



# Properties of the Higgs boson

Linda Finco on behalf of the ATLAS and CMS Collaborations

INFN Torino

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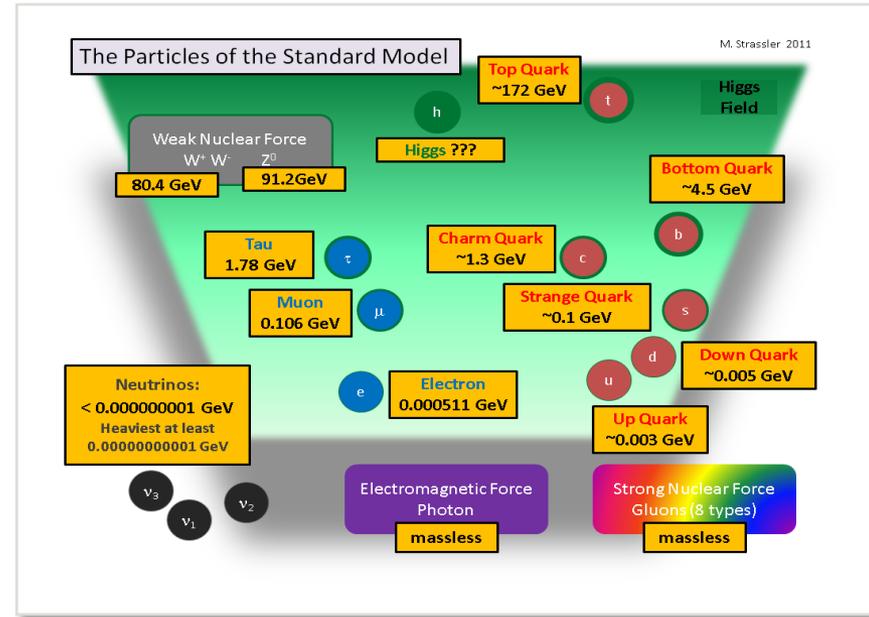
**31<sup>st</sup> Lepton-Photon Conference - Melbourne**

# The Brout-Englert-Higgs Mechanism

The BEH complex scalar field

- Permeates the entire universe
- Gives mass to the elementary particles

To verify its existence, we must find the associated Higgs boson



## BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS

*Tait Institute of Mathematical Physics, University of Edinburgh, Scotland*

Received 27 July 1964

Recently a number of people have discussed the Goldstone theorem <sup>1,2</sup>): that any solution of a Lorentz-invariant theory which violates an internal symmetry operation of that theory must contain a massless scalar particle. Klein and Lee <sup>3</sup>) showed that this theorem does not necessarily apply in non-relativistic theories and implied that their considerations would apply equally well to Lorentz-invariant field theories. Gilbert <sup>4</sup>), how-

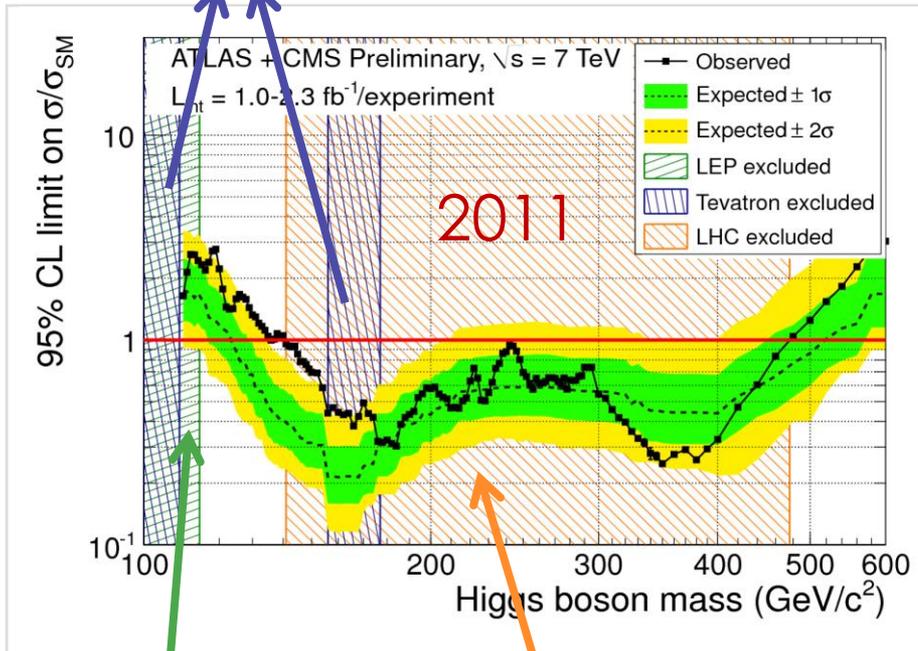
ever, gave a proof that the failure of the Goldstone theorem in the nonrelativistic case is of a type which cannot exist when Lorentz invariance is imposed on a theory. The purpose of this note is to show that Gilbert's argument fails for an important class of field theories, that in which the conserved currents are coupled to gauge fields. Following the procedure used by Gilbert <sup>4</sup>), let us consider a theory of two hermitian scalar fields

# The long road of the Higgs boson

~2010: Start of LHC

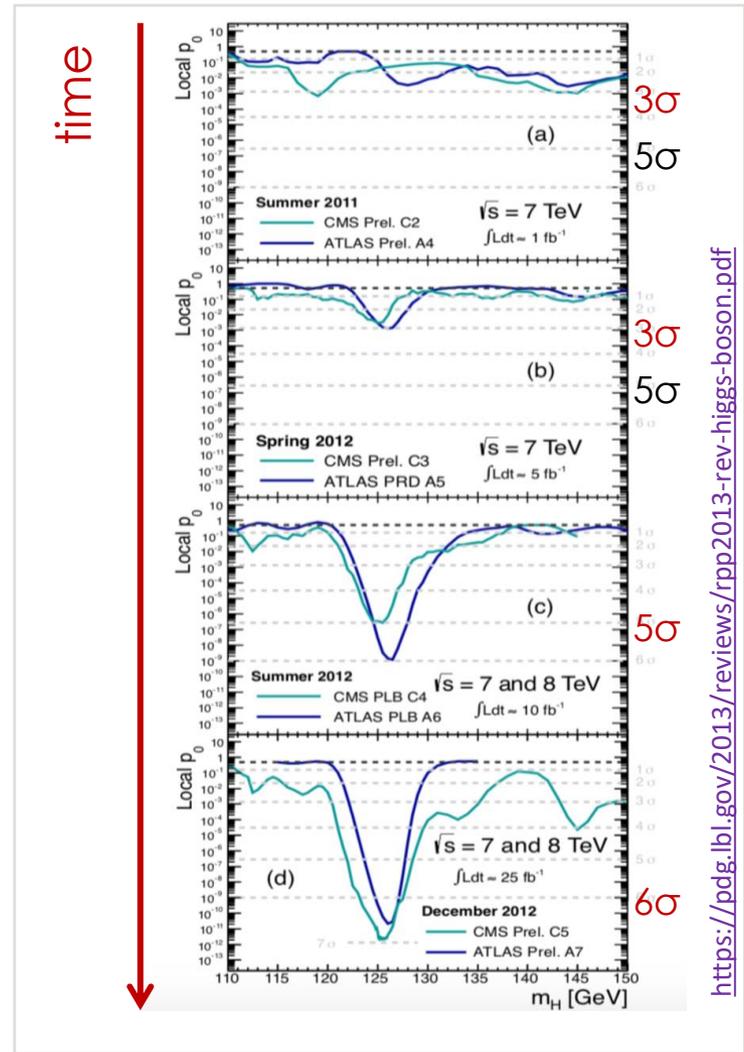
2012: Higgs boson discovery!

Tevatron:  $156 < m_H < 177 \text{ GeV}$



LEP:  $m_H < 114.4 \text{ GeV}$

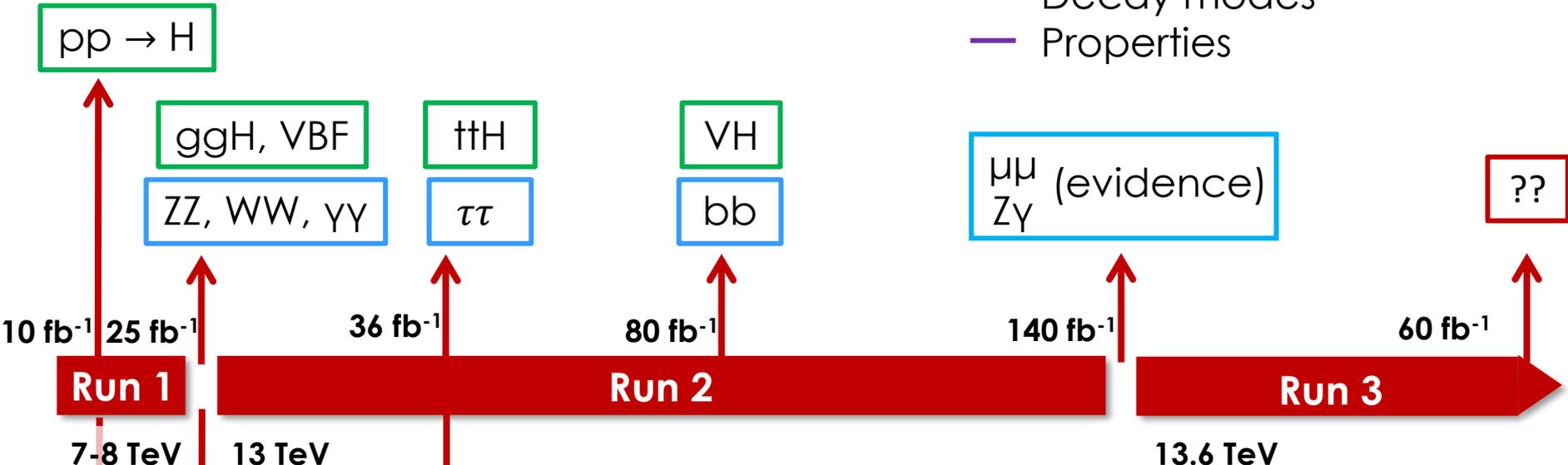
ATLAS and CMS combined:  
 $141 < m_H < 476 \text{ GeV}$  excluded



