Higgs-boson physics at the LHC: from discovery to precision physics

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Outline

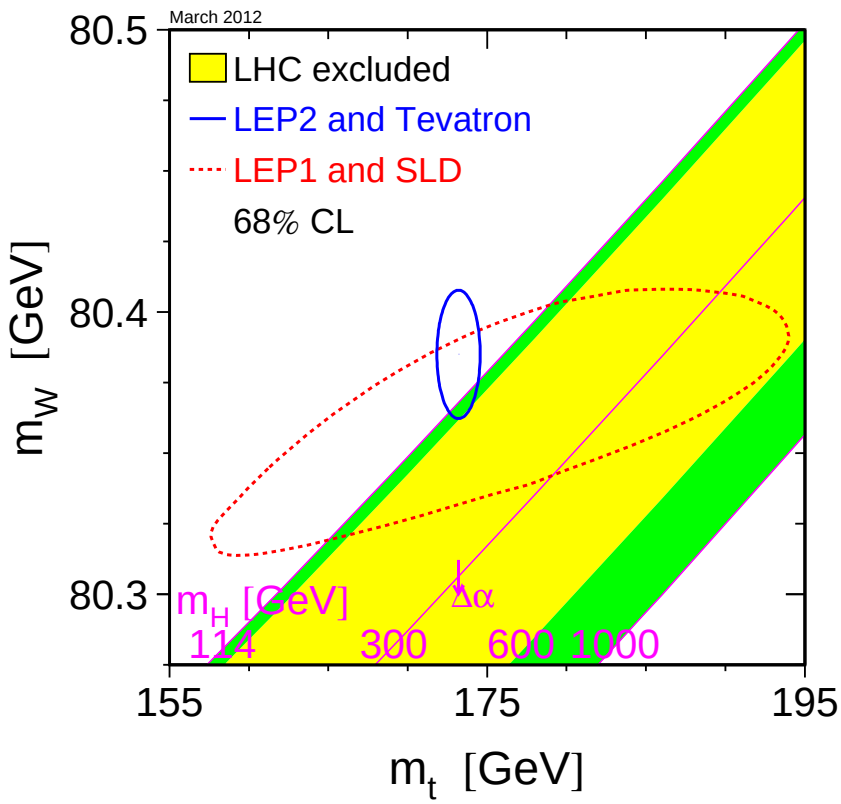
- Discovering the Higgs boson as first evidence of new physics
  - → Pre-LHC: the SM Higgs mechanism as the simplest possible realization of the EW symmetry ⟶ true/false? will $M_{\rm H}$ tell us about $\Lambda_{\rm NP}$?
  - → **LHC-Run I**: found a SM-like Higgs boson at $\mathbf{M_H \simeq 125}$ **GeV** ⟶ $\Lambda_{\rm N}P \approx$ TeV range.
  - → **LHC-Run II**: **higher energy**, **higher statistics**, **higher precision** ⟶ **Higgs-boson precision physics** can explore indirect evidence of new physics while searching for direct evidence.
- Higgs-boson precision physics requires accurate theoretical predictions
  - → Inclusive and exclusive total cross sections: highlights of recent results.
  - → Distributions: important handles on new-physics effects.
- Disentangling evidence of new physics from Higgs-boson properties
  - → Model-specific approach: more stringent, but biased.
  - → Model-indepependent approach: **Higgs Effective Field Theory**.
  - → **EW+Higgs precision fits**: a first template for future studies.

Precision EW fits pointed to a light Higgs boson

Spontaneous symmetry breaking of $SU(2)_L \times U(1)_Y \to U(1)_Q$ via
the SM Higgs mechanism + SM renormalizability imply:

→ tree-level relations among parameters (e.g. $M_W = M_Z \cos\theta_W$)

→ systematic control of loop corrections



$M_{\rm H}$ only free parameter of the SM:

$$\Downarrow$$

$$m_W = 80.385 \pm 0.015 \text{ GeV}$$

$$m_t = 173.2 \pm 0.90 \text{ GeV}$$

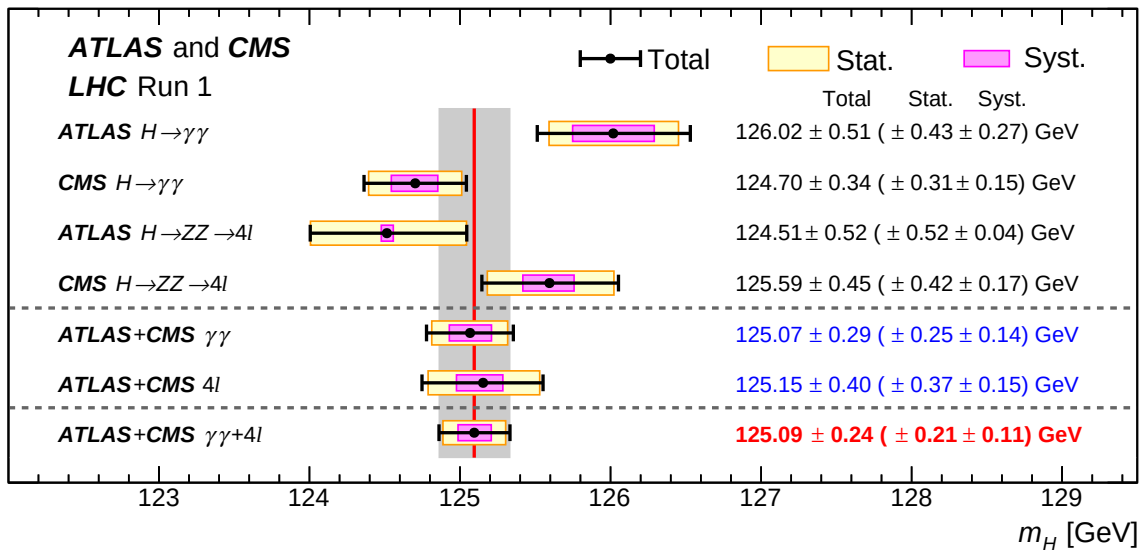
$$\Downarrow$$

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

$$M_H < 152\,(171) \text{ GeV}$$

Measured in Run I of the LHC: $M_{\rm H} = 125.09 \pm 0.24$ GeV

LHC Run I has discovered the Higgs, measured its mass and spin ...



ATLAS+CMS, Phys. Rev. Lett. 114, 191803

M_H promoted to EW precision observable!

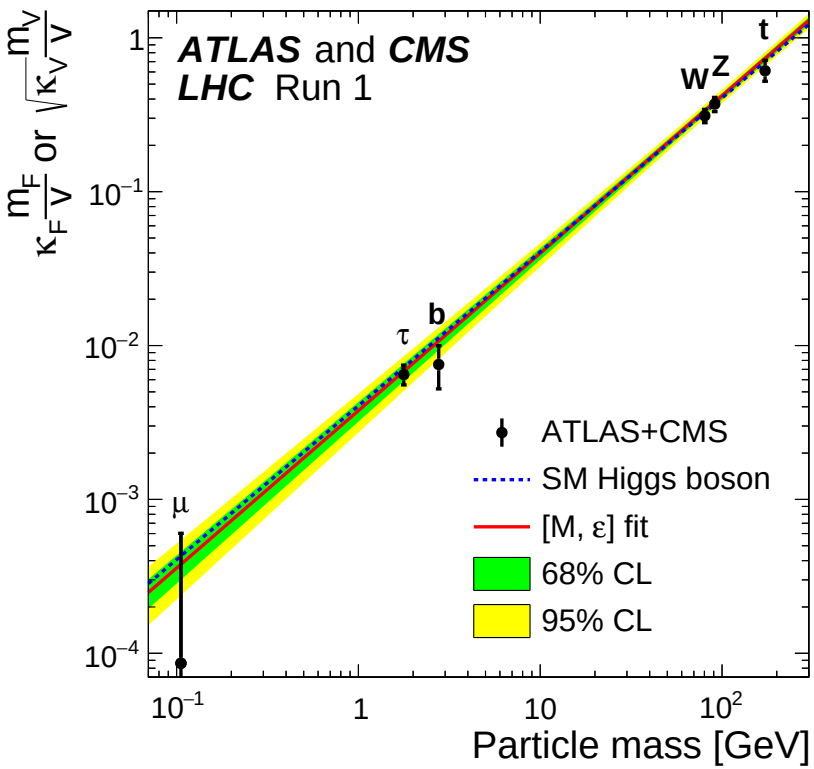
Effects of New Physics can now be more clearly disentangled in both EW observables and Higgs-boson couplings

