“Real world” energy growth in EFT fits

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Tuesday 26th Nov 2024

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Preface

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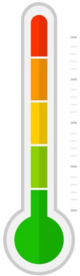
This is **not** an in-depth discussion of Standard Model Effective Field Theory (**SMEFT**), top physics, nor any analyses which use it to search for or constrain BSM physics.

Rather, SMEFT can be considered a case-study of the LHC community pushing analysis into more complex directions:

→ Where can the complexity come from?

→ What impact does this have on my computational resources? How much do I need?

The question I most wish to probe is **"what impact is my work having in terms of the resources, energy and carbon used?"** → **Carbon calculations are intended to be illustrative not accurate metrics**

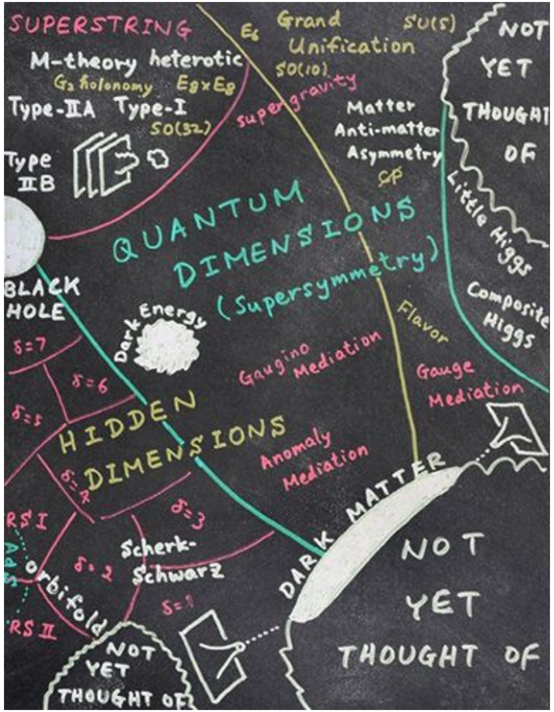


This talk will be a bit "open-ended"
I am not an environmental researcher

→ My conclusions are biased by my own (hopefully well-informed) opinion.

Motivating the SMEFT

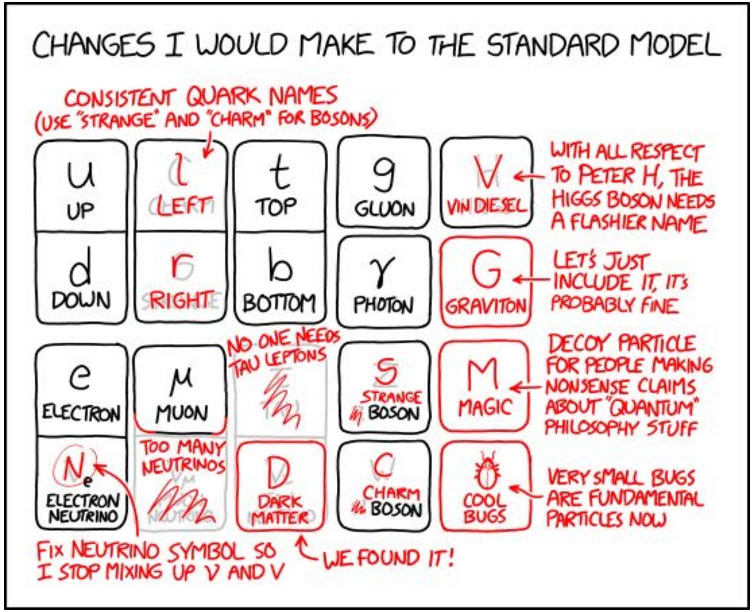
What are we looking for?



Daniel Dominguez/Hitoshi Murayama

We have no single, well-motivated “**GOTCHA**” theory 🤷
→ No “smoking gun” discovery

?



