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

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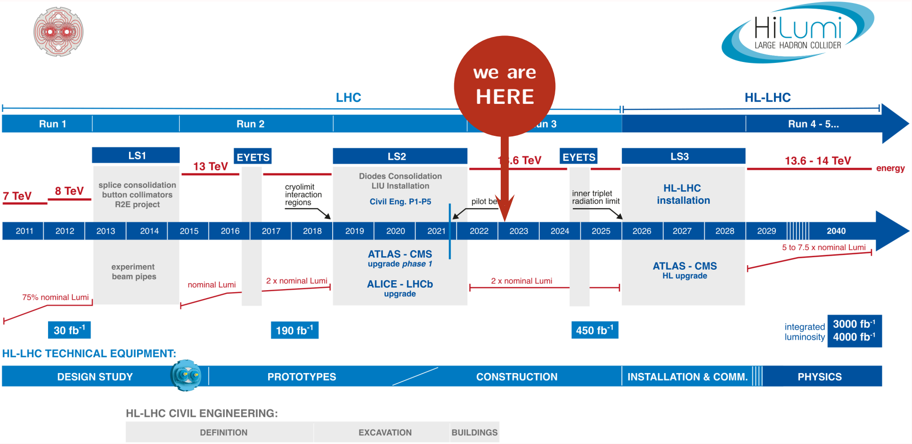
Where we are - LHC perspective



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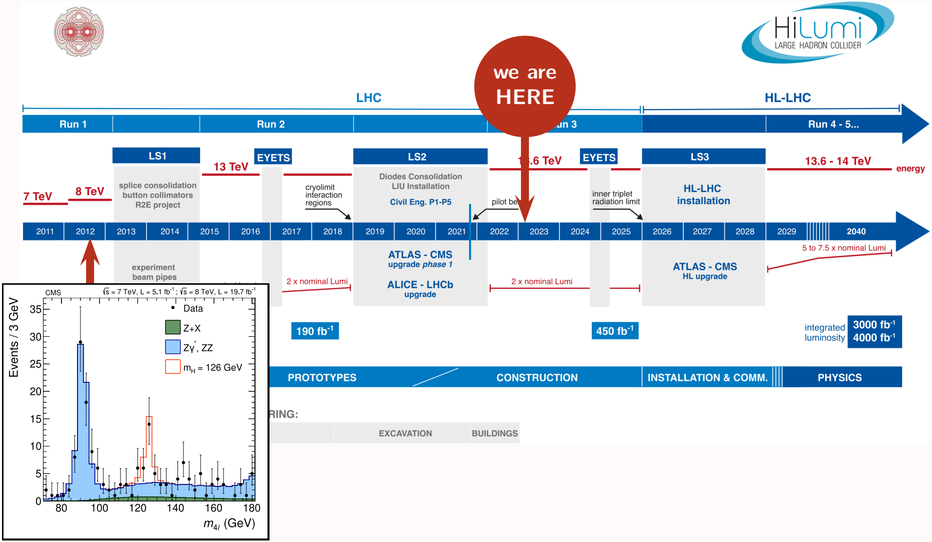

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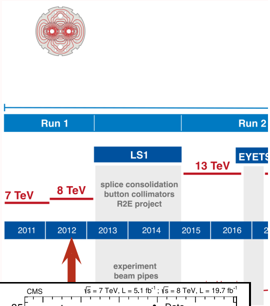

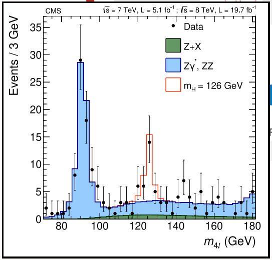

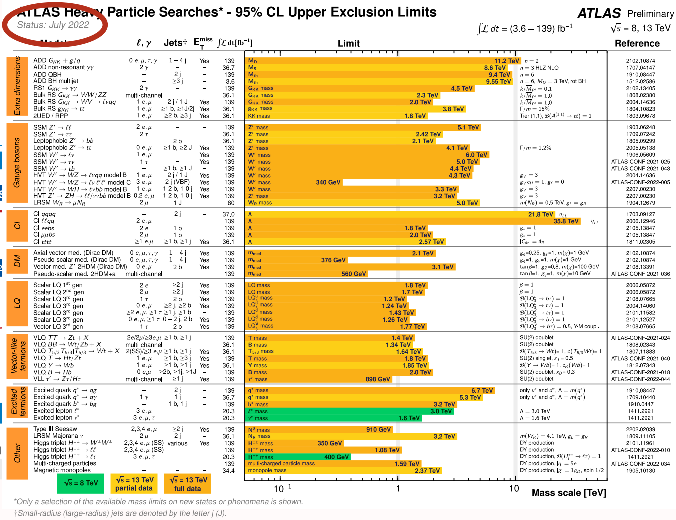

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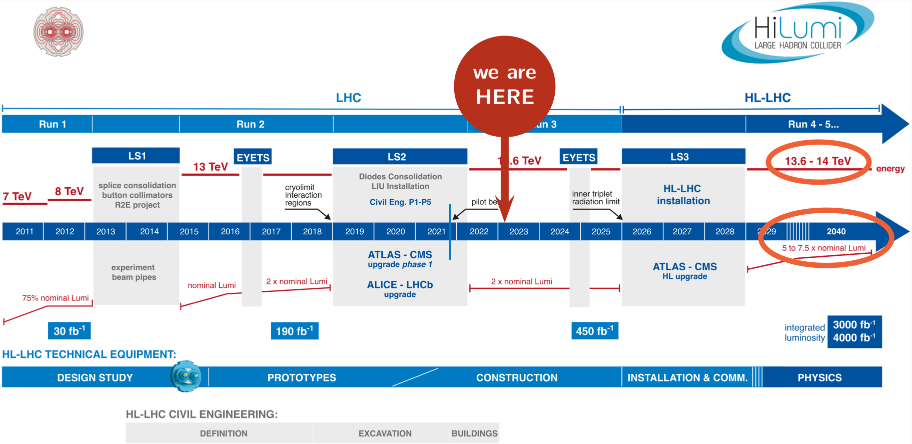


Targeting non-resonant signals of new physics

no clear indications of specific BSM scenarios

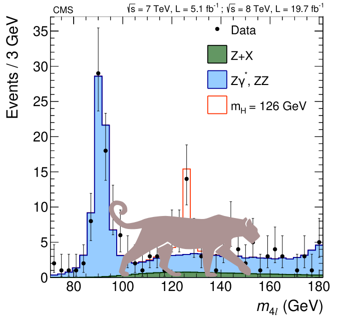
+

strong reduction of statistical uncertainties

↓

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

CMS-HIG-13-002



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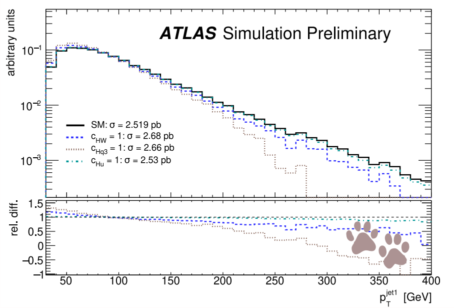
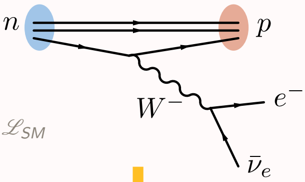


