The SMEFT framework

Ilaria Brivio

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based on 1701.06424, 1703.10924, 1709.06492 with Y. Jiang and M. Trott

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 (v/Λ or E/Λ):

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

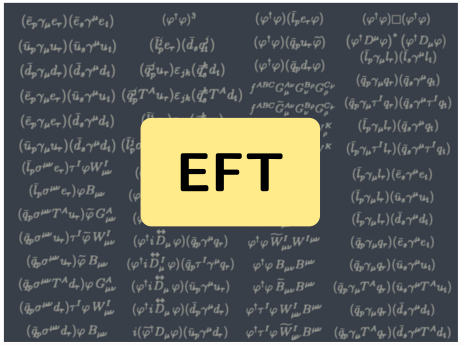
$\mathcal{L}_n = \sum_i C_i \mathcal{O}_i^{d=n}$

C_i free parameters (Wilson coefficients)

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

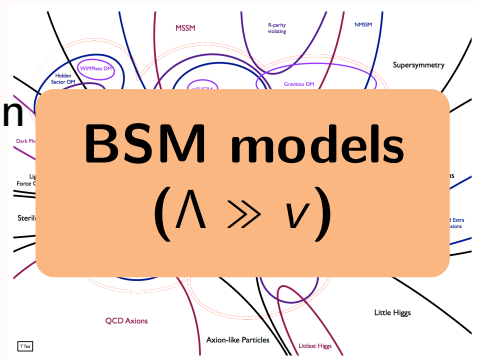
Why the SMEFT?

constraints



interpretation

matching



BSM models
($\Lambda \gg v$)

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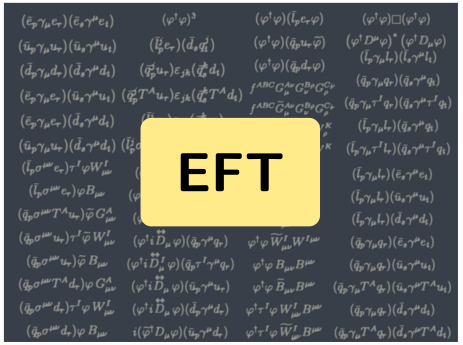

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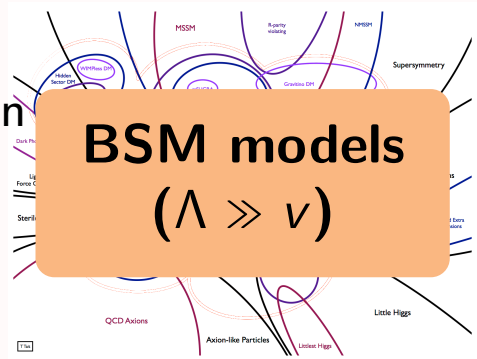

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the only QFT providing
a systematic classification of
all the UV effects compatible with
SM symmetries + field content

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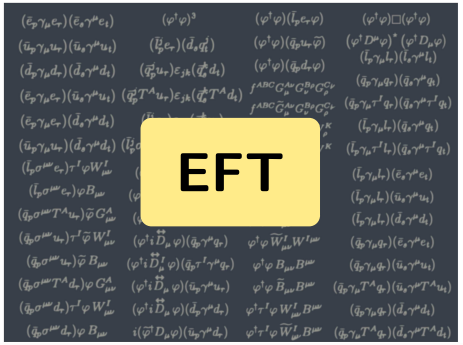

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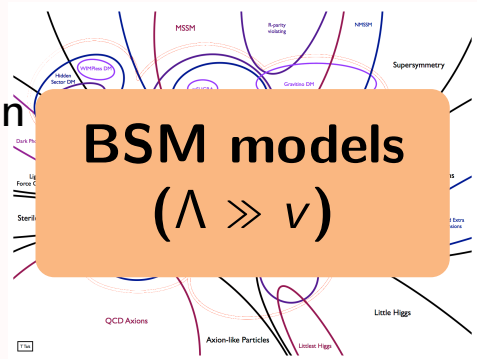

the only QFT providing
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knowledge of UV
<u>not</u> required

↓

well suited for the current situation

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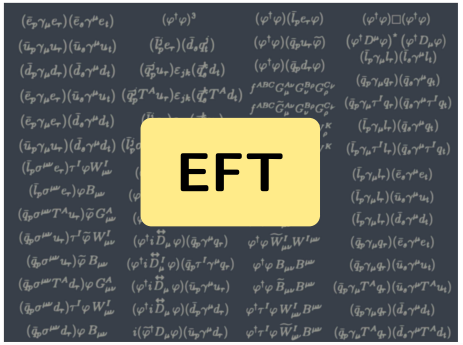

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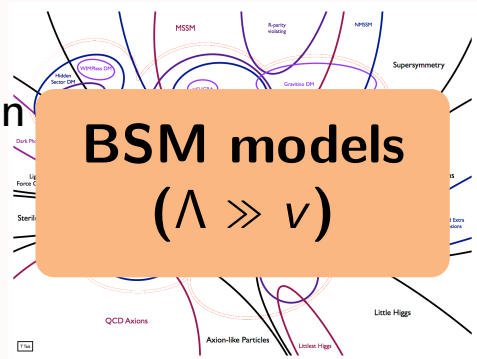

BSM models
($\Lambda \gg v$)

a **smart framework** for data recording and interpretation

the only QFT providing **a systematic classification** of all the UV effects compatible with SM symmetries + field content

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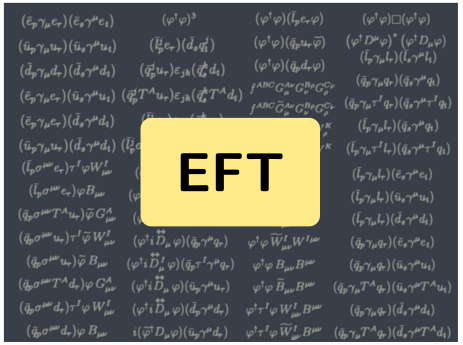
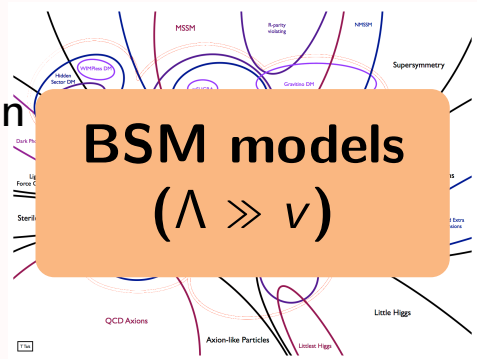


interpretation →

← matching



BSM models ($\Lambda \gg v$)

a **smart framework** for data recording and interpretation

↓

a general, powerful tool for handling future data

the only QFT providing **a systematic classification** of all the UV effects compatible with SM symmetries + field content

knowledge of UV <u>not</u> required

↓

well suited for the current situation

The SMEFT – where we are

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

The SMEFT – where we are

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

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

$N_f = 3 \rightarrow$	**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 – where we are

Weinberg PRL43(1979)1566

Lehman 1410.4193
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Leung,Love,Rao Z.Ph.C31(1986)433
Buchmüller,Wyler Nucl.Phys.B268(1986)621
Grzadkowski et al 1008.4884

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- complete bases available for $\mathcal{L}_5$, $\mathcal{L}_6$, $\mathcal{L}_7$

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$\mathcal{L}_5$: Majorana ν masses

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$\mathcal{L}_5$: Majorana ν masses

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

- complete RGE available

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

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- many tree-level calculations of Higgs / EW / flavor observables
- 1-loop results available for selected processes

Pruna,Signer 1408.3565
Hartmann,(Shepherd),Trott 1505.02646,1507.03568,1611.09879
Ghezzi,Gomez-Ambrosio,Passarino,Uccirati 1505.03706
Gauld,Pecjak,Scott 1512.02508
Deutschmann,Duhr,Maltoni,Vryonidou 1708.00460
Dawson,Giardino 1801.01136

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- 1-loop results available for selected processes
- formulation in R_ξ gauge

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

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- complete RGE available
- many tree-level calculations of Higgs / EW / flavor observables
- 1-loop results available for selected processes
- formulation in R_ξ gauge
- various tools available for numerical analysis

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

What's a basis?

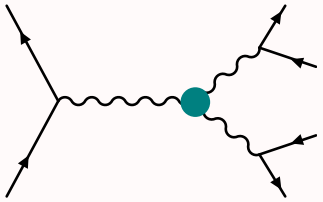
A complete parameterization of independent effects at the S-matrix level:

redundancies via **integration by parts** and **equations of motion** are removed.

The EOM equivalence is not intuitive sometimes.

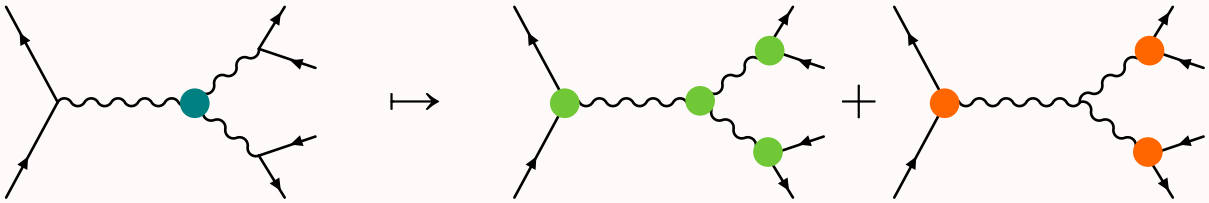
Example:

BSM model $\longrightarrow W^a_{\mu\nu} D^\mu H^\dagger \sigma^a D^\nu H$ affecting



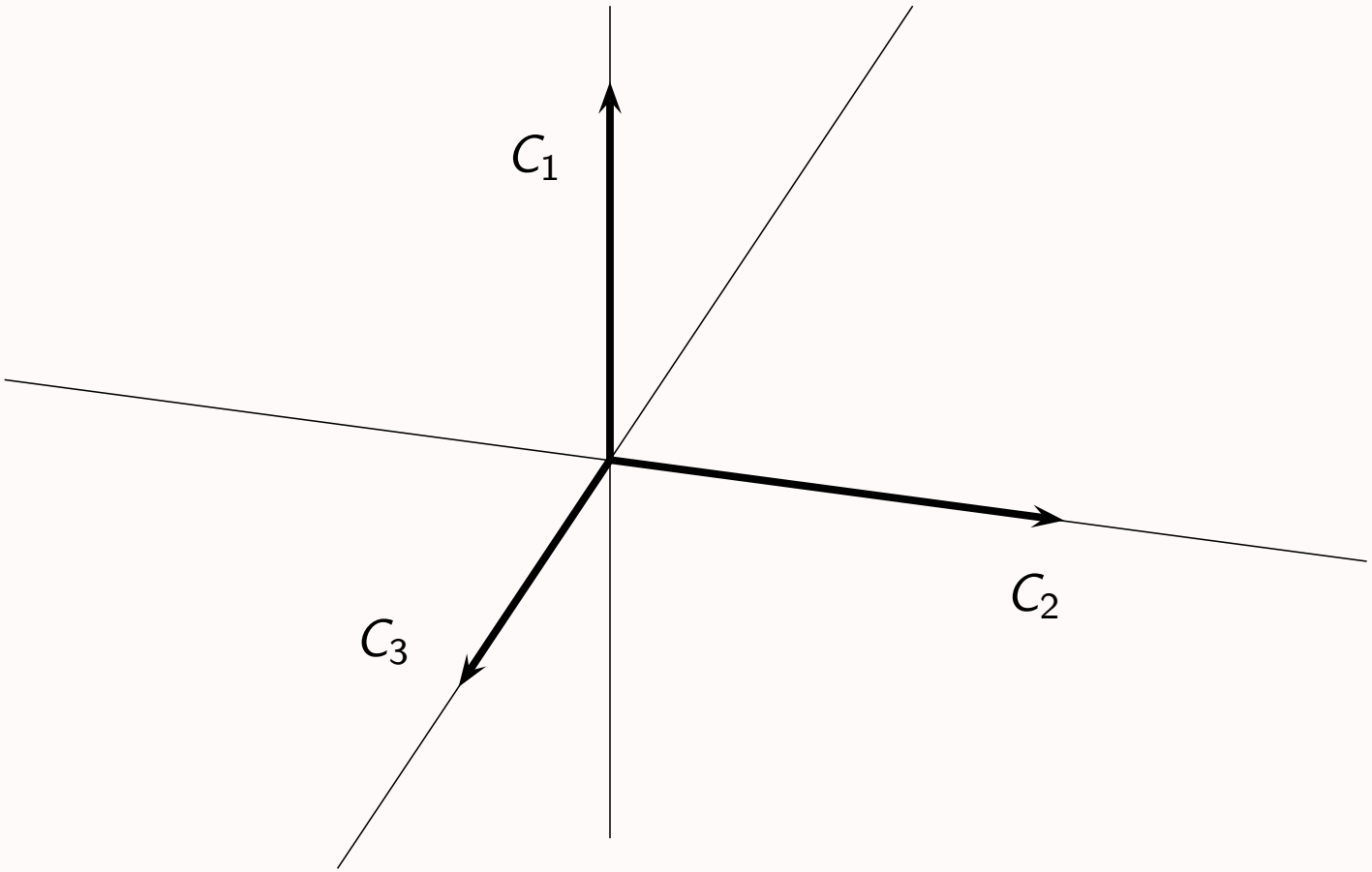
Using the Warsaw basis:

$$W^a_{\mu\nu} D^\mu H^\dagger \sigma^a D^\nu H \quad \mapsto \quad \mathcal{Q}_{HW},\ \mathcal{Q}_{HWB},\ \mathcal{Q}^{(3)}_{Hq},\ \mathcal{Q}^{(3)}_{Hl} + \text{Higgs ops.}$$



What's a basis?

