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Proposal for Higgs/EFT WG topics

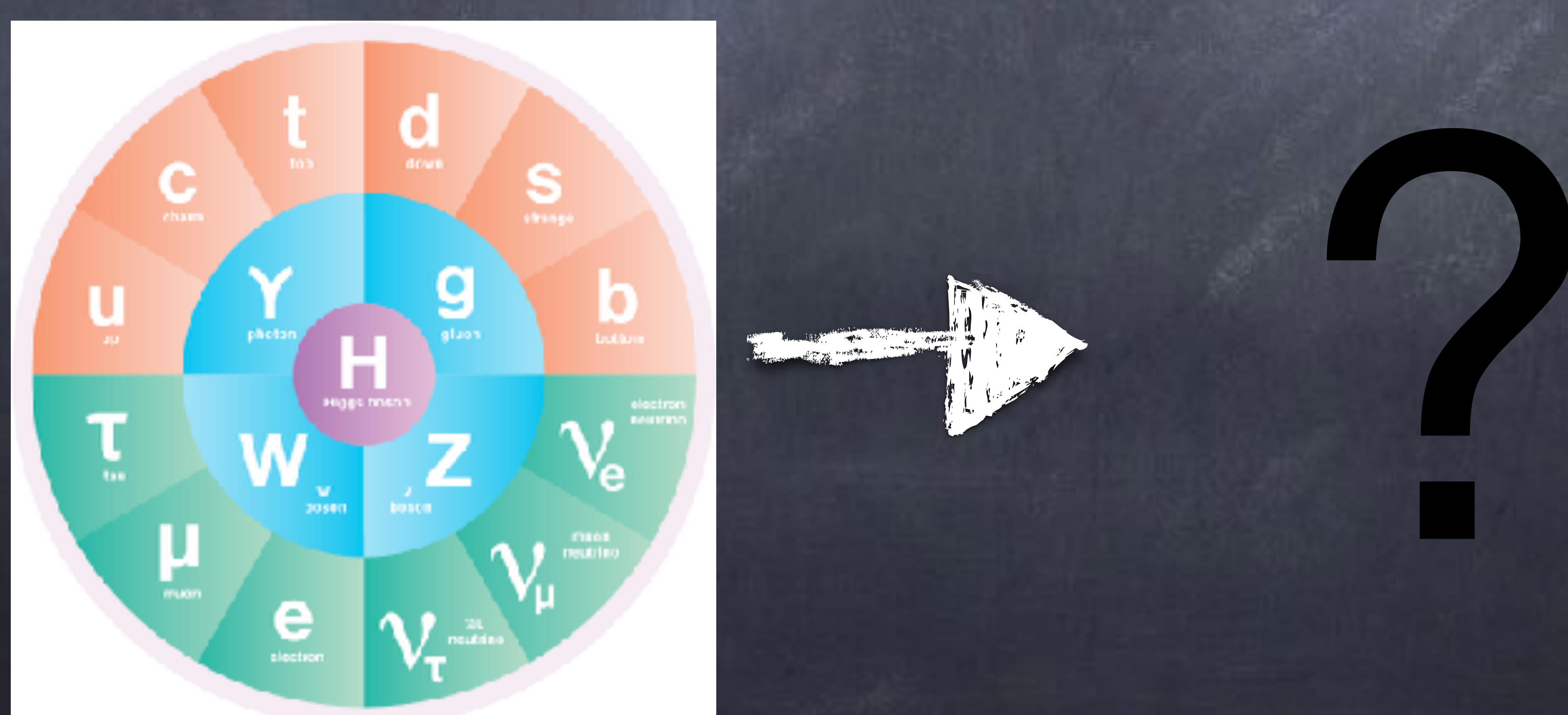
Pune, 26 February 2018

Why EFT

Status report

- SM has been excessively successful in describing all collider and low-energy experiments. Discovery of the 125 GeV Higgs boson is the last piece of puzzle that falls into place. There are no more free parameters in the SM.

- We know physics beyond SM exists (neutrino masses, dark matter, inflation, baryon asymmetry). There are also some theoretical hints for new physics (strong CP problem, flavor hierarchies, gauge coupling unifications, naturalness problem)

