Hunting New Physics footprints: the SMEFT program for the LHC

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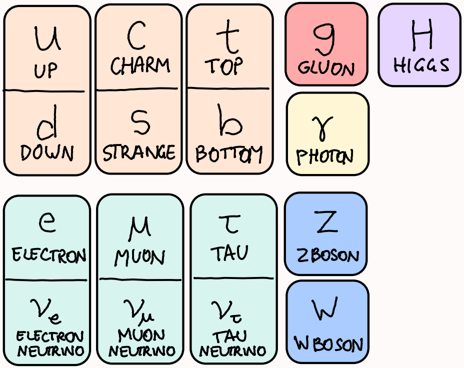
– Introduction –

The Standard Model of Particle Physics

a puzzle solved over a century!

unifies 3 of the 4 known fundamental interactions: electromagnetism, **weak** and strong forces
and explains how known particles acquire mass through the Higgs mechanism

$$\mathscr{L}_{SM} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W^i_{\mu\nu}W^{i\mu\nu} - \frac{1}{4}G^A_{\mu\nu}G^{A\mu\nu} - \frac{g_s^2}{16\pi^2}\theta G^A_{\mu\nu}\tilde{G}^{A\mu\nu}$$
$$+ \sum_f \bar{f}i\not{D}f - \left[\bar{Q}Y_u\tilde{H}u + \bar{Q}Y_dHd + \bar{L}Y_lHe + \text{h.c.}\right]$$
$$+ D_\mu H^\dagger D^\mu H + \frac{m_h^2}{2}H^\dagger H - \lambda(H^\dagger H)^2$$



Gauge principle

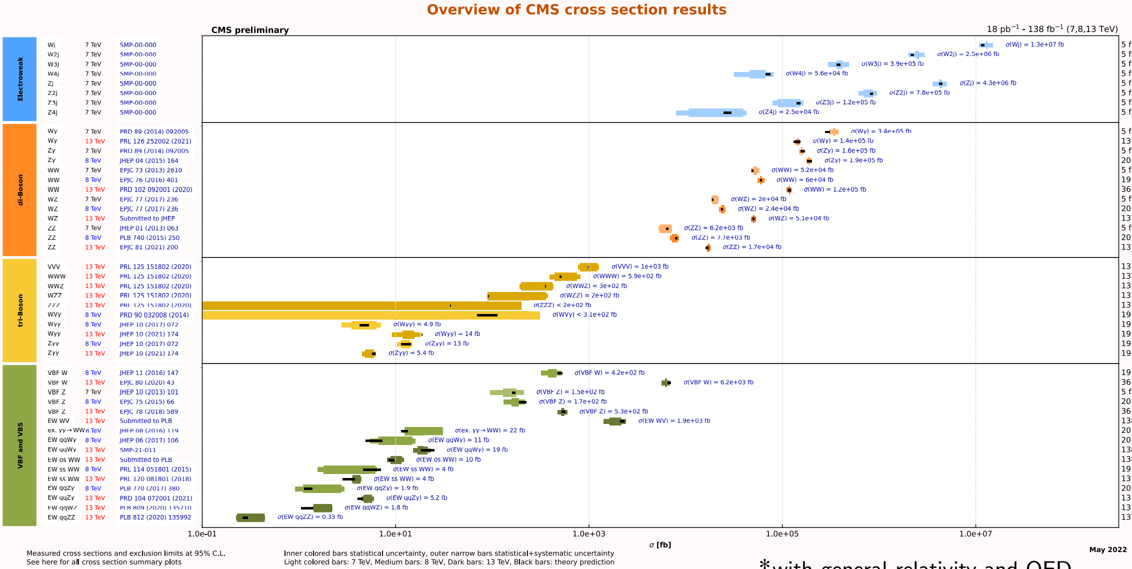
interactions are described by **symmetries** (SU(3)×SU(2)×U(1))

particles are classified in symmetry representations

→ fully determines interaction patterns

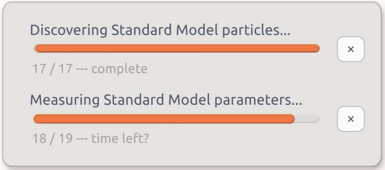
→ everything predicted as a function of 19 independent parameters

One of the most accurately tested theories ever*



*with general relativity and QED

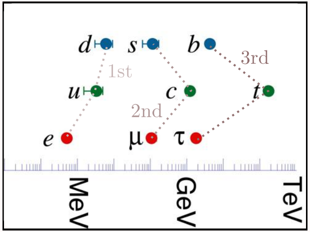
Beyond the Standard Model?



- the SM is self-consistent & works really well
- all particles in the SM have been discovered
- 18/19 parameters have been measured
  (although not *all interactions* have been observed)

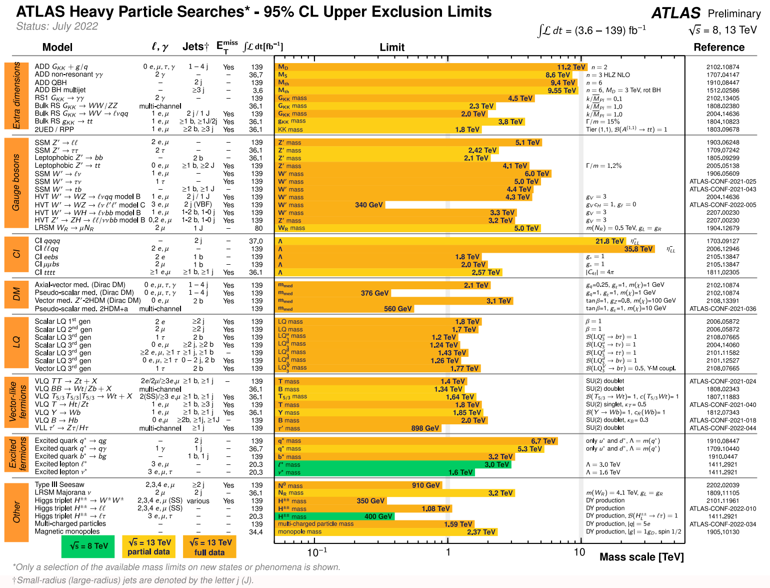
however, most likely it's NOT the ultimate theory of Nature!

Experimentally observed	**Theoretically unsatisfactory**
Dark Matter	Why $m_h = 125\,\mathrm{GeV}$?
Neutrino masses & mixings	Flavor puzzle
Matter-Antimatter asymmetry	Lack of $\not{CP}$ in the strong force
Gravity	...

