VBS & EFTs

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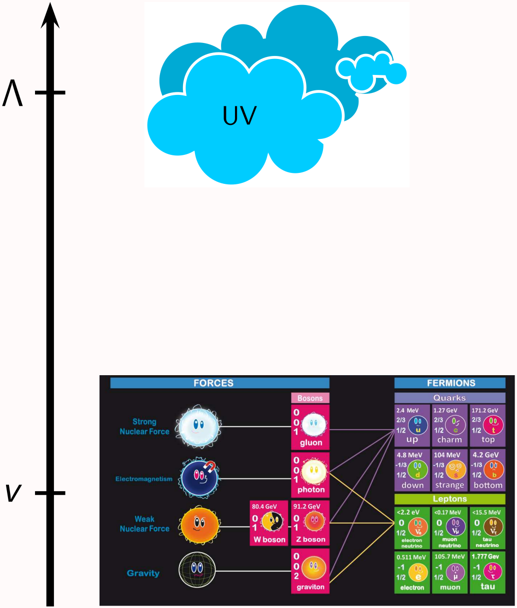
The idea of Effective Field Theories



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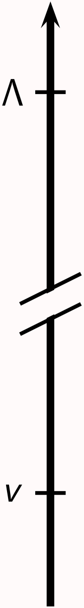
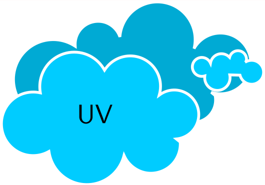
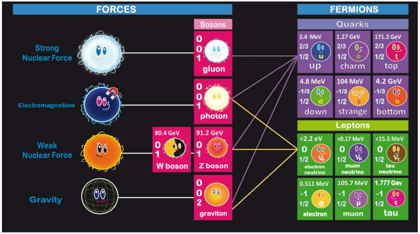


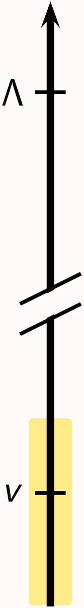


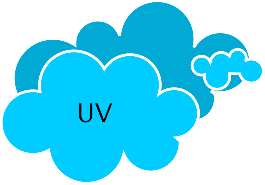
a clear separation

$$\Lambda \ll v$$



The idea of Effective Field Theories





a clear separation

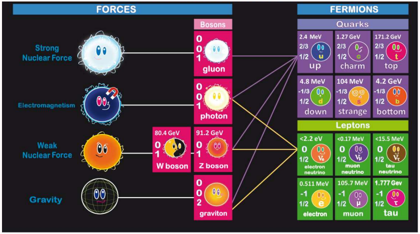
$$\Lambda \ll v$$

the effect of the UV in the region are organized in an expansion in

$$\frac{E \sim v}{\Lambda} \ll 1$$

↕

ordered by canonical dimension



The SMEFT

SMEFT = Effective Field Theory with SM fields + symmetries

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

$\mathcal{L}_n = \sum_i C_i \mathcal{O}_i^{d=n}$

C_i - free parameters (Wilson coefficients)

$\mathcal{O}_i$ - GAUGE INVARIANT operators that form a complete basis

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- any UV compatible with the SM in the low energy limit can be matched onto the SMEFT
- a convenient phenomenological approach: systematically classifies <u>all</u> the possible new physics signals
- allows to compute with NO REFERENCE to the UV

The SMEFT: in practice

We consider B, L conservation and only first order deviations → only $\mathcal{L}_6$

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2}\mathcal{L}_6 \qquad\qquad \mathcal{L}_6 = \sum_i C_i \mathcal{O}_i$$

there are 59 + hc = 76 operators = (parameters in the flavor blind limit)
With arbitrary flavor indices the parameters are 2499.

