From Flavor to Top, Higgs, and beyond

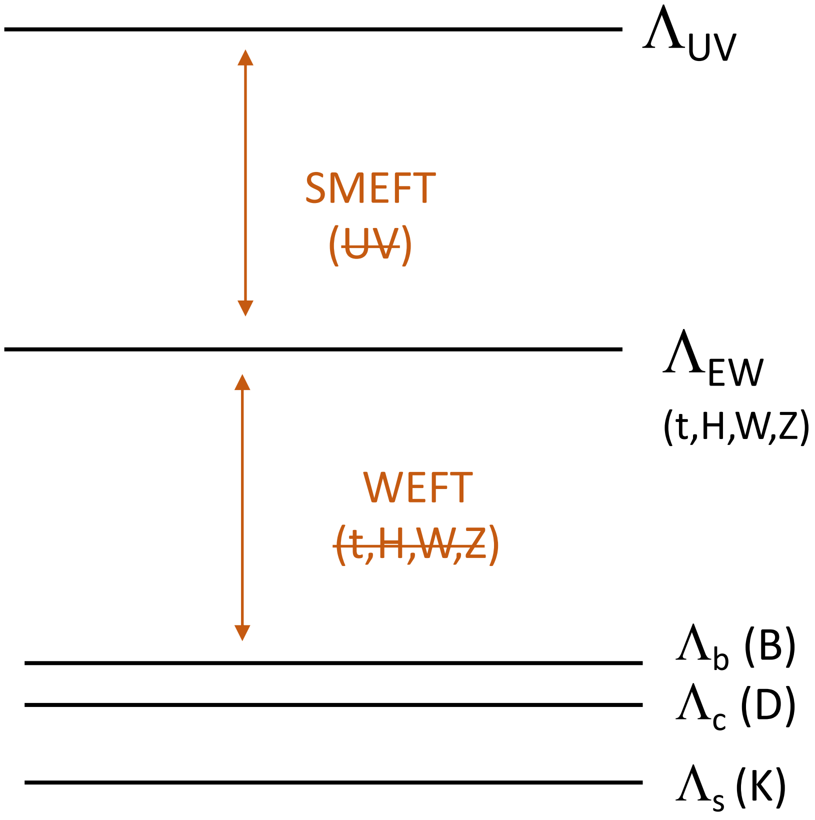
Through the language of Effective Field Theories

Electroweak, Strong, and New Interactions:
A symposium to celebrate Guido Martinelli's 70^{th} birthday

Roma – Accademia Nazionale dei Lincei
26 Settembre 2022

Laura Reina
(Florida State University)

From Flavor to Top, Higgs, and beyond ....



BSM

SMEFT fit of EW, Higgs, top, flavor

LHC: Higgs discovery
Tevatron: top discovery

$H_{eff}(\Delta F=2)$
$H_{eff}(\Delta F=1)$

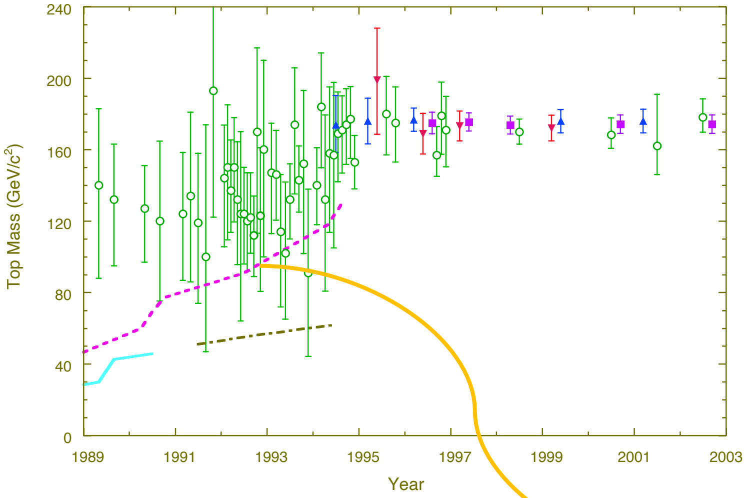
NLO QCD+QED

ε'/ε

$B \to X_s \gamma$

M. Ciuchini
E. Franco
G. Martinelli
L. Silvestrini

Top from prediction to discovery



C. Quigg [hep-ph/0404228]

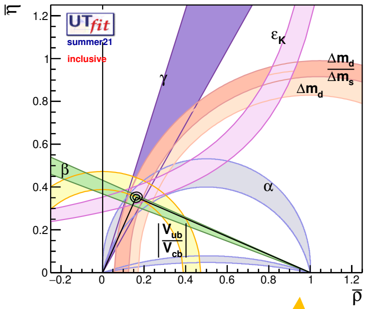
green dots ⟶ indirect fits

blue triangles ⟶ CDF

red triangles ⟶ D0

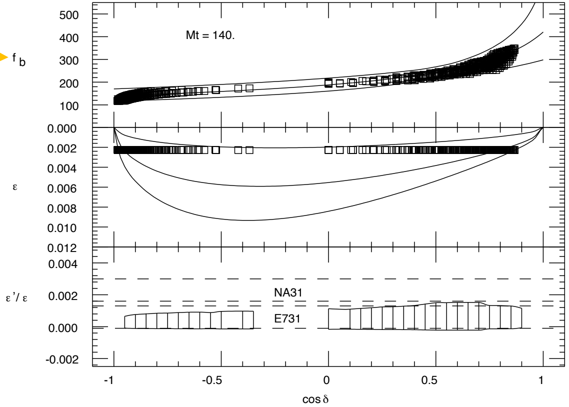
purple squares ⟶ world average

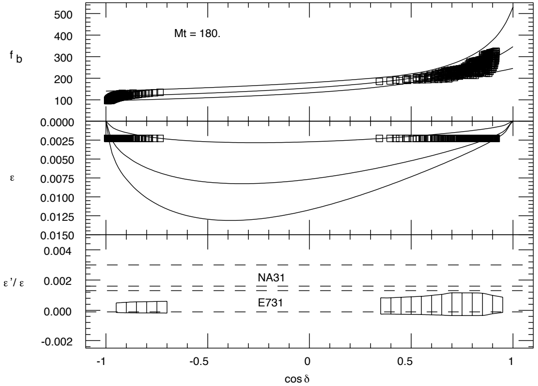
lines ⟶ various lower bounds



Effective Hamiltonians beyond the Leading Order and their applications

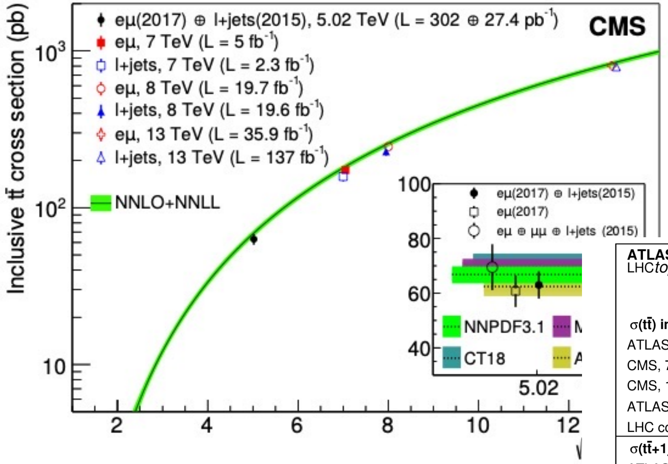
[L.R. – PhD thesis]

