Recent developments in the SM-EFT program

Ilaria Brivio

Institut für Theoretische Physik,
Universität Heidelberg

What's an Effective Field Theory?

a field theory valid in a regime $\delta \ll 1$

$\updownarrow$

Taylor expansion in δ

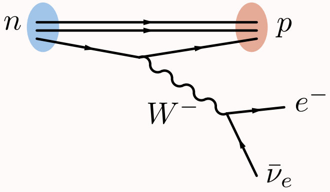
What's an Effective Field Theory?

a field theory valid in a regime $\boldsymbol{\delta} \ll \mathbf{1}$

$\updownarrow$

Taylor expansion in $\boldsymbol{\delta}$

Classic example: **Fermi's interaction** for β-decays



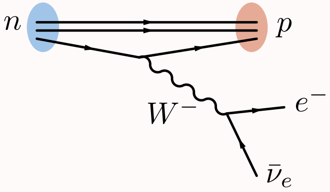
What's an Effective Field Theory?

a field theory valid in a regime $\boldsymbol{\delta} \ll \mathbf{1}$

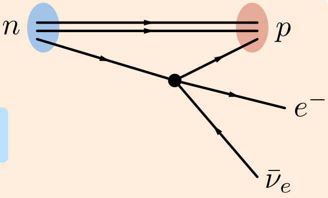
↕

Taylor expansion in $\boldsymbol{\delta}$

Classic example: **Fermi's interaction** for β-decays



$\boldsymbol{\delta} = \frac{E}{m_W}$



$\propto G_F \sim \frac{1}{m_W^2} + \mathcal{O}\left(\frac{E^4}{m_W^4}\right)$

What's an Effective Field Theory?

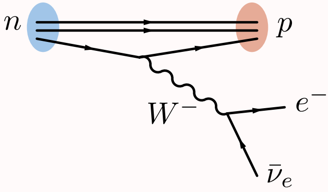
a field theory valid in a regime $\boldsymbol{\delta} \ll \mathbf{1}$

$\updownarrow$

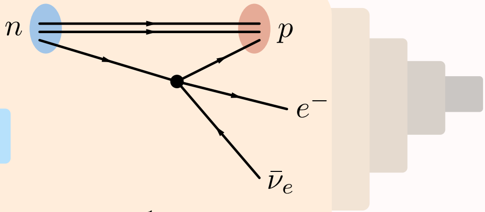
Taylor expansion in $\boldsymbol{\delta}$

Classic example: **Fermi's interaction** for β-decays

irrelevant / not needed

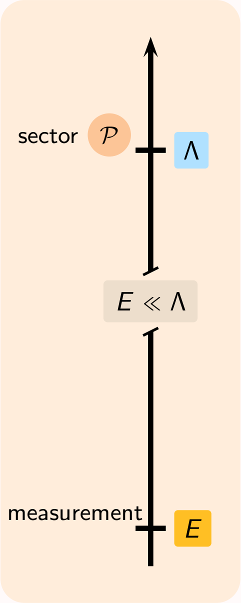


$\boldsymbol{\delta} = \frac{E}{m_W}$

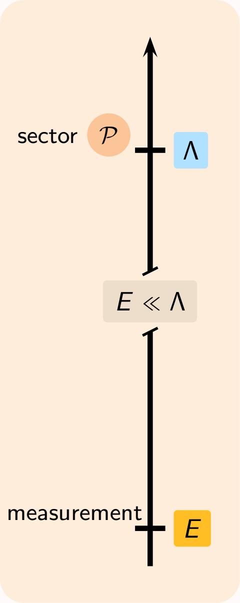


$\propto G_F \sim \frac{1}{m_W^2}$ $+\mathcal{O}\left(\frac{E^4}{m_W^4}\right)$

EFTs: from the bottom-up



typically $\boxed{\delta = \frac{E}{\Lambda}}$

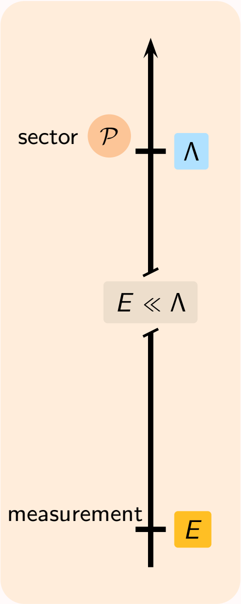


typically $\boxed{\delta = \frac{E}{\Lambda}}$

fields
symmetries $\xrightarrow{\delta}$ $\mathcal{L}_{EFT}^{(n)}$: <u>all</u> allowed operators at δ^n

free parameters C_i

EFTs: from the bottom-up



typically $\delta = \dfrac{E}{\Lambda}$

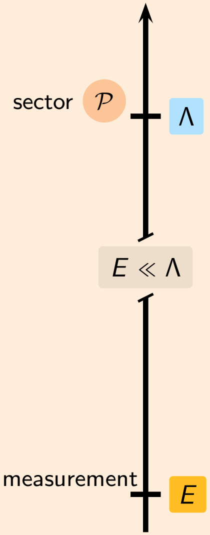
knowledge of $\mathcal{P}$ is not required

details of $\mathcal{P}$ can be inferred measuring C_i

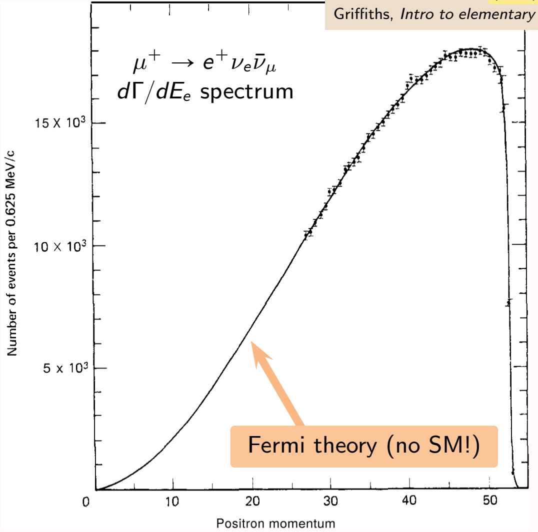
fields
symmetries $\xrightarrow{\delta}$ $\mathcal{L}_{EFT}^{(n)}$: <u>all</u> allowed operators at δ^n

free parameters C_i

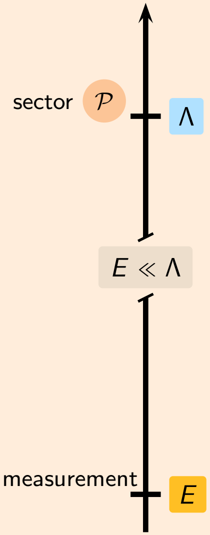
EFTs: from the bottom-up



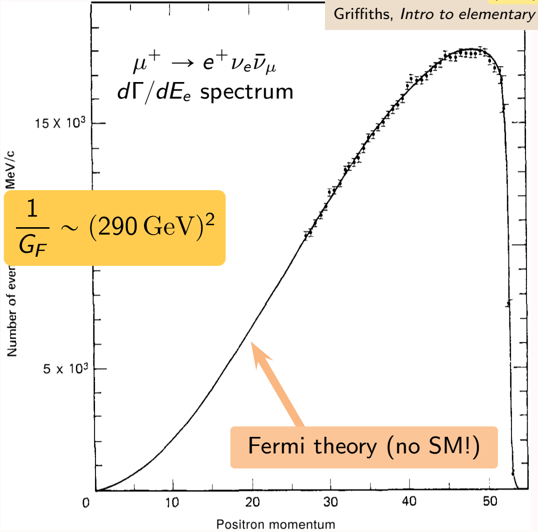
Bardon et al. PRL 14 (1965) 449
Griffiths, *Intro to elementary particles*



