Higgs-boson phenomenology
a broad perspective

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EWSB and the energy frontier

- The understanding of the EWSB is at the core of some of the remaining fundamental questions in particle physics and cosmology.
- The discovery of a Higgs boson at the LHC has made this connection even more compelling and intriguing:
  - $\rightarrow$ why $M_H \ll M_{pl}$? $\rightarrow$ hierarchy problem
  - $\rightarrow$ why only one scalar? more (pseudo)scalars?
  - $\rightarrow$ elementary? composite?
  - $\rightarrow$ ...

  Answering these questions necessarily involves physics beyond the SM.
- **Higgs physics** has been **at the core of the LHC physics program** and will continue to be for the HL/HE-LHC upgrades, as well as for all future colliders currently under discussion.
  - $\hookrightarrow$ **Searches** for **new signatures** (more scalars, exotic decays, ...).
  - $\hookrightarrow$ **Indirect constraints** from SM Higgs properties.

Searching for and interpreting evidence of new physics

↪ **Model-specific** approach: more stringent, yet arbitrary.

↪ **Effective Field Theory** approach: less arbitrary, more systematic, but less prone to simple prescriptions

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

expansion in Λ (scale of NP), set validity of its application.

$$\Downarrow$$

- We need both.
- We will see examples of both during this talk.

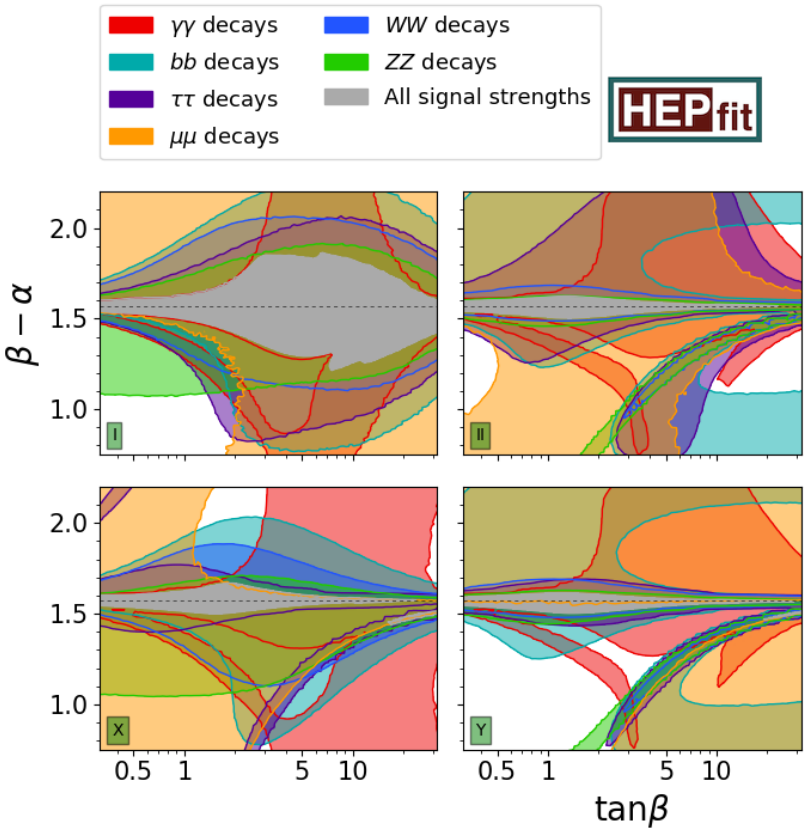
↪ **Dedicated discussions on EFT at LHCP 2019**:

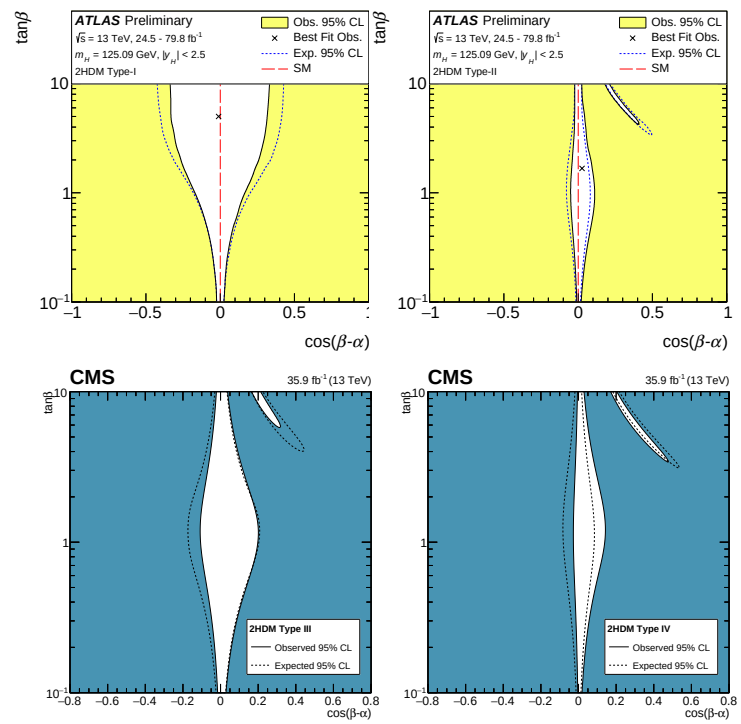
▷ Tuesday May 21, Higgs Parallel Session

▷ Friday May 24, 10:36-11:00, Plenary: Discussion on LHC sensitivity with EFT

Broad spectrum of searches, old and new ideas

2HDM

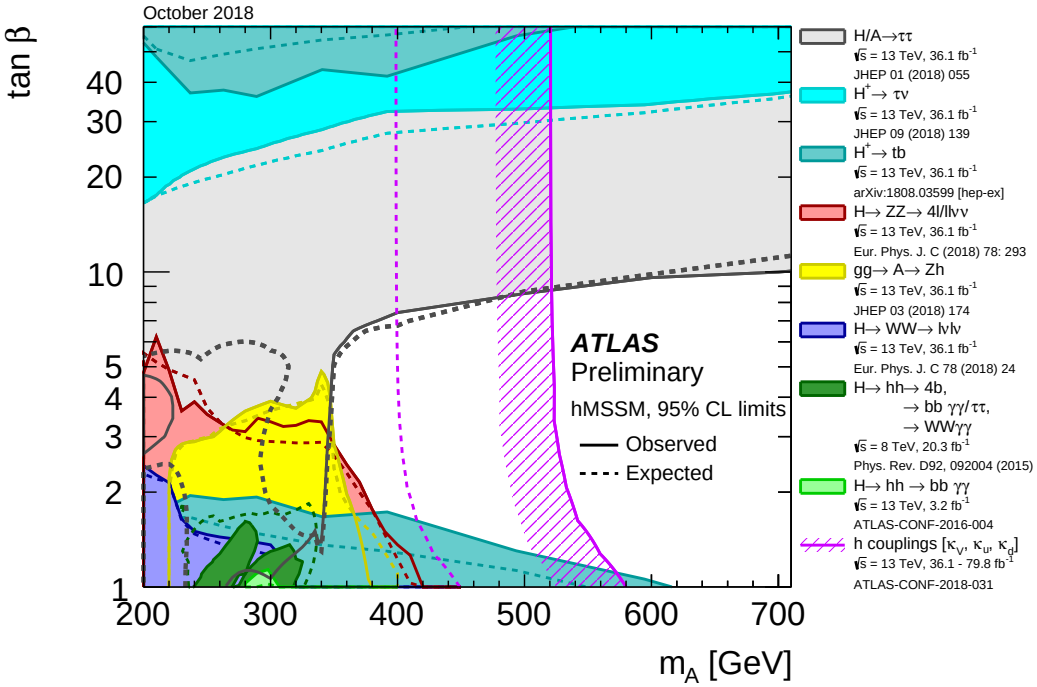


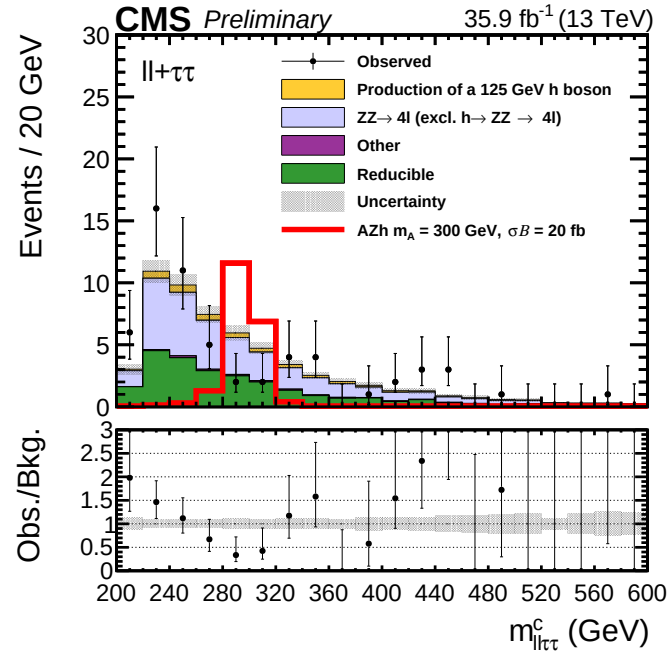


[Eberhardt, Chowdhury, arXiv:1711.02095]

Alignement scenario $\longrightarrow$ consistent with SM-like couplings and EWPO.

Heavy-scalar and charged-scalar searches further explore parameter space.





