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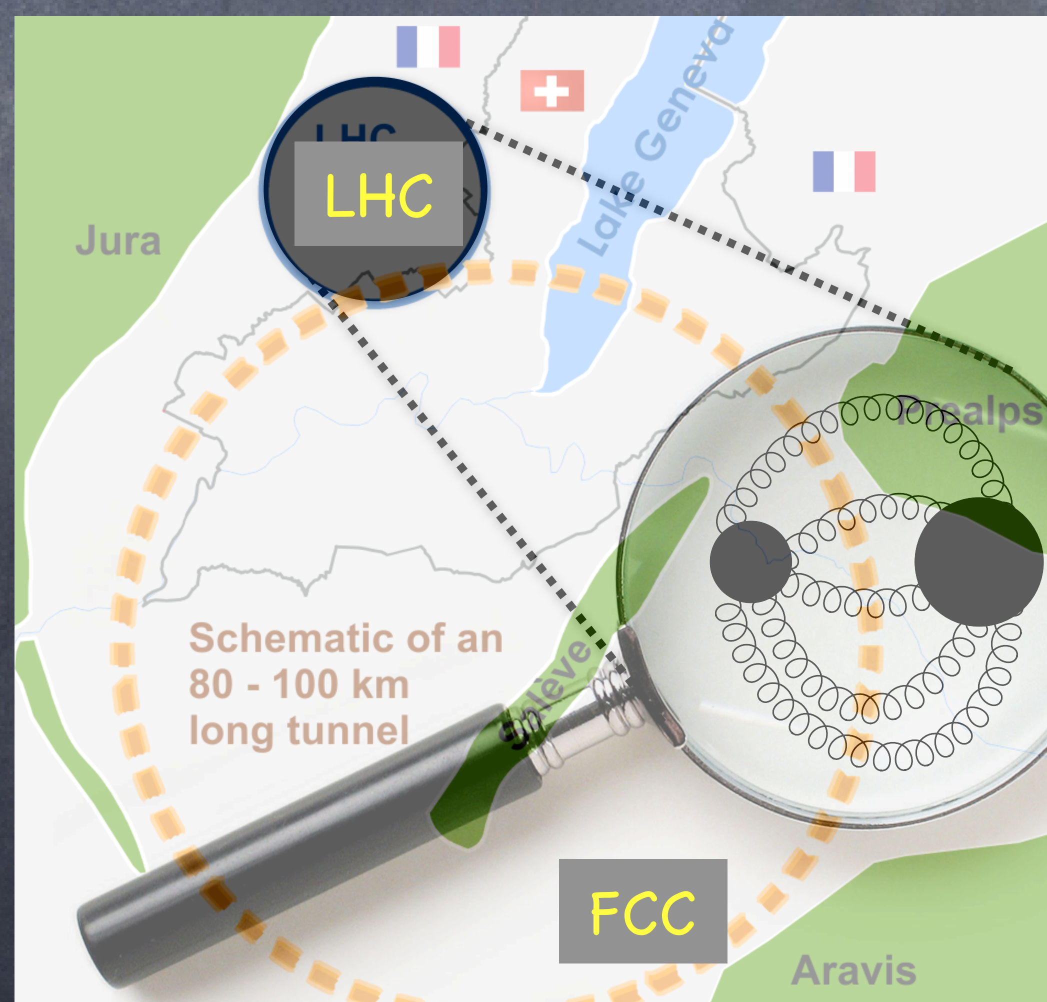
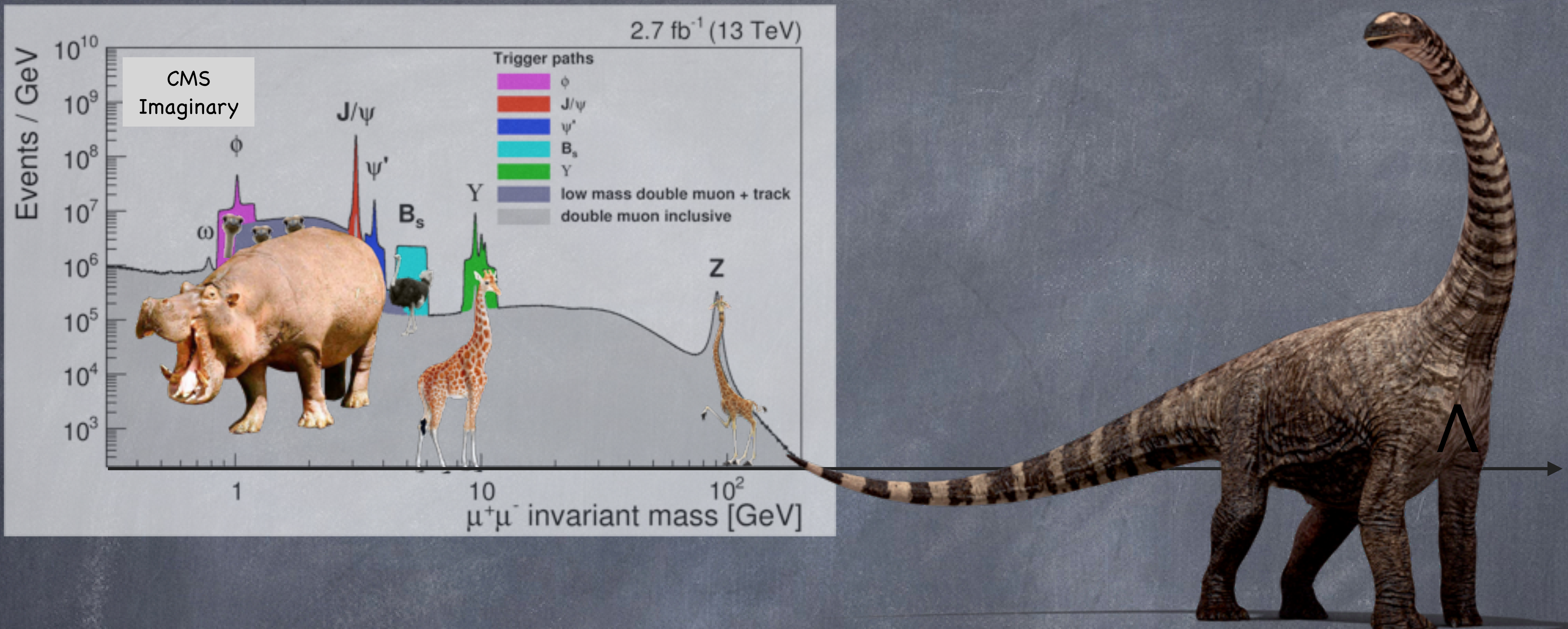
EFT at FCC

CERN, 17 January 2017



Philosophy
of
EFT

Fantastic Beasts and Where To Find Them



- It is quite likely that mass scale Λ of BSM particles is beyond kinematic reach of current and near-future colliders
- If that is true, EFT may be only way to collect partial information about BSM structure (much like Fermi theory taught us about W and Z before they could be produced)
- Even if new particles can be reached directly, EFT useful and compact framework for practical calculations at E << Λ (much like we still use Fermi effective theory to calculate weak decays of particles with m << mZ)

SM EFT Approach to BSM

Basic assumptions

- Much as in SM, relativistic QFT with linearly realized SU(3)xSU(2)xU(1) local symmetry spontaneously broken by VEV of Higgs doublet field

- Mass scale Λ of new particles separated from characteristic energy scale E of experiment, $\Lambda \gg E$, such that experimental observables can be expanded in powers of E/Λ

SM EFT Lagrangian expanded in inverse powers of Λ, equivalently in operator dimension D

$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}^{D=5} + \frac{1}{\Lambda^2}\mathcal{L}^{D=6} + \frac{1}{\Lambda^3}\mathcal{L}^{D=7} + \frac{1}{\Lambda^4}\mathcal{L}^{D=8} + \dots$$

Lepton number or B-L violating,
hence too small to probed at present
and near-future colliders

By assumption,
subleading
to D=6

Generated by integrating out
heavy particle with mass scale Λ
In large class of BSM models,
describe leading effects of new physics
on collider observables at E << Λ

Advantages of SM EFT

- Framework general enough to describe leading effects of a large class of BSM scenarios
- Theoretical correlations between signal and background and different signal channels taken into account
- Very easy to recast SM EFT results as constraints on specific BSM models
- SM EFT is consistent QFT, so that calculations and predictions can be systematically improved (higher-loops, higher order terms in EFT expansion if needed). In particular, SM EFT is renormalizable when working at given order in $1/\Lambda$ expansion
- Some tools to assess validity of $1/\Lambda$ expansion

Many possible D=6 operators!

