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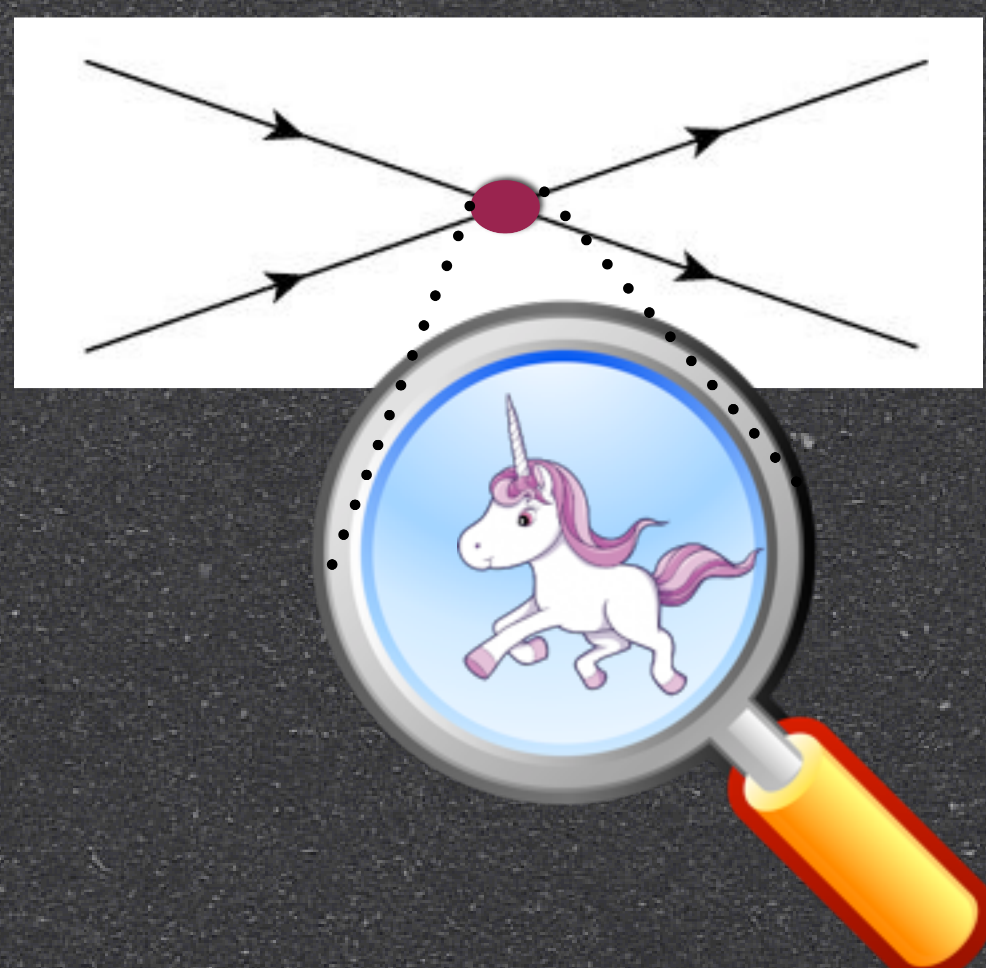
Lectures on Effective Field Theory Approach to Physics Beyond the Standard Model



part 2

Plan

Part I

- Short introduction and motivations
- (Illustrated) philosophy of effective field theory

Part II

- Effective Lagrangian for physics beyond the SM
- From D=6 operators to collider observables

Part III

- Constraints on EFT from LHC Higgs physics

Effective Lagrangian
for physics
beyond the Standard Model

Standard Model

Assumptions:

- QM + Poincare invariance = QFT
- Local symmetry SU(3)xSU(2)xU(1)
- Matter content and its quantum numbers
- Brout-Englert-Higgs mechanism of electroweak symmetry breaking via a single SU(2) doublet field H $H = \frac{1}{\sqrt{2}}\begin{pmatrix} \dots \\ v+h+\dots \end{pmatrix}$
- Renormalizability

$$\mathcal{L}_{\rm SM} = -\frac{1}{4g_s^2}G^2_{\mu\nu,a} - \frac{1}{4g_L^2}W^2_{\mu\nu,i} - \frac{1}{4g_Y^2}B^2_{\mu\nu} + i\sum_{f=q,\ell}\bar{f}\bar{\sigma}_\mu D_\mu f + i\sum_{f=u,d,e} f^c\sigma_\mu D_\mu \bar{f}^c - HqY_u u^c - H^\dagger qY_d d^c - H^\dagger \ell Y_e e^c \; + \text{h.c.} + D_\mu H^\dagger D_\mu H + m_H^2 H^\dagger H - \lambda(H^\dagger H)^2$$

Consequences:

- Operators up to dimension 4
- Has 18 free parameters (19 with θqcd), all measured (constrained)
- Fits in T-shirt

Standard Model

Completely defined by:
- QM + Poincare invariance = QFT
- Local symmetry SU(3)xSU(2)xU(1)
- Matter content and its quantum numbers
- Brout-Englert-Higgs mechanism of electroweak symmetry breaking via a single SU(2) doublet field H
- Renormalizability

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

$$\begin{aligned}\mathcal{L}_{\rm SM} = & -\frac{1}{4g_s^2}G^2_{\mu\nu,a} - \frac{1}{4g_L^2}W^2_{\mu\nu,i} - \frac{1}{4g_Y^2}B^2_{\mu\nu} \\ & + i\sum_{f=q,\ell}\bar{f}\bar{\sigma}_\mu D_\mu f + i\sum_{f=u,d,e} f^c\sigma_\mu D_\mu \bar{f}^c \\ & - HqY_u u^c - H^\dagger q Y_d d^c - H^\dagger \ell Y_e e^c \text{ +h.c.} \\ & + D_\mu H^\dagger D_\mu H + m_H^2 H^\dagger H - \lambda(H^\dagger H)^2\end{aligned}$$

Some predictions at lowest order

- Couplings of gauge bosons to fermions universal and fixed by fermion's quantum numbers

$$\begin{aligned} g^{Af} &= Q_f \frac{g_L g_Y}{\sqrt{g_L^2 + g_Y^2}} \equiv eQ_f \\ g_L^{Wf} &= g_L \\ g^{Zf} &= \sqrt{g_L^2 + g_Y^2}\,(T_f^3 - s_\theta^2 Q_f) \end{aligned}$$

- Z and W boson mass ratio related to Weinberg angle

$$\frac{m_W}{m_Z} = \frac{g_L}{\sqrt{g_L^2 + g_Y^2}} \equiv c_\theta$$

- Higgs coupling to gauge bosons proportional to their mass squared

$$\left(\frac{h}{v} + \frac{h^2}{2v^2}\right)(2m_W^2\, W_\mu^+ W_\mu^- + m_Z^2\, Z_\mu Z_\mu)$$

- Higgs coupling to fermions proportional to their mass

$$-\frac{h}{v}\sum_f m_f \bar{f} f$$

- Triple and quartic vector boson couplings proportional to gauge couplings

$$\begin{aligned}\mathcal{L}_{\rm TGC}^{\rm SM} = & ie\left[A_{\mu\nu}\, W_\mu^+ W_\nu^- + (W_{\mu\nu}^+ W_\mu^- - W_{\mu\nu}^- W_\mu^+)\, A_\nu\right] \\ & + ig_L c_\theta \left[(W_{\mu\nu}^+ W_\mu^- - W_{\mu\nu}^- W_\mu^+)\, Z_\nu + Z_{\mu\nu}\, W_\mu^+ W_\nu^-\right]\end{aligned}$$

EFT approach to BSM

- SM is probably a correct theory the weak scale, at least as the lowest order term in an effective theory expansion
- If new particles are heavy, their effects can be parametrized by higher-dimensional operators added to the SM Lagrangian
- EFT framework offers a systematic expansion around the SM organized in terms of operator dimensions, with higher dimensional operator suppressed by the mass scale Λ of new physics

EFT Approach to BSM

Basic assumptions

- QM + Poincare invariance = QFT

- Local symmetry SU(3)xSU(2)xU(1)

- Matter content and its quantum numbers

- Brout-Englert-Higgs mechanism of electroweak symmetry breaking via a single SU(2) doublet field H

Alternatively, non-linear Lagrangians with derivative expansion

- ~~Renormalizability~~

EFT Approach to BSM

- As in Fermi theory of muon decay, EFT should give a perfectly adequate description of certain physics processes (e.g. Higgs decays) though application range may be limited (for example, associated V +H production)

- As in weak meson decays, EFT may be superior to concrete UV models as a calculation too, at least if new physics scale is well above TeV

- As in chiral perturbation theory, we will parametrize our ignorance by allowing all higher-order operators with arbitrary coefficients, and trying to determine these coefficients from experiment

Effective Theory Approach to BSM

Building effective Lagrangian

- Start with SM Lagrangian as lowest order term
- Add higher-dimensional operators with D=5,6.... in expansion in 1/Λ where Λ is a high scale of new physics
- At each level D, include *all* non-redundant operators consistent SM field content and local symmetry

