Top, Higgs and Effective Field Theory

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The SMEFT

fundamental assumptions:
- new physics nearly decoupled: $\Lambda \gg (v, E)$
- at the accessible scale: **SM** fields + symmetries

☛ a Taylor expansion in canonical dimensions ($\delta = v/\Lambda$ or E/Λ):

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \dots$$

$\mathcal{L}_n = \sum_i C_i \mathcal{O}_i^{d=n}$

C_i free parameters (Wilson coefficients)

$\mathcal{O}_i$ invariant operators that form a complete, non redundant basis

The Warsaw basis

Grzadkowski,Iskrzynski,Misiak,Rosiek 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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

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

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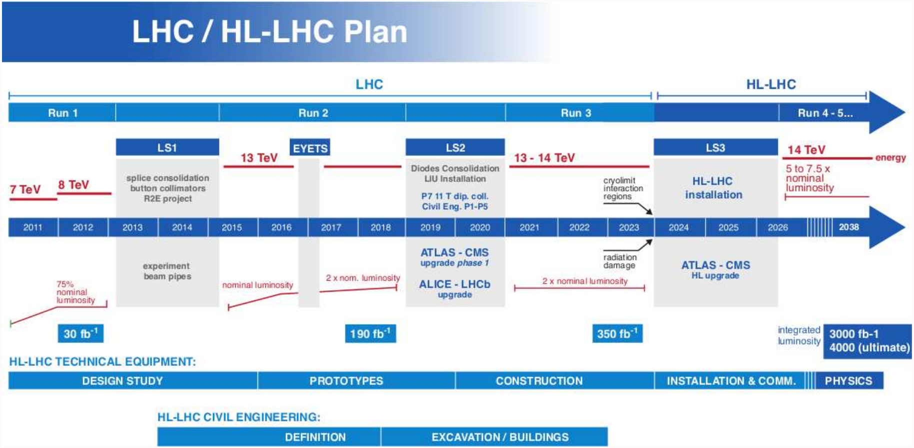
$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	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}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		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}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$		

Big plans



LHC / HL-LHC Plan
LHC
HL-LHC
Run 1
Run 2
Run 3
Run 4 - 5...
LS1
EYETS
LS2
LS3
7 TeV
8 TeV
13 TeV
13 - 14 TeV
14 TeV
energy
splice consolidation
button collimators
R2E project
Diodes Consolidation
LIU Installation
P7 11 T dip. coll.
Civil Eng. P1-P5
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HL-LHC
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2026
2038
experiment
beam pipes
ATLAS - CMS
upgrade phase 1
ALICE - LHCb
upgrade
radiation
damage
ATLAS - CMS
HL upgrade
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luminosity
nominal luminosity
2 x nom. luminosity
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30 fb-1
190 fb-1
350 fb-1
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HL-LHC TECHNICAL EQUIPMENT:
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PHYSICS
HL-LHC CIVIL ENGINEERING:
DEFINITION
EXCAVATION / BUILDINGS

Big plans


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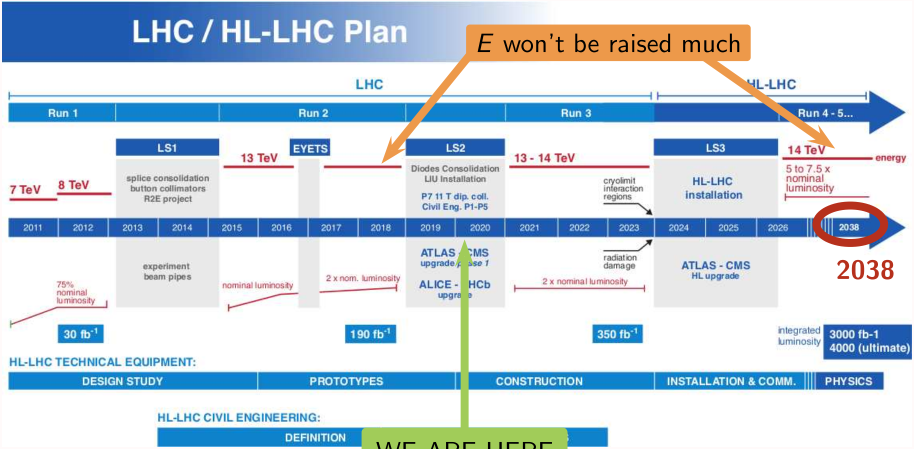
Big plans

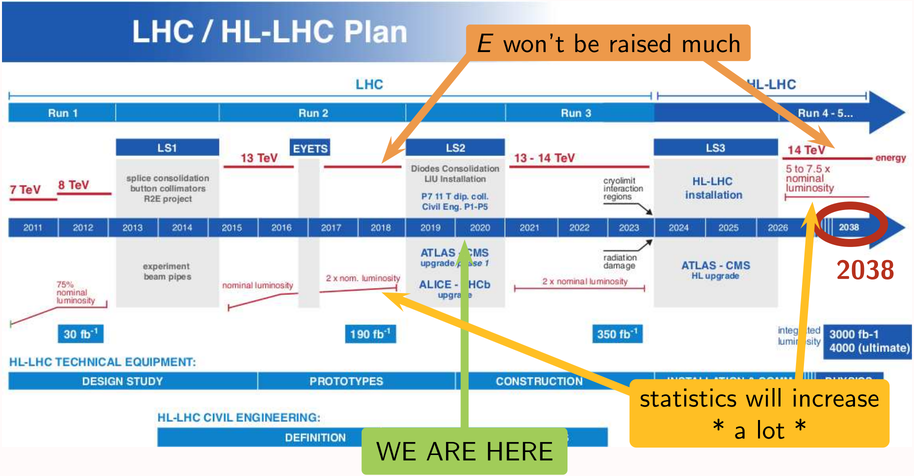


E won't be raised much

2038

WE ARE HERE

Big plans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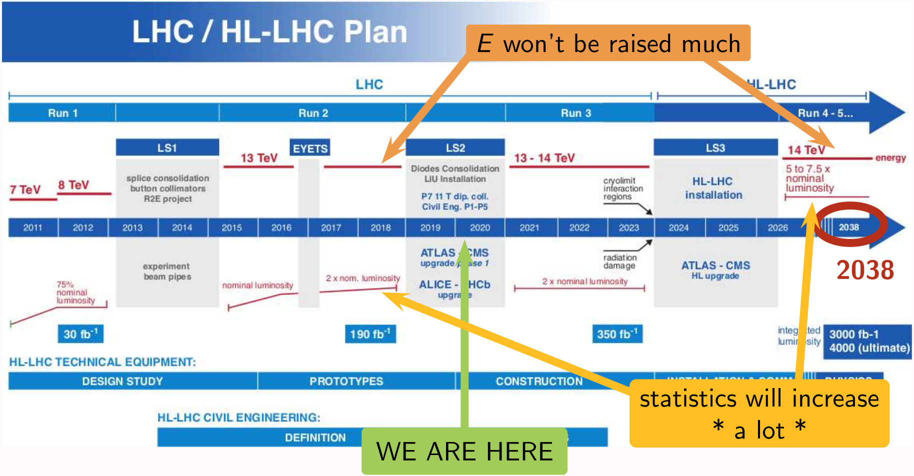
statistics will increase
* a lot *

Big plans



there's much room for improvement in precision → worth having a systematic program for **indirect searches**

The SMEFT is a powerful tool for this

- **full QFT** with its own regularization/renormalization schemes

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  → rationale for expected size of contributions: power counting
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  [works with non-perturbative UV too]

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- a universal language for interpretation of measurements

SMEFT @ LHC: how many parameters?

