Some recent developments in the SMEFT

#SMEFT

M. Trott, PI 2019



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Motivation and theory framework

More info: The Standard Model as an Effective Field Theory review, Phys.Rept. 793 (2019) 1-98 Ilaria Brivio, Michael Trott <u>https://arxiv.org/pdf/1706.08945.pdf</u>

What is the big picture?



We are gathering lots of data at energy scales close to the mass of the Higgs for years to come

Future facilities expected to continue this trend.

The massive LHC data set:

The data set in context:

Year	Centre-of-mass	Integrated
	energy range	luminosity
	[GeV]	$[\mathrm{pb}^{-1}]$
1989	88.2 - 94.2	1.7
1990	88.2 - 94.2	8.6
1991	88.5 - 93.7	18.9
1992	91.3	28.6
1993	89.4, 91.2, 93.0	40.0
1994	91.2	64.5
1995	89.4, 91.3, 93.0	39.8

LEP1

Year	Mean energy	Luminosity	
	\sqrt{s} [GeV]	$[pb^{-1}]$	
1995, 1997	130.3	6	
	136.3	6	
	140.2	1	
1996	161.3	12	
	172.1	12	
1997	182.7	60	
1998	188.6	180	
1999	191.6	30	
	195.5	90	
	199.5	90	
	201.8	40	
2000	204.8	80	
	206.5	130	
	208.0	8	
Total	130 - 209	745	

LEP2



CMS/day!





What was discovered at LHC, a particle





• What is this new particle phenomena?

and a theory...the Standard Model EFT

• The SM, an SU(3) xSU(2)xU(1) gauge theory:

$$\begin{split} \mathcal{L}_{\mathrm{SM}} &= -\frac{1}{4} G^A_{\mu\nu} G^{A\mu\nu} - \frac{1}{4} W^I_{\mu\nu} W^{I\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + (D_\mu H^\dagger) (D^\mu H) + \sum_{\psi=q,u,d,l,e} \overline{\psi} \, i \not\!\!\!D \, \psi \\ &- \lambda \left(H^\dagger H - \frac{1}{2} v^2 \right)^2 - \left[H^{\dagger j} \overline{d} \, Y_d \, q_j + \widetilde{H}^{\dagger j} \overline{u} \, Y_u \, q_j + H^{\dagger j} \overline{e} \, Y_e \, l_j + \mathrm{h.c.} \right], \end{split}$$



- A fundamental scalar Higgs is a NEW type of particle.
- The interaction strengths of the Higgs with the other SM particles are <u>not fixed in magnitude by a gauge symmetry.</u>

The Standard model EFT

• The SM, an SU(3) xSU(2)xU(1) gauge theory:



$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \frac{1}{\Lambda_{\delta L \neq 0}} \mathcal{L}_5 + \frac{1}{\Lambda^2} \mathcal{L}_6 + \cdots$$



Glashow 1961, Weinberg 1967 (Salam 1967)

Weinberg 1979, Wilczek and Zee 1979

Leung, Love, Rao 1984, <u>Buchmuller</u> Wyler 1986, <u>Grzadkowski, Iskrzynski, Misiak, Rosiek</u> 2010

What wasn't discovered at LHC

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2018

ATLAS Preliminary

Sta	tus: July 2018						$\int \mathcal{L} dt = (3)$	3.2 – 79.8) fb ⁻¹	\sqrt{s} = 8, 13 TeV
	Model	<i>ℓ</i> ,γ	Jets†	E ^{miss} T	∫£ dt[fl	⁻¹] Limit	5		Reference
Extra dimensions	ADD $G_{KK} + g/q$ ADD non-resonant $\gamma\gamma$ ADD QBH ADD BH high $\sum p_T$ ADD BH multijet RS1 $G_{KK} \rightarrow \gamma\gamma$ Bulk RS $G_{KK} \rightarrow WW/ZZ$ Bulk RS $g_{KK} \rightarrow tt$ 2UED / RPP	$\begin{array}{c} 0 \ e, \mu \\ 2 \ \gamma \\ - \\ \geq 1 \ e, \mu \\ - \\ 2 \ \gamma \\ multi-channe \\ 1 \ e, \mu \\ 1 \ e, \mu \end{array}$	1 - 4j - 2j $\ge 2j$ $\ge 3j$ - - ≥ 1 b, $\ge 1J/2$ ≥ 2 b, $\ge 3j$	Yes - - - 2) Yes Yes	36.1 36.7 37.0 3.2 3.6 36.7 36.1 36.1 36.1	М _D M _S M _{th} M _{th} G _{KK} mass G _{KK} mass g _{KK} mass KK mass	7.7 TeV 8.6 TeV 8.9 TeV 8.2 TeV 9.55 TeV 4.1 TeV 2.3 TeV 3.8 TeV 1.8 TeV	$\begin{array}{l} n=2\\ n=3 \ \text{HLZ NLO}\\ n=6\\ n=6, \ M_D=3 \ \text{TeV, rot BH}\\ n=6, \ M_D=3 \ \text{TeV, rot BH}\\ k/\overline{M}_{Pl}=0.1\\ k/\overline{M}_{Pl}=1.0\\ \Gamma/m=15\%\\ \text{Tier }(1,1), \ \mathcal{B}(A^{(1,1)}\rightarrow tt)=1 \end{array}$	1711.03301 1707.04147 1703.09217 1606.02265 1512.02586 1707.04147 CERN-EP-2018-179 1804.10823 1803.09678
Gauge bosons	$\begin{array}{l} \mathrm{SSM}\; Z' \to \ell\ell \\ \mathrm{SSM}\; Z' \to \tau\tau \\ \mathrm{Leptophobic}\; Z' \to bb \\ \mathrm{Leptophobic}\; Z' \to tt \\ \mathrm{SSM}\; W' \to \ell\nu \\ \mathrm{SSM}\; W' \to \tau\nu \\ \mathrm{HVT}\; V' \to WV \to qqqq \; \mathrm{model} \\ \mathrm{HVT}\; V' \to WH/ZH \; \mathrm{model}\; \mathrm{B} \\ \mathrm{LRSM}\; W'_R' \to tb \end{array}$	$\begin{array}{c} 2 \ e, \mu \\ 2 \ \tau \\ - \\ 1 \ e, \mu \\ 1 \ r, \mu \\ 1 \ \tau \end{array}$ B 0 e, μ multi-channe	- 2 b ≥ 1 b, ≥ 1J/2 - 2 J el el	_ _ 2j Yes Yes Yes _	36.1 36.1 36.1 79.8 36.1 79.8 36.1 36.1 36.1	Z' mass Z' mass Z' mass Z' mass W' mass W' mass V' mass V' mass W' mass W' mass	4.5 TeV 2.42 TeV 2.1 TeV 3.0 TeV 5.6 TeV 3.7 TeV 4.15 TeV 2.93 TeV 3.25 TeV	$\Gamma/m = 1\%$ $g_V = 3$ $g_V = 3$	1707.02424 1709.07242 1805.09299 1804.10823 ATLAS-CONF-2018-017 1801.06992 ATLAS-CONF-2018-016 1712.06518 CERN-EP-2018-142
CI	Cl qqqq Cl ℓℓqq Cl tttt	_ 2 e,μ ≥1 e,μ	2 j _ ≥1 b, ≥1 j	– – Yes	37.0 36.1 36.1	Λ Λ Λ	2.57 TeV	21.8 TeV η_{LL}^- 40.0 TeV η_{LL}^- $ C_{4t} = 4\pi$	1703.09217 1707.02424 CERN-EP-2018-174
DM	Axial-vector mediator (Dirac DM Colored scalar mediator (Dirac I $VV_{\chi\chi}$ EFT (Dirac DM)) 0 e, μ DM) 0 e, μ 0 e, μ	$\begin{array}{c} 1-4 \ j \\ 1-4 \ j \\ 1 \ J, \leq 1 \ j \end{array}$	Yes Yes Yes	36.1 36.1 3.2	m _{med} 1. m _{med} M, 700 GeV	.55 TeV 1.67 TeV	$\begin{split} g_q = & 0.25, g_\chi = & 1.0, m(\chi) = 1 \text{ GeV} \\ g = & 1.0, m(\chi) = & 1 \text{ GeV} \\ m(\chi) < & 150 \text{ GeV} \end{split}$	1711.03301 1711.03301 1608.02372
ГО	Scalar LQ 1 st gen Scalar LQ 2 nd gen Scalar LQ 3 rd gen	2 e 2 μ 1 e,μ	≥ 2 j ≥ 2 j ≥1 b, ≥3 j	– – Yes	3.2 3.2 20.3	LQ mass 1.1 Te LQ mass 1.05 TeV LQ mass 640 GeV	<u>v</u>	$\begin{split} \beta &= 1\\ \beta &= 1\\ \beta &= 0 \end{split}$	1605.06035 1605.06035 1508.04735
Heavy quarks	$ \begin{array}{l} VLQ \ TT \rightarrow Ht/Zt/Wb + X \\ VLQ \ BB \rightarrow Wt/Zb + X \\ VLQ \ T_{5/3} \ T_{5/3} T_{5/3} \rightarrow Wt + X \\ VLQ \ Y \rightarrow Wb + X \\ VLQ \ B \rightarrow Hb + X \\ VLQ \ QQ \rightarrow WqWq \end{array} $	multi-channe multi-channe $2(SS)/\ge 3 e, \mu$ $1 e, \mu$ $0 e, \mu, 2 \gamma$ $1 e, \mu$	el el $\mu \ge 1 \text{ b}, \ge 1 \text{ j}$ $\ge 1 \text{ b}, \ge 1 \text{ j}$ $\ge 1 \text{ b}, \ge 1 \text{ j}$ $\ge 4 \text{ j}$	Yes Yes Yes Yes	36.1 36.1 36.1 3.2 79.8 20.3	T mass 1.33 B mass 1.34 T _{5/3} mass - Y mass 1.4 B mass 1.21 T Q mass 690 GeV	7 TeV 1 TeV 1.64 TeV 14 TeV FeV	SU(2) doublet SU(2) doublet $\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3}Wt) = 1$ $\mathcal{B}(Y \rightarrow Wb) = 1, c(YWb) = 1/\sqrt{2}$ $\kappa_B = 0.5$	ATLAS-CONF-2018-XXX ATLAS-CONF-2018-XXX CERN-EP-2018-171 ATLAS-CONF-2016-072 ATLAS-CONF-2018-XXX 1509.04261
Excited fermions	Excited quark $q^* \rightarrow qg$ Excited quark $q^* \rightarrow q\gamma$ Excited quark $b^* \rightarrow bg$ Excited lepton ℓ^* Excited lepton γ^*	- 1 γ - 3 e,μ 3 e,μ,τ	2 j 1 j 1 b, 1 j -		37.0 36.7 36.1 20.3 20.3	q* mass q* mass b* mass f* mass y* mass	6.0 TeV 5.3 TeV 2.6 TeV 3.0 TeV 1.6 TeV	only u^* and d^* , $\Lambda = m(q^*)$ only u^* and d^* , $\Lambda = m(q^*)$ $\Lambda = 3.0 \text{ TeV}$ $\Lambda = 1.6 \text{ TeV}$	1703.09127 1709.10440 1805.09299 1411.2921 1411.2921
Other	Type III Seesaw LRSM Majorana ν Higgs triplet $H^{\pm\pm} \rightarrow \ell \ell$ Higgs triplet $H^{\pm\pm} \rightarrow \ell \tau$ Monotop (non-res prod) Multi-charged particles Magnetic monopoles	$1 e, \mu 2 e, \mu 2,3,4 e, \mu (SS 3 e, \mu, \tau 1 e, \mu - - - - - - - - - -$	≥ 2 j 2 j S) - 1 b - - - √s = 13	Yes - - Yes - -	79.8 20.3 36.1 20.3 20.3 20.3 7.0	Nº mass 560 GeV Nº mass 870 GeV H** mass 870 GeV H** mass 400 GeV spin-1 invisible particle mass 657 GeV multi-charged particle mass 785 GeV monopole mass 1.34 10 ⁻¹ 10 ⁻¹	2.0 TeV I TeV 1 1	$m(W_R) = 2.4$ TeV, no mixing DY production DY production, $\mathcal{B}(H_L^{\pm\pm} \rightarrow \ell \tau) = 1$ $a_{non-res} = 0.2$ DY production, $ q = 5e$ DY production, $ g = 1g_D$, spin 1/2 Mass scale [TeV]	ATLAS-CONF-2018-020 1506.06020 1710.09748 1411.2921 1410.5404 1504.04188 1509.08059

