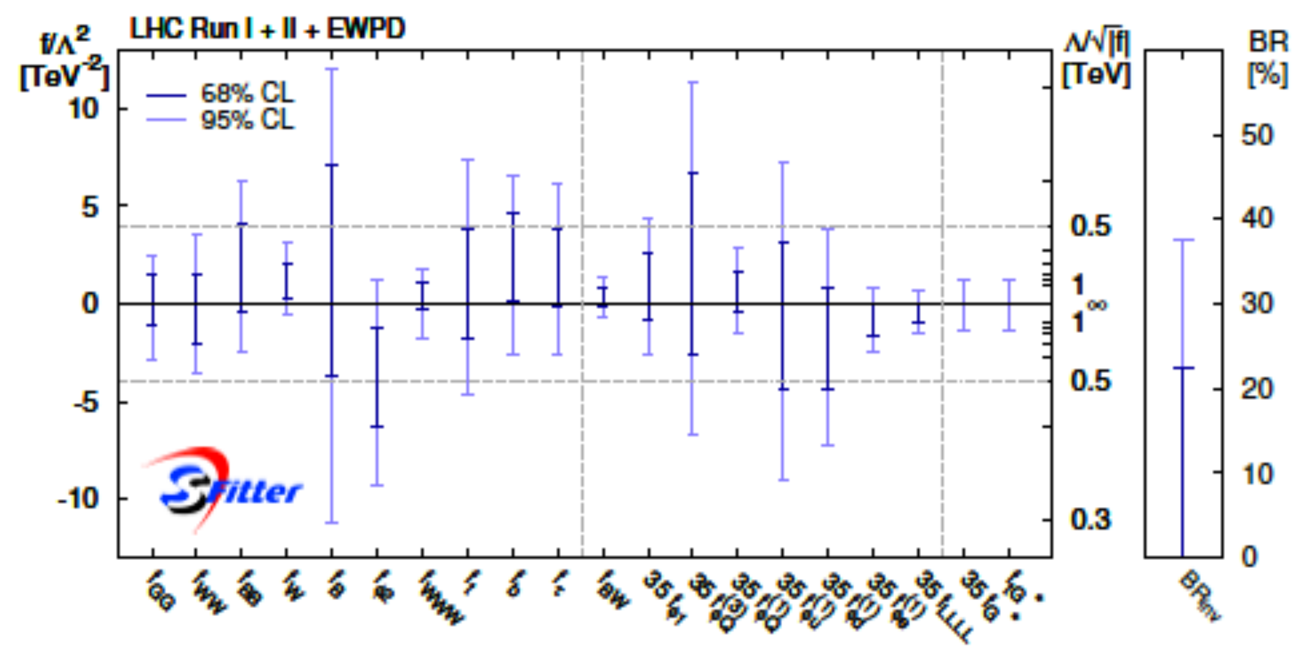
- gg → h
- gg → hj
- tth
- gg → hh
- gg → hz
- thj
- gg → ZZ

Top-Higgs are deeply connected

Global fit results

1. Higgs+WW+EWPO



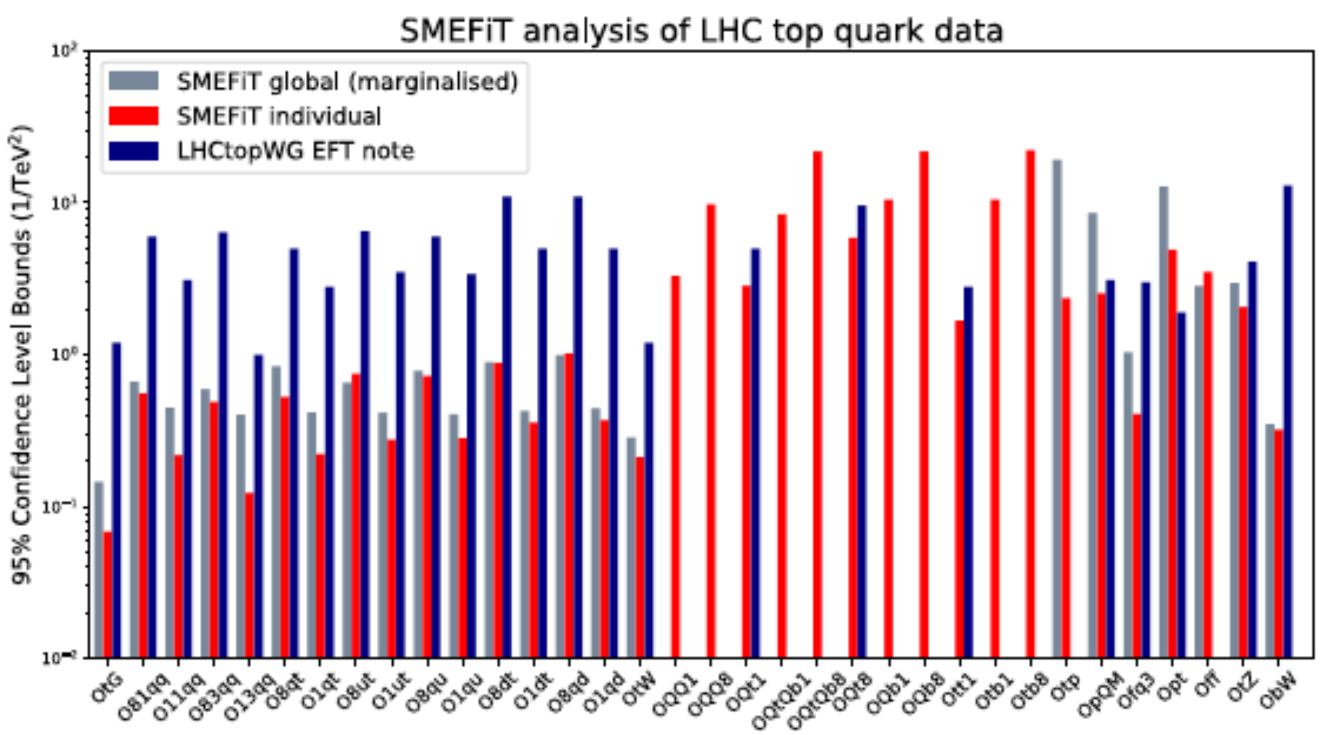


Ellis, Murphy, Sanz, You arXiv:1803.03252 Biekotter, Corbett, Plehn arXiv:1812.07587

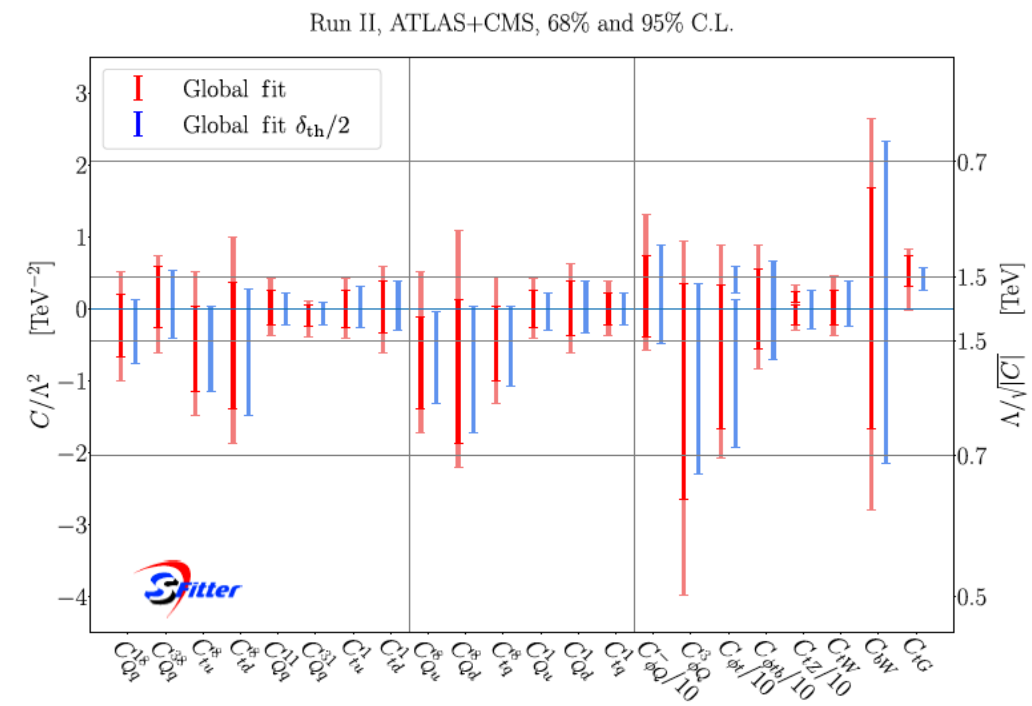
Higgs+Weak final states

Global fit results

2.Top



Hartland, Maltoni, Nocera, Rojo, Slade, EV and Zhang arXiv:1901.05965



Brivio, Bruggisser, Maltoni, Moutafis, Plehn, EV, Westhoff, Zhang arXiv:1910.03606

Top final states

Questions

Current approach (EFT fits) largely ignores the interplay between top and Higgs

Questions:

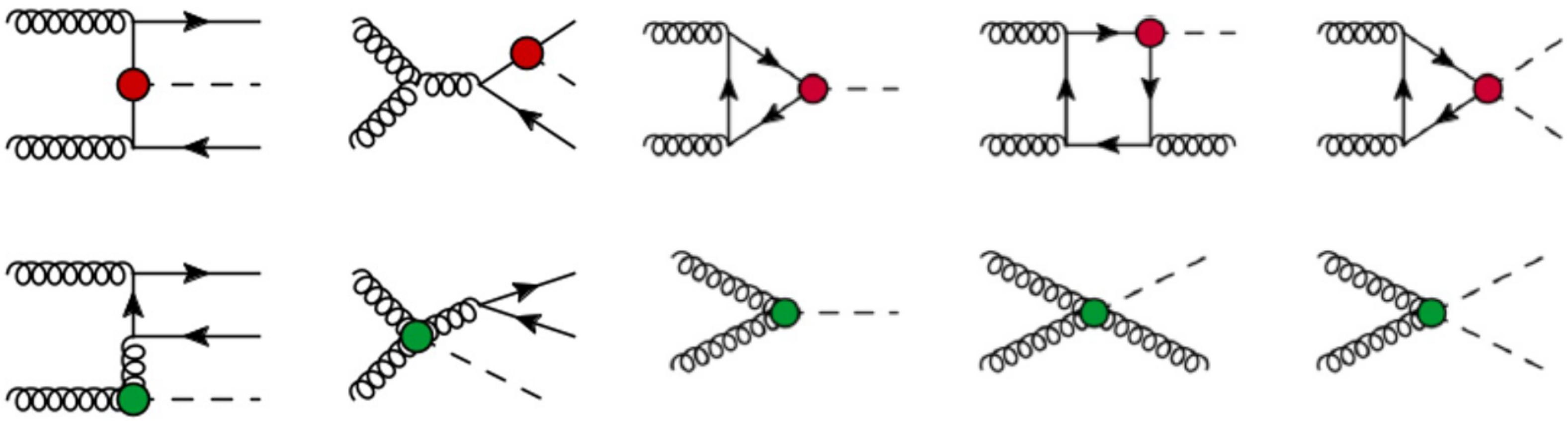
1. **Should we keep the two sectors separate?**

2. **Can we keep the two sectors separate?**

Can a combination help?

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

(cf. k_t, k_g)

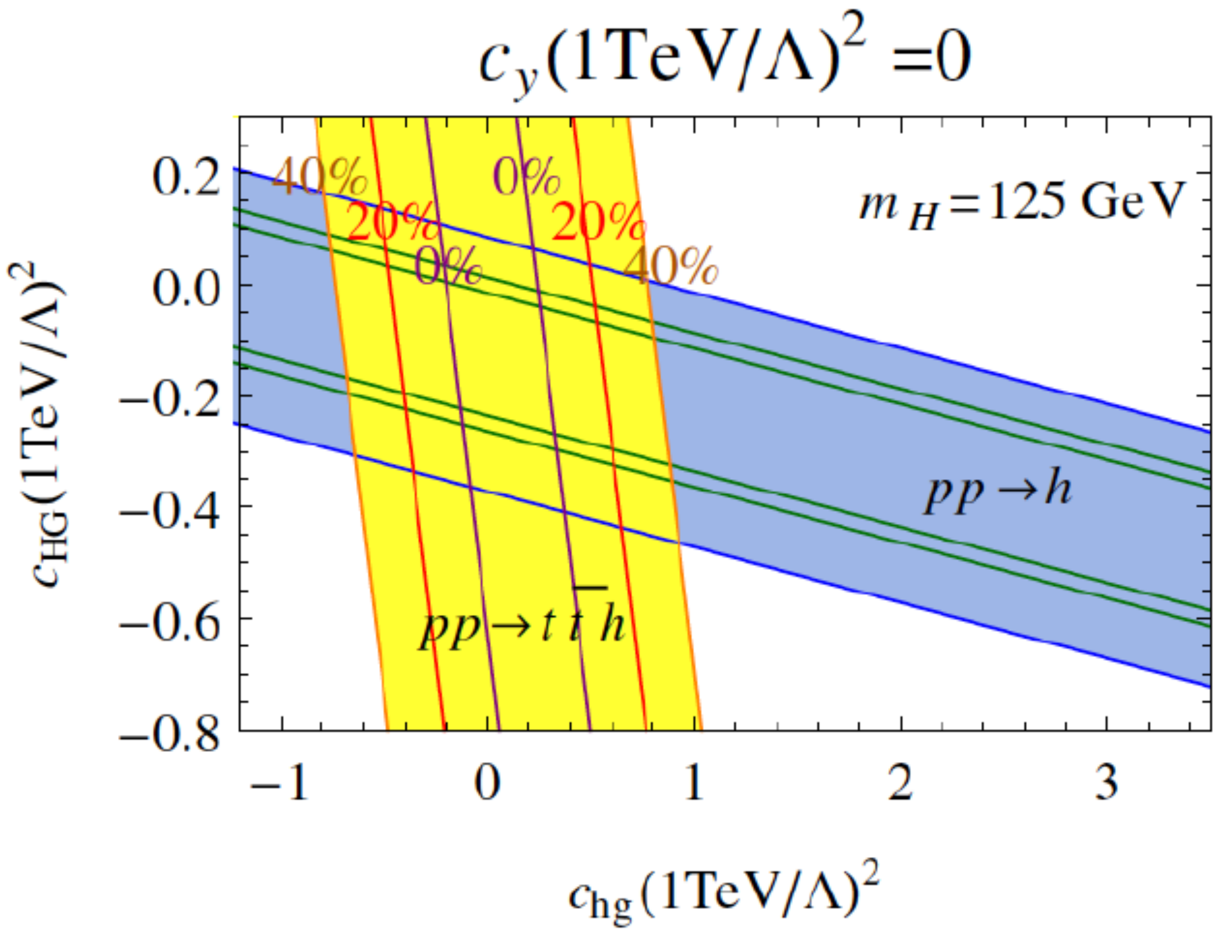


ttH

H, H+j, HH

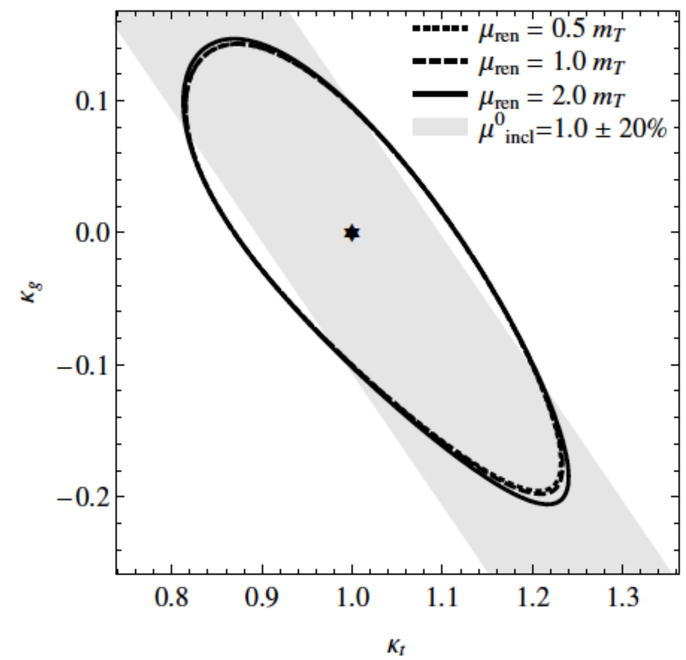
Use with 1) ttH and 2) H, H+j to break degeneracy between operators and extract maximal information on these operators