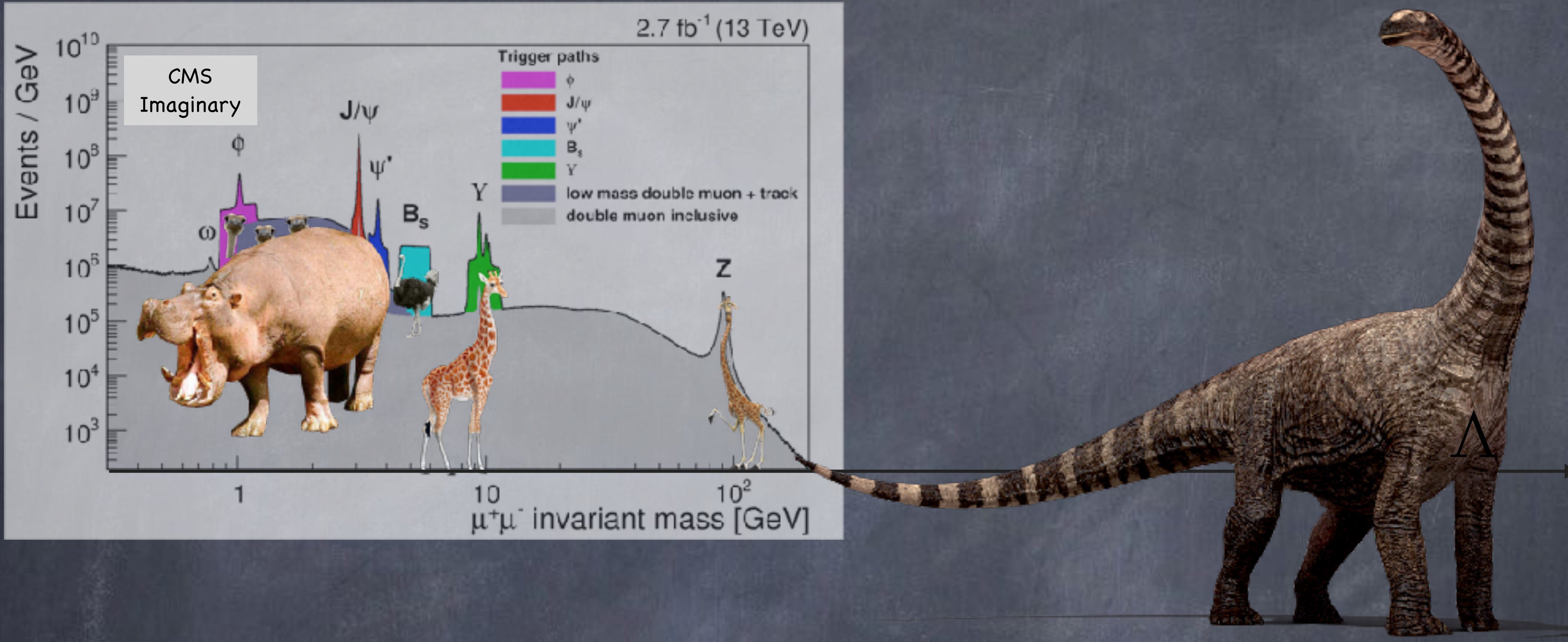


Post LHC era

- No evidence for new particles beyond the SM up to ~1 TeV
- Theoretical motivations that have been driving most new particle searches now appear highly doubtful. We don't have a good idea about the scale Λ of new physics
- At this point, further progress most likely will come from precision measurements

?

Fantastic Beasts and Where To Find Them



- The hope is these measurements will allow us to estimate the scale Λ of new physics, as a target for the next high-energy machines (LHC-HE, FCC, RTEC)

- Furthermore, comprehensive precision program may give us partial information about BSM structure (much like observables in the Fermi Theory had taught us about W and Z well before they could be produced in colliders, or as LEP precision measurements had given us a possible window or top/Higgs masses before their respective discoveries)

SMEFT

Basic assumptions

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

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} \dots \\ v + h(x) + \dots \end{pmatrix}$$

- SMEFT Lagrangian expanded in inverse powers of Λ, equivalently in operator dimension D

$$v \ll \Lambda \ll \Lambda_L$$

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

Generated by integrating out lepton number or B-L violating heavy particles with mass scale Λ_L, responsible for neutrino masses

Subleading wrt D=5/6 if Λ_L/Λ high enough

Generated by integrating out heavy particles with mass scale Λ

In large class of BSM models that conserve B-L, D=6 operators capture leading effects of new physics on collider observables at E << Λ

$\Lambda_L \lesssim$ 10^15 GeV

TeV $\lesssim \Lambda \lesssim$?

Buchmuller,Wyler (1986)

Grządkowski et al. 1008.4884

Alonso et al 1312.2014

Dimension-6 operators

Warsaw basis

Grządkowski et al. 1008.4884

Bosonic CP-even		Bosonic CP-odd	
O_H	$(H^\dagger H)^3$		
$O_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$		
O_{HD}	$\left\vert H^\dagger D_\mu H\right\vert^2$		
O_{HG}	$H^\dagger H\, G^a_{\mu\nu}G^a_{\mu\nu}$	$O_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^a_{\mu\nu}G^a_{\mu\nu}$
O_{HW}	$H^\dagger H\, W^i_{\mu\nu}W^i_{\mu\nu}$	$O_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^i_{\mu\nu}W^i_{\mu\nu}$
O_{HB}	$H^\dagger H\, B_{\mu\nu}B_{\mu\nu}$	$O_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu}B_{\mu\nu}$
O_{HWB}	$H^\dagger\sigma^i H\, W^i_{\mu\nu}B_{\mu\nu}$	$O_{H\widetilde{W}B}$	$H^\dagger\sigma^i H\, \widetilde{W}^i_{\mu\nu}B_{\mu\nu}$
O_W	$\epsilon^{ijk}W^i_{\mu\nu}W^j_{\nu\rho}W^k_{\rho\mu}$	$O_{\widetilde{W}}$	$\epsilon^{ijk}\widetilde{W}^i_{\mu\nu}W^j_{\nu\rho}W^k_{\rho\mu}$
O_G	$f^{abc}G^a_{\mu\nu}G^b_{\nu\rho}G^c_{\rho\mu}$	$O_{\widetilde{G}}$	$f^{abc}\widetilde{G}^a_{\mu\nu}G^b_{\nu\rho}G^c_{\rho\mu}$

Table 2.2: Bosonic D=6 operators in the Warsaw basis.

Yukawa	
$[O^\dagger_{eH}]_{IJ}$	$H^\dagger H e^c_I H^\dagger \ell_J$
$[O^\dagger_{uH}]_{IJ}$	$H^\dagger H u^c_I \widetilde{H}^\dagger q_J$
$[O^\dagger_{dH}]_{IJ}$	$H^\dagger H d^c_I H^\dagger q_J$

