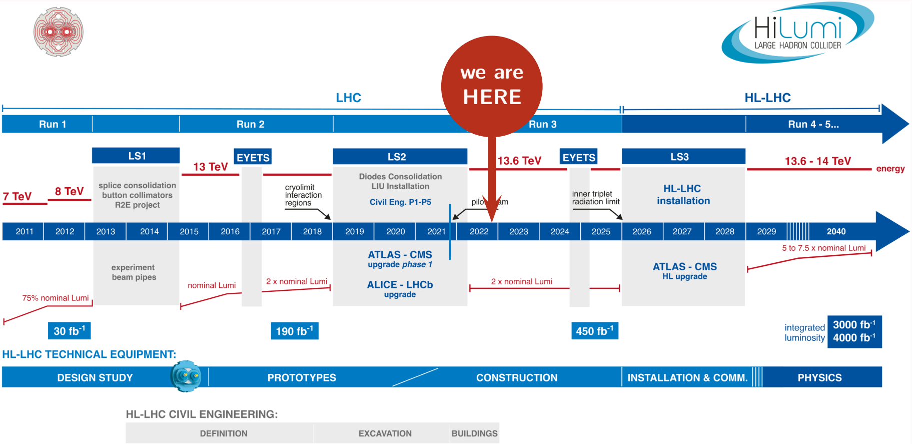
The hunt for non-resonant signals of new physics at the LHC

Ilaria Brivio

University of Zurich & Università di Bologna

Where we are - LHC perspective



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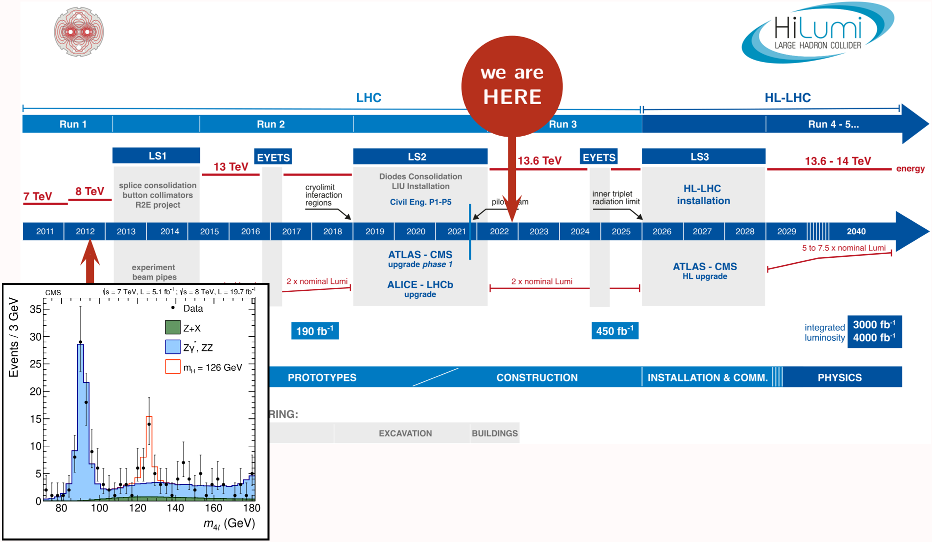

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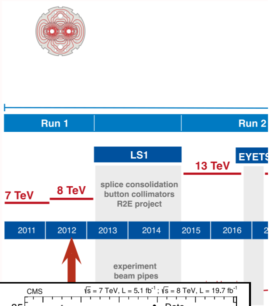

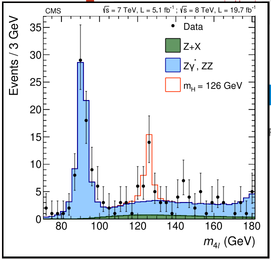

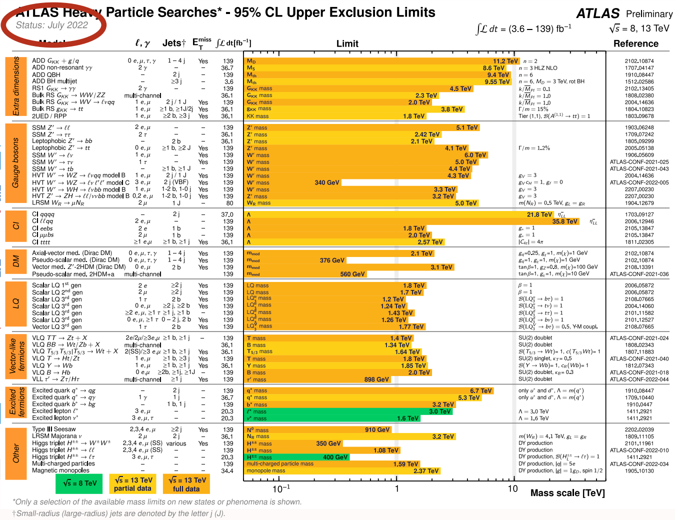

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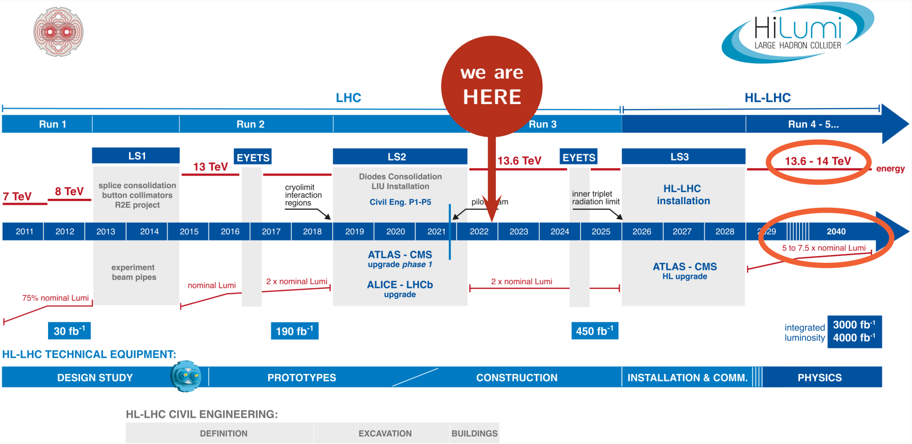