*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).

What wasn't discovered at LHC

ATLAS Preliminary

Mass scale [TeV]

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2018

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Gal

$\sqrt{s} = 8, 13 \text{ TeV}$ $\int \mathcal{L} dt = (3.2 - 79.8) \text{ fb}^{-1}$ Jets† E_T^{miss} ∫⊥ dt[fb⁻¹] Model ℓ, γ Limit Reference 0 e,μ 1 – 4 i ADD $G_{KK} + g/q$ Yes 36.1 7.7 TeV n = 21711.03301 ADD non-resonant $\gamma\gamma$ 2γ 36.7 8.6 TeV n = 3 HLZ NLO 1707.04147 2 j ADD QBH _ 37.0 8.9 TeV n = 61703.09217 ADD BH high $\sum p_T$ $\geq 1 e, \mu$ ≥ 2 j -3.2 8.2 TeV n = 6, $M_D = 3$ TeV, rot BH 1606.02265 ADD BH multijet _ ≥3 j _ 3.6 9.55 TeV n = 6, $M_D = 3$ TeV, rot BH 1512.02586 RS1 $G_{KK} \rightarrow \gamma \gamma$ 2γ 36.7 4.1 TeV $k/\overline{M}_{Pl} = 0.1$ 1707.04147 Bulk RS $G_{KK} \rightarrow WW/ZZ$ multi-channel 36.1 2.3 TeV $k/\overline{M}_{PI} = 1.0$ CERN-EP-2018-179 Bulk RS $g_{KK} \rightarrow tt$ $1 e, \mu \ge 1 b, \ge 1 J/2 j$ Yes 36.1 3.8 TeV $\Gamma/m = 15\%$ 1804.10823 $\text{Tier}\,(1,1),\,\mathcal{B}\bigl(A^{(1,1)}\to tt\bigr)=1$ 2UED / RPP 1 e,μ \geq 2 b, \geq 3 j Yes 36.1 1.8 TeV 1803.09678 SSM $Z' \rightarrow \ell \ell$ 2 e, µ 36.1 4.5 TeV 1707.02424 2.42 TeV SSM $Z' \rightarrow \tau \tau$ 2τ _ 36.1 1709.07242 Leptophobic $Z' \rightarrow bb$ 2 b _ 36.1 2.1 TeV 1805.09299 Leptophobic $Z' \rightarrow tt$ 1 e,μ $\geq 1 \text{ b}, \geq 1 \text{J/2j}$ Yes 36.1 3.0 TeV $\Gamma/m = 1\%$ 1804 10823 SSM $W' \rightarrow \ell v$ 1 e,μ 79.8 5.6 TeV ATLAS-CONF-2018-017 Yes SSM $W' \rightarrow \tau v$ 1τ Yes 36.1 ۱۸/ 3.7 TeV 1801.06992 HVT $V' \rightarrow WV \rightarrow qqqq$ model B 0 e,μ 2 J 79.8 4.15 TeV $g_V = 3$ ATLAS-CONF-2018-016 HVT $V' \rightarrow WH/ZH$ model B multi-channel 36.1 2.93 TeV $g_V = 3$ 1712.06518 LRSM $W'_P \rightarrow tb$ multi-channel 36.1 3.25 TeV CERN-EP-2018-142 CI qqqq 21.8 TeV η_{LL}^- 2 j 37.0 1703 09217 G CI ℓℓ qq 2 e, µ _ 36.1 40.0 TeV η_{LL} 1707.02424 2.57 TeV CI tttt ≥1 e,µ ≥1 b, ≥1 j Yes 36.1 $|C_{4t}| = 4\pi$ CERN-EP-2018-174 Axial-vector mediator (Dirac DM) 0 e,μ 1 – 4 j Yes 36.1 1.55 TeV g_q =0.25, g_χ =1.0, $m(\chi) = 1$ GeV 1711.03301 DM Colored scalar mediator (Dirac DM) 0 e, µ 1 – 4 i g=1.0, $m(\chi) = 1 \text{ GeV}$ Yes 1711 03301 36.1 1.67 TeV VV_{XX} EFT (Dirac DM) $1 J, \leq 1 j$ $m(\chi) < 150 \text{ GeV}$ 1608.02372 0 e,μ Yes 3.2 700 GeV Scalar LQ 1st gen ≥ 2 j 1.1 TeV $\beta = 1$ 2 e _ 3.2 1605.06035 ГQ Scalar LQ 2nd gen 2μ ≥ 2 j _ 3.2 1.05 TeV $\beta = 1$ 1605.06035 $\beta = 0$ 1508.04735 Scalar LQ 3rd gen ≥1 b, ≥3 j Yes 20.3 1 e, µ VLQ $TT \rightarrow Ht/Zt/Wb + X$ multi-channel 36.1 1.37 TeV SU(2) doublet ATLAS-CONF-2018-XXX $VLQ BB \rightarrow Wt/Zb + X$ 1.34 TeV SU(2) doublet ATLAS-CONF-2018-XXX multi-channel 36.1 VLQ $T_{5/3} T_{5/3} | T_{5/3} \rightarrow Wt + X$ 2(SS)/≥3 $e, \mu \ge 1$ b, ≥1 j Yes 36.1 1.64 TeV $\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3}Wt) = 1$ CERN-EP-2018-171 $\mathsf{VLQ} \ Y \to Wb + X$ $1 e, \mu \ge 1 b, \ge 1j$ 3.2 1.44 TeV $\mathcal{B}(Y \rightarrow Wb) = 1, c(YWb) = 1/\sqrt{2}$ ATLAS-CONF-2016-072 Yes VLQ $B \rightarrow Hb + X$ 0 e,μ, 2 γ \geq 1 b, \geq 1j Yes 79.8 1.21 TeV $\kappa_B = 0.5$ ATLAS-CONF-2018-XXX VLQ $QQ \rightarrow WqWq$ 1 e.u ≥ 4 j Yes 20.3 1509.04261 2 j Excited quark $q^* \rightarrow qg$ 37.0 6.0 TeV only u^* and d^* , $\Lambda = m(q^*)$ 1703.09127 _ Excited quark $q^* \rightarrow q\gamma$ 1γ 1 j _ 36.7 5.3 TeV only u^* and d^* , $\Lambda = m(q^*)$ 1709.10440 _ 2.6 TeV Excited quark $b^* \rightarrow bg$ 1 b, 1 j 36.1 1805.09299 _ Excited lepton ℓ^* 3 e,µ $\Lambda = 3.0 \text{ TeV}$ 20.3 1411.2921 Excited lepton v^* 3 e, μ, τ _ 20.3 $\Lambda = 1.6 \text{ TeV}$ 1411.2921 Type III Seesaw 560 GeV ATLAS-CONF-2018-020 1 e,μ ≥ 2 j Yes 79.8 LRSM Maiorana v 2 j $m(W_R) = 2.4$ TeV, no mixing 2 e,µ _ 20.3 1506.06020 Higgs triplet $H^{\pm\pm} \rightarrow \ell \ell$ 2,3,4 e, µ (SS) 36.1 870 GeV DY production 1710.09748 Higgs triplet $H^{\pm\pm} \rightarrow \ell \tau$ DY production, $\mathcal{B}(H_{\iota}^{\pm\pm} \rightarrow \ell \tau) = 1$ 3 e, μ, τ _ 20.3 1411.2921 <u>Of</u> Monotop (non-res prod) Yes 20.3 $a_{non-res} = 0.2$ 1410.5404 1 e, µ 1 b Multi-charged particles _ _ 20.3 DY production, |a| = 5e1504.04188 Magnetic monopoles DY production, $|g| = 1g_D$, spin 1/2 1509.08059 7.0 √s = 8 TeV √s = 13 TeV 10⁻¹ 10 1

