Untangling the SMEFT
- electroweak constraints -

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The SMEFT

SMEFT = Effective Field Theory with SM fields + symmetries

a systematic expansion in canonical dimensions $(v, E/\Lambda)$:

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

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

C_i free parameters (Wilson coefficients)

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

- any UV compatible with the SM in the low energy limit can be matched onto the SMEFT
- a convenient phenomenological approach: systematically classifies all the possible new physics signals

The SMEFT - structure

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ν Majorana masses

Weinberg PRL43(1979)1566

leading deviations from the SM

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

\# operators known
basis available only for $\mathcal{L}_7$

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

The SMEFT - structure

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Our focus: $\mathcal{L}_6 = \sum_i C_i \mathcal{Q}_i$

# operators (B, L cons.)	**59 + h.c. = 76**	
# parameters (3 gen.)	**2499**	Alonso, Jenkins, Manohar, Trott 1312.2014

The SMEFT - structure

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

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the # can be reduced imposing **symmetries**:
CP, B, L, $U(3)^5$ (MFV)
+
selecting convenient kinematic regions

The SMEFT - structure

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

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different bases available → we pick the "Warsaw" one. Grzadkowski et al. 1008.4884

The Warsaw basis

Gzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

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

The Warsaw basis

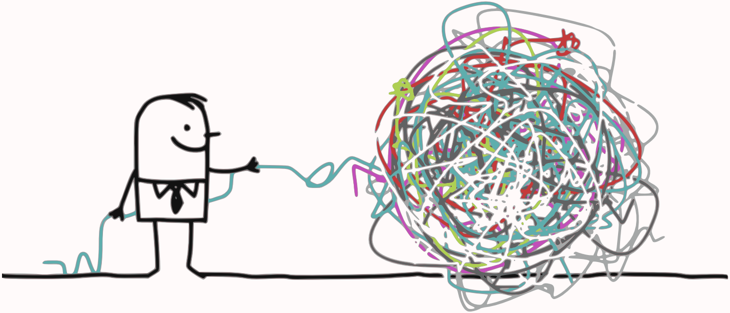
Gzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

A big knot!

in principle all these operators are around at the same time!
any given observable receives corrections by several Wilson coefficients



We want to untangle this without breaking any strings
=
extract reliable constraints (possibly measurements!) without introducing any bias

Untangling the SMEFT

A some care in handling the theory

B precise measurements

A may be subtle but it is feasible

→ easier on pole observables compared to tails of dist.

→ more examples in the rest of the talk

B . . . how precise?!

On poles:

$$\text{NP impact} \sim \frac{v^2 \overset{\text{UV coupling to SM}}{g}}{\underset{\text{mass of new resonances}}{M^2}} = \frac{v^2}{\Lambda^2} \ \text{EFT cutoff}$$

$$g \simeq 1 \quad \underset{\text{(LHC reach)}}{M \gtrsim 2-3 \text{ TeV}} \to 1\%$$

at least!

On tails:

$$\text{NP impact} \sim \frac{E^2 g}{M^2} = \frac{E^2}{\Lambda^2} \to \text{few - tens } \%$$

Untangling the SMEFT

Ⓐ some care in handling the theory

Ⓑ precise measurements

---

summarizing: there's a strong complementarity

	pole obs.	**tails of dist.**
Ⓐ	safest	need a lot of care
Ⓑ	need 1 %	ok with tens of %

☛ As a first step we stick to pole observables

A global ongoing effort

The Wilson coefficients of the SMEFT are been constrained by several groups (mostly gauge and Higgs couplings)

Just in the last years:

very incomplete list!

Corbett et al. 1207.1344 1211.4580 1304.1151 1411.5026 1505.05516

Englert,Freitas,Müllheitner,Plehn,Rauch,Spira,Walz 1403.7191

Ellis,Sanz,You 1404.3667 1410.7703

Falkowski,Gonzalez-Alonso,Greljo,Marzocca 1508.00581

Englert,Kogler,Schulz,Spannowsky 1511.05170

Butter,Éboli,Gonzalez-Fraile,Gonzalez-Garcia,Plehn,Rauch 1604.03105

Freitas,López-Val,Plehn 1607.08251

Krauss,Kuttimalai,Plehn 1611.00767

...

