The Standard Model Effective Field Theory

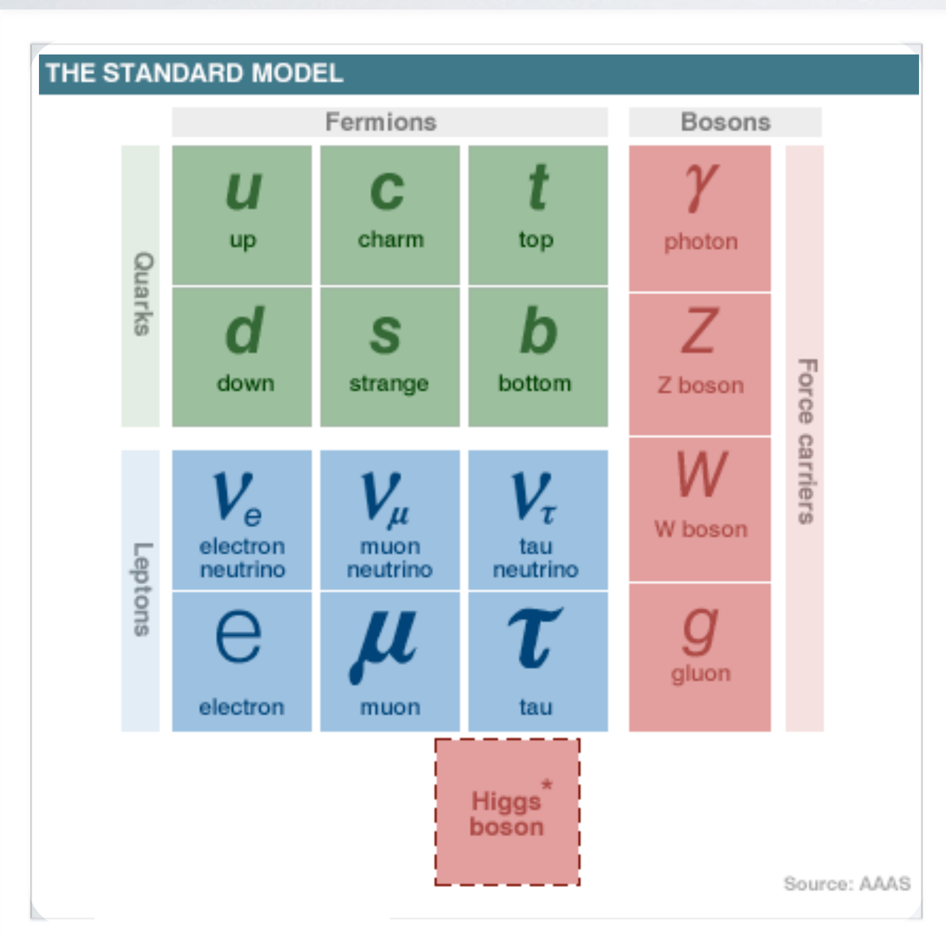
#SMEFT

M. Trott, 2019

The Standard model ...

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

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



- 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

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

$$q \to U_q q, \qquad l \to U_l l, \qquad u \to U_u u, \qquad d \to U_d d, \qquad e \to U_e e.$$

here $S_Q = \mathrm{SU(3)_{Q_L}} \otimes \mathrm{SU(3)_{U_R}} \otimes \mathrm{SU(3)_{D_R}}$ $\qquad S_L = \mathrm{SU(3)_{L_L}} \otimes \mathrm{SU(3)_{E_R}}$

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

$$\mathcal{L}_{SM} = \mathcal{L}_{SM}^{G_F} + \left[H^{\dagger j} \overline{d} \cancelto{0}{Y_d} q_j + \widetilde{H}^{\dagger j} \overline{u} \cancelto{0}{Y_u} q_j + H^{\dagger j} \overline{e} \cancelto{0}{Y_e} l_j + \mathrm{h.c.} \right]$$

Technically you can think of the Yukawas as symmetry breaking spurions

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

Flavour Symmetry

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

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

- 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.

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

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

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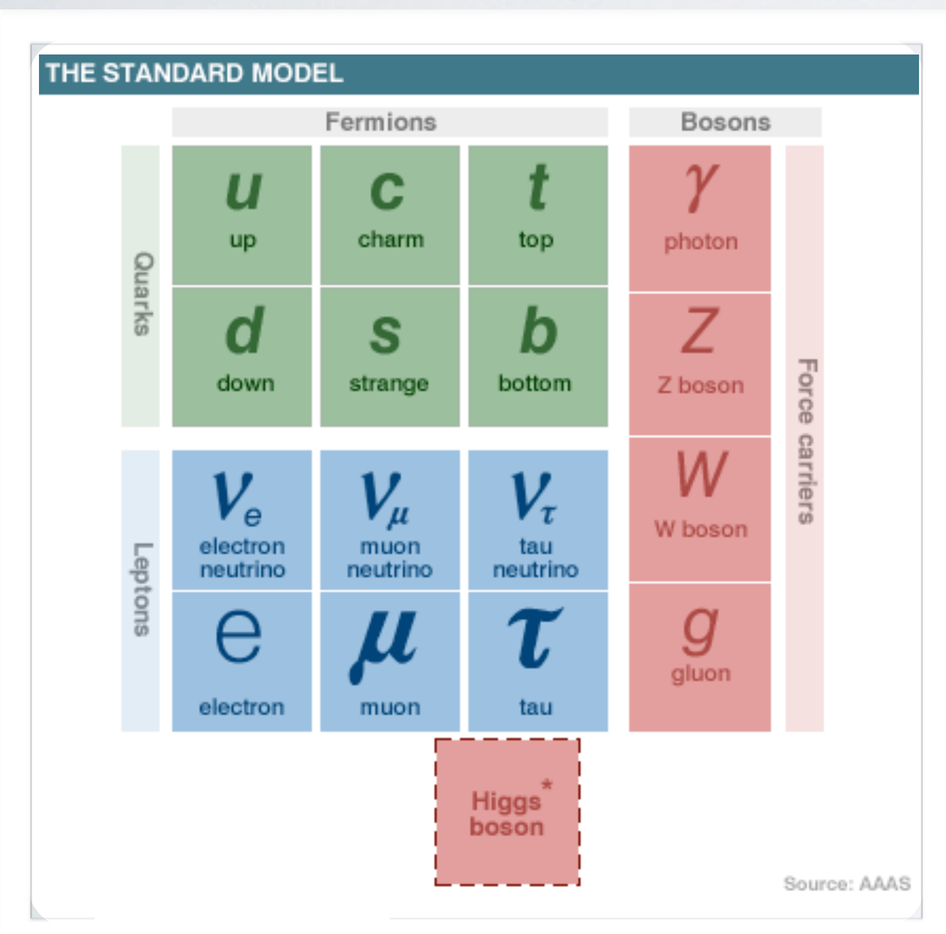

- We can count the number of parameters present in the theory.

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

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

N^2 real parameters in NxN

$2N-1$ relative phases

$(N-1)^2$ physical parameters

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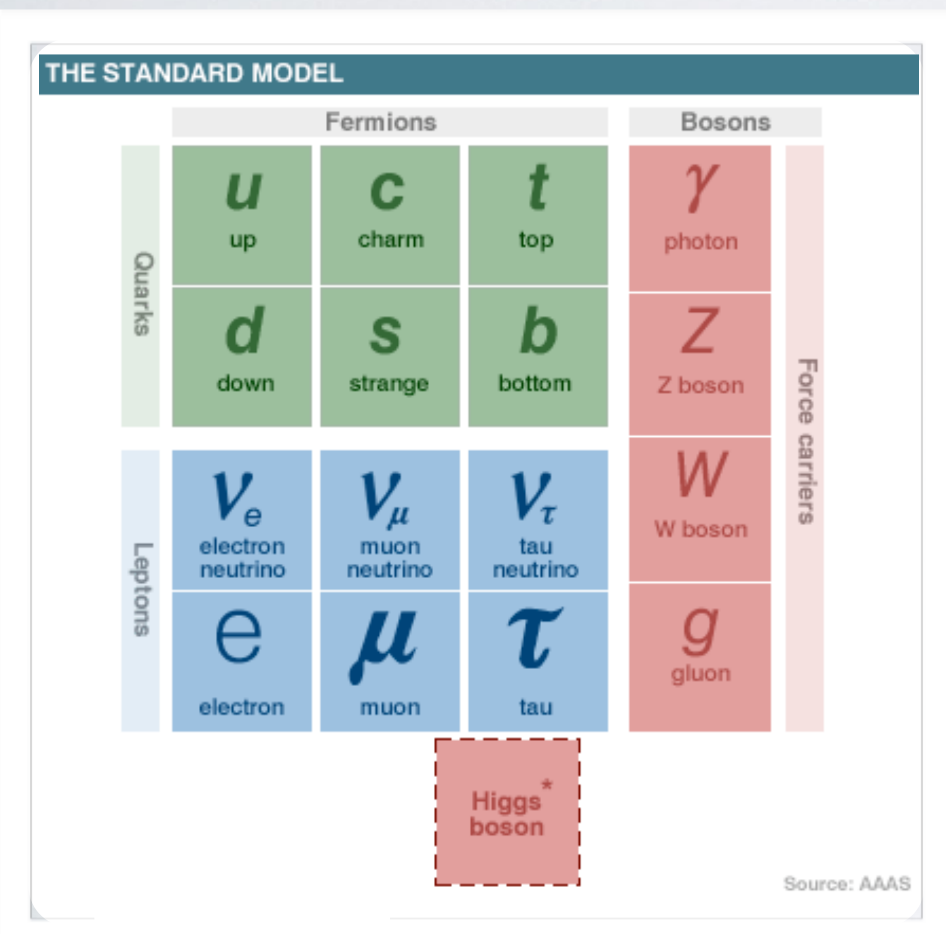


- We can count the number of parameters present in the theory.

