

Higgs physics highlights at the LHC

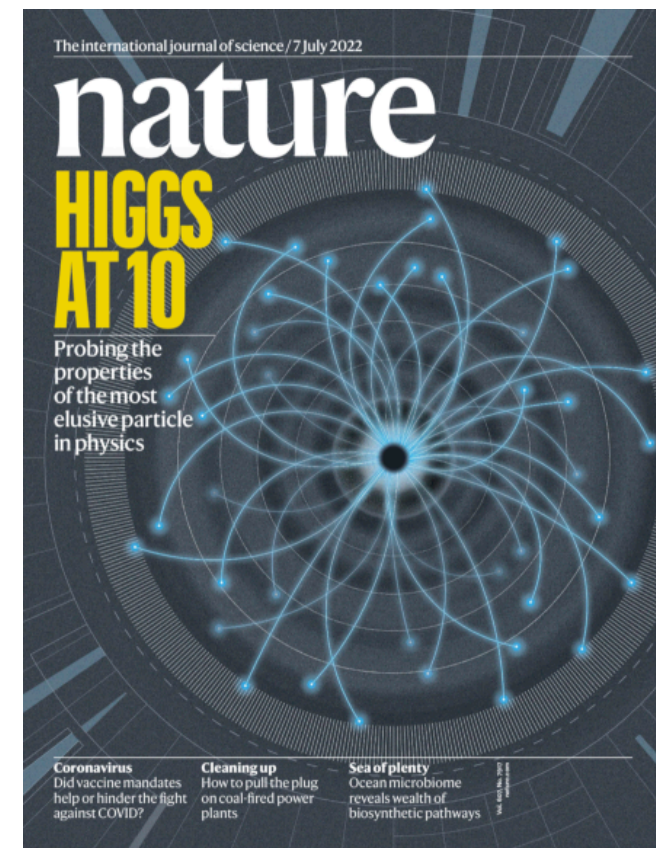
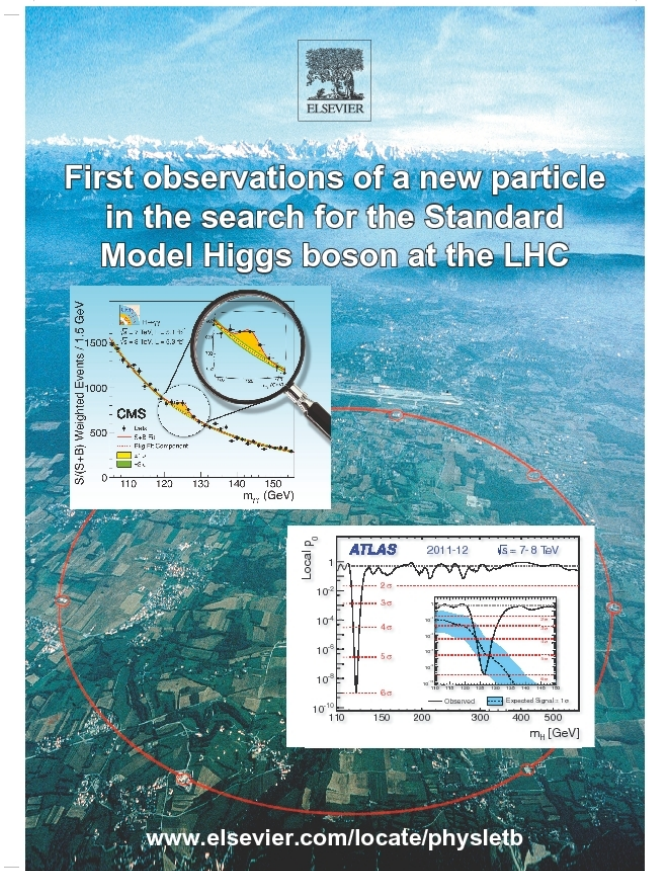
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第二届 *TeV* 物理前沿专题研讨会暨第33届 *LHC Mini-Workshop*
Beijing, 19 September 2026

The Higgs boson

- **The Higgs boson** was discovered by the ATLAS and CMS experiments at the Large Hadron Collider (LHC) in 2012
 - a major milestone for particle physics
- It opened a new way to refine our understanding of the electroweak sector
 - many studies of **Higgs boson properties** have been performed
 - deviation from the Standard Model (SM) predictions on Higgs boson properties would provide clue for new physics



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Why is the electroweak interaction so much stronger than gravity?

- Are there new particles close to the mass of the Higgs boson?
- Is the Higgs boson elementary or made of other particles?
- Are there anomalies in the interactions of the Higgs boson with the W and Z bosons?

Why is there more matter than antimatter in the Universe?

- Are there charge-parity violating Higgs decays?
- Are there anomalies in the Higgs self-coupling that would imply a strong first-order early-Universe electroweak phase transition?
- Are there multiple Higgs sectors?

What is dark matter?

- Can the Higgs boson provide a portal to dark matter or a dark sector?
- Is the Higgs lifetime consistent with the Standard Model?
- Are there new decay modes of the Higgs boson?

What is the origin of the vast range of quark and lepton masses in the Standard Model?

- Are there modified interactions to the Higgs boson and known particles?
- Does the Higgs boson decay into pairs of quarks or leptons with distinct flavours (for example, $H \rightarrow \mu^+ \tau^-$)?

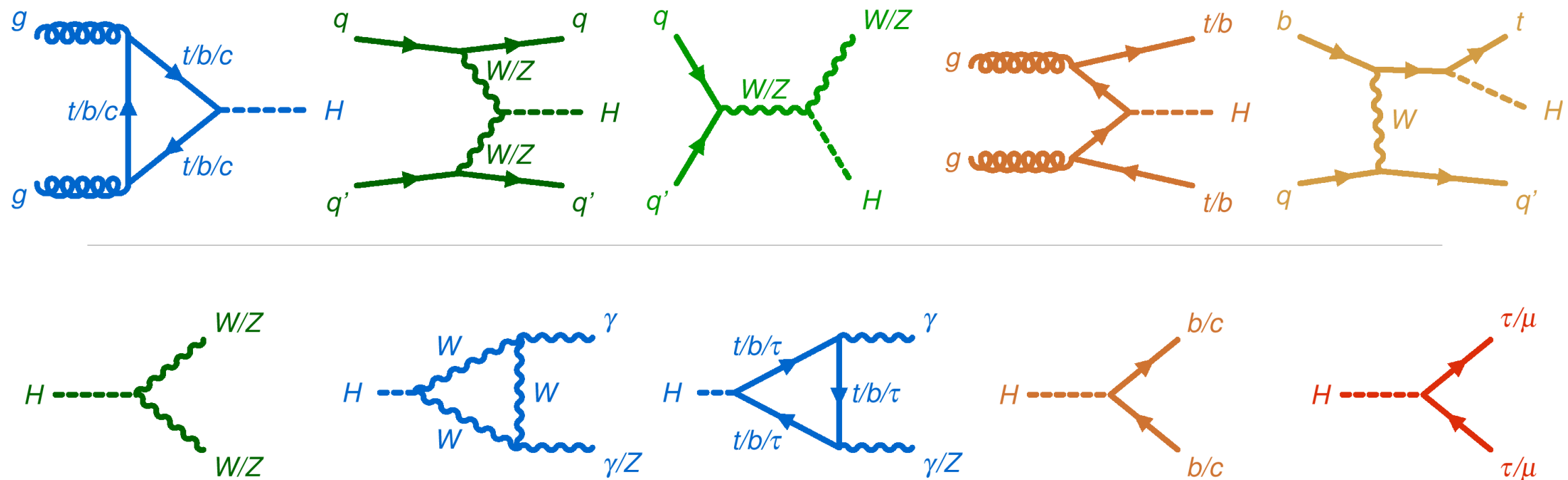
What is the origin of the early Universe inflation?

- Any imprint in cosmological observations?

Gavin P. Salam, Lian-Tao Wang & Giulia Zanderighi, Nature 607 (2022) 41-47

Measurements of Higgs coupling properties

Higgs coupling property measurements



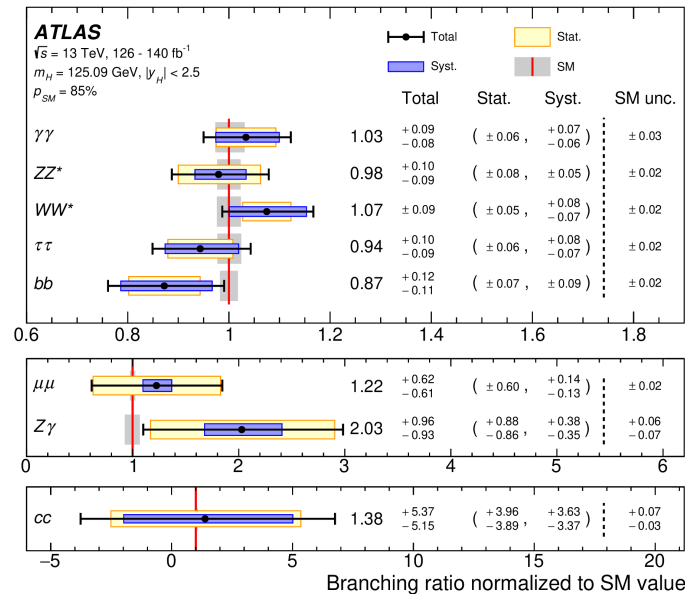
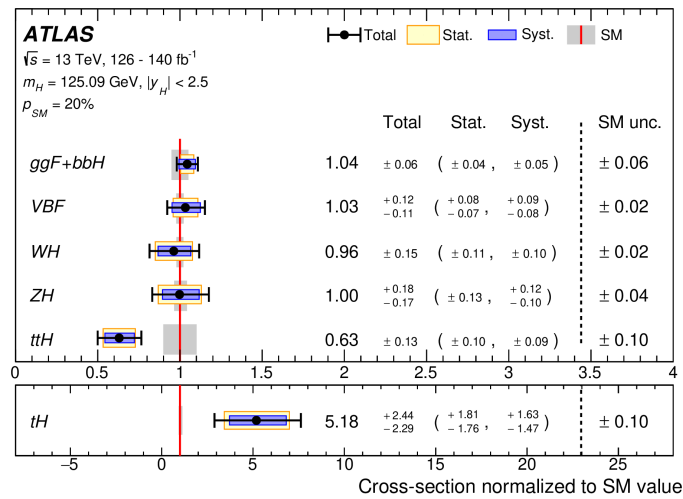
- ATLAS/CMS perform combination based on analyses of **various Higgs decay channels**
 - Each decay channel targets **multiple Higgs production modes**

Higgs production and decay rates

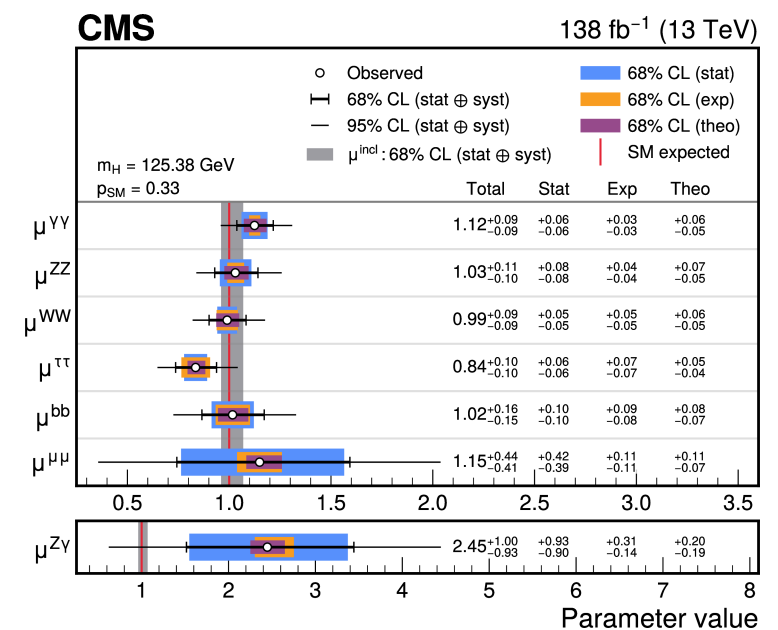
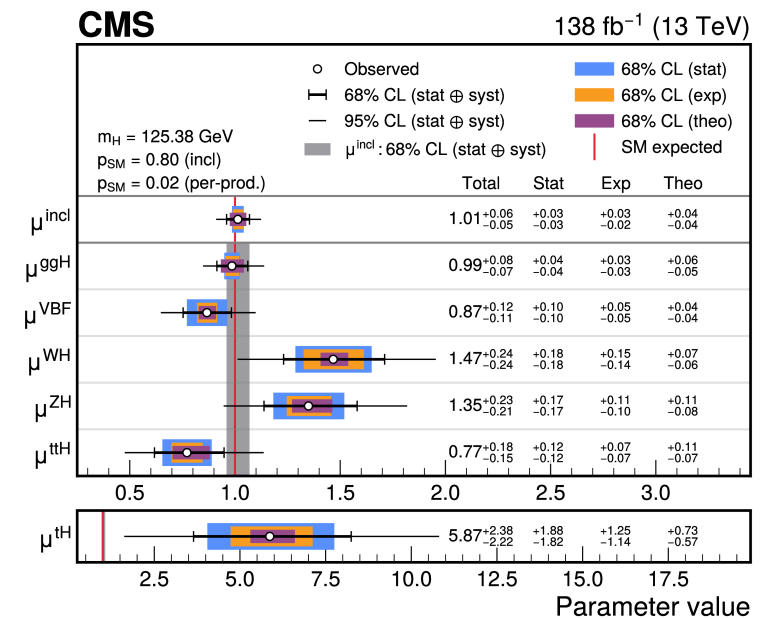
[arxiv:2608.07332](https://arxiv.org/abs/2608.07332)

[Rep. Prog. Phys. 89 \(2026\) 087801](#)

ATLAS



CMS



- All major production modes (ggF, VBF, WH, ZH, ttH) and decay modes ($H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$, $H \rightarrow WW$, $H \rightarrow \tau\tau$, $H \rightarrow bb$) are observed

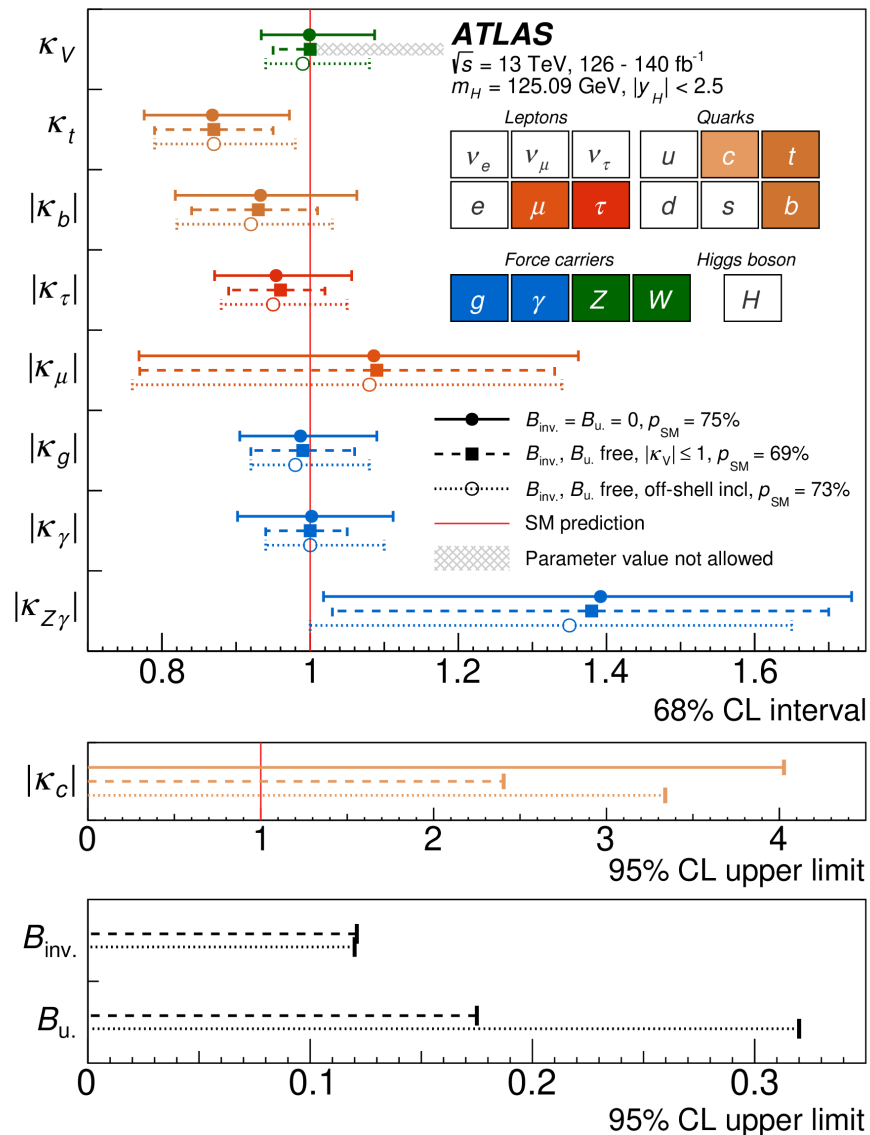
Higgs boson couplings with “kappa”

[arxiv:2608.07332](https://arxiv.org/abs/2608.07332)

[Rep. Prog. Phys. 89 \(2026\) 087801](#)