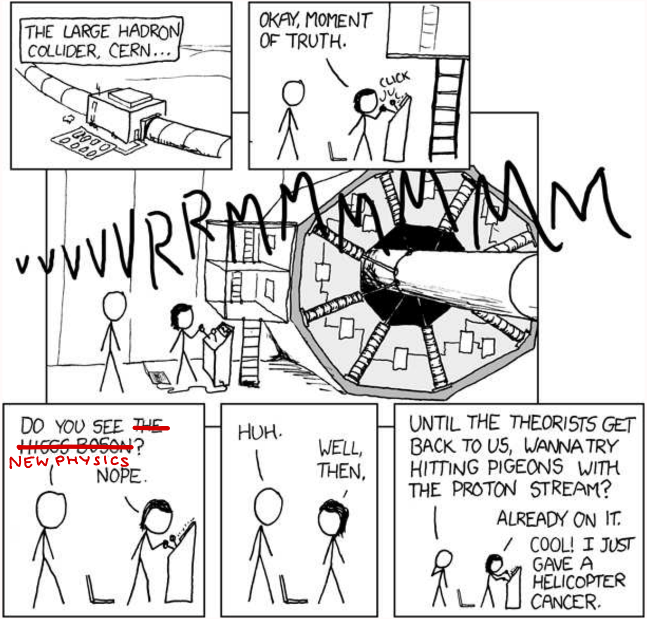


+ there is no reason why this theory or energy range should be special

Searches for beyond-SM resonances so far



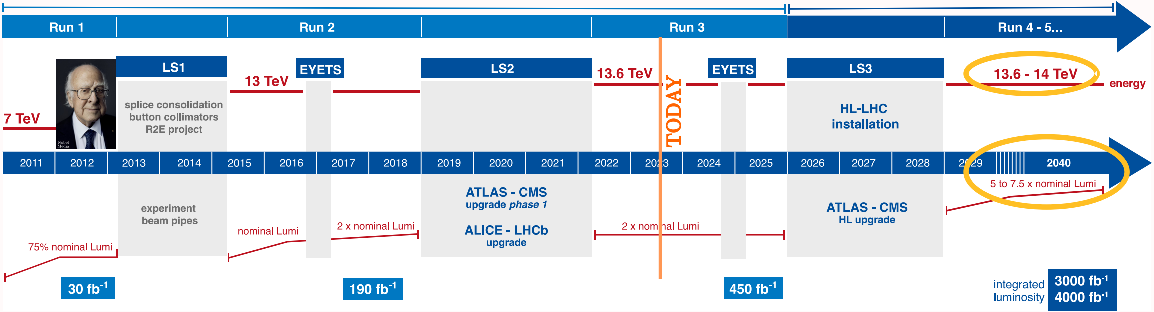
xkcd.com/401/


THE LARGE HADRON COLLIDER, CERN...
OKAY, MOMENT OF TRUTH.
CLICK
VVVVVRRRMMMMMMMMM
DO YOU SEE ~~THE HIGGS BOSON~~?
NEW PHYSICS
NOPE.
HUH.
WELL, THEN.
UNTIL THE THEORISTS GET BACK TO US, WANNA TRY HITTING PIGEONS WITH THE PROTON STREAM?
ALREADY ON IT.
COOL! I JUST GAVE A HELICOPTER CANCER.

The LHC as a precision machine

$\gtrsim$ **95%** of LHC data still has to be collected!

adapted from `project-hl-lhc-industry.web.cern.ch`



it has been estimated that measurements with **% precision** will be possible e.g. CERN report 1902.00134

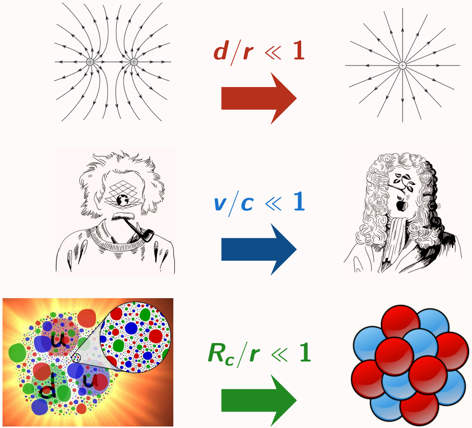
→ not only resonances! we can also look for small, indirect **traces** of new physics

– Effective Field Theories –

All Theories are Effective

an **Effective Theory** is obtained from a more fundamental one taking a kinematic or parametric limit
→ typically ET = the LO in an **expansion**

- ET typically **simpler** than the full theory in the pertinent regime
- one **doesn't need to know** the full theory to calculate! the ET is enough



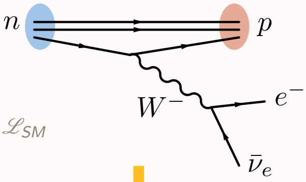
separation of scales/decoupling

Newtonian gravity can be formulated w/o general relativity
nuclear physics can be formulate w/o QCD
chemistry can be formulated w/o SM. . .

→ we expect any theory to be replaced by another one going to higher energies
(until the ultimate Theory of Everything)

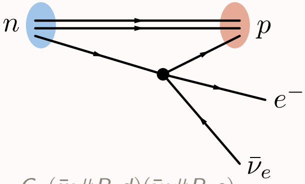
Effective Field Theories

Fermi Theory of β decay



$\mathscr{L} = \mathscr{L}_{SM}$

$q^2 < m_N^2 \ll m_W^2$



$\mathscr{L} = -G_F(\bar{u}\gamma^\mu P_L d)(\bar{\nu}\gamma^\mu P_L e)$

E

Λ

Full theory

$\rightarrow$ renormalizable: $[\mathscr{L}] = 4$

TAYLOR SERIES in ($\mu/\Lambda \ll 1$)

μ

Effective Field Theory

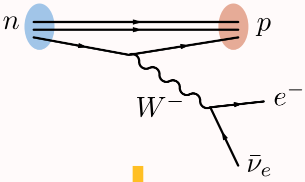
$$\mathscr{L}_{EFT} = \mathscr{L}_4 + \frac{1}{\Lambda}\mathscr{L}_5 + \frac{1}{\Lambda^2}\mathscr{L}_6 + \frac{1}{\Lambda^3}\mathscr{L}_7 \ldots$$

Appelquist,Carazzone 1975

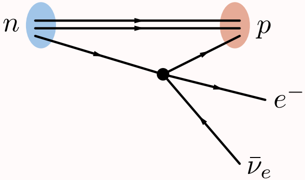
$\rightarrow$ heavy DOFs are removed: cannot be produced at $E \ll M$
$\rightarrow$ local, analytic, higher-dimensional terms added to $\mathscr{L}$

Effective Field Theories

Fermi Theory of β decay



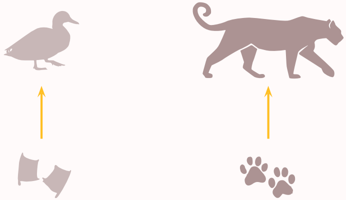
$q^2 < m_N^2 \ll m_W^2$



Bottom-up paradigm

measuring EFT parameters **reveals properties** of full theory

→ *complement* direct searches, reach into higher energies



EFT fully specified by **fields+symmetries at E** $= \mu$

→ no reference to underlying model

→ free couplings that can be measured!