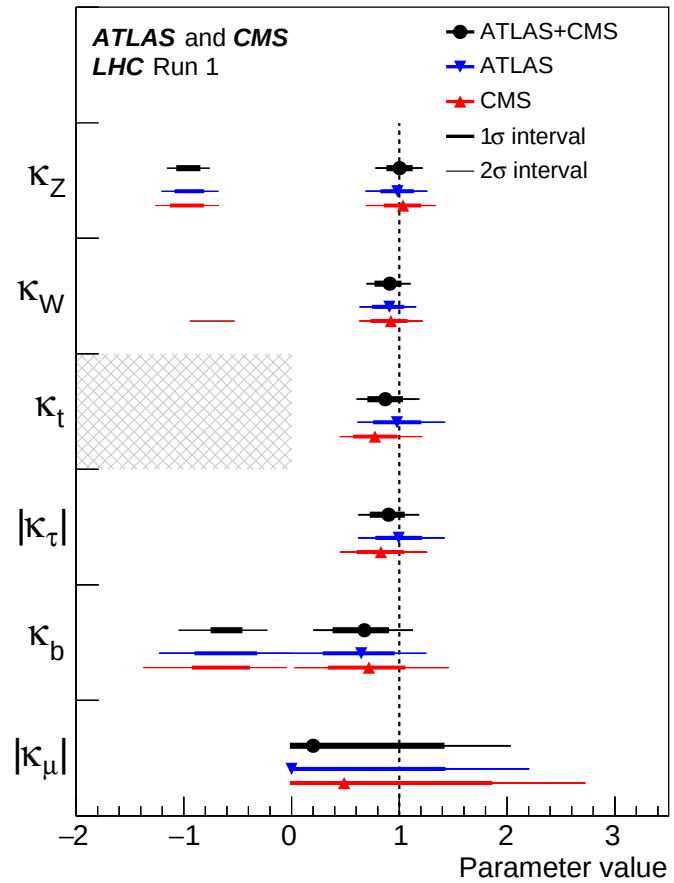
Moreover, from decays ($H \to VV$ and $H \to f\bar{f}$)

- → Spin: highly constrained to be $s = 0$
- → Parity: scalar vs pseudoscalar, exploring the tensor structure of decay amplitudes

... and also provided measurements of its couplings

$5\ \mathrm{fb}^{-1}@\sqrt{s} = 7\ \mathrm{TeV} + 20\ \mathrm{fb}^{-1}@\sqrt{s} = 8\ \mathrm{TeV}$



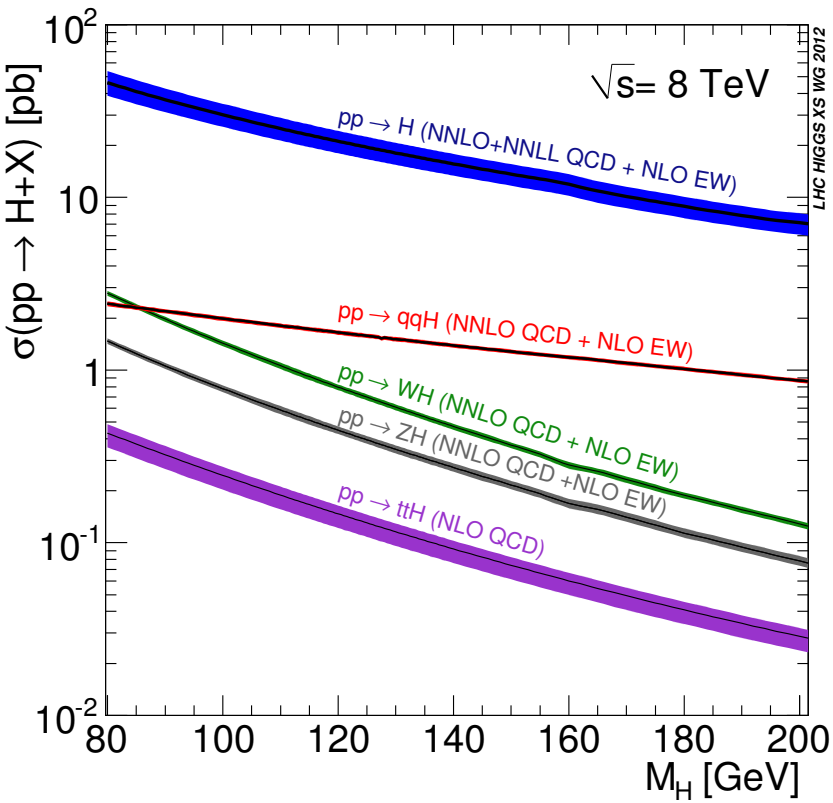


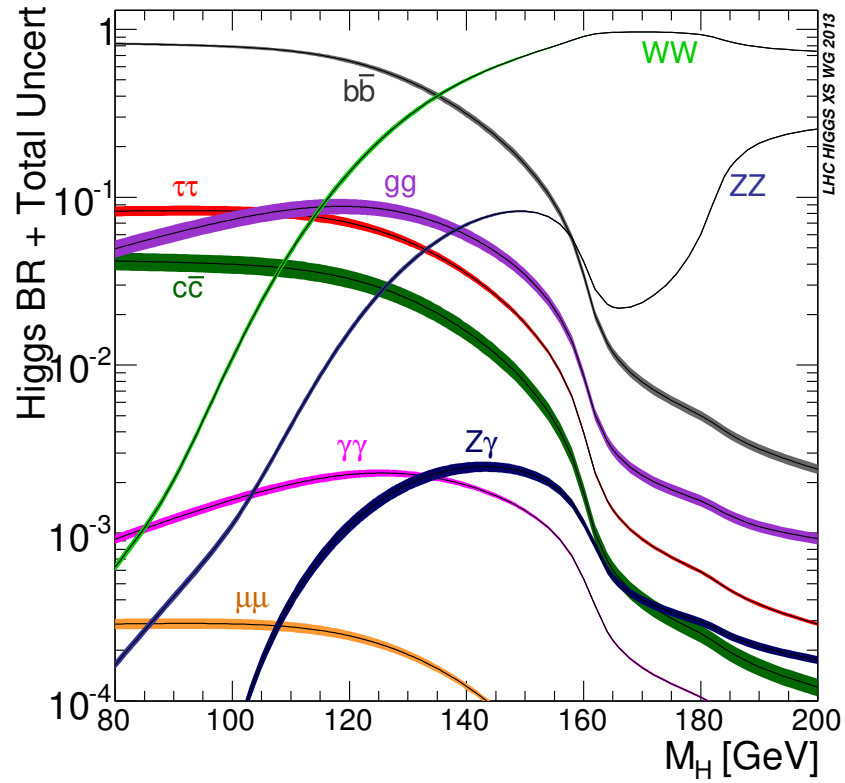
Assuming no new physics in loops, $\mathrm{BR}_{\mathrm{BSM}} = 0$, and $\kappa_j \geq 0$,

- → Couplings to gauge boson and top measured to 20-30% via main production and decay modes: $gg \to H$, $H \to ZZ, W^+W^-$ (also $t\bar{t}H$)
- → Couplings to fermions still preliminary: $gg \to H, H \to \mu^+\mu^-, \tau^+\tau^-$, $VH, H \to b\bar{b}$

Hidden in these numbers and plots . . .