More exotic scenarios

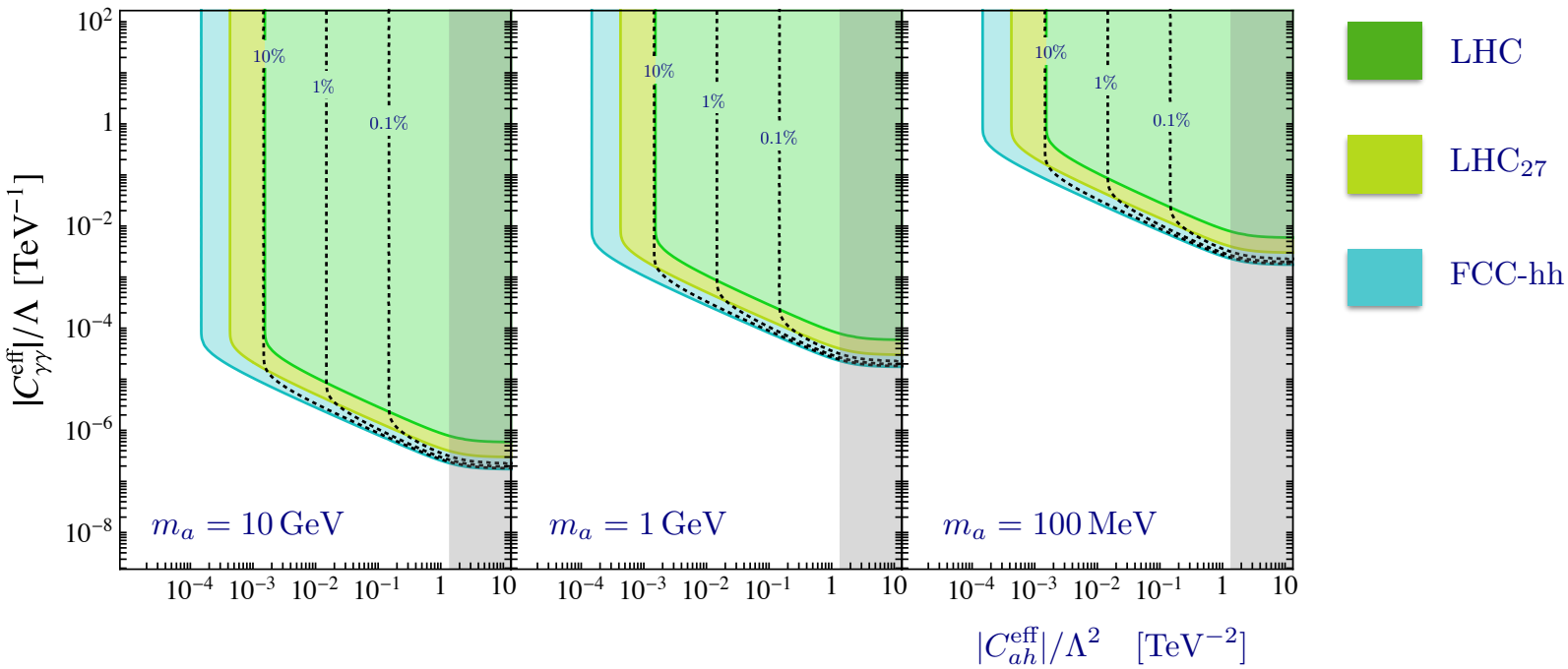
- Higgs FCNC decays ($H \to e\tau$, $H \to \mu\tau$, $t \to Hc$, ...)
- Higgs decays to BSM gauge bosons ($U(1)_{\text{dark}}$)
- Higgs decays to light scalars ($H \to aa$, $a =$ axion-like particle or ALP)

↪ **Several talks at LHCP 2019**:

▷ Wednesday May 22, Higgs Parallel Session

▷ Thursday May 23, Plenary on Higgs/EW

Axion-like particles (ALP)



[Bauer, Heiler, Neubert, Thamm, arXiv:1808.10323]

ALP: pseudo-Goldstone bosons of SB global symmetry (NP at scale Λ)

$\hookrightarrow$ *light* pseudoscalar messangers of NP

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm a} + \cdots + \frac{C_{\gamma\gamma}}{\Lambda} a F^{\mu\nu} \tilde{F}_{\mu\nu} + \cdots + \frac{C_{ah}}{\Lambda^2} (\partial^\mu a)(\partial_\mu a)\phi^\dagger\phi + \frac{C_{aZ}}{\Lambda^3} (\partial^\mu a)(\phi^\dagger i D_\mu \phi)\phi^\dagger\phi + \cdots$$

LHC gives access in particular to: $H \to Za \to l^+l^-2\gamma$ and $H \to aa \to 4\gamma$

$\hookrightarrow$ models with extra singlet-scalar very important templates for future collider studies!

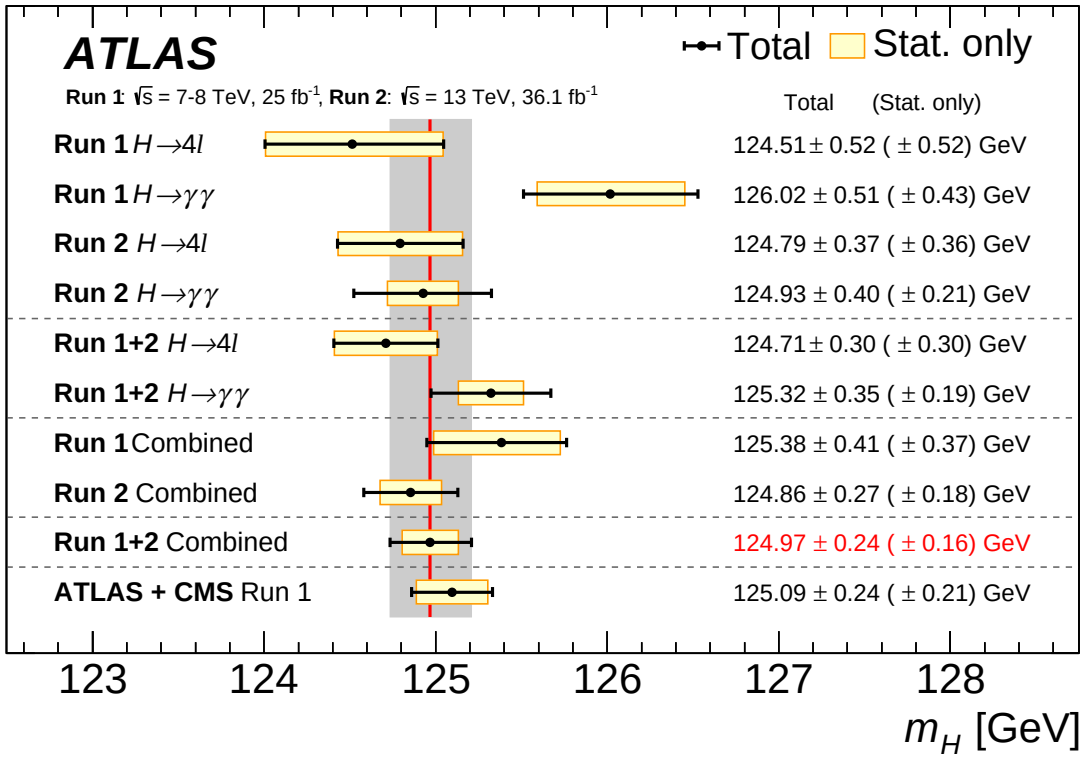
[see e.g, Heinemann and Nir, arXiv:1905.00382]

EWSB, precision physics, and the energy frontier

- Precision is intrinsic to having a predictive theory like the Standard Model of particle physics.
- Precision is effective when both theory and experiments have a way to reach comparable accuracy and improve it systematically.
- Particle physics has a very succesful history of constraining *new physics* through precision measurements in:
  - → Precision fits of electroweak observables (LEP, SLD, Tevatron, LHC)
    ↪ indirectly constrained M_H
- After Run II and towards the HL-LHC: crucial to develop the LHC Higgs precision program:
  - → precision measurement of Higgs properties (mass, couplings, width)
  - → constraints on anomalous interactions

Explore indirect evidence of new physics while searching for direct one.

LHC Run I+Run II: promoted M_H to EW precision observable



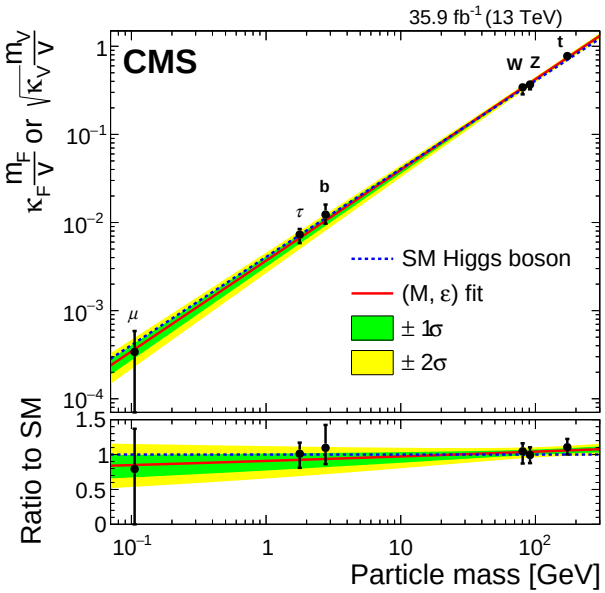
[ATLAS-CONF-2019-005]

The SM *paradigm* of EWSB ($\rightarrow$ relation between v, M_H, and λ) is fixed.