Depends

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observables, including/excluding quadratic terms

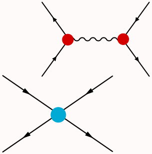
Focusing on interference $\mathcal{A}_{SM}\mathcal{A}_6^*$ only

Selection **due to SM kinematics / symmetries** in the presence of:

- resonances in SM
- FCNCs op.
- dipole op. (interf. $\sim m_f$)
- ...

ψ^4 operators generally **suppressed** wrt. "pole operators" by

$$\left(\frac{\Gamma_B m_B}{v^2}\right)^n \sim \begin{array}{ll} 1/300 & (\text{Z,W}) \\ 1/10^6 & (h) \end{array}$$

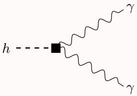


If quadratic terms $|\mathcal{A}_6|^2$ are included, more operators contribute

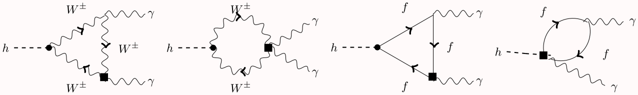
SMEFT @ LHC: how many parameters?

Depends on choices of
- low energy symmetries. e.g. flavor
- observables, including/excluding quadratic terms
- EFT calculation accuracy

loop order



$C_{HW}\,,\ C_{HB}\,,\ C_{HWB}$



$+\ C_W\,,\ C_{HD}\,,\ C_{eW}\,,$
$C_{eB}\,,\ C_{uW}\,,\ C_{uB}\,,\ C_{dW}\,,$
$C_{dB}\,,\ C_{eH}\,,\ C_{uH}\,,\ C_{dH}$

Hartmann,Trott 1505.02646,1507.03568
Ghezzi,Gomez-Ambrosio,Passarino,Uccirati 1505.03706
Dedes,Paraskevas,Rosiek,Suxho,Trifyllis 1805.00302

EFT order

$+$ dimension 8 $+\ \ldots$

SMEFT @ LHC: how many parameters?

Depends on choices of low energy symmetries. e.g. flavor

observables, including/excluding quadratic terms

EFT calculation accuracy

For reference:

	total $N_f = 3$	unsuppressed interf.*
general	2499	~ 46
MFV	~ 108	~ 30
$U(3)^5$	~ 70	~ 24

Brivio,Jiang,Trott 1709.06492

* parameters entering $H/Z/W$ resonance-dominated processes, interference only.

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requires **global fits**

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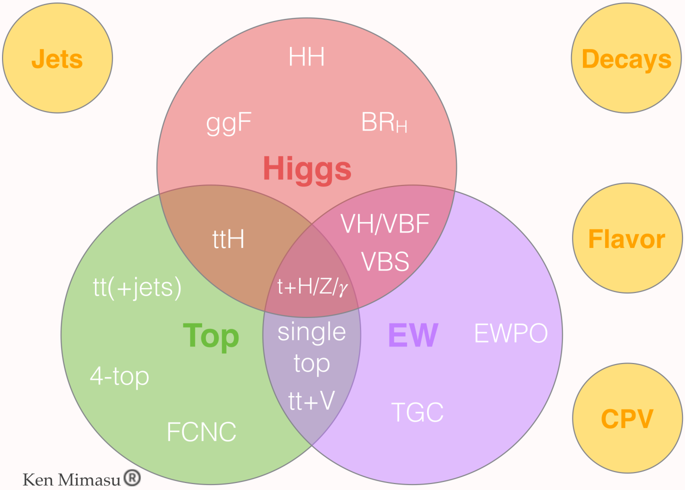
Global SMEFT analyses

ultimate goal: measure as many SMEFT parameters as possible
fitting predictions that include all relevant terms



Higgs and EW fit

- $U(3)^5$ flavor symmetry
- all relevant interactions included
- tree-level, interference only

Brivio, Hays, Smith, Trott, Žemaitytė in preparation

23 **relevant operators**

also: Ellis, Murphy, Sanz, You 1803.03252 **20**

Z,W couplings

$$\begin{aligned}
\mathcal{Q}_{Hl}^{(1)} &= (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{l}\gamma^\mu l)\\
\mathcal{Q}_{He} &= (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)\\
\mathcal{Q}_{Hq}^{(1)} &= (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)\\
\mathcal{Q}_{Hq}^{(3)} &= (iH^\dagger \overleftrightarrow{D}^i_\mu H)(\bar{q}\sigma^i\gamma^\mu q)\\
\mathcal{Q}_{Hu} &= (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)\\
\mathcal{Q}_{Hd} &= (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)
\end{aligned}$$

Bhabha scattering

$$\begin{aligned}
\mathcal{Q}_{ee} &= (\bar{e}\gamma^\mu e)(\bar{e}\gamma^\mu e)\\
\mathcal{Q}_{le} &= (\bar{l}\gamma^\mu l)(\bar{e}\gamma^\mu e)\\
\mathcal{Q}_{ll} &= (\bar{l}_p\gamma^\mu l_p)(\bar{l}_r\gamma^\mu l_r)
\end{aligned}$$

$$\begin{aligned}
\mathcal{Q}_{HD} &= (D_\mu H^\dagger H)(H^\dagger D^\mu H)\\
\mathcal{Q}_{HWB} &= (H^\dagger\sigma^i H)W^i_{\mu\nu}B^{\mu\nu}\\
\mathcal{Q}_{Hl}^{(3)} &= (iH^\dagger \overleftrightarrow{D}^i_\mu H)(\bar{l}\sigma^i\gamma^\mu l)\\
\mathcal{Q}'_{ll} &= (\bar{l}_p\gamma^\mu l_r)(\bar{l}_r\gamma^\mu l_p)
\end{aligned}$$

input quantities

$$\begin{aligned}
\mathcal{Q}_{Hbox} &= (H^\dagger H)\,\Box\,(H^\dagger H)\\
\mathcal{Q}_{HG} &= (H^\dagger H)G^a_{\mu\nu}G^{a\mu\nu}\\
\mathcal{Q}_{HB} &= (H^\dagger H)B_{\mu\nu}B^{\mu\nu}\\
\mathcal{Q}_{HW} &= (H^\dagger H)W^i_{\mu\nu}W^{i\mu\nu}\\
\mathcal{Q}_{uH} &= (H^\dagger H)(\bar{q}\tilde{H}u)\\
\mathcal{Q}_{dH} &= (H^\dagger H)(\bar{q}Hd)\\
\mathcal{Q}_{eH} &= (H^\dagger H)(\bar{l}He)\\
\mathcal{Q}_{G} &= \varepsilon_{abc}G^{a\nu}_\mu G^{b\rho}_\nu G^{c\mu}_\rho\\
\mathcal{Q}_{uG} &= (\bar{q}\sigma^{\mu\nu}T^a\tilde{H}u)G^a_{\mu\nu}
\end{aligned}$$