☛ Here: EWPD close to the Z pole + low energy measurements

Global fit to EW precision data - observables

This talk: results from Berthier,Trott. 1502.02570, 1508.05060
Berthier,Bjørn,Trott 1606.06693

103 observables included

- EWPD near the Z pole: Γ_Z, $R^0_{\ell,c,b}$, $A_{FB}^{\ell,c,b,\mu,\tau}$, σ^0_h
- W mass
- $e^+e^- \to f\bar{f}$ at TRISTAN,PEP,PETRA,SpS,Tevatron,LEP,LEPII
- bhabha scattering at LEPII
- Low energy precision measurements
  - ν-lepton scattering
  - ν-nucleon scattering
  - ν trident production
  - atomic parity violation
  - parity violation in eDIS
  - Møller scattering
  - universality in β decays (CKM unitarity)

Similar works: Han,Skiba 0412166, Ciuchini,Franco,Mishima,Silvestrini 1306.4644, Pomarol,Riva 1308.2803, Falkowski,Riva 1411.0669

Global fit to EW precision data - parameters

there are 19 Wilson coefficients participating, assuming CP + $U(3)^5$

$\tilde{C}_{He}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)$
$\tilde{C}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$
$\tilde{C}_{Hd}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$
$\tilde{C}_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}\gamma^\mu l)$
$\tilde{C}_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{l}\sigma^i\gamma^\mu l)$
$\tilde{C}_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$
$\tilde{C}_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{q}\sigma^i\gamma^\mu q)$
$\tilde{C}_{HWB}$	$W^i_{\mu\nu}B^{\mu\nu}H^\dagger\sigma^i H$
$\tilde{C}_{HD}$	$(H^\dagger D_\mu H)(D^\mu H^\dagger H)$

$\tilde{C}_{ll}$	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$
$\tilde{C}_{ee}$	$(\bar{e}\gamma_\mu e)(\bar{e}\gamma^\mu e)$
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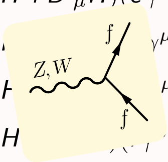

$\tilde{C}_{ll}$	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$
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Global fit to EW precision data - parameters

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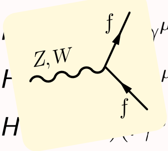

$\tilde C_{He}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar e\gamma^\mu e)$	$\tilde C_{ll}$	$(\bar l\gamma_\mu l)(\bar l\gamma^\mu l)$
$\tilde C_{Hu}$	$($ $\gamma^\mu u)$	$\tilde C_{ee}$	$(\bar e\gamma_\mu e)(\bar e\gamma^\mu e)$
$\tilde C_{Hd}$	$(H$ $^\mu d)$	$\tilde C_{eu}$	$(\bar e\gamma_\mu e)(\bar u\gamma^\mu u)$
$\tilde C^{(1)}_{Hl}$	$(H$ $l)$	$\tilde C_{ed}$	$(\bar e\gamma_\mu e)(\bar d\gamma^\mu d)$
$\tilde C^{(3)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar l\sigma^i\gamma^\mu l)$	$\tilde C_{le}$	$(\bar l\gamma_\mu l)(\bar e\gamma^\mu e)$
$\tilde C^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q\gamma^\mu q)$	$\tilde C_{lu}$	$(\bar l\gamma_\mu l)(\bar u\gamma^\mu u)$
$\tilde C^{(3)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar q\sigma^i\gamma^\mu q)$	$\tilde C_{ld}$	$(\bar l\gamma_\mu l)(\bar d\gamma^\mu d)$
$\tilde C_{HWB}$	$W^i_{\mu\nu}$ $\to \delta s^2_\theta$ $^i H$	$\tilde C^{(1)}_{lq}$	$(\bar l\gamma_\mu l)(\bar q\gamma^\mu q)$
$\tilde C_{HD}$	$(H^\dagger D_\mu H)(D^\mu H^\dagger H)$	$\tilde C^{(3)}_{lq}$	$(\bar l\sigma^i\gamma_\mu l)(\bar q\sigma^i\gamma^\mu q)$
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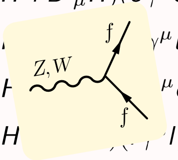