State-of-the-art theoretical predictions for H production and decay rates



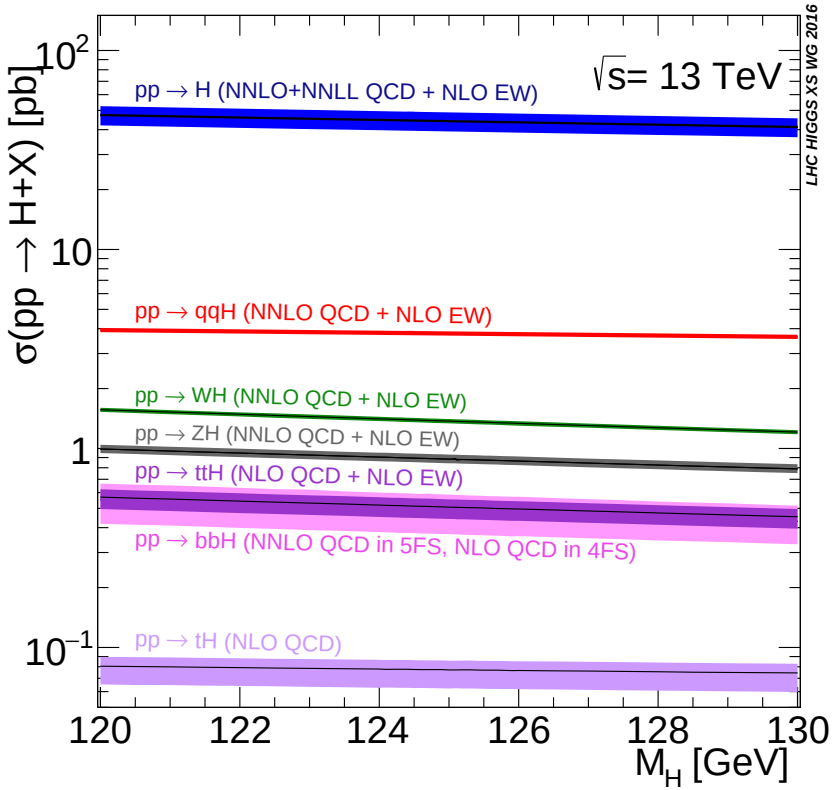


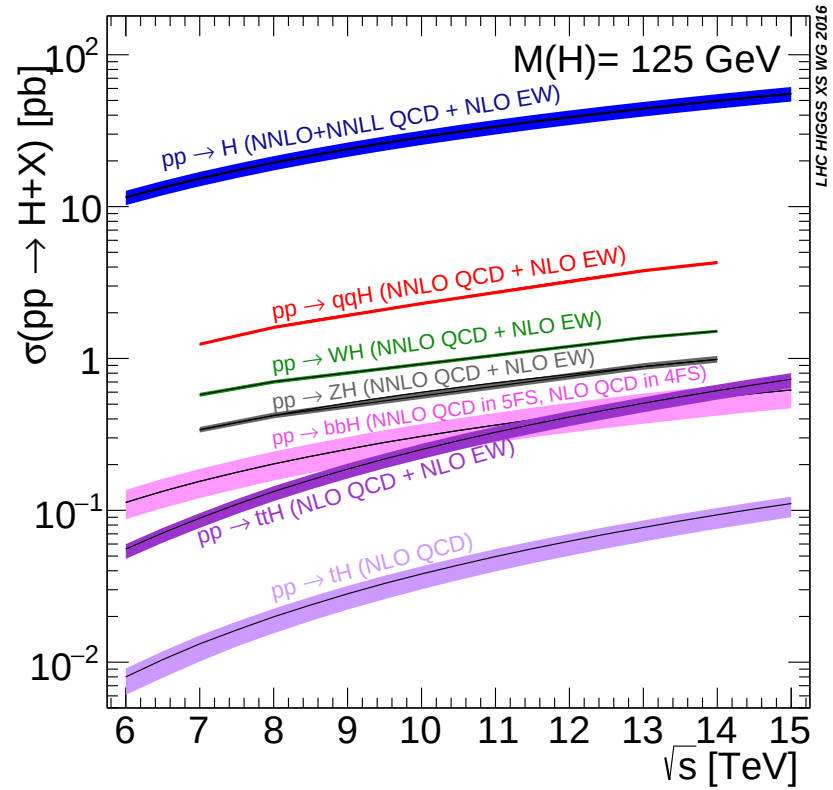
→ Main focus on total cross sections and branching ratios

→ Include NLO/NNLO QCD and NLO EW.

→ Residual perturbative uncertainties below 10-15%

Updated for Run II

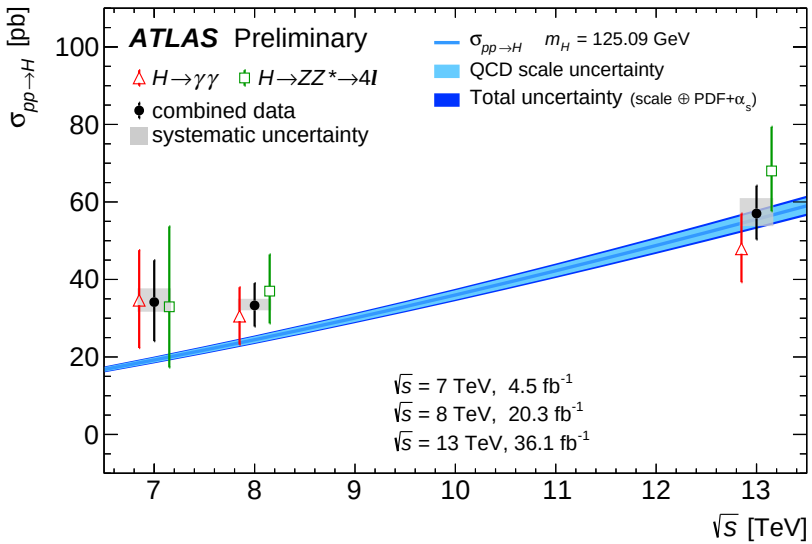




↪ 4th CERN Yellow Report of the Higgs XS Working Group [arXiv:1610.07922]

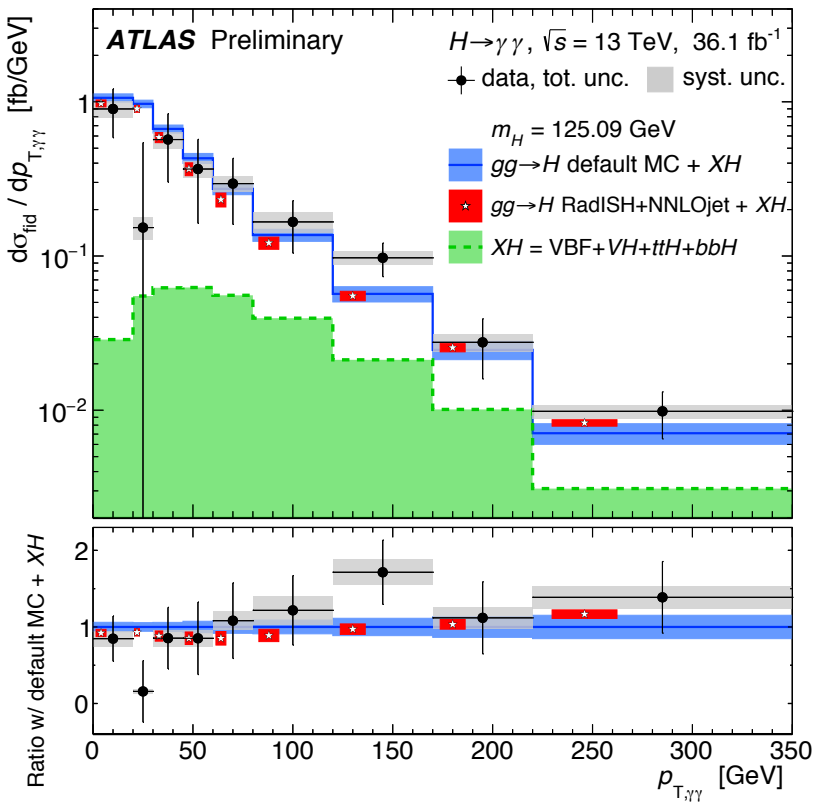
Run II explores Higgs physics at different energy scales: new challenges

