Some recent developments in the SMEFT

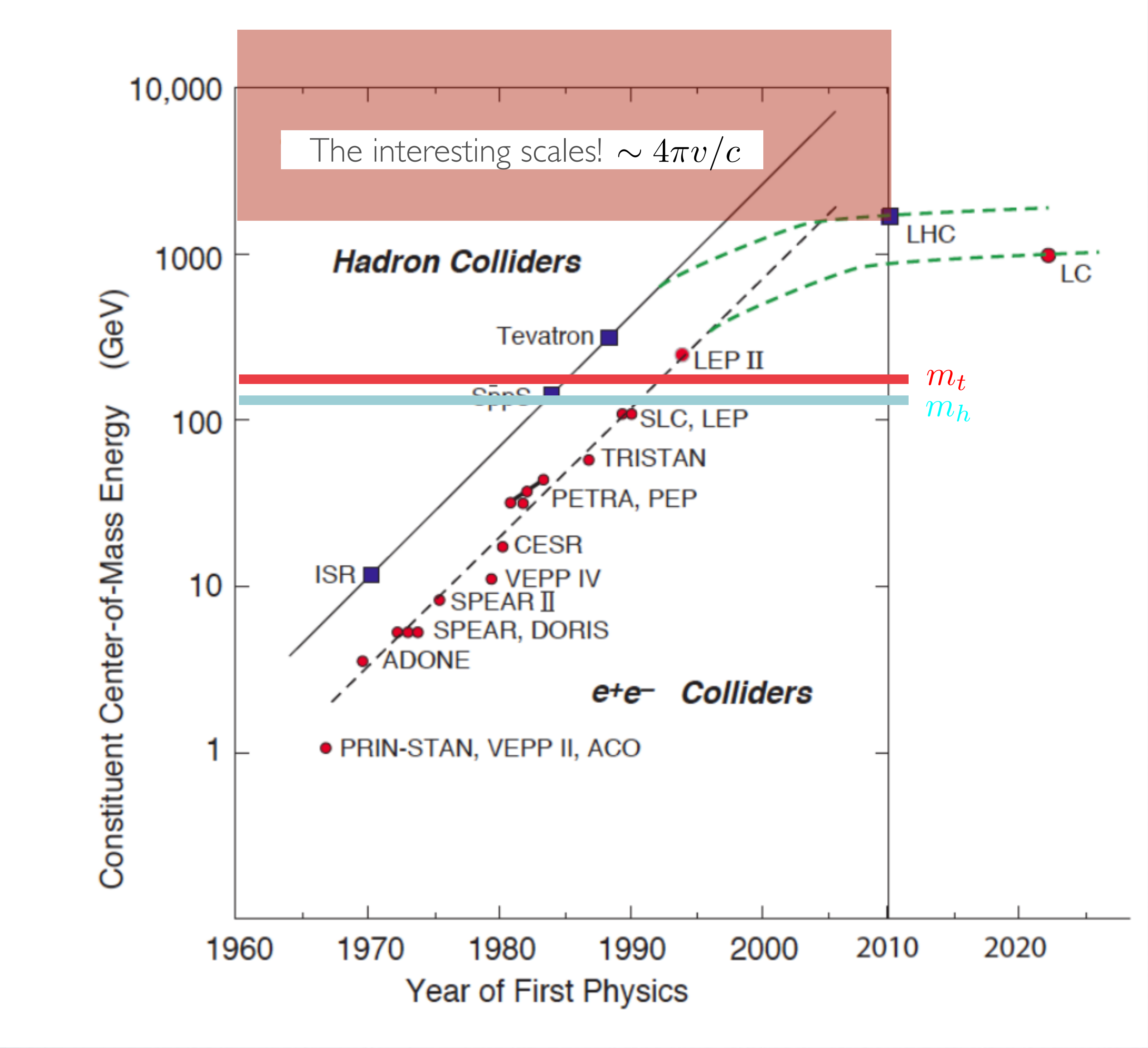
#SMEFT

M. Trott, PI 2019

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 https://arxiv.org/pdf/1706.08945.pdf

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:

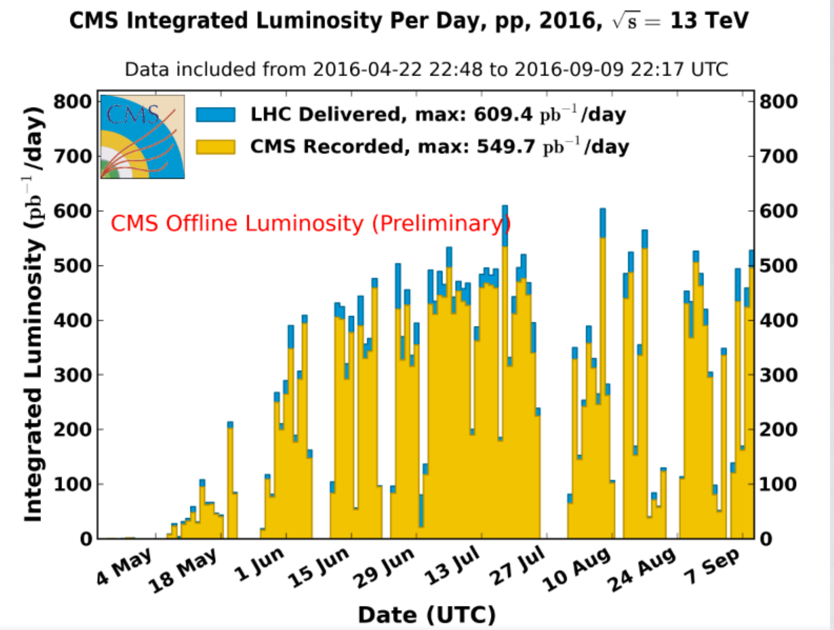
The data set in context:

Year	Centre-of-mass energy range [GeV]	Integrated luminosity [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 $\sqrt{s}$ [GeV]	Luminosity [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

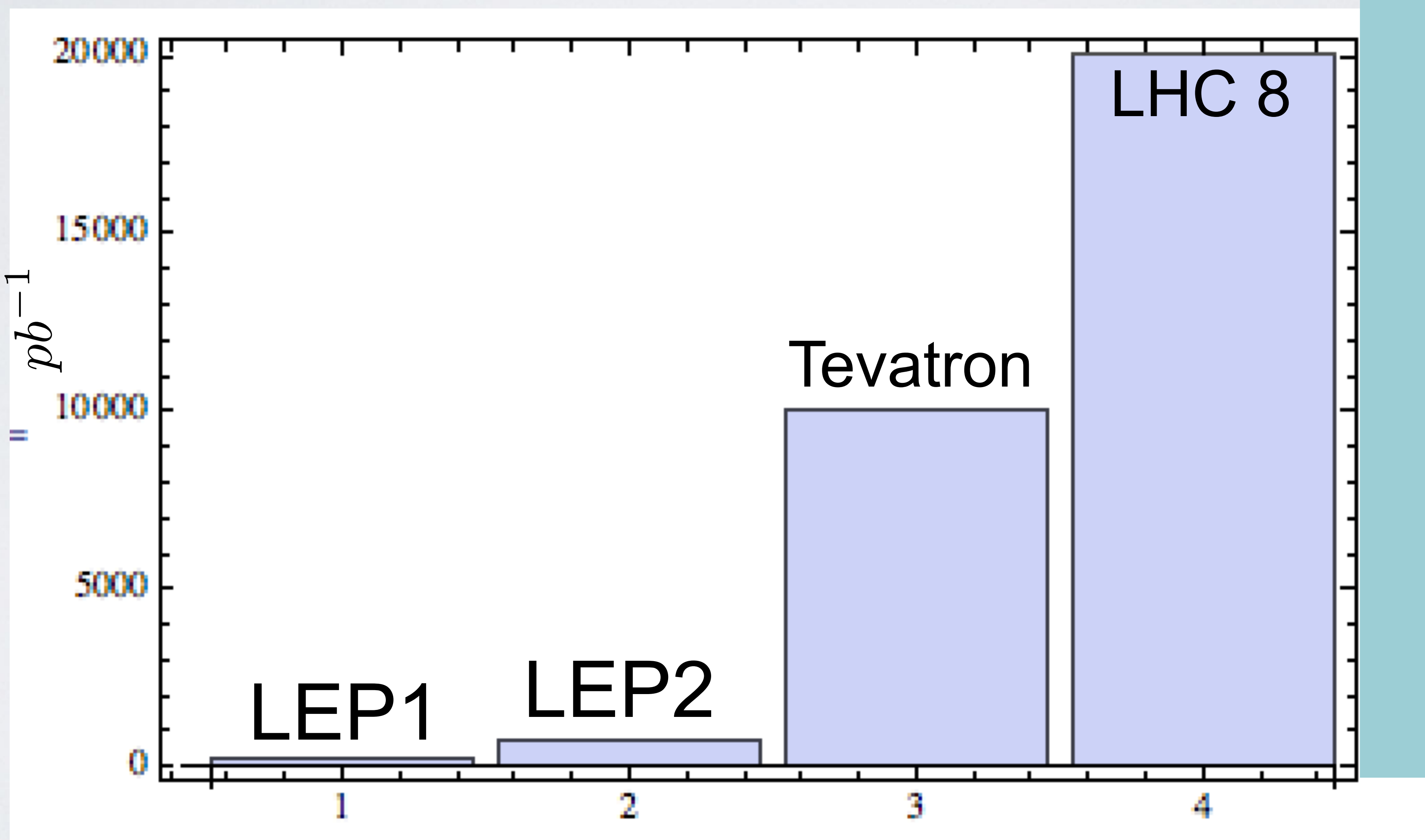
LEP2



CMS/day!

Rapid growth in data on SM states

LHC 13
2016



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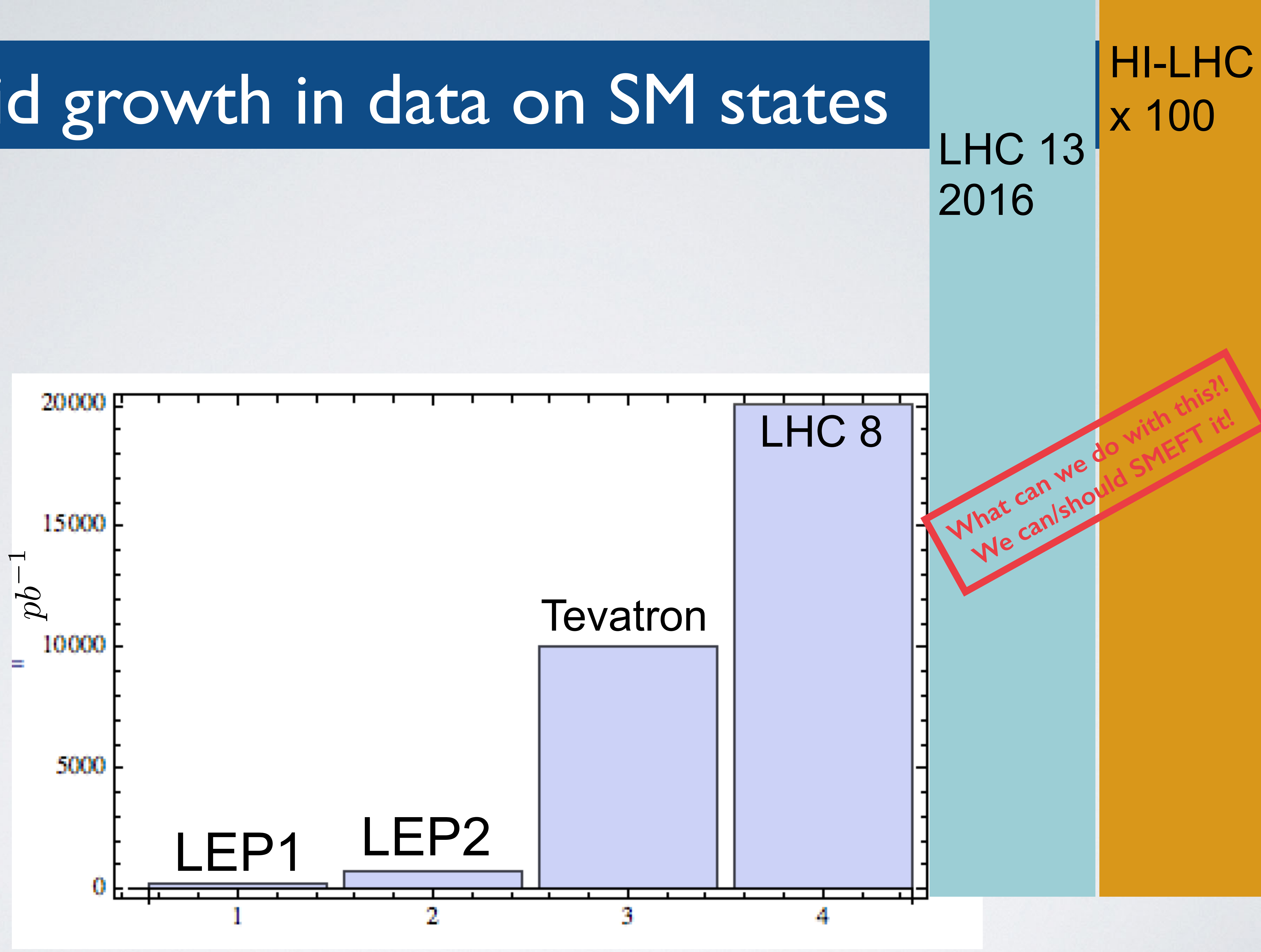
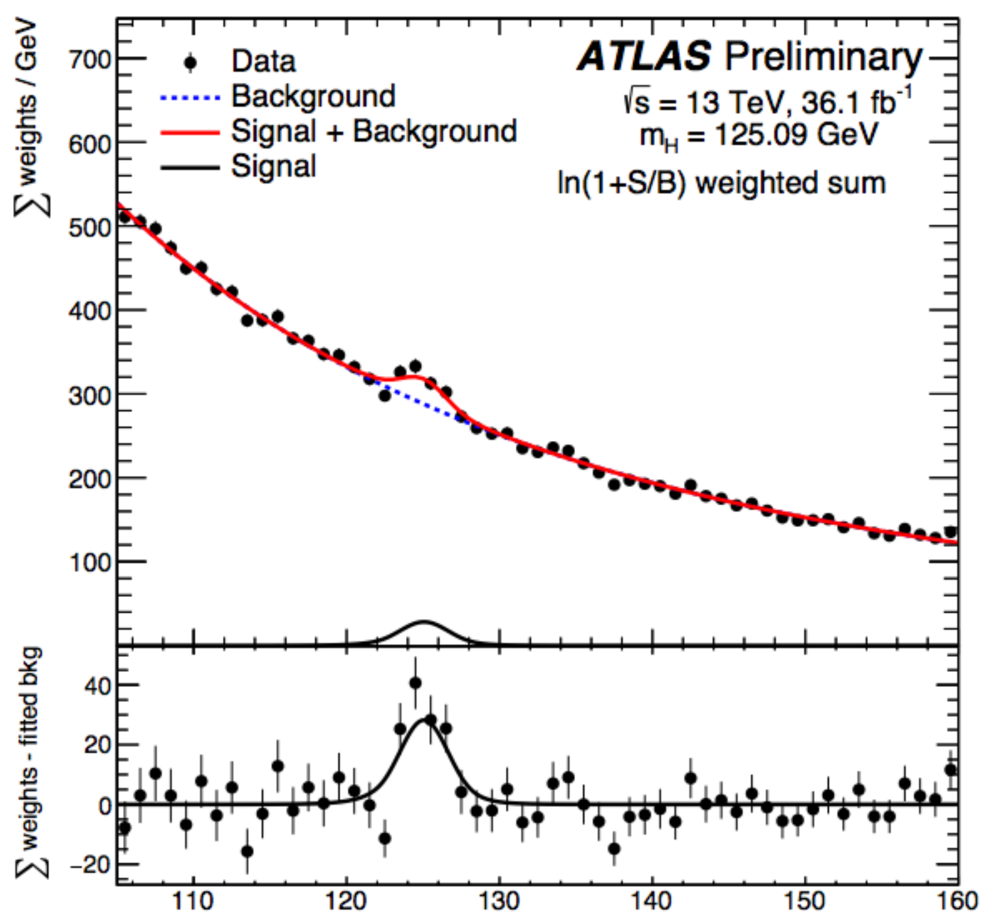
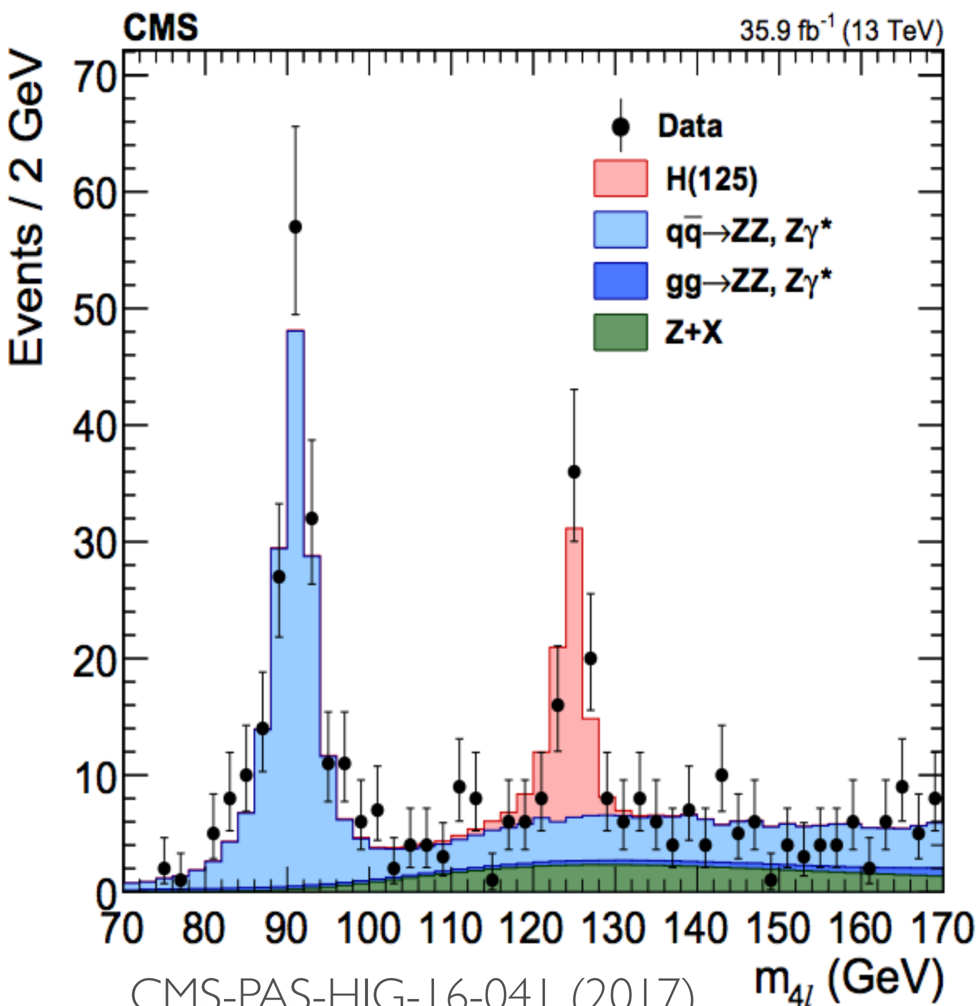


