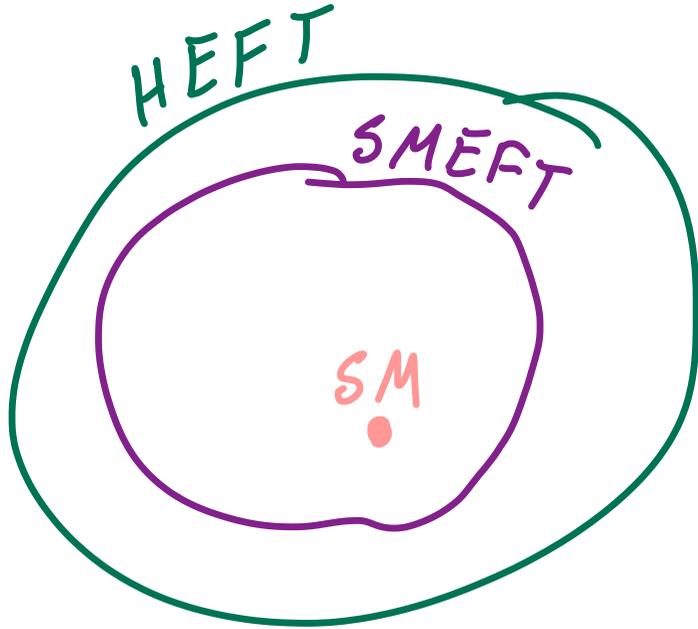


Is SMEFT Enough?



Tim Cohen
University of Oregon

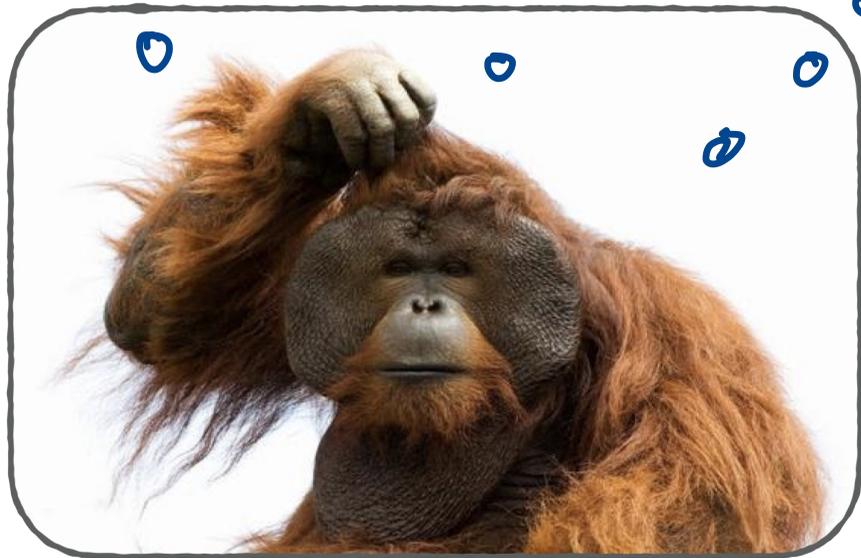
Higgs 2021
Oct 21



Where's
the
new Physics?

How
best to
search?

Can we
be systematic?

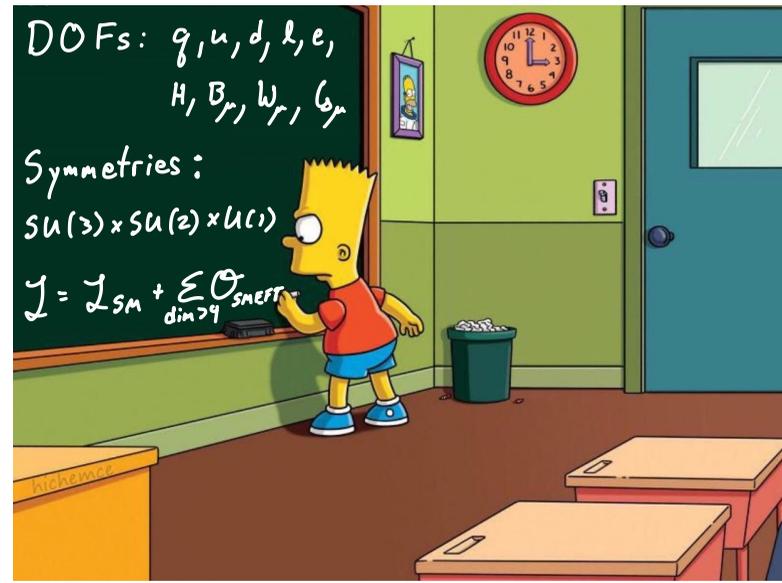


How to organize BSM predictions?