H processes

PRELIMINARY

TGC

$$\mathcal{Q}_{W} = \varepsilon_{ijk}W^{i\nu}_\mu W^{j\rho}_\nu W^{k\mu}_\rho$$

Higgs and EW fit: main features

Brivio,Hays,Smith,Trott,Žemaitytė in preparation

- $U(3)^5$ flavor symmetry
- all relevant interactions included
- tree-level, interference only
- analytic predictions (as much as possible)
  - Better control on possible **divergences** / phase space integration
  - Control on different diagram contributions (e.g. γ-mediated in $h \to 4f$)
  - Cancellation effects are reproduced exactly
  - All EFT contributions can be **linearized out** (relevant for propagator corrections)

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  - **doubly-resonant *WW*** production computed in Berthier,Bjørn,Trott 1606.06693
  - for Higgs we want to use **STXS**

LesHouches 2015 1605.0469
LHCHXSWG 1610.0792
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⇝ see talk by **André**

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$$n_k = \mathcal{L}_k \sum_{i,f} (\sigma \cdot B)_{if} (\varepsilon \cdot A)_{if}$$

lumi

prod xs $i \to h$

decay BR $h \to f$

efficiency

acceptance

Global fit to n_k $\quad\rightarrow\quad$ $(\sigma \cdot B)_{if}$ for defined i, f categories.

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  - **doubly-resonant *WW*** production computed in Berthier, Bjørn, Trott 1606.06693
  - for Higgs we want to use **STXS**

LesHouches 2015 1605.0469
LHCHXSWG 1610.0792
Berger et al. 1906.0275

⇝ see talk by **André**

$$n_k = \mathcal{L}_k \sum_{i,f} (\sigma \cdot B)_{if} (\varepsilon \cdot A)_{if}$$

lumi

prod xs $i \to h$

decay BR $h \to f$

efficiency

acceptance

Brivio, Corbett, Trott 1906.06949

Global fit to $n_k \quad \rightarrow \quad (\sigma \cdot B)_{if}$ for defined i, f categories.

H → 4f in the SMEFT

Improved $h \to 4f$ results

Brivio,Corbett,Trott 1906.06949

- removing narrow width approx on Z, W
- including Z, W propagator corrections

H → 4f in the SMEFT

Improved $h \to 4f$ results ▸ removing narrow width approx on Z, W

Brivio,Corbett,Trott 1906.06949 ▸ including Z, W propagator corrections

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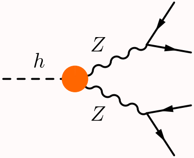
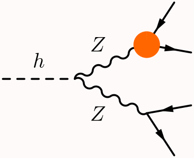
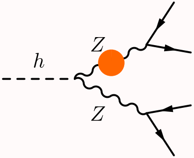
① corrections to SM diagrams







$\propto g_{\mu\nu}$ (SM-like)
$\propto g_{\mu\nu} p\cdot q - p_\nu q_\mu$ $(Z_{\mu\nu} Z^{\mu\nu} h)$

$\delta g_L, \delta g_R$

$$\frac{-i m_Z \delta\Gamma_Z + (2m_Z - i\Gamma_Z)\delta m_Z}{p^2 - m_Z^2 + i\Gamma_Z m_Z}$$

↑
hard to extract from MC simulation!

H → 4f in the SMEFT

Improved $h \to 4f$ results
- removing narrow width approx on Z, W
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Brivio,Corbett,Trott 1906.06949

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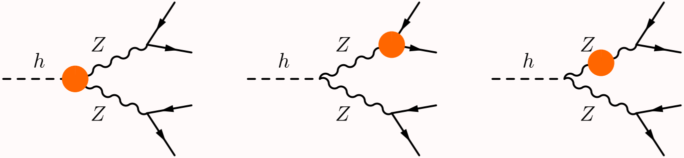
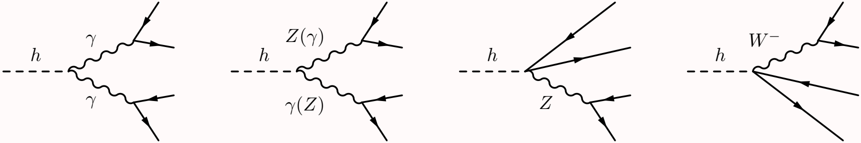
① corrections to SM diagrams



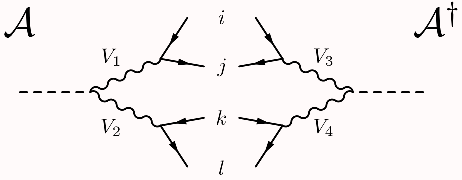
② genuine SMEFT diagrams



Estimating $\delta\Gamma/\Gamma_{SM}$ analytically

Brivio,Corbett,Trott 1906.06949

fully analytical treatment. automated with general decomposition:



$$\mathcal{A}\mathcal{A}^\dagger \sim g_{HV_1V_2}\, g_{HV_3V_4} \sum_n \mathcal{T}^{(n)}$$

$$\mathcal{T}^{(n)} = \mathcal{K}^{(n)}\left(g^{ij,V_1}_{L,R}, g^{ij,V_3}_{L,R}, g^{kl,V_2}_{L,R}, g^{kl,V_4}_{L,R}\right) \; \mathcal{F}^{(n)}_{V_1V_2V_3V_4}(p_a, m_a), \quad a = \{i,j,k,l\}$$

for $m_a \equiv 0$ there are only **8** independent $\mathcal{F}_{V_1V_2V_3V_4}$. For each $\{V\}$ set:

- numerical integration of phase space: `Vegas` in `Mathematica` T. Hahn 0404043
- cross-check: `RAMBO` + 2 independent parameterizations of phase space

