Higgs Hunting 2021

Theory highlights and concluding remarks

Laura Reina
Florida State University

Particle physics in the LHC era: a unique time

We are only here

Many years of HL running ahead of us!

So much of the LHC physics potential is ahead of us:

↪ c.o.m. energy will increase from 13 TeV to 14 TeV.

↪ 2-fold increase in statistics by the end of Run 3.

↪ 20-fold increase in statistics by the end of the HL-LHC!

The LHC era: Exploring the TeV scale

- **LHC Run 1**: the **Higgs discovery** has been a game changer.
- **LHC Run 2**: **a wealth of new measurements**.
  - ▷ Improved precision measurements of SM processes, total and differential rates.
  - ▷ Entering the era of precision Higgs physics.
  - ▷ More stringent bounds on new physics scenarios.
- The **LHC Run 3** and the **HL-LHC** are **a reality**.
- Updated scenarios for **future colliders are being proposed** based on LHC results, HL-LHC projections, and theory recommendations.
- Intriguing results coming from **rare processes**, **flavour physics**, **cosmology**, ... can give important indications.

With no evidence of new physics or a preferred way beyond the Standard Model **progress crucially relies on our ability to discern, describe, and interpret the complexity of LHC events**.

Higgs physics has been **at the core of the LHC physics program** and will continue to be so for Run 3 and the HL-LHC upgrade, as well as for all future colliders currently under discussion.

↪ **Measuring anomalies** in **SM Higgs properties** (couplings, CP, . . .).

↪ **Searching** for **new signatures** (anomalous interactions, exotic decays, new particles, . . .).

↪ See ATLAS and CMS talks

The role of theory is very challenging

↪ **Posing the right questions!**

↪ **Setting the SM framework unambiguously.**

↪ **Recognizing and interpreting new phenomena**

- ↪ **Model-specific** approach: more stringent, yet arbitrary.
- ↪ **Effective Field Theory** approach: less arbitrary, more systematic, but less prone to a simple, direct interpretation.

Several contributions presented at this meeting

↪ See talks by Craig, Gori, Mantani, Michel, Pages, Pellen, Plehn, Ramos, Ravasio, Tong, ...

Key Question: What is the origin of the EW scale?

The Higgs discovery has posed us some fundamental questions and given us a unique handle on BSM physics.

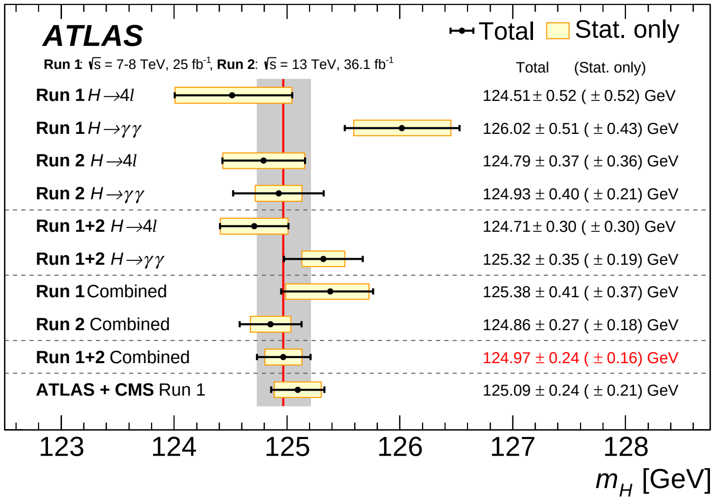
- Why the $M_H \ll M_{pl}$ hierarchy problem? What are the implications for Naturalness? (→ **Naturalness strategy**)
- Can we uncover the nature of UV physics from precision Higgs measurements? (→ **Elementary vs composite**? **Yukawa force**? **One/more Higgses**?)
- Can Higgs physics gives us insight into **flavor physics** and vice versa?
- Can we measure the shape of the **Higgs potential**?
- Can Higgs physics point us to new physics that could also explain the nature of **dark matter** and the origin of **baryogenesis**?

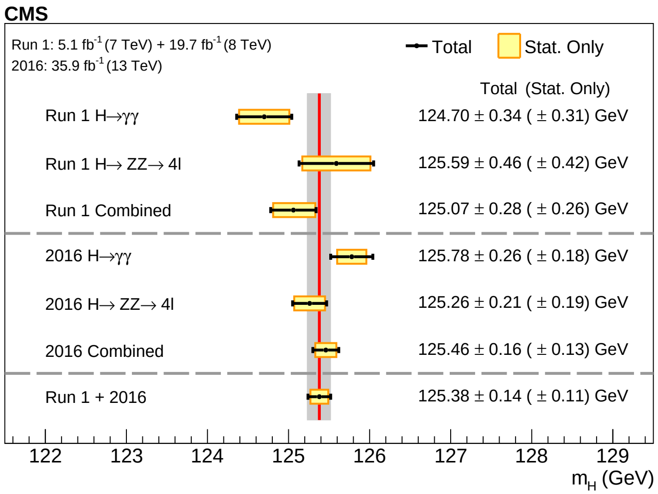
↪ See Craig's, Pages's, and Plehn's talks

Pursuing these theory-motivated benchmarks will shape our investigation and understanding of BSM physics.

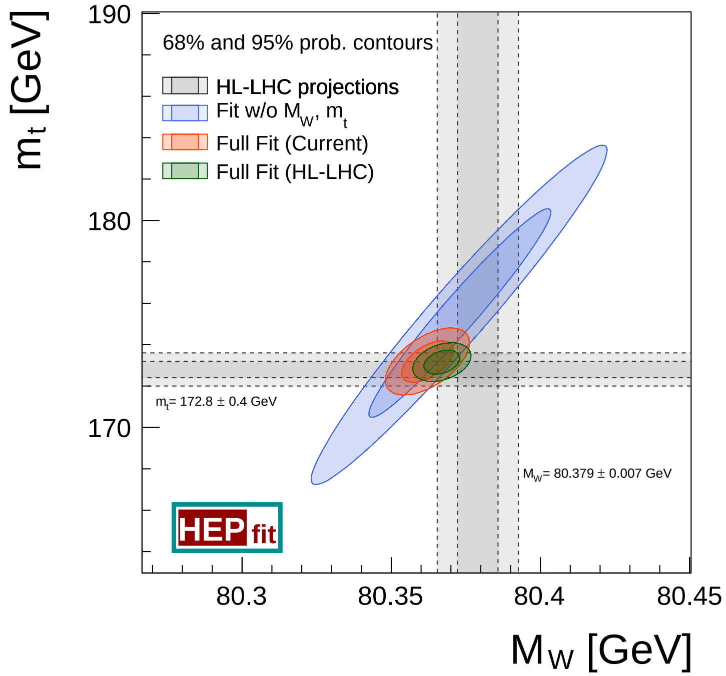
Setting the SM framework

LHC Run 1+Run 2: M_H promoted to EW precision observable





Crucial to realize the EW precision program of the HL-LHC.

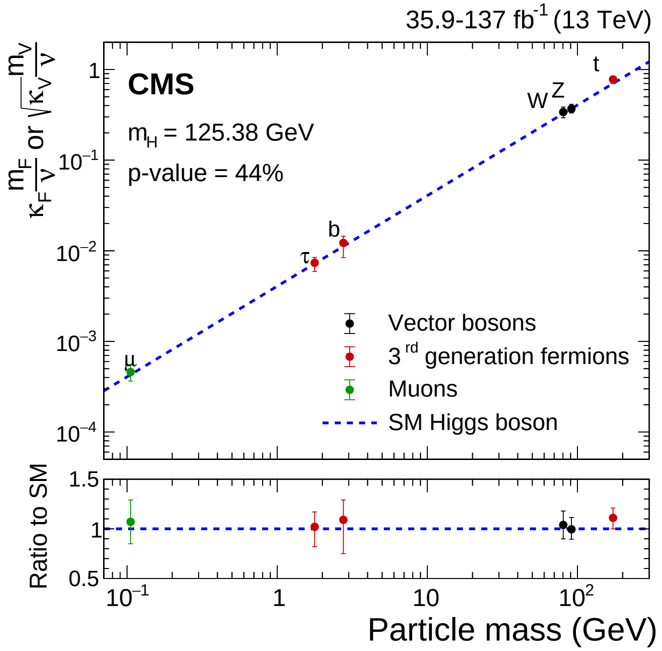


Still a crucial constraint for all BSM models

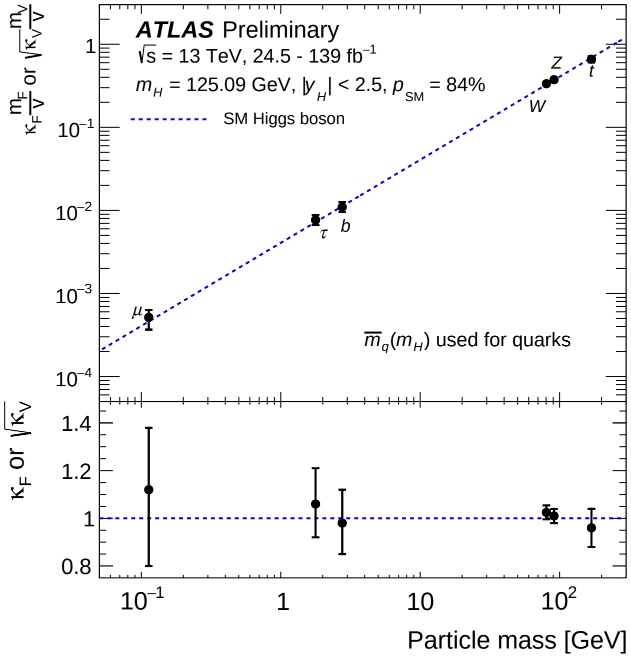
↪ See Tong's talks

Effects of New Physics can now be more clearly disentangled in both EW observables and Higgs-boson couplings $\longleftrightarrow$ $\boxed{\text{probing EWSB}}$

