Measurements on SM Higgs at ATLAS and CMS

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SUSY24: The 31st International Conference on Supersymmetry and Unification of Fundamental Interactions

June 10 to 14, 2024, Madrid, Spain.

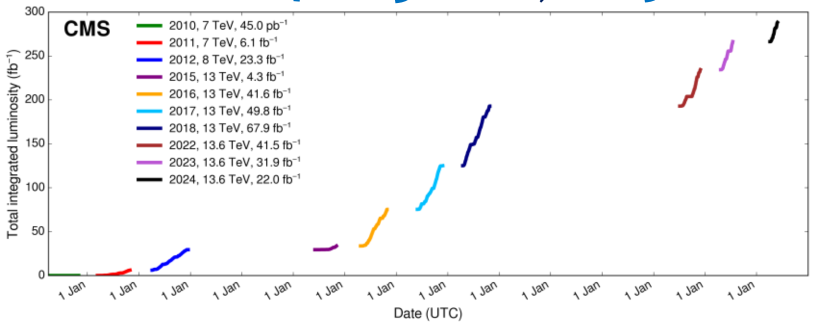
ATLAS Higgs results: **papers**, conference notes

CMS Higgs results: **papers**, preliminary results

Grant PID2020-113341RB-100 funded by

The long road of the Higgs boson: a worldwide effort

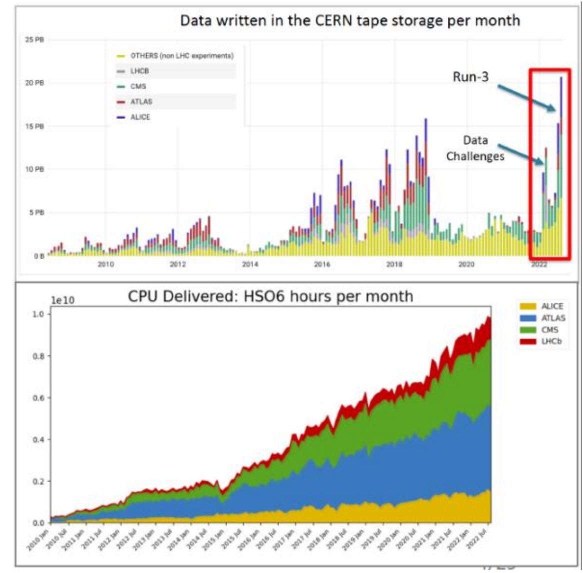
LHC: from 7 to 13.6 TeV, L >250 fb^{-1}



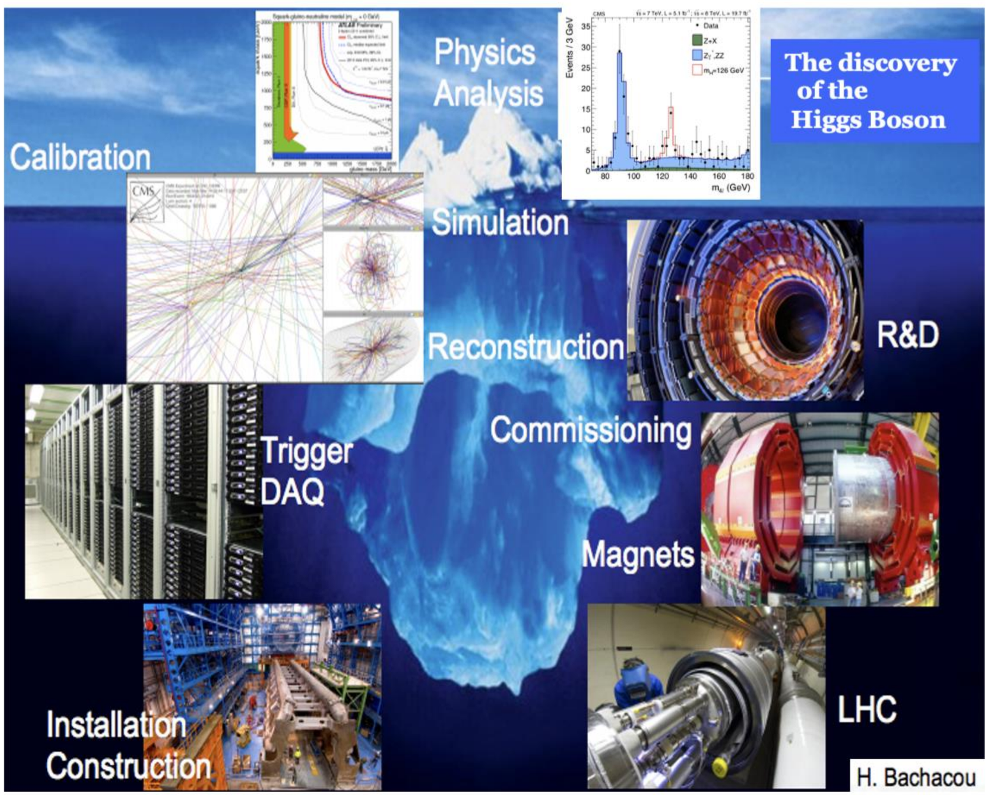
Run2 wrt Run1, Lumi ×10 more

σ ×2−4 larger, **Higgs ×30 more**

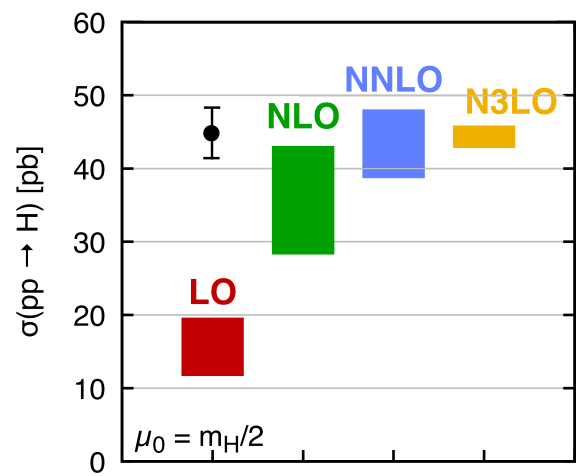
The WLCG



Superb detector performance



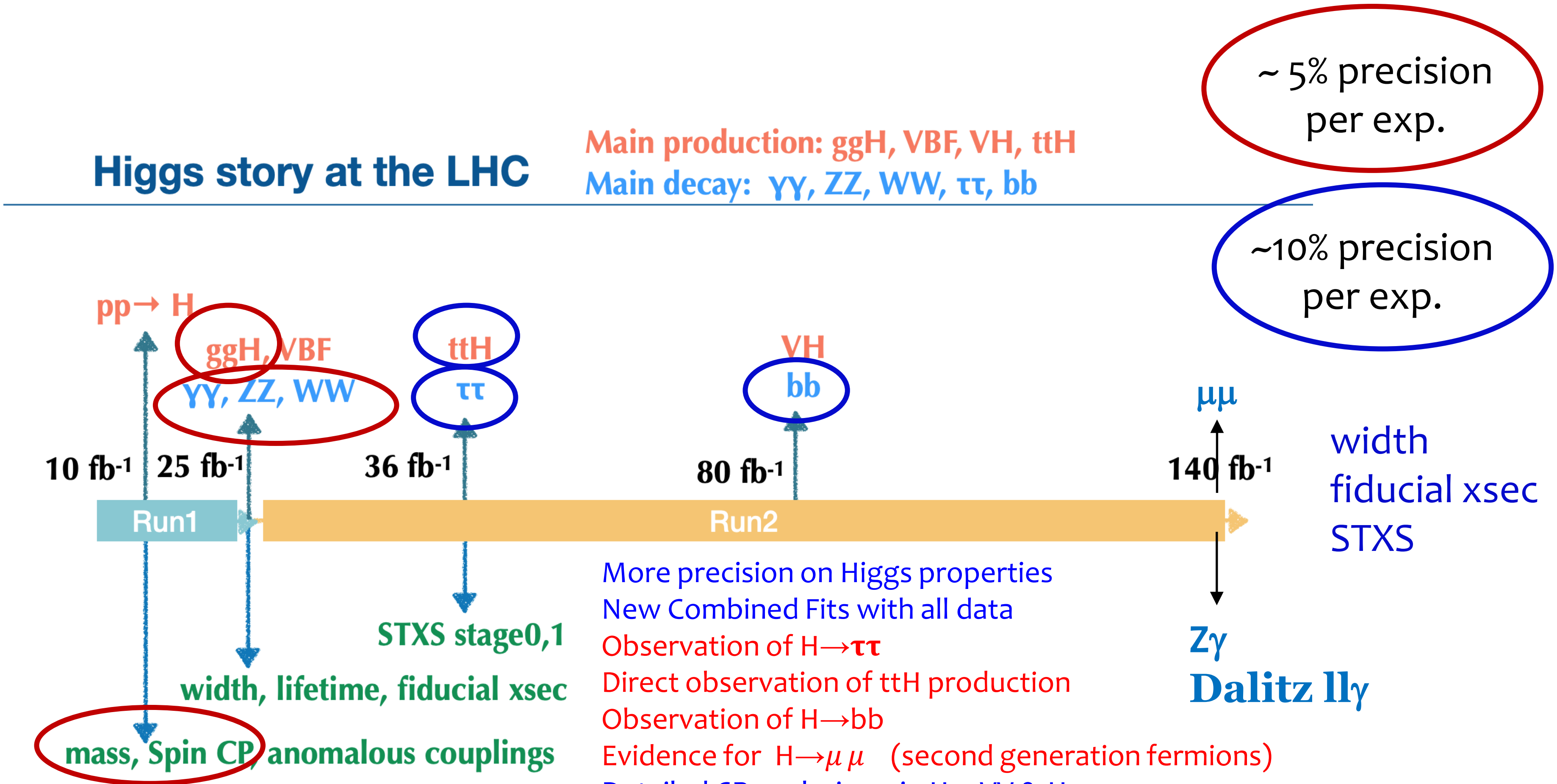
The LHCHXSWG



Introduction and Outline

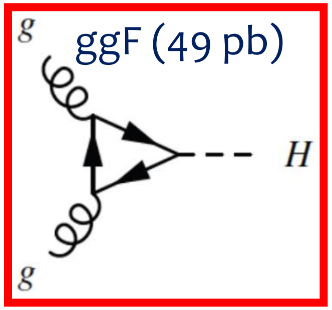
- The discovery of the Higgs boson in 2012 by ATLAS and CMS fulfilled one of the main aims of the LHC:
  - **Identifying a mass generation mechanism for the SM**
- It has given us access to a new sector of the SM with new lines of enquiry to follow:
  - Yukawa couplings, a new type of interaction to investigate
  - Gauge–scalar boson interactions
  - The parameters of the Higgs potential, and its self coupling
- Determination of the properties of the new scalar particle at LHC:
  - Detailed measurements of Higgs boson mass, width (lifetime), couplings (interactions), CP symmetry, kinematics, and more,
  - Standard Model Higgs Boson Cross Sections and Branching Fractions, STXS, differential measurements, EFT interpretations.
- No direct observation of new physics at the LHC after the Higgs boson discovery

From the 4 of July 2012 to the end of Run2

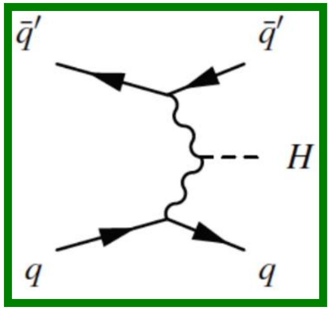


C. Mariotti, ICHEP 22

SM Higgs Production and decay at the LHC

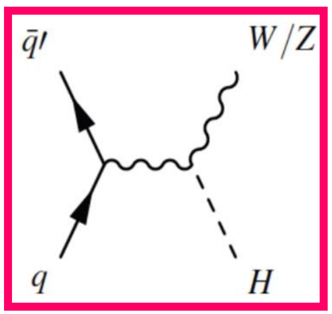


Gluon Fusion
(WH 1.4 pb, ZH 0.9 pb)

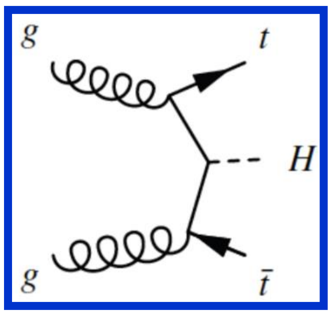


VBF 3.8 pb

Vector-Boson Fusion

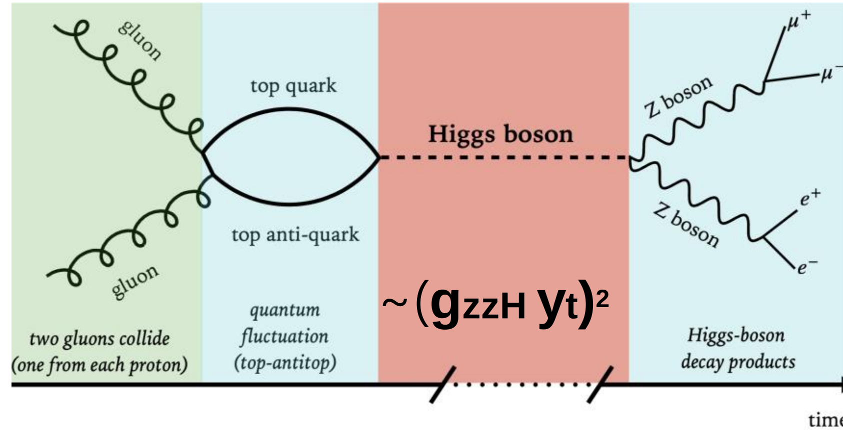


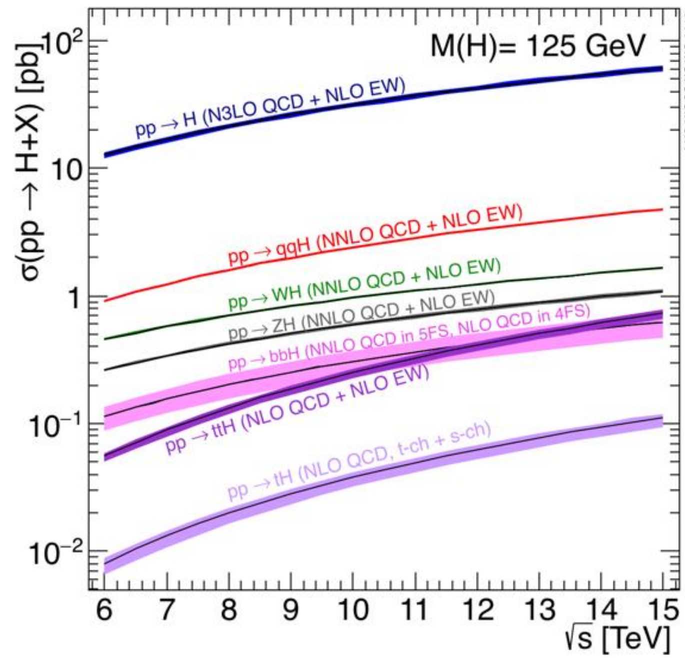
Higgs-strahlung



ttH (0.5 pb)

Top Fusion ($t\bar{t}H$)





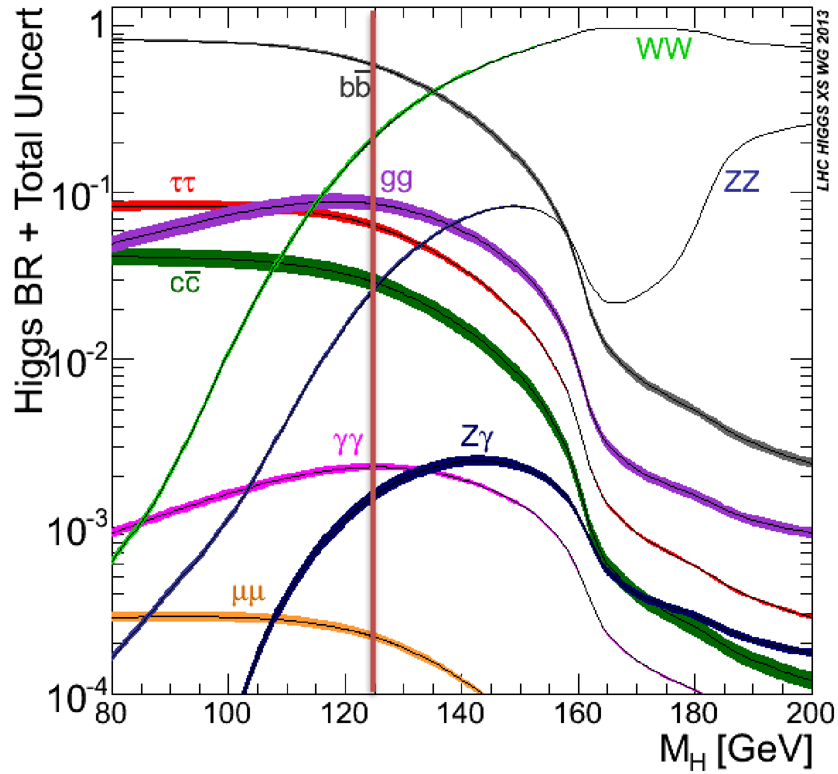
ATLAS and CMS observed 5 different Higgs "production modes" and 5 different "decay modes" in 6 years following discovery

Decay of the Higgs Boson

Need **multi-purpose detectors** like ATLAS and CMS to find the Higgs boson and measure its properties at the LHC!

Had the Higgs boson been 50 GeV heavier, it would have been impossible to detect more than just two channels ZZ and WW

Had the Higgs been just 10 GeV lighter, the decays to WW and ZZ would have been impossible so far…

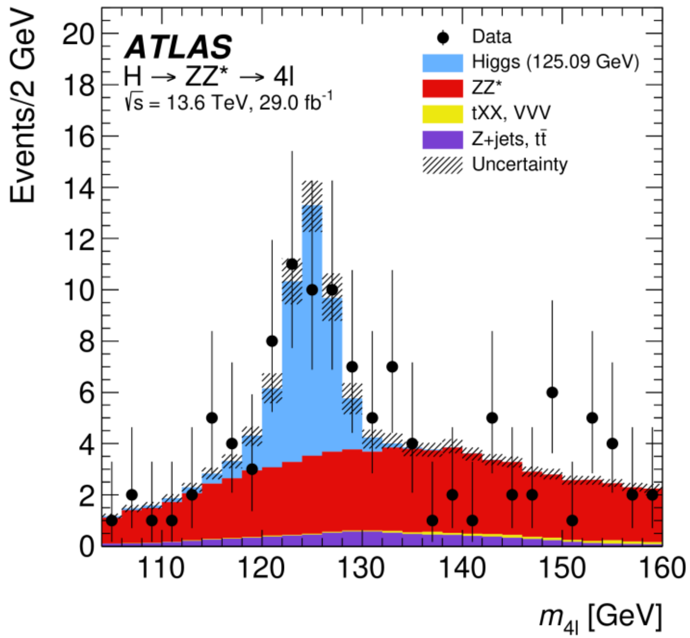


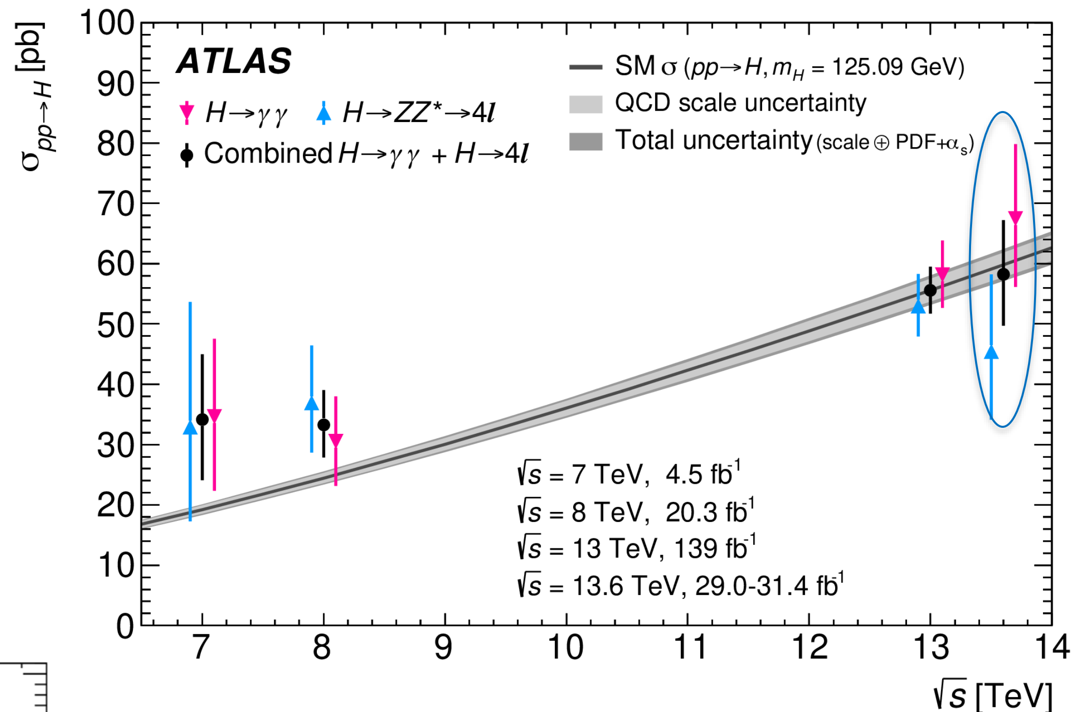
A region in m_H where:

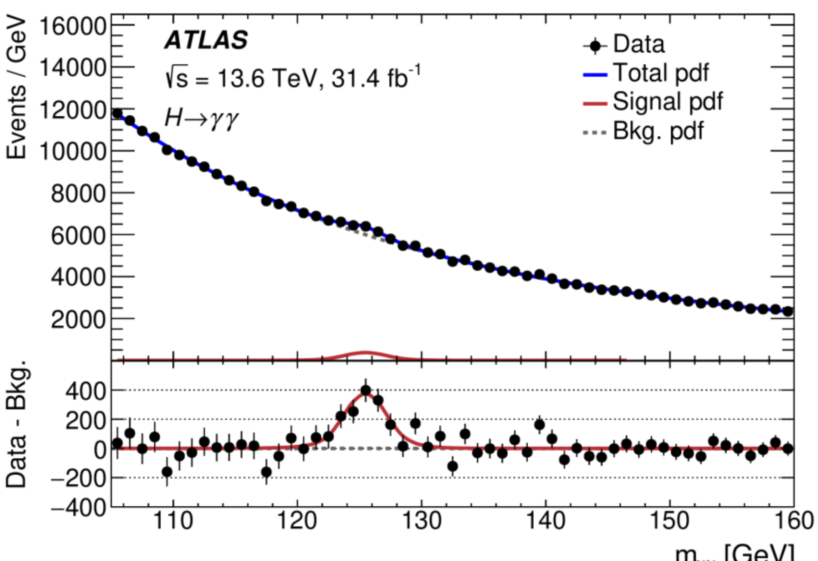
- Very good combination of signal-strength for the whole set of decay channels below the top-antitop threshold
- Cross sections are large, Natural width is negligible

Cross sections at 13.6 TeV

Eur. Phys. J. C 84 (2024) 78







Measurements performed with 2022 data at **13.6 TeV**, and **~30 fb^{-1}**.

