SMEFT (and beyond) at colliders

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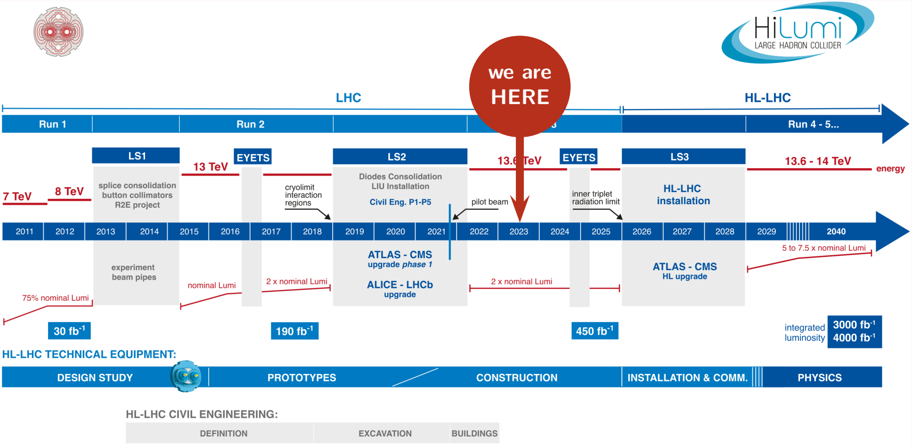
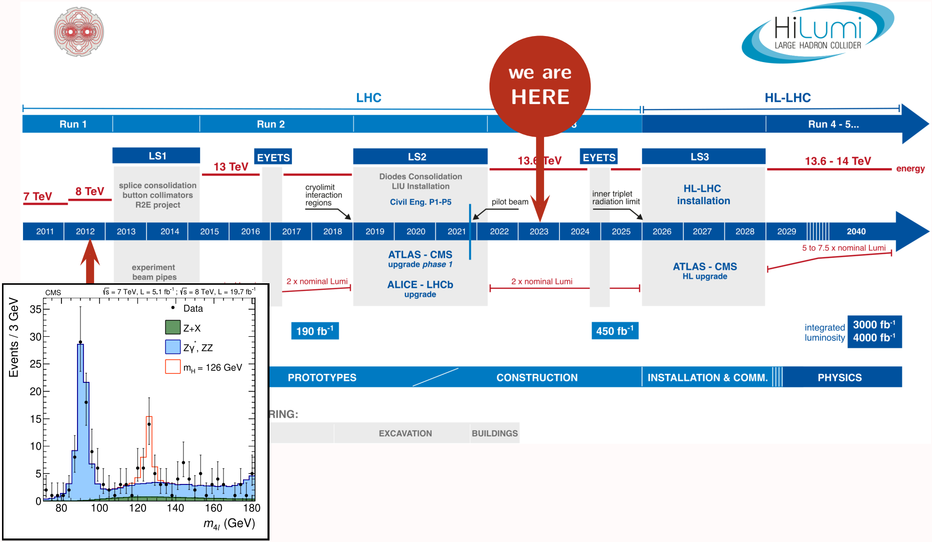
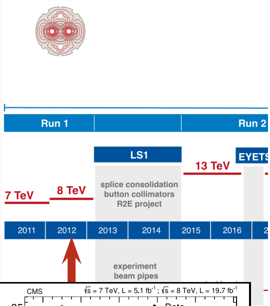
Where we are - LHC perspective

