SMEFT studies of LHC data: status and perspective

Ilaria Brivio

Institut für Theoretische Physik,
Universität Heidelberg

What is SMEFT?

SMEFT = **S**tandard **M**odel **E**ffective **F**ield **T**heory

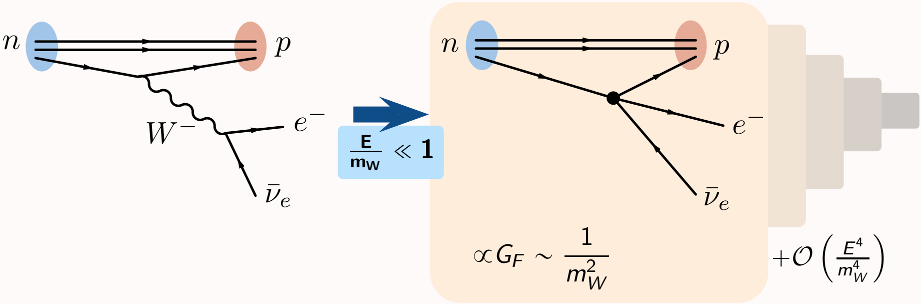
What is SMEFT?

SMEFT = **S**tandard **M**odel **E**ffective **F**ield **T**heory

What is an EFT?

a field theory that approximates another one in a specific kinematic/parameters limit

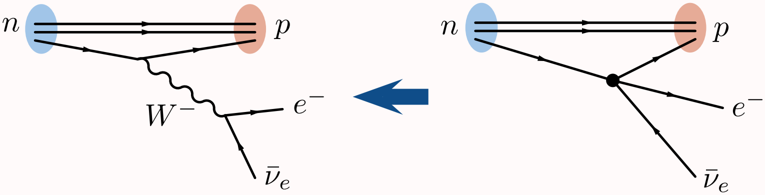
Example: Fermi interactions



EFT = QFT valid in a regime $\mathbf{E/m_W} \ll \mathbf{1}$ ⟷ Taylor expansion in $\mathbf{E/m_W}$

- **hierarchy** of physical effects determined by low-E fields and symmetries
- **details** of underlying physics are irrelevant

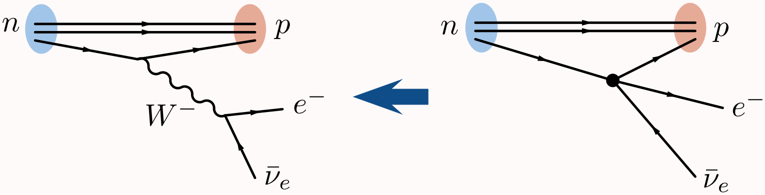
Example: Fermi interactions



the EFT can also be formulated from the bottom up. One specifies:

fields & symmetries at the E of the measurement + **power counting**

Example: Fermi interactions



the EFT can also be formulated from the bottom up. One specifies:

fields & symmetries at the E of the measurement + **power counting**

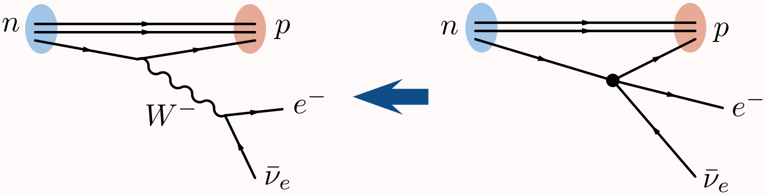
$\Rightarrow \quad \mathscr{L}_{EFT} = \sum_i C_i \mathcal{O}_i$

C_i = Wilson coefficients:
free, dimensionful parameters

encode the (unknown) **UV** details

$\mathcal{O}_i$ = operators
interactions terms classified in expansion orders
encode the **IR** physics

Example: Fermi interactions



the EFT can also be formulated **from the bottom up**. One specifies:

fields & symmetries at the E of the measurement + **power counting**

$\Rightarrow \quad \mathscr{L}_{EFT} = \sum_i C_i \mathcal{O}_i$

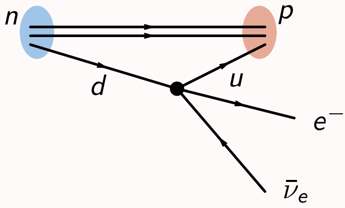
knowledge of the SM is **not required**.

the EFT can match **any model** leading to β decays.

Example: Fermi interactions, from the bottom up

1933 4-fermion interaction made of known fields $(+\nu)$ and QED-invariant

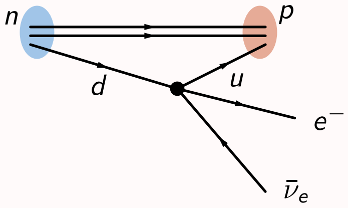
$G_F(\bar{p}\gamma_\mu n)(\bar{e}\gamma_\mu \nu)$



Example: Fermi interactions, from the bottom up

1933 4-fermion interaction made of known fields $(+\nu)$ and QED-invariant

$G_F(\bar{p}\gamma_\mu n)(\bar{e}\gamma_\mu \nu)$



- energy spectra $\Rightarrow$ $G_F \simeq (290\,\mathrm{GeV})^{-2}$ $\simeq v^{-2}$ $\rightarrow$ scale of underlying physics!
- all β-decays have the same G_F
- angular distributions $\Rightarrow$ the currents have *left-handed* chirality

$\rightarrow$ very strong hints at the nature of EW interactions

SMEFT is the new Fermi theory

Standard **M**odel **E**ffective **F**ield **T**heory:
The EFT constructed with **Standard Model** field & symmetries

→ expansion in **canonical dimensions** d:

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

$$\mathcal{L}_d = \sum_i C_i \mathcal{O}_i^{(d)}$$

Introducing explicitly a new-physics scale parameter Λ, all C_i are dimensionless.
→ Taylor series in v/Λ or E/Λ (multi-scale!)

At each order, $\mathcal{O}_i^{(d)}$ form a complete, non-redundant **basis**

First relevant order: $\mathcal{L}_6$ → up to 2499 parameters

d=6: 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}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde W B}$	$\varphi^\dagger \tau^I \varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

d=6: 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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$		

SMEFT is the new Fermi theory

Standard **M**odel **E**ffective **F**ield **T**heory:
The EFT constructed with **Standard Model** field & symmetries

→ expansion in **canonical dimensions** d:

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

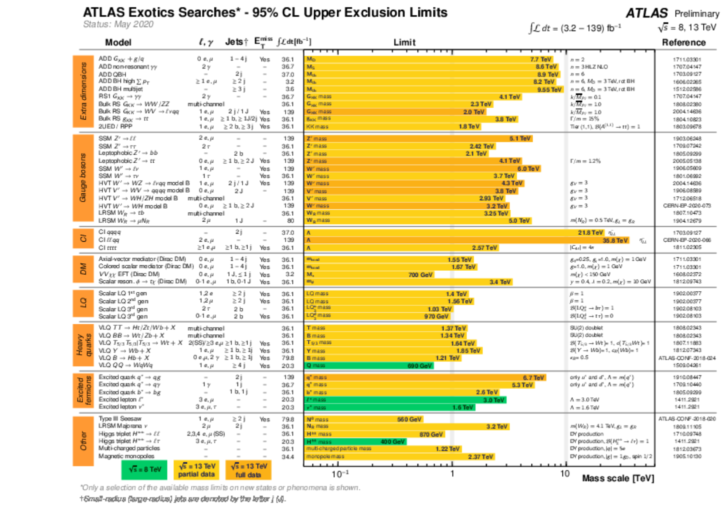
$$\mathcal{L}_d = \sum_i C_i \mathcal{O}_i^{(d)}$$

SMEFT describes ∼ **any beyond-SM physics living at $\Lambda \gg v$**
(nearly decoupled)

measure C_i to extract information about BSM!

A worthy challenge!

