UCL Université catholique de Louvain

Mapping SMEFT & HC with Rosetta

Adam Falkowski, Benjamin Fuks, Kentarou Mawatari,
Ken Mimasu, Francesco Riva, Veronica Sanz

arXiv:1508.05895
Eur. Phys. J. C, 75(12), 1-14

arXiv:1605.02584
LH proceedings, contribution 18

7th December 2016

Outline

- SMEFT, anomalous couplings & maps between
- Rosetta
  - Progress on Higgs Characterisation implementation
  - Will not discuss POs explicitly but the same points apply in general

Closely linked to WG2 draft proposal: *[LHCHXSWG-INT-2015-001]*

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGEFTbases

SM Effective Field Theory

- Basis: minimal set of independent operators up to field redefinitions, integration by parts, Fierz identities & e.o.m
  - SILH, Warsaw, … - linearly realised EWSB with SU(2)xU(1) invariance manifest

$$\mathcal{O}_W = \left[\Phi^\dagger \sigma_k \overleftrightarrow{D}^\mu \Phi\right] D^\nu W^k_{\mu\nu}$$

  - BSM Primaries - linearly realised EWSB expressed in the mass eigenbasis with implicit SU(2)xU(1) invariance

$$\mathcal{O}_{w\Box} = h W^-_\mu \partial_\nu W^{\mu\nu}_+$$

- Model deviations from SM augmented by new momentum structures
  - At leading order: tree-level interference with SM & squared terms
  - At NLO: Renormalisation group running effects & operator mixing

[Alonso, Jenkins, Manohar & Trott; JHEP 1310 (2013) 087, JHEP 1401 (2014) 035 & JHEP 1404 (2014) 159*]*

in "Warsaw" basis

Anomalous couplings

- Do not require SU(2) invariance: “low energy” Lagrangian after EWSB, i.e. Higgs Characterisation
- Anomalous couplings written in the mass eigenbasis
  - Physically intuitive & can directly calculate/implement MC generators
  - SU(3) x $U(1)_Q$ gauge symmetry only
  - Expansion in canonical dimension, derivatives,…
  - Most general set of interactions given field content & reduced symmetry
- Related to POs except defined at the Lagrangian level vs. amplitude level
  - At LO, POs can be written as a linear combination of AC parameters

[F. Maltoni et al.; Eur.Phys.J. C74 (2014) 2710]
[F. Demartin et al.; Eur.Phys.J. C74 (2014) 3065 & Eur.Phys.J. C75 (2015) 267]

Higgs Characterisation

- Anomalous coupling Lagrangian for Higgs couplings
  - General Lorentz structures in EW gauge-Higgs & Yukawa sector
  - Gluon-gluon effective vertex (LO)
  - Currently used by experimental collaborations for some Higgs analyses *[ATLAS; Eur.Phys.J. C75 (2015) 476]*
- UFO (FeynRules) model at NLO in QCD
  - VBF, VH + CP-violating,…
- Related model: BSM Characterisation (LO)
  - Extends to a larger set of operators: all except four fermion
  - Based on collection of Lorentz structure in Higgs Basis definition
  - Output for ROSETTA: basis translator program which implements maps from popular EFT basis choices to the mass eigenbasis

Higgs Characterisation

$$\mathcal{L}_0^f = -\sum_{f=t,b,\tau} \bar\psi_f \big(c_\alpha \kappa_{Hff} g_{Hff} + i s_\alpha \kappa_{Aff} g_{Aff}\, \gamma_5\big)\psi_f X_0\,,\qquad c_\alpha \equiv \cos\alpha\,,\quad s_\alpha \equiv \sin\alpha\,,$$

CP-admixture:
Convenient but "redundant"