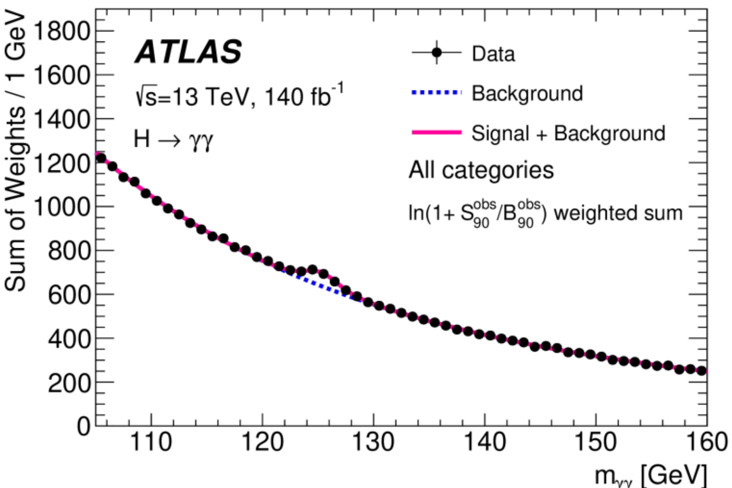
H → γγ and **H → ZZ* → 4ℓ** fiducial cross section measurements extrapolated to full phase space combined:

σ_H = 58.2 ± 8.7 pb (exp: 59.9 ± 2.6 pb)

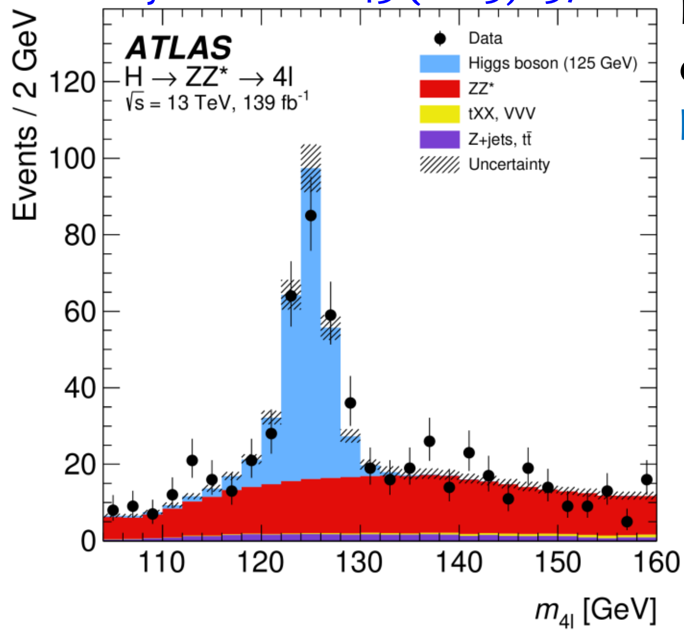
Main uncertainty, for now, statistical.

Higgs mass: ATLAS and CMS

Phys. Lett. B 847 (2023) 138315



Phys. Lett. B 843 (2023) 137880

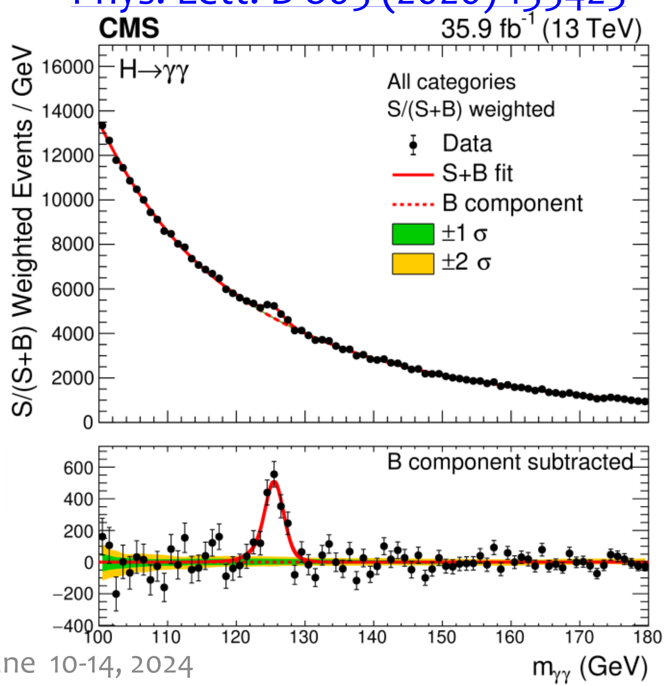


Exploit best resolution channels: **H → γγ** and **H → ZZ* → 4ℓ**

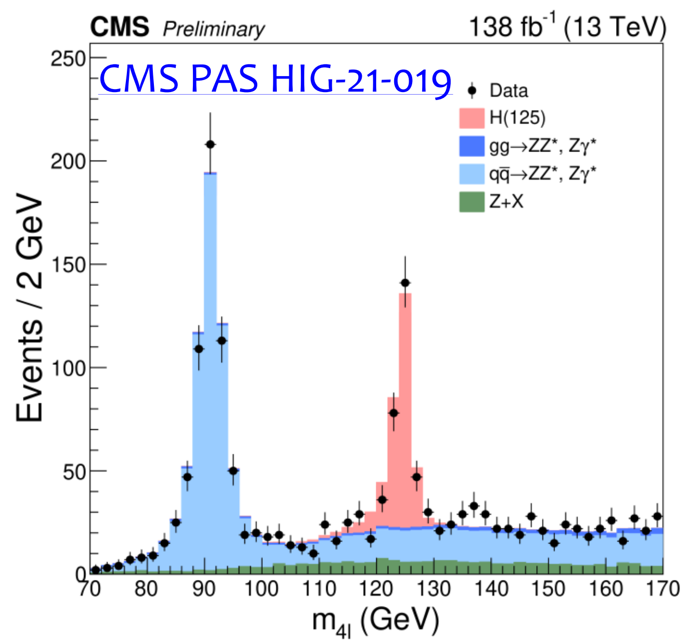
m_H was measured in decays to **γγ** or **4ℓ** (**ℓ=** e or μ)

Employ fine-grained classification (**H → γγ**) and per-event uncertainties (**H → ZZ* → 4ℓ**)

Phys. Lett. B 805 (2020) 135425



CMS PAS HIG-21-019



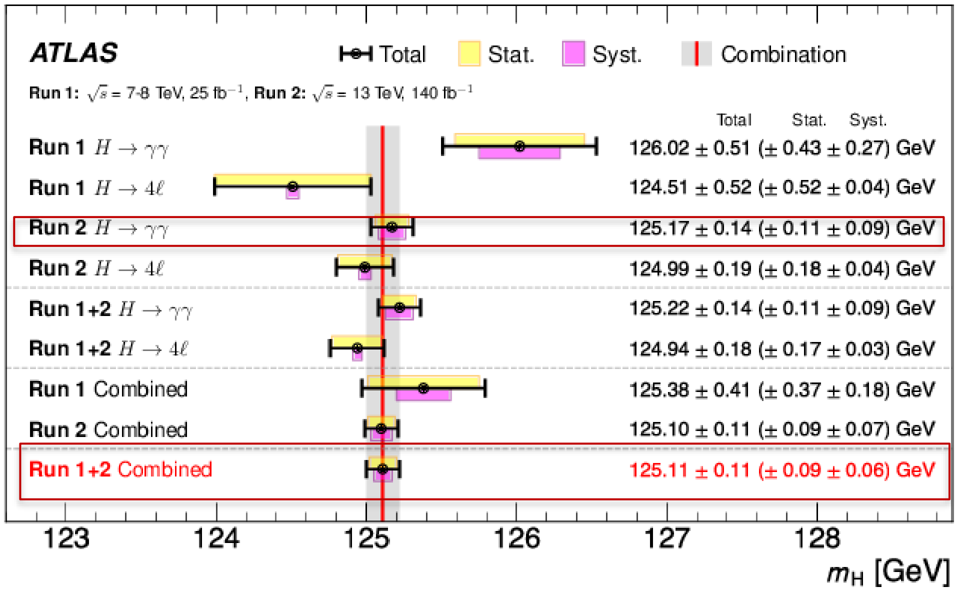
H → **γγ** relies on ECAL energy, very large background

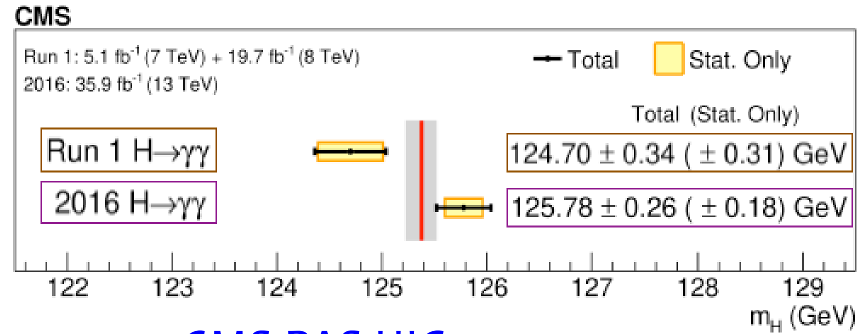
H → 4ℓ uses e/μ tracks (and ECAL), very low statistics, and high "purity"

Higgs mass: ATLAS and CMS

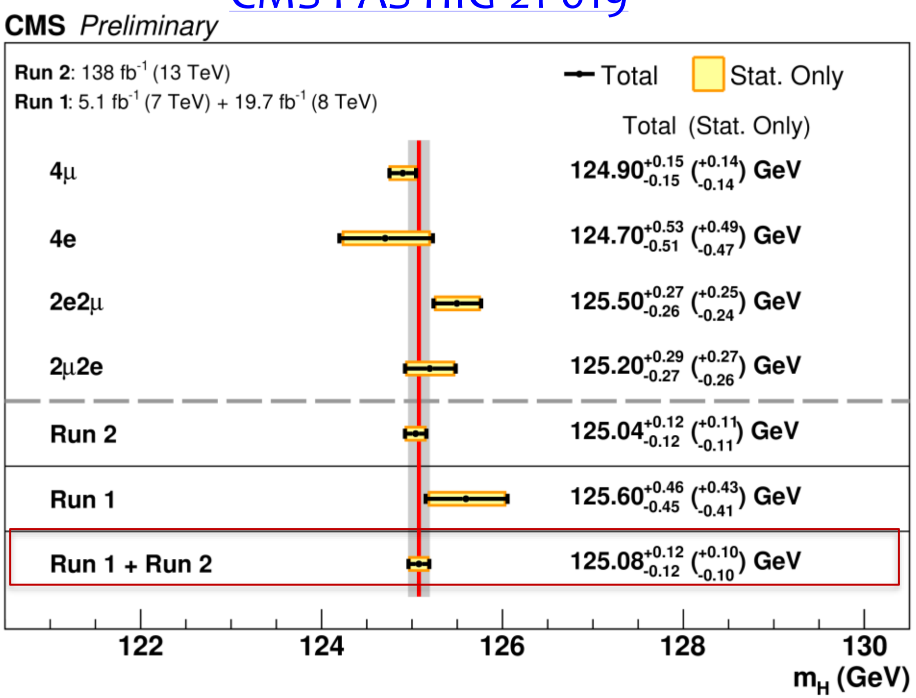
ATLAS-HIGG-2023-011
arXiv:2404.05498

Phys. Lett. B 805 (2020) 135425





CMS PAS HIG-21-019



ATLAS and CMS measure masses of **125.11±0.11** and **125.08±0.12 GeV** **consistent**!

The measurements are still statistics limited

CMS $H \rightarrow \gamma\gamma$ result with full Run 2, coming soon

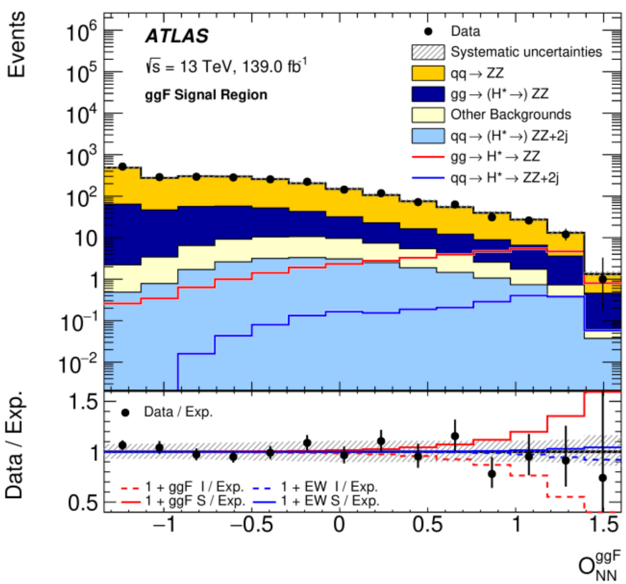
+Direct constraint on Γ_H, **Γ_H < 60 MeV** @ 68% CL

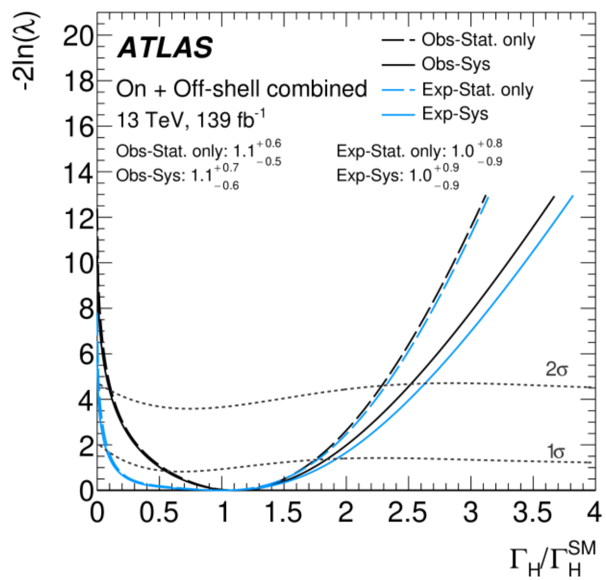
Higgs width:

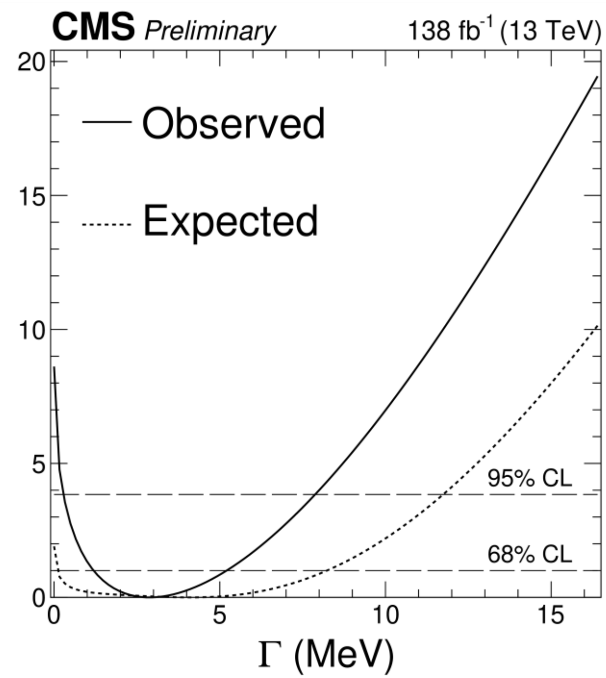
- Expected "width" (4.1 MeV) inversely related to lifetime (1.6×10^{-22} s)
- Exploit coupling ratio between **off- and on-shell production**
- ATLAS and CMS measure using **$H \to ZZ \to 4\ell$** events with mass > 220 GeV, and **$2\ell 2\nu$** in the off-shell analysis, probing interference with non-Higgs $ZZ \to 4\ell$
- Event categories and complex multivariate discriminants for optimal measurement, 3D observable (CMS) / NN (ATLAS) ➔ comparable sensitivity **O(70%) precision - 2-3 MeV.**

$\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV @ 68% CL

$\Gamma_H = 2.9^{+1.9}_{-1.4}$ MeV @ 68% CL







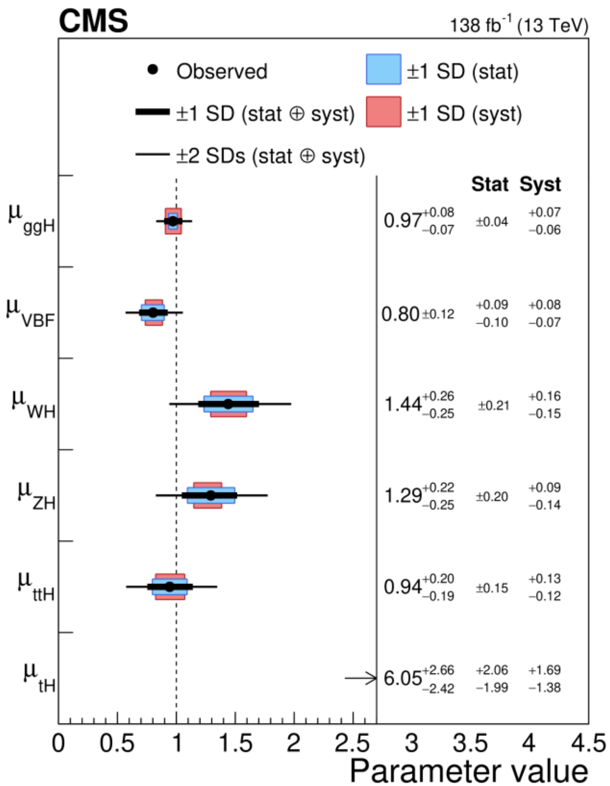
Phys. Lett. B 846 (2023)138223

CMS PAS HIG-21-019

Higgs production measurements

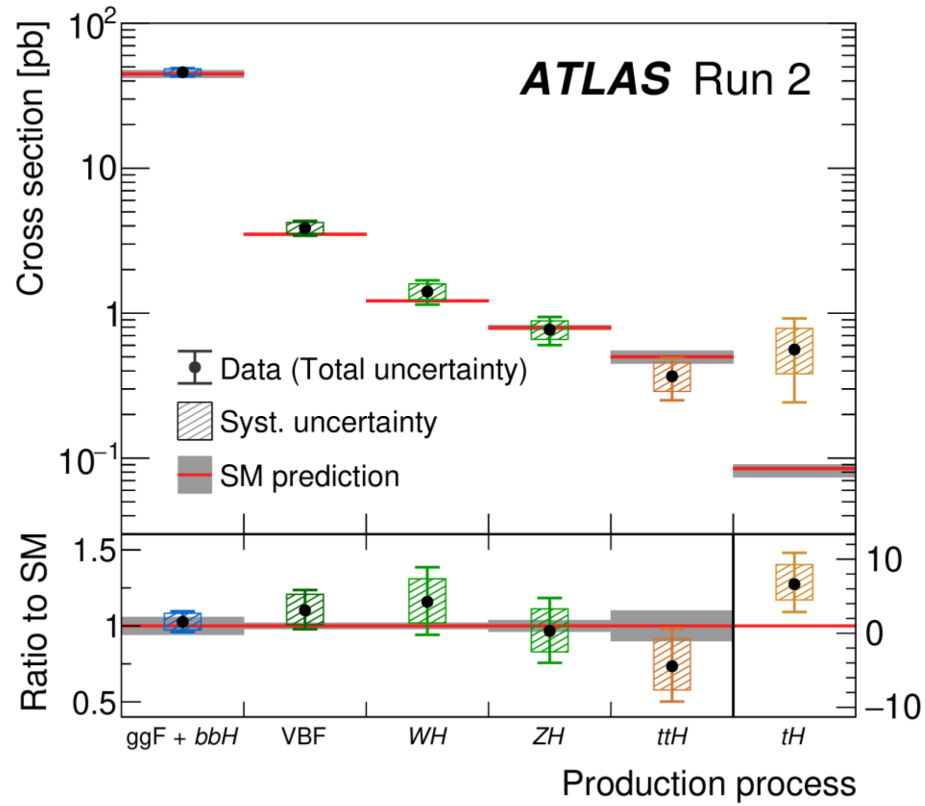
Nature 607 (2022) 52
ATLAS-HIGG-2023-011
arXiv:2404.05498

CMS: Nature 607 (2022) 60



Total cross-section / Standard Model prediction

$$\mu = 1.05 \pm 0.06 = 1.05 \pm 0.03\,(\text{stat.}) \pm 0.03\,(\text{exp.}) \pm 0.04\,(\text{sig. th.}) \pm 0.02\,(\text{bkg. th.}).$$