What was discovered at LHC, a particle

- Discovery of a (Higgs like) $J^P \sim 0^+$ particle in 2012



ATLAS-CONF-2017-045 (2017)



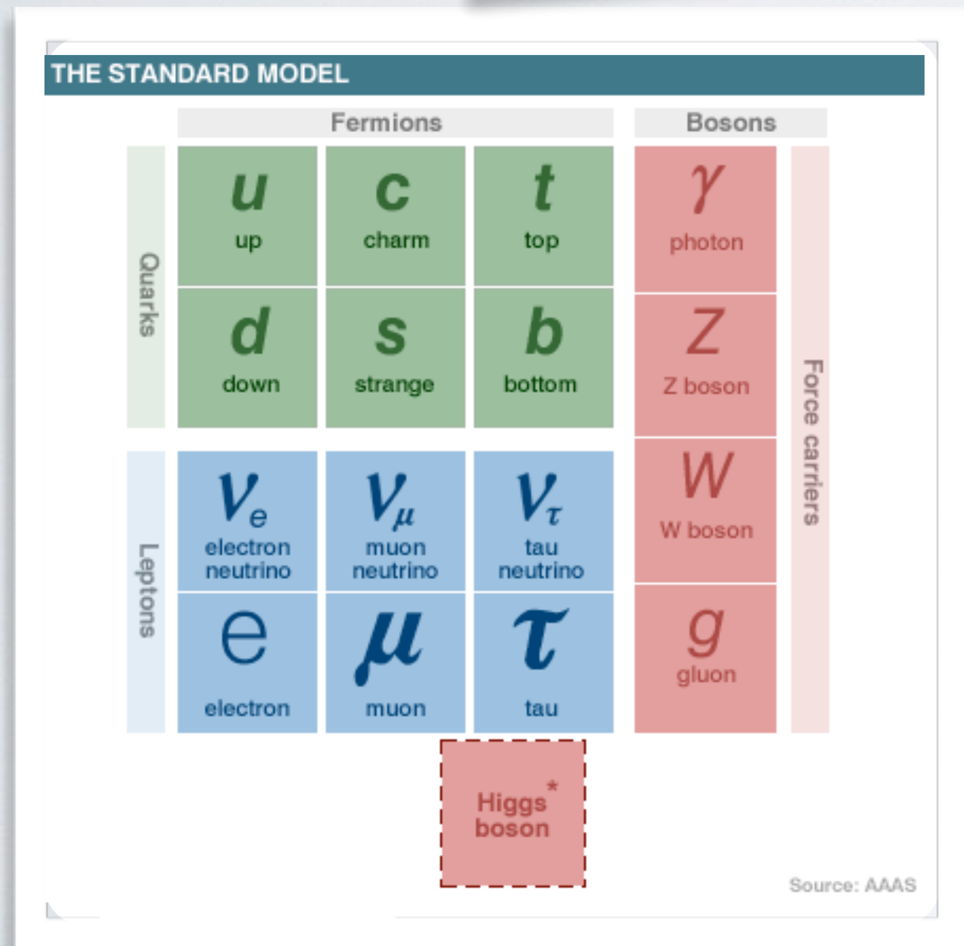
CMS-PAS-HIG-16-041 (2017)

- What is this new particle phenomena?

and a theory…the Standard Model EFT

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

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



- 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

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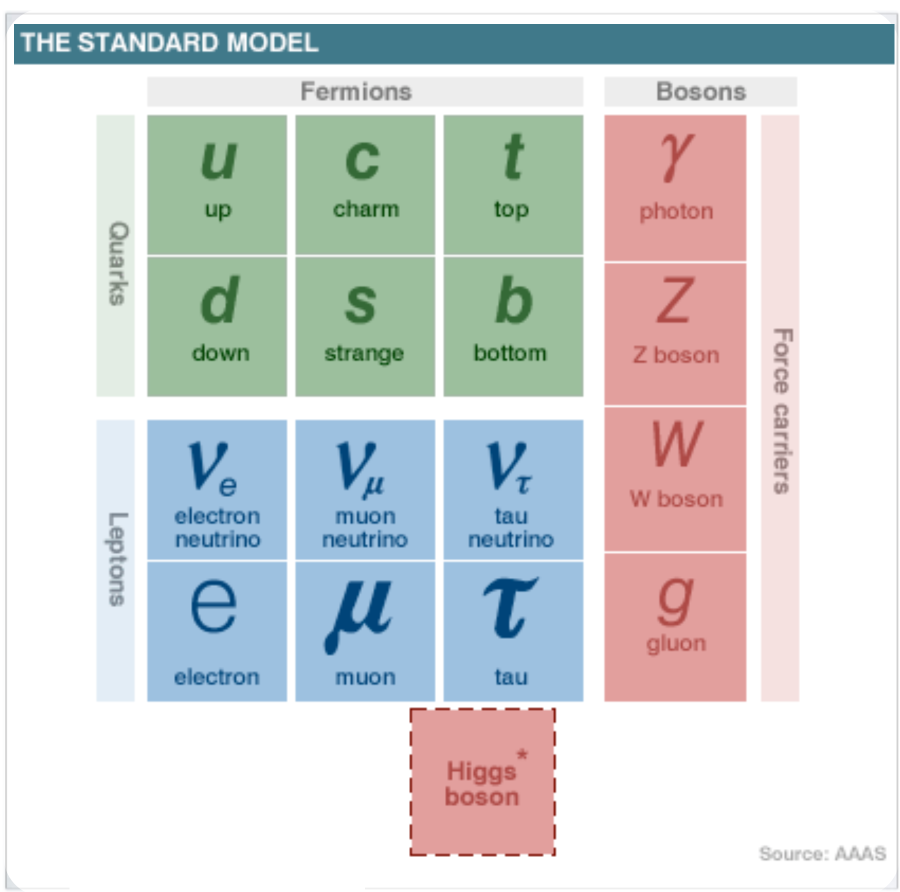


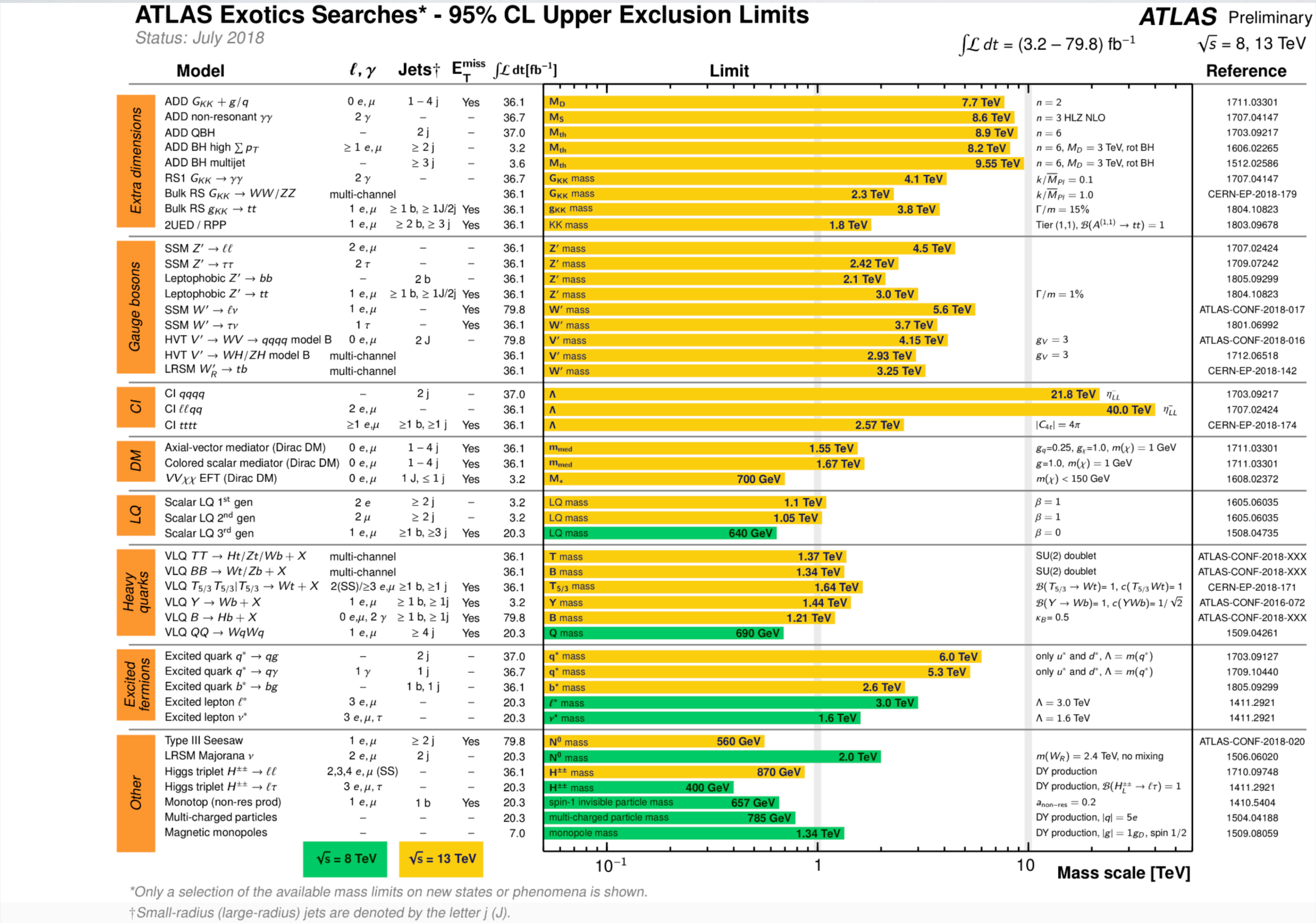
$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \frac{1}{\Lambda_{\delta L \neq 0}} \mathcal{L}_5 + \frac{1}{\Lambda^2} \mathcal{L}_6 + \cdots$$

Glashow 1961, Weinberg 1967 (Salam 1967)