Kleiss,Stirling,Ellis
Comput.Phys.Commun.40(1986)359

Analytic results for the total Higgs width

Brivio,Corbett,Trott 1906.06949

- full inclusive calculation including $h \to \gamma\gamma, gg, b\bar{b}, c\bar{c}, \tau^+\tau^-, Z\gamma, 4f$
- tree-level, interference only
- $U(3)^5$ flavor symmetry

with $\{m_W, m_Z, G_F\}$ inputs, $\tilde{C} = C(v/\Lambda)^2$:

$$
\begin{aligned}
\frac{\delta\Gamma_{h,full}^{SMEFT}}{\Gamma_h^{SM}} \simeq\ & 1 - 1.50\,\tilde{C}_{HB} - 1.21\,\tilde{C}_{HW} + 1.21\,\tilde{C}_{HWB} + 50.6\,\tilde{C}_{HG} \\
& + 1.83\,\tilde{C}_{H\Box} - 0.43\,\tilde{C}_{HD} + 1.17\,\tilde{C}'_{ll} \\
& - 7.85\,\hat{Y}_{\underset{cc}{u}}\,\mathrm{Re}\tilde{C}_{uH} - 48.5\,\hat{Y}_{\underset{bb}{d}}\,\mathrm{Re}\tilde{C}_{dH} - 12.3\,\hat{Y}_{\underset{\tau\tau}{\ell}}\,\mathrm{Re}\tilde{C}_{eH} \\
& + 0.002\,\tilde{C}_{Hq}^{(1)} + 0.06\,\tilde{C}_{Hq}^{(3)} + 0.001\,\tilde{C}_{Hu} - 0.0007\,\tilde{C}_{Hd} \\
& - 0.0009\,\tilde{C}_{Hl}^{(1)} - 2.32\,\tilde{C}_{Hl}^{(3)} - 0.0006\,\tilde{C}_{He}
\end{aligned}
$$

partial inclusive widths and $\{\alpha_{\rm em}, m_Z, G_F\}$ input scheme also available.

Higgs production and acceptance corrections

Production

Brivio,Hays,Smith,Trott,Žemaitytė in preparation

- $gg \to h$
- $qq \to qqh$ (VBF/VH)
- $qq/gg \to hll/hl\nu$ (VH)
- $gg \to t\bar{t}h$
- $qq \to thj$

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known to NLO SMEFT

Manohar,Wise 0601212
Deutschmann,Duhr,Maltoni,Vryonidou 1708.00460
Grazzini,Ilnicka,Spira 1806.08832

parton level inferred from $h \to 4l$ via crossing sym.

in progress

Maltoni,Vryonidou,Zhang 1607.05330

Degrande,Maltoni,Mimasu,Vryonidou, Zhang 1804.07773

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Acceptance

$A = \frac{n_{\rm kin.cuts}}{n_{\rm tot}}$ assumed to be SM-like in STXS extraction

- SMEFT terms with **non-SM Lorentz** structure $\left(hV_{\mu\nu}V^{\mu\nu}, \quad hV_\mu\bar{\psi}\gamma^\mu\psi\dots\right)$ modify distributions $\to$ ΔA
- ΔA calculable for cuts in Lorentz-invariants, requires MC for arbitrary cuts
- ΔA depends most on decay channel, less on production [preliminary]

Top sector fit

⇝ see talk by **Eleni**

Brivio, Bruggisser, Maltoni, Moutafis, Plehn, Vryonidou, Westhoff, Zhang 1910.03606

- $U(2)_q \times U(2)_u \times U(2)_d$
- top interactions only for now
- up to NLO QCD, quadratic SMEFT

predicitons: SMEFT@NLO

22 relevant operators

also: Hartland, Maltoni, Nocera, Rojo, Slade, Vryonidou, Zhang 1901.05965 **34**

$t\bar{t}Z, t\bar{t}W$

tZ

single t

$t\bar{t}$

$$\mathcal{Q}_{tB} = (\bar{Q}\tilde{H}\sigma^{\mu\nu}t)B_{\mu\nu}$$
$$\mathcal{Q}_{Ht} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{t}\gamma^\mu t)$$

$$\mathcal{Q}_{tG} = (\bar{Q}\tilde{H}\sigma^{\mu\nu}T^A t)G^A_{\mu\nu}$$

$$\mathcal{Q}_{bW} = (\bar{Q}H\sigma^{\mu\nu}\sigma^k b)W^k_{\mu\nu}$$
$$\mathcal{Q}_{Htb} = (i\tilde{H}^\dagger D_\mu H)(\bar{t}\gamma^\mu b)$$

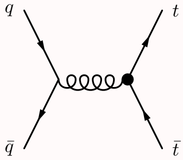
$$\mathcal{Q}^1_{Qu} = (\bar{Q}\gamma_\mu Q)(\bar{u}\gamma^\mu u) \qquad \mathcal{Q}^8_{Qu} = (\bar{Q}\gamma_\mu T^A Q)(\bar{u}\gamma^\mu T^A u)$$
$$\mathcal{Q}^1_{Qd} = (\bar{Q}\gamma_\mu Q)(\bar{d}\gamma^\mu d) \qquad \mathcal{Q}^8_{Qd} = (\bar{Q}\gamma_\mu T^A Q)(\bar{d}\gamma^\mu T^A d)$$
$$\mathcal{Q}^1_{tu} = (\bar{t}\gamma_\mu t)(\bar{u}\gamma^\mu u) \qquad \mathcal{Q}^8_{tu} = (\bar{t}\gamma_\mu T^A t)(\bar{u}\gamma^\mu T^A u)$$
$$\mathcal{Q}^1_{td} = (\bar{t}\gamma_\mu t)(\bar{d}\gamma^\mu d) \qquad \mathcal{Q}^8_{td} = (\bar{t}\gamma_\mu T^A t)(\bar{d}\gamma^\mu T^A d)$$
$$\mathcal{Q}^{1,1}_{Qq} = (\bar{Q}\gamma_\mu Q)(\bar{q}\gamma^\mu q) \qquad \mathcal{Q}^{1,8}_{Qq} = (\bar{Q}\gamma_\mu T^A Q)(\bar{q}\gamma^\mu T^A q)$$
$$\mathcal{Q}^1_{tq} = (\bar{t}\gamma_\mu t)(\bar{q}\gamma^\mu q) \qquad \mathcal{Q}^8_{tq} = (\bar{t}\gamma_\mu T^A t)(\bar{q}\gamma^\mu T^A q)$$

$$\mathcal{Q}^3_{HQ} = (iH^\dagger \overleftrightarrow{D}^i_\mu H)(\bar{Q}\sigma^i\gamma^\mu Q)$$
$$\mathcal{Q}^1_{HQ} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q)$$
$$\mathcal{Q}_{tW} = (\bar{Q}\tilde{H}\sigma^{\mu\nu}\sigma^k t)W^k_{\mu\nu}$$

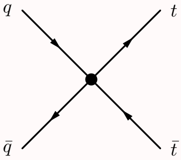
$$\mathcal{Q}^{3,8}_{Qq} = (\bar{Q}\gamma_\mu\sigma^k T^A Q)(\bar{q}\gamma^\mu\sigma^k T^A q)$$
$$\mathcal{Q}^{3,1}_{Qq} = (\bar{Q}\gamma_\mu\sigma^k T^A Q)(\bar{q}\gamma^\mu\sigma^k T^A q)$$

