Higgs rare and exotic productions and decays at the LHC

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Workshop on New Physics Searches at Colliders
Nanjing University (Suzhou Campus), April 16-20, 2026

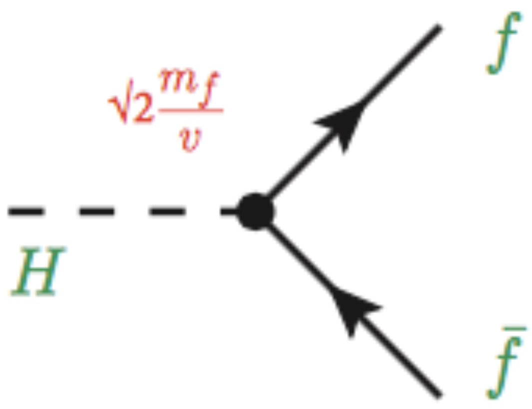
Contents of this talk

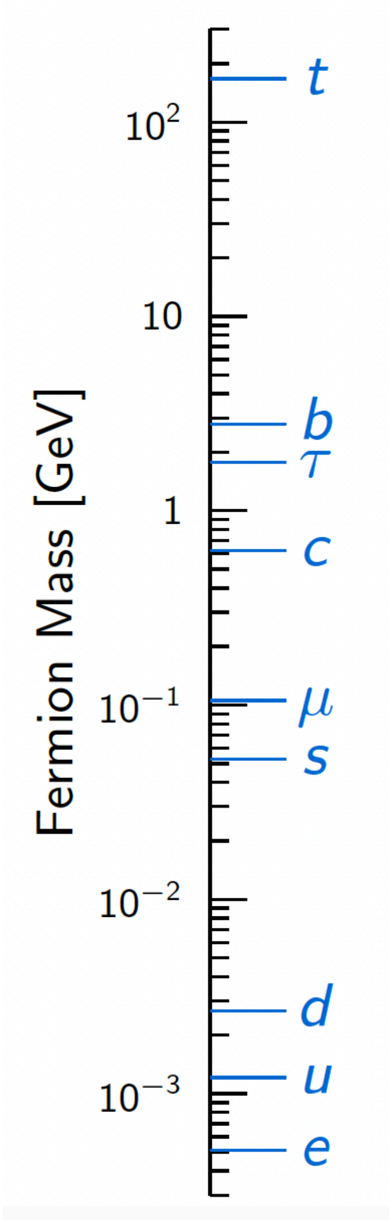
- **Rare and exotic productions and decays of Higgs boson are important portals to new physics**
- **ATLAS and CMS experiments have a large program to study these processes and keep improving sensitivities**
  - Focus on recent results that I am involved with
- Results of Higgs rare and exotic decays
  - H→ff, H→llγ, H→aa
- Results of Higgs rare and exotic productions
  - HH, X→HH/HY

$H \rightarrow ff$

Yukawa couplings

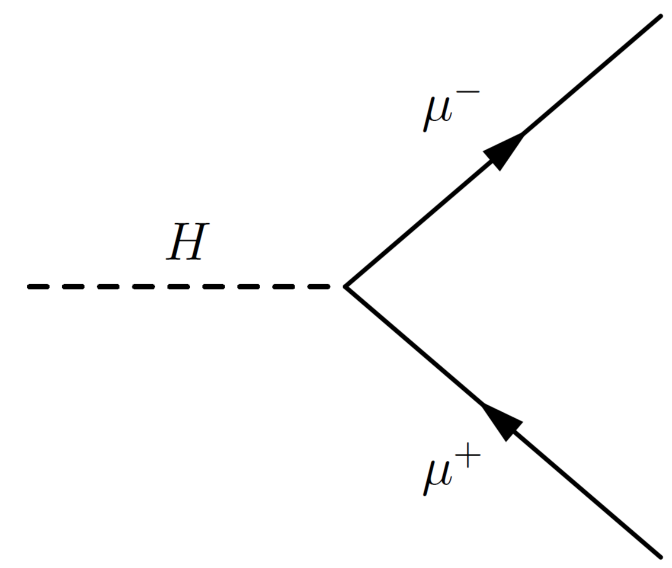
- In Standard Model, Higgs boson couples to fermions (quarks and leptons) through Yukawa interactions
  - **giving masses to quarks and leptons**
- Yukawa interactions are the least constrained sector of the Higgs physics
  - **important to study the Yukawa sector, which may provide important indication 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



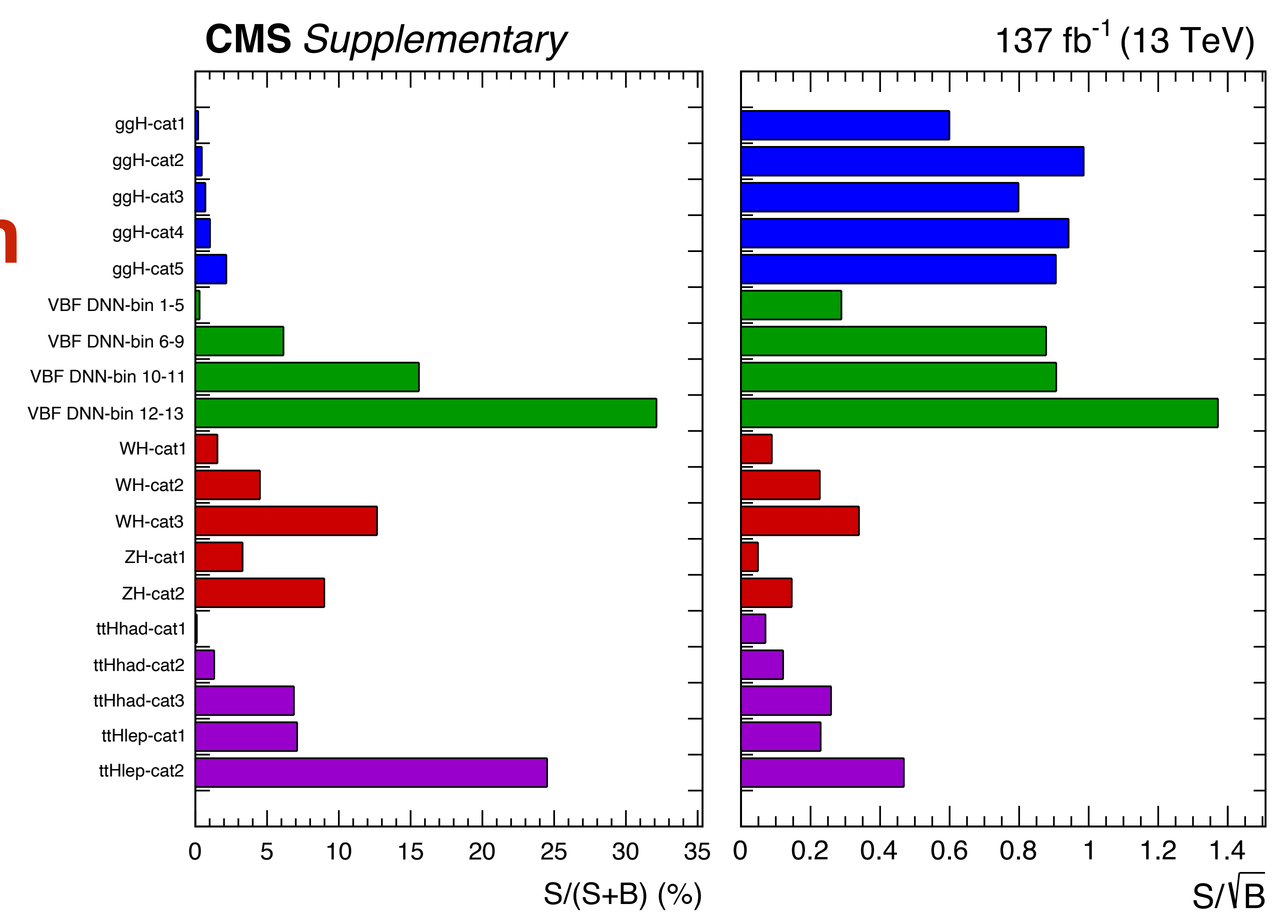


H→μμ decay

- 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

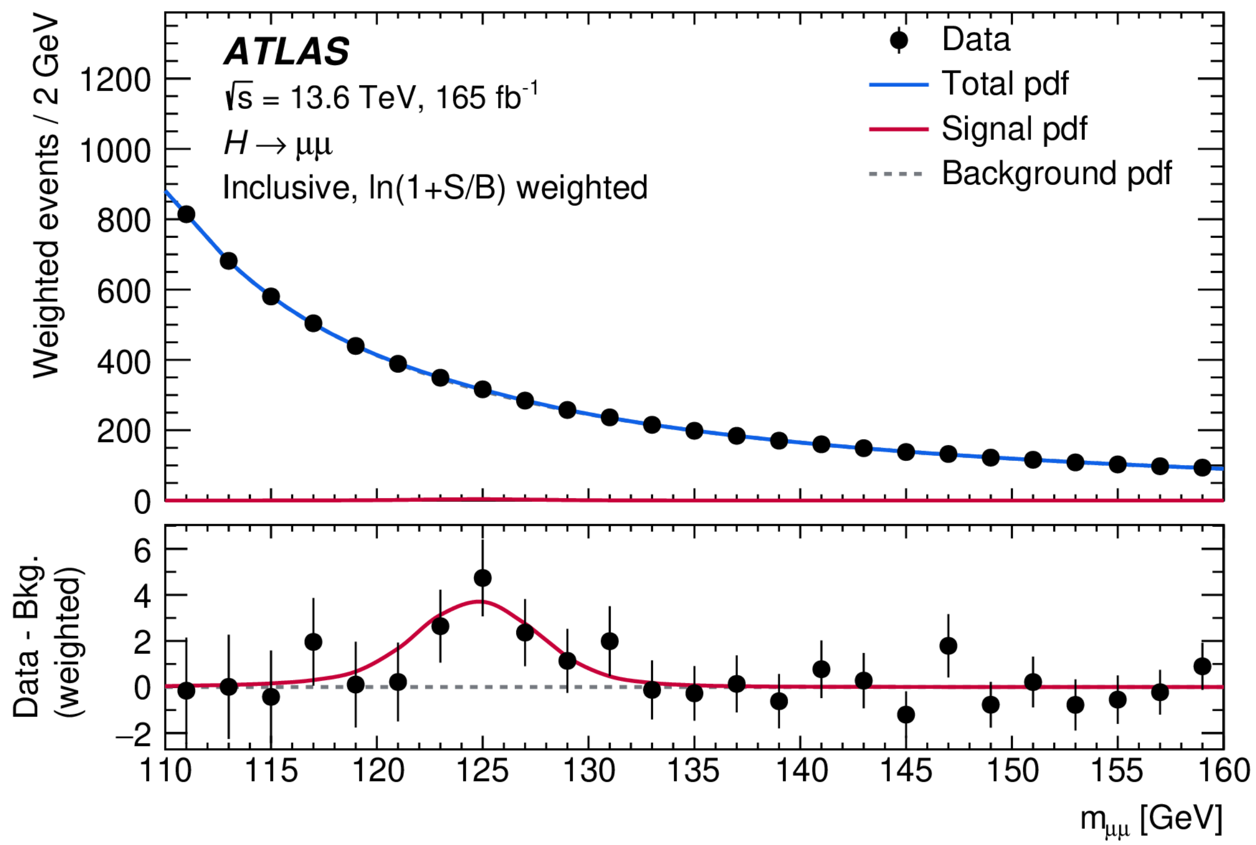


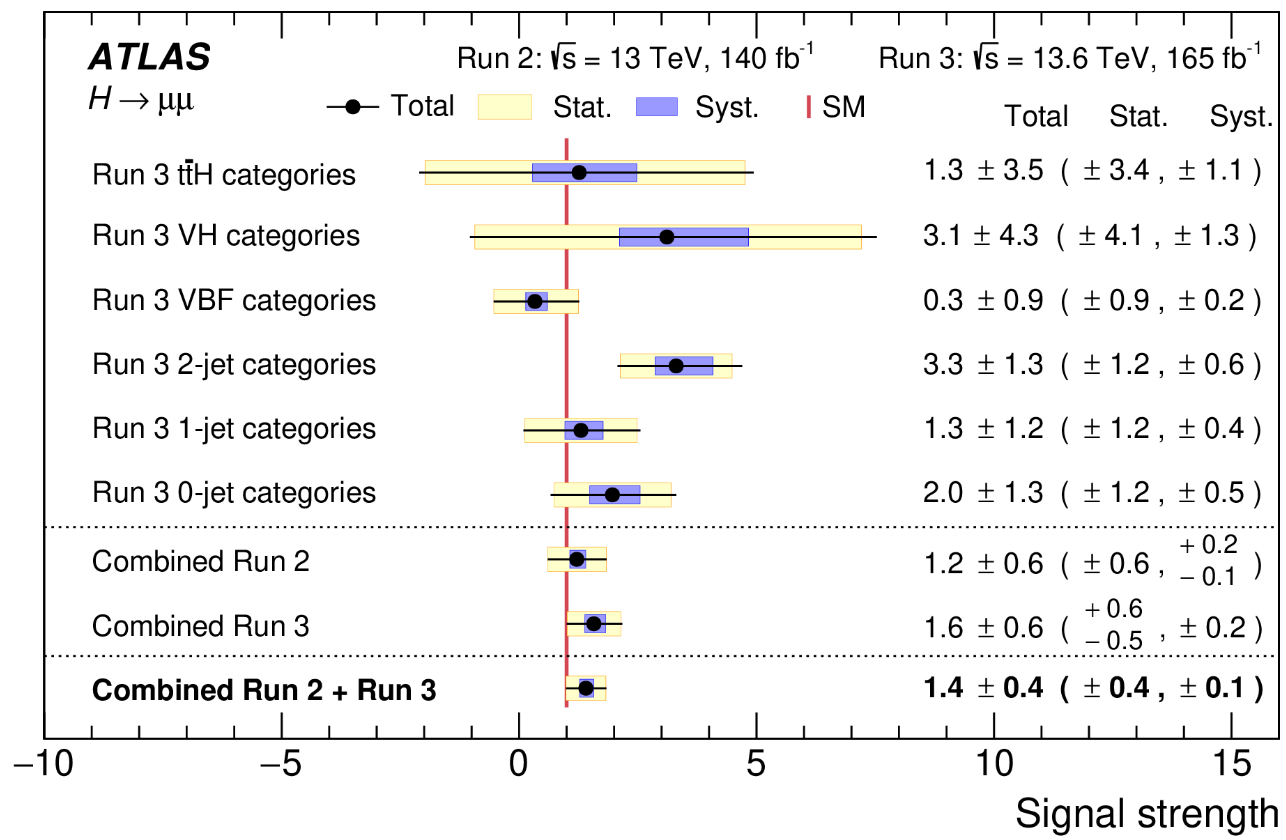
- **The Higgs decay to two muons offers the best opportunity to observe the Higgs couplings with second-generation fermions at the LHC**
  - Small branching ratio in SM (2×10^{-4})
  - key ingredients of the analysis: for sure optimal di-mu mass resolution, but also extreme optimization of the categories for best S/B



