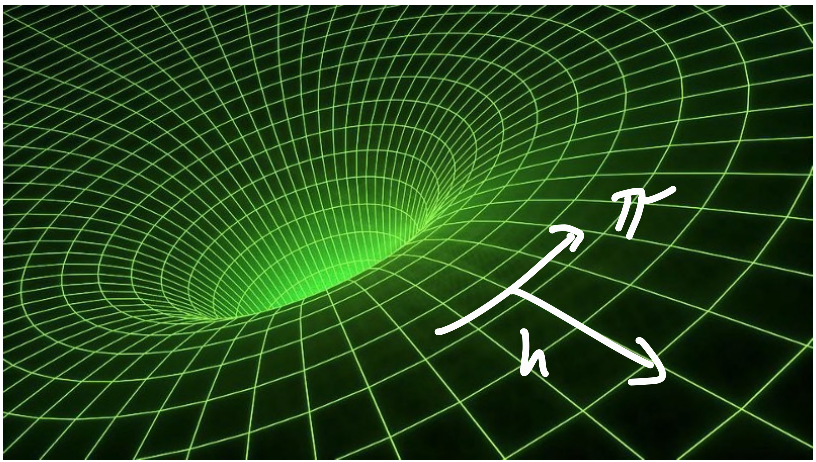
Non-decoupling New Particles and EFT Geometry at FCC



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FCC Phenomenology Workshop


Build the FCC!

Where's the new physics?

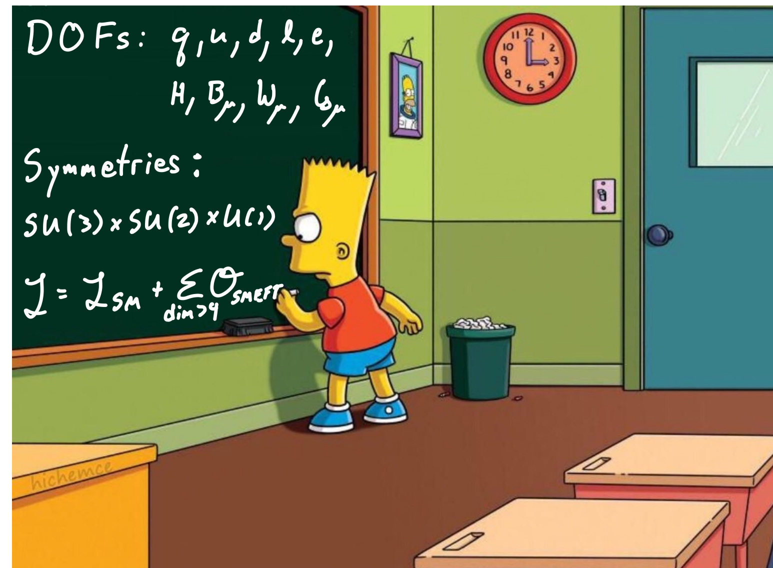
How best to search?

Can we be systematic?

How to organize BSM predictions?

Simplified Models

Effective Field Theory



The Standard Model as EFT

"Heavy physics decouples"

- Only SM dofs
- Symmetries: Lorentz + $SU(3)\times SU(2)\times U(1)$

Realize electroweak symmetry

linearly or non-linearly

SMEFT HEFT

SMEFT $(v=0)$

Let $\vec{\varphi}$ be an $O(4)$ vector

$$\vec{\varphi} \to O\vec{\varphi}$$

Identify $H = \frac{1}{\sqrt{2}}\begin{pmatrix} \varphi_1 + i\varphi_2 \\ \varphi_4 + i\varphi_3 \end{pmatrix}$

s.t. $\langle H \rangle \neq 0 \Leftrightarrow \langle \varphi_4 \rangle \neq 0$

SMEFT $(v=0)$

$$\mathcal{L}_{SMEFT} = A(|H|^2)\,|\partial H|^2 + \frac{1}{2} B(|H|^2)\left[\partial(|H|^2)\right]^2 - \tilde{V}(|H|^2) + \mathcal{O}(\partial^4)$$

$A, B, \tilde{V}$ are real analytic @ origin $|H|=0$

$\Rightarrow$ have convergent Taylor expansion @ $|H|=0$

($A(0)=1 \Rightarrow$ canonical norm)

Think of φ_i as Cartisian coords on manifold

$\vec{\varphi}=0$ is invariant point under $O(4)$ transformations

HEFT ($v \neq 0$)

Non-linearly realized sym breaking

$O(4)/O(3)$ Calan, Coleman, Wess, Zumino (1969)

Polar coordinates: h (physical Higgs)

$\vec{n}$ (Goldstone bosons)

$$\vec{\varphi} = (v_0 + h)\,\vec{n} \quad \text{w/} \quad \vec{n} = \begin{pmatrix} n_1 = \pi_1/v \\ n_2 = \pi_2/v \\ n_3 = \pi_3/v \\ n_4 = \sqrt{1 - n_i^2} \end{pmatrix}$$