Targeting non-resonant signals of new physics

no clear indications of specific BSM scenarios

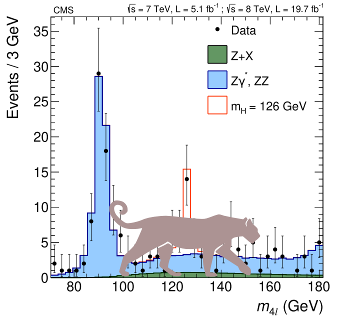
+

strong reduction of statistical uncertainties

↓

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

CMS-HIG-13-002



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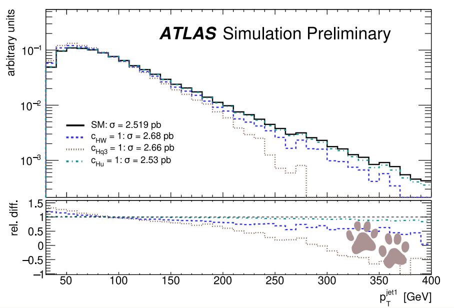
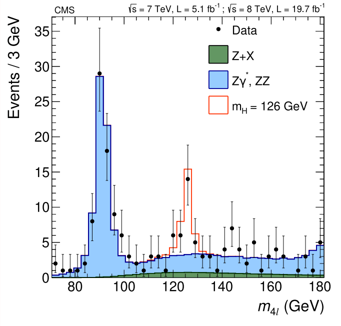


ATL-PHYS-PUB-2019-042

Targeting non-resonant signals of new physics



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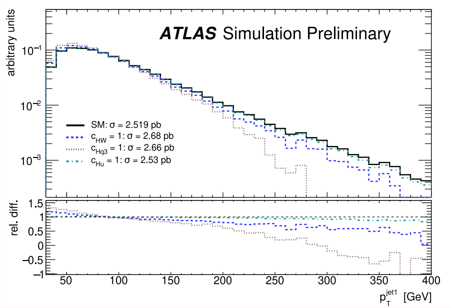


ATL-PHYS-PUB-2019-042

- complementary to direct searches. will become more relevant in next Runs
- key idea: implement **a comprehensive, agnostic program** 
- **Effective Field Theories** are a natural framework
  - → allow a (model-independent) NP interpretation of non-resonant effects
  - → well-defined mapping between theories in UV and at EW scale
  - → proper QFTs: renormalizable order-by-order, syst. improvable in loops
  - → allow combination with non-LHC measurements. “global likelihood”

SMEFT

Standard **M**odel **E**ffective **F**ield **T**heory:
The EFT constructed with **Standard Model** fields & symmetries

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \dots$$

$$\mathcal{L}_d = \sum_i C_i \mathcal{O}_i^{(d)}$$

C_i = Wilson coefficients

$\mathcal{O}_i^{(d)}$ = gauge-invariant operators

SMEFT describes **any nearly-decoupled ($\Lambda \gg v$) BSM physics**
with "good" analyticity/geometry properties in the scalar sector

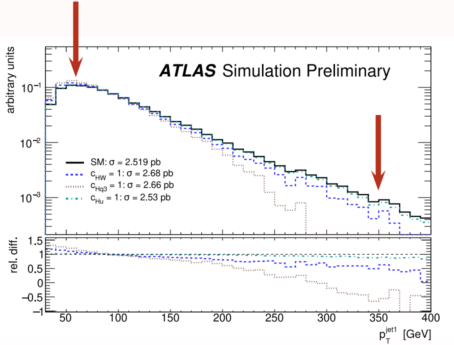
- default candidate for LHC/global program
- underwent enormous developments in past decade

Challenges for the bottom-up SMEFT program

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

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

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

The development of SMEFT - quick wrap up

theory

- bases up to $d = 9$
- Hilbert series
- on-shell methods
- positivity
- unitarity bounds
- geometry

predictions

- RGEs for $d = 6$ and $d = 8$ (partial)
- predictions to NLO EW and NLO QCD
- first 2-loop results
- automation of RGE
- Monte Carlo at LO and NLO QCD
- predictions and studies for Higgs, top, diboson, VBS, Drell-Yan, dijet. . .
- SMEFT in PDFs

fits

- fitting technology/tools
- information geometry PCA, Fisher info. . .
- strategies to extract differential info

map to other theories

- matching to 1-loop with functional methods
- automation of matching to models
- matching to LEFT
- analysis of LHC + lower-E results

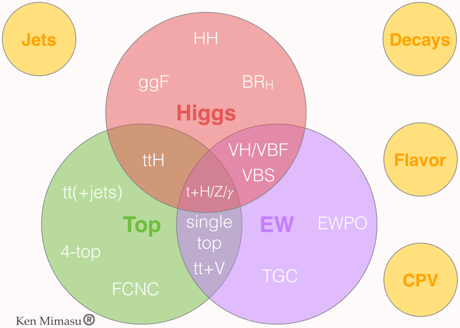
Combine, combine, combine

2499 parameters in the most general case

can be reduced
- assuming symmetries: flavor, CP
- taking advantage of kinematic suppressions

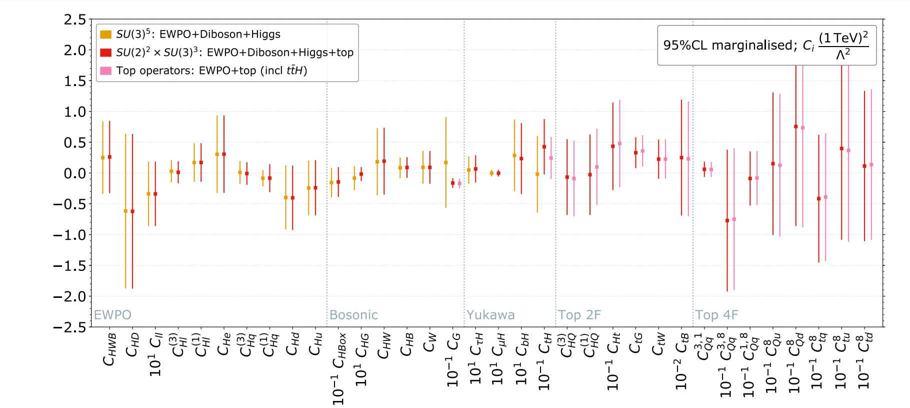
beyond this combining different measurements is necessary

- to access as many operators as we can
- to avoid bias in interpretation
  i.e. miss a potential deviation or assign it to the wrong op.