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\mathcal{L}^{D=5} + \frac{1}{\Lambda^2}\mathcal{L}^{D=6} + \ldots$$

$$\Lambda \gg v$$

In practice, more convenient to absorb Λ into Wilson coefficients

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{SM} + \frac{1}{v}\mathcal{L}^{D=5} + \frac{1}{v^2}\mathcal{L}^{D=6} + \ldots$$

$$c_i^D = \frac{v^{D-4}}{\Lambda^{D-4}} \ll 1$$

Dimension 5 Lagrangian

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{SM} + \frac{1}{v}\mathcal{L}^{D=5} + \frac{1}{v^2}\mathcal{L}^{D=6} + \ldots$$

$$c_i^D = \frac{v^{D-4}}{\Lambda^{D-4}} \ll 1$$

$$\mathcal{L}^{D=5} = -(L_i H) c_{ij} (L_j H) + \text{h.c.}$$

- At dimension 5, the only operators one can construct are so-called Weinberg operators who break the lepton number
- After EW breaking they give rise to Majorana mass terms for SM (left-handed) neutrinos $\mathcal{L}^{D=5} = -\frac{1}{2}(v+h)^2 \nu_i c_{ij} \nu_j$
- Neutrino oscillation experiments suggest that these operators are present (unless right-handed neutrinos are light or neutrinos are Dirac)
- However, to match the measurements, their coefficients have to be extremely small, c ~ 10^-11
- Therefore dimension 5 operators have no observable impact on collider phenomenology

Dimension 6 Lagrangian

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{SM} + \frac{1}{v}\mathcal{L}^{D=5} + \frac{1}{v^2}\mathcal{L}^{D=6} + \dots$$

$$c_i^D = \frac{v^{D-4}}{\Lambda^{D-4}} \ll 1$$

- First attempts to classify dimension-6 operators back in 1986

Buchmuller,Wyler pre-arxiv (1986)

- First complete and non-redundant set of operators explicitly written down only in 2010

Grządkowski et al. 1008.4884

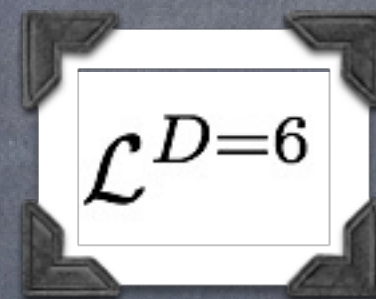
- Operators can be traded for other operators using integration by parts, field redefinition, equations of motion, Fierz transformation, etc
- Because of that, one can choose many different bases == non-redundant sets of operators

D=6 Bases

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

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

HISZ basis — Hagiwara et al (1993)



Higgs basis — LHCHXSWG-INT-2015-001

Warsaw Basis — Grządkowski et al. 1008.4884

Primary basis — Gupta et al 1405.0181

- All bases are equivalent, but some may be more ~~equivalent~~ convenient for specific applications
- Physics description (EWPT, Higgs, RG running) in any of these bases contains the same information, provided **all** operators contributing to that process are taken into account

Example of a basis: Warsaw Basis

Bosonic CP-even		Bosonic CP-odd	
O_H	$\left[\partial_\mu (H^\dagger H)\right]^2$		
O_T	$\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$		
O_{6H}	$(H^\dagger H)^3$		
O_{GG}	$g_s^2 H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu}$	$O_{\widetilde{GG}}$	$g_s^2 H^\dagger H\, \widetilde{G}^a_{\mu\nu} G^a_{\mu\nu}$
O_{WW}	$g_L^2 H^\dagger H\, W^i_{\mu\nu} W^i_{\mu\nu}$	$O_{\widetilde{WW}}$	$g_L^2 H^\dagger H\, \widetilde{W}^i_{\mu\nu} W^i_{\mu\nu}$
O_{BB}	$g_Y^2 H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$	$O_{\widetilde{BB}}$	$g_Y^2 H^\dagger H\, \widetilde{B}_{\mu\nu} B_{\mu\nu}$
O_{WB}	$g_L g_Y H^\dagger \sigma^i H\, W^i_{\mu\nu} B_{\mu\nu}$	$O_{\widetilde{WB}}$	$g_L g_Y H^\dagger \sigma^i H\, \widetilde{W}^i_{\mu\nu} B_{\mu\nu}$
O_{3W}	$g_L^3 \epsilon^{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$	$O_{\widetilde{3W}}$	$g_L^3 \epsilon^{ijk} \widetilde{W}^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$
O_{3G}	$g_s^3 f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$	$O_{\widetilde{3G}}$	$g_s^3 f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$

Table 2: Bosonic $d = 6$ operators in the Warsaw basis.

Grządkowski et al.
1008.4884

Assuming baryon and lepton number conservation,
59 different
kinds of operators,
of which 17 are complex

2499 distinct operators, including flavor structure and CP conjugates

Alonso et al 1312.2014

Example of a basis: Warsaw Basis

Yukawa

$[O_e]_{IJ}$	$-(H^\dagger H - \frac{v^2}{2})\frac{\sqrt{m_I m_J}}{v} e^c_I H^\dagger \ell_J$
$[O_u]_{IJ}$	$-(H^\dagger H - \frac{v^2}{2})\frac{\sqrt{m_I m_J}}{v} u^c_I \widetilde{H}^\dagger q_J$
$[O_d]_{IJ}$	$-(H^\dagger H - \frac{v^2}{2})\frac{\sqrt{m_I m_J}}{v} d^c_I H^\dagger q_J$

Vertex

$[O_{H\ell}]_{IJ}$	$i\bar{\ell}_I\bar{\sigma}_\mu \ell H^\dagger \overleftrightarrow{D}_\mu H$
$[O'_{H\ell}]_{IJ}$	$i\bar{\ell}_I\sigma^i\bar{\sigma}_\mu \ell H^\dagger \sigma^i \overleftrightarrow{D}_\mu H$
$[O_{He}]_{IJ}$	$ie^c_I\sigma_\mu\bar{e}^c_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O_{Hq}]_{IJ}$	$i\bar{q}_I\bar{\sigma}_\mu q_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O'_{Hq}]_{IJ}$	$i\bar{q}_I\sigma^i\bar{\sigma}_\mu q_J H^\dagger \sigma^i \overleftrightarrow{D}_\mu H$
$[O_{Hu}]_{IJ}$	$iu^c_I\sigma_\mu\bar{u}^c_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O_{Hd}]_{IJ}$	$id^c_I\sigma_\mu\bar{d}^c_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O_{Hud}]_{IJ}$	$iu^c_I\sigma_\mu\bar{d}^c_J \widetilde{H}^\dagger D_\mu H$

Dipole

$[O_{eW}]_{IJ}$	$g_L\frac{\sqrt{m_I m_J}}{v} e^c_I\sigma_{\mu\nu}H^\dagger\sigma^i\ell_J W^i_{\mu\nu}$
$[O_{eB}]_{IJ}$	$g_Y\frac{\sqrt{m_I m_J}}{v} e^c_I\sigma_{\mu\nu}H^\dagger\ell_J B_{\mu\nu}$
$[O_{uG}]_{IJ}$	$g_s\frac{\sqrt{m_I m_J}}{v} u^c_I\sigma_{\mu\nu}T^a\widetilde{H}^\dagger q_J\, G^a_{\mu\nu}$
$[O_{uW}]_{IJ}$	$g_L\frac{\sqrt{m_I m_J}}{v} u^c_I\sigma_{\mu\nu}\widetilde{H}^\dagger\sigma^i q_J\, W^i_{\mu\nu}$
$[O_{uB}]_{IJ}$	$g_Y\frac{\sqrt{m_I m_J}}{v} u^c_I\sigma_{\mu\nu}\widetilde{H}^\dagger q_J\, B_{\mu\nu}$
$[O_{dG}]_{IJ}$	$g_s\frac{\sqrt{m_I m_J}}{v} d^c_I\sigma_{\mu\nu}T^a H^\dagger q_J\, G^a_{\mu\nu}$
$[O_{dW}]_{IJ}$	$g_L\frac{\sqrt{m_I m_J}}{v} d^c_I\sigma_{\mu\nu}\bar{H}^\dagger\sigma^i q_J\, W^i_{\mu\nu}$
$[O_{dB}]_{IJ}$	$g_Y\frac{\sqrt{m_I m_J}}{v} d^c_I\sigma_{\mu\nu}H^\dagger q_J\, B_{\mu\nu}$

Table 3: Two-fermion d=6 operators in the Warsaw basis. Here, I, J are the flavor indices. For complex operators the complex conjugate operator is implicit.