We can think of it as a set of coordinates in a multidimensional space



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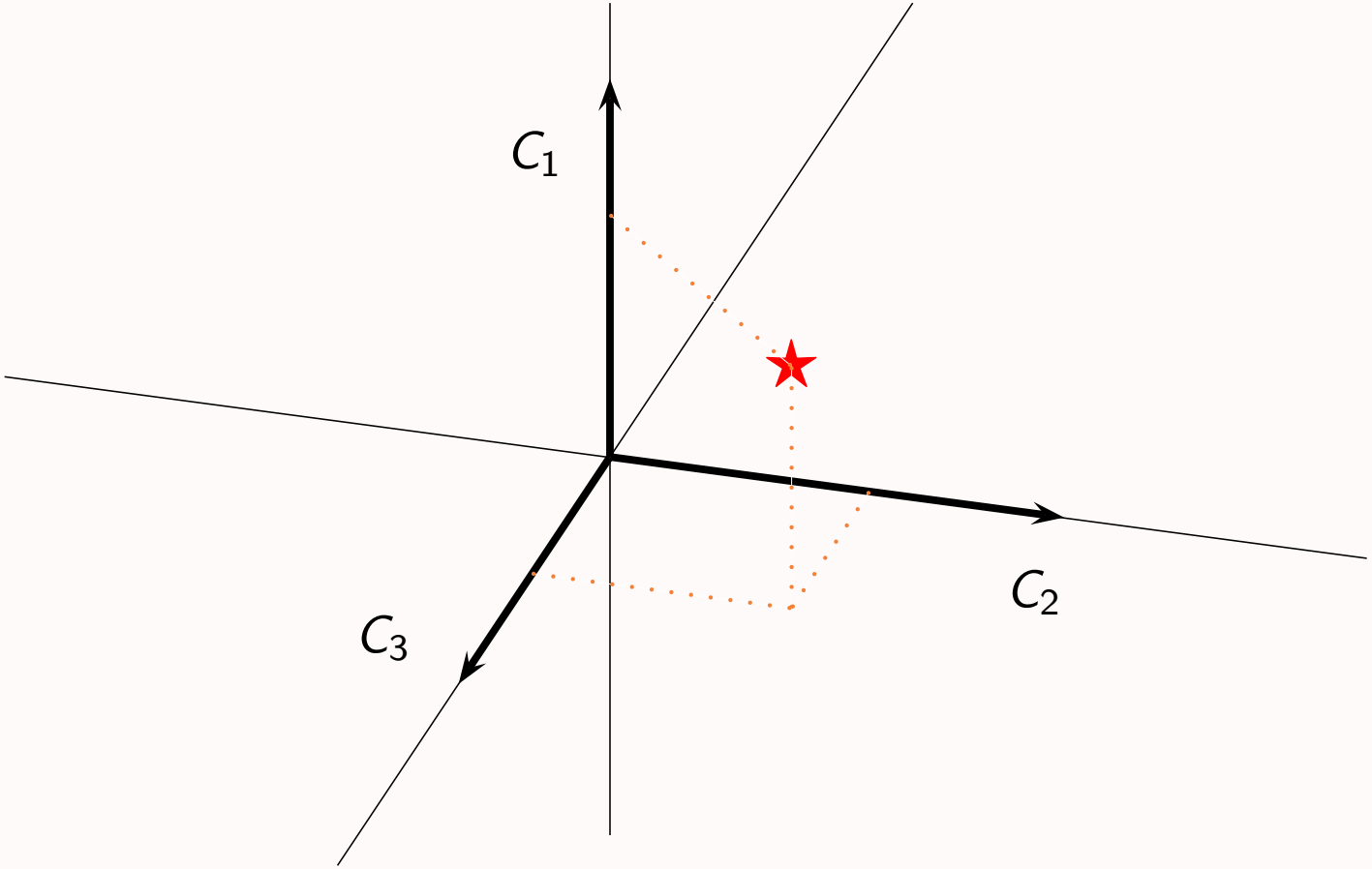

we want to know where we are!

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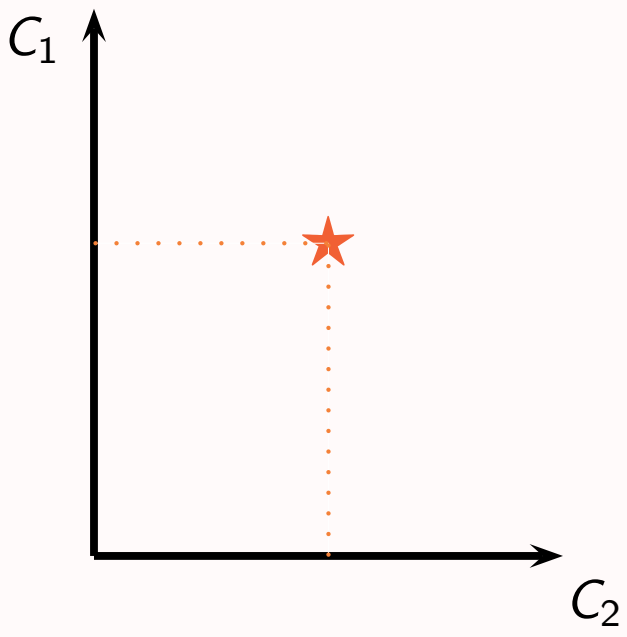
An important comment



What's a basis?

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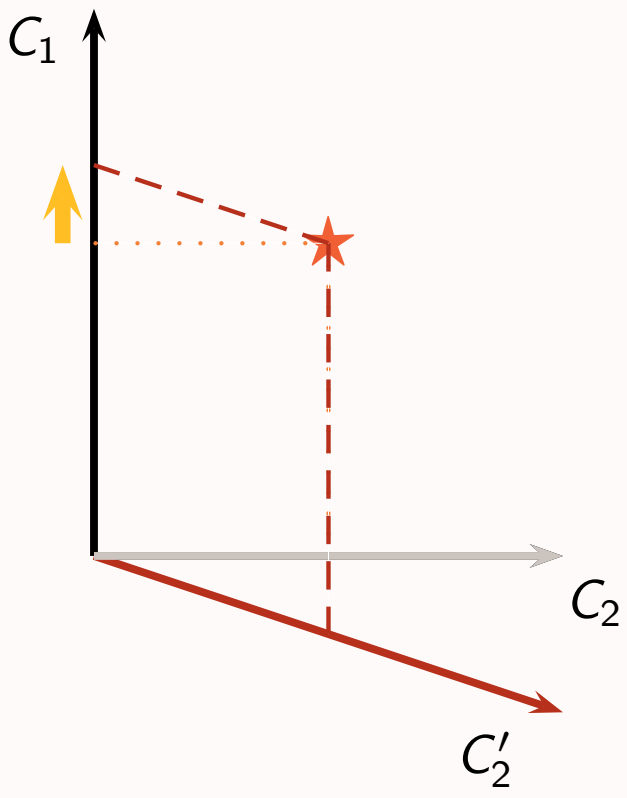
An important comment

the value of a coefficient
(and its physical meaning)
depends on how the rest of
the basis is chosen!

the complete set should
always be specified



The SMEFTsim package

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

Brivio, Jiang, Trott 1709.06492
feynrules.irmp.ucl.ac.be/wiki/SMEFT

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**

⇝ **backup**

3. automatic **parameter shifts** due to the choice of an input parameters set

Main scope:

estimate **tree-level** $|\mathcal{A}_{SM}\mathcal{A}^*_{d=6}|$ **interference** terms → theo. accuracy ∼ %

* at the moment only LO, unitary gauge implementation

The SMEFTsim package

We implemented 6 different frameworks

Brivio, Jiang, Trott 1709.06492

③ flavor structures $\left\{ \begin{array}{l} \text{general} \\ U(3)^5 \text{ symmetric} \\ \text{linear MFV} \end{array} \right.$ $\times$ ② input schemes $\left\{ \begin{array}{l} \hat{\alpha}_{\rm em}, \hat{m}_Z, \hat{G}_f \\ \hat{m}_W, \hat{m}_Z, \hat{G}_f \end{array} \right.$

in 2 independent, equivalent models sets (A, B): best for debugging and validation

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

wiki: SMEFT

Standard Model Effective Field Theory -- The SMEFTsim package

Authors

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

Pre-exported UFO files (include restriction cards)

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

A global ongoing effort

The Wilson coefficients of the SMEFT are been constrained by several groups

Just in the last years:

very incomplete list!

Corbett et al. 1207.1344 1211.4580 1304.1151 1411.5026 1505.05516

Ciuchini,Franco,Mishima,Silvestrini 1306.4644

de Blas et al. 1307.5068, 1410.4204, 1608.01509, 1611.05354, 1710.05402

Pomarol, Riva 1308.2803

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

Ellis,Sanz,You 1404.3667 1410.7703

Falkowski,Riva 1411.0669

Falkowski,Gonzalez-Alonso,Greljo,Marzocca 1508.00581

Berthier,(Bjørn),Trott 1508.05060, 1606.06693

Englert,Kogler,Schulz,Spannowsky 1511.05170 13 TeV update → see Raquel's talk

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

Freitas,López-Val,Plehn 1607.08251

Falkowski,Golzalez-Alonso,Greljo,Marzocca,Son 1609.06312

Krauss,Kuttimalai,Plehn 1611.00767

Ellis,Murphy,You,Sanz 1803.03252

...