JHEP 01 (2021) 148

H→μμ decay

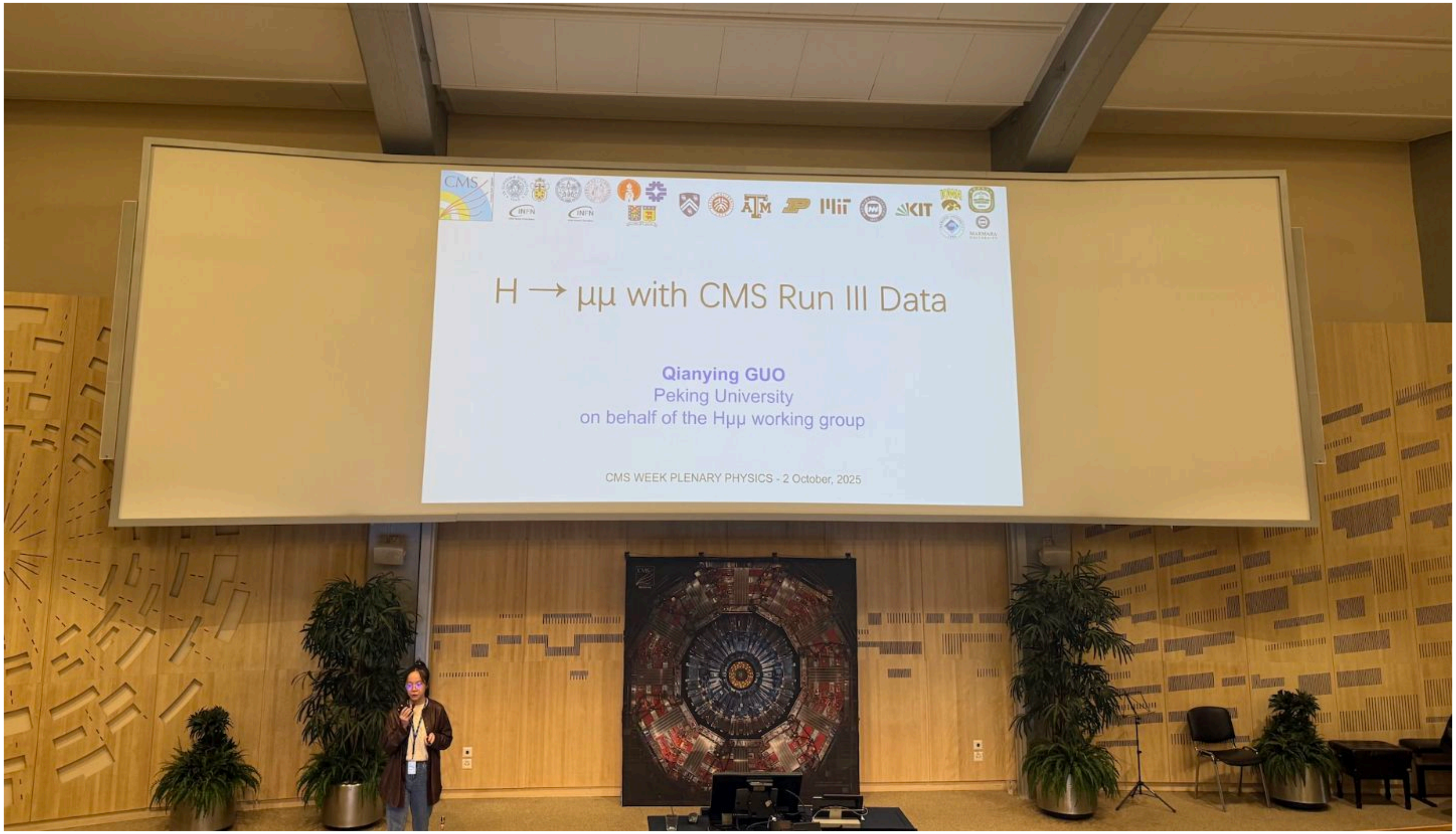




Phys. Rev. Lett. 135 (2025) 231802

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

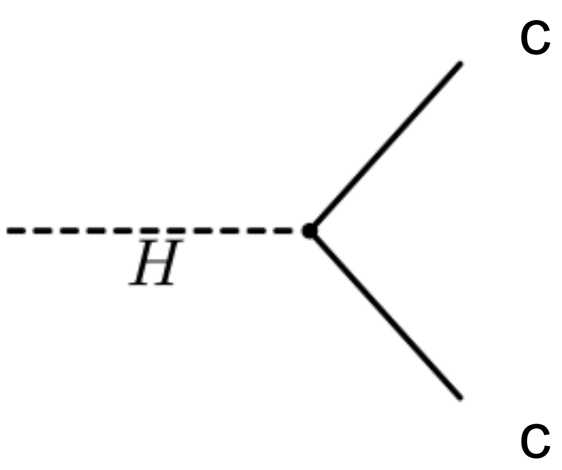
H→$\mu\mu$ decay

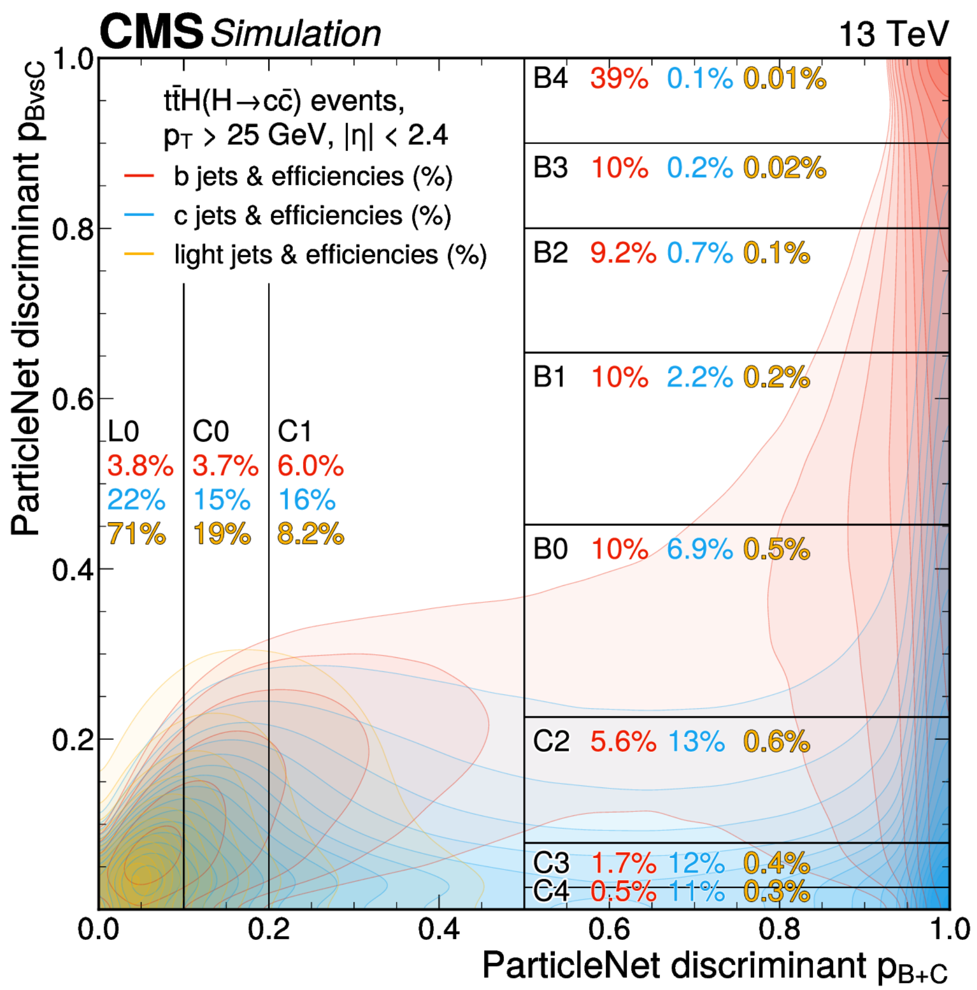


- Working on full Run 3 analysis
  - hopefully observe the H→μμ decay with more than 5σ

H→cc̄ decay

- **H→cc̄ decay** is currently the main channel to probe Higgs coupling to c quarks
  - 20×smaller BR than H → bb̄
  - Less distinct charm signature in detector





Phys. Rev. Lett. 136 (2026) 011801

CMS ttH H→cc̄

- First search for H→cc̄ in ttH 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.)**

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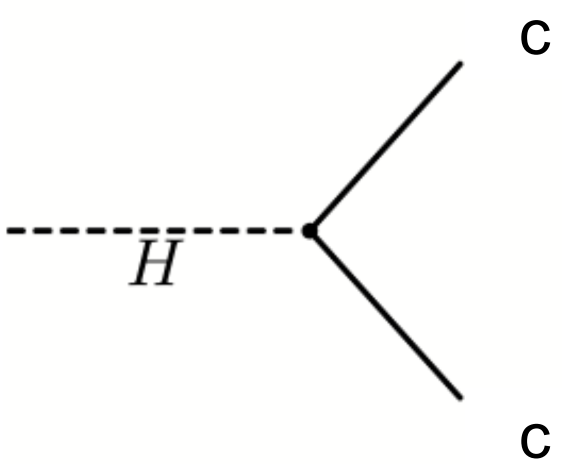
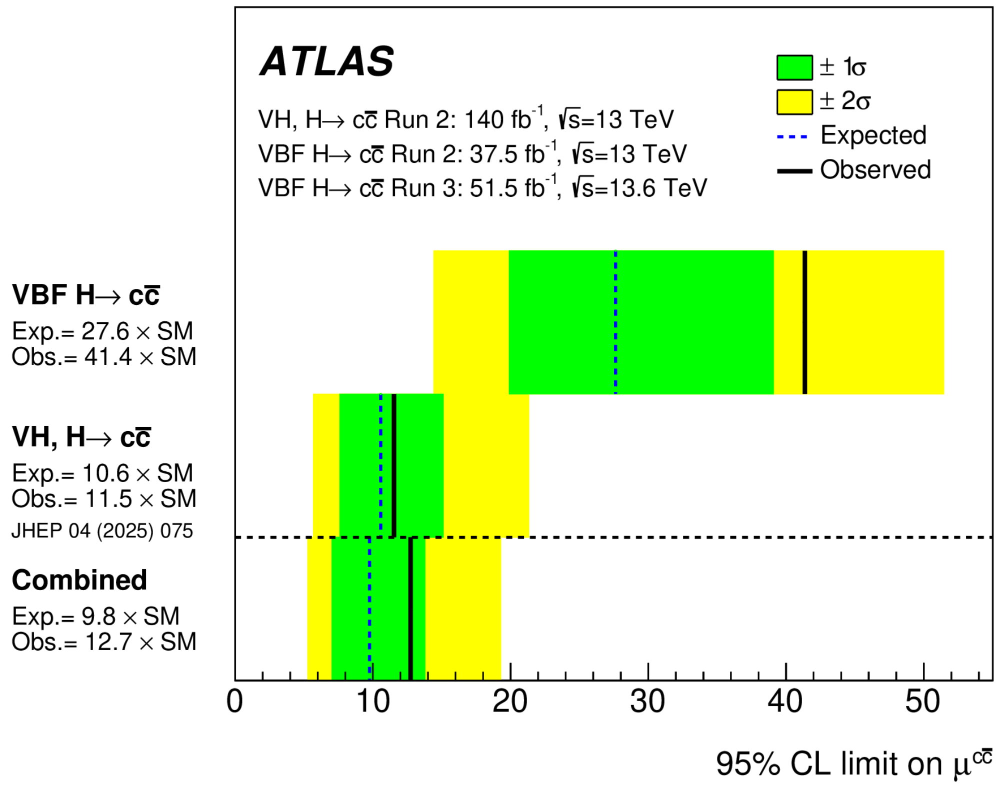




arxiv:2511.21911

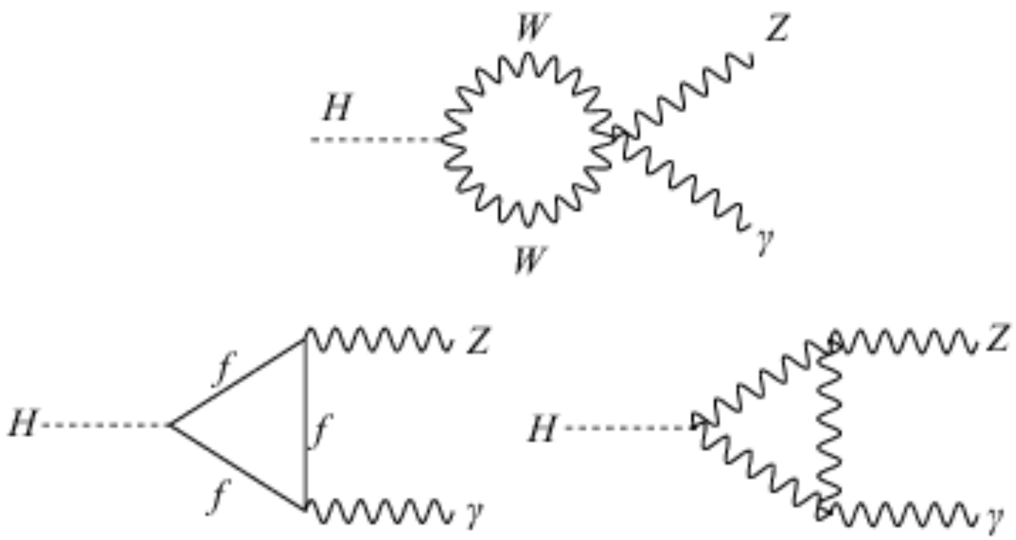
ATLAS VBF H→cc̄

- First search for H→cc̄ 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:
  - **|Kc| < 4.7 (3.9) obs. (exp.)**