Breaking degeneracies

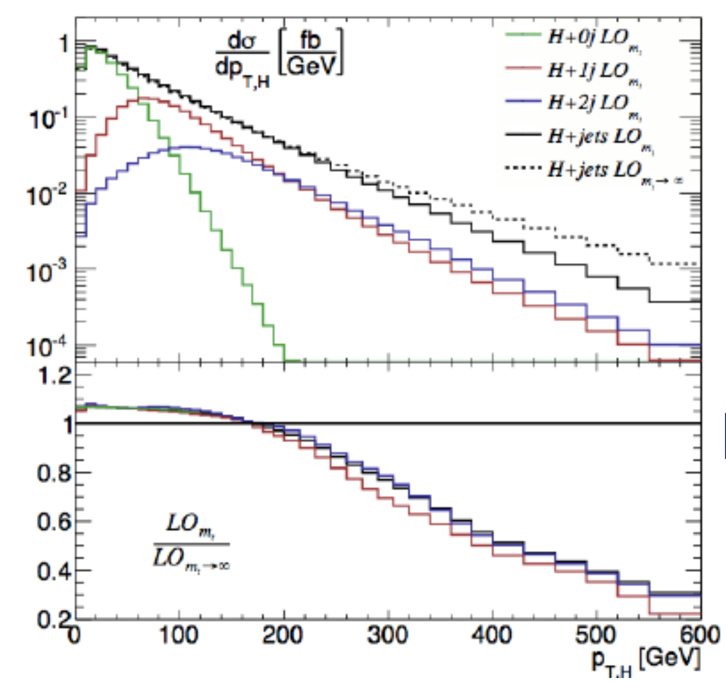


Degrande et al arXiv:1205.1065

Use ttH



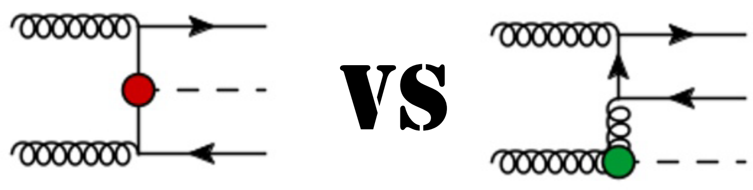
Grojean et al arXiv: 1312.3317

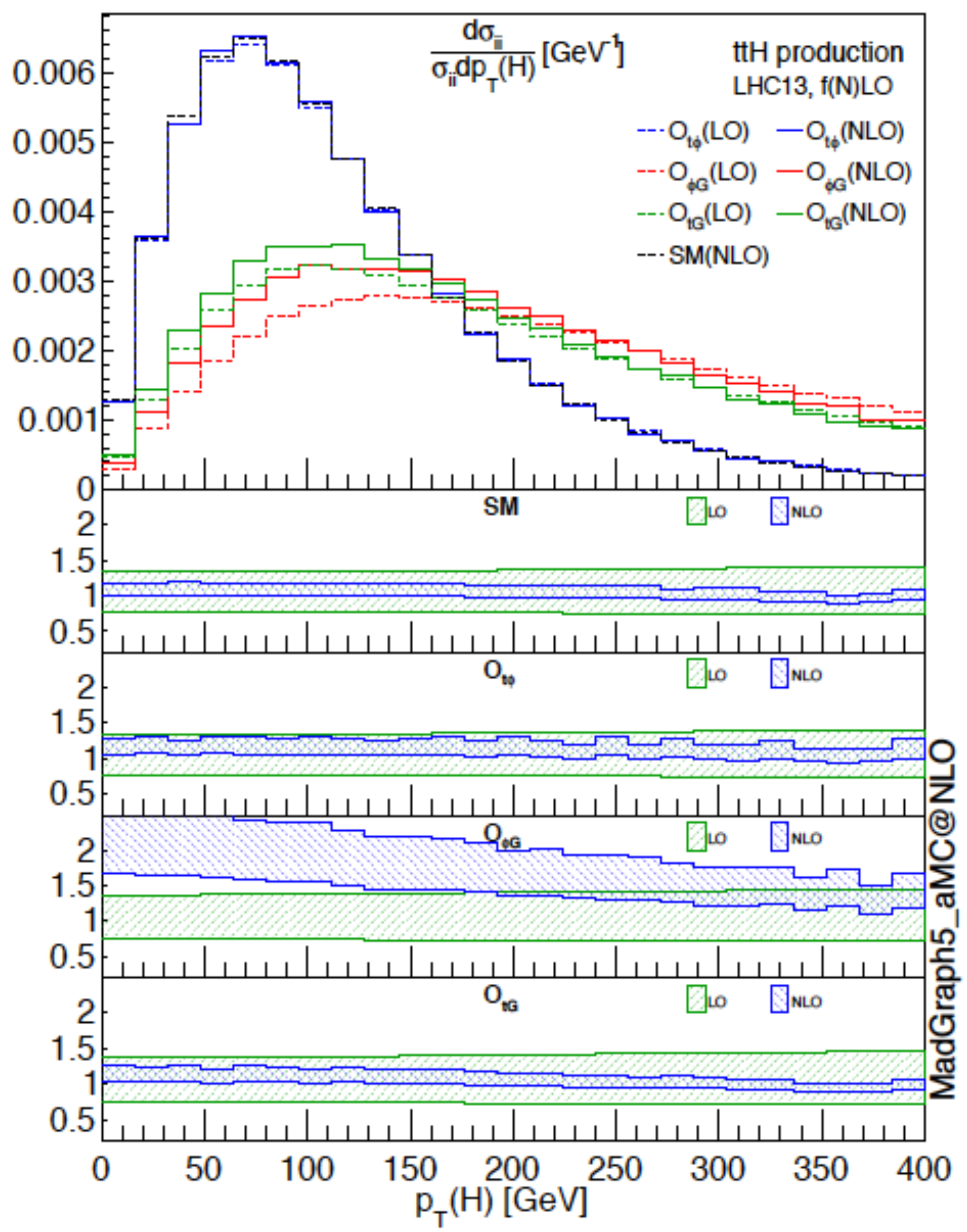


Buschmann et al arXiv:1410.5806

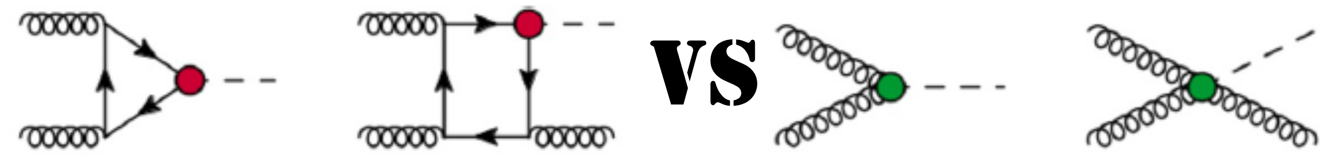
Use boosted Higgs

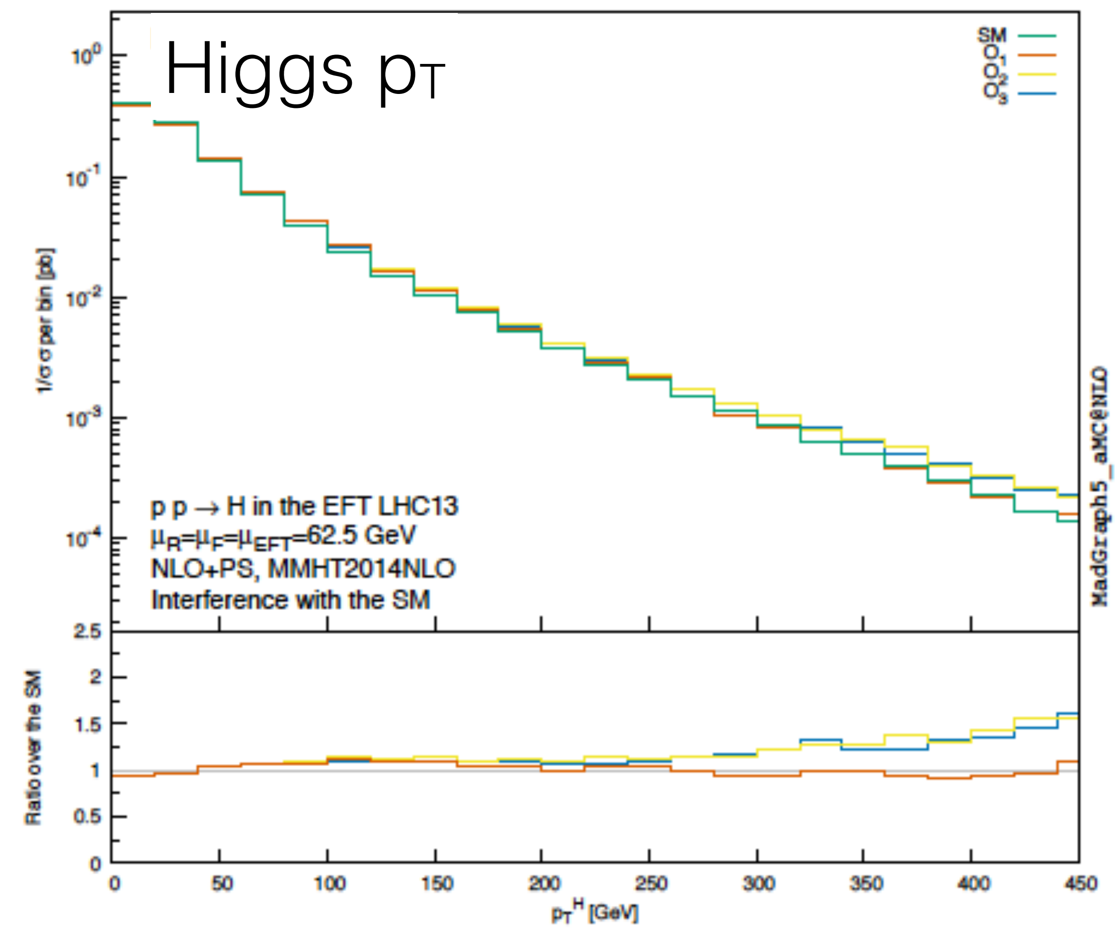
The impact of differential information





Maltoni, EV, Zhang arXiv:1607.05330



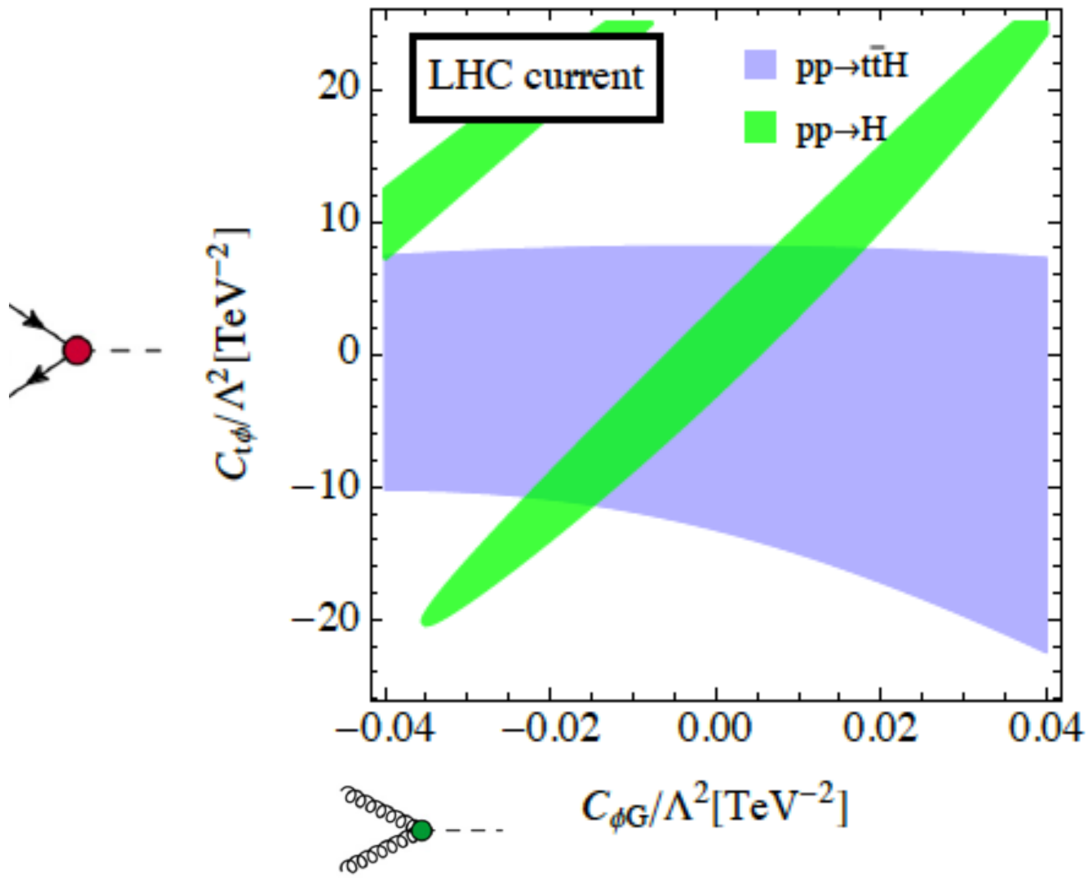


Deutschmann, Duhr, Maltoni, EV arXiv:1708.00460

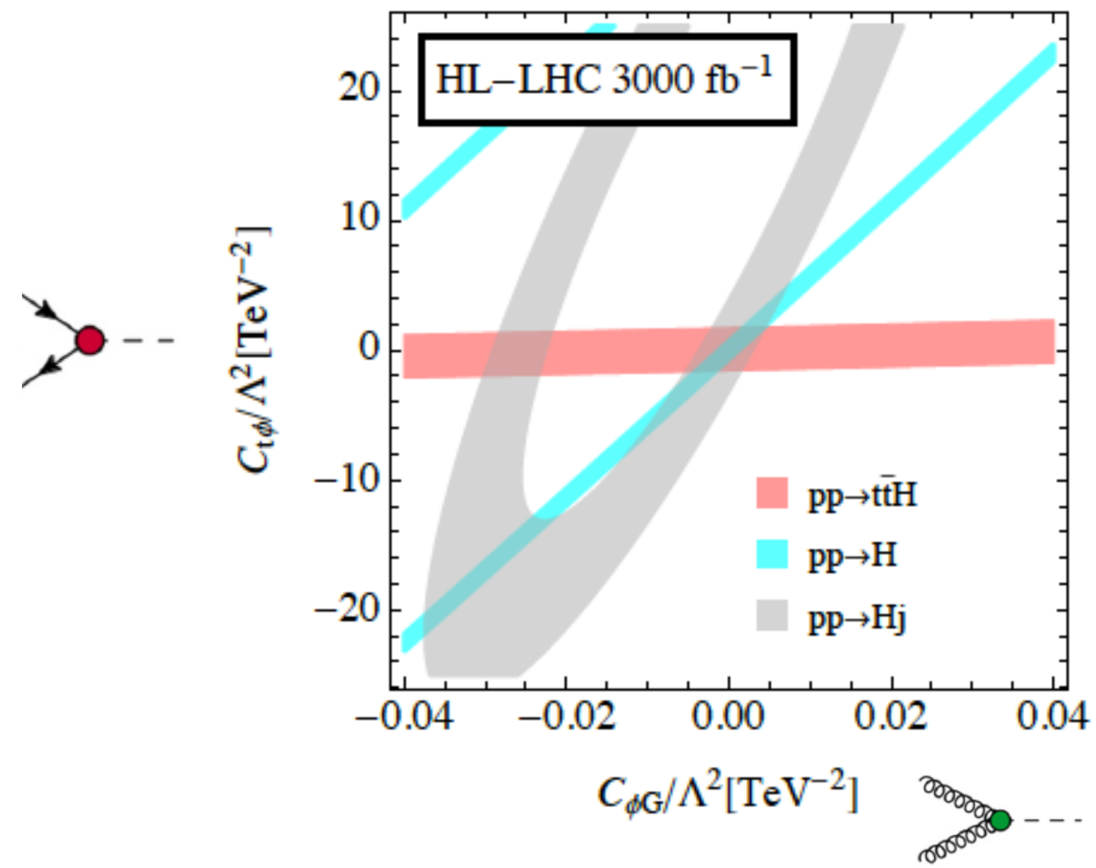
See also Grazzini et al 1612.00283

Different shapes for different operators

Present and future prospects



Current limits using LHC measurements



14TeV projection 3000 fb^{-1}

Maltoni, EV, Zhang arXiv:1607.05330

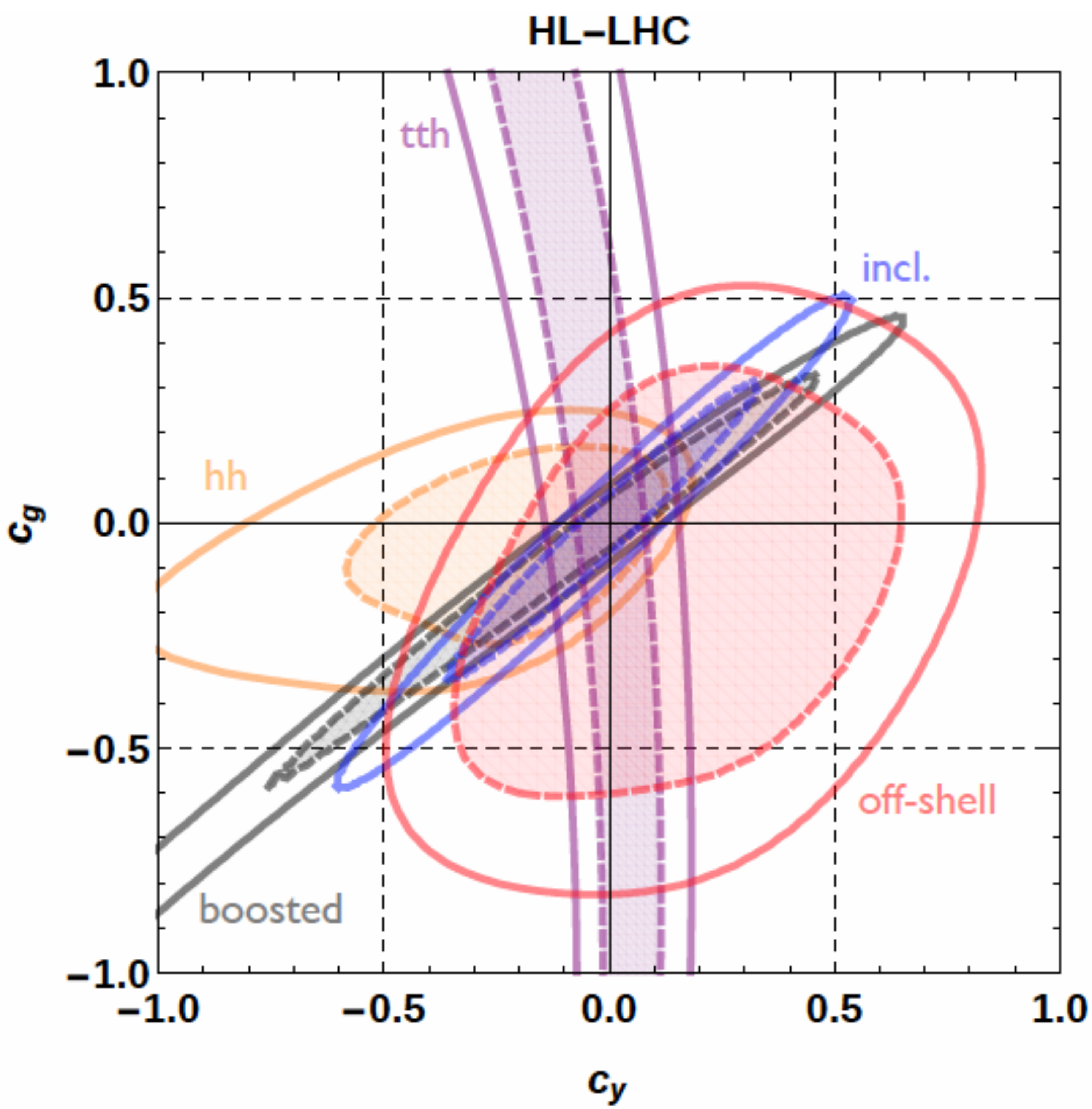
How to extract maximal information?

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

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

Lots of processes
Combination:

- inclusive H
- boosted Higgs
- ttH
- HH
- off-shell Higgs



