Shedding light on new physics with Effective Field Theories

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What is an Effective Field Theory?

A pragmatic definition:

it's a field theory that describes the **IR limit** of an underlying UV sector in terms of only the light degrees of freedom

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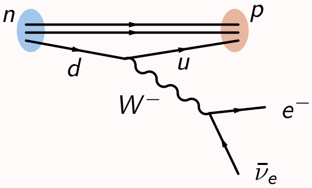
A classical example: **Fermi's interaction** for β-decays

"True" theory: Electroweak interactions



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it's a field theory that describes the **IR limit** of an underlying UV sector in terms of only the light degrees of freedom

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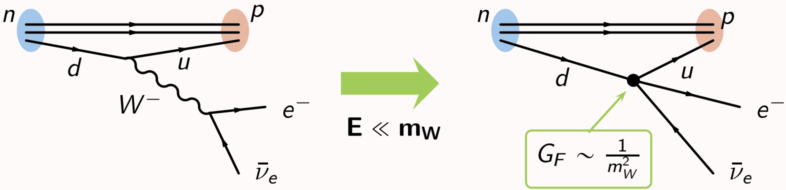
EFT: Fermi's interactions



$$\mathcal{A}\left(\frac{1}{m_W^2}\right)$$

$$\mathcal{A}(0) + \frac{1}{m_W^2}\left(\times \quad + \dots \right) + \mathcal{O}\left(m_W^{-4}\right)$$

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):

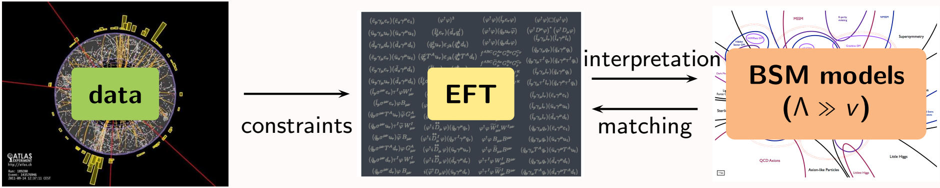
$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \dots$$

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

C_i free parameters (Wilson coefficients)

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

Why the SMEFT?



data constraints **EFT**

interpretation

matching

BSM models
($\Lambda \gg v$)

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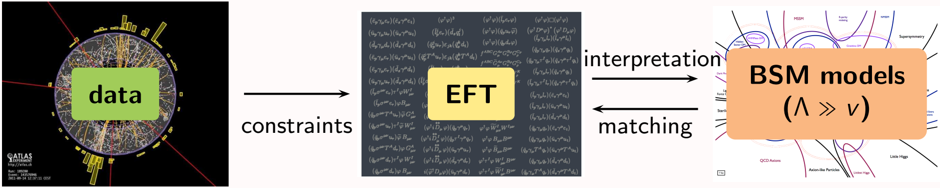

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BSM models
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the only QFT providing
a systematic classification of
all the UV effects compatible with
SM symmetries + field content

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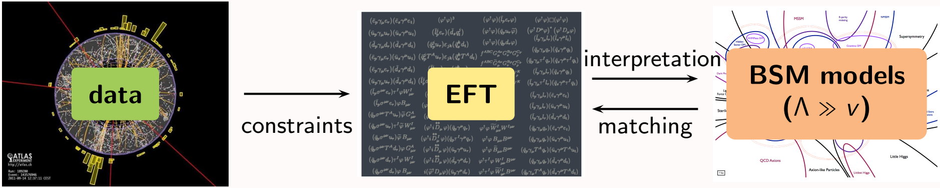

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knowledge of UV
<u>not</u> required

↓

well suited for the current situation

Why the SMEFT?

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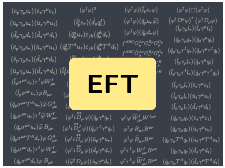
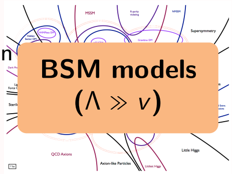


EFT

interpretation →

← matching



BSM models
($\Lambda \gg v$)

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

the only QFT providing
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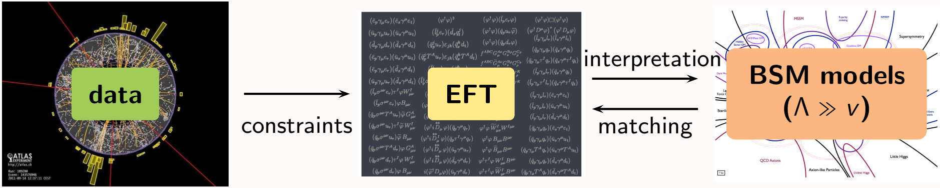

data

constraints

EFT

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 – recent developments

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

The SMEFT – recent developments

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

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$\mathbf{N_f = 3} \rightarrow$ 12 2499 948 36971

- # of parameters known for all orders

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

The SMEFT – recent developments

Weinberg PRL43(1979)1566

Lehman 1410.4193
Henning,Lu,Melia,Murayama 1512.03433

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

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

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

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

- complete RGE available

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

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- 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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- 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
  [MC generation, analytic calculation, fitting, matching, RGE running...]

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

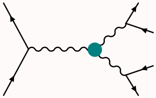
What's a basis?

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.

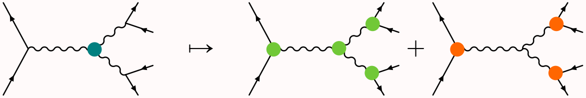
Example:

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



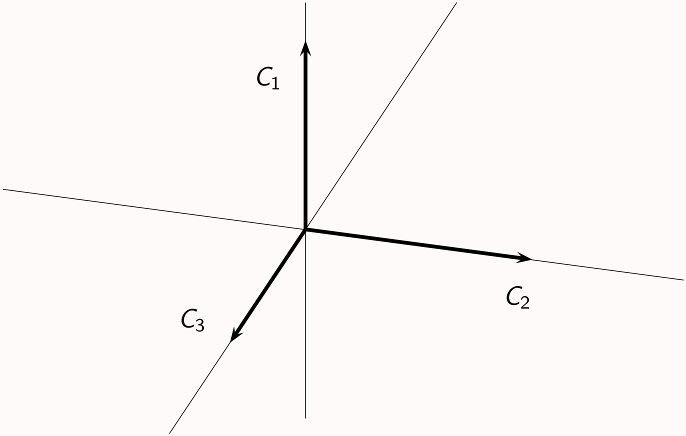
Using the Warsaw basis:

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



What's a basis?