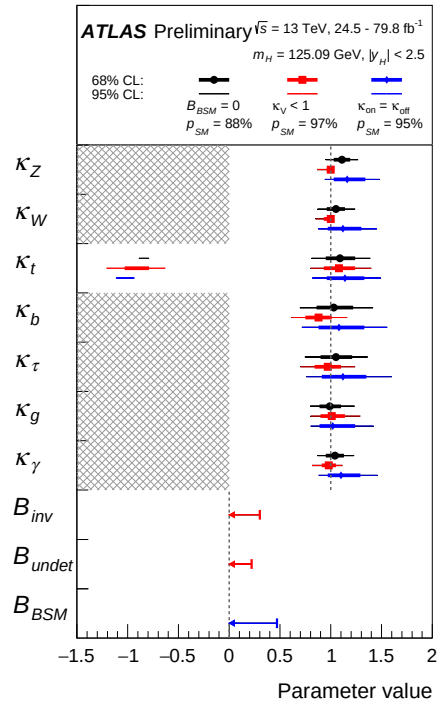
$$\Downarrow$$

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

LHC Run I+Run II: first measurements of Higgs couplings



[CMS, arXiv:1809.10733]



[ATLAS-CONF-2019-005]

κ_i	ATLAS	CMS	HL-LHC
κ_Z	$1.10^{+0.08}_{-0.08}$	$0.99^{+0.11}_{-0.12}$	2.4%
κ_W	$1.05^{+0.08}_{-0.08}$	$1.10^{+0.12}_{-0.17}$	2.2%
κ_t	$1.02^{+0.11}_{-0.10}$	$1.11^{+0.12}_{-0.10}$	3.4%
κ_b	$1.06^{+0.19}_{-0.18}$	$-1.10^{+0.33}_{-0.23}$	3.7%
κ_τ	$1.07^{+0.15}_{-0.15}$	$1.01^{+0.16}_{-0.20}$	1.9%
κ_μ	< 1.51 at 95% CL.	$0.79^{+0.58}_{-0.79}$	4.3%

$$\kappa_i = g_{Hi}/g_{Hi}^{\rm SM}$$

→ Higgs couplings to gauge bosons measured to 10-15% level.

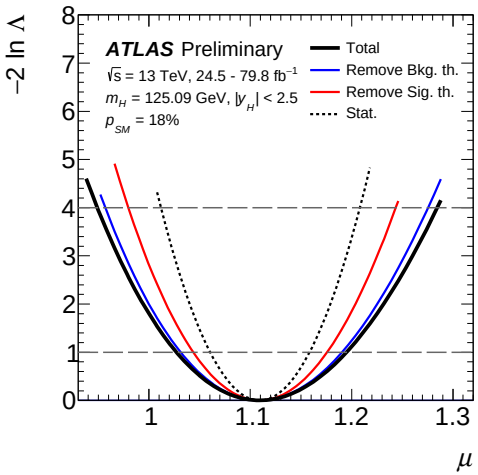
→ Higgs couplings to 3rd-generation fermions measured at 20-30% level.

→ First bound on Higgs self-coupling ($\kappa_\lambda = \lambda_3/\lambda_3^{\rm SM}$)
[ATL-PHYS-PUB-2019-009]: $-3.2 \leq \kappa_\lambda \leq 11.9 \quad (95\%\,\text{CL})$.

↪ **See talks at LHCP 2019**:

▷ Monday May 20, Higgs Parallel Session

... where theoretical systematics plays a substantial role



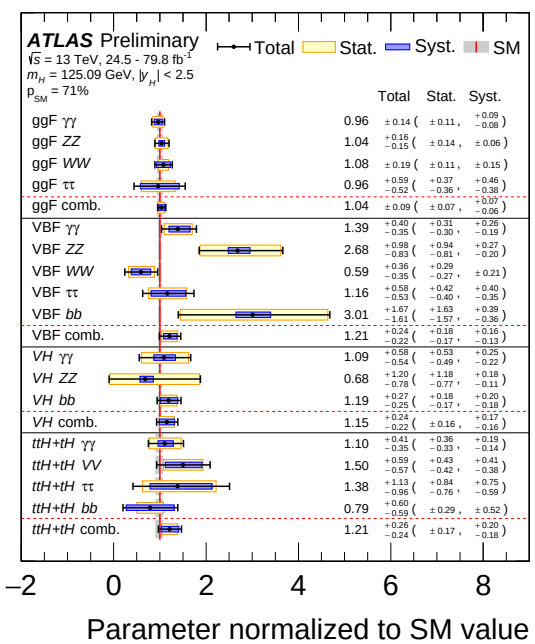
Uncertainty source	$\Delta\mu/\mu$ [%]
Statistical uncertainty	4.4
Systematic uncertainties	6.2
Theory uncertainties	4.8
Signal	4.2
Background	2.6
Experimental uncertainties (excl. MC stat.)	4.1
Luminosity	2.0
Background modeling	1.6
Jets, $E_{\mathrm{T}}^{\mathrm{miss}}$	1.4
Flavour tagging	1.1
Electrons, photons	2.2
Muons	0.2
τ-lepton	0.4
Other	1.6
MC statistical uncertainty	1.7
Total uncertainty	7.6

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

$$\mu = 1.11^{+0.09}_{-0.08} \text{ (combined)}$$

by production channel:

Uncertainty source	$\frac{\Delta\sigma_{\mathrm{ggF}}}{\sigma_{\mathrm{ggF}}}$ [%]	$\frac{\Delta\sigma_{\mathrm{VBF}}}{\sigma_{\mathrm{VBF}}}$ [%]	$\frac{\Delta\sigma_{WH}}{\sigma_{WH}}$ [%]	$\frac{\Delta\sigma_{ZH}}{\sigma_{ZH}}$ [%]	$\frac{\Delta\sigma_{t\bar{t}H+tH}}{\sigma_{t\bar{t}H+tH}}$ [%]
Statistical uncertainties	6.4	15	21	23	14
Systematic uncertainties	6.2	12	22	17	15
Theory uncertainties	3.4	9.2	14	14	12
Signal	2.0	8.7	5.8	6.7	6.3
Background	2.7	3.0	13	12	10
Experimental uncertainties (excl. MC stat.)	5.0	6.5	9.9	9.6	9.2
Luminosity	2.1	1.8	1.8	1.8	3.1
Background modeling	2.5	2.2	4.7	2.9	5.7
Jets, $E_{\mathrm{T}}^{\mathrm{miss}}$	0.9	5.4	3.0	3.3	4.0
Flavour tagging	0.9	1.3	7.9	8.0	1.8
Electrons, photons	2.5	1.7	1.8	1.5	3.8
Muons	0.4	0.3	0.1	0.2	0.5
τ-lepton	0.2	1.3	0.3	0.1	2.4
Other	2.5	1.2	0.3	1.1	0.8
MC statistical uncertainties	1.6	4.8	8.8	7.9	4.4
Total uncertainties	8.9	19	30	29	21



[ATLAS-CONF-2019-005]

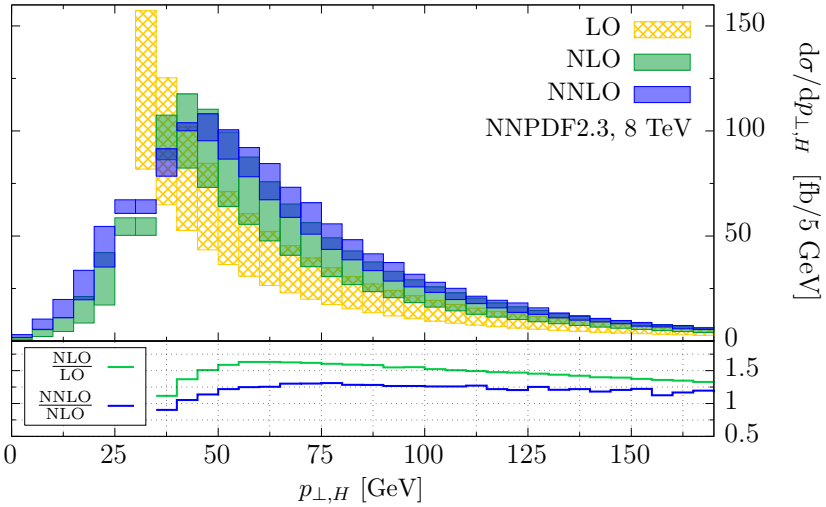
What does it imply for theory?

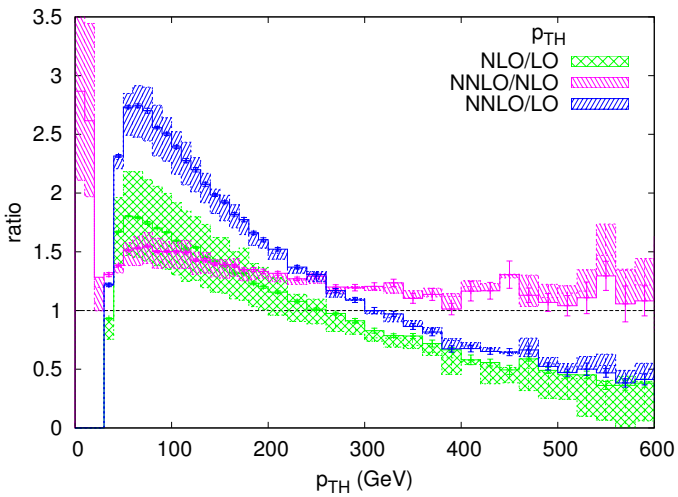
- Experimental errors on inclusive and exclusive observables significantly reduced to below 10% require
  - ↪ **NNLO QCD** known for all processes (except $t\bar{t}H$), **N^{3}LO QCD** known for $gg \to H$ and $b\bar{b} \to H$.
  - ↪ NLO **EW+QCD corrections** known for all processes.
  - ↪ **Resummation** of specific kinematic- or cut-induced large (logarithmic) need to be included.
  - ↪ Effects previously neglected need to be reconsidered (mass effects, ...).

  ▷ [See B. Mistlberger's talk at LHCP 2019, Monday, May 20: Higgs parallel Session]
- Most importantly: higher statistics gives access to distributions
  - ↪ Need **at least NLO accuracy**, for both **signal** and **background**.
  - ↪ Need systematic control in **matching to parton-shower Monte Carlo** event generators (NLO+PS, towards NNLO+PS)

    ▷ [See E. Re's talk at LHCP 2019, Tuesday, May 21: Higgs parallel Session]
  - ↪ Need to assure validity of theory predictions in all kinematic regimes.
- Higgs couplings from loop effects (EW corrections, EW precision observables, etc.): may complement their direct extraction from Higgs processes.