$$\begin{aligned}\mathcal{L}_0^V = \bigg\{ & c_\alpha \kappa_{\rm SM} \big[\tfrac{1}{2} g_{HZZ}\, Z_\mu Z^\mu + g_{HWW}\, W^+_\mu W^{-\mu}\big] \\ & - \frac{1}{4}\big[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma}\, A_{\mu\nu}A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma}\, A_{\mu\nu}\widetilde{A}^{\mu\nu}\big] \\ & - \frac{1}{2}\big[c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma}\, Z_{\mu\nu}A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma}\, Z_{\mu\nu}\widetilde{A}^{\mu\nu}\big] \\ & - \frac{1}{4}\big[c_\alpha \kappa_{Hgg} g_{Hgg}\, G^a_{\mu\nu}G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg}\, G^a_{\mu\nu}\widetilde{G}^{a,\mu\nu}\big] \\ & - \frac{1}{4}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HZZ}\, Z_{\mu\nu}Z^{\mu\nu} + s_\alpha \kappa_{AZZ}\, Z_{\mu\nu}\widetilde{Z}^{\mu\nu}\big] \\ & - \frac{1}{2}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HWW}\, W^+_{\mu\nu}W^{-\mu\nu} + s_\alpha \kappa_{AWW}\, W^+_{\mu\nu}\widetilde{W}^{-\mu\nu}\big] \\ & - \frac{1}{\Lambda} c_\alpha \big[\kappa_{H\partial\gamma}\, Z_\nu \partial_\mu A^{\mu\nu} + \kappa_{H\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} + \big(\kappa_{H\partial W}\, W^+_\nu \partial_\mu W^{-\mu\nu} + h.c.\big)\big] \bigg\} X_0\end{aligned}$$

'Custodial' symmetry

From SMEFT to AC

- EFT expansions are mappings from UV theories
  - Linear: Higgs is a doublet, $SU(2)_L$ symmetry also present
  - Non-linear: Higgs as a singlet + chiral EW Lagrangian
- Anomalous coupling Lagrangians are a general parametrisation at the mass eigenbasis level
  - Larger parameter space than SMEFT
- From SMEFT: break EW symmetry and map to the mass eigenbasis in order to make predictions for the LHC
  - Result is a special case of an AC Lagrangian (e.g. Higgs Basis)
  - Generally a one-way map EFT → AC & parameters will be (cor)related

[A. Falkowski et.al; LHCHXSWG-INT-2015-001]

SMEFT & AC: map

$$\mathcal{O}_H = \frac{\bar{c}_H}{2}\partial_\mu\left(\Phi^\dagger\Phi\right)\partial^\mu\left(\Phi^\dagger\Phi\right)$$
$$= \frac{\bar{c}_H}{\Lambda^2}\frac{v^2}{2}\partial_\mu h\partial^\mu h + \mathcal{O}(h^3, h^2)$$
$$h \to h(1+\delta h), \quad \delta h = -\frac{\bar{c}_H}{\Lambda^2}\frac{v^2}{4}$$

$$\mathcal{O}_W|_{\Phi=\langle\Phi\rangle} = \frac{ig}{2}\bar{c}_W\left[\Phi^\dagger T_{2k}\overleftrightarrow{D}^\mu\Phi\right]D^\nu W^k_{\mu\nu}|_{\Phi=\langle\Phi\rangle}$$
$$= \frac{gv^2}{16}\bar{c}_W\left[2gW_+^{\mu\nu}W^-_{\mu\nu} + g(W_3^{\mu\nu} - g'B^{\mu\nu})W^3_{\mu\nu}\right] + \text{aGC}$$
$$W^\mu_\pm \to W^\mu_\pm\left[1+\delta W\right]$$
$$B^\mu \to B^\mu\left[1+\delta B\right] + yW_3^\mu$$
$$W_3^\mu \to W_3^\mu\left[1+\delta W\right] + zB^\mu$$

$$y + z \equiv -\frac{v^2}{\Lambda^2}\frac{gg'}{4}\left(\bar{c}_B + \frac{\bar{c}_W}{2}\right)$$

- Canonical mass eigenbasis Lagrangian generically different from the SM case
  - Non canonical kinetic terms & kinetic mixing
  - Infinite freedom in how one redefines fields (equivalent up to $1/\Lambda^2$)
  - EFT contributions to masses and couplings
- Some extra book-keeping required…

SMEFT & AC: map

- 'SM-like' EW sector is modified
  - New relations between SM inputs and EW parameters
  - $v(G_F, c_i)$, $\sin\theta_W(m_W, m_Z, \alpha_{EM}, c_i)$, …
  - Higgs couplings rescaled
  - Z couplings to fermions
  - SM gauge bosons self interactions
  - Many of these effects are constrained pre-LHC (i.e. by EWPO)
- Additional $1/\Lambda^2$ pieces on top of "naïve" direct effects from new operators/Lorentz structures
  - Depends on SM input scheme used
  - Can contribute to SM backgrounds!