EFTs: from the bottom-up

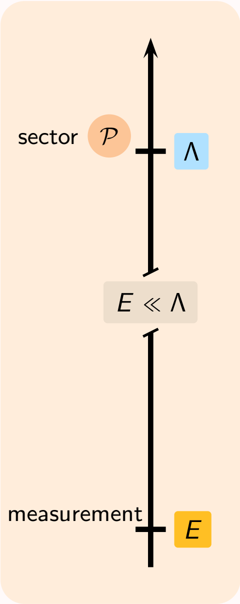


Bardon et al. PRL 14 (1965) 449
Griffiths, *Intro to elementary particles*

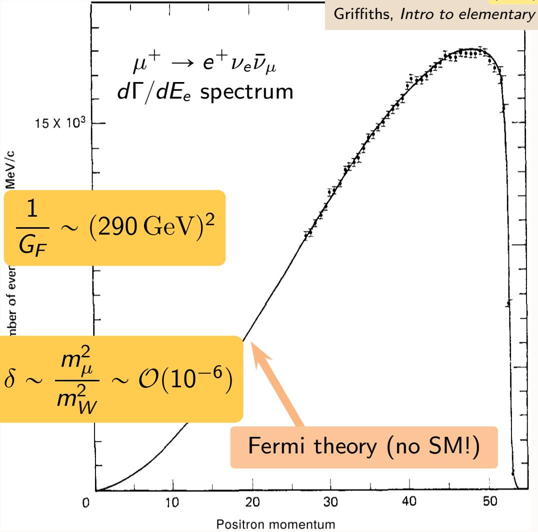


$$\frac{1}{G_F} \sim (290\,\mathrm{GeV})^2$$

EFTs: from the bottom-up



Bardon et al. PRL 14 (1965) 449
Griffiths, *Intro to elementary particles*



$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$
$d\Gamma/dE_e$ spectrum

$$\frac{1}{G_F} \sim (290\,\mathrm{GeV})^2$$

$$\delta \sim \frac{m_\mu^2}{m_W^2} \sim \mathcal{O}(10^{-6})$$

Fermi theory (no SM!)

An EFT to go beyond the SM: 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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar l_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar e_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$

The Warsaw basis

Grzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884

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

Why the SMEFT?

SMEFT describes **BSM effects @LHC**
in scenarios where BSM is out of collider reach

Why the SMEFT?

SMEFT describes **BSM effects @LHC**
in scenarios where BSM is <u>out</u> of collider reach

- \+ a proper QFT, with regularization/renormalization schemes
- \+ minimal commitment to a specific UV
- \+ systematically includes all BSM effects, compatible with assumptions
- \+ universal language for data interpretation: can connect to <u>other experiments</u>

Why the SMEFT?

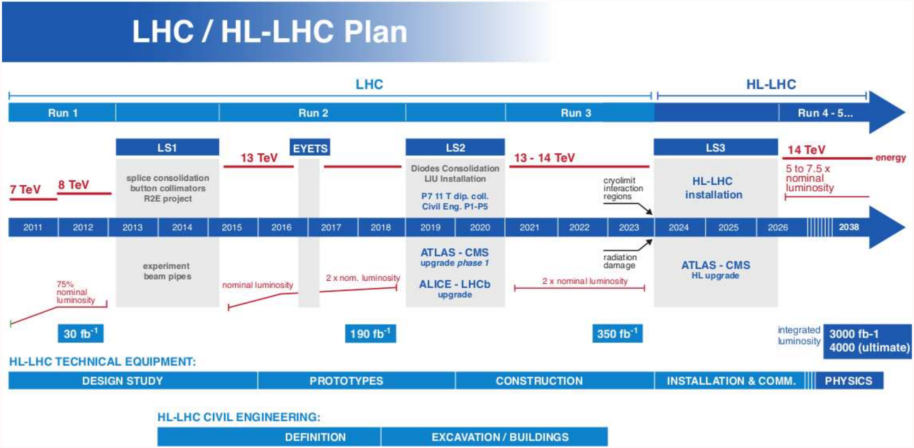
SMEFT describes **BSM effects @LHC**
in scenarios where BSM is out of collider reach

- \+ a proper QFT, with regularization/renormalization schemes
- \+ minimal commitment to a specific UV
- \+ systematically includes all BSM effects, compatible with assumptions
- \+ universal language for data interpretation: can connect to other experiments

↓

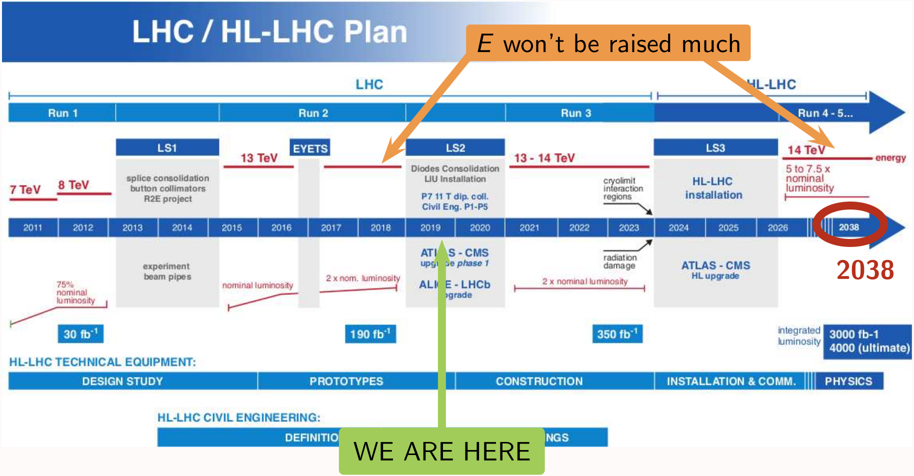
suitable for **a systematic program for indirect searches of NP @LHC**

LHC: plans for the future

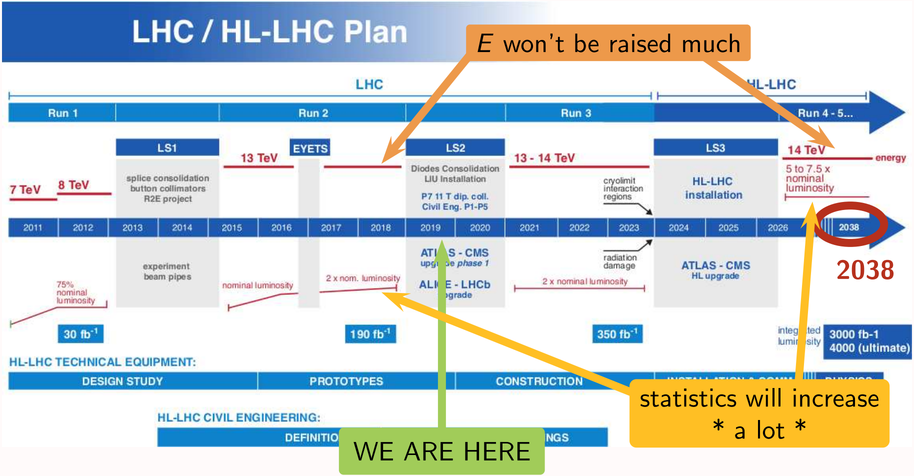


LHC: plans for the future

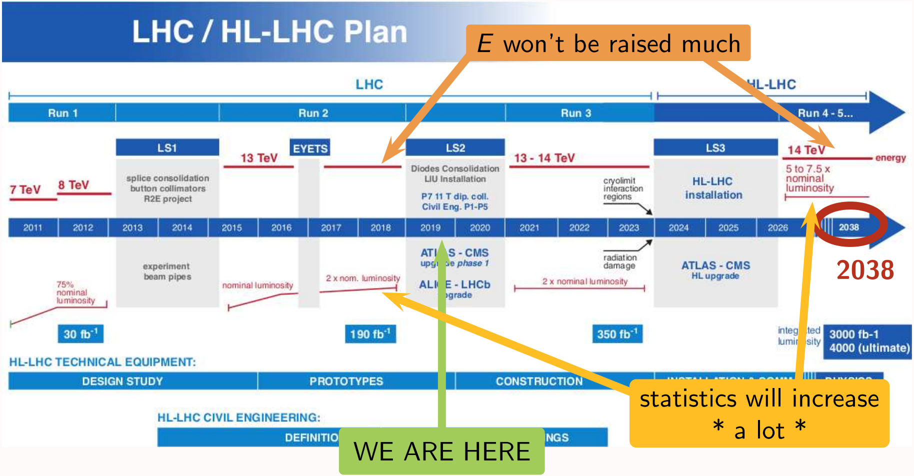
LHC: plans for the future



LHC: plans for the future



LHC: plans for the future



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

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**

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

$N_f = 3 \rightarrow$ **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

Lehman 1410.4193
Henning,Lu,Melia,Murayama 1512.03433

Li,Ren,Shu,Xiao,Yu,Zheng 2005.00008
Murphy 2005.00059

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

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

- $\#$ of parameters known for all orders
- complete bases available for $\mathcal{L}_5$, $\mathcal{L}_6$, $\mathcal{L}_7$, $\mathcal{L}_8$

