Higgs Physics: current status and prospects from the experiment side

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On behalf of the ATLAS and CMS Collaboration

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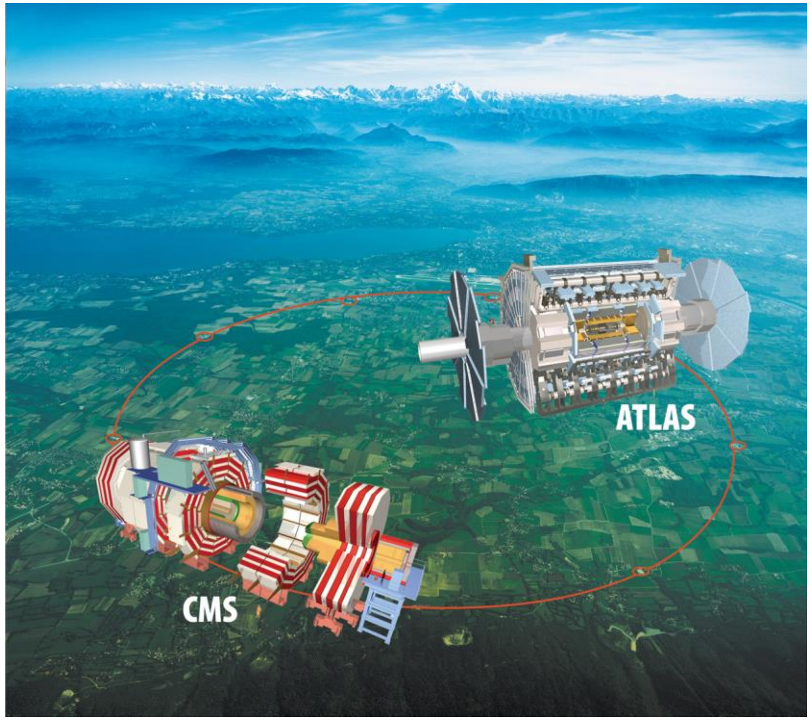
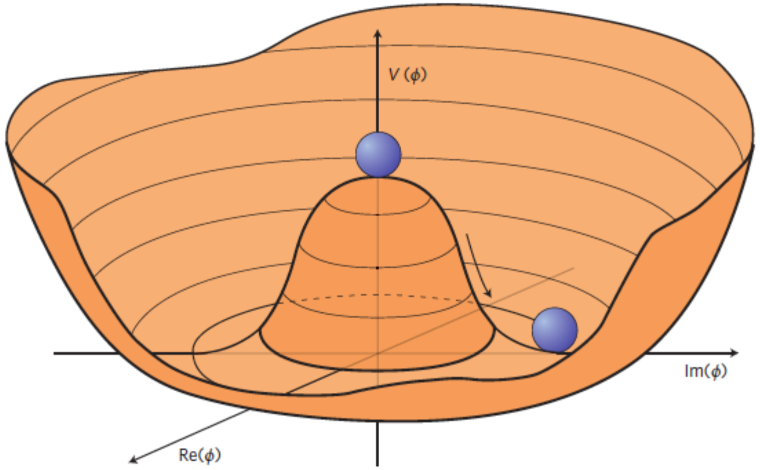
Introduction

- The ATLAS and CMS experiments at the Large Hadron Collider (LHC) are currently the two most important experiments which study the Higgs boson.

- The Higgs boson was discovered by both experiments in 2012. Studying the Higgs boson is key to test the precision of the Standard Model.

- Higgs physics provides an opportunity to discover physics beyond the Standard Model.

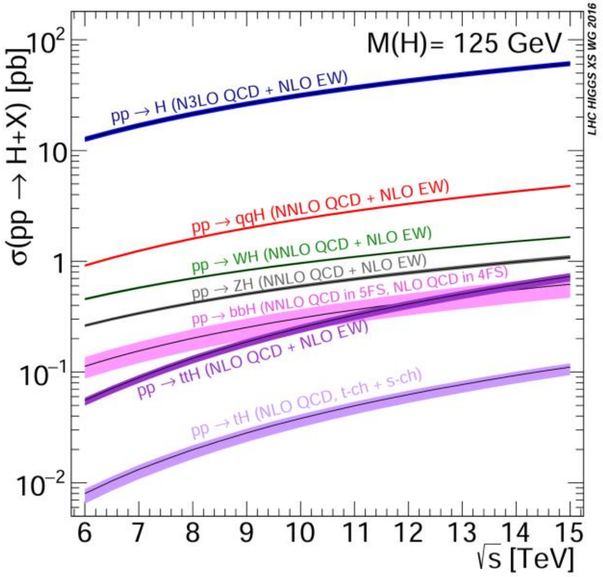




Higgs Physics at the LHC

Higgs Production Process at the LHC

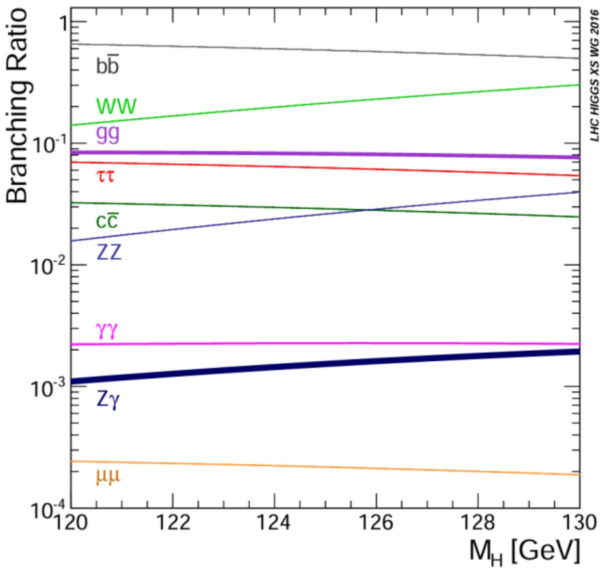
- Single Higgs:
  - Gluon-gluon fusion (*ggF*): 87%
  - Vector boson fusion (*VBF*): 7%
  - In association with a vector boson (*WH, ZH*): 4%
  - In association with two top or bottom quarks ($t\bar{t}H$, $b\bar{b}H$): 1%
  - *tH:* < 1%
- Di-Higgs production



arXiv:1708.00794

Higgs Decays studied at the LHC

- Bosonic decay: $H \to \gamma\gamma, H \to ZZ, H \to WW, H \to Z\gamma$
- Fermionic decay: $H \to bb, H \to cc, H \to \tau\tau, H \to \mu\mu$
- Invisible and BSM decays

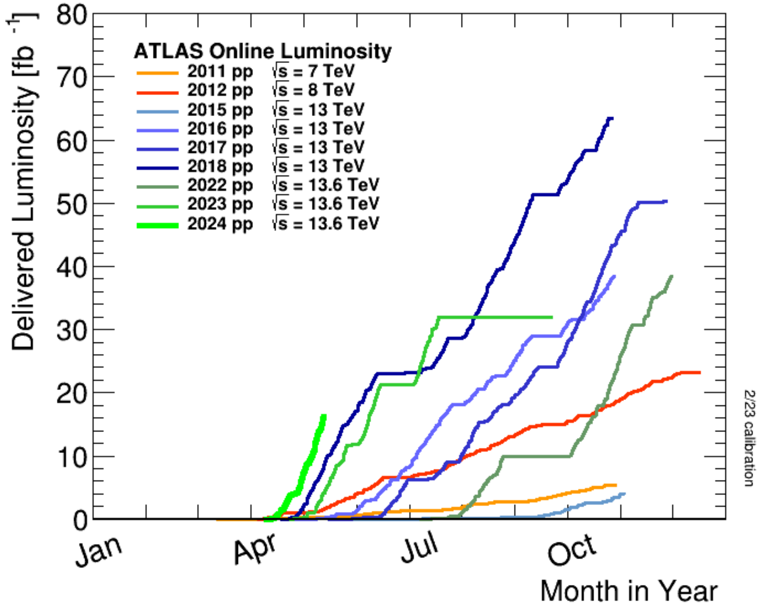


arXiv:1708.00794

Higgs Physics at the LHC

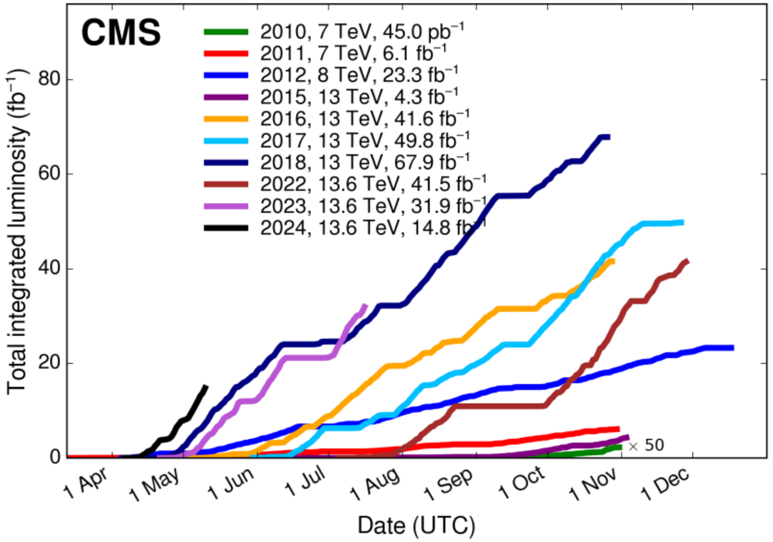
<u>What we are measuring at LHC:</u>

- Higgs properties:
  - Mass
  - Width
  - CP
  - Coupling with other particles
    - Production cross sections
    - Decay branching Ratios
- Higgs self-coupling



<u>Data:</u>

- Using data collected by the ATLAS and the CMS detectors:
  - Run 1: 7-8 TeV
  - Run 2: 13 TeV
  - Ongoing Run 3: 13.6 TeV
  - Future High-lumi LHC