One example of non-redundant set, so-called SILH basis

Giudice et al hep-ph/0703164

Contino et al 1303.3876

Table 97: Bosonic D=6 operators in the SILH basis.

Bosonic CP-even		Bosonic CP-odd	
O_H	$\frac{1}{2v^2}\left[\partial_\mu(H^\dagger H)\right]^2$		
O_T	$\frac{1}{2v^2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$		
O_6	$-\frac{\lambda}{v^2}(H^\dagger H)^3$		
O_g	$\frac{g_s^2}{m_W^2} H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu}$	$\widetilde{O}_g$	$\frac{g_s^2}{m_W^2} H^\dagger H\, \widetilde{G}^a_{\mu\nu} G^a_{\mu\nu}$
O_γ	$\frac{g'^2}{m_W^2} H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$	$\widetilde{O}_\gamma$	$\frac{g'^2}{m_W^2} H^\dagger H\, \widetilde{B}_{\mu\nu} B_{\mu\nu}$
O_W	$\frac{ig}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D}_\mu H\right) D_\nu W^i_{\mu\nu}$		
O_B	$\frac{ig'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \partial_\nu B_{\mu\nu}$		
O_{HW}	$\frac{ig}{m_W^2}\left(D_\mu H^\dagger \sigma^i D_\nu H\right) W^i_{\mu\nu}$	$\widetilde{O}_{HW}$	$\frac{ig}{m_W^2}\left(D_\mu H^\dagger \sigma^i D_\nu H\right) \widetilde{W}^i_{\mu\nu}$
O_{HB}	$\frac{ig'}{m_W^2}\left(D_\mu H^\dagger D_\nu H\right) B_{\mu\nu}$	$\widetilde{O}_{HB}$	$\frac{ig}{m_W^2}\left(D_\mu H^\dagger D_\nu H\right) \widetilde{B}_{\mu\nu}$
O_{2W}	$\frac{1}{m_W^2} D_\mu W^i_{\mu\nu} D_\rho W^i_{\rho\nu}$		
O_{2B}	$\frac{1}{m_W^2} \partial_\mu B_{\mu\nu} \partial_\rho B_{\rho\nu}$		
O_{2G}	$\frac{1}{m_W^2} D_\mu G^a_{\mu\nu} D_\rho G^a_{\rho\nu}$		
O_{3W}	$\frac{g^3}{m_W^2} \epsilon^{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$	$\widetilde{O}_{3W}$	$\frac{g^3}{m_W^2} \epsilon^{ijk} \widetilde{W}^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$
O_{3G}	$\frac{g_s^3}{m_W^2} f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$	$\widetilde{O}_{3G}$	$\frac{g_s^3}{m_W^2} f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$

Table 98: Two-fermion dimension-6 operators in the SILH basis. They are the same as in the Warsaw basis, except that the operators $[O_{H\ell}]_{11}$, $[O'_{H\ell}]_{11}$ are absent by definition. We define $\sigma_{\mu\nu} = i[\gamma_\mu, \gamma_\nu]/2$. In this table, e, u, d are always right-handed fermions, while ℓ and q are left-handed. For complex operators the complex conjugate operator is implicit.

Vertex		Yukawa and Dipole	
$[O_{H\ell}]_{ij}$	$\frac{i}{v^2}\bar\ell_i \gamma_\mu \ell_j H^\dagger \overleftrightarrow{D}_\mu H$	$[O_e]_{ij}$	$\frac{\sqrt{2m_{e_i} m_{e_j}}}{v^3} H^\dagger H \bar\ell_i H e_j$
$[O'_{H\ell}]_{ij}$	$\frac{i}{v^2}\bar\ell_i \sigma^k \gamma_\mu \ell_j H^\dagger \sigma^k \overleftrightarrow{D}_\mu H$	$[O_u]_{ij}$	$\frac{\sqrt{2m_{u_i} m_{u_j}}}{v^3} H^\dagger H \bar q_i \tilde H u_j$
$[O_{He}]_{ij}$	$\frac{i}{v^2}\bar e_i \gamma_\mu \bar e_j H^\dagger \overleftrightarrow{D}_\mu H$	$[O_d]_{ij}$	$\frac{\sqrt{2m_{d_i} m_{d_j}}}{v^3} H^\dagger H \bar q_i H d_j$
$[O_{Hq}]_{ij}$	$\frac{i}{v^2}\bar q_i \gamma_\mu q_j H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{eW}]_{ij}$	$\frac{g}{m_W^2}\frac{\sqrt{2m_{e_i} m_{e_j}}}{v} \bar\ell_i \sigma^k H \sigma_{\mu\nu} e_j W^k_{\mu\nu}$
$[O'_{Hq}]_{ij}$	$\frac{i}{v^2}\bar q_i \sigma^k \gamma_\mu q_j H^\dagger \sigma^k \overleftrightarrow{D}_\mu H$	$[O_{eB}]_{ij}$	$\frac{g'}{m_W^2}\frac{\sqrt{2m_{e_i} m_{e_j}}}{v} \bar\ell_i H \sigma_{\mu\nu} e_j B_{\mu\nu}$
$[O_{Hu}]_{ij}$	$\frac{i}{v^2}\bar u_i \gamma_\mu u_j H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{uG}]_{ij}$	$\frac{g_s}{m_W^2}\frac{\sqrt{2m_{u_i} m_{u_j}}}{v} \bar q_i \tilde H \sigma_{\mu\nu} T^a u_j G^a_{\mu\nu}$
$[O_{Hd}]_{ij}$	$\frac{i}{v^2}\bar d_i \gamma_\mu d_j H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{uW}]_{ij}$	$\frac{g}{m_W^2}\frac{\sqrt{2m_{u_i} m_{u_j}}}{v} \bar q_i \sigma^k \tilde H \sigma_{\mu\nu} u_j W^k_{\mu\nu}$
$[O_{Hud}]_{ij}$	$\frac{i}{v^2}\bar u_i \gamma_\mu d_j \tilde H^\dagger D_\mu H$	$[O_{uB}]_{ij}$	$\frac{g'}{m_W^2}\frac{\sqrt{2m_{u_i} m_{u_j}}}{v} \bar q_i \tilde H \sigma_{\mu\nu} u_j B_{\mu\nu}$
		$[O_{dG}]_{ij}$	$\frac{g_s}{m_W^2}\frac{\sqrt{2m_{d_i} m_{d_j}}}{v} \bar q_i H \sigma_{\mu\nu} T^a d_j G^a_{\mu\nu}$
		$[O_{dW}]_{ij}$	$\frac{g}{m_W^2}\frac{\sqrt{2m_{d_i} m_{d_j}}}{v} \bar q_i \sigma^k H \sigma_{\mu\nu} d_j W^k_{\mu\nu}$
		$[O_{dB}]_{ij}$	$\frac{g'}{m_W^2}\frac{\sqrt{2m_{d_i} m_{d_j}}}{v} \bar q_i H \sigma_{\mu\nu} d_j B_{\mu\nu}$

Table 99: Four-fermion operators in the SILH basis. They are the same as in the Warsaw basis [614], except that the operators $[O_{\ell\ell}]_{1221}$, $[O_{\ell\ell}]_{1122}$, $[O_{uu}]_{3333}$ are absent by definition. In this table, e, u, d are always right-handed fermions, while ℓ and q are left-handed. A flavour index is implicit for each fermion field. For complex operators the complex conjugate operator is implicit.