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1008.4884

Assuming baryon and lepton number conservation, 59 different kinds of operators, of which 17 are complex

2499 distinct operators, including flavor structure and CP conjugates

Alonso et al 1312.2014

Example of a basis: Warsaw Basis

$(\bar{R}R)(\bar{R}R)$

O_{ee}	$(e^c\sigma_\mu\bar{e}^c)(e^c\sigma_\mu\bar{e}^c)$
O_{uu}	$(u^c\sigma_\mu\bar{u}^c)(u^c\sigma_\mu\bar{u}^c)$
O_{dd}	$(d^c\sigma_\mu\bar{d}^c)(d^c\sigma_\mu\bar{d}^c)$
O_{eu}	$(e^c\sigma_\mu\bar{e}^c)(u^c\sigma_\mu\bar{u}^c)$
O_{ed}	$(e^c\sigma_\mu\bar{e}^c)(d^c\sigma_\mu\bar{d}^c)$
O_{ud}	$(u^c\sigma_\mu\bar{u}^c)(d^c\sigma_\mu\bar{d}^c)$
O'_{ud}	$(u^c\sigma_\mu T^a\bar{u}^c)(d^c\sigma_\mu T^a\bar{d}^c)$

$(\bar{L}L)(\bar{R}R)$

$O_{\ell e}$	$(\bar{\ell}\bar{\sigma}_\mu\ell)(e^c\sigma_\mu\bar{e}^c)$
$O_{\ell u}$	$(\bar{\ell}\bar{\sigma}_\mu\ell)(u^c\sigma_\mu\bar{u}^c)$
$O_{\ell d}$	$(\bar{\ell}\bar{\sigma}_\mu\ell)(d^c\sigma_\mu\bar{d}^c)$
O_{qe}	$(\bar{q}\bar{\sigma}_\mu q)(e^c\sigma_\mu\bar{e}^c)$
O_{qu}	$(\bar{q}\bar{\sigma}_\mu q)(u^c\sigma_\mu\bar{u}^c)$
O'_{qu}	$(\bar{q}\bar{\sigma}_\mu T^a q)(u^c\sigma_\mu T^a\bar{u}^c)$
O_{qd}	$(\bar{q}\bar{\sigma}_\mu q)(d^c\sigma_\mu\bar{d}^c)$
O'_{qd}	$(\bar{q}\bar{\sigma}_\mu T^a q)(d^c\sigma_\mu T^a\bar{d}^c)$

$(\bar{L}L)(\bar{L}L)$

$O_{\ell\ell}$	$(\bar{\ell}\bar{\sigma}_\mu\ell)(\bar{\ell}\bar{\sigma}_\mu\ell)$
O_{qq}	$(\bar{q}\bar{\sigma}_\mu q)(\bar{q}\bar{\sigma}_\mu q)$
O'_{qq}	$(\bar{q}\bar{\sigma}_\mu\sigma^i q)(\bar{q}\bar{\sigma}_\mu\sigma^i q)$
$O_{\ell q}$	$(\bar{\ell}\bar{\sigma}_\mu\ell)(\bar{q}\bar{\sigma}_\mu q)$
$O'_{\ell q}$	$(\bar{\ell}\bar{\sigma}_\mu\sigma^i\ell)(\bar{q}\bar{\sigma}_\mu\sigma^i q)$

$(\bar{L}R)(\bar{L}R)$

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

Table 4: Four-fermion d=6 operators in the Warsaw basis. Flavor indices are implicit. For complex operators the complex conjugate operator is implicit.

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1008.4884

Assuming baryon and lepton number conservation, 59 different kinds of operators, of which 17 are complex

2499 distinct operators, including flavor structure and CP conjugates

Alonso et al 1312.2014

Matching new physics to D=6 Lagrangian

Example #1: Type-II Two Higgs Doublet Model

Why 2 Higgs doublets

- We've already had one, so why not 2 ;)
- Appears in almost all supersymmetric models
- A nice and fairly simple model with a reasonable number of parameters that affect LHC physics in a non-trivial way

Example #1: Type-II Two Higgs Doublet Model

Z2 basis: doublets Φ1 and Φ2, both of which can have VEVs

$$\langle \Phi_1 \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} c_\beta \end{pmatrix}$$

$$\langle \Phi_2 \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} s_\beta \end{pmatrix}$$

Scalar potential has softly broken Z2 symmetry under which Φ1 has eigenvalue +1 and Φ2 has eigenvalue -1

$$V = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + m_{12}^2 \left[\Phi_1^\dagger \Phi_2 + \text{h.c.} \right] + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \frac{\lambda_5}{2} \left[(\Phi_1^\dagger \Phi_2)^2 + \text{h.c.} \right]$$

Yukawa couplings also respect Z2 symmetry where uc has eigenvalue -1 and dc and ec have eigenvalue +1
This is 1 out of 4 possible choices where absence of FCNC is automatic

$$-\mathcal{L}_{\text{Yukawa}} = \frac{1}{c_\beta} \tilde{\Phi}_2^\dagger u^c Y_u q + \frac{1}{s_\beta} \Phi_1^\dagger d^c Y_d q + \frac{1}{s_\beta} \Phi_1^\dagger e^c Y_e \ell + \text{h.c.}$$

$$[\tilde{\Phi}_i]_a \equiv \epsilon_{ab} [\Phi_i^*]_b$$

Example #1: Type-II Two Higgs Doublet Model

To derive EFT, it is better to rotate to VEV basis with doublets H1 and H2 where only H1 has a VEV

$$\Phi_1 = c_\beta H_1 - s_\beta H_2,$$
$$\Phi_2 = s_\beta H_1 + c_\beta H_2$$

VEVless Higgs contains physical charged scalars and pseudoscalar while one with VEV hosts Goldstone bosons eaten by W and Z

$$H_1 = \begin{pmatrix} -iG^+ \\ \frac{1}{\sqrt{2}}(v + h_1 + iG_z) \end{pmatrix} \qquad \langle H_1 \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h_2 + iA) \end{pmatrix} \qquad \langle H_2 \rangle = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

Scalar potential looks a tad more complicated, but only 5 out 7 couplings Z are independent

$$\begin{aligned} V =& Y_1 H_1^\dagger H_1 + Y_2 H_2^\dagger H_2 + Y_3 \left[H_1^\dagger H_2 + \text{h.c.}\right] \\ &+ \frac{Z_1}{2}(H_1^\dagger H_1)^2 + \frac{Z_2}{2}(H_2^\dagger H_2)^2 + Z_3 (H_1^\dagger H_1)(H_2^\dagger H_2) \\ &+ Z_4 (H_1^\dagger H_2)(H_2^\dagger H_1) + \frac{Z_5}{2}\left[(H_1^\dagger H_2)^2 + \text{h.c.}\right] \\ &+ Z_6 H_1^\dagger H_1 \left[H_1^\dagger H_2 + \text{h.c.}\right] + Z_7 H_2^\dagger H_2 \left[H_1^\dagger H_2 + \text{h.c.}\right]. \end{aligned}$$

In VEV basis, both Higgs doublet couple to fermions

$$\begin{aligned} -\mathcal{L}_{\text{Yukawa}} =& \tilde{H}_1^\dagger u^c Y_u q + \frac{c_\beta}{s_\beta}\tilde{H}_2^\dagger u^c Y_u q \\ &+ H_1^\dagger d^c Y_d q - \frac{s_\beta}{c_\beta} H_2^\dagger d^c Y_d q \\ &+ H_1^\dagger e^c Y_e \ell - \frac{s_\beta}{c_\beta} H_2^\dagger e^c Y_e \ell + \text{h.c.} \end{aligned}$$

Example #1: Type-II Two Higgs Doublet Model

Masses of scalar eigenstates

$$m_{H^+}^2 = Y_2 + \frac{Z_3}{2}v^2$$

$$m_A^2 = Y_2 + \frac{Z_3 + Z_4 - Z_5}{2}v^2$$

$$m_h^2 \approx Z_1 v^2$$

for Y2>>V^2

$$m_H^2 \approx Y_2 + \frac{Z_3 + Z_4 + Z_5}{2}v^2$$

For Y2>>v^2, all extra scalars are heavy, while our Higgs boson is light.
This is a limit where EFT must be valid.
We identify Y2= Λ^2 and derive EFT for SM degrees of freedom
to leading order in 1/Λ expansion by integrating out H2,
where H1 is identified with SM Higgs doublet
This can be achieved by solving equations of motion to leading order in 1/Λ
and putting solution back into 2HDM Lagrangian
(the same result can be obtained by matching scattering amplitudes of light particles, as we did before for the Fermi theory)

$$H_2 \approx \frac{1}{\Lambda^2}\left[-Z_6 H_1\left(H_1^\dagger H_1 - \frac{v^2}{2}\right) + \frac{c_\beta}{s_\beta}u^c Y_u \tilde{q} + \frac{s_\beta}{c_\beta}d^c Y_d q + \frac{s_\beta}{c_\beta}e^c Y_e \ell\right]$$

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{SM}(H_1, V_\mu, \psi) + \frac{1}{\Lambda^2}\left[Z_6 H_1^\dagger\left(H_1^\dagger H_1 - \frac{v^2}{2}\right) - \frac{c_\beta}{s_\beta}\bar{\tilde{q}} Y_u^\dagger \bar{u}^c - \frac{s_\beta}{c_\beta}\bar{q} Y_d^\dagger \bar{d}^c - \frac{s_\beta}{c_\beta}\bar{\ell} Y_e^\dagger \bar{e}^c\right]$$
$$\times\left[Z_6 H_1\left(H_1^\dagger H_1 - \frac{v^2}{2}\right) - \frac{c_\beta}{s_\beta}u^c Y_u \tilde{q} - \frac{s_\beta}{c_\beta}d^c Y_d q - \frac{s_\beta}{c_\beta}e^c Y_e \ell\right]$$