ATLAS

CMS



EW boson: 5%

3rd generation fermion: 10%

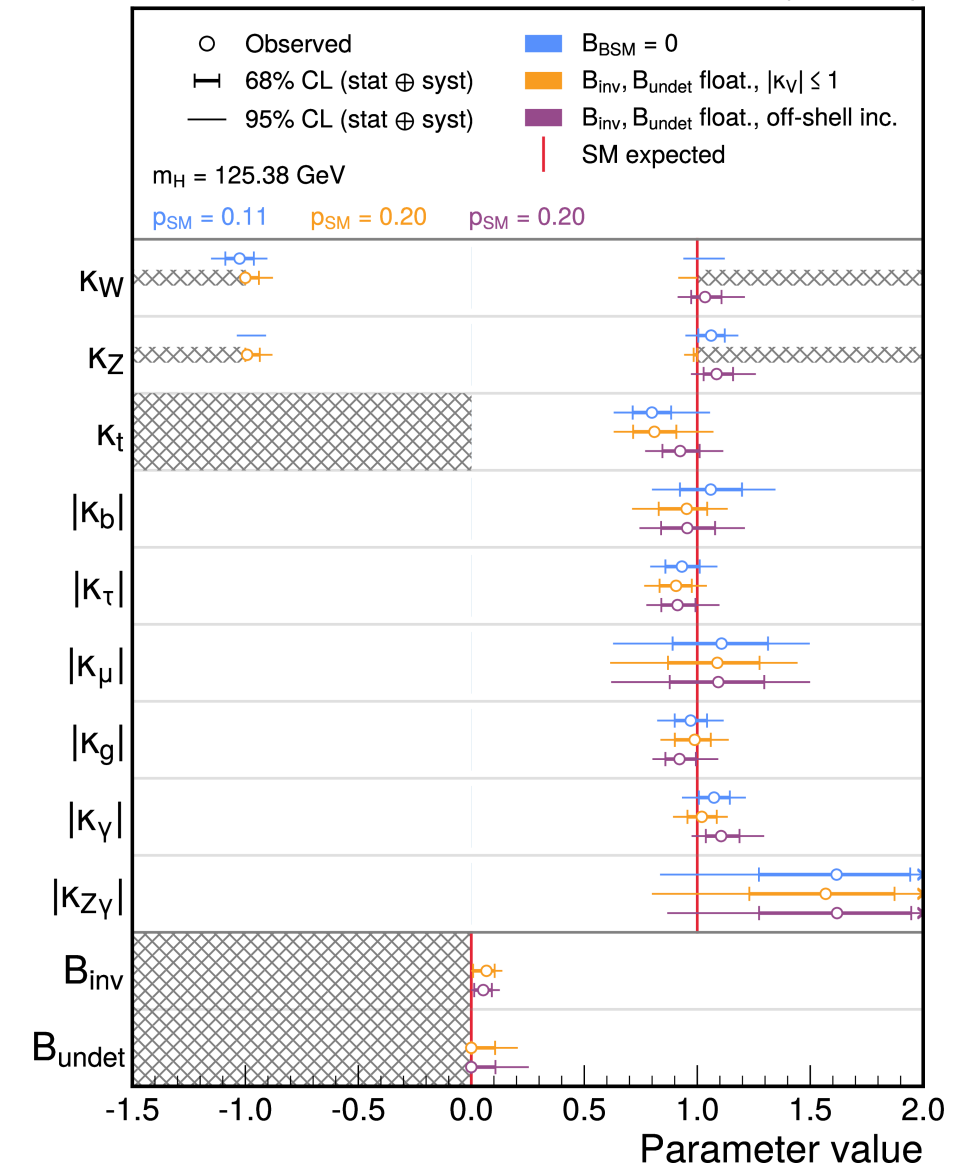
Massless boson: 6-7%

Invisible BR: $< \sim 12\%$

Undetected BR: $< \sim 30\%$

CMS

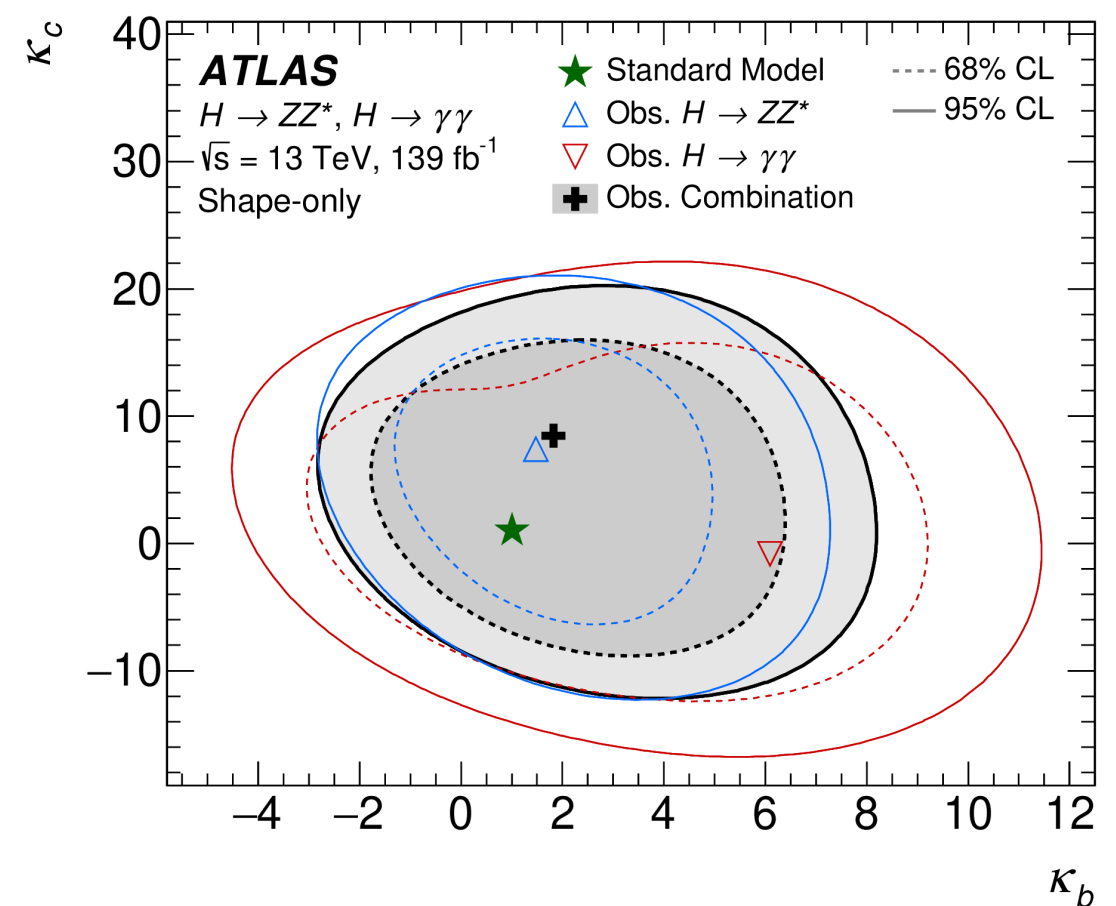
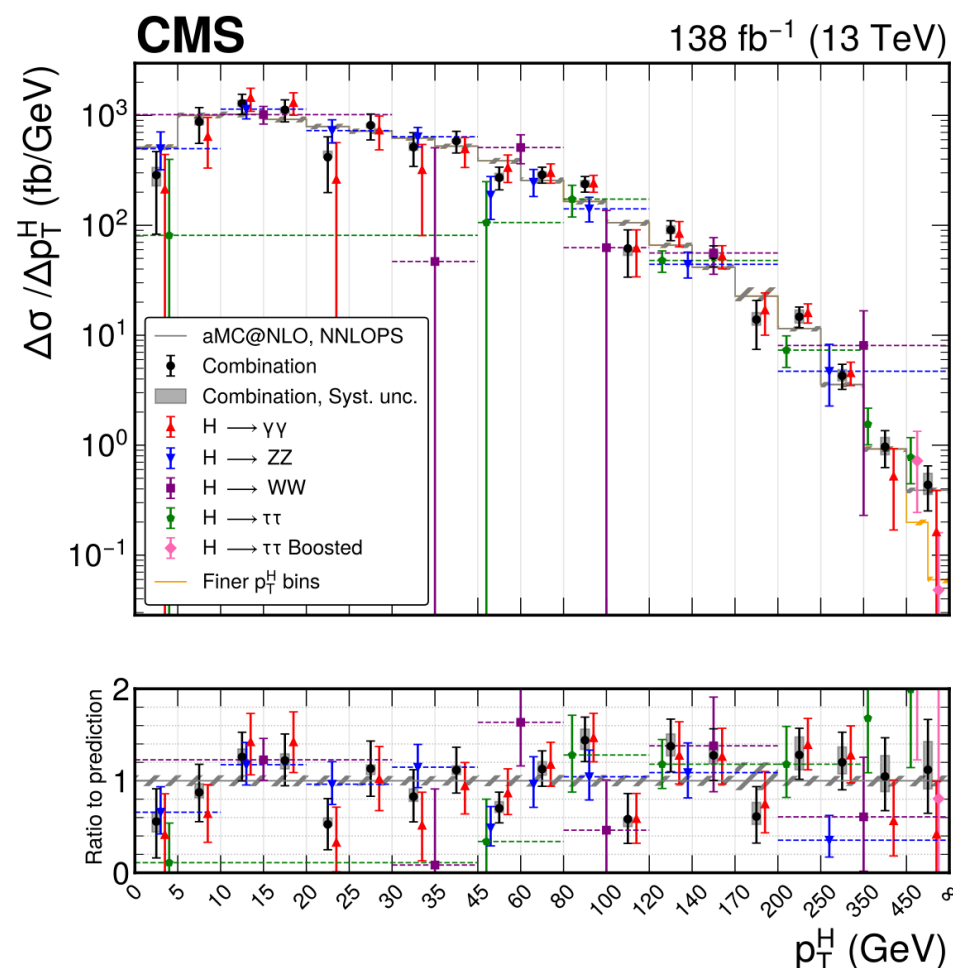
138 fb^{-1} (13 TeV)



- Assign coupling modifier to each interaction vertex (e.g. κ_W , κ_t ...)
- Results with different assumptions on the total Higgs boson decay width are provided

Fiducial cross sections

- Define fiducial phase space and measure cross section inclusively or differentially to minimize dependence on theoretical uncertainties and provide sensitivity to BSM effects
 - Measured in different decay modes ($H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$, $H \rightarrow WW$, $H \rightarrow \tau\tau$, $H \rightarrow bb$) and in combination
 - Results are **currently in agreement with the SM predictions** and can be interpreted using kappa models

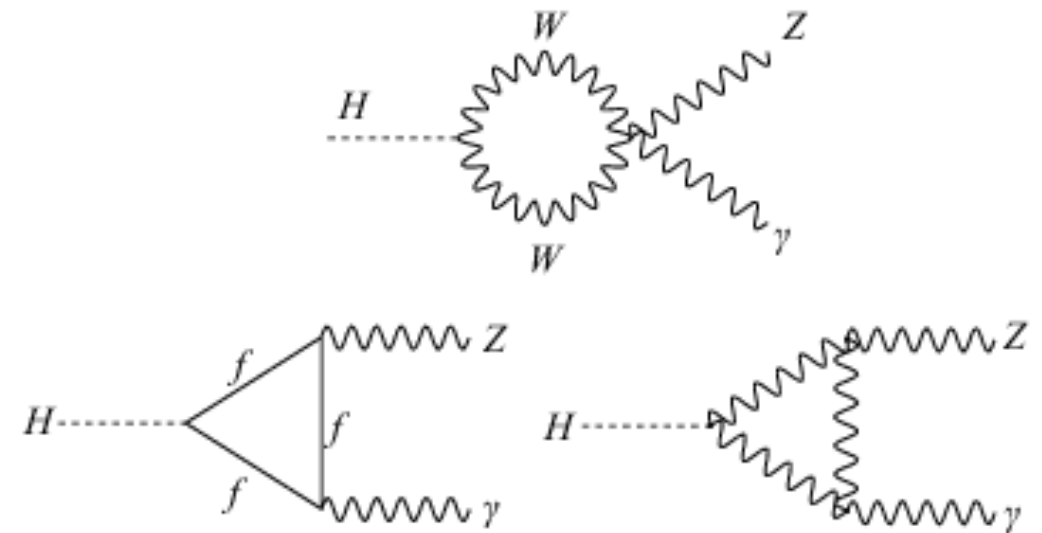


[JHEP 04 \(2026\) 093](#)

[JHEP05\(2023\)028](#)

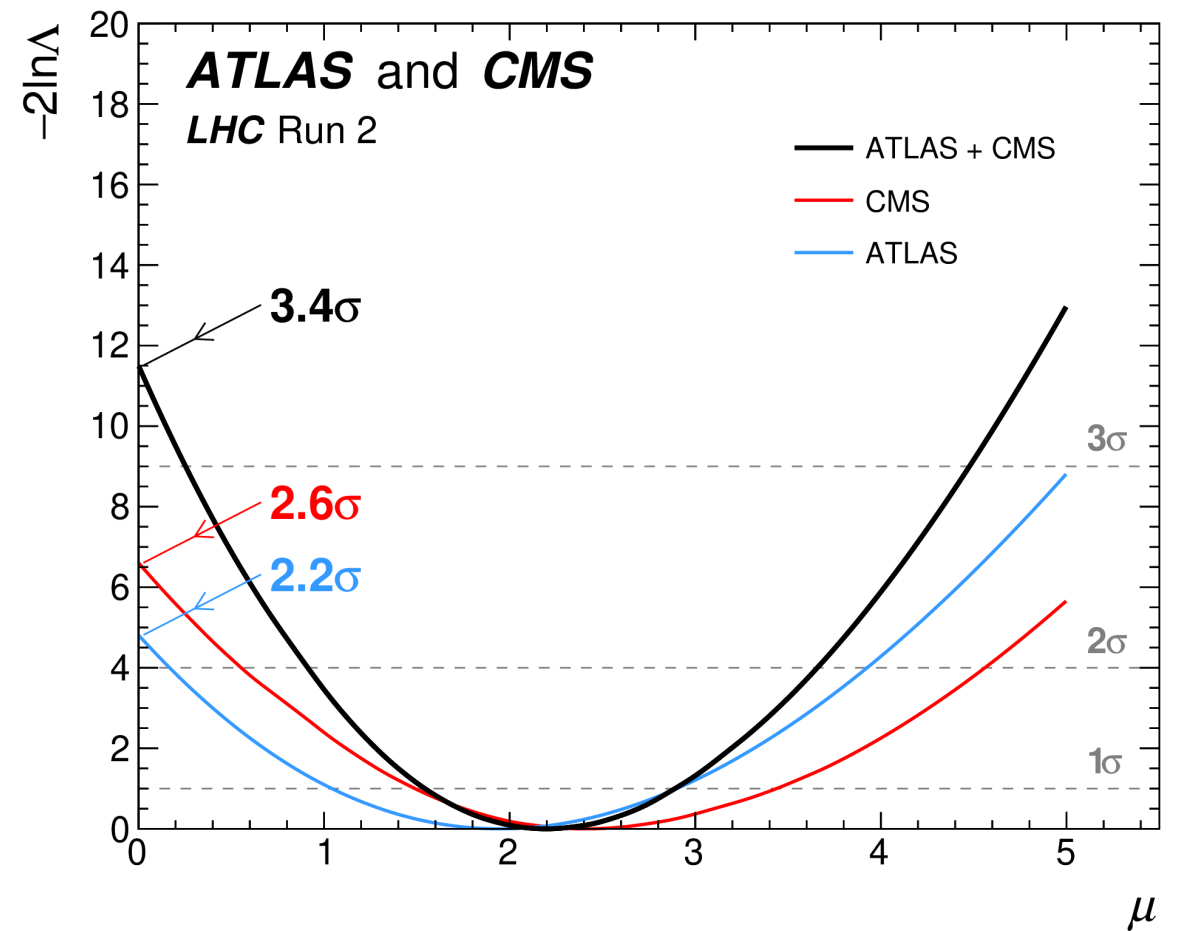
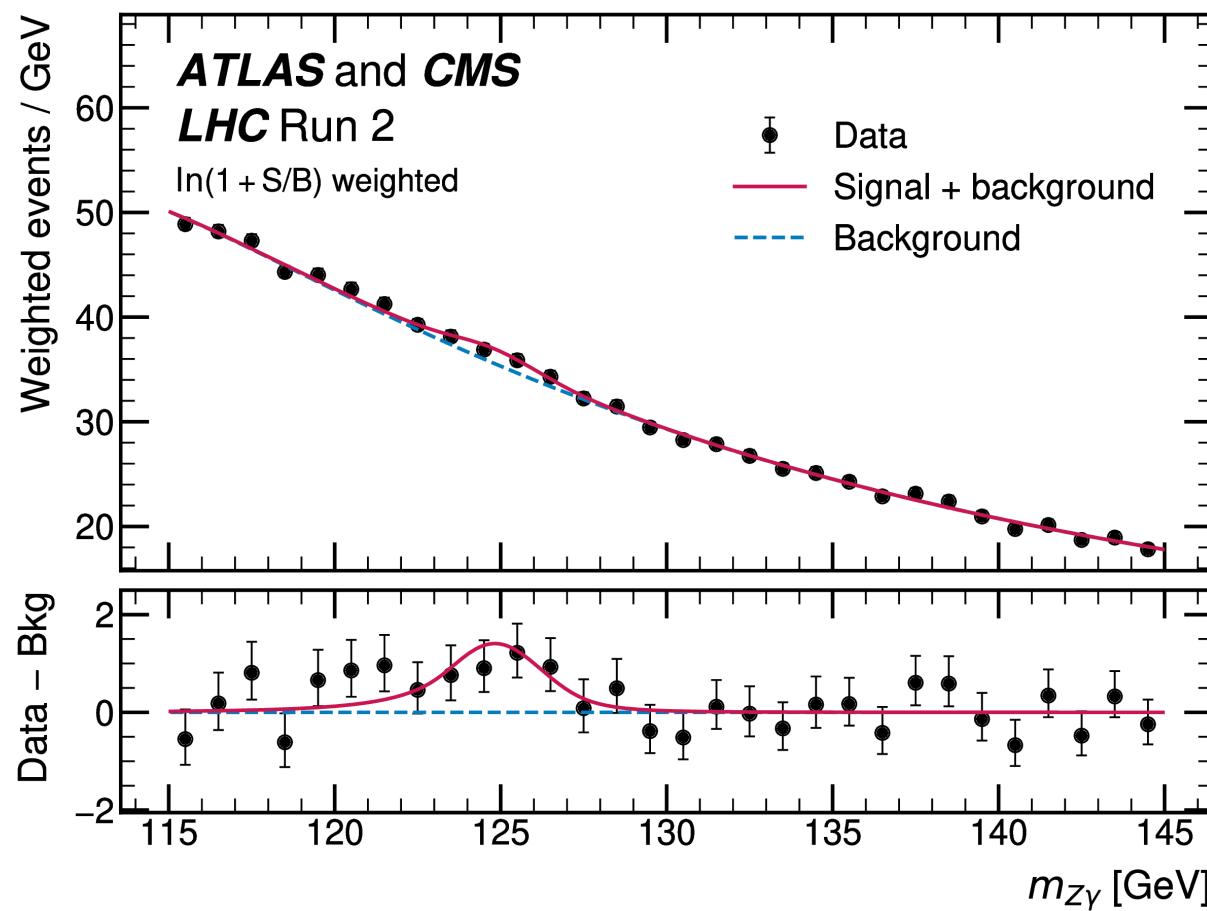
$H \rightarrow Z\gamma$ decay

- BSM particles & couplings could be present in the quantum loops
- Difference between $H \rightarrow Z\gamma$ decay and $H \rightarrow \gamma\gamma/H \rightarrow ZZ$ decay sensitive to new physics
 - (e.g. Qing-Hong Cao et al. *Phys. Lett. B* 789 (2019) 233)
- Select events with two leptons (mll ~ 90 GeV) and one photon and separate them to multiple categories to target various production modes
- Fit in $l\bar{l}\gamma$ mass distribution over all categories



$H \rightarrow Z\gamma$ decay

[Phys. Rev. Lett. 132 \(2024\) 021803, Featured in Physics](#)

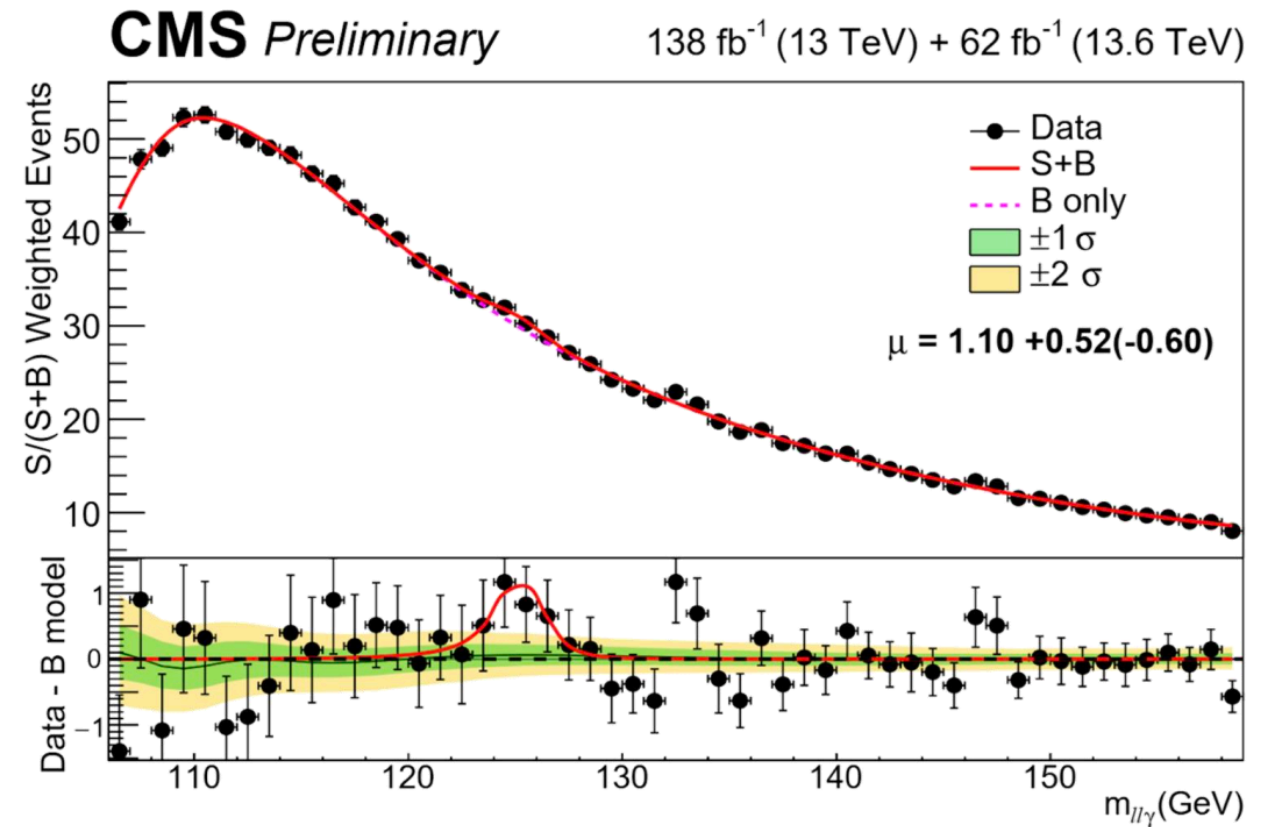
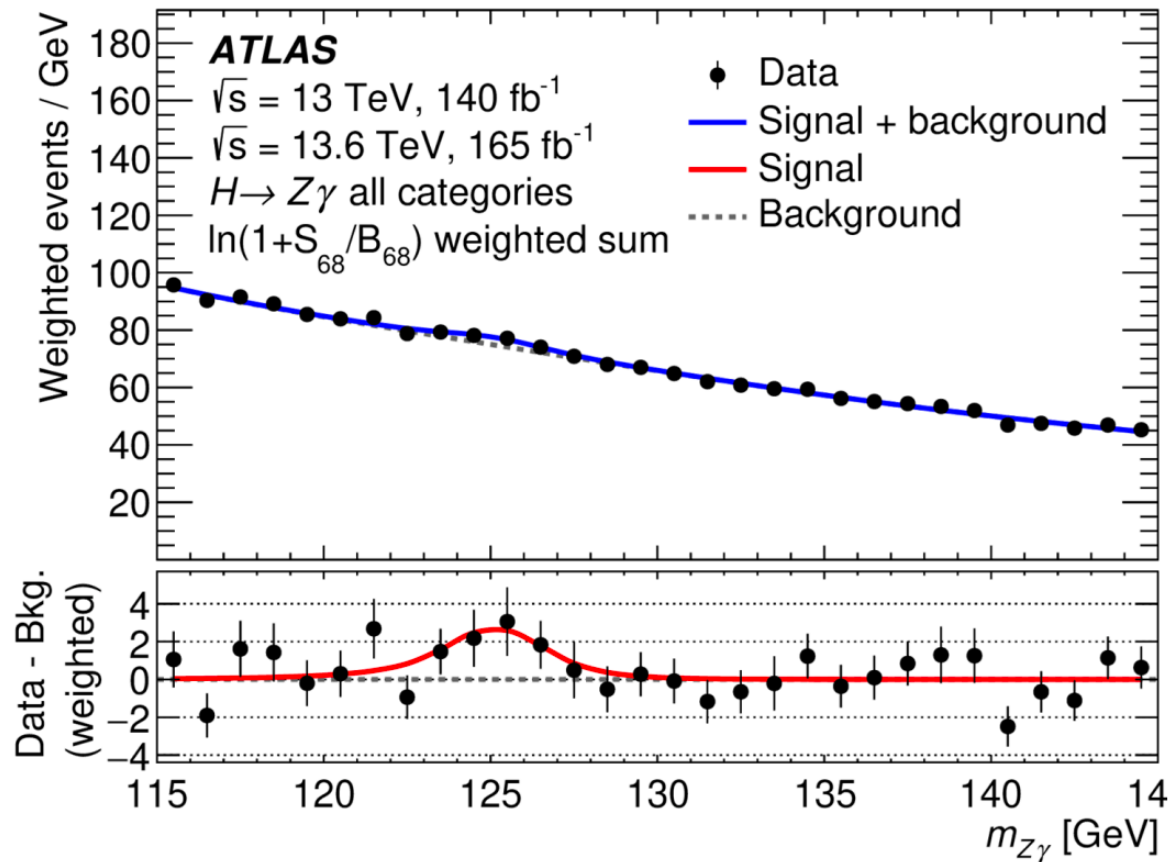