[Trott & Passarino; LHCHXSWG-DRAFT-2016-005]
[Falkowski et.al; LHCHXSWG-INT-2015-001]
[Williams, KM & Sanz; JHEP 1608 (2016) 039]
[Ge, He & Xiao; JHEP 1610 (2016) 007]
[Degrande, Fuks, Mawatari, KM, Sanz; 1609.04833]

SMEFT & AC: interpretation

- AC implementations do not “need” to consider such things by construction
  - Potentially complicates the ‘one-way map’
  - There is a way to at least preserve SM input relations (Higgs Basis)
- If AC are used to simulate signal & interpret data
  - From a pure Lorentz structure basis, the EFT parameter space is a subset of the general AC description
  - Mapping constraints from a multi parameter AC fit to an EFT interpretation may be tricky & relevant parameter space is larger than it originally seems
  - e.g. $H \to WW$: might also need to include rescalings of the WW background
  - Assess how big these effects can be

Higgs basis

- A detailed description is contained in the HXSWG note
  - Based on "BSM primaries" *[R. Gupta, A. Pomarol & F. Riva; PRD 91 (2015) 035001]*
  - Constructs a practically complete set of mass eigenbasis operators mapped from a dimension-6 Linear EFT
- Anomalous couplings Lagrangian supplemented with
  - SU(2) preserving relations → "dependent" parameters
  - Modifications to EW parameters, masses, couplings etc.
- Field redefinitions chosen to "minimise" their impact
  - Preserve SM relations for EW parameters in terms of (α_{EW}, G_F, M_Z) inputs
  - All field redefinition effects are deferred W-mass shift and (h, W, Z) boson coupling modifications

Dependent parameters

- To reconcile the 76 (2499) free parameters in the SMEFT with the larger set of AC parameters
    - Set of AC parameters obtained when mapped from SMEFT are related
    - e.g. modifications to Higgs couplings with vector bosons are constrained by a set of equations
    - Freedom in choosing the set of 76 (2499) parameters to describe Higgs Basis

$$\begin{aligned}\mathcal{L}_{\rm hvv} \;=\; & \frac{h}{v}\Big[(1+\delta c_w)\frac{g^2v^2}{2}W_\mu^+W_\mu^- + (1+\delta c_z)\frac{(g^2+g'^2)v^2}{4}Z_\mu Z_\mu \\ & + c_{ww}\frac{g^2}{2}W_{\mu\nu}^+W_{\mu\nu}^- + \tilde{c}_{ww}\frac{g^2}{2}W_{\mu\nu}^+\tilde{W}_{\mu\nu}^- + c_{w\Box}g^2\left(W_\mu^-\partial_\nu W_{\mu\nu}^+ + \text{h.c.}\right) \\ & + c_{gg}\frac{g_s^2}{4}G_{\mu\nu}^aG_{\mu\nu}^a + c_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}A_{\mu\nu} + c_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2}Z_{\mu\nu}A_{\mu\nu} + c_{zz}\frac{g^2+g'^2}{4}Z_{\mu\nu}Z_{\mu\nu} \\ & + c_{z\Box}g^2Z_\mu\partial_\nu Z_{\mu\nu} + c_{\gamma\Box}gg'Z_\mu\partial_\nu A_{\mu\nu}\end{aligned}$$

$$\begin{aligned}\delta c_w &= \delta c_z + 4\delta m, \\ c_{ww} &= c_{zz} + 2s_\theta^2 c_{z\gamma} + s_\theta^4 c_{\gamma\gamma}, \\ c_{w\Box} &= \frac{1}{g^2-g'^2}\left[g^2c_{z\Box} + g'^2c_{zz} - e^2s_\theta^2c_{\gamma\gamma} - (g^2-g'^2)s_\theta^2c_{z\gamma}\right], \\ c_{\gamma\Box} &= \frac{1}{g^2-g'^2}\left[2g^2c_{z\Box} + (g^2+g'^2)c_{zz} - e^2c_{\gamma\gamma} - (g^2-g'^2)c_{z\gamma}\right].\end{aligned}$$

Obvious similarity to HC

Higgs basis: definition

Set of free redefinition parameters

$$
\begin{aligned}
G^a_\mu &\to (1+\delta_G)G^a_\mu, \quad W^\pm_\mu \to (1+\delta_W)W^\pm_\mu, \quad Z_\mu \to (1+\delta_Z)Z_\mu, \quad A_\mu \to (1+\delta_A)A_\mu + \delta_{AZ}Z_\mu, \\
v &\to v(1+\delta v), \quad g_s \to g_s(1+\delta g_s), \quad g \to g(1+\delta g), \quad g' \to g'(1+\delta g'), \\
\lambda &\to \lambda(1+\delta\lambda), \quad h \to (1+\delta_1)h + \delta_2 h^2/v + \delta_3 h^3/v^2, \qquad (3.1)
\end{aligned}
$$

Fixing conditions

#1 All kinetic and mass terms are diagonal and canonically normalized. In particular, higher-derivative kinetic terms are absent. — essential

#2 The non-derivative photon and gluon interactions with fermions are the same as in the SM.