$\vec{n} \in S^3 \qquad \vec{n}\cdot\vec{n} = 1$

HEFT $(v \neq 0)$

$O(4)$ transformation: $h \to h$, $\vec{n} \to O\vec{n}$

$\Rightarrow \vec{n}$ in non-linear rep

$$\mathcal{L}_{HEFT} = \frac{1}{2}\left[\mathbb{K}(h)\right]^2 (\partial h)^2 + \frac{1}{2}\left[v F(h)\right]^2 (\partial \vec{n})^2$$

$$- V(h) + \mathcal{O}(\partial^4)$$

$\langle h \rangle = 0$

$(\mathbb{K}(0) = 1$ is canonical norm$)$

HEFT ($v \neq 0$)

Does HEFT know that $\langle H \rangle = v$?

Alonso, Jenkins, Manohar (AJM) 1605.03602

$\Rightarrow$ There might be special place on manifold $h_* = -v$ where $O(4)$ symmetry is manifest

Determined by $F(h_*) = 0$

If $h = h_*$ exists $\Rightarrow$

HEFT $\rightarrow$ SMEFT possible

HEFT $\longrightarrow$ SMEFT ?

Map:

$$|H|^2 = \frac{1}{2}\vec{\varphi}\cdot\vec{\varphi} = \frac{1}{2}(v+h)^2$$

$$|\partial H|^2 = \frac{1}{2}(\partial\vec{\varphi})^2 = \frac{1}{2}(\partial h)^2 + \frac{1}{2}(v+h)^2(\partial\vec{n})^2$$

$$(\partial|H|^2)^2 = (\vec{\varphi}\cdot\partial\vec{\varphi})^2 = (v+h)^2(\partial h)^2$$

Naively:

$$\mathcal{L}_{HEFT} = \frac{v^2 F}{2|H|^2}|\partial H|^2 + \frac{1}{2}(\partial|H|^2)^2\frac{1}{2|H|^2}\left(K^2 - \frac{v^2F^2}{2|H|^2}\right)$$

$$+ \tilde{V}(|H|^2) + \mathcal{O}(\partial^4)$$

Analytic @ $|H|=0$?

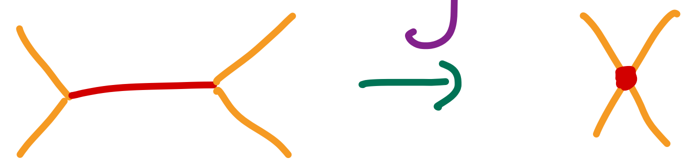
Light BSM and Analyticity

Given $\mathcal{L}_{UV}$ integrate out heavy State $\Rightarrow \mathcal{L}_{1LPI}$. Expand and truncate $\Rightarrow$ $\mathcal{L}_{EFT}$

We will use functional methods

2 examples:

1) tree exchange



2) loop exchange

* see also arXiv: 2011.02484 by TC, Lu, Zhang

Tree Exchange

Extend SM with singlet scalar $\mathcal{S}$

$$\mathcal{L}_{BSM} = \frac{1}{2}\mathcal{S}\left(-\partial^2 - m^2 - \lambda|H|^2\right)\mathcal{S} - a|H|^2\mathcal{S} + b\,\mathcal{S}^3$$

Integrate out $\mathcal{S}$ using EOM (neglect ∂):

$$\mathcal{S}[H] = \frac{1}{b}\left(-m^2 + \lambda|H|^2 + \sqrt{(m^2+\lambda|H|^2) - 2ab|H|^2}\right)$$

$$\Rightarrow V_{ILPI} = V_{SM} - \frac{1}{3b^2}\left(m^2+\lambda|H|^2\right)\left[\left(m^2+\lambda|H|^2\right)^2 - 3ab|H|^2\right] + \frac{1}{3b^2}\left[\left(m^2+\lambda|H|^2\right) - 2ab|H|^2\right]^{3/2}$$

Tree Exchange $\Rightarrow$ SMEFT

Expand

$$V_{ILPI} = V_{SM} - \frac{1}{3b^2}\left(m^2 + \lambda'|H|^2\right)\left[\left(m^2+\lambda'|H|^2\right)^2 - 3ab|H|^2\right]$$
$$+ \frac{1}{3b^2}\left[\left(m^2+\lambda'|H|^2\right) - 2ab|H|^2\right]^{3/2}$$

in $|H|^2/m^2 \Rightarrow$ Local SMEFT expansion

Tree Exchange $\Rightarrow$ HEFT

But if $m^2 = 0$ ...

$$V_{ILPI} = V_{SM} + \frac{1}{3b^2}\left[3ab\lambda|H|^4 - \lambda^3|H|^6 + \left(-2ab|H|^2 + \lambda^2|H|^4\right)^{3/2}\right]$$

is non-analytic about $|H| = 0$

$\Rightarrow$ HEFT (will revisit)

