EFTs of Weakly-Interacting Light Particles and Their Phenomenology

Huayang Song

Institute Theoretic of Physics

第十二届新物理研讨会

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Search for New Physics

Status:

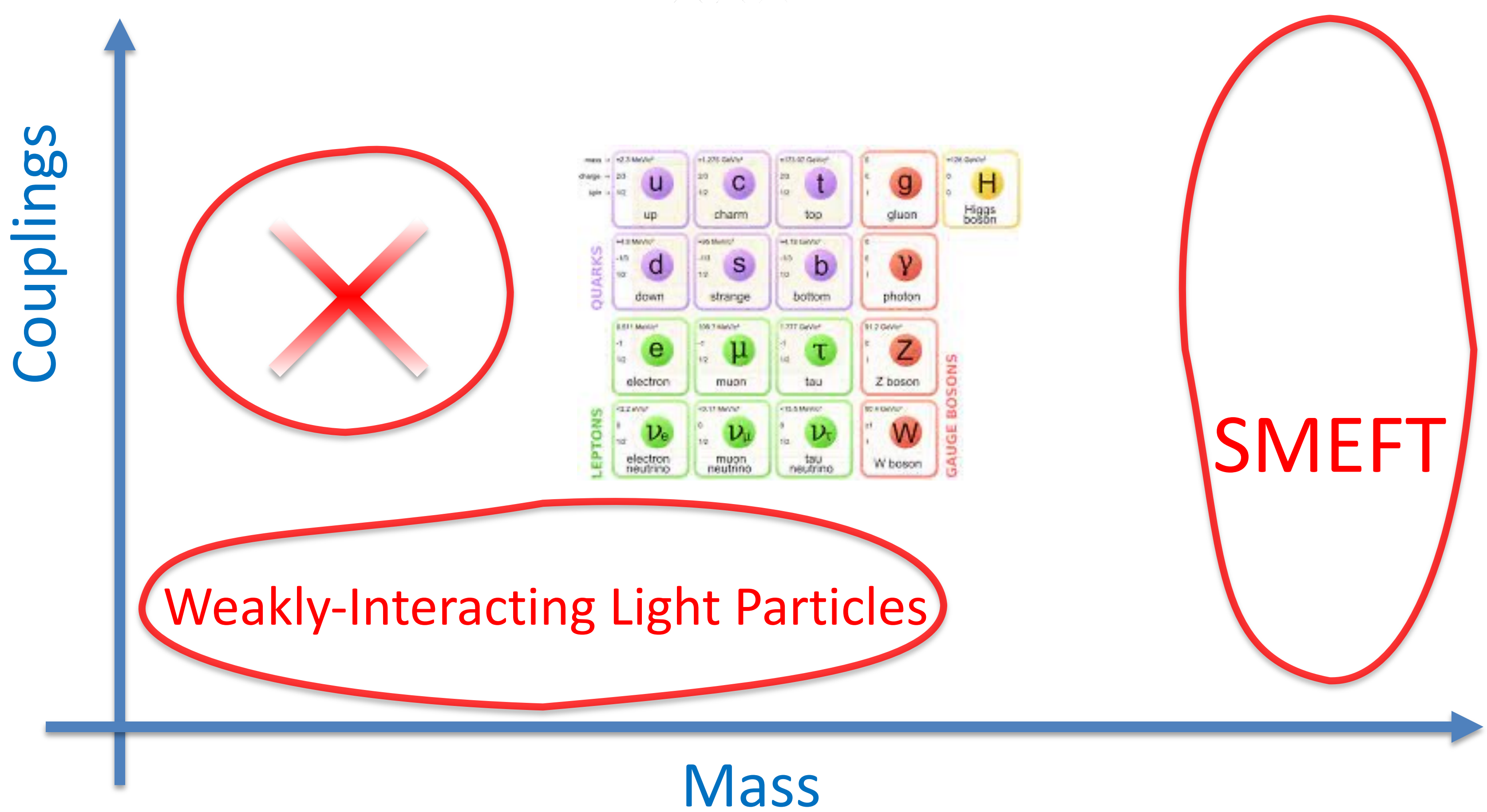
- No new particles are directly found with mass up to ~ 1 *TeV* and $\mathcal{O}(1)$ couplings
- Experiment anomalies and theoretical challenges need new physics