#3 Tree-level relations between the electroweak parameters and input observables are the same as the SM ones in Eq. (2.3).

} Simplify inputs

#4 Two-derivative self-interactions of the Higgs boson (e.g. $h\partial_\mu h \partial_\mu h$) are absent.

#5 In the Higgs boson interactions with gauge bosons, the derivative does not act on the Higgs (e.g., there is no $\partial_\mu h V_\nu V_{\mu\nu}$ terms).

} Simplify interactions

#6 For each fermion pair, the coefficient of the vertex-like Higgs interaction terms $\left(2\frac{h}{v} + \frac{h^2}{v^2}\right) V_\mu \bar{f}\gamma_\mu f$ is equal to the vertex correction to the respective $V_\mu \bar{f}\gamma_\mu f$ interaction. — dependent parameter convention

Higgs basis: from SILH

$$\begin{aligned}
\delta_G &= \frac{4g_s^2}{g^2}\bar{c}_g, \\
\delta_W &= \bar{c}_W, \\
\delta_Z &= \bar{c}_W + \frac{g'^2}{g^2}\bar{c}_B + \frac{4g'^4}{g^2(g^2+g'^2)}\bar{c}_\gamma, \\
\delta_{AZ} &= \frac{g'}{g}(\bar{c}_W - \bar{c}_B) - \frac{8g'^3}{g(g^2+g'^2)}\bar{c}_\gamma, \\
\delta_A &= \frac{4g'^2}{g^2+g'^2}\bar{c}_\gamma \\
\delta v &= \frac{[\bar{c}'_{H\ell}]_{22}}{2}, \\
\delta g_s &= -\frac{4g_s^2}{g^2}\bar{c}_g, \\
\delta g &= -\frac{g^2}{g^2-g'^2}\left(\bar{c}_W + \bar{c}_{2W} + \frac{g'^2}{g^2}\bar{c}_B + \frac{g'^2}{g^2}\bar{c}_{2B} - \frac{1}{2}\bar{c}_T + \frac{1}{2}[\bar{c}'_{H\ell}]_{22}\right), \\
\delta g' &= \frac{g'^2}{g^2-g'^2}\left(\bar{c}_W + \bar{c}_{2W} + \frac{g'^2}{g^2}\bar{c}_B + \frac{g'^2}{g^2}\bar{c}_{2B} - \frac{1}{2}\bar{c}_T + \frac{1}{2}[\bar{c}'_{H\ell}]_{22} - 4\frac{g^2-g'^2}{g^2}\bar{c}_\gamma\right), \\
\delta\lambda &= \bar{c}_H - \frac{3}{2}\bar{c}_6 - [\bar{c}'_{H\ell}]_{22}, \\
\delta_1 &= -\frac{\bar{c}_H}{2}, \qquad \delta_2 = -\frac{\bar{c}_H}{2}, \qquad \delta_3 = -\frac{\bar{c}_H}{6}.
\end{aligned}$$

Conditions can be achieved without loss of generality

Starting from SILH:

1) Break EWSB
2) Apply redefinitions
3) Identify independent operators with combinations of SILH parameters
4) Obtain translation

Identical exercise for e.g. Warsaw

Higgs basis: result

- Hybrid between dimension-6 linear EFT and AC
- Translations to and from Warsaw, SILH, HISZ known
- Translation to Higgs Characterisation practically trivial
  - Indirectly, mapping from above descriptions to HC obtainable
- Implemented the Rosetta package in a user-friendly way
  - Higgs Basis provides a connection to a a LO FeynRules model: BSM Characterisation = Higgs Basis operators set without SU(2) relations (true AC Lagrangian)
  - Compatibility of dimension-6 EFT parameter sets with many HEP tools on the market implemented in terms of AC (VBFNLO, HAWK, HiggsPair,…)

https://rosetta.hepforge.org

Rosetta

- Tool seeking to unify basis/AC descriptions, acting as a "hub" for EFT analyses/calculations/fits/tools
- An extendable *framework* for communication (translation) between "bases" (EFT, AC,…)
  - Command-line executable
  - SLHA style input/output parameter cards
  - Zeroth-order: implementation of numerical (multi-step) translation functions mapping one set of parameters to another
  - Flavour structure simplifications: diagonal, universal
  - Interfaces to third party software such as eHDECAY (Higgs BR), Lilith (Higgs signal strengths), EWPO goodness-of-fit,…

