On the road to the Standard Model

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[RA & Mia West hep-ph/2109.13290]

Outline

A * Electro-weak theory in the LHC era

B * Electro-weak effective field theory

C * Exploring Quotient Space

Part A

Electro-weak theory in the LHC era

A: Electro-weak theory in LHC era

EXP

* Brought us h (0^+)
* Gave us a sketch of h properties
* No other "new" phenomena (B-anomalies nonwithstanding)

TH

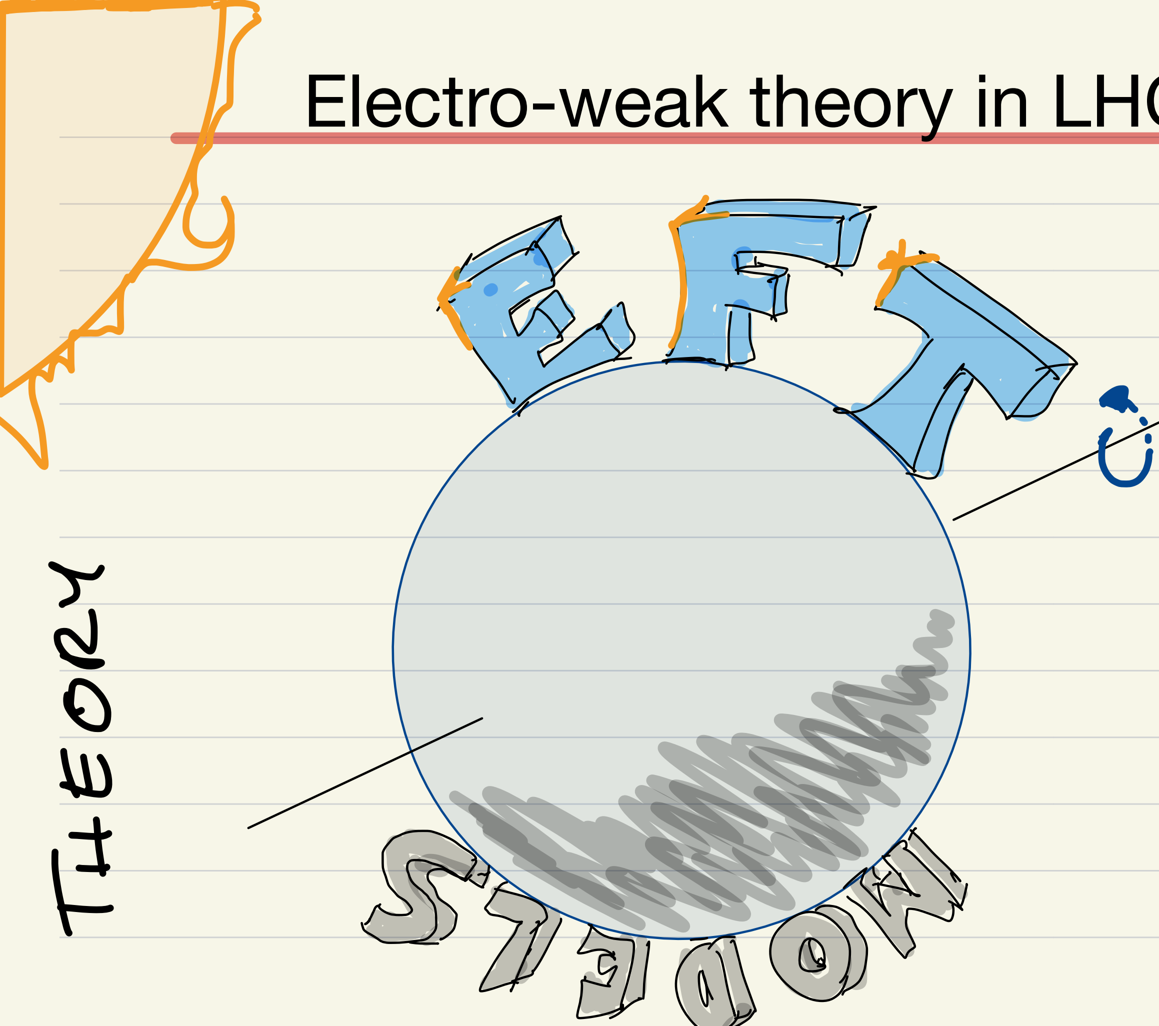
* Told you so! Unitarity etc
* Yeah, yeah, sure but what else?
* Nothing? But, but...
  I) Hierarchy problem!
  II) Dark matter!
  III) Our elegant, comprehensive & compelling theories!

