The hunt for non-resonant signals of new physics at the LHC

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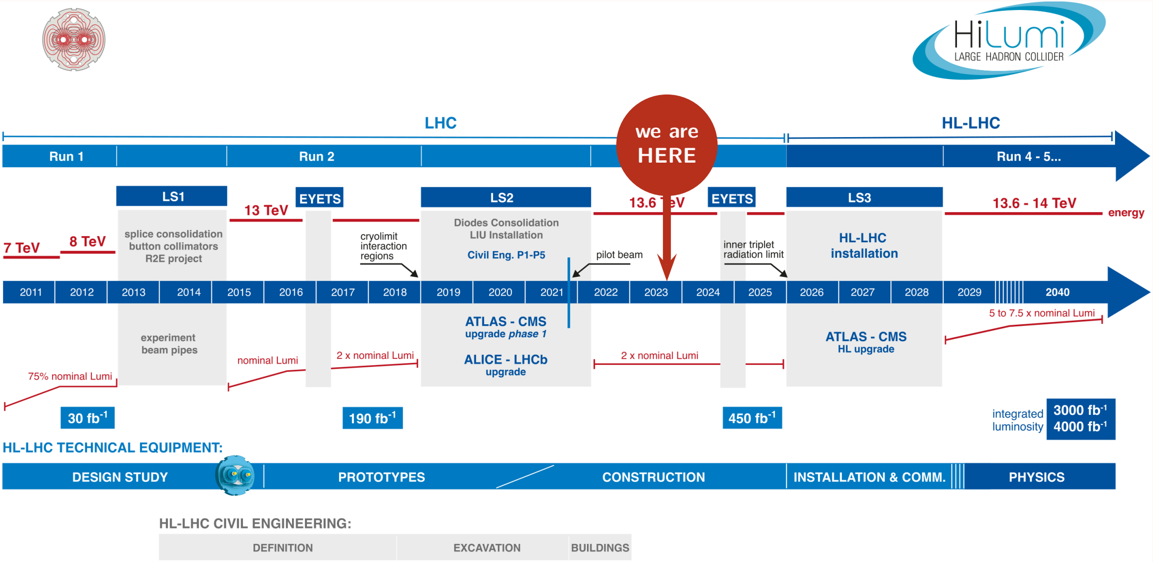
Where we are - LHC perspective



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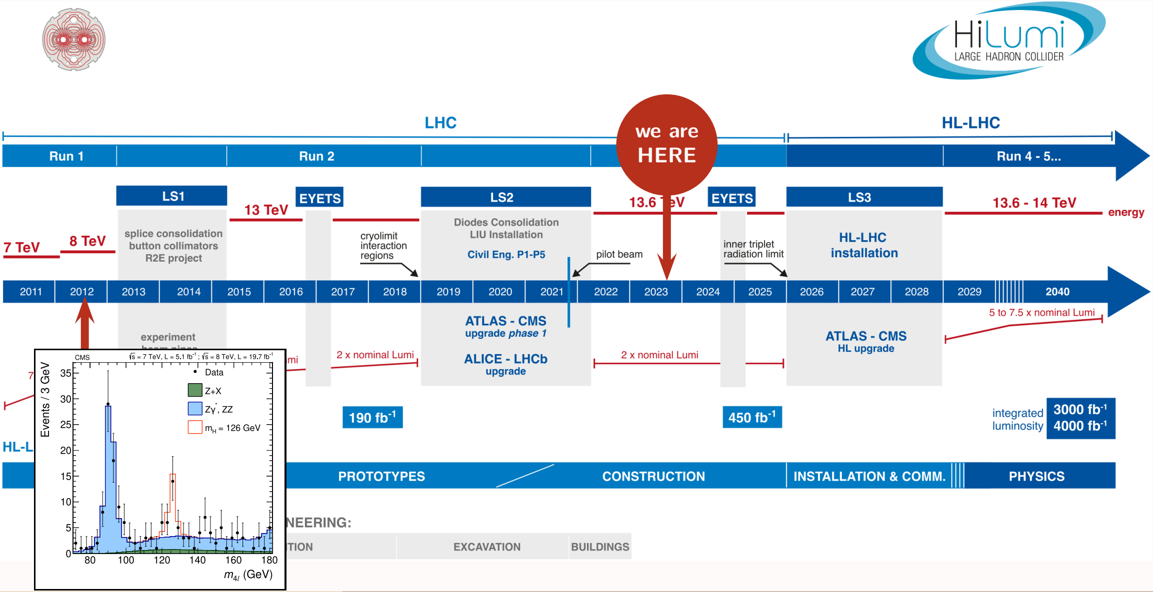

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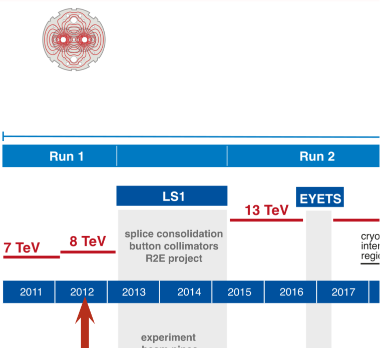
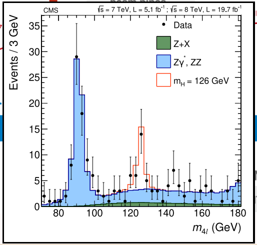
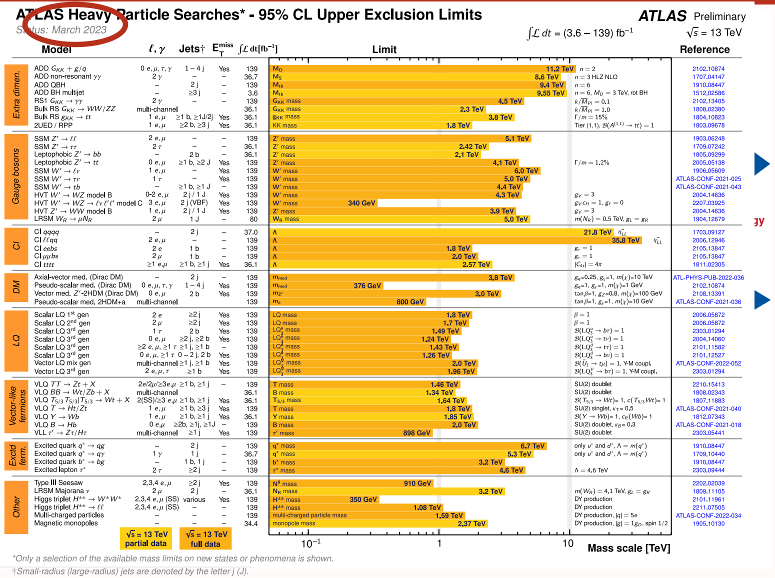
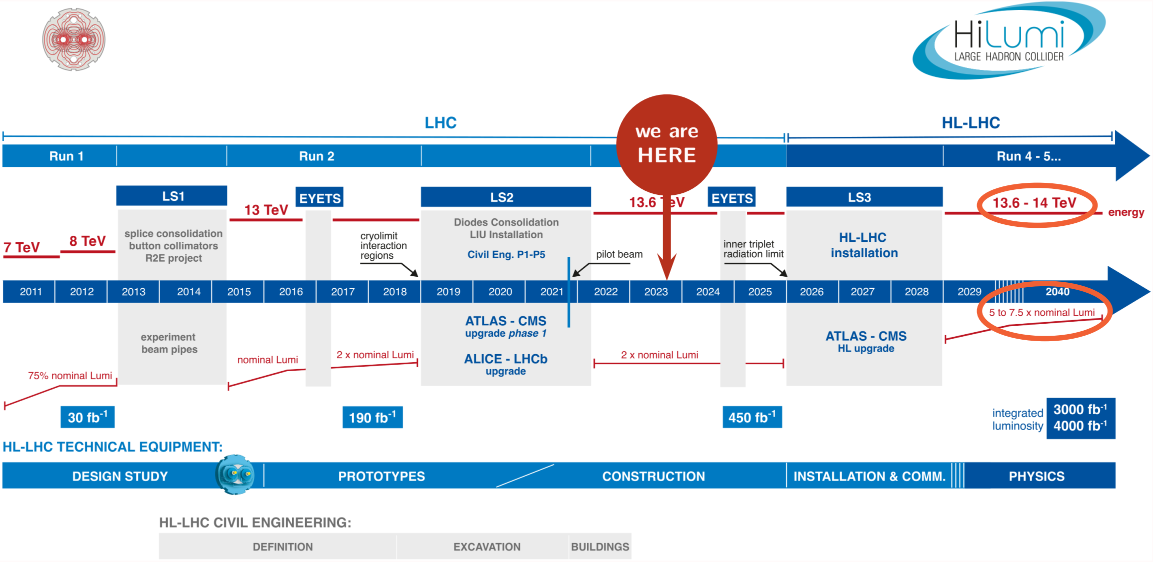






Where we are - LHC perspective



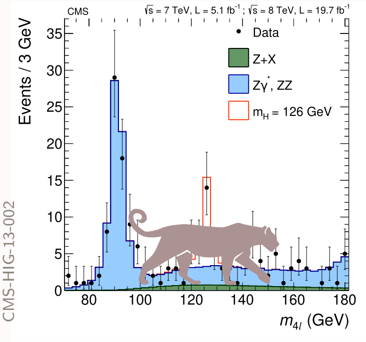
Targeting non-resonant signals of new physics

no clear indications of specific BSM scenarios + strong reduction of statistical uncertainties