Vertex		Dipole	
$[O^{(1)}_{H\ell}]_{IJ}$	$i\bar{\ell}_I\bar{\sigma}_\mu\ell_J H^\dagger \overleftrightarrow{D}_\mu H$	$[O^\dagger_{eW}]_{IJ}$	$e^c_I\sigma_{\mu\nu}H^\dagger\sigma^i\ell_J W^i_{\mu\nu}$
$[O^{(3)}_{H\ell}]_{IJ}$	$i\bar{\ell}_I\sigma^i\bar{\sigma}_\mu\ell_J H^\dagger\sigma^i \overleftrightarrow{D}_\mu H$	$[O^\dagger_{eB}]_{IJ}$	$e^c_I\sigma_{\mu\nu}H^\dagger\ell_J B_{\mu\nu}$
$[O_{He}]_{IJ}$	$ie^c_I\sigma_\mu\bar{e}^c_J H^\dagger \overleftrightarrow{D}_\mu H$	$[O^\dagger_{uG}]_{IJ}$	$u^c_I\sigma_{\mu\nu}T^a\widetilde{H}^\dagger q_J\, G^a_{\mu\nu}$
$[O^{(1)}_{Hq}]_{IJ}$	$i\bar{q}_I\bar{\sigma}_\mu q_J H^\dagger \overleftrightarrow{D}_\mu H$	$[O^\dagger_{uW}]_{IJ}$	$u^c_I\sigma_{\mu\nu}\widetilde{H}^\dagger\sigma^i q_J\, W^i_{\mu\nu}$
$[O^{(3)}_{Hq}]_{IJ}$	$i\bar{q}_I\sigma^i\bar{\sigma}_\mu q_J H^\dagger\sigma^i \overleftrightarrow{D}_\mu H$	$[O^\dagger_{uB}]_{IJ}$	$u^c_I\sigma_{\mu\nu}\widetilde{H}^\dagger q_J\, B_{\mu\nu}$
$[O_{Hu}]_{IJ}$	$iu^c_I\sigma_\mu\bar{u}^c_J H^\dagger \overleftrightarrow{D}_\mu H$	$[O^\dagger_{dG}]_{IJ}$	$d^c_I\sigma_{\mu\nu}T^a H^\dagger q_J\, G^a_{\mu\nu}$
$[O_{Hd}]_{IJ}$	$id^c_I\sigma_\mu\bar{d}^c_J H^\dagger \overleftrightarrow{D}_\mu H$	$[O^\dagger_{dW}]_{IJ}$	$d^c_I\sigma_{\mu\nu}\bar{H}^\dagger\sigma^i q_J\, W^i_{\mu\nu}$
$[O_{Hud}]_{IJ}$	$iu^c_I\sigma_\mu\bar{d}^c_J \widetilde{H}^\dagger D_\mu H$	$[O^\dagger_{dB}]_{IJ}$	$d^c_I\sigma_{\mu\nu}H^\dagger q_J\, B_{\mu\nu}$

Table 2.3: Two-fermion D=6 operators in the Warsaw basis. The flavor indices are denoted by I, J. For complex operators (O_{Hud} and all Yukawa and dipole operators) the corresponding complex conjugate operator is implicitly included.

$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
O_{ee}	$\eta(e^c\sigma_\mu\bar{e}^c)(e^c\sigma_\mu\bar{e}^c)$	$O_{\ell e}$	$(\bar{\ell}\bar{\sigma}_\mu\ell)(e^c\sigma_\mu\bar{e}^c)$
O_{uu}	$\eta(u^c\sigma_\mu\bar{u}^c)(u^c\sigma_\mu\bar{u}^c)$	$O_{\ell u}$	$(\bar{\ell}\bar{\sigma}_\mu\ell)(u^c\sigma_\mu\bar{u}^c)$
O_{dd}	$\eta(d^c\sigma_\mu\bar{d}^c)(d^c\sigma_\mu\bar{d}^c)$	$O_{\ell d}$	$(\bar{\ell}\bar{\sigma}_\mu\ell)(d^c\sigma_\mu\bar{d}^c)$
O_{eu}	$(e^c\sigma_\mu\bar{e}^c)(u^c\sigma_\mu\bar{u}^c)$	O_{eq}	$(e^c\sigma_\mu\bar{e}^c)(\bar{q}\bar{\sigma}_\mu q)$
O_{ed}	$(e^c\sigma_\mu\bar{e}^c)(d^c\sigma_\mu\bar{d}^c)$	O_{qu}	$(\bar{q}\bar{\sigma}_\mu q)(u^c\sigma_\mu\bar{u}^c)$
O_{ud}	$(u^c\sigma_\mu\bar{u}^c)(d^c\sigma_\mu\bar{d}^c)$	O'_{qu}	$(\bar{q}\bar{\sigma}_\mu T^a q)(u^c\sigma_\mu T^a\bar{u}^c)$
O'_{ud}	$(u^c\sigma_\mu T^a\bar{u}^c)(d^c\sigma_\mu T^a\bar{d}^c)$	O_{qd}	$(\bar{q}\bar{\sigma}_\mu q)(d^c\sigma_\mu\bar{d}^c)$
		O'_{qd}	$(\bar{q}\bar{\sigma}_\mu T^a q)(d^c\sigma_\mu T^a\bar{d}^c)$

$(\bar{L}L)(\bar{L}L)$		$(\bar{L}R)(\bar{L}R)$	
$O_{\ell\ell}$	$\eta(\bar{\ell}\bar{\sigma}_\mu\ell)(\bar{\ell}\bar{\sigma}_\mu\ell)$	O_{quqd}	$(u^c q^j)\epsilon_{jk}(d^c q^k)$
O_{qq}	$\eta(\bar{q}\bar{\sigma}_\mu q)(\bar{q}\bar{\sigma}_\mu q)$	O'_{quqd}	$(u^c T^a q^j)\epsilon_{jk}(d^c T^a q^k)$
O'_{qq}	$\eta(\bar{q}\bar{\sigma}_\mu\sigma^i q)(\bar{q}\bar{\sigma}_\mu\sigma^i q)$	$O_{\ell equ}$	$(e^c\ell^j)\epsilon_{jk}(u^c q^k)$
$O_{\ell q}$	$(\bar{\ell}\bar{\sigma}_\mu\ell)(\bar{q}\bar{\sigma}_\mu q)$	$O'_{\ell equ}$	$(e^c\bar{\sigma}_{\mu\nu}\ell^j)\epsilon_{jk}(u^c\bar{\sigma}^{\mu\nu}q^k)$
$O'_{\ell q}$	$(\bar{\ell}\bar{\sigma}_\mu\sigma^i\ell)(\bar{q}\bar{\sigma}_\mu\sigma^i q)$	$O_{\ell edq}$	$(\bar{\ell}\bar{e}^c)(d^c q)$

Table 2.4: Four-fermion D=6 operators in the Warsaw basis. Flavor indices are suppressed here to reduce the clutter. The factor η is equal to $1/2$ when all flavor indices are equal (e.g. in $[O_{ee}]_{1111}$), and $\eta = 1$ otherwise. For each complex operator the complex conjugate should be included.

