Higgs rare and exotic decays at CMS

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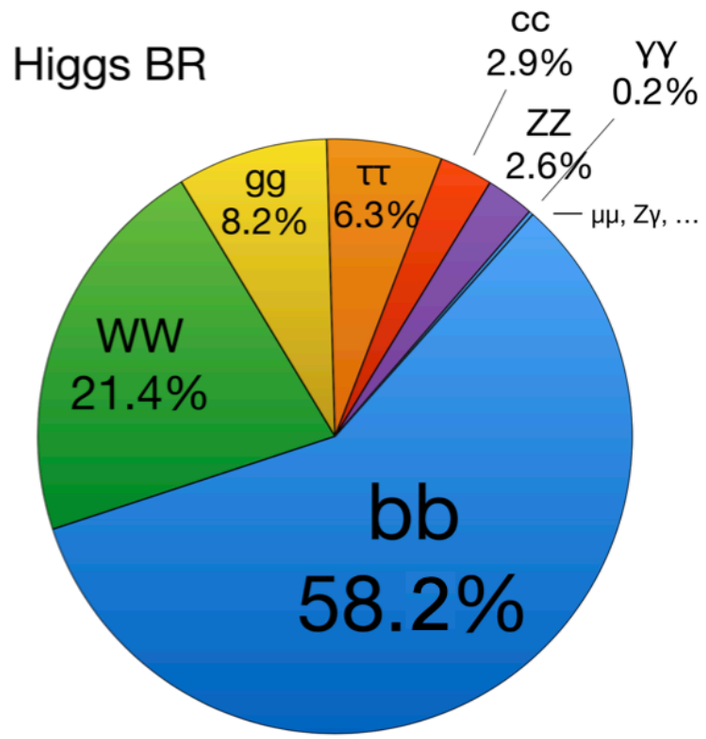
Contents of this talk

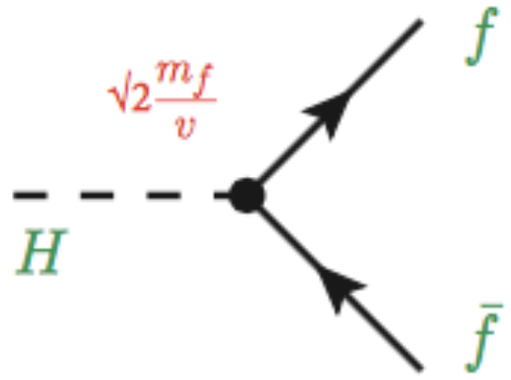
- **Rare and exotic decays of Higgs boson are important portals to new physics**
- **CMS experiment has a large program to study these processes and keep improving sensitivities**
  - Focus on results recently released
  - Results of Higgs rare decays
    - H→ff, H→llγ, H→meson
  - Results of Higgs exotic decays
    - H→invisible, H→aa



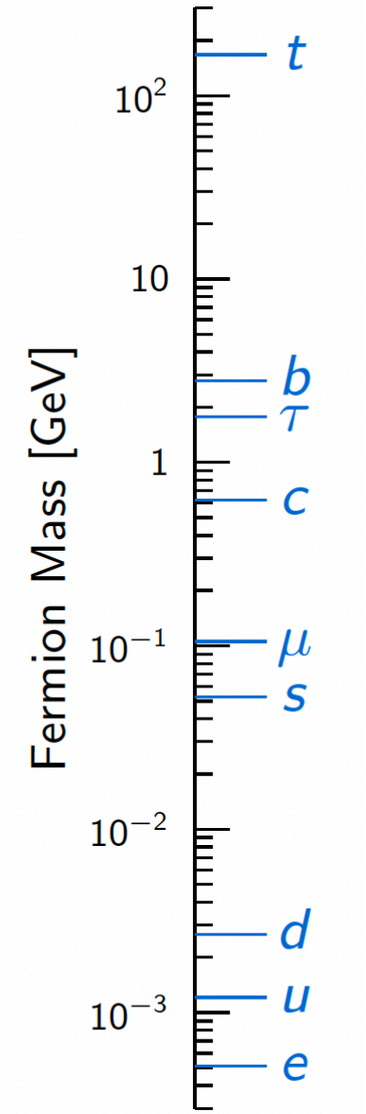
$H \to ff$

Yukawa couplings

- In Standard Model, Higgs boson couples to fermions (quarks and leptons) through Yukawa interactions
  - **giving masses to quarks and leptons**

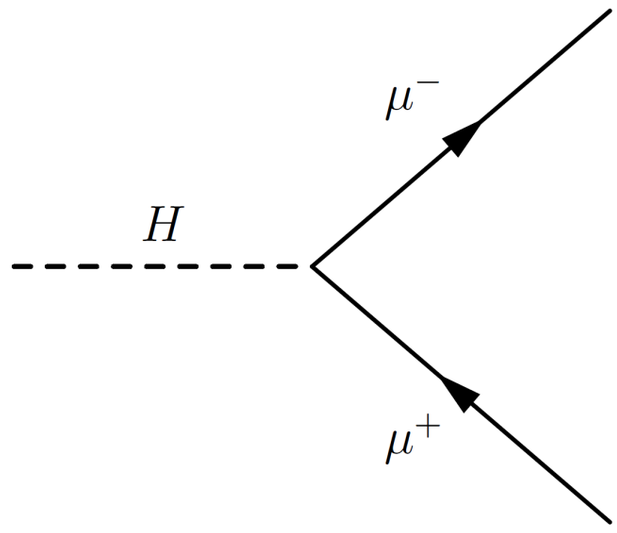


- Yukawa interactions are the least constrained sector of the Higgs physics
  - **important to study the Yukawa sector, which may provide important indication for the origin of the fermion mass pattern**
- Experimental signatures: **$t\bar{t}H$ production**, **$H\to\tau\tau$ decay**, **$H\to b\bar{b}$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

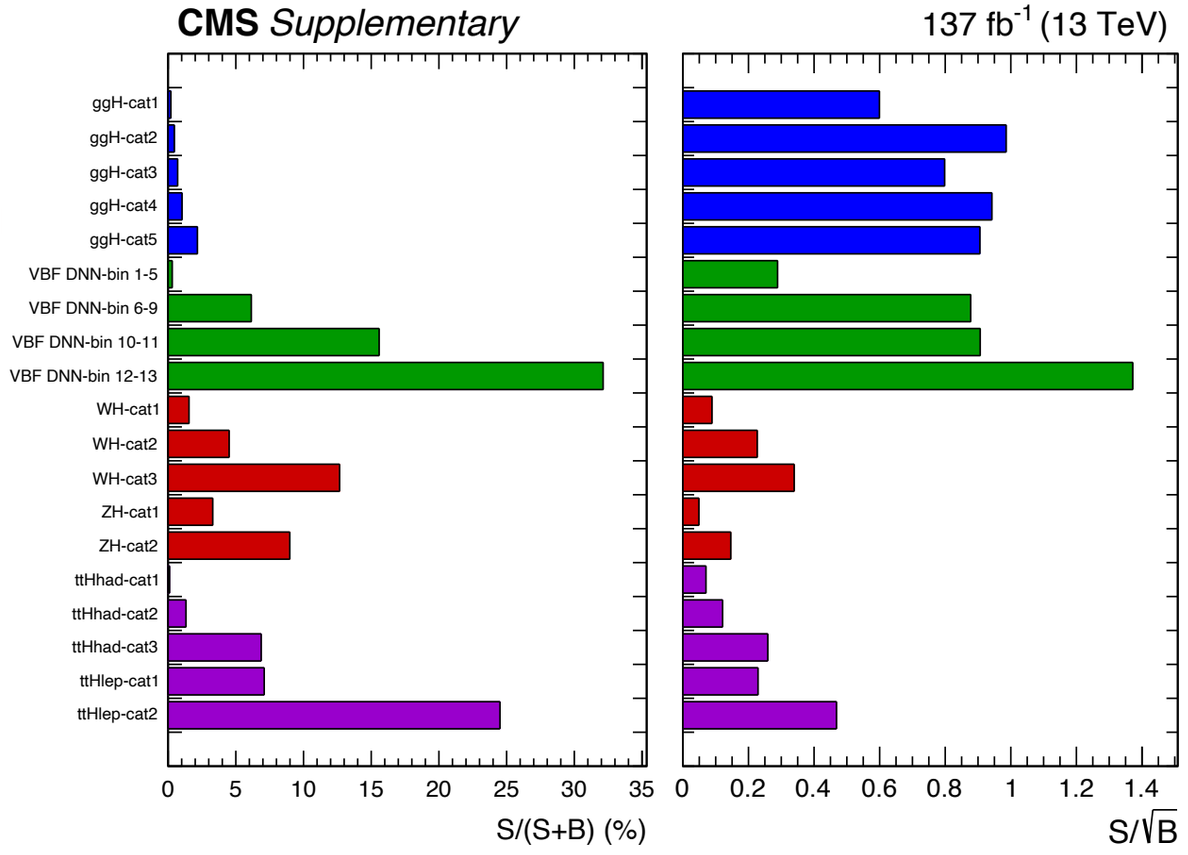


H→*μμ* decay

- 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

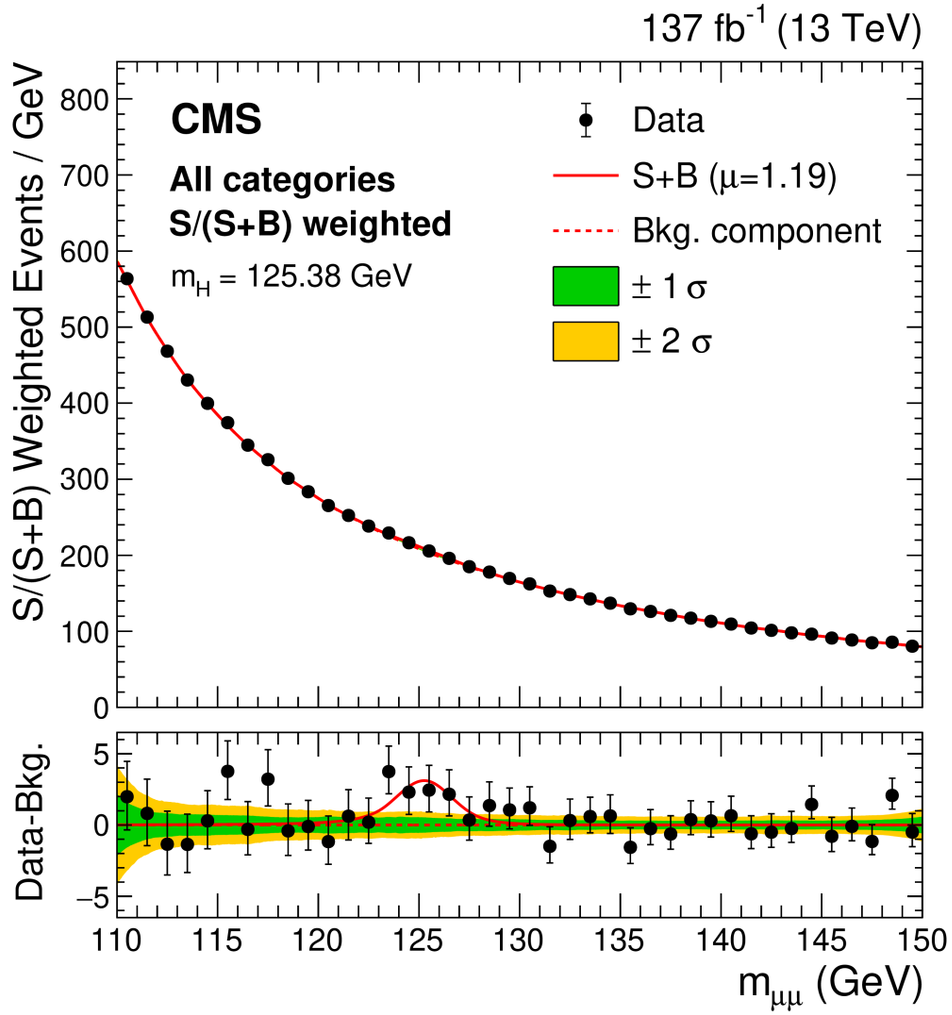


- **The Higgs decay to two muons offers the best opportunity to observe the Higgs couplings with second-generation fermions at the LHC**
  - Small branching ratio in SM (2×10^{-4})
  - key ingredients of the analysis: for sure optimal di-mu mass resolution, but also extreme optimization of the categories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



JHEP 01 (2021) 148

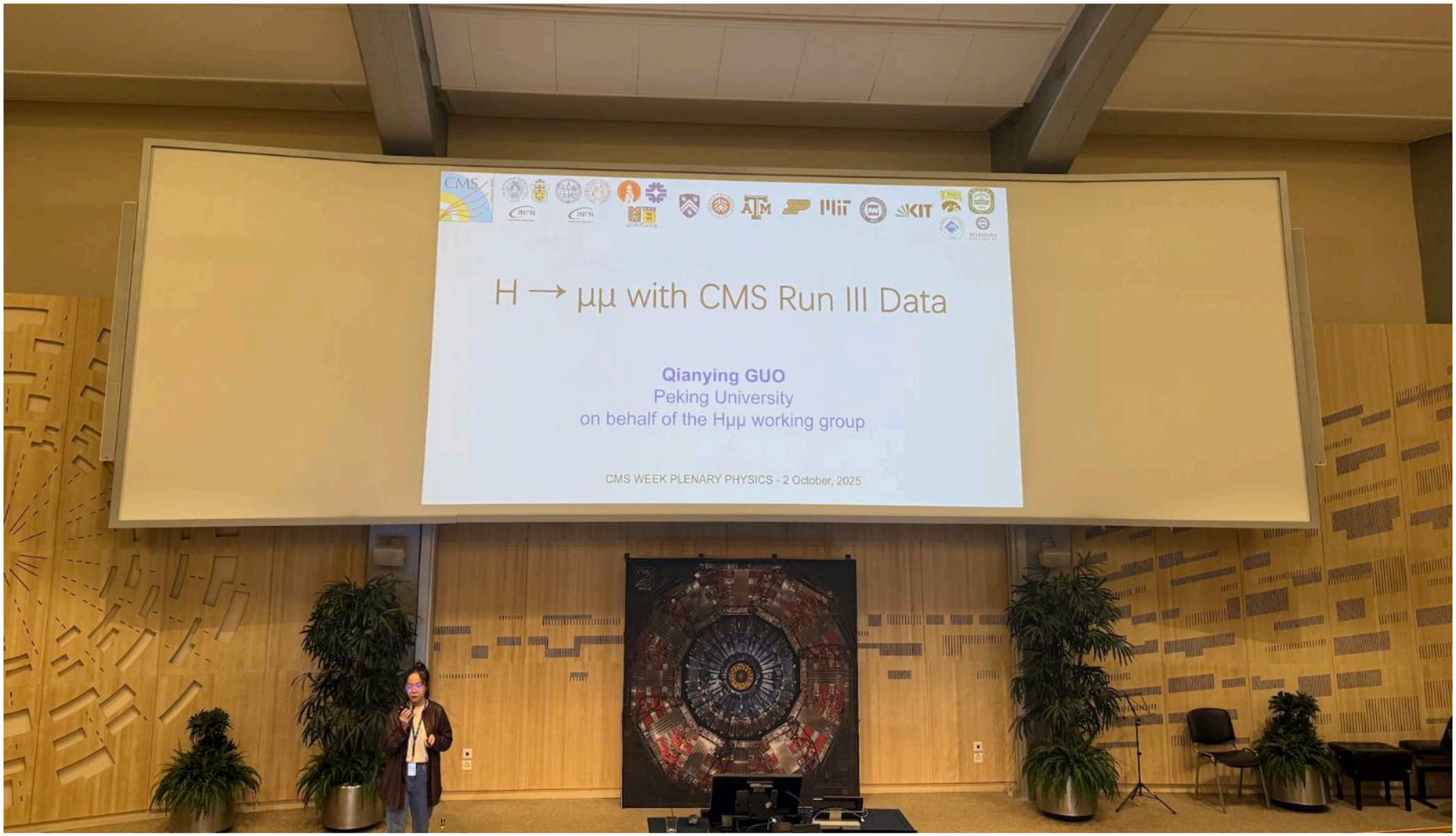
H→μμ decay



JHEP 01 (2021) 148

- The observed H→μμ significance in CMS full Run 2 result is **3.0σ** (expected 2.5σ)
- These results provide **first evidence** for the Higgs couplings to second generation fermions

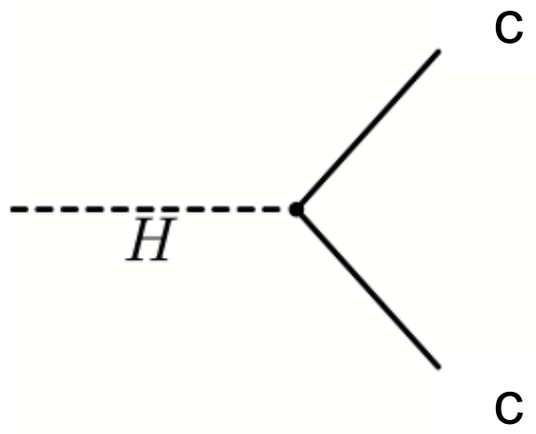
H→*μμ* decay

