The SM-EFT program: some recent developments

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An EFT for BSM searches: 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}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
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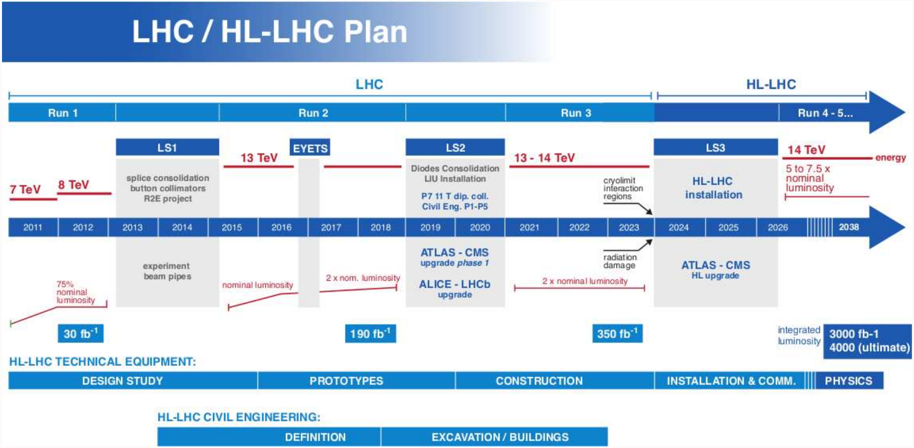
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$		

LHC: plans for the future



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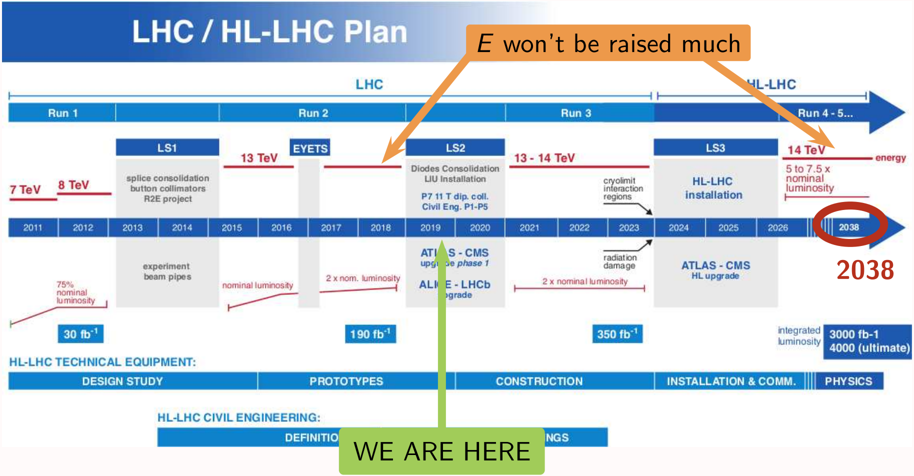

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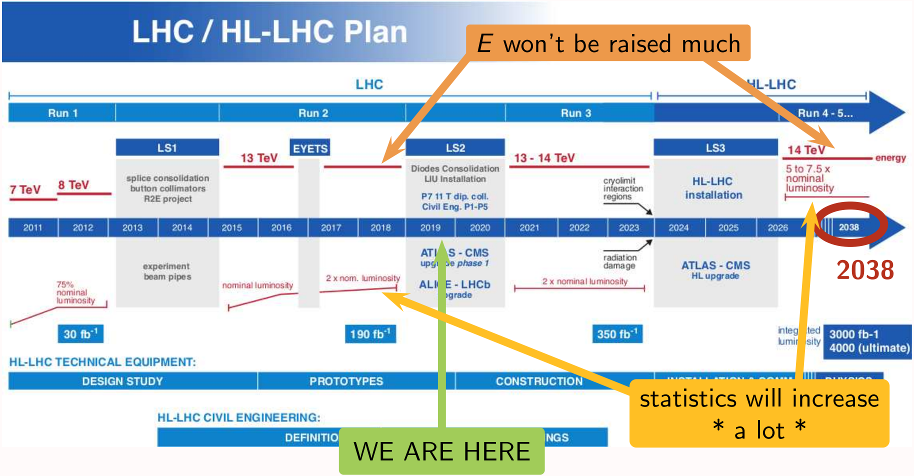