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



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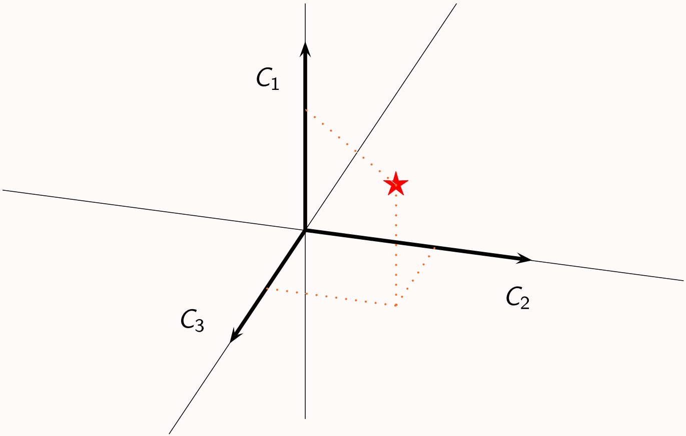
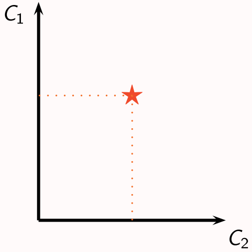


We want to know **where we are** exactly in this space

What's a basis?

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

an important comment



What's a basis?

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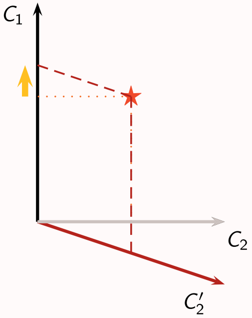
an important comment

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

the complete set
is required



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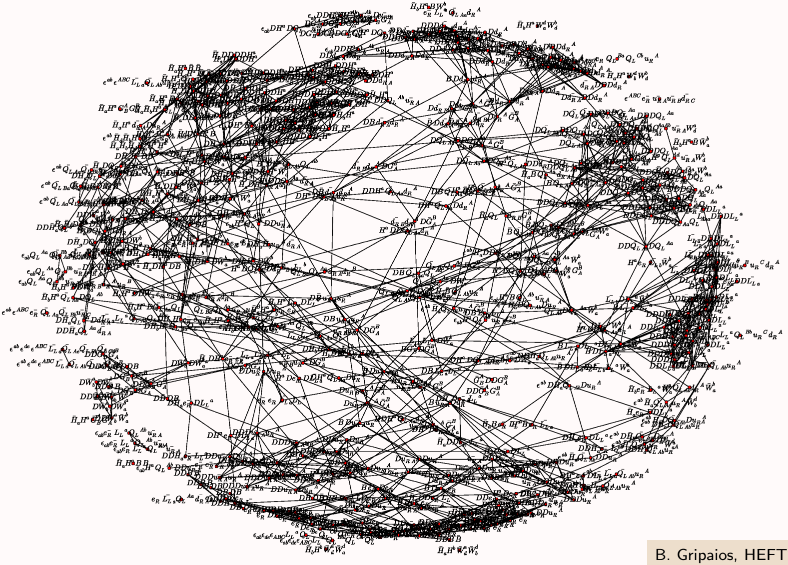

B. Gripaios, HEFT2018

Finding where we are - long term plan

ideal global fit

- include as many **coefficients** as possible
- combine different **datasets**:

EWPD + Higgs + diboson/EW + top + flavor + ...

combining data from different "sectors" is crucial

- constraints from different directions are required to break degeneracies
- RGE effects between measurements at different energies (e.g. LHC vs flavor) → large mixings

it's time to make this happen!

An ongoing effort

Subsets of the Wilson coefficients have 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

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

...

Finding where we are - first steps

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
- ...

Finding where we are - first steps

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In practice: we can only do partial fits because of

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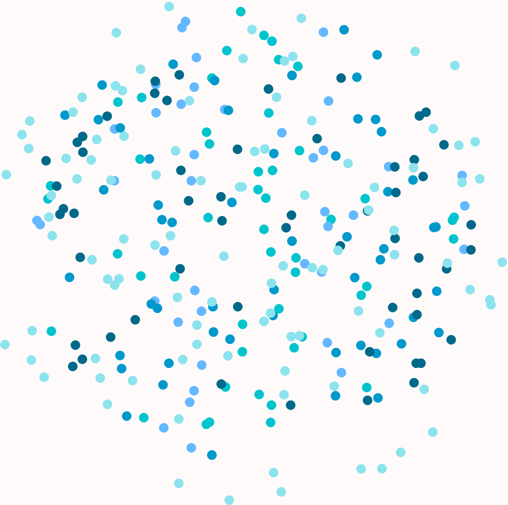
- ...

the parameter space needs to be reduced

can we drop many parameters and still get general constraints?
YES, choosing smart observables

Designing a strategy

a too large # of operators to constrain



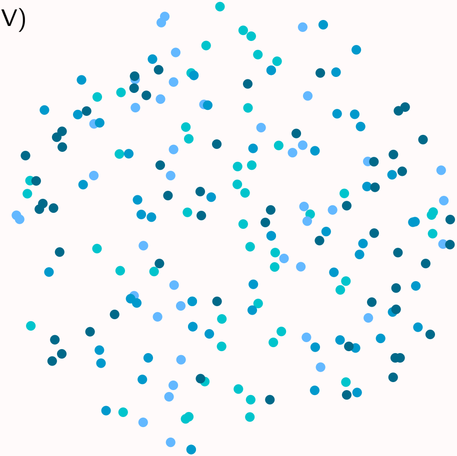
Designing a strategy

a too large # of operators to constrain

- **symmetries**

flavor ($U(3)^5$, MFV)
CP
...

choose a scenario with less parameters



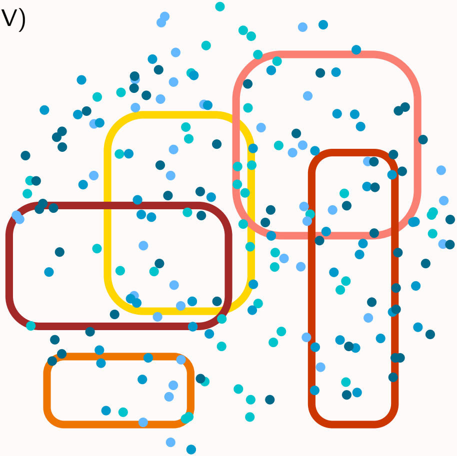
Designing a strategy

a too large # of operators to constrain

- **symmetries**

flavor ($U(3)^5$, MFV)
CP
...