Example #1: Type-II Two Higgs Doublet Model

Bosonic CP-even		Bosonic CP-odd	
O_H	$[\partial_\mu (H^\dagger H)]^2$		
O_T	$\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$		
O_{6H}	$(H^\dagger H)^3$		
O_{GG}	$g_s^2 H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu}$	$O_{\widetilde{GG}}$	$g_s^2 H^\dagger H\, \widetilde{G}^a_{\mu\nu} G^a_{\mu\nu}$
O_{WW}	$g_L^2 H^\dagger H\, W^i_{\mu\nu} W^i_{\mu\nu}$	$O_{\widetilde{WW}}$	$g_L^2 H^\dagger H\, \widetilde{W}^i_{\mu\nu} W^i_{\mu\nu}$
O_{BB}	$g_Y^2 H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$	$O_{\widetilde{BB}}$	$g_Y^2 H^\dagger H\, \widetilde{B}_{\mu\nu} B_{\mu\nu}$
O_{WB}	$g_L g_Y H^\dagger \sigma^i H\, W^i_{\mu\nu} B_{\mu\nu}$	$O_{\widetilde{WB}}$	$g_L g_Y H^\dagger \sigma^i H\, \widetilde{W}^i_{\mu\nu} B_{\mu\nu}$
O_{3W}	$g_L^3 \epsilon^{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$	$O_{\widetilde{3W}}$	$g_L^3 \epsilon^{ijk} \widetilde{W}^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$
O_{3G}	$g_s^3 f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$	$O_{\widetilde{3G}}$	$g_s^3 f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$

Table 2: Bosonic $d = 6$ operators in the Warsaw basis.

Yukawa	
$[O_e]_{IJ}$	$-(H^\dagger H - \frac{v^2}{2})\frac{\sqrt{m_I m_J}}{v} e^c_I H^\dagger \ell_J$
$[O_u]_{IJ}$	$-(H^\dagger H - \frac{v^2}{2})\frac{\sqrt{m_I m_J}}{v} u^c_I \widetilde{H}^\dagger q_J$
$[O_d]_{IJ}$	$-(H^\dagger H - \frac{v^2}{2})\frac{\sqrt{m_I m_J}}{v} d^c_I H^\dagger q_J$

Vertex		Dipole	
$[O_{H\ell}]_{IJ}$	$i\bar{\ell}_I \bar{\sigma}_\mu \ell H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{eW}]_{IJ}$	$g_L \frac{\sqrt{m_I m_J}}{v} e^c_I \sigma_{\mu\nu} H^\dagger \sigma^i \ell_J W^i_{\mu\nu}$
$[O'_{H\ell}]_{IJ}$	$i\bar{\ell}_I \sigma^i \bar{\sigma}_\mu \ell H^\dagger \sigma^i \overleftrightarrow{D}_\mu H$	$[O_{eB}]_{IJ}$	$g_Y \frac{\sqrt{m_I m_J}}{v} e^c_I \sigma_{\mu\nu} H^\dagger \ell_J B_{\mu\nu}$
$[O_{He}]_{IJ}$	$ie^c_I \sigma_\mu \bar{e}^c_J H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{uG}]_{IJ}$	$g_s \frac{\sqrt{m_I m_J}}{v} u^c_I \sigma_{\mu\nu} T^a \widetilde{H}^\dagger q_J\, G^a_{\mu\nu}$
$[O_{Hq}]_{IJ}$	$i\bar{q}_I \bar{\sigma}_\mu q_J H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{uW}]_{IJ}$	$g_L \frac{\sqrt{m_I m_J}}{v} u^c_I \sigma_{\mu\nu} \widetilde{H}^\dagger \sigma^i q_J\, W^i_{\mu\nu}$
$[O'_{Hq}]_{IJ}$	$i\bar{q}_I \sigma^i \bar{\sigma}_\mu q_J H^\dagger \sigma^i \overleftrightarrow{D}_\mu H$	$[O_{uB}]_{IJ}$	$g_Y \frac{\sqrt{m_I m_J}}{v} u^c_I \sigma_{\mu\nu} \widetilde{H}^\dagger q_J\, B_{\mu\nu}$
$[O_{Hu}]_{IJ}$	$iu^c_I \sigma_\mu \bar{u}^c_J H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{dG}]_{IJ}$	$g_s \frac{\sqrt{m_I m_J}}{v} d^c_I \sigma_{\mu\nu} T^a H^\dagger q_J\, G^a_{\mu\nu}$
$[O_{Hd}]_{IJ}$	$id^c_I \sigma_\mu \bar{d}^c_J H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{dW}]_{IJ}$	$g_L \frac{\sqrt{m_I m_J}}{v} d^c_I \sigma_{\mu\nu} \bar{H}^\dagger \sigma^i q_J\, W^i_{\mu\nu}$
$[O_{Hud}]_{IJ}$	$iu^c_I \sigma_\mu \bar{d}^c_J \tilde{H}^\dagger D_\mu H$	$[O_{dB}]_{IJ}$	$g_Y \frac{\sqrt{m_I m_J}}{v} d^c_I \sigma_{\mu\nu} H^\dagger q_J\, B_{\mu\nu}$

Table 3: Two-fermion d=6 operators in the Warsaw basis. Here, I, J are the flavor indices. For complex operators the complex conjugate operator is implicit.

Matching

$$c_{6H} = \frac{Z_6^2 v^2}{\Lambda^2}$$

$$[c_u]_{IJ} = -\sqrt{2}\frac{c_\beta}{s_\beta}\frac{Z_6 v^2}{\Lambda^2}\delta_{IJ}$$

$$[c_d]_{IJ} = [c_e]_{IJ} = \sqrt{2}\frac{c_\beta}{s_\beta}\frac{Z_6 v^2}{\Lambda^2}\delta_{IJ}$$

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{SM}(H_1, V_\mu, \psi) + \frac{1}{\Lambda^2}\left[Z_6 H_1^\dagger\left(H_1^\dagger H_1 - \frac{v^2}{2}\right) - \frac{c_\beta}{s_\beta}\tilde{\bar{q}} Y_u^\dagger \bar{u}^c - \frac{s_\beta}{c_\beta}\bar{q} Y_d^\dagger \bar{d}^c - \frac{s_\beta}{c_\beta}\bar{\ell} Y_e^\dagger \bar{e}^c\right]$$
$$\times\left[Z_6 H_1\left(H_1^\dagger H_1 - \frac{v^2}{2}\right) - \frac{c_\beta}{s_\beta} u^c Y_u \tilde{q} - \frac{s_\beta}{c_\beta} d^c Y_d q - \frac{s_\beta}{c_\beta} e^c Y_e \ell\right]$$

Example #1: Type-II Two Higgs Doublet Model

$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
O_{ee}	$(e^c\sigma_\mu\bar{e}^c)(e^c\sigma_\mu\bar{e}^c)$	$O_{\ell e}$	$(\bar{\ell}\bar{\sigma}_\mu\ell)(e^c\sigma_\mu\bar{e}^c)$
O_{uu}	$(u^c\sigma_\mu\bar{u}^c)(u^c\sigma_\mu\bar{u}^c)$	$O_{\ell u}$	$(\bar{\ell}\bar{\sigma}_\mu\ell)(u^c\sigma_\mu\bar{u}^c)$
O_{dd}	$(d^c\sigma_\mu\bar{d}^c)(d^c\sigma_\mu\bar{d}^c)$	$O_{\ell d}$	$(\bar{\ell}\bar{\sigma}_\mu\ell)(d^c\sigma_\mu\bar{d}^c)$
O_{eu}	$(e^c\sigma_\mu\bar{e}^c)(u^c\sigma_\mu\bar{u}^c)$	O_{qe}	$(\bar{q}\bar{\sigma}_\mu q)(e^c\sigma_\mu\bar{e}^c)$
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}	$(\bar{q}\bar{\sigma}_\mu T^a q)(d^c\sigma_\mu T^a\bar{d}^c)$

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

Table 4: Four-fermion d=6 operators in the Warsaw basis. Flavor indices are implicit. For complex operators the complex conjugate operator is implicit.

?

What about the remaining 4 fermion operators?
E.g. why (lbar ecbar) (ec l) is not in the Warsaw basis?

