SMEFT, SM Effective Field Theory

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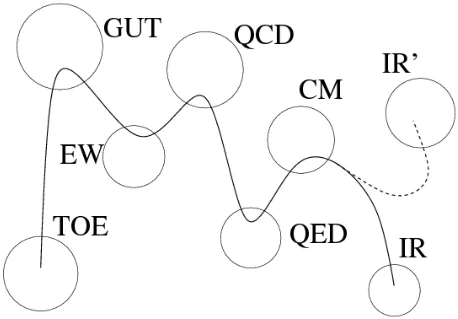
Outline

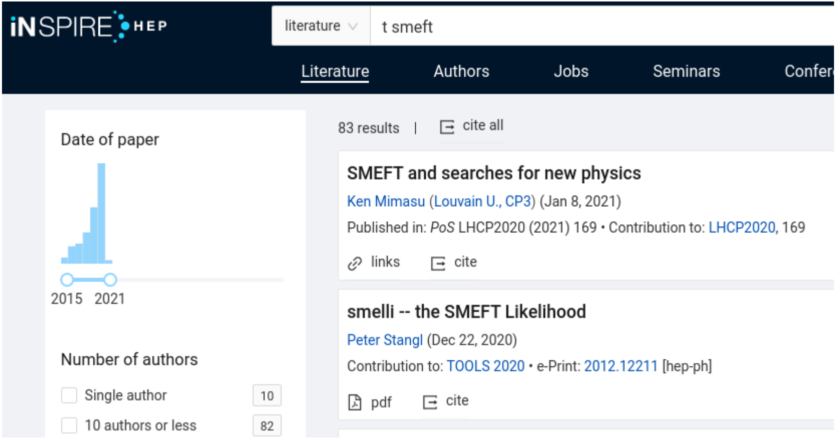
(Functional) RG flow of the Theory Of Everything (TOE)



Polónyi János, Central Eur.J.Phys. 1 (2003)

Dream: TOE -> Gravity + SM as an emergent effective theory,
Predicting everything (spectrum,$g_i, m_i, \ldots$) - Top-down appr.
Interesting physics everywhere - Theories of something, EFT

SMEFT



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SMEFT and searches for new physics
Ken Mimasu (Louvain U., CP3) (Jan 8, 2021)
Published in: PoS LHCP2020 (2021) 169 • Contribution to: LHCP2020, 169
links
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smelli -- the SMEFT Likelihood
Peter Stangl (Dec 22, 2020)
Contribution to: TOOLS 2020 • e-Print: 2012.12211 [hep-ph]
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Literature

- Adam Falkowski: Saclay Lectures on Effective Field Theories (2017)
- Ilaria Brivio, Michael Trott, The Standard Model as an Effective Field Theory, Phys.Rept. 793 (2019) 1-98 • e-Print: 1706.08945 [hep-ph]

EFT reviews

- I.Z. Rothstein, TASI Lectures on Effective Field Theories (2003), hep-ph/0308266
- A.V. Manohar, Lect.Notes Phys. 479 (1997) 311-362.

Effective Theories (Philosophy)

Everything depends in everything - lose predictivity

- Theory: describes phenomena in a given regime
- Effective: simple, calculable predictions
- inevitably not complete, not fundamental d.o.f. may be emergent

$\Longrightarrow$ Useful predictions, finite # of parameters

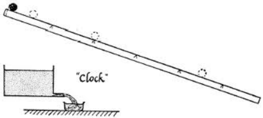
- good EFT (Effective Theory) can be improved systematically
  e.g. small parameter $\pi\pi$, graviton scattering
- Helps: Separation of scales
  relevant + irrelevant operators (see later)
  (Observation: dynamics at other Energies does not matter)

Outline

Galilei-féle Esési Törvény / GET*

Kísérletek útján (1638)

$$\Delta v = g \Delta t$$



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Természettörvény:

$$\text{GET} \qquad \ddot{z} = -g \implies T = \sqrt{2h/g} \qquad \text{pre} - \text{Newton}$$

Galilei: közegellenállás csak komplikáció, $\rho \gg \rho_{lev.}$ egyformán esnek
kísérleti ellenőrzés, GET - "nem tévedünk nagyot"
$\rightarrow$korrekciók, őrzik a tér-idő szimmetriáit, eltolás, forgatás, idő-eltolás

$$\ddot{z} = -g + c \cdot z, \qquad c \rightarrow \frac{a}{R} = \frac{g}{R_F} \sim \text{targy meretetol nem fugg}$$

EFT extra tagok természetesek, őrzik a szimmetriákat.

Galilei-féle Esési Törvény / MGET*

Óvatosan, η

$$\text{MGET} \qquad \ddot{z} = -g\left(1 - \eta\frac{z}{R} + ..\right) \rightarrow z(t) = \ldots$$

$$T = \sqrt{\frac{2h}{g}}\left(1 + \frac{\eta}{2}\frac{h}{R_F} + \mathcal{O}(\frac{h^2}{R_F^2})\right)$$

$h = 200\text{m} \;\; T = 6.5 + \eta \cdot 0,1s$
Közelítő törvény, Mérések $\rightarrow$ $\eta = 2 \pm m.h.$ korrekciók
Newton elmélet felváltja MGET-t, $\eta = 2$ számolható!

Korrekciókat tekinthetünk a fundamentális Newton elmélet nélkül is MGET pontosabb, ugyan több paraméter - Newton irányába

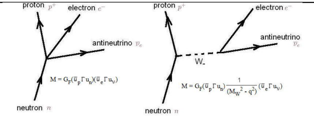
$1/r^2$ tv módosítása Merkúr perihélium elfordulása Einstein előtt/ James D. Wells, 2013

Effective Theories (EFT), Top-down

Dynamical phenomena, scales are separated
Full theory: Integrating out Heavy d.o.f.
"coarse graining"

$$\mathscr{L}(H,L) \to \mathscr{L}(L)$$

$g^i_L(H)$ and new couplings, local in filed theory (FT)
H,L $\sim$mass, momenta, velocity,...
Fermi 4-fermion int'n, Landau-Ginzburg SC, (L^{QCD}_{chiral})



a. Fermi's 4-point Interaction, 1934   b. Weak Interaction mediated by boson, 1938

$$G_F = \frac{g^2}{4\sqrt{2}}\frac{1}{M_W^2}$$

Effective description of the fundamental theory, given accuracy

EFT, Bottom-up

Unknown fundamental theory,
Guides the improvement, modification of existing theory
- experimentally testable $\to$ (may) point to fundamental theory

Principles

- Symmetries
- Naturalness (observed/existing scales, $\mathcal{O}(1)$ parameters)

Weinberg(1979)
selfconsistent theories with all the terms allowed by symmetries,
Symmetry breaking terms allowed.
Enough measurement -> predictive

- Laws $\to$ symmetries are more important!

EFT, Bottom-up, General

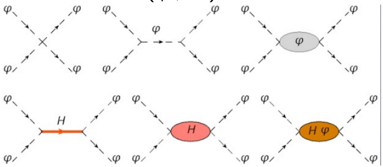
- Lagrangian
  - Most general allowed by symmetries
  - Expansion (generally)by energy
- Calculate and renormalize
  - start with the smallest order
  - renormalize the parameters
- Phenomenology, processes
  - measure the (finite #) param's
  - correlations, new processess are already predictions

Differences:

- Not only R(enormalizable) terms
- Expansion in energy (p,m)

Effective Lagrangian, light-Heavy

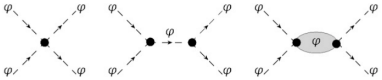
QFT with light ϕ and "heavy" fields H $\mathscr{L}_{UV}(\phi, H)$,



Scattering 2→2 of light fields ϕ

At low energies H's not excited, too heavy

Effective theory of ϕ reproduces the full ampl. with H, ϕ $\mathscr{L}_{eff}(\phi)$



Effective 2→2 scattering ϕ

Effects of "inner" H, $\mathscr{L}_{eff}(\phi) \neq \mathscr{L}_{UV}(\phi, 0)$

Examples:

- light by light scattering below m_e, no contact terms (E-H)
- muon decay, $m_\mu \ll M_W$

Integrating out in Path Integral

Simpler description without heavy H, eliminate
Amplitudes of light, heavy fields from generating functional, diff, w.r.t J_i

$$Z_{UV}[J_\phi, J_H] = \int [D\phi][DH] \exp[i \int d^4x \left(\mathscr{L}_{UV}(\phi, H) + J_\phi \phi + J_H H\right)].$$

Only light scat's, no source for heavy, encode the dynamics in $\mathscr{L}_{eff}(\phi)$

$$Z_{EFT}[J_\phi] = \int [D\phi] \exp[i \int d^4x \left(\mathscr{L}_{eff}(\phi) + J_\phi \phi\right)].$$

Give the same correlation functions , $\Gamma[\Phi, H]$ to generate 1PI amp˜s
Generally

$$\mathscr{L}_{eff}(\phi) \supset \phi^2 \left(\Box + M^2\right)^{-1} \phi^2 \mathrm{non-local},$$

$\sim$propagation of heavy H, If $M \gg E, m_\phi$ - can make it local,

$$\left(\Box + M^2\right)^{-1} \simeq \frac{1}{M^2} - \frac{1}{M^4} \Box + \ldots$$

Only deal with local˜ in what follows.