Rosetta

- Rosetta includes the SILH, Warsaw and Higgs bases with flavour general translations between all of of them in any direction
- New basis: translation to one basis = translation to all bases (multi-step possible & automatically resolved)
- Many potential uses in terms of applying work previously done using one basis to your favourite one
- HISZ, BSMC, HC (new), future: HEL(@NLO)

HC in Rosetta

- Translations between BSMC and HC implemented (new in version 2.1) output compatible with FeynRules model
  - Redundancy in CP admixture angle “fixed” by setting $\cos(\alpha) = 1/\sqrt{2}$ in BSMC to HC translation (also Λ set to v for simplicity)
  - Allows for most general couplings but means $k_i = \sqrt{2}$ gives SM limit
- Custodial symmetric constraint (k_{SM}) more problematic
  - Although only one operator (c_T) in SILH basis explicitly violates CS, “effective” violation w.r.t. SM arises due to redefinition of Weinberg angle
  - $m_W(m_Z,\alpha_{EM},G_F)$ is different from SM and consequently also HWW vs HZZ
  - Current HC implementation cannot account for this → warning when these couplings are different in the BSMC instance that we are translating to HC
  - Consistent with having W mass shift, δm=0, in Higgs Basis

AC to EFT: mapping back

- Not possible in general
  - Only special cases of AC parameter choices can consistently map back to SMEFT (Higgs Basis & versions thereof)
- Can we try to be practical?
  - A translation from BSMC back to the Higgs Basis has been implemented
  - Explicitly checks whether values of "dependent" couplings supplied are consistent with their expected value as a function of independent parameters - warning if not
  - It may be complicated to try to fulfil these by hand…
  - Example: just switching on C_{zz} parameter in Higgs Basis (k_{HZZ} in HC) gives contributions to C_{ww}, $C_{w\Box}$, $C_{\gamma\Box}$, hhvv equivalents, aTGCs & aQGCs!

SMEFT & POs

Possible Rosetta implementation will follow discussions & recommendations given in this meeting!

$$
\begin{aligned}
\kappa_{ZZ} &= 1+\delta c_z + g^2 c_{z\Box} \,, \\
\kappa_{WW} &= 1+\delta c_w + g^2 c_{w\Box} \,, \\
\varepsilon_{Zf} &= \frac{2m_Z}{v}\left(\delta g^{Zf} + \frac{g^2}{2}(T_3^f - Q_f s_\theta^2)c_{z\Box} + \frac{e^2 Q_f}{2} c_{\gamma\Box}\right), \\
\varepsilon_{Wf} &= \frac{\sqrt{2}m_W}{v}\left(\delta g^{Wf} + \frac{g^2}{2} c_{w\Box}\right), \\
\varepsilon_{ZZ} &= \varepsilon_{ZZ}^{\mathrm{SM-1L}} - \frac{g^2+g'^2}{2} c_{zz} \,, \qquad\qquad \text{(A.3)} \\
\varepsilon_{Z\gamma} &= \varepsilon_{Z\gamma}^{\mathrm{SM-1L}} - \frac{gg'}{2} c_{z\gamma} \,, \\
\varepsilon_{\gamma\gamma} &= \varepsilon_{\gamma\gamma}^{\mathrm{SM-1L}} - \frac{e^2}{2} c_{\gamma\gamma} \,, \\
\varepsilon_{WW} &= \varepsilon_{WW}^{\mathrm{SM-1L}} - \frac{g^2}{2} c_{ww} \,,
\end{aligned}
$$

Discussion…

SILH operators

	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}	$\frac{g_s^3}{m_W^2} f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$	$\widetilde{O}_{3G}$	$\frac{g_s^3}{m_W^2} f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$