*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).*

Masses of EW scale ($\sim g \, v$) states $\, m_W, m_Z, m_t, m_h \,$

Michael Trott, IPMU

What wasn't discovered at LHC

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2018

01	alus. July 2010								$\int \mathcal{L} dt = ($	3.2 – 79.8) fb⁻¹	√s	= 8, 13 TeV
	Model	<i>ℓ</i> , γ	Jets†	E_{T}^{miss}	∫£ dt[f	b ⁻¹]		Limit			R	eference
Extra dimensions	ADD $G_{KK} + g/q$ ADD non-resonant $\gamma\gamma$ ADD QBH ADD BH high $\sum p_T$ ADD BH multijet RS1 $G_{KK} \rightarrow \gamma\gamma$ Bulk RS $G_{KK} \rightarrow WW/ZZ$ Bulk RS $g_{KK} \rightarrow tt$ 2UED / RPP	$0 e, \mu$ 2γ $-$ $2 \frac{1}{2} e, \mu$ $1 e, \mu$ $1 e, \mu$	$1 - 4 j$ $- 2 j$ $\geq 2 j$ $\geq 3 j$ $- 3 j$ $\geq 1 b, \geq 1 J/2$ $\geq 2 b, \geq 3$	Yes - 2j Yes j Yes	36.1 36.7 37.0 3.2 3.6 36.7 36.1 36.1 36.1	M _D M _S M _{th} M _{th} M _{th} G _{KK} mass g _{KK} mass KK mass			7.7 TeV 8.6 TeV 8.9 TeV 8.2 TeV 9.55 TeV 4.1 TeV 2.3 TeV 3.8 TeV 1.8 TeV	$\begin{split} n &= 2\\ n &= 3 \text{ HLZ NLO}\\ n &= 6\\ n &= 6, M_D = 3 \text{ TeV, rot BH}\\ n &= 6, M_D = 3 \text{ TeV, rot BH}\\ k/\overline{M}_{Pl} &= 0.1\\ k/\overline{M}_{Pl} &= 1.0\\ \Gamma/m &= 15\%\\ \text{Tier (1,1), } \mathcal{B}(A^{(1,1)} \rightarrow tt) = 1 \end{split}$	CE	1711.03301 1707.04147 1703.09217 1606.02265 1512.02586 1707.04147 RN-EP-2018-179 1804.10823 1803.09678
Gauge bosons	$\begin{array}{l} \mathrm{SSM}\; Z' \to \ell\ell \\ \mathrm{SSM}\; Z' \to \tau\tau \\ \mathrm{Leptophobic}\; Z' \to bb \\ \mathrm{Leptophobic}\; Z' \to tt \\ \mathrm{SSM}\; W' \to \ell\nu \\ \mathrm{SSM}\; W' \to \tau\nu \\ \mathrm{HVT}\; V' \to WV \to qqqq \mbox{ model B} \\ \mathrm{HVT}\; V' \to WH/ZH \mbox{ model B} \\ \mathrm{LRSM}\; W'_R \to tb \end{array}$	$2 e, \mu$ 2τ $-$ $1 e, \mu$ 1τ $del B 0 e, \mu$ $3 multi-channe$ multi-channe	- 2 b ≥ 1 b, ≥ 1J/ - 2 J H al	– – Yes Yes –	36.1 36.1 36.1 79.8 36.1 79.8 36.1 36.1 36.1	Z' mass Z' mass Z' mass Z' mass W' mass V' mass V' mass W' mass			4.5 TeV 2.42 TeV 2.1 TeV 3.0 TeV 5.6 TeV 3.7 TeV 4.15 TeV 2.93 TeV 3.25 TeV	$\Gamma/m = 1\%$ $g_V = 3$ $g_V = 3$	ATLA ATLA CE	1707.02424 1709.07242 1805.09299 1804.10823 S-CONF-2018-017 1801.06992 S-CONF-2018-016 1712.06518 RN-EP-2018-142
CI	CI qqqq CI ℓℓqq CI tttt	_ ≥1 e,μ	2 j _ ≥1 b, ≥1 j	– – Yes	37.0 36.1 36.1	Λ Λ Λ			2.57 TeV	$\begin{array}{c c} \hline 21.8 \ \text{TeV} & \eta_{LL}^- \\ \hline & 40.0 \ \text{TeV} & \eta_{LL}^- \\ C_{4t} = 4\pi \end{array}$	CE	1703.09217 1707.02424 RN-EP-2018-174
MQ	Axial-vector mediator (Dirac Colored scalar mediator (Dirac $VV_{\chi\chi}$ EFT (Dirac DM)	DM) 0 e, μ ac DM) 0 e, μ 0 e, μ	$\begin{array}{c} 1-4 \ j \\ 1-4 \ j \\ 1 \ J, \leq 1 \ j \end{array}$	Yes Yes Yes	36.1 36.1 3.2	m _{med} m _{med} M _*		1.55 1.6 700 GeV	TeV 7 TeV	$\begin{split} g_q = &0.25, g_{\chi} = &1.0, m(\chi) = 1 \text{ GeV} \\ g = &1.0, m(\chi) = 1 \text{ GeV} \\ m(\chi) < &150 \text{ GeV} \end{split}$		1711.03301 1711.03301 1608.02372
ГО	Scalar LQ 1 st gen Scalar LQ 2 nd gen Scalar LQ 3 rd gen	2 e 2 μ 1 e,μ	$ \begin{array}{c} \geq 2 \ j \\ \geq 2 \ j \\ \geq 1 \ b, \geq 3 \ j \end{array} $	_ _ Yes	3.2 3.2 20.3	LQ mass LQ mass LQ mass		1.1 TeV 1.05 TeV 640 GeV		$\begin{aligned} \beta &= 1\\ \beta &= 1\\ \beta &= 0 \end{aligned}$		1605.06035 1605.06035 1508.04735
Heavy quarks	$ \begin{array}{l} VLQ \ TT \rightarrow Ht/Zt/Wb + X \\ VLQ \ BB \rightarrow Wt/Zb + X \\ VLQ \ T_{5/3} T_{5/3} T_{5/3} \rightarrow Wt + \\ VLQ \ T \rightarrow Wb + X \\ VLQ \ B \rightarrow Hb + X \\ VLQ \ QQ \rightarrow WqWq \end{array} $	multi-channe multi-channe X $2(SS)/\ge 3 e,\mu$ 1 e,μ 0 $e,\mu, 2 \gamma$ 1 e,μ	$\iota \ge 1 \text{ b}, \ge 1 \text{ j}$ $\ge 4 \text{ j}$	Yes Yes Yes Yes	36.1 36.1 3.2 79.8 20.3	T mass B mass T _{5/3} mass Y mass B mass Q mass		1.37 Tr 1.34 Te 1.6 1.44 T 1.21 TeV 690 GeV	eV 9V 4 TeV TeV	SU(2) doublet SU(2) doublet $\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3}Wt) = 1$ $\mathcal{B}(Y \rightarrow Wb) = 1, c(YWb) = 1/\sqrt{2}$ $\kappa_B = 0.5$	ATLA ATLA CE ATLA ATLA	S-CONF-2018-XXX S-CONF-2018-XXX RN-EP-2018-171 S-CONF-2016-072 S-CONF-2018-XXX 1509.04261
Excited	Excited quark $q^* \rightarrow qg$ Excited quark $q^* \rightarrow q\gamma$ Excited quark $b^* \rightarrow bg$ Excited lepton ℓ^* Excited lepton ν^*	- 1 γ - 3 e,μ 3 e,μ,τ	2 j 1 j 1 b, 1 j -	- - - -	37.0 36.7 36.1 20.3 20.3	q* mass q* mass b* mass (* mass v* mass		14	6.0 TeV 5.3 TeV 2.6 TeV 3.0 TeV	only u^* and d^* , $\Lambda = m(q^*)$ only u^* and d^* , $\Lambda = m(q^*)$ $\Lambda = 3.0 \text{ TeV}$ $\Lambda = 1.6 \text{ TeV}$		1703.09127 1709.10440 1805.09299 1411.2921 1411.2921
Other	Type III Seesaw LRSM Majorana ν Higgs triplet $H^{\pm\pm} \rightarrow \ell \ell$ Higgs triplet $H^{\pm\pm} \rightarrow \ell \tau$ Monotop (non-res prod) Multi-charged particles Magnetic monopoles	1 e,μ 2 e,μ 2,3,4 e,μ (SS 3 e,μ,τ 1 e,μ 	≥ 2 j 2 j ;) – 1 b – - -	Yes - - Yes - - 3 TeV	79.8 20.3 36.1 20.3 20.3 20.3 7.0	N ⁰ mass N ⁰ mass H ^{±±} mass H ^{±±} mass spin-1 invis multi-charg monopole	sible particle ma ed particle ma mass	560 GeV 870 GeV 400 GeV ass 657 GeV ass 785 GeV 1.34 Te	2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing DY production DY production, $\mathcal{B}(H_L^{\pm\pm} \rightarrow \ell \tau) = 1$ $a_{non-res} = 0.2$ DY production, $ q = 5e$ DY production, $ g = 1g_D$, spin 1/2	ATLA	S-CONF-2018-020 1506.06020 1710.09748 1411.2921 1410.5404 1504.04188 1509.08059
							10 -	1	I	Mass scale [TeV]		

These bounds have been pushed away from

ATLAS Preliminary

 $v \sim m_h$

*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).

