Higgs boson: current status from the experiment side

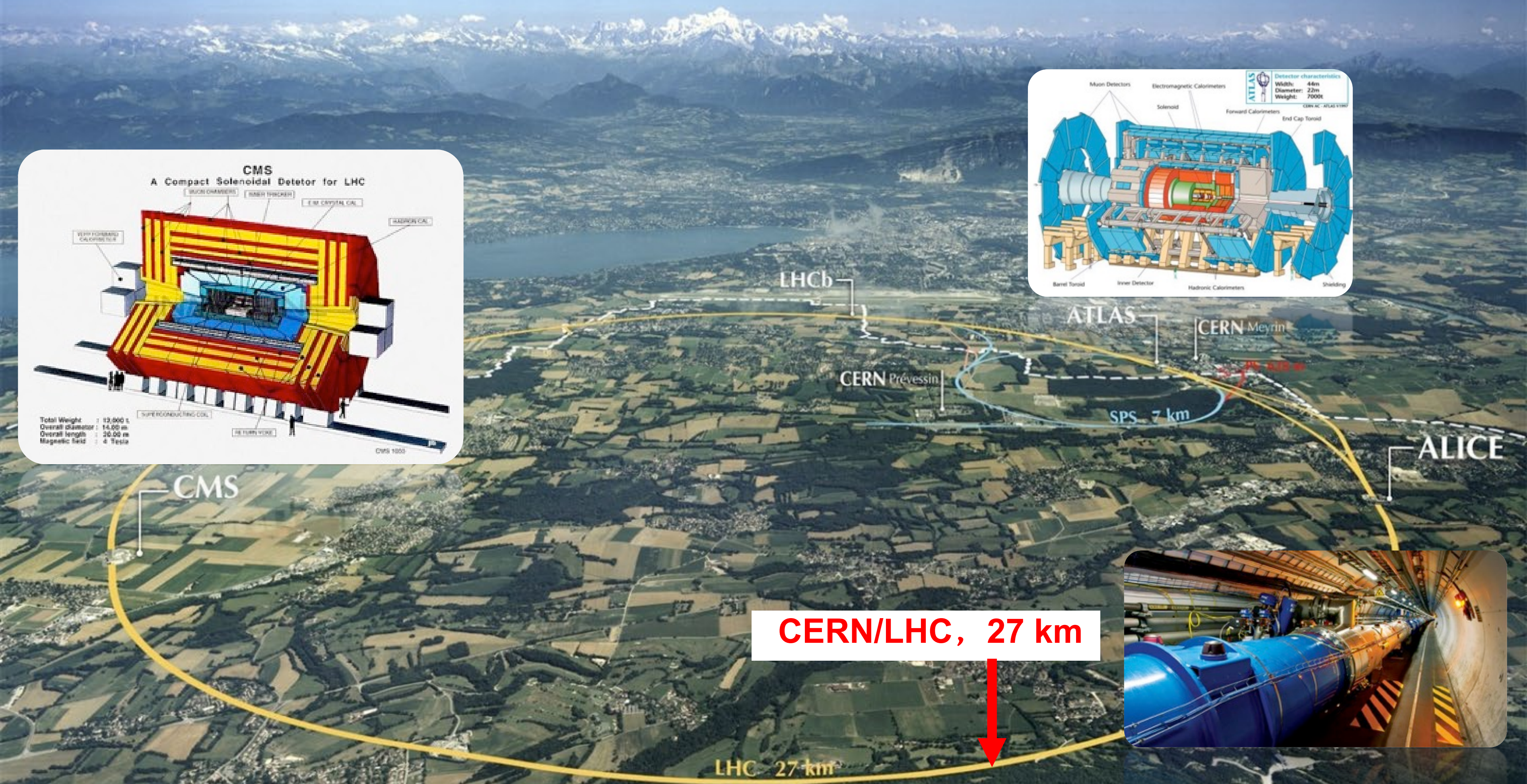
Jin Wang[1]
On behalf of the ATLAS and CMS Collaboration

1. Institute of High Energy Physics, CAS

25th April 2023

CorfuFA: Workshop on Future Accelerators

ATLAS and CMS in LHC

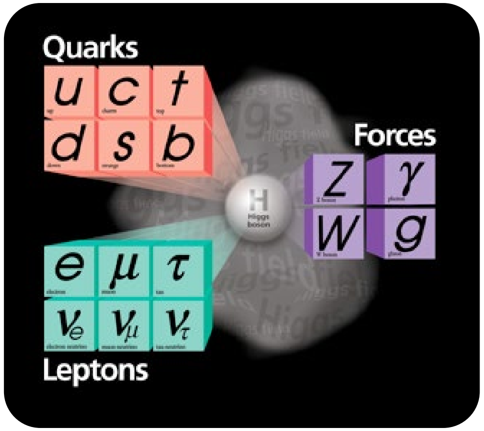


Large Hadron Collider (LHC) : Largest accelerator and currently the only place to study the Higgs boson

ATLAS and CMS: General purpose detectors in LHC with Higgs physics as one of the main goals

Higgs physics

- The discovery of Higgs boson in 2012 by ATLAS and CMS experiments in LHC
  - A great success of the Standard Model (SM)
  - Opens a new era of particle physics
    - Opportunities to better understanding of electroweak symmetry breaking and test of Standard Model precision
    - Windows for new physics searches



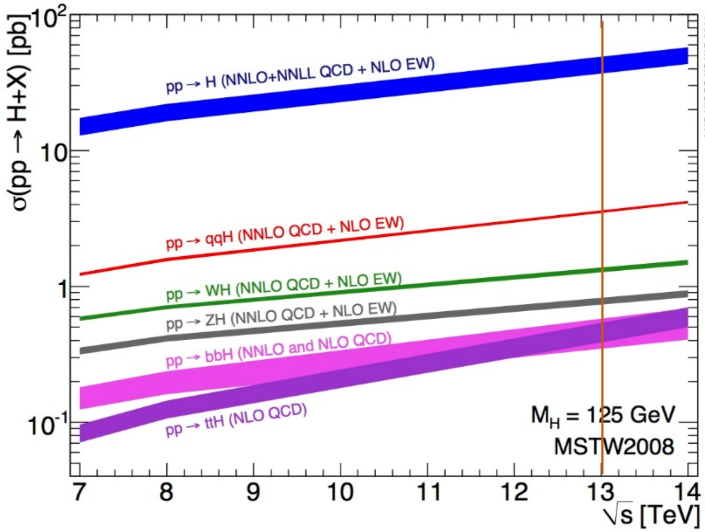
- Many important questions remain unanswered in SM:
  - neutrino mass, hierarchy problem, matter – antimatter asymmetry, the nature of dark matter and dark energy etc.
- Higgs physics could be the key to answer these questions

- LHC Run 2 provided more statistics allowing for more precise measurements of Higgs properties including
  - Higgs production cross-sections, couplings, mass, width, CP, Higgs self-coupling

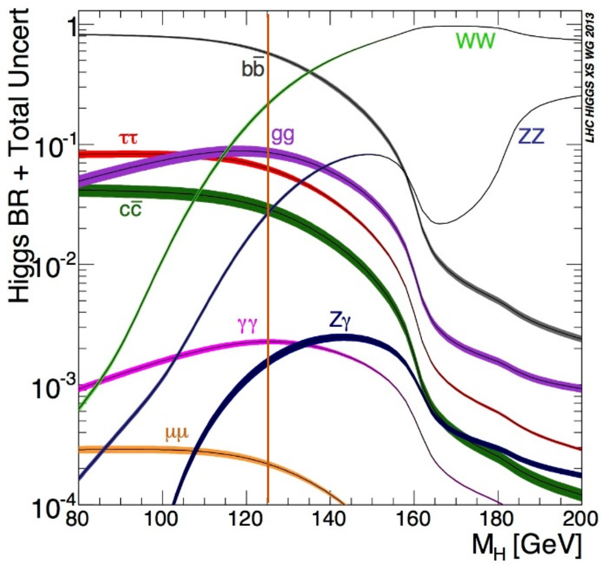
Higgs production cross section and couplings

Higgs production cross section and coupling measurements

Higgs production



Higgs decay

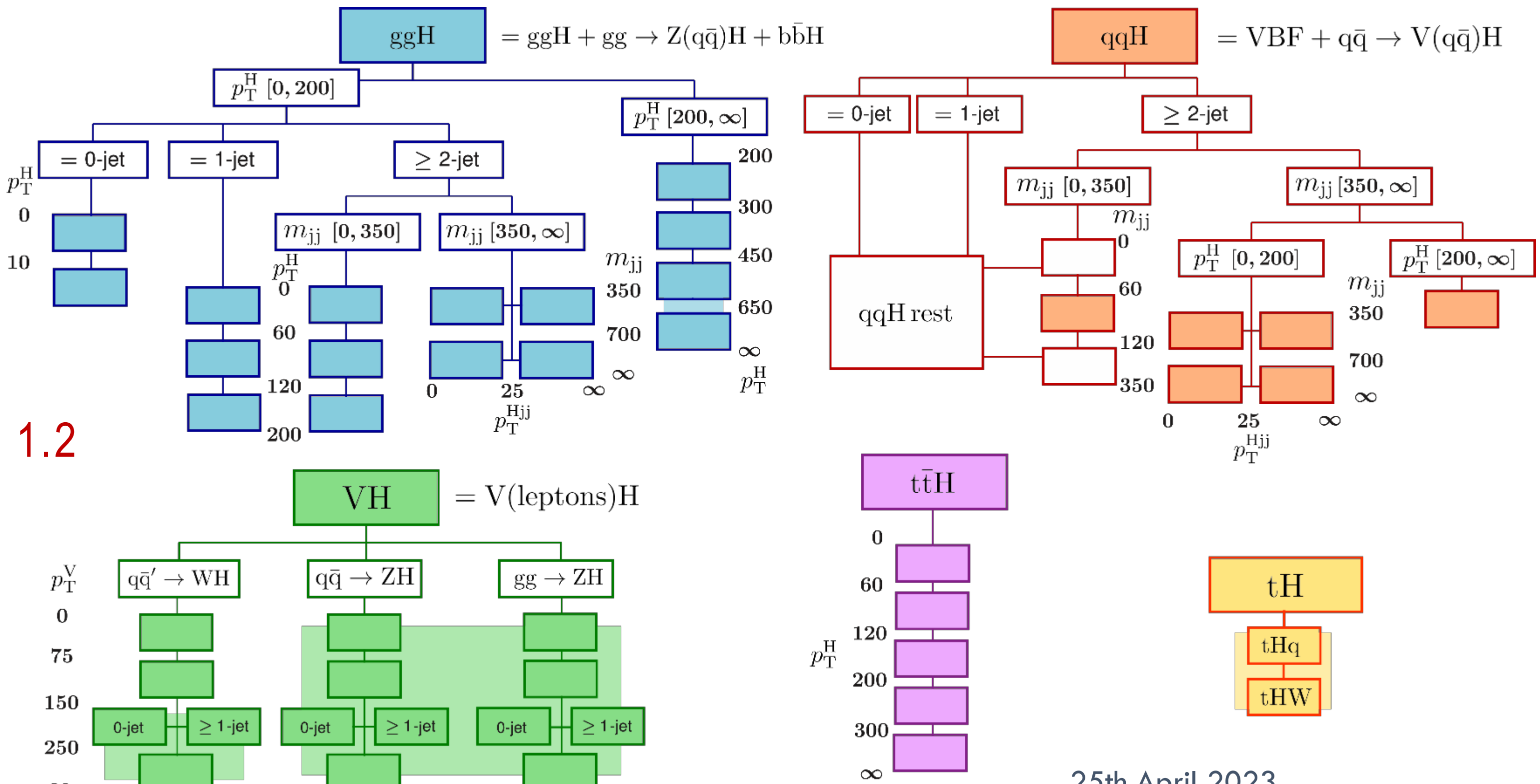


- Measurements of the Higgs production cross sections and couplings
  - Excellent tests of SM
  - Probe anomalies from BSM contributions
- All main production processes and decay channels established
- Now studying Higgs with more precise measurements and looking for rare corners
  - Finer phase-space regions, more differential, exploring extreme kinematics
  - Couplings to second generation fermions, rare decay channels

Simplified template cross section in Run2

- Simplified template cross section (STXS) framework further splits production mode cross-sections into various phase-space regions (bins)
  - Look into more details of the SM prediction
  - Isolate regions sensitive to Beyond Standard Model (BSM) effects
  - Increase the bin granularity with more data, defined as different stages
    - Refined STXS bins with stage 1.2 for recent Higgs measurements

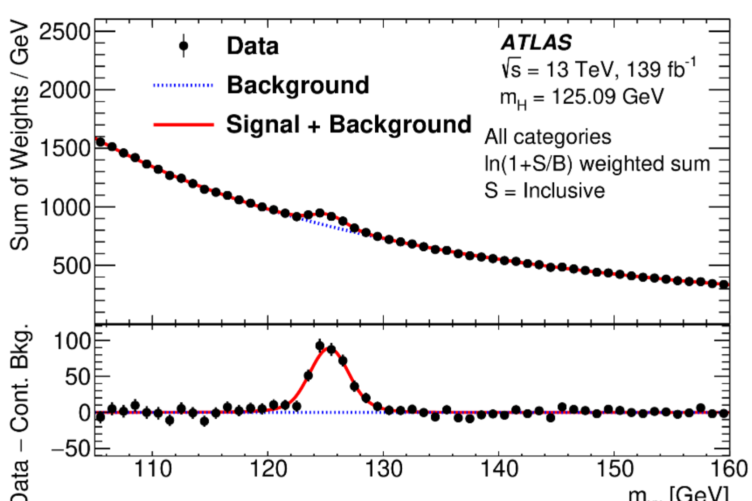
Stage 1.2



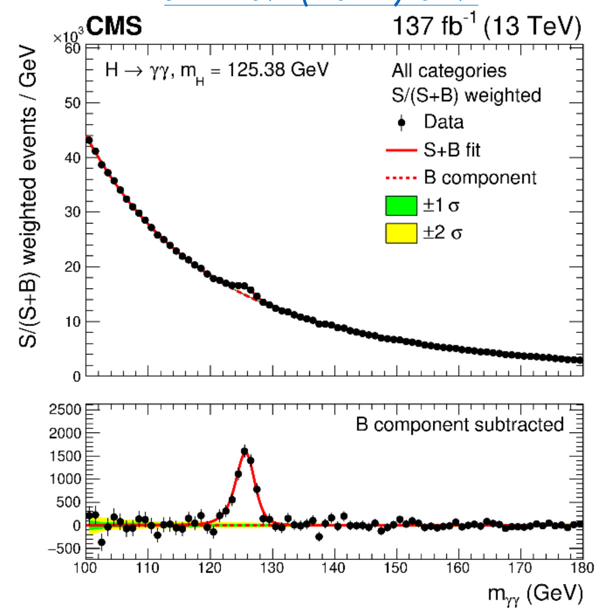
$Higgs \to \gamma\gamma$ analysis

- $Higgs \to \gamma\gamma$ channel with small branching ratio (BR) but very clean signature
  - Benefit from the excellent photon resolution in ATLAS and CMS
  - Distinct narrow signal peak over continuous backgrounds
- Events selected to match STXS bins and categorized for sensitivity
  - Events classified using multi-class Booted Decision Trees (BDTs) methods or simple cuts to match STXS bins
  - Separate MVAs or categorization used to maximum signal significance in each event class
- Cross sections extracted by fitting signal and background models to mass spectrum of data

