Institute of High Energy Physics
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Higgs Combination in CMS

Higgs potential 2022

25th July 2022

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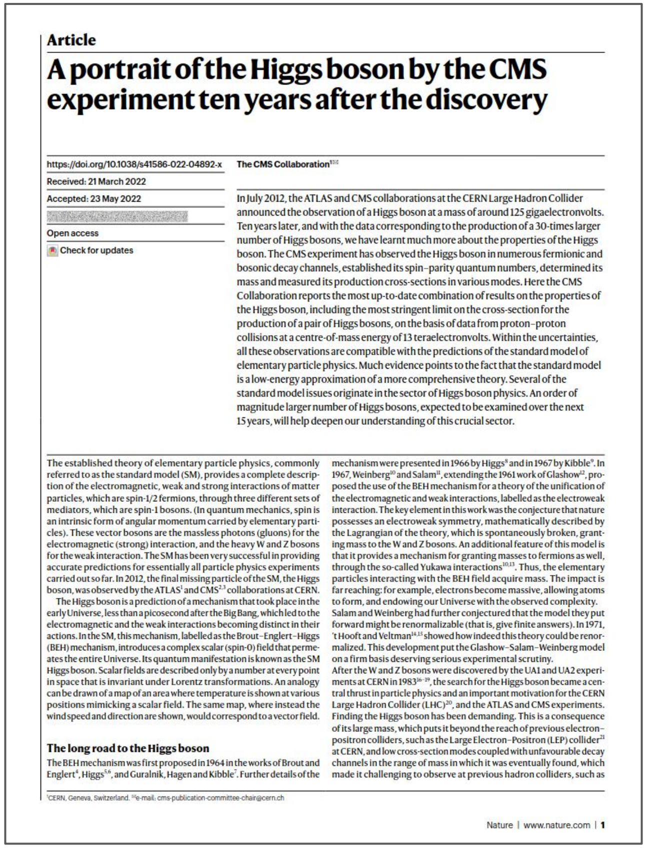
Outline

- Introduction and motivations

- Results



Article

A portrait of the Higgs boson by the CMS experiment ten years after the discovery

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The CMS Collaboration[1✉]

In July 2012, the ATLAS and CMS collaborations at the CERN Large Hadron Collider announced the observation of a Higgs boson at a mass of around 125 gigaelectronvolts. Ten years later, and with the data corresponding to the production of a 30-times larger number of Higgs bosons, we have learnt much more about the properties of the Higgs boson. The CMS experiment has observed the Higgs boson in numerous fermionic and bosonic decay channels, established its spin–parity quantum numbers, determined its mass and measured its production cross-sections in various modes. Here the CMS Collaboration reports the most up-to-date combination of results on the properties of the Higgs boson, including the most stringent limit on the cross-section for the production of a pair of Higgs bosons, on the basis of data from proton–proton collisions at a centre-of-mass energy of 13 teraelectronvolts. Within the uncertainties, all these observations are compatible with the predictions of the standard model of elementary particle physics. Much evidence points to the fact that the standard model is a low-energy approximation of a more comprehensive theory. Several of the standard model issues originate in the sector of Higgs boson physics. An order of magnitude larger number of Higgs bosons, expected to be examined over the next 15 years, will help deepen our understanding of this crucial sector.

The established theory of elementary particle physics, commonly referred to as the standard model (SM), provides a complete description of the electromagnetic, weak and strong interactions of matter particles, which are spin-1/2 fermions, through three different sets of mediators, which are spin-1 bosons. (In quantum mechanics, spin is an intrinsic form of angular momentum carried by elementary particles). These vector bosons are the massless photons (gluons) for the electromagnetic (strong) interaction, and the heavy W and Z bosons for the weak interaction. The SM has been very successful in providing accurate predictions for essentially all particle physics experiments carried out so far. In 2012, the final missing particle of the SM, the Higgs boson, was observed by the ATLAS[1] and CMS[2,3] collaborations at CERN.

The Higgs boson is a prediction of a mechanism that took place in the early Universe, less than a picosecond after the Big Bang, which led to the electromagnetic and the weak interactions becoming distinct in their actions. In the SM, this mechanism, labelled as the Brout–Englert–Higgs (BEH) mechanism, introduces a complex scalar (spin-0) field that permeates the entire Universe. Its quantum manifestation is known as the SM Higgs boson. Scalar fields are described only by a number at every point in space that is invariant under Lorentz transformations. An analogy can be drawn of a map of an area where temperature is shown at various positions mimicking a scalar field. The same map, where instead the wind speed and direction are shown, would correspond to a vector field.

The long road to the Higgs boson

The BEH mechanism was first proposed in 1964 in the works of Brout and Englert[4], Higgs[5,6], and Guralnik, Hagen and Kibble[7]. Further details of the mechanism were presented in 1966 by Higgs[8] and in 1967 by Kibble[9]. In 1967, Weinberg[10] and Salam[11], extending the 1961 work of Glashow[12], proposed the use of the BEH mechanism for a theory of the unification of the electromagnetic and weak interactions, labelled as the electroweak interaction. The key element in this work was the conjecture that nature possesses an electroweak symmetry, mathematically described by the Lagrangian of the theory, which is spontaneously broken, granting mass to the W and Z bosons. An additional feature of this model is that it provides a mechanism for granting masses to fermions as well, through the so-called Yukawa interactions[10,13]. Thus, the elementary particles interacting with the BEH field acquire mass. The impact is far reaching: for example, electrons become massive, allowing atoms to form, and endowing our Universe with the observed complexity. Salam and Weinberg had further conjectured that the model they put forward might be renormalizable (that is, give finite answers). In 1971, 't Hooft and Veltman[14,15] showed how indeed this theory could be renormalized. This development put the Glashow–Salam–Weinberg model on a firm basis deserving serious experimental scrutiny.