<https://pdg.lbl.gov/2013/reviews/rpp2013-rev-higgs-boson.pdf>

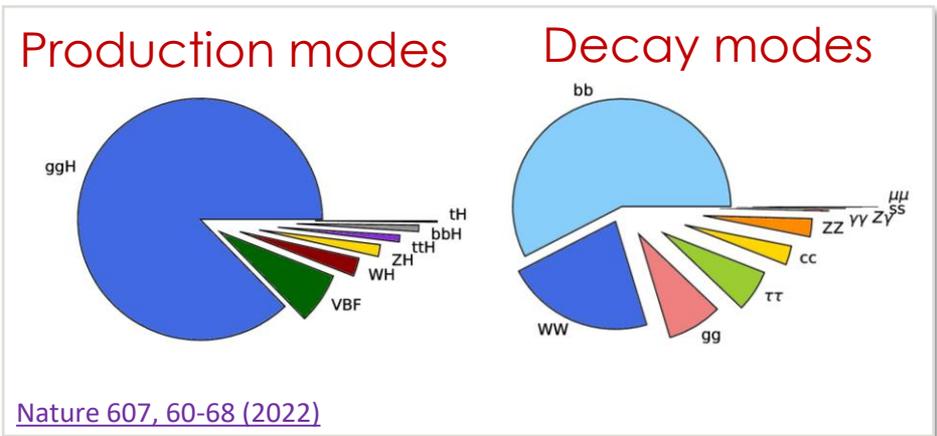
# The long road of the Higgs boson

- Production modes
- Decay modes
- Properties

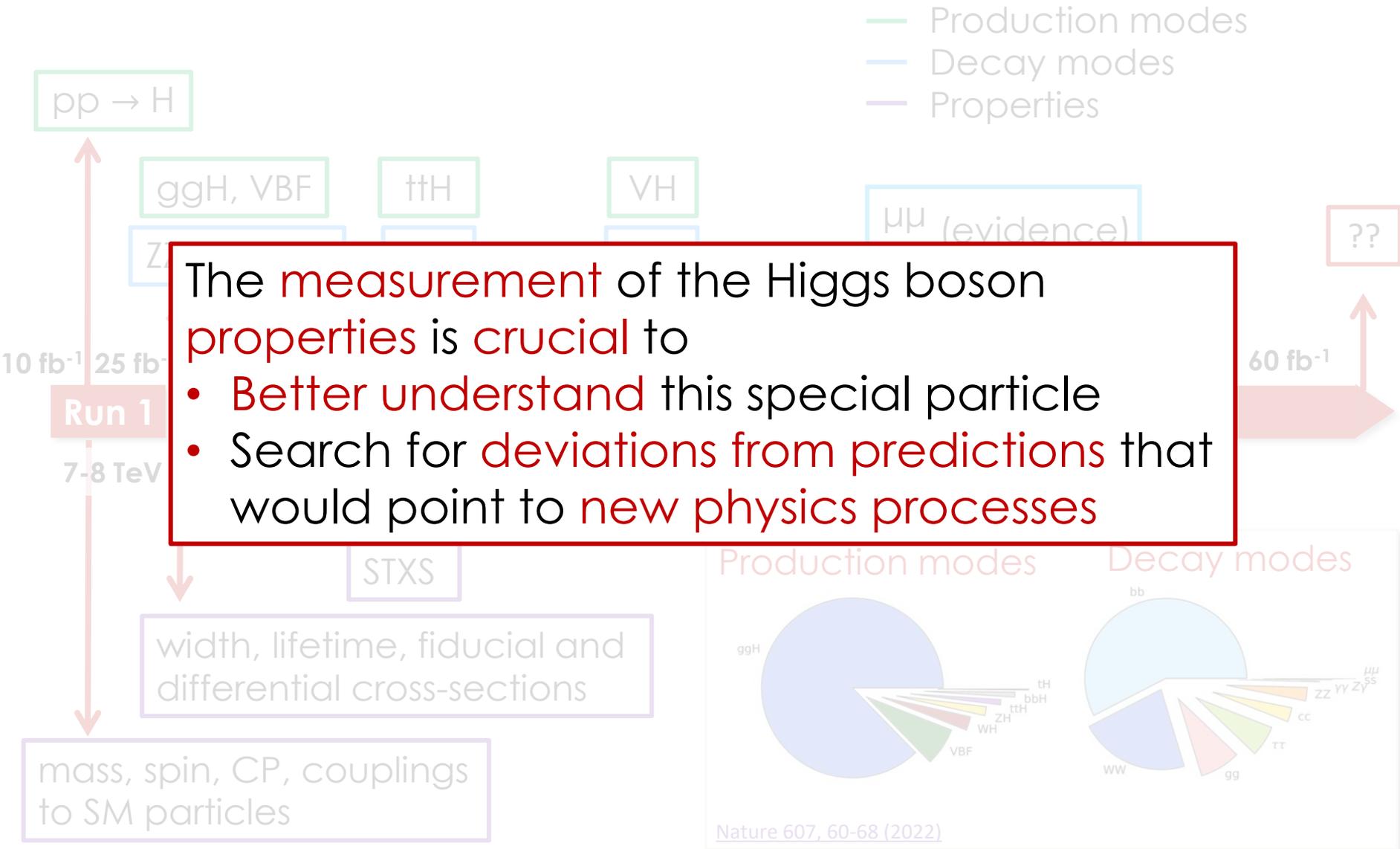


width, lifetime, fiducial and differential cross-sections

mass, spin, CP, couplings to SM particles

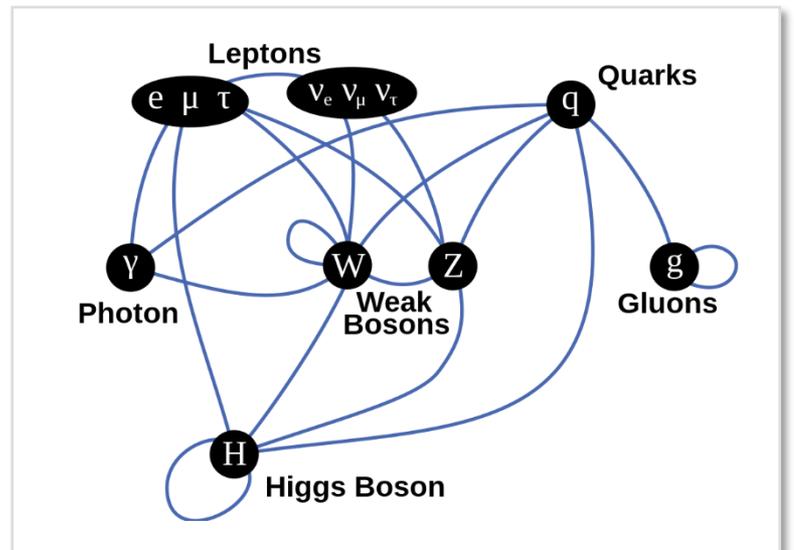


# The long road of the Higgs boson



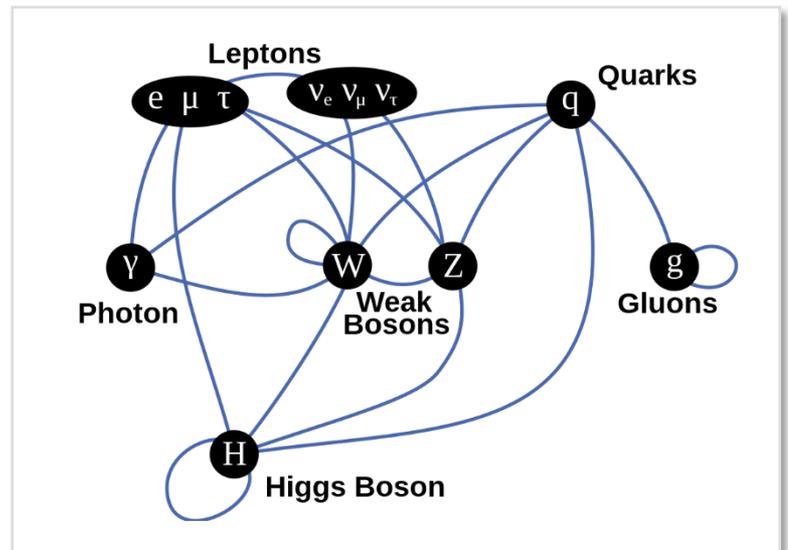
# Higgs boson properties

- Electric charge
- Spin angular momentum
- Parity-Charge conjugation
- Mass
- Width
- Cross-sections, branching ratios and signal strength
- Couplings



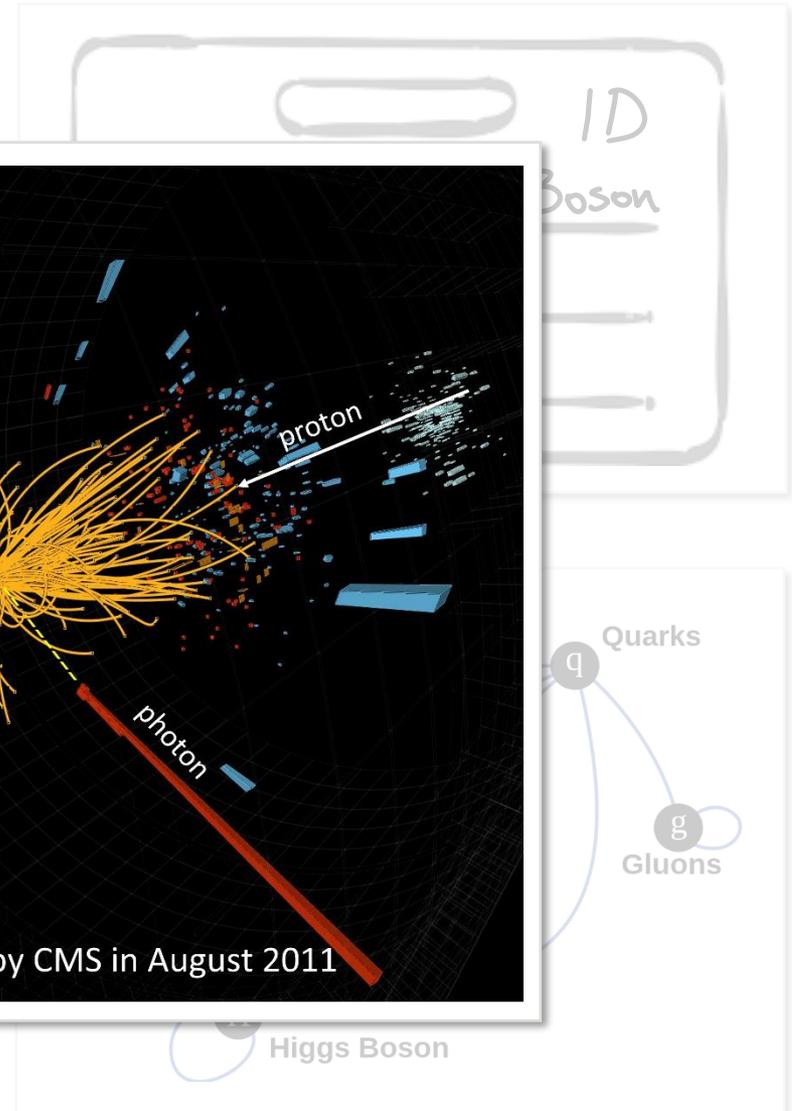
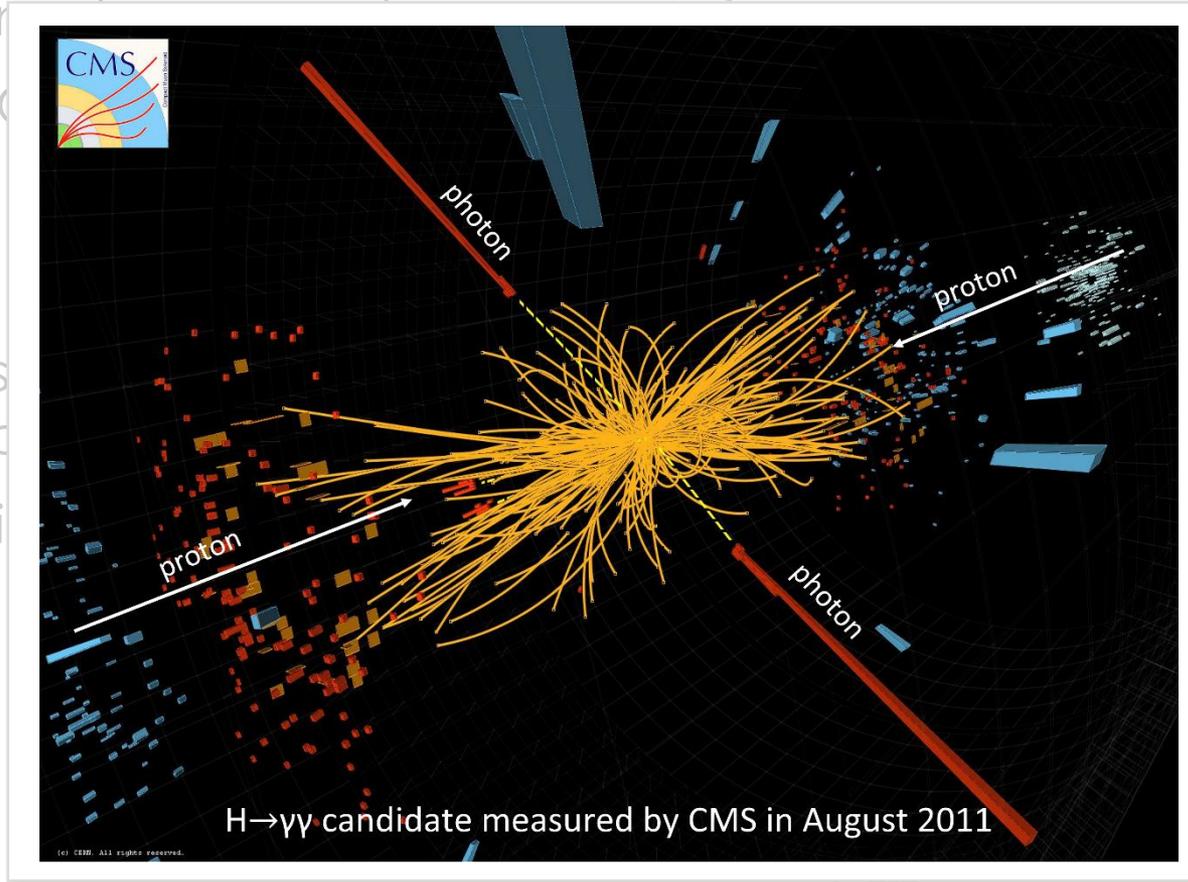
# Higgs boson properties

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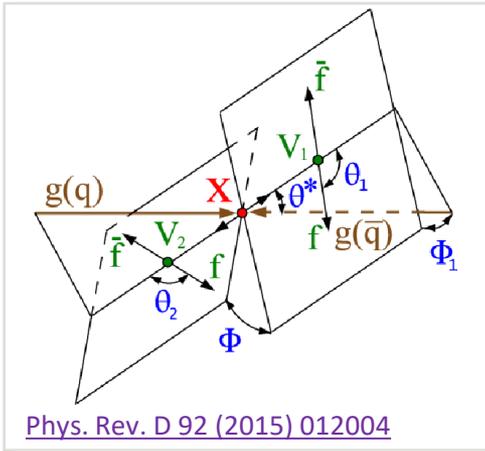
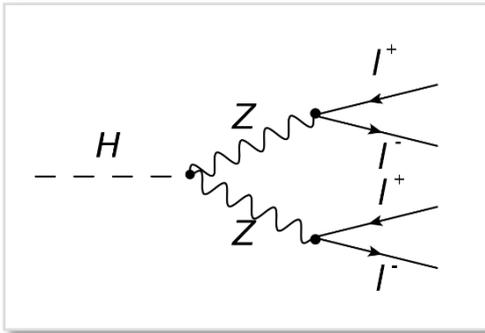
# Higgs boson properties

- Electric charge  $Q = 0$
- Spin and parity
- Parity-odd
- Mass
- Width
- Cross-section ratios
- Couplings

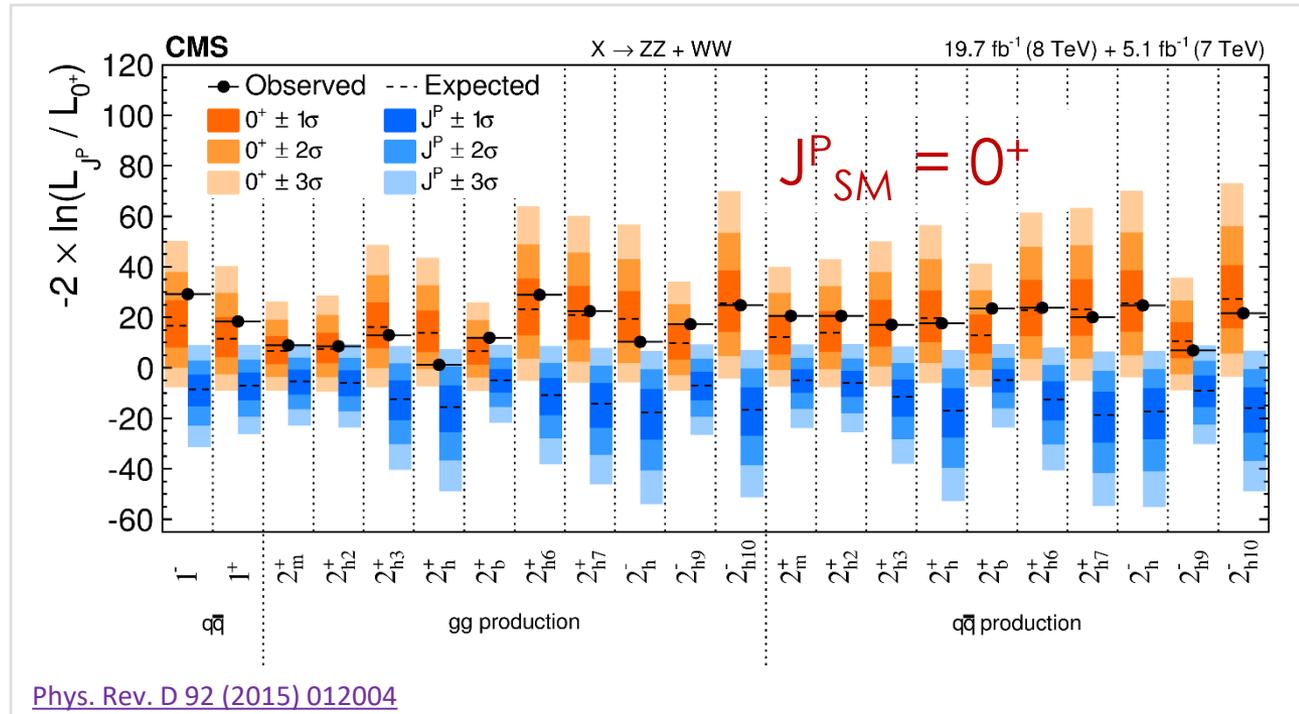


# Higgs boson spin and parity

- Probed via **angular correlations** in diboson decays ( $WW, ZZ, \gamma\gamma$ )
- **Many** alternative spin-parity **hypotheses** tested
- Data compatible with **spin zero** and **even parity**, as predicted by **SM**