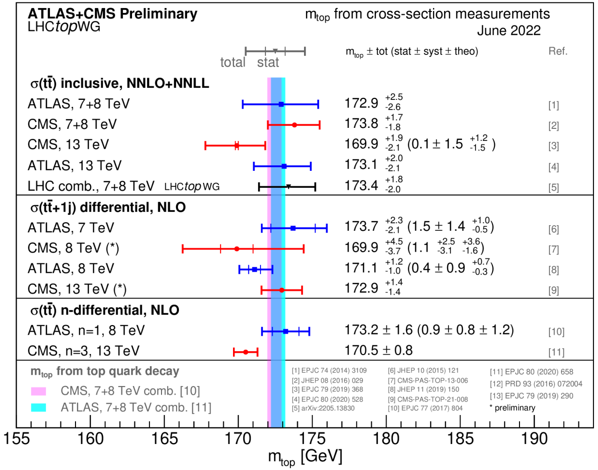


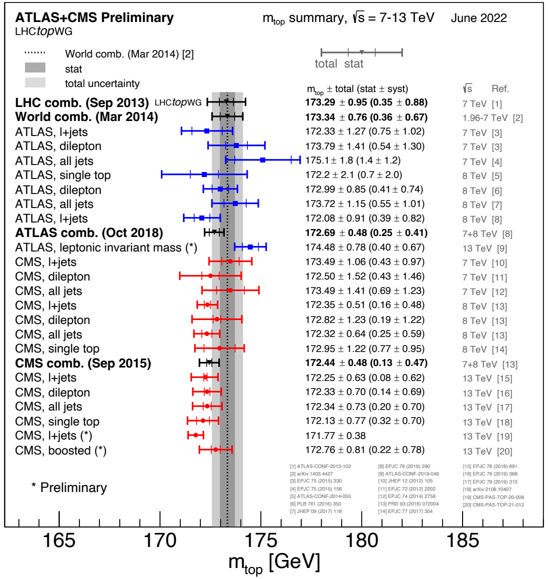


Top

from discovery to precision physics



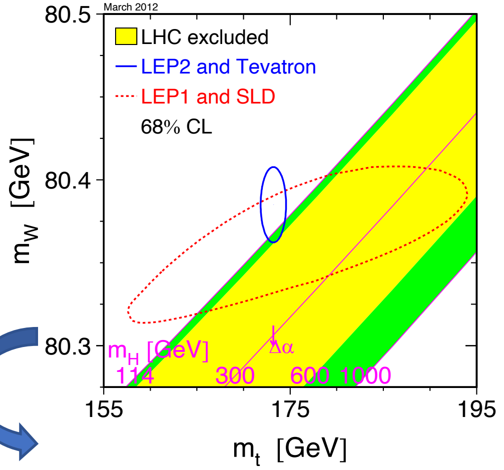




M_t becomes a crucial input in precision fits of the SM (EW and flavor)