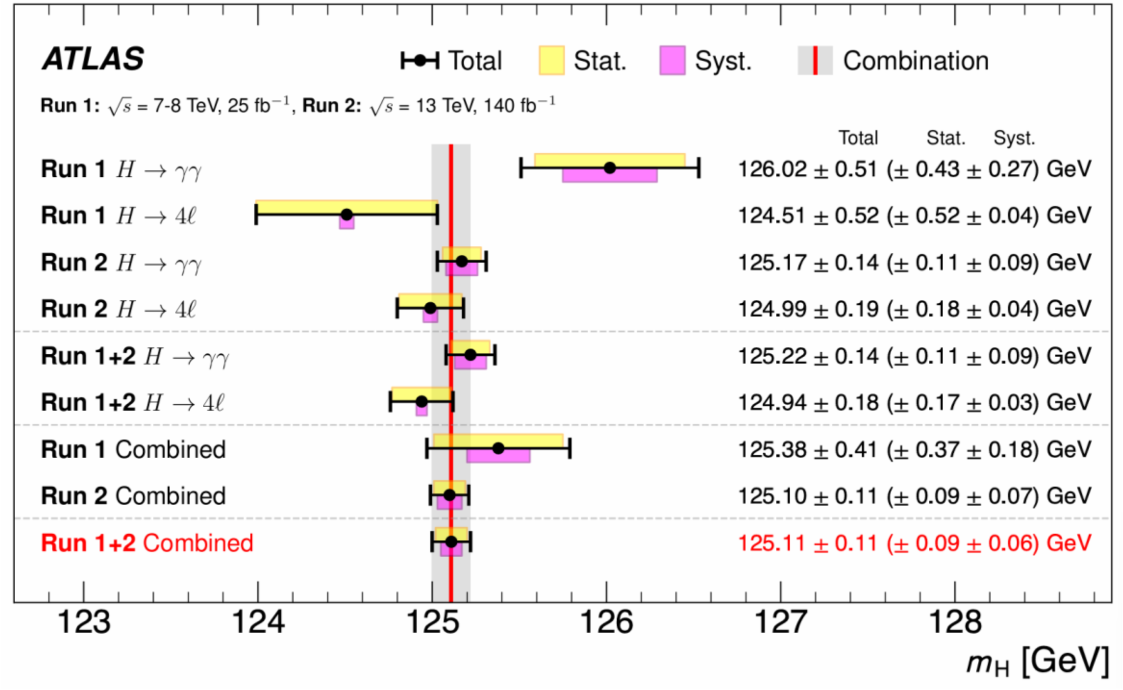


Higgs Mass and Width

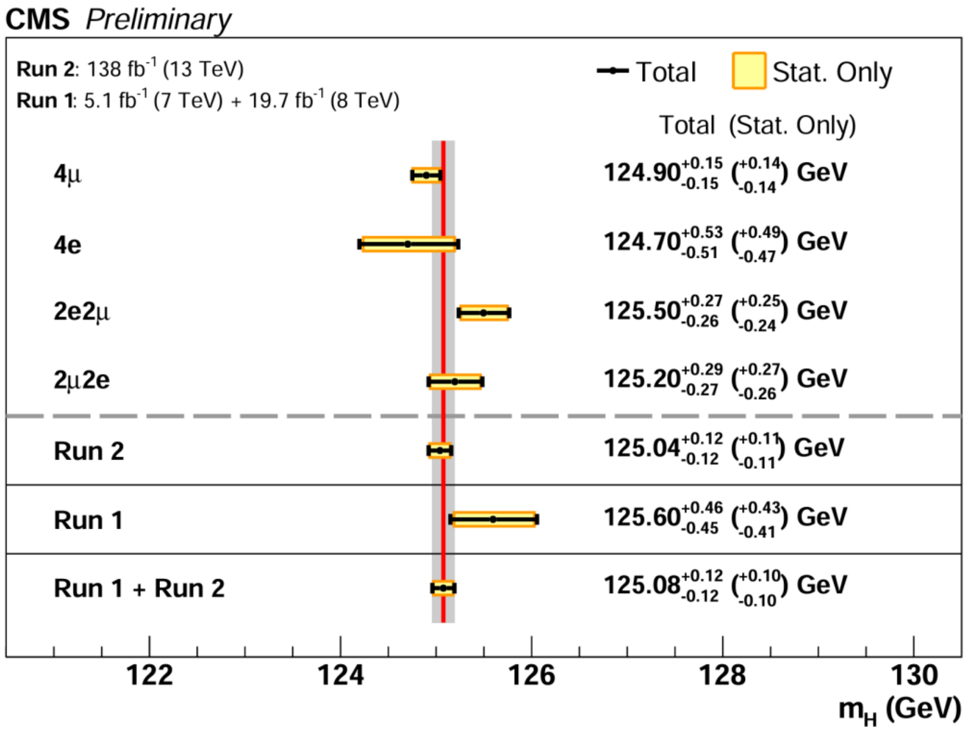
Higgs Mass

- ATLAS and CMS have measured the Higgs mass in the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4l$ channels in Run 1 and Run 2.
- Run 1 and Run 2 results combined. Mass measured with better 0.1 % precision.

arXiv:2404.05498



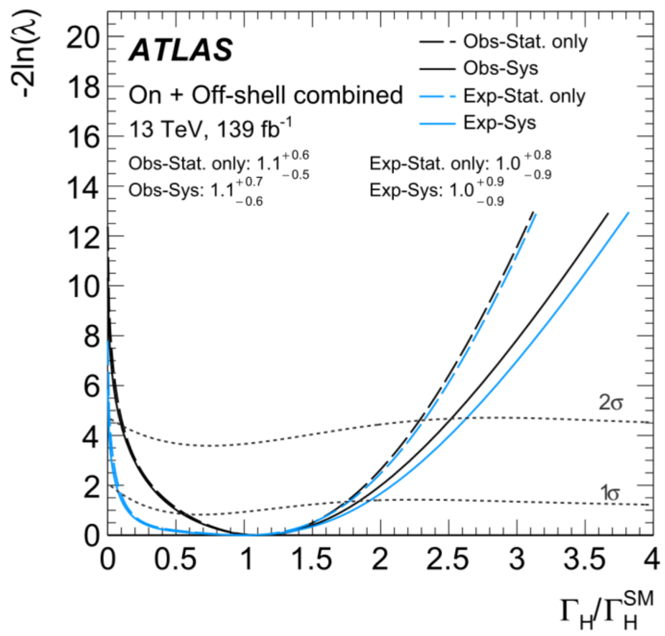
CMS-PAS-HIG-21-019



Higgs Width

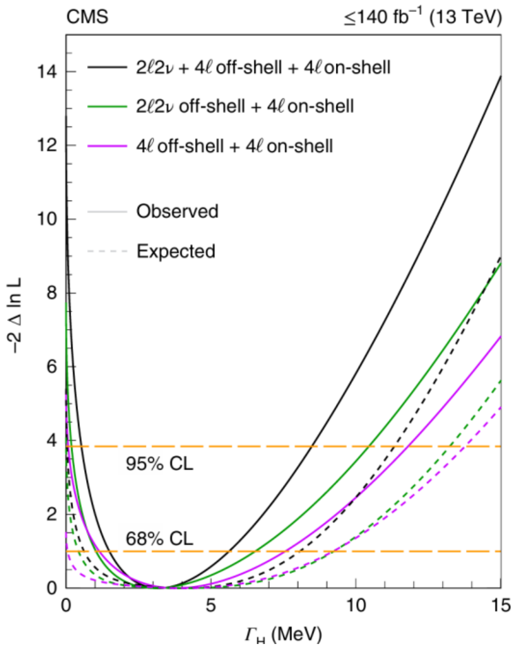
- Width can be measured in the $H \to \gamma\gamma$ and $H \to ZZ \to 4l/2\upsilon 2l$ channels.
- On-shell measurement:
  - Use line-shape of the on-shell Higgs mass distribution
  - Limited by the detector resolution.
- Off-shell measurement:
  - $\sigma_{gg\to H\to ZZ}^{on-shell} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{m_H \Gamma_H}, \sigma_{gg\to H\to ZZ}^{off-shell} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{m_{ZZ}}$
  - Infer width by using the event yield ratio between the on-shell and the off-shell Higgs

Phys. Lett. B 846 (2023) 138223



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

arXiv:2202.06923



$\Gamma_H = 2.9^{+2.3}_{-1.7}$ MeV

Higgs CP

Higgs CP

- Extra source of CP violation needed to explain the matter-antimatter imbalance.

- Run 1 results show that a pure CP-odd Higgs is not likely.

- CP-odd interaction of the Higgs boson is still possible:
  - Fermionic couplings: mixing angle between CP-even and CP-odd components
  - Bosonic couplings: higher order CP-odd terms

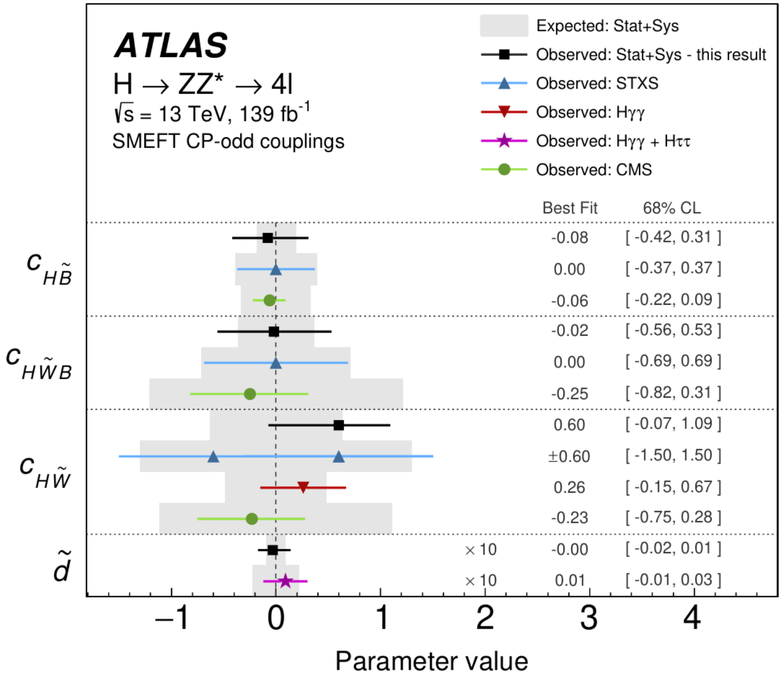
- In Run 2, ATLAS and CMS are targeting:
  - Production vertices: HVV, Htt, Hgg
  - Decay vertices: $H\tau\tau$

- High light a few recent Run 2 results.

Higgs CP

HVV couplings in $H \to \gamma\gamma, H \to ZZ$

- ATLAS studied VBF production of Higgs in the $\gamma\gamma$ and $4l$ final states. Set limits on the CP-odd contributions in the HVV couplings.
- CMS studied Higgs production in association with two jets, a vector boson, or top quarks. Simultaneously measured the HVV, Hgg and Htt couplings.
- Results interpreted using EFT. Setting limits on CP-odd higher dimensional operators.
- Results agree with the Standard Model.



arXiv:2304.09612

CMS

Coupling	Observed	Expected
$c_{H\Box}$	$0.04^{+0.43}_{-0.45}$	$0.00^{+0.75}_{-0.93}$
c_{HD}	$-0.73^{+0.97}_{-4.21}$	$0.00^{+1.06}_{-4.60}$
c_{HW}	$0.01^{+0.18}_{-0.17}$	$0.00^{+0.39}_{-0.28}$
c_{HWB}	$0.01^{+0.20}_{-0.18}$	$0.00^{+0.42}_{-0.31}$
c_{HB}	$0.00^{+0.05}_{-0.05}$	$0.00^{+0.03}_{-0.08}$
$c_{H\tilde{W}}$	$-0.23^{+0.51}_{-0.52}$	$0.00^{+1.11}_{-1.11}$
$c_{H\tilde{W}B}$	$-0.25^{+0.56}_{-0.57}$	$0.00^{+1.21}_{-1.21}$
$c_{H\tilde{B}}$	$-0.06^{+0.15}_{-0.16}$	$0.00^{+0.33}_{-0.33}$