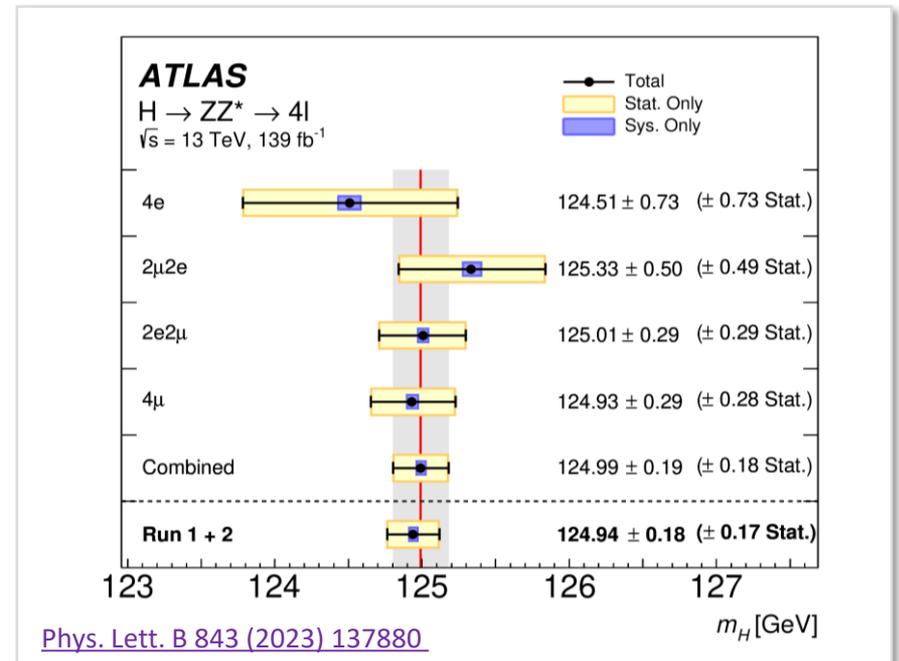
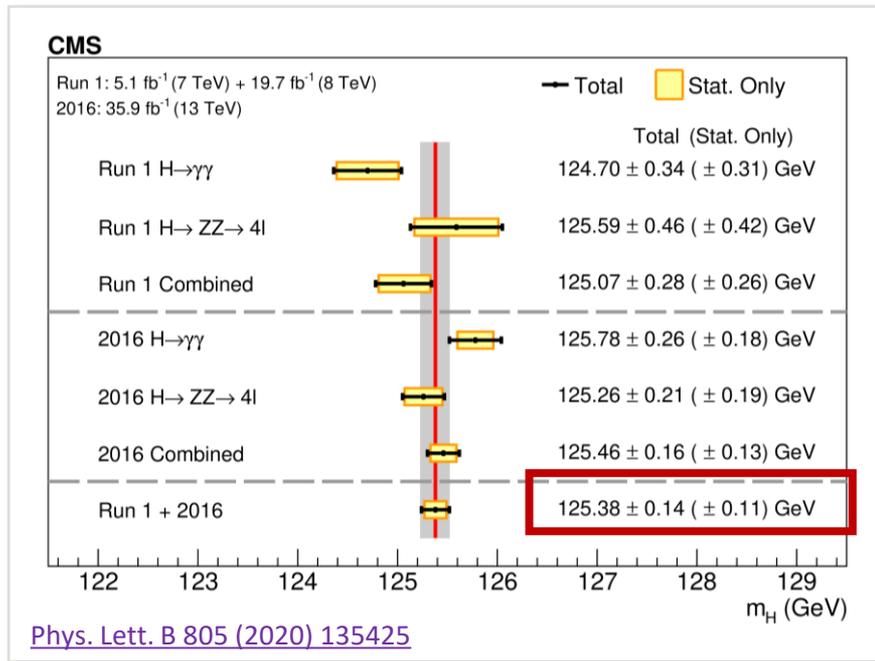
Phys. Rev. D 92 (2015) 012004



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# Higgs boson mass

- Only **free SM parameter**, it defines **production and decay rates**
- Measured with  $H \rightarrow \gamma\gamma$  and  $H \rightarrow ZZ \rightarrow 4l$ , thanks to their **high resolution**
  - Precision dominated by statistics and experimental systematics
  - Precise photons, electrons and muons energy scale and resolution are crucial
- **CMS** measurement **most precise** up to now (0.11% of uncertainty), still based on **partial Run 2 dataset** ( $36 \text{ fb}^{-1}$ )

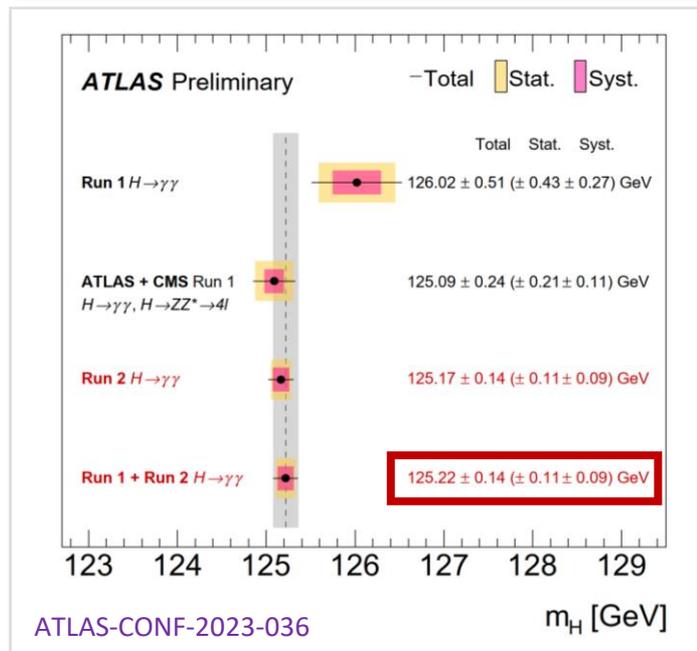
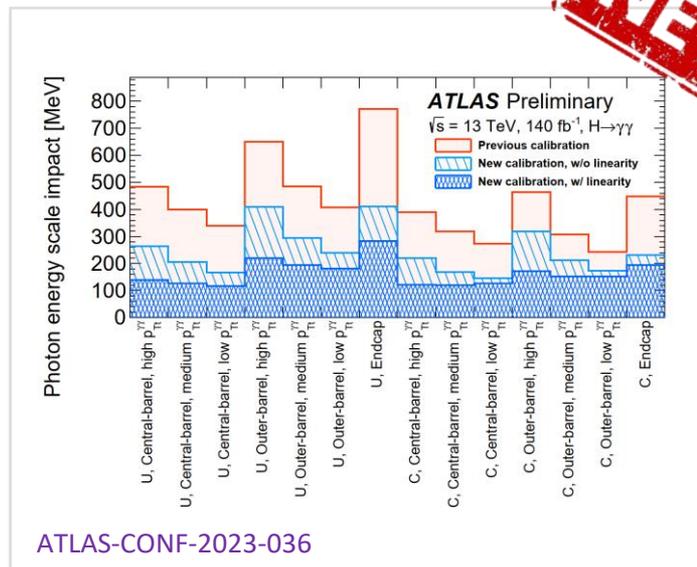


# Higgs boson mass

New  $H \rightarrow \gamma\gamma$  measurement using full Run 2 data:

- Increased data sample ( $\sim 4x$ )
- Improved estimation of photon energy scale with significantly reduced ( $\sim 3x$ ) uncertainties
- Optimized event classification strategy

*Most precise measurement from a single channel!*

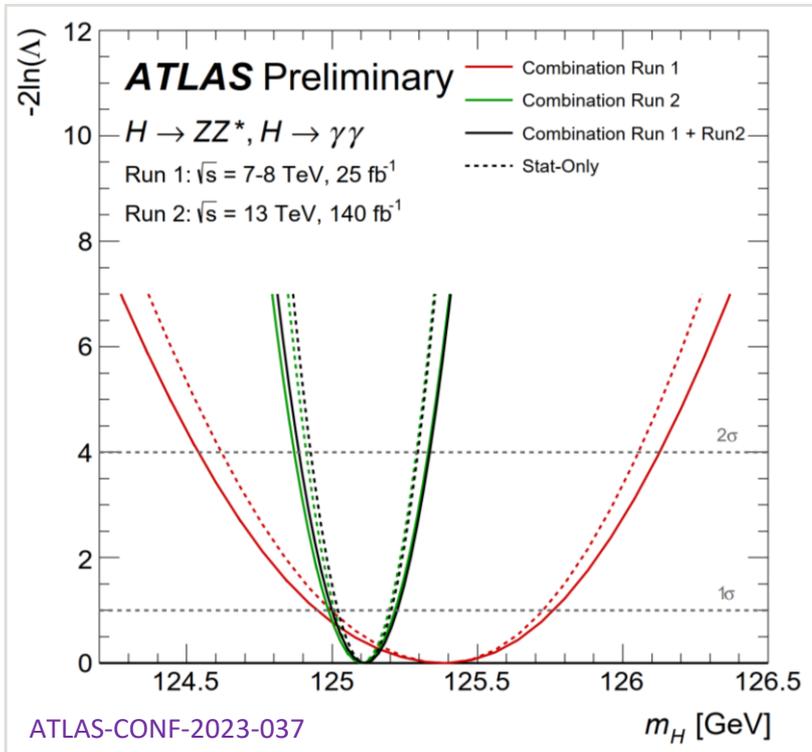


# Higgs boson mass



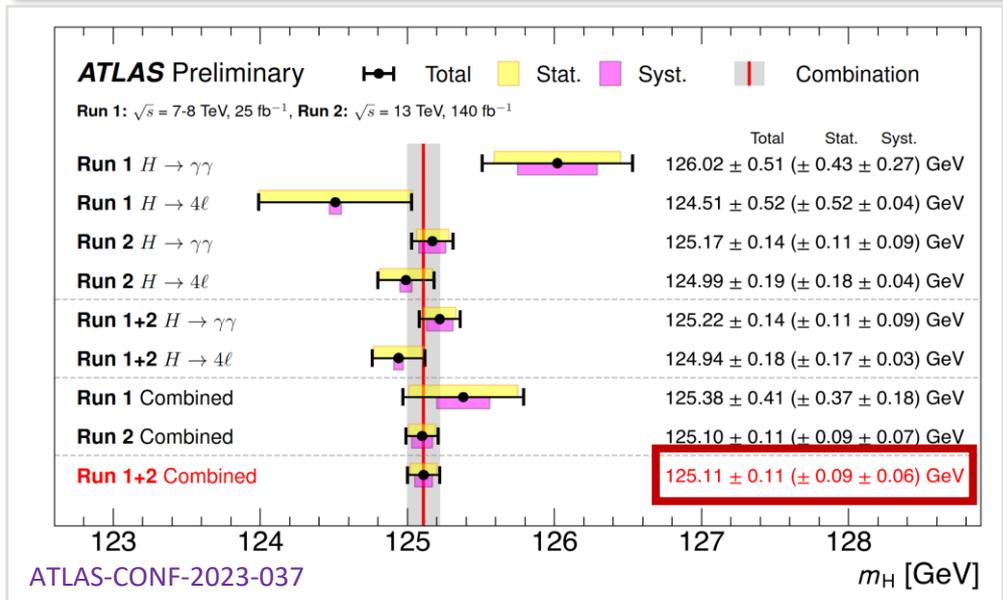
- ATLAS full-Run 2 measurement, combining  $H \rightarrow ZZ \rightarrow 4l$  and  $H \rightarrow \gamma\gamma$
- 0.09% of uncertainty

*New most precise measurement!*



Source	Systematic uncertainty on $m_H$ [MeV]
$e/\gamma$ $E_T$ -independent $Z \rightarrow ee$ calibration	44
$e/\gamma$ $E_T$ -dependent electron energy scale	28
$H \rightarrow \gamma\gamma$ interference bias	17
$e/\gamma$ photon lateral shower shape	16
$e/\gamma$ photon conversion reconstruction	15
$e/\gamma$ energy resolution	11
$H \rightarrow \gamma\gamma$ background modelling	10
Muon momentum scale	8
All other systematic uncertainties	7

ATLAS-CONF-2023-037



# Higgs boson width

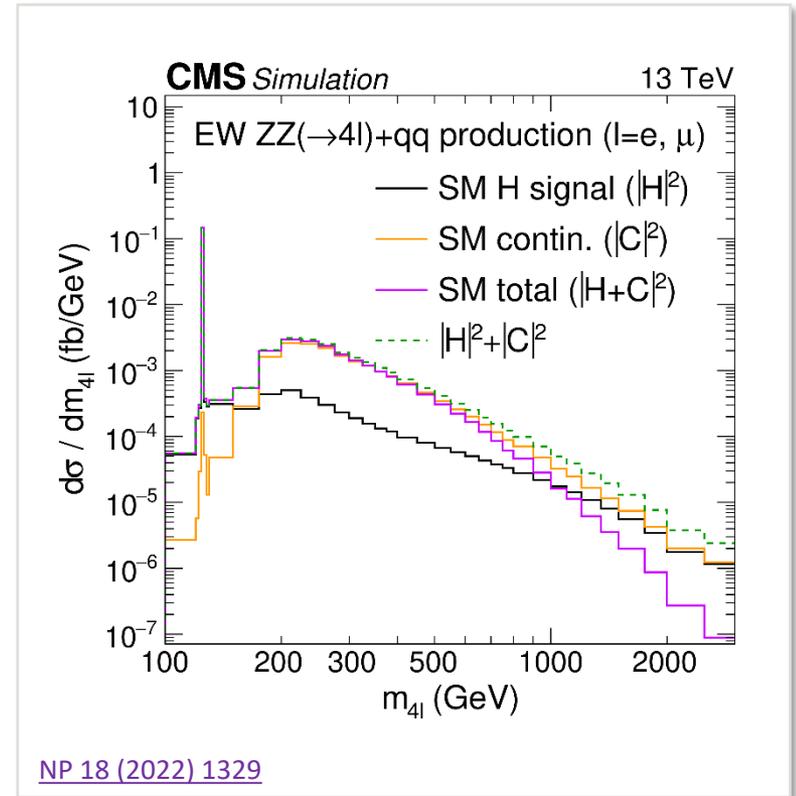
- Standard Model predicts  $\Gamma_H \sim 4 \text{ MeV}$
- Direct measurement strongly limited by experimental resolution
- Assuming equal on-shell and off-shell couplings:

$$\sigma_{\text{on-shell}}^{gg \rightarrow H \rightarrow ZZ^*} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{m_H \Gamma_H}$$

$$\sigma_{\text{off-shell}}^{gg \rightarrow H^* \rightarrow ZZ} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{(2m_Z)^2}$$