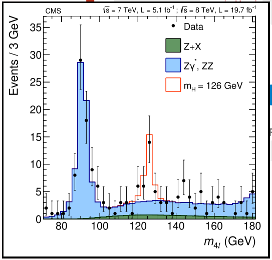


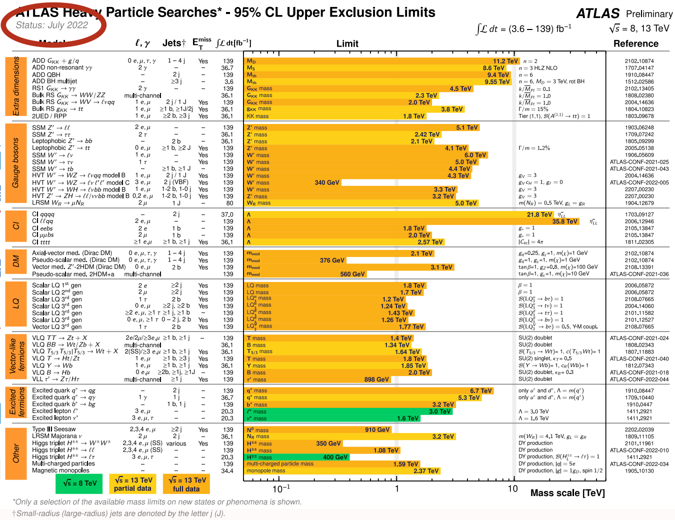
Where we are - LHC perspective



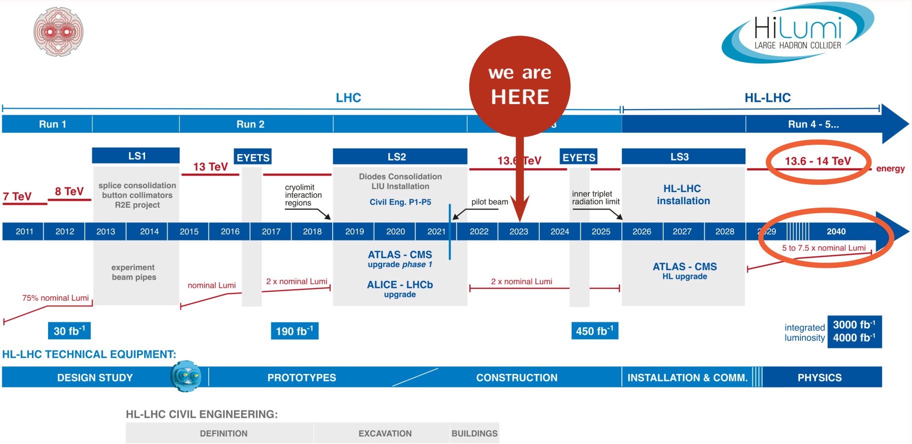
Where we are - LHC perspective







Where we are - LHC perspective



> 95% of LHC data still has to be collected!

Targeting non-resonant signals of new physics

no clear indications of specific BSM scenarios

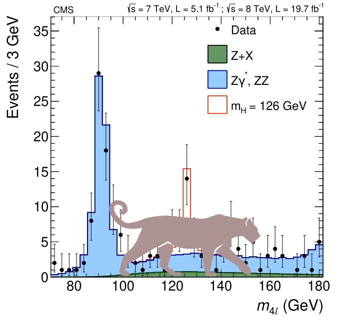
+

strong reduction of statistical uncertainties

↓

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

CMS-HIG-13-002



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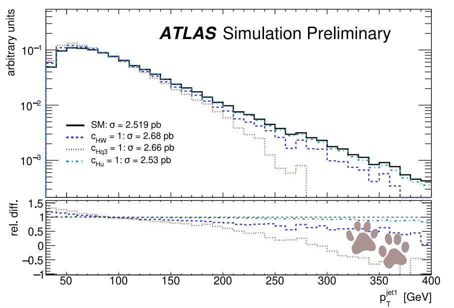
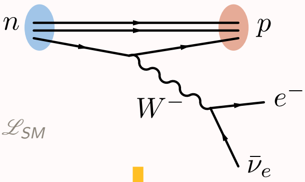


ATL-PHYS-PUB-2019-042

Effective Field Theories

Classic example:
Fermi Theory of β decay



Λ

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

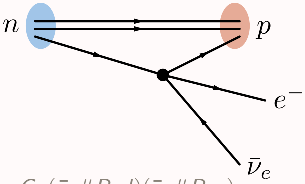
E

Full theory

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

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

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

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

Effective Field Theories

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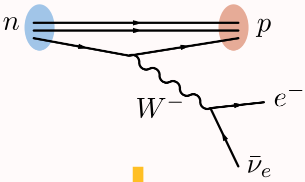
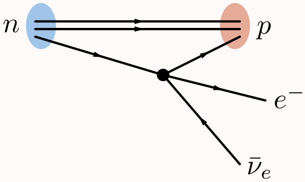
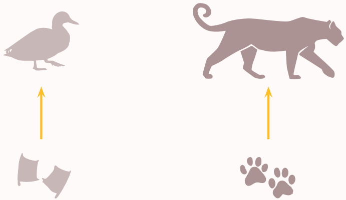