$H + j$ calculated at NNLO in HEFT ($m_t \to \infty$)



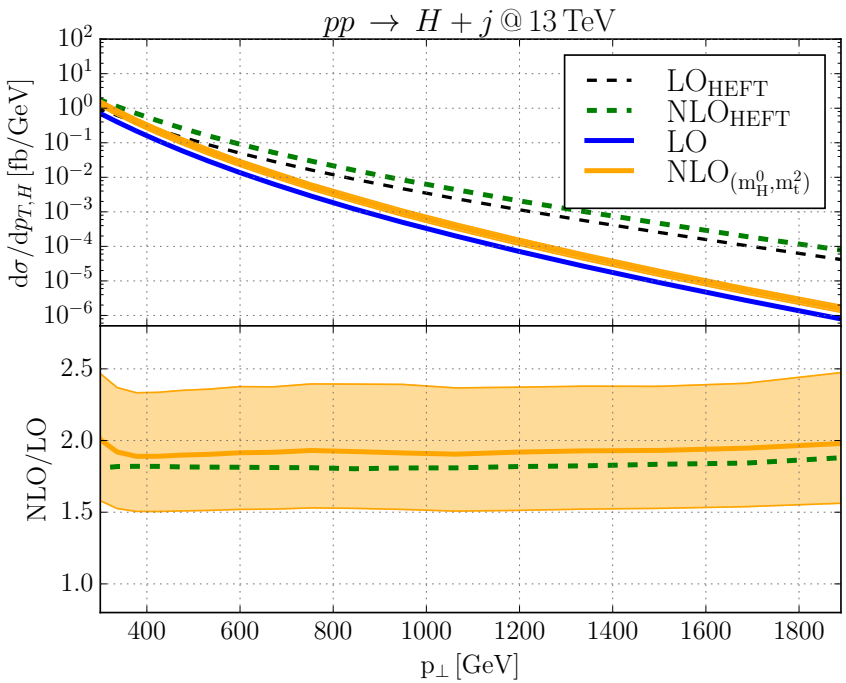


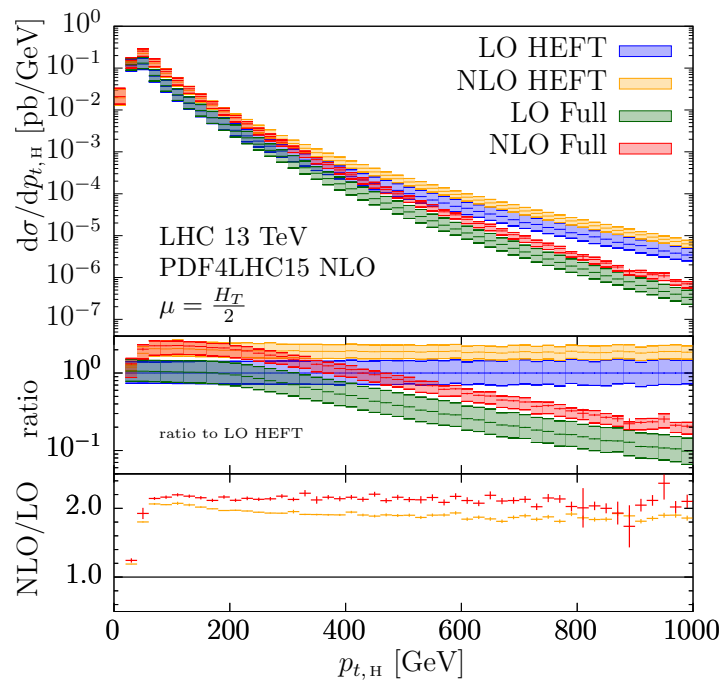
r.h.s: [Chen, Gehrmann, Glover, Jaquier, arXiv:1408.5325]

l.h.s.: [Bhoughezal, Caola, Melnikov, Petriello, Schulze, arXiv:1504.07922]

- ↪ Extra jets present in all Higgs signatures: used to improve S/B ratios.
- ↪ **Impact ubiquitously all Higgs searching channels** (events binned by number of jets: H+0j, H+1j, ...).
- ↪ **High-$\mathbf{p_T}$**: very important to improve by retrieving exact m_t dependence → disentangle **new-physics loop effects** in Hgg and $H\gamma\gamma$, and **anomalous structures** in Higgs couplings.
- ↪ **Low-$\mathbf{p_T}$**: sensitive to light-quark masses in ggH loop → measure $\mathbf{g_{Hb}}$, $\mathbf{g_{Hc}}$ [Bishara et al., arXiv:1606.09253]. Need to calculate it reliably → resummation of large logs. of p_T/m_H, m_q/p_T, and m_q/m_H.

Higgs p_T spectrum: high p_T, exact m_t dependence at NLO



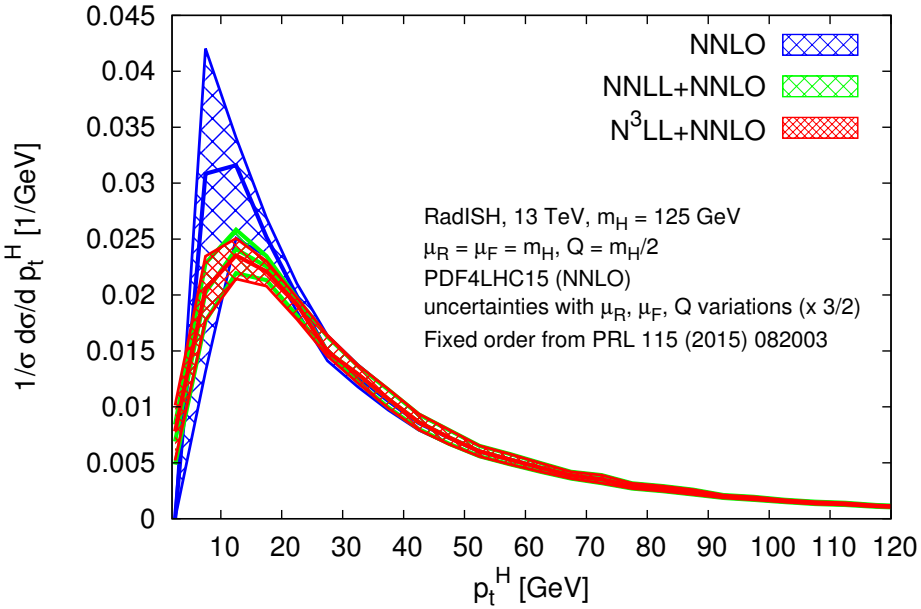


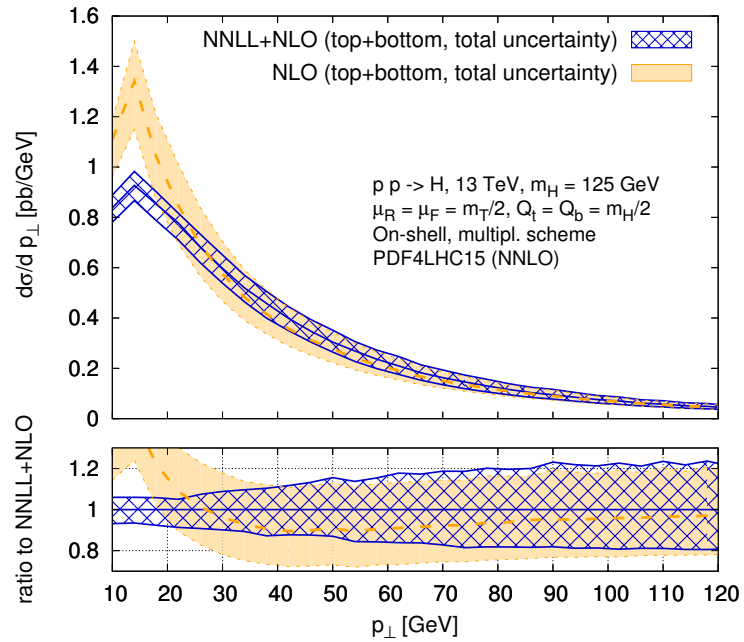
r.h.s: [Jones, Kerner, Luisoni, arXiv:1802.00349]

l.h.s.: [Kudashkin, Lindert, Melnikov, Wever, arXiv:1801.08226]

- ↪ Important agreement: analytical result under the assumption $m_{t,H} \ll p_T^H$ (Kudashkin et al.) vs exact numerical result (Jones et al.)
- ↪ Large QCD effects (K factor), but very similar to HEFT.
- ↪ Can combine with NNLO HEFT K factor?

