SMEFT: selected results & open questions

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SMEFT

Standard **M**odel **E**ffective **F**ield **T**heory:
The EFT constructed with **Standard Model** field & symmetries

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

$$\mathcal{L}_d = \sum_i C_i \mathcal{O}_i^{(d)}$$

C_i = Wilson coefficients

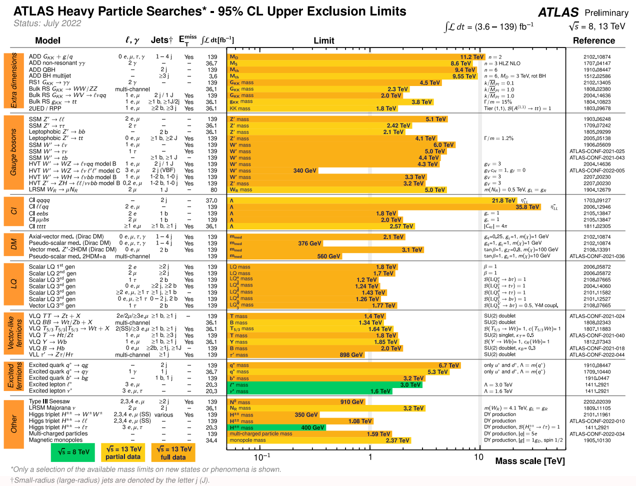
$\mathcal{O}_i^{(d)}$ = gauge-invariant operators

At each order, $\mathcal{O}_i^{(d)}$ form a complete, non-redundant **basis**

SMEFT describes **any nearly-decoupled ($\Lambda \gg v$) BSM physics**
with “good” analyticity/geometry properties in the scalar sector