EFT

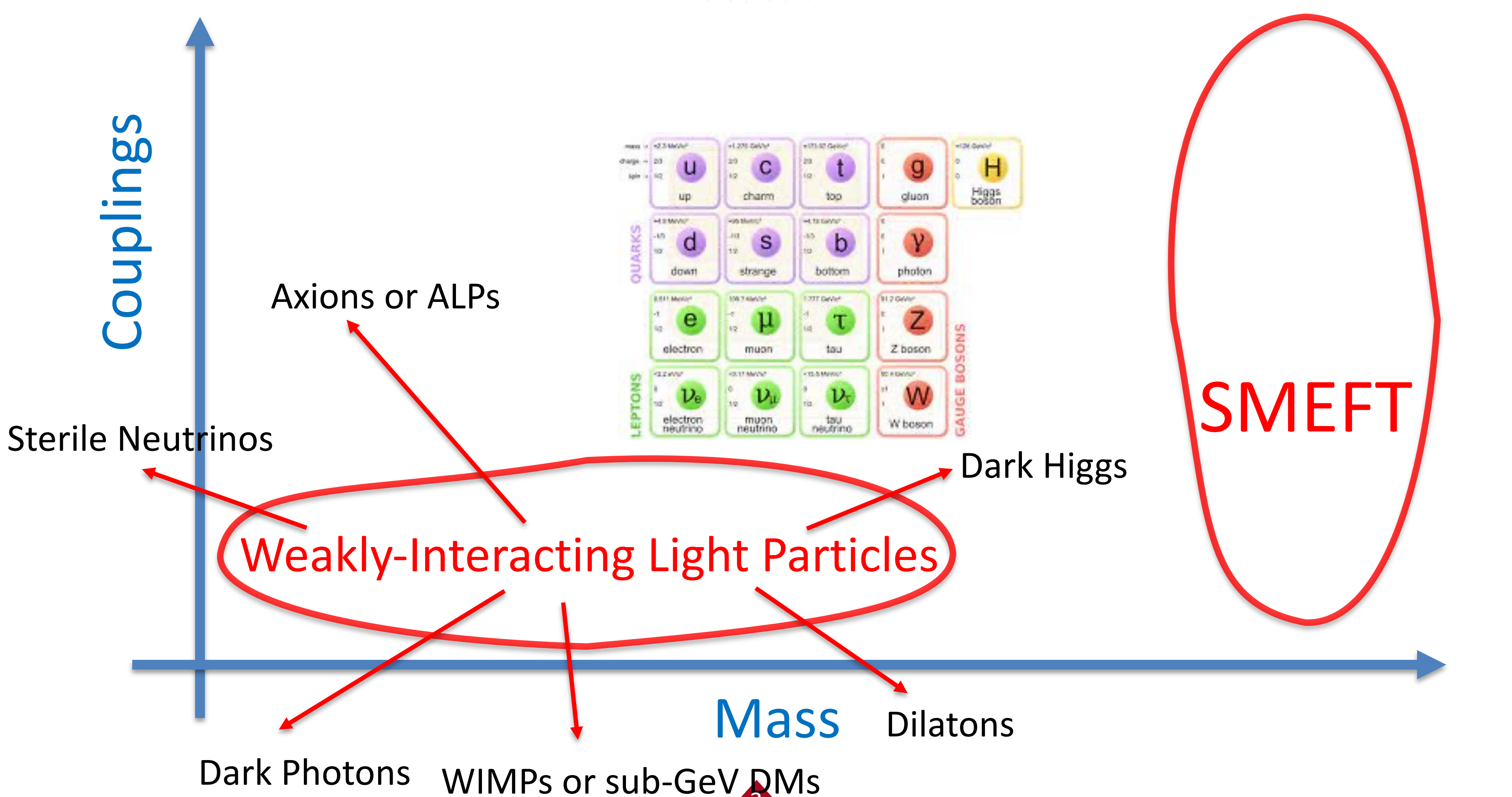
SMEFT

Search for New Physics

DoFs are correct or enough?



Weakly-Interacting Light Particles (WILPs)



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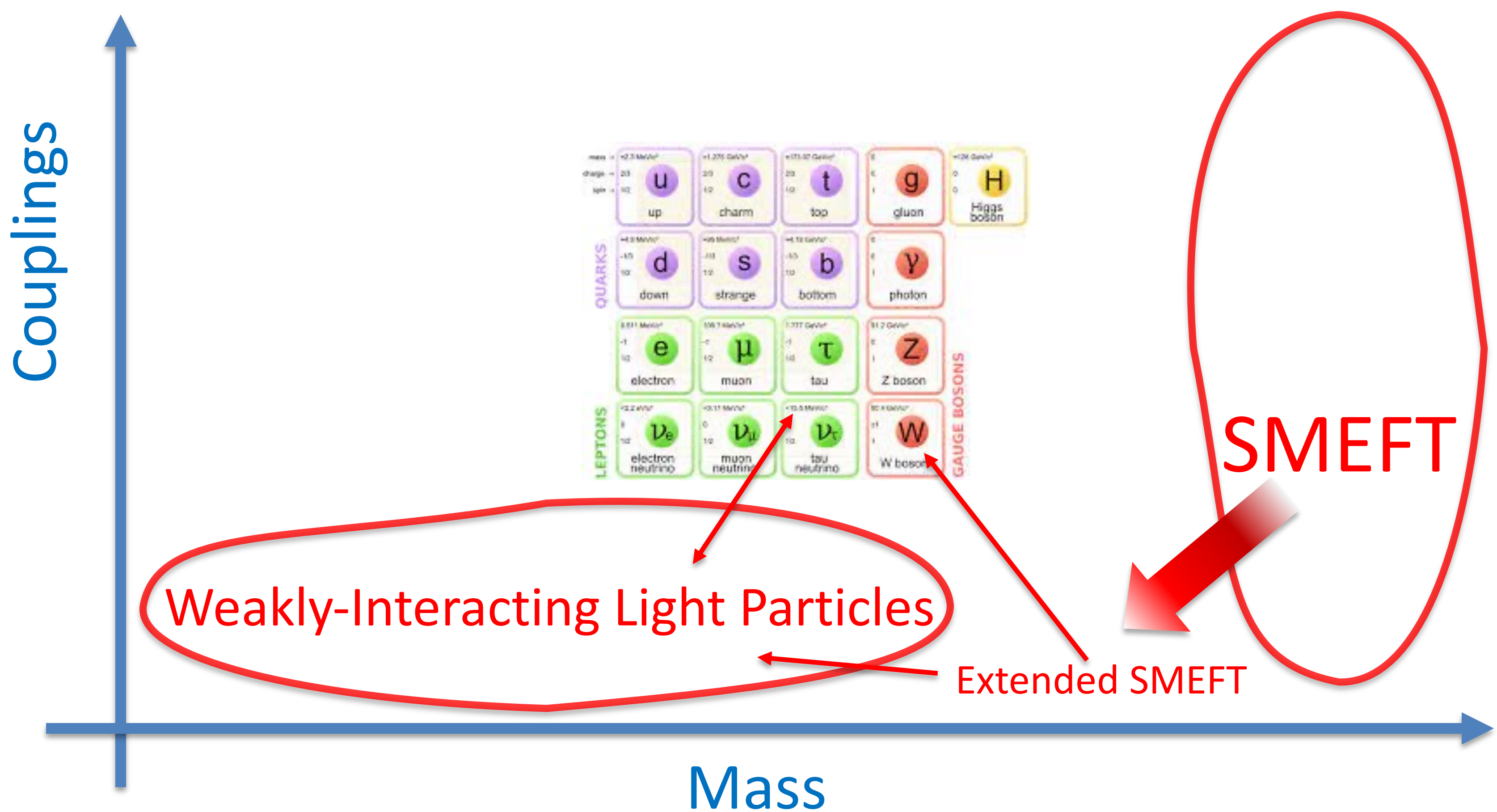