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

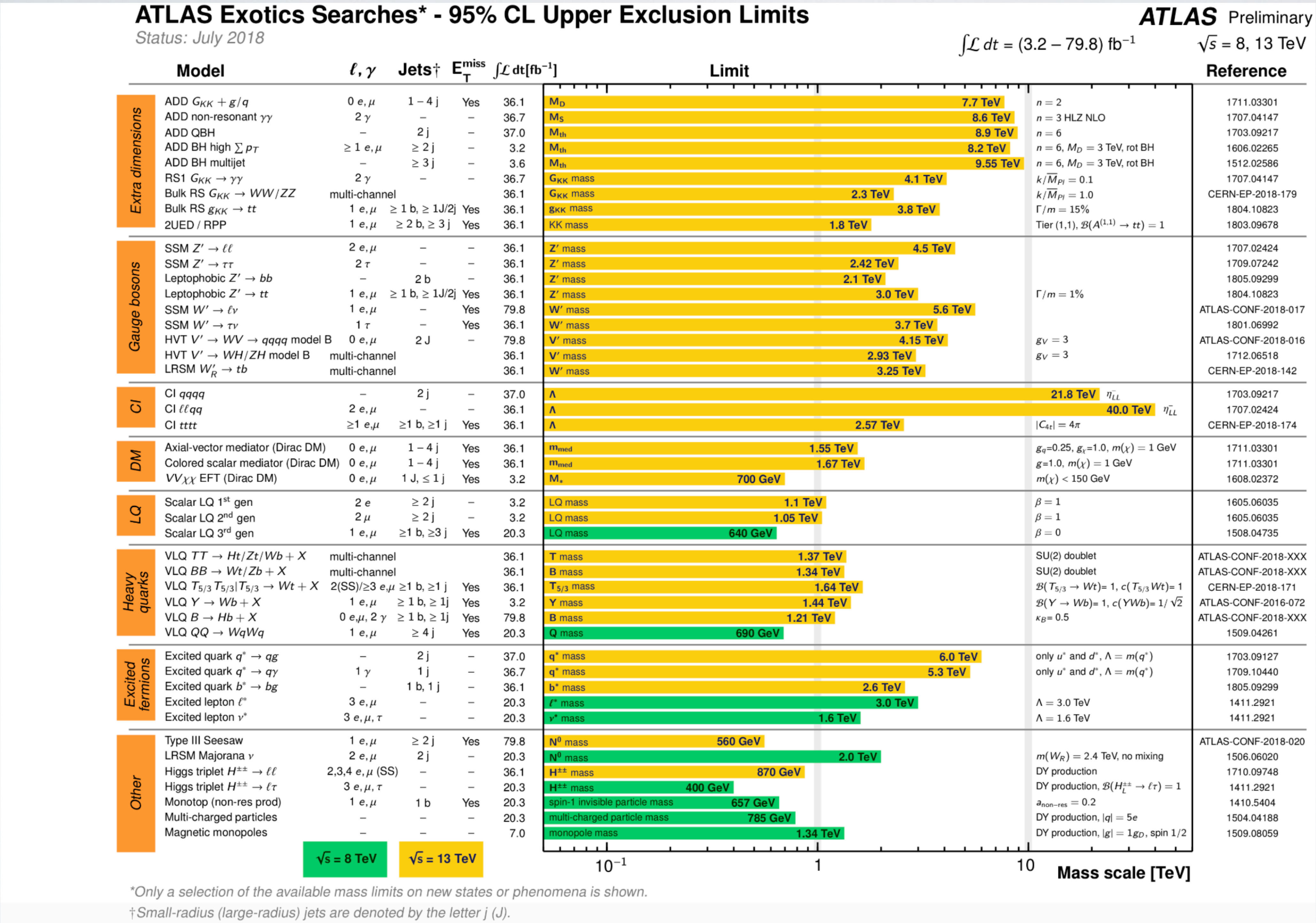
$\theta_{12}, \theta_{13}, \theta_{23}, \delta$: 4 quark mixing

$g_1,\ g_2,\ g_3$: 3 gauge couplings

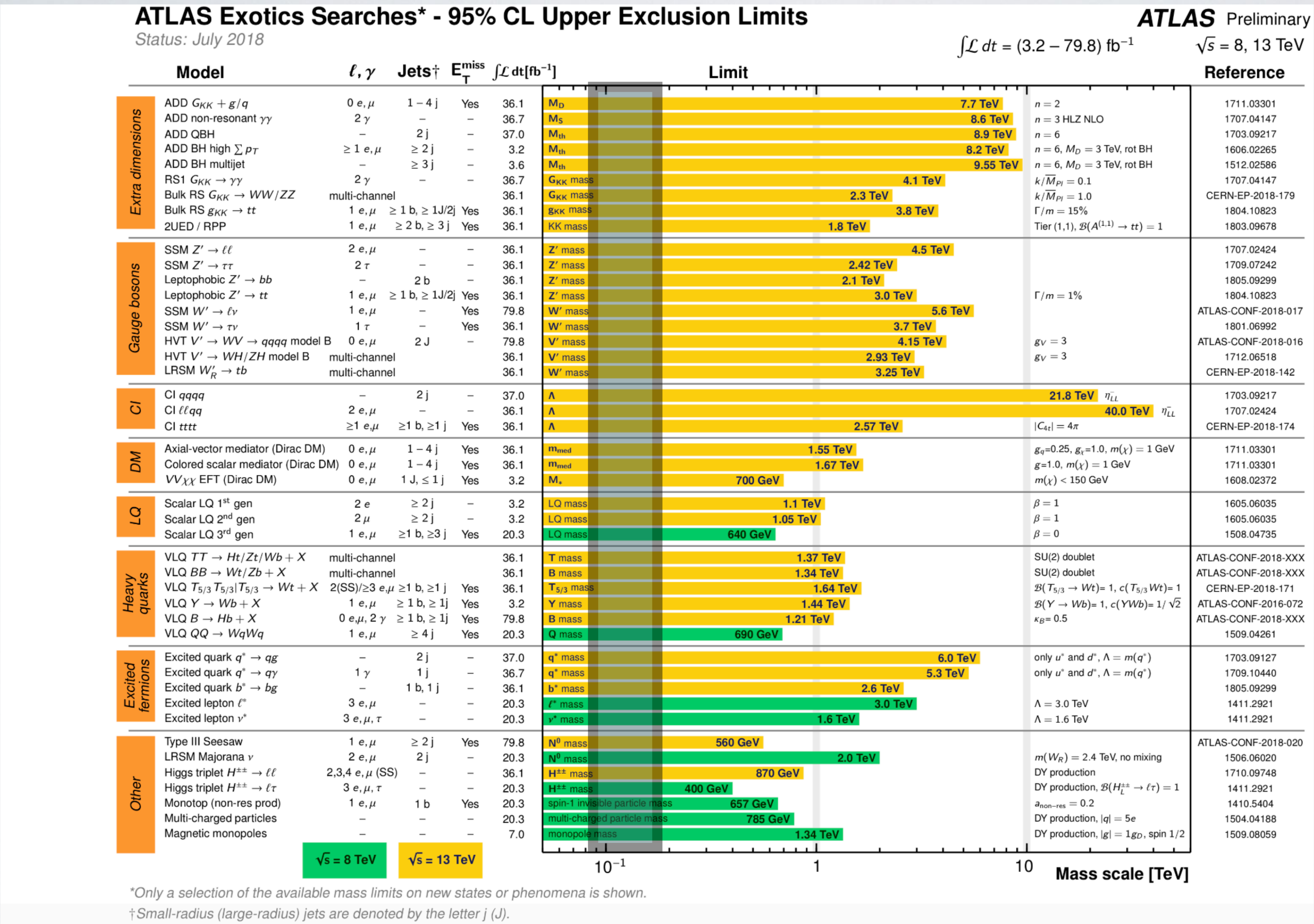
v, λ : 2 EW sector

This is the 18 parameters you hear about...

RunII and beyond: Resonance limits to local operators

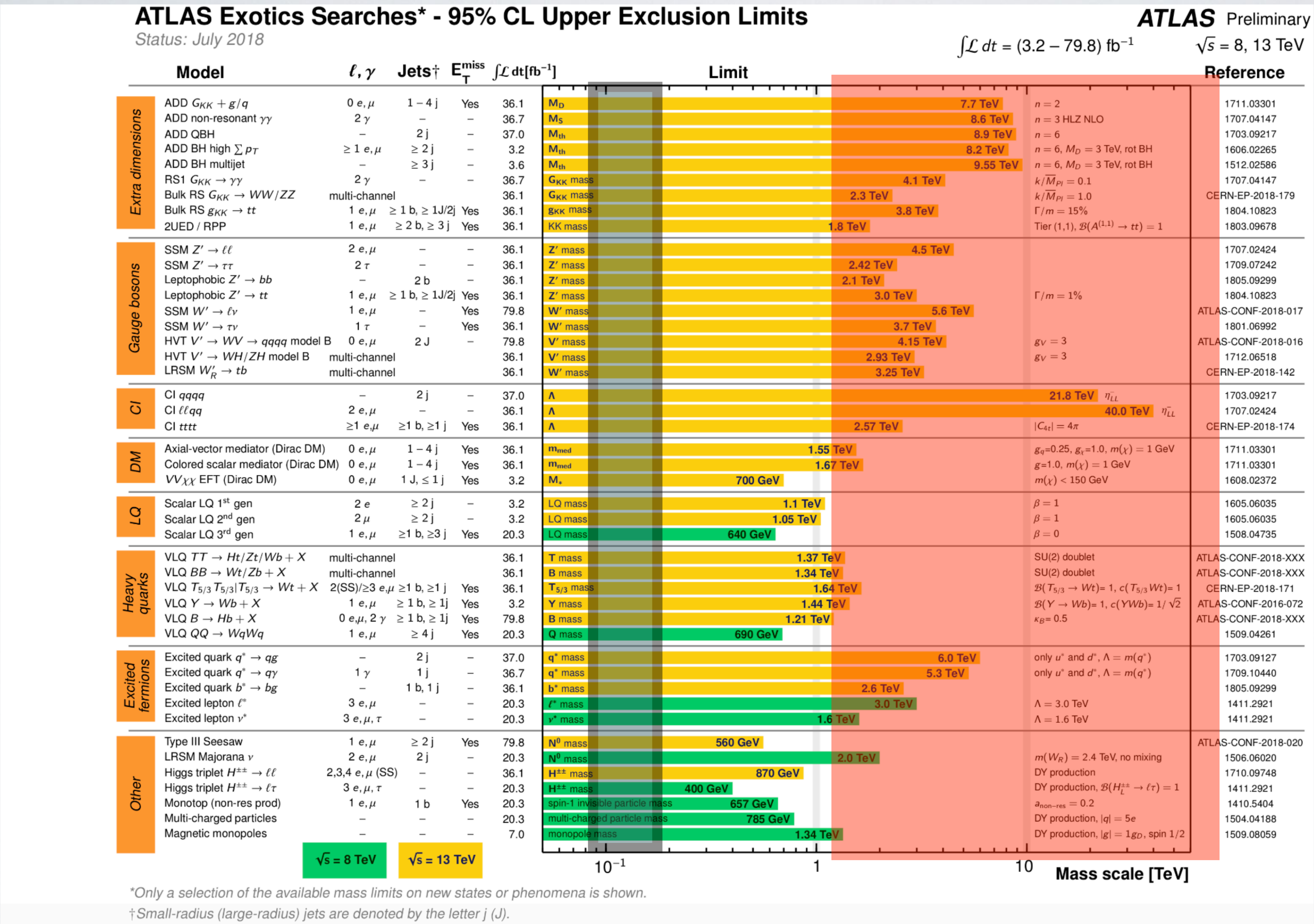


RunII and beyond: Resonance limits to local operators



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

RunII and beyond: Resonance limits to local operators



Now that these bounds have been pushed away from v

USE that

$$v/M < 1$$

to simplify/for more powerful conclusions:

- bound many models at once
- bound multiple resonances at same time

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:

$\phi_q \to e^{i\,\phi_q}\,\phi_q$	global U(1) of baryon number
$\phi_\ell \to e^{i\,\phi_\ell}\,\phi_\ell$	global U(1) of lepton number

- Other approx symmetries:

$SU(2)_L \times SU(2)_R \to SU(2)_c$	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:

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

- 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:
$\Lambda_{\Delta L} = 10^{16}\,\text{GeV}$

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- 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

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_{\delta L \neq 0}} \mathcal{L}_5 + \frac{1}{\Lambda^2_{\delta B = 0}} \mathcal{L}_6 + \frac{1}{\Lambda^2_{\delta B \neq 0}} \mathcal{L}'_6 + \frac{1}{\Lambda^3_{\delta L \neq 0}} \mathcal{L}_7 + \frac{1}{\Lambda^4} \mathcal{L}_8 + \cdots$$

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

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:

$$\widetilde X_{\mu\nu} = \tfrac{1}{2}\varepsilon_{\mu\nu\rho\sigma}X^{\rho\sigma} \quad (\varepsilon_{0123} = +1)$$

$$\widetilde\varphi^j = \varepsilon_{jk}(\varphi^k)^\star \qquad \varepsilon_{12} = +1$$

$$\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi \equiv i\varphi^\dagger\left(D_\mu - \overleftarrow{D}_\mu\right)\varphi$$

$$\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi \equiv i\varphi^\dagger\left(\tau^I D_\mu - \overleftarrow{D}_\mu\tau^I\right)\varphi$$

LO SMEFT = dim 6 shifts

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

$8:(\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$

$8:(\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8:(\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8:(\bar{L}R)(\bar{R}L)+\mathrm{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8:(\bar{L}R)(\bar{L}R)+\mathrm{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$

Complexity <u>is</u> scaling up…

In Warsaw basis arXiv:1008.4884 (SMEFT standard basis)

$$\frac{1}{\Lambda^2_{\delta B=0}}\mathcal{L}_6$$

Class		N_{op}	CP-even n_g	1	3	CP-odd n_g	1	3
1	g^3X^3	4	2	2	2	2	2	2
2	H^6	1	1	1	1	0	0	0
3	H^4D^2	2	2	2	2	0	0	0
4	$g^2X^2H^2$	8	4	4	4	4	4	4
5	$y\psi^2H^3$	3	$3n_g^2$	3	27	$3n_g^2$	3	27
6	$gy\psi^2XH$	8	$8n_g^2$	8	72	$8n_g^2$	8	72
7	ψ^2H^2D	8	$\frac{1}{2}n_g(9n_g+7)$	8	51	$\frac{1}{2}n_g(9n_g-7)$	1	30
ψ^4 8 :	$(\bar{L}L)(\bar{L}L)$	5	$\frac{1}{4}n_g^2(7n_g^2+13)$	5	171	$\frac{7}{4}n_g^2(n_g-1)(n_g+1)$	0	126
8 :	$(\bar{R}R)(\bar{R}R)$	7	$\frac{1}{8}n_g(21n_g^3+2n_g^2+31n_g+2)$	7	255	$\frac{1}{8}n_g(21n_g+2)(n_g-1)(n_g+1)$	0	195
8 :	$(\bar{L}L)(\bar{R}R)$	8	$4n_g^2(n_g^2+1)$	8	360	$4n_g^2(n_g-1)(n_g+1)$	0	288
8 :	$(\bar{L}R)(\bar{R}L)$	1	n_g^4	1	81	n_g^4	1	81
8 :	$(\bar{L}R)(\bar{L}R)$	4	$4n_g^4$	4	324	$4n_g^4$	4	324
8 :	All	25	$\frac{1}{8}n_g(107n_g^3+2n_g^2+89n_g+2)$	25	1191	$\frac{1}{8}n_g(107n_g^3+2n_g^2-67n_g-2)$	5	1014
Total		59	$\frac{1}{8}(107n_g^4+2n_g^3+213n_g^2+30n_g+72)$	53	1350	$\frac{1}{8}(107n_g^4+2n_g^3+57n_g^2-30n_g+48)$	23	1149

Table 2. Number of CP-even and CP-odd coefficients in $\mathcal{L}^{(6)}$ for n_g flavors. The total number of coefficients is $(107n_g^4+2n_g^3+135n_g^2+60)/4$, which is 76 for $n_g=1$ and 2499 for $n_g=3$.

2499

arXiv:1312.2014 Alonso, Jenkins, Manohar, Trott

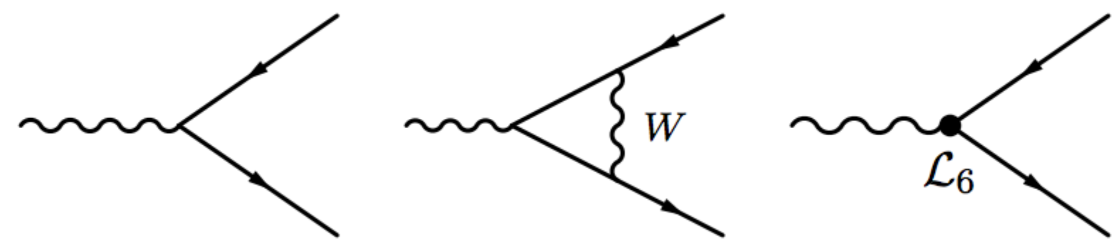
.. are there too many parameters?

- Number of parameters convolution of power counting

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

<u>+ numerical suppression due to interference with SM and resonance domination, or not</u>

- EX - flavour indicies for neutral currents:



$$\mathcal{A}^h_{ik} \simeq \frac{3 \bar{v}_T \, \bar{g}_2^3}{16^2 \, \pi^2 \, \hat{m}_W} \bar{\psi}_i \left[y_i \, V^\dagger_{ik} \, V_{kj} \frac{m_k^2}{\hat{m}_W^2} P_L + y_j \, V^\dagger_{kj} \, V_{ik} \frac{m_k^2}{\hat{m}_W^2} P_R \right] \psi_j, + \cdots$$

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

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 [10]	23 [10]	~ 23
General SMEFT ($n_f = 3$)	1350 [10]	1149 [10]	~ 46
$\mathrm{U}(3)^5$ SMEFT	~ 52	~ 17	~ 24
MFV SMEFT	~ 108	-	~ 30

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

- 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

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

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

$$
\begin{aligned}
Q^{duq\ell}_{prst} &= \epsilon_{\alpha\beta\gamma}\epsilon_{ij}(d^{\alpha}_{p} C u^{\beta}_{r})(q^{i\gamma}_{s} C \ell^{j}_{t}) \,, \\
Q^{qque}_{prst} &= \epsilon_{\alpha\beta\gamma}\epsilon_{ij}(q^{i\alpha}_{p} C q^{j\beta}_{r})(u^{\gamma}_{s} C e_{t}) \,, \\
Q^{qqq\ell}_{prst} &= \epsilon_{\alpha\beta\gamma}\epsilon_{il}\epsilon_{jk}(q^{i\alpha}_{p} C q^{j\beta}_{r})(q^{k\gamma}_{s} C \ell^{l}_{t}) \,, \\
Q^{duue}_{prst} &= \epsilon_{\alpha\beta\gamma}(d^{\alpha}_{p} C u^{\beta}_{r})(u^{\gamma}_{s} C e_{t}) \,,
\end{aligned}
$$

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 : $\Gamma_p \approx c^2 \dfrac{m_p^5}{\Lambda^4}$ 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.

$$\begin{aligned}\mathcal{L}_{B'} = &-\frac{1}{4} B'_{\mu\nu} B'^{\mu\nu} - g_1 \, \mathsf{y}_\psi \, \overline{\psi} \, \not{B}' \, \psi + (D^\mu H)^\dagger (D_\mu H) + \mathcal{C}_B (H^\dagger \overleftrightarrow{D}^\mu H)(D^\nu B_{\mu\nu}), \\ &+ \mathcal{C}_{BH} (D^\mu H)^\dagger \, (D^\nu H) \, B'_{\mu\nu} + C^{(1)}_{\underset{tt}{Hl}} Q^{(1)}_{\underset{tt}{Hl}} + C_{\underset{tt}{He}} \, Q_{\underset{tt}{He}} + C^{(1)}_{\underset{tt}{Hq}} Q^{(1)}_{\underset{tt}{Hq}} + C_{\underset{tt}{Hu}} \, Q_{\underset{tt}{Hu}}, \\ &+ C_{\underset{tt}{Hd}} Q_{\underset{tt}{Hd}} + C_{HB} \, Q_{HB} + C_T \, (H^\dagger \overleftrightarrow{D}^\mu H) \, (H^\dagger \overleftrightarrow{D}^\mu H).\end{aligned}$$

Over complete set of ops depending on B^μ

1706.08945 I. Brivio, MT

- Perform a field redefinition $B'_\mu \to B_\mu + b_2 \dfrac{H^\dagger \, i \overleftrightarrow{D}_\mu H}{\Lambda^2}$ then $\mathcal{L}_{B}{}' - g_1 \, b_2 \Delta B$

<u>The physics is not changed by this choice of path integral variable.</u>

SMEFT requires a GLOBAL approach

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

- CHOOSE $b_2 = \mathcal{C}_B$ THEN

$$\mathcal{L}_{B'} = -\frac{1}{4} B'_{\mu\nu} B'^{\mu\nu} - g_1\, \mathsf{y}_\psi\, \overline{\psi}\, \not{B}'\, \psi + (D^\mu H)^\dagger (D_\mu H) + \cancel{\mathcal{C}_B (H^\dagger \overleftrightarrow{D}^\mu H)(D^\nu B_{\mu\nu})},$$
$$+ \mathcal{C}_{BH} (D^\mu H)^\dagger (D^\nu H) B'_{\mu\nu} + C^{(1)}_{\underset{tt}{Hl}} Q^{(1)}_{\underset{tt}{Hl}} + C_{\underset{tt}{He}} Q_{\underset{tt}{He}} + C^{(1)}_{\underset{tt}{Hq}} Q^{(1)}_{\underset{tt}{Hq}} + C_{\underset{tt}{Hu}} Q_{\underset{tt}{Hu}},$$
$$+ C_{\underset{tt}{Hd}} Q_{\underset{tt}{Hd}} + C_{HB} Q_{HB} + C_T (H^\dagger \overleftrightarrow{D}^\mu H)(H^\dagger \overleftrightarrow{D}^\mu H).$$