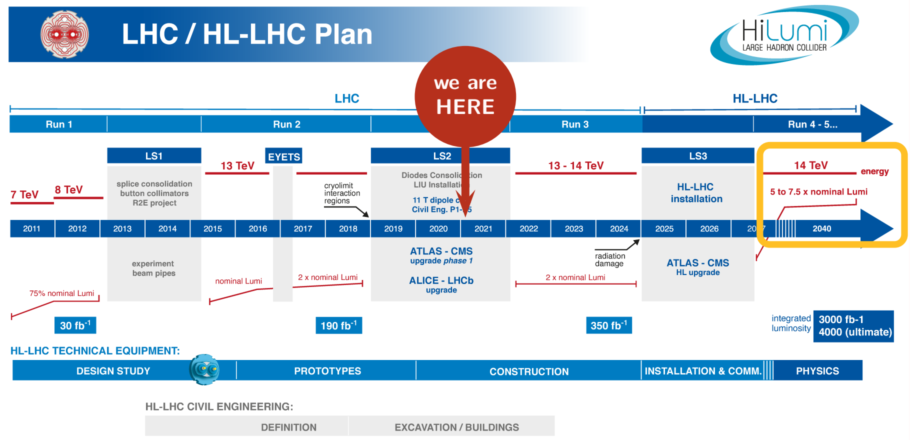
new physics seems indeed nearly decoupled



A worthy challenge!

new physics seems indeed nearly decoupled

collider physics is entering a precision era



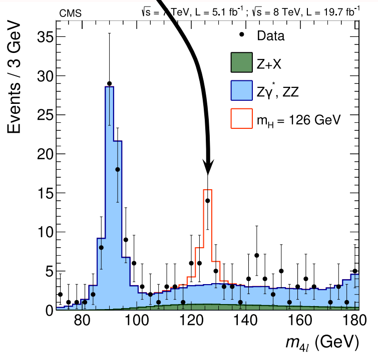
A worthy challenge!

new physics seems indeed nearly decoupled

collider physics is entering a precision era

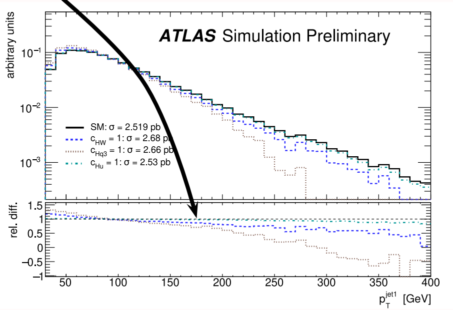
indirect searches
more and more competitive with direct ones

direct



CMS-HIG-13-002

indirect



ATL-PHYS-PUB-2019-042

A worthy challenge!

new physics seems indeed nearly decoupled

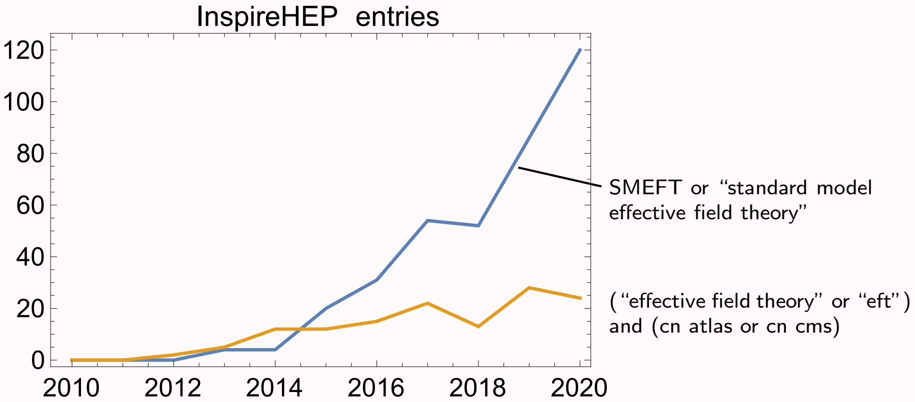
collider physics is entering a precision era

indirect searches
more and more competitive with direct ones

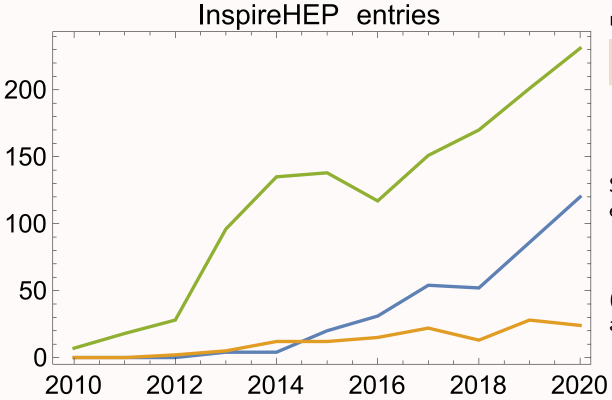
SMEFT-based searches at the LHC are crucial

+ a proper QFT:
  renormalizable order by order, well-defined radiative corrections and RGE
+ minimal commitment to a specific UV
+ systematically includes all BSM effects, compatible with assumptions
+ universal language for data interpretation: can connect to other experiments

A booming field



A booming field



refersto:recid:866649

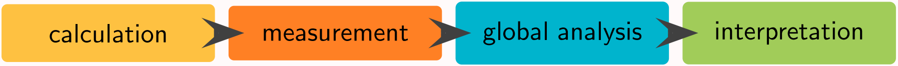
Grzadkowski,Iskrzynski,Misiak,Rosiek
1008.4884

SMEFT or "standard model effective field theory"

("effective field theory" or "eft") and (cn atlas or cn cms)

+ dedicated seminar series, conferences, working groups. . .

SMEFT @ LHC: status



SMEFT @ LHC: status

calculation ➤ measurement ➤ global analysis ➤ interpretation

- ☑ # parameters known for all orders

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

SMEFT @ LHC: status

calculation ➤ measurement ➤ global analysis ➤ interpretation

- ☑ # parameters known for all orders
- ☑ complete bases up to $d = 9$

5: Weinberg PRL43(1979)1566
6: Buchmller,Wyler Nucl.Phys.B268(1986)621, Grzadkowski et al 1008.4884
7: Lehman 1410.4193, Henning,Lu,Melia,Murayama 1512.0343
8: Li,Ren,Shu,Xiao,Yu,Zheng 2005.00008, Murphy 2005.00059
9: Li,Ren,Xiao,Yu,Zheng 2007.07899, Liao,Ma 2007.08125

SMEFT @ LHC: status

calculation ➤ measurement ➤ global analysis ➤ interpretation

- ☑ # parameters known for all orders
- ☑ complete bases up to $d = 9$
- ☑ interplay with helicity amplitudes

Shadmi,Weiss 1809.09644
Henning,Melia 1901.06747,1902.06754,1902.06747
Ma,Shu,Xiao 1902.06752
Aoude,Machado 1905.11433
Durieux,Kitahara,(Machado),Shadmi,Weiss 1909.10551,2008.09652
Durieux,Machado 1912.08827
Craig,Jiang,Li,Sutherland 2001.00017

SMEFT @ LHC: status

calculation ➤ measurement ➤ global analysis ➤ interpretation

- ☑ # parameters known for all orders
- ☑ complete bases up to $d = 9$
- ☑ interplay with helicity amplitudes
- ☑ geometric formulation

Alonso,Jenkins,Manohar 1511.00724,1605.03602
Dedes,Materkowska,Paraskevas,Rosiek,Suxho 1704.03888
Helset,Paraskevas,Trott 1803.08001
Corbett,Helset,Trott 1909.08470
(Hays),Helset,Martin,Trott 2001.01453,2007.00565

SMEFT @ LHC: status

calculation ➤ measurement ➤ global analysis ➤ interpretation

- ☑ # parameters known for all orders
- ☑ complete bases up to $d = 9$
- ☑ interplay with helicity amplitudes
- ☑ geometric formulation
- ☑ RGE up to $d = 6$

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

SMEFT @ LHC: status

calculation ➤ measurement ➤ global analysis ➤ interpretation

- ☑ # parameters known for all orders
- ☑ complete bases up to $d = 9$
- ☑ interplay with helicity amplitudes
- ☑ geometric formulation
- ☑ RGE up to $d = 6$
- ☑ flavor structure

Brivio,Jiang,Trott 1709.06492
Bordone,Catà,Feldmann 1910.02641
Faroughy,Isidori,Wilsch,Yamamoto 2005.05366
Brivio 2012.11343

SMEFT @ LHC: status

calculation ➤ measurement ➤ global analysis ➤ interpretation

- ☑ # parameters known for all orders
- ☑ complete bases up to $d = 9$
- ☑ interplay with helicity amplitudes
- ☑ geometric formulation
- ☑ RGE up to $d = 6$
- ☑ flavor structure
- ☑ NLO SMEFT

Pruna,Signer 1408.3565
Hartmann,(Shepherd),Trott 1505.02646,1507.03568,1611.09879
Ghezzi,Gomez-Ambrosio,Passarino,Uccirati 1505.03706
(Cullen,Gauld),Pecjak,Scott 1512.02508,1904.06358,2007.15238
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
+ several NLO QCD

SMEFT @ LHC: status

calculation ➤ measurement ➤ global analysis ➤ interpretation

- ☑ # parameters known for all orders
- ☑ complete bases up to $d = 9$
- ☑ interplay with helicity amplitudes
- ☑ geometric formulation
- ☑ RGE up to $d = 6$
- ☑ flavor structure
- ☑ NLO SMEFT
- ☑ connection to WET/LEFT

Jenkins,Manohar,Stoffer 1709.04486
Dekens,Stoffer 1908.05295

SMEFT @ LHC: status

calculation ➤ measurement ➤ global analysis ➤ interpretation

☑ automation

- basis handling — Falkowski et al 1508.05895 Aebischer et al 1712.05298 Criado 1901.03501
- matching & running — (Celis),Fuentes-Martin,(Ruiz-Femenia),Vicente,Virto 1704.04504,2010.16341 Aebischer,Kumar,Straub 1804.05033
- Feynman rules — Dedes,(Materkowska),Paraskevas,Rosiek,Suxho,(Trifyllis) 1704.03888,1904.03204, Brivio,Jiang,Trott 1907.04692 Corbett 2010.15852
- LO predictions — Alloul,Fuks,Sanz 1310.5150 Durieux,Mattelaer 1802.07237 Brivio,(Jiang,Trott) 1907.04692,2012.11343
- NLO QCD predictions — Degrande,Durieux,Maltoni,Mimasu,Vryonidou 2008.11743