- In ATLAS+CMS combined result, the observed $H \rightarrow Z\gamma$ significance is **3.4σ** (expected 1.6σ)
- **First evidence** of the $H \rightarrow Z\gamma$ decay
- Signal strength is 2.2 ± 0.7 : agrees with theoretical expectation within **1.9σ**

H→Zγ decay

[arxiv:2507.12598](https://arxiv.org/abs/2507.12598)

[CMS-PAS-HIG-25-010](#)

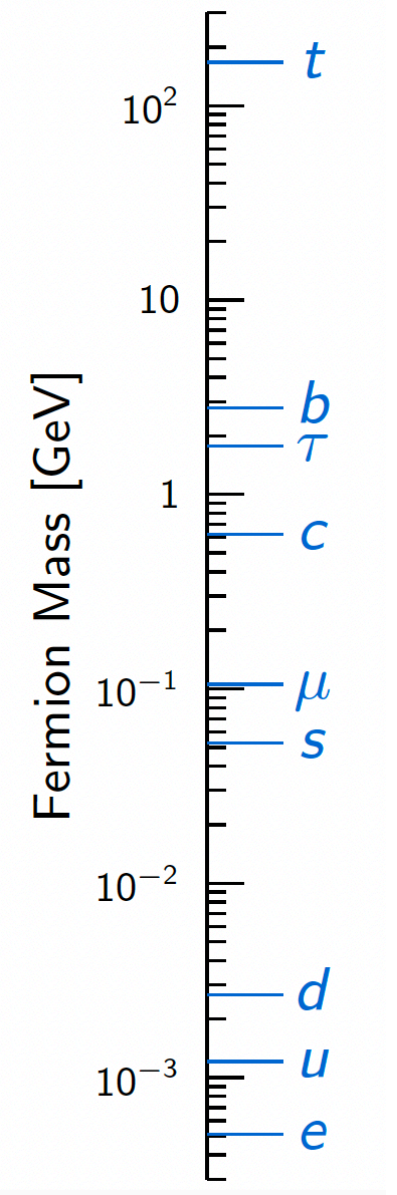
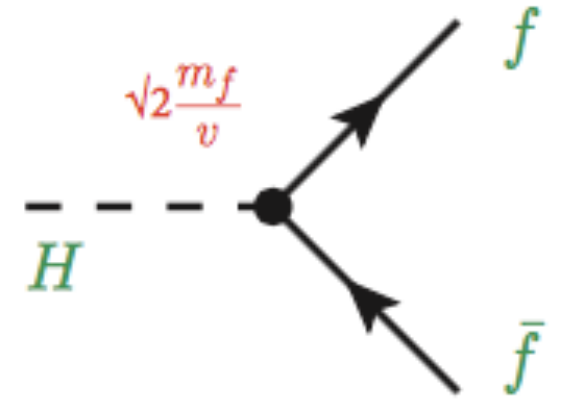


- The observed H→Zγ significance in ATLAS full Run 2 + partial Run 3 (2022-2024) result is **2.5σ** (expected 1.9σ). Signal strength: $1.3 +0.6 -0.5$
- The observed H→Zγ significance in CMS full Run 2 + partial Run 3 (2022-2023) result is **1.9σ** (expected 2.3σ). Signal strength: $1.1 +0.5 -0.6$
- The CMS achieves better expected significance with less data:
 - Re-analyzing Run 2, signal mass resolution, background mass shape, etc.

Higgs Yukawa couplings

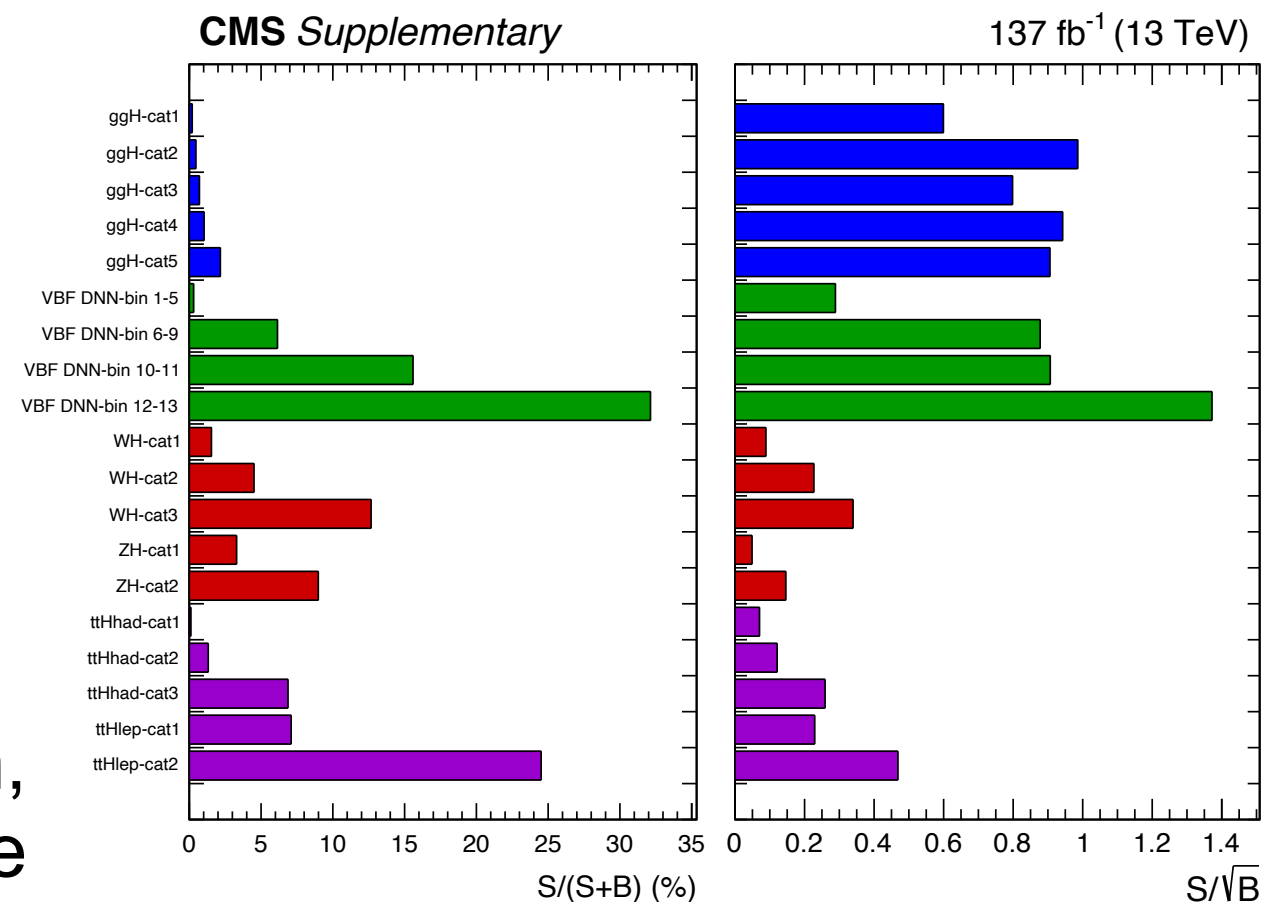
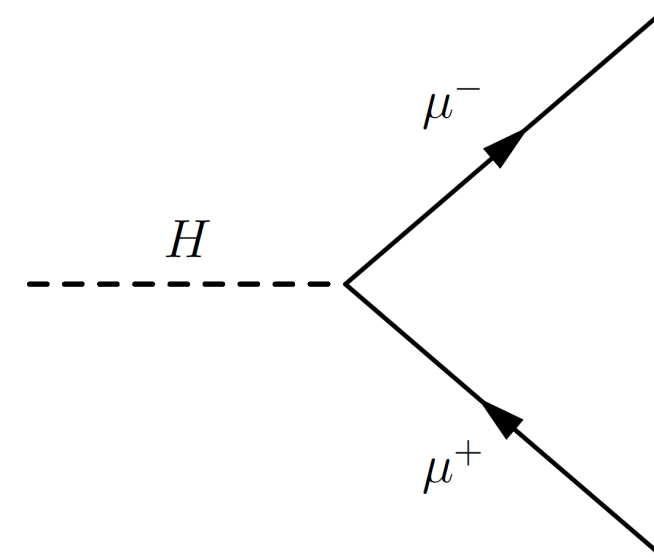
Yukawa couplings

- In Standard Model, Higgs boson couples to fermions (quarks and leptons) through Yukawa interactions
 - **giving masses to quarks and leptons**
- Yukawa interactions are the least constrained sector of the Higgs physics
 - **important to study the Yukawa sector, which may provide important indication for the origin of the fermion mass pattern**
- Experimental signatures: **$t\bar{t}H$ production**, **$H \rightarrow \tau\tau$ decay**, **$H \rightarrow b\bar{b}$ decay**, etc.
 - In SM, Yukawa couplings are proportional to fermion masses; BSM physics can modify coupling strengths



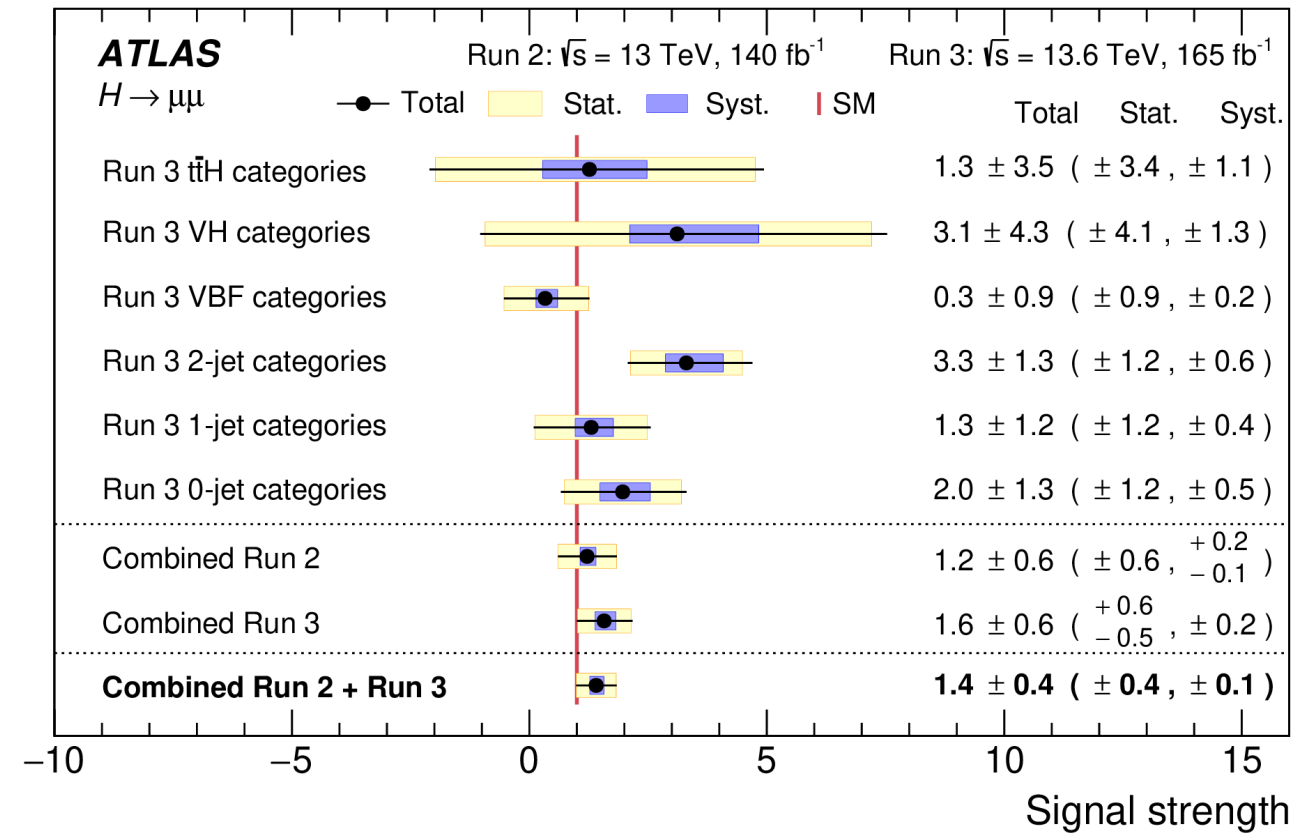
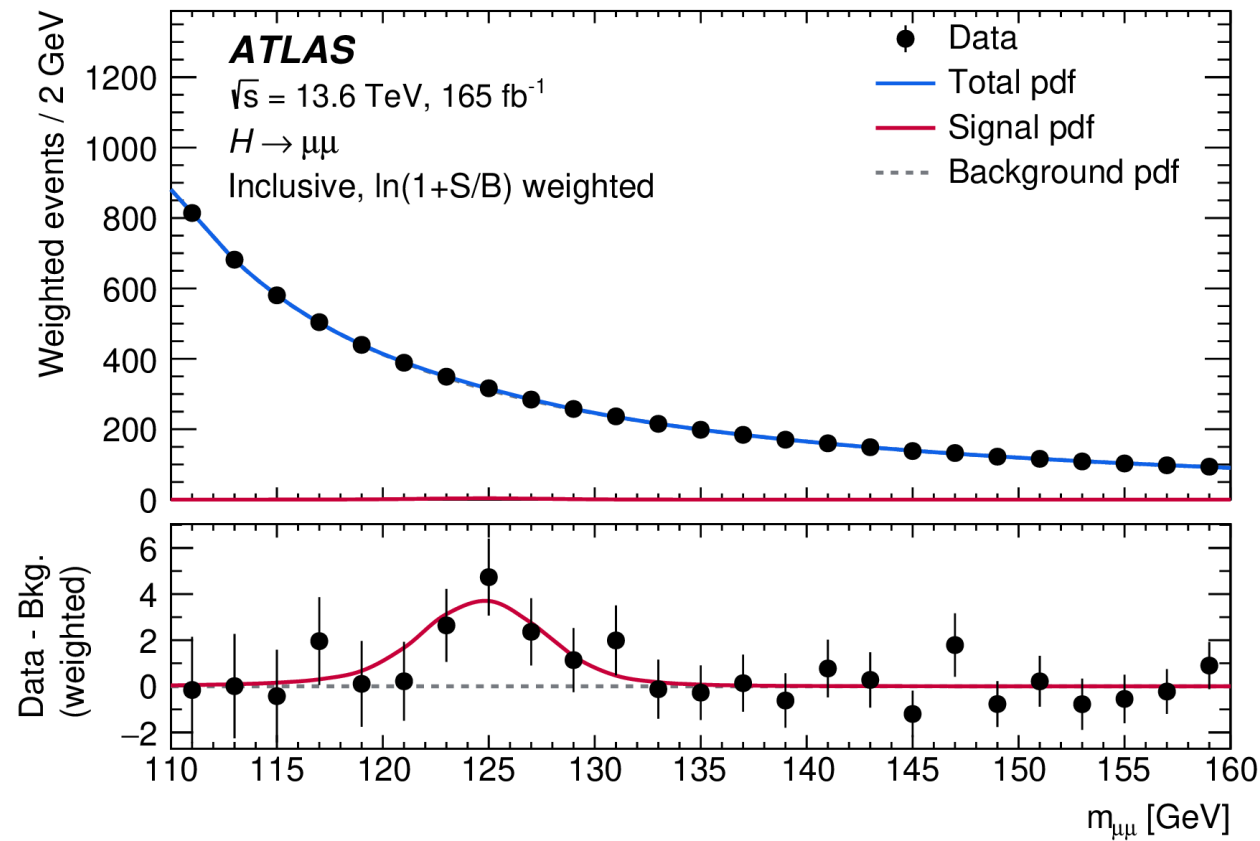
$H \rightarrow \mu\mu$ decay

- The couplings between the Higgs boson and third-generation fermions (top quark, bottom quark, τ lepton) have already been observed
- The Higgs couplings with fermions of the other generations have not been established
- **The Higgs decay to two muons offers the best opportunity to observe the Higgs couplings with second-generation fermions at the LHC**
- key ingredients of the analysis: for sure optimal di-mu mass resolution, but also extreme optimization of the categories for best S/B



[JHEP 01 \(2021\) 148](#)

$H \rightarrow \mu\mu$ decay

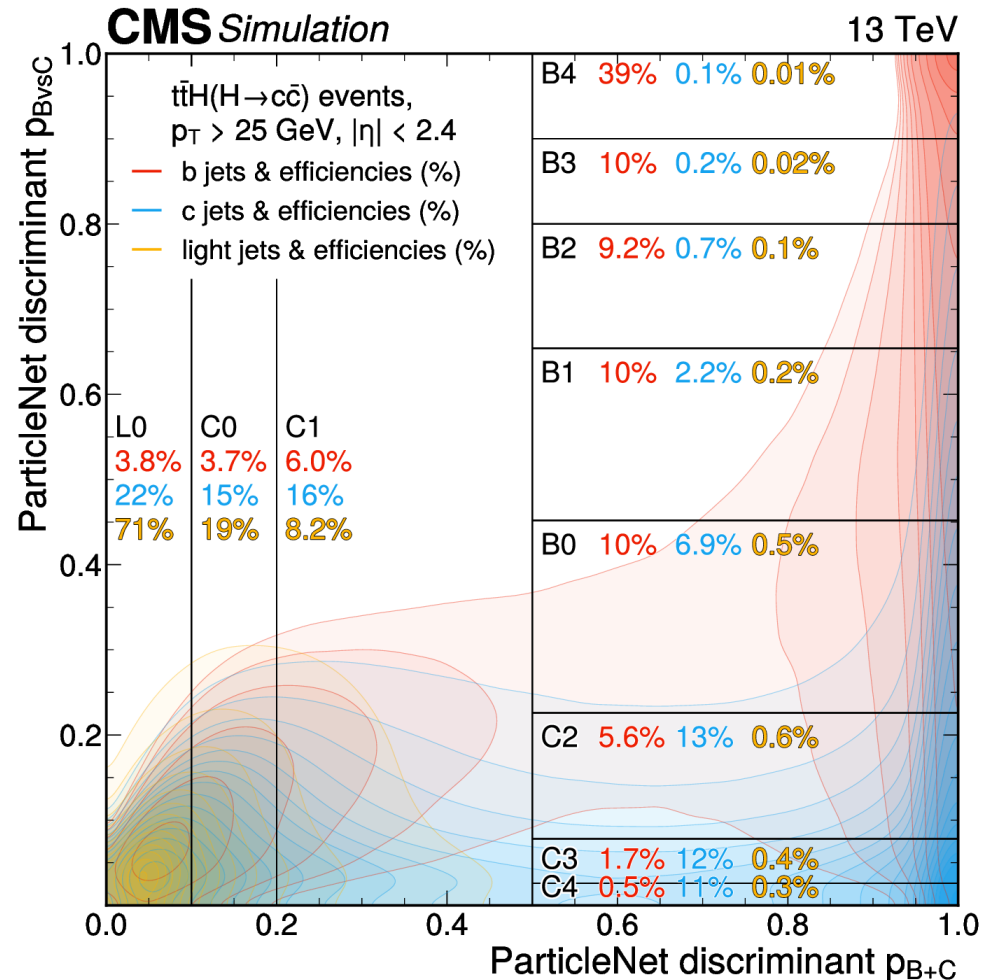
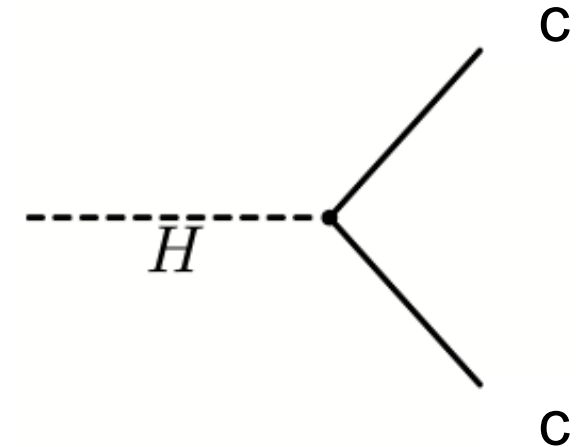


Phys. Rev. Lett. 135 (2025) 231802

- The observed $H \rightarrow \mu\mu$ significance in ATLAS full Run 2 + partial Run 3 (2022-2024) result is **3.4 σ** (expected 2.5 σ)
 - First evidence at ATLAS
- The observed $H \rightarrow \mu\mu$ significance in CMS full Run 2 result is **3.0 σ** (expected 2.5 σ)
 - First evidence; benefit from better muon resolution

$H \rightarrow c\bar{c}$ decay

- **$H \rightarrow c\bar{c}$ decay** is currently the main channel to probe Higgs coupling to c quarks
 - 20×smaller BR than $H \rightarrow b\bar{b}$
 - Less distinct charm signature in detector