↓

new strategies for NP searches targeting **non-resonant** signals

CMS-HIG-13-002



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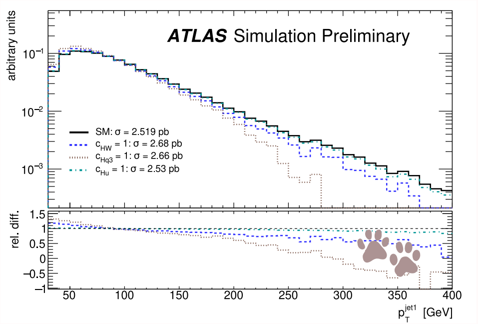
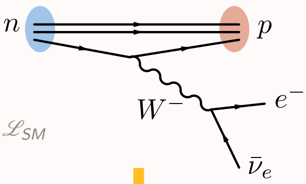


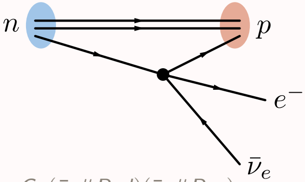
ATL-PHYS-PUB-2019-042

Fermi Theory of β decay



$\mathscr{L} = \mathscr{L}_{SM}$

$q^2 < m_N^2 \ll m_W^2$



$\mathscr{L} = -G_F(\bar{u}\gamma^\mu P_L d)(\bar{\nu}\gamma^\mu P_L e)$

E

Λ

Full theory

$\rightarrow$ renormalizable: $[\mathscr{L}] = 4$

TAYLOR SERIES in ($\mu/\Lambda \ll 1$)

μ

Effective Field Theory

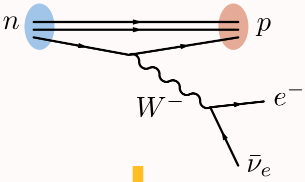
$$\mathscr{L}_{EFT} = \mathscr{L}_4 + \frac{1}{\Lambda}\mathscr{L}_5 + \frac{1}{\Lambda^2}\mathscr{L}_6 + \frac{1}{\Lambda^3}\mathscr{L}_7 \ldots$$

Appelquist,Carazzone 1975

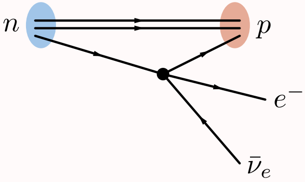
$\rightarrow$ heavy DOFs are removed: cannot be produced at $E \ll M$
$\rightarrow$ local, analytic, higher-dimensional terms added to $\mathscr{L}$

Effective Field Theories

Fermi Theory of β decay



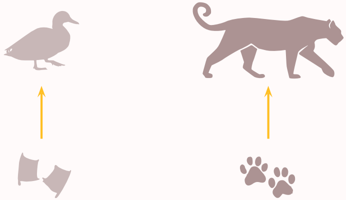
$$q^2 < m_N^2 \ll m_W^2$$



Bottom-up paradigm

measuring EFT parameters **reveals properties** of full theory

→ *complement* direct searches, reach into higher energies



EFT fully specified by **fields+symmetries at E** $= \mu$

→ no reference to underlying model

→ free couplings that can be measured!

The Standard Model Effective Field Theory – SMEFT

promoting the Standard Model to an EFT → add **higher-dimensional** terms made of SM **fields** and respecting the SM **symmetries**

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \dots \qquad \mathcal{L}_d = \sum_i C_i \mathcal{O}_i^{(d)}$$

C_i = Wilson coefficients

$\mathcal{O}_i^{(d)}$ = gauge-invariant operators forming a basis: a complete, non-redundant set

Buchmüller,Wyler 1986

- describes **any beyond-SM theory**, provided it lives at $\Lambda \gg v$
- a complete catalogue of all allowed beyond-SM effects, organized by expected size
- not experiment-specific! can be used as **a common framework** for LHC *and* other experiments
- a proper QFT! renormalizable order-by-order, systematically improvable in loops

SMEFT at $d = 6$: the Warsaw basis

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

Grzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884

free parameters

go down to O(100) imposing flavor symmetries, CP, B

Faroughy et al 2005.05366
Greljo et al 2203.09561
IB 2012.11343

they are ∼never all relevant at the same time

SMEFT at $d = 6$: the Warsaw basis

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$		

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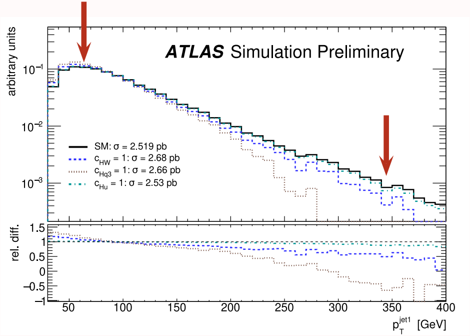
Challenges for the bottom-up SMEFT program

1. being **sensitive** to indirect BSM effects → needs uncertainty reduction

in bulk $\sim \frac{v^2}{\Lambda^2} = \frac{v^2 g_{UV}}{M^2}$. $\qquad g_{UV} \simeq 1, \quad M \simeq 2\,\mathrm{TeV} \rightarrow$ 1.5%

on tails $\sim \frac{E^2}{\Lambda^2} \simeq \frac{E^2 g_{UV}}{M^2}$ $\qquad E \simeq 1\,\mathrm{TeV}, M \simeq 3\,\mathrm{TeV} \rightarrow$ 10%



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2. making sure that, if we observe one, we **interpret it correctly**. needs:
   - retaining <u>all relevant contributions</u>: all operators, NLO corrections...

     ↓

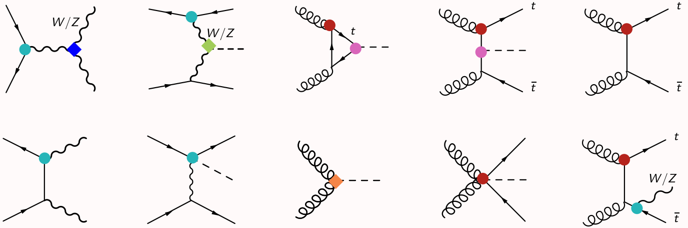
     – handling many parameters in predictions and fits
     – understanding the theory structure
   - correct understanding of uncertainties and correlations
   - systematic mapping to BSM models

A complex game

many free parameters entering many places → scaling complexity + non-trivial interconnections

typically each process is corrected by $\mathcal{O}(10)$ parameters:
constrains a direction in parameter space

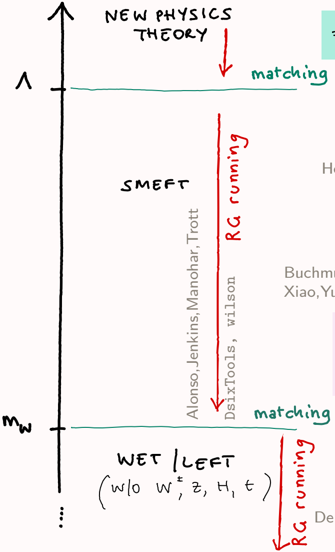
each parameter enters
multiple processes



Global analyses combining several measurements are necessary

- to access as many operators as we can
- to avoid bias in interpretation [safer than ad-hoc choices]

A field with many ramifications



FUNCTIONAL METHODS
Henning,Lu,Murayama,delAguila,Kunst,Santiago,Drozd,Ellis,Quevillon,You, Zhang,Fuentes-Martin,Portoles,Ruiz-Femenia,Krämer,Summ,Voigt. . .
`Matchmaker-eft`, `Matchete`, `STrEAM`, `CoDEx`

COUNTING FREE PARAMETERS
Henning,Lu,Melia,Murayama

CONSTRUCTING OP. BASES
Buchmüller,Wyler,Lehman,Li,Ren,Shu, Xiao,Yu,Zheng,Ma,Murphy. . .

ENSURING PHYSICAL AMPLITUDES (causal, unitary ....)
Adams,Arkani-Hamed,Nicolis, Rattazzi,deRham,Riva,Li, Xu,Tolley,Zhou,Zhang. . .

ANALYTIC CALCULATIONS
Hartmann,Trott,Corbett,Passarino, Dedes,Rosiek,Baglio,Giardino,Dawson, Pecjak,Scott,Grazzini,Maltoni,Alioli. . .

MONTE CARLO SIMULATIONS
IB,Degrande,Durieux,Maltoni,Mimasu, Vryonidou,Zhang. . . `SMEFTsim`, `SMEFT@NLO`

STUDIES OF EFT EFFECTS IN PDF, PS ...
Ubiali,Carrazza,Degrande,Rojo,Greljo, Iranipour,Kassabov,Madigan,Moore, Haisch,Scott,Wiesemann,Zanderighi,Zanoli. . .

FITTING TOOLS
`SMEFiT`, `HEPfit`, `EFTfitter`, `fitmaker`, `sfitter`. . .

INFORMATION GEOMETRY
Brehmer,Cranmer,Kling, Plehn,Tait. . .

LIKELIHOOD INFERENCE
Brehmer,Cranmer,Louppe,Pavez, Glioti,Panico,Wulzer. . .

