The SMEFT program at the LHC: status and prospects

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What's an Effective Field Theory?

a field theory valid in a regime $\delta \ll 1$

$\updownarrow$

Taylor expansion in δ

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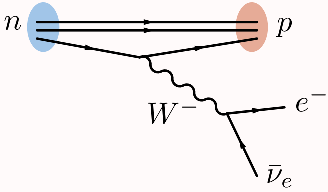
↕

Taylor expansion in $\boldsymbol{\delta}$

Classic example: **Fermi's interaction** for β-decays



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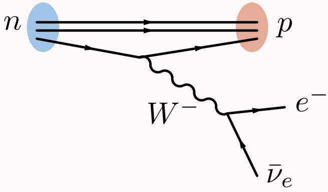
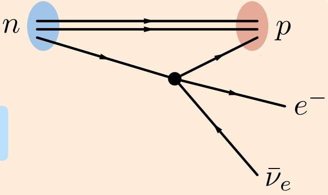


$$\delta = \frac{E}{m_W}$$



$$\propto G_F \sim \frac{1}{m_W^2} + \mathcal{O}\left(\frac{E^4}{m_W^4}\right)$$

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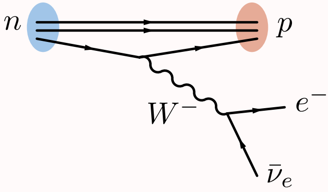
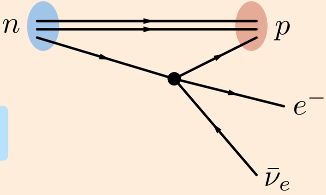


$\delta = \frac{E}{m_W}$

irrelevant / not needed

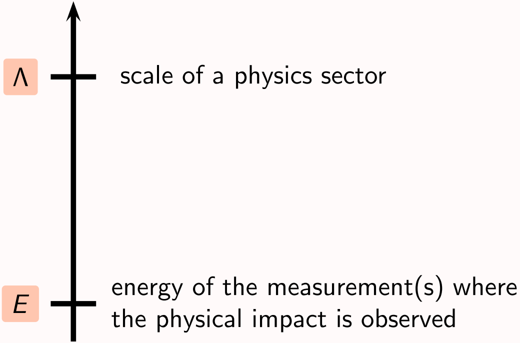


$$\propto G_F \sim \frac{1}{m_W^2} + \mathcal{O}\left(\frac{E^4}{m_W^4}\right)$$

EFTs for unknown UV sectors: bottom-up

main strength: can be constructed order-by-order in δ
without knowing the underlying physics
→ free parameters to be fixed from data

Fermi theory: the expansion parameter is a *scale separation* $\delta = \dfrac{E}{\Lambda} \ll 1$



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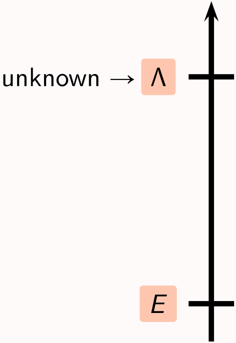

assuming $\Lambda \gg E$, define dynamical fields + symmetries
construct **all** allowed terms up to some power in E/Λ

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Fermi theory: the expansion parameter is a *scale separation* $\delta = \dfrac{E}{\Lambda} \ll 1$

unknown $\rightarrow$ Λ

$1/\sqrt{G_F} \sim 300\,\mathrm{GeV}$
LH currents, $\not{CP}$...

infer properties of underlying physics

measure EFT parameters G_F

E

assuming $\Lambda \gg E$, define dynamical fields + symmetries
construct **all** allowed terms up to some power in E/Λ

SMEFT

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

→ expansion in **canonical dimensions** d (Taylor series in v/Λ or E/Λ)

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

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

C_i = Wilson coefficients

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

At each order, $\mathcal{O}_i^{(d)}$ form a complete, non-redundant **basis**

SMEFT describes $\sim$ **any beyond-SM physics living at $\Lambda \gg v$**
(nearly decoupled)

$\mathcal{L}_6$: 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}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

$\mathcal{L}_6$: the Warsaw basis

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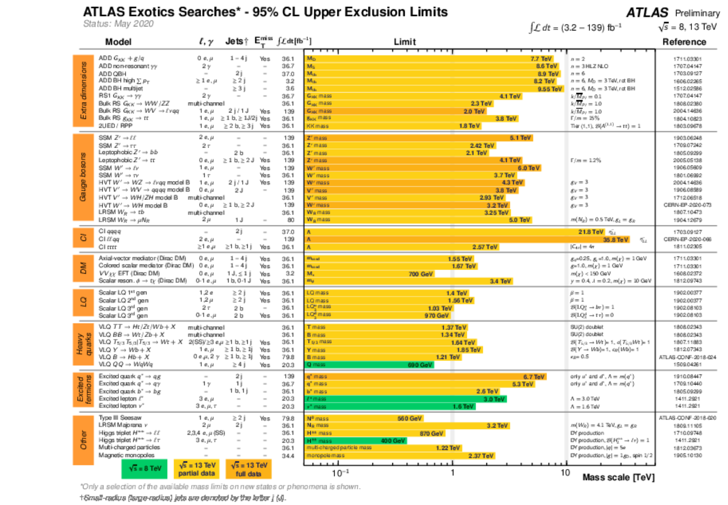
$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$		

SMEFT for indirect searches at LHC

new physics seems indeed
nearly decoupled



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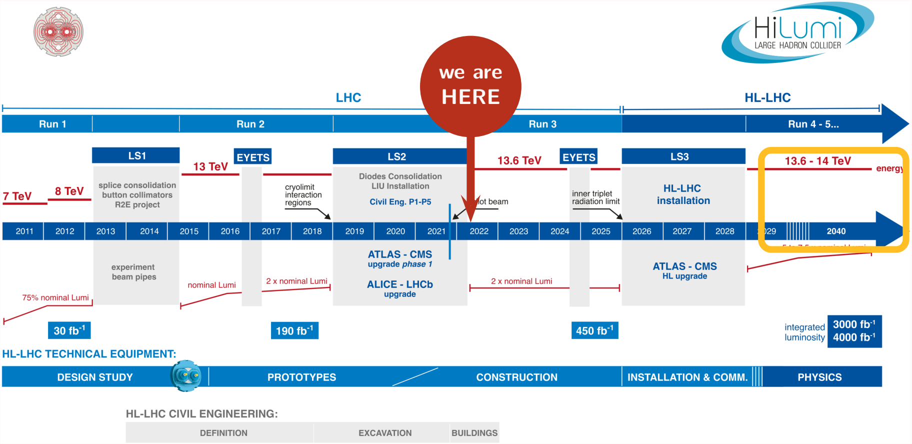
collider physics is entering a precision era



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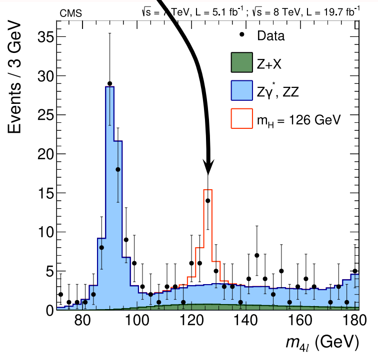
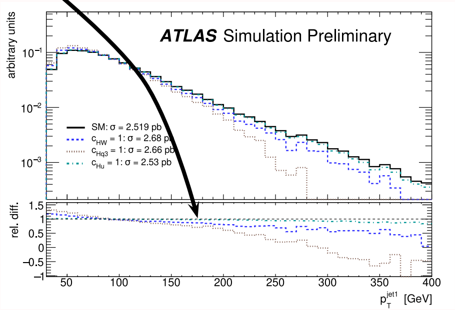
indirect searches
more and more competitive with direct ones

direct



CMS-HIG-13-002

indirect



ATL-PHYS-PUB-2019-042

SMEFT for indirect searches at LHC

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more and more competitive with direct ones

SMEFT-based searches at the LHC are crucial

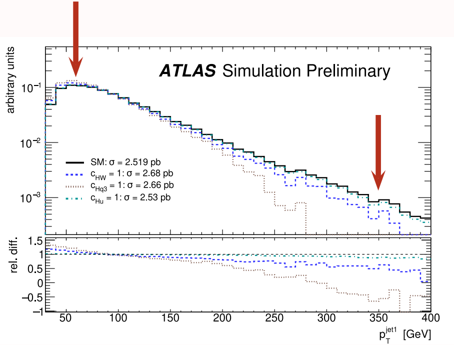
- a proper QFT:
  renormalizable order by order, well-defined radiative corrections and RGE
- minimal commitment to a specific UV
- systematically includes all BSM effects, compatible with assumptions
- universal language for data interpretation: can connect to other experiments

Challenges

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

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

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



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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%