ATL-PHYS-PUB-2019-042

Effective Field Theories

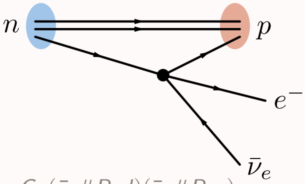
Classic example:

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

Simplified theory (EFT)

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

$\rightarrow$ typically truncated at 1st or 2nd order

Effective Field Theories

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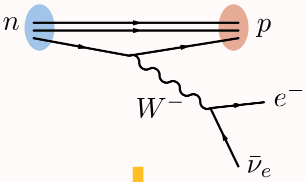
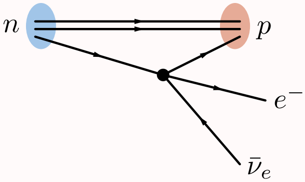
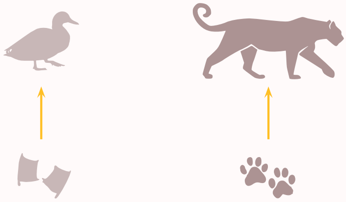


$q^2 < m_N^2 \ll m_W^2$



Bottom-up paradigm

<u>measurements</u> of EFT parameters reveal properties of underlying full theory
→ *complement* direct searches
→ reach into higher energies



EFT ≡ fields+symmetries at E $= \mu$
constructed as a self-consistent theory
→ no reference to models
→ free couplings

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

- allows **model-independent** NP interpretation
- well-defined mapping between theories in UV and at EW scale
- **proper QFT**: renormalizable order-by-order, system. improvable in loops
- allows combination with **non-LHC** measurements: "global likelihood"

SMEFT at $d = 6$: the Warsaw basis

Grzadkowski, Iskrzynski, Misiak, Rosiek 1008.4884

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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	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}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger \tau^I \varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$

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$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

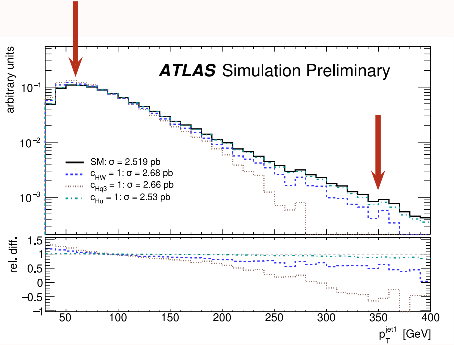
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k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

Challenges for the bottom-up SMEFT program

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

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

on tails $\sim \frac{E^2}{\Lambda^2} \simeq \frac{E^2 g_{UV}}{M^2}$ $\quad E \simeq 1\,\text{TeV}, M \simeq 3\,\text{TeV} \to$ 10%



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2. making sure that, if we observe one, we **interpret it correctly**. needs:

- retaining all relevant contributions: all operators, NLO corrections. . .

  ↓

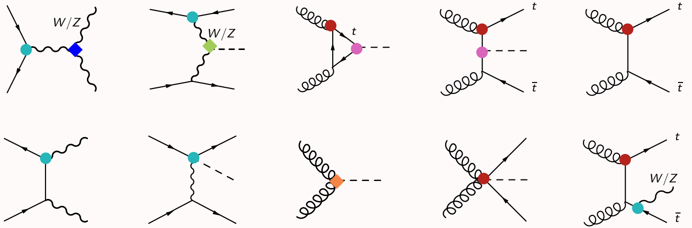
  – handling many parameters in predictions and fits
  – understanding the theory structure
- correct understanding of uncertainties and correlations
- systematic mapping to BSM models

The need for global analyses

$\mathscr{L}_6$ has **2499** parameters in the most general case
$\mathcal{O}(\mathbf{100})$ with flavor symmetries and CP

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

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

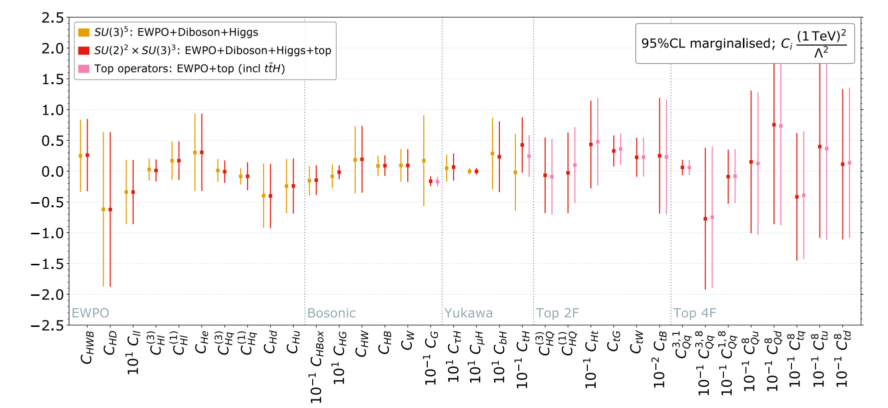
map to other theories

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

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

SMEFT combinations by ATLAS & CMS

ATLAS: mostly Higgs and EW

- Higgs prod+decay combination ATLAS-CONF-2021-053
- $H \to WW^*$ in ggF and VBF + WW production ATL-PHYS-PUB-2021-010
- Higgs (STXS) + diff. VV + Zjj + EWPO (LEP+SLC) ATL-PHYS-PUB-2022-037

CMS: mostly Top

- $ttV + ttH + tHq + tVq$ TOP-19-001
- $ttZ + ttH$ TOP-21-003

LHC EFT WG: organising a "fitting exercise" lpcc.web.cern.ch/lhc-eft-wg

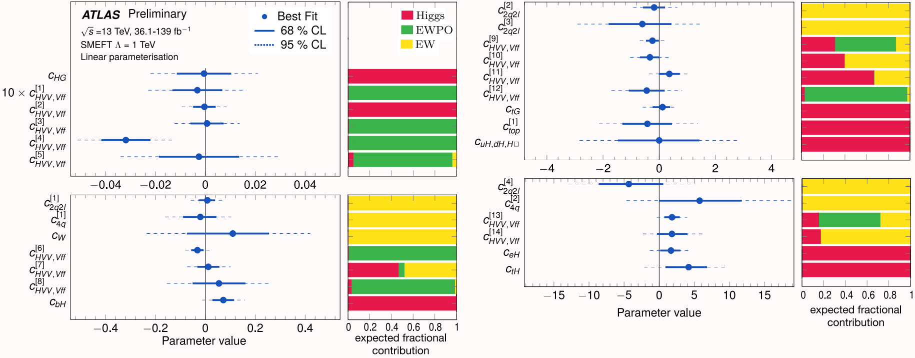
- first attempt at combining **across groups + across experiments**
- will use public data. code will be open access
- main goal: sync predictions and analysis frameworks across ATLAS and CMS

Example: latest ATLAS combination

ATL-PHYS-PUB-2022-037

- predictions: $gg \to h, gg \to zh, h \to gg$: MC NLO QCD SMEFT@NLO: Degrande et al 2008.11743
  $h \to \gamma\gamma$: NLO EW Dawson,Giardino 1807.11504. also: Hartmann,Trott,Passarino,Dedes,Rosiek. . .
  rest: MC LO SMEFTsim v3: IB 2012.11343

- Principal Component Analysis constrains fit eigenvectors



What's missing for a successful SMEFT program?