Non-redundant set of ops depending on B^μ

1706.08945 I. Brivio, MT

- BUT terms that remain SHIFTED $\mathcal{L}_B - g_1\, b_2 \Delta B$

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

EWPD, diboson, Higgs data all modified globally

Z,W couplings

$$
\begin{aligned}
\mathcal{Q}_{Hl}^{(1)} &= (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{l}\gamma^\mu l)\\
\mathcal{Q}_{He} &= (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)\\
\mathcal{Q}_{Hq}^{(1)} &= (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)\\
\mathcal{Q}_{Hq}^{(3)} &= (iH^\dagger \overleftrightarrow{D}^i_\mu H)(\bar{q}\sigma^i\gamma^\mu q)\\
\mathcal{Q}_{Hu} &= (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)\\
\mathcal{Q}_{Hd} &= (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)
\end{aligned}
$$

Top data

$$
\begin{aligned}
\mathcal{Q}^{(1)}_{\substack{qq\\prst}} &= (\bar{q}_p\gamma^\mu q_r)(\bar{q}_s\gamma_\mu q_t),\\
\mathcal{Q}^{(3)}_{\substack{qq\\prst}} &= (\bar{q}_p\gamma^\mu\tau^I q_r)(\bar{q}_s\gamma_\mu\tau_I q_t),\\
\mathcal{Q}_{\substack{uu\\prst}} &= (\bar{u}_p\gamma^\mu u_r)(\bar{u}_s\gamma_\mu u_t),\\
\mathcal{Q}^{(1)}_{\substack{ud\\prst}} &= (\bar{u}_p\gamma^\mu u_r)(\bar{d}_s\gamma_\mu d_t),\\
\mathcal{Q}^{(8)}_{\substack{ud\\prst}} &= (\bar{u}_p\gamma^\mu T^A u_r)(\bar{d}_s\gamma_\mu T^A d_t),
\end{aligned}
$$

Bhabha scattering

$$
\begin{aligned}
\mathcal{Q}_{ee} &= (\bar{e}\gamma^\mu e)(\bar{e}\gamma^\mu e)\\
\mathcal{Q}_{le} &= (\bar{l}\gamma^\mu l)(\bar{e}\gamma^\mu e)\\
\mathcal{Q}_{ll} &= (\bar{l}_p\gamma^\mu l_p)(\bar{l}_r\gamma^\mu l_r)
\end{aligned}
$$

$$\mathcal{Q}_W = \varepsilon_{ijk} W^{i\nu}_\mu W^{j\rho}_\nu W^{k\mu}_\rho$$

TGC /multi-boson

Field redefinitions are WHY a global SMEFT is needed

$$
\begin{aligned}
\mathcal{Q}_{HD} &= (D_\mu H^\dagger H)(H^\dagger D^\mu H)\\
\mathcal{Q}_{HWB} &= (H^\dagger\sigma^i H)W^i_{\mu\nu}B^{\mu\nu}\\
\mathcal{Q}_{Hl}^{(3)} &= (iH^\dagger \overleftrightarrow{D}^i_\mu H)(\bar{l}\sigma^i\gamma^\mu l)\\
\mathcal{Q}'_{ll} &= (\bar{l}_p\gamma^\mu l_r)(\bar{l}_r\gamma^\mu l_p)
\end{aligned}
$$

input quantities

B anomalies

$$
\begin{aligned}
\mathcal{Q}^{(1)}_{\substack{lq\\iisb}} &= (\bar{\ell}_i\gamma^\mu\ell_i)(\bar{s}\gamma_\mu b),\\
\mathcal{Q}^{(3)}_{\substack{lq\\iisb}} &= (\bar{\ell}_i\tau^I\gamma^\mu\ell_i)(\bar{s}\,\tau_I\,\gamma_\mu b).
\end{aligned}
$$

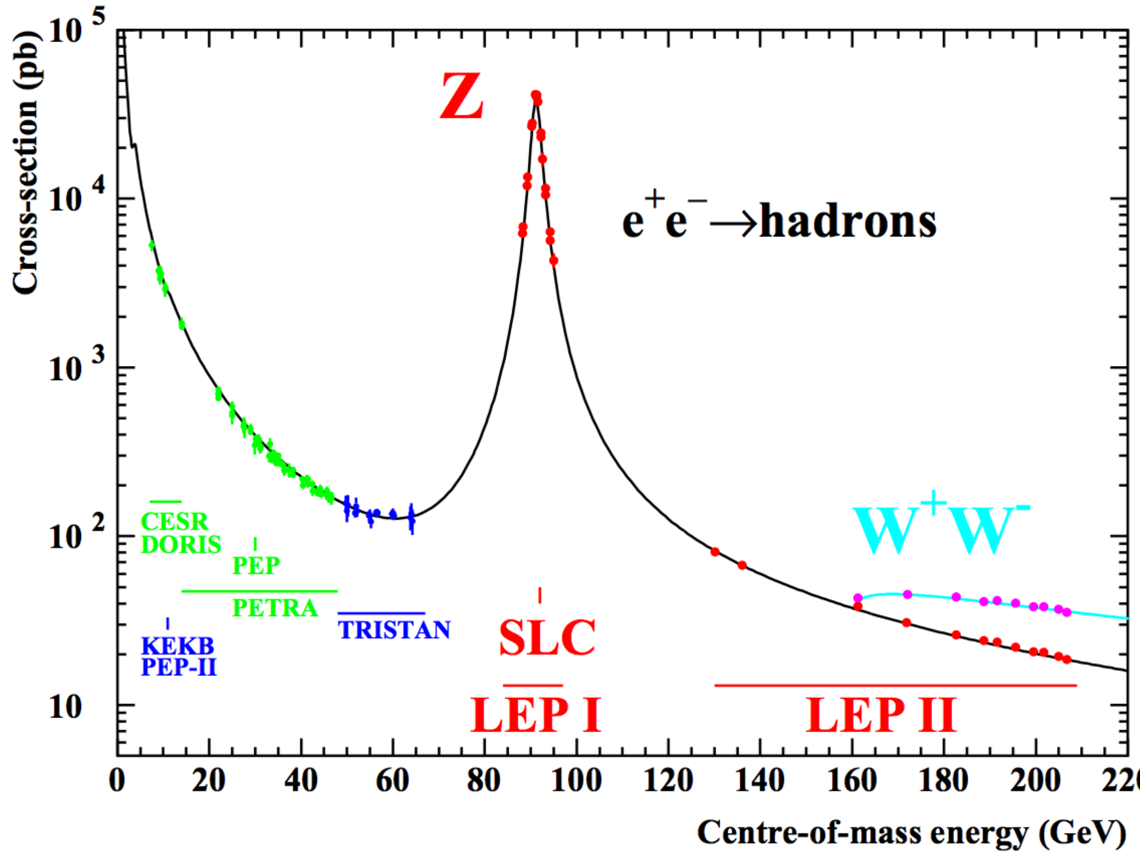
$$
\begin{aligned}
\mathcal{Q}_{Hbox} &= (H^\dagger H)\,\Box\,(H^\dagger H)\\
\mathcal{Q}_{HG} &= (H^\dagger H)G^a_{\mu\nu}G^{a\mu\nu}\\
\mathcal{Q}_{HB} &= (H^\dagger H)B_{\mu\nu}B^{\mu\nu}\\
\mathcal{Q}_{HW} &= (H^\dagger H)W^i_{\mu\nu}W^{i\mu\nu}\\
\mathcal{Q}_{uH} &= (H^\dagger H)(\bar{q}\tilde{H}u)\\
\mathcal{Q}_{dH} &= (H^\dagger H)(\bar{q}Hd)\\
\mathcal{Q}_{eH} &= (H^\dagger H)(\bar{q}e)\\
\mathcal{Q}_G &= \varepsilon_{abc}G^{a\nu}_\mu G^{b\rho}_\nu G^{c\mu}_\rho\\
\mathcal{Q}_{uG} &= (\bar{q}\sigma^{\mu\nu}T^a\tilde{H}u)G^a_{\mu\nu}
\end{aligned}
$$

H processes

We are looking for few % to 10's% effects in SMEFT.

How do we know the SM EW sector Lagrangian parameters?

LEP EWPD measurements



- 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

$$\sigma^Z_{\bar{f}f} = \sigma^{peak}_{\bar{f}f} \frac{s\Gamma_Z^2}{(s-m_Z^2)^2 + s^2\Gamma_Z^2/m_Z^2}$$

Peak shape is fit to:

$$\sigma^{peak}_{\bar{f}f} = \frac{\sigma^0_{\bar{f}f}}{R_{QED}} \qquad \sigma^0_{\bar{f}f} = \frac{12\pi\,\Gamma_{ee}\,\Gamma_{\bar{f}f}}{m_Z^2\,\Gamma_Z^2} \qquad R^0_\ell = \frac{\Gamma_{had}}{\Gamma_\ell}$$

Parameters extracted: $(m_Z^2, \Gamma_Z, R^0_\ell, \sigma^0_{had})$

Muon decay

- Decay of $\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$ measured far below the W pole.
- Probes the effective lagrangian $\hat{v}_T = \frac{1}{2^{1/4}\sqrt{\hat{G}_F}},$