A: Electro-weak theory in LHC era

THEORY

* The hierarchy problem has not gone away
  - Re-examine assumptions: naturalness vs so-what-ism
  - what is Λ_{UV}? Λ_{UV}
  - Bare minimum understand scalars in gravity
* Dark matter
  - A 'stronger' case for New Physics but harder to pin down
  - Will the Wimp-miracle come to pass?
* Or maybe search elsewhere / wait?

Electro-weak theory in LHC era



- Effective field theory (EFT):
  Place to go when no new states
- Déjà-vu cycle

A: Electro-weak theory in LHC era

- LHC: no new particles
  → examine the properties/interactions of particles at hand ←

  theory: a) Particle content
  + b) Symmetries (Lorentz $\otimes$ Gauge)
  + c) Identify expansion parameter

  Effective Field Theory

  Note Generality

A: Electro-weak theory in LHC era

- LHC: no new particles

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theory: a) Particle content

+ b) Symmetries (Lorentz $\otimes$ Gauge)

+ c) Identify expansion parameter

Effective Field Theory

Note Generality

- Déjà-vu but is it different this time?

An exp-compatible limit in EFT yields a closed or self consistent theory (SM)

As opposed to Fermi th or beauty w/o top

A: Electro-weak theory in LHC era

Has all of this attention brought novelty to theory?

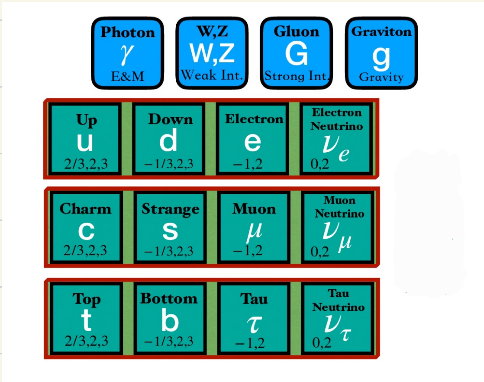
- Closed formula for one-loop corrections
  - RGE analysis, matching, ... [Drozd, Ellis, Quevillon, You '15] [Henning, Lu, Murayama, '14] [del Aguila, Kunszt, Santiago '16]
- Holomorphic structure & amplitude methods
  - Helicity weights, Non-renormalization theorems [R.A., Jenkins, Manohar, '14] [Cheung, Shen, '15] [Bern, Parra, Sawyer, '20]
- Solving the "basis counting" problem
  - Hilbert series, conformal group, ... [Henning, Melia, Murayama, Lu '15] [Lehman, Martin, '15]
- Automation of techniques in EFT

& Geometry!

Part B

Electro-weak effective field theory

Electro - weak effective field theory



Rewind to 2011:

Massive W, Z, Massless γ

fermions in $SU(2)_L \times U(1)_Y$ reps.

- Matter - Vector boson interactions $\longrightarrow$ Gauge theory

$$D_\mu q_L = \left(\partial_\mu + i \tfrac{g}{2} W_\mu \cdot \sigma + i g' Q_Y B_\mu\right) q_L$$

- Pure Gauge theory has no d.o.f. to yield masses!

Need scalars φ^a living in (W, Z)-space $= SU_L(2)\times U_Y(1)/U_{em}(1)$

Electro - weak effective field theory

scalars φ^a living in (W, Z)-space $= SU_L(2) \times U_Y(1) / U_{em}(1)$

Theory for scalars in a coset: Callan Coleman Wess Zumino

In practice:

$\mathcal{U}$: • 2×2, $\mathcal{U}^\dagger \mathcal{U} = 1$, $\det(\mathcal{U}) = 1$ (3 d.o.f.)