A typical issue: flat directions

e.g. $q\bar{q} \to t\bar{t}$ at LO:



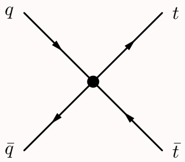
C_{tG}



8 terms: 2 $\chi_q \times 2\chi_t \times$ 2 color contractions
+ singlet/triplet isospin for LL currents
↕
10 operators for each initial state (u/d)

A typical issue: flat directions

e.g. $q\bar{q} \rightarrow t\bar{t}$ at LO:



<u>notation</u>:

$C^{color}_{\chi_q \chi_t}$

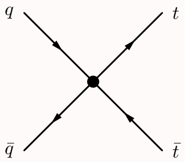
$\beta_t^2 = 1 - 4m_t^2/s$

$c_t = \cos\theta(\vec{p}_t, \vec{p}_q)$ in c.m. frame

$$\Delta\sigma^{int}_{t\bar{t}} \propto \left[C^8_{LL} + C^8_{RR} + C^8_{LR} + C^8_{RL} \right] \left(1 + \beta_t^2 c_t^2 + \frac{2m_t^2}{s} \right) + \left[C^8_{LL} + C^8_{RR} - C^8_{LR} - C^8_{RL} \right] 2\beta_t c_t$$

A typical issue: flat directions

e.g. $q\bar{q} \to t\bar{t}$ at LO:



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LO, interference only can *never* distinguish $LL \leftrightarrow RR$ or $LR \leftrightarrow RL$

$\to$ breaking: NLO QCD
$(C_i C_j)$ terms
other processes in the fit (e.g. single-top)

A typical issue: flat directions

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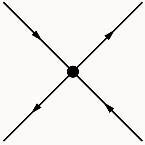

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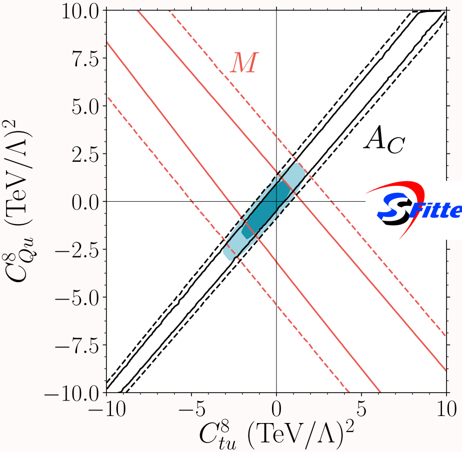
other processes in the fit (e.g. single-top)

LO, interference only *can* distinguish $(LL + RR) \leftrightarrow (LR + RL)$

Same vs. different chiralities in $t\bar{t}$

$$\Delta\sigma^{int}_{t\bar{t}} \propto \left[C^8_{LL} + C^8_{RR} + C^8_{LR} + C^8_{RL}\right]\left(1 + \beta_t^2 c_t^2 + \frac{2m_t^2}{s}\right) + \left[C^8_{LL} + C^8_{RR} - C^8_{LR} - C^8_{RL}\right] 2\beta_t c_t$$



likelihood contours:

$\ln(L_{\max}/L) =$ 1/2 ——

2 - - - - -

($\sim \Delta\chi^2 = 1, 4$ in Gaussian limit)

Same vs. different chiralities in $t\bar{t}$

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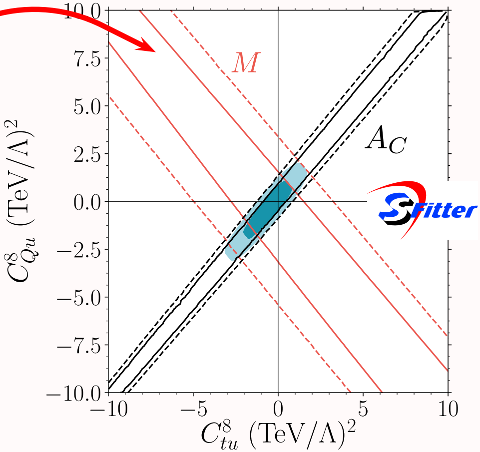
$\sigma_{t\bar{t}} + m_{t\bar{t}}$ dist



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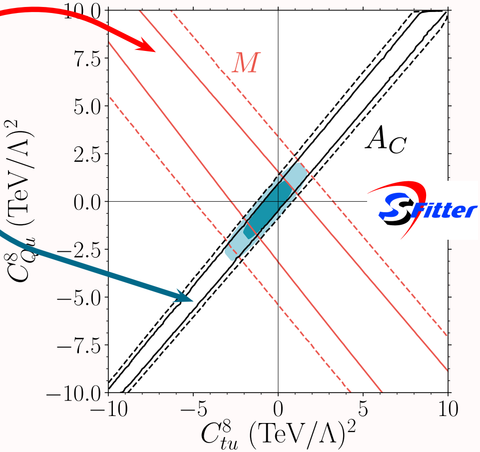
$\sigma_{t\bar{t}} + m_{t\bar{t}}$ dist

charge asymmetry
A_C



likelihood contours:

$\ln(L_{\max}/L) =$ 1/2 ——
2 - - - - -

($\sim \Delta\chi^2 = 1, 4$ in Gaussian limit)

$u\bar{u}$ vs $d\bar{d}$ initial state in $t\bar{t}$

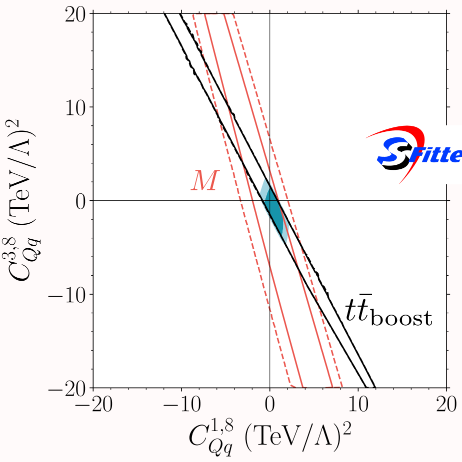
Singlet vs triplet $SU(2)$ contractions:

$$\mathcal{Q}_{Qq}^{1,8} = (\bar{Q}\gamma_\mu T^A Q)(\bar{q}_i\gamma^\mu T^A q_i) \qquad \mathcal{Q}_{Qq}^{3,8} = (\bar{Q}\gamma_\mu T^A\sigma^k Q)(\bar{q}_i\gamma^\mu T^A\sigma^k q_i)$$

$$Q = \binom{t}{b}, \quad q_i = \left(\binom{u}{d}, \binom{c}{s}\right)$$

u,d identical at parton level
only difference: PDF $\leftrightarrow x$

$r(x) = [u\bar{u}]/[d\bar{d}]$
↳ $(r+1)C_{Qq}^{18} + (r-1)C_{Qq}^{38}$ constrained
$(r-1)C_{Qq}^{18} - (r+1)C_{Qq}^{38}$ blind