Motivations to prefer $\mathscr{L}_{eff}(\phi)$ vs.$\mathscr{L}_{UV}(\phi, H)$

- Simplicity
  Calculations within EFT may be more effcicient, multi-loops
  Cancellation in UV th understood by power counting in EFT
- Calculability
  In UV disparate scales $\rightarrow$large log's, problem
  EFT techniques - resum large logs in RG flow of EFT param's
- Agnosticity,Ignorance
  Unknown UV theory, as in case of the SM
  Difficult to calculate, e.g. low-E QCD
  EFT ignorance in free parameters (Wilson coeff)

$$\mathscr{L}_{EFT} \simeq \sum_i c_i^{UV}(\mu) O_i^{IR}(\mu)$$

Scaling and Power Counting

$\mathscr{L}_{eff}(\phi)$ local, but generally infinite number of int'n terms
Needs to organize calculations, relevance- power counting
Relativistic theories M_H, heavy ptcle, $1/M_H$ natural expansion par.
Observables expanded in E/M_H

$$S_{\rm EFT}(\phi) = \int d^4x \left[(\partial_\mu \phi)^2 - m^2\phi^2 - \kappa\mu\phi^3 - \lambda\phi^4 - \sum_{n+d>4} \frac{c_{n,d}}{\Lambda^{n+d-4}} \phi^{n-1}\partial^d \phi \right],$$

n,d,$>(\geq)0$ and$[\phi] = mass^1$, Λ, μ to have dimensionless action, $\Lambda \sim M_H$
Rescale to see relative importance

$$x_\mu \to \xi x'_\mu, \quad \begin{array}{ll} \xi \to 0 & \text{small distance} \\ \xi \to \infty & \text{large distance} \end{array}$$

$$S_{\rm EFT}(\phi) = \int d^4x' \left[\xi^2(\partial_\mu \phi)^2 - m^2\xi^4\phi^2 - \kappa\mu\xi^4\phi^3 - \lambda\xi^4\phi^4 - \sum_{n+d>4} \frac{c_{n,d}\xi^{4-d}}{\Lambda^{n+d-4}} \phi^{n-1}\partial^d \phi \right]$$

Rescale $\phi \to \xi\phi'$ kanonical kinetic terms dominant in the PI/path

$$S_{\mathrm{EFT}}(\phi) = \int d^4x' \left[(\partial_\mu \phi')^2 - m^2\xi^2(\phi')^2 - \kappa(\xi\mu)(\phi')^3 - \lambda(\phi')^4 - \sum_{n+d>4} \frac{c_{n,d}}{(\xi\Lambda)^{n+d-4}} (\phi')^{n-1}\partial^d \phi' \right].$$

$\xi \to \infty$ all terms suppressed in the sum **IRRELEVANT**

$$D = n + d - 4, \text{canonical} \quad \textit{dimension}$$

Keep terms up to D_{max}, observables in $1/\Lambda$ orders
RELEVANT TERMS, $\xi^2\phi^2$-mass and cubic $(\xi\mu)\phi^3$(expansion depends on $\mu \sim \Lambda, or \ll \Lambda$)
MARGINAL interaction $\lambda\phi^4$,
loop corrections modify to REL-IRREL (not in CFT's)
No large scale -> number of derivatives

$\hbar$ counting

General selection rule, keep $\hbar$
Action $[S] = \hbar$ in the Path Integral $exp(iS/\hbar)$
kinetic term, fields $\hbar^{1/2}$
Coeff. off interaction term n fields $\hbar^{1-n/2}$ (any # derivatives)

$$S_{\mathrm{EFT}}(\phi) = \int d^4x \left[(\partial_\mu \phi)^2 - m^2\phi^2 - \kappa\mu\phi^3 - \lambda\phi^4 - \sum_{n+d>4} \frac{c_{n,d}}{\Lambda^{n+d-4}} \phi^{n-1} \partial^d \phi \right],$$

$\hbar$ dimensions

$$[m^2] = \hbar^0 \; [\kappa] = \hbar^{-1/2} \; [\lambda] = \hbar^{-1} \; [c_{n,d}] = \hbar^{1-n/2}$$

Additional estimate of importance/magnitude for $\Lambda \sim M_H$
Consider 1 gauge coupling g_*, similarly $[g_*] = \hbar^{-1/2}$
Estimates, 1 parameter case, tree : $c_{n,d} \sim g_*^{n-2} \quad g_*^4|_{n=6}$
Loops, extra $\hbar(\sim g_*^2)$, generated by 1-loop $c_{n,d} \sim \frac{g_*^n}{(4\pi)^2}$
Symmetries give additional selection rules, e.g. for hierarchical masses

Outline

Toy model of light (ϕ) and H real scalars

Tree-, loop level matching, on-shell- off-shell matching
get rid off redundant operators
UV theory, Z_2 symmetry $\phi \to -\phi$, no odd powers

$$\begin{aligned} \mathcal{L}_{\rm UV} &= \frac{1}{2}\left[(\partial_\mu \phi)^2 - m_L^2\phi^2 + (\partial_\mu H)^2 - M^2 H^2\right] \\ &- \frac{\lambda_0}{4!}\phi^4 - \frac{\lambda_1}{2}M\phi^2 H - \frac{\lambda_2}{4}\phi^2 H^2. \end{aligned}$$

H^3, H^4 left out, no change, in $\phi^2 H$, M factored out, diff. scaling

$$\mathcal{L}_{\rm EFT} = \frac{1}{2}\left[(\partial_\mu \phi)^2 - m^2\phi^2\right] - C_4\frac{\phi^4}{4!} - \frac{C_6}{M^2}\frac{\phi^6}{6!} + \mathcal{O}(M^{-4}).$$

$1/M$ powers $\sum_d \frac{C_d}{M^{d-4}} O_d$, O_d canonical dim. d, truncate at 6
Non-redundant operators O_4 and O_6, no odd O's Z_2, call it *unbox basis*

Redundant operators $\mathscr{O}(M^{-2})$

Possible dim-6 operators are redundant - no change in physics

$$\hat{O}_6 \equiv (\Box\phi)^2, \quad \tilde{O}_6 \equiv \phi\Box\phi^3, \quad \tilde{O}'_6 \equiv \phi^2\Box\phi^2, \quad \tilde{O}''_6 \equiv \phi^2\partial_\mu\phi\partial_\mu\phi, \quad \dots$$

Integration by parts $\tilde{O}''_6$ and $\tilde{O}'_6$ traded to $\tilde{O}_6$ $\phi^2 \Box \phi^2 = \frac{4}{3}\phi^3 \Box \phi$, ...
Using class. equation of motion (EOM), $\tilde{O}_6, \hat{O}_6 \to O_4, O_6$ of $\mathscr{L}_{EFT}$
THEOREM: Shifting higher dim operators by terms ~EOM does not change the S matrix elements [13]
Field redefinition does not change the physical content, consequence of the equivalence theorem see

[13] C. Arzt, *Reduced effective Lagrangians*, *Phys. Lett.* **B342** (1995) 189–195, [hep-ph/9304230].

[14] J. S. R. Chisholm, *Change of variables in quantum field theories*, *Nucl. Phys.* **26** (1961), no. 3 469–479.

[15] S. R. Coleman, J. Wess, and B. Zumino, *Structure of phenomenological Lagrangians. 1.*, *Phys. Rev.* **177** (1969) 2239–2247.

Highly non-trivial

Using classical EOM

Equation of motion

$$\Box\phi + m^2\phi + \frac{C_4}{6}\phi^3 = \mathscr{O}(M^{-2})$$

Replace by 'old' terms in $\mathscr{L}_{EFT}$ for on-shell amplitudes

$$\frac{1}{M^2}\phi^3\Box\phi = -\frac{m^2}{M^2}\phi^4 - \frac{C_4}{6M^2}\phi^6 + \mathcal{O}(M^{-4}).$$

Param's in $\mathscr{L}_{EFT}$ are still free, $\tilde{O}_6$ can be left out w/o lost
Using the inverse replace $O_6 \to \tilde{O}_6$ get in jargon *box basis* from unboxed

$$\mathcal{L}_{\rm EFT} \;=\; \frac{1}{2}\left[(\partial_\mu\phi)^2 - m^2\phi^2\right] - \tilde{C}_4\frac{\phi^4}{4!} - \frac{\tilde{C}_6}{4!M^2}\phi^3\Box\phi + \mathcal{O}(M^{-4}).$$

Same prediction at any order of Perturbation Theory
up to $\mathscr{O}(M^{-4})$ for on-shell scattering amplitudes

Mapping the 2 basis

Same predictions with the map

$$\tilde{C}_4 = C_4 - \frac{m^2}{5M^2}\frac{C_6}{C_4},$$
$$\tilde{C}_6 = -\frac{C_6}{5C_4}.$$

Equivalent with a non-linear $\phi \to \phi\left(1 - \frac{C_6}{120 C_4 M^2}\phi^2\right)$

Exercise1: Express the op $\hat{O}_6$ by op's in original $\mathscr{L}_{EFT}$! Give the map between double-box and unbox basis!

$\hbar$ dimensions, action $\hbar^1$, fields $\hbar^{1/2}$, coeff of int'n term $\hbar^{1-n/2}$
UV theory dimensions

$$[\lambda_0] = \hbar^{-1}\ [\lambda_1] = \hbar^{-1/2}\ [\lambda_2] = \hbar^{-1}$$

EFT theory

$$[\hat{C}_6] = \hbar^0\ [C_4] = \hbar^{-1}\ [\tilde{C}_6] = \hbar^{-1}\ [C_6] = \hbar^{-2}$$

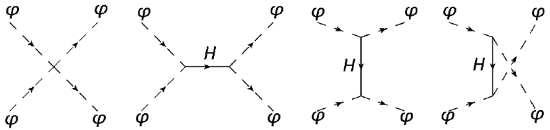
Matching, Tree-level

Matching the UV theory and EFT: fix the EFT Wilson coeff's such that on-shell scattering ampl's are the same in the two framework.

Up to fixed order in $1/M$ and loop expansions

Tree-level matching ϕ propagator is trivial $\qquad m^2 = m_L^2$.