$H \rightarrow ll\gamma$

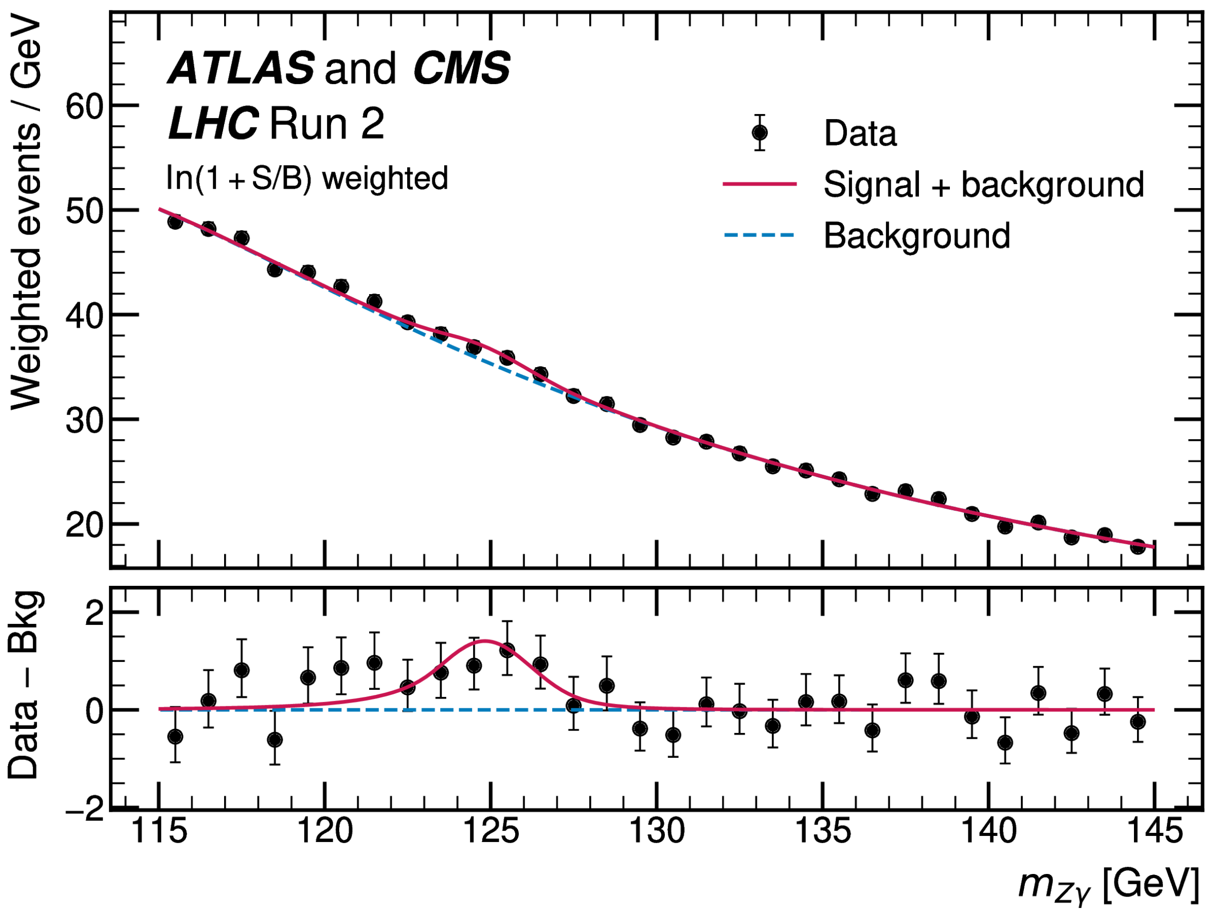
H→Zγ decay

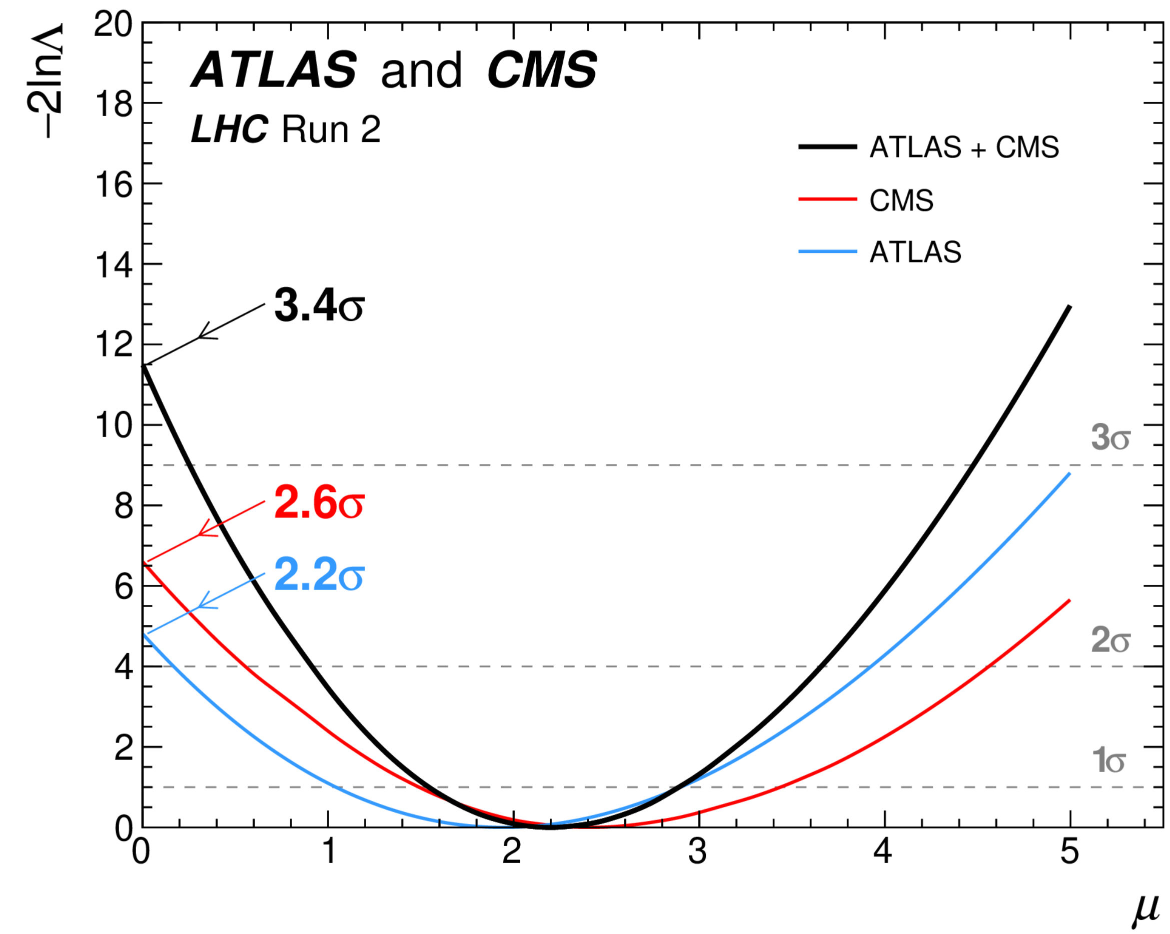
- BSM particles & couplings could be present in the quantum loops
- Difference between H→Zγ decay and H→γγ/H→ZZ decay sensitive to new physics
  - (e.g. Qing-Hong Cao et al. *Phys. Lett. B* 789 (2019) 233)
  - Small branching ratio in SM (1.6x10^{-3}); main bkg: non-Higgs Zγ, Z+jets
- Select events with two leptons (mll ~90 GeV) and one photon and separate them to multiple categories to target various production modes
- Fit in llγ mass distribution over all categories (Z kin fit improves mass resolution)



H→Zγ decay

Phys. Rev. Lett. 132 (2024) 021803, Featured in Physics

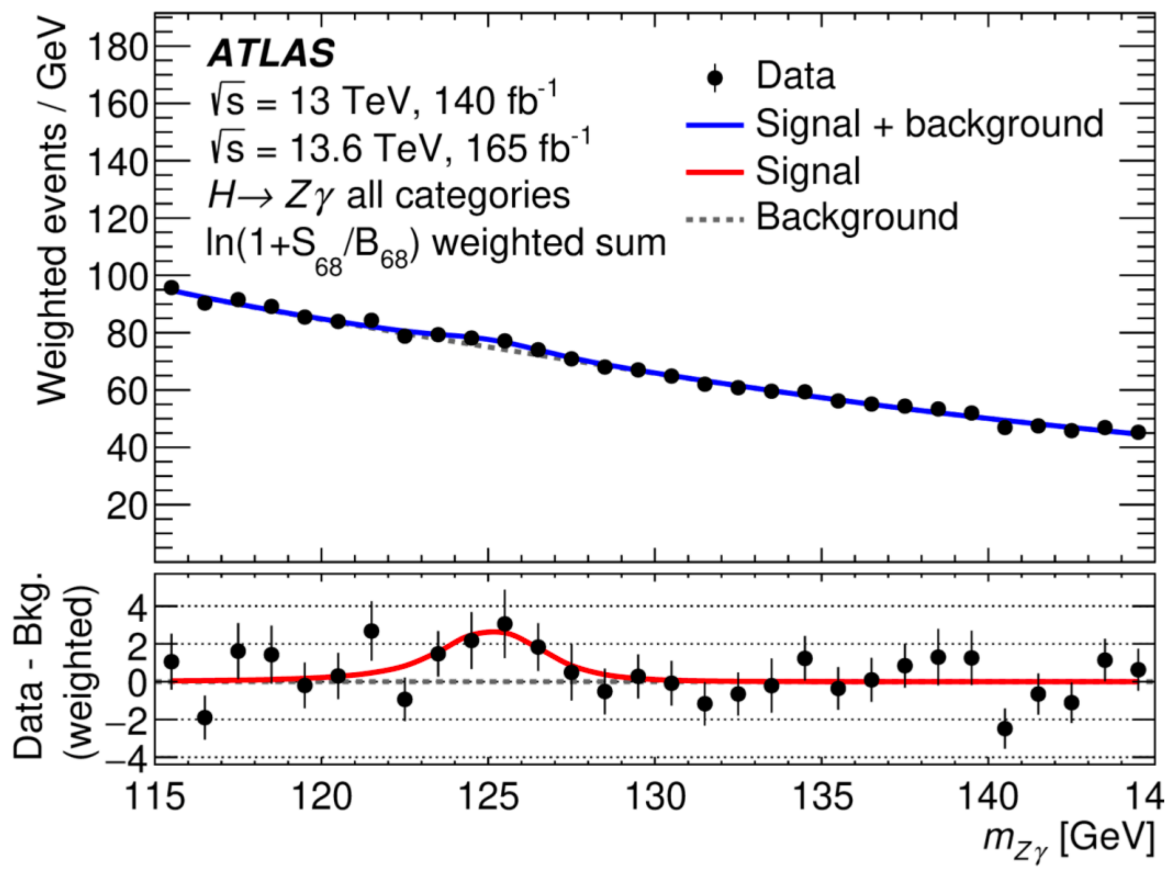


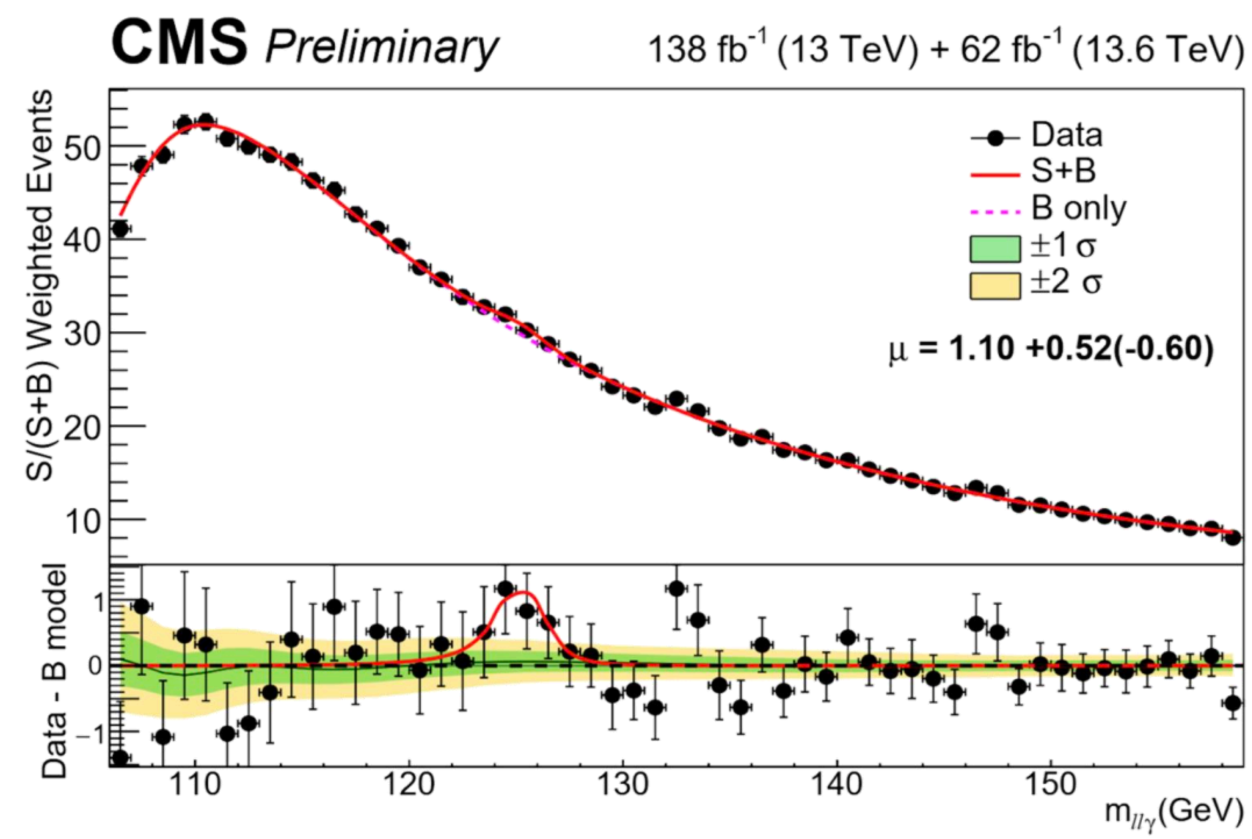


- In ATLAS+CMS combined result, the observed H→Zγ significance is **3.4σ** (expected 1.6σ)
  - **First evidence** of the H→Zγ decay
- Signal strength is 2.2 ± 0.7: agrees with theoretical expectation within **1.9σ**
- With the ongoing Run-3, we will be able to improve the precision of this rare Higgs decay

H→Zγ decay

arxiv:2507.12598 CMS-PAS-HIG-25-010

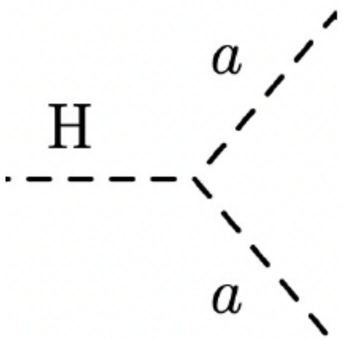




- The observed H→Zγ significance in ATLAS full Run 2 + partial Run 3 (2022-2024) result is **2.5σ** (expected 1.9σ). Signal strength: 1.3 +0.6 -0.5
- The observed H→Zγ significance in ATLAS full Run 2 + partial Run 3 (2022-2023) result is **1.9σ** (expected 2.3σ). Signal strength: 1.1 +0.5 -0.6
- The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

