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

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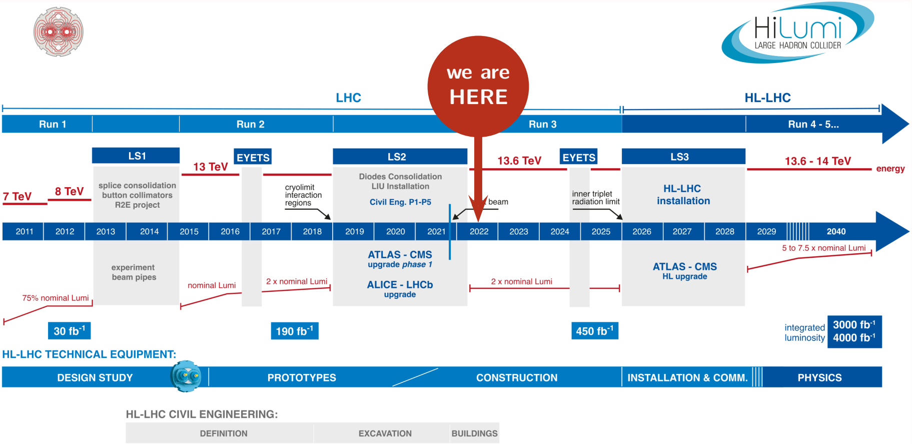
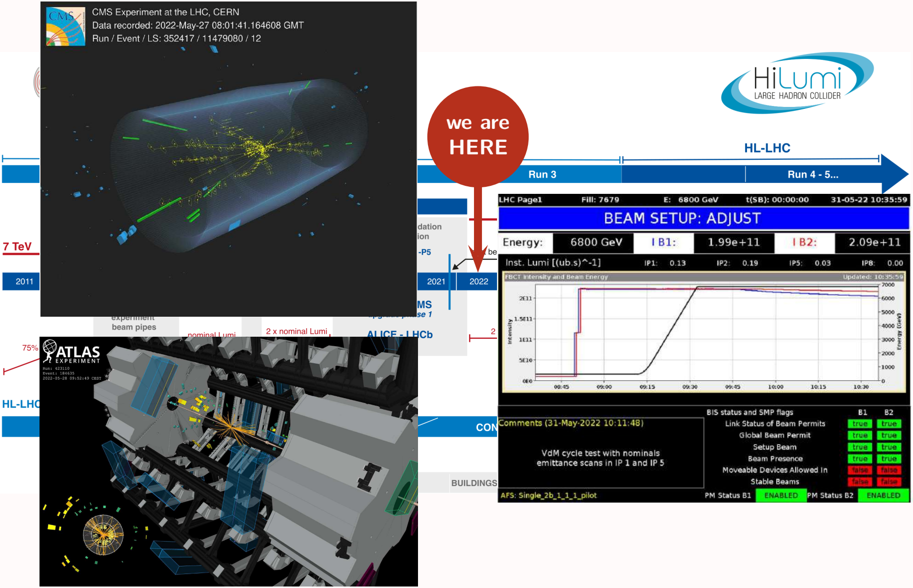
Hello! ☺

10 years since Higgs discovery
3 years since last in-person HEFT in Louvain-la-Neuve
. . . finally in person in Granada!

Where we are - LHC perspective

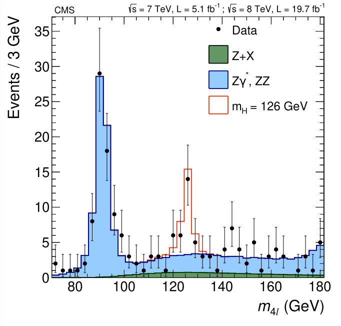


Where we are - LHC perspective



Targeting non-resonant signals of new physics

CMS-HIG-13-002



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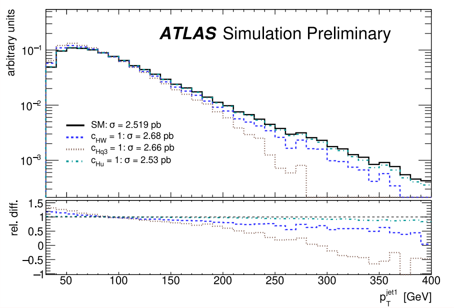


ATL-PHYS-PUB-2019-042

- complementary to resonance searches. “leave no stone unturned”
- exploit higher statistics. will become more relevant in next Runs
- key idea: implement **a comprehensive, agnostic program**
- **EFTs** are a natural framework
  → allow a NP interpretation of non-resonant effects
  → allow combination with non-LHC measurements. “global likelihood”

