Shedding light on new physics with Effective Field Theories

Ilaria Brivio

Niels Bohr Institute, Copenhagen

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

centre for particle physics
Discovery

The Niels Bohr
International Academy

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CAN.

What is an Effective Field Theory?

A pragmatic definition:

it's a field theory that describes the **IR limit** of an
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only the light degrees of freedom

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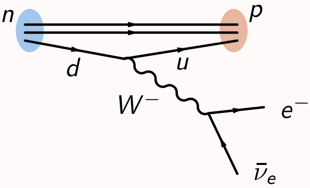
"True" theory: Electroweak interactions



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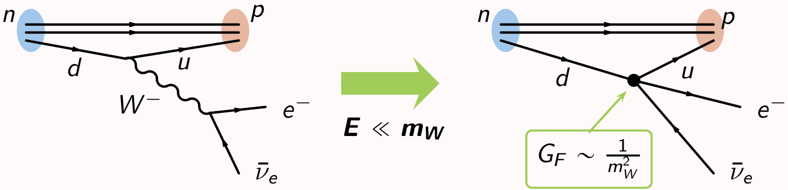
"True" theory: Electroweak interactions EFT: Fermi's interactions



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

$$\mathcal{A}(0)+\frac{1}{m_W^2}\Bigg($$

$$+\ldots\Bigg)+\mathcal{O}\left(m_W^{-4}\right)$$

The Standard Model as an EFT

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):

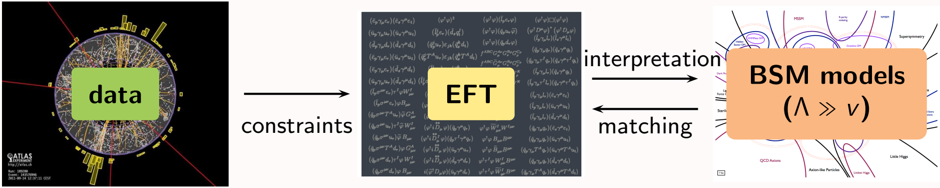
$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \dots$$

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

C_i free parameters (Wilson coefficients)

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

Why the SMEFT?



data → constraints → **EFT** $\xrightarrow{\text{interpretation}}$ **BSM models ($\Lambda \gg v$)**

EFT $\xleftarrow{\text{matching}}$ **BSM models**

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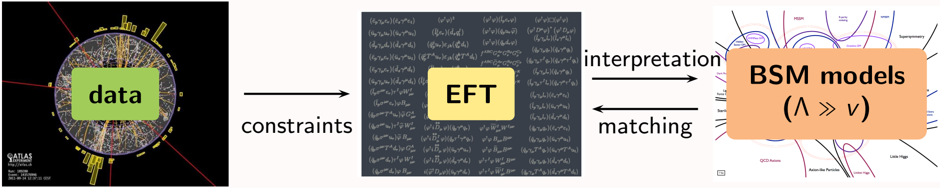

data → constraints → **EFT**

EFT → interpretation → **BSM models ($\Lambda \gg v$)**

BSM models → matching → **EFT**

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

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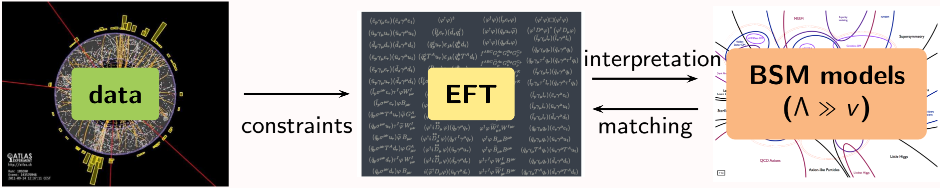

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knowledge of UV
<u>not</u> required

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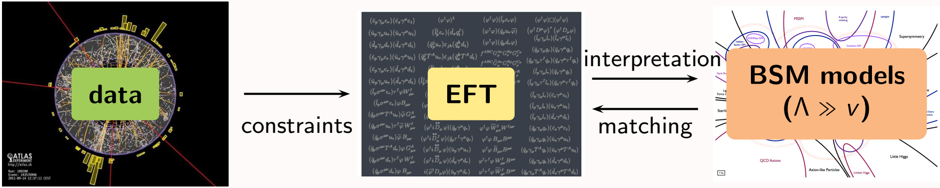

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a **smart framework** for data recording and interpretation

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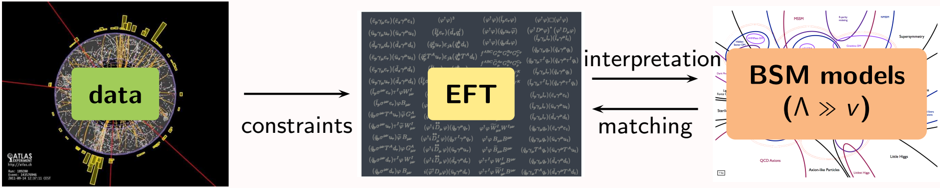

data

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

a general, powerful tool for handling future data

the only QFT providing
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The SMEFT – where we are

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

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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

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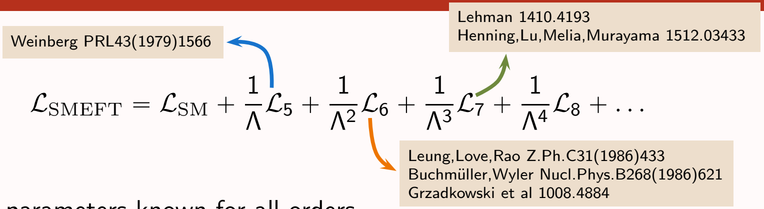

Weinberg PRL43(1979)1566

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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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$\mathcal{L}_5$: 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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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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Dedes,Materkowska,Paraskevas,Rosiek,Suxho 1704.03888
Helset,Paraskevas,Trott to appear

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- 1-loop results available for selected processes
- formulation in R_ξ gauge
- various tools available for numerical analysis

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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q^{(1)}_{\varphi l}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q^{(3)}_{\varphi l}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	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}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q^{(1)}_{\varphi q}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q^{(3)}_{\varphi q}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	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}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde W B}$	$\varphi^\dagger \tau^I \varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$

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

Basis independence

What's a basis' physical meaning?

Gives a complete parameterization of independent effects at the S-matrix level.

Sometimes not intuitive, because we tend to think at the couplings level.

e.g.: field redefinitions connect operators with different impact

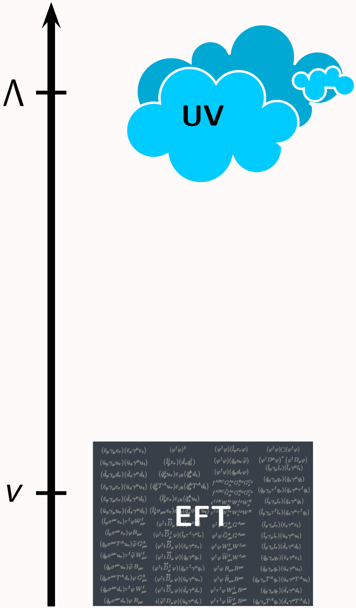
$$(D^\mu W^i_{\mu\nu})(iH^\dagger \overleftrightarrow{D}^{\mu\, i} H) \quad \longleftrightarrow \quad g_2\left[2H^\dagger H(D_\mu H^\dagger D^\mu H) + \frac{\mathcal{Q}_{H\Box}}{2} + \frac{\mathcal{Q}^{(3)}_{Hq} + \mathcal{Q}^{(3)}_{Hl}}{2}\right]$$

kin. terms + TGC/QGC

Higgs + Vff couplings

the resulting S-matrices are equivalent (they are **basis independent**)
once all the contributions have been included