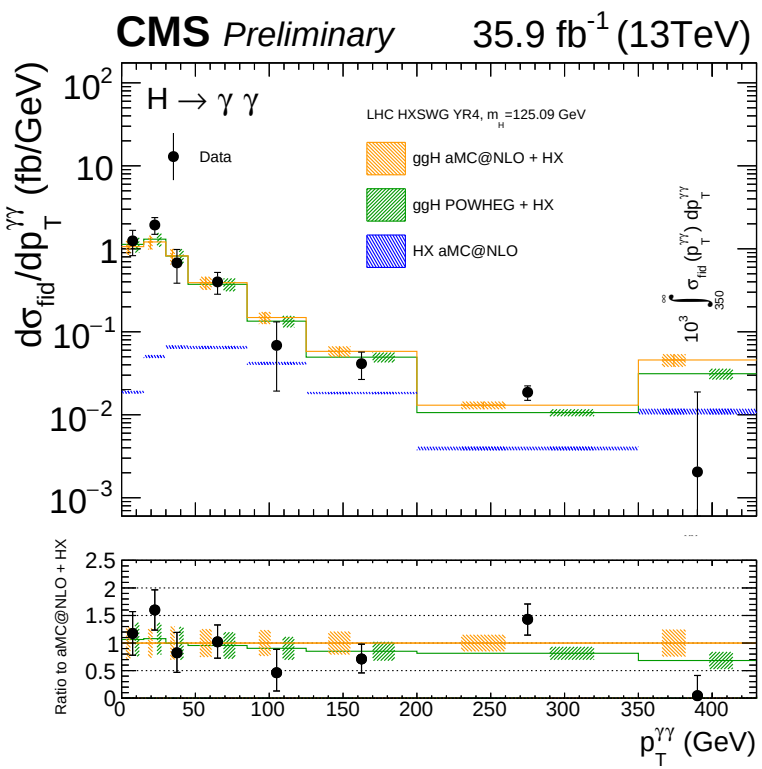
From Run I to Run II: higher energy, higher statistics



Total cross sections give only partial information.

Looking for anomalies in distribution will be at the core of the Higgs program of Run II





From Run I to Run II: new challenges

Given the higher energies and higher statistics of Run II:

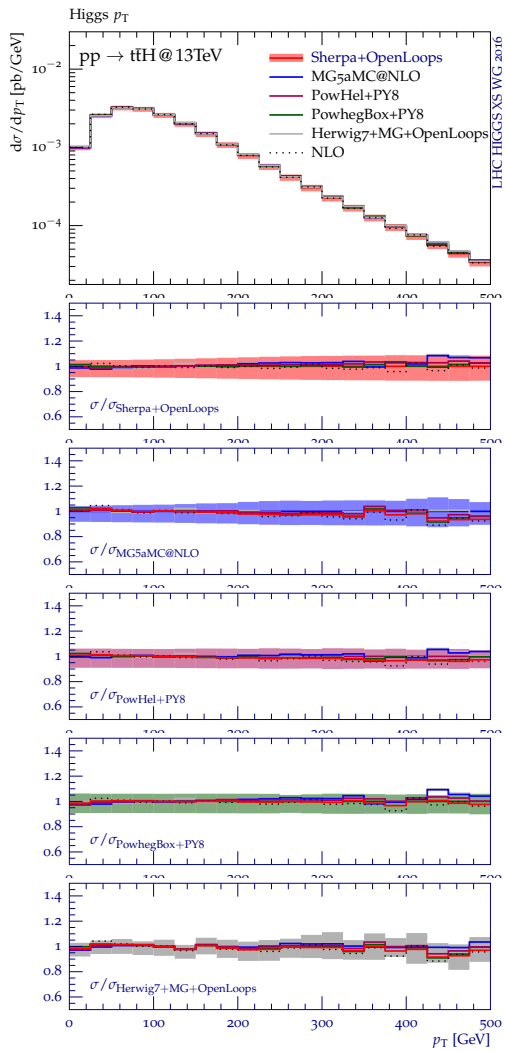
- Have access to rare production modes, e.g. $t\bar{t}H$, tH, ...
- Experimental errors on inclusive and exclusive observables will be significantly reduced to below 10%
  - ↪ **NNLO QCD** needed for several processes (few $2 \to 2$ processes already calculated), or **N^{3}LO QCD** (as for $gg \to H$).
  - ↪ **Resummation** of specific kinematic- or cut-induced large (logarithmic) corrections become important.
  - ↪ Need to control first order of **EW corrections** and **QCD+EW**.
- Higher statistics give access to distributions
  - ↪ Need **beyond LO distribution**, for both **signal** and **background**.
  - ↪ Need systematic control of accuracy in **matching to parton-shower Monte Carlo**.

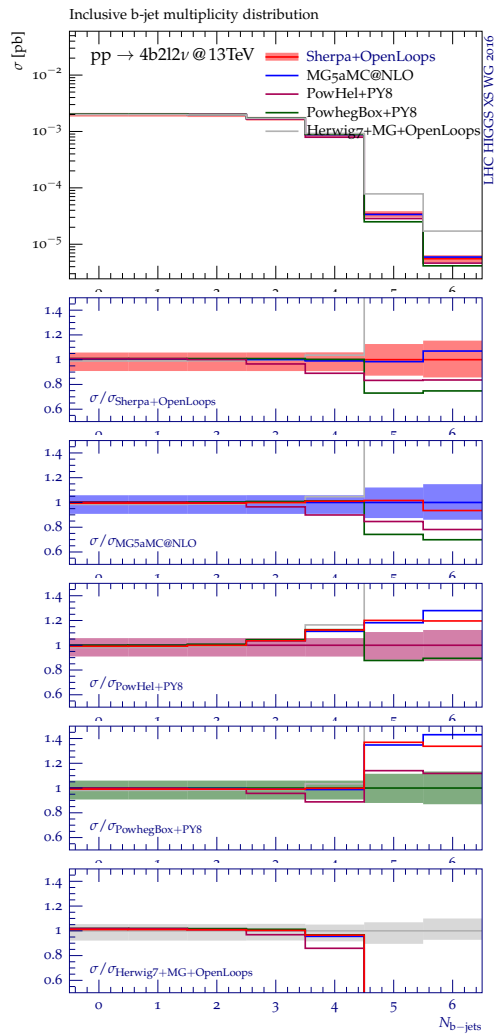
- Look for effects of New Physics (NP)
  - ↪ **NP** can just **rescale the Higgs-boson couplings**: $\kappa_X = y_{HX}/y_{HX}^{SM}$
  - ↪ **NP** can **introduce new structures** in Higgs couplings:
  - ↪ NP effects in EWPO very constrained, and **effects on distribution** more evident in the **high-energy tails**.
- High-energy tails of distributions need to be accurately predicted
  - ↪ loop **mass-effects** need to be calculated (e.g. $m_t \to \infty$ not accurate).
  - ↪ resum classes of EW corrections (W/Z radiation).
  - ↪ Higgs production highly off-shell $\to$ dependence on Γ_H

Need comprehensive, possibly model-independent, yet modular interpretation of anomalies in terms of NP

Validation of NLO+PS tools, $t\bar{t}H, H \to b\bar{b}$

[Pozzorini, L.R., et al., HXSWG YR4]





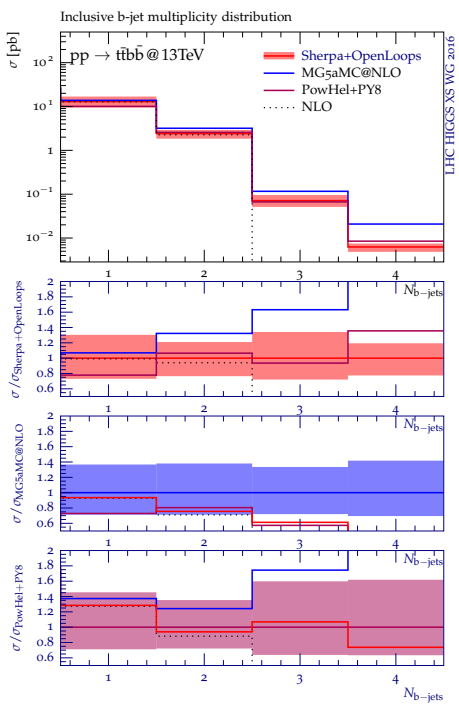
Comparison with and w/o top decays,
$t \to be^+\nu_e$
$\bar{t} \to \bar{b}\mu^-\nu_\mu$