⇝ Peter Stangl

SMEFT

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

- well-known by this audience $\rightsquigarrow$ many talks in the next 3 days
- default candidate for LHC/global program
- underwent enormous developments in past decade

The development of SMEFT - quick wrap up

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

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

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

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

Some challenges ahead

what's missing for the LHC program to be successful?
i.e. measure some deviation at LHC & interpret correctly in terms of BSM

[personal/pragmatic point of view, not even trying to make a complete list]

- bring down **error bars**. aiming for 1 - 10 % (for $d = 6$!)

  $$\frac{v^2}{\Lambda^2} = 1.5\% \text{ at } \Lambda = 2\,\mathrm{TeV} \qquad \frac{E^2}{\Lambda^2} = 11\% \text{ at } E = 1\,\mathrm{TeV}, \Lambda = 3\,\mathrm{TeV}$$

  high precision needed also in EFT predictions!
  → computationally challenging, mainly due to phase space integration
  → hardest for NLO QCD (at high p_T) and/or pure interference

- better understanding/treatment of EFT-born **theory uncertainties**
- direct involvement of **experiments**
  → better treatment of syst. uncertainties and **correlations**
- learn how to handle & understand **likelihoods with** $50+$ **parameters**

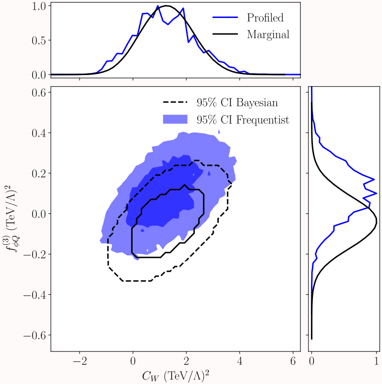
Bayesian statistics

IB,Bruggisser,Geoffray,Luchmann,Lübbe,Plehn in preparation

Switching from Frequentist to Bayesian can simplify fits in many dimensions
→ faster convergence to Gaussian shape → much less expensive computationally

already used in HEPfit, SMEFiT...

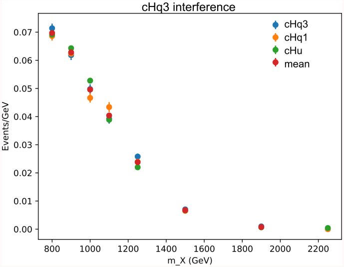
PRELIMINARY

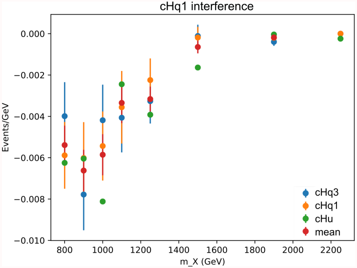


- in large fits, results are similar due to central limit thm
- main diffs. due to treatment of nuisance parameters in likelihood definition (integrated over vs. profiled)

Theory uncertainties from EFT

- uncertainties in EFT **predictions**. in principle vary term-by-term





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Theory uncertainties from EFT

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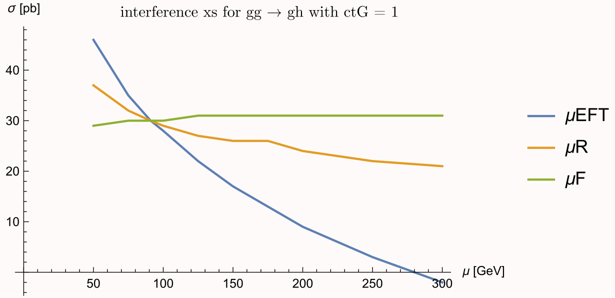

→ effect only partially compensated by mixing into C_{HG}

Theory uncertainties from EFT

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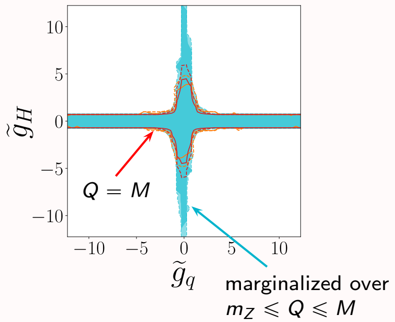
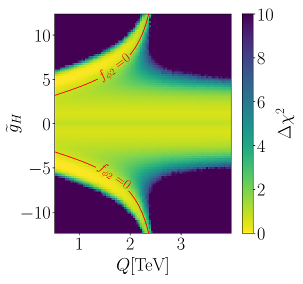
- uncertainties due to **matching scale** choice

