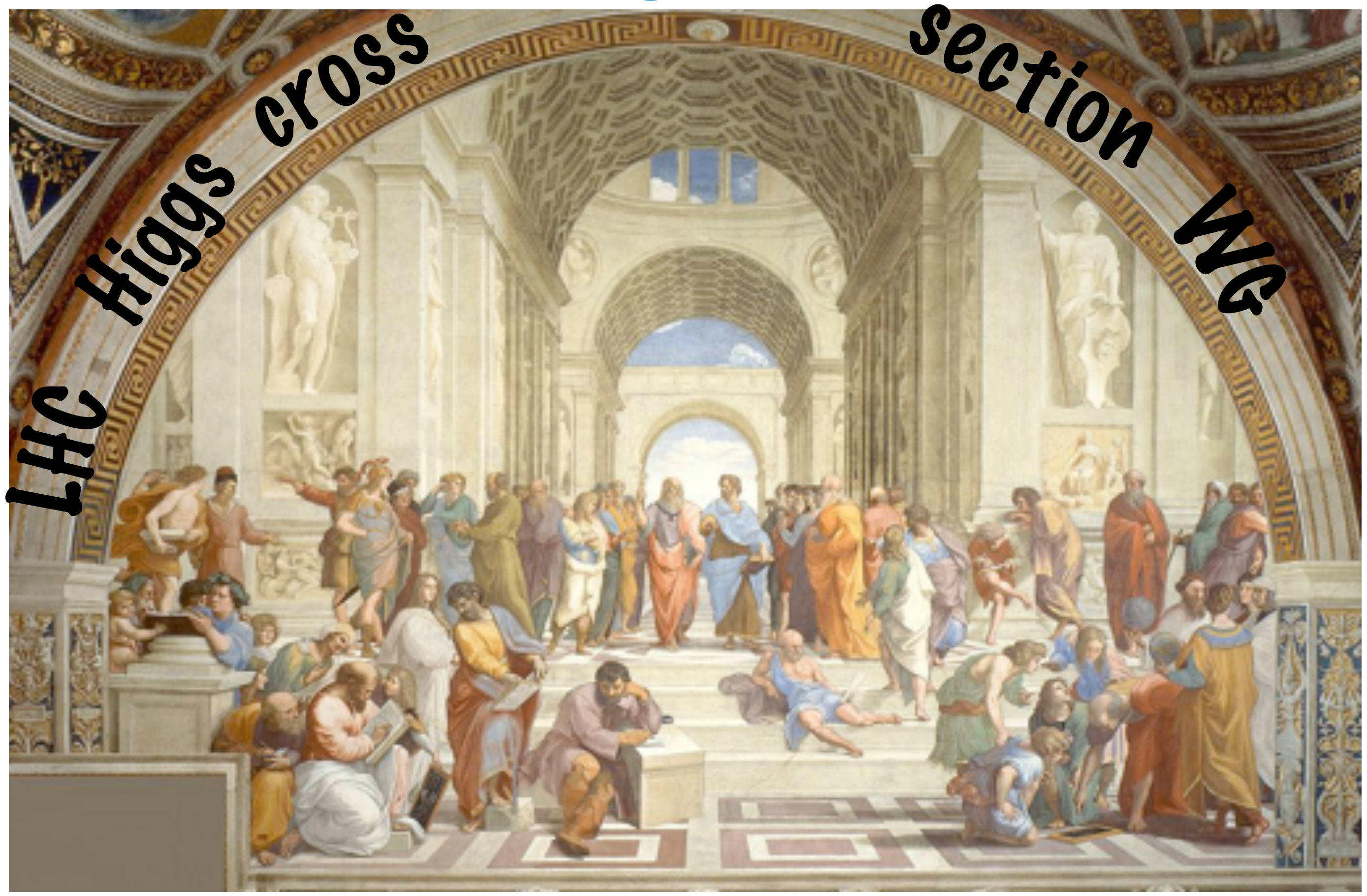
# EFT lessons from the Higgs experience

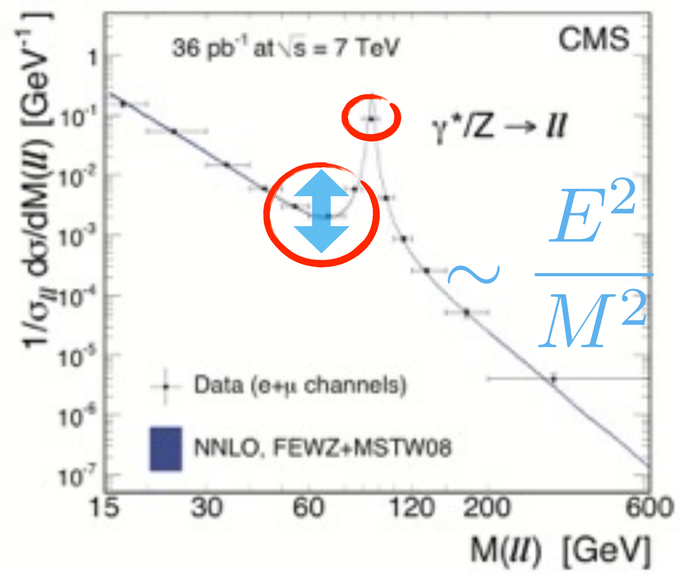



Francesco Riva
(CERN)