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{SM}(H_1, V_\mu, \psi) + \frac{1}{\Lambda^2}\left[Z_6 H_1^\dagger\left(H_1^\dagger H_1 - \frac{v^2}{2}\right) - \frac{c_\beta}{s_\beta}\tilde{\bar{q}}Y_u^\dagger\bar{u}^c - \frac{s_\beta}{c_\beta}\bar{q}Y_d^\dagger\bar{d}^c - \frac{s_\beta}{c_\beta}\bar{\ell}Y_e^\dagger\bar{e}^c\right]$$
$$\times\left[Z_6 H_1\left(H_1^\dagger H_1 - \frac{v^2}{2}\right) - \frac{c_\beta}{s_\beta}u^c Y_u\tilde{q} - \frac{s_\beta}{c_\beta}d^c Y_d q - \frac{s_\beta}{c_\beta}e^c Y_e\ell\right]$$

Example #1: Type-II Two Higgs Doublet Model

$(\bar{R}R)(\bar{R}R)$	
O_{ee}	$(e^c\sigma_\mu\bar{e}^c)(e^c\sigma_\mu\bar{e}^c)$
O_{uu}	$(u^c\sigma_\mu\bar{u}^c)(u^c\sigma_\mu\bar{u}^c)$
O_{dd}	$(d^c\sigma_\mu\bar{d}^c)(d^c\sigma_\mu\bar{d}^c)$
O_{eu}	$(e^c\sigma_\mu\bar{e}^c)(u^c\sigma_\mu\bar{u}^c)$
O_{ed}	$(e^c\sigma_\mu\bar{e}^c)(d^c\sigma_\mu\bar{d}^c)$
O_{ud}	$(u^c\sigma_\mu\bar{u}^c)(d^c\sigma_\mu\bar{d}^c)$
O'_{ud}	$(u^c\sigma_\mu T^a\bar{u}^c)(d^c\sigma_\mu T^a\bar{d}^c)$

$(\bar{L}L)(\bar{R}R)$	
$O_{\ell e}$	$(\bar\ell\bar\sigma_\mu\ell)(e^c\sigma_\mu\bar{e}^c)$
$O_{\ell u}$	$(\bar\ell\bar\sigma_\mu\ell)(u^c\sigma_\mu\bar{u}^c)$
$O_{\ell d}$	$(\bar\ell\bar\sigma_\mu\ell)(d^c\sigma_\mu\bar{d}^c)$
O_{qe}	$(\bar{q}\bar\sigma_\mu q)(e^c\sigma_\mu\bar{e}^c)$
O_{qu}	$(\bar{q}\bar\sigma_\mu q)(u^c\sigma_\mu\bar{u}^c)$
O'_{qu}	$(\bar{q}\bar\sigma_\mu T^a q)(u^c\sigma_\mu T^a\bar{u}^c)$
O_{qd}	$(\bar{q}\bar\sigma_\mu q)(d^c\sigma_\mu\bar{d}^c)$
O'_{qd}	$(\bar{q}\bar\sigma_\mu T^a q)(d^c\sigma_\mu T^a\bar{d}^c)$

$(\bar{L}L)(\bar{L}L)$	
$O_{\ell\ell}$	$(\bar\ell\bar\sigma_\mu\ell)(\bar\ell\bar\sigma_\mu\ell)$
O_{qq}	$(\bar{q}\bar\sigma_\mu q)(\bar{q}\bar\sigma_\mu q)$
O'_{qq}	$(\bar{q}\bar\sigma_\mu\sigma^i q)(\bar{q}\bar\sigma_\mu\sigma^i q)$
$O_{\ell q}$	$(\bar\ell\bar\sigma_\mu\ell)(\bar{q}\bar\sigma_\mu q)$
$O'_{\ell q}$	$(\bar\ell\bar\sigma_\mu\sigma^i\ell)(\bar{q}\bar\sigma_\mu\sigma^i q)$

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

Table 4: Four-fermion d=6 operators in the Warsaw basis. Flavor indices are implicit. For complex operators the complex conjugate operator is implicit.

?

What about the remaining 4 fermion operators? E.g. why (lbar ecbar) (ec l) is not in the Warsaw basis?

Answer: it is there, but hiding… Using Fierz identity

$$[\bar\sigma_\mu]_{\dot\alpha}^{\ \alpha}[\sigma_\mu]_{\beta}^{\ \dot\beta} = 2\delta_\beta^\alpha\delta_{\dot\alpha}^{\dot\beta}$$

one derives

$$(e_I^c\ell_J)(\bar\ell_K\bar{e}_L^c) = -\frac{1}{2}(\bar\ell_K\bar\sigma_\mu\ell_J)(e_I^c\sigma_\mu e_L^c)$$

Exercise: derive Wilson coefficients of all 4-fermion operators

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{SM}(H_1, V_\mu, \psi) + \frac{1}{\Lambda^2}\left[Z_6 H_1^\dagger\left(H_1^\dagger H_1 - \frac{v^2}{2}\right) - \frac{c_\beta}{s_\beta}\tilde{\bar{q}}Y_u^\dagger\bar{u}^c - \frac{s_\beta}{c_\beta}\bar{q}Y_d^\dagger\bar{d}^c - \frac{s_\beta}{c_\beta}\bar\ell Y_e^\dagger\bar{e}^c\right]$$
$$\times\left[Z_6 H_1\left(H_1^\dagger H_1 - \frac{v^2}{2}\right) - \frac{c_\beta}{s_\beta}u^c Y_u\tilde{q} - \frac{s_\beta}{c_\beta}d^c Y_d q - \frac{s_\beta}{c_\beta}e^c Y_e\ell\right]$$

Example #1: Type-II Two Higgs Doublet Model

Lessons learned:

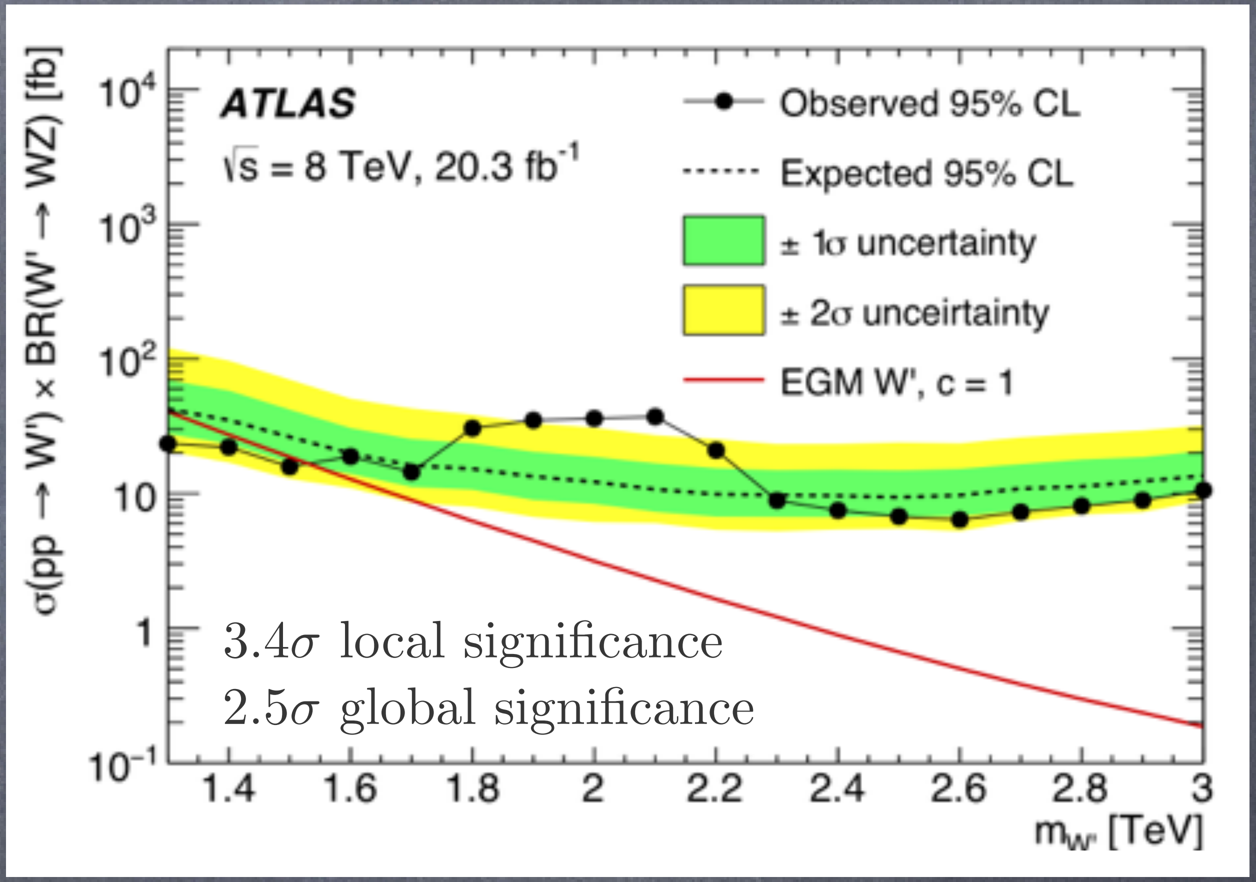
- A subset of all possible dimension-6 operators appear in the low-energy EFT for 2HDM at tree-level
- Note that 2HDM has more parameters than dimension-6 EFT, e.g. ($\lambda 2$-$\lambda 5$ quartic couplings vs only Z6 entering in EFT). EFT allows one to quickly identify which combinations of coupling of UV theory can be constrained in low-energy measurements.
- Matching to dimension-6 operators in given basis is not always trivial. E.g. integrating out scalars requires using Fierz identities to match to Warsaw basis operators (this also means that Warsaw basis is not the most convenient one from the point of view of 2HDM; one could construct an equivalent basis where matching would be simpler)

Matching new physics to D=6 Lagrangian

Example #2: Vector Triplet Resonance

Why vector triplet?

