The Standard Model Effective Field Theory

#SMEFT

M. Trott, 2019

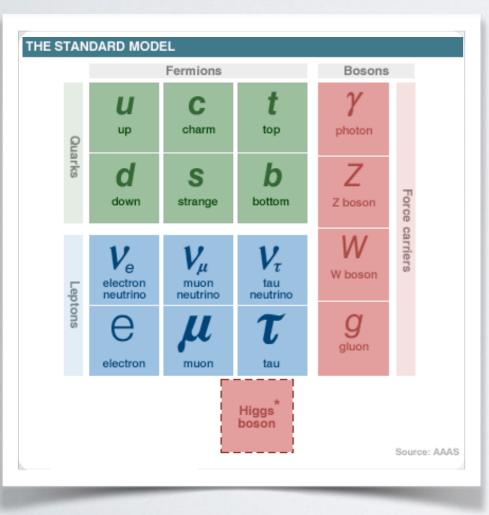


Michael Trott, Nordic Winter School on Particle Physics and Cosmology

The Standard model ...

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

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



• We can count the number of parameters present in the theory.

 $m_e, m_\mu, m_\tau, m_u, m_d, m_c, m_s, m_t, m_b$: 9 masses

Flavour Symmetry

The global flavour symmetry of the SM is

 $G_F = U(3)^5 = S_Q \otimes S_L \otimes U(1)^5$

 $q \rightarrow U_q q, \qquad l \rightarrow U_l l, \qquad u \rightarrow U_u u, \qquad d \rightarrow U_d d, \qquad e \rightarrow U_e e.$ here $S_Q = SU(3)_{Q_L} \otimes SU(3)_{U_R} \otimes SU(3)_{D_R} \qquad S_L = SU(3)_{L_L} \otimes SU(3)_{E_R}$

In the SM a well defined sense in which this flavour symmetry is restored:

$$\mathcal{L}_{SM} = \mathcal{L}_{SM}^{G_F} + \left[H^{\dagger j} \overline{d} Y_{d} q_j + \widetilde{H}^{\dagger j} \overline{u} Y_{d} q_j + H^{\dagger j} \overline{e} Y_{e} l_j + \text{h.c.} \right]$$

$$0 \qquad 0 \qquad 0$$

Technically you can think of the Yukawas as symmetry breaking spurions

$$Y_u \sim (3, 1, \overline{3}), Y_d \sim (1, 3, \overline{3})$$

Flavour Symmetry

 Can make separate rotations on the left and right handed fermion fields. Leaves kinetic terms in the Lagrangian invariant:

$$\mathcal{L}_{kin} = \bar{Q}_L^i \, i \, \partial \!\!\!/ \, Q_L + \bar{L}_L^i \, i \, \partial \!\!\!/ \, L_L + \bar{u}_R \, i \, \partial \!\!\!/ \, u_R + \bar{d}_R \, i \, \partial \!\!\!/ \, d_R$$

- When Yukawa's turned on the inability to simultaneously diagonalise the yukawas and charged current interactions leads to flavour violation.
- Diagonalize the fermion masses and different components of the doublets rotated

$$\begin{pmatrix} U_L \\ D_L \end{pmatrix} = \mathcal{U}(U,L) \begin{pmatrix} U'_L \\ \mathcal{U}(U,L)^{\dagger} \mathcal{U}(D,L) D'_L \end{pmatrix}$$

$$V_{CKM}$$

Flavour Symmetry

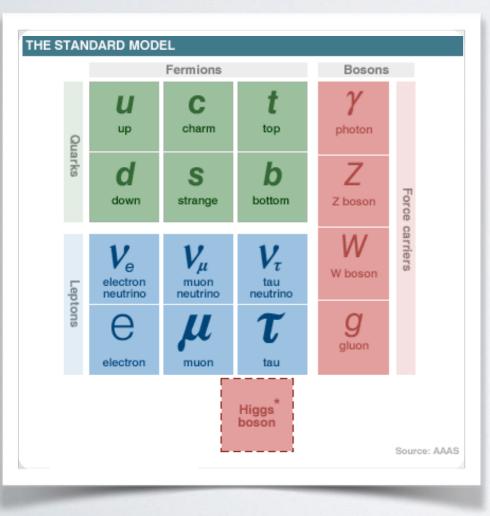
- Structure of the breaking of G_F is what is important.
- NO flavour changing neutral currents at tree level in the SM.
 Flavour changing charged currents allowed and present.

$$\frac{g_2}{\sqrt{2}} W^+ \bar{u}_L \gamma^\mu d_L = \frac{g_2}{\sqrt{2}} W^+ \bar{u'}_L \gamma^\mu V_{CKM} d'_L$$

$$\begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}$$

The Standard model ...

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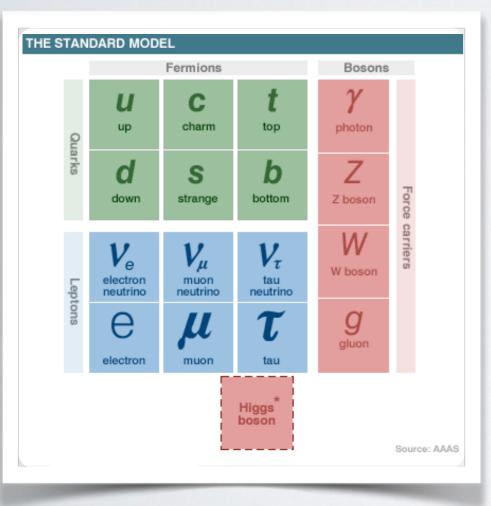
• We can count the number of parameters present in the theory.

 $m_e, m_\mu, m_\tau, m_u, m_d, m_c, m_s, m_t, m_b$: 9 masses

 $\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} N^2 \text{ real parameters in NxN} \\ 2N-1 \text{ relative phases} \\ (N-1)^2 \text{ physical parameters} \end{pmatrix}$

The Standard model ...

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



• We can count the number of parameters present in the theory.

 $m_e, m_\mu, m_\tau, m_u, m_d, m_c, m_s, m_t, m_b$: 9 masses $\theta_{12}, \theta_{13}, \theta_{23}, \delta$: 4 quark mixing g_1, g_2, g_3 : 3 gauge couplings v, λ : 2 EW sectorThis is the 18 parameters you hear about...

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 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 dim _ ≥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 KK mass 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 кк mas $\text{Tier}\,(1,1),\,\mathcal{B}\bigl(A^{(1,1)}\to tt\bigr)=1$ 2UED / RPP 1 e,μ $\geq 2 \text{ b}, \geq 3 \text{ j}$ Yes 36.1 1.8 TeV 1803.09678 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 mass Leptophobic $Z' \rightarrow bb$ 2 b _ 36.1 2.1 TeV 1805.09299 , oq 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 apr SSM $W' \rightarrow \tau v$ 1τ _ Yes 36.1 W' mass 3.7 TeV 1801.06992 a c 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 2 j 37.0 21.8 TeV η_{LL}^- 1703 09217 G Clllqq 2 e, µ _ 36.1 40.0 TeV η_{LL} 1707.02424 CI tttt ≥1 e,µ ≥1 b, ≥1 j Yes 36.1 2.57 TeV $|C_{4t}| = 4\pi$ 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 Yes $g=1.0, m(\chi) = 1 \text{ GeV}$ 36.1 1.67 TeV 1711 03301 VV XX EFT (Dirac DM) $1 J_{, \leq 1 j}$ $m(\chi) < 150 \text{ GeV}$ 0 e, µ Yes 3.2 700 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 $\beta = 0$ 1508.04735 Scalar LQ 3rd gen 1 e, µ ≥1 b, ≥3 j Yes 20.3 VLQ $TT \rightarrow Ht/Zt/Wb + X$ 36.1 1.37 TeV SU(2) doublet ATLAS-CONF-2018-XXX multi-channe 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)/ \geq 3 $e,\mu \geq$ 1 b, \geq 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 $VLQ \ Y \to Wb + X$ $\geq 1 \text{ b}, \geq 1 \text{ j}$ 3.2 $\mathcal{B}(Y \rightarrow Wb) = 1, c(YWb) = 1/\sqrt{2}$ ATLAS-CONF-2016-072 1 e.u Yes 1.44 TeV 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 _ Excited quark $q^* \rightarrow q\gamma$ 1γ 1 j _ 36.7 5.3 TeV only u^* and d^* , $\Lambda = m(q^*)$ 1709.10440 Excited quark $b^* \rightarrow bg$ 2.6 TeV 1 b, 1 j _ 36.1 1805.09299 Excited lepton ℓ^* 3 e,µ 20.3 $\Lambda = 3.0 \text{ TeV}$ 1411.2921 Excited lepton v^* 3 e, μ, τ _ 20.3 $\Lambda = 1.6 \text{ TeV}$ 1411.2921 1.6 TeV Type III Seesaw 1 e, µ ≥ 2 j Yes 79.8 560 GeV ATLAS-CONF-2018-020 LRSM Maiorana v 2 j 2 e,µ 20.3 $m(W_R) = 2.4$ TeV, no mixing 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 ŧ $a_{\rm non-res} = 0.2$ Monotop (non-res prod) 1 b Yes 20.3 1410 5404 1 e, µ Multi-charged particles _ 20.3 DY production, $|a| = 5\epsilon$ 1504.04188 Magnetic monopoles DY production, $|g| = 1g_D$, spin 1/2 1509.08059 7.0

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

√s = 13 TeV

10⁻¹

√s = 8 TeV

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

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Mass scale [TeV]