After the W and Z bosons were discovered by the UA1 and UA2 experiments at CERN in 1983[16–19], the search for the Higgs boson became a central thrust in particle physics and an important motivation for the CERN Large Hadron Collider (LHC)[20], and the ATLAS and CMS experiments. Finding the Higgs boson has been demanding. This is a consequence of its large mass, which puts it beyond the reach of previous electron–positron colliders, such as the Large Electron–Positron (LEP) collider[21] at CERN, and low cross-section modes coupled with unfavourable decay channels in the range of mass in which it was eventually found, which made it challenging to observe at previous hadron colliders, such as

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Focus on Nature 607, 60–68 (2022) results

- Paper accepted by Nature for 10th anniversary of H discovery

What can we do with the Run 2 Higgs measurements?

- Test compatibility with SM
  - Precise measurements of the main H production XS and decay BR
- Measurement of H coupling to fermions and vector bosons
  - Probe anomalies from BSM contributions
- Probe properties of the H potential from H self-coupling
- What is not covered?
  - HHVV coupling
  - H couplings to some 2nd (and 1st) generation charged fermions

Accessible via HH (Jin Wang talk)

Hcc measurements (C.Li talk) not included in this combination

Analyses included in the combination

Analyses	Lumi (fb^{-1})	ggH	qqH	VH	ttH and tH
H(γγ)	138	X	X	X	X
H(ZZ)	138	X	X	X	X
H(WW)	138	X	X	X	X
H(Zγ)	138	X	X		
H(bb)	36(ttH) 77(VH) 138(ggH)	X	X	X	X
H(ττ)	138	X	X	X	X
ttH multilepton(ττ, WW, and ZZ)	138				X
H(μμ)	138	X	X		X
H(invisible)	138	X	X	X	

- Main H production and decay channels covered
- In part with Simplified Template Cross section stage 1.2 granularity

Evolution since discovery

H Discovery (up to 5.1 fb^{-1} at 7 TeV and 5.3 fb^{-1} at 8 TeV)

$\mu = 0.87 \pm 0.23$ [dominated by stat.]

Run 1 comb (up to 5.1 fb^{-1} at 7 TeV and 19.7 fb^{-1} at 8 TeV)

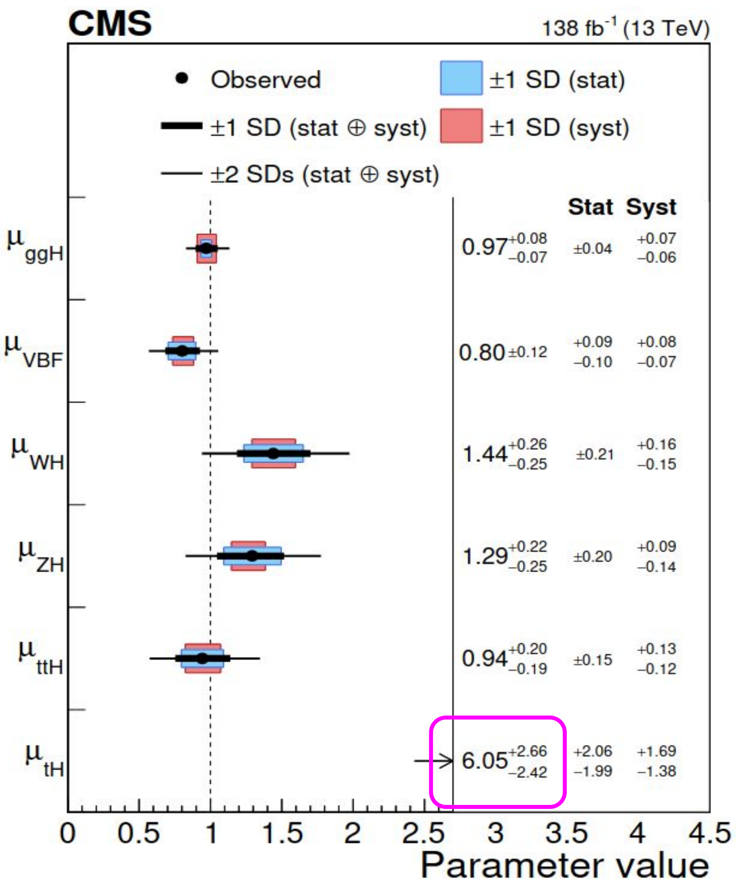
$\mu = 1.00 \pm 0.13$ [+0.08/-0.07 (theory) ± 0.07 (exp.) ± 0.09 (stat.)]

