Summary of ATLAS Higgs Physics

BSM 2023 Hurgada (Egypt) 6-9 November

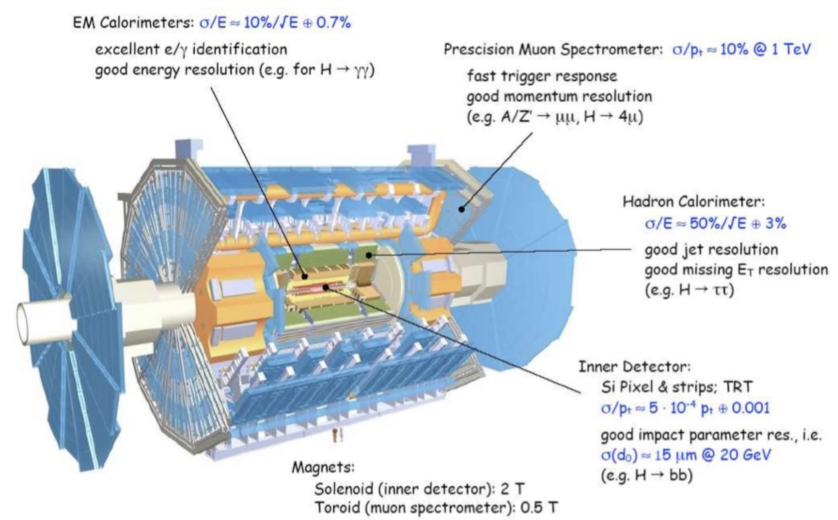
Giada Mancini LNF INFN

Introduction

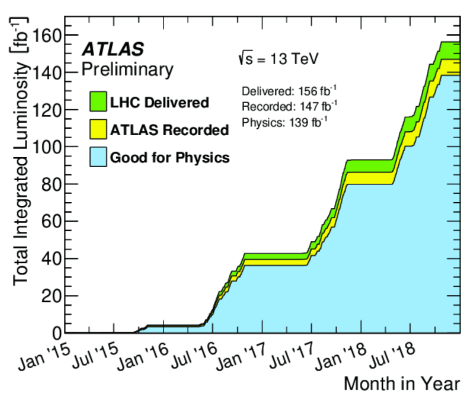
After the Higgs discovery the overall goal is precision measurements to search for deviations from the SM predictions.

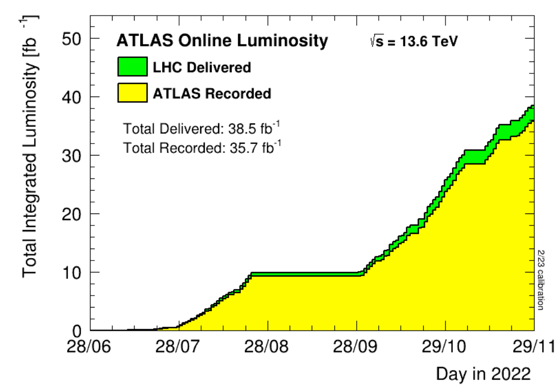
The 13 TeV Run 2 dataset enabled several new Higgs boson measurements in different decay channels and production modes, interpretation in various BSM frameworks:

- Unprecedent precision levels of the Higgs boson properties
- New Physics investigated in several BSM frameworks
- Searches for rare decays lead to first evidences



Focus on the most updated measurements of the Higgs boson properties performed by the ATLAS experiment with Run 2 dataset (~**140 fb^{-1} of good pp collision data**) …with a first look to new data at 13.6 TeV (**~36 fb^{-1}**)!





Outline

The Higgs boson …

Mass

CP structure

Width

Couplings

Simplified Template Cross Section

Fiducial, Differential and Total Cross Section

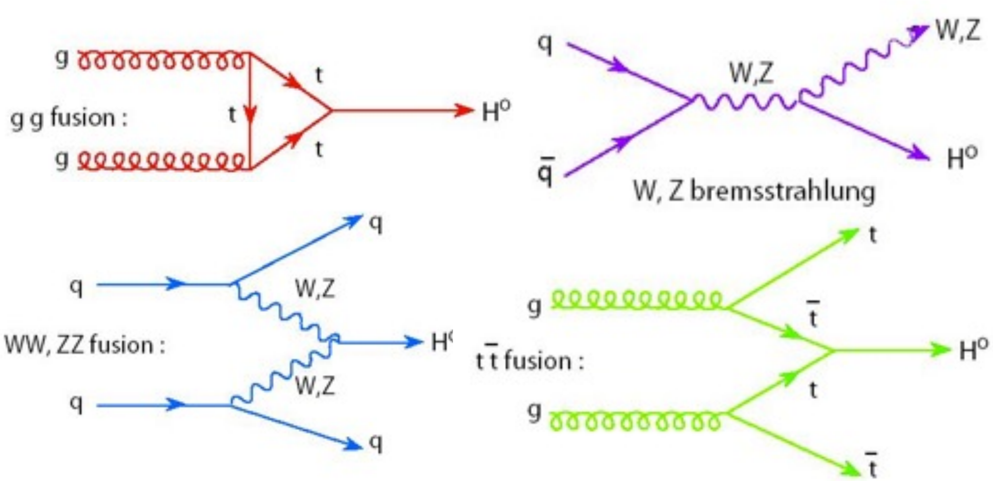
$H \rightarrow Z\gamma$ decay

Invisible decay

Self-coupling

Production and decay modes

The Higgs production at LHC can occur through the following mechanisms:



ggF: is the dominant production mode, $\sigma^{ggF}/\sigma^{TOT}$ = 87% @ 13 TeV.

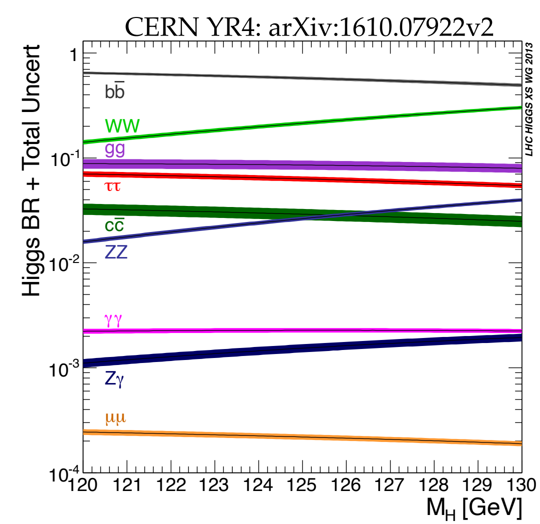
VBF: whose signature is characterized by H+2jet forward, $\sigma^{VBF}/\sigma^{TOT}$ = 7% @ 13 TeV.

VH: whose signature is composed by a H associated to a W or a Z boson, σ^{VH}/σ^{TOT} = 4% @ 13 TeV.

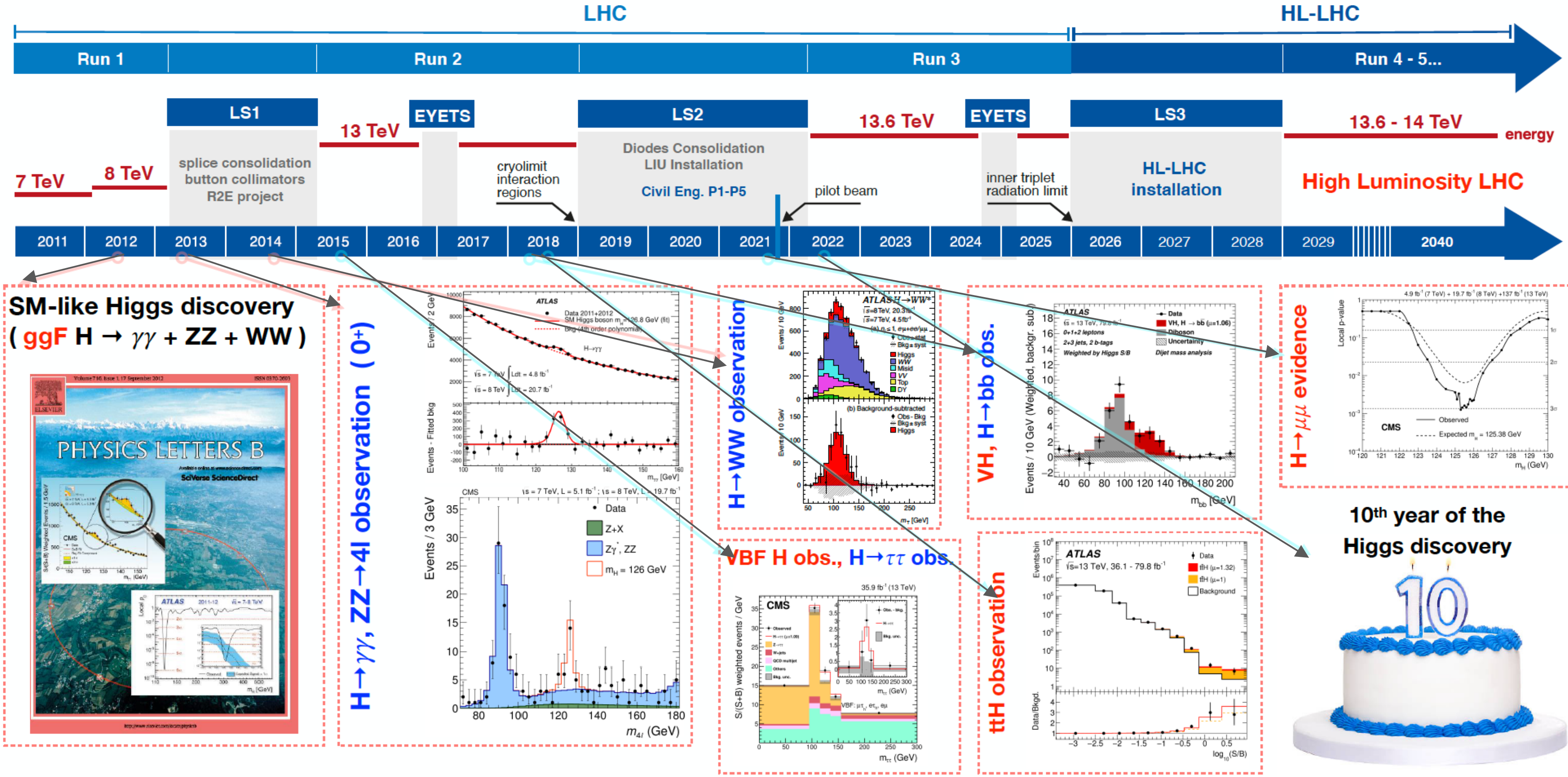
ttH-bbH: in which the H is associated to tt-bar/bb-bar pairs, $\sigma^{ttH+bbH}/\sigma^{TOT}$ = 2% @ 13 TeV.