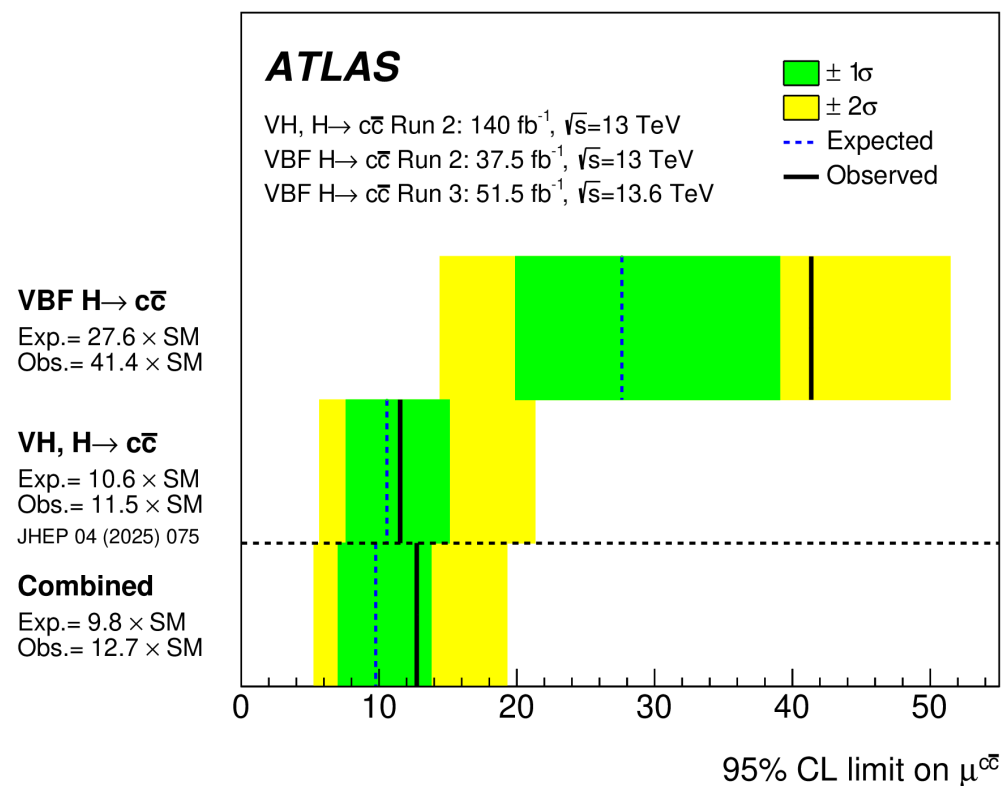
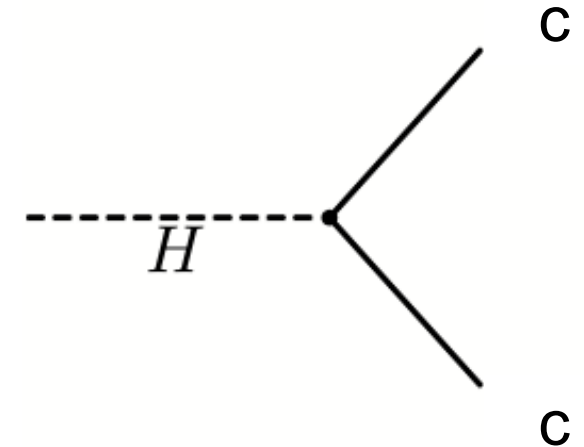
CMS $t\bar{t}H H \rightarrow c\bar{c}$

- First search for $H \rightarrow c\bar{c}$ in $t\bar{t}H$ production channel
 - Graph convolutional NN for simultaneous ID of b- and c-jets (**PNet**)
 - Multiclass event classifier-based (**ParT**)
- In combination with VH, most stringent constraint to date
 - **$|Kc| < 3.5$ (2.7) obs. (exp.)**

Phys. Rev. Lett. 136 (2026) 011801

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[arxiv:2511.21911](https://arxiv.org/abs/2511.21911)

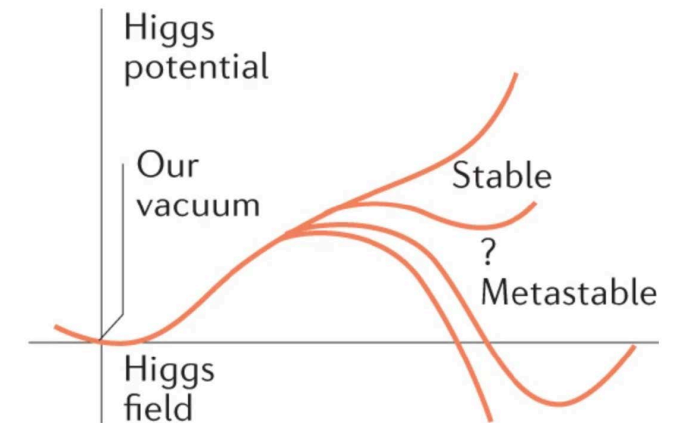
ATLAS VBF $H \rightarrow c\bar{c}$

- First search for $H \rightarrow c\bar{c}$ in VBF production channel
 - GN2transformer tagger for flavour identification
 - Adversarial NN decorrelated from di-jet Higgs candidate mass
- In combination with VH, constraint on Higgs-charm Yukawa coupling modifier:
 - **$|K_c| < 4.7$ (3.9) obs. (exp.)**

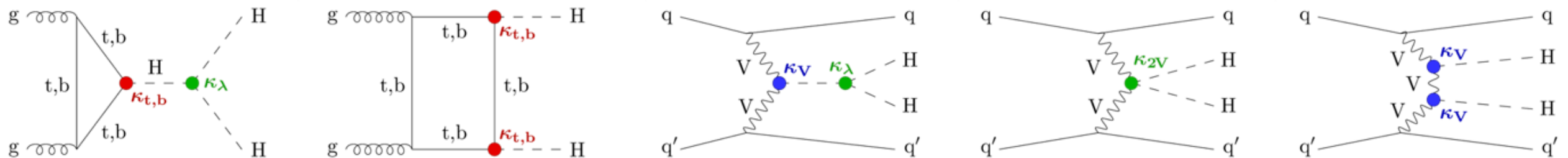
Higgs boson self-couplings

Higgs boson self-couplings

- **Higgs self-coupling is one of the deepest questions of SM and may provide a portal to new physics beyond it**
- Vacuum stability, early universe evolution, ...
- **Double Higgs production is the way to directly probe Higgs self-couplings at the LHC**
- Extremely low cross-section in the SM
- Non-SM self-coupling strength can change cross-section and kinematics of double Higgs production
- Many final states are analyzed: $bbbb$, $bb\tau\tau$, $bb\gamma\gamma$, ...

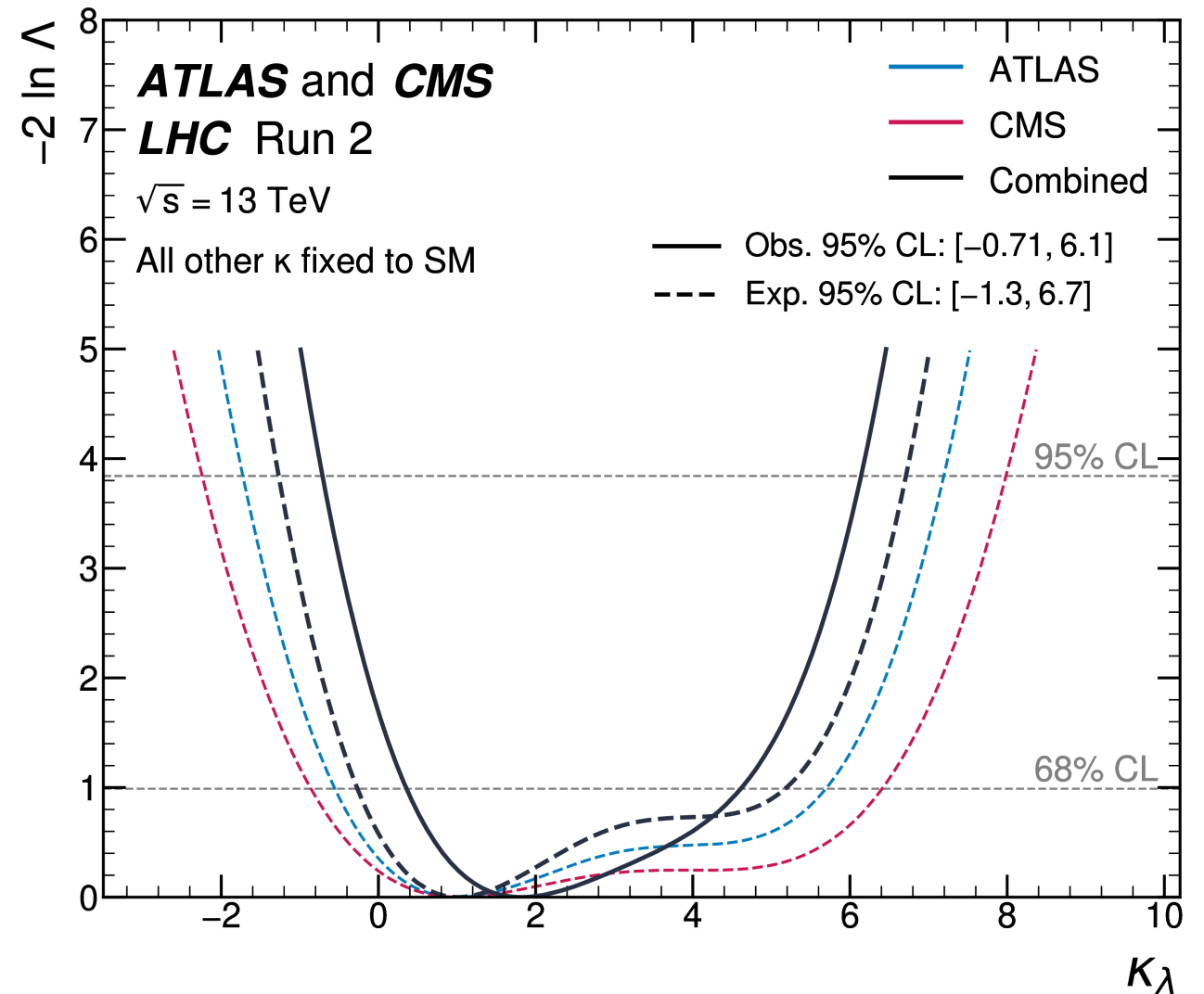
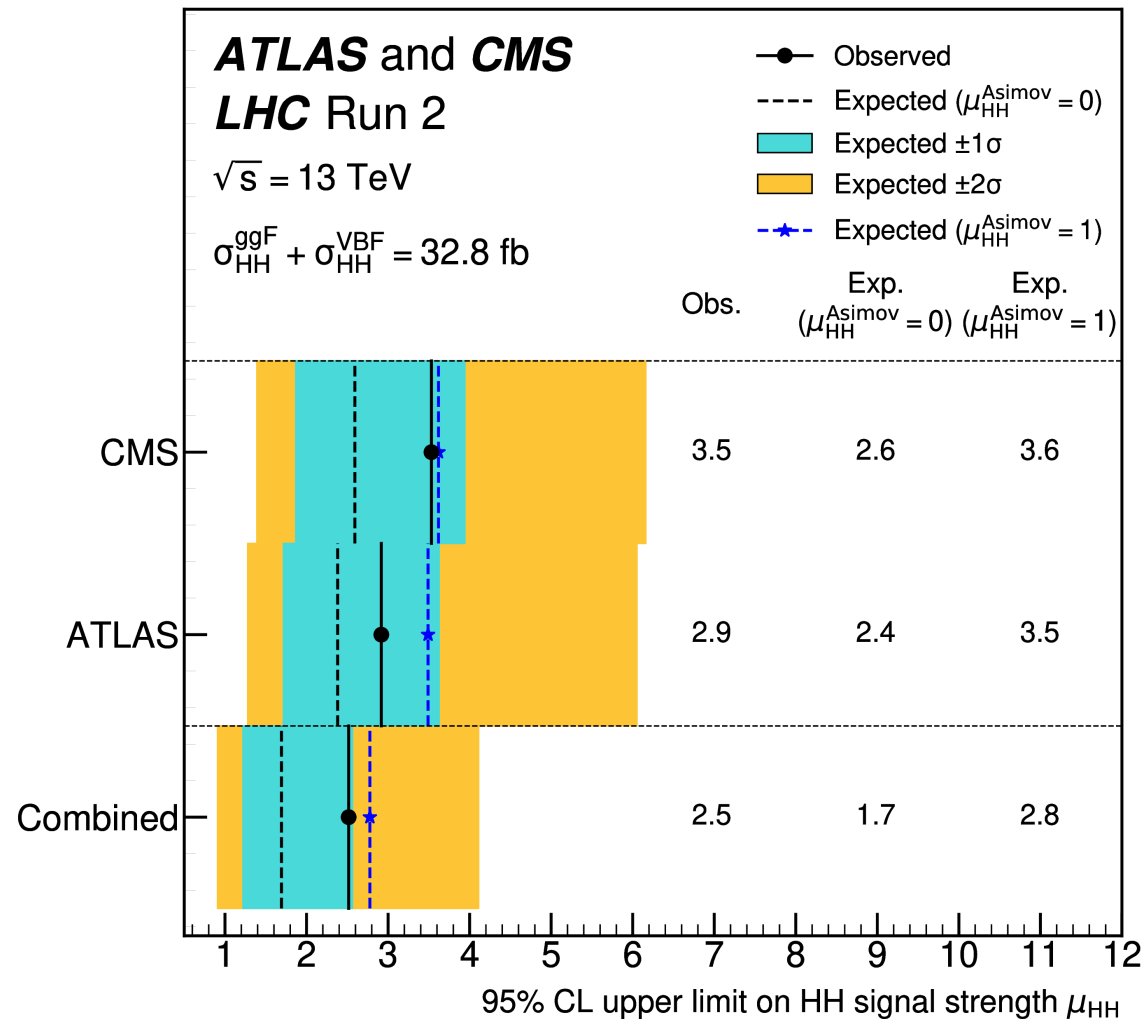


Higgs boson pair production



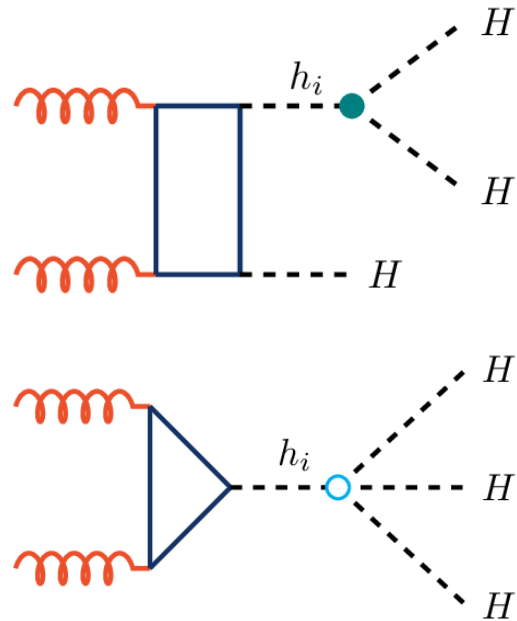
LHC Double Higgs search combination

[arxiv:2602.23991](https://arxiv.org/abs/2602.23991), accepted by PRL



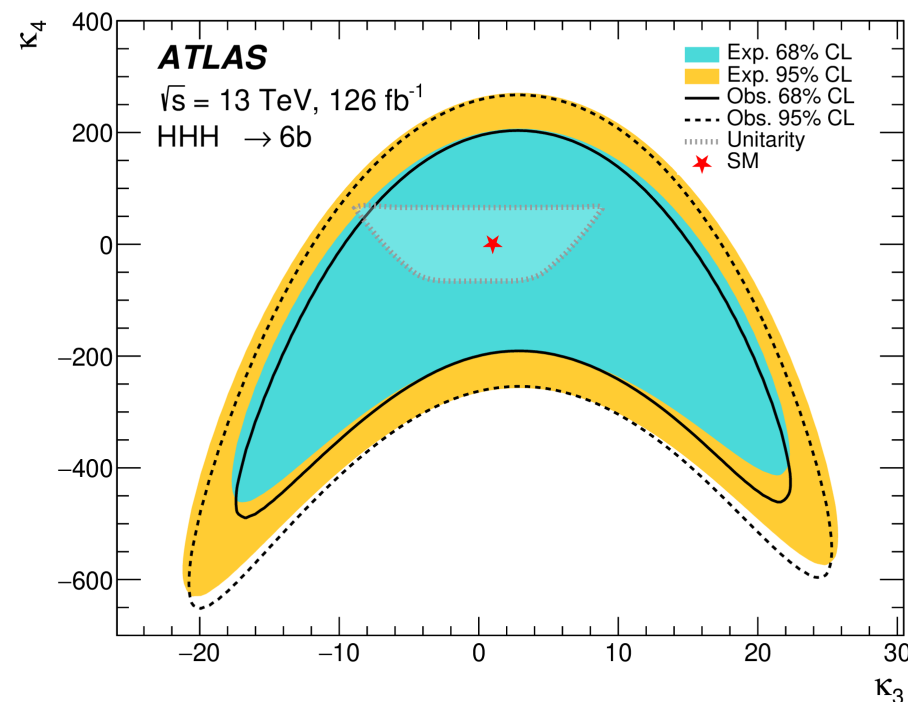
- Limit of double Higgs cross section: 2.5 times SM prediction
- HHH coupling strength: $-0.71 < \kappa_\lambda < 6.1$; HHVV coupling strength: $0.73 < \kappa_{2V} < 1.3$

Triple Higgs search



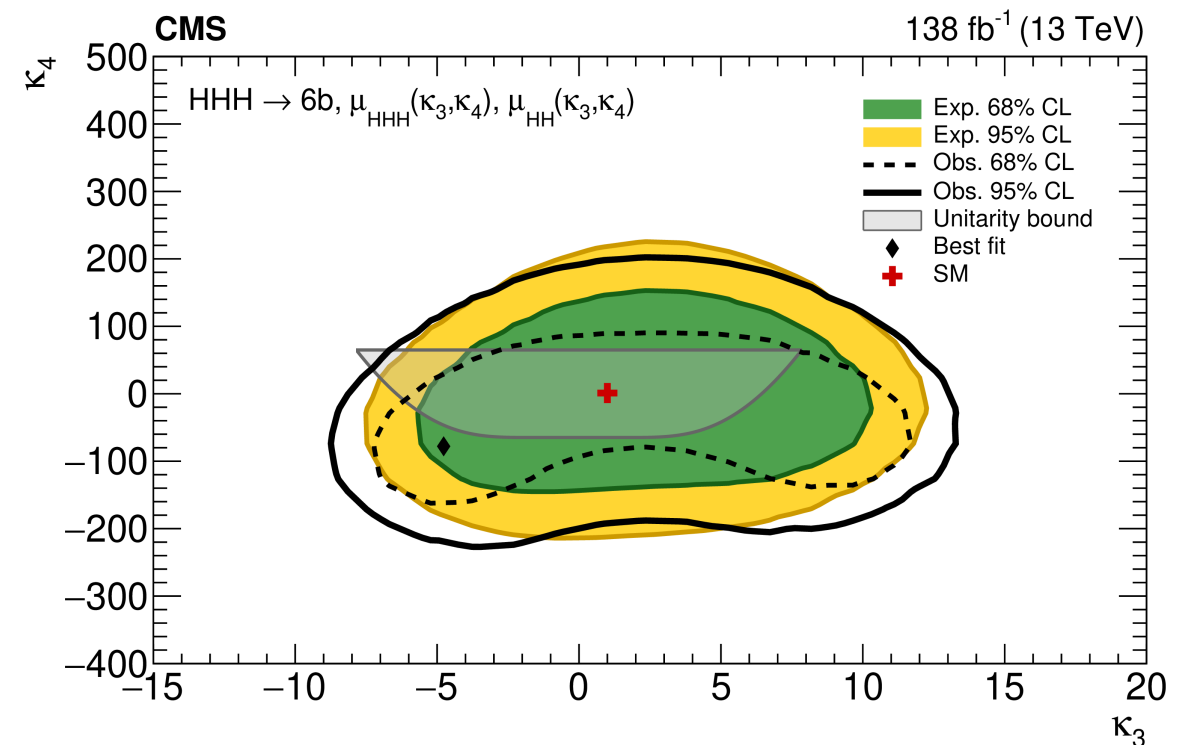
- Triple Higgs production is uniquely sensitive to both trilinear and quartic Higgs self-couplings simultaneously
- The first searches for triple Higgs boson production were completed in the 6b final state

ATLAS



[Phys. Rev. D 111 \(2025\) 032006](#)

CMS

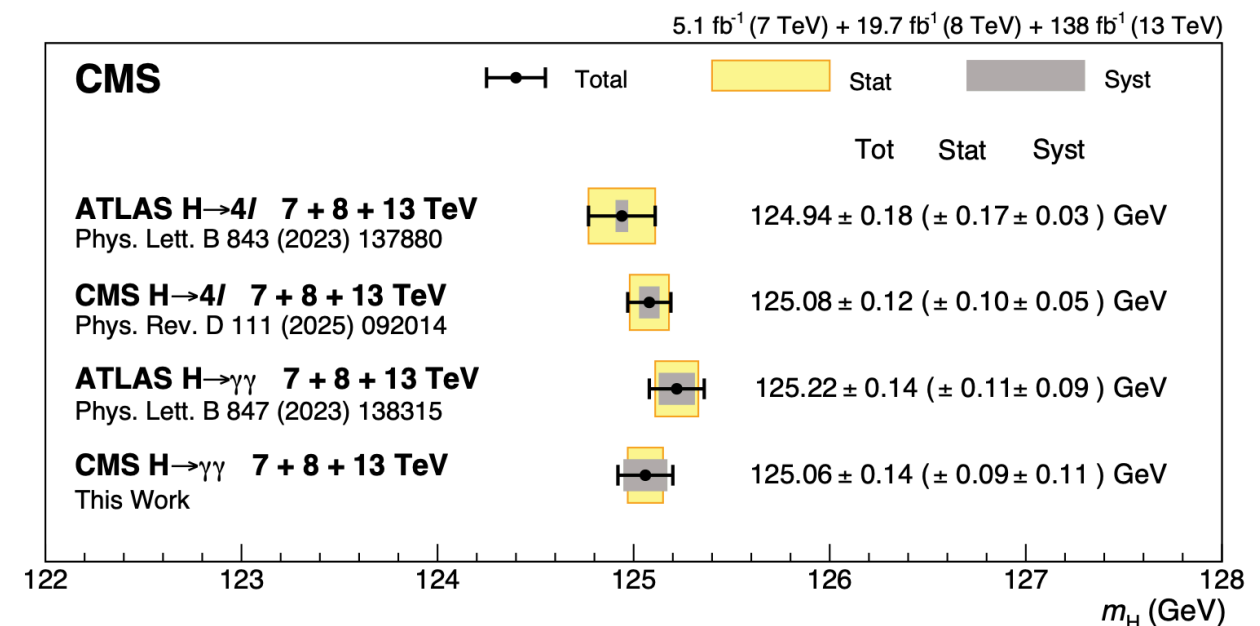


[arxiv:2607.05145](#)