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

Enough for everyone :)

Alonso et al 1312.2014, Henning et al 1512.03433

Possible Indo-French EFT projects

Project #1:
Higgs EFT Fit

Project #1: Higgs EFT Fit

Why now

- Flurry of fitting activity peaking in 2012, later exponentially decaying
- Most recent comprehensive Higgs EFT fit from Sfitter survivors in arXiv:1604.03105
- Since then, new 13 TeV data, and more to come any time now
- More and more differential distributions become available
- Also, quite a lot of theoretical improvements (NLO corrections, new clever observables, automatized EFT tools, ...)

Project #1: Higgs EFT Fit

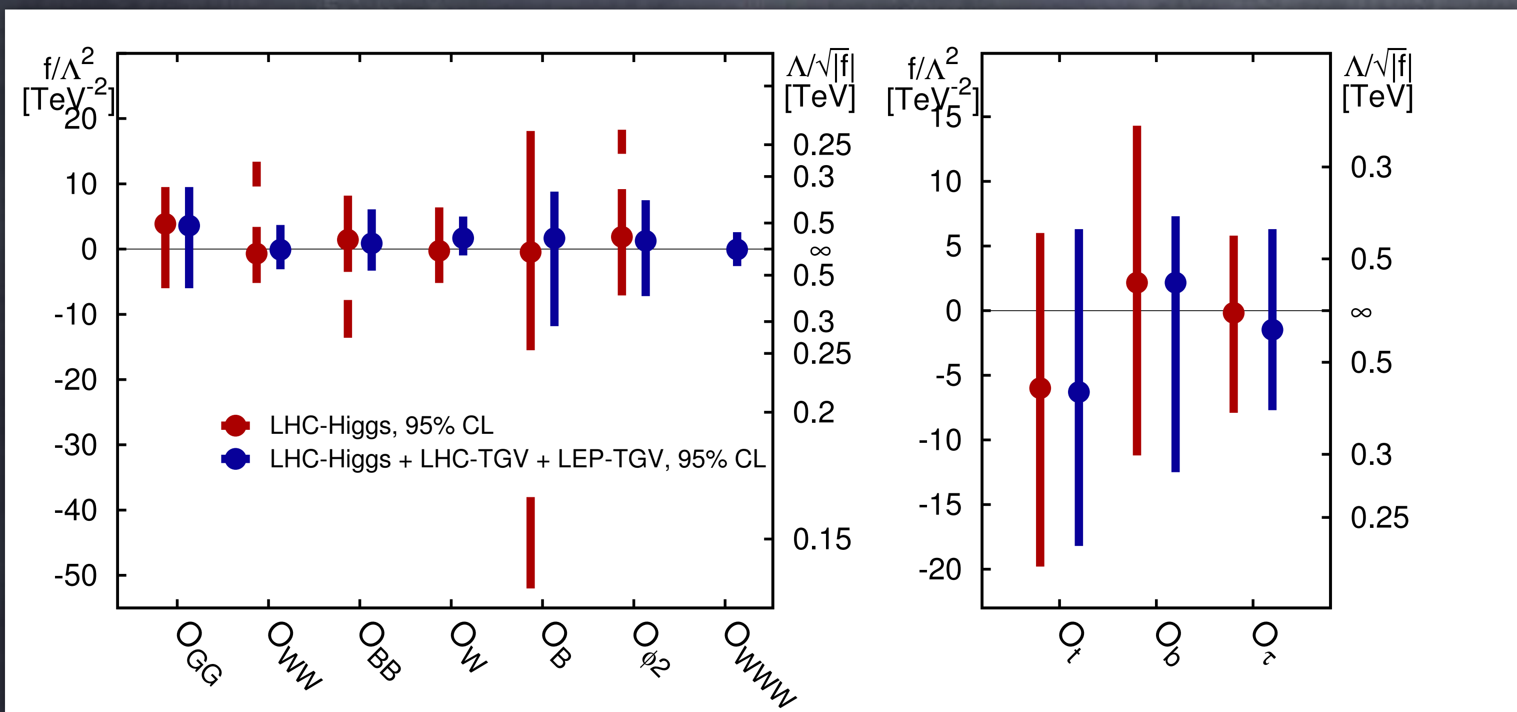
Specifications

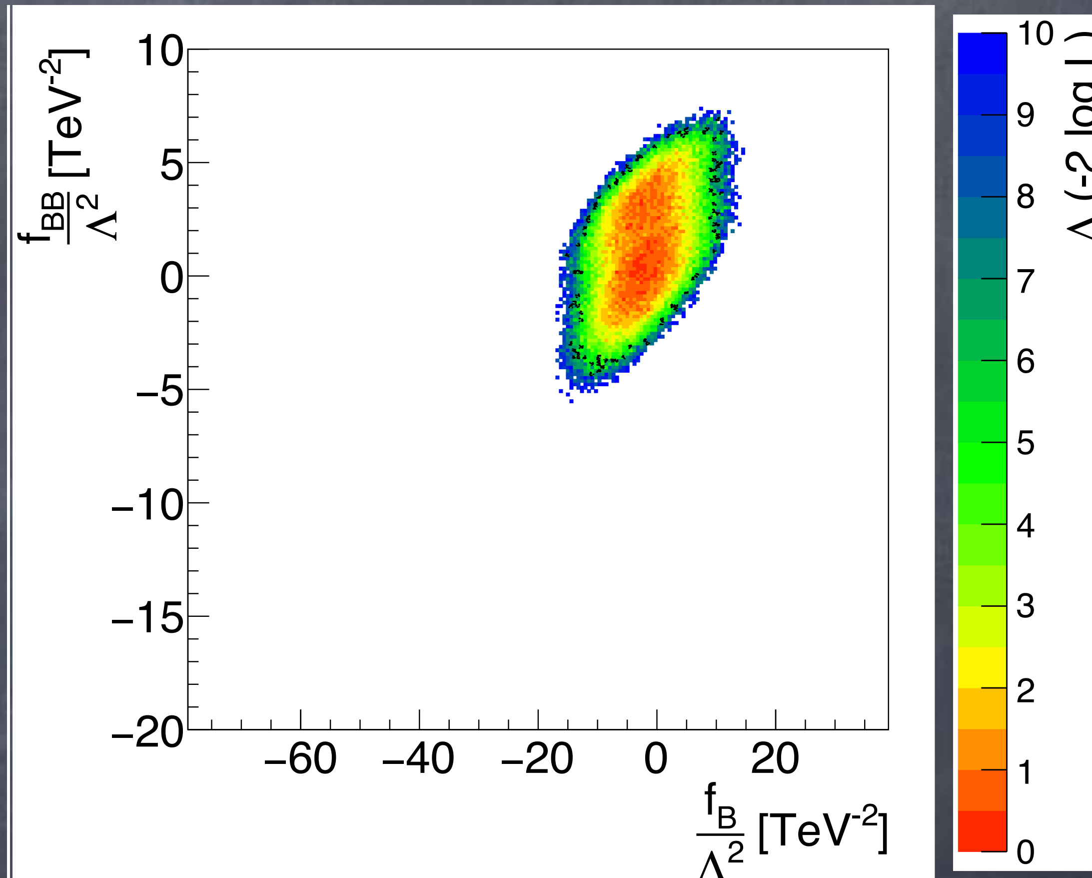
- SMEFT framework with dimension-6 operators.
- Should use experimental input not only from rates but also from differential distributions
- Combine Higgs and diboson data (WW, WZ, Wγ)
- Produce public likelihood function for a large set dimension-6 Wilson coefficients including all correlations
- Offer regular updates, web page, and interface to other HEP tools

Project #1: Higgs Fit

Butter et al
1604.03105

Sample output





$$\frac{f_W}{\Lambda^2} = (2.2 \pm 1.9)\ \text{TeV}^{-2} \qquad \frac{f_B}{\Lambda^2} = (3.0 \pm 8.4)\ \text{TeV}^{-2} \qquad \frac{f_{WWW}}{\Lambda^2} = (0.55 \pm 1.4)\ \text{TeV}^{-2}$$