SILH operators

Yukawa and Dipole	
$[O_e]_{ij}$	$\frac{\sqrt{2m_{e_i}m_{e_j}}}{v^3} H^\dagger H \bar{\ell}_i H e_j$
$[O_u]_{ij}$	$\frac{\sqrt{2m_{u_i}m_{u_j}}}{v^3} H^\dagger H \bar{q}_i \widetilde{H} u_j$
$[O_d]_{ij}$	$\frac{\sqrt{2m_{d_i}m_{d_j}}}{v^3} H^\dagger H \bar{q}_i H d_j$
$[O_{eW}]_{ij}$	$\frac{g}{m_W^2}\frac{\sqrt{2m_{e_i}m_{e_j}}}{v} \bar{\ell}_i \sigma^k H \sigma_{\mu\nu} e_j W^k_{\mu\nu}$
$[O_{eB}]_{ij}$	$\frac{g'}{m_W^2}\frac{\sqrt{2m_{e_i}m_{e_j}}}{v} \bar{\ell}_i H \sigma_{\mu\nu} e_j B_{\mu\nu}$
$[O_{uG}]_{ij}$	$\frac{g_s}{m_W^2}\frac{\sqrt{2m_{u_i}m_{u_j}}}{v} \bar{q}_i \tilde{H} \sigma_{\mu\nu} T^a u_j G^a_{\mu\nu}$
$[O_{uW}]_{ij}$	$\frac{g}{m_W^2}\frac{\sqrt{2m_{u_i}m_{u_j}}}{v} \bar{q}_i \sigma^k \tilde{H} \sigma_{\mu\nu} u_j W^k_{\mu\nu}$
$[O_{uB}]_{ij}$	$\frac{g'}{m_W^2}\frac{\sqrt{2m_{u_i}m_{u_j}}}{v} \bar{q}_i \tilde{H} \sigma_{\mu\nu} u_j B_{\mu\nu}$
$[O_{dG}]_{ij}$	$\frac{g_s}{m_W^2}\frac{\sqrt{2m_{d_i}m_{d_j}}}{v} \bar{q}_i H \sigma_{\mu\nu} T^a d_j G^a_{\mu\nu}$
$[O_{dW}]_{ij}$	$\frac{g}{m_W^2}\frac{\sqrt{2m_{d_i}m_{d_j}}}{v} \bar{q}_i \sigma^k H \sigma_{\mu\nu} d_j W^k_{\mu\nu}$
$[O_{dB}]_{ij}$	$\frac{g'}{m_W^2}\frac{\sqrt{2m_{d_i}m_{d_j}}}{v} \bar{q}_i H \sigma_{\mu\nu} d_j B_{\mu\nu}$