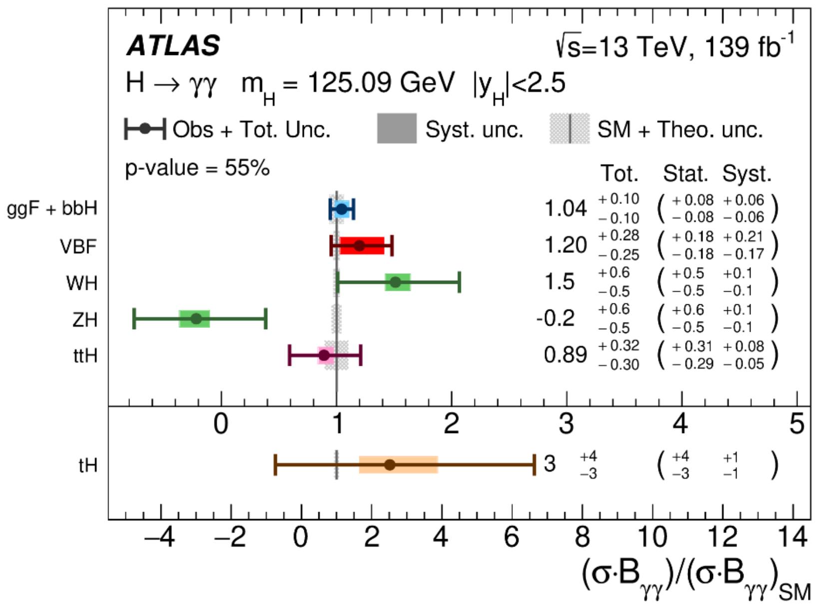
arXiv:2207.00348



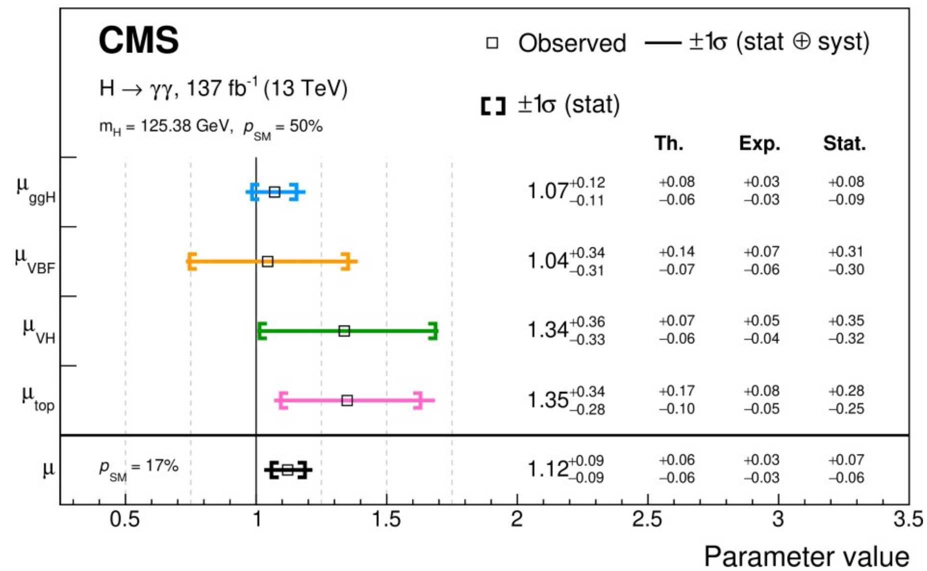
JHEP 07 (2021) 027



$Higgs \rightarrow \gamma\gamma$ results



arXiv:2207.00348



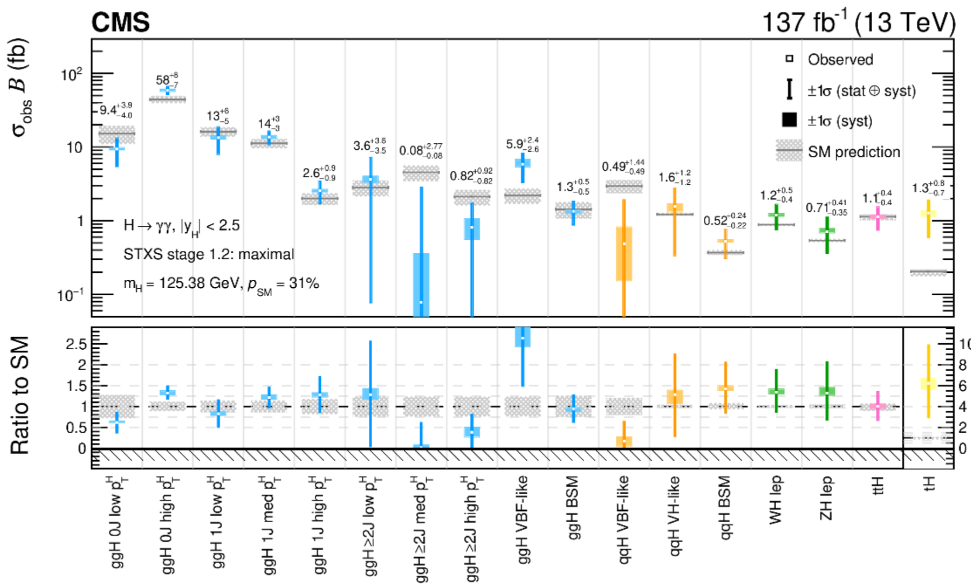
JHEP 07 (2021) 027

- Total cross sections measured are at 10% level from both ATLAS and CMS.
- Systematic uncertainties smaller or comparable to the statistical uncertainties

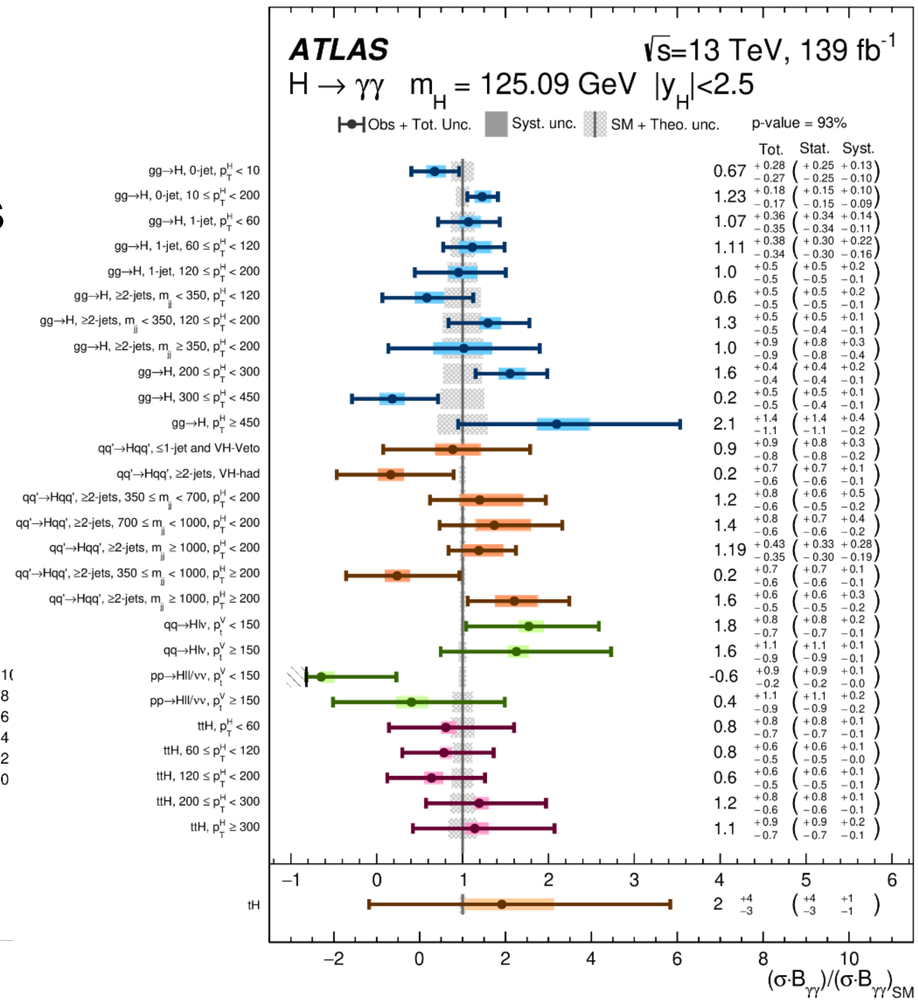
$Higgs \rightarrow \gamma\gamma$ results

- Good agreement between measured cross sections and SM predictions
- Reaching better sensitivity to more bins with full Run2 data
  - ttH is firstly measured in 5 p_T^H bins

arXiv:2207.00348

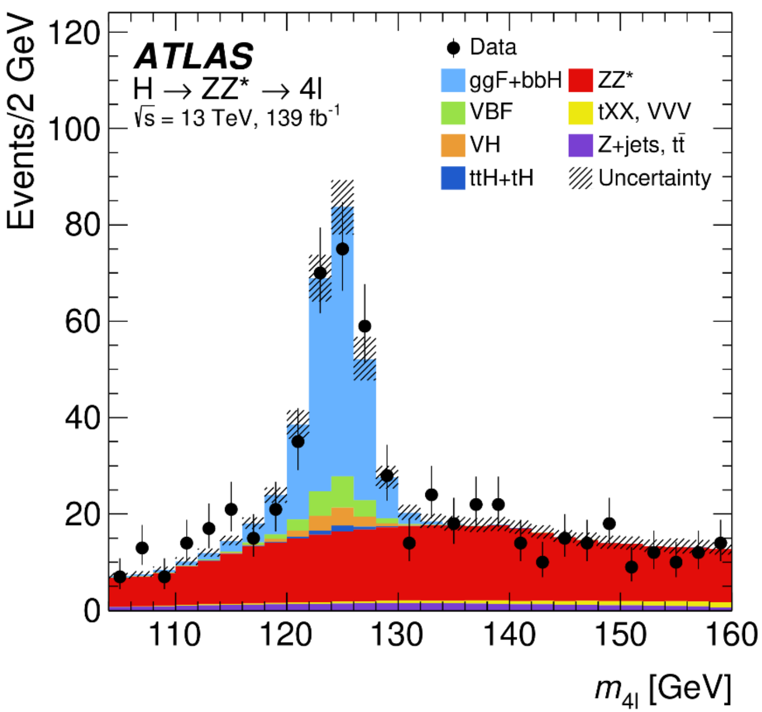


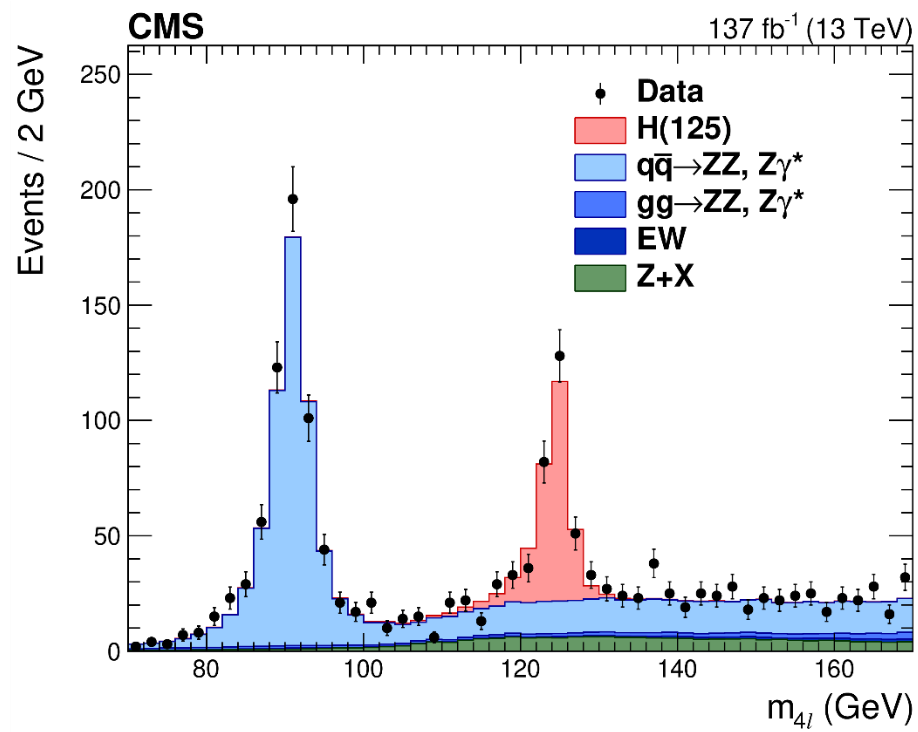
JHEP 07 (2021) 027



$Higgs \rightarrow ZZ \rightarrow 4l$ analysis

- Final states features with 4 leptons from ZZ decay
  - large signal-to-background ratio with low background rate
  - complete reconstruction of the final state products with good lepton resolution
- Main background from non-resonant ZZ production

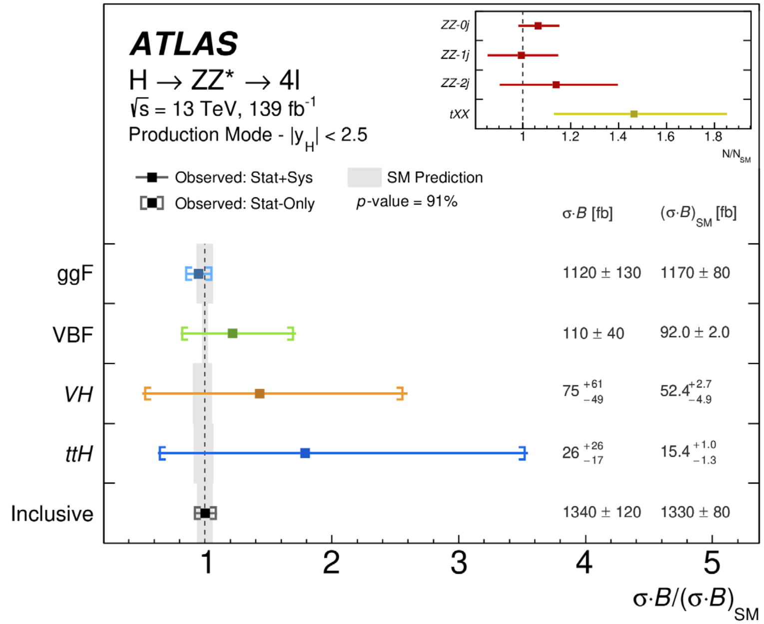




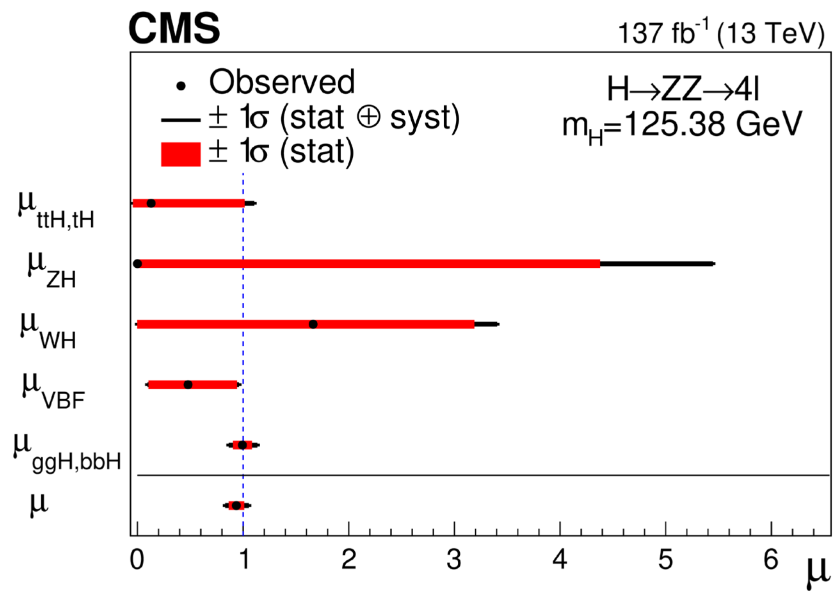
Eur. Phys. J. C 80 (2020) 957

Eur. Phys. J. C 81 (2021) 488

$Higgs \rightarrow ZZ \rightarrow 4l$ results



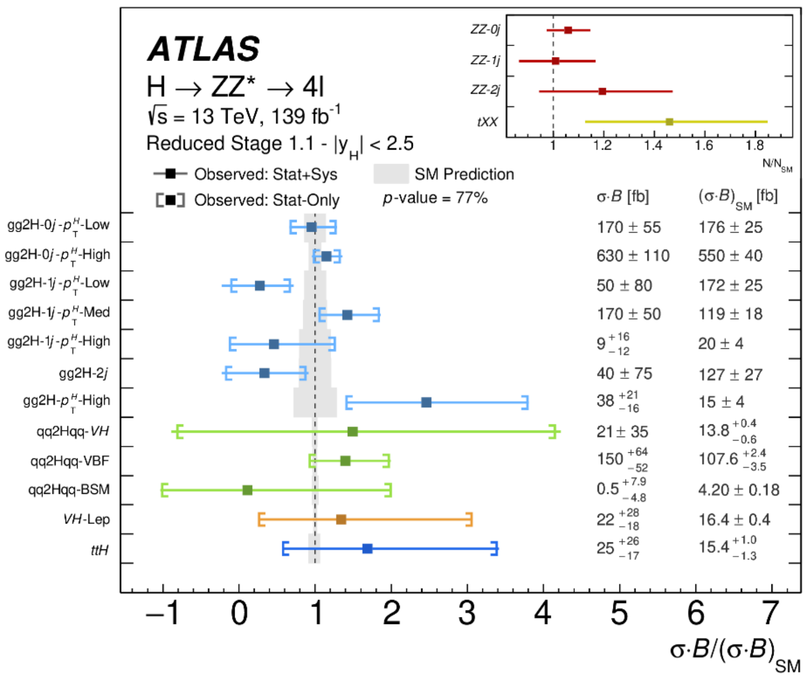
[Eur. Phys. J. C 80 (2020) 957]