Decay channels:

- H->ZZ*->4l: pure channel but very low statistics ($BR_{H\to ZZ^*\to 4l} \sim 2 \cdot 10^{-4}$)
- H->γγ : simple final state but low BR and large background
- H->WW*->lνlν: good sensitivity but low mass resolution
- H->bb: huge bkg, best accesible via VH production
- H->ττ: very large bkg, best accesible via VBF and boosted H production
- H->Zγ & H->μμ: low BR



Evolution



Mass (ATLAS+CMS): 125.09 ± 0.24 (± 0.21 ± 0.11) GeV

Width: $\Gamma_H < 22.7$ MeV @ 95% CL

Spin/CP: SM Higgs $J^{CP} = 0^{++}$

First Differential XS as function of Higgs and jet kin variables

Couplings: Results in terms of Signal Strength: $\mu = \frac{(\sigma \cdot BR)_{obs}}{(\sigma \cdot BR)_{SM}}$

and Coupling modifiers (κ-framework)

$$\kappa_j^2 = \frac{\sigma_j}{(\sigma_j)_{SM}} \qquad \kappa_j^2 = \frac{\Gamma^j}{(\Gamma^j)_{SM}}$$

Beginning of Precision Era…

Precise measurements of Higgs mass, width, couplings and differential XS

More stringent constraints on anomalous Higgs boson couplings with other SM particles

Interpretation of the results in different theoretical framework (EFT, PO, etc.)

…walking towards higher energy and higher luminosity!

Higgs Boson Mass

H→ZZ*→4l and H→$\gamma\gamma$ are the most sensitive channels

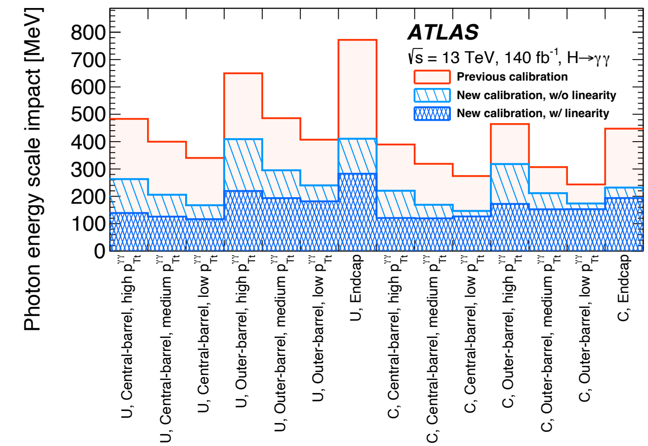
Clear signature final states

High mass resolution 1-2 %

Main uncertainties:

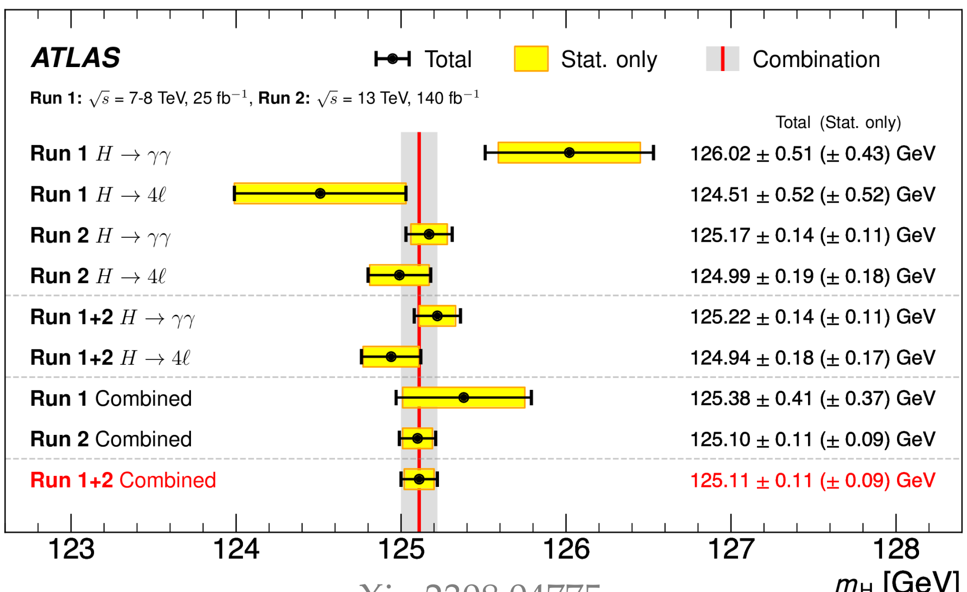
Electron / photon energy scale and muon momentum scale

-> H->γγ great improvement in photon energy scale calibration

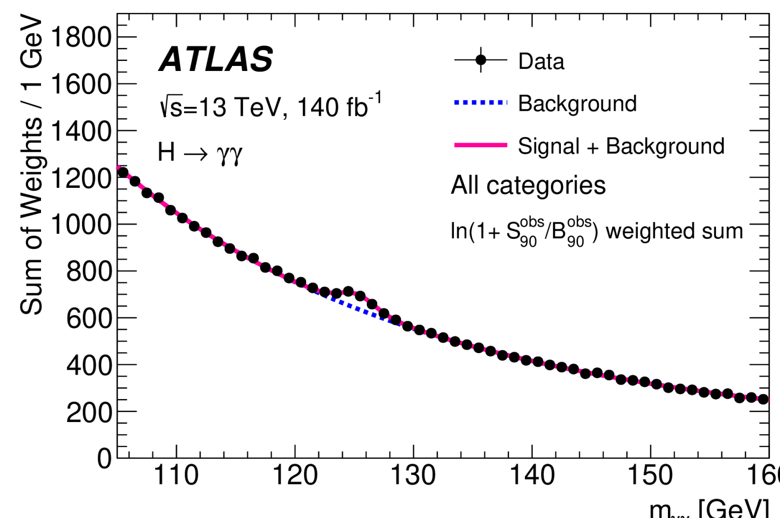


ATLAS: Results @ 140 fb-1 (+Run1)

$$\mathbf{m_H = 125.11 \pm 0.11\ (\pm 0.09)\ GeV}$$



arXiv:2308.04775



arXiv:2308.07216

Looking for:

- Modifications of the coupling with vector bosons (*HVV*) and fermions (*Hff*) via **coupling modifiers (k_j)**: parametrizing production and decay, coupling modifiers as multiplicative factors, narrow width approximation

$$\sigma_i \cdot \mathrm{BR}^f = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_H} \qquad \text{where} \qquad \kappa_j^2 = \Gamma^j / \Gamma^j_{SM} \qquad \kappa_j^2 = \sigma_j / \sigma_j^{SM}$$

-> k_j=1 refers to the Standard Model case (SM)

- Interpret the results in terms of anomalous Higgs boson couplings

  BSM effects in the Higgs sector can be probed in an Effective Field Theory (EFT) approach assuming some high scale of NP (Λ) adding higher dimension BSM operators to the SM Lagrangian (SM reproduces the low-energy limit of a more fundamental description)

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \bar{c}_i^{(6)} O_i^{(6)}$$

Wilson coefficients ($\bar{c}_i^{(6)}$)

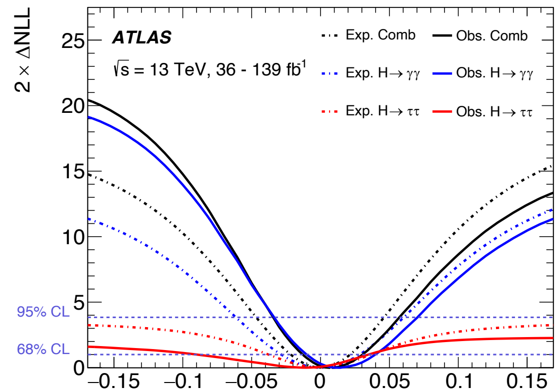
-> New physics at high mass scale introduces new types/structures of Higgs boson couplings, which change the Higgs boson kinematics with respect to the SM

Higgs Boson CP structure

Use of observables optimized (e.g. OptimalObservables, OO) to discriminate different CP hypothesis -> Rate (e.g. signal strenght, $\mu = (\sigma\ BR)_{obs}/(\sigma\ BR)_{SM}$) cannot disentangle anomalous CP-even or CP-odd effects, observable shapes does!

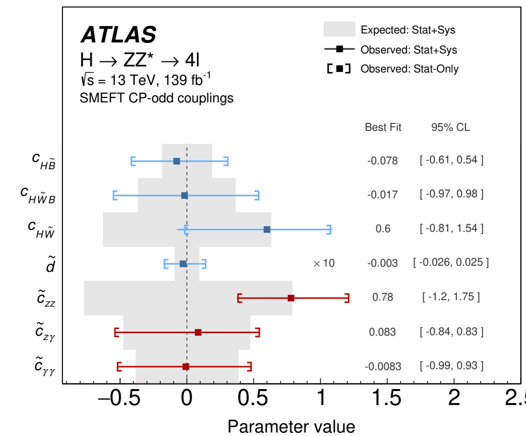
HVV vertex studied in the VBF production and H→ZZ* decay

- Limits from $H\to\gamma\gamma$+$H\to\tau\tau$ combination
- Summary EFT coupling CP-odd constraint