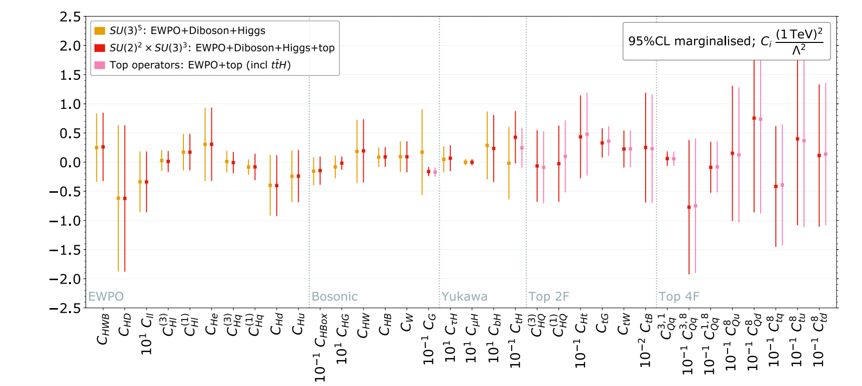
amazing progress was made in the last decade

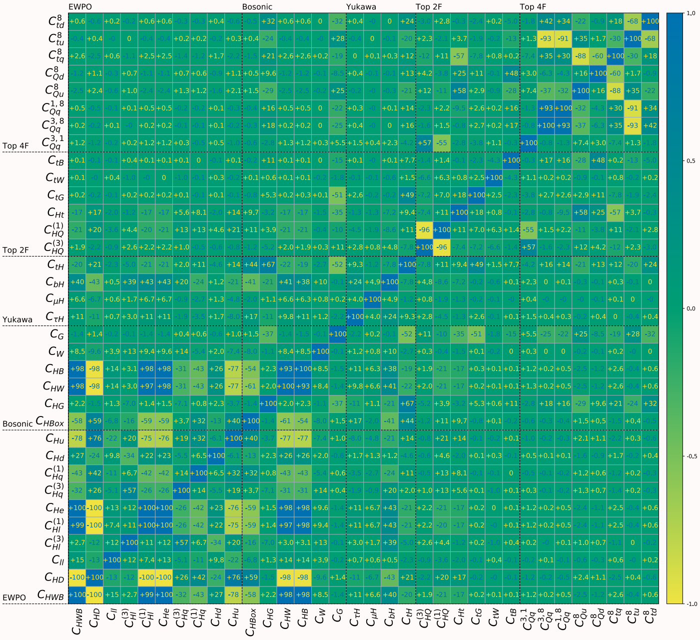
SMEFT analyses: state of the art

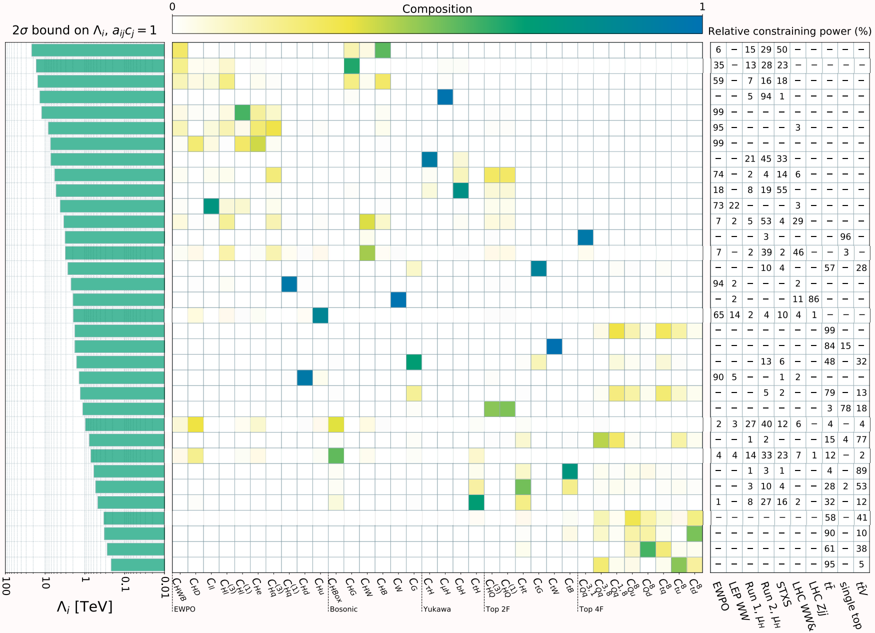
- theory fits: Higgs + EW (incl LEP) + top quark typically **30-35** param.
- SMEFT theory predictions: computed at tree-level / 1-loop in QCD

$$|\mathcal{M}_{SMEFT}|^2 = |\mathcal{M}_{SM}|^2 + \sum_\alpha \frac{C_\alpha}{\Lambda^2}\mathcal{M}_\alpha\mathcal{M}^\dagger_{SM} + \sum_{\alpha\beta}\frac{C_\alpha C_\beta}{\Lambda^4}\mathcal{M}_\alpha\mathcal{M}^\dagger_\beta$$

Ellis,Madigan,Mimasu,Sanz,You 2012.02779
also: Ethier,Maltoni,Mantani,Nocera,Rojo 2105.00006




EWPO
Bosonic
Yukawa
Top 2F
Top 4F
C^8_{td} C^8_{tu} C^8_{tq} C^8_{Qd} C^8_{Qu} $C^{1,8}_{Qq}$ $C^{3,8}_{Qq}$ $C^{3,1}_{Qq}$
C_{tB} C_{tW} C_{tG} C_{Ht} $C^{(1)}_{HQ}$ $C^{(3)}_{HQ}$
C_{tH} C_{bH} $C_{\mu H}$ $C_{\tau H}$
C_G C_W C_{HB} C_{HW} C_{HG} C_{HBox}
C_{Hu} C_{Hd} $C^{(1)}_{Hq}$ $C^{(3)}_{Hq}$ C_{He} $C^{(1)}_{Hl}$ $C^{(3)}_{Hl}$ C_{ll} C_{HD} C_{HWB}
1.0
0.5
0.0
-0.5
-1.0



2σ bound on Λ_i, $a_{ij}c_j = 1$
100 10 1 0.1 0.01
Λ_i [TeV]
Composition
0 1
C_{HWB} C_{HD} C_{ll} $C_{Hl}^{(3)}$ $C_{Hl}^{(1)}$ C_{He} $C_{Hq}^{(3)}$ $C_{Hq}^{(1)}$ C_{Hd} C_{Hu}
EWPO
C_{HBox} C_{HG} C_{HW} C_{HB} C_W C_G
Bosonic
$C_{\tau H}$ $C_{\mu H}$ C_{bH} C_{tH}
Yukawa
$C_{HQ}^{(3)}$ $C_{HQ}^{(1)}$ C_{Ht} C_{tG} C_{tW} C_{tB}
Top 2F
$C_{Qq}^{3,1}$ $C_{Qq}^{3,8}$ $C_{Qq}^{1,8}$ C_{Qu}^{8} C_{Qd}^{8} C_{tq}^{8} C_{tu}^{8} C_{td}^{8}
Top 4F
Relative constraining power (%)
EWPO, LEP WW, Run 1, μH, Run 2, μH, STXS, LHC WW&, LHC Zjj, tt̄, single top, ttV
6 – 15 29 50 – – – – –
35 – 13 28 23 – – – – –
59 – 7 16 18 – – – – –
– – 5 94 1 – – – – –
99 – – – – – – – – –
95 – – – – 3 – – – –
99 – – – – – – – – –
– – 21 45 33 – – – – –
74 – 2 4 14 6 – – – –
18 – 8 19 55 – – – – –
73 22 – – – 3 – – – –
7 2 5 53 4 29 – – – –
– – – 3 – – – – 96 –
7 – 2 39 2 46 – – 3 –
– – – 10 4 – – 57 – 28
94 2 – – – 2 – – – –
– 2 – – – 11 86 – – –
65 14 2 4 10 4 1 – – –
– – – – – – – 99 – –
– – – – – – – 84 15 –
– – – 13 6 – – 48 – 32
90 5 – – 1 2 – – – –
– – – 5 2 – – 79 – 13
– – – – – – – 3 78 18
2 3 27 40 12 6 – 4 – 4
– – 1 2 – – – 15 4 77
4 4 14 33 23 7 1 12 – 2
– – 1 3 1 – – 4 – 89
– – 3 10 4 – – 28 2 53
1 – 8 27 16 2 – 32 – 12
– – – – – – – 58 – 41
– – – – – – – 90 – 10
– – – – – – – 61 – 38
– – – – – – – 95 – 5

SMEFT combined analyses in ATLAS and CMS

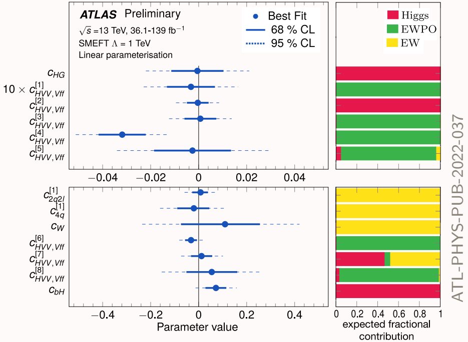
LHC experiments gearing up to do dedicated combination