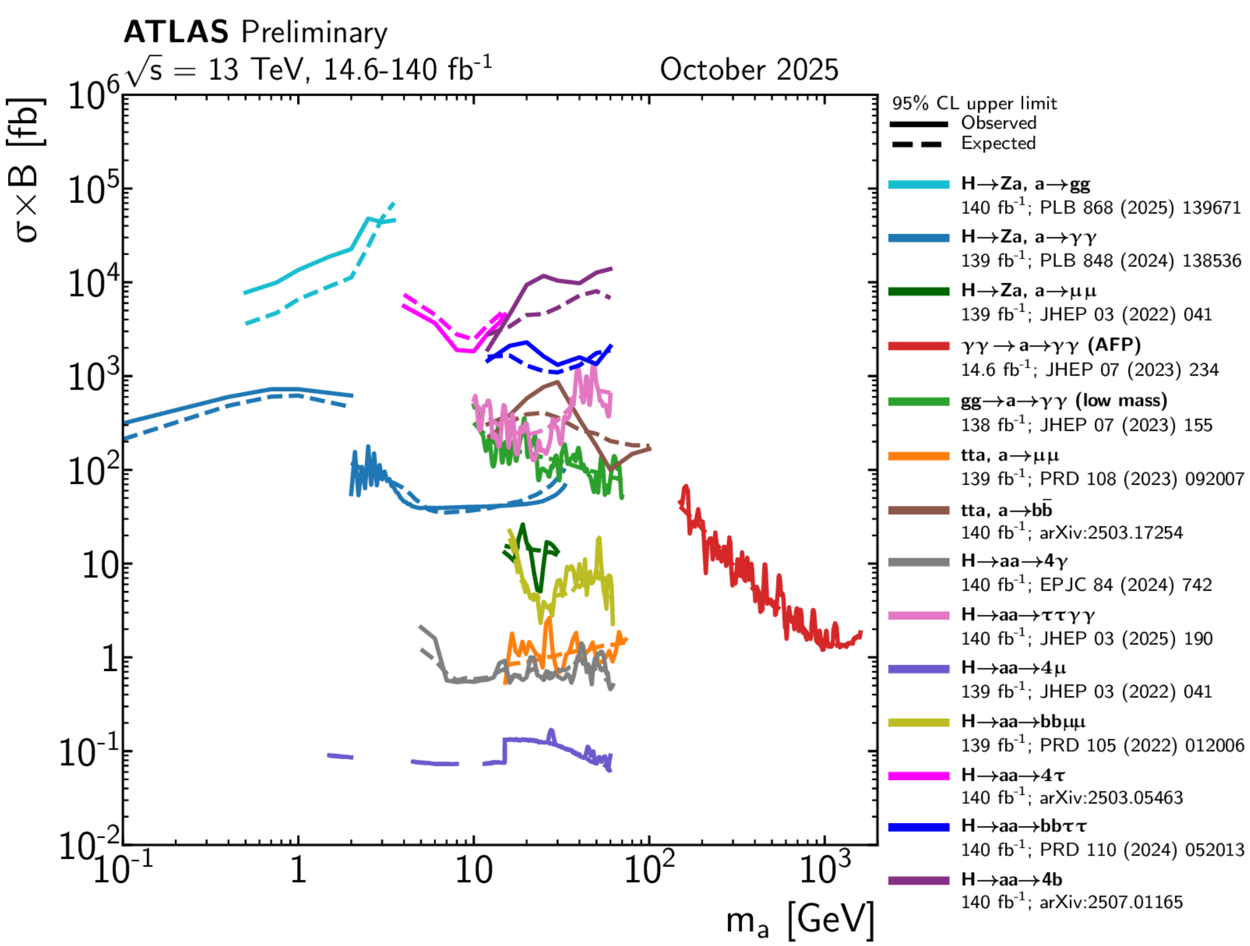
$H \to aa$

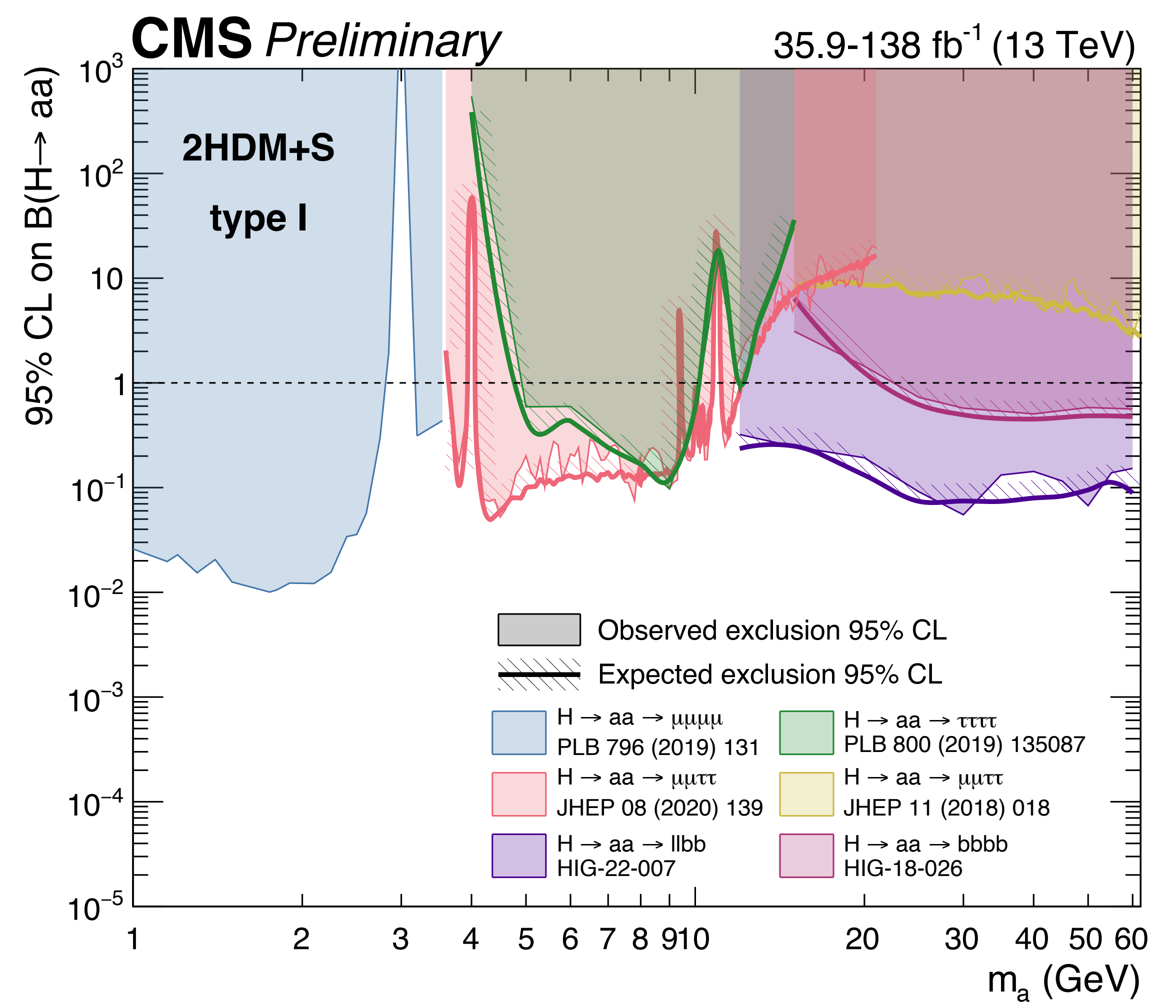
H→aa



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

Many final states are analyzed: bbbb, bbll, llll, …



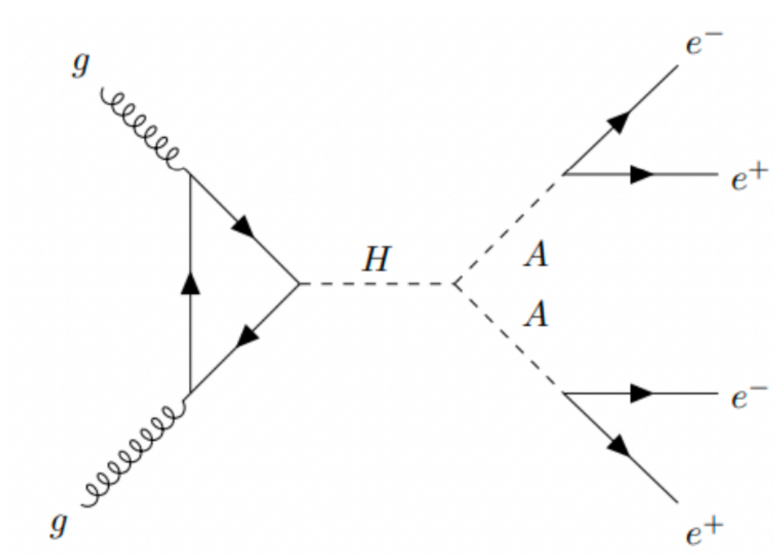


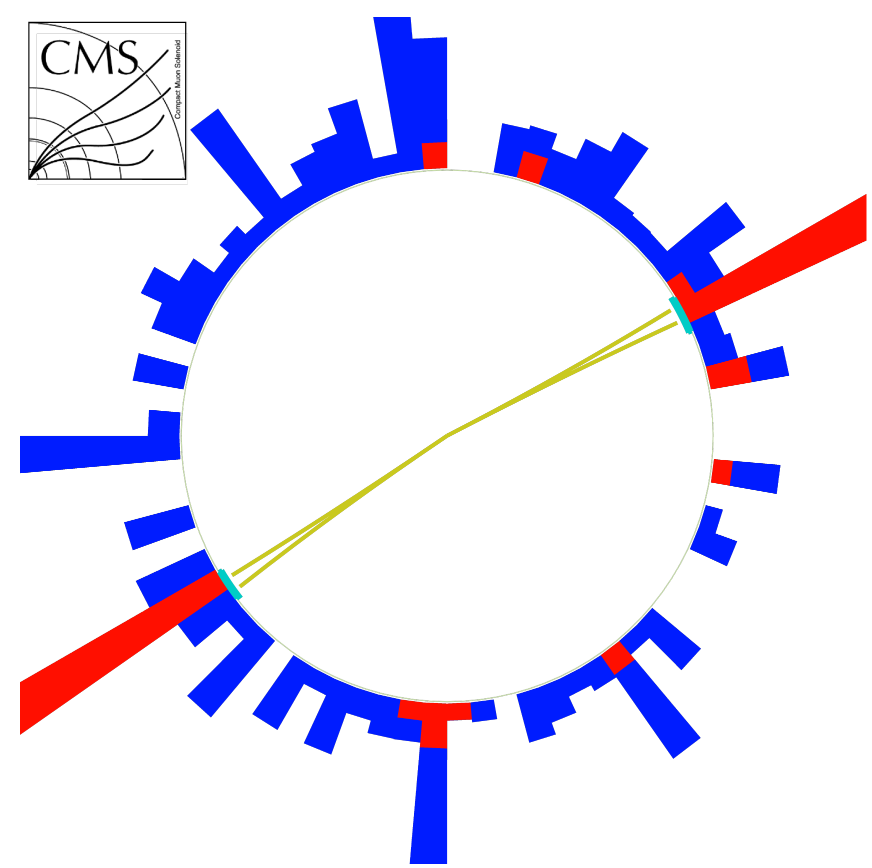
ATLAS Summary Plots

CMS Summary Plots

H→aa→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→aa→4electrons, with a novel multivariate identification technique
  - Showing LHC's potential as a unique axion-like particle search facility





arxiv:2511.19563, accepted by PRL

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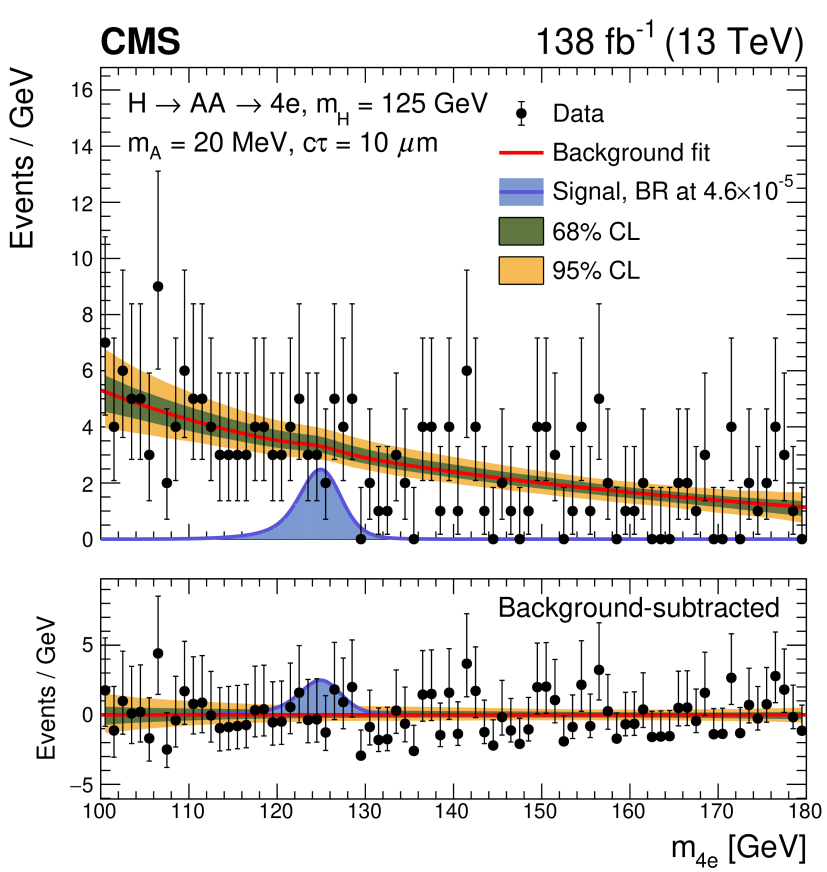
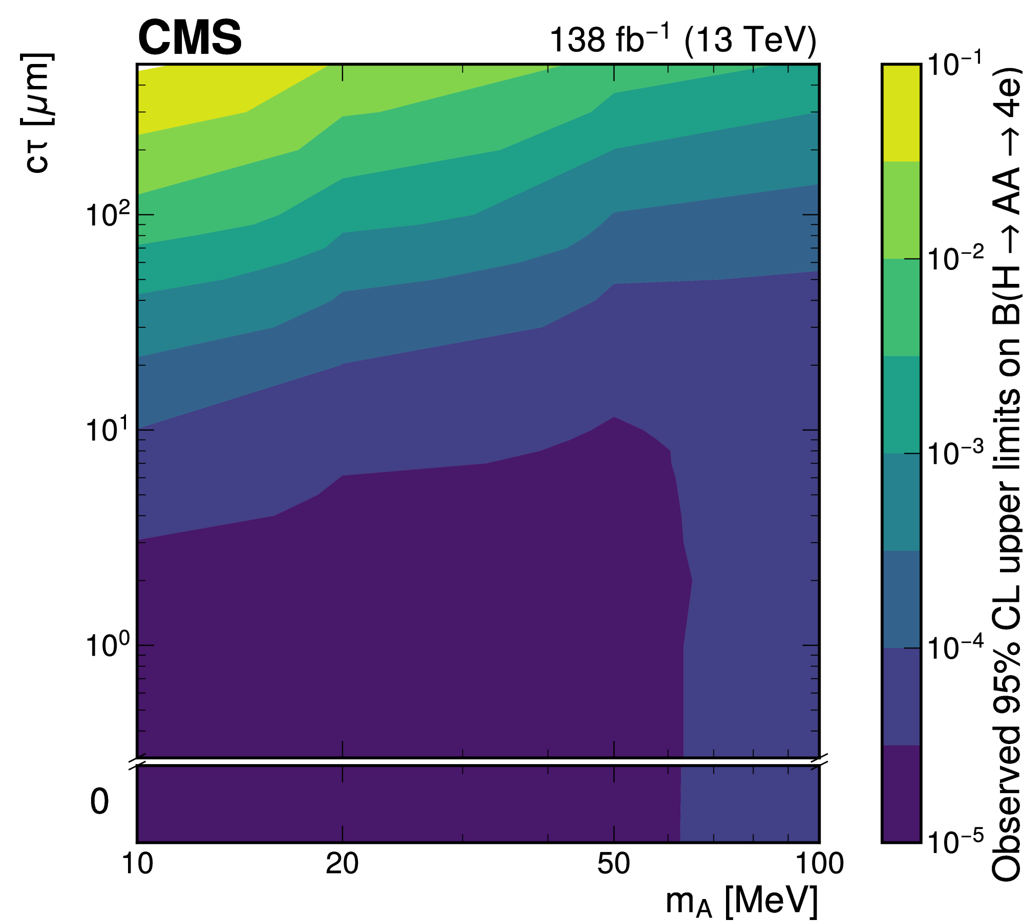