fit matched to heavy vector triplet model, $M = 4\,\mathrm{TeV}$

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





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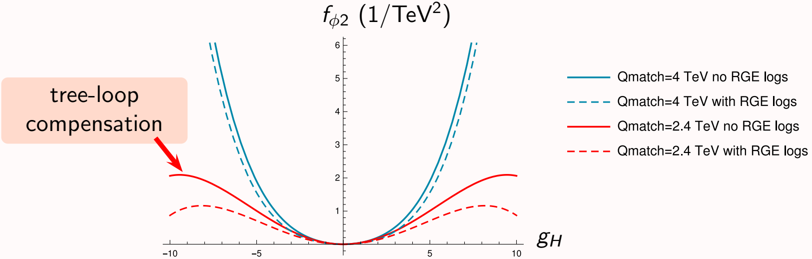


$$f_{\phi 2} \simeq 0.04\, g_H^2 \left(1 + 0.1 \log \frac{m_V}{Q}\right) + 10^{-3}\, g_H^4 \left(1 - 2.4 \log \frac{m_V}{Q}\right)$$

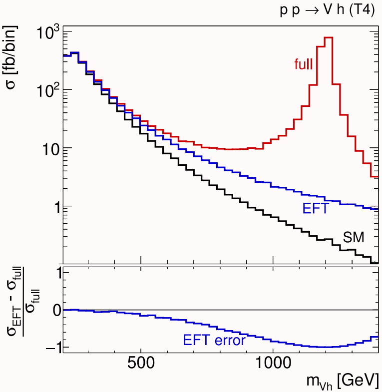
flips sign for $Q \lesssim m_V/1.52$

Theory uncertainties from EFT

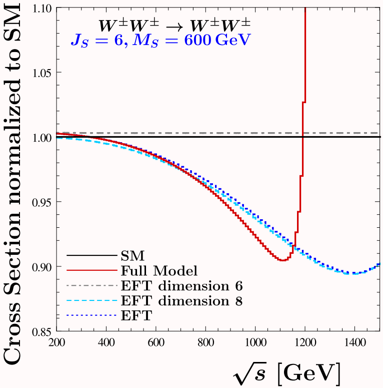
- uncertainties in EFT **predictions**. in principle vary term-by-term
- uncertainties due to missing higher orders in loops
- uncertainties due to running & mixing coefficients (**EFT scale**)
- uncertainties due to **matching scale** choice
- uncertainties due to **missing higher EFT orders** / unknown 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

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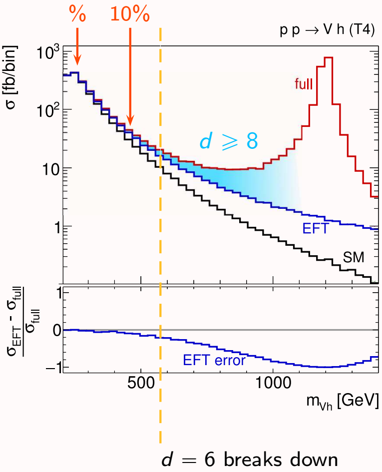

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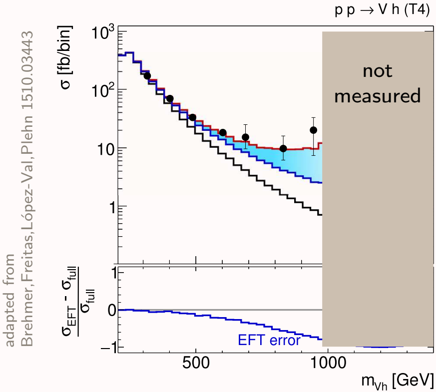


top-down: C_i fixed by matching
→ EFT not valid in high-E region

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

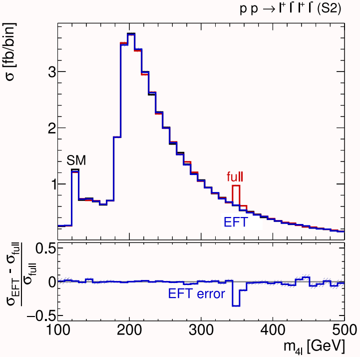
uncertainty band:
Trott et al 1508.05060,2007.00565,2106.13794,
Hays,Martin,Sanz,Setford 1808.00442
Shepherd et al 1812.07575,1907.13160