(xkcd 2351)

Motivating the SMEFT

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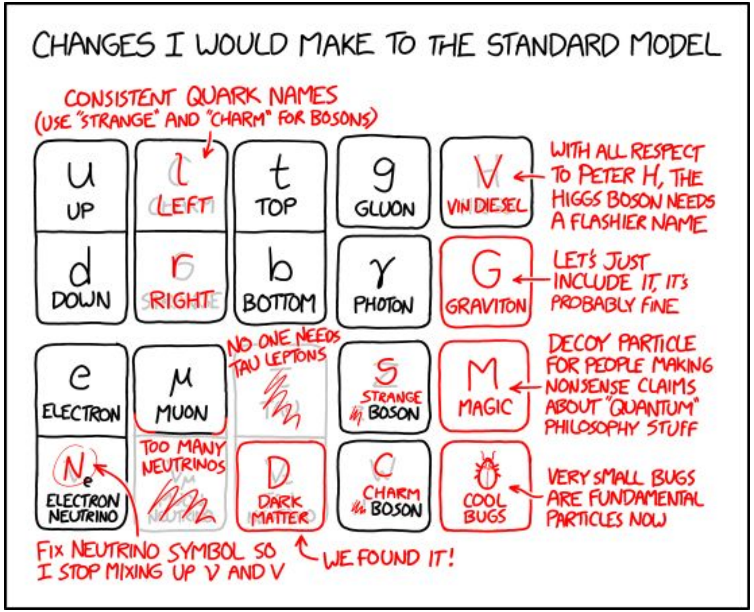
Daniel Dominguez/Hitoshi Murayama

What are we even looking for?



(xkcd 2351)

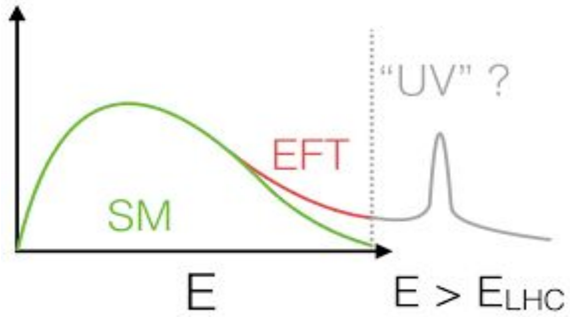
The SMEFT & top physics

Standard Model Effective Field Theory (SMEFT) proposes a higher-dimensional extension to the SM:

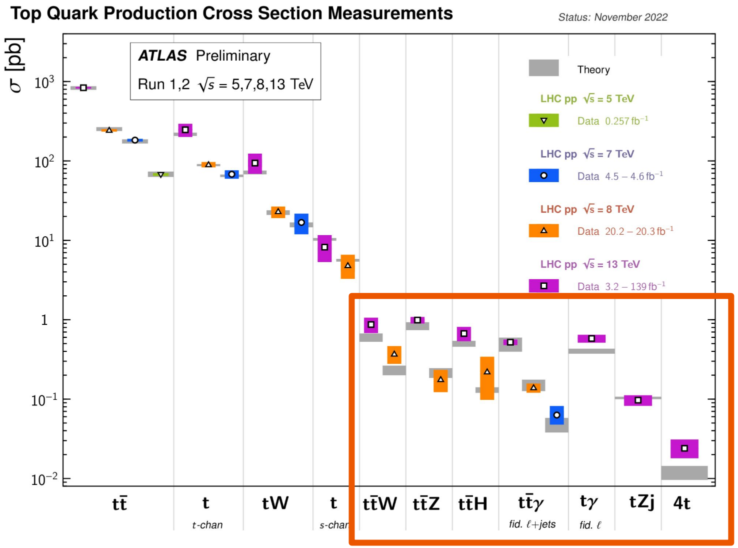
$$L_{SMEFT} = L_{SM} + L_6 + \ldots \qquad (1)$$

$$L_6 = 1/\Lambda^2 (\sum C_\alpha Q_\alpha) \qquad (2)$$

parameterising new physics at some directly-inaccessible UV scale in terms of **effective interaction vertices** scaled by **Wilson coefficients.**



UV energy growth & EFTs, Ken Mimasu



ATLAS top quark production cross section measurements summary (ATL-PHYS-PUB-2024-006).

Large mass of the top quark makes it phenomenologically interesting for BSM studies through the SMEFT.