choose a
scenario with
less parameters



given observables
are sensitive to
different sets
of operators

↓

still needs a
large global fit

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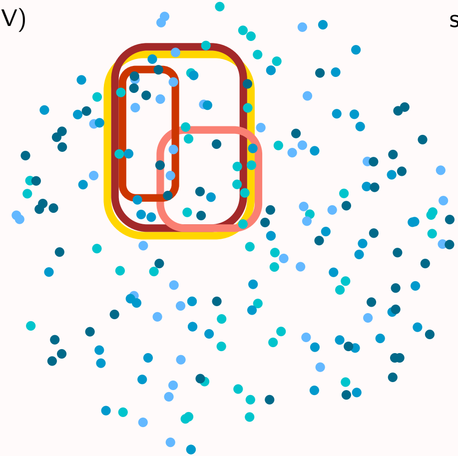

we'd rather have:
a set of **observables**
sensitive to a close,
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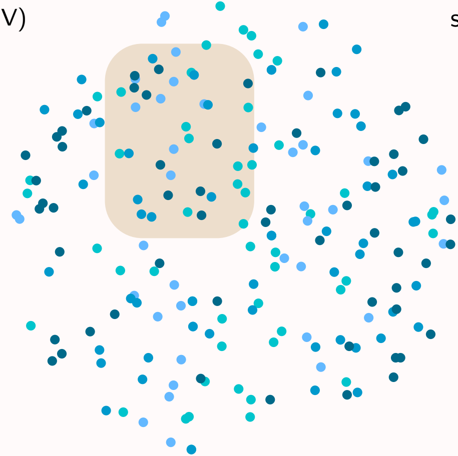

we'd rather have: a set of **observables** sensitive to a close, manageable set of operators

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extract general constraints on these, <u>independently</u> of the others

Designing a strategy

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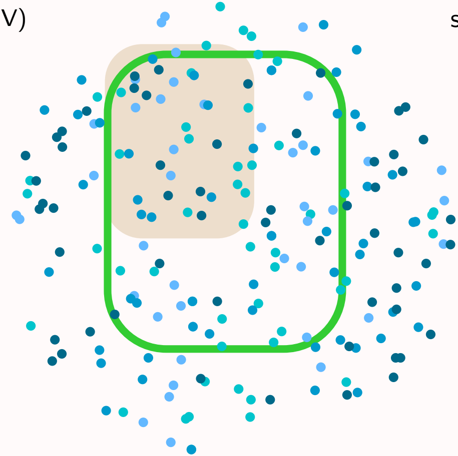

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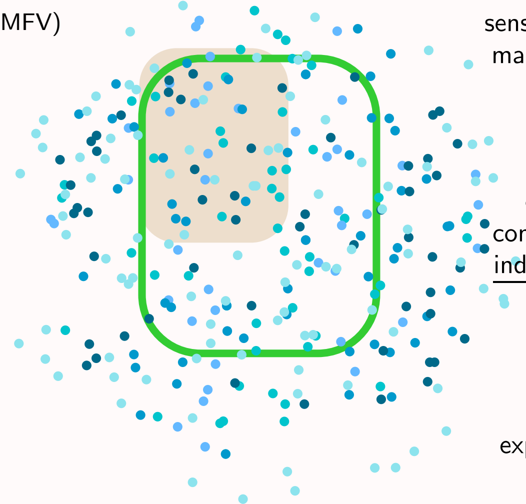

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Constructing convenient observables

looking for an optimal set of observables

- only **a few** operators contributing significantly
- many observables **share the same** relevant ops.
- sufficient experimental **sensitivity**

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

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

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Constructing convenient observables

Example – close to a pole

Brivio, Jiang, Trott 1709.06492

most ψ^4 operators give diagrams with less resonances

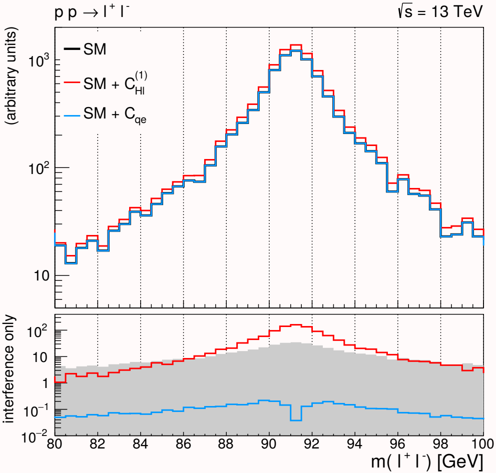
expected to be **suppressed** wrt. "pole operators" by

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

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

$n = \#$ missing resonances

Drell-Yan via Z resonance ➜



Constructing convenient observables

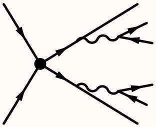
Example – close to a pole

Brivio,Jiang,Trott 1709.06492

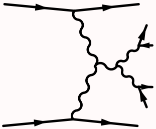
most ψ^4 operators give diagrams with less resonances

! 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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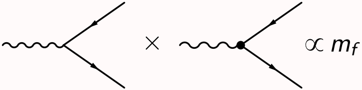
- for operators with interference $\propto m_f$

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



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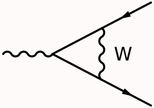
- in specific kinematic regions. e.g. for ψ^4 ops. close to W, Z, *h* **poles**
- for operators with interference $\propto m_f$
- for operators inducing FCNC

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



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

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- for operators with interference $\propto m_f$
- for operators inducing FCNC
- . . .

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	$\{C_{ll}, C'_{ll}\} \in \mathbb{R}$	2
	Total Count	~ 24

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

What is the precision needed?

A back-of-an-envelope estimate:

on poles

UV coupling to SM

$$\text{NP impact} \sim \frac{v^2 g}{M^2} = \frac{v^2}{\Lambda^2}$$

EFT cutoff

mass of new resonances

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

(LHC reach)

What is the precision needed?