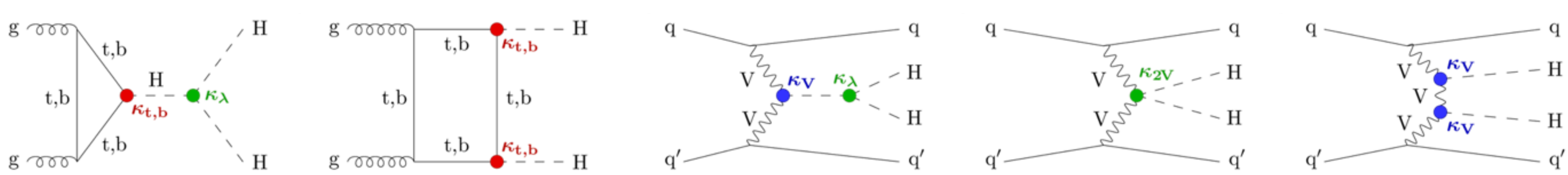
arxiv:2511.19563, accepted by PRL

HH production

Higgs boson self-couplings

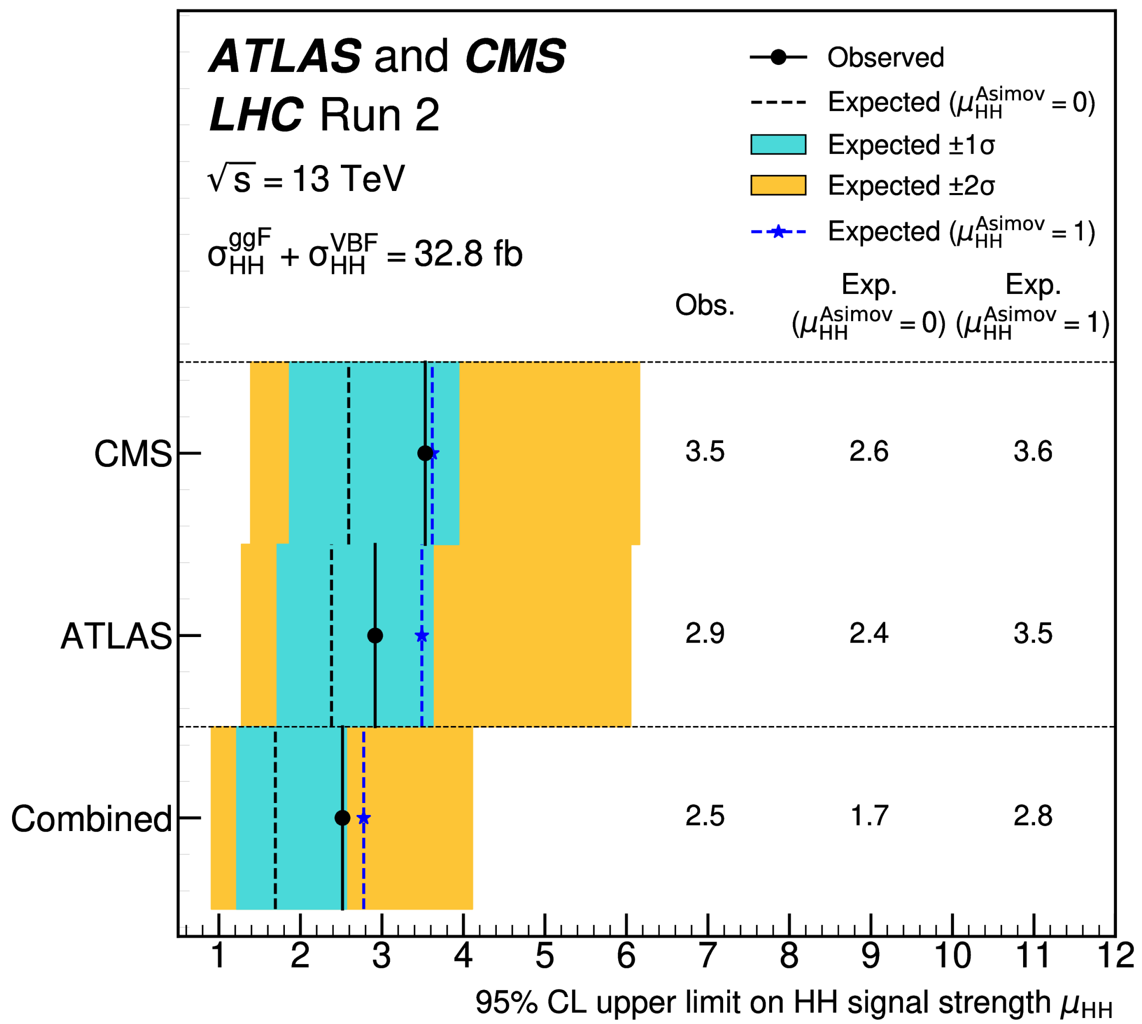
- **Higgs self-coupling is one of the deepest questions of SM and may provide a portal to new physics beyond it**
  - Vacuum stability, early universe evolvement, …
- **Double Higgs production is the way to directly probe Higgs self-couplings at the LHC**
  - Extremely low cross-section in the SM
  -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

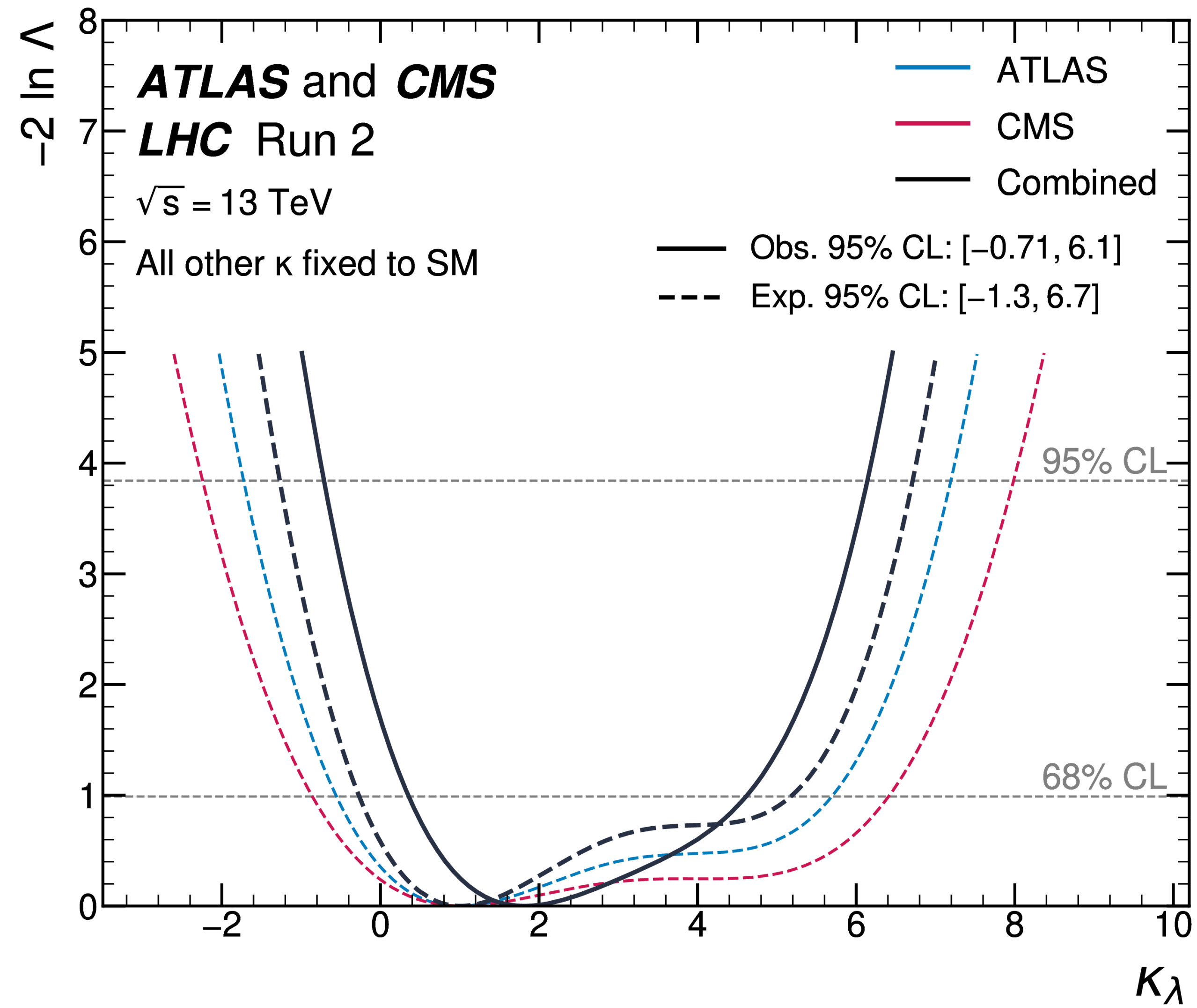
Higgs boson pair production



LHC Double Higgs search combination

arxiv:2602.23991, submitted to PRL





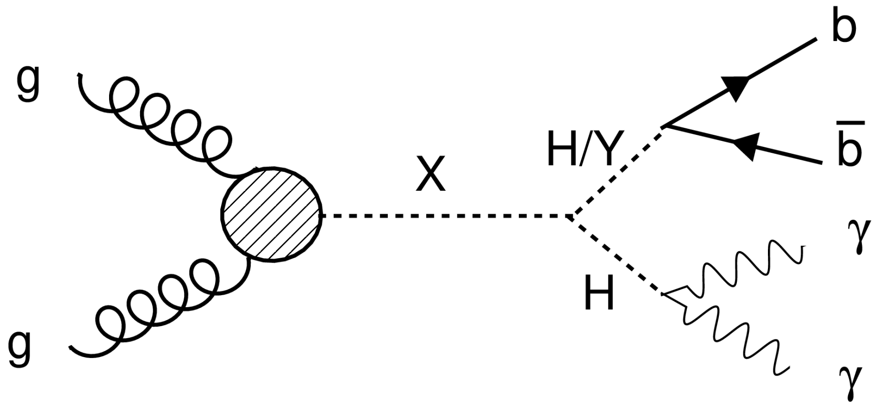
- Limit of double Higgs cross section: 2.5 times SM prediction
- HHH coupling strength: $-0.71<\kappa_\lambda<6.1$; HHVV coupling strength: $0.73<\kappa_{2V}<1.3$

$X \to HH/HY$

Resonant production of Higgs boson

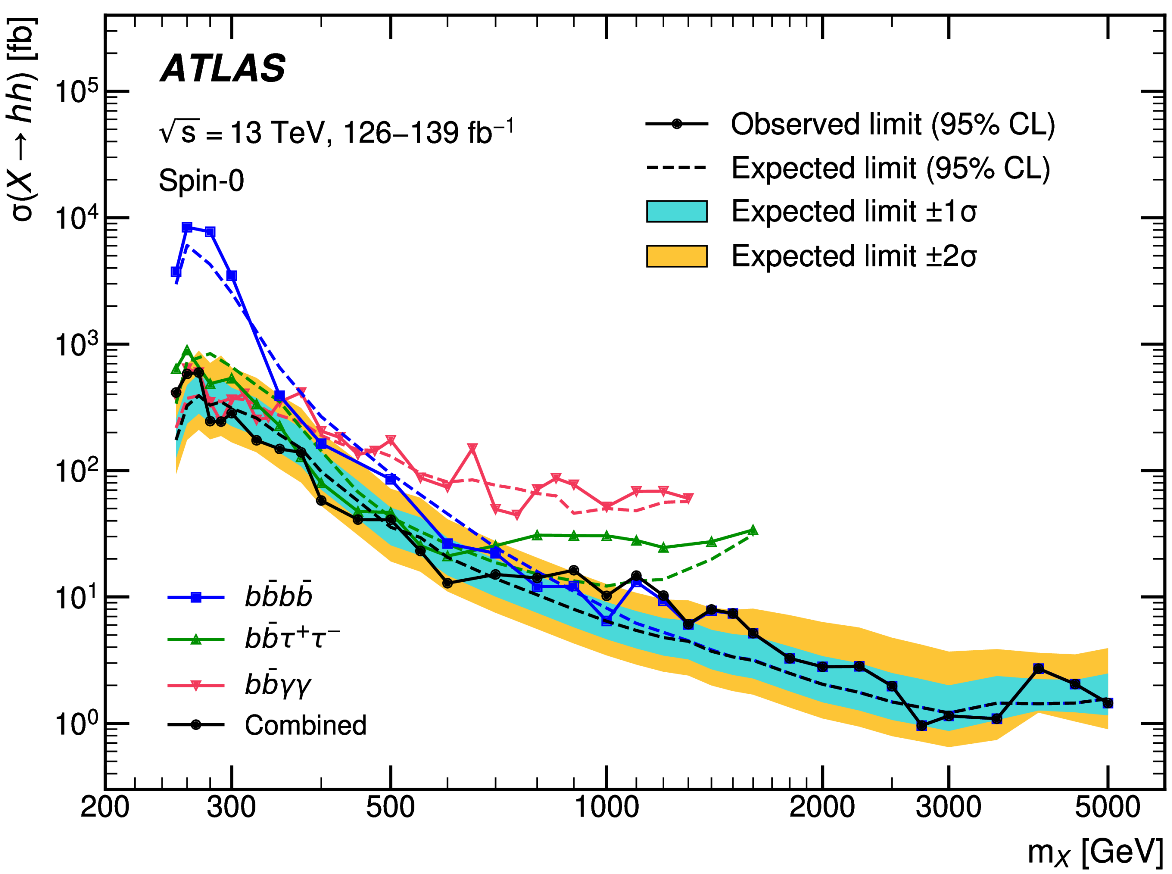
- Heavy resonance search channels including at least one Higgs boson have formed an important part of the program of new physics searches at the LHC