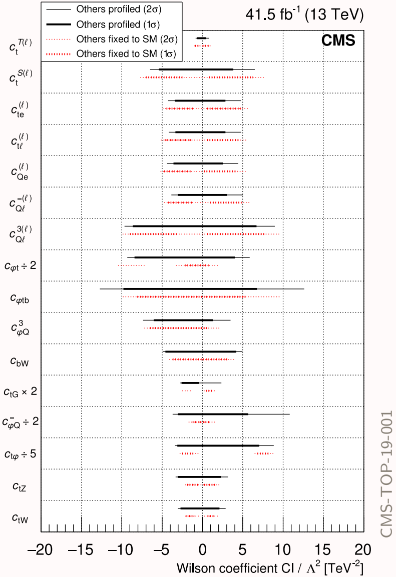
important in order to use the full experimental information:
better uncertainty and correlation estimates

ultimate goal: a cross-experiment cross-sector combined study

a dedicated
CERN Working Group
created in 2020
to coordinate

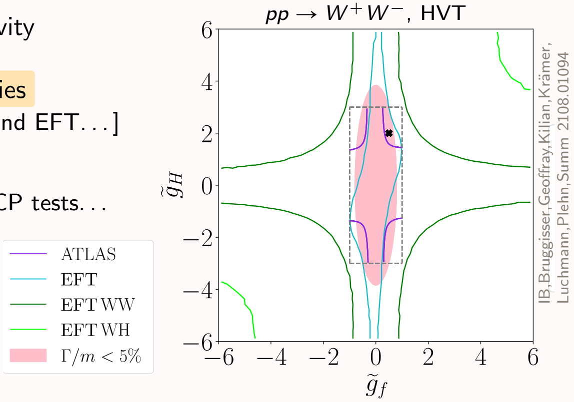
lpcc.web.cern.ch/lhc-eft-wg





Some open fronts

- treatment of RG effects: 2-loop RGE, account for running+mixing in MC...
- improve theory predictions: optimize MC strategies, include EFT in backgrounds, PDFs...
- properly account for experimental **uncertainties and correlations** in fits
- define optimal observables to improve sensitivity
- understand and treat SMEFT-born uncertainties
  [scale dependence, missing higher orders in loops and EFT...]
- incorporate **more processes**:
  VBS, high-multiplicity final states, flavor physics, CP tests...
- handle 50+ dimensional likelihood
- explore interplay with resonance searches
- explore alternative EFT setups?



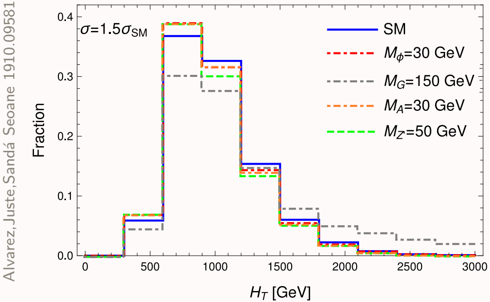
Non-resonant signals from light NP

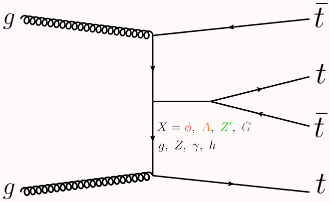
Non-resonant signals can also be induced by new light states

→ off-shell, in the limit $\sqrt{s} \gg m$ → typically happens for heavy final states

→ most relevant if they have momentum-enhanced couplings (EFT)

$pp \to \bar{t}t\bar{t}t$





graviton G has $d = 5$ coupling ($G_{\mu\nu}\bar{t}_R\gamma^\mu D^\nu t_R$), all others are $d = 4$

top-philic → not ruled out by direct searches

An interesting case: Axion-Like Particles

ALP = pseudo-Goldstone boson from breaking of BSM symmetry

Examples:

Peccei-Quinn symm.	$\rightarrow$	QCD axion	Peccei,Quinn 1977, Weinberg 1978 Wilczek 1978
Lepton number	$\rightarrow$	Majoron	Gelmini,Roncadelli 1981 Langacker,Peccei,Yanagida 1986
Flavor symm.	$\rightarrow$	Flavon	Wilczek 1982

Fundamental properties

- neutral, pseudo-scalar: spin 0, odd parity
- approx. shift symmetry $a(x) \rightarrow a(x) + c$ $\Rightarrow m_a$ **naturally small**

Why so interesting?

- naturally the lightest remnant of heavy NP sectors $\rightarrow$ easiest to discover
- spontaneous symmetry breakings are **ubiquitous** in BSM $\rightarrow$ high relevance
- under certain conditions: good **DM** candidate

ALP Effective Field Theory

- ALPs can be described in a **EFT** where heavy sector is integrated out
- SM fields + a & SM symmetries + ALP shift sym. (+ CP)
- Cutoff: f_a (ALP char. scale, reminiscent of f_π). LO: dimension 5

CP even: Georgi,Kaplan,Randall PLB169B(1986)73

$$
\begin{aligned}
\mathcal{L}_{ALP} = & \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{m_a^2}{2} a^2 \\
& + C_{\tilde{B}} O_{\tilde{B}} + C_{\tilde{W}} O_{\tilde{W}} + C_{\tilde{G}} O_{\tilde{G}} \\
& + C_u O_u + C_d O_d + C_e O_e + C_Q O_Q + C_L O_L \quad + \mathcal{O}(f_a^{-2})
\end{aligned}
$$

$$
O_{\tilde{B}} = -\frac{a}{f_a} B_{\mu\nu} \tilde{B}^{\mu\nu} \qquad O_{\tilde{W}} = -\frac{a}{f_a} W^I_{\mu\nu} \tilde{W}^{I\mu\nu} \qquad O_{\tilde{G}} = -\frac{a}{f_a} G^A_{\mu\nu} \tilde{G}^{A\mu\nu}
$$

$$
O_{f,ij} = \frac{\partial^\mu a}{f_a} (\bar{f}_i \gamma^\mu f_j) \qquad \to C_f : \quad N_g \times N_g \text{ symmetric matrices in flavor space}
$$

Recent developments in ALP EFT

relatively simple EFT → convenient theory playground. recently borrowed some expertise from SMEFT

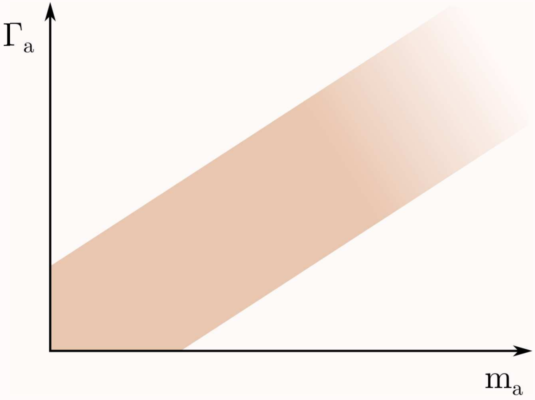
- discussion on basis completeness — Chala,Guedes,Ramos,Santiago 2012.09017; Bauer,Neubert,Renner,Schnubel,Thamm 2012.12272; Bonilla,IB,Gavela,Sanz 2107.11392
- RGE evolution, including CP-odd and shift-breaking terms — Das Bakshi,Machado-Rodriguez,Ramos 2306.08036
- RGE mixing into SMEFT — Galda,Neubert,Renner 2105.01078
- comprehensive 1-loop study, incl. finite parts — Bonilla,IB,Gavela,Sanz 2107.11392
- unitarity constraints — IB,Éboli,González-García 2106.05977
- flavor-invariant parameterization of shift-breakings — Bonnefoy,Grojean,Kley 2206.04182
- Operator basis up to dim-8 — Song,Sun,Yu 2305.16770
- Hilbert series for operator counting — Grojean,Kley,Yao 2307.08563
- Global analysis of LEP, LHC and flavor data — Bruggisser,Grabitz,Westhoff 2308.11703

ALPs at the LHC

Why?

- tree-level access to **couplings to heavy SM particles** (W, Z, h, t)
- access to **heavy ALPs** $(m_a \gtrsim 10s$ GeV$)$

How?



ALPs at the LHC

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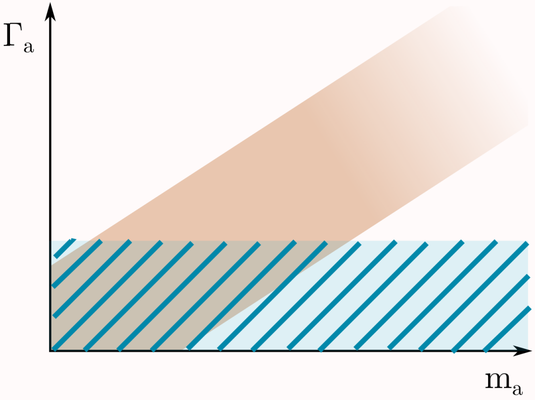
How?

stable ALP

$\downarrow$

$\not{E}_T$



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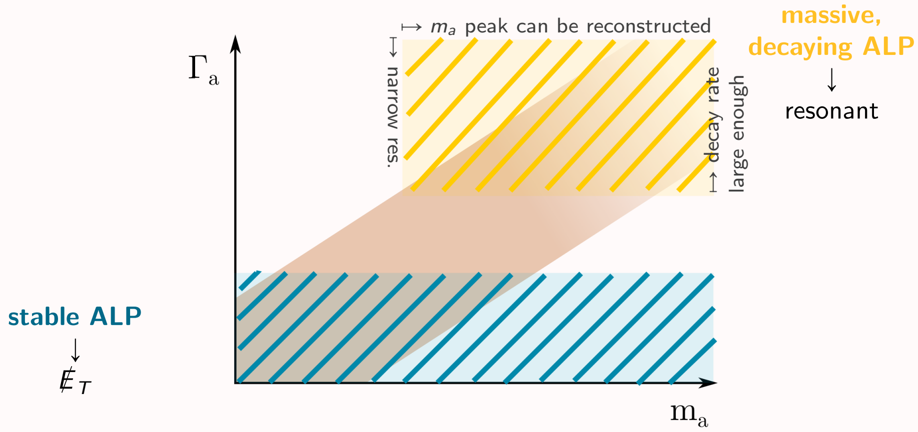