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

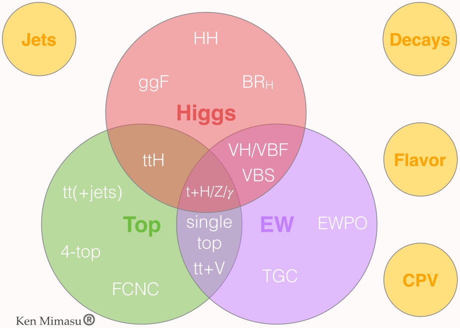
Combine, combine, combine

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

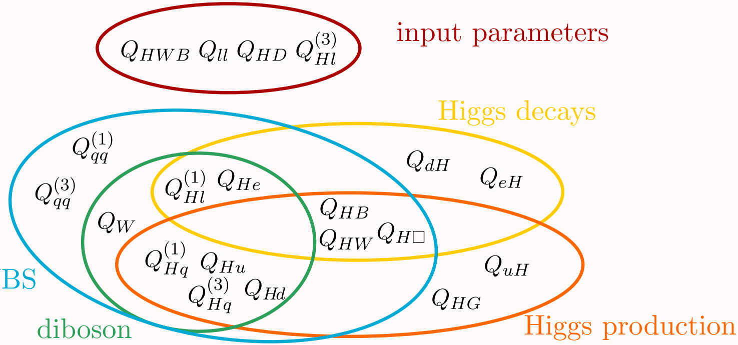
- to access as many operators as we can
- to avoid bias in interpretation
  i.e. miss a potential deviation or assign it to the wrong op.



SMEFT fits @LHC

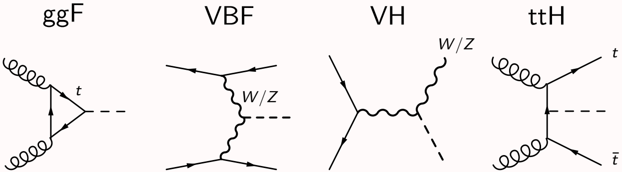
Example: SMEFT for EW and Higgs sectors

leading Warsaw basis operators in Higgs and EW processes: ~ 20



+ CP odd + flavor indices + others entering through loop corrections ...

SMEFT in Higgs production



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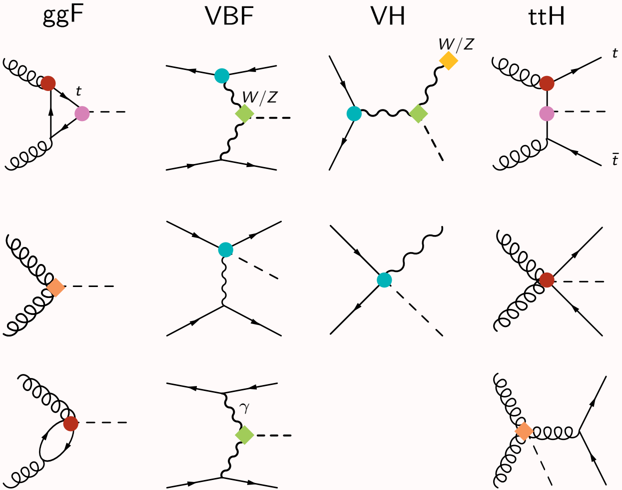
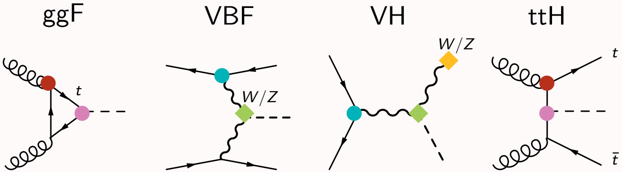


SMEFT in Higgs production



dim 6 SMEFT predictions

$$|\mathcal{A}_{\rm SMEFT}|^2 = \left[|\mathcal{A}_{SM}|^2 + \sum_i \frac{C_i}{\Lambda^2} \mathcal{A}_i \mathcal{A}_{SM}^\dagger + \sum_{ij} \frac{C_i C_j^*}{\Lambda^2} \mathcal{A}_i \mathcal{A}_j^\dagger \right] \times K_{SM}$$

linear quadratics

Simplified Template Cross Sections (STXS)

Higgs combinations:

$$n_k = \mathcal{L}_k \sum_{i,f} (\sigma_i \cdot B_f)(\varepsilon \cdot A)_{if}$$

lumi ($\mathcal{L}_k$)

prod xs $i \to h$ (σ_i)

decay BR $h \to f$ (B_f)

efficiency (ε)

acceptance (A)

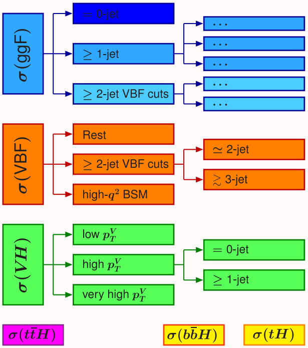
ATLAS HIGG-2018-28
ATLAS-CONF-2020-053

Brivio,Corbett,Trott 1906.06949

fit to n_k $\quad\rightarrow\quad$ $(\sigma_i \cdot B_f)$ for defined i, f categories.

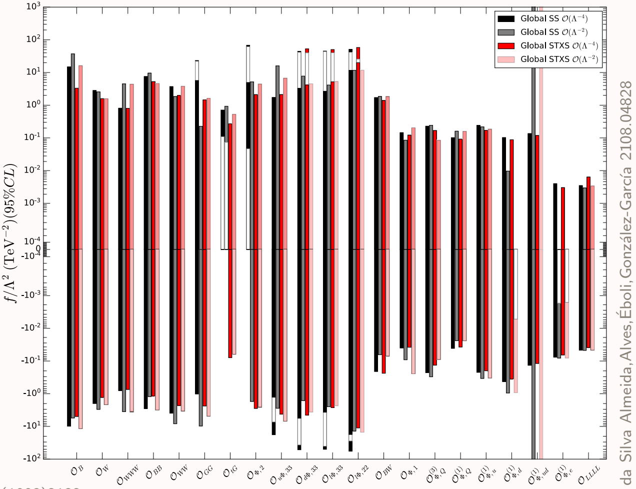
STXS define **production categories**:
unfolded XS organized in "macro-bins"
$\rightarrow$ minimize selection cuts + modeling bias
better reproducibility

- defined in stages: finer and finer bins
- include $f = \{\gamma\gamma,\, 4\ell,\, 2\ell 2\nu,\, \tau\tau,\, b\bar{b}\}$



LesHouches 2015 1605.0469, 2019 2003.01700
LHCHXSWG 1610.0792,
Berger et al. 1906.02754

typically: EWPO from LEP
+ diboson measurements (LEP2/LHC)
+ Higgs production/decay rates (STXS)

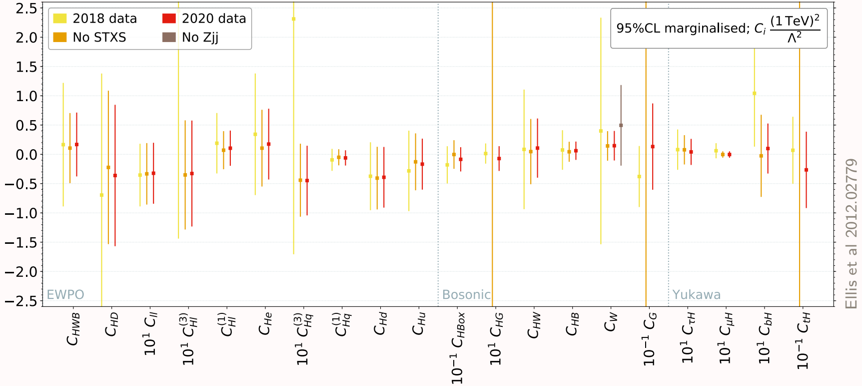


HISZ basis

Hagiwara et al PRD48(1993)2182

Higgs + EW fit results

typically: EWPO from LEP
+ diboson measurements (LEP2/LHC)
+ Higgs production/decay rates (STXS)



Warsaw basis Grzadkowski et al 1008.4884

Extensive literature, covering many sectors

- **Higgs + EW**

  Alves et al 1211.4580,1805.11108, Butter et al 1604.03105
  Corbett et al 1509.01585, de Blas et al 1608.01509,1710.05402,1910.14012
  Ellis,Murphy,Sanz,You 1803.03252, Biekötter,Corbett,Plehn 1812.07587
  da Silva Almeida et al 1812.01009, 2108.04828
  Dawson,Homiller,Lane 2007.01296, Dawson,Giardino 2201.09887

- **top**

  Englert et al 1506.08845,1512.05560,1901.03164 + ICHEP2020 proc.
  Cirigliano,Dekens,deVries,Mereghetti 1605.04311 Hartland et al 1901.05965
  Durieux,Irles,Miralles,Peñuelas,Pöschl 1907.10619, IB et al 1910.0306
  Miralles et al 2107.13917