Higgs p_T spectrum: low p_T, resum large log. corrections



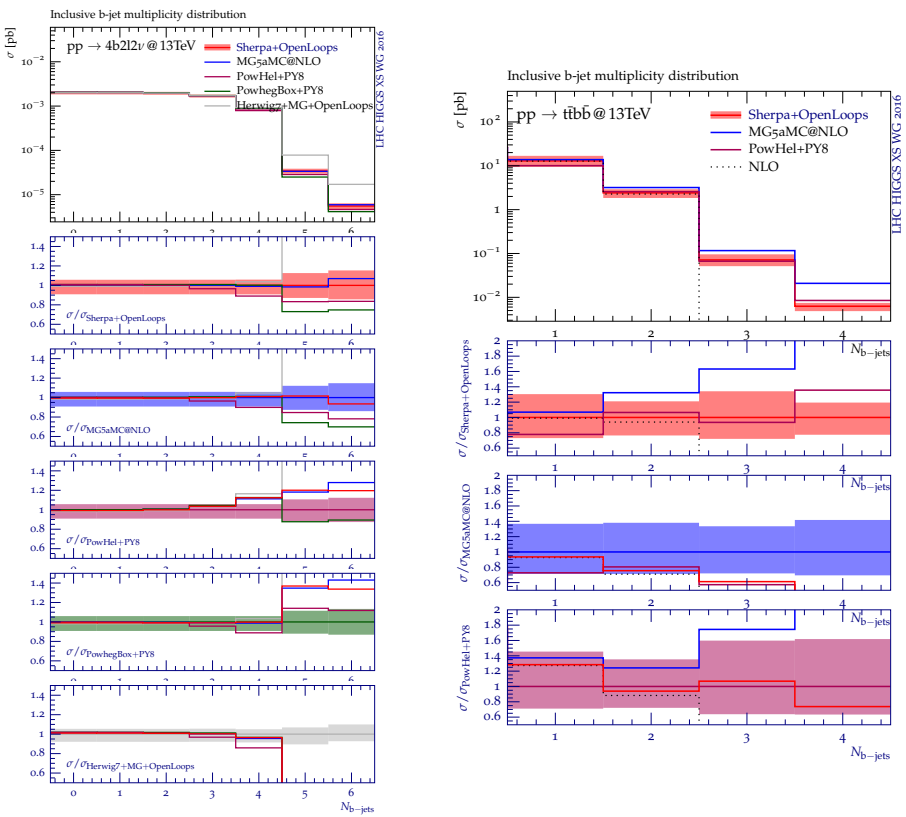


r.h.s: [Bizoń, Monni, Re, Rottoli, Torrielli, arXiv:1705.09127]

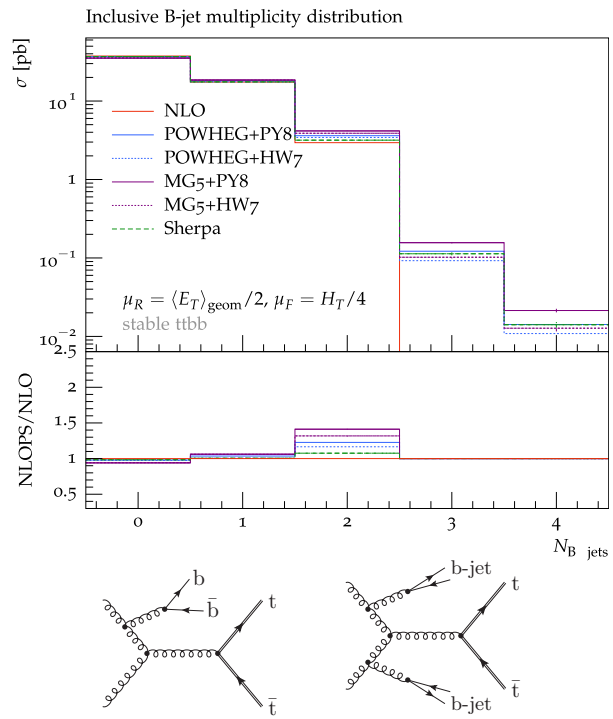
l.h.s.: [Caola, Lindert, Melnikov, Monni, Tancredi, Wever, arXiv:1804.07632]

- ↪ Resumming large logarithms for $p_T \ll M_H$.
- ↪ Including mass corrections for $m_b \ll p_T \ll m_t$ (bottom-top interference).
- ↪ Low-p_T spectrum accuracy at 10-15% level.

$t\bar{t}H(H \to b\bar{b})$, NLO+PS validation



[Preliminary]



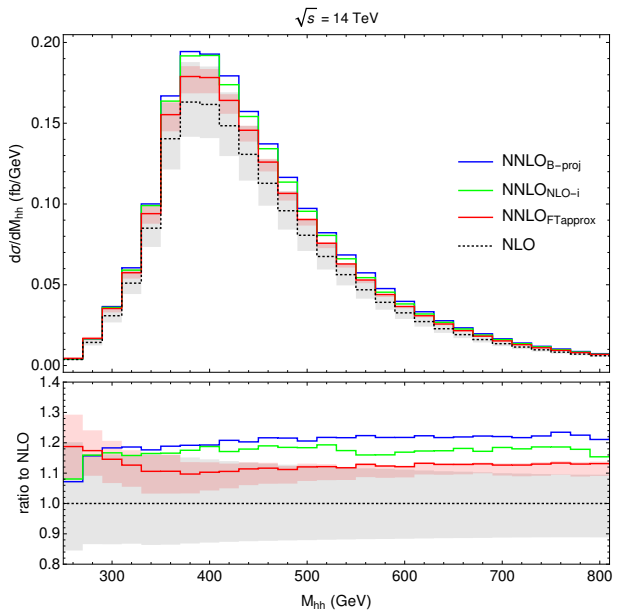
[Pozzorini, et al., Higgs XS Working Group]

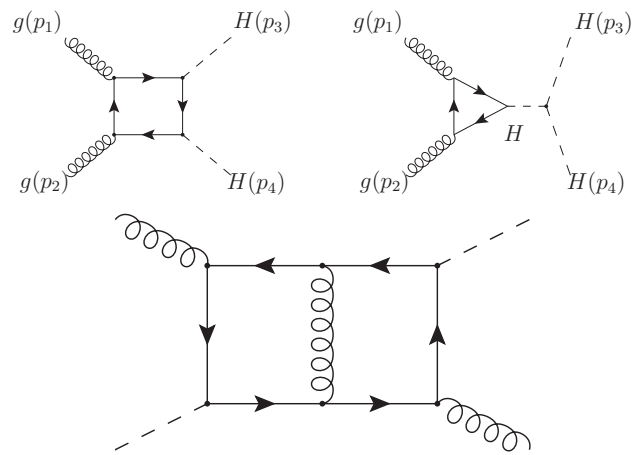
- ↪ crucial to measure g_{Ht}: **discovered** (5σ!) in Run II.
- ↪ **Signal well understood** (including NLO QCD+EW and PS).
- ↪ $\mathbf{t\bar{t} + b}$ **jets**: dominant backgrounds for $t\bar{t}H(\to b\bar{b})$.
- ↪ NLO+PS tools: initially large discrepancies, being resolved by in depth **studies of NLO PS tools** plus **NLO calculation of** $\mathbf{t\bar{t}b\bar{b} + j}$ [Pozzorini et al.], and NLO merging of $X + jj$ and $X + b\bar{b}$ [Siegert et al., arXiv:1904.09382]

  ↪[See T. Jezo's talk at LHCP 2019, Thursday, May 23: Top parallel Session]

HH production at NNLO, full m_t dependence

Measuring the Higgs-boson trilinear coupling





[Borowka, et al., arXiv:1604.06447, Grazzini, et al., arXiv:1803.02463]

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

↪ Including full m_t effects at NLO QCD:

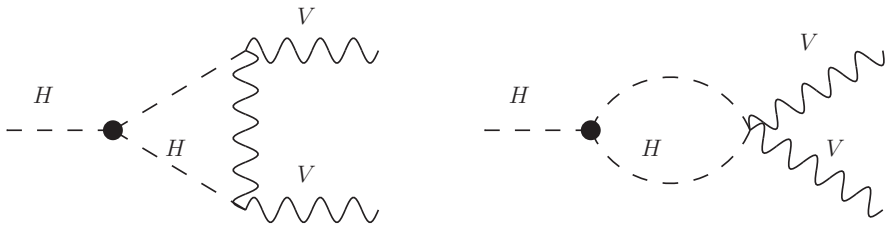
$$\sigma_{\rm NLO}(13\,{\rm TeV}) = 27.78^{+13.8\%}_{-12.8\%} \quad \longrightarrow \quad \sigma_{\rm NNLO_{FTapprox}}(13\,{\rm TeV}) = 31.05^{+2.2\%}_{-5.0\%}$$

Most recent experimental result for $\kappa_\lambda = \lambda_3/\lambda_3^{\rm SM}$, [ATLAS-CONF-2016-049]

$$-3.2 \leq \kappa_\lambda \leq 11.9 \quad (95\%\,{\rm CL})$$

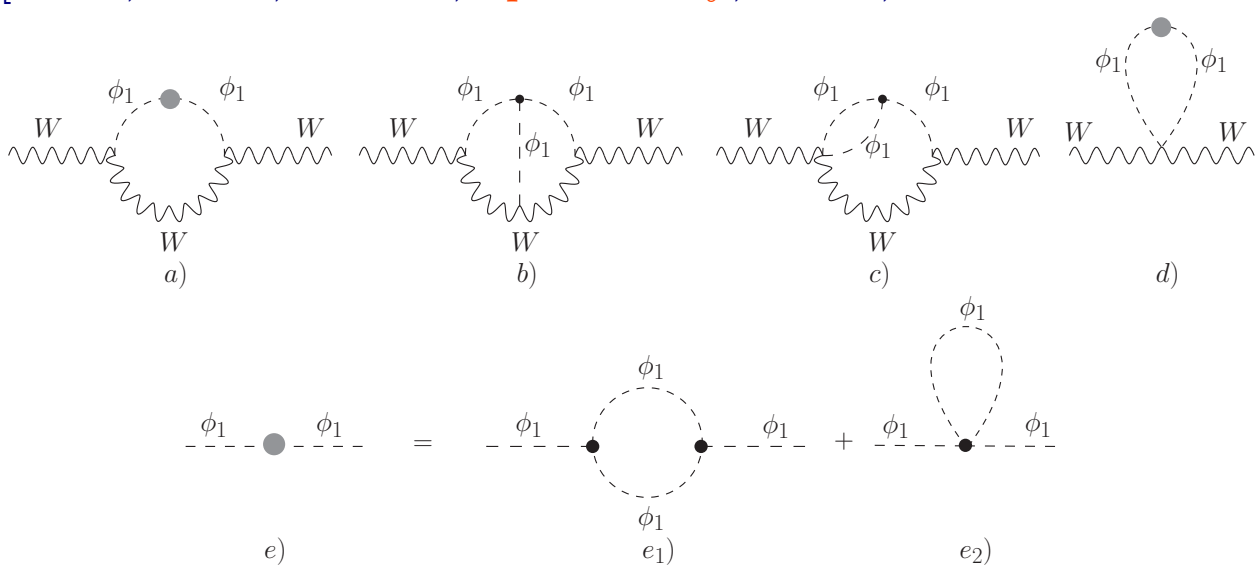
Or, extract trilinear coupling from indirect loop effects