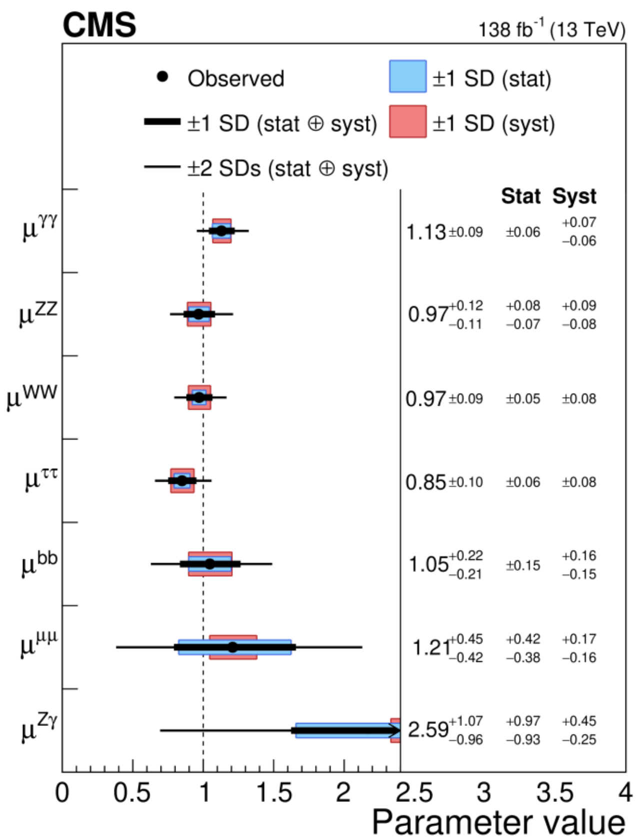
Run 2 measurements for gluon fusion **ggH**, vector boson fusion **VBF**, and **WH**, **ZH** an **t(t)H** associated production

Precision **better than 10%** for ggF, **10-20% precision** on most other production modes

SM test over many orders of magnitude

Higgs decays

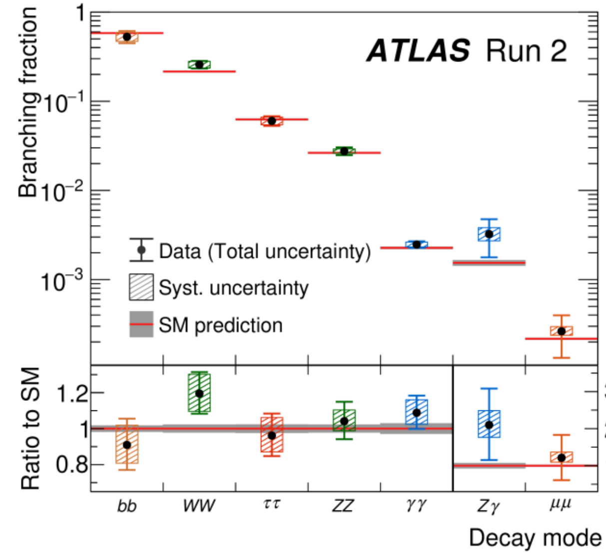
CMS: Nature 607 (2022) 60

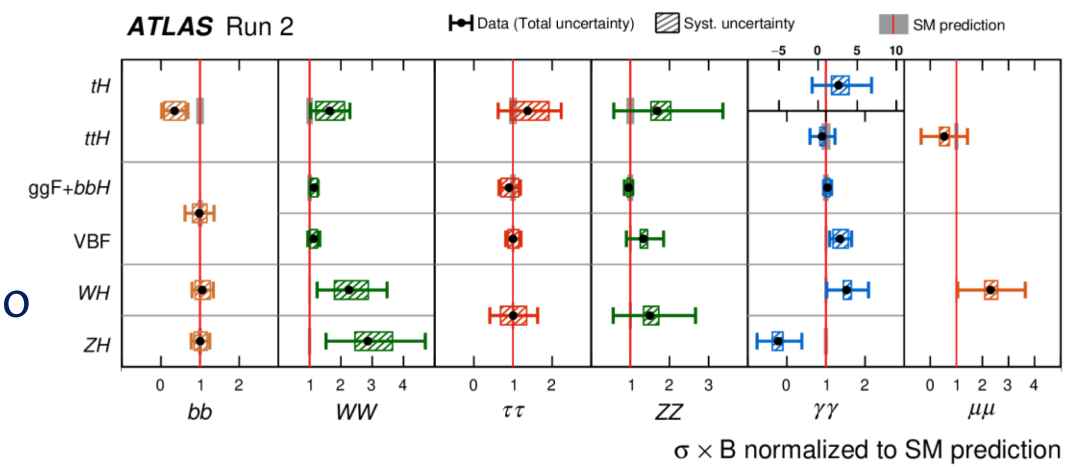


Nature 607 (2022) 52

ATLAS-HIGG-2023-011 arXiv:2404.05498

Observed event rate divided by predicted SM event rate for different combinations of Higgs boson production and decay processes



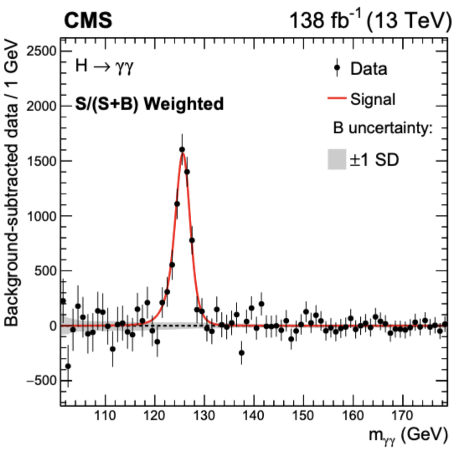


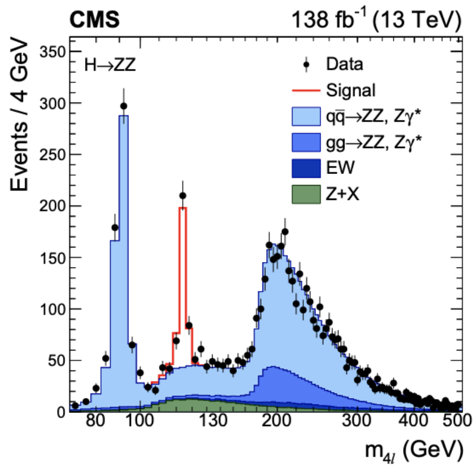
ATLAS and CMS measure decays to **γγ, ZZ*, WW*, bb, ττ**, and **μμ** with **10-50%** uncertainty.

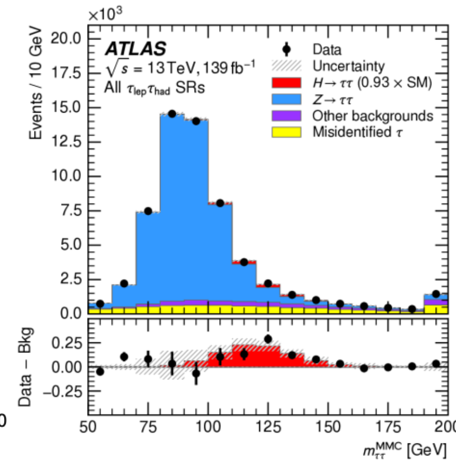
SM test over many orders of magnitude

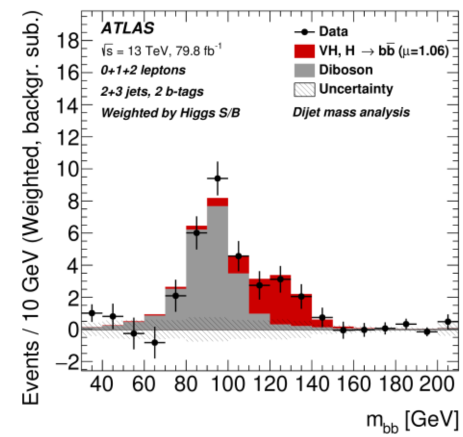
Bosonic channels   Fermionic channels

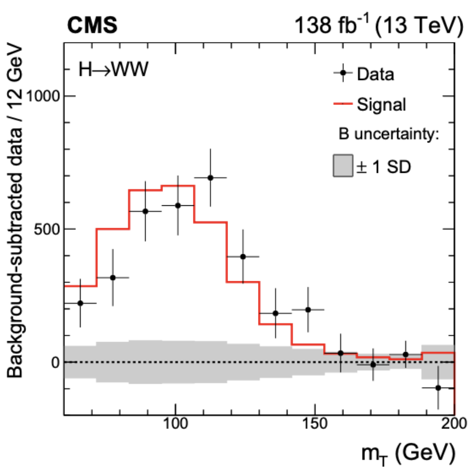
- The discovery channels: γγ, ZZ (high sensitivity, high resolution),WW, (high sensitivity, low resolution) dominated Run 1 results, **precision** in Run 2.
- H -> bb (low sensitivity, low resolution) observed, H -> **cc, μμ, Zγ**, evidence with Run 2.

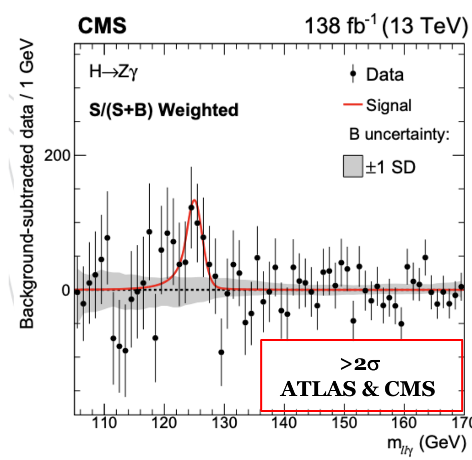




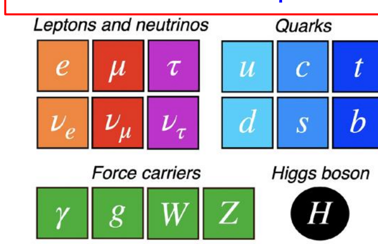


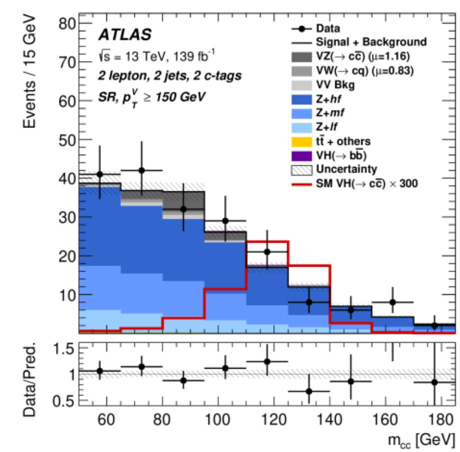






These are the ATLAS/CMS
Run-2 legacy results!
Full run-2 data sample



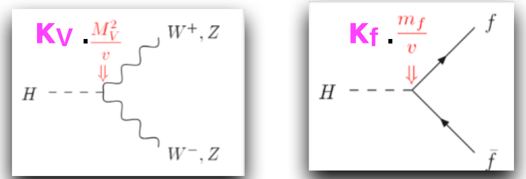


Nature 607 (2022) 52
Nature 607 (2022) 60

Higgs couplings

CMS: Nature 607 (2022) 60

Coupling modifier interpretation



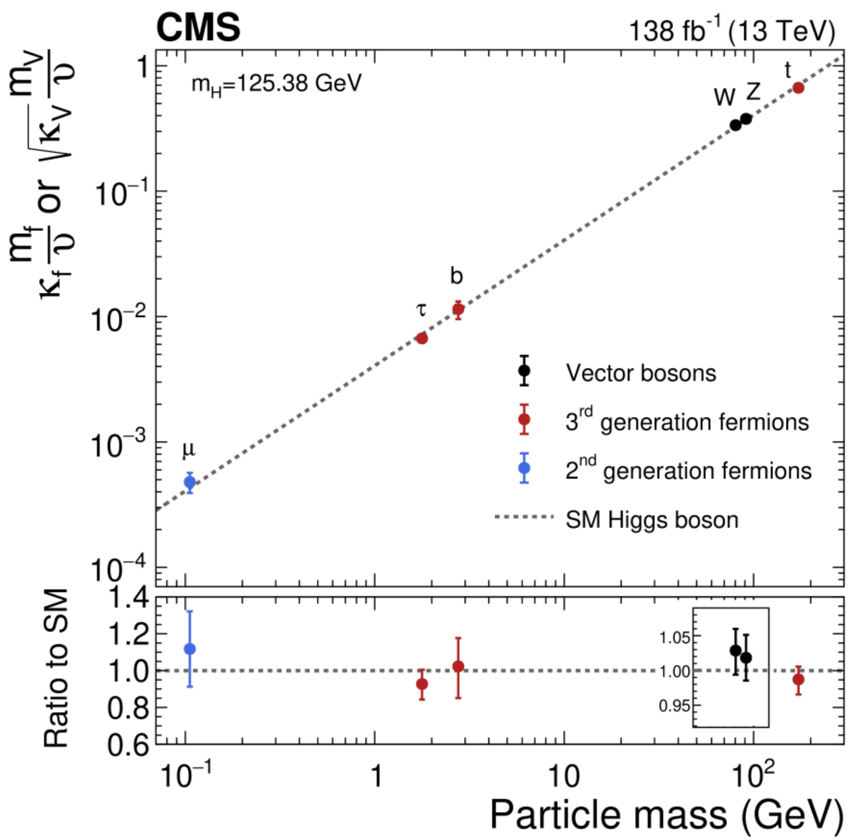
$$\sigma(i \to H \to f) = \sigma_i B_f = \frac{\sigma_i(\boldsymbol{\kappa})\Gamma_f(\boldsymbol{\kappa})}{\Gamma_H(\boldsymbol{\kappa}, B_{\text{inv.}}, B_{\text{u.}})}$$

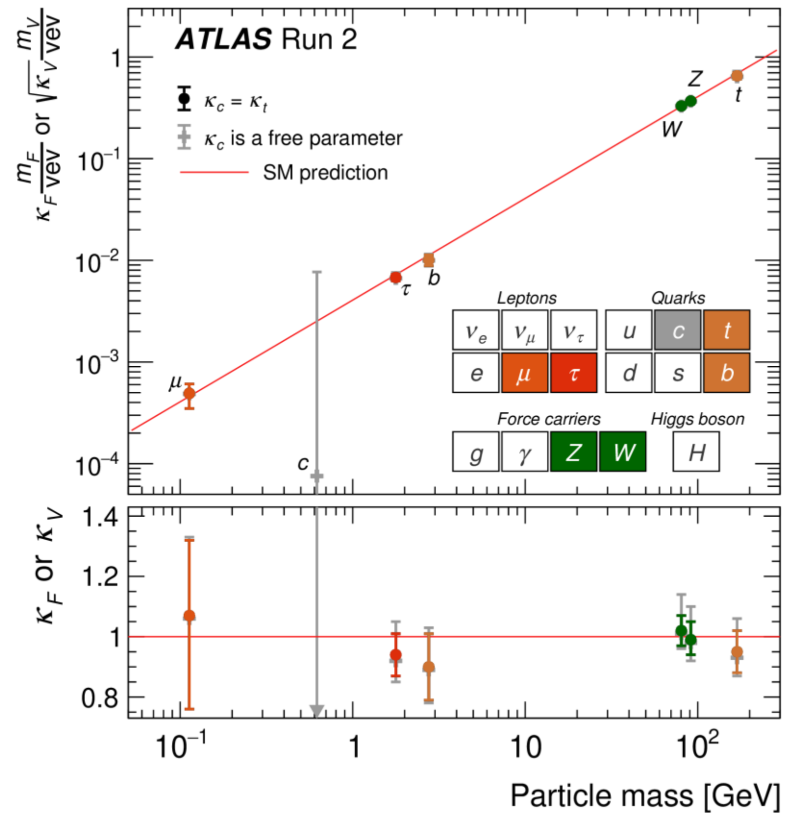
Nature 607 (2022) 52

ATLAS-HIGG-2023-011 arXiv:2404.05498

$$\sigma_i \times B(H \to f) = \frac{\kappa_i^2 \kappa_f^2}{\kappa_H^2} \sigma_i^{\text{SM}} \times B^{\text{SM}}(H \to f)$$

Determine coupling modifiers for **W/Z bosons**, **t** and **b** quarks, **τ** and **μ**.



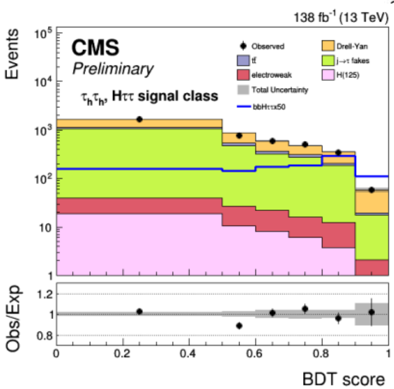


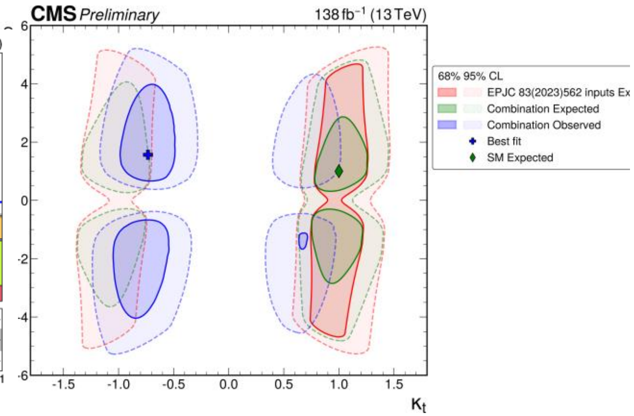
SM test over many orders of magnitude

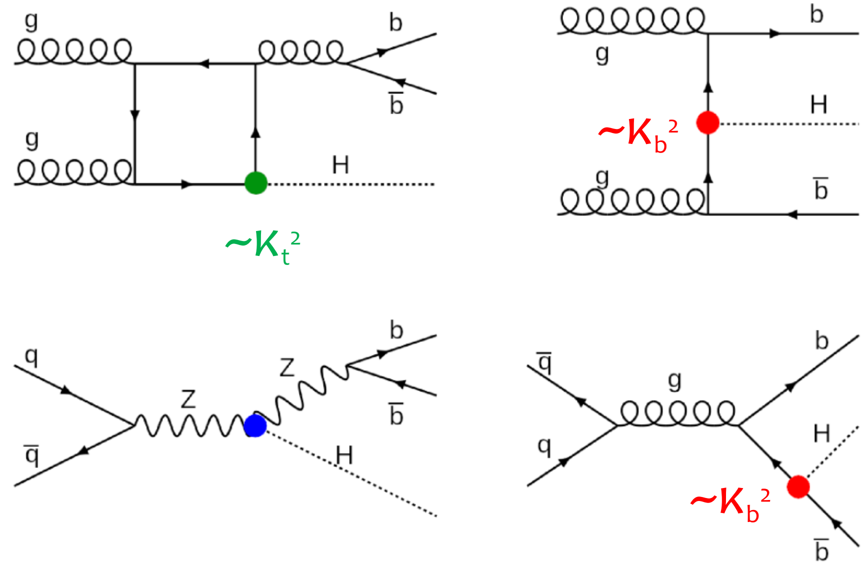
CMS: bbH

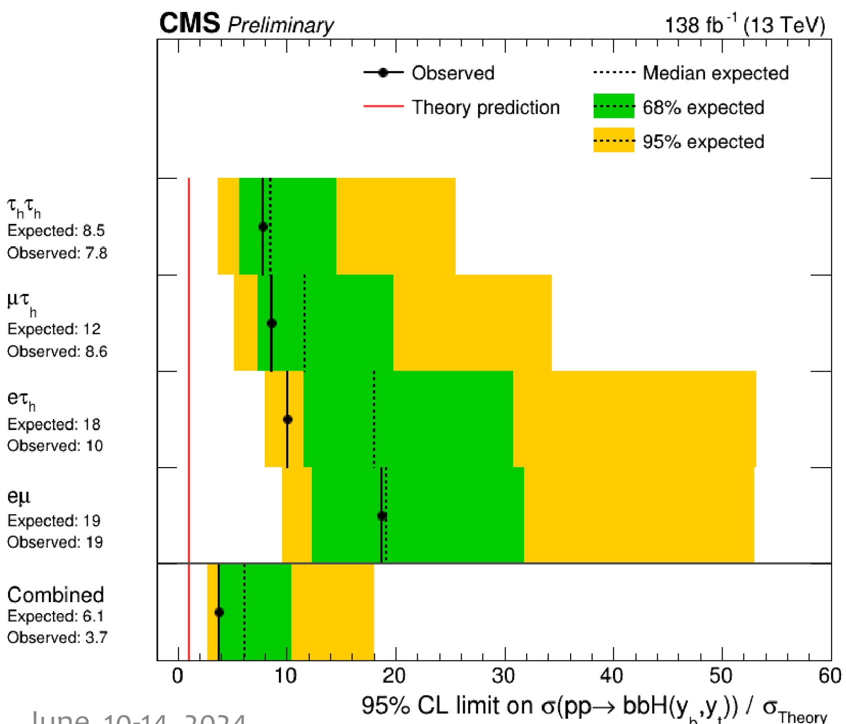
CMS PAS HIG-23-003

Large Run 2 data set ➔ probe rare Higgs production processes









- First search for bbH associated production (via b-fusion and gluon fusion) released by CMS, in **H → ττ** or **H → WW* → 2τ/ℓ+2ν** events.
- Interference between diagrams with or without H-bb coupling.
- **Sensitivity to bbH production at the level of 6 times SM prediction.**
- **Constraints** in **κ_t, κ_b** plane, combining with non b-associated H➔ττ measurement