The EFT approach



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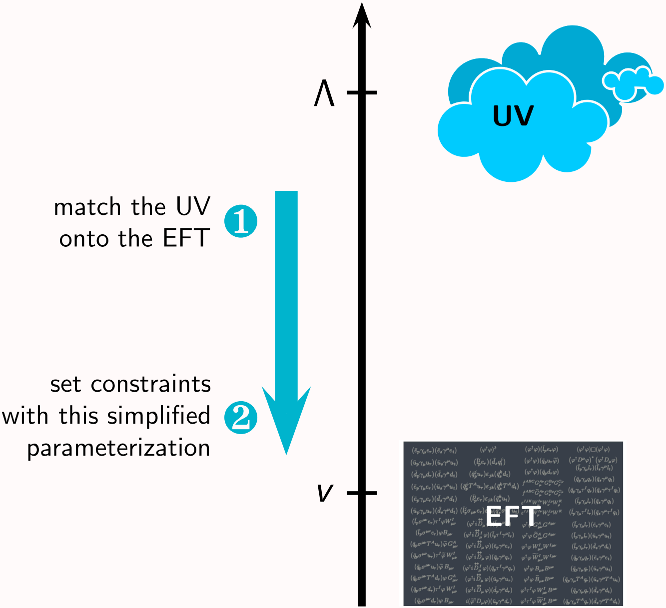

match the UV onto the EFT ①

set constraints with this simplified parameterization ②

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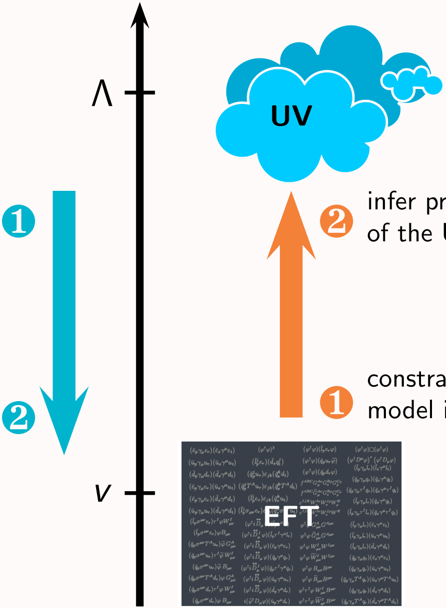


match the UV
onto the EFT ➊

set constraints
with this simplified ➋
parameterization

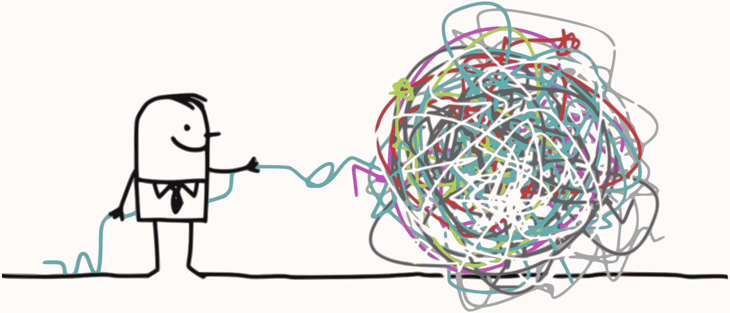
➋ infer properties
of the UV sector

➊ constrain the EFT in a
model independent way

Untangling the SMEFT

A big knot!

many operators around at the same time in any given observables



we want to untangle this without breaking any strings

[extract reliable constraints (or measurements!)
possibly without introducing any bias]

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

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

. . .

Untangling the SMEFT

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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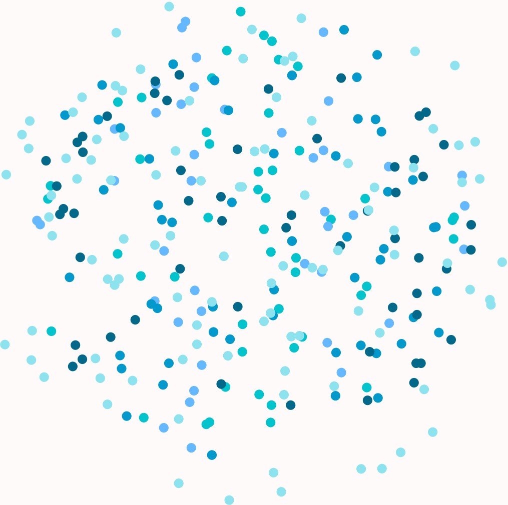
the parameter space needs to be reduced choosing observables and coefficients in a smart way

Another look at the knot

a too large # of operators to constrain



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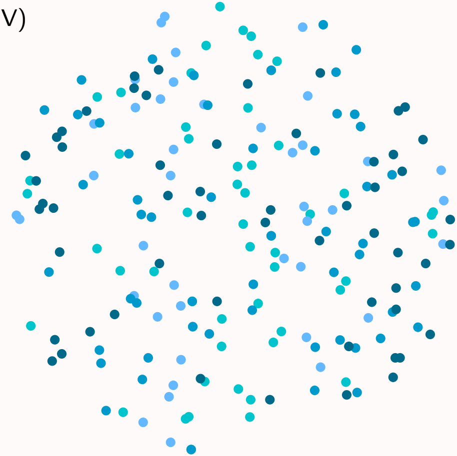
- **symmetries**

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

choose a
scenario with
less parameters



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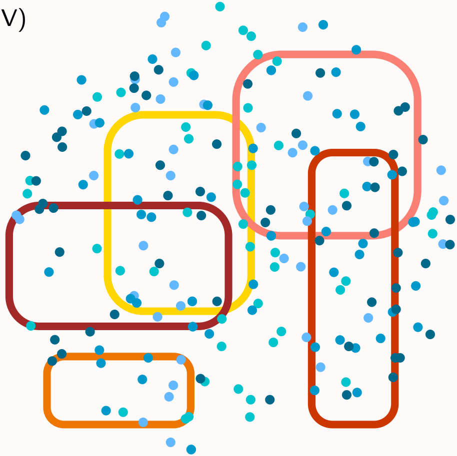


given observables
are sensitive to
different sets
of operators

↓

still needs a
large global fit

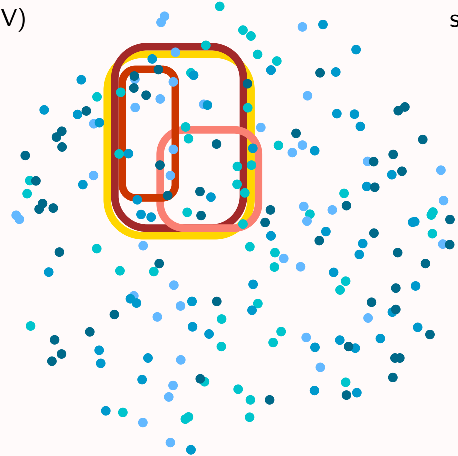
Another look at the knot

a too large # of operators to constrain

- **symmetries**

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

choose a scenario with less parameters



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

Another look at the knot

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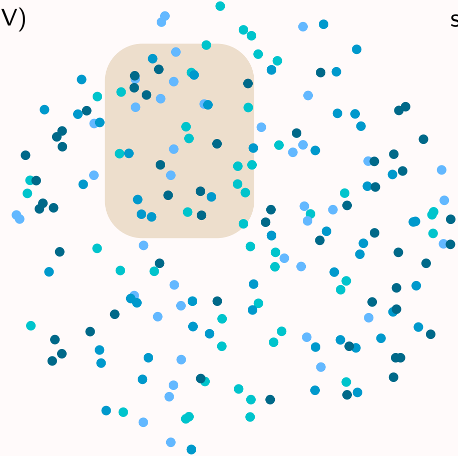