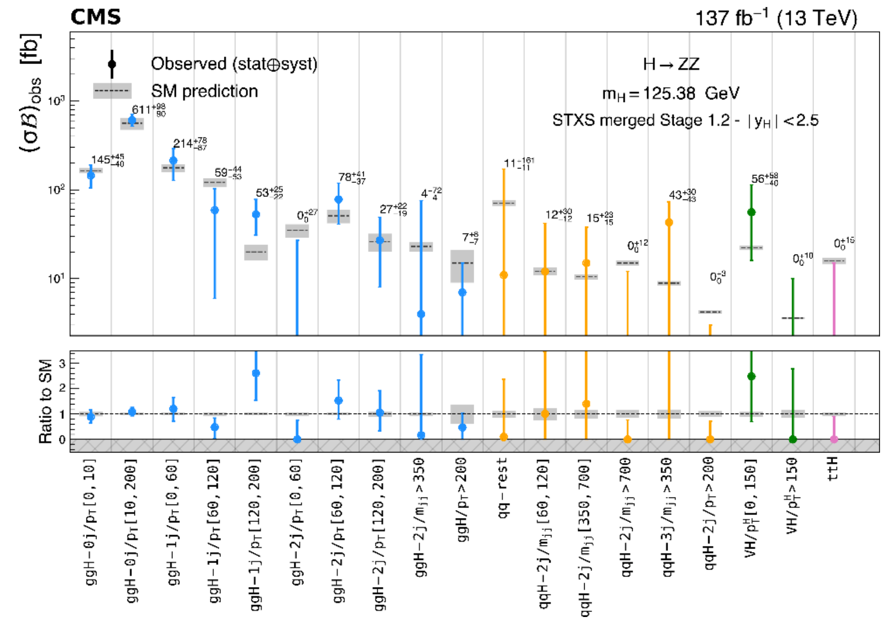


[Eur. Phys. J. C 81 (2021) 488]

- Inclusive measurements with ~10% uncertainties
- Results agree well with SM predictions

$Higgs \rightarrow ZZ \rightarrow 4l$ results





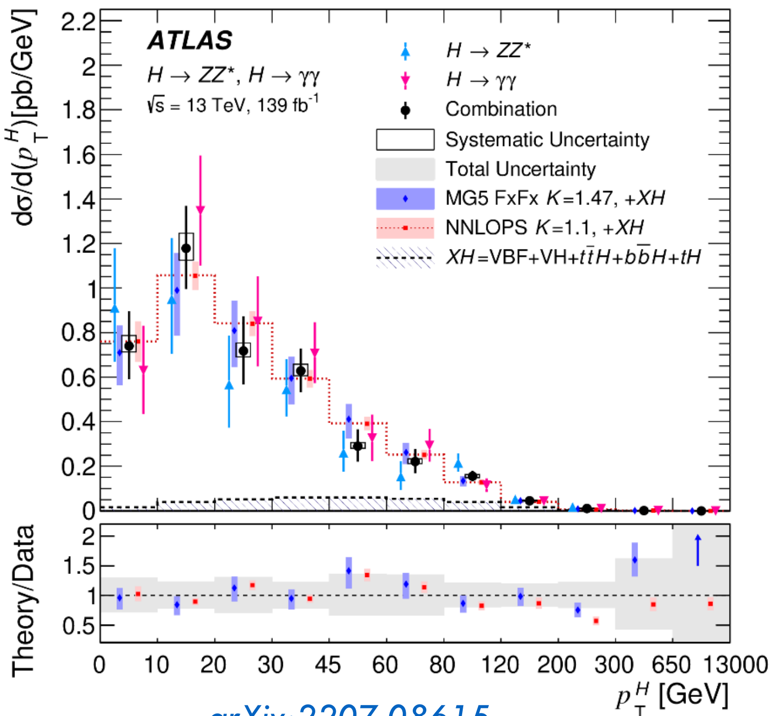
[Eur. Phys. J. C 80 (2020) 957]

[Eur. Phys. J. C 81 (2021) 488]

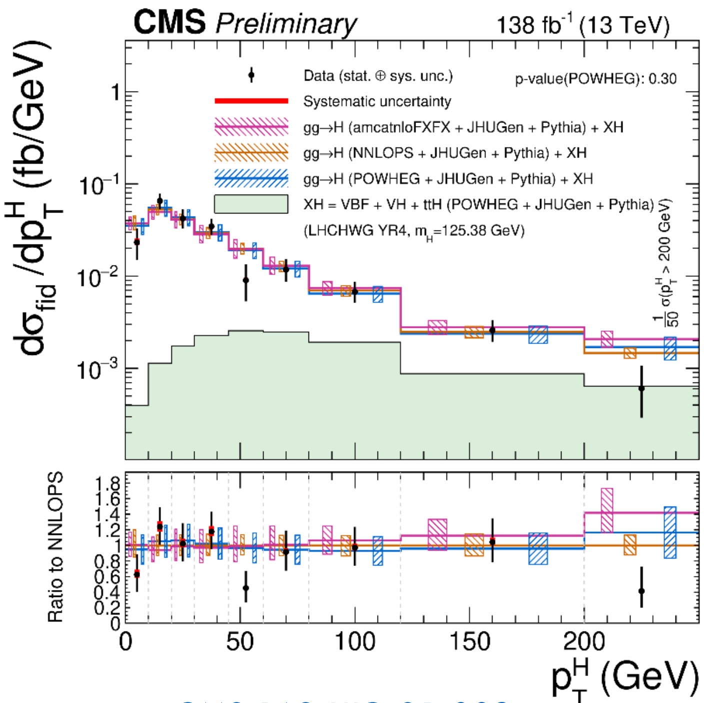
- STXS results also show good compatibility with SM
  - Precision limited by statistics

$Higgs \to ZZ$ differential cross sections

- Measured in fiducial volume defined to match experimental selections
  - Reduce detector effects, model independent
- Measurements of XS as function of several observables
  - Looking in to details of kinematics
  - Sensitive to BSM effects



arXiv:2207.08615

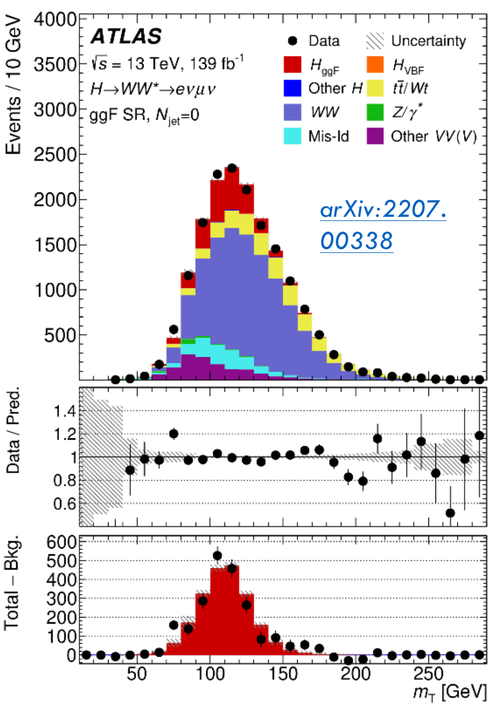


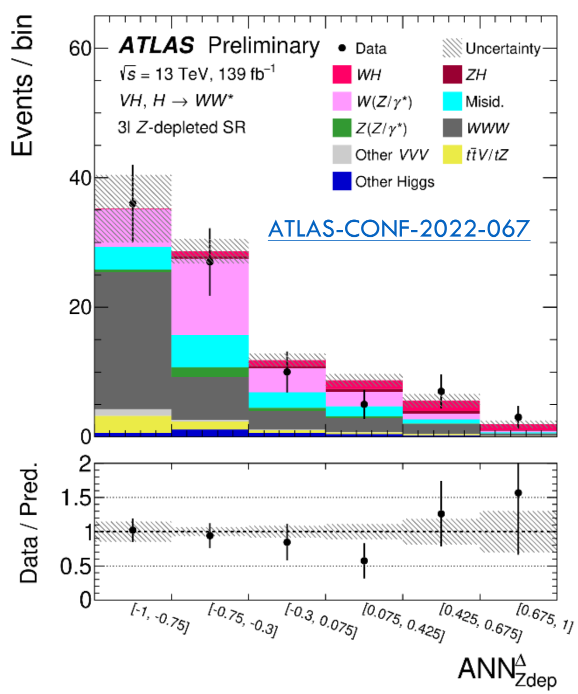
CMS-PAS-HIG-21-009

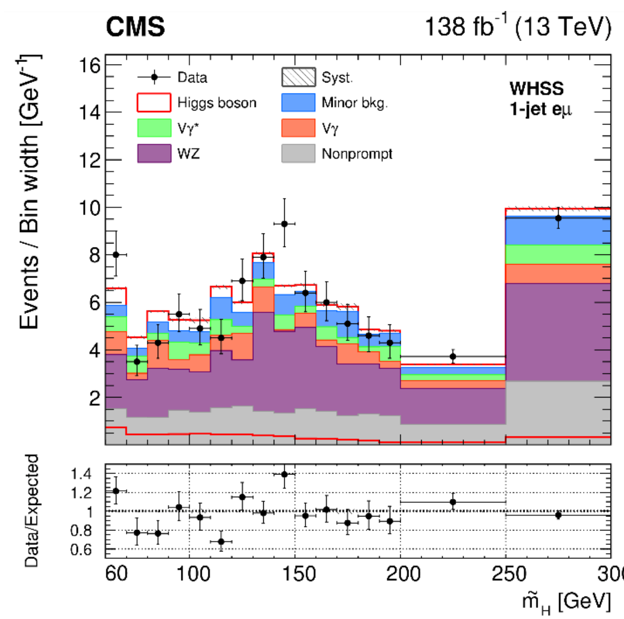
Results statistic limited, observation consistent with SM

$H \to WW^*$ results

- $H \to WW^*$ with higher branching ratios and complex background
  - Study gluon fusion, vector boson fusion, and associate production with a W or Z boson
  - Targeting events with at least one leptonically decaying W boson
- Exploring various MVA approaches and kinematic fitting to reject backgrounds and extract signals
  - ATLAS: m_T in ggH, NN in qqH, ANN, RNN and BDT in VH
  - CMS: counting, m_{ll}, $\tilde{m}_H$, BDT, DNN





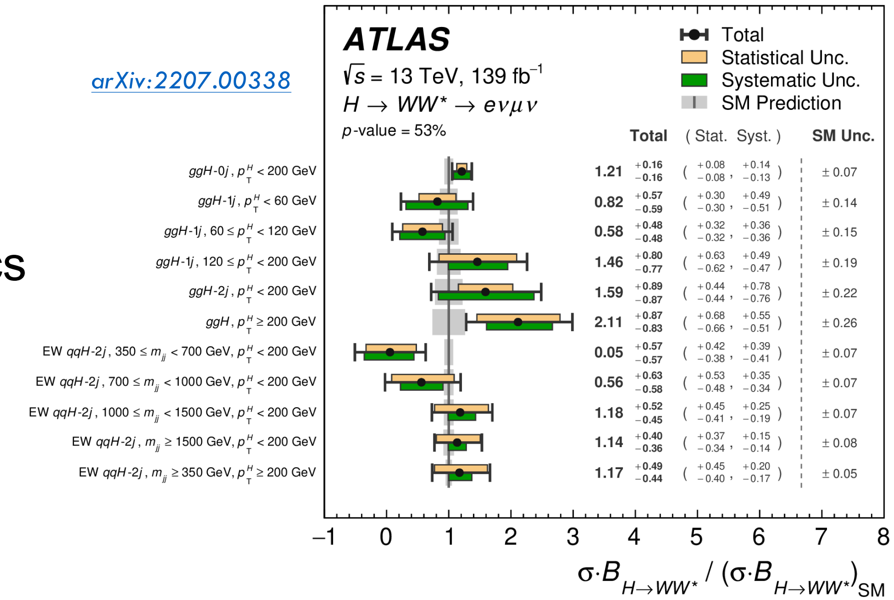


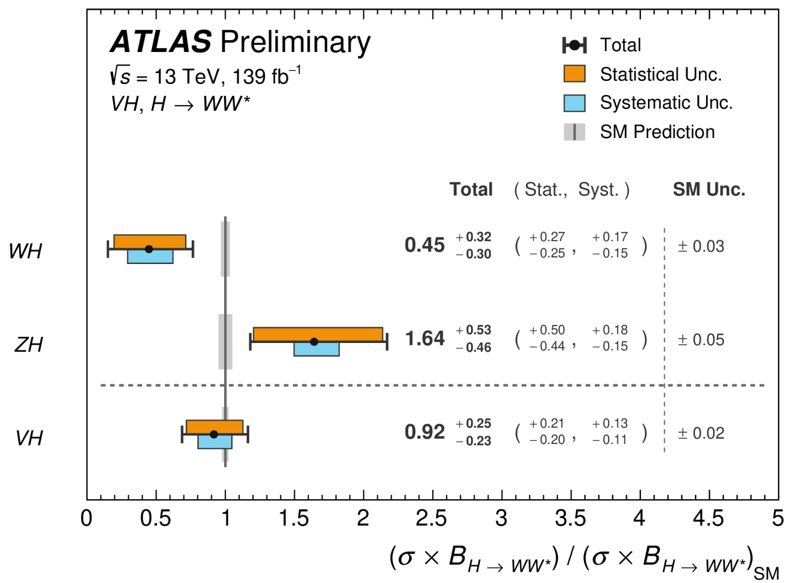
Accepted by Eur. Phys. J. C

$H \rightarrow WW^*$ results

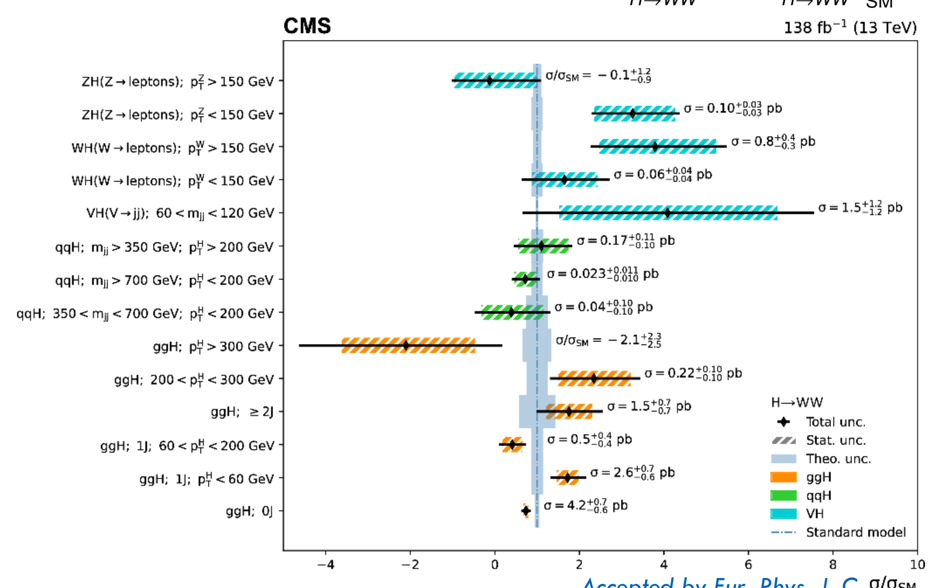
- Increased data statistics provide analysis sensitivity in ggF and VBF STXS bins
- Direct probe of HV coupling, kinematics sensitive to BSM effects