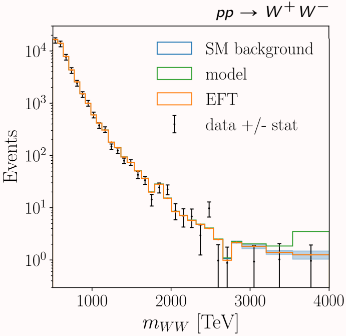
compute at d=8
Boughezal,Mereghetti,Petriello
2106.05337

safe scenarios ↔ no energy growth ↔ small effects

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

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





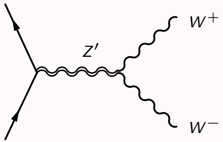
adapted from
Brehmer, Freitas, López-Val, Plehn 1510.03443

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

price to pay: % effects only

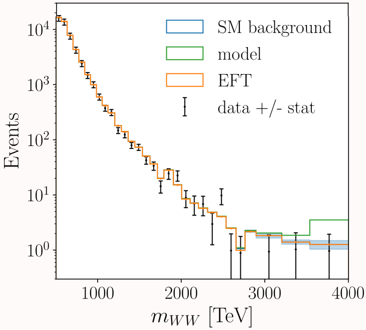
→ most sensitivity from lowest error region (∼ bulk)

Direct searches can help



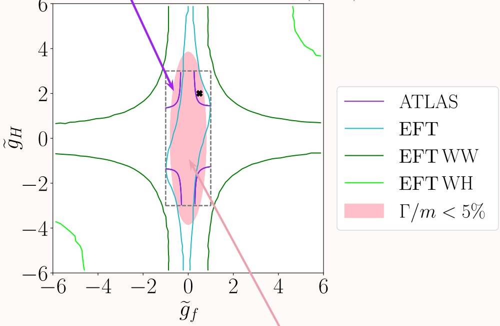
$$m_{Z'} = m_V = 4 \text{ TeV}$$

data: ATLAS 2004.14636



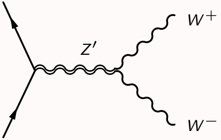
bound from
WW resonance search

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



resonance s. only valid
for narrow Z'

Direct searches can help



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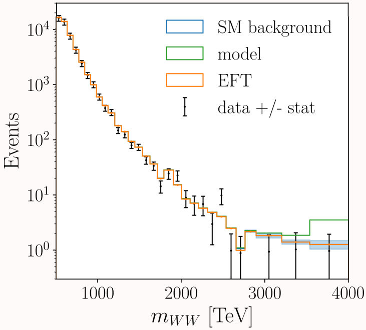
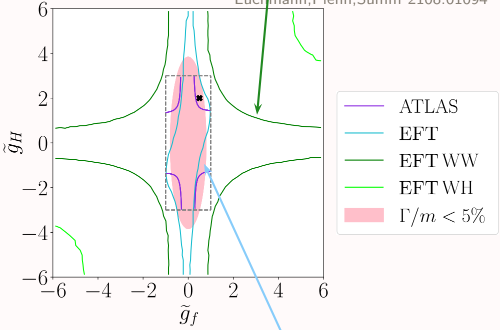


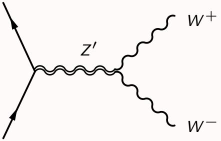
bound from EFT fit to *WW* spectrum

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



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

Direct searches can help



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

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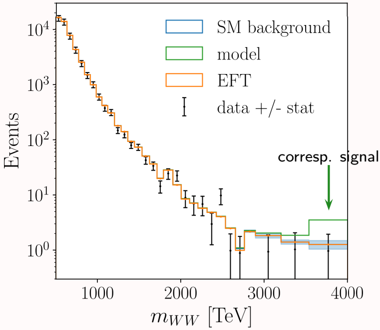
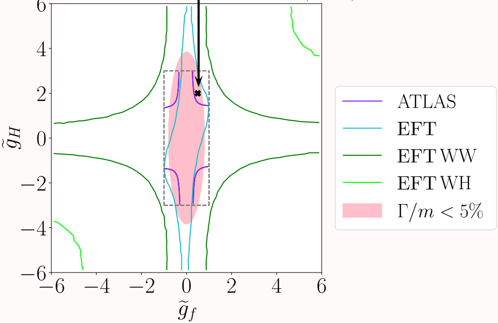


point excluded by resonance s.
but allowed by EFT

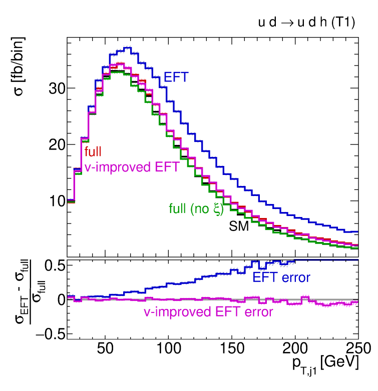
IB,Bruggisser,Geoffray,Kilian,Krämer, Luchmann,Plehn,Summ 2108.01094

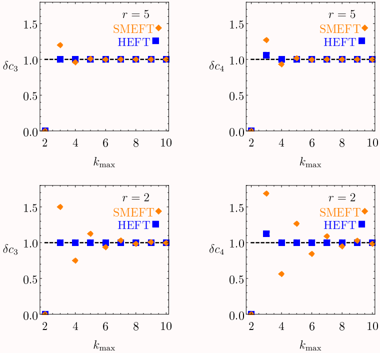


SMEFT or HEFT?