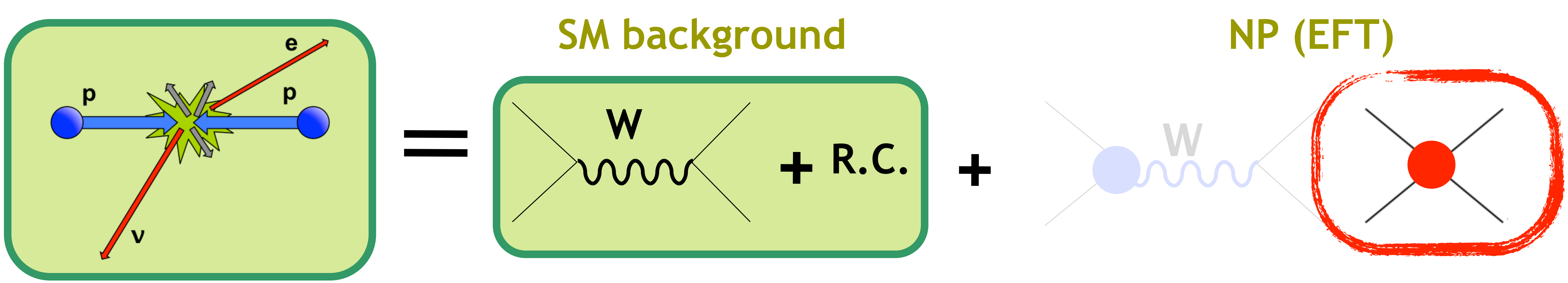
$$\rho = \begin{pmatrix} 1.00 & -0.012 & -0.062 \\ -0.012 & 1.00 & -0.0012 \\ -0.062 & -0.0012 & 1.00 \end{pmatrix} .$$

Project #2:

Comprehensive EFT description of Drell-Yan lepton production at LHC

Project #3: Drell-Yan EFT

Two-fermion production (via charged or neutral currents) can be affected by 4-fermion SMEFT operators



Borrowed from Martin Gonzalez-Alonso

$$\mathcal{A} \sim \mathcal{A}_{SM}\left(1+\alpha_6\frac{x^2}{\Lambda^2}+\alpha_8\frac{x^2}{\Lambda^4}+\ldots\right)$$

$$\mathcal{O} \sim \mathcal{O}_{SM}\left(1+\alpha_6\frac{x^2}{\Lambda^2}+(\alpha_6^2+\alpha_8)\frac{x^2}{\Lambda^4}+\ldots\right)$$

$x = (v, E) << \Lambda$

Precision vs Energy in EFT

Two distinct interesting situations

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

$$\frac{\sigma}{\sigma_{\rm SM}} \approx \left|1+\frac{c_6 m^2}{\Lambda^2}\right|^2$$

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

For Higgs decays,
and tree EFT operator c6 ~ g*^2
given experimental precision ε = 10%

$$\Lambda \gtrsim \begin{cases} 7\ \text{TeV} & g_* \sim 4\pi \\ 0.6\ \text{TeV} & g_* \sim 1 \end{cases}$$

High-energy tails of distributions
(e.g. Drell-Yan production)