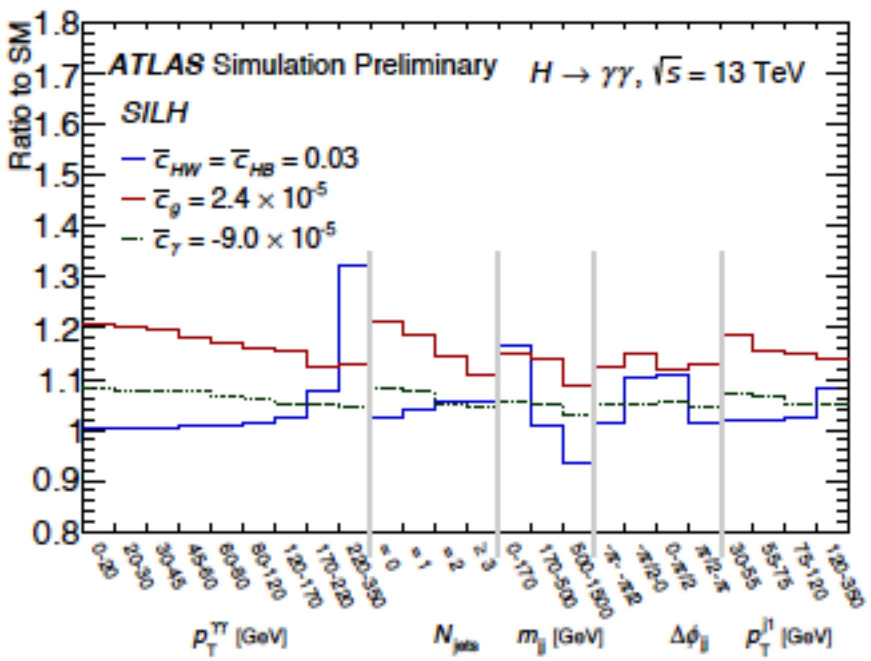
Azatov, Grojean, Paul, Salvioni arXiv:1608.00977

Towards experimental SMEFT analysis

Theorists have been looking at this interplay for some time…

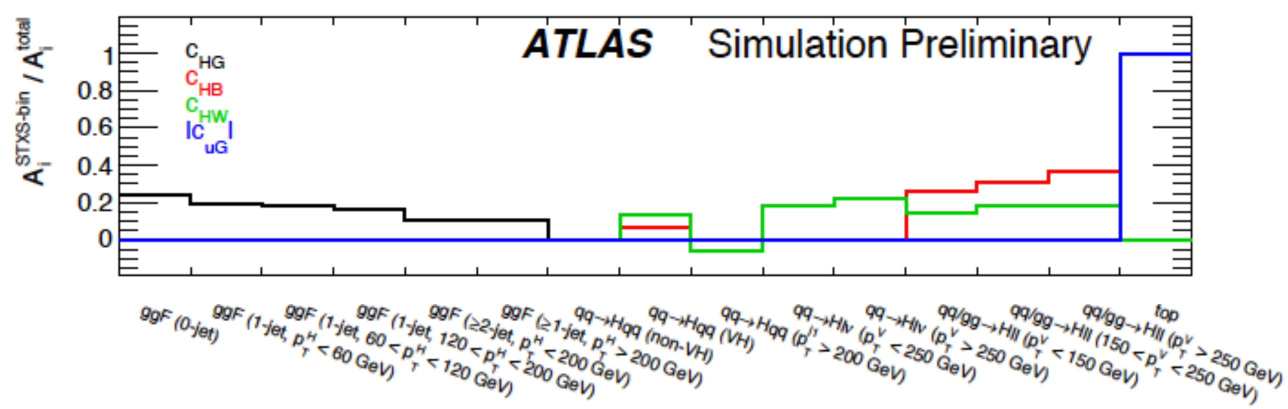
ATLAS-CONF-2019-029

$$\mathcal{L}_{\rm eff}^{\rm SMEFT} \supset \quad \overline{C}_{HG} O'_g + \overline{C}_{HW} O'_{HW} + \overline{C}_{HB} O'_{HB} + \overline{C}_{HWB} O'_{HWB}$$



ATL-PHYS-PUB-2019-042

Measured region	$\sigma_{\rm int}/\sigma_{\rm SM}$
$gg \to H$ (0-jet)	$35.0 \cdot c_{HG}$
$gg \to H$ (1-jet, $p_T^H < 60$ GeV)	$28.3 \cdot c_{HG}$
$gg \to H$ (1-jet, $60 < p_T^H < 120$ GeV)	$26.1 \cdot c_{HG}$
$gg \to H$ (1-jet, $120 < p_T^H < 200$ GeV)	$23.1 \cdot c_{HG}$
$gg \to H$ ($\geq$ 2-jet, $p_T^H < 200$ GeV)	$16.0 \cdot c_{HG}$
$gg \to H$ ($\geq$ 1-jet, $p_T^H > 200$ GeV)	$15.6 \cdot c_{HG}$



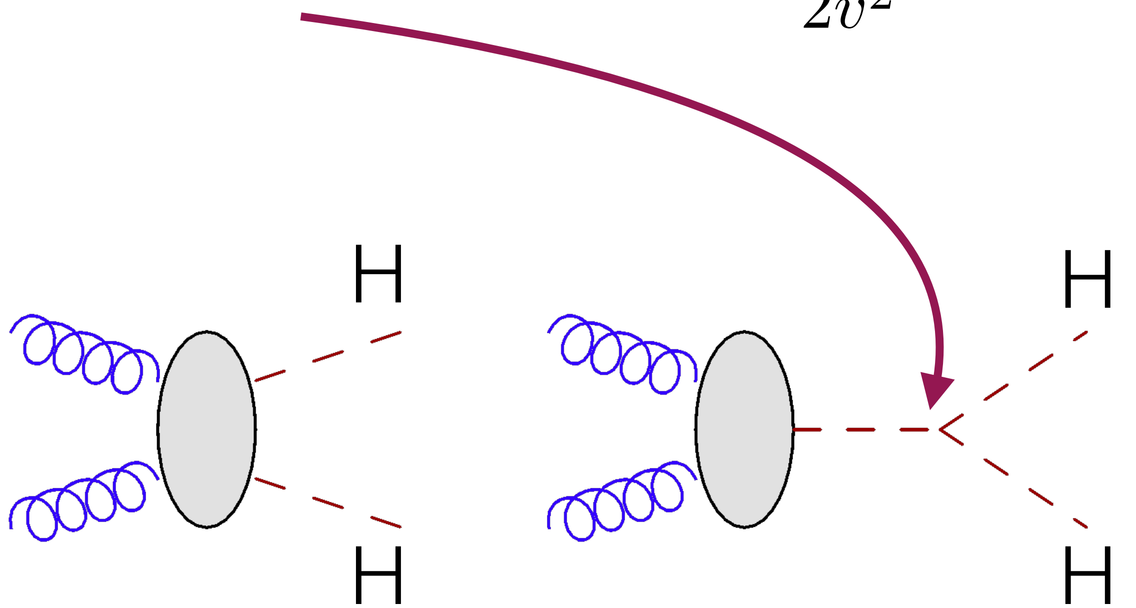
Where is the top Yukawa?

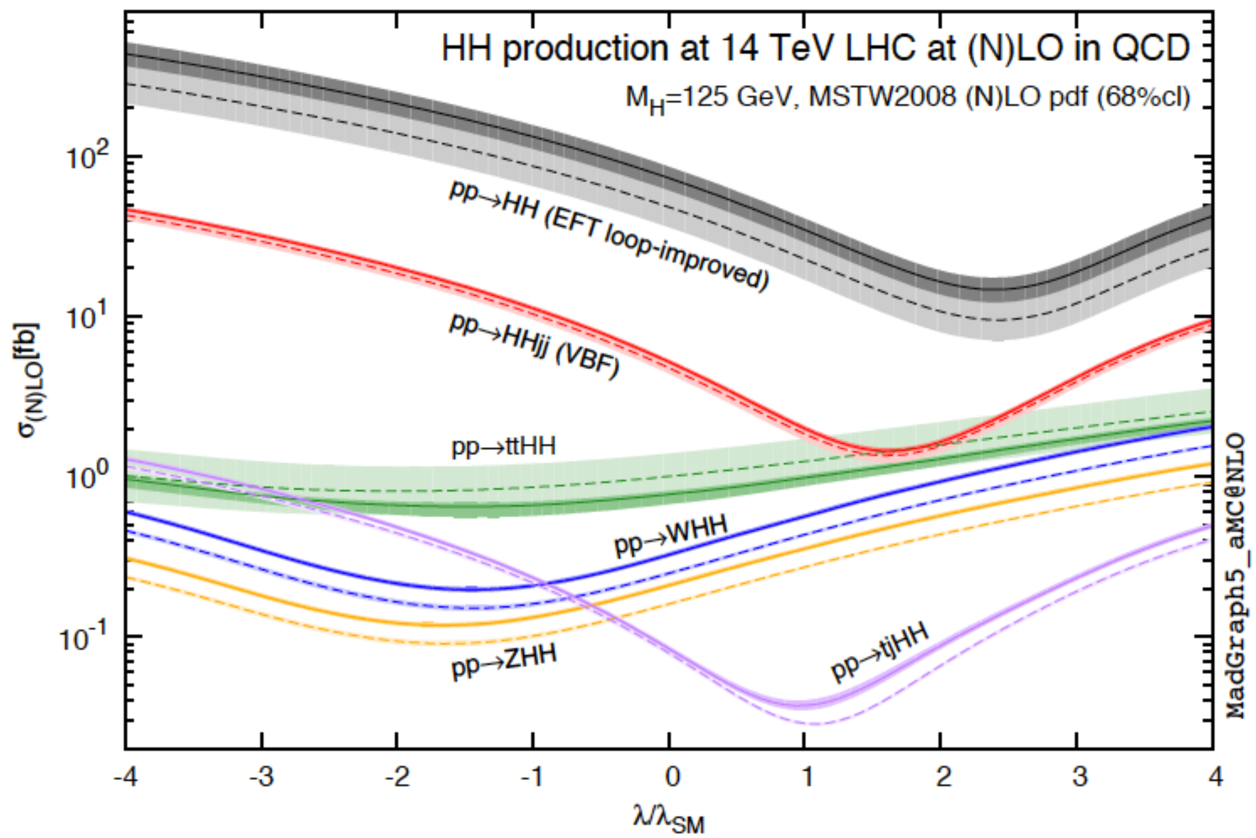
Double Higgs production

HH and the Higgs potential

$$V(H) = \frac{1}{2}M_H^2 H^2 + \lambda_{HHH} v H^3 + \frac{1}{4}\lambda_{HHHH} H^4$$