A = for being sensitive B = for interpreting deviations correctly

0. (experimentally established anomalies) *[personal point of view, not a complete list!]*

1. A reduction of uncertainties on SM predictions + systematics

2. A B modeling & treatment of EFT-born **uncertainties**
from MC simulation, missing higher order in loops and EFT, scale dependence...

3. B correct treatment of correlations → involvement of experiments

Bißmann,Erdmann,Grunwald,Hiller,Kröninger 1912.06090

4. B understanding SMEFT corrections 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

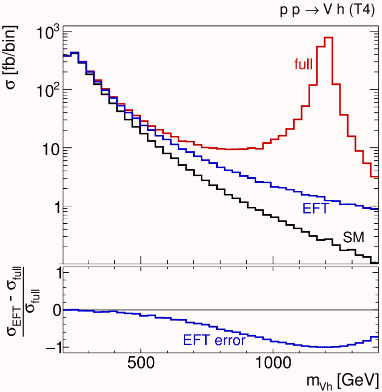
5. B more refined process treatment: exploit differential info, target ~~CP~~, flavor...

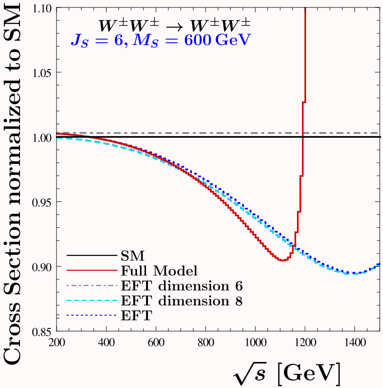
6. B handling & understanding $\sim$ 50-dimensional likelihoods

Impact of higher order operators

EFT obtained from matching to full model

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

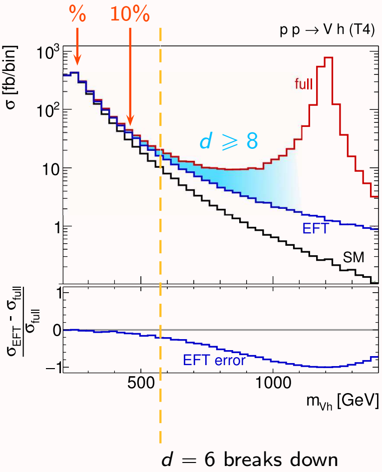




adapted from
Lang, Liebler, Schäfer-Siebert, Zeppenfeld 2103.16517

Impact of higher order operators

EFT obtained from matching to full model



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

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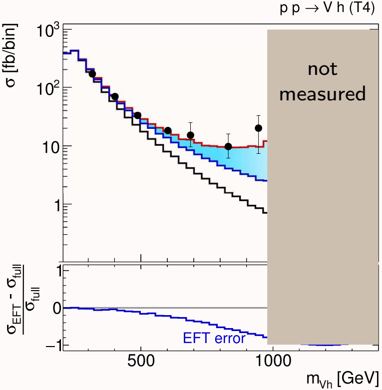


top-down: C_i fixed by matching
→ EFT not valid in high-E region

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

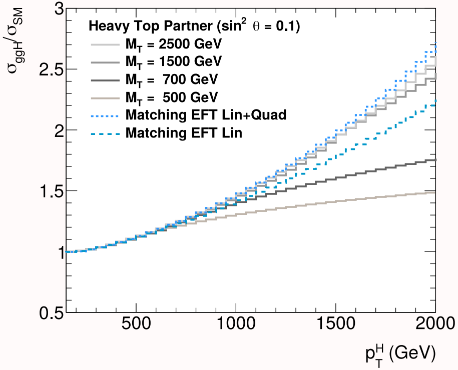
uncertainty band:
Trott et al 1508.05060, 2007.00565, 2106.13794
Hays, Martin, Sanz, Setford 1808.00442
Shepherd et al 1812.07575, 1907.13160

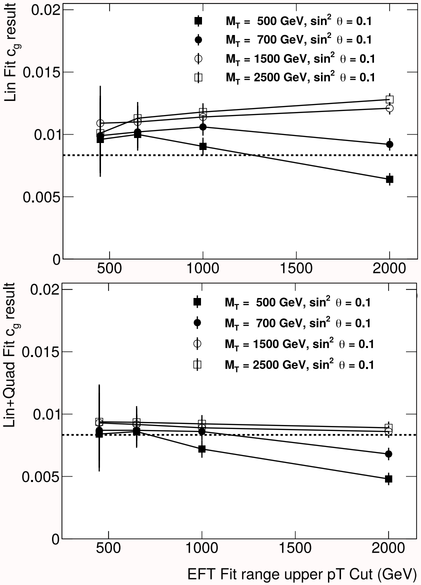
compute at $O(\Lambda^{-4})$
Boughezal, Mereghetti, Petriello 2106.05337
Asteriadis, Dawson, Fontes, Homiller, Sullivan 2110.06929, 2205.01561, 2212.03258

Battaglia, Grazzini, Spira, Wiesemann 2109.02987

p_T^H from heavy top partner

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

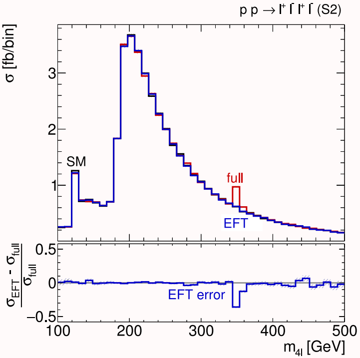




safe scenarios ↔ no energy growth ↔ small effects

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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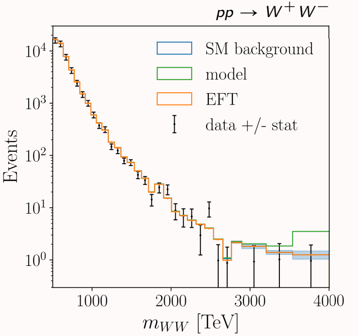


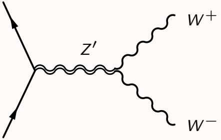
Brivio,Bruggisser,Geoffray,Kilian,Krämer,
Luchmann,Plehn,Summ 2108.01094

price to pay: % effects only

→ most sensitivity from lowest error region (∼ bulk)