[Degrassi, Giardino, Maltoni, Pagani, arXiv:1607.04251] $\longrightarrow \quad \kappa_\lambda > -14.3$



[Degrassi, Fedele, Giardino, arXiv:1702.01737] $\longrightarrow \quad -14 < \kappa_\lambda < 18$

[Kribs, Maier, Rzehah, Spannowsky, Waite, arXiv:1702.07678] $\longrightarrow \quad -14 < \kappa_\lambda < 17.4$



Combining EWPO and Higgs observables

Bounds on of κ_V and κ_f: Higgs vs Higgs+EWPO

$\kappa_V \to$ all g_{HV}

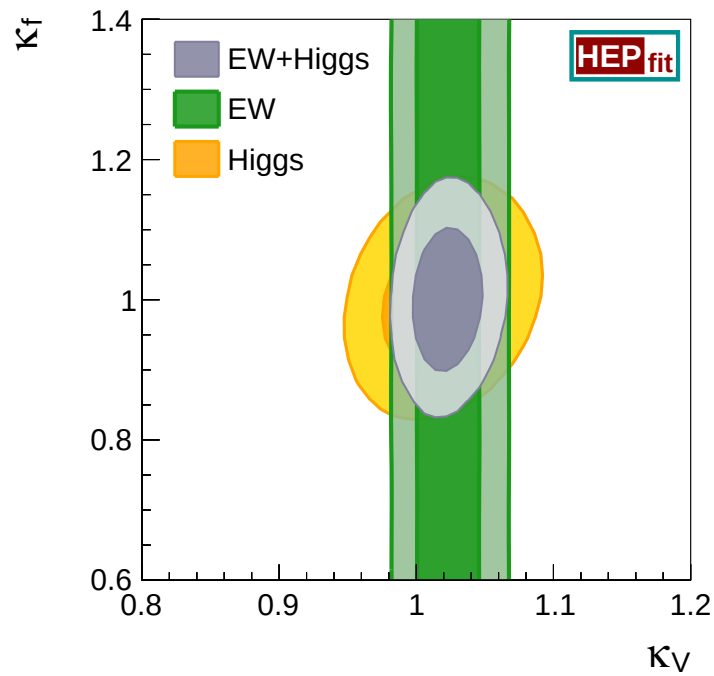
$\kappa_f \to$ all g_{Hf}

Higgs only

	68%	95%	correlation	
κ_V	1.02 ± 0.03	[0.97, 1.08]	1.00	
κ_f	0.98 ± 0.07	[0.84, 1.12]	0.24	1.00

Higgs+EWPO

	68%	95%	correlation	
κ_V	1.02 ± 0.02	[0.99, 1.06]	1.00	
κ_f	1.00 ± 0.06	[0.88, 1.12]	0.14	1.00



$$\sigma_i = \sigma_i^{\rm SM} + \delta\sigma_i$$
$$\Gamma_j = \Gamma_j^{\rm SM} + \delta\Gamma_j$$

$\sigma_i^{\rm SM}$, $\Gamma_j^{\rm SM}$ $\to$ from Higgs XS WG (CERN Yellow Report, arXiv:1610.07922)

$\delta\sigma_i \to$ using Madgraph (with our UFO files)+K-factors (from Higgs XS WG)

$\delta\Gamma_j \to$ eHdecay [Contino et al., arXiv:1403.3381]

SM Effective Field Theory: bounds on SMEFT coefficients

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

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

considering:

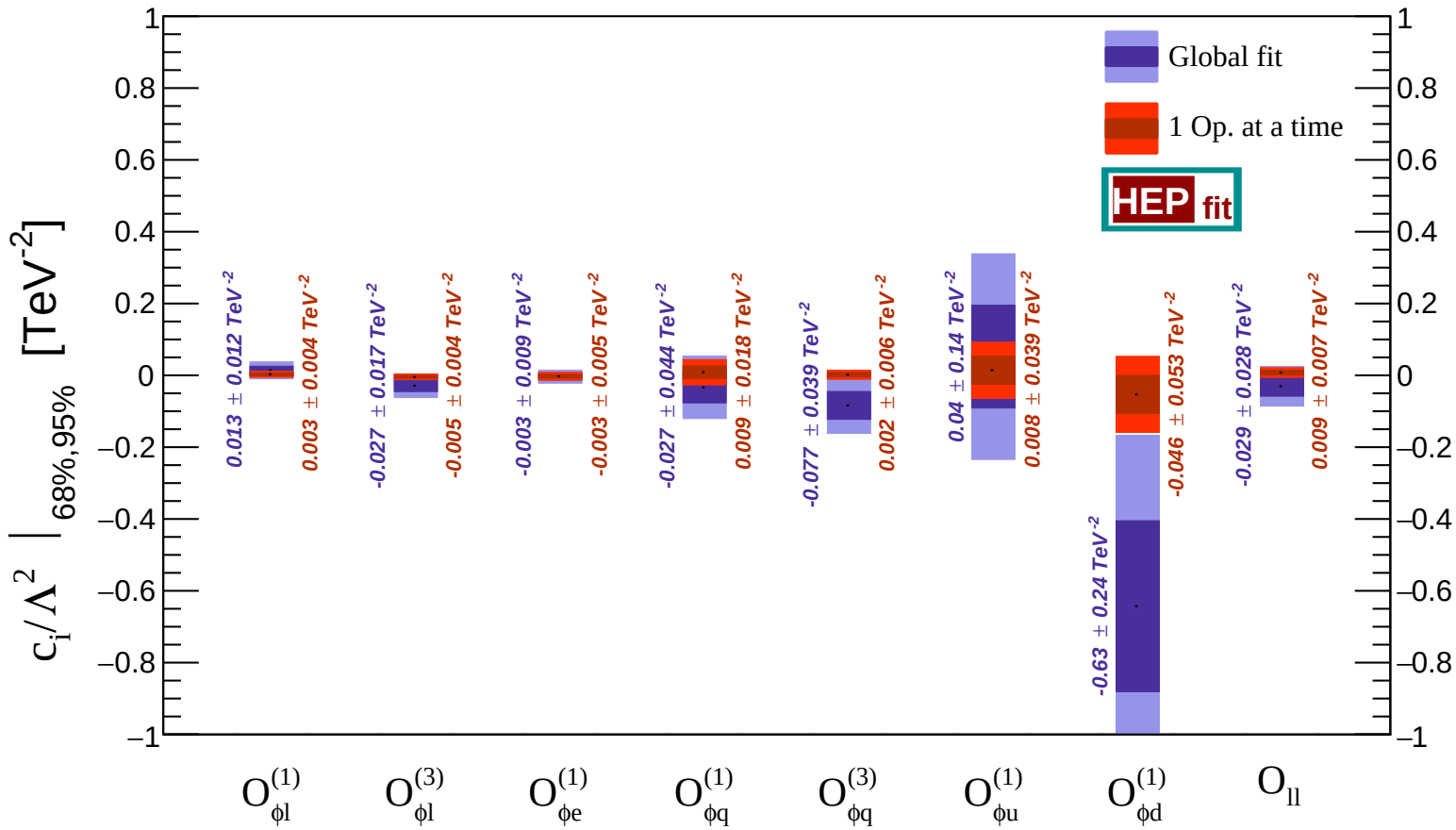
- → one Higgs doublet of $SU(2)_L$, linearly realized SSB
- → **$\mathbf{d = 6}$ operators only**, obeying SM gauge symmetry, L and B conservation
  - ↪ expansion in $(p, v)/\Lambda$
  - ↪ **truncation at linear order** $\rightarrow O((p, v)^2/\Lambda^2)$ **to be verified a posteriori**.

and requiring:

- → flavour universality: 59 operators
  [basis by Grzadkowski et al., JHEP 1010 (2010) 085]
- → CP even operators only, with at least one Higgs: 27 operators
- → only operators contributing to the observables considered: 19 operators
- → $C_i = C_i(\Lambda_{\text{EW}})$, no running $C_i(\Lambda) \rightarrow C_i(\Lambda_{\text{EW}})$ included so far.