$$\lambda_{HHH} = \lambda_{HHHH} = \frac{M_H^2}{2v^2}$$

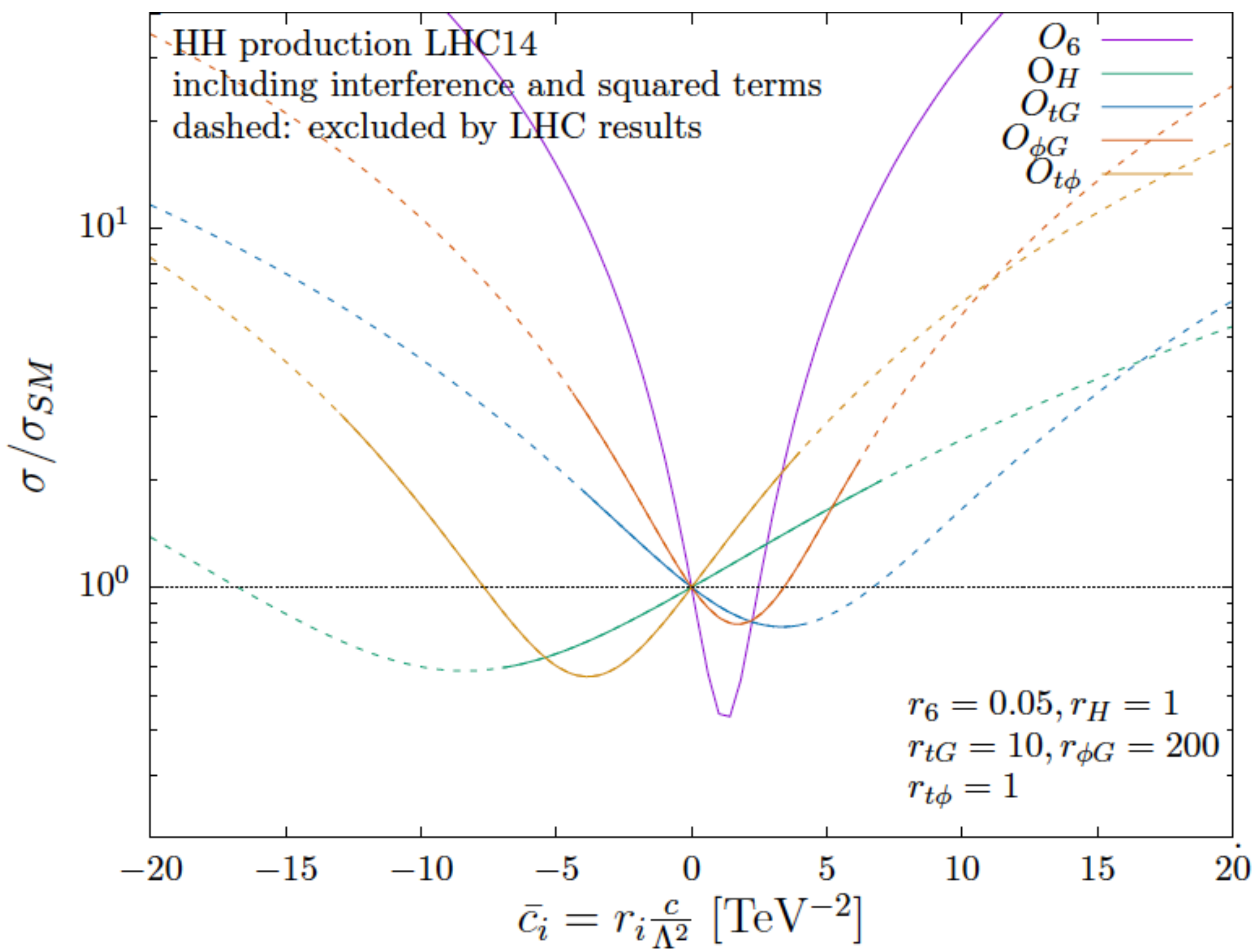


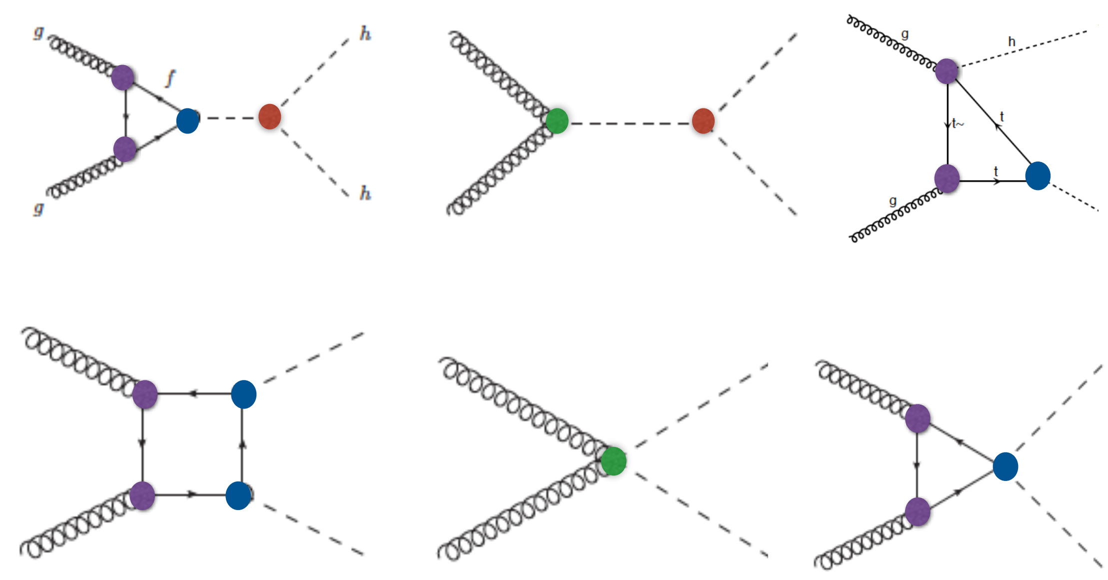


Phys.Lett. B732 (2014) 142-149

A challenging process at the LHC

HH in the EFT





top Yukawa, ggh(h) coupling, top-gluon interaction, Higgs self-coupling

The present

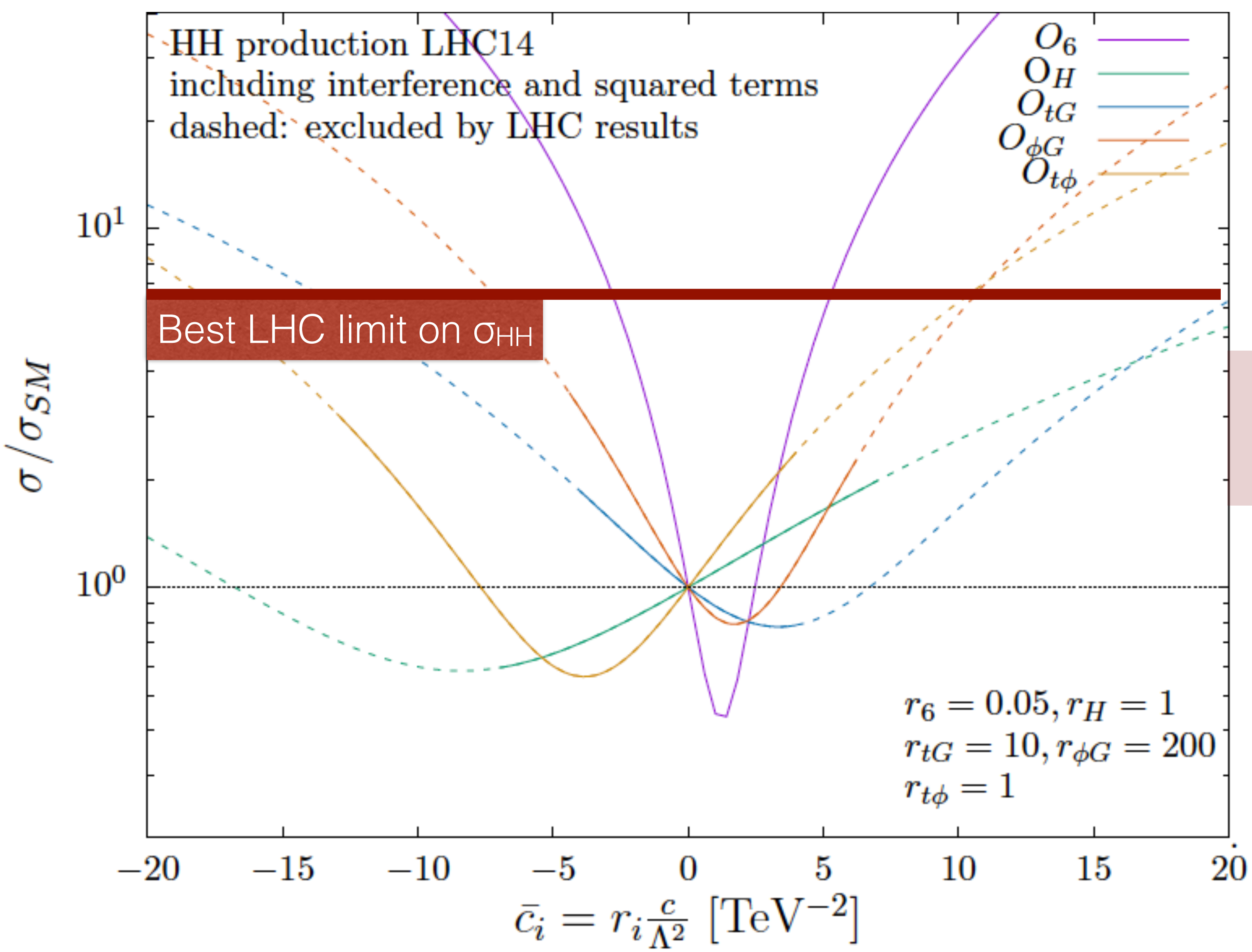
Given the current constraints on σ(HH), σ(H) and the ttH measurement, the Higgs self-coupling can be currently constrained "ignoring" other couplings

The future

Precise knowledge of other Wilson coefficients will be needed to bound λ as the bound gets closer to SM

Differential distributions will also be necessary

HH in the EFT



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

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

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

$$O_6 = -\lambda(\phi^\dagger\phi)^3$$

$$O_H = \frac{1}{2}(\partial_\mu(\phi^\dagger\phi))^2$$

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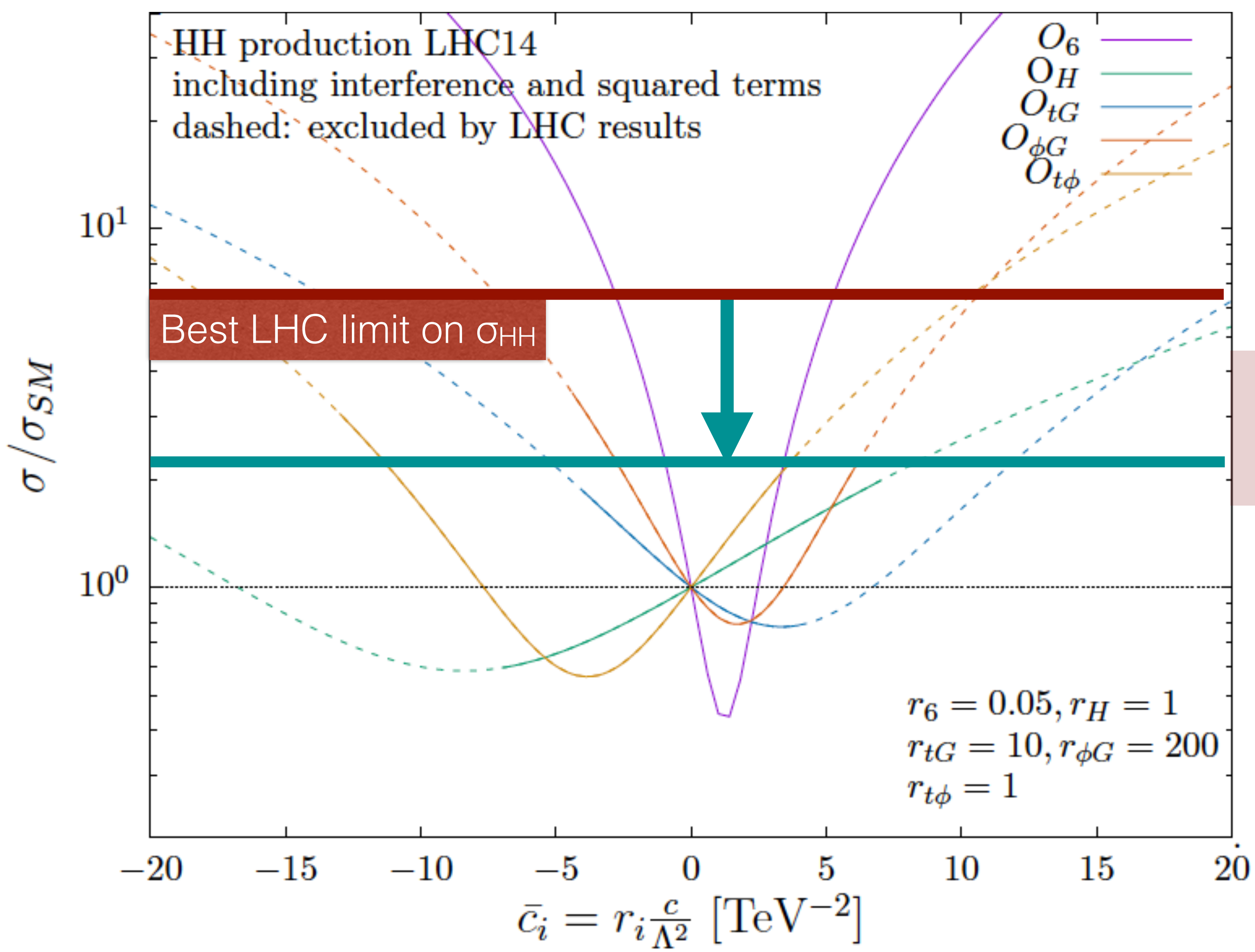

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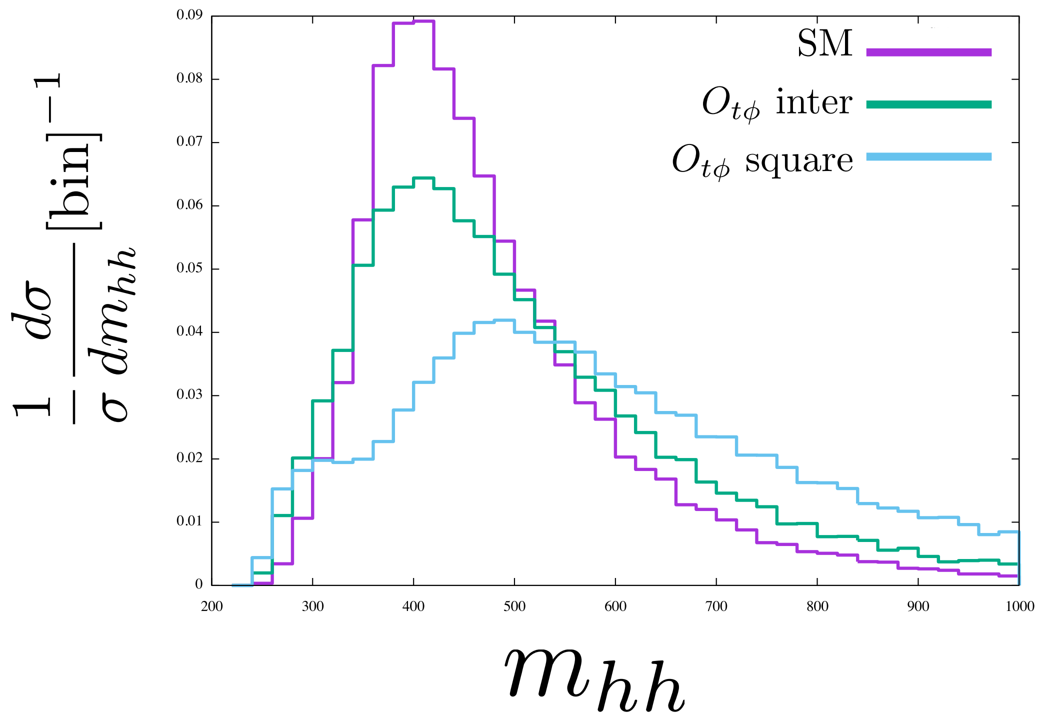
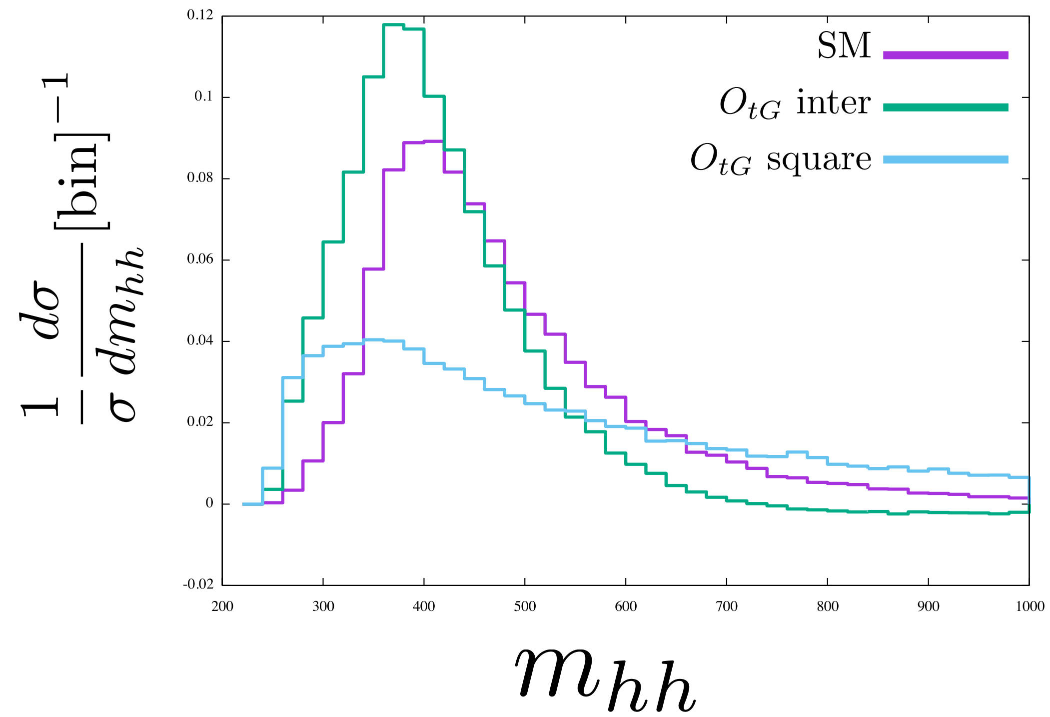
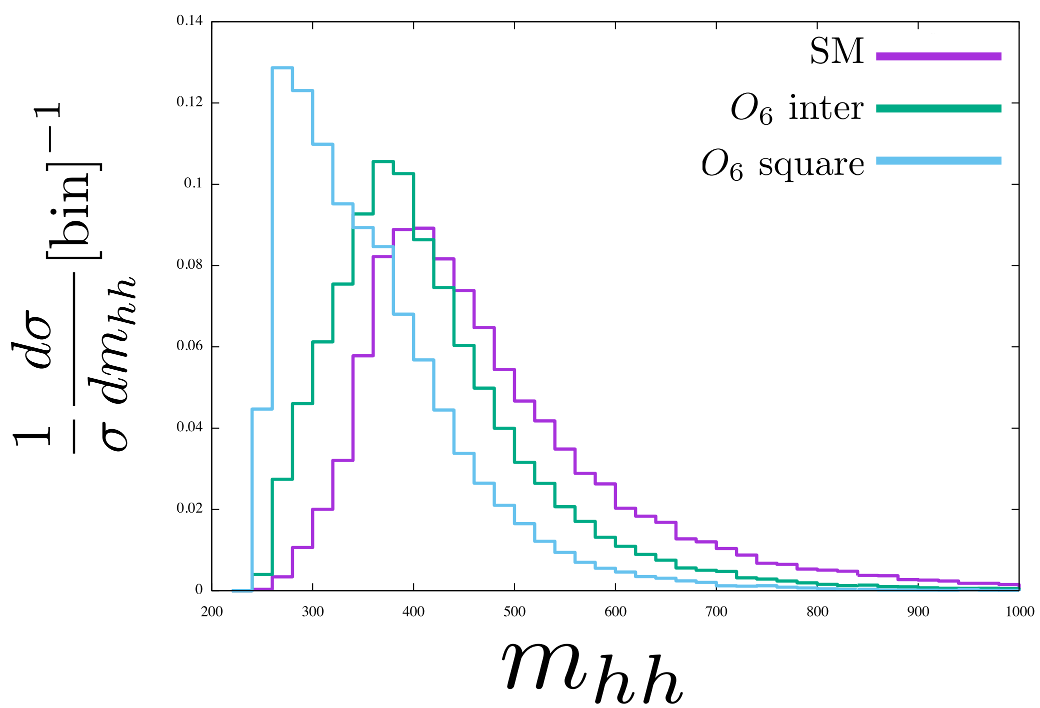
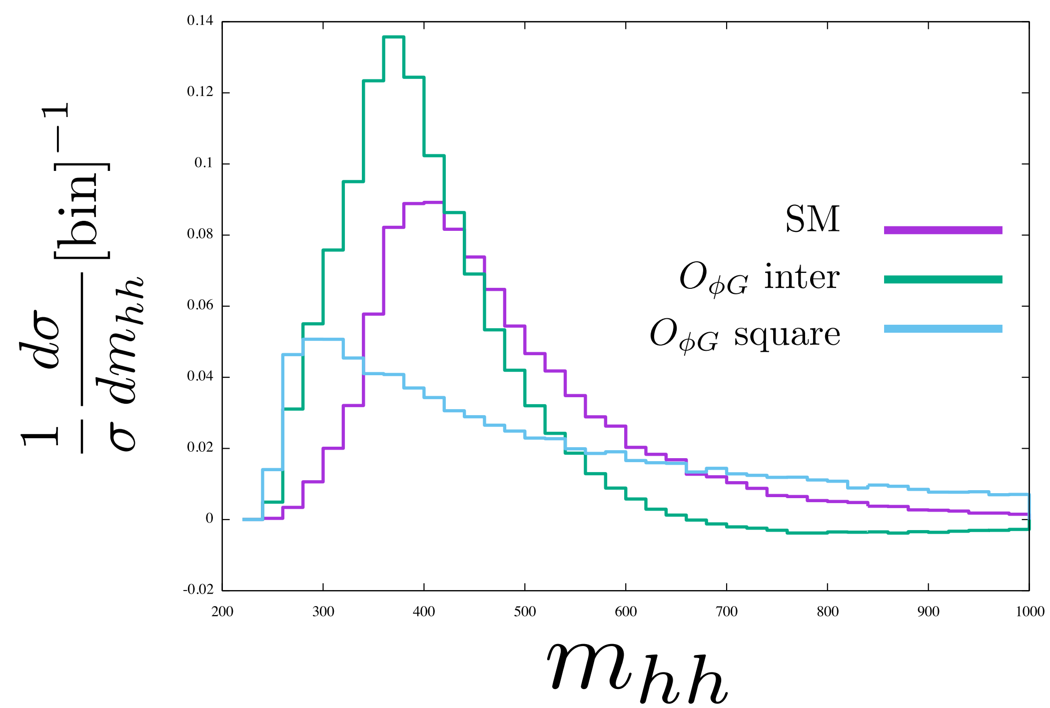
Differential results for HH