- **Higgs + EW + top**

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

- **top + B physics**

  Bißmann,(Erdmann),Grunwald,Hiller,Kröninger 1909.13632, 2012.10456
  Bruggisser,Schäfer,Westhoff,VanDyk 2101.07273

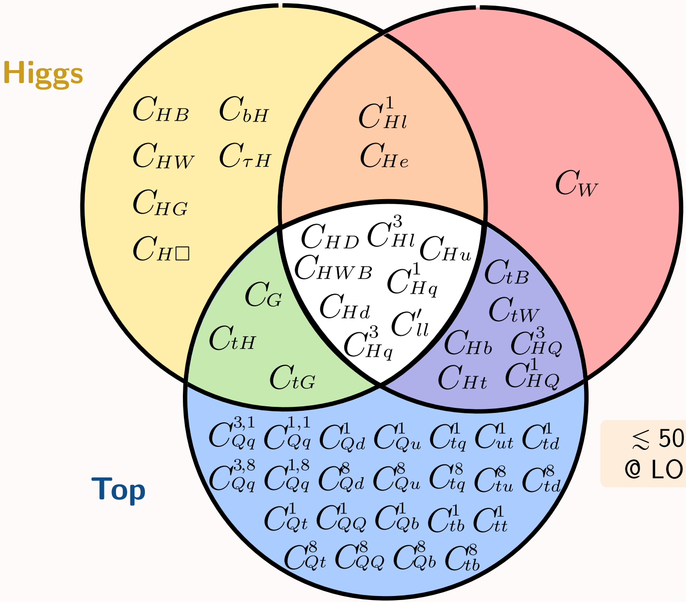
- **diboson (+ VBS)**

  Baglio,Dawson,Homiller,(Lane,Lewis) 1812.00214, 1909.11576, 2003.07862
  Ethier,Gomez-Ambrosio,Magni,Rojo 2101.03180
  Bellan,Boldrini,Brambilla,Brusa,IB et al 2108.03199

references list incomplete!

Some general features

- currently up to 20 – 30 parameters simultaneously
- most often: frequentist likelihood (χ^2) analysis
  replica models / toys also used
  moving to bayesian inference for many parameters
- most SMEFT predictions are at tree level
  NLO QCD most used for top physics and $gg \to h$.
  available also for diboson processes, automated in MG5.
  NLO EW harder. not automated.
  available only for EWPO and most Higgs decays
- results typically reported in multiple setups: linear/quadratic, LO/NLO . . .
- information geometry (Fisher information matrix), Partial Component Analysis used to show multi-dimensional information, determine impact of individual constraints



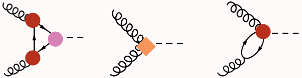
$\lesssim$ 50 parameters
@ LO interference

Combining Higgs and top

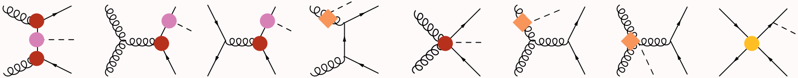
1. top operators → Higgs / EW processes
2. non-top operators → top processes

Grazzini,Ilnicka,Spira,(Wiesemann) 1612.00283, 1806.08832,
(Maltoni),Vryonidou,Zhang 1607.05330, 1804.09766
Deutschmann,Duhr,Maltoni,Vryonidou 1708.00460

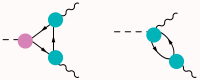
$gg \to h$



$t\bar{t}h$



$h \to \gamma\gamma$



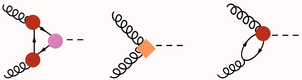
- C_{tH} operator → $t\bar{t}H$ vertex
- $C_{tG} \to t\bar{t}G + t\bar{t}GG + t\bar{t}GH + t\bar{t}GGH$
- $C_{tW}, C_{tB}, C_{HQ}^{(3)}, C_{HQ}^{(1)}, C_{Ht} \to t\bar{t}V + t\bar{t}VH$

Combining Higgs and top

1. **top operators → Higgs / EW processes**
2. non-top operators → top processes

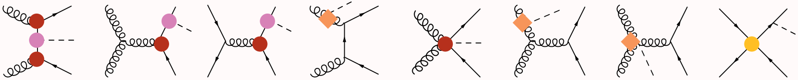
Grazzini,Ilnicka,Spira,(Wiesemann) 1612.00283, 1806.08832,
(Maltoni),Vryonidou,Zhang 1607.05330, 1804.09766
Deutschmann,Duhr,Maltoni,Vryonidou 1708.00460

$gg \to h$



$\leftrightarrow$ $t\bar{t}$
$\swarrow\!\!\nearrow$

$t\bar{t}h$



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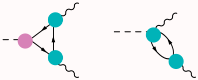
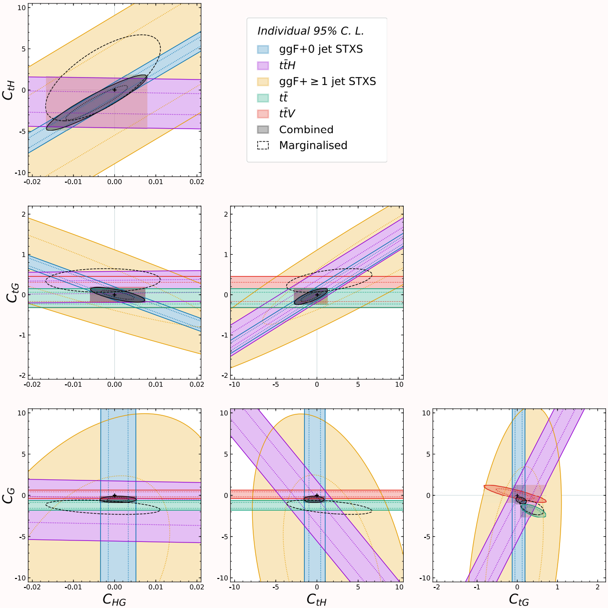


$\leftrightarrow$ $t\bar{t}V$, single-t

- C_{tH} operator $\to t\bar{t}H$ vertex
- $C_{tG} \to t\bar{t}G + t\bar{t}GG + t\bar{t}GH + t\bar{t}GGH$
- $C_{tW}, C_{tB}, C_{HQ}^{(3)}, C_{HQ}^{(1)}, C_{Ht} \to t\bar{t}V + t\bar{t}VH$

$\leftrightarrow$ interplay with C_{HG}
$\swarrow\!\!\nearrow$

Example: complementarities in top + Higgs



Ellis, Madigan, Mimasu, Sanz, You 2012.02779

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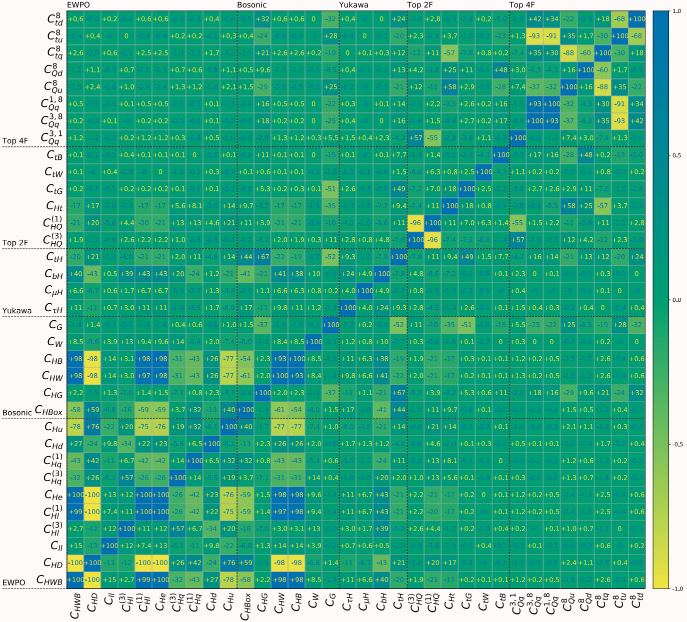