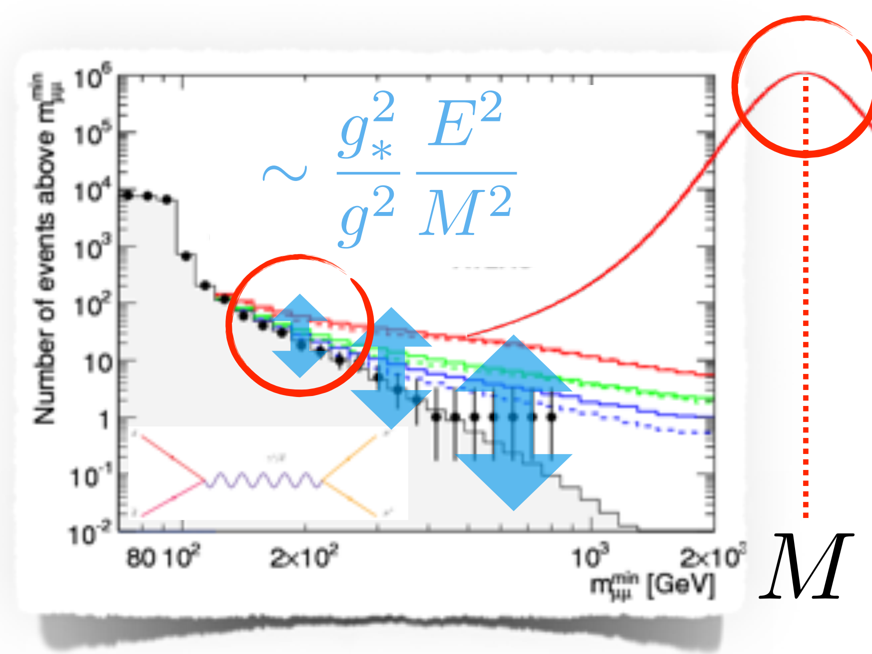
# Motivation

## What scenarios are best tested in indirect (EFT) searches?

- **Weakly coupled New Physics: best in resonant (direct) searches**




- **Strongly coupled New Physics: best in SM precision tests**
  (!Not QCD, but a new $g_* \gg g_s, y_t, \ldots$ !)




We miss the resonance, but get its tail

# Motivation

## Most well-motivated scenario of new strong coupling:

**Composite Higgs models** **with** **Fermion Partial Compositeness (top in particular)**

$$\mathcal{L}_{\rm SILH} = \frac{c_H}{2f^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right)$$
$$-\frac{c_6\lambda}{f^2}\left(H^\dagger H\right)^3 + \left(\frac{c_y y_f}{f^2} H^\dagger H \bar{f}_L H f_R + \text{h.c.}\right)$$
$$+\frac{i c_W g}{2m_\rho^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i + \frac{i c_B g'}{2m_\rho^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)(\partial^\nu B_{\mu\nu})$$
$$+\frac{i c_{HW} g}{16\pi^2 f^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{i c_{HB} g'}{16\pi^2 f^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$
$$+\frac{c_\gamma g'^2}{16\pi^2 f^2}\frac{g^2}{g_\rho^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{c_g g_S^2}{16\pi^2 f^2}\frac{y_t^2}{g_\rho^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}.$$

$$\frac{c_t y_t}{f^2} H^\dagger H \bar{q}_L \tilde{H} t_R + h.c. + \frac{i c_R}{f^2} H^\dagger D_\mu H \bar{t}_R \gamma^\mu t_R \,.$$
$$+ \frac{c_{4t}}{f^2}(\bar{t}_R \gamma^\mu t_R)(\bar{t}_R \gamma_\mu t_R)\,.$$

(SILH)Giudice,Grojean,Pomarol,Rattazzi'07

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# What I've learned from EFTs in Higgs physics

(many of these things are obvious…now)

# 1) the k framework 1307.1347

(= modifications of the SM couplings involving h in the unitary gauge)

$$\frac{\sigma_{WH}}{\sigma_{WH}^{SM}} = \kappa_W^2 \qquad \frac{\Gamma_{ZZ^{(*)}}}{\Gamma_{ZZ^{(*)}}^{SM}} = \kappa_Z^2$$

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- Good for exploratory analysis (of SM hypothesis)

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PRO:
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CONTRA:
- Not so Simple and intuitive in more complex situations

$$\frac{\sigma_{ggH}}{\sigma_{ggH}^{SM}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases}$$