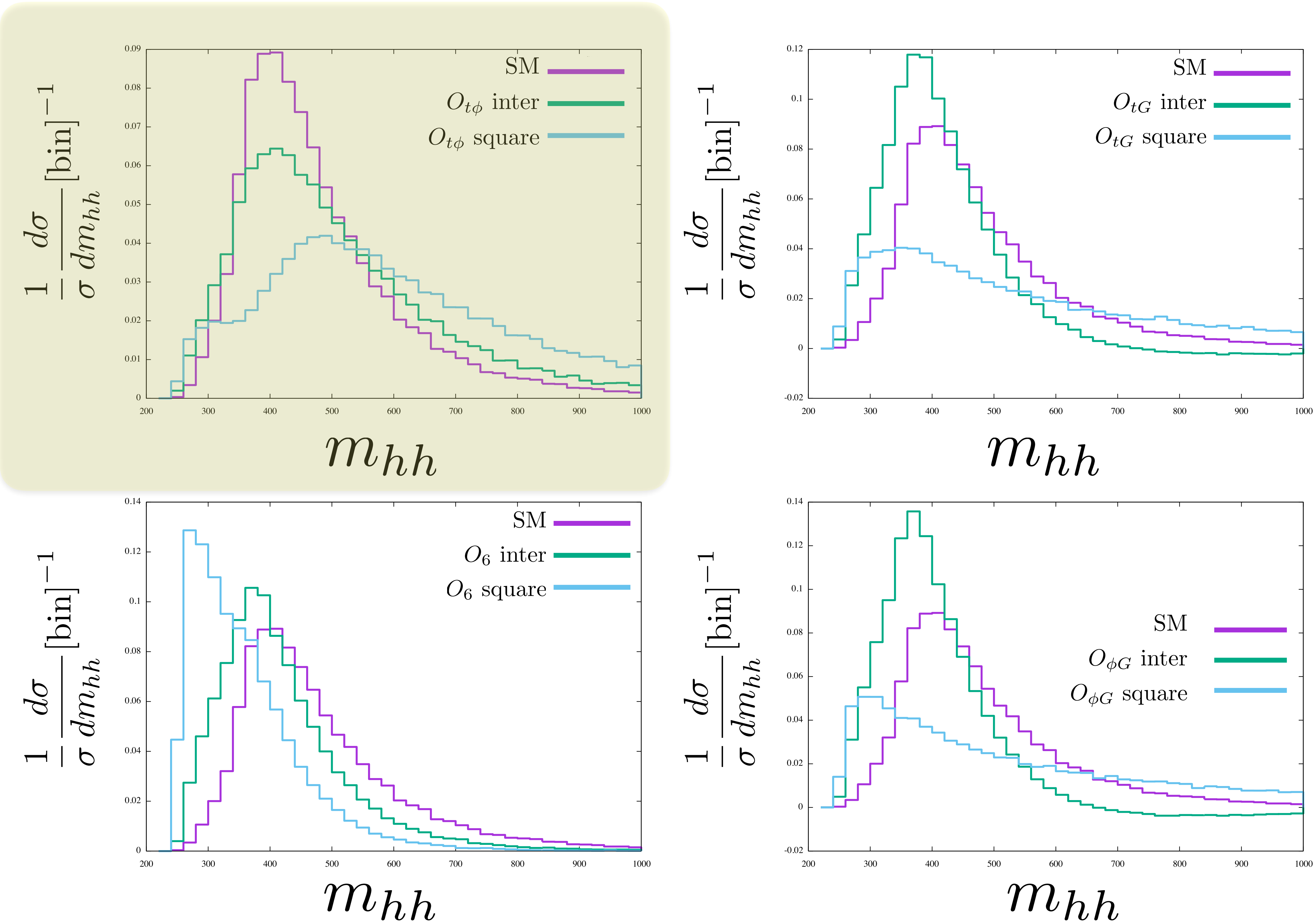






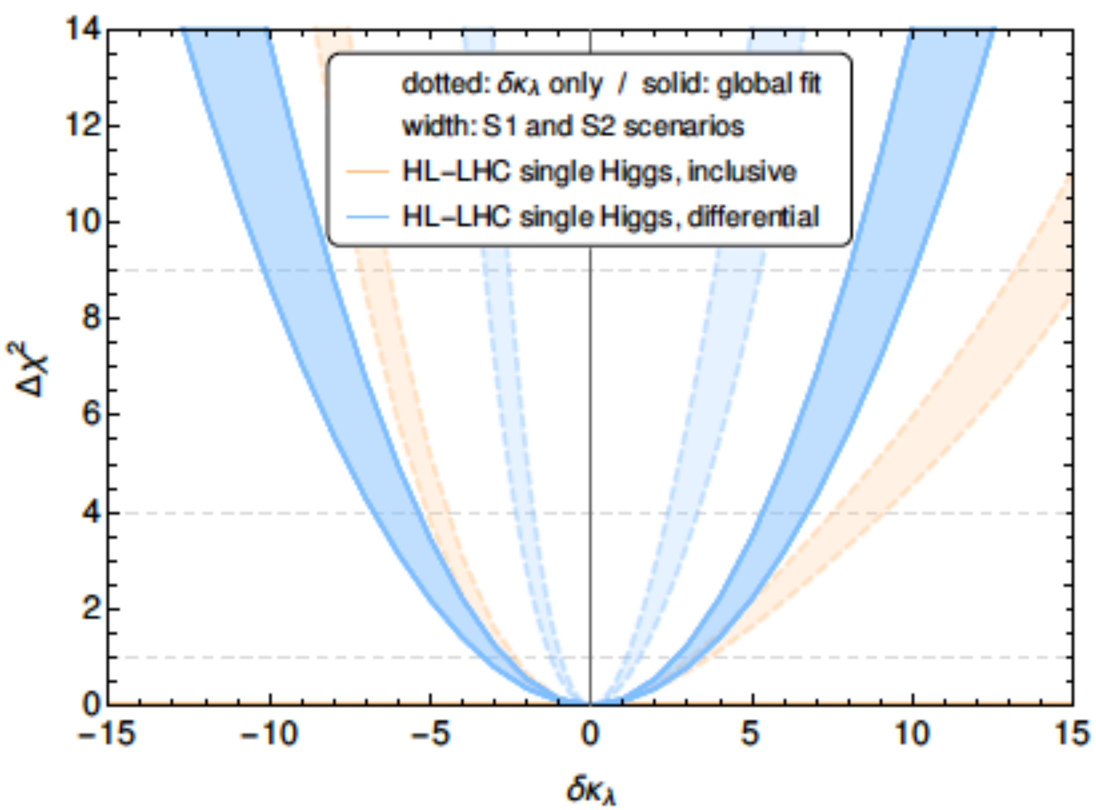


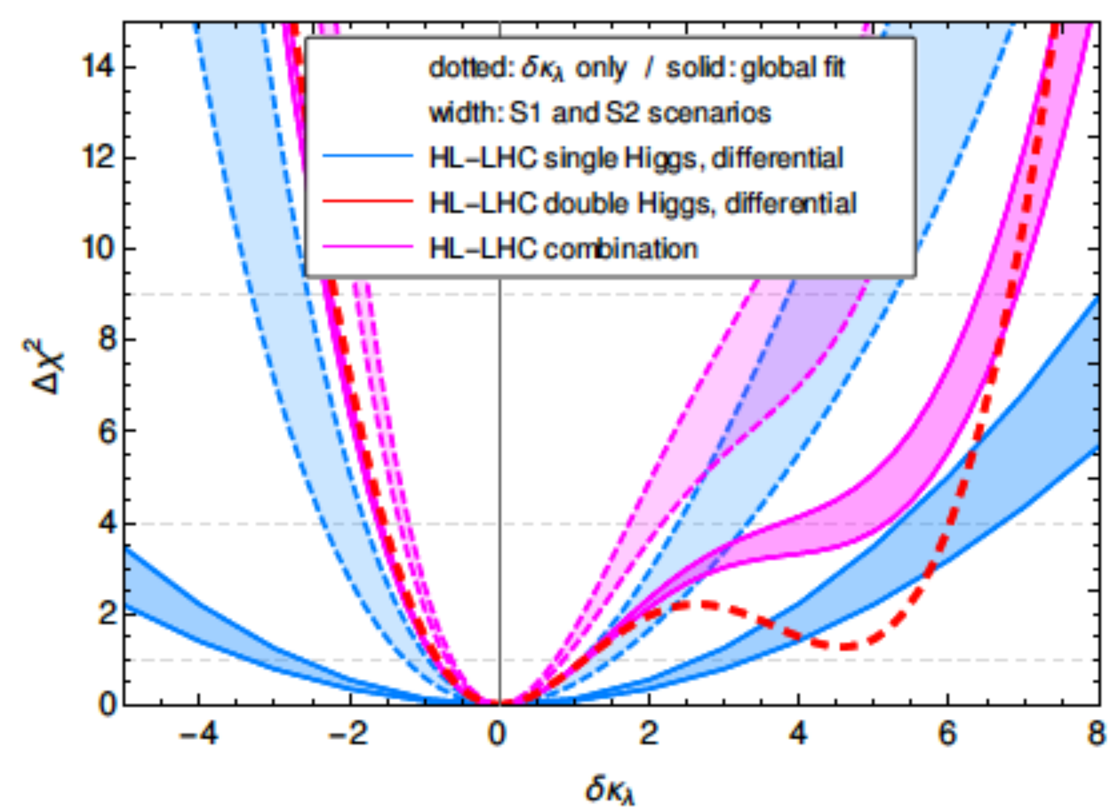
Differential results for HH

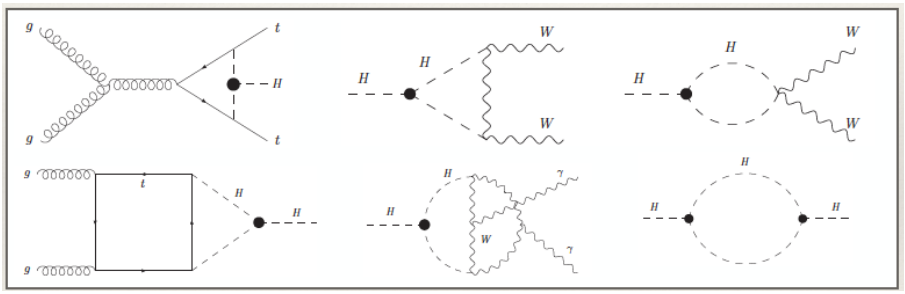


Top-Higgs interplay in HH

Future prospects for Higgs self-coupling:







Di Vita et al. arXiv:1704.01953 and HH white paper

Degeneracy with Yukawa and contact ggH operators worsens HHH sensitivity

Exploring the interplay further

Top EW couplings

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

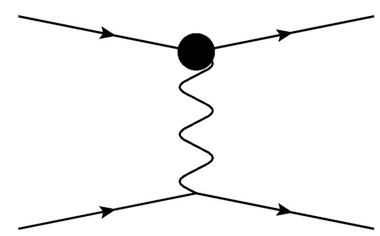
$$O^{(1)}_{\varphi Q} = i\frac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right) (\bar{Q}\gamma^\mu Q)$$

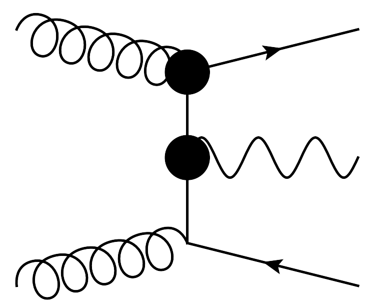
$$O_{\varphi t} = i\frac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right) (\bar{t}\gamma^\mu t)$$

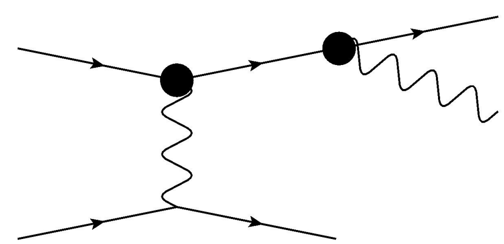
$$O_{tW} = y_t g_w (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi} W^I_{\mu\nu}$$

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

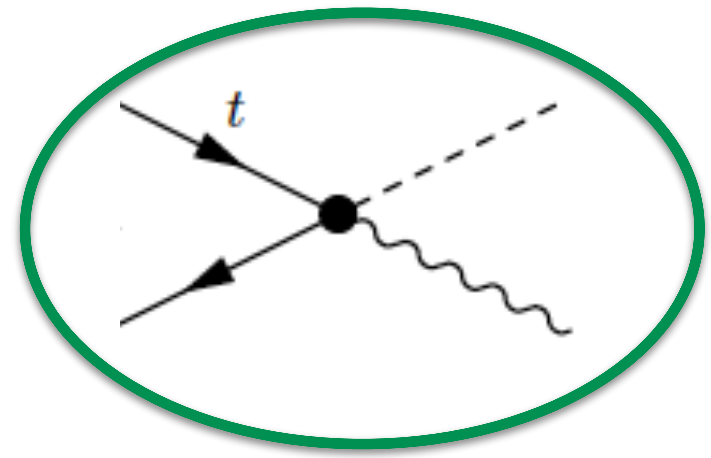
Typically searched for in







Also relevant for:



New Higgs interactions

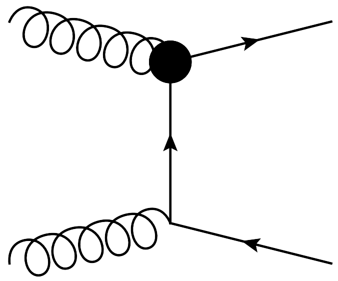
relevant for tHj, gg>HZ
gg>ZZ, H>Zγ

Aren't these constrained from top fits?