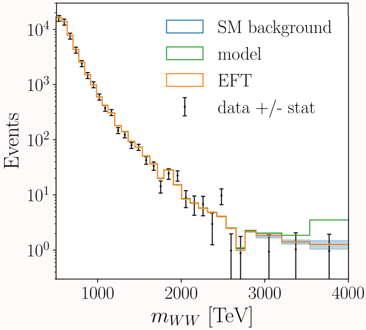
Interplay with direct searches

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

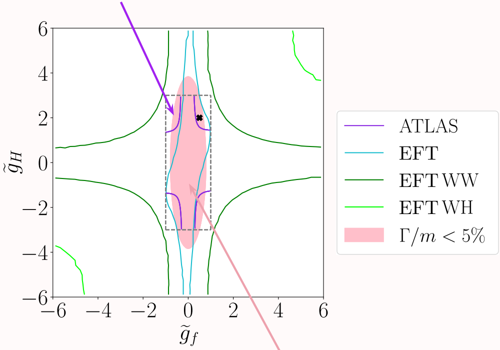


$$m_{Z'} = m_V = 4\ \text{TeV}$$

data: ATLAS 2004.14636



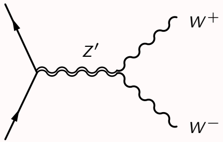
bound from
WW resonance search



resonance s. only valid
for narrow Z'

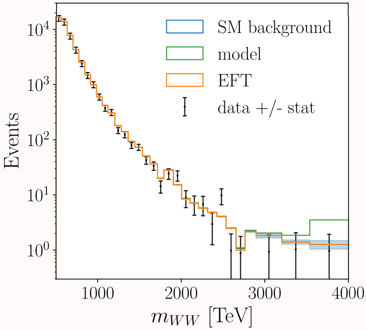
Interplay with direct searches

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

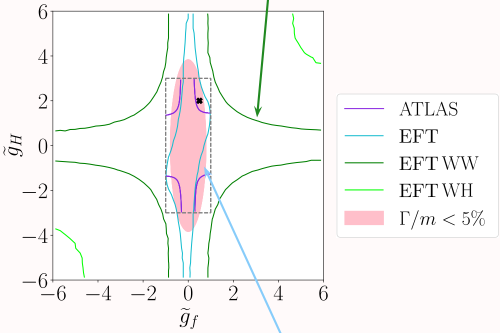


$$m_{Z'} = m_V = 4 \text{ TeV}$$

data: ATLAS 2004.14636



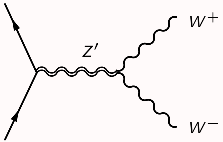
bound from EFT fit to WW spectrum



bound from EFT fit to all obs. (incl. EWPO, Higgs)

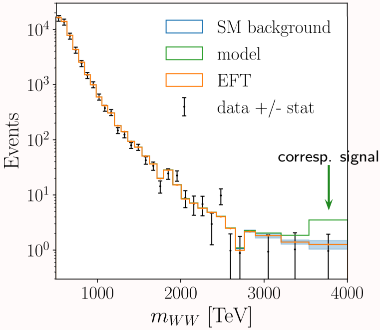
Interplay with direct searches

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

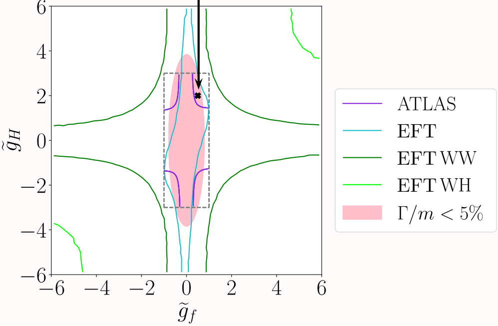


$$m_{Z'} = m_V = 4 \text{ TeV}$$

data: ATLAS 2004.14636



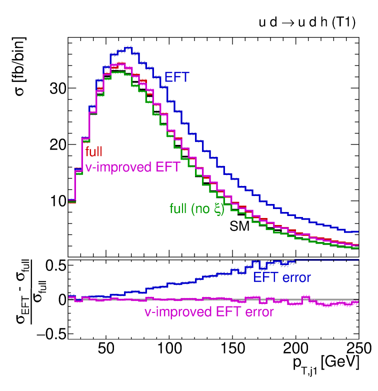
point excluded by resonance s.
but allowed by EFT

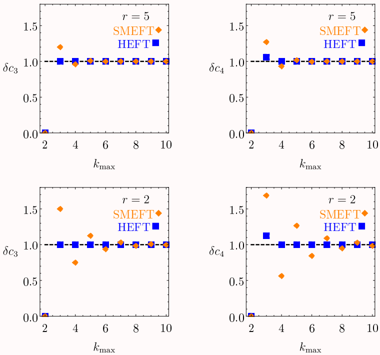


SMEFT or HEFT?

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 same as matching to **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...

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

- HEFT expands **around vacuum**, SMEFT around $H = 0$
- at level of truncated EFT:

  IB et al 1311.1823,1604.06801, Buchalla et al 1307.5017,1511.00988..

  → split couplings with different # of Higgs legs

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

  → enhanced anomalous interactions among Goldstones = W_L, Z_L

- recent **geometric interpretation** proves that

  Alonso,Jenkins,Manohar 1511.00724,1605.03602

  there are BSM theories that admit HEFT but not SMEFT
  – 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

Non-resonant signals from light NP

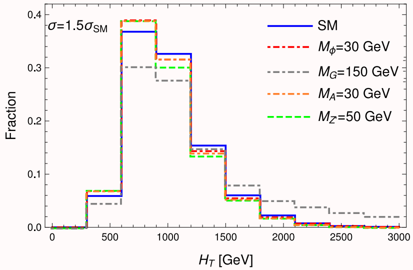
Non-resonant signals can also be induced by new light states

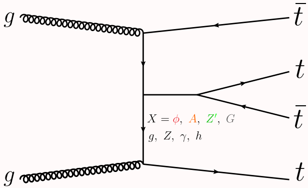
→ off-shell, in the limit $\sqrt{s} \gg m$ → typically happens for heavy final states

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

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

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.	$\rightarrow$	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

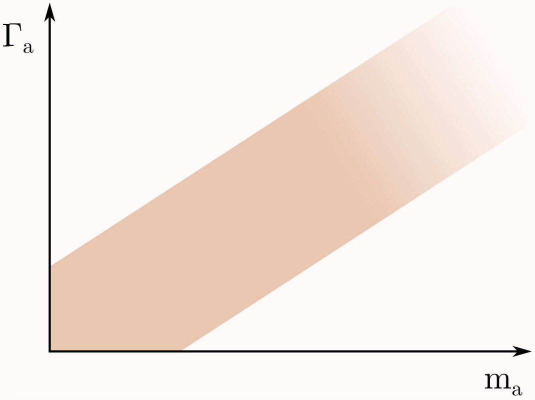
- discussion on basis completeness — Chala,Guedes,Ramos,Santiago 2012.09017; Bauer,Neubert,Renner,Schnubel,Thamm 2012.12272; Bonilla,IB,Gavela,Sanz 2107.11392
- RGE evolution
- RGE mixing into SMEFT — Galda,Neubert,Renner 2105.01078
- comprehensive 1-loop study, incl. finite parts — Bonilla,IB,Gavela,Sanz 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** $(m_a \gtrsim 10s\ \text{GeV})$

How?