Classification of Singlet Particles

We only consider SM singlet particles with spin up to 1.

$$h = 0: \quad \phi \sim 1$$

$$h = -\frac{1}{2}: \quad \psi \sim \lambda_\alpha$$

$$h = \frac{1}{2}: \quad \psi^\dagger \sim \tilde{\lambda}^{\dot{\beta}}$$

$$h = -1: \quad X_L \sim \lambda_\alpha \lambda_\beta$$

$$h = 1: \quad X_R \sim \tilde{\lambda}^{\dot{\alpha}} \tilde{\lambda}^{\dot{\beta}}$$

$$p \sim \lambda_\alpha \tilde{\lambda}^{\dot{\beta}}$$

The independent and complete effective operators can be constructed systematically via the Young tensor method.

Li *et al.* 20', 20', 22'

ABC4EFT

See Zhe Ren's talk

Goldstone Bosons

What makes Numbu-Goldstone bosons different from generic scalars?

- In terms of operators: non-linearly realized symmetry on G/H

$$\pi_i^a \to \pi_i^a + \epsilon_i^a + \cdots$$

G-invariant operators (e.g. $\mathrm{tr}(u_\mu u^\mu)$) built from $u_\mu \sim D_\mu \pi$

- In terms of amplitudes: Adler's zero condition

$$\mathcal{M}(p_\pi) \to p_\pi \quad \text{for} \quad p_\pi \to 0$$

$$\lim_{p_\pi \to 0} \sum_{i=1}^{D} c_i \mathcal{B}^i = \sum_{i=1}^{D} c_i \lim_{p_\pi \to 0} \mathcal{B}^i = 0$$

Basis for scalars

$\{\mathcal{B}^i | i = 1, 2, \ldots, D\}$

$\mathcal{B}'^i$ Basis for Goldstones

Goldstone Bosons (ALPs)

Axions or axion-like particles are pseudoscalars corresponding to some $U(1)$ symmetries breaking and possessing shift symmetry.

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu a \partial^\mu a + c_{\widetilde{B}}\frac{a}{f_a}B_{\mu\nu}\widetilde{B}^{\mu\nu} + c_{\widetilde{W}}\frac{a}{f_a}W^a_{\mu\nu}\widetilde{W}^{a\mu\nu} + c_{\widetilde{G}}\frac{a}{f_a}G^\lambda_{\mu\nu}\widetilde{G}^{\lambda\mu\nu}$$

$$+ c_u\frac{\partial_\mu a}{f_a}(\overline{u}_R\gamma^\mu u_R) + c_d\frac{\partial_\mu a}{f_a}\left(\overline{d}_R\gamma^\mu d_R\right) + c_e\frac{\partial_\mu a}{f_a}(\overline{e}_R\gamma^\mu e_R)$$

$$+ c_Q\frac{\partial_\mu a}{f_a}\left(\overline{Q}_L\gamma^\mu Q_L\right)_{i,j\neq 1,1} + c_L\frac{\partial_\mu a}{f_a}\left(\overline{L}_L\gamma^\mu L_L\right)_{i\neq j}$$

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Georgi *et al.* 86'

Chala *et al.* 20', Bauer *et al.* 20'

$$-\frac{a}{f_a}\left(c_{QHu}\overline{Q}_L\widetilde{H}u_R + c_{QHd}\overline{Q}_L H d_R + c_{LHe}\overline{Q}_L H e_R + \text{h.c.}\right)$$

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dim-6 $(D_\mu s)(D^\mu s)H_i H^{\dagger i}$

dim-8 $\epsilon^{ik}\epsilon^{jl}(D^\mu s)H_k(D_\mu H_l)(L_{p_i}L_{r_j})$ $L=2$ s is a majoron

Majorona & Dirac Fermions

For scalars, one can combine two real scalars into a complex one. An extra $U(1)$ symmetry should be imposed for the complex scalars in the operators.

One can perform similar thing in fermion case.

$$\mathcal{L} \supset -m\chi_1\chi_1 - m\chi_2\chi_2 + h.c. \qquad \begin{pmatrix}\chi_1\\ \chi_2\end{pmatrix} \xrightarrow{SO(2)} \begin{pmatrix}\cos\phi & -\sin\phi\\ \sin\phi & \cos\phi\end{pmatrix}\begin{pmatrix}\chi_1\\ \chi_2\end{pmatrix}$$

$$\chi_L = \chi_1 + i\chi_2 \quad \chi_R = \chi_1 - i\chi_2 \longrightarrow \mathcal{L} \supset -m\overline{\chi}_L\chi_R + h.c.$$

$$U(1): \quad \chi_L \to e^{i\phi}\chi_L \text{ and } \chi_R \to e^{-i\phi}\chi_R$$

Hence we construct EFT for $n_\chi = 2$ Majorona fermions and assign opposite $U(1)$ charges for them to obtain EFT for a Dirac fermion. (Double DoFs)

Massive vectors (Dark Photon)

How to describe a massive vector boson?