Simplified Models



Effective Field Theory



The Standard Model as EFT

"Heavy physics decouples"

- Only SM degrees of freedom
- Symmetries (Lorentz + $SU(3) \times SU(2) \times U(1)$)

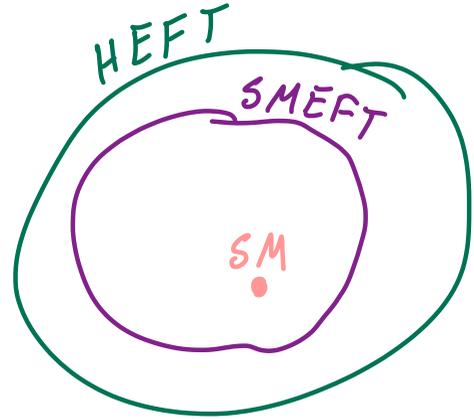
Realize electroweak symmetry

linear or non-linearly
↑ ↑
SMEFT $\mathcal{L}(H^a)$ HEFT $\mathcal{L}(h, \pi^i)$

To SMEFT or to HEFT?

HEFT \gg SMEFT

What (perturbative) BSM
models require HEFT??



Based on

TC, Craig, Lu, Sutherland

arXiv:2008.08597 and 2108.03240

+ Banta arXiv:2110.02967 (see Ian's parallel talk)

EFT Matching

Let ϕ be set of light fields
and Φ be set of heavy fields

"Matching" is systematic procedure
to derive an EFT description valid for

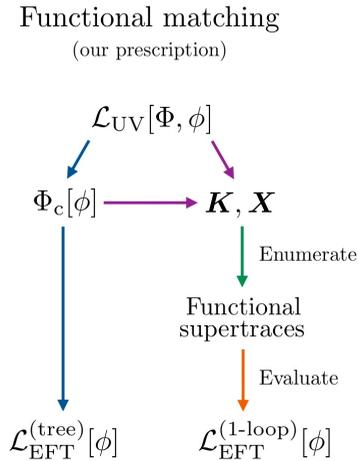
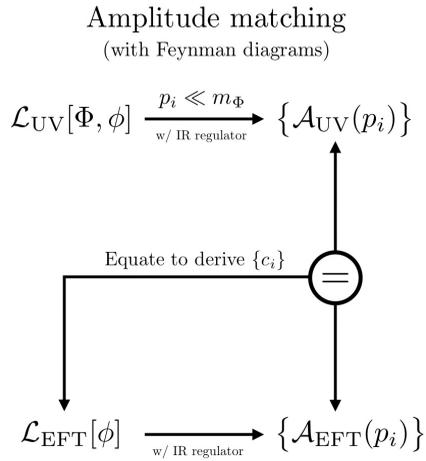
$$E \sim m_\phi \ll M_\Phi$$



"Connects UV
params to
EFT params"

see TC's EFT lectures arXiv:1903.03622

Functional EFT Matching



- Evaluate path integral directly

- No need to specify basis in advance

TC, Lu, Zhang arXiv: 2011.02484

Automated supertrace evaluation

STREAM: TC, Lu, Zhang arXiv: 2011.02484

SuperTracer: Fuentes-Martin, et al 2012.08506

Is SMEFT Enough?

Want well defined EFT



1) Local expansion
(Analytic function of fields)

2) Convergent expansion

Simplifying assumptions

- 1) Scalars only
- 2) custodial sym $O(4)$

SMEFT ($v=0$)

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

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

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

Think of H as Cartesian coords on manifold

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)

$$\vec{\varphi} = (v_0 + h) \vec{n} \quad w/$$

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

$$\vec{n} = \begin{pmatrix} n_1 = \pi_1/v \\ n_2 = \pi_2/v \\ n_3 = \pi_3/v \\ n_4 = \sqrt{1 - n_i^2} \end{pmatrix}$$

HEFT ($v \neq 0$)

$O(4)$ transformation: $h \rightarrow h$, $\vec{n} \rightarrow O\vec{n}$
 $\Rightarrow \vec{n}$ in non-linear rep

$$\mathcal{L}_{\text{HEFT}} = \frac{1}{2} [\mathbb{K}(h)]^2 (\partial h)^2 + \frac{1}{2} [v F(h)]^2 (\partial \vec{n})^2 - V(h) + \mathcal{O}(\partial^4)$$