• $D_\mu \mathcal{U} = \partial_\mu \mathcal{U} + i\frac{g}{2} W\cdot\sigma\, \mathcal{U} + \mathcal{U}\, i\frac{g'}{2}\sigma_3 B$

Nature described by:

$$\mathcal{L} = \frac{v^2}{2} \mathrm{Tr}\left(D_\mu \mathcal{U}^\dagger D^\mu \mathcal{U}\right) - m_\psi \bar{\Psi}_L \mathcal{U} \Psi_R + \text{h.c.} + \mathcal{L}_{Gauge}$$

$(v = 246\,\text{GeV})$

[Appelquist & Bernard PRD22 80']
[Longhitano PRD22 80']
[Feruglio IMPJ A8 93']…

Electro - weak effective field theory

- We need not specify a parametrization of $\mathcal{U}(\varphi)$ though in practice we do:

$$\mathcal{U}(\varphi) = e^{i\vec{\sigma}\cdot\vec{\varphi}/v} \quad \text{or} \quad \mathcal{U}(\varphi) = \sqrt{1-\frac{\varphi^2}{v^2}} + i\frac{\vec{\varphi}}{v}\cdot\vec{\sigma} \quad \text{or} \ \ldots$$

yet we know all should physically be the same...

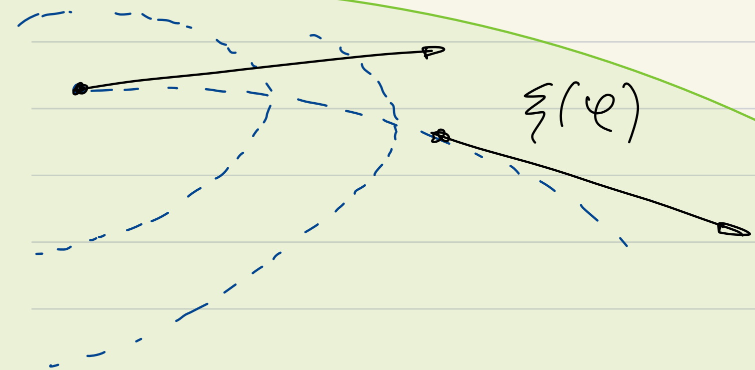
- Our fields φ transform non-linearly

$$\delta_i \varphi^a = \xi_i^a(\varphi) \qquad \text{CCWZ} \quad \xi\frac{\delta}{\delta\varphi}\bar{\mathcal{U}} = \frac{\delta}{\delta\varepsilon}\mathcal{G}(\varepsilon)\,\bar{\mathcal{U}}\,R^{\dagger}(\varphi,\varepsilon)$$

- Cut-off fixed by $v = 246$ GeV, $\mathcal{A}_{W_L W_L} = \frac{s}{v^2}$.

Geometry

Does bring new light to our theory



φ-manifold

- Observables in our theory given by φ-manifold

$$U^\dagger U \text{ '='} \det(U) = 1 \Rightarrow S^3$$

Indeed $SU(2)\times U(1)/U(1) \sim S^3$

- ξ are the killing vectors

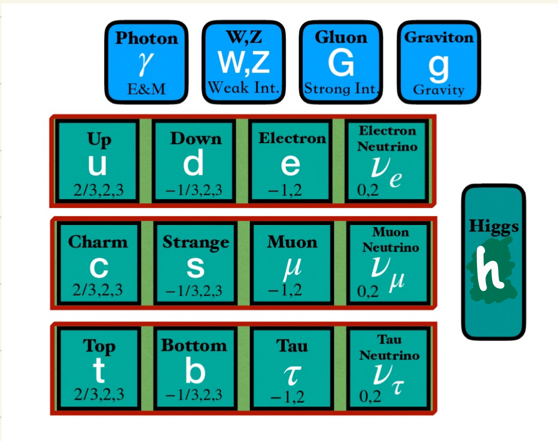
$$\xi^a_i \, \xi^b_{j,a} - \xi^a_j \, \xi^b_{i,a} = f_{ij}^{\ \ k} \, \xi^b_k$$