Constraining the SMEFT space

Ideally: a giant global fit to very precise measurements where all the C_i are free parameters

In practice: we can only do partial fits because of

- limited computational possibilities
- insufficient # of measurements
- insufficient experimental accuracy
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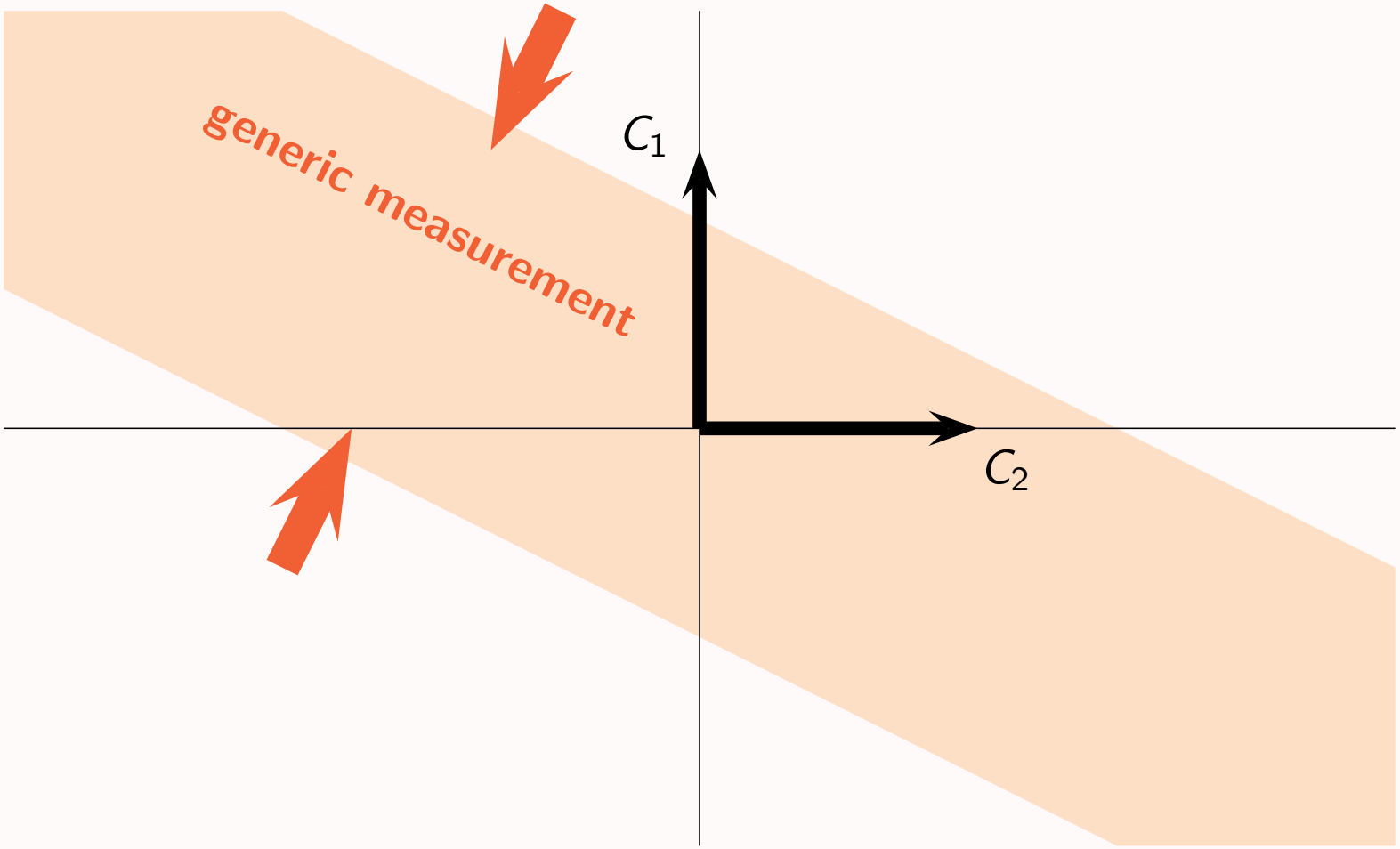
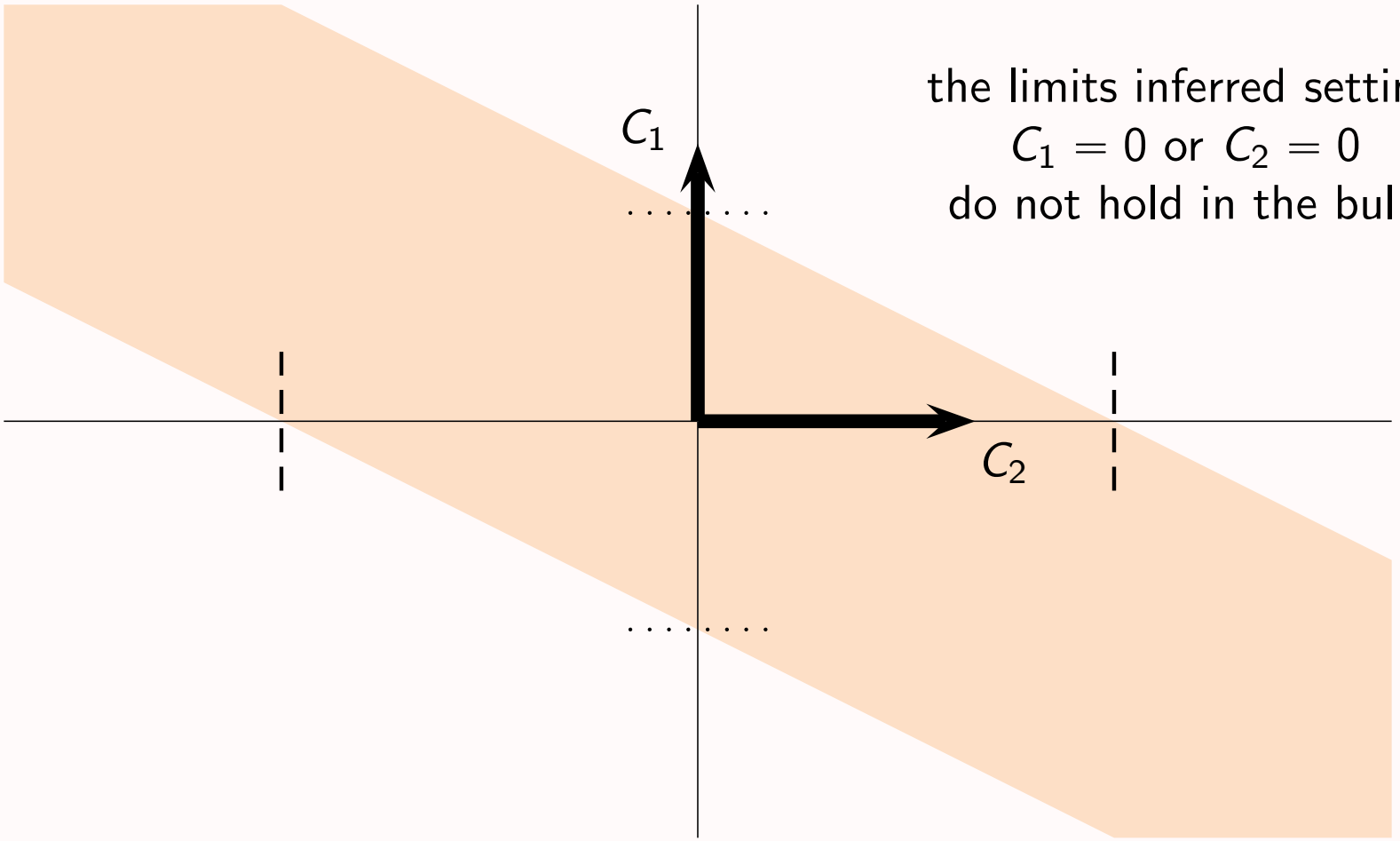
can we drop many parameters and still find where we are?

YES, choosing smart observables!