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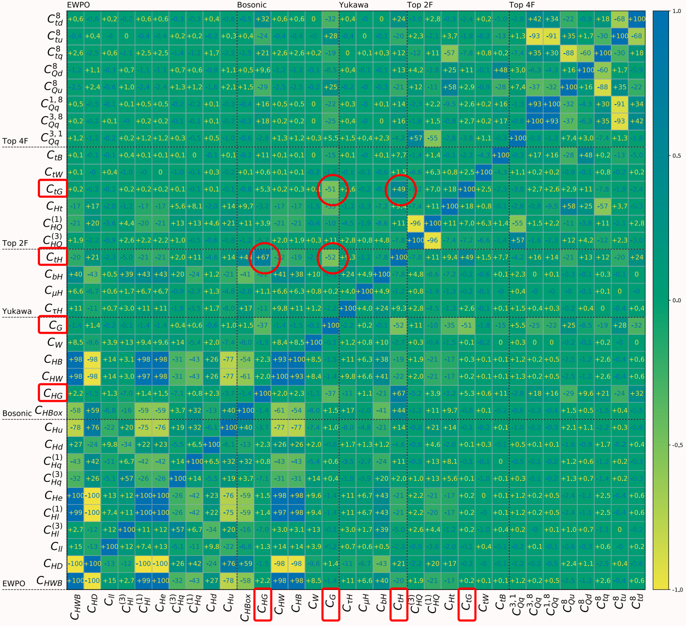
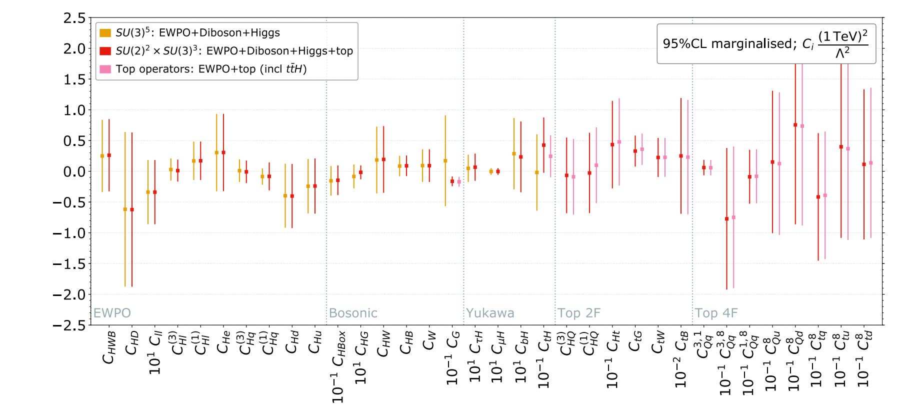


Ellis,Madigan,Mimasu,Sanz,You 2012.02779

Top + EW + Higgs: global results

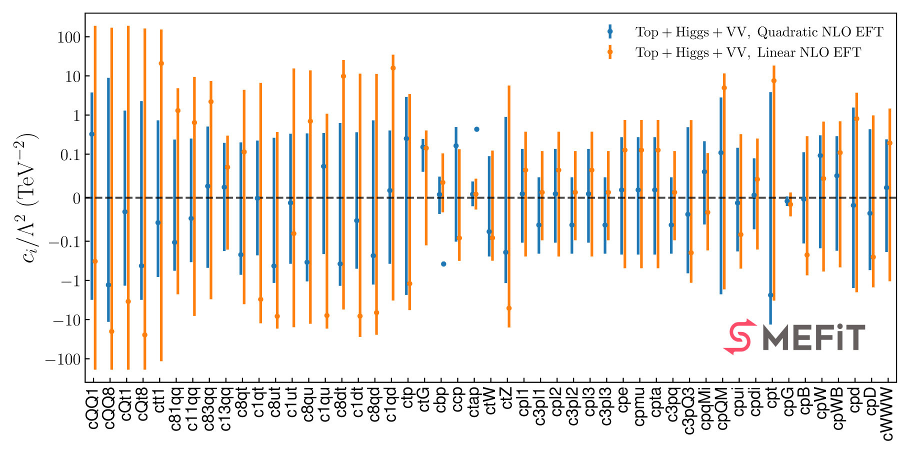
Ellis, Madigan, Mimasu, Sanz, You 2012.02779



34 param, linear, LO + ggH

Top + EW + Higgs: global results

Ethier,Maltoni,Mantani,Nocera,Rojo 2105.00006



50 param (36 indep.), linear+quadratic, NLO QCD

Where is this going?

The long-term idea (∼personal view)

EFT parameterisations for LHC measurements are **here to stay**, independently of observation of new resonances.

Will become a standard analysis procedure, to be brought to future colliders too

- the best parameterisation of **non-resonant BSM effects in shapes**
  → allows SM tests at differential level

  can be easily simulated, is theoretically consistent
  (≠ anomalous couplings, form-factors / pseudo-observables)

- will serve as **book-keeping** → LHC legacy results easily reinterpretable

- will enable combinations of LHC and non-LHC data (e.g. flavor)
  → one "universal map" of constraints on heavy-BSM

In practice: (near) future directions

1. More refined SMEFT **predictions**
   higher orders in loops and in EFT ($d \geqslant 8$), EFT in backgrounds, improved technology for predictions (Monte Carlo, ML...)
2. **Larger** global fits
   more complex processes, complementary to usual ones, bring sensitivity to new parameters (e.g. VBS, tWZ, CP violation, flavor...)
3. **Higher-quality** constraints
   more precise measurements and SM predictions, more differential measurements
4. Better **uncertainties and correlations** treatment
   better understanding of PDF/scale dependence in EFT predictions,
   ATLAS, CMS to provide more information and do combined analyses directly
   ATL-PHYS-PUB-2019-042,ATLAS-CONF-2020-053,ATLAS 2004.03447,ATLAS-CONF-2021-053,
   ATL-PHYS-PUB-2021-010,CMS-PAS-HIG-19-005,CMS 2012.04120...
5. More and more working in **(simplified) model** setups
   "make the ends meet" in top-down vs bottom-up approaches
6. Should we move to **HEFT**?
7. **What if** we see an anomaly (e.g. m_W)? What if we discover a particle?

Increasing complexity & interplay

Ex.: including more processes / loop corrections increases top-Higgs interplay

$gg \to tZj$

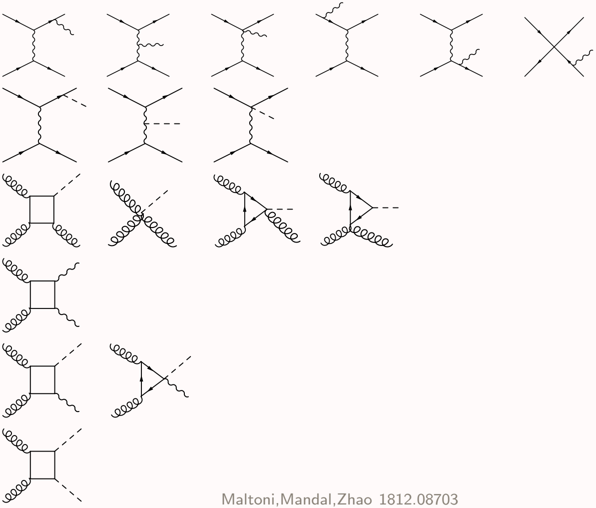
$gg \to thj$

$gg \to hg$

$gg \to ZZ, \gamma\gamma$

$gg \to Zh$

$gg \to hh$



Maltoni,Mandal,Zhao 1812.08703
Degrande,Maltoni,Mimasu,Vryonidou,Zhang 1804.07773
Hartland,Maltoni,Nocera,Rojo,Slade,Vryonidou,Zhang 1901.05965

More differential information

more statistics → finer binning
higher-dim. histograms → better shape analyses
interplay of kin. variables

one of the most important improvements for future runs.
not fully accounted for in current projections!

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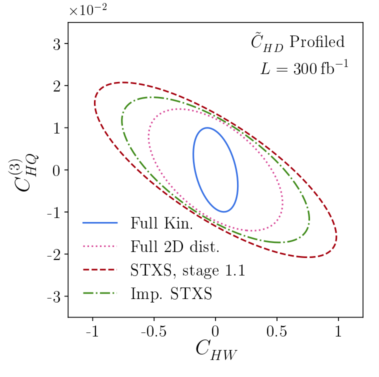

Brehmer,Dawson,Homiller,Kling, Plehn 1908.06980

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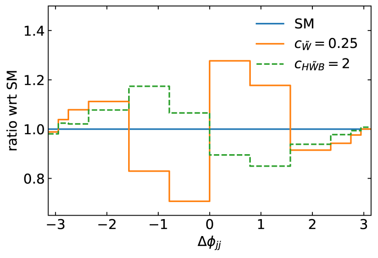

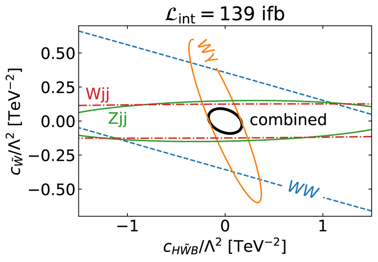

Biekötter,Gregg,Krauss,Schönherr 2102.01115

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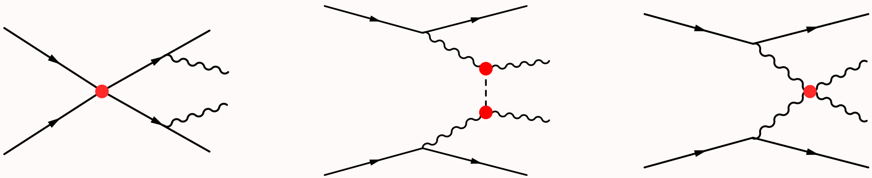
“New” processes: Vector Boson Scattering