Similar story for corrections to $|\partial H|^2$ & $(\partial|H|^2)^2$

Loop Exchange

Singlet extension w/ $a = b = 0$

$$\mathcal{L}_{BSM} = \frac{1}{2} S' \left(-\partial^2 - m^2 - \lambda |H|^2 \right) S'$$

Leading BSM correction at one loop

Use functional matching (Coleman-Weinberg for V_{1LPI})

$$m_S^2 = m^2 + \frac{\lambda}{2} v^2 \Rightarrow \int d^4x \, \mathcal{L}_{1LPI}^{1\text{-loop}} = i \log \det \left(\partial^2 + m^2 + \lambda |H|^2 \right)$$

Loop Exchange

$$\mathcal{L}_{1LPI} = |\partial H|^2 - \cancel{\mu_h^2 |H|^2} + \frac{1}{2}\lambda_h |H|^4$$

$$+ \frac{1}{16\pi^2}\left(m^2 + \lambda|H|^2\right)^2 \left(\ln \frac{\mu_h^2}{m^2+\lambda|H|^2} + \frac{3}{2}\right)$$

$$+ \frac{1}{16\pi^2}\,\frac{1}{6}\,\frac{\lambda^2}{m^2+\lambda^2|H|^2}\left(\partial|H|^2\right)^2$$

When $m^2 \neq 0 \Rightarrow$ expand to derive local SMEFT,

but $m^2 = 0 \Rightarrow \log\left(\mu_h^2/\lambda|H|^2\right)$ non-analytic!

$\Rightarrow$ need HEFT (will revisit)

Is Analyticity Enough?

Does requiring A, B, $\tilde{V}$ be analytic ensure SMEFT?

Field redefinitions do not change physics (must be analytic and include linear term)

Cannot remove non-analyticity w/ H redef

What about using redefs of h?

Field Redefinitions of h

Let

$$\mathcal{L} = \frac{1}{2}\left(1+\frac{h}{2v}\right)^2(\partial h)^2 + \frac{1}{2}(v+h)^2\left(\frac{3}{4}+\frac{h}{4v}\right)^2(\partial\vec{n})^2 - V$$

$$= \frac{1}{4}\left(1+\frac{\sqrt{2|H|^2}}{v}+\frac{|H|^2}{2v^2}\right)|\partial H|^2$$

$$+\frac{1}{4v^2}\left(\frac{v}{\sqrt{2|H|^2}}+\frac{3}{4}\right)\frac{1}{2}\left(\partial|H|^2\right)^2 - \tilde{V}$$

$$\boxed{\begin{array}{l} \text{w/ } V=V(h) \\ V'(0)=0 \\ V \text{ analytic} \end{array}}$$

Looks like no SMEFT expansion...

Field Redefinitions of h

But let $h_1 = h + \frac{1}{4v} h^2$ (no shift in min of V)

$$\Rightarrow \partial_\mu h_1 = \left(1 + \frac{h}{2v}\right) \partial_\mu h$$

and $(v_1 + h_1)^2 = (v+h)^2 \left(\frac{3}{4} + \frac{h}{4v}\right)$ $\quad v_1 = \frac{3}{4} v$

$$\Rightarrow \mathcal{L} = \frac{1}{2}(\partial_\mu h_1)^2 + \frac{1}{2}(v_1 + h_1)^2 (\partial \vec{n})^2 + V$$

$$= |\partial H_1|^2 + \tilde{V} \Rightarrow \text{SMEFT!}$$

Field Redefinitions of h

We learned that analytic field redefs of h can obscure analyticity in terms of H.

Field redefs within HEFT can obscure SMEFT

When should/must one use HEFT?

Practical Criterion

One should match onto HEFT when integrating out a state whose mass is near (or below) the electroweak scale

Check radius of convergence for EFT expansion

Practical Criterion

Radius of convergence:

$$\mathcal{L} \supset \sum_m \frac{c_m}{\Lambda^{2m-4}} |H|^{2m} \supset \lambda_{h^3} h^3$$

$$= \sum_m \frac{2^{1-m}}{3} m(m-1)(2m-1) c_m \left(\frac{v}{\Lambda}\right)^{2m-4} v h^3$$

$\Rightarrow$ if $\Lambda \sim v$ and $c_m \sim 1$

$\Rightarrow$ SMEFT does not converge

Applying the Practical Criterion

Revisit singlet loop example

$$V^{1\text{-loop}} = \frac{1}{16\pi^2}\left(m^2+\lambda|H|^2\right)^2\left(\ln\frac{\Lambda^2}{m^2+\lambda|H|^2}+\frac{3}{2}\right)$$