A back-of-an-envelope estimate:

UV coupling to SM

on poles $$\text{NP impact} \sim \frac{v^2 g}{M^2} = \frac{v^2}{\Lambda^2}$$ **EFT cutoff**

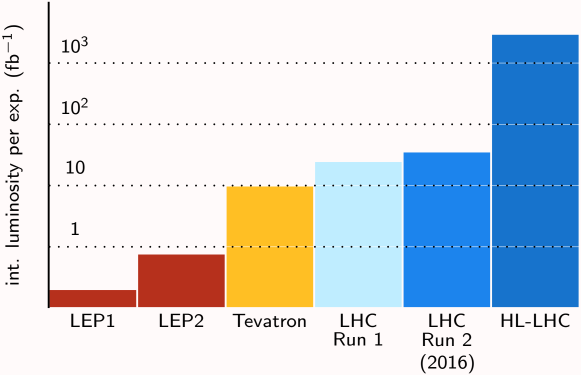
mass of new resonances

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

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

Keeping in mind. . .

. . . there's a HUGE amount of data to come in the next 20 years!



statistics will increase $\sim \sqrt{L}$

$$\text{for 13-14 TeV} \rightarrow \text{increase by a factor} \sqrt{\frac{3000\ \text{fb}^{-1}}{36\ \text{fb}^{-1}}} \simeq 9$$

while the energy won't be significantly raised.

A strong complementarity

Ⓐ parameter space reduction

Ⓑ experimental precision required

	pole observables	**tails of dist.**
Ⓐ	remarkable	difficult (ψ^4)
Ⓑ	need 1 %	ok with tens of %

poles and tails are complementary!

☛ A good idea: do poles first, incorporate tails later

As a case study: EWPD close to the Z-pole

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, $R^0_{\ell,c,b}$, $A^{\ell,c,b,\mu,\tau}_{FB}$, 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 + $U(3)^5$

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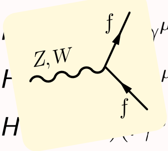

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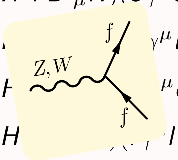

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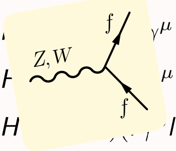

$\to \delta s^2_\theta$

$\to \delta m^2_Z$

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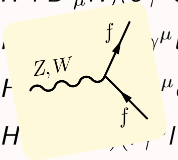

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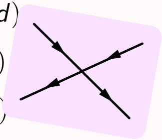

Global fit to EW precision data - method

Basics of the fit method

Likelihood:

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

$$\Big\downarrow$$

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

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

⇝ **backup**

Global fit to EW precision data - results

103 observables

Berthier, Trott. 1508.05060

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

Global fit to EW precision data - results

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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

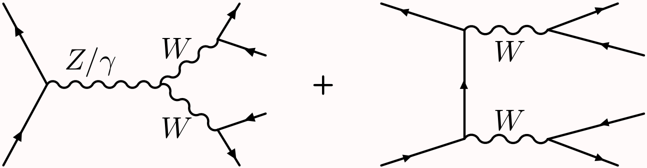
Adding $\bar{\psi}\psi \to \bar{\psi}\psi\bar{\psi}\psi$ production from LEP2

Berthier, Bjørn, Trott 1606.06693

177 observables

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

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



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

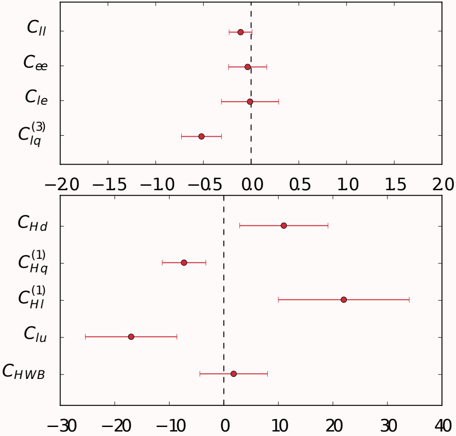
Adding $\bar{\psi}\psi \to \bar{\psi}\psi\bar{\psi}\psi$ production from LEP2

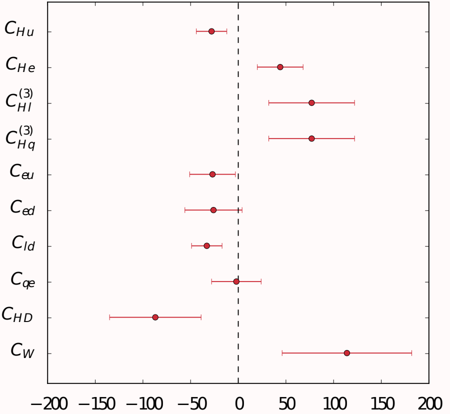
Berthier, Bjørn, Trott 1606.06693

177 observables

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

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





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Berthier, Bjørn, Trott 1606.06693

177 observables

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

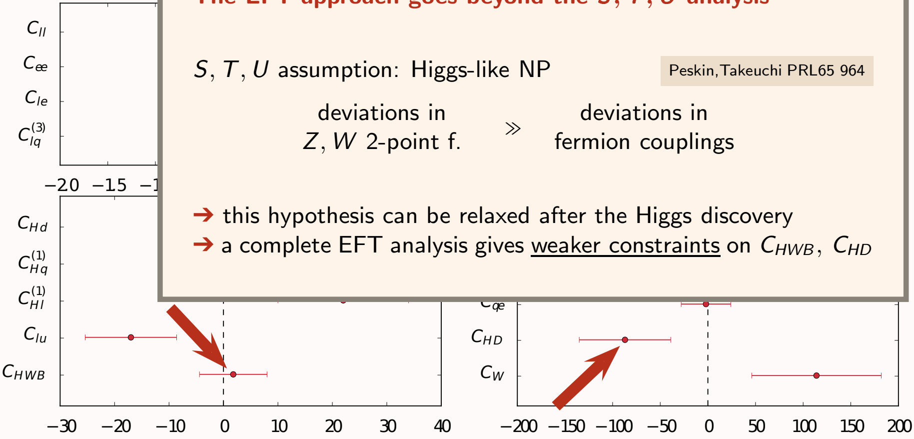
The EFT approach goes beyond the S, T, U analysis

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}



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Berthier, Bjørn, Trott 1606.06693