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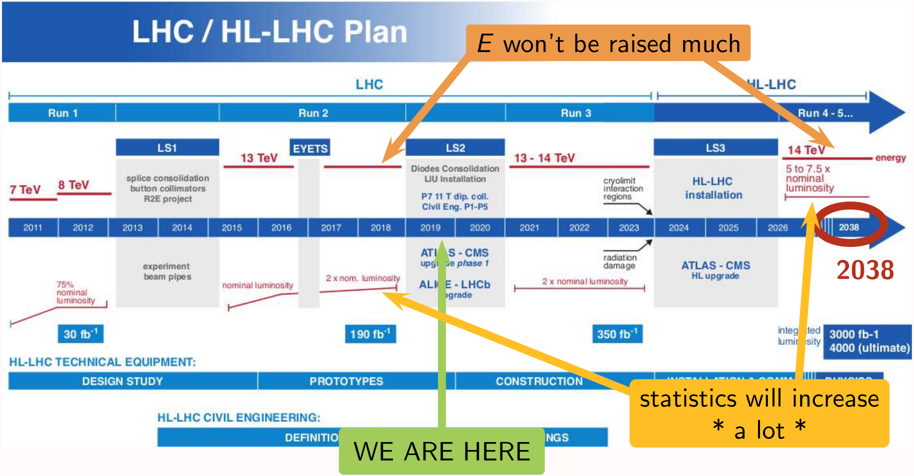

there's much room for improvement in precision →

worth having
a systematic program
for **indirect searches**

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☞ full QFTs with their own regularization/renormalization schemes not just anomalous couplings!

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- calculations are done **order by order in** $\delta = (E/\Lambda)$
  $\to$ rationale for expected size of contributions: power counting
  $\to$ systematically improvable

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  → only input: low E fields & symmetries
  → works even if the UV is *non-perturbative*
  e.g. chiral perturbation theory: $\pi - \pi$ scattering computed in 1966

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- a universal language for interpretation of measurements

The SMEFT – recent theory developments

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

The SMEFT – recent theory developments

B cons. $N_f = 1 \rightarrow$ 2 76 22 895

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$N_f = 3 \rightarrow$ 12 2499 948 36971

- # of parameters known for all orders

Lehman 1410.4193
Lehman,Martin 1510.00372
Henning,Lu,Melia,Murayama 1512.03433

The SMEFT – recent theory developments

Weinberg PRL43(1979)1566

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Leung,Love,Rao Z.Ph.C31(1986)433
Buchmüller,Wyler Nucl.Phys.B268(1986)621
Grzadkowski et al 1008.4884

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Henning,Lu,Murayama 1412.1837,1604.01019
del Aguila,Kunszt,Santiago 1602.00126
Drozd,Ellis,Quevillon,You 1512.03003
Ellis,Quevillon,You,Zhang 1604.02445,1706.07765
Fuentes-Martin,Portoles,Ruiz-Femenia 1607.02142
Zhang 1610.00710
(Krämer),Summ,Voigt 1806.05171, 1908.04798

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Shadmi,Weiss 1809.09644
Henning,Melia 1901.06747,1902.06754,1902.06747
Ma,Shu,Xiao 1902.06752
Durieux,Kitahara,Shadmi,Weiss, 1909.10551

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$\mathcal{L}_6$: leading deviations from SM

- complete RGE available

Alonso,Jenkins,Manohar,Trott 1308.2627,1310.4838,1312.2014
Grojean,Jenkins,Manohar,Trott 1301.2588
Alonso,Chang,Jenkins,Manohar,Shotwell 1405.0486
Ghezzi,Gomez-Ambrosio,Passarino,Uccirati 1505.03706

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Pruna,Signer 1408.3565
Hartmann,(Shepherd),Trott 1505.02646,1507.03568,1611.09879
Ghezzi,Gomez-Ambrosio,Passarino,Uccirati 1505.03706
(Cullen,Gauld),Pecjak,Scott 1512.02508,1904.06358
Dawson,Giardino 1801.01136,1807.11504,1808.05948,1909.02000
Deutschmann,Duhr,Maltoni,Vryonidou 1708.00460
Grazzini,Ilnicka,Spira 1806.08832
Boughezal,Chen,Petriello,Wiegand 1907.00997
Dedes,Paraskevas,Rosiek,Suxho,Trifyllis 1805.00302 ...