- It was found this year ;)
- Predicted by technicolor and composite Higgs models
- Nice simple model leading to higher-derivative Higgs couplings at tree level



Example #2: Vector Triplet Resonance

A new SU(2) triplet of heavy vector bosons,
coupled to SM SU(2) Higgs and fermionic currents:

$$\Delta\mathcal{L} = -\frac{1}{4}V^i_{\mu\nu}V^i_{\mu\nu} + \frac{m_V^2}{2}V^i_\mu V^i_\mu + \frac{i}{2}\kappa_H V^i_\mu H^\dagger\sigma^i \overleftrightarrow{D}_\mu H + \frac{1}{2}\kappa_F V^i_\mu \sum_{f\in\ell,q} \bar{f}\sigma^i\bar{\sigma}_\mu f$$

For, simplicity, couplings to fermions assumed universal.
Thus, model has 3 free parameters: mV, κH, and κF.
This time we identify mV with EFT expansion parameter Λ.
Solving equations of motions to leading order in 1/Λ:

$$V^i_\mu = -\frac{1}{\Lambda^2}\left(\frac{i}{2}\kappa_H H^\dagger\sigma^i \overleftrightarrow{D}_\mu H + \frac{1}{2}\kappa_F \sum_{f\in\ell,q} \bar{f}\sigma^i\bar{\sigma}_\mu f\right)$$

Effective Lagrangian

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} - \frac{1}{8\Lambda^2}\left(i\kappa_H H^\dagger\sigma^i \overleftrightarrow{D}_\mu H + \kappa_F \sum_{f\in\ell,q} \bar{f}\sigma^i\bar{\sigma}_\mu f\right)^2$$

Example #2: Vector Triplet Resonance

Effective Lagrangian can also be obtained another way by 1st shifting: $W^i_\mu \to W^i_\mu - \frac{\kappa_F}{g_L} V^i_\mu$

$$\Delta\mathcal{L} = -\frac{1}{4}V^i_{\mu\nu}V^i_{\mu\nu} + \frac{m_V^2}{2}V^i_\mu V^i_\mu + \frac{i}{2}(\kappa_H - \kappa_F)V^i_\mu H^\dagger\sigma^i \overleftrightarrow{D}_\mu H + \frac{\kappa_F}{g_L}V^i_\mu D_\nu W^i_{\mu\nu} + \ldots$$

Note that the new vector field does not couple to fermions anymore.
Solving equations of motions to leading order in $1/\Lambda$, and plugging back,
we obtain the effective Lagrangian:

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} - \frac{1}{2\Lambda^2}\left(\frac{i}{2}(\kappa_H - \kappa_F)H^\dagger\sigma^i \overleftrightarrow{D}_\mu H + \frac{\kappa_F}{g_L}D_\nu W^i_{\mu\nu}\right)^2$$

As compared to

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} - \frac{1}{8\Lambda^2}\left(i\kappa_H H^\dagger\sigma^i \overleftrightarrow{D}_\mu H + \kappa_F \sum_{f\in\ell,q}\bar{f}\sigma^i\bar{\sigma}_\mu f\right)^2$$

Which one is right? Answer: both!
The equivalence can be proven by using the SM equations of motion:

$$D_\nu W^i_{\mu\nu} = \frac{ig_L}{2}H^\dagger\sigma^i \overleftrightarrow{D}_\mu H + \frac{g_L}{2}\sum_{f\in\ell,q}\bar{f}\sigma^i\bar{\sigma}_\mu f$$

Example #2: Vector Triplet Resonance

Yukawa

$[O_e]_{IJ}$	$-(H^\dagger H - \frac{v^2}{2})\frac{\sqrt{m_I m_J}}{v} e^c_I H^\dagger \ell_J$
$[O_u]_{IJ}$	$-(H^\dagger H - \frac{v^2}{2})\frac{\sqrt{m_I m_J}}{v} u^c_I \widetilde{H}^\dagger q_J$
$[O_d]_{IJ}$	$-(H^\dagger H - \frac{v^2}{2})\frac{\sqrt{m_I m_J}}{v} d^c_I H^\dagger q_J$

Vertex

$[O_{H\ell}]_{IJ}$	$i\bar{\ell}_I \bar{\sigma}_\mu \ell H^\dagger \overleftrightarrow{D}_\mu H$
$[O'_{H\ell}]_{IJ}$	$i\bar{\ell}_I \sigma^i \bar{\sigma}_\mu \ell H^\dagger \sigma^i \overleftrightarrow{D}_\mu H$
$[O_{He}]_{IJ}$	$ie^c_I \sigma_\mu \bar{e}^c_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O_{Hq}]_{IJ}$	$i\bar{q}_I \bar{\sigma}_\mu q_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O'_{Hq}]_{IJ}$	$i\bar{q}_I \sigma^i \bar{\sigma}_\mu q_J H^\dagger \sigma^i \overleftrightarrow{D}_\mu H$
$[O_{Hu}]_{IJ}$	$iu^c_I \sigma_\mu \bar{u}^c_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O_{Hd}]_{IJ}$	$id^c_I \sigma_\mu \bar{d}^c_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O_{Hud}]_{IJ}$	$iu^c_I \sigma_\mu \bar{d}^c_J \tilde{H}^\dagger D_\mu H$

Dipole

$[O_{eW}]_{IJ}$	$g_L \frac{\sqrt{m_I m_J}}{v} e^c_I \sigma_{\mu\nu} H^\dagger \sigma^i \ell_J W^i_{\mu\nu}$
$[O_{eB}]_{IJ}$	$g_Y \frac{\sqrt{m_I m_J}}{v} e^c_I \sigma_{\mu\nu} H^\dagger \ell_J B_{\mu\nu}$
$[O_{uG}]_{IJ}$	$g_s \frac{\sqrt{m_I m_J}}{v} u^c_I \sigma_{\mu\nu} T^a \widetilde{H}^\dagger q_J\, G^a_{\mu\nu}$
$[O_{uW}]_{IJ}$	$g_L \frac{\sqrt{m_I m_J}}{v} u^c_I \sigma_{\mu\nu} \widetilde{H}^\dagger \sigma^i q_J\, W^i_{\mu\nu}$
$[O_{uB}]_{IJ}$	$g_Y \frac{\sqrt{m_I m_J}}{v} u^c_I \sigma_{\mu\nu} \widetilde{H}^\dagger q_J\, B_{\mu\nu}$
$[O_{dG}]_{IJ}$	$g_s \frac{\sqrt{m_I m_J}}{v} d^c_I \sigma_{\mu\nu} T^a H^\dagger q_J\, G^a_{\mu\nu}$
$[O_{dW}]_{IJ}$	$g_L \frac{\sqrt{m_I m_J}}{v} d^c_I \sigma_{\mu\nu} \bar{H}^\dagger \sigma^i q_J\, W^i_{\mu\nu}$
$[O_{dB}]_{IJ}$	$g_Y \frac{\sqrt{m_I m_J}}{v} d^c_I \sigma_{\mu\nu} H^\dagger q_J\, B_{\mu\nu}$

Table 3: Two-fermion d=6 operators in the Warsaw basis. Here, I, J are the flavor indices. For complex operators the complex conjugate operator is implicit.

Matching:

$$[c'_{H\ell}]_{JJ} = [c'_{Hq}]_{JJ} = -\kappa_H \kappa_F \frac{v^2}{4\Lambda^2}$$

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} - \frac{1}{8\Lambda^2}\left(i\kappa_H H^\dagger \sigma^i \overleftrightarrow{D}_\mu H + \kappa_F \sum_{f\in \ell,q} \bar{f}\sigma^i \bar{\sigma}_\mu f \right)^2$$

Example #2: Vector Triplet Resonance

Bosonic CP-even		Bosonic CP-odd	
O_H	$\left[\partial_\mu (H^\dagger H)\right]^2$		
O_T	$\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$		
O_{6H}	$(H^\dagger H)^3$		
O_{GG}	$g_s^2 H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu}$	$O_{\widetilde{GG}}$	$g_s^2 H^\dagger H\, \widetilde{G}^a_{\mu\nu} G^a_{\mu\nu}$
O_{WW}	$g_L^2 H^\dagger H\, W^i_{\mu\nu} W^i_{\mu\nu}$	$O_{\widetilde{WW}}$	$g_L^2 H^\dagger H\, \widetilde{W}^i_{\mu\nu} W^i_{\mu\nu}$
O_{BB}	$g_Y^2 H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$	$O_{\widetilde{BB}}$	$g_Y^2 H^\dagger H\, \widetilde{B}_{\mu\nu} B_{\mu\nu}$
O_{WB}	$g_L g_Y H^\dagger \sigma^i H\, W^i_{\mu\nu} B_{\mu\nu}$	$O_{\widetilde{WB}}$	$g_L g_Y H^\dagger \sigma^i H\, \widetilde{W}^i_{\mu\nu} B_{\mu\nu}$
O_{3W}	$g_L^3 \epsilon^{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$	$O_{\widetilde{3W}}$	$g_L^3 \epsilon^{ijk} \widetilde{W}^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$
O_{3G}	$g_s^3 f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$	$O_{\widetilde{3G}}$	$g_s^3 f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$

Table 2: Bosonic $d = 6$ operators in the Warsaw basis.