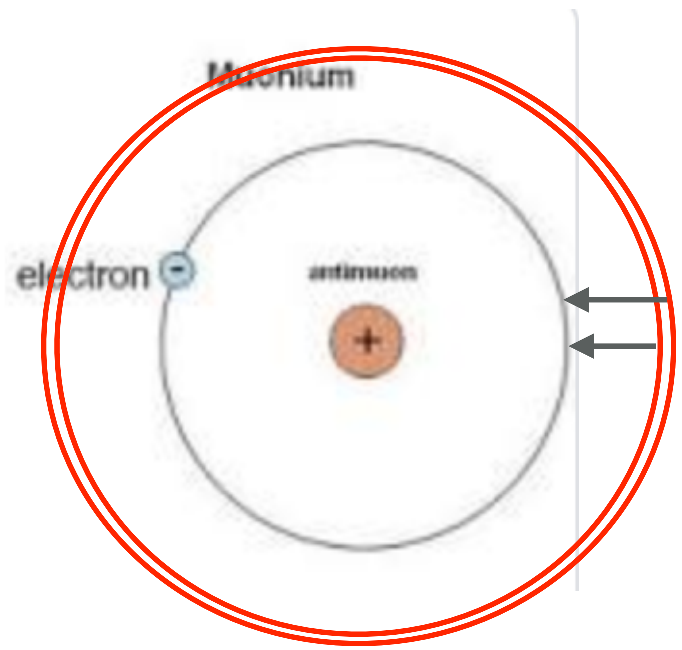
$$\mathcal{L}_{G_f} = \frac{-4G_F}{\sqrt{2}} \left(\bar{\nu}_\mu \gamma^\mu P_L \mu\right) \left(\bar{e} \gamma_\mu P_L \nu_e\right)$$

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

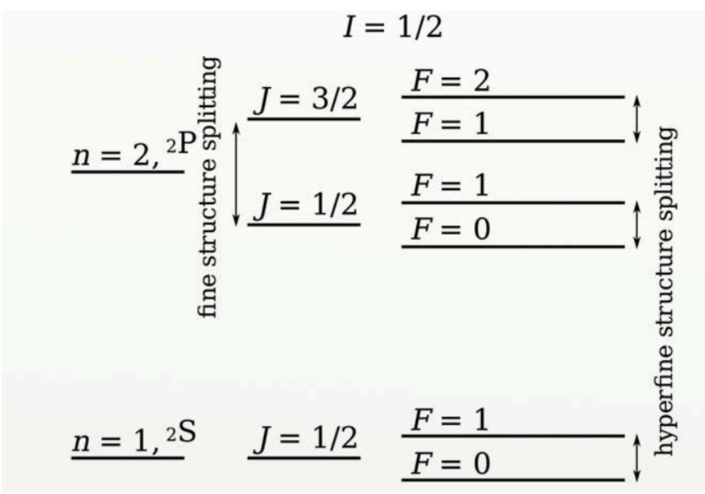
Need the mass of the muon to determine G_F

Muon mass/Electron mass

- Muon electron mass ratio can be measured in muonium



Spin-orbit interaction perturbs Hamiltonian leeds to Zeeman hyperfine splitting

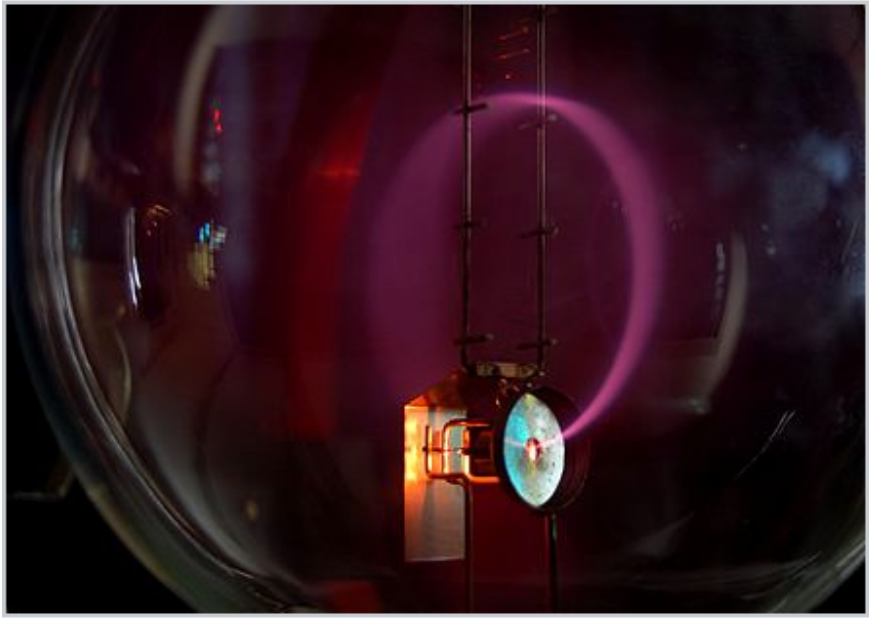


Allows an extraction of ratio m_μ/m_e

- 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

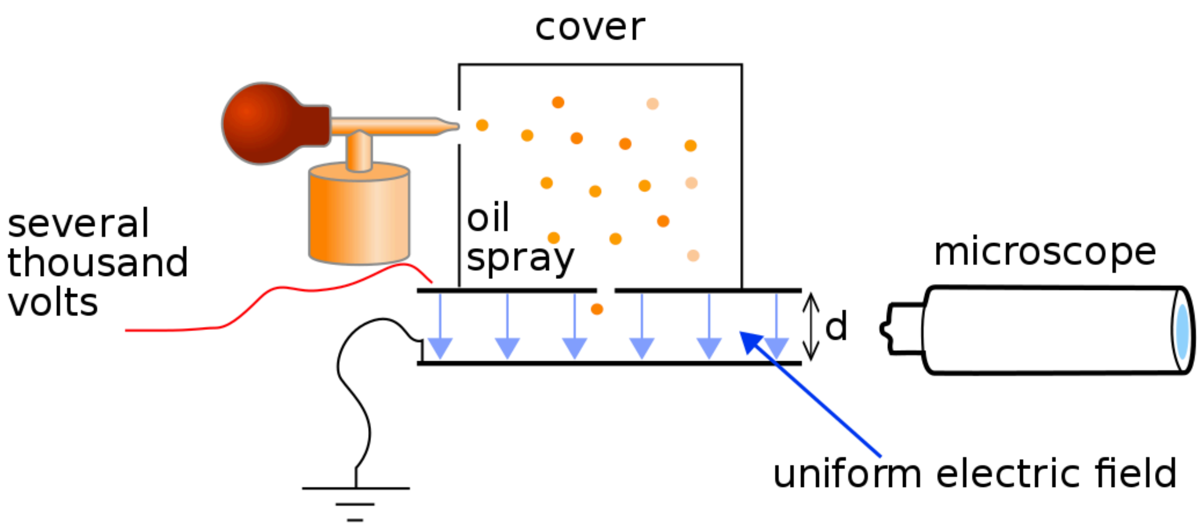


$$\mathbf{F} = Q(\mathbf{E} + \mathbf{v} \times \mathbf{B}),$$

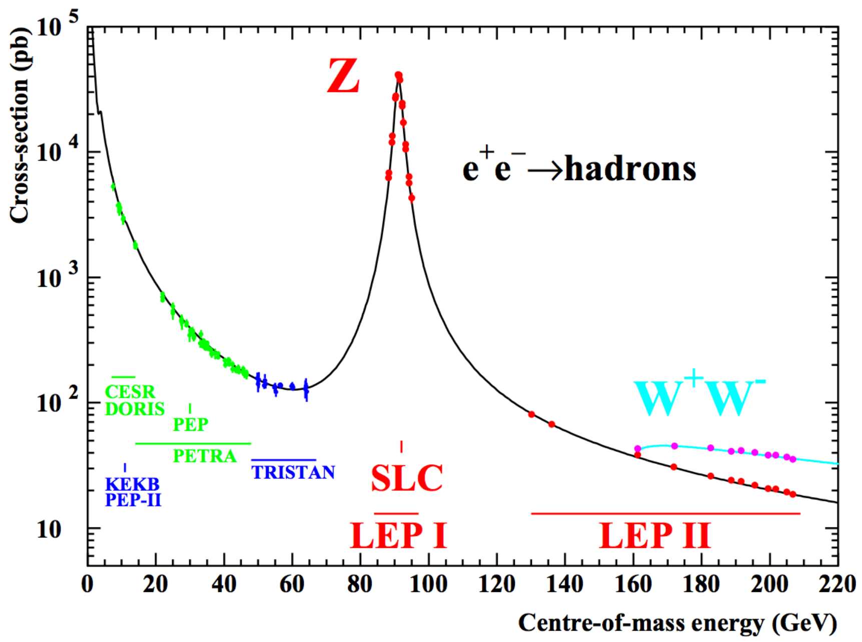
$$\mathbf{F} = m\mathbf{a} = m\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t}$$

$$\left(\frac{m}{Q}\right)\mathbf{a} = \mathbf{E} + \mathbf{v} \times \mathbf{B}.$$

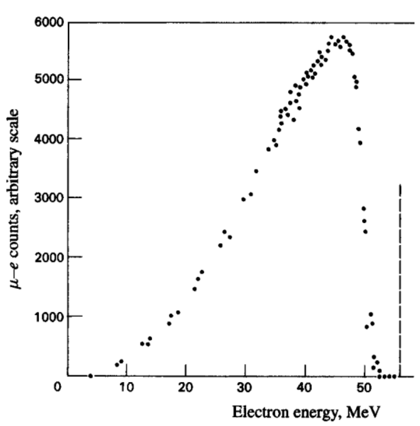
- Oil drop experiment can be used to extract the charge of the electron.

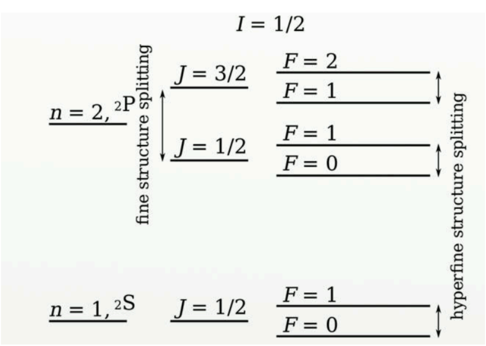


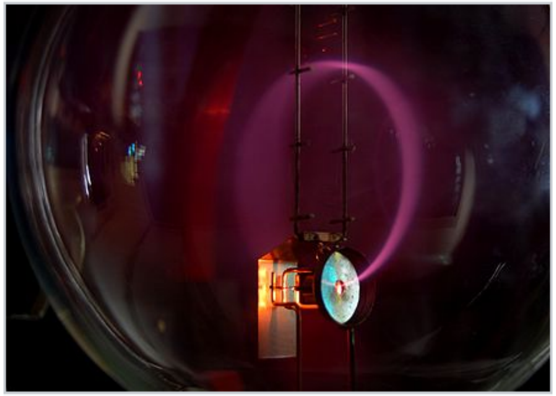
How do we know the SM EW sector input parameters?