State-of-the-art SMEFT fits: H + EW + Top

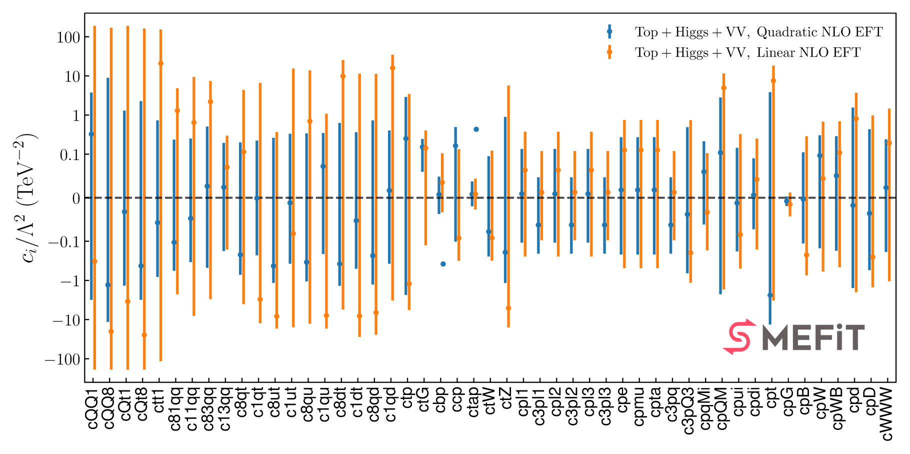
Ellis, Madigan, Mimasu, Sanz, You 2012.02779



34 param, $U(3)^5$ flavor sym, linear, LO + ggH

State-of-the-art SMEFT fits: H + EW + Top

Ethier,Maltoni,Mantani,Nocera,Rojo 2105.00006



50 param (36 indep.), $U(2)^2 \times U(3) \times U(1)^3$ flavor sym, linear+quadratic, NLO QCD

SMEFT fits: typical features

- many **dimensions**: state-of-the-art 30–35 LHC target (EW+H+top) ~ 50

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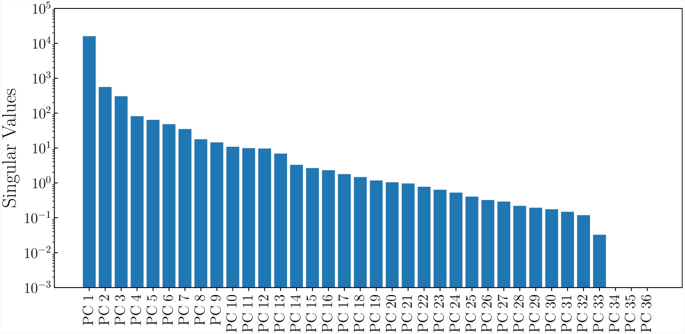

Ethier et al 2105.00006

SMEFT fits: typical features

- many **dimensions**: state-of-the-art 30–35 LHC target (EW+H+top) ~ 50
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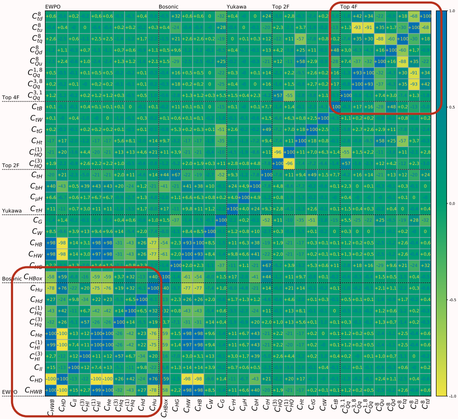
- weakly broken flat directions → highly **correlated** sub-spaces



Ellis,Madigan,Mimasu,Sanz,You 2012.02779

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Results derived in different setups to understand the structure of the fit space

- linear $\leftrightarrow$ linear + quadratics
- LO $\leftrightarrow$ NLO
- individual $\leftrightarrow$ marginalised/profiled
- comparisons between different fitting methods
- Fisher information
- Principal Component Analysis
- sub-fits to check impact of individual datasets

What's missing for a successful SMEFT program?

[personal/pragmatic point of view, not attempting to make a complete list.]

A = for being sensitive   B = for interpreting deviations correctly

0. (experimentally established anomalies)

1. A reduction of uncertainties on SM predictions + systematics

2. A B streamline treatment & reduction of EFT-born uncertainties

3. B correct treatment of correlations → involvement of experiments

Bißmann,Erdmann,Grunwald,Hiller,Kröninger 1912.06090

4. B including SMEFT beyond ME: PDF, PS, acceptances

Carrazza et al 1905.05215, Greljo et al. 2104.02723, Iranipour,Ubiali 2201.07240
Goldouzian et al 2012.06872, Haisch et al 2204.00663, ATL-PHYS-PUB-2022-037

5. B more refined process treatment: exploit differential info, target ~~CP~~, flavor...

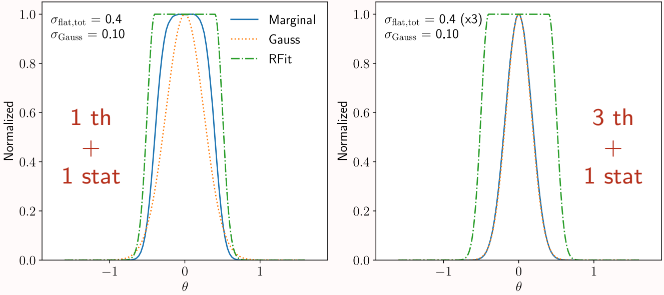
6. B handling & understanding ∼ 50-dimensional likelihoods