- Proca Lagrangian: $\mathcal{L} \supset -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{1}{2}m_X^2 X_\mu X^\nu - \epsilon B_{\mu\nu}X^{\mu\nu}$

  breaks gauge symmetry, two building block $X_{\mu\nu}$ and X_μ (related by EoMs), $(X_\mu X^\mu)^2$? M. Reece 1808.09966

- Stueckelberg Lagrangian:

$$X_\mu \longrightarrow X_\mu + \partial_\mu \alpha(x)$$

$$\pi \longrightarrow \pi + m_X \alpha(x).$$

$$\mathcal{L}_{\text{Stueck}} = -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{1}{2}m_X^2(X_\mu - \frac{1}{m_X}\partial_\mu\pi)(X^\mu - \frac{1}{m_X}\partial^\mu\pi) - \frac{1}{2}(\partial^\mu X_\mu + m_X\pi)(\partial^\nu X_\nu + m_X\pi)$$

gauge-fixing $\longrightarrow$

$$-\frac{1}{2\xi}(\partial^\mu X_\mu + \xi m_X\pi)(\partial^\nu X_\nu + \xi m_X\pi)$$

$$U \equiv e^{i\frac{\pi}{m_X}}$$

$$\mathcal{L}'_{\text{Stueck}} = -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{m_X^2}{2}(D_\mu U)^\dagger D^\mu U - \frac{1}{2\xi}(\partial^\mu X_\mu - i\xi m_X^2 \ln U)^2$$

$\xi = \infty$, $U = 1$ $\longrightarrow$

$$m_X^2 X_\mu X^\mu/2.$$

Massive vectors (Dark Photon)

Can EFT indeed includes $(X_\mu X^\mu)^2$?

Higgs mechanism

$$\mathcal{L}_{\text{Dark }\gamma+\text{Dark Higgs}} = -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} + D_\mu S^\dagger D^\mu S + \mu^2 S^\dagger S - \lambda\left(S^\dagger S\right)^2$$

$$S = \frac{1}{\sqrt{2}}\left(v_S + \sigma\right)e^{-i\frac{\pi}{v_S}}$$

$$\begin{aligned}\mathcal{L}_{\text{Dark }\gamma+\text{Dark Higgs}} = &-\frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{1}{2}g^2 v_S^2\left(X_\mu - \frac{1}{g v_S}\partial_\mu\pi\right)\left(X^\mu - \frac{1}{g v_S}\partial^\mu\pi\right)\\ &+\frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{2}2\lambda v_S^2\sigma^2 - \lambda v\sigma^3 - \frac{1}{4}\lambda\sigma^4\\ &+\left(\frac{\sigma}{v} + \frac{\sigma^2}{2v^2}\right)\left(g v X_\mu - \partial_\mu\pi\right)\left(g v X^\mu - \partial^\mu\pi\right)\end{aligned}$$

Integrate out σ

$$\begin{aligned}\mathcal{L}^{\text{EFT}}_{\text{Dark }\gamma+\text{Dark Higgs}-\sigma} = &-\frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{1}{2}g^2 v_S^2\left(X_\mu - \frac{1}{g v_S}\partial_\mu\pi\right)\left(X^\mu - \frac{1}{g v_S}\partial^\mu\pi\right)\\ &+\frac{g^4 v_S^2}{2m_\sigma^2}\left[\left(X_\mu - \frac{1}{g v_S}\partial_\mu\pi\right)\left(X^\mu - \frac{1}{g v_S}\partial^\mu\pi\right)\right]^2 + \cdots\end{aligned}$$

Massive vectors

How to build EFTs for massive vectors

- Building blocks: u_μ and $X_{\mu\nu}$
- Power counting: u_μ has dimension 1 (chiral dimension)

HEFT

***dim*-4 operators**

Class	Type	Stueckelberg	Unitary	F
F_L^2	$X_L B_L$	$B_{L\mu\nu} X_L{}^{\mu\nu}$	✓	
$u\psi\bar{\psi}$	$u e_c e_c^\dagger$	$(e_{cp}\sigma^\mu e^\dagger_{cr})u_\mu$	$(e_{cp}\sigma^\mu e^\dagger_{cr})X_\mu$	
	$uLL^\dagger$	$(L_{p_i}\sigma^\mu L^\dagger{}_r{}^i)u_\mu$	$(L_{p_i}\sigma^\mu L^\dagger{}_r{}^i)X_\mu$	
	$uQQ^\dagger$	$(Q_{p_{ai}}\sigma^\mu Q^\dagger{}_r{}^{ai})u_\mu$	$(Q_{p_{ai}}\sigma^\mu Q^\dagger{}_r{}^{ai})X_\mu$	
	$u d_c d_c^\dagger$	$(d_{cp}{}^a\sigma^\mu d^\dagger_{cra})u_\mu$	$(d_{cp}{}^a\sigma^\mu d^\dagger_{cra})X_\mu$	
	$u u_c u_c^\dagger$	$(u_{cp}{}^a\sigma^\mu u^\dagger_{cra})u_\mu$	$(u_{cp}{}^a\sigma^\mu u^\dagger_{cra})X_\mu$	
$u^2\phi^2$	$u^2 H H^\dagger$	$H_i H^{\dagger i} u_\mu u^\mu$	$H_i H^{\dagger i} X_\mu X^\mu$	
u^4	u^4	$u_\mu u^\mu u_\nu u^\nu$	$X_\mu X^\mu X_\nu X^\nu$	

***dim*-4 operators**

Class	Type	Real	Complex	F	Z_2
F_L^2	$X_L B_L$	$B_{L\mu\nu} X_L{}^{\mu\nu}$			
$u\psi\bar{\psi}$	$u e_c e_c^\dagger$	$(e_{cp}\sigma^\mu e^\dagger_{cr})X_\mu$			
	$uLL^\dagger$	$(L_{p_i}\sigma^\mu L^\dagger{}_r{}^i)X_\mu$			
	$uQQ^\dagger$	$(Q_{p_{ai}}\sigma^\mu Q^\dagger{}_r{}^{ai})X_\mu$			
	$u d_c d_c^\dagger$	$(d_{cp}{}^a\sigma^\mu d^\dagger_{cra})X_\mu$			
	$u u_c u_c^\dagger$	$(u_{cp}{}^a\sigma^\mu u^\dagger_{cra})X_\mu$			
$u^2\phi^2$	$u u^\dagger H H^\dagger$	$H_i H^{\dagger i} X_\mu X^\mu$	$H_i H^{\dagger i} X^\dagger_\mu X^\mu$		✓
u^4	$u^2 u^{\dagger 2}$	$X_\mu X^\mu X_\nu X^\nu$	$X^\dagger_\mu X^\mu X^\dagger_\nu X^\nu$		✓
			$X^\dagger_\mu X^{\dagger\mu} X_\nu X^\nu$		✓