Measurement of Higgs mass/width, spin/CP

Higgs mass

- **Higgs mass** is the only free parameter in the SM Higgs sector.
- Measured in channels with best resolution:
 $H \rightarrow ZZ^* \rightarrow 4l$ and $H \rightarrow \gamma\gamma$
 - ATLAS Run 1+full Run 2 combination: 125.11 ± 0.11 GeV (0.1% precision)
 - CMS Run 1+full Run 2 combination: coming soon

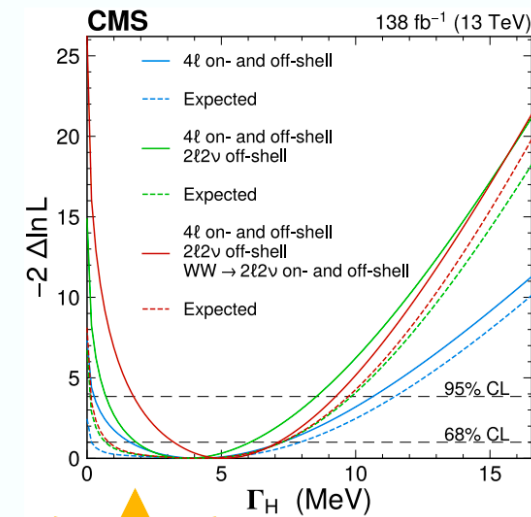


[arxiv:2607.28396](https://arxiv.org/abs/2607.28396)

Higgs width

- SM prediction of **Higgs width**: 4.1 MeV
 - direct measurement limited by detector resolution
- Constrain Higgs width by comparing on-shell and off-shell Higgs rates using $H \rightarrow ZZ$ and $H \rightarrow WW$
- $\sigma_{\text{off-shell}} / \sigma_{\text{on-shell}} \propto \Gamma_H$
- In $\gamma\gamma$ channel, interference between Higgs signal and continuous background can cause Higgs mass shift
 - this effect can also constrain Higgs width

CMS off-shell and on-shell ZZ+WW

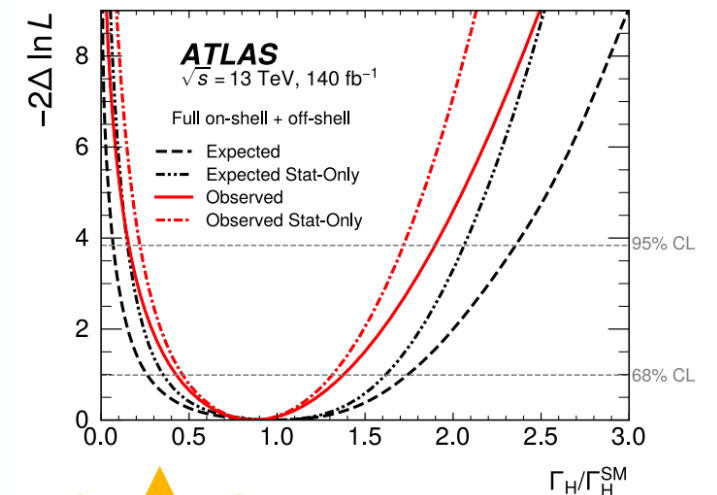


arXiv: 2607.23352

$5.2^{+2.0}_{-1.8}$ MeV

5.0(2.9) σ on off-shell production

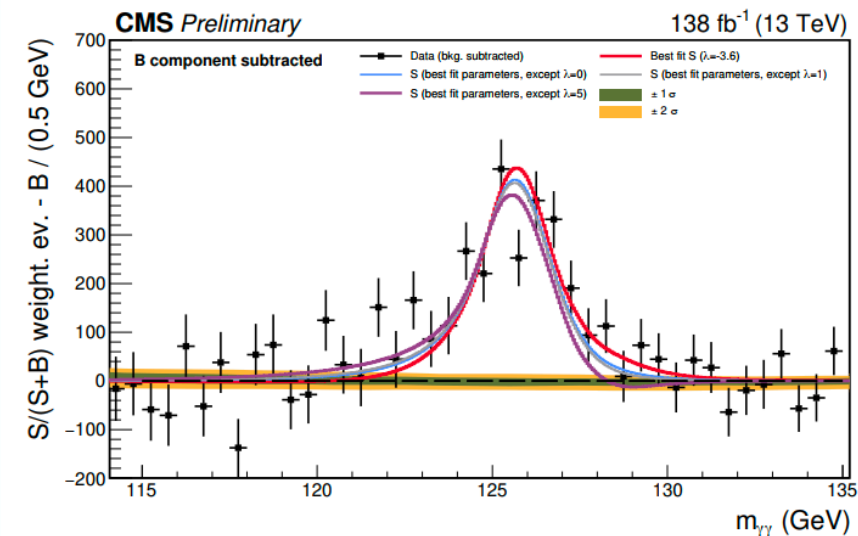
ATLAS off-shell ZZ+WW and on-shell all decay/production



CERN-EP-2026-228

$4.1^{+3.2}_{-2.7}$ MeV

3.7(2.9) σ on off-shell production



CMS-HIG-25-004

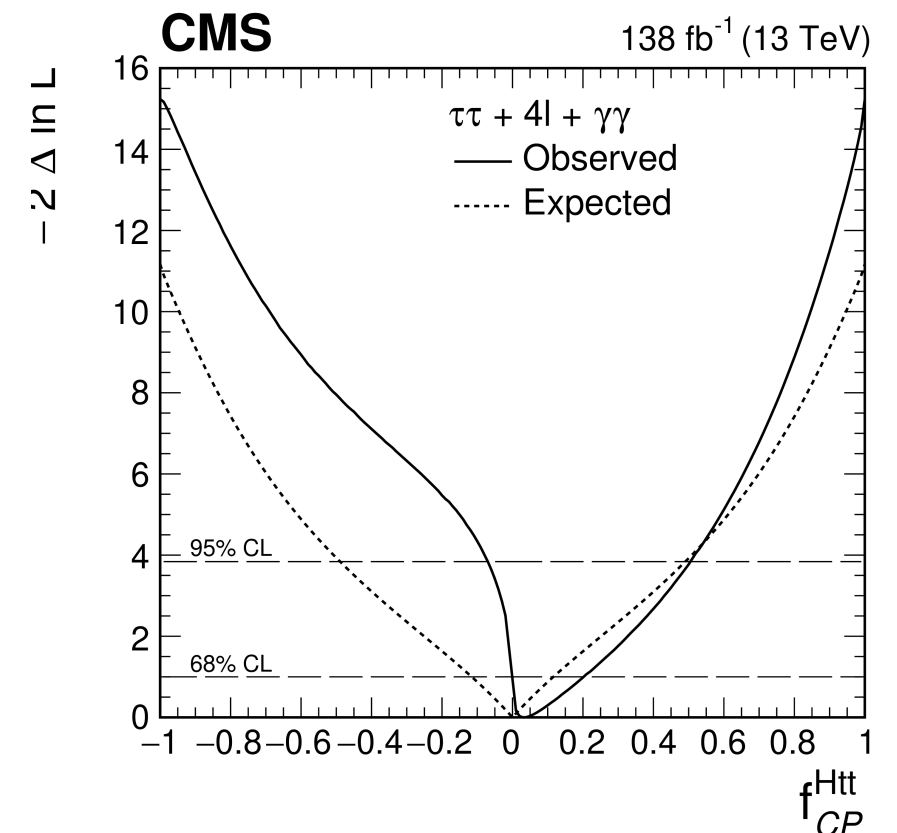
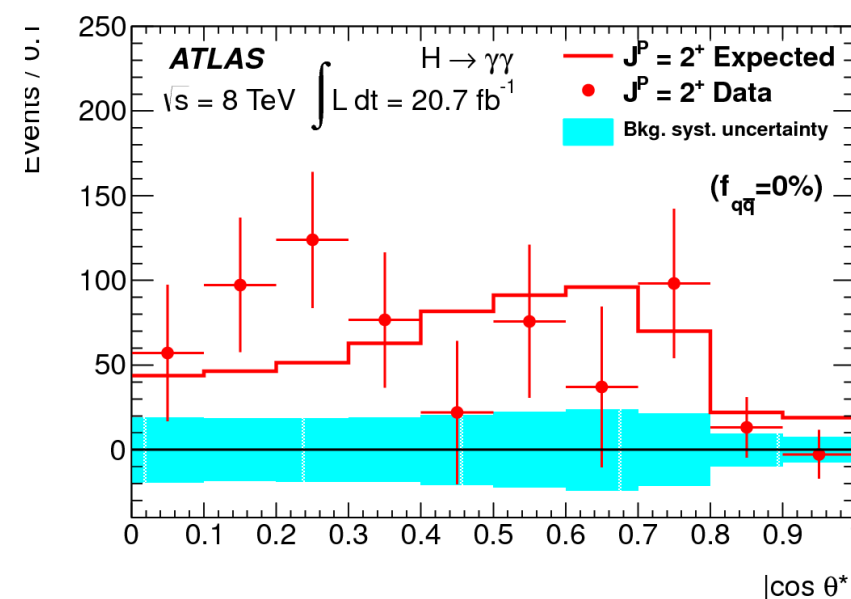
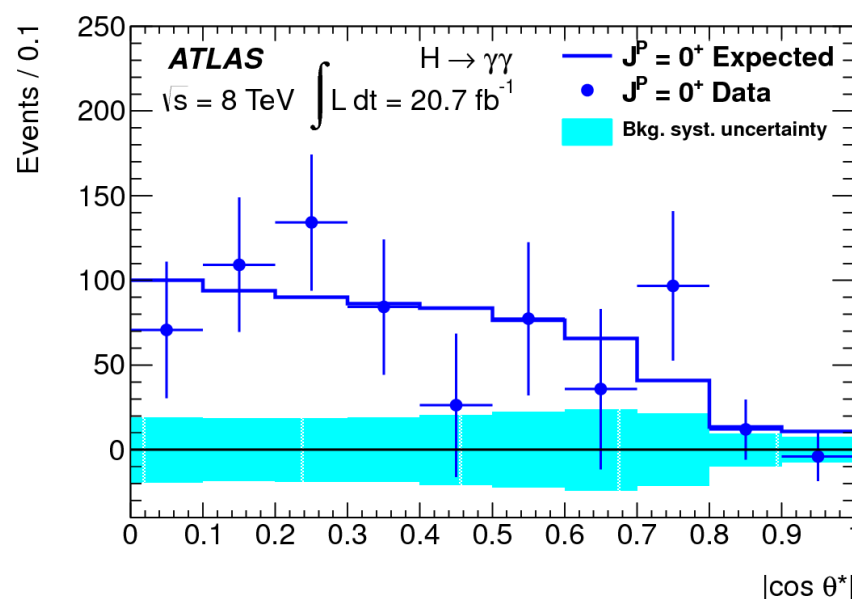
< 92 MeV

Higgs spin/CP

- The SM Higgs boson is a scalar: **spin**-zero, **CP**-even
 - The observed boson was verified to be spin-zero in Run 1
- Non-CP-even couplings of the Higgs boson were searched
 - Data disfavor the pure CP-odd scenario, stringent constraints on CP mixing are given

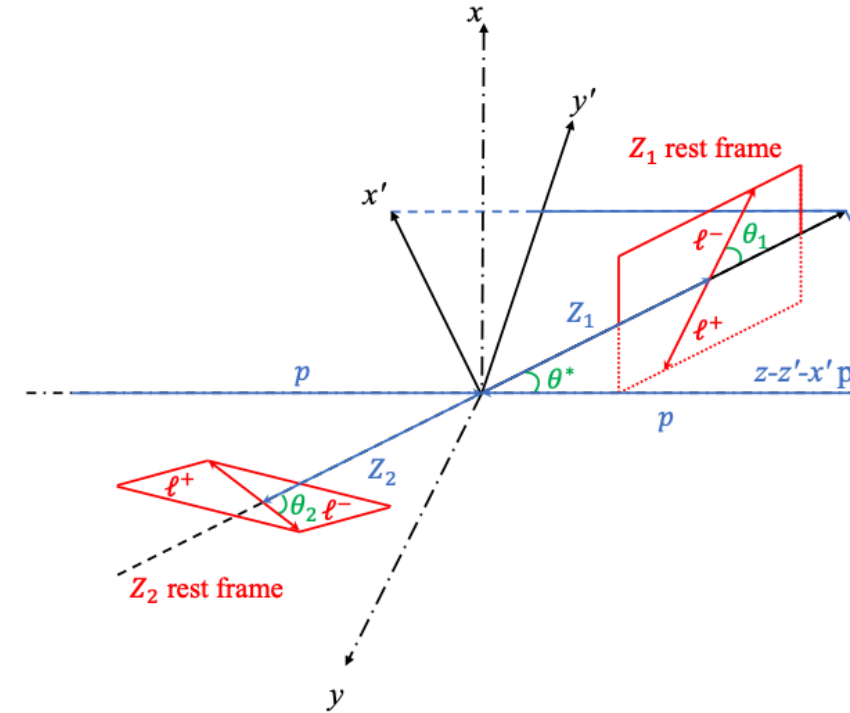
Phys. Lett. B 726 (2013) 120

Phys. Rev. D 108 (2023) 032013



Quantum entanglement

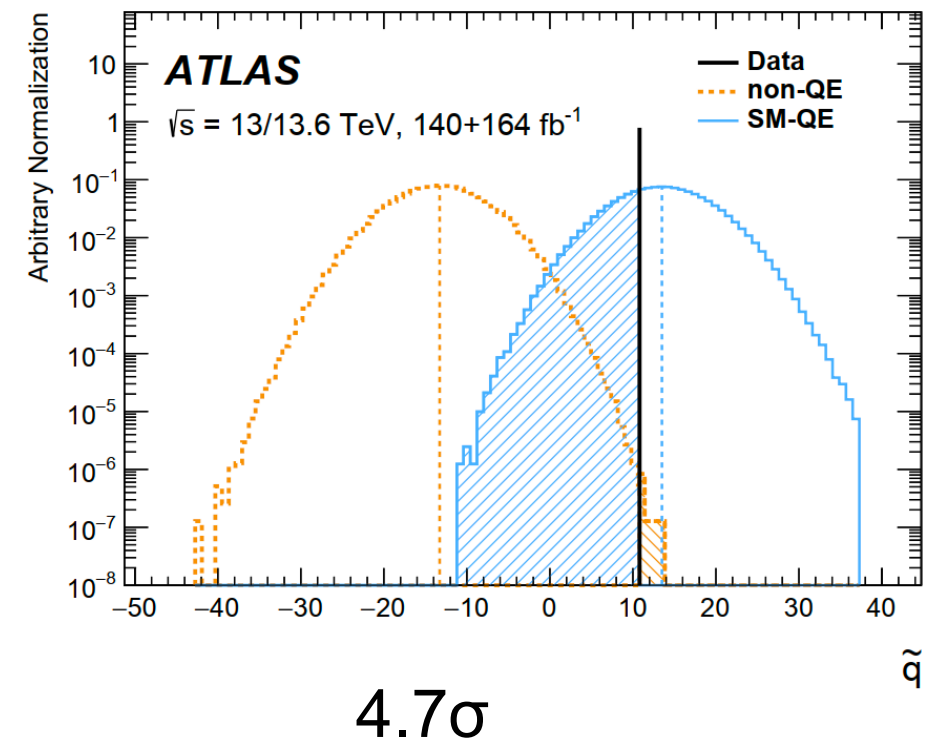
- ATLAS/CMS provide strong evidence of quantum entanglement between massive bosons (spin qutrits) in the $H \rightarrow ZZ^* \rightarrow 4l$ process
- Two approaches (with different assumptions) are used to perform the measurement



[arxiv2603.26463](https://arxiv.org/abs/2603.26463)

Coefficient	$C_{2,1,2,-1}$			$C_{2,2,2,-2}$		
Channel	$2e2\mu$	$4e + 4\mu$	Combined	$2e2\mu$	$4e + 4\mu$	Combined
Observed	-0.98 ± 0.64	-0.44 ± 0.63	-0.71 ± 0.45	0.00 ± 0.64	0.15 ± 0.61	0.08 ± 0.44
SM expected	-0.97			0.64		
Leading uncertainty components						
Fake-lepton bkg.	± 0.16	± 0.16	± 0.12	± 0.11	± 0.18	± 0.12
Irreducible bkg.	± 0.05	± 0.04	± 0.04	± 0.01	± 0.01	± 0.01
Interference	—	± 0.04	± 0.02	—	± 0.03	± 0.02
EW NLO effects	± 0.02	± 0.01	± 0.01	< 0.01	< 0.01	< 0.01
Migration	± 0.01	± 0.02	± 0.01	± 0.01	± 0.02	± 0.01
Statistical	± 0.62	± 0.61	± 0.43	± 0.63	± 0.58	± 0.43

$$c_{2M_1 2M_2} = 40\pi \Re \left(Y_2^{M_1}(\theta_1, \phi_1) \times Y_2^{M_2}(\theta_2, \phi_2) \right)$$

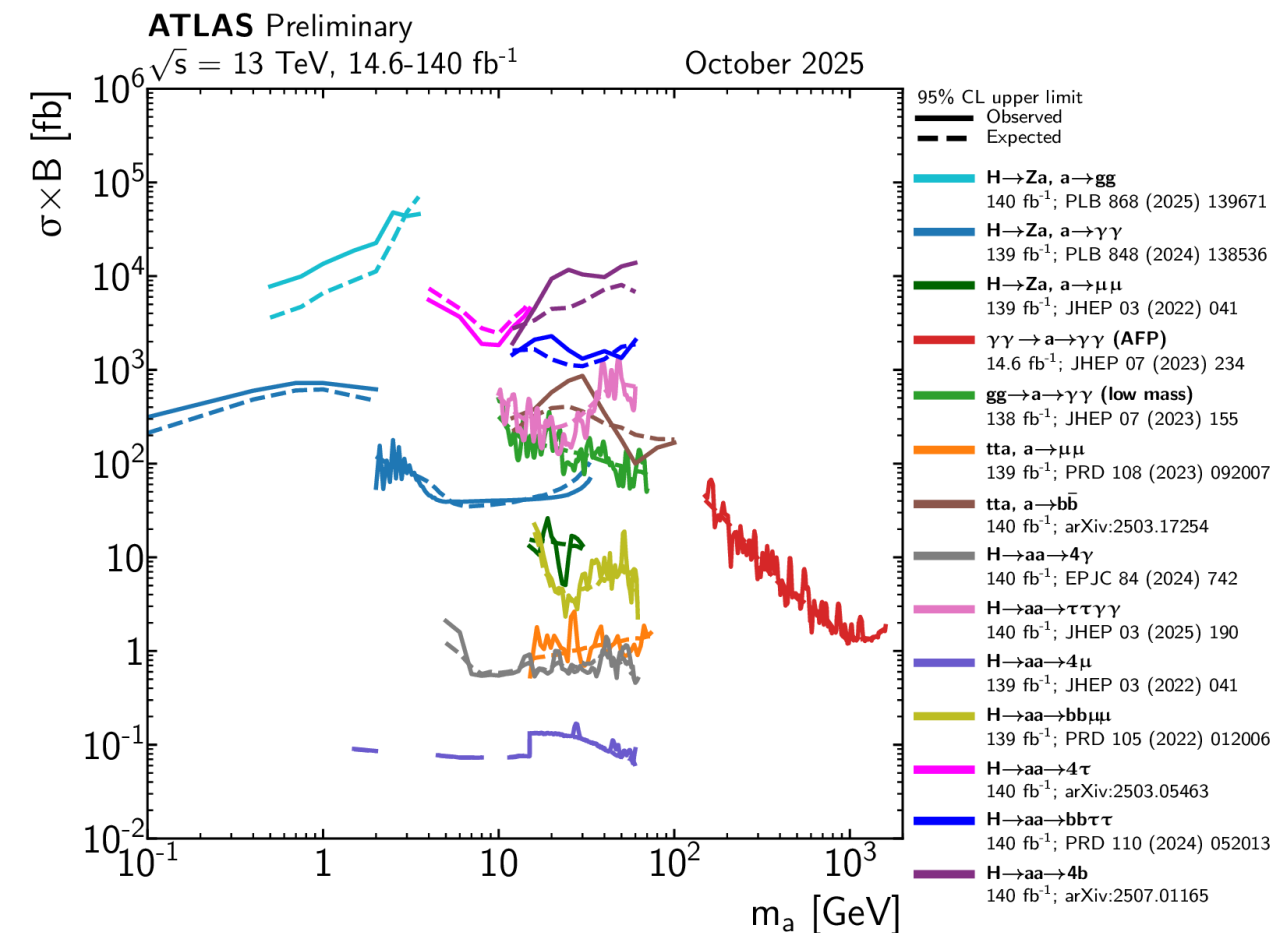
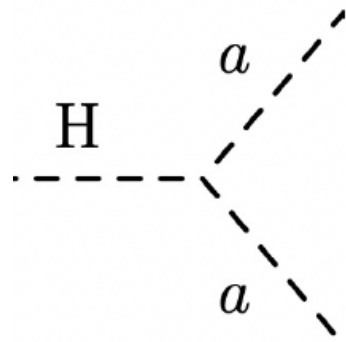