SMEFT: expand in $X_{SMEFT} = \dfrac{\lambda|H|^2}{m^2}$

HEFT: expand in $X_{HEFT} = \dfrac{\lambda\left(|H|^2-\frac{1}{2}v^2\right)}{m^2+\frac{1}{2}\lambda v^2}$

so that $m^2\left(1+X_{SMEFT}\right) = m_{phys}^2\left(1+X_{HEFT}\right)$

Applying the Practical Criterion

$$V^{1\text{-loop}} = \frac{1}{16\pi^2}\left(m^2+\lambda|H|^2\right)^2\left(\ln\frac{\Lambda_n^2}{m^2+\lambda|H|^2}+\frac{3}{2}\right)$$

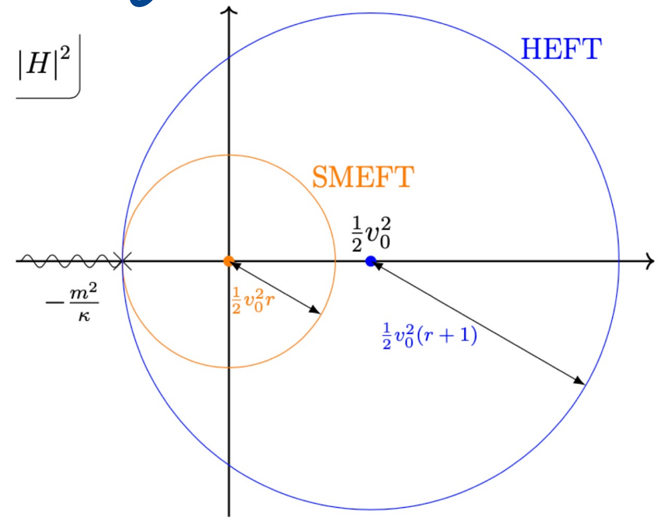
$$V_{SMEFT} \supset \ldots + \sum_{k=3}^{k_{max}} \frac{2(-1)^k}{k(k-1)(k-2)} \mathcal{X}_{SMEFT}^k$$

$$V_{HEFT} \supset \ldots + \sum_{k=3}^{k_{max}} \frac{2(-1)^k}{k(k-1)(k-2)} \mathcal{X}_{HEFT}^k$$