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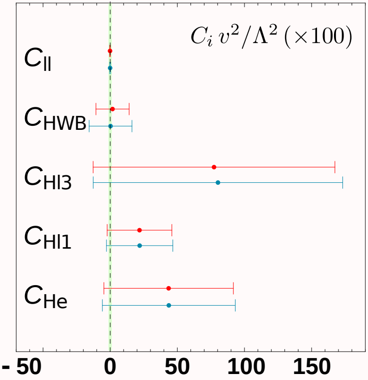
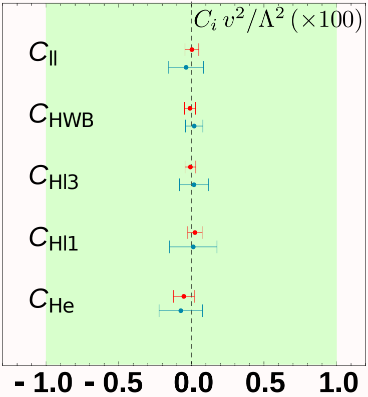
2σ regions



profiling over the others



for comparison:
one coefficient at a time

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Berthier, Bjørn, Trott 1606.06693

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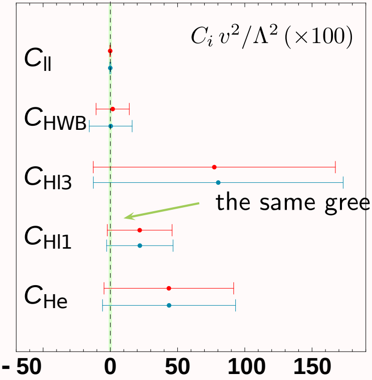
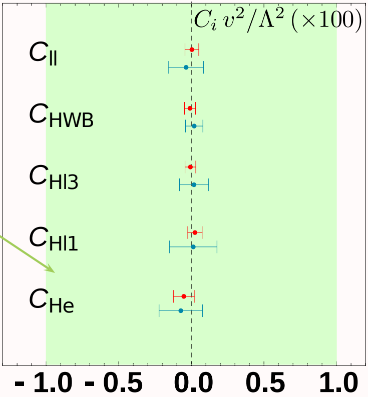


profiling over the others

the same green band!



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Berthier,Bjørn,Trott 1606.06693

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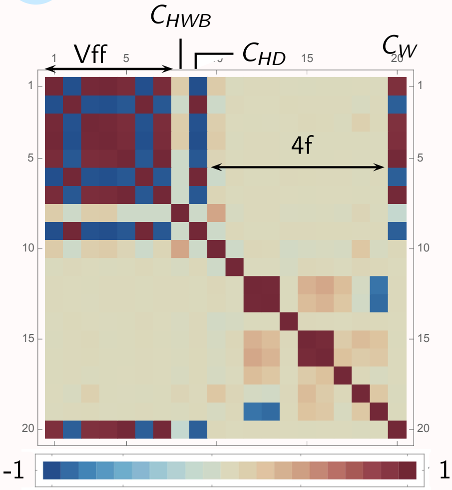


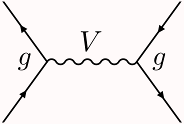
the fit space is **highly correlated**

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



at tree level + $m_f/m_V \ll (C_i/\Lambda^2)$ this S-matrix has a

reparameterization invariance $\begin{cases} V_\mu \to V_\mu(1+\varepsilon) \\ g \to g/(1+\varepsilon) \end{cases}$

$$\updownarrow$$

$\begin{cases} \mathcal{Q}_{HW} = W^i_{\mu\nu} W^{i\mu\nu} H^\dagger H \\ \mathcal{Q}_{HB} = B_{\mu\nu} B^{\mu\nu} H^\dagger H \end{cases}$ cannot be constrained in Z-pole data

The invariance is **broken** in the SMEFT when including processes with TGCs.

(e.g. WW production)

⇝ **backup**

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

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

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

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Grojean,Skiba,Terning 0602154

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

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Grojean,Skiba,Terning 0602154

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not constrained in $2 \to 2$ + **not affecting $2 \to 2$** ⇒ flat direction

not constrained in $2 \to 4$ + **probed in $2 \to 4$** ⇒ constrained!

independently of which operators are retained in the basis!

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Grojean,Skiba,Terning 0602154

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

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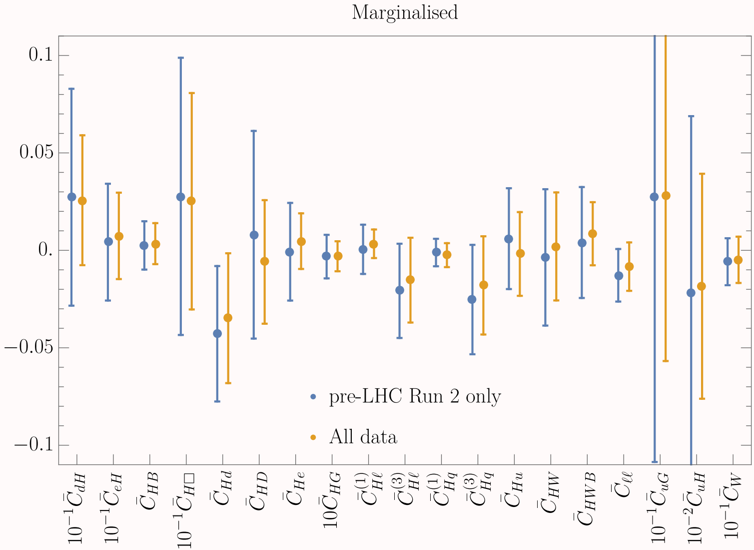
✓ This result has been checked using two **input parameter schemes**: $\{\alpha_{\rm ew}, m_Z, G_F\}$ and $\{m_W, m_Z, G_F\}$

⇝ **backup**

Higgs data also breaks the invariance

EWPD + WW prod. + Higgs (LHC Run1+2)

Ellis,Murphy,You,Sanz 1803.03252



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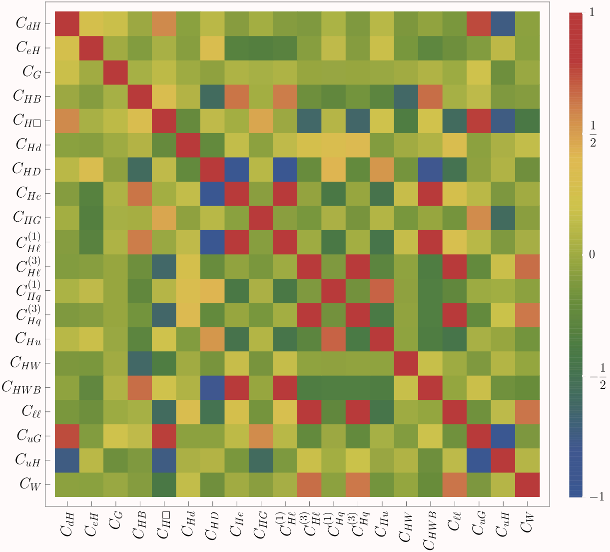
Ellis,Murphy,You,Sanz 1803.03252



EWPD fit: take-home message

we have seen the "basis connection" in action.