- Not supported by physical hypothesis

$hW_\mu W^\mu$ V

$hF_{\mu\nu}F^{\mu\nu}$ V

$hW_{\mu\nu}W^{\mu\nu}$ X

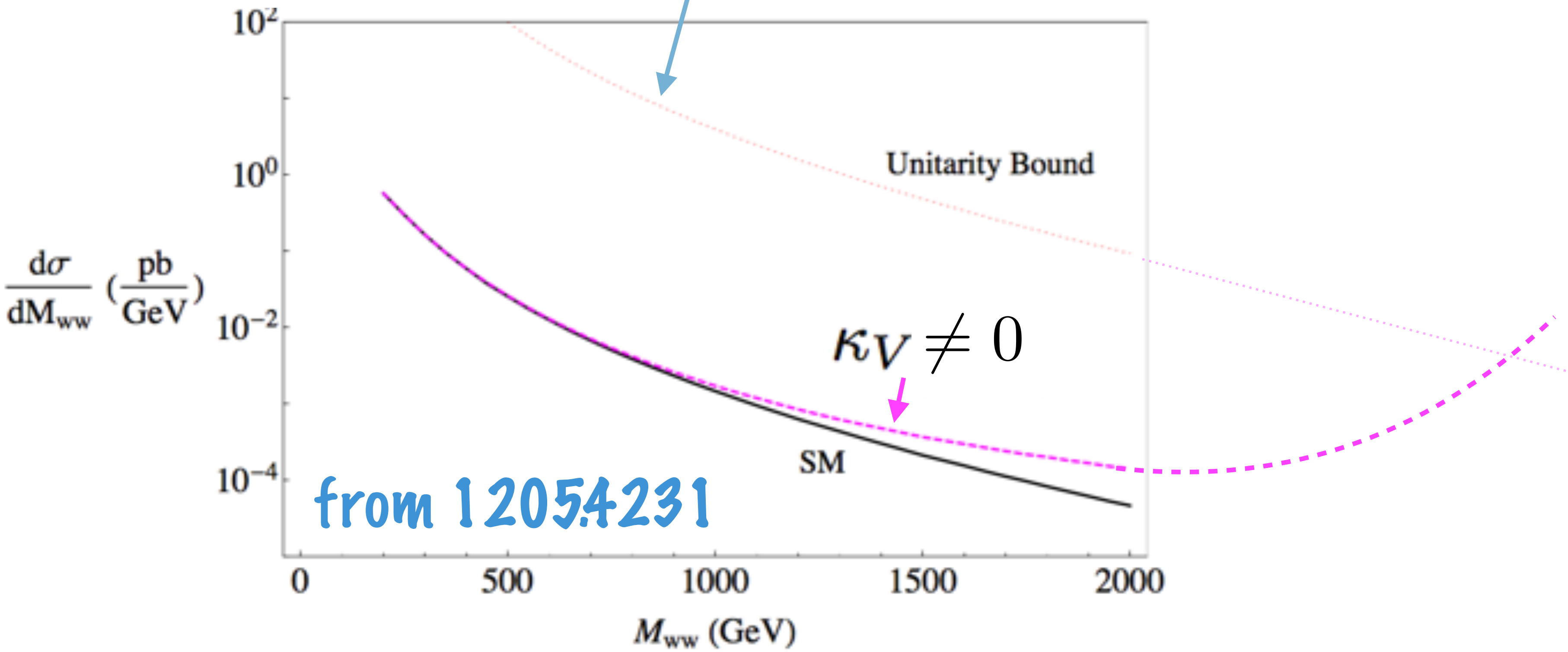
- Not renormalizable (in the broad sense: no counter terms within the k-framework to cancel all infinities)

# (k-framework=incomplete EFT)

(EFT=theory with a cutoff)

**Any departure from the SM (without new resonances) is an EFT...**
**...only sometimes it's hard to see.**

Theories with so large $\sigma$ don't exist (unitarity violation)