LHC Run 1+Run 2: first measurement of SM Higgs couplings



[CMS, JHEP 01 (2021) 148]



[ATLAS-CONF-2020-027]

κ_i	ATLAS	CMS	HL-LHC
κ_Z	$1.02^{+0.06}_{-0.06}$	$0.96^{+0.07}_{-0.07}$	1.5%
κ_W	$1.05^{+0.06}_{-0.06}$	$-1.11^{+0.14}_{-0.09}$	1.7%
κ_t	$0.96^{+0.08}_{-0.08}$	$1.01^{+0.11}_{-0.11}$	3.4%
κ_b	$0.98^{+0.14}_{-0.13}$	$1.18^{+0.19}_{-0.27}$	3.7%
κ_τ	$1.06^{+0.15}_{-0.14}$	$0.94^{+0.12}_{-0.12}$	1.9%
κ_μ	$1.12^{+0.26}_{-0.32}$	$0.92^{+0.55}_{-0.87}$	4.3%

$$\kappa_i = \frac{g_{Hi}}{g_{Hi}^{\mathrm{SM}}}$$

↪ Higgs couplings to gauge bosons measured to 5-10% level.

↪ Higgs couplings to 3^{rd}-generation fermions measured at 10-20%

↪ First measurement of Higgs couplings to 2^{nd}-generation fermions: κ_μ!

↪ **Projections for HL-LHC look impressive!**

↪ **Next challenge: probe new structures!** (EFT interactions, C$\not{P}$, ...)

↪ **Ultimate challenge: measuring the Higgs self-coupling(s).**

Exploring CP-violation in Higgs couplings

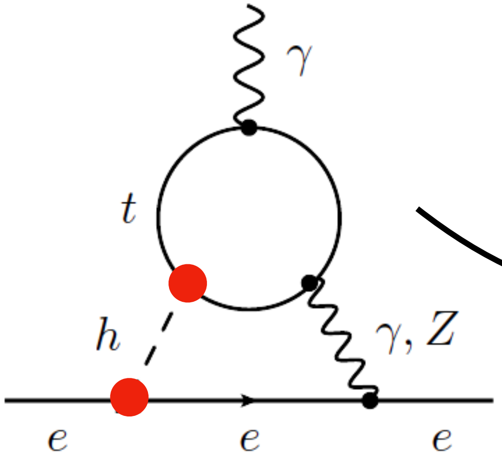
$\hookrightarrow$ See Gori's talk

If the **Higgs has CP violating couplings**:

$$\mathcal{L} \supset -\frac{y_f}{\sqrt{2}}\left(\kappa_f \bar{f} f + i\tilde{\kappa}_f \bar{f}\gamma_5 f\right) h$$

for example from dim. 6 operators:

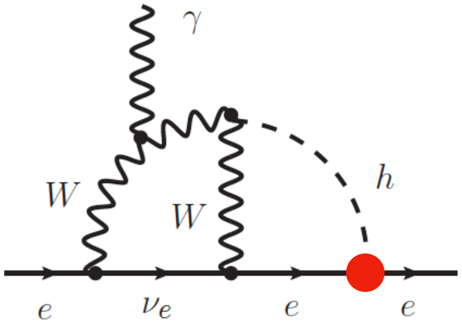
$$\frac{c}{M^2}|H|^2 \bar{e}_L H e_R$$



$$\frac{d_e}{e} = \frac{16}{3}\frac{\alpha}{(4\pi)^3}\sqrt{2}G_F m_e \left[\kappa_e \tilde{\kappa}_t f_1(x_{t/h}) + \tilde{\kappa}_e \kappa_t f_2(x_{t/h})\right]$$

electron EDM bound

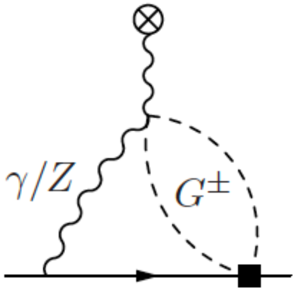
$$|\tilde{\kappa}_e| \lesssim 1.7 \times 10^{-2}$$
$$|\tilde{\kappa}_t| \lesssim 1.0 \times 10^{-2}$$



For the first time computed in Altmannshofer et al, 1503.04830

Gauge-dependent contributions to the EDM.

To achieve a gauge invariant result, one needs to add diagrams like:



UV-divergent.

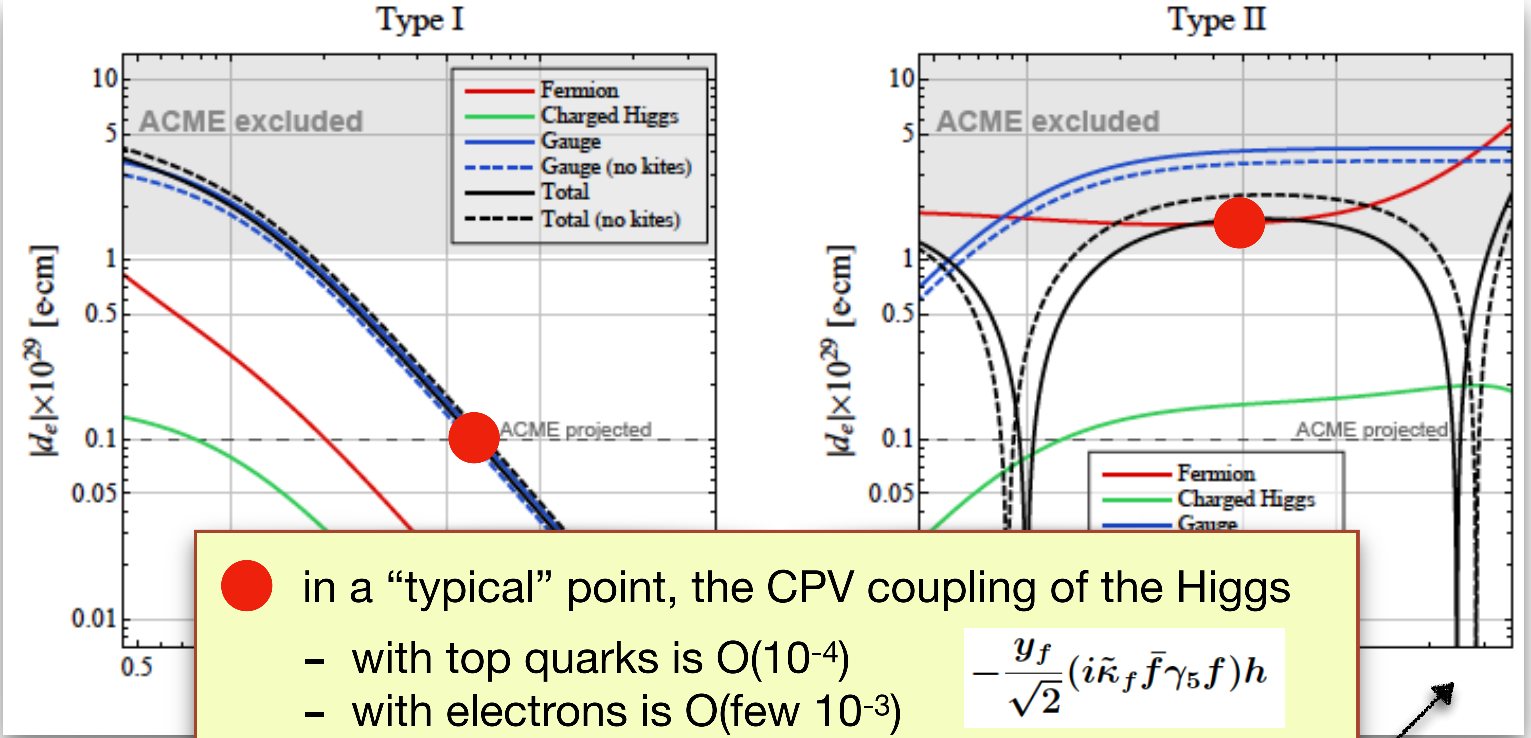
Problem of EFT approach

Altmannshofer, SG, Hamer, Patel, 2009.01258

A concrete Example: a complex 2HDM

Example benchmark:

Altmannshofer, SG, Hamer, Patel, 2009.01258



● in a “typical” point, the CPV coupling of the Higgs

- with top quarks is O(10^{-4})
- with electrons is O(few 10^{-3})

$$-\frac{y_f}{\sqrt{2}}(i\tilde{\kappa}_f\bar{f}\gamma_5 f)h$$

Cancellations

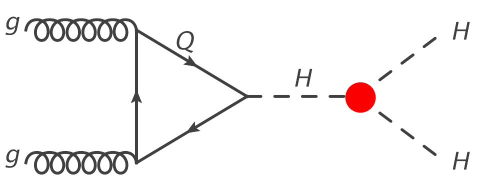
In the decoupling limit:

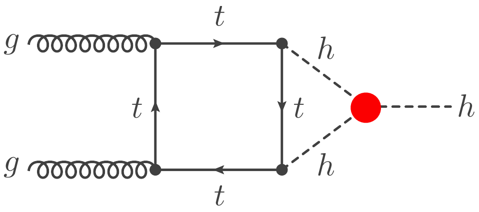
$$\text{Type I:}\quad d_e = -1.06\times10^{-27}e\,\text{cm}\times\left(\frac{1\,\text{TeV}}{M}\right)^2\,\text{Im}(\lambda_5)\quad\cos^2\beta\left[1+0.07\ln\left(\frac{M}{1\,\text{TeV}}\right)\right],$$

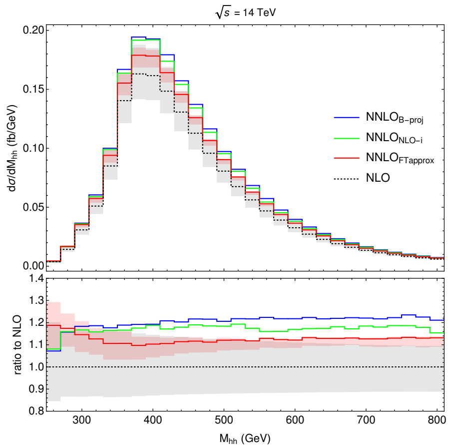
$$\text{Type II:}\quad d_e = 0.47\times10^{-27}e\,\text{cm}\times\left(\frac{1\,\text{TeV}}{M}\right)^2\,\text{Im}(\lambda_5)\left\{\sin^2\beta\left[1+0.16\ln\left(\frac{M}{1\,\text{TeV}}\right)\right]-1.26\cos^2\beta\right\}$$

The ultimate challenge: measuring the Higgs potential

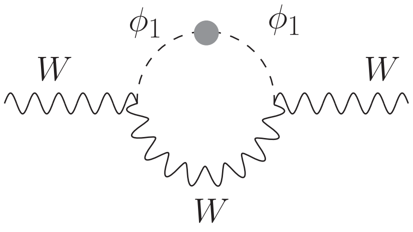
From double/single Higgs production
(cannot rely on large m_t approx.)
(Borowka et al., 1604.06447; Grazzini et al., 1803.02463)

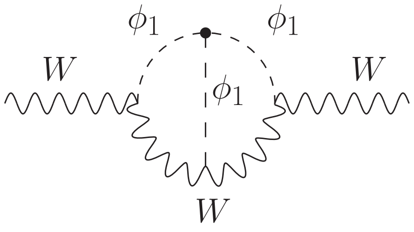


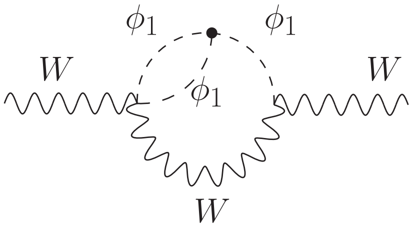


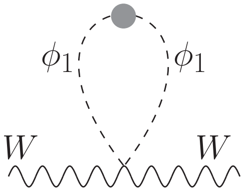


From indirect effects (Degrassi et al., 1702.01737; Kribs et al., 1702.07678)









Collider	Accuracy on κ_λ	Running Years
HL-LHC	50%	12
HE-LHC	10-20%	20
ILC(500)	27%	21
CLIC(1500)	36%	15
CLIC(3000)	+11%, -7%	23
FCC(hh)	5%	13

Higgs self-coupling(s) ↔ EWSB

- ↪ Double vs single H production?
- ↪ Indirect measurement?
- ↪ Can we measure both λ_3 and λ_4?

Odds can change by exploring all ideas!

Higgs self-coupling

Higgs self-coupling and baryogenesis

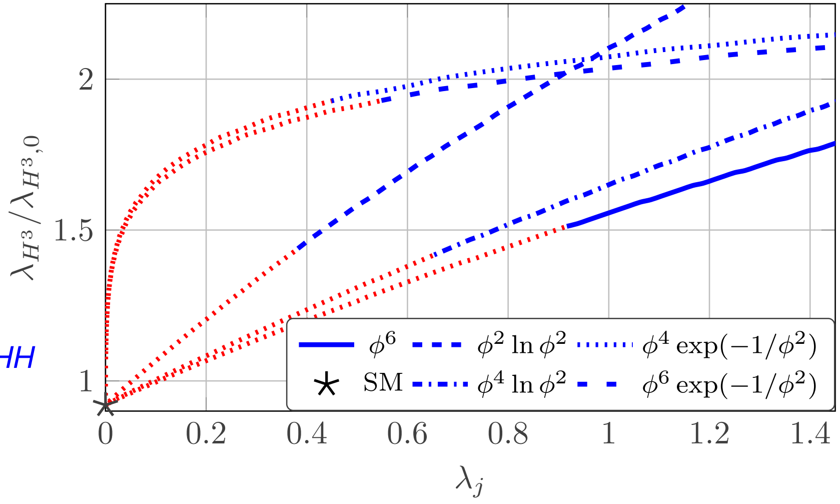
- Sakharov conditions

  baryon number violation
  C and CP violation
  departure from thermal equilibrium $\rightarrow$ 1st-order e-w phase transition
- D6-Higgs potential [Grojean, Servant, Wells]
  general potential [Reichert, Eichhorn, Gies, Pawlowski, TP, Scherer]

$$\Delta V_6 = \lambda_6 \frac{\phi^6}{\Lambda^2}$$

$$\Delta V_{\ln,2} = -\lambda_{\ln,2} \frac{\phi^2 \Lambda^2}{100} \ln \frac{\phi^2}{2\Lambda^2} \qquad \Delta V_{\ln,4} = \lambda_{\ln,4} \frac{\phi^4}{10} \ln \frac{\phi^2}{2\Lambda^2}$$

$$\Delta V_{\exp,4} = \lambda_{\exp,4} \phi^4 \exp\left(-\frac{2\Lambda^2}{\phi^2} + 23 \right) \qquad \Delta V_{\exp,6} = \lambda_{\exp,6} \frac{\phi^6}{\Lambda^2} \exp\left(-\frac{2\Lambda^2}{\phi^2} + 26 \right)$$

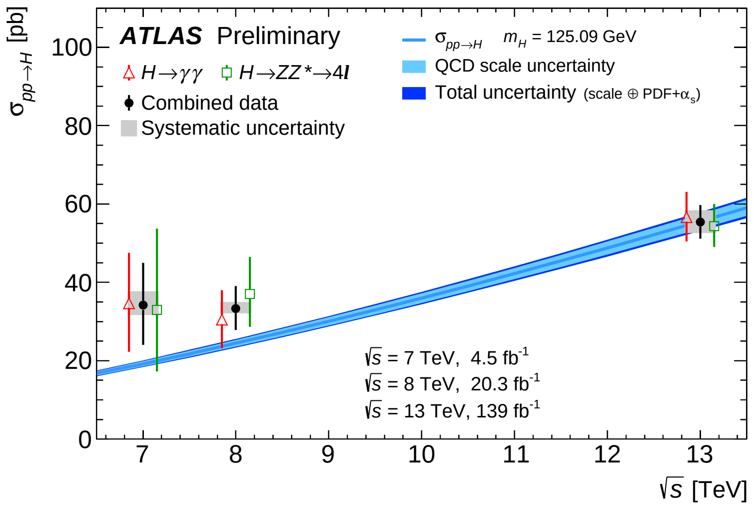


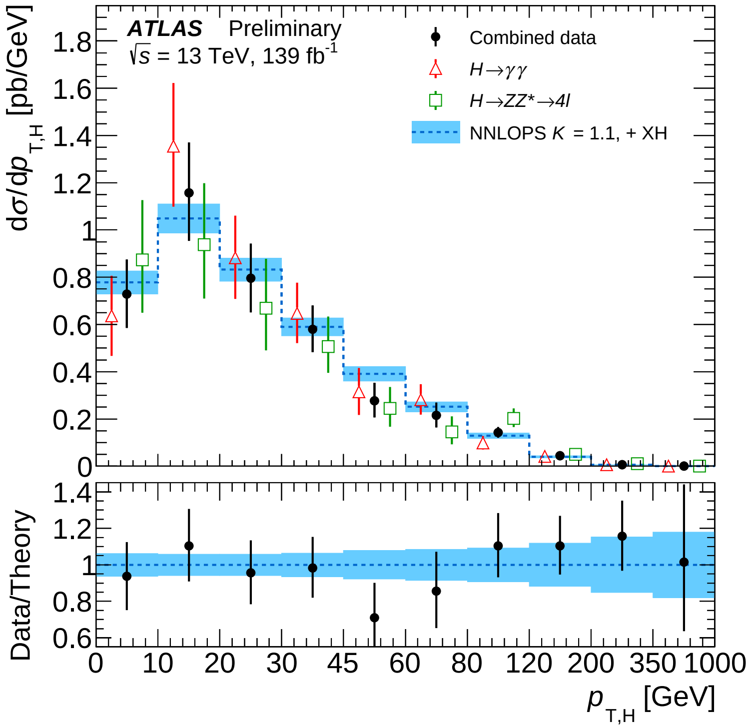
$\Rightarrow$ requiring 50% enhanced λ_{HHH}

$\hookrightarrow$ See Plehn's talk

A unique physics program in front of us!