The Standard Model Effective Field Theory – SMEFT

promoting the Standard Model to an EFT → add **higher-dimensional** terms made of SM **fields** and respecting the SM **symmetries**

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \dots \qquad \mathcal{L}_d = \sum_i C_i \mathcal{O}_i^{(d)}$$

C_i = Wilson coefficients

$\mathcal{O}_i^{(d)}$ = gauge-invariant operators forming a basis: a complete, non-redundant set

Buchmüller,Wyler 1986

- describes **any beyond-SM theory**, provided it lives at $\Lambda \gg v$
- a complete catalogue of all allowed beyond-SM effects, organized by expected size
- not experiment-specific! can be used as **a common framework** for LHC *and* other experiments
- a proper QFT! renormalizable order-by-order, systematically improvable in loops

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

Grzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884

free parameters

go down to O(100) imposing flavor symmetries, CP, B

Faroughy et al 2005.05366
Greljo et al 2203.09561
IB 2012.11343

they are ∼never all relevant at the same time

SMEFT at $d = 6$: the Warsaw basis

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

Grzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884

free parameters

go down to O(100) imposing flavor symmetries, CP, B

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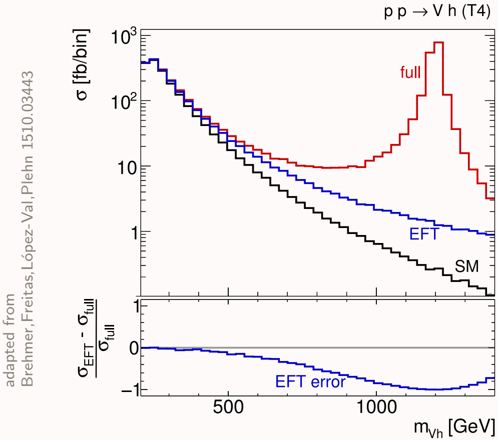
they are ∼never all relevant at the same time

How SMEFT works in practice

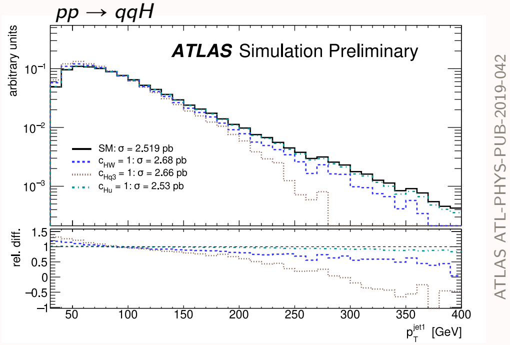
Top-Down

heavy BSM leaves residual footprints at visible energies



Bottom-Up

SMEFT operators cause deviations from SM predictions



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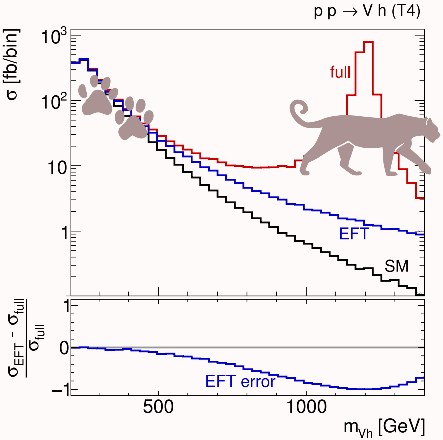
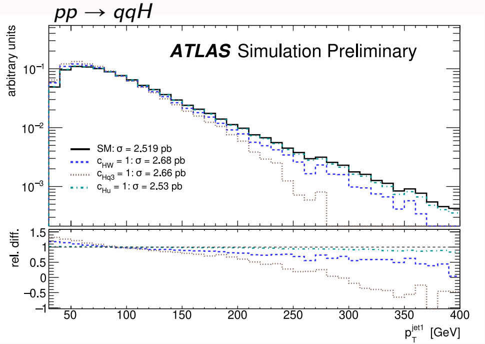


adapted from Brehmer, Freitas, López-Val, Plehn 1510.03443

Bottom-Up

SMEFT operators cause deviations from SM predictions



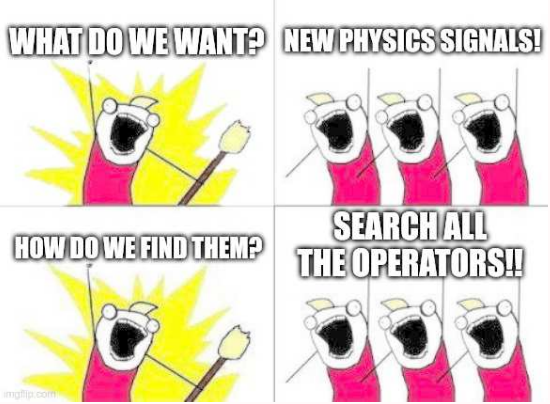
ATLAS ATL-PHYS-PUB-2019-042

– The SMEFT program –

An ambitious goal: model-independent new physics searches

previous sections recap:

- SM is NOT the ultimate theory of nature
- NO definitive clues about where to find new physics, could be **outside of LHC reach**
- LHC evolving into a **precision** machine
- SMEFT gives **full catalogue** of effects generated by heavy new physics
- measuring SMEFT parameters we can **reconstruct** new physics properties



in practice:

a broad measurements campaign targeting as many SMEFT effects as possible

Two main challenges

1. being sensitive to indirect BSM effects → needs uncertainty reduction

in bulk $\sim \frac{v^2}{\Lambda^2} = \frac{v^2 g_{UV}}{M^2}$. $g_{UV} \simeq 1, \quad M \simeq 2\,\mathrm{TeV} \rightarrow$ 1.5%

on tails $\sim \frac{E^2}{\Lambda^2} \simeq \frac{E^2 g_{UV}}{M^2}$ $E \simeq 1\,\mathrm{TeV}, M \simeq 3\,\mathrm{TeV} \rightarrow$ 10%

precision calculations in the SM
are **vital** for the SMEFT business!

Two main challenges

1. being sensitive to indirect BSM effects → needs uncertainty reduction

$$\text{in bulk} \sim \frac{v^2}{\Lambda^2} = \frac{v^2 g_{UV}}{M^2}. \qquad g_{UV} \simeq 1, \quad M \simeq 2\,\mathrm{TeV} \to 1.5\%$$

$$\text{on tails} \sim \frac{E^2}{\Lambda^2} \simeq \frac{E^2 g_{UV}}{M^2} \qquad E \simeq 1\,\mathrm{TeV}, M \simeq 3\,\mathrm{TeV} \to 10\%$$

2. making sure that, if we observe a deviation, we interpret it correctly
   - retaining **all relevant contributions**: all operators, NLO corrections...