Runll and beyond: Resonance limits to local operators

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits **ATLAS** Preliminary Status: July 2018 $\sqrt{s} = 8, 13 \text{ TeV}$ $\int \mathcal{L} dt = (3.2 - 79.8) \text{ fb}^{-1}$ Jets $\dagger E_{\tau}^{\text{miss}} \int \mathcal{L} dt [fb^{-1}]$ Model Limit ℓ, γ Reference 0 e,μ 1 – 4 i ADD $G_{KK} + g/q$ Yes 36.1 n = 21711.03301 ADD non-resonant $\gamma\gamma$ 2γ 36.7 8.6 TeV n = 3 HLZ NLO 1707.04147 Now that these 2 j ADD QBH 1703.09217 37.0 8.9 TeV n = 6ADD BH high $\sum p_T$ $\geq 1 e, \mu$ ≥ 2 j _ 3.2 n = 6, $M_D = 3$ TeV, rot BH 1606.02265 3.2 TeV ADD BH multijet _ ≥3 j _ 3.6 n = 6, $M_D = 3$ TeV, rot BH 1512 02586 bounds have been RS1 $G_{KK} \rightarrow \gamma \gamma$ 2γ 36.7 4.1 TeV $k/\overline{M}_{Pl} = 0.1$ 1707.04147 Bulk RS $G_{KK} \rightarrow WW/ZZ$ multi-channel 36.1 $k/\overline{M}_{Pl} = 1.0$ CERN-EP-2018-179 pushed away from Bulk RS $g_{KK} \rightarrow tt$ $1 e, \mu \ge 1 b, \ge 1J/2j$ Yes 36.1 8.8 TeV $\Gamma/m = 15\%$ 1804.10823 2UED / RPP 1 e,μ \geq 2 b, \geq 3 j Yes 36.1 $\mathsf{Tier}\,(1,1),\,\mathcal{B}\bigl(A^{(1,1)}\to tt\bigr)=1$ 1803.09678 8 TeV SSM $Z' \rightarrow \ell \ell$ 2 e.µ 36.1 4.5 TeV 1707.02424 SSM $Z' \rightarrow \tau \tau$ 2τ 36.1 2.42 TeV 1709.07242 \mathcal{U} Leptophobic $Z' \rightarrow bb$ 2 b 36.1 1805.09299 2.1 TeV , oq Leptophobic $Z' \rightarrow tt$ 1 e,μ $\geq 1 \text{ b}, \geq 1 \text{J/2j}$ Yes 36.1 $\Gamma/m = 1\%$ 1804 10823 SSM $W' \rightarrow \ell v$ 1 e, µ 79.8 5.6 TeV ATLAS-CONF-2018-017 Yes SSM $W' \rightarrow \tau v$ 1τ Yes 36.1 3.7 TeV 1801.06992 HVT $V' \rightarrow WV \rightarrow qqqq$ model B 0 e,μ 2 J 79.8 ATLAS-CONF-2018-016 $g_V = 3$ 4.15 TeV HVT $V' \rightarrow WH/ZH$ model B multi-channel 36.1 .93 TeV $g_V = 3$ 1712.06518 LRSM $W'_P \rightarrow tb$ multi-channel 36.1 3.25 TeV CERN-EP-2018-142 **USE** that CI qqqq 2 j 37.0 1703 09217 21.8 TeV η₁ 5 CIllgg 2 e, µ _ 36.1 .0 TeV η_{LL} 1707.02424 $|C_{4t}| = 4\pi$ CI tttt ≥1 e,µ ≥1 b, ≥1 j Yes 36.1 2.57 TeV CERN-EP-2018-174 Axial-vector mediator (Dirac DM) 0 e,μ 1 – 4 j Yes 36.1 1.55 TeV g_q =0.25, g_{χ} =1.0, $m(\chi) = 1$ GeV 1711.03301 MO v/M < 1Colored scalar mediator (Dirac DM) 0 e, µ 1 – 4 i Yes 36.1 $g=1.0, m(\chi) = 1 \text{ GeV}$ 1711 03301 1.67 TeV VV_{XX} EFT (Dirac DM) $1 J_{, \leq 1 j}$ 0 e, µ Yes 3.2 700 GeV $m(\chi) < 150 \text{ GeV}$ 1608.02372 Scalar LQ 1st gen ≥ 2 j 1.1 TeV $\beta = 1$ 2 e _ 3.2 1605.06035 g Scalar LQ 2nd gen 2μ ≥ 2 j _ 3.2 1.05 TeV $\beta = 1$ 1605.06035 Yes 1508.04735 Scalar LQ 3rd gen ≥1 b, ≥3 j 20.3 $\beta = 0$ 1 e, µ to simplify/for more VLQ $TT \rightarrow Ht/Zt/Wb + X$ multi-channel 36.1 1.37 TeV SU(2) double ATLAS-CONF-2018-XXX VLQ $BB \rightarrow Wt/Zb + X$ 1.34 TeV SU(2) doublet ATLAS-CONF-2018-XXX multi-channel 36.1 VLQ $T_{5/3}T_{5/3}|T_{5/3} \rightarrow Wt + X$ $\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3}Wt) = 1$ 2(SS)/≥3 *e*,*µ* ≥1 b, ≥1 j Yes 36.1 1.64 TeV CERN-EP-2018-171 powerful conclusions: $VLQ \ Y \to Wb + X$ $\geq 1 \text{ b}, \geq 1 \text{ j}$ 3.2 ATLAS-CONF-2016-072 1 e.u Yes 1.44 Te $\mathcal{B}(Y \to Wb) = 1, c(YWb) = 1/\sqrt{2}$ VLQ $B \rightarrow Hb + X$ 0 e,μ, 2 γ ≥ 1 b, ≥ 1 j Yes 79.8 1.21 TeV $\kappa_B = 0.5$ ATLAS-CONF-2018-XXX VLQ $QQ \rightarrow WqWq$ 1 e.u ≥ 4 i Yes 20.3 1509 04261 2 j Excited quark $q^* \rightarrow qg$ 37.0 6.0 TeV only u^* and d^* , $\Lambda = m(q^*)$ 1703.09127 bound many Excited quark $q^* \rightarrow q\gamma$ 1γ 1 j _ 36.7 only u^* and d^* , $\Lambda = m(q^*)$ 1709.10440 5.3 TeV Excited quark $b^* \rightarrow bg$ 1 b, 1 j _ 36.1 2.6 TeV 1805.09299 Excited lepton ℓ^* 3 e,µ 20.3 $\Lambda = 3.0 \text{ TeV}$ 1411.2921 models at once Excited lepton v^* 3 e, μ, τ _ 20.3 $\Lambda = 1.6 \text{ TeV}$ 1411.2921 .6 TeV Type III Seesaw 1 e, µ ≥ 2 j Yes 79.8 560 GeV ATLAS-CONF-2018-020 LRSM Maiorana v 2 j $m(W_R) = 2.4$ TeV, no mixing 2 e, µ 20.3 1506.06020 _ Higgs triplet $H^{\pm\pm} \rightarrow \ell \ell$ 2,3,4 e, µ (SS) 36.1 870 GeV DY production 1710.09748 Higgs triplet $H^{\pm\pm} \rightarrow \ell \tau$ bound multiple 3 e, μ, τ 20.3 DY production, $\mathcal{B}(H_{l}^{\pm\pm} \rightarrow \ell \tau) = 1$ 1411.2921 _ Monotop (non-res prod) Yes 20.3 $a_{non-res} = 0.2$ 1410 5404 1 e, µ 1 b Multi-charged particles _ 20.3 DY production, $|a| = 5\epsilon$ 1504.04188 Magnetic monopoles DY production, $|g| = 1g_D$, spin 1/21509 08059 7.0 resonances at **.** I √s = 13 TeV √s = 8 TeV 10⁻¹ 1 10 Mass scale [TeV] same time *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).

Deviations then look like local contact operator effects in EFT

Michael Trott, IPMU

When you do measurements below a particle threshold



• Observable is a function of the Lorentz invariants:

f(s,t,u)

Generally an analytic function of these invariants, except in special regions of phase space, ex. where an internal state goes on-shell.

IF the collision probe does not reach $\sim m^2_{heavy}$ THEN observable's dependence on that scale simplified

EFT approach not a guess.

General approach based on S matrix theory and motivated by experimental situation. You can Taylor expand in LOCAL functions (operators)

$$\langle \rangle \sim O_{SM}^0 + \frac{f_1(s,t,u)}{M_{heavy}^2} + \frac{f_2(s,t,u)}{M_{heavy}^4} + \cdots$$

This is the core idea of EFT interpretations of the data.