From **Run 2** data: not only total but also **differential cross sections**.

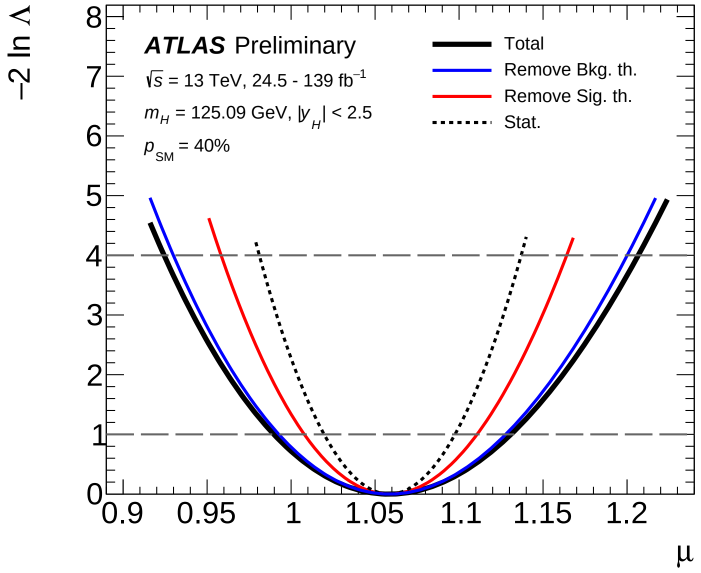




We can **explore new physics in different regimes**.

Is theory ready to take the challenge?

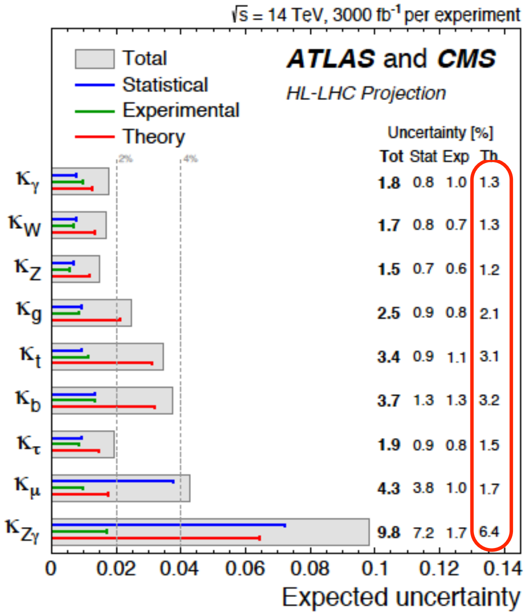
Theoretical systematics: warning of a possible limiting factor



$$\mu_{if} = \frac{\sigma_i}{\sigma_i^{SM}} \times \frac{B_f}{B_f^{SM}}$$

LHC: Large Theory systematics

$$\Downarrow$$



HL-LHC (S2: Theory syst. half of LHC)
Error dominated by Theory systematics

$$\kappa = \frac{g_{HX}}{g_{HX}^{SM}} = 1 + \Delta\kappa \longrightarrow \Delta\kappa \approx O\left(\frac{v}{\Lambda}\right)$$

↪ **Higher precision probes higher Λ**

Breakdown of residual uncertainties:

$$\mu_{\mathrm{ATLAS}} = 1.06 \pm 0.07 = 1.06 \pm 0.04(\mathrm{stat.}) \pm 0.03(\mathrm{exp.})^{+0.05}_{-0.04}(\mathrm{sig.th.}) \pm 0.02(\mathrm{bkg.th.})$$
$$\mu_{\mathrm{CMS}} = 1.02^{+0.07}_{-0.06} = 1.02 \pm 0.04(\mathrm{stat.}) \pm 0.04(\mathrm{exp.}) \pm 0.04(\mathrm{th.})$$

↪ See talks by Bonanomi and Zhou

With no evidence of new physics or a preferred way beyond the Standard Model, but compelling arguments to explore the TeV scale,
progress crucially relies on our ability to discern, describe, and interpret the complexity of LHC events.

What does complexity mean for theory?

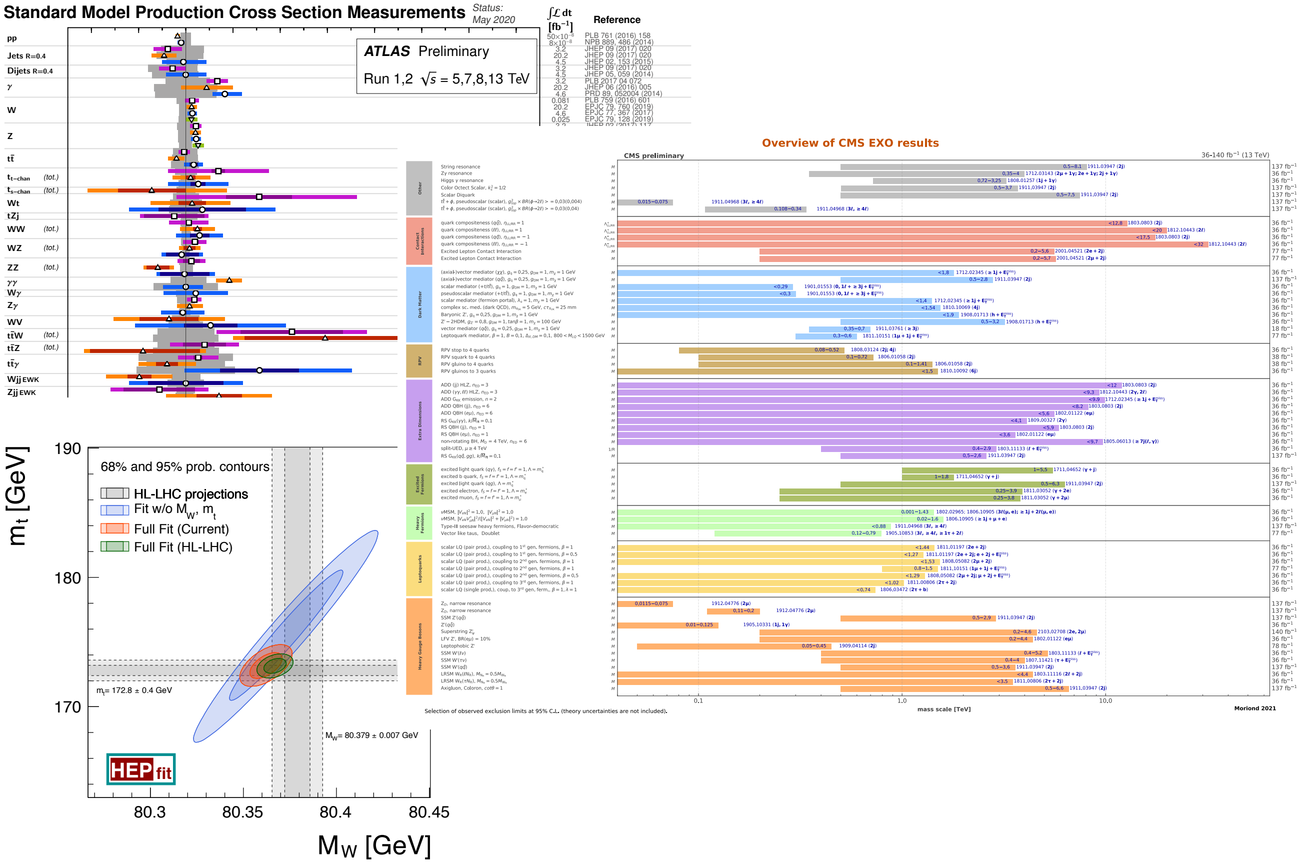
Embracing complexity in modelling and interpreting LHC events.

- Push precision for *standard candles* and improve description of key processes.
  - Higher-order perturbative QCD and EW corrections.
    - **N^{2}LO QCD** for all processes (total rates and distributions) and **N^{3}LO QCD** for keystone processes ($gg \to H$, $pp \to \gamma^*/Z/W^\pm$,...).
    - **NLO EW+QCD corrections** for all processes.
    - **Improved PDF** (>NLO QCD, QED)
    - **Resummation** of specific kinematic- or cut-induced large (logarithmic) corrections needs to be included.
    - Effects previously neglected need to be reconsidered (mass effects, . . .).
    - **NNLO+PS matching to parton-shower Monte Carlo** event generators
  - Extended precision to high-multiplicity processes.
    - Include accurate modelling of final-state decays.
    - Study off-shell effects.
  - Non-pertubative effects.
- Use cutting-edge techniques to extract more information from otherwise difficult data.
  - Precursor: jet substructure.
  - New approach to QCD dynamics via ML/DL techniques.
  - ML/AI algorithms to select difficult signals.

- Parametrize new physics in terms of more general effective interactions.
    - Parametrize BSM via EFT extension of SM Lagrangian.

$$\mathcal{L}_{\mathrm{SM}}^{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \sum_{d>4} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

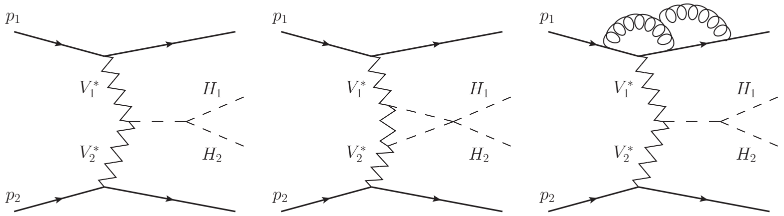
    - Constrain parameter space via SM fits and direct search results.
    - Connect to flavour physics within usual EFT language (SMEFT → WET).
    - Account for NP effects at all levels (signal, background, PDF fits, ...)
    - Interpret patterns by connecting to specific benchmark models.