Real → Complex: Double DoFs

Building Blocks Summary

Sector	Building block	Lorentz group	$SU(3)_C$	$SU(2)_W$	$U(1)_Y$	$U(1)$
SM	$G_{L/R}$	$(1,0)/(0,1)$	$\mathbf{8}$	$\mathbf{1}$	0	0
	$W_{L/R}$	$(1,0)/(0,1)$	$\mathbf{1}$	$\mathbf{3}$	0	0
	$B_{L/R}$	$(1,0)/(0,1)$	$\mathbf{1}$	$\mathbf{1}$	0	0
	$L/L^\dagger$	$(\frac{1}{2},0)/(0,\frac{1}{2})$	$\mathbf{1}$	$\mathbf{2}$	$\mp\frac{1}{2}$	0
	$e_c/e_c^\dagger$	$(\frac{1}{2},0)/(0,\frac{1}{2})$	$\mathbf{1}$	$\mathbf{1}$	± 1	0
	$Q/Q^\dagger$	$(\frac{1}{2},0)/(0,\frac{1}{2})$	$\mathbf{3}/\overline{\mathbf{3}}$	$\mathbf{2}$	$\pm\frac{1}{6}$	0
	$u_c/u_c^\dagger$	$(\frac{1}{2},0)/(0,\frac{1}{2})$	$\overline{\mathbf{3}}/\mathbf{3}$	$\mathbf{1}$	$\mp\frac{2}{3}$	0
	$d_c/d_c^\dagger$	$(\frac{1}{2},0)/(0,\frac{1}{2})$	$\overline{\mathbf{3}}/\mathbf{3}$	$\mathbf{1}$	$\pm\frac{1}{3}$	0
	$H/H^\dagger$	$(0,0)$	$\mathbf{1}$	$\mathbf{2}$	$\pm\frac{1}{2}$	0
Real scalar	s	$(0,0)$	$\mathbf{1}$	$\mathbf{1}$	0	0
Complex Scalar	$S/S^\dagger$	$(0,0)$	$\mathbf{1}$	$\mathbf{1}$	0	$\pm q_S$
Real Goldstone	$u_\mu = D_\mu s$	$(\frac{1}{2},\frac{1}{2})$	$\mathbf{1}$	$\mathbf{1}$	0	0
Complex Goldstone	$u_\mu = D_\mu S$ $u_\mu^\dagger = D_\mu S^\dagger$	$(\frac{1}{2},\frac{1}{2})$	$\mathbf{1}$	$\mathbf{1}$	0	$\pm q_u$
Majorana fermion	$\chi/\chi^\dagger$	$(\frac{1}{2},0)/(0,\frac{1}{2})$	$\mathbf{1}$	$\mathbf{1}$	0	$\pm q_M$
Dirac fermion	$\chi_L/\chi_L^\dagger$	$(\frac{1}{2},0)/(0,\frac{1}{2})$	$\mathbf{1}$	$\mathbf{1}$	0	$\pm q_D$
	$\chi_{Rc}/\chi_{Rc}^\dagger$	$(\frac{1}{2},0)/(0,\frac{1}{2})$	$\mathbf{1}$	$\mathbf{1}$	0	$\mp q_D$
Real Vector	X_L/X_R	$(1,0)/(0,1)$	$\mathbf{1}$	$\mathbf{1}$	0	0
Complex Vector	X_L/X_R	$(1,0)/(0,0)$	$\mathbf{1}$	$\mathbf{1}$	0	$+q_V$
	$X_L^\dagger/X_R^\dagger$	$(1,0)/(0,1)$	$\mathbf{1}$	$\mathbf{1}$	0	$-q_V$

Summary of SEFT

Singlet			dim-4	dim-5	dim-6	dim-7	dim-8
ϕEFT Scalar	Real	w/o $\mathbf{Z_2}$	-	$9+6n_f^2$	$10+n_f+7n_f^2$	$30+n_f+\frac{965}{12}n_f^2 +\frac{3}{2}n_f^3+\frac{397}{12}n_f^4$	$\frac{1}{12}(516+36n_f+1241n_f^2 +42n_f^3+661n_f^4)$
		w/ $\mathbf{Z_2}$	-	-	$10+6n_f^2$	$n_f+n_f^2$	$\frac{1}{12}(516+1085n_f^2 +18n_f^3+397n_f^4)$
	Complex		-	-	$12+11n_f^2$	$n_f+n_f^2$	$58+\frac{1745}{12}n_f^2 +\frac{3}{2}n_f^3+\frac{397}{12}n_f^4$
χEFT Fermion	Majorana	w/o $\mathbf{Z_2}$	$2n_f$	2	$2+8n_f +6n_f^2+13n_f^3$	$\frac{4}{3}(12+14n_f +9n_f^2+25n_f^3)$	$18+68n_f +56n_f^2+181n_f^3$
		w $\mathbf{Z_2}$	-	2	$2+5n_f^2$	$4(4+3n_f^2)$	$18+2n_f+57n_f^2$
	Dirac		-	4	$7+10n_f^2$	$22+28n_f^2$	$43+n_f+113n_f^2$
VEFT Vector	Real	w/o $\mathbf{Z_2}$	$4+5n_f^2$	-	$37+71n_f^2$	$\frac{2}{3}(8n_f^2+7n_f^4)$	$\frac{1}{12}(4836+13529n_f^2 +6n_f^3+4477n_f^4)$
		w/ $\mathbf{Z_2}$	2	-	$22+21n_f^2$	$n_f+n_f^2$	$\frac{1}{6}(1152+2503n_f^2 +231n_f^4)$
	Complex		3	-	$51+42n_f^2$	n_f^2	$\frac{1}{3}(1617+2579n_f^2 +3n_f^2+346n_f^4$