     ↓

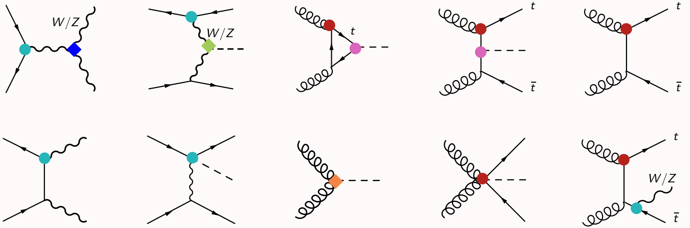
     – handling many parameters in predictions and fits
     – understanding the theory structure
   - correct understanding of uncertainties and correlations
   - systematic mapping to BSM models

A complex game

many free parameters entering many places → scaling complexity + non-trivial interconnections

typically each process is corrected by $\mathcal{O}(10)$ parameters:
constrains a direction in parameter space

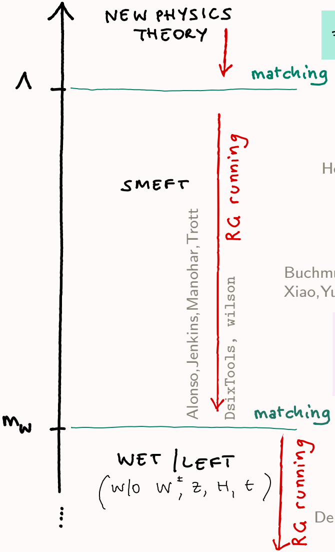
each parameter enters
multiple processes



Global analyses combining several measurements are necessary

- to access as many operators as we can
- to avoid bias in interpretation [safer than ad-hoc choices]

A field with many ramifications



Dekens,Stoffer,Jenkins,Manohar

FUNCTIONAL METHODS
Henning,Lu,Murayama,delAguila,Kunst,Santiago,Drozd,Ellis,Quevillon,You, Zhang,Fuentes-Martin,Portoles,Ruiz-Femenia,Krämer,Summ,Voigt. . .
`Matchmaker-eft, Matchete, STrEAM, CoDEx`

COUNTING FREE PARAMETERS
Henning,Lu,Melia,Murayama

CONSTRUCTING OP. BASES
Buchmüller,Wyler,Lehman,Li,Ren,Shu, Xiao,Yu,Zheng,Ma,Murphy. . .

ENSURING PHYSICAL AMPLITUDES (causal, unitary ....)
Adams,Arkani-Hamed,Nicolis, Rattazzi,deRham,Riva,Li, Xu,Tolley,Zhou,Zhang. . .

ANALYTIC CALCULATIONS
Hartmann,Trott,Corbett,Passarino, Dedes,Rosiek,Baglio,Giardino,Dawson, Pecjak,Scott,Grazzini,Maltoni,Alioli. . .

MONTE CARLO SIMULATIONS
IB,Degrande,Durieux,Maltoni,Mimasu, Vryonidou,Zhang. . . `SMEFTsim,SMEFT@NLO`

STUDIES OF EFT EFFECTS IN PDF, PS ...
Ubiali,Carrazza,Degrande,Rojo,Greljo, Iranipour,Kassabov,Madigan,Moore, Haisch,Scott,Wiesemann,Zanderighi,Zanoli. . .

FITTING TOOLS
`SMEFiT,HEPfit,EFTfitter, fitmaker,sfitter...`

INFORMATION GEOMETRY
Brehmer,Cranmer,Kling, Plehn,Tait. . .

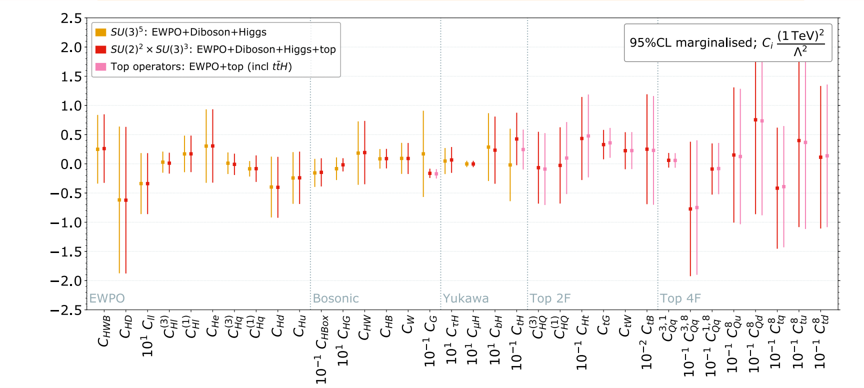
LIKELIHOOD INFERENCE
Brehmer,Cranmer,Louppe,Pavez, Glioti,Panico,Wulzer. . .

amazing progress was made in the last decade

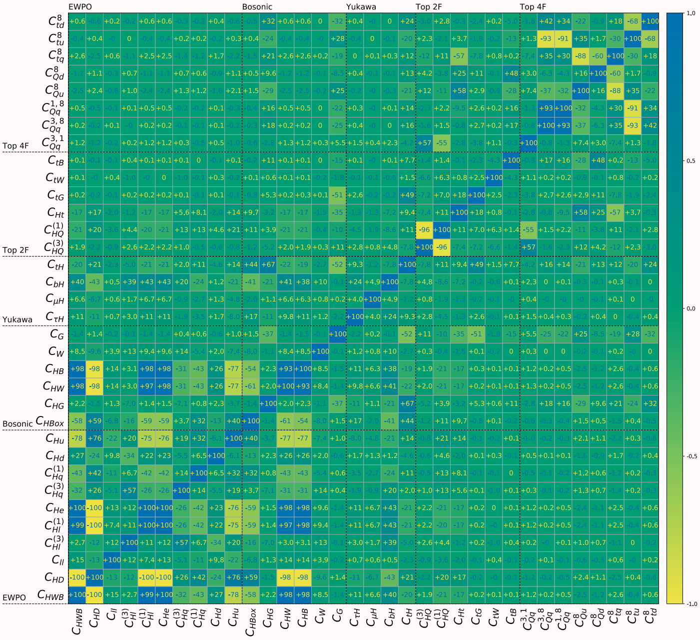
SMEFT analyses: state of the art

- theory fits: Higgs + EW (incl LEP) + top quark typically **30-35** param.
- SMEFT theory predictions: computed at tree-level / 1-loop in QCD

$$|\mathcal{M}_{SMEFT}|^2 = |\mathcal{M}_{SM}|^2 + \sum_\alpha \frac{C_\alpha}{\Lambda^2}\mathcal{M}_\alpha\mathcal{M}^\dagger_{SM} + \sum_{\alpha\beta}\frac{C_\alpha C_\beta}{\Lambda^4}\mathcal{M}_\alpha\mathcal{M}^\dagger_\beta$$



Ellis, Madigan, Mimasu, Sanz, You 2012.02779
also: Ethier, Maltoni, Mantani, Nocera, Rojo 2105.00006