$q^2 < m_N^2 \ll m_W^2$



Bottom-up paradigm

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



EFT $\equiv$ fields+symmetries at E $= \mu$
constructed as a self-consistent theory
→ no reference to UV model
→ couplings: free parameters

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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi \widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi \widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I\gamma^\mu q_r)$
$Q_{\varphi \widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi \widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

SMEFT at $d=6$: the Warsaw basis

Grzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884

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

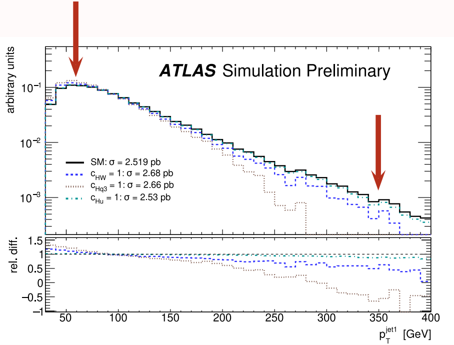
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	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 $\sim \frac{v^2}{\Lambda^2} = \frac{v^2 g_{UV}}{M^2}$. $\quad g_{UV} \simeq 1, \quad M \simeq 2\,\mathrm{TeV} \rightarrow$ 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 a deviation, we interpret it correctly

- 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

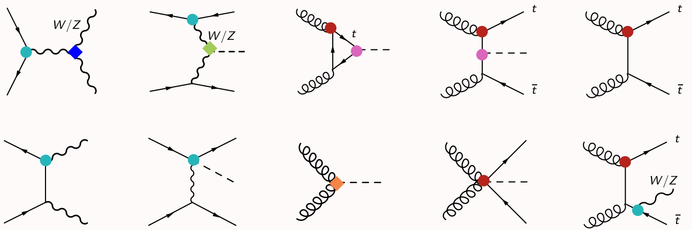
The need for global analyses

$\mathscr{L}_6$ has **2499** parameters in the most general case

$\mathcal{O}(\mathbf{100})$ with flavor symmetries and CP [more on this later]

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

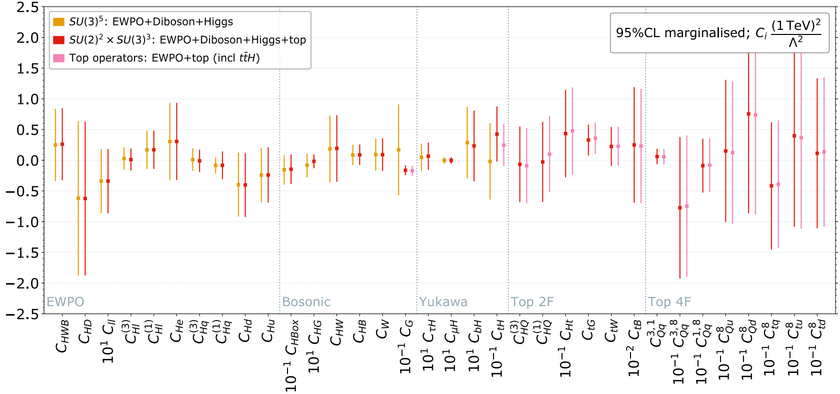
map to other theories

- 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

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



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

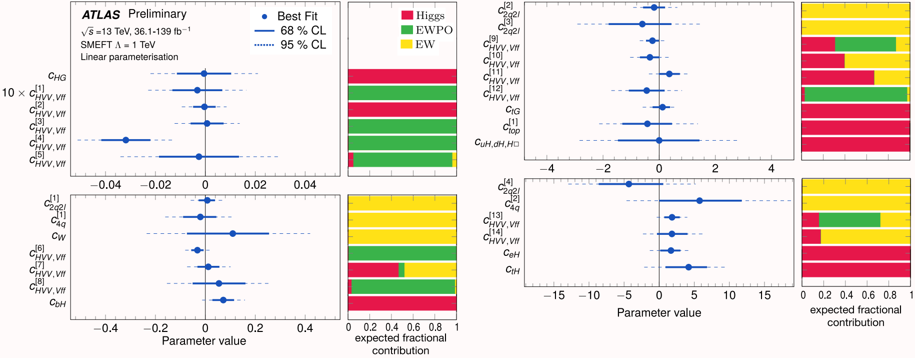
- first attempt at combining **across groups + across experiments**
- will use public data. code will be open access
- main goal: sync predictions and analysis frameworks across ATLAS and CMS