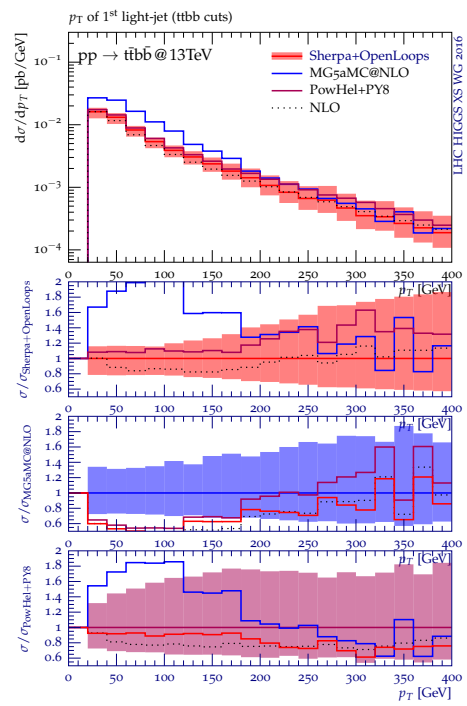
Proved very good compatibility within scale uncertainty

$N_{\text{b-jets}} > 4$
$\hookrightarrow$ shower effects
$\hookrightarrow$ more meaningful to investigate in the context of specific experimental analyses.

Validation of NLO+PS tools, $t\bar{t} + b$ jets

Realistic background study: problems in controlling the parton shower systematics.





↪ switch off top decays, hadronization, UE

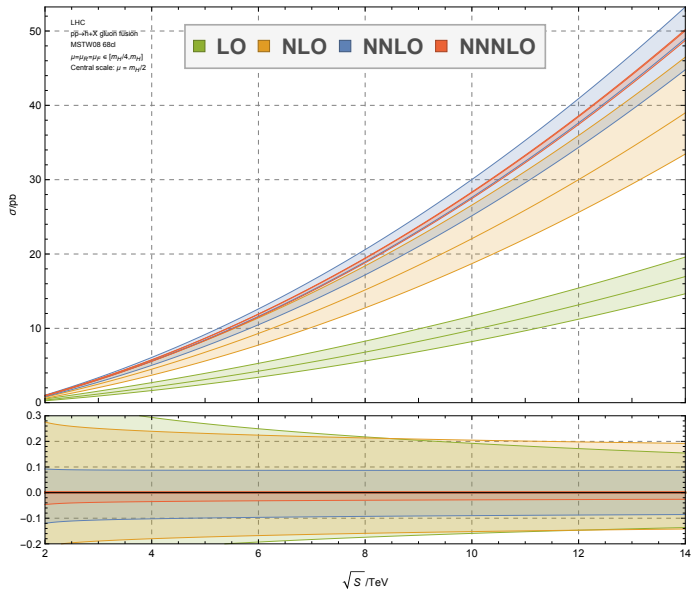
↪ To better compare the effect of

- different matchings
- different parton showers
- different flavor scheme

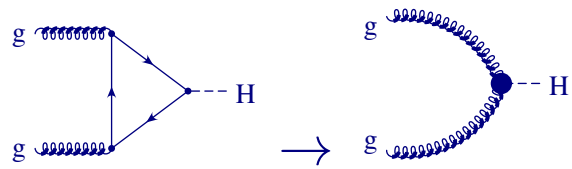
Discrepancies emerge that will have to be understood if we want to resolve the very large systematic uncertainties that affects experimental analyses

↪ **progress being made within the $t\bar{t}H$ HXSWG**.

$gg \to H$ calculated at N^{3}LO



EFT: $m_t \to \infty$ limit



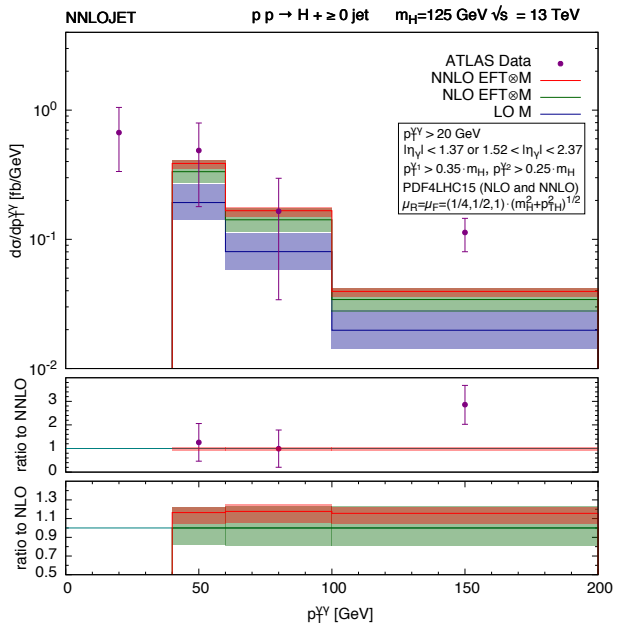
dominated by soft-dynamics
$(z \to 1, z = M_H^2/\hat{s})$

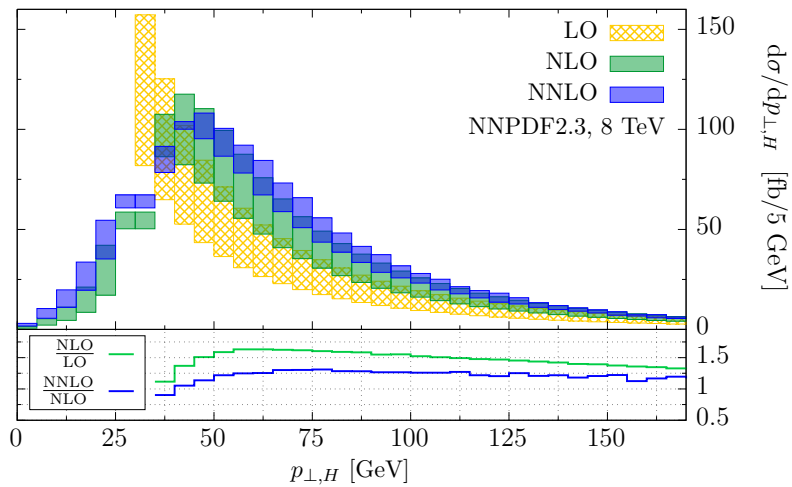
$$\sigma = 48.58^{+2.22}_{-3.27}(\text{th}) + 1.56(\alpha_s + \text{PDF})\,\text{pb}$$

[Anastasiou, Duhr, Dulat, Herzog, Mistlberger, arXiv:1503.06056]

- ↪ Fundamental building block of the whole Higgs-boson physics program: overall signal normalization.
- ↪ Dramatically improves theoretical accuracy (from 40% to 5-6%).
- ↪ Error reduced below or close to the level of EW corrections ($\approx 5\%$).
- ↪ Impact of N^{3}LL resummation on top of N^3 LO very small.