Marginalisation

→ already used in HEPfit, SMEFiT, EFTfitter... deBlas et al 1905.03764, Ethier et al 2105.00006, Castro et al 1605.05585

compared to Profiling: **more convenient for large-dimensional fits**

- not the same interpretation! but results should be close to each other when many measurements and uncertainties are included (central limit thm)
- applied on nuisance par. to combine uncertainties on individual measurements + on SMEFT par. to obtain 1D or 2D likelihoods
- main difference: uncertainty treatment

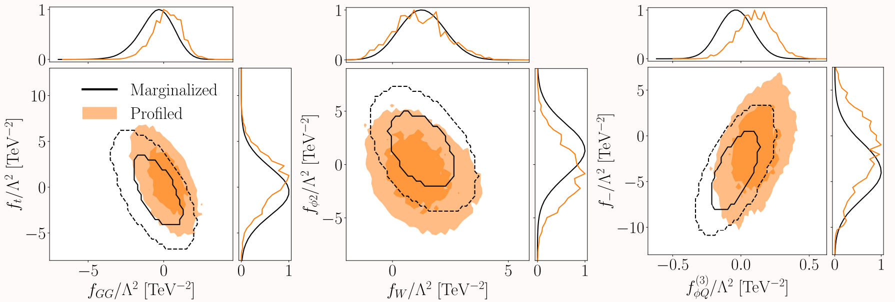


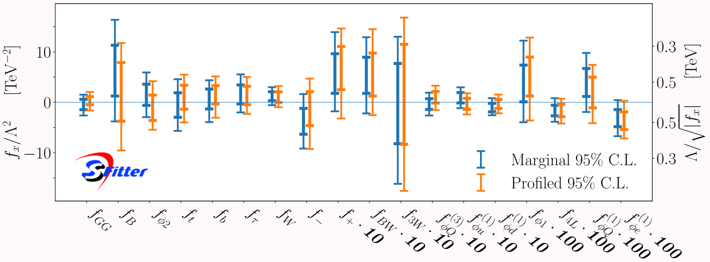
IB, Bruggisser, Elmer, Geoffray, Luchmann, Plehn 2208.08454

- faster convergence to Gaussian shape ⇒ way less computationally expensive

Marginalisation - 18D fits

IB,Bruggisser,Elmer,Geoffray,Luchmann,Plehn 2208.08454

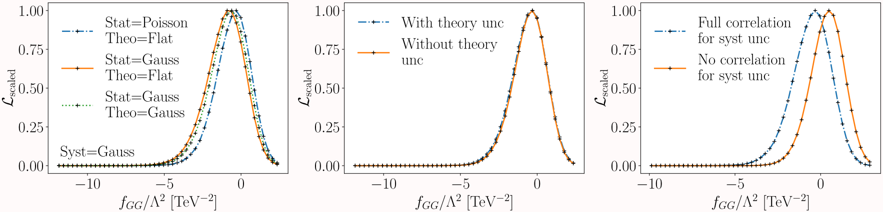




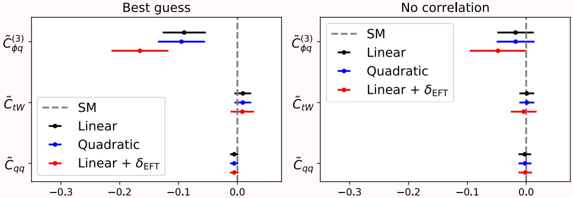
Marginalisation: the role of correlations

when marginalising over (many) nuisance parameters,
it is not so relevant whether they are originally modeled as flat, poisson or Gauss

the largest difference is seen changing **correlations**



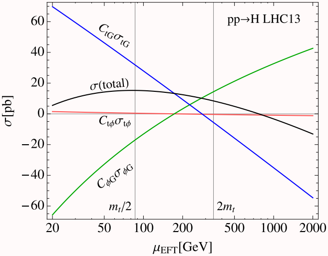
observed also in
Bißmann,Erdmann,Grunwald,
Hiller,Kröninger 1912.06090



Theory uncertainties on EFT predictions

$$\sigma_{SMEFT} = \sigma_{SM}\left[1 + a_i C_i + b_{ij} C_i C_j + \ldots\right] \qquad a_i = a_i^0 \pm \Delta a_i$$

- uncertainties from dependence on SM quantities (eg. input schemes, scales), from MC simulations ...
- uncertainties due to **running & mixing** coefficients (EFT scale)



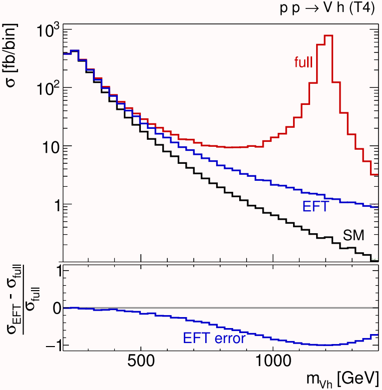
Maltoni,Vryonidou,Zhang 1607.05330

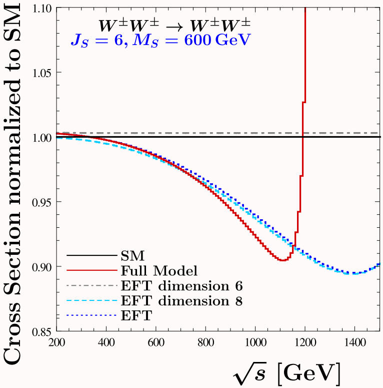
- uncertainties due to missing **higher orders in loops** (QCD/EW)
- uncertainties due to **missing higher EFT orders** / unknown cutoff size

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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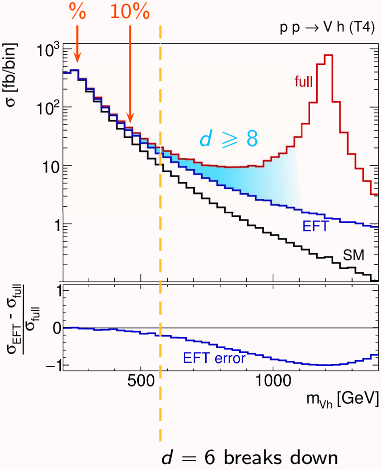

