The Higgs sector, effectively

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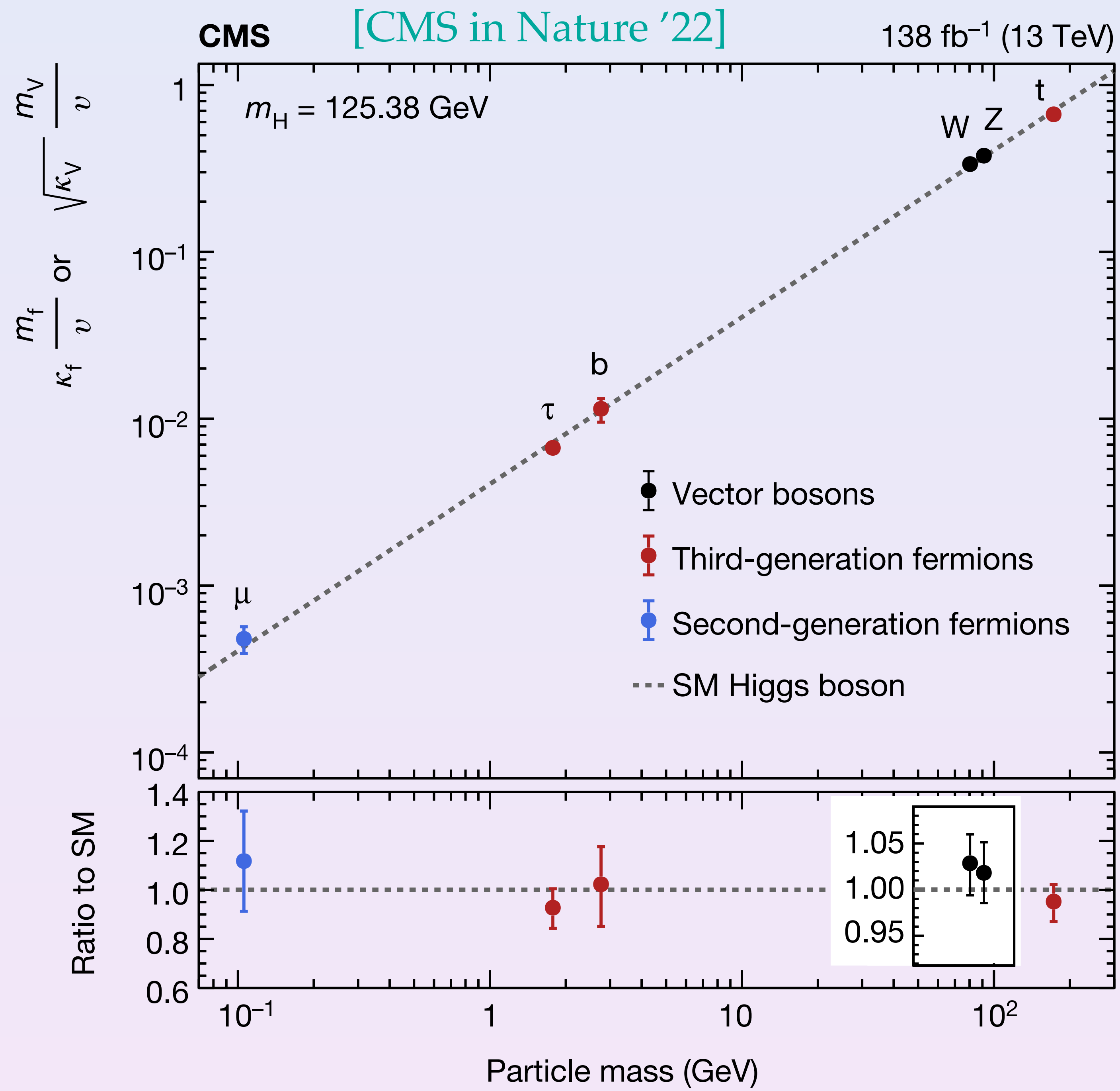
Higgs Couplings

- Higgs couplings to massive vector bosons and third generation fermions measured with amazing precision

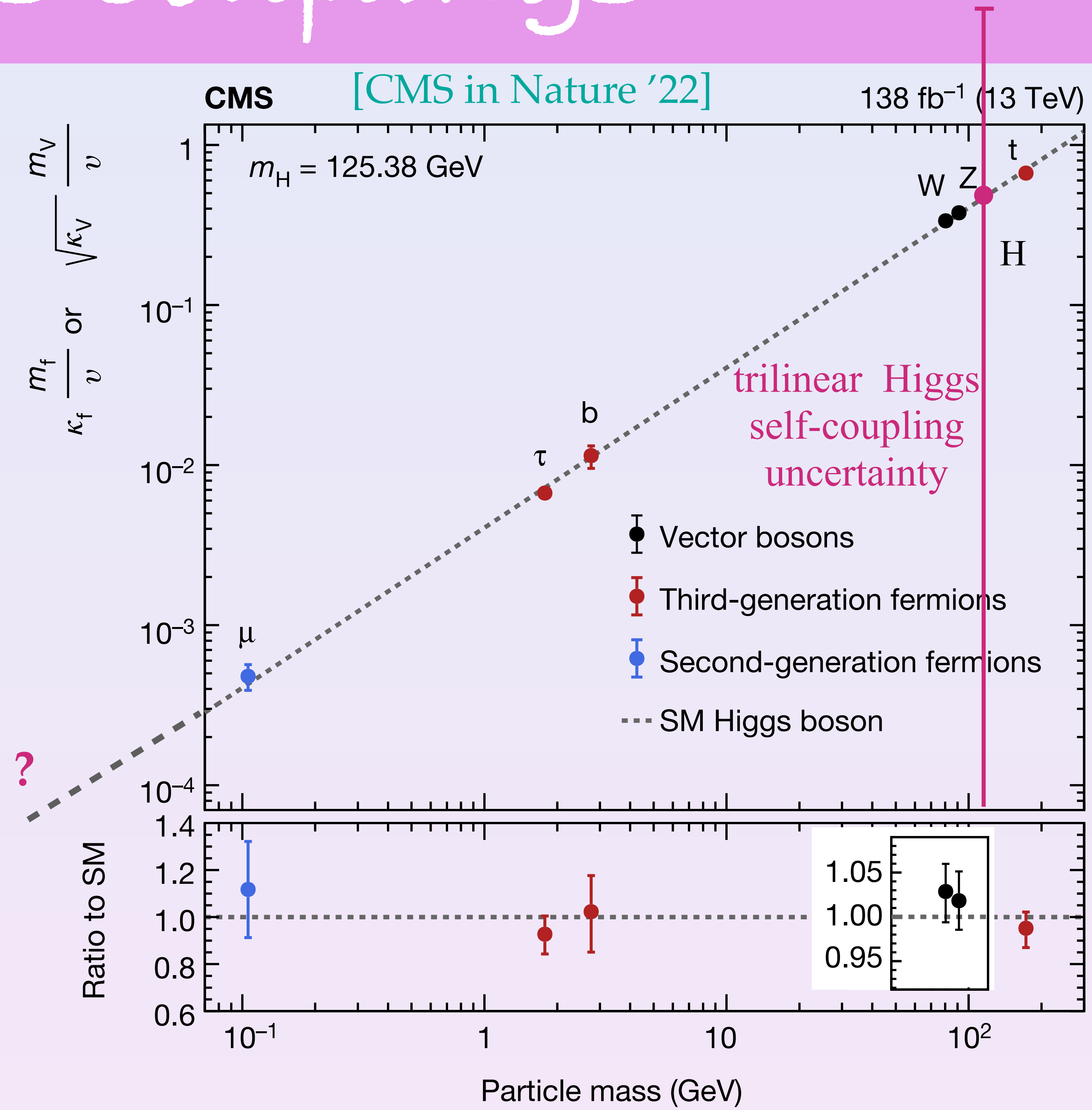


Higgs Couplings

- Higgs couplings to massive vector bosons and third generation fermions measured with amazing precision

- first/(second) generation? Higgs self-couplings?

- More generically: Constrain Effective Lagrangian where several operators modify the Higgs interactions



The Higgs sector, effectively

$$\text{SM} \subset \text{SMEFT} \subset \text{HEFT} \subset \text{Bootstrapped amplitudes}$$

(for single process)

SMEFT= Standard Model Effective field Theory

HEFT= Higgs Effective field Theory (or electroweak chiral Lagrangian)

The Higgs sector, effectively

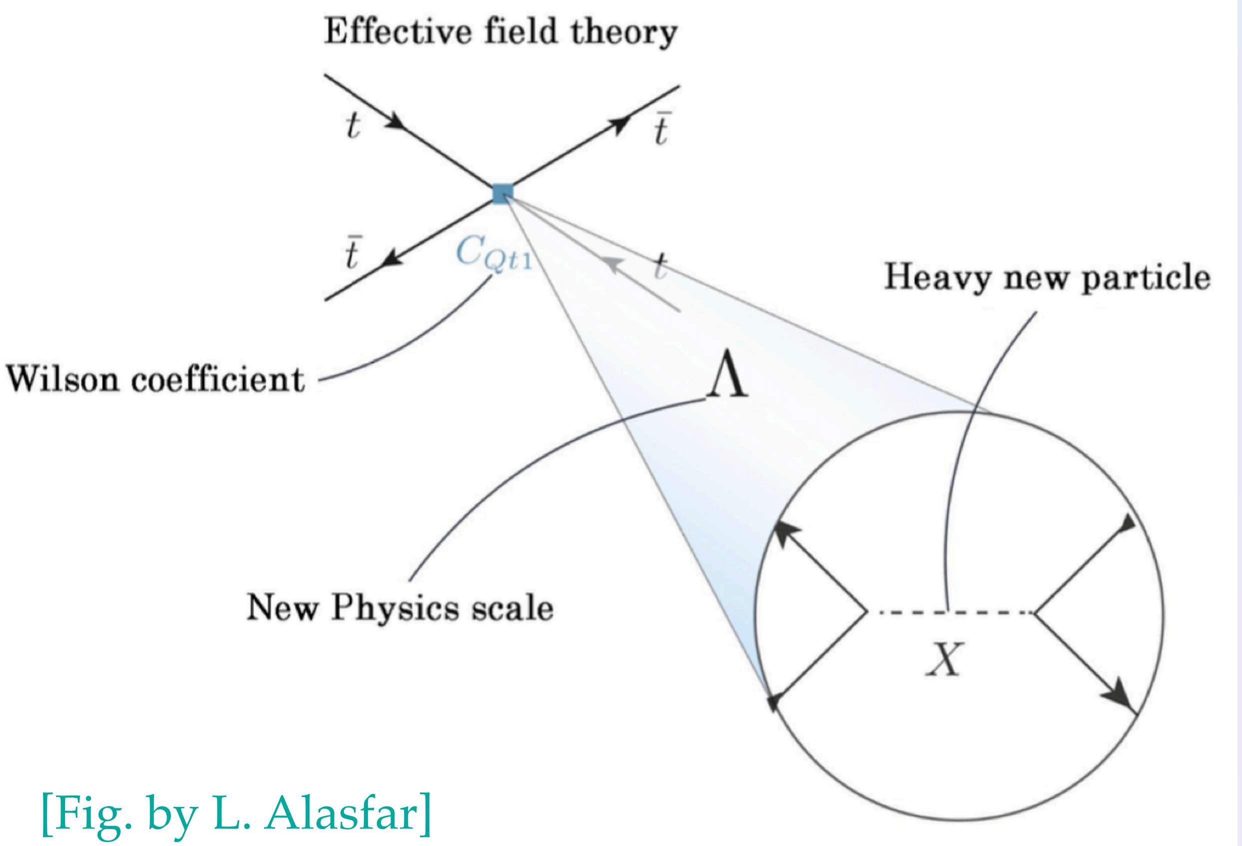
SM ⊂ SMEFT ⊂ HEFT ⊂ Bootstrapped amplitudes
(for single process)

covered by Eleni — first part of this talk — second part of this talk

SMEFT= Standard Model Effective field Theory

HEFT= Higgs Effective field Theory (or electroweak chiral Lagrangian)