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?

Higgs EFT

Feruglio 9301281, Grinstein,Trott 0704.1505, Buchalla,Catà 1203.6510, Alonso et al 1212.3305. . .

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

- less restrictive symmetry assumptions → more parameters
- separate couplings with different # of Higgs legs   IB et al 1311.1823,1604.06801, Buchalla et al 1307.5017,1511.00988..

$$D_\mu\Phi^\dagger D^\mu\Phi \to \mathrm{Tr}(D_\mu\mathbf{U}^\dagger D^\mu\mathbf{U})\left(1 + a\frac{h}{v} + b\frac{h^2}{v^2} + \dots\right)$$

- enhanced anomalous interactions among Goldstones = W_L, Z_L
- there are BSM theories that admit HEFT but not SMEFT   Alonso,Jenkins,Manohar 1511.00724,1605.03602
  – with BSM sources of EWSB   Cohen et al 2008.0597,Banta et al 2110.02967
  – with BSM particles that take $> 1/2$ of their mass from EWSB
- more **convergent** than SMEFT
- only consistent if $\Lambda \lesssim 4\pi v \sim 3\,\mathrm{TeV}$ (unitarity violation)   Cohen et al 2108.03240

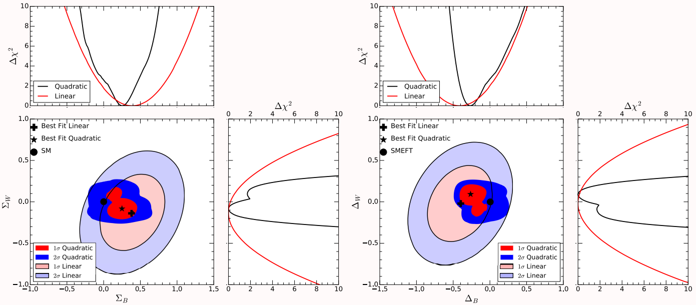
Non-SMEFT non-resonant signals: HEFT

phenomenologically, HEFT generalizes SMEFT

in principle, can give distinctive signals in

- comparison of processes with **different # of Higgs legs**
  $VV \to n \times h$ Buchalla,Capozi,Celis,Heinrich,Scyboz 1806.05162
  Gomez-Ambrosio,Llanes-Estrada,Salas-Bernardez,Sanz-Cillero 2204.01763
- processes with **Goldstones** (Z_L, W_L)
  $VV \to VV$

global fits in Higgs + EW sector IB et al 1311.1823,1604.06801, Buchalla et al 1511.00988
Corbett,Éboli,Goncalves,Gonzalez-Fraile,Plehn 1511.08188
Éboli,Gonzalez-Garcia,Martines 2112.11468



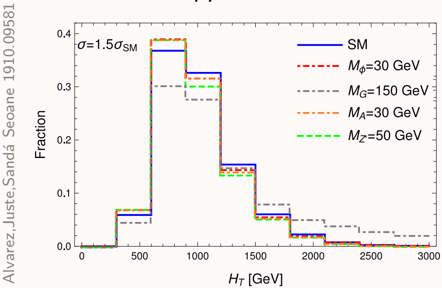
Non-SMEFT non-resonant signals: light NP

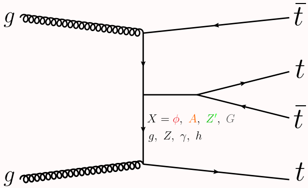
Non-resonant signals can also be induced by new light states

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

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

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





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

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

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

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

Recent developments in ALP EFT

relatively simple EFT → nice playground
recently borrowed some expertise from SMEFT