Fits to the SMEFT in top physics

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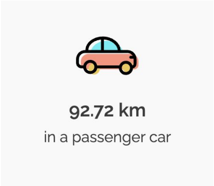
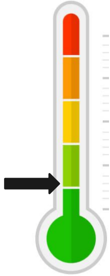
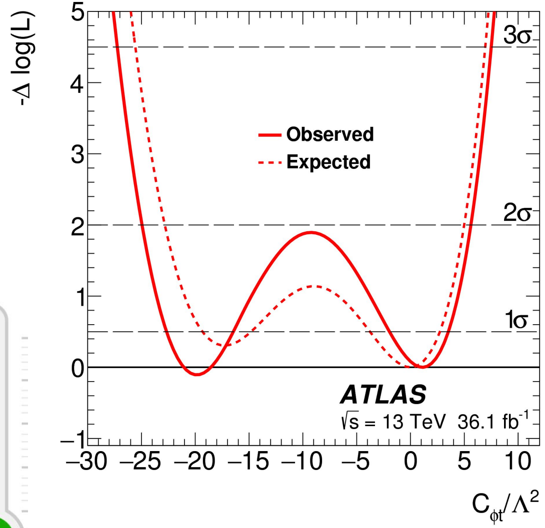
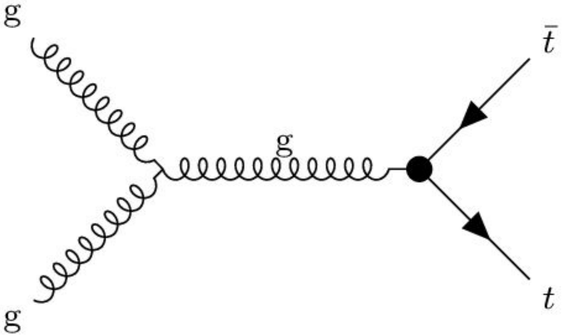


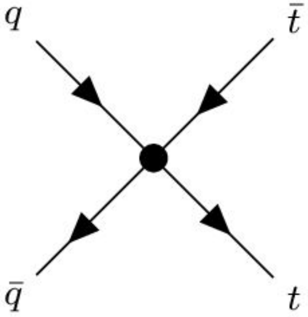


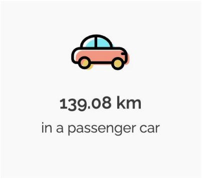


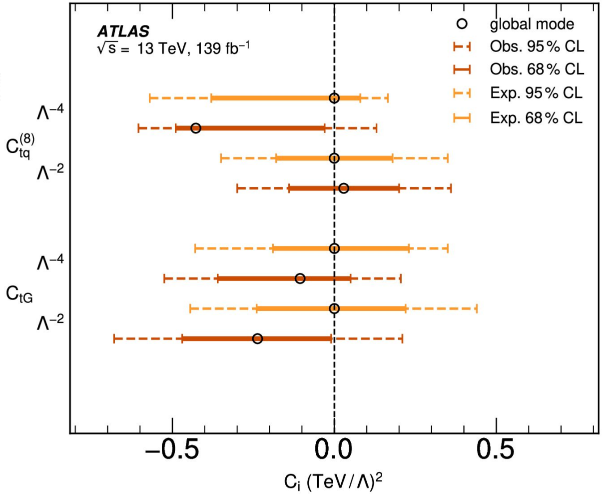
Single parameter EFT fit using measurements of ttZ, ATLAS (Phys. Rev. D 99 (2019) 072009).



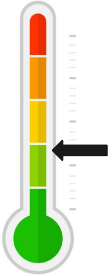
EFT contributions from (above) C_{tG} and (below) $C_{tq}^{(8)}$







Two-parameter EFT fit in top-quark pair production measurements, ATLAS (JHEP 06 (2022) 063).