General "BSM is heavy" approach is SMEFT



Complexity is scaling up...

Linear EFT - built of H doublet + higher D ops

 $\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_{\delta L \neq 0}} \mathcal{L}_{5} + \frac{1}{\Lambda_{\delta B = 0}^{2}} \mathcal{L}_{6} + \frac{1}{\Lambda_{\delta B \neq 0}^{2}} \mathcal{L}_{6} + \frac{1}{\Lambda_{\delta L \neq 0}^{3}} \mathcal{L}_{7} + \frac{1}{\Lambda^{4}} \mathcal{L}_{8} + \cdots$

14 operators, or 18 parameters (+ 1 op and then 19 with strong CP)

1 operator, and 7 extra parameters

Complexity <u>is</u> scaling up...



Practical applications of the SMEFT

LEP EWPD measurements in SMEFT



EWPD is a scan through the Z pole

 $\sim 40 \, pb^{-1}$ off peak data $\sim 155 \, pb^{-1}$ on peak data

The pseudo-observable LEP data is not subject to large intrinsic measurement bias transitioning from SM to SMEFT.

LEP EWPD measurements in SMEFT



Ω

EWPD is a scan through the Z pole

 $\sim 40 \, pb^{-1}$ off peak data $\sim 155 \, pb^{-1}$ on peak data

Simultaneous PO fit to

$$\sigma_{\bar{f}f}^Z = \sigma_{\bar{f}f}^{peak} \frac{s\Gamma_Z^2}{(s - m_Z^2)^2 + s^2\Gamma_Z^2/m_Z^2}$$

Peak shape is fit to:

$$\sigma_{\bar{f}f}^{peak} = \frac{\sigma_{\bar{f}f}^{0}}{R_{QED}} \qquad \sigma_{\bar{f}f}^{0} = \frac{12\pi\,\Gamma_{ee}\,\Gamma_{\bar{f}f}}{m_{Z}^{2}\,\Gamma_{Z}^{2}} \qquad R_{\ell}^{0} = \frac{\Gamma_{had}}{\Gamma_{\ell}}$$
Parameters extracted: $\left(m_{Z}^{2}, \Gamma_{Z}, R_{\ell}^{0}, \sigma_{had}^{0}\right)$

• This is a multi-scale problem

$$\hat{lpha}$$
 $p^2\simeq 0$
 \hat{G}_F $p^2\simeq m_\mu^2$
 \hat{M}_Z $p^2\simeq m_Z^2$

$$\begin{split} \hat{e} &= \sqrt{4\pi \hat{\alpha}_{ew}}, \qquad \hat{v}_T = \frac{1}{2^{1/4} \sqrt{\hat{G}_F}}, \\ \hat{g}_1 &= \frac{\hat{e}}{c_{\hat{\theta}}}, \qquad \hat{g}_2 = \frac{\hat{e}}{s_{\hat{\theta}}}, \\ s_{\hat{\theta}}^2 &= \frac{1}{2} \left[1 - \sqrt{1 - \frac{4\pi \hat{\alpha}}{\sqrt{2} \hat{G}_F \hat{M}_Z^2}} \right], \qquad \hat{M}_W^2 = \hat{M}_Z^2 c_{\hat{\theta}}^2, \\ \hat{g}_Z &= -\frac{\hat{g}_2}{c_{\hat{\theta}}}, \end{split}$$

	Observable	Experimental Value	Ref.	SM Theoretical Value	Ref.
	$\hat{m}_Z[\text{GeV}]$	91.1875 ± 0.0021	[19]	-	-
	$M_W[{ m GeV}]$	80.385 ± 0.015	[49]	80.365 ± 0.004	[50]
	$\Gamma_Z[\text{GeV}]$	2.4952 ± 0.0023	[19]	2.4942 ± 0.0005	[48]
Compare to	R^0_ℓ	20.767 ± 0.025	[19]	20.751 ± 0.005	[48]
	R_c^0	0.1721 ± 0.0030	[19]	0.17223 ± 0.00005	[48]
LEP data:	R_b^0	0.21629 ± 0.00066	[19]	0.21580 ± 0.00015	[48]
	σ_h^0 [nb]	41.540 ± 0.037	[19]	41.488 ± 0.006	[48]
	A_{FB}^ℓ	0.0171 ± 0.0010	[19]	0.01616 ± 0.00008	[32]
	A^c_{FB}	0.0707 ± 0.0035	[19]	0.0735 ± 0.0002	[32]
	A^b_{FB}	0.0992 ± 0.0016	[19]	0.1029 ± 0.0003	[32]



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This is a multi-scale problem



Leading order (LO) SMEFT analysis



• Lagrangian parameters inferred from inputs now corrected by local contact operators $\sqrt{2\langle H^{\dagger}H\rangle} \sim 246 \,\text{GeV}$

$$\begin{aligned} \mathbf{\Theta} \mathbf{K} &= \mathbf{K} \quad \mathbf{K} \\ \mathbf{\delta} g_{1} &= \bar{g}_{1} - \hat{g}_{1} = \frac{\hat{g}_{1}}{2c_{2\hat{\theta}}} \left[s_{\hat{\theta}}^{2} \left(\sqrt{2}\delta G_{F} + \frac{\delta m_{Z}^{2}}{\hat{m}_{Z}^{2}} \right) + c_{\hat{\theta}}^{2} s_{2\hat{\theta}} \bar{v}_{T}^{2} C_{HWB} \right], \\ \delta s_{\theta}^{2} &= s_{\bar{\theta}}^{2} - s_{\hat{\theta}}^{2} = 2c_{\hat{\theta}}^{2} s_{\hat{\theta}}^{2} \left(\frac{\delta g_{1}}{\hat{g}_{1}} - \frac{\delta g_{2}}{\hat{g}_{2}} \right) + \bar{v}_{T}^{2} \frac{s_{2\hat{\theta}} c_{2\hat{\theta}}}{2} C_{HWB}. \end{aligned}$$

Leading order (LO) SMEFT analysis



Lagrangian parameters inferred from inputs now corrected by local contact operators

Leading order (LO) SMEFT analysis

• For measurements of LEPI near Z pole data and W mass at LO:



- Relevant four fermion operator at LO is introduced due to $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$ As used to extract G_F and all other four fermion ops neglected.
- Some basis dependence in this, but $O(10) \ll 76$ as $\Gamma_{W,Z}/M_{W,Z} \ll 1$

Directly fitting the Z data



This likelihood is now internally available in ATLAS

 EWPD Studies that id. correlations in SMEFT as a key issue

Han and Skiba <u>http://arxiv.org/abs/hep-ph/0412166</u> Berthier, Bjorn, Trott 1606.06693 Brivio, Trott 1701.06424

EWPD flat direction example.

• For measurements of LEPI near Z pole data and W mass at LO:

 Rescaling invariance presence in EWPD: Brivio, MT 1701.06424

$$(V,g) \leftrightarrow \left(V'(1+\epsilon), g'(1-\epsilon)\right),$$

 $\sqrt{2\langle H^{\dagger}H\rangle} \sim 246 \,\mathrm{GeV}$

Effects like this cancel out in subsets of measurements.

- Note the crucial role of the Higgs classical background field here.
- Systematically a reason why the constraints on the C_i in the SMEFT fit space is highly correlated.

SMEFT reparameterization invariance

At one scale, you can get rid of the effect of the operators

$$H^{\dagger}HB^{\mu\nu}B_{\mu\nu}, \quad H^{\dagger}HW^{\mu\nu}W_{\mu\nu}$$

 $\langle y_{h}g_{1}^{2}Q_{HB}\rangle_{S_{R}} \rightarrow \frac{g_{1}^{2}\bar{v}_{T}^{2}}{4\Lambda^{2}}B^{\mu\nu}B_{\mu\nu}, \quad \langle g_{2}^{2}Q_{HW}\rangle_{S_{R}} \rightarrow \frac{g_{2}^{2}\bar{v}_{T}^{2}}{2\Lambda^{2}}W_{I}^{\mu\nu}W_{\mu\nu}^{I}.$
 $\bar{\psi}\psi \rightarrow \bar{\psi}\psi$
• via $B \rightarrow \mathcal{B}(1 + C_{HB}v^{2}), \quad g_{1} \rightarrow \bar{g}_{1}(1 - C_{HB}v^{2})$
Which leaves $Bg_{1} \rightarrow \mathcal{B}\bar{g}_{1}$ invariant.