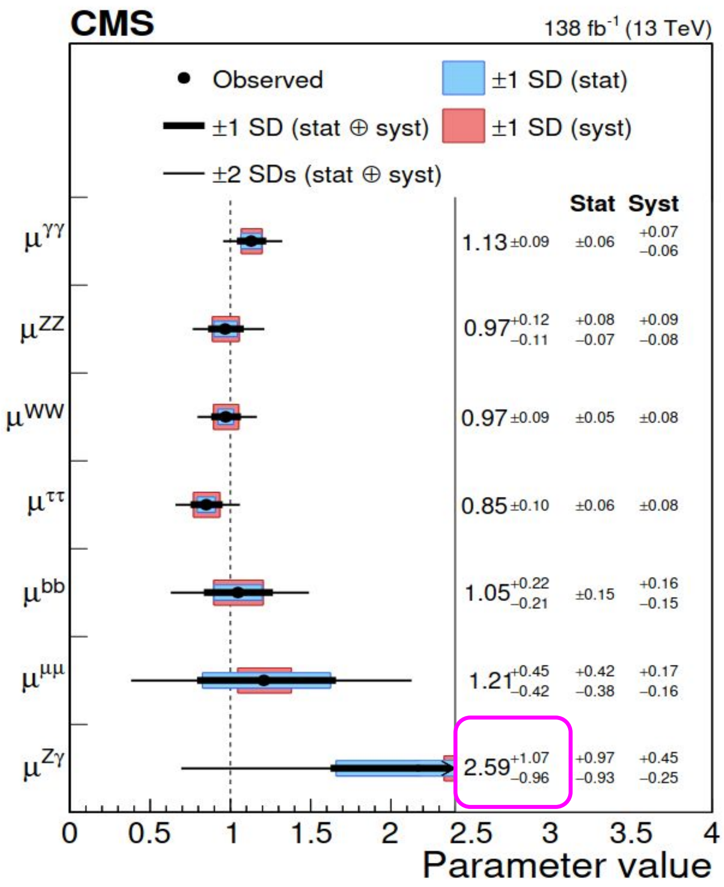
This combination (up to 138 fb^{-1} at 13 TeV)

$\mu = 1.002 \pm 0.057$ [± 0.036 (theory) ± 0.033 (exp.) ± 0.029 (stat.)]

- Systematics uncertainties crucial for H measurements today and even more in future
  - Reduce exp. uncertainties with improved or new approaches
  - Need of more precise theory predictions

Test XS and BR compatibility with the SM



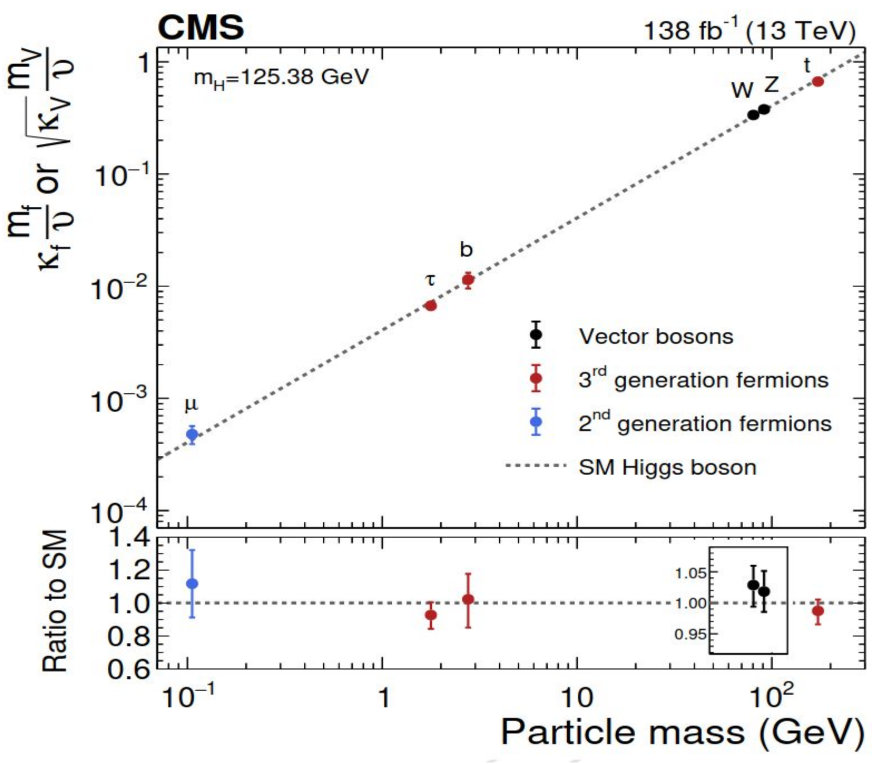


- ➢ Good compatibility for main H production XS & decay BR
- ➢ Intriguing excesses in μ_{tH} and in $\mu_{Z\gamma}$ → interesting to probe with Run 3 data