Extend precision to high multiplicity processes and fiducial signatures.

Double Higgs production via VBF at the LHC

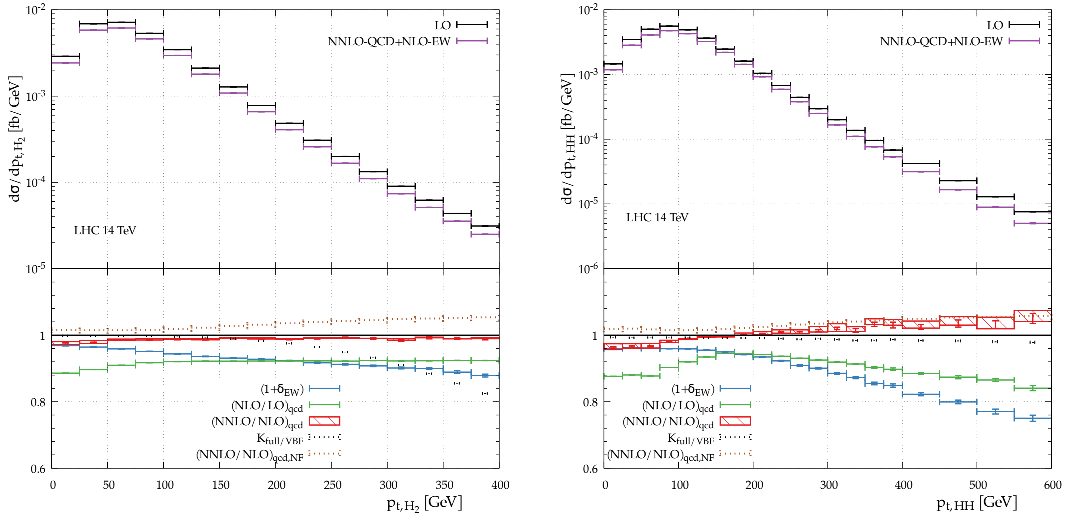
$\hookrightarrow$ See Pellen's talk



$pp \to HHjj$

manly VBF but also $VHH \to HHjj$

- VBF and $VHH \to HHjj$ at NLO QCD+EW
- VBF-only approximation at NNLO QCD+NLO QED

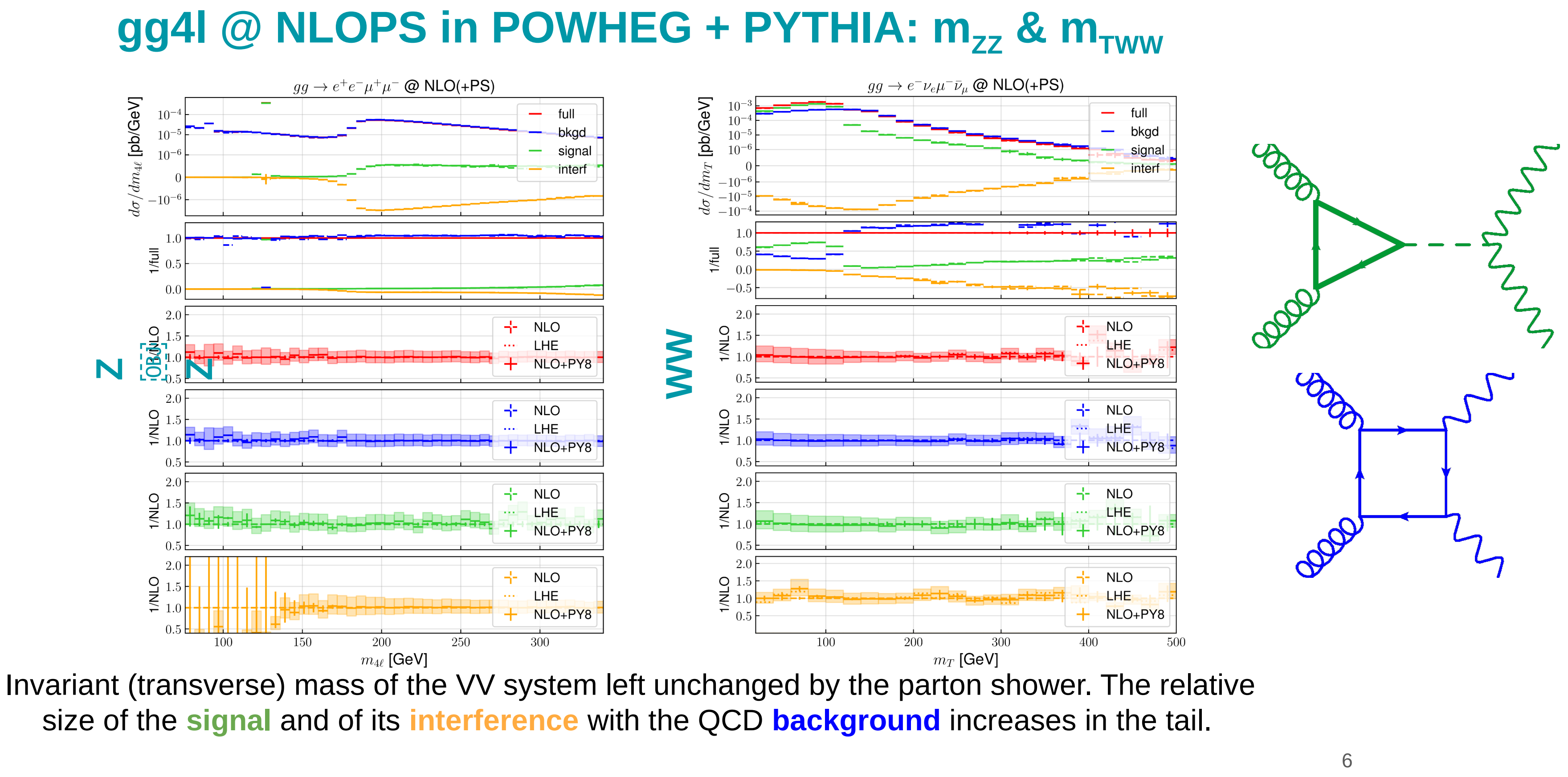


(Dreyer et al., 2005.13341)

- Effect of VBF approximation up to 20%.
- EW Sudakov logarithms in tails of distributions: -25%.
- EW corrections comparable to QCD ones.

NLO+PS generator for $gg \to H \to VV$ including non-resonant and off-shell effects

↪ See Ravasio's talk



gg4l @ NLOPS in POWHEG + PYTHIA: m_{ZZ} & m_{TWW}

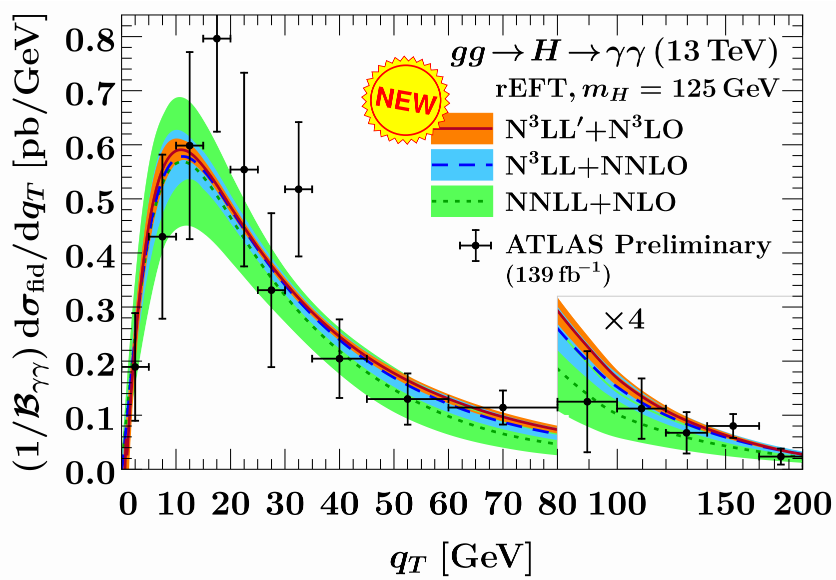
Invariant (transverse) mass of the VV system left unchanged by the parton shower. The relative size of the **signal** and of its **interference** with the QCD **background** increases in the tail.