$(\bar L L)(\bar L L)$ and $(\bar L R)(\bar L R)$		$(\bar R R)(\bar R R)$		$(\bar L L)(\bar R R)$	
$O_{\ell\ell}$	$\frac{1}{v^2}(\bar\ell\gamma_\mu\ell)(\bar\ell\gamma_\mu\ell)$	O_{ee}	$\frac{1}{v^2}(\bar e\gamma_\mu e)(\bar e\gamma_\mu e)$	$O_{\ell e}$	$\frac{1}{v^2}(\bar\ell\gamma_\mu\ell)(\bar e\gamma_\mu e)$
O_{qq}	$\frac{1}{v^2}(\bar q\gamma_\mu q)(\bar q\gamma_\mu q)$	O_{uu}	$\frac{1}{v^2}(\bar u\gamma_\mu u)(\bar u\gamma_\mu u)$	$O_{\ell u}$	$\frac{1}{v^2}(\bar\ell\gamma_\mu\ell)(\bar u\gamma_\mu u)$
O'_{qq}	$\frac{1}{v^2}(\bar q\gamma_\mu\sigma^i q)(\bar q\gamma_\mu\sigma^i q)$	O_{dd}	$\frac{1}{v^2}(\bar d\gamma_\mu d)(\bar d\gamma_\mu d)$	$O_{\ell d}$	$\frac{1}{v^2}(\bar\ell\gamma_\mu\ell)(\bar d\gamma_\mu d)$
$O_{\ell q}$	$\frac{1}{v^2}(\bar\ell\gamma_\mu\ell)(\bar q\gamma_\mu q)$	O_{eu}	$\frac{1}{v^2}(\bar e\gamma_\mu e)(\bar u\gamma_\mu u)$	O_{eq}	$\frac{1}{v^2}(\bar q\gamma_\mu q)(\bar e\gamma_\mu e)$
$O'_{\ell q}$	$\frac{1}{v^2}(\bar\ell\gamma_\mu\sigma^i\ell)(\bar q\gamma_\mu\sigma^i q)$	O_{ed}	$\frac{1}{v^2}(\bar e\gamma_\mu e)(\bar d\gamma_\mu d)$	O_{qu}	$\frac{1}{v^2}(\bar q\gamma_\mu q)(\bar u\gamma_\mu u)$
O_{quqd}	$\frac{1}{v^2}(\bar q^j u)\epsilon_{jk}(\bar q^k d)$	O_{ud}	$\frac{1}{v^2}(\bar u\gamma_\mu u)(\bar d\gamma_\mu d)$	O'_{qu}	$\frac{1}{v^2}(\bar q\gamma_\mu T^a q)(\bar u\gamma_\mu T^a u)$
O'_{quqd}	$\frac{1}{v^2}(\bar q^j T^a u)\epsilon_{jk}(\bar q^k T^a d)$	O'_{ud}	$\frac{1}{v^2}(\bar u\gamma_\mu T^a u)(\bar d\gamma_\mu T^a d)$	O_{qd}	$\frac{1}{v^2}(\bar q\gamma_\mu q)(\bar d\gamma_\mu d)$
$O_{\ell equ}$	$\frac{1}{v^2}(\bar\ell^j e)\epsilon_{jk}(\bar q^k u)$			O'_{qd}	$\frac{1}{v^2}(\bar q\gamma_\mu T^a q)(\bar d\gamma_\mu T^a d)$
$O'_{\ell equ}$	$\frac{1}{v^2}(\bar\ell^j\sigma_{\mu\nu} e)\epsilon_{jk}(\bar q^k\sigma^{\mu\nu} u)$				
$O_{\ell edq}$	$\frac{1}{v^2}(\bar\ell^j e)(\bar d q^j)$				

Full set has 2499 distinct operators, including flavor structure and CP conjugates

Alonso et al 1312.2014, Henning et al 1512.03433

Observable effects of D=6 operators

- Corrections to Higgs self-couplings

$$\mathcal{L} \supset \frac{m_h^2}{2v}\left(1+\delta\lambda_3\right)h^3$$

- Corrections to SM Z and W boson couplings to fermions (so-called vertex corrections)

$$\mathcal{L}_{vff} = \frac{g_L}{\sqrt{2}}\left(W_\mu^+\bar{u}\bar{\sigma}_\mu(V_{\rm CKM}+\delta g_L^{Wq})d + W_\mu^+ u^c\sigma_\mu \delta g_R^{Wq}\bar{d}^c + W_\mu^+\bar{\nu}\bar{\sigma}_\mu(I+\delta g_L^{W\ell})e + \text{h.c.}\right)$$
$$+\sqrt{g_L^2+g_Y^2}Z_\mu\left[\sum_{f\in u,d,e,\nu}\bar{f}\bar{\sigma}_\mu(T_f^3 - s_\theta^2 Q_f + \delta g_L^{Zf})f + \sum_{f^c\in u^c,d^c,e^c} f^c\sigma_\mu(-s_\theta^2 Q_f + \delta g_R^{Zf})\bar{f}^c\right]$$

- Corrections to SM Higgs couplings to matter and new tensor structures of these interactions

$$\mathcal{L}_{\rm hvv} = \frac{h}{v}[2(1+\delta c_w)m_W^2 W_\mu^+W_\mu^- + (1+\delta c_z)m_Z^2 Z_\mu Z_\mu$$
$$+c_{ww}\frac{g_L^2}{2}W_{\mu\nu}^+W_{\mu\nu}^- + \tilde{c}_{ww}\frac{g_L^2}{2}W_{\mu\nu}^+\tilde{W}_{\mu\nu}^- + c_{w\Box}g_L^2\left(W_\mu^-\partial_\nu W_{\mu\nu}^+ + \text{h.c.}\right)$$
$$+c_{gg}\frac{g_s^2}{4}G_{\mu\nu}^a G_{\mu\nu}^a + c_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}A_{\mu\nu} + c_{z\gamma}\frac{eg_L}{2c_\theta}Z_{\mu\nu}A_{\mu\nu} + c_{zz}\frac{g_L^2}{4c_\theta^2}Z_{\mu\nu}Z_{\mu\nu}$$
$$+c_{z\Box}g_L^2 Z_\mu\partial_\nu Z_{\mu\nu} + c_{\gamma\Box}g_L g_Y Z_\mu\partial_\nu A_{\mu\nu}$$
$$+\tilde{c}_{gg}\frac{g_s^2}{4}G_{\mu\nu}^a\tilde{G}_{\mu\nu}^a + \tilde{c}_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}\tilde{A}_{\mu\nu} + \tilde{c}_{z\gamma}\frac{eg_L}{2c_\theta}Z_{\mu\nu}\tilde{A}_{\mu\nu} + \tilde{c}_{zz}\frac{g_L^2}{4c_\theta^2}Z_{\mu\nu}\tilde{Z}_{\mu\nu}]$$

- Corrections to triple and quartic gauge couplings and new tensor structures of these interactions

$$\mathcal{L}_{\rm tgc} = ie\left[\left(W_{\mu\nu}^+W_\mu^- - W_{\mu\nu}^-W_\mu^+\right)A_\nu + (1+\delta\kappa_\gamma)A_{\mu\nu}W_\mu^+W_\nu^-\right]$$
$$+ig_Lc_\theta\left[(1+\delta g_{1,z})\left(W_{\mu\nu}^+W_\mu^- - W_{\mu\nu}^-W_\mu^+\right)Z_\nu + (1+\delta\kappa_z)Z_{\mu\nu}W_\mu^+W_\nu^-\right]$$
$$+i\frac{e}{m_W^2}\lambda_\gamma W_{\mu\nu}^+W_{\nu\rho}^-A_{\rho\mu} + i\frac{g_Lc_\theta}{m_W^2}\lambda_z W_{\mu\nu}^+W_{\nu\rho}^-Z_{\rho\mu}$$