Summary of sEFT

For a Goldstone singlet (*aEFT*), we find

dim-5: 6 (44)
dim-6: 1 (1)
dim-7: 44 (356)
dim-8: 32 (520)

Consistent with Grojean, et al. 2307.08563

All operators involving majoron with explicit shift symmetry start at *dim*-8

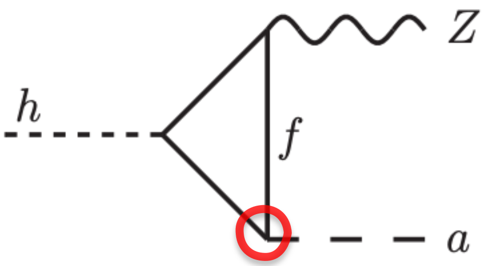
$$\epsilon^{ik}\epsilon^{jl}(D^\mu s)H_k(D_\mu H_l)(L_{p_i}L_{r_j}) \quad \epsilon^{ik}\epsilon^{jl}(D^\nu s)H_k(D^\mu H_l)(L_{p_i}\sigma_{\mu\nu}L_{r_j})$$

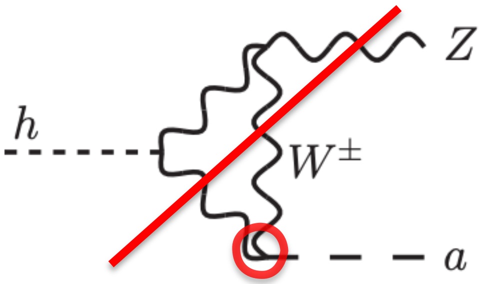
$$\epsilon^{ij}(D^\mu s)(d_{cp}{}^a L_{ri})(L_{sj}\sigma_\mu u^\dagger_{cta}) \quad \epsilon_{abc}(D^\mu s)(d_{cp}{}^a L_{si})(d_{cr}{}^b \sigma_\mu Q^\dagger{}_t{}^{ci})$$

$$\epsilon_{abc}(D^\mu s)(d_{cp}{}^a d_{cr}{}^b)(d_{cs}{}^c \sigma_\mu e^\dagger_{ct})$$

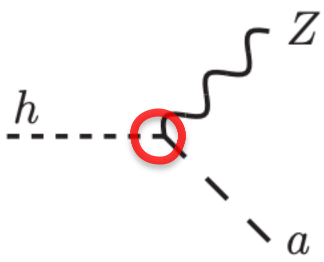
Phenomenology

Example 1: exotic decays of Higgs into ALPs





dim-5 operators



dim-7 operators

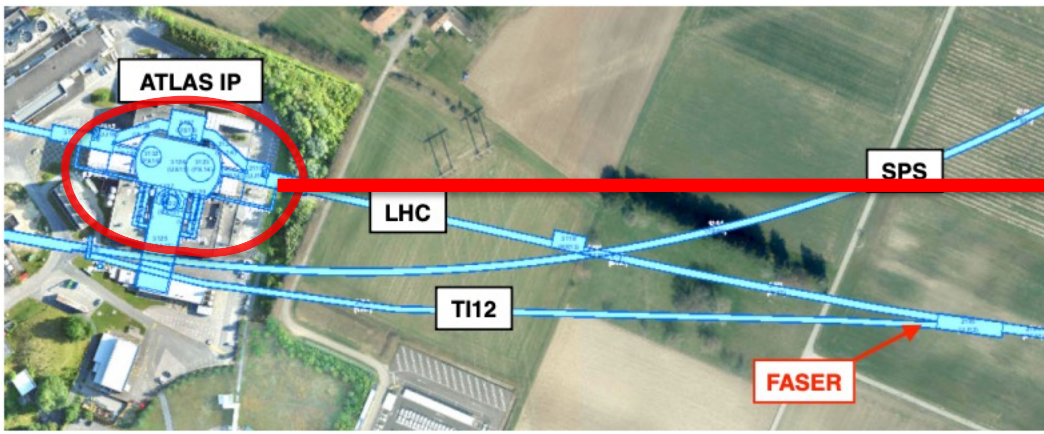
$(\partial^\mu a)(H^\dagger \partial_\mu H) H^\dagger H$

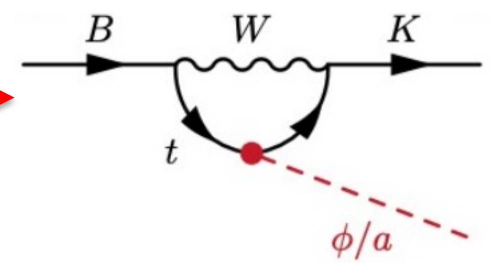
$$C_{Zh}^{\rm eff} \approx C_{Zh}^{(5)} - 0.016\, c_{tt} + 0.030\, C_{Zh}^{(7)} \left[\frac{1\,\text{TeV}}{\Lambda}\right]^2$$

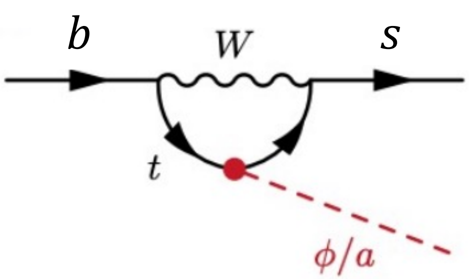
Bauer *et al. 17'*
Bauer *et al. 16'*

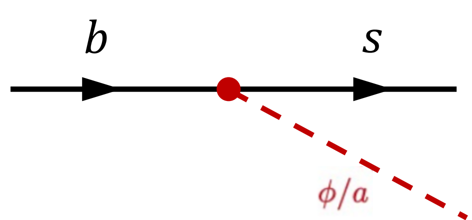
Phenomenology

Example 2: Light scalars @ FASER









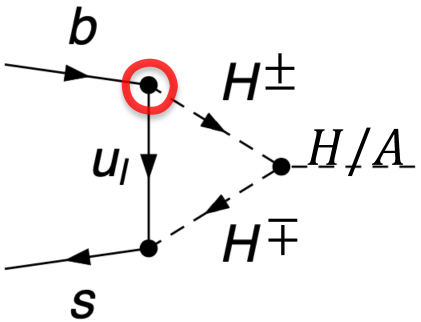
$$\mathcal{L}_{eff} = \frac{\phi}{v}\sum \xi_{\phi}^{ij} m_{f_j} \bar{f}_i P_R f_j + h.c.$$