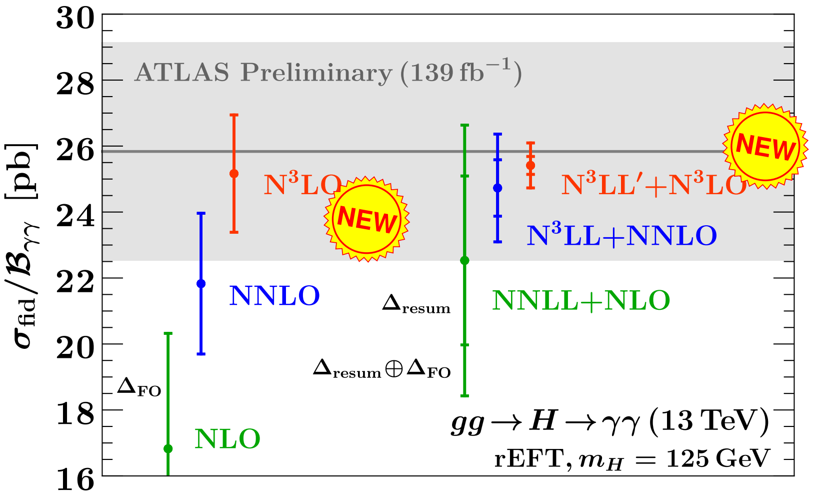
- Contribute at NNLO QCD to $pp \to VV \to 4l$
- QCD background is dominant and cannot be distinguished from the signal.
- Sensitive to $H \to VV$
- Offshell Higgs cross section important to determine $\Gamma_H \ll$ detector resolution.
- Implemented in POWHEG BOX RES, with V leptonic decays.

Fiducial predictions for $gg \to H \to \gamma\gamma$ at 3 loops

$\hookrightarrow$ See Michel's talk

- Inclusive cross section known at N^3LO (Anastasiou et al.)
- But LHC experiments apply kinematic selection cuts on Higgs decay products.
- Need complete interplay of QCD corrections and $O(1)$ fiducial acceptance.





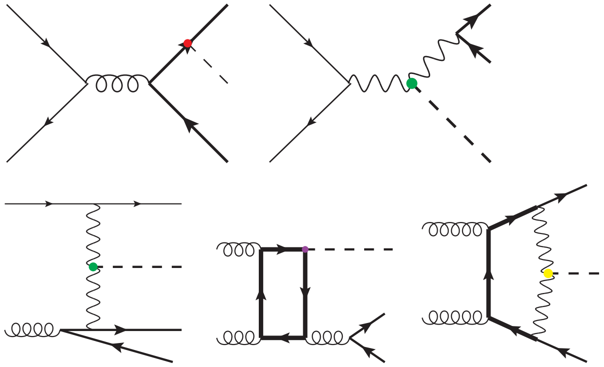
- Consider $gg \to H \to \gamma\gamma$ with ATLAS fiducial cuts (on p_T^γ and eta^γ).
- Computed fiducial spectrum for $q_T \equiv p_T^H = p_T^{\gamma\gamma}$ at $N^3LL'+N^3LO$.
- Computed total fiducial cross section at N^3LO, improved by resummation.

Use cutting-edge techniques to extract more information from otherwise difficult data.

$b\bar{b}H$: direct measurement of y_b obfuscated by several SM backgrounds

NLO QCD+EW corrections pollute the sensitivity to y_b and makes a cut base analysis hopeless: **RIP Hb$\bar{\mathbf{b}}$** [Pagani, Shao, Zaro, arXiv:2005.10277]

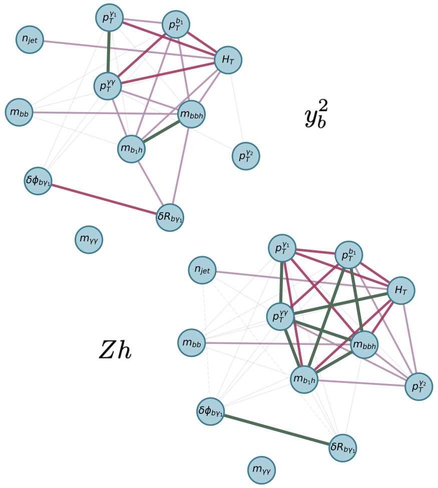
ratios	$\frac{\sigma(y_b^2)}{\sigma(y_b^2)+\sigma(\kappa_Z^2)} \equiv \frac{\sigma_{\mathrm{NLO}_{\mathrm{QCD+EW}}}}{\sigma_{\mathrm{NLO}_{\mathrm{all}}}}$ (y_b vs. κ_Z)	$\frac{\sigma(y_b^2)}{\sigma(y_b^2)+\sigma(y_t^2)+\sigma(y_b y_t)}$ (y_b vs. y_t)	$\frac{\sigma(y_b^2)}{\sigma(y_b^2)+\sigma(y_t^2)+\sigma(y_b y_t)+\sigma(\kappa_Z^2)}$ (y_b vs. κ_Z and y_t)
NO CUT	0.69	0.32	0.28
$N_{j_b} \geq 1$	0.37 (0.48)	0.19	0.14
$N_{j_b} = 1$	0.46 (0.60)	0.20	0.16
$N_{j_b} \geq 2$	0.11	0.11	0.06

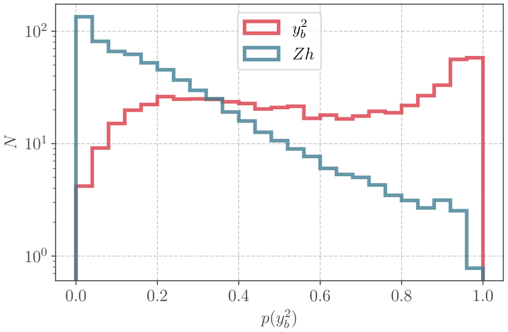


A kinematic-shape based analysis based on game theory (Shapley values) and BDT opened new possibilities: **Resurrecting $b\bar{b}h$ with kinematic shapes**

[Grojean, Paul, Qian, arXiv:2011.13945]

New techniques will open the possibility of turning problematic processes into powerful tests of the quantum structure of the SM.





Parametrize new physics in terms of more general effective interactions.

Parametrizing New Physics beyond specific BSM models

Extension of the SM Lagrangian by $d > 4$ effective field theory (EFT) operators:

$$\mathcal{L}_{\rm SM}^{\rm EFT} = \mathcal{L}_{\rm SM} + \sum_{d>4} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

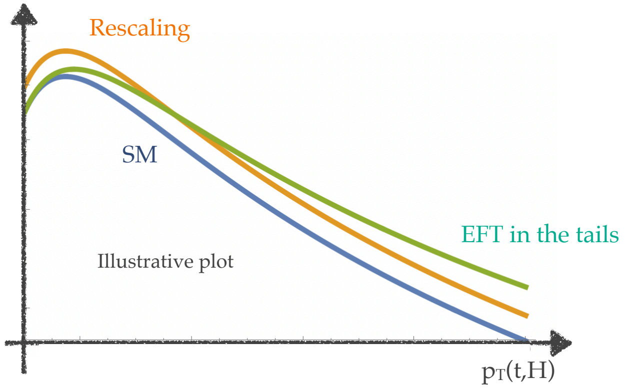
where

$$\mathcal{L}_d = \sum_i C_i^{(d)} \mathcal{O}_i^{(d)}, \quad \left[\mathcal{O}_i^{(d)}\right] = d\,,$$

under the assumption that new physics lives at a scale $\Lambda > \sqrt{s}$.

Expansion in $(v, E)/\Lambda$: affects all SM observables at both low and high-energy.

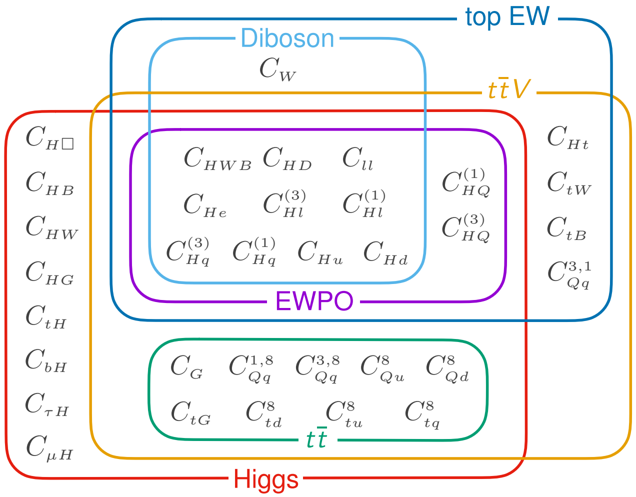
- SM masses, couplings → rescaling
- shape of distributions → more visible in high-energy tails



Systematic, yet complex approach.

$\Downarrow$

Studying correlations among operators can point to specific BSM patterns.