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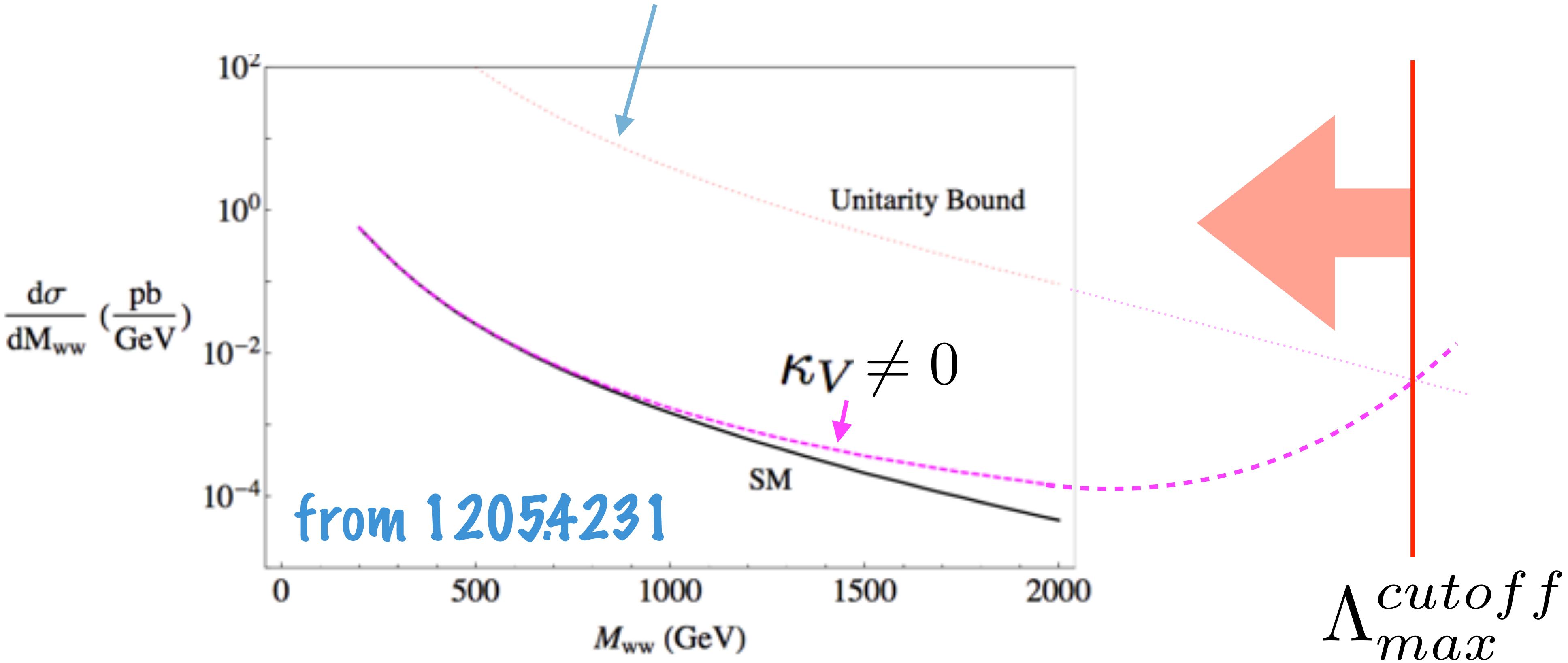



Breaking the SM relations (gauge invariance) leads to a theory with only an effective range of validity: an EFT

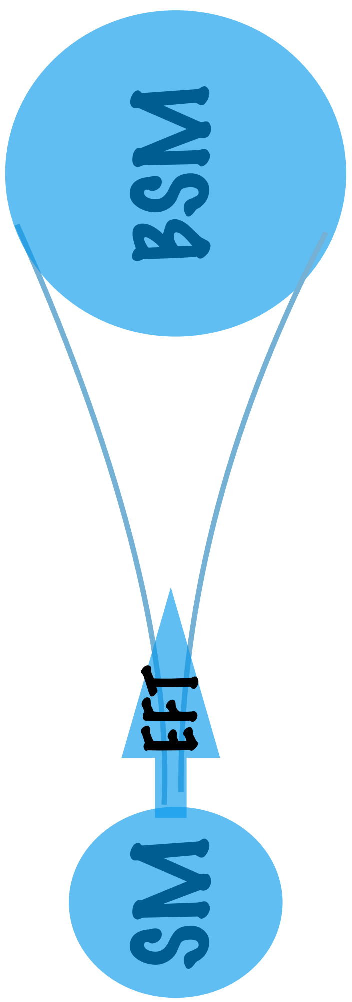
# 2) Effective Field Theories

**EFT: natural language for departures from SM, without resonances**

- **Expand all possible New Physics models in** $E/M \ll 1$ (physical mass)

$$\mathcal{L}_{\rm eff} = L\left(\frac{D_\mu}{M}, \frac{H}{M}, \frac{\Psi}{M^{3/2}}, \frac{F_{\mu\nu}}{M^2}\right) \simeq \mathcal{L}_{\rm SM} + \sum_i \frac{c_i^{(6)}}{M^2}\mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{M^4}\mathcal{O}_j^{(8)} + \cdots$$

$\mathcal{O}_i^{(D)}$ = field operators of dimension-D



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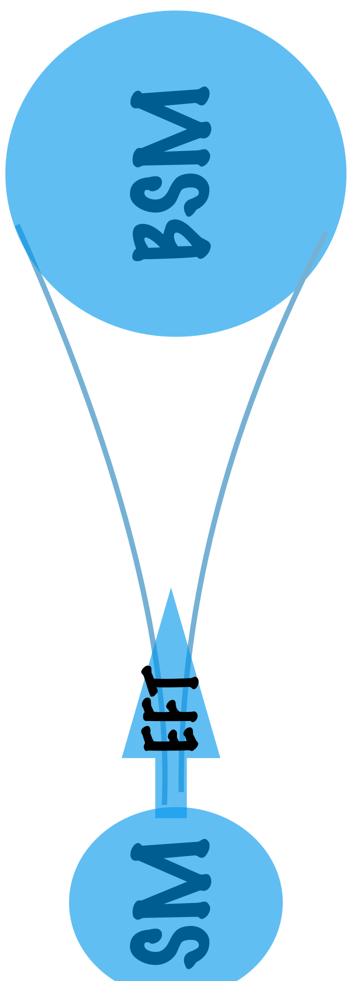
**Wilson coefficients:** $c_i^{(D)} \sim (\text{coupling})^{n_i-2}$ (coupling → $g_*$)