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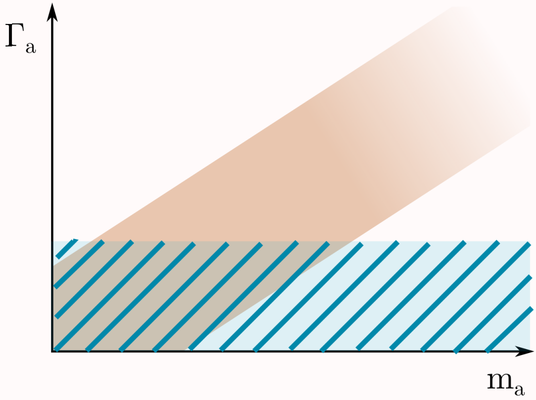
How?

stable ALP

$\downarrow$

$\not{E}_T$



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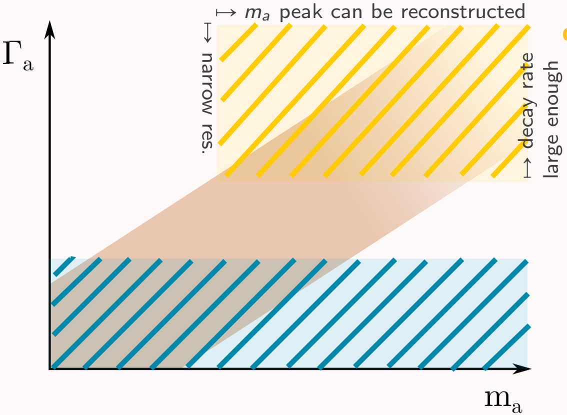
How?

stable ALP
↓
$\not{E}_T$



massive, decaying ALP
↓
resonant

ALPs at the LHC

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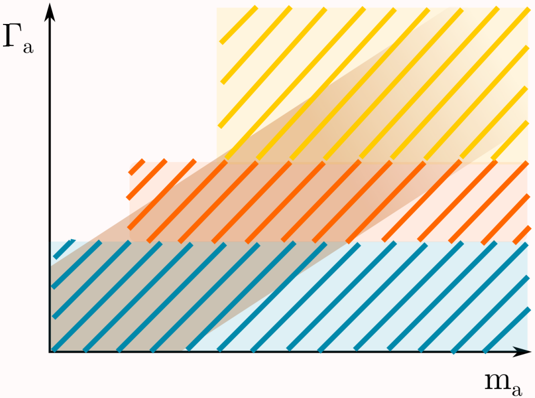
stable ALP
↓
$\not{E}_T$



massive, decaying ALP
↓
resonant

long-lived ALP
↓
displaced vertices

ALPs at the LHC

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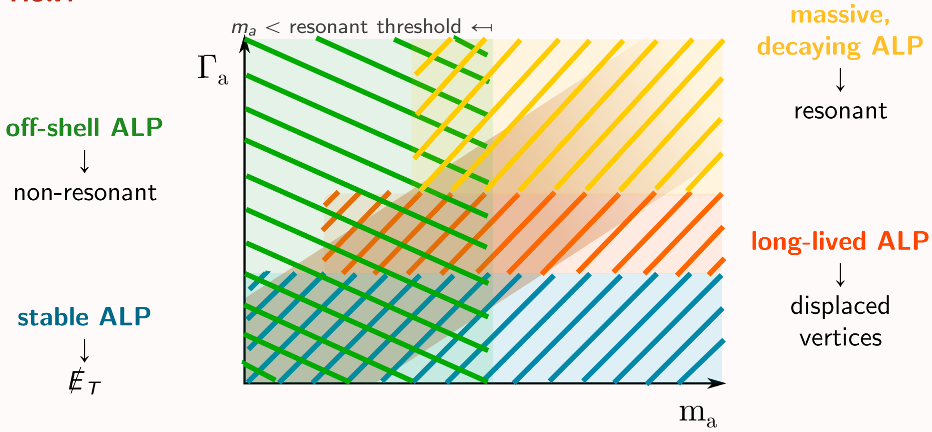
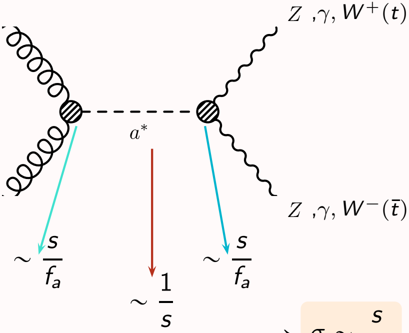
How?

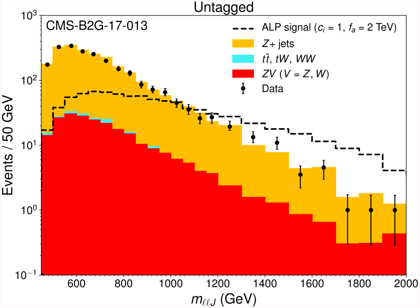


Non-resonant ALP signals at LHC

$ZZ, \gamma\gamma, t\bar{t}$: 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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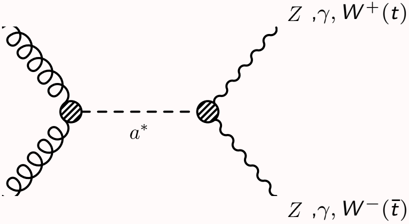
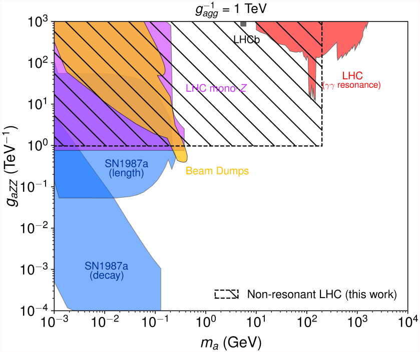




puts a constraint on $(g_{aGG} \times g_{aVV})$ product
for g_{aGG} not too small, competitive bounds on g_{aVV}

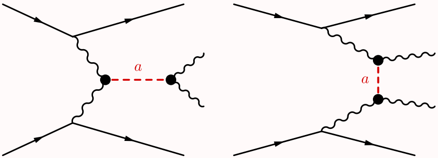
Non-resonant searches in VBS

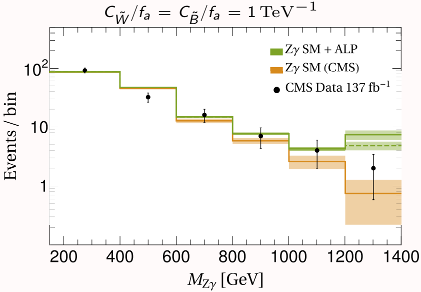
Bonilla, IB, Machado-Rodríguez, Trocóniz 2202.03450

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





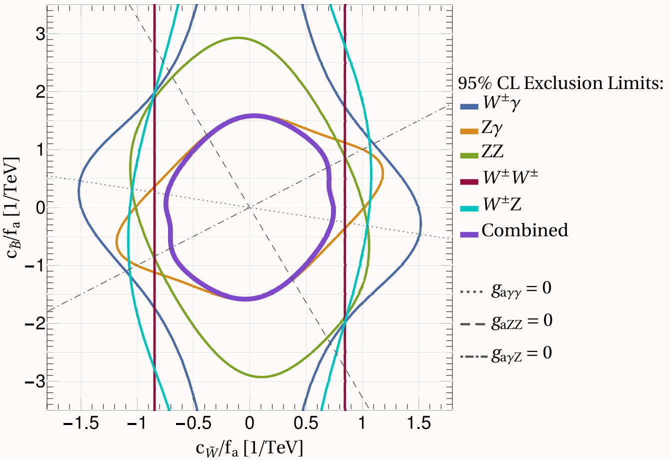
$$\sigma = \sigma_{SM} + \sigma_{\text{int.}}/f_a^2 + \sigma_{ALP}/f_a^4$$