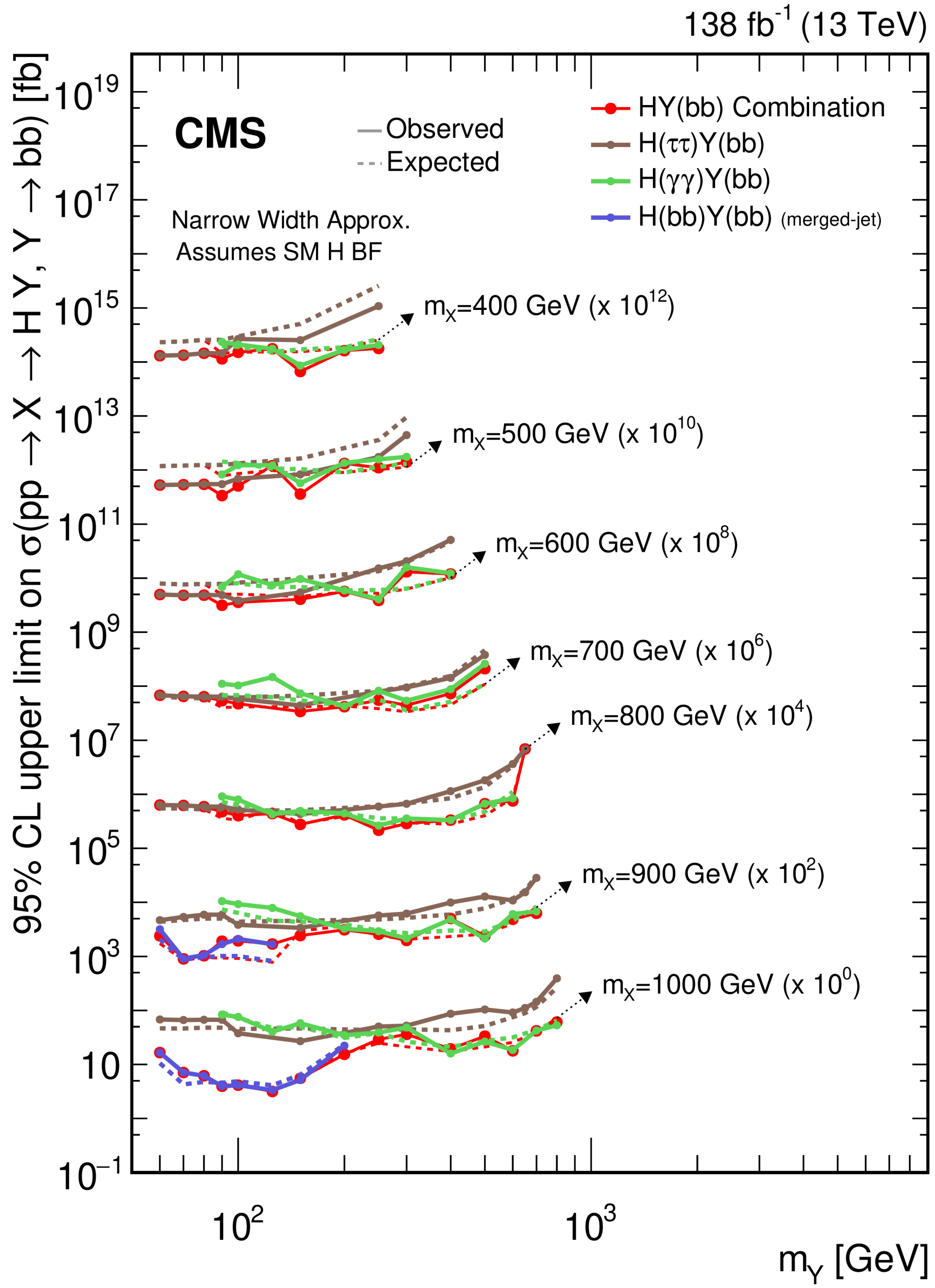
- Sensitive to many new physics models, including extended Higgs sectors and extra dimensions



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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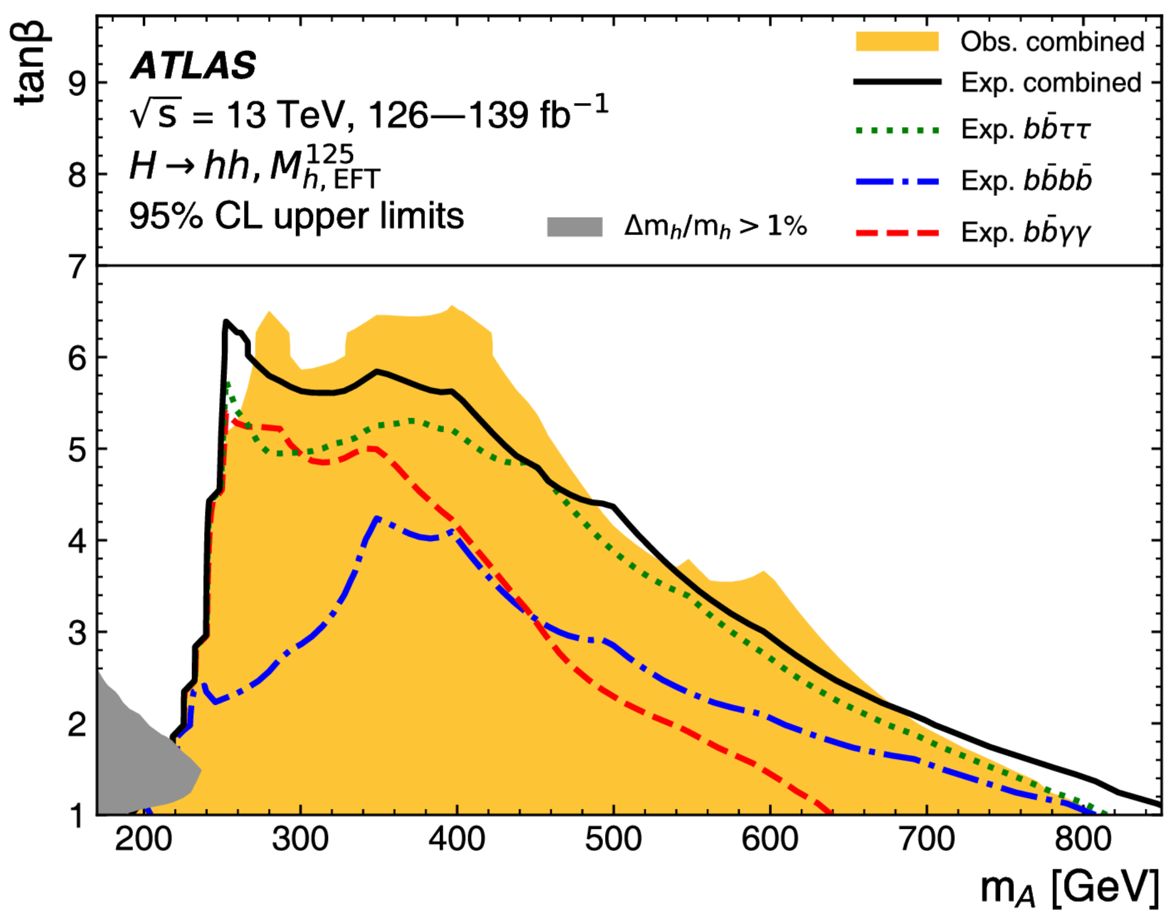
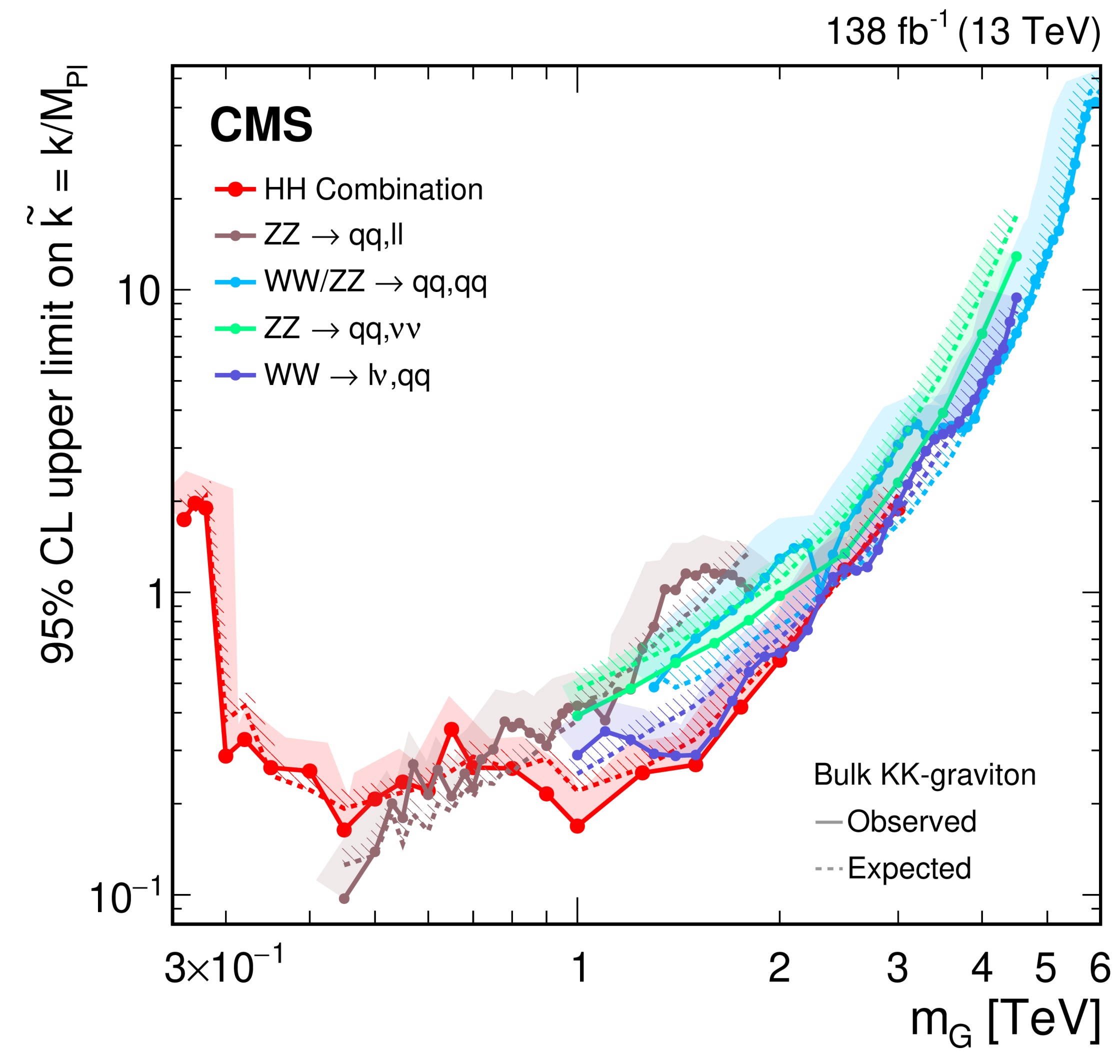


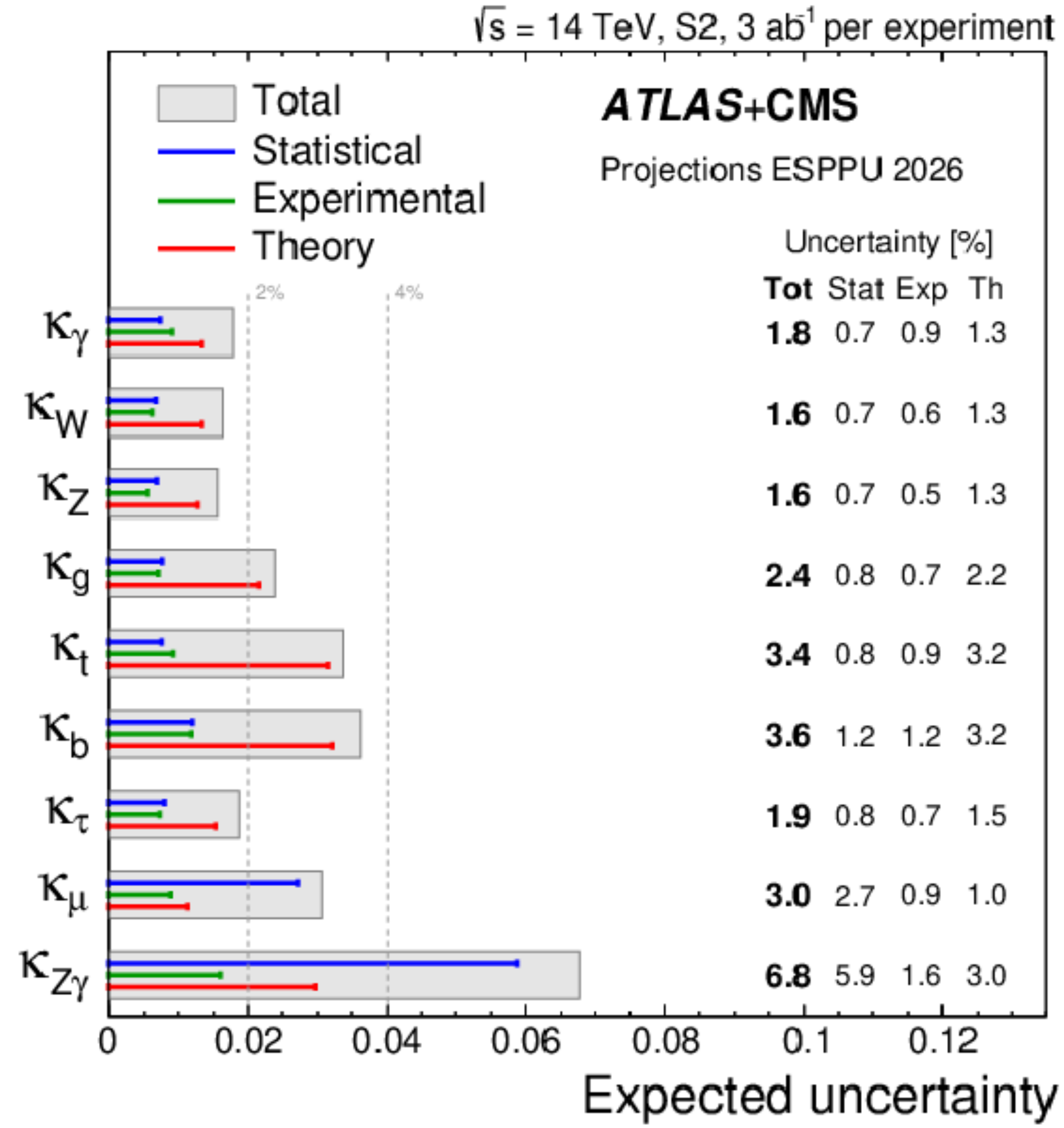


Phys. Rev. Lett. 132 (2024) 231801

Physics Reports 1115 (2025) 368

Summary

- **LHC experiments have a large program to study Higgs boson rare and exotic production and decays and keep improving sensitivities**
  - Results are so far consistent with the SM predictions
  - Evidence of H→μμ and H→Zγ
  - Constraints of Higgs self-couplings
  - etc.
- **Run 3 is ongoing and HL-LHC is coming. Stay tune for the new results!**