Constraining the EFT space

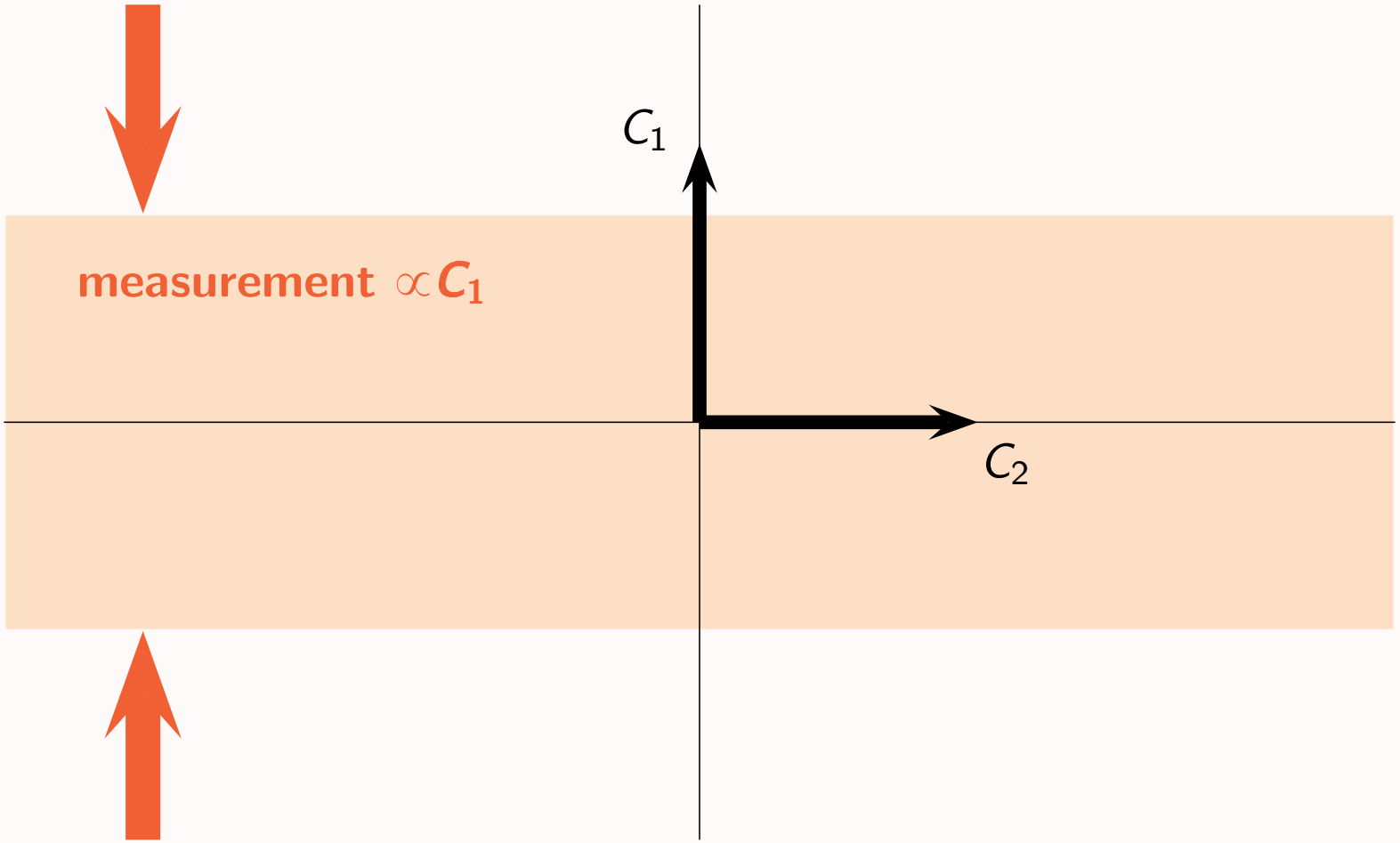


Constraining the EFT space



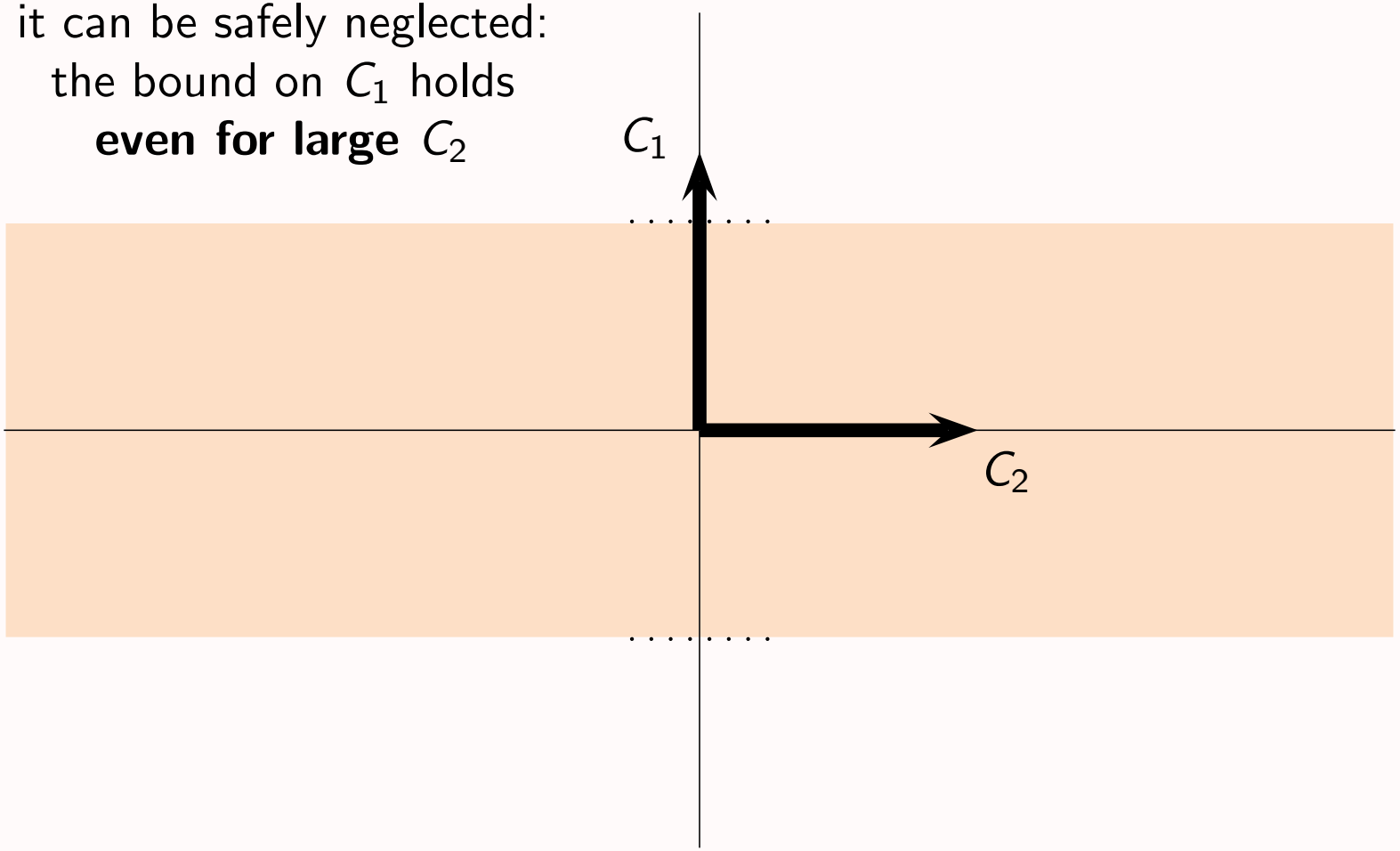
the limits inferred setting
$C_1 = 0$ or $C_2 = 0$
do not hold in the bulk

Constraining the EFT space



Constraining the EFT space

if C_2 does not modify the observable,
it can be safely neglected:
the bound on C_1 holds
even for large C_2



Generalizing to a multidimensional case

We need a set of observables sensitive <u>only</u> to a limited subset $\{\bar{C}_i\}$

$\downarrow$

the constraints inferred on $\{\bar{C}_i\}$ hold **in general**, independently of the orthogonal directions

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☛ Task: design observables to isolate the dependence on given operators.

Identifying convenient observables

Main idea:

the dominant effect should be the **tree-level interference** $|\mathcal{A}_{SM}\mathcal{A}^*_{d=6}| \sim \frac{C_i}{\Lambda^2}$.

whenever this is suppressed, the coefficient C_i *can be neglected* even if $C_i \neq 0$

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Interference is suppressed, e.g.:

- in specific kinematic regions. e.g. for ψ^4 ops. close to W, Z, h **poles**

Identifying convenient observables

Example – close to a pole

Brivio, Jiang, Trott 1709.06492

most ψ^4 operators give diagrams with less resonances

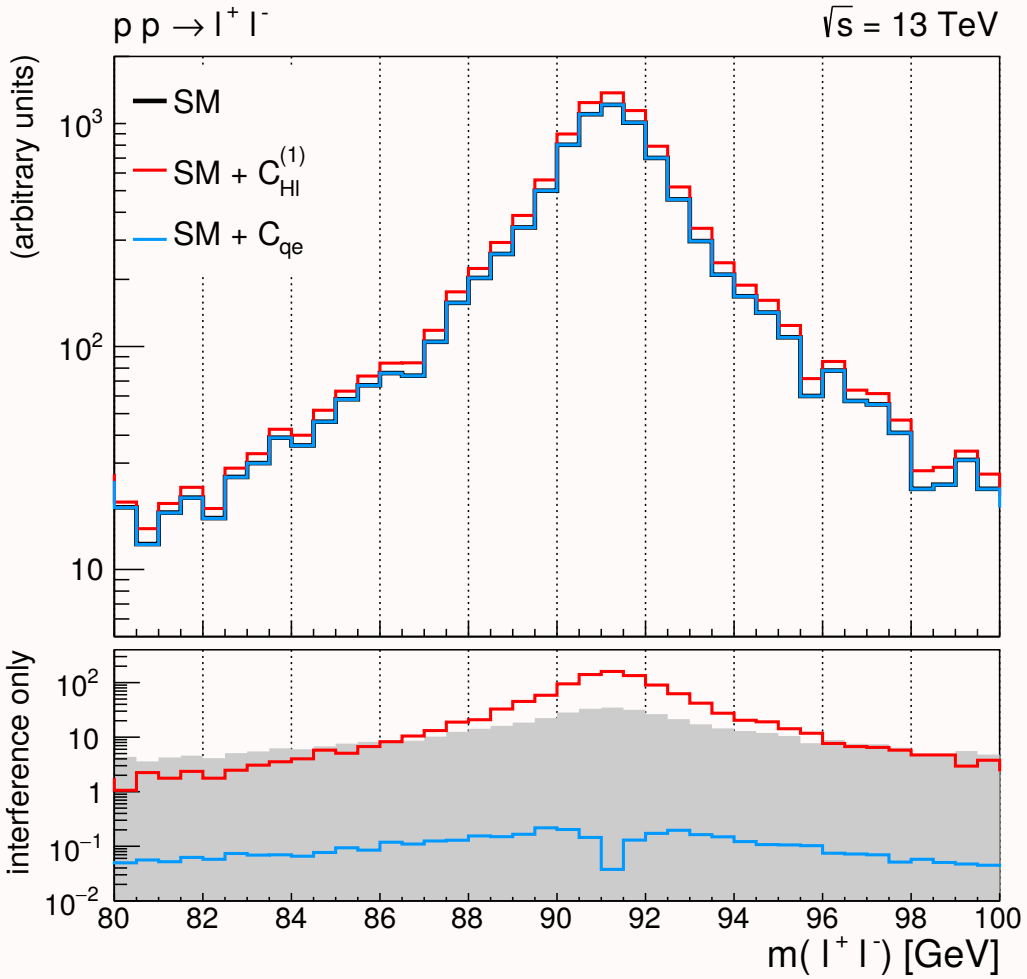
expected to be **suppressed** wrt. "pole operators" by

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

$B = \{Z, W, h\}$

$n = \#$ missing resonances

Drell-Yan via Z resonance ➜



Identifying convenient observables

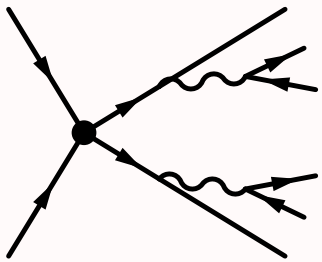
Example – close to a pole

Brivio, Jiang, Trott 1709.06492

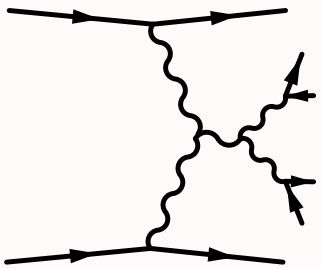
most ψ^4 operators give diagrams with less resonances

! Not *always* the case. The impact must be checked case by case

E.g. VBS



vs



the 4-fermion diagram is not removed by poles selection.

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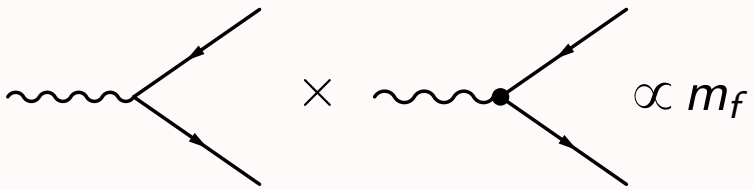
- if $\propto m_f$

Example: dipole operators can be neglected for $f \neq t, b$



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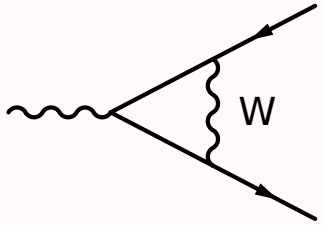
- if $\propto m_f$
- for operators inducing FCNC

$\mathcal{A}_{SM}$ is very suppressed:



$$\sim \frac{m_j^2 V_{jk}^* V_{ji}}{32\pi^2 m_W^2}$$

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- ...

Brivio,Jiang,Trott 1709.06492

	total $N_f = 3$	WZH poles
general	2499	~ 46
MFV	~ 108	~ 30
$U(3)^5$	~ 70	~ 24

The counts reduce significantly!

WZH pole parameters

Breakdown for the $U(3)^5$ flavor symmetric case:

Class	Parameters	$N_f = 3$
1	$C_W \in \mathbb{R}$	1
3	$\{C_{HD}, C_{H\Box}\} \in \mathbb{R}$	2
4	$\{C_{HG}, C_{HW}, C_{HB}, C_{HWB}\} \in \mathbb{R}$	4
5	$\{C_{uH}, C_{dH}\} \in \mathbb{R}$	~ 2
6	$\{C_{uW}, C_{uB}, C_{uG}, C_{dW}, C_{dB}, C_{dG}\} \in \mathbb{R}$	~ 6
7	$\{C_{Hl}^{(1)}, C_{Hl}^{(3)}, C_{Hq}^{(1)}, C_{Hq}^{(3)}, C_{He}, C_{Hu}, C_{Hd}\} \in \mathbb{R}$,	~ 7
8	$\{C_{ll}, \mathcal{C}_{ll}\} \in \mathbb{R}$	2
	Total Count	~ 24

a **combination** of different classes of observables is required to access all the 24 parameters

Road-map and challenges

Towards a general EFT analysis of precision measurements:

1. Complete a "WHZ poles program"

   Brivio, Jiang, Trott 1709.06492

   - design optimized experimental analyses

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Brivio, Jiang, Trott 1709.06492

Experimental precision needed

On poles: NP impact $\sim \frac{v^2 g}{M^2} = \frac{v^2}{\Lambda^2}$

UV coupling to SM

mass of new resonances

EFT cutoff

$$g \simeq 1 \quad M \gtrsim 2 - 3 \text{ TeV} \rightarrow 1\%$$

(LHC reach)

On tails: NP impact $\sim \frac{E^2 g}{M^2} = \frac{E^2}{\Lambda^2} \rightarrow$ few - tens %

Road-map and challenges

Towards a general EFT analysis of precision measurements:

1. Complete a "WHZ poles program" Brivio, Jiang, Trott 1709.06492
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   difficulties:
   - many parameters involved ($(\bar{\psi}\psi)^2$ operators)
   - EFT validity issues

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   Brivio, Jiang, Trott 1709.06492

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   difficulties:
   - many parameters involved ($(\bar{\psi}\psi)^2$ operators)
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3. Improve the accuracy of SMEFT predictions

   - better treatment of theoretical uncertainties due to neglected higher orders + radiative corrections, initial/final state radiation etc
   - new statistical tools to make the most out of the fit information

     Brehmer, Cranmer, Kling, Plehn 1612.05261, 1712.02350
     Murphy 1710.02008

     see Felix's talk yesterday

   - loop calculations in the SMEFT
   - inclusion of $d = 8$ operators (construct a basis!)

Further goals to keep in mind: SMEFT vs HEFT

The SMEFT is not the only EFT that extends the SM!

Important alternative: **HEFT**

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Main idea: the Higgs does not need to be in a doublet

Appelquist, Bernard PRD22 200
Longhitano PRD22 1166
Nucl.Phys.B188 118

$$H = \frac{v+h}{\sqrt{2}} \mathbf{U} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

h

independent

$\mathbf{U} = e^{i\pi^I \sigma^I / v}$

treated as a singlet
with arbitrary couplings

$$\mathcal{F}(h) = 1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \dots$$

Grinstein, Trott 0704.1505
Contino 1005.4269

adimensional

derivative expansion $\sim \chi$PT

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Grinstein, Trott 0704.1505
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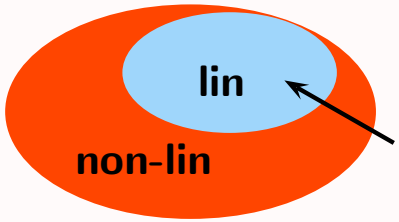
adimensional

derivative expansion $\sim \chi$PT

$\longrightarrow$ a **very general** EFT



contains the SMEFT
as a particular limit

$\longrightarrow$ matches composite Higgs models + other UVs with significant **nonlinear** effects in the EWSB sector (dilaton, inflaton...)