EWPO
Bosonic
Yukawa
Top 2F
Top 4F
C^8_{td} C^8_{tu} C^8_{tq} C^8_{Qd} C^8_{Qu} $C^{1,8}_{Qq}$ $C^{3,8}_{Qq}$ $C^{3,1}_{Qq}$
C_{tB} C_{tW} C_{tG} C_{Ht} $C^{(1)}_{HQ}$ $C^{(3)}_{HQ}$
C_{tH} C_{bH} $C_{\mu H}$ $C_{\tau H}$
C_G C_W C_{HB} C_{HW} C_{HG} C_{HBox}
C_{Hu} C_{Hd} $C^{(1)}_{Hq}$ $C^{(3)}_{Hq}$ C_{He} $C^{(1)}_{Hl}$ $C^{(3)}_{Hl}$ C_{ll} C_{HD} C_{HWB}
1.0
0.5
0.0
-0.5
-1.0

Relative constraining power (%)

	EWPO	LEP WW	Run 1, μH	Run 2, μH	STXS	LHC WW&	LHC Zjj	$t\bar{t}$	single top	$t\bar{t}V$
1	6	–	15	29	50	–	–	–	–	–
2	35	–	13	28	23	–	–	–	–	–
3	59	–	7	16	18	–	–	–	–	–
4	–	–	5	94	1	–	–	–	–	–
5	99	–	–	–	–	–	–	–	–	–
6	95	–	–	–	–	3	–	–	–	–
7	99	–	–	–	–	–	–	–	–	–
8	–	–	21	45	33	–	–	–	–	–
9	74	–	2	4	14	6	–	–	–	–
10	18	–	8	19	55	–	–	–	–	–
11	73	22	–	–	–	3	–	–	–	–
12	7	2	5	53	4	29	–	–	–	–
13	–	–	–	3	–	–	–	–	96	–
14	7	–	2	39	2	46	–	–	3	–
15	–	–	–	10	4	–	–	57	–	28
16	94	2	–	–	–	2	–	–	–	–
17	–	2	–	–	–	11	86	–	–	–
18	65	14	2	4	10	4	1	–	–	–
19	–	–	–	–	–	–	–	99	–	–
20	–	–	–	–	–	–	–	84	15	–
21	–	–	–	13	6	–	–	48	–	32
22	90	5	–	–	1	2	–	–	–	–
23	–	–	–	5	2	–	–	79	–	13
24	–	–	–	–	–	–	–	3	78	18
25	2	3	27	40	12	6	–	4	–	4
26	–	–	1	2	–	–	–	15	4	77
27	4	4	14	33	23	7	1	12	–	2
28	–	–	1	3	1	–	–	4	–	89
29	–	–	3	10	4	–	–	28	2	53
30	1	–	8	27	16	2	–	32	–	12
31	–	–	–	–	–	–	–	58	–	41
32	–	–	–	–	–	–	–	90	–	10
33	–	–	–	–	–	–	–	61	–	38
34	–	–	–	–	–	–	–	95	–	5

SMEFT combined analyses in ATLAS and CMS

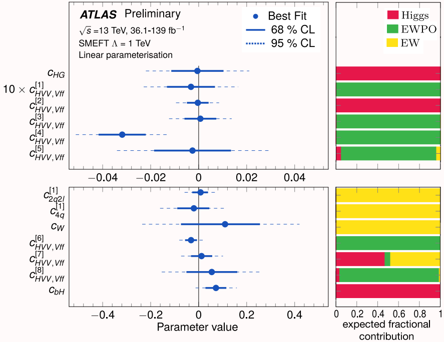
LHC experiments gearing up to do dedicated combination

important in order to use the full experimental information:
better uncertainty and correlation estimates

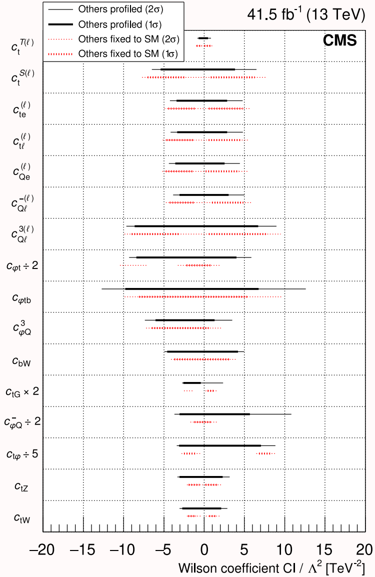
ultimate goal: a cross-experiment cross-sector combined study

a dedicated
CERN Working Group
created in 2020
to coordinate

lpcc.web.cern.ch/lhc-eft-wg



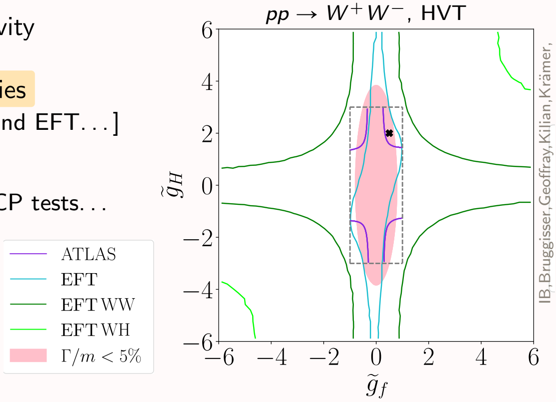
ATL-PHYS-PUB-2022-037



CMS-TOP-19-001

Some open fronts

- treatment of RG effects : 2-loop RGE, account for running+mixing in MC...
- improve theory predictions: optimize MC strategies, include EFT in backgrounds, PDFs...
- properly account for experimental **uncertainties and correlations** in fits
- define optimal observables to improve sensitivity
- understand and treat SMEFT-born uncertainties
  [scale dependence, missing higher orders in loops and EFT...]
- incorporate **more processes**:
  VBS, high-multiplicity final states, flavor physics, CP tests...
- handle 50+ dimensional likelihood
- explore interplay with resonance searches
- explore alternative EFT setups?