SMEFT predictions in practice: SMEFTsim

SMEFTsim

a set of models that enable
LO Monte Carlo simulations
with the complete Warsaw basis

Brivio, Jiang, Trott 1709.06492
Brivio 2012.11343
SMEFTsim.github.io

Automates all the steps required:

1. bosonic: make kinetic terms canonical, define vev. properly
   fermionic: fix flavor structure
2. choose input parameters
3. Feynman diagram calculation (MC). subtlety: propagator corrections

Example: $h \to e^+ e^- \mu^+ \mu^-$ at tree-level, $\mathcal{O}(\Lambda^{-2})$ = SM-$\mathcal{L}_6$ interference

analytic result derived in Brivio, Corbett, Trott 1906.06949

SMEFT flavor structure

also: Faroughy,Isidori,Wilsch,Yamamoto 2005.05366

w/o flavor assumptions $\mathcal{L}_6$ has 2499 free parameters

$$O_{He,pr} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r) \quad \text{has } \mathbf{9} \text{ independent par.}$$

$$O_{ledq,prst} = (\bar{l}^i_p e_r)(\bar{d}_s q^i_t) \quad \text{has } \mathbf{162}$$

freedom can be reduced imposing a **symmetry**. Maximal:

$$U(3)^5 \equiv U(3)_q \times U(3)_u \times U(3)_d \times U(3)_l \times U(3)_e$$

→ only invariant contractions allowed
→ Yukawa couplings typically promoted to **spurions**:

$$Y_u \mapsto \Omega_u Y_u \Omega_q^\dagger, \quad Y_d \mapsto \Omega_d Y_d \Omega_q^\dagger, \quad Y_e \mapsto \Omega_e Y_e \Omega_l^\dagger$$

$$O_{He,pr}\,\delta_{pr} \quad \text{has } \mathbf{1} \text{ independent par.}$$

$$O_{ledq,prst}\,(Y_e^\dagger)_{pr}(Y_d)_{st} \quad \text{has } \mathbf{2}$$

$\mathcal{L}_6 + U(3)^5$ has **85** free parameters

SMEFT flavor structure

also: Faroughy,Isidori,Wilsch,Yamamoto 2005.05366

several options implemented:

`general`	free indices	2499
`U35`	$U(3)_q \times U(3)_u \times U(3)_d \times U(3)_l \times U(3)_e$	85
`MFV`	$U(3)_q \times U(3)_u \times U(3)_d \times U(3)_l \times U(3)_e$ $+$leading spurion insertions $\propto Y_u Y_u^\dagger, Y_d Y_d^\dagger, \dots$	120
`topU31`	$U(2)_q \times U(2)_u \times U(2)_d \times U(3)_l \times U(3)_e$	182
`top`	$U(2)_q \times U(2)_u \times U(2)_d \times U(1)^3_{l+e}$	275

Input parameters

SM

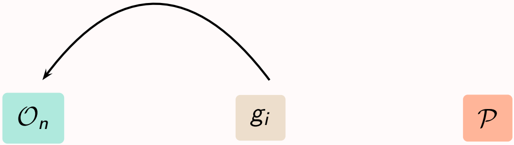
input obs.	$\mathcal{L}$ param.	predicted obs.
$\mathcal{O}_n$	g_i	$\mathcal{P}$
α_s, d_N, $m_Z, \alpha_{\rm em}$, G_F, m_h, m_f, meson decay/osc	g_s, θ_{QCD}, g_1, g_w, v, λ, y_f, $\theta_{1,2,3}, \delta$ CKM	m_W, Γ_h, Γ_Z, $\sigma(pp \to X)$ ...

Input parameters

SM

$G_F = \frac{1}{\sqrt{2}v^2}$

$\mathcal{O}_n = F_n^{SM}(g)$

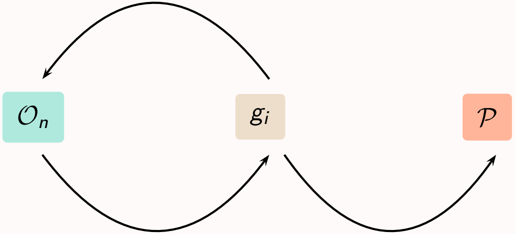


Input parameters

SM

$G_F = \frac{1}{\sqrt{2}v^2}$

$\mathcal{O}_n = F_n^{SM}(g)$



$g_i = K_i^{SM}(\mathcal{O})$

$\mathcal{P} = P^{SM}(g) = P^{SM}(K^{SM}(\mathcal{O}))$

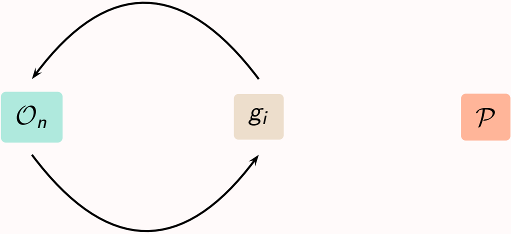
$v = \frac{1}{2^{1/4}\sqrt{G_F}}$

Input parameters

SMEFT

$$G_F = \frac{1}{\sqrt{2}v^2} + \frac{1}{\sqrt{2}\Lambda^2}\left(2C_{Hl}^{(3)} - C'_{ll}\right) + \dots$$

$$\mathcal{O}_n = F_n^{SM}(g) + \frac{1}{\Lambda^2}F_n^{(2)}(g, C) + \dots$$

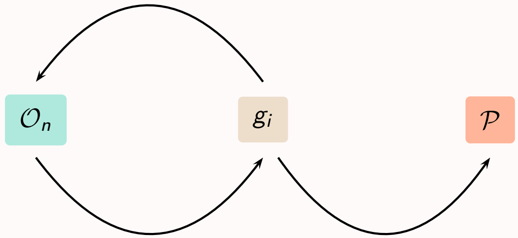


$$g_i = K_i^{SM}(\mathcal{O}) + \frac{1}{\Lambda^2}K_i^{(2)}(\mathcal{O}, C) + \dots \quad , \qquad K_i^{(2)} = -\left[\frac{\partial F^{SM}}{\partial g}\right]_{in}^{-1} F_n^{(2)}$$

$$v = \frac{1}{2^{1/4}\sqrt{G_F}} + \frac{1}{2^{3/4}G_F^{3/2}}\frac{2C_{Hl}^{(3)} - C'_{ll}}{2\Lambda^2} + \dots$$

Input parameters

SMEFT



$$\mathcal{P} = P^{SM}(g) + \frac{1}{\Lambda^2}\left[P^{(2)}(g) - \frac{\partial P^{SM}}{\partial g_i}\left[\frac{\partial F_n^{SM}}{\partial g_i}\right]^{-1} F_n^{(2)}\right] + \ldots$$

direct corr.

input shift contribution

EW input schemes

Two most used options for the EW sector:

$$\{\alpha_{\rm em}, m_Z, G_F\} \to \Delta\alpha_{\rm em} \equiv 0$$

$$\to \Delta m_W^2 \neq 0 \quad (\sim C_{HD}, C_{HWB}, C_{Hl}^{(3)}, C'_{ll})$$

$$\{m_W, m_Z, G_F\} \to \Delta\alpha_{\rm em} \neq 0 \quad (\sim C_{HD}, C_{HWB}, C_{Hl}^{(3)}, C'_{ll})$$

$$\to \Delta m_W^2 \equiv 0$$

EW input schemes

Two most used options for the EW sector:

$$\{\alpha_{\rm em}, m_Z, G_F\} \to \Delta\alpha_{\rm em} \equiv 0$$

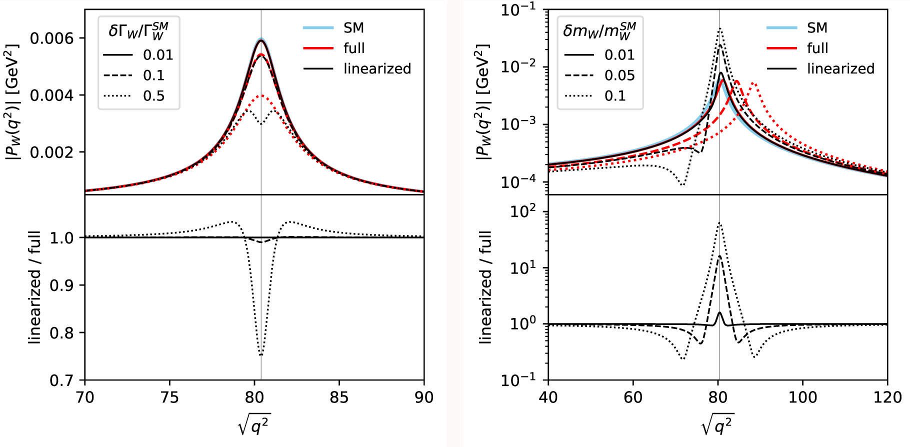
$$\to \Delta m_W^2 \neq 0 \quad (\sim C_{HD}, C_{HWB}, C_{Hl}^{(3)}, C'_{ll})$$

$$\{m_W, m_Z, G_F\} \to \Delta\alpha_{\rm em} \neq 0 \quad (\sim C_{HD}, C_{HWB}, C_{Hl}^{(3)}, C'_{ll})$$

$$\to \Delta m_W^2 \equiv 0$$

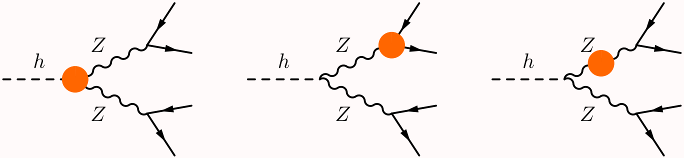
Propagator corrections

$$\frac{i(-\eta^{\mu\nu}+q^\mu q^\nu/m_W^2)}{p^2-m_W^2+i\Gamma_W m_W}\left[1+\frac{i m_W\,\Delta\Gamma_W}{p^2-m_W^2+i\Gamma_W m_W}-\frac{(2m_W-i\Gamma_W)\,\Delta m_W}{p^2-m_W^2+i\Gamma_W m_W}\right]+\mathcal{O}(\Lambda^{-4})$$