- flat directions, naively not expected
- strong correlations among coefficients
- fitting all the parameters simultaneously, EWPD alone is not so constraining

these are general, widespread issues in (partial) SMEFT analyses!

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these are general, widespread issues in (partial) SMEFT analyses!

It's important to have a tool that can
handle **all the operators** simultaneously and
allow a numerical estimate of their impact

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** $|\mathcal{A}_{\mathbf{SM}}\mathcal{A}^*_{\mathbf{d=6}}|$ **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 $\left\{\begin{array}{l}\text{general}\\ U(3)^5 \text{ symmetric}\\ \text{linear MFV}\end{array}\right.$ × 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

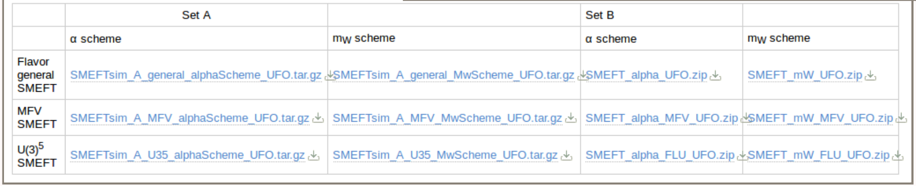
Authors

Ilaria Brivio, Yun Jiang and Michael Trott

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

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

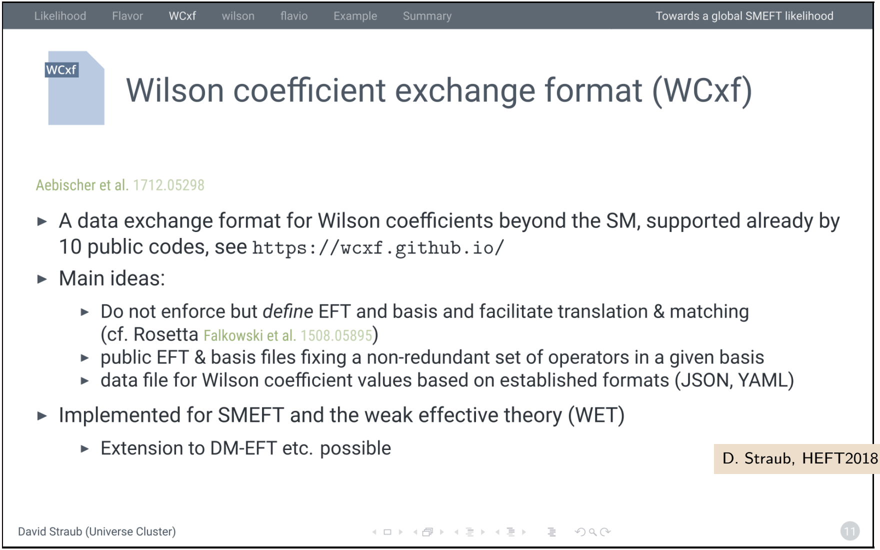
Pre-exported UFO files (include restriction cards)



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

The SMEFTsim package

SMEFTsim supports the `WCxf` format.



Likelihood Flavor WCxf wilson flavio Example Summary Towards a global SMEFT likelihood

Wilson coefficient exchange format (WCxf)

Aebischer et al. 1712.05298

- A data exchange format for Wilson coefficients beyond the SM, supported already by 10 public codes, see `https://wcxf.github.io/`
- Main ideas:
  - Do not enforce but *define* EFT and basis and facilitate translation & matching (cf. Rosetta Falkowski et al. 1508.05895)
  - public EFT & basis files fixing a non-redundant set of operators in a given basis
  - data file for Wilson coefficient values based on established formats (JSON, YAML)
- Implemented for SMEFT and the weak effective theory (WET)
  - Extension to DM-EFT etc. possible

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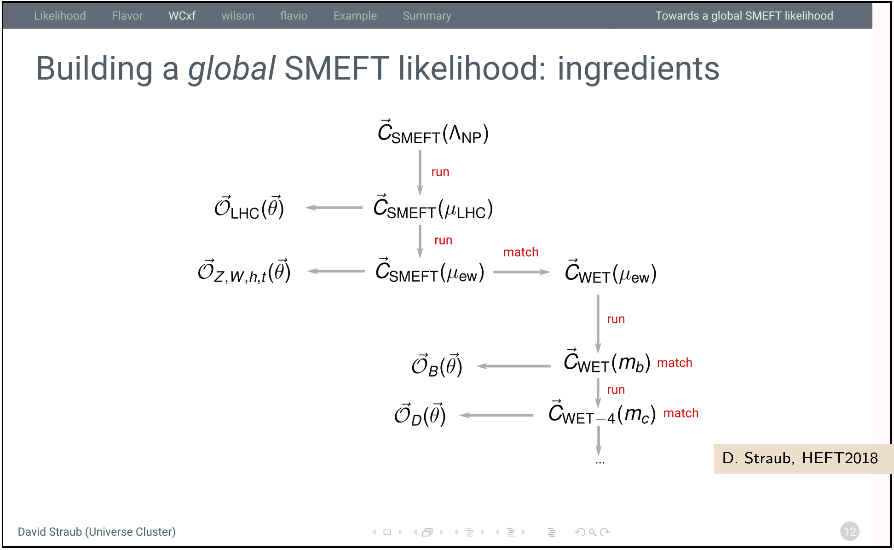
D. Straub, HEFT2018

A global SMEFT likelihood



Likelihood Flavor WCxf wilson flavio Example Summary Towards a global SMEFT likelihood