arXiv:2207.00338





ATLAS-CONF-2022-067

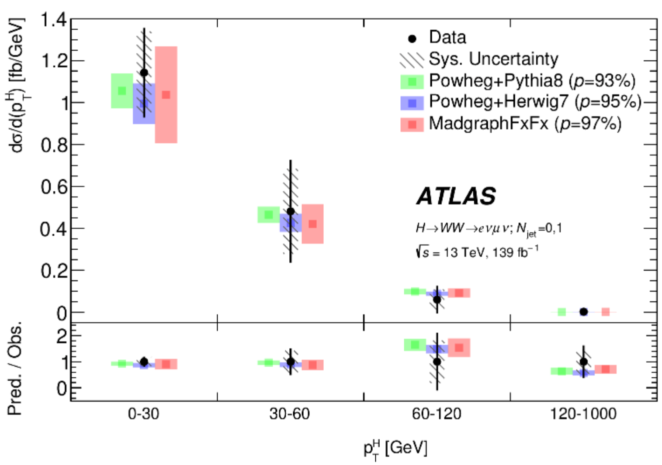


Accepted by Eur. Phys. J. C

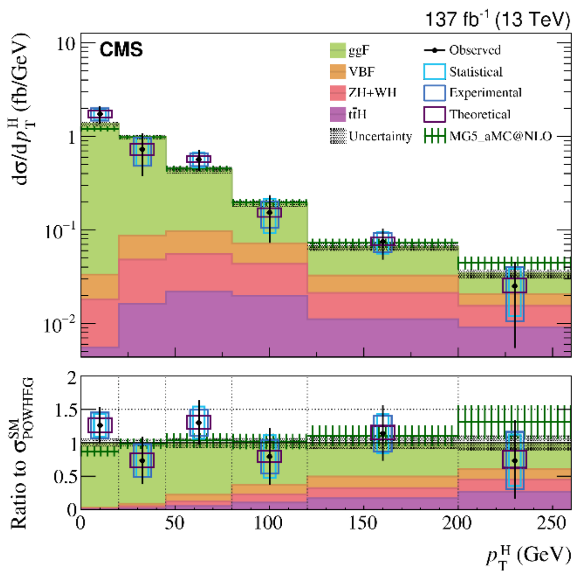
$H \to WW^*$ results

- Differential XS measured in ggF and VBF production modes
- Extended with EFT interpretations
  - SMEFT Wilson coefficients from CP-even and CP-odd operators obtained with only one Wilson coefficient left floating at a time

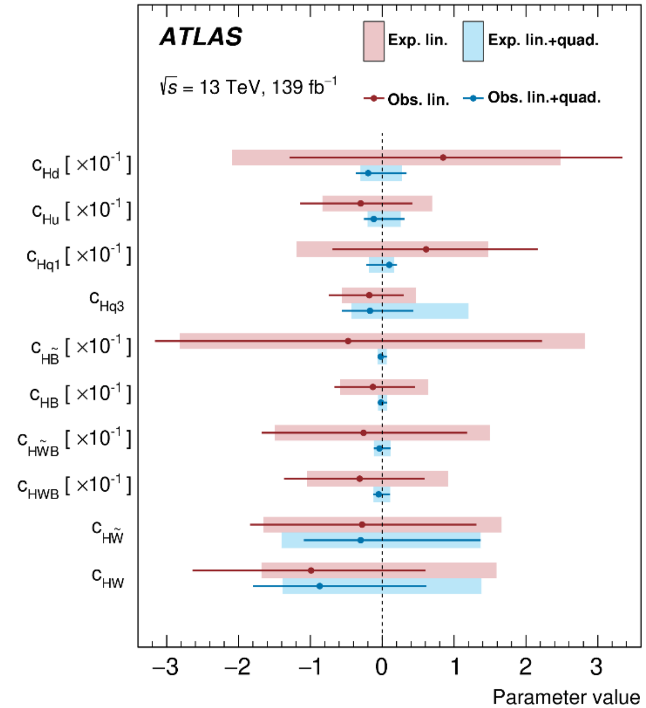
arXiv:2301.06822



JHEP 03 (2021) 003



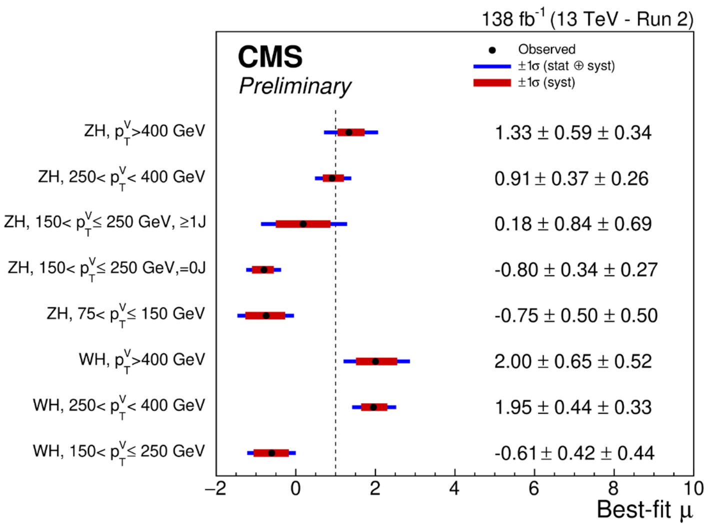
arXiv:2304.03053



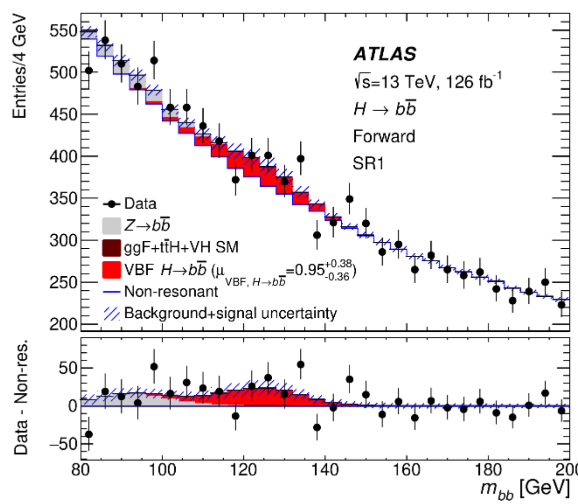
$H \rightarrow bb$ results

- $H \rightarrow bb$ with largest branching ratio and suffers from large multijet-QCD background
  - ATLAS/CMS VHbb: studied both resolved and boosted topologies
  - ATLAS/CMS VBFbb: multiple event categories based on the BDT response, targeting VBF, ggH and Z(bb) + jets processes

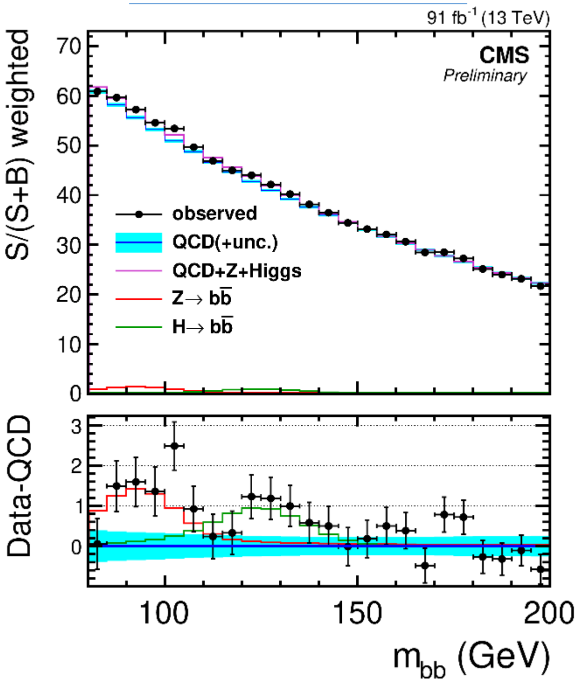
CMS-PAS-HIG-20-001



Eur. Phys. J. C. 81 (2021) 537

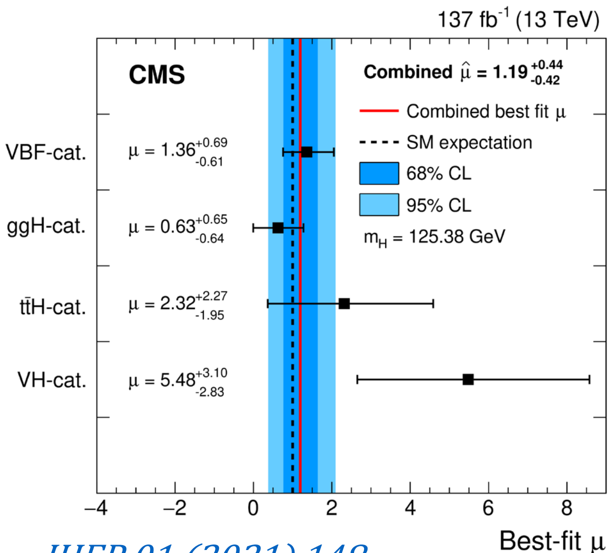


CMS-PAS-HIG-22-009



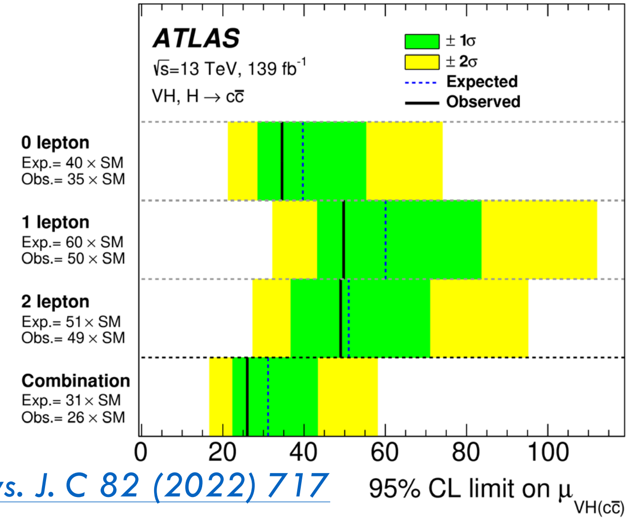
Coupling to second generation fermions

- $H \to \mu\mu$
  - Very small branching ratio (0.02%)
  - Very good resolution
- ATLAS: *Phys. Lett. B 812(2021) 135980*
  - $\mu = 1.2 \pm 0.6$
  - 2 σ significance
- CMS: *JHEP 01 (2021) 148*
  - $\mu = 1.19\,^{+0.40}_{-0.39}\,(stat.)\,^{+0.15}_{-0.14}\,(syst.)$
  - **3 σ significance !**



JHEP 01 (2021) 148

- $H \to cc$
  - small branching ratio (3%)
  - Large QCD backgrounds
- ATLAS: *Eur. Phys. J. C 82 (2022) 717*
  - Observed (expected) upper limit at 95% C.L
    - 26 (31) times the SM prediction
- CMS Resolved: *accepted by PRL*
  - Upper limits: 14 (7.6) times the SM prediction
- CMS Boosted: *accepted by PRL*
  - Upper limits: 47 (39) times the SM prediction



Eur. Phys. J. C 82 (2022) 717

Combined Higgs coupling measurements

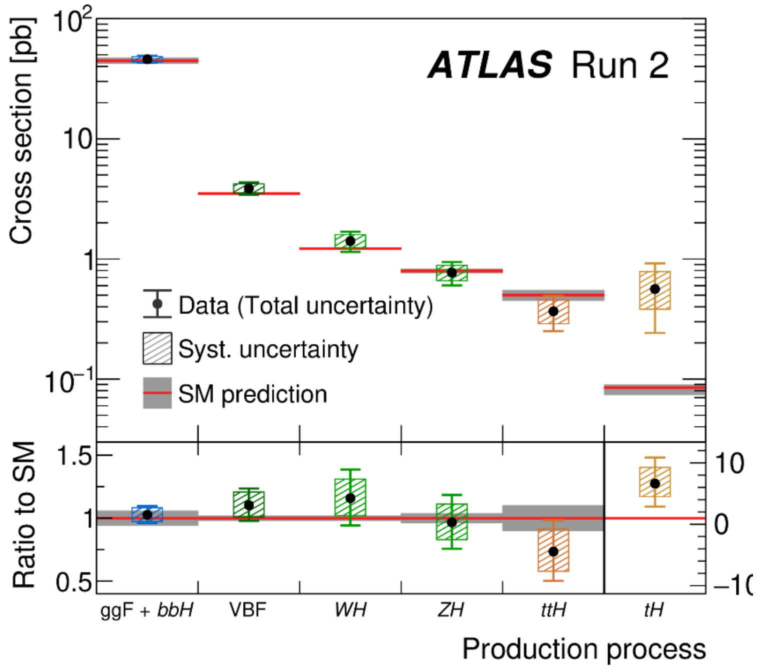
- Maximum Higgs production cross section and coupling analysis sensitivity with combination of different Higgs production and decays
- Recent results with full Run2 dataset produced by ATLAS and CMS for the 10 year anniversary of the Higgs boson discovery
  - All main Higgs production and decay channels covered with addition of rare channels

Analysis input (example from CMS)	**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	

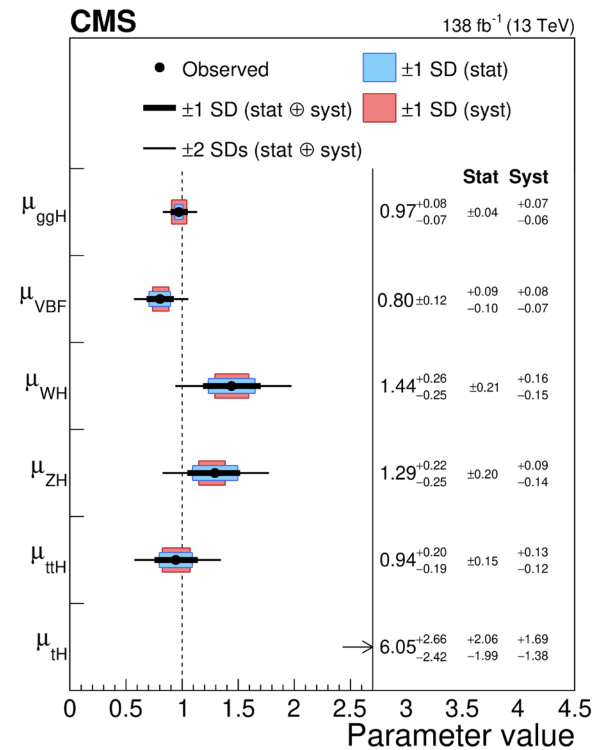
Higgs production signal strength

- Signal strength: ratio of the measured cross section and the SM expectation
- Global signal strength measured for all production and decays together
  - ATLAS: μ = 1.05 ± 0.03(stat.) ± 0.03(exp.) ± 0.04(sig . th.) ± 0.02(bkg . th.)
  - CMS: μ = 1.002 ± 0.029(stat.) ± 0.033(exp.) ± 0.036(theory)
- Signal strength per production mode