Radius of Convergence

Define $r = \dfrac{m^2}{\kappa v^2/2}$

s.t. $r \to \infty$ as $m^2 \to \infty$



Then

$$X_{SMEFT} \sim \frac{1}{r}$$

$$X_{HEFT} \sim \frac{1}{r+1}$$

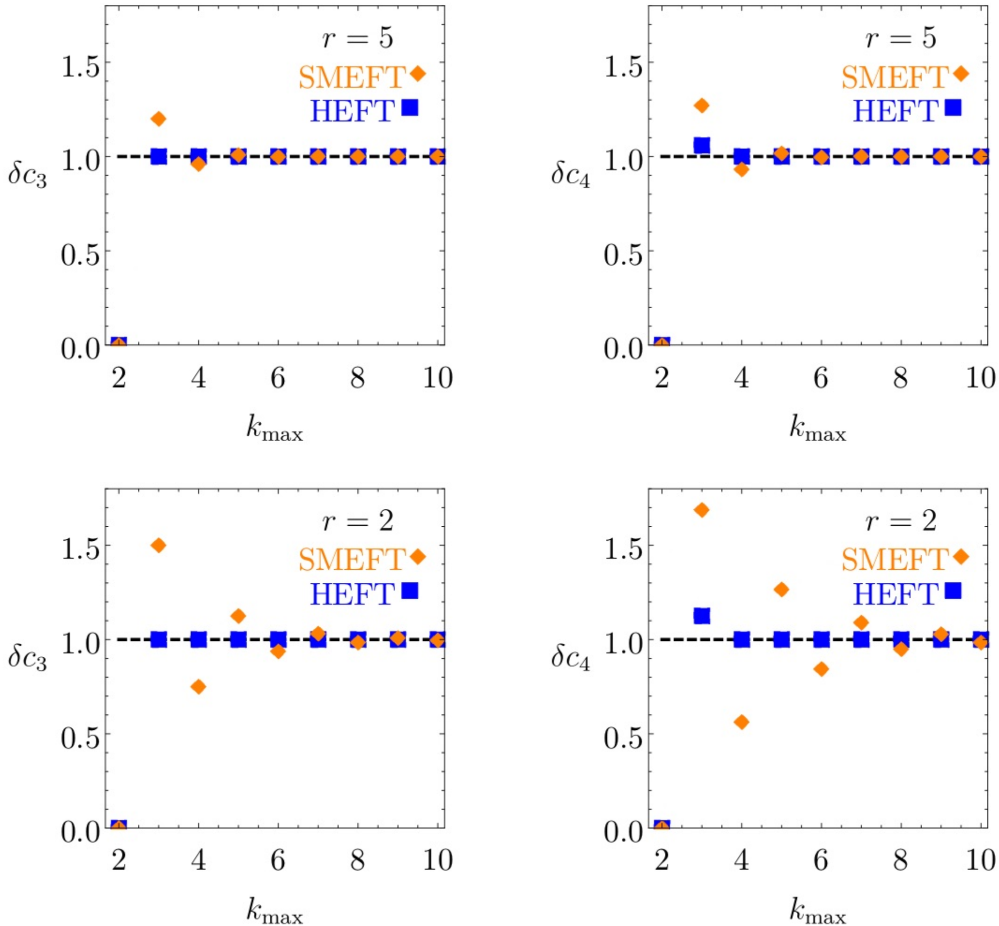
$r > 1$: both converge

$0 < r \leq 1$: SMEFT does not converge

$r = 0$: SMEFT does not exist

Rate of Convergence

Correction to h^3



Correction to h^4

Curvature Invariants

We saw examples where particle gets all of its mass from Higgs

$\Rightarrow$ SMEFT does not exist

But could be obscured by field redef

Want basis independent check

Goal classify UV theories that require HEFT

Curvature Invariants

(AJM)

Analog w/ GR: define metric on moduli space

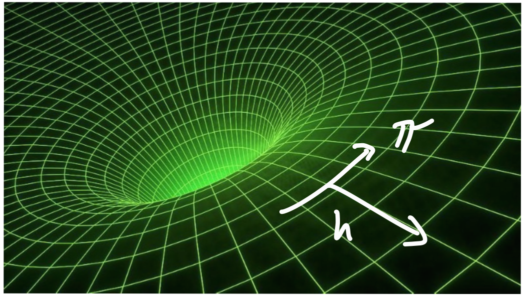
Note $$(\partial \vec{n})^2 = \left(\delta_{ij} + \frac{n_i n_j}{1-n^2}\right)(\partial^\mu n_i)(\partial_\mu n_j)$$

$$\Rightarrow \mathcal{L}_{HEFT} \supset \frac{1}{2}\left[\underline{K}(h)\right]^2(\partial h)^2 + \frac{1}{2}\left[v F(h)\right]^2(\partial \vec{n})^2$$

$\Rightarrow$ metric

$$g_{hh} = \underline{K}^2$$

$$g_{ij} = vF^2\left(\delta_{ij} + \frac{n_i n_j}{1-n^2}\right)$$



Curvature Invariants

metric

$$g_{hh} = \mathbb{K}^2$$

$$g_{ij} = vF^2\left(\delta_{ij} + \frac{n_i n_j}{1-n^2}\right)$$

Ricci scalar

$$R = -\frac{2N_\varphi}{\mathbb{K}^2 F}\left[\left(\partial_h^2 F\right) - \left(\partial_h \mathbb{K}\right)\left(\frac{1}{\mathbb{K}}\partial_h F\right)\right] + \frac{N_\varphi(N_\varphi - 1)}{v^2 F^2}\left[1 - \left(\frac{v}{\mathbb{K}}\partial_h F\right)^2\right]$$

HEFT is a Black Hole

Conjecture: Checking finiteness of R & V is sufficient.

Two classes of models need HEFT:

Conical singularity: BSM state gets all of its mass from H

Horizon: BSM sources of symmetry breaking

Conical Singularity

Ex: Singlet w/ $S|H|^2$ & S^3 $\Rightarrow$ tree level

$$\Rightarrow R(h=-v) = \frac{a^2}{m^4} N_\varphi (N_\varphi + 1)$$

finite w/ $m^2 \neq 0$ but diverges as $m^2 \to 0$

Ex: Singlet w/ $S^2|H|^2$ $\Rightarrow$ loop level

$$\Rightarrow R(h=-v) = \frac{1}{192\pi^2} \frac{\lambda}{3m^2} N_\varphi (N_\varphi + 1)$$

but $R|_{m^2=0} = \frac{N_\varphi(N_\varphi - 1)}{(v+h)^2} \frac{\lambda}{96\pi^2 + \lambda} \xrightarrow[h \to -v]{} \infty$

Horizon

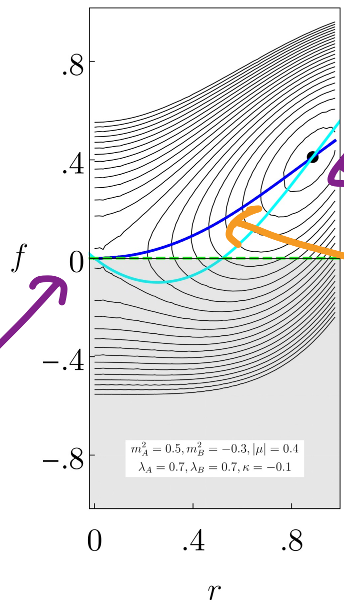
(see our recent application to the 2HDM in arXiv:2304.09884)

We provide three examples in paper.

