LHCHXSWG2

Update on EFT basis note and (linear) EFT in YR4

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Goals of EFT note

- Review connection of EFT with SM + dimension-6 operators to collider phenomenology
- Review formalism (bases) commonly used in literature and provide translation between them
- Provide a common notation to facilitate comparison between different experimental analyses at LHC
- Propose a new formalism (Higgs basis) that is particularly convenient for tree-level EFT analyses of LHC Higgs searches

Changes since July meeting

- Eq 4.18 and 4.32, forgotten dipole interactions of leptons with W added. Also, changed definition of dipole interactions with quarks and provide translation to Warsaw and SILH
- Eq 4.37, added double Higgs interactions with electroweak gauge bosons,
- In Table 1, factored out fermion masses in Yukawa operators changed in Warsaw and SILH basis, for more straightforward implementation of MFV in Monte Carlo tools
- Added translation from SILH' (Appendix A1) and HISZ basis (Appendix A2) to Higgs basis,
- Eq B.20, modified the photon gauge fixing term so as to avoid kinetic mixing in the gauge fixed Lagrangian,
- Below Eq. B.23, more details on the ghost Lagrangian added
- Rosetta is out, see 1508.05895

Recent reorganization

(after note last sent around by email)

- Almost no changes in formulas (except dipoles)
- Ordering reorganized: Sections 3 and 4 swapped

1	2	3	4	5
Intro EFT	SM & notation	D=6 operators in SU(3)xSU(2)xU(1) formalism	Phenomenological effective Lagrangian after SU(2)xU(1) broken by Higgs VEV	Higgs basis
		Introduced Warsaw and SILH bases and map between two	Map Wilson coefficients in Warsaw and SILH bases to interaction terms in effective Lagrangian	Defined by set of independent couplings in effective Lagrangian

Before EW symmetry breaking

- Heavy new physics parametrized by $SU(3)xSU(2)xU(1)$ invariant operators constructed out of SM matter and Higgs fields
- Most commonly used sets operators: Warsaw basis and SILH basis
- Consistent and concise formalism.
- Why go further? Connection to collider phenomenology not transparent
- Leading corrections to partial Higgs width and production rates depend on linear combination of many Wilson coefficients
- Also, constraints from precision tests on Wilson coefficients not transparent

Phenomenological Effective Lagrangian

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- Effective Lagrangian with dimension-6 operators mapped into phenomenological effective Lagrangian for mass eigenstates after electroweak symmetry breaking (photon,W,Z,Higgs boson, top, etc).

- By construction, effective Lagrangian has several features making relation between parameters and observables more transparent

- Feature #1: In tree-level Lagrangian, all kinetic terms are canonically normalized, there's no higher-derivative kinetic terms, and no kinetic mixing between mass eigenstates. In particular, all oblique corrections from new physics are zero, except for a correction to the W boson mass

$$\mathcal{L}_{\text{kin}} = -\frac{1}{2}W^+_{\mu\nu}W^-_{\mu\nu} - \frac{1}{4}Z_{\mu\nu}Z_{\mu\nu} - \frac{1}{4}A_{\mu\nu}A_{\mu\nu} + (1+2\delta m)m_W^2 W^+_\mu W^-_\mu + \frac{m_Z^2}{2}Z_\mu Z_\mu$$

$$m_Z = \frac{\sqrt{g^2+g'^2}v}{2}$$

$$\alpha = \frac{gg'}{\sqrt{g^2+g'^2}}$$

$$\tau_\mu = \frac{384\pi^3 v^4}{m_\mu^5}$$

- Feature #2: Tree-level relation between the couplings in the Lagrangian and SM input observables is the same as in the SM

- Feature #3: Higgs boson has no derivative self-interactions

$$\cancel{h(\partial_\mu h)^2}$$

- Feature #4: Vertex corrections to SM Vff interactions and Higgs boson contact hVff interactions are correlated

$$\delta g^{Vf}\left(1+\frac{h}{v}\right)V_\mu \bar{f}\gamma_\mu f$$

Phenomenological Effective Lagrangian

- Features #1-#4 can always be obtained, without any loss of generality, starting from any dimension-6 basis and using integration by parts, fields and couplings redefinition

- These features greatly simplify connection between Lagrangian parameters and collider observables at tree level

- For example, vertex corrections δg to Z interactions with fermions directly translate to partial Z widths measured at LEP

- Similarly corrections to Higgs couplings to matter translate directly Higgs partial widths and production rates that can be constrained at LHC