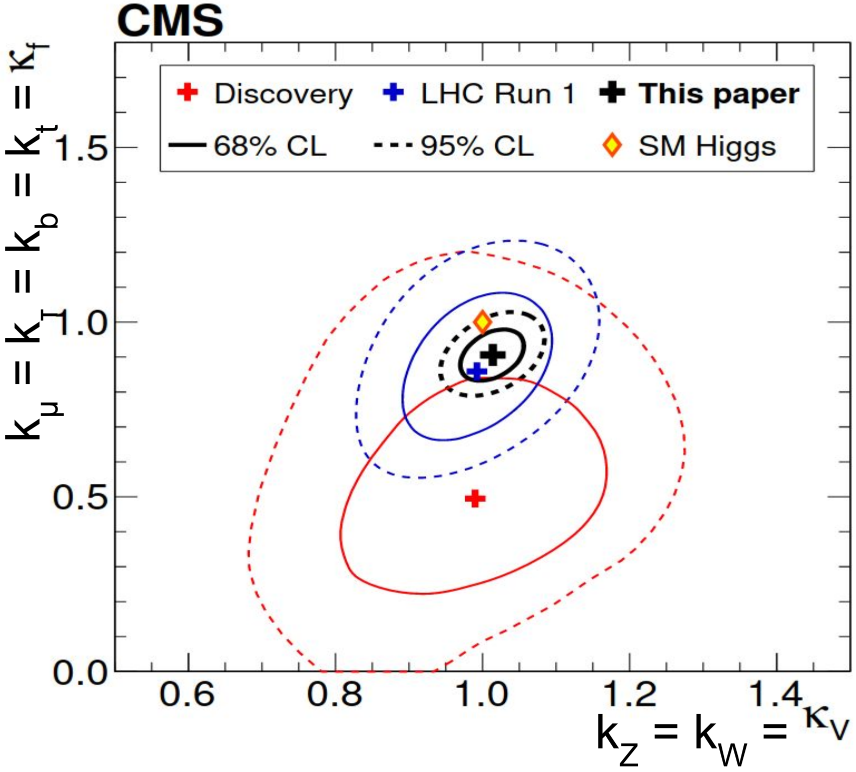
H couplings to fermions and vector bosons

- Coupling modifiers k_i to quantify couplings deviations from SM predictions

H couplings vs particle mass



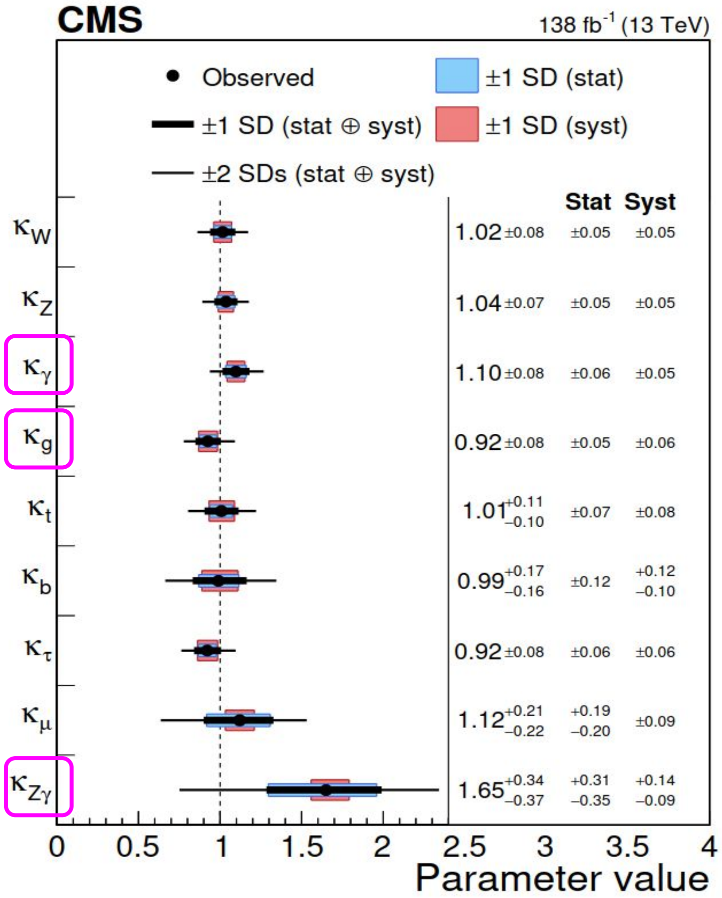
Likelihood scan of (k_f, k_V)