• LEP data also can't see what is EOM equivalent to these operators in $\psi\psi
ightarrow \psi\psi$

$$\langle \mathsf{y}_h \, g_1^2 Q_{HB} \rangle_{S_R} = \left\langle \sum_{\substack{\psi_\kappa = u, d, \\ q, e, l}} \mathsf{y}_k \, g_1^2 \, \overline{\psi}_\kappa \, \gamma_\beta \psi_\kappa \, (H^\dagger \, i \overleftrightarrow{D}_\beta H) + \frac{g_1^2}{2} \left(Q_{H\Box} + 4Q_{HD} \right) - \frac{1}{2} g_1 \, g_2 \, Q_{HWB} \rangle_{S_R},$$

$$\langle g_2^2 Q_{HW} \rangle_{S_R} = \langle g_2^2 \left(\overline{q} \, \tau^I \gamma_\beta q + \overline{l} \, \tau^I \gamma_\beta l \right) \left(H^\dagger \, i \overleftrightarrow{D}_\beta^I H \right) + 2 \, g_2^2 \, Q_{H\Box} - 2 \, g_1 \, g_2 \, \mathsf{y}_h \, Q_{HWB} \rangle_{S_R}.$$

SMEFT reparameterization invariance

Flat directions discovered in the 2 to 2 scattering data set project onto these be careful and keep all EOM equivalent combinations of operators

$$w_1^{\alpha} = -w_B - 2.59 w_W$$
 $w_2^{\alpha} = -w_B + 4.31 w_W.$

The message is not "there are too many parameters" but globally combine data sets in SMEFT, so you get consistent results



Weakly broken as new degeneracy introduced: Weakly broken due to t channel vs s channel kinematics

$$Q_W = \epsilon^{IJK} W^{I\nu}_{\mu} W^{J\rho}_{\nu} W^{K\mu}_{\rho}$$

One loop/Gauge Fixing

SMEFT decay widths of the Z at one loop



- LSZ defn: $\langle Z|S|\bar{\psi}_i\psi_i\rangle = (1+\frac{\Delta R_Z}{2})(1+\Delta R_{\psi_i})i\mathcal{A}_{Z\bar{\psi}_i\psi_i}.$
- Need to loop improve the extraction of parameters AND the decay process of interest.

input shifts decay process (wavefunction&process) see also : Passarino et al arXiv:1607.01236 , arXiv:1505.03706

Loops present

 ~ 30 massive loops in addition to the RGE dim reg results of arXiv:1301.2588 Grojean, Jenkins, Manohar, Trott arXiv:1308.2627,1309.0819,1310.4838 Jenkins, Manohar, Trott arXiv: 1312.2014 Alonso, Jenkins, Manohar, Trott



Main conclusions

 MORE PARAMETERS (At least) the following operators contribute at one loop to EWPD, that are not present at tree level.

 $\{C_{qq}^{(1)}, C_{qq}^{(3)}, C_{qu}^{(1)}, C_{uu}, C_{qd}^{(1)}, C_{ud}^{(1)}, C_{\ell q}^{(1)}, C_{\ell q}^{(3)}, C_{\ell u}, C_{qe}, C_{HB} + C_{HW}, C_{uB}, C_{uW}, C_{uH}\}.$

Distinctions between operators made at LO not relevant



Need to combine data sets carefully due to hierarchies in experimental precision and different scales of measurements

SMEFT Subtleties

• $\Gamma(h \to \gamma \gamma)$ Defining the basis of operators as

 $\mathcal{O}_i = (\mathcal{O}_{HB}, \mathcal{O}_{HW}, \mathcal{O}_{HWB}, \mathcal{O}_W, \mathcal{O}_{eB}, \mathcal{O}_{eB}^*, \mathcal{O}_{uB}, \mathcal{O}_{uB}^*, \mathcal{O}_{dB}, \mathcal{O}_{dB}^*, \mathcal{O}_{eW}, \mathcal{O}_{eW}^*, \mathcal{O}_{uW}, \mathcal{O}_{uW}^*, \mathcal{O}_{dW}, \mathcal{O}_{dW}^*)$

 $\begin{aligned} \mathcal{L}_{6}^{(0)} &= Z_{SM} \, Z_{i,j} \, C_{i} \, \mathcal{O}_{j}^{(r)}, \\ &= Z_{SM} \, \mathcal{N}_{HB} \, \mathcal{O}_{HB}^{(r)} + Z_{SM} \, \mathcal{N}_{HW} \, \mathcal{O}_{HW}^{(r)} + Z_{SM} \, \mathcal{N}_{HWB} \, \mathcal{O}_{HWB}^{(r)}. \end{aligned}$

• 3x3 sub-matrix of ops that contribute at tree level

and first at one loop

$$Z_{i,j} = \frac{1}{16 \pi^2} \left[\begin{pmatrix} \frac{g_1^2}{4} - \frac{9g_2^2}{4} + 6\lambda + Y & 0 & g_1^2 \\ 0 & -\frac{3g_1^2}{4} - \frac{5g_2^2}{4} + 6\lambda + Y & g_2^2 \\ \frac{3g_2^2}{2} & \frac{g_1^2}{2} & -\frac{g_1^2}{4} + \frac{9g_2^2}{4} + 2\lambda + Y \end{pmatrix} \right]$$

• Counter-term subtraction is proportional to v

$$\begin{pmatrix} 0 & -\frac{15}{2}g_2^4 & \frac{3}{2}g_2^4 \\ -(y_l + y_e) Y_e & 0 & -\frac{1}{2}Y_e \\ -(y_l + y_e) Y_e^{\dagger} & 0 & -\frac{1}{2}Y_e^{\dagger} \\ -N_c (y_q + y_u) Y_u & 0 & \frac{1}{2}N_c Y_u \\ -N_c (y_q + y_u) Y_u^{\dagger} & 0 & \frac{1}{2}N_c Y_u^{\dagger} \\ -N_c (y_q + y_d) Y_d & 0 & -\frac{1}{2}N_c Y_d \\ -N_c (y_q + y_d) Y_d^{\dagger} & 0 & -\frac{1}{2}N_c Y_d^{\dagger} \\ 0 & -\frac{1}{2}Y_e & -(y_l + y_e) Y_e \\ 0 & -\frac{1}{2}N_c Y_u & N_c (y_q + y_u) Y_u \\ 0 & -\frac{1}{2}N_c Y_u & N_c (y_q + y_u) Y_u^{\dagger} \\ 0 & -\frac{1}{2}N_c Y_u & N_c (y_q + y_u) Y_u^{\dagger} \\ 0 & -\frac{1}{2}N_c Y_d & -N_c (y_q + y_d) Y_d \end{pmatrix}$$

The required loops.

• Calculate in BF method, in R_{ξ} gauge, for operators that contribute at tree level



Renormalization conditions

The finite terms that are fixed by renormalization conditions (at one loop) in the theory enter as

$$\langle h(p_h)|S|\gamma(p_a,\alpha),\gamma(p_b,\beta)\rangle_{BSM} = (1+\frac{\delta R_h}{2})(1+\delta R_A)(1+\delta R_e)^2 i \sum_{x=a..o} \mathcal{A}_x.$$
Cancels!

Remaining finite terms fixed by defining in renormalization conditions on the couplings and two point function residues and poles

$$\delta R_h = -rac{\partial \Pi_{hh}(p^2)}{\partial p^2}|_{p^2=m_h^2} \qquad \delta R_e = -rac{1}{2}\delta R_A,$$
This relation follows

This relation follows from a Ward identity using BFM.

NLO SMEFT

• The final tree result is of the form

1505.02646 Hartmann, Trott 1507.03568 Hartmann, Trott

$$\begin{split} \frac{i\,\mathcal{A}_{lotal}^{NP}}{i\,v\,e^{2}\,\mathcal{A}_{\alpha\beta}^{h\gamma\gamma}} &= C_{\gamma\gamma}\left(1 + \frac{\delta R_{h}}{2} + \frac{\delta\,v}{v}\right), \\ &+ \left(\frac{C_{\gamma\gamma}}{16\,\pi^{2}}\left(\frac{g_{1}^{2}}{4} + \frac{3\,g_{2}^{2}}{4} + \delta\right) + \frac{C_{HWB}}{16\,\pi^{2}}\left(-3\,g_{2}^{2} + 4\lambda\right)\right)\log\left(\frac{m_{h}^{2}}{\Lambda^{2}}\right), \\ &+ \frac{C_{\gamma\gamma}}{16\,\pi^{2}}\left(\left(\frac{g_{1}^{2}}{4} + \frac{g_{2}^{2}}{4} + \lambda\right)\mathcal{I}[m_{Z}^{2}] + \left(\frac{g_{2}^{2}}{2} + 2\lambda\right)\mathcal{I}[m_{W}^{2}] + (\sqrt{3}\,\pi - 6)\,\lambda\right), \\ &+ \frac{C_{HWB}}{16\,\pi^{2}}\left(2e^{2}\left(1 + 6\frac{m_{W}^{2}}{m_{h}^{2}}\right) - 2\,g_{2}^{2}\left(1 + \log\left(\frac{m_{W}^{2}}{m_{h}^{2}}\right)\right) + (4\lambda - g_{2}^{2})\mathcal{I}[m_{W}^{2}], \\ &+ 4\left(3e^{2} - g_{2}^{2} - 6e^{2}\frac{m_{W}^{2}}{m_{h}^{2}}\right)\mathcal{I}_{y}[m_{W}^{2}]\right), \\ &- \frac{g_{2}^{2}C_{HW}}{4\,\pi^{2}}\left(3\frac{m_{W}^{2}}{m_{h}^{2}} + \left(4 - \frac{m_{h}^{2}}{m_{W}^{2}} - 6\frac{m_{W}^{2}}{m_{h}^{2}}\right)\mathcal{I}_{y}[m_{W}^{2}]\right). \end{split} \tag{3.6} \end{split}$$

$$\begin{aligned} \\ \text{Where} \qquad \mathcal{I}[m^{2}] \equiv \int_{0}^{1}dx\,\log\left(\frac{m^{2} - m_{h}^{2}x\,(1 - x)}{m_{h}^{2}}\right), \quad \mathcal{I}_{y}[m^{2}] \equiv \int_{0}^{1 - x}dy\int_{0}^{1}dx\,\frac{m^{2}}{m^{2} - m_{h}^{2}x\,(1 - x - y)}, \end{aligned}$$

SMEFT gauge fixing issues.