SMEFT for indirect searches at LHC

new physics seems indeed nearly decoupled



ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: July 2022

Model	ℓ, γ	Jets†	E_T^{miss}	$\int\mathcal{L}\,dt$[fb^{-1}]	Limit			Reference
ADD $G_{KK} + g/q$	$0\ e, \mu, \tau, \gamma$	1 – 4 j	Yes	139	M_D	11.2 TeV	$n = 2$	2102.10874
ADD non-resonant $\gamma\gamma$	$2\ \gamma$	–	–	36.7	M_S	8.6 TeV	$n = 3$ HLZ NLO	1707.04147
ADD QBH	–	2 j	–	139	M_{th}	9.4 TeV	$n = 6$	1910.08447
ADD BH multijet	–	≥3 j	–	3.6	M_{th}	9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
RS1 $G_{KK} \to \gamma\gamma$	$2\ \gamma$	–	–	139	G_{KK} mass	4.5 TeV	$k/\overline{M}_{Pl} = 0.1$	2102.13405
Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass	2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
Bulk RS $G_{KK} \to WV \to \ell\nu qq$	$1\ e, \mu$	2 j / 1 J	Yes	139	G_{KK} mass	2.0 TeV	$k/\overline{M}_{Pl} = 1.0$	2004.14636
Bulk RS $g_{KK} \to tt$	$1\ e, \mu$	≥1 b, ≥1J/2j	Yes	36.1	g_{KK} mass	3.8 TeV	$\Gamma/m = 15\%$	1804.10823
2UED / RPP	$1\ e, \mu$	≥2 b, ≥3 j	Yes	36.1	KK mass	1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
SSM $Z' \to \ell\ell$	$2\ e, \mu$	–	–	139	Z' mass	5.1 TeV		1903.06248
SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	36.1	Z' mass	2.42 TeV		1709.07242
Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass	2.1 TeV		1805.09299
Leptophobic $Z' \to tt$	$0\ e, \mu$	≥1 b, ≥2 J	Yes	139	Z' mass	4.1 TeV	$\Gamma/m = 1.2\%$	2005.05138
SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	139	W' mass	6.0 TeV		1906.05609
SSM $W' \to \tau\nu$	$1\ \tau$	–	Yes	139	W' mass	5.0 TeV		ATLAS-CONF-2021-025
SSM $W' \to tb$	–	≥1 b, ≥1 J	–	139	W' mass	4.4 TeV		ATLAS-CONF-2021-043
HVT $W' \to WZ \to \ell\nu qq$ model B	$1\ e, \mu$	2 j / 1 J	Yes	139	W' mass	4.3 TeV	$g_V = 3$	2004.14636
HVT $W' \to WZ \to \ell\nu\,\ell'\ell'$ model C	$3\ e, \mu$	2 j (VBF)	Yes	139	W' mass	340 GeV	$g_V c_H = 1$, $g_f = 0$	ATLAS-CONF-2022-005
HVT $W' \to WH \to \ell\nu bb$ model B	$1\ e, \mu$	1-2 b, 1-0 j	Yes	139	W' mass	3.3 TeV	$g_V = 3$	2207.00230
HVT $Z' \to ZH \to \ell\ell/\nu\nu bb$ model B	$0{,}2\ e, \mu$	1-2 b, 1-0 j	Yes	139	Z' mass	3.2 TeV	$g_V = 3$	2207.00230
LRSM $W_R \to \mu N_R$	$2\ \mu$	1 J	–	80	W_R mass	5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI $qqqq$	–	2 j	–	37.0	Λ	21.8 TeV	η_{LL}^-	1703.09127
CI $\ell\ell qq$	$2\ e, \mu$	–	–	139	Λ	35.8 TeV	η_{LL}^-	2006.12946
CI $eebs$	$2\ e$	1 b	–	139	Λ	1.8 TeV	$g_* = 1$	2105.13847
CI $\mu\mu bs$	$2\ \mu$	1 b	–	139	Λ	2.0 TeV	$g_* = 1$	2105.13847
CI $tttt$	$\geq 1\ e, \mu$	≥1 b, ≥1 j	Yes	36.1	Λ	2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$	1811.02305
Axial-vector med. (Dirac DM)	$0\ e, \mu, \tau, \gamma$	1 – 4 j	Yes	139	m_{med}	2.1 TeV	g_q=0.25, g_χ=1, $m(\chi)$=1 GeV	2102.10874
Pseudo-scalar med. (Dirac DM)	$0\ e, \mu, \tau, \gamma$	1 – 4 j	Yes	139	m_{med}	376 GeV	g_q=1, g_χ=1, $m(\chi)$=1 GeV	2102.10874
Vector med. Z'-2HDM (Dirac DM)	$0\ e, \mu$	2 b	Yes	139	m_{med}	3.1 TeV	tanβ=1, g_Z=0.8, $m(\chi)$=100 GeV	2108.13391
Pseudo-scalar med. 2HDM+a	multi-channel			139	m_{med}	560 GeV	tanβ=1, g_χ=1, $m(\chi)$=10 GeV	ATLAS-CONF-2021-036
Scalar LQ 1st gen	$2\ e$	≥2 j	Yes	139	LQ mass	1.8 TeV	$\beta = 1$	2006.05872
Scalar LQ 2nd gen	$2\ \mu$	≥2 j	Yes	139	LQ mass	1.7 TeV	$\beta = 1$	2006.05872
Scalar LQ 3rd gen	$1\ \tau$	2 b	Yes	139	LQ_3^u mass	1.2 TeV	$\mathcal{B}(LQ_3^u \to b\tau) = 1$	2108.07665
Scalar LQ 3rd gen	$0\ e, \mu$	≥2 j, ≥2 b	Yes	139	LQ_3^u mass	1.24 TeV	$\mathcal{B}(LQ_3^u \to t\nu) = 1$	2004.14060
Scalar LQ 3rd gen	$\geq 2\ e, \mu, \geq 1\ \tau$	≥1 j, ≥1 b	–	139	LQ_3^d mass	1.43 TeV	$\mathcal{B}(LQ_3^d \to t\tau) = 1$	2101.11582
Scalar LQ 3rd gen	$0\ e, \mu, \geq 1\ \tau$	0 – 2 j, 2 b	Yes	139	LQ_3^d mass	1.26 TeV	$\mathcal{B}(LQ_3^d \to b\nu) = 1$	2101.12527
Vector LQ 3rd gen	$1\ \tau$	2 b	Yes	139	LQ_3^V mass	1.77 TeV	$\mathcal{B}(LQ_3^V \to b\tau) = 0.5$, Y-M coupl.	2108.07665
VLQ $TT \to Zt + X$	$2e/2\mu/\geq 3e{,}\mu$	≥1 b, ≥1 j	–	139	T mass	1.4 TeV	SU(2) doublet	ATLAS-CONF-2021-024
VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass	1.34 TeV	SU(2) doublet	1808.02343
VLQ $T_{5/3}T_{5/3}\lvert T_{5/3} \to Wt + X$	2(SS)/$\geq 3\ e{,}\mu$	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass	1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
VLQ $T \to Ht/Zt$	$1\ e, \mu$	≥1 b, ≥3 j	Yes	139	T mass	1.8 TeV	SU(2) singlet, κ_T= 0.5	ATLAS-CONF-2021-040
VLQ $Y \to Wb$	$1\ e, \mu$	≥1 b, ≥1 j	Yes	36.1	Y mass	1.85 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
VLQ $B \to Hb$	$0\ e{,}\mu$	≥2b, ≥1j, ≥1J	–	139	B mass	2.0 TeV	SU(2) doublet, κ_B= 0.3	ATLAS-CONF-2021-018
VLL $\tau' \to Z\tau/H\tau$	multi-channel	≥1 j	Yes	139	τ' mass	898 GeV	SU(2) doublet	ATLAS-CONF-2022-044
Excited quark $q^* \to qg$	–	2 j	–	139	q^* mass	6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1910.08447
Excited quark $q^* \to q\gamma$	$1\ \gamma$	1 j	–	36.7	q^* mass	5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
Excited quark $b^* \to bg$	–	1 b, 1 j	–	139	b^* mass	3.2 TeV		1910.0447
Excited lepton ℓ^*	$3\ e, \mu$	–	–	20.3	ℓ^* mass	3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
Excited lepton ν^*	$3\ e, \mu, \tau$	–	–	20.3	ν^* mass	1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Type III Seesaw	$2{,}3{,}4\ e, \mu$	≥2 j	Yes	139	N^0 mass	910 GeV		2202.02039
LRSM Majorana ν	$2\ \mu$	2 j	–	36.1	N_R mass	3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
Higgs triplet $H^{\pm\pm} \to W^\pm W^\pm$	$2{,}3{,}4\ e, \mu$ (SS)	various	Yes	139	$H^{\pm\pm}$ mass	350 GeV	DY production	2101.11961
Higgs triplet $H^{\pm\pm} \to \ell\ell$	$2{,}3{,}4\ e, \mu$ (SS)	–	–	139	$H^{\pm\pm}$ mass	1.08 TeV	DY production	ATLAS-CONF-2022-010
Higgs triplet $H^{\pm\pm} \to \ell\tau$	$3\ e, \mu, \tau$	–	–	20.3	$H^{\pm\pm}$ mass	400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
Multi-charged particles	–	–	–	139	multi-charged particle mass	1.59 TeV	DY production, $\lvert q\rvert = 5e$	ATLAS-CONF-2022-034
Magnetic monopoles	–	–	–	34.4	monopole mass	2.37 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1905.10130

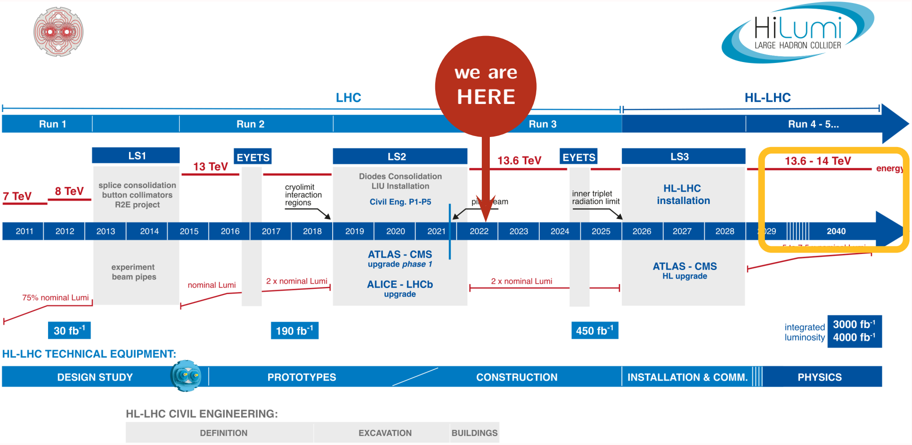
*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