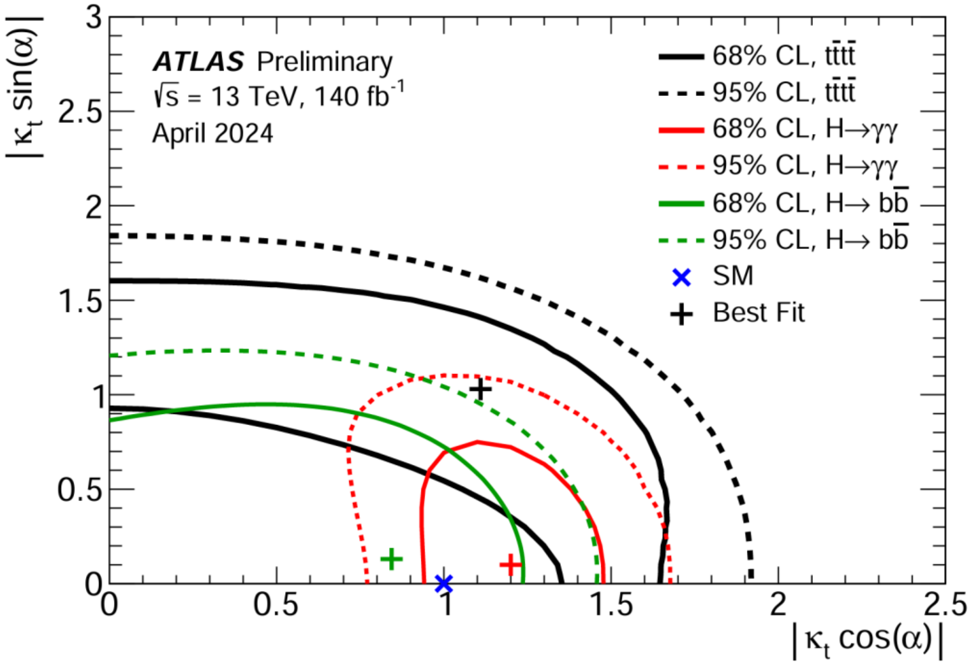
PhysRevD.104.052004

Higgs CP

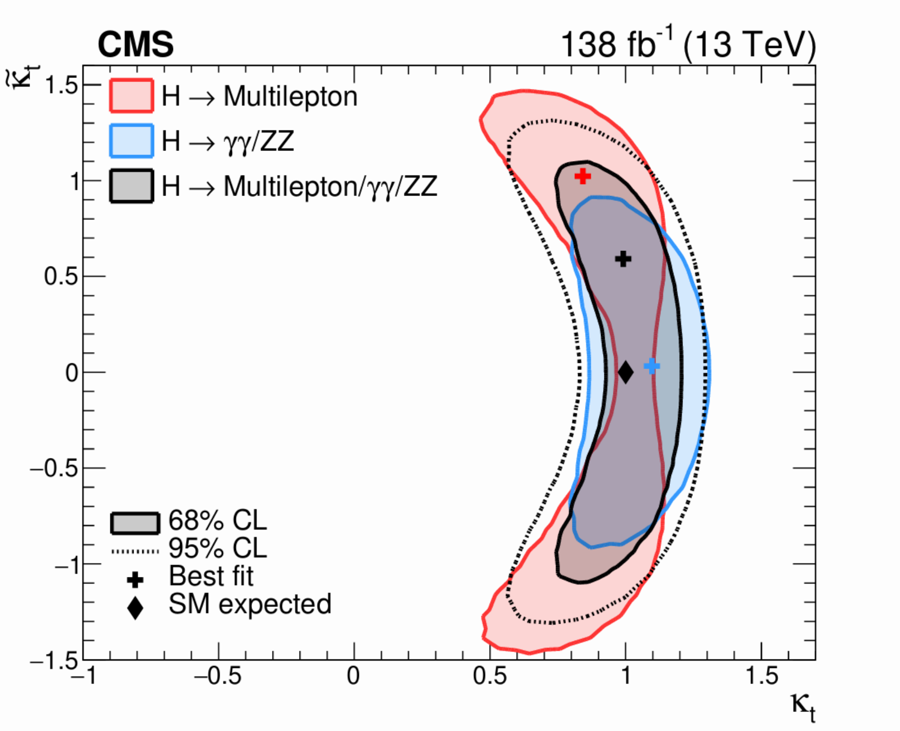
Top-Higgs Yukawa coupling

- ATLAS studied Higgs production in association with top quarks in the $\gamma\gamma$ and $b\bar{b}$ final states.
- CMS combined results of the *ZZ*, $\gamma\gamma$ and multilepton final states.
- Set limits on the coupling modifier (κ) /mixing angle (α) between CP-even and CP-odd components. Results are compatible with the Standard Model.

Phys. Rev. Lett. 125 (2020) 061802



HEP07(2023)092



Higgs Coupling

Signal strength modifier: μ framework

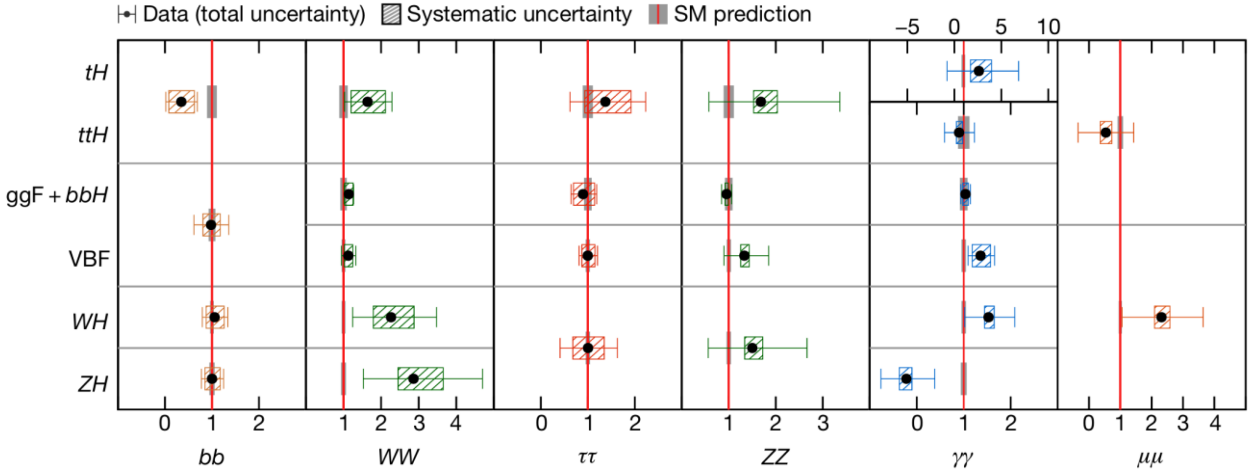
- ggH, VBF, VH, tH/ttH productions and $\gamma\gamma, ZZ, WW, bb, \tau\tau$ decays have been observed with significance above five Sigmas.

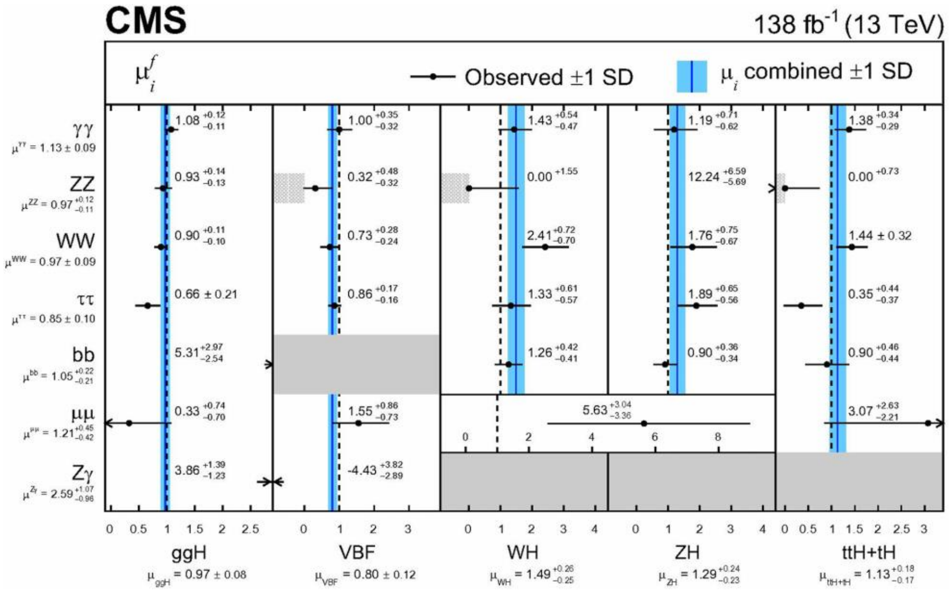
- Study the agreement between the observed Higgs event yields with the SM prediction.
- For the $\mathrm{i} \to H \to f$ process, the single signal strength modifier is $\mu_{if} = \frac{\sigma_i^{obs} B_f^{obs}}{\sigma_i^{SM} B_f^{SM}}$.

- Run 2 global signal strength modifier:
  - ATLAS:
    μ = 1.002 ± 0.057
  - CMS:
    μ = 1.05±0.06

- Good agreement with the Standard Model

ATLAS *Nature* **volume 607**, pages52–59 (2022)





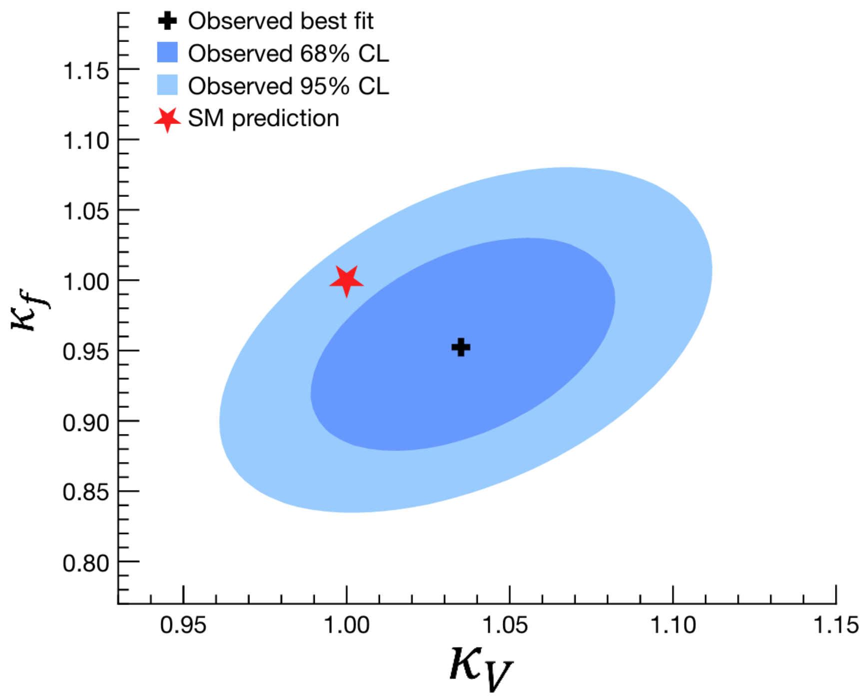
Nature **volume 607**, pages60–68 (2022)

Coupling modifiers: κ Framework

- BSM contributions may affect the productions and decays in a correlated way.
- Coupling strength modifiers κ introduced to modify the Higgs coupling strength to different particle types.
- All κs are one in the Standard Model.

- Model 1: one modifier κ_V for Z and W, and one modifier κ_f for all fermions.
- Loop-induced processes are parameterized in terms of the fundamental standard couplings.
- Good agreement with the Standard Model.