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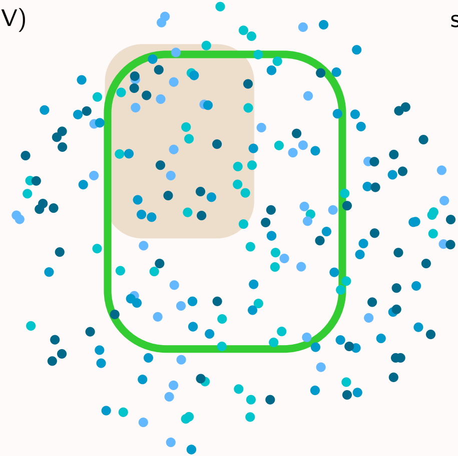

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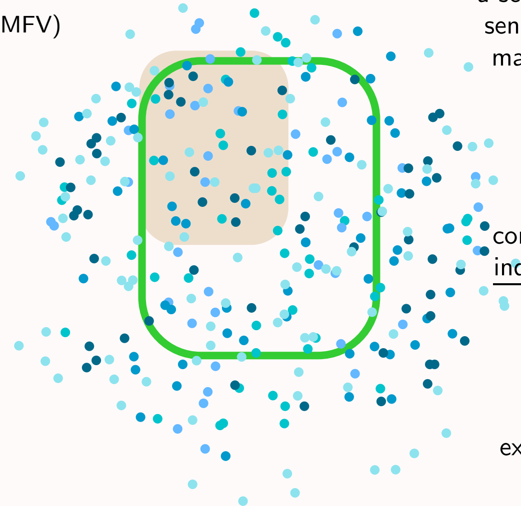

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A convenient strategy

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

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A convenient strategy

Example – close to a pole

Brivio, Jiang, Trott 1709.06492

most ψ^4 operators give diagrams with less resonances

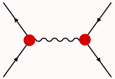
expected to be **suppressed** wrt. "pole operators" by

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

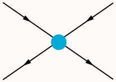
$B = \{Z, W, h\}$

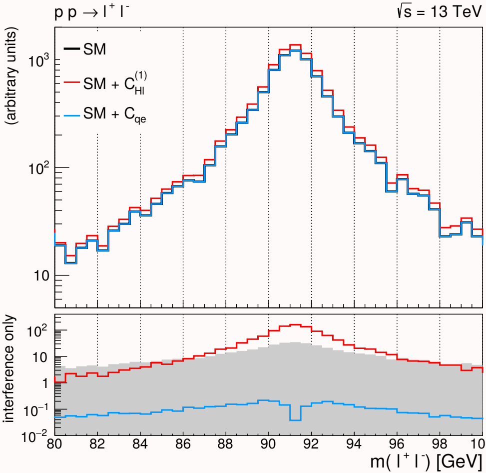
$n = \#$ missing resonances

Drell-Yan via Z resonance ➜



vs.





A convenient strategy

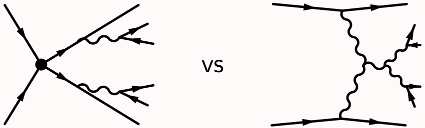
Example – close to a pole

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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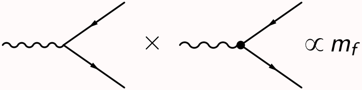
- for operators with interference $\propto m_f$

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



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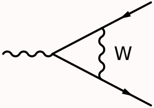
- in specific kinematic regions. e.g. for ψ^4 ops. close to W, Z, *h* **poles**
- for operators with interference $\propto m_f$
- for operators inducing FCNC

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



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

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- . . .

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

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

$$g \simeq 1 \quad M \gtrsim \underbrace{2-3\ \text{TeV}}_{\text{(LHC reach)}} \to \boxed{1\%}$$ **at least!**

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

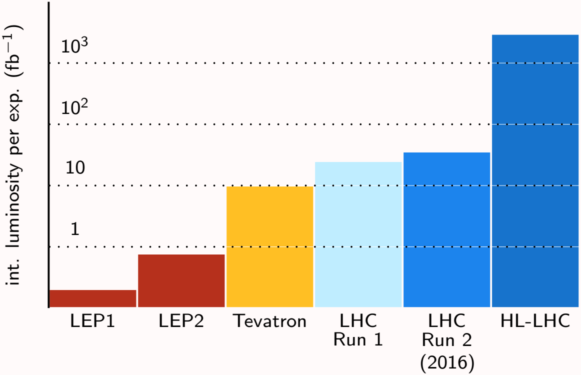
at least!

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 %

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

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

Global fit to EW precision data - parameters

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

$\tilde{C}_{He}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)$
$\tilde{C}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$
$\tilde{C}_{Hd}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$
$\tilde{C}_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}\gamma^\mu l)$
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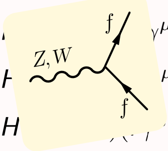

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$\tilde{C}_{Hl}^{(1)}$	$(H \quad l)$	$\tilde{C}_{ed}$	$(\bar{e}\gamma_\mu e)(\bar{d}\gamma^\mu d)$
$\tilde{C}_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{l}\sigma^i\gamma^\mu l)$	$\tilde{C}_{le}$	$(\bar{l}\gamma_\mu l)(\bar{e}\gamma^\mu e)$
$\tilde{C}_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$	$\tilde{C}_{lu}$	$(\bar{l}\gamma_\mu l)(\bar{u}\gamma^\mu u)$
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$\tilde{C}_{HD}$	$(H^\dagger D_\mu H)(D^\mu H^\dagger H)$	$\tilde{C}_{lq}^{(3)}$	$(\bar{l}\sigma^i\gamma_\mu l)(\bar{q}\sigma^i\gamma^\mu q)$
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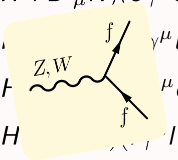

$\to \delta s_\theta^2$

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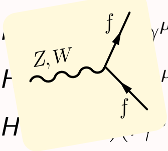

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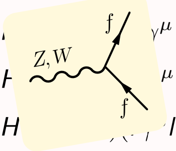

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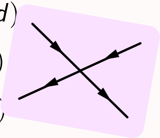

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Global fit to EW precision data - method

Basics of the fit method

Likelihood:

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

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

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

⇝ **backup**

Global fit to EW precision data - results

Berthier, Trott. 1508.05060

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

Global fit to EW precision data - results

103 observables

Berthier, Trott. 1508.05060

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

there are 2 unconstrained directions

well known: first noticed in Han, Skiba 0412166

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

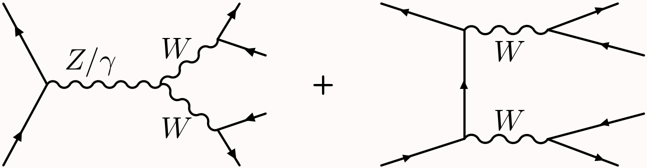
Adding $\bar{\psi}\psi \to \bar{\psi}\psi\bar{\psi}\psi$ production from LEP2