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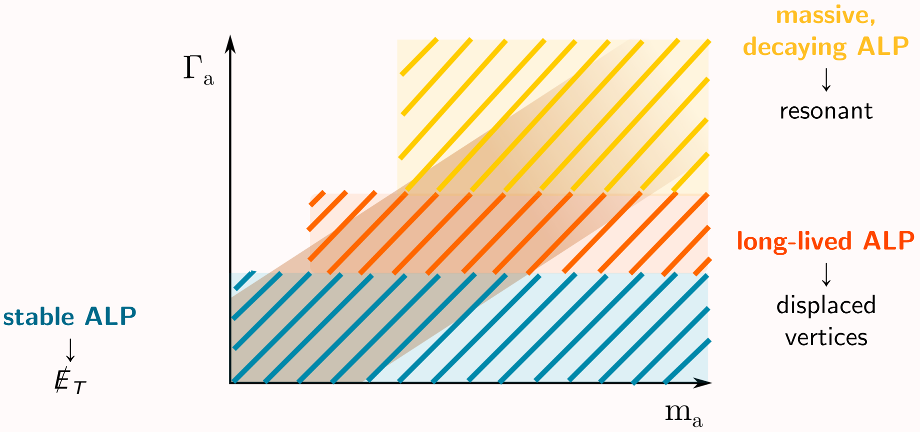

ALPs at the LHC

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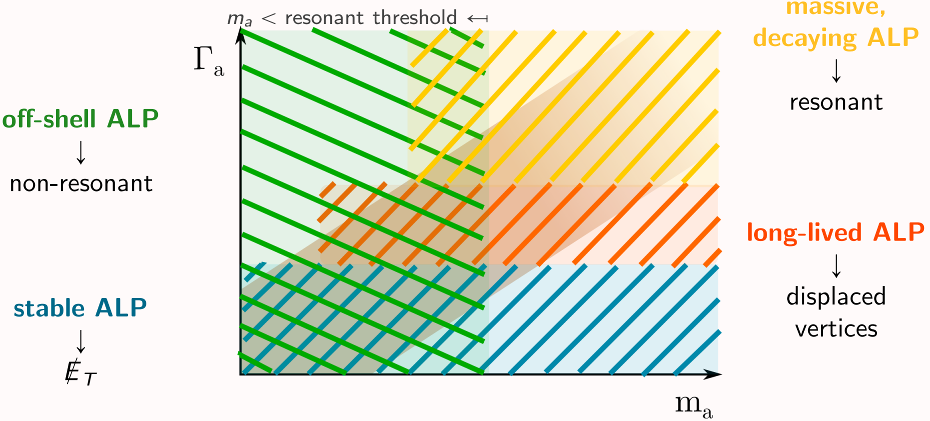
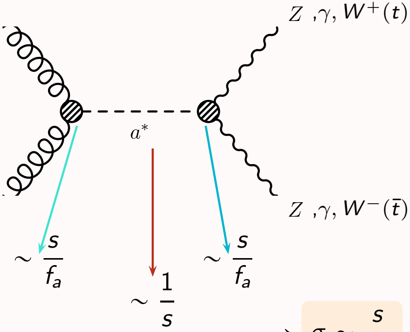
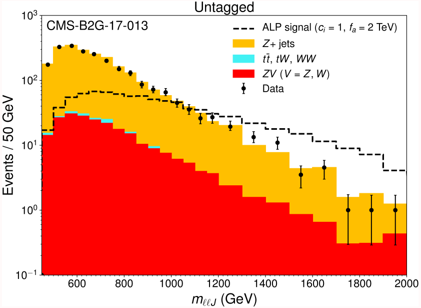


Non-resonant ALP signals at LHC

ZZ, $\gamma\gamma$, $t\bar{t}$: Gavela,No,Sanz,Troconiz 1905.12953, CMS PAS B2G-20-013 2111.13669
WW, $Z\gamma$: Carrá,Goumarre,Gupta,Heim,Heinemann,Küchler,Meloni,Quilez,Yap 2106.10085

ALP off-shell for $m_a \ll m_1 + m_2 \leqslant \sqrt{s}$ "too light to be resonant"





$\rightarrow \sigma \sim \frac{s}{f_a^4}$ independent of m_a, Γ_a

Non-resonant ALP signals at LHC

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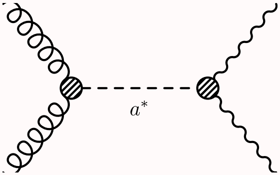
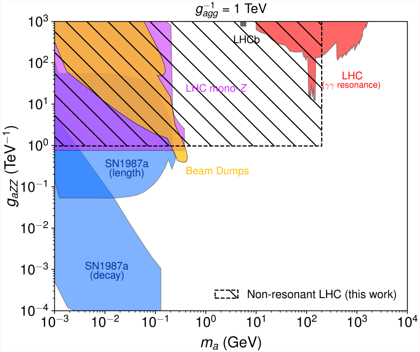




puts a constraint on $(g_{aGG} \times g_{aVV})$ product
for g_{aGG} not too small, competitive bounds on g_{aVV}

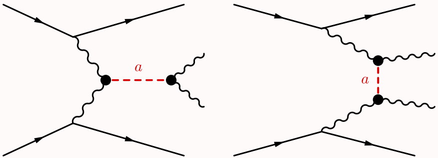
Non-resonant searches in VBS

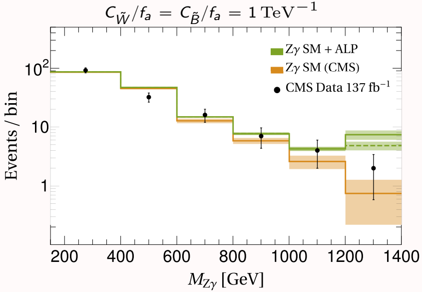
Bonilla, IB, Machado-Rodríguez, Trocóniz 2202.03450

same principle, applied to Vector Boson Scattering

→ independent of g_{aGG} (if pure ALP signal dominates, adding $C_{\tilde{G}}$ does not worsen bounds)

→ compare to actual analyses by CMS: $W^\pm W^\pm$, $W^\pm Z$, $W^\pm\gamma$, $Z\gamma$, ZZ





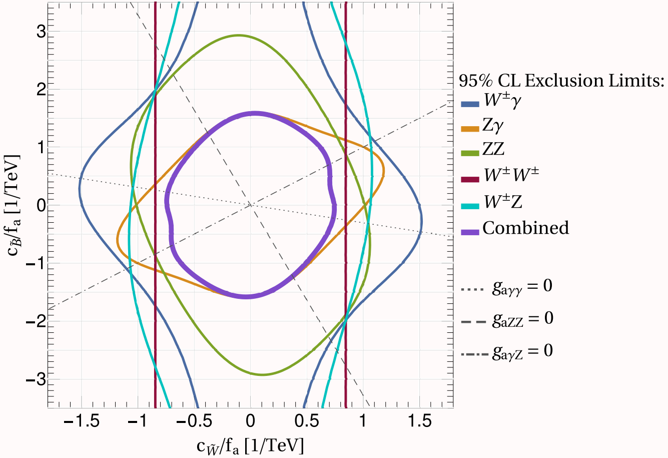
$$\sigma = \sigma_{SM} + \sigma_{\rm int.}/f_a^2 + \sigma_{ALP}/f_a^4$$

$$\sigma_{\rm int.} = C_{\tilde{B}}^2\,\sigma_{B2} + C_{\tilde{W}}^2\,\sigma_{W2} + C_{\tilde{B}}C_{\tilde{W}}\,\sigma_{WB}$$

$$\sigma_{ALP} = C_{\tilde{B}}^4\,\sigma_{B4} + C_{\tilde{W}}^4\,\sigma_{W4} + C_{\tilde{B}}^2C_{\tilde{W}}^2\,\sigma_{W2B2} + C_{\tilde{B}}^3C_{\tilde{W}}\,\sigma_{B3W} + C_{\tilde{B}}C_{\tilde{W}}^3\,\sigma_{BW3}$$