- Observables are coordinate-tranformation independent

$$\mathrm{Tr}(\partial_\mu U^\dagger \partial^\mu U) \equiv \partial_\mu \varphi^a g_{ab}(\varphi) \partial^\mu \varphi^b \; ; \quad A = R[g] \cdot s$$

Electro - weak effective field theory

But it's not 2011... As promised by unitarity LHC found a new particle



$h \qquad 0^+$

A singlet under $SU(2)_L \times U(1)_Y$ which is therefore assimilated as:

[Bagger, Barger et al. 9306256]
[Koulovassilopoulos & Chivukula 9312317]
[Grinstein & Trott 0704.1505] …

$$\mathcal{L} = \frac{1}{2}\partial_\mu h \partial^\mu h - V(h) + \frac{v^2}{2} F(h)^2 \langle D_\mu U^\dagger D^\mu U \rangle - m_\psi Y(h) \bar{\Psi}_L U \Psi_R + h.c. + \dots$$

$$+ \sum_{i,k} c_{i,k} \mathcal{O}^i_k$$

This is **HEFT**

$\left(\text{CHM} \longrightarrow (f) \quad F\left(\frac{h}{f}\right) \right)$

Electro - weak effective field theory

Extra assumption takes us to ...

h, φ^a come in a pack: $H = U(\varphi)\begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix}$

H is a linear $(2, 1/2)$ rep. of $SU(2)_L \times U(1)_Y$

e.g.

$$D_\mu H^\dagger D^\mu H = \frac{(v+h)^2}{2}\langle D_\mu U^\dagger D^\mu U\rangle + \frac{\partial_\mu h \partial^\mu h}{2}$$

so: $F(h) = \left(1 + \frac{h}{v}\right)$

Electro - weak effective field theory

h, φ^a come in a pack: $H = U(\varphi)\begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix}$

H is a linear $(2, 1/2)$ rep. of $SU(2)_L \times U(1)_Y$

$$\mathcal{L} = D_\mu H^\dagger D^\mu H - V(H) - \bar{\Psi}_L Y(\tilde{H}, H)\Psi_R + \mathcal{L}_{\text{Gauge}+\Psi} + \sum_{i,k} C^i_k O^k_i$$

We start our expansion by dimension with H "one more"

e.g. $\frac{c}{\Lambda^2} \cdot H^\dagger H \, D_\mu H^\dagger D^\mu H$

This is

SMEFT

Electro - weak effective field theory

- Hopefully this discussion made clear that

  SMEFT <u>can always be written as</u> HEFT

  but <u>not the other way</u>!

- Special cases (as SM) not easy to identify in HEFT

Geometry:

$$g = \begin{pmatrix} 1 & \\ & F^2(h)\, g_{ab}(\varphi) \end{pmatrix}$$

$$\text{Constant curvature} = \begin{cases} +\text{ve} & S^4 \quad \text{CHM} \\ 0 & \mathbb{R}^4 \quad \text{SM} \\ -\text{ve} & \mathbb{H}^4 \quad ? \end{cases}$$