The SMEFT – recent theory developments

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

- # of parameters known for all orders
- complete bases available for $\mathcal{L}_5$, $\mathcal{L}_6$, $\mathcal{L}_7$, $\mathcal{L}_8$
- efficient matching techniques developed: CDE/UOLEA

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

The SMEFT – recent theory developments

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

- # of parameters known for all orders
- complete bases available for $\mathcal{L}_5$, $\mathcal{L}_6$, $\mathcal{L}_7$, $\mathcal{L}_8$
- efficient matching techniques developed: CDE/UOLEA
- relation with the amplitude method

Shadmi,Weiss 1809.09644
Henning,Melia 1901.06747,1902.06754,1902.06747
Ma,Shu,Xiao 1902.06752
Aoude,Machado 1905.11433
Durieux,Kitahara,Shadmi,Weiss 1909.10551
Durieux,Machado 1912.08827
Craig,Jiang,Li,Sutherland 2001.00017

The SMEFT – recent theory developments

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

- # of parameters known for all orders
- complete bases available for $\mathcal{L}_5$, $\mathcal{L}_6$, $\mathcal{L}_7$, $\mathcal{L}_8$
- efficient matching techniques developed: CDE/UOLEA
- relation with the amplitude method

$\mathcal{L}_6$: 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
Miro,Ingoldby,Riembau 2005.06983
Baratella,Fernandez,Pomarol 2005.07129

The SMEFT – recent theory developments

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

- \# of parameters known for all orders
- complete bases available for $\mathcal{L}_5$, $\mathcal{L}_6$, $\mathcal{L}_7$, $\mathcal{L}_8$
- efficient matching techniques developed: CDE/UOLEA
- relation with the amplitude method

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

- complete RGE available
- 1-loop results available for select processes

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 . . .

The SMEFT – recent theory developments

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

- \# of parameters known for all orders
- complete bases available for $\mathcal{L}_5$, $\mathcal{L}_6$, $\mathcal{L}_7$, $\mathcal{L}_8$
- efficient matching techniques developed: CDE/UOLEA
- relation with the amplitude method

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

- complete RGE available
- 1-loop results available for select processes
- geometry of the scalar sector (R_ξ gauge, Ward identities, . . .)

Dedes,Materkowska,Paraskevas,Rosiek,Suxho 1704.03888
Helset,Paraskevas,Trott 1803.08001
Corbett,Helset,Trott 1909.08470
Helset,Martin,Trott 2001.01453

The SMEFT – recent theory developments

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

- # of parameters known for all orders
- complete bases available for $\mathcal{L}_5$, $\mathcal{L}_6$, $\mathcal{L}_7$, $\mathcal{L}_8$
- efficient matching techniques developed: CDE/UOLEA
- relation with the amplitude method

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

- complete RGE available
- 1-loop results available for select processes
- geometry of the scalar sector (R_ξ gauge, Ward identities, ...)
- comprehensive studies of flavor structure

Bordone,Catà,Feldmann 1910.02641
Faroughy,Isidori,Wilsch,Yamamoto 2005.05366

The SMEFT – recent theory developments

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

- \# of parameters known for all orders
- complete bases available for $\mathcal{L}_5$, $\mathcal{L}_6$, $\mathcal{L}_7$, $\mathcal{L}_8$
- efficient matching techniques developed: CDE/UOLEA
- relation with the amplitude method

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

- complete RGE available
- 1-loop results available for select processes
- geometry of the scalar sector (R_ξ gauge, Ward identities, ...)
- comprehensive studies of flavor structure
- matching to Low Energy EFT (below m_W)

Jenkins,Manohar,Stoffer 1709.04486
Dekens,Stoffer 1908.05295

The SMEFT – recent theory developments

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

- # of parameters known for all orders
- complete bases available for $\mathcal{L}_5$, $\mathcal{L}_6$, $\mathcal{L}_7$, $\mathcal{L}_8$
- efficient matching techniques developed: CDE/UOLEA
- relation with the amplitude method

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

- complete RGE available
- 1-loop results available for select processes
- geometry of the scalar sector (R_ξ gauge, Ward identities, …)
- comprehensive studies of flavor structure
- 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

SMEFT @ LHC: how many parameters?

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

SMEFT @ LHC: how many parameters?

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

observables, including/excluding quadratic terms

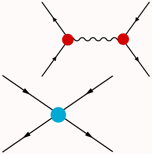
Focusing on interference $\mathcal{A}_{SM}\mathcal{A}_6^*$ only

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

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



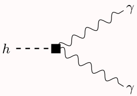
If quadratic terms $|\mathcal{A}_6|^2$ are included, more operators contribute

SMEFT @ LHC: how many parameters?

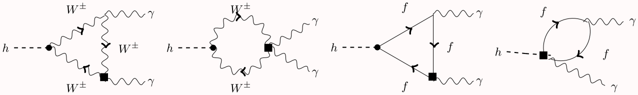
Depends on choices of

- 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.

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

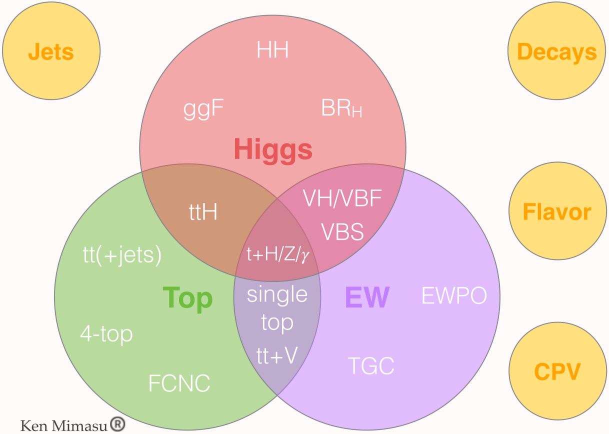
requires **global fits**

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

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



EW sector: Higgs and EW processes

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

Brivio, Hays, Smith, Trott, Žemaitytė in preparation

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

Z,W couplings

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

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

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)

Higgs and EW fit: main features

Brivio,Hays,Smith,Trott,Žemaitytė in preparation

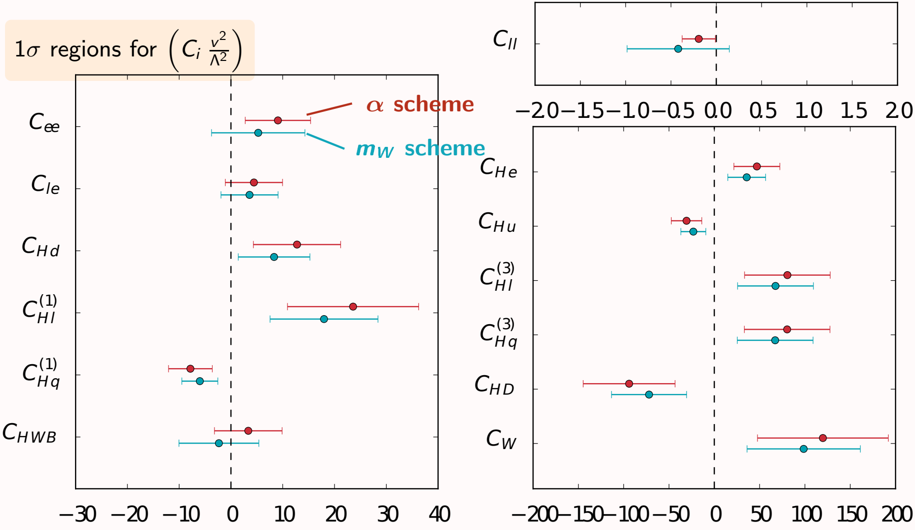
- $U(3)^5$ flavor symmetry
- all relevant interactions included
- tree-level, interference only
- analytic predictions (as much as possible)
  - **EW** observables: all well known at tree level
  - **doubly-resonant *WW*** production computed in Berthier,Bjørn,Trott 1606.06693
  - for Higgs we want to use **STXS**