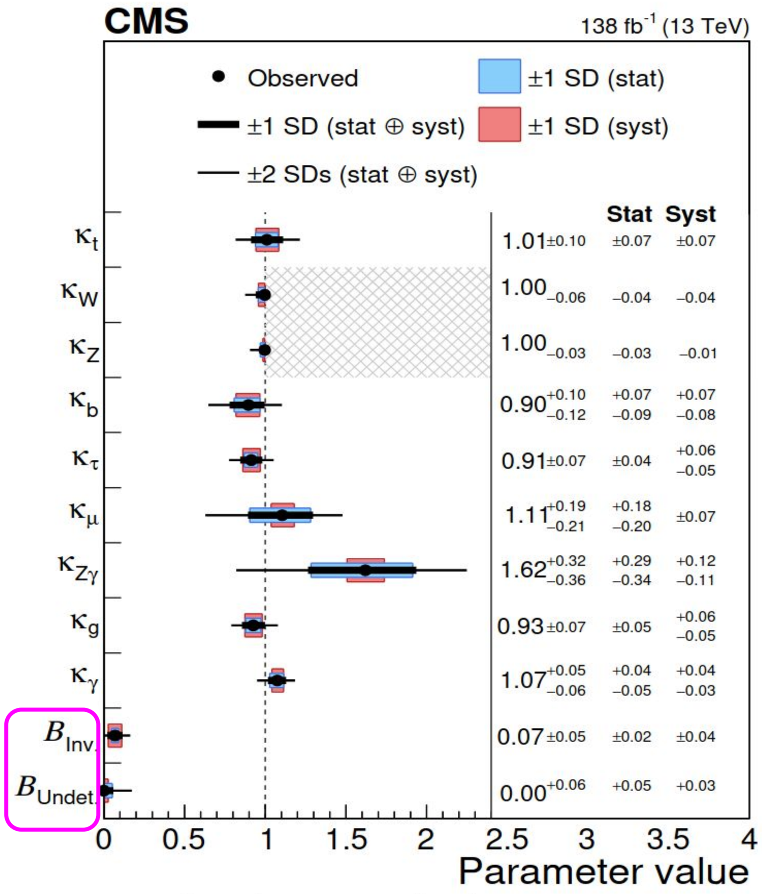


➢ Good compatibility with SM
  - ○ Precision of ~3% on vector boson and of 5-20% on fermion coupl.

H couplings a little more general

Measurement assuming effective couplings for ggH, Hɣɣ, and HZɣ → Assuming also H decays to invisible(MET) & undetectable