SMEFT for indirect searches at LHC

new physics seems indeed nearly decoupled

significant reduction of statistical uncertainties



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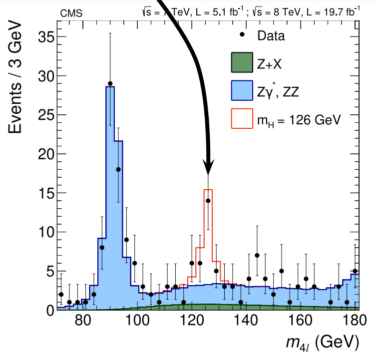
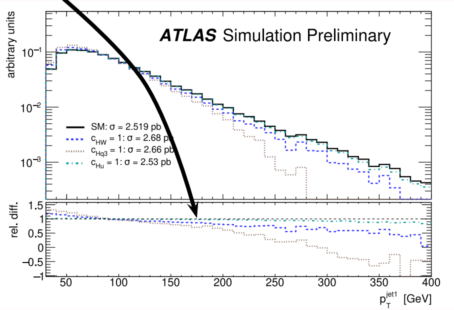
indirect searches
more and more competitive with direct ones

direct



CMS-HIG-13-002

indirect



ATL-PHYS-PUB-2019-042

SMEFT for indirect searches at LHC

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↓

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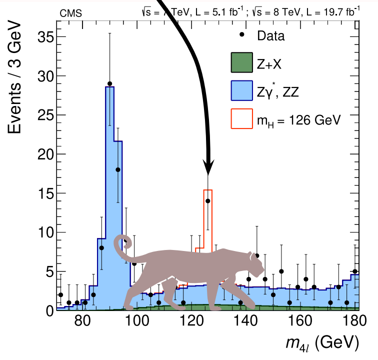
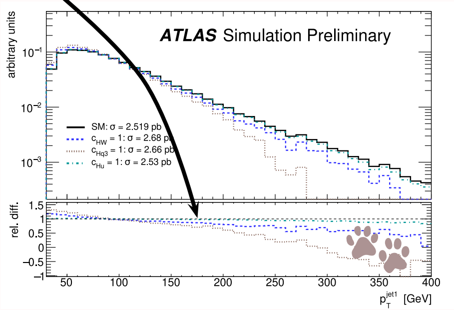
direct



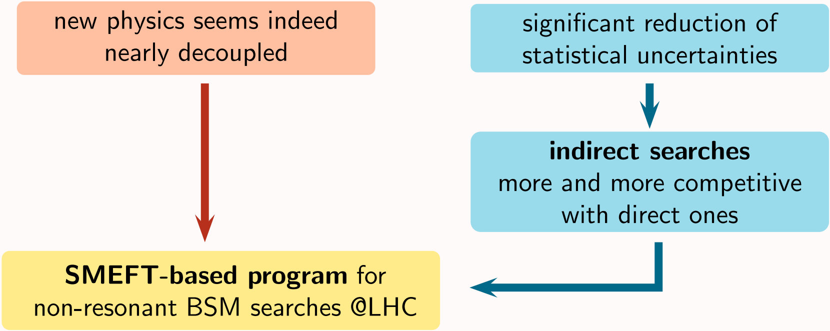
CMS-HIG-13-002

indirect



ATL-PHYS-PUB-2019-042

SMEFT for indirect searches at LHC



new physics seems indeed nearly decoupled

significant reduction of statistical uncertainties

indirect searches more and more competitive with direct ones

SMEFT-based program for non-resonant BSM searches @LHC

allows minimal commitment to a specific UV + connection to other experiments

↓

most ambitious goal: **be agnostic and let data point us to new physics**

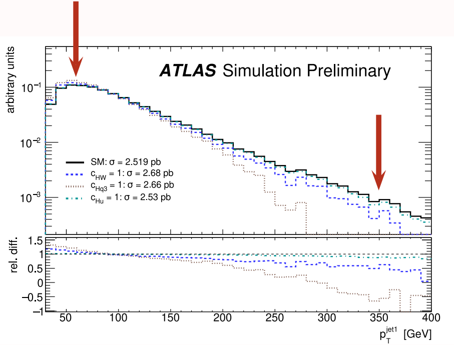
in practice:
- retain <u>all</u> SMEFT contributions in predictions
- fit all C_i/Λ^2 at the same time, **combining** several measurements

Two challenges for the bottom-up SMEFT program

A. being sensitive to indirect BSM effects

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

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



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B. making sure that, if we observe a deviation, we interpret it correctly

needs:

- 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

Where are we? State-of-the-art SMEFT fits

- combine observables in
  - EW [EWPO + diboson]
  - Higgs [prod + decay]
  - top [$\bar{t}t$ + $\bar{t}tV$ + decay]
- constrain **30 – 35** parameters simultaneously. [LHC target ~ 50]
- employ diverse fitting techniques. . .

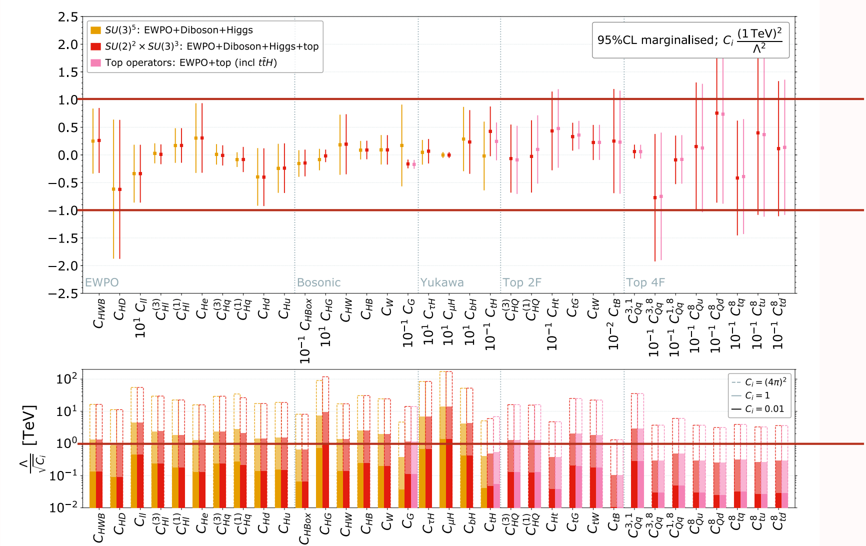
  frequentist/bayesian/replica model statistics, various uncertainty modelings, markov chains, nested sampling. . .
- . . . and methods for presenting results