$\tilde C_{He}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar e\gamma^\mu e)$	$\tilde C_{ll}$	$(\bar l\gamma_\mu l)(\bar l\gamma^\mu l)$
$\tilde C_{Hu}$	$($ … $\gamma^\mu u)$	$\tilde C_{ee}$	$(\bar e\gamma_\mu e)(\bar e\gamma^\mu e)$
$\tilde C_{Hd}$	$(H$ … $^\mu d)$	$\tilde C_{eu}$	$(\bar e\gamma_\mu e)(\bar u\gamma^\mu u)$
$\tilde C^{(1)}_{Hl}$	$(H$ … $l)$	$\tilde C_{ed}$	$(\bar e\gamma_\mu e)(\bar d\gamma^\mu d)$
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$\to \delta s_\theta^2$

$\to \delta m_Z^2$

Global fit to EW precision data - parameters

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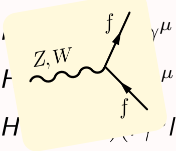

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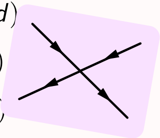
$\tilde{C}^{(1)}_{lq}$	$(\bar{l}\gamma_\mu l)(\bar{q}\gamma^\mu q)$
$\tilde{C}^{(3)}_{lq}$	$(\bar{l}\sigma^i\gamma_\mu l)(\bar{q}\sigma^i\gamma^\mu q)$
$\tilde{C}_{qe}$	$(\bar{q}\gamma_\mu q)(\bar{e}\gamma^\mu e)$



Global fit to EW precision data - method

Basics of the fit method

Likelihood:

$$L(C_i) = \frac{1}{\sqrt{(2\pi)^n \det V}} \exp\left(-\frac{1}{2}\left(\hat{O}-\bar{O}\right)^T V^{-1}\left(\hat{O}-\bar{O}\right)\right)$$

$$\chi^2 = -2\log L(C_i)$$

extract best-fit values on each C_i
after profiling the χ^2 over the others

Global fit to EW precision data - method

Basics of the fit method

Likelihood:

$$L(C_i) = \frac{1}{\sqrt{(2\pi)^n \det V}} \exp\left(-\frac{1}{2}\left(\hat{O}-\bar{O}\right)^T V^{-1}\left(\hat{O}-\bar{O}\right)\right)$$

 # observables

SMEFT prediction (C_i)

exp. measurement

covariance matrix $V_{i,j} = \Delta_i^{\mathrm{exp}}\rho_{ij}^{\mathrm{exp}}\Delta_j^{\mathrm{exp}} + \Delta_i^{\mathrm{th}}\rho_{ij}^{\mathrm{th}}\Delta_j^{\mathrm{th}}$

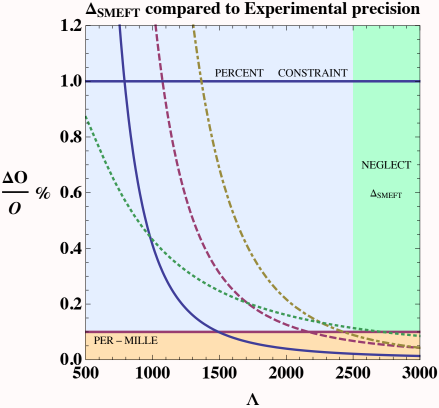
error on O_i

correlation mat.

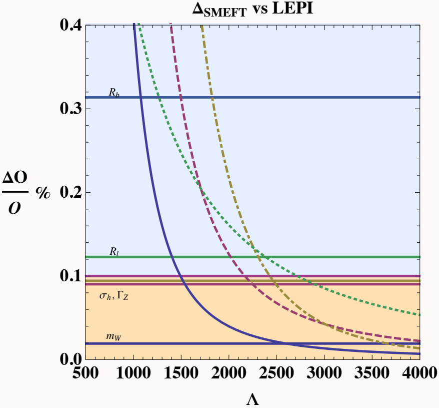
$$\Delta_i^{\mathrm{th}} = \sqrt{\Delta_{i,\mathrm{SM}}^2 + \Delta_{\mathrm{SMEFT}}^2\bar{O}_i^2}$$

Δ_{SMEFT}

SMEFT uncertainty:
- → impact of $d \geqslant 8$ operators + radiative corrections
- → initial/final state radiation
- → ...