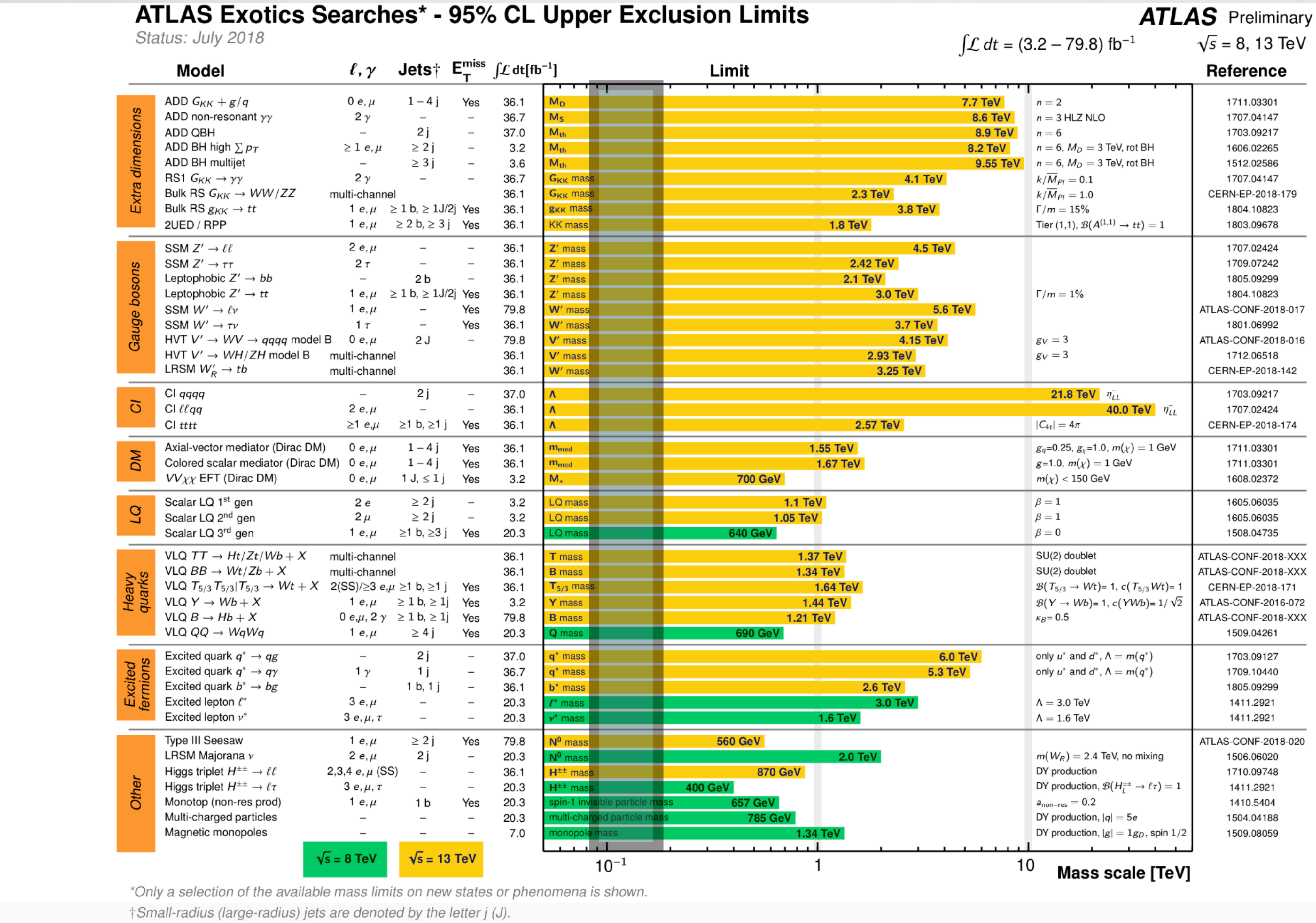
Weinberg 1979, Wilczek and Zee 1979

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

What wasn't discovered at LHC

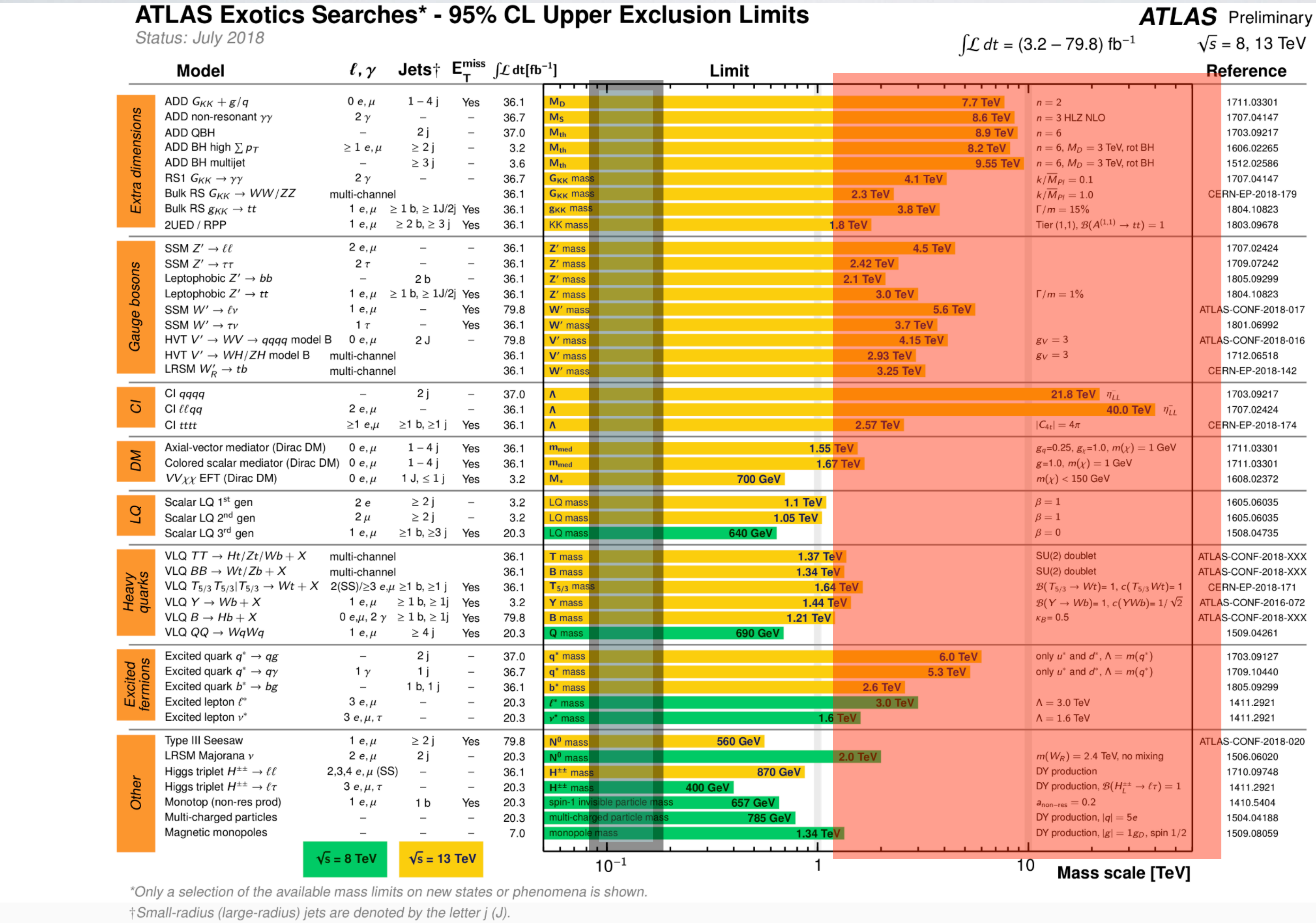


What wasn’t discovered at LHC



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

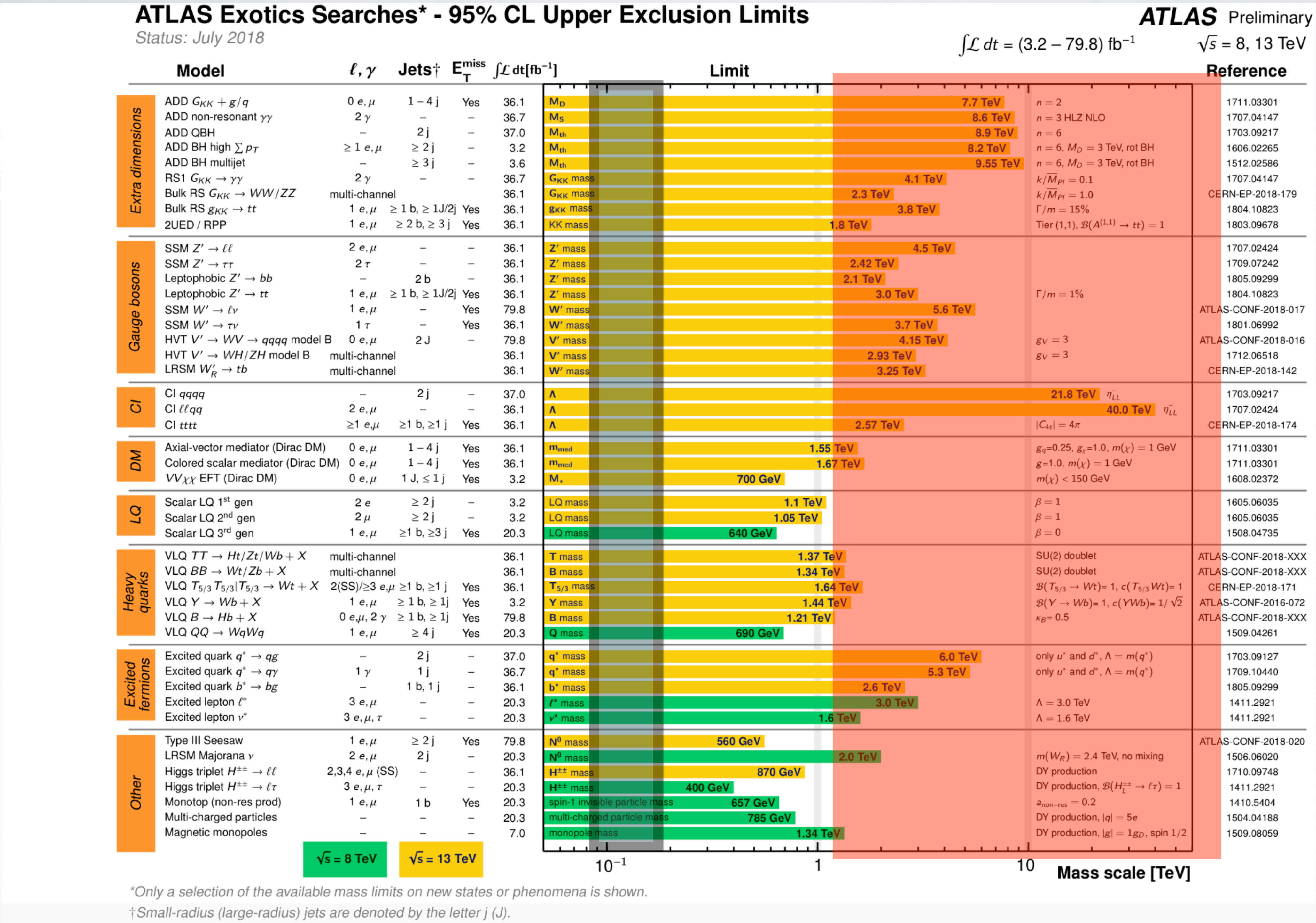
What wasn't discovered at LHC



These bounds have been pushed away from

$$v \sim m_h$$

RunII and beyond: Resonance limits to local operators



Now that these bounds have been pushed away from v

USE that

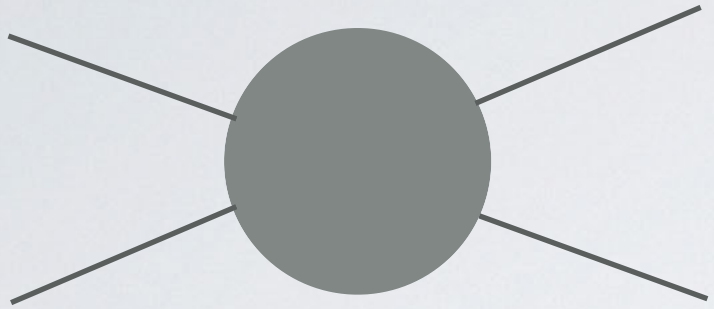
$$v/M < 1$$

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

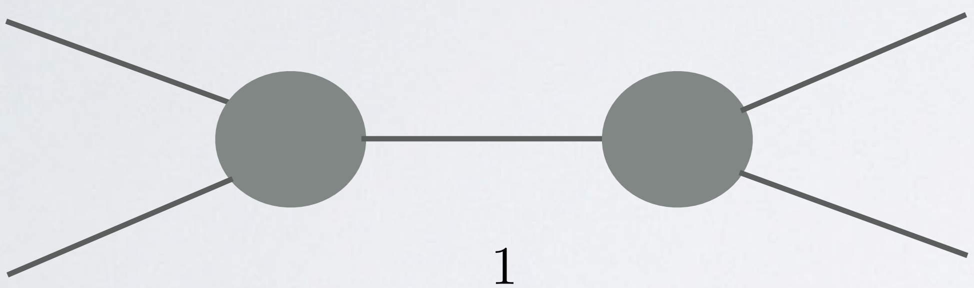
When you do measurements below a particle threshold



- 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.



$$\sim \frac{1}{s - m^2 + i\Gamma(s)\, m}$$

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

- You can Taylor expand in LOCAL functions (operators)

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

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

EFT approach not a guess.

General approach based on S matrix theory and motivated by experimental situation.

General "BSM is heavy" approach is SMEFT

No BSM resonance seen

Decoupling

$v/M < 1$

VERY! Efficient to constrain BSM/interpret the data in EFT

no other (hidden) light states.