Example: H → 4f in the SMEFT

① corrections to SM diagrams

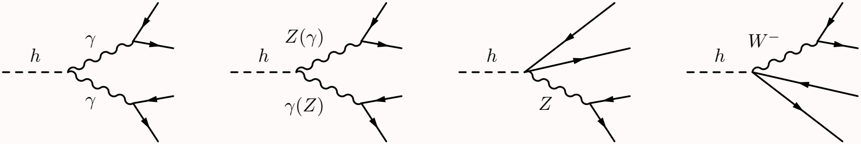


$\propto g_{\mu\nu}$ (SM-like)
$\propto g_{\mu\nu} p{\cdot}q - p_\nu q_\mu$ $(Z_{\mu\nu} Z^{\mu\nu} h)$

$\delta g_L, \delta g_R$

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

② genuine SMEFT diagrams



Example: $h \to 4f$ in the SMEFT

Results with $U(3)^5$ symmetry, $\{m_W, m_Z, G_F\}$ inputs.

$$\Gamma = \Gamma_{SM}\left[1 + \sum_\alpha \bar{C}_\alpha N_\alpha\right], \qquad \bar{C}_\alpha = C_\alpha \frac{v^2}{\Lambda^2}$$

↓

	$\bar{q}q \to h\bar{q}q$ VBF-like		$h \to e^+e^-\mu^+\mu^-$	
	direct	propagators	direct	propagators
$\bar{C}_{He}$		$5.32 \cdot 10^{-5}$	-1.724	0.153
$\bar{C}^{(1)}_{Hl}$		$5.32 \cdot 10^{-5}$	2.144	0.153
$\bar{C}^{(3)}_{Hl}$	-6	$1.351 \cdot 10^{-3}$	-3.856	1.147
$\bar{C}^{(1)}_{Hq}$	0.109	$-1.363 \cdot 10^{-4}$		-0.39
$\bar{C}^{(3)}_{Hq}$	-5.345	$-1.423 \cdot 10^{-3}$		-1.353
$\bar{C}_{Hu}$	-0.323	$-7.092 \cdot 10^{-5}$		-0.203
$\bar{C}_{Hd}$	0.103	$5.24 \cdot 10^{-5}$		0.150
$\bar{C}'_{ll}$	3	$-1. \cdot 10^{-3}$	3	-0.839

SMEFT @ LHC: status

calculation ➤ measurement ➤ global analysis ➤ interpretation

- ☑ Higgs + EW

  Alves et al 1211.4580,1805.11108, Butter et al 1604.03105
  Corbett et al 1509.01585, de Blas et al 1608.01509,1710.05402,1910.14012
  Ellis,Murphy,Sanz,You 1803.03252 da Silva Almeida et al 1812.01009
  Biekötter,Corbett,Plehn 1812.07587, Dawson,Homiller,Lane 2007.01296

- ☑ top

  Englert et al 1506.08845,1512.05560,1901.03164
  Cirigliano,Dekens,deVries,Mereghetti 1605.04311 Hartland et al 1901.05965
  Brivio et al 1910.0306, Durieux,Irles,Miralles,Peñuelas,Pöschl 1907.10619

- ☑ Higgs + EW + top

  Ellis,Madigan,Mimasu,Sanz,You 2012.02779

- ☑ top + B physics

  Bißmann,(Erdmann),Grunwald,Hiller,Kroöninger 1909.13632, 2012.10456
  Bruggisser,Schäfer,Westhoff,VanDyk 2101.07273

- ☑ diboson (+ VBS)

  Baglio,Dawson,Homiller,(Lane,Lewis) 1812.00214, 1909.11576, 2003.07862
  Ethier,Gomez-Ambrosio,Magni,Rojo 2101.03180

- ☑ Higgs combination within ATLAS

  2004.03447, ATLAS-CONF-2020-053

- ☑ impact analysis of NLO corrections and quadratic SMEFT terms
- ☑ several statistical methods: information geometry, bayesian reweighting, replica model, Partial Component Analysis. . .

Global analysis of top quark observables

- $U(2)_q \times U(2)_u \times U(2)_d$
- top interactions only $\rightarrow$ 24 param.
- up to NLO QCD, quadratic SMEFT (predictions with SMEFT@NLO)
- fitted with **SFitter**

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

also: **SMEFiT**. Hartland, Maltoni, Nocera, Rojo, Slade, Vryonidou, Zhang 1901.05965
TopFitter 1506.08845, 1512.03360

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

tZ

single t

$t\bar{t}$

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

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

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

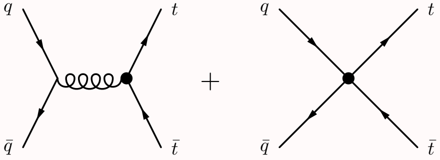
$$\mathcal{Q}^1_{Qu} = (\bar{Q}\gamma_\mu Q)(\bar{u}\gamma^\mu u) \qquad \mathcal{Q}^8_{Qu} = (\bar{Q}\gamma_\mu T^A Q)(\bar{u}\gamma^\mu T^A u)$$
$$\mathcal{Q}^1_{Qd} = (\bar{Q}\gamma_\mu Q)(\bar{d}\gamma^\mu d) \qquad \mathcal{Q}^8_{Qd} = (\bar{Q}\gamma_\mu T^A Q)(\bar{d}\gamma^\mu T^A d)$$
$$\mathcal{Q}^1_{tu}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

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

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

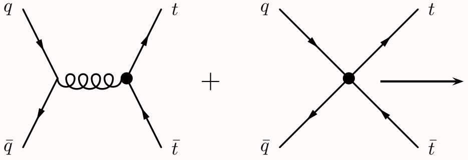
A typical issue: flat directions

e.g. $q\bar{q} \to t\bar{t}$ at tree-level, linear order in C_i:



A typical issue: flat directions

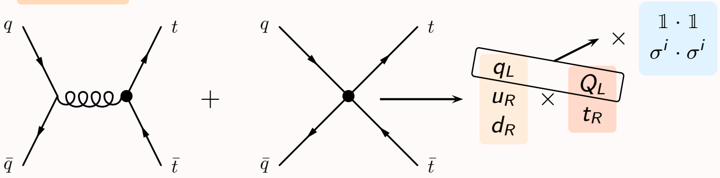
e.g. $q\bar{q} \rightarrow t\bar{t}$ at tree-level, linear order in C_i:



$\begin{matrix} q_L \\ u_R \\ d_R \end{matrix} \times \begin{matrix} Q_L \\ t_R \end{matrix}$

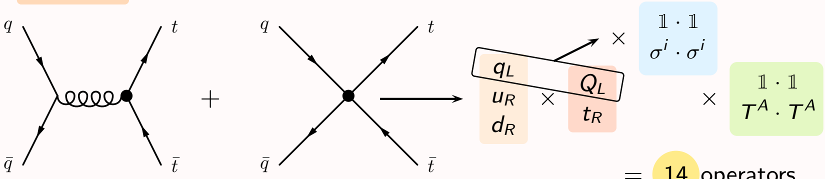
A typical issue: flat directions

e.g. $q\bar{q} \rightarrow t\bar{t}$ at tree-level, linear order in C_i:



A typical issue: flat directions

e.g. $q\bar{q} \to t\bar{t}$ at tree-level, linear order in C_i:



= 14 operators

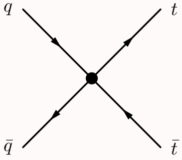
interfering with SM:

7 4-fermion operators

$$C^8_{LL} \sim C^{(1,8)}_{Qq},\ C^{(3,8)}_{Qq}$$
$$C^8_{LR} \sim C^8_{tq}$$
$$C^8_{RL} \sim C^8_{Qu},\ C^8_{Qd}$$
$$C^8_{RR} \sim C^8_{tu},\ C^8_{td}$$

A typical issue: flat directions

e.g. $q\bar{q} \to t\bar{t}$ at tree-level, linear order in C_i:



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

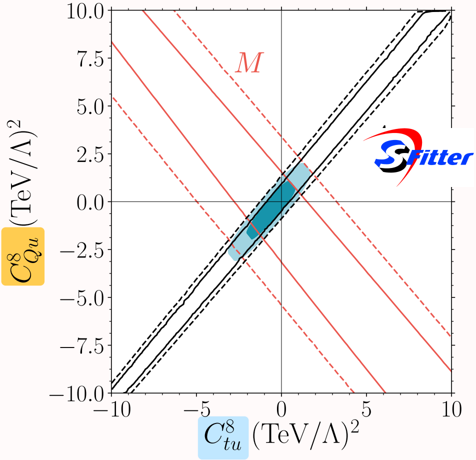
$$\Delta\sigma_{t\bar{t}}^{int} \propto \left[C_{LL}^8 + C_{RR}^8 + C_{LR}^8 + C_{RL}^8\right]\left(1 + \beta_t^2 c_t^2 + \frac{2m_t^2}{s}\right) + \left[C_{LL}^8 + C_{RR}^8 - C_{LR}^8 - C_{RL}^8\right] 2\beta_t c_t$$

breaking down each pairs requires
→NLO QCD
→ $(C_i C_j)$ terms
→ other processes (eg. single top)

the two pairs can be distinguished already at this order, with **kinematics**

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:

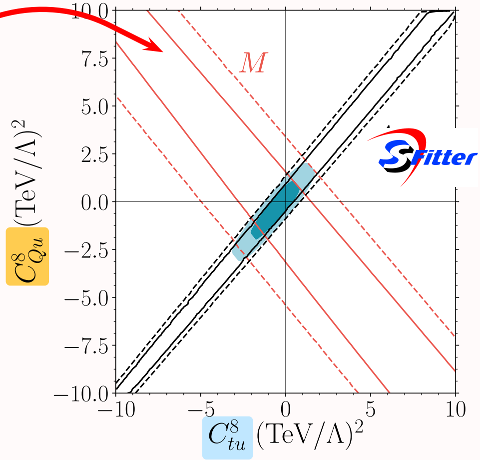
$\ln L_{\max} - \ln L =$ 1/2 ———
2 - - - - -

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

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

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

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



likelihood contours:

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

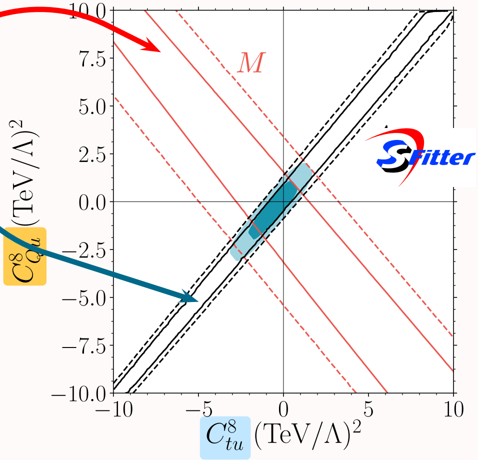
($\sim \Delta\chi^2 = 1, 4$ in Gaussian limit)

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

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

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

charge asymmetry
A_C



likelihood contours:

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

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

Impact of quadratic SMEFT contributions

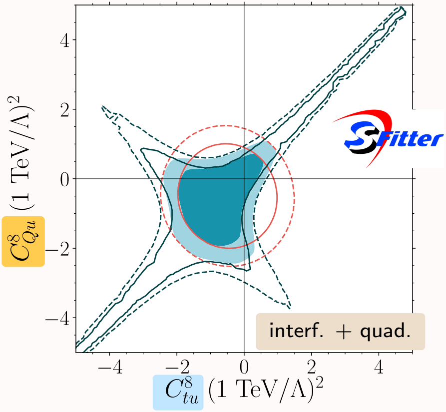
$$\Delta\sigma^{quad}_{t\bar{t}} \propto \Big[(C^8_{LL})^2 + (C^8_{RR})^2 + (C^8_{LR})^2 + (C^8_{RL})^2 + \frac{9}{2}\Big((C^1_{LL})^2 + (C^1_{RR})^2 + (C^1_{LR})^2 + (C^1_{RL})^2\Big)\Big]\,(1+\beta_t^2 c_t^2)$$
$$+ \Big[(C^8_{LL})^2 + (C^8_{RR})^2 - (C^8_{LR})^2 - (C^8_{RL})^2 + \frac{9}{2}\Big((C^1_{LL})^2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

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

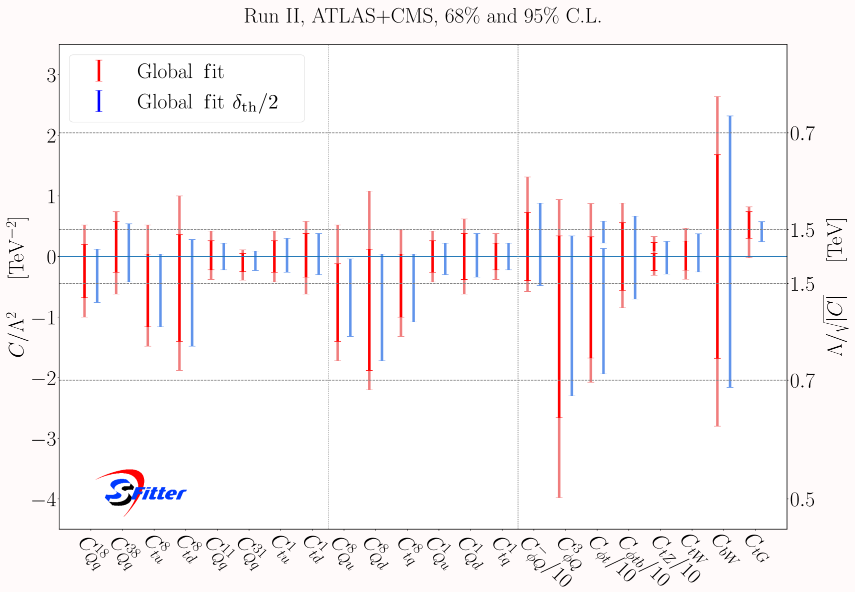
likelihood contours:

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

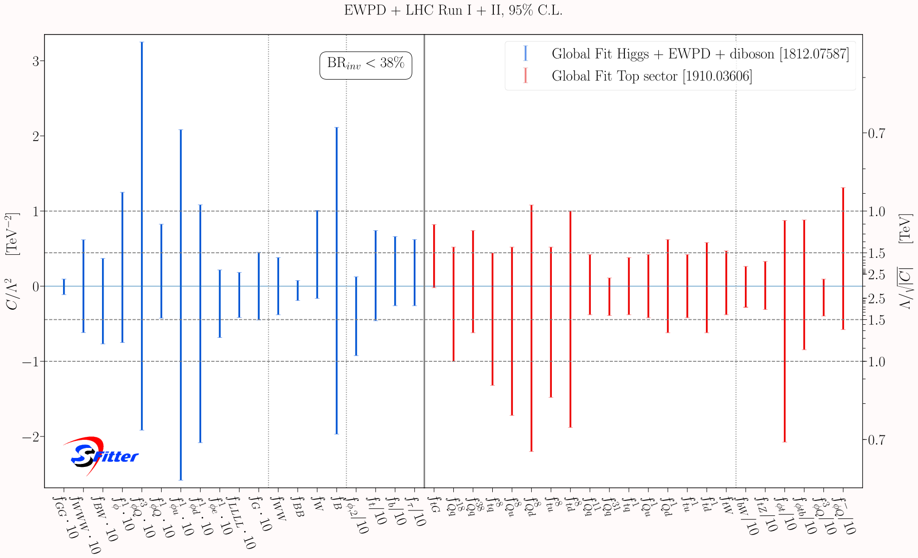
($\sim \Delta\chi^2 = 1, 4$ in Gaussian limit)



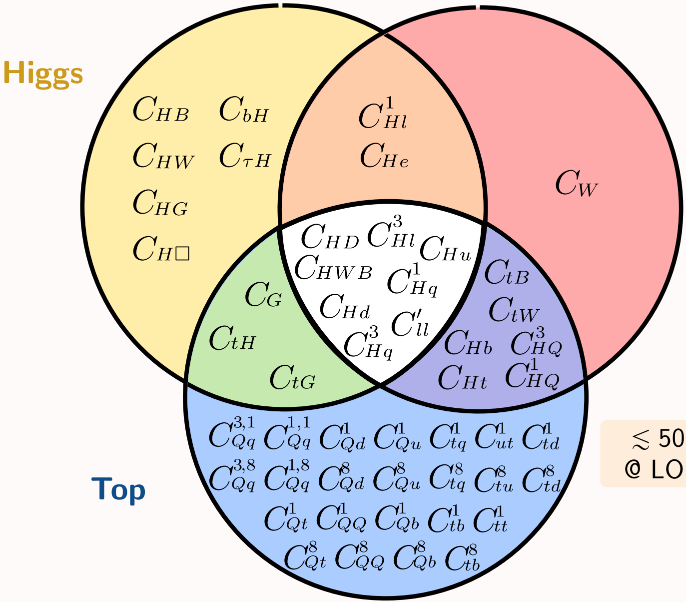
Global analysis of top quark observables