Rely on "EFT submanifold" picture

Ex: Abelian toy model w/ vevs f & r

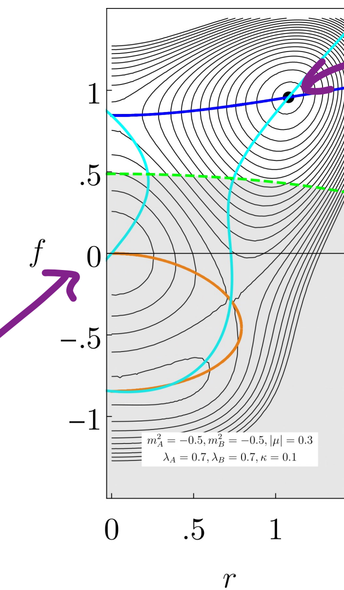
$m^2_{BSM} > 0$



physical vac

SMEFT trajectory

fixed point



physical vac

fixed point

$m^2_{BSM} < 0$

no SMEFT trajectory

$\Rightarrow$ HEFT

Non-Decoupling New Particles

Does HEFT have experimentally viable UV completions? "Loryons"

We characterize all Loryons satisfying

- Color singlets have integer E/M charge
- Those possessing E/M charges decay promptly
- Fermionic Loryons introduced in pairs so we can write Custodially Symmetric Yukawa Couplings

Loryon Catalog

Notation

- Custodial irrep $[L, R]_Y$

  $SU(2)_{L/R}$, $U(1)_Y$

- SM charges $(C, L)_Y$

  $SU(3)_C$, $SU(2)_L$, $U(1)_Y$

Must get at least half their mass from the Higgs $\Rightarrow$ Candidate UV completion of HEFT

Loryon Catalog

Scalars

SM Reps	$(1,1)_Y$	$(1,2)_Y$	$(1,3)_Y$	$(1,4)_Y$	$(1,L)_Y$	$(3,1)_Y$	$(3,2)_Y$
Field	S_Y	Φ_{2Y}	Ξ_Y	Θ_{2Y}	$X_{L,Y}$	$\omega_{\|3Y\|}$	$\Pi_{\|6Y\|}$

	$R=1$	2	3	4	5	6	7	8
$L=1$	$\|Y_{max}\|=3$	$\frac{5}{2}$	2	$\frac{3}{2}$	1	$\frac{1}{2}$	0	$\times$
2	$\frac{7}{2}$	4	$\frac{7}{2}$	4	$\frac{9}{2}$	5	$\frac{11}{2}$	5
3	3	$\frac{7}{2}$	4	$\frac{9}{2}$	4	$\frac{9}{2}$	5	$\frac{11}{2}$
4	$\frac{7}{2}$	3	$\frac{7}{2}$	4	$\frac{9}{2}$	5	$\frac{11}{2}$	5
5	3	$\frac{7}{2}$	4	$\frac{7}{2}$	4	$\frac{9}{2}$	5	$\frac{11}{2}$
6	$\frac{5}{2}$	3	$\frac{7}{2}$	4	$\frac{9}{2}$	5	$\frac{9}{2}$	4
7	3	$\frac{7}{2}$	3	$\frac{5}{2}$	2	$\frac{3}{2}$	1	$\frac{1}{2}$
8	$\frac{3}{2}$	1	$\frac{1}{2}$	0	$\times$	$\times$	$\times$	$\times$

Loryon Catalog

Vector-like Fermions

SM Reps	$(1,1)_Y$	$(1,2)_Y$	$(1,3)_Y$	$(1,L)_Y$	$(3,1)_Y$
Field	E_Y	Δ_{2Y}	Σ_Y	$K_{L,Y}$	$P_{\lvert 3Y \rvert}$

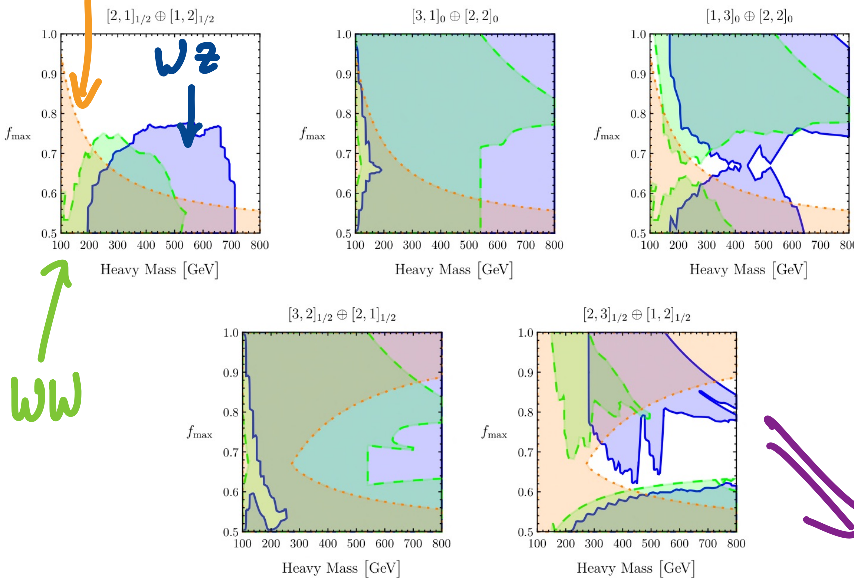
	$R = 1$	2	3	4	5	6	7	8
$L = 1$	$\lvert Y_{max} \rvert = 3$	$\frac{5}{2}$	2	$\frac{3}{2}$	1	$\frac{1}{2}$	0	$\times$
2	$\frac{7}{2}$	3	$\frac{7}{2}$	4	$\frac{9}{2}$	5	$\frac{11}{2}$	5
3	3	$\frac{7}{2}$	3	$\frac{7}{2}$	4	$\frac{9}{2}$	5	$\frac{11}{2}$
4	$\frac{5}{2}$	3	$\frac{7}{2}$	4	$\frac{7}{2}$	4	$\frac{9}{2}$	5
5	3	$\frac{5}{2}$	3	$\frac{7}{2}$	4	$\frac{9}{2}$	5	$\frac{9}{2}$
6	$\frac{5}{2}$	3	$\frac{7}{2}$	3	$\frac{5}{2}$	2	$\frac{3}{2}$	1
7	2	$\frac{3}{2}$	1	$\frac{1}{2}$	0	$\times$	$\times$	$\times$
8	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$