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The idea

LHC data SMEFT UV models

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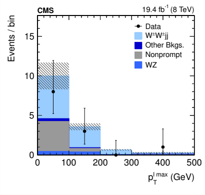
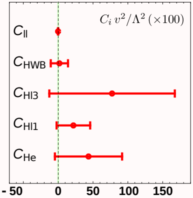
The idea

LHC data —set constraints→ SMEFT   UV models





The SMEFT: in practice

We consider B, L conservation and only first order deviations → **only $\mathcal{L}_6$**

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there are 59 + hc = **76** operators = (parameters in the flavor blind limit)
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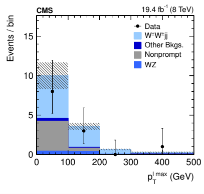
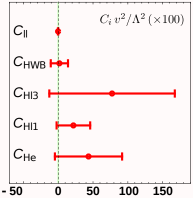
The idea

LHC data → (set constraints) → SMEFT ⇄ UV models (match to the EFT / interpret bounds)

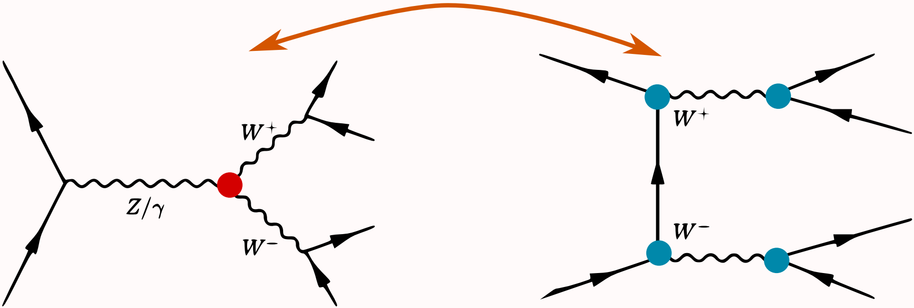




the EFT language is very general: the constraints can be mapped later to any model

An important point: gauge invariance!

An example:
gauge invariance relates TGC and Vff corrections.
the Equations of Motion can transform TGC operators into Vff!



Non-gauge invariant parameterizations (e.g. $\kappa_{Z,\gamma}$, $g_1^{Z,\gamma}$) cannot deal with this.

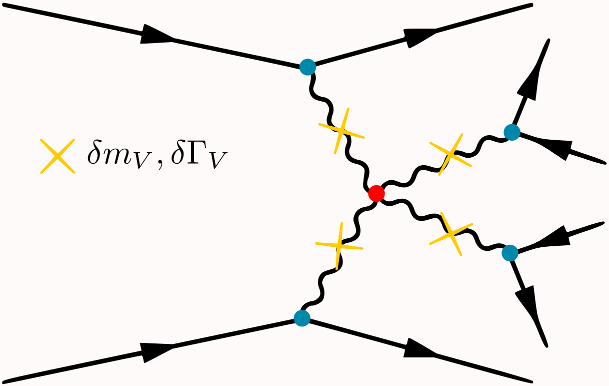
Coefficients of an EFT basis always give EOM equivalent parameterizations

→ not a matter of anomalous TGC / Zff but **anomalous amplitude**!

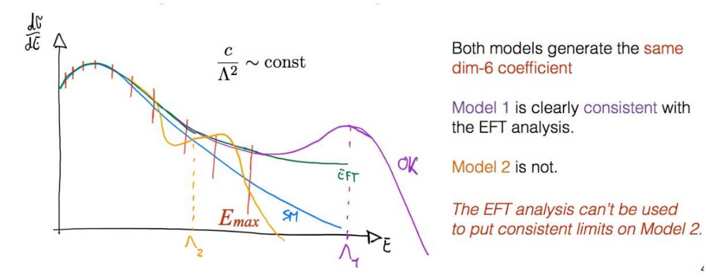
An important point: gauge invariance!