- Contact 4-fermion interactions

One flavor $(I=1\ldots3)$	Two flavors $(I<J=1\ldots3)$
$[O_{\ell\ell}]_{IIII} = \frac{1}{2}(\bar{\ell}_I\bar{\sigma}_\mu\ell_I)(\bar{\ell}_I\bar{\sigma}_\mu\ell_I)$	$[O_{\ell\ell}]_{IIJJ} = (\bar{\ell}_I\bar{\sigma}_\mu\ell_I)(\bar{\ell}_J\bar{\sigma}_\mu\ell_J)$
	$[O_{\ell\ell}]_{IJJI} = (\bar{\ell}_I\bar{\sigma}_\mu\ell_J)(\bar{\ell}_J\bar{\sigma}_\mu\ell_I)$
$[O_{\ell e}]_{IIII} = (\bar{\ell}_I\bar{\sigma}_\mu\ell_I)(e_I^c\sigma_\mu\bar{e}_I^c)$	$[O_{\ell e}]_{IIJJ} = (\bar{\ell}_I\bar{\sigma}_\mu\ell_I)(e_J^c\sigma_\mu\bar{e}_J^c)$
	$[O_{\ell e}]_{JJII} = (\bar{\ell}_J\bar{\sigma}_\mu\ell_J)(e_I^c\sigma_\mu\bar{e}_I^c)$
	$[O_{\ell e}]_{IJJI} = (\bar{\ell}_I\bar{\sigma}_\mu\ell_J)(e_J^c\sigma_\mu\bar{e}_I^c)$
$[O_{ee}]_{IIII} = \frac{1}{2}(e_I^c\sigma_\mu\bar{e}_I^c)(e_I^c\sigma_\mu\bar{e}_I^c)$	$[O_{ee}]_{IIJJ} = (e_I^c\sigma_\mu\bar{e}_I^c)(e_J^c\sigma_\mu\bar{e}_J^c)$

- ... and much more

Important: correlations between different parameters describing deviations from SM

SM EFT in practice

- At first sight, working with a theory with 2499 parameters seems hopeless.
- However, typically, working at fixed order in loop expansion, a much smaller set of operators relevant for given process
- Moreover, using constraints from previous experiments (e.g. from low-energy precision experiments, or from Z-pole) may further reduce number of relevant operators
- Importance of convenient parametrization of space of dimension-6 operators that makes explicit poorly constrained directions
- Importance of global fits to make full use of experimental constraints

Origin of dimension-6 operators

Example: heavy singlet vector in UV

$$\mathcal{L}_{\rm UV} \supset -\frac{1}{4}V_{\mu\nu}V_{\mu\nu} + \frac{\Lambda^2}{2}V_\mu V_\mu + \frac{i}{2}V_\mu g_H H^\dagger \overleftrightarrow{D}_\mu H + V_\mu \sum_f g_f \bar{f}\bar{\sigma}_\mu f + \ldots$$

Tree-level operators in EFT

$$\mathcal{L}_{\rm EFT} \supset \frac{g_H^2}{4\Lambda^2}(H^\dagger \overleftrightarrow{D}_\mu H)^2 - \frac{i g_H}{\Lambda^2} H^\dagger \overleftrightarrow{D}_\mu H \sum_f g_f \bar{f}\bar{\sigma}_\mu f - \frac{1}{2\Lambda^2}\sum_{f,f'} g_f g_{f'} (\bar{f}\bar{\sigma}_\mu f)(\bar{f}'\bar{\sigma}_\mu f') + \ldots$$

	Bosonic CP-even
O_H	$\frac{1}{2v^2}\left[\partial_\mu(H^\dagger H)\right]^2$
O_T	$\frac{1}{2v^2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$
O_6	$-\frac{\lambda}{v^2}(H^\dagger H)^3$
O_g	$\frac{g_s^2}{m_W^2} H^\dagger H\, G^a_{\mu\nu}G^a_{\mu\nu}$
O_γ	$\frac{g'^2}{m_W^2} H^\dagger H\, B_{\mu\nu}B_{\mu\nu}$
O_W	$\frac{ig}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D}_\mu H\right) D_\nu W^i_{\mu\nu}$
O_B	$\frac{ig'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \partial_\nu B_{\mu\nu}$
O_{HW}	$\frac{ig}{m_W^2}\left(D_\mu H^\dagger \sigma^i D_\nu H\right) W^i_{\mu\nu}$
O_{HB}	$\frac{ig'}{m_W^2}\left(D_\mu H^\dagger D_\nu H\right) B_{\mu\nu}$
O_{2W}	$\frac{1}{m_W^2} D_\mu W^i_{\mu\nu} D_\rho W^i_{\rho\nu}$
O_{2B}	$\frac{1}{m_W^2} \partial_\mu B_{\mu\nu} \partial_\rho B_{\rho\nu}$
O_{2G}	$\frac{1}{m_W^2} D_\mu G^a_{\mu\nu} D_\rho G^a_{\rho\nu}$
O_{3W}	$\frac{g^3}{m_W^2}\epsilon^{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$
O_{3G}	$\frac{g_s^3}{m_W^2} f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$

	Vertex
$[O_{H\ell}]_{ij}$	$\frac{i}{v^2}\bar{\ell}_i\gamma_\mu \ell_j H^\dagger \overleftrightarrow{D}_\mu H$
$[O'_{H\ell}]_{ij}$	$\frac{i}{v^2}\bar{\ell}_i\sigma^k\gamma_\mu \ell_j H^\dagger \sigma^k \overleftrightarrow{D}_\mu H$
$[O_{He}]_{ij}$	$\frac{i}{v^2}\bar{e}_i\gamma_\mu \bar{e}_j H^\dagger \overleftrightarrow{D}_\mu H$
$[O_{Hq}]_{ij}$	$\frac{i}{v^2}\bar{q}_i\gamma_\mu q_j H^\dagger \overleftrightarrow{D}_\mu H$
$[O'_{Hq}]_{ij}$	$\frac{i}{v^2}\bar{q}_i\sigma^k\gamma_\mu q_j H^\dagger \sigma^k \overleftrightarrow{D}_\mu H$
$[O_{Hu}]_{ij}$	$\frac{i}{v^2}\bar{u}_i\gamma_\mu u_j H^\dagger \overleftrightarrow{D}_\mu H$
$[O_{Hd}]_{ij}$	$\frac{i}{v^2}\bar{d}_i\gamma_\mu d_j H^\dagger \overleftrightarrow{D}_\mu H$
$[O_{Hud}]_{ij}$	$\frac{i}{v^2}\bar{u}_i\gamma_\mu d_j \tilde{H}^\dagger D_\mu H$

	$(\bar{L}L)(\bar{L}L)$ and $(\bar{L}R)(\bar{L}R)$		$(\bar{R}R)(\bar{R}R)$
$O_{\ell\ell}$	$\frac{1}{v^2}(\bar{\ell}\gamma_\mu\ell)(\bar{\ell}\gamma_\mu\ell)$	O_{ee}	$\frac{1}{v^2}(\bar{e}\gamma_\mu e)(\bar{e}\gamma_\mu e)$
O_{qq}	$\frac{1}{v^2}(\bar{q}\gamma_\mu q)(\bar{q}\gamma_\mu q)$	O_{uu}	$\frac{1}{v^2}(\bar{u}\gamma_\mu u)(\bar{u}\gamma_\mu u)$
O'_{qq}	$\frac{1}{v^2}(\bar{q}\gamma_\mu\sigma^i q)(\bar{q}\gamma_\mu\sigma^i q)$	O_{dd}	$\frac{1}{v^2}(\bar{d}\gamma_\mu d)(\bar{d}\gamma_\mu d)$
$O_{\ell q}$	$\frac{1}{v^2}(\bar{\ell}\gamma_\mu\ell)(\bar{q}\gamma_\mu q)$	O_{eu}	$\frac{1}{v^2}(\bar{e}\gamma_\mu e)(\bar{u}\gamma_\mu u)$
$O'_{\ell q}$	$\frac{1}{v^2}(\bar{\ell}\gamma_\mu\sigma^i\ell)(\bar{q}\gamma_\mu\sigma^i q)$	O_{ed}	$\frac{1}{v^2}(\bar{e}\gamma_\mu e)(\bar{d}\gamma_\mu d)$
O_{quqd}	$\frac{1}{v^2}(\bar{q}^j u)\epsilon_{jk}(\bar{q}^k d)$	O_{ud}	$\frac{1}{v^2}(\bar{u}\gamma_\mu u)(\bar{d}\gamma_\mu d)$
O'_{quqd}	$\frac{1}{v^2}(\bar{q}^j T^a u)\epsilon_{jk}(\bar{q}^k T^a d)$	O'_{ud}	$\frac{1}{v^2}(\bar{u}\gamma_\mu T^a u)(\bar{d}\gamma_\mu T^a d)$
$O_{\ell equ}$	$\frac{1}{v^2}(\bar{\ell}^j e)\epsilon_{jk}(\bar{q}^k u)$		
$O'_{\ell equ}$	$\frac{1}{v^2}(\bar{\ell}^j\sigma_{\mu\nu} e)\epsilon_{jk}(\bar{q}^k\sigma^{\mu\nu} u)$		
$O_{\ell edq}$	$\frac{1}{v^2}(\bar{\ell}^j e)(\bar{d}q^j)$		