Global analysis of top quark observables



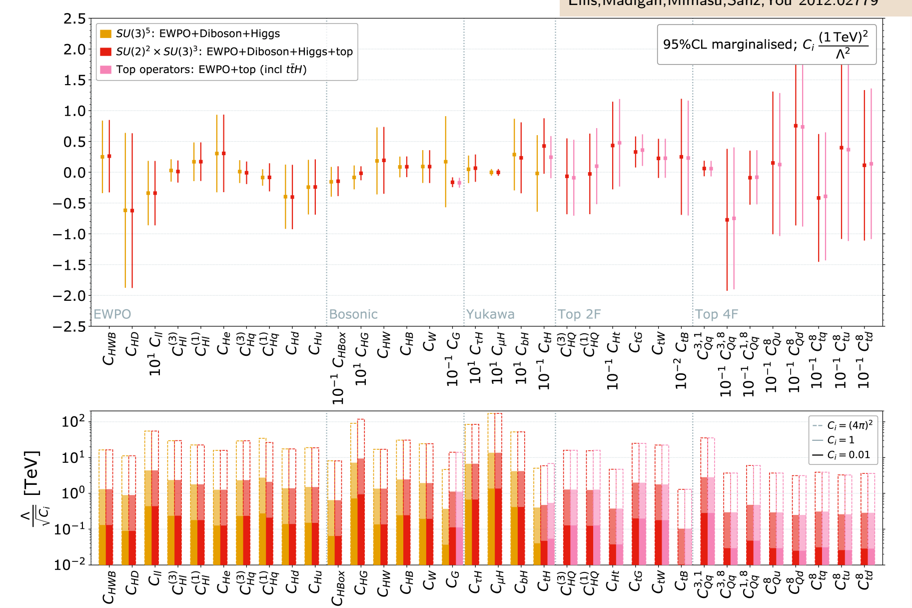
Next step: top + EW + Higgs



$\lesssim$ 50 parameters
@ LO interference

Next step: top + EW + Higgs

Ellis, Madigan, Mimasu, Sanz, You 2012.02779



SMEFT @ LHC: status

calculation → measurement → global analysis → interpretation

SMEFT @ LHC: status

calculation ➤ measurement ➤ global analysis ➤ interpretation

- CDE / UOLEA: up to 1-loop
  Henning,Lu,Murayama 1412.1837,1604.01019
  del Aguila,Kunszt,Santiago 1602.00126
  Drozd,Ellis,Quevillon,You 1512.03003
  Boggia,Gomez-Ambrosio,Passarino 1603.03660
  Ellis,Quevillon,(Vuong),You,Zhang 1604.02445,1706.07765,2006.16260
  Fuentes-Martin,Portoles,Ruiz-Femenia 1607.02142
  Zhang 1610.00710, Cohen,Lu,Zhang 2011.02484
  (Krämer),Summ,Voigt 1806.05171,1908.04798
- matching via amplitudes up to 1-loop
  Craig,Jiang,Li,Sutherland 2001.00017
- complete tree-level dictionary
  de Blas,Criado,Pérez-Victoria,Santiago 1711.10391
- "v-improved" matching
  (Brehmer),Freitas,López-Val,Plehn 1510.03443, 1607.08251
- automated matching
  Criado 1710.06445, Bashki,Chakrabortty,Kumar Patra 1808.04403
  Cohen,Lu,Zhang 2012.07851
  Fuentes-Martin,König,Pagès,Thomsen,Wilsch 2012.08506
- reduced fits
  Gorbahn,No,Sanz 1502.07352, Drozd,Ellis,Quevillon,You 1504.02409
  Ellis,(Madigan,Mimasu,Murphy),Sanz,You 1803.03252,2012.02779
  Dawson,Homiller,Lane 2007.01296,2102.02823
  Bakshi,Chakrabortty,Englert,Spannowsky,Stylianou 2009.13394
  Anisha,Bakshi,Chakrabortty,Kumar Patra 2010.04088

Example: SM + vector triplet

Brivio,Bruggisser,Geoffray,Krämer,Plehn,Summ in preparation

$$\mathcal{L}_V = -\frac{1}{4} V^i_{\mu\nu} V^{i\mu\nu} - \frac{g_M}{2} V^i_{\mu\nu} W^{i\mu\nu} + \frac{m_V^2}{2} V^i_\mu V^{i\mu} + \frac{g_H}{2} V^i_\mu (H^\dagger i \overleftrightarrow{D}^{i\mu} H)$$
$$+ \frac{g_l}{2} V^-_\mu \bar{\ell} \gamma^\mu \sigma^i \ell + \frac{g_q}{2} V^-_\mu \bar{q} \gamma^\mu \sigma^i q + \frac{g_{VH}}{2} (H^\dagger H) V^i_\mu V^{i\mu}$$

Example: SM + vector triplet

Brivio,Bruggisser,Geoffray,Krämer,Plehn,Summ in preparation

$$\mathcal{L}_V = -\frac{1}{4}V^i_{\mu\nu}V^{i\mu\nu} - \frac{g_M}{2}V^i_{\mu\nu}W^{i\mu\nu} + \frac{m_V^2}{2}V^i_\mu V^{i\mu} + \frac{g_H}{2}V^i_\mu(H^\dagger i\overleftrightarrow{D}^{i\mu}H)$$
$$+\frac{g_l}{2}V^-_\mu\bar{\ell}\gamma^\mu\sigma^i\ell + \frac{g_q}{2}V^-_\mu\bar{q}\gamma^\mu\sigma^i q + \frac{g_{VH}}{2}(H^\dagger H)V^i_\mu V^{i\mu}$$

↓

field redefinition to remove kinetic mixing

$$\begin{cases} V^i_\mu \to \dfrac{1}{\sqrt{1-g_M^2}}V^i_\mu \\ W^i_\mu \to W^i_\mu - \dfrac{g_M}{\sqrt{1-g_M^2}}V^i_\mu \end{cases}$$

↓

matching onto Warsaw basis, up to 1-loop

↓

SMEFT fit → constraints on g_i couplings

Example: SM + vector triplet

Brivio,Bruggisser,Geoffray,Krämer,Plehn,Summ in preparation

$$\mathcal{L}_V = -\frac{1}{4}V^i_{\mu\nu}V^{i\mu\nu} - \frac{g_M}{2}V^i_{\mu\nu}W^{i\mu\nu} + \frac{m_V^2}{2}V^i_\mu V^{i\mu} + \frac{g_H}{2}V^i_\mu(H^\dagger i\overleftrightarrow{D}^{i\mu}H)$$
$$+\frac{g_l}{2}V^-_\mu\bar{\ell}\gamma^\mu\sigma^i\ell + \frac{g_q}{2}V^-_\mu\bar{q}\gamma^\mu\sigma^i q + \frac{g_{VH}}{2}(H^\dagger H)V^i_\mu V^{i\mu}$$

e.g. $Q^{(3)}_{Hl} = (H^\dagger i\overleftrightarrow{D}^{i\mu}H)(\bar{\ell}\gamma^\mu\sigma^i\ell)$

$$(C^{(3)}_{Hl})_{ij} = -\frac{g_l g_H}{4m_V^2}\delta_{ij} + \frac{1}{36864\pi^2 m_V^2}\frac{\delta_{ij}}{1-g_M^2}\Big[g_w^4(288+1531g_M^2+2989g_M^4)$$
$$+g_w^3(2642g_Hg_M + 2340_g lg_M + 7942g_Hg_M^3 + 6732g_lg_M^3)$$
$$+g_w^2(g_l^2(-102+3054g_M^2)+g_H^2(49+5711g_M^2))$$
$$+g_wg_M(1080g_H^3+5400g_H^2g_l+2304g_Hg_l^2+432g_l^3+1440h_Hg_{VH}+1440g_lg_{VH})$$
$$+g_Hg_l(1080g_H^2-360g_Hg_l+432g_l^2+1440g_{VH}+(1+g_w^2)(2160+12600g_M^2))$$
$$+1440g_M^2g_{VH}\Big] + \frac{3}{3032\pi^2m_V^2}(g_l-g_H)(g_l+g_wg_M)(Y_eY_e^\dagger)_{ij}$$

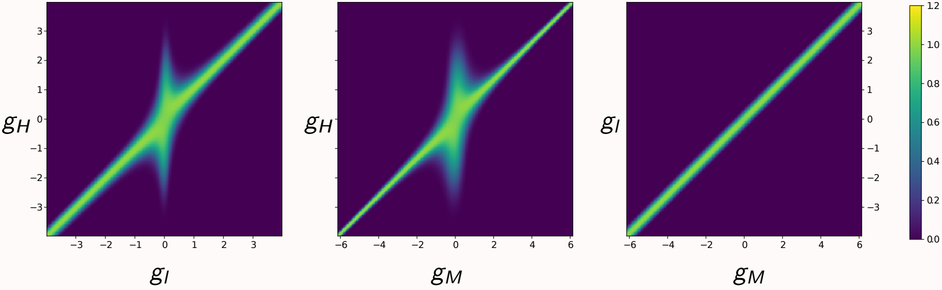
Example: SM + vector triplet

$$\mathcal{L}_V = -\frac{1}{4} V^i_{\mu\nu} V^{i\mu\nu} - \frac{g_M}{2} V^i_{\mu\nu} W^{i\mu\nu} + \frac{m_V^2}{2} V^i_\mu V^{i\mu}$$
$$+ \frac{g_H}{2} V^i_\mu (H^\dagger i \overleftrightarrow{D}^{i\mu} H) + \frac{g_l}{2} V^-_\mu \bar{\ell}\gamma^\mu \sigma^i \ell$$

fit to EWPO+EW+Higgs preliminary!