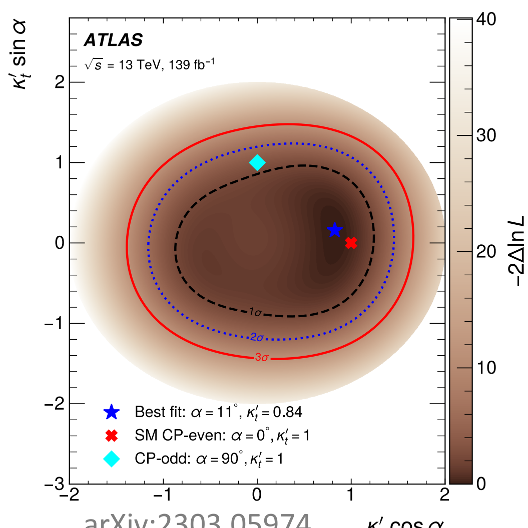
Phys. Rev. Lett. 131 (2023) 061802

arXiv:2304.09612

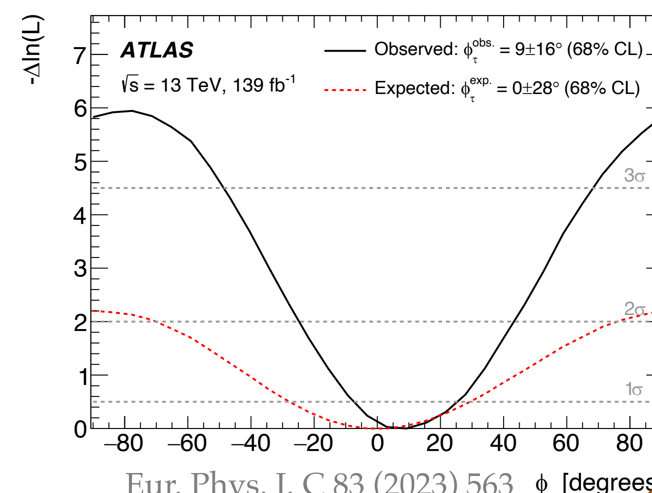


Hff vertex studied in the ttH/tH production and H→ττ decay

- using decay via ttH with H->bb limits on $k_t\cos\alpha$ and $k_t\sin\alpha$
- Limits on CP mixing angle in $H\to\tau\tau$ decay



arXiv:2303.05974



Eur. Phys. J. C 83 (2023) 563

Higgs Boson width

SM Higgs width Γ_H=4.1 MeV → experimental resolution O(1-2 GeV) are too small to allow direct measurements

Indirect measurement from the ratio of the on-shell / off-shell Higgs boson production

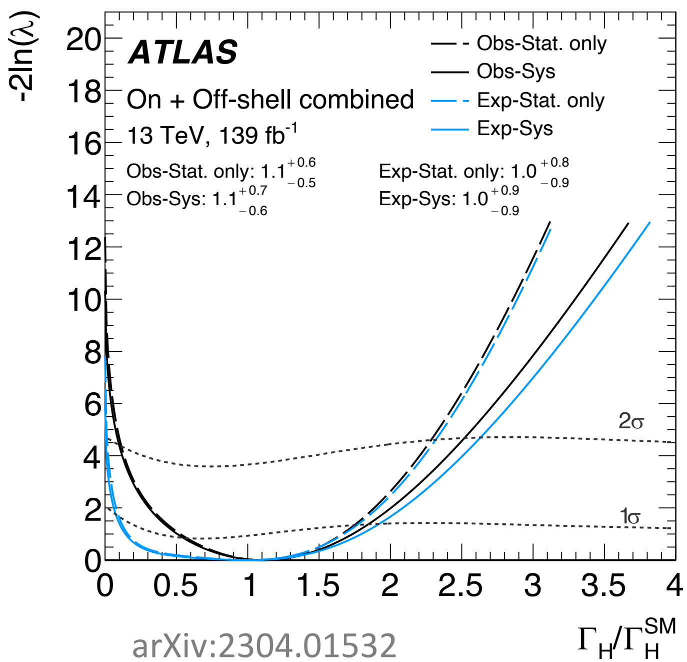
$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{\text{ggH}} g^2_{\text{HZZ}}}{m_H \Gamma_H} \qquad \sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{\text{ggH}} g^2_{\text{HZZ}}}{m^2_{ZZ}} \Rightarrow \frac{\Gamma_H}{\Gamma_H^{SM}} = \frac{\mu_{\text{off-shell}}}{\mu_{\text{on-shell}}}$$

H→ZZ*→ 4l and 2l2ν channels performed this measurements with full Run 2 dataset

ATLAS: $\mu_{\text{off-shell}} = 1.1 \pm 0.6\ (3.3\ \sigma)$

First evidence of **off-shell** Higgs boson production

ATLAS: $\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV



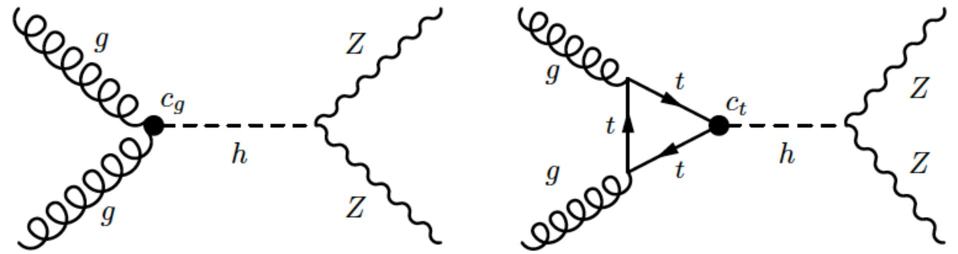
arXiv:2304.01532

Consider contribution involving a point-like gluon-gluon fusion and a top loop induced ggF.

$$\mathcal{L}_{\mathrm{SMEFT}} \supset \mathcal{L}_{\mathrm{SM}} + \mathcal{L}^{\text{dim-6}}$$

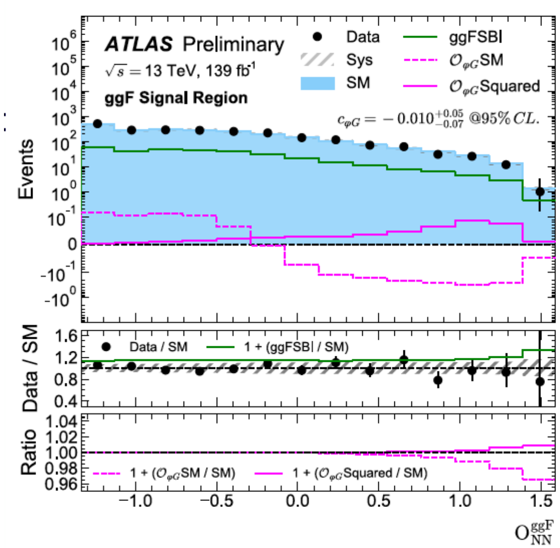
$$= - c_t \frac{m_t}{v}\bar{t}tH + c_g \frac{g_s^2 H}{48\pi^2 v} G_{\mu\nu}G^{\mu\nu} \quad (\mathrm{CP-even})$$

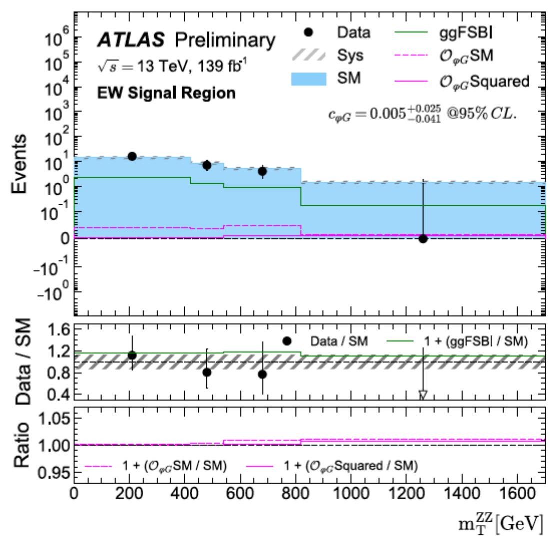
$$+ i\tilde{c}_t \frac{m_t}{v}\bar{t}\gamma_5 tH + \tilde{c}_g \frac{g_s^2 H}{32\pi^2 v} G_{\mu\nu}\tilde{G}^{\mu\nu} \quad (\mathrm{CP-odd})$$

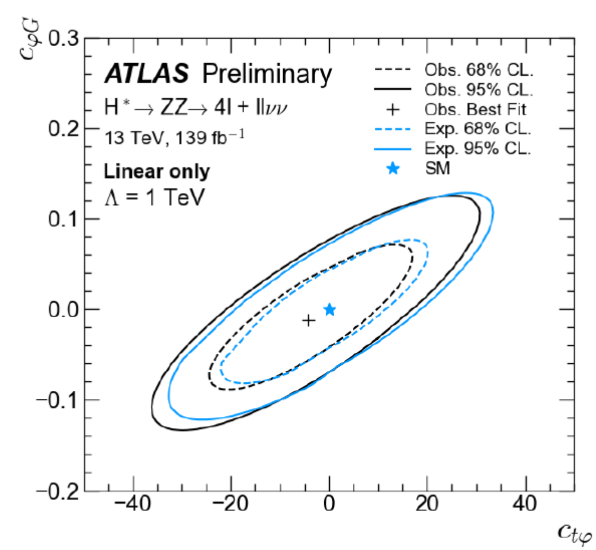


$$O_{\mathrm{NN}} = \log_{10} \frac{P_{\mathrm{S}}}{P_{\mathrm{B}} + P_{\mathrm{NI}}}$$

NN multiclassifier trained against Signal (P_S), interfering bkg (gg->ZZ, P_B), and non interfering bkg (qq->ZZ, P_{NI})





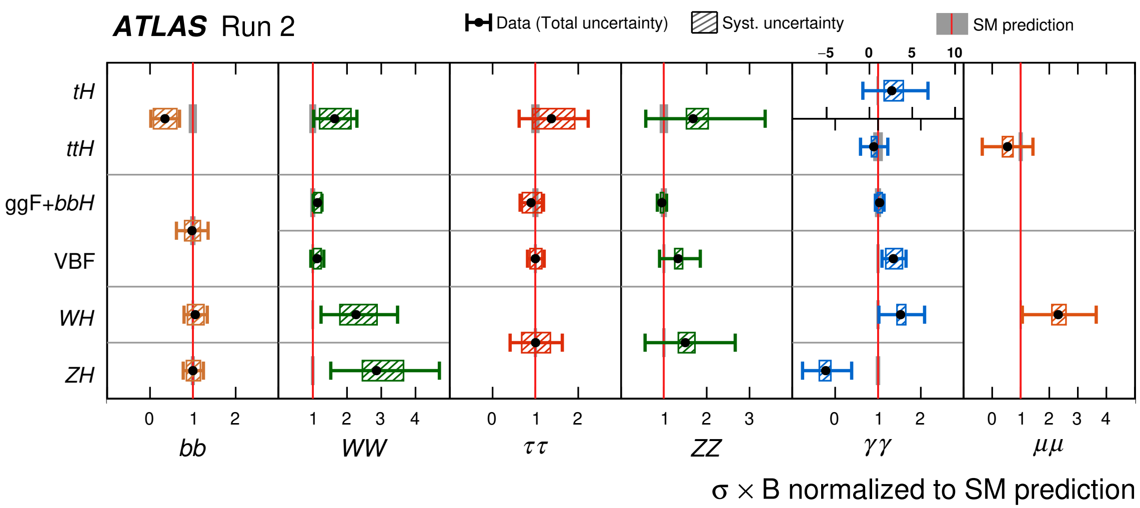


Higgs Boson Couplings

Production cross section and decay branching ratio are a way to probe the strength of the Higgs boson coupling with SM particles and possible BSM effects

After 10 years from the discovery both the experiments provided the combined measurements of its couplings.