Δ_{SMEFT} compared to Experimental precision



Δ_{SMEFT} vs LEPI

Berthier, Trott 1508.05060

in the fit: taken to be a fixed flat relative uncertainty $0 \leqslant \Delta_{\mathrm{SMEFT}} \leqslant 1\%$

Global fit to EW precision data - results

103 observables

Berthier, Trott. 1508.05060

19 Wilson coefficients participating, assuming CP + $U(3)^5$

there are 2 unconstrained directions

well known: first noticed in Han, Skiba 0412166

- The Fisher matrix $\mathcal{I}_{ij} = \dfrac{1}{2}\dfrac{\partial^2\chi^2}{\partial C_i \partial C_j}$ has 2 null eigenvalues
- constraining all the parameters after profiling over the others is not possible

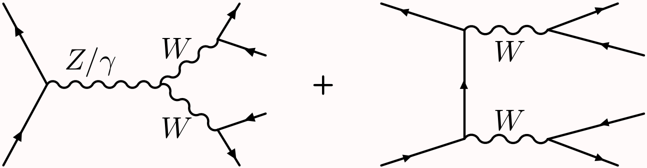
Adding $\bar{\psi}\psi \to \bar{\psi}\psi\bar{\psi}\psi$ production from LEP2

Berthier,Bjørn,Trott 1606.06693

177 observables

20 Wilson coefficients, assuming CP + $U(3)^5$

One extra parameter: C_W $W^i_{\mu\nu} W^{j\nu\rho} W^{k\mu}_{\rho}$



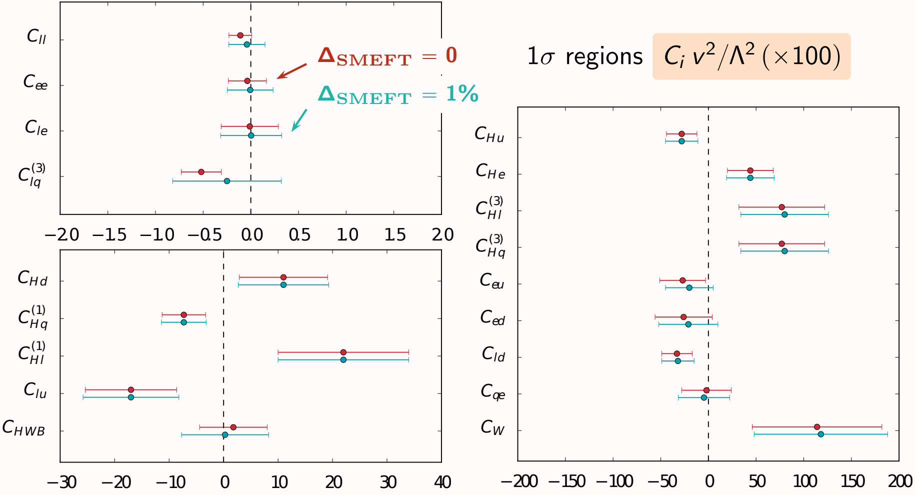
→ **the flat directions are lifted** → we can set constraints on all the C_i

Adding $\bar{\psi}\psi \to \bar{\psi}\psi\bar{\psi}\psi$ production from LEP2

Berthier,Bjørn,Trott 1606.06693

177 observables

20 Wilson coefficients, assuming CP + $U(3)^5$



1σ regions $C_i\, v^2/\Lambda^2\, (\times 100)$

$\Delta_{\text{SMEFT}} = 0$

$\Delta_{\text{SMEFT}} = 1\%$

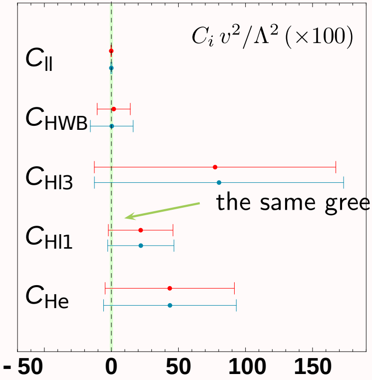
Adding $\bar{\psi}\psi \to \bar{\psi}\psi\bar{\psi}\psi$ production from LEP2

Berthier,Bjørn,Trott 1606.06693

177 observables

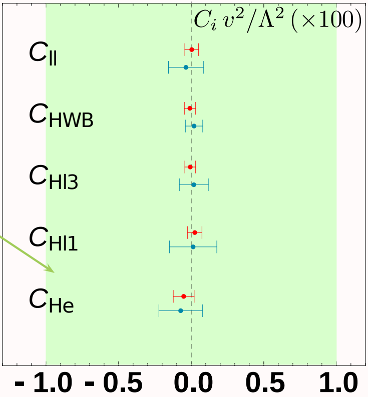
20 Wilson coefficients, assuming CP + $U(3)^5$

2σ regions



the same green band!