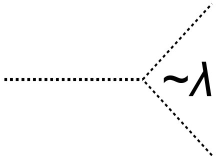




Stat. unc ≅ syst unc except for k_μ and and $k_{Z\gamma}$

Both invisible and undetectable BR’s compatible with zero

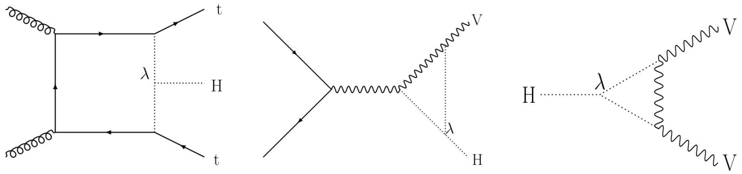
Constraints on the H self-coupling



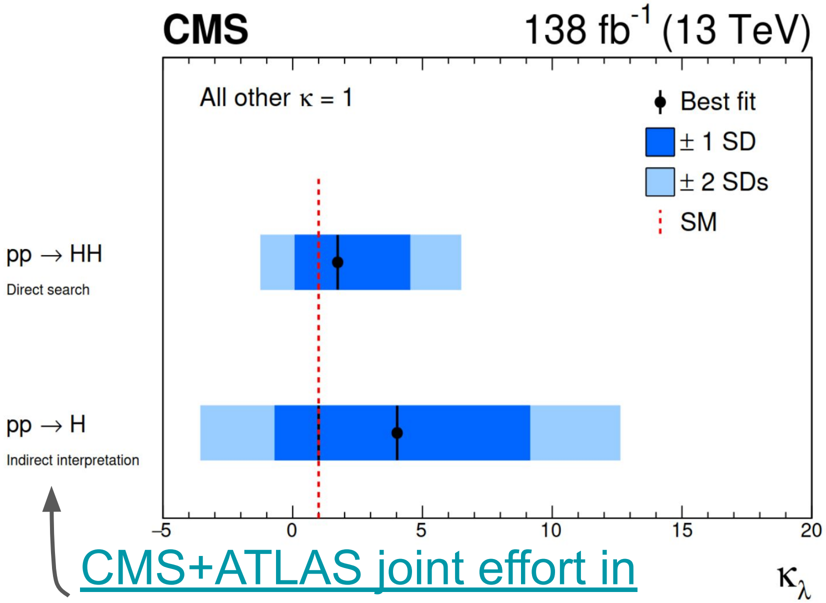
$k_\lambda = \lambda/\lambda_{SM}$

- k_λ-dependent NLO electroweak corrections to H XS and BR

Examples of k_λ-dependent diagrams for single-H prod. mechanisms and H→VV decay

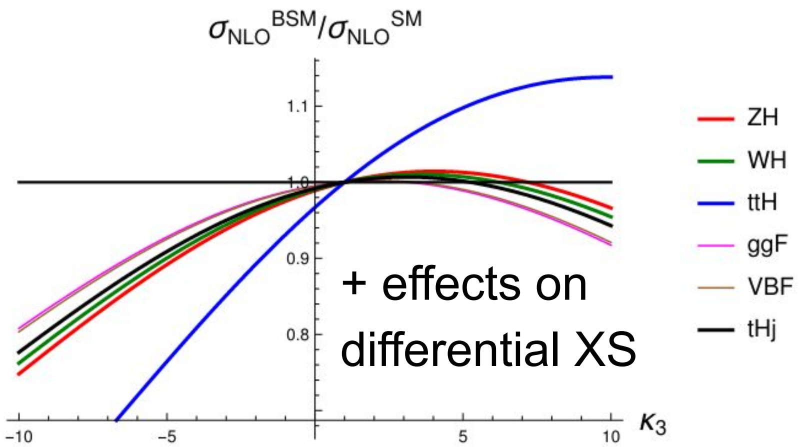


k_λ measurement from HH vs from single-H



CMS+ATLAS joint effort in modeling differential H XS's vs kλ

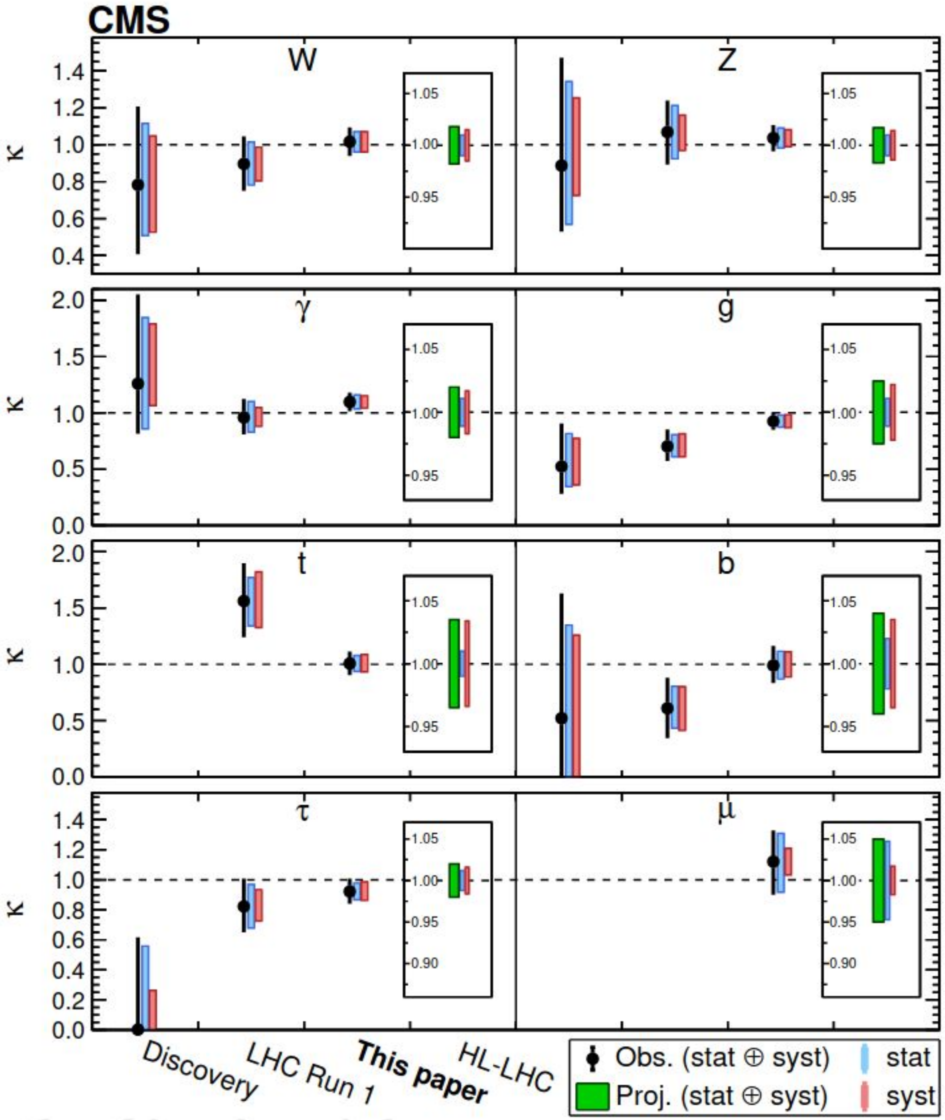
Modification of total XS vs k_λ



+ effects on differential XS

- ➢ single-H constrain on k_λ non-negligible wrt HH one
- ➢ First CMS measurement from single-H considering differential effects

Evolution from the H discovery towards HL-LHC



- ➢ At HL-LHC high precision tests of the SM
  - ○ Precision below 5% for all the considered couplings
- ➢ Potential for more extensive tests
  - ○ H-HH comb including k_λ in the fit
  - ○ EFT interpretations

Summary

- H combination provides extensive tests of the SM
    - H production XS's, decay BR's, H couplings + self-coupling
- Statistical uncertainties comparable to systematics ones
- Overall observed good compatibility with SM
    - Intriguing excesses in μ_{tH} and in $\mu_{Z\gamma}$
- First measurement of k_λ from single-H taking into account effects on differential XS at CMS
- At HL-LHC high precision tests of the SM