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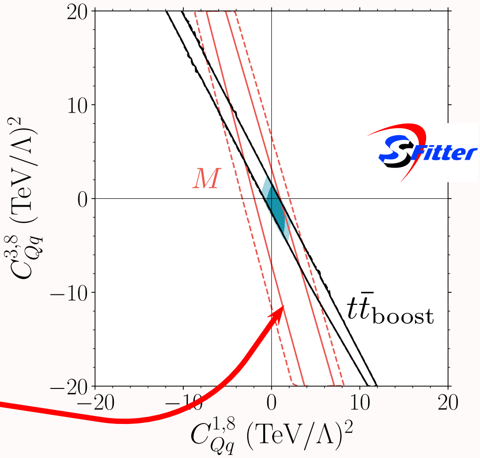

$\sigma_{t\bar{t}} + m_{t\bar{t}}$ dist

bulk kin. region

$r \approx 2$

$u\bar{u}$ vs $d\bar{d}$ initial state in $t\bar{t}$

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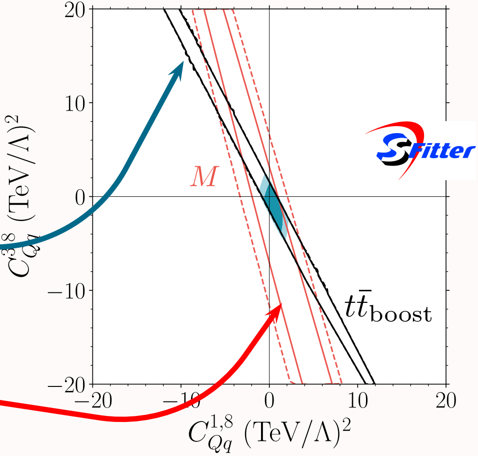
last bins of p_T dist in high-p_T regime $r \approx 3$

$\sigma_{t\bar{t}} + m_{t\bar{t}}$ dist bulk kin. region $r \approx 2$



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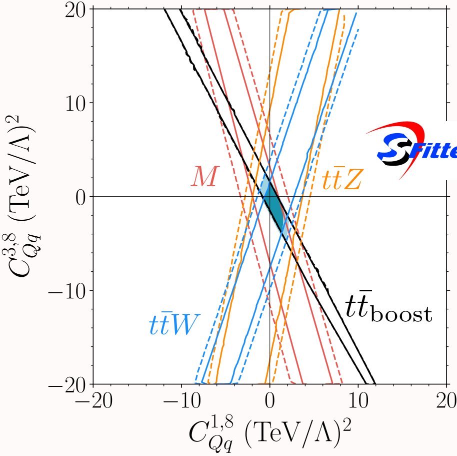
further breaking:
$t\bar{t}W$, $t\bar{t}Z$



Impact of quadratic SMEFT contributions

$$|A_{SMEFT}|^2 = |A_{SM} + A_6|^2 = |A_{SM}|^2 + \text{Re}\left[A_{SM}A_6^\dagger\right] + |A_6|^2$$

Impact of quadratic SMEFT contributions

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- $|A_6|^2 \sim 1/\Lambda^4$

  $\rightarrow$ when SMEFT expansion holds: $|A_6|^2 \ll A_{SM} A_6^\dagger \ll |A_{SM}|^2$

  $\rightarrow$ $|A_6|^2$ same size as SMEFT uncertainties:

$$A_{SM} A_8 \qquad A_{SM} A_6^{2\ insertions} \qquad A_{SM} A_6^{\mathcal{L},sq}$$

Impact of quadratic SMEFT contributions

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  - $\rightarrow$ $|A_6|^2$ same size as SMEFT uncertainties:

$$A_{SM} A_8 \qquad A_{SM} A_6^{2\, insertions} \qquad A_{SM} A_6^{\mathcal{L},sq}$$

- whenever precision is not enough $(C_i)^2$ dominate the fit:

  constraining $C_i \lesssim \mathcal{O}(1)$ requires $(E/\Lambda)^2 \simeq \mathcal{O}(5-10)\%$

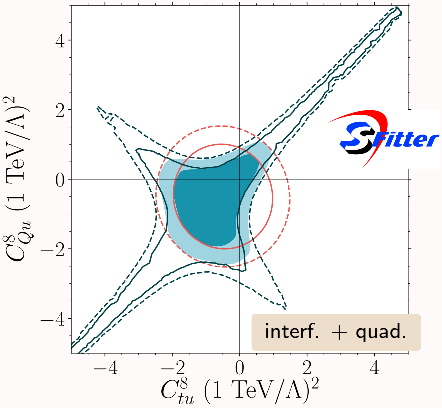
- often included as a **cross check of convergence**.
- quadratics improve bounds via geometric effects

Impact of quadratic SMEFT contributions

$$\begin{aligned}\Delta\sigma_{t\bar t}^{quad} \propto & \left[(C_{LL}^8)^2 + (C_{RR}^8)^2 + (C_{LR}^8)^2 + (C_{RL}^8)^2 + \frac{9}{2}\left((C_{LL}^1)^2 + (C_{RR}^1)^2 + (C_{LR}^1)^2 + (C_{RL}^1)^2\right)\right](1+\beta_t^2 c_t^2) \\ & + \left[(C_{LL}^8)^2 + (C_{RR}^8)^2 - (C_{LR}^8)^2 - (C_{RL}^8)^2 + \frac{9}{2}\left((C_{LL}^1)^2 + (C_{RR}^1)^2 - (C_{LR}^1)^2 - (C_{RL}^1)^2\right)\right] 2\beta_t c_t \\ & + \left[C_{LL}^8 C_{LR}^8 + C_{RR}^8 C_{RL}^8 + \frac{9}{2}\left(C_{LL}^1 C_{LR}^1 + C_{RR}^1 C_{RL}^1\right)\right] 4m_t^2/s\end{aligned}$$

Impact of quadratic SMEFT contributions

$$\Delta\sigma^{quad}_{t\bar{t}} \propto \left[(C^8_{LL})^2 + (C^8_{RR})^2 + (C^8_{LR})^2 + (C^8_{RL})^2 + \frac{9}{2}\left((C^1_{LL})^2 + (C^1_{RR})^2 + (C^1_{LR})^2 + (C^1_{RL})^2\right)\right] \boxed{(1+\beta_t^2 c_t^2)}$$
$$+ \left[(C^8_{LL})^2 + (C^8_{RR})^2 - (C^8_{LR})^2 - (C^8_{RL})^2 + \frac{9}{2}\left((C^1_{LL})^2 + (C^1_{RR})^2 - (C^1_{LR})^2 - (C^1_{RL})^2\right)\right] \boxed{2\beta_t c_t}$$
$$+ \left[C^8_{LL}C^8_{LR} + C^8_{RR}C^8_{RL} + \frac{9}{2}\left(C^1_{LL}C^1_{LR} + C^1_{RR}C^1_{RL}\right)\right] \boxed{4m_t^2/s}$$