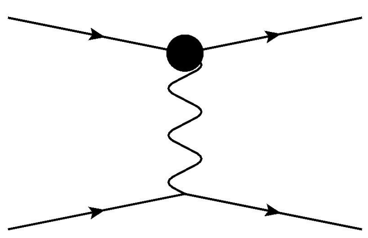
A detour into top EFT fits

Rich top phenomenology:

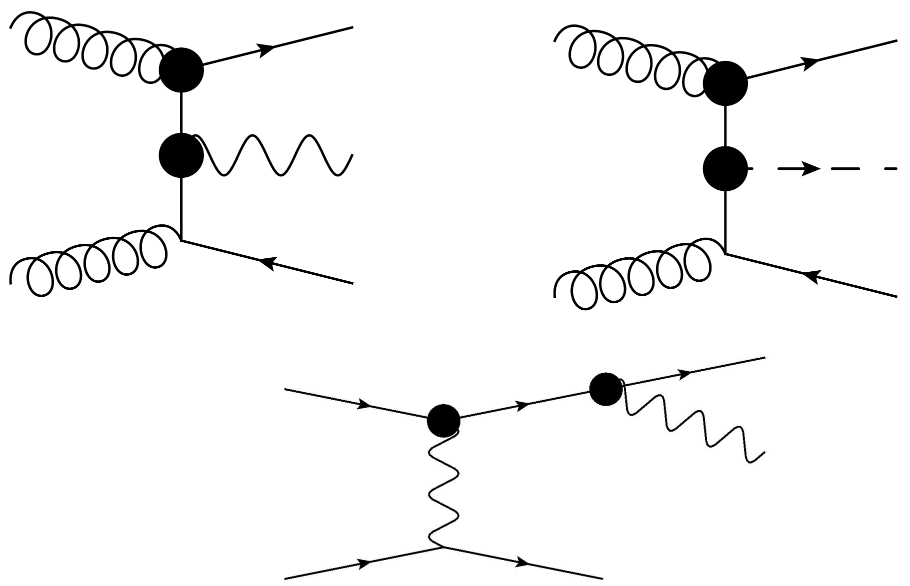
pair production



single



associated production



How can each process help?

Observables and theory predictions

Data

Top-pair production
W-helicities

4 tops, ttbb, top-pair associated production

Single top
t-channel, s-channel, tW, tZ

Dataset	n_{dat}
ATLAS_tt_8TeV_ljets [$m_{t\bar{t}}$]	7
CMS_tt_8TeV_ljets [y_t]	10
CMS_tt2D_8TeV_dilep [$(m_{t\bar{t}}, y_t)$]	16
CMS_tt_13TeV_ljets2 [$y_{t\bar{t}}$]	8
CMS_tt_13TeV_dilep [$y_{t\bar{t}}$]	6
CMS_tt_13TeV_ljets_2016 [y_t]	11
ATLAS_WhelF_8TeV	3
CMS_WhelF_8TeV	3
CMS_ttbb_13TeV	1
CMS_tttt_13TeV	1
ATLAS_tth_13TeV	1
CMS_tth_13TeV	1
ATLAS_ttZ_8TeV	1
ATLAS_ttZ_13TeV	1
CMS_ttZ_8TeV	1
CMS_ttZ_13TeV	1
ATLAS_ttW_8TeV	1
ATLAS_ttW_13TeV	1
CMS_ttW_8TeV	1
CMS_ttW_13TeV	1
CMS_t_tch_8TeV_dif	6
ATLAS_t_tch_8TeV [y_t]	4
ATLAS_t_tch_8TeV [$y_{\bar{t}}$]	4
ATLAS_t_sch_8TeV	1
CMS_t_tch_13TeV_dif [y_t]	4
CMS_t_sch_8TeV	1
ATLAS_tW_inc_8TeV	1
CMS_tW_inc_8TeV	1
ATLAS_tW_inc_13TeV	1
CMS_tW_inc_13TeV	1
ATLAS_tZ_inc_13TeV	1
CMS_tZ_inc_13TeV	1
Total	**102**

One distribution from each dataset, to avoid double counting

Theoretical predictions

Process	SM	SMEFT
$t\bar{t}$	NNLO QCD	NLO QCD
single-t (t-ch)	NNLO QCD	NLO QCD
single-t (s-ch)	NLO QCD	NLO QCD
tW	NLO QCD	NLO QCD
tZ	NLO QCD	LO QCD + NLO SM K-factors
$t\bar{t}W(Z)$	NLO QCD	LO QCD + NLO SM K-factors
$t\bar{t}h$	NLO QCD	LO QCD + NLO SM K-factors
$t\bar{t}t\bar{t}$	NLO QCD	LO QCD + NLO SM K-factors
$t\bar{t}b\bar{b}$	NLO QCD	LO QCD + NLO SM K-factors

Baseline fit includes:

- Best available SM predictions
- NLO EFT predictions
- $O(1/\Lambda^4)$ terms

Global fit Setup

Theory

(N)NLO QCD for SM
NLO QCD for SMEFT

Data

Top pair production and single top (differential)
Associated production with W,Z,H
W helicity fractions
Parton-level

Global SMEFT fit of the top-quark sector

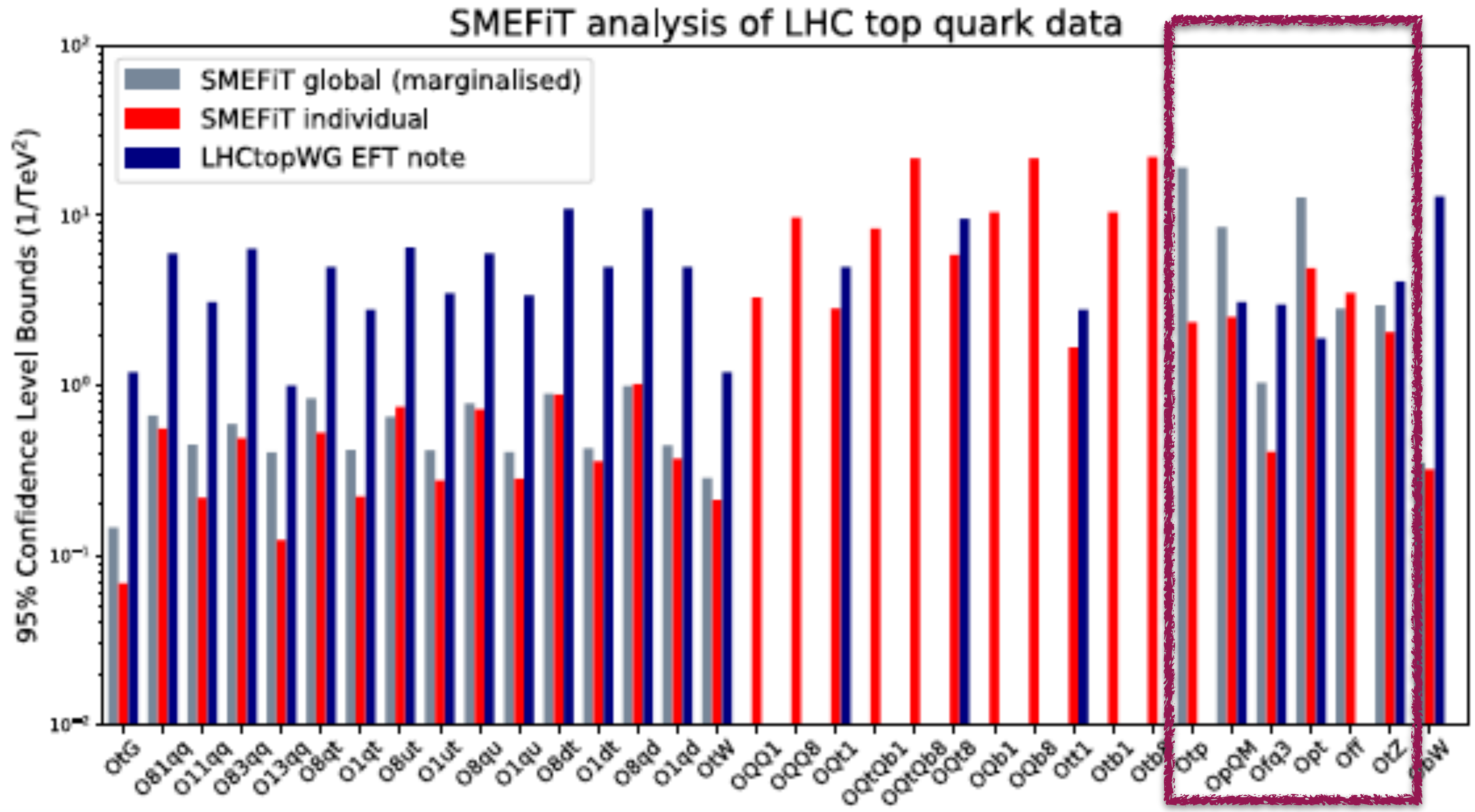
Theoretical and experimental uncertainties/Correlations

Methodology

Fit results can be used to bound specific UV complete models
New data can be straightforwardly added
Plan to extend to Higgs, gauge sector etc

Output

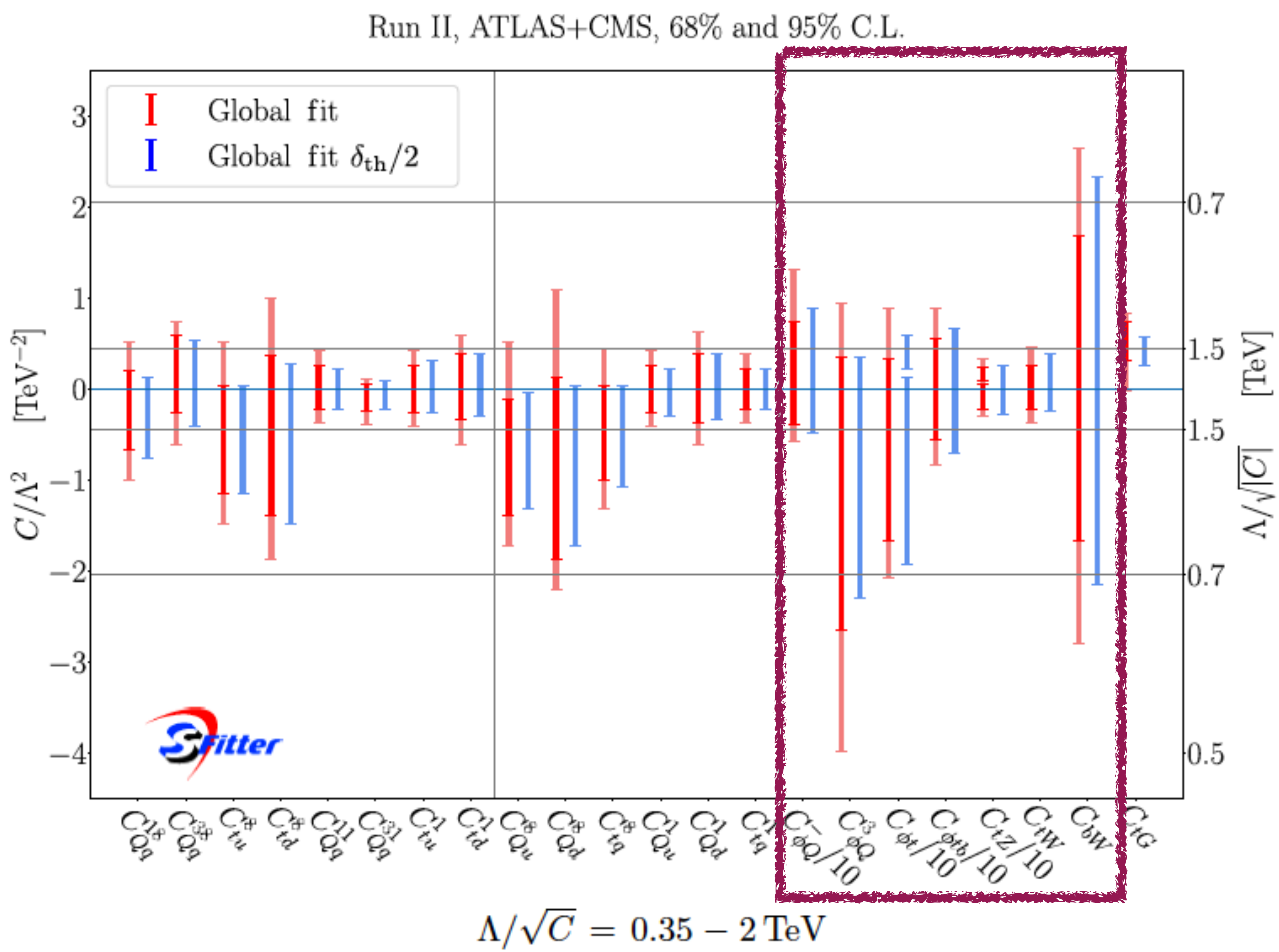
Global top fit results (1)



Top-Z interaction
Top Yukawa

Hartland, Maltoni, Nocera, Rojo, Slade, EV and Zhang, arXiv:1901.05965 (SMEFiT analysis)

Global top fit results (2)



Brivio, Bruggisser, Maltoni, Moutafis, Plehn, EV, Westhoff, Zhang arXiv:1910.03606 (SFitter analysis)

Going back to the interplay

- Top fits show that several top operators are poorly constrained
- This is particularly true for the operators modifying the top-Z interaction

What does that mean for Higgs production?
Which processes do we have to look at (worry about)?