ATLAS *Nature* **volume 607**, pages52–59 (2022)



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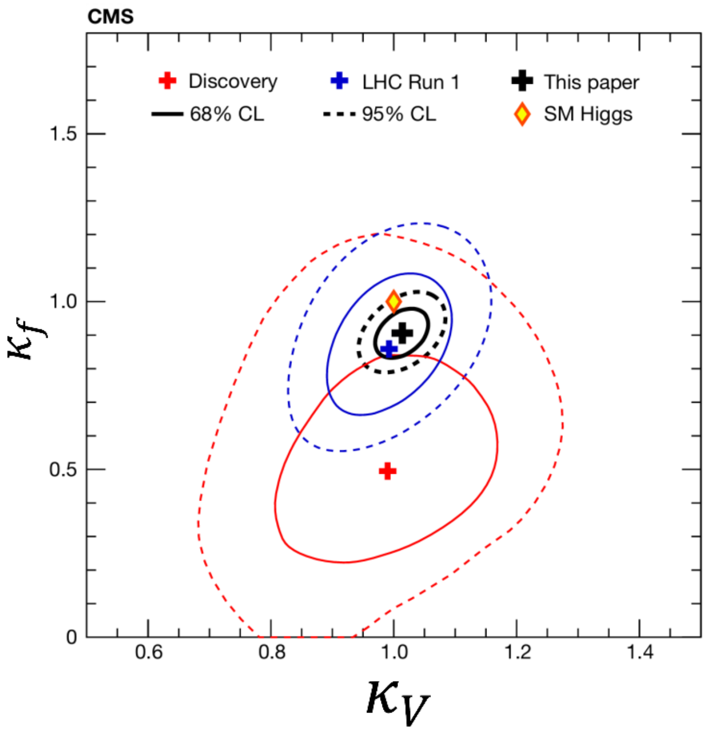

Coupling modifiers: κ Framework

- More modifiers possible with the full Run 2 data.
- Model 2: different modifiers for μ, τ, b, t, Z, W
- Loop-induced processes are parameterized in terms of the fundamental standard couplings.
- Result shows as a function of mass. Good agreement with the Standard Model.

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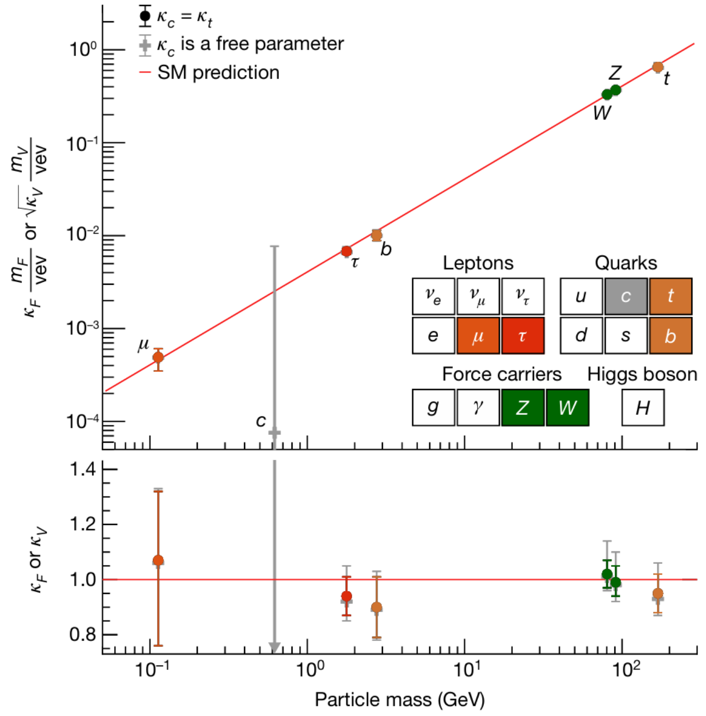

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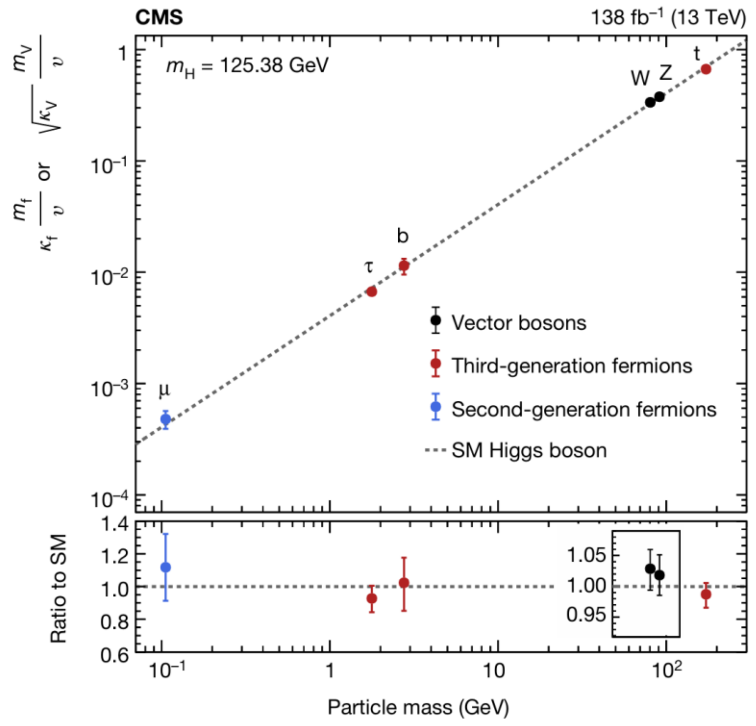

Coupling modifiers: κ Framework

- Loops-induced processes may have BSM contributions.
- Model 3: add new modifiers for $Z\gamma$, gluons and photons. ATLAS also considers invisible or undetected BSM decays.
- Good agreement with the Standard Model.

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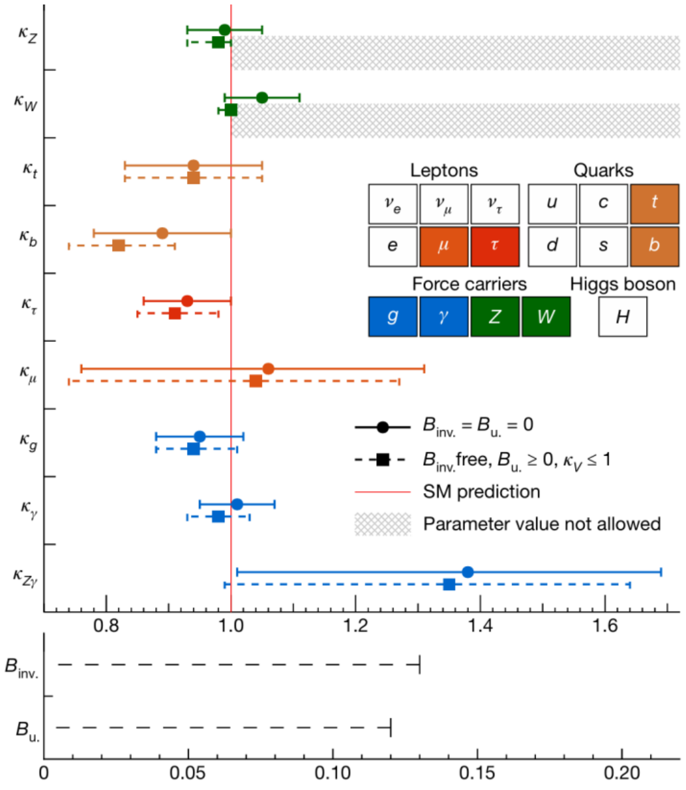

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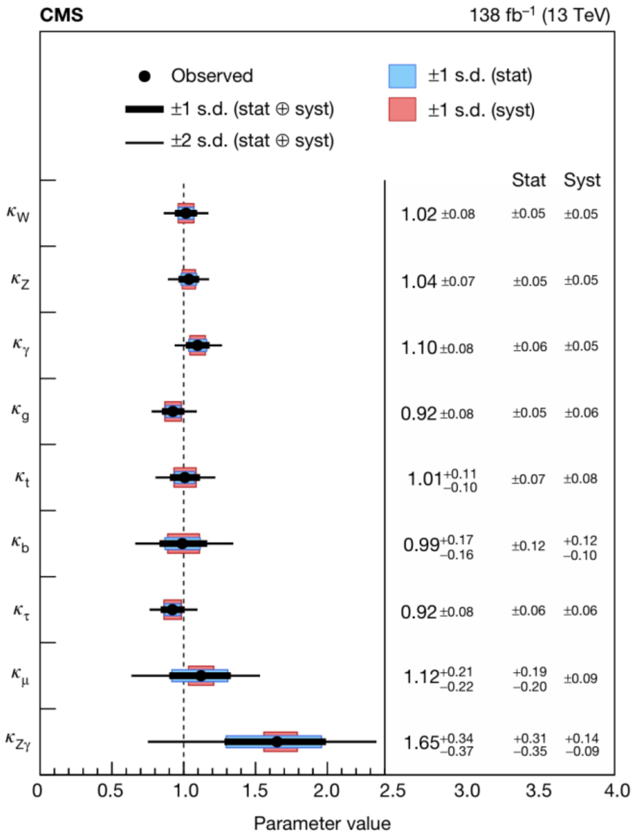
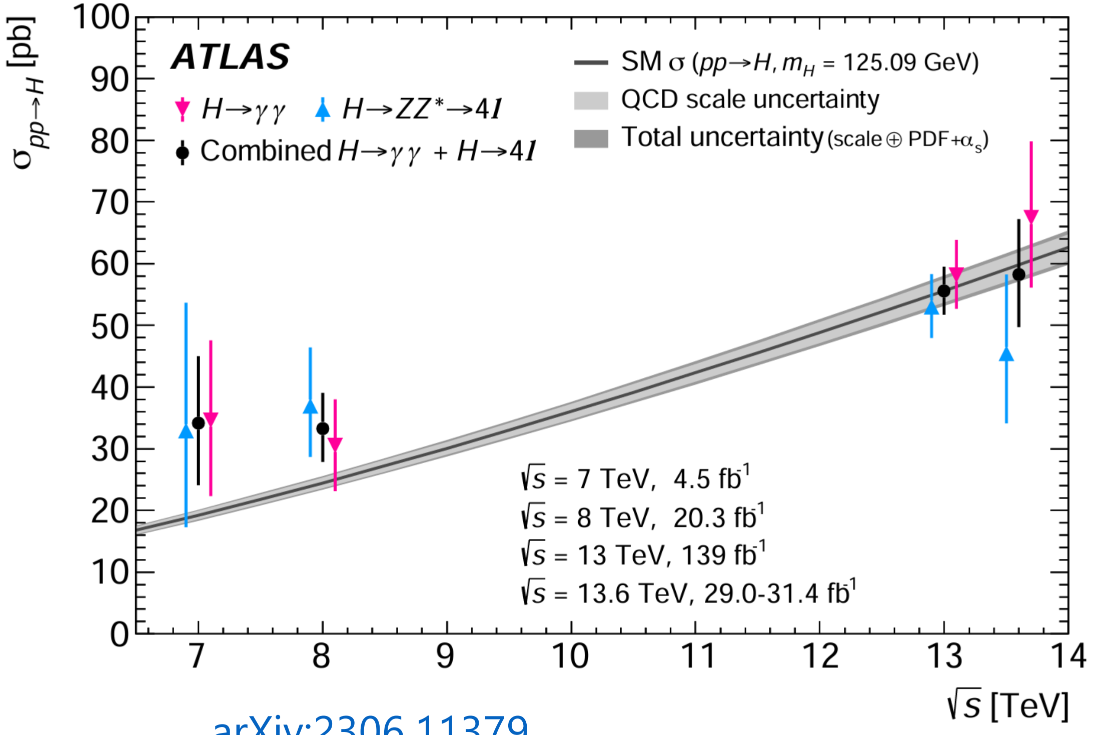