Runll and beyond: Resonance limits to local operators

ATLAS Preliminary

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

St	atus: July 2018					••	$\int \mathcal{L} dt = (3)$.2 – 79.8) fb ⁻¹	$\sqrt{s} = 8, 13 \text{ TeV}$
	Model	<i>ℓ</i> ,γ	Jets†	E_{T}^{miss}	∫£ dt[fb	⁻¹]	Limit		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	$\begin{array}{c} 0 \ e, \mu \\ 2 \ \gamma \\ - \\ \geq 1 \ e, \mu \\ - \\ 2 \ \gamma \\ multi-chann \\ 1 \ e, \mu \\ 1 \ e, \mu \end{array}$	$\begin{array}{c} 1-4 \ j \\ - \\ 2 \ j \\ \geq 2 \ j \\ \geq 3 \ j \\ - \\ \text{nel} \\ \geq 1 \ \text{b}, \geq 1 \ \text{J} \\ \geq 2 \ \text{b}, \geq 3 \end{array}$		36.1 36.7 37.0 3.2 3.6 36.7 36.1 36.1 36.1	М _D M ₅ М _{th} М _{th} G _{KK} mass G _{KK} mass g _{KK} mass KK mass	8.6 TeV 8.9 TeV 8.2 TeV 9.55 TeV 4.1 TeV 2.3 TeV 3.8 TeV		1711.03301 1707.04147 1703.09217 1606.02265 1512.02586 1707.04147 CERN-EP-2018-179 1804.10823 1803.09678
Gauge bosons	$\begin{array}{l} \text{SSM } Z' \to \ell\ell \\ \text{SSM } Z' \to \tau\tau \\ \text{Leptophobic } Z' \to bb \\ \text{Leptophobic } Z' \to tt \\ \text{SSM } W' \to \ell\nu \\ \text{SSM } W' \to \tau\nu \\ \text{HVT } V' \to WV \to qqqq \text{ mode} \\ \text{HVT } V' \to WH/ZH \text{ model B} \\ \text{LRSM } W'_R \to tb \end{array}$	1 e,μ 1 τ		- - 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 W' mass W' mass V' mass V' mass W' mass	5.6 TeV 3.7 TeV 4.15 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	– – j Yes	37.0 36.1 36.1	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 DN Colored scalar mediator (Dirac $VV_{\chi\chi}$ EFT (Dirac DM)	, .,	1 - 4 j 1 - 4 j $1 J, \le 1 j$	Yes Yes Yes	36.1 36.1 3.2	m _{med} m _{med} M _*	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	– – j Yes	3.2 3.2 20.3	LQ mass LQ mass LQ mass	1.05 TeV	$\begin{aligned} \beta &= 1\\ \beta &= 1\\ \beta &= 0 \end{aligned}$	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 + X \\ VLQ \ T \rightarrow Wb + X \\ VLQ \ B \rightarrow Hb + X \\ VLQ \ QQ \rightarrow WqWq \end{array} $	1 e, µ	el	j Yes	36.1 36.1 36.1 3.2 79.8 20.3	T mass B mass T _{5/3} mass Y mass B mass Q mass	1.34 TeV 1.64 TeV 1.44 TeV	SU(2) doublet SU(2) doublet $\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3}Wt) = 1$ $\mathcal{B}(Y \rightarrow Wb) = 1, c(YWb) = 1/\sqrt{2}$ $\kappa_B = 0.5$	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	2j 1j 1b,1j –	- - - -	37.0 36.7 36.1 20.3 20.3	q* massq* massb* masst* masst* massv* mass	5.3 TeV 2.6 TeV 3.0 TeV	only u° and d° , $\Lambda = m(q^{\circ})$ only u° and d° , $\Lambda = m(q^{\circ})$ $\Lambda = 3.0 \text{ TeV}$ $\Lambda = 1.6 \text{ TeV}$	1703.09127 1709.10440 1805.09299 1411.2921 1411.2921
Other	Type III Seesaw LRSM Majorana v 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 (S 3 e, μ, τ 1 e, μ - -	- 1 b - -	Yes - Yes -	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 invisible multi-charged monopole mas	870 GeV 400 GeV e particle mass 657 GeV particle mass 785 GeV iss 1.34 TeV	$\begin{split} m(W_{\rm R}) &= 2.4 \text{ TeV, no mixing} \\ \text{DY production} \\ \text{DY production}, \ \mathcal{B}(H_L^{\pm\pm} \to \ell \tau) = 1 \\ a_{\rm non-res} &= 0.2 \\ \text{DY production}, \ q &= 5e \\ \text{DY production}, \ g &= 1g_D, \ \text{spin } 1/2 \end{split}$	ATLAS-CONF-2018-020 1506.06020 1710.09748 1411.2921 1410.5404 1504.04188 1509.08059
	-	√s = 8 TeV	√s = 13	3 TeV		10	D ⁻¹ 1 10	Mass scale [TeV]	

*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 $\, m_W, m_Z, m_t, m_h \,$

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 Now that these ADD non-resonant $\gamma\gamma$ 2γ 36.7 8.6 TeV n = 3 HLZ NLO 1707.04147 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 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 1 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 Ŋ 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 $Y \rightarrow Wb + X$ $\geq 1 \text{ b}, \geq 1 \text{ j}$ 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 ToV 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

Global Symmetries in the SM and SMEFT

- If BSM already present in measurements, simply need to make more precise measurements, or go to higher scales (or both) to unravel it. This will require ever more precise theory - EFT techniques essential.
- Effective symmetries offer further insight:

$$\begin{array}{ll} \phi_q \to e^{i \phi_q} \phi_q & \text{global U(1) of baryon number} \\ \phi_\ell \to e^{i \phi_\ell} \phi_\ell & \text{global U(1) of lepton number} \end{array}$$

• Other approx symmetries:

 $SU(2)_L \times SU(2)_R \rightarrow SU(2)_c$ custodial, preserved in simple Higgs sector broken by Yukawas and hypercharge $U(3)^5$ flavour symmetry broken only by Yukawas in the SM - "MFV"

Lepton Number

 Model independent minimal extension of the SM to accommodate neutrino mass and observed oscillations. Leading operator that can violate Lepton number of dim 5:

Charge conjugation defined as

$$\psi^c = C \overline{\psi}^T$$
 with $C = -i \gamma_2 \gamma_0$

Neutrino mass differences:

$$\delta M_{\nu} \sim 10^{-11} - 10^{-13} [\text{GeV}] \sim \frac{v^2 \delta C_{mn}}{\Lambda}$$

Sometimes people infer: $\Lambda_{\Delta L} = 10^{16} \, \text{GeV}$

Lepton Number

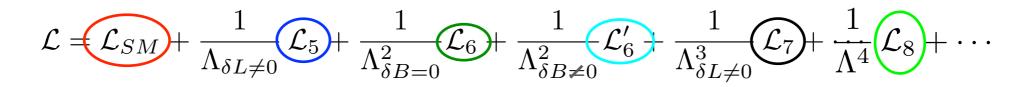
 Model independent minimal extension of the SM to accommodate neutrino mass and observed oscillations. Leading operator that can violate Lepton number of dim 5:

Number of parameters augmented to...

 $m_e, m_{\mu}, m_{\tau}, m_u, m_d, m_c, m_s, m_t, m_b$: 9 masses $\theta_{12}, \theta_{13}, \theta_{23}, \delta$: 4 quark mixing g_1, g_2, g_3 : 3 gauge couplings v, λ : 2 EW sector $s_{12}, s_{13}, s_{23}, \delta_{\nu}, m_{\nu_e}, m_{\nu_{\mu}}, m_{\nu_{\tau}}$: 7 neutrino parameters

SMEFT:development cycle

SMEFT - built of H doublet + higher D ops



Glashow 1961, Weinberg 1967 (Salam 1967)

Weinberg 1979, Wilczek and Zee 1979



Leung, Love, Rao 1984, Buchmuller Wyler 1986, Grzadkowski, Iskrzynski, Misiak, Rosiek 2010

Weinberg 1979, Abbott Wise 1980



Lehman 1410.4193, Henning et al. 1512.03433



Lehman, Martin 1510.00372, Henning et al. 1512.03433

The Lagrangian expansion theory technology is a solved problem Henning et al arXiv:1706.0852.

LO SMEFT = dim 6 shifts

Warsaw basis: 1008.4884 Grzadkowski, Iskrzynski, Misiak, Rosiek

	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}	$(arphi^\dagger arphi)^3$	$Q_{e\varphi}$	$(arphi^\dagger arphi) (ar l_p e_r arphi)$	
$Q_{\widetilde{G}}$	$f^{ABC}\widetilde{G}^{A u}_{\mu}G^{B ho}_{ u}G^{C\mu}_{ ho}$	$Q_{arphi \Box}$	$(\varphi^{\dagger}\varphi)\Box(\varphi^{\dagger}\varphi)$	Q_{uarphi}	$(arphi^\dagger arphi) (ar q_p u_r \widetilde arphi)$	
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}	$(arphi^{\dagger}arphi)(ar{q}_p d_r arphi)$	
$Q_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}^{I\nu}_{\mu}W^{J\rho}_{\nu}W^{K\mu}_{\rho}$					
	$X^2 arphi^2$	$\psi^2 X arphi$		$\psi^2 \varphi^2 D$		
$Q_{arphi G}$	$arphi^\dagger arphi G^A_{\mu u} G^{A\mu u}$	Q_{eW}	$(ar{l}_p \sigma^{\mu u} e_r) au^I arphi W^I_{\mu u}$	$Q^{(1)}_{arphi l}$	$(\varphi^{\dagger}i\overleftrightarrow{D}_{\mu}\varphi)(\bar{l}_{p}\gamma^{\mu}l_{r})$	
$Q_{arphi \widetilde{G}}$	$arphi^\dagger arphi \widetilde{G}^A_{\mu u} G^{A\mu u}$	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}	$(ar q_p \sigma^{\mu u} T^A u_r) \widetilde arphi G^A_{\mu u}$	$Q_{arphi e}$	$(arphi^\dagger i \overleftrightarrow{D}_\mu arphi) (ar{e}_p \gamma^\mu e_r)$	
$Q_{arphi \widetilde{W}}$	$arphi^\dagger arphi \widetilde{W}^I_{\mu u} W^{I\mu u}$	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}	$(ar q_p \sigma^{\mu u} u_r) \widetilde arphi B_{\mu u}$	$Q^{(3)}_{arphi q}$	$(arphi^\dagger i \overset{\leftrightarrow}{D}{}^I_\mu arphi) (ar{q}_p au^I \gamma^\mu q_r)$	
$Q_{arphi \widetilde{B}}$	$arphi^\dagger arphi \widetilde{B}_{\mu u} B^{\mu u}$	Q_{dG}	$(ar q_p \sigma^{\mu u} T^A d_r) arphi G^A_{\mu u}$	$Q_{arphi u}$	$(\varphi^{\dagger}i\overleftrightarrow{D}_{\mu}\varphi)(ar{u}_{p}\gamma^{\mu}u_{r})$	
$Q_{arphi WB}$	$arphi^\dagger au^I arphi W^I_{\mu u} B^{\mu u}$	Q_{dW}	$(ar q_p \sigma^{\mu u} d_r) au^I arphi W^I_{\mu u}$	$Q_{arphi d}$	$(arphi^\dagger i \overleftrightarrow{D}_\mu arphi) (ar{d}_p \gamma^\mu d_r)$	
$Q_{arphi \widetilde{W}B}$	$\varphi^\dagger \tau^I \varphi \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(ar q_p \sigma^{\mu u} d_r) arphi B_{\mu u}$	$Q_{arphi u d}$	$i(\widetilde{arphi}^{\dagger}D_{\mu}arphi)(ar{u}_{p}\gamma^{\mu}d_{r})$	