Anomalies in Top-quark EW couplings (W,Z,H) possible hint of BSM physics

Higgs from prediction to discovery

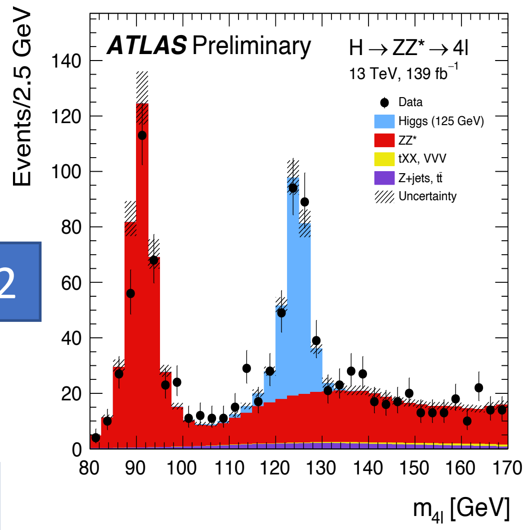


From EW fits

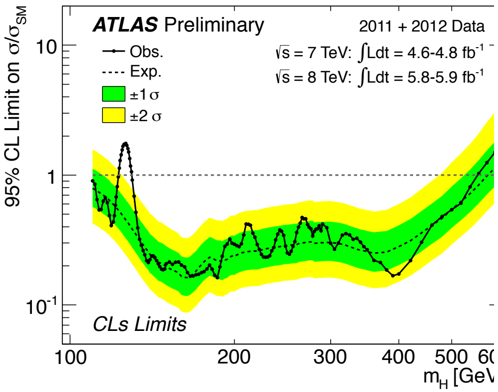
$M_H = 94^{+29}_{-24}$ GeV

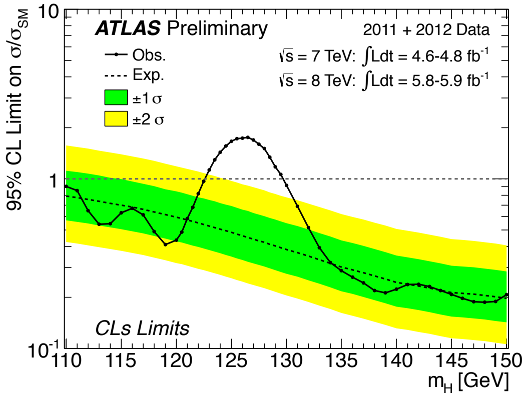
$M_H < 152\text{-}171$ GeV

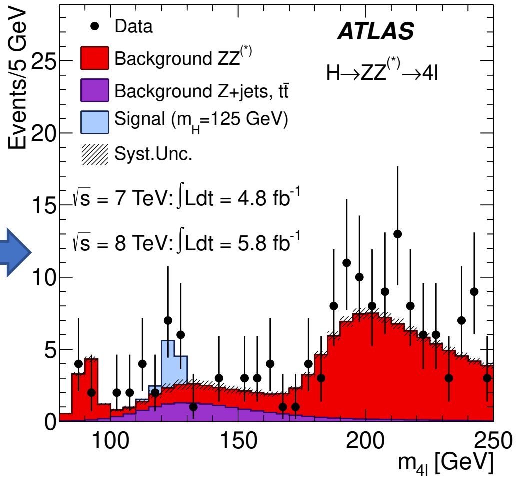
LHC@Run1+2



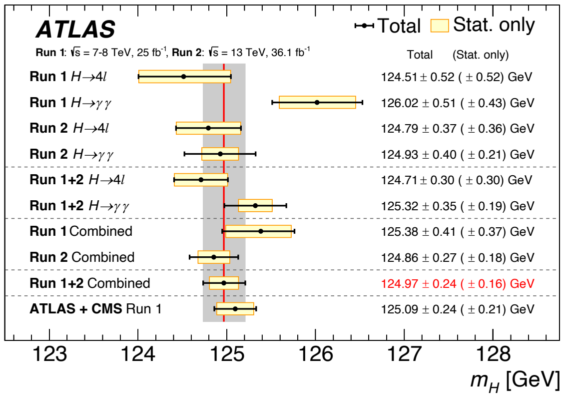
LHC@Run1: $M_H = 125.09 \pm 0.24$ GeV

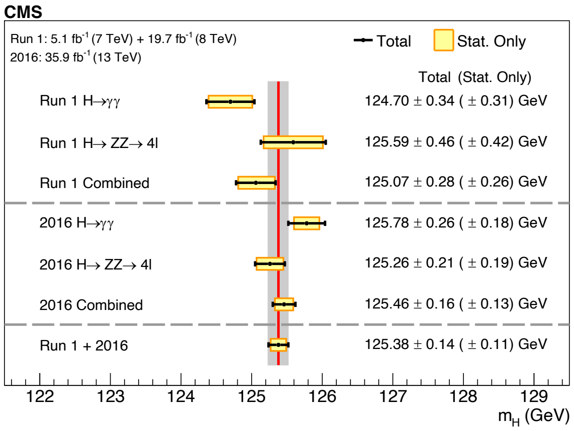


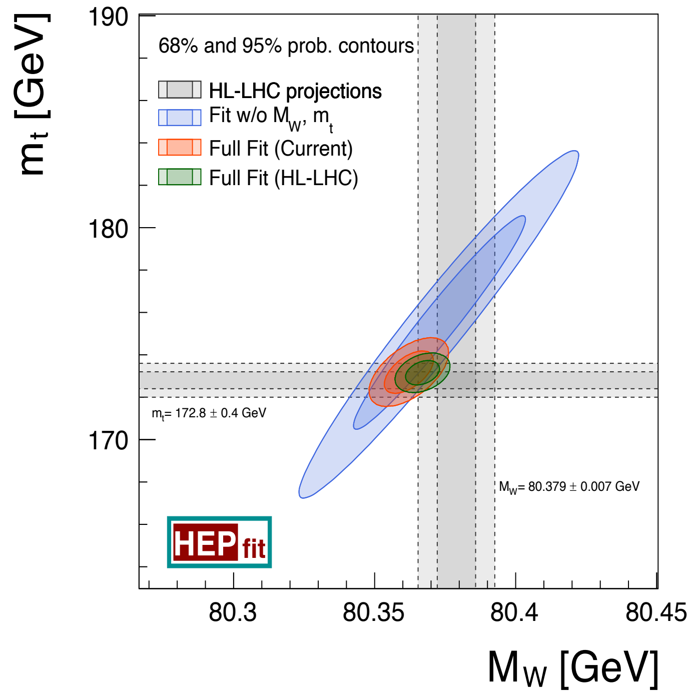




Higgs from discovery to precision physics



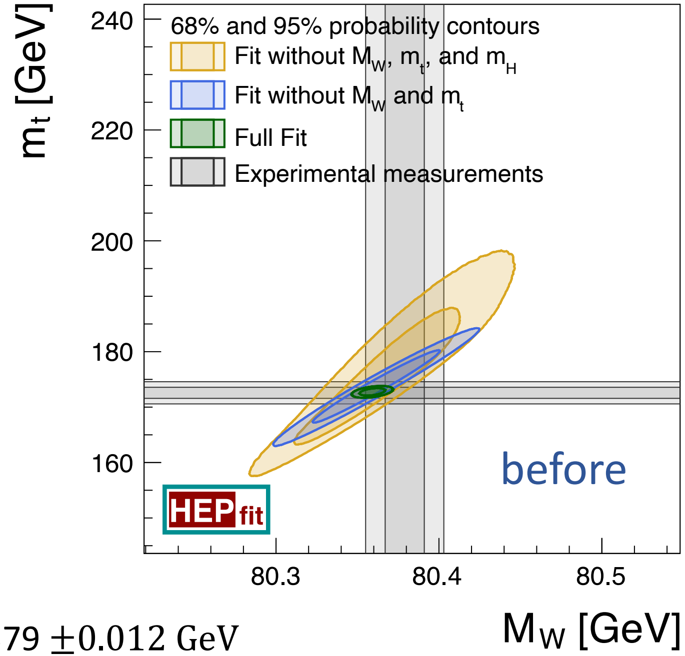




M_H promoted to EW precision observable

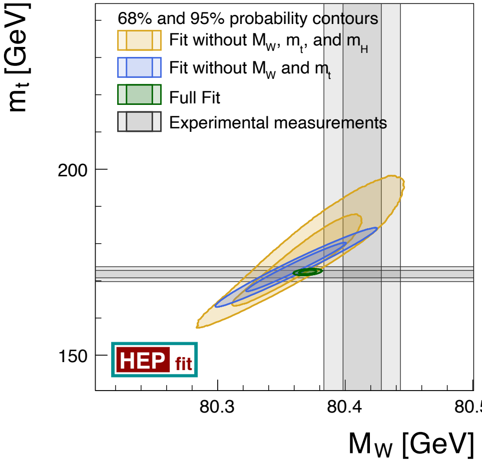
Stress-testing the SM

A recent challenge: CDF new M_W measurement



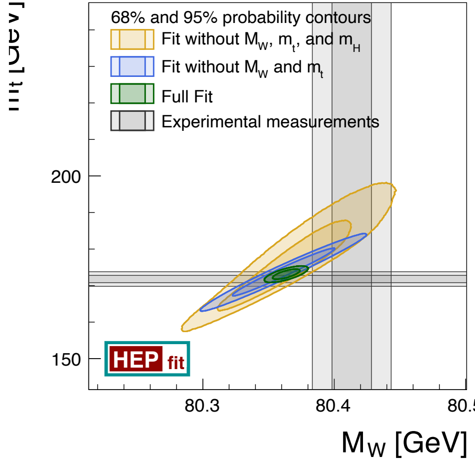
De Blas et al. [2204.04204]

M_W=80.379 ±0.012 GeV



after "standard"