Fiducial and differential cross sections

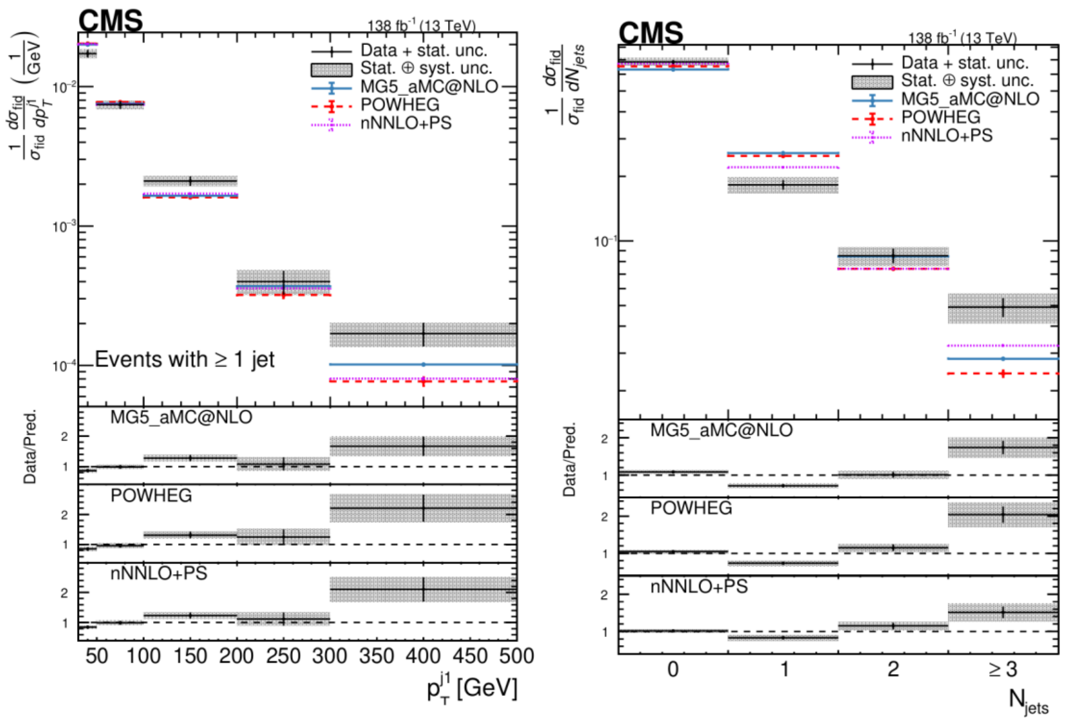
- BSM physics affects the kinematic distributions in Higgs productions and decays. Not described by the κ Framework.
- Fiducial and differential cross sections further scrutinize the Standard Model Higgs coupling.
- Differential cross sections are now also calculated in channels with low signal/background ratios.

ATLAS H$\gamma\gamma$ and HZZ fiducial XS including early Run3 data



arXiv:2306.11379

CMS Run 2 HZZ differential XS

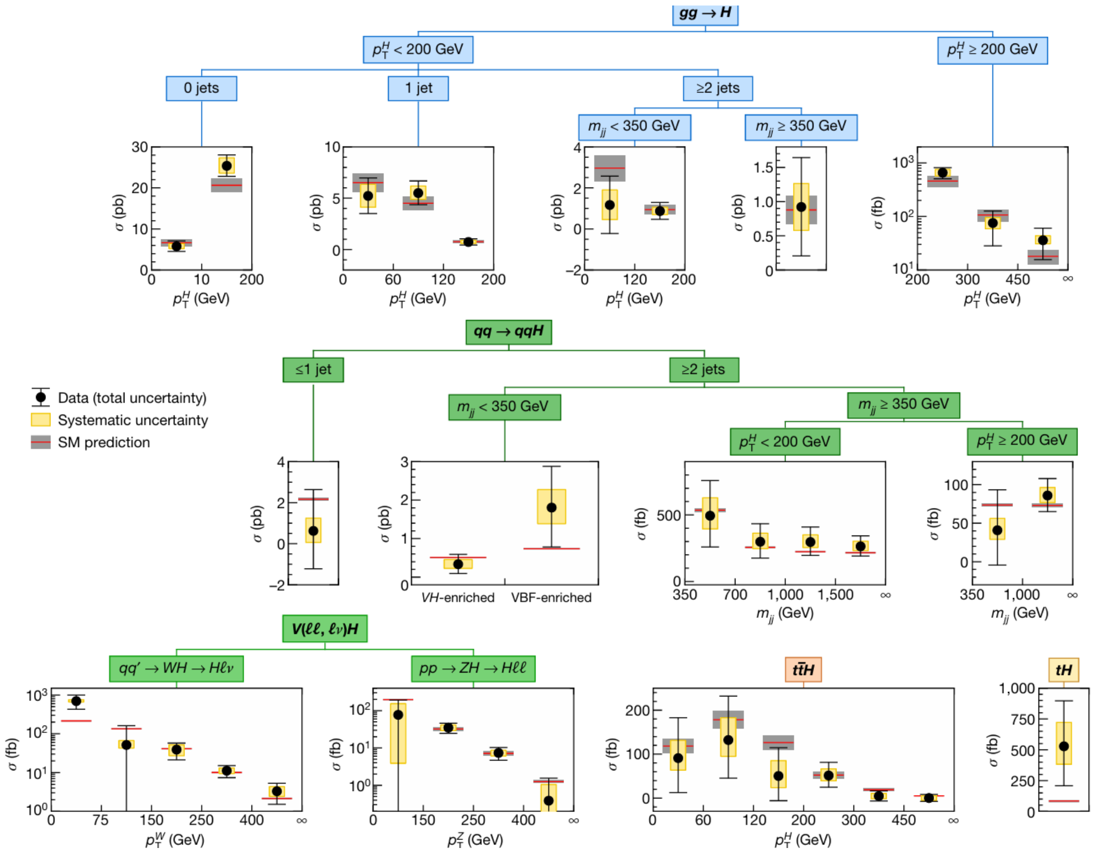


arXiv:2404.02711

Simplified template cross sections (STXS)

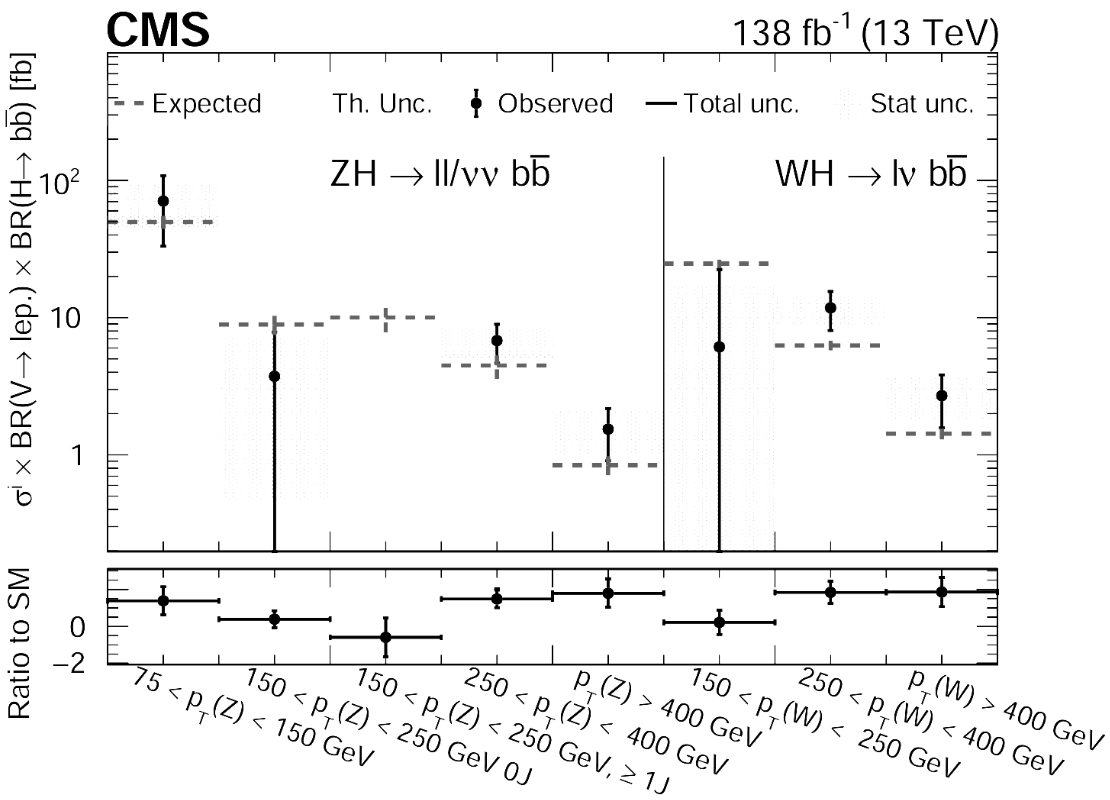
- Measure cross sections in pre-defined kinematic bins.
- Provides sensitivity to BSM physics and reduces theory uncertainties.

ATLAS Run 2 STXS combination



[*Nature* **volume 607**, pages52–59 (2022)]