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

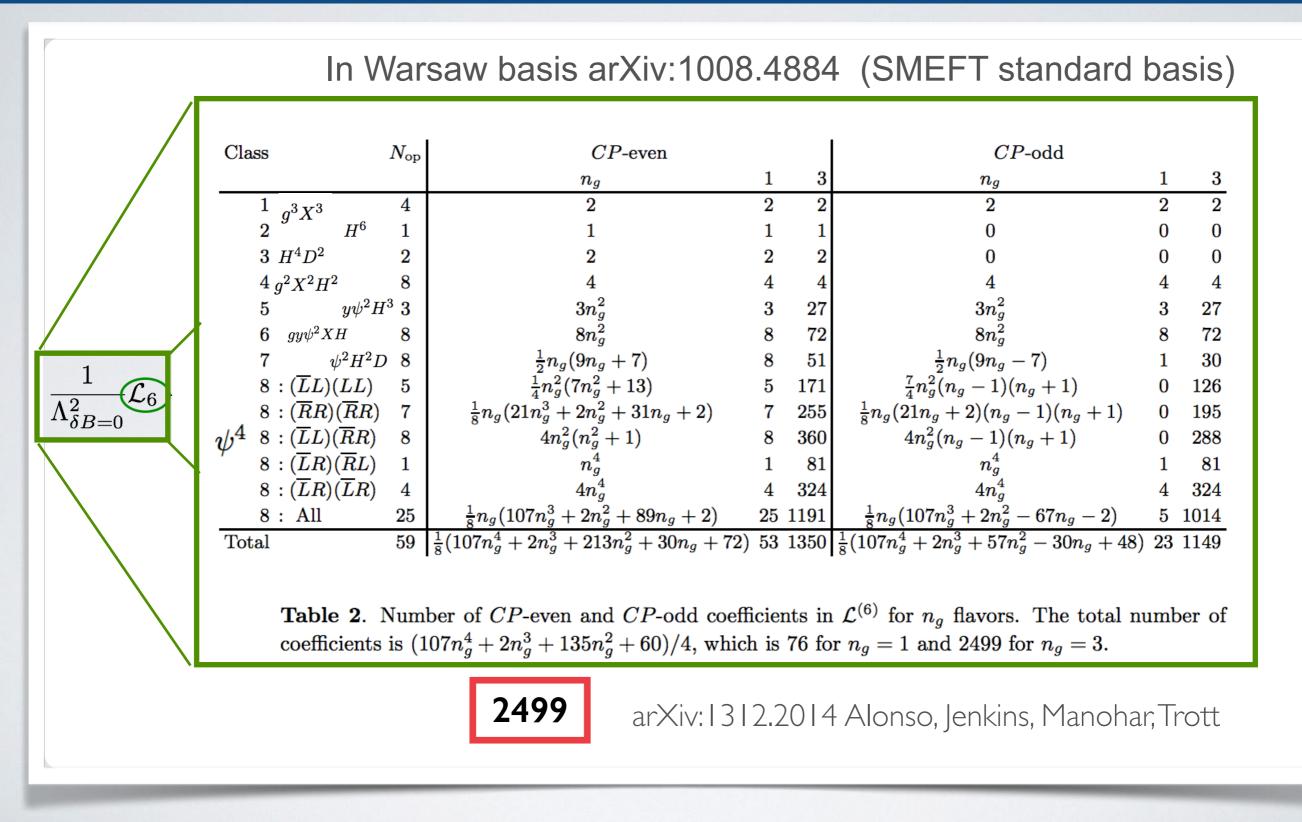
6 gauge dual ops
28 non dual
operators
25 four fermi ops
59 + h.c.
operators
NOTATION:
$\widetilde{X}_{\mu\nu} = \frac{1}{2} \varepsilon_{\mu\nu\rho\sigma} X^{\rho\sigma} \ (\varepsilon_{0123} = +1)$
$\widetilde{arphi}^{j}=arepsilon_{jk}(arphi^{k})^{\star}$ $arepsilon_{12}=+1$
$arphi^\dagger i \overleftrightarrow{D}_\mu arphi \equiv i arphi^\dagger \left(D_\mu - \overleftarrow{D}_\mu ight) arphi$

LO SMEFT = dim 6 shifts

Four fermion operators: 1008.4884 Grzadkowski, Iskrzynski, Misiak, Rosiek

	$8:(ar{L}L)(ar{L}L)$	$8:(\bar{R}R)(\bar{R}R)$				$8:(ar{L}L)(ar{R}R)$
Q_{ll}	$Q_{ll} = (ar{l}_p \gamma_\mu l_r) (ar{l}_s \gamma^\mu l_t)$		$(ar{e}_p \gamma_\mu e_r) (ar{e}_s \gamma^\mu e_t)$		Q_{le}	$(ar{l}_p\gamma_\mu l_r)(ar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{\left(1 ight)}$	$(ar{q}_p \gamma_\mu q_r) (ar{q}_s \gamma^\mu q_t)$	Q_{uu}	$(ar{u}_p \gamma_\mu u_r)$	$(ar{u}_s \gamma^\mu u_t)$	Q_{lu}	$(ar{l}_p \gamma_\mu l_r) (ar{u}_s \gamma^\mu u_t)$
$Q_{qq}^{\left(3 ight)}$	$(ar{q}_p \gamma_\mu au^I q_r) (ar{q}_s \gamma^\mu au^I q_t)$	Q_{dd}	$(ar{d}_p \gamma_\mu d_r) (ar{d}_s \gamma^\mu d_t)$		Q_{ld}	$(ar{l}_p\gamma_\mu l_r)(ar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{\left(1 ight) }$	$(ar{l}_p\gamma_\mu l_r)(ar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(ar{e}_p \gamma_\mu e_r)$	$(ar{u}_s \gamma^\mu u_t)$	Q_{qe}	$(ar q_p \gamma_\mu q_r) (ar e_s \gamma^\mu e_t)$
$Q_{lq}^{\left(3 ight) }$	$(ar{l}_p \gamma_\mu au^I l_r) (ar{q}_s \gamma^\mu au^I q_t)$	Q_{ed}	$(ar{e}_p \gamma_\mu e_r)$	$(ar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{\left(1 ight)}$	$(ar q_p \gamma_\mu q_r) (ar u_s \gamma^\mu u_t)$
		$Q_{ud}^{\left(1 ight) }$	$(\bar{u}_p \gamma_\mu u_r)$	$(ar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{\left(8 ight)}$	$(ar q_p \gamma_\mu T^A q_r) (ar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{\left(8 ight)}$	$(ar{u}_p \gamma_\mu T^A u_r) (ar{d}_s \gamma^\mu T^A d_t)$		$Q_{qd}^{\left(1 ight)}$	$(ar q_p \gamma_\mu q_r) (ar d_s \gamma^\mu d_t)$
					$Q_{qd}^{\left(8 ight)}$	$(ar{q}_p \gamma_\mu T^A q_r) (ar{d}_s \gamma^\mu T^A d_t)$
	$8:(\bar{L}R)(\bar{R})$	L) + h.c	. 8	$(\bar{L}R)(\bar{L}R) +$	h.c.	
	Q_{ledq} $(ar{l}_p^j e$	$(\bar{d}_s q_{tj})$	$Q_{quqd}^{(1)}$	$(ar{q}_p^j u_r) \epsilon_{jk} (ar{q}_s^k d_t)$		
			$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r) \epsilon_{jk} (\bar{q}_s^k T^A d_t)$		t)
			$Q_{lequ}^{\left(1 ight)}$	$(ar{l}_p^j e_r) \epsilon_{jk}$	$(ar{q}_s^k u_t)$	
			$Q_{lequ}^{\left(3 ight) }$	$(ar{l}^j_p\sigma_{\mu u}e_r)\epsilon_{jk}$	$(ar{q}_s^k \sigma^{\mu u} u$	$_{t})$

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



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

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

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

Baryon Number

 In the SMEFT one can have dimension 6 decay of the proton through the operators

$$\begin{split} Q_{prst}^{duq\ell} &= \epsilon_{\alpha\beta\gamma}\epsilon_{ij}(d_p^{\alpha}Cu_r^{\beta})(q_s^{i\gamma}C\ell_t^j)\,,\\ Q_{prst}^{qque} &= \epsilon_{\alpha\beta\gamma}\epsilon_{ij}(q_p^{i\alpha}Cq_r^{j\beta})(u_s^{\gamma}Ce_t)\,,\\ Q_{prst}^{qqq\ell} &= \epsilon_{\alpha\beta\gamma}\epsilon_{il}\epsilon_{jk}(q_p^{i\alpha}Cq_r^{j\beta})(q_s^{k\gamma}C\ell_t^l)\,,\\ Q_{prst}^{duue} &= \epsilon_{\alpha\beta\gamma}(d_p^{\alpha}Cu_r^{\beta})(u_s^{\gamma}Ce_t)\,, \end{split}$$

Although an anomalous symmetry, the RGE of these operators respects Baryon number, so the single insertion of B violating operators only mix among themselves.