profiling over the others



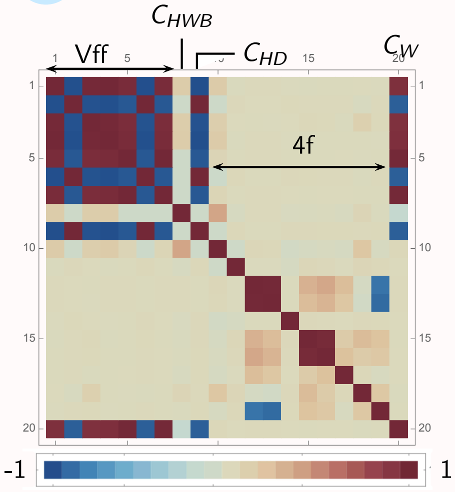
for comparison:
one coefficient at a time

Adding $\bar{\psi}\psi \rightarrow \bar{\psi}\psi\bar{\psi}\psi$ production from LEP2

Berthier, Bjørn, Trott 1606.06693

177 observables

20 Wilson coefficients, assuming CP + $U(3)^5$



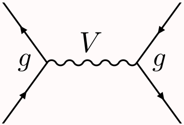
the fit space is highly correlated

taking 1 op. at a time breaks the correlation, giving artificially stronger constraints

Understanding the unconstrained directions

the first fit considered only $\bar\psi\psi \to \bar\psi\psi$ processes

Brivio,Trott 1701.06424



$$V_{\mu\nu}V^{\mu\nu} + g\bar\psi\gamma^\mu\psi V_\mu \xrightarrow{} (1+2\varepsilon)V_{\mu\nu}V^{\mu\nu} + g\bar\psi\gamma^\mu\psi V_\mu + \mathcal{O}(\varepsilon^2)$$

$(*)$ $V_\mu \to V_\mu(1+\varepsilon)$
$g \to g/(1+\varepsilon)$

non canonical kinetic term.
→ OK adjusting LSZ

at tree level +
$m_f/m_V \ll \varepsilon$

the S-matrix has a reparameterization invariance

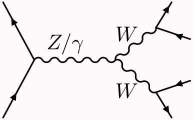
operators modifying the kinetic term normalization have no impact here

$\updownarrow$

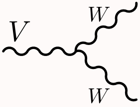
these C_i can be removed from the amplitude via $(*)$

Breaking the invariance

…needs a process with a TGC! $\bar\psi\psi \to \bar\psi\psi\bar\psi\psi$



In the SMEFT:



rescaling of kinetic term
$gW^i_{\mu\nu}W^{j\mu}W^{k\nu}$

still invariant

not physical.
can be removed via
$(g, V) \to ((1-C)g, (1+C)V)$

extra contributions @ $d=6$
$B_{\mu\nu}W^{i\mu\nu}H^\dagger\sigma^iH$
$W^i_{\mu\nu}D^\mu H^\dagger\sigma^iD^\nu H$
$B_{\mu\nu}D^\mu H^\dagger\sigma^iD^\nu H$

NOT invariant!

induce shifts that
cannot be removed
via (g, V) rescaling

Formulation at the operator level

$\bar\psi\psi \to \bar\psi\psi$ *at tree level and in the limit* $m_\psi/m_Z \ll 1$ are insensitive to

$$\mathcal{Q}_{HW} = W^i_{\mu\nu} W^{i\mu\nu} H^\dagger H$$

$$\mathcal{Q}_{HB} = B_{\mu\nu} B^{\mu\nu} H^\dagger H$$

! **not only these though**
but any combination equivalent to them via EOM:

$$\frac{\mathcal{Q}_{HW}}{2} = \frac{2i}{g} W^i_{\mu\nu} D^\mu H^\dagger \sigma^i D^\nu H + 2H^\dagger H (D_\mu H^\dagger D^\mu H) + \frac{\mathcal{Q}_{H\Box}}{2} - \frac{t_\theta}{2}\mathcal{Q}_{HWB} + \frac{\mathcal{Q}^{(3)}_{Hq} + \mathcal{Q}^{(3)}_{Hl}}{2}$$

$$\frac{\mathcal{Q}_{HB}}{2} = \frac{2i}{g'} B_{\mu\nu} D^\mu H^\dagger D^\nu H + \frac{\mathcal{Q}_{H\Box}}{2} - \frac{\mathcal{Q}_{HWB}}{2t_\theta} + 2\mathcal{Q}_{HD} + \frac{\mathcal{Q}^{(1)}_{Hq}}{6} + \frac{2}{3}\mathcal{Q}_{Hu} - \frac{\mathcal{Q}_{Hd}}{3} - \frac{\mathcal{Q}^{(1)}_{Hl}}{2} - \mathcal{Q}_{He}$$