A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery
Nature 607, pages 52-59 (2022)



p-value = 72%

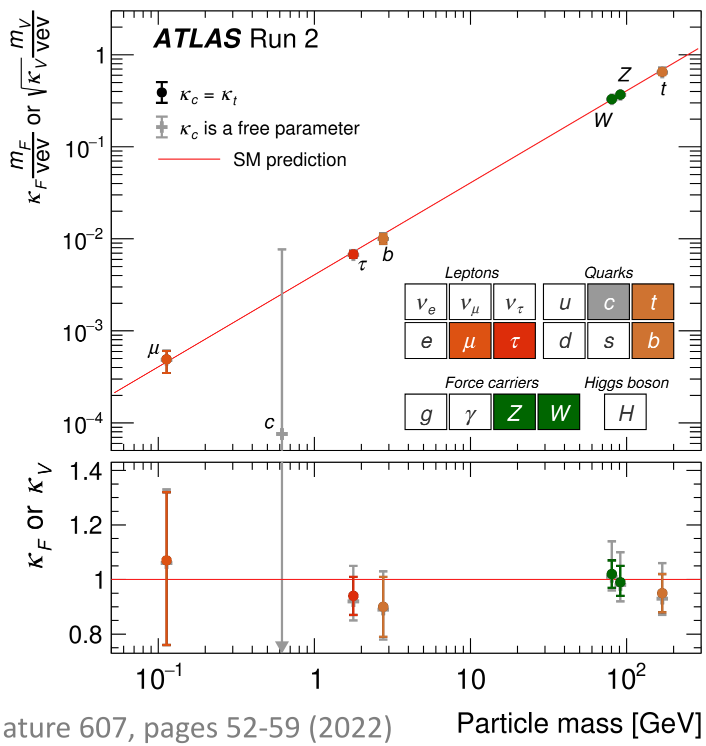
- analyses are typically grouped per decay mode, with few exceptions when more decays need to be grouped together to increase statistics (ttH)
- di-boson modes (γγ, WW) sensitive to all production modes (ZZ) only to ggF due to low stat, fermionic modes sensitive to VH (bb) and VBF modes (ττ)

Results interpreted in terms of Higgs boson coupling strength multipliers κ in multiple scenarios

- coupling scaling with particle mass nicely verified by experiment

$$g_{Hf\bar{f}} = \frac{m_f}{\mathrm{VEV}}$$

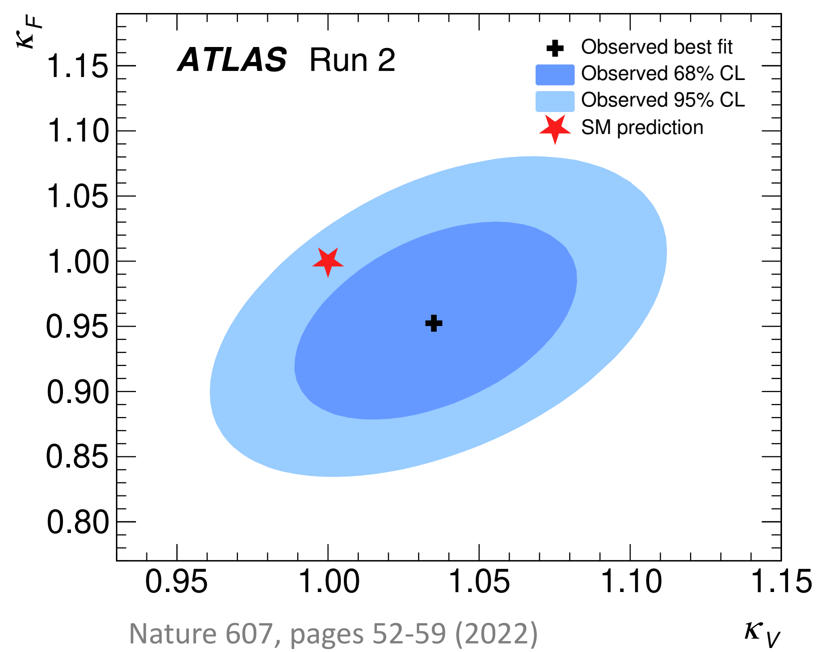
$$g_{HVV} = \frac{m_V^2}{\mathrm{VEV}}$$



Nature 607, pages 52-59 (2022)

Coupling with quark charm
ATLAS: $\kappa_c < 5.7$ @ 95% C.L.

Universal coupling strength modifiers κ_V (vector bosons) and κ_F (fermions)



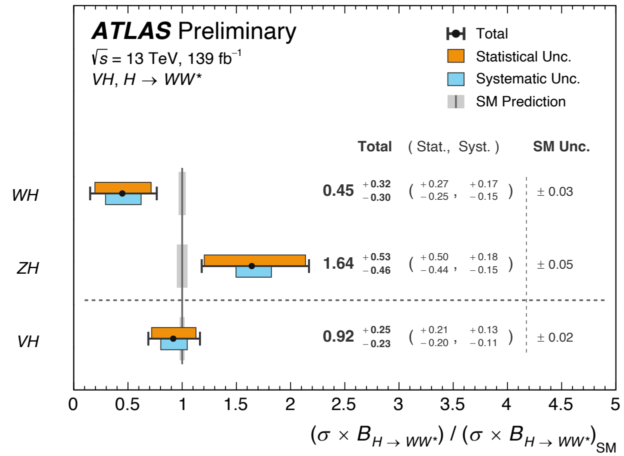
Nature 607, pages 52-59 (2022)

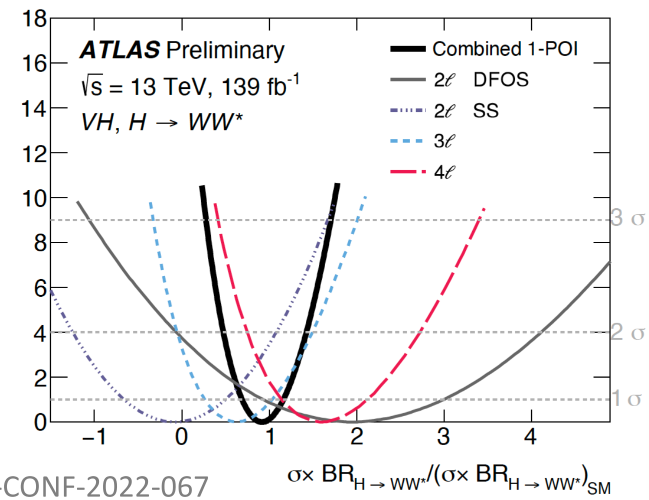
Higgs Boson Couplings (NEW)

VH, H→WW*

$\sigma_{WH}\times B_{H\to WW^*} = 0.13\ ^{+0.08}_{-0.07}\,(\text{stat.})\ ^{+0.05}_{-0.04}\,(\text{syst.})$ pb

$\sigma_{ZH}\times B_{H\to WW^*} = 0.31\ ^{+0.09}_{-0.08}\,(\text{stat.}) \pm 0.03\,(\text{syst.})$ pb





ATLAS-CONF-2022-067

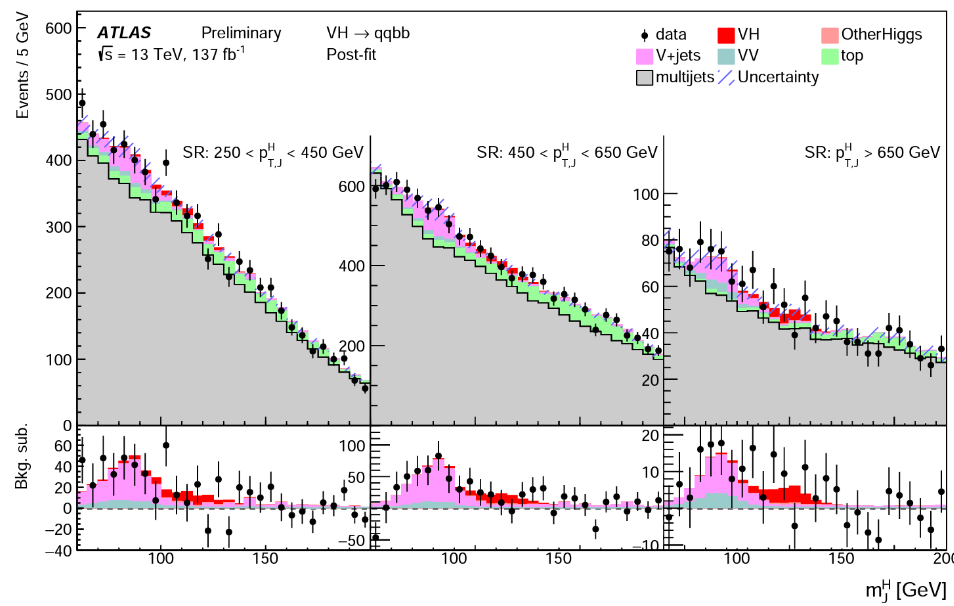
VH, H→bb (all hadrons)