Effective Field Theory

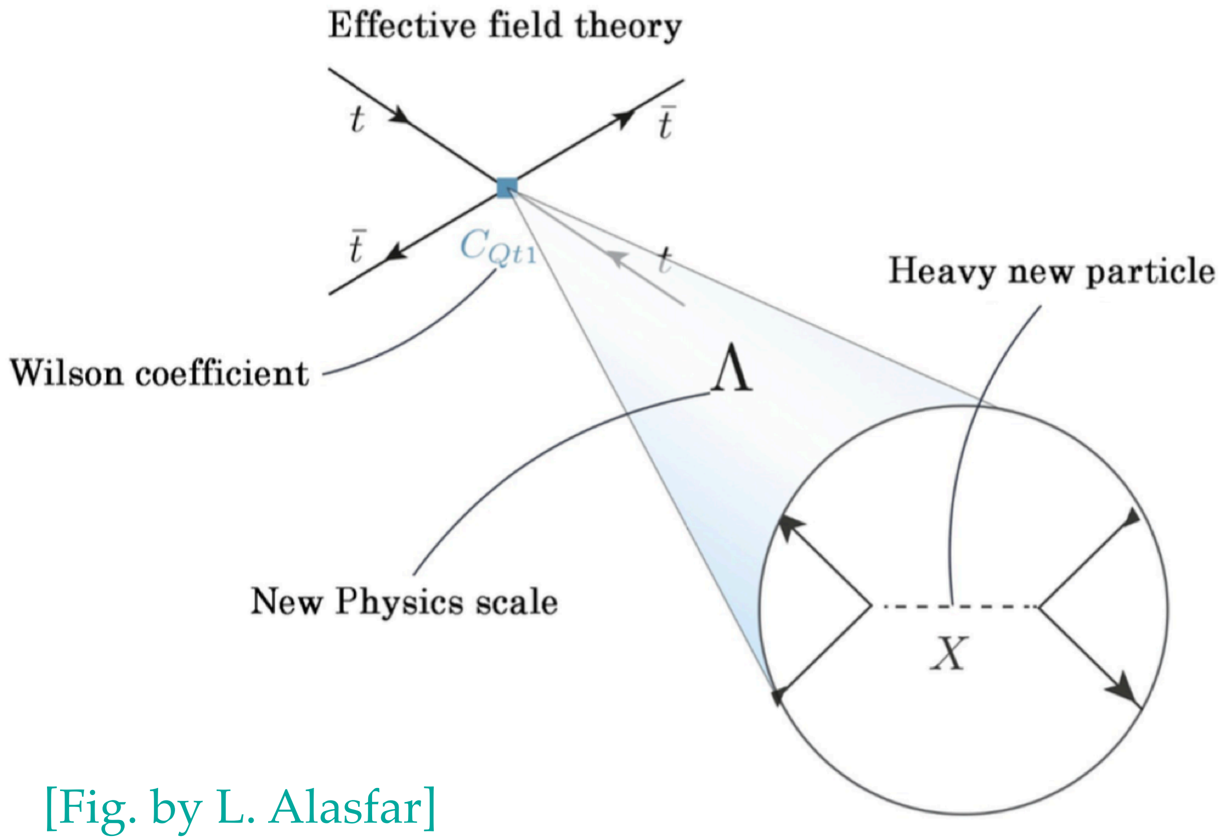


[Fig. by L. Alasfar]

Ingredients for an Effective Field Theory

particle content → let's take the one of the SM

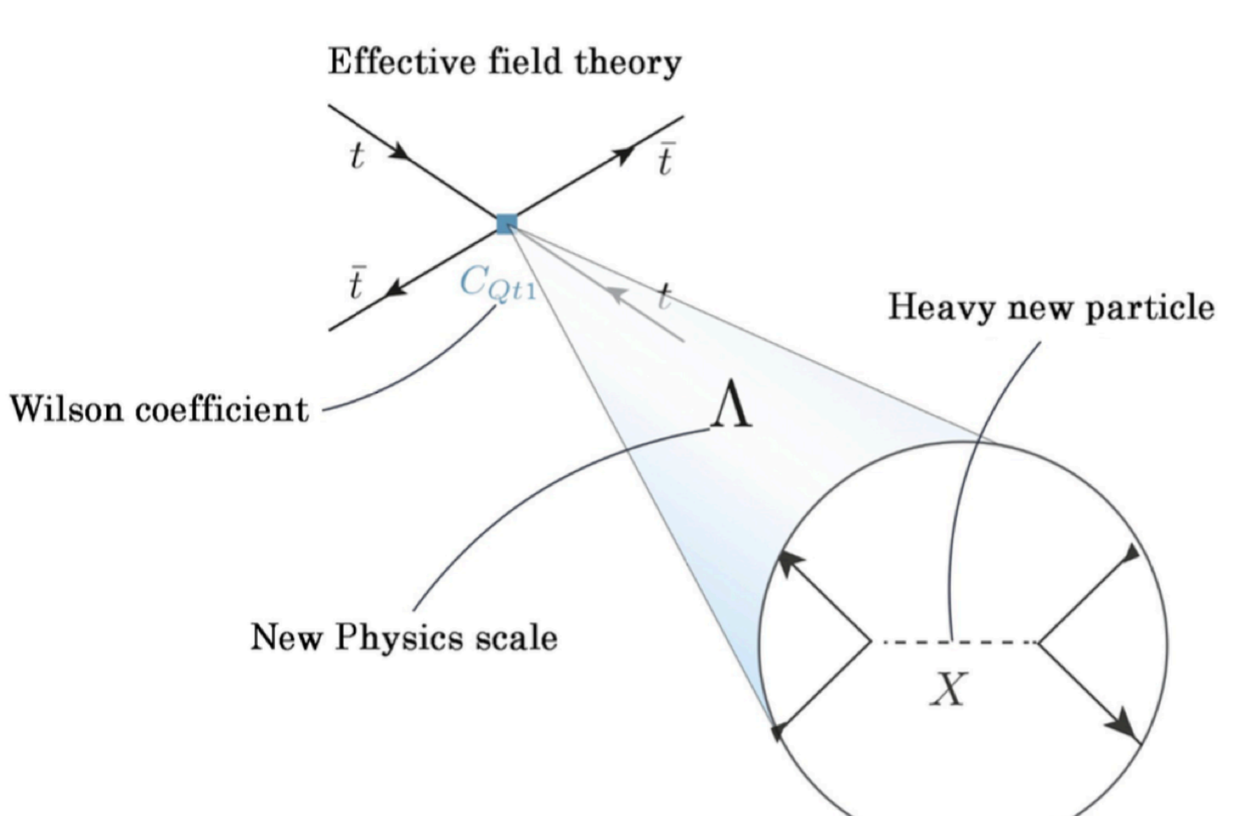
Effective Field Theory



[Fig. by L. Alasfar]

Ingredients for an Effective Field Theory

particle content	→	let's take the one of the SM
symmetries	→	let's take the one of the SM, but how should the Higgs boson transform under it?



[Fig. by L. Alasfar]

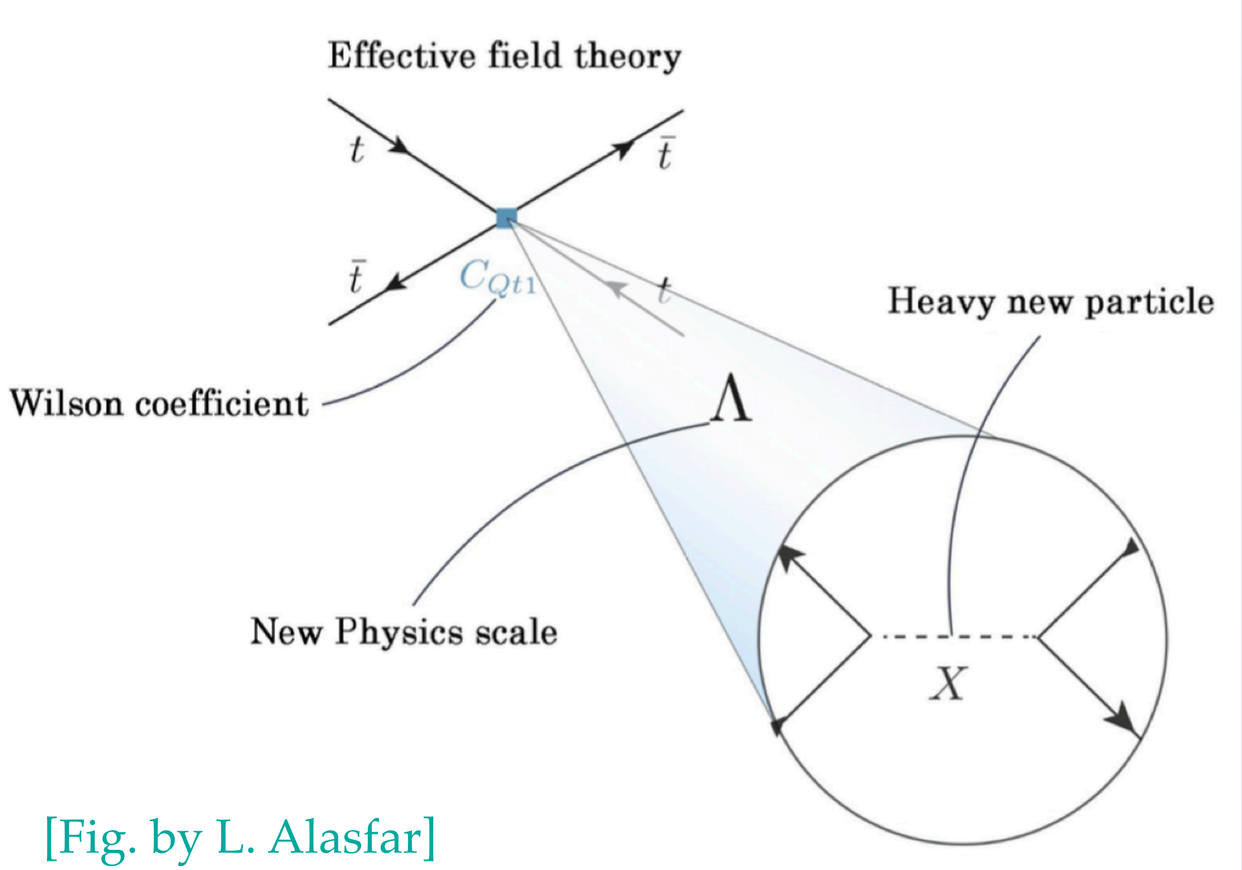
Ingredients for an Effective Field Theory

particle content → let's take the one of the SM

symmetries → let's take the one of the SM, but how should the Higgs boson transform under it?