Building a *global* SMEFT likelihood: ingredients

$$\begin{tikzcd}
 & \vec{C}_{\text{SMEFT}}(\Lambda_{\text{NP}}) \arrow[d, "\text{run}"] & \\
\vec{\mathcal{O}}_{\text{LHC}}(\vec{\theta}) & \vec{C}_{\text{SMEFT}}(\mu_{\text{LHC}}) \arrow[l] \arrow[d, "\text{run}"] & \\
\vec{\mathcal{O}}_{Z,W,h,t}(\vec{\theta}) & \vec{C}_{\text{SMEFT}}(\mu_{\text{ew}}) \arrow[l] \arrow[r, "\text{match}"] & \vec{C}_{\text{WET}}(\mu_{\text{ew}}) \arrow[d, "\text{run}"] \\
 & \vec{\mathcal{O}}_{B}(\vec{\theta}) & \vec{C}_{\text{WET}}(m_b)\ \text{match} \arrow[l] \arrow[d, "\text{run}"] \\
 & \vec{\mathcal{O}}_{D}(\vec{\theta}) & \vec{C}_{\text{WET}-4}(m_c)\ \text{match} \arrow[l] \arrow[d] \\
 & & \dots
\end{tikzcd}$$

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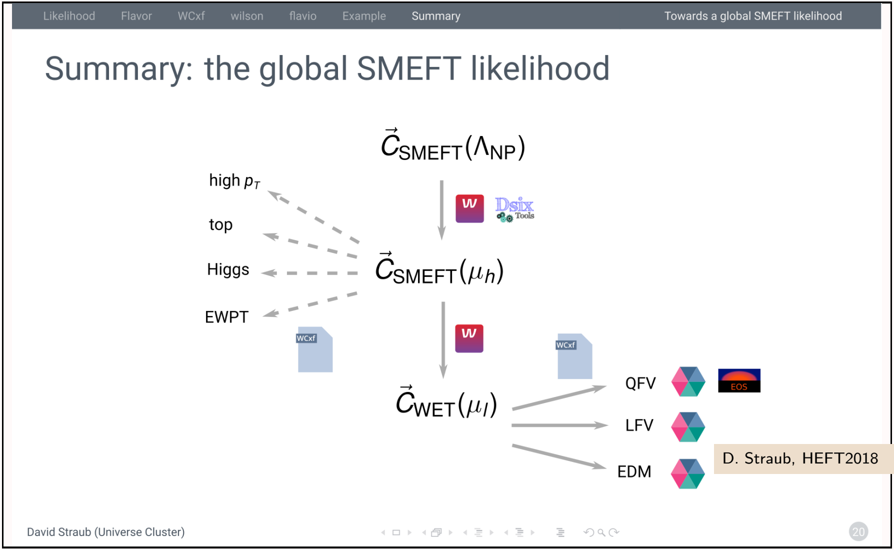
12

D. Straub, HEFT2018

A global SMEFT likelihood



Likelihood Flavor WCxf wilson flavio Example Summary Towards a global SMEFT likelihood

Summary: the global SMEFT likelihood

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20

D. Straub, HEFT2018

Road-map and challenges

1. Complete a "WHZ poles program"
   - design optimized experimental analyses

Brivio,Jiang,Trott 1709.06492

Road-map and challenges

1. Complete a “WHZ poles program”

   Brivio,Jiang,Trott 1709.06492

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2. Include tails of kinematic distributions

   difficulties:
   - many parameters involved ($(\bar{\psi}\psi)^2$ operators)
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Brivio,Jiang,Trott 1709.06492

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3. Improve the analysis tools

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

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

- can machine learning help?

Brehmer,Cranmer,Louppe,Pavez 1805.00013,1805.00020

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4. Improve the accuracy of SMEFT predictions

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

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Brivio,Jiang,Trott 1709.06492

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Brehmer,Cranmer,Kling,Plehn 1612.05 1710.02008

- can machine learning help?

Brehmer,Cranmer,Loup

4. Improve the accuracy of SMEFT predictions

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

Backup slides

Field redefinitions vs EOMs

Consider the field φ. The Lagrangian $\mathcal{L}_4$ has the form

$$\mathcal{L}_4 = \varphi A + \partial_\mu \varphi B^\mu$$

The associated **EOM** is $\partial_\mu B^\mu = A$

σ : $d = 3$ object with the same quantum numbers as φ
The most general, redundant Lagrangian at $d = 6$ must have the form

$$\mathcal{L}_6 = \frac{c_1}{\Lambda^2}\,\sigma A + \frac{c_2}{\Lambda^2}\,\partial_\mu \sigma B^\mu$$

Correspondingly, the most general **field redefinition** is $\varphi \to \varphi + k\dfrac{\sigma}{\Lambda^2}$

Applying the EOM on $\mathcal{L}_6$:

$$\partial_\mu \sigma B^\mu = -\sigma \partial_\mu B^\mu = \sigma A$$

→ one of the two operators is redundant → I remove it.

Applying field redef. on $\mathcal{L}_4$:

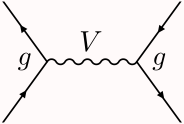
$$\mathcal{L}_4 + \mathcal{L}_6 \to \mathcal{L}_4 + \frac{k + c_1}{\Lambda^2}\sigma A + \frac{k + c_2}{\Lambda^2}\partial_\mu \sigma B^\mu$$

→ I can choose $k = -c_1$ or $k = -c_2$ and remove a redundancy.

Understanding the unconstrained directions

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

Brivio,Trott 1701.06424



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

$$(*)\begin{array}{c} V_\mu \to V_\mu(1+\varepsilon) \\ g \to g/(1+\varepsilon) \end{array}$$

non canonical kinetic term.
→ OK adjusting LSZ

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

the S-matrix has a reparameterization invariance

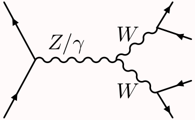
operators modifying the kinetic term normalization have no impact here

$\updownarrow$

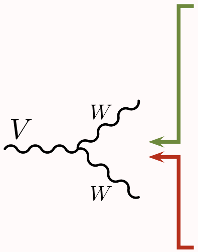
these C_i can be removed from the amplitude via $(*)$

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

NOT invariant!