Berthier, Bjørn, Trott 1606.06693

177 observables

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

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



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

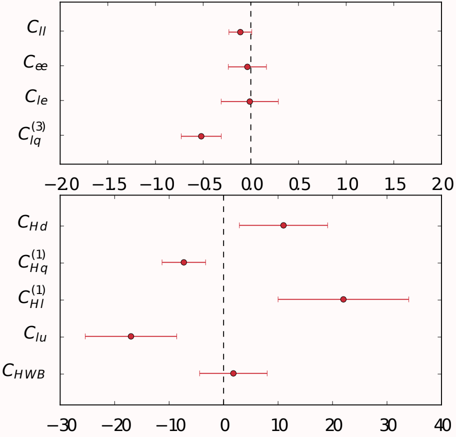
Adding $\bar{\psi}\psi \to \bar{\psi}\psi\bar{\psi}\psi$ production from LEP2

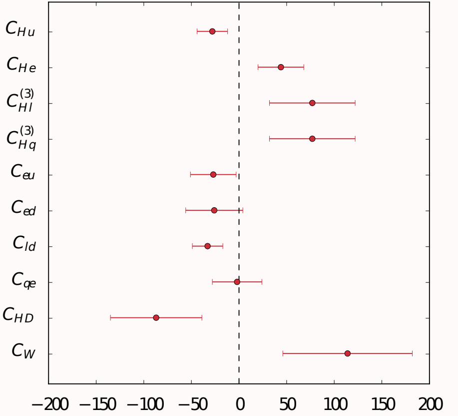
Berthier,Bjørn,Trott 1606.06693

177 observables

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

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





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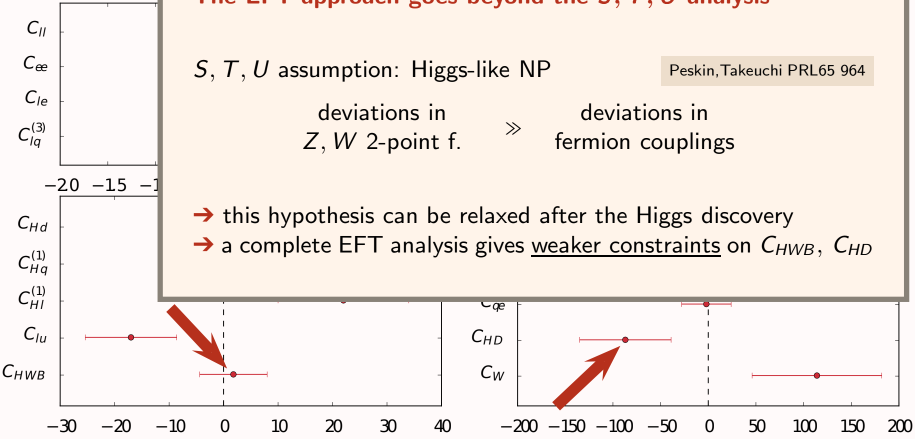

The EFT approach goes beyond the S, T, U analysis

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 weaker constraints on C_{HWB}, C_{HD}

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

Berthier, Bjørn, Trott 1606.06693

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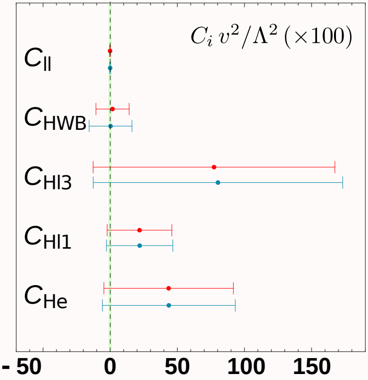
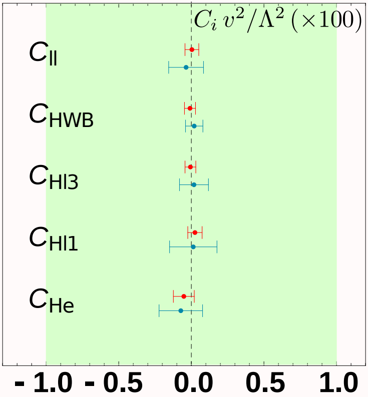
2σ regions



profiling over the others



for comparison:
one coefficient at a time

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Berthier, Bjørn, Trott 1606.06693

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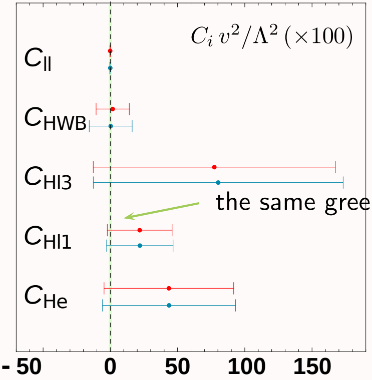
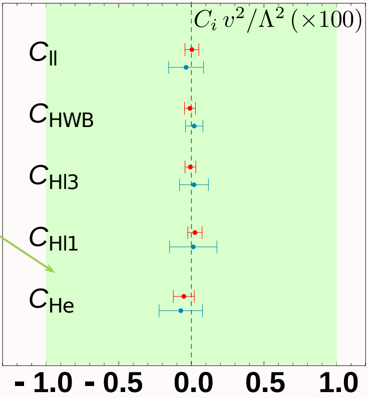


the same green band!

profiling over the others



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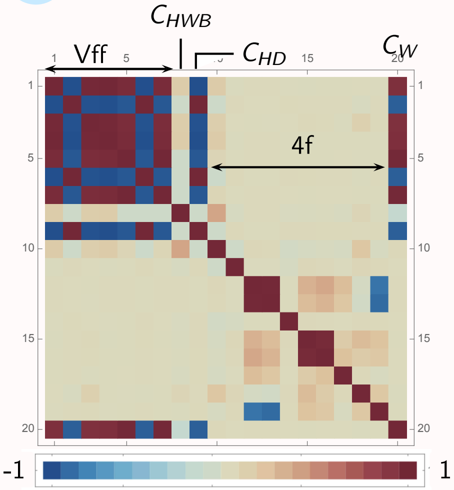


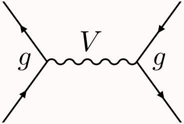
the fit space is **highly correlated**

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)

$\rightsquigarrow$ **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

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

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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 $2 \to 2$** ⇒ flat direction

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

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

independently of which operators are retained in the basis!

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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**: $\{\alpha_{\text{ew}}, m_Z, G_F\}$ and $\{m_W, m_Z, G_F\}$

⇝ **backup**

Remarks & caveats

1. the invariance is **a basis-independent property** of 2 → 2 observables:

   retaining $W^i_{\mu\nu} D^\mu H^\dagger \sigma^i D^\nu H$ instead of another operator
   → the unconstrained direction is just $W^i_{\mu\nu} D^\mu H^\dagger \sigma^i D^\nu H$ (same for B)

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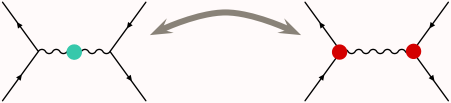

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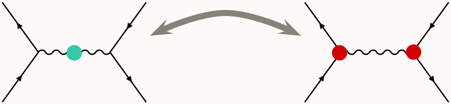

3. correlations are a general, widespread issue in SMEFT analyses

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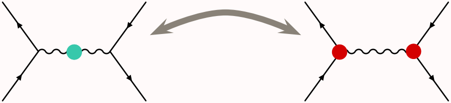


3. correlations are a general, widespread issue in SMEFT analyses

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

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

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

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**

$\rightsquigarrow$ **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 $\begin{cases} \text{general} \\ U(3)^5 \text{ symmetric} \\ \text{linear MFV} \end{cases}$ × ② input schemes $\begin{cases} \hat{\alpha}_{\rm em},\, \hat{m}_Z,\, \hat{G}_f \\ \hat{m}_W,\, \hat{m}_Z,\, \hat{G}_f \end{cases}$