for correct IR behaviour: 3 GBs, 1 Higgs needed

Effective Field Theory



[Fig. by L. Alasfar]

Ingredients for an Effective Field Theory

particle content ⟶ let's take the one of the SM

symmetries ⟶ let's take the one of the SM, but how should the Higgs boson transform under it?

truncation rule ⟶ power counting rule needed

HEFT power counting

in collaboration with Ilaria Brivio and Konstantin Schmid

Power counting

With Naive Dimensional Analysis, reinstating powers of $c = \hbar$ and with $\hbar^{-1/2} \sim 4\pi$

$$\mathscr{L} \supset \frac{\Lambda^4}{(4\pi)^2} \left(\frac{\partial_\mu}{\Lambda}\right)^q \left(\frac{4\pi\phi}{\Lambda}\right)^s \left(\frac{4\pi\psi}{\Lambda^{3/2}}\right)^f \left(\frac{g}{4\pi}\right)^{n_g} \left(\frac{\lambda}{(4\pi)^2}\right)^{n_\lambda} \left(\frac{4\pi v}{\Lambda}\right)^{n_v}$$

[Manohar, Georgi '84; Gavela, Jenkins, Manohar, Merlo '16]

q counts number of derivatives

Power counting

With Naive Dimensional Analysis, reinstating powers of $c = \hbar$ and with $\hbar^{-1/2} \sim 4\pi$

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[Manohar, Georgi '84; Gavela, Jenkins, Manohar, Merlo '16]

s counts number of bosons fields

Power counting

With Naive Dimensional Analysis, reinstating powers of $c = \hbar$ and with $\hbar^{-1/2} \sim 4\pi$

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[Manohar, Georgi '84; Gavela, Jenkins, Manohar, Merlo '16]

f counts number of fermionic fields

Power counting

With Naive Dimensional Analysis, reinstating powers of $c = \hbar$ and with $\hbar^{-1/2} \sim 4\pi$

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[Manohar, Georgi '84; Gavela, Jenkins, Manohar, Merlo '16]

n_g counts number of gauge and Yukawa couplings

Power counting

With Naive Dimensional Analysis, reinstating powers of $c = \hbar$ and with $\hbar^{-1/2} \sim 4\pi$

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[Manohar, Georgi '84; Gavela, Jenkins, Manohar, Merlo '16]

n_λ counts number of scalar potential couplings

Power counting

With Naive Dimensional Analysis, reinstating powers of $c = \hbar$ and with $\hbar^{-1/2} \sim 4\pi$

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[Manohar, Georgi '84; Gavela, Jenkins, Manohar, Merlo '16]

n_v counts VEV insertions

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SMEFT:

Assuming that $\Lambda \gg v$ allows us to power count N_Λ

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[Manohar, Georgi '84;
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SMEFT:

Assuming that $\Lambda \gg v$ allows us to power count N_Λ

$$\mathscr{L} = \mathscr{L}_{SM} + \sum_i \frac{c_{\mathcal{O}}}{\Lambda^i} \mathcal{O}_i$$

for Higgs physics
$i \geq 2$

respects the SM gauge symmetries, all fields transform as in SM

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HEFT:
The prize of splitting the SU(2) doublet of GBs and Higgs is that the theory becomes non-unitary at $\Lambda > 4\pi v$

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We cannot expand in N_Λ → Power count in chiral dimension $N_\chi = N_\Lambda + N_{4\pi}$

[Buchalla, Cata, Krause '13]

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We cannot expand in N_Λ → Power count in chiral dimension $N_\chi = N_\Lambda + N_{4\pi}$

$N_\Lambda, N_{4\pi}$ are inverse powers

Chiral dimension

$$\mathscr{L} \supset \frac{\Lambda^4}{(4\pi)^2} \left(\frac{\partial_\mu}{\Lambda}\right)^q \left(\frac{4\pi\phi}{\Lambda}\right)^s \left(\frac{4\pi\psi}{\Lambda^{3/2}}\right)^f \left(\frac{g}{4\pi}\right)^{n_g} \left(\frac{\lambda}{(4\pi)^2}\right)^{n_\lambda} \left(\frac{4\pi v}{\Lambda}\right)^{n_v}$$

From the NDA scaling we see easily that the chiral dimension counts up by

0 units for each boson field $\phi = \varphi, A_\mu$
for each VEV v

chiral dimension
$N_\chi = N_\Lambda + N_{4\pi}$

1/2 unit for each fermionic field ψ

1 unit for each gauge/Yukawa coupling
for each derivative

2 units for coupling of scalar interaction φ^4

HEFT Lagrangian

LO Lagrangian

$$\mathcal{L}_{LO} = -\frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} - \frac{1}{4}W^I_{\mu\nu}W^{I\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{v^2}{4}\mathrm{Tr}\left(\mathbf{V}_\mu \mathbf{V}^\mu\right)\mathcal{F}_C(h) - \lambda v^4 \mathcal{V}(h)$$
$$+ i\overline{Q}_L \not{D} Q_L + i\overline{Q}_R \not{D} Q_R + i\overline{L}_L \not{D} L_L + i\overline{L}_R \not{D} L_R$$
$$- \frac{v}{\sqrt{2}}\left(\overline{Q}_L \mathbf{U}\mathcal{Y}_Q(h) Q_R + \mathrm{h.c.}\right) - \frac{v}{\sqrt{2}}\left(\overline{L}_L \mathbf{U}\mathcal{Y}_L(h) L_R + \mathrm{h.c.}\right) ,$$

Goldstone matrix

$$\mathbf{U} = e^{\frac{i\pi^a\sigma^a}{v}} \qquad \mathbf{V}_\mu = (D_\mu \mathbf{U})\mathbf{U}^\dagger$$

Flare functions

$$\mathcal{F}_C(h) = 1 + \sum_{n=1}^{\infty} a_C^{(n)} \left(\frac{h}{v}\right)^n ,$$

$$\mathcal{V}(h) = \frac{h^2}{v^2} + a_V^{(3)}\frac{h^3}{v^3} + a_V^{(4)}\frac{h^4}{4v^4} + \sum_{n=5}^{\infty} a_V^{(n)} \left(\frac{h}{v}\right)^n ,$$

$$\mathcal{Y}_Q(h) = \mathrm{diag}\left(\mathcal{Y}_U(h), \mathcal{Y}_D(h)\right) , \qquad \mathcal{Y}_L(h) = \mathrm{diag}\left(0, \mathcal{Y}_E(h)\right) ,$$

$$\mathcal{Y}_{U,D,E}(h) = Y_{u,d,e}\left(1 + \sum_{n=1}^{\infty} a_{u,d,e}^{(n)} \left(\frac{h}{v}\right)^n\right) ,$$

LO Lagrangian

$$\begin{aligned}\mathcal{L}_{LO} = &-\frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} - \frac{1}{4}W^I_{\mu\nu}W^{I\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{v^2}{4}\mathrm{Tr}\left(\mathbf{V}_\mu \mathbf{V}^\mu\right)\mathcal{F}_C(h) - \lambda v^4 \mathcal{V}(h)\\ &+ i\overline{Q}_L \not{D} Q_L + i\overline{Q}_R \not{D} Q_R + i\overline{L}_L \not{D} L_L + i\overline{L}_R \not{D} L_R\\ &- \frac{v}{\sqrt{2}}\left(\overline{Q}_L \mathbf{U}\mathcal{Y}_Q(h) Q_R + \mathrm{h.c.}\right) - \frac{v}{\sqrt{2}}\left(\overline{L}_L \mathbf{U}\mathcal{Y}_L(h) L_R + \mathrm{h.c.}\right),\end{aligned}$$

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The choice of the LO Lagrangian ($N_\chi = 2$) is convention (i.e. could also contain 4 fermion operators, custodial violating operators, …)

HEFT cross sections

[Brivio, RG, Schmid 'in prep]

Count all occurrences of $p \sim m$

$$\mathcal{M} \sim p^{4-n}(4\pi)^{n-2} \left(\frac{p}{\Lambda}\right)^{N^p_{\Lambda,\mathcal{M}}} \left(\frac{4\pi v}{\Lambda}\right)^{N_{v,\mathcal{M}}} \left(\frac{g}{4\pi}\right)^{N_{g,\mathcal{M}}} \left(\frac{y}{4\pi}\right)^{N_{y,\mathcal{M}}} \left(\frac{\lambda}{(4\pi)^2}\right)^{N_{\lambda,\mathcal{M}}}$$

where n is the number of legs

At the level of the cross section

$$\int d\mathrm{PS}_k = \int \prod_{j=1}^{k} \frac{dq_j}{(2\pi)^3 2E_j} q_j^2 d\Omega_j (2\pi)^4 \delta^4 \left(q_{\mathrm{init}} - \sum_n q_n\right) \quad \sim \quad p^{2k-4}(4\pi)^{3-2k}$$

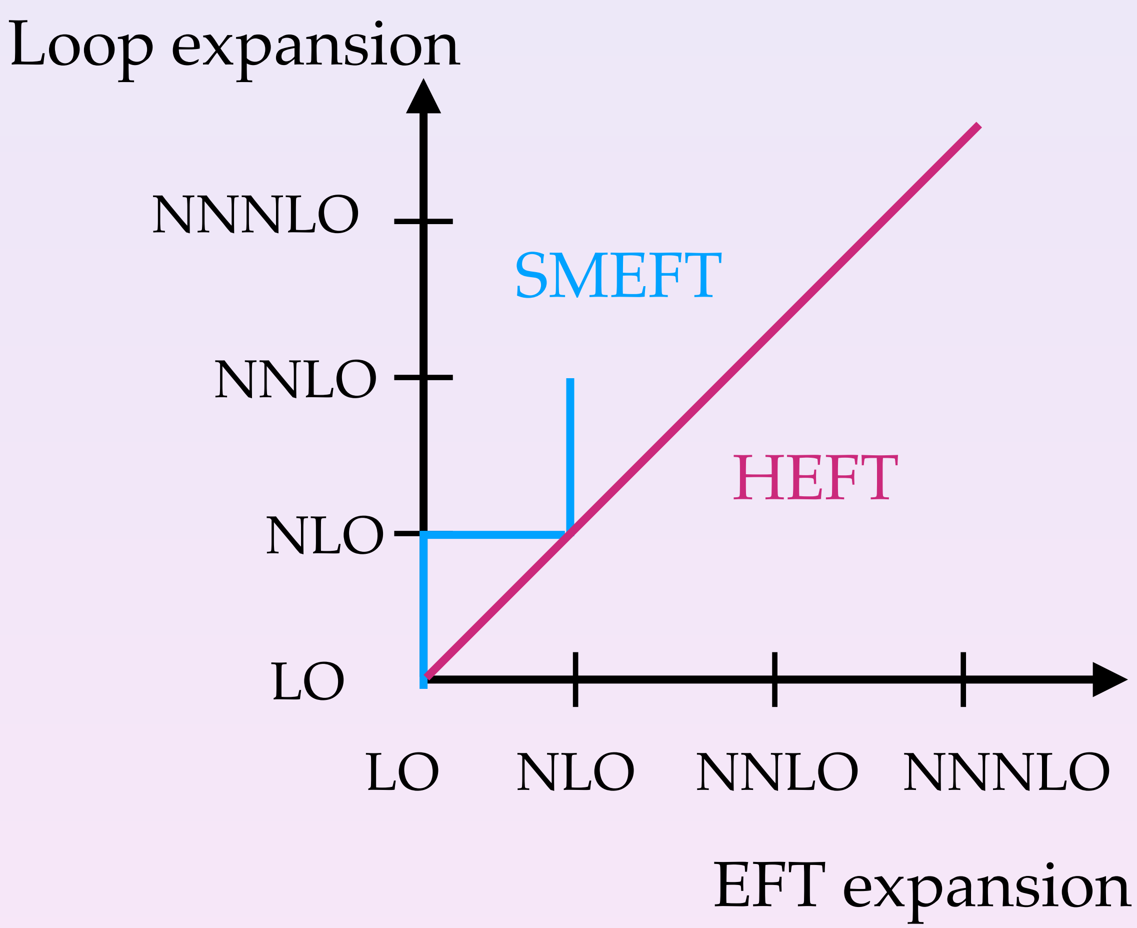
dependence on number of legs necessary for cancellation of IR divergencies at same order in counting