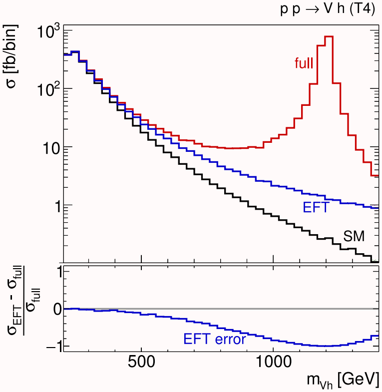


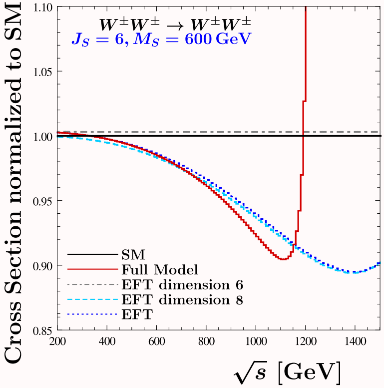
IB,Bruggisser,Geoffray,Kilian,Krämer, Luchmann,Plehn,Summ 2108.01094

Impact of higher order operators

EFT obtained from matching to full model

adapted from Brehmer,Freitas,López-Val,Plehn 1510.03443

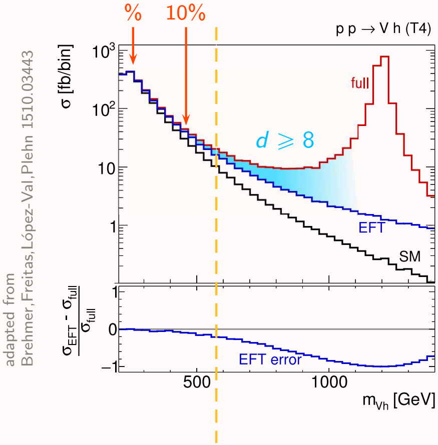




adapted from Lang,Liebler,Schäfer-Siebert,Zeppenfeld 2103.16517

Impact of higher order operators

EFT obtained from matching to full model

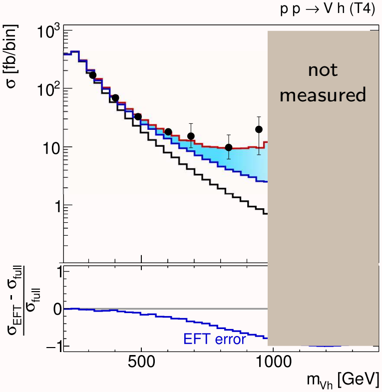


$d = 6$ breaks down

Impact of higher order operators

EFT obtained from matching to full model

adapted from Brehmer,Freitas,López-Val,Plehn 1510.03443



top-down: C_i fixed by matching
→ EFT not valid in high-E region

bottom-up: fit C_i to data
tends to make EFT match full result
→ find wrong values of C_i

how to keep this into account?

sliding upper cut:
Contino,Falkowski,Goertz, Grojean,Riva 1604.06444

uncertainty band:
Trott et al 1508.05060,2007.00565,2106.13794
Hays,Martin,Sanz,Setford 1808.00442
Shepherd et al 1812.07575,1907.13160

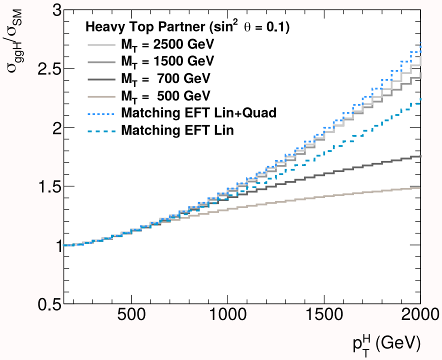
compute at $O(\Lambda^{-4})$
Boughezal,Mereghetti,Petriello 2106.05337
Asteriadis,Dawson,Fontes,Homiller,Sullivan 2110.06929,2205.01561,2212.03258

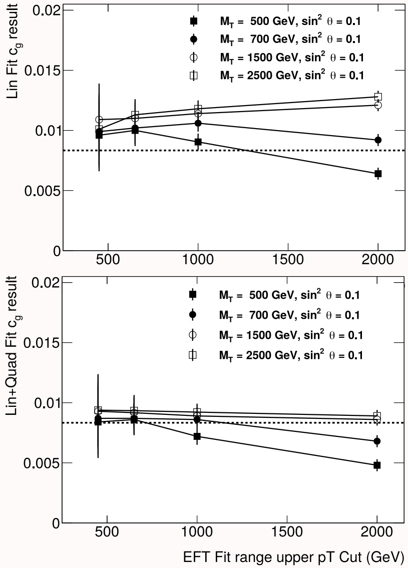
Benchmarking these proposals: sliding upper cut

Battaglia,Grazzini,Spira,Wiesemann 2109.02987

p_T^H from heavy top partner

fit result $\stackrel{?}{=}$ value from matching
$\rightarrow$ check impact of upp. cut + quadratics

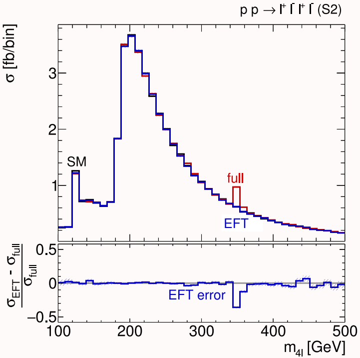




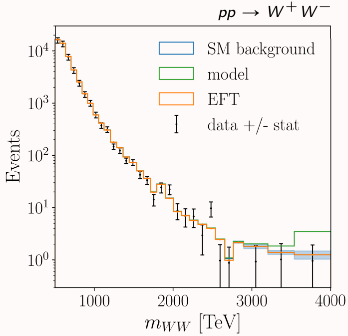
safe scenarios ↔ no energy growth ↔ small effects

typical cases where $d = 6$ works well **across the whole visible spectrum**:

- observables w/o E dependence (1 → 2 decays)
- BSM scenarios with very narrow and/or heavy states



adapted from
Brehmer,Freitas,López-Val,Plehn 1510.03443

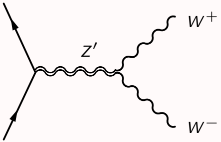


Brivio,Bruggisser,Geoffray,Kilian,Krämer,
Luchmann,Plehn,Summ 2108.01094

price to pay: % effects only

→ most sensitivity from lowest error region (∼ bulk)

Interplay with direct searches

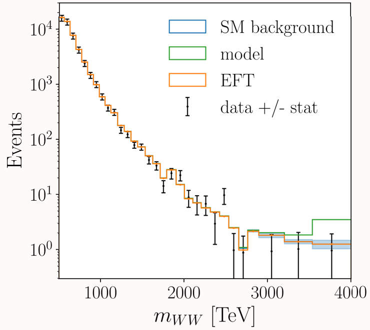


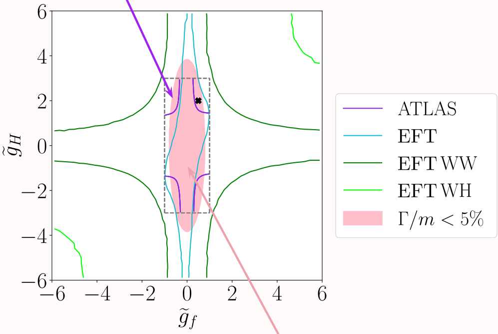
IB,Bruggisser,Geoffray,Kilian,Krämer, Luchmann,Plehn,Summ 2108.01094

$m_{Z'} = m_V = 4$ TeV

bound from
WW resonance search

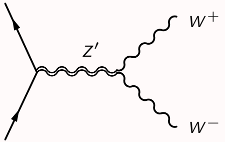
data: ATLAS 2004.14636





resonance s. only valid
for narrow Z'