UV-EFT connection

- Assume coefficient of D=6 EFT operator measures Coupling^2/Mass^2 in UV theory. Assuming that coefficient has been measured, taking strong Coupling ~ 4π gives upper bound on new physics mass scale Λ

- Sometimes this counting is modified when operator is induced at a loop level in UV theory or by additional powers of couplings

- With some (motivated) assumptions about UV physics, one can work out rules to assign powers of mass, coupling and loop factors to each EFT operator

Example tree-induced operator

$$\frac{c_{\rm exp}}{{\rm TeV}^2} = \frac{g_*^2}{\Lambda^2} \Rightarrow \Lambda \lesssim \frac{4\pi}{\sqrt{c_{\rm exp}}}{\rm TeV}$$

Example 1-loop-induced operator

$$\frac{c_{\rm exp}}{{\rm TeV}^2} = \frac{g_*^2}{16\pi^2\Lambda^2} \Rightarrow \Lambda \lesssim \frac{1}{\sqrt{c_{\rm exp}}}{\rm TeV}$$

Example tree-induced operator + selection rules

$$\frac{c_{\rm exp}}{{\rm TeV}^2} = \frac{g_*^2 y_f}{\Lambda^2} \Rightarrow \Lambda \lesssim \frac{\sqrt{y_f}}{\sqrt{c_{\rm exp}}}{\rm TeV}$$

Liu et al 1603.03064

	$\|H\|^2$	$\|H\|^4$	$\mathcal{O}_H$	$\mathcal{O}_6$	$\mathcal{O}_V$	$\mathcal{O}_{2V}$	$\mathcal{O}_{3V}$	$\mathcal{O}_{HV}$	$\mathcal{O}_{VV}$	$\mathcal{O}_{y_\psi}$
ALH	m_*^2	g_*^2	g_*^2	g_*^4	g_V	$\frac{g_V^2}{g_*^2}$	$\frac{g_V^2}{g_*^2} g_V$	g_V	g_V^2	$y_\psi g_*^2$
GSILH	$\frac{y_t^2}{16\pi^2} m_*^2$	$\frac{y_t^2}{16\pi^2} g_*^2$	g_*^2	$\frac{y_t^2}{16\pi^2} g_*^4$	g_V	$\frac{g_V^2}{g_*^2}$	$\frac{g_V^2}{g_*^2} g_V$	g_V	$\frac{y_t^2}{16\pi^2} g_V^2$	$y_\psi g_*^2$
SILH	$\frac{y_t^2}{16\pi^2} m_*^2$	$\frac{y_t^2}{16\pi^2} g_*^2$	g_*^2	$\frac{y_t^2}{16\pi^2} g_*^4$	g_V	$\frac{g_V^2}{g_*^2}$	$\frac{g_V^2}{16\pi^2} g_V$	$\frac{g_*^2}{16\pi^2} g_V$	$\frac{y_t^2}{16\pi^2} g_V^2$	$y_\psi g_*^2$

Model	$\mathcal{O}_{2V}$	$\mathcal{O}_{3V}$	$\mathcal{O}_{HW}$	$\mathcal{O}_{HB}$	$\mathcal{O}_V$	$\mathcal{O}_{VV}$	$\mathcal{O}_H$	$\mathcal{O}_{y_\psi}$
Remedios (sect. 4.1)	1	g_*						
Remedios+MCHM (sect. 4.2.1)	1	g_*	g	g'	g_V	g_V^2	g_*^2	$y_\psi g_*^2$
Remedios+$ISO(4)$ (sect. 4.2.2)	1	g_*	g_*	g'	g_V	g_V^2	λ_h	$y_\psi \lambda_h$

A few issues of relevance for FCC

Precision vs Energy in EFT

Two distinct interesting situations

Observables at fixed mass scale m (e.g. Z or Higgs decays)

$$\frac{\sigma}{\sigma_{SM}} = \left|1 + \frac{c_6 m^2}{\mathrm{TeV}^2}\right|^2$$

Increasing UV scales probed in EFT achieved solely by increasing measurements precision

For Higgs decays,
and tree EFT operator ~g*^2
given experimental precision ε

$$\Lambda_{\max} \sim \frac{2\mathrm{TeV}}{\sqrt{\epsilon}} \approx \begin{cases} 7\ \mathrm{TeV} & \epsilon = 10\% \\ 20\ \mathrm{TeV} & \epsilon = 1\% \\ 70\ \mathrm{TeV} & \epsilon = 0.1\% \end{cases}$$

High-energy tails of distributions (e.g. 2-fermion production)

$$\frac{\sigma}{\sigma_{SM}} = \left|1 + \frac{c_6 E^2}{\mathrm{TeV}^2}\right|^2 \quad \mathrm{or} \quad \left|1 + \frac{c_6 v^2}{\mathrm{TeV}^2}\right|^2$$

Increasing UV scales probed in EFT may be achieved by increasing energy scale of measurement

For E^2 dependent observable,
and tree EFT operator ~g*^2
given order 1 experimental precision

$$\Lambda_{\max} \sim \frac{4\pi E}{\sqrt{\epsilon}} \approx \begin{cases} 40\ \mathrm{TeV} & \epsilon = 10\%,\ E = 1\ \mathrm{TeV} \\ 400\ \mathrm{TeV} & \epsilon = 10\%,\ E = 10\ \mathrm{TeV} \\ 1000\ \mathrm{TeV} & \epsilon = 10\%,\ E = 30\ \mathrm{TeV} \end{cases}$$

In many cases, increasing energy may be more straightforward than increasing precision

For specific real-life example, see talks of F. Riva and J. Ruderman

Higgs self-interactions in EFT

Some D=6 operators may need to wait till FCC to be meaningfully probed

Bosonic CP-even	
O_H	$\frac{1}{2v^2}\left[\partial_\mu(H^\dagger H)\right]^2$
O_T	$\frac{1}{2v^2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$
O_6	$-\frac{\lambda}{v^2}(H^\dagger H)^3$
O_g	$\frac{g_s^2}{m_W^2} H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu}$
O_γ	$\frac{g'^2}{m_W^2} H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$
O_W	$\frac{ig}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D}_\mu H\right) D_\nu W^i_{\mu\nu}$
O_B	$\frac{ig'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \partial_\nu B_{\mu\nu}$
O_{HW}	$\frac{ig}{m_W^2}\left(D_\mu H^\dagger \sigma^i D_\nu H\right) W^i_{\mu\nu}$
O_{HB}	$\frac{ig'}{m_W^2}\left(D_\mu H^\dagger D_\nu H\right) B_{\mu\nu}$
O_{2W}	$\frac{1}{m_W^2} D_\mu W^i_{\mu\nu} D_\rho W^i_{\rho\nu}$
O_{2B}	$\frac{1}{m_W^2} \partial_\mu B_{\mu\nu} \partial_\rho B_{\rho\nu}$
O_{2G}	$\frac{1}{m_W^2} D_\mu G^a_{\mu\nu} D_\rho G^a_{\rho\nu}$
O_{3W}	$\frac{g^3}{m_W^2} \epsilon^{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$
O_{3G}	$\frac{g_s^3}{m_W^2} f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$

One example: non-derivative Higgs self-interaction (may contain crucial hints concerning generation mechanism of Higgs potential)