$H + j$ calculated at NNLO





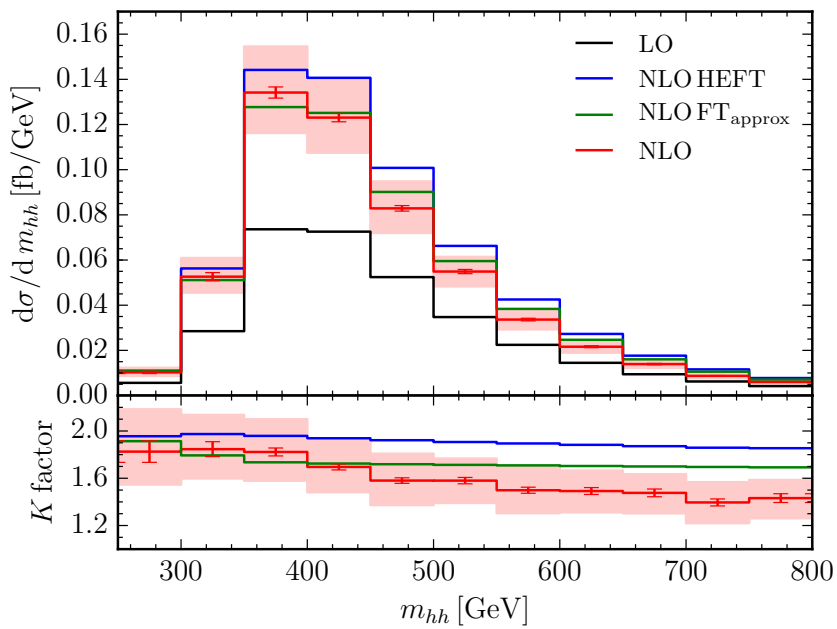
[Chen, Gehrmann, Glover, Jaquier, arXiv:1408.5325]

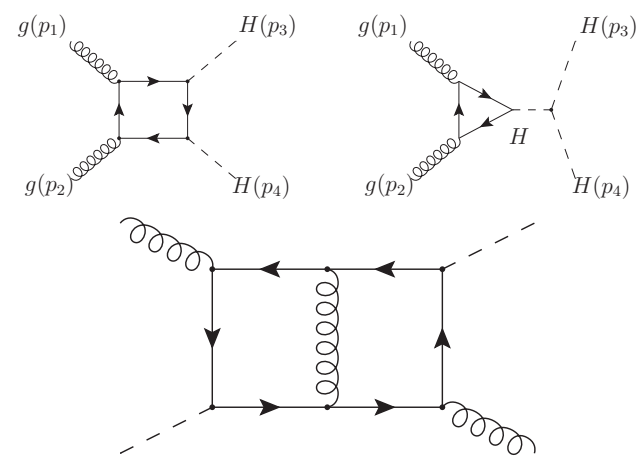
[Bhoughezal, Caola, Melnikov, Petriello, Schulze, arXiv:1504.07922]

- ↪ Impact all Higgs searching channels, from WW to $\gamma\gamma$ (signal binned by number of jets: H+0j, H+1j, ...)
- ↪ Very important to improve by including mass effects (m_t and m_b) at **high momentum** → disentangle **new-physics loop effects** in Hgg and $H\gamma\gamma$, and new effects from **anomalous tensor structures** in Higgs couplings. progress: [Bonciani et al. (2016), Neumann et al. (2016), Lindert et al. (2017)]

HH production at NLO, full m_t dependence

Measuring the Higgs-boson trilinear coupling:





[Borowka, et al., arXiv:1604.06447]

↪ above top threshold $m_t \to 0$ (EFT) cannot be trusted.

↪ gives warning also for ZH production at NNLO ($gg \to ZH$).

Alternatively: extract trilinear coupling from indirect loop effects

[Degrassi, Giardino, Maltoni, Pagani, arXiv:1607.04251]

Many more crucial contributions . . .

in both Signal and Background studies

- ↪ higher-order calculation of multi-particle final states
- ↪ optimization and validation of NLO parton-shower Monte Carlo
- ↪ off-shell effects
- ↪ interference effects (signal-background)
- ↪ . . .

Indirect evidence of new physics

Naturalness $\longrightarrow$ amount of **fine tuning "allowed"** for M_H

$$M_H^2 = M_{0,H}^2 + O(\Lambda_{\rm UV}^2) \qquad\qquad (\Lambda_{\rm UV} \to \Lambda_{\rm NP})$$

- $\hookrightarrow$ If new physics has to mitigate the amount of fine tuning: $\Lambda_{\rm NP} \approx$ TeV
- $\hookrightarrow$ If not: $\Lambda_{\rm N}P$ can be much larger.

Effective Field Theory approach can systematically account for all effects of new physics as an expansion in $\Lambda_{\rm NP}$ ($\to \Lambda$)

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{d>4} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d, \quad \text{with} \quad \mathcal{L}_d = \sum_i C_i \mathcal{O}_i, \quad [\mathcal{O}_i] = d\,,$$

- $\hookrightarrow$ respect the SM gauge symmetry $\to$ limited number of anomalous couplings
- $\hookrightarrow$ constraining effects in EW precision observables and Higgs-boson production/decay will provide a lower bound on $\Lambda_{\rm NP}$ and help defining the field content of NP models.

Run II of the LHC will determine the path down the road.

Higgs Effective Field Theories: a model-independent approach

[Numerous studies. Results presented here are from:

de Blas, Ciuchini, Franco, Mishima,Pierini, L.R., Silvestrini, arXiv:1608.01509]

Extension of the SM Lagrangian by $d > 4$ operators,

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{d>4} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d, \quad \text{with} \quad \mathcal{L}_d = \sum_i C_i \mathcal{O}_i, \quad [\mathcal{O}_i] = d\,,$$

Consider:

- → $d = 6$ operators only, obeying SM gauge symmetry, L and B conservation
- → one Higgs doublet of $SU(2)_L$, linearly realized SSB
- → assuming flavor universality: 59 operators
  [basis by Grzadkowski et al., JHEP 1010 (2010) 085]
- → CP even and with at least one Higgs: 27 operators
- → contributing to the observables considered: 17 operators
- → with a specific model in mind: running $C_i(\Lambda) \to C_i(\Lambda_{\rm EW})$ more meaningful
- → otherwise take $C_i = C_i(\Lambda_{\rm EW})$, no running included

$$\mathcal{O}_{\phi G} = (\phi^\dagger \phi)\, G^A_{\mu\nu} G^{A\mu\nu}$$
$$\mathcal{O}_{\phi W} = (\phi^\dagger \phi)\, W^I_{\mu\nu} W^{I\mu\nu}$$
$$\mathcal{O}_{\phi B} = (\phi^\dagger \phi)\, B_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_{\phi WB} = (\phi^\dagger \tau^I \phi)\, W^I_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_{\phi D} = (\phi^\dagger D^\mu \phi)^* \, (\phi^\dagger D_\mu \phi)$$
$$\mathcal{O}_{\phi \Box} = (\phi^\dagger \phi)^* \Box (\phi^\dagger \phi)$$

bosonic operators

$\longrightarrow$ corrections to:

- oblique parameters
- $hVV \longrightarrow \kappa_V$
- WWZ and $WW\gamma$

$$\mathcal{O}^{(1)}_{\phi L} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\overline{L} \gamma^\mu L)$$
$$\mathcal{O}^{(3)}_{\phi L} = (\phi^\dagger i \overleftrightarrow{D}^I_\mu \phi)(\overline{L} \tau^I \gamma^\mu L)$$
$$\mathcal{O}_{\phi e} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\overline{e}_R \gamma^\mu e_R)$$
$$\mathcal{O}^{(1)}_{\phi Q} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\overline{Q} \gamma^\mu Q)$$
$$\mathcal{O}^{(3)}_{\phi Q} = (\phi^\dagger i \overleftrightarrow{D}^I_\mu \phi)(\overline{Q} \tau^I \gamma^\mu Q)$$
$$\mathcal{O}_{\phi u} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\overline{u}_R \gamma^\mu u_R)$$
$$\mathcal{O}_{\phi d} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\overline{d}_R \gamma^\mu d_R)$$
$$\mathcal{O}_{\phi ud} = i(\widetilde{\phi}^\dagger D_\mu \phi)(\overline{u}_R \gamma^\mu d_R)$$

single-fermionic-vector-current operators

$\longrightarrow$ corrections to:

- $hf\bar{f} \longrightarrow \kappa_f$
- $Vf\bar{f}$

single-fermionic-scalar-current operators

$$\mathcal{O}_{e\phi} = (\phi^\dagger\phi)(\bar{L}\, e_R \phi)$$
$$\mathcal{O}_{u\phi} = (\phi^\dagger\phi)(\bar{Q}\, u_R \widetilde{\phi})$$
$$\mathcal{O}_{d\phi} = (\phi^\dagger\phi)(\bar{Q}\, d_R \phi)$$

$\longrightarrow$ corrections to:

- oblique parameters
- Yukawa couplings
- $hf\bar{f}$

four-fermion operator

$$\mathcal{O}_{LL} = (\bar{L}\gamma^\mu L)(\bar{L}\gamma^\mu L)$$

$\longrightarrow$ corrections to:

- G_F extraction from μ decay

<u>Notice</u>: $Vf\bar{f}$ and indirect effects (e.g. G_F) strongly constrained by EW precision observables.