Further goals to keep in mind: SMEFT vs HEFT

The HEFT has seen a very intense development recently:

Operator basis & pheno	Buchalla et al. 1203.6510 1307.5017 1310.2574 1511.00988
	Alonso et.al. 1212.3305 Brivio et al. 1311.1823 1405.5412 1604.06801 Gavela et.al. 1406.6367 1409.1571 Hierro et al. 1510.07899 Merlo et al. 1612.04832
	Delgado et al. 1308.1629 1311.5993 1404.2866 1609.06206 Dobado et al. 1507.06386
	Corbett et al 1511.08188
Power counting	Buchalla et al. 1312.5624 1603.03062 Gavela et al. 1601.07551
Renormalization and RGE	Gavela et al. 1409.1571 Buchalla et al. 1710.06412 Alonso,Kanshin,Saa 1710.06848
Relation to specific scenarios	Alonso et al. 1409.1589 Feruglio et al. 1603.05668 Gavela et al. 1610.08083 Hernández-Leon,Merlo 1703.02064

Further goals to keep in mind: SMEFT vs HEFT

SMEFT and HEFT are intrinsically different

identifying which of the two describes Nature
would give fundamental insights in the origin of EWSB

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Key measurements

- Higgs+gauge couplings and their (de)correlations
- high-E region of processes with external V_L. VBS is particularly important

see Jakob's talk

Complications

- larger # of parameters
- require looking at tails and/or comparing $n \geqslant 2$ measurements

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see if the SMEFT breaks down

a general and accurate SMEFT analysis is needed!

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Backup slides

Field redefinitions

Gauge bosons

$$\mathcal{L}_{\rm SMEFT} \supset -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W^I_{\mu\nu}W^{I\mu\nu} - \frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} +$$
$$+ C_{HB}(H^\dagger H)B_{\mu\nu}B^{\mu\nu} + C_{HW}(H^\dagger H)W^I_{\mu\nu}W^{I\mu\nu} + C_{HWB}(H^\dagger\sigma^I H)W^I_{\mu\nu}B^{\mu\nu}$$
$$+ C_{HG}(H^\dagger H)G^a_{\mu\nu}G^{a\mu\nu}$$

to have **canonically normalized kinetic terms** we need to

1. redefine fields and couplings keeping (gV_μ) unchanged:

$$\begin{aligned} \mathcal{B}_\mu &\to B_\mu(1 + C_{HB}v^2) & g_1 &\to g_1(1 - C_{HB}v^2) \\ \mathcal{W}^I_\mu &\to W^I_\mu(1 + C_{HW}v^2) & g_2 &\to g_2(1 - C_{HW}v^2) \\ \mathcal{G}^a_\mu &\to G^a_\mu(1 + C_{HG}v^2) & g_s &\to g_s(1 - C_{HG}v^2) \end{aligned}$$

2. correct the rotation to mass eigenstates:

$$\begin{pmatrix} \mathcal{W}^3_\mu \\ \mathcal{B}_\mu \end{pmatrix} = \begin{pmatrix} 1 & -v^2 C_{HWB}/2 \\ -v^2 C_{HWB}/2 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix}$$

(equivalent to a shift of the Weinberg angle)

Alonso, Jenkins, Manohar, Trott 1312.2014

Field redefinitions

Higgs

$$\mathcal{L}_{\rm SMEFT} \supset \frac{1}{2} D_\mu H^\dagger D^\mu H + C_{H\Box}(H^\dagger H)(H^\dagger \Box H) + C_{HD}(H^\dagger D_\mu H)^*(H^\dagger D^\mu H)$$

to have a canonically normalized kinetic term, in unitary gauge, we need to replace

$$h \to h\left(1 + v^2 C_{H\Box} - \frac{v^2}{4} C_{HD}\right)$$

Alonso, Jenkins, Manohar, Trott 1312.2014

Shifts from input parameters

SM case.

Parameters in the canonically normalized Lagrangian : $\bar{v}, \bar{g}_1, \bar{g}_2, s_{\bar{\theta}}$

The values can be inferred from the measurements e.g. of $\{\alpha_{\rm em}, m_Z, G_f\}$:

$$\alpha_{\rm em} = \frac{\bar{g}_1 \bar{g}_2}{\bar{g}_1^2 + \bar{g}_2^2} \qquad m_Z = \frac{\bar{g}_2 \bar{v}}{2 c_{\bar{\theta}}} \qquad G_f = \frac{1}{\sqrt{2}\bar{v}^2} \quad \rightarrow \quad \begin{aligned} \hat{v}^2 &= \frac{1}{\sqrt{2} G_f} \\ \sin\hat{\theta}^2 &= \frac{1}{2}\left(1 - \sqrt{1 - \frac{4\pi\alpha_{\rm em}}{\sqrt{2} G_f m_Z^2}}\right) \\ \hat{g}_1 &= \frac{\sqrt{4\pi\alpha_{\rm em}}}{\cos\hat{\theta}} \\ \hat{g}_2 &= \frac{\sqrt{4\pi\alpha_{\rm em}}}{\sin\hat{\theta}} \end{aligned}$$

in the SM at tree-level $\bar{\kappa} = \hat{\kappa}$

Shifts from input parameters

SMEFT case.

Parameters in the canonically normalized Lagrangian : $\bar{v}, \bar{g}_1, \bar{g}_2, s_{\bar{\theta}}$

The values can be inferred from the measurements e.g. of $\{\alpha_{\rm em}, m_Z, G_f\}$:

$$\alpha_{\rm em} = \frac{\bar{g}_1 \bar{g}_2}{\bar{g}_1^2 + \bar{g}_2^2}\left[1 + \bar{v}^2 C_{HWB} \frac{\bar{g}_2^3/\bar{g}_1}{\bar{g}_1^2 + \bar{g}_2^2}\right]$$

$$m_Z = \frac{\bar{g}_2 \bar{v}}{2 c_{\bar{\theta}}} + \delta m_Z(C_i)$$

$$G_f = \frac{1}{\sqrt{2}\bar{v}^2} + \delta G_f(C_i)$$

$$\rightarrow$$

$$\hat{v}^2 = \frac{1}{\sqrt{2} G_f}$$

$$\sin\hat{\theta}^2 = \frac{1}{2}\left(1 - \sqrt{1 - \frac{4\pi\alpha_{\rm em}}{\sqrt{2} G_f m_Z^2}}\right)$$

$$\hat{g}_1 = \frac{\sqrt{4\pi\alpha_{\rm em}}}{\cos\hat{\theta}}$$

$$\hat{g}_2 = \frac{\sqrt{4\pi\alpha_{\rm em}}}{\sin\hat{\theta}}$$

in the SM at tree-level $\bar{\kappa} = \hat{\kappa}$

in the SMEFT $\bar{\kappa} = \hat{\kappa} + \delta\kappa(C_i)$

Shifts from input parameters

To have numerical predictions it is necessary to replace $\bar{\kappa} \to \hat{\kappa} + \delta\kappa(C_i)$ for all the parameters in the Lagrangian.

$\{\alpha_{\rm em}, m_Z, G_f\}$ scheme

$$\delta m_Z^2 = m_Z^2 \hat{v}^2 \left(\frac{c_{HD}}{2} + 2 c_{\hat{\theta}} s_{\hat{\theta}} c_{HWB} \right)$$

$$\delta G_f = \frac{\hat{v}^2}{\sqrt{2}} \left((c_{Hl}^{(3)})_{11} + (c_{Hl}^{(3)})_{22} - (c_{ll})_{1221} \right)$$

$$\delta g_1 = \frac{s_{\hat{\theta}}^2}{2(1-2s_{\hat{\theta}}^2)} \left(\sqrt{2}\delta G_f + \delta m_Z^2/m_Z^2 + 2\frac{c_{\hat{\theta}}^3}{s_{\hat{\theta}}} c_{HWB} \hat{v}^2 \right)$$

$$\delta g_2 = -\frac{c_{\hat{\theta}}^2}{2(1-2s_{\hat{\theta}}^2)} \left(\sqrt{2}\delta G_f + \delta m_Z^2/m_Z^2 + 2\frac{s_{\hat{\theta}}^3}{c_{\hat{\theta}}} c_{HWB} \hat{v}^2 \right)$$

$$\delta s_\theta^2 = 2 c_{\hat{\theta}}^2 s_{\hat{\theta}}^2 (\delta g_1 - \delta g_2) + c_{\hat{\theta}} s_{\hat{\theta}} (1 - 2 s_{\hat{\theta}}^2) c_{HWB} \hat{v}^2$$

$$\delta m_h^2 = m_h^2 \hat{v}^2 \left(2 c_{H\Box} - \frac{c_{HD}}{2} - \frac{3 c_H}{2 lam} \right)$$

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$$\delta G_f = \frac{\hat{v}^2}{\sqrt{2}} \left((c_{Hl}^{(3)})_{11} + (c_{Hl}^{(3)})_{22} - (c_{ll})_{1221} \right)$$

$$\delta g_1 = -\frac{1}{2} \left(\sqrt{2} \delta G_f + \frac{1}{s_{\hat{\theta}}^2} \frac{\delta m_Z^2}{m_Z^2} \right)$$

$$\delta g_2 = -\frac{1}{\sqrt{2}} \delta G_f$$

$$\delta s_\theta^2 = 2 c_{\hat{\theta}}^2 s_{\hat{\theta}}^2 (\delta g_1 - \delta g_2) + c_{\hat{\theta}} s_{\hat{\theta}} (1 - 2 s_{\hat{\theta}}^2) c_{HWB} \hat{v}^2$$

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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_h^0
- 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 - 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 $V_{i,j} = \Delta_i^{\rm exp} \rho_{ij}^{\rm exp} \Delta_j^{\rm exp} + \Delta_i^{\rm th} \rho_{ij}^{\rm th} \Delta_j^{\rm th}$

error on O_i

correlation mat.

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

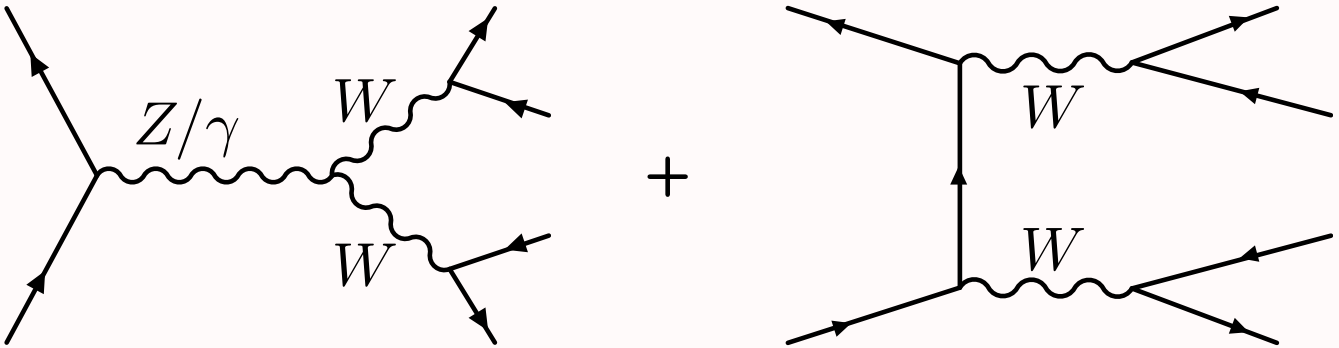
Adding $\bar{\psi}\psi \to \bar{\psi}\psi\bar{\psi}\psi$ production from LEP2