$$sH^{\dagger i}(d_{cp}{}^{a} Q_{r\,ai})$$

Phenomenology

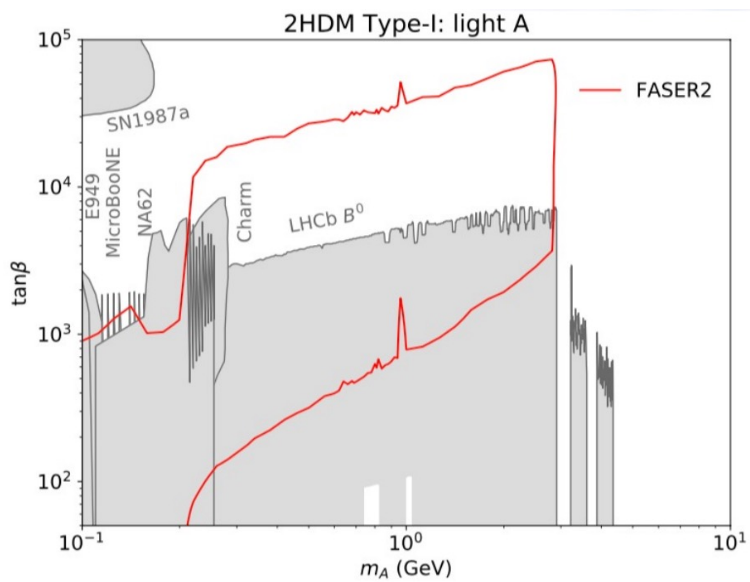
Example 2: Light scalars @ FASER

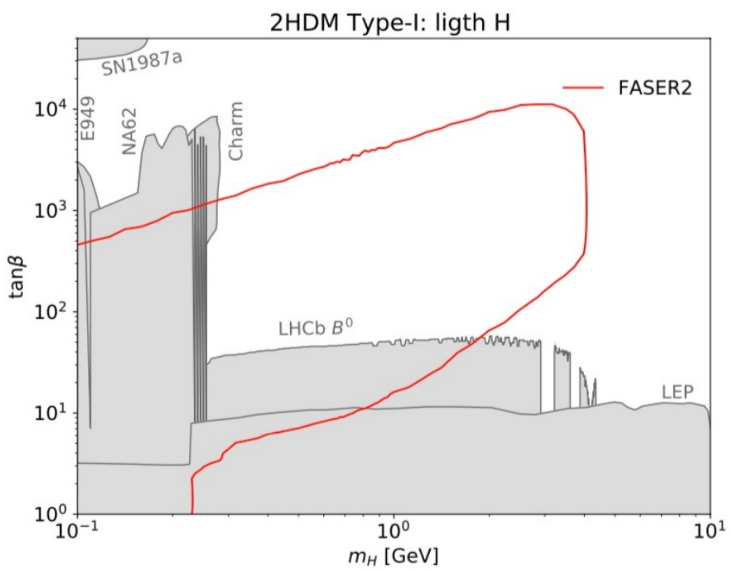
Consider Type-I 2HDM as a UV model



$\sim \tan^{-1}\beta$

Similar to mimimal model (Dark Higgs)

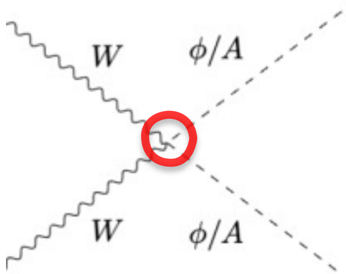




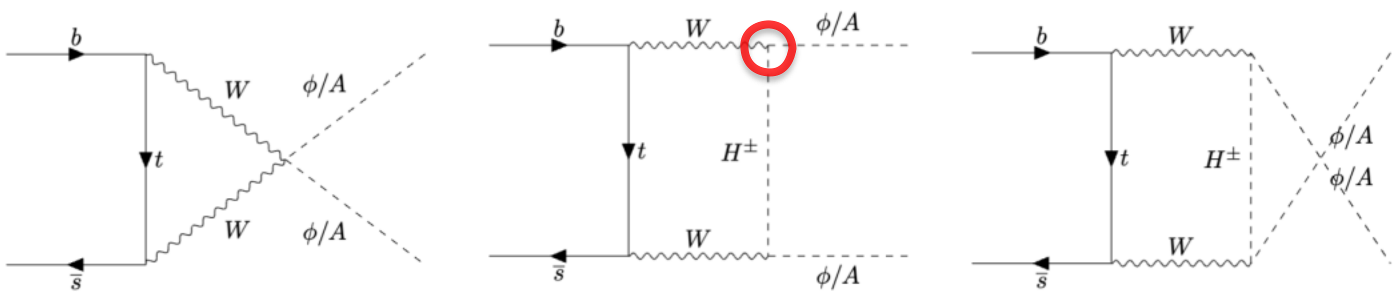
Phenomenology

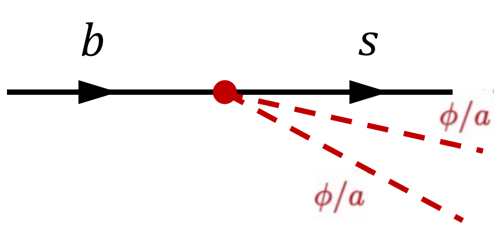
Example 2: Light scalars @ FASER

Consider Type-I 2HDM as a UV model



$\sim g^2$ Governed by gauge symmetry and not suppressed





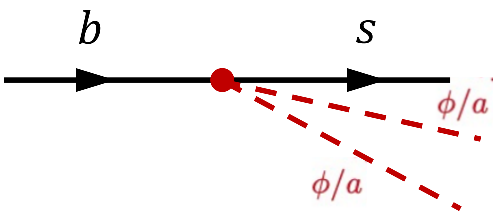
$$\mathcal{L} \supset \xi^{ij}_{\phi\phi}\frac{\phi^2}{v^2}m_j\bar{f}_iP_Rf_j + \xi^{ij}_{AA}\frac{A^2}{v^2}m_j\bar{f}_iP_Rf_j + h.c.$$