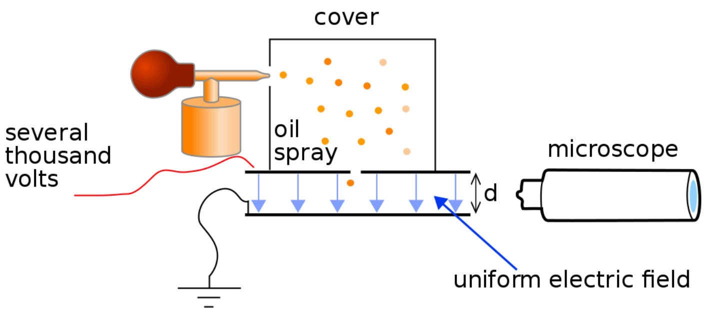


$$(m_Z^2, \Gamma_Z, R_\ell^0, \sigma_{had}^0)$$



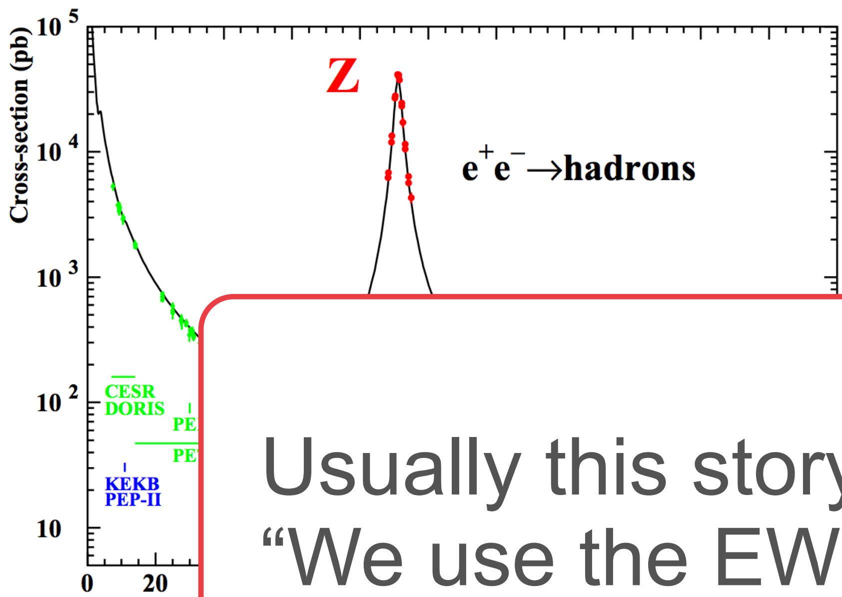






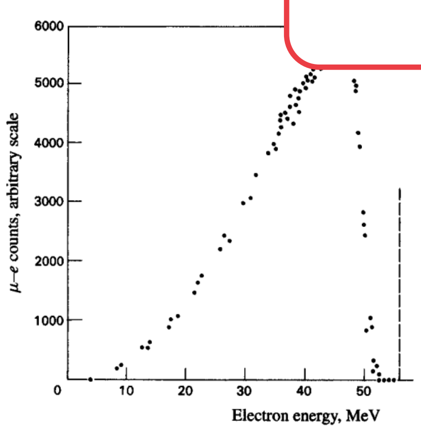
$$(G_F, \alpha_{ew}, m_e, m_\mu)$$

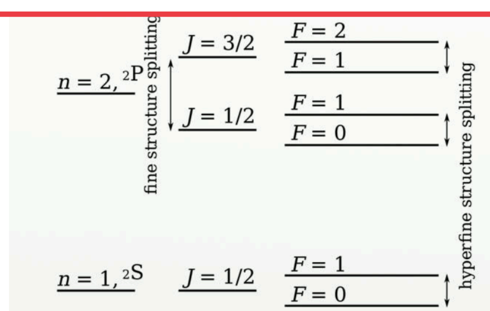
How do we know the SM EW sector input parameters?

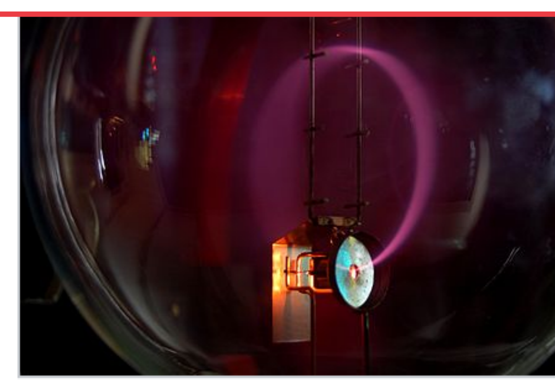


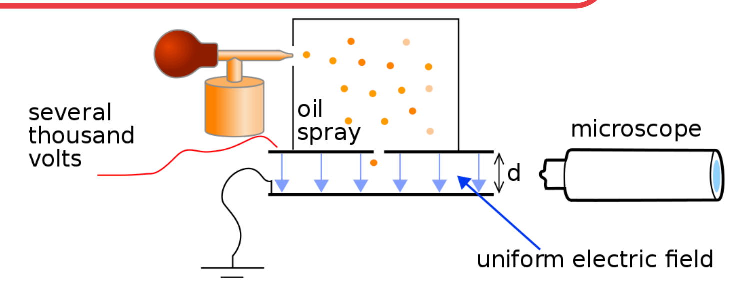
$$(m_Z^2, \Gamma_Z, R_\ell^0, \sigma^0_{had})$$

Usually this story is just boiled down to
“We use the EW input parameter scheme (G_F, α_{ew}, m_Z)“









$$(G_F, \alpha_{ew}, m_e, m_\mu)$$

SM, usual approach to EWPD

- This is a multi-scale problem

$$\hat{\alpha} \quad p^2 \simeq 0$$

$$\hat{G}_F \quad p^2 \simeq m_\mu^2$$

$$\hat{M}_Z \quad p^2 \simeq m_Z^2$$

$$\hat{e} = \sqrt{4\pi\hat{\alpha}_{ew}}, \qquad \hat{v}_T = \frac{1}{2^{1/4}\sqrt{\hat{G}_F}},$$

$$\hat{g}_1 = \frac{\hat{e}}{c_{\hat{\theta}}}, \qquad \hat{g}_2 = \frac{\hat{e}}{s_{\hat{\theta}}},$$

$$s^2_{\hat{\theta}} = \frac{1}{2}\left[1 - \sqrt{1 - \frac{4\pi\hat{\alpha}}{\sqrt{2}\hat{G}_F\hat{M}_Z^2}}\right], \qquad \hat{M}_W^2 = \hat{M}_Z^2 c^2_{\hat{\theta}},$$

$$\hat{g}_Z = -\frac{\hat{g}_2}{c_{\hat{\theta}}},$$

Compare to LEP data:

Observable	Experimental Value	Ref.	SM Theoretical Value	Ref.
$\hat{m}_Z$[GeV]	91.1875 ± 0.0021	[19]	-	-
M_W[GeV]	80.385 ± 0.015	[49]	80.365 ± 0.004	[50]
Γ_Z[GeV]	2.4952 ± 0.0023	[19]	2.4942 ± 0.0005	[48]
R^0_ℓ	20.767 ± 0.025	[19]	20.751 ± 0.005	[48]
R^0_c	0.1721 ± 0.0030	[19]	0.17223 ± 0.00005	[48]
R^0_b	0.21629 ± 0.00066	[19]	0.21580 ± 0.00015	[48]
σ^0_h [nb]	41.540 ± 0.037	[19]	41.488 ± 0.006	[48]
A^ℓ_{FB}	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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$$\mathcal{L}_{SM}(\mu^2 = m_Z^2)$$

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$\hat{M}_Z$ $\quad p^2 \simeq m_Z^2$

Then Z decay widths are predicted as:

$$\Gamma\left(Z \to \psi\bar{\psi}\right) = \frac{\sqrt{2}\,\bar{G}_F \bar{M}_Z^3\, N_C^\psi}{3\pi}\left(|\bar{g}_V^\psi|^2 + |\bar{g}_A^\psi|^2\right)$$

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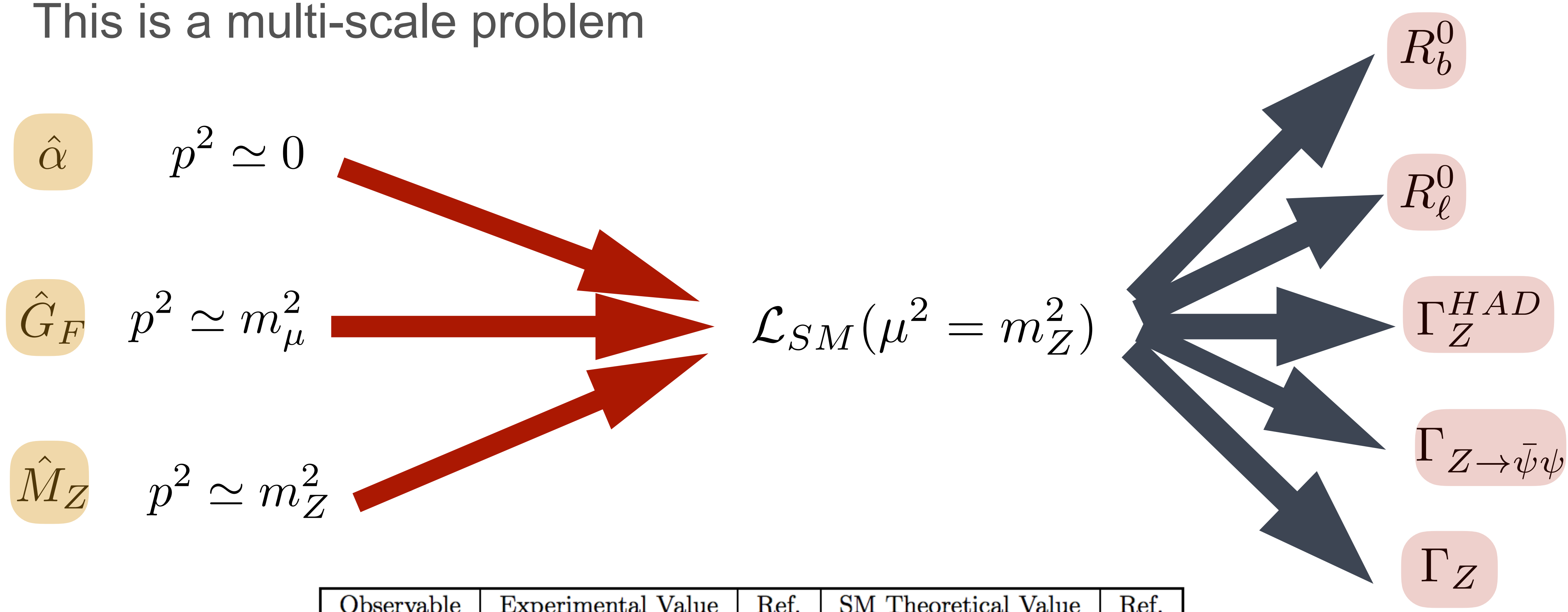

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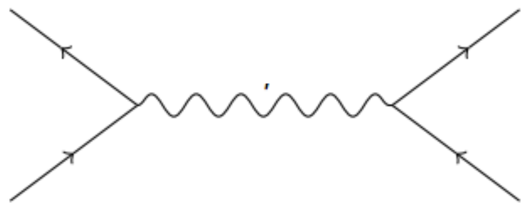
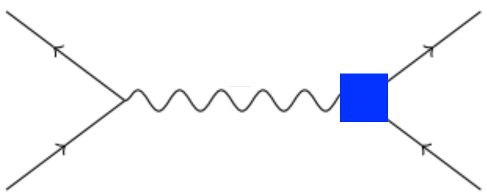
SMEFT Muon decay

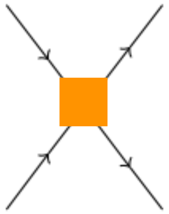
- Decay of $\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$ still measured far below the W pole.