Ideally, for the constraints to be as model independent as possible it is necessary to compute the whole observable in the EFT

$\rightarrow$ $\sim$ **20** parameters in total (flavor blind)



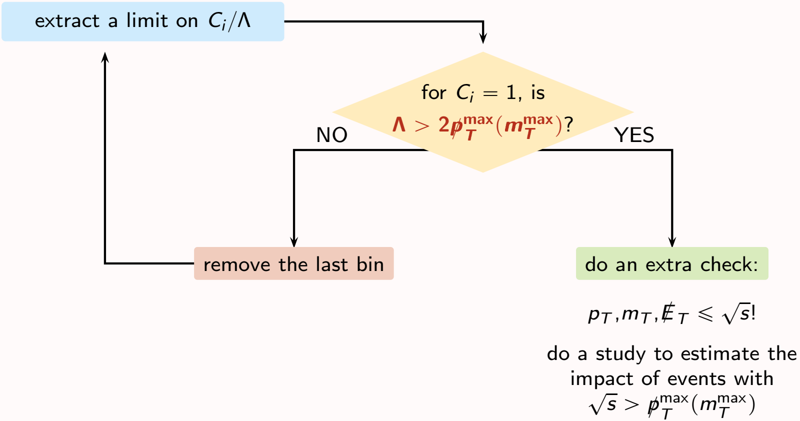
FAQ - EFT validity



- the validity of the EFT in the tails of distributions is a big problem: when doing the analysis Λ is unknown + the actual energy scale of the process is not accessible.
- direct searches are indicative but model dependent (absence of discoveries $\neq$ EFT is valid)
- at best: consistency checks a posteriori

FAQ - EFT validity

Basic algorithm: set a kinematic cut $\not{p}_T^{max}(m_T^{max})$ [Example from 1701.05379]



The big challenge: determine what is **the actual energy** flowing in the process

FAQ - Unitarization

some debate in the preliminary meeting!

6. What do we learn / how to interpret if an EFT parameter is found to be non-zero at a value that requires unitarization?

Theorist's view: naively the EFT is just not valid in the kinematic region that we used to extract the value.

The unitarization procedure **does not restore the EFT validity**
→ not useful for the EFT interpretation

FAQ - TGC vs QGC

2. Does it makes sense to look and set limits for aQGC if aTGC are not seen?
   a. Can we have theories that predict aQGC but not triple?
   b. Currently aQGC limits assume aTGC to be 0 is this a reasonable assumption?

7. Is interesting to fit aTGC and aQGC together?

It is <u>always</u> great to have new independent measurements,

regardless of the theoretical setup (EFT/model etc)

→ **YES**, it makes a lot of sense to look for aQGC

FAQ - TGC vs QGC

The scenario at dimension 6 with the Warsaw basis:

TGC

$$-ig_{WWV}\left[g_1^V\left(W^+_{\mu\nu}W^{-\mu}V^\nu - W^-_{\mu\nu}W^{+\mu}V^\nu\right) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu}\right] - i\lambda_V V^{\mu\nu}W^{+\rho}_\nu W^-_{\rho\mu}$$

g_1^γ	1	g_1^Z	$1-\frac{v^2}{4c_{2\theta}}\left(C_{HD}+4C_{Hl}^{(3)}-2C_{ll}+4t_\theta C_{HWB}\right)$
κ_γ	$1+\frac{v^2}{t_\theta}C_{HWB}$	κ_Z	$1-\frac{v^2}{4c_{2\theta}}\left(C_{HD}+4C_{Hl}^{(3)}-2C_{ll}+4s_{2\theta}C_{HWB}\right)$
λ_γ	$6C_W s_\theta$	λ_Z	$6C_W c_\theta$

QGC

$$g^2/2\left[g_{WW}^{(1)}\left((W^+_\mu W^-_\nu)^2 - (W^+_\mu W^{-\mu})^2\right) + g_{VV'}^{(1)}\left(W^{+\mu}W^{-\nu}\frac{V_\mu V'_\nu + V_\nu V'_\mu}{2} - W^+_\mu W^{-\mu}V_\nu V'^\nu\right)\right]$$