M_W=80.4133 ±0.0088 GeV



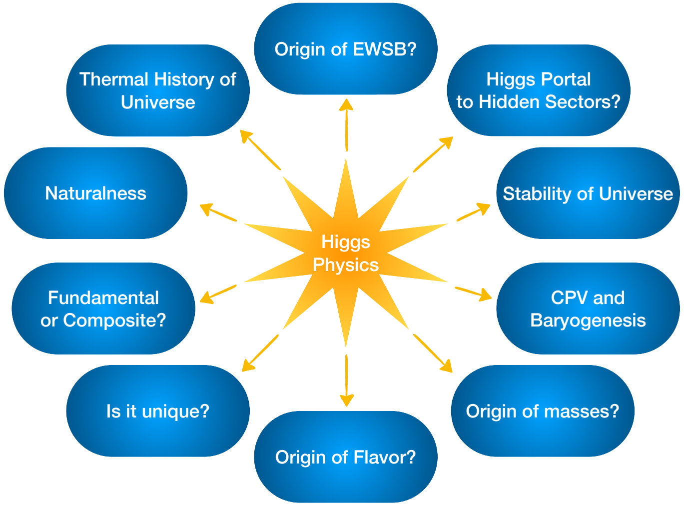
after "conservative"

M_W=80.4133 ±0.015 GeV

The big open questions

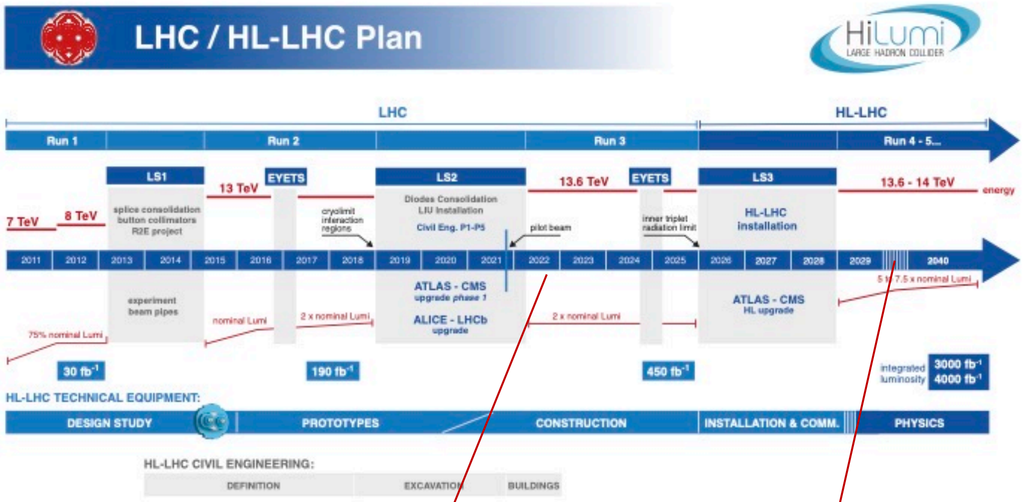
What is the origin of the EW scale?

The discovery of the Higgs boson has sharpened the big open questions and given us a unique handle on BSM physics.



- Why the $M_H \ll M_{planck}$ **hierarchy problem**?
- What are the implications for **Naturalness**?
- Can we uncover the origin of BSM physics from precision measurement of Higgs properties (couplings, width, …). **Elementary vs composit**? **One Higgs**? **More**?
- Can we measure the shape of the **Higgs potential** ⟶ **Higgs self coupling(s)**
- Can Higgs properties give us **insights on flavor** and vice versa?
  - Couplings to heavy flavors (bottom, **top**, ..)
  - Couplings to light quarks and leptons

The LHC era: exploring the TeV scale



We are only here

Many years of HL running ahead of us

Indirectly via Higgs and Top:

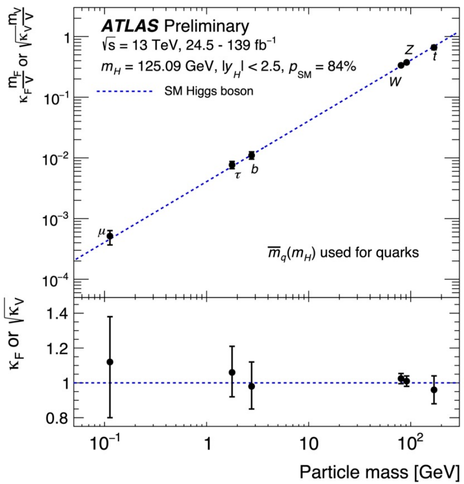
- Run 2 delivery for Higgs couplings outperformed expectations

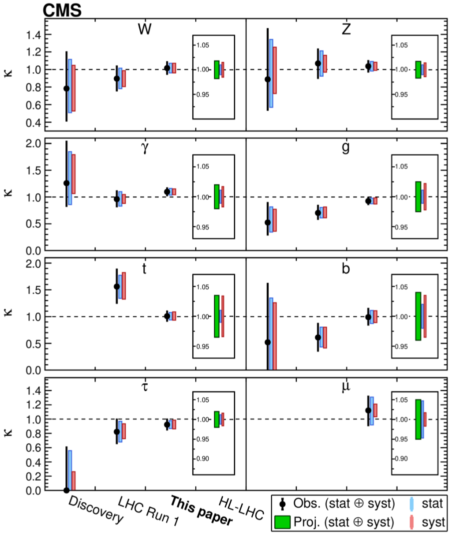
- LHC will define top physics till the next high-energy collider
  - e^+e^- > 500 GeV
  - pp@100 TeV
  - $\mu+\mu^-$ > 10 TeV

➔ 2-fold increase in statistics by the end of Run 3
➔ 20-fold increase in statistics by the end of HL-LHC!

Higgs zooming on couplings

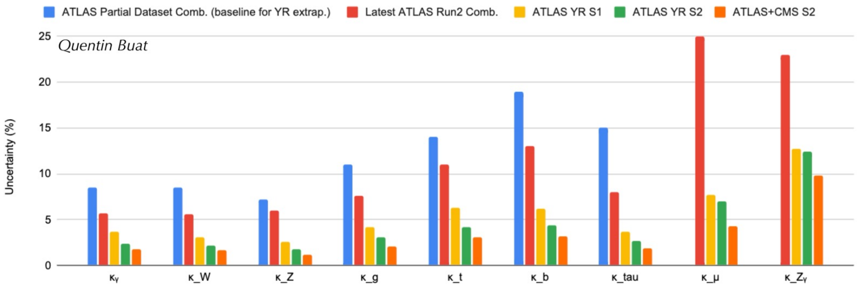
$\kappa = g_X / g_X^{SM}$



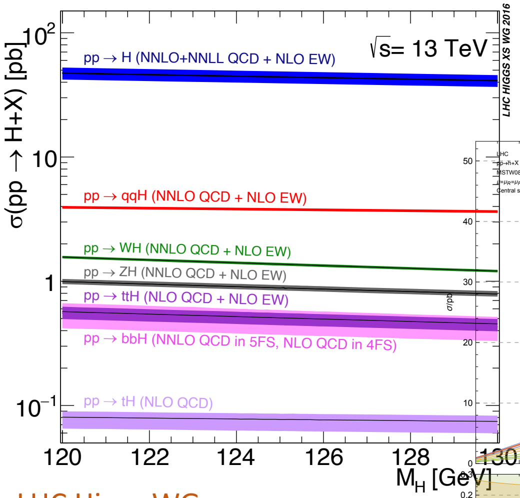


- ➢ Couplings to W/Z at 5-10 %, couplings to 3rd generation fermions to 10-20%
- ➢ First measurements of couplings to 2nd generation fermions
- ➢ HL-LHC projections from YR: 2-5 % on most couplings and <50% on Higgs self-coupling