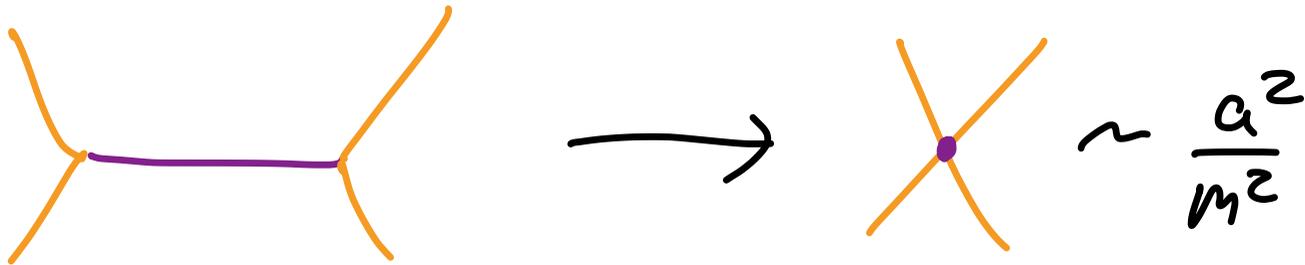
$$\langle h \rangle = 0$$

Example Model

Extend SM with singlet scalar S

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

Tree-level matching



Tree Exchange

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

Integrate out S' :

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

Tree Exchange \Rightarrow SMEFT

Expand

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

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

Tree Exchange \Rightarrow HEFT

But if $m^2 = 0 \dots$

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

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

\Rightarrow HEFT

(See paper for loop example.)

It is tempting to conclude...

If a BSM particle gets
all its mass from the Higgs

⇒ HEFT is required



What about field redefinitions? 



Alonso, Jenkins, Manohar (AJM) arXiv:1605.03602

HEFT \rightarrow SMEFT?

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

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

etc.

Naively:

$$\mathcal{L}_{\text{HEFT}} = \frac{v^2 F}{2 |H|^2} |\partial H|^2 + \frac{1}{2} (\partial |H|^2)^2 \frac{1}{2 |H|^2} \left(\mathbb{K}^2 - \frac{v^2 F^2}{2 |H|^2} \right)$$
$$+ \tilde{V}(|H|^2) + \mathcal{O}(\partial^4)$$

Analytic @ $|H|=0$?

Field Redefinitions of h

Let

$$\begin{aligned}\mathcal{L} &= \frac{1}{2} \left(1 + \frac{h}{2v}\right)^2 (\partial h)^2 + \frac{1}{2} (v+h)^2 \left(\frac{3}{4} + \frac{h}{4v}\right)^2 (\partial \dot{h})^2 - V \\ &= \frac{1}{4} \left(1 + \frac{\sqrt{2|H|^2}}{v} + \frac{|H|^2}{2v^2}\right) (\partial H)^2 \\ &\quad + \frac{1}{4v^2} \left(\frac{v}{\sqrt{2|H|^2}} + \frac{3}{4}\right) \frac{1}{2} (\partial |H|^2)^2 - \tilde{V}\end{aligned}$$

w/ $V=V(h)$
 $V'(0)=0$
 V analytic

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

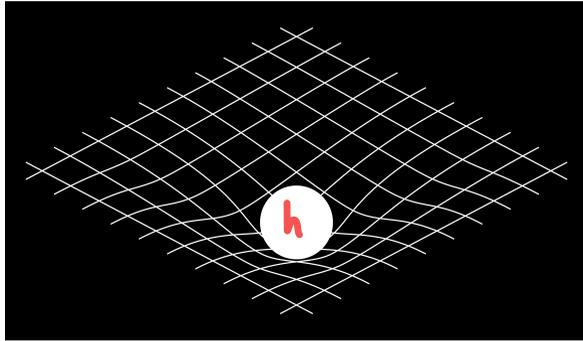
$$\begin{aligned} \Rightarrow \mathcal{I} &= \frac{1}{2} (\partial_\mu h_1)^2 + \frac{1}{2} (v_1 + h_1)^2 (\partial \vec{n})^2 + V \\ &= |\partial H_1|^2 + \tilde{V} \Rightarrow \text{SMEFT!} \end{aligned}$$

Geometry of the Scalar Sector

AJM

Want a formulation that is independent of field redefinitions.

field redef \equiv Coordinate change



Derived "Curvature Criterion" to diagnose when HEFT is required (TC, Craig, Lu, Sutherland)

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

Is SMEFT Enough?