LesHouches 2015 1605.0469
LHCHXSWG 1610.0792
Berger et al. 1906.0275

Fit to EWPD from LEP

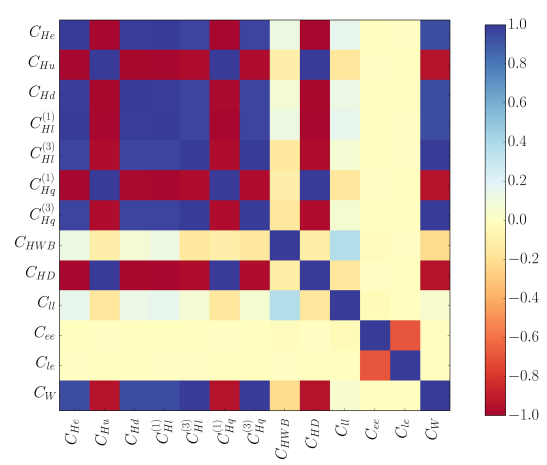
Z-pole + m_W + bhabha + WW (LEP2)

Berthier,(Bjørn),Trott 1508.05060,1606.06693
Brivio,Trott 1701.06424



Fit to EWPD from LEP

Correlation matrix (α scheme)



2 blind directions in EWPD

Grojean,Skiba,Terning 0602154

↕

reparameterization invariance of $2 \to 2$ scattering

Brivio,Trott 1701.06424

WW breaks (weakly) the invariance leaving strong correlations

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)
  - **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

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

lumi

prod xs $i \to h$

decay BR $h \to f$

efficiency

acceptance

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

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)
  - **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

$$n_k = \underbrace{\mathcal{L}_k}_{\text{lumi}} \sum_{i,f} (\underbrace{\sigma}_{\text{prod xs } i \to h} \cdot \underbrace{B}_{\text{decay BR } h \to f})_{if} (\underbrace{\varepsilon}_{\text{efficiency}} \cdot \underbrace{A}_{\text{acceptance}})_{if}$$

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

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)
  - **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

$$n_k = \underbrace{\mathcal{L}_k}_{\text{lumi}} \sum_{i,f} (\underbrace{\sigma}_{\text{prod xs } i \to h} \cdot \underbrace{B}_{\text{decay BR } h \to f})_{if} (\underbrace{\varepsilon}_{\text{efficiency}} \cdot \underbrace{A}_{\text{acceptance}})_{if}$$

Brivio,Corbett,Trott 1906.06949

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

The Higgs width in the SMEFT

leading channels:

$$H \to \bar{f}f$$

$$H \to gg$$

$$H \to \gamma\gamma$$

$$H \to \bar{f}f\gamma$$

$$H \to 4f$$

- $4f, \gamma\gamma, \bar{b}b$ most relevant ones individually
- **all** need to be calculated for $\delta\Gamma_H^{\mathrm{tot}} \to Br$

The Higgs width in the SMEFT

leading channels:

$H \to \bar{f}f$

$H \to gg$

$H \to \gamma\gamma$

$H \to \bar{f}f\gamma$

$H \to 4f$

$$\frac{\Gamma(H \to \bar{f}f)}{\Gamma_{SM}(H \to \bar{f}f)} \simeq 1 + 2\delta g_{Hff}$$

$$\delta g_{Hff} = \underbrace{\bar{C}_{H\Box} - \frac{\bar{C}_{HD}}{4}} - \underbrace{\bar{C}_{Hl}^{(3)} + \frac{\bar{C}'_{ll}}{2}} - \underbrace{\bar{C}_{fH}}$$

Alonso, Jenkins, Manohar, Trott 1312.2014

- renorm. of the H field
- contrib. to μ decay $\to G_F \to v$
- direct $\mathcal{O}_{fH}$ contribution $\left(-\frac{3}{2}\bar{C}_{fH}\right)$
 $+$
 contrib. to $m_f \to y_f$ $\left(+\frac{1}{2}\bar{C}_{fH}\right)$

- $4f, \gamma\gamma, \bar{b}b$ most relevant ones individually
- **all** need to be calculated for $\delta\Gamma_H^{\rm tot} \to Br$

The Higgs width in the SMEFT

leading channels:

$H \to \bar{f} f$

$H \to gg$

$H \to \gamma\gamma$

$H \to \bar{f} f \gamma$

$H \to 4f$

$$\frac{\Gamma(h \to gg)}{\Gamma^{SM}(h \to gg)} \simeq 1 + \frac{16\pi^2}{g_s^2 I^g} \bar{C}_{HG}, \qquad I^g \simeq 0.375$$

Manohar,Wise 0601212

- $4f, \gamma\gamma, \bar{b}b$ most relevant ones individually
- **all** need to be calculated for $\delta\Gamma_H^{\mathrm{tot}} \to Br$

The Higgs width in the SMEFT

leading channels:

$H \to \bar{f} f$

$H \to gg$

$H \to \gamma\gamma$

$H \to \bar{f} f \gamma$

$H \to 4f$

$$\frac{\Gamma(h \to \gamma\gamma)}{\Gamma^{SM}(h \to \gamma\gamma)} \simeq 1 + \frac{16\pi^2}{e^2 I^\gamma} \mathscr{C}_{\gamma\gamma}, \qquad I^\gamma \simeq -1.65$$

$$\mathscr{C}_{\gamma\gamma} = s_\theta^2 \bar{C}_{HW} + c_\theta^2 \bar{C}_{HB} - s_\theta c_\theta \bar{C}_{HWB}$$

Bergström,Hulth Nucl.Phys.B259(1985)137
Manohar,Wise 0601212

- $4f, \gamma\gamma, \bar{b}b$ most relevant ones individually
- **all** need to be calculated for $\delta\Gamma_H^{\rm tot} \to Br$

The Higgs width in the SMEFT

leading channels:

$H \to \bar{f}f$

$H \to gg$

$H \to \gamma\gamma$

$H \to \bar{f}f\gamma$

$H \to 4f$

$$\frac{\Gamma(h\to\gamma\gamma)}{\Gamma^{SM}(h\to\gamma\gamma)} \simeq 1 + \frac{16\pi^2}{e^2 I^\gamma}\mathscr{C}_{\gamma\gamma}, \qquad I^\gamma \simeq -1.65$$

$$\mathscr{C}_{\gamma\gamma} = s_\theta^2\,\bar{C}_{HW} + c_\theta^2\,\bar{C}_{HB} - s_\theta c_\theta\,\bar{C}_{HWB}$$

Bergström,Hulth Nucl.Phys.B259(1985)137
Manohar,Wise 0601212

loop-factor enhancement
in the relative correction:

tree-level SMEFT vs loop SM

- $4f, \gamma\gamma, \bar{b}b$ most relevant ones individually
- **all** need to be calculated for $\delta\Gamma_H^{\rm tot} \to Br$

The Higgs width in the SMEFT

leading channels:

$H \to \bar{f}f$

$H \to gg$

$H \to \gamma\gamma$

$\boxed{H \to \bar{f}f\gamma}$

$\boxed{H \to 4f}$

available as $H \to ZZ^*$, $H \to WW^* \quad \times Br(Z, W)$ relying on narrow width approx. for Z, W.

good in SM but **not sufficient** in the SMEFT!

main reason: tree $\gamma\gamma, Z\gamma$ mediated diagrams

also missing:

- CC - NC interference
- crossed-current interference in ZZ diagrams
- $\delta\Gamma_V$, δm_V^2 corrections for off-shell boson

- $4f, \gamma\gamma, \bar{b}b$ most relevant ones individually
- **all** need to be calculated for $\delta\Gamma_H^{\rm tot} \to Br$

The Higgs width in the SMEFT

leading channels:

$H \to \bar{f}f$

$H \to gg$

$H \to \gamma\gamma$

$H \to \bar{f}f\gamma$

$H \to 4f$

available as $H \to ZZ^*$, $H \to WW^* \quad \times Br(Z,W)$ relying on narrow width approx. for Z, W.

good in SM but **not sufficient** in the SMEFT!

main reason: tree $\gamma\gamma, Z\gamma$ mediated diagrams

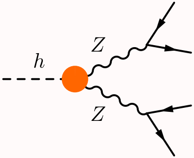
also missing:

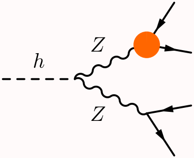
- CC - NC interference
- crossed-current interference in ZZ diagrams
- $\delta\Gamma_V$, δm_V^2 corrections for off-shell boson

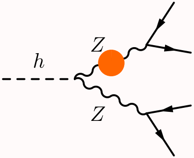
- $4f, \gamma\gamma, \bar{b}b$ most relevant ones individually
- **all** need to be calculated for $\delta\Gamma_H^{\text{tot}} \to Br$