$g_{WW}^{(1)}$	$1-\frac{v^2c_\theta^2}{2c_{2\theta}}\left(C_{HD}+4C_{Hl}^{(3)}-2C_{ll}+4t_\theta C_{HWB}\right)$	$g_{\gamma\gamma}^{(1)}/s_\theta^2$	1
$g_{Z\gamma}^{(1)}/s_{2\theta}$	$1-\frac{v^2}{4c_{2\theta}}\left(C_{HD}+4C_{Hl}^{(3)}-2C_{ll}+4t_\theta C_{HWB}\right)$		
$g_{ZZ}^{(1)}/c_\theta^2$	$1-\frac{v^2}{2c_{2\theta}}\left(C_{HD}+4C_{Hl}^{(3)}-2C_{ll}+4t_\theta C_{HWB}\right)$		

$+$ structures from $C_W\epsilon_{IJK}W^I_{\mu\nu}W^{J\nu\rho}W^{K\mu}_\rho$

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7. Is interesting to fit aTGC and aQGC together?

The scenario at dimension 6 with the Warsaw basis:

- if all the TGCs are zero, the QGCs are also zero. (not very interesting)

  → the answer to 2.b is **NO**. in general: setting something to zero by hand is a strong (potentially dangerous) assumption

- all the QGC depend on the same combination of coefficients as δg_1^Z

  → if we find deviations, it would be interesting to check their correlation

  → the answer to 7 is **YES**. A fit with both TGC and QGC would be ideal. Even better: combine with LEP data

However the actual answer to 2.a is **YES**

FAQ - TGC vs QGC

The dimension 6 SMEFT scenario is not the only possible one!

There are others that are very interesting and allow
decorrelated aTGC and aQGC

1. special theories in which $d = 8$ operators dominate over $d = 6$
   → e.g. "Remedios" ⇝ F. Riva
   → at dimension 8 the structure of the QGC is much richer. e.g. 1604.03555

2. scenarios in which the right EFT is <u>not</u> the SMEFT but the **HEFT**

   VBS is an important signature of the HEFT, so there's a vast literature about it that should be explored ⇝ Dobado,Delgado,Herrero,Llanes-Estrada...

HEFT = Non-linear EFT = EW chiral Lagrangian

Main idea: the Higgs does not need to be in a doublet

$$H = \frac{v+h}{\sqrt{2}}\,\mathbf{U}\begin{pmatrix}0\\1\end{pmatrix}$$

independent

h

treated as a singlet
with arbitrary couplings

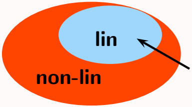
$$\mathcal{F}(h) = 1 + 2a\frac{h}{b} + b\frac{h^2}{v^2} + \dots$$

$\mathbf{U} = e^{i\pi^I\sigma^I/v}$

adimensional

derivative expansion $\sim$ χPT

$\longrightarrow$ a **very general** EFT



contains the linear as a particular limit

$\longrightarrow$ matches composite Higgs models + other UVs with significant nonlinear effects in the EWSB sector

aQGC in the HEFT

$$\mathscr{L}_{4X} \equiv g^2\Big\{ g^{(1)}_{ZZ}(Z_\mu Z^\mu)^2 + g^{(1)}_{WW}\, W^+_\mu W^{+\mu} W^-_\nu W^{-\nu} - g^{(2)}_{WW}(W^+_\mu W^{-\mu})^2$$
$$+ g^{(3)}_{VV'}\, W^{+\mu} W^{-\nu}\left(V_\mu V'_\nu + V'_\mu V_\nu\right) - g^{(4)}_{VV'}\, W^+_\nu W^{-\nu} V^\mu V'_\mu$$
$$+ i g^{(5)}_{VV'}\, e^{\mu\nu\rho\sigma} W^+_\mu W^-_\nu V_\rho V'_\sigma \Big\}$$