scaled likelihood

$m_V = 2\,\mathrm{TeV}$, tree-level matching



all g_i unconstrained

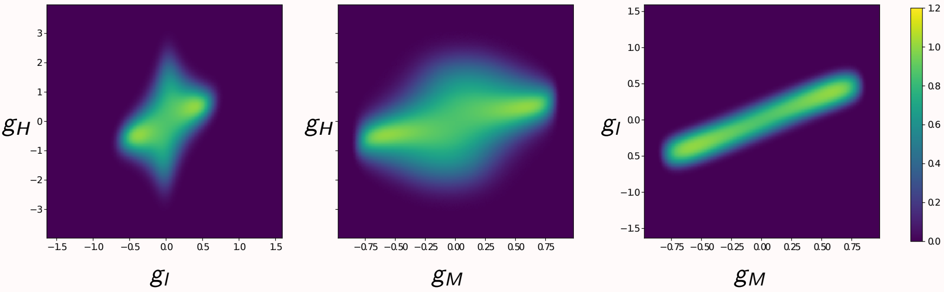
Example: SM + vector triplet

$$\mathcal{L}_V = -\frac{1}{4}V^i_{\mu\nu}V^{i\mu\nu} - \frac{g_M}{2}V^i_{\mu\nu}W^{i\mu\nu} + \frac{m_V^2}{2}V^i_\mu V^{i\mu}$$
$$+\frac{g_H}{2}V^i_\mu(H^\dagger i\overleftrightarrow{D}^{i\mu}H) + \frac{g_l}{2}V^-_\mu\bar{\ell}\gamma^\mu\sigma^i\ell$$

fit to EWPO+EW+Higgs **preliminary!**

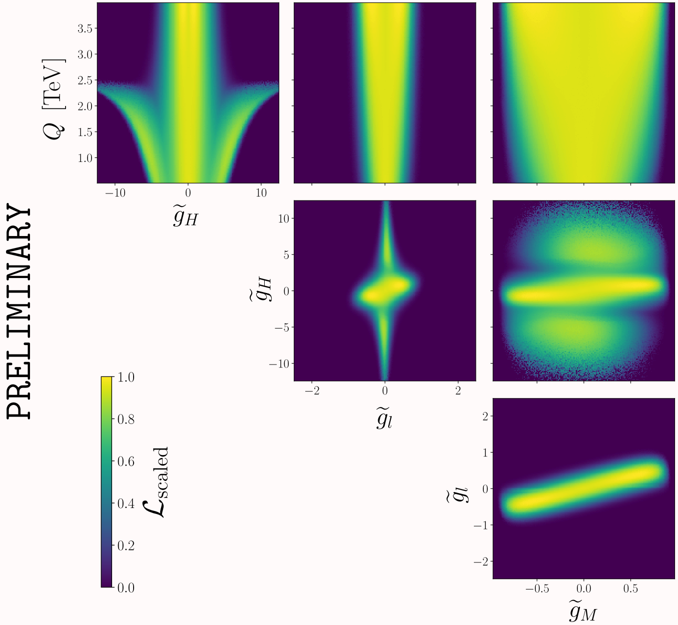
scaled likelihood

$m_V = 2\,\mathrm{TeV}$, 1-loop matching



$|g_l| \lesssim 0.7$ $\quad |g_H| \lesssim 2.5$ $\quad |g_M| \lesssim 0.8$

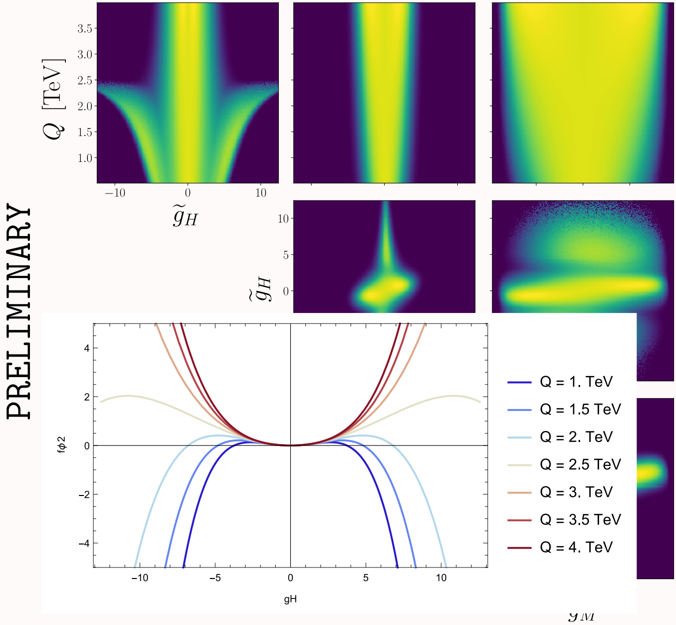
SM + vector triplet: matching scale dependence



$m_V = 4\,\text{TeV}$

1-loop matching

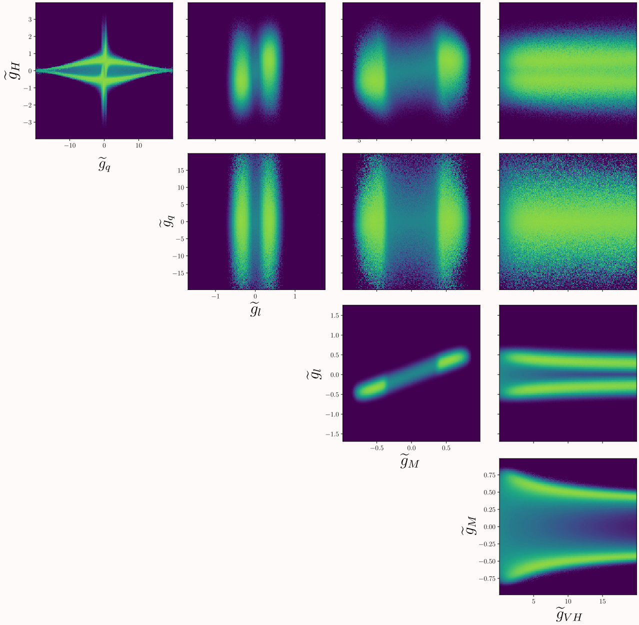
SM + vector triplet: matching scale dependence



$m_V = 4\,\mathrm{TeV}$

1-loop matching

SM + vector triplet: 5-parameter fit



PRELIMINARY

$m_V = 2\,\mathrm{TeV}$
$Q = m_V$

1-loop matching

SMEFT @ LHC: open questions

calculation ➤ measurement ➤ global analysis ➤ interpretation

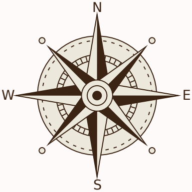
- treatment of SMEFT uncertainties, $\mathcal{L}_8$ terms
- anomaly constraints?
- automation of NLO SMEFT EW
- more NLO SMEFT results
- machine learning predictions?
- SMEFT effects in PDFs, hadronization, extraction of α_s...

- SMEFT or HEFT?
- how to combine with direct searches?
- 1-loop matching dictionary
- 2-loop RG running

- fits with 50-60 parameters
- combination EW+Higgs+top+flavor
- combinations within the experiments
- improved treatment of correlations, uncertainties etc

Summary

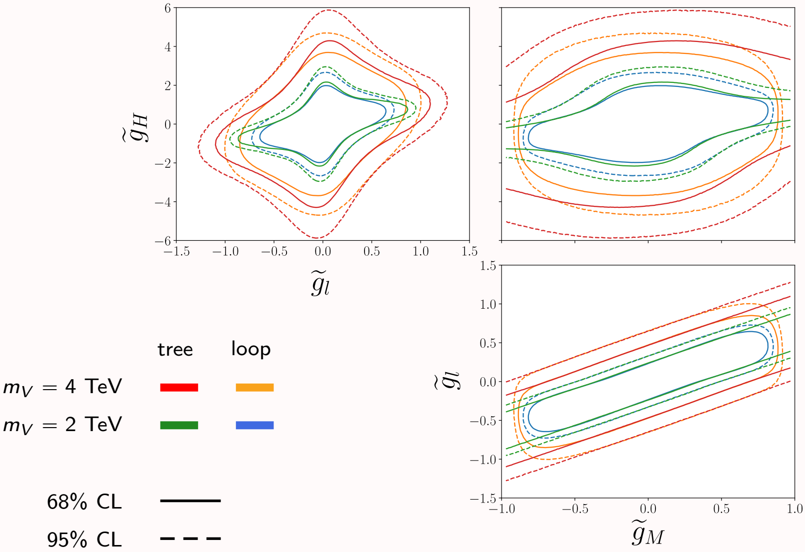
- SMEFT is the best framework for indirect searches of new physics at LHC
  - → current direct bounds consistent with $(v/\Lambda_{BSM}) \ll 1$
  - → collider physics entering **precision era**
- A challenging task! Developments are needed in
  - precision calculations
  - numerical predictions & analysis strategies
  - statistical analyses
  - theory understanding
  - ...