Ethier et al 2101.03180, Bellan,Boldrini,Brambilla,Brivio et al 2108.03199

interesting from SMEFT point of view because

- gives access to $VV \to VV$ scattering, crucial probe of EWSB dynamics
- probes simultaneously $qqqq$, HVV and TGC/QGC operators
- comes in several $V_1V_2 = \{W^\pm, Z, \gamma\}$ channels → discrimination power
- bound to improve significantly at next Runs



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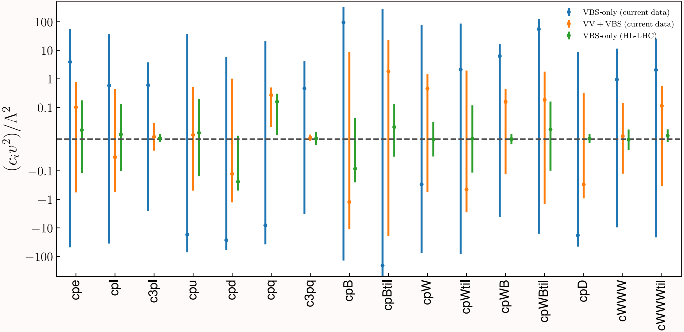
Ethier,Gomez-Ambrosio,Magni,Rojo 2101.03180



SMEFT corrections to VBS at $d = 6$

Bellan, Boldrini, Brambilla, IB, Brusa, Cetorelli, Chiusi, Covarelli, Del Tatto, Govoni, Massironi, Olivi, Ortona, Pizzati, Tarabini, Vagnerini, Vernazza, Xiao 2108.03199

- representative set of 14 operators

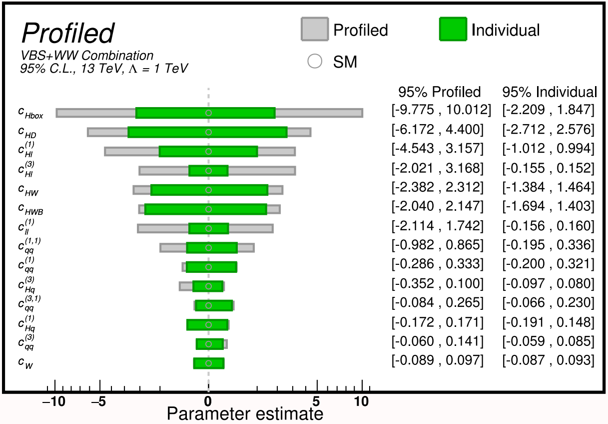
$Q_{Hl}^{(1)}$	$= (H^\dagger i\overleftrightarrow{D} H)(\bar{l}_p\gamma^\mu l_p)$	$Q_{Hl}^{(3)}$	$= (H^\dagger i\overleftrightarrow{D}^i H)(\bar{l}_p\sigma^i\gamma^\mu l_p)$
$Q_{Hq}^{(1)}$	$= (H^\dagger i\overleftrightarrow{D} H)(\bar{q}_p\gamma^\mu q_p)$	$Q_{Hq}^{(3)}$	$= (H^\dagger i\overleftrightarrow{D}^i H)(\bar{q}_p\sigma^i\gamma^\mu q_p)$
$Q_{qq}^{(1)}$	$= (\bar{q}_p\gamma_\mu q_p)(\bar{q}_r\gamma^\mu q_r)$	$Q_{qq}^{(1,1)}$	$= (\bar{q}_p\gamma_\mu q_r)(\bar{q}_r\gamma^\mu q_p)$
$Q_{qq}^{(3)}$	$= (\bar{q}_p\gamma_\mu\sigma^i q_p)(\bar{q}_r\gamma^\mu\sigma^i q_r)$	$Q_{qq}^{(3,1)}$	$= (\bar{q}_p\gamma_\mu\sigma^i q_r)(\bar{q}_r\gamma^\mu\sigma^i q_p)$
Q_{HD}	$= (H^\dagger D_\mu H)(H^\dagger D^\mu H)$	$Q_{H\Box}$	$= (H^\dagger H)\Box(H^\dagger H)$
Q_{HWB}	$= (H^\dagger\sigma^i H)W_{\mu\nu}^i B^{\mu\nu}$	Q_{HW}	$= (H^\dagger H)W_{\mu\nu}^i W^{i\mu\nu}$
Q_W	$= \varepsilon^{ijk}W_\mu^{i\nu}W_\nu^{j\rho}W_\rho^{k\mu}$	$Q_{ll}^{(1)}$	$= (\bar{l}_p\gamma_\mu l_r)(\bar{l}_r\gamma^\mu l_p)$

- 4 VBS→ ℓ processes ($W^\pm W^\pm$, W^+W^-, $W^\pm Z$, ZZ)
  + 1 VBS→ ℓJ process ($VZ, V = Z, W$)
  + 1 diboson process ($qq \to W^+W^-$)
- simulated **full 2 → 6(4)** processes, incl. non-resonant diagrams
- parton level analysis: only **expected limits**, no comparison to data yet

similar studies: Gomez-Ambrosio 1809.04189, Dedes Kozow, Szleper 2011.07367, Ethier et al 2101.03180

SMEFT in VBS: main results

- VBS constrains the most 4-quark operators and Q_W
  all these are dominated by **ssWW**



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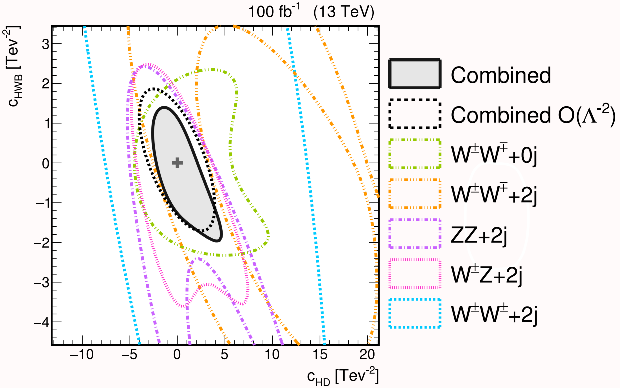

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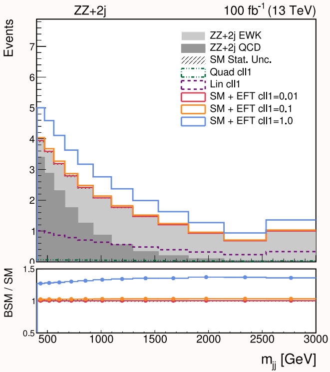

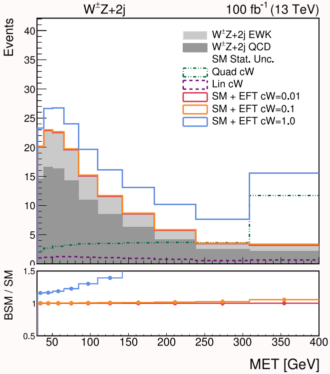

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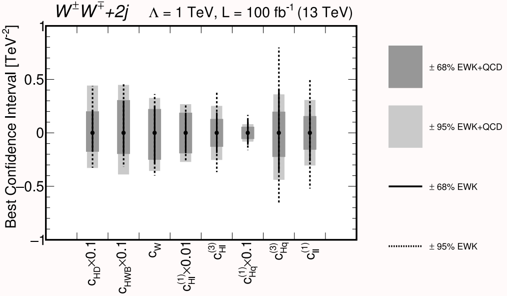
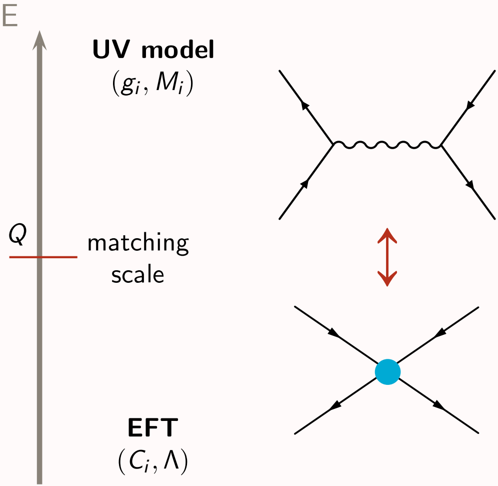
- VBS competitive with diboson for "input" operators: $Q_{HWB}, Q_{HD}, Q_{Hl}^{(3)}, Q'_{ll}$
- for several operators, constraints are dominated by **linear** terms → "safe"
- adding SMEFT corrections to QCD backgrounds never worsens the results



Matching to UV models

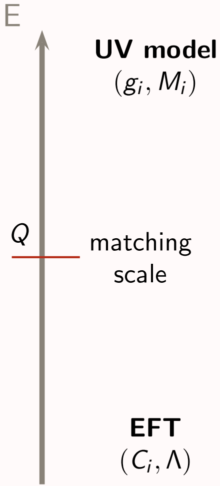


imposing all matrix elements are equal at $\mu = Q$

$\downarrow$

C_i, Λ as function of (g_i, M_i)

Matching to UV models



done efficiently up to 1-loop in UV model
via functional methods:

Covariant Derivative Expansion or

Universal One-Loop Effective Action

$$S_{eff}[\phi] = S[\Phi_0] + \frac{i}{2}\,\mathrm{Tr}\log\left(-\left.\frac{\delta^2 S}{\delta\Phi^2}\right|_{\Phi_0}\right)$$

light fields

heavy fields. $\Phi = \Phi_0 + \eta$

Henning,Lu,Murayama,deAguila,Santiago,Ellis,Quevillon,You,Fuentes-Martin,
Cohen,Lu,Zhang,Krämer,Summ,Voigt,Dittmaier,Passarino. . .