Full Run2 results drastically improve partial Run 2 results (baseline for YR projections)

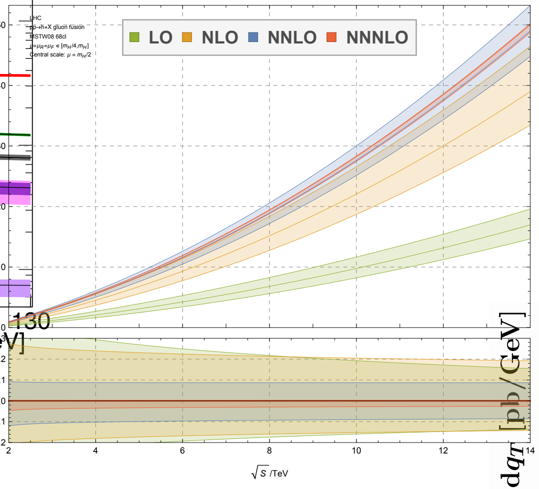


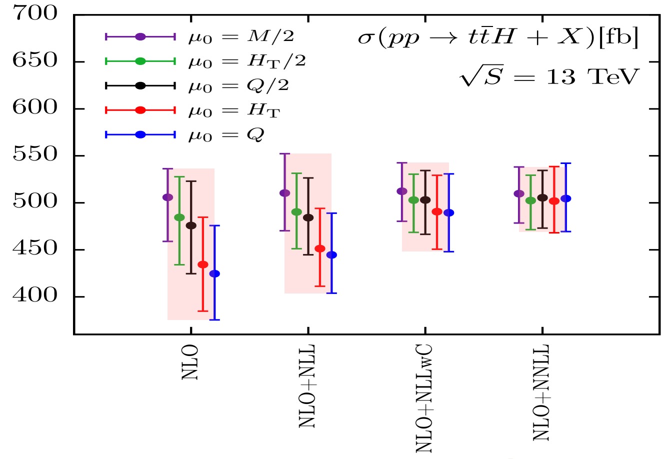
Theory has come a long way



LHC Higgs WG

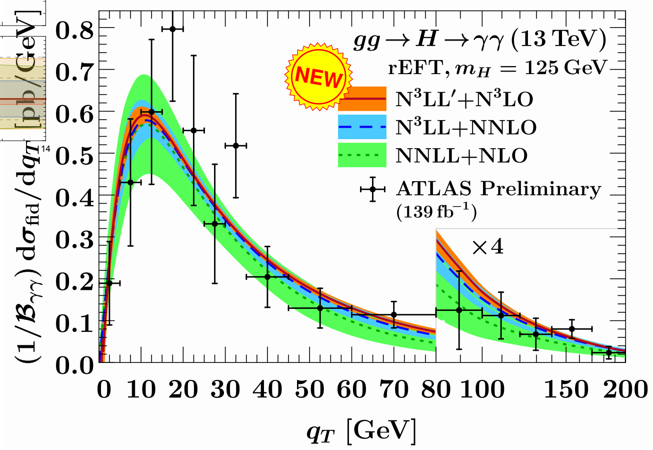
Anastasiou et al. [1502.06056]





Kulesza et al. [1812.08622]

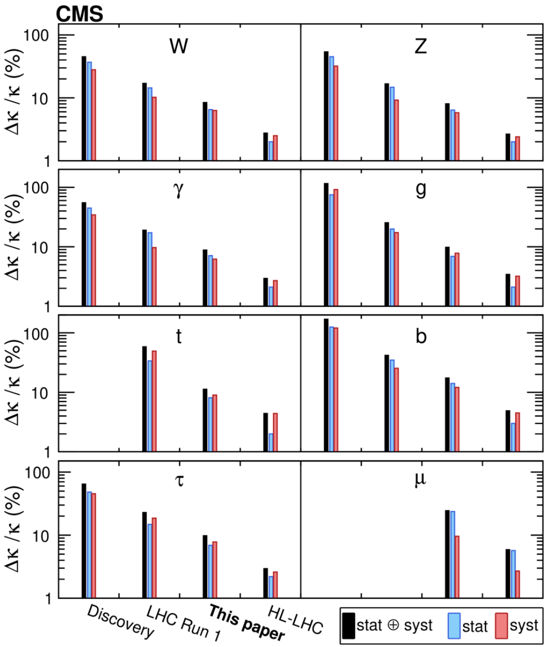
Poncelet et al.

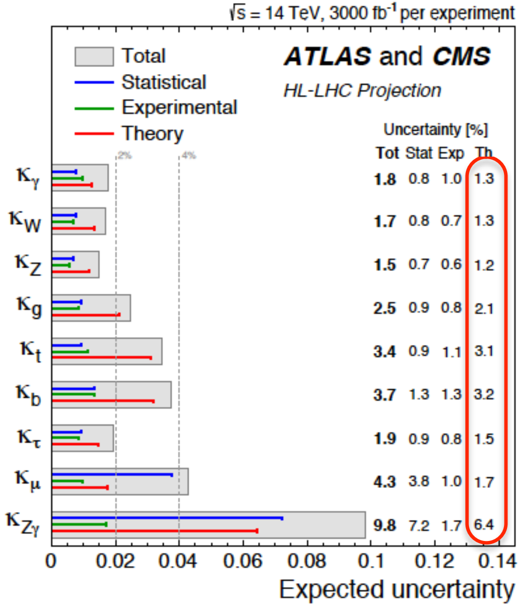


Several backgrounds also know at
NLO QCD+EW or improved NLO (+NNLL)
(e.g. W/Z+j, ttbb, ttW, ttZ, ttγ, …)

Higgs

zooming on couplings, a little more …





Generically:

$\Delta\kappa/\kappa \sim O(v^2/\Lambda^2)$

For new physics at 1 TeV expect deviations of O(6%)