ATLAS and CMS **VH** production

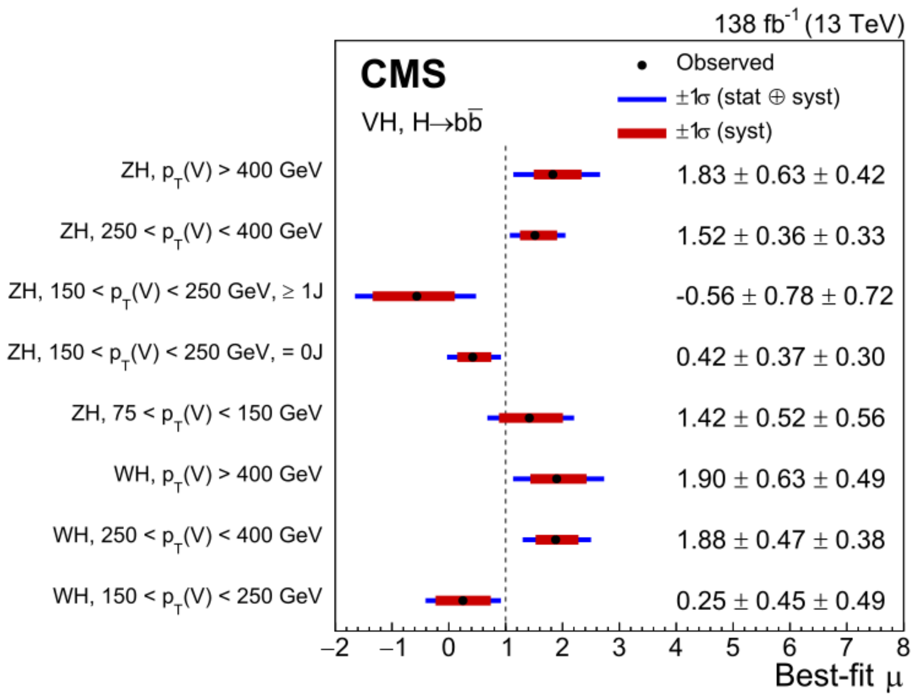
Relatively rare production process, study in large-branching fraction final states **ττ** or **bb**, and rely on multivariate analysis techniques (NN) to improve sensitivity

Final states based on the vector boson decay mode

0 leptons ($Z \rightarrow \nu\nu$), 1 lepton ($W \rightarrow e\nu, W \rightarrow \mu\nu$) or 2 leptons ($Z \rightarrow ee, ZZ \rightarrow \mu\mu$)

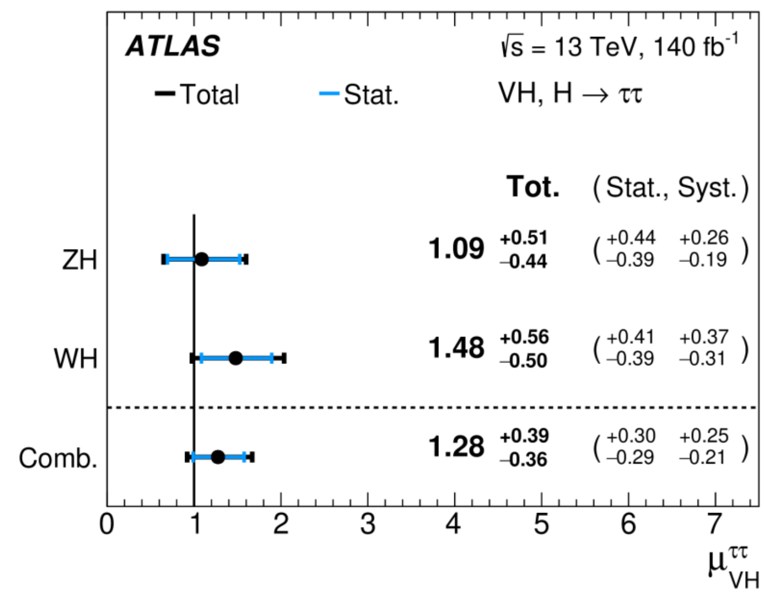
Inclusive **μ=1.15±0.21**, per-production mode signal strengths **and STXS**

arXiv:2312.07562 (acc. by PRD)



H → ττ: $\tau_{had}\tau_{had}, \tau_{had}\tau_e, \tau_{had}\tau_\mu$, dominant background: $W(\ell\nu)Z(\tau\tau)$ for WH and $ZZ \rightarrow 4\ell$ for ZH.

arXiv:2312.02394 (sub. to PLB)

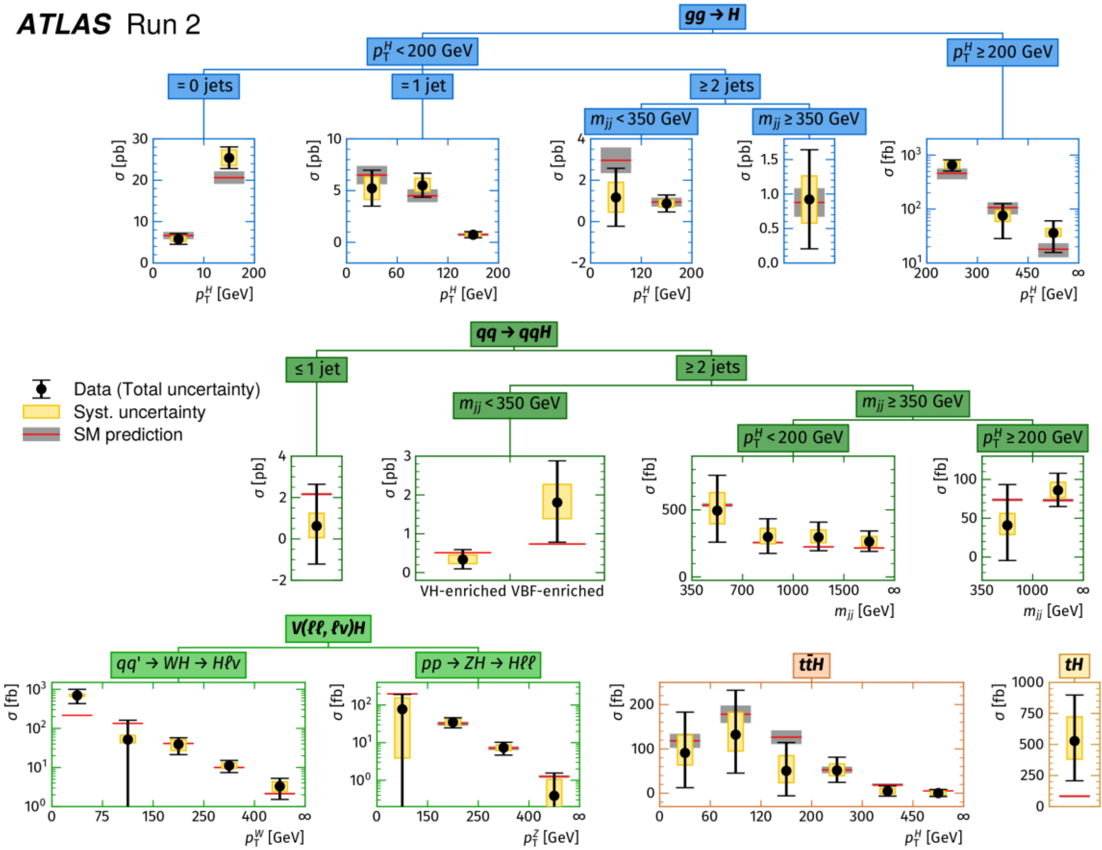


Observed (expected) significance of **4.2 (3.6)** standard deviations

Probing new physics with precision: STXS

Nature 607 (2022) 52
ATLAS-HIGG-2023-011
arXiv:2404.05498

Simplified template cross sections: STXS framework, a logical evolution of the per process signal strength
LHCXSWG YR4



Measurements from ATLAS and CMS as a function of *many* observables: Higgs momentum (p_T), extra jets, angles, etc., separated by production & decay

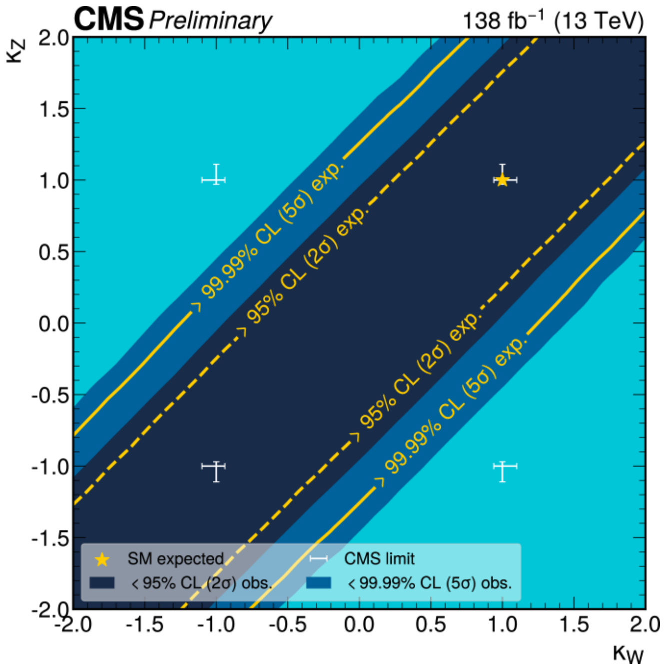
Measurement definitions are common for ATLAS, CMS and theory to ease combination, minimize theoretical uncertainties and maximize experimental sensitivity

Measurement in exclusive fiducial Regions phase space ("bins") specific to the different production modes.

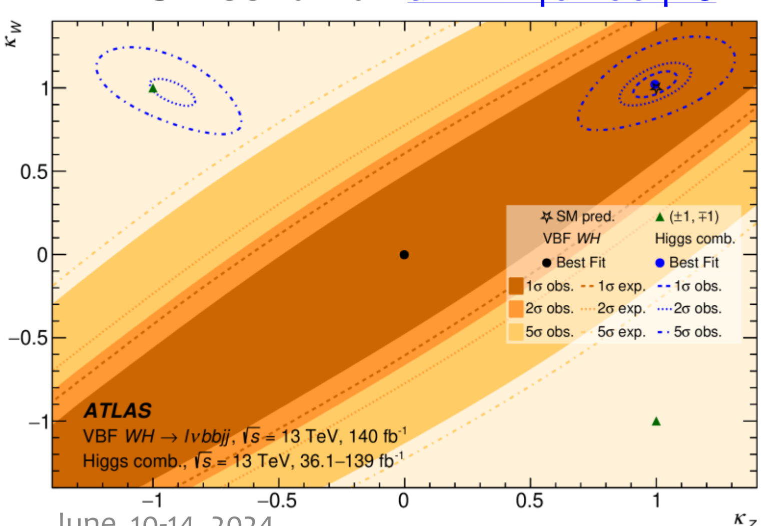
- **Isolate possible BSM contributions in high p_T and high mass bins.**
- Could see signs of new physics with particles too heavy to create at the LHC: **Effective Field Theory (EFT)**
- **Increasing level of precision**

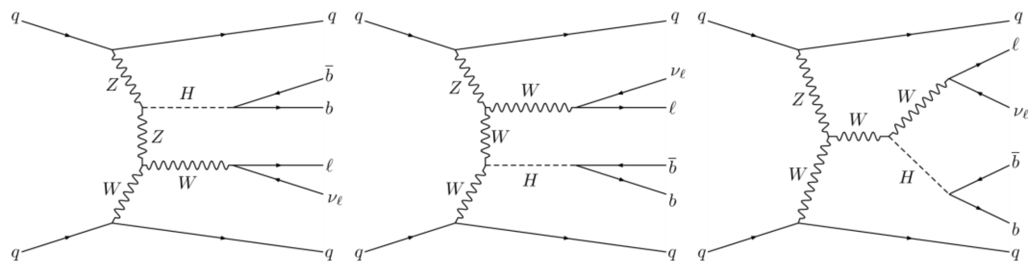
Sign of Higgs coupling to W vs. Z

CMS PAS HIG-23-007



ATLAS-HIGG-2021-021 arXiv:2402.00426





- VBF production of WH sensitive to relative sign $\lambda_{WZ} = \kappa_W / \kappa_Z$
- New from ATLAS and CMS, Higgs coupling to W and Z have same sign
  - Opposite-sign couplings would create excess WH events via **vector-boson scattering (VBS)** with high transverse momentum (p_T "boost")
- ATLAS looks for 2 small jets from H → bb, CMS uses 1 large-radius jet (boosted Higgs), both obtain similar measured precision
- The opposite-sign coupling hypothesis λ_{WZ} **<0**, is excluded with significance much greater than **5σ**

ATLAS + CMS: **H → Zγ**

Phys. Rev. Lett. 132 (2024) (arXiv:2309.03501)

ATLAS and CMS together obtained **first evidence of H → Zγ decays**

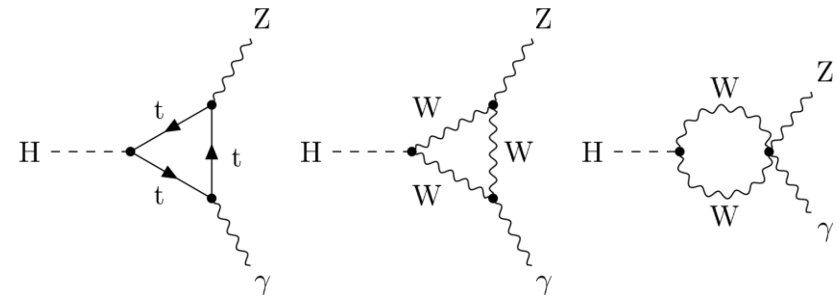
*Only 0.15% of all Higgs decays … and **0.01%** when Z → ℓℓ is required*

Loop processes sensitive to possible higher-mass particles Beyond the Standard Model (BSM)

Observed [expected] signal strength

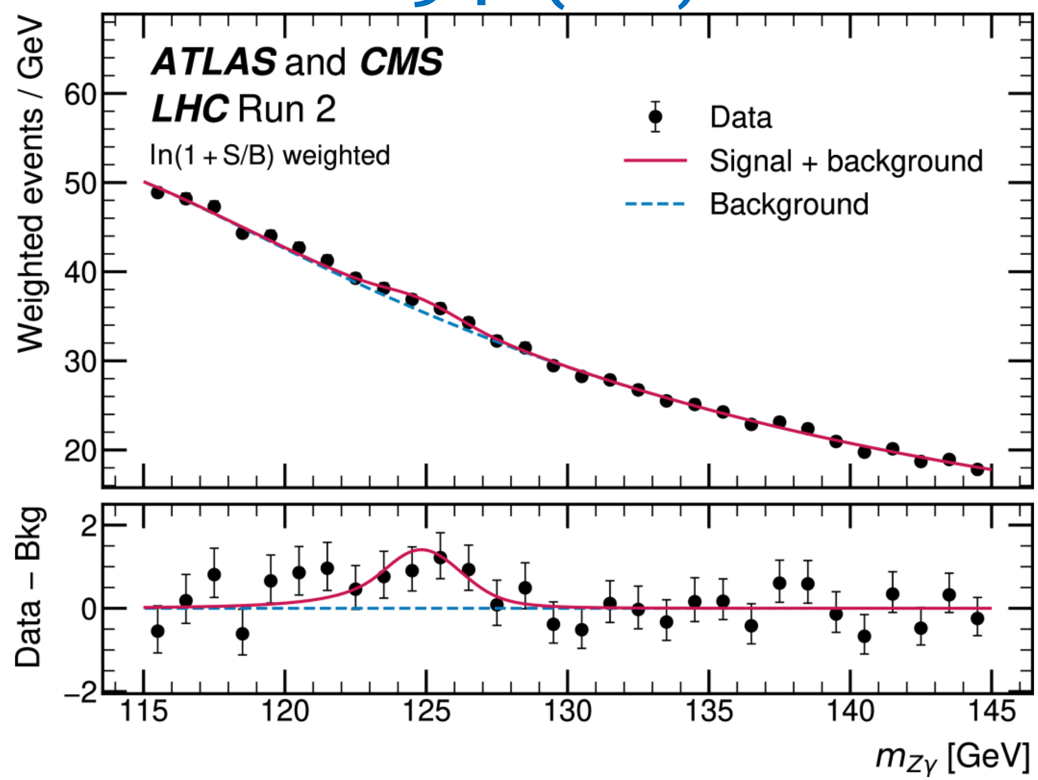
$\mu = 2.2 \pm 0.6(\text{stat})\ ^{+0.3}_{-0.2}(\text{syst})$

$[1.0 \pm 0.6\ (\text{stat}) \pm 0.2\ (\text{syst})]$



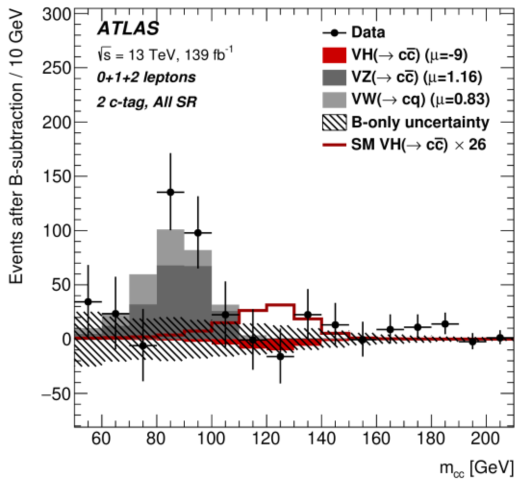
Observed (expected) local significance:

3.4σ (1.6σ)



ATLAS:Higgs coupling to charm quark

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



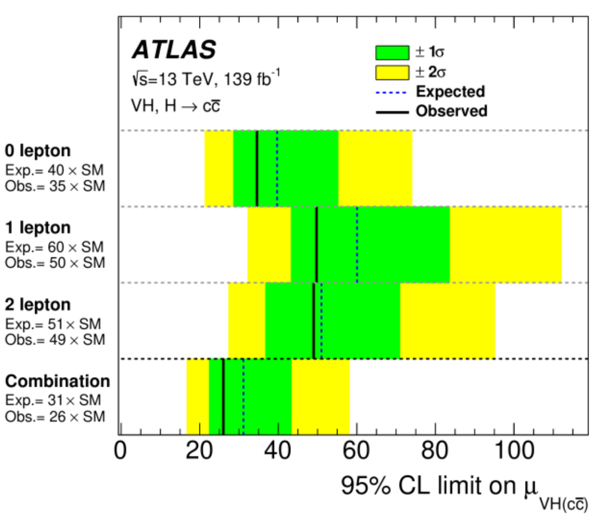
Inclusive H → cc decay search with 139 fb^{-1}:

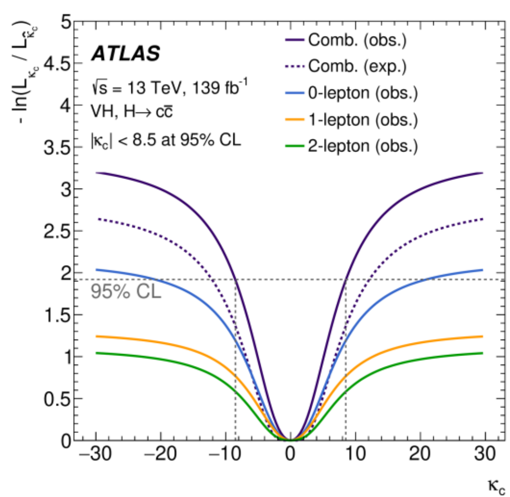
- *pp* → VH → *ℓℓcc*, *or ℓ νcc or νν cc*, **charm-jet tagging**
- Control regions to constrain the ttbar and W/Z+jets backgrounds.
- Constraints on $\boldsymbol{k_c}$ when all the other Higgs couplings are SM like is set to $\boldsymbol{k_c}$**< 8.5 at 95 %CL**

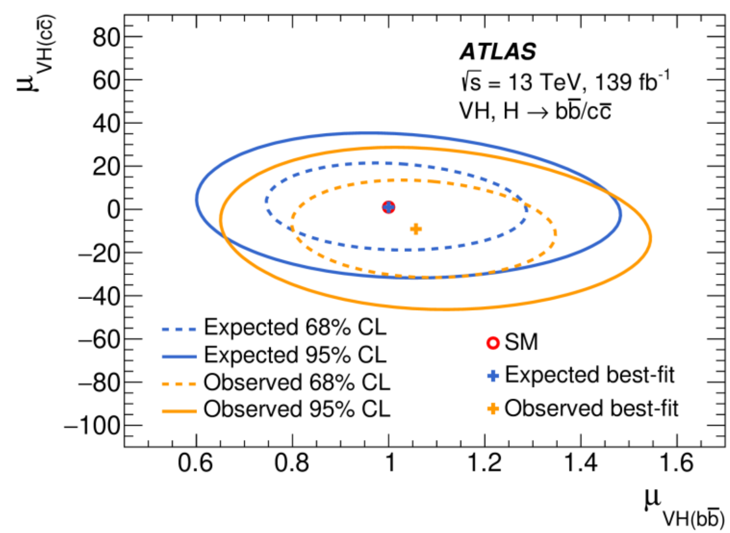
μ(VH, H→*cc*) < 26(31) obs(exp) at 95% CL

Average efficiency of 27% to tag c-jets in simulated tt̄ events, and b- and light-jet misidentification rates of 8% and 1.6%

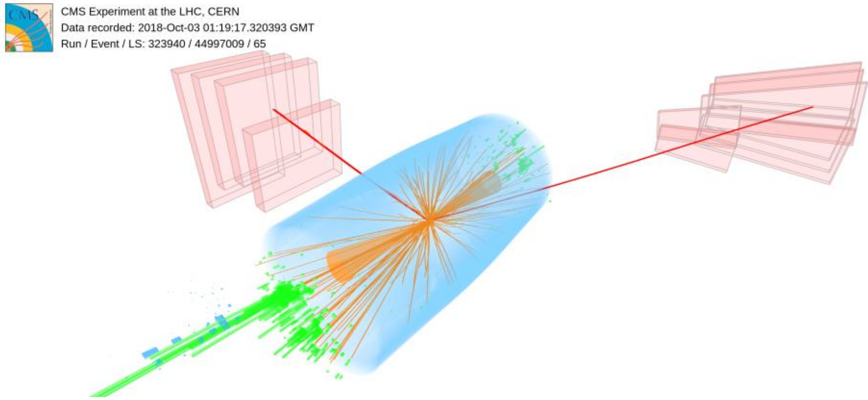
Combination of VHbb and VHcc analyses thanks to the orthogonality of tagging selection