  linear vs linear+quadratics, LO vs NLO, individual vs marginalised/profiled, Fisher information, Principal component analysis. . .
- including **enough measurements** to constrain all parameters is solved except for some degeneracies in 4-fermion operators → flavor physics
- **sensitivity**: Higgs/EW parameters $\Lambda \gtrsim 1 - 2$ TeV

  most Top parameters less constrained

Higgs + EW + Top combinations

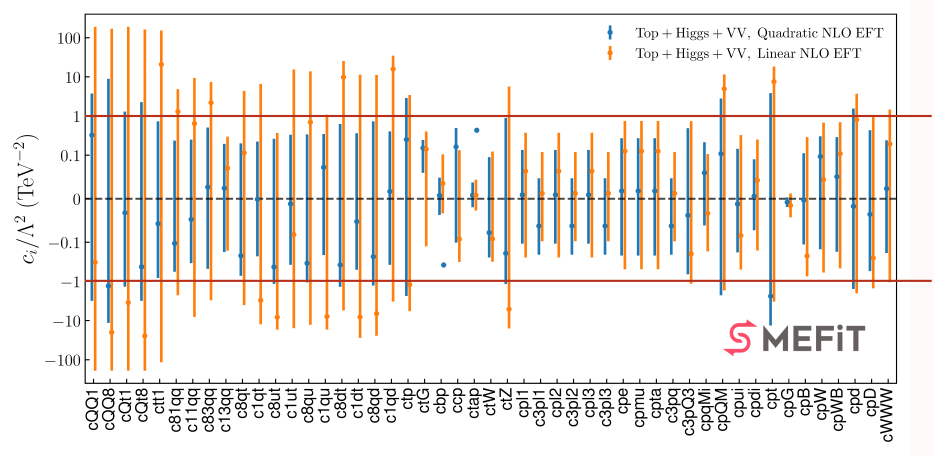
Ellis,Madigan,Mimasu,Sanz,You 2012.02779



34 param, $U(3)^5$ flavor sym, linear, LO + ggH

Higgs + EW + Top combinations

Ethier, Maltoni, Mantani, Nocera, Rojo, Slade, Vryonidou, Zhang 2105.00006



50 param (36 indep.), $U(2)^2 \times U(3) \times U(1)^3$ flavor sym, linear+quadratic, NLO QCD

Directions in the fit space

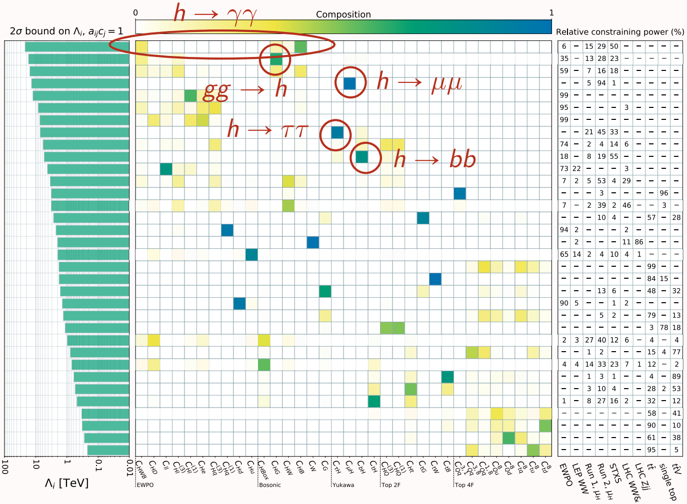
→ with linear SMEFT predictions, fit can be decomposed into uncorrelated constraints

→ **very large hierarchies** between bounds

Principal Component Analysis

eigensystem of the Fisher matrix

$$I_{ij} = -\frac{\partial^2 \log \mathcal{L}}{\partial C_i \partial C_j}$$



Relative constraining power (%)

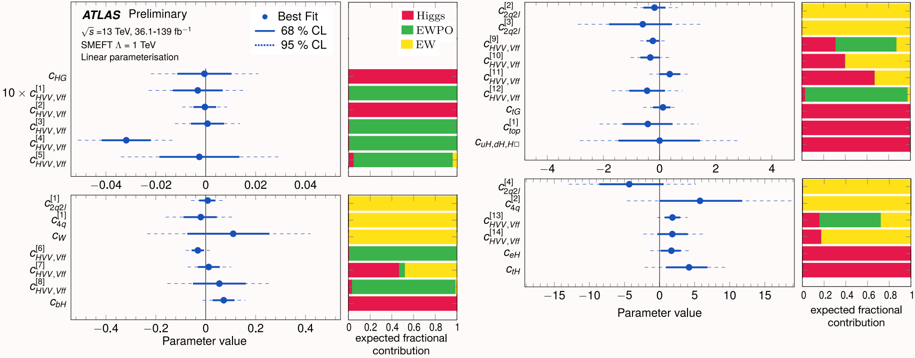
EWPO	LEP WW	Run 1, μ_H	Run 2, μ_H	STXS	LHC WW&	LHC Zjj	$t\bar{t}$	single top	$t\bar{t}V$
6	–	15	29	50	–	–	–	–	–
35	–	13	28	23	–	–	–	–	–
59	–	7	16	18	–	–	–	–	–
–	–	5	94	1	–	–	–	–	–
99	–	–	–	–	–	–	–	–	–
95	–	–	–	–	3	–	–	–	–
99	–	–	–	–	–	–	–	–	–
–	–	21	45	33	–	–	–	–	–
74	–	2	4	14	6	–	–	–	–
18	–	8	19	55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

Ellis et al 2012.02779

Global fits within experiments

a few combined analyses already performed! improving quickly

- ATLAS: so far mostly Higgs and EW ATLAS-CONF-2021-053, ATL-PHYS-PUB-2021-010, ATL-PHYS-PUB-2022-037. . .
- CMS: so far mostly Top TOP-19-001, TOP-21-003. . .
- cross-experiment "fitting exercise" ongoing under EFT WG



What's missing for a successful SMEFT program?

[personal/pragmatic point of view, not attempting to make a complete list. feel free to disagree!]