- Still probes the effective lagrangian

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







So now

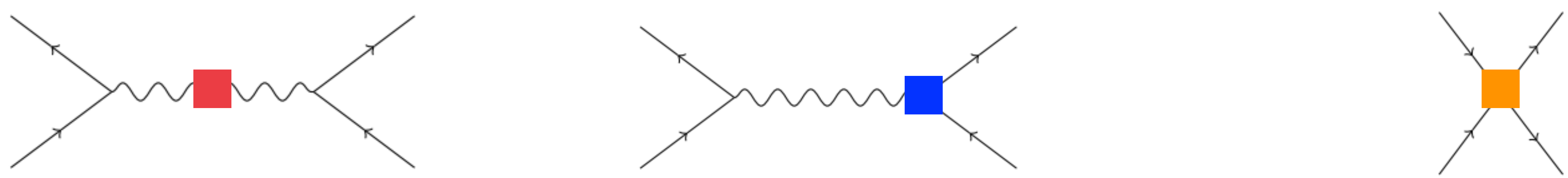
$$-\frac{4\mathcal{G}_F}{\sqrt{2}} = -\frac{2}{v_T^2} + \left(C_{\substack{ll \\ \mu ee\mu}} + C_{\substack{ll \\ e\mu\mu e}}\right) - 2\left(C^{(3)}_{\substack{Hl \\ ee}} + C^{(3)}_{\substack{Hl \\ \mu\mu}}\right)$$

$$\delta G_F$$

SMEFT EWPD

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

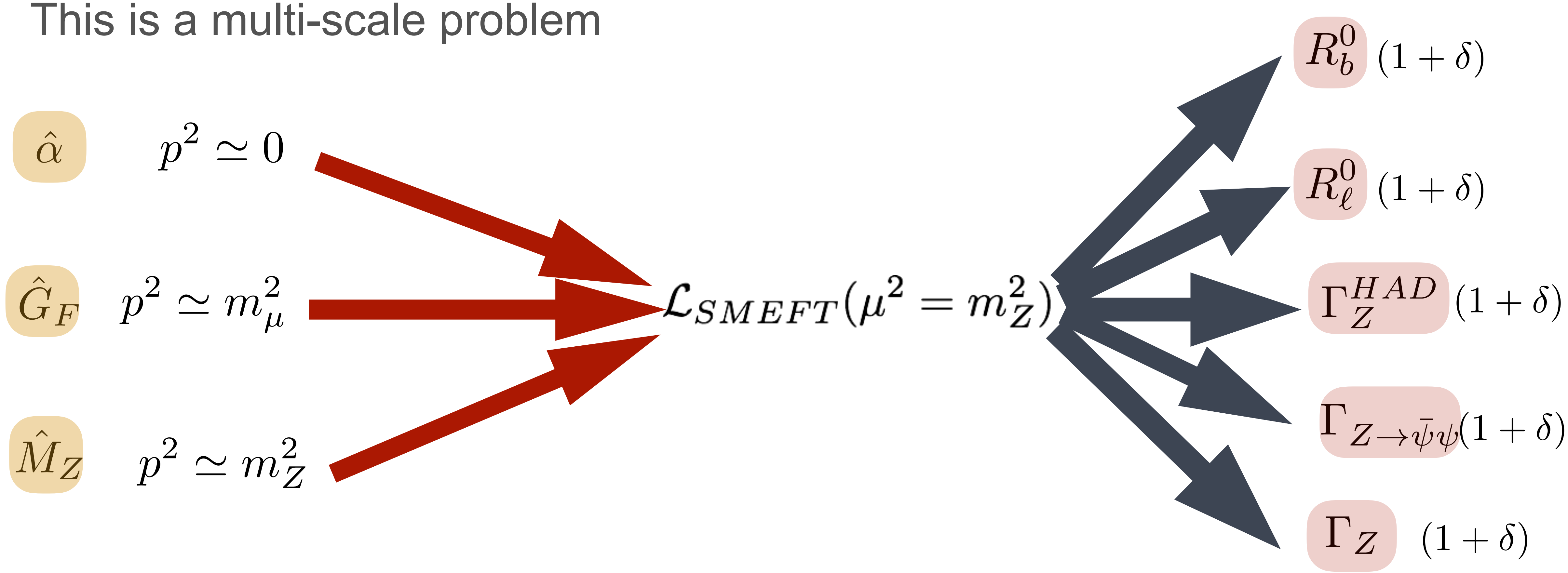
$$\boxed{Q_{HWB}, Q_{HD}}, \boxed{Q_{H\ell}^{(1)}, Q_{H\ell}^{(3)}, Q_{Hq}^{(1)}, Q_{Hq}^{(3)}, Q_{He}, Q_{Hu}, Q_{Hd}}, \boxed{Q_{\ell\ell}}$$



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

Leading order (LO) SMEFT analysis

- This is a multi-scale problem



- Lagrangian parameters inferred from inputs now corrected by local contact operators

$$\delta\kappa = \bar{\kappa} - \hat{\kappa}$$

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

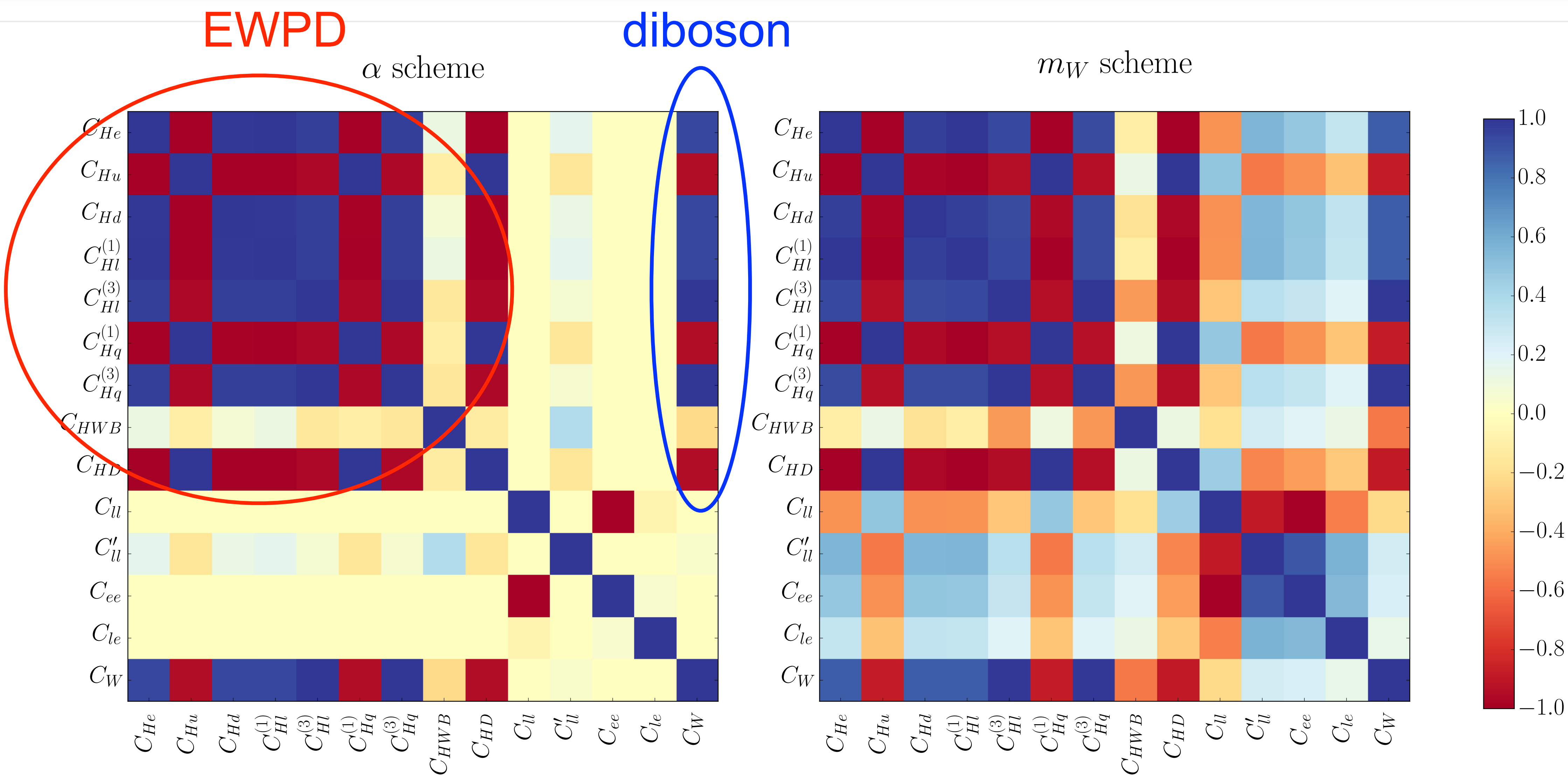
ex:

$$\delta g_1 = \bar{g}_1 - \hat{g}_1 = \frac{\hat{g}_1}{2c_{2\hat{\theta}}}\left[s_{\hat{\theta}}^2\left(\sqrt{2}\delta G_F + \frac{\delta m_Z^2}{\hat{m}_Z^2}\right) + c_{\hat{\theta}}^2\, s_{2\hat{\theta}}\bar{v}_T^2 C_{HWB}\right],$$

$$\delta s_{\theta}^2 = s_{\bar{\theta}}^2 - s_{\hat{\theta}}^2 = 2c_{\hat{\theta}}^2 s_{\hat{\theta}}^2\left(\frac{\delta g_1}{\hat{g}_1} - \frac{\delta g_2}{\hat{g}_2}\right) + \bar{v}_T^2\frac{s_{2\hat{\theta}}c_{2\hat{\theta}}}{2}C_{HWB}.$$

The corrections depend on the scheme choice

What emerges as global constraints?