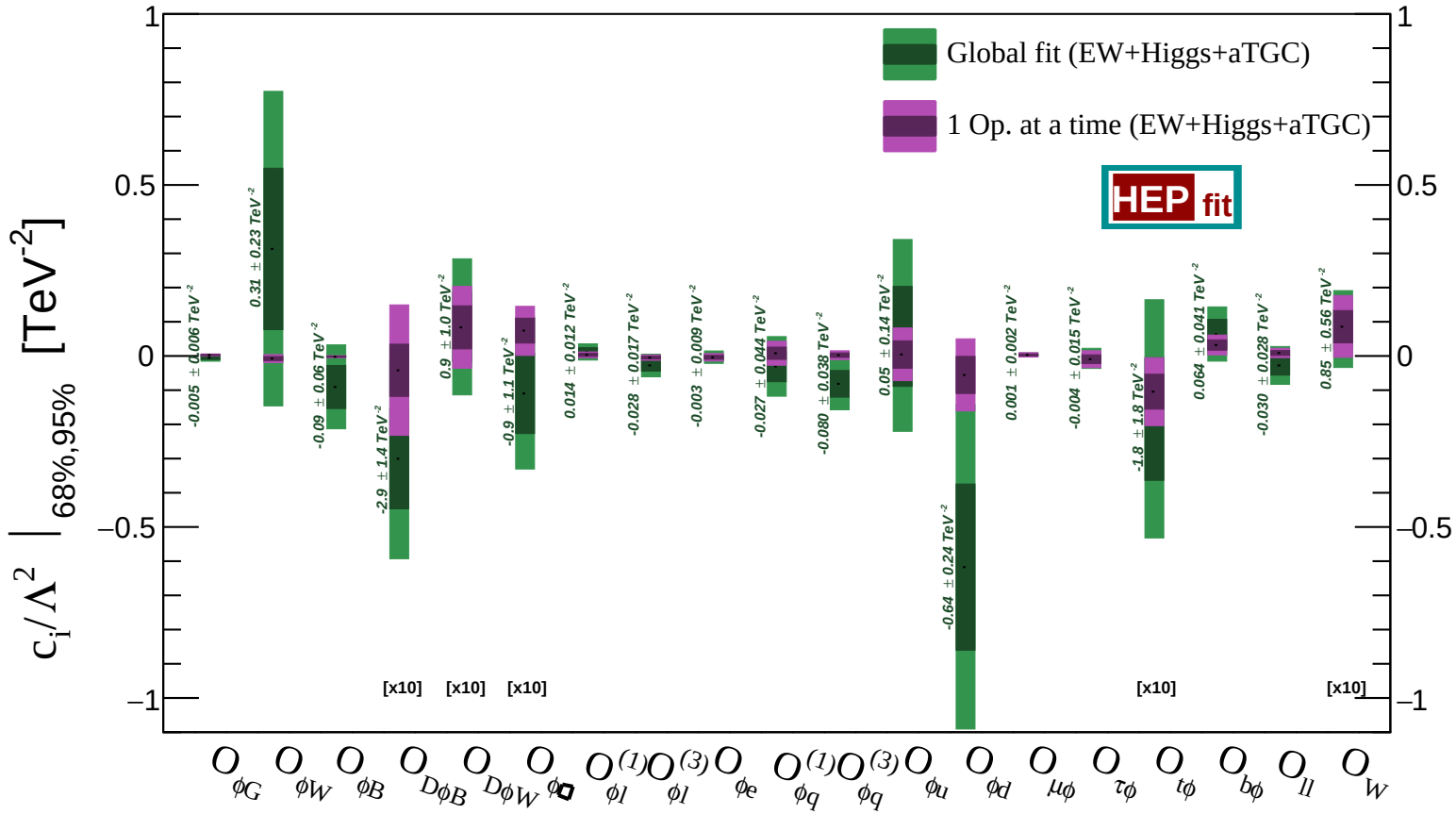
95% bounds on coefficients of d=6 interactions

→ **Combined global EW fit** of 8 constrained operators.



Large difference between global and individual bounds → Large correlations

→ **Combined global EW+Higgs fit** of extended set of operators.



Large difference between global and individual bounds → Large correlations

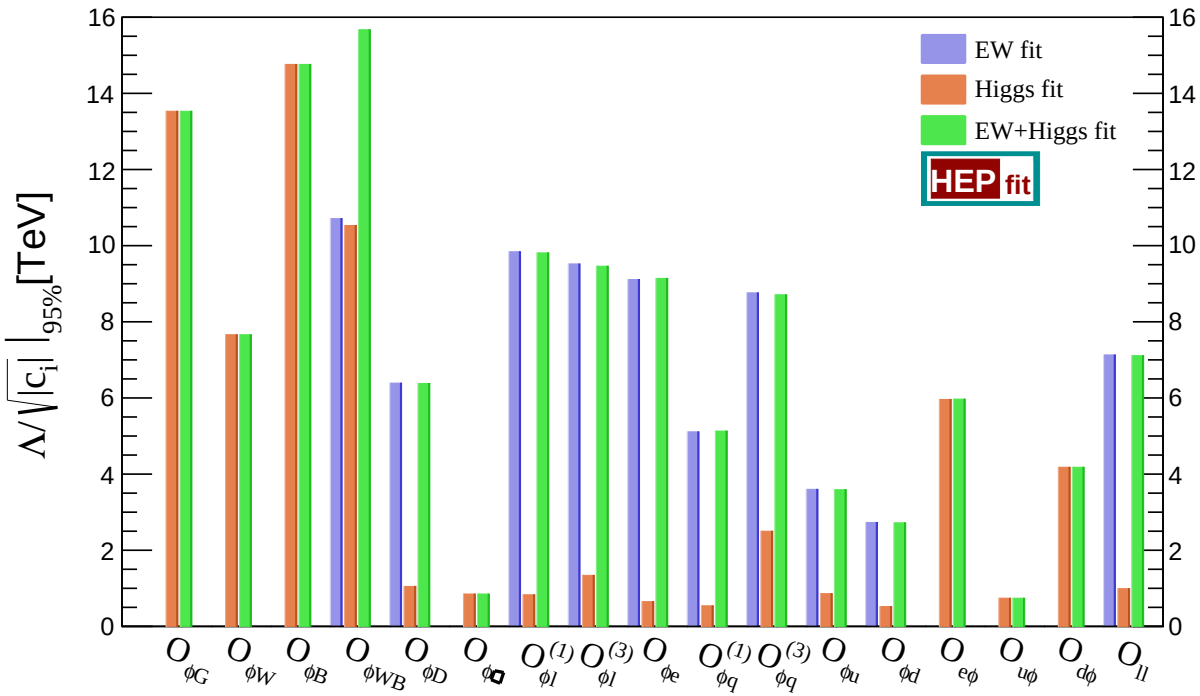
↪ **Theory analyses limited by provided information** from exp. analyses.

↪ Experimental studies should **aim for global fit** (not only a few operators).

95% bounds on coefficients of d=6 interactions

→ Extended set of operators, switching on **one operator at a time**

Coefficient	95% prob. range C_i/Λ^2 [TeV^{-2}]	95% prob. lower bound on Λ [TeV] ($\lvert C_i\rvert = 1$)
$C_{\phi G}$	[−0.00029, 0.0059]	13.5
$C_{\phi W}$	[−0.019, 0.0040]	7.63
$C_{\phi B}$	[−0.0051, 0.0011]	14.7
$C_{\phi WB}$	[−0.0045, 0.0038]	15.7
$C_{\phi D}$	[−0.027, 0.00092]	6.38
$C_{\phi\Box}$	[0.015, 1.4]	0.85
$C_{\phi L}^{(1)}$	[−0.0052, 0.012]	9.81
$C_{\phi L}^{(3)}$	[−0.013, 0.0030]	9.46
$C_{\phi e}^{(1)}$	[−0.015, 0.0070]	9.14
$C_{\phi Q}^{(1)}$	[−0.027, 0.043]	5.13
$C_{\phi Q}^{(3)}$	[−0.0111, 0.015]	8.71
$C_{\phi u}$	[−0.072, 0.082]	3.59
$C_{\phi d}$	[−0.16, 0.050]	2.72
$C_{e\phi}$	[−0.034, 0.015]	5.97
$C_{u\phi}$	[−2.0, −0.050]	0.74
$C_{d\phi}$	[0.0031, 0.061]	4.18
C_{LL}	[−0.0048, 0.022]	7.11



↪ EWPO constraints still more stringent: **Higgs bounds ≤ EWPO bounds**

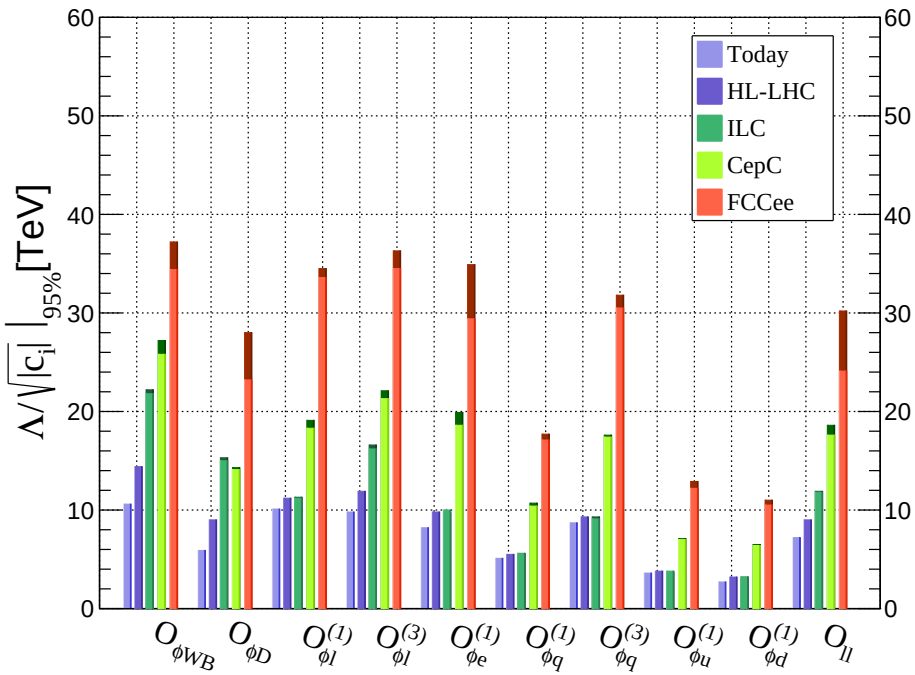
↪ Need to incrementally move towards more **global fits**.

↪ Need to use **more observables**: Higgs kinematic distributions, EW triple-gauge-coupling measurements, ...