SMEFT

observed scalar in doublet

HEFT

observed scalar not in doublet

0704.1505 Grinstein, Trott (for distinction)

Basics of the SMEFT formulation: IR operator form

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

UV dependent Wilson coefficient and suppression scale

Complexity is scaling up…

Linear EFT - built of H doublet + higher D ops

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

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

1 operator, and 7 extra parameters

Complexity is scaling up…

In Warsaw basis arXiv:1008.4884 (SMEFT standard basis)

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

Class		$N_{\rm op}$	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

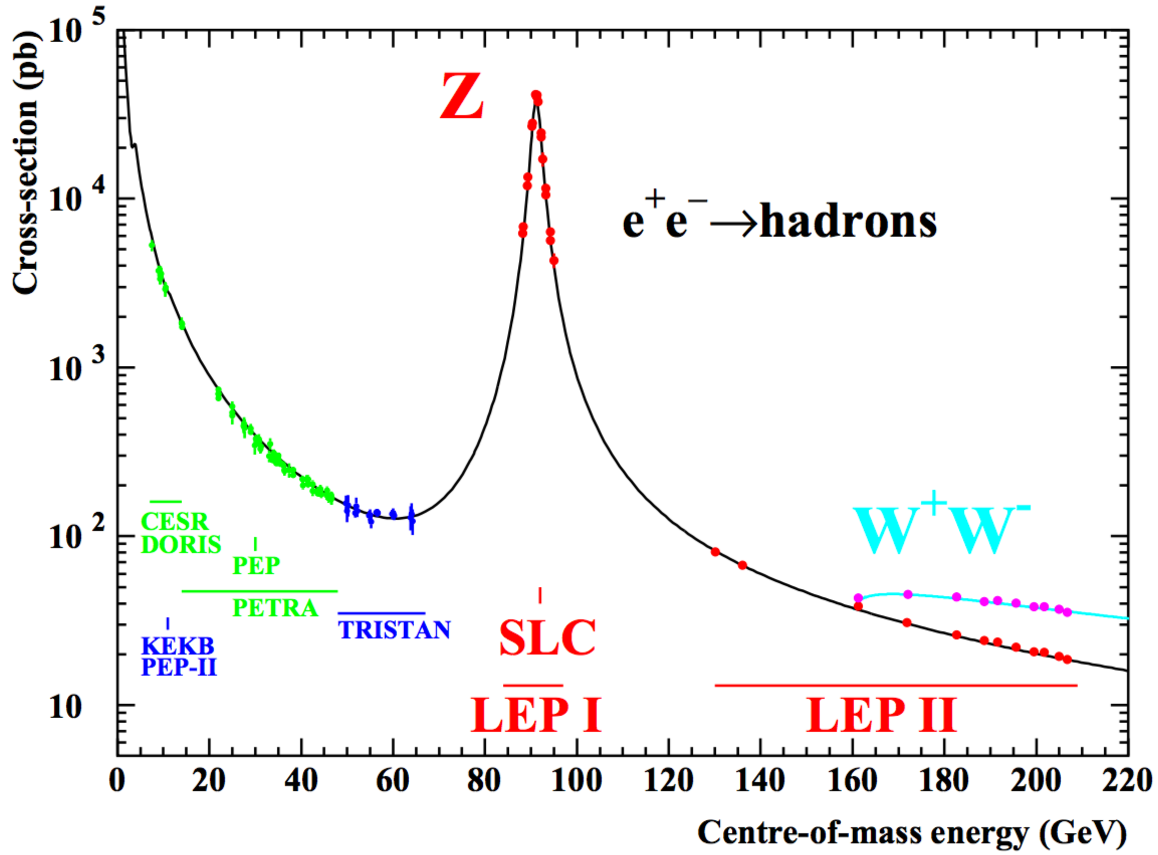
Table 2. Number of CP-even and CP-odd coefficients in $\mathcal{L}^{(6)}$ for n_g flavors. The total number of coefficients is $(107n_g^4+2n_g^3+135n_g^2+60)/4$, which is 76 for $n_g=1$ and 2499 for $n_g=3$.

2499

arXiv:1312.2014 Alonso, Jenkins, Manohar, Trott

Practical applications of the SMEFT

LEP EWPD measurements in SMEFT



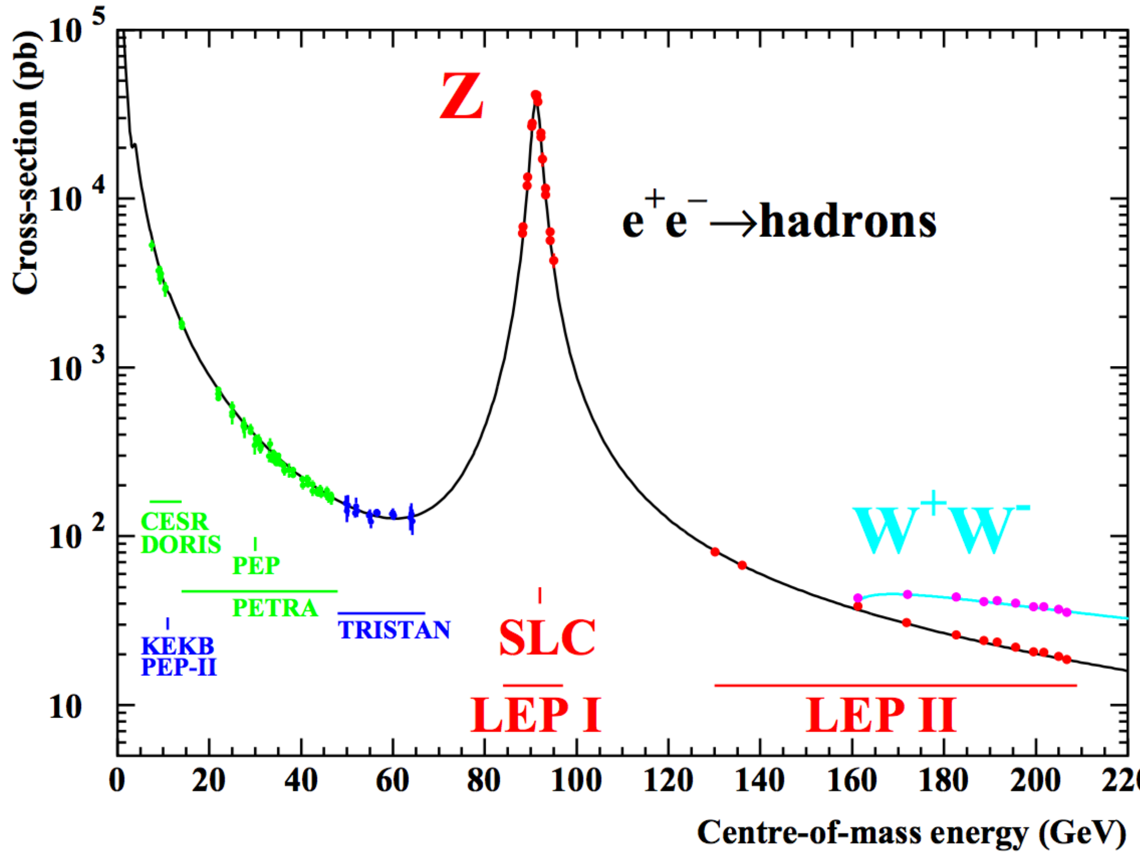
- EWPD is a scan through the Z pole

$\sim 40\, pb^{-1}$ 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



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

SM, usual approach to EWPD

- This is a multi-scale problem

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

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

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

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

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

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

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

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_ℓ^0	20.767 ± 0.025	[19]	20.751 ± 0.005	[48]
R_c^0	0.1721 ± 0.0030	[19]	0.17223 ± 0.00005	[48]
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_{FB}^c	0.0707 ± 0.0035	[19]	0.0735 ± 0.0002	[32]
A_{FB}^b	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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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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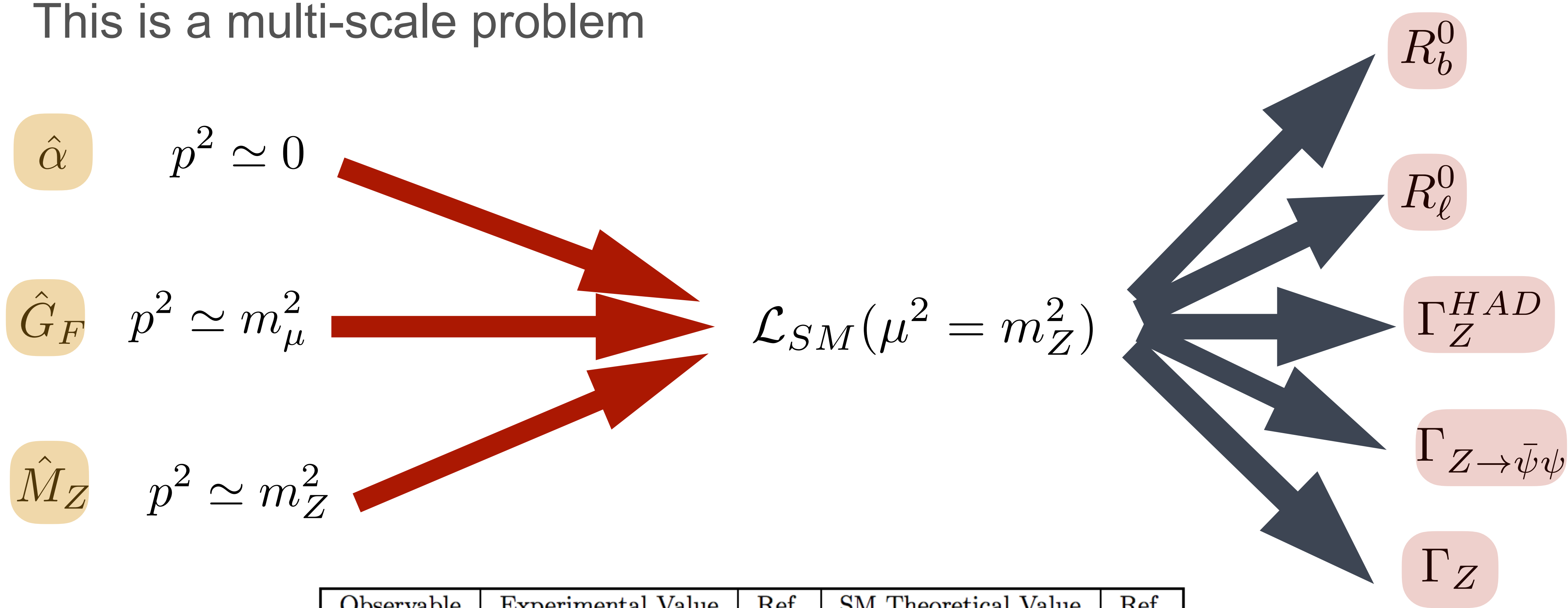

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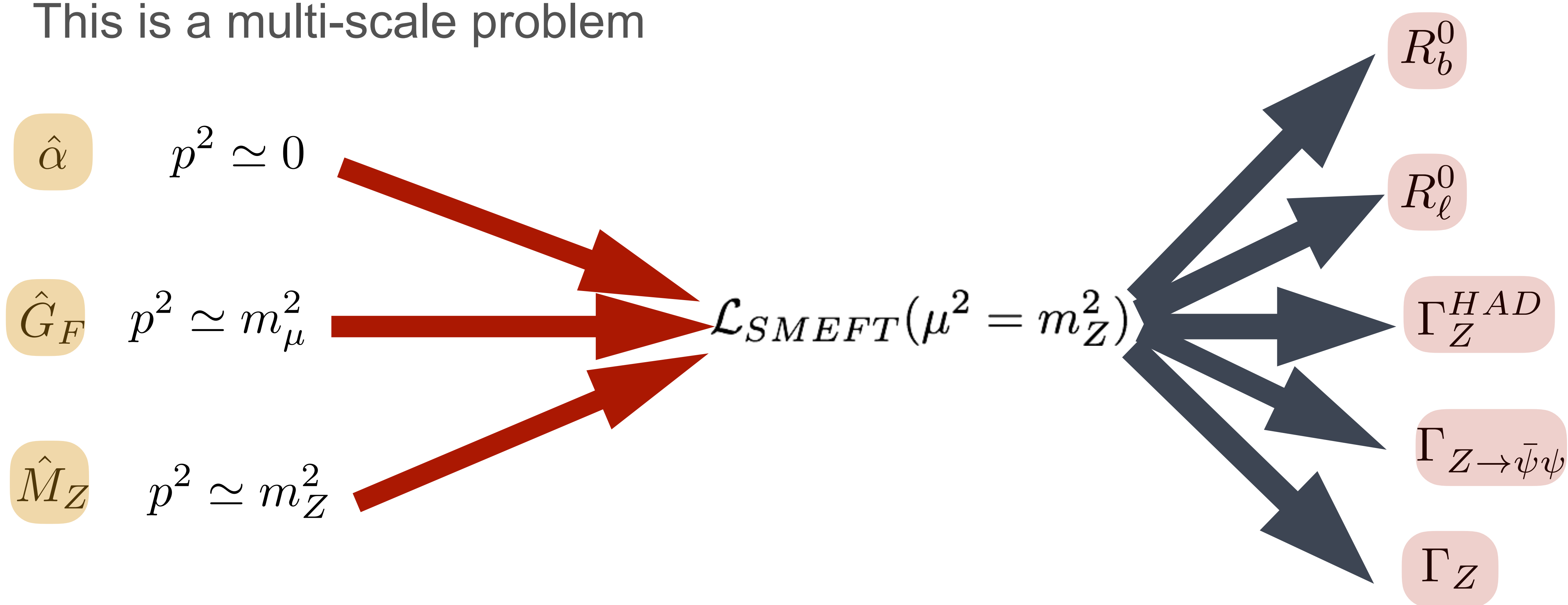
Leading order (LO) SMEFT analysis

- This is a multi-scale problem



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

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

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

ex:

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

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

Leading order (LO) SMEFT analysis

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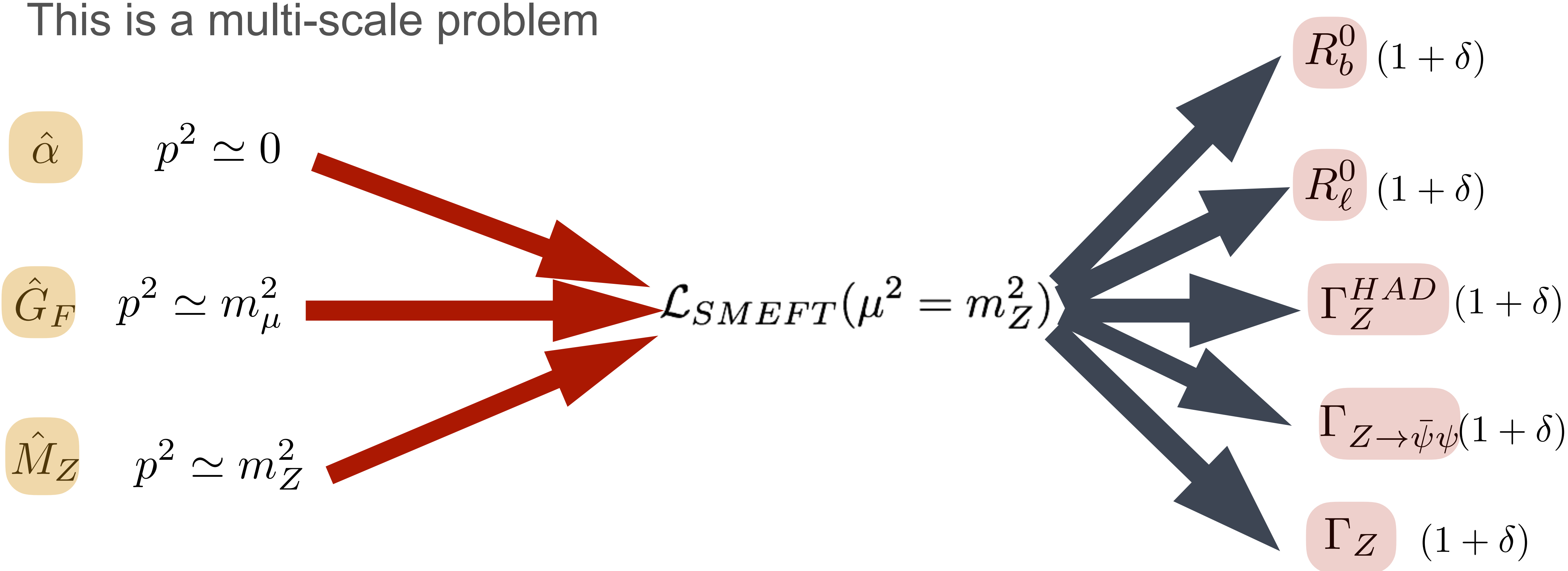
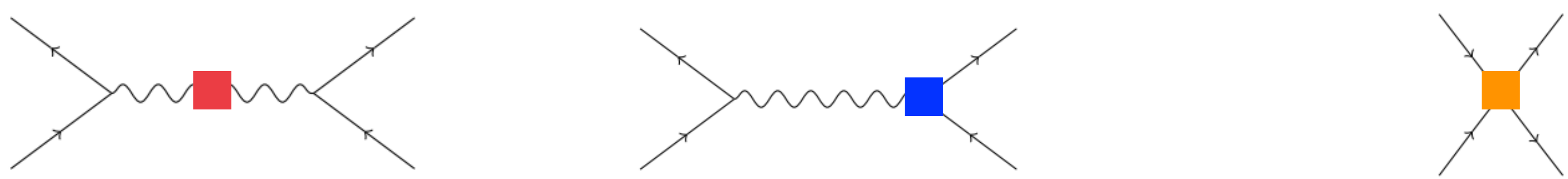


- Lagrangian parameters inferred from inputs now corrected by local contact operators

Leading order (LO) SMEFT analysis

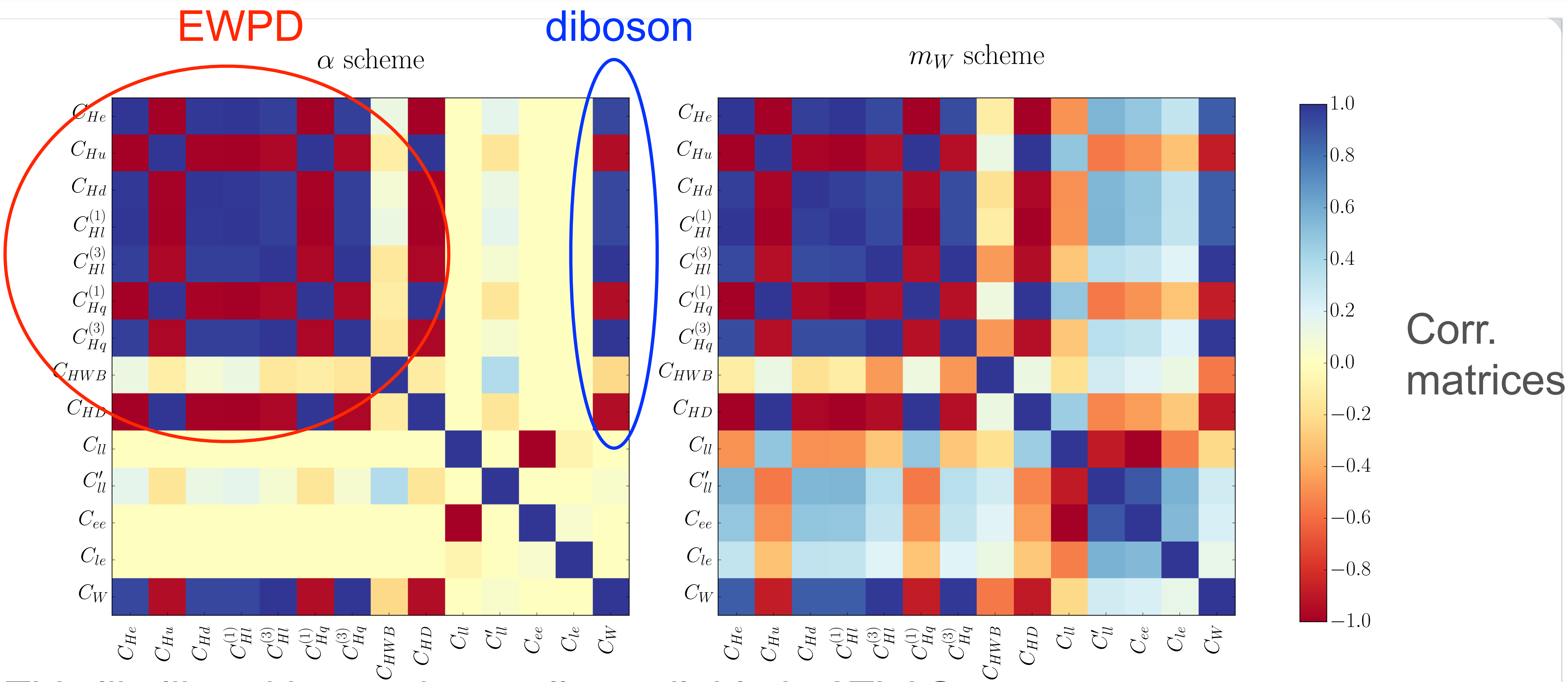
- For measurements of LEPI near Z pole data and W mass at LO:

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



- 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 $\Gamma_{W,Z}/M_{W,Z} \ll 1$

Directly fitting the Z data

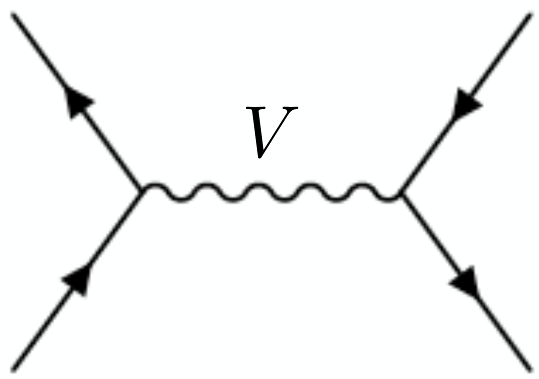


- This likelihood is now internally available in ATLAS
- EWPD Studies that id. correlations in SMEFT as a key issue

Han and Skiba http://arxiv.org/abs/hep-ph/0412166
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

$$H^\dagger H B^{\mu\nu} B_{\mu\nu}, \quad H^\dagger H W^{\mu\nu} W_{\mu\nu}$$

$$\langle y_h\, g_1^2 Q_{HB}\rangle_{S_R} \to \frac{g_1^2\, \bar{v}_T^2}{4\,\Lambda^2} B^{\mu\nu} B_{\mu\nu}, \quad \langle g_2^2 Q_{HW}\rangle_{S_R} \to \frac{g_2^2\, \bar{v}_T^2}{2\,\Lambda^2} W_I^{\mu\nu} W^I_{\mu\nu}.$$

$\bar{\psi}\psi \to \bar{\psi}\psi$

- via $B \to \mathcal{B}(1 + C_{HB} v^2), \qquad g_1 \to \bar{g}_1(1 - C_{HB} v^2)$

  Which leaves $B\, g_1 \to \mathcal{B}\, \bar{g}_1$ invariant.

- LEP data also can't see what is EOM equivalent to these operators in $\bar{\psi}\psi \to \bar{\psi}\psi$

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

$$\langle g_2^2 Q_{HW}\rangle_{S_R} = \boxed{\langle g_2^2\, (\overline{q}\, \tau^I \gamma_\beta q + \bar{l}\, \tau^I \gamma_\beta l)\, (H^\dagger\, i \overleftrightarrow{D}^I_\beta H) + 2\, g_2^2\, Q_{H\Box} - 2\, g_1\, g_2\, y_h\, Q_{HWB}\rangle_{S_R}.}$$

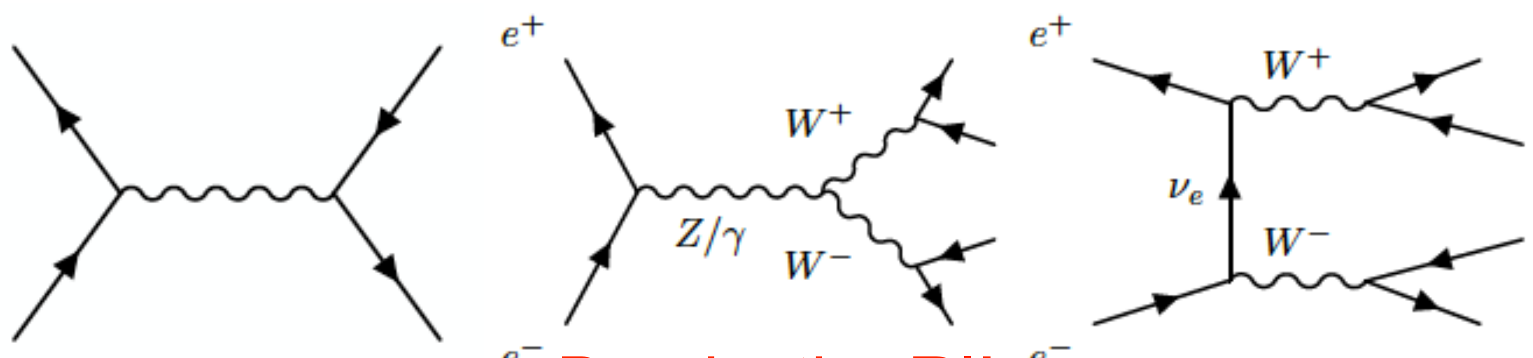
SMEFT reparameterization invariance

- Flat directions discovered in the 2 to 2 scattering data set project onto these EOM equivalent combinations of operators

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

be careful and keep all operators!

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



RI not broken Breaks the RI! RI not broken

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

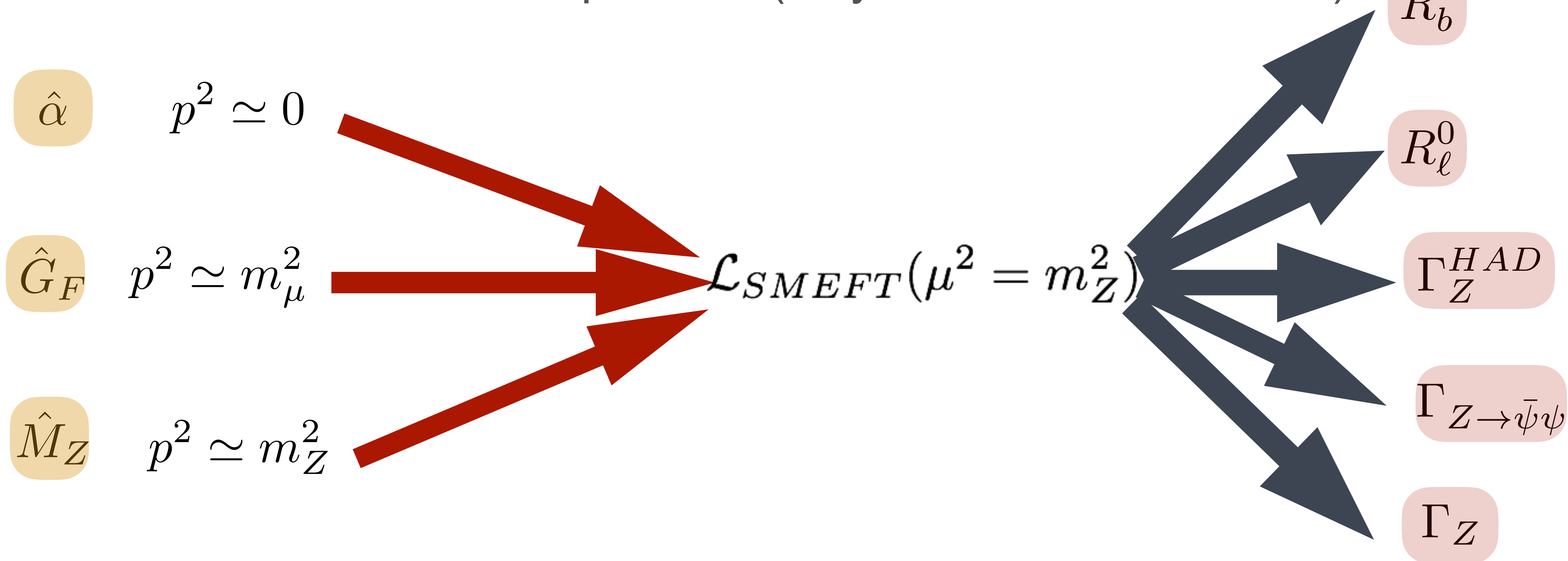
$$Q_W = \varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$$

One loop/Gauge Fixing

SMEFT decay widths of the Z at one loop

arXiv:1611.09879 One Loop Z C. Hartmann, W. Shepherd, MT

- This is a multi-scale hard problem (only $\propto y_t, \lambda$ sorted to date)