All good agreement with SM



Nature 607 (2022) 52-59

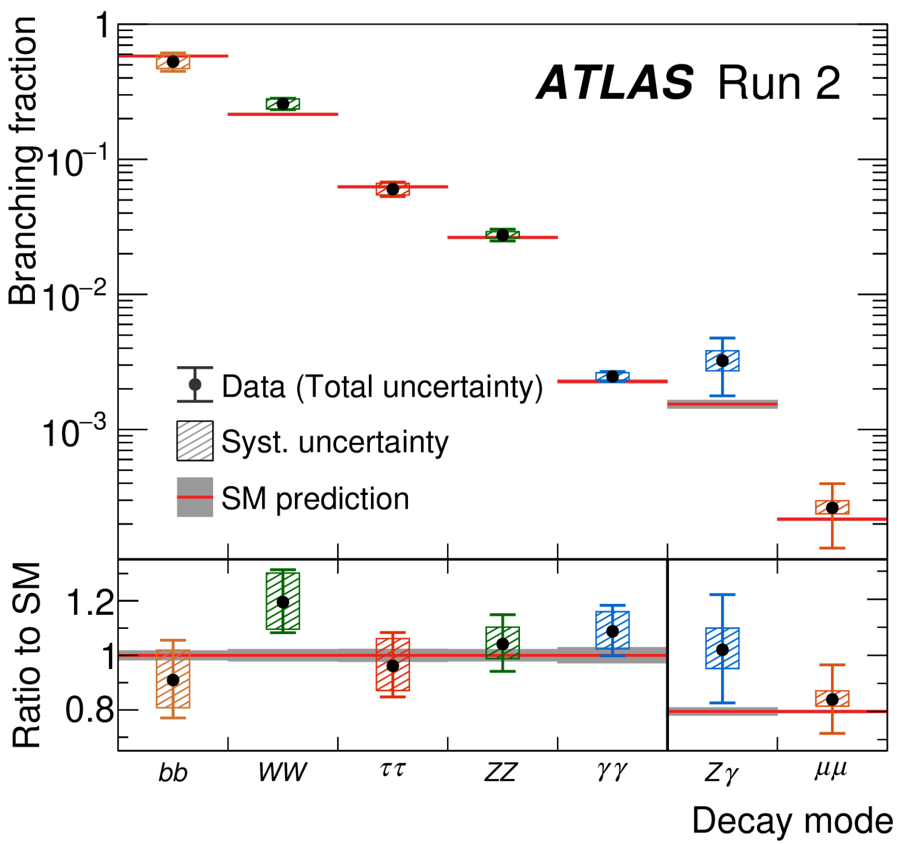


Nature 607 (2022) 60-68

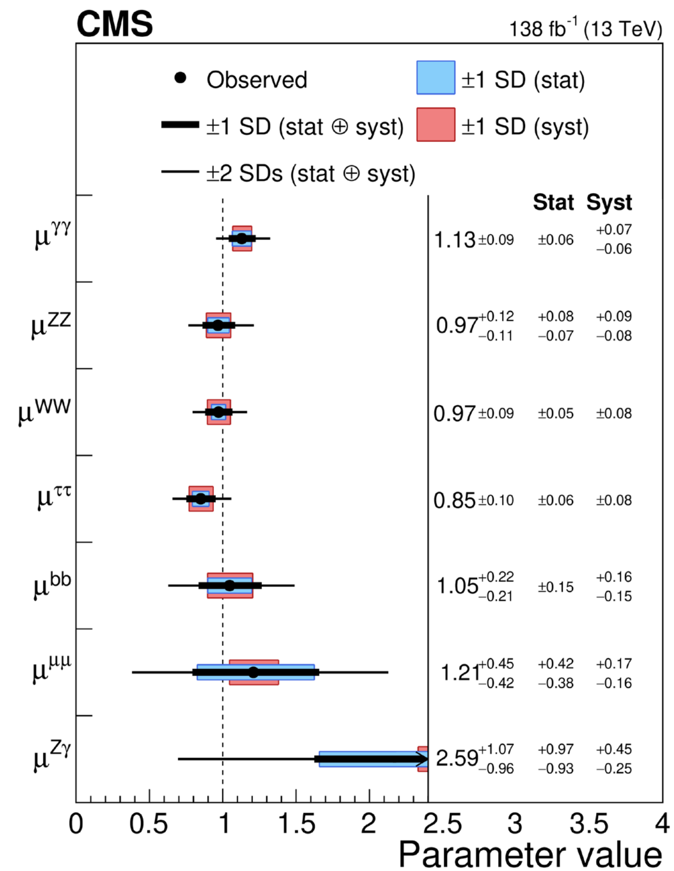
- Systematics uncertainties becomes comparable to statistic uncertainties

Higgs decay signal strength

- Signal strength per decay channel
- Leading 5 main decay modes observed with more than 5σ significance



Nature 607 (2022) 52-59

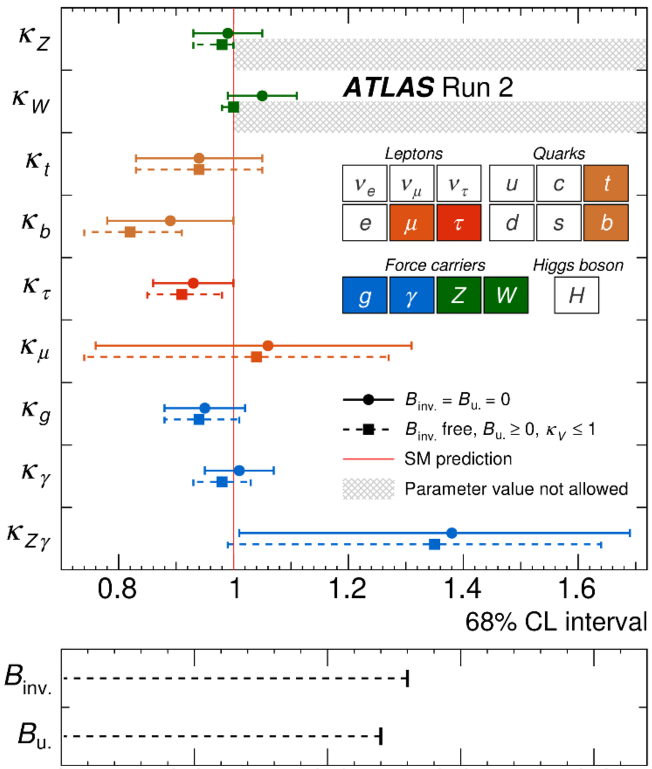


Nature 607 (2022) 60-68

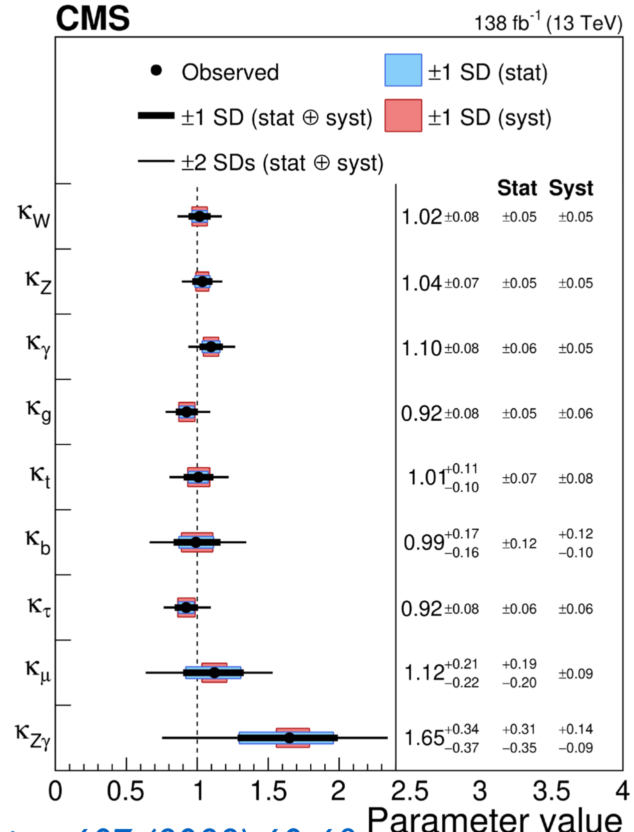
Observations agree well with SM prediction

κ framework

- Kappa framework: assign coupling modifier to each Higgs interaction vertex
  - Free floating in the combination of all production and decay modes
  - Flexible with assumptions that allows for the presence of non-SM particles in the loop induced processes



Nature 607 (2022) 52-59

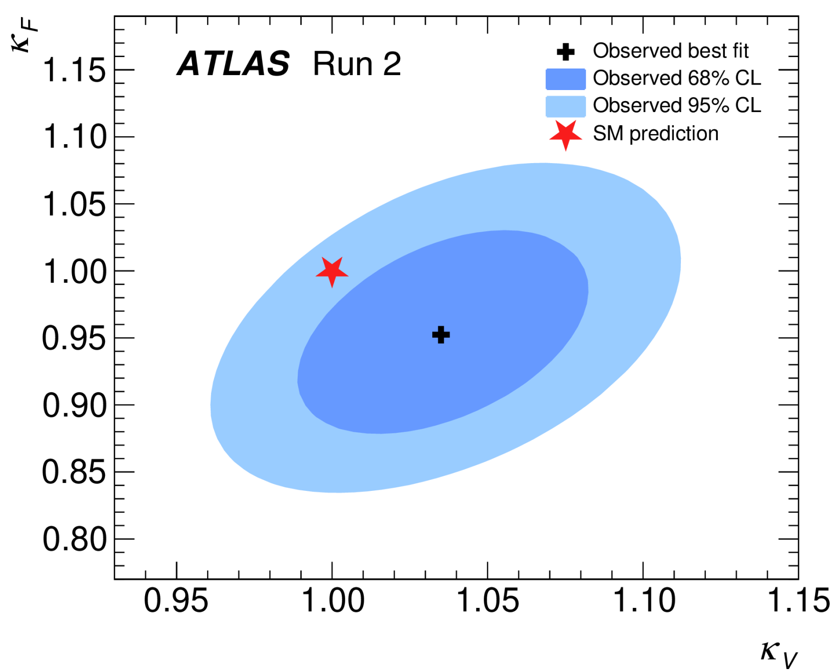


Nature 607 (2022) 60-68

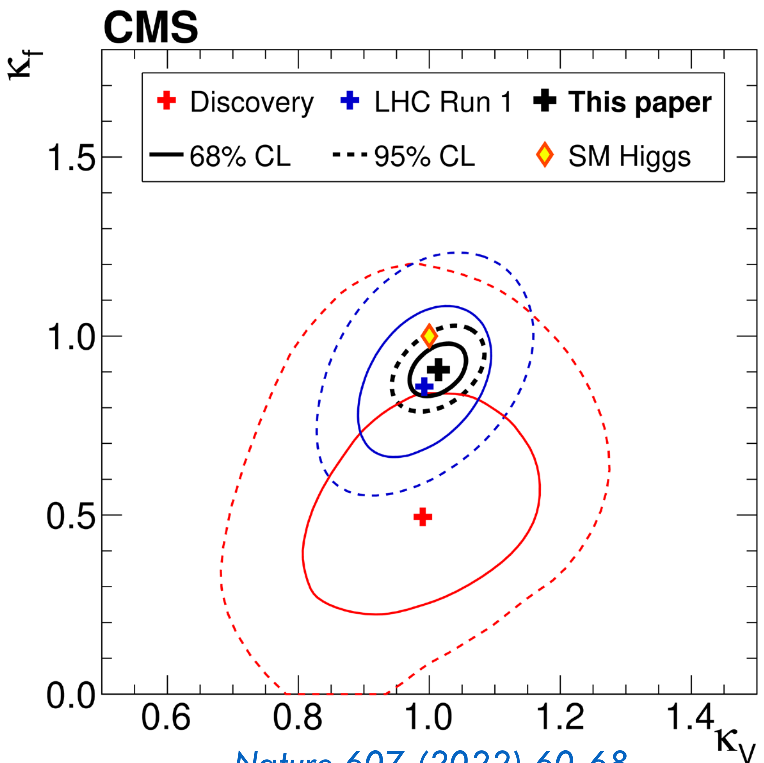
Results compatible with SM

κ framework

- Single modifier for vector bosons k_V and single modifier for fermion coupling k_f



Nature 607 (2022) 52-59

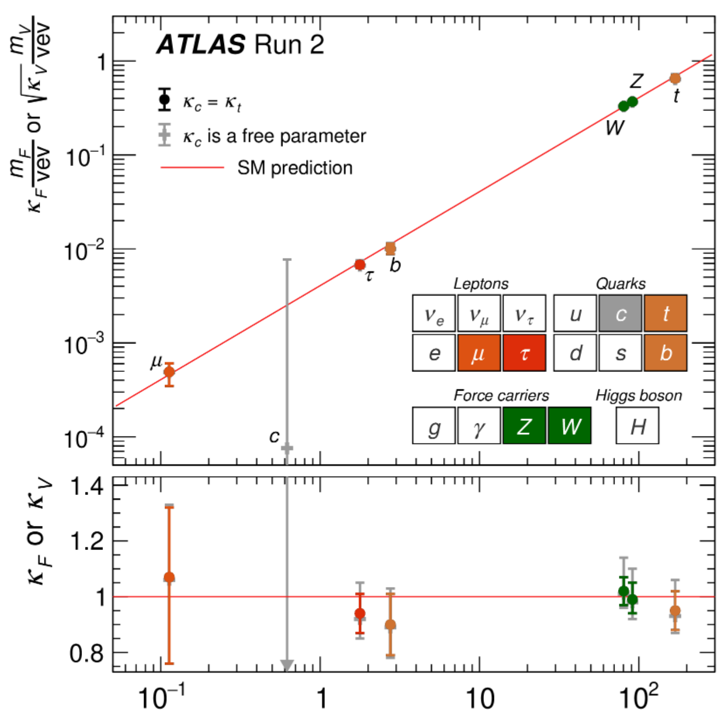


Nature 607 (2022) 60-68

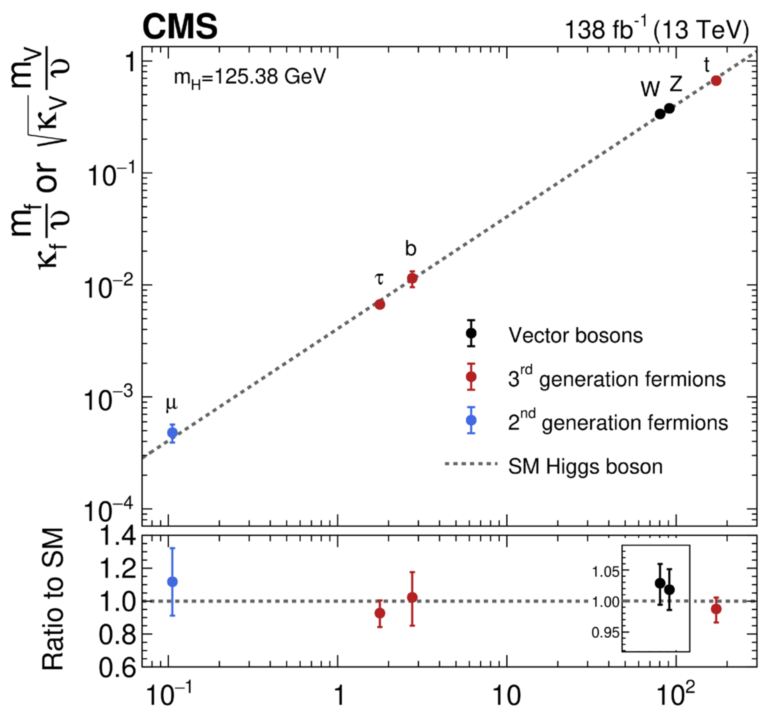
- Observed results compatible with SM prediction within 2 σ
- Significant improvement on sensitivity in Run2 comparing to discovery and Run 1

Coupling versus mass

- Higgs couplings to individual particles well align with particle masses
  - ATLAS plot with two fit scenarios
    - $k_c = k_t$ (coloured circle markers), or k_c left free-floating in the fit (grey cross markers)
  - Loop-induced processes are assumed to have the SM structure
  - Assume no non-SM Higgs decays