Higgs exotic decay

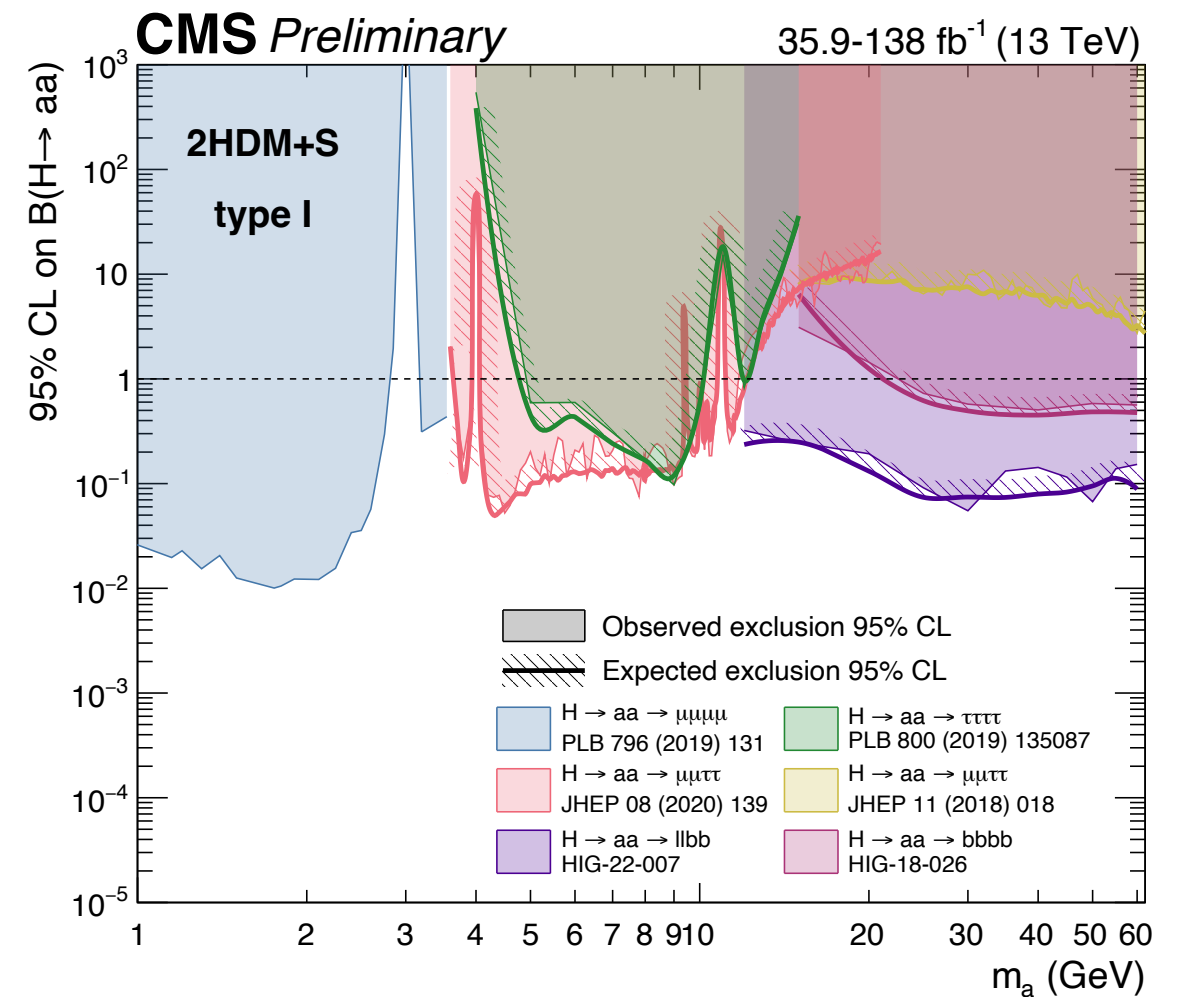
Higgs exotic decay

Higgs decays to pseudoscalars predicted by various BSM models: two-Higgs-doublet-like models, axion-like particle, etc.

Many final states are analyzed: $b\bar{b}b\bar{b}$, $b\bar{b}l\bar{l}$, $l\bar{l}l\bar{l}$, ...



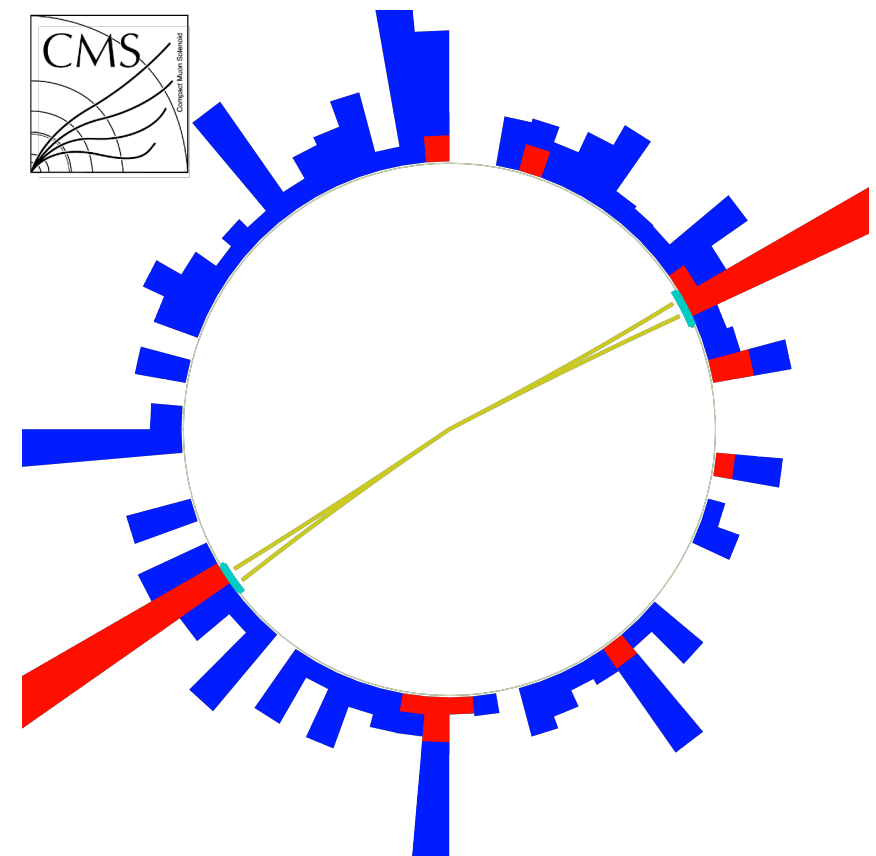
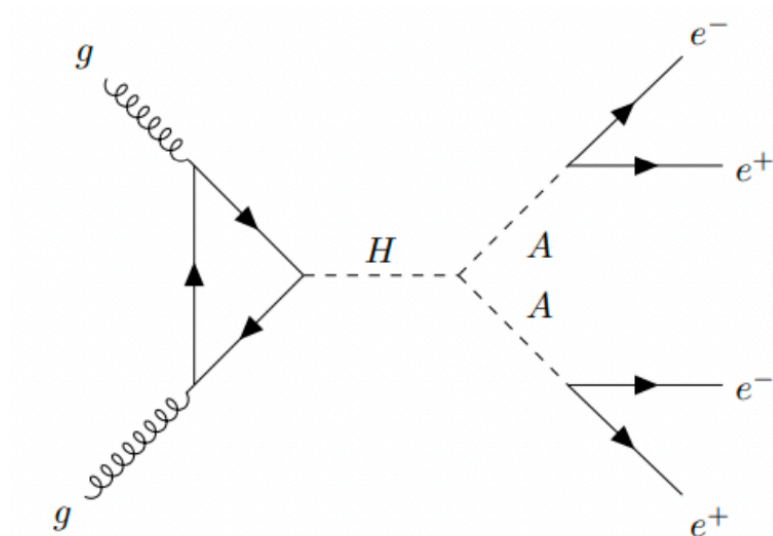
ATLAS Summary Plots



CMS Summary Plots

$H \rightarrow aa \rightarrow eeee$

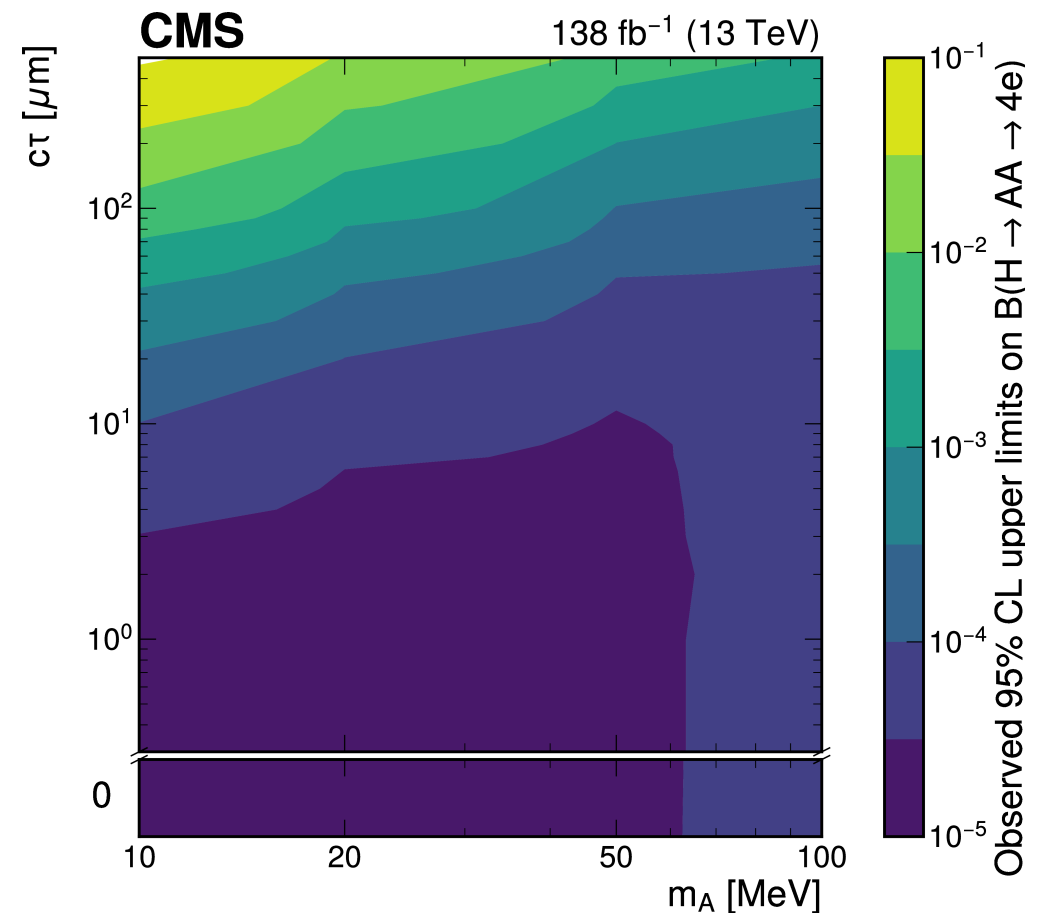
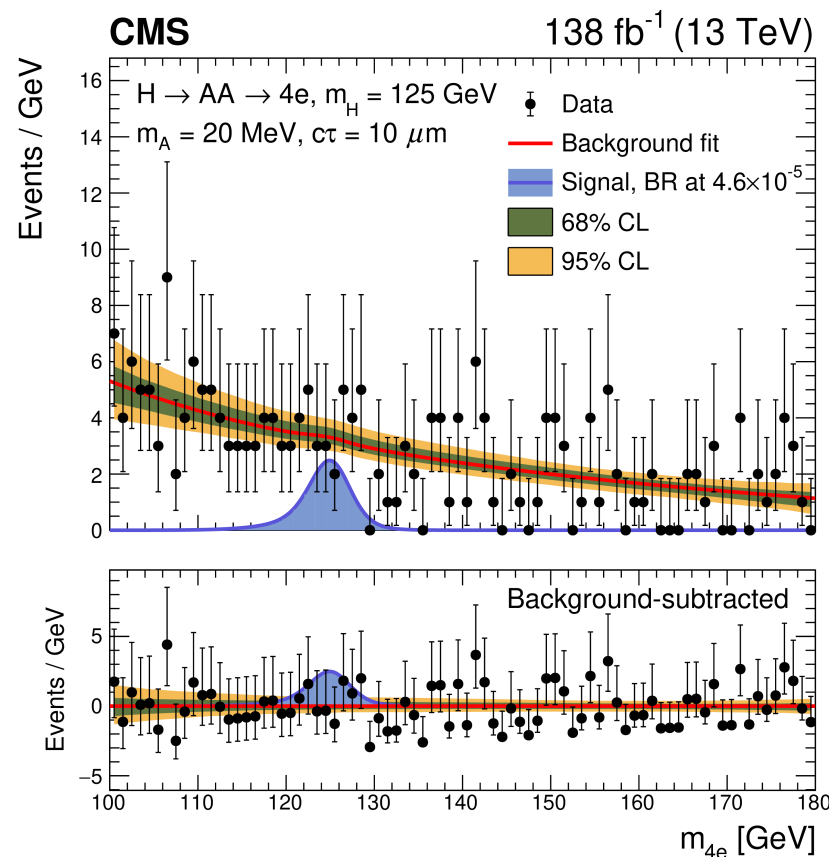
- ATOMKI anomaly gives us additional motivation to search for tens of MeV ALPs
 - Electron channel is important for searching for ALPs in that range
 - Theoretical work by Liu Jia et al: [JHEP 05 \(2021\) 138](#)
- CMS preforms first search for $H \rightarrow aa \rightarrow 4\text{electrons}$, with a novel multivariate identification technique
 - Showing LHC's potential as a unique axion-like particle search facility



[Phys. Rev. Lett. 136 \(2026\) 181807](#)

$H \rightarrow aa \rightarrow eeee$

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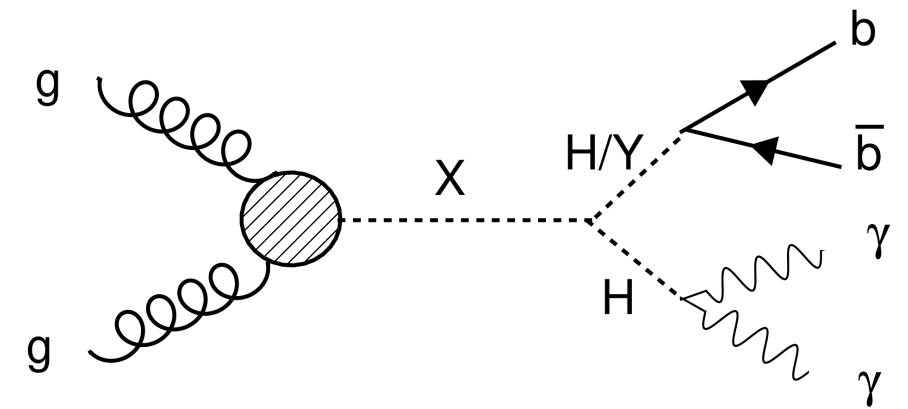


[Phys. Rev. Lett. 136 \(2026\) 181807](#)

Higgs resonant production

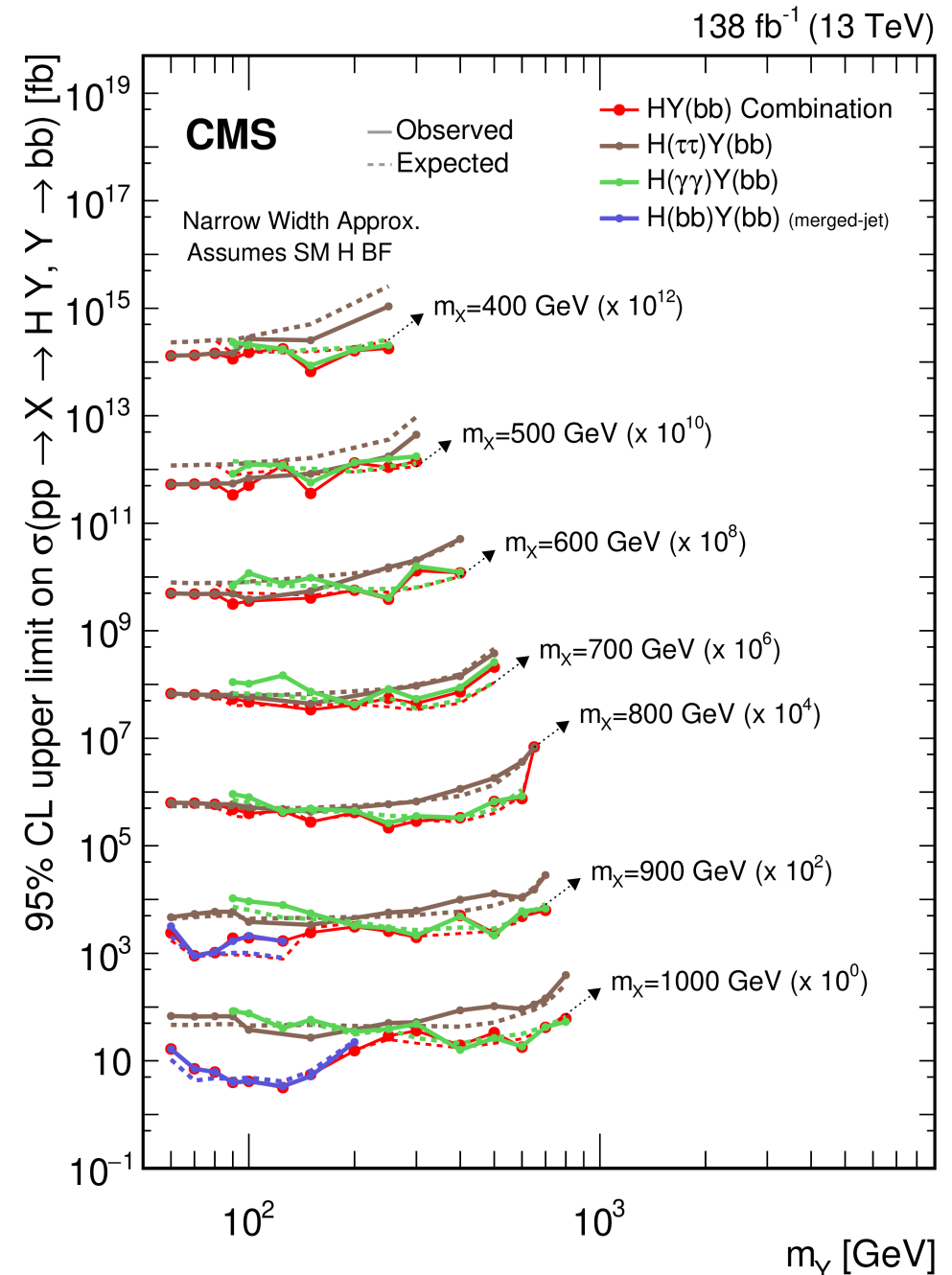
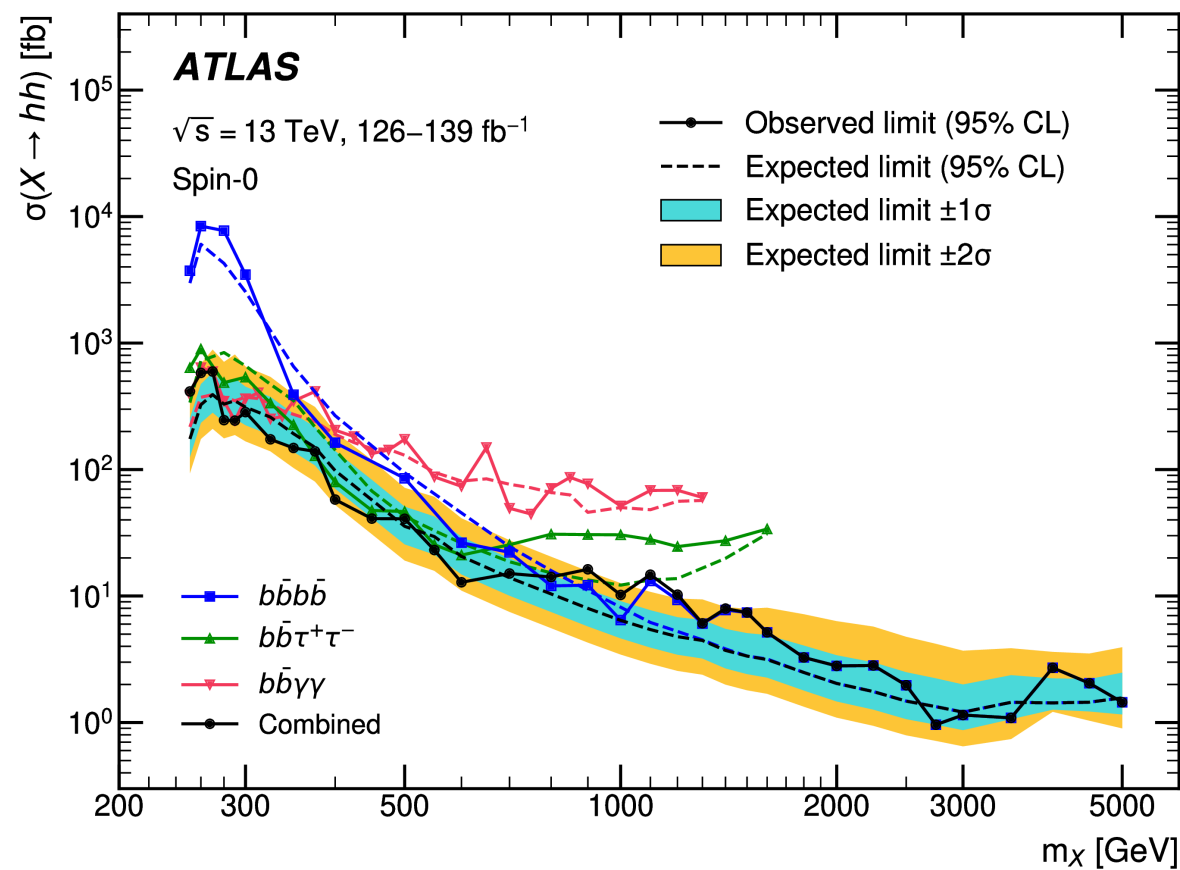
Resonant production of Higgs boson