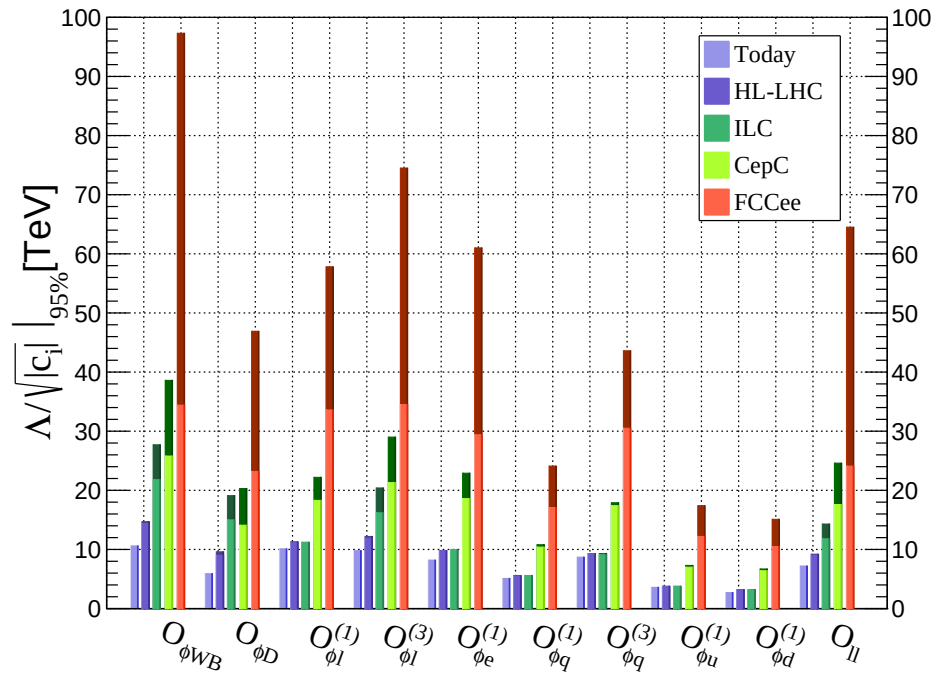
↪ incrementally **release flavour universality** → t-quark observables (b, τ).

Interesting to explore perspective at future colliders.

Projected bounds for Λ



with/without theoretical errors



with/without theoretical and parametrical errors

$\hookrightarrow$ **Most recent study**:

J. de Blas et al., Higgs boson studies at future particle colliders, arxiv:1905.03764

prepared for the

"*Symposium on the Update of the European Strategy for Particle Physics*",

Granada, May 13-16 2019.

Outlook and Conclusions

- After the discovery of the Higgs-boson during Run I of the LHC, a major effort to **develop a full-fledged precision program to measure its couplings** has been growing.
- **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.

Back-up slides

SM Effective Field Theory: bounds on SMEFT coefficients

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

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

considering:

- → one Higgs doublet of $SU(2)_L$, linearly realized SSB
- → **$\mathbf{d = 6}$ operators only**, obeying SM gauge symmetry, L and B conservation
  - ↪ expansion in $(p, v)/\Lambda$
  - ↪ **truncation at linear order** $\rightarrow O((p, v)^2/\Lambda^2)$ **to be verified a posteriori**.

and furthermore requiring:

- → flavour universality: 59 operators
  [basis by Grzadkowski et al., JHEP 1010 (2010) 085]
- → CP even operators only, with at least one Higgs: 27 operators
- → only operators contributing to the observables considered: 17 operators
- → $C_i = C_i(\Lambda_{\text{EW}})$, no running $C_i(\Lambda) \rightarrow C_i(\Lambda_{\text{EW}})$ included so far.

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

bosonic operators

$\longrightarrow$ corrections to:

- oblique parameters (in red)
- $HVV \longrightarrow \kappa_V$
- WWZ and $WW\gamma$

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

single-fermionic-vector-current operators

$\longrightarrow$ corrections to:

- $Vf\bar{f}$ (in blue)
- $HVf\bar{f}$

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:

- Yukawa couplings
- $Hf\bar{f} \longrightarrow \kappa_f$

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>:

Only highlighted operators (10) enters EWPO, and only 8 combinations can be constrained $\longrightarrow$ substitute $\mathcal{O}_{\phi WB}$ and $\mathcal{O}_{\phi D}$ in global fit.

The fitting procedure → `HEPfit`

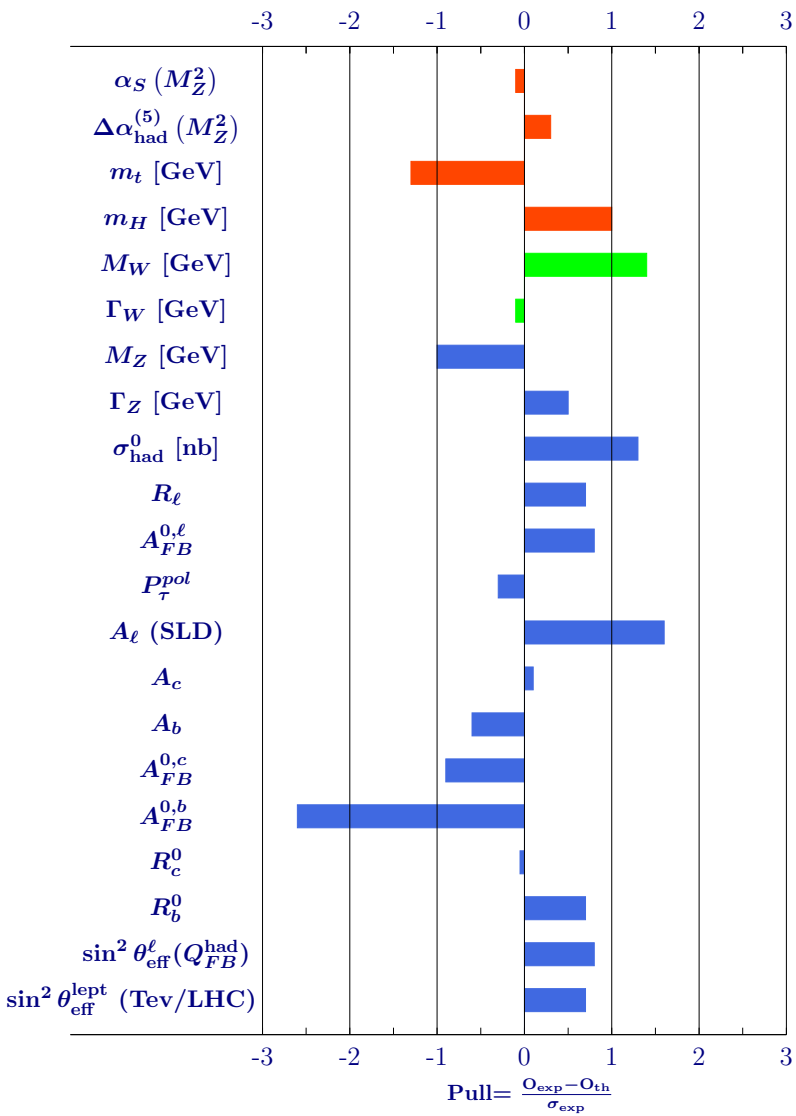
- Both **EWPO and Higgs observables** calculated as a **SM core plus corrections**:
  - ↪ The SM cores includes all existing higher order corrections.
  - ↪ The NP corrections are at the lowest order in all SM couplings.
- **Experimental results** are taken from the most recent published analyses (approx. **Moriond 2019**).
- The fitting procedure uses a Bayesan statistical analysis (BAT, Bayesan Analysis Toolkit) [Caldwell et al., arXiv:0808.2552].
- **Stand-alone** or **library mode** to **compute observables in a given model**:
  - ↪ **Implemented models**:
    - ↪ SM,
    - ↪ Oblique parameters (S,T,U), ε_i parameters, Modified $Zb\bar{b}$ couplings,
    - ↪ Modified Higgs couplings (κ_i), SMEFT (d=6),
    - ↪ 2HDM, ...
  - ↪ **Implemented observables**: EWPO, Higgs signal strengths, Flavour ($\Delta F = 2$, UT, rare B decays).

Fits of electroweak precision data

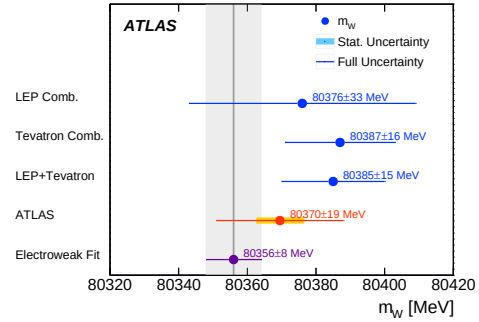
- Set of **input parameters**
  - → **fixed**: G_F, α (best measured)
  - → **floating**: M_Z, M_H, m_t, $\alpha_s(M_Z)$, $\Delta\alpha_{\rm had}^{(5)}$
- **Compute EW precision observables** (EWPO), including all known higher-order corrections (in a given renormalization scheme):
  - → M_W, Γ_W (LEP2/Tevatron, LHC)
  - → Z-pole observables: Γ_Z, A_f, $A_{FB}^{l,0}$, ... (LEP/SLD, Tevatron, LHC)
- **Perform best fit** and compare with experimental measurement: tension might signal new physics.
- Several comprehensive frameworks:
  - → GAPP [Erler]
  - → ZFITTER [Akhundov, Arbuzov, S.Riemann, T.Riemann]
  - → Gfitter [Baak, Cúth, Haller, Hoecker, Kogler, Mönig, Schott, Stelzer]
  - → HEPfit [de Blas, Ciuchini, Franco, Mishima, Pierini, L.R., Silvestrini]

  plus independent studies [see e.g. Ellis, Murphy, Sanz, You, arXiv:1803.03252]

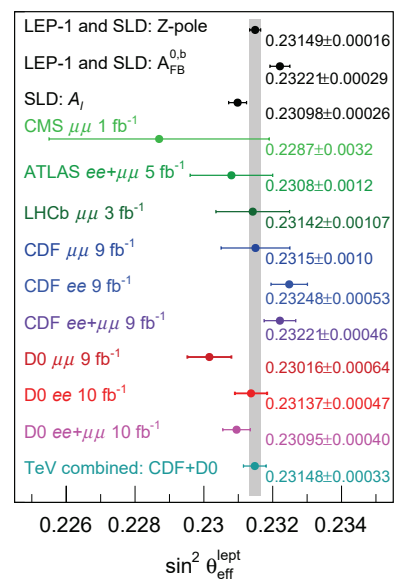
Including most recent LHC/Tevatron results



M_W: first LHC measurement



$\sin^2\theta_{eff}^{lept}$: first LHC measurements



[HEPfit, LHCP 2018]

Plus most recent m_t and α_s results.