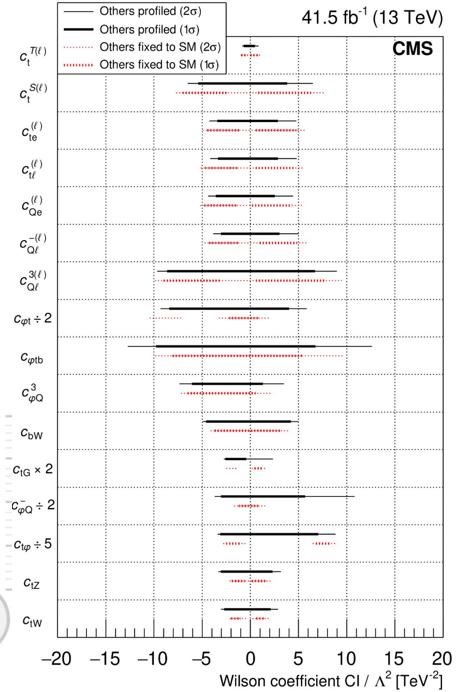


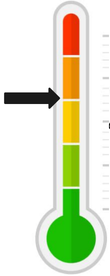
Fits to the SMEFT in top physics

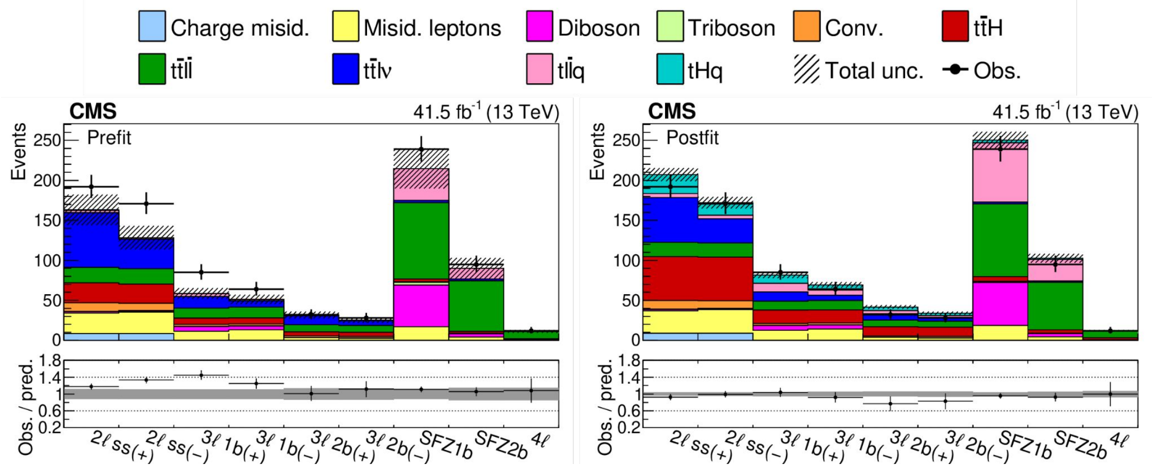
Seeing more efforts recently to expand into multi-process, multi-operator fits

→ Consistent with model-agnostic philosophy of the SMEFT
→ Can benefit from increased information

→ Cost? Have to work with larger and more complex workspaces





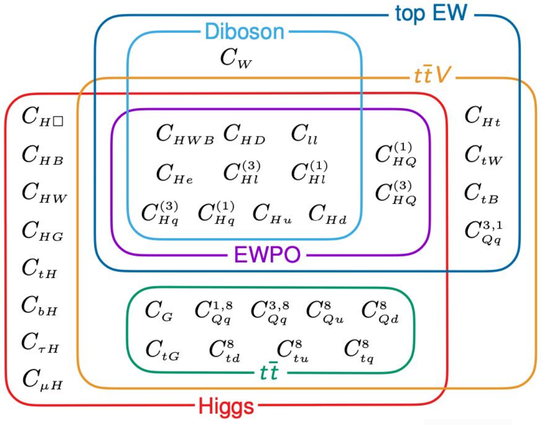


Multi-operator fit of multiple top-quark production processes, CMS (JHEP 03 (2021) 095).

1.1
flights NYC-Melbourne

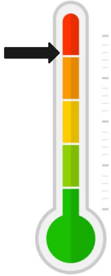
Targeting more complex (global) fits

A priori, global fits are well-motivated from the theory alone. Given infinite data



Overlapping EFT dependencies, Ellis, J. *et al* (JHEP 04 (2021) 279).