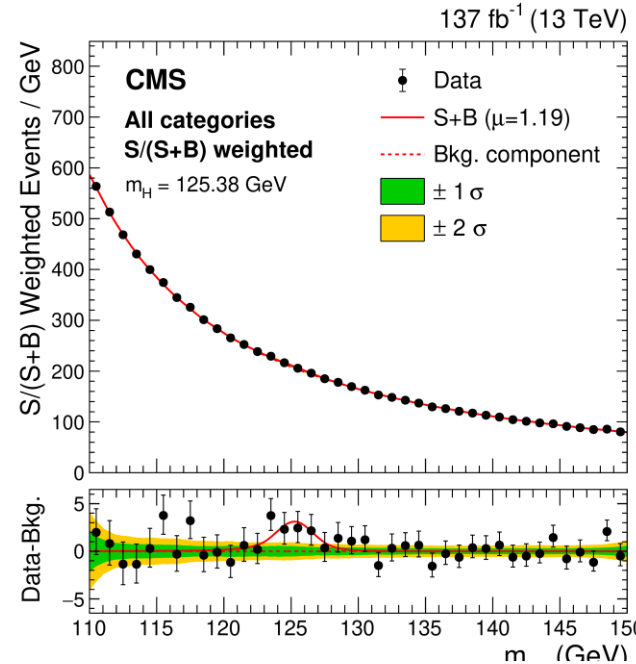




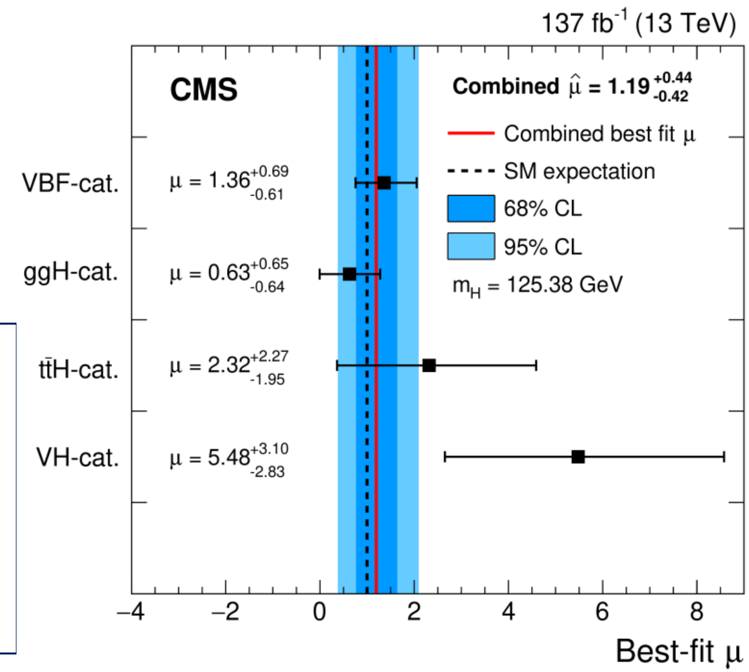


CMS: H→ μμ [JHEP 01 (2021) 148]





- **Yukawa couplings between H and muons**
  - **Trigger: Single Muon**
- **Multiple categories targeting different Higgs production modes**
- **Main channels: ggH and VBF productions**

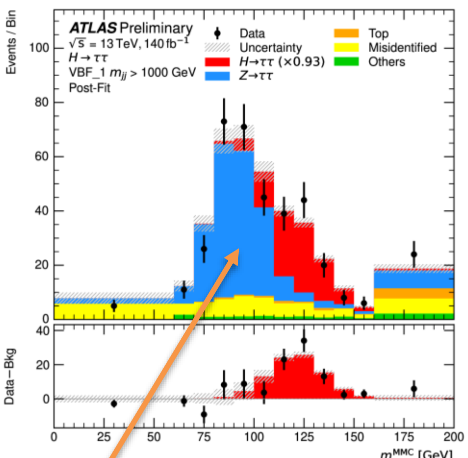


- **Signal strength: $\mu = 1.19^{+0.44}_{-0.42}$**
- **$0.85 < k_{\mu} < 1.29$**
- **First evidence of H decay to muons (3.0 std dev)**

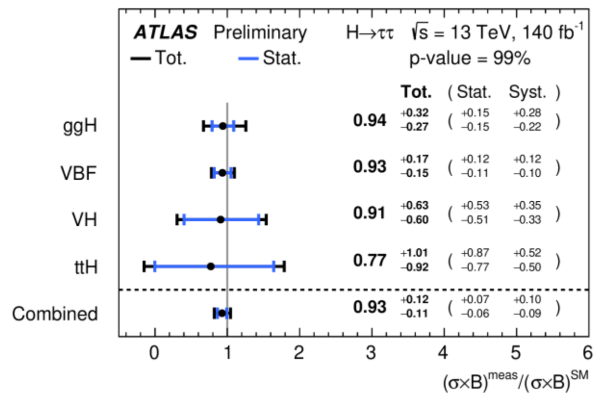
ATLAS STXS H → ττ

ATLAS-CONF-2024-007

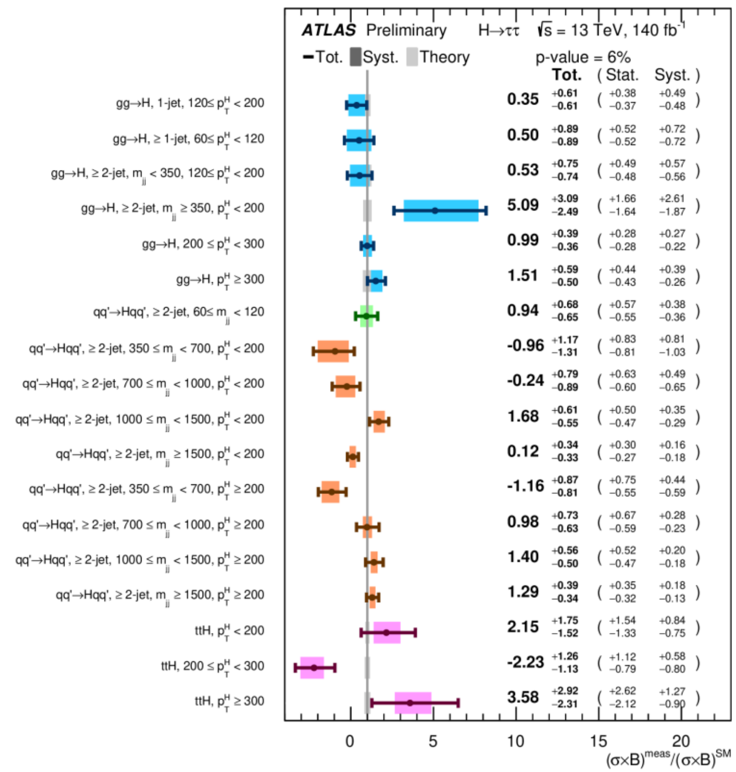
- Number of measured STXS bins doubled wrt previous measurement, Higgs production with decays in 18 STXS bins
  - Most precise VBF production measurement and also probes high $p_T(H)$
  - $p_T(H)$ reconstruction using novel NN exploiting E_T^{miss} and ττ variables.
  - ML methods: BDT for VBF categories, enhance separation between VBF and ggH/Z → ττ; multiclass BDT for ttH categories to separate ttH from tt and Z → ττ.



Main background Z → ττ, template shape and embedding

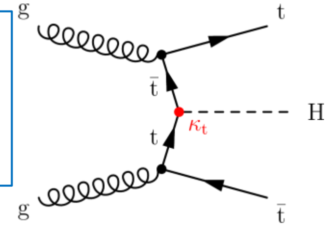


VBF, slightly better precision wrt last publication due to improved categorization.
ttH, refined MVA leads to 25% improvement.

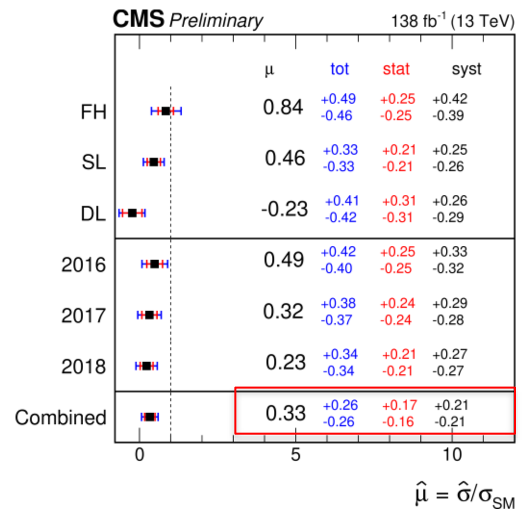


ttH, H→bb

Latest **ATLAS** results
Phys. Lett. B. 849 (2024) 138469
Probing the CP nature of the top-Higgs Yukawa coupling.

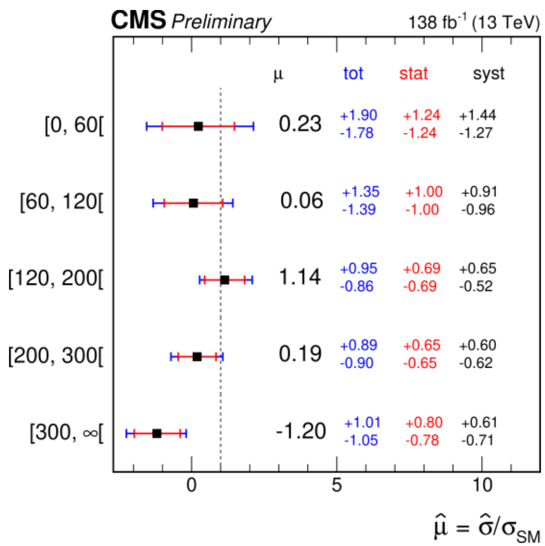


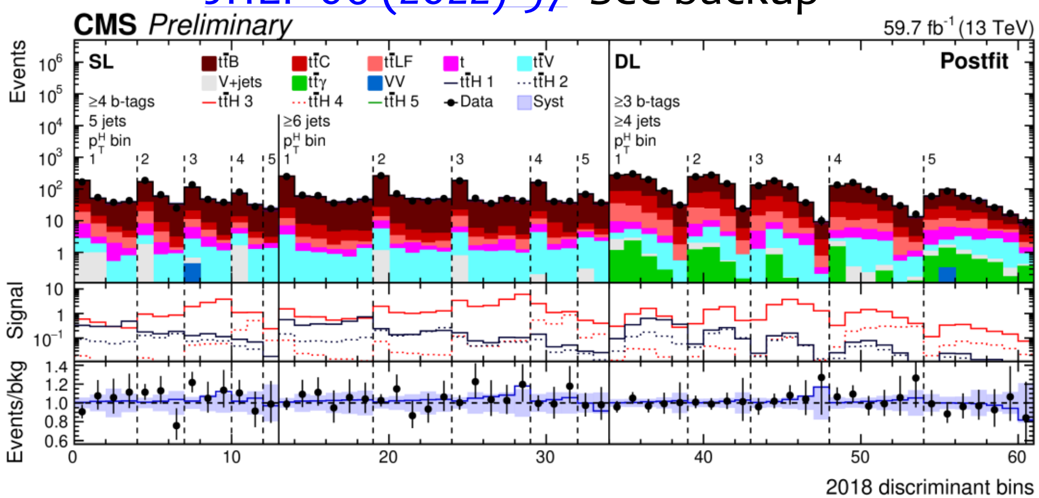
- **CMS-PAS-HIG-19-011 ttH and tH with H→bb in three final states 0,1 or 2 leptons**
- High p_T b jets and depending on channel, jets, isolated electrons , muons or missing transverse momentum
- Dominant background: QCD multijet (0ℓ channel) and tt + jets.
- Normalization of ttB and ttC constrained by fit to data
- ANN used to separate S from B, binary (0ℓ) or multi classification (1ℓ, 2ℓ)
- **Obs. significance of 1.3σ (exp. 4.1σ). Compatibility of ttH signal strength to SM expectation above 2σ.**



ATLAS: μ= 0.35 ± 0.20 (stat) ± 0.29 (syst)

JHEP 06 (2022) 97 See backup

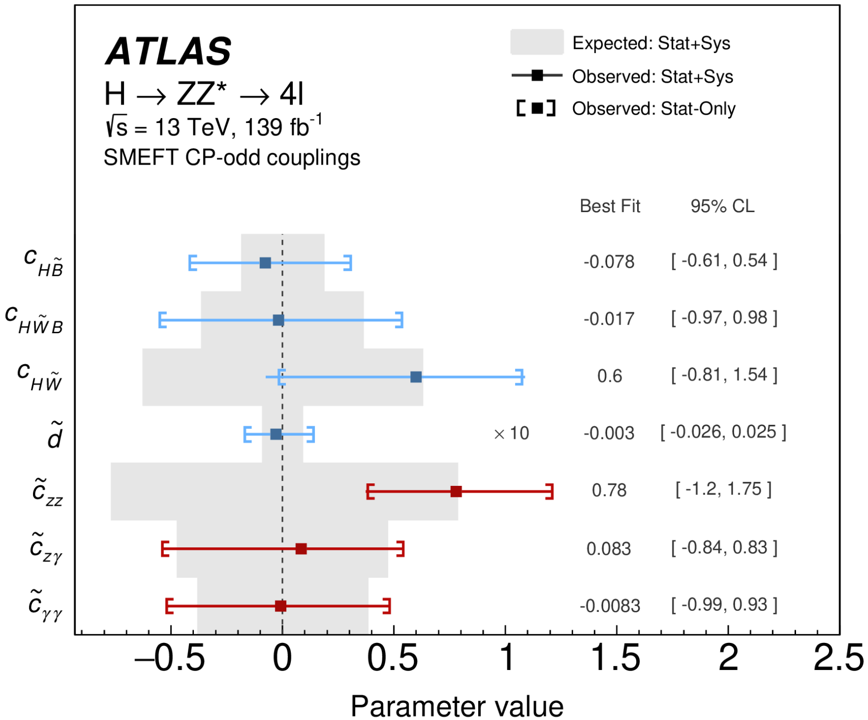




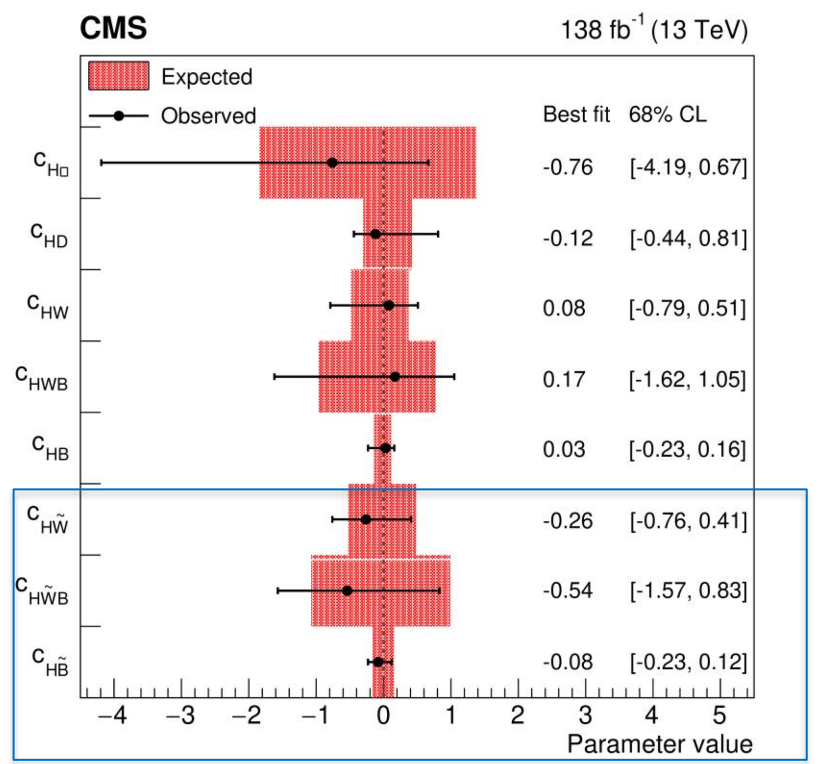
Study of CP symmetry

- EFTs allow to interpret measurements extending the SM with BSM operators of higher order, with possible modifications of rates, branching ratios and kinematics.
- Higgs boson confirmed to be **spin-0**, and consistent with **CP++** since LHC Run 1
- Pure CP-odd state excluded ≠ CP-even state ➔ active field of study
- Compatible with the SM expectation so far

JHEP 05 (2024) 105



arXiv:2403.00657 (acc by EPJC)



Constraints on **CP-odd** Wilson coefficients in SMEFT **H➔ZZ➔4l**

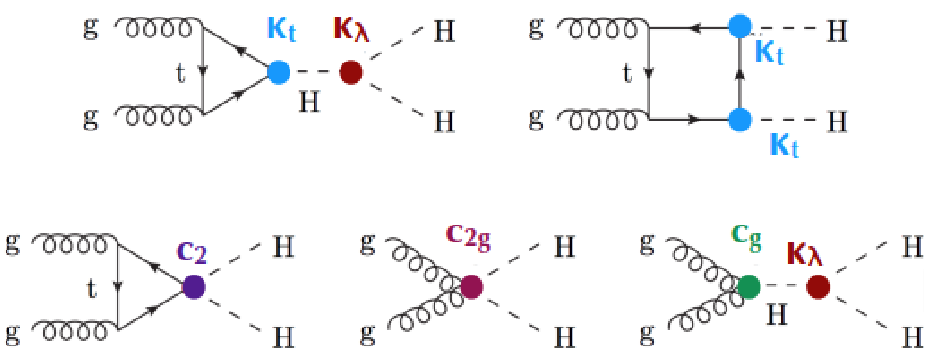
Constraints on **CP-even and CP-odd** Wilson coefficients **H➔WW➔2l2ν**

Search for Double Higgs

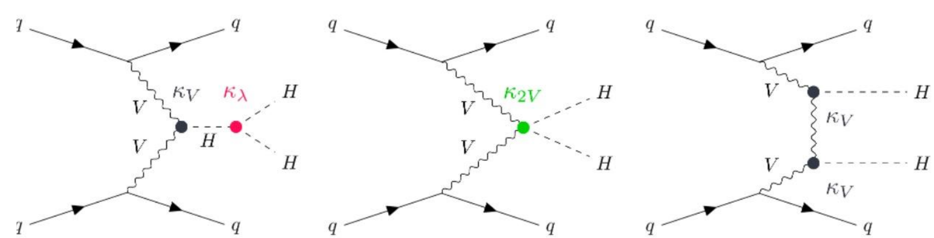
See talks on Thursday from Elvira Martin and Marin Mlinarevic

The measurement of the Higgs boson self-coupling is a fundamental test of the SM as it probes the shape of the Higgs potential. The SM description of the Higgs potential is encoded in two parameters: $\mathbf{m_h}$ and $\boldsymbol{\lambda}$. Given the Higgs boson mass $\mathbf{m_h}$ and VEV v , the Higgs self-coupling $\boldsymbol{\lambda = m_h^2/v^2 = 0.13}$ is fully determined.

HH production allows to probe the self-coupling



Vector Boson Fusion (VBF)



- Anomalous Higgs boson couplings has strong effect on cross-section and m(hh) shape
- EFT approach parametrizes new physics modifications to $\kappa_\lambda = \lambda/\lambda_{SM}$ and $\kappa_t = y_t/y_{t,SM}$ and new contact interactions c_2 , c_{2g} , c_g

Double Higgs production

- The di-Higgs cross section depends on the production mode, but it's ~1000 times rarer than single-Higgs

$$\sigma^{SM}(pp \rightarrow HH) \sim \frac{1}{1000} \cdot \sigma^{SM}(pp \rightarrow H)$$

Gluon-Gluon Fusion

Leading HH production mode

Destructive interference between square and triangle, $\boldsymbol{\sigma_{ggF}}$ **= 31.05 fb** @NNLO

Direct access to k_λ

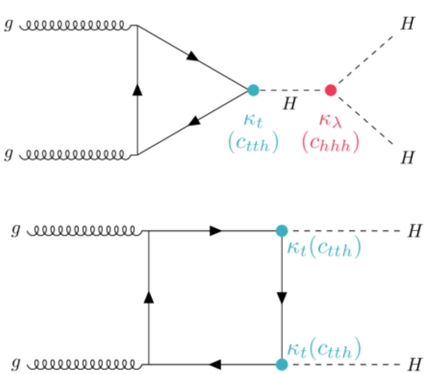
Vector Boson Fusion

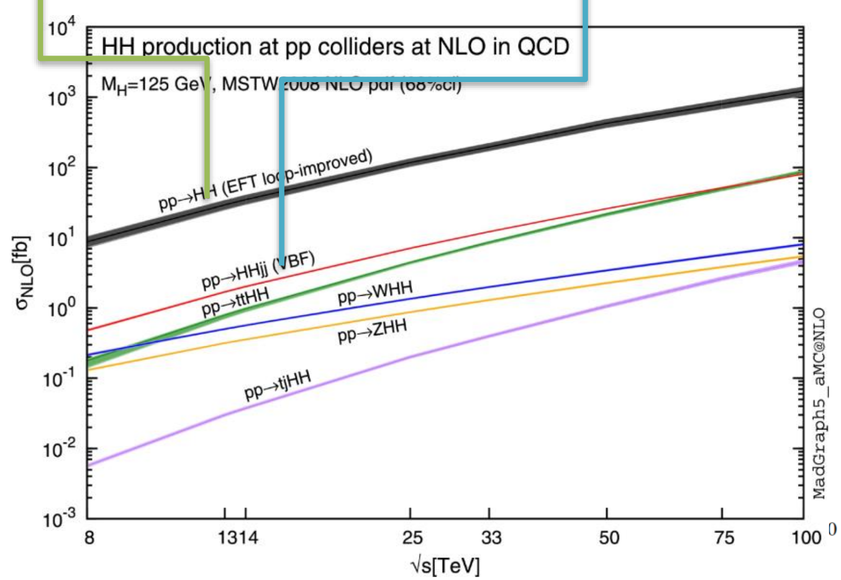
Second leading production

Signature from high energy jets

$\boldsymbol{\sigma_{VBF}}$ **= 1.73 fb @N3LO**

Direct access to k_λ, k_v, k_{2v}





in fb

$\sqrt{s}$	13 TeV
ggF HH	$31.05^{+2.2\%}_{-5.0\%} \pm 3.0\%$
VBF HH	$1.73^{+0.03\%}_{-0.04\%} \pm 2.1\%$
ZHH	$0.363^{+3.4\%}_{-2.7\%} \pm 1.9\%$
W^+HH	$0.329^{+0.32\%}_{-0.41\%} \pm 2.2\%$
W^-HH	$0.173^{+1.2\%}_{-1.3\%} \pm 2.8\%$
$t\bar{t}HH$	$0.775^{+1.5\%}_{-4.3\%} \pm 3.2\%$
$tjHH$	$0.0289^{+5.5\%}_{-3.6\%} \pm 4.7\%$

Double Higgs final states

Given the current **luminosity** and the **experimental conditions**, a good sensitivity is achieved with

- **Large branching ratio** ($H \to bb$)
- **Very good selection purity** ($H \to \tau\tau$, $H \to \gamma\gamma$)
- Not a single **golden** channel but at least three very useful.