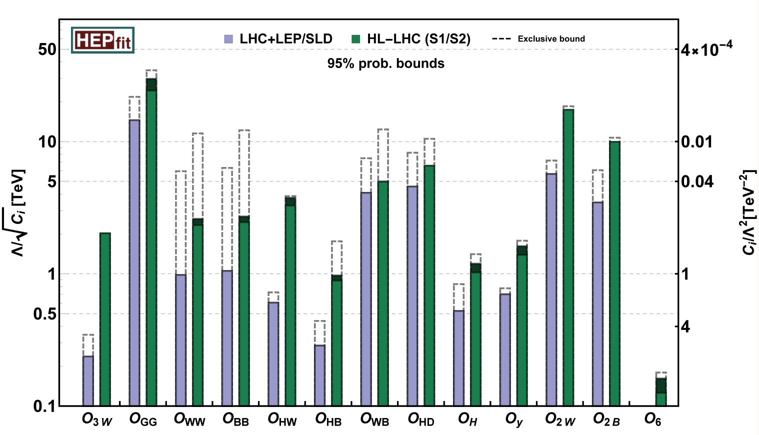
- A community effort: combining is key
  - → both theory and experiment increasingly involved
  - → first exp. combination **EW + Higgs + top** sectors upcoming
  - → incorporation of constraints from **flavor** experiments
  - → complementarity with **direct** searches

Backup slides

SM + vector triplet: contours for 3D fit

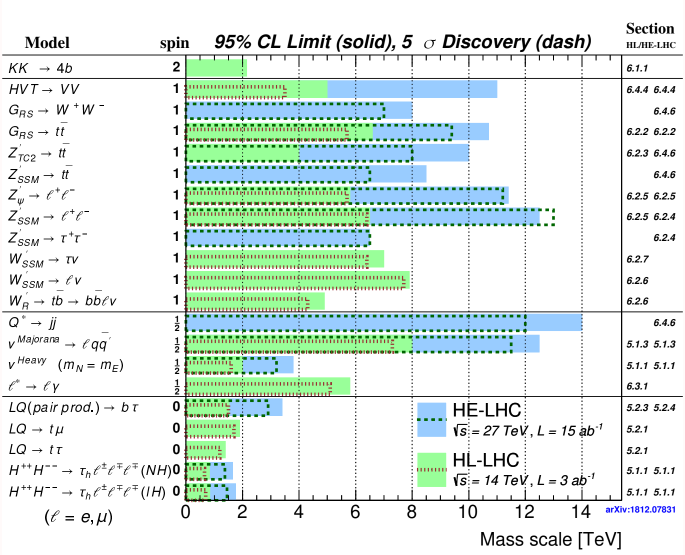


Prospects for HL-LHC



Yellow report on LH-LHC and HE-LHC physics 1902.00134

Prospects for HL-LHC



Yellow report on LH-LHC and HE-LHC physics 1812.07831

Finite renormalization (input parameters)

SM

(pseudo)-observables
$\mathcal{O}$

α_s, d_N
m_Z, $\alpha_{\rm em}$
$\mu \to e\nu\nu$, m_h
m_f
meson decay/osc

→

$\mathcal{L}$ parameters p

QCD	g_s, θ_{QCD}
EW	g, g'
Higgs	v, λ
Yukawa	y_f
CKM	$\theta_{1,2,3}, \delta$

→

analytical / MC
predictions
for any SM process

Finite renormalization (input parameters)

SM

(pseudo)-observables $\mathcal{O}$

α_s, d_N
m_Z, $\alpha_{\rm em}$
$\mu \to e\nu\nu$, m_h
m_f
meson decay/osc

→

$\mathcal{L}$ parameters p

QCD	g_s, θ_{QCD}
EW	g, g'
Higgs	v, λ
Yukawa	y_f
CKM	$\theta_{1,2,3}, \delta$

→

analytical / MC **predictions** for any SM process

usual procedure

1. choose set $\mathcal{O}$ to define all p unambiguously
2. calculate $\mathcal{O}(p)$ at given order
3. invert the relations $\to p(\mathcal{O})$
4. the renormalized p has a well-defined numerical value

Finite renormalization (input parameters)

SMEFT

(pseudo)-observables $\mathcal{O}$

α_s, d_N
m_Z, $\alpha_{\rm em}$
$\mu \to e\nu\nu$, m_h
m_f
meson decay/osc

→

$\mathcal{L}$ parameters p

QCD	g_s, θ_{QCD}
EW	g, g'
Higgs	v, λ
Yukawa	y_f
CKM	$\theta_{1,2,3}, \delta$
EFT	$\mathbf{C_i}$

→

analytical / MC **predictions** for any SM process

SMEFT procedure

1. choose set $\mathcal{O}$ to define all p_{SM} unambiguously
2. calculate $\mathcal{O}(p_{SM}, \mathbf{C_i})$ at given order
3. invert the relations expanding around the SM solution

$$\to p_{SM}(\mathcal{O}) + \delta p(\mathbf{C_i})$$

4. p_{SM} has a numerical value, δp encodes EFT corrections

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

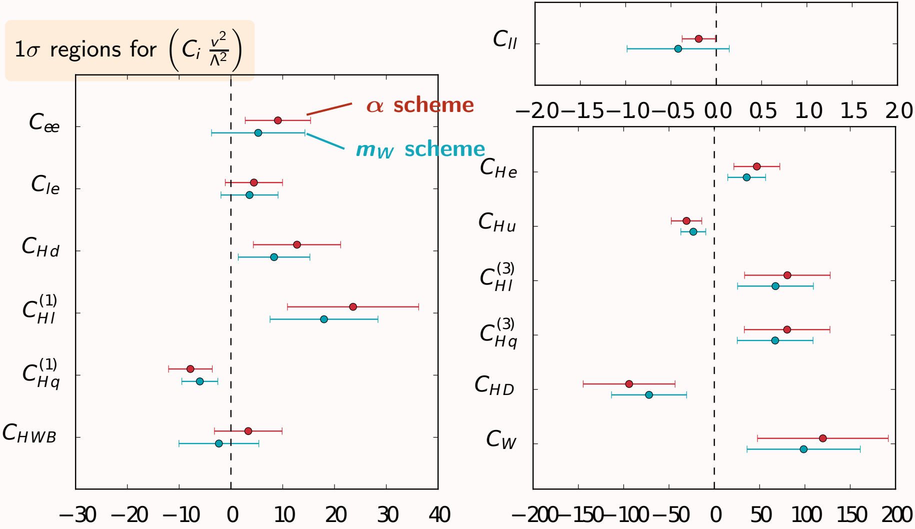
- 4 measurements of W helicity at 7, 8, 13 TeV

Fit to EWPD from LEP

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

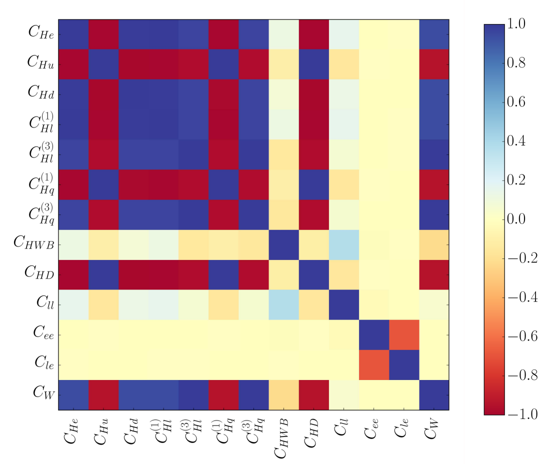
Berthier,(Bjørn),Trott 1508.05060,1606.06693
Brivio,Trott 1701.06424

1σ regions for $\left(C_i \frac{v^2}{\Lambda^2}\right)$



Fit to EWPD from LEP

Correlation matrix (α scheme)



2 blind directions in EWPD

Grojean, Skiba, Terning 0602154

↕

reparameterization invariance of 2 → 2 scattering

Brivio, Trott 1701.06424

WW breaks (weakly) the invariance leaving strong correlations

Higgs production and acceptance corrections

Production

Brivio,Hays,Smith,Trott,Žemaitytė in preparation

- $gg \to h$ — known to NLO SMEFT
- $qq \to qqh$ (VBF/VH)
- $qq/gg \to hll/hl\nu$ (VH) — parton level inferred from $h \to 4l$ via crossing sym.
- $gg \to t\bar{t}h$
- $qq \to thj$ — in progress

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

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 $(hV_{\mu\nu}V^{\mu\nu}, \quad hV_\mu\bar\psi\gamma^\mu\psi\dots)$ modify distributions $\to$ ΔA
- ΔA calculable for cuts in Lorentz-invariants, requires MC for arbitrary cuts