$n_i$: number of fields in $\mathcal{O}_i^{(D)}$ independently of D

(can be seen by counting powers of $\hbar \neq 1$)

Manohar,Georgi'84; Cohen,Kaplan,Nelson'97; Luty'97; Giudice,Grojean,Pomarol,Rattazzi,'07




**Two expansions:**

- $\dfrac{E}{M} \ll 1$

- $\dfrac{v}{f} \ll 1$ ?

$f$: $M/g_*$ can be < M

If this expansion not good (like technicolor): non-linear EFT

# 2) Effective Field Theories

PRO:

- Renormalizable (∞ absorbed by EFT counterterms)

▸ NLO extendable

- Well-defined physical hypothesis and cut-off M
- Matchable to specific UV

UV hypothesis=EFT restrictions (e.g custodial symm., Universality, scale separation)

▸ Predictive

- Tool for comparing direct/indirect searches

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PRO/CONTRA

- EFT Validity (well-defined hypotheses must be verified)
  Contino,Falkowski,Goertz,Grojean'16
- Different bases: Full basis must be specified to quote bounds
  Different choices=different properties manifest

(see "Rosetta",Falkowski,Fuks,Mawatari,Mimasu,Riva,Sanz'15)

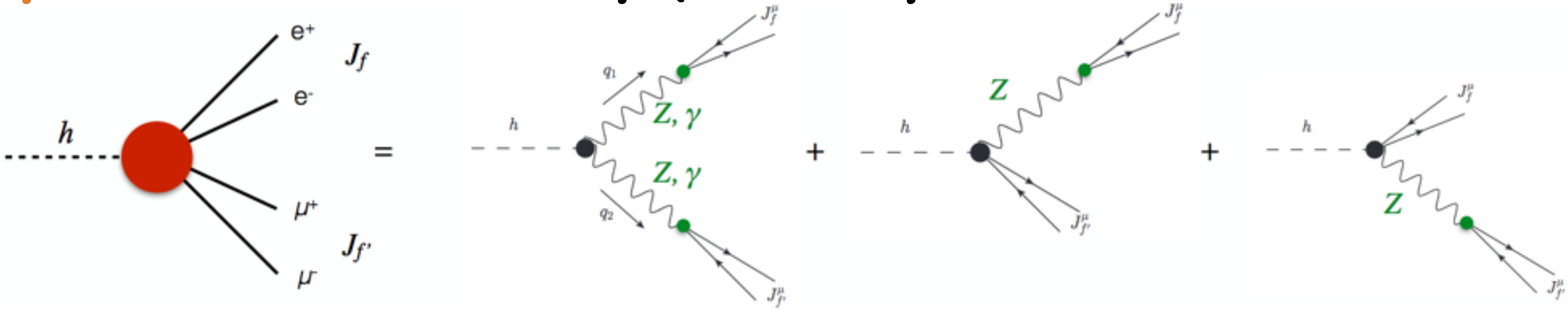
(...more later)

# 3) Pseudo Observables (POs)

(Same validity issue as EFT)

Expansion on the residues of physical SM poles

For h->Vff:
Gonzalez-Alonso,Greljo,Isidori,Marzocca'14

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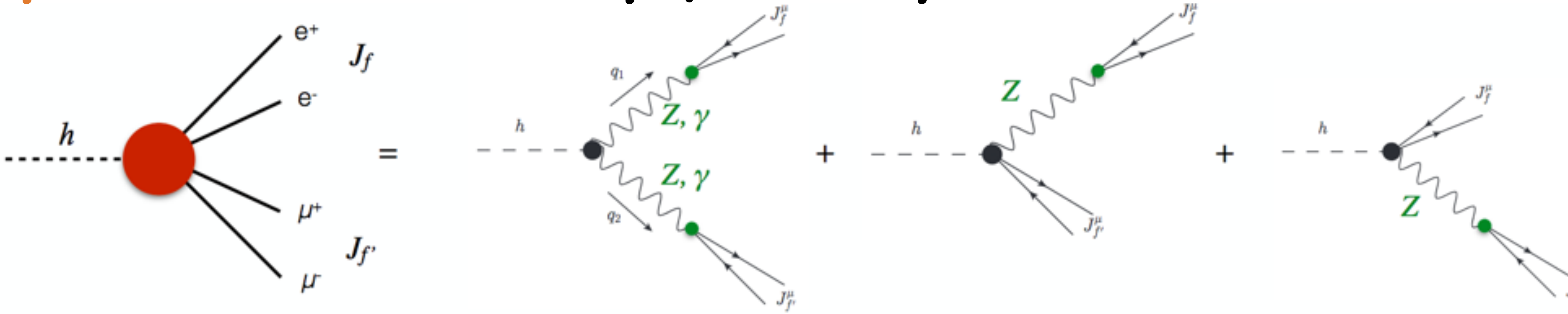