Improved systematics probes higher scales

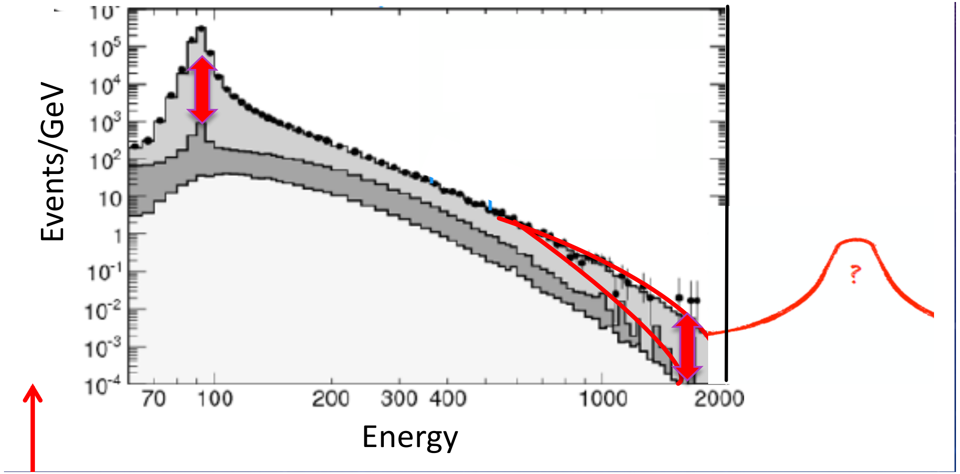
↕

Theory could become main limitation

Theory need to improve modeling and interpretation of LHC events, in particular when new physics may not be a simple rescaling of SM interactions

Beyond total rates

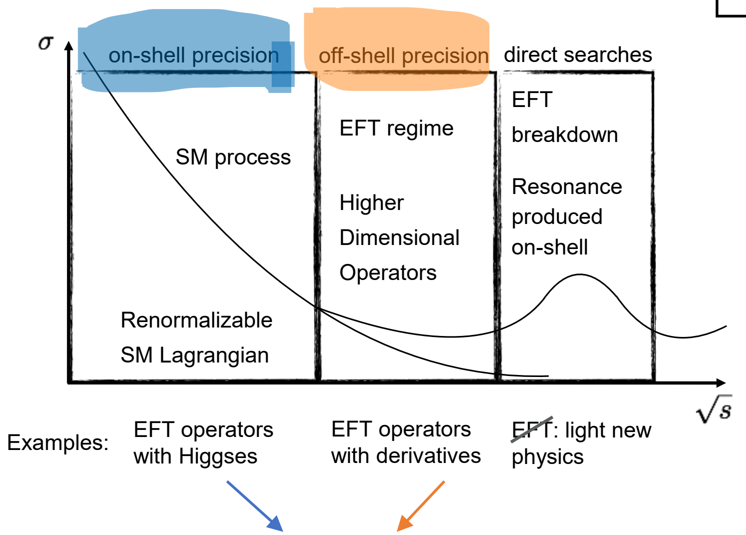
Extending the SM via effective interactions above the EW scale ⟶ **SMEFT**



$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \left(\frac{1}{\Lambda^2}\sum_i C_i O_i + \text{h.c.}\right) + O(\Lambda^{-4})$$

dim=6

dim>8



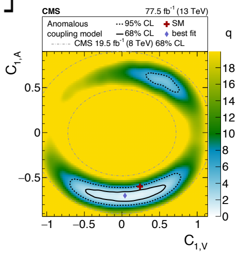
Crucial to control EFT sensitive regions

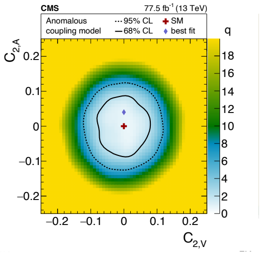
Need SM precision calculations at differential level both at **lower energy,** where rates are large and at **higher energy** where rates are small but effects of new physics may be more visible.

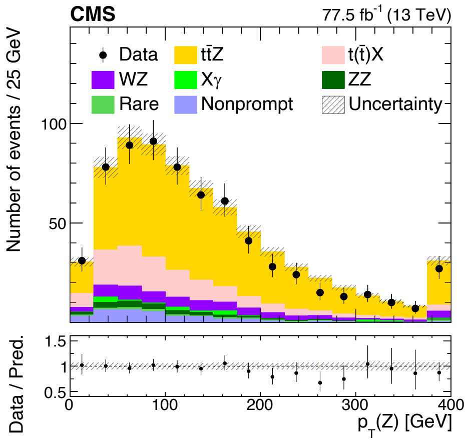
Ex: Interpreting $t\bar{t}Z$ measurements

Anomalous top couplings

$$\mathcal{L} = e\bar{u}(p_t)\left[\gamma^\mu(C_{1,V} + \gamma_5 C_{1,A}) + \frac{i\sigma^{\mu\nu}q_\nu}{M_Z}(C_{2,V} + i\gamma_5 C_{2,A})\right] v(p_{\bar{t}})Z_\mu$$





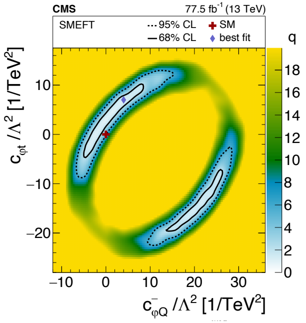


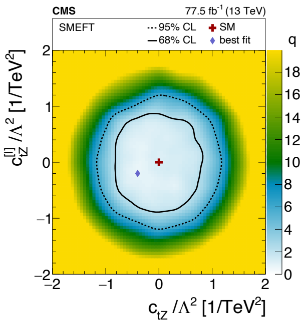
Effective operators

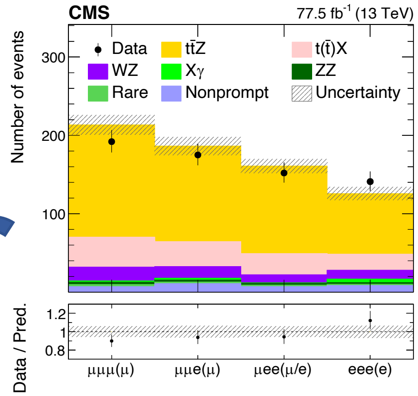
$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \left(\frac{1}{\Lambda^2}\sum_i C_i O_i + \text{h.c.}\right) + O(\Lambda^{-4})$$

$$\begin{aligned}
O_{uZ} &= -s_W O_{uB} + c_W O_{uW} \\
O_{uB} &= (\bar{q}\sigma^{\mu\nu}u)(\epsilon\varphi^* B_{\mu\nu}) \\
O_{uW} &= (\bar{q}\tau^I\sigma^{\mu\nu}u)(\epsilon\varphi^* W^I_{\mu\nu}) \\
O_{\varphi u} &= (\bar{u}\gamma^\mu u)(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi) \\
O^-_{\varphi q} &= O^1_{\varphi q} - O^3_{\varphi q} \\
O^1_{\varphi q} &= (\bar{q}\gamma^\mu q)(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi) \\
O^3_{\varphi q} &= (\bar{q}\tau^I\gamma^\mu q)(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)
\end{aligned}$$

...