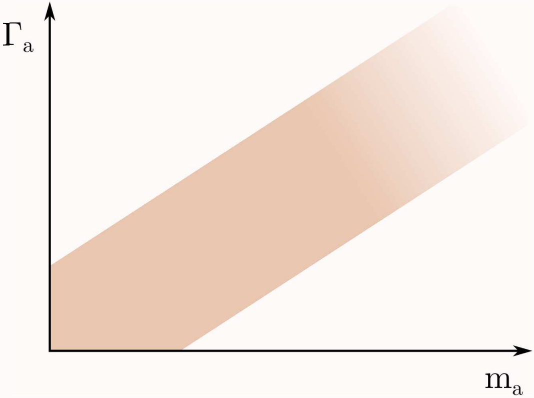
- discussion on basis completeness
  Chala,Guedes,Ramos,Santiago 2012.09017
  Bauer,Neubert,Renner,Schnubel,Thamm 2012.12272
  Bonilla,IB,Gavela,Sanz 2107.11392
- RGE evolution
- RGE mixing into SMEFT
  Galda,Neubert,Renner 2105.01078
  ⇝ Sophie's talk
- comprehensive 1-loop study, incl. finite parts
  Bonilla,IB,Gavela,Sanz 2107.11392
- unitarity constraints
  IB,Éboli,González-García 2106.05977
- shift-invariants
  Bonnefoy,Grojean,Kley 2206.04182
  ⇝ Quentin's talk

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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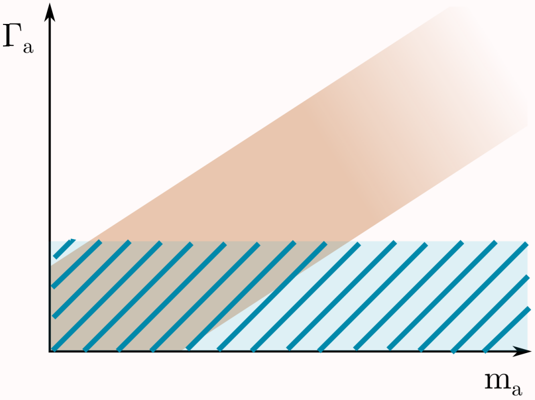
How?

stable ALP

↓

$\not{E}_T$



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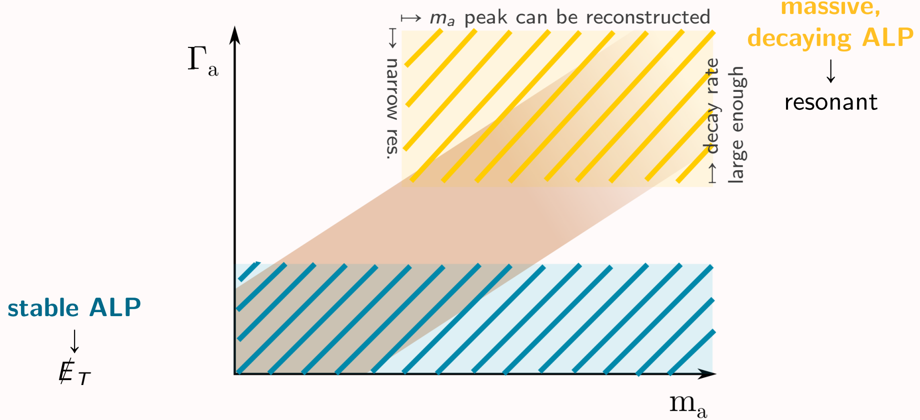

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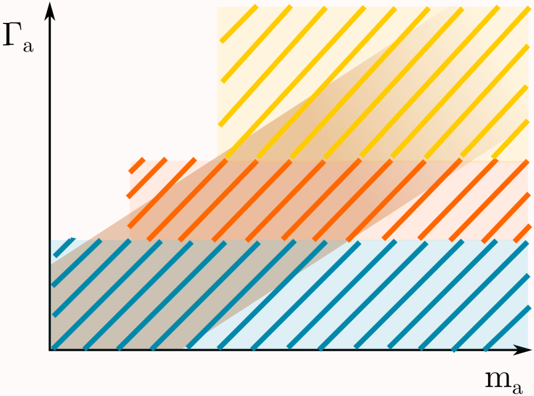


massive, decaying ALP
↓
resonant

long-lived ALP
↓
displaced vertices

stable ALP
↓
$\not{E}_T$

ALPs at the LHC

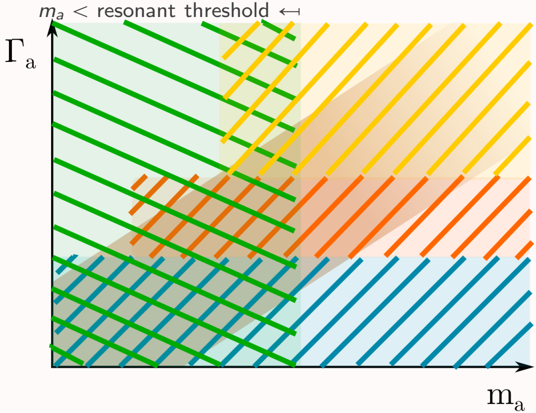
Why?