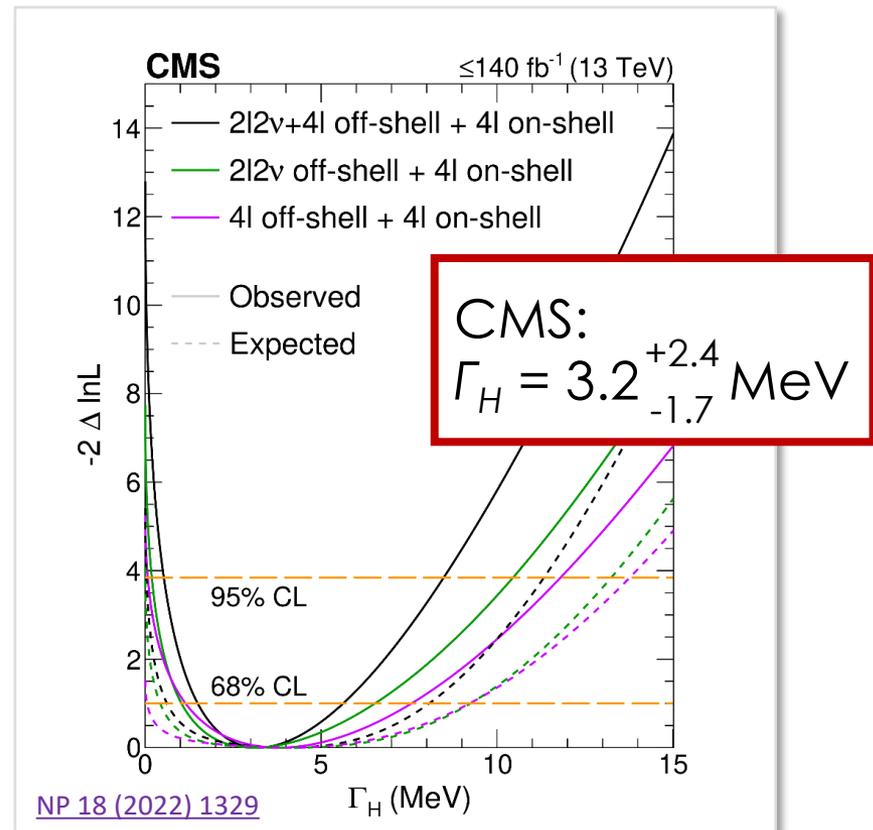
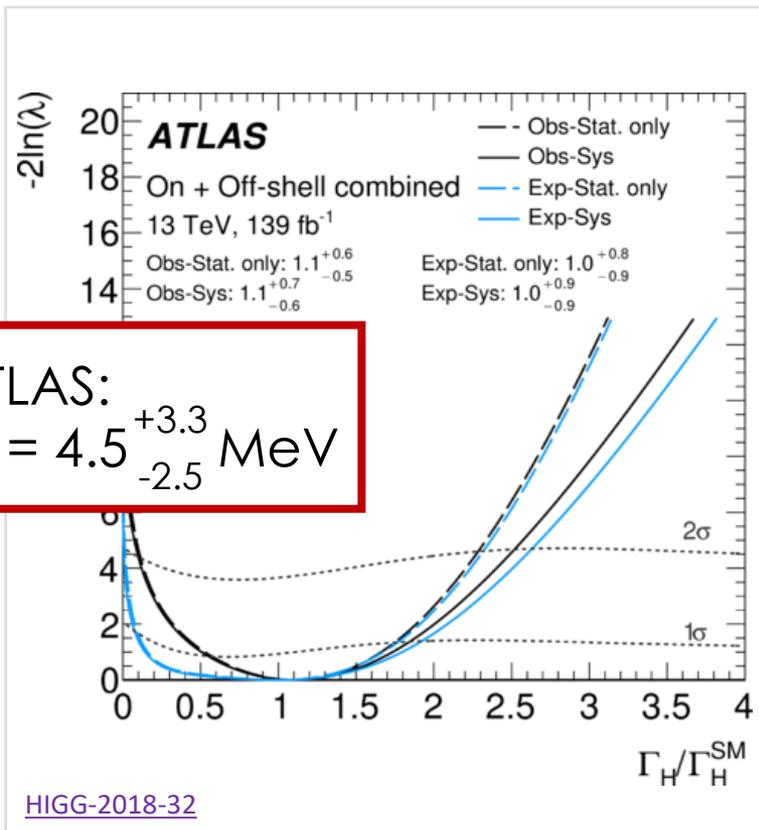
$$\frac{\mu_{\text{off-shell}}}{\mu_{\text{on-shell}}} = \frac{\Gamma}{\Gamma_{\text{SM}}}$$

*A real breakthrough after the discovery of the Higgs boson!*



# Higgs boson width

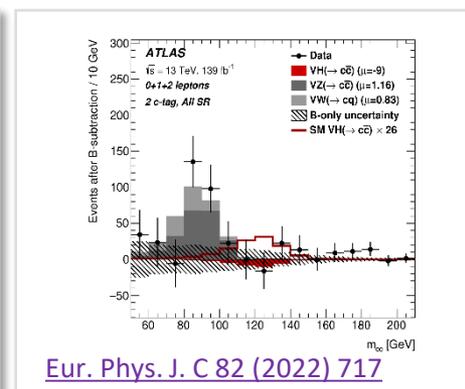
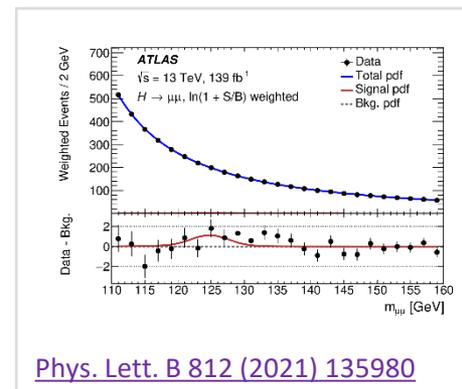
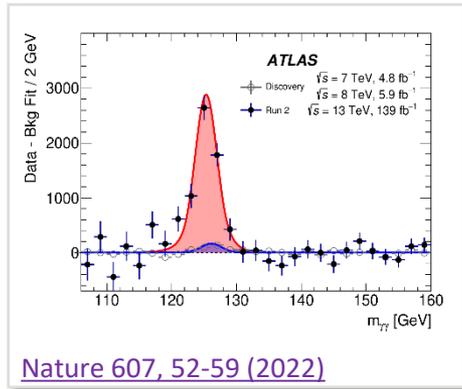
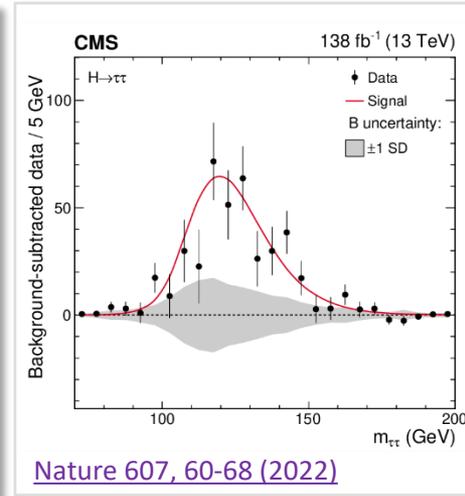
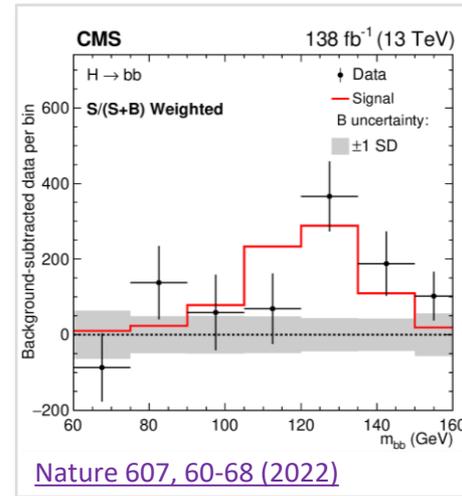
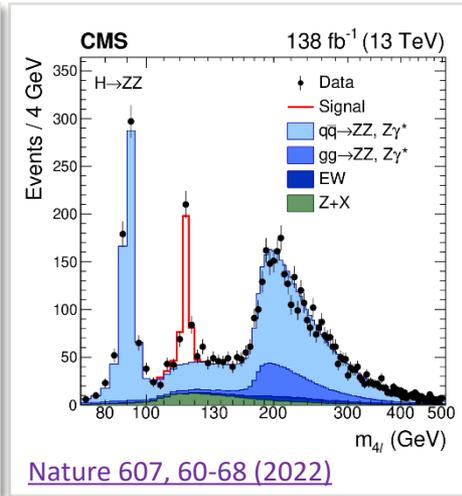
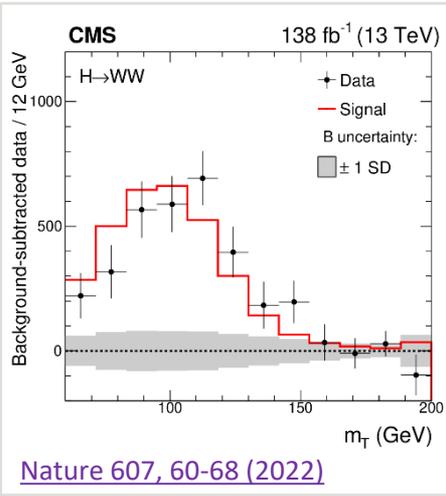
- Indirect measurement from the on-shell/off-shell Higgs boson production
- Measured in the  $H \rightarrow ZZ \rightarrow 4l$  and  $H \rightarrow ZZ \rightarrow 2l2\nu$  decay channels
- First evidence of off-shell Higgs boson production



# Higgs decays to bosons and fermions

## Bosons

## Fermions



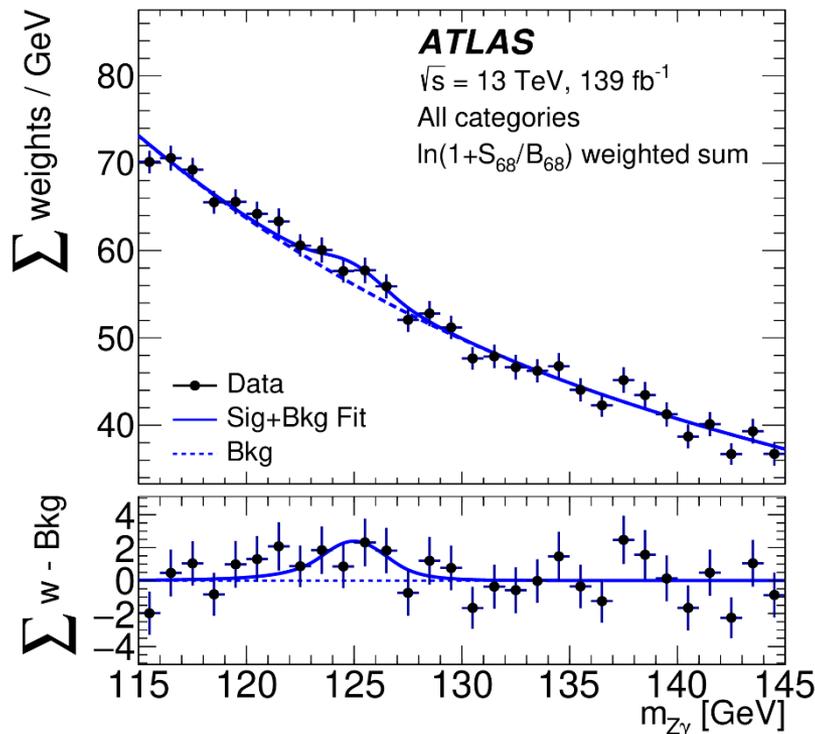
In the SM, the Higgs boson interaction is proportional to  $m_V^2$  and  $m_f$

# Higgs to $Z\gamma$

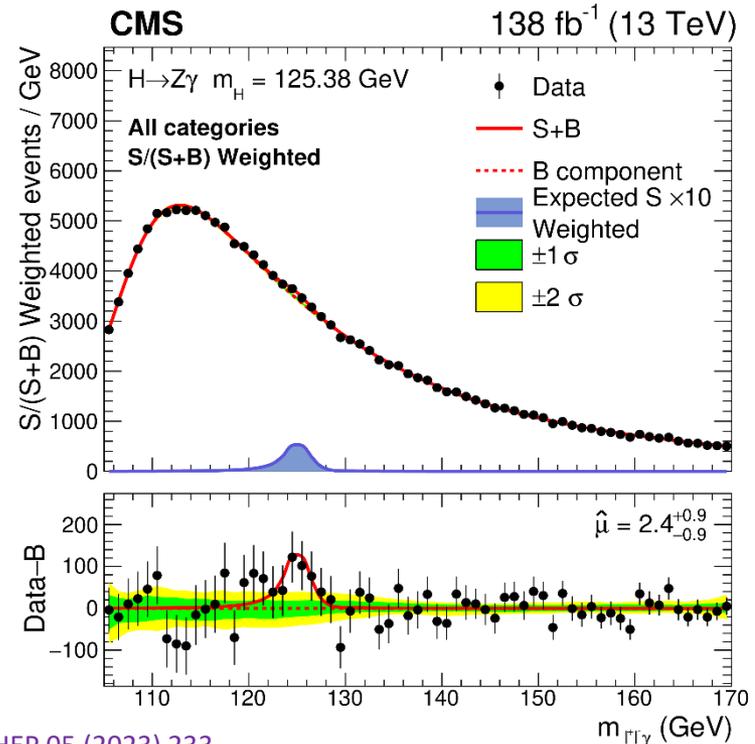
- Very small signal:  $\mathcal{B}(H \rightarrow Z\gamma) \sim 1.5 \times 10^{-3}$
- Z leptonic decay ensures a **clean signature** ( $m_{ll} > 50$  GeV)
- Photon requested to be **well isolated**