Example1: HZ in gluon fusion

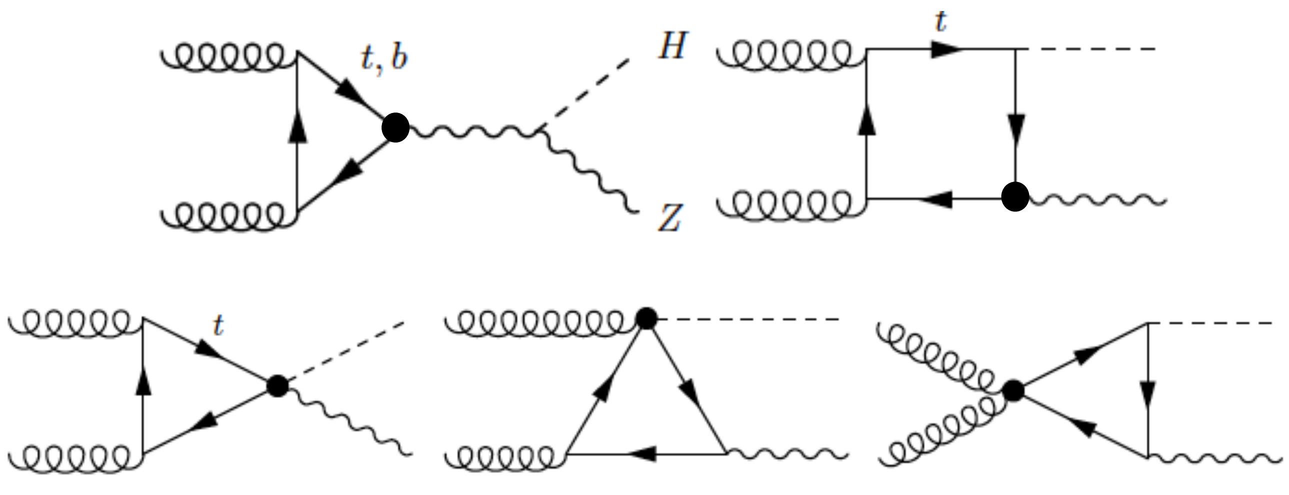
$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right) (\bar{Q}\gamma^\mu \tau^I Q)$$

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

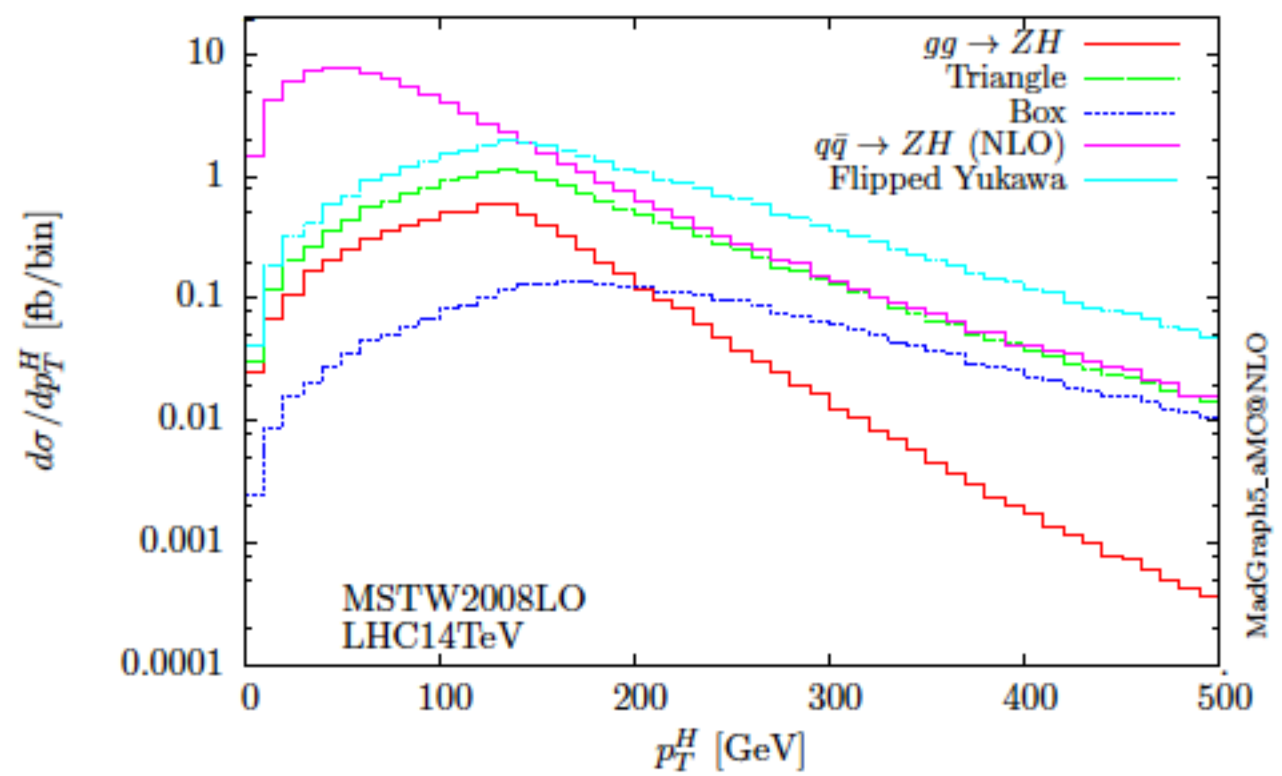
$$O_{\varphi t} = i\frac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right) (\bar{t}\gamma^\mu t)$$

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

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

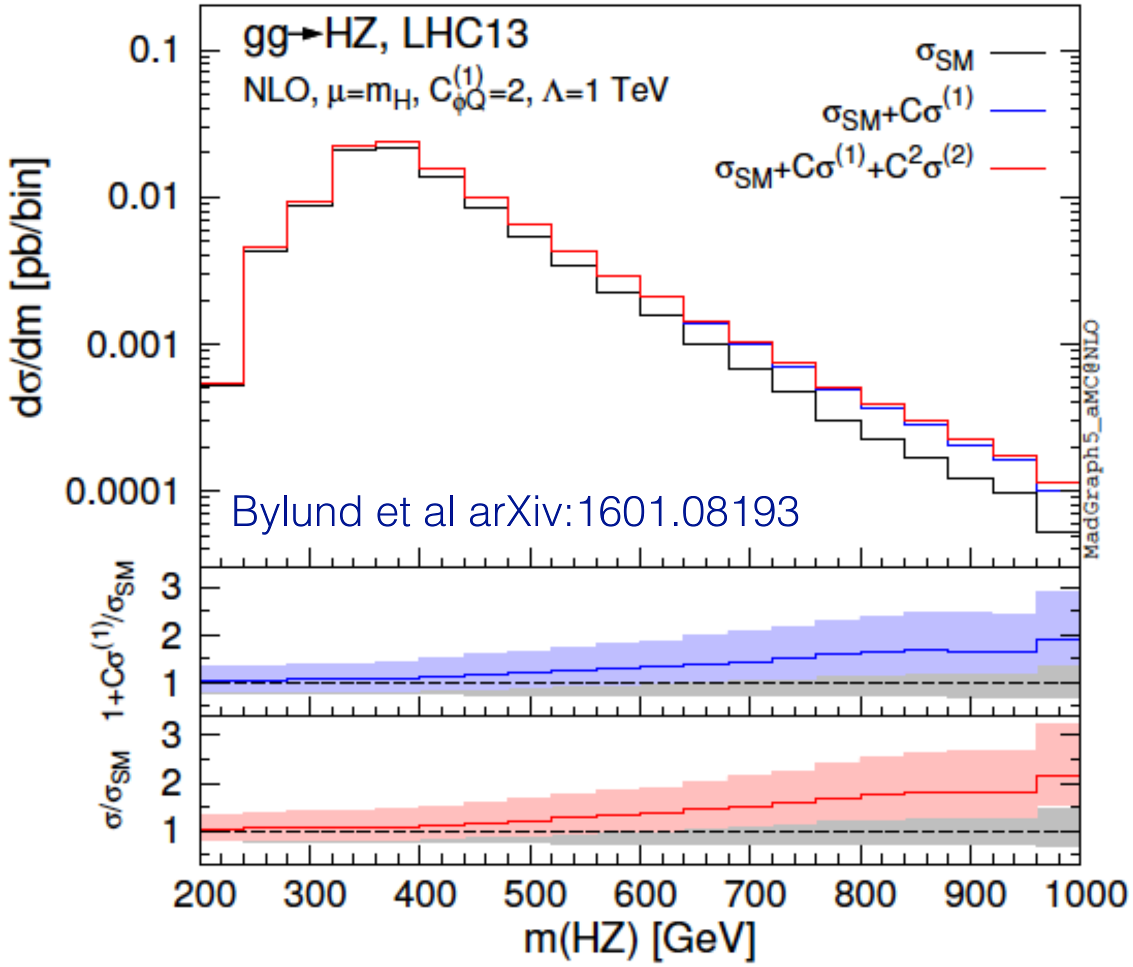


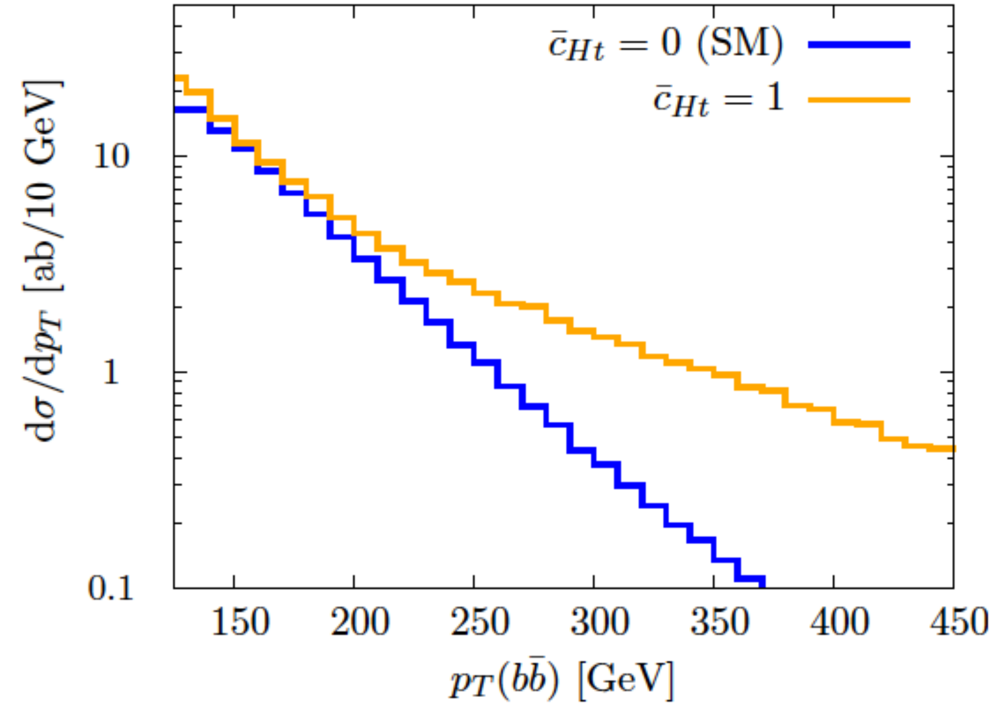
Sensitive also to the relative phase of the top and Z Higgs couplings

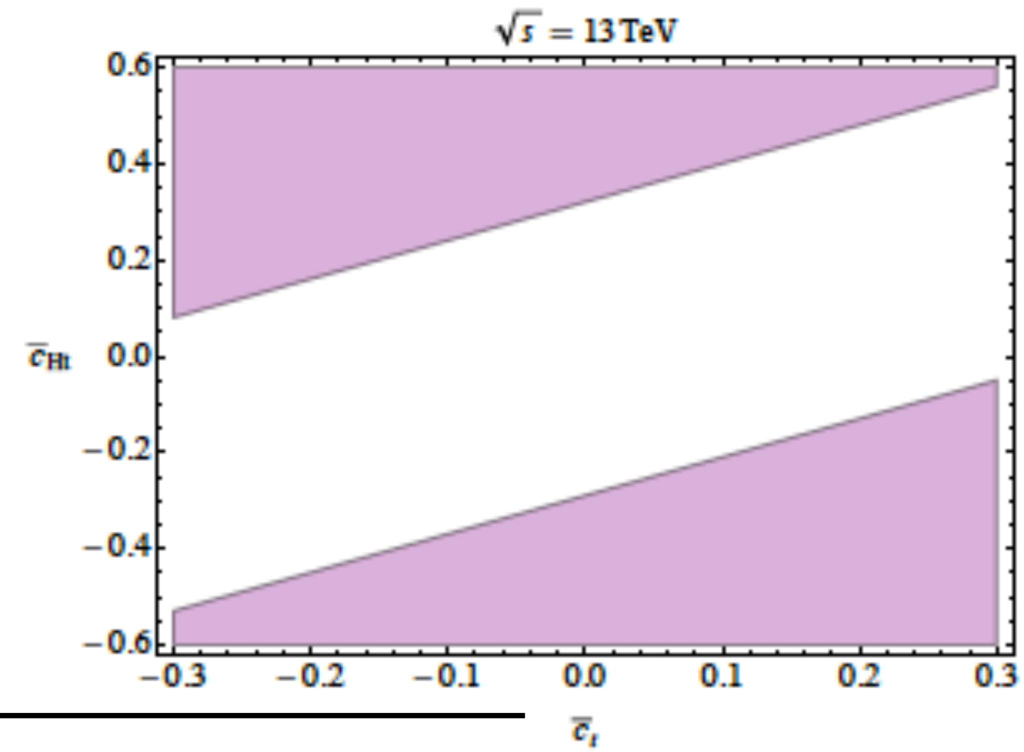


Hespel, Maltoni, EV arXiv:1503.01656

HZ in gluon fusion







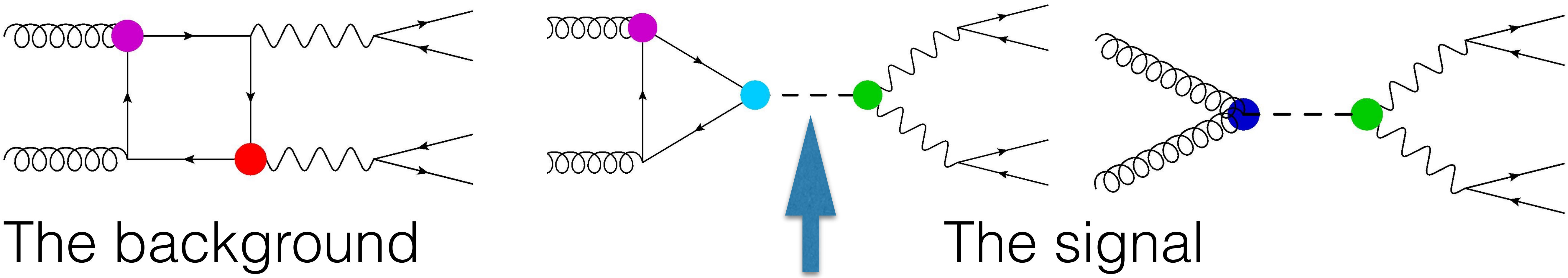
Differential information important

$$\mathcal{O}_{Ht} = \frac{i\bar{c}_{Ht}}{v^2}(\bar{t}_R\gamma^\mu t_R)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)\,,$$

$$\mathcal{O}_t = -\frac{\bar{c}_t}{v^2} y_t \Phi^\dagger\Phi\,\Phi^\dagger \cdot \bar{Q}_L\, t_R + \text{h.c.}$$