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

How?

off-shell ALP
↓
non-resonant

stable ALP
↓
$\not{E}_T$



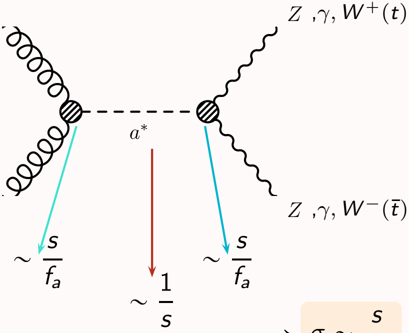
massive, decaying ALP
↓
resonant

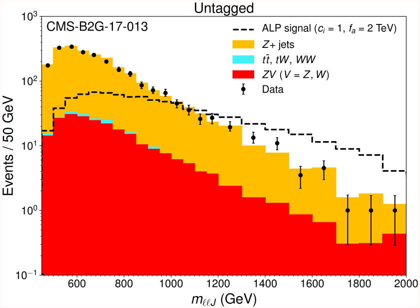
long-lived ALP
↓
displaced vertices

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"





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

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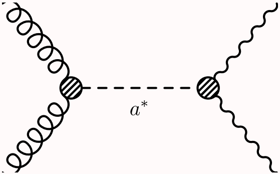
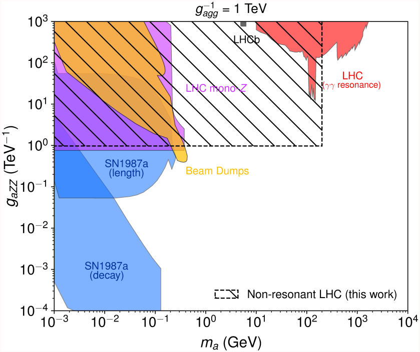




puts a constraint on $(g_{aGG} \times g_{aVV})$ product
for g_{aGG} not too small, competitive bounds on g_{aVV}

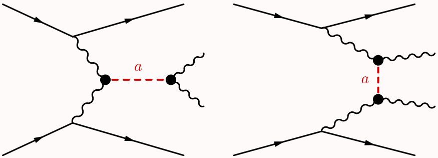
Non-resonant searches in VBS

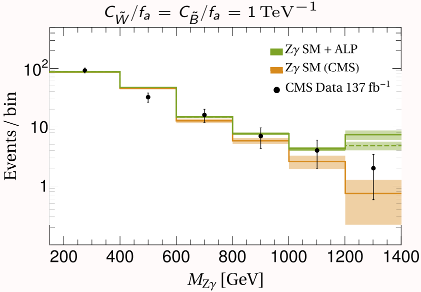
Bonilla, IB, Machado-Rodríguez, Trocóniz 2202.03450

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





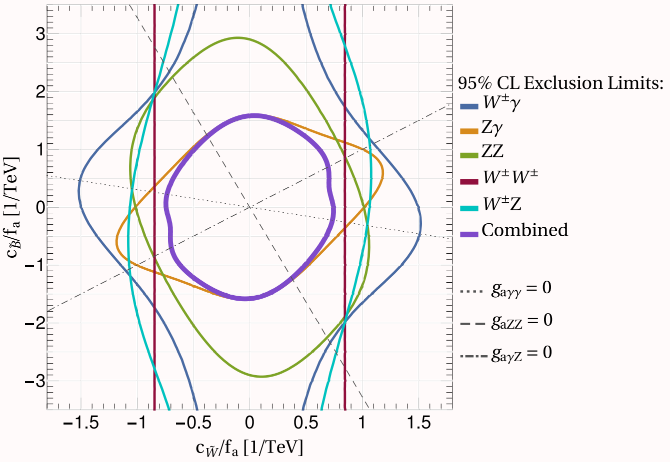
$$\sigma = \sigma_{SM} + \sigma_{\rm int.}/f_a^2 + \sigma_{ALP}/f_a^4$$