1311.1823

	Coeff. $\times e^2/4s^2_\theta$	Chiral	Linear $\times v^2$
$\Delta g^{(1)}_{WW}$	1	$\frac{s^2_{2\theta}}{e^2 c_{2\theta}} c_T + \frac{8s^2_\theta}{c_{2\theta}} c_1 + 4c_3 + 2c_{11} - 16c_{12} + 8c_{13}$	$\frac{c_W}{2} + \frac{s^2_\theta}{c_{2\theta}} c_{BW} - \frac{s^2_{2\theta}}{4c_{2\theta} e^2} c_{\Phi 1}$
$\Delta g^{(2)}_{WW}$	1	$\frac{s^2_{2\theta}}{e^2 c_{2\theta}} c_T + \frac{8s^2_\theta}{c_{2\theta}} c_1 + 4c_3 - 4c_6 - \frac{v^2}{2} c_{\Box h} - 2c_{11} - 16c_{12} + 8c_{13}$	$\frac{c_W}{2} + \frac{s^2_\theta}{c_{2\theta}} c_{BW} - \frac{s^2_{2\theta}}{4c_{2\theta} e^2} c_{\Phi 1}$
$\Delta g^{(1)}_{ZZ}$	$\frac{1}{c^4_\theta}$	$c_6 + \frac{v^2}{8} c_{\Box h} + c_{11} + 2c_{23} + 2c_{24} + 4c_{26}$	–
$\Delta g^{(3)}_{ZZ}$	$\frac{1}{c^2_\theta}$	$\frac{s^2_{2\theta} c^2_\theta}{e^2 c_{2\theta}} c_T + \frac{2s^2_{2\theta}}{c_{2\theta}} c_1 + 4c^2_\theta c_3 - 2s^4_\theta c_9 + 2c_{11} + 4s^2_\theta c_{16} + 2c_{24}$	$\frac{c_W c^2_\theta}{2} + \frac{s^2_{2\theta}}{4c_{2\theta}} c_{BW} - \frac{s^2_{2\theta} c^2_\theta}{4e^2 c_{2\theta}} c_{\Phi 1}$
$\Delta g^{(4)}_{ZZ}$	$\frac{1}{c^2_\theta}$	$\frac{2s^2_{2\theta} c^2_\theta}{e^2 c_{2\theta}} c_T + \frac{4s^2_{2\theta}}{c_{2\theta}} c_1 + 8c^2_\theta c_3 - 4c_6 - \frac{v^2}{2} c_{\Box h} - 4c_{23}$	$c_W c^2_\theta + 2\frac{s^2_{2\theta}}{4c_{2\theta}} c_{BW} - \frac{s^2_{2\theta} c^2_\theta}{2e^2 c_{2\theta}} c_{\Phi 1}$
$\Delta g^{(3)}_{\gamma\gamma}$	s^2_θ	$-2c_9$	–
$\Delta g^{(3)}_{\gamma Z}$	$\frac{s_\theta}{c_\theta}$	$\frac{s^2_{2\theta}}{e^2 c_{2\theta}} c_T + \frac{8s^2_\theta}{c_{2\theta}} c_1 + 4c_3 + 4s^2_\theta c_9 - 4c_{16}$	$\frac{c_W}{2} + \frac{s^2_\theta}{c_{2\theta}} c_{BW} - \frac{s^2_{2\theta}}{4c_{2\theta} e^2} c_{\Phi 1}$
$\Delta g^{(4)}_{\gamma Z}$	$\frac{s_\theta}{c_\theta}$	$\frac{2s^2_{2\theta}}{e^2 c_{2\theta}} c_T + \frac{16s^2_\theta}{c_{2\theta}} c_1 + 8c_3$	$c_W + 2\frac{s^2_\theta}{c_{2\theta}} c_{BW} - \frac{s^2_{2\theta}}{2c_{2\theta} e^2} c_{\Phi 1}$
$\Delta g^{(5)}_{\gamma Z}$	$\frac{s_\theta}{c_\theta}$	$8c_{14}$	–