arxiv:2504.00672

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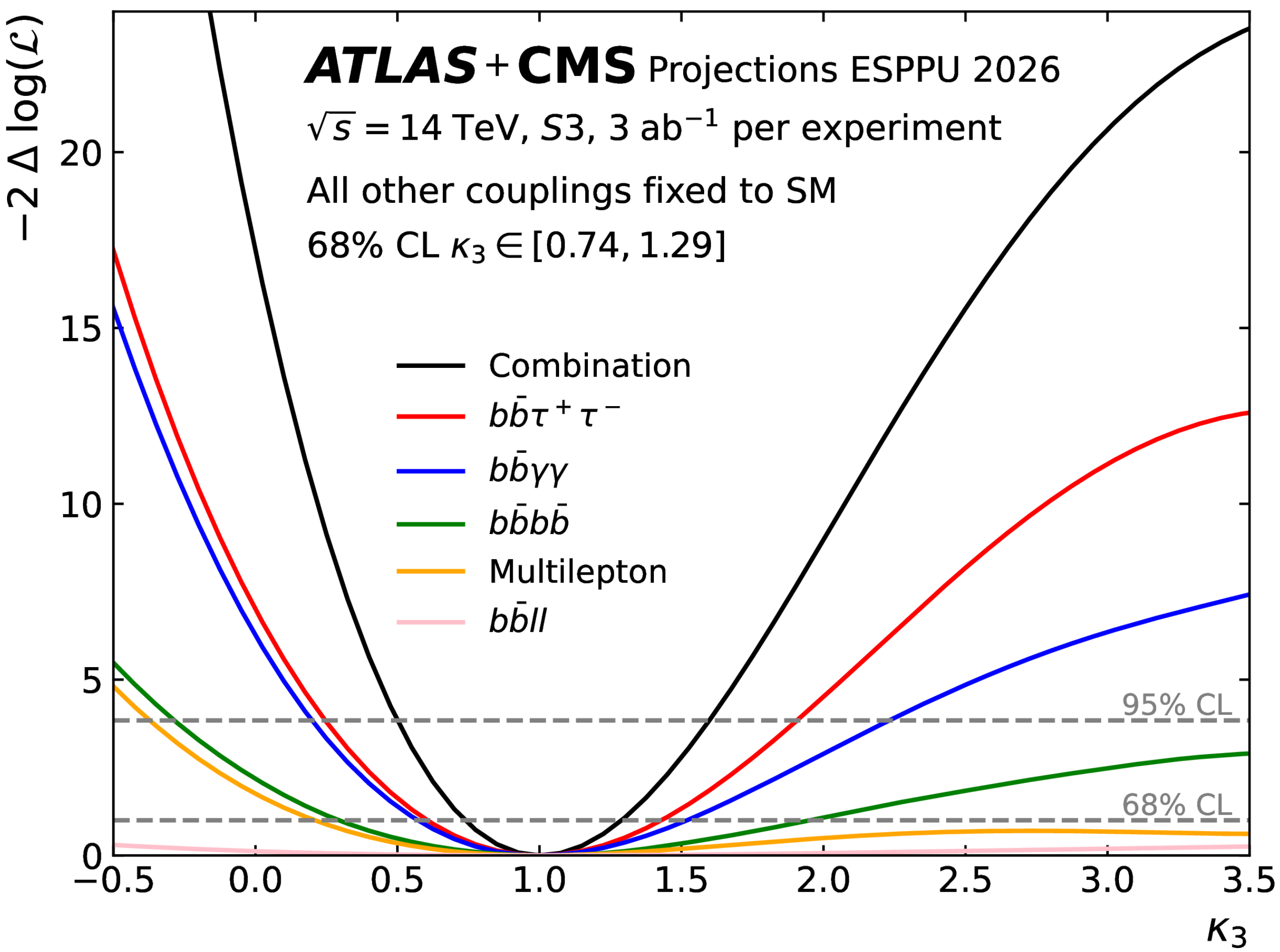


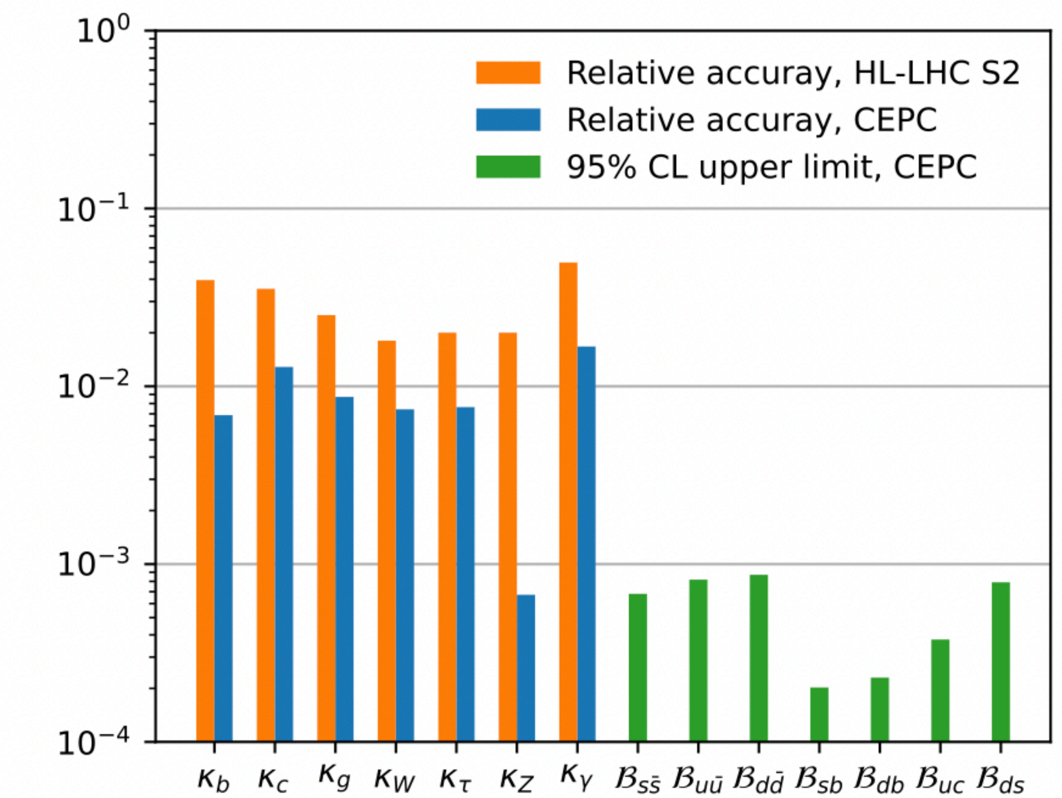
arxiv:2504.00672

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 → ss, uu, dd and H → 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 $H \to b\bar{b}/c\bar{c}/gg$, 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



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广告

第二届TeV物理前沿专题研讨会

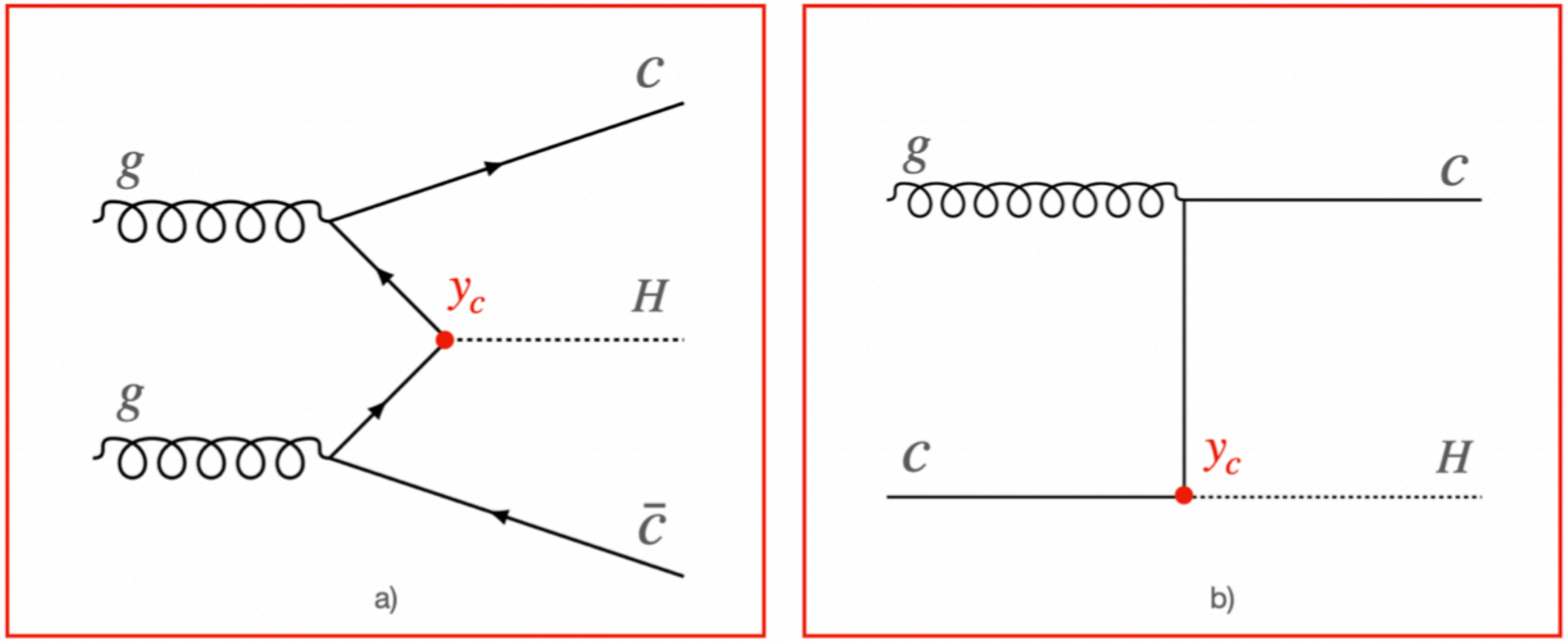
- 26年秋
- 北京大学

欢迎建议主题!

Thank you!

c(c)H production

c(c)H production

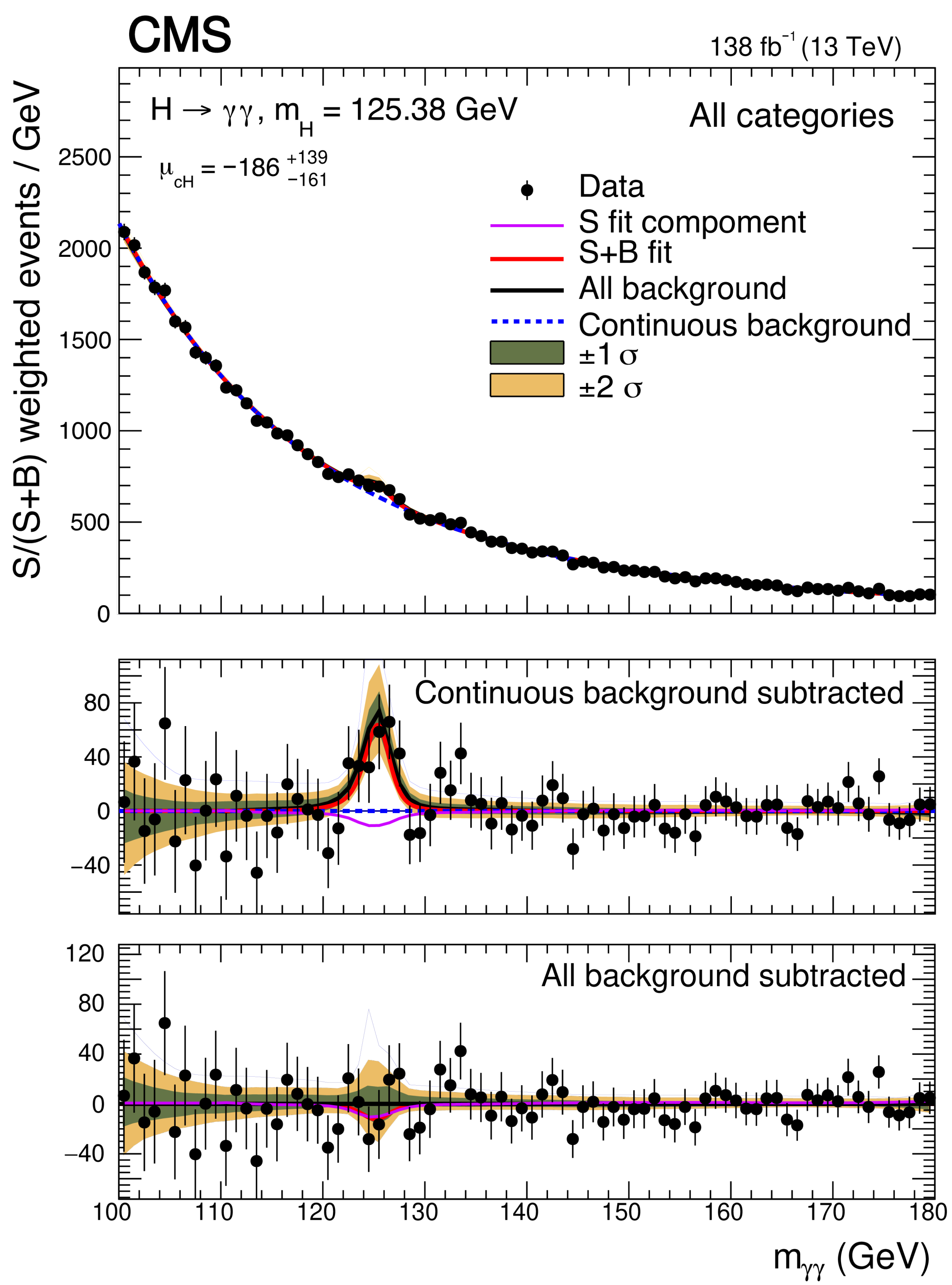


- To improve the experimental sensitivity for Higgs coupling to c quarks, one possibility is to look for c(c)H production
  - Challenging because of ggH background

c(c)H production

- CMS presents the first search for cH, focusing on the diphoton decay channel of the Higgs boson (JHEP 11 (2025) 060)
  - The observed allowed interval on κ_c, the Higgs boson-charm quark coupling modifier, is **$|\kappa_c| < 38.1$**