top EW

Diboson

C_W

$t\bar{t}V$

$C_{H\Box}$ C_{HB} C_{HW} C_{HG} C_{tH} C_{bH} $C_{\tau H}$ $C_{\mu H}$

C_{HWB} C_{HD} C_{ll}

C_{He} $C_{Hl}^{(3)}$ $C_{Hl}^{(1)}$

$C_{Hq}^{(3)}$ $C_{Hq}^{(1)}$ C_{Hu} C_{Hd}

$C_{HQ}^{(1)}$ $C_{HQ}^{(3)}$

C_{Ht} C_{tW} C_{tB} $C_{Qq}^{3,1}$

EWPO

C_G $C_{Qq}^{1,8}$ $C_{Qq}^{3,8}$ C_{Qu}^{8} C_{Qd}^{8}

C_{tG} C_{td}^{8} C_{tu}^{8} C_{tq}^{8}

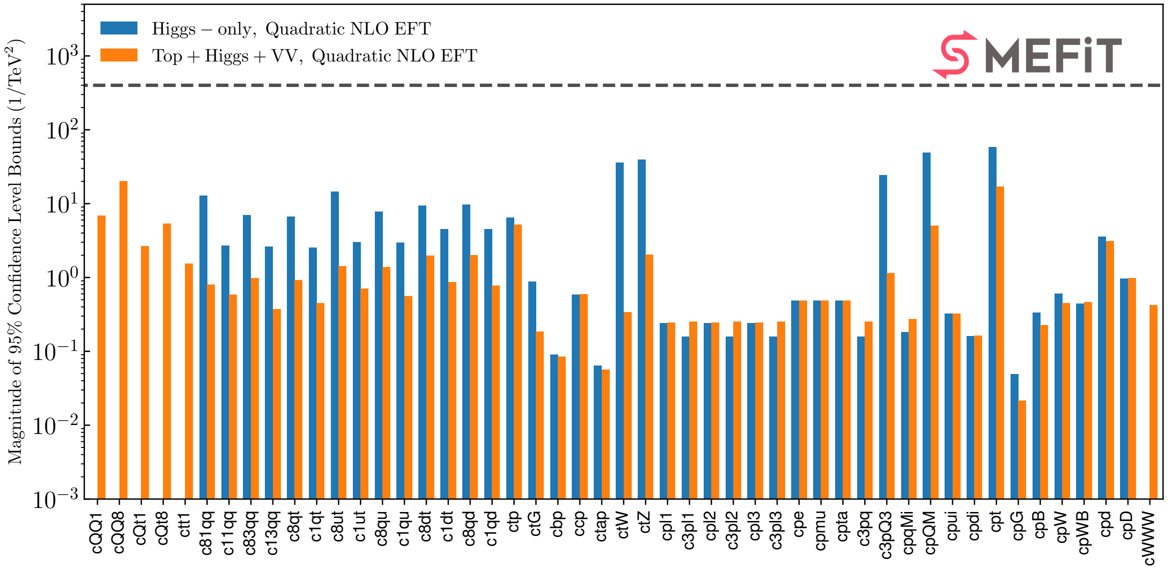
$t\bar{t}$

Higgs

← [Ellis, Madigan, Mimasu, Sanz, You, arXiv:2012.02779]

Global SMEFT fits: Gauge+Higgs+Top

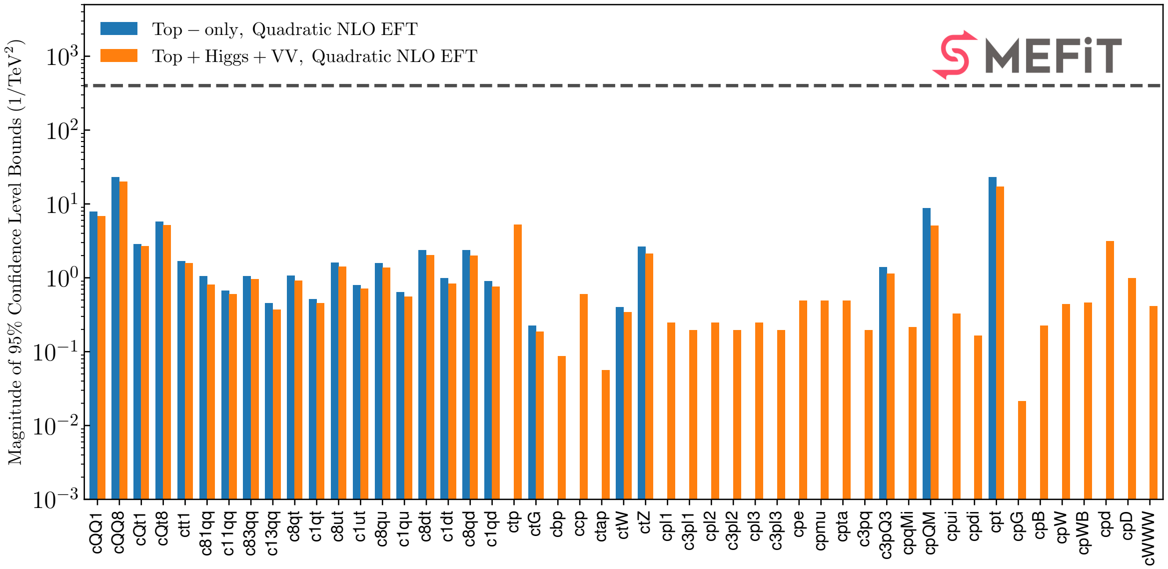
↪ See Mantani's talk



Theory

(N)NLO QCD+NLO EW SM XS

Linear vs Quadratic SMEFT



Data

Higgs data (incl, diff. STXS)

Top quark data

Diboson data (LEP+LHC)

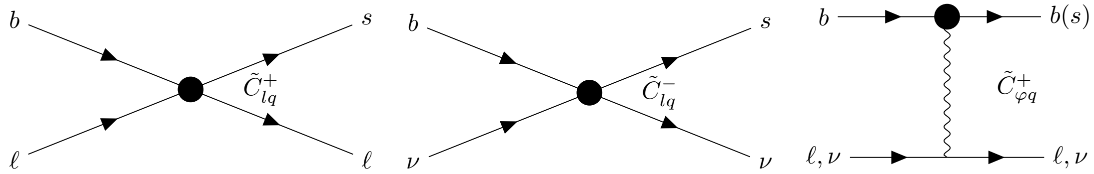
Constrain new physics via flavour observables

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

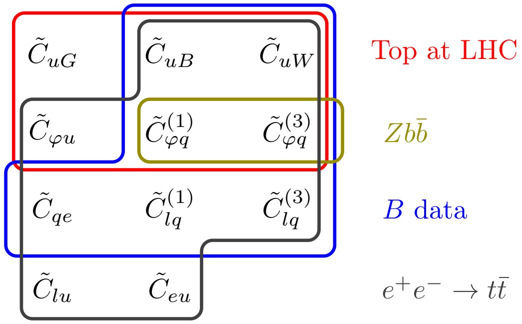
where

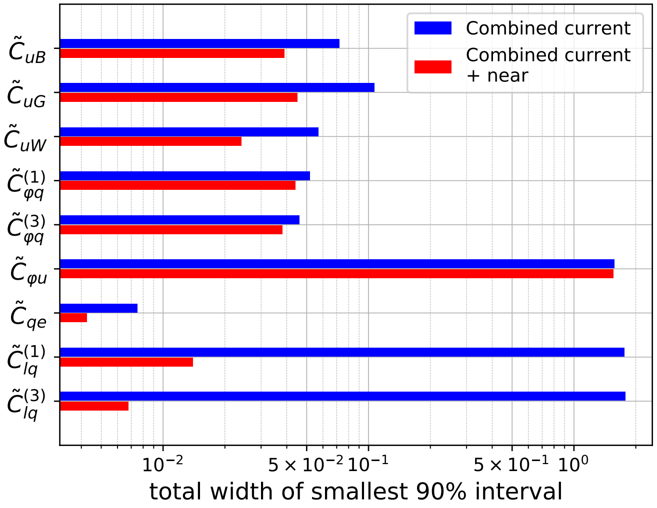
$\mathcal{O}_i^{\rm WEFT} \rightarrow$ 4-fermion operators of quarks(except t) and leptons

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



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



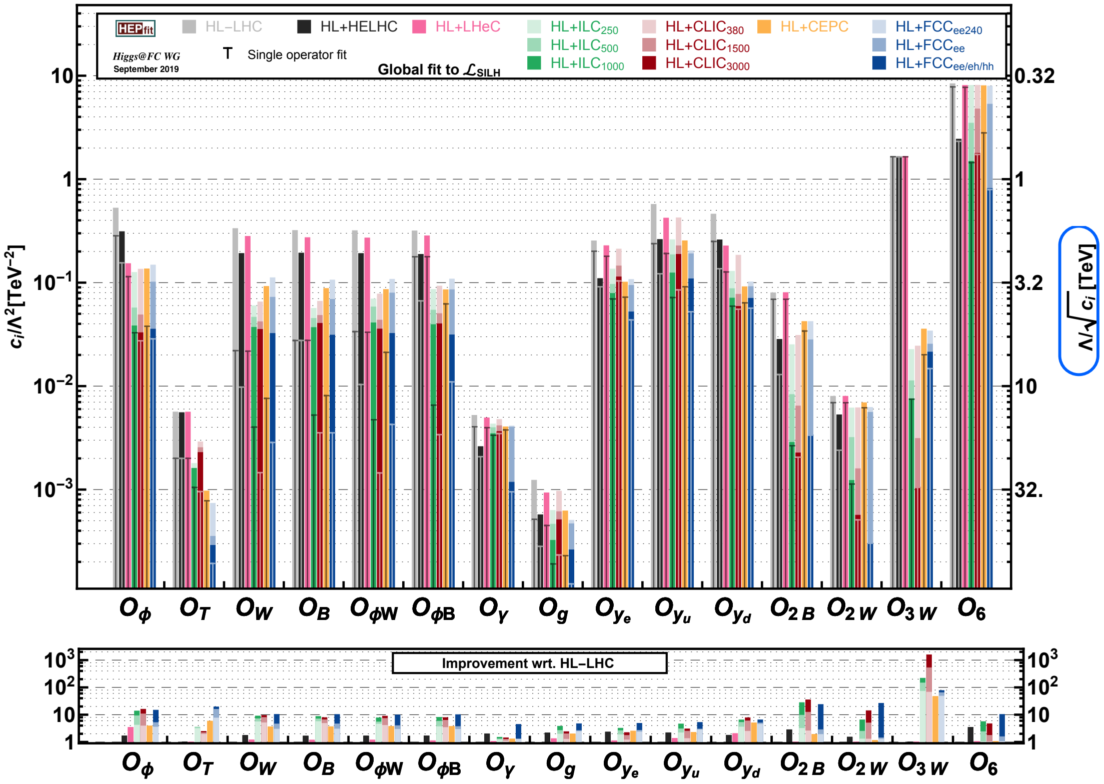


near → including HL-LHC and Belle II

[Bißman, Grunwald, Hiller, Kröninger, arXiv:2012.10456]

Bounding the scale of new physics: EFT

Global fit to EFT operators Combining EW+Higgs PO



$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{d>4} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d$$

with

$$\mathcal{L}_d = \sum_i C_i^{(d)} \mathcal{O}_i^{(d)}, \quad \left[\mathcal{O}_i^{(d)}\right] = d$$

$$\leftarrow \mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)}$$

[J. de Blas et al., arXiv:1905.03764]

Important goals:

↪ Study effects of neglected higher orders in EFT: **reduce *interpretation* errors**.