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

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

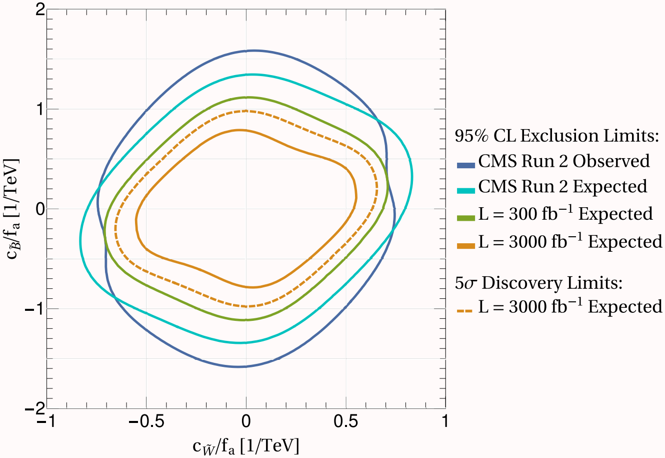
Non-resonant searches in VBS: Run 2 results

gauge invariant param. → all EW couplings simultaneously accounted for

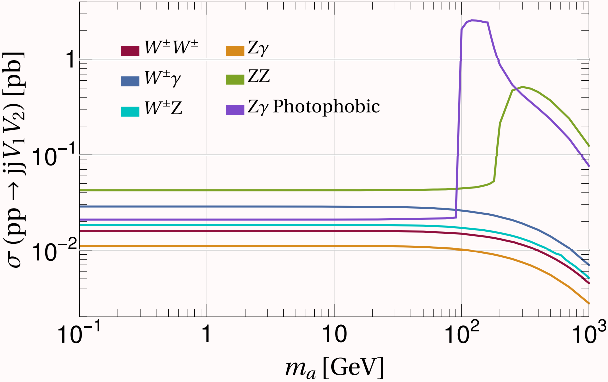


Non-resonant searches in VBS: projections

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



Dependence on ALP mass and width

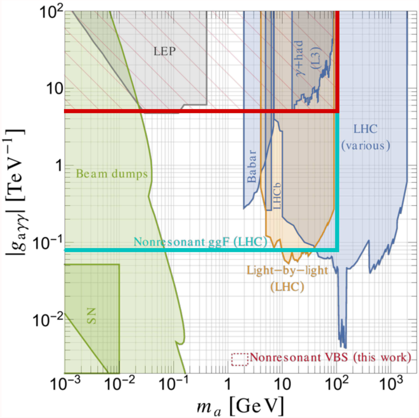


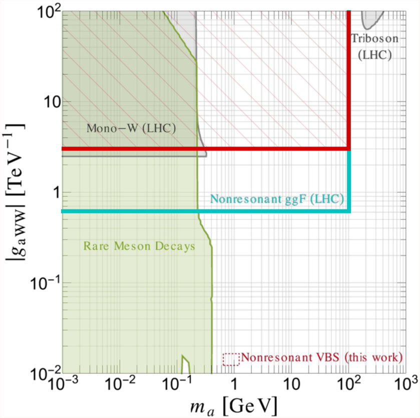
- as long as $q^2 \gg m_a, \Gamma_a$, **independent** of exact values of mass and width
  "reverse" of an EFT ($q^2 \gg m^2$ vs $q^2 \ll m^2$ limit)
- XS stable up until $m_a \lesssim 100$ GeV

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

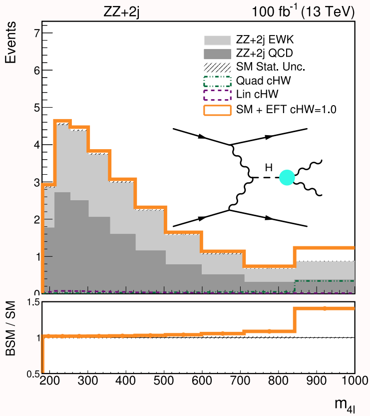
} relevant to break flat directions





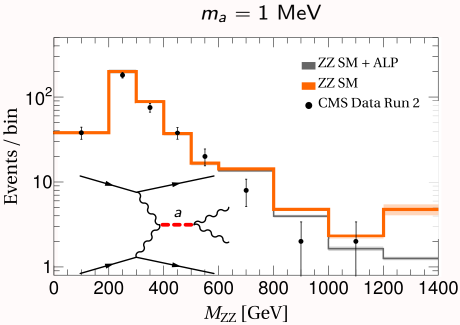
SMEFT vs ALPs in VBS

$pp \to jjZZ$ in SMEFT



Bellan,Boldrini,Brambilla,IB et al 2108.03199

$pp \to jjZZ$ with an ALP



Bonilla,IB,Machado,Trocóniz 2202.03450

⇝ Antonio Vagnerini

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... → relevant at $\sqrt{s} \gg m$
- Distinguishing SMEFT / HEFT / other sources is an open task