HEFT power counting

[Brivio, RG, Schmid 'in prep]

In the end we should count loops, external legs and chiral dimension of couplings

$$N^{s,\mathscr{M}}_{HEFT} = n - 2 + 2L + \sum_{i \in vert} N_{\chi,i}$$



SMEFT power counting keeps EFT expansion independent of loop expansion

HEFT power counting counts loops, so one is constrained on the diagonal

HEFT power counting

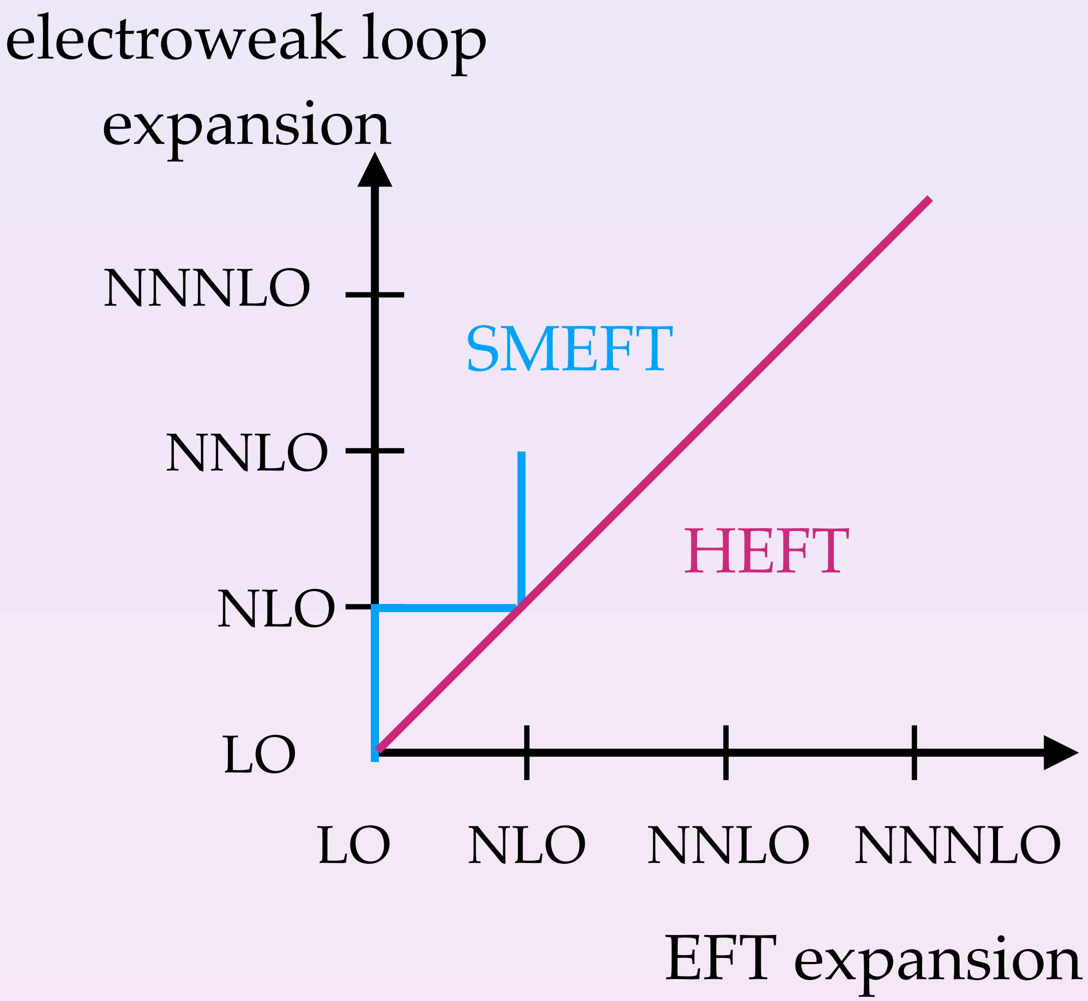
[Brivio, RG, Schmid 'in prep]

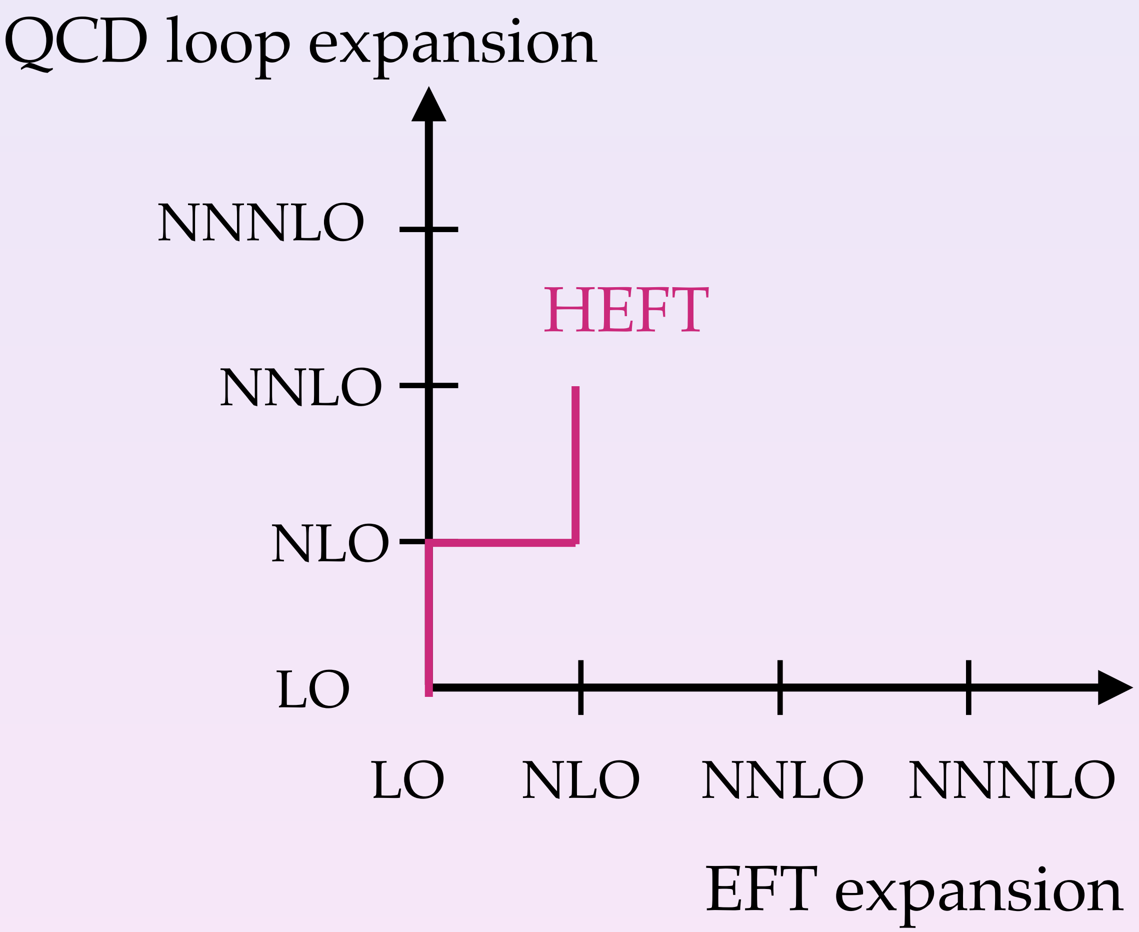
In the end we should count loops, external legs and chiral dimension of couplings

$$N^{s,\mathcal{M}}_{HEFT} = n - 2 + 2L + \sum_{i \in vert} N_{\chi,i}$$

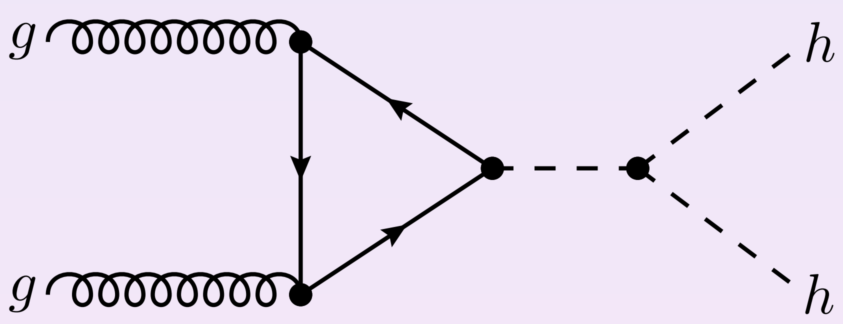
counting $g_s \sim p \sim m$ not necessary instead we can count alternatively

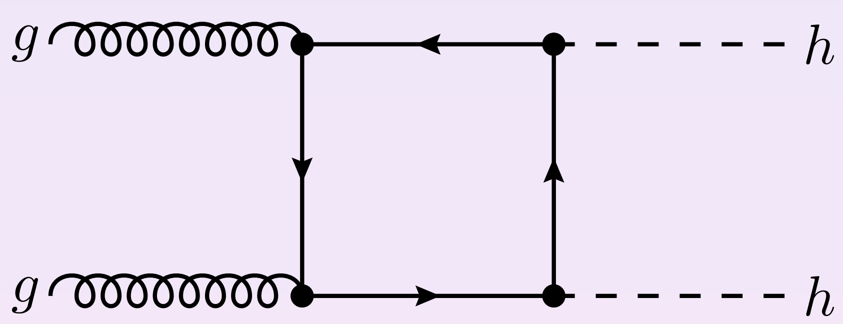
$$N^{\mathcal{M}}_{HEFT} = N^{s,\mathcal{M}}_{HEFT} - N^{\mathcal{M}}_{g_s}$$