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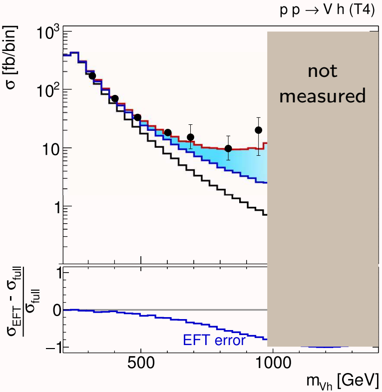


adapted from
Brehmer,Freitas,López-Val,Plehn 1510.03443

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

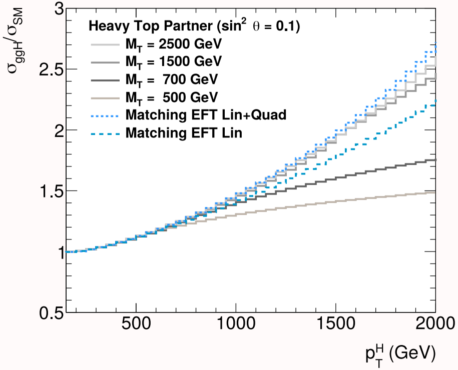
compute at $O(\Lambda^{-4})$
Boughezal,Mereghetti,Petriello 2106.05337
Asteriadis,Dawson,Fontes,Homiller,Sullivan
2110.06929,2205.01561,2212.03258

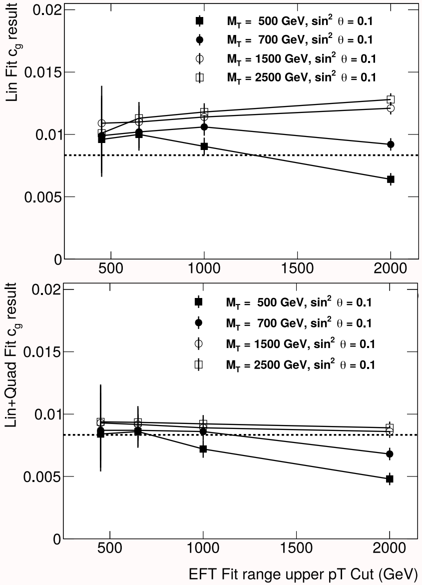
Benchmarking these proposals: sliding upper cut

Battaglia, Grazzini, Spira, Wiesemann 2109.02987

p_T^H from heavy top partner

fit result $\overset{?}{=}$ value from matching
$\rightarrow$ check impact of upp. cut + quadratics

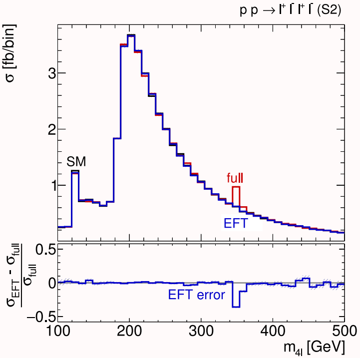




safe scenarios ↔ no energy growth ↔ small effects

typical cases where $d = 6$ works well **across the whole visible spectrum**:

- observables w/o E dependence (1 → 2 decays)
- BSM scenarios with very narrow and/or heavy states



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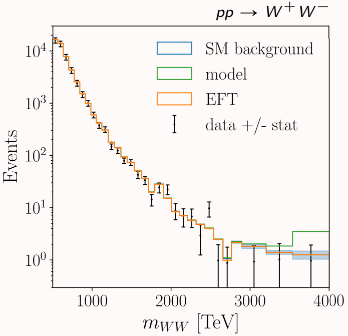


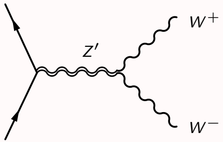
Brivio, Bruggisser, Geoffray, Kilian, Krämer, Luchmann, Plehn, Summ 2108.01094

price to pay: % effects only

→ most sensitivity from lowest error region (∼ bulk)

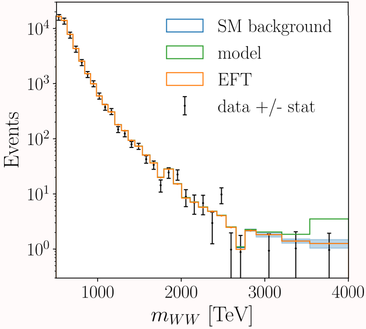
Interplay with direct searches

IB,Bruggisser,Geoffray,Kilian,Krämer, Luchmann,Plehn,Summ 2108.01094

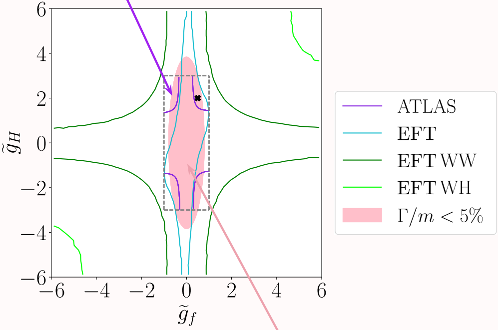


$$m_{Z'} = m_V = 4 \text{ TeV}$$

data: ATLAS 2004.14636



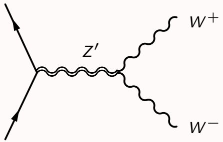
bound from
WW resonance search



resonance s. only valid
for narrow Z'

Interplay with direct searches

IB, Bruggisser, Geoffray, Kilian, Krämer, Luchmann, Plehn, Summ 2108.01094



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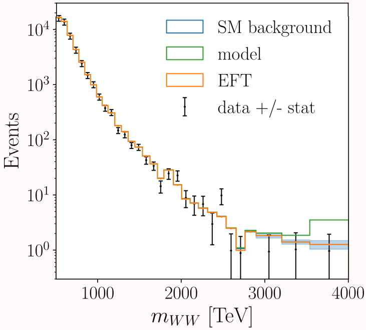
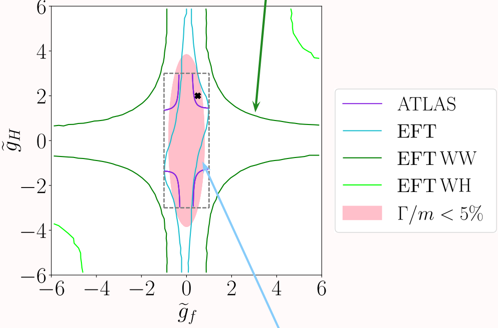