Formulation at the operator level

$\bar\psi\psi \to \bar\psi\psi$ *at tree level and in the limit* $m_\psi/m_Z \ll 1$ are insensitive to

$$\mathcal{Q}_{HW} = W^i_{\mu\nu} W^{i\mu\nu} H^\dagger H$$

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Grojean,Skiba,Terning 0602154

$$\underline{\frac{\mathcal{Q}_{HW}}{2}} = \underline{\frac{2i}{g} W^i_{\mu\nu} D^\mu H^\dagger \sigma^i D^\nu H + 2H^\dagger H (D_\mu H^\dagger D^\mu H)} + \underline{\frac{\mathcal{Q}_{H\Box}}{2} - \frac{t_\theta}{2}\mathcal{Q}_{HWB} + \frac{\mathcal{Q}^{(3)}_{Hq} + \mathcal{Q}^{(3)}_{Hl}}{2}}$$

not constrained in 2 → 2 + **not affecting 2 → 2** ⇒ flat direction

not constrained in 2 → 4 + **probed in 2 → 4** ⇒ constrained!

independently of which operators are retained in the basis!

Formulation at the operator level

$\bar{\psi}\psi \to \bar{\psi}\psi$ *at tree level and in the limit* $m_\psi/m_Z \ll 1$ are insensitive to

$$\mathcal{Q}_{HW} = W^i_{\mu\nu} W^{i\mu\nu} H^\dagger H$$

$$\mathcal{Q}_{HB} = B_{\mu\nu} B^{\mu\nu} H^\dagger H$$

Grojean,Skiba,Terning 0602154

$$\frac{\mathcal{Q}_{HW}}{2} = \frac{2i}{g} W^i_{\mu\nu} D^\mu H^\dagger \sigma^i D^\nu H + 2H^\dagger H (D_\mu H^\dagger D^\mu H) + \frac{\mathcal{Q}_{H\Box}}{2} - \frac{t_\theta}{2}\mathcal{Q}_{HWB} + \frac{\mathcal{Q}^{(3)}_{Hq} + \mathcal{Q}^{(3)}_{Hl}}{2}$$

$$\frac{\mathcal{Q}_{HB}}{2} = \frac{2i}{g'} B_{\mu\nu} D^\mu H^\dagger D^\nu H + \frac{\mathcal{Q}_{H\Box}}{2} - \frac{\mathcal{Q}_{HWB}}{2t_\theta} + 2\mathcal{Q}_{HD} + \frac{\mathcal{Q}^{(1)}_{Hq}}{6} + \frac{2}{3}\mathcal{Q}_{Hu} - \frac{\mathcal{Q}_{Hd}}{3} - \frac{\mathcal{Q}^{(1)}_{Hl}}{2} - \mathcal{Q}_{He}$$

The flat directions are a linear superposition of these 2 vectors!

Remarks

The invariance is always there in $\bar{\psi}\psi \to \bar{\psi}\psi$,
but it does not show up as blind directions in some cases.

For example:

1. with a basis that includes $\{\mathcal{Q}_{HW},\ \mathcal{Q}_{HB},\ W^i_{\mu\nu}D^\mu H^\dagger\sigma^i D^\nu H,\ B_{\mu\nu}D^\mu H^\dagger D^\nu H\}$

   → the unconstrained directions are
   $W^i_{\mu\nu}D^\mu H^\dagger\sigma^i D^\nu H, \quad B_{\mu\nu}D^\mu H^\dagger D^\nu H$ themselves

   Han,Skiba 0412166

2. with a non gauge-invariant set of parameters. e.g. $\{g_1^Z, \kappa_Z, g_1^\gamma, \kappa_\gamma, \lambda, \dots\}$

   → the information contained in the EOM relations is lost.

relevant physical information is missing within this approach!