Fermionic Loryons

LEP

WZ

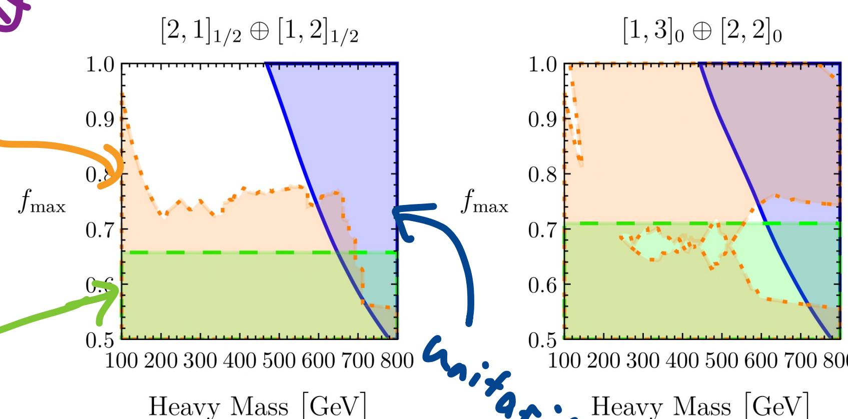
WW



Open parameter space!

direct search

Precision EW



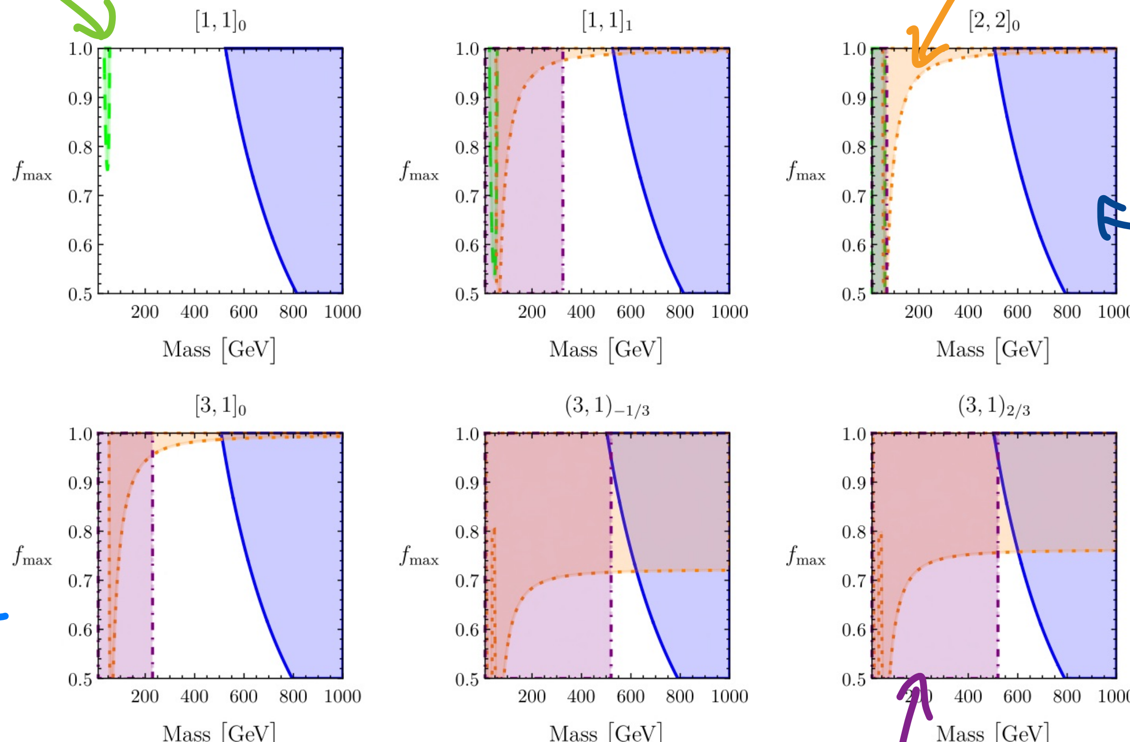
unitarity

(Double use of colors ... 😬)