- $A_{WW} = R_\varphi\, s$

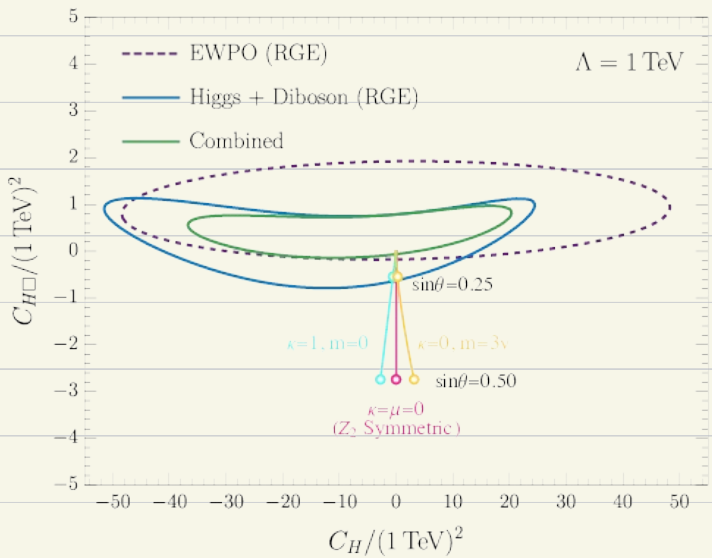
- $A_{Wh} = R_h\, s$

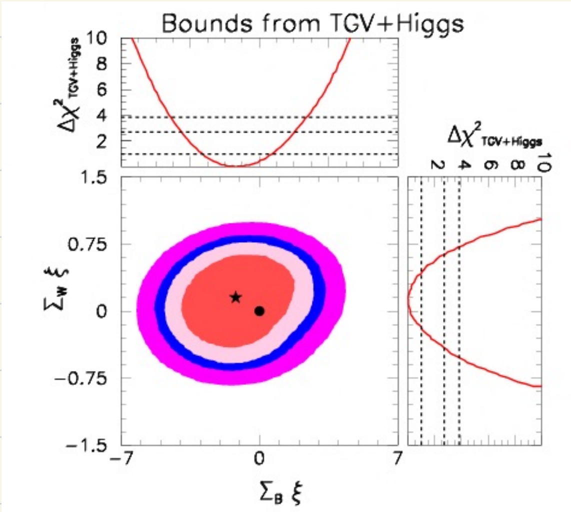
Electro - weak effective field theory

Translate LHC into theory

SMEFT

HEFT





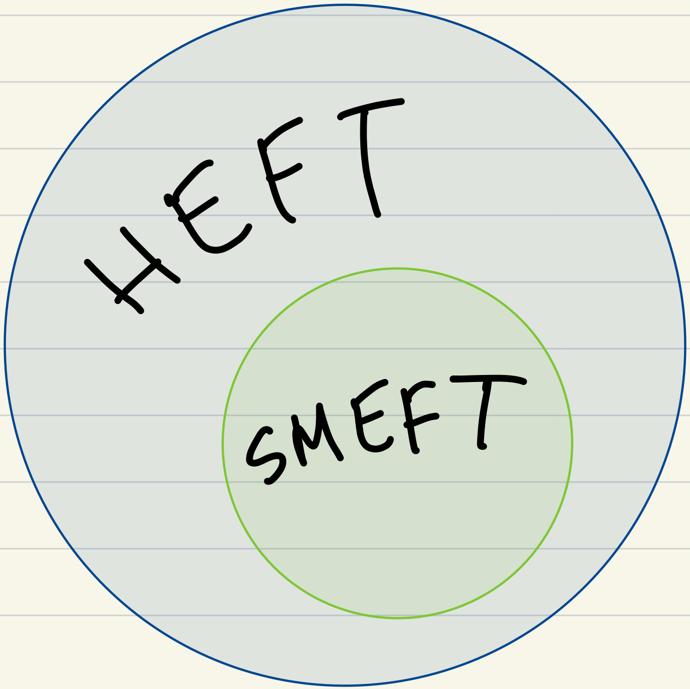
[Brivio, Corbett, Eboli, Gavela, Glez-Fraile '13]

[Dawson, Homiller, Lane '20]

Language of LHC ?

Electro - weak effective field theory

The question to address here



• SM ?

[Quotient theories
≡ HEFT/SMEFT]

Part C

Exploring Quotient Space

Exploring Quotient Space

How do we characterize it?

This is an arbitrary function

HEFT $\quad \frac{1}{2}(\partial h)^2 + \frac{v^2}{2} F(h)^2 \langle D_\mu U^\dagger D^\mu U \rangle$

SMEFT $\quad = G(H^\dagger H) D_\mu H^\dagger D^\mu H + \tilde{G}(H^\dagger H)(D_\mu H^\dagger H)^2$

These have a Taylor expansion but otherwise also arbitrary

∞ # parameters $\quad$ vs $\quad$ ∞ # parameters

Exploring Quotient Space

What is fundamentally different ?