Non-resonant searches in VBS: Run 2 results

gauge invariant param. → all EW couplings simultaneously accounted for

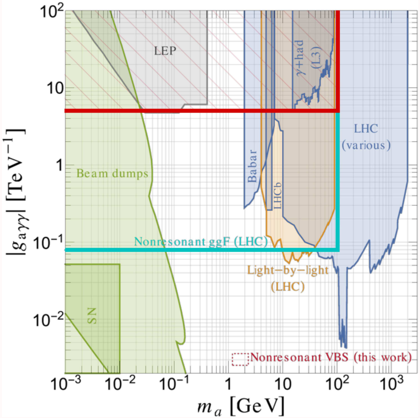


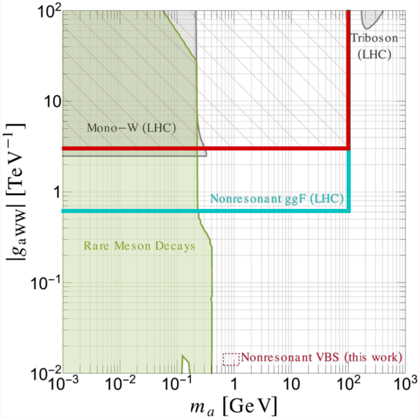
Comparison with other constraints

main values

- strongest bound on g_{aZZ}, g_{aWW} for $m_a \in [0.1, 100]$ GeV
- independent of $C_{\tilde{G}}$
- independent of m_a, Γ_a as long as $<$ threshold

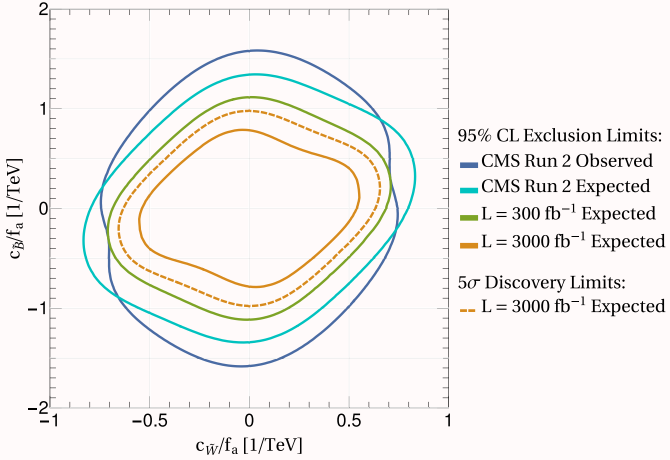
} relevant to break flat directions





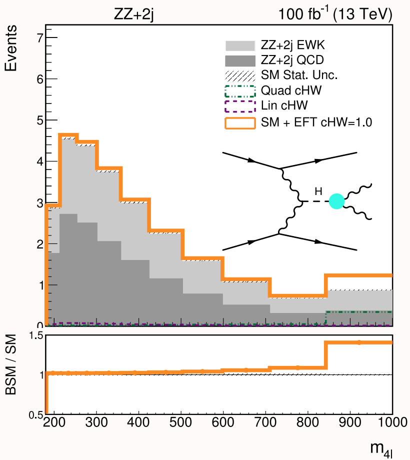
Non-resonant searches in VBS: projections

HL-LHC: sensitivity improves $\times 5-8$ on XS $\rightarrow$ $\times 1.5-1.7$ on C_i/f_a



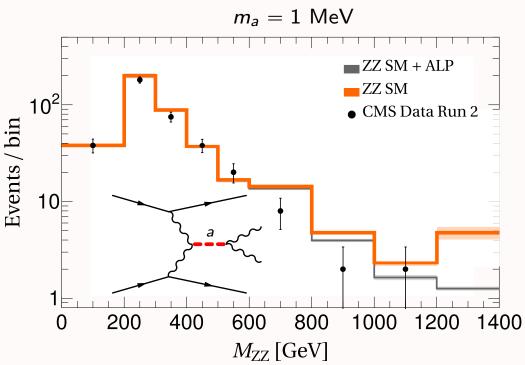
SMEFT vs ALPs in VBS

$pp \to jjZZ$ in SMEFT



Bellan, Boldrini, Brambilla, IB et al 2108.03199

$pp \to jjZZ$ with an ALP



Bonilla, IB, Machado, Trocóniz 2202.03450

Wrapping up

- the Standard Model of particle physics is **extremely successful, but not the ultimate theory!**
- the Large Hadron Collider at CERN hasn't found evidence for **new resonances** yet
- in the next 20 years, it will collect 20 times more data than today → **a precision machine!**
- SMEFT and EFTs in general can help us make the most out of this dataset!
  → a very **challenging program**, being developed by theory and experiments
- Non-resonant signals interesting also for light new physics, e.g. top-philic bosons, ALPs...
  → relevant at $\sqrt{s} \gg m$
  → can help cover **unexplored regions** of parameter space
- Interplay of non-resonant signals from heavy and light states not much explored yet

COMETA

a newly approved COST Action!

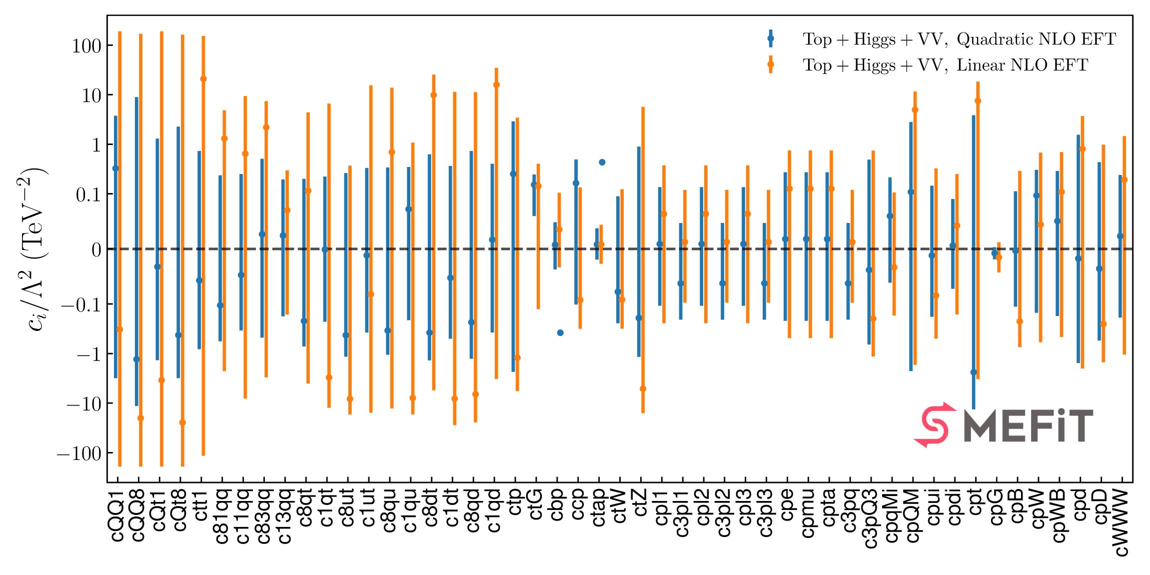
"COmprehensive Multiboson Experiment-Theory Action"

- very broad scientific program
  - **SMEFT/HEFT studies** of multi-boson processes (as many H/W/Z as wished), also with global perspective
  - **precision calculations** and development of MC, PS etc
  - **W, Z polarizations**: conventions, higher-order predictions, MC
  - development of **ML-based tools**, together with ML experts outside academia: polarization taggers, jet taggers for VBF topologies, optimal observables. . .
- € for networking: will organize **workshops, schools, topical meetings** + funds for short/medium-term **visits** to other institutions within Europe
- currently $\sim$ 1/3 theorists + 2/3 experimentalists + a few ML experts
- funding will start in November, activities in 2024 – 2027

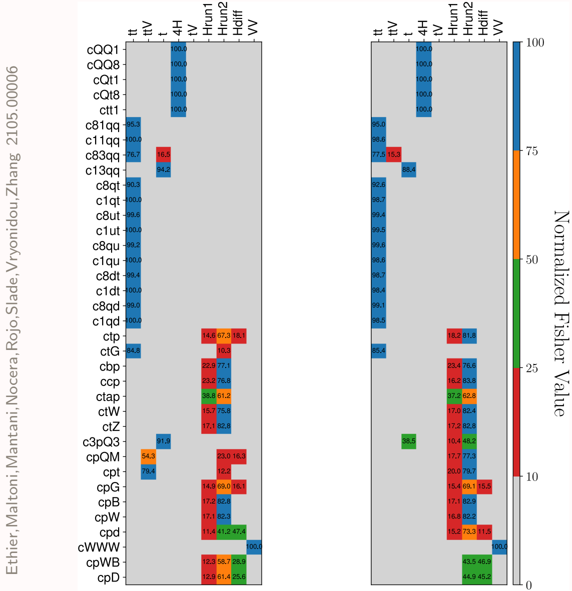
sign up & **more info** at `www.cost.eu/actions/CA22130/`