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**PRO:**
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- Minimizes theory input (both SM loops and BSM )
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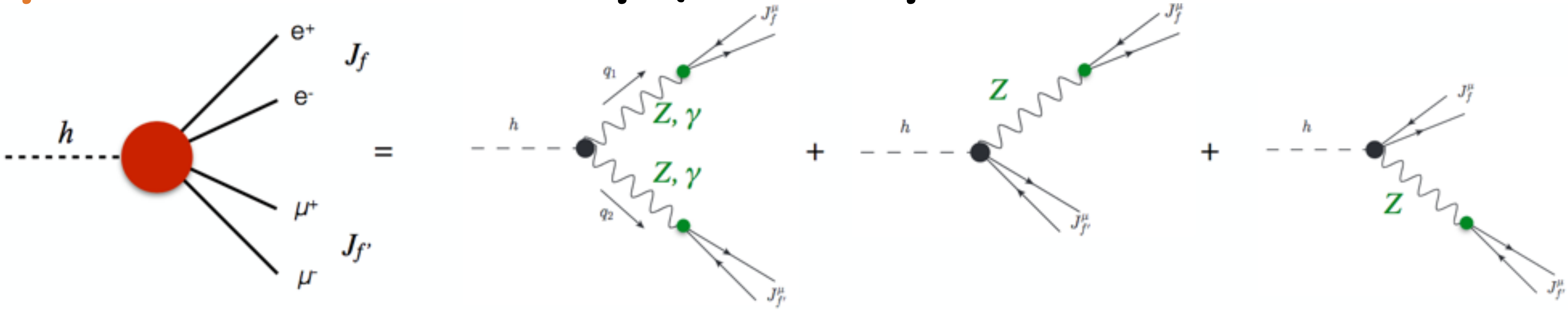


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CONTRA
- Top-down perspective important to design POs

(e.g. approximate symmetries+strong coupling=importance of higher-order operators)

Liu,Pomarol,Rattazzi,FR'16

# EFT - different bases

Field redefinitions in EFT have no physical effects, but modify EFT operators $O(1/M^2)$ up to higher order effects $O(1/M^4)$

→ redundancy analogous to gauge invariance

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A) SILH PRO: Matching to Universal BSM theories
(most well-motivated: where Higgs only is composite)

Giudice et al' 07

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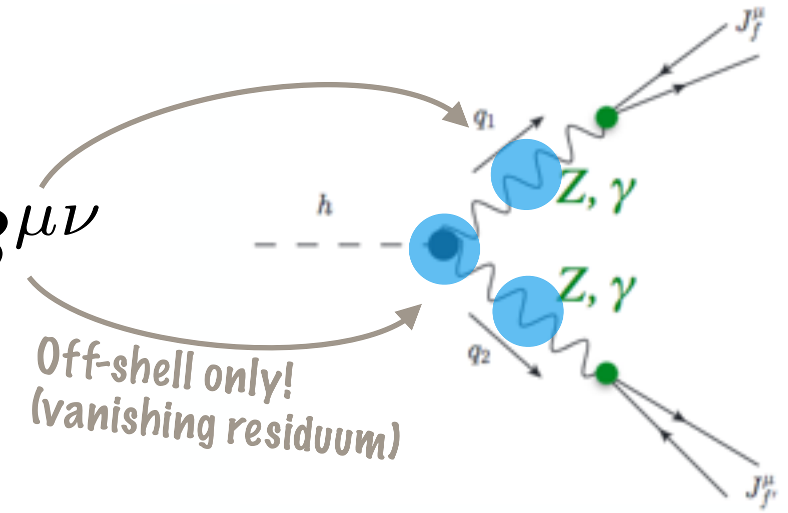
CONTRA: Off-shell contributions/propagator corrections

→ less intuitive comparison with experiment

$$\mathcal{O}_B = H^\dagger D_\mu H D_\nu B^{\mu\nu}$$



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Field redefinitions in EFT have no physical effects, but modify EFT operators O(1/M²) up to higher order effects O(1/M⁴)

→ redundancy analogous to gauge invariance

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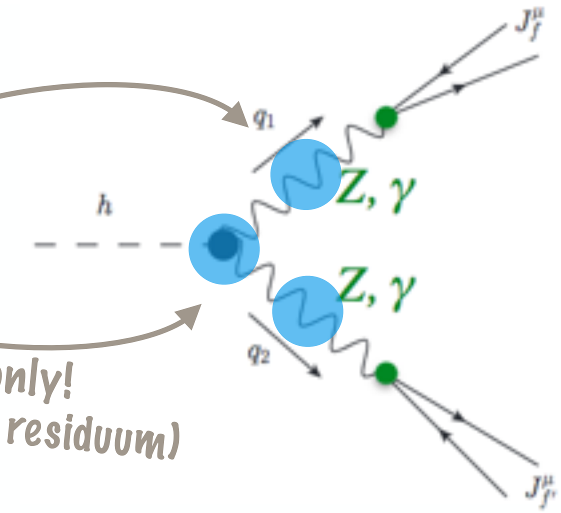