- **Run 1** Only few channels covered
- **Early Run 2** At least one $H \to bb$ or multileptons
- **Full Run 2** several new final states and production modes investigated by ATLAS and CMS

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

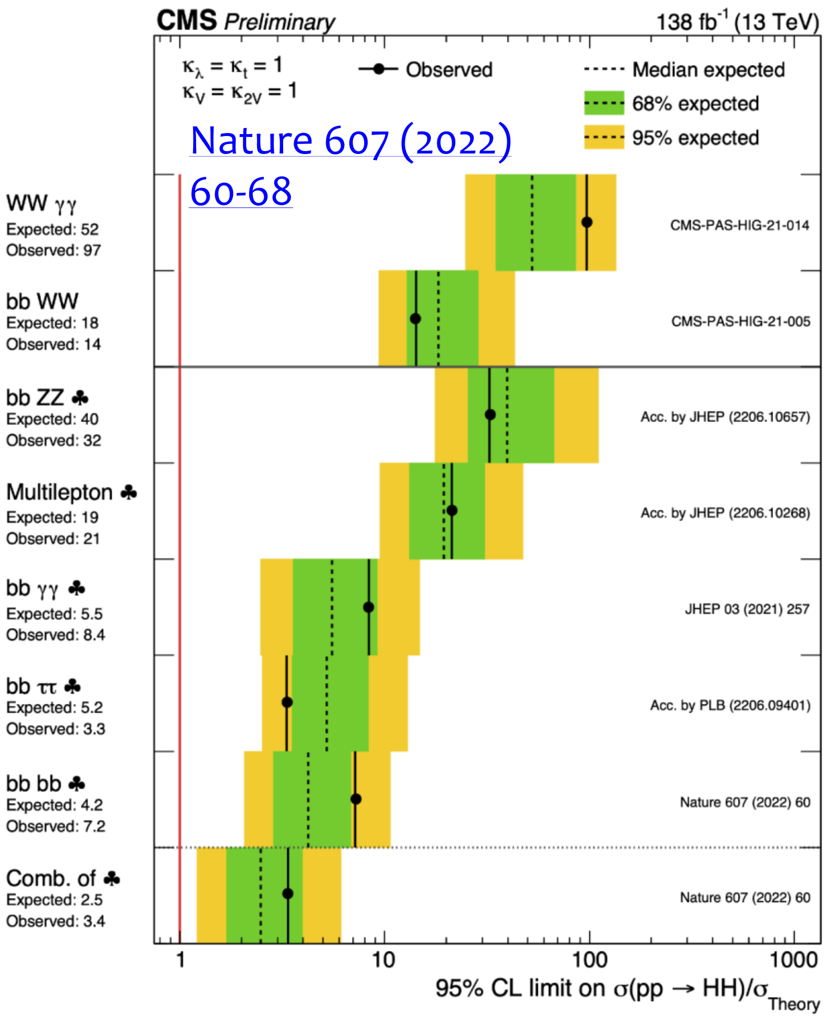
Limits on double Higgs production

No single channel dominates overall sensitivity, **combination** is essential.

Result is a few times SM value already!

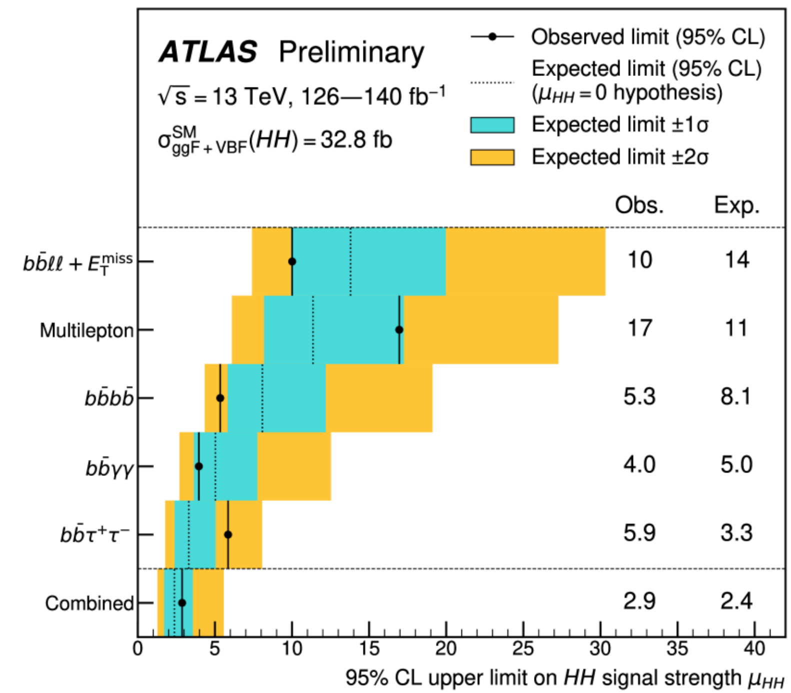
CMS $\mu_{ggF} < 3.4$ (2.5 exp.)

ATLAS $\mu_{ggF} < 2.9$ (2.4 exp.)



Nature 607 (2022) 60-68

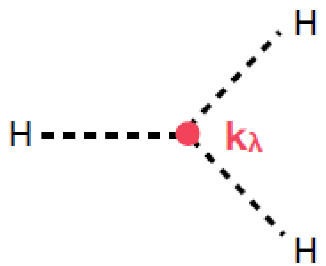
ATLAS-CONF-2024-006

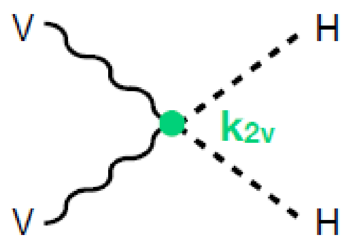


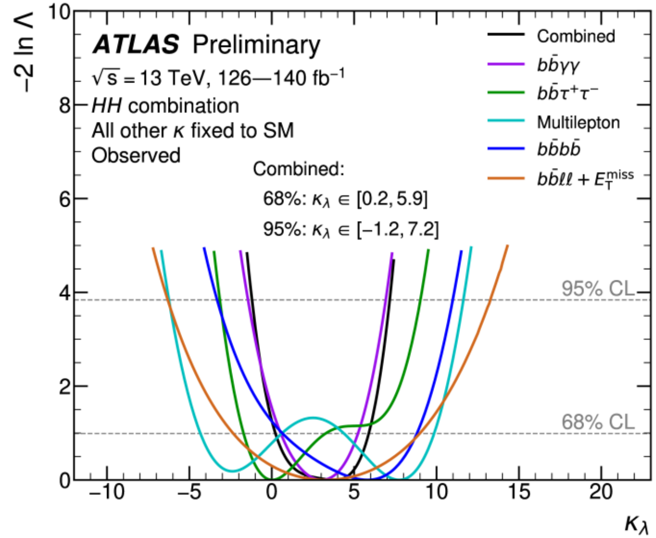
The goal in Run-3 is either to find an anomalous production (resonant or non-resonant) or to set cross-section limits closer to the SM expectation

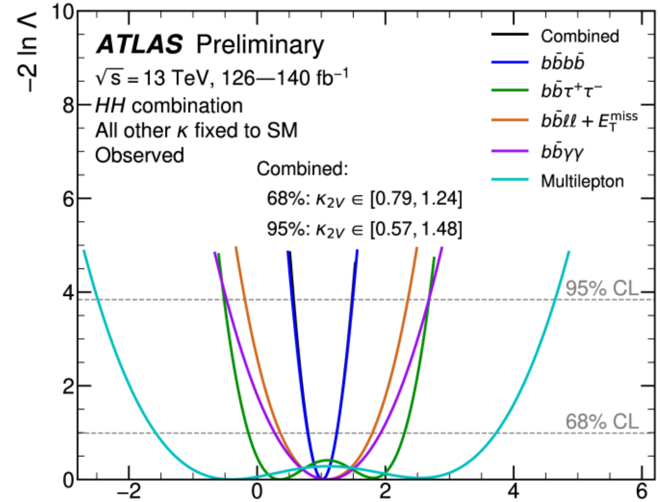
Double Higgs anomalous couplings

The limits on di-Higgs production cross section show a **strong dependence** on the k_λ and k_{2V}

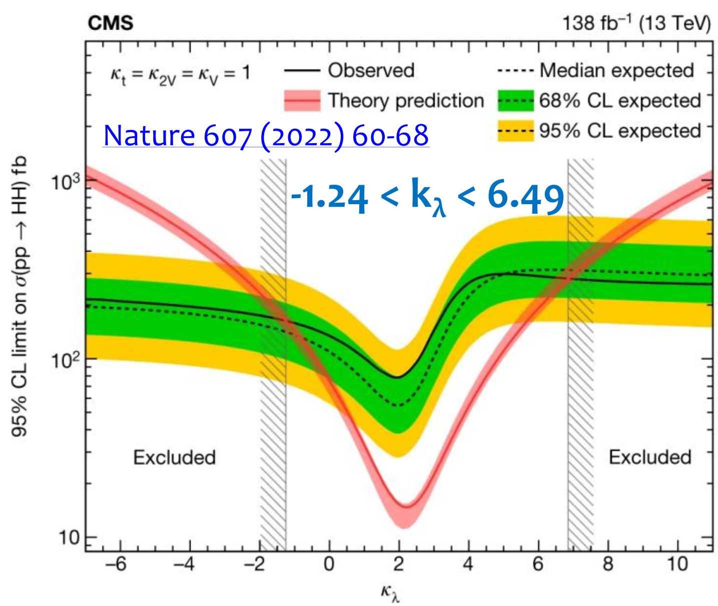


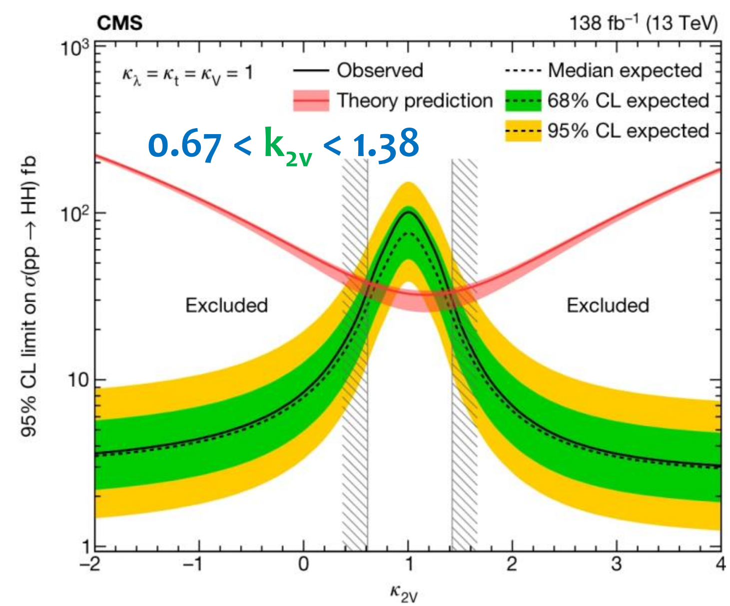






ATLAS-CONF-2024-006



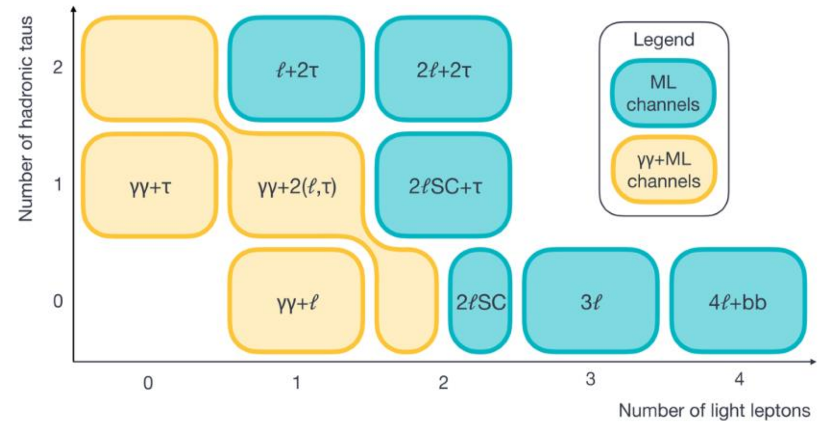


$k_{2V} \neq 0$

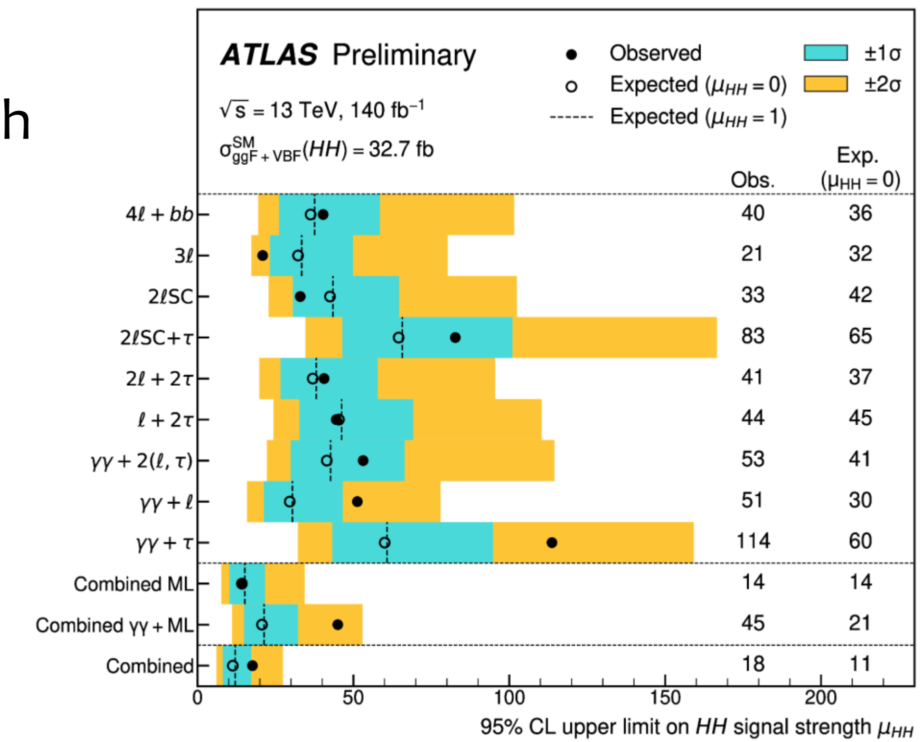
Existence of VVHH coupling

di-Higgs next steps

- To improve sensitivity:
  - More advanced analysis techniques
  - Combination with Single-Higgs
  - Include new final states
  - Investigate new regimes

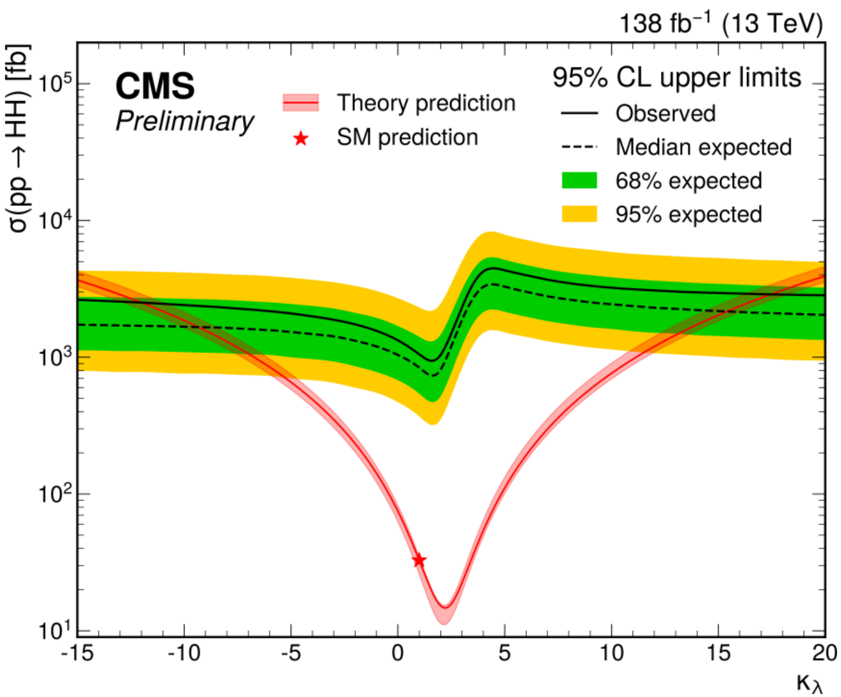


- HH Multilepton (ATLAS), ATLAS-CONF-2024-005: Search for HH production in multilepton decay with a **holistic way**, performed for the **first time by ATLAS**
- Targeting HH→4V, HH→VVττ, HH→4τ, HH→γγVV, HH→bbZZ
- Categories based on multiplicity of e/μ, τ_h and γ
- **$\sigma_{HH} < 18$ (11) σ^{SM}_{HH}**
- **No single channel** dominates the sensitivity

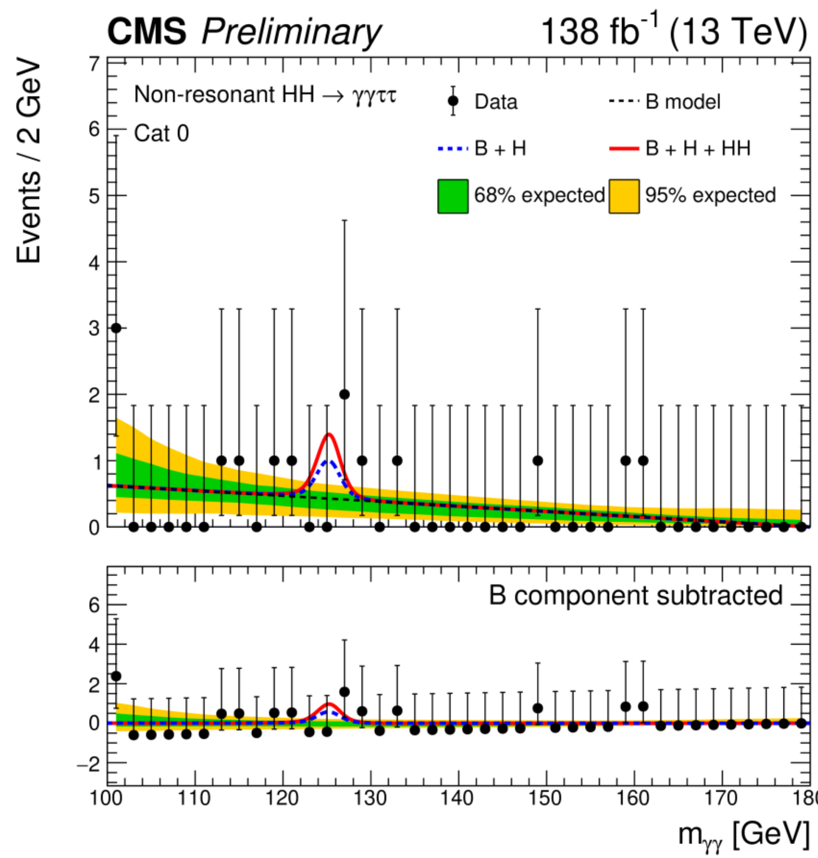


di-Higgs next steps

- Search for HH production in the $\gamma\gamma\tau\tau$ final state, covered for the first time by CMS, [CMS-PAS-HIG-22-012]
- Very low branching ratio but benefit from good di-photon resolution. The main challenge comes from limited statistics
  - Low stand-alone sensitivity, but interesting result when added to combinations



Assuming other H couplings SM-like,
95% CL on k_λ is: $-13 < k_\lambda < 18$, (-11,16 exp.)