A = for being sensitive

B = for interpreting deviations correctly

0. (experimentally established anomalies)

1. A reduction of uncertainties on SM predictions + systematics

2. A B streamline treatment & reduction of EFT-born uncertainties

3. B correct treatment of correlations → involvement of experiments

Bißmann,Erdmann,Grunwald,Hiller,Kröninger 1912.06090

4. B including SMEFT beyond ME: PDF, PS, acceptances ⇝ **Maria** and **Uli**'s talks

Carrazza et al 1905.05215, Greljo et al. 2104.02723, Iranipour,Ubiali 2201.07240
Goldouzian et al 2012.06872, Haisch et al 2204.00663, ATL-PHYS-PUB-2022-037

5. B more refined process treatment: exploit differential info, target $\cancel{CP}$, flavor. . .

6. B handling & understanding ∼ 50-dimensional likelihoods

SMEFT uncertainties: from MC simulations

$$\sigma_{SMEFT} = \sigma_{SM}\left[1 + a_i C_i + b_{ij} C_i C_j + \ldots\right]$$

a_i, b_{ij} typically determined at tree/1-loop order with MC simulations

→ important to have **precise determinations**!
cancellations must be reproduced, σ_{SMEFT} must be positive $\forall C_i \ldots$

→ uncertainties mainly arise from phase space integration.
limitations in N_{events} due to need to simulate many (easily $\mathcal{O}(100)$) signal components

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via direct simulation

MG5 allows to simulate individual SMEFT components

👍 phase sp. integration covers all relevant regions

👎 not exactly the same across components
pure interference treatment unclear

→ potentially large Δ_{stat} in differences/ratios
→ relations among components not enforced

via reweighting

$$w_{SMEFT} = w_0 \frac{|\mathcal{M}_{SMEFT}|^2}{|\mathcal{M}_0|^2}$$

👍 SMEFT/SM ratios reproduced exactly event-by-event

👎 very large $\mathcal{M}$ ratios amplify statistical errors

assumes "factorization" of phase-sp. integration.
only true for $N_{\text{events}} \to \infty$
→ result can depend on initial sample

SMEFT uncertainties: from MC simulations

$$\sigma_{SMEFT} = \sigma_{SM}\left[1 + a_i C_i + b_{ij} C_i C_j + \ldots\right]$$

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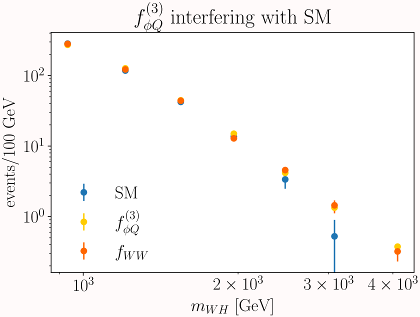
via **direct simulation**

via **reweighting**

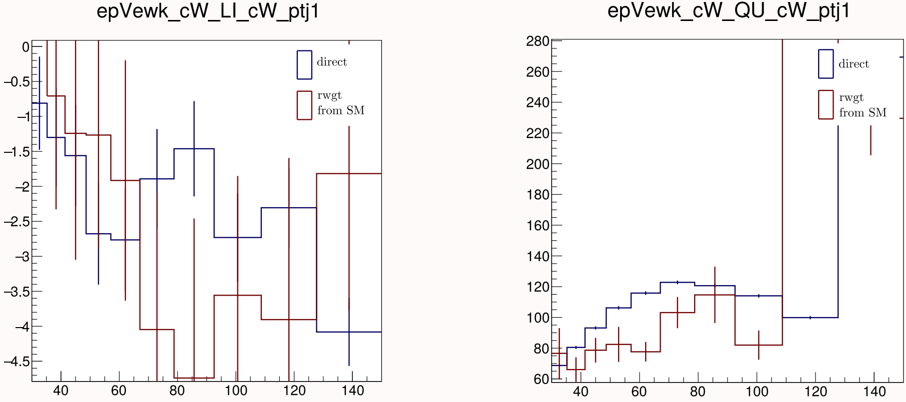


plot by Nina Elmer

Examples

plots courtesy of G. Boldrini

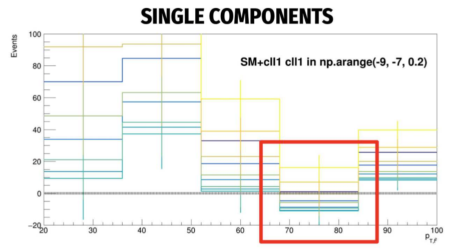
$p_T^{j_1}$ for $pp \to jjjje^+\nu_e$
generated with 10^6 events for direct, 2×10^6 for rwgt (before cuts)



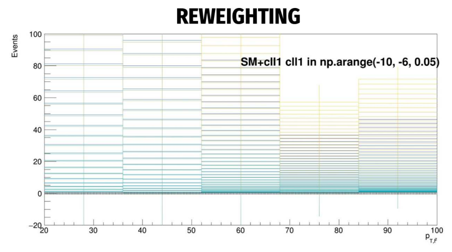
Examples

plots courtesy of G. Boldrini

$p_T^{l_2}$ for $pp \to e^+e^-\mu^+\mu^-$, generated with $N_{events} = \mathcal{O}(10^6)$



SINGLE COMPONENTS



REWEIGHTING

A general remark on SMEFT uncertainties

$$\sigma_{SMEFT} = \sigma_{SM}\left[1 + a_i C_i + b_{ij} C_i C_j + \dots\right]$$

uncertainties apply on the individual pre-factors, e.g.: $a_i = a_i^0 \pm \Delta a_i$

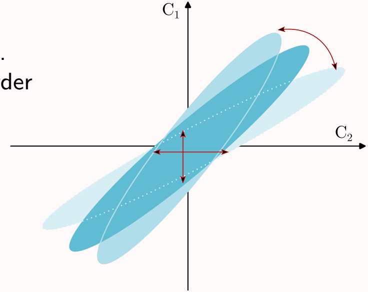
↓

uncertainties in SMEFT are not just numbers, but **directions** in fit space!

this effect is very relevant in global fits (B)

→ in fits: so far global TH uncertainties on σ_{SMEFT}. accounting for directionality in the likelihood harder

→ including proper errors could be useful to account for operator-dependent effects



Scale dependence

SMEFT operators **run and mix** (Alonso),Jenkins,Manohar,Trott '13

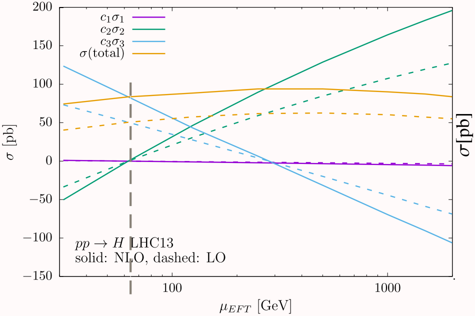
→ bounds are put on $C(\mu_0)$ defined at a certain scale μ_0.