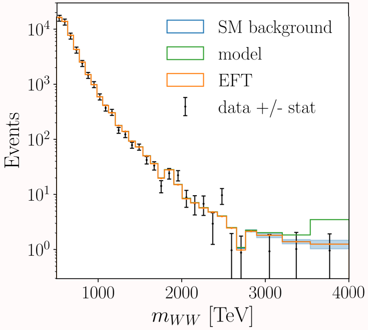
Interplay with direct searches



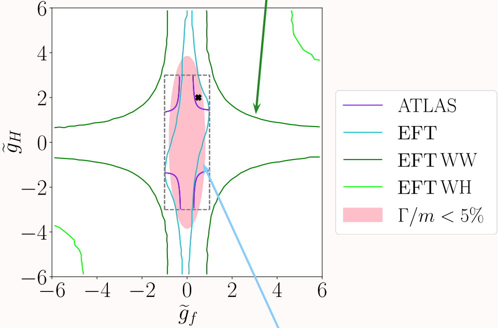
$$m_{Z'} = m_V = 4\ \text{TeV}$$

IB, Bruggisser, Geoffray, Kilian, Krämer, Luchmann, Plehn, Summ 2108.01094

data: ATLAS 2004.14636

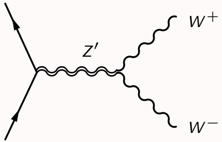


bound from EFT fit to *WW* spectrum



bound from EFT fit to <u>all</u> obs. (incl. EWPO, Higgs)

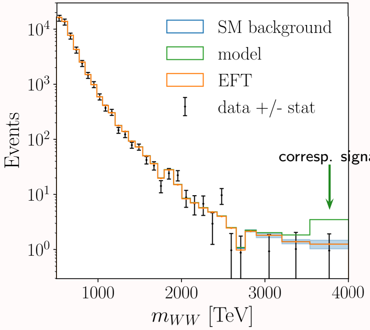
Interplay with direct searches



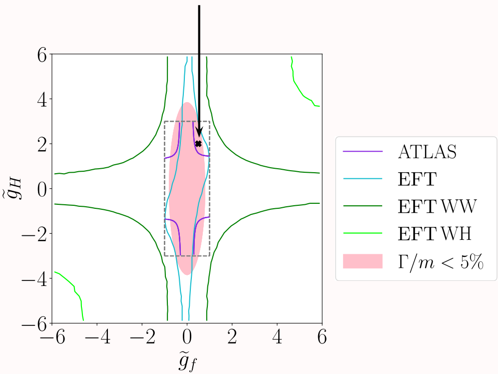
$m_{Z'} = m_V = 4$ TeV

IB, Bruggisser, Geoffray, Kilian, Krämer, Luchmann, Plehn, Summ 2108.01094

data: ATLAS 2004.14636



point excluded by resonance s. but allowed by EFT

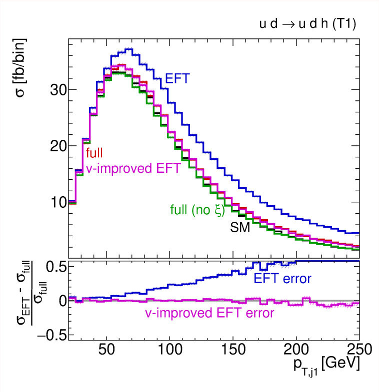


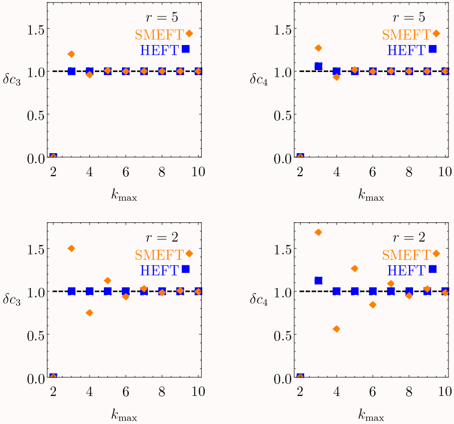
SMEFT or HEFT?

a component of the $d = 6$ vs model discrepancy can be removed by reabsorbing
higher powers of v within $d = 6$ coefficients instead of leaving them to $d \geqslant 8$

conceptually same as matching to **HEFT** instead

Brehmer,Freitas,López-Val,Plehn 1510.03443





Cohen,Craig,Lu,Sutherland 2008.08597

which EFT is most convenient?

An alternative to SMEFT? the Higgs EFT

changing the symmetry properties of the Higgs field changes the classification of BSM effects

Feruglio 9301281, Grinstein,Trott 0704.1505, Buchalla,Catà 1203.6510, Alonso et al 1212.3305, IB et al 1311.1823,1604.06801, Buchalla et al 1307.5017,1511.00988. . .

$$H \mapsto \frac{v + h}{\sqrt{2}}\,\mathbf{U}, \qquad \mathbf{U} = \exp\left(\frac{i\vec{\sigma}\cdot\vec{\pi}}{v}\right)$$

HEFT $\supset$ SMEFT $\supset$ SM

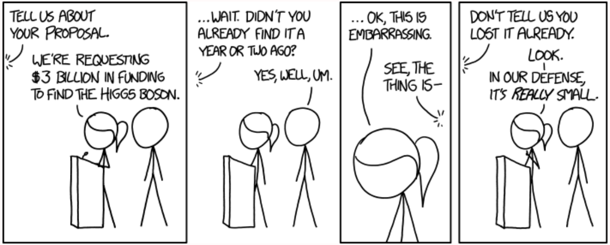
- HEFT expands **around vacuum**, SMEFT around $H = 0$
- recent **geometric interpretation** proves that Alonso,Jenkins,Manohar 1511.00724,1605.03602
  there are BSM theories that admit HEFT but not SMEFT
  – with BSM sources of EWSB Cohen et al 2008.0597,Banta et al 2110.02967
  – with BSM particles that take $> 1/2$ of their mass from EWSB
- HEFT more **convergent** than SMEFT
- unclear whether unique HEFT phenomenological signatures exist

Wrapping up

- the Standard Model of particle physics is **extremely successful, but not the ultimate theory!**
- the Large Hadron Collider at CERN hasn't found evidence for **new resonances** yet
- in the next 20 years, it will collect 20 times more data than today → **a precision machine!**
- SMEFT and EFTs in general can help us make the most out of this dataset!
  → a very **challenging program**, being developed by theory and experiments

(hopefully)
a powerful way to obtain **guidance**
for the future of particle physics!

xkcd.com/1437/



COMETA

a newly approved COST Action!

“COmprehensive Multiboson Experiment-Theory Action”

very broad scientific program

- **SMEFT/HEFT studies** of multi-boson processes (as many H/W/Z as wished), also with global perspective
- **precision calculations** and development of MC, PS etc
- **W, Z polarizations**: conventions, higher-order predictions, MC
- development of **ML-based tools**, together with ML experts outside academia: polarization taggers, jet taggers for VBF topologies, optimal observables...