The fitting procedure → `HEPfit`

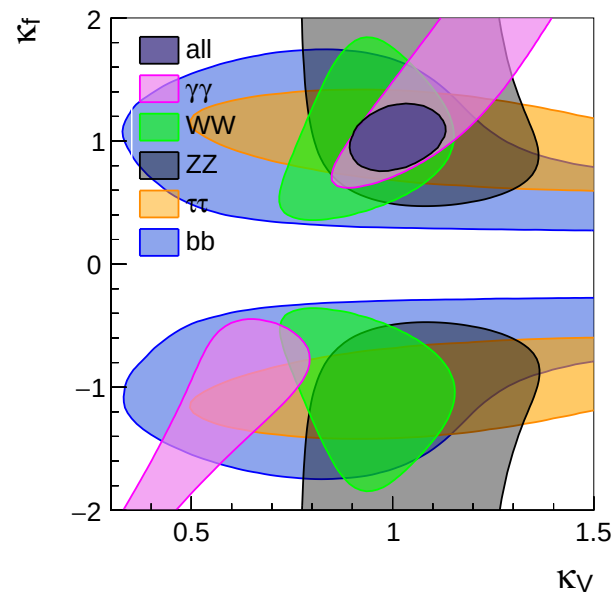
[The HEPfit Collaboration, `https://github.com/silvest/HEPfit`]

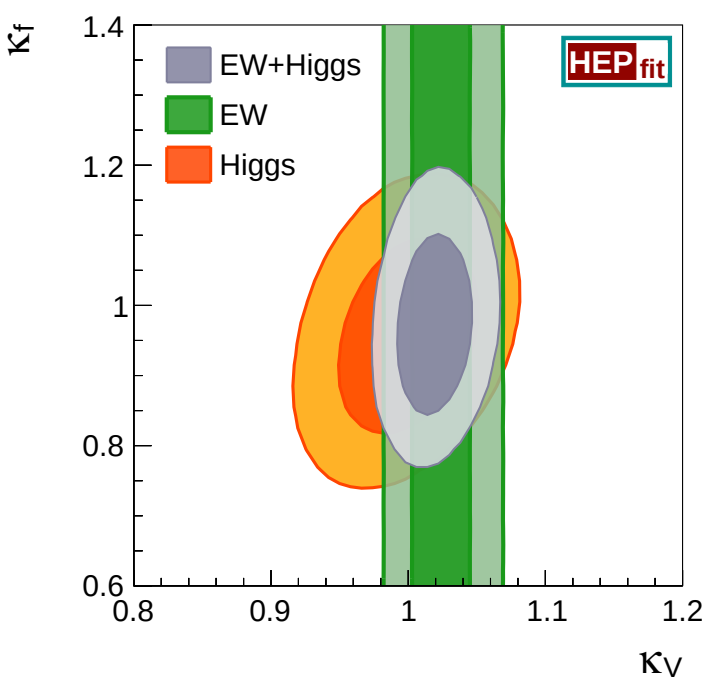
- Both electroweak and Higgs observables are calculated as a SM core plus corrections:
  - ↪ the SM cores include all existing higher order corrections
  - ↪ the NP corrections are at the lowest order in all SM couplings.
- Experimental results are taken from the most recent published analyses
  - ↪ see Higgs analyses example on next slide
- The fit procedure uses BAT (Bayesan Analysis Toolkit) where experimental likelihoods are taken as priors, and posteriors are calculated using a Markov Chain Monte Carlo.
  (Caldwell et al., arXiv:0808.2552)

Bounds on EFT in terms of κ_V and κ_f

Higgs only

	68%	95%	correlation	
κ_V	1.01 ± 0.03	[0.95, 1.07]	1.00	
κ_f	0.98 ± 0.07	[0.86, 1.12]	0.29	1.00





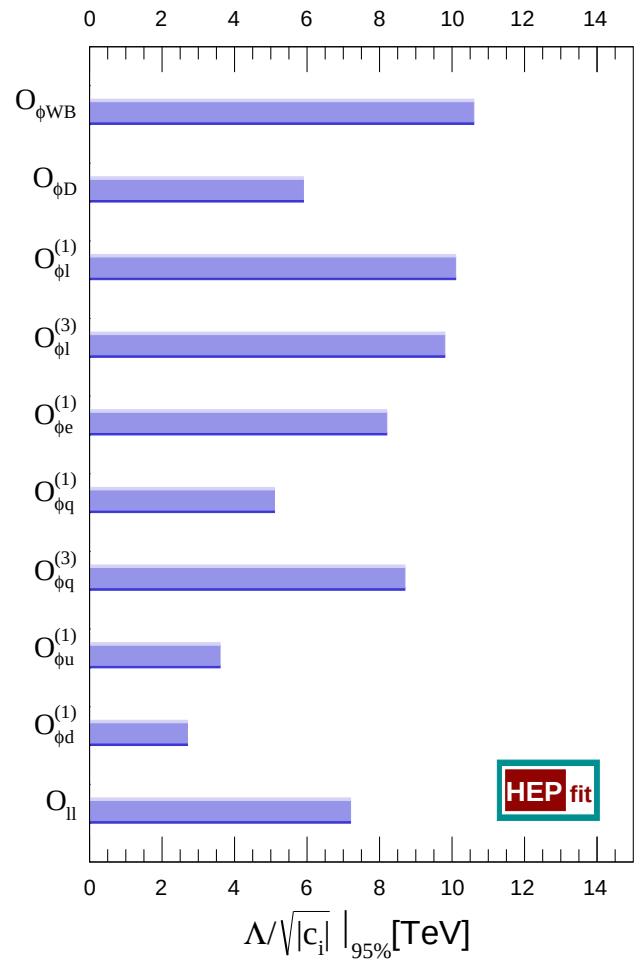
Higgs+EWPO

	68%	95%	correlation	
κ_V	1.02 ± 0.02	[0.99, 1.06]	1.00	
κ_f	0.99 ± 0.07	[0.86, 1.62]	0.17	1.00

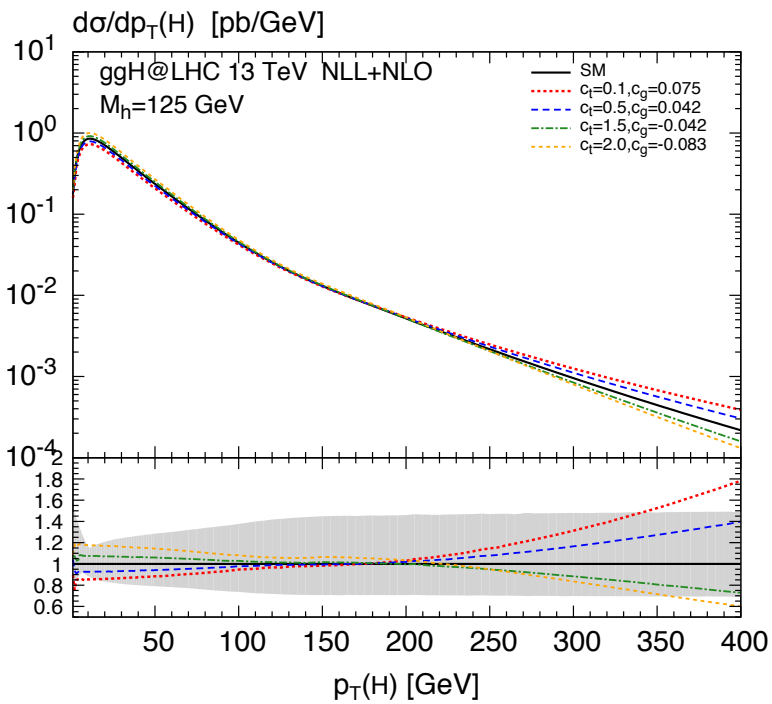
95% bounds on coefficients of d=6 interactions