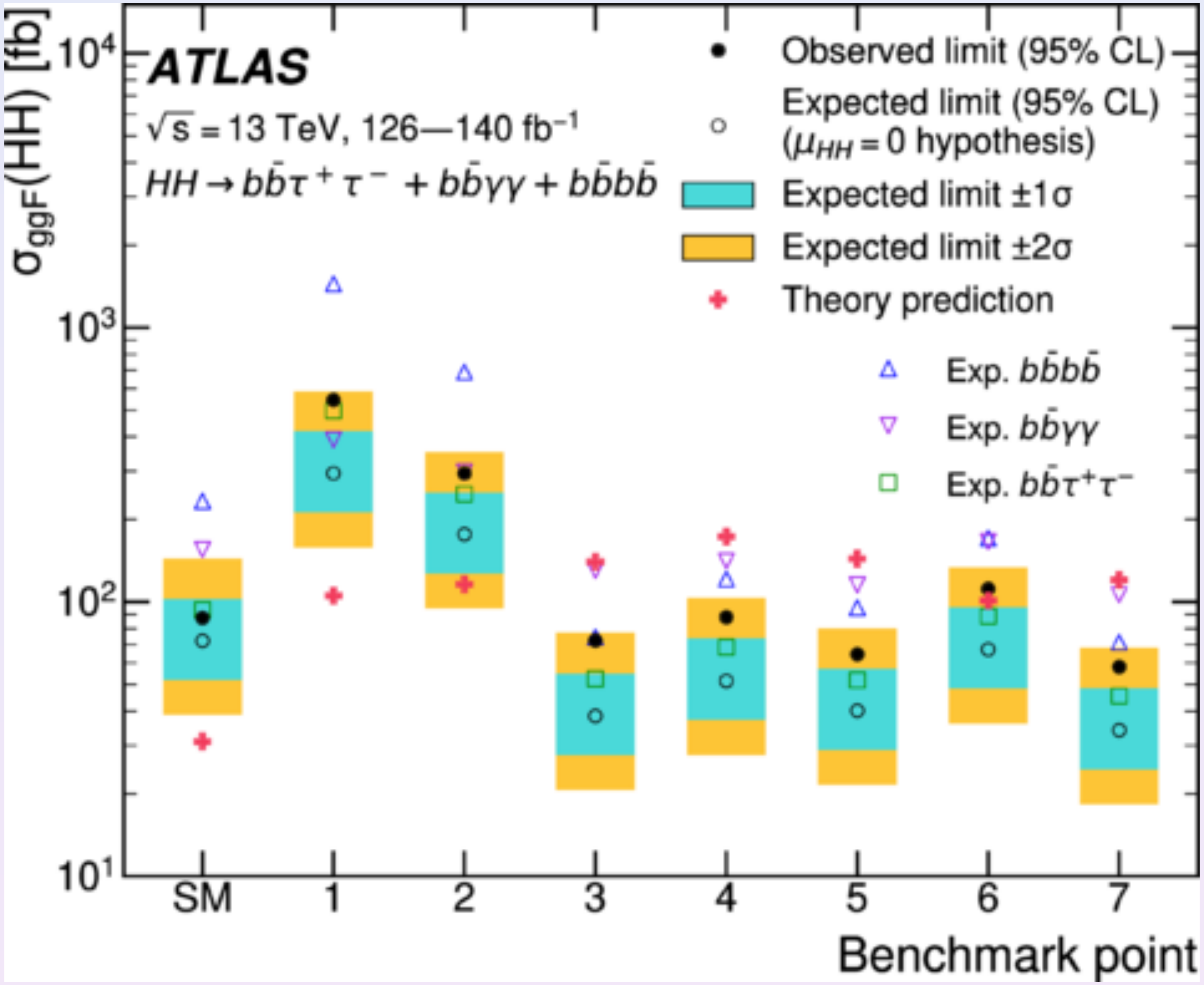
A HEFT example: Higgs Pair production





in collaboration with Ilaria Brivio and Konstantin Schmid

EFT searches in HH



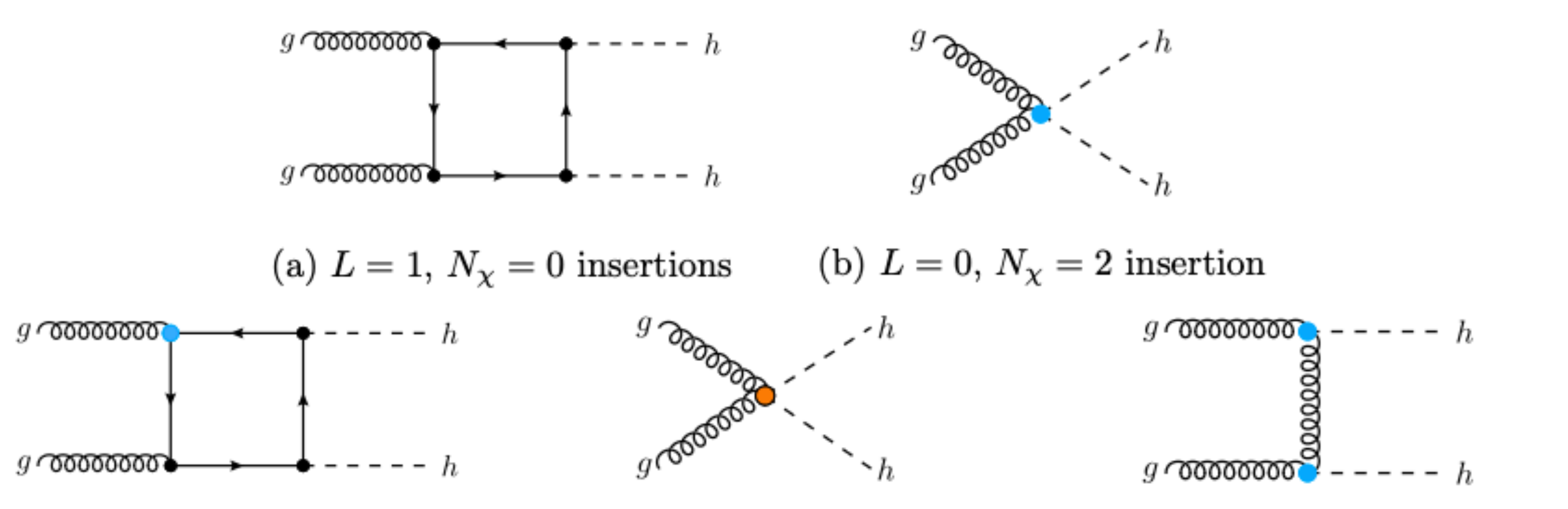
[ATLAS Collaboration '24]

Non-resonant di-Higgs EFT searches are built on kinematic benchmark scenarios to account for EFT modifications of m_{hh} shapes

[Carvalho et al. '15; Capozzi, Heinrich '19; Alasfar et al. '23]

[Brivio, RG, Schmid 'in prep]

Loop and higher orders in N_χ in operators can arise at same order



(a) $L = 1,\ N_\chi = 0$ insertions (b) $L = 0,\ N_\chi = 2$ insertion

(c) $L = 1,\ N_\chi = 2$ insertion (d) $L = 0,\ N_\chi = 4$ insertion (e) $L = 0$, two $N_\chi = 2$ insertions

Consider up to $N^{s,\mathscr{M}}_{HEFT} = 6$

HEFT in HH

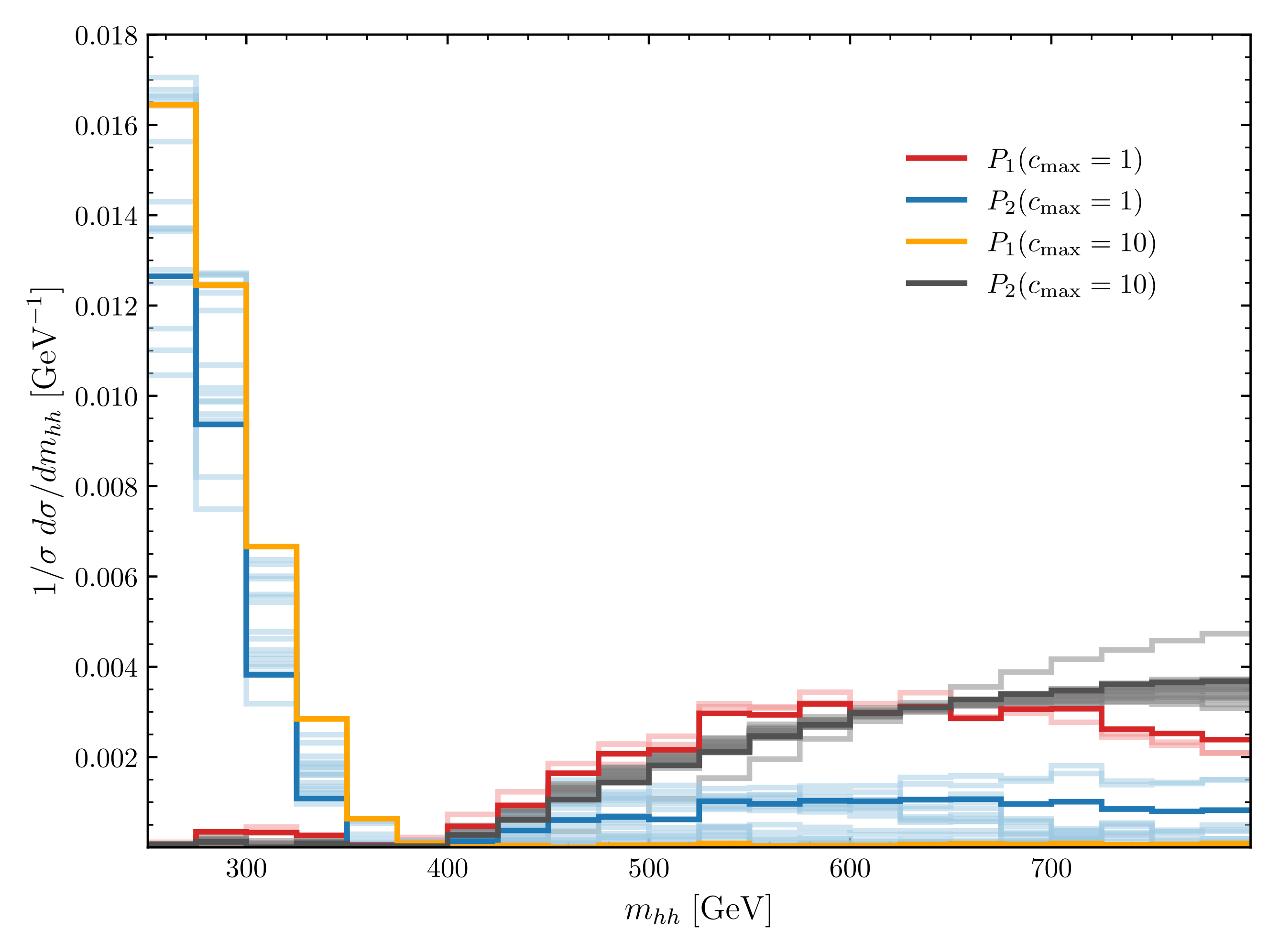
[Brivio, RG, Schmid 'in prep]

$$\mathcal{L}_{\text{HEFT}} \supset \mathcal{L}_\kappa + \delta\mathcal{L}$$

$$\mathcal{L}_\kappa = \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_h^2 h^2 - a_{\lambda^3}\lambda v h^3 - \frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} + i\bar{t}\not{D}t - \frac{y_t v}{\sqrt{2}}\left(a_t\frac{h}{v} + b_t\frac{h^2}{v^2}\right)\bar{t}t + \frac{g_s^2}{16\pi^2}G^a_{\mu\nu}G^{a\mu\nu}\left(a_g\frac{h}{v} + b_g\frac{h^2}{v^2}\right)$$

$$\delta\mathcal{L} = \frac{y_t b_D}{4\pi\Lambda}\frac{1}{v^2}(\partial_\mu h)^2\bar{t}t + \frac{g_s y_t}{4\pi\Lambda}\left(\bar{t}_L\sigma^{\mu\nu}G^a_{\mu\nu}T^a t_R + \text{h.c.}\right)\left(d_c + a_c\frac{h}{v} + b_c\frac{h^2}{v^2}\right) + \frac{g_s^2 b_g^{(1)}}{16\pi^2\Lambda^2}\frac{h^2}{v^2}(D^\mu G^{a\nu\lambda})(D_\mu G^a_{\nu\lambda}) + \frac{g_s^2 b_g^{(2)}}{16\pi^2\Lambda^2}\frac{h}{v}G^{a\lambda\nu}G^{a\mu}_{\lambda}\frac{1}{v}(\partial_\mu\partial_\nu h).$$