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

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

Non-resonant searches in VBS: Run 2 results

gauge invariant param. → all EW couplings simultaneously accounted for

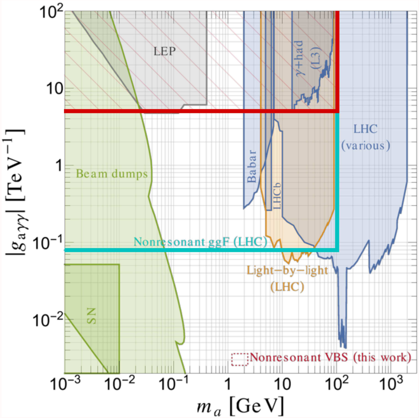


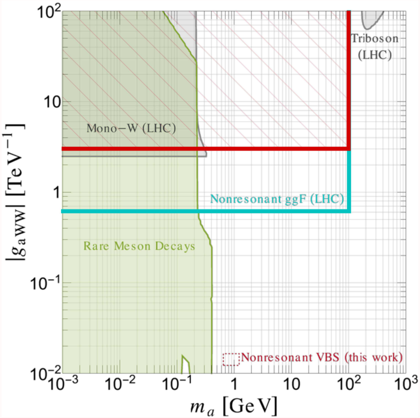
Comparison with other constraints

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

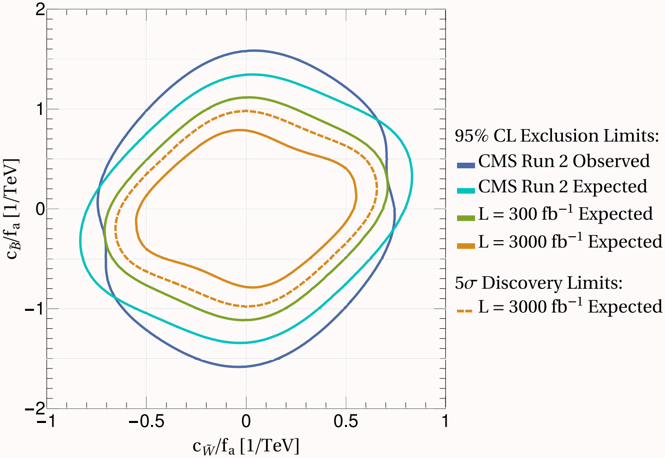
} relevant to break flat directions





Non-resonant searches in VBS: projections

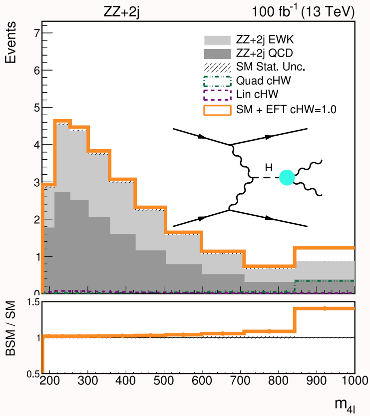
HL-LHC: sensitivity improves $\times 5-8$ on XS $\rightarrow$ $\times 1.5-1.7$ on C_i/f_a

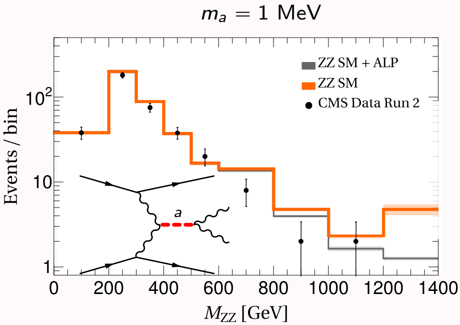


SMEFT vs ALPs in VBS

$pp \to jjZZ$ in SMEFT

$pp \to jjZZ$ with an ALP





Bellan,Boldrini,Brambilla,IB et al 2108.03199

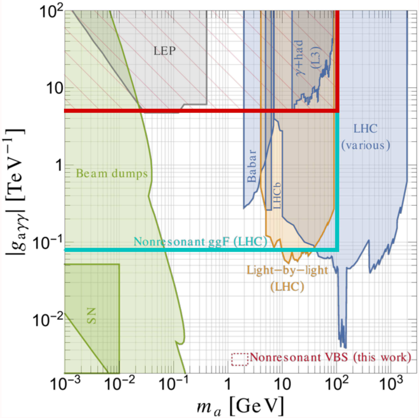
Bonilla,IB,Machado,Trocóniz 2202.03450

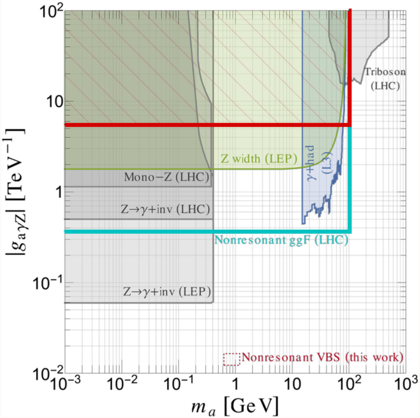
Summary

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

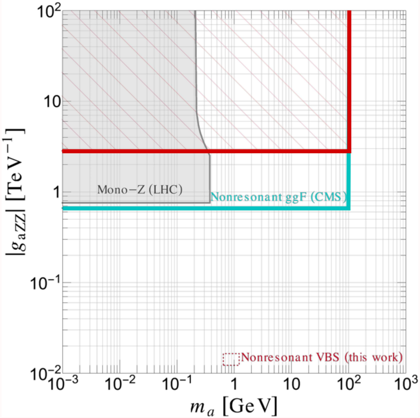
Backup slides

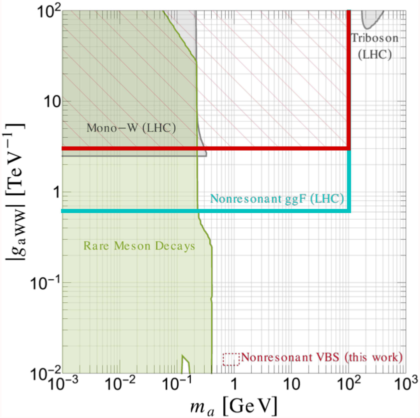
Bounds on ALP couplings



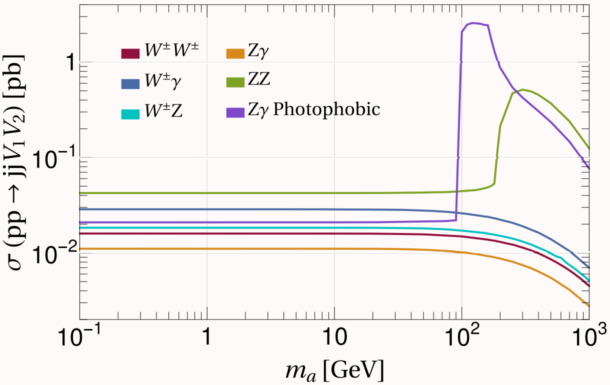


Bounds on ALP couplings





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

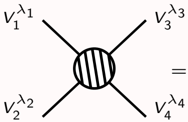
Perturbative unitarity

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

V_i = vector bosons or scalars

λ_i = helicities (V:$\lambda_i = 0, \pm 1$, S:$\lambda_i \equiv 0$), $\lambda = \lambda_1 - \lambda_2, \mu = \lambda_3 - \lambda_4$