A case study: SM + Heavy Vector Triplet

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

$$\mathcal{L}_{HVT} = -\frac{1}{4} V^i_{\mu\nu} V^{i\mu\nu} - \frac{g_M}{2} V^i_{\mu\nu} W^{i\mu\nu} + \frac{m_V^2}{2} V^i_\mu V^{i\mu} + \frac{g_H}{2} V^i_\mu (H^\dagger i \overleftrightarrow{D}^{i\mu} H) + \frac{g_l}{2} V^i_\mu \bar{\ell}\gamma^\mu \sigma^i \ell + \frac{g_q}{2} V^i_\mu \bar{q}\gamma^\mu \sigma^i q + \frac{g_{VH}}{2} (H^\dagger H) V^i_\mu V^{i\mu}$$

del Aguila,de Blas,Perez-Victoria 1005.399
de Blas,Lizana,Perez-Victoria 1211.2229
Pappadopulo,Thamm,Torre,Wulzer 1402.4431

$V_i \to W'^\pm, Z'$

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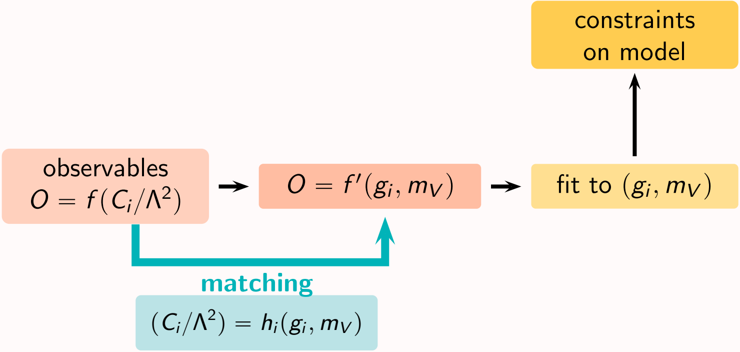

similar approach in: daSilva Almeida,Alves,Éboli,González-García 2108.04828

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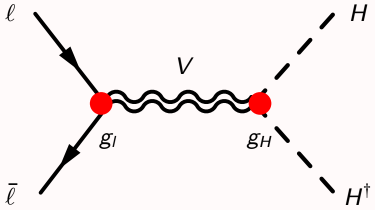
$$(C_{Hl}^{(3)})_{ij} = -\frac{g_l g_H}{4 m_V^2}\delta_{ij}$$



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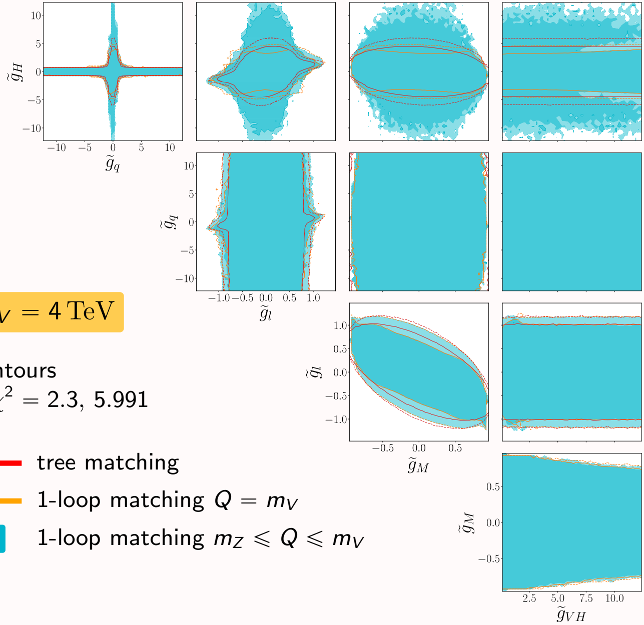
$$(C_{Hl}^{(3)})_{ij} = -\frac{g_l g_H}{4m_V^2}\delta_{ij} + \frac{1}{36864\pi^2 m_V^2}\frac{\delta_{ij}}{1-g_M^2}\Big[g_w^4(288+1531g_M^2+2989g_M^4)$$
$$+ g_w^3(2642g_Hg_M + 2340_g lg_M + 7942g_Hg_M^3 + 6732g_lg_M^3)$$
$$+ g_w^2(g_l^2(-102+3054g_M^2) + g_H^2(49+5711g_M^2))$$
$$+ g_wg_M(1080g_H^3 + 5400g_H^2g_l + 2304g_Hg_l^2 + 432g_l^3 + 1440h_Hg_{VH} + 1440g_lg_{VH})$$
$$+ g_Hg_l(1080g_H^2 - 360g_Hg_l + 432g_l^2 + 1440g_{VH} + (1+g_w^2)(2160+12600g_M^2))$$
$$+ 1440g_M^2g_{VH}\Big] + \frac{3}{3032\pi^2 m_V^2}(g_l - g_H)(g_l + g_wg_M)(Y_eY_e^\dagger)_{ij}$$

Heavy vector triplet: tree vs loop matching

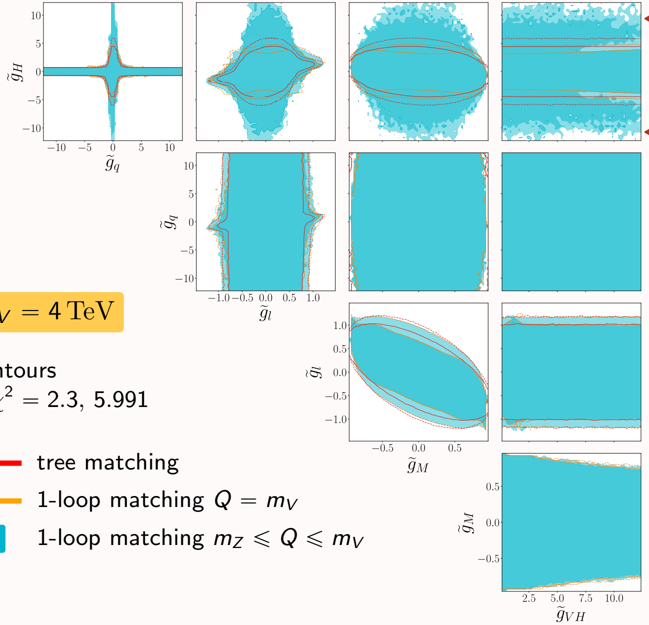


$m_V = 4\,\mathrm{TeV}$

contours
$\Delta\chi^2 = 2.3,\ 5.991$

- tree matching
- 1-loop matching $Q = m_V$
- 1-loop matching $m_Z \leqslant Q \leqslant m_V$

Heavy vector triplet: tree vs loop matching



profiling over Q worsens g_H bound by a factor 2

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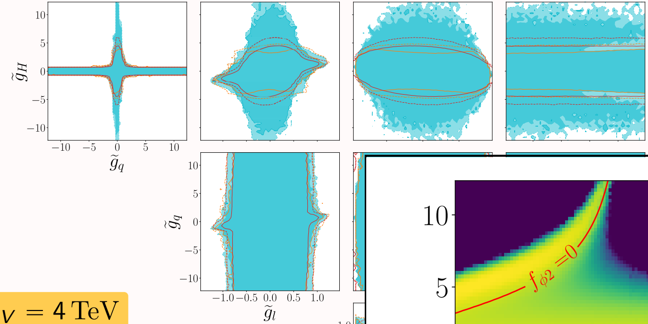