1405.0486 Alonso, Chiang, Jenkins, Manohar, Shotwell L. Abbott and M. B. Wise, Phys.Rev. D22, 2208 (1980)

Decays go as : $\Gamma_p \approx c^2 \frac{m_p^5}{\Lambda^4}$ exp limit: $\geq 8.2 \times 10^{33}$ yrs leads to: $\Lambda \gtrsim 10^{16} \,\mathrm{GeV}$

SMEFT requires a GLOBAL approach

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \mathcal{L}^{(7)} + ..., \qquad \mathcal{L}^{(d)} = \sum_{i=1}^{n_d} \frac{C_i^{(d)}}{\Lambda^{d-4}} Q_i^{(d)} \quad \text{for } d > 4,$$

• The operators are defined in a BASIS, fixed by SM field redefinitions.

$$\begin{aligned} \mathcal{L}_{B'} &= -\frac{1}{4} B'_{\mu\nu} B^{'\mu\nu} - g_1 \, \mathsf{y}_{\psi} \, \overline{\psi} \, B' \, \psi + (D^{\mu}H)^{\dagger} (D_{\mu}H) + \mathcal{C}_B (H^{\dagger} \overleftrightarrow{D}^{\mu}H) (D^{\nu}B_{\mu\nu}), \\ &+ \mathcal{C}_{BH} (D^{\mu}H)^{\dagger} \, (D^{\nu}H) \, B'_{\mu\nu} + C^{(1)}_{Hl} Q^{(1)}_{Hl} + C_{He} \, Q_{He} + C^{(1)}_{Hq} Q^{(1)}_{Hq} + C_{Hu} \, Q_{Hu}, \\ &+ C_{Hd} \, Q_{Hd} + C_{HB} \, Q_{HB} + C_T \, (H^{\dagger} \overleftrightarrow{D}^{\mu}H) \, (H^{\dagger} \overleftrightarrow{D}^{\mu}H). \end{aligned}$$

Over complete set of ops depending on B^{μ}

1706.08945 I. Brivio, MT

Perform a field redefinition

$$B'_{\mu}
ightarrow B_{\mu} + b_2 rac{H^{\dagger} i \overleftrightarrow{D}_{\mu} H}{\Lambda^2}$$

then

$$\mathcal{L}_B{'}-g_1\,b_2\Delta B$$

The physics is not changed by this choice of path integral variable.

SMEFT requires a GLOBAL approach

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \mathcal{L}^{(7)} + ..., \qquad \mathcal{L}^{(d)} = \sum_{i=1}^{n_d} \frac{C_i^{(d)}}{\Lambda^{d-4}} Q_i^{(d)} \quad \text{for } d > 4,$$

• CHOOSE
$$b_2 = C_B$$
 THEN

$$\begin{split} \mathcal{L}_{B'} &= -\frac{1}{4} B'_{\mu\nu} B'^{\mu\nu} - g_1 \, \mathsf{y}_{\psi} \, \overline{\psi} \, B' \, \psi + (D^{\mu} H)^{\dagger} (D_{\mu} H) + \mathcal{C}_B (H^{\dagger} \overrightarrow{D^{\mu}} H) (D^{\nu} B_{\mu\nu}), \\ &+ \mathcal{C}_{BH} (D^{\mu} H)^{\dagger} \, (D^{\nu} H) \, B'_{\mu\nu} + C^{(1)}_{Hl} Q^{(1)}_{Hl} + C_{He} \, Q_{He} + C^{(1)}_{Hq} Q^{(1)}_{Hq} + C_{Hu} \, Q_{Hu}, \\ &+ C_{Hd} \, Q_{Hd} + C_{HB} \, Q_{HB} + C_T \, (H^{\dagger} \, \overrightarrow{D^{\mu}} H) \, (H^{\dagger} \, \overrightarrow{D^{\mu}} H). \end{split}$$

Non-redundant set of ops depending on B^{μ}

16a

1706.08945 I. Brivio, MT

BUT terms that remain SHIFTED

 $\mathcal{L}_B - g_1 \, b_2 \Delta B$

$$\Delta B = \mathsf{y}_l Q_{Hl}^{(1)} + \mathsf{y}_e Q_{He} + \mathsf{y}_q Q_{Hq}^{(1)} + \mathsf{y}_u Q_{Hu} + \mathsf{y}_d Q_{Hd}, \quad + \mathsf{y}_H (Q_{H\Box} + 4 Q_{HD}) + \frac{1}{g_1} B^{\mu\nu} \partial_\mu (H^{\dagger} i \overleftrightarrow{D}_{\nu} H).$$

EWPD, diboson, Higgs data all modified globally

$$\begin{aligned} & \mathcal{Z}, \mathsf{W} \text{ couplings} \\ & \mathcal{Q}_{Hl}^{(1)} = (iH^{\dagger} \overrightarrow{D}_{\mu} H)(\overline{l}\gamma^{\mu} l) \\ & \mathcal{Q}_{He} = (iH^{\dagger} \overrightarrow{D}_{\mu} H)(\overline{e}\gamma^{\mu} e) \\ & \mathcal{Q}_{Hq}^{(1)} = (iH^{\dagger} \overrightarrow{D}_{\mu} H)(\overline{e}\gamma^{\mu} q) \\ & \mathcal{Q}_{Hq}^{(3)} = (iH^{\dagger} \overrightarrow{D}_{\mu} H)(\overline{q}\gamma^{\mu} q) \\ & \mathcal{Q}_{Hq}^{(3)} = (iH^{\dagger} \overrightarrow{D}_{\mu} H)(\overline{q}\gamma^{\mu} q) \\ & \mathcal{Q}_{Hu} = (iH^{\dagger} \overrightarrow{D}_{\mu} H)(\overline{q}\gamma^{\mu} q) \\ & \mathcal{Q}_{Hd} = (iH^{\dagger} \overrightarrow{D}_{\mu} H)(\overline{d}\gamma^{\mu} d) \end{aligned} \\ \end{aligned}$$

$$\begin{aligned} & \mathsf{Top data} \\ & \mathcal{Q}_{qq}^{(1)} = (\overline{q}_{p}\gamma^{\mu}q_{r})(\overline{q}_{s}\gamma_{\mu}q_{l}), \\ & \mathcal{Q}_{qq}^{(3)} = (\overline{q}_{p}\gamma^{\mu})(\overline{q}_{s}\gamma^{\mu}q_{l}), \\ & \mathcal{Q}_{prst}^{(3)} = (\overline{q}_{p}\gamma^{\mu}\tau^{\mu})(\overline{q}_{s}\gamma_{\mu}u_{l}), \\ & \mathcal{Q}_{prst}^{(1)} = (\overline{u}_{p}\gamma^{\mu}u_{r})(\overline{d}_{s}\gamma_{\mu}d_{l}), \\ & \mathcal{Q}_{ud}^{(1)} = (\overline{u}_{p}\gamma^{\mu}u_{r})(\overline{d}_{s}\gamma_{\mu}d_{l}), \\ & \mathcal{Q}_{ud}^{(3)} = (\overline{u}_{p}\gamma^{\mu}T^{A}u_{r})(\overline{d}_{s}\gamma_{\mu}T^{A}d_{l}), \end{aligned} \\ \end{aligned}$$

Field redefinitions are WHY a global SMEFT is needed

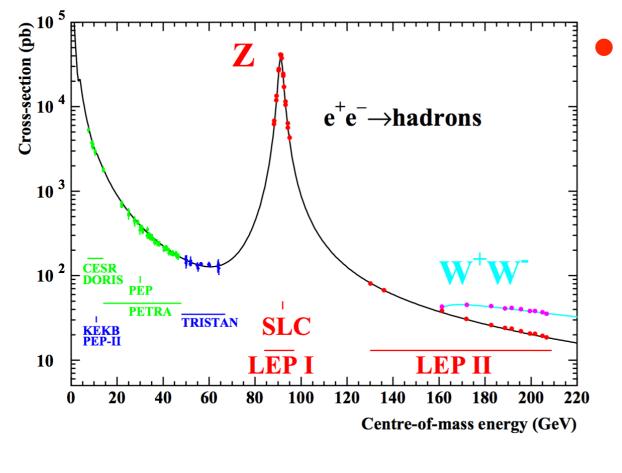
$$\begin{aligned} \mathcal{Q}_{HD} &= (D_{\mu}H^{\dagger}H)(H^{\dagger}D^{\mu}H) \\ \mathcal{Q}_{HWB} &= (H^{\dagger}\sigma^{i}H)W_{\mu\nu}^{i}B^{\mu\nu} \\ \mathcal{Q}_{HI}^{(3)} &= (iH^{\dagger}\overrightarrow{D}_{\mu}^{i}H)(\overline{l}\sigma^{i}\gamma^{\mu}l) \\ \mathcal{Q}_{HI}^{(3)} &= (iH^{\dagger}\overrightarrow{D}_{\mu}^{i}H)(\overline{l}\sigma^{i}\gamma^{\mu}l) \\ \mathcal{Q}_{HI}^{(3)} &= (\overline{l}_{i}\gamma^{\mu}l_{r})(\overline{l}_{r}\gamma^{\mu}l_{p}) \\ \vdots &\vdots &\vdots \\ \mathbf{\hat{U}}_{isb}^{(3)} &= (\overline{l}_{i}\tau^{I}\gamma^{\mu}\ell_{i})(\overline{s}\tau_{I}\gamma_{\mu}b). \end{aligned}$$