	$\|H\|^2$	$\|H\|^4$	$\mathcal{O}_H$	$\mathcal{O}_6$	$\mathcal{O}_V$	$\mathcal{O}_{2V}$	$\mathcal{O}_{3V}$	$\mathcal{O}_{HV}$	$\mathcal{O}_{VV}$	$\mathcal{O}_{y_\psi}$
ALH	m_*^2	g_*^2	g_*^2	g_*^4	g_V	$\frac{g_V^2}{g_*^2}$	$\frac{g_V^2}{g_*^2} g_V$	g_V	g_V^2	$y_\psi g_*^2$
GSILH	$\frac{y_t^2}{16\pi^2} m_*^2$	$\frac{y_t^2}{16\pi^2} g_*^2$	g_*^2	$\frac{y_t^2}{16\pi^2} g_*^4$	g_V	$\frac{g_V^2}{g_*^2}$	$\frac{g_V^2}{g_*^2} g_V$	g_V	$\frac{y_t^2}{16\pi^2} g_V^2$	$y_\psi g_*^2$
SILH	$\frac{y_t^2}{16\pi^2} m_*^2$	$\frac{y_t^2}{16\pi^2} g_*^2$	g_*^2	$\frac{y_t^2}{16\pi^2} g_*^4$	g_V	$\frac{g_V^2}{g_*^2}$	$\frac{g_V^2}{16\pi^2} g_V$	$\frac{g_*^2}{16\pi^2} g_V$	$\frac{y_t^2}{16\pi^2} g_V^2$	$y_\psi g_*^2$

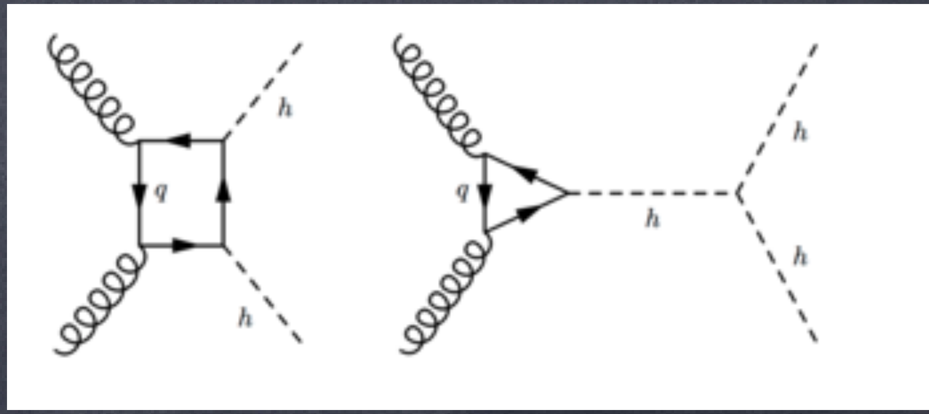
$$\mathcal{L} \supset \frac{m_h^2}{2v}(1+\delta\lambda_3)\, h^3$$

$$\delta\lambda_3 = \left(\bar{c}_6 - \frac{3}{2}\bar{c}_H - \frac{1}{2}[\bar{c}'_{H\ell}]_{22}\right).$$

$\|\delta\lambda_3\|$	Λ [TeV]	n_{best}	Λ_{SMEFT} [TeV]
0.01	4.5	9	160
0.1	3.9	6	50
1	3.1	4	16
10	2.0	2	5.0
20	1.6	1	2.8
40	1.1	1	1.4

- Measurement of Higgs self-couplings convoluted with measurement of other Higgs couplings

- May need differential distributions and/or resolving different double Higgs production mode to extract corrections to self-coupling



LHCHXSWG 1610.07922

Bishara et el 1611.03860

Higher-point vertices

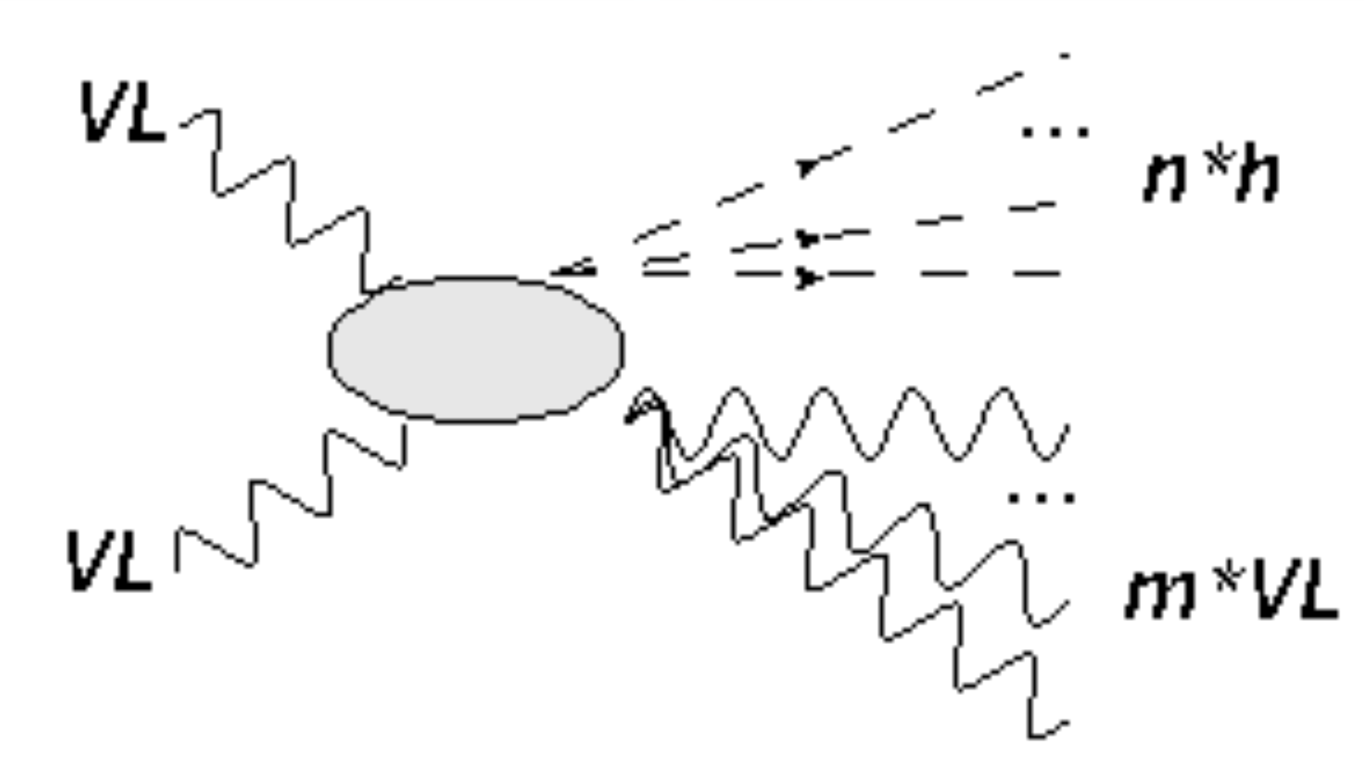
- EFT Lagrangian with D=6 operators predicts contains contact vertices with larger number of fields than in SM
- One currently unexplored example is new interactions of Higgs boson with 3 gauge bosons
- In EFT, their coefficients are related to the anomalous triple gauge couplings (equivalently, to higher-derivative Higgs couplings)
- At LHC not much hope to probe these, due to phase space suppression -> interesting to explore FCC capabilities

$$\begin{aligned}\mathcal{L}_{h\gamma ww} &= e g_L^2 \frac{h}{v}\left\{2 i c_{w\Box}\partial_\nu W^+_\mu W^-_\mu A_\nu - i c_{w\Box}\partial_\mu W^+_\nu W^-_\mu A_\nu - i c_{w\Box}\partial_\mu W^+_\mu W^-_\nu A_\nu \right.\\ &\left. - i c_{ww} W^+_{\mu\nu} W^-_\mu A_\nu + \text{h.c.}\right\} - i e g_L^2 \frac{h}{v} A_{\mu\nu} W^+_\mu W^-_\nu \left(3 c_{w\Box} + c_{z\gamma} + s_\theta^2 c_{\gamma\gamma}\right) \quad (1.3)\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{hzww} &= i\sqrt{g_L^2 + g_Y^2}\, g_L^2 \frac{h}{v}\left\{-\left(c_{w\Box}(2 + c_\theta^2) + c_{ww} c_\theta^2\right) W^+_{\mu\nu} W^-_\mu Z_\nu + c_{w\Box} s_\theta^2 (\partial_\mu W^+_\mu W^-_\nu - \partial_\nu W^+_\mu W^-_\mu) Z_\nu + \right.\\ &- i\sqrt{g_L^2 + g_Y^2}\, g_L^2 \frac{h}{v} Z_{\mu\nu} W^+_\mu W^-_\nu \left(3 c_{w\Box} c_\theta^2 + c_{ww} - s_\theta^2 c_{z\gamma} - s_\theta^4 c_{\gamma\gamma}\right).\end{aligned}$$