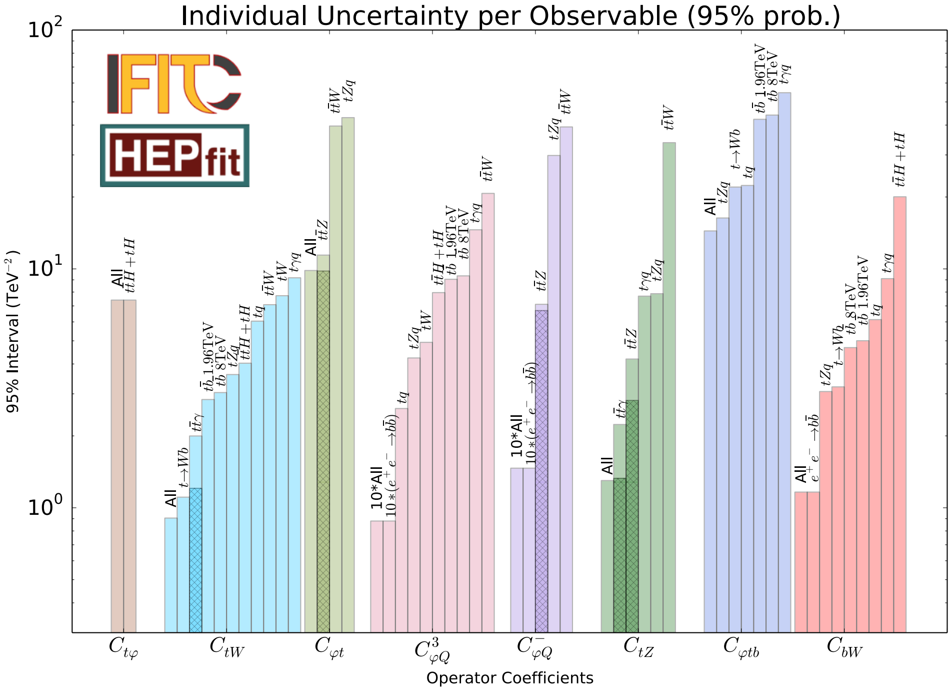
CMS [arXiv:1907.11270]

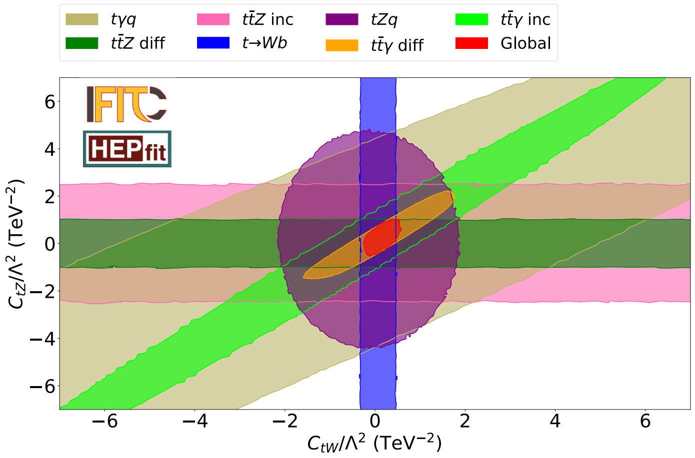
ttZ searches in 3l and 4l signatures

EFT allows multiple probes

Global fits of top observables

V. Miralles, et al. [arXiv:2107.13917]



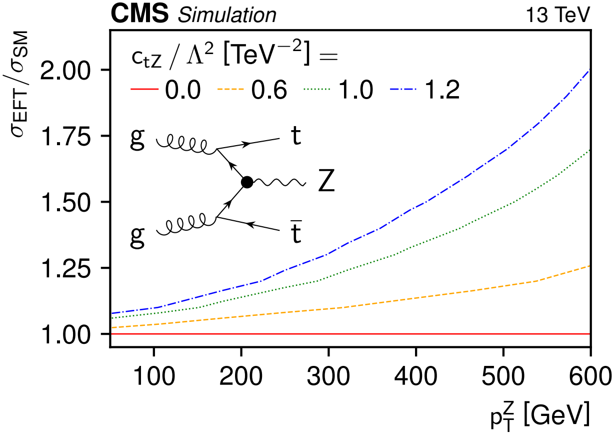


Kinematic distributions add substantial constraining power

Accurate modelling of $t\bar{t}$+X differential cross sections and signatures becomes crucial

… exploring boosted kinematics and off-shell signatures

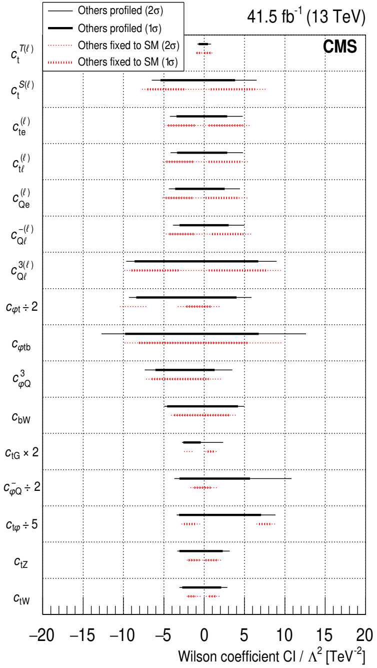
Top pair + boosted Z/H



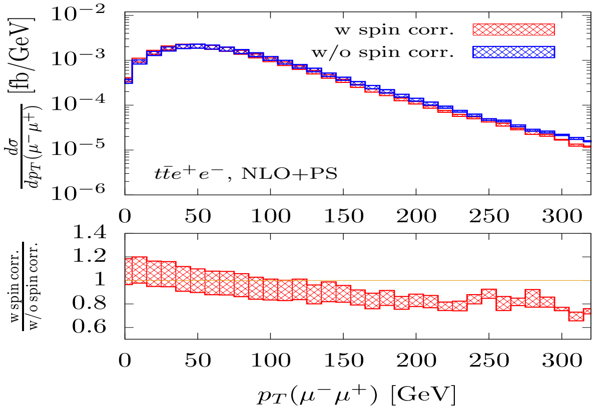
$$\delta\eta_{\rm SM} \sim g_{\rm BSM}^2 \frac{E^2}{M^2}$$