→ residual scale dependence present, depends on process and operator

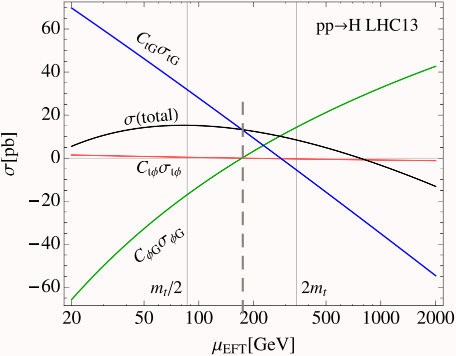
→ typically smaller in (absolute) size for NLO calculations

$gg \to h$

Deutschmann,Duhr,Maltoni,Vryonidou 1708.00460



Maltoni,Vryonidou,Zhang 1607.05330



$O_1 = O_{t\phi}/y_t^3 \quad O_2 = O_{\phi G}\, g_s^2/y_t^2 \quad O_3 = O_{tG}/y_t$

Scale dependence

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$h \to \bar{b}b$ Cullen,Pecjak,Scott 1904.06358

$$\frac{\Gamma^{LO}_{SMEFT}(m_H)}{\Gamma^{LO}_{SM}(m_H)} = \Delta^{\mathrm{LO}}(m_H, m_H) = (1 \pm 0.08) + \frac{(\bar{v}^{(\ell)})^2}{\Lambda^2_{\mathrm{NP}}} \Big\{ (3.74 \pm 0.36)\tilde{C}_{HWB} + (2.00 \pm 0.21)\tilde{C}_{H\Box} - (1.41 \pm 0.07)\frac{\bar{v}^{(\ell)}}{\overline{m}_b^{(\ell)}}\tilde{C}_{bH} + (1.24 \pm 0.14)\tilde{C}_{HD}$$

$$\pm 0.35\tilde{C}_{HG} \pm 0.19\tilde{C}^{(1)}_{Hq} \pm 0.18\tilde{C}_{Ht} \pm 0.11\tilde{C}^{(3)}_{Hq} \pm 0.08\frac{\bar{v}^{(\ell)}}{\overline{m}_b^{(\ell)}}\tilde{C}^{(1)}_{qtqb} \pm 0.03\frac{\tilde{C}_{tW}}{\bar{e}^{(\ell)}} \pm 0.03(\tilde{C}_{HW} + \tilde{C}_{tH}) + \ldots \Big\},$$

[uncertainties from ×2 variations of both SM and C scales. $\tilde{C}$ defined at $\mu_0 = m_H$]

Scale dependence

SMEFT operators **run and mix** (Alonso),Jenkins,Manohar,Trott '13

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$h \to \bar{b}b$

Cullen,Pecjak,Scott 1904.06358

$$\begin{aligned}\Delta^{\text{NLO}}(m_H, m_H) = 1.13^{+0.01}_{-0.04} + \frac{(\bar{v}^{(\ell)})^2}{\Lambda^2_{\text{NP}}}\Big\{ &\left(4.16^{+0.05}_{-0.14}\right) \tilde{C}_{HWB} + \left(2.40^{+0.04}_{-0.09}\right) \tilde{C}_{H\Box} \\ &+ \left(-1.73^{+0.04}_{-0.03}\right) \frac{\bar{v}^{(\ell)}}{\overline{m}_b^{(\ell)}} \tilde{C}_{bH} + \left(1.33^{+0.01}_{-0.04}\right) \tilde{C}_{HD} + \boxed{\left(2.75^{+0.49}_{-0.48}\right) \tilde{C}_{HG}} \\ &+ \left(-0.12^{+0.04}_{-0.01}\right) \tilde{C}^{(3)}_{Hq} + \left(-0.08^{+0.05}_{-0.01}\right) \tilde{C}_{Ht} + \left(0.06^{+0.00}_{-0.05}\right) \tilde{C}^{(1)}_{Hq} \\ &+ \left(0.03^{+0.02}_{-0.01}\right) \frac{\bar{v}^{(\ell)}}{\overline{m}_b^{(\ell)}} \tilde{C}^{(1)}_{qtqb} + \left(0.00^{+0.07}_{-0.04}\right) \frac{\tilde{C}_{tG}}{g_s} + \left(-0.03^{+0.01}_{-0.01}\right) \tilde{C}_{tH} \\ &+ \left(0.03^{+0.01}_{-0.01}\right) \tilde{C}_{HW} + \left(-0.01^{+0.01}_{-0.00}\right) \tilde{C}_{tW} + \ldots \Big\}.\end{aligned}$$

[uncertainties from ×2 variations of both SM and C scales. $\tilde{C}$ defined at $\mu_0 = m_H$]

Missing higher orders

in loops ⇝ **Eleni and Darren**'s talk

status: several processes at NLO QCD (1-loop automated)
a few to NLO EW: $\mu \to e\gamma$, $h \to VV, \bar{f}f$, EWPO Pruna,Signer,Hartmann,Trott,Passarino, Dawson,Giardino,Pecjak,Scott,Dedes. . .
first ex. at NNLO+PS: Vh, $h \to \bar{b}b$ Haisch et al 2204.00663 ⇝ **Uli**'s talk

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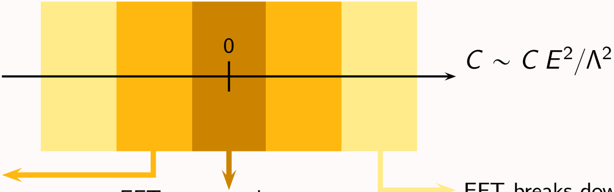
first ex. at NNLO+PS: Vh, $h \to \bar{b}b$ Haisch et al 2204.00663 ⇝ **Uli**'s talk

in the EFT expansion ↔ EFT validity



EFT can be constructed
but poorly convergent

$C^2 \sim C$

$d \geqslant 8$ required

EFT very good approx.

$C^2 \ll C \ll 1$

$\mathcal{O}(\Lambda^{-4})$ negligible

EFT breaks down

$C^2 > C > 1$

unitarity violation. . .