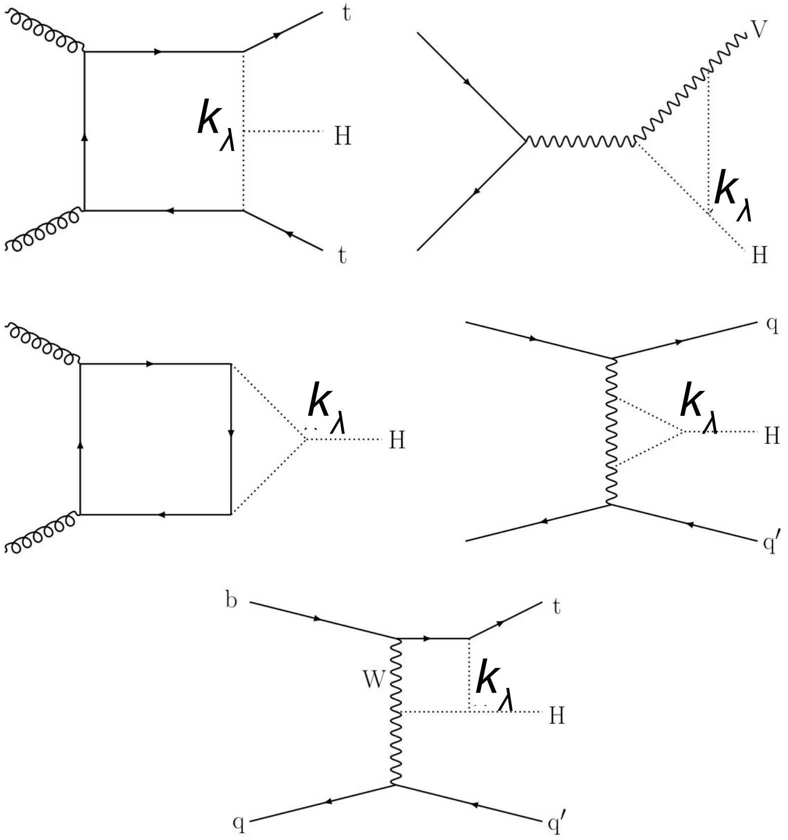
Exciting time ahead in Run 3 and beyond!

BACKUP

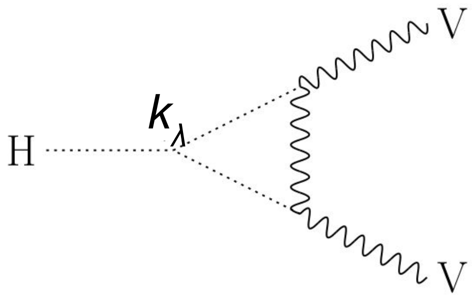
Trilinear self-coupling in single-H mechanisms

- k_λ-dependent NLO electroweak corrections to single-H XS and BR

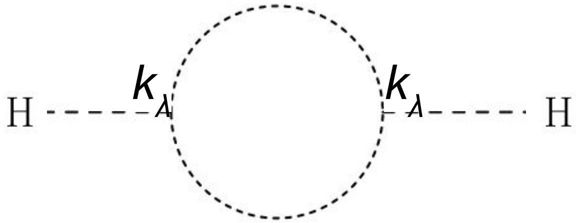
Examples of k_λ-dependent diagrams for single-H prod. mechanisms $O(k_\lambda)$



Example of k_λ-dependent diagrams for H→VV decay

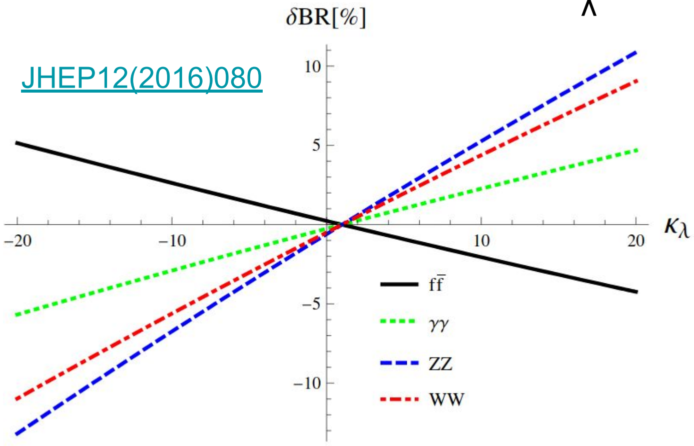


One universal correction for H wave-function renormalization $O(k_\lambda^2)$



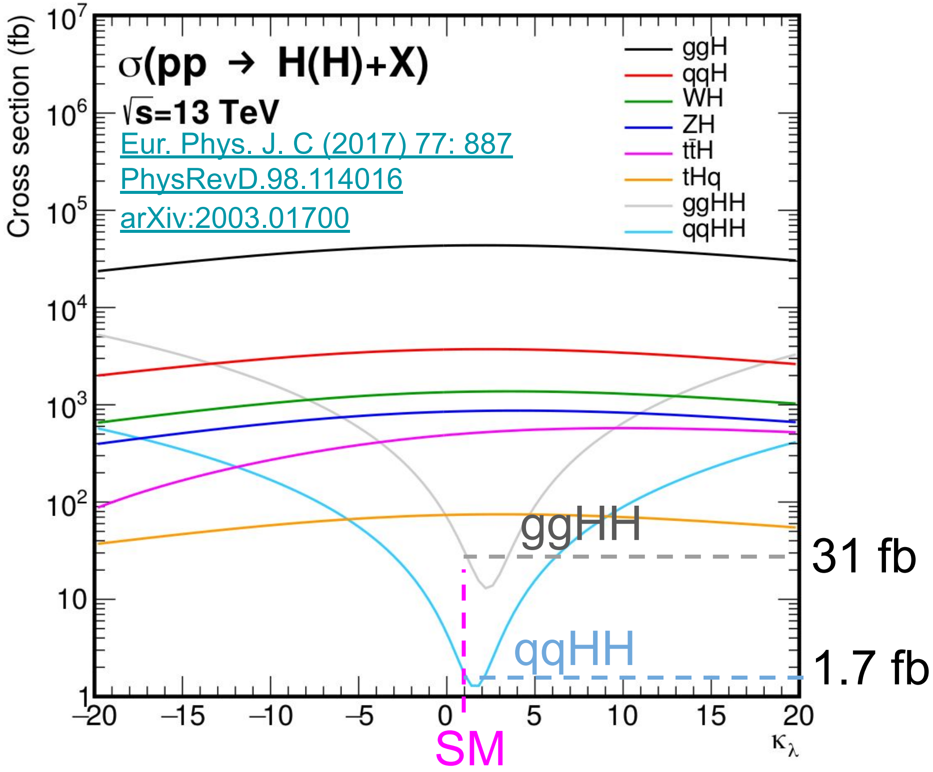
Effect of k_λ corrections on Higgs XS and BR