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

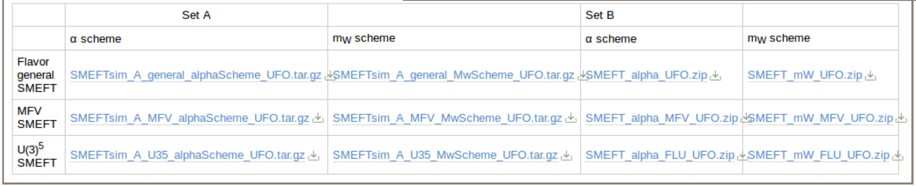
Authors

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

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

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2. Include tails of kinematic distributions

   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

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

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Top-down: the Neutrino Option

The issue: dynamics of the Higgs potential

The Higgs potential gives a successful parameterization of the electroweak symmetry breaking

$$V_c(H^\dagger H) = -\frac{m^2}{2}\,(H^\dagger\, H) + \lambda\,(H^\dagger\, H)^2$$

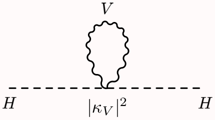
but it lacks **a dynamical origin**! ⟷ several theoretical **problems**:

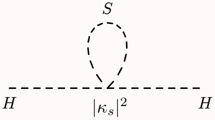
hierarchy, stability, triviality,
phase transition? . . .

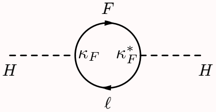
The hierarchy problem in an EFT perspective

Brivio, Trott 1706.08945

Heavy new physics can give loop corrections to $(H^\dagger H)$







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Brivio,Trott 1706.08945

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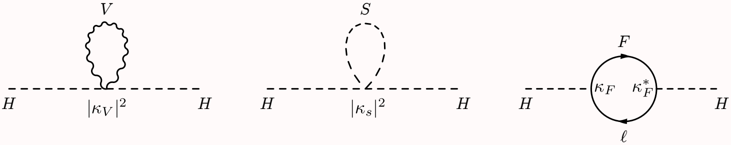

$\downarrow$ integrating it out

threshold matching contributions at $E < m_i$

[loops in DR+$\overline{MS}$ in the lim $v/m_i \to 0$]

$$\Delta V(H^\dagger H) \simeq H^\dagger H \left(\frac{3|\kappa_v|^2\ m_v^2\ N_v}{16\,\pi^2} + \frac{|\kappa_s|^2\ m_s^2\ N_s}{16\,\pi^2} - \frac{|\kappa_F|^2\ m_F^2\ N_F}{16\,\pi^2} \right) + \ldots$$

The hierarchy problem in an EFT perspective

Brivio,Trott 1706.08945

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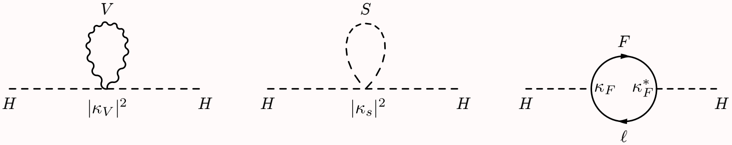

↓ integrating it out

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these corrections are always proportional to the scale integrated out

→ one of the main complications when UV completing the potential

Traditional solutions

Common approaches:

(a) SUSY way: extra symmetry to **force cancellations** among thresholds

(b) Composite way: shift symmetry to protect $H^\dagger H$

↓

potential **generated radiatively**.

$$V(H) \simeq \frac{g_{SM}^2 \Lambda^2}{8\pi^2}\left(-a\, H^\dagger H + b\,\frac{(H^\dagger H)^2}{f^2}\right)$$

Bellazzini,Csáki,Serra 1401.2457

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Troubles:

Bellazzini,Csáki,Serra 1401.2457

- both require resonances not far from TeV scale

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potential **generated radiatively**.

$$V(H) \simeq \frac{g_{SM}^2 \Lambda^2}{8\pi^2} \left(-a\, H^\dagger H + b\, \frac{(H^\dagger H)^2}{f^2} \right)$$

Bellazzini,Csáki,Serra 1401.2457

Troubles:

- both require resonances not far from TeV scale
- the potential must be generated at once. That's not trivial!

tuning of a, b ↔ complex spectrum / symmetry setup

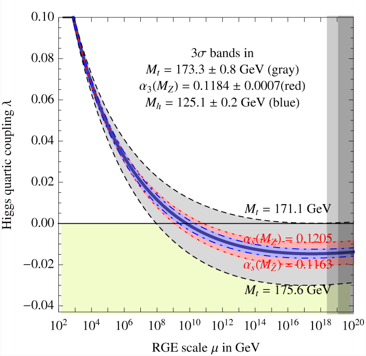
needed to get

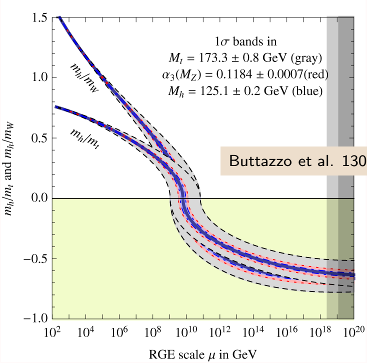
the right shape + $\mathbf{\frac{v^2}{f^2} = \frac{a}{b} \lesssim 1}$

Trying to change perspective

Having measured the Higgs mass opens new possibilities!

An important one: controlling the running of the potential to very high energies.





Buttazzo et al. 1307.3536

Trying to change perspective

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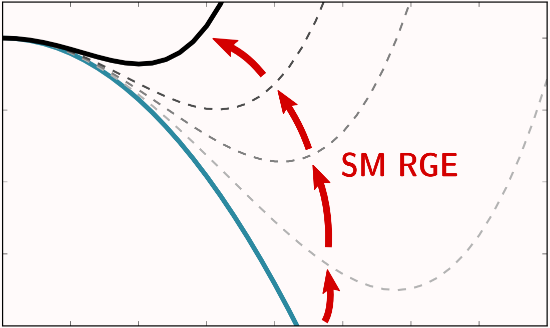
An important one: controlling the running of the potential to very high energies.



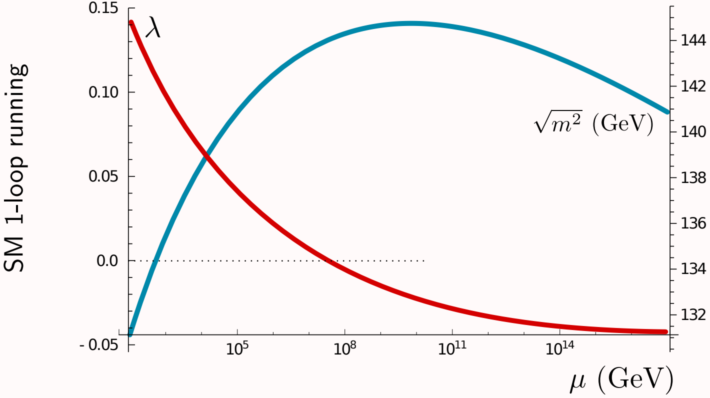
We can move the stabilization problem from the TeV to a much higher scale

- evade the problem of missing discoveries
- use **a trivial spectrum + the SM RG running** to obtain the mexican hat