$\mathcal{L}_6^{(1)} - X^3$		$\mathcal{L}_6^{(6)} - \psi^2 XH$		$\mathcal{L}_6^{(8b)} - (\bar{R}R)(\bar{R}R)$	
Q_G	$f^{abc}G_\mu^{a\nu}G_\nu^{b\rho}G_\rho^{c\mu}$	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\sigma^i HW^i_{\mu\nu}$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{\widetilde{G}}$	$f^{abc}\widetilde{G}_\mu^{a\nu}G_\nu^{b\rho}G_\rho^{c\mu}$	Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)HB_{\mu\nu}$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$
Q_W	$\varepsilon^{ijk}W_\mu^{i\nu}W_\nu^{j\rho}W_\rho^{k\mu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^a u_r)\widetilde{H}\,G^a_{\mu\nu}$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{\widetilde{W}}$	$\varepsilon^{ijk}\widetilde{W}_\mu^{i\nu}W_\nu^{j\rho}W_\rho^{k\mu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\sigma^i\widetilde{H}\,W^i_{\mu\nu}$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$
$\mathcal{L}_6^{(2)} - H^6$		Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{H}\,B_{\mu\nu}$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$
Q_H	$(H^\dagger H)^3$	Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^a d_r)H\,G^a_{\mu\nu}$	$Q^{(1)}_{ud}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$
$\mathcal{L}_6^{(3)} - H^4D^2$		Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\sigma^i H\,W^i_{\mu\nu}$	$Q^{(8)}_{ud}$	$(\bar{u}_p\gamma_\mu T^a u_r)(\bar{d}_s\gamma^\mu T^a d_t)$
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)H\,B_{\mu\nu}$		
Q_{HD}	$(D^\mu H^\dagger H)\,(H^\dagger D_\mu H)$				
$\mathcal{L}_6^{(4)} - X^2H^2$		$\mathcal{L}_6^{(7)} - \psi^2 H^2 D$		$\mathcal{L}_6^{(8c)} - (\bar{L}L)(\bar{R}R)$	
Q_{HG}	$H^\dagger H\,G^a_{\mu\nu}G^{a\mu\nu}$	$Q^{(1)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{H\widetilde{G}}$	$H^\dagger H\,\widetilde{G}^a_{\mu\nu}G^{a\mu\nu}$	$Q^{(3)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{l}_p\sigma^i\gamma^\mu l_r)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{HW}	$H^\dagger H\,W^i_{\mu\nu}W^{I\mu\nu}$	Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{H\widetilde{W}}$	$H^\dagger H\,\widetilde{W}^i_{\mu\nu}W^{i\mu\nu}$	$Q^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{HB}	$H^\dagger H\,B_{\mu\nu}B^{\mu\nu}$	$Q^{(3)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{q}_p\sigma^i\gamma^\mu q_r)$	$Q^{(1)}_{qu}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{H\widetilde{B}}$	$H^\dagger H\,\widetilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$	$Q^{(8)}_{qu}$	$(\bar{q}_p\gamma_\mu T^a q_r)(\bar{u}_s\gamma^\mu T^a u_t)$
Q_{HWB}	$H^\dagger\sigma^i H\,W^i_{\mu\nu}B^{\mu\nu}$	Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$	$Q^{(1)}_{qd}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{H\widetilde{W}B}$	$H^\dagger\sigma^i H\,\widetilde{W}^i_{\mu\nu}B^{\mu\nu}$	Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p\gamma^\mu d_r)$	$Q^{(8)}_{qd}$	$(\bar{q}_p\gamma_\mu T^a q_r)(\bar{d}_s\gamma^\mu T^a d_t)$
$\mathcal{L}_6^{(5)} - \psi^2 H^3$		$\mathcal{L}_6^{(8a)} - (\bar{L}L)(\bar{L}L)$		$\mathcal{L}_6^{(8d)} - (\bar{L}R)(\bar{R}L), (\bar{L}R)(\bar{L}R)$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$	Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ledq}	$(\bar{l}^j_p e_r)(\bar{d}_s q_{tj})$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r\widetilde{H})$	$Q^{(1)}_{qq}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	$Q^{(1)}_{quqd}$	$(\bar{q}^j_p u_r)\varepsilon_{jk}(\bar{q}^k_s d_t)$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$	$Q^{(3)}_{qq}$	$(\bar{q}_p\gamma_\mu\sigma^i q_r)(\bar{q}_s\gamma^\mu\sigma^i q_t)$	$Q^{(8)}_{quqd}$	$(\bar{q}^j_p T^a u_r)\varepsilon_{jk}(\bar{q}^k_s T^a d_t)$
		$Q^{(1)}_{lq}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	$Q^{(1)}_{lequ}$	$(\bar{l}^j_p e_r)\varepsilon_{jk}(\bar{q}^k_s u_t)$
		$Q^{(3)}_{lq}$	$(\bar{l}_p\gamma_\mu\sigma^i l_r)(\bar{q}_s\gamma^\mu\sigma^i q_t)$	$Q^{(3)}_{lequ}$	$(\bar{l}^j_p\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}^k_s\sigma^{\mu\nu}u_t)$