Off-shell only!
(vanishing residuum)

**B) Warsaw**

Grzadkowski et al '10

PRO: Matching to BSM with composite fermions

CONTRA: like SILH (propagator corrections)

# EFT-Equivalent Bases

**Different combinations of operators contribute to different observables → global fit entangled**

LEP1 ‰

TGC %

Higgs

Grzadkowski et al '10
Skiba,Han,'05
Jenkins,Manohar,Trott'13

## Warsaw

$$\mathcal{O}_T = (H^\dagger \overleftrightarrow{D}_\mu H)^2$$
$$\mathcal{O}_{He} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R\gamma^\mu e_R)$$
$$\mathcal{O}_{HL} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}_L\gamma^\mu L_L)$$
$$\mathcal{O}'_{HL} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{L}_L\sigma^a\gamma^\mu L_L)$$
$$\mathcal{O}_{WB} = igg'H^\dagger\sigma^a H W^a_{\mu\nu}B^{\mu\nu}$$

+quarks(4)

$$\mathcal{O}_{WW} = g^2|H|^2 W^a_{\mu\nu}W^{a\mu\nu}$$
$$\mathcal{O}_{BB} = g'^2|H|^2 B_{\mu\nu}B^{\mu\nu}$$
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$$\mathcal{O}_{y_f} = y_f|H|^2\bar{f}_L\widetilde{H}f_R \qquad f=u,d,e$$
$$\mathcal{O}_H = (\partial^\mu|H|^2)^2$$

Mixes Z-pole/TGC

Separates TGC/Higgs

Giudice et al' 07
Elias-Miro et al '13
Contino et al '13

## SILH

$$\mathcal{O}_T = (H^\dagger \overleftrightarrow{D}_\mu H)^2$$
$$\mathcal{O}_{He} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R\gamma^\mu e_R)$$
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# EFT - different bases

## C) BSM Primaries/Higgs basis

Gupta,Pomarol,FR'14    LHCHCSWG-1610.07922

Use EoM and IbP to eliminate all off-shell effects and propagator corrections -> only vertices modified

vertex correction

$$\Delta\mathcal{L}^h_{Z\gamma} = \kappa_{Z\gamma}\left(\frac{h}{v}+\frac{h^2}{2v^2}\right)\left[t_{\theta_W}A_{\mu\nu}Z^{\mu\nu} + \frac{c_{2\theta_W}}{2c^2_{\theta_W}}Z_{\mu\nu}Z^{\mu\nu} + W^+_{\mu\nu}W^{-\mu\nu}\right].$$

other corrections related by dim-6 Lagrangian

$$\Delta\mathcal{L}^V_{ee} = \delta g^Z_{eL}\frac{\hat{h}^2}{v^2}\left[Z^\mu\bar{e}_L\gamma_\mu e_L - \frac{c_{\theta_W}}{\sqrt{2}}(W^{+\mu}\bar{\nu}_L\gamma_\mu e_L + \text{h.c.})\right]$$

$$\Delta\mathcal{L}_{g_1^Z} = \delta g_1^Z\Big[igc_{\theta_W}\left(Z^\mu(W^{+\nu}W^-_{\mu\nu}-\text{h.c.})+Z^{\mu\nu}W^+_\mu W^-_\nu\right) - 2gc^2_{\theta_W}\frac{h}{v}\left(W^-_\mu J^\mu_- + \text{h.c.} + \frac{c_{2\theta_W}}{c^3_{\theta_W}}Z_\mu J^\mu_Z + \frac{2s^2_{\theta_W}}{c_{\theta_W}}Z_\mu J^\mu_{em}\right)$$

$$+\frac{e^2v}{2c^2_{\theta_W}}hZ_\mu Z^\mu + g^2c^2_{\theta_W}v\,\Delta_h - g^2c^2_{\theta_W}\left(W^+_\mu W^{-\mu} + \frac{c_{2\theta_W}}{2c^4_{\theta_W}}Z_\mu Z^\mu\right)\left(\frac{5h^2}{2}+\frac{2h^3}{v}+\frac{h^4}{2v^2}\right)\Big].$$

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PRO: Equivalent to POs at tree-level
Relations implied by dim-6 hypothesis are manifest