multi-Higgs production as test of linear EFT

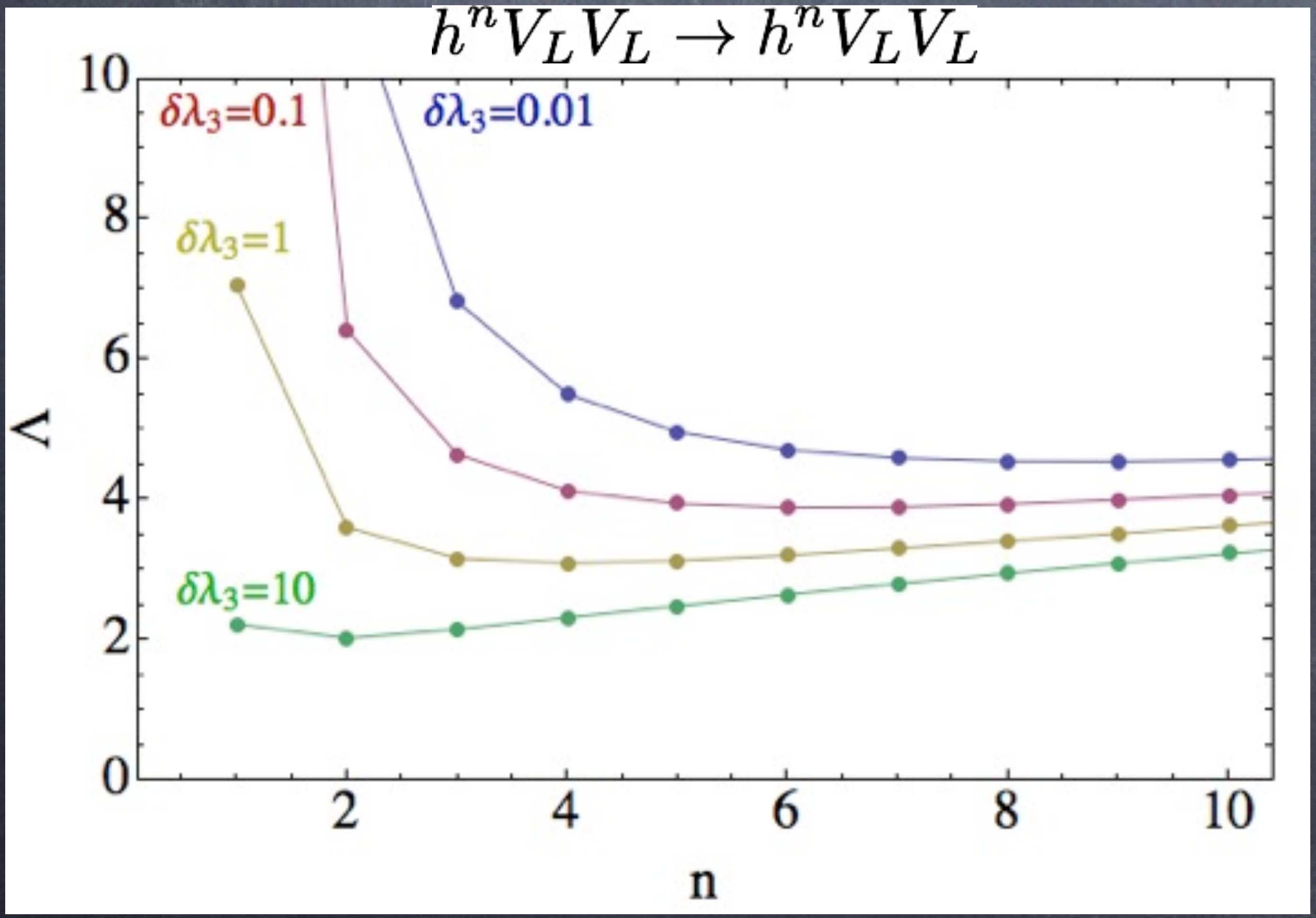
Work in progress
with R.Rattazzi



Going beyond SM EFT to non-linear EFT, multi-Higgs production becomes strong at scales of order 4πv, even for small deviation of Higgs self-couplings from SM. Strong test of linear EFT at FCC

$$\mathcal{M}(V_L V_L \to h^n) \sim \frac{n! m_h^2}{v^n} \delta\lambda_3$$

$$\Lambda \lesssim \frac{4\pi v \sqrt{(n-2)!}}{|\delta\lambda_3|^{\frac{1}{n-2}}}$$



$h^n V_L V_L \to h^n V_L V_L$

$\lvert\delta\lambda_3\rvert$	Λ [TeV]	$n_{\rm best}$	$\Lambda_{\rm SMEFT}$ [TeV]
0.01	4.5	9	160
0.1	3.9	6	50
1	3.1	4	16
10	2.0	2	5.0
20	1.6	1	2.8
40	1.1	1	1.4

Much more than just S and T...

Oblique corrections: $\delta\mathcal{M}(V_{1,\mu}\to V_{2,\nu})=\eta_{\mu\nu}\left(\delta\Pi^{(0)}_{V_1V_2}+\delta\Pi^{(2)}_{V_1V_2}p^2+\delta\Pi^{(4)}_{V_1V_2}p^4+\ldots\right)+p_\mu p_\nu(\ldots)$

$$\alpha S=-4\frac{g_L g_Y}{g_L^2+g_Y^2}\delta\Pi^{(2)}_{3B}$$
$$\alpha T=\frac{\delta\Pi^{(0)}_{11}-\delta\Pi^{(0)}_{33}}{m_W^2}$$
$$\alpha U=\frac{4g_Y^2}{g_L^2+g_Y^2}\left(\delta\Pi^{(2)}_{11}-\delta\Pi^{(2)}_{33}\right)$$

$$\alpha V=m_W^2\left(\delta\Pi^{(4)}_{11}-\delta\Pi^{(4)}_{33}\right)$$
$$\alpha W=-m_W^2\delta\Pi^{(4)}_{33}$$
$$\alpha X=-m_W^2\delta\Pi^{(4)}_{3B}$$
$$\alpha Y=-m_W^2\delta\Pi^{(4)}_{BB}$$

Peskin Takeuchi
pre-arxiv

Barbieri et al
hep-ph/0405040

Equivalent to restricted form of flavor-diagonal vertex corrections, 4-fermion operators and W-mass corrections:

$$[\delta g^{Zf}]_{ij}=\delta_{ij}\alpha\left\{T^3_f\frac{T-W-\frac{g_Y^2}{g_L^2}Y}{2}+Q_f\frac{2g_Y^2T-(g_L^2+g_Y^2)S+2g_Y^2W+\frac{2g_Y^2(2g_L^2-g_Y^2)}{g_L^2}Y}{4(g_L^2-g_Y^2)}\right\}$$
$$\delta m=\frac{\alpha}{4(g_L^2-g_Y^2)}\left[2g_L^2T-(g_L^2+g_Y^2)S+2g_Y^2W+2g_Y^2Y\right]$$

$$[c_{\ell\ell}]_{IIJJ}=\alpha\left[W-\frac{g_Y^2}{g_L^2}Y\right]\qquad[c_{\ell\ell}]_{IJJI}=-2\alpha W,\qquad I<J$$
$$[c_{\ell\ell}]_{IIII}=-\alpha\left[W+\frac{g_Y^2}{g_L^2}Y\right]$$
$$[c_{\ell e}]_{IIJJ}=-\frac{2g_Y^2}{g_L^2}\alpha Y\qquad[c_{ee}]_{IIJJ}=-\frac{4g_Y^2}{g_L^2}\alpha Y$$

Wells Zhang
1510.08462

EFT vs Oblique Parameters

- Measurements of some oblique parameters may be improved in hadron colliders as compared to previous leptonic machines
- However, even bigger advantage is that hadron colliders are exploring directions of EFT space that are weakly or not at all constrained by lepton machines
- This is obvious for operators whose effects grow with energy, such as 2-quark-2-lepton or 4-quark operators. However, important input may also come from lower energies.
- For example, couplings of Z boson to light quarks were not all constrained in model independent way in LEP, and constraints can be very much improved using Drell-Yan production in proton-proton collisions.