Want well defined EFT

✓ 1) Local expansion
(Analytic function of fields)
"HEFT is a black hole"

2) Convergent expansion



Practical Criterion

Radius of convergence:

$$\mathcal{I} \supset \sum_m \frac{C_m}{\Lambda^{2m-4}} |H|^{2m} \supset \lambda_h^2 h^3$$

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

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

SMEFT does not converge

Applying the Practical Criterion

BSM Singlet loop example $\mathcal{L} \supset \frac{\lambda}{2} S^2 |H|^2$

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

SMEFT: expand in $\Sigma_{\text{SMEFT}} = \frac{\lambda |H|^2}{m^2}$

HEFT: expand in $\Sigma_{\text{HEFT}} = \frac{\lambda (|H|^2 - \frac{1}{2} v^2)}{m^2 + \frac{1}{2} \lambda v^2}$

so that $m^2 (1 + \Sigma_{\text{SMEFT}}) = m_{\text{phys}}^2 (1 + \Sigma_{\text{HEFT}})$

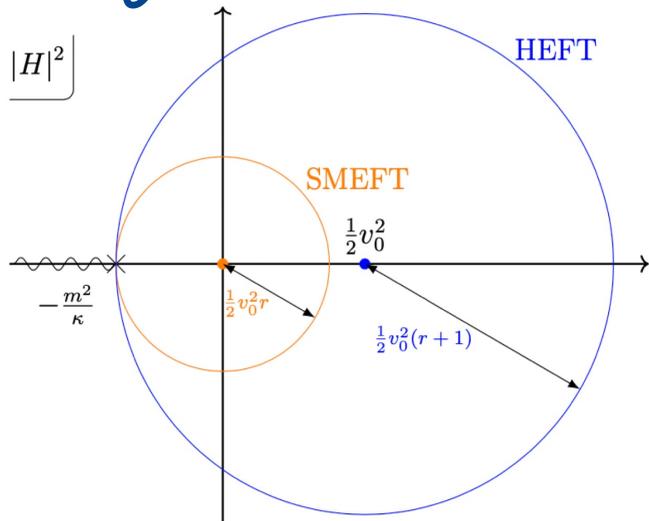
Radius of Convergence

Define $r = \frac{m^2}{2\alpha v^2/2}$

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

Then $\chi_{\text{SMEFT}} \sim \frac{1}{r}$

$\chi_{\text{HEFT}} \sim \frac{1}{r+1}$



- $r > 1$: both converge
- $0 < r \leq 1$: SMEFT does not converge
- $r = 0$: SMEFT does not exist

Unitarity Violation in HEFT

HEFT is non-decoupling

⇒ expect unitarity violation

analyticity ↔ unitarity



geometry



TC, Craig, Lu, Sutherland
arXiv:2108.03240

Geometric amplitude for
 2 Goldstone $\rightarrow n$ Higgs scattering

Finite radius of convergence $\Rightarrow E \lesssim 4\pi v$, $n = \mathcal{O}(\text{few})$

Is SMEFT Enough?

Want well defined EFT

✓ 1) Local expansion
(Analytic function of fields)

"HEFT is a black hole"

✓ 2) Convergent expansion



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

Lorion Catalog

Notation

- Custodial irrep $[L, R]_Y$
- SM charges $(C, L)_Y \leftarrow U(1)_Y$
 $\begin{matrix} \nearrow \\ SU(3)_C \end{matrix} \quad \begin{matrix} \nearrow \\ SU(2)_L \end{matrix}$

$\nwarrow SU(2)_{L/R}$

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

Loryon Catalog

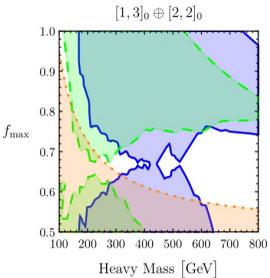
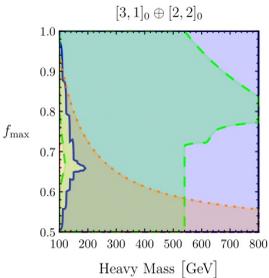
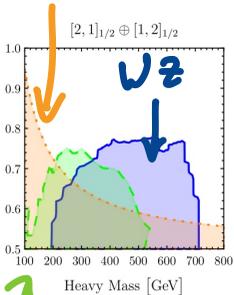
SCALARS

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

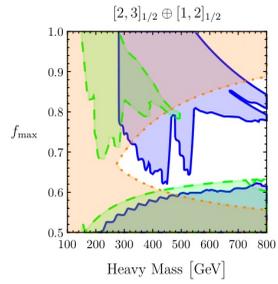
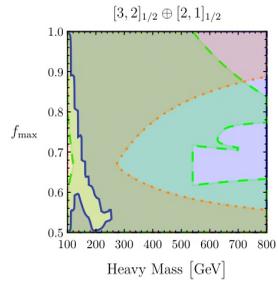
Fermionic Loryons

LEP



Open parameter space!