- Can be easily implemented in Monte Carlo codes to generate events

$$\mathcal{L}_{\rm eff} \supset \sqrt{g^2+g'^2}\left(T^3_f - s^2_\theta Q_f + \delta g^{Zf}\right) Z_\mu \bar{f}\gamma_\mu f$$

$$\delta\Gamma(Z \to f f)$$

AA, 1505.00046

$$\mathcal{L}_{\rm eff} \supset \frac{h}{v} m_f \left(1+\delta y_f\right) \bar{f} f$$

$$\delta\Gamma(h \to f f)$$

Rosetta, 1508.05895

Similar "EFT Primaries" of Gupta, Riva, Pomarol 1405.0181

Higgs Basis

- Pick up subset of independent couplings in phenomenological effective Lagrangian which is in 1-to-1 correspondence with Wilson coefficients in Warsaw or SILH basis and use these to span the basis of d=6 operators
- Other couplings in effective Lagrangian can be expressed by independent couplings using maps from Warsaw or SILH basis provided in EFT note

Higgs Basis parameters

Couplings affecting LHC Higgs phenomenology at tree level that are strongly constrained by precision tests

$$\delta m,\ \delta g_L^{Ze},\ \delta g_R^{Ze},\ \delta g_L^{W\ell},\ \delta g_L^{Zu},\ \delta g_R^{Zu},\ \delta g_L^{Zd},\ \delta g_R^{Zd},\ \delta g_R^{Wq},$$
$$d_{Gu},\ d_{Gd},\ d_{Ae},\ d_{Au},\ d_{Ad},\ d_{Ze},\ d_{Zu},\ d_{Zd},$$
$$\tilde{d}_{Gu},\ \tilde{d}_{Gd},\ \tilde{d}_{Ae},\ \tilde{d}_{Au},\ \tilde{d}_{Ad},\ \tilde{d}_{Ze},\ \tilde{d}_{Zu},\ \tilde{d}_{Zd}$$

Couplings affecting LHC Higgs phenomenology at tree level that are *not* strongly constrained by precision tests

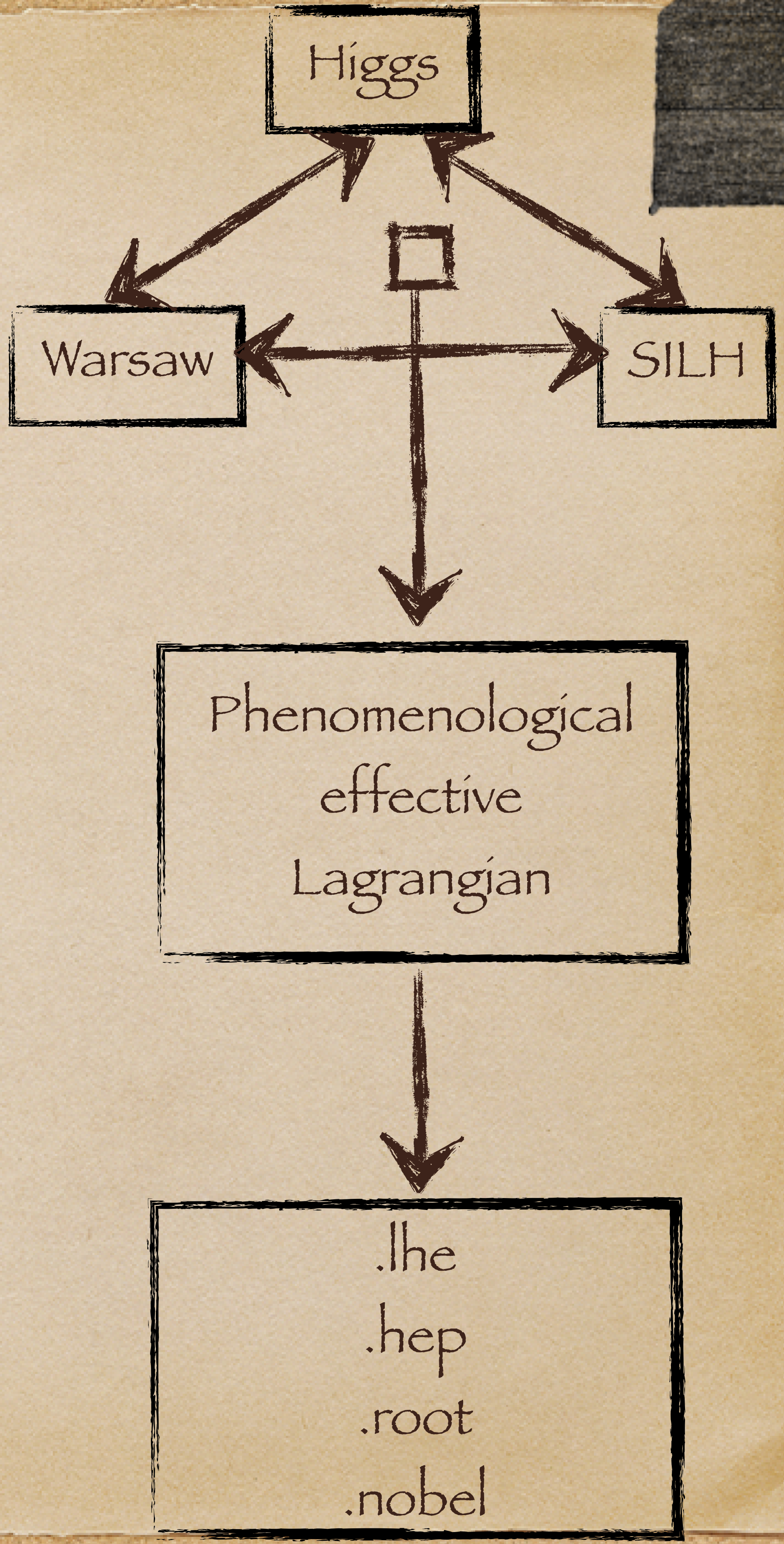
CP even : $\delta c_z \quad c_{z\Box} \quad c_{zz} \quad c_{z\gamma} \quad c_{\gamma\gamma} \quad c_{gg} \quad \delta y_u \quad \delta y_d \quad \delta y_e \quad \delta\lambda_3$