2-to-2 on-shell scattering. In the UV theory



$$\begin{aligned}\mathcal{M}_4^{\rm UV} &= -\lambda_0 - \lambda_1^2 M^2 \left[\frac{1}{s-M^2} + \frac{1}{t-M^2} + \frac{1}{u-M^2}\right] \\ &\approx -\lambda_0 + 3\lambda_1^2 + \frac{\lambda_1^2}{M^2}(s+t+u) + \mathcal{O}(M^{-4}) \\ &\approx -\lambda_0 + 3\lambda_1^2 + \frac{4m_L^2\lambda_1^2}{M^2} + \mathcal{O}(M^{-4})\end{aligned}$$

where s,t,u are the usual Mandelstam variables, & $s+t+u = 4m_L^2$.

2-to-2 in EFT, only the first contact term

$$M_4^{EFT} = -C_4$$

Matching $\mathrm{M}_4^{\mathrm{EFT}} = \mathrm{M}_4^{\mathrm{UV}} + \mathscr{O}(\mathrm{M}^{-2})$

$$C_4 = \lambda_0 - 3\lambda_1^2 - 4\lambda_1^2 \frac{m_L^2}{M^2} \qquad \text{unbox}$$

Matching in the box basis, !derivative 4-vertex!

$$M_4^{EFT} = -\tilde{C}_4 + \frac{m^2}{M^2}\tilde{C}_6$$

$$\tilde{C}_4 - \frac{m^2}{M^2}\tilde{C}_6 = \lambda_0 - 3\lambda_1^2 - 4\lambda_1^2 \frac{m_L^2}{M^2} \qquad \text{box}$$

consistent with unbox using the map!

Matching C_6, Tree-level, 6 point*

To match C_6, calculate the 6-point function, complicated.
Result gives the mapping, up to $\mathcal{O}(M^{-2})$, unbox basis C_4!

$$
\begin{aligned}
m^2 &= m_L^2, \\
C_4 &= \lambda_0 - 3\lambda_1^2 - 4\lambda_1^2 \frac{m_L^2}{M^2}, \\
C_6 &= 45\lambda_1^2\lambda_2 - 20\lambda_0\lambda_1^2 + 60\lambda_1^4.
\end{aligned}
$$

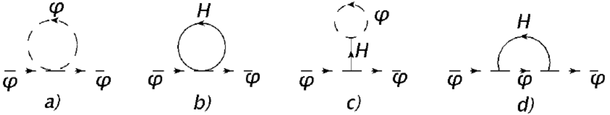
Box basis matching condition

$$
\begin{aligned}
m^2 &= m_L^2, \\
\tilde{C}_4 &= \lambda_0 - 3\lambda_1^2 - \frac{9m_L^2}{M^2}\frac{\lambda_1^2\lambda_2}{\lambda_0 - 3\lambda_1^2}, \\
\tilde{C}_6 &= 4\lambda_1^2 - 9\frac{\lambda_1^2\lambda_2}{\lambda_0 - 3\lambda_1^2}.
\end{aligned}
$$

So far tree level. (in Path integral simpler)

One-loop Matching, 2-point function

With 1PI 2-point function, Tree level
$\Pi_0^{EFT} = p^2 - m^2$ and $\Pi_0^{UV} = p^2 - m_L^2$, add 1-loop corrections



EFT, only a), unbox basis, in dimensional regularization (dimreg)

$$\begin{aligned}\delta\Pi^{\mathrm{EFT}} &= (-i)\frac{-iC_4}{2}\int\frac{d^dk}{(2\pi)^d}\frac{i}{k^2-m^2}\\ &= C_4\frac{m^2}{32\pi^2}\left[\frac{1}{\bar{\epsilon}}+\log\left(\frac{\mu^2}{m^2}\right)+1\right].\end{aligned}$$

where $1/\bar{\varepsilon} = 1/\varepsilon + \gamma_E + \log(4\pi)$, μ dim. par. in dimreg
Physical mass, pole of $\Pi(p^2)$, $\overline{\mathrm{MS}}$ scheme, dropping $1/\bar{\varepsilon}$ terms

$$m_{\mathrm{phys}}^2 = m^2 - C_4\frac{m^2}{32\pi^2}\left[\log\left(\frac{\mu^2}{m^2}\right)+1\right].$$

LHS physical observable, independent of the arbitrary scale μ

1-loop, 2-point function

Running parameter m^2 in the $\mathscr{L}_{EFT}$ at 1-loop, μ indep. RHS

$$\frac{dm^2}{d\log\mu} = C_4 \frac{m^2}{32\pi^2}\left[\log\left(\frac{\mu^2}{m^2}\right)+1\right]$$

Box basis

$$\begin{aligned}\delta\tilde{\Pi}^{\mathrm{EFT}} &= -\frac{i\tilde{C}_4}{2!}\int\frac{d^dk}{(2\pi)^d}\frac{1}{k^2-m^2}+(-i)\frac{i\tilde{C}_6}{2!4M^2}\int\frac{d^dk}{(2\pi)^d}\frac{2i(k^2+m^2)}{k^2-m^2}\\ &= \tilde{C}_4\frac{m^2}{32\pi^2}\left[\frac{1}{\bar{\epsilon}}+\log\left(\frac{\mu^2}{m^2}\right)+1\right]-\tilde{C}_6\frac{p^2+m^2}{64\pi^2}\frac{m^2}{M^2}\left[\frac{1}{\bar{\epsilon}}+\log\left(\frac{\mu^2}{m^2}\right)+1\right].\end{aligned}$$

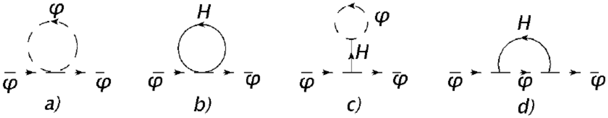
Only on-shell coincide, differ off-shell, different p^2 dependence, different wave-function renormalization $\delta_\phi = 0$

$$\tilde{\delta}_\phi \equiv \frac{d\delta\tilde{\Pi}^{\mathrm{EFT}}}{dp^2}\Big|_{p^2=m^2_{\mathrm{phys}}} = -\frac{\tilde{C}_6}{64\pi^2}\frac{m^2}{M^2}\left[\frac{1}{\bar{\epsilon}}+\log\left(\frac{\mu^2}{m^2}\right)+1\right],$$

physical mass (sol'n $p^2-m^2+\delta\tilde{\Pi}^{EFT}=0$) same after mapping $C_{4,6}$

$$m^2_{\mathrm{phys}} = m^2 - \frac{m^2}{32\pi^2}\left(\tilde{C}_4-\frac{m^2}{M^2}\tilde{C}_6\right)\left[\log\left(\frac{\mu^2}{m^2}\right)+1\right],$$

1-loop Matching, UV side



a) same diagram different parameters, b) H in loop

$$\mathcal{M}_2^{\rm UV,a)} = \lambda_0 \frac{m_L^2}{32\pi^2}\left[\frac{1}{\bar{\epsilon}} + \log\left(\frac{\mu^2}{m_L^2}\right) + 1\right] . \quad \mathcal{M}_2^{\rm UV,b)} = \lambda_2 \frac{M^2}{32\pi^2}\left[\frac{1}{\bar{\epsilon}} + \log\left(\frac{\mu^2}{M^2}\right) + 1\right] .$$

Tad-pole c)

$$\mathcal{M}_2^{\rm UV,c)} = (-i)(-i\lambda_1 M)^2 \frac{1}{0^2 - M^2}\int \frac{d^dk}{(2\pi)^d}\frac{i}{k^2 - m^2} = -\lambda_1^2 \frac{m_L^2}{32\pi^2}\left[\frac{1}{\bar{\epsilon}} + \log\left(\frac{\mu^2}{m_L^2}\right) + 1\right]$$

Mixed loop, evaluated at $p^2 = m_L^2$

$$\begin{aligned}\mathcal{M}_2^{\rm UV,d)} &= (-i)(-i\lambda_1 M)^2 \int \frac{d^dk}{(2\pi)^d}\frac{i^2}{(k^2 - M^2)((k+p)^2 - m_L^2)} \\ &\to \lambda_1^2 \frac{M^2}{16\pi^2}\left[\frac{1}{\bar{\epsilon}} + \log\left(\frac{\mu^2}{M^2}\right) + 1\right] + \lambda_1^2 \frac{m_L^2}{32\pi^2}\left[-2\log\left(\frac{M^2}{m_L^2}\right) + 1\right] \\ &+ \lambda_1^2 \frac{m_L^4}{48\pi^2 M^2}\left[-6\log\left(\frac{M^2}{m_L^2}\right) + 5\right] .\end{aligned}$$

Matching the masses

EFT, $\overline{\text{MS}}$ $\quad m^2_{\text{phys}} = m^2 - C_4 \frac{m^2}{32\pi^2}\left[\log\left(\frac{\mu^2}{m^2}\right)+1\right].$ Compare with

UV,$\overline{\text{MS}}$ $\quad m^2_{\text{phys}} \;=\; m_L^2 - \left(\lambda_0 - 3\lambda_1^2 - 4\lambda_1^2\frac{m_L^2}{M^2}\right)\frac{m_L^2}{32\pi^2}\left[\log\left(\frac{\mu^2}{m_L^2}\right)+1\right]$ $+\ldots$

Physical mass is the same in UV & EFT→matching equation

$$
\begin{aligned}
m^2(\mu) \;&=\; m_L^2(\mu) - \frac{1}{32\pi^2}\log\left(\frac{\mu^2}{M^2}\right)\left[M^2\left(\lambda_2+2\lambda_1^2\right)+2\lambda_1^2 m_L^2 + 4\lambda_1^2\frac{m_L^4}{M^2}\right] \\
&- \;\frac{1}{32\pi^2}\left[M^2\left(\lambda_2+2\lambda_1^2\right)+3\lambda_1^2 m_L^2+\frac{22}{3}\lambda_1^2\frac{m_L^4}{M^2}\right].
\end{aligned}
$$

$\log(\mu^2/m_L^2)$ cancels out. Simpler choosing the single scale $\mu = M$

$$
m^2(M) = m_L^2(M) - \frac{1}{32\pi^2}\left[M^2\left(\lambda_2+2\lambda_1^2\right)+3\lambda_1^2 m_L^2+\frac{22}{3}\lambda_1^2\frac{m_L^4}{M^2}\right].
$$

Choosing $\mu \sim M$, high matching scale no large log's
Pertubation theory works $\lambda_1^2\,[\lambda_2]\log(\mu^2/M^2)$ not large

UV senitivity of scalar masses (hidden H.P.)