- Heavy resonance search channels including at least one Higgs boson have formed an important part of the program of new physics searches at the LHC
- Sensitive to many new physics models, including extended Higgs sectors and extra dimensions



Resonant production of Higgs boson

- Summarizing and combining search channels, ATLAS and CMS obtain cross section limits on resonant production of Higgs boson and constraints on relevant new physics models

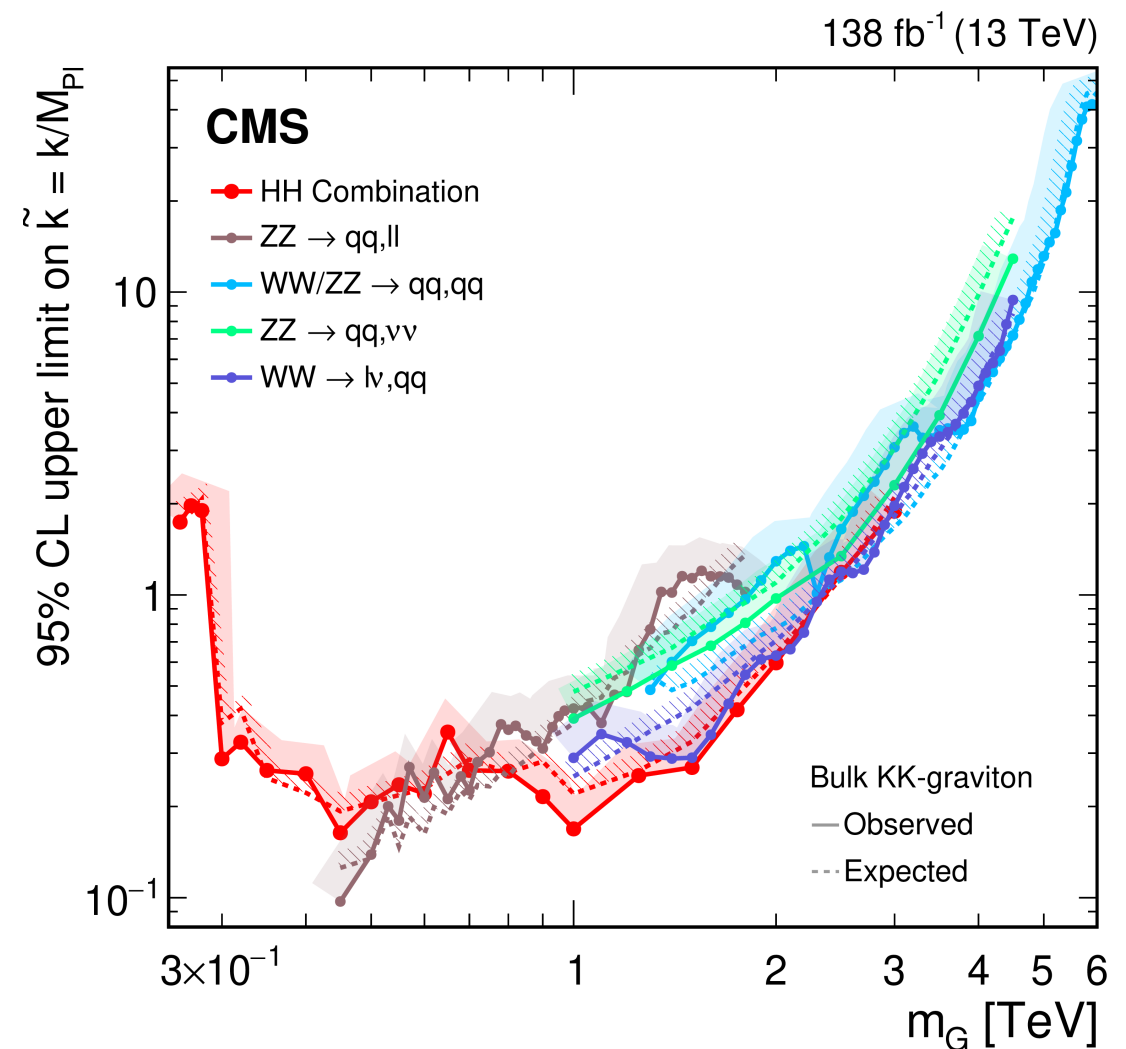
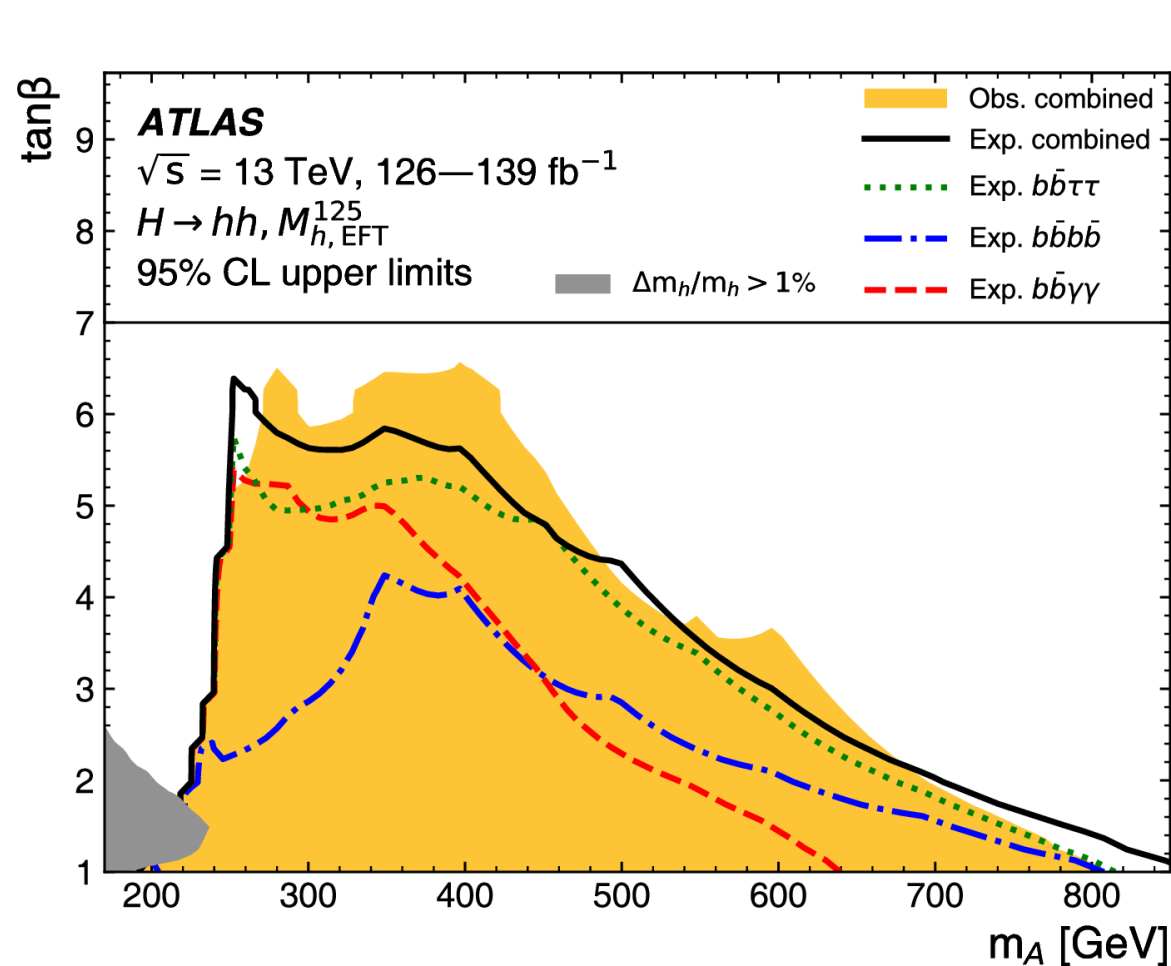


[Phys. Rev. Lett. 132 \(2024\) 231801](#)

[Physics Reports 1115 \(2025\) 368](#)

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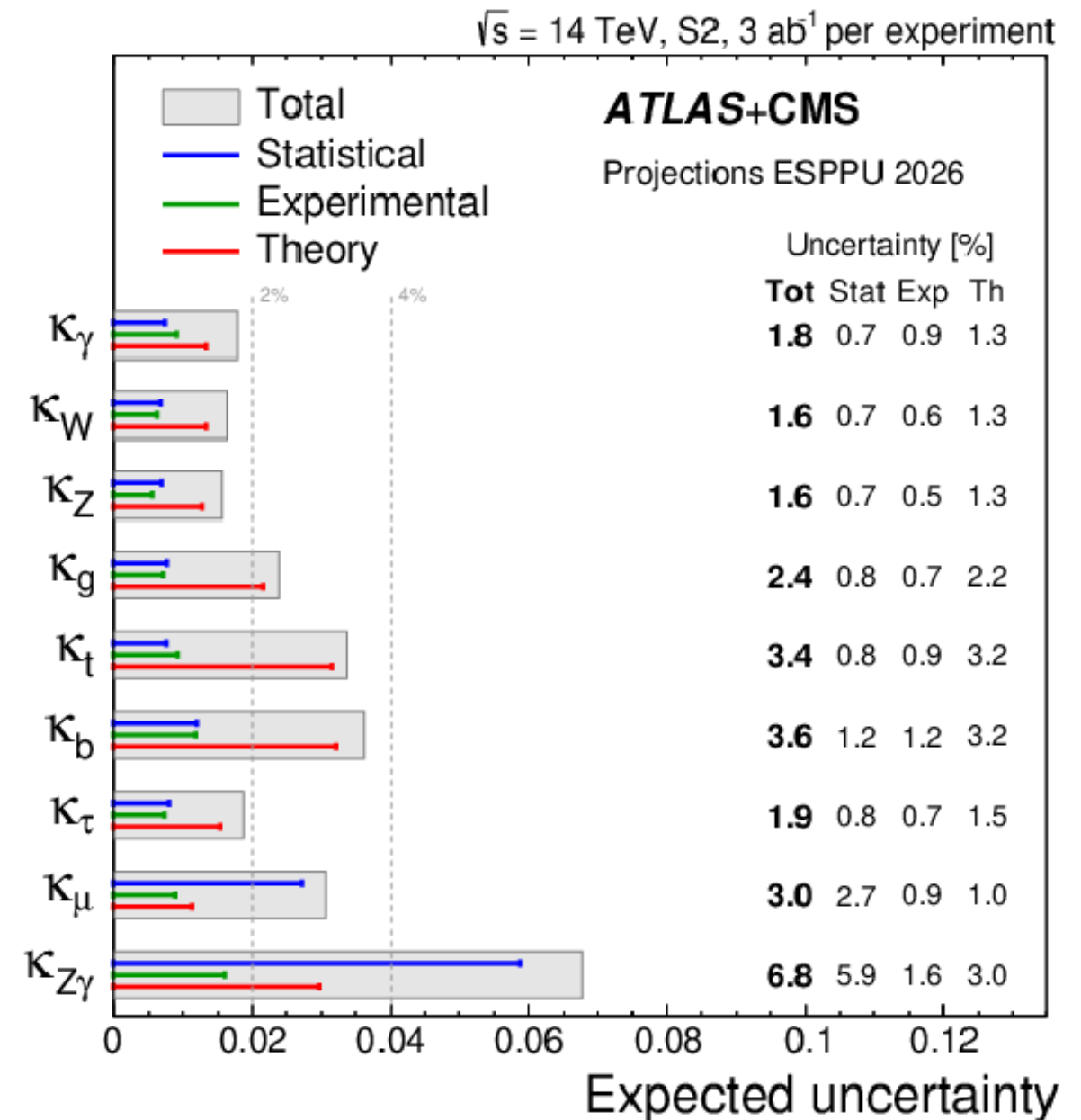


[Phys. Rev. Lett. 132 \(2024\) 231801](#)

[Physics Reports 1115 \(2025\) 368](#)

Summary and outlook

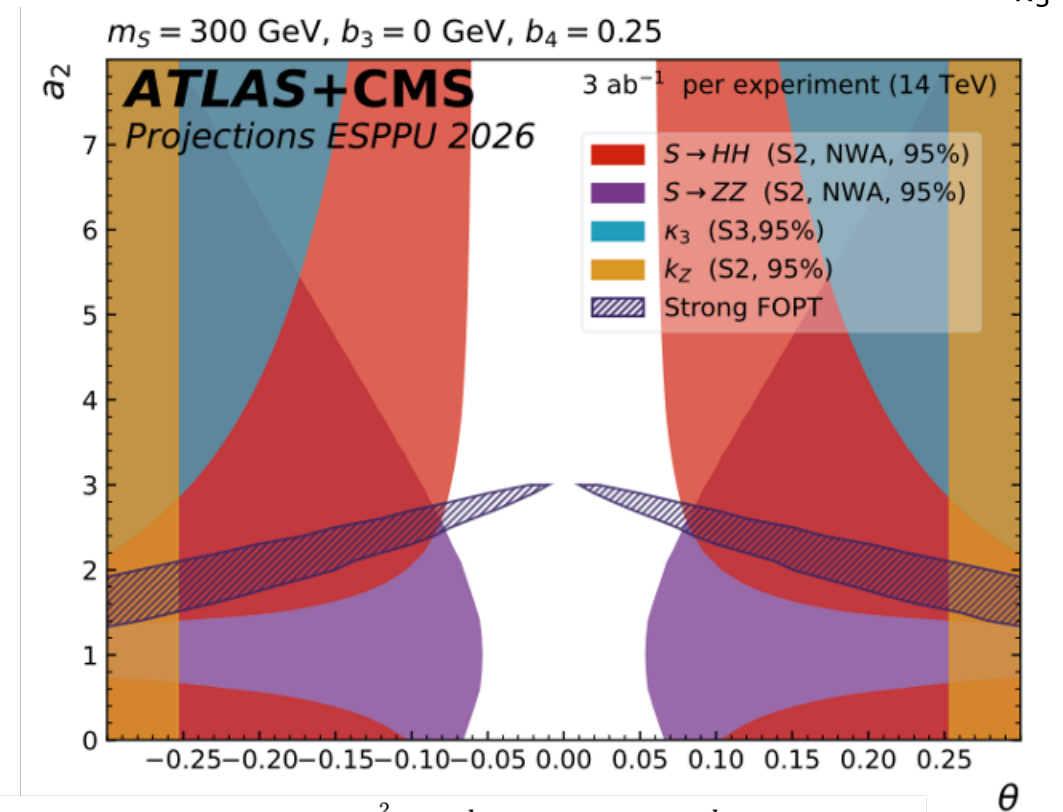
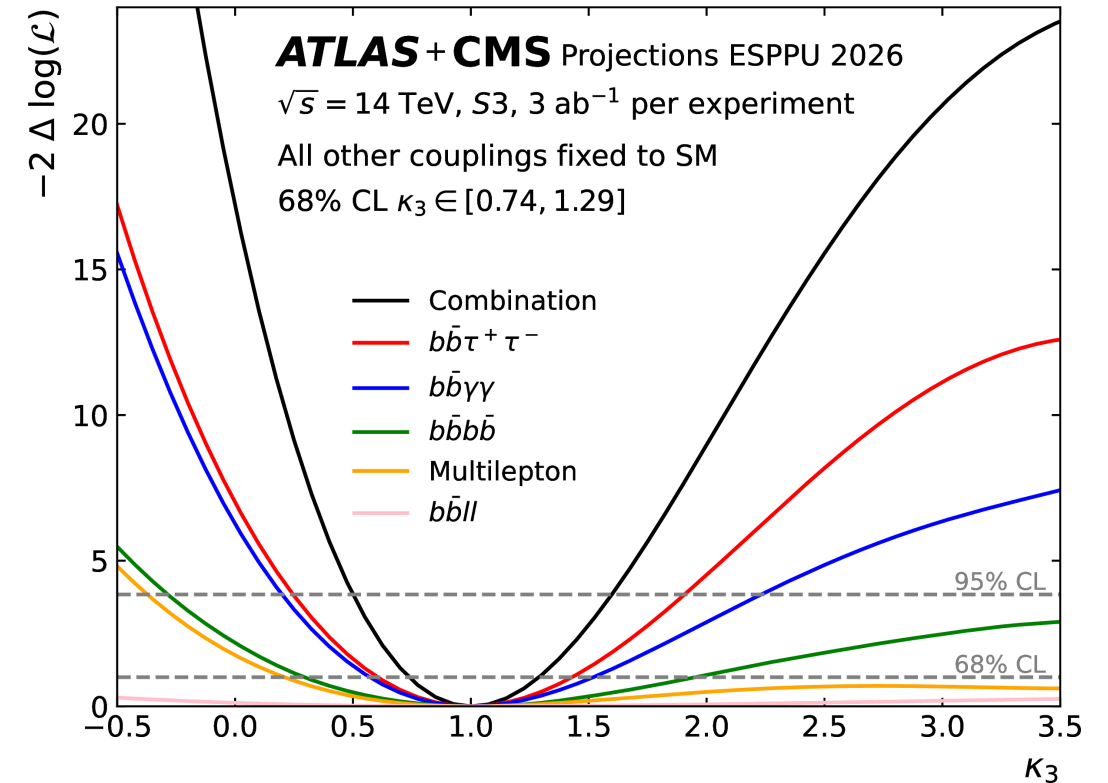
- **LHC experiments have a large program to study Higgs boson and keep improving sensitivities**
- Results are so far consistent with the SM predictions
- Evidence of $H \rightarrow \mu\mu$ and $H \rightarrow Z\gamma$
- Constraints of Higgs self-couplings
- etc.
- **Run 3 is finished and HL-LHC is coming. Stay tune for the new results!**



[arxiv:2504.00672](https://arxiv.org/abs/2504.00672)

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$$V(\Phi, S) = -\mu_H^2 |\Phi|^2 + \lambda_H |\Phi|^4 + b_1 S - \frac{\mu_S^2}{2} S^2 + \frac{b_4}{4} S^4 + \frac{a_2}{2} |\Phi|^2 S^2 + \frac{b_3}{3} S^3 + \frac{a_1}{2} |\Phi|^2 S.$$

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Thank you!

第二届TeV物理前沿专题研讨会 暨第33届LHC Mini-Workshop

2026年9月18日-20日 · 北京

会议简介:

为促进国内TeV物理前沿研究领域的学术交流与合作,北京大学高能物理研究中心拟于2026年9月18-20日(9月18日报到)在北京春晖园温泉度假酒店举办“第二届TeV物理前沿专题研讨会暨第33届LHC Mini-Workshop”。本次会议旨在搭建理论物理与实验物理的交流平台,推动TeV物理前沿研究的创新发展。

会议主题:

- 1、希格斯物理
- 2、极化与量子纠缠
- 3、喷注子结构与强子化过程
- 4、QCD精确计算与检验
- 5、有效场论与检验
- 6、AI在高能物理中的应用

主办单位:

北京大学高能物理研究中心

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朱华星 (北京大学)
周 辰 (北京大学)

本地组委会:

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朱华星
周 辰 (Chair)



会议网址:

<https://indico.ihep.ac.cn/event/29954/>

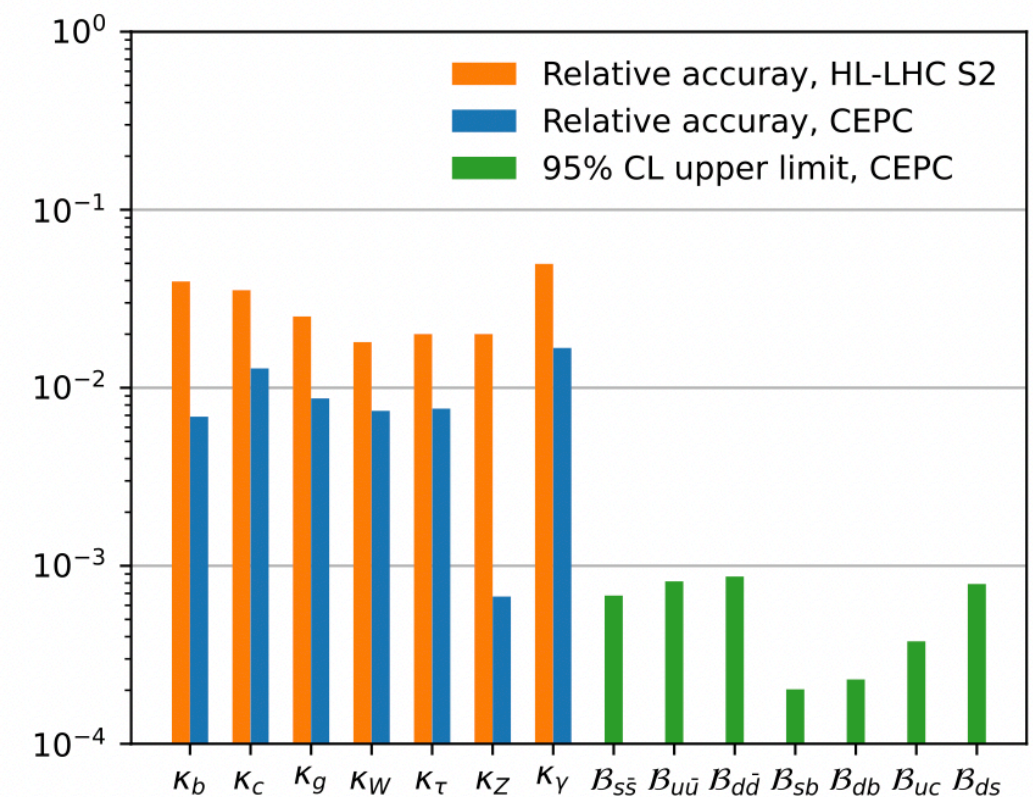


Higgs rare and exotic decays at CEPC

- We apply AI-based jet-origin identification to Higgs rare and exotic decay measurements at CEPC
- The upper limits at 95% confidence level on the branching ratios of $H \rightarrow ss, uu, dd$ and $H \rightarrow sb, db, uc, ds$ can be determined to 2×10^{-4} to 1×10^{-3} , which are greatly improved upon previous studies

TABLE I. Summary of background yields from $H \rightarrow b\bar{b}/c\bar{c}/gg, Z$, and W prior to the flavor-based event selection, along with the expected upper limits on Higgs decay branching ratios at 95% CL under the background-only hypothesis.