→ Might expect to find new physics with the best-fit configuration of the SM+SMEFT

However, SMEFT comes at a cost:

→ 2499 (dim-6) new parameters each impacting a range of processes at the LHC
→ A highly non-trivial challenge to eliminate degeneracies

Wilk’s theorem violations & systematics

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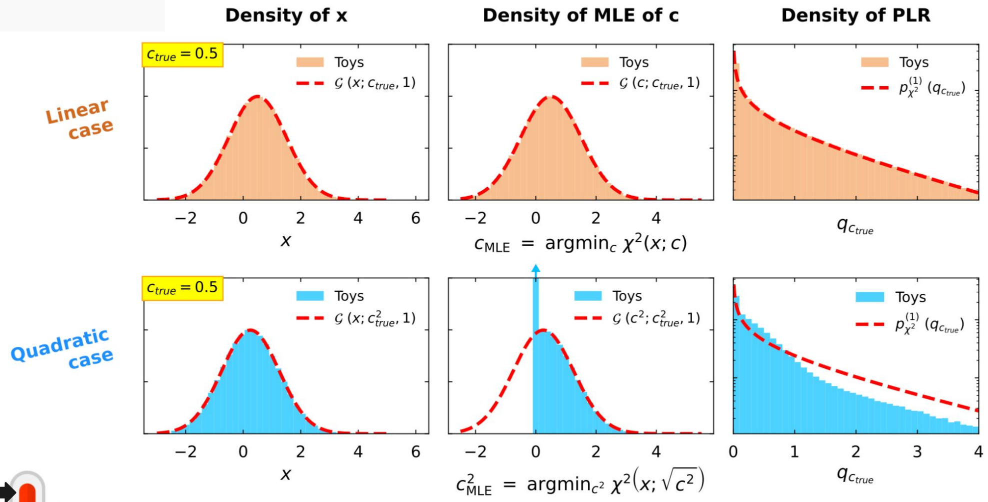
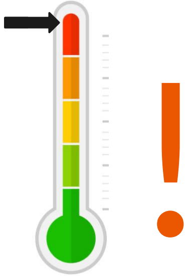


← Cover your Bases, F. U. Bernlochner, et al (arXiv:2207.01350v2)

Source	Type	c_{tW}	$c_{t\varphi}$	$c_{Q\ell}^{-(\ell)}$	$c_{t\ell}^{(\ell)}$
Integrated luminosity	rate	6%	2%	1%	<1%
JES	rate+shape	6%	2%	1%	<1%
b jet tag		1%	5%	8%	<1%
b jet tag HF fraction	rate+shape				
b jet tag HF stats (linear)	rate+shape				
b jet tag HF stats (quadratic)	rate+shape				
b jet tag LF fraction	rate+shape				
b jet tag LF stats (linear)	rate+shape				
b jet tag LF stats (quadratic)	rate+shape				
cjet mistag		<1%	12%	8%	2%
b jet tag charm (linear)	rate+shape				
b jet tag charm (quadratic)	rate+shape				
PDF (gg)	rate	1%	<1%	<1%	<1%
PDF ($gg_{t\bar{t}H}$)	rate	<1%	1%	<1%	<1%
PDF ($q\bar{q}$)	rate	1%	<1%	<1%	<1%
PDF (qg_{tHq})	rate	<1%	<1%	<1%	<1%
$\mu_{R,F}$ scale ($t\bar{t}H$)	rate	2%	5%	<1%	<1%
$\mu_{R,F}$ scale ($t\bar{t}\gamma$)	rate	1%	1%	<1%	<1%
$\mu_{R,F}$ scale ($t\bar{t}V$)	rate	15%	4%	1%	<1%
$\mu_{R,F}$ scale (tHq)	rate	1%	1%	<1%	<1%
$\mu_{R,F}$ scale (V)	rate	<1%	<1%	<1%	<1%
$\mu_{R,F}$ scale (VV)	rate	<1%	<1%	<1%	<1%



Most EFT fits at the LHC use **profile likelihood** which assumes Wilk’s theorem

→ This may be *violated* for quadratic EFT effects
→ No “oven-ready” solution yet

…but what about each systematic also using profile likelihood?