?

$$(H^\dagger \sigma^i \overleftrightarrow{D}_\mu H)(H^\dagger \sigma^i \overleftrightarrow{D}_\mu H)$$

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} - \frac{1}{8\Lambda^2}\left(i\kappa_H H^\dagger \sigma^i \overleftrightarrow{D}_\mu H + \kappa_F \sum_{f\in \ell,q} \bar{f}\sigma^i \bar{\sigma}_\mu f\right)^2$$

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O_{WW}	$g_L^2 H^\dagger H\, W^i_{\mu\nu} W^i_{\mu\nu}$	$O_{\widetilde{WW}}$	$g_L^2 H^\dagger H\, \widetilde{W}^i_{\mu\nu} W^i_{\mu\nu}$
O_{BB}	$g_Y^2 H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$	$O_{\widetilde{BB}}$	$g_Y^2 H^\dagger H\, \widetilde{B}_{\mu\nu} B_{\mu\nu}$
O_{WB}	$g_L g_Y H^\dagger \sigma^i H\, W^i_{\mu\nu} B_{\mu\nu}$	$O_{\widetilde{WB}}$	$g_L g_Y H^\dagger \sigma^i H\, \widetilde{W}^i_{\mu\nu} B_{\mu\nu}$
O_{3W}	$g_L^3 \epsilon^{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$	$O_{\widetilde{3W}}$	$g_L^3 \epsilon^{ijk} \widetilde{W}^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$
O_{3G}	$g_s^3 f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$	$O_{\widetilde{3G}}$	$g_s^3 f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$

Table 2: Bosonic $d = 6$ operators in the Warsaw basis.

?

$$(H^\dagger \sigma^i \overleftrightarrow{D}_\mu H)(H^\dagger \sigma^i \overleftrightarrow{D}_\mu H)$$

$$\left(\partial_\mu (H^\dagger H)\right)^2 - 4(H^\dagger H)(D_\mu H^\dagger D_\mu H)$$

?

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} - \frac{1}{8\Lambda^2}\left(i\kappa_H H^\dagger \sigma^i \overleftrightarrow{D}_\mu H + \kappa_F \sum_{f\in \ell,q} \bar{f}\sigma^i \bar{\sigma}_\mu f\right)^2$$

Example #2: Vector Triplet Resonance

	Bosonic CP-even		Bosonic CP-odd
O_H	$[\partial_\mu (H^\dagger H)]^2$		
O_T	$\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$		
O_{6H}	$(H^\dagger H)^3$		
O_{GG}	$g_s^2 H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu}$	$O_{\widetilde{GG}}$	$g_s^2 H^\dagger H\, \widetilde{G}^a_{\mu\nu} G^a_{\mu\nu}$
O_{WW}	$g_L^2 H^\dagger H\, W^i_{\mu\nu} W^i_{\mu\nu}$	$O_{\widetilde{WW}}$	$g_L^2 H^\dagger H\, \widetilde{W}^i_{\mu\nu} W^i_{\mu\nu}$
O_{BB}	$g_Y^2 H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$	$O_{\widetilde{BB}}$	$g_Y^2 H^\dagger H\, \widetilde{B}_{\mu\nu} B_{\mu\nu}$
O_{WB}	$g_L g_Y H^\dagger \sigma^i H\, W^i_{\mu\nu} B_{\mu\nu}$	$O_{\widetilde{WB}}$	$g_L g_Y H^\dagger \sigma^i H\, \widetilde{W}^i_{\mu\nu} B_{\mu\nu}$
O_{3W}	$g_L^3 \epsilon^{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$	$O_{\widetilde{3W}}$	$g_L^3 \epsilon^{ijk} \widetilde{W}^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$
O_{3G}	$g_s^3 f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$	$O_{\widetilde{3G}}$	$g_s^3 f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$

Table 2: Bosonic $d = 6$ operators in the Warsaw basis.

?

$$(H^\dagger \sigma^i \overleftrightarrow{D}_\mu H)(H^\dagger \sigma^i \overleftrightarrow{D}_\mu H)$$

$$\left(\partial_\mu (H^\dagger H)\right)^2 - 4(H^\dagger H)(D_\mu H^\dagger D_\mu H)$$

?

$$H \to H\left(1 - \frac{1}{2}|H|^2\right)$$

$$(H^\dagger H)(D_\mu H^\dagger D_\mu H) \to -\frac{1}{2} O_H + 2\lambda O_{6H} - \frac{1}{\sqrt{2}} \sum_f [O_f]_{JJ}$$

$$(H^\dagger \sigma^i \overleftrightarrow{D}_\mu H)^2 = 3 O_H - 8\lambda O_{6H} + 2\sqrt{2} \sum_f [O_f]_{JJ}$$

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} - \frac{1}{8\Lambda^2}\left(i\kappa_H H^\dagger \sigma^i \overleftrightarrow{D}_\mu H + \kappa_F \sum_{f \in \ell, q} \bar{f} \sigma^i \bar{\sigma}_\mu f\right)^2$$

Example #2: Vector Triplet Resonance

Warsaw Basis

	Bosonic CP-even		Bosonic CP-odd
O_H	$[\partial_\mu(H^\dagger H)]^2$		
O_T	$\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$		
O_{6H}	$(H^\dagger H)^3$		
O_{GG}	$g_s^2 H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu}$	$O_{\widetilde{GG}}$	$g_s^2 H^\dagger H\, \widetilde{G}^a_{\mu\nu} G^a_{\mu\nu}$
O_{WW}	$g_L^2 H^\dagger H\, W^i_{\mu\nu} W^i_{\mu\nu}$	$O_{\widetilde{WW}}$	$g_L^2 H^\dagger H\, \widetilde{W}^i_{\mu\nu} W^i_{\mu\nu}$
O_{BB}	$g_Y^2 H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$	$O_{\widetilde{BB}}$	$g_Y^2 H^\dagger H\, \widetilde{B}_{\mu\nu} B_{\mu\nu}$
O_{WB}	$g_L g_Y H^\dagger \sigma^i H\, W^i_{\mu\nu} B_{\mu\nu}$	$O_{\widetilde{WB}}$	$g_L g_Y H^\dagger \sigma^i H\, \widetilde{W}^i_{\mu\nu} B_{\mu\nu}$
O_{3W}	$g_L^3 \epsilon^{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$	$O_{\widetilde{3W}}$	$g_L^3 \epsilon^{ijk} \widetilde{W}^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$
O_{3G}	$g_s^3 f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$	$O_{\widetilde{3G}}$	$g_s^3 f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$

Table 2: Bosonic $d = 6$ operators in the Warsaw basis.

	Yukawa
$[O_e]_{IJ}$	$-(H^\dagger H - \frac{v^2}{2})\frac{\sqrt{m_I m_J}}{v} e^c_I H^\dagger \ell_J$
$[O_u]_{IJ}$	$-(H^\dagger H - \frac{v^2}{2})\frac{\sqrt{m_I m_J}}{v} u^c_I \widetilde{H}^\dagger q_J$
$[O_d]_{IJ}$	$-(H^\dagger H - \frac{v^2}{2})\frac{\sqrt{m_I m_J}}{v} d^c_I H^\dagger q_J$

	Vertex		Dipole
$[O_{H\ell}]_{IJ}$	$i\bar{\ell}_I \bar{\sigma}_\mu \ell H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{eW}]_{IJ}$	$g_L \frac{\sqrt{m_I m_J}}{v} e^c_I \sigma_{\mu\nu} H^\dagger \sigma^i \ell_J W^i_{\mu\nu}$
$[O'_{H\ell}]_{IJ}$	$i\bar{\ell}_I \sigma^i \bar{\sigma}_\mu \ell H^\dagger \sigma^i \overleftrightarrow{D}_\mu H$	$[O_{eB}]_{IJ}$	$g_Y \frac{\sqrt{m_I m_J}}{v} e^c_I \sigma_{\mu\nu} H^\dagger \ell_J B_{\mu\nu}$
$[O_{He}]_{IJ}$	$ie^c_I \sigma_\mu e^c_J H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{uG}]_{IJ}$	$g_s \frac{\sqrt{m_I m_J}}{v} u^c_I \sigma_{\mu\nu} T^a \widetilde{H}^\dagger q_J\, G^a_{\mu\nu}$
$[O_{Hq}]_{IJ}$	$i\bar{q}_I \bar{\sigma}_\mu q_J H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{uW}]_{IJ}$	$g_L \frac{\sqrt{m_I m_J}}{v} u^c_I \sigma_{\mu\nu} \widetilde{H}^\dagger \sigma^i q_J\, W^i_{\mu\nu}$
$[O'_{Hq}]_{IJ}$	$i\bar{q}_I \sigma^i \bar{\sigma}_\mu q_J H^\dagger \sigma^i \overleftrightarrow{D}_\mu H$	$[O_{uB}]_{IJ}$	$g_Y \frac{\sqrt{m_I m_J}}{v} u^c_I \sigma_{\mu\nu} \widetilde{H}^\dagger q_J\, B_{\mu\nu}$
$[O_{Hu}]_{IJ}$	$iu^c_I \sigma_\mu \bar{u}^c_J H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{dG}]_{IJ}$	$g_s \frac{\sqrt{m_I m_J}}{v} d^c_I \sigma_{\mu\nu} T^a H^\dagger q_J\, G^a_{\mu\nu}$
$[O_{Hd}]_{IJ}$	$id^c_I \sigma_\mu \bar{d}^c_J H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{dW}]_{IJ}$	$g_L \frac{\sqrt{m_I m_J}}{v} d^c_I \sigma_{\mu\nu} \bar{H}^\dagger \sigma^i q_J\, W^i_{\mu\nu}$
$[O_{Hud}]_{IJ}$	$iu^c_I \sigma_\mu \bar{d}^c_J \tilde{H}^\dagger D_\mu H$	$[O_{dB}]_{IJ}$	$g_Y \frac{\sqrt{m_I m_J}}{v} d^c_I \sigma_{\mu\nu} H^\dagger q_J\, B_{\mu\nu}$