The fields are redefined at each order in the power counting, this leads to the appearance of L6 Wilson coefficients in the gauge fixing term.

$${\cal L}_{FP} = -ar u^lpha \, {\delta G^lpha \over \delta heta^eta} \, u^eta.$$

Some operators in \mathcal{L}_6 then source ghosts!



• This cancels the unusual divergences in $\ \Gamma_{SMEFT}(h
ightarrow \gamma\gamma)$ exactly.

 The mismatch of the mass eigenstates in the SMEFT with the SM means gauge fixing in the former also results in some interesting local contact operators

$$-\frac{c_w \, s_w}{\xi_B \, \xi_W} (\xi_B - \xi_W) \left(\partial^\mu A_\mu \, \partial^\nu \, Z_\nu \right) - \frac{C_{HWB} v^2 (s_w^2 - c_w^2) (s_w^2 \xi_B + c_w^2 \xi_W)}{\xi_B \, \xi_W} \left(\partial^\mu A_\mu \, \partial^\nu \, Z_\nu \right) \cdot$$

SMEFT gauge fixing solution!

Problem: contact operators change mass and weak eigenstate relationship. This can be understood as a "curved field space" due to the contact operators.

Solution:define a gauge fixing term on the "curved field space"

$$\begin{split} \mathcal{L}_{\mathrm{GF}} &= -\frac{\hat{g}_{AB}}{2\xi} \mathcal{G}^{A} \mathcal{G}^{B}, \\ \mathcal{G}^{X} &\equiv \partial_{\mu} \mathcal{W}^{X,\mu} - \tilde{\epsilon}^{X}_{\ CD} \hat{\mathcal{W}}^{C}_{\mu} \mathcal{W}^{D,\mu} + \frac{\xi}{2} \hat{g}^{XC} \phi^{I} \hat{h}_{IK} \tilde{\gamma}^{K}_{C,J} \hat{\phi}^{J}. \\ \int \mathcal{D}F \det \left[\frac{\Delta \mathcal{G}^{A}}{\Delta \alpha^{B}} \right] e^{i \left(S[F+\hat{F}] + \mathcal{L}_{\mathrm{GF}} + \hat{g}_{CD} J^{C}_{\mu} \mathcal{W}^{D,\mu} + \hat{h}_{IJ} J^{I}_{\phi} \phi^{J} \right)}. \end{split}$$

SMEFT gauge fixing solution!

 $\equiv \frac{1}{2} h_{IJ}(\phi) \left(D_{\mu} \phi \right)^{I} \left(D^{\mu} \phi \right)^{J}.$

$$\mathcal{L}_{ ext{scalar,kin}} = \left(D_{\mu}H\right)^{\dagger} \left(D^{\mu}H\right) + C_{H\Box}\left(H^{\dagger}H\right) \Box \left(H^{\dagger}H\right) + C_{HD}\left(H^{\dagger}D_{\mu}H\right)^{*} \left(H^{\dagger}D^{\mu}H\right),$$

$$\begin{split} \mathcal{L}_{\rm GF} &= -\frac{\hat{g}_{AB}}{2\,\xi} \mathcal{G}^A \, \mathcal{G}^B, \\ \mathcal{G}^X &\equiv \partial_\mu \mathcal{W}^{X,\mu} - \tilde{\epsilon}^X_{\ CD} \hat{\mathcal{W}}^C_\mu \mathcal{W}^{D,\mu} + \frac{\xi}{2} \hat{g}^{XC} \phi^I \, \hat{h}_{IK} \, \tilde{\gamma}^K_{C,J} \hat{\phi}^J. \\ \int \mathcal{D}F \, \det \left[\frac{\Delta \mathcal{G}^A}{\Delta \alpha^B} \right] e^{i \left(S[F + \hat{F}] + \mathcal{L}_{\rm GF} + \hat{g}_{CD} J^C_\mu \mathcal{W}^{D,\mu} + \hat{h}_{IJ} J^I_\phi \phi^J \right)}. \end{split}$$

SMEFT gauge fixing solution!

$$egin{split} \mathcal{L}_{ ext{scalar,kin}} = \left(D_{\mu} H
ight)^{\dagger} \left(D^{\mu} H
ight) + C_{H\Box} \left(H^{\dagger} H
ight) \Box \left(H^{\dagger} H
ight) \ + C_{HD} \left(H^{\dagger} D_{\mu} H
ight)^{st} \left(H^{\dagger} D^{\mu} H
ight), \end{split}$$

$$\equiv \frac{1}{2} h_{IJ}(\phi) \left(D_{\mu} \phi \right)^{I} \left(D^{\mu} \phi \right)^{J}.$$

$$\begin{split} \mathcal{L}_{\rm WB} &= -\frac{1}{4} W^a_{\mu\nu} W^{a,\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \frac{C_{HB}}{\Lambda^2} H^{\dagger} H B_{\mu\nu} B^{\mu\nu} \\ &+ \frac{C_{HW}}{\Lambda^2} H^{\dagger} H W^a_{\mu\nu} W^{a,\mu\nu} + \frac{C_{HWB}}{\Lambda^2} H^{\dagger} \sigma^a H W^a_{\mu\nu} B^{\mu\nu}, \end{split}$$

$$\equiv -rac{1}{4}g_{AB}(H)\mathcal{W}^{A}_{\mu
u}\mathcal{W}^{B,\mu
u},$$

$$egin{split} \mathcal{L}_{ ext{GF}} &= -rac{\hat{g}_{AB}}{2\,\xi} \mathcal{G}^A \, \mathcal{G}^B, \ \mathcal{G}^X &\equiv \partial_\mu \mathcal{W}^{X,\mu} - ilde{\epsilon}^X_{\ CD} \hat{\mathcal{W}}^C_\mu \mathcal{W}^{D,\mu} + rac{\xi}{2} \hat{g}^{XC} \phi^I \, \hat{h}_{IK} \, ilde{\gamma}^K_{C,J} \hat{\phi}^J. \ \int \mathcal{D}F \, ext{det} \left[rac{\Delta \mathcal{G}^A}{\Delta lpha^B}
ight] e^{i \left(S[F+\hat{F}] + \mathcal{L}_{ ext{GF}} + \hat{g}_{CD}} J^C_\mu \mathcal{W}^{D,\mu} + \hat{h}_{IJ} J^I_\phi \phi^J
ight). \end{split}$$

$$\gamma_{1,J}^{I} = \begin{bmatrix} 0 & 0 & 0 & -1 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}, \quad \gamma_{2,J}^{I} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \\ -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}, \quad \gamma_{3,J}^{I} = \begin{bmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \end{bmatrix}, \quad \gamma_{4,J}^{I} = \begin{bmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{bmatrix}$$



SMEFTsim

- 2 input parameter schemes, with all higher dimensional operators included
- 3 symmetry cases: General flavour indicies and phases (2499 parameters!) arXiv:1312.2014 Alonso, Jenkins, Manohar, Trott

Minimal Flavour Violation SMEFT at LO

Fully flavour symmetric SMEFT at LO

- SMEFTsim designed to take the grind out of these studies, canonical normalization and input relations all done for user.
- See: feynrules.irmp.ucl.ac.be/wiki/SMEFT

SMEFTsim paper : <u>https://arxiv.org/abs/1709.06492</u>

This code undergoing validation in new LPCC effort to develop SMEFT results/tools for LHC experiment. Contact Trott/Maltoni for more details on this effort/to contribute.

.. are there too many parameters?

Number of parameters convolution of power counting

$$\langle \rangle \sim O_{SM}^0 + \frac{f_1(s,t,u)}{M_{heavy}^2} + \frac{f_2(s,t,u)}{M_{heavy}^4} + \cdots$$

+ numerical suppression due to interference with SM and resonance domination, or not

• EX - flavour indicies for neutral currents: $\mathcal{A}_{ik}^{h} \simeq \frac{3\bar{v}_{T}\,\bar{g}_{2}^{3}}{16^{2}\,\pi^{2}\,\hat{m}_{W}}\,\bar{\psi}_{i}\left[y_{i}\,V_{ik}^{\dagger}\,V_{kj}\frac{m_{k}^{2}}{\hat{m}_{W}^{2}}P_{L}+y_{j}\,V_{kj}^{\dagger}\,V_{ik}\frac{m_{k}^{2}}{\hat{m}_{W}^{2}}P_{R}\right]\psi_{j},+\cdots$

$$\mathcal{A}^Z_{ik} \simeq -rac{3\sqrt{ar{g}_1^2 + ar{g}_2^2}\,ar{g}_2^2\,V^\star_{jk}\,V_{ji}}{32\,\pi^2}rac{m_j^2}{m_W^2}ar{\psi}_k\,\gamma^\mu\,P_L\,\psi_i\,\epsilon^Z_\mu + \cdots\,,$$

This IR SM physics projects out parameters.

Leading "WHZ pole parameters"

Case	CP even	CP odd	WHZ Pole parameters
General SMEFT $(n_f = 1)$	53 [<mark>10</mark>]	23 [10]	~ 23
General SMEFT $(n_f = 3)$	1350 [<mark>10</mark>]	1149 [<mark>10</mark>]	~ 46
$U(3)^5$ SMEFT	~ 52	~ 17	~ 24
MFV SMEFT	~ 108	-	~ 30

Brivio, Jiang, MT <u>https://arxiv.org/abs/1709.06492</u>

 So long as a measurement is dominated by a near on-shell region of phase space of a narrow boson (like W,Z,H) many other parameters suppressed by

$$\left(\frac{\Gamma_B m_B}{\bar{v}_T^2}\right) \frac{\{\operatorname{Re}(C), \operatorname{Im}(C)\}}{g_{SM} C_i},$$

$$\left(\frac{\Gamma_B m_B}{p_i^2}\right) \frac{\{\operatorname{Re}(C), \operatorname{Im}(C)\}}{g_{SM} C_k},$$

Measurement/facility design can DEFINE a subset of SMEFT parameters in a fit

The evolution of Higgs studies

State of the art Higgs properties

How do we learn about the properties of the Higgs?