T^J = amplitude for J-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:

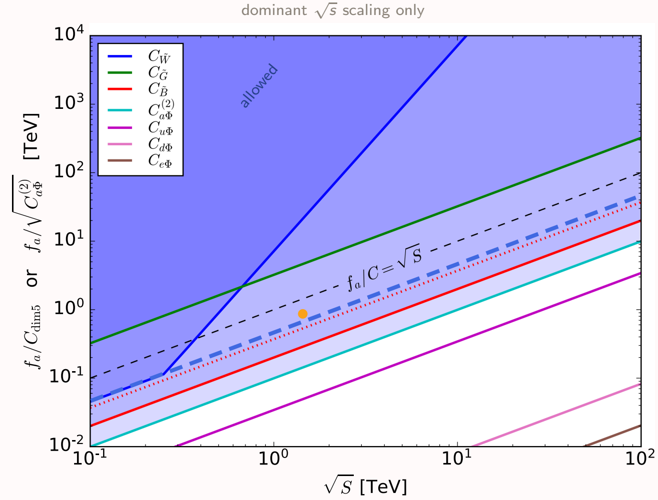
$$V_1 V_2 \to V_3 V_4 \qquad V_1 a \to V_2 a \qquad V_1 V_2 \to aa \qquad V_1 V_2 \to V_3 a$$
$$ha \to ha \qquad hh \to aa \qquad f_1 \bar{f}_2 \to Va$$

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

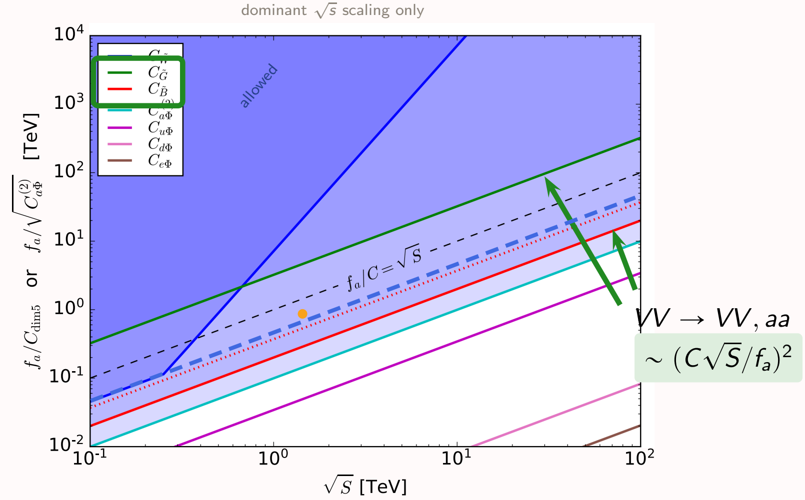
4. apply elastic unitarity requirement $|t^J| \leqslant 1$ on each eigenvalue

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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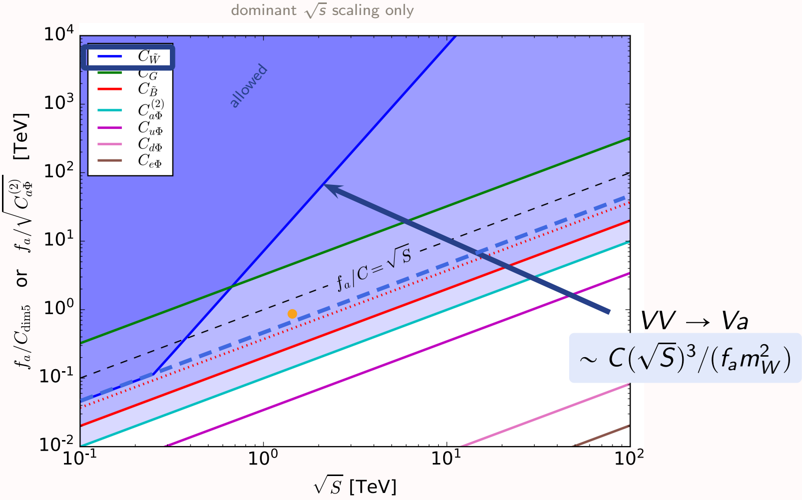
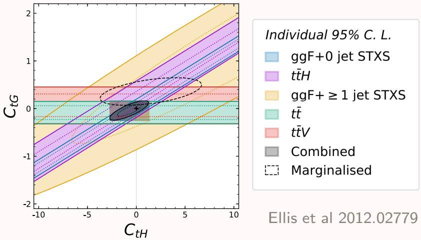


⚠ $\sqrt{s}$ overall scale, cannot be interpreted "literally" in specific processes

SMEFT fits: generalities

Typical observables included

- EWPO (LEP)
- Diboson (WZ, WW)
- Higgs production & decay (STXS + BR)
- $\bar{t}t$, $\bar{t}tV$, single top production
- Top decays



Ellis et al 2012.02779

Diverse statistics techniques employed

- frequentist/bayesian, Markov chains/Nested Sampling/replica models. . .
- uncertainties most often gaussian
  more sophisticated treatment → more complex likelihood structure

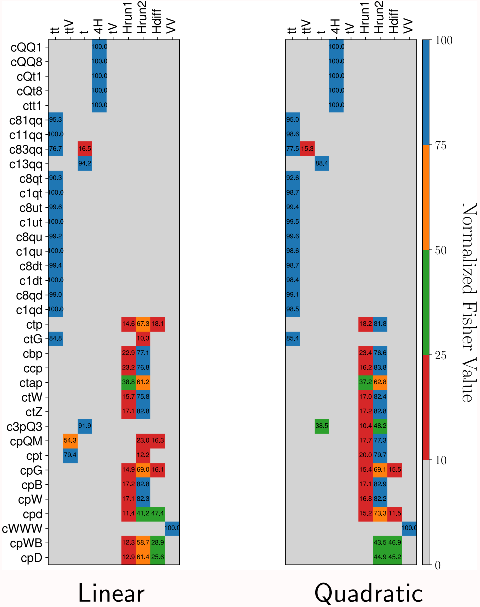
Fisher information matrix

$$I_{ij} = -E\left[\frac{\partial^2 \log \mathcal{L}_{\text{observed}}(\vec{C})}{\partial C_i \partial C_j}\right]$$

compute for sub-datasets and normalize to 1 for each coefficient

↓

strongest constraint on each C_i



Ethier et al 2105.00006

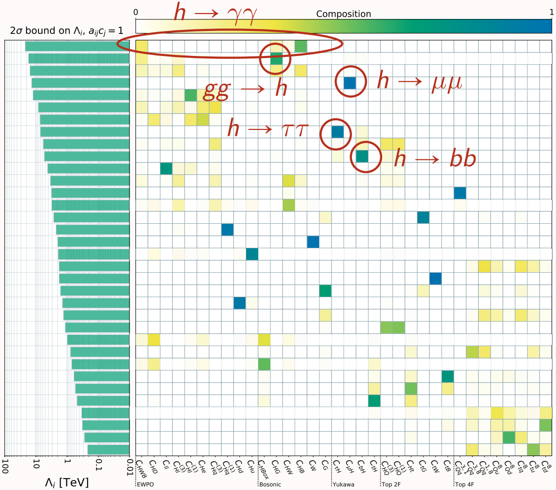
see also: Brehmer et al 1612.05261,1712.02350,1908.06980