Missing higher orders

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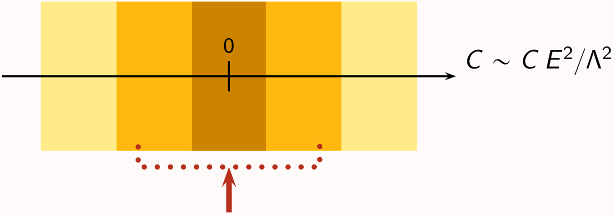


using SMEFT amounts to assuming a range

hard to define a priori!
we don't know Λ, and we are measuring over a broad energy range

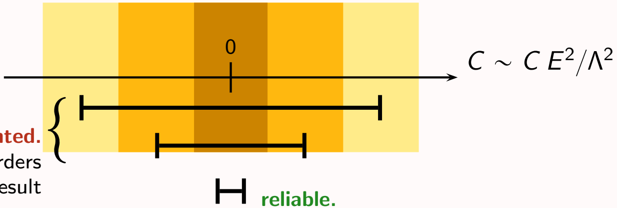
Missing higher orders

in loops ⇝ **Eleni and Darren**'s talk

status: several processes at NLO QCD (1-loop automated)
a few to NLO EW: $\mu \to e\gamma$, $h \to VV, \bar{f}f$, EWPO Pruna,Signer,Hartmann,Trott,Passarino, Dawson,Giardino,Pecjak,Scott,Dedes...
first ex. at NNLO+PS: Vh, $h \to \bar{b}b$ Haisch et al 2204.00663 ⇝ **Uli**'s talk

in the EFT expansion ↔ EFT validity

safe option: bounds self-consistency. measurements @LHC not always “good enough”



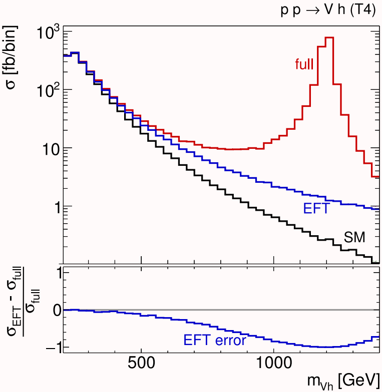
EFT validity not granted.
inclusion of higher EFT orders
can change this result

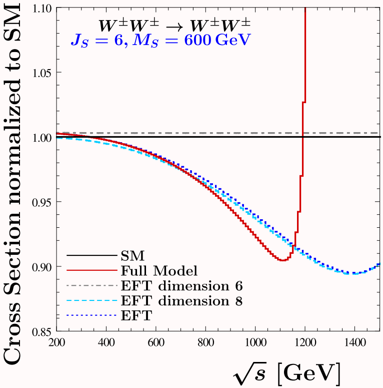
reliable.
can be done with pure linear terms at $d = 6$

Impact of $d \geqslant 8$ operators

EFT obtained from matching to full model

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

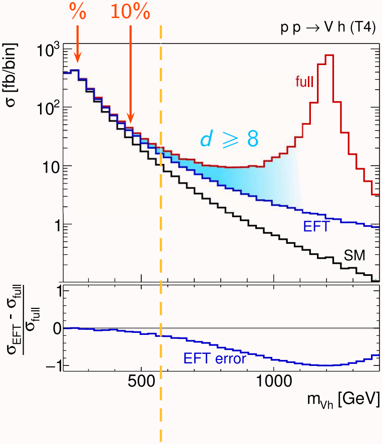




adapted from
Lang,Liebler,Schäfer-Siebert,Zeppenfeld 2103.16517

Impact of $d \geqslant 8$ operators

EFT obtained from matching to full model

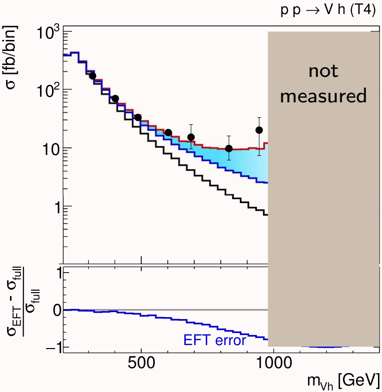


$d = 6$ breaks down

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

Impact of $d \geqslant 8$ 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

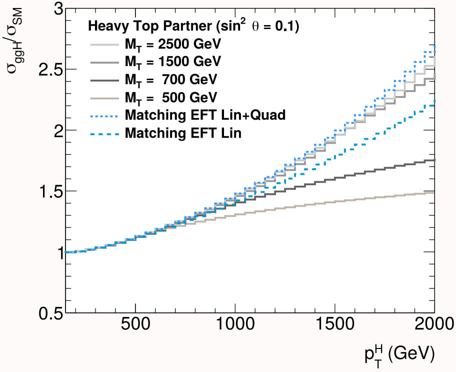
compute at d=8
Boughezal,Mereghetti,Petriello
2106.05337
Dawson,(Fontes),Homiller,Sullivan
2110.06929, 2205.01561

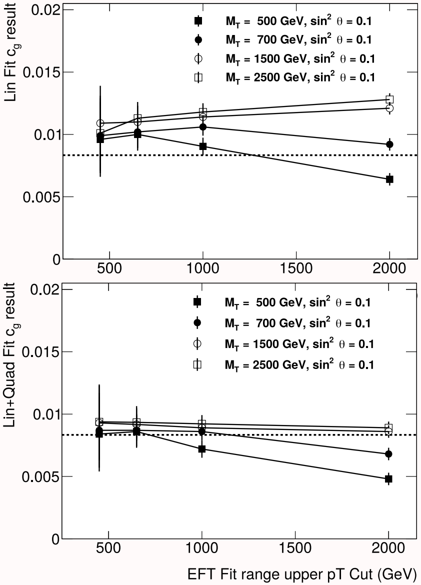
Benchmarking these proposals: sliding upper cut

Battaglia, Grazzini, Spira, Wiesemann 2109.02987

p_T^H from heavy top partner

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

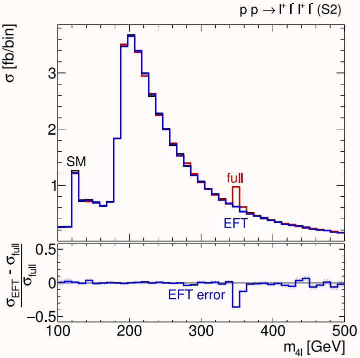




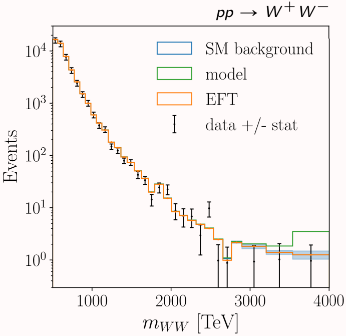
safe scenarios ↔ no energy growth ↔ small effects