CP odd : $\tilde{c}_{zz} \quad \tilde{c}_{z\gamma} \quad \tilde{c}_{\gamma\gamma} \quad \tilde{c}_{gg} \quad \phi_u \quad \phi_d \quad \phi_e$

Remaining couplings do not affect LHC Higgs phenomenology at tree level

Rosetta

- Implements translation between D=6 bases most commonly used in literature derived in the note
- Implements phenomenological effective Lagrangian and maps parameters in any basis into it
- From now on, studying EFT collider phenomenology in any basis is simple and fun



Summary

- Plan is to finalize note, and incorporate it (minus some technical details) into YR4
- Last round of comments from WG2, and then send it around to all WG
- To do: translation to original Warsaw basis to connect to 1-loop EFT calculations in 1505.03706 and 1507.03568
- Name change: Higgs basis -> h-basis ?
(due to name conflict with Higgs basis in 2HDM)

Backup

Effective Theory Approach to BSM

Basic assumptions

- New physics scale Λ separated from EW scale v, Λ > v
- Linearly realized SU(3)xSU(2)xU(1) local symmetry spontaneously broken by VEV of Higgs doublet field (see O.Cata's talk this afternoon for non-linear EFT)

EFT Lagrangian beyond the SM expanded in operator dimension D

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

Lepton number violating,
hence too small to probe at LHC

Subleading
to D=6 when Λ >> v
and generic Wilson
coefficient

For D=6 Lagrangian several
complete non-redundant set of operators
(so-called basis)
proposed in the literature

Warsaw Basis — Grządkowski et al. 1008.4884, Alonso et al 1312.2014

SILH basis — Giudice et al hep-ph/0703164, Contino et al 1303.3876

Primary/Higgs basis — Gupta et al 1405.0181, LHCHXSWG-INT-2015-001

Higgs Basis: Higgs couplings to matter

- In HB, Higgs couplings to gauge bosons described by 6 CP even and 4 CP odd parameters that are unconstrained by LEP-1

- D=6 EFT with linearly realized SU(3)xSU(2)xU(1) enforces relations between Higgs couplings to gauge bosons (otherwise, 5 more parameters)

- Corrections to Higgs Yukawa couplings to fermions are also unconstrained by EWPT

- Assuming flavor blind Yukawa corrections, LHC Higgs physics parametrized by 9 CP even and 6 CP odd parameters

$$\text{CP even}: \quad \delta c_z \quad c_{z\Box} \quad c_{zz} \quad c_{z\gamma} \quad c_{\gamma\gamma} \quad c_{gg}$$
$$\text{CP odd}: \quad \tilde{c}_{zz} \quad \tilde{c}_{z\gamma} \quad \tilde{c}_{\gamma\gamma} \quad \tilde{c}_{gg}$$

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

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

relative correction to W mass

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$$\text{CP even}: \quad \delta y_u \quad \delta y_d \quad \delta y_e$$
$$\text{CP odd}: \quad \phi_u \quad \phi_d \quad \phi_e$$

$$\mathcal{L}_{\rm hff} = -\sum_{f=u,d,e} m_f f^c (I + \delta y_f e^{i\phi_f}) f + \text{h.c.}$$