Principal Component Analysis

eigensystem of the Fisher matrix

→ identify the **best and worst constrained** directions in the fit space

→ unconstrained directions = vectors with eigenvalue 0



Relative constraining power (%)

EWPO	LEP WW	Run 1, μH	Run 2, μH	STXS	LHC WW&	LHC Zjj	$t\bar{t}$	single top	$t\bar{t}V$
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

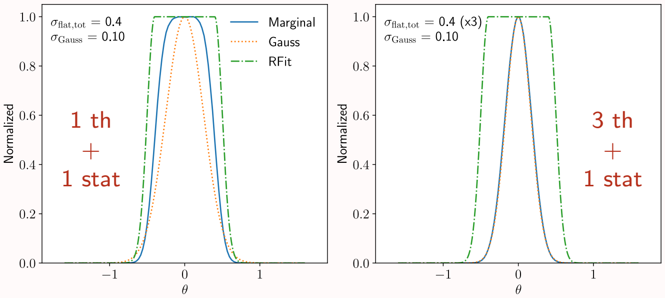
Ellis et al 2012.02779

Marginalisation for large-d likelihoods

also: HEPfit: deBlas et al 1905.03764, SMEFiT: Ethier et al 2105.00006, EFTfitter: Castro et al 1605.05585

marginalising vs profiling

- not the same interpretation! but results should be similar 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

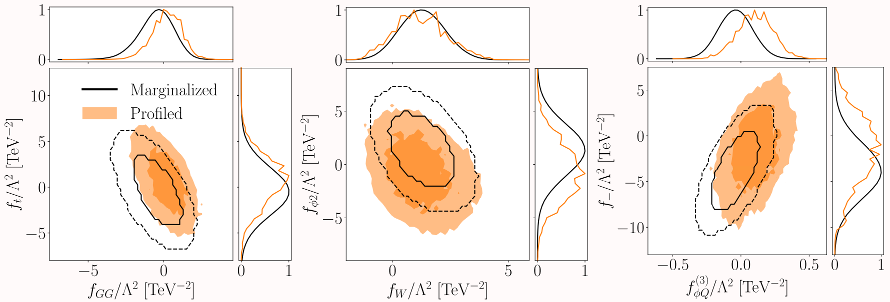


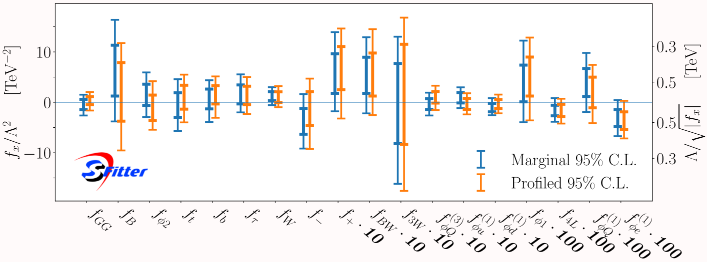
IB, Bruggisser, Elmer, Geoffray, Luchmann, Plehn 2208.08454

- faster convergence to Gaussian shape ⇒ way less computationally expensive

Marginalisation - 18D fits

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

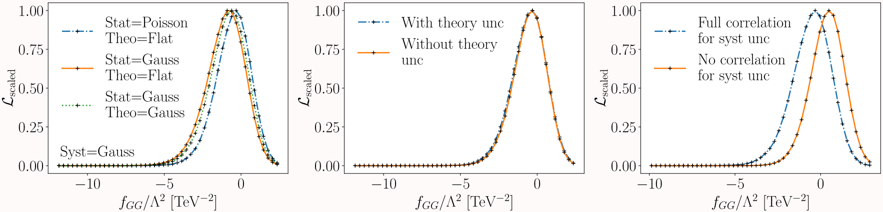




Marginalisation: the role of correlations

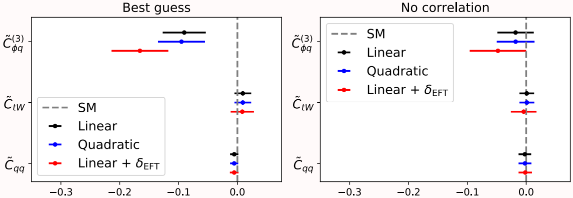
when marginalising over (many) nuisance parameters,
it is not so relevant whether they are originally modeled as flat, poisson or Gauss

the largest difference is seen changing **correlations**



observed also in

Bißmann,Erdmann,Grunwald,
Hiller,Kröninger 1912.06090



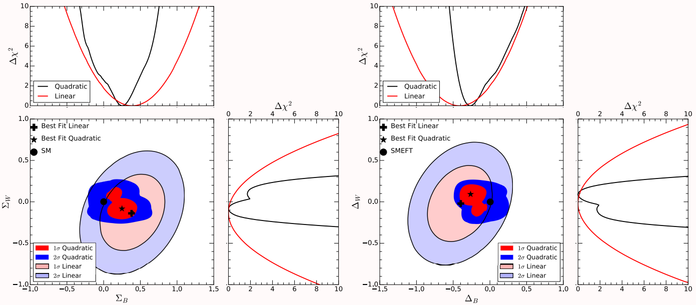
Non-SMEFT non-resonant signals: HEFT

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



HEFT sigma and delta definitions

SMEFT

$$O_B = \frac{ig'}{2}(D_\mu\Phi^\dagger)B^{\mu\nu}(F_\nu\Phi) \qquad O_W = \frac{ig}{2}(D_\mu\Phi^\dagger)W^{\mu\nu}(D_\nu\Phi)$$

HEFT

$$P_2 = \frac{i}{4\pi}B_{\mu\nu}\,\mathrm{Tr}(\mathbf{T}[\mathbf{V}^\mu,\mathbf{V}^\nu])F_2 \qquad P_3 = \frac{i}{4\pi}\,\mathrm{Tr}(W_{\mu\nu}[\mathbf{V}^\mu,\mathbf{V}^\nu]F_3$$

$$P_4 = \frac{i}{4\pi}B_{\mu\nu}\,\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\partial^\nu F_4 \qquad P_5 = \frac{i}{4\pi}\,\mathrm{Tr}(\mathbf{T}\,W_{\mu\nu})\,\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\partial^\nu F_5$$

Definitions

$$\Sigma_B = \frac{1}{\pi g t_\theta}(2c_2 + a_4) \qquad \Delta_B = \frac{1}{\pi g t_\theta}(2c_2 - a_4)$$

$$\Sigma_W = \frac{1}{2\pi g}(2c_3 - a_5) \qquad \Delta_W = \frac{1}{2\pi g}(2c_3 + a_5)$$