Berthier, Bjørn, Trott 1606.06693

177 observables

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

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



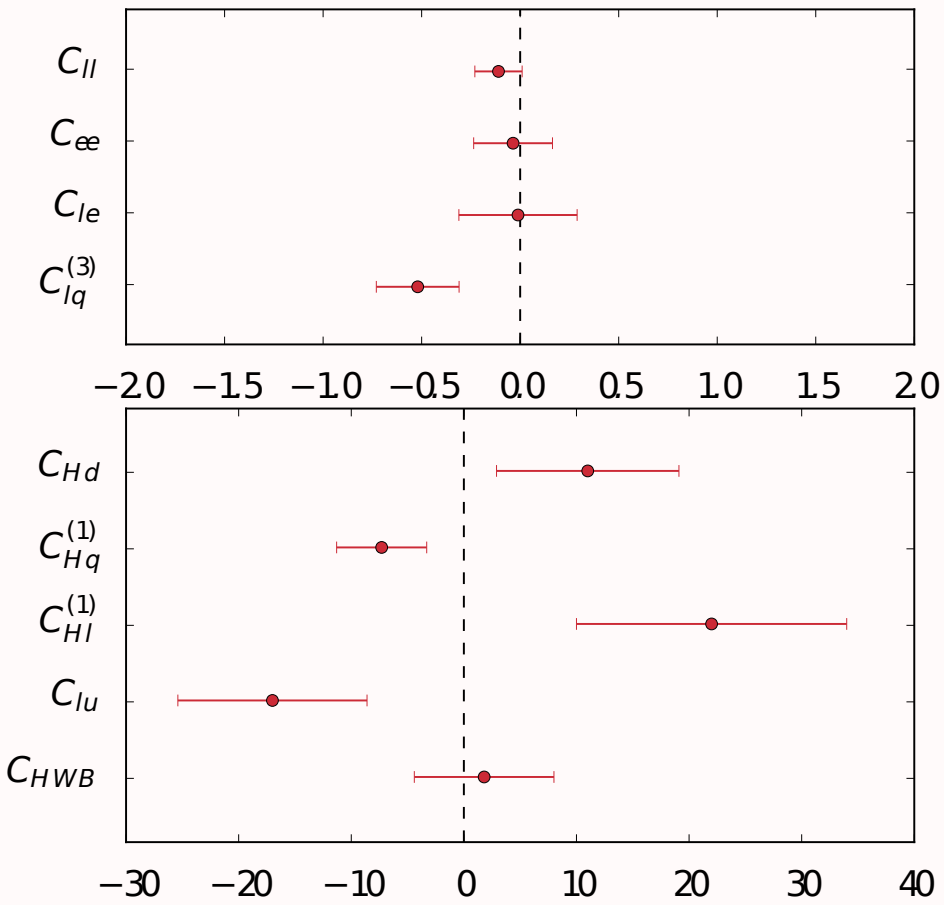
→ **the flat directions are lifted** → we can set constraints on all the C_i

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

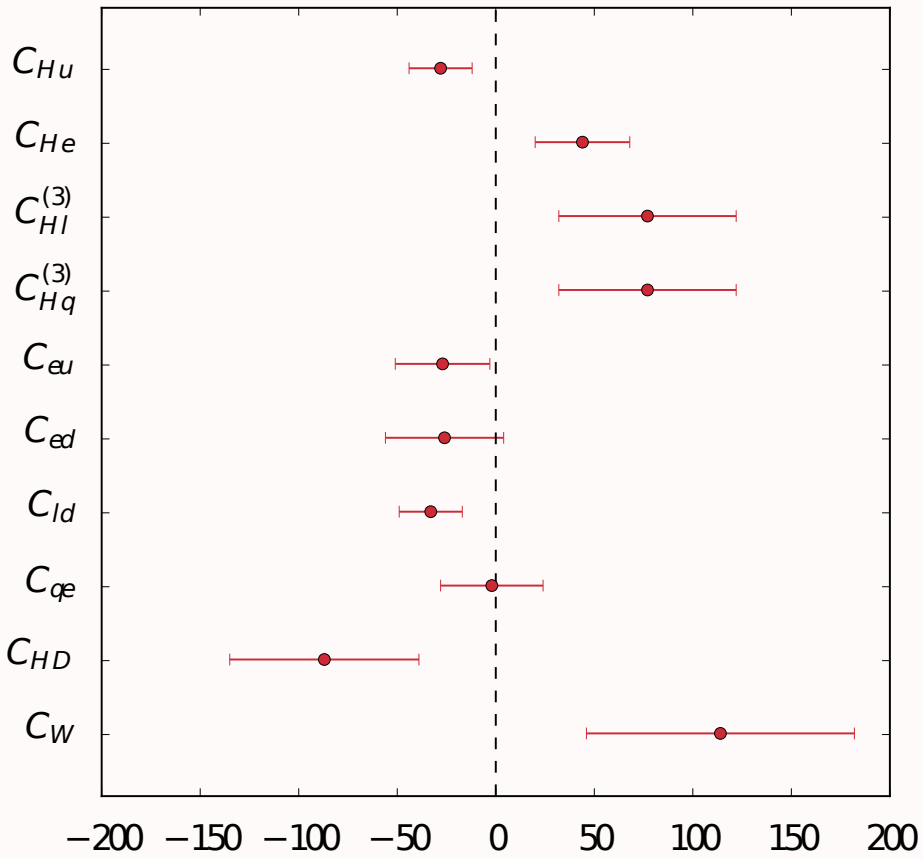
Berthier, Bjørn, Trott 1606.06693

177 observables

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



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



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

Berthier, Bjørn, Trott 1606.06693

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The EFT approach goes beyond the S, T, U analysis

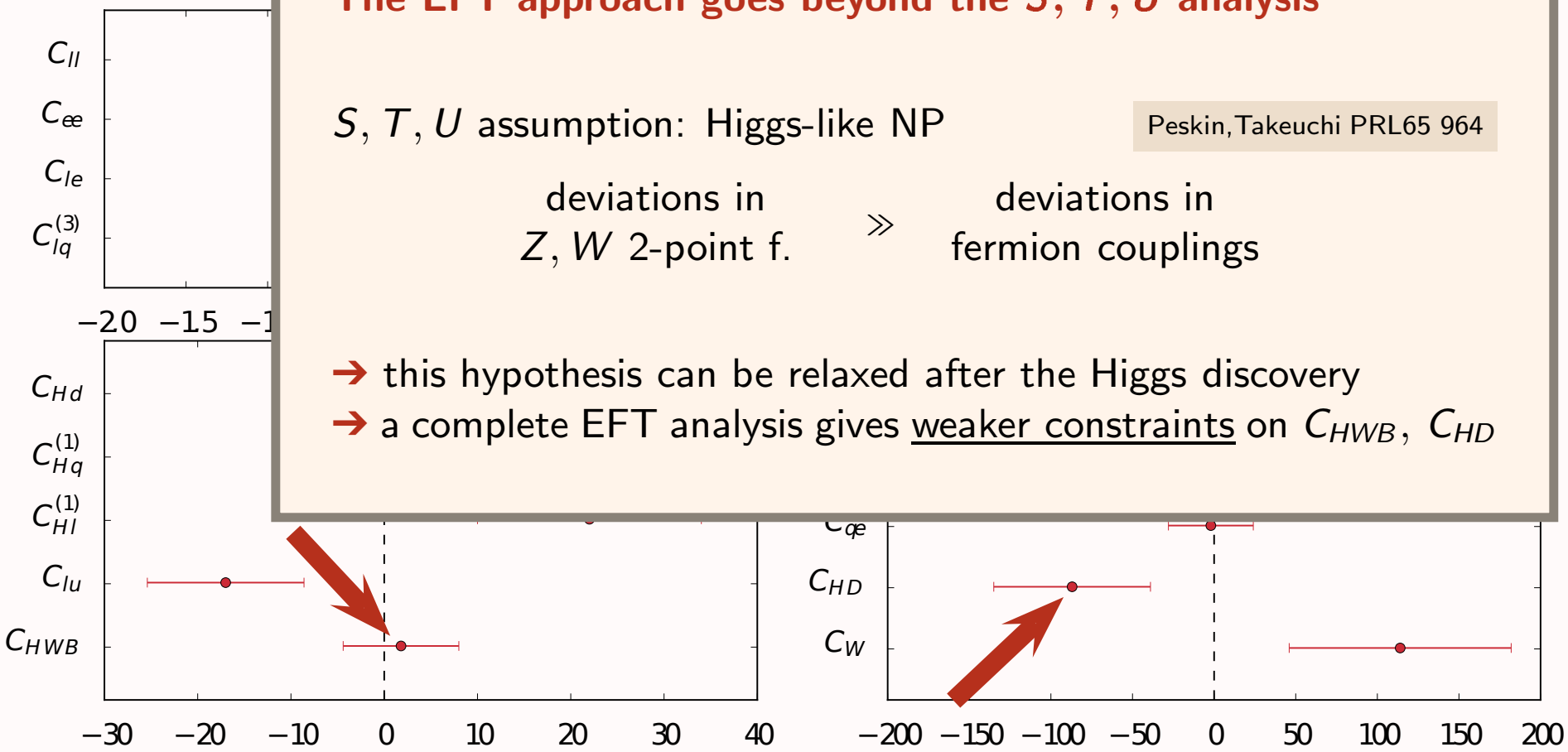
S, T, U assumption: Higgs-like NP

Peskin, Takeuchi PRL65 964

deviations in Z, W 2-point f. $\gg$ deviations in fermion couplings

➔ this hypothesis can be relaxed after the Higgs discovery

➔ a complete EFT analysis gives <u>weaker constraints</u> on C_{HWB}, C_{HD}



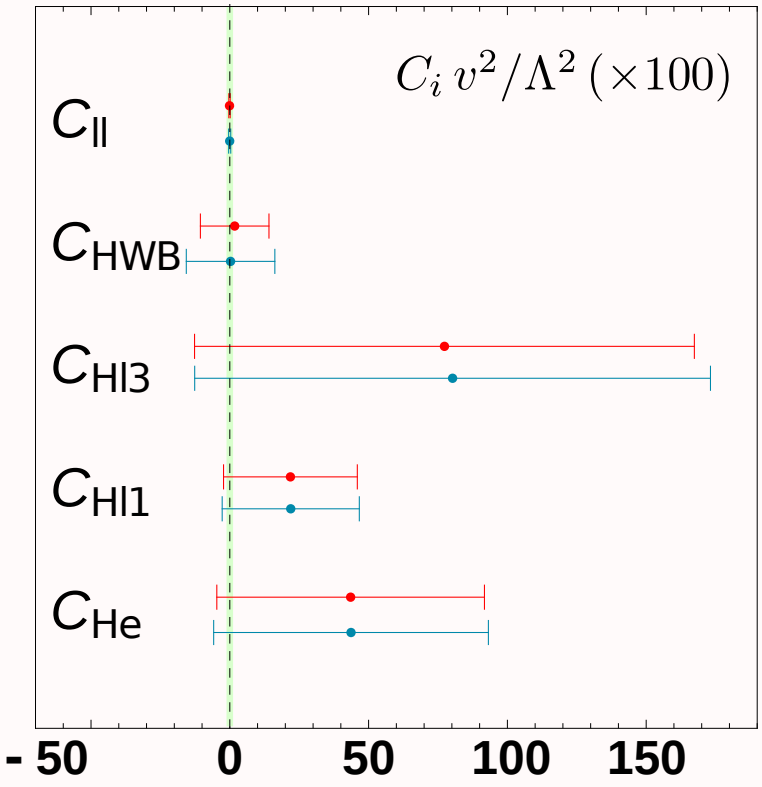
Adding $\bar{\psi}\psi \to \bar{\psi}\psi\bar{\psi}\psi$ production from LEP2