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Dedes, Materkowska, Paraskevas, Rosiek, Suxho 1704.03888
Helset, Paraskevas, Trott 1803.08001
Corbett, Helset, Trott 1909.08470

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Jenkins,Manohar,Stoffer 1709.04486
Dekens,Stoffer 1908.05295

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- formulation in R_ξ gauge, Ward identities
- matching to Low Energy EFT (below m_W)
- various tools available for numerical analysis ⇝ SMEFT-Tools (1910.11003)
  [MC generation, analytic calculation, fitting, matching, RGE running...]

SMEFT @ LHC: how many parameters?

Depends

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observables, including/excluding quadratic terms

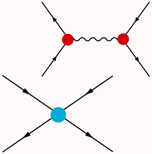
Focusing on interference $\mathcal{A}_{SM}\mathcal{A}_6^*$ only

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

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

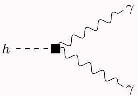


If quadratic terms $|\mathcal{A}_6|^2$ are included, more operators contribute

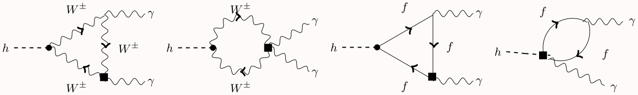
SMEFT @ LHC: how many parameters?

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 $+ \ldots$

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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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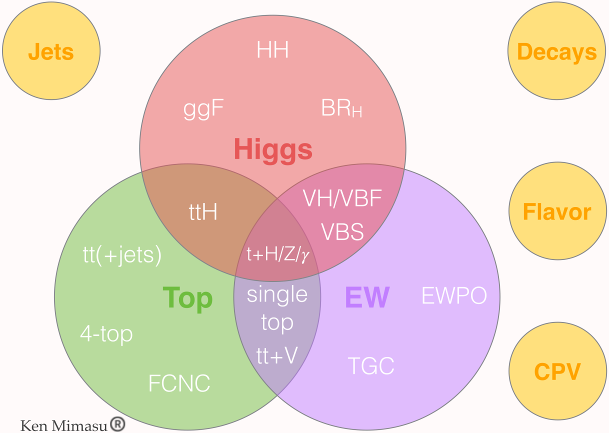
Global SMEFT analyses

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

- individual processes necessarily have blind directions
- combination of different processes / sectors required



Example 1: Higgs and EW processes

Brivio,Hays,Smith,Trott,Žemaitytė in preparation

- $U(3)^5$ flavor symmetry
- all relevant interactions included **23 relevant operators**
- tree-level, interference only

<u>also</u>: Ellis,Murphy,Sanz,You 1803.03252 **20**

Z,W couplings

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

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

input quantities

Bhabha scattering

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

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

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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  - **EW** observables: all well known at tree level
  - **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

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$\#$ signal evts. in analysis k:

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

lumi

prod xs $i \to h$

decay BR $h \to f$

efficiency

acceptance

Global exp. fit to $n_k \to (\sigma \cdot B)_{if}$ for defined i, f categories.
Assumes SM ε, A!

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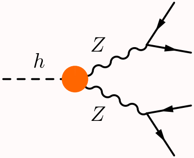
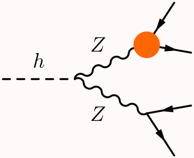
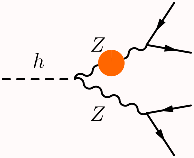
Assumes SM ε, A!

Inclusive width H $\to$ 4f in the SMEFT

① corrections to SM diagrams







$\propto g_{\mu\nu}$ (SM-like)

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

$\delta g_L, \delta g_R$

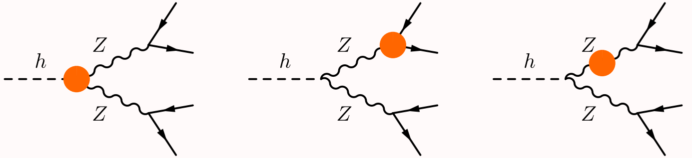
$$\frac{-i m_Z \delta\Gamma_Z + (2m_Z - i\Gamma_Z)\delta m_Z}{p^2 - m_Z^2 + i\Gamma_Z m_Z}$$