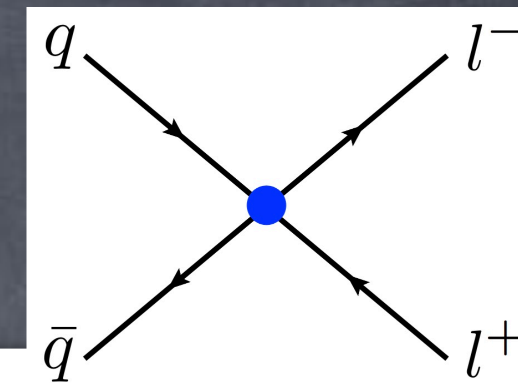
$$\frac{\sigma}{\sigma_{\rm SM}} \approx \left|1+\frac{c_6 E^2}{\Lambda^2}\right|^2$$

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

For observable at E ~ 2 TeV,
and tree EFT operator c6 ~ g*^2
given experimental precision ε = 10%

$$\Lambda \gtrsim \begin{cases} 110\ \text{TeV} & g_* \sim 4\pi \\ 9\ \text{TeV} & g_* \sim 1 \end{cases}$$

Drell-Yan production



Complementarity of LHC and low-energy measurements

$(ee)(qq)$

	$[c_{\ell q}^{(3)}]_{1111}$	$[c_{\ell q}]_{1111}$	$[c_{\ell u}]_{1111}$	$[c_{\ell d}]_{1111}$	$[c_{eq}]_{1111}$	$[c_{eu}]_{1111}$	$[c_{ed}]_{1111}$
Low-energy	0.45 ± 0.28	1.6 ± 1.0	2.8 ± 2.1	3.6 ± 2.0	-1.8 ± 1.1	-4.0 ± 2.0	-2.7 ± 2.0
$\text{LHC}_{1.5}$	$-0.70^{+0.66}_{-0.74}$	$2.5^{+1.9}_{-2.5}$	$2.9^{+2.4}_{-2.9}$	$-1.6^{+3.4}_{-3.0}$	$1.6^{+1.8}_{-2.2}$	$1.6^{+2.5}_{-1.5}$	$-3.1^{+3.6}_{-3.0}$
$\text{LHC}_{1.0}$	$-0.84^{+0.85}_{-0.92}$	$3.6^{+3.6}_{-3.7}$	$4.4^{+4.4}_{-4.7}$	$-2.4^{+4.8}_{-4.7}$	$2.4^{+3.0}_{-3.2}$	$1.9^{+2.5}_{-1.9}$	$-4.6^{+5.4}_{-4.1}$
$\text{LHC}_{0.7}$	$-1.0^{+1.4}_{-1.5}$	5.9 ± 7.2	7.4 ± 9.0	-3.6 ± 8.7	3.8 ± 5.9	$2.1^{+3.8}_{-2.9}$	-8 ± 10

$(\mu\mu)(qq)$

	$[c_{\ell q}^{(3)}]_{2211}$	$[c_{\ell q}]_{2211}$	$[c_{\ell u}]_{2211}$	$[c_{\ell d}]_{2211}$	$[c_{eq}]_{2211}$	$[c_{eu}]_{2211}$	$[c_{ed}]_{2211}$
Low-energy	-0.2 ± 1.2	4 ± 21	18 ± 19	-20 ± 37	40 ± 390	-20 ± 190	40 ± 390
$\text{LHC}_{1.5}$	$-1.22^{+0.62}_{-0.70}$	1.8 ± 1.3	2.0 ± 1.6	-1.1 ± 2.0	1.1 ± 1.2	$2.5^{+1.8}_{-1.4}$	-2.2 ± 2.0
$\text{LHC}_{1.0}$	$-0.72^{+0.81}_{-0.87}$	$3.2^{+4.0}_{-3.5}$	$3.9^{+4.8}_{-4.4}$	$-2.3^{+4.9}_{-4.7}$	$2.3^{+3.1}_{-3.2}$	$1.6^{+2.3}_{-1.8}$	-4.4 ± 5.3
$\text{LHC}_{0.7}$	$-0.7^{+1.3}_{-1.4}$	$3.2^{+10.3}_{-4.8}$	$4.3^{+12.5}_{-6.4}$	-3.6 ± 9.0	3.8 ± 6.2	$1.6^{+3.4}_{-2.7}$	-8 ± 11

Chirality-violating operators ($\mu = 1$ TeV)

	$[c_{\ell equ}]_{1111}$	$[c_{\ell edq}]_{1111}$	$[c_{\ell equ}^{(3)}]_{1111}$	$[c_{\ell equ}]_{2211}$	$[c_{\ell edq}]_{2211}$	$[c_{\ell equ}^{(3)}]_{2211}$
Low-energy	$(-0.6 \pm 2.4)10^{-4}$	$(0.6 \pm 2.4)10^{-4}$	$(0.4 \pm 1.4)10^{-3}$	$0.014(49)$	$-0.014(49)$	$-0.09(29)$
$\text{LHC}_{1.5}$	0 ± 2.0	0 ± 2.6	0 ± 0.91	0 ± 1.2	0 ± 1.6	0 ± 0.56
$\text{LHC}_{1.0}$	0 ± 2.9	0 ± 3.7	0 ± 1.4	0 ± 2.9	0 ± 3.7	0 ± 1.4
$\text{LHC}_{0.7}$	0 ± 5.3	0 ± 6.6	0 ± 2.6	0 ± 5.5	0 ± 6.9	0 ± 2.6

AA, Gonzalez-Alonso, Mimouni
1706.03783

Project #3: Drell-Yan EFT

Motivations

- Currently only theorist level recasts available, assuming one 4-fermion operator present at a time - not sufficient for many applications
- Sensitivity often better than for low-energy precision measurements
- Unique access to heavy quark (b and c) 4-fermion operators (possible consequences for models addressing B-meson anomalies)