Table 3: Two-fermion d=6 operators in the Warsaw basis. Here, I, J are the flavor indices. For complex operators the complex conjugate operator is implicit.

Matching:

$$c_H = \frac{3v^2\kappa_H^2}{8\Lambda^2}$$

$$c_{6H} = -\frac{\lambda v^2 \kappa_H^2}{\Lambda^2}$$

$$[c'_{H\ell}]_{JJ} = [c'_{Hq}]_{JJ} = -\kappa_H \kappa_F \frac{v^2}{4\Lambda^2}$$

$$[c_f]_{IJ} = \frac{v^2\kappa_H^2}{2\sqrt{2}\Lambda^2}\delta_{IJ}$$

+ 4 fermion operators

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} - \frac{1}{8\Lambda^2}\left(i\kappa_H H^\dagger \sigma^i \overleftrightarrow{D}_\mu H + \kappa_F \sum_{f\in\ell,q} \bar{f}\sigma^i\bar{\sigma}_\mu f\right)^2$$

Example #2: Vector Triplet Resonance

SILH Basis

	Bosonic CP-even		Bosonic CP-odd
O_H	$[\partial_\mu(H^\dagger H)]^2$		
O_T	$\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$		
O_{6H}	$(H^\dagger H)^3$		
O_{GG}	$g_s^2 H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu}$	$O_{\widetilde{GG}}$	$g_s^2 H^\dagger H\, \widetilde{G}^a_{\mu\nu} G^a_{\mu\nu}$
O_{BB}	$g_Y^2 H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$	$O_{\widetilde{BB}}$	$g_Y^2 H^\dagger H\, \widetilde{B}_{\mu\nu} B_{\mu\nu}$
O_W	$\frac{i}{2} g_L \left(H^\dagger \sigma^i \overleftrightarrow{D}_\mu H\right) D_\nu W^i_{\mu\nu}$		
O_B	$\frac{i}{2} g_Y \left(H^\dagger \overleftrightarrow{D}_\mu H\right) \partial_\nu B_{\mu\nu}$		
O_{HW}	$i g_L \left(D_\mu H^\dagger \sigma^i D_\nu H\right) W^i_{\mu\nu}$	$O_{\widetilde{HW}}$	$i g_L \left(D_\mu H^\dagger \sigma^i D_\nu H\right) \widetilde{W}^i_{\mu\nu}$
O_{HB}	$i g_Y \left(D_\mu H^\dagger D_\nu H\right) B_{\mu\nu}$	$O_{\widetilde{HB}}$	$i g_Y \left(D_\mu H^\dagger D_\nu H\right) \widetilde{B}_{\mu\nu}$
O_{2W}	$D_\mu W^i_{\mu\nu} D_\rho W^i_{\rho\nu}$		
O_{2B}	$\partial_\mu B_{\mu\nu} \partial_\rho B_{\rho\nu}$		
O_{2G}	$D_\mu G^a_{\mu\nu} D_\rho G^a_{\rho\nu}$		
O_{3W}	$g_L^3 \epsilon^{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$	$O_{\widetilde{3W}}$	$g_L^3 \epsilon^{ijk} \widetilde{W}^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$
O_{3G}	$g_s^3 f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$	$O_{\widetilde{3G}}$	$g_s^3 f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$

Table 5: Bosonic $d = 6$ operators in the SILH basis.

Yukawa

$[O_e]_{IJ}$	$-(H^\dagger H - \frac{v^2}{2})\frac{\sqrt{m_I m_J}}{v} e^c_I H^\dagger \ell_J$
$[O_u]_{IJ}$	$-(H^\dagger H - \frac{v^2}{2})\frac{\sqrt{m_I m_J}}{v} u^c_I \widetilde{H}^\dagger q_J$
$[O_d]_{IJ}$	$-(H^\dagger H - \frac{v^2}{2})\frac{\sqrt{m_I m_J}}{v} d^c_I H^\dagger q_J$

Vertex		Dipole	
$[O_{H\ell}]_{IJ}$	$i\bar{\ell}_I \bar{\sigma}_\mu \ell H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{eW}]_{IJ}$	$g_L \frac{\sqrt{m_I m_J}}{v} e^c_I \sigma_{\mu\nu} H^\dagger \sigma^i \ell_J W^i_{\mu\nu}$
$[O'_{H\ell}]_{IJ}$	$i\bar{\ell}_I \sigma^i \bar{\sigma}_\mu \ell H^\dagger \sigma^i \overleftrightarrow{D}_\mu H$	$[O_{eB}]_{IJ}$	$g_Y \frac{\sqrt{m_I m_J}}{v} e^c_I \sigma_{\mu\nu} H^\dagger \ell_J B_{\mu\nu}$
$[O_{He}]_{IJ}$	$i e^c_I \sigma_\mu \bar{e}^c_J H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{uG}]_{IJ}$	$g_s \frac{\sqrt{m_I m_J}}{v} u^c_I \sigma_{\mu\nu} T^a \widetilde{H}^\dagger q_J\, G^a_{\mu\nu}$
$[O_{Hq}]_{IJ}$	$i\bar{q}_I \bar{\sigma}_\mu q_J H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{uW}]_{IJ}$	$g_L \frac{\sqrt{m_I m_J}}{v} u^c_I \sigma_{\mu\nu} \widetilde{H}^\dagger \sigma^i q_J\, W^i_{\mu\nu}$
$[O'_{Hq}]_{IJ}$	$i\bar{q}_I \sigma^i \bar{\sigma}_\mu q_J H^\dagger \sigma^i \overleftrightarrow{D}_\mu H$	$[O_{uB}]_{IJ}$	$g_Y \frac{\sqrt{m_I m_J}}{v} u^c_I \sigma_{\mu\nu} \widetilde{H}^\dagger q_J\, B_{\mu\nu}$
$[O_{Hu}]_{IJ}$	$i u^c_I \sigma_\mu \bar{u}^c_J H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{dG}]_{IJ}$	$g_s \frac{\sqrt{m_I m_J}}{v} d^c_I \sigma_{\mu\nu} T^a H^\dagger q_J\, G^a_{\mu\nu}$
$[O_{Hd}]_{IJ}$	$i d^c_I \sigma_\mu \bar{d}^c_J H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{dW}]_{IJ}$	$g_L \frac{\sqrt{m_I m_J}}{v} d^c_I \sigma_{\mu\nu} \bar{H}^\dagger \sigma^i q_J\, W^i_{\mu\nu}$
$[O_{Hud}]_{IJ}$	$i u^c_I \sigma_\mu \bar{d}^c_J \tilde{H}^\dagger D_\mu H$	$[O_{dB}]_{IJ}$	$g_Y \frac{\sqrt{m_I m_J}}{v} d^c_I \sigma_{\mu\nu} H^\dagger q_J\, B_{\mu\nu}$

Table 3: Two-fermion d=6 operators in the Warsaw basis. Here, I, J are the flavor indices. For complex operators the complex conjugate operator is implicit.

Exercise: find Wilson coefficients in the SILH basis

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} - \frac{1}{2\Lambda^2}\left(\frac{i}{2}(\kappa_H - \kappa_F) H^\dagger \sigma^i \overleftrightarrow{D}_\mu H + \frac{\kappa_F}{g_L} D_\nu W^i_{\mu\nu}\right)^2$$

Example #2: Vector Triplet Resonance

Lessons learned:

- A subset of all possible dimension-6 operators appear in the low-energy EFT for vector triplet model at tree-level
- These are very different operators than the ones appearing in 2HDM. Therefore, to be model independent, one should simultaneously constrain *all* dimension-6 operators
- This approach is basis independent - results can always be transformed from one basis to another, provided all operators are taken into account. However, matching to particular models may simpler in particular bases, e.g. matching to composite Higgs models is more straightforward using SILH rather than Warsaw basis