$\uparrow$

hard to extract from MC simulation!
full treatment requires analytic calculation

Inclusive width H → 4f in the SMEFT

① corrections to SM diagrams



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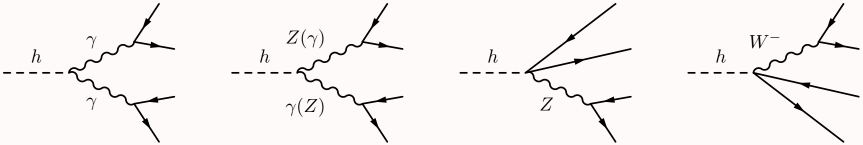
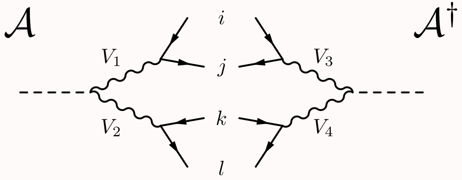
② genuine SMEFT diagrams



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

Brivio,Corbett,Trott 1906.06949

fully analytical treatment. automated with general decomposition:



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

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

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, $\tilde{C} = C(v/\Lambda)^2$:

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

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

The SMEFTsim package

an **UFO & FeynRules model** with*:

Brivio, Jiang, Trott 1709.06492

1. the complete B-conserving Warsaw basis for 3 generations, including all complex phases and $\cancel{CP}$ terms
2. automatic field redefinitions to have **canonical kinetic terms** and **parameter shifts** due to the choice of an input parameters set
3. 6 implementations: 3 flavor assumptions $\times$ 2 input schemes

feynrules.irmp.ucl.ac.be/wiki/SMEFT

wiki: SMEFT

Standard Model Effective Field Theory -- The SMEFTsim package

Authors

Ilaria Brivio, Yun Jiang and Michael Trott

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NBIA and Discovery Center, Niels Bohr Institute, University of Copenhagen

Pre-exported UFO files (include restriction cards)

	Set A		Set B	
	α scheme	m_W scheme	α scheme	m_W scheme
Flavor general SMEFT	SMEFTsim_A_general_alphaScheme_UFO.tar.gz	SMEFTsim_A_general_MwScheme_UFO.tar.gz	SMEFT_alpha_UFO.zip	SMEFT_mW_UFO.zip
MFV SMEFT	SMEFTsim_A_MFV_alphaScheme_UFO.tar.gz	SMEFTsim_A_MFV_MwScheme_UFO.tar.gz	SMEFT_alpha_MFV_UFO.zip	SMEFT_mW_MFV_UFO.zip
$U(3)^5$ SMEFT	SMEFTsim_A_U35_alphaScheme_UFO.tar.gz	SMEFTsim_A_U35_MwScheme_UFO.tar.gz	SMEFT_alpha_FLU_UFO.zip	SMEFT_mW_FLU_UFO.zip

* LO, unitary gauge implementation

Cross-check with SMEFTsim

e.g. $h \to e^+ \mu^- \bar{\nu}_\mu \nu_e$

$$\frac{\Gamma_{SMEFT}}{\Gamma_{SM}} = 1 + \sum_i a_i \left(\frac{v^2}{\Lambda^2} C_i\right)$$

	theory	MG interf	MG full xs
CHW	-1.48743	-1.48844	-1.48002
CHbox	2.	1.99786	2.00819
CHD	-0.5	-0.499802	-0.495254
CHl3	-3.76422	-3.77082	-3.76292
Cll1	3.	2.99626	2.99819

analytic calculation

Brivio,Corbett,Trott 1906.06949

$y_i / \Gamma_{h \to e^+ \nu_e \mu^- \bar{\nu}_\mu, SM}$ from pure interference

$y_i / \Gamma_{h \to e^+ \nu_e \mu^- \bar{\nu}_\mu, SM}$ from linearized full width

$\delta\Gamma_W$ omitted here: requires hacking propagator corrections in MC

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validated with theory

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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

$A = \dfrac{n_{\rm kin.cuts}}{n_{\rm tot}}$ 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]