Project #3: Drell-Yan EFT

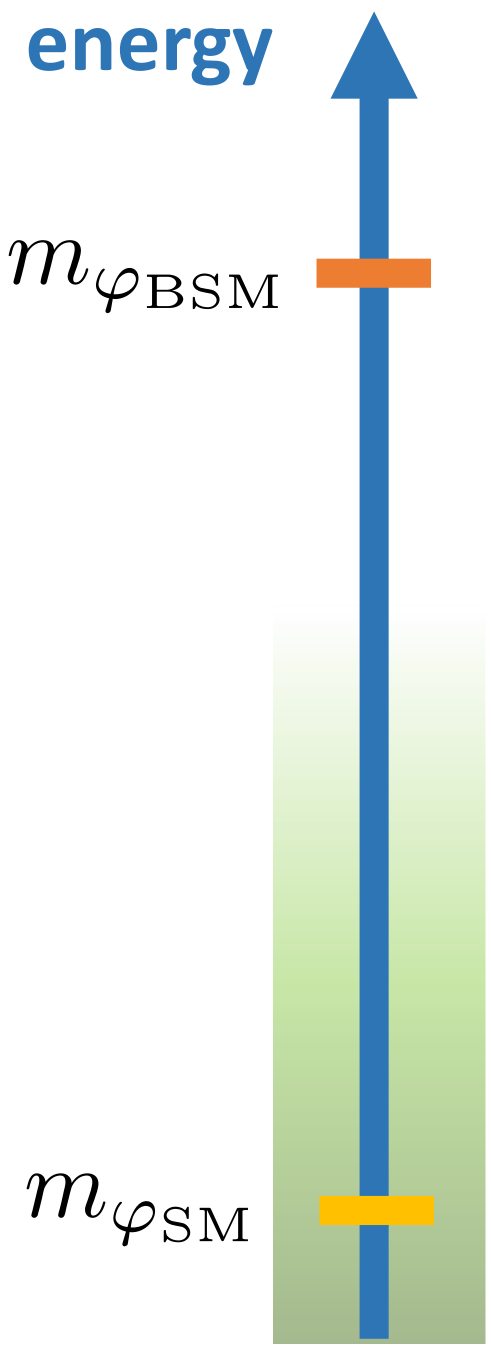
Specifications

- SMEFT framework with dimension-6 operators
- Experimental input from differential cross-sections (triple mll, yZ, pTZ, differential distributions available in ee and $\mu\mu$ channels)
- In τ and $e\nu/\mu\nu$ final states no differential cross section measurements currently available so recast is necessary
- Combine charged- and neutral current information to better break degeneracy between operators
- Produce public likelihood function for a large set dimension-6 Wilson coefficients including all correlations
- Marginalized over experimental and theoretical systematics

Project #3:

Automated EFT - UV matching with functional formalism

Project #3: Automated EFT-UV matching



$$\mathcal{L}_{\rm UV}[\varphi_{\rm BSM}, \varphi_{\rm SM}]$$

↓ ***match*** *(UV ←→ EFT dictionary)*

$$\mathcal{L}_{\rm EFT}[\varphi_{\rm SM}] = \mathcal{L}_{\rm SM} + \sum_i c_i \, \mathcal{O}_i \, (\mu \sim m_{\varphi_H})$$

↓ ***run*** *(resum large logs)*

$$\mathcal{L}_{\rm EFT}[\varphi_{\rm SM}] = \mathcal{L}_{\rm SM} + \sum_i c_i \, \mathcal{O}_i \, (\mu \sim E_{\rm exp})$$

↓ ***calculate*** *(model-independent)*

observables (cross sections, etc.)

Slide from Z. Zhang

Project #3: Automated EFT-UV matching

Motivations

- To translate EFT bounds as constraints on BSM, one needs to know matching between the two
- Ideally, one writes BSM model in some public format, and from that input EFT Wilson coefficients are automatically calculated
- Ongoing efforts in MatchMaker project using standard Feynman diagrams approach (Anastasiou et al)
- Recently powerful EFT-UV matching techniques have been developed: Gaillard-Cheyette, Henning et al. 1604.01019, ... , Zhang 1610.00710, ... , Ellis et al 1706.07765

Project #3: Automated EFT-UV matching

$$\mathcal{L}_{\rm UV} = \mathcal{L}_{\rm SM} + (\Phi^\dagger F(x) + \text{h.c.}) + \Phi^\dagger (P^2 - M^2 - U(x))\Phi + \mathcal{O}(\Phi^3)$$

$$\begin{aligned}
\mathcal{L}^{\rm eff}_{\text{1-loop}}[\phi] \supset -ic_s \Big\{ & f_1^i + f_2^i U_{ii} + f_3^i G'^2_{\mu\nu,ij} + f_4^{ij} U_{ij}^2 \\
& + f_5^{ij} (P_\mu G'_{\mu\nu,ij})^2 + f_6^{ij} (G'_{\mu\nu,ij})(G'_{\nu\sigma,jk})(G'_{\sigma\mu,ki}) + f_7^{ij} [P_\mu, U_{ij}]^2 + f_8^{ijk} (U_{ij} U_{jk} U_{ki}) \\
& + f_9^{ij} (U_{ij} G'_{\mu\nu,jk} G'_{\mu\nu,ki}) \\
& + f_{10}^{ijkl} (U_{ij} U_{jk} U_{kl} U_{li}) + f_{11}^{ijk} U_{ij} [P_\mu, U_{jk}][P_\mu, U_{ki}] \\
& + f_{12,a}^{ij} [P_\mu, [P_\nu, U_{ij}]] [P_\mu, [P_\nu, U_{ji}]] + f_{12,b}^{ij} [P_\mu, [P_\nu, U_{ij}]] [P_\nu, [P_\mu, U_{ji}]] \\
& + f_{12,c}^{ij} [P_\mu, [P_\mu, U_{ij}]] [P_\nu, [P_\nu, U_{ji}]] \\
& + f_{13}^{ijk} U_{ij} U_{jk} G'_{\mu\nu,kl} G'_{\mu\nu,li} + f_{14}^{ijk} [P_\mu, U_{ij}] [P_\nu, U_{jk}] G'_{\nu\mu,ki} \\
& + \left(f_{15a}^{ijk} U_{i,j} [P_\mu, U_{j,k}] - f_{15b}^{ijk} [P_\mu, U_{i,j}] U_{j,k} \right) [P_\nu, G'_{\nu\mu,ki}] \\
& + f_{16}^{ijklm} (U_{ij} U_{jk} U_{kl} U_{lm} U_{mi}) + f_{17}^{ijkl} U_{ij} U_{jk} [P_\mu, U_{kl}][P_\mu, U_{li}] + f_{18}^{ijkl} U_{ij} [P_\mu, U_{jk}] U_{kl} [P_\mu, U_{li}] \\
& + f_{19}^{ijklmn} (U_{ij} U_{jk} U_{kl} U_{lm} U_{mn} U_{ni}) \Big\} .
\end{aligned}$$