$$s^2 {H^\dagger}^i ({d_{cp}}^a Q_{rai})$$

Phenomenology

Example 2: Light scalars @ FASER

Consider Type-I 2HDM as a UV model



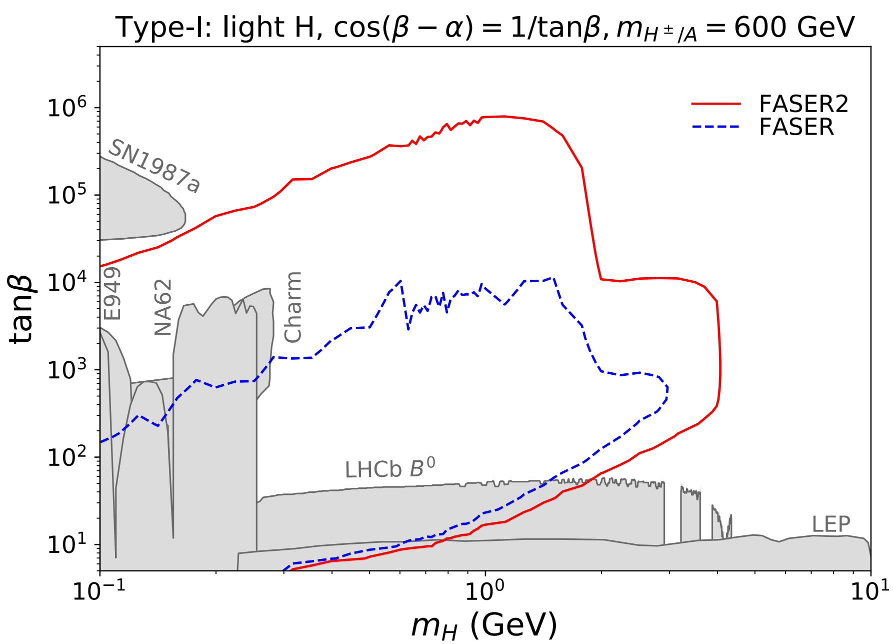
$$\mathcal{L} \supset \xi^{ij}_{\phi\phi}\frac{\phi^2}{v^2} m_j \bar{f}_i P_R f_j + \xi^{ij}_{AA}\frac{A^2}{v^2} m_j \bar{f}_i P_R f_j + h.c.$$

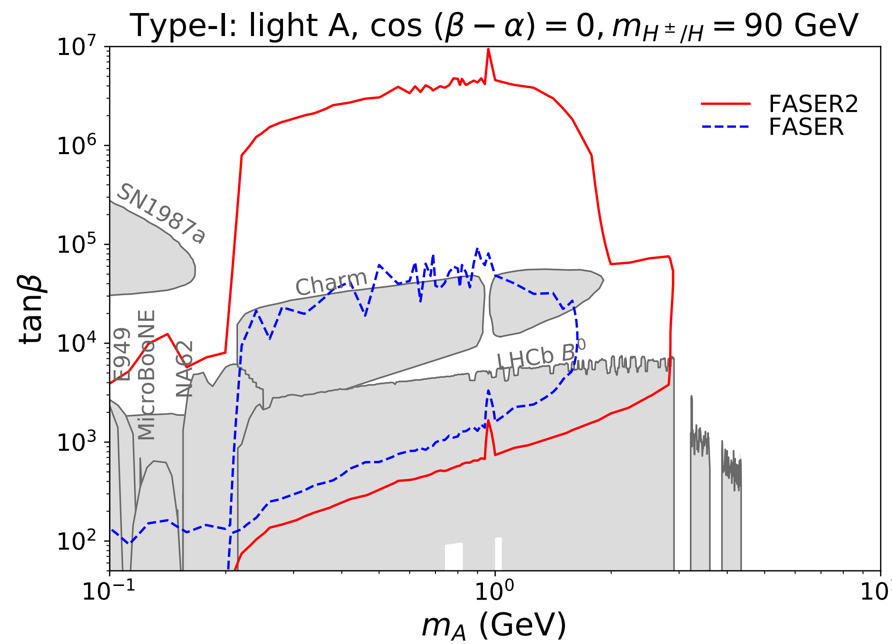
$$\xi^{ij}_{\phi\phi} \simeq \xi^{ij}_{AA} \simeq \frac{g^2}{64\pi^2}\sum_k V^*_{ki}\left[f_0(x_k, x_{H^\pm}) + f_1(x_k, x_{H^\pm})\log x_k + f_2(x_k, x_{H^\pm})\log x_{H^\pm}\right] V_{kj} + \mathcal{O}(\cos(\beta-\alpha), 1/\tan\beta)$$

Phenomenology

Example 2: Light scalars @ FASER

Consider Type-I 2HDM as a UV model





See Wei Su's talk

Summary and outlook

- Summary of results:
  1. Operators for Goldstones (*aEFT*) with explicit shift symmetry
  2. How to obtain basis for massive vector bosons (appending Goldstones systematically)
  3. EFTs for weakly-interacting light particles (*ϕEFT, χEFT, VEFT*) up to *dim*-8
  4. Light scalars at FASER, higher *dim* operators are phenomenological relevant in some model (Type-I 2HDM)

- Matching & running between *sEFTs* above *EW* scale and below *EW* scale

- Constraints on more general long-lived light scalars (pure EFT analysis and a2HDM & s2HDM)