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

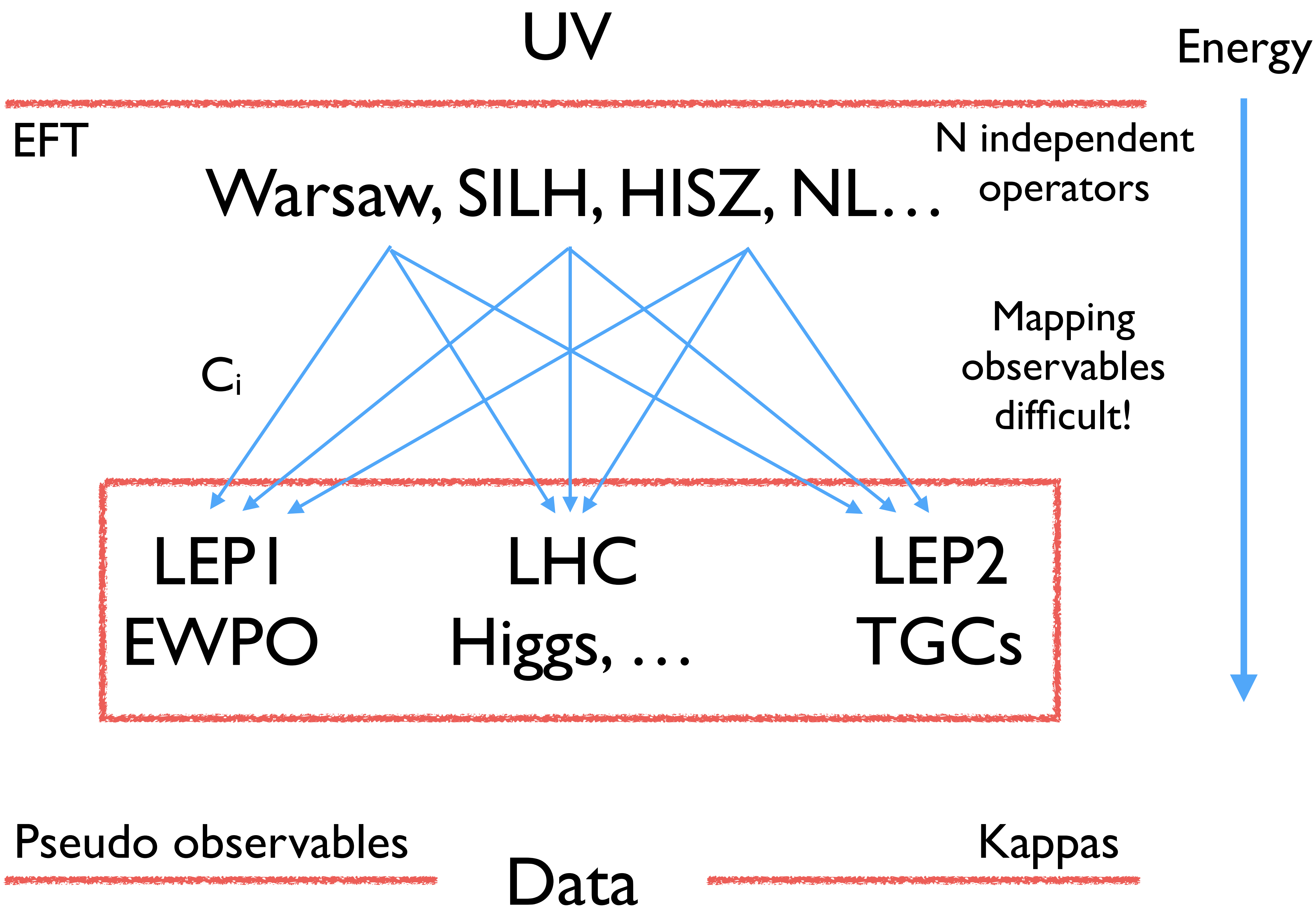
SILH operators

$(\bar{L}L)(\bar{R}R)$	
$O_{\ell e}$	$\frac{1}{v^2}(\bar{\ell}\gamma_\mu \ell)(\bar{e}\gamma_\mu e)$
$O_{\ell u}$	$\frac{1}{v^2}(\bar{\ell}\gamma_\mu \ell)(\bar{u}\gamma_\mu u)$
$O_{\ell d}$	$\frac{1}{v^2}(\bar{\ell}\gamma_\mu \ell)(\bar{d}\gamma_\mu d)$
O_{eq}	$\frac{1}{v^2}(\bar{q}\gamma_\mu q)(\bar{e}\gamma_\mu e)$
O_{qu}	$\frac{1}{v^2}(\bar{q}\gamma_\mu q)(\bar{u}\gamma_\mu u)$
O'_{qu}	$\frac{1}{v^2}(\bar{q}\gamma_\mu T^a q)(\bar{u}\gamma_\mu T^a u)$
O_{qd}	$\frac{1}{v^2}(\bar{q}\gamma_\mu q)(\bar{d}\gamma_\mu d)$
O'_{qd}	$\frac{1}{v^2}(\bar{q}\gamma_\mu T^a q)(\bar{d}\gamma_\mu T^a d)$