Englert et al arXiv:1603.05304

Example 2: Off-shell Higgs production



The background

The signal

The Higgs width

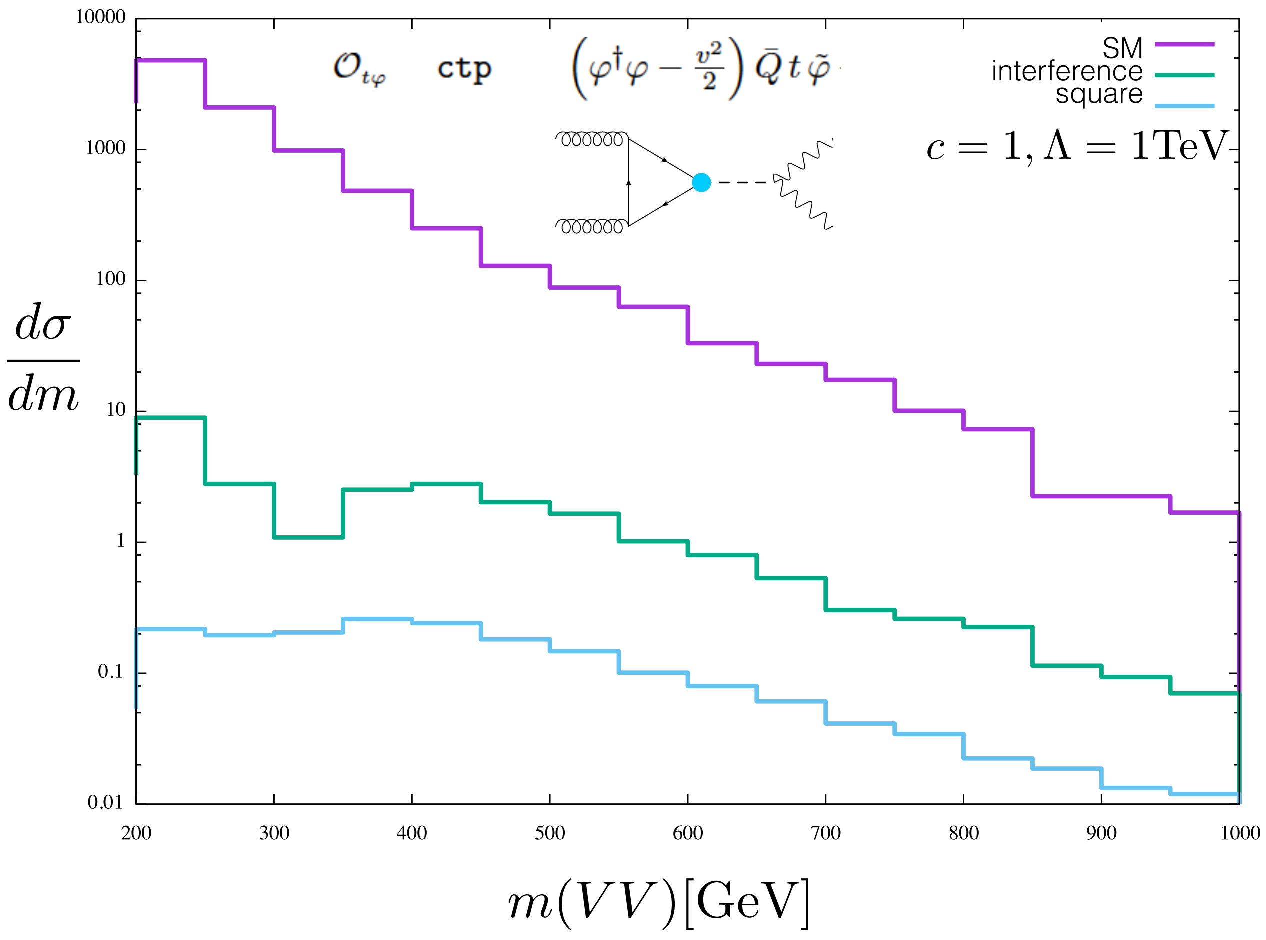
Higgs operators

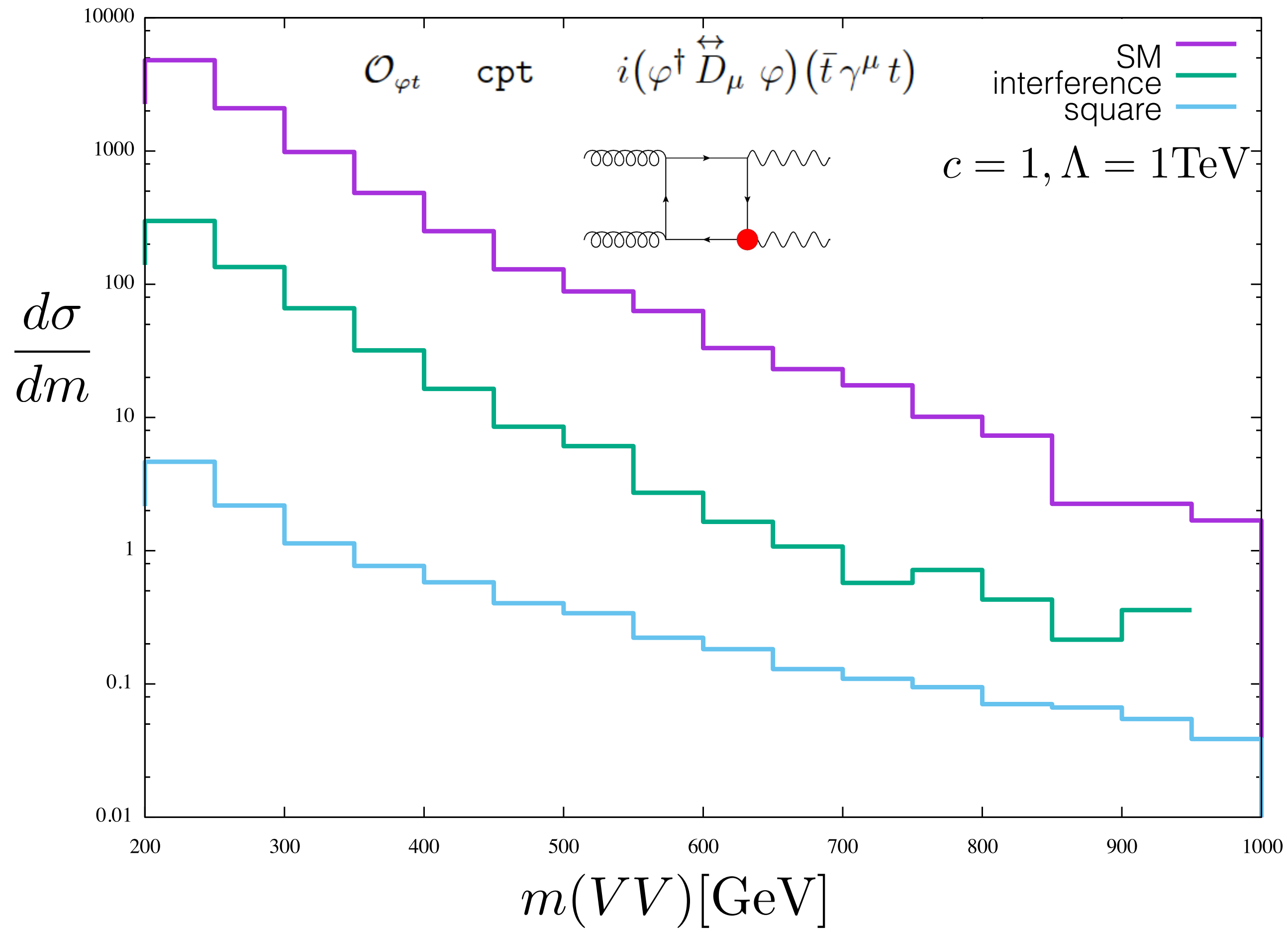
$\mathcal{O}_{\varphi G}$	cpG	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) G^{\mu\nu}_A\, G^A_{\mu\nu}$	$\mathcal{O}_{\varphi W}$	cpW	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W^{\mu\nu}_I\, W^I_{\mu\nu}$
$\mathcal{O}_{\varphi B}$	cpBB	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) B^{\mu\nu}\, B_{\mu\nu}$	$\mathcal{O}_{\varphi W B}$	cpWB	$(\varphi^\dagger\tau_I\varphi)\, B^{\mu\nu}W^I_{\mu\nu}$
$\mathcal{O}_{\varphi}$	cp	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)^3$	$\mathcal{O}_{\varphi d}$	cdp	$\partial_\mu(\varphi^\dagger\varphi)\partial^\mu(\varphi^\dagger\varphi)$
$\mathcal{O}_{\varphi D}$	cpDC	$(\varphi^\dagger D^\mu\varphi)^\dagger(\varphi^\dagger D_\mu\varphi)$			

Top operators

$\mathcal{O}_{t\varphi}$	ctp	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) \bar{Q}\, t\, \tilde{\varphi} + \text{h.c.}$	$\mathcal{O}_{tW}$	ctW	$i(\bar{Q}\tau^{\mu\nu}\, \tau_I\, t)\, \tilde{\varphi}\, W^I_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{tG}$	ctG	$ig_s\, (\bar{Q}\tau^{\mu\nu}\, T_A\, t)\, \tilde{\varphi}\, G^A_{\mu\nu} + \text{h.c.}$	$\mathcal{O}_{tB}$	-	$i(\bar{Q}\tau^{\mu\nu}\, t)\, \tilde{\varphi}\, B_{\mu\nu} + \text{h.c.}$
$\mathcal{O}^{(3)}_{\varphi Q}$	cpQ3	$i(\varphi^\dagger \overleftrightarrow{D}_\mu\, \tau_I\varphi)(\bar{Q}\,\gamma^\mu\,\tau^I Q)$	$\mathcal{O}_{tZ}$	ctZ	$-\sin\theta_W \mathcal{O}_{tB} + \cos\theta_W \mathcal{O}_{tW}$
$\mathcal{O}^{(-)}_{\varphi Q}$	cpQM	$\mathcal{O}^{(1)}_{\varphi Q} - \mathcal{O}^{(3)}_{\varphi Q}$	$\mathcal{O}_{\varphi t}$	cpt	$i(\varphi^\dagger \overleftrightarrow{D}_\mu\, \varphi)(\bar{t}\,\gamma^\mu\, t)$

Top couplings in gg>ZZ

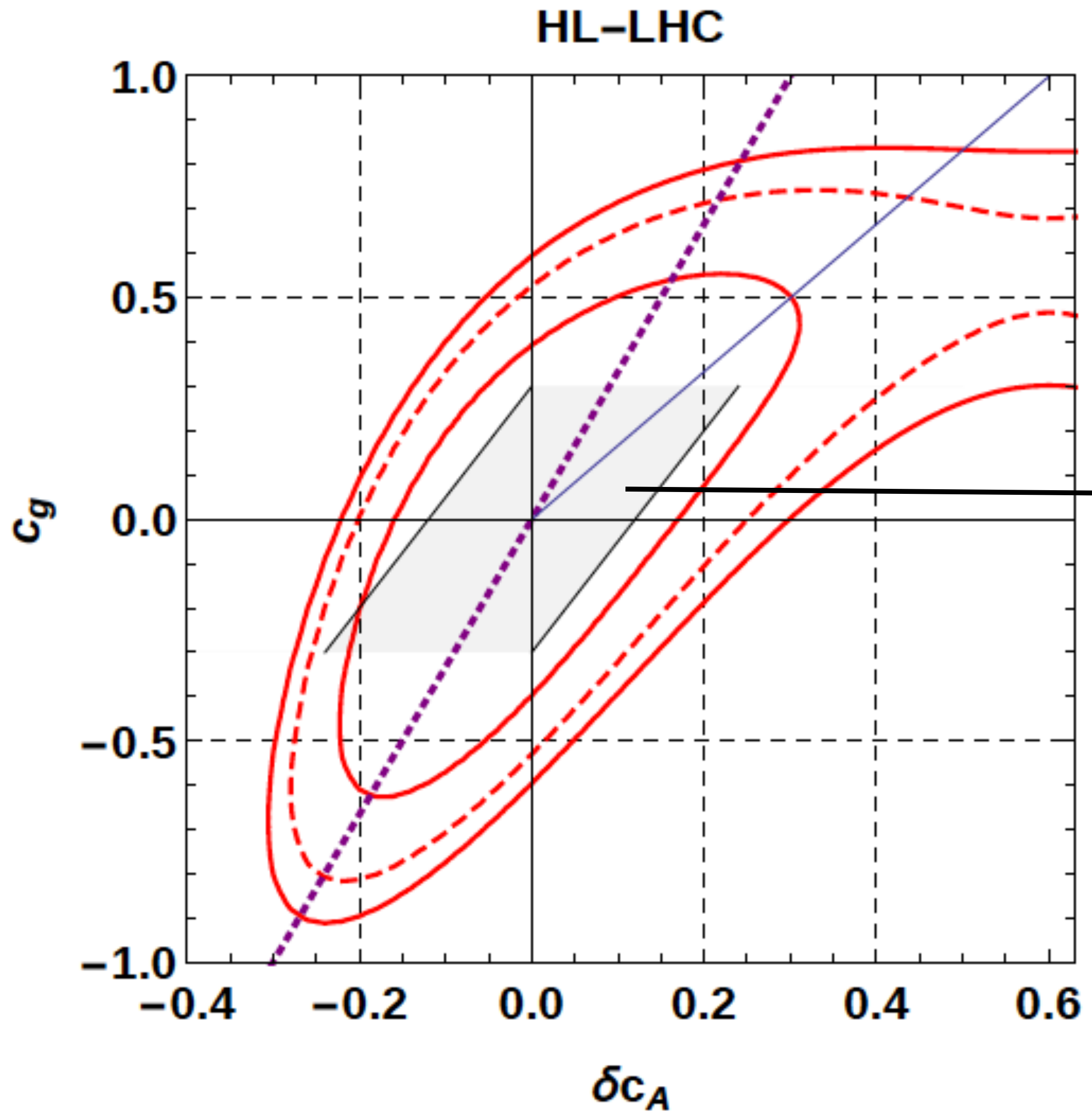




Current bound from top processes: c~10

O(1) effects allowed in the tail

A new source of information on ttZ



4-parameter fit:

c_t, c_g, c_V, c_A

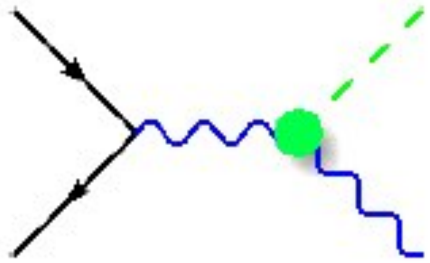
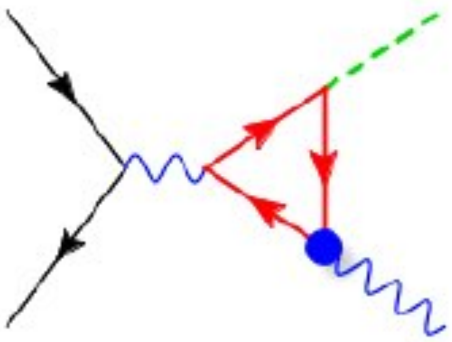
Constraint from gg to ZH
Englert et al arXiv:1603.05304

Constraints on ttZ couplings competitive with ttZ process

Azatov, Grojean, Paul, Salvioni arXiv:1608.00977

See also: Englert, Soreq, Spannowsky arXiv:1410.5440

Loops for tree-level processes

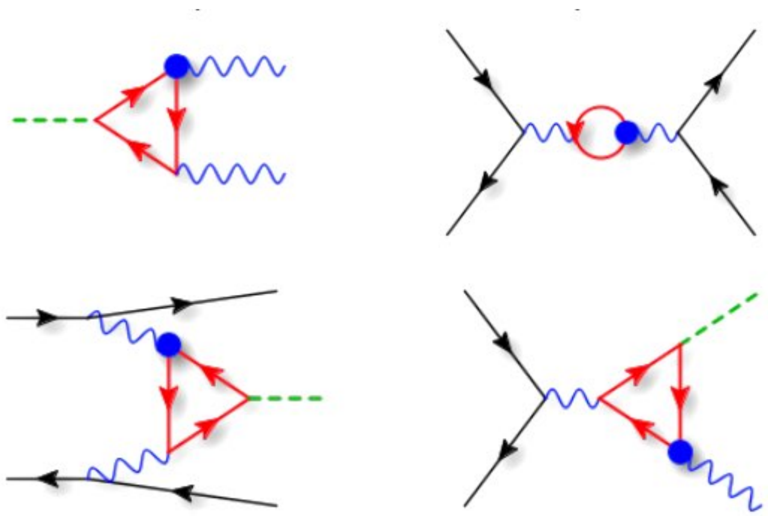
Are we measuring  or  ?

NLO EW in SMEFT may not be small:

$$\mathcal{O}(\alpha_{EW}/\pi \cdot C_t/C_H) \quad \textbf{instead of} \quad \mathcal{O}(\alpha_{EW}/\pi)$$

→ Weak corrections can be important for unconstrained operators

Towards weak loops in the EFT



+

$$O_{t\varphi} = \bar{Q}t\tilde{\varphi}\,(\varphi^\dagger\varphi) + h.c.,$$
$$O_{\varphi Q}^{(3)} = (\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{Q}\gamma^\mu\tau^I Q),$$
$$O_{\varphi tb} = (\tilde{\varphi}^\dagger iD_\mu\varphi)(\bar{t}\gamma^\mu b) + h.c.,$$
$$O_{tB} = (\bar{Q}\sigma^{\mu\nu}t)\,\tilde{\varphi}B_{\mu\nu} + h.c.,$$
$$O_{\varphi t} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{t}\gamma^\mu t),$$
$$O_{\varphi Q}^{(1)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{Q}\gamma^\mu Q),$$
$$O_{tW} = (\bar{Q}\sigma^{\mu\nu}\tau^I t)\,\tilde{\varphi}W^I_{\mu\nu} + h.c.,$$

+ **Current constraints from top LHC measurements**

Poor knowledge of top couplings leads to uncertainties on Higgs measurements at the LHC:

	$\gamma\gamma$	γZ	bb	WW^*	ZZ^*
gg	(-100%,1980%)	(-88%,200%)	(-40%,48%)	(-40%,47%)	(-40%,46%)
VBF	(-100%,1880%)	(-88%,170%)	(-6.1%,5.3%)	(-6.8%,6.7%)	(-8.8%,9.2%)
WH	(-100%,1880%)	(-88%,170%)	(-5.5%,4.2%)	(-6.1%,5.6%)	(-7.8%,7.9%)
ZH	(-100%,1880%)	(-87%,170%)	(-6.5%,5.9%)	(-7.1%,7.1%)	(-9.4%,9.9%)

loop-induced ($\gamma\gamma$, γZ) — tree-level (ZZ^*: VBF, WH, ZH)

EV, Zhang arXiv:1804.09766

Conclusions

Current approach (EFT fits) largely ignores the interplay between top and Higgs

1. **Should we keep the two sectors separate?**
No, top-Higgs interplay helps us break degeneracies.

2. **Can we keep the two sectors separate?**
No, with limited information on top couplings one-loop Higgs processes can be significantly modified

Conclusions

Current approach (EFT fits) largely ignores the interplay between top and Higgs

1. **Should we keep the two sectors separate?**
No, top-Higgs interplay helps us break degeneracies.

2. **Can we keep the two sectors separate?**
No, with limited information on top couplings one-loop Higgs processes can be significantly modified

Let's not forget the loops

Thank you for your attention

EFT Loops in Monte Carlo

Aim to obtain a complete Monte Carlo implementation based on:

- Warsaw basis
- Degrees of freedom for top operators as in arXiv:1802.07237 (LHCTopWG)

Current status:

- 73 degrees of freedom (top, Higgs, gauge):
    - CP-conserving
    - Flavour assumption: $U(2)_Q \times U(2)_u \times U(3)_d \times U(3)_L \times U(3)_e$
- 0/2F@NLO operators validated (with previous partial NLO implementations) → **http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO**
- 4F@NLO operators validation: on-going

Future plans

- Full NLO model release (4F@NLO)
- Other flavour assumptions
- CP-violating effects

Work in progress with: C. Degrande, G. Durieux, F. Maltoni, K. Mimasu, C. Zhang