Modern way of UV sensitivity

$$m^2(M) = m_L^2(M) - \frac{1}{32\pi^2}\left[M^2\left(\lambda_2 + 2\lambda_1^2\right) + 3\lambda_1^2 m_L^2 + \frac{22}{3}\lambda_1^2 \frac{m_L^4}{M^2}\right].$$

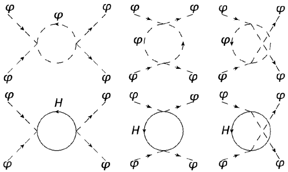
Are δm^2 regularization dependent in low-E theory?

$$\delta m^2 \sim m^2 \text{dimreg} \quad ? \quad \delta m^2 \sim \Lambda^2/16\pi^2 \text{cutoff}$$

Fine tuning depends on regularization?
Natural $m^2 \sim M^2/(16\pi^2)$, simple scaling
To arrive at $m \ll M/4\pi$, m_L has to be tuned to $M/4\pi$ for cancellation.
UV sensitivity (of scalars) is independent of the regularization.

1-loop matching, 4-point functions

$\lambda_1 = 0$, simplify, many diagrams in the UV model, EFT first row



TREE-level $C_4 = \lambda_0$, $C_6 = 0$.

$$\mathcal{M}_4^{\rm EFT} = -C_4 + \frac{C_4^2}{32\pi^2}\left[f(s,m)+f(t,m)+f(u,m)\right] + \frac{3C_4^2}{32\pi^2}\left(\frac{1}{\bar\epsilon}+\log\left(\frac{\mu^2}{m^2}\right)+2\right)+\frac{C_6 m^2}{32\pi^2 M^2}\left(\frac{1}{\bar\epsilon}+\log\left(\frac{\mu^2}{m^2}\right)+1\right)$$

unbox basis

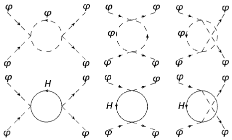
here $f(s,m) \equiv \sqrt{1-\frac{4m^2}{s}}\log\left(\frac{2m^2-s+\sqrt{s(s-m^2)}}{2m^2}\right)$. With $\delta\phi$=0 wavefunction ren.

$$S_4^{EFT} = \left.\frac{\mathcal{M}_4^{EFT}(\overline{\rm MS})}{(1+\delta\phi^2)}\right|_{p_i^2=m^2_{phys}}$$

Different p-dep. off-shell $\tilde{\mathcal{M}}_4^{EFT}$ and $\tilde{\delta}_\phi$, but same S_4^{EFT} in box basis. S_4^{EFT} independent of μ, get RG equations for C_4 in $\overline{\rm MS}$

$$\frac{dC_4}{d\log\mu} = \frac{3}{16\pi^2}C_4^2 + \frac{m^2}{16\pi^2 M^2}C_6$$

1-loop 4-point, UV side



$\lambda_1 = 0$, UV , H-loops

$$\mathcal{M}_4^{\rm UV} = -\lambda_0 + \frac{3\lambda_0^2}{32\pi^2}\left(\frac{1}{\bar\epsilon} + \log\left(\frac{\mu^2}{m^2}\right) + 2\right) + \frac{3\lambda_2^2}{32\pi^2}\left(\frac{1}{\bar\epsilon} + \log\left(\frac{\mu^2}{M^2}\right) + 2\right)$$
$$+ \frac{\lambda_0^2}{32\pi^2}\left[f(s,m) + f(t,m) + f(u,m)\right] + \frac{\lambda_2^2}{32\pi^2}\left[f(s,M) + f(t,M) + f(u,M)\right]$$

$1/M$ expanded,

$$\mathcal{M}_4^{\rm UV} \approx -\lambda_0 + \frac{3\lambda_0^2}{32\pi^2}\left(\frac{1}{\bar\epsilon} + \log\left(\frac{\mu^2}{m^2}\right) + 2\right) + \frac{3\lambda_2^2}{32\pi^2}\left(\frac{1}{\bar\epsilon} + \log\left(\frac{\mu^2}{M^2}\right)\right) + \frac{m^2\lambda_2^2}{48\pi^2 M^2} + \frac{\lambda_0^2}{32\pi^2}\left[f(s,m) + f(t,m) + f(u,m)\right].$$

$\overline{\rm MS}$ and μ ren. scale, 1-loop matching condition for C_4 ($C_6^{TREE} = 0!$)

$$C_4 = \lambda_0 - \frac{3\lambda_2^2}{32\pi^2}\log\left(\frac{\mu^2}{M^2}\right) - \frac{\lambda_2^2 m^2}{48\pi^2 M^2}$$

Only $\log\left(\frac{\mu^2}{M^2}\right)$, no $\log\left(\frac{\mu^2}{m_L{}^2}\right)$, choice $\mu \sim M$ - no large logs in matching

$$C_4(M) = \lambda_0(M) - \frac{\lambda_2^2 m^2}{48\pi^2 M^2} \quad \text{simplified}$$

RG equations in EFT

$\mu \sim M$ simplifies matching, EFT couplings at $\mu \ll M$ evolve with RG
Observables (m_{phys}, S_{ab}) independent of μ ren. scale
$(C_4^{TREE} = \lambda_0 - 3\lambda_1^2 - \ldots)$

$$\begin{aligned}\frac{dm^2}{d\log\mu} &= \frac{m^2 C_4}{16\pi^2}, \\ \frac{dC_4}{d\log\mu} &= \frac{1}{16\pi^2}\left[3C_4^2 + \frac{m^2}{M^2}C_6\right].\end{aligned}$$

RHS standard ϕ^4 results+$\mathcal{O}(1/M^2)$ corr. from dim-6 operator, C_6
General, at 1-loop, higher dim Wilson C_i contribute to lower dim, w/ explicit mass parameters in the EFT
Solve first for physical meaning

$$m^2(\mu) = m^2(M)\left(\frac{\mu}{M}\right)^{C_4/16\pi^2}$$

For perturbative corrections ($a^x \simeq 1 + x\log a$)

$$m^2(\mu) \simeq m^2(M)\left[1 + \frac{C_4}{16\pi^2}\log\left(\frac{\mu}{M}\right)\right]$$

This is the 1-loop physical mass in UV theory, with C_4 mapping
RG equation resums the large logs for small c. $C_4 \ll 16\pi^2$

Summary L-H EFT

Calculate ϕ scatt. ampl's at $E \ll M$, M heavy scale

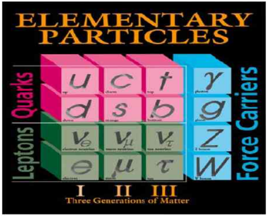
- Express C_i of $\mathscr{L}_{EFT}$ at scale M with $\mathscr{L}^{UV}$'s matching eqautions, different basis-different $C_i's$
- RG equations evolve C_i Wilson coeff's to $\mu \sim E$
- Calculate the Amplitude in EFT with parameteres at $\mu \sim E$
- Beyond $\mathscr{O}(1/M^2)$ go for higher operator, dim-8,-..,
  generalize matching
  1-loop $\rightarrow$generalize matching, RG runnning to higher loops

In full theory with 2-scalars, more complicated diagrams, multiple large logs, perturbation theory breaks down
Bottom-up, if EFT violates pert. unitarity at $\Lambda \sim 4\pi M/\sqrt{C_6}$ one can try to match the EFT to a hypothetical L-H system.

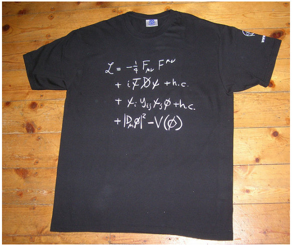
Outline

The Standard Model

- Standard Model local gauge QFT, $SU(3)_C \times SU_L(2) \times U_Y(1)$
- 3 femionic matter family (spin-1/2)
  Interactions mediated by spin-1 gauge bosons
  All particles discovered
- SSB by a $SU_L(2)$doublet Higgs
- Symmetries+Renormalizability
  Interactions unique
- B,L accidental symmetries

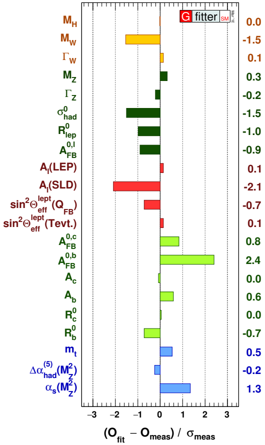


SM particles & Lagrangian



The Standard Model

- Excellent agreement w/ experiments
  Tevatron, LEP,SLC, LHC
- 4+3 Fit parameters
  $M_Z, M_H, \Delta\alpha_h^{(5)}(M_Z), \alpha_s(M_Z),\ m_{c,b,t}$
  (Later use 3 electroweak input par's)
- $P = \frac{O_{fit} - O_{meas}}{\sigma_{meas}}$ pull faktor
- All below 3σ , ($\sim$2.4 $A_{FB}^{0,b}, R_b^0$)
  $g_\mu - 2$, μ anomalous magnetic moment
- $M_H = 125.10 \pm 0.14$ GeV, LHC

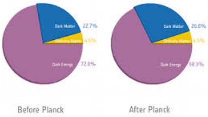


GFITTER pull faktor (2018)

SM cons, -

- Not AF, $U_Y(1)$, $\lambda\Phi^4$ not fund.
  Landau pole! $g = \frac{g_0}{g_0 - \beta \ln(\frac{\Lambda}{m})}$
- Unstable/metastable vacuum
- Gravity not included,
  $M_{Planck} = \sqrt{\frac{\hbar c}{G}} \simeq 1.2 \times 10^{19}$ GeV
  -quantum gravity.
- Naturalness, H.P.- 'red herring'
  M_{Higgs} sensitive to higher scales
  New physics close to EW
- Many accidental paramater:19

- Dark matter, energy (Λ)
- Neutrino mass (oscillation)
- Barion assymetry of the Universe
  $\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 6 \cdot 10^{-9}$
- Inflation



g,g',g_s	M_Z,M_H	$3m_l$+$6m_q$	CKM θ_i,δ	θ_{QCD}	m_ν+CKM
3	2	9	3+1	1	7-9(Maj.)