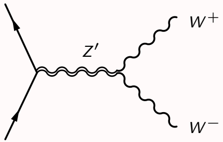
bound from EFT fit to WW spectrum



bound from EFT fit to <u>all</u> obs.
(incl. EWPO, Higgs)

Interplay with direct searches

IB,Bruggisser,Geoffray,Kilian,Krämer, Luchmann,Plehn,Summ 2108.01094



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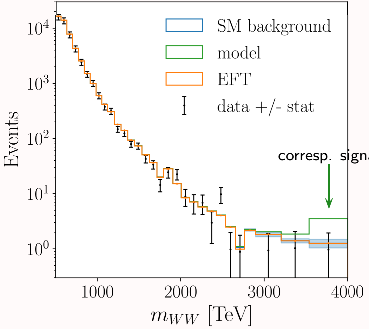
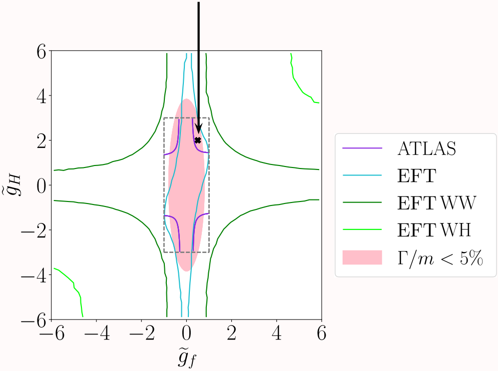


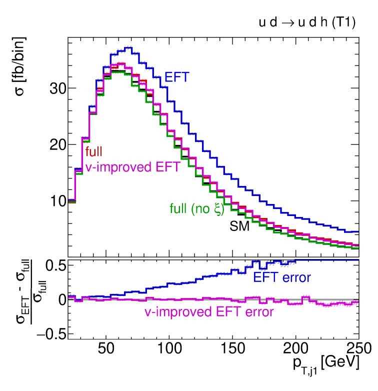
point excluded by resonance s.
but allowed by EFT



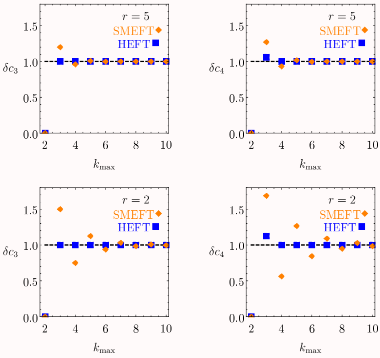
SMEFT or HEFT?

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 similar to using **HEFT** instead



Brehmer,Freitas,López-Val,Plehn 1510.03443



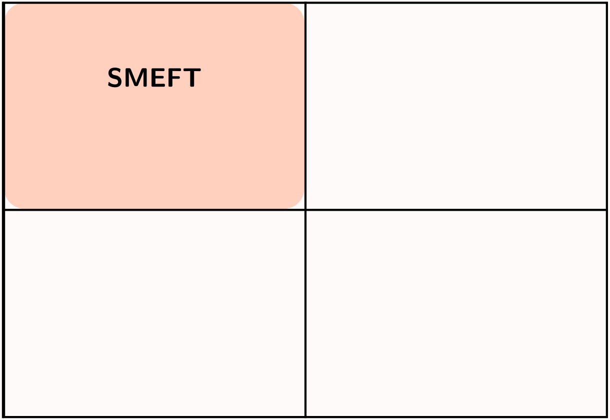
Cohen,Craig,Lu,Sutherland 2008.08597

which EFT is most convenient?

Non-resonant signals beyond SMEFT

NP assumptions H doublet ✔ = Higgs $SU(2)$ doublet structure recovered

~~light NP~~
($\lesssim$100 GeV)



Non-resonant signals beyond SMEFT

NP assumptions	H doublet ✔	H ~~doublet~~
~~light NP~~ (≲100 GeV)	**SMEFT**	Higgs EFT (**HEFT**)
✔ light NP **X** = axions, ALPs, HNL, dark γ, DM…	SMEFT + **X**	HEFT + **X**

Higgs SU(2) doublet structure
badly or not at all recovered at low E

Non-SMEFT non-resonant signals: light NP

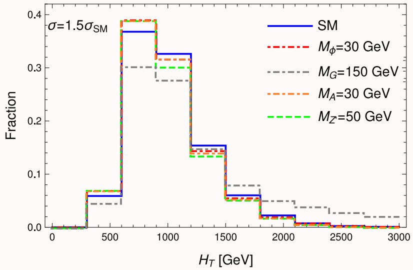
Non-resonant signals can also be induced by new light states

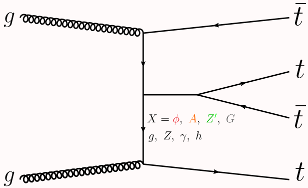
→ off-shell, in the limit $\sqrt{s} \gg m$ → typically happens for heavy final states

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

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

Alvarez, Juste, Sandá Seoane 1910.09581





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

Fundamental properties

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

Why so interesting?

- naturally the lightest remnant of heavy NP sectors → easiest to discover
- spontaneous symmetry breakings are **ubiquitous** in BSM → 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

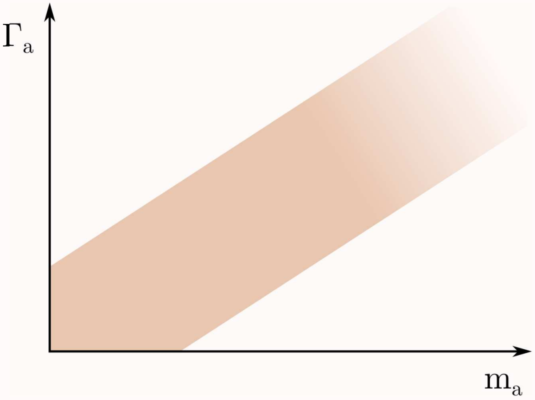
- discussion on basis completeness — Chala,Guedes,Ramos,Santiago 2012.09017; Bauer,Neubert,Renner,Schnubel,Thamm 2012.12272; Bonilla,IB,Gavela,Sanz 2107.11392
- RGE evolution
- RGE mixing into SMEFT — Galda,Neubert,Renner 2105.01078
- comprehensive 1-loop study, incl. finite parts — Bonilla,IB,Gavela,Sanz 2107.11392
- unitarity constraints — IB,Éboli,González-García 2106.05977
- flavor-invariant parameterization of shift-breakings — Bonnefoy,Grojean,Kley 2206.04182

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?