$$\begin{aligned} \mathcal{Q}_{Hbox} &= (H^{\dagger}H) \square (H^{\dagger}H) \\ \mathcal{Q}_{HG} &= (H^{\dagger}H)B_{\mu\nu}B^{\mu\nu} \\ \mathcal{Q}_{HW} &= (H^{\dagger}H)W_{\mu\nu}^{i}W^{i\mu\nu} \\ \mathcal{Q}_{HW} &= (H^{\dagger}H)(\overline{q}Hu) \\ \mathcal{Q}_{dH} &= (H^{\dagger}H)(\overline{q}Hd) \\ \mathcal{Q}_{eH} &= (H^{\dagger}H)(\overline{q}e) \\ \mathcal{Q}_{G} &= \varepsilon_{abc}G_{\mu}^{a\nu}G_{\nu}^{b\rho}G_{\rho}^{c\mu} \\ \mathcal{Q}_{uG} &= (\overline{q}\sigma^{\mu\nu}T^{a}\widetilde{H}u)G_{\mu\nu}^{a} \end{aligned}$$

$$\begin{aligned} \mathbf{W}e \text{ are looking for few \% to 10's\% effects in SMEFT.} \end{aligned}$$

How do we know the SM EW sector Lagrangian parameters?

LEP EWPD measurements



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: $(m_{Z}^{2}, \Gamma_{Z}, R_{\ell}^{0}, \sigma_{had}^{0})$

Muon decay

- Decay of $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$ measured far below the W pole.
- Probes the effective lagrangian $\hat{v}_T =$

$$\hat{y}_T = \frac{1}{2^{1/4}\sqrt{\hat{G}_F}},$$

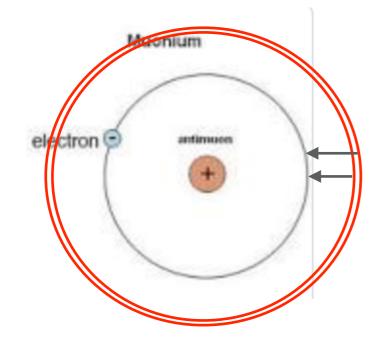
$$\mathcal{L}_{G_f} = \frac{-4G_F}{\sqrt{2}} \left(\bar{\nu}_{\mu} \gamma^{\mu} P_L \mu \right) \left(\bar{e} \gamma_{\mu} P_L \nu_e \right)$$

Through the total decay width $\Gamma = \frac{G_F^2 m_{\mu}^5}{192\pi^3}$

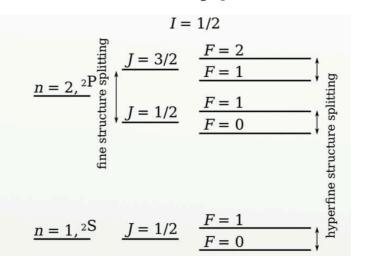
Need the mass of the muon to determine G_F

Muon mass/Electron mass

Muon electron mass ratio can be measured in muonium



Spin-orbit interaction perturbs Hamiltonian leeds to Zeeman hyperfine splitting

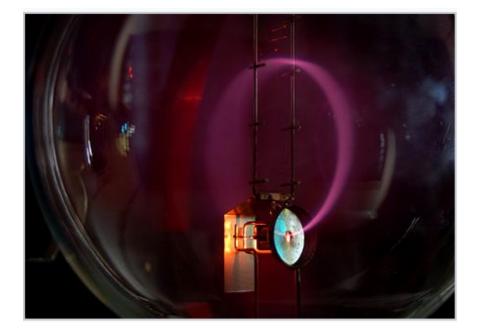


Allows an extraction of ratio m_{μ}/m_{e}

Then we need to know the electron mass! How to we get it?

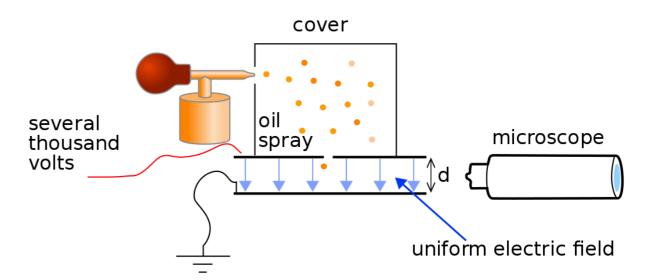
Electron mass/charge

Motion of electron in a magnetic field gives mass/charge ratio

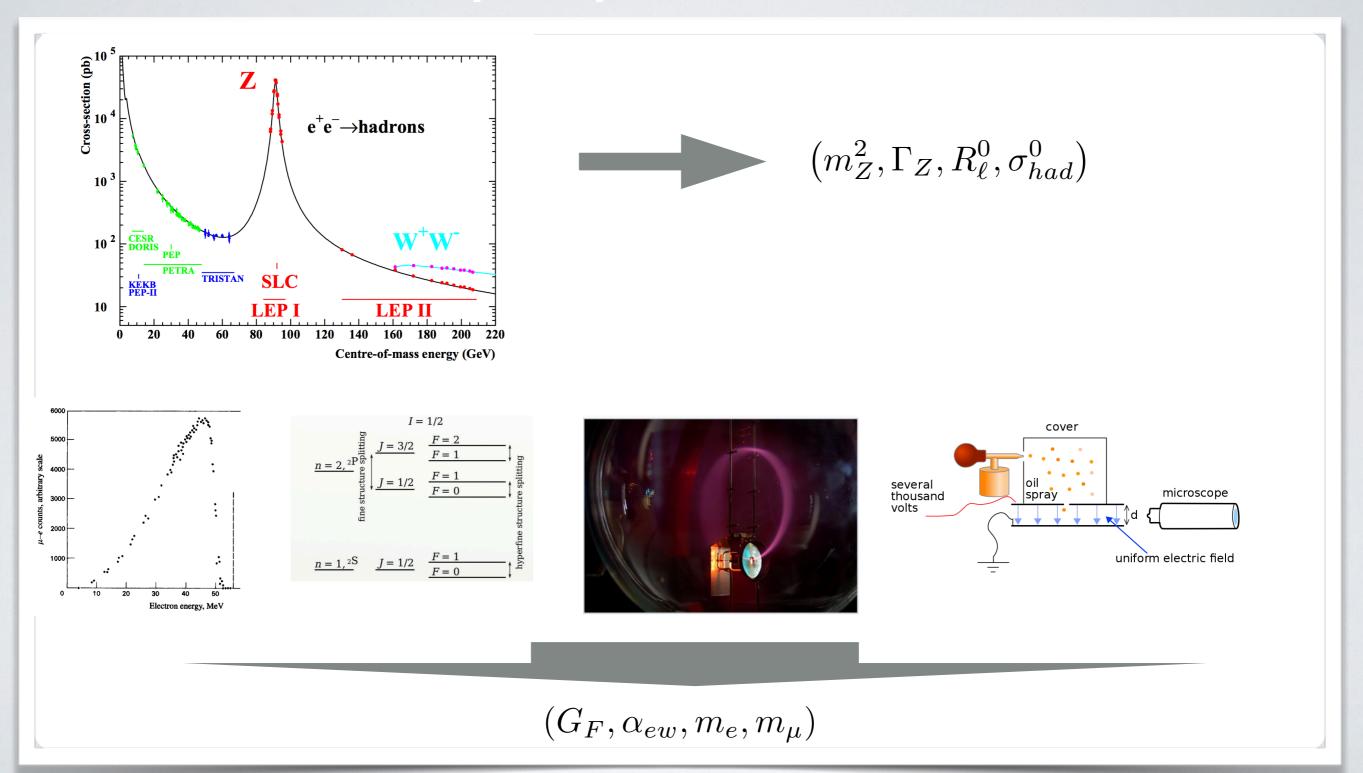


Oil drop experiment can be used to extract the charge of the electron.