H $\rightarrow$ 4f in the SMEFT

① corrections to SM diagrams







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

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

$\delta g_L, \delta g_R$

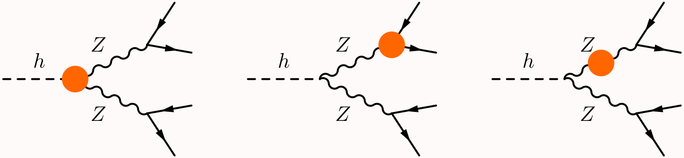
$$\frac{-i m_Z \delta\Gamma_Z + (2m_Z - i\Gamma_Z)\delta m_Z}{p^2 - m_Z^2 + i\Gamma_Z m_Z}$$

$\uparrow$

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

H $\to$ 4f in the SMEFT

① corrections to SM diagrams

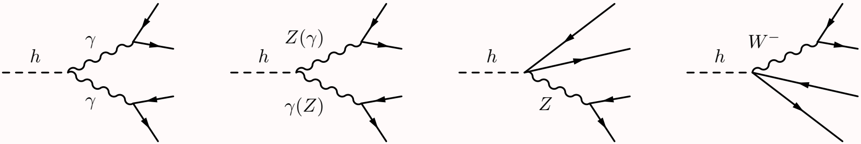


$\propto g_{\mu\nu}$ (SM-like)
$\propto g_{\mu\nu} p{\cdot}q - p_\nu q_\mu$ $(Z_{\mu\nu} Z^{\mu\nu} h)$

$\delta g_L, \delta g_R$

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

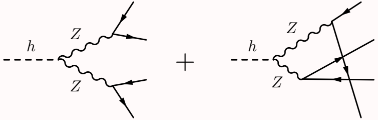
② genuine SMEFT diagrams



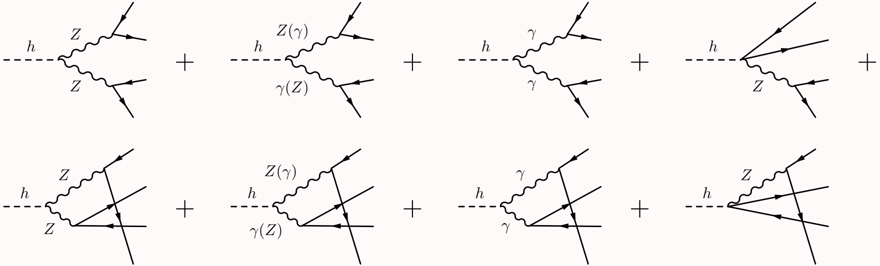
H $\rightarrow$ 4f in the SMEFT - complexity

$h \rightarrow e^+ e^- e^+ e^-$

SM



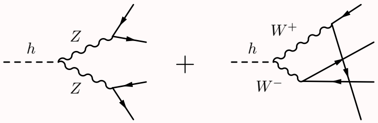
interfering with



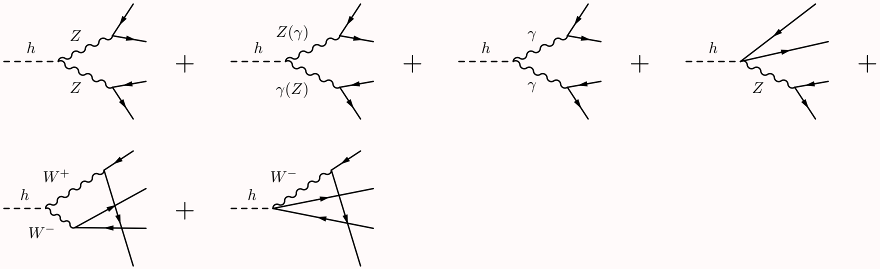
H $\rightarrow$ 4f in the SMEFT - complexity

$h \to \bar{u}\, u\, \bar{d}\, d$

SM

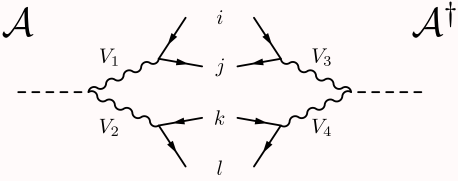


interfering with



$H \to 4f$ - analytic calculation

fully analytical treatment. automated with general decomposition:



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

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

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

$H \to 4f$ analytic - results

Example: $H \to e^+e^-\mu^+\mu^-$ $\quad m_f \equiv 0$, m_W scheme

$$\frac{\delta\Gamma(H\to e^+e^-\mu^+\mu^-)}{\Gamma_{\rm SM}(H\to e^+e^-\mu^+\mu^-)} = \sum_i a_i\,\bar C_i = \sum_i a_i\left(C_i\frac{v^2}{\Lambda^2}\right)$$

	$\bar C_{HW}$	$\bar C_{HB}$	$\bar C_{HWB}$	$\bar C_{H\Box}$	$\bar C_{HD}$	$\bar C_{Hl}^{(1)}$	$\bar C_{Hl}^{(3)}$	$\bar C_{He}$	$\bar C_{Hq}^{(1)}$	$\bar C_{Hq}^{(3)}$	$\bar C_{Hu}$	$\bar C_{Hd}$	$\bar C'_{ll}$
Z	-0.78	-0.22	0.30	2	0.17	4.38	-1.62	-3.52					3.
A	1.04	-1.08	-0.68										
E						-2.23	-2.23	1.80					
G			-0.38		0.06	0.15	1.14	0.15	-0.39	-1.34	-0.20	0.15	-0.83
tot	0.26	-1.30	-0.76	2.	0.23	2.30	-2.71	-1.58	-0.39	-1.34	-0.20	0.15	2.17

Z	corrections to SM diagram
A	γ diagrams
E	contact diagrams ($HZee$)
G	$\delta\Gamma_Z^{\rm tot}/\Gamma_{Z,SM}$ on + off-shell Z

H → 4f analytic - results

Example: $H \to e^+e^-\mu^+\mu^-$ $\quad m_f \equiv 0$, m_W scheme

$$\frac{\delta\Gamma(H\to e^+e^-\mu^+\mu^-)}{\Gamma_{\rm SM}(H\to e^+e^-\mu^+\mu^-)} = \sum_i a_i \bar{C}_i = \sum_i a_i \left(C_i \frac{v^2}{\Lambda^2}\right)$$

	$\bar{C}_{HW}$	$\bar{C}_{HB}$	$\bar{C}_{HWB}$	$\bar{C}_{H\Box}$	$\bar{C}_{HD}$	$\bar{C}_{Hl}^{(1)}$	$\bar{C}_{Hl}^{(3)}$	$\bar{C}_{He}$	$\bar{C}_{Hq}^{(1)}$	$\bar{C}_{Hq}^{(3)}$	$\bar{C}_{Hu}$	$\bar{C}_{Hd}$	$\bar{C}'_{ll}$
Z	-0.78	-0.22	0.30	2	0.17	4.38	-1.62	-3.52					3.
A	1.04	-1.08	-0.68										
E						-2.23	-2.23	1.80					
G			-0.38		0.06	0.15	1.14	0.15	-0.39	-1.34	-0.20	0.15	-0.83
tot	0.26	-1.30	-0.76	2.	0.23	2.30	-2.71	-1.58	-0.39	-1.34	-0.20	0.15	2.17

Z	corrections to SM diagram
A	γ diagrams
E	contact diagrams ($HZee$)
G	$\delta\Gamma_Z^{\rm tot}/\Gamma_{Z,SM}$ on + off-shell Z

Cross-check: MadGraph with SMEFTsim

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 ~~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

`ilaria.brivio@nbi.ku.dk, yunjiang@nbi.ku.dk, michael.trott@cern.ch`

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

Pre-exported UFO files (include restriction cards)

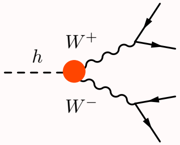
	Set A		Set B	
	α scheme	m_W scheme	α scheme	m_W scheme
Flavor general SMEFT	SMEFTsim_A_general_alphaScheme_UFO.tar.gz	SMEFTsim_A_general_MwScheme_UFO.tar.gz	SMEFT_alpha_UFO.zip	SMEFT_mW_UFO.zip
MFV SMEFT	SMEFTsim_A_MFV_alphaScheme_UFO.tar.gz	SMEFTsim_A_MFV_MwScheme_UFO.tar.gz	SMEFT_alpha_MFV_UFO.zip	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: MadGraph with SMEFTsim