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

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

$$\alpha_{\rm em} = \frac{\bar{g}_1 \bar{g}_2}{\bar{g}_1^2 + \bar{g}_2^2} \qquad m_Z = \frac{\bar{g}_2 \bar{v}}{2 c_{\bar{\theta}}} \qquad G_f = \frac{1}{\sqrt{2}\bar{v}^2}$$

$$\rightarrow$$

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

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

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

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

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

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

$$\begin{aligned} \alpha_{\rm em} &= \frac{\bar{g}_1\bar{g}_2}{\bar{g}_1^2+\bar{g}_2^2}\left[1+\bar{v}^2 C_{HWB}\frac{\bar{g}_2^3/\bar{g}_1}{\bar{g}_1^2+\bar{g}_2^2}\right] \\ m_Z &= \frac{\bar{g}_2\bar{v}}{2c_{\bar{\theta}}} + \delta m_Z(C_i) \qquad \to \\ G_f &= \frac{1}{\sqrt{2}\bar{v}^2} + \delta G_f(C_i) \end{aligned}$$

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

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

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

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

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

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

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

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

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

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.

$\{m_W, m_Z, G_f\}$ scheme

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

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

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

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

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

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

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

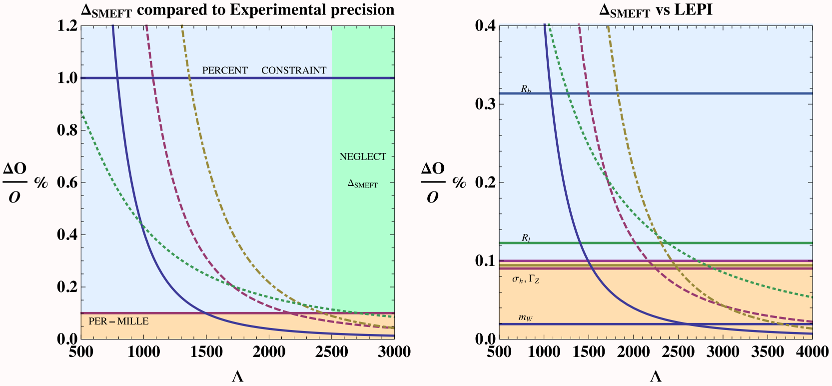
error on O_i

correlation mat.

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

$\Delta_{\rm SMEFT}$

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



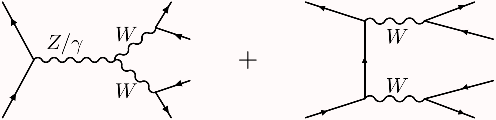
Berthier, Trott 1508.05060

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

one needs to expand $\big\downarrow$

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

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

$\alpha_{\rm em}(0)^{-1} = 137.035999139(31)$

in the Thomson limit

BUT

$\alpha_{\rm em}(m_Z)^{-1} = 127.950 \pm 0.017$

(0.013%)

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

← large uncertainties, mainly from hadronic contribution

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

(Tevatron combined)

also: recently measured at LHC!

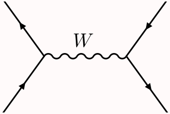
80.370 ± 0.019 GeV

Atlas 1701.07240

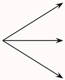
m_W as an input parameter

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 $\delta\Gamma_W, \delta N \equiv 0$.

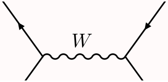
Is it still OK for $\delta\Gamma_W, \delta N \neq 0$? **YES!**

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

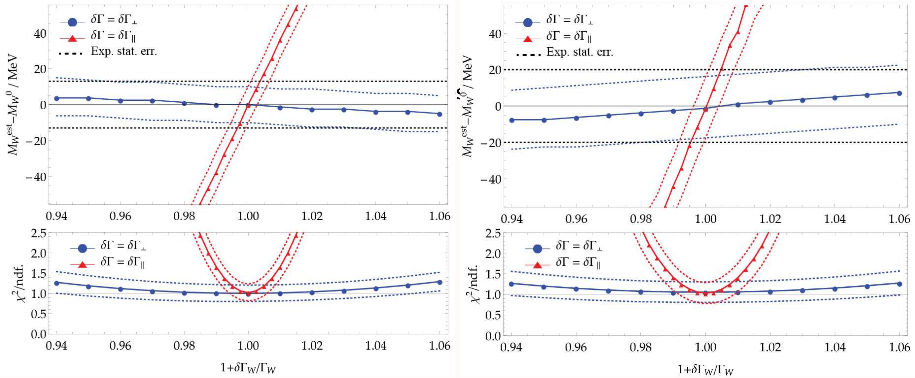
m_W as an input parameter

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



SMEFT corrections $\rightarrow$ δm_W, $\delta \Gamma_W$



$\alpha_{\rm em}$ 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:

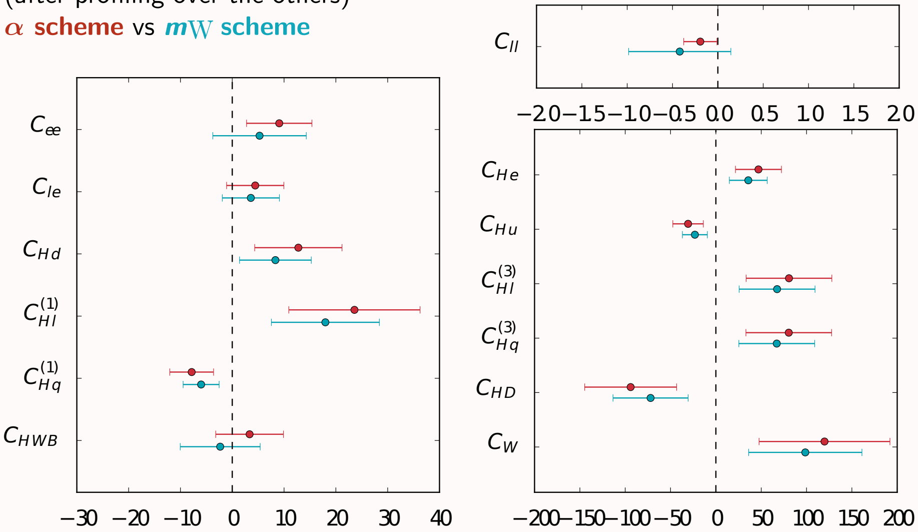
1. if $\bar\psi\psi \to \bar\psi\psi\bar\psi\psi$ is not included $\Rightarrow$ flat directions compatible with the reparam. invariance structure. ✓

   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