Loop and higher orders in N_χ in operators can arise at same order



Consider up to $N^{s,\mathcal{M}}_{HEFT} = 6$

Kinematic distributions beyond the ones in [Carvalho et al. '15; Capozzi, Heinrich '19] possible

HEFT in HH: Cluster analysis

Re-do a cluster analysis, use chi2-test

$$\chi^2(P_1, P_2) = \sum_{i \in bins} \frac{(D_{1,i} - D_{2,i})^2}{\Delta_i^2 (D_{i,1}^2 + D_{i,2}^2)}$$

Two points in parameter space follow the same kinematic benchmark if

$$\chi^2(P_1, P_2) < \chi^2_{thres}$$

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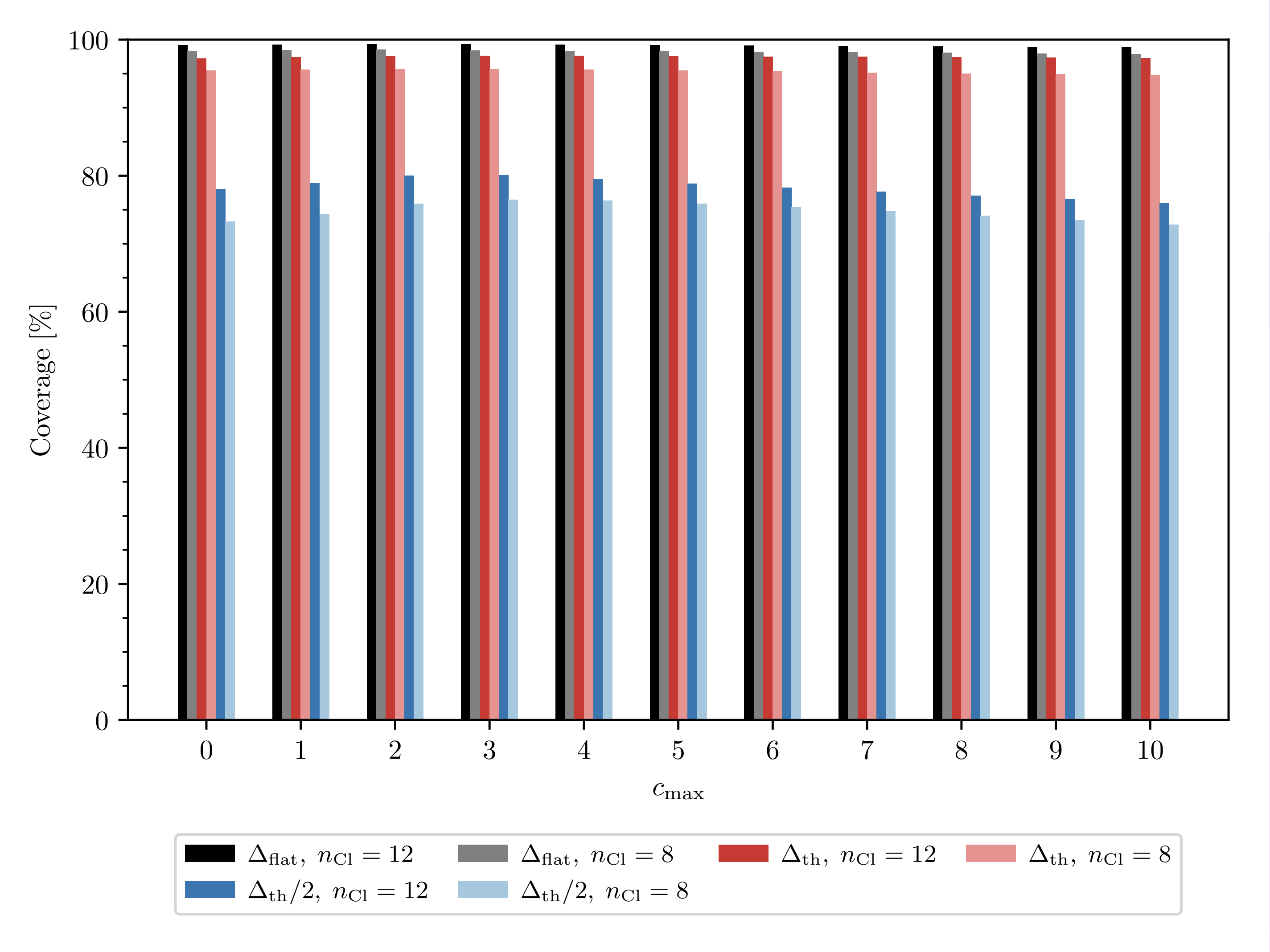


[Brivio, RG, Schmid 'in prep]

UV model for HEFT

in collaboration with Iñigo Asiáin and Lorenzo Tiberi

UV models for HEFT

Assuming custodial symmetry, SMEFT is invariant under $O(4)$ [Alonso, Jenkins, Manohar '15, '16 Falkowski, Rattazzi '19, Cohen, Craig, Lu, Sutherland '20]

$$\vec{\phi} = \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \\ \phi_4 \end{pmatrix} \qquad \vec{\phi}' = O\vec{\phi} \qquad \text{can be inserted in} \qquad H = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

cartesian coordinates on scalar manifold

Lagrangian

$$\mathcal{L} = a(|H|^2)(\partial |H|^2) + b(|H|^2)(\partial |H|^2)^2 + \ldots$$

analytic at origin

HEFT

$$h \qquad \vec{\pi} = \begin{pmatrix} \pi_1/v \\ \pi_2/v \\ \pi_3/v \\ \frac{1}{v}\sqrt{v^2 - (\pi_1^2 + \pi_2^2 + \pi_3^2)} \end{pmatrix} \qquad h' \to h \qquad \vec{\pi}' = O\vec{\pi}$$

polar coordinates on scalar manifold

$$\mathcal{L} = \tilde{a}(h^2)(\partial h^2) + \tilde{b}(|\vec{\pi}|^2)(\partial |\vec{\pi}|^2) + \ldots$$

UV models for HEFT

HEFT and SMEFT are equivalent when relations can be inverted, but this is obscured by field redefinitions

[Cohen, Craig, Lu, Sutherland '20; Gomez-Ambrosio, Llanes-Estrada, Salas-Bernárdez, Sanz-Cillero '22]

Models that realise HEFT can be classified according to [Cohen, Craig, Lu, Sutherland '20]

- new states obtain more than 50% of their mass from electroweak symmetry breaking "Loryons"
- BSM symmetry breaking: integrating out states with new sources of symmetry breaking

Example Model: Scalar Singlet

$$V(H,\Phi) = \mu_1^2|H|^2 + \lambda_H|H|^4 + \frac{1}{2}\mu_2^2\Phi^2 + \mu_4|H|^2\Phi + \frac{1}{2}\lambda_3|H|^2\Phi^2 + \frac{1}{3}\mu_3\Phi^3 + \frac{1}{4}\lambda_2\Phi^4$$

Scalars can acquire a VEV

$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_H + h \end{pmatrix}, \qquad \Phi = (v_S + S),$$

and they mix

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} h \\ S \end{pmatrix}$$

mass matrix

$$M^2 = \begin{pmatrix} m_{hh} & m_{hS} \\ m_{hS} & m_{SS} \end{pmatrix}$$

$$m_{hh} = 2v_H^2\lambda_H\,,$$
$$m_{hS} = v_H\left(\mu_4 + \lambda_3 v_S\right)\,,$$
$$m_{SS} = \mu_2^2 + \frac{1}{2}\left(\lambda_3 v_H^2 + 6v_S^2\lambda_2 + 4v_S\mu_3\right)\,,$$

UV models for HEFT HH

[Asiáin, RG, Tiberi 'in prep]

Example Model: Scalar Singlet

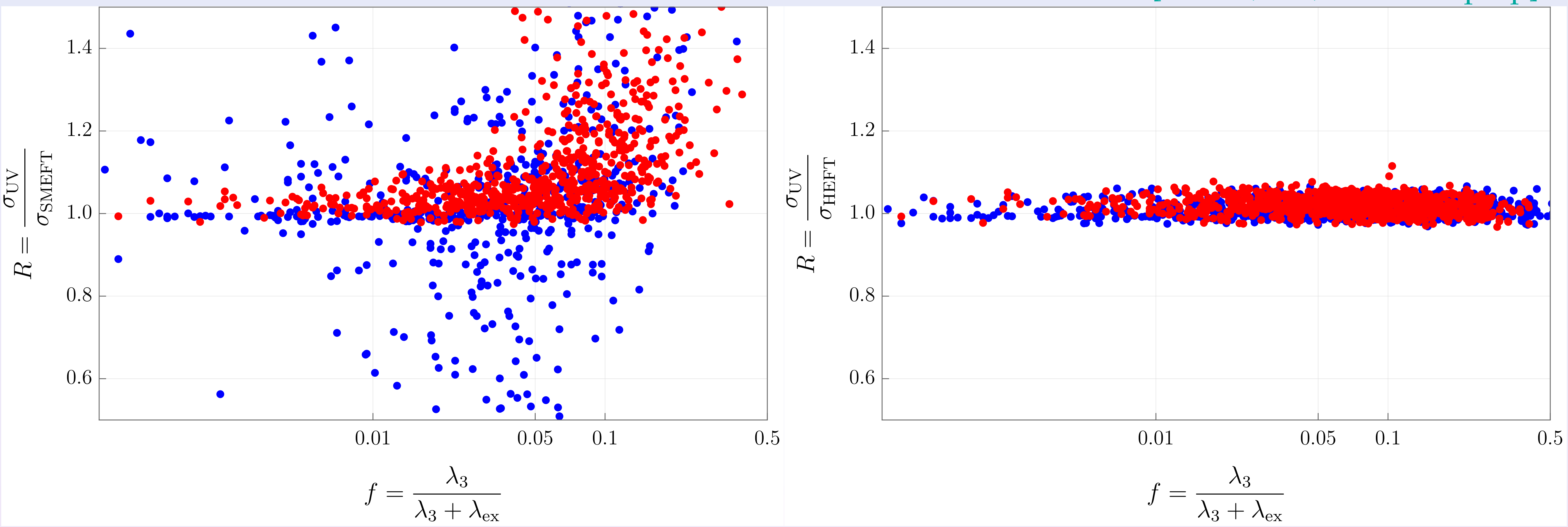
$$V(H,\Phi) = \mu_1^2|H|^2 + \lambda_H|H|^4 + \frac{1}{2}\mu_2^2\Phi^2 + \mu_4|H|^2\Phi + \frac{1}{2}\lambda_3|H|^2\Phi^2 + \frac{1}{3}\mu_3\Phi^3 + \frac{1}{4}\lambda_2\Phi^4$$