- 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

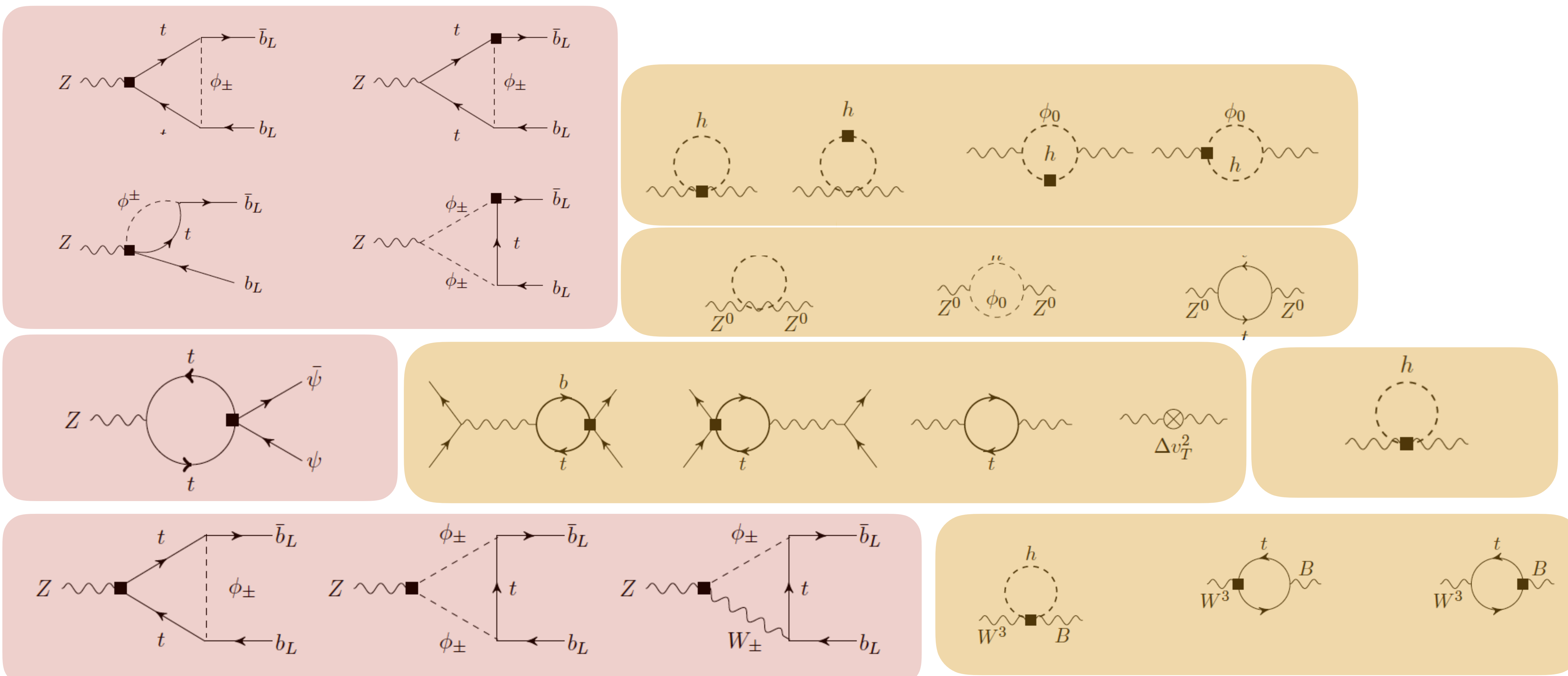
Loops present

- ~ 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

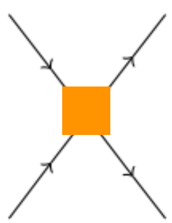


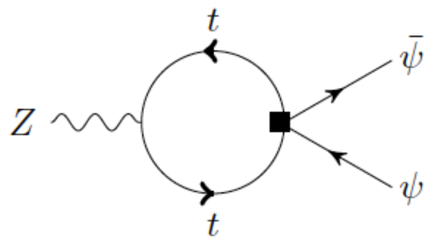
Main conclusions

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

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

- 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

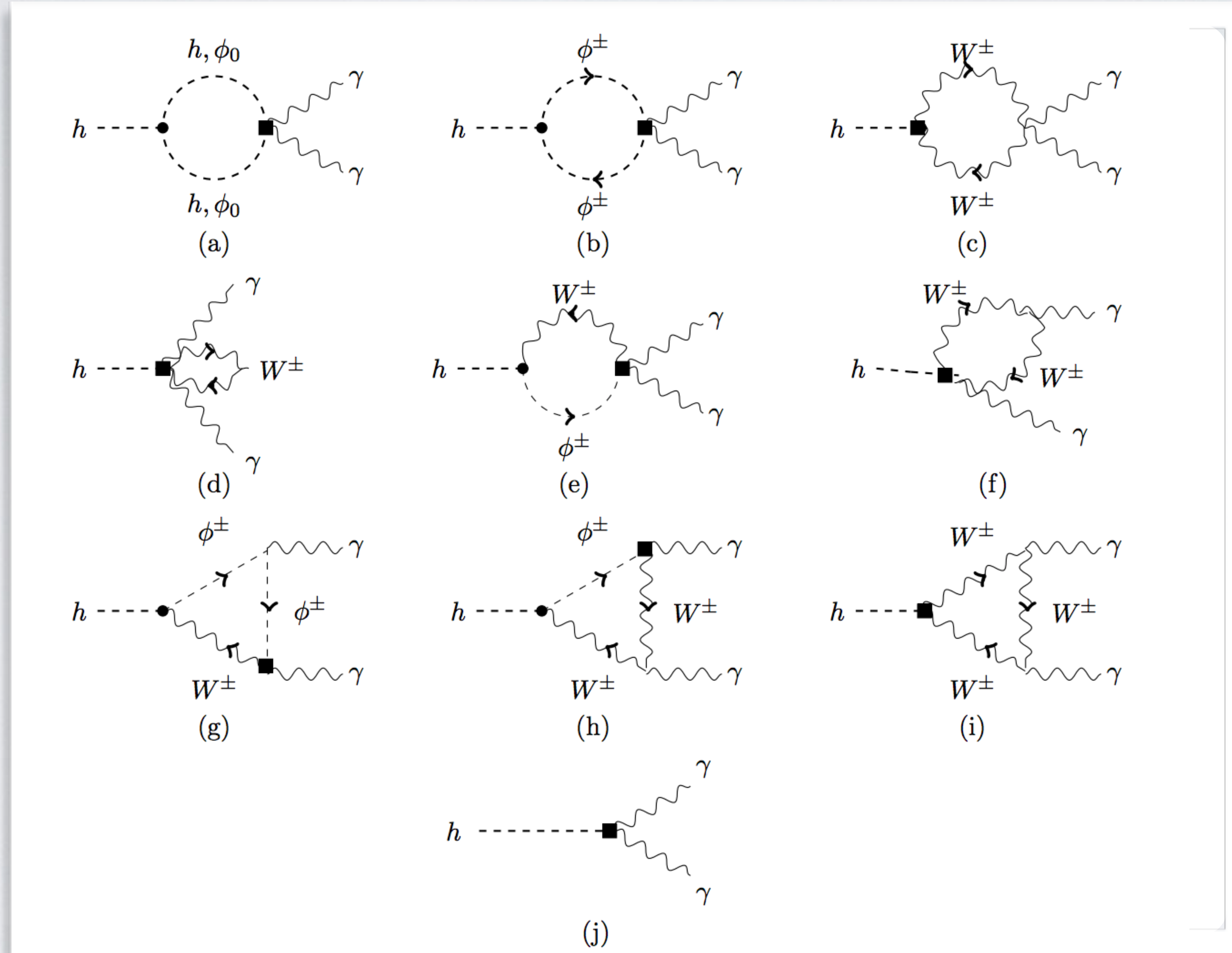
$$Z_{i,j} = \frac{1}{16\,\pi^2} \begin{pmatrix} \frac{g_1^2}{4} - \frac{9g_2^2}{4} + 6\lambda + Y & 0 & g_1^2 \\ 0 & -\frac{3g_1^2}{4} - \frac{5g_2^2}{4} + 6\lambda + Y & g_2^2 \\ \frac{3g_2^2}{2} & \frac{g_1^2}{2} & -\frac{g_1^2}{4} + \frac{9g_2^2}{4} + 2\lambda + Y \end{pmatrix}$$

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

- Counter-term subtraction is proportional to v

The required loops.

- Calculate in BF method, in R_ξ gauge, for operators that contribute at tree level



- Gauge dependence cancels ✓ remaining divergences cancel exactly ✓

Renormalization conditions

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

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

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

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

This relation follows from a Ward identity using BFM.

NLO SMEFT

1505.02646 Hartmann, Trott
1507.03568 Hartmann, Trott

- The final tree result is of the form

$$
\begin{aligned}
\frac{i\,\mathcal{A}^{NP}_{total}}{i\,v\,e^2\,A^{h\gamma\gamma}_{\alpha\beta}} &= C_{\gamma\gamma}\left(1+\frac{\delta R_h}{2}+\frac{\delta\,v}{v}\right),\\
&+\left(\frac{C_{\gamma\gamma}}{16\,\pi^2}\left(\frac{g_1^2}{4}+\frac{3\,g_2^2}{4}+6\,\lambda\right)+\frac{C_{HWB}}{16\,\pi^2}\left(-3\,g_2^2+4\,\lambda\right)\right)\log\left(\frac{m_h^2}{\Lambda^2}\right),\\
&+\frac{C_{\gamma\gamma}}{16\,\pi^2}\left(\left(\frac{g_1^2}{4}+\frac{g_2^2}{4}+\lambda\right)\mathcal{I}[m_Z^2]+\left(\frac{g_2^2}{2}+2\lambda\right)\mathcal{I}[m_W^2]+(\sqrt{3}\,\pi-6)\,\lambda\right),\\
&+\frac{C_{HWB}}{16\,\pi^2}\left(2e^2\left(1+6\frac{m_W^2}{m_h^2}\right)-2\,g_2^2\left(1+\log\left(\frac{m_W^2}{m_h^2}\right)\right)+(4\,\lambda-g_2^2)\;\mathcal{I}[m_W^2],\right.\\
&\qquad\left.+4\left(3e^2-g_2^2-6e^2\frac{m_W^2}{m_h^2}\right)\mathcal{I}_y[m_W^2]\right),\\
&-\frac{g_2^2\,C_{HW}}{4\,\pi^2}\left(3\,\frac{m_W^2}{m_h^2}+\left(4-\frac{m_h^2}{m_W^2}-6\frac{m_W^2}{m_h^2}\right)\mathcal{I}_y[m_W^2]\right).
\end{aligned}
\tag{3.6}
$$

Where

$$C_{\gamma\gamma}^{NP}=C_{HB}+C_{HW}-C_{HWB}$$

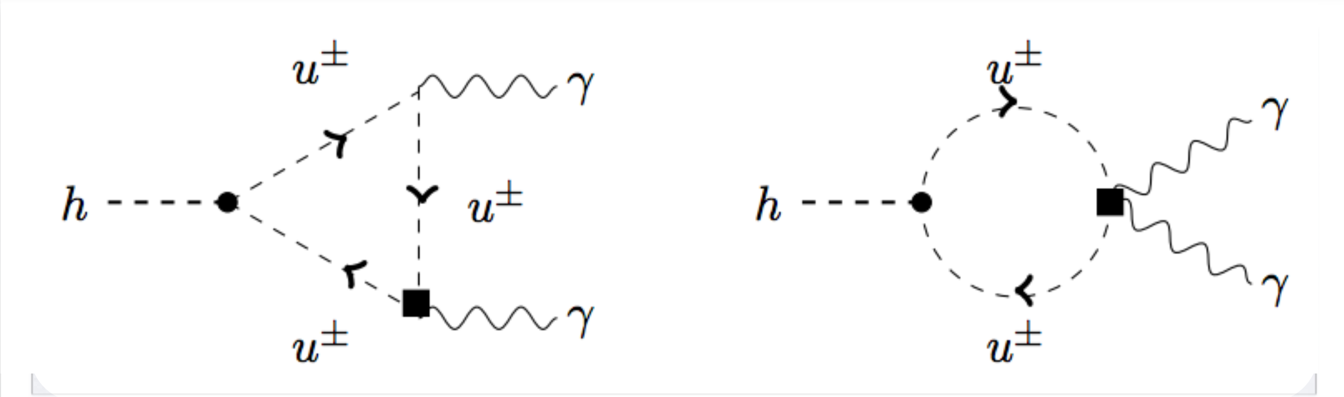
$$\mathcal{I}[m^2]\equiv\int_0^1 dx\,\log\left(\frac{m^2-m_h^2\,x\,(1-x)}{m_h^2}\right),\quad \mathcal{I}_y[m^2]\equiv\int_0^{1-x}dy\int_0^1 dx\,\frac{m^2}{m^2-m_h^2\,x\,(1-x-y)},$$

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.

$$\mathcal{L}_{FP} = -\bar{u}^\alpha \, \frac{\delta G^\alpha}{\delta \theta^\beta} \, u^\beta.$$

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



- This cancels the unusual divergences in $\Gamma_{SMEFT}(h \to \gamma\gamma)$ 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

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

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"

arXiv:1803.08001 Helset, Paraskevas, Trott

$$\mathcal{L}_{\rm GF} = -\frac{\hat{g}_{AB}}{2\,\xi}\mathcal{G}^A\,\mathcal{G}^B,$$

$$\mathcal{G}^X \equiv \partial_\mu \mathcal{W}^{X,\mu} - \tilde{\epsilon}^X_{\ CD}\hat{\mathcal{W}}^C_\mu \mathcal{W}^{D,\mu} + \frac{\xi}{2}\hat{g}^{XC}\phi^I\,\hat{h}_{IK}\,\tilde{\gamma}^K_{C,J}\hat{\phi}^J.$$

$$\int \mathcal{D}F \det\left[\frac{\Delta\mathcal{G}^A}{\Delta\alpha^B}\right] e^{i\left(S[F+\hat{F}]+\mathcal{L}_{\rm GF}+\hat{g}_{CD}J^C_\mu \mathcal{W}^{D,\mu}+\hat{h}_{IJ}J^I_\phi\phi^J\right)}.$$

SMEFT gauge fixing solution!

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

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

$$\mathcal{L}_{\rm GF} = -\frac{\hat{g}_{AB}}{2\,\xi} \mathcal{G}^A \mathcal{G}^B ,$$

$$\mathcal{G}^X \equiv \partial_\mu \mathcal{W}^{X,\mu} - \tilde{\epsilon}^X_{CD} \hat{\mathcal{W}}^C_\mu \mathcal{W}^{D,\mu} + \frac{\xi}{2} \hat{g}^{XC} \phi^I \, \hat{h}_{IK} \, \tilde{\gamma}^K_{C,J} \hat{\phi}^J .$$

$$\int \mathcal{D}F \det \left[\frac{\Delta \mathcal{G}^A}{\Delta \alpha^B} \right] e^{i \left(S[F+\hat{F}] + \mathcal{L}_{\rm GF} + \hat{g}_{CD} J^C_\mu \mathcal{W}^{D,\mu} + \hat{h}_{IJ} J^I_\phi \phi^J \right)} .$$

SMEFT gauge fixing solution!

$$\mathcal{L}_{\text{scalar,kin}} = (D_\mu H)^\dagger (D^\mu H) + C_{H\Box} (H^\dagger H) \Box (H^\dagger H) + C_{HD} (H^\dagger D_\mu H)^* (H^\dagger D^\mu H), \qquad \equiv \frac{1}{2} h_{IJ}(\phi) (D_\mu \phi)^I (D^\mu \phi)^J .$$

$$\mathcal{L}_{\text{WB}} = -\frac{1}{4} W^a_{\mu\nu} W^{a,\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \frac{C_{HB}}{\Lambda^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{C_{HW}}{\Lambda^2} H^\dagger H W^a_{\mu\nu} W^{a,\mu\nu} + \frac{C_{HWB}}{\Lambda^2} H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}, \qquad \equiv -\frac{1}{4} g_{AB}(H) \mathcal{W}^A_{\mu\nu} \mathcal{W}^{B,\mu\nu},$$

$$\mathcal{L}_{\text{GF}} = -\frac{\hat{g}_{AB}}{2\,\xi} \mathcal{G}^A \mathcal{G}^B,$$

$$\mathcal{G}^X \equiv \partial_\mu \mathcal{W}^{X,\mu} - \tilde{\epsilon}^X_{CD} \hat{\mathcal{W}}^C_\mu \mathcal{W}^{D,\mu} + \frac{\xi}{2} \hat{g}^{XC} \phi^I \hat{h}_{IK} \tilde{\gamma}^K_{C,J} \hat{\phi}^J .$$

$$\int \mathcal{D}F \det \left[\frac{\Delta \mathcal{G}^A}{\Delta \alpha^B} \right] e^{i\left(S[F+\hat{F}] + \mathcal{L}_{\text{GF}} + \hat{g}_{CD} J^C_\mu \mathcal{W}^{D,\mu} + \hat{h}_{IJ} J^I_\phi \phi^J\right)}.$$

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

SMEFTsim

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 : https://arxiv.org/abs/1709.06492

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.