Example: latest ATLAS combination

ATL-PHYS-PUB-2022-037

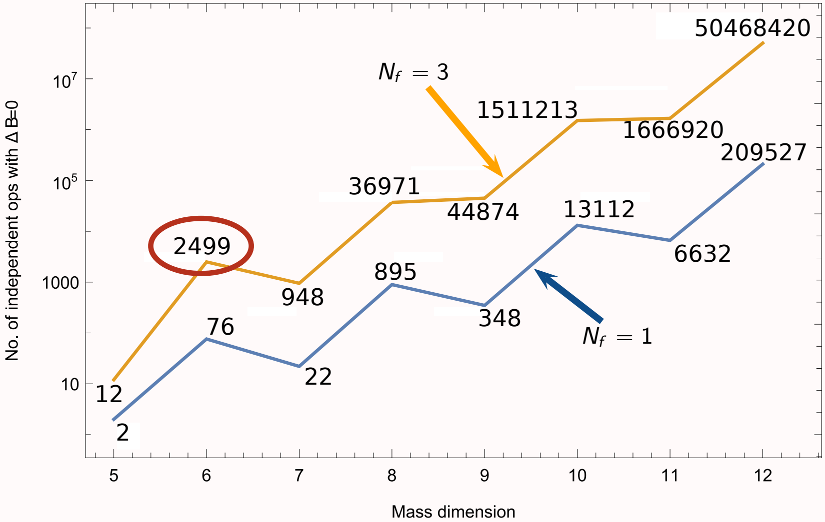
- predictions: $gg \to h, gg \to zh, h \to gg$: MC NLO QCD SMEFT@NLO: Degrande et al 2008.11743
  $h \to \gamma\gamma$: NLO EW Dawson,Giardino 1807.11504. also: Hartmann,Trott,Passarino,Dedes,Rosiek...
  rest: MC LO SMEFTsim v3: IB 2012.11343

- Principal Component Analysis constrains fit eigenvectors



A very large parameter space

Henning,Lu,Melia,Murayama 1512.03433



A very large <u>flavorful</u> parameter space

Classification within Warsaw basis

Grzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884

Class	CP	$\not{CP}$	Total
X^3	2	2	4
$\varphi^6 + \varphi^4 D^2$	3	-	3
$\varphi^2 X^2$	4	4	8
$\varphi^2 \psi^2$	27	27	54
$\varphi X \psi^2$	72	72	144
$\varphi^2 D \psi^2$	51	30	81
$(\bar{L}L)(\bar{L}L)$	171	126	297
$(\bar{R}R)(\bar{R}R)$	255	195	450
$(\bar{L}L)(\bar{R}R)$	360	288	648
$(\bar{L}R)(\bar{R}L)$	81	81	162
$(\bar{L}R)(\bar{L}R)$	324	324	648

- most parameters from **fermionic** terms
- **flavor** has dramatic impact on counting

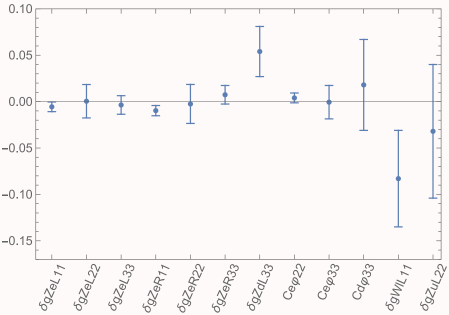
Examples:

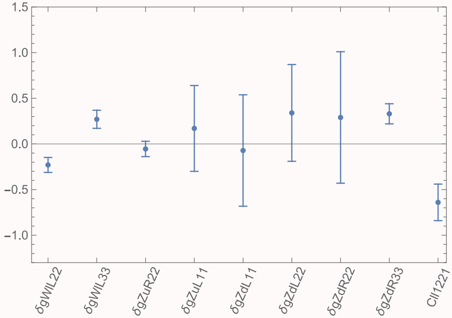
$B_{\mu\nu}(\bar{q}_i\sigma^{\mu\nu}d_j)\varphi$	9 + 9
$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_i\gamma^\mu u_j)$	6 + 3
$(\bar{l}_i\gamma_\mu l_j)(\bar{l}_k\gamma^\mu l_l)$	27 + 18
$(\bar{e}_i\gamma_\mu e_j)(\bar{u}_k\gamma^\mu u_l)$	45 + 36
$(\bar{l}_i^l e_j)(\bar{d}_k q_l^l)$	81 + 81

Flavor sensitivity from EWPO

Falkowski,Straub 1911.07866
also: Efrati,Falkowski,Soreq 1503.07872

- EWPO + Higgs signal strengths + diboson (no top) → **31** parameters
- no FCNC, but each flavor treated independently
- linear parameterization





however, not easily generalizable to LHC observables.
4-fermion operators harder to target.

Flavor symmetries

many good reasons:

Bordone,Catà,Feldmann 1910.02641
Faroughy,Isidori et al 2005.05366
Greljo,Palavrić,Thomsen 2203.09561
IB 2012.11343

- ✔ much fewer free parameters
- ✔ LHC cannot distinguish all quark flavors anyway
- ✔ FV/FUV/FCNC are not a primary target
- ✔ implement a possible flavor power counting

in practice

- some flavor combinations are **forbidden**
- some combinations are allowed but **not independent**

	no sym.	$U(3)^5$	
$B_{\mu\nu}(\bar{q}_i\sigma^{\mu\nu}d_j)\varphi$	9 + 9	0	-
$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_i\gamma^\mu u_j)$	6 + 3	1	δ_{ij}
$(\bar{l}_i\gamma_\mu l_j)(\bar{l}_k\gamma^\mu l_l)$	27 + 18	2	$\delta_{ij}\delta_{kl}, \delta_{il}\delta_{kj}$
$(\bar{e}_i\gamma_\mu e_j)(\bar{u}_k\gamma^\mu u_l)$	45 + 36	1	$\delta_{ij}\delta_{kl}$
$(\bar{l}_i^I e_j)(\bar{d}_k q_l^I)$	81 + 81	0	-

Flavor power counting

in general, the flavor symmetry is always broken by some **spurion**
this is needed to allow the SM flavor structure

spurion insertions are suppressions → a “flavor expansion” on top of the EFT one

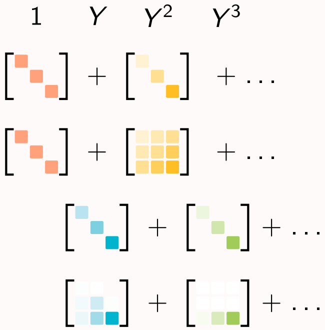
Example: **MFV** $= U(3)^5$ broken by SM Yukawas as spurions [up basis]

$$(\bar{u}_i\gamma^\mu u_j) \quad C_{ij} = C^{(0)}\delta_{ij} + C^{(2)}(Y_u^\dagger Y_u)_{ij} + \dots$$

$$(\bar{d}_i\gamma^\mu d_j) \quad C_{ij} = C^{(0)}\delta_{ij} + C^{(2)}(Y_d^\dagger Y_d)_{ij} + \dots$$

$$(\bar{q}_i\tilde{\varphi} u_j) \quad C_{ij} = C^{(1)}(Y_u)_{ij} + C^{(3)}(Y_u Y_u^\dagger Y_u)_{ij} + \dots$$

$$(\bar{q}_i\varphi d_j) \quad C_{ij} = C^{(1)}(Y_d)_{ij} + C^{(3)}(Y_d Y_d^\dagger Y_d)_{ij} + \dots$$