Check of input scheme independence

input parameters choice

$\{\alpha_{\rm em}, m_Z, G_F\}$ vs $\{m_W, m_Z, G_F\}$

↑ a very convenient scheme
for computing in the SMEFT!
(→ backup)

compared in a fit with a reduced set of observables:

Brivio, Trott 1701.06424

LEP1 + Bhabha scattering + LEP2 ($\bar\psi\psi \to WW \to \bar\psi\psi\bar\psi\psi$)

Results:

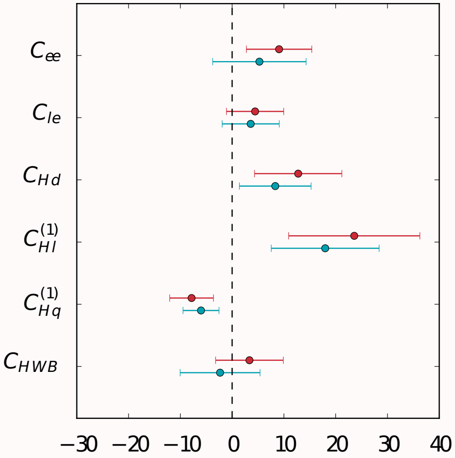
1. if $\bar\psi\psi \to \bar\psi\psi\bar\psi\psi$ is not included ⇒ flat directions compatible with the reparam. invariance structure. ✓

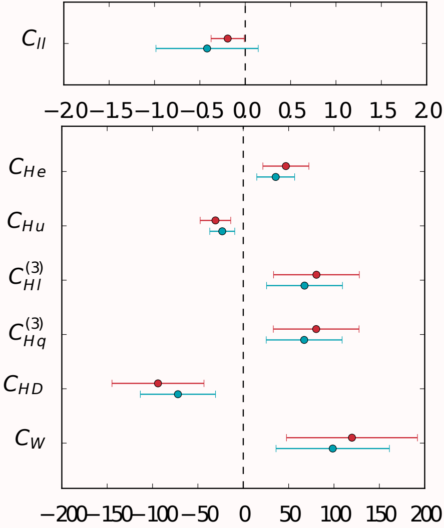
   NOT obvious a priori: $\alpha_{\rm em}$, m_Z come from $\bar\psi\psi \to \bar\psi\psi$

2. the constraints are **scheme dependent** but not worse than with the $\alpha_{\rm em}$ scheme

Comparison of fit results

1σ regions for $C_i\, v^2/\Lambda^2$ with $\Delta_{\rm SMEFT} = 0$
(after profiling over the others)
α scheme vs **m_W scheme**



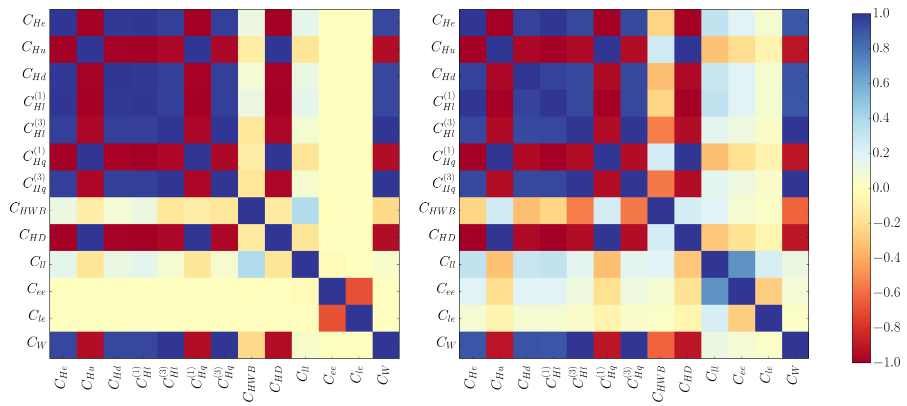


Comparison of fit results

Correlation matrices:

α scheme

m_W scheme



Summary

A **precision program** based on the EFT approach can and should be pursued at the LHC

needs:

- sufficient experimental **precision** (∼% on poles)
- **careful theoretical** treatment
  - pole observables are safer
  - include $\Delta_{\rm SMEFT}$
  - avoid 1-at-a-time
  - respect gauge invariance
  - SMEFT @ NLO...

Global fits to EWPD give 2 flat directions that can be understood in terms of a **reparameterization invariance**

→ broken in $\bar\psi\psi \to \bar\psi\psi\bar\psi\psi$ processes (TGC diagram)

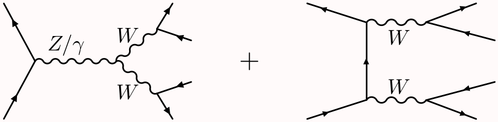
→ independent of the input scheme chosen

Backup slides

Focus on $\bar{\psi}\psi \to \bar{\psi}\psi\bar{\psi}\psi$

This process is relevant in EW fits!
So it needs to be computed as accurately as possible.