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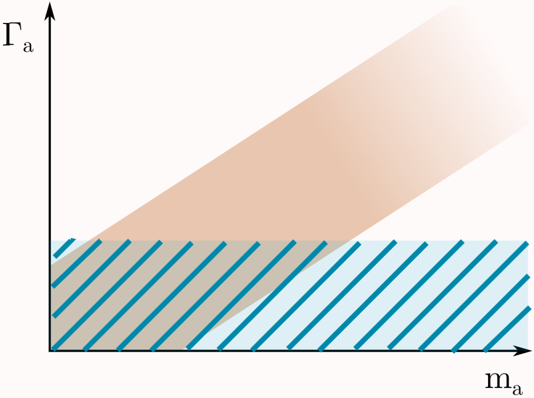

stable ALP
↓
$\not{E}_T$

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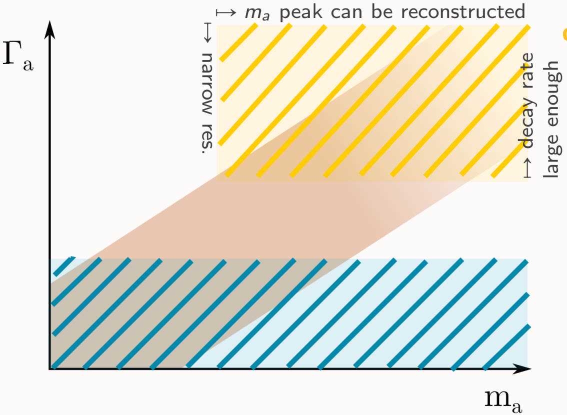
How?

massive, decaying ALP
↓
resonant



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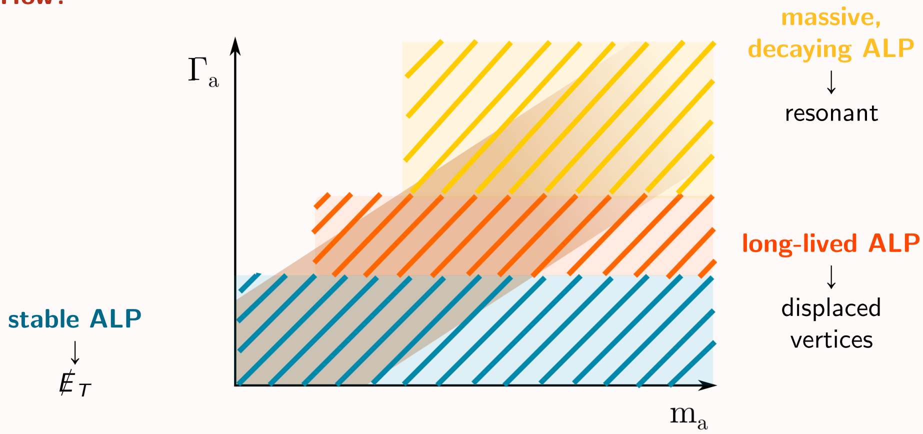


ALPs at the LHC

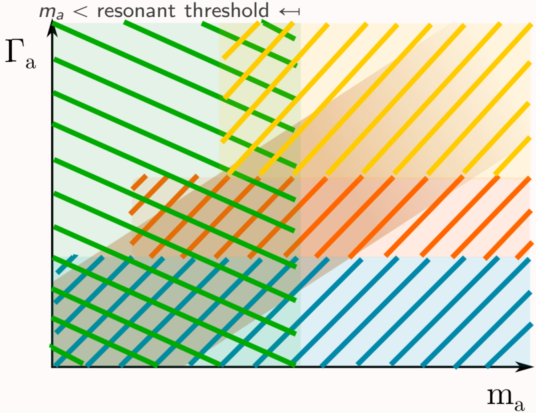
Why?

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

How?

off-shell ALP
↓
non-resonant

stable ALP
↓
$\not{E}_T$



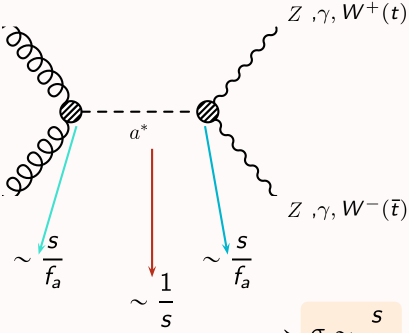
massive, decaying ALP
↓
resonant

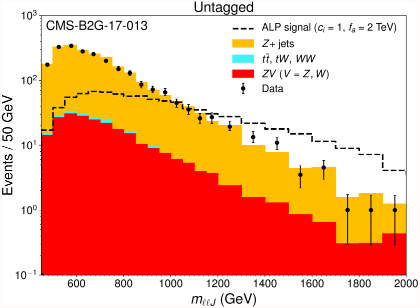
long-lived ALP
↓
displaced vertices

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"





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

Non-resonant ALP signals at LHC

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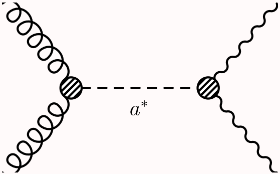
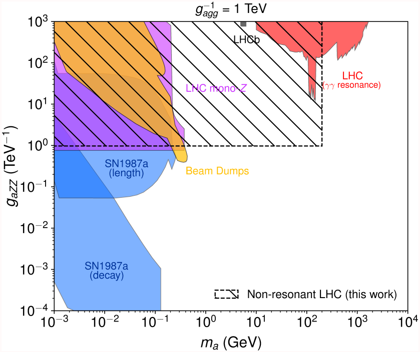




puts a constraint on $(g_{aGG} \times g_{aVV})$ product
for g_{aGG} not too small, competitive bounds on g_{aVV}