Effects in tails of distributions but also anomalous shapes

Top+additional leptons

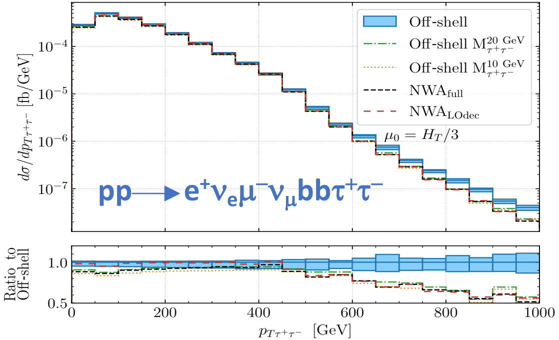


[CMS: arXiv:2012.04120]



M. Ghezzi et al. [2112.08892]

Off-shell studies

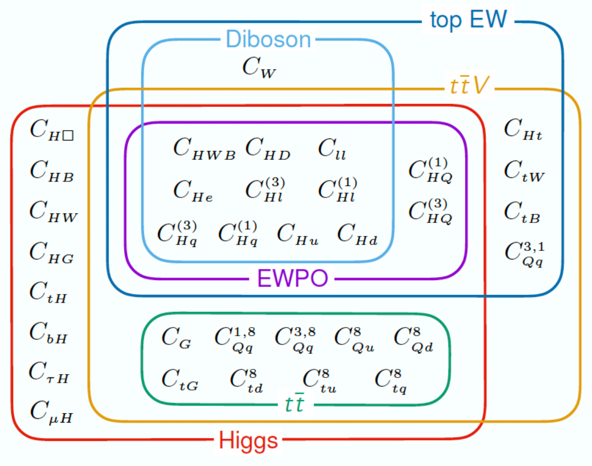


G. Bevilacqua et al. [2203.15688]

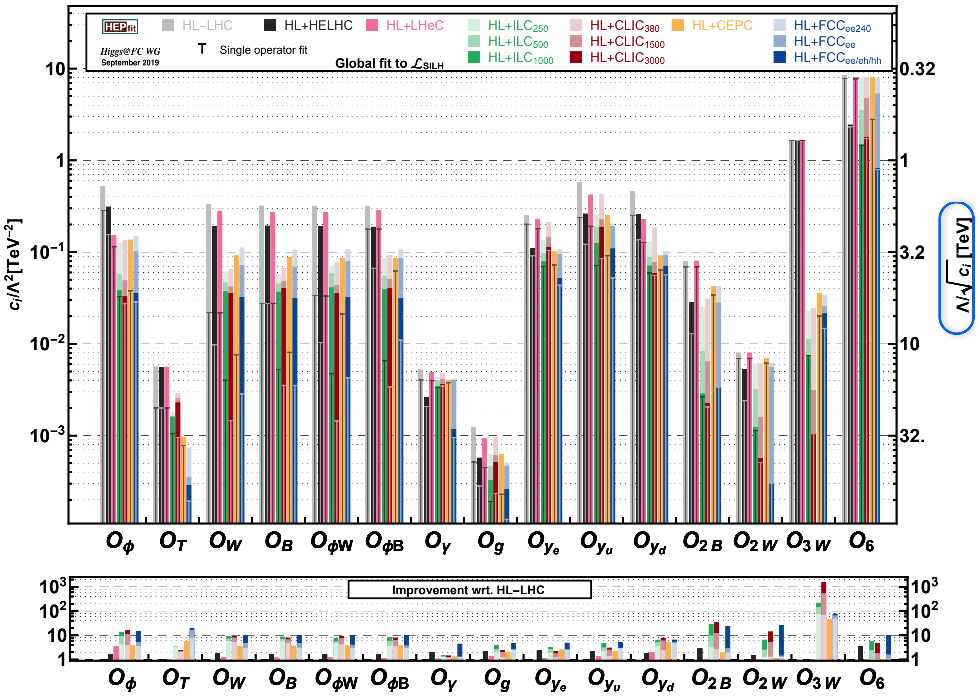
Pointing to the need for precision in modelling signatures from $t\bar{t}$+X processes in regions where on-shell calculations may not be accurate enough

EFT global fits

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \left(\frac{1}{\Lambda^2} \sum_i C_i O_i + \text{h.c.} \right) + O(\Lambda^{-4})$$



EW + Higgs



EFT connects different processes with large correlations: pattern of coefficients give insights on underlying BSM model

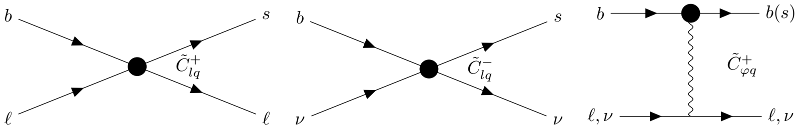
… adding EW + Higgs + top and flavor!

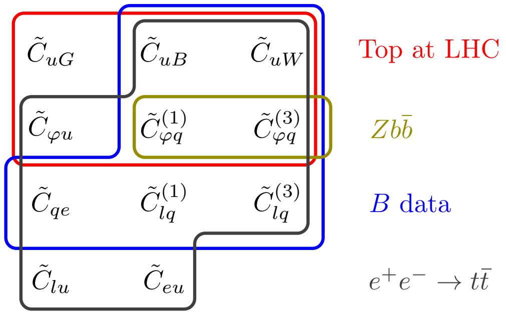
$$\mathcal{L}_{\rm SM}^{\rm EFT} \xrightarrow{\Lambda \ll \Lambda_{EW}} \mathcal{L}_{\rm Weak}^{\rm EFT} = \sum_{i=1}^{10} C_i^{\rm WEFT} \mathcal{O}_i^{\rm WEFT}$$

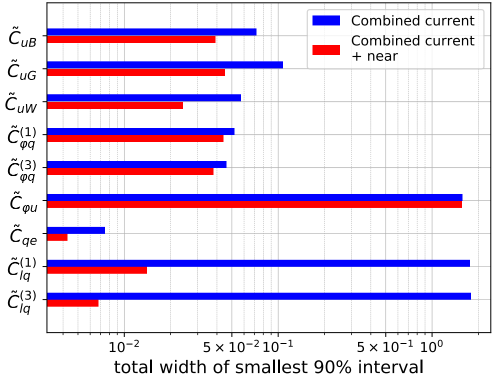
where

$\mathcal{O}_i^{\rm WEFT} \rightarrow$ 4-fermion operators of quarks(except t) and leptons

$C_i^{\rm WEFT} \rightarrow$ depend on $C_i^{\rm SMEFT}$







near:
including Belle II
and HL-LHC

Strong constraint from B-meson semileptonic decays
and intriguing relation with flavor anomalies

Bissman et al. [arXiv:2-12.10456]