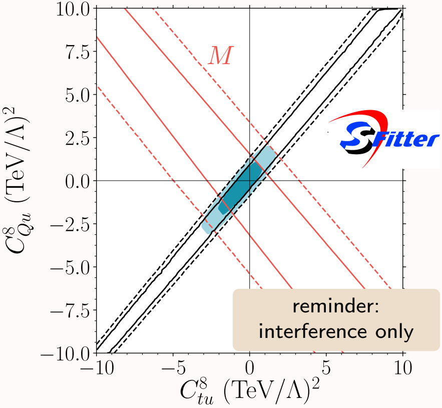


Impact of quadratic SMEFT contributions

$$\Delta\sigma_{t\bar t}^{quad} \propto \Big[(C_{LL}^8)^2 + (C_{RR}^8)^2 + (C_{LR}^8)^2 + (C_{RL}^8)^2 + \frac{9}{2}\Big((C_{LL}^1)^2 + (C_{RR}^1)^2 + (C_{LR}^1)^2 + (C_{RL}^1)^2 \Big) \Big] \boxed{(1+\beta_t^2 c_t^2)}$$

$$+ \Big[(C_{LL}^8)^2 + (C_{RR}^8)^2 - (C_{LR}^8)^2 - (C_{RL}^8)^2 + \frac{9}{2}\Big((C_{LL}^1)^2 + (C_{RR}^1)^2 - (C_{LR}^1)^2 - (C_{RL}^1)^2 \Big) \Big] \boxed{2\beta_t c_t}$$

$$+ \Big[C_{LL}^8 C_{LR}^8 + C_{RR}^8 C_{RL}^8 + \frac{9}{2}\Big(C_{LL}^1 C_{LR}^1 + C_{RR}^1 C_{RL}^1 \Big) \Big] \boxed{4m_t^2/s}$$



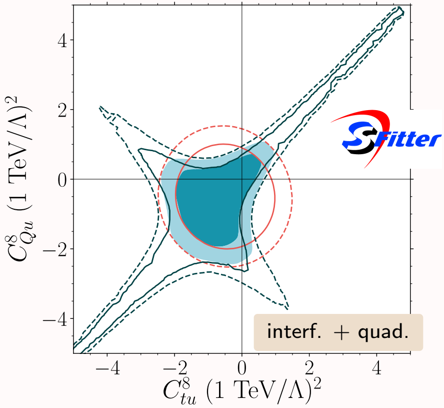
Impact of quadratic SMEFT contributions

$$\Delta\sigma^{quad}_{t\bar{t}} \propto \Big[(C^8_{LL})^2 + (C^8_{RR})^2 + (C^8_{LR})^2 + (C^8_{RL})^2 + \frac{9}{2}\Big((C^1_{LL})^2 + (C^1_{RR})^2 + (C^1_{LR})^2 + (C^1_{RL})^2 \Big) \Big] \boxed{(1+\beta_t^2 c_t^2)}$$

$$+ \Big[(C^8_{LL})^2 + (C^8_{RR})^2 - (C^8_{LR})^2 - (C^8_{RL})^2 + \frac{9}{2}\Big((C^1_{LL})^2 + (C^1_{RR})^2 - (C^1_{LR})^2 - (C^1_{RL})^2 \Big) \Big] \boxed{2\beta_t c_t}$$

$$+ \Big[C^8_{LL} C^8_{LR} + C^8_{RR} C^8_{RL} + \frac{9}{2}\Big(C^1_{LL} C^1_{LR} + C^1_{RR} C^1_{RL} \Big) \Big] \boxed{4m_t^2/s}$$

Quadratic terms modify the **geometry** of the fit



Impact of quadratic SMEFT contributions

$$
\begin{aligned}
\Delta\sigma^{quad}_{t\bar{t}} \propto & \left[(C^8_{LL})^2 + (C^8_{RR})^2 + (C^8_{LR})^2 + (C^8_{RL})^2 + \frac{9}{2}\left((C^1_{LL})^2 + (C^1_{RR})^2 + (C^1_{LR})^2 + (C^1_{RL})^2\right)\right](1+\beta_t^2 c_t^2) \\
& + \left[(C^8_{LL})^2 + (C^8_{RR})^2 - (C^8_{LR})^2 - (C^8_{RL})^2 + \frac{9}{2}\left((C^1_{LL})^2 + (C^1_{RR})^2 - (C^1_{LR})^2 - (C^1_{RL})^2\right)\right] 2\beta_t c_t \\
& + \left[C^8_{LL}C^8_{LR} + C^8_{RR}C^8_{RL} + \frac{9}{2}\left(C^1_{LL}C^1_{LR} + C^1_{RR}C^1_{RL}\right)\right] 4m_t^2/s
\end{aligned}
$$

Quadratic terms modify the **geometry** of the fit

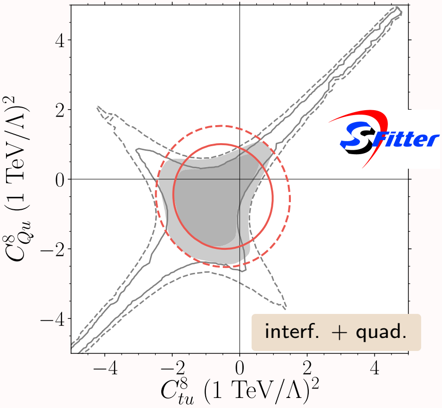
typical measurements $\sim \sum_i + C_i^2$
$\Rightarrow$ **radial constraint**