ATLAS:  $2.2(1.2)\sigma$

CMS:  $2.7(1.2)\sigma$



[Phys. Lett. B 809 \(2020\) 135754](#)

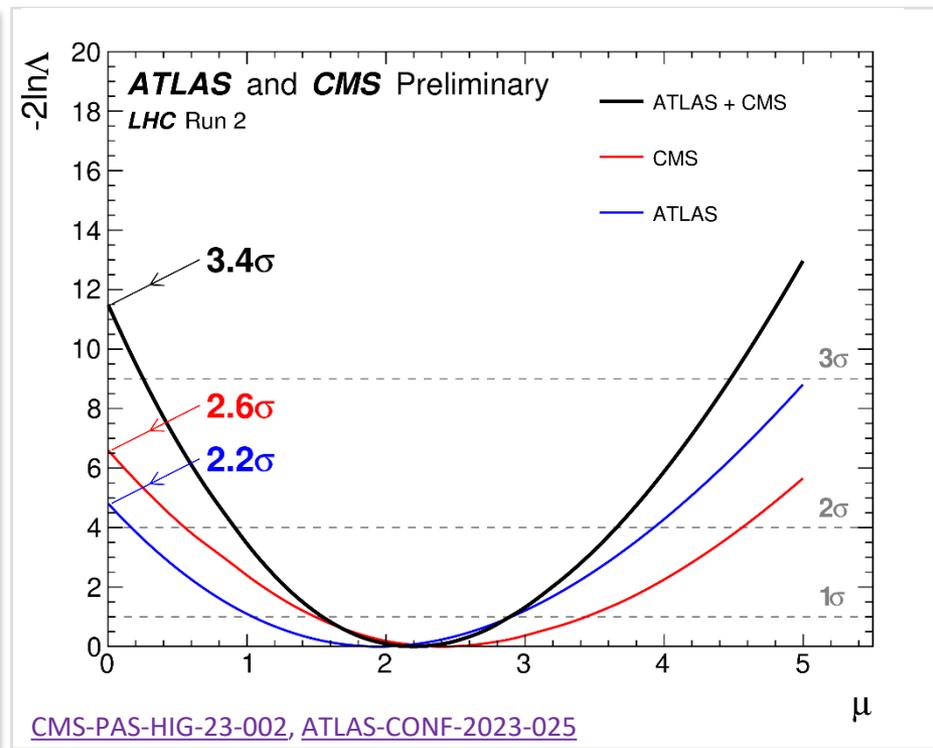
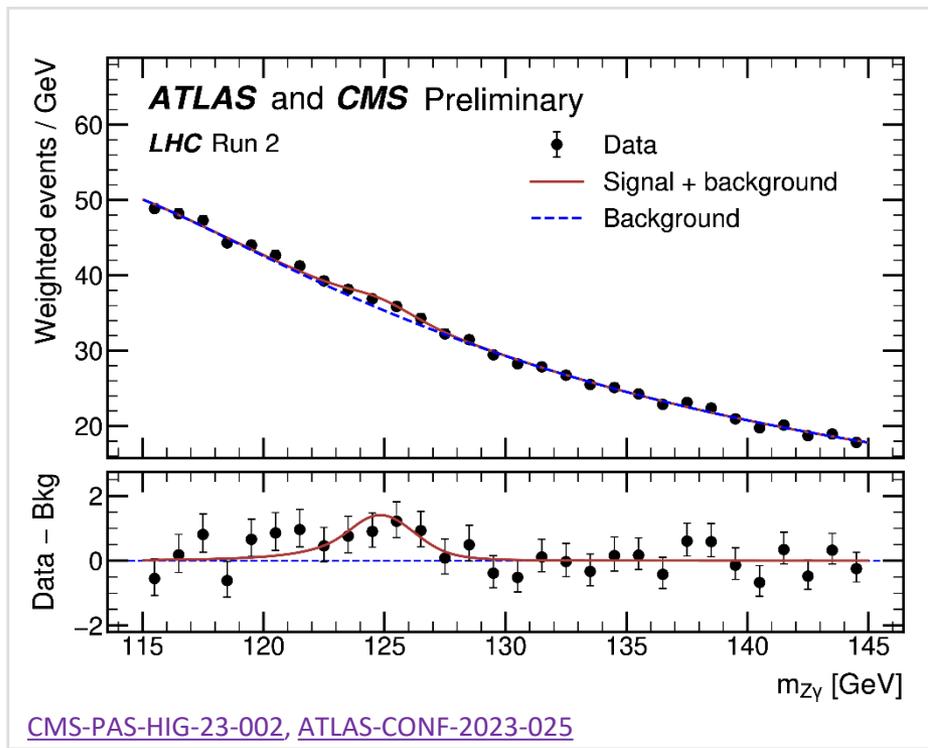


[JHEP 05 \(2023\) 233](#)

# Higgs to $Z\gamma$ – ATLAS and CMS combination

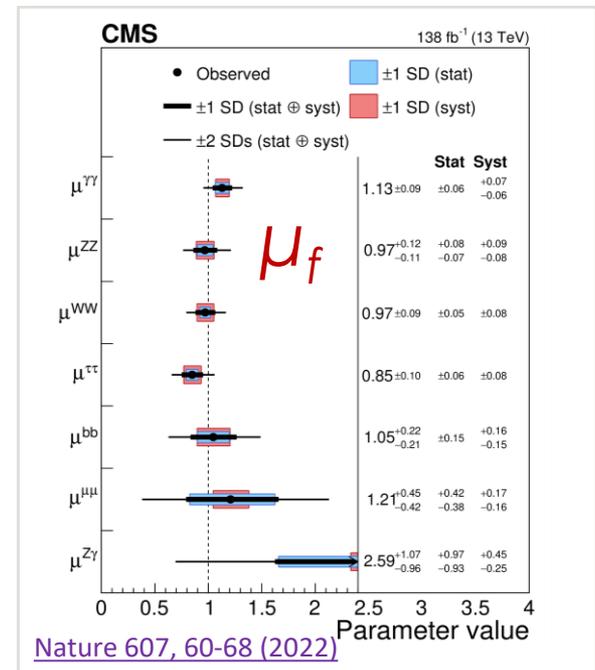
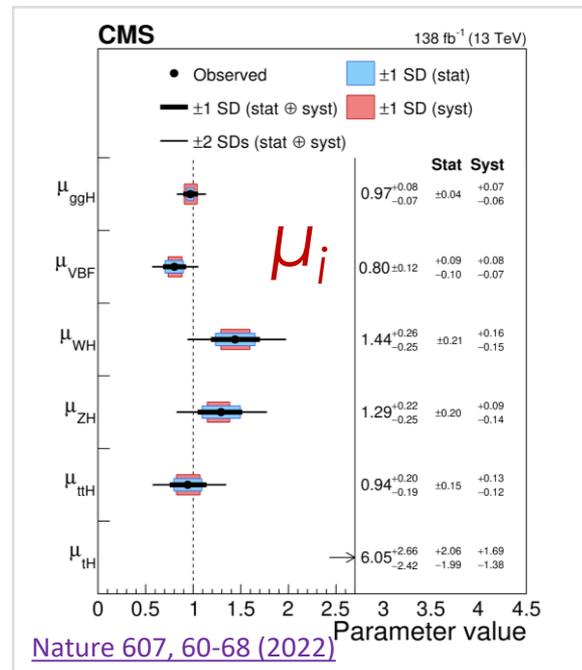
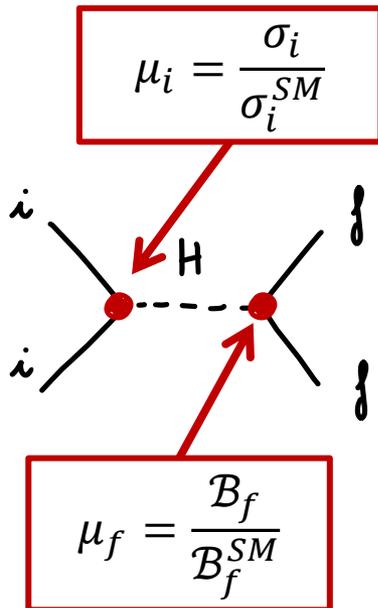
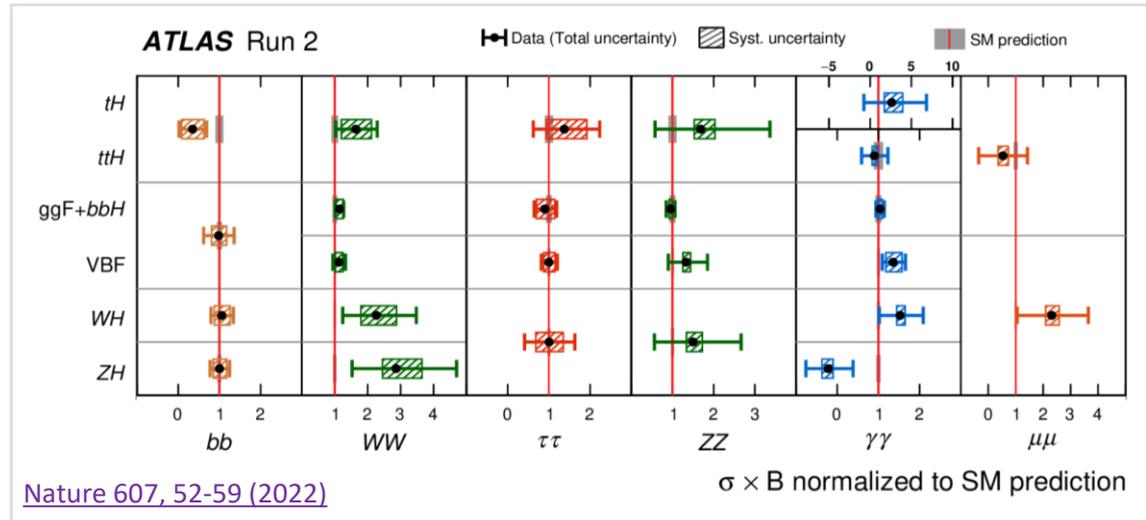
- Similar strategy adopted
- Main differences: **bkg uncertainties** evaluation and **Higgs mass value**
- **First evidence** of the decay process

$$\mu = 2.2 \pm 0.7 \text{ with local significance } 3.4(1.6)\sigma$$



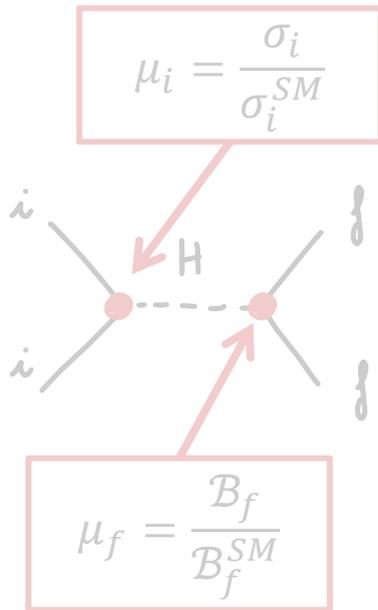
# Cross-sections and branching fractions

- Inclusive cross-section **first quantity to measure** when establishing a channel
- Signal strength modifiers**  $\mu$  scale cross-sections and branching fractions relative to the SM