Corr. matrices

- Correlation matrices in a likelihood for the SMEFT

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

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


feynrules.irmp.ucl.ac.be/wiki/SMEFT

1406.2332.pdf

Wiki | Timeline | View Tickets

wiki: SMEFT

Standard Model Effective Field Theory -- The SMEFTsim package

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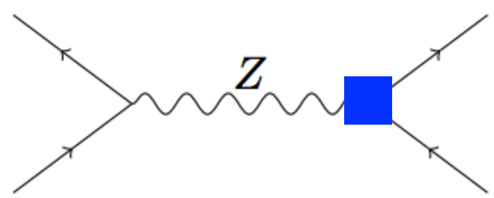
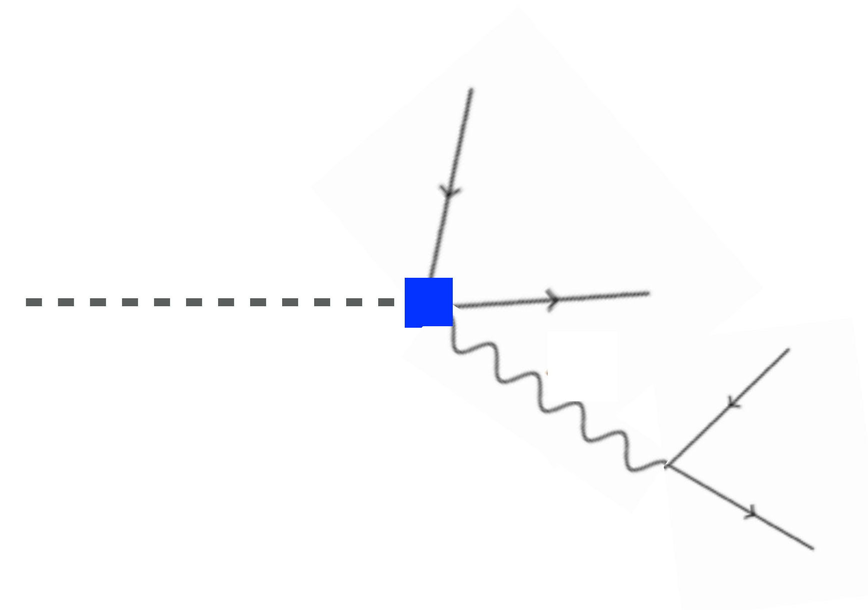
Should Higgs data matter? - YES!

- Higgs data has new parameters but many are also in EWPD (with flat directions)

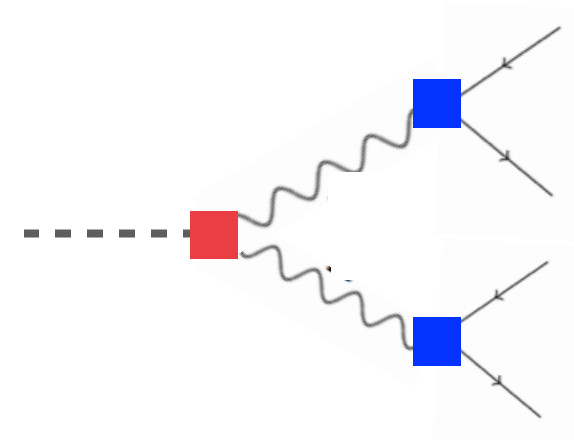
	$\psi^2\varphi^2 D$
$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{l}_p\gamma^\mu l_r)$
$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{u}_p\gamma^\mu u_r)$
$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p\gamma^\mu d_r)$





- Higgs data adds new operators

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



Global fit – observables [preliminary]

126 observables included so far

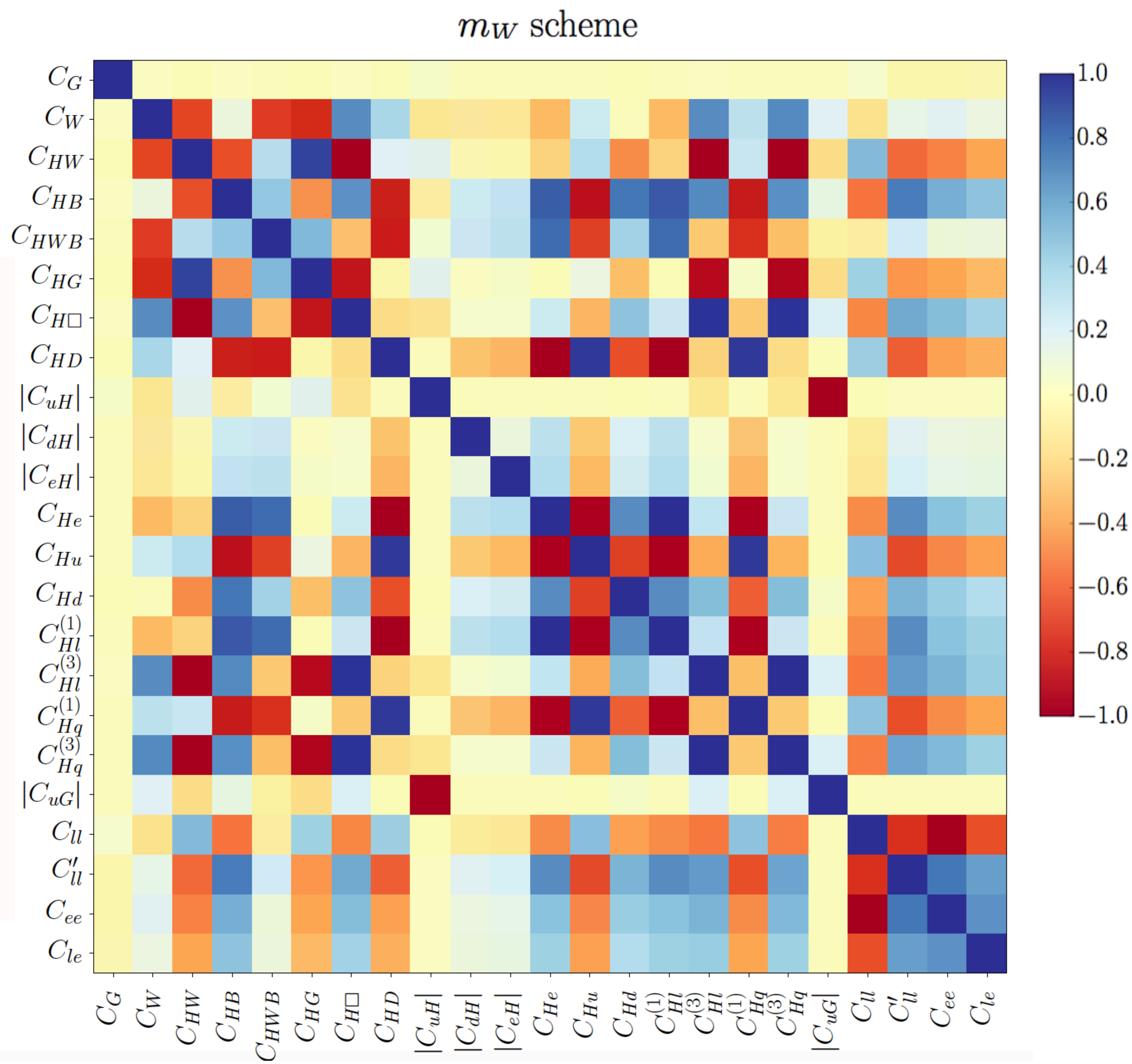
- 10 near-Z-pole EWPO: Γ_Z, $R^0_{\ell,c,b}$, $A_{FB}^{\ell,c,b,\mu,\tau}$, σ^0_h LEPI combination hep-ex/0509008
- 21 distribution bins for bhabha scattering at LEPII LEPII combination 1302.3415
- 74 dist. bins for W^+W^- production at LEPII
  L3: hep-ex/0409016
  OPAL: 0708.1311
  ALEPH: Eur.Phys.J. C38 (2004) 147
  differential combined: 1302.3415
- 21 STXS for Higgs measurements in $H \to \gamma\gamma$ and $H \to 4\ell$ at LHC
  - ATLAS (36 fb^{-1}) ATLAS-CONF-2017-047
  - CMS (36 fb^{-1}) CMS PAS HIG-17-031

Global fit – correlations [preliminary]

Provided by I. Brivio

Best fit (profiled)

$\bar{C}_{HG}$	0.00094 $\pm$ 0.000385784
$\bar{C}'_{ll}$	0.0032 $\pm$ 0.00837061
$\bar{C}^{(1)}_{Hq}$	-0.017 $\pm$ 0.0125669
$\bar{C}_{Hd}$	0.0016 $\pm$ 0.028008
$\bar{C}^{(1)}_{Hl}$	0.050 $\pm$ 0.0374125
$\bar{C}_{HB}$	0.062 $\pm$ 0.0436375
$\bar{C}_{Hu}$	-0.061 $\pm$ 0.0482166
$\bar{C}^{(3)}_{Hl}$	0.042 $\pm$ 0.0536819
$\bar{C}^{(3)}_{Hq}$	0.040 $\pm$ 0.0554775
$\bar{C}_{HWB}$	0.058 $\pm$ 0.0630901
$\bar{C}_{He}$	0.097 $\pm$ 0.0750314
$\bar{C}_{le}$	0.088 $\pm$ 0.0753358



Best fit (profiled)

$\bar{C}_W$	0.0084 $\pm$ 0.107913
$\bar{C}_{HD}$	-0.18 $\pm$ 0.13943
$\bar{C}_{HW}$	-0.11 $\pm$ 0.145152
$\bar{C}_{Hbox}$	-0.039 $\pm$ 0.165857
$\lvert\bar{C}_{eH}\rvert$	0.090 $\pm$ 0.171895
$\lvert\bar{C}_{dH}\rvert$	0.10 $\pm$ 0.202495
$\bar{C}_G$	0.44 $\pm$ 0.217008
$\lvert\bar{C}_{uG}\rvert$	-0.20 $\pm$ 0.664419
$\lvert\bar{C}_{uH}\rvert$	2.2 $\pm$ 5.05548
$\bar{C}_{ll}$	-8.8 $\pm$ 9.67349
$\bar{C}_{ee}$	9.2 $\pm$ 10.0279

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