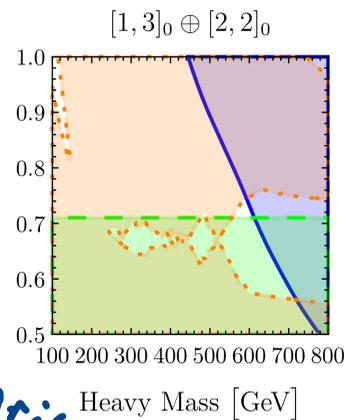
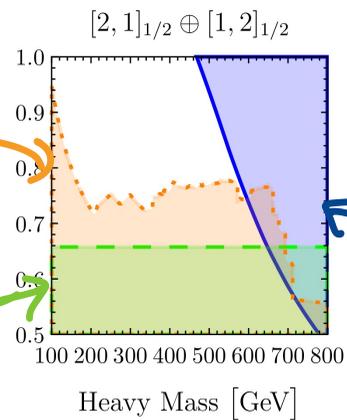
WW



(Double use of colors ... 😬)

Direct search

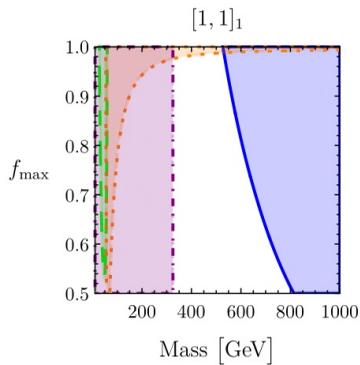
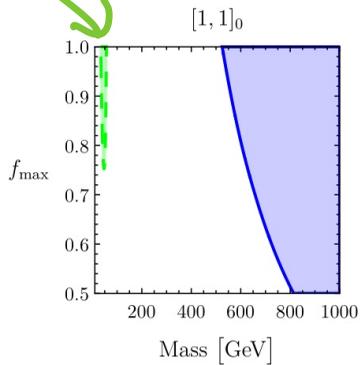
Precision EW



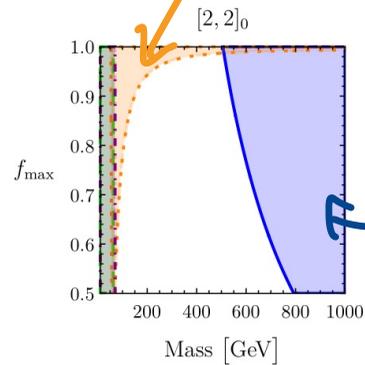
Unitarity

Scalar Longons

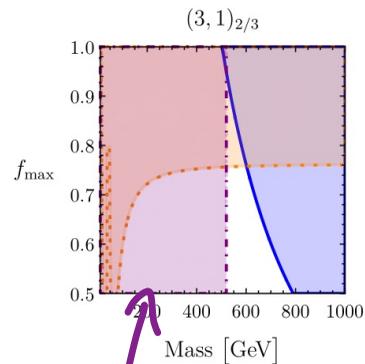
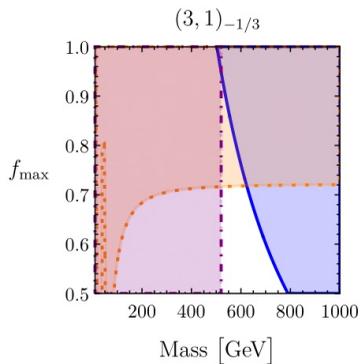
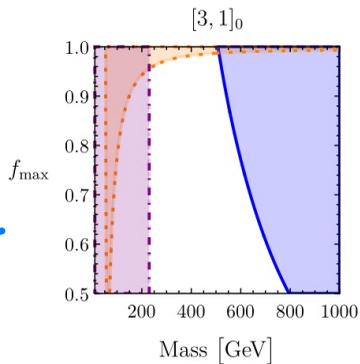
Higgs decay



$\mathcal{M}_\tau, \mathcal{M}_g$



Unitarity



direct searches

Open
Parameter
Space!

- EFT is useful for parametrizing BSM
- SMEFT: linear realized EW sym
decoupling manifest
- HEFT: non-linear realized EW sym
useful when BSM scale near v
- HEFT required
 - BSM state gets all mass from H
 - BSM source of sym breaking
- HEFT violates unitarity @ $E \lesssim 4\pi v$
- Viable Loryon parameter space exists!