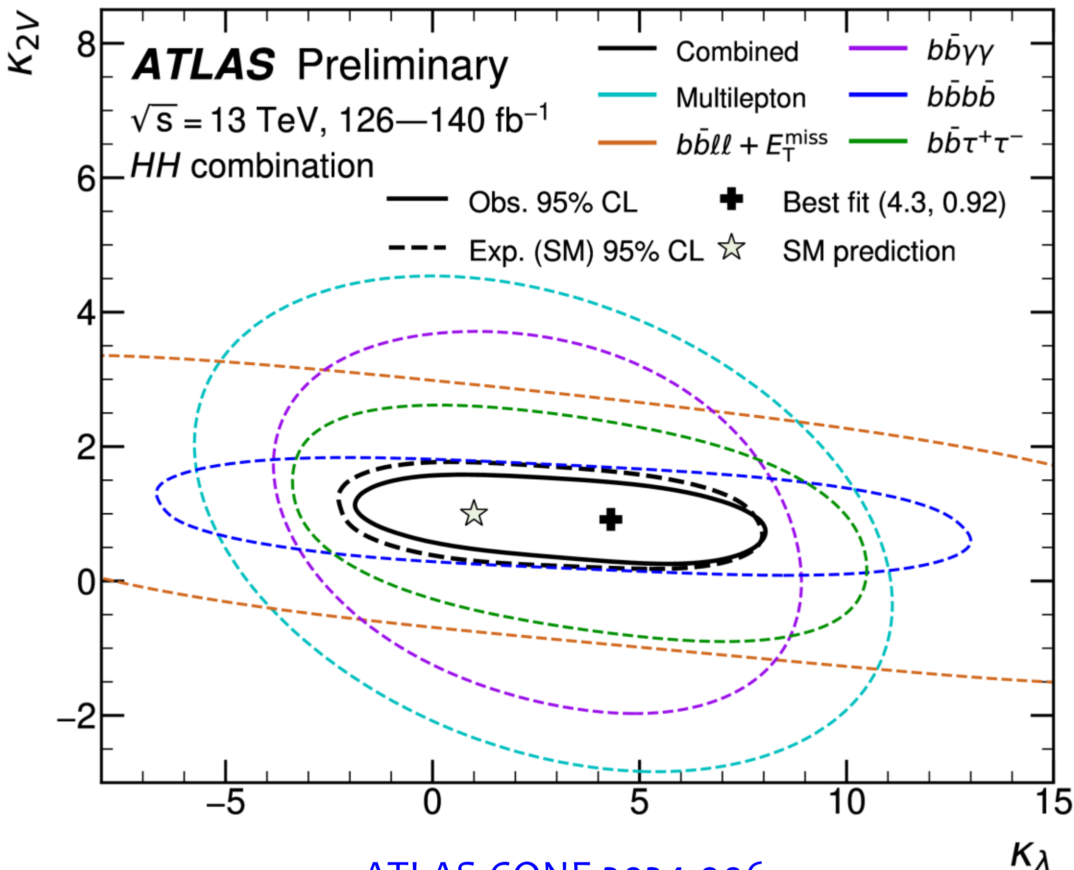
di-Higgs next steps

CMS-PAS-B2G-21-001
arXiv:2404.17193

- VBF HH→4b (ATLAS) via ggF and VBF in resolved and boosted regimes.

Resolved
- H reconstructed as two jets
- Largest fraction of signal
- Large multi-jet QCD background
- Dominates low p_T region

Boosted
- H reconstructed as large jet
- O(%) signal acceptance
- Lower multi-jet QCD contribution
- Improvement in boosted object reconstruction



ATLAS-CONF-2024-006

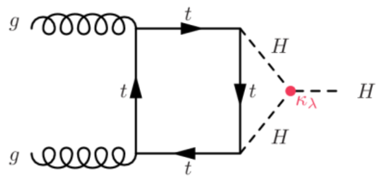
k_λ sensitivity driven by **resolved**

k_{2v} sensitivity dominated by **boosted, $k_{2v} \neq 0$ for any value of k_λ**

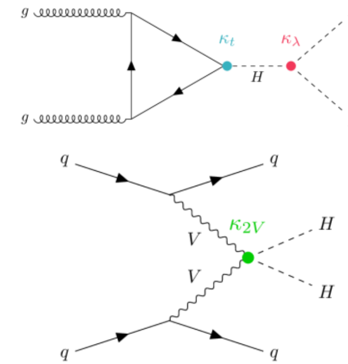
Combination Higgs/di-Higgs

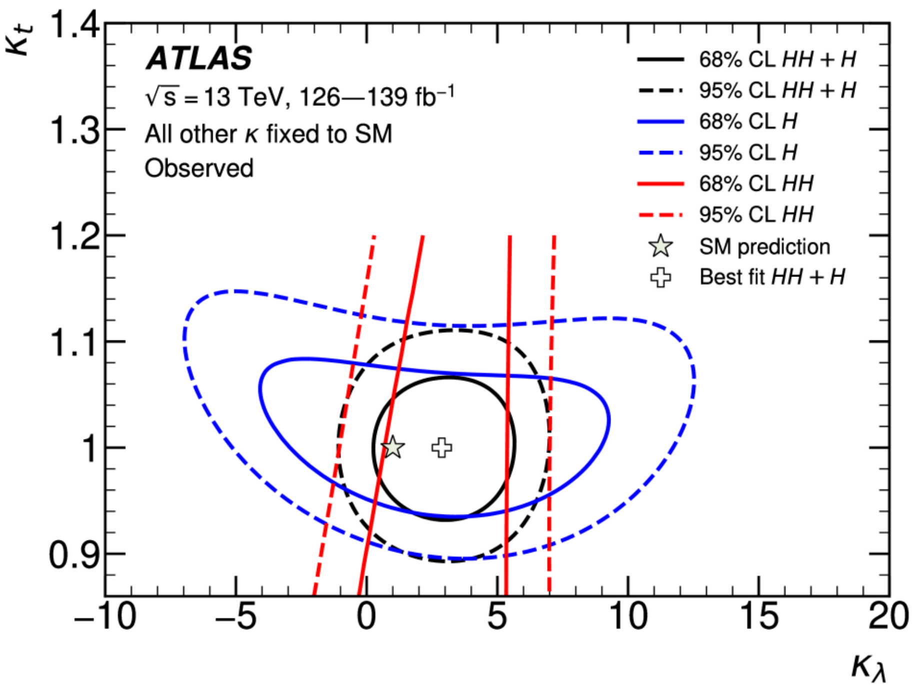
CMS-PAS-HIG-23-006
Phys. Lett. B 843 (2023)

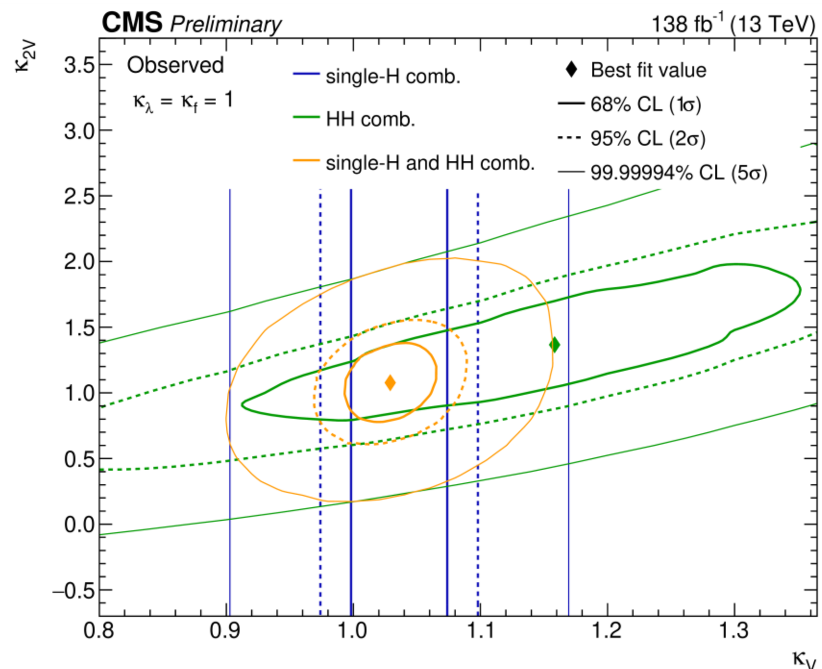
- **Single-Higgs**
- Constrain H couplings to fermions and vector bosons
- Access to k_λ via NLO EW corrections



- **Di-Higgs**
- High sensitivity to k_λ and k_{2V}
- Weak constraints on other couplings







Constraints on k_t and k_v are driven by single-Higgs
Constraints on k_λ and k_{2v} are driven by di-Higgs

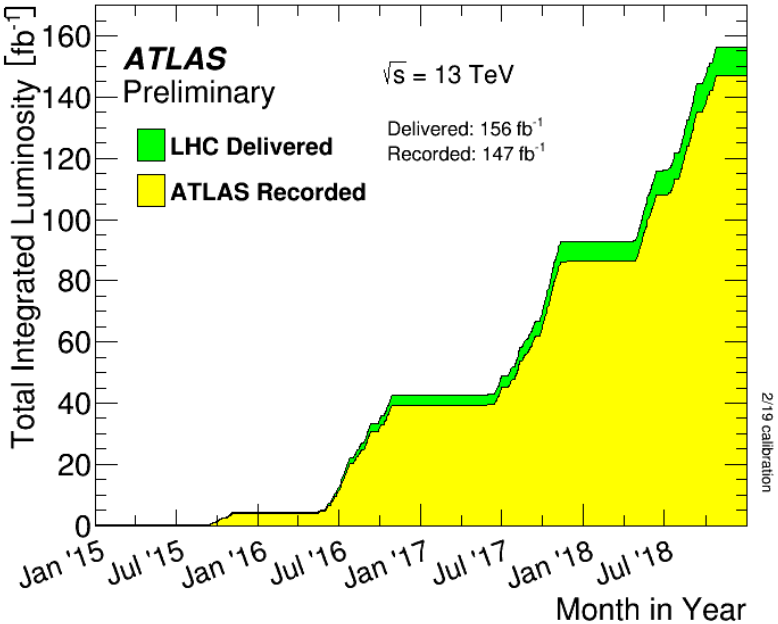
k_{2v} = 0 excluded **at > 5σ** for any value of k_v

Summary

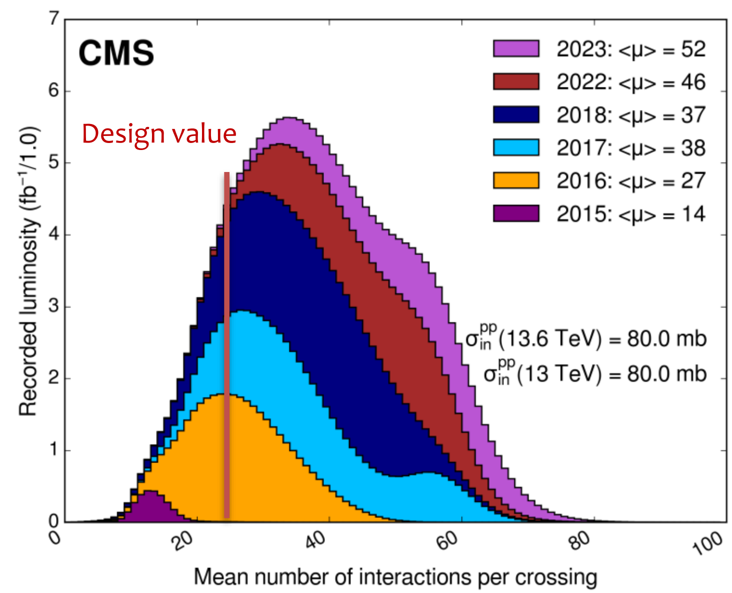
- The Higgs boson particle was discovered in 2012
  - Properties of H boson measured with unparalleled precision by ATLAS + CMS
  - Approaching the ultimate precision from Run 2
  - An enormous effort by a community: reaching from the theorists, the accelerator physicists, computing experts, detector builders and the analyzers ...
- It couples to bosons, to leptons and to quarks of the 3rd generation
  - **Just seen first evidence that it also couples to the 2nd generation**
    - **$H \rightarrow cc$** : most stringent limits on κ_c to date
    - **$H \rightarrow \mu\mu$: 3.0 std dev evidence** of the decay
  - A spectacular improvement in the experimental **HH program** has been achieved during the LHC Run 2:
    - Upper limit on HH cross section by each experiment: $\sigma_{HH} < 2\text{-}3 \times \sigma_{SMHH}$
  - Run 3 well underway ➔ expect more Higgs measurements at 13.6 TeV soon
  - Much more to be learned about the Higgs boson with Run 3 and HL-LHC data !
  - **Precision measurements of the Higgs are increasingly important and, in many aspects, drive the future of HEP**

Backup slides

LHC data taking at 13 and 13.6 TeV:



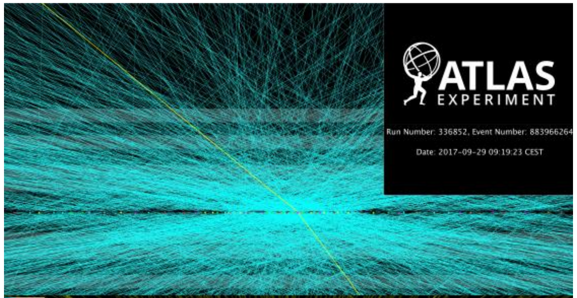
LHC Run-2 data-taking offered an unprecedented physics potential: probing **high-precision Higgs** and other Standard Model processes, detecting very rare processes, and exploring new physics via direct and indirect measurements

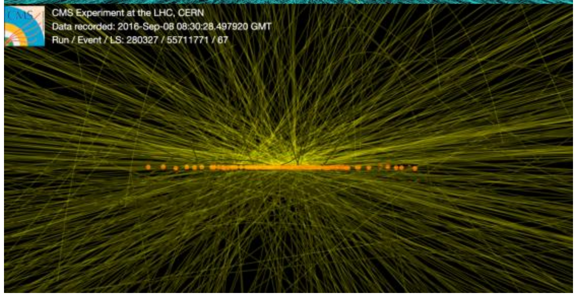


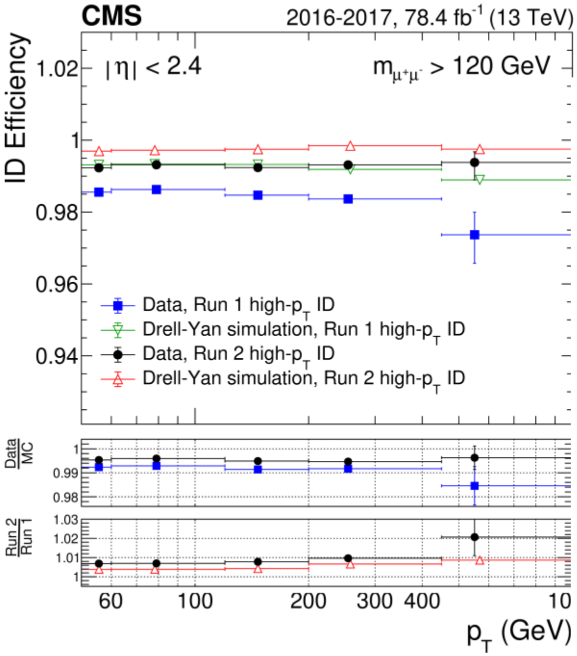
- The LHC had an excellent **Run 2**, delivering ≈ **160 fb^{-1}** to both experiments! (29 fb^{-1} in Run 1)
- Both experiments recorded data with superb overall Run 2 data taking efficiency: **ATLAS 95.6%, CMS 93.4%,**
- After over three years of upgrade and maintenance work, the Large Hadron Collider in July 2022 started its third period of operation **Run 3** with a record-breaking **energy** of **13.6 TeV** and **peak luminosity** of **2 x 10^{34} cm^{-2}s^{-1}** (>**80 fb^{-1} in Run 3**)

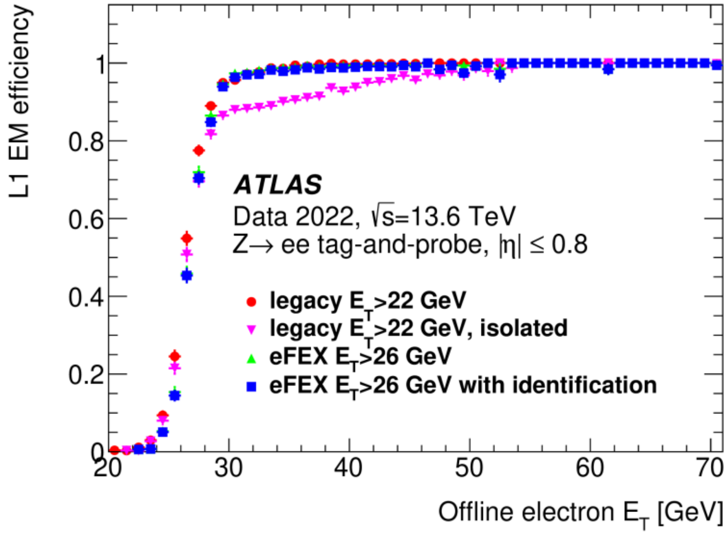
ATLAS and CMS, reconstruction challenges

- Both experiments have excellent reconstruction and calibration performance in the conditions of Run 2 and 3
  - Continuous improvements in the **reconstruction software**, **calibrations**, understandings of efficiencies, systematic uncertainties etc. over a wide p_T range, to cope with Run 3 increase in instantaneous luminosity and pileup









A better understanding of the detectors along with data-driven and machine learning techniques mean that object calibrations and efficiencies are often now better even in the harsher environment of Run 2 and 3

The experimental conditions at the LHC

- **The LHC is a discovery machine: the ultimate goal is to experimentally find the answers to the open questions about fundamental particles and interactions.**

- The big challenge at the LHC is the huge range of cross sections that needs to be understood:
  - Huge cross section for "uninteresting" processes
  - Large cross sections for previously known processes
  - Medium cross section for not so-well studied processes
  - Low cross section for discovery processes
- It should be noted that all challenges at LHC are produced exactly for this reason:
  - Large backgrounds: interesting physics swamped by known processes.
  - Large Pile-Up: to be able to produce some small number of very interesting events, need to produce so many of un-interesing ones that they even happen in the same crossing!
  - Large available energy implies the chance to produce a lot of soft or medium-pT stuff affecting the reconstruction

General Comments on SM Higgs searches and measurements

Blind analysis methods are used in ~all Higgs searches at ATLAS/CMS.

We searched **explicitly** for the SM Higgs boson: most analyses use unique properties of the SM Higgs boson to optimize their search sensitivity relative to known SM backgrounds.

This means that analyses are **model dependent** (i.e., the SM!) to varying degrees, and the significance of an observed excess is within the context of a search for the SM Higgs boson.

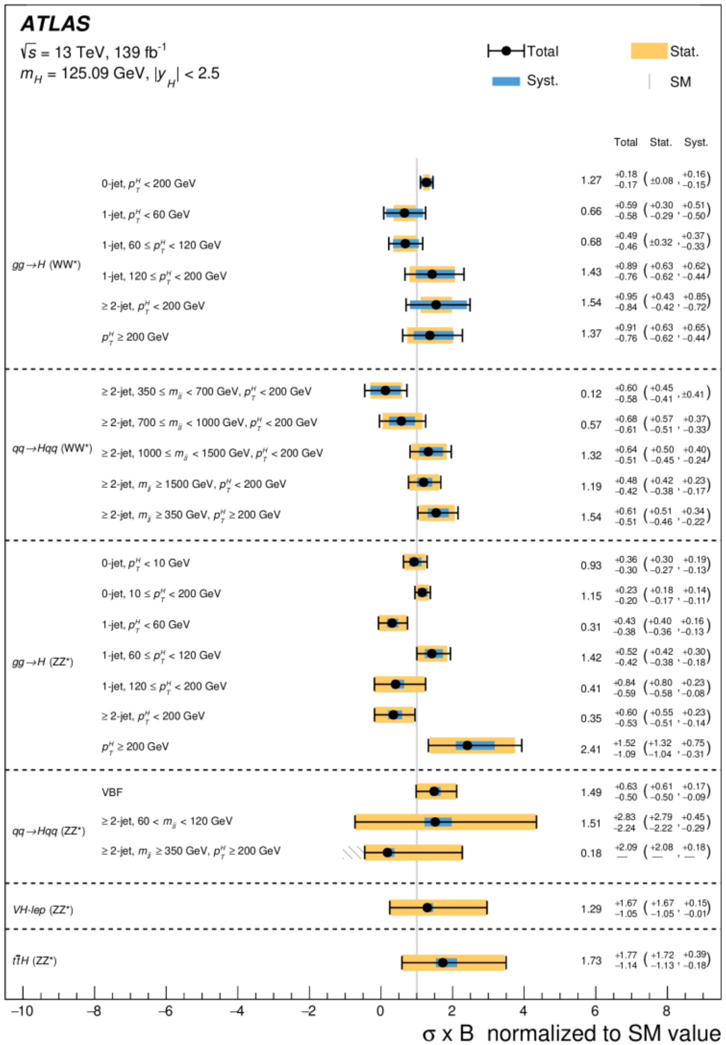
Due to *historical* agreement , we quote 'signal strength' (μ) relative to SM:

$$\mu \equiv \sigma \times \mathrm{BF}/\sigma_{\mathrm{SM}} \times \mathrm{BF}_{\mathrm{SM}}$$

The product of production and decay couplings is what can be measured, then, **the LHC experiments study a multitude of Higgs production and decay modes**, with complementary sensitivities

Probing new physics with precision: STXS

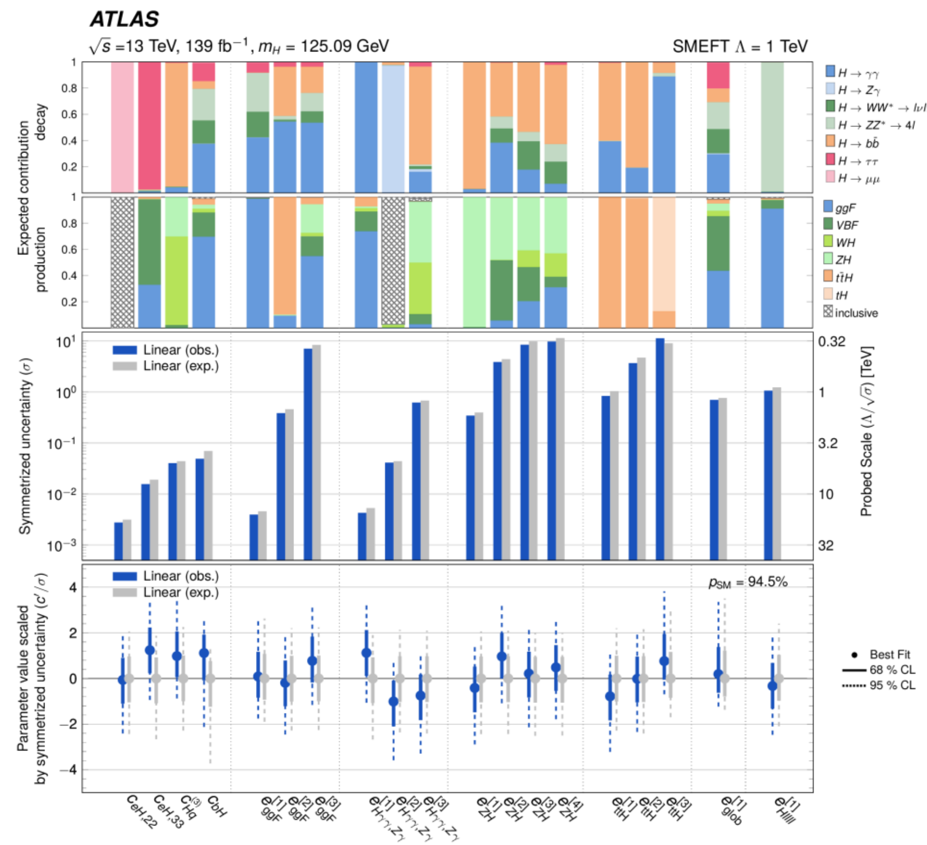
Nature 607 (2022) 52
ATLAS-HIGG-2023-011
arXiv:2404.05498