Match to HEFT and SMEFT

	HEFT	SMEFT
c_{hVV}	$1-\frac{1}{2}\theta^2$	$1-\frac{1}{2}\theta^2+\frac{v_S v_H \lambda_3}{m_2^2}\theta$
c_{hhVV}	$1-2\theta^2$	$1-2\theta^2+\frac{4v_S v_H \lambda_3}{m_2^2}\theta$
c_{hhh}	$1-\frac{3}{2}\theta^2+\frac{\lambda_3 v_H^2}{m_1^2}\theta^2$	$1-\frac{3}{2}\theta^2+\frac{\lambda_3 v_H^2}{m_1^2}\theta^2+\frac{3v_H v_S \lambda_3}{m_2^2}\theta$
c_t	$1-\frac{1}{2}\theta^2$	$1-\frac{1}{2}\theta^2+\frac{v_S v_H \lambda_3}{m_2^2}\theta$
c_{2t}	$-\frac{1}{2}\theta^2$	$-\frac{1}{2}\theta^2+\frac{v_S v_H \lambda_3}{m_2^2}\theta$

Coincide in the limit of small mixing angle and small v_S

[Asiáin, RG, Tiberi 'in prep]



red points: $v_s \in [0, 0.1 v_H]$

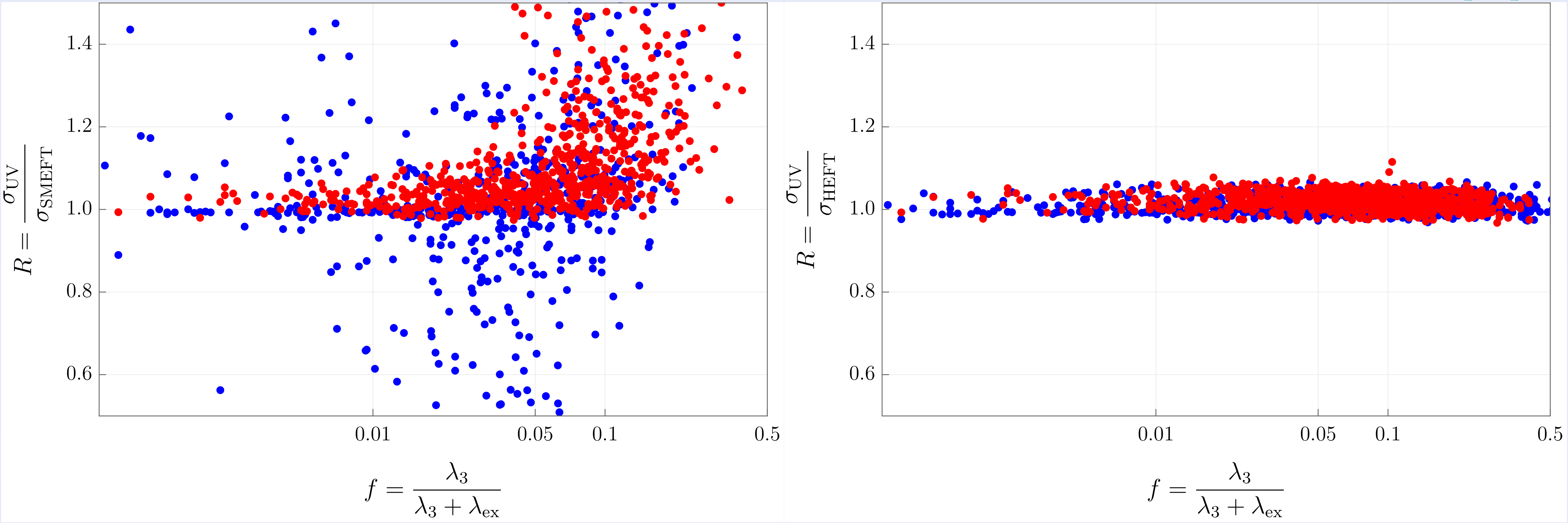
blue points: $v_s \in [0, 5 v_H]$

$$f = \frac{\lambda_3}{\lambda_3 + \frac{2\mu_2^2}{v_H^2}} = \frac{\lambda_3}{\lambda_3 + \lambda_{\rm ex}}$$

is a measure how much of the singlet mass comes from EWSB

UV models for HEFT HH

[Asiáin, RG, Tiberi 'in prep]



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$$f = \frac{\lambda_3}{\lambda_3 + \frac{2\mu_2^2}{v_H^2}} = \frac{\lambda_3}{\lambda_3 + \lambda_{ex}}$$

is a measure how much of the singlet mass comes from EWSB

→ HEFT is the better EFT to be used in Higgs pair production for singlet model

Amplitudes

in collaboration with Alejo Rossia and Michał Ryzkowski
arXiv: 2509.02680

Amplitudes

[RG, Rossia, Ryczkowski '25]

We can even be more general using amplitude techniques

Idea: Check with amplitudes where HEFT and SMEFT depart, in a processes that can test differences

Multi-Higgs production

[RG, Rossia, Ryczkowski '25]

We can even be more general using amplitude techniques

Idea: Check with amplitudes where HEFT and SMEFT depart, in a processes that can test differences

Multi-Higgs production

? Is SMEFT falsifiable (in multi-Higgs production)? ?

[Gomez-Ambrosio, Llanes-Estrada, Salas-Bernárdez, Sanz-Cillero '22]

Concentrate for the time being on gluon - Higgs interactions

OnShell Amplitudes

Lorentz invariance

Global symmetries

Locality

Helicity and little group scaling

Physical degrees of freedom

bootstrap →

Simple scattering amplitudes

Emergence of gauge symmetries

bottom-up approach to EFTs without field redefinition ambiguities

[Shadmi, Weiss '18; Durieux et al. '19, Huber, De Angelis '21, …]

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bottom-up approach to EFTs without field redefinition ambiguities

[Shadmi, Weiss '18; Durieux et al. '19, Huber, De Angelis '21, …]

Building blocks (based on spinor-helicity formalism) are

[Elvang, Huang '13, Arkani-Hamed et al '17]

Momenta: $p_{\alpha\dot{\alpha}} \equiv p_\mu \sigma^\mu_{\alpha\dot{\alpha}} \equiv |p\rangle_\alpha [p|_{\dot{\alpha}}\,, \quad \overline{p}^{\dot{\alpha}\alpha} \equiv p_\mu \overline{\sigma}^{\mu\,\dot{\alpha}\alpha} \equiv |p]^{\dot{\alpha}} \langle p|^\alpha\,,$

Spinors: $u_+(p) = |p],\quad u_-(p) = |p\rangle\,,$ $\overline{u}_+(p) = [p|,\quad \overline{u}_-(p) = \langle p|\,,$

Polarisation vectors: $\epsilon^\mu_+(p) = = \frac{1}{\sqrt{2}} \frac{\langle \xi|\sigma^\mu|p]}{\langle p|\xi\rangle}\,,$ $\epsilon^\mu_-(p) = \frac{1}{\sqrt{2}} \frac{\langle p|\sigma^\mu|\xi]}{[p|\xi]}\,,$

Strategy:

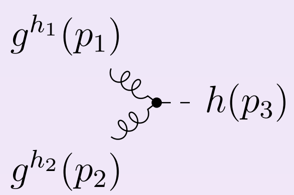
Build non-factorisable and factorisable on shell amplitudes multiplied by kinematic invariants, check if and how they arise in SMEFT and HEFT

Double Higgs

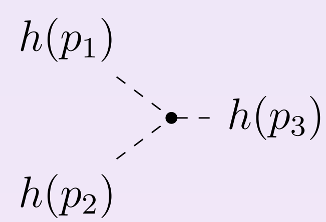
Non-Factorisable

$$\mathcal{M}\left(g^{a,+}(p_1);g^{b,+}(p_2);h(p_3);h(p_4)\right)_{\text{NF}} = i\,\delta^{ab}c^{++}_{gghh}\;[1|2]^2\;,$$
$$\mathcal{M}\left(g^{a,+}(p_1);g^{b,-}(p_2);h(p_3);h(p_4)\right)_{\text{NF}} = i\delta^{ab}c^{+-}_{gghh}\;[1|\mathbf{3}-\mathbf{4}|2\rangle^{\,2}\;,$$

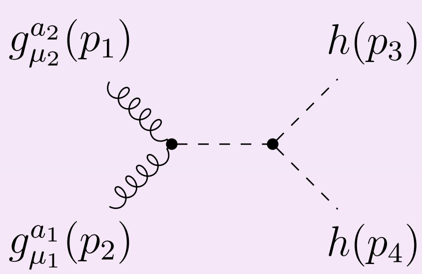
Factorisable



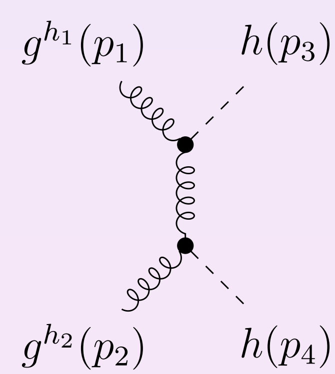
$$= \mathcal{M}\left(g_1^{a,h_1};g_2^{b,h_2};h\right) = i\,\delta^{ab}\,[1|2]^n\,g_{-\ell}(s_{12},\Lambda)\,,$$



$$= \mathcal{M}\left(h;h;h\right) = i\,c_{3h}\,.$$



$$= \mathcal{M}\left(g_1^{a,+};g_2^{b,+};h_3;h_4\right)_{s\text{–ch.}} = -\delta^{ab}\frac{c_{3h}\,c_{ggh}}{s_{12}-m_h^2}[1|2]^2\,.$$



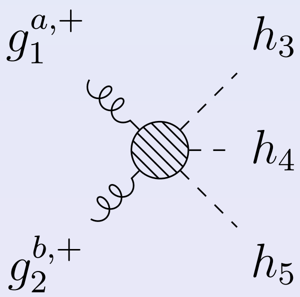
$$\mathcal{M}\left(g_1^{a,+};g_2^{b,-};h_3;h_4\right)_{t+u\text{–ch.}}$$
$$= -\,\delta^{ab}\frac{|c_{ggh}|^2}{4}[1|\mathbf{3}-\mathbf{4}|2\rangle^2\left(\frac{1}{s_{13}}+\frac{1}{s_{23}}\right),$$
$$= -\,\delta^{ab}\frac{|c_{ggh}|^2}{4}[1|\mathbf{3}-\mathbf{4}|2\rangle^2\frac{2m_h^2-s_{12}}{s_{13}s_{23}}\,.$$