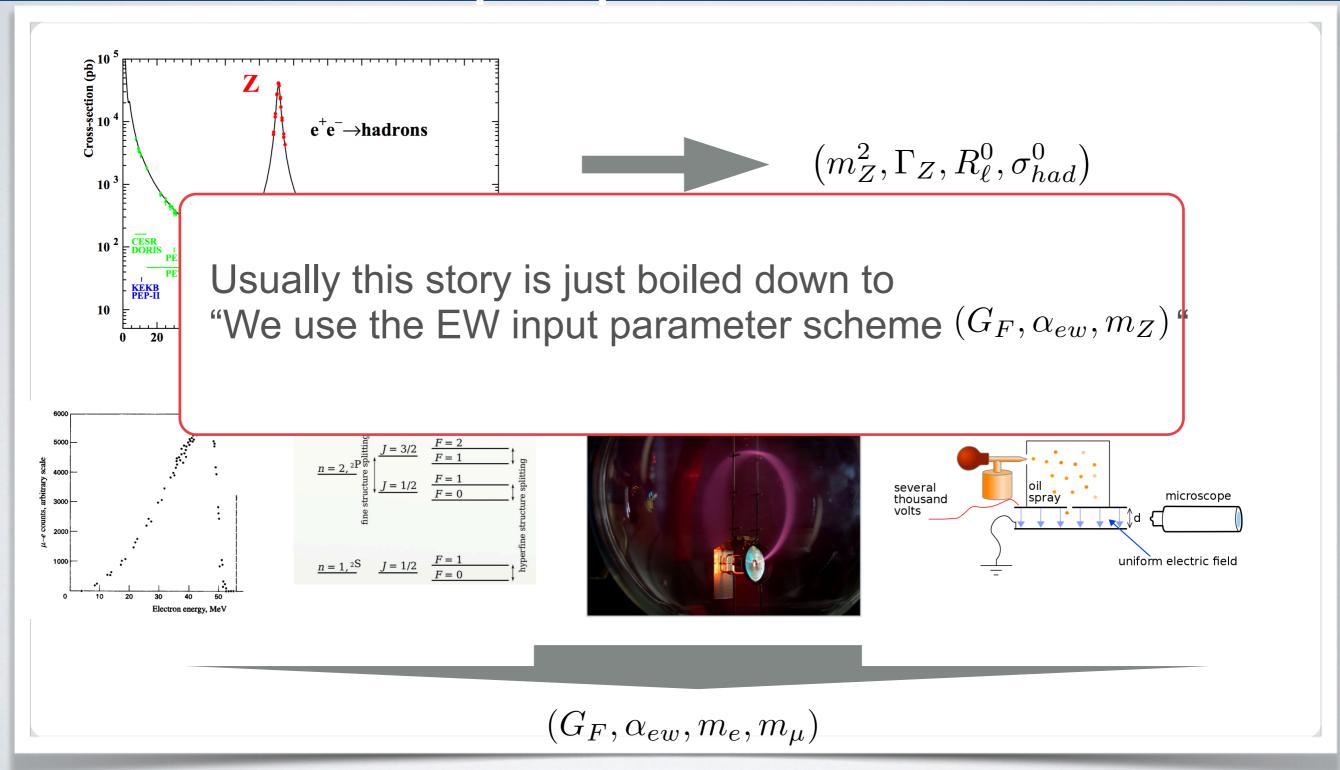
$$egin{aligned} \mathbf{F} &= Q(\mathbf{E} + \mathbf{v} imes \mathbf{B}), \ \mathbf{F} &= m \mathbf{a} = m rac{\mathrm{d} \mathbf{v}}{\mathrm{d} t} \ &\left(rac{m}{Q}
ight) \mathbf{a} = \mathbf{E} + \mathbf{v} imes \mathbf{B}. \end{aligned}$$



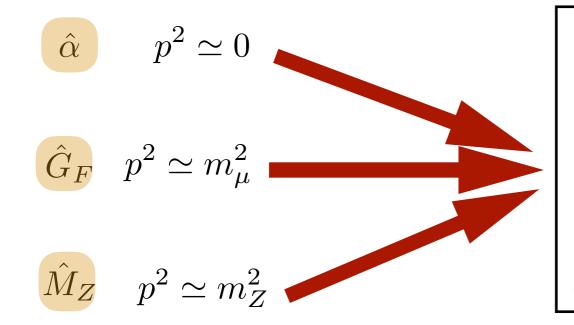
How do we know the SM EW sector input parameters?



How do we know the SM EW sector input parameters?

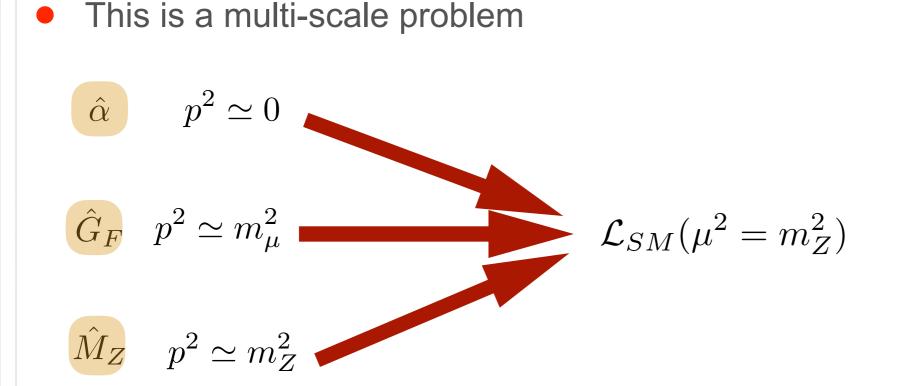


This is a multi-scale problem



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

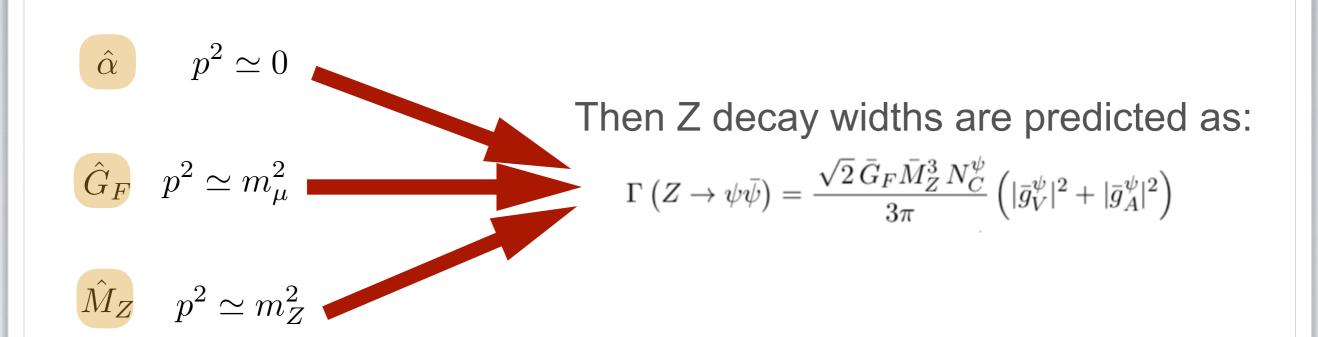
	Observable	Experimental Value	Ref.	SM Theoretical Value	Ref.
	$\hat{m}_Z[\text{GeV}]$	91.1875 ± 0.0021	[19]	-	-
	$M_W[{ m GeV}]$	80.385 ± 0.015	[49]	80.365 ± 0.004	[50]
	$\Gamma_Z[\text{GeV}]$	2.4952 ± 0.0023	[19]	2.4942 ± 0.0005	[48]
Compare to	R^0_ℓ	20.767 ± 0.025	[19]	20.751 ± 0.005	[48]
	R_c^0	0.1721 ± 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]