Modification of H BR vs k_λ



JHEP12(2016)080

Modification of total XS vs k_λ



Eur. Phys. J. C (2017) 77: 887

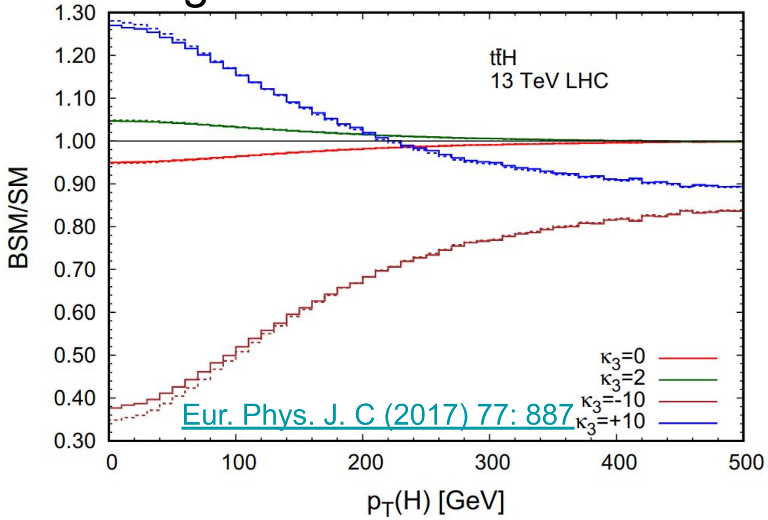
PhysRevD.98.114016

arXiv:2003.01700

- Effect on double-H @LO →large variation
- Around SM single-H XS's are larger than double-H

Modification of differential. XS

- Larger variations for VH and ttH



Eur. Phys. J. C (2017) 77: 887

See also JHEP 1709 (2017) 069

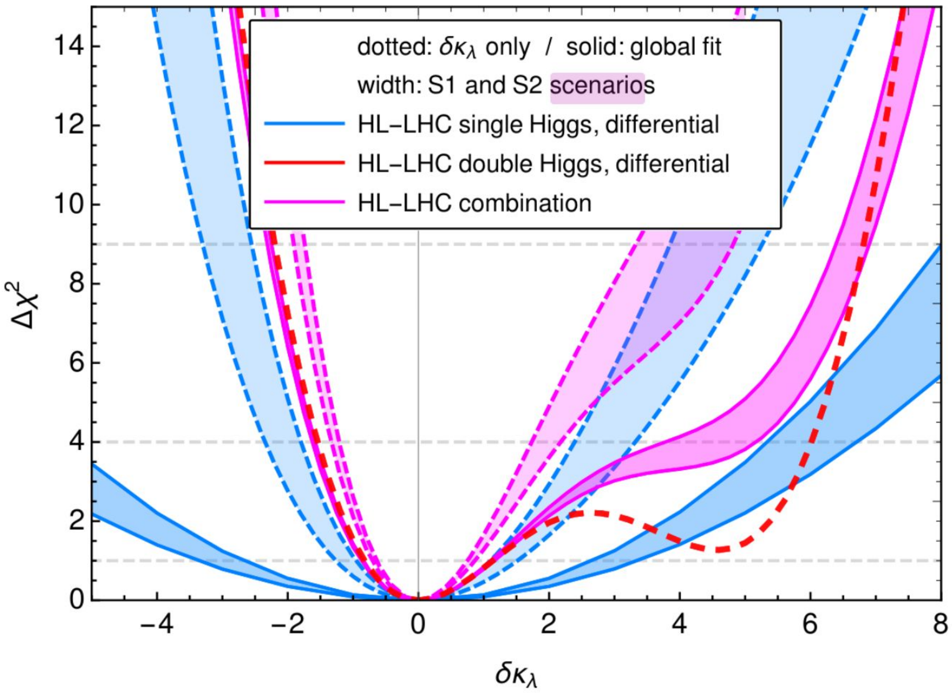
Global fit

- BSM phenomena affecting k_λ should reasonably introduce deviations in other H couplings

➢ Simultaneous fit of all H couplings

➢ Complementarity of constraints from single-H and HH fully exploited in their combination

CERN Yellow report Vol. 7 (2019)



➢ Challenging because of overlap between single-H and HH selections

➢ NOT impossible! ATLAS preliminary result