Backup slides

SMEFT fit results



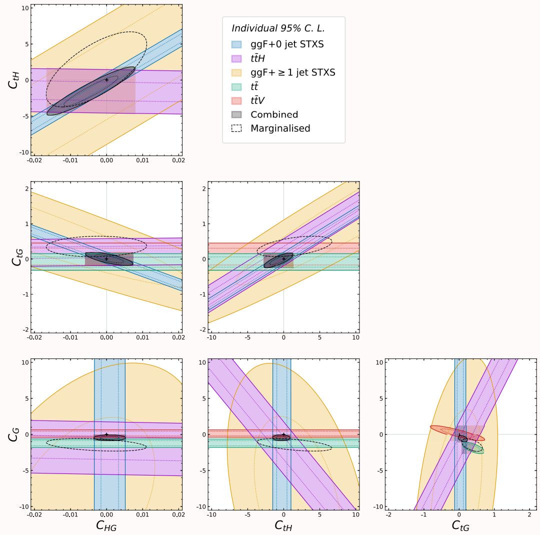
Fisher information



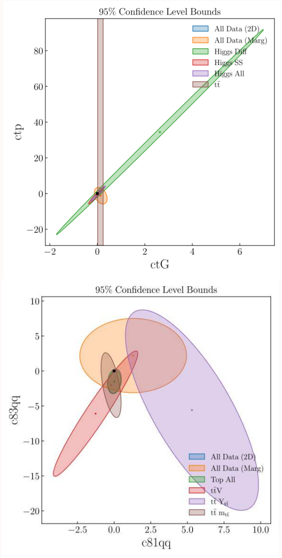
C_{tG} mostly constrained by $t\bar{t}$

ttV op. constrained by $h \to \gamma\gamma$, single-t, $t\bar{t}V$

Top and Higgs interplay



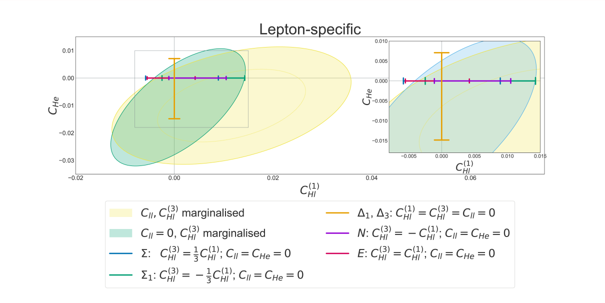
Ellis, Madigan, Mimasu, Sanz, You 2012.02779

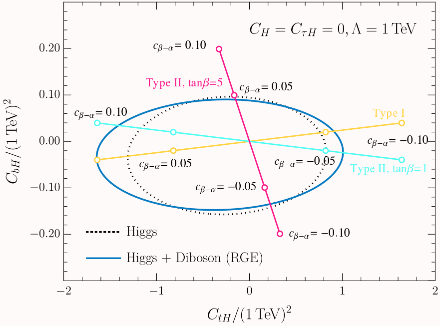


Ethier, Maltoni, Mantani, Nocera, Rojo 2105.00006

Reduced fits via matching to UV models

Ellis,Madigan,Mimasu,Sanz,You 2012.02779

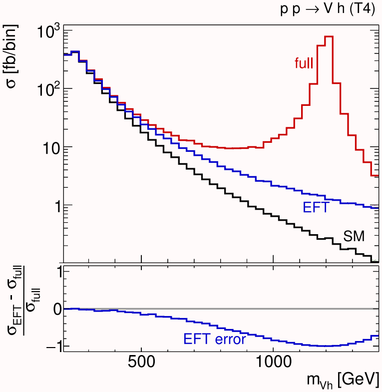




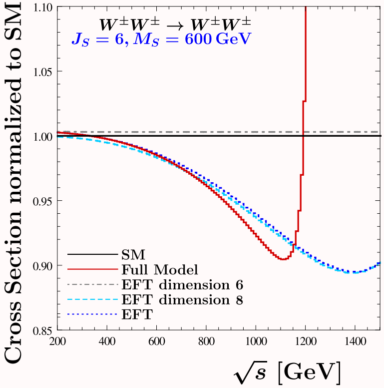
Dawson,Homiller,Lane 2007.01296

Impact of higher order operators

EFT obtained from matching to full model



adapted from Brehmer,Freitas,López-Val,Plehn 1510.03443



adapted from Lang,Liebler,Schäfer-Siebert,Zeppenfeld 2103.16517

Impact of higher order operators

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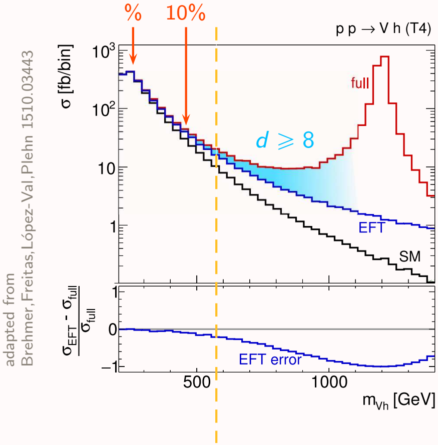
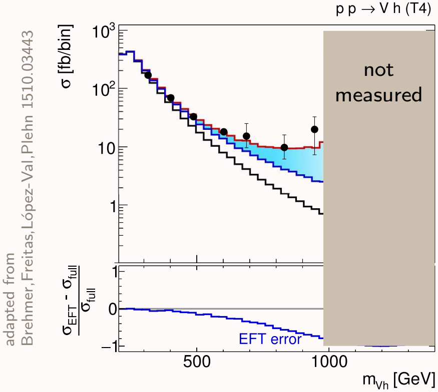


$d = 6$ breaks down

Impact of higher order operators

EFT obtained from matching to full model



top-down: C_i fixed by matching
→ EFT not valid in high-E region

bottom-up: fit C_i to data
tends to make EFT match full result
→ find wrong values of C_i

how to keep this into account?

sliding upper cut:
Contino,Falkowski,Goertz, Grojean,Riva 1604.06444

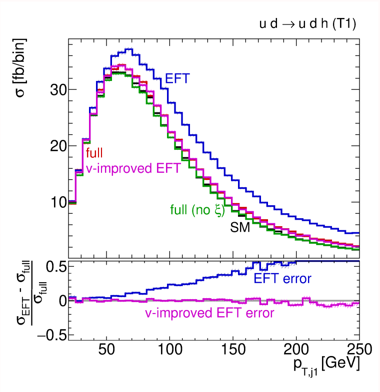
uncertainty band:
Trott et al 1508.05060,2007.00565,2106.13794
Hays,Martin,Sanz,Setford 1808.00442
Shepherd et al 1812.07575,1907.13160

compute at $O(\Lambda^{-4})$
Boughezal,Mereghetti,Petriello 2106.05337
Asteriadis,Dawson,Fontes,Homiller,Sullivan 2110.06929,2205.01561,2212.03258

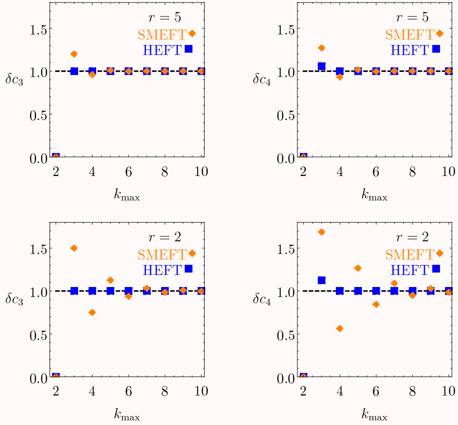
SMEFT or HEFT?

a component of the $d = 6$ vs model discrepancy can be removed by reabsorbing higher powers of v within $d = 6$ coefficients instead of leaving them to $d \geqslant 8$

conceptually same as matching to **HEFT** instead



Brehmer,Freitas,López-Val,Plehn 1510.03443



Cohen,Craig,Lu,Sutherland 2008.08597

which EFT is most convenient?

What is HEFT?

rather than H doublet:
singlet h + Goldstones $\mathbf{U}$

Feruglio 9301281, Grinstein,Trott 0704.1505, Buchalla,Catà 1203.6510, Alonso et al 1212.3305, IB et al 1311.1823,1604.06801, Buchalla et al 1307.5017,1511.00988...

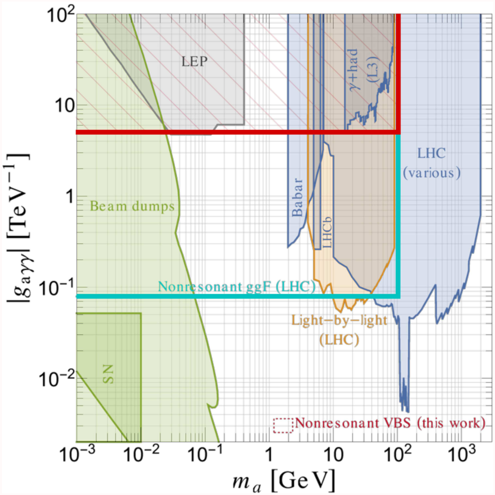
$$H \mapsto \frac{v+h}{\sqrt{2}}\mathbf{U}, \qquad \mathbf{U} = \exp\left(\frac{i\vec{\sigma}\cdot\vec{\pi}}{v}\right)$$

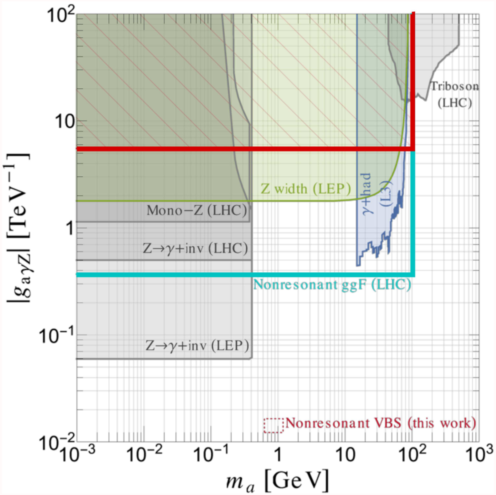
HEFT $\supset$ SMEFT $\supset$ SM

- **more general** than SMEFT because implements weaker symmetry requirement
- **more complicated** power counting, mix of χPT and canonical dimensions
- **more operators** order-by-order in the expansions

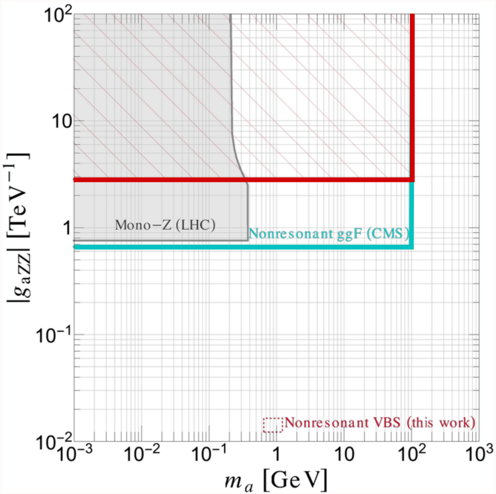
however, the $H \to h, \mathbf{U}$ map above must be an **unphysical** field redefinition!