Several symmetry options

less restrictive symmetry → more independent parameters

adapted from Greljo,Palavric,Thomsen 2203.09561

SMEFT $\mathcal{O}(1)$ terms (dim-6, $\Delta B = 0$)		Lepton sector									
		MFV_L		$\mathrm{U}(2)^2\times\mathrm{U}(1)^2$		$\mathrm{U}(2)^2$		$\mathrm{U}(1)^3$		No symm.	
Quark sector	MFV_Q	41	6	59	6	62	9	93	18	207	132
	$\mathrm{U}(2)^2\times\mathrm{U}(3)_d$	72	10	95	10	100	15	140	28	281	169
	$\mathrm{U}(2)^3\times\mathrm{U}(1)_{d_3}$	86	10	111	10	116	12	158	28	305	175
	$\mathrm{U}(2)^3$	93	17	118	17	124	23	168	38	321	191
	No symmetry	703	570	756	591	786	621	906	705	1350	1149

not all of them enter observables of interest!

typical counts for current H + EW + top fits: between 25 and 50

largely depends on:

- processes included
- tree / loop
- linear / quadratic

state-of-the-art fitting tools can handle 30 – 35 simultaneously

Automation

- `SMEFTflavor` : construction of full set of invariants in Warsaw basis, imposing arbitrary flavor symmetries with spurions Greljo,Palavric,Thomsen 2203.09561 github.com/aethomsen/SMEFTflavor

- UFO models for Monte Carlo simulations already implement:

$U(3)^5$	`SMEFTsim U35, MFV`
$U(2)^3_{q,u,d} \times U(3)^2_{l,e}$	`SMEFTsim topU3l`
$U(2)^3_{q,u,d} \times U(1)^3_{l+e}$	`SMEFTsim top, dim6top`
$U(2)^2_{q,u} \times U(3)_d \times U(1)^3_{l+e}$	`SMEFT@NLO`

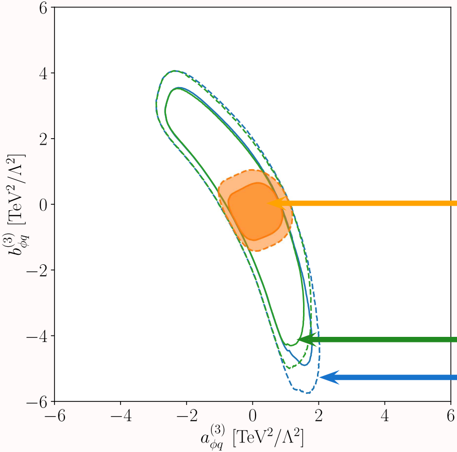
SMEFTsim: IB,(Jiang,Trott) 1709.06492, 2012.11343
SMEFT@NLO: Degrande,Durieux,Maltoni,Mimasu,Vryonidou,Zhamg 2008.11743
dim6top: Durieux,Zhang 1802.07237

→ allow to simulate directly in terms of parameters in symmetric $\mathscr{L}_6$
→ typically interfaced to MadGraph5_aMC@NLO

Combining top constraints with B physics

Bruggisser, Schäfer, vanDyk, Westhoff 2101.07273
also: Aoude, Hurth, Renner, Shepherd 2003.05432
+ **Kevin's talk**

$C^{(3)}_{\phi q} = a^{(3)}_{\phi q}\,\mathbb{1} + b^{(3)}_{\phi q}\,(Y_u Y_u^\dagger)$ in up basis $\qquad O^{(3)}_{\phi q} = (\phi^\dagger i \overleftrightarrow{D}^I_\mu \phi)(\bar{q}\gamma^\mu \tau^I q)$



$Z\bar{t}t$: $\sim (a + b\,y_t^2)$
$Z\bar{b}b$: $\sim (a + b\,(VY_u^2V^\dagger)_{33})$
$W\bar{t}b$: $\sim (a + b\,y_t^2)V_{33}$
$Z\bar{b}s$: $\sim b\,(VY_u^2V^\dagger)_{32}$
$W\bar{b}c$: $\sim (a + b\,y_c^2)V^*_{13}$
...

top + $(B_s \to \mu^+\mu^-)$ + $(B \to X_s\gamma)$

top + $(B_s \to \mu^+\mu^-)$

top

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 already made on both TH and EXP sides
- Program is challenging! many parameters and measurements needed
- Flavor has a major role
  - most parameter space is **flavorful**
  - difficult to break down, especially at hadron colliders
  - so far **H+EW+top** fits separate from **flavor physics** constraints
  - ambitious goal for future:
    one "universal" likelihood combining both sectors