€ for networking: will organize **workshops, schools, topical meetings**
+ funds for short/medium-term **visits** to other institutions within Europe

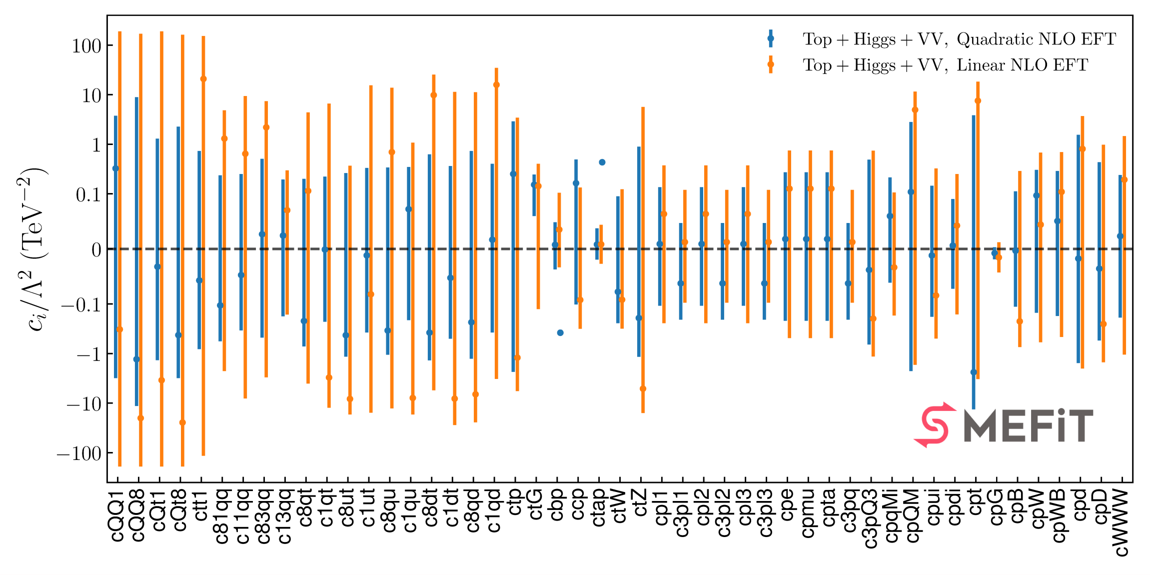
currently $\sim$ 1/3 theorists + 2/3 experimentalists + a few ML experts

funding will start in November, activities in 2024 – 2027

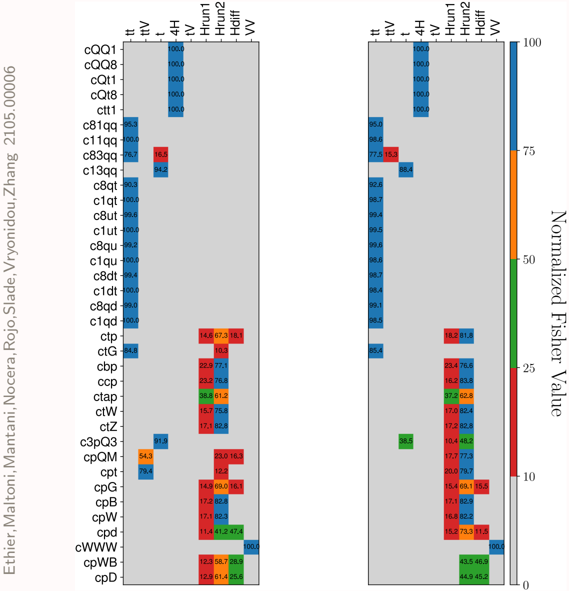
sign up & **more info** at `www.cost.eu/actions/CA22130/`

Backup slides

SMEFT fit results



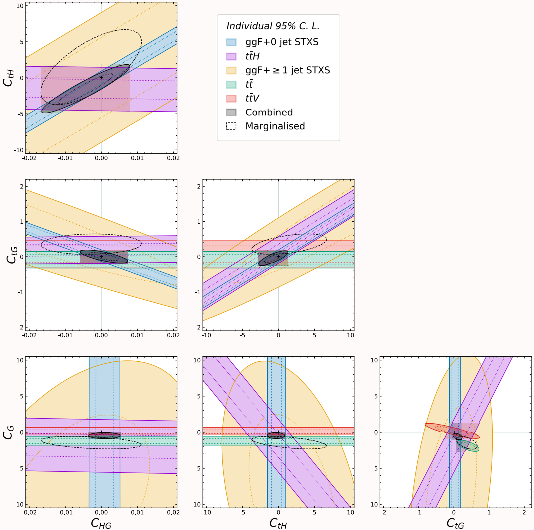
Fisher information



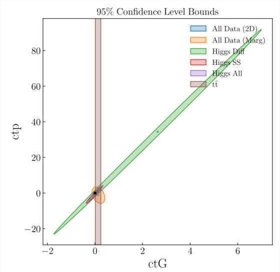
C_{tG} mostly constrained by $t\bar{t}$

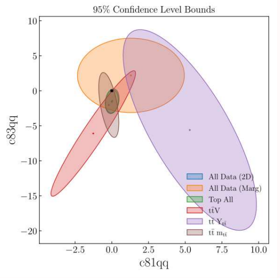
ttV op. constrained by $h \to \gamma\gamma$, single-t, $t\bar{t}V$

Top and Higgs interplay



Ellis,Madigan,Mimasu,Sanz,You 2012.02779

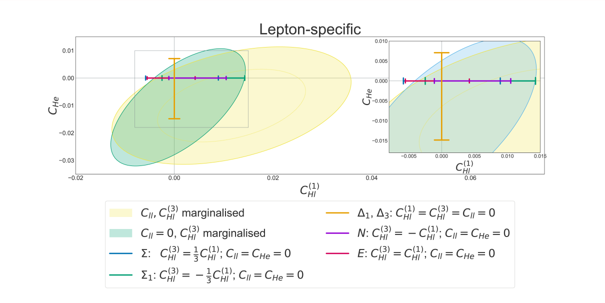


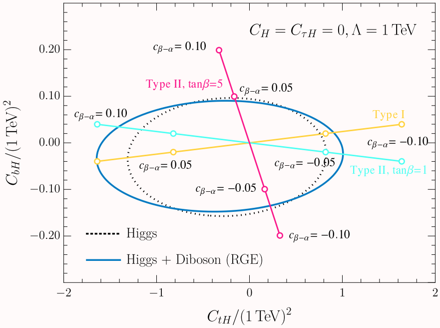


Ethier,Maltoni,Mantani,Nocera,Rojo 2105.00006

Reduced fits via matching to UV models

Ellis,Madigan,Mimasu,Sanz,You 2012.02779





Dawson,Homiller,Lane 2007.01296