Difficult to compete

$$[\delta g_L^{We}]_{ii} = \begin{pmatrix} -1.00 \pm 0.64 \\ -1.36 \pm 0.59 \\ 1.95 \pm 0.79 \end{pmatrix} \times 10^{-2},$$

$$[\delta g_L^{Ze}]_{ii} = \begin{pmatrix} -0.26 \pm 0.28 \\ 0.1 \pm 1.1 \\ 0.16 \pm 0.58 \end{pmatrix} \times 10^{-3}, \quad [\delta g_R^{Ze}]_{ii} = \begin{pmatrix} -0.37 \pm 0.27 \\ 0.0 \pm 1.3 \\ 0.39 \pm 0.62 \end{pmatrix} \times 10^{-3},$$

$$[\delta g_L^{Zu}]_{ii} = \begin{pmatrix} -0.8 \pm 3.1 \\ -0.16 \pm 0.36 \\ -0.28 \pm 3.8 \end{pmatrix} \times 10^{-2}, \quad [\delta g_R^{Zu}]_{ii} = \begin{pmatrix} 1.3 \pm 5.1 \\ -0.38 \pm 0.51 \\ \times \end{pmatrix} \times 10^{-2},$$

$$[\delta g_L^{Zd}]_{ii} = \begin{pmatrix} -1.0 \pm 4.4 \\ 0.9 \pm 2.8 \\ 0.33 \pm 0.16 \end{pmatrix} \times 10^{-2}, \quad [\delta g_R^{Zd}]_{ii} = \begin{pmatrix} 2.9 \pm 16 \\ 3.5 \pm 5.0 \\ 2.30 \pm 0.82 \end{pmatrix} \times 10^{-2}.$$

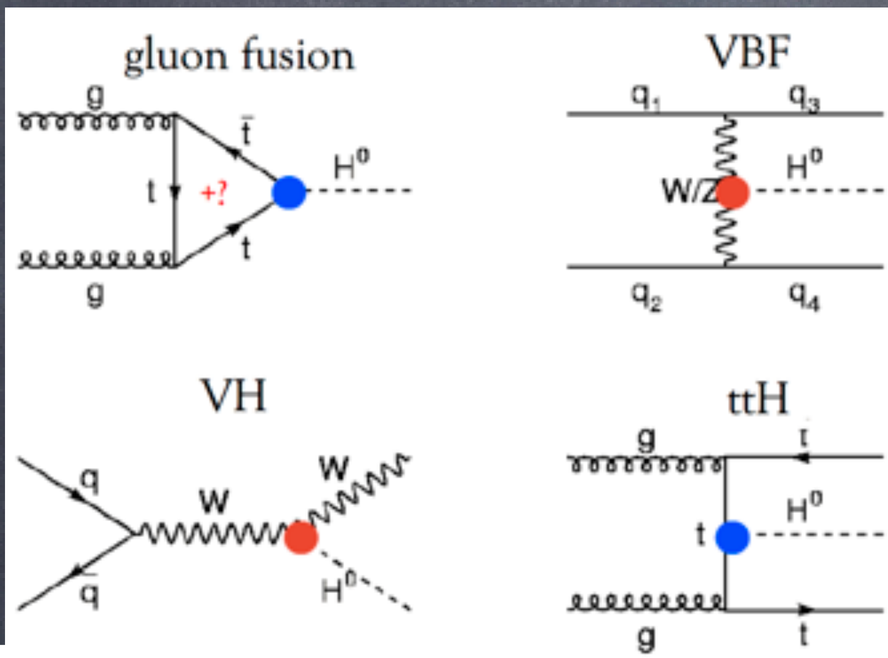
Opportunit knocking

Efrati,AA,Soreq
1503.07872

Energy Dependence of Higgs production

$$\frac{\sigma_{ggh}}{\sigma_{ggh}^{\rm SM}} \simeq 1 + 237 c_{gg} + 2.06\delta y_u - 0.06\delta y_d.$$

$$\frac{\sigma_{VBF}}{\sigma_{VBF}^{\rm SM}} \simeq 1 + 1.49\delta c_w + 0.51\delta c_z - \begin{pmatrix}1.08\\1.11\\1.23\end{pmatrix} c_{w\Box} - 0.10 c_{ww} - \begin{pmatrix}0.35\\0.35\\0.40\end{pmatrix} c_{z\Box}$$
$$-0.04 c_{zz} - 0.10 c_{\gamma\Box} - 0.02 c_{z\gamma}$$
$$\to 1 + 2\delta c_z - 2.25 c_{z\Box} - 0.83 c_{zz} + 0.30 c_{z\gamma} + 0.12 c_{\gamma\gamma}.$$



Already at LHC, Higgs measurements at different proton collision energy greatly enhance discriminating power of data due to reducing degeneracies among EFT parameters. Interesting to explore whether running FCC at different proton energies is advantageous from EFT point of view

$$\frac{\sigma_{Wh}}{\sigma_{Wh}^{\rm SM}} \simeq 1 + 2\delta c_w + \begin{pmatrix}6.39\\6.51\\6.96\end{pmatrix} c_{w\Box} + \begin{pmatrix}1.49\\1.49\\1.50\end{pmatrix} c_{ww}$$
$$\to 1 + 2\delta c_z + \begin{pmatrix}9.26\\9.43\\10.08\end{pmatrix} c_{z\Box} + \begin{pmatrix}4.35\\4.41\\4.63\end{pmatrix} c_{zz} - \begin{pmatrix}0.81\\0.84\\0.93\end{pmatrix} c_{z\gamma} - \begin{pmatrix}0.43\\0.44\\0.48\end{pmatrix} c_{\gamma\gamma}$$

$$\frac{\sigma_{Zh}}{\sigma_{Zh}^{\rm SM}} \simeq 1 + 2\delta c_z + \begin{pmatrix}5.30\\5.40\\5.72\end{pmatrix} c_{z\Box} + \begin{pmatrix}1.79\\1.80\\1.82\end{pmatrix} c_{zz} + \begin{pmatrix}0.80\\0.82\\0.87\end{pmatrix} c_{\gamma\Box} + \begin{pmatrix}0.22\\0.22\\0.22\end{pmatrix} c_{z\gamma},$$
$$\to 1 + 2\delta c_z + \begin{pmatrix}7.61\\7.77\\8.24\end{pmatrix} c_{z\Box} + \begin{pmatrix}3.31\\3.35\\3.47\end{pmatrix} c_{zz} - \begin{pmatrix}0.58\\0.60\\0.65\end{pmatrix} c_{z\gamma} + \begin{pmatrix}0.27\\0.28\\0.30\end{pmatrix} c_{\gamma\gamma}.$$

	Higgs Run1	Higgs Run1&2
δc_z	-0.15 ± 0.21	-0.10 ± 0.12
c_{zz}	0.66 ± 0.60	-0.49 ± 0.34
$c_{z\Box}$	-0.35 ± 0.41	0.18 ± 0.12
$c_{\gamma\gamma}$	-0.0080 ± 0.0087	0.0077 ± 0.0076
$c_{z\gamma}$	-0.007 ± 0.058	-0.015 ± 0.076
c_{gg}	-0.0056 ± 0.0025	-0.0042 ± 0.0009
δy_u	0.51 ± 0.37	0.22 ± 0.15
δy_d	-0.49 ± 0.31	-0.46 ± 0.20
δy_e	-0.29 ± 0.32	-0.10 ± 0.13

$\begin{pmatrix}7\\8\\13\end{pmatrix}$ TeV

Summary

- SM EFT may well be all there is at the FCC
- It is important to estimate quantitatively how the FCC could improve coverage of parameter space of dimension-6 operators compared to the LHC, lepton colliders, and low-energy experiments