↪ Study effects of adding **SM corrections** (QCD+EW NLO) → mixing through evolution.

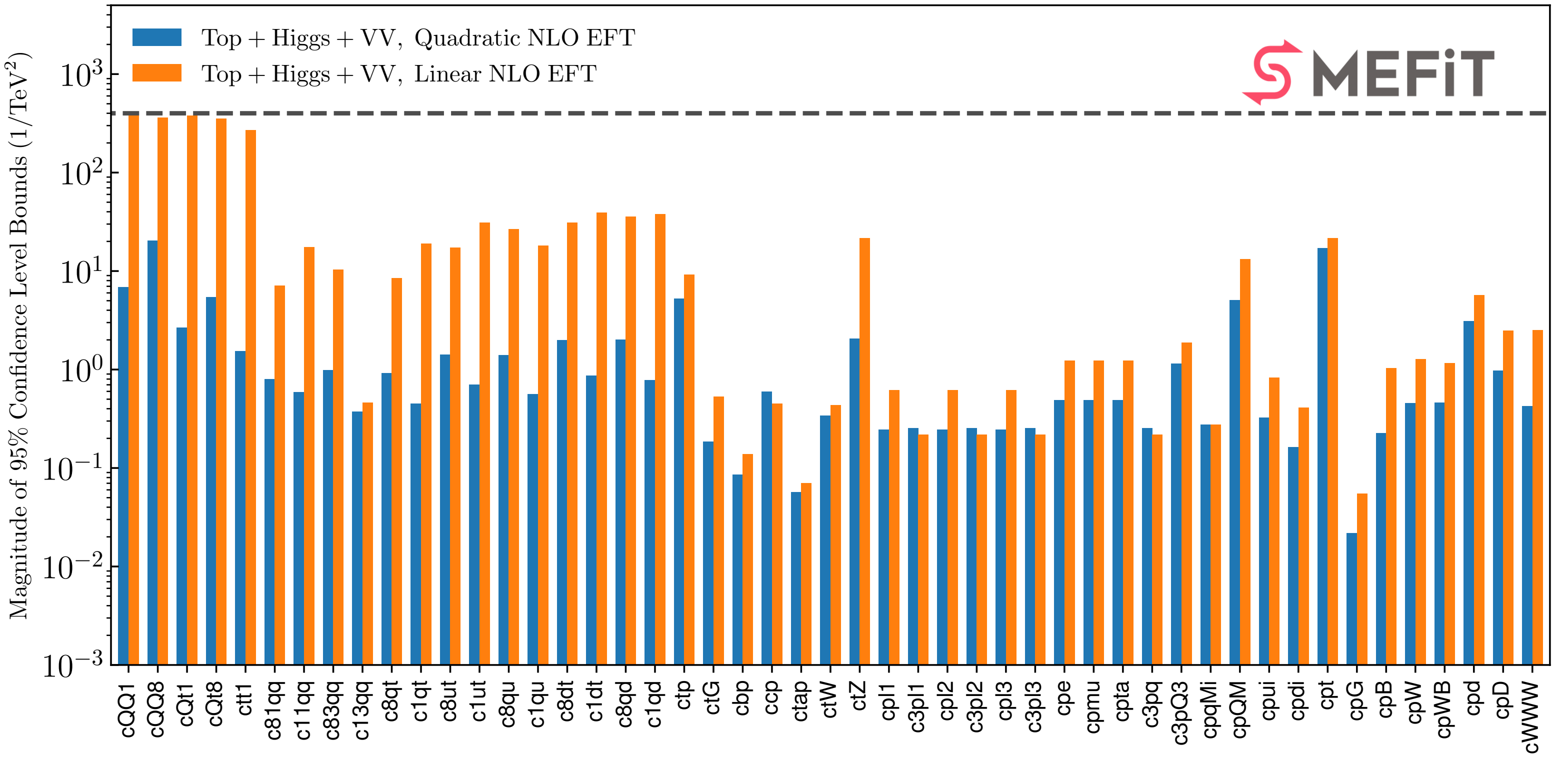
↪ Consider **global fit**, not just single operators.

↪ Extend set of fitted observables (distributions, STXS, etc.).

↪ Study inclusion of **theory errors** and their correlations in global fits.

Global SMEFT fits: validity of linear approximation

↪ See Mantani's talk



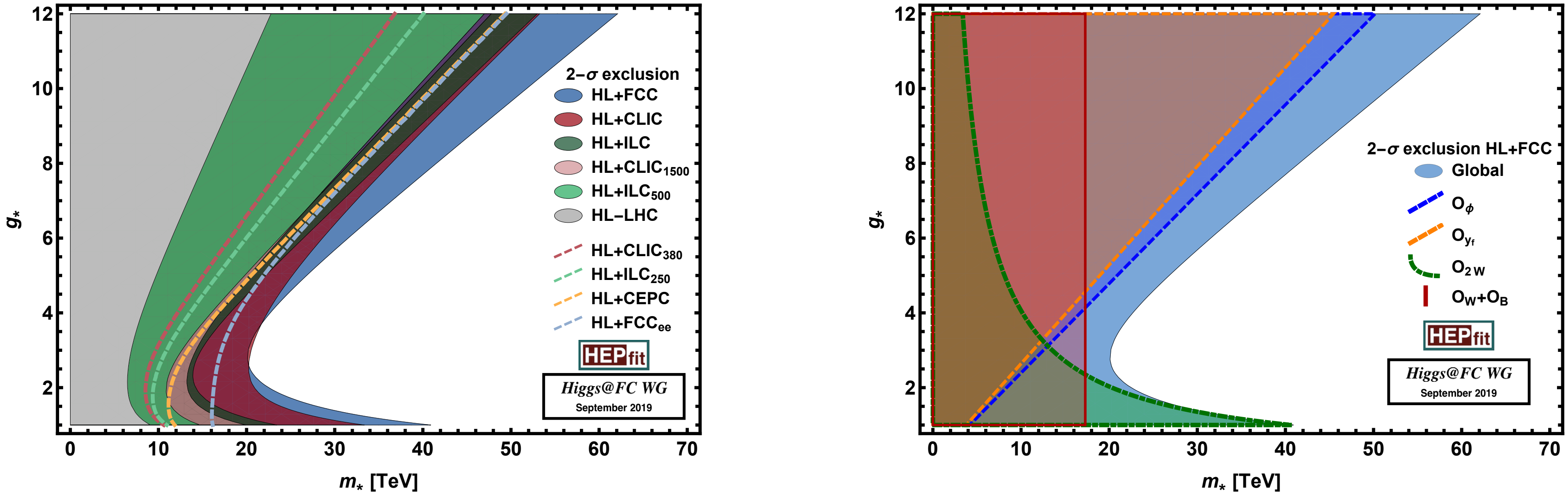
$$\mathcal{O} = \mathcal{O}_{SM} + \frac{C_i^2}{\Lambda^2}\mathcal{O}_i^{INT} + \frac{C_i C_j}{\Lambda^4}\mathcal{O}_{ij}^{SQ}$$

Only testing the sensitivity of the fit. Moving forward:

- ↪ Isolate sectors that could be more/less sensitive (no linear contributions)
- ↪ Test results in renormalized EFT → See Ramos's talk
- ↪ If indication of strong dynamics, compare to benchmark models.

Bounding the scale of new physics: specific models

Example of a **composite Higgs model**:



[J. de Blas et al., arXiv:1905.03764]

g^*, m^* → coupling and mass scale of the new resonances

$g^*, m^* \leftrightarrow \{O_\phi, O_6, O_T, O_W, O_B, O_{2W}, \ldots\}$

Where the bottom-up meets the top-down!

Outlook

- The Higgs physics program ahead of us is extremely intriguing and promises to start answering some of the remaining fundamental questions in particle physics.
- Groundbreaking new ideas and more powerful techniques allow us to take much higher challenges: **embrace the complexity of LHC events!**
- **Indirect evidence of new physics** from Higgs, top, and EW precision measurements could come from the synergy between
  - → pushing theoretical predictions to a new level of accuracy,
  - → a systematic approach to the study of new effective interactions,
  - → the intuition and experience of many years of Beyond SM searches!
- **Increasing the precision on SM observables** could **allow to test higher scales** of new physics: a factor of 10 in precision could give access to scales well above 10 TeV.
- **Direct evidence** of new physics will boost this process, as the discovery of a Higgs-boson has prompted and guided us in this new era of LHC physics.

Thank you!!

to the organizers and all the participants