Raw events are process to measured event rates.

State of the art Higgs properties

Raw events are processed to measured (relative) event rates.



Under a SM like assumption Raw events are processed to measured (relative) event rates. **ATLAS** Preliminary Hend Total ____ Stat. = Syst. = SM **ATLAS** Preliminary Hend Total ____ Stat. = Syst. = SM $\sqrt{s} = 13 \text{ TeV}, 36.1 - 79.8 \text{ fb}^{-1}$ $\sqrt{s} = 13 \text{ TeV}, 36.1 - 79.8 \text{ fb}^{-1}$ m_H = 125.09 GeV, |y₁| < 2.5 $m_{H} = 125.09 \text{ GeV}, |y_{..}| < 2.5$ Stat. Syst. Total Total Stat. Syst. $1.13 \pm {}^{0.13}_{0.13}$ ($\pm {}^{0.12}_{0.11}$, $\pm {}^{0.06}_{0.06}$ σ_{aaF}^{ZZ} $0.89 \pm \begin{smallmatrix} 0.15 \\ 0.13 \end{smallmatrix} (\pm \begin{smallmatrix} 0.12 \\ 0.11 \end{smallmatrix} , \pm \begin{smallmatrix} 0.08 \\ 0.06 \end{smallmatrix})$ $B_{\gamma\gamma}/B_{ZZ}$ $1.17 \pm {}^{0.29}_{0.24}$ ($\pm {}^{0.23}_{0.21}$, $\pm {}^{0.17}_{0.13}$) $\sigma_{VBF} / \sigma_{aaF}$ $0.94 \pm \begin{smallmatrix} 0.19 \\ 0.17 \end{smallmatrix} (\pm \begin{smallmatrix} 0.14 \\ 0.12 \end{smallmatrix} , \pm \begin{smallmatrix} 0.14 \\ 0.12 \end{smallmatrix})$ B_{WW}/B_{77} $1.64 \pm {}^{0.74}_{0.58}$ ($\pm {}^{0.57}_{0.46}$, $\pm {}^{0.47}_{0.35}$ $\sigma_{\text{WH}}/\sigma_{\text{agF}}$ $B_{\tau\tau}/B_{ZZ}$ $0.87\pm \begin{smallmatrix} 0.27\\ 0.22 \end{smallmatrix}$ ($\pm \begin{smallmatrix} 0.19\\ 0.17 \end{smallmatrix}$, $\pm \begin{smallmatrix} 0.18\\ 0.15 \end{smallmatrix}$) $0.76 \pm 0.51 \ (\pm 0.41 \ ,\pm 0.29 \ .26 \ ,\pm 0.29 \ .26 \ ,\pm 0.29 \ .26$ σ_{ZH}/σ_{aaF} $0.81 \pm {}^{0.37}_{0.28}$ ($\pm {}^{0.25}_{0.19}$, $\pm {}^{0.27}_{0.19}$ B_{bb}/B_{77} 0 0.5 -0.5 2.53 -0.50 0.515 2.5 3 3.5 4.5 Parameter normalized to SM value Parameter normalized to SM value Narrow width Factorisation of

Production and decay

 You need a theory to do the inference to define the relative event rates. This analysis uses a "SM like" assumption at many key points.

State of the art Higgs properties

Various operator based perturbations can appear







A: "We are looking into it."

Н

	X^3		$arphi^6$ and $arphi^4 D^2$	$\psi^2 arphi^3$		
Q_G	$f^{ABC}G^{A u}_\mu G^{B ho}_ u G^{C\mu}_ ho$	Q_{arphi}	$(\varphi^{\dagger}\varphi)^{3}$	$Q_{e\varphi}$	$(arphi^\dagger arphi) (ar l_p e_r arphi)$	
$Q_{\widetilde{G}}$	$f^{ABC}\widetilde{G}^{A u}_{\mu}G^{B ho}_{ u}G^{C\mu}_{ ho}$	$Q_{arphi\square}$	$(\varphi^{\dagger}\varphi)\Box(\varphi^{\dagger}\varphi)$	$Q_{u\varphi}$	$(arphi^\dagger arphi)(ar q_p u_r \widetilde arphi)$	
Q_W	$\varepsilon^{IJK}W^{I\nu}_{\mu}W^{J\rho}_{\nu}W^{K\mu}_{\rho}$	$Q_{arphi D}$	$\left(arphi^{\dagger} D^{\mu} arphi ight)^{\star} \left(arphi^{\dagger} D_{\mu} arphi ight)$	Q_{darphi}	$(arphi^\dagger arphi) (ar q_p d_r arphi)$	
$Q_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}^{I\nu}_{\mu}W^{J\rho}_{\nu}W^{K\mu}_{\rho}$					
$X^2 \varphi^2$		$\psi^2 X arphi$		$\psi^2 \varphi^2 D$		
$Q_{arphi G}$	$arphi^\dagger arphi G^A_{\mu u} G^{A\mu u}$	Q_{eW}	$(ar{l}_p \sigma^{\mu u} e_r) au^I arphi W^I_{\mu u}$	$Q^{(1)}_{arphi l}$	$(arphi^\dagger i \overleftrightarrow{D}_\mu arphi) (ar{l}_p \gamma^\mu l_r)$	
$Q_{arphi \widetilde{G}}$	$arphi^\dagger arphi \widetilde{G}^A_{\mu u} G^{A\mu u}$	Q_{eB}	$(ar{l}_p \sigma^{\mu u} e_r) arphi B_{\mu u}$	$Q^{(3)}_{arphi l}$	$(arphi^\dagger i \overleftrightarrow{D}^I_\mu arphi) (ar{l}_p au^I \gamma^\mu l_r)$	
$Q_{arphi W}$	$arphi^\dagger arphi W^I_{\mu u} W^{I\mu u}$	Q_{uG}	$(ar q_p \sigma^{\mu u} T^A u_r) \widetilde arphi G^A_{\mu u}$	$Q_{arphi e}$	$(arphi^\dagger i \overleftrightarrow{D}_\mu arphi) (ar{e}_p \gamma^\mu e_r)$	
$Q_{\varphi \widetilde{W}}$	$arphi^\dagger arphi \widetilde{W}^I_{\mu u} W^{I\mu u}$	Q_{uW}	$(ar q_p \sigma^{\mu u} u_r) au^I \widetilde arphi W^I_{\mu u}$	$Q^{(1)}_{arphi q}$	$(arphi^\dagger i \overleftrightarrow{D}_\mu arphi) (ar{q}_p \gamma^\mu q_r)$	
$Q_{arphi B}$	$arphi^\dagger arphi B_{\mu u} B^{\mu u}$	Q_{uB}	$(ar q_p \sigma^{\mu u} u_r) \widetilde arphi B_{\mu u}$	$Q^{(3)}_{arphi q}$	$(arphi^\dagger i \overleftrightarrow{D}^I_\mu arphi) (ar{q}_p au^I \gamma^\mu q_r)$	
$Q_{arphi \widetilde{B}}$	$arphi^\dagger arphi \widetilde{B}_{\mu u} B^{\mu u}$	Q_{dG}	$(ar q_p \sigma^{\mu u} T^A d_r) arphi G^A_{\mu u}$	$Q_{\varphi u}$	$(arphi^\dagger i \overleftrightarrow{D}_\mu arphi) (ar{u}_p \gamma^\mu u_r)$	
$Q_{\varphi WB}$	$arphi^\dagger au^I arphi W^I_{\mu u} B^{\mu u}$	Q_{dW}	$(ar q_p \sigma^{\mu u} d_r) au^I arphi W^I_{\mu u}$	$Q_{arphi d}$	$(\varphi^{\dagger}i\overleftrightarrow{D}_{\mu}\varphi)(ar{d}_{p}\gamma^{\mu}d_{r})$	
$Q_{\varphi \widetilde{W}B}$	$arphi^\dagger au^I arphi \widetilde{W}^I_{\mu u} B^{\mu u}$	Q_{dB}	$(ar q_p \sigma^{\mu u} d_r) arphi B_{\mu u}$	$Q_{\varphi ud}$	$i(\widetilde{arphi}^{\dagger}D_{\mu}arphi)(ar{u}_{p}\gamma^{\mu}d_{r})$	

Table 2: Dimension-six operators other than the four-fermion ones.

More precision on the EXP side

 In years to come the precision of experimental determinations will only increase. Future facilities (ILC, FCC etc) will push precision further.

Combined Higgs coupling measurements

2030+ knowledge A. De Wit HL-LHC projection





Requires more developments on TH side

What do we need?

- Loop corrections in the SMEFT
- Better understanding of the effects of sub-leading terms on leading term data analysis
- Global fits exploiting multiple data sets and properly treating the different scales
- Better TH produced code tools for EXP
- Understanding of many aspects of formal field theory in the SMEFT

Summary

- The Higgs boson is unprecedented as a fundamental particle to discover.
- The EXP program is strongly focused on resolving its properties as precisely as possible for years to come
- The SMEFT is the theoretical framework that allows and enables this to happen in a well defined, systematically improvable QFT.
- Interest in this theory is really exploding.
 We know what to do to develop this theory in parallel with the experimental program.