First measurement of the VH is performed in the fully hadronic final state

Significance(VH) =1.7σ

$\sigma_{VH}\times B_{H\to bb} = 3.3 \pm 1.5\,(\text{stat.})\ ^{+1.9}_{-1.5}\,(\text{syst.})$ pb

in agreement with the SM prediction

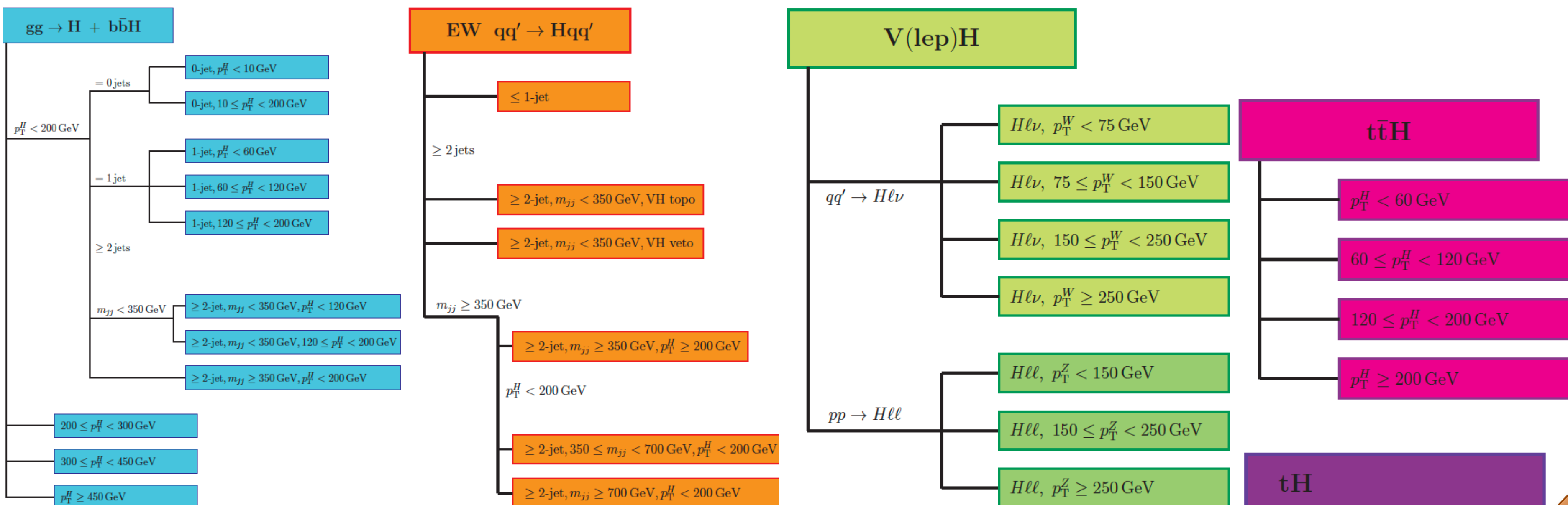


ATLAS-CONF-2023-067

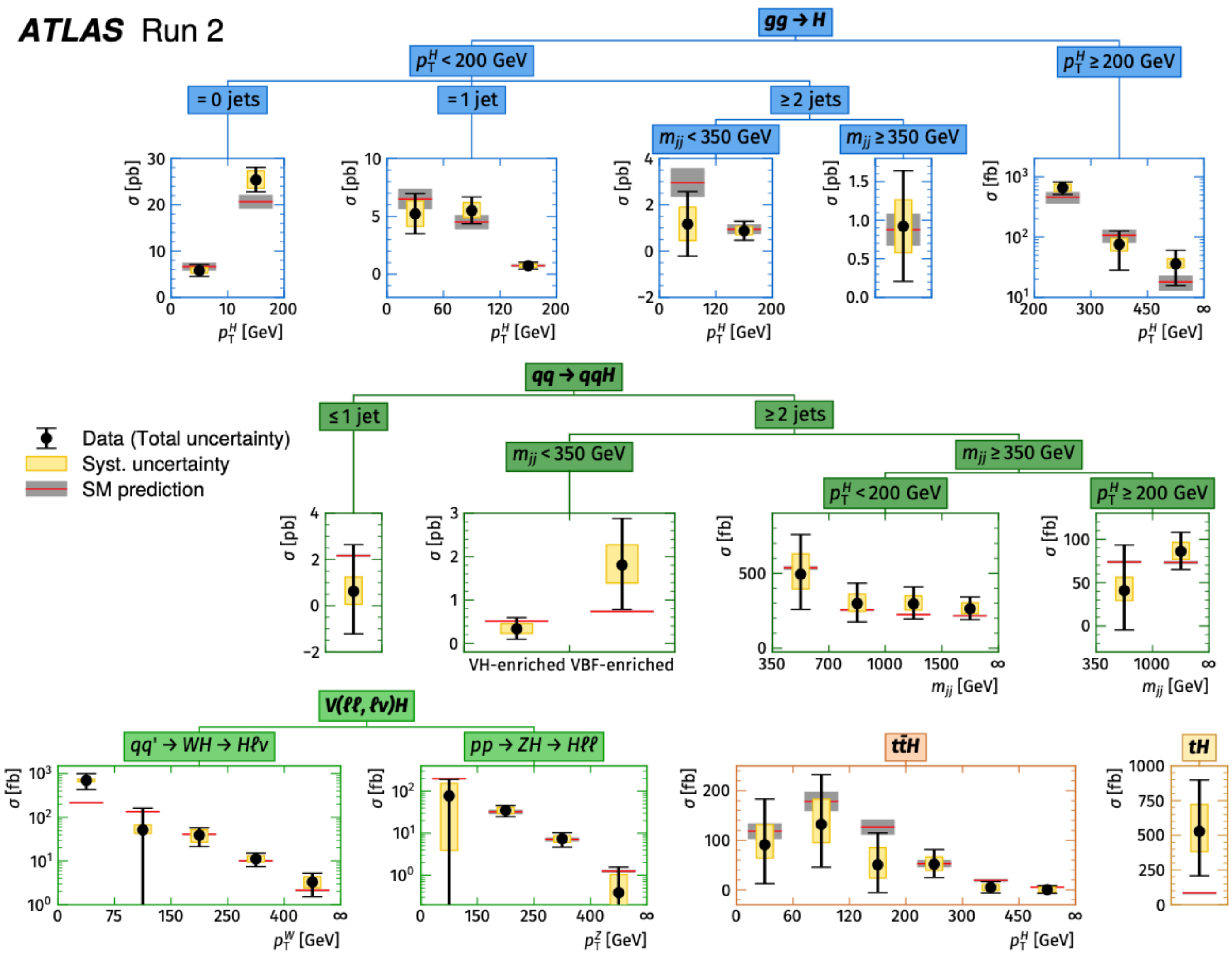
Higgs Boson Simplified Template Cross Sections (STXS)

STXS framework defines exclusive regions in the Higgs phase space of the Higgs production processes, based on the kinematics of the Higgs and of the particles/jets produced in association

- separate measurement and interpretation steps to reduce in a systematic fashion the theory dependencies folded into the measurements (dependence on theoretical uncertainties and on the underlying physics model)
- provide more finely-grained measurements (and hence more information for theoretical interpretations) while at the same time allowing and benefiting from the global combination of the measurements in all decay channels
- Maximizing experimental sensitivity also to possible BSM effects



Higgs Boson Simplified Template Cross Sections



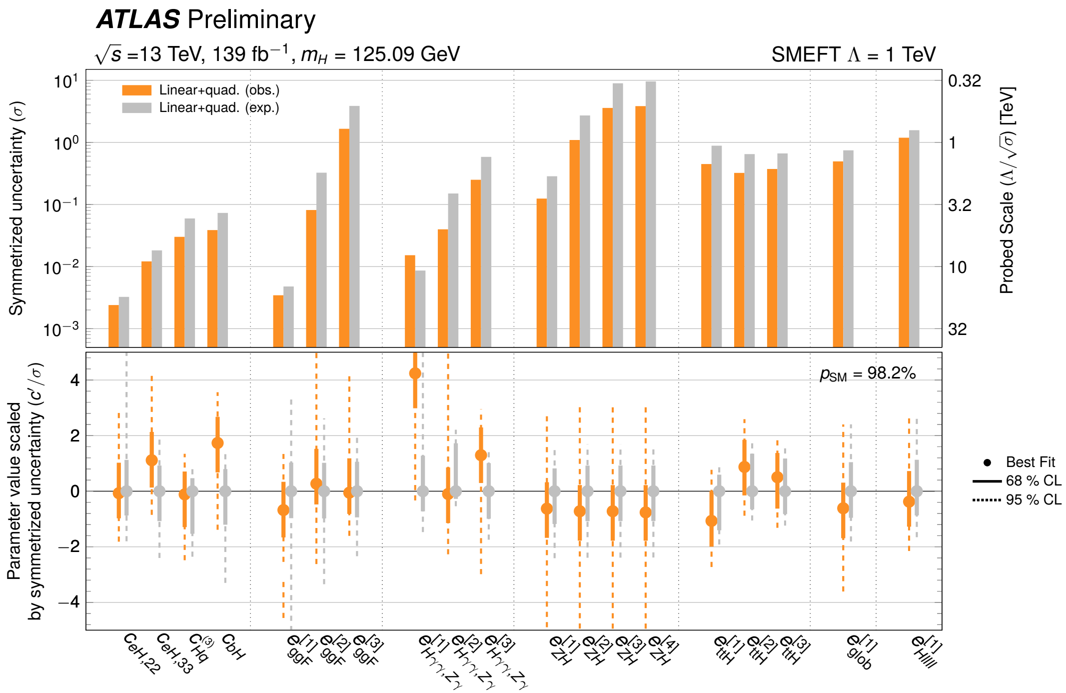
ATLAS

Joint measurement of 36 regions combining the results in the 5 observed decay channels (bb, WW, ττ, ZZ, γγ).