aTGC in the HEFT

$$\begin{aligned}\mathscr{L}_{WWV} = &- ig_{WWV}\Big\{g_1^V\Big(W^+_{\mu\nu}W^{-\,\mu}V^\nu - W^+_\mu V_\nu W^{-\,\mu\nu}\Big) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu}\\ &- ig_5^V\varepsilon^{\mu\nu\rho\sigma}\left(W^+_\mu\partial_\rho W^-_\nu - W^-_\nu\partial_\rho W^+_\mu\right)V_\sigma +\\ &+ g_6^V\left(\partial_\mu W^{+\mu}W^{-\nu} - \partial_\mu W^{-\mu}W^{+\nu}\right)V_\nu\Big\}\end{aligned}$$

1311.1823

$g_{WWZ} = g\cos\theta\,,\quad g_{WW\gamma} = e$

	Coeff. $\times e^2/s^2_\theta$	Chiral	Linear $\times v^2$
$\Delta\kappa_\gamma$	1	$-2c_1 + 2c_2 + c_3 - 4c_{12} + 2c_{13}$	$\frac{1}{8}(c_W + c_B - 2c_{BW})$
Δg_6^γ	1	$-c_9$	–
Δg_1^Z	$\frac{1}{c^2_\theta}$	$\frac{s^2_{2\theta}}{4e^2c_{2\theta}}c_T + \frac{2s^2_\theta}{c_{2\theta}}c_1 + c_3$	$\frac{1}{8}c_W + \frac{s^2_\theta}{4c_{2\theta}}c_{BW} - \frac{s^2_{2\theta}}{16e^2c_{2\theta}}c_{\Phi,1}$
$\Delta\kappa_Z$	1	$\frac{s^2_\theta}{e^2c_{2\theta}}c_T + \frac{4s^2_\theta}{c_{2\theta}}c_1 - \frac{2s^2_\theta}{ct^2}c_2 + c_3 - 4c_{12} + 2c_{13}$	$\frac{1}{8}c_W - \frac{s^2_\theta}{8ct^2}c_B + \frac{s^2_\theta}{2c_{2\theta}}c_{BW} - \frac{s^2_\theta}{4e^2c_{2\theta}}c_{\Phi,1}$
Δg_5^Z	$\frac{1}{c^2_\theta}$	c_{14}	–
Δg_6^Z	$\frac{1}{c^2_\theta}$	$s^2_\theta c_9 - c_{16}$	–

FAQ - basis

3. Is there a preferred EFT base, if so, which one and why?

No, as long as it's a BASIS = a set of gauge invariant operators
(the kappas of the Zeppenfeld parameterization in the previous slide are not a basis!)

A popular one is the **Warsaw basis**. This is advantageous for some technical reasons related to removing derivative operators, and the only one for which the complete RGE running is available

FAQ - predictions

4. Expected aTGC and aQGC values for different theoretical models. Where or how can we get this numbers? I found this table somewhere (not sure of the origin of this) but I would like to be able to produce something like this for EFTs for different theoretical models :

This question is not well posed in the EFT, as the EFT is model independent.

In the EFT the TGC and QGC are expressed as functions of the Wilson coefficients C_i.

If you wonder about the numerical precision needed: $\lesssim 10\%$

FAQ - deviations

5. What do we learn / how to interpret if a given EFT parameter is found to be non-zero?

It means that one operator gives a non-zero contribution = we found new physics!

Which operator it is can give indications about what kind of UV may be underlying, although I don't think we'd need to go further than the EFT interpretation

Ideal plans for the future

1. Figure how to produce experimental constraints on EFT parameters
   - Determine a parameterization with **d=6**, trying to keep gauge invariance and avoiding setting stuff to zero. How many are feasible?
   - UFO model with the complete SMEFT on the way!
   - SMEFT vs **HEFT**: extremely interesting!
   - Combination with other datasets?

2. Establish a way to report data in a flexible/model-independent way, crosssections + distributions that may be used by theorists in the future