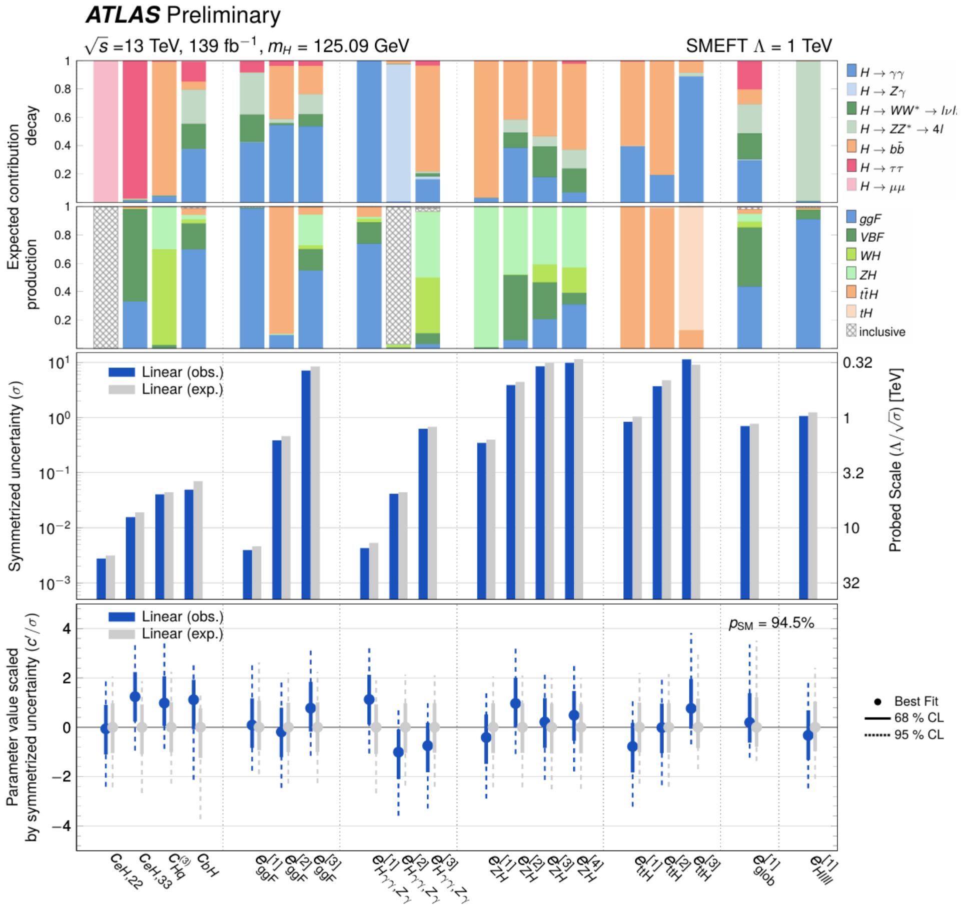
CMS Run 2 Hbb STXS result



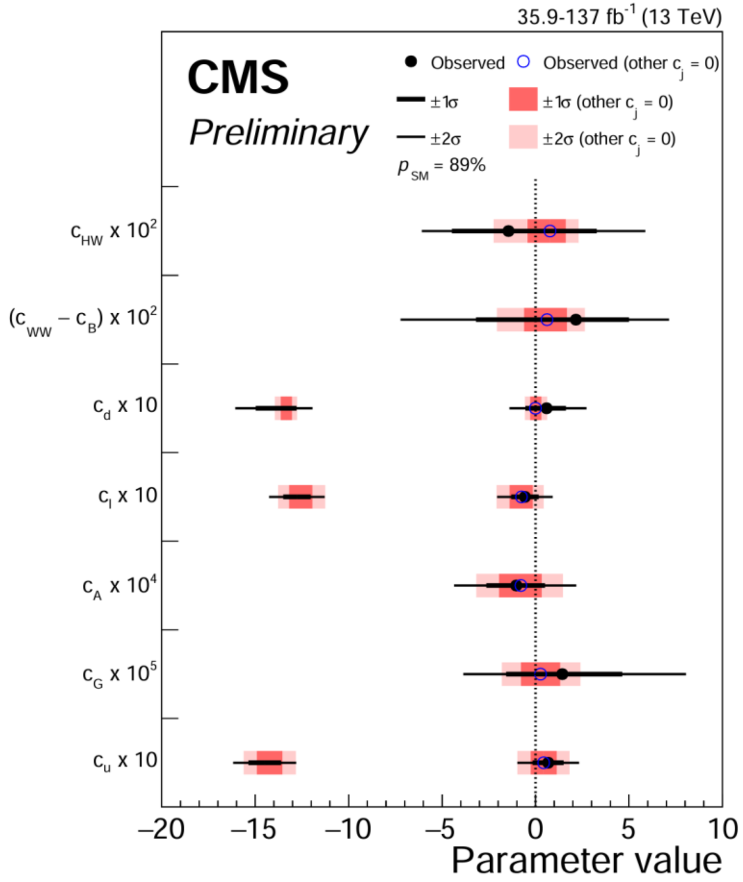
[arXiv:2312.07562]

Effective field theory

- The STXS measurement can be interpreted using the EFT.
- ATLAS and CMS use combined STXS measure to constrain the Wilson coefficients.



[ATLAS-CONF-2023-05](#)



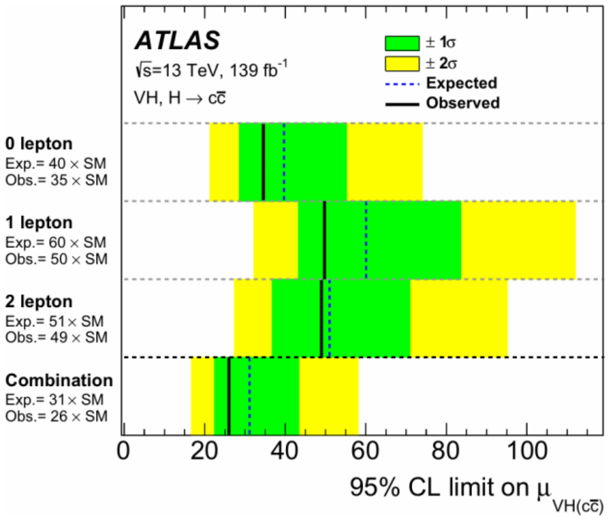
[CMS-PAS-HIG-19-005](#)

Couplings to second generation

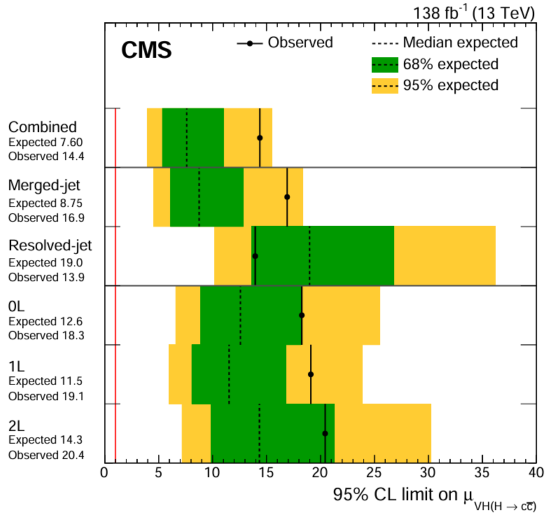
- Higgs coupling to second generation can be significantly modified by BSM physics.

H → cc searches

- Search for VH production.
- Three channels depending on the number of charged leptons in the final states.
- Limit on signal strength
  - ATLAS: 26 times SM prediction
  - CMS: 20.4 times SM prediction



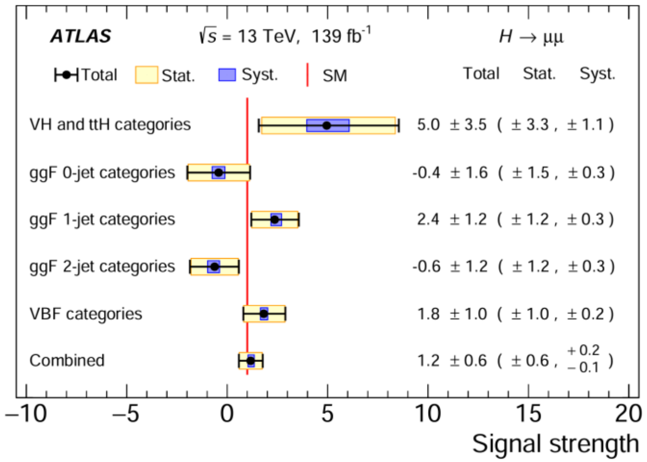
[Eur. Phys. J. C 82 (2022) 717]



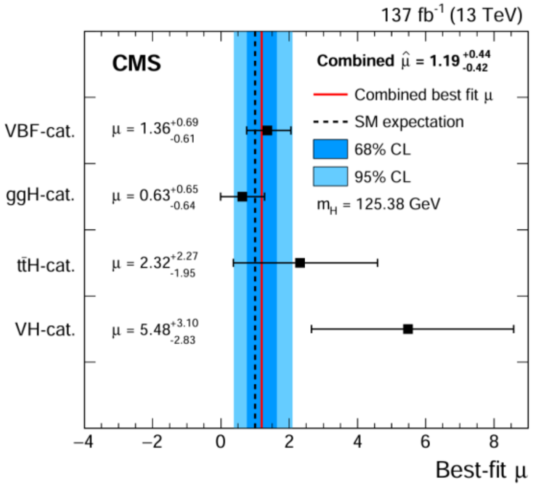
[arXiv:2205.05550]

H → *μμ* searches

- Search for ggH, VBF, VH, ttH production.
- Observed (expected) significance
  - ATLAS: 2.0σ (1.7σ)
  - CMS: 3.0σ (2.5σ)



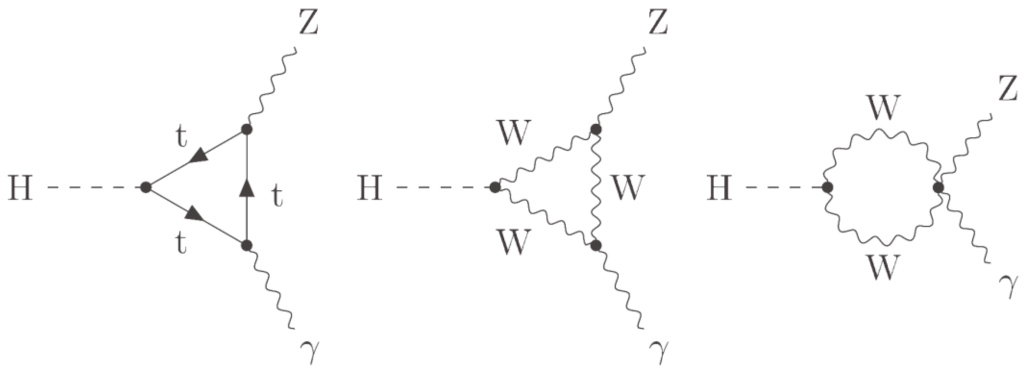
[arXiv:2007.07830]

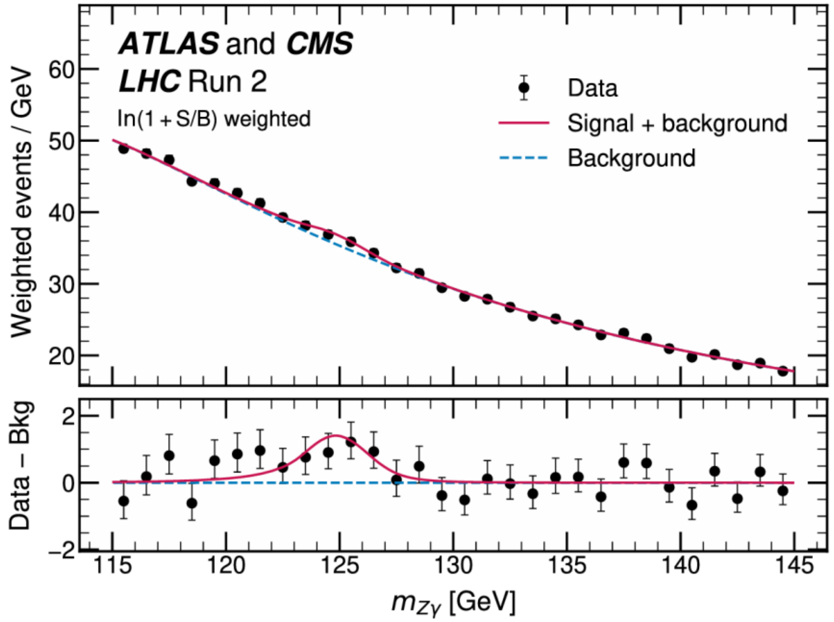


[arXiv:2009.04363]