OnShell Double Higgs

Amplitude	Helicity	Spinor structure	Coeff.	Dimension	Minimal order SMEFT	Minimal order HEFT
Three-point						
$gg \to h$	$++$	$[1\|2]^2$	c_{ggh}	$-1\,(1/\overline{\Lambda})$	$6\,(v/\Lambda^2)$	NLO*
$hh \to h$	-	-	c_{hhh}	$1\,(\overline{\Lambda})$	4	LO
Four-point						
$hh \to hh$	-	-	c_{4h}	0	4	LO
$gg \to hh$	$++$	$[1\|2]^2$	c^{++}_{gghh}	$-2\,(1/\overline{\Lambda}^2)$	$6\,(1/\Lambda^2)$	NLO*
	$+-$	$[1\|\mathbf{3}-\mathbf{4}\|2\rangle^2$	c^{+-}_{gghh}	$-4\,(1/\overline{\Lambda}^4)$	$8\,(1/\Lambda^4)$	NNLO*

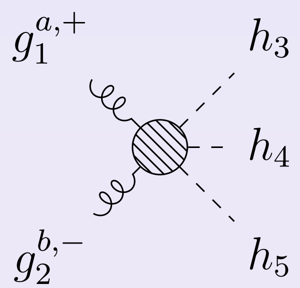
All structures arise at same order, in SMEFT more coefficients but same physics

OnShell Triple Higgs



$$= \mathcal{M}\left(g_1^{a,+}; g_2^{b,+}; h_3; h_4; h_5\right)_{\text{NF}} = i\,\delta^{ab}\,c_{gghhh}^{++,(1)}[1|2]^2$$

$$+\, i\,\delta^{ab}\,c_{gghhh}^{++,(2)}\left([1|\mathbf{34}|2][1|\mathbf{43}|2] + [1|\mathbf{35}|2][1|\mathbf{53}|2] + [1|\mathbf{45}|2][1|\mathbf{54}|2]\right)$$



$$= \mathcal{M}\left(g_1^{a,+}; g_2^{b,-}; h_3; h_4; h_5\right)_{\text{NF}}$$

$$= i\,\delta^{ab}\,c_{gghhh}^{+-}\left(([1|\mathbf{3}|2\rangle)^2 + ([1|\mathbf{4}|2\rangle)^2 + ([1|\mathbf{5}|2\rangle)^2\right),$$

Amplitude	Helicity	Spinor structure	Coeff.	Dimension	Minimal SMEFT order	Minimal HEFT order
			Five-point			
$hh \to hhh$	-	-	c_{5h}	0	$6\,(v/\Lambda^2)$	LO
$gg \to hhh$	$++$	$[1|2]^2$	$c_{gghhh}^{++,(1)}$	$-3\,(1/\overline{\Lambda}^3)$	$8\,(v/\Lambda^4)$	NLO*
	$++$	$[1|\mathbf{34}|2]^2$	$c_{gghhh}^{++,(2)}$	$-7\,(1/\overline{\Lambda}^7)$	$12\,(v/\Lambda^8)$	N³LO*
	$+-$	$[1|\mathbf{3}|2\rangle^2$	c_{gghhh}^{+-}	$-5\,(1/\overline{\Lambda}^5)$	$10\,(v/\Lambda^6)$	NNLO*

contributions arise at different orders

we cannot *falsify* just probe convergence

Conclusion

- Higgs effective field theory more general than SMEFT but more complicated power counting

- HEFT in Higgs pair production can bring changes in kinematic distributions so far not considered, if they can be probed depends on the uncertainty

- UV physics that requests HEFT is *non-decoupling*

- HEFT and SMEFT show different convergence pattern in multi-Higgs production

Conclusion

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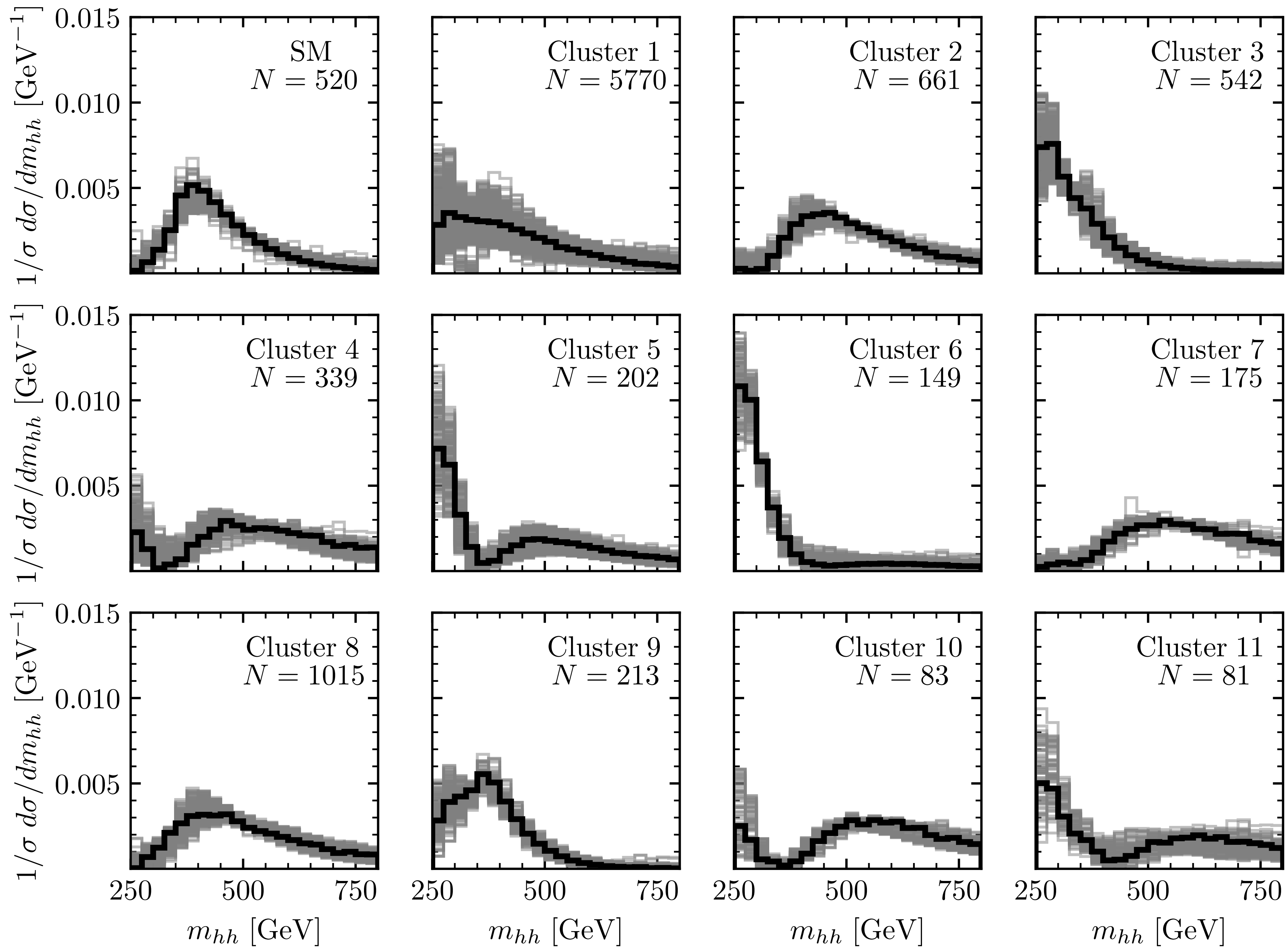
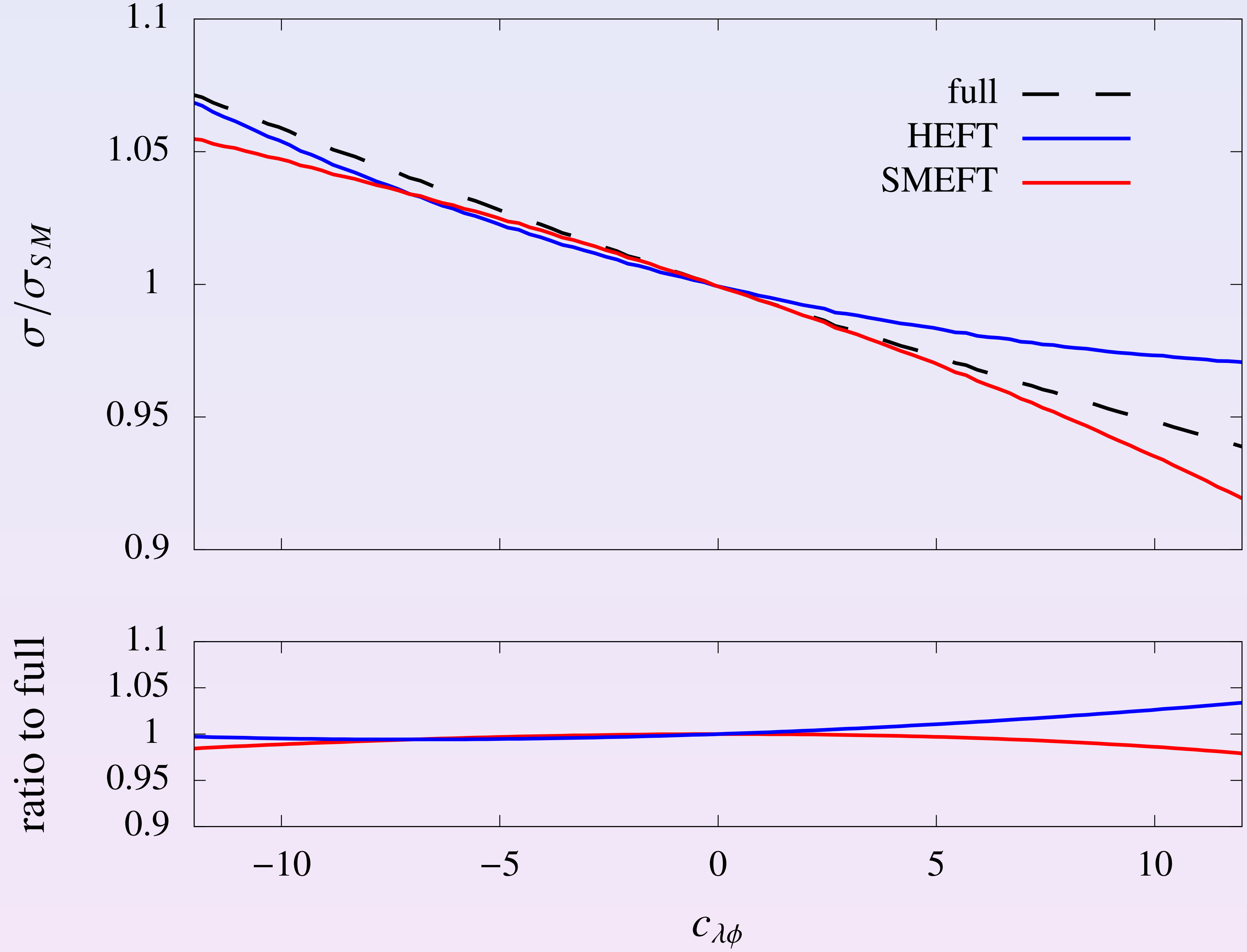
Thanks for you attention !

Kinematic distributions



kappa-Lagrangian

Colored scalar model



$$\mathcal{L} \supset D_\mu \omega_1^\dagger D^\mu \omega_1 - M_{ex}^2 \omega_1^\dagger \omega_1 - \frac{c_{\lambda\phi}}{2} \omega_1^\dagger \omega_1 \Phi^\dagger \Phi \qquad \omega_1 = (1,3)_{-1/3}$$