After the LEP/LHC , LEP paradox

LEP: new physics, what scale? H.P. $\rightarrow 1-3$TeV!
No direct/indirect evidence $\Rightarrow$ SM effective theory
Fundamental d.o.f. are the SM ones
Drop RENORMALIZABILITY, allow for $D > 4$ operators
Systematic expansion in dim of O_d, composed of SM fields

$$\begin{aligned}\mathscr{L} &= \mathscr{L}_{SM} + \frac{1}{\Lambda_L}\sum_i c_i^{(5)}\mathscr{O}_i^{D=5} + \frac{1}{\Lambda^2}\sum_i c_i^{(6)}\mathscr{O}_i^{D=6} + \\ &\quad + \frac{1}{\Lambda_L^3}\sum_i c_i^{(7)}\mathscr{O}_i^{D=7} + \frac{1}{\Lambda^4}\sum_i c_i^{(8)}\mathscr{O}_i^{D=8} + \dots\end{aligned}$$

Double expansion in $1/\Lambda_L$ and $1/\Lambda$, useful for $v \ll \Lambda_L, \Lambda$.
Expect to parametrize large class of new physics with heavy particles
New Phys. constraints after matching the constrained Wilson coefficients
$\mathscr{L}^5 = \frac{1}{\Lambda_L} c_{ff'}^{(5)} \Phi\Phi L_f L_{f'}$ ν tömeg, see-saw.

Odd-even dim operators

Dim-5 operator (H-Higgs, L-Lepton doublet, I,J flavour)

$$\mathcal{O}_{IJ}^{D=5} = \left(\varepsilon_{ij} H^i L_I^j\right) \left(\varepsilon_{kl} H^k L_J^l\right)$$

L and (B-L) violating, generates Majoranna mass terms $\frac{v^2}{\Lambda_L} c_{IJ}^{(5)} \nu_I \nu_J$

From $m_\nu \lesssim$eV , get $\Lambda_L / c^{(5)} \geq 10^{15}$GeV, for the eigenvalues

Assume Λ and Λ_L are far away, only deal with even operators

$$v \ll \Lambda, \qquad \Lambda^2 \ll v\Lambda_L$$

B,L conserving odd operators are still subdominant

- Leading contribution to collider physics D=6
- Naively symmetry breaking operators are more suppressed

broken symmetry	operators	Λ scale
B,L	$(QQQL)/\Lambda^2$	10^{12-13} TeV
flavor 1-2. gen., CP	$(\bar{d}s\bar{d}s)/\Lambda^2$	1000 TeV
flavor 2-3.gen	$m_b\left(\bar{s}\sigma_{\mu\nu}F^{\mu\nu}b\right)/\Lambda^2$	50 TeV

Warsaw basis

- Different higher dim operators can lead to same S-matrix - REDUNDANCY
- Get rid off, by
  - using equation of motion (EOM)
  - integrating by parts
  - field redefinitions
  - Fierz transformation
- Not obvious relations $O_{bosonic} \leftrightarrow \sum \left(a_{2i} \bar{\Psi}\Psi + a_{4i} \left(\bar{\Psi}\Psi\right) \left(\bar{\Psi}\Psi\right) \right)$
- Buchmüller, Wyler ('86) $\rightarrow$ minimal set Gradzkowski et al. '10
- 59 operators in non-redundant basis
- can define new basis via transformations
- 2499 parameters - B,L and flavour symmetries reduce it
- 28 op's including the Higgs (doublet)
- special alternatives, SILH basis, Strongly Interacting Light Higgs, fits for strong BSM sector ('07-'13 completed)

Warsaw basis 2

- Purely Bosonic operators

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

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

Double Lorentz-indices implicitly contracted with $\eta_{\mu\nu} =< 1, -1, -1, -1 >$
Deal with O_{HD}

.

Warsaw basis, Two-fermion-boson operators

Yukawa	
$[O_{eH}^\dagger]_{IJ}$	$H^\dagger H e_I^c H^\dagger \ell_J$
$[O_{uH}^\dagger]_{IJ}$	$H^\dagger H u_I^c \widetilde{H}^\dagger q_J$
$[O_{dH}^\dagger]_{IJ}$	$H^\dagger H d_I^c H^\dagger q_J$

Vertex		Dipole	
$[O_{H\ell}]_{IJ}$	$i\bar{\ell}_I \bar{\sigma}_\mu \ell_J H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{eW}^\dagger]_{IJ}$	$e_I^c \sigma_{\mu\nu} H^\dagger \sigma^i \ell_J W_{\mu\nu}^i$
$[O_{H\ell}^{(3)}]_{IJ}$	$i\bar{\ell}_I \sigma^i \bar{\sigma}_\mu \ell_J H^\dagger \sigma^i \overleftrightarrow{D}_\mu H$	$[O_{eB}^\dagger]_{IJ}$	$e_I^c \sigma_{\mu\nu} H^\dagger \ell_J B_{\mu\nu}$
$[O_{He}]_{IJ}$	$ie_I^c \sigma_\mu \bar{e}_J^c H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{uG}^\dagger]_{IJ}$	$u_I^c \sigma_{\mu\nu} T^a \widetilde{H}^\dagger q_J G_{\mu\nu}^a$
$[O_{Hq}]_{IJ}$	$i\bar{q}_I \bar{\sigma}_\mu q_J H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{uW}^\dagger]_{IJ}$	$u_I^c \sigma_{\mu\nu} \widetilde{H}^\dagger \sigma^i q_J W_{\mu\nu}^i$
$[O_{Hq}^{(3)}]_{IJ}$	$i\bar{q}_I \sigma^i \bar{\sigma}_\mu q_J H^\dagger \sigma^i \overleftrightarrow{D}_\mu H$	$[O_{uB}^\dagger]_{IJ}$	$u_I^c \sigma_{\mu\nu} \widetilde{H}^\dagger q_J B_{\mu\nu}$
$[O_{Hu}]_{IJ}$	$iu_I^c \sigma_\mu \bar{u}_J^c H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{dG}^\dagger]_{IJ}$	$d_I^c \sigma_{\mu\nu} T^a H^\dagger q_J G_{\mu\nu}^a$
$[O_{Hd}]_{IJ}$	$id_I^c \sigma_\mu \bar{d}_J^c H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{dW}^\dagger]_{IJ}$	$d_I^c \sigma_{\mu\nu} \bar{H}^\dagger \sigma^i q_J W_{\mu\nu}^i$
$[O_{Hud}]_{IJ}$	$iu_I^c \sigma_\mu \bar{d}_J^c \tilde{H}^\dagger D_\mu H$	$[O_{dB}^\dagger]_{IJ}$	$d_I^c \sigma_{\mu\nu} H^\dagger q_J B_{\mu\nu}$

Table 3: Two-fermion D=6 operators in the Warsaw basis. The flavor indices are denoted by I, J. For complex operators (O_{Hud} and all Yukawa and dipole operators) the corresponding complex conjugate operator is implicitly included.

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Warsaw basis, Four-fermion- operators

$(\bar{R}R)(\bar{R}R)$	
O_{ee}	$\eta(e^c\sigma_\mu\bar{e}^c)(e^c\sigma_\mu\bar{e}^c)$
O_{uu}	$\eta(u^c\sigma_\mu\bar{u}^c)(u^c\sigma_\mu\bar{u}^c)$
O_{dd}	$\eta(d^c\sigma_\mu\bar{d}^c)(d^c\sigma_\mu\bar{d}^c)$
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}	$(u^c\sigma_\mu\bar{u}^c)(d^c\sigma_\mu\bar{d}^c)$
$O_{ud}^{(8)}$	$(u^c\sigma_\mu T^a\bar{u}^c)(d^c\sigma_\mu T^a\bar{d}^c)$

$(\bar{L}L)(\bar{R}R)$	
$O_{\ell e}$	$(\bar{\ell}\bar{\sigma}_\mu\ell)(e^c\sigma_\mu\bar{e}^c)$
$O_{\ell u}$	$(\bar{\ell}\bar{\sigma}_\mu\ell)(u^c\sigma_\mu\bar{u}^c)$
$O_{\ell d}$	$(\bar{\ell}\bar{\sigma}_\mu\ell)(d^c\sigma_\mu\bar{d}^c)$
O_{eq}	$(e^c\sigma_\mu\bar{e}^c)(\bar{q}\bar{\sigma}_\mu q)$
O_{qu}	$(\bar{q}\bar{\sigma}_\mu q)(u^c\sigma_\mu\bar{u}^c)$
$O_{qu}^{(8)}$	$(\bar{q}\bar{\sigma}_\mu T^a q)(u^c\sigma_\mu T^a\bar{u}^c)$
O_{qd}	$(\bar{q}\bar{\sigma}_\mu q)(d^c\sigma_\mu\bar{d}^c)$
$O_{qd}^{(8)}$	$(\bar{q}\bar{\sigma}_\mu T^a q)(d^c\sigma_\mu T^a\bar{d}^c)$