The key idea

have some very heavy UV set the initial conditions at a high scale

interesting region: where $\lambda \lesssim 0$: $\mu \sim 10 - 100$ PeV



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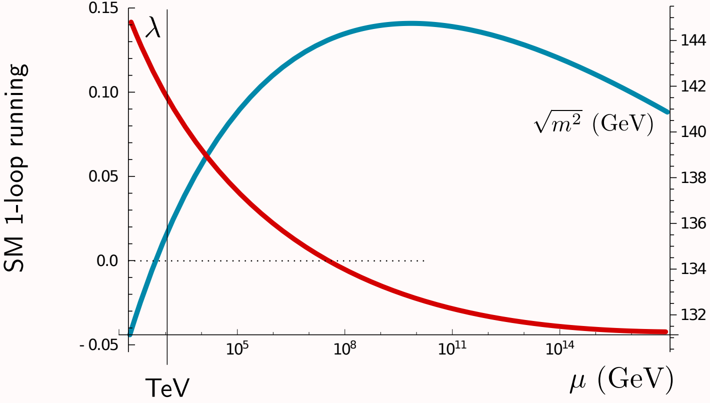

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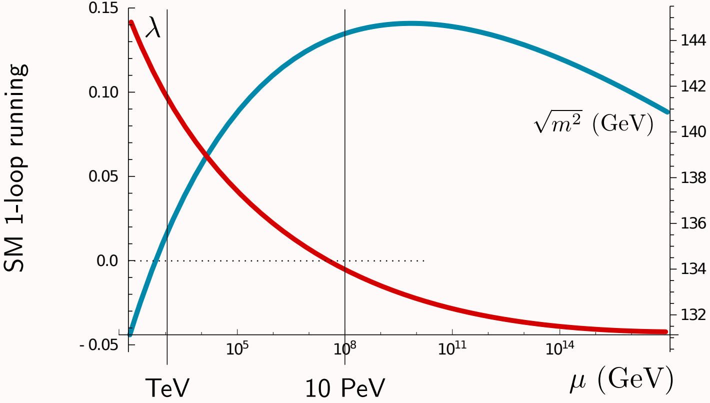

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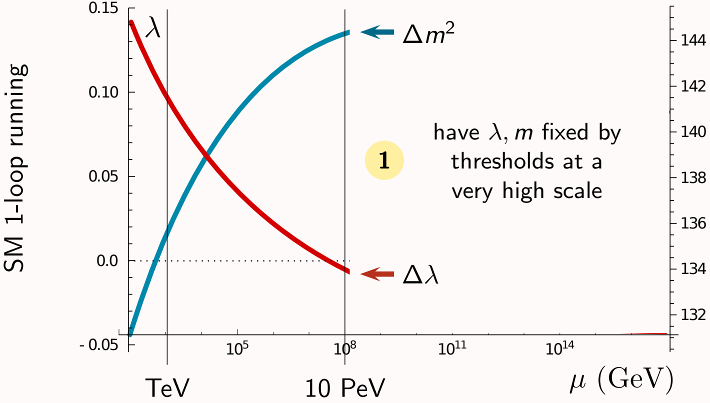
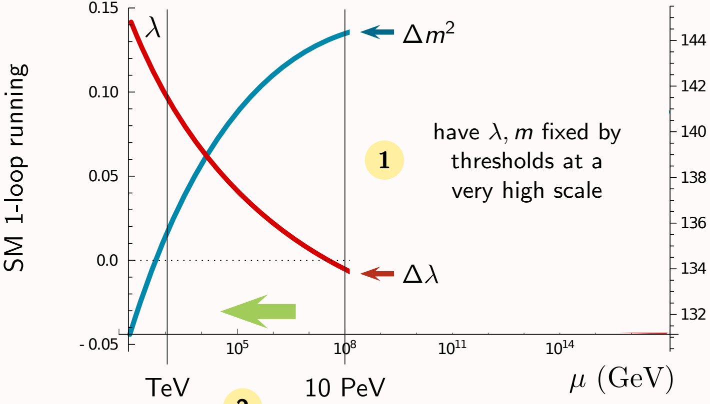


have λ, *m* fixed by thresholds at a very high scale

The key idea

have some very heavy UV set the initial conditions <u>at a high scale</u>

interesting region: where $\lambda \lesssim 0$: $\mu \sim 10 - 100$ PeV



① have λ, *m* fixed by thresholds at a very high scale

② run it down with SM RGE

A compelling case: type I seesaw

minimal extension of the SM: adds 3 heavy Majorana neutrinos $N \equiv N^c$

$$\mathcal{L}_N = \frac{1}{2}\overline{N}(i\partial\!\!\!/ - M)N - \frac{1}{2}\left[\overline{N}\,\omega^*\,\tilde{H}^T\ell_L^c + \overline{N}\,\omega\,\tilde{H}^\dagger\ell_L + \text{h.c.}\right]$$

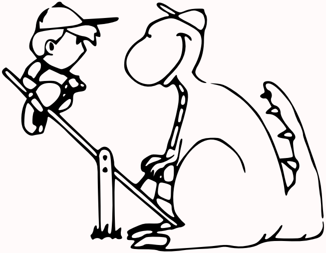
integrating out the N gives the Weinberg operator: $\frac{1}{2}(\bar{\ell_L^c}\omega^T\tilde{H}^*)M^{-1}(\tilde{H}^\dagger\omega\ell_L)$

→ light neutrino masses $m_\nu = \frac{v^2}{2}\,\omega^T M^{-1}\omega$

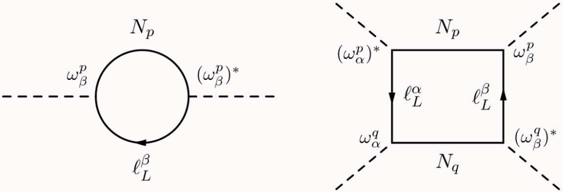
Minkowski 1977
Gell-Mann,Ramond,Slansky 1979
Mohapatra,Senjanovic 1980
Yanagida 1980

2 free quantities:

- $M = \mathrm{diag}(M_1, M_2, M_3)$
- ω a 3 × 3 matrix in flavor space



❶ Thresholds from the seesaw



$$\Delta\, m^2 = M_p^2 \frac{|\omega_p|^2}{8\,\pi^2} \qquad \Delta\,\lambda = -5\frac{(\omega_q\cdot\omega^{p,\star})(\omega_p\cdot\omega^{q,\star})}{64\,\pi^2}.$$

Vissani hep-ph/9709409
Casas et al hep-ph/9904295

We need to assume these are the dominant contributions to λ, m^2 at $\mu \simeq M$

- nearly-vanishing *classical* potential at $\mu \gtrsim M$:
  approximate scale invariance + explicit breaking only from Majorana mass
- threshold contributions **from other NP** are subdominant wrt these
- **SM contributions** to the Coleman-Weinberg potential are also smaller.
  OK for $M|\omega| \gg v, \Lambda_{QCD}$.

❷ Running down

Coupled differential system

- **1-loop SM RGE** for $\{\lambda,\ m^2,\ Y_t,\ g_1,\ g_2,\ g_3\}$
- 1-loop **boundary conditions** ($\sim$ degenerate N_p)

$$\lambda(M) = \boxed{-9\frac{5}{64\pi^2}|\omega|^4} \qquad m^2(M) = \boxed{\frac{3|\omega|^2}{8\pi^2}\,M^2}$$

$$Y_t(m_t) = 0.9460 \qquad g_1(m_t) = 0.3668$$

$$g_2(m_t) = 0.6390 \qquad g_3(m_t) = 1.1671$$

solve for $\left|\begin{array}{r} \lambda(m_t) = 0.127 \\ m^2(m_t) = (132.2\,\mathrm{GeV})^2 \end{array}\right.$ → “best-fit” values for $M, |\omega|$

Test: this fixes the m_ν scale. Can we get realistic values?