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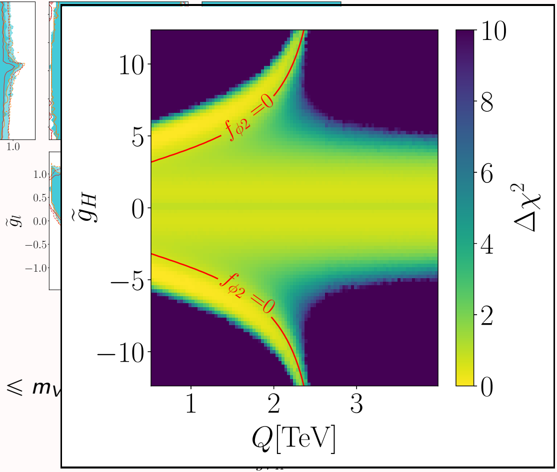
1-loop matching $Q = m_V$

1-loop matching $m_Z \leqslant Q \leqslant m_V$

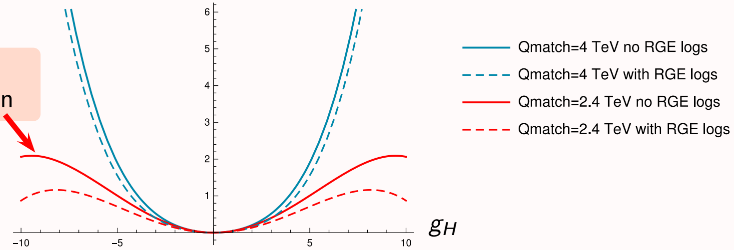


Heavy vector triplet: matching scale dependence

extra "leaves" around lines where $f_{\phi 2} \simeq 0 \simeq f_{u\phi}$

$f_{\phi 2}$ $(1/\text{TeV}^2)$ – $f_{u\phi}$ similar

tree-loop compensation

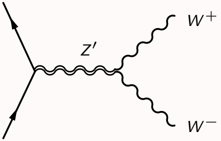


$$f_{\phi 2} \simeq 0.04\, g_H^2 \left(1 + 0.1 \log \frac{m_V}{Q}\right) + 10^{-3}\, g_H^4 \left(1 - 2.4 \log \frac{m_V}{Q}\right)$$

flips sign for $Q \lesssim m_V/1.52$

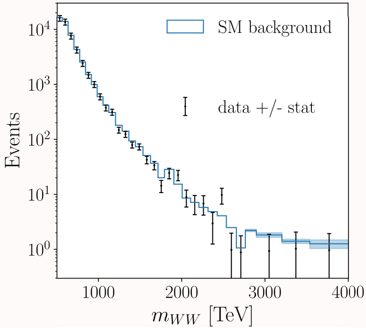
→ we treated this as a new systematic error. currently poorly understood

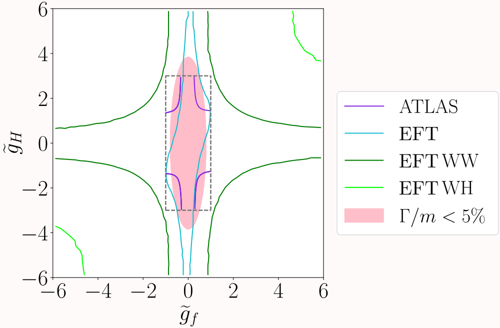
SMEFT vs direct searches: WW case



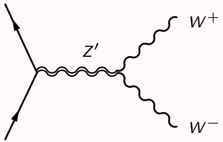
$$m_{Z'} = m_V = 4 \text{ TeV}$$

ATLAS 2004.14636





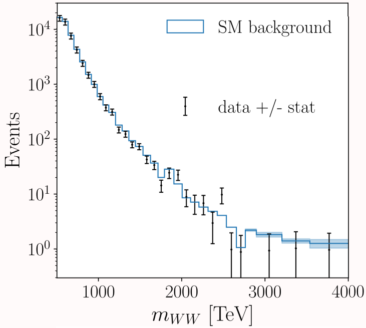
SMEFT vs direct searches: WW case

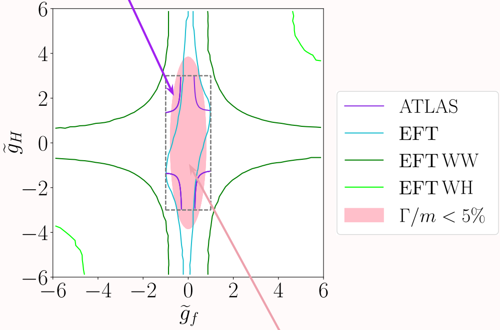


$$m_{Z'} = m_V = 4 \text{ TeV}$$

bound from
WW resonance search

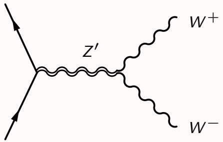
ATLAS 2004.14636





resonance s. only valid
for narrow Z'

SMEFT vs direct searches: WW case



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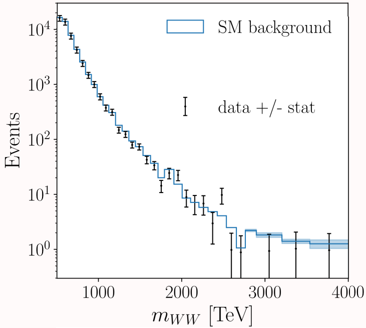
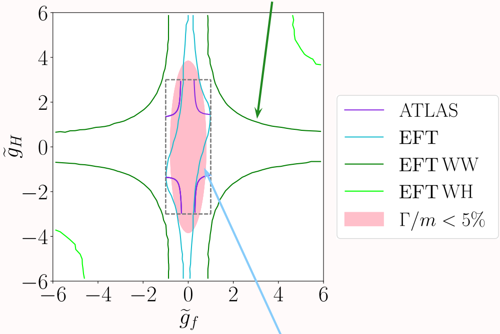
ATLAS 2004.14636

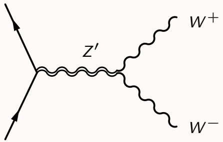


bound from EFT fit to *WW* spectrum



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

SMEFT vs direct searches: WW case



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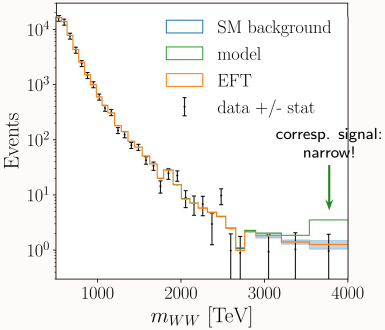
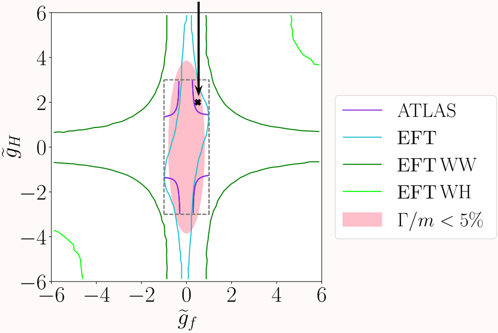
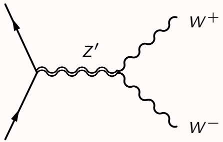


point excluded by resonance s. but allowed by EFT



SMEFT vs direct searches: WW case



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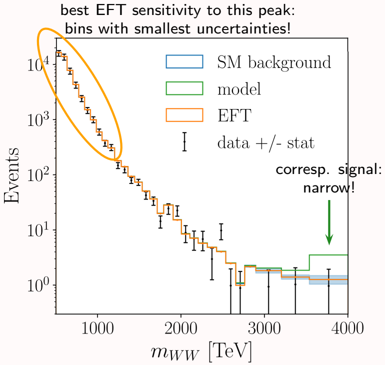
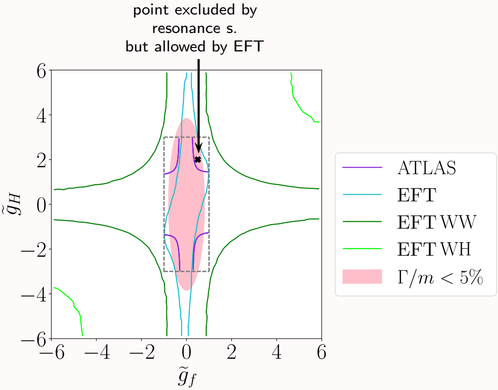
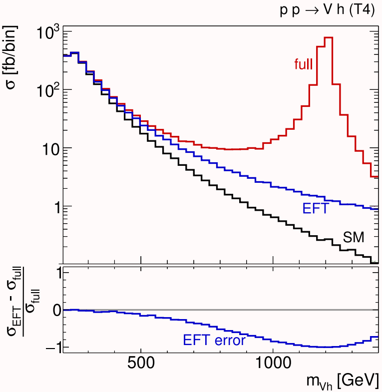