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

$(\bar{L}R)(\bar{L}R)$	
O_{quqd}	$(u^c q^j)\epsilon_{jk}(d^c q^k)$
$O_{quqd}^{(8)}$	$(u^c T^a q^j)\epsilon_{jk}(d^c T^a q^k)$
$O_{\ell equ}$	$(\bar{\ell}^j\bar{e}^c)\epsilon_{jk}(\bar{q}^k\bar{u}^c)$
$O_{\ell equ}^{(3)}$	$(\bar{\ell}^j\bar{\sigma}_{\mu\nu}\bar{e}^c)\epsilon_{jk}(\bar{q}^k\bar{\sigma}^{\mu\nu}u^c)$
$O_{\ell edq}$	$(\bar{\ell}\bar{e}^c)(d^c q)$

Table 4: Four-fermion D=6 operators in the Warsaw basis. Flavor indices are suppressed here to reduce the clutter. The factor η is equal to 1/2 when all flavor indices are equal (e.g. in $[O_{ee}]_{1111}$), and $\eta = 1$ otherwise. For each complex operator the com-

Warsaw basis, view of M. Trott

- Warsaw basis: 1008.4884 Grzadkowski, Iskrzynski, Misiak,Rosiek

$1: X^3$		$2: H^6$		$3: H^4D^2$		$5: \psi^2 H^3 + \text{h.c.}$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_H	$(H^\dagger H)^3$	$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	Q_{eH}	$(H^\dagger H)(\bar l_p e_r H)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$			Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$	Q_{uH}	$(H^\dagger H)(\bar q_p u_r \widetilde H)$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$					Q_{dH}	$(H^\dagger H)(\bar q_p d_r H)$
$Q_{\widetilde W}$	$\epsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$						

$4: X^2H^2$		$6: \psi^2 XH + \text{h.c.}$		$7: \psi^2 H^2 D$	
Q_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I H W^I_{\mu\nu}$	$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar l_p \gamma^\mu l_r)$
$Q_{H\widetilde G}$	$H^\dagger H\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$	$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar l_p \tau^I \gamma^\mu l_r)$
Q_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde H\, G^A_{\mu\nu}$	Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar e_p \gamma^\mu e_r)$
$Q_{H\widetilde W}$	$H^\dagger H\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde H\, W^I_{\mu\nu}$	$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar q_p \gamma^\mu q_r)$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde H\, B_{\mu\nu}$	$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{H\widetilde B}$	$H^\dagger H\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r) H\, G^A_{\mu\nu}$	Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar u_p \gamma^\mu u_r)$
Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I H\, W^I_{\mu\nu}$	Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar d_p \gamma^\mu d_r)$
$Q_{H\widetilde WB}$	$H^\dagger \tau^I H\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$	Q_{Hud} + h.c.	$i(\widetilde H^\dagger D_\mu H)(\bar u_p \gamma^\mu d_r)$

6 gauge dual ops

28 non dual operators

25 four fermi ops

59 + h.c. operators

Warsaw basis, Four-fermion/M.Trott

- Four fermion operators: 1008.4884 Grzadkowski, Iskrzynski, Misiak,Rosiek

$8:(\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$

$8:(\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8:(\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8:(\bar{L}R)(\bar{R}L)+\text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8:(\bar{L}R)(\bar{L}R)+\text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

Warsaw basis, parameter counting

In Warsaw basis arXiv:1008.4884 (SMEFT standard basis)

$$\frac{1}{\Lambda^2_{\delta B=0}}\mathcal{L}_6$$

Class	N_{op}	CP-even n_g	1	3	CP-odd n_g	1	3
1 g^3X^3	4	2	2	2	2	2	2
2 H^6	1	1	1	1	0	0	0
3 H^4D^2	2	2	2	2	0	0	0
4 $g^2X^2H^2$	8	4	4	4	4	4	4
5 $y\psi^2H^3$	3	$3n_g^2$	3	27	$3n_g^2$	3	27
6 $gy\psi^2XH$	8	$8n_g^2$	8	72	$8n_g^2$	8	72
7 ψ^2H^2D	8	$\frac{1}{2}n_g(9n_g+7)$	8	51	$\frac{1}{2}n_g(9n_g-7)$	1	30
ψ^4 8 : $(\bar{L}L)(\bar{L}L)$	5	$\frac{1}{4}n_g^2(7n_g^2+13)$	5	171	$\frac{7}{4}n_g^2(n_g-1)(n_g+1)$	0	126
8 : $(\bar{R}R)(\bar{R}R)$	7	$\frac{1}{8}n_g(21n_g^3+2n_g^2+31n_g+2)$	7	255	$\frac{1}{8}n_g(21n_g+2)(n_g-1)(n_g+1)$	0	195
8 : $(\bar{L}L)(\bar{R}R)$	8	$4n_g^2(n_g^2+1)$	8	360	$4n_g^2(n_g-1)(n_g+1)$	0	288
8 : $(\bar{L}R)(\bar{R}L)$	1	n_g^4	1	81	n_g^4	1	81
8 : $(\bar{L}R)(\bar{L}R)$	4	$4n_g^4$	4	324	$4n_g^4$	4	324
8 : All	25	$\frac{1}{8}n_g(107n_g^3+2n_g^2+89n_g+2)$	25	1191	$\frac{1}{8}n_g(107n_g^3+2n_g^2-67n_g-2)$	5	1014
Total	59	$\frac{1}{8}(107n_g^4+2n_g^3+213n_g^2+30n_g+72)$	53	1350	$\frac{1}{8}(107n_g^4+2n_g^3+57n_g^2-30n_g+48)$	23	1149

Table 2. Number of CP-even and CP-odd coefficients in $\mathcal{L}^{(6)}$ for n_g flavors. The total number of coefficients is $(107n_g^4+2n_g^3+135n_g^2+60)/4$, which is 76 for $n_g=1$ and 2499 for $n_g=3$.

2499

arXiv:1312.2014 Alonso, Jenkins, Manohar, Trott

- Linearly realised symmetries (exact or softly broken) of the SMEFT relate parameters

Warsaw basis, transformations

- Missing terms?
- Redundant op's removed
- $O'_{HD} = (H^\dagger H)\, D_\mu H^\dagger D_\mu H$
- integrating by parts

$$O'_{HD} = (H^\dagger H)\left[\Box (H^\dagger H) - H^\dagger D_\mu D_\mu H - D_\mu D_\mu H^\dagger H\right]$$

Use H EOM in the last 2 terms

$$\Box H \;=\; \mu_H^2 H - 2\lambda(H^\dagger H) - j_H,$$

$$j_H \;\equiv\; -\bar{u}^c y_u^\dagger \tilde{q} + d^c y_d q + e^c y_e \ell, \qquad \tilde{q}_i \equiv \epsilon_{ij}\bar{q}_j.$$

$$O'_{HD} = -\mu_H^2 (H^\dagger H)^2 + \frac{1}{2}(H^\dagger H)\Box(H^\dagger H) + 2\lambda(H^\dagger H)^3 + \frac{1}{2}H^\dagger H\left[-\bar{u}^c y_u^\dagger \tilde{q} + d^c y_d q + e^c y_e \ell + \text{h.c.}\right]$$

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

Now all terms in the Warsaw basis, bosonic <-> fermionic op's

To reproduce O'_{HD} need lots of different operators

Systematic Hilbert-series techniques, H.Murayama et.al.'15-16

Exercise 2. Express in Warsaw basis $B_{\mu\nu} D_\mu H^\dagger D_\nu H$!

Power counting for Wilson c's*

Importance of Wilson c's estimated from UV physics w/o expt.

- $\hbar$ counting - see dependence only on Λ, g_*^{NP}, tree level

$$
\begin{aligned}
O_H = |H|^6 : &\qquad c_H \sim g_*^4, \\
O_{eH} = |H|^2 \bar{\ell} H e_c : &\qquad c_{eH} \sim g_*^3, \\
O_{H\Box} = |H|^2 \Box |H|^2 : &\qquad c_H \sim g_*^2, \\
O_W = \epsilon_{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu} : &\qquad c_W \sim g_*,
\end{aligned}
$$

$H^6 \sim \hbar^3 = \hbar^2_{cg} \hbar_{action}$. $[g_*] = \hbar^{-1/2}$.

Naive estimates subject to physics constraints.

$g_* \sim 10 \gg 1$, means $c_H \sim \mathscr{O}(10^4)$, but it produces Higgs quartic(~.12)
λH^4,suggest $\lambda \sim g_*^2$without fine tuning, some (shift-) symmetry protects,
leads to $c_H \sim \lambda g_*^2 \leq 10$
Chiral symmetry protects $c_{eH} \sim y_e g_*^2$, must be prop. to Yukawa.
Fundamental W's produced prop. to g_L and via loops to reduce $\hbar$,
$c_W \sim g_L^3/16\pi^2 \leq 10^{-3}|_{\Lambda=1\,TeV}$.

Use of EFT - New Physics(NP) or pure SMEFT

- Study self-consistent theory, SMEFT. It is not NP
  SMEFT is different th than any NP model even with matching

  $$\mathscr{L}_{SMEFT} \neq \mathscr{L}_{SM} + \mathscr{L}_{NP} \text{ counterterms, } \mathrm{Z}_{\mathrm{SMEFT}} \neq \mathrm{Z}_{\mathrm{SM}} + \mathrm{Z}_{\mathrm{NP}}$$

  Understand SMEFT (it's geometry), interface with data, Michael Trott,...
- Emerging pattern of c_i's in SMEFT points towards NP
  Experiment may show certain linear combination of O_i is there. Which NP is behind?