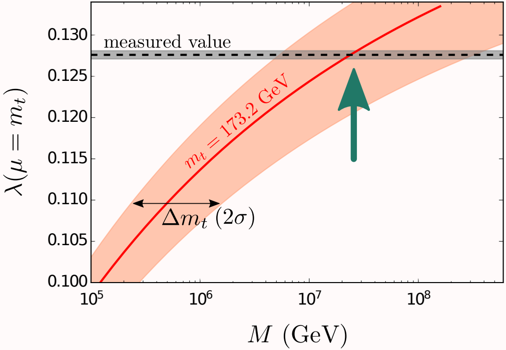
Results

$\lambda(m_t)$ is not sensitive to $|\omega|$ but depends significantly on M

↓

best fit $M \simeq 10^{7.4}$ GeV $\simeq$ 25 PeV

! large uncertainty due to m_t



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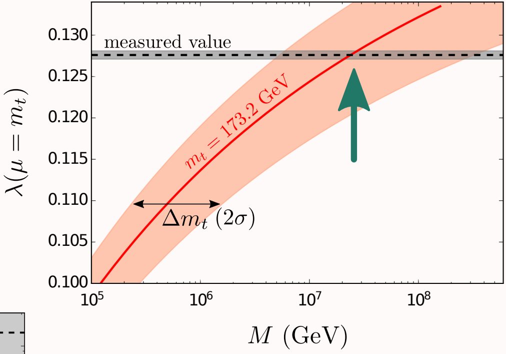

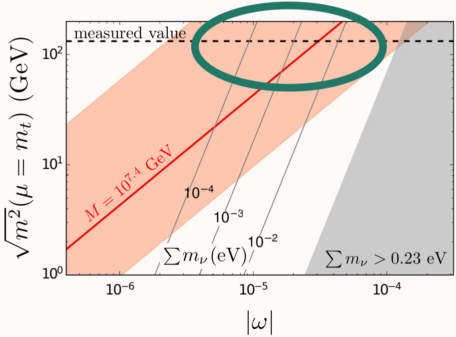

with fixed M, $m^2(m_t)$ determines uniquely $|\omega| \simeq 10^{-4.5}$

↓

$$\sum |m_\nu| = \frac{3|\omega|^2}{2} \frac{v^2}{M} \simeq 3 \cdot 10^{-3} \text{ eV}$$

Results

$\lambda(m_t)$ is not sensitive to $|\omega|$ but
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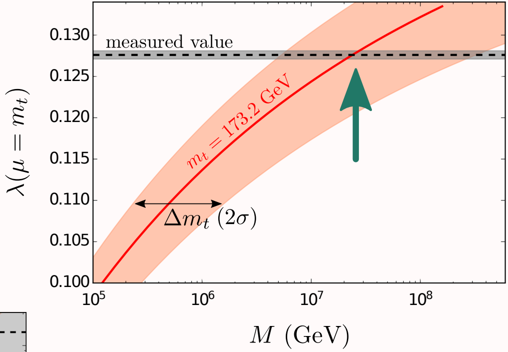

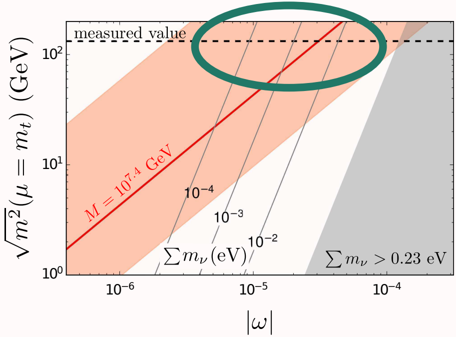

with fixed M, $m^2(m_t)$ determines
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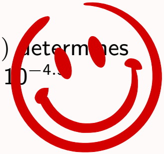
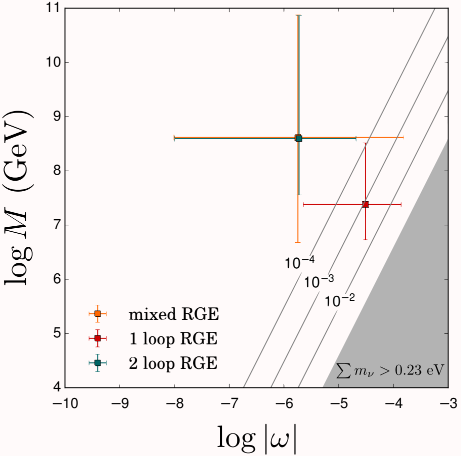


↓

$$\sum |m_\nu| = \frac{3|\omega|^2}{2}\,\frac{v^2}{M} \simeq 3 \cdot 10^{-3}\ \text{eV}$$

The neutrino option: troubles

- High **numerical sensitivity** to top mass + RGE order
- No thermal leptogenesis in this scenario (needs $|\omega| \gtrsim 10^{-4}$)
  Davoudiasl,Lewis 1404.6260
- No BSM signatures predicted (besides ν masses) up to the PeV
- Does NOT solve the hierarchy problem



New challenge:

construct a UV leading to

Majorana masses + quasi-conformal potential at the PeV scale

The neutrino option: good points

- it's minimal
- λ, m^2, m_ν can all be generated with the correct values
- neutrino mass splittings and mixing can be accommodated! (adjusted with additional parameters)
- ties the **breaking of scale invariance** with that of the **lepton number** → SM terms are accidentally protected!
- no BSM signatures predicted (besides ν masses) up to the PeV
- the key idea of generating the potential at high scale is general! Can be applied to other UVs

Backup slides

Basis independence

What's a "basis"?

Recipe:

1. write all possible $d = 6$ invariants in $\mathcal{L}_6$
2. remove redundancies applying gauge independent field redefinitions on $\mathcal{L}_4$

e.g.

$$H_j \to H_j + \eta_1 \frac{D^2 H_j}{\Lambda^2} + \eta_2 \frac{\bar{e}\,\ell_j\, Y_e}{\Lambda^2} + \eta_3 \frac{\bar{d}\, q_j\, Y_d}{\Lambda^2} + \eta_4 \frac{(\bar{u}\epsilon\, q_j)^\star\, Y_u^\star}{\Lambda^2} + \eta_5 \frac{H^\dagger H\, H_j}{\Lambda^2}$$

$$B_\mu \to B_\mu + \beta_1 \frac{\bar{\psi}\gamma_\mu\psi}{\Lambda^2} + \beta_2 \frac{H^\dagger\, i\overleftrightarrow{D}_\mu H}{\Lambda^2} + \beta_3 \frac{D^\alpha B_{\alpha\mu}}{\Lambda^2} + \beta_4 \frac{H^\dagger H\, B_\mu}{\Lambda^2}$$

$$e \to e + \varepsilon_1 \frac{\bar{\ell} i \not{D} H Y_e^\dagger}{\Lambda^2} + \varepsilon_2 \frac{\bar{\ell} i \overleftarrow{\not{D}} H Y_e^\dagger}{\Lambda^2} + \varepsilon_3 \frac{H^\dagger H e}{\Lambda^2} + \varepsilon_4 \frac{D^2 e}{\Lambda^2}$$

choosing the free parameters $(\eta_i,\, \beta_i,\, \varepsilon_i)$ so as to cancel an operator from $\mathcal{L}_6$

- formally equivalent to applying EOMs on $\mathcal{L}_6$
- use an **algorithm** that avoids reintroducing the same terms