CMS (JHEP 03 (2021) 095)

What's the way forward?

139.08 km
in a passenger car

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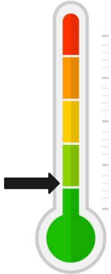
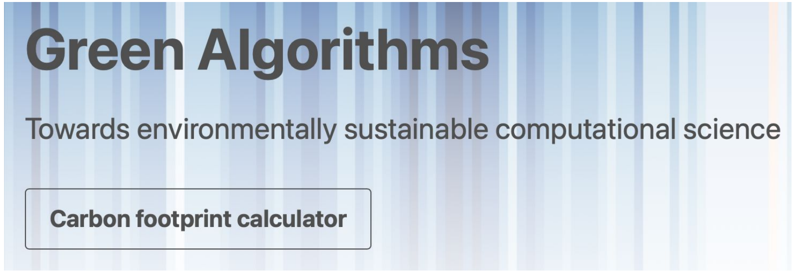
More complex EFT fits are bound to be computationally challenging

→ Carbon costs bound to increase
→ Work in-progress across LHC to optimise and expand EFT analysis

However, EFT-driven analysis is still in its infancy

→ An exciting opportunity (to do this right)
→ Can strive to optimise workflows





(Adv. Sci. 2021, 2100707)

ATLAS EXPERIMENT

ATLAS PUB Note
ATL-PHYS-PUB-2023-030
22nd September 2023

CERN

Roadmap towards future combinations and Effective Field Theory interpretations of top+X processes

The ATLAS Collaboration

(ATL-PHYS-PUB-2023-030)

Since new physics hasn't been found yet using simpler approaches, more complex approaches are needed → **More complex models or fits?**

→ Learn from previous steps to avoid repeating wasteful mistakes

Conclusions & my thoughts

Currently in an era of the unknown at the LHC

→ Pushing more analysis work into new and challenging directions
→ Such as with the SMEFT to target new physics model-agnostically
→ Pushing the envelope to more inclusive, "global" scenarios

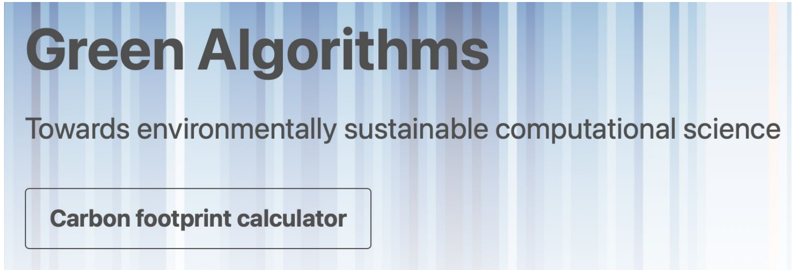
However, our efforts are not without cost…

→ **Computational cost & complexity** is expected to increase
→ Especially for the HL-LHC programme
- A new set of challenges in exchange for more statistical sensitivity
- Understanding experimental and theory systematics likely to be key

Frameworks such as the SMEFT are an exciting opportunity to advance LHC physics in pursuit of BSM physics

→ Still early days
→ So let's learn as much as we can now to avoid unfortunate "waste" later on

Backup - Carbon calculations



(Adv. Sci. 2021, 2100707)

Pessimistically assume a local server in the UK made up of

8 CPU cores (any)
8 Nvidia Tesla P100 PCIe GPUs
16 GB RAM

Single-parameter, single process EFT fit computing (base) time of 20 hrs

<u>Runtimes as a % of base time</u>

Two-parameter fit:	150%
CMS top+x fit:	1500%
Global fit:	15 000%
Wilk's violations:	35 000%