.

From BSM to operators 1

- ~Fermi theory, heavy neutral V_μ coupled to Ψ-current

$$\mathscr{L}_{UV} \supset V_\mu \left(g_{Vf,L} \bar{f} \bar{\sigma}_\mu f + g_{Vf,R} \bar{f}^c \bar{\sigma}_\mu f^c \right)$$

Exchange of V's, below M_V generates 4-fermion term in Table 4.

$$\mathscr{L}_{EFT} \supset -\frac{1}{2M_V^2} \left(g_{Vf,L} \bar{f} \bar{\sigma}_\mu f + g_{Vf,R} \bar{f}^c \bar{\sigma}_\mu f^c \right)^2$$

Match it to Warsaw basis

$$\frac{c_{f_1 f_2}}{\Lambda^2} = -\frac{g_{V,f_1} g_{V,f_2}}{M_V^2}$$

Low energy probes only c_{ij}/Λ^2 - only the ratio is determined
Only perturbative upper bound $c_i \leq 4\pi$.

From BSM to operators 2

- Composite Higgs heavy complex X_μ coupled to H-covariant

$$\mathscr{L}_{UV} \supset g_X X_\mu H^\dagger D_\mu H + h.c.$$

Higgs composite of new strongly charged q-like partons
X_μ is a ρ-meson like resonance in the strong sector
In EFT derivative 4-H contact terms

$$\mathscr{L}_{EFT} \supset -\frac{g_X^2}{2M_V^2} \left| H^\dagger D_\mu H \right|^2$$

So far tree-level - some only generated at loop-level

From BSM to operators 3 - loop level

- $O_{HG} = H^\dagger H G^a_{\mu\nu} G^a_{\mu\nu}$, c_{HG} H-gluon only generated at 1-loop
  Coloured scalar $\tilde{t}_c$ mass M_T, ∼quantum # righthanded top partner scalar restore naturalness.

  $$\mathscr{L}_{UV} \supset -y_T H^\dagger H \tilde{t}_c^\dagger \tilde{t}_c$$

  Emerges in SUSY models, where top-partner scalars
  No tree-level effect on scatt. ampl's
- Modifies the h-production in $gg \to h$ via the triangle+bubble
  In EFT the coresponding tree-level term

  $$\frac{c_{HG}}{\Lambda^2} = \frac{y_T^2 g_s^2}{256\pi^2 M_T^2}$$

  2-loop factor.

From operators to observables

Phenomenology with mass eigenstates after EWSB

2 way to deviate from the SM

1. Modified couplings, corrections to SM-like interactions
2. New vertices, new interaction terms (never seen beefore :)

Coupling modified by $O_{He} = ie_c \sigma_\mu \bar{e}_c \left(H^\dagger D_\mu H - D_\mu H^\dagger H \right)$ from Table 3.
Z-boson couplings to the e_c right-handed electron

$$\frac{c_{He}}{\Lambda^2} O_{He} \to -\frac{c_{He}\sqrt{g_L^2 + g_Y^2}\, v^2}{2\Lambda^2} Z_\mu e_c \sigma_\mu \bar{e}_c$$

Effect1: shifts the int'n strength originally defined by T^3, Q, q.#

$$g_{Ze}^{SM} = \sqrt{g_L^2 + g_Y^2}\, s_\theta^2 \quad \Delta g_{Ze} = -\frac{c_{He}\sqrt{g_L^2 + g_Y^2}\, v^2}{2\Lambda^2}$$

Effect2: new vertex, with 2 rh electron ($v^2 \to vh$)

$$\frac{c_{He}}{\Lambda^2} O_{He} \to -\frac{c_{He}\sqrt{g_L^2 + g_Y^2}\, v}{2\Lambda^2} h Z_\mu e_c \sigma_\mu \bar{e}_c$$

New h-3fields! Contribute to h decay to 4leptons, studied at LHC

Coupling shift vs. new vertex

No invariant way to separate coupling shifts from a new vertex, field redefinitions are allowed - equivalence theorem: same physics

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu h)^2 - \frac{m_h^2}{2}h^2 - \frac{m_h^2}{2v}\left(1 + \delta_1 \frac{v^2}{\Lambda^2}\right) h^3 - \delta_2 \frac{v}{\Lambda^2} h \partial_\mu h \partial_\mu h + \dots$$

δ_1 modification of triple Higgs coupling, δ_2 new interaction - generated by both of $O_H, O_{H\Box}$ dim-6.
Contribute to $hh \to hh$, or $pp \to hh$ hh-production at LHC
Field redefinition can eliminate δ_2 term

$$h \to h + \delta_2 \frac{v}{2\Lambda^2} h^2$$

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 - \frac{m_h^2}{2}h^2 - \frac{m_h^2}{2v}\left(1 + (\delta_1 + \delta_2)\frac{v^2}{\Lambda^2}\right) h^3 + \dots,$$

Different $\mathscr{L}$ give same physics- equivalence theorem, explicit calculation
The effect of δ_2 interaction is hidden in the modified h-W,Z,Ψ interactions

Connect operators to Precision observables -shift the SM input par's

$$\mathrm{EW\ parameters}\ g_L, g_Y, v \leftarrow G_F, \alpha(0), M_Z^2(M_Z)$$

At tree-level

$$\sqrt{2}G_F = \frac{1}{v^2}, \quad \alpha = \frac{g_L^2 g_Y^2}{4\pi(g_L^2 + g_Y^2)}, \quad m_Z^2 = \frac{(g_L^2 + g_Y^2)v^2}{4}.$$

BSM, tree-level contribution to observables, O_{HD} to the Z-mass

$$\frac{c_{HD}}{\Lambda^2}|H^\dagger D_\mu H|^2 \to \frac{c_{HD}v^2}{2\Lambda^2}\frac{(g_L^2 + g_Y^2)v^2}{8}Z_\mu Z_\mu.$$

But c_{HD} not constrained with the precision of M_Z 0,01%!

Disentangle it (c_{HD}) from the SM inputs

M_Z measurement affects g_L, g_Y, v .

Precision observables*, definitions

Define deviations carefully, similarly to EW Δr, or S, T, U par's

$$\eta_{\mu\nu}\left(\Pi_{WW}(p^2)W^+_\mu W^-_\mu + \frac{1}{2}\Pi_{ZZ}(p^2)Z_\mu Z_\mu + \frac{1}{2}\Pi_{\gamma\gamma}(p^2)A_\mu A_\mu + \Pi_{Z\gamma}(p^2)Z_\mu A_\mu\right) +$$

$\Pi_{VV} = m_V^2 - p^2$, kanonical kinetic term, all SM loop, BSM, tree- loop-

Couplings shifted in interactions e.g.

$$[g_L^{We}]_{IJ} = g_{L,0}\left(\delta_{IJ} + [\delta g_L^{We}]_{IJ}\right),$$

$$[g^{Zf}]_{IJ} = \sqrt{g_{L,0}^2 + g_{Y,0}^2}\left(T_3^f - Q_f\frac{g_{Y,0}^2}{g_{L,0}^2 + g_{Y,0}^2} + [\delta g^{Zf}]_{IJ}\right).$$

g_{Y0}, g_{L0} are $SU_L(2)\times U_Y(1)$ gauge coupling -not related to input obs's

$$\begin{aligned}\mathcal{L} \supset\ & \frac{g_{L,0}g_{Y,0}}{\sqrt{g_{L,0}^2+g_{Y,0}^2}}A_\mu\sum_f Q_f(\bar{e}_I\bar{\sigma}_\mu e_I + e_I^c\sigma_\mu\bar{e}_I^c) \\ + & \left[\frac{[g_L^{We}]_{IJ}}{\sqrt{2}}W_\mu^+\bar{\nu}_I\bar{\sigma}_\mu e_J + W_\mu^+\frac{[g_L^{Wq}]_{IJ}}{\sqrt{2}}\bar{u}_I\bar{\sigma}_\mu d_J + \frac{[g_R^{Wq}]_{IJ}}{\sqrt{2}}\ W_\mu^+ u_I^c\bar{\sigma}_\mu\bar{d}_J^c + \text{h.c.}\right] \\ + & Z_\mu\sum_{f=u,d,e,\nu}[g_L^{Zf}]_{IJ}\bar{f}_I\bar{\sigma}_\mu f_J + Z_\mu\sum_{f=u,d,e}[g_R^{Zf}]_{IJ}f_I^c\bar{\sigma}_\mu\bar{f}_J^c.\end{aligned}$$

SM limit: all δg vanish

Input relation at tree level

Tree level relation is changed, assuming small deviations, linear dev.

$$2\sqrt{2}G_F \approx \frac{2}{v_0^2}\left(1 - \frac{\delta\Pi_{WW}(0)}{m_W^2} + \delta g_L^{We} + \delta g_L^{W\mu} - \frac{1}{2}[c_{\ell\ell}]_{1221} - [c_{\ell\ell}^{(3)}]_{1122}\right),$$

$$\alpha(0) = \frac{g_{L,0}^2 g_{Y,0}^2}{4\pi(g_{L,0}^2 + g_{Y,0}^2)}\left(1 + \delta\Pi'_{\gamma\gamma}(0)\right),$$

$$m_Z^2(m_Z) = \frac{(g_{L,0}^2 + g_{Y,0}^2)v_0^2}{4} + \delta\Pi_{ZZ}(m_Z^2).$$

with $[c_{ll}^{(3)}]\left(\bar{l}_I\bar{\sigma}_\mu\sigma^i l_I\right)\left(\bar{l}_J\bar{\sigma}_\mu\sigma^i l_J\right)$ 4-fermion op. in the Lagrangian