Nature 607 (2022) 52-59

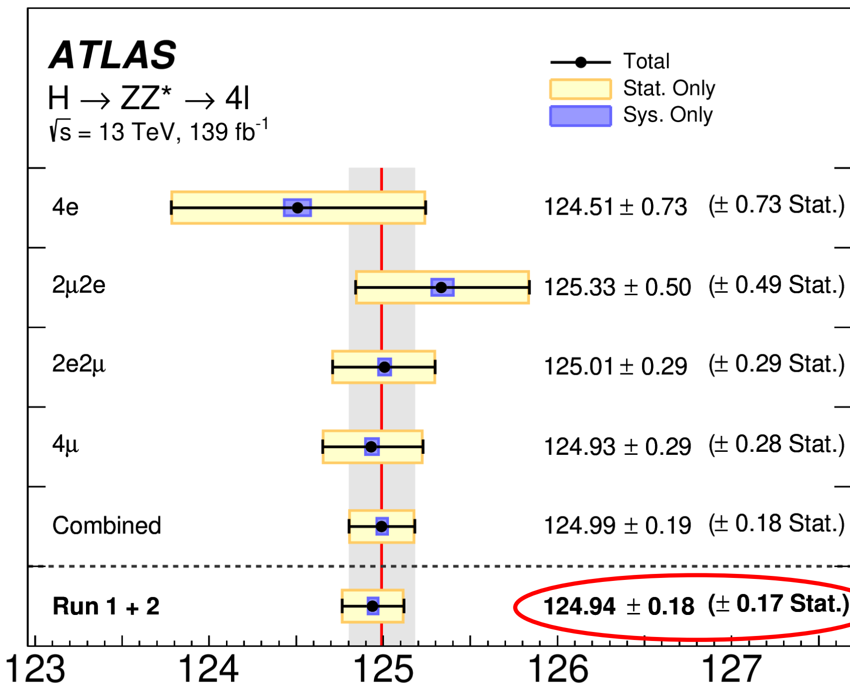


Nature 607 (2022) 60-68

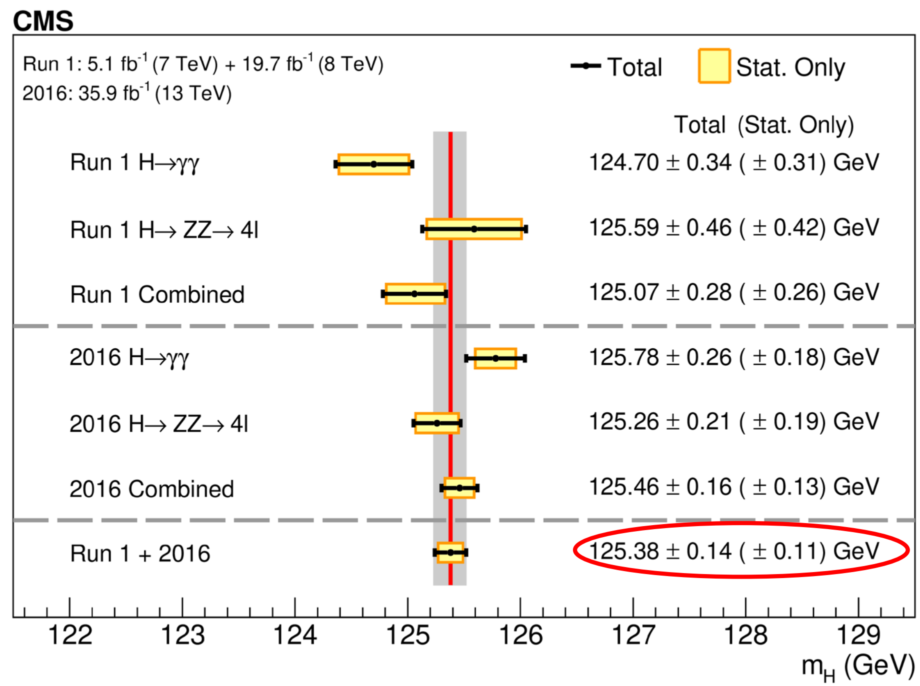
Higgs mass and width

Higgs mass measurements

- Higgs mass is the only free parameter in SM Higgs sector
  - Determines Higgs production and decay rates
  - Tells the stability of the universe and its fate
- Higgs mass measured with $H \to \gamma\gamma$ and $H \to ZZ$ channels in ATLAS and CMS
  - Best mass resolution and complete reconstruction of the final state



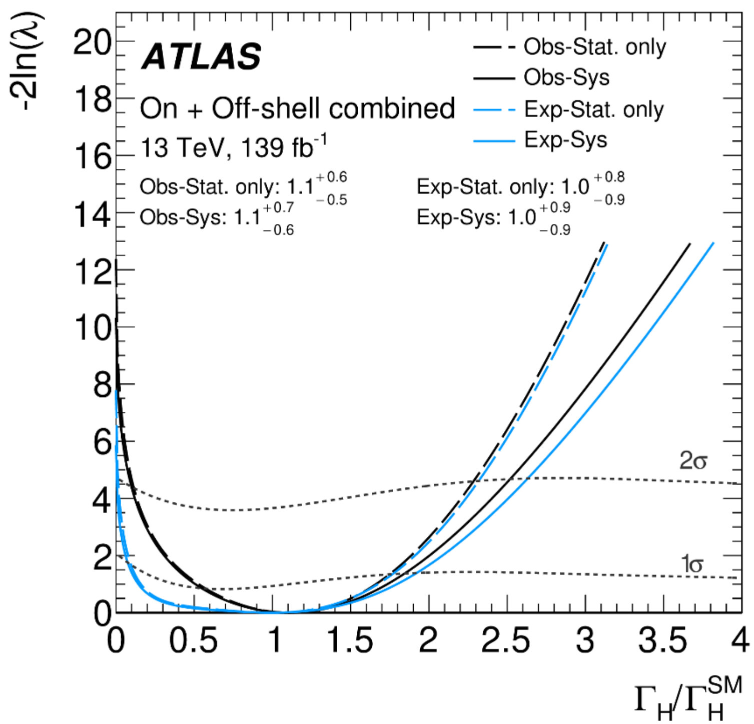
arXiv:2207.00320

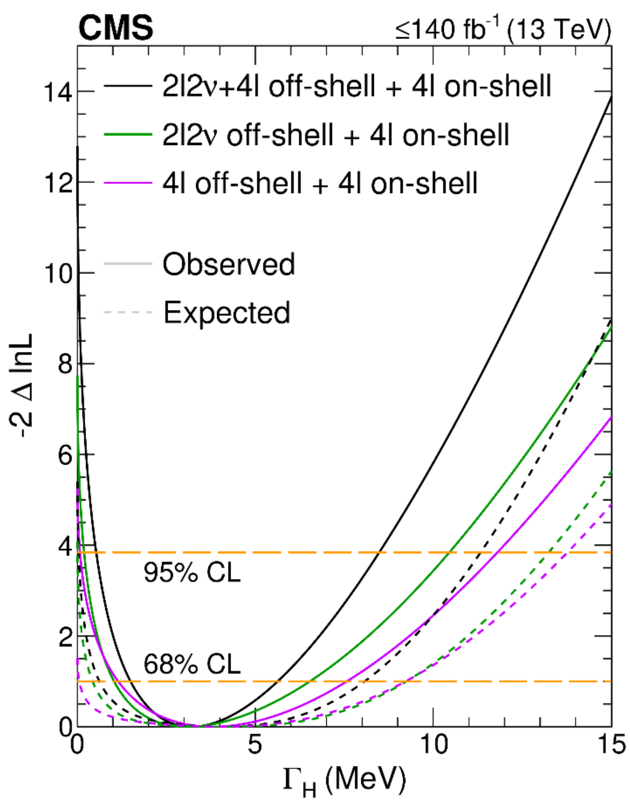


Phys. Lett. B 805 (2020) 135425

Higgs width

- Difficult for direct measurement of Higgs width due to detector resolution
  - Detector resolution (1-2GeV) >> Higgs width Γ_H (4.1MeV)
- Indirect measurement with $H \rightarrow ZZ$ channel by comparing on-shell and off-shell productions $\frac{\Gamma_H}{\Gamma_H^{SM}} = \frac{\mu_{off-shell}}{\mu_{on-shell}}$





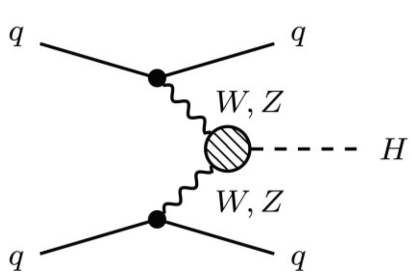
$\Gamma_H = 4.6 ^{+2.6}_{-2.5}\ MeV\ @\ 68\%\ C.L.$

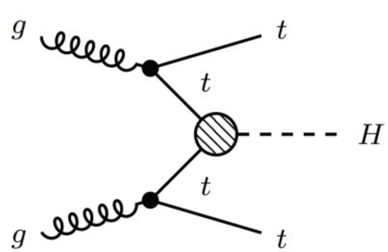
$\Gamma_H = 3.2 ^{+2.4}_{-1.7}\ MeV\ @\ 68\%\ C.L.$

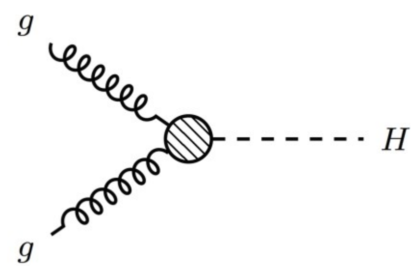
CP properties of Higgs couplings

CP properties of Higgs couplings

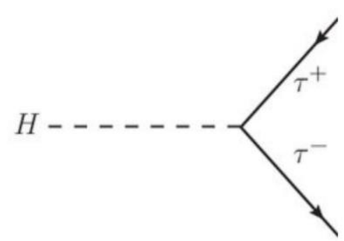
- Run1 Higgs analysis by ATLAS and CMS in favor of spin 0 CP even SM Higgs
  - CP studies in Run1 mainly based on Higgs decay vertexes
- Small anomalous interactions like CP-odd Higgs couplings still possible
- New Higgs CP analyses in Run2 by ATLAS and CMS targeting
  - Higgs production vertexes: HVV, Htt, Hgg





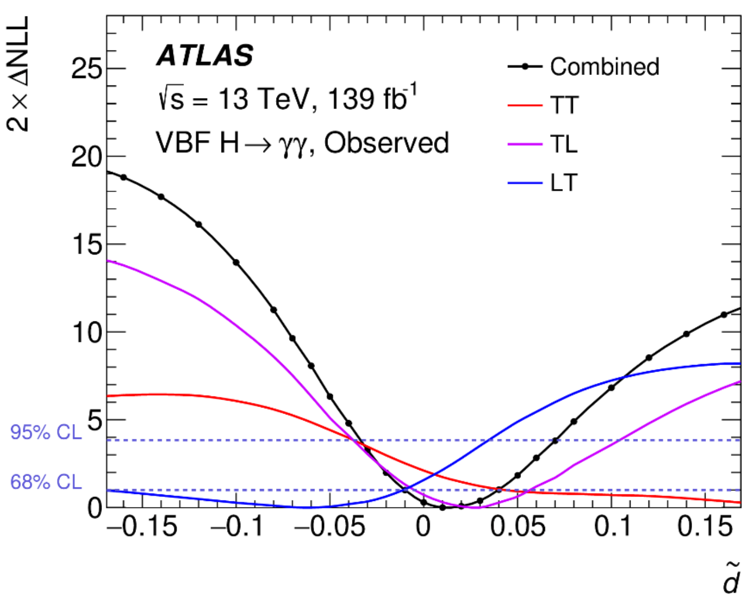


  - Higgs decay vertex: $H\tau\tau$

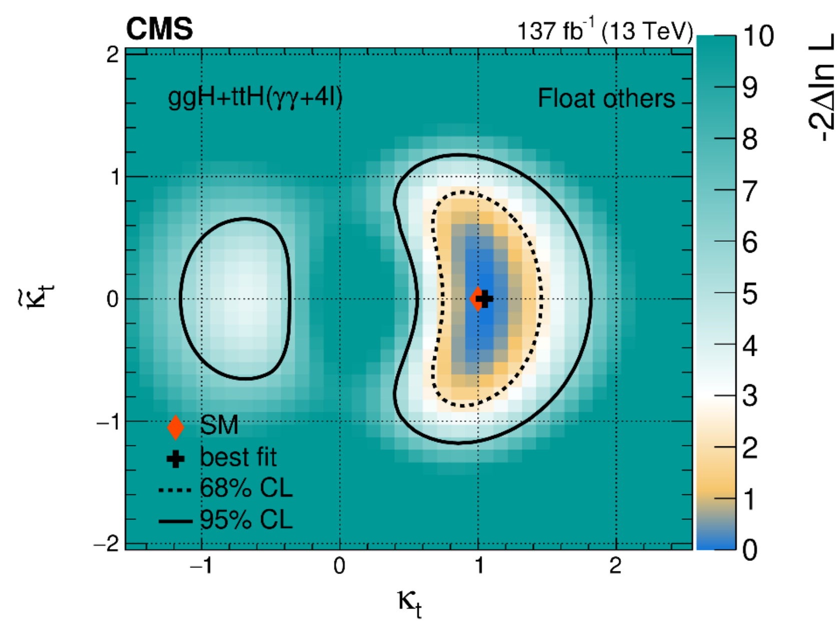


CP property of Hgg and HVV coupling

- Test of CP invariance in $H \to \gamma\gamma$ in ATLAS:
  - Probe the CP structure of interactions between the Higgs boson and electroweak gauge bosons with Optimal Observable method
- CP studies with $H \to ZZ$ combing with $H \to \gamma\gamma$ in CMS
  - First study of CP properties of the Htt and effective Hgg couplings with both gluon fusion and top-associated processes
  - Results also interpreted in the framework of effective field theory



arXiv:2208.02338

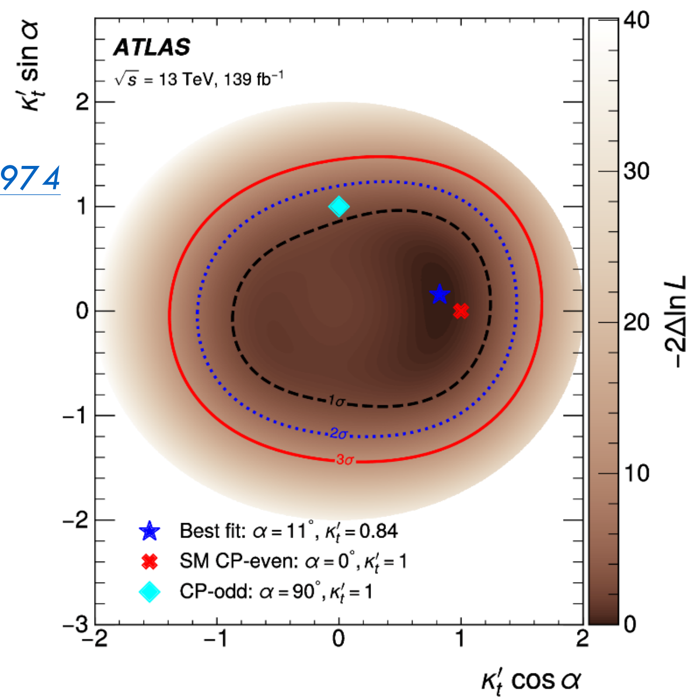


Phys. Rev. D 104 (2021) 052004

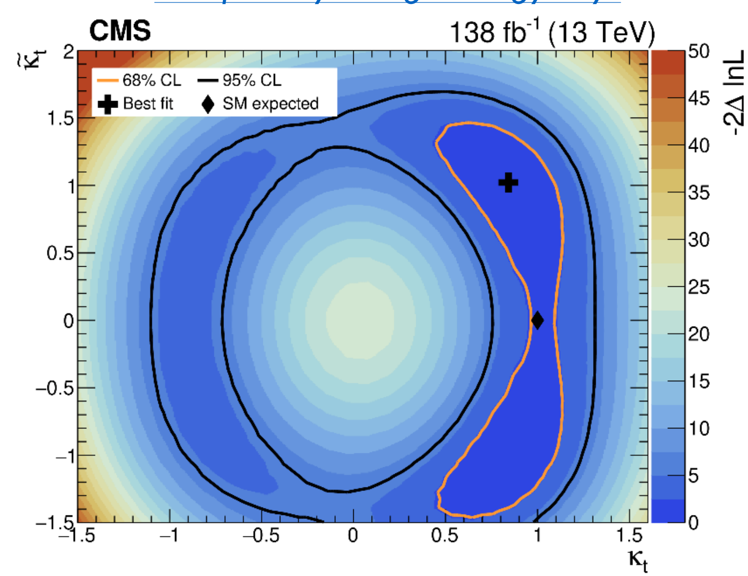
CP property of Htt coupling

- Probing the CP nature of the top-Higgs Yukawa coupling in ttH and tH with $H \to bb$ decays in ATLAS
  - Mixing angle between CP-even and CP-odd couplings measured to be $\alpha = 11^{\circ}\,{}^{+52^{\circ}}_{-73^{\circ}}$
- Search for CP violation in ttH and tH production in multilepton channels in CMS
  - Two-dimensional confidence regions set on CP-even and CP-odd top-Higgs Yukawa coupling modifiers k_t and $\tilde{k}_t$