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other corrections related by dim-6 Lagrangian

$$\Delta\mathcal{L}^V_{ee} = \delta g^Z_{eL}\frac{\hat{h}^2}{v^2}\left[Z^\mu \bar{e}_L\gamma_\mu e_L - \frac{c_{\theta_W}}{\sqrt{2}}(W^{+\mu}\bar{\nu}_L\gamma_\mu e_L + \text{h.c.})\right]$$

$$\Delta\mathcal{L}_{g_1^Z} = \delta g_1^Z\Big[igc_{\theta_W}\left(Z^\mu(W^{+\nu}W^-_{\mu\nu} - \text{h.c.}) + Z^{\mu\nu}W^+_\mu W^-_\nu\right) - 2gc^2_{\theta_W}\frac{h}{v}\left(W^-_\mu J^\mu_- + \text{h.c.} + \frac{c_{2\theta_W}}{c^3_{\theta_W}}Z_\mu J^\mu_Z + \frac{2s^2_{\theta_W}}{c_{\theta_W}}Z_\mu J^\mu_{em}\right)$$

$$+\frac{e^2 v}{2c^2_{\theta_W}}hZ_\mu Z^\mu + g^2c^2_{\theta_W}v\,\Delta_h - g^2c^2_{\theta_W}\left(W^+_\mu W^{-\mu} + \frac{c_{2\theta_W}}{2c^4_{\theta_W}}Z_\mu Z^\mu\right)\left(\frac{5h^2}{2} + \frac{2h^3}{v} + \frac{h^4}{2v^2}\right)\Big].$$

PRO: Equivalent to POs at tree-level
Relations implied by dim-6 hypothesis are manifest

CONTRA: EW symmetry not manifest
(NLO effects must be borrowed from other bases)

# EFT-Equivalent Bases

| | Warsaw | SILH | BSM primaries |
|---|---|---|---|
| | Grzadkowski et al '10<br>Skiba,Han,'05<br>Jenkins,Manohar,Trott'13 | Giudice et al' 07<br>Elias-Miro et al '13<br>Contino et al '13 | |
| LEP1 ‰ | $\mathcal{O}_T = (H^\dagger \overleftrightarrow{D}_\mu H)^2$<br>$\mathcal{O}_{He} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R\gamma^\mu e_R)$<br>$\mathcal{O}_{HL} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}_L\gamma^\mu L_L)$<br>$\mathcal{O}'_{HL} = (iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H)(\bar{L}_L\sigma^a\gamma^\mu L_L)$<br>$\mathcal{O}_{WB} = igg' H^\dagger\sigma^a H W^a_{\mu\nu}B^{\mu\nu}$<br>+quarks(4) | $\mathcal{O}_T = (H^\dagger \overleftrightarrow{D}_\mu H)^2$<br>$\mathcal{O}_{He} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R\gamma^\mu e_R)$<br>$\mathcal{O}_W = ig(H^\dagger\sigma^a \overleftrightarrow{D^\mu} H)D^\nu W^a_{\mu\nu}$ | $\Delta\mathcal{L}^V_{ee}$ |
| TGC % | | $\mathcal{O}_B = ig'(H^\dagger \overleftrightarrow{D^\mu} H)\partial^\nu B_{\mu\nu}$<br>$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger\sigma^a(D^\nu H)W^a_{\mu\nu}$ | $\Delta\mathcal{L}_{g_1^Z}$<br>$\Delta\mathcal{L}_{\kappa_\gamma}$ |
| Higgs | $\mathcal{O}_{WW} = g^2\|H\|^2 W^a_{\mu\nu}W^{a\mu\nu}$<br>$\mathcal{O}_{BB} = g'^2\|H\|^2 B_{\mu\nu}B^{\mu\nu}$<br>$\mathcal{O}_{GG} = g_s^2\|H\|^2 G^A_{\mu\nu}G^{A\mu\nu}$<br>$\mathcal{O}_{y_f} = y_f\|H\|^2\bar{f}_L\tilde{H}f_R \quad f=u,d,e$<br>$\mathcal{O}_H = (\partial^\mu\|H\|^2)^2$ | $\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$<br>$\mathcal{O}_{BB} = g'^2\|H\|^2 B_{\mu\nu}B^{\mu\nu}$<br>$\mathcal{O}_{GG} = g_s^2\|H\|^2 G^A_{\mu\nu}G^{A\mu\nu}$<br>$\mathcal{O}_{y_f} = y_f\|H\|^2\bar{f}_L\tilde{H}f_R \quad f=u,d,e$<br>$\mathcal{O}_H = (\partial^\mu\|H\|^2)^2$ | $\Delta\mathcal{L}^h_{\gamma\gamma}$<br>$\Delta\mathcal{L}^h_{Z\gamma}$<br>$\Delta\mathcal{L}^h_{GG}$<br>$\Delta\mathcal{L}^h_{ff}$<br>$\Delta\mathcal{L}^h_{V_\mu V^\mu}$ |

**Warsaw:**

Mixes Z-pole/TGC

Separates TGC/Higgs

Matches to UV with, e.g. composite fermions

**SILH:**

Separates Z-pole/TGC

Mixes TGC/Higgs

Matches to universal UV (CH/SUSY)

**BSM primaries:**

Minimizes correlations

# Conclusions

In Higgs physics no conclusion...

- k-framework: not well-defined
- EFT: well-defined hypotheses
- PO: intuitively closer to exp

Must be brought forward as single entity
to get the most out of experiments and at the
same time test well-defined hypotheses

# Conclusions