2499 dim-6 operators ➔ reduced to less than 200 through symmetries

50 remaining CP-conserving operators relevant for Higgs sector

Degeneracies ➔ identify & study **19** independent directions



CMS: Boosted $H \rightarrow \tau\tau$

[CMS PAS HIG-21-017](#) (new)

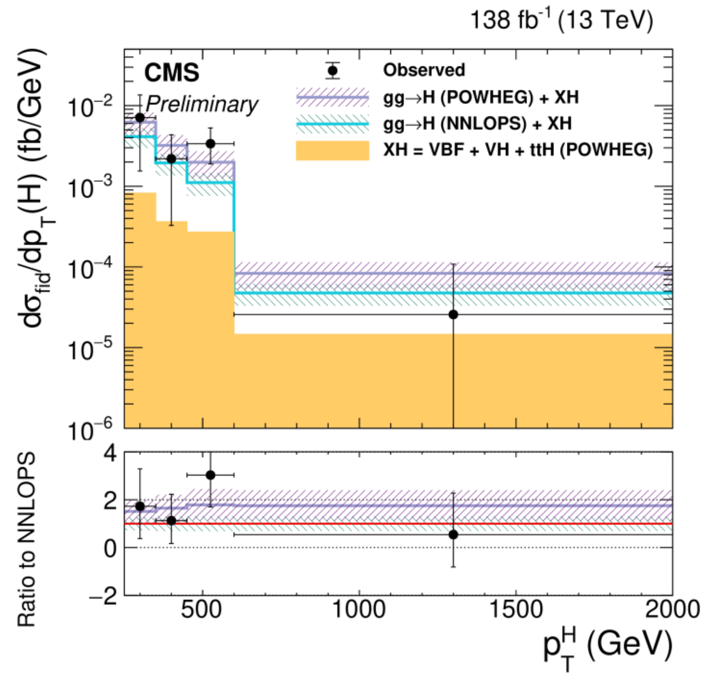
- Highly Lorentz-boosted Higgs boson (**p^H_T > 250 GeV**) to **a pair of collimated τ leptons**

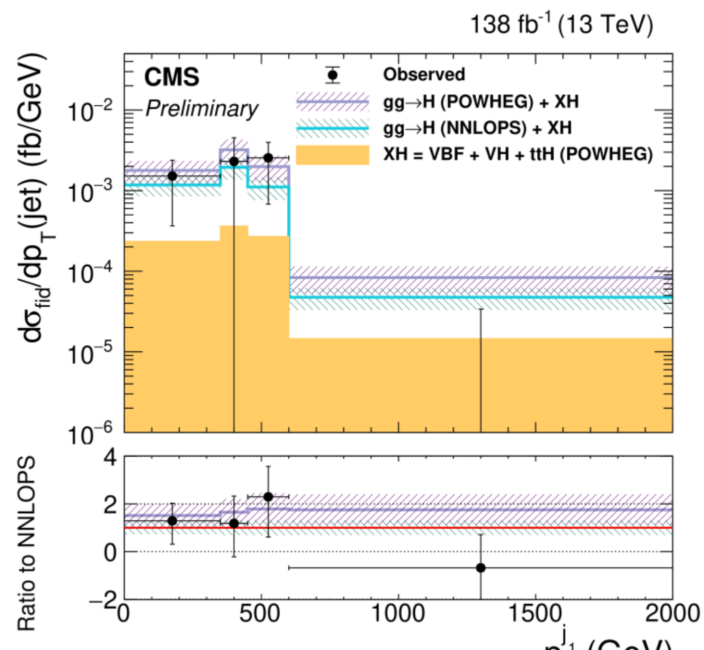
- A dedicated boosted **τ_{had}** reconstruction algorithm and a multi-class NN with three output nodes : signal, $Z \rightarrow \tau\tau$ and fake backgrounds $\rightarrow$ A binned maximum likelihood fit between three NN outputs

- **Background estimations:** irreducible $Z \rightarrow \tau\tau$, fake backgrounds estimated from data other backgrounds estimated by MC simulations

- Observed (expected) significance **3.5σ (2.2σ)**
- Main systematics : fake backgrounds, tau ID, QCD scale uncertainty

- Best fit value of inclusive fiducial cross section is **$1.96^{+0.86}_{-0.69}$ pb**, consistent with the SM: **1.20 pb**

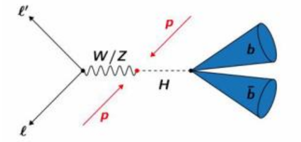


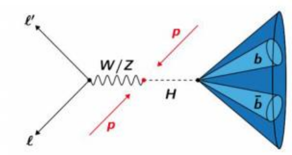


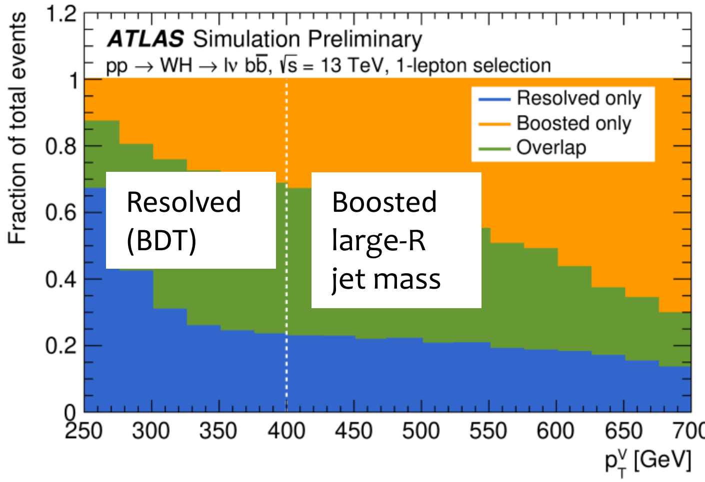
ATLAS: VH, H→bb

CMS results in CMS-PAS-HIG-20-001
Inclusive signal strength:
μ=0.58$_{-0.18}^{+0.19}$
observed significance of 3.3σ(exp. 5.2σ)

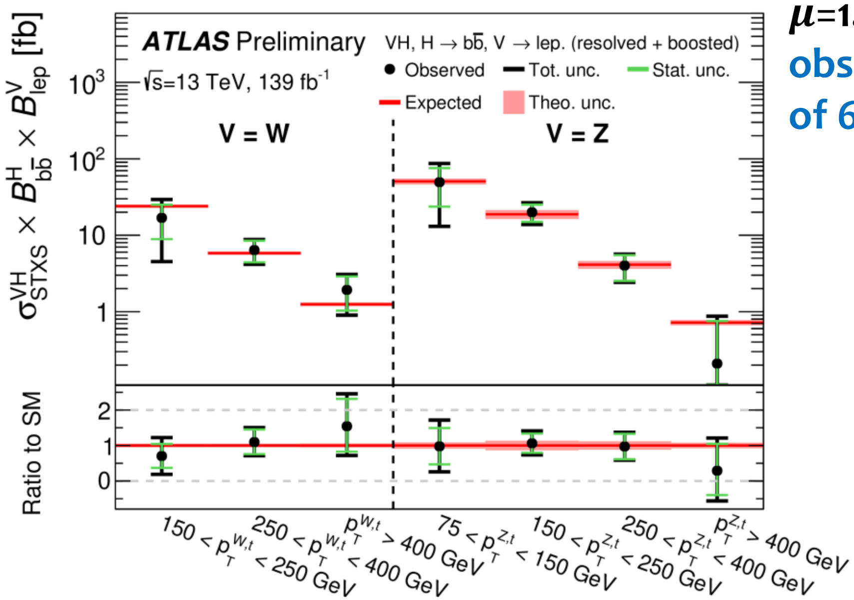
VH, H→bb extensively studied using full Run 2 dataset
Resolved: EPJC 81 (2021) 178, Boosted PLB 816 (2021)



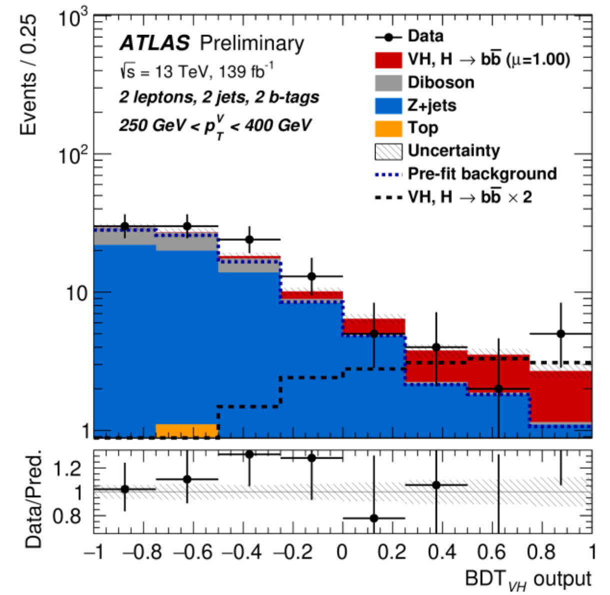




- Combination of the two analyses: ATLAS CONF 2021 051
- Combined using p_T^V>400 GeV events for boosted only
- Uncertainties dominated by b tagging, jet, signal and V+jets modelling.
- STXS measurement in combined analysis with 7 bins.

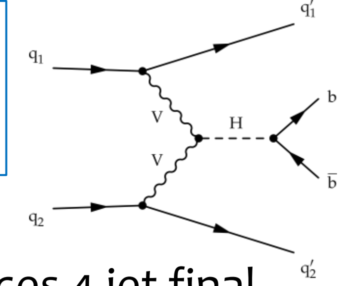


μ=1.00$_{-0.17}^{+0.18}$
observed significance of 6.4σ(exp. 6.3σ)



CMS: VBF, H→bb

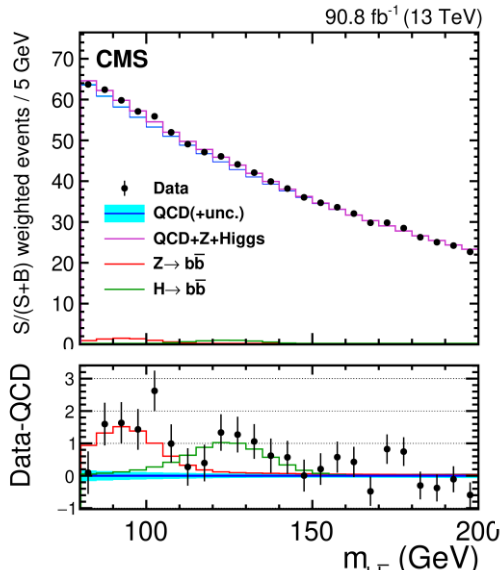
ATLAS results in Eur. Phys. J. C. 81 (2021) 537
μ_{Hbb}=0.95$_{-0.31}^{+0.31}$(stat)$_{-0.17}^{+0.2}$(syst)
observed significance of 2.7σ (exp. 2.9 σ)

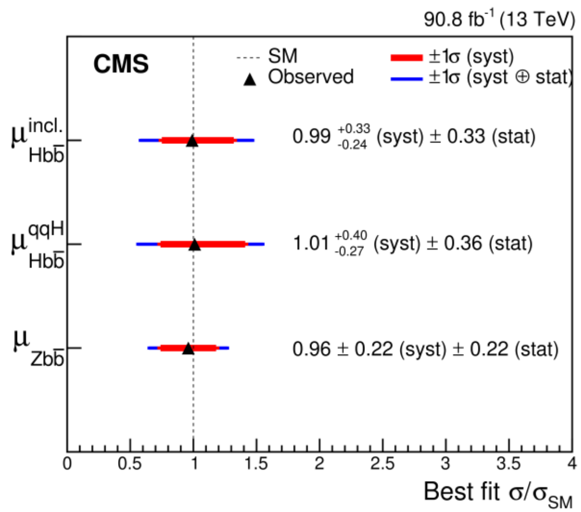


2308.01253 **VBF production of Higgs boson followed by H→bb** decay produces 4 jet final state, 2 jets in central region (from H→bb) and 2 in forward and backward directions relative to beam line with large rapidity separation (VBF jets)

Dominant background:
- QCD multijet: Estimated by fit to data in the side bands of the m_{bb} distribution
- Z+Jets: Estimated from simulation

BDT used to separate signal from background in 18 categories, 5 per year for VBF, 2 per year for ggH and 2 per year for Z+Jets, Signal is extracted from the m_{bb} distribution





(ggH constrained to SM pred.):
μ_{Hbb}^{qqH}**=1.01$_{-0.27}^{+0.40}$(syst)±0.36(stat)**
Obs. significance of 2.4σ (exp. 2.7σ)

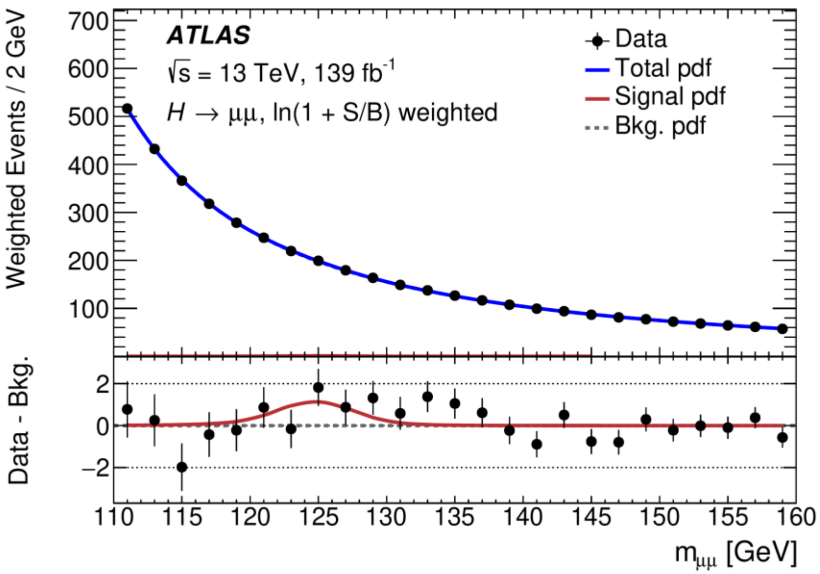
Inclusive signal strength (qqH+ggH):
$\mu_{Hbb}^{incl.}$**=0.99$_{-0.24}^{+0.33}$(syst)±0.33(stat)**
Obs. significance of 2.6σ (exp. 2.9σ)

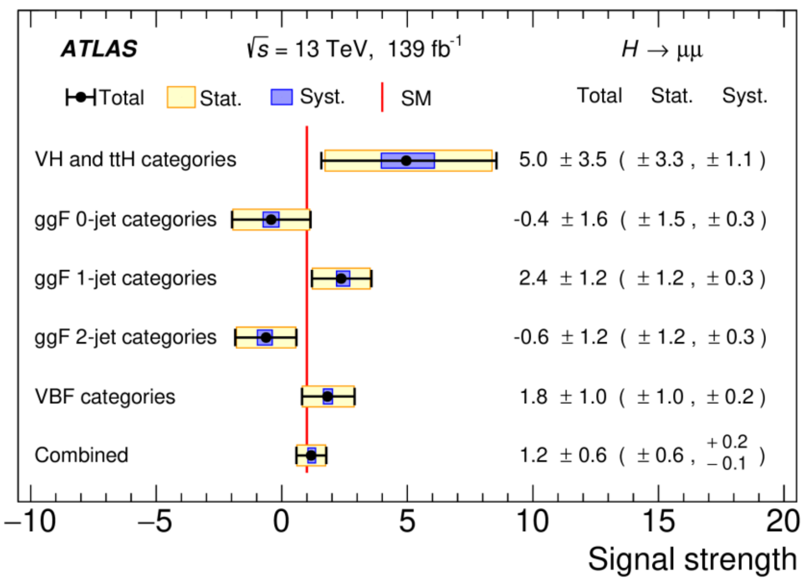
ATLAS: Couplings to 2nd generation: H→ μμ

PLB 812 (2021) 135980

- **$BR_{SM}(H\rightarrow \mu\mu) = 2.17 \times 10^{-4}$**, and large irreducible DY → μμ background
  - S/B ~ 0.2% for inclusive events at 125 GeV
- **To increase sensitivity:**
  - MVA categorization to select events at high S/B, e.g. from VBF
  - New FSR recovery to improve $\sigma(m_{\mu\mu})$
  - Rejection of jets from pileup
- **Signal extraction from $m_{\mu\mu}$ fit**
  - background parametrization: inclusive "core" pdf + per-category empirical transfer function (with less free parameters)

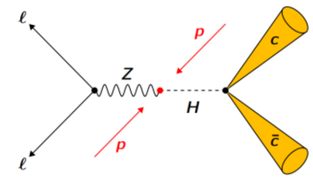
Signal strength: μ = 1.2 ± 0.6
Significance: 2.0 obs. (1.7 exp.) σ
Observed BR limit at 95% CL < 4.7×10^{-4}

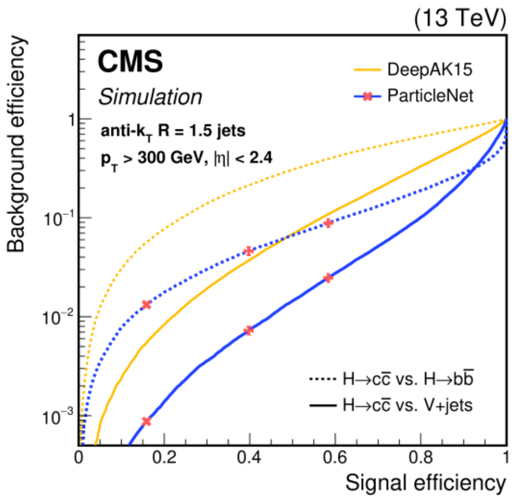




CMS:Higgs coupling to charm quark

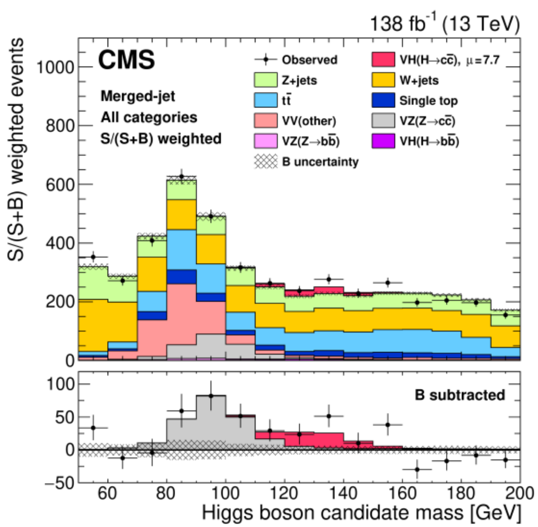
(Phys. Rev. Lett. 131 (2023) 061801), (Phys. Rev. Lett. 131 (2023) 041801)

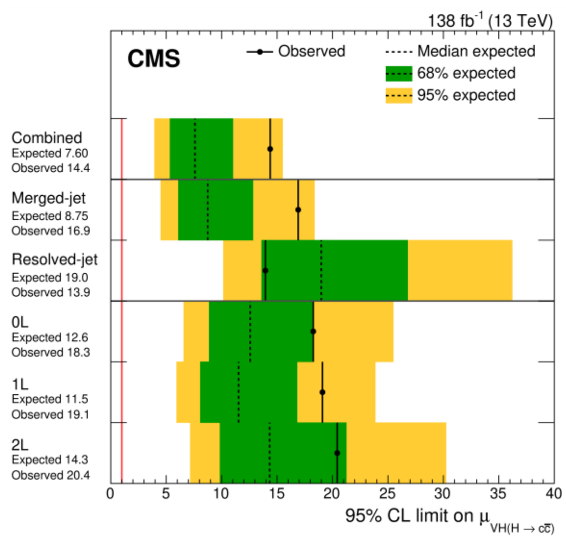




Inclusive H → cc decay search with 138 fb^{-1}:

- **Yukawa couplings between H and charm quark**
- B(H → cc) = 2.9 x 10^{-2} ($^{+5\%}_{-2\%}$)
- Trigger: MET or single/double iso lepton
- Multijet backgrounds and need to perform **charm-jet tagging**
- Main channel considered: *pp* → VH → *ℓℓcc*
- “Resolved-jet” and “Merged-jet” (single large-*R* jet) topologies





Upper limits on B set at 95% CL:

$\mu_{VH(H\to cc)}$ = **14 (7.6 $^{+3.4}_{-2.3}$)** the SM prediction

$1.1 < |\kappa_c| < 5.5$ ($|\kappa_c| < 3.4$)

Validation of analysis strategy:

Search for the analogous SM process VZ(Z → cc)

Best fit: $\mu_{VZ(Z\to cc)}$ = **1.01 $^{+0.23}_{-0.21}$**

5.7 std dev of observed significance