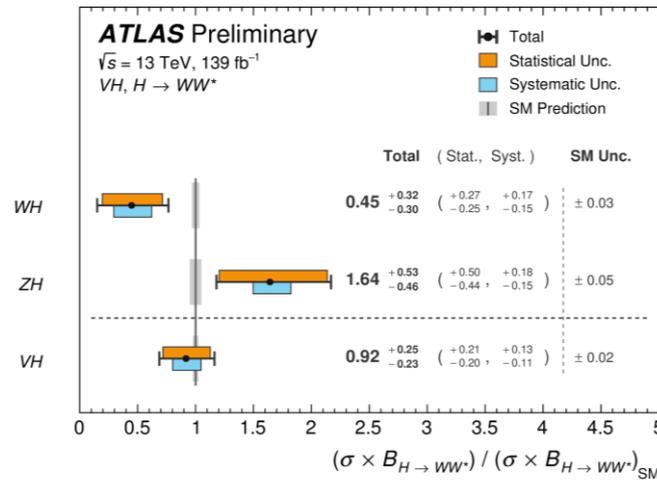


# Cross-sections and branching fractions

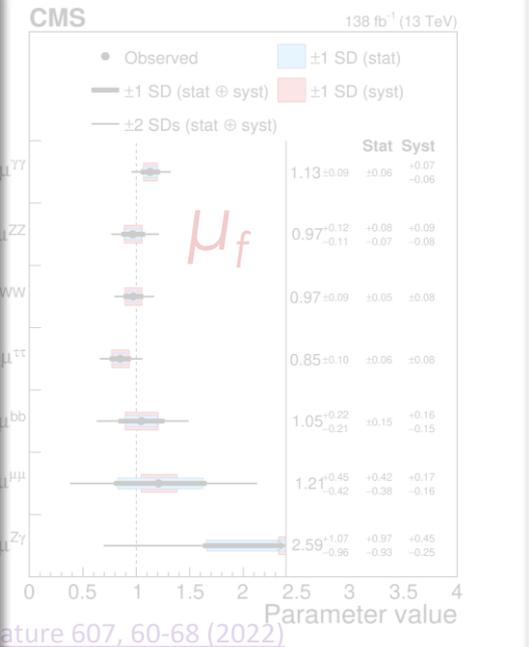
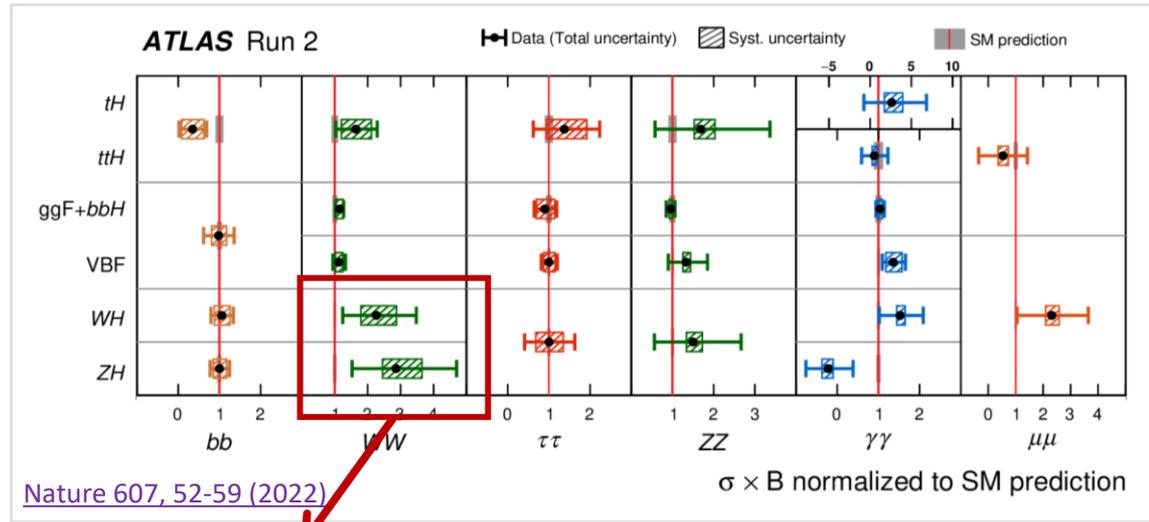
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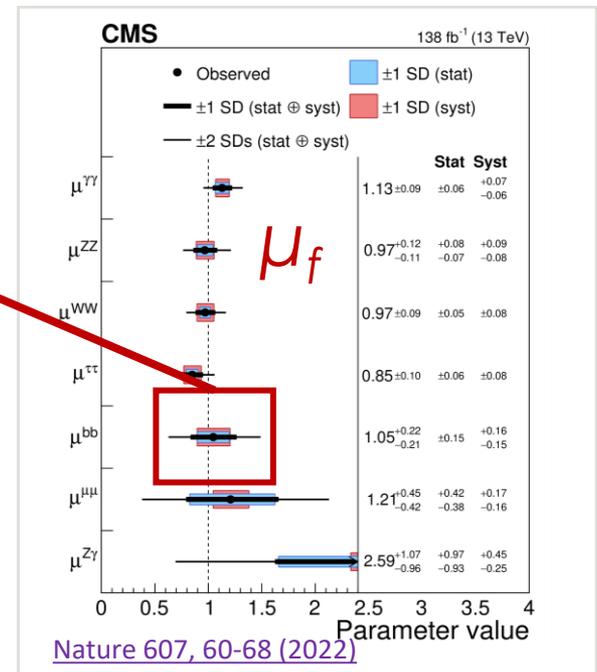
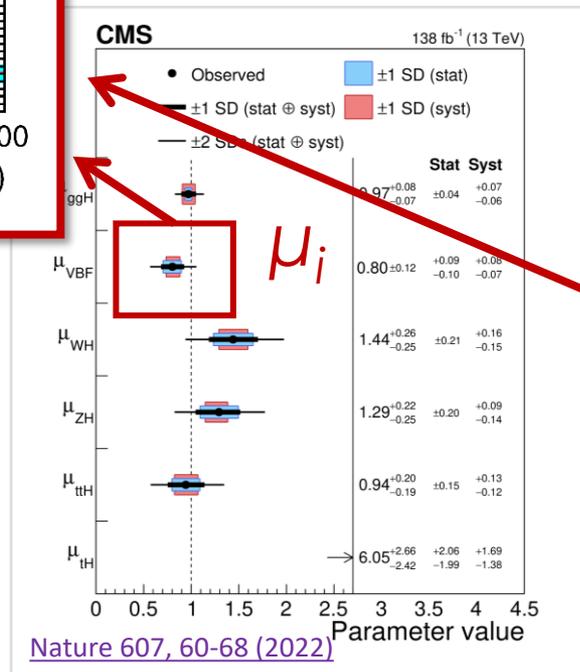
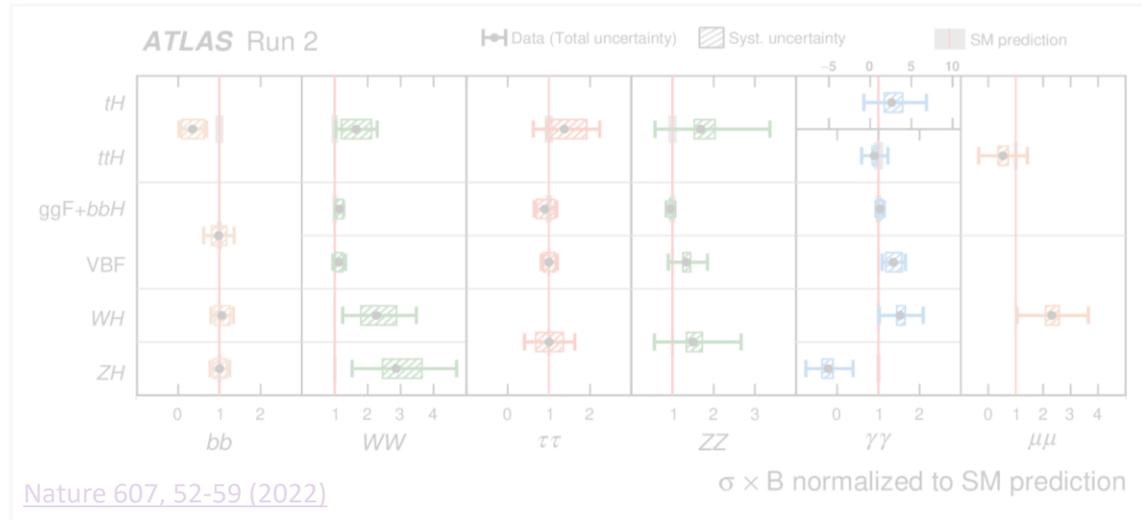
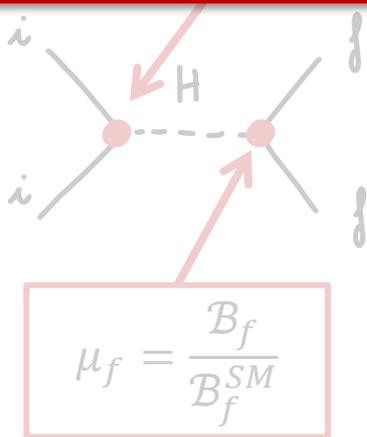
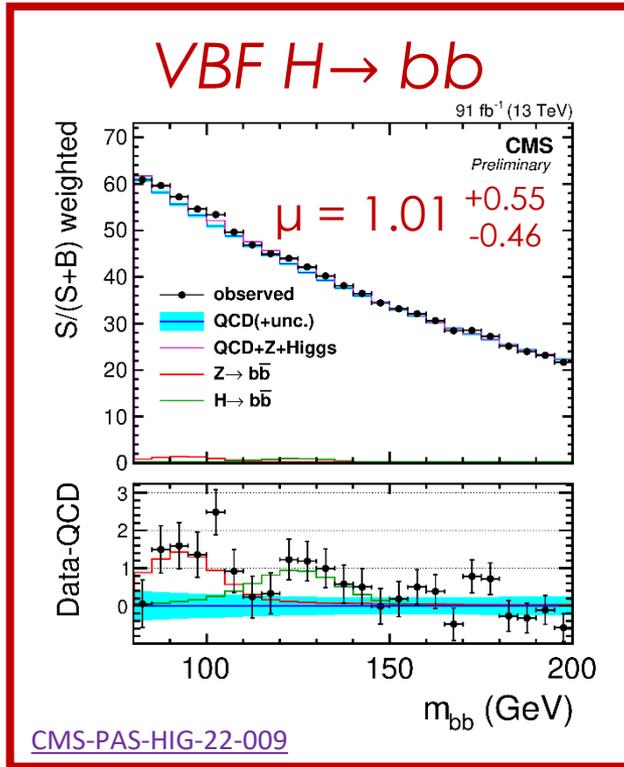
## VH $H \rightarrow WW$



ATLAS-CONF-2022-067

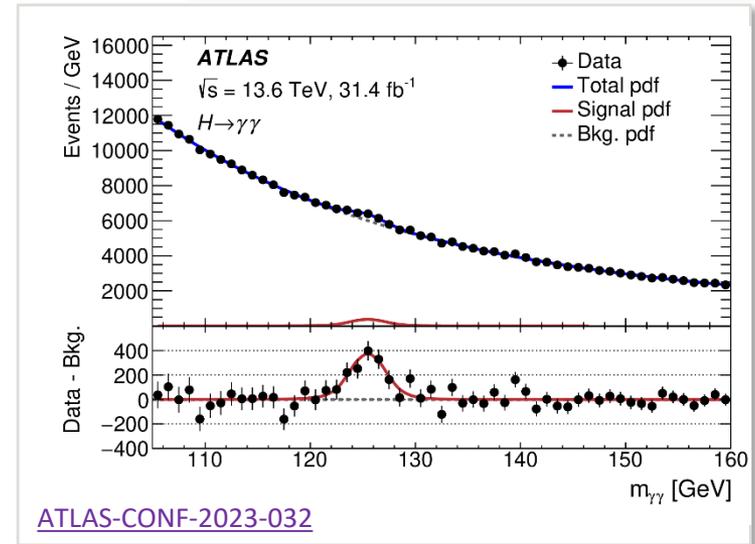
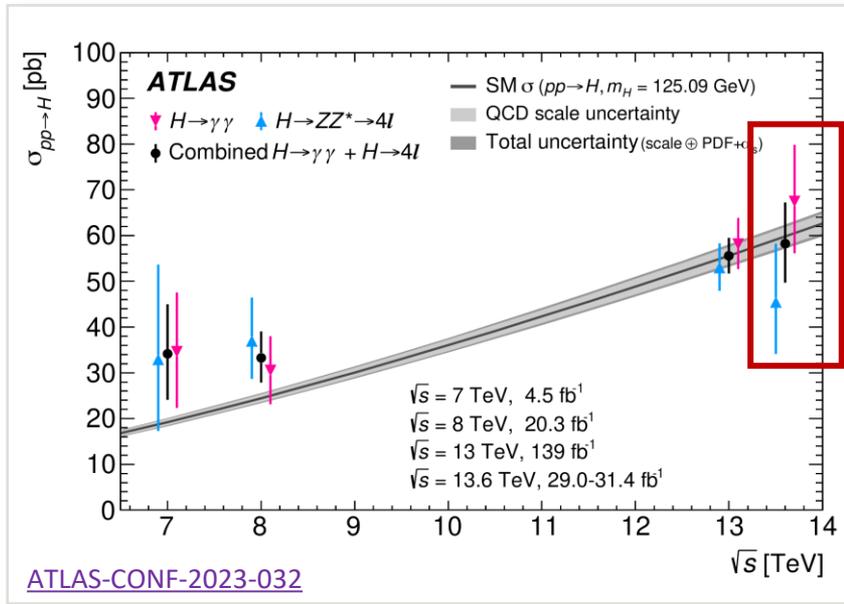
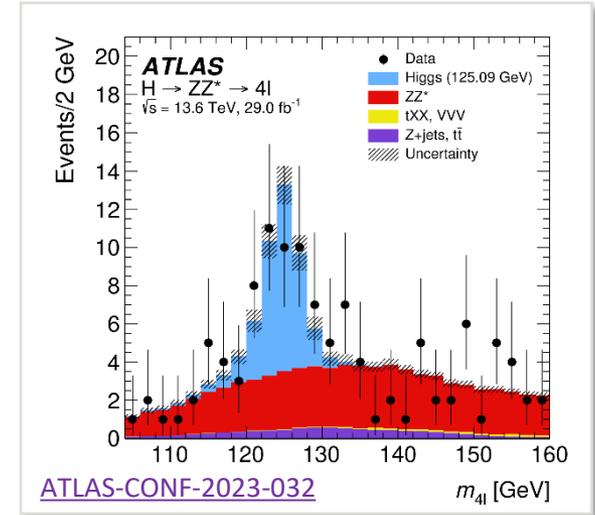


# Cross-sections and branching fractions



# First cross-sections at 13.6 TeV

- First measurement of Higgs boson production cross-section at 13.6 TeV by ATLAS in  $H \rightarrow ZZ \rightarrow 4l$  and  $H \rightarrow \gamma\gamma$  channels
- Same analysis strategy as in Run 2
- Around  $30 \text{ fb}^{-1}$  used (collected in 2022)

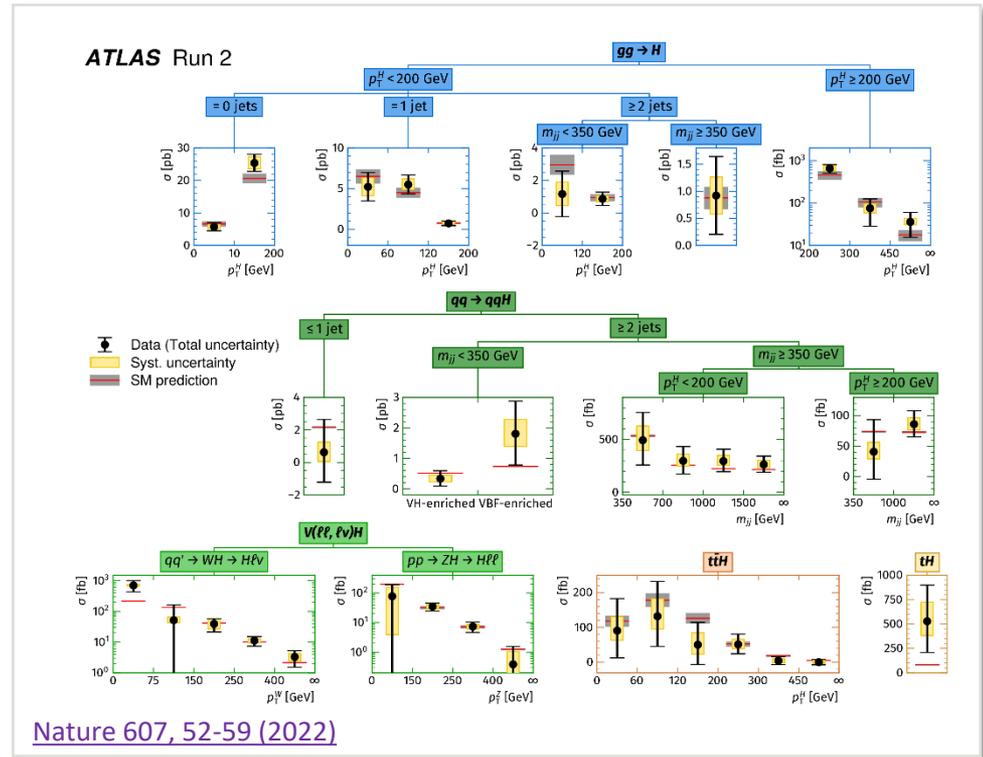
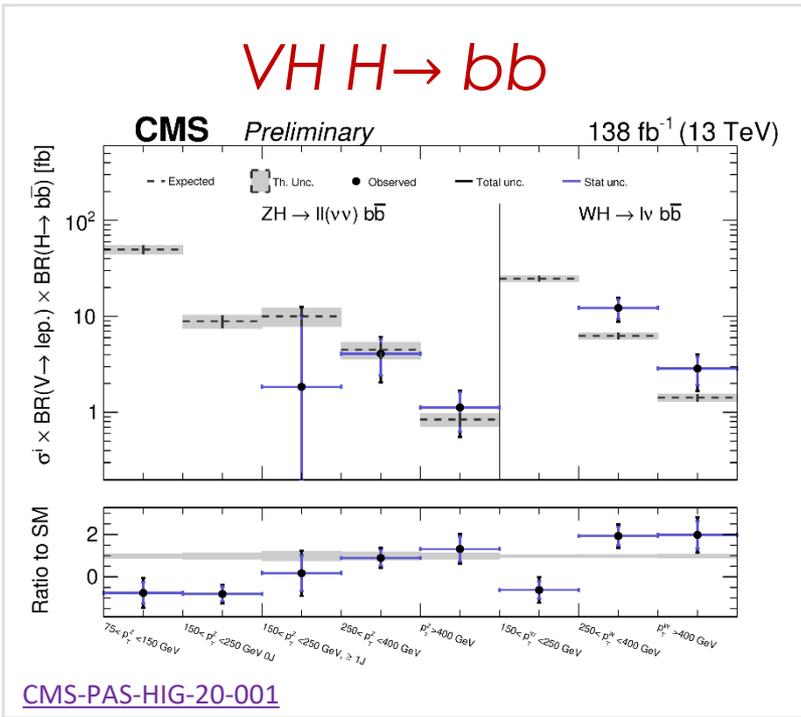