Good agreement with SM:
p-value 94%

The modifications to the tree-level Higgs boson couplings to fermions can be generated by dimension-6 Operators of the SM_{EFT} Lagrangian:

- Constraints can thus be inferred with a SMEFT interpretation of the combined measurement of production and decay rates and STXS
- Constraints are set on a rotated basis wrt the Warsaw basis to maximize the sensitivity

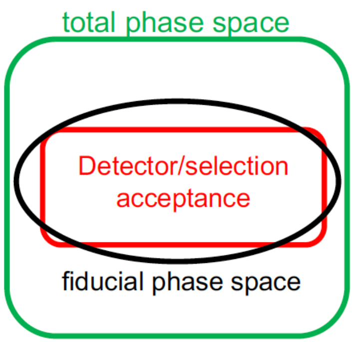


ATLAS-CONF-2023-052

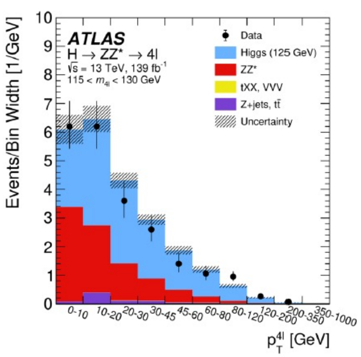
Higgs Boson Fiducial Cross Section

The fiducial phase space is based on the detector acceptance and is defined to minimize the extrapolation effects and mimic the detector & analysis acceptance

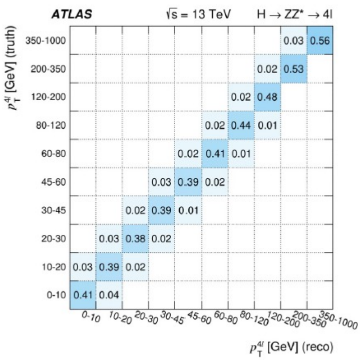
- Most model independent way to study the properties of the Higgs boson
- Reduce sensitivity for BSM effects compared to dedicated analyses
- Observable sensitive to: Higgs boson production kinematics, associated jet kinematics, decay kinematics (both in production and decay) e.g. to probe spin-CP of the Higgs boson and allowing to scrutinize the SM Lagrangian structure of the Higgs boson interactions



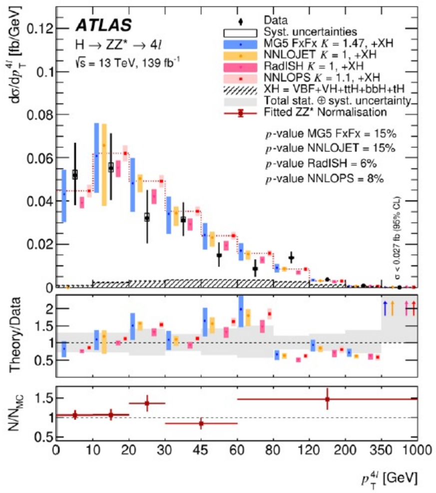
Reco distribution



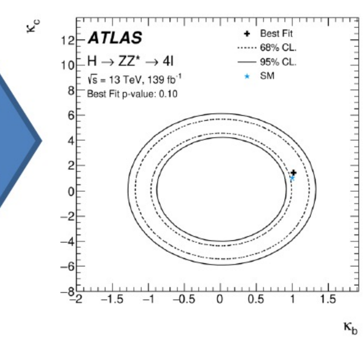
Unfolding



Diff XS distribution

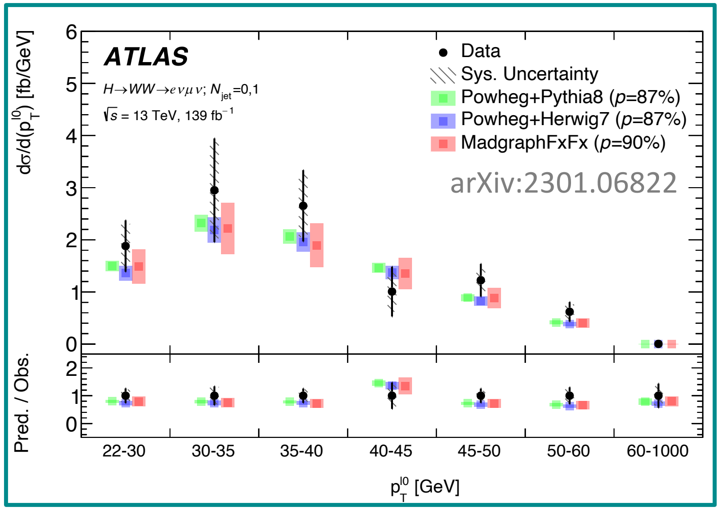


Interpretation

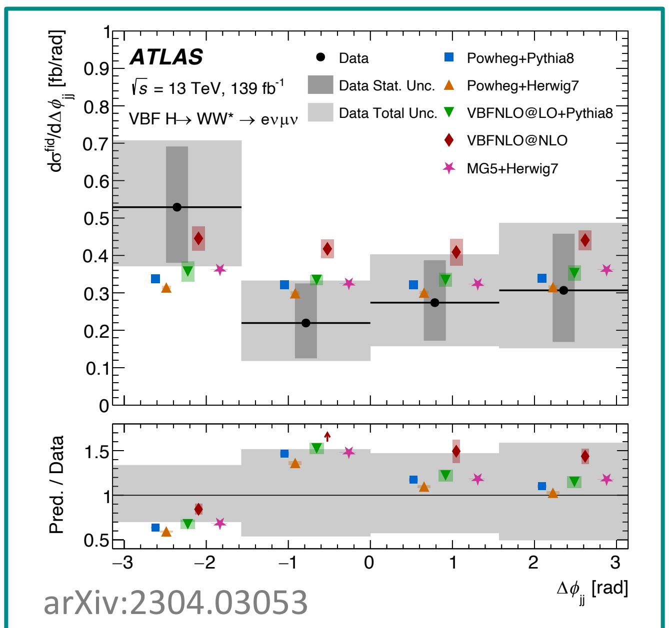


Higgs Boson Fiducial Cross Section: H->WW*

ggF H→WW*: 0,1 jets

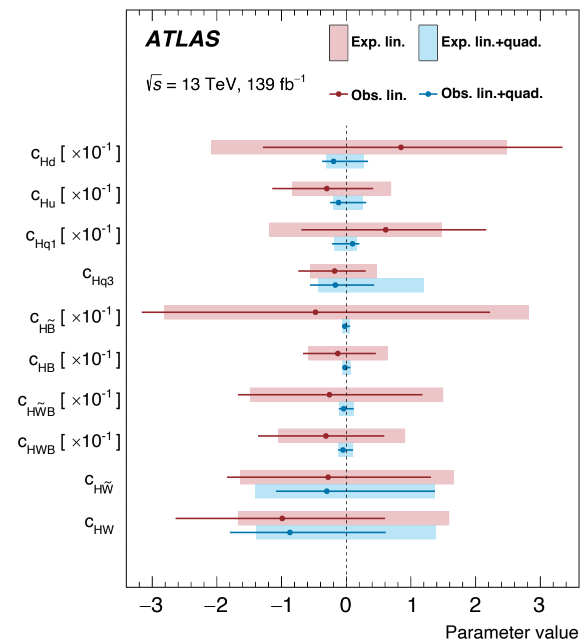


VBF H→WW*: ≥2jets



$\sigma^{\rm fid}_{\rm VBF} = 1.68 \pm 0.40$ fb $= 1.68 \pm 0.33$ (stat) ± 0.23 (syst) fb.

The sensitivity of differential distributions to several dim-6 operators is studied in order to put constraints on the wilson coefficients investigating both CP-even and CP-odd anomalous interactions of vector bosons with the Higgs field

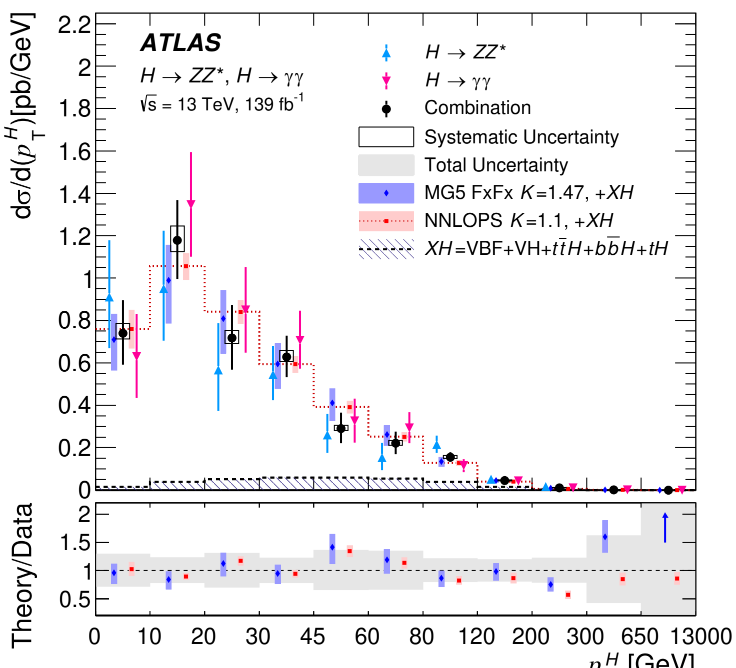


Higgs Boson Cross Section: Combination

Combine the results extrapolating to the full phase space (larger theory uncertainties)

→ sensible reduction of the statistical error

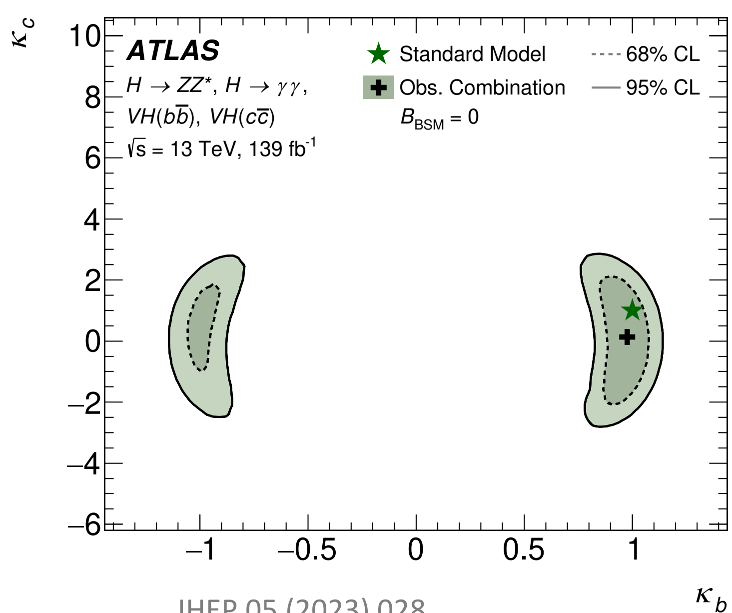
Interpretation of the differential distribution in different framework



JHEP 05 (2023) 028

ZZ+$\gamma\gamma$ → + direct measurements VH(bb) and VH(cc)

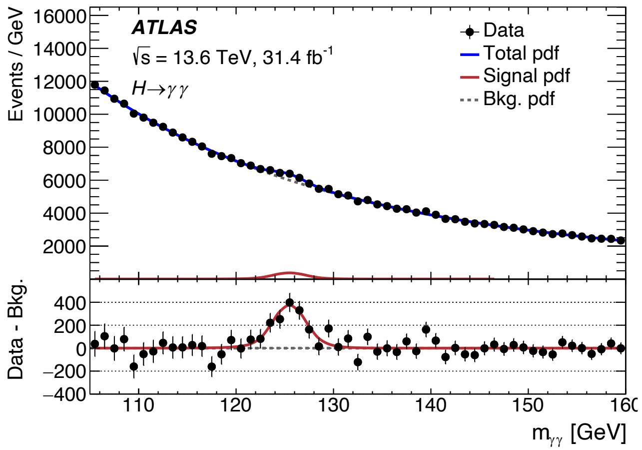
Constraint on the Yukawa coupling to the charm quark
$-2.47 < \kappa_c < 2.53$
@ 95% C.L.

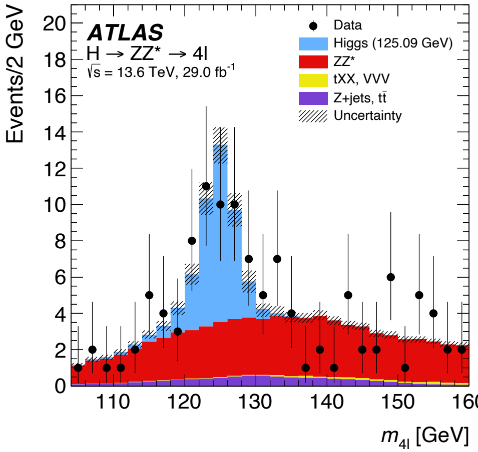


JHEP 05 (2023) 028

First measurement of the Higgs boson production cross section @ 13.6 TeV performed by ATLAS in $H\to ZZ^*\to 4l$ and $H\to\gamma\gamma$ decay channels and combined

- Collected luminosity of 31.4 fb^{-1} for $H\to\gamma\gamma$ and 29.0 fb^{-1} for $H\to ZZ^*\to 4l$ (only runs with muon triggers) in 2022



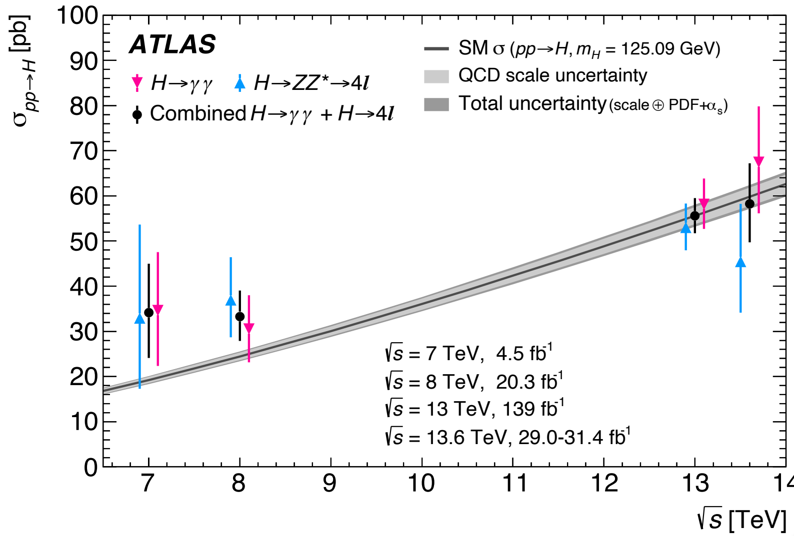


arXiv:2306.11379

Fiducial cross section results per channel extracted from fit of the invariant mass $m_{\gamma\gamma}$ or m_{4l} in the fiducial phase space, correcting for the fiducial efficiency
Combination of the total cross section

$$\sigma_{total} = 58.2 \pm 8.7 \text{ pb}$$

(SM: 59.9 ± 2.6 pb)

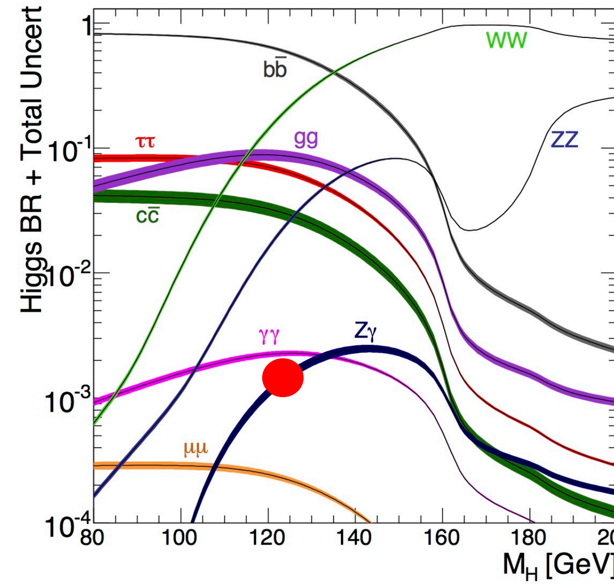


Very rare decay! Important for probing the Higgs properties and for validating SM/BSM theories

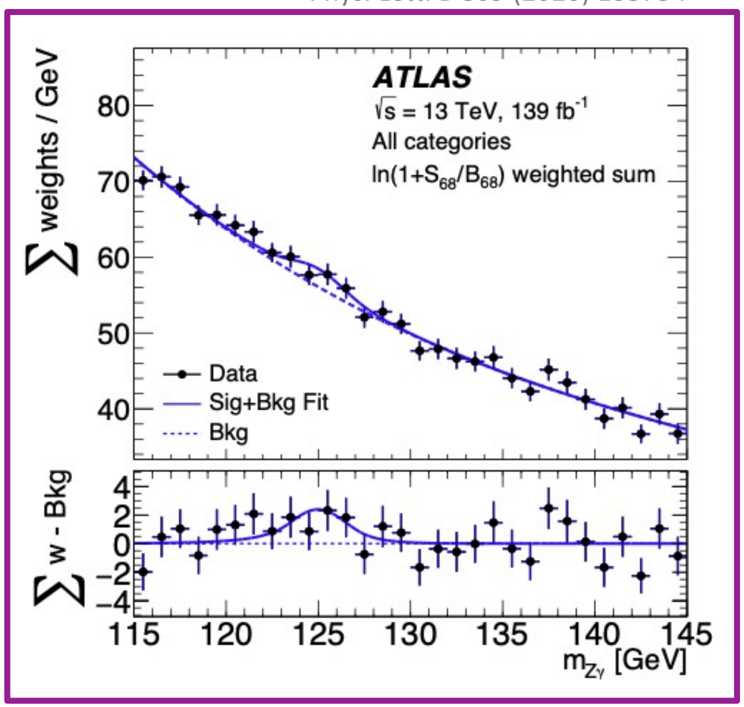
-> 6 categories (1 VBF and 5 lepton flavour and Zγ kinematics)

Not observed yet, but…using full Run2 data both experiments observed an **excess**

ATLAS: $\mu_{sig} = 2.0{+}1.0$, local significance 2.2(1.2) σ



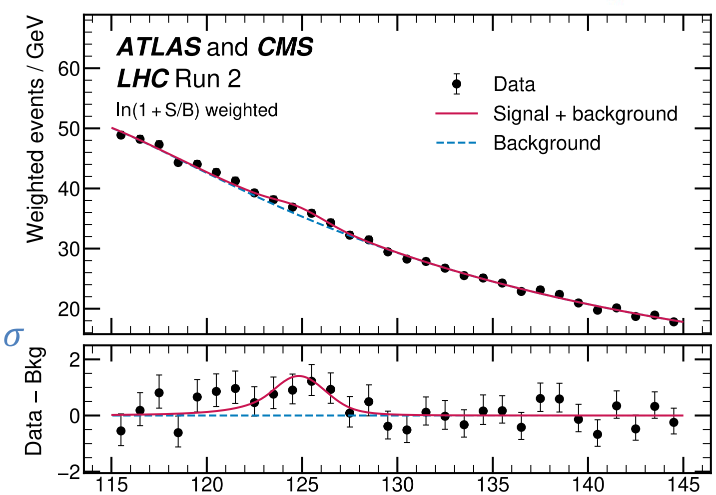
Phys. Lett. B 809 (2020) 135754



Combination with CMS brings to the evidence of **3.4σ**!

$\mu_{sig} = 2.2 \pm 0.7$

SM compatibility: 1.9 σ



arXiv:2309.03501

Probe possible Higgs decay in WIMPs (Dark Matter candidates):

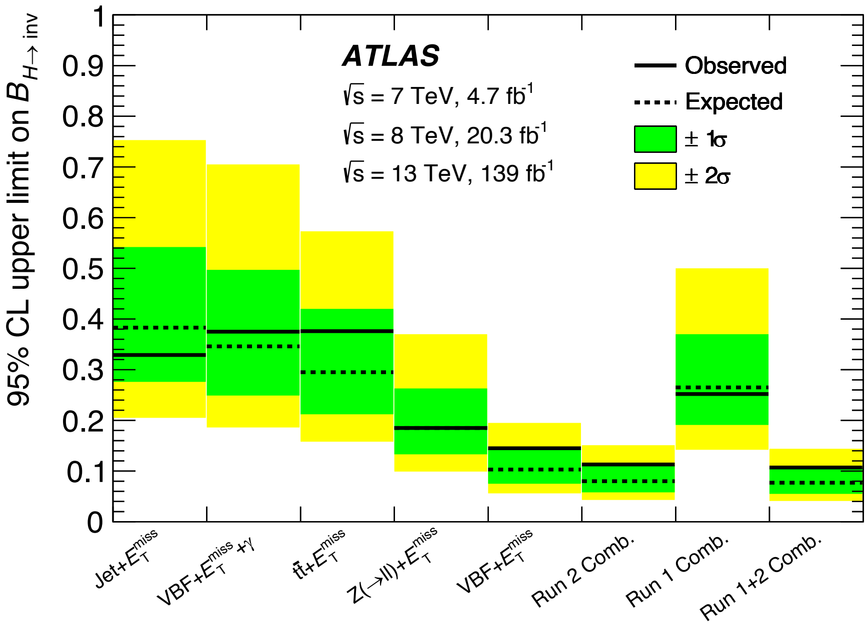
- Presence of missing transverse momentum (E_T^{miss}) in the interaction

SM expectation BR(H→inv) = 0.1% (given by ZZ*→4ν)

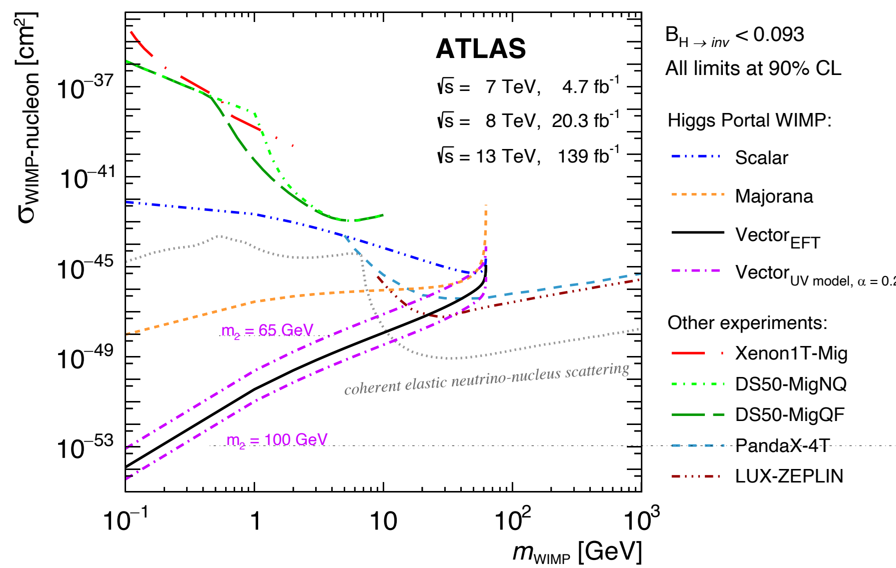
-> Combination between all the signature investigated in Run 2 (+Run 1)

Assuming that all extra contribution to the Higgs width comes from invisible decays:
ATLAS: BR(H→inv)< 0.107 at 95% CL (0.077 expected)

arXiv:2301.10731



arXiv:2301.10731



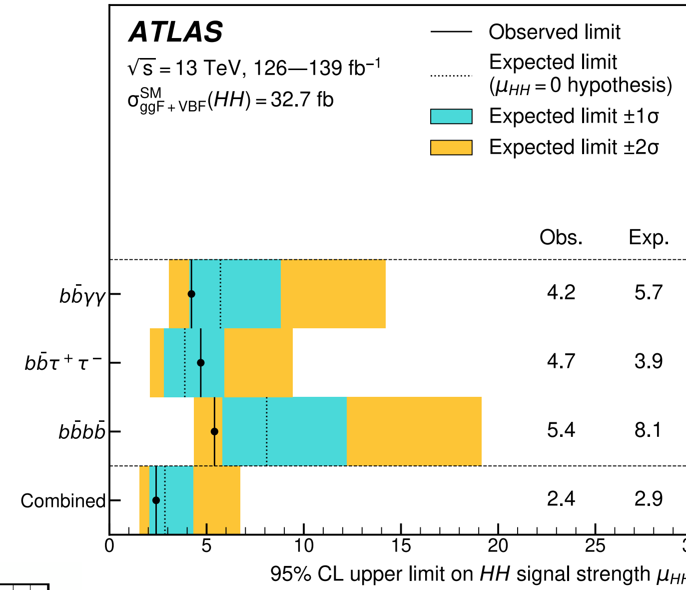
- using a specific model is possible to translate the upper limit on the BRs to a DM-nucleon XS
- results are competitive with direct searches

Higgs boson self coupling

arXiv:2211.01216

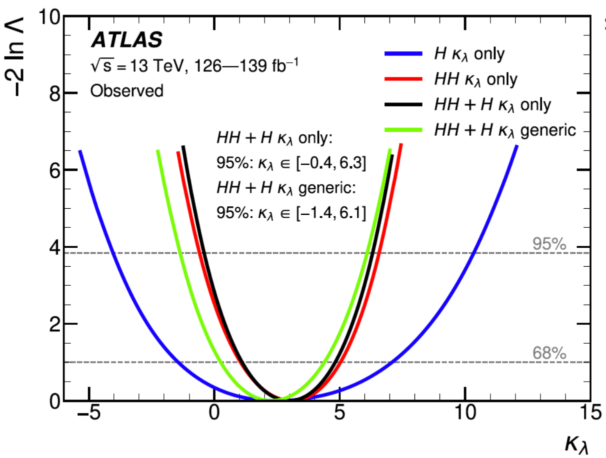
Higgs boson self-coupling λ is a fundamental parameter of the SM;

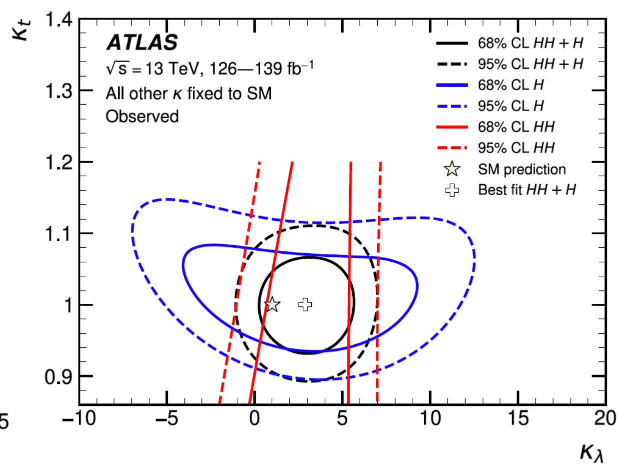
it affects the HH production at leading order and the single Higgs boson production and decay at NLO.



Combined results from di-Higgs searches (bbbb, bb$\gamma\gamma$, bb$\tau\tau$,bbZZ)

Constraint on σ_{HH} and κ_λ





HH+H combination	$-0.4 < \kappa_\lambda < 6.3$
HH+H combination, κ_t floating	$-0.4 < \kappa_\lambda < 6.3$

@ 95% C.L.

ATLAS: combination HH+H
$-0.4 < \kappa_\lambda < 6.3$ @ 95 % C.L.

arXiv:2211.01216

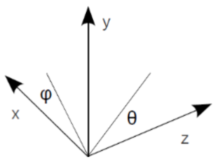
Conclusions

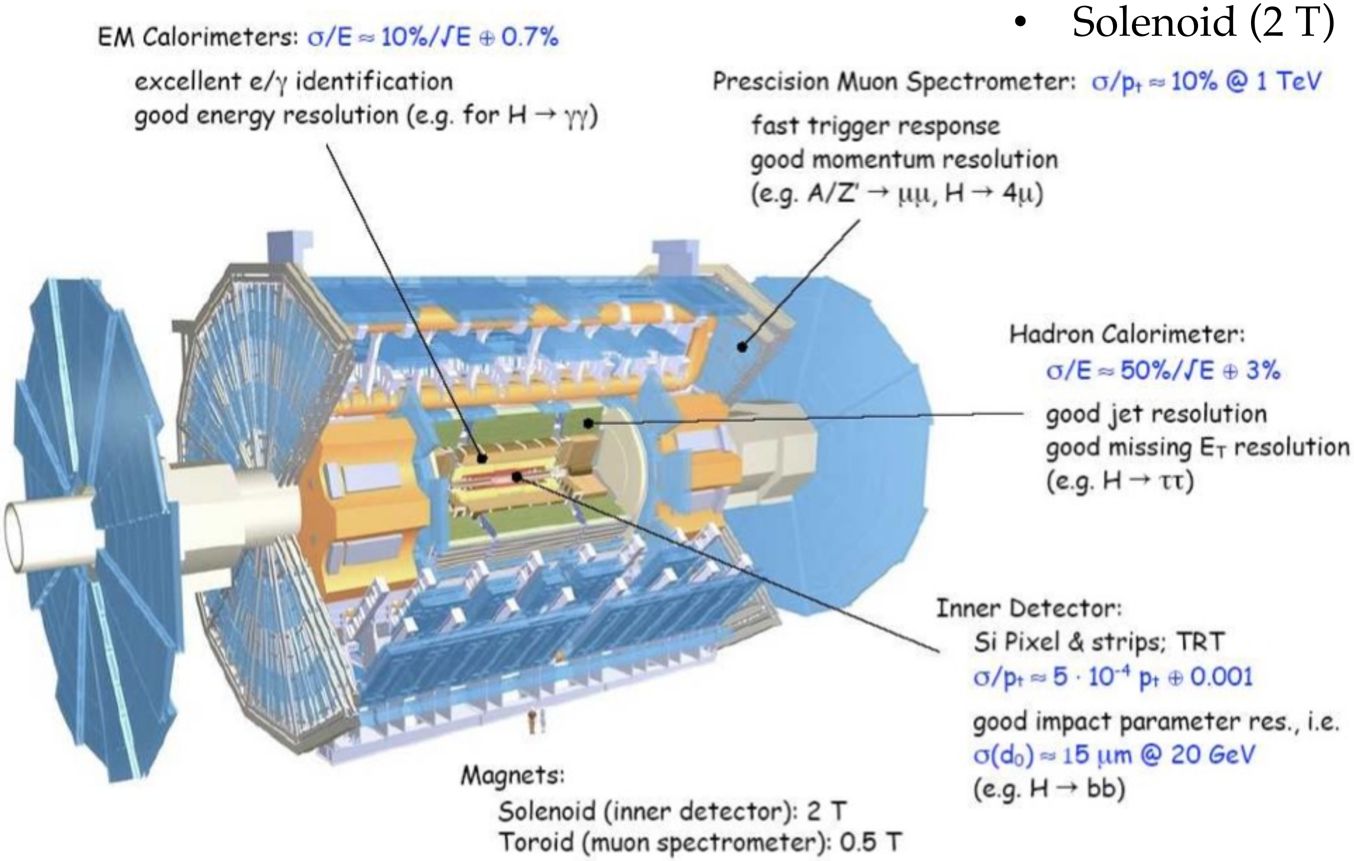
- In LHC Run2 the enhancement of statistics allow to investigate Higgs boson properties, performing precision measurements and probing its couplings with SM particles and possible BSM effects
- All the measurements are in good agreement with SM expectations
- Higgs boson couplings are measured with up to 5% level accuracy
- Higgs mass measured with a precision at sub-permill level (110 MeV)
- No hint of BSM effects or CP violation
- First evidence of off-shell Higgs boson production
- First evidence of $H \rightarrow Z\gamma$ decay (Rare Higgs boson decays start to become accessible with the increasing of the collected data samples)
- First constraints on Higgs coupling with charm quark and on self-couplings
  - exclusion of null-self coupling could become accessible in the next few years
- …and first measurement @ 13.6 TeV!
- Looking forward for new updated results with full Run 2 dataset and new coming data at 13.6 TeV

Thanks for your attention!

Backup

A Thoroidal LHC ApparatuS





Inner Detector:

- Silicon trackers (pixel and microstrip)
- Gas trackers (with measurement of the transition radiation, TRT)
- Solenoid (2 T)

Electromagnetic Calorimeter:

- Sampling Pb+LAr

Hadronic Calorimeter:

- Fe+scintillator
- LAr technology

Muon System:

- Superconducting thoroids
- Precision tracking chambers
- Trigger chambers