Quotient theories :

$\boxed{\text{No } h_* \text{ exists} \,/\, F(h_*) = 0}$

$\boxed{\text{Or } \lim_{h \to h_*} F \to 0 \quad \text{but } \nabla^n R \text{ singular}}$

[RA, Manohar & Jenkins 1511.00724]
[Craig, Cohen, Lu & Sutherland 2008.08597]

As follows from linearization lemma [CCWZ]

Exploring Quotient Space

Who lives here?

[Craig, Cohen, Sutherland & Lu 2008.08597]

Th where one other scalar rep ϕ participates in EWSB

$\rightarrow \quad (246\,\mathrm{GeV})^2 = v^2 = v_h^2 + v_\phi^2 \;; \qquad \frac{1}{v+h}$

* EFT ($\int D\phi$): shift in $\langle h \rangle$ does not restore EWS, is singular
* Φ - field does not decouple $\quad m_\phi^2 \simeq \lambda_\phi v_\phi^2 \leq (4\pi)(v^2)$

A: This theory does not yield the SM in any EFT limit

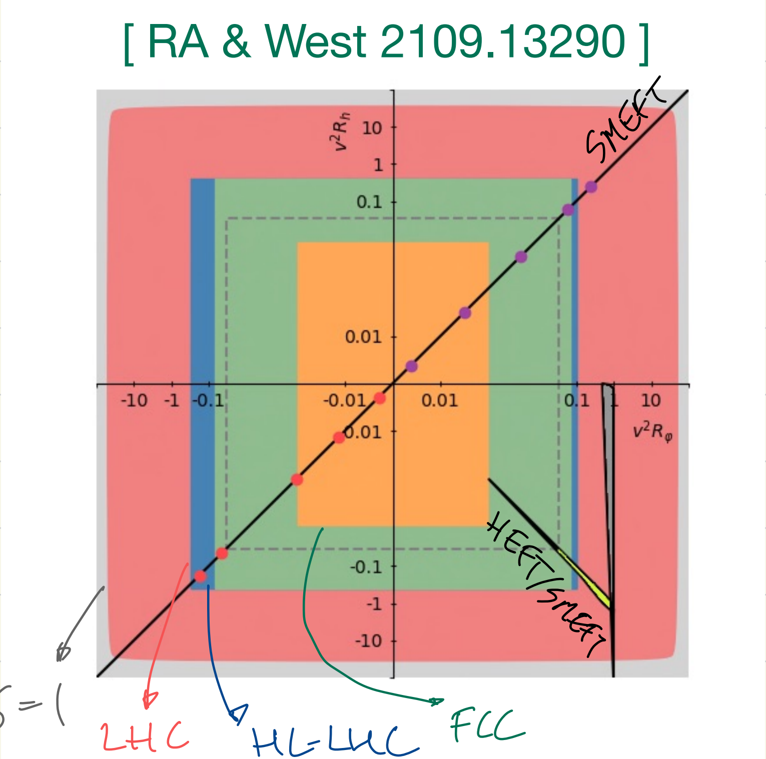
Exploring Quotient Space

Visualize this road-block in curvature

SMEFT

$$\mathcal{L}_{SM} - g_\alpha M_\phi H^\dagger \phi H - M_\phi^2 \phi^2$$

$$R_h = R_\varphi \sim \frac{g_\alpha^2}{M_\phi^2}$$



HEFT/SMEFT

$$\mathcal{L}_{SM} - V(H, \phi)$$

$$\langle H \rangle = v_h, \quad \langle \phi \rangle = v_\phi$$

$$v^2 = v_h^2 + 8/3\, v_\phi^2$$

$$R_h = -R_\varphi \sim \frac{m_h^2 m_\phi^2}{\lambda^2 v^6}$$

Exploring Quotient Space

Can we generalize this
without resorting to models?