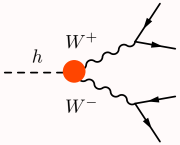
e.g. $h \to e^+ \mu^- \bar{\nu}_\mu \nu_e$

contribution from $C_{HW}(H^\dagger H)(W^a_{\mu\nu} W^{a\mu\nu})$



Cross-check: MadGraph with SMEFTsim

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



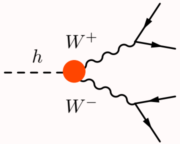
contribution from $C_{HW}(H^\dagger H)(W^a_{\mu\nu} W^{a\mu\nu})$

in `MadGraph5` + `SMEFTsim`, with fixed `cHW`:

- `generate h > e+ mu- vm~ ve NP=0` → value of Γ_{SM} (tree)

Cross-check: MadGraph with SMEFTsim

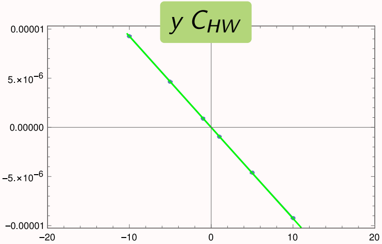
e.g. $h \to e^+\mu^-\bar{\nu}_\mu\nu_e$



contribution from $C_{HW}(H^\dagger H)(W^a_{\mu\nu}W^{a\mu\nu})$

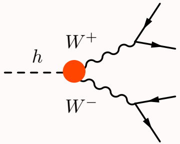
in `MadGraph5` + `SMEFTsim`, with fixed `cHW`:

- `generate h > e+ mu- vm~ ve NP=0` $\to$ value of Γ_{SM} (tree)
- `generate h > e+ mu- vm~ ve NP^2==1` $\to$ value of $\delta\Gamma$ from $\mathcal{A}_{SM}\mathcal{A}_6^*$



Cross-check: MadGraph with SMEFTsim

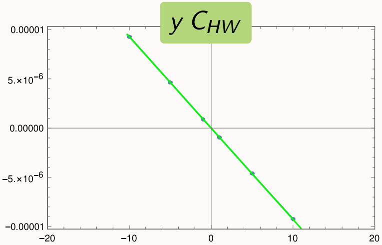
e.g. $h \to e^+ \mu^- \bar{\nu}_\mu \nu_e$

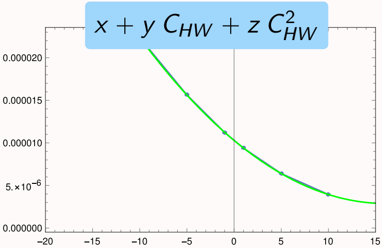


contribution from $C_{HW}(H^\dagger H)(W^a_{\mu\nu} W^{a\mu\nu})$

in `MadGraph5` + `SMEFTsim`, with fixed `cHW`:

- `generate h > e+ mu- vm~ ve NP=0` $\to$ value of Γ_{SM} (tree)
- `generate h > e+ mu- vm~ ve NP^2==1` $\to$ value of $\delta\Gamma$ from $\mathcal{A}_{SM}\mathcal{A}_6^*$
- `generate h > e+ mu- vm~ ve` $\to$ value of $(\Gamma_{SM} + \delta\Gamma)$ from $|\mathcal{A}_{SM} + \mathcal{A}_6|^2$





Cross-check: MadGraph with SMEFTsim

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

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

	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

Cross-check: MadGraph with SMEFTsim

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

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

two SMEFTsim columns are consistent

	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

Cross-check: MadGraph with SMEFTsim

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

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

validated with theory

two SMEFTsim columns are consistent

	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

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.

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)
- $gg \to t\bar{t}h$
- $qq \to thj$

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)
- $gg \to t\bar{t}h$
- $qq \to thj$

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

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)
- $gg \to t\bar{t}h$
- $qq \to thj$

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

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]

Top quark sector

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

predictions: SMEFT@NLO

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

22 **relevant operators**

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

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

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

$t\bar{t}$

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

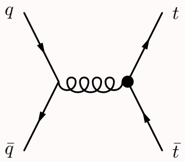
$$\mathcal{Q}^1_{Qu} = (\bar{Q}\gamma_\mu Q)(\bar{u}\gamma^\mu u) \qquad \mathcal{Q}^8_{Qu} = (\bar{Q}\gamma_\mu T^A Q)(\bar{u}\gamma^\mu T^A u)$$
$$\mathcal{Q}^1_{Qd} = (\bar{Q}\gamma_\mu Q)(\bar{d}\gamma^\mu d) \qquad \mathcal{Q}^8_{Qd} = (\bar{Q}\gamma_\mu T^A Q)(\bar{d}\gamma^\mu T^A d)$$
$$\mathcal{Q}^1_{tu}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

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

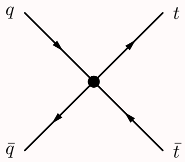
$$\mathcal{Q}^{3,8}_{Qq} = (\bar{Q}\gamma_\mu\sigma^k T^A Q)(\bar{q}\gamma^\mu\sigma^k T^A q)$$
$$\mathcal{Q}^{3,1}_{Qq} = (\bar{Q}\gamma_\mu\sigma^k T^A Q)(\bar{q}\gamma^\mu\sigma^k T^A q)$$

A typical issue: flat directions

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



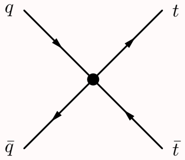
C_{tG}



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)

A typical issue: flat directions

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



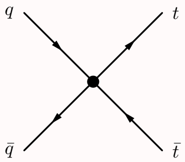
<u>notation</u>:

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



<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

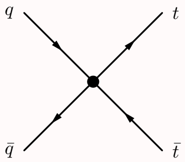
$$\Delta\sigma^{int}_{t\bar{t}} \propto \left[C^8_{LL} + C^8_{RR} + C^8_{LR} + C^8_{RL} \right] \left(1 + \beta_t^2 c_t^2 + \frac{2m_t^2}{s}\right) + \left[C^8_{LL} + C^8_{RR} - C^8_{LR} - C^8_{RL} \right] 2\beta_t c_t$$

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

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



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

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

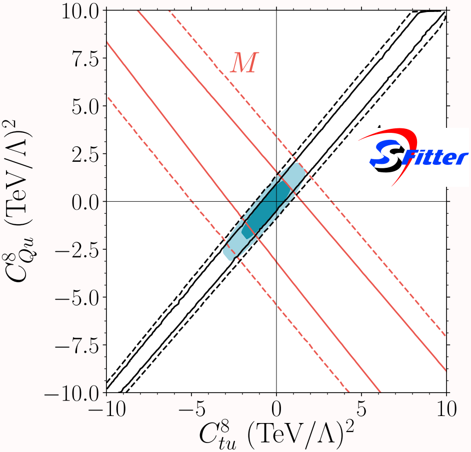
LO, interference only can *never* distinguish $LL \leftrightarrow RR$ or $LR \leftrightarrow RL$

$\to$ breaking: NLO QCD
$(C_i C_j)$ terms
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:

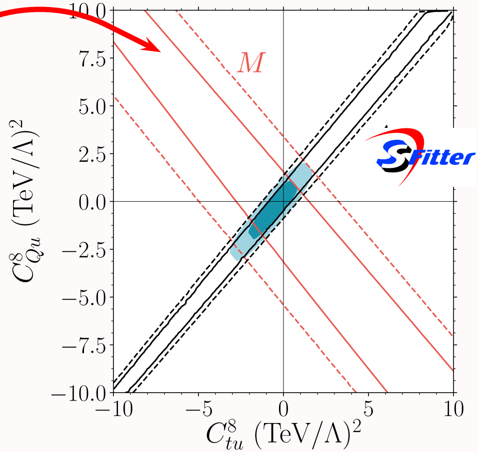
$\ln L_{\max} - \ln L =$ 1/2 ———
2 - - - - -

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

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

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

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



likelihood contours:

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

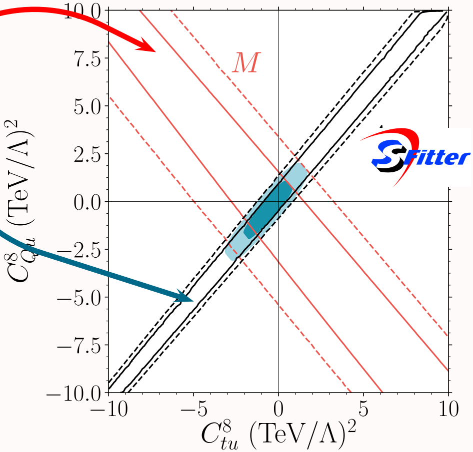
($\sim \Delta\chi^2 = 1, 4$ in Gaussian limit)

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

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

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

charge asymmetry
A_C



likelihood contours:

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

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

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

Singlet vs triplet $SU(2)$ contractions:

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

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

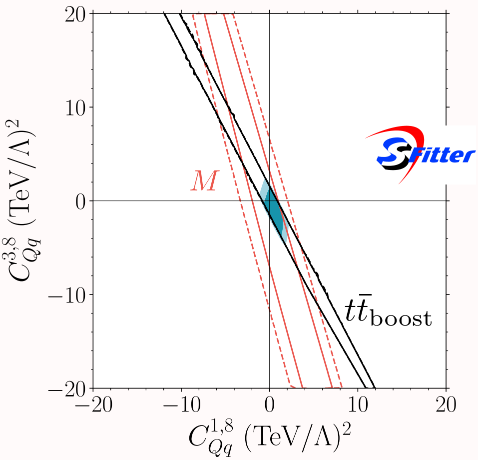
u,d identical at parton level

only difference: PDF $\leftrightarrow x$

$r(x) = [u\bar{u}]/[d\bar{d}]$

↳ $(r+1)C^{18}_{Qq} + (r-1)C^{38}_{Qq}$ constrained

$(r-1)C^{18}_{Qq} - (r+1)C^{38}_{Qq}$ blind



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

Singlet vs triplet $SU(2)$ contractions:

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

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

u,d identical at parton level

only difference: PDF $\leftrightarrow x$

$r(x) = [u\bar{u}]/[d\bar{d}]$

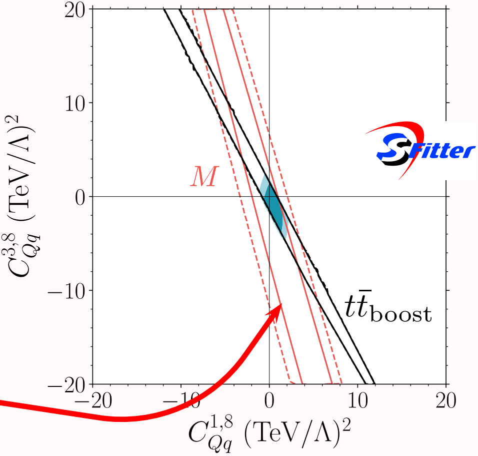
$\hookrightarrow$ $(r+1)C^{18}_{Qq} + (r-1)C^{38}_{Qq}$ constrained

$(r-1)C^{18}_{Qq} - (r+1)C^{38}_{Qq}$ blind

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

bulk kin. region

$r \approx 2$



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

Singlet vs triplet $SU(2)$ contractions:

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

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

u,d identical at parton level

only difference: PDF $\leftrightarrow x$

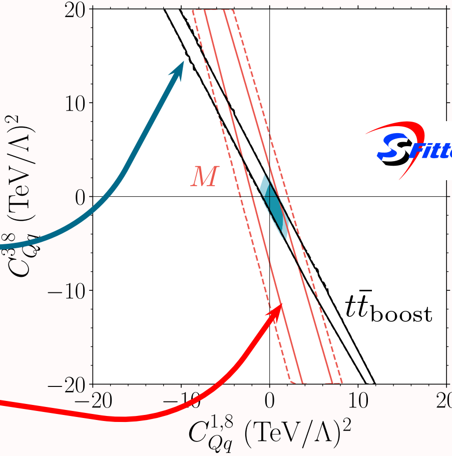
$r(x) = [u\bar{u}]/[d\bar{d}]$

$\hookrightarrow (r+1)C^{18}_{Qq} + (r-1)C^{38}_{Qq}$ constrained

$(r-1)C^{18}_{Qq} - (r+1)C^{38}_{Qq}$ blind

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
$r \approx 2$



$u\bar{u}$ 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

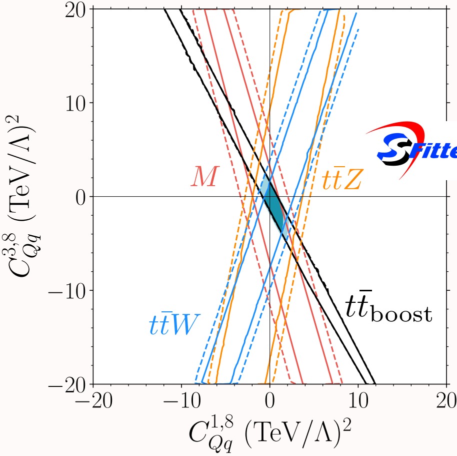
only difference: PDF $\leftrightarrow x$

$r(x) = [u\bar{u}]/[d\bar{d}]$

$\hookrightarrow$ $(r+1)C_{Qq}^{18} + (r-1)C_{Qq}^{38}$ constrained

$(r-1)C_{Qq}^{18} - (r+1)C_{Qq}^{38}$ blind

further breaking:
including total rates of
$t\bar{t}W$, $t\bar{t}Z$



Impact of quadratic SMEFT contributions

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

Impact of quadratic SMEFT contributions

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

Impact of quadratic SMEFT contributions

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

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

  $\rightarrow$ 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

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

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

  $\rightarrow$ 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:

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

- 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

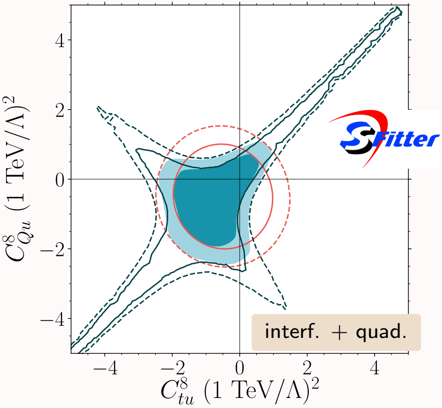
$$\begin{aligned}\Delta\sigma_{t\bar{t}}^{quad} \propto & \left[(C_{LL}^8)^2 \boxed{+(C_{RR}^8)^2} + (C_{LR}^8)^2 \boxed{+(C_{RL}^8)^2} + \frac{9}{2}\left((C_{LL}^1)^2 + (C_{RR}^1)^2 + (C_{LR}^1)^2 + (C_{RL}^1)^2\right)\right]\left(1+\beta_t^2 c_t^2\right)\\ & + \left[(C_{LL}^8)^2 \boxed{+(C_{RR}^8)^2}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

Impact of quadratic SMEFT contributions

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

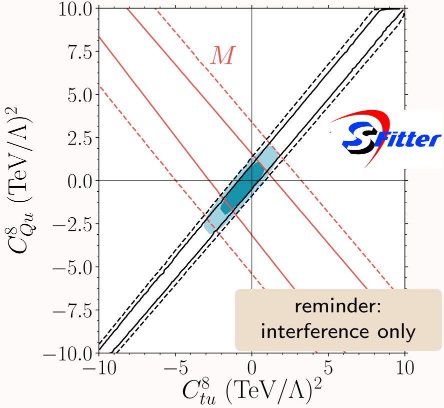
$$+ \Big[(C^8_{LL})^2 + (C^8_{RR})^2 - (C^8_{LR})^2 - (C^8_{RL})^2 + \frac{9}{2}\Big((C^1_{LL})^2 + (C^1_{RR})^2 - (C^1_{LR})^2 - (C^1_{RL})^2\Big)\Big] \boxed{2\beta_t c_t}$$

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



Impact of quadratic SMEFT contributions

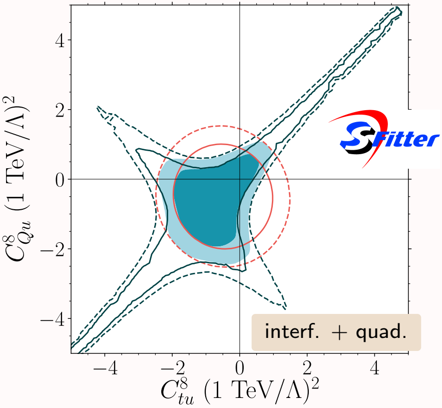
$$
\begin{aligned}
\Delta\sigma^{quad}_{t\bar{t}} \propto & \left[(C^8_{LL})^2 + (C^8_{RR})^2 + (C^8_{LR})^2 + (C^8_{RL})^2 + \frac{9}{2}\left((C^1_{LL})^2 + (C^1_{RR})^2 + (C^1_{LR})^2 + (C^1_{RL})^2 \right) \right] \boxed{(1+\beta_t^2 c_t^2)} \\
& + \left[(C^8_{LL})^2 + (C^8_{RR})^2 - (C^8_{LR})^2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