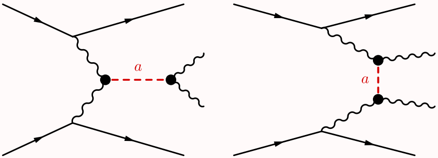
Non-resonant searches in VBS

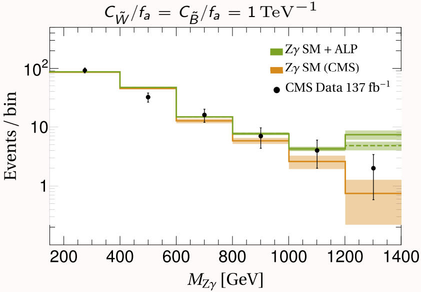
Bonilla, IB, Machado-Rodríguez, Trocóniz 2202.03450

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: $W^\pm W^\pm, W^\pm Z, W^\pm\gamma, Z\gamma, ZZ$





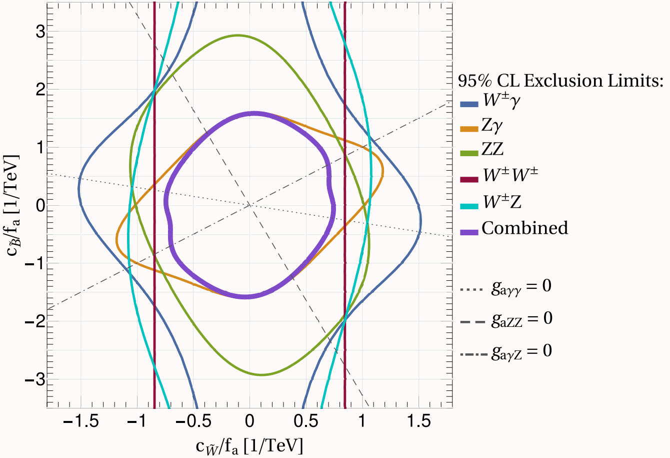
$$\sigma = \sigma_{SM} + \sigma_{\rm int.}/f_a^2 + \sigma_{ALP}/f_a^4$$

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

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

Non-resonant searches in VBS: Run 2 results

gauge invariant param. → all EW couplings simultaneously accounted for

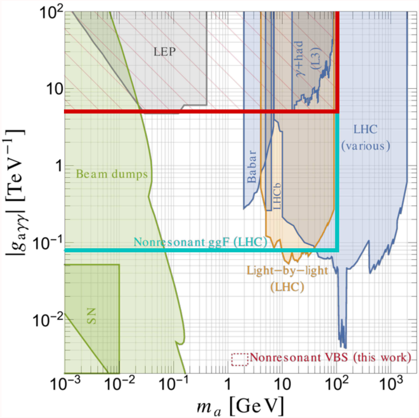


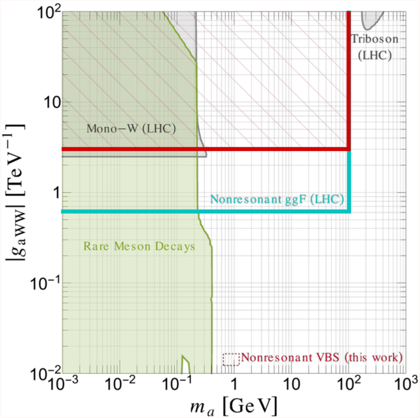
Comparison with other constraints

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

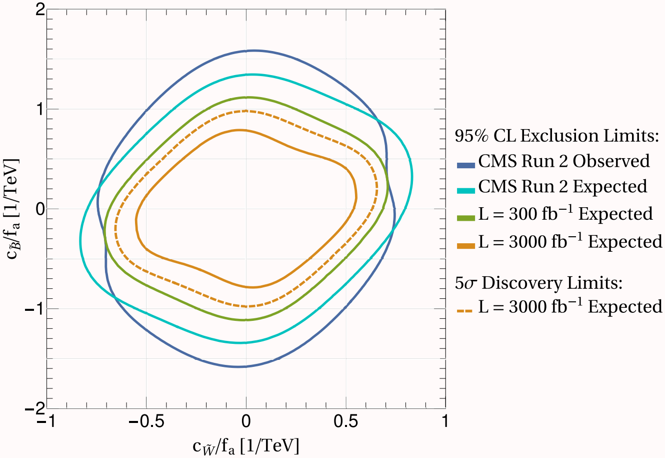
} relevant to break flat directions





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

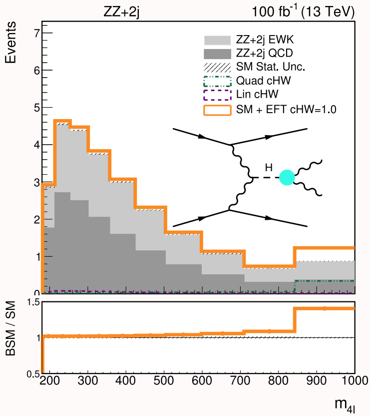


SMEFT vs ALPs in VBS

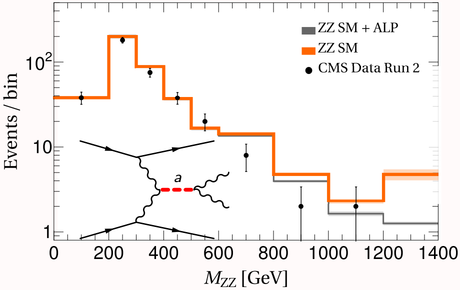
$pp \to jjZZ$ in SMEFT

$pp \to jjZZ$ with an ALP

Bellan,Boldrini,Brambilla,IB et al 2108.03199



$m_a = 1$ MeV



Bonilla,IB,Machado,Trocóniz 2202.03450

Summary

- Non-resonant signals are a main target for the LHC in the future runs
- SMEFT is the default choice for a global program
- Enormous improvements made, some (technical) challenges still ahead
- **Alternative EFTs** are also good candidates for a BSM interpretation
- Non-resonant signals interesting also for light NP
  e.g. top-philic bosons, ALPs... $\rightarrow$ relevant at $\sqrt{s} \gg m$
- Distinguishing SMEFT / HEFT / other sources is an open challenge