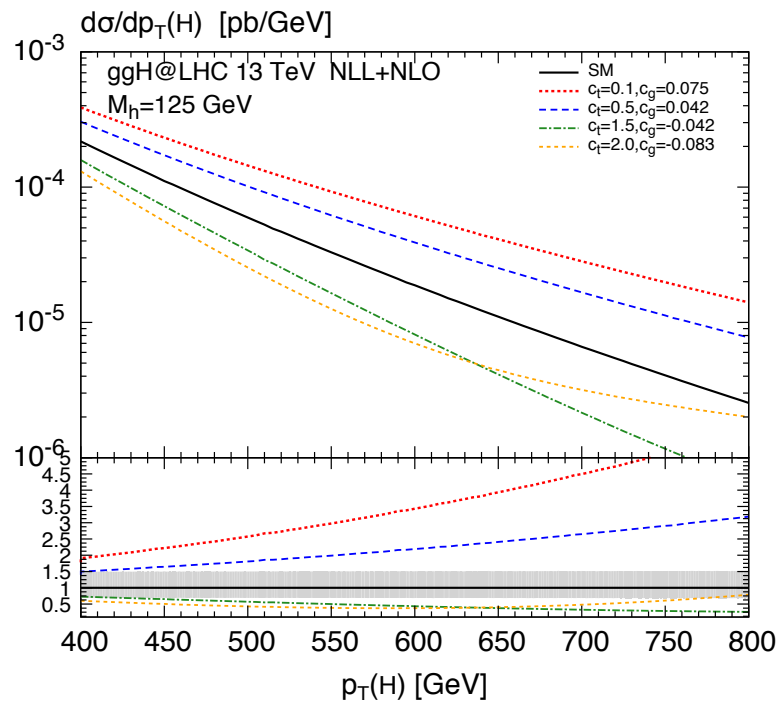
→ Switching on one operator at a time

Coefficient	EW+Higgs C_i/Λ^2 [TeV^{-2}] at 95%	Λ [TeV] $C_i = \pm 1$
$C_{\phi WB}$	$[-0.010, 0.005]$	11
$C_{\phi D}$	$[-0.032, 0.006]$	5.9
$C_{\phi L}^{(1)}$	$[-0.006, 0.011]$	10
$C_{\phi L}^{(3)}$	$[-0.013, 0.006]$	9.8
$C_{\phi e}$	$[-0.017, 0.006]$	8.2
$C_{\phi Q}^{(1)}$	$[-0.026, 0.044]$	5.1
$C_{\phi Q}^{(3)}$	$[-0.010, 0.015]$	8.7
$C_{\phi u}$	$[-0.068, 0.086]$	3.6
$C_{\phi d}$	$[-0.151, 0.058]$	2.7
C_{LL}	$[-0.010, 0.022]$	7.2



BSM effects on Higgs p_T in $gg \to H$





[Grazzini, Ilnicka, Spira, Weisemann, arXiv:1612.00283]

$$O_1 = |H|^2 G^a_{\mu\nu} G^{a.\mu\nu} \quad \longrightarrow \quad \frac{\alpha_s}{\pi v} c_g \, h G^a_{\mu\nu} G^{a,\mu\nu} \quad \leftarrow$$

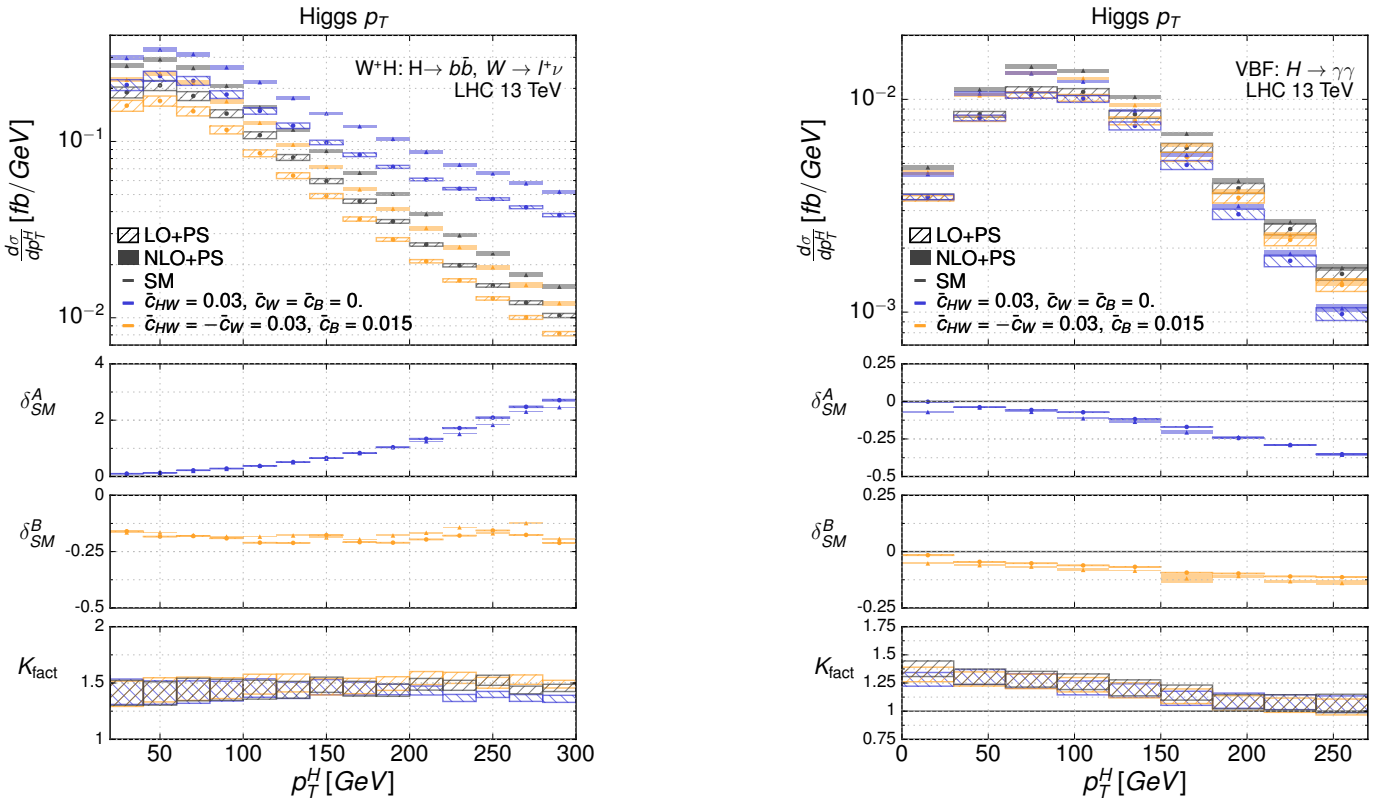
$$O_2 = |H|^2 \bar{Q}_L H^c u_R + h.c. \quad \longrightarrow \quad \frac{m_t}{v} c_t \, h t\bar{t} \quad \leftarrow$$

$$O_3 = |H|^2 \bar{Q}_L H d_R + h.c. \quad \longrightarrow \quad \frac{m_b}{v} c_b \, h b\bar{b}$$

...

Include O_1, O_2, and O_3 in NLO+NLL computation: **simultaneous effects of two or more operators affects high-energy tail of the spectrum**.

BSM effects on Higgs p_T in VH and VBF



[Degrande, Fuks, Mawatari, Mimasu, Sanz, arXiv:1612.00283]

↪ Includes NLO QCD matched to PS, validated with both MG5aMC@NLO and POWHEG-BOX.

↪ Studied consistency of EFT approach.

Outlook and Conclusions

- After the discovering the Higgs-boson during Run I of the LHC and measuring its main properties, **Run II** of the LHC **will develop a full-fledged precision program to measure its couplings**.
- **Indirect evidence of new physics** from Higgs-boson and EW precision measurements could come from the synergy between
  - → accurate theoretical prediction,
  - → a systematic approach to the study of new effective interactions,
  - → the intuition and experience of many years of Beyond SM searches!
- **Increasing the precision of input parameters** could **allow to test higher scales** of new physics: a factor of 10 in precision could give access to scales as high as 100 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.