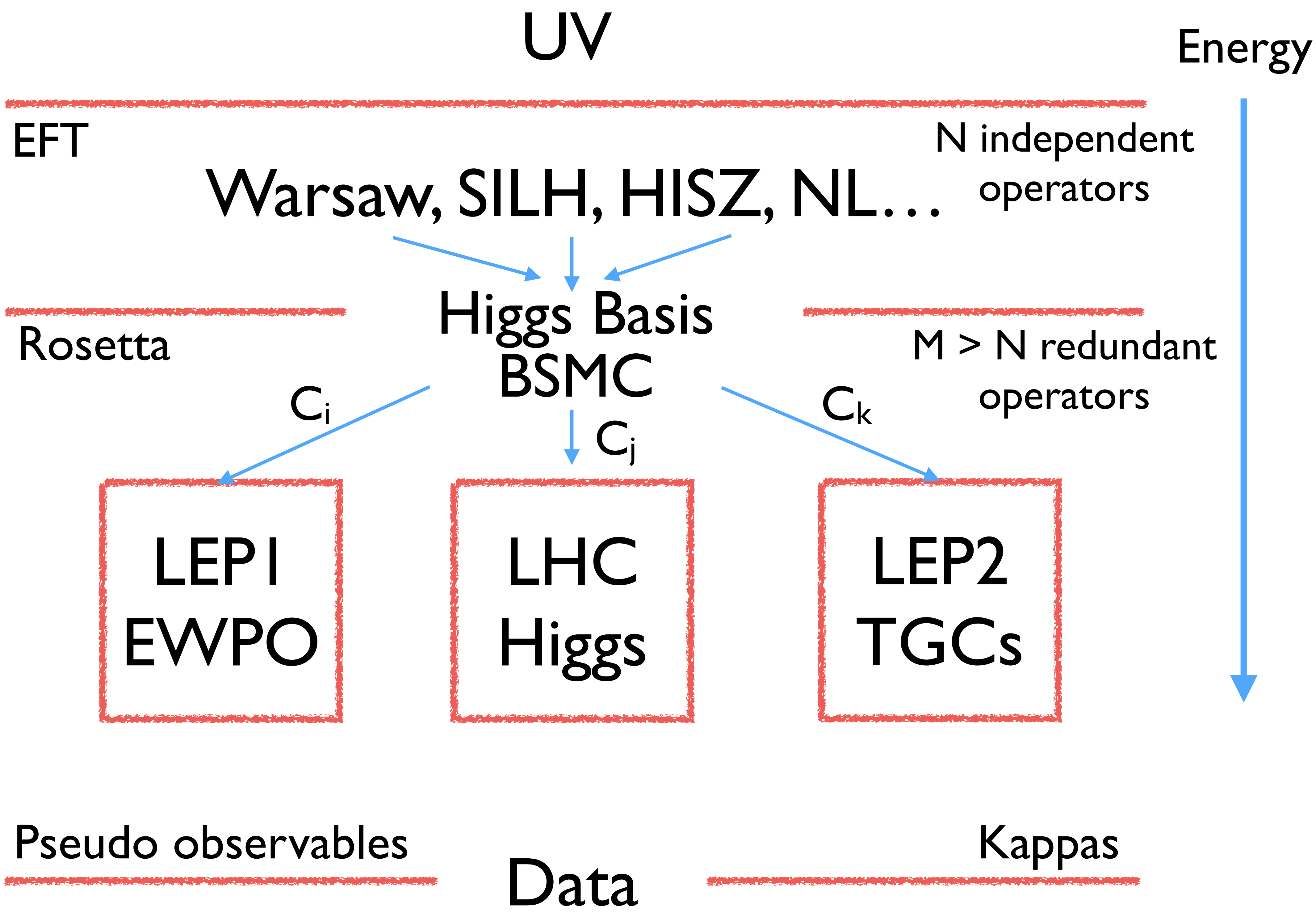
$(\bar{R}R)(\bar{R}R)$	
O_{ee}	$\frac{1}{v^2}(\bar{e}\gamma_\mu e)(\bar{e}\gamma_\mu e)$
O_{uu}	$\frac{1}{v^2}(\bar{u}\gamma_\mu u)(\bar{u}\gamma_\mu u)$
O_{dd}	$\frac{1}{v^2}(\bar{d}\gamma_\mu d)(\bar{d}\gamma_\mu d)$
O_{eu}	$\frac{1}{v^2}(\bar{e}\gamma_\mu e)(\bar{u}\gamma_\mu u)$
O_{ed}	$\frac{1}{v^2}(\bar{e}\gamma_\mu e)(\bar{d}\gamma_\mu d)$
O_{ud}	$\frac{1}{v^2}(\bar{u}\gamma_\mu u)(\bar{d}\gamma_\mu d)$
O'_{ud}	$\frac{1}{v^2}(\bar{u}\gamma_\mu T^a u)(\bar{d}\gamma_\mu T^a d)$

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

EFT cartoon


UV
Energy
EFT
N independent operators
Warsaw, SILH, HISZ, NL…
Mapping observables difficult!
C_i
LEP1
EWPO
LHC
Higgs, …
LEP2
TGCs
Pseudo observables
Data
Kappas

EFT cartoon



UV
Energy
EFT
Warsaw, SILH, HISZ, NL…
N independent operators
Higgs Basis
BSMC
Rosetta
M > N redundant operators
C_i
C_j
C_k
LEP1 EWPO
LHC Higgs
LEP2 TGCs
Pseudo observables
Kappas
Data