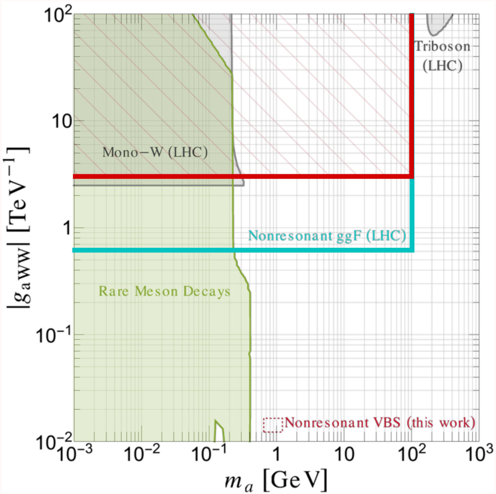
Bounds on ALP couplings



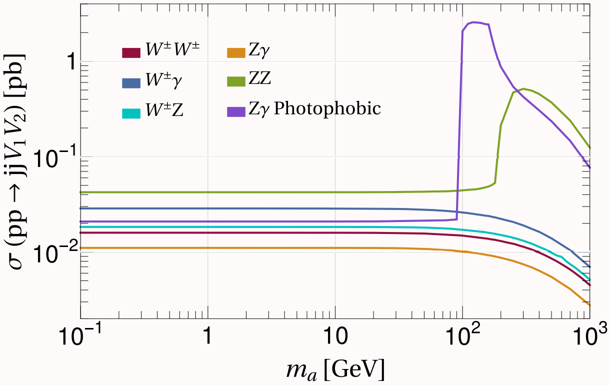


Bounds on ALP couplings





Dependence on ALP mass and width

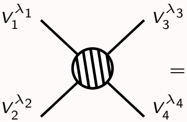


- as long as $q^2 \gg m_a, \Gamma_a$, **independent** of exact values of mass and width
  "reverse" of an EFT ($q^2 \gg m^2$ vs $q^2 \ll m^2$ limit)
- XS stable up until $m_a \lesssim 100$ GeV

Perturbative unitarity

partial-wave decomposition for $2 \to 2$ scattering: Jacob,Wick 1959

$$V_i = \text{vector bosons or scalars}$$
$$\lambda_i = \text{helicities } (\text{V:}\lambda_i = 0, \pm 1,\ \text{S:}\lambda_i \equiv 0),\quad \lambda = \lambda_1 - \lambda_2,\ \mu = \lambda_3 - \lambda_4$$
$$T^J = \text{amplitude for } J\text{-wave scattering}$$



$$= 16\pi \sum_J (2J+1)\sqrt{1+\delta^{V_2\lambda_2}_{V_1\lambda_1}}\sqrt{1+\delta^{V_4\lambda_4}_{V_3\lambda_3}}\, e^{i(\lambda-\mu)\phi} d^J_{\lambda\mu}(\theta)\ \ T^J(V_1^{\lambda_1} V_2^{\lambda_2} \to V_3^{\lambda_3} V_4^{\lambda_4})$$

unitarity $= |T^J(V_1^{\lambda_1} V_2^{\lambda_2} \to V_1^{\lambda_1} V_2^{\lambda_2})| \leqslant 1$ for $s \gg (M_1 + M_2)^2$ [defined for *elastic* scattering]

unitarity violation= unphysical pred.
- → the theory is not valid: new dynamical **states** must be included
- → pert. expansion is not valid: entering a **non-perturbative** regime

in ALP EFT: $|T^J| \sim \left[C_i \frac{\sqrt{s}}{f_a}\right]^n \left[\frac{\sqrt{s}}{m_W}\right]^m$ becomes > 1 for large $\sqrt{s}$ or (C_i/f_a)

Perturbative unitarity in ALP EFT

Calculation strategy

IB,Éboli,González-García 2106.05977
also: Corbett,Éboli,González-García 1411.5026,1705.09294

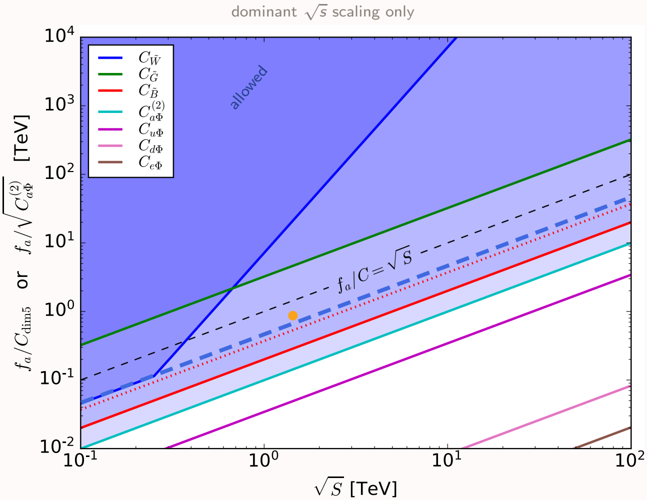
1. compute partial waves for all possible $2 \to 2$ processes in large $\sqrt{s}$ lim:

$$V_1 V_2 \to V_3 V_4 \qquad V_1 a \to V_2 a \qquad V_1 V_2 \to aa \qquad V_1 V_2 \to V_3 a$$

$$ha \to ha \qquad hh \to aa \qquad f_1 \bar{f}_2 \to Va$$

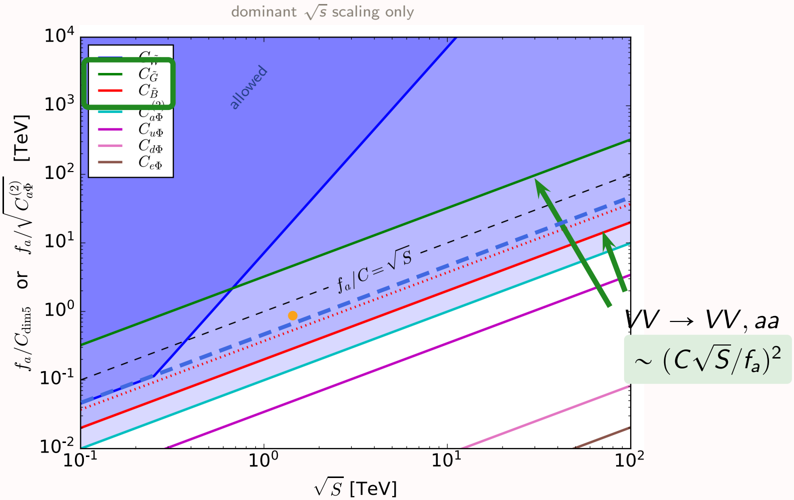
2. construct $T^{J=0}$, $T^{J=1}$ matrices in final states (particle and helicity) space
   $\to$ block-diagonal classifying processes by Q and color contraction
3. **diagonalize** T^J matrices $\to$ "overall" constraint on theory
4. apply elastic unitarity requirement $|t^J| \leqslant 1$ on each eigenvalue

Unitarity constraints on ALP couplings



⚠ $\sqrt{s}$ overall scale, cannot be interpreted “literally” in specific processes

Unitarity constraints on ALP couplings



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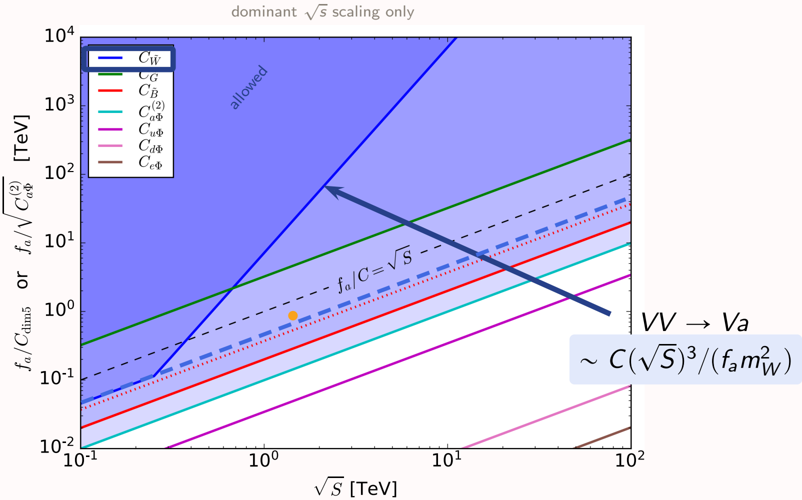
Unitarity constraints on ALP couplings



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