Compare

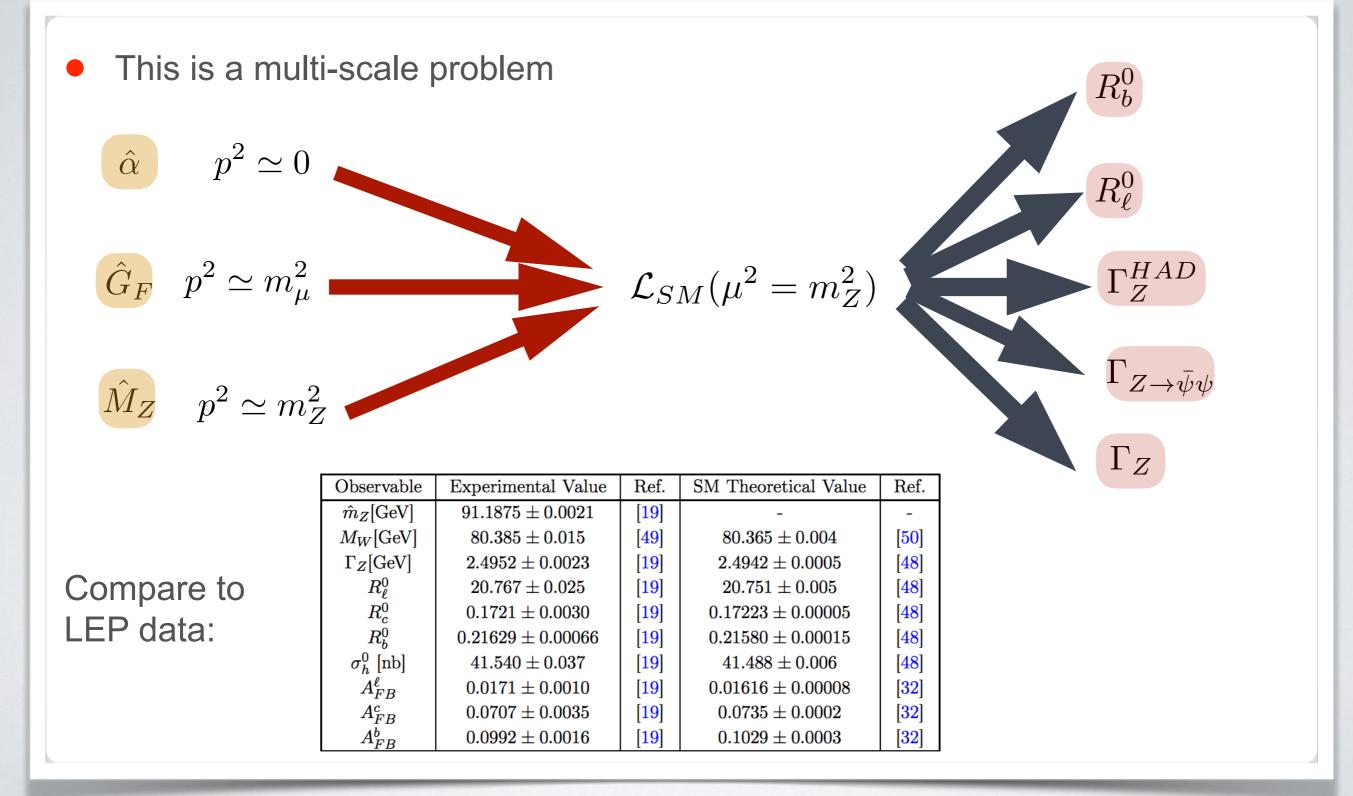
LEP data

	Observable	Experimental Value	Ref.	SM Theoretical Value	Ref.
	\hat{m}_Z [GeV]	91.1875 ± 0.0021	[19]	-	-
	$M_W[\text{GeV}]$	80.385 ± 0.015	[49]	80.365 ± 0.004	[50]
	$\Gamma_Z[\text{GeV}]$	2.4952 ± 0.0023	[19]	2.4942 ± 0.0005	[48]
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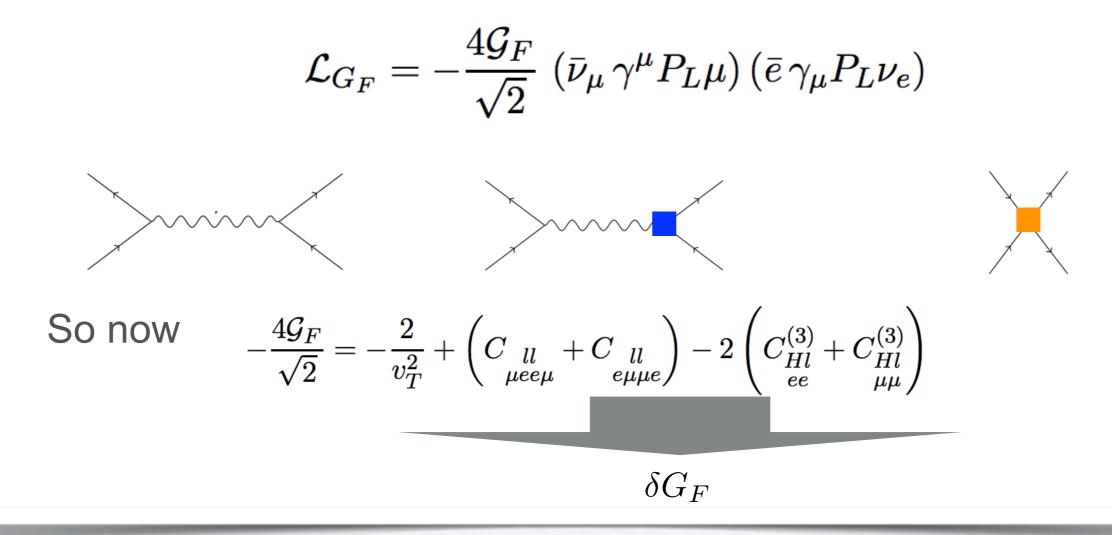
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This is a multi-scale problem



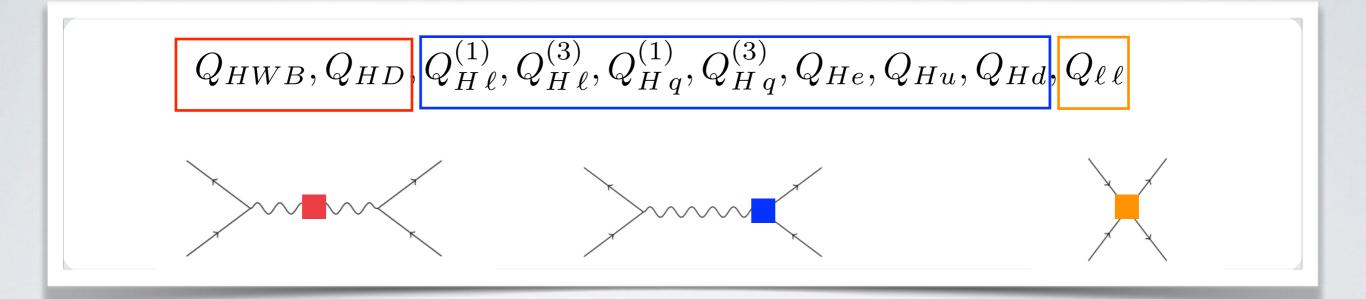
SMEFT Muon decay

- Decay of $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$ still measured far below the W pole.
- Still probes the effective lagrangian



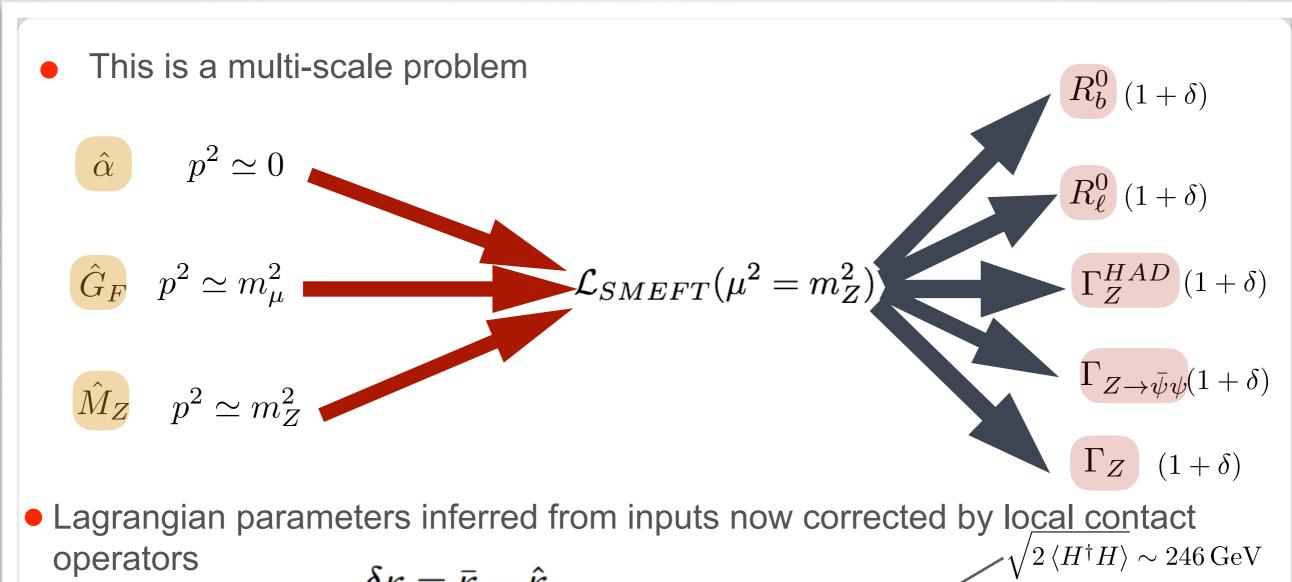
SMEFT EWPD

• 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 $\Gamma_{W,Z}/M_{W,Z} \ll 1$

Leading order (LO) SMEFT analysis

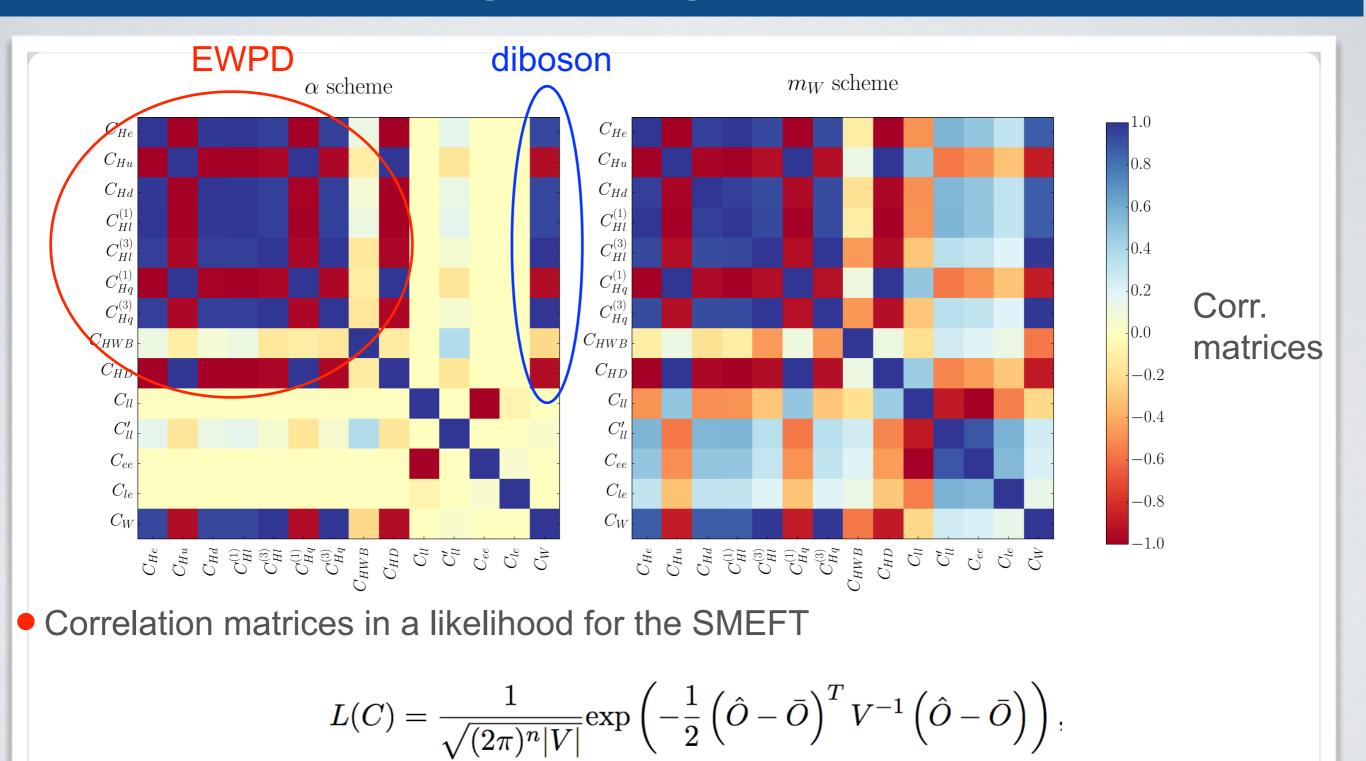


ex:

$$\begin{aligned} \delta \kappa &= \kappa - \kappa \\ \delta g_1 &= \bar{g}_1 - \hat{g}_1 = \frac{\hat{g}_1}{2c_{2\hat{\theta}}} \left[s_{\hat{\theta}}^2 \left(\sqrt{2}\delta G_F + \frac{\delta m_Z^2}{\hat{m}_Z^2} \right) + c_{\hat{\theta}}^2 s_{2\hat{\theta}} \bar{v}_T^2 C_{HWB} \right] \\ \delta s_{\theta}^2 &= s_{\bar{\theta}}^2 - s_{\hat{\theta}}^2 = 2c_{\hat{\theta}}^2 s_{\hat{\theta}}^2 \left(\frac{\delta g_1}{\hat{g}_1} - \frac{\delta g_2}{\hat{g}_2} \right) + \bar{v}_T^2 \frac{s_{2\hat{\theta}} c_{2\hat{\theta}}}{2} C_{HWB}. \end{aligned}$$