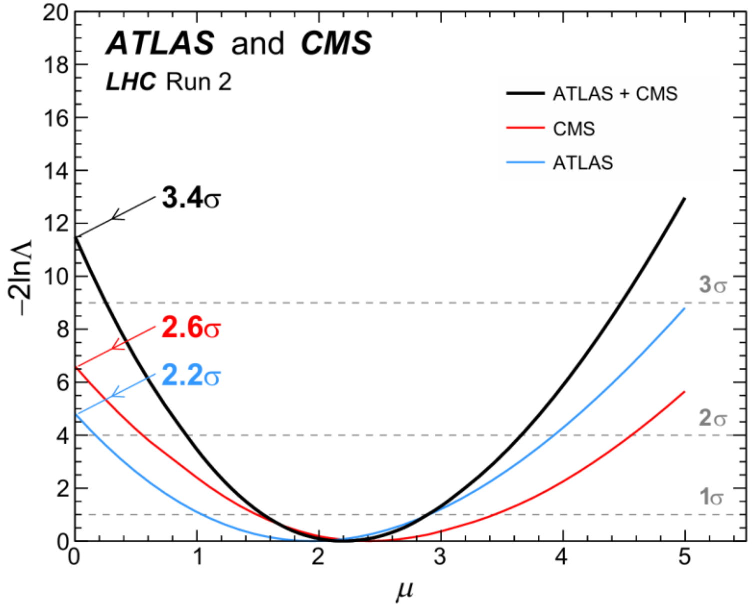
Higgs decays into Zγ

- $\mathrm{H} \to \mathrm{Z}\gamma$ decay has a small branching ratio (1.5×10^{-3}) in the Standard Model.
- Many BSM scenarios increase the branching ratio.
- ATLAS and CMS searched for $\mathrm{H} \to \mathrm{Z}\gamma$ where the Z decays into electrons or muons. Results combined.
  - observed event yield: 2.2 ± 0.7 times SM prediction
  - observed (expected) local significance: 3.4σ (1.6σ)





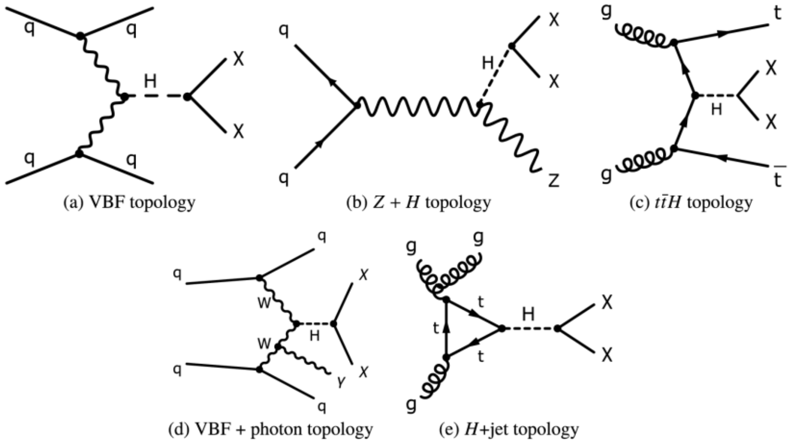
PhysRevLett.132.021803

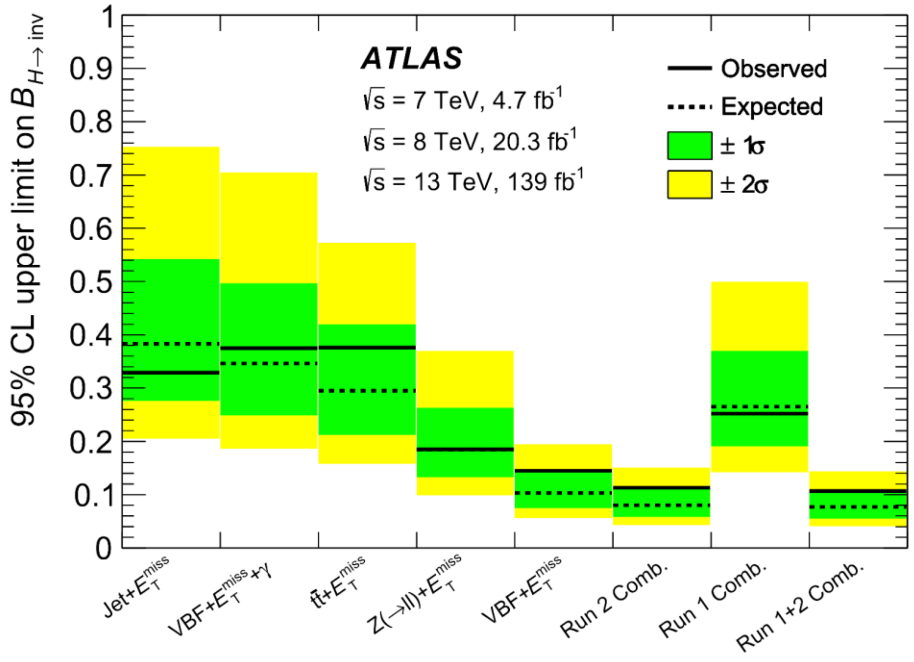


PhysRevLett.132.021803

Higgs decays into invisible particles

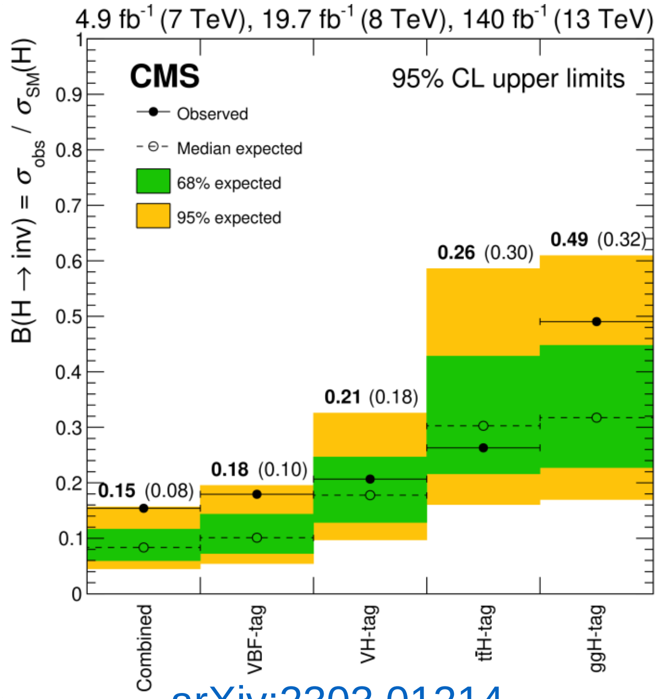
- In BSM theories, Higgs boson acts as a portal between the dark sector and the SM sector.
- In the SM, the branching ratio is less than 0.1%.
- ATLAS and CMS have searched for Higgs invisible decays. No excess found.
- Limits set on the branching ratio.





B <0.107 (exp 0.077) at 95% CL

arXiv:2301.10731



B <0.15 (exp 0.08) at 95% CL

arXiv:2303.01214

Higgs Self-coupling

Higgs self-coupling

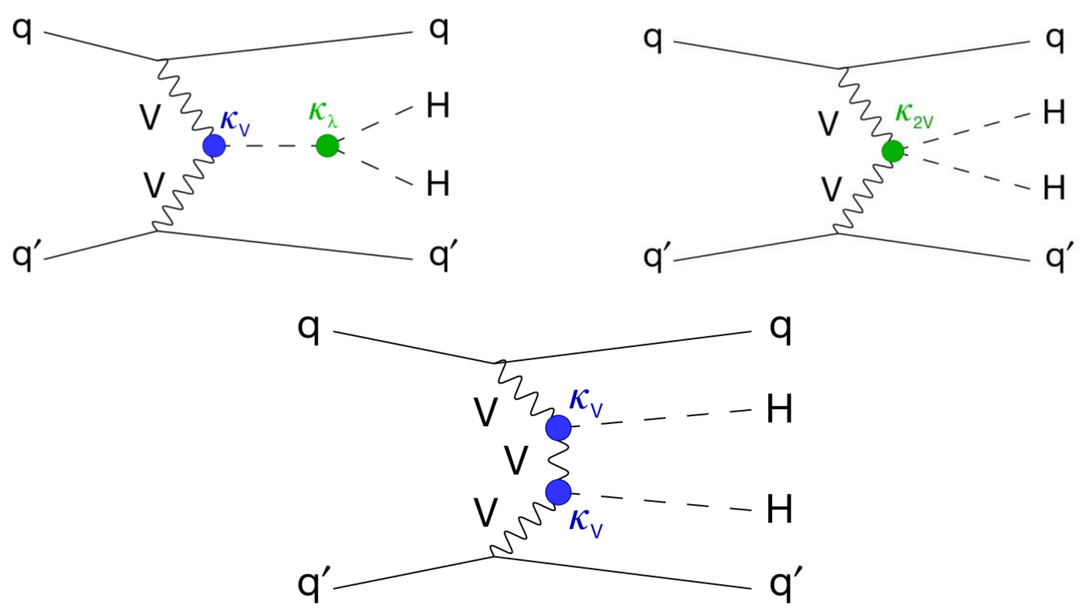
- Important to understand Higgs potential

- Ways to study Higgs self-coupling at LHC
  - Direct HH measurement
  - indirectly set limits using the single Higgs measurement

- Two main DiHiggs production mode:
  - Gluon-gluon fusion ~31.05 fb at 13 TeV
    - Destructive interference
    - Studied using modifiers $\kappa_\lambda, \kappa_t, \kappa_b$
  - Vector boson fusion ~ 1.73 fb at 13 TeV
    - Quartic coupling
    - Studied using modifiers $\kappa_{2V}, \kappa_\lambda, \kappa_V$

Gluon-gluon fusion

Vector boson fusion



Higgs self-coupling

- Prefer direct searches in channels with large branching ratio, strong signature for background rejection.
  - Run 2 searches in: bbbb, bbττ, bb$\gamma\gamma$, bbZZ, bbWW, WW$\gamma\gamma$, multi-lepton (WWWW+WWττ+ ττττ)
- Results combined to improve the sensitivity.
- Also searching for BSM resonance in the above channels.