$$\sigma_{\text{fid}}^{\gamma\gamma} = 76^{+14}_{-13} (67.6 \pm 3.7) \text{ fb} \quad \sigma_{\text{fid}}^{4l} = 2.80 \pm 0.74 (3.67 \pm 0.19) \text{ fb}$$

$$\sigma_{\text{tot}} = 58.2 \pm 8.7 (59.9 \pm 2.6) \text{ pb}$$

# The Simplified Template Cross-Section

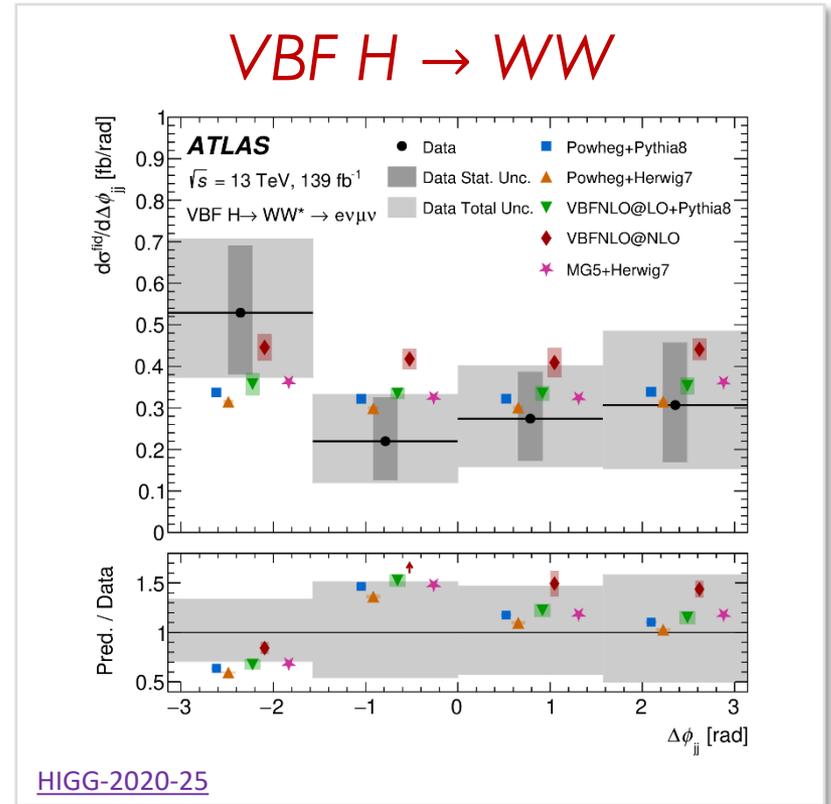
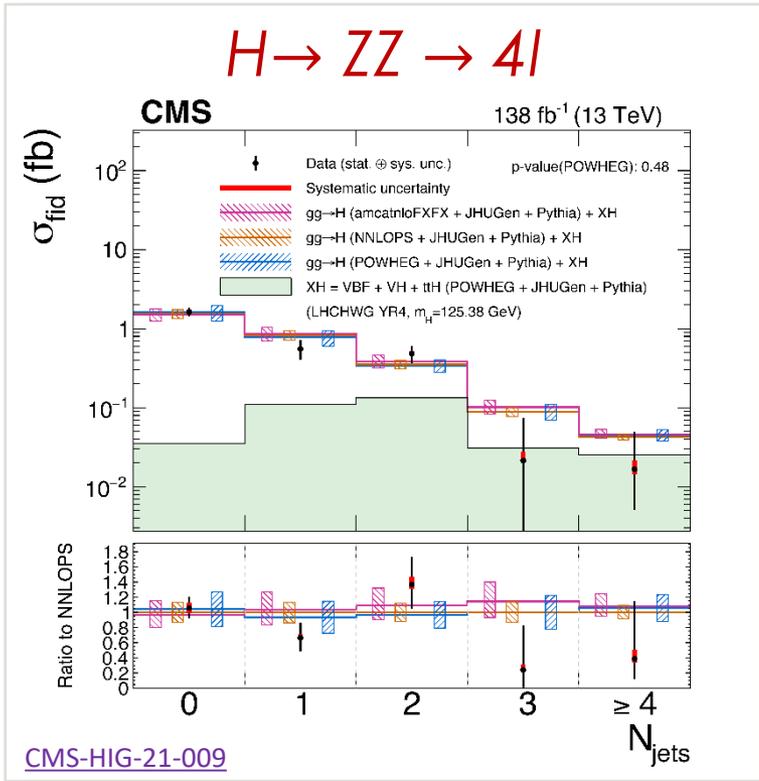
- Maximize sensitivity to **isolate BSM** effects while **reducing theory dependence**
- Exploit **many variables** simultaneously



- Inclusive** over the Higgs decays - easier combination of the **many channels explored**
- Cross-sections in **mutually exclusive regions** of phase space (separated into prod. modes)

# Differential distributions

- Higgs production at LHC described by **kinematic variables** and **jet multiplicity**, which help understanding QCD effects



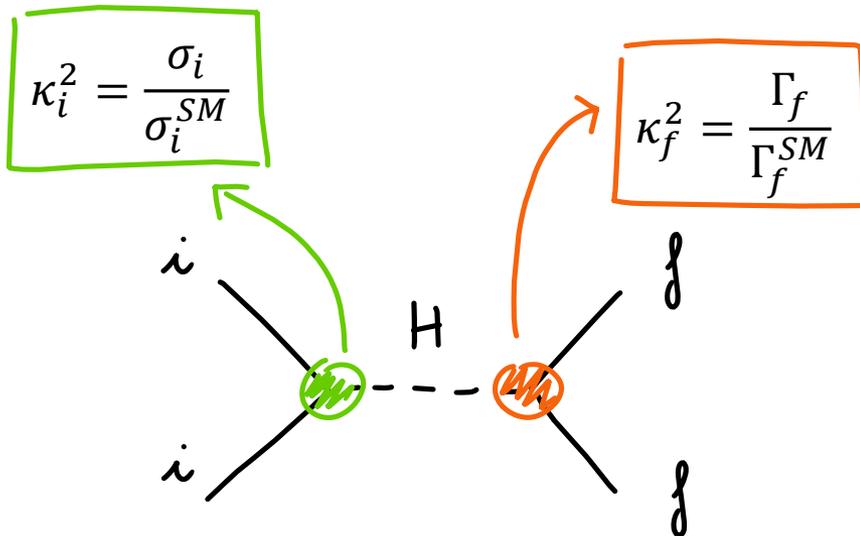
- Differential cross-section measurements in **several channels**

# Higgs boson couplings

- $\sigma(ii \rightarrow H)$  and  $\mathcal{B}(H \rightarrow ff)$  at LO are proportional to the square of **effective Higgs boson couplings** to the corresponding particle
- To test SM deviations, **modified couplings** are defined, denoted by **scale factors  $\kappa$**
- The coupling modifier framework parametrizes **production** and **decay modes inclusively**

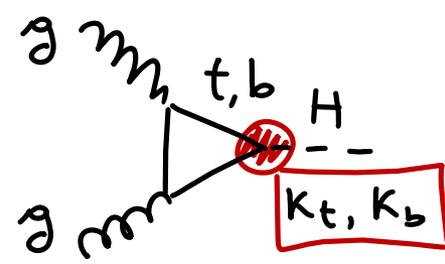
$$\sigma_i \times \mathcal{B}_f = \frac{\sigma_i \times \Gamma_f}{\Gamma_H}$$

$$\sigma_i \propto g_i^2 \quad \Gamma_f \propto g_f^2$$



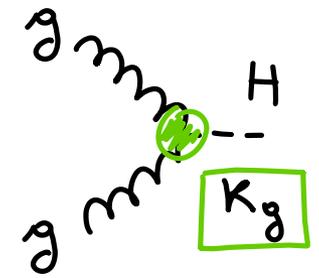
$$\sigma_i \times \mathcal{B}_f = \sigma_i^{SM} \times \mathcal{B}_f^{SM} \times \kappa_i^2 \times \kappa_f^2$$

In case of loops:



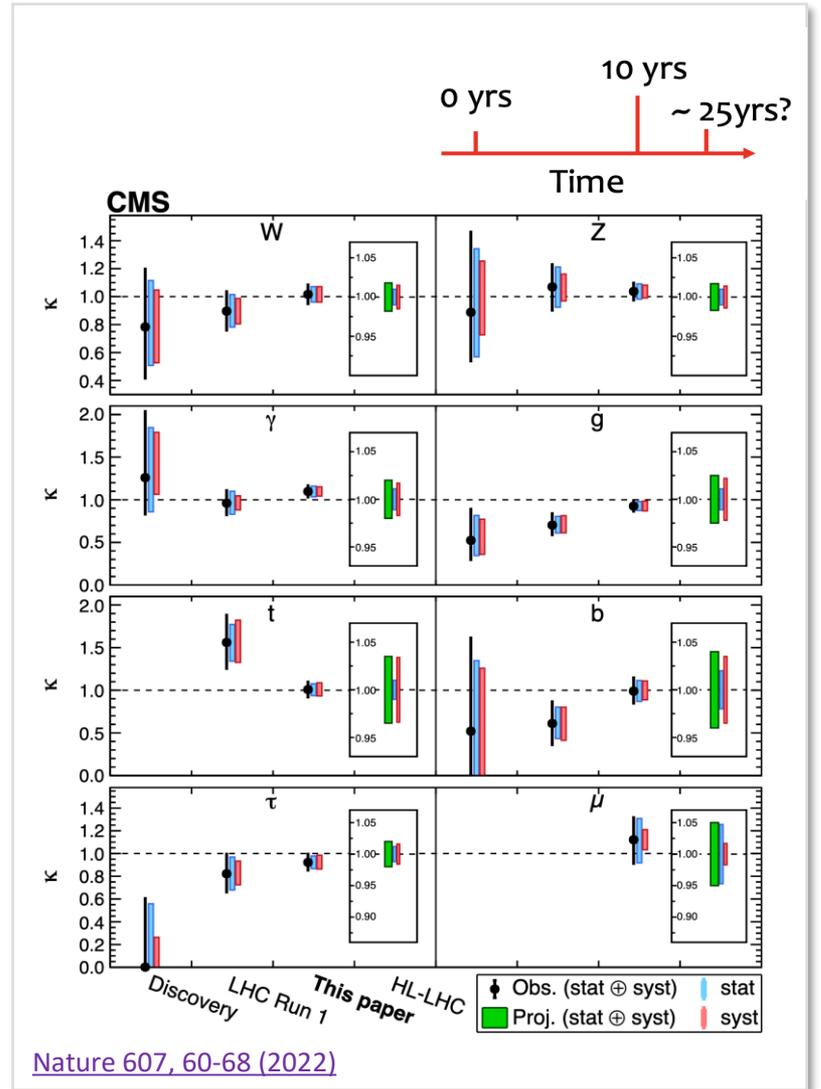
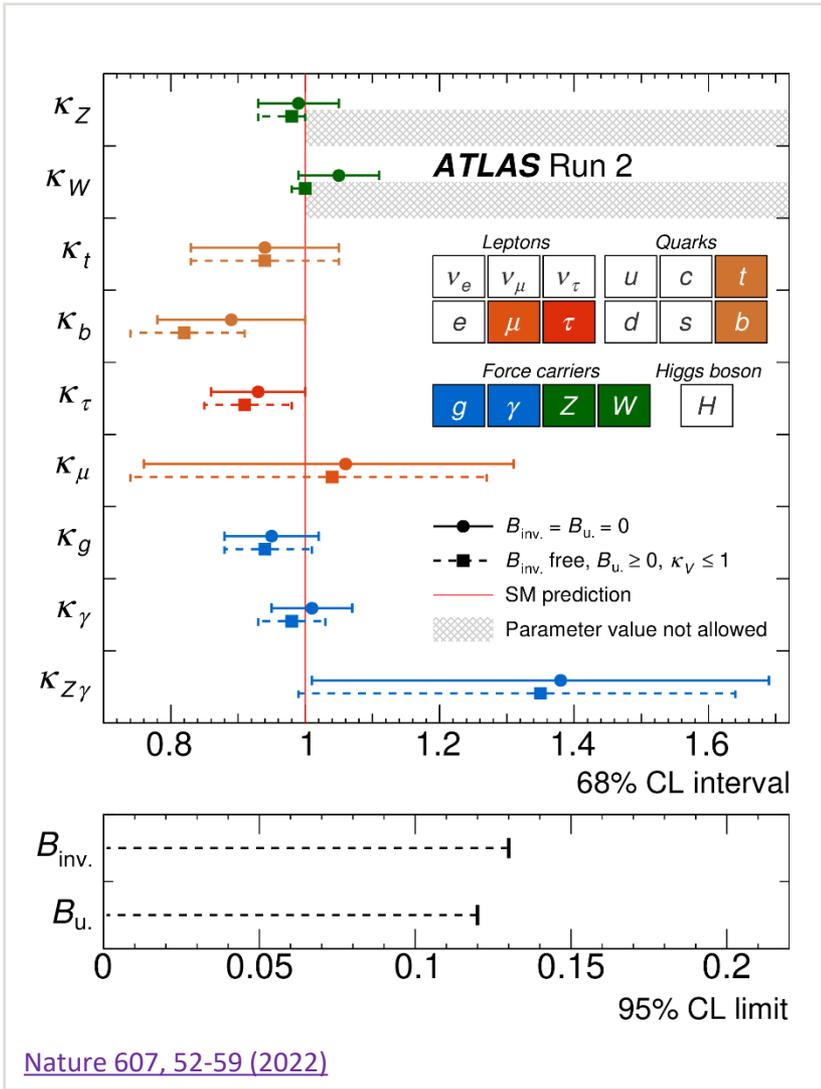
Resolved loop