arXiv:2303.05974



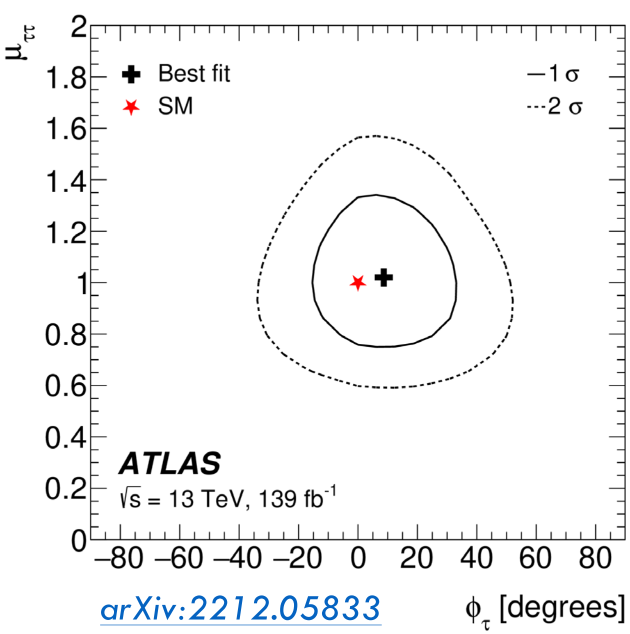
Accepted by J. High Energy Phys



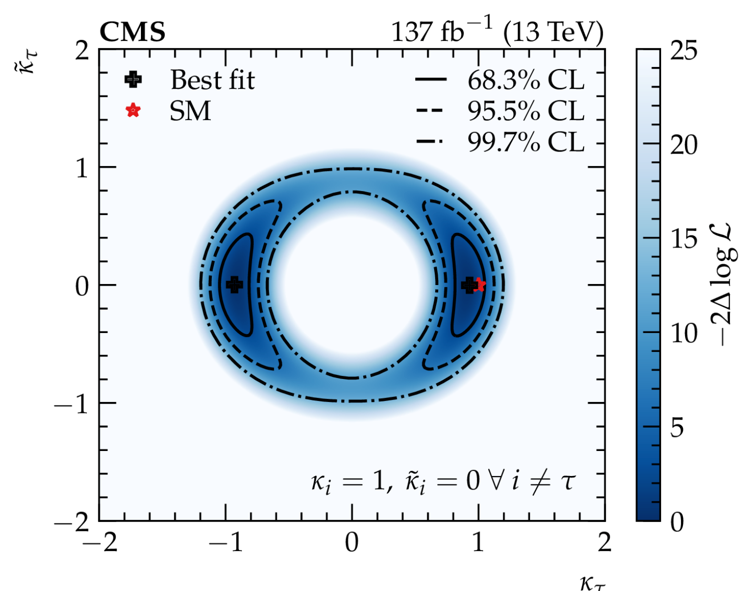
No significant fractional CP-odd contributions observed

CP properties of $H \to \tau\tau$ decay

- Study of CP properties of Higgs boson interactions with τ-leptons in ATLAS
  - CP-violating interactions described by a single mixing angle parameter ϕτ
    - Mixing angle ϕτ measured to be 9 ± 16°
  - Pure CP-odd hypothesis disfavoured at a level of 3.4 standard deviations
- Measurement of CP properties of $H \to \tau\tau$ decay from CMS using full Run 2 data
  - Exploits the angular correlation between the decay planes of τ leptons from Higgs decays
    - Effective mixing angle between CP-even and CP-odd τ Yukawa couplings: −1 ± 19°
  - Data disfavor the pure CP-odd scenario at 3.0 standard deviations



arXiv:2212.05833

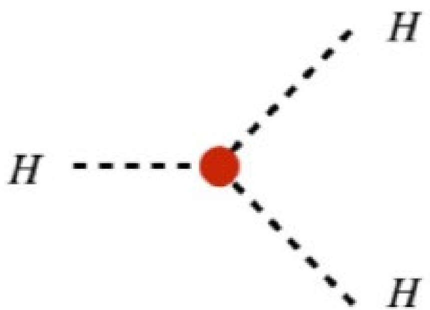


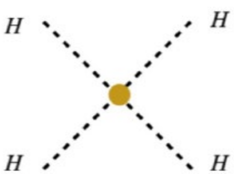
JHEP 06 (2022) 012

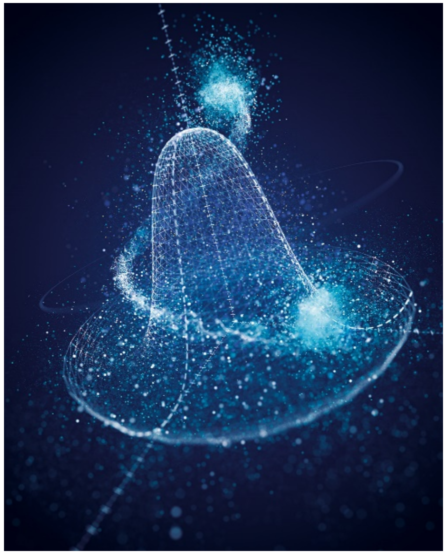
Higgs self-coupling

Higgs self-coupling measurement

- Higgs self-coupling crucial for understanding the Higgs field potential
  - Understand the electroweak symmetry breaking mechanism
- $V = \mu^2 H^2 + \frac{\mu^2}{v} H^3 + \frac{\mu^2}{4v^2} H^4$





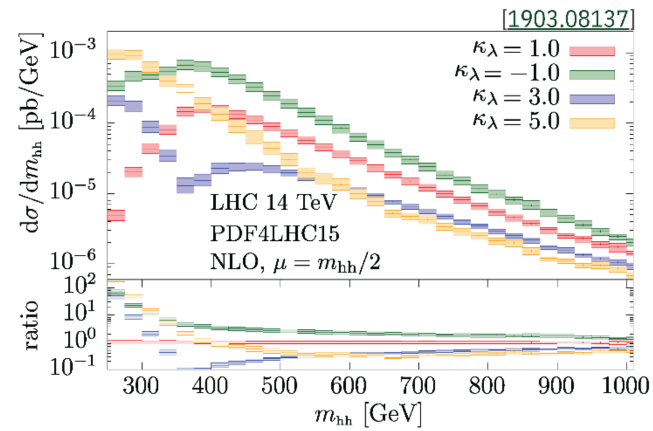


- Higgs self-coupling with HH and H in ATLAS and CMS
  - Measure coupling modifiers k_λ
    - $k_\lambda = \lambda/\lambda_{SM}$
  - Direct probes from HH measurements
  - Indirect constraints from H measurement

HH production modes

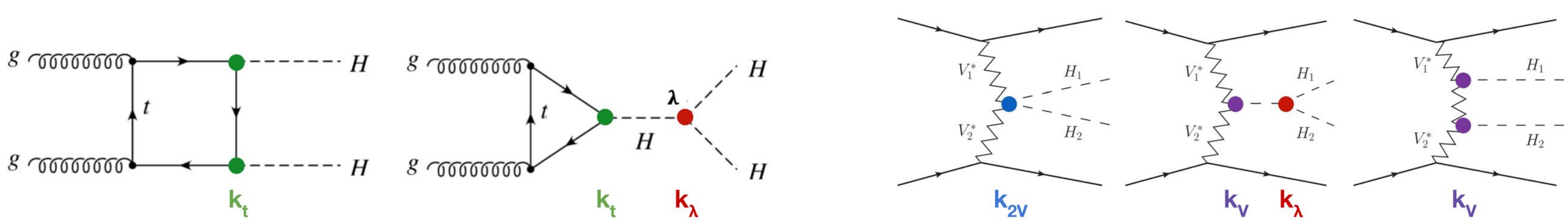
- HH production challenging to measure due to its small cross section
  - $\sigma_{HH} \sim \frac{\sigma_H}{1000}$ in SM at 13TeV
  - Two main production modes
    - $\sigma_{ggF} = 31.05\ fb$ SM @13TeV
      - Dominant channel for studying self-coupling
      - Destructive interference
    - $\sigma_{VBF} = 1.73\ fb$ SM @13TeV
      - Only channel to access quartic VVHH coupling
- k_λ determines HH production cross section
- Spectrum of m_{HH} depends on k_λ
  - Softer for large $|k_\lambda|$

$\kappa_\lambda = \lambda/\lambda^{SM}$ also dictates signal kinematics:



Gluon-gluon fusion (**ggF**)

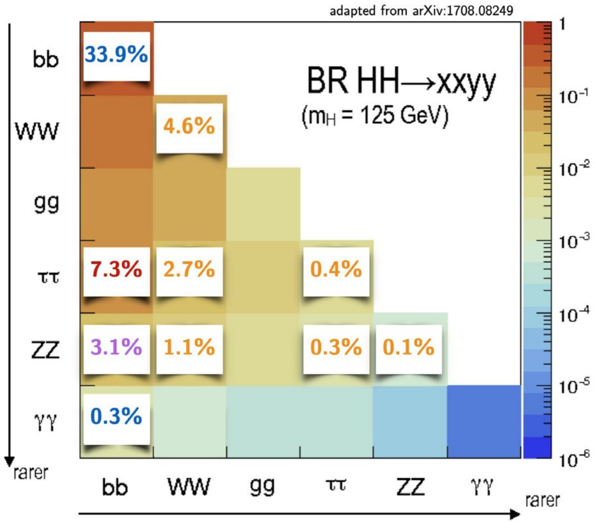
Vector-boson fusion (**VBF**)



Various Higgs coupling modifiers (coupling over SM prediction): $k_\lambda, k_{2V}, k_t, k_V$

HH combination with full Run 2 data

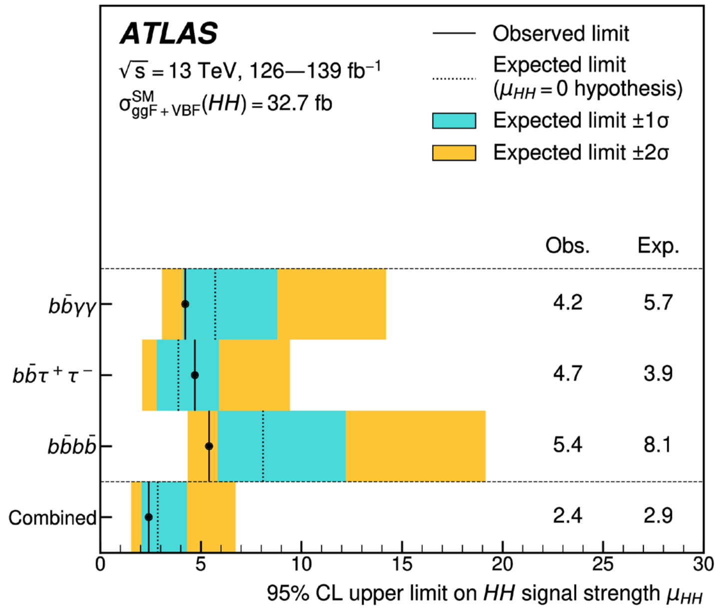
- Best HH sensitivity via combination of all available decay channels
  - Using full Run 2 data with ~140 fb^{-1}
  - Included the most sensitive channels



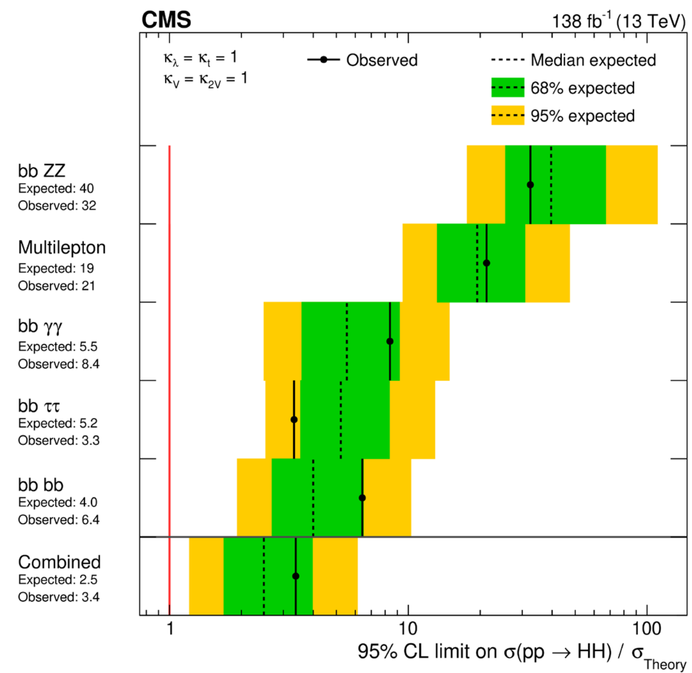
- HH search evolution since early Run 2 besides more data
  - Inclusion of more channels
  - Measurement of quartic couplings with VBF HH production mechanism
  - Extensive usage of machine learning, selection/tagging optimization
  - Boosted topologies, additional final states

Limits on the HH production signal strength

arXiv:2211.01216



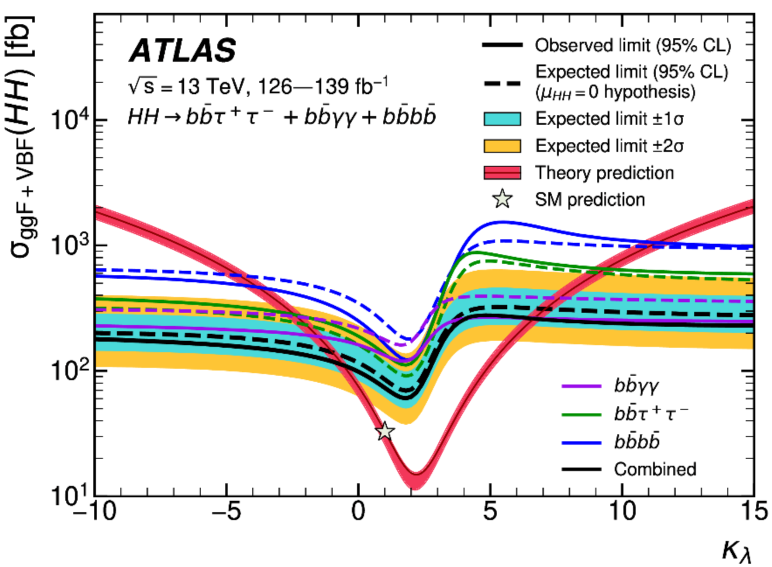
Nature 607 (2022) 60-68



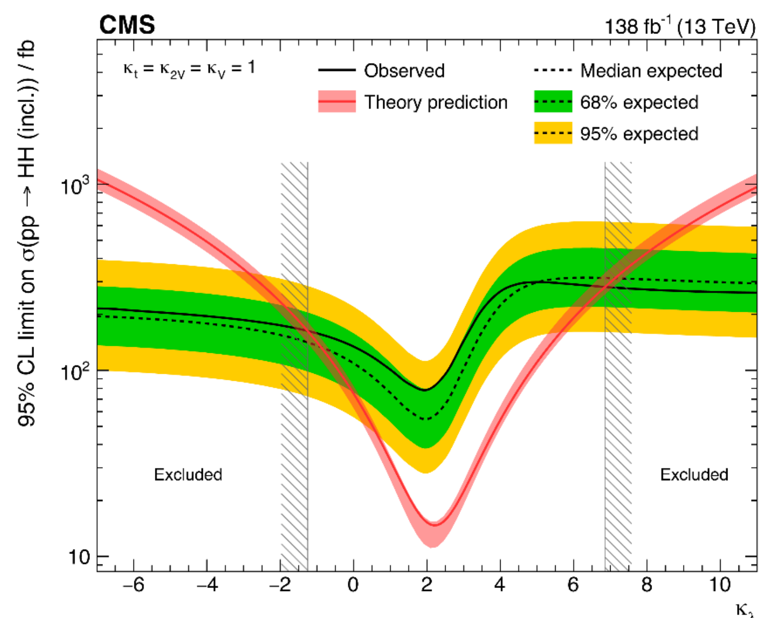
- Expected and observed limits on the HH signal strength
  - Most stringent limits (best observed) from ATLAS: $2.4\ (2.9)\ \times SM$
  - Best sensitivity (best expected) on HH limit from CMS: $3.4\ (2.5)\ \times SM$
  - Significant improvement comparing to early Run 2 results
  - Sensitivity in HL-LHC sufficient to establish the existence of the SM HH production