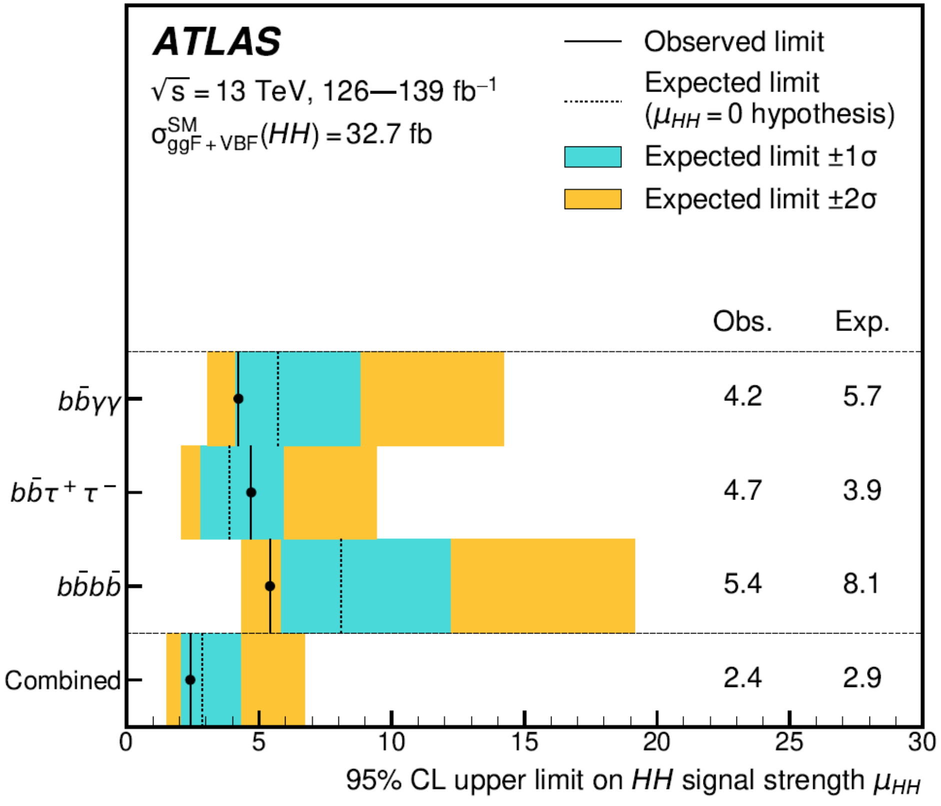
10.3390/sym14020260

	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%

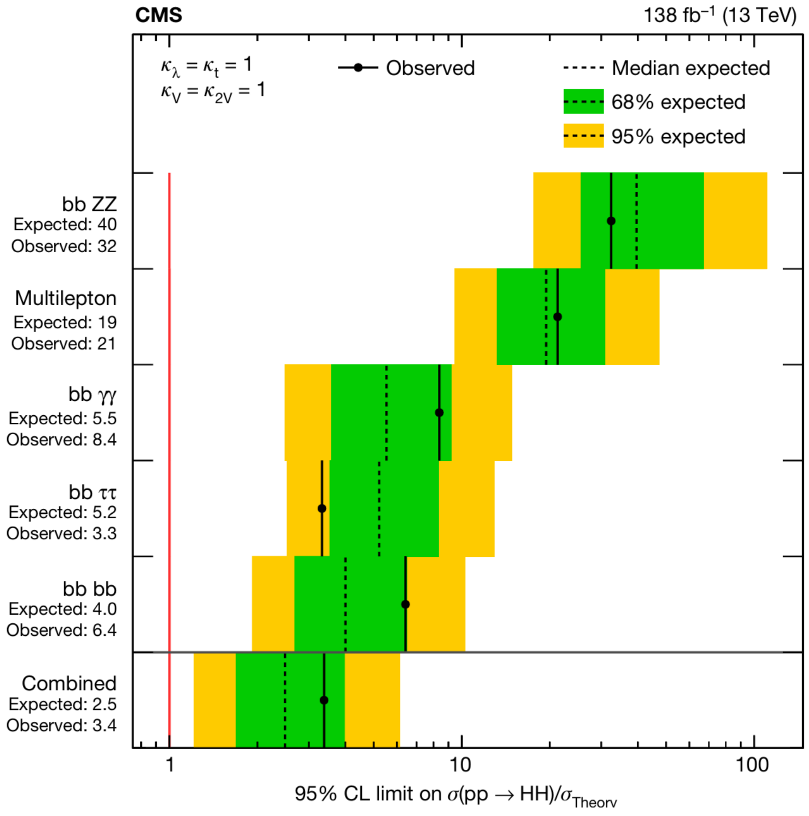
Higgs self-coupling

- Observed (expected) limits on the HH signal strength:
  - ATLAS: 2.4 (2.9) times SM prediction
  - CMS: 3.4 (2.5) times SM prediction

arXiv:2211.01216

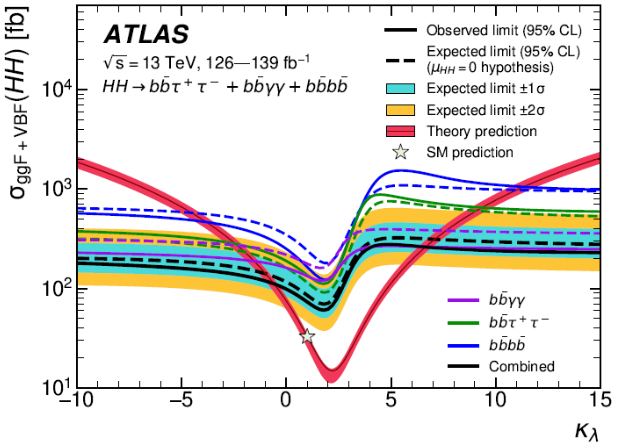


Nature **volume 607**, pages60–68 (2022)

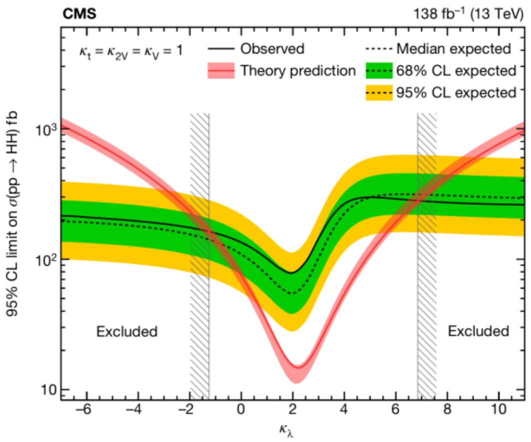


Higgs self-coupling

- Limit on Higgs self-coupling modifier.
  - ATLAS: -0.6< κ_λ < 6.6 at 95% CL
  - CMS: $-1.24 < \kappa_\lambda < 6.49$ at 95% CL



arXiv:2211.01216



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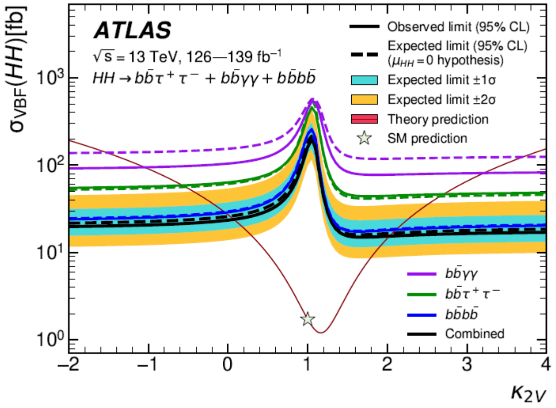
- Limit on VVHH coupling modifier.
  - ATLAS: 0.1 < κ_{2V} < 2 at 95% CL
  - CMS: 0.67 < κ_{2V} < 1.38 at 95% CL



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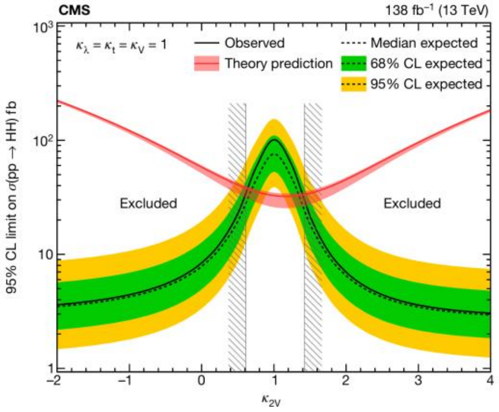

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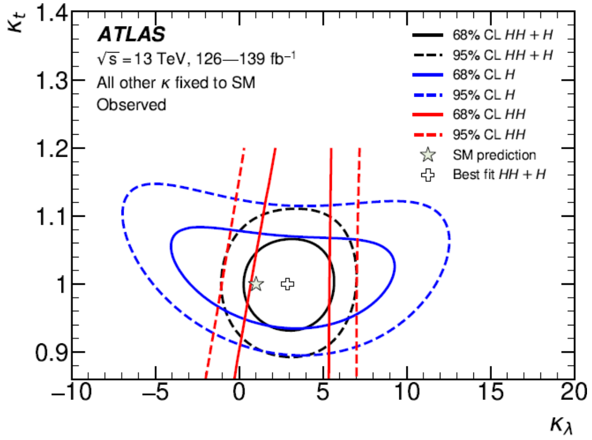
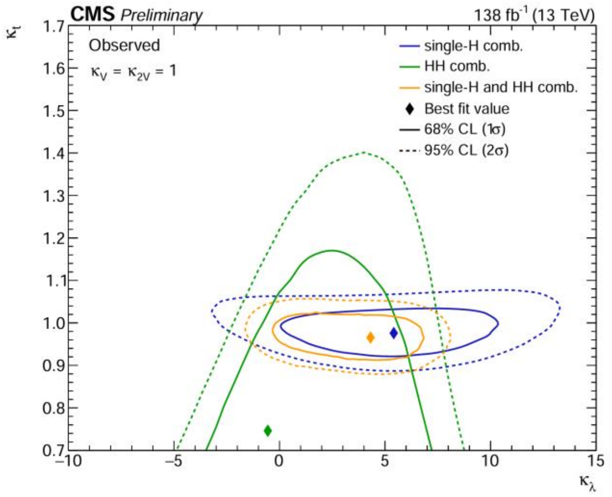
Higgs self-coupling

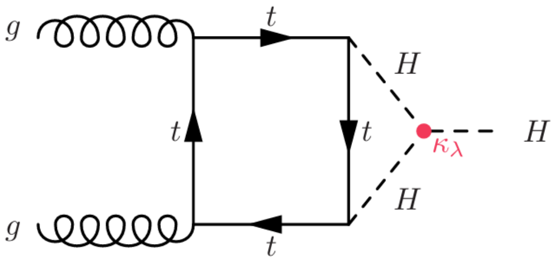
- Higgs self-coupling also contributes to single Higgs production.
- Constrain coupling modifier indirectly using single Higgs measurement.

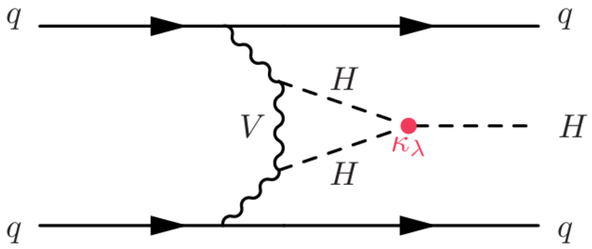


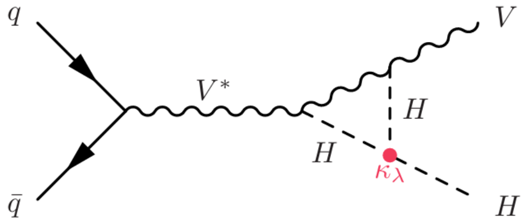
arXiv:2211.01216

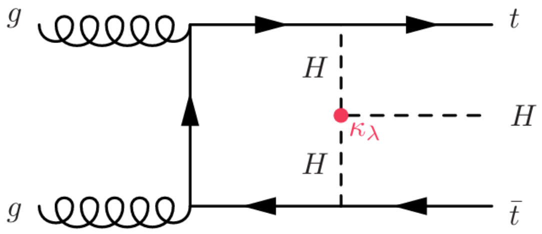


CMS-PAS-HIG-23-006









Summary

- With the full Run 2 and early Run 3 data collected by the ATLAS and CMS detectors:
  - All main Higgs production and decays have been observed.
  - Improved sensitive to rare processes such as HH production and $\mu\mu$, Zγ decays.
  - Higgs properties and coupling have been measured with better precision.

- Many methods used to scrutinize the Standard Model
  - μ framework, κ framework, STXS, EFT

- So far, the observation agrees with the standard model.

- Awaiting more exciting Higgs results in Run 3 and future High-Luminosity LHC (See Jelena's talk).