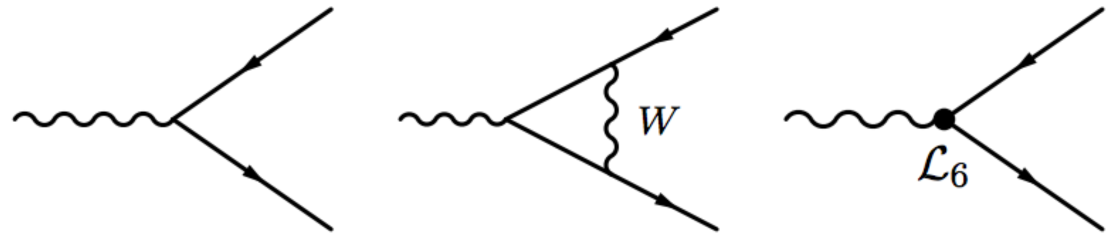
.. are there too many parameters?

- Number of parameters convolution of power counting

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

<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

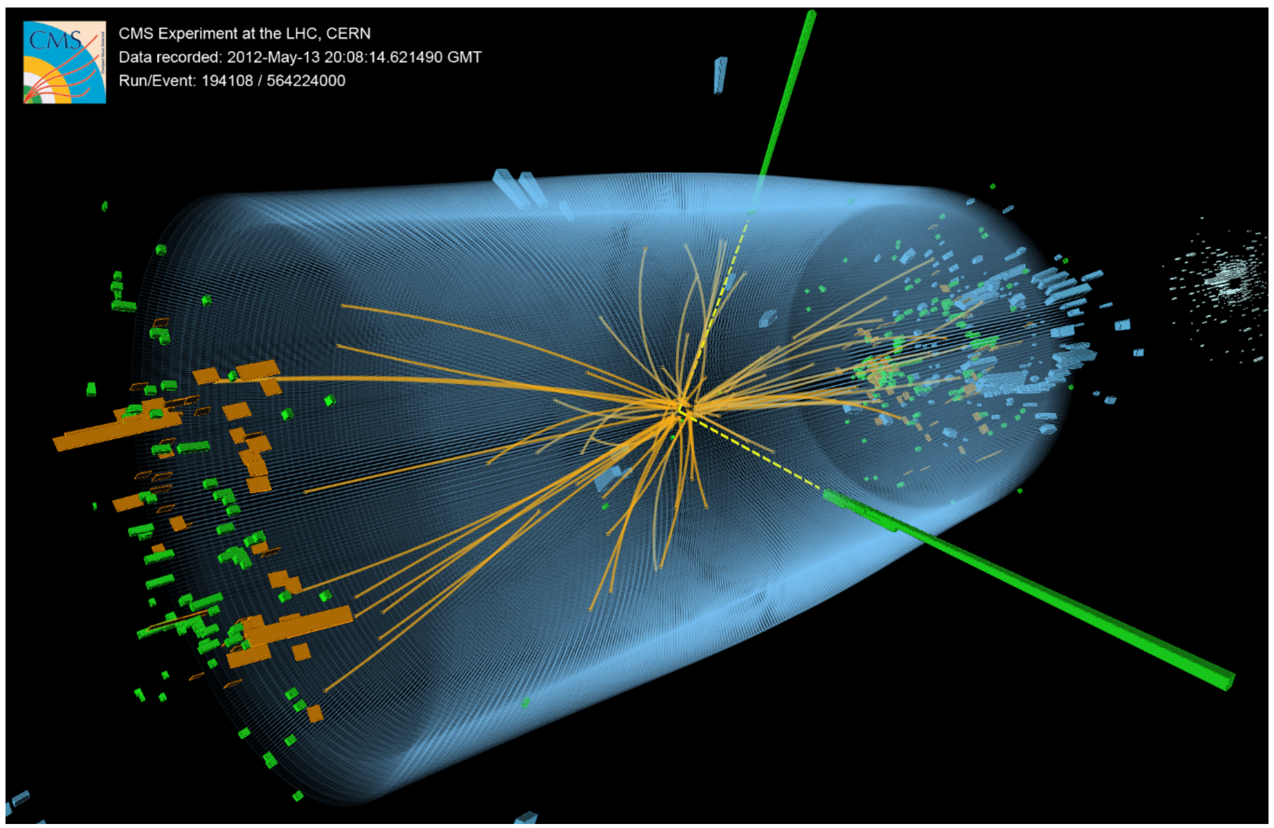
$$\left(\frac{\Gamma_B\, m_B}{\bar{v}_T^2}\right)\frac{\{\mathrm{Re}(C),\mathrm{Im}(C)\}}{g_{SM}\, C_i}, \qquad \left(\frac{\Gamma_B\, m_B}{p_i^2}\right)\frac{\{\mathrm{Re}(C),\mathrm{Im}(C)\}}{g_{SM}\, C_k},$$

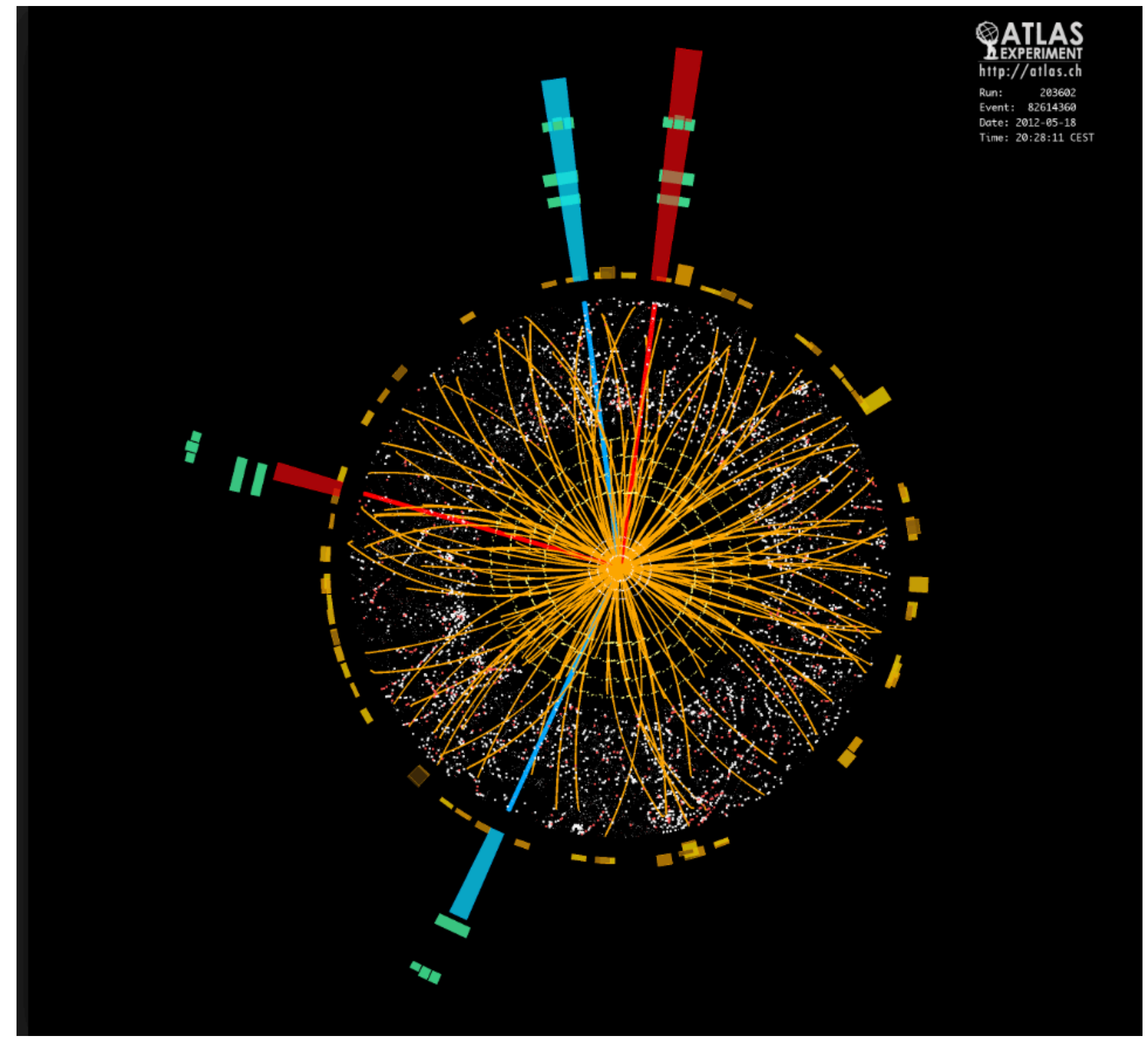
Measurement/facility design can DEFINE a subset of SMEFT parameters in a fit

The evolution of Higgs studies

State of the art Higgs properties

- How do we learn about the properties of the Higgs?

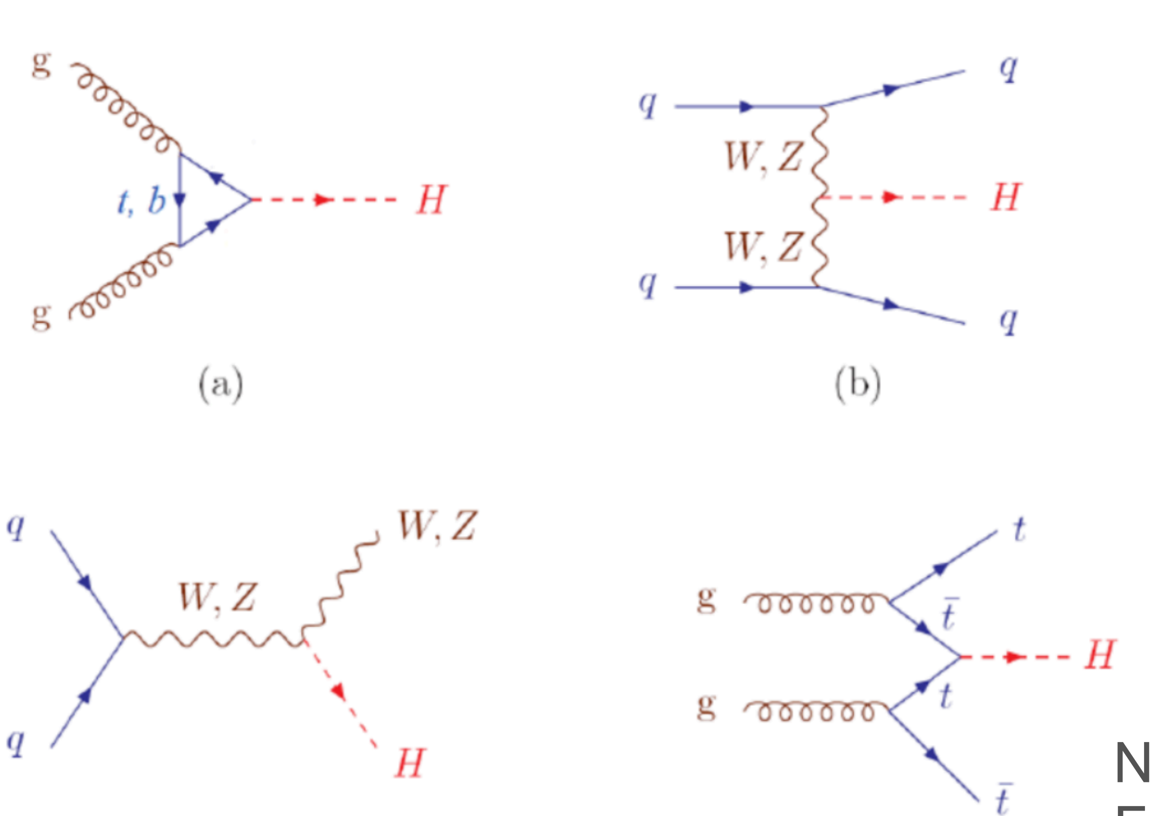


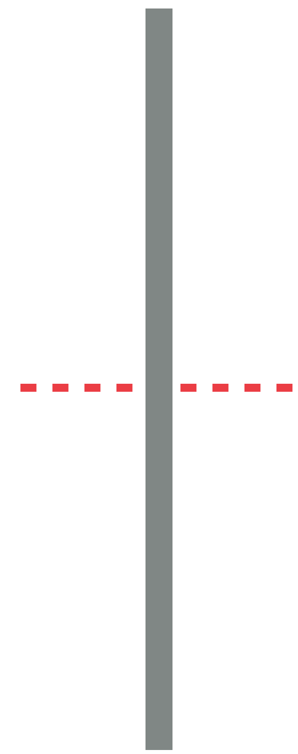


- Raw events are process to measured event rates.