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



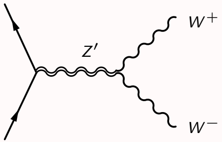
Brivio,Bruggisser,Geoffray,Kilian,Krämer,
Luchmann,Plehn,Summ 2108.01094

price to pay: % effects only

→ most sensitivity from <u>lowest error</u> region (∼ bulk)

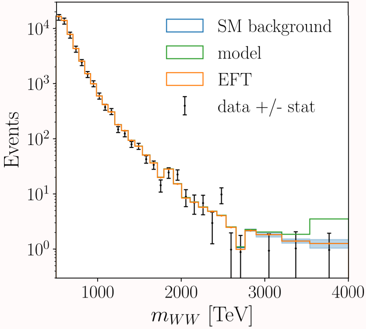
Interplay with direct searches

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

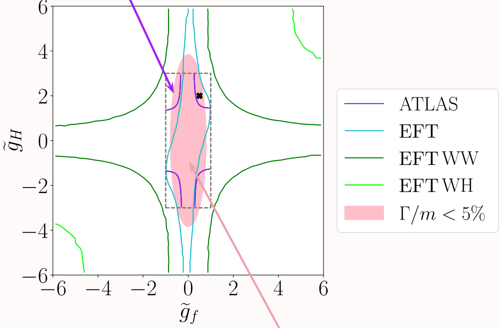


$$m_{Z'} = m_V = 4\ \text{TeV}$$

data: ATLAS 2004.14636



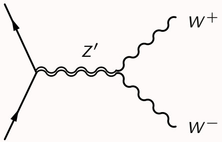
bound from
WW resonance search



resonance s. only valid
for narrow Z'

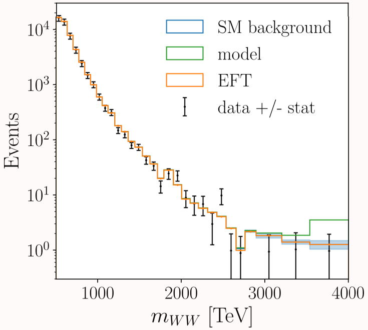
Interplay with direct searches

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

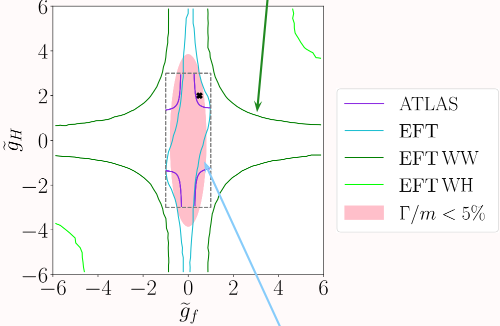


$$m_{Z'} = m_V = 4 \text{ TeV}$$

data: ATLAS 2004.14636



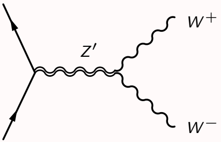
bound from EFT fit to *WW* spectrum



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

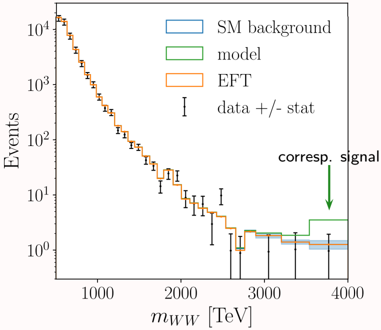
Interplay with direct searches

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



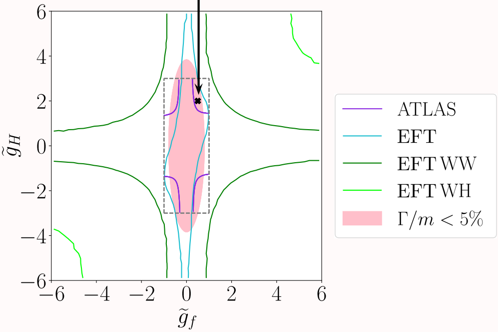
$$m_{Z'} = m_V = 4\ \text{TeV}$$

data: ATLAS 2004.14636



corresp. signal

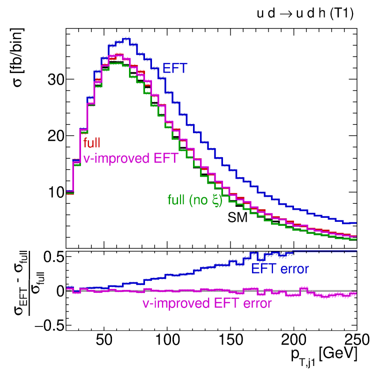
point excluded by resonance s.
but allowed by EFT



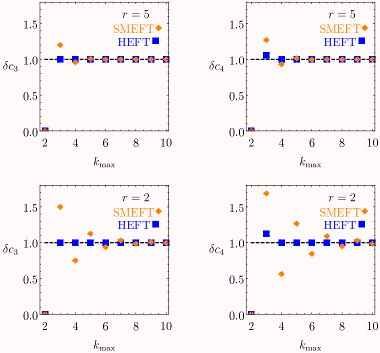
SMEFT or HEFT?

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 similar to using **HEFT** instead



Brehmer,Freitas,López-Val,Plehn 1510.03443



Cohen,Craig,Lu,Sutherland 2008.08597

which EFT is most convenient?

Summary

- **SMEFT program**:
  global, agnostic search for NP signals in precision measurements

- 2 challenges: sensitivity and accurate interpretation

- Enormous improvements made in past decade.
  Achieved global H+EW+Top fits with NLO QCD accuracy.
  Many processes studied, sensitivity reaching into multi-TeV range.
  Experiments getting involved.

- Some (technical) challenges still ahead.
  From EFT point of view, not yet streamlined: inclusion of EFT-specific uncertainties, especially from higher EFT orders

- would HEFT be more suitable in poorly convergent cases?

- Interplay with direct searches worth exploring: complementary regimes

Backup slides

$\mathcal{L}_6$: the Warsaw basis

Grzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884

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

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

$\mathcal{L}_6$: the Warsaw basis

Grzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

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