* This is an arbitrary function

$$\frac{1}{2}(\partial h)^2 + \frac{v^2}{2} F(h)^2 \langle D_\mu U^\dagger D^\mu U \rangle$$

$$= G(H^\dagger H) D_\mu H^\dagger D^\mu H + \tilde{G}(H^\dagger H)(D_\mu H^\dagger H)^2$$

* These have a Taylor expansion
but otherwise also arbitrary

∞ # parameters vs ∞ # parameters

$(R_\varphi \neq R_h$ @ $1/\Lambda^4)$

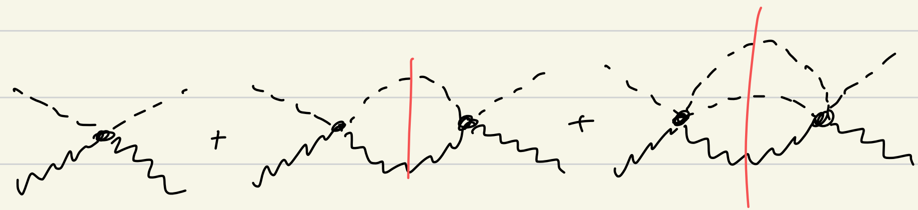
Exploring Quotient Space

For our example Unitarity was an ingredient

Maybe it is the key?

[Rattazi & Falkowsky 1511.00724]
[Craig, Cohen, Lu & Sutherland 20]

$$\left[F \sim \frac{1}{h+v_*} \right] + \left(\quad \right]$$



$$\simeq \sum \left(\frac{h}{v_*}\right)^n \quad + \quad \text{Each } \left(\frac{s}{(4\pi v_*)^2}\right)^n a_n < n!$$

$$= \sum \frac{a_n}{n!}\left(\frac{E}{4\pi v_*}\right)^{2n} \underset{a_n=1}{\sim} e^{\left(E/4\pi v_*\right)^2}$$

Exploring Quotient Space

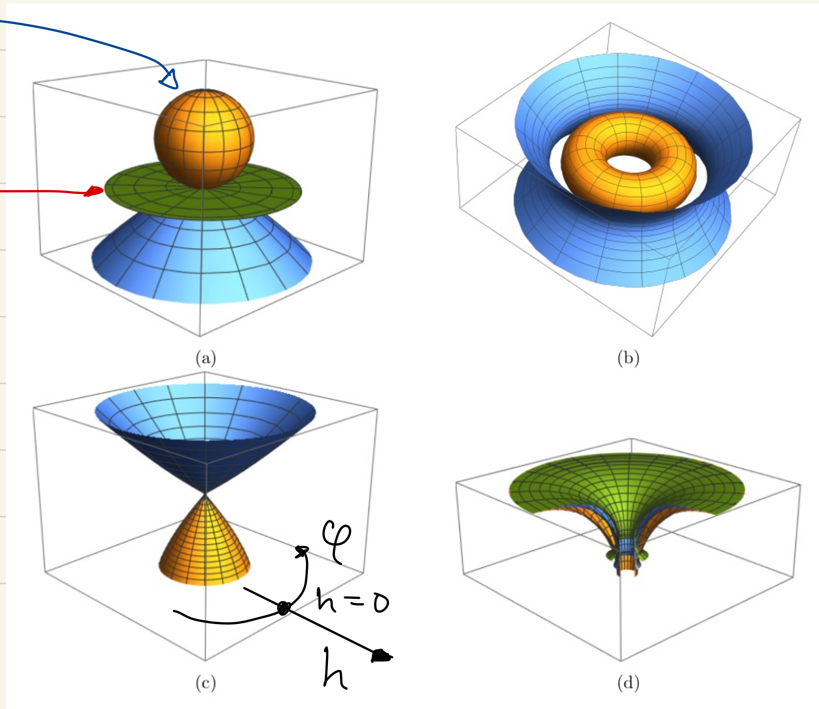
Visualize the possible manifolds

[RA & West 2109.13290]

Composite Higgs

SM

F(h) > 0



Conical Divergences

Our example model

F(h) > 0

but locally resembles S.M. to arbitrary order

Summary

→ HEFT comprises & goes beyond SMEFT

→ This 'beyond' is largely unknown

→ It might be within reach of collider