	Bkg (10^3)			Upper limits on Br (10^{-3})						
	H	Z	W	$s\bar{s}$	$u\bar{u}$	$d\bar{d}$	sb	db	uc	ds
$\nu\bar{\nu}H$	151	20	2.1	0.81	0.95	0.99	0.26	0.27	0.46	0.93
$\mu^+\mu^-H$	50	25	0	2.6	3.0	3.2	0.5	0.6	1.0	3.0
e^+e^-H	26	16	0	4.1	4.6	4.8	0.7	0.9	1.6	4.3
Comb.	...	...	...	0.75	0.91	0.95	0.22	0.23	0.39	0.86

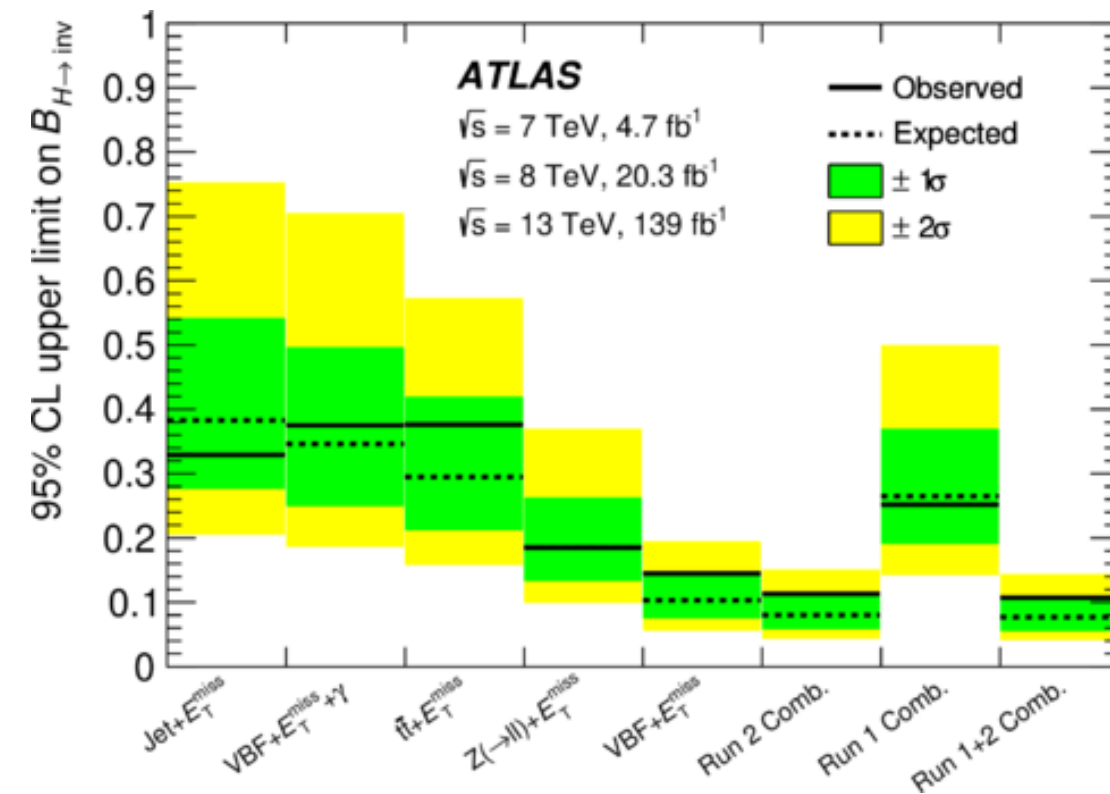
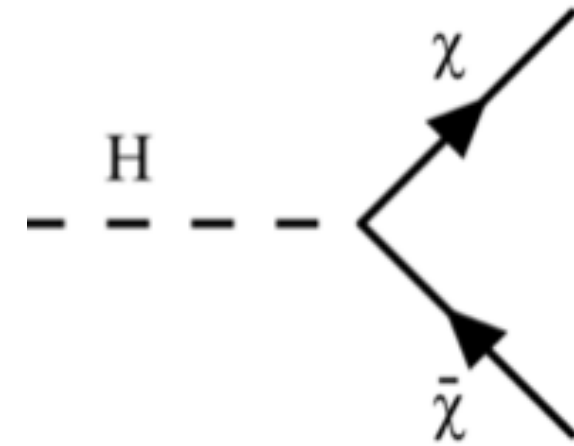


[Phys. Rev. Lett. 132 \(2024\) 221802](#)

$H \rightarrow$ invisible

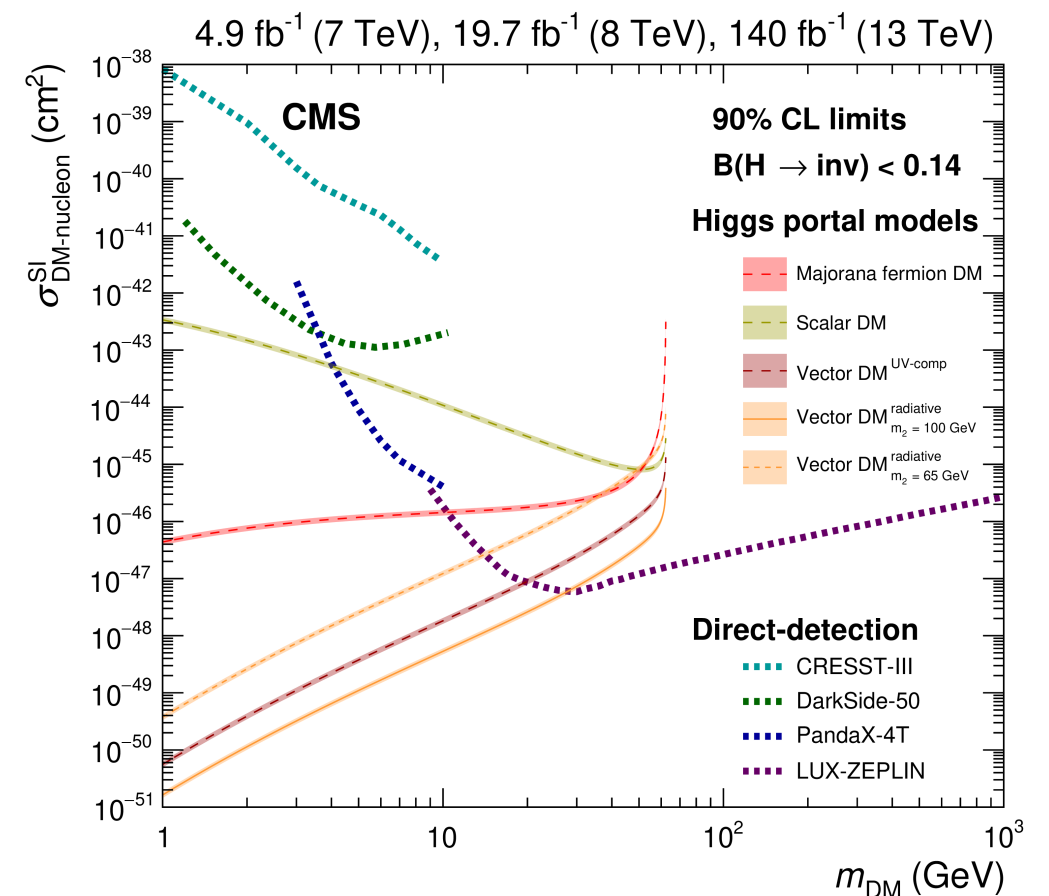
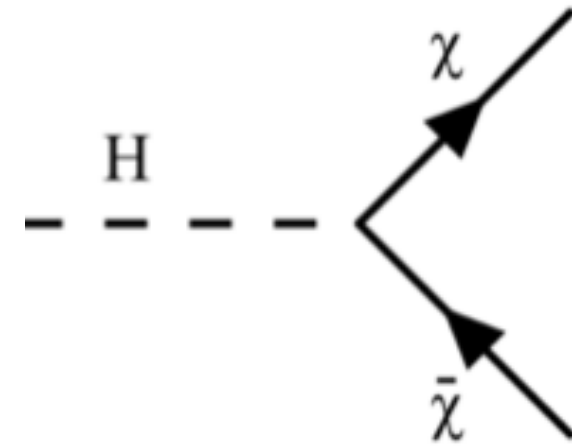
Search for Higgs $\rightarrow$ invisible decay

- The Higgs discovery has opened up a new path to discover Dark Matter.
- Higgs $\rightarrow$ invisible decay is favored by so-called "Higgs portal" model
- Combine VBF, ggF, VH and ttH channels
- Run 2 observed (expected) limits on branching ratios:
 - ATLAS: $BR < 11\%$ (8%) ([Phys. Lett. B 842 \(2023\) 137963](#))
 - CMS: $BR < 15\%$ (8%) ([Eur. Phys. J. C 83 \(2023\) 933](#))
- Results are interpreted as limit on DM-nucleon scattering in Higgs portal model



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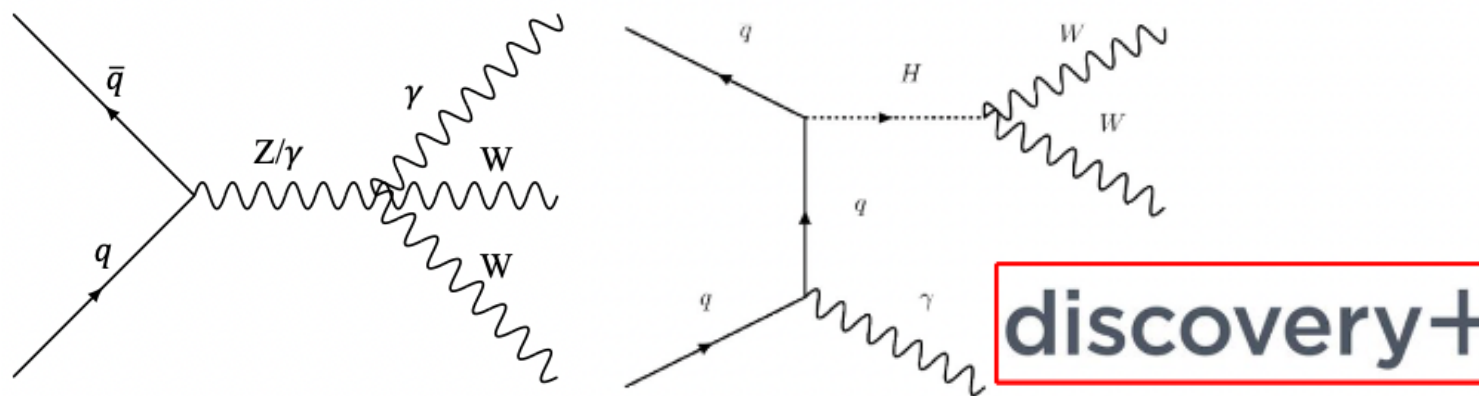


Higgs physics studies in electroweak and top measurements

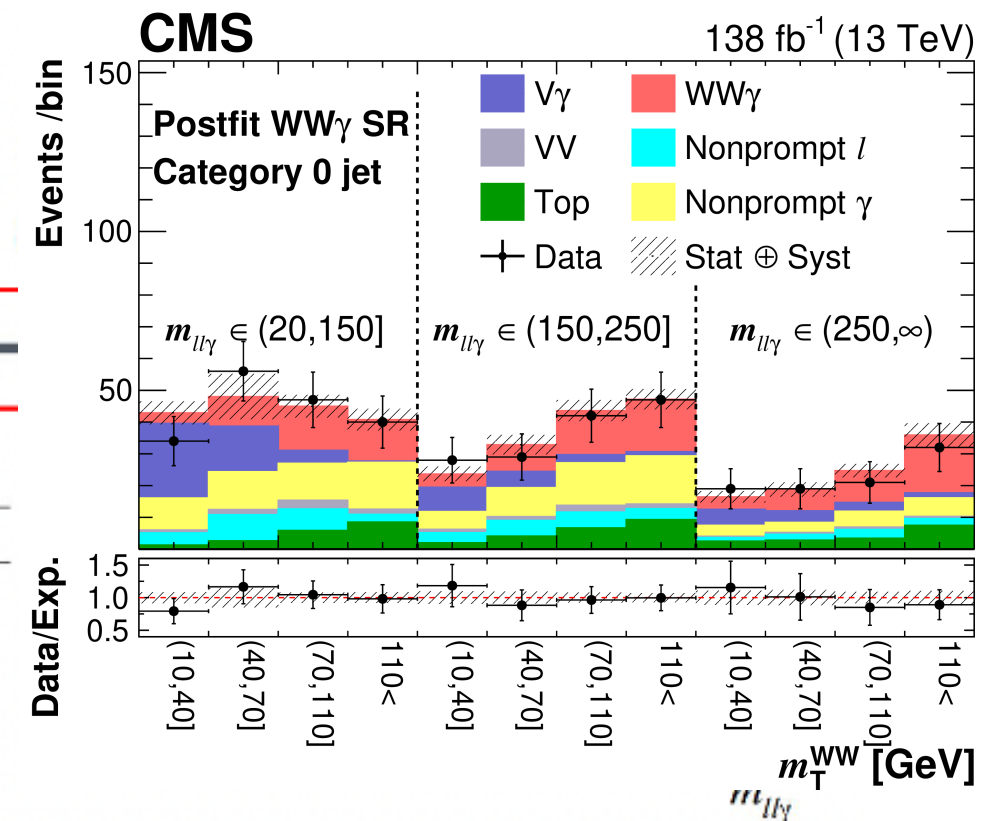
First observation of $WW\gamma$ production

[arxiv:2310.05164](https://arxiv.org/abs/2310.05164) published by PRL

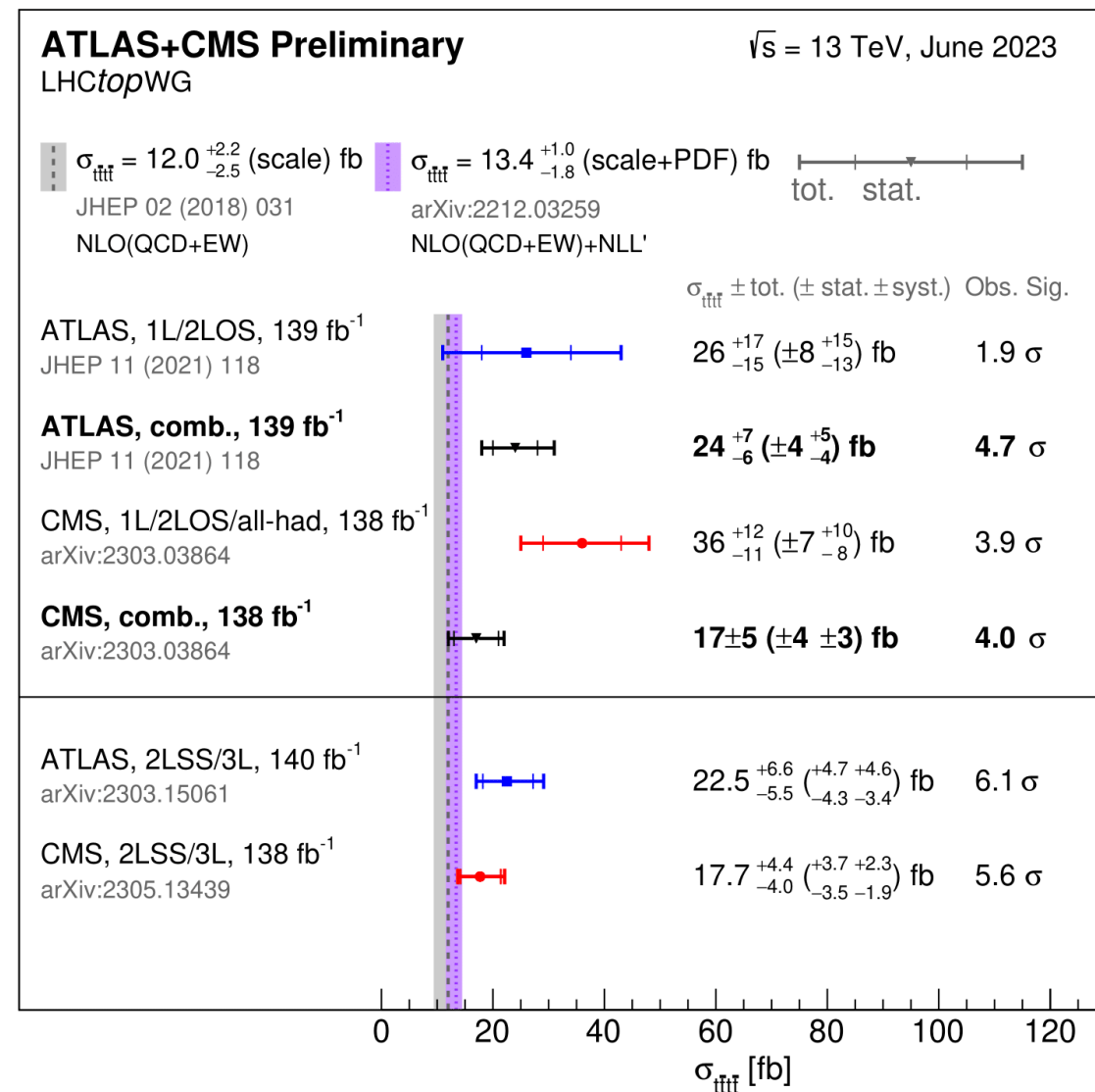
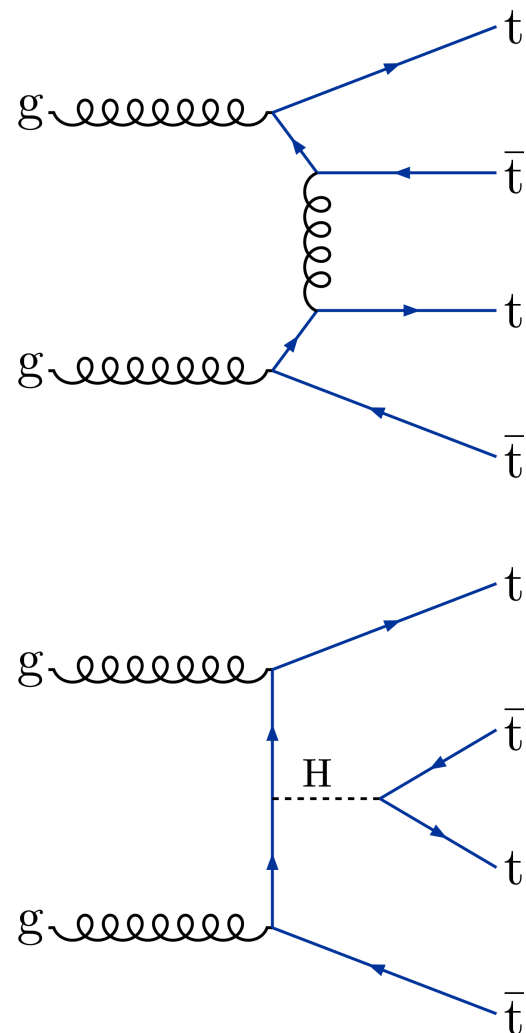
- First observation (**5.6σ**) of $WW\gamma$ production
 - Provide the best sensitivity for Yukawa couplings between Higgs and light quarks



Process	σ_{up} pb exp.(obs.)	Yukawa couplings limits exp.(obs.)
$u\bar{u} \rightarrow H + \gamma \rightarrow e\mu\gamma$	0.067 (0.085)	$ \kappa_u \leq 13000$ (16000)
$d\bar{d} \rightarrow H + \gamma \rightarrow e\mu\gamma$	0.058 (0.072)	$ \kappa_d \leq 14000$ (17000)
$s\bar{s} \rightarrow H + \gamma \rightarrow e\mu\gamma$	0.049 (0.068)	$ \kappa_s \leq 1300$ (1700)
$c\bar{c} \rightarrow H + \gamma \rightarrow e\mu\gamma$	0.067 (0.087)	$ \kappa_c \leq 110$ (200)



Observation of four top production



[Eur. Phys. J. C 83 \(2023\) 496](#)

[Phys. Lett. B 847 \(2023\) 138290](#)

- Observation by ATLAS and CMS experiments independently
 - this process is extremely rare compared to top-pair production, but it is already a measurement limited by systematics
- Results provides sensitivity to the Higgs-top Yukawa coupling