Impact of quadratic SMEFT contributions

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

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



Impact of quadratic SMEFT contributions

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

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

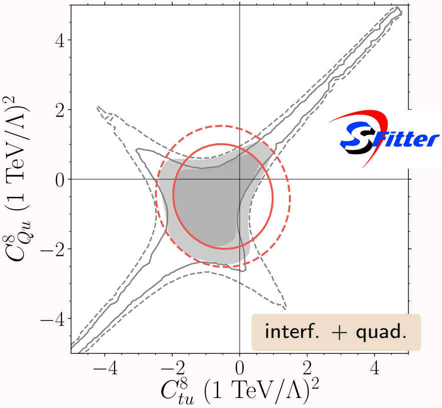
typical measurements $\sim \sum_i + C_i^2$
$\Rightarrow$ **radial constraint**

$\downarrow$

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

$\downarrow$

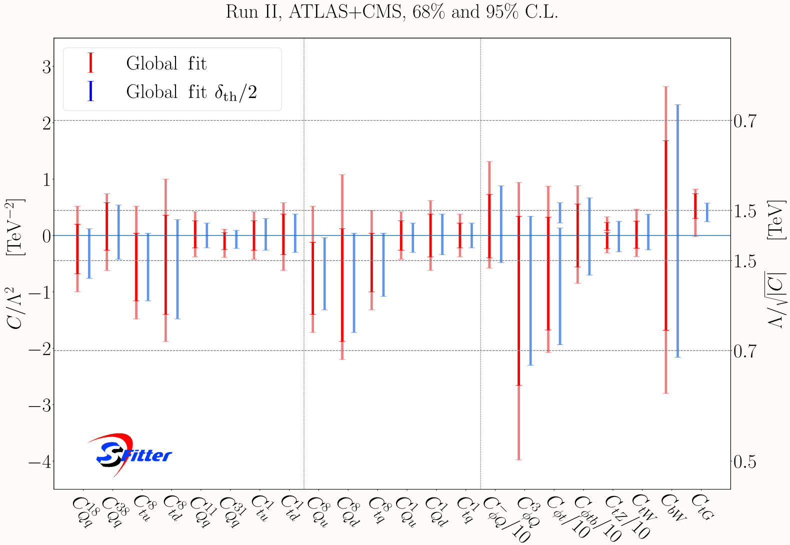
angular flat directions remain



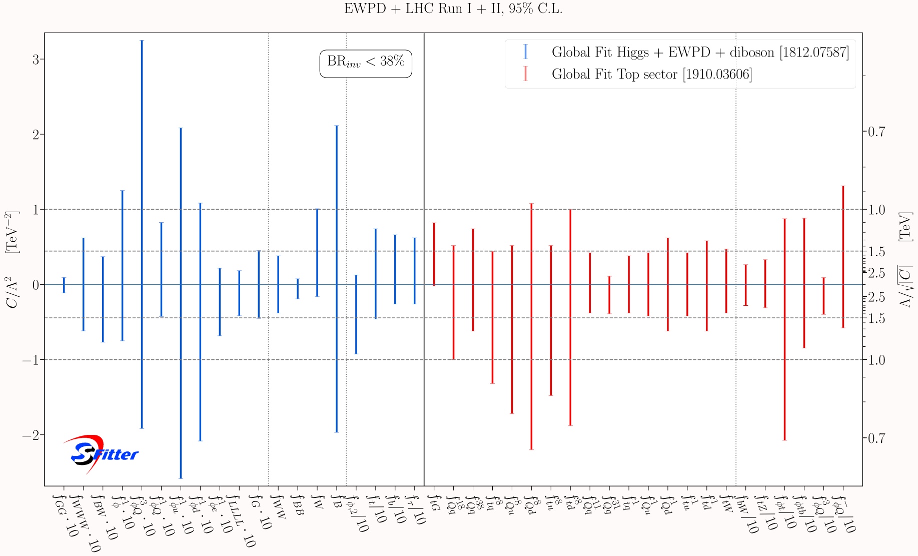
Global fit to top processes: results

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

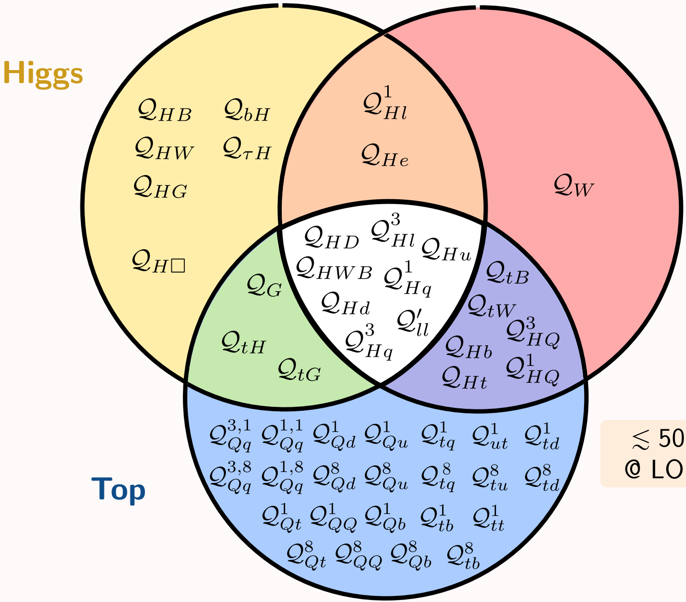
Brivio,Bruggisser,Maltoni,Moutafis,Plehn, Vryonidou,Westhoff,Zhang 1910.03606



Top fit vs EW+Higgs fit results



Top+EW+Higgs: next step



$\lesssim$ 50 parameters
@ LO interference

What next?

- Indirect searches of BSM physics @LHC will become more and more important in the next runs.

What next?

- 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!

What next?

- 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!
- we need precision – **EFT effects** in PDFs, acceptances, efficiencies ...
  – **NLO** SMEFT calculations
  – optimizing exp. analyses?

What next?

- 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!
- we need precision
  - **EFT effects** in PDFs, acceptances, efficiencies ...
  - **NLO** SMEFT calculations
  - optimizing exp. analyses?
- we need computational tools
  - signal **generation** strategies for exp.
  - exploit analytic results: **reweighting** tools

What next?

- 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!
- we need precision
  - **EFT effects** in PDFs, acceptances, efficiencies ...
  - **NLO** SMEFT calculations
  - optimizing exp. analyses?
- we need computational tools
  - signal **generation** strategies for exp.
  - exploit analytic results: **reweighting** tools
- we need scalable fitting technology
  - go beyond projection onto C_i
  - machine learning?
  - information geometry?

What next?

- 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!
- we need precision
  - **EFT effects** in PDFs, acceptances, efficiencies ...
  - **NLO** SMEFT calculations
  - optimizing exp. analyses?
- we need computational tools
  - signal **generation** strategies for exp.
  - exploit analytic results: **reweighting** tools
- we need scalable fitting technology
  - go beyond projection onto C_i
  - machine learning?
  - information geometry?
- we need good theory understanding

What next?

- 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!
- we need precision
  - **EFT effects** in PDFs, acceptances, efficiencies ...
  - **NLO** SMEFT calculations
  - optimizing exp. analyses?
- we need computational tools
  - signal **generation** strategies for exp.
  - exploit analytic results: **reweighting** tools
- we need scalable fitting technology
  - go beyond projection onto C_i
  - machine learning?
  - information geometry?
- we need good theory understanding

What next?

- 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!

- we need precision
  – **EFT effects** in PDFs, acceptances, efficiencies ...
  – **NLO** SMEFT calculations
  – optimizing exp. analyses?

- we need computational tools
  – signal **generation**
  – exploit analytic res ools

- we need scalable fitting technology
  – go beyond
  – machine le
  – informatio

- we need good theory understanding

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