↓

n-dimensional fit space **compact** already with 1 measurement

↓

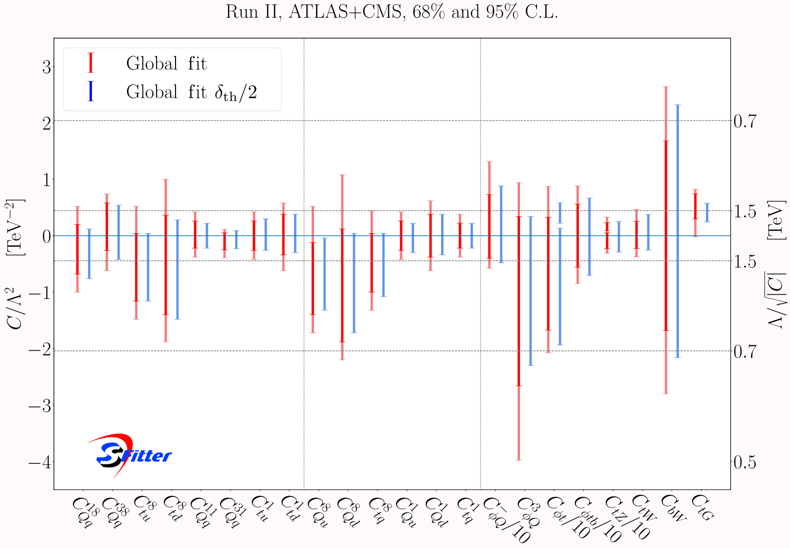
angular flat directions remain



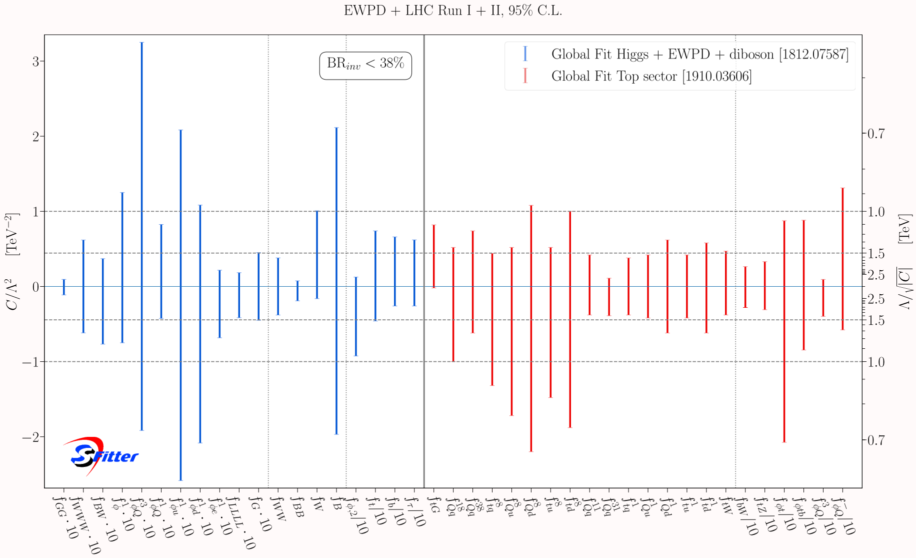
Global fit to top processes: results

fit to $t\bar{t}$, $t\bar{t}Z$, $t\bar{t}W$, single-t, W helicity in t decays

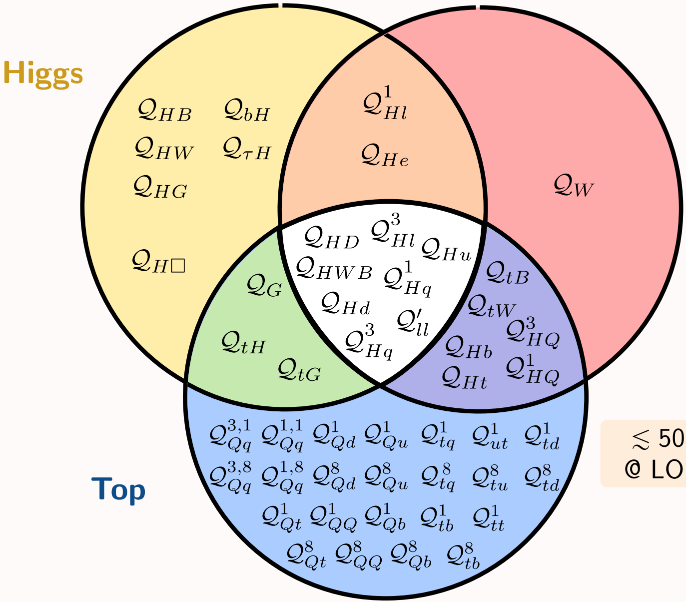
Brivio,Bruggisser,Maltoni,Moutafis,Plehn, Vryonidou,Westhoff,Zhang 1910.03606



Top vs EW+Higgs results



Top+EW+Higgs: next step



$\lesssim$ 50 parameters
@ LO interference

Recap & take-home

- Indirect searches of BSM physics @LHC will become more and more important in the next runs
- The **SMEFT** is a well-defined QFT framework to do this systematically: go beyond SM stress-test!
- 20-30 parameters for the basic scenario in a Higgs/EW/top analysis
- Higgs + EW analyis → good **analytic** control …and improving
  → EFT effects beyond signal being addressed
- top analysis → precision approaching interesting region!
  → NLO QCD important
  → care required to break **large degeneracies**
  → quadratic terms have strong impact through geometry

Backup slides

EW + Higgs fit – observables [preliminary]

118 observables included so far

- 8 near-Z-pole EWPO: Γ_Z, $R^0_{\ell,c,b}$, $A^{\ell,c,b}_{FB}$, σ^0_h LEPI combination hep-ex/0509008
- 21 distribution bins for bhabha scattering at LEPII LEPII combination 1302.3415
- 74 dist. bins for W^+W^- production at LEPII
  L3: hep-ex/0409016
  OPAL: 0708.1311
  ALEPH: Eur.Phys.J. C38 (2004) 147
  differential combined: 1302.3415
- 15 inclusive obs. for Higgs measurements in $H \to \gamma\gamma$ and $H \to 4\ell$ at LHC
  - ATLAS ($36\ \text{fb}^{-1}$) ATLAS-CONF-2017-047
  - CMS ($36\ \text{fb}^{-1}$) CMS PAS HIG-17-031

Top fit – observables

$pp \to t\bar{t}$

- 5 $\sigma_{t\bar{t}}$ measurements at 8 and 13 TeV
- 5 A_C measurements at 8 and 13 TeV
- 2 $d\sigma/dm_{t\bar{t}}$ dist. at 8 and 13 TeV (15 bins tot)
- 4 $d\sigma/dp_T^t(p_T^1, p_T^h)$ dist. at 8 and 13 TeV (30 bins tot)
- 1 $d^2\sigma/dm_{t\bar{t}}dt_{t\bar{t}}$ dist at 8 TeV (16 bins)
- 2 dist in high-p_T region ($p_T^t, m_{t\bar{t}}$) at 8 and 13 TeV (13 bins tot)

$pp \to t\bar{t}Z, pp \to t\bar{t}W$

- 2 $\sigma_{t\bar{t}V}$ measurements for each V at 8 and 13 TeV

Single-top

- 6 $\sigma_{tq,\bar{t}q}$ measurements in t-channel at 7, 8, 13 TeV
- 3 $\sigma_{t\bar{b},\bar{t}b}$ measurements in s-channel at 7, 8 TeV
- 6 $\sigma_{tW,\bar{t}W}$ measurements in tW channel at 7, 8, 13 TeV
- 1 σ_{tZq} measurement in tZq at 13 TeV

Top decays

- 4 measurements of W helicity at 7, 8, 13 TeV