Berthier, Bjørn, Trott 1606.06693

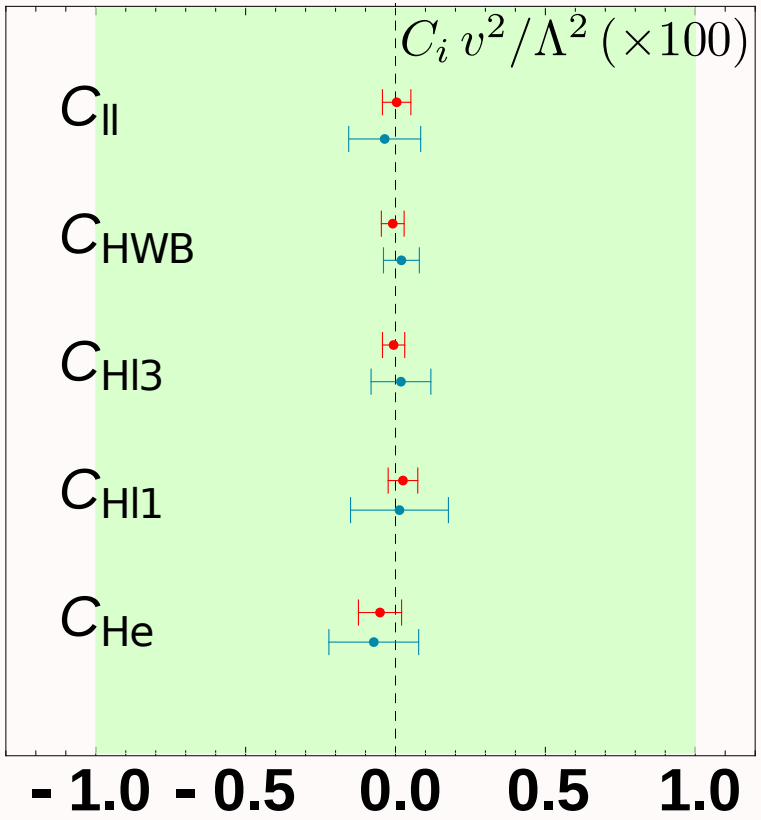
177 observables

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

2σ regions



profiling over the others



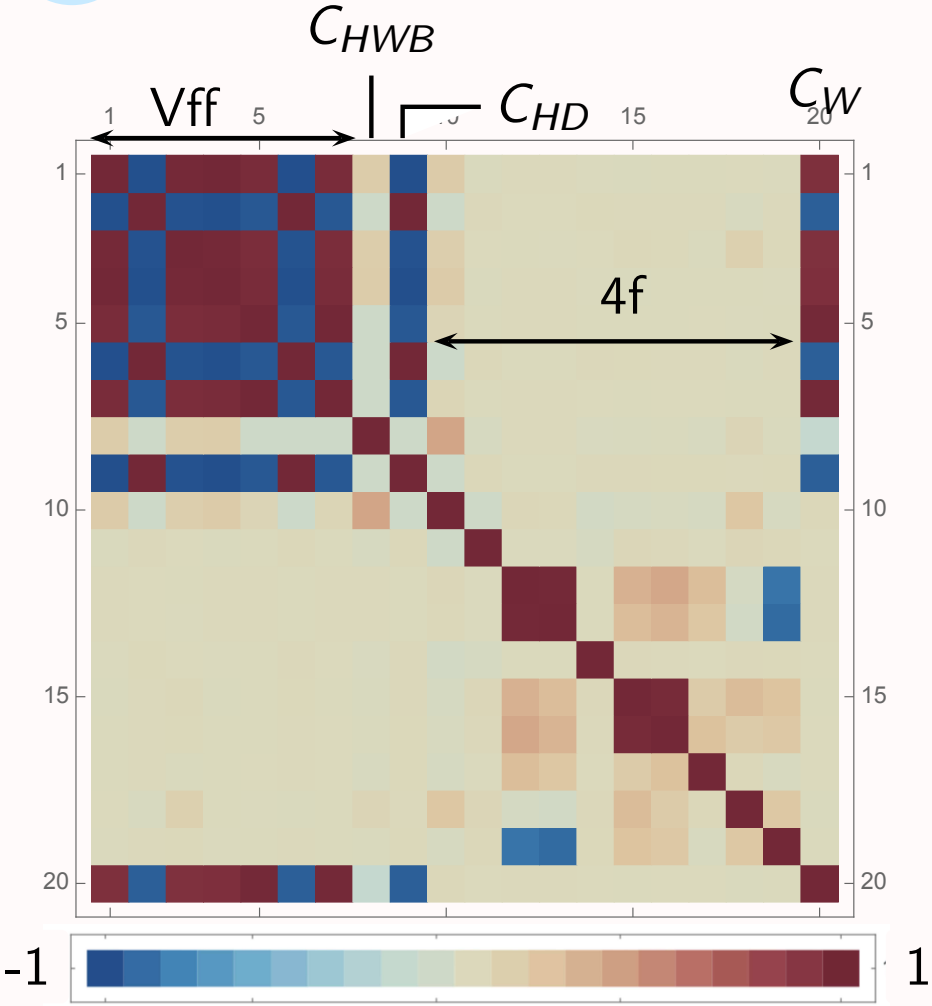
for comparison:
one coefficient at a time

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 + $U(3)^5$



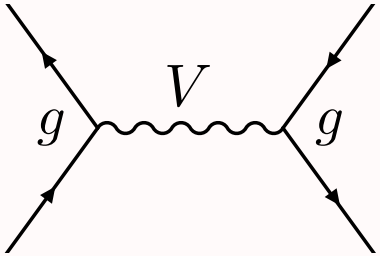
the fit space is **highly correlated**

removing one or more coefficients breaks the correlation, affecting dramatically the constraints

Understanding the unconstrained directions

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

Brivio, Trott 1701.06424



$$V_{\mu\nu}V^{\mu\nu} + g\bar{\psi}\gamma^\mu\psi V_\mu \xrightarrow[(*)\ V_\mu \to V_\mu(1+\varepsilon),\ g \to g/(1+\varepsilon)]{} (1+2\varepsilon)V_{\mu\nu}V^{\mu\nu} + g\bar{\psi}\gamma^\mu\psi V_\mu + \mathcal{O}(\varepsilon^2)$$

non canonical kinetic term.
$\to$ OK adjusting LSZ

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

the S-matrix has a reparameterization invariance

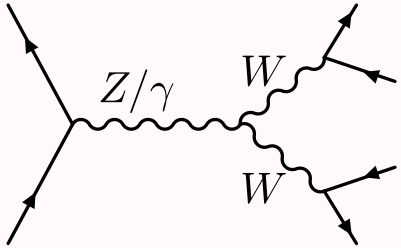
operators modifying the kinetic term normalization have <u>no</u> impact here

$\updownarrow$

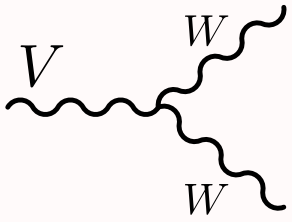
these C_i can be removed from the amplitude via $(*)$

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

NOT invariant!

induce shifts that
<u>cannot</u> 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

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Grojean,Skiba,Terning 0602154

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

not constrained in $2 \to 2$	$+$	**not affecting** $2 \to 2$	$\Rightarrow$	flat direction
not constrained in $2 \to 4$	$+$	**probed in** $2 \to 4$	$\Rightarrow$	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

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

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Grojean,Skiba,Terning 0602154

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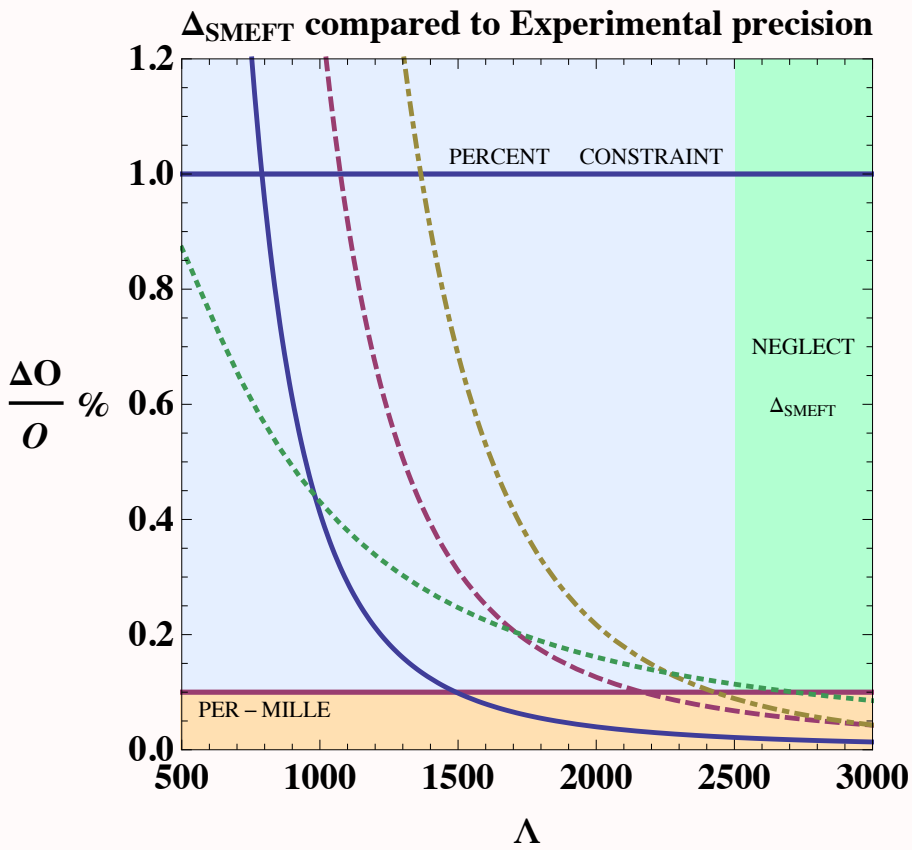
$$\frac{\mathcal{Q}_{HB}}{2} = \frac{2i}{g'} B_{\mu\nu} D^\mu H^\dagger D^\nu H + \frac{\mathcal{Q}_{H\Box}}{2} - \frac{\mathcal{Q}_{HWB}}{2t_\theta} + 2\mathcal{Q}_{HD} + \frac{\mathcal{Q}^{(1)}_{Hq}}{6} + \frac{2}{3}\mathcal{Q}_{Hu} - \frac{\mathcal{Q}_{Hd}}{3} - \frac{\mathcal{Q}^{(1)}_{Hl}}{2} -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

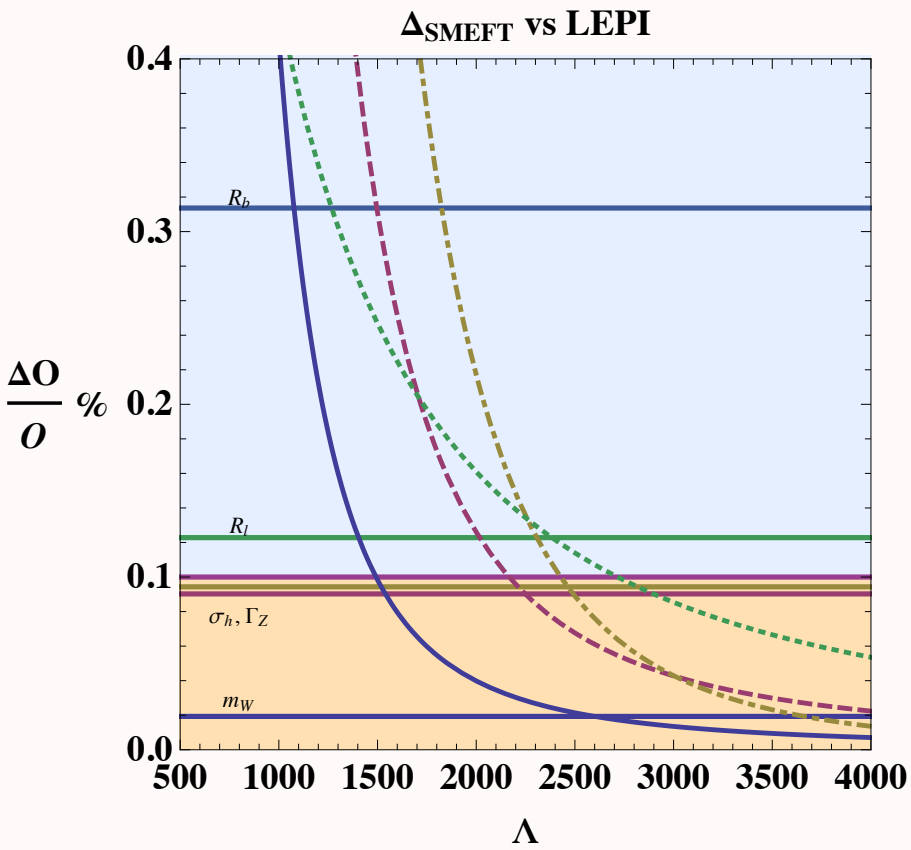
The flat directions are a linear superposition of these 2 vectors!