Example 2: top quark processes

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

tZ

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

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

single t

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

$t\bar{t}$

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

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

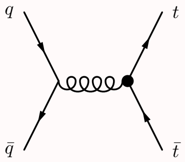
$$\mathcal{Q}^3_{HQ} = (iH^\dagger \overleftrightarrow{D}^i_\mu H)(\bar{Q}\sigma^i\gamma^\mu Q)$$
$$\mathcal{Q}^1_{HQ} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q)$$
$$\mathcal{Q}_{tW} = (\bar{Q}\tilde{H}\sigma^{\mu\nu}\sigma^k t)W^k_{\mu\nu}$$

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

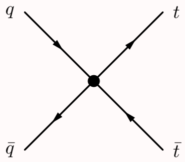
A typical issue: flat directions

In any given process, there's typically a **degeneracy of parameters**
→ needs a smart choice of observables and combination of different processes

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
$\updownarrow$
10 operators for each initial state (u/d)

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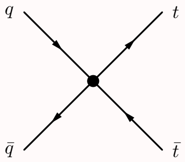


notation:

$C^{color}_{\chi_q \chi_t}$
$\beta_t^2 = 1 - 4m_t^2/s$
$c_t = \cos\theta(\vec{p}_t, \vec{p}_q)$ in c.m. frame

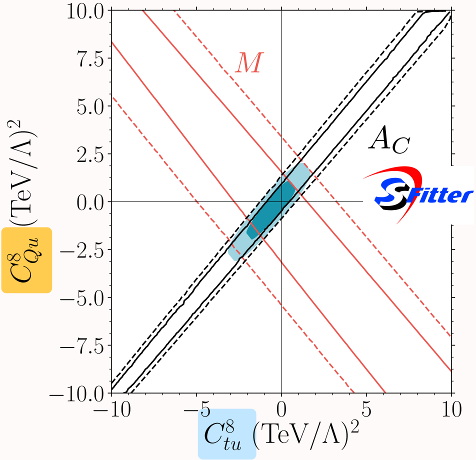
$$\Delta\sigma^{int}_{t\bar{t}} \propto \left[C^8_{LL} + C^8_{RR} + C^8_{LR} + C^8_{RL} \right] \left(1 + \beta_t^2 c_t^2 + \frac{2m_t^2}{s} \right) + \left[C^8_{LL} + C^8_{RR} - C^8_{LR} - C^8_{RL} \right] 2\beta_t c_t$$

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

→ breaking needs NLO QCD effects / quadratic contributions / inclusion of other processes in the fit (e.g. single-top)

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

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



likelihood contours:

$\ln L_{\max} - \ln L =$ 1/2 ———

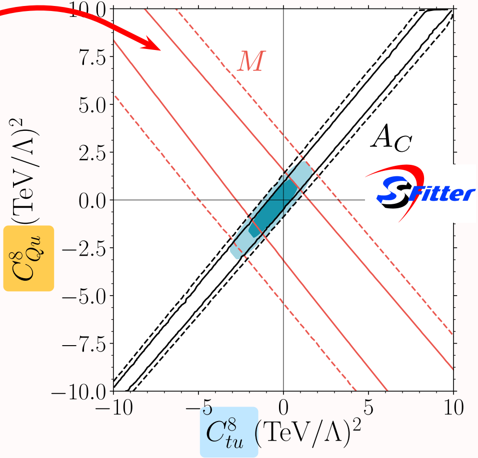
2 - - - - -

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

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

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

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



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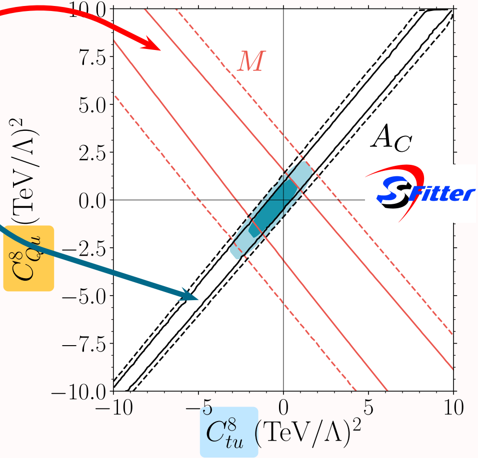
$\sigma_{t\bar{t}} + m_{t\bar{t}}$ dist

charge asymmetry
A_C



likelihood contours:

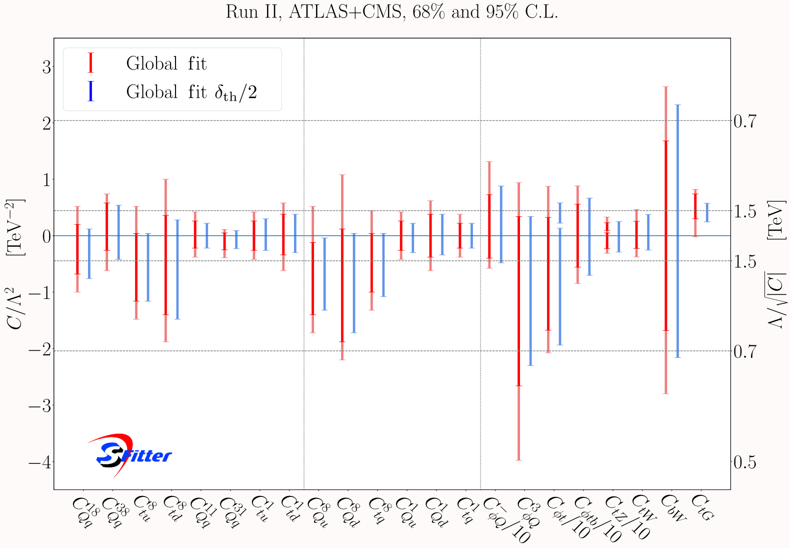
$\ln L_{\max} - \ln L =$ 1/2 ———
2 - - - - -

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

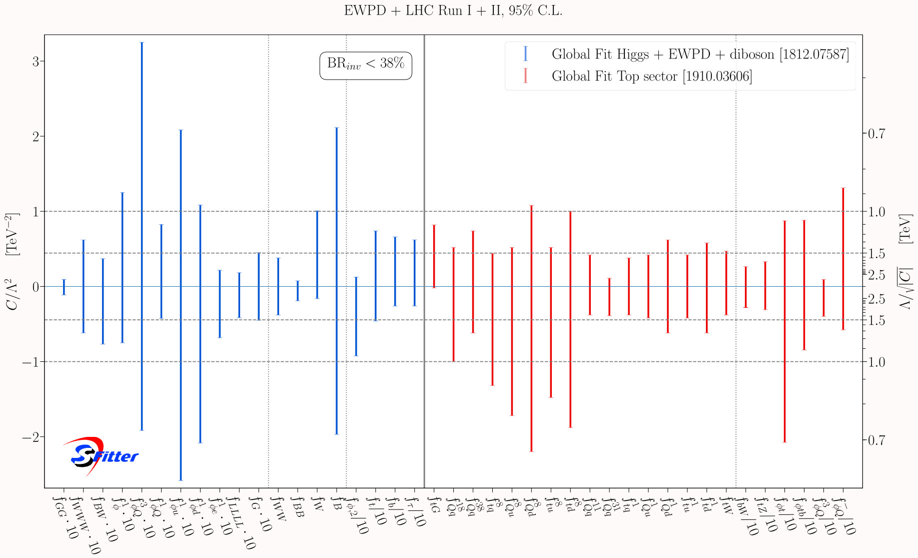
Global fit to top processes: results

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 fit vs previous EW+Higgs fit results



Summary & outlook

- Indirect searches of BSM physics @LHC will become more and more significant
- The **SMEFT** is a well-defined QFT framework to do this systematically. Not just SM stress-test but a means to understand the global picture
- Global analyses are required.
  - EW + Higgs and top sector have been explored
  - next: EW + Higgs + top ... + B physics
- Work in progress to improve accuracy: NLO, go beyond narrow-width, acceptance corrections ...
- ATLAS/CMS also interested in doing EFT analyses directly. Some studies already public.
- Fitting technology is important. Need:
  – correct estimate of correlations, uncertainties
  – powerful tools for interpretation (machine learning, geometry...)

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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 ($36\ \mathrm{fb}^{-1}$) ATLAS-CONF-2017-047
  - CMS ($36\ \mathrm{fb}^{-1}$) 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