Scalar Loryons

Higgs decay

h_γ, h_g



unitarity

Open Parameter Space!

direct searches

Future Prospects

- HL-LHC Higgs coupling improvements on κ_g and κ_γ rules out colored triplet scalars.
- Improved precision on $\kappa_{Z\gamma}$ will also have impact

Rep	$[1,1]_1$	$[3,1]_0$	$[1,3]_0$	$[2,2]_0$	$[3,3]_0$	$[4,2]_0$	$[2,4]_0$	$[2,3]_{-1/2}$	$[2,1]_{1/2} \oplus [1,2]_{1/2}$	$[1,3]_0 \oplus [2,2]_0$
$\frac{\sum \eta_i C_i^{Z\gamma}}{\sum \eta_i Q_i^2}$	$-.12$	$.38$	$-.12$	$.13$	$.13$	$.30$	$-.032$	$-.008$	$-.019$	$-.019$

- Higgs wavefunction deviation has minimal impact

$$\mathcal{O}_H \equiv \frac{c_H}{\Lambda^2}\frac{1}{2}\left(\partial^\mu |H|^2\right)^2$$

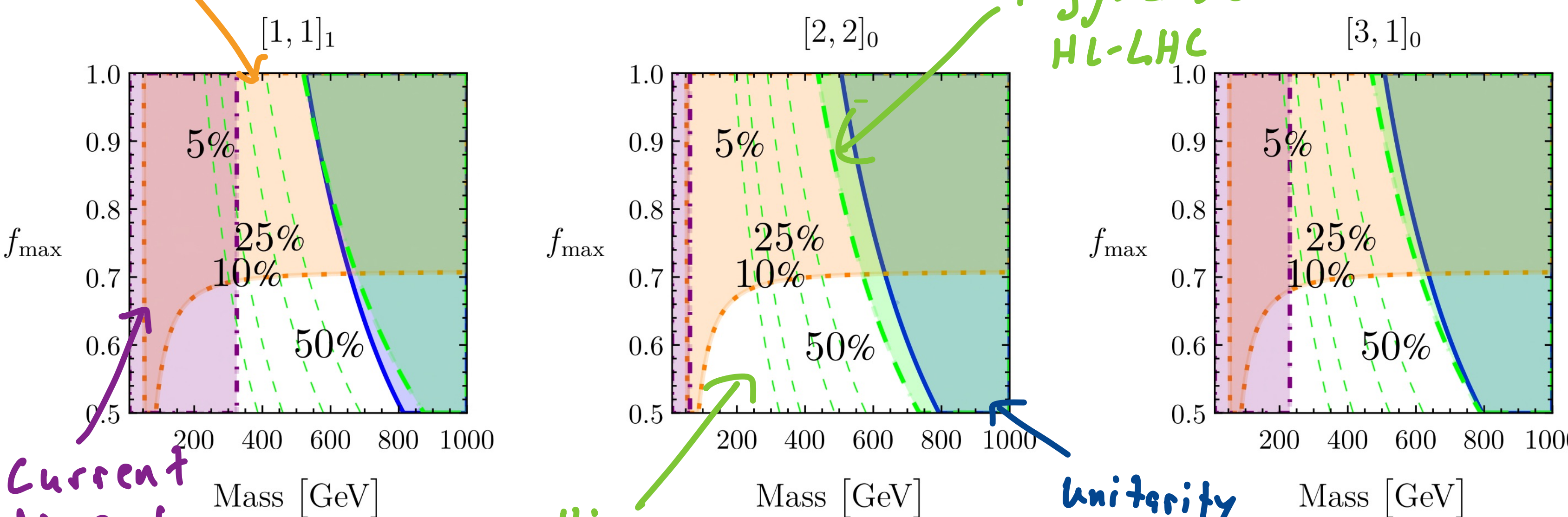
projected constraint $\frac{\Lambda}{\sqrt{c_H}} \sim 1.4\,\mathrm{TeV}$

Future Prospects

Higgs cubic coupling constraint helps

Scalar Loryons

$h\gamma\gamma + hgg$ @ HL-LHC



Can FCC determine if electroweak symmetry can be linearly realized around scales of $\mathcal{O}(m_h)$?

- Dedicated study needs to be done
- Probe remaining Loryon parameter space?
- Explore models with extra electroweak symmetry breaking (see our 2HDM example)
- Unitarity violation @ $4\pi v$ in Goldstone + Higgs scattering

See TC, Craig, Lu, Sutherland [arXiv: 2108.03240]