Berthier,Bjørn,Trott 1606.06502



Critical points:

1. better computing the full amplitude than using narrow width approx. (ensures gauge invariance)

2. even so, in the SMEFT:  $= \dfrac{1}{p^2 - m_{W0}^2 - \delta m_W^2}, \quad m_{W0} = \dfrac{\bar{g}\bar{v}}{2}$

one needs to expand ↓

$$\frac{1}{p^2 - m_{W0}^2}\left(1 + \frac{\delta m_W^2}{p^2 - m_{W0}^2}\right)$$

technically, we expand around a pole which is *not* the physical one. . .

this is not really gauge invariant!

m_W as an input parameter

Idea: if m_W was an input, the expansion would be around the physical pole

→ we can replace the usual $\{\alpha_{\rm em}, m_Z, G_F\}$ scheme with a $\{m_W, m_Z, G_F\}$

Brivio, Trott 1701.06424

other benefits

- easier loop calculations in the SMEFT
- smaller logs from perturbative corrections:
  m_W is measured at a scale closer to m_Z, m_h, m_t...

do we lose precision? not too much!

giving up $\alpha_{\rm em}$ for Z pole measurement is not a big deal

$\alpha_{\rm em}(0)^{-1} = 137.035999139(31)$ BUT $\alpha_{\rm em}(m_Z)^{-1} = 127.950 \pm 0.017$ (0.013%)

in the Thomson limit

$$\alpha_{\rm em}(m_Z) = \frac{\alpha_{\rm em}(0)}{1 - \Delta\alpha(m_Z)}$$

← large uncertainties, mainly from hadronic contribution

$m_W = 80.387 \pm 0.016$ GeV (0.019%)

(Tevatron combined)

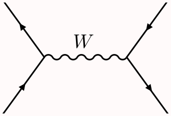
also: recently measured at LHC!

80.370 ± 0.019 GeV Atlas 1701.07240

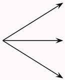
m_W as an input parameter

also: it has been checked that the Tevatron measurement of m_W does not have any experimental bias when applied to the SMEFT

Bjørn, Trott 1606.06502



transverse obs: $m_T, p_{T\ell}, \not{E}_T$



SMEFT corrections

δm_W

$\delta\Gamma_W$

δN (normalization)

the measurement is done in the SM: assumes $\delta\Gamma_W, \delta N \equiv 0$.

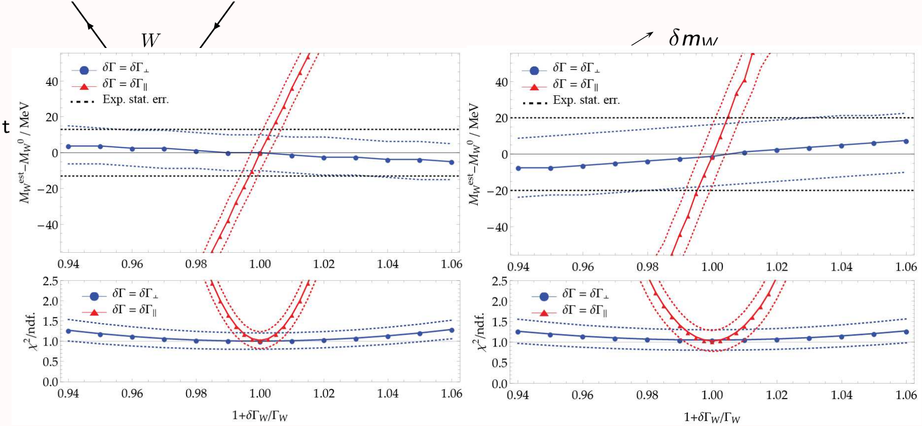
Is it still OK for $\delta\Gamma_W, \delta N \neq 0$? **YES!**

$\alpha_{\rm em}$ has not been checked, so it may require an extra theoretical error!

m_W as an input parameter

also: it has been checked that the Tevatron measurement of m_W does <u>not</u> have any experimental bias when applied to the SMEFT

Bjørn, Trott 1606.06502



$\alpha_{\rm em}$ has not been checked, so it may require an extra theoretical error!