OR



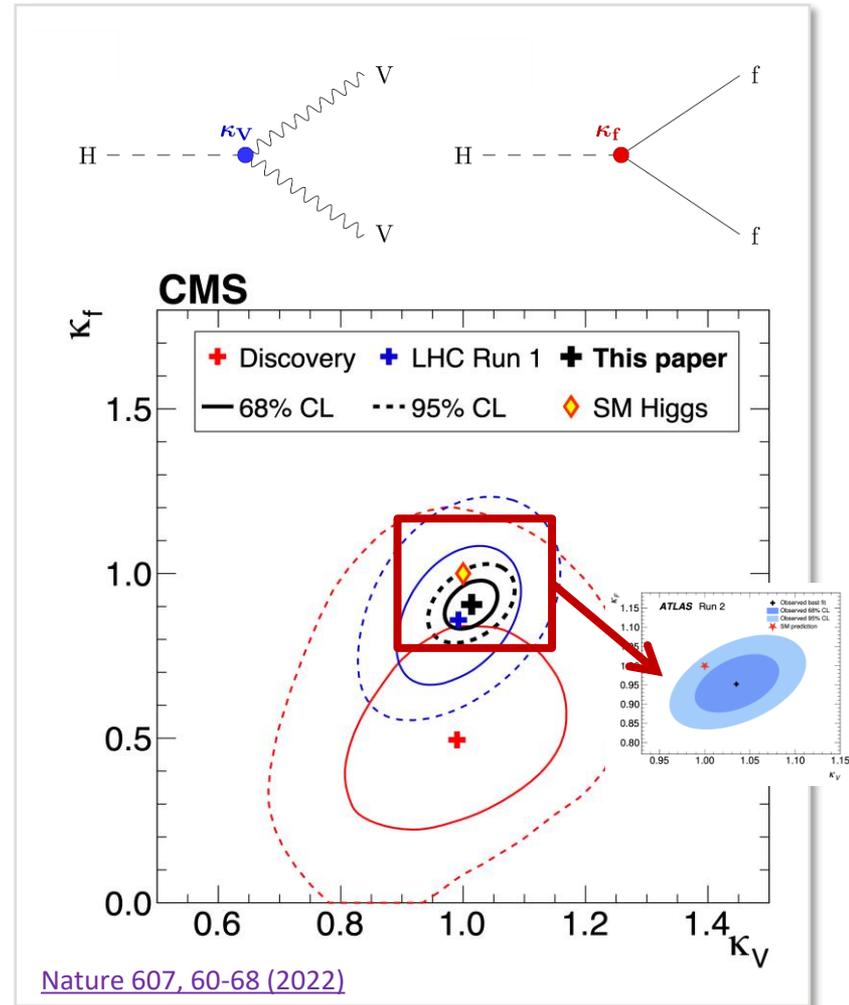
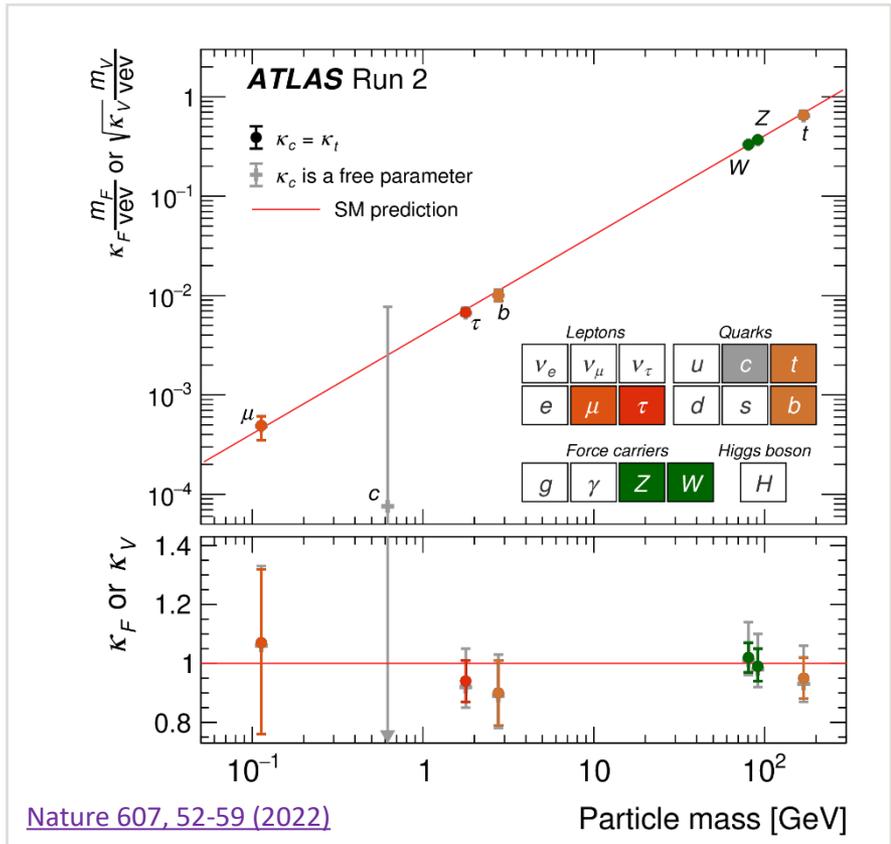
Effective coupling modifier

# The $\kappa$ framework



# The $\kappa$ framework

- Scale all vector boson couplings with  $\kappa_V$ , all fermion couplings with  $\kappa_f$
- Notice improvement with time, from **discovery** to **run 1** to **run 2**



*The Higgs boson couples with the particle mass!*

# Anomalous interactions

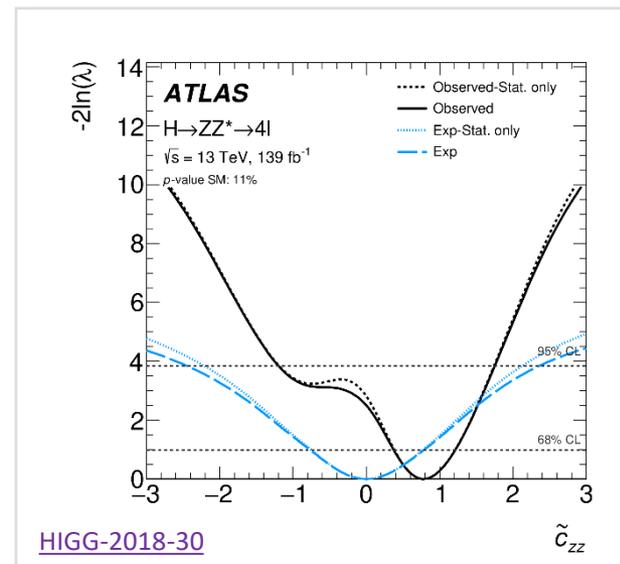
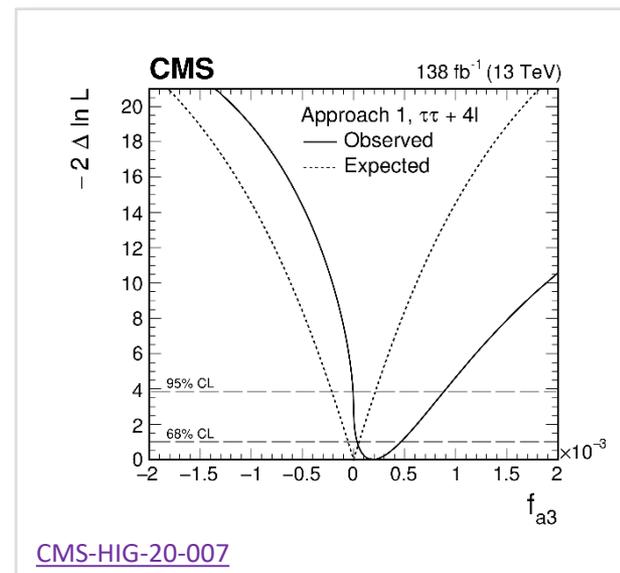
- Through the study of  $\kappa$  parameters, effects of **CP mixing** can be explored

$$A(H \rightarrow ff) = -\frac{m_f}{v} \bar{\psi}_f (\kappa_f + i\tilde{\kappa}_f \gamma_5) \psi_f$$

$$A(H \rightarrow VV) \sim (A_1 + A_1^{BSM}) m_V^2 + A_2 + A_3$$

$$0^+ \quad 0^- \quad \text{Tree-level} \quad \text{loop} \quad f_{a3} \sim \frac{|A_{0^-}|^2}{|A_{0^+}|^2 + |A_{0^-}|^2}$$

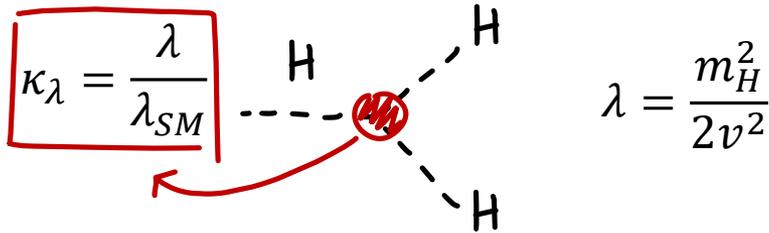
- CP structure** of Higgs couplings probed for  $t, \tau, g, Z, W$ , with a **variety of production and decay modes**
- Two approaches: **anomalous coupling** and **EFT** interpretations
- Measurement globally agrees with **SM  $0^+$**



# Higgs self-coupling

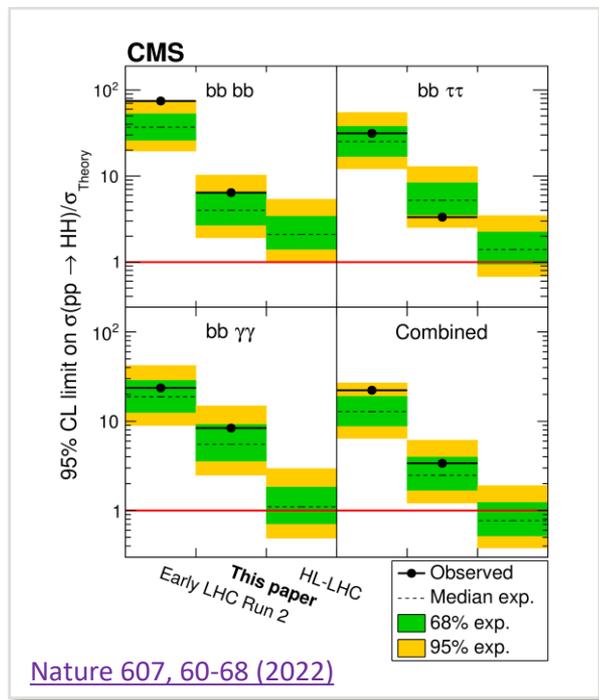
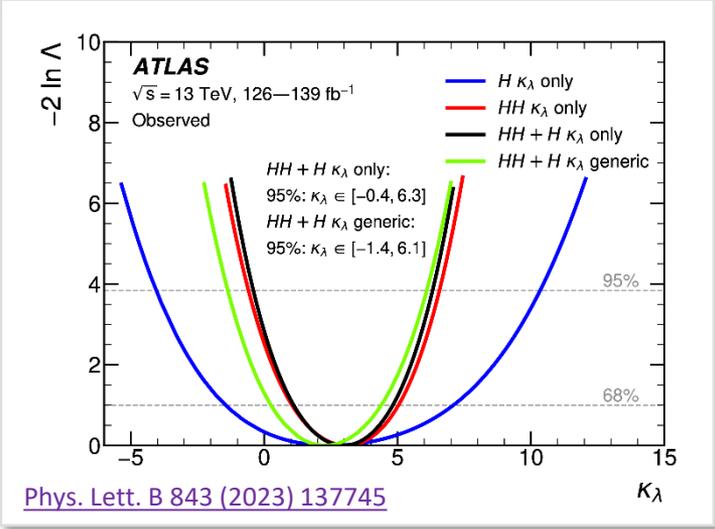
- The potential energy of the Higgs field is

$$V(\Phi) = \frac{1}{2} m_H^2 \phi^2 + \boxed{\sqrt{\frac{\lambda}{2}} m_H \phi^3} + \frac{1}{4} \lambda \phi^4$$



- H self-interaction can be measured via Higgs boson pair production
  - $10^3$  times rarer than single H processes
- Many channels analysed
- Sensitivity better than 3 times the SM

ATLAS:  $-0.4 < \kappa_\lambda < 6.3$  at 95% C.L.  
 CMS:  $-1.24 < \kappa_\lambda < 6.49$  at 95% C.L.



# Conclusions

- The Higgs boson is a profoundly different kind of particle
- Its discovery is of un-measurable value and it has been only possible thanks to the work of thousands of people
- During the last 11 years, ATLAS and CMS have deeply investigated its nature, going from observation to precise measurements
- All measurements made so far are found to be consistent with the SM, but many BSM scenarios predict only %-level deviations
- Run 3 era just began: next years will be crucial to shed light on New Physics phenomena



# Related talks at Lepton-Photon

- [“Higgs boson mass measurement at CMS”](#), Andrey Korytov
- [“Probing the nature of electroweak symmetry breaking with Higgs boson pairs in ATLAS”](#), Yu Nakahama Higuchi
- [“Measurements of Higgs boson properties \(mass, width, and Spin/CP\) with the ATLAS detector”](#), Trevor Vickey
- [“Measurements of Higgs boson production and decay rates and their interpretation with the ATLAS experiment”](#), Andrew Mehta

...And many more!