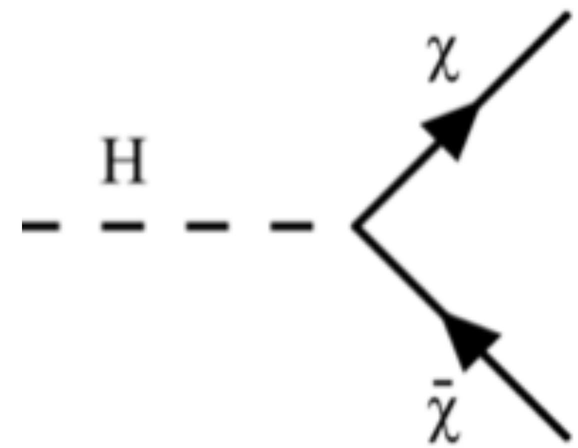
- ATLAS performs cross section measurement in H+c final state (dominated by ggF) (JHEP 02 (2025) 045)

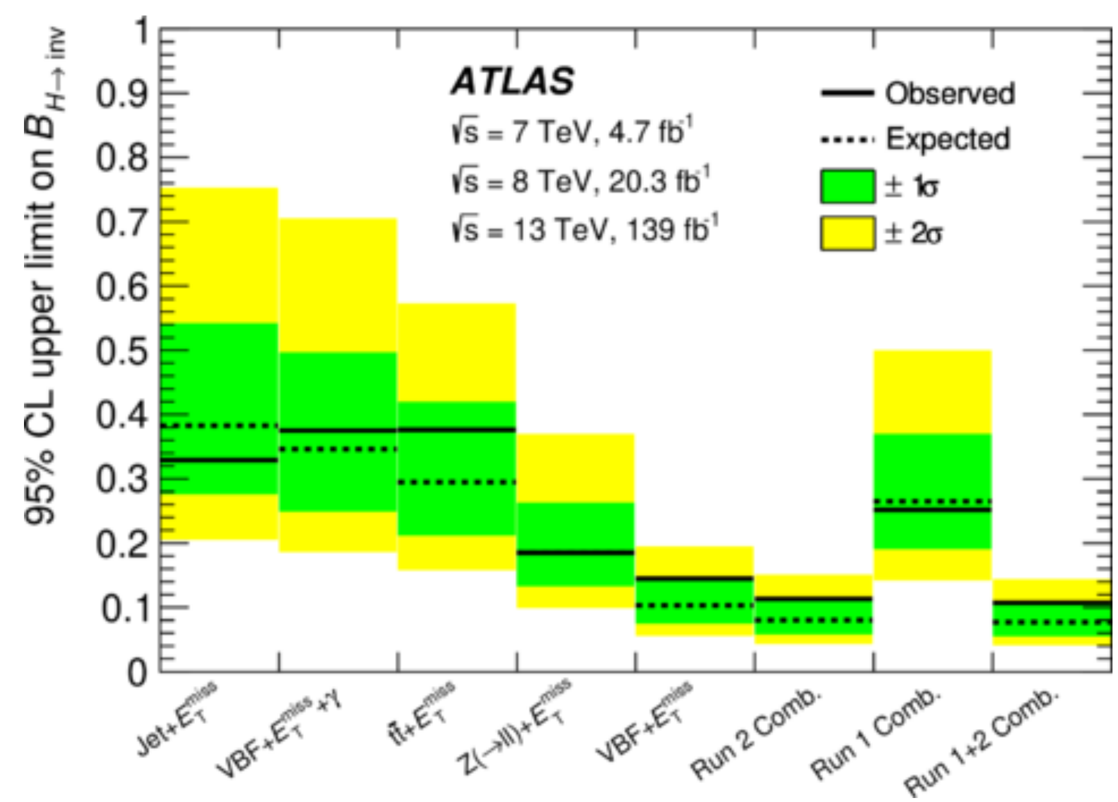


H→invisible

Search for Higgs→invisible decay

- The Higgs discovery has opened up a new path to discover Dark Matter.
  - Higgs→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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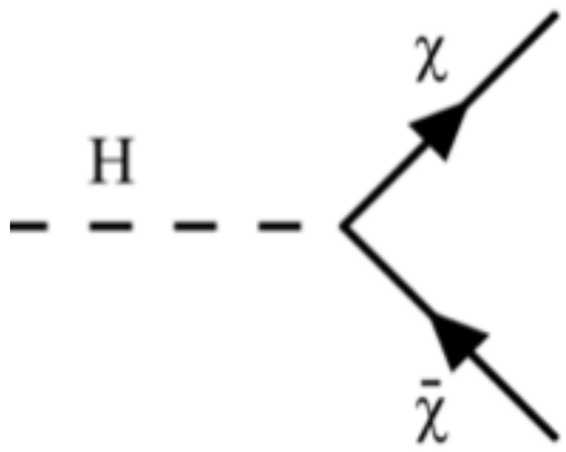
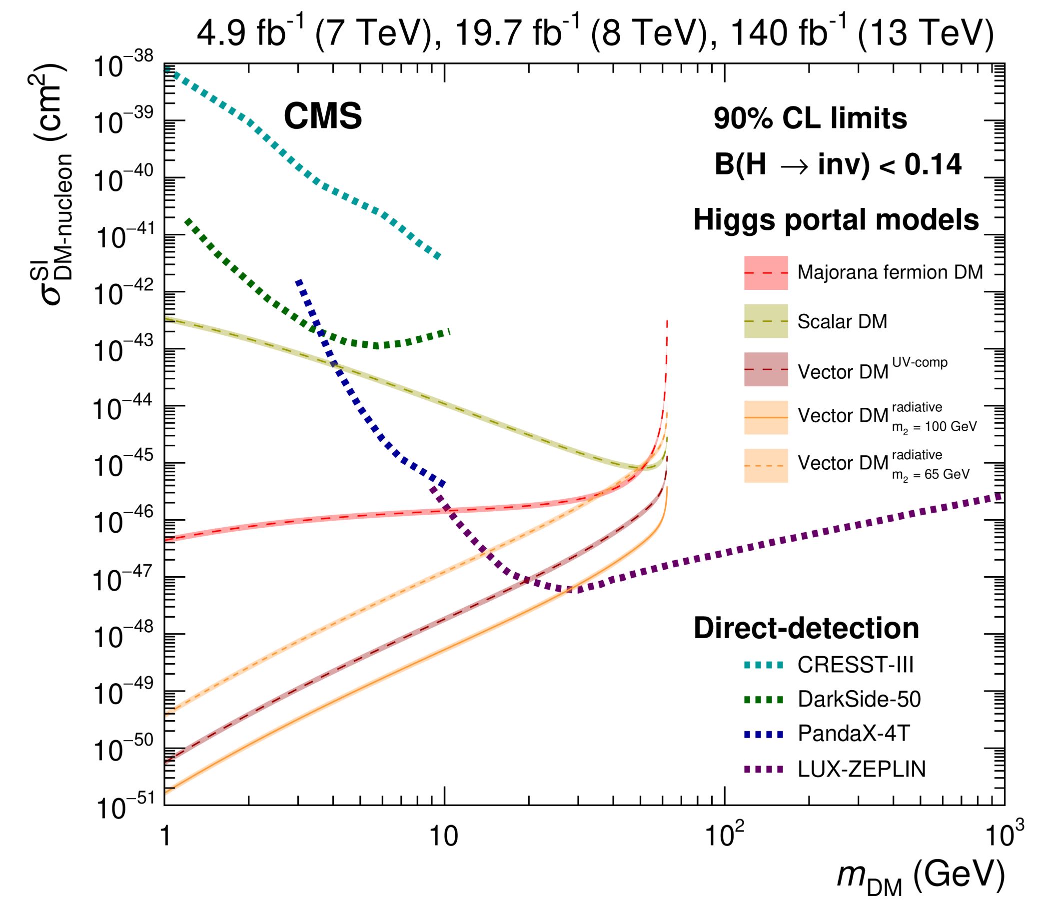


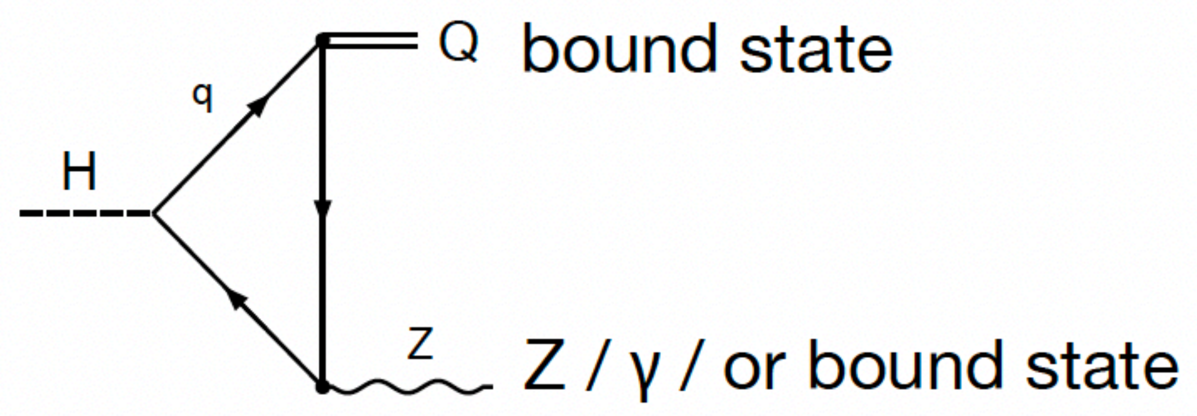


$H \to mesons$

Higgs decays to mesons

- Higgs decays to mesons can be used to study Higgs couplings to light, charm and bottom quarks, as well as new physics in the loops

- Look into associated production to reduce background



Higgs decays to mesons

- The quarkonium decays to two muons leave a clear signature inside the detectors

ATLAS, quarkonium+photon

Decay channel	95% CL_s upper limits: Branching fraction, Higgs boson [10^{-4}] Expected	Higgs boson [10^{-4}] Observed	Z boson [10^{-6}] Expected	Z boson [10^{-6}] Observed	$\sigma \times \mathcal{B}$: Higgs boson [fb] Observed	Z boson [fb] Observed
$J/\psi\,\gamma$	$1.9^{+0.8}_{-0.5}$	2.1	$0.6^{+0.3}_{-0.2}$	1.2	12	71
$\psi(2S)\,\gamma$	$8.5^{+3.8}_{-2.4}$	10.9	$2.9^{+1.3}_{-0.8}$	2.3	61	135
$\Upsilon(1S)\,\gamma$	$2.8^{+1.3}_{-0.8}$	2.6	$1.5^{+0.6}_{-0.4}$	1.0	14	59
$\Upsilon(2S)\,\gamma$	$3.5^{+1.6}_{-1.0}$	4.4	$2.0^{+0.8}_{-0.6}$	1.2	24	71
$\Upsilon(3S)\,\gamma$	$3.1^{+1.4}_{-0.9}$	3.5	$1.9^{+0.8}_{-0.5}$	2.3	19	135

CMS, quarkonium +Z and 2 quarkonium

Process	Observed	Expected	Observed	
Higgs boson channel	Longitudinal	Longitudinal	Unpolarized	Transverse
$\mathcal{B}(H \to ZJ/\psi)$	1.9×10^{-3}	$(2.6^{+1.1}_{-0.7}) \times 10^{-3}$	2.4×10^{-3}	2.8×10^{-3}
$\mathcal{B}(H \to Z\psi(2S))$	6.6×10^{-3}	$(7.1^{+2.8}_{-2.0}) \times 10^{-3}$	8.3×10^{-3}	9.4×10^{-3}
$\mathcal{B}(H \to J/\psi J/\psi)$	3.8×10^{-4}	$(4.6^{+2.0}_{-0.6}) \times 10^{-4}$	4.7×10^{-4}	5.2×10^{-4}
$\mathcal{B}(H \to \psi(2S)J/\psi)$	2.1×10^{-3}	$(1.4^{+0.6}_{-0.4}) \times 10^{-3}$	2.6×10^{-3}	2.9×10^{-3}
$\mathcal{B}(H \to \psi(2S)\psi(2S))$	3.0×10^{-3}	$(3.3^{+1.5}_{-0.9}) \times 10^{-3}$	3.6×10^{-3}	4.7×10^{-3}
$\mathcal{B}(H \to \Upsilon(nS)\Upsilon(mS))$	3.5×10^{-4}	$(3.6^{+0.2}_{-0.3}) \times 10^{-4}$	4.3×10^{-4}	4.6×10^{-4}
$\mathcal{B}(H \to \Upsilon(1S)\Upsilon(1S))$	1.7×10^{-3}	$(1.7^{+0.1}_{-0.1}) \times 10^{-3}$	2.0×10^{-3}	2.2×10^{-3}
Z boson channel				
$\mathcal{B}(Z \to J/\psi J/\psi)$	11×10^{-7}	$(9.5^{+3.8}_{-2.6}) \times 10^{-7}$	14×10^{-7}	16×10^{-7}
$\mathcal{B}(Z \to \Upsilon(nS)\Upsilon(mS))$	3.9×10^{-7}	$(4.0^{+0.3}_{-0.3}) \times 10^{-7}$	4.9×10^{-7}	5.6×10^{-7}
$\mathcal{B}(Z \to \Upsilon(1S)\Upsilon(1S))$	1.8×10^{-6}	$(1.8^{+0.1}_{-0.0}) \times 10^{-6}$	2.2×10^{-6}	2.4×10^{-6}

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Higgs decays to mesons

- Some bounds states can decay into kaons and pions, which have good mass resolution at low pT

ATLAS, ωγ and K*γ

Channel	95% CL upper limit	
	Expected	Observed
$H \to \omega\gamma\ [10^{-4}]$	$3.0^{+1.2}_{-0.8}$	1.5
$Z \to \omega\gamma\ [10^{-7}]$	$5.7^{+2.3}_{-1.6}$	3.8
$H \to K^*\gamma\ [10^{-5}]$	$12.2^{+4.9}_{-3.4}$	8.9

CMS, ϕZ and ρZ

	Observed	Median expected	±68% expected	±95% expected
Isotropic decay	0.36%	0.33%	0.23–0.46%	0.18–0.61%
Z and ϕ longitudinally polarized	0.31%	0.27%	0.20–0.39%	0.15–0.52%
Z and ϕ transversely polarized	0.40%	0.36%	0.26–0.50%	0.19–0.68%

	Observed	Median expected	±68% expected	±95% expected
Isotropic decay	1.21%	0.73%	0.52–1.04%	0.38–1.41%
Z and ρ longitudinally polarized	1.04%	0.63%	0.44–0.89%	0.32–1.20%
Z and ρ transversely polarized	1.31%	0.80%	0.57–1.14%	0.41–1.54%

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