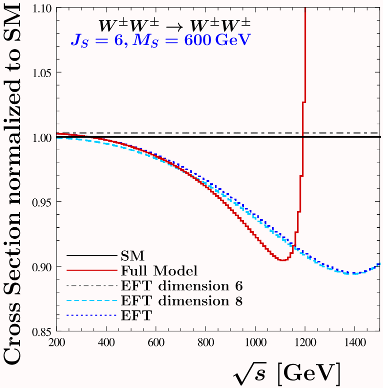


Impact of $d \geqslant 8$ operators

EFT obtained from matching to full model

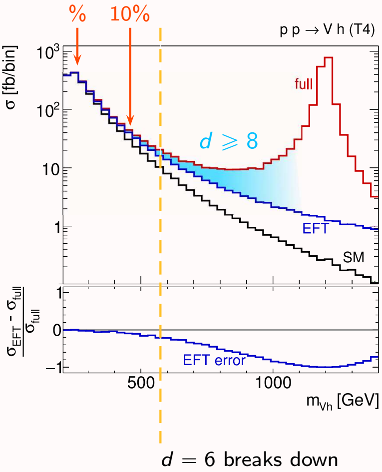
adapted from Brehmer,Freitas,López-Val,Plehn 1510.03443





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

EFT obtained from matching to full model



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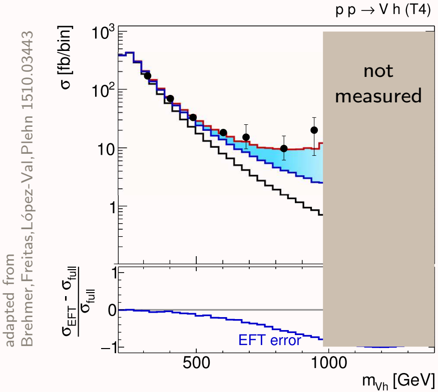


top-down: C_i fixed by matching
→ EFT not valid in high-E region

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

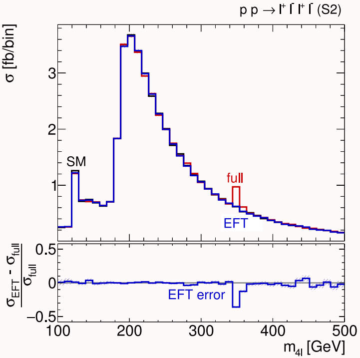
uncertainty band:
Trott et al 1508.05060,2007.00565,2106.13794,
Hays,Martin,Sanz,Setford 1808.00442
Shepherd et al 1812.07575,1907.13160

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



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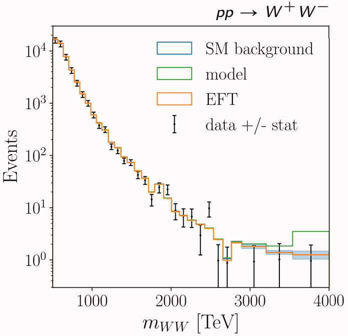


Brivio,Bruggisser,Geoffray,Kilian,Krämer,
Luchmann,Plehn,Summ 2108.01094

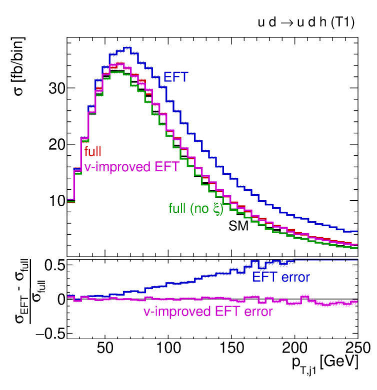
price to pay: % effects only

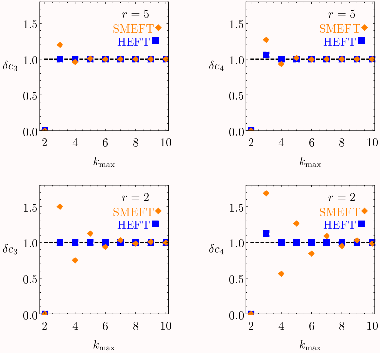
→ most sensitivity from lowest error region (∼ bulk)

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

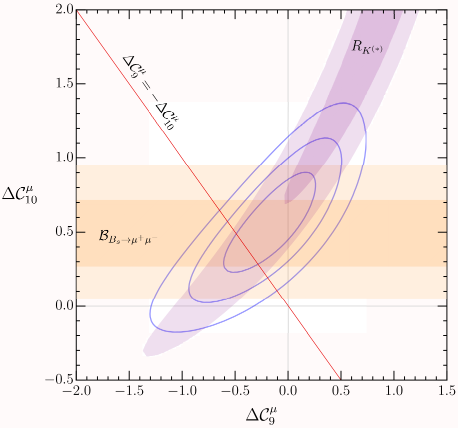
$$D_\mu\Phi^\dagger D^\mu\Phi \to \text{Tr}(D_\mu\mathbf{U}^\dagger D^\mu\mathbf{U})\left(1 + a\frac{h}{v} + b\frac{h^2}{v^2} + \dots\right)$$

- enhanced anomalous interactions among Goldstones = W_L, Z_L
- 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
- only consistent if $\Lambda \leqslant 4\pi v$ (unitarity violation) Cohen et al 2108.03240

What if. . .

. . . an anomaly shows up?

as for B-anomalies: dedicated studies focused on interesting parameters/models



Cornella,Faroughy,Fuentes-Martin,Isidori,Neubert 2103.16658

nonzero values of effective operators

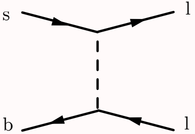
$$O_9^\ell = (\bar{s}_L\gamma^\mu b_L)(\bar{\ell}\gamma_\mu\ell)$$
$$O_{10}^\ell = (\bar{s}_L\gamma^\mu b_L)(\bar{\ell}\gamma_\mu\gamma_5\ell)$$

↓

combine with constraints from Drell-Yan, $B_s - \bar{B}_s$ mixing etc

↓

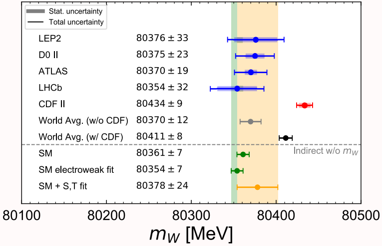
leptoquarks as preferred (combined) explanation



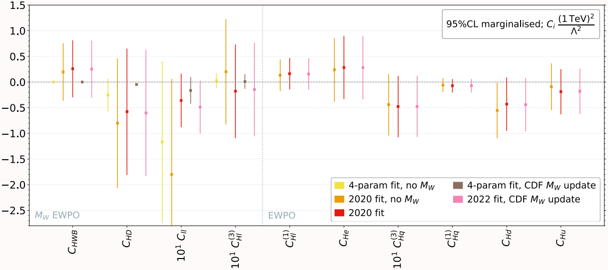
what about the CDF m_W measurement then?

CDF II measurement is in tension with previous ones at LEP and at ATLAS!

Bagnaschi, Ellis, Madigan, Mimasu, Sanz, You 2204.05260



if we *assume* there is an actual deviation there: mostly **T parameter (C_{HD})**



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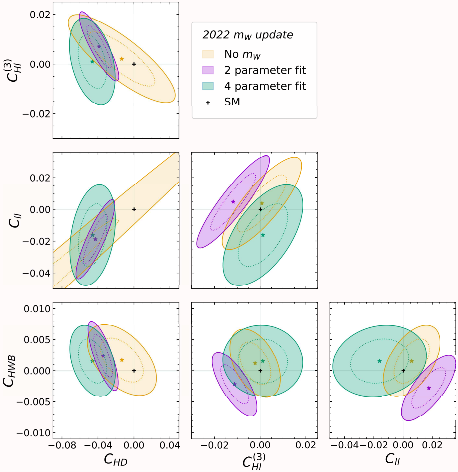

similar: Strumia 2204.04191, deBlas et al 2204.04204, diLuzio,Gröber,Paradisi 2204.05284, Fan,Li,Liu,Lyu 2204.04805, Asadi et al 2204.05283, daSilva Almeida et al 2204.10130 ...

. . . we discover a new particle?

☞ new particles hardly come alone. need sectors / multiplet partners

- extend EFT field content
- gauge invariance: observation in one channel ⇒ other predicted signals
- **restrict** EFT parameter space to coefficients motivated by extensions containing the new particle → more efficient searches
- use matching knowledge to get quickly a comprehensive map of the new particle's **effects at lower E** → everything consistent?
- . . .

→ lots of examples from 750GeV literature (2016)

Summary

- SMEFT is the best framework for indirect searches of new physics at LHC
  → current direct bounds consistent with $(v/\Lambda_{BSM}) \ll 1$
  → collider physics entering **precision era**
- Combining different measurements is key to constraining as many coefficients as possible and avoiding bias
- Studies in EW, Higgs and top sectors are theoretically advanced but more improvements are needed for this to become standard business
- a lot to stay tuned for in the next years!
  → more precise measurements: fits entering relevant regime
  → more exp info available (differential meas, new processes, correlations. . .)
  → streamline mapping to models for better interpretation
  → better predictions and fitting technology
  . . .