This result has been checked using two **inp**
$\{\alpha_{\rm ew}, m_Z, G_F\}$ and $\{m_W,$

$\Delta_{\rm SMEFT}$

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





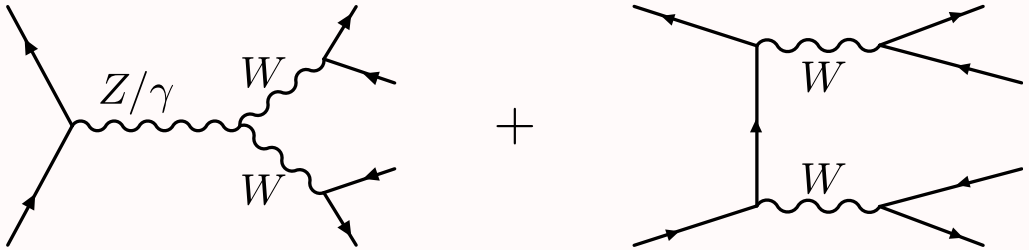
Berthier, Trott 1508.05060

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

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: $\sim\sim\sim\sim = \dfrac{1}{p^2 - m_{W0}^2 - \delta m_W^2}, \quad m_{W0} = \dfrac{\bar{g}\,\bar{v}}{2}$

one needs to expand $\downarrow$

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

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)

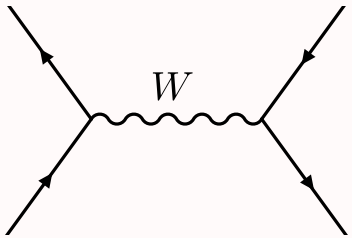
also: recently measured at LHC!

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 <u>not</u> 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 $\rightarrow$ δm_W, $\delta \Gamma_W$, δN (normalization)

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

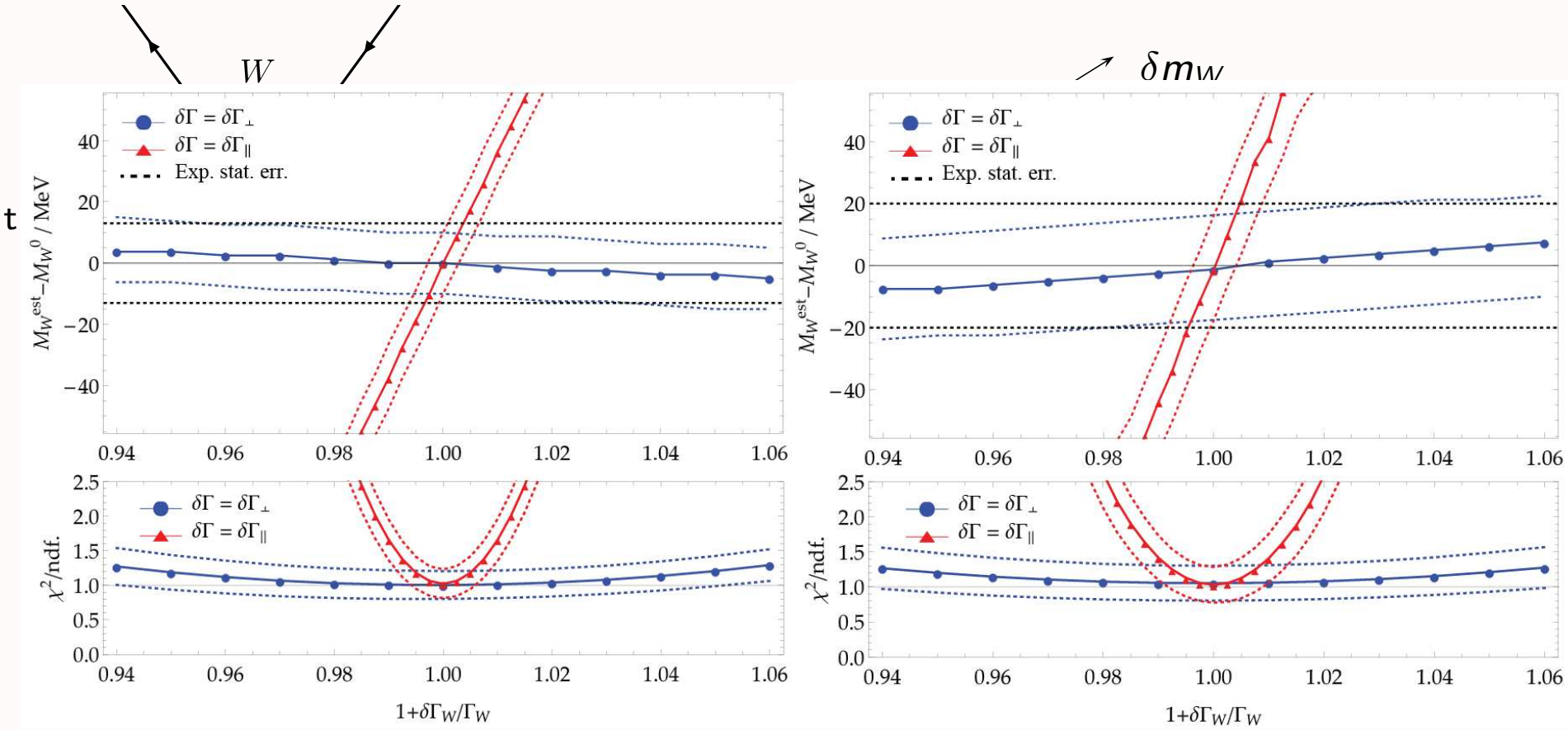
Is it still OK for $\delta\Gamma_W, \delta N \neq 0$? **YES!**

$\alpha_{\rm em}$ 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 not 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!

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:

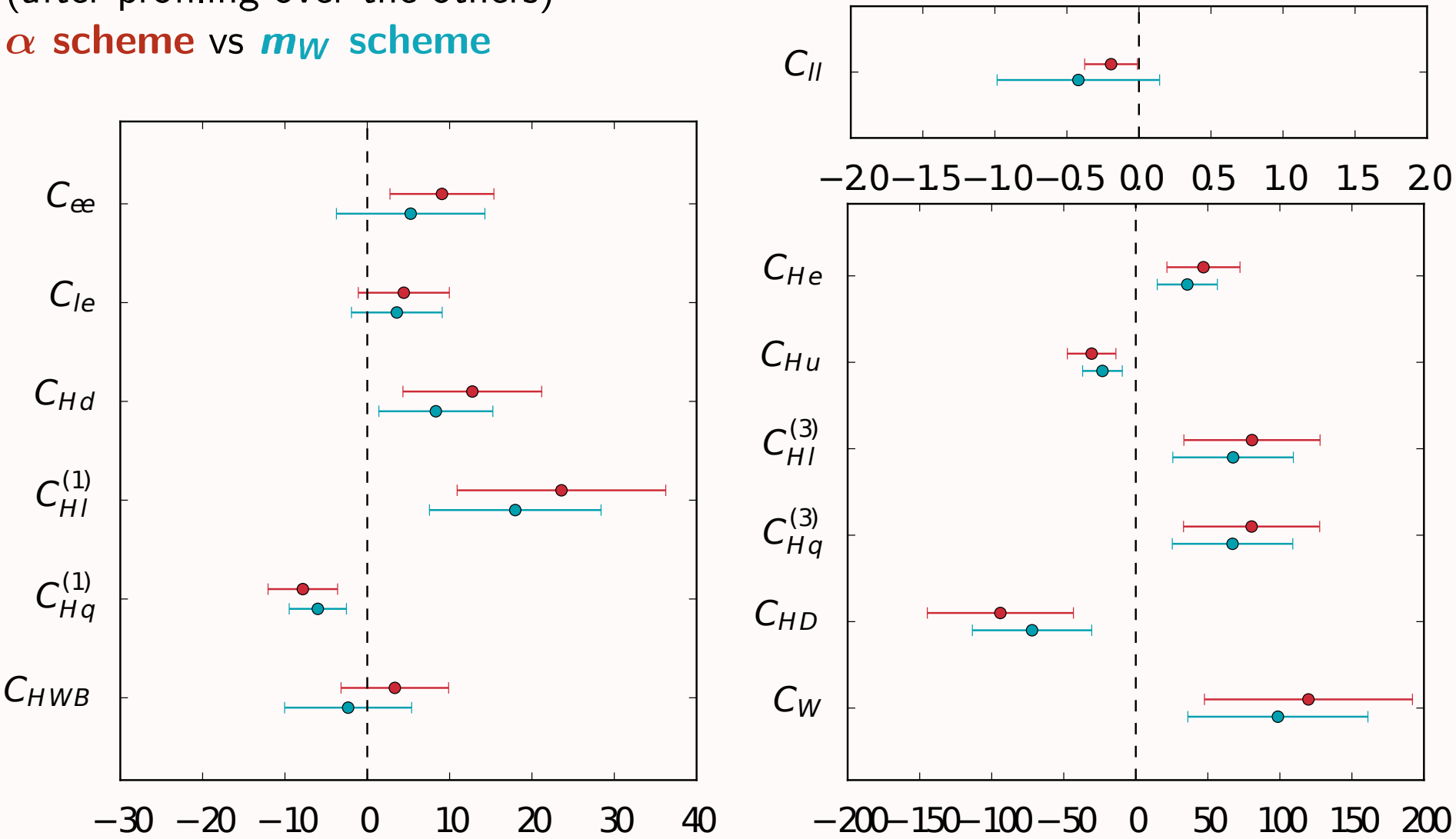
1. if $\bar\psi\psi \to \bar\psi\psi\bar\psi\psi$ is not included ⇒ flat directions compatible with the reparam. invariance structure.

   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

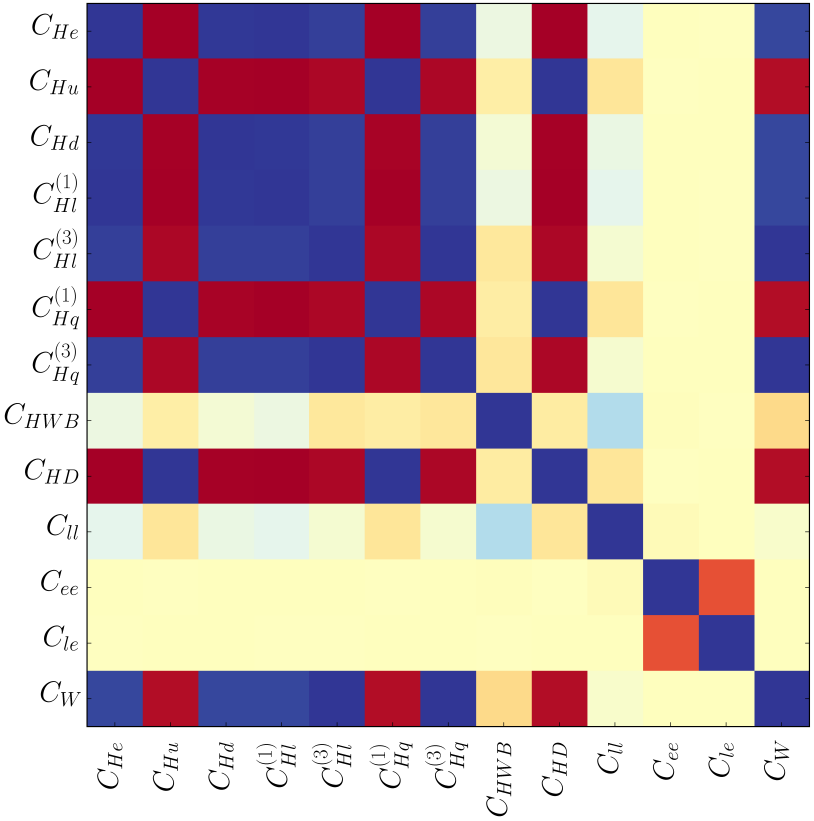
1σ regions for $C_i\, v^2/\Lambda^2$ with $\Delta_{\rm SMEFT} = 0$
(after profiling over the others)
α scheme vs **m_W scheme**



Comparison of fit results

Correlation matrices:

α scheme



m_W scheme