Borrowed from T, You slides

$$\int \frac{d^d q}{(2\pi)^d} \frac{q^{\mu_1} \cdots q^{\mu_{2n_c}}}{(q^2 - M_i^2)^{n_i} (q^2 - M_j^2)^{n_j} \cdots (q^2)^{n_L}} \equiv g^{\mu_1 \ldots \mu_{2n_c}} \mathcal{I}[q^{2n_c}]^{n_i n_j \ldots n_L}_{ij \ldots 0}$$

Universal coefficient	Operator
$f_2^i = \mathcal{I}_i^1$	U_{ii}
$f_3^i = 2\mathcal{I}[q^4]_i^4$	$G_i'^{\mu\nu} G'_{\mu\nu,i}$
$f_4^{ij} = \frac{1}{2}\mathcal{I}_{ij}^{11}$	$U_{ij} U_{ji}$
$f_5^i = 16\mathcal{I}[q^6]_i^6$	$[P^\mu, G'_{\mu\nu,i}][P_\rho, G_i'^{\rho\nu}]$
$f_6^i = \frac{32}{3}\mathcal{I}[q^6]_i^6$	$G'^{\mu}{}_{\nu,i} G'^{\nu}{}_{\rho,i} G'^{\rho}{}_{\mu,i}$
$f_7^{ij} = \mathcal{I}[q^2]_{ij}^{22}$	$[P^\mu, U_{ij}][P_\mu, U_{ji}]$
$f_8^{ijk} = \frac{1}{3}\mathcal{I}_{ijk}^{111}$	$U_{ij} U_{jk} U_{ki}$
$f_9^i = 8\mathcal{I}[q^4]_i^5$	$U_{ii} G_i'^{\mu\nu} G'_{\mu\nu,i}$
$f_{10}^{ijkl} = \frac{1}{4}\mathcal{I}_{ijkl}^{1111}$	$U_{ij} U_{jk} U_{kl} U_{li}$
$f_{11}^{ijk} = 2\big(\mathcal{I}[q^2]_{ijk}^{122} + \mathcal{I}[q^2]_{ijk}^{212}\big)$	$U_{ij}[P^\mu, U_{jk}][P_\mu, U_{ki}]$
$f_{12}^{ij} = 4\mathcal{I}[q^4]_{ij}^{33}$	$[P^\mu, [P_\mu, U_{ij}]]\,[P^\nu, [P_\nu, U_{ji}]]$
$f_{13}^{ij} = 4\big(\mathcal{I}[q^4]_{ij}^{33} + 2\mathcal{I}[q^4]_{ij}^{42} + 2\mathcal{I}[q^4]_{ij}^{51}\big)$	$U_{ij} U_{ji} G_i'^{\mu\nu} G'_{\mu\nu,i}$
$f_{14}^{ij} = -8\mathcal{I}[q^4]_{ij}^{33}$	$[P^\mu, U_{ij}][P^\nu, U_{ji}] G'_{\nu\mu,i}$
$f_{15}^{ij} = 4\big(\mathcal{I}[q^4]_{ij}^{33} + \mathcal{I}[q^4]_{ij}^{42}\big)$	$\big(U_{ij}[P^\mu, U_{ji}] - [P^\mu, U_{ij}]U_{ji}\big)[P^\nu, G'_{\nu\mu,i}]$
$f_{16}^{ijklm} = \frac{1}{5}\mathcal{I}_{ijklm}^{11111}$	$U_{ij} U_{jk} U_{kl} U_{lm} U_{mi}$
$f_{17}^{ijkl} = 2\big(\mathcal{I}[q^2]_{ijkl}^{2112} + \mathcal{I}[q^2]_{ijkl}^{1212} + \mathcal{I}[q^2]_{ijkl}^{1122}\big)$	$U_{ij} U_{jk}[P^\mu, U_{kl}][P_\mu, U_{li}]$
$f_{18}^{ijkl} = \mathcal{I}[q^2]_{ijkl}^{2121} + \mathcal{I}[q^2]_{ijkl}^{2112} + \mathcal{I}[q^2]_{ijkl}^{1221} + \mathcal{I}[q^2]_{ijkl}^{1212}$	$U_{ij}[P^\mu, U_{jk}] U_{kl}[P_\mu, U_{li}]$
$f_{19}^{ijklmn} = \frac{1}{6}\mathcal{I}_{ijklmn}^{111111}$	$U_{ij} U_{jk} U_{kl} U_{lm} U_{mn} U_{ni}$

General expressions for one-loop effective Lagrangian in terms of UV Lagrangian and master integrals already exist in literature

Drozd et a 1512.03003

Ellis et a 1706.07765

Project #3: Drell-Yan EFT

Specifications

- Public code taking any UV Lagrangian as input (e.g. in Feynrules format) and returning dimension-6 Wilson coefficients in analytic and numerical form in one or several popular bases

Project #4:
CP-violating TGV

Project #4: CPV TGV

Motivations

- Some experimental studies in LEP-2. For LHC, pre-2010 analysis by Kumar et al 0801.2891. Recent ILC study by Rahaman and Singh 1711.04551. Certainly, topic not exhausted yet
- In SMEFT framework, interesting to study LHC sensitivity to CP-violating dimension-6 operators affecting WWZ and WWγ couplings as they also relate to some CP-violating Higgs couplings
- Recent progress on CP-conserving ones (circumventing non-interference theorems) may give useful lessons for this project as well