The corrections depend on the scheme choice

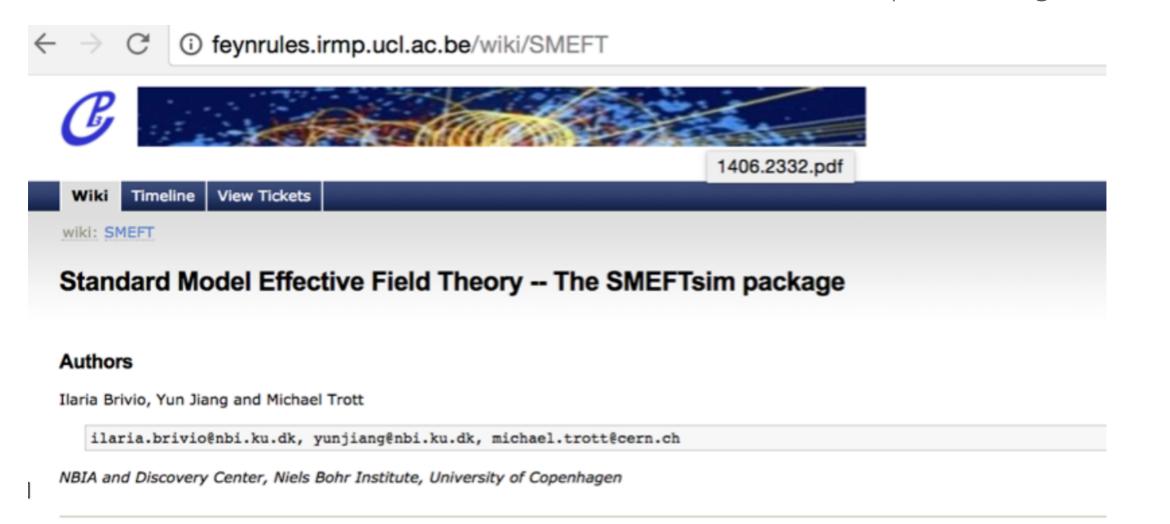
What emerges as global constraints?



Automation of this approach

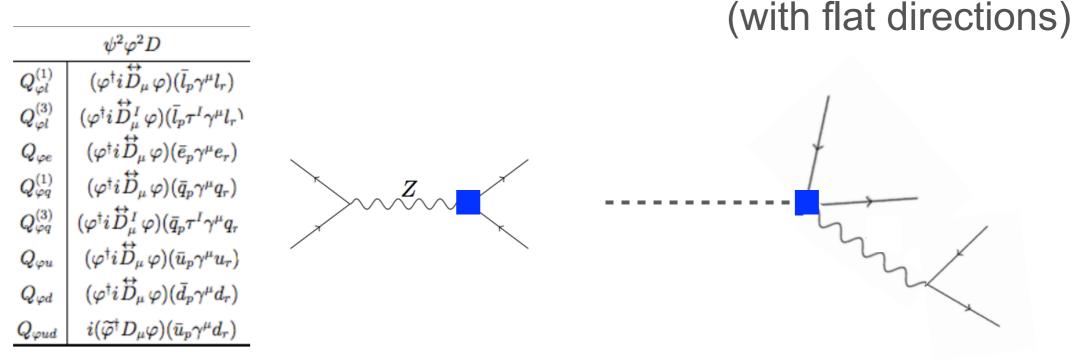
- Need to keep all operators and carefully compute S matrix elements avoiding uncontrolled approximations (and human error)
- Automation of leading order SMEFT in the SMEFTsim package now

https://arxiv.org/abs/1709.06492



Should Higgs data matter? - YES!

Higgs data has new parameters but many are also in EWPD



Higgs data adds new operators

$$\begin{aligned} \mathcal{L} &= \frac{1}{4} (\overline{g}_2{}^2 + \overline{g}_1{}^2) v_T h(\mathcal{Z}_{\mu})^2 \left[1 + c_{H,\text{kin}} + v_T^2 C_{HD} \right] + \frac{1}{2} \overline{g}_1 \overline{g}_2 v_T^3 h(\mathcal{Z}_{\mu})^2 C_{HWB} \\ &+ v_T h(\mathcal{Z}_{\mu\nu})^2 \left(\frac{\overline{g}_2{}^2 C_{HW} + \overline{g}_1{}^2 C_{HB} + \overline{g}_1 \overline{g}_2 C_{HWB}}{\overline{g}_2{}^2 + \overline{g}_1{}^2} \right) \\ &c_{H,\text{kin}} \equiv \left(C_{H\Box} - \frac{1}{4} C_{HD} \right) v^2, \end{aligned}$$

Global fit – observables [preliminary]

126 observables included so far

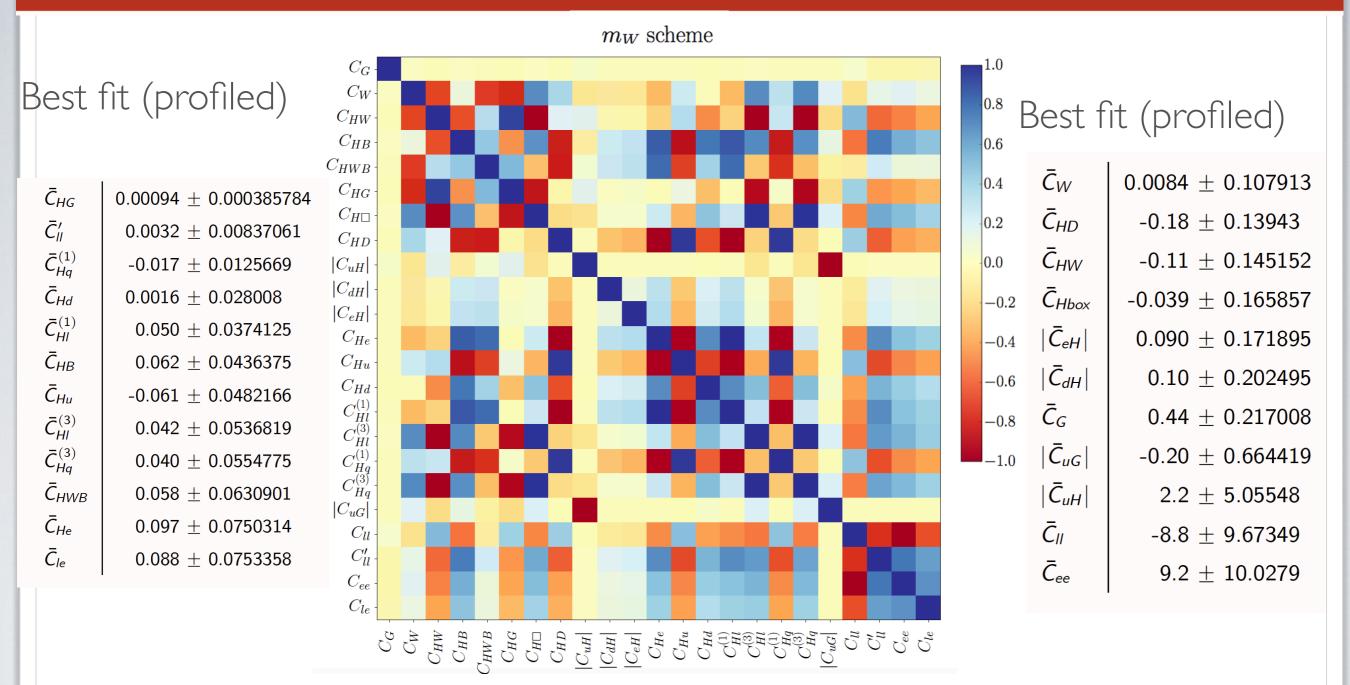
- ► 10 near-Z-pole EWPO: Γ_Z , $R^0_{\ell,c,b}$, $A^{\ell,c,b,\mu,\tau}_{FB}$, σ^0_h LEPI combination hep-ex/0509008
- 21 distribution bins for bhabha scattering at LEPII LEPII combination 1302.3415
- ► 74 dist. bins for W⁺W⁻ production at LEPII OPAL: 0708.1311 ALEPH: Eur.Phys.J. C38 (2004) 147 differential combined: 1302.3415
- ▶ 21 STXS for Higgs measurements in $H \rightarrow \gamma \gamma$ and $H \rightarrow 4\ell$ at LHC
 - ► ATLAS (36 fb⁻¹) ATLAS-CONF-2017-047
 - ► CMS (36 fb⁻¹) CMS PAS HIG-17-031

Ilaria Brivio

Provided by I. Brivio

Global fit – correlations [preliminary]

Provided by I. Brivio



Ongoing fit being developed by : I. Brivio, C. Hays, G. Zemaityte, MT see also Ellis, Murphy, Sanz, You 1803.03252 23 parameters simultaneously constrained, ~ pole parameter set