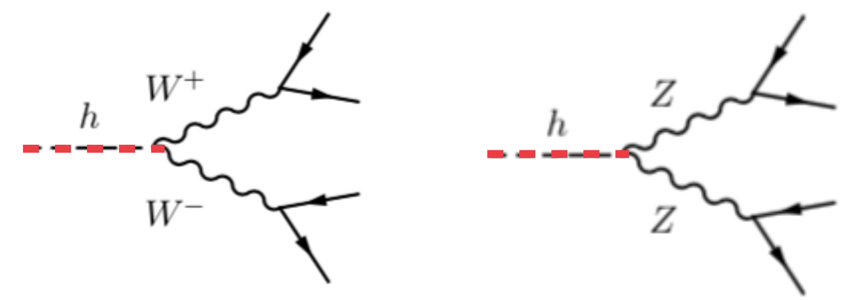
State of the art Higgs properties

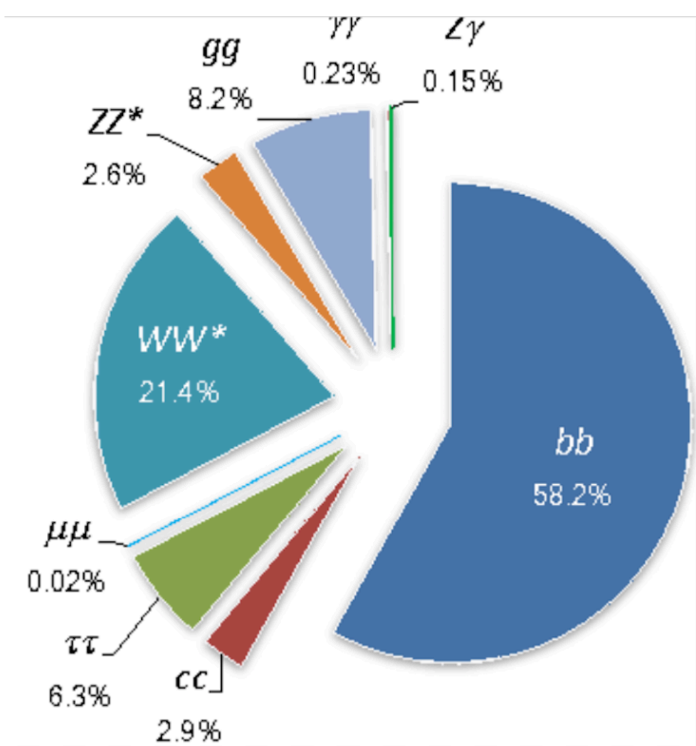
- Raw events are processed to measured (relative) event rates.





Narrow width
Factorisation of
Production and decay



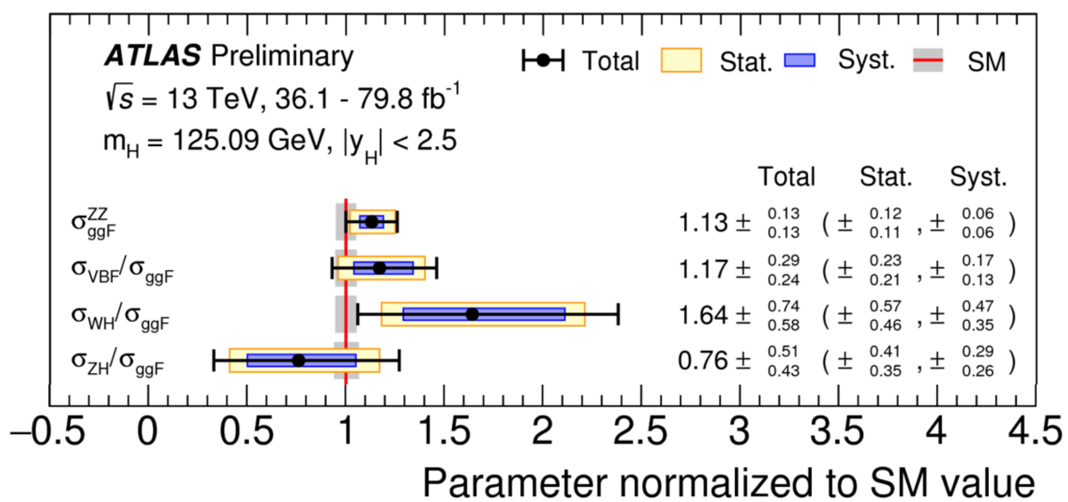


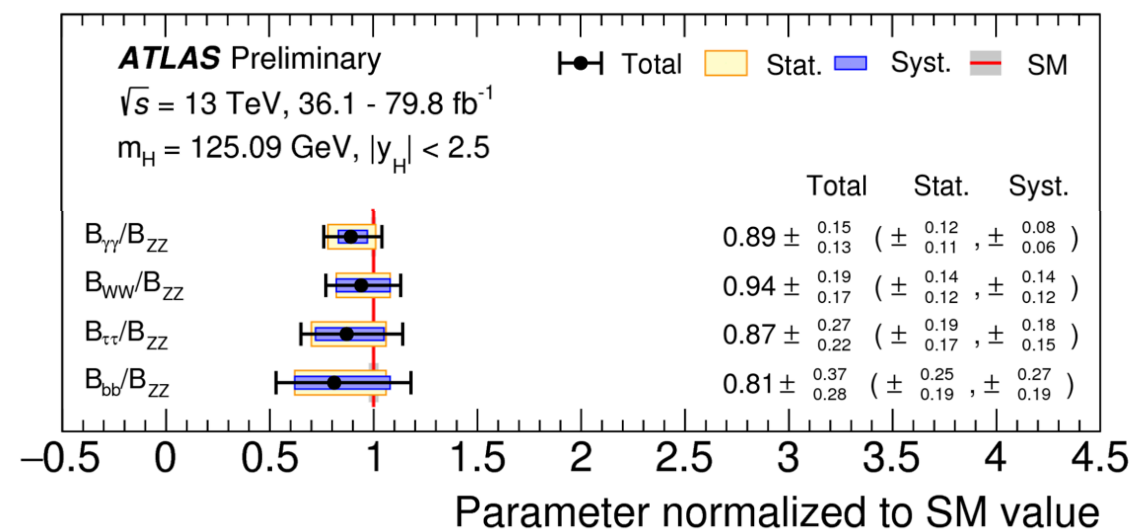
Higgs production

Higgs decay

Under a SM like assumption

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



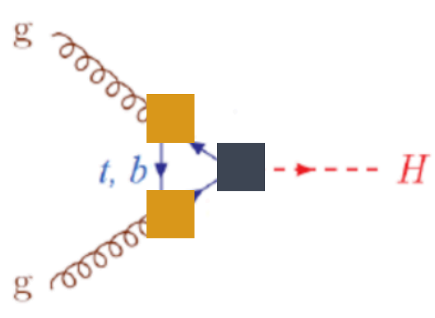


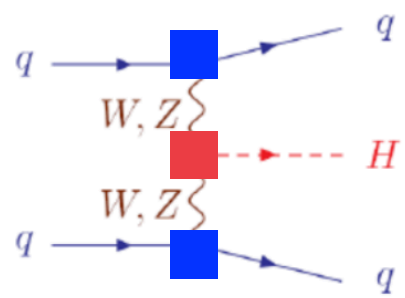
Narrow width
Factorisation of
Production and decay

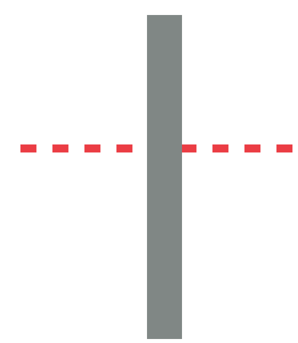
- You need a theory to do the inference to define the relative event rates. This analysis uses a “SM like” assumption at many key points.

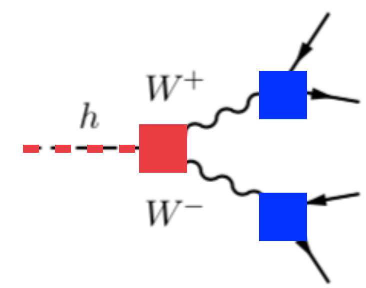
State of the art Higgs properties

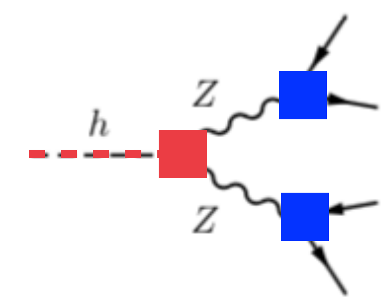
- Various operator based perturbations can appear

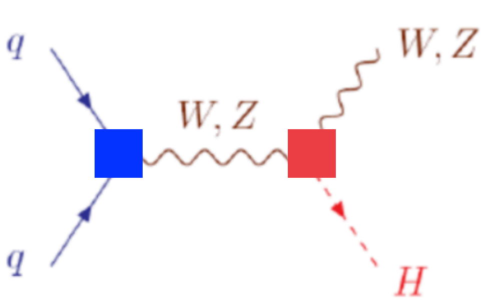


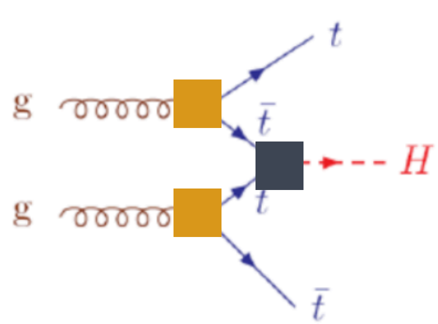












X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$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

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

- Q: Does the analysis "SM like" assumption fail in the SMEFT? Can we use the result?
- A: "We are looking into it."

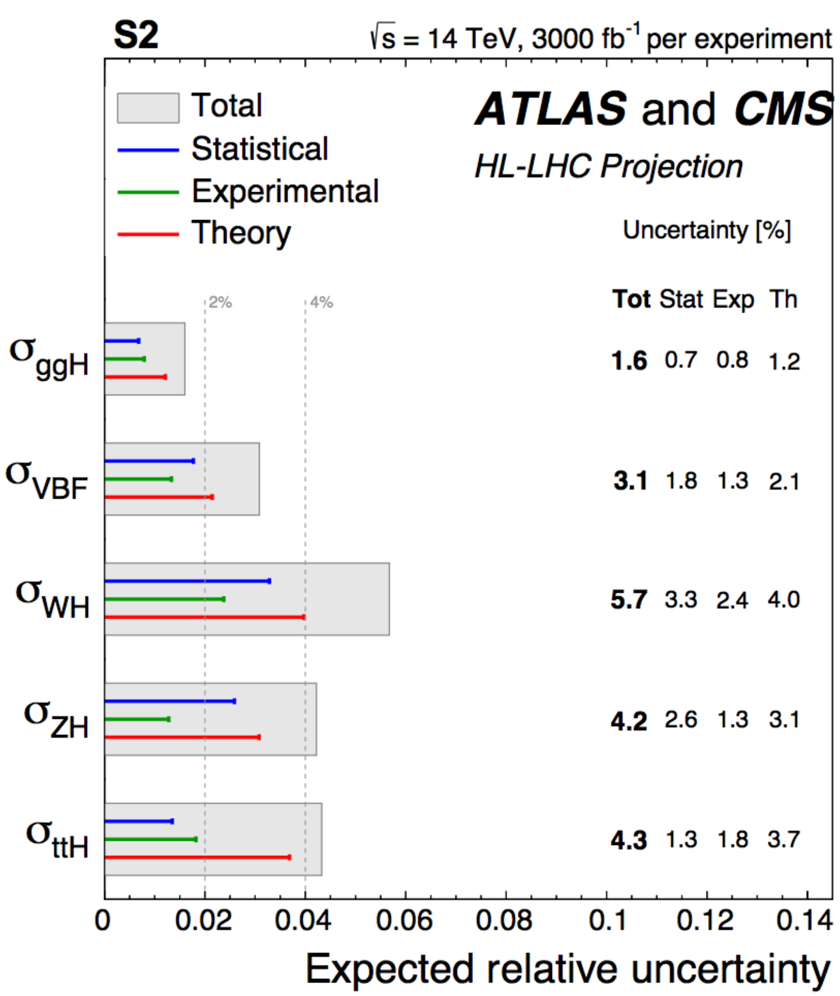
More precision on the EXP side

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

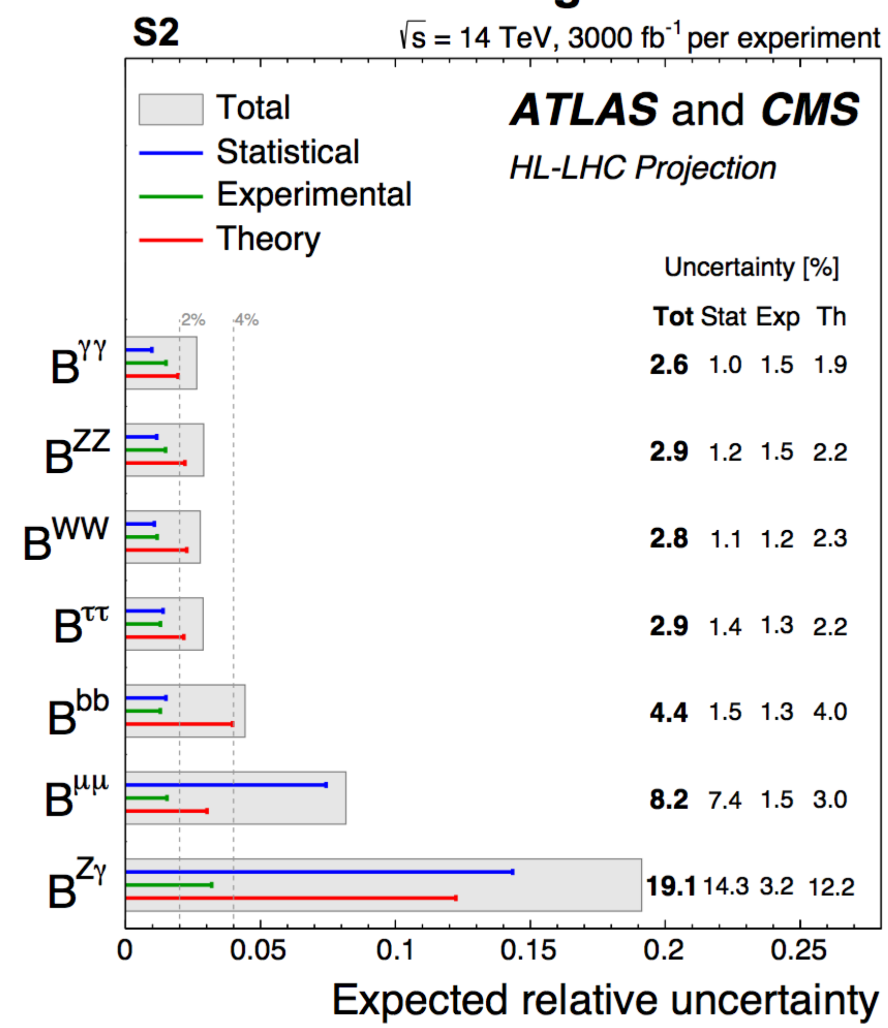
Combined Higgs coupling measurements

2030+ knowledge
A. De Wit HL-LHC projection

Production cross sections



Branching ratios



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.