Redefine $v_0 = v(1+\delta v), \qquad g_{L,0} = g_L(1+\delta g_L), \qquad g_{Y,0} = g_Y(1+\delta g_Y),$

To satisfy the input relation redefine

$$\delta v = \frac{1}{2}\left(-\frac{\delta\Pi_{WW}(0)}{m_W^2} + \delta g_L^{We} + \delta g_L^{W\mu} - \frac{1}{2}[c_{\ell\ell}]_{1221} - [c_{\ell\ell}^{(3)}]_{1122}\right),$$

$$\delta g_L = \frac{g_L^2}{4(g_L^2 - g_Y^2)v^2}\left[-\frac{2\delta\Pi_{ZZ}(m_Z^2)}{m_Z^2} + \frac{2\delta\Pi_{WW}(0)}{m_W^2} + \frac{2g_Y^2\delta\Pi'_{\gamma\gamma}(0)}{g_L^2} + [c_{\ell\ell}]_{1221} + 2[c_{\ell\ell}^{(3)}]_{1122} - 2\delta g_L^{We} - 2\delta g_L^{W\mu}\right],$$

$$\delta g_Y = \frac{g_Y^2}{4(g_L^2 - g_Y^2)v^2}\left[\frac{2\delta\Pi_{ZZ}(m_Z^2)}{m_Z^2} - \frac{2\delta\Pi_{WW}(0)}{m_W^2} - \frac{2g_L^2\delta\Pi'_{\gamma\gamma}(0)}{g_Y^2} - [c_{\ell\ell}]_{1221} - 2[c_{\ell\ell}^{(3)}]_{1122} + 2\delta g_L^{We} + 2\delta g_L^{W\mu}\right].$$

SM limit: all δg vanish

Precision observables, prediction

Idea is to separate/uncorrelate the precise input on g_{Y0}, g_{L0}, v_0 from BSM contribution. Remove G_F, α, m_Z from the new physics fit

$$m_W^2(m_W) = \frac{g_{L,0}^2 v_0^2}{4} + \delta\Pi_{WW}(m_W^2)$$

Redefinitions relate with numerical input valued par's the corrections to measurement (m_W)

$$m_W^2 = \frac{g_L^2 v^2}{4} + \frac{1}{g_L^2 - g_Y^2}\left(g_Y^2 \delta\Pi_{WW}(0) - \frac{g_L^4}{g_L^2 + g_Y^2}\delta\Pi_{ZZ}(m_Z^2) + g_Y^2 m_W^2 \delta\Pi'_{\gamma\gamma}(0)\right) + \delta\Pi_{WW}(m_W^2)$$

Valid for any BSM scenario, See O_{HD},Shifts $\delta\Pi_{ZZ} = \frac{c_{HD} v^2}{2\Lambda^2} m_Z^2$, redefine $m_Z \rightarrow$contributes to m_W with $\frac{\delta m_W}{m_W} = (2.6 \pm 1.9) \cdot 10^{-4}$ (exp,th errors)

$$\frac{\delta m_W}{m_W} = \frac{\delta m_W^2}{2 m_W^2} = -\frac{c_{HD} g_L^2 v^2}{4(g_L^2 - g_Y^2)\Lambda^2}. \implies \frac{c_{HD}}{\Lambda^2} = \frac{-1.2 \pm 0.9}{(10\ \text{TeV})^2}.$$

Only NP $c_{HD} \sim g_*^2 \sim 1$, weakly coupled theory, M_W probes up to 10 TeV strongly coupled, $g_* \sim 4\pi$ up to 100 TeV, far better than direct reach!

SMEFT vs. HEFT (84 vs. 6 Inspire titles)

SM and SMEFT assumes the existence of weak doublet H.
Consequence of requiring

- Three GB π^i eaten up by the longitidinal components of W,Z
- One singlet scalar h of H, ensures exact unitarization of all energy amplitudes with external π^ifields

Relax exact unitarization for low energy processes, observables. It needs unitarization only up to the cutoff
H replaced by singlet h $J^P = 0^+$ scalar and (non-lienarly relaized) pion in the CCWZ formalism of Callan-Coleman-Wess-Zumino, minmal IR assumptions. Different theories, distinguishable expansions.

$$SM(H,\Lambda \to \infty) \supset SM(H,\Lambda \neq \infty) \supset SM(h,\Lambda \neq \infty)$$

In certain HEFT has cases better and broader convergence, depends on the observable.

The κ formalism/framework

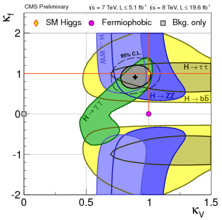
It is not an EFT approach to Higgs data, ad hoc rescaling of SM coulings to limit or spot deviations in partial/total width of H.

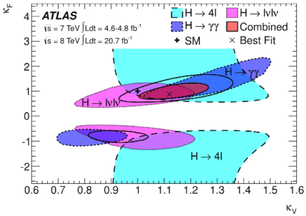
No direct EFT relation in SMEFT or HEFT, Pseudo observables

$$\sigma(gg \to H) \cdot \mathrm{BR}(H \to \gamma\gamma) = \frac{\kappa_g^2\, \kappa_\gamma^2}{\kappa_H^2}\, \sigma(gg \to H)_{\mathrm{SM}} \cdot \mathrm{BR}(H \to \gamma\gamma)_{\mathrm{SM}}\,,$$

where κ_H rescales the total H-width, $\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{SM}} = \kappa_\gamma^2$ and $\frac{\sigma_{ggH}}{\sigma_{ggH}^{SM}} = \kappa_g^2$.

Very old fig's with common κ_f and κ_V pointing towards the SM





Global fit to SMEFT

- Ellis, Sanz et al. 1803,252.
- Precision EW data, LEP&LHC $W^+W^- \to$4l's, and H production LHC Run1,2
- Warsaw basis 11 operators diboson, 9 Higgs production $c_{ii}^{(6)}/v^2$ is used
- Precision observables $\Delta S, T \neq 0$

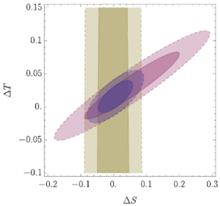


Figure 1: *Fits to the ΔS and ΔT parameters [121–126] using Z-pole, W mass, and LEP 2 WW scattering measurements (red), using LHC Run 1 and Run 2 Higgs results (dark yellow), and all the data (blue). The darker and lighter shaded regions are allowed at 1 and 2σ, respectively. We see that the Higgs measurements at the LHC have similar impacts to the electroweak precision measurements, and are largely complementary, emphasizing the need for a combined global fit.*

$$\frac{v^2}{\Lambda^2}C_{HWB} = \frac{g_1 g_2}{16\pi}\Delta S, \quad \frac{v^2}{\Lambda^2}C_{HD} = -\frac{g_1 g_2}{2\pi\,(g_1+g_2)}\Delta T\,,$$

Global fit to SMEFT 2

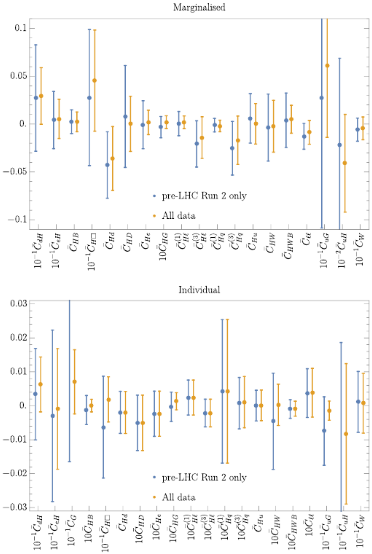


Figure 2: *Results from global fits in the Warsaw basis (orange) including all operators simultaneously (upper panel) and switching each operator on individually (lower panel). Also shown are fits omitting the LHC Run 2 data (blue). We display the best-fit values and 95% CL ranges.*

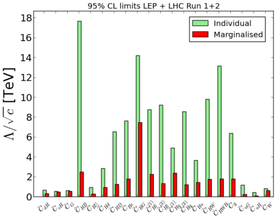


Figure 8: *Summary of the 95% CL bounds on the sensitivity (in TeV) for an $\mathcal{O}(1)$ Wilson coefficient, obtained from marginalised (red) and individual (green) fits to the 20 dimension-6 operators entering in electroweak precision tests, diboson and Higgs measurements at LEP, SLC, and LHC Run 1 and 2.*

Ellis, Sanz et al. 1803,252. χ^2/dof is the same for SM and SMEFT

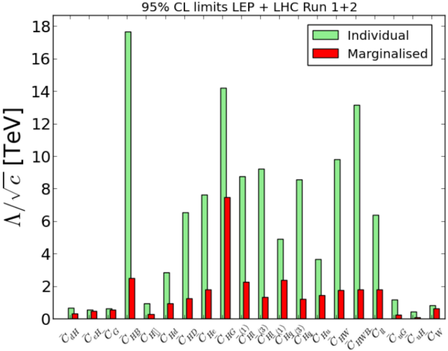


Figure 8: *Summary of the 95% CL bounds on the sensitivity (in TeV) for an $\mathcal{O}(1)$ Wilson coefficient, obtained from marginalised (red) and individual (green) fits to the 20 dimension-6 operators entering in electroweak precision tests, diboson and Higgs measurements at LEP, SLC, and LHC Run 1 and 2.*

Summary and Outlook

- EFT is at work, different/simpler organized calculation
- Need a good expansion parameter
- Non-redundant basis, not unique -unchanged physics
- Match it via physical observables to the UV theory if it is known
- SMEFT needs global approach, few percent effects expected
- dim-8 $W^{\pm}, Z$ operators analyzed at LHC - see talk, Pásztor G.
- Look for New Physics or Test the New Model (SMEFT) - interesting