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 $\mathcal{L}_4$:

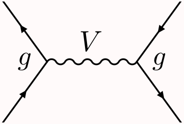
$$\mathcal{L}_4 + \mathcal{L}_6 \to \mathcal{L}_4 + \frac{k + c_1}{\Lambda^2}\sigma A + \frac{k + c_2}{\Lambda^2}\partial_\mu \sigma B^\mu$$

→ 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



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

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

non canonical kinetic term.
→ OK adjusting LSZ

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

the S-matrix has a reparameterization invariance

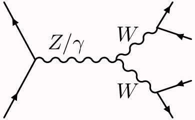
operators modifying the kinetic term normalization have <u>no</u> impact here

$\updownarrow$

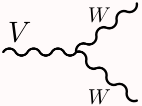
these C_i can be removed from the amplitude via $(*)$

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

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

$$\rightarrow$$

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

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

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

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

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

$$\begin{aligned} \alpha_{\rm em} &= \frac{\bar{g}_1\bar{g}_2}{\bar{g}_1^2+\bar{g}_2^2}\left[1+\bar{v}^2 C_{HWB}\frac{\bar{g}_2^3/\bar{g}_1}{\bar{g}_1^2+\bar{g}_2^2}\right] \\ m_Z &= \frac{\bar{g}_2\bar{v}}{2c_{\bar{\theta}}} + \delta m_Z(C_i) \\ G_f &= \frac{1}{\sqrt{2}\bar{v}^2} + \delta G_f(C_i) \end{aligned} \quad \rightarrow \quad \begin{aligned} \hat{v}^2 &= \frac{1}{\sqrt{2}G_f} \\ \sin\hat{\theta}^2 &= \frac{1}{2}\left(1-\sqrt{1-\frac{4\pi\alpha_{\rm em}}{\sqrt{2}G_f m_Z^2}}\right) \\ \hat{g}_1 &= \frac{\sqrt{4\pi\alpha_{\rm em}}}{\cos\hat{\theta}} \\ \hat{g}_2 &= \frac{\sqrt{4\pi\alpha_{\rm em}}}{\sin\hat{\theta}} \end{aligned}$$

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

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

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

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

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

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

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

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

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.

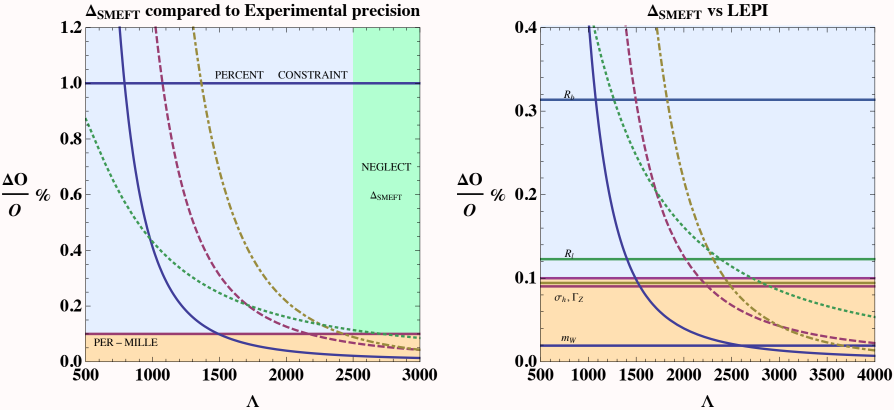
$$\Delta_i^{\rm th} = \sqrt{\Delta_{i,{\rm SM}}^2 + \Delta_{\rm SMEFT}^2\bar{O}_i^2}$$

$\Delta_{\rm SMEFT}$

SMEFT uncertainty: → impact of $d \geqslant 8$ operators + radiative corrections

→ initial/final state radiation

→ . . .



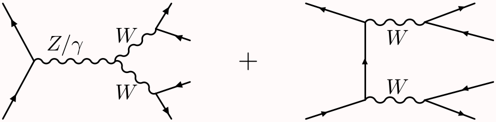
Berthier, Trott 1508.05060

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 ↓

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

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 $\{m_W, m_Z, G_F\}$

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other benefits

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

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

in the Thomson limit

(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

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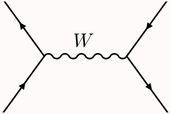

transverse obs: $m_T, p_{T\ell}, \not{E}_T$

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!**

α_{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

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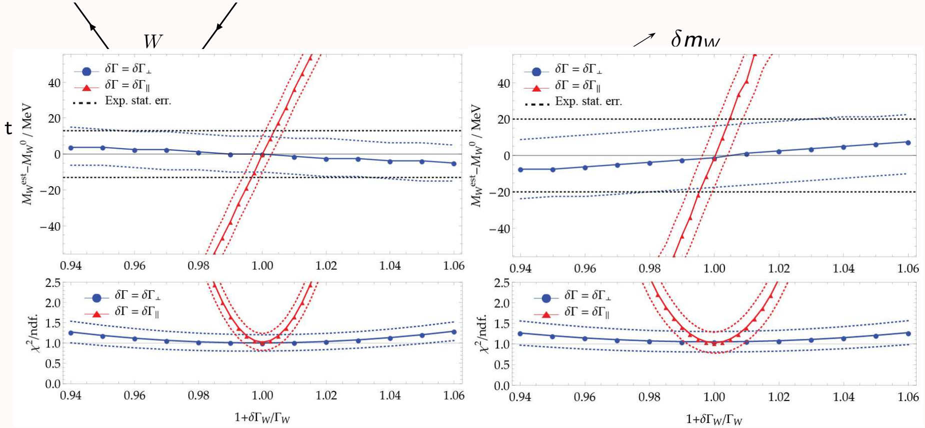

α_{em} has not been checked, so it may require an extra theoretical error!

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:

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

Results:

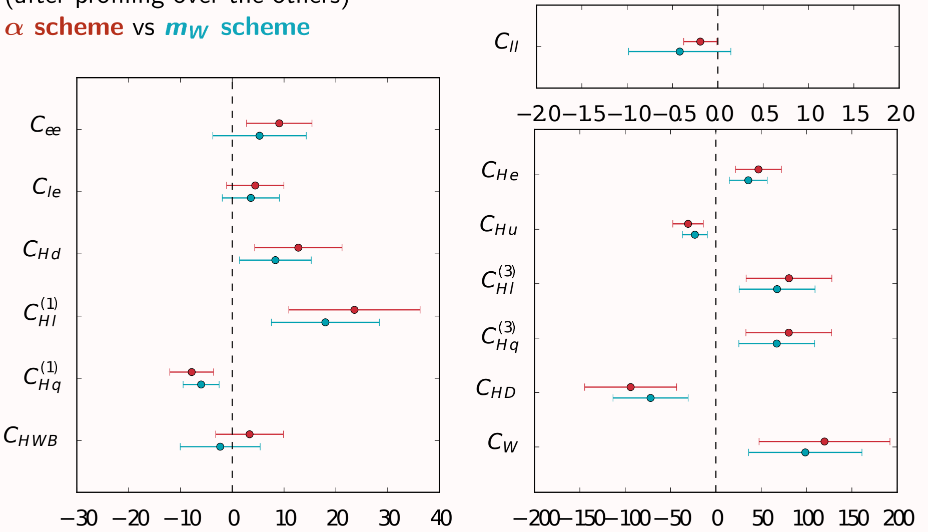
1. if $\bar\psi\psi \to \bar\psi\psi\bar\psi\psi$ is not included ⇒ flat directions compatible with the reparam. invariance structure. ✓

   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