Constraints on Higgs self-coupling

- 95% CL interval for Higgs self-coupling k_λ
  - ATLAS observed (expected) : $-0.6 < k_\lambda < 6.6$ $(-2.1 < k_\lambda < 7.8)$
  - CMS observed (expected) : $-1.24 < k_\lambda < 6.49$ $(-2.28 < k_\lambda < 7.94)$



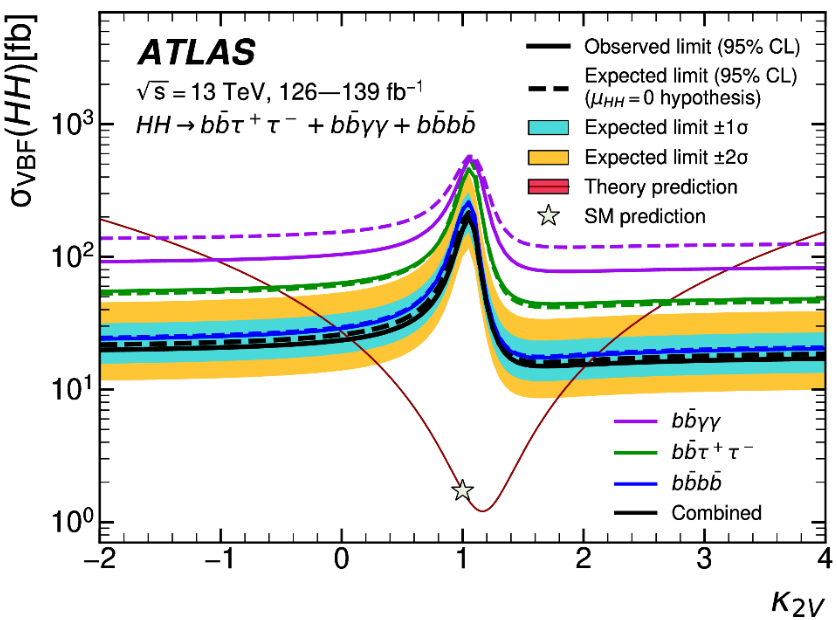
arXiv:2211.01216



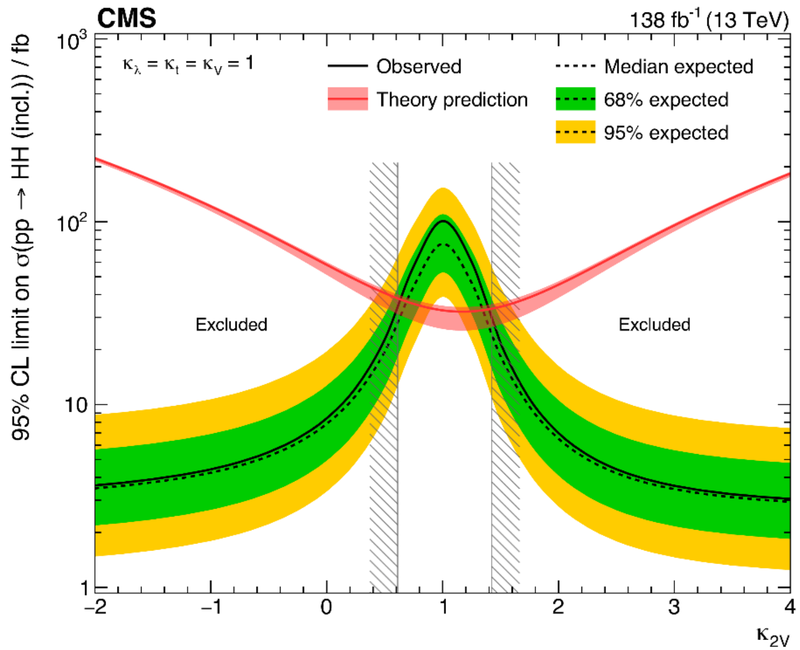
Nature 607 (2022) 60-68

Limits on quartic couplings

- 95% CL interval for quartic VVHH coupling k_{2V}
  - ATLAS observed (expected) : $0.1 < k_{2V} < 2.0$ ($0.0 < k_{\lambda} < 2.1$)
  - CMS observed (expected) : $0.67 < k_{2V} < 1.38$ ($0.61 < k_{\lambda} < 1.42$)
- $\kappa_{2V} = 0$ is excluded assuming SM values for all other ks



arXiv:2211.01216

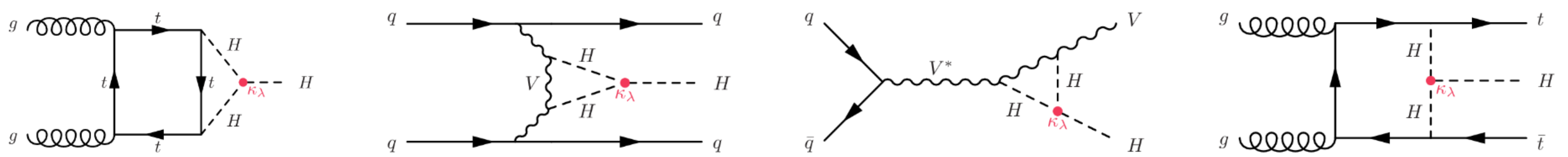


Nature 607 (2022) 60-68

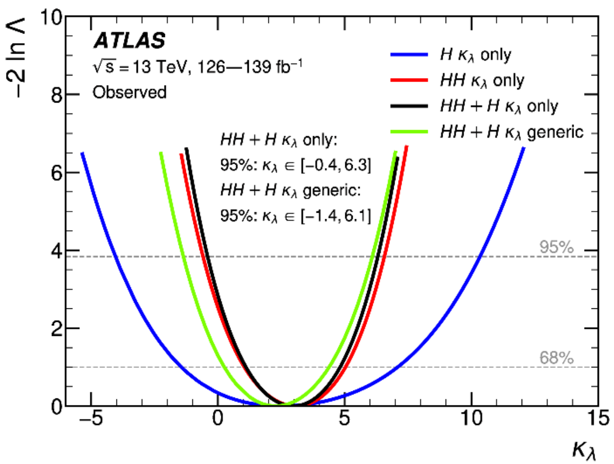
Indirect constraints on Higgs self-coupling

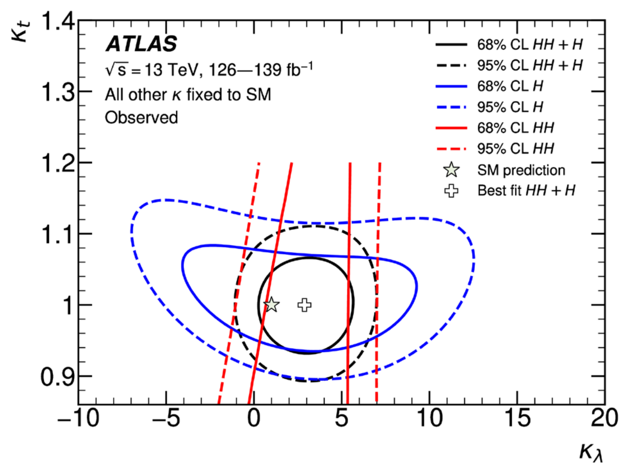
- Single Higgs production cross section and decay branching ratios affected by k_λ with NLO electroweak corrections

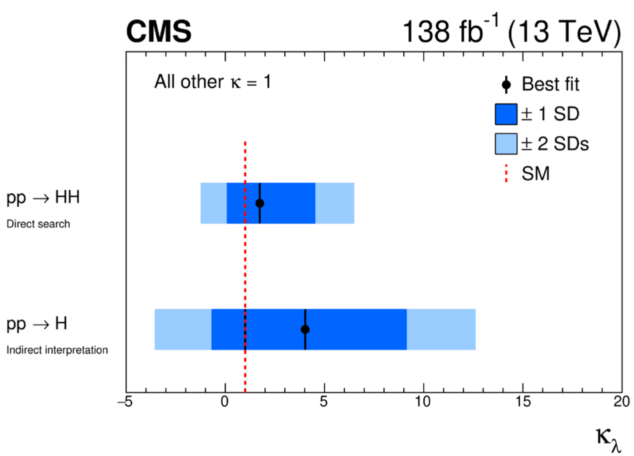
Example of k_λ in single Higgs production



- Single Higgs combination provides complementary constraints on Higgs self-coupling
- HH+H combination for Higgs self-coupling allows a more model independent measurement



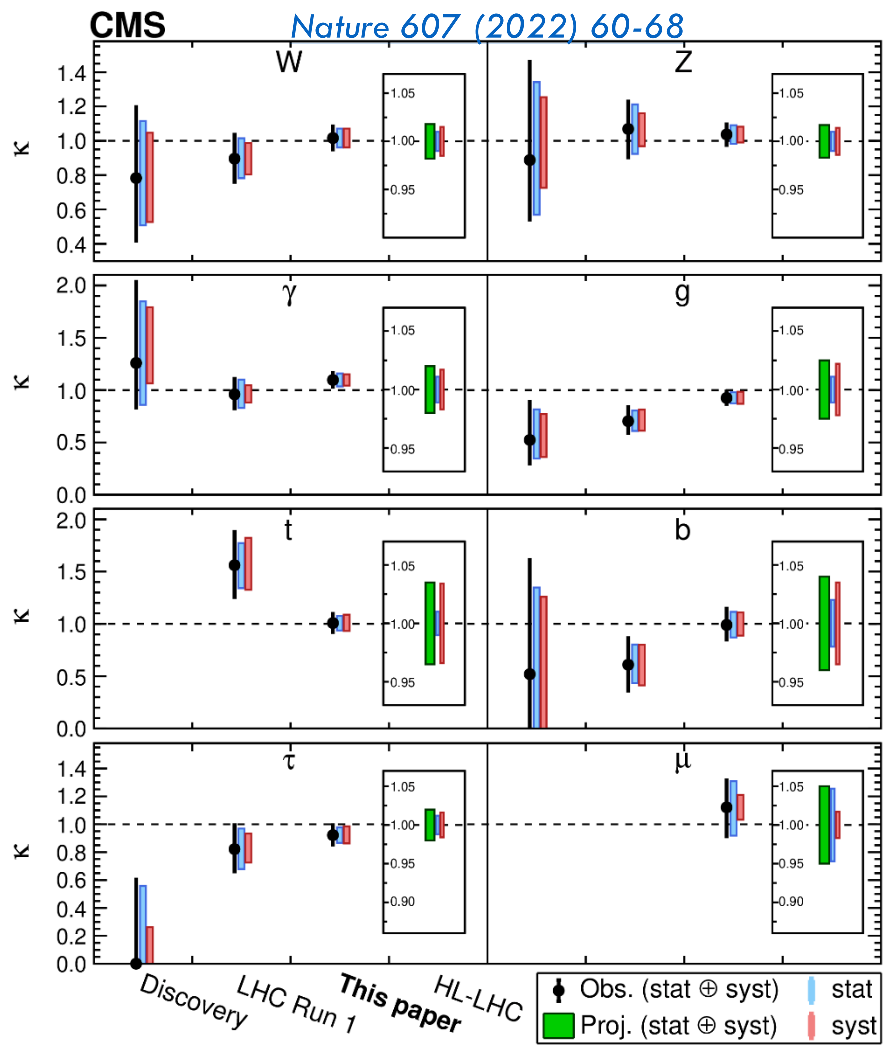


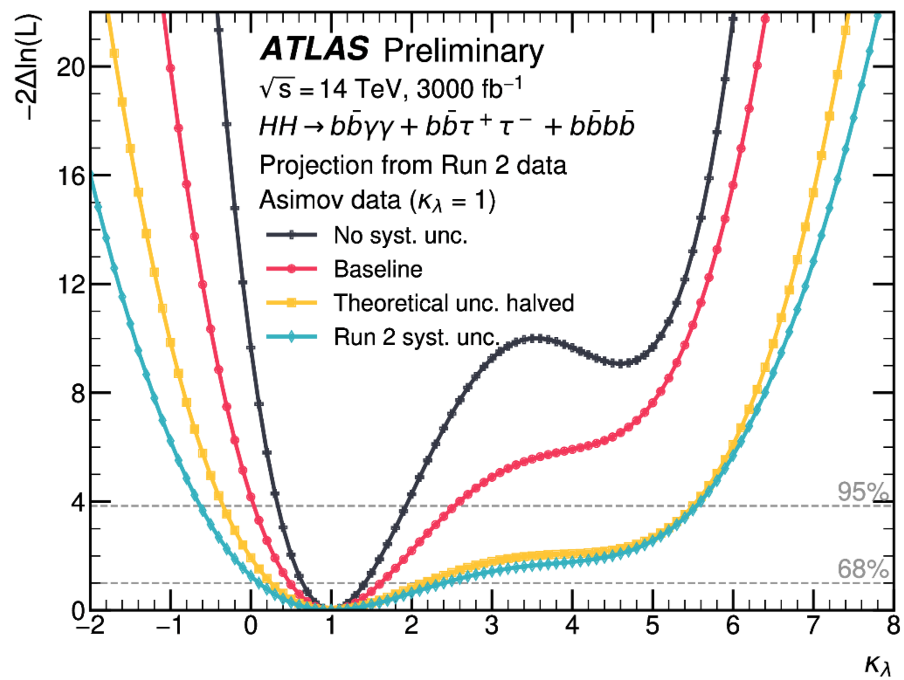


arXiv:2211.01216

Nature 607 (2022) 60-68

Higgs measurements towards HL-LHC

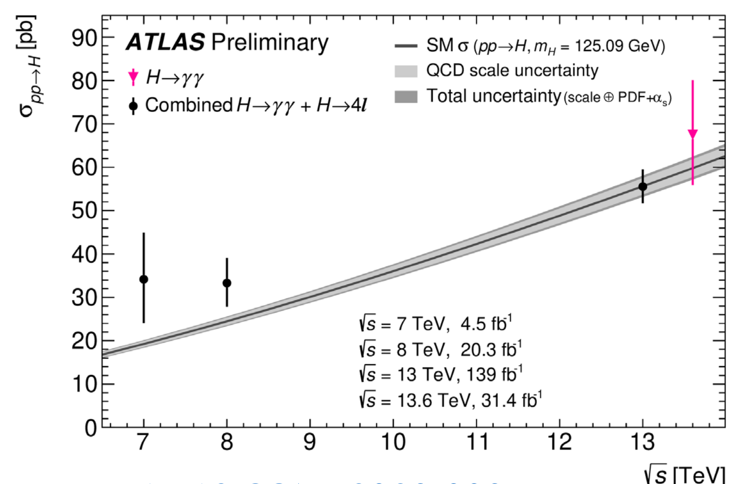




- Huge improvements on Higgs coupling precision since Higgs discovery
- Precision test of SM and establishment of Higgs self-coupling expected in HL-LHC

Summary

- A summary of recent Higgs property measurement results from ATLAS and CMS experiments using full Run 2 data
  - Higgs cross section and couplings measured with better precision and details
  - The Higgs boson mass measured with a precision of the order to 0.1%
  - The best width measurement extracted by comparing on-shell with off-shell decay
  - CP structures tested in HVV, Htt, Hgg and $H\tau\tau$ couplings
  - Higgs self-coupling constrained with non-resonant HH combination as well as single Higgs combination results
- Significant improvement on precisions of Higgs measurements achieved in Run 2 with respect to the Higgs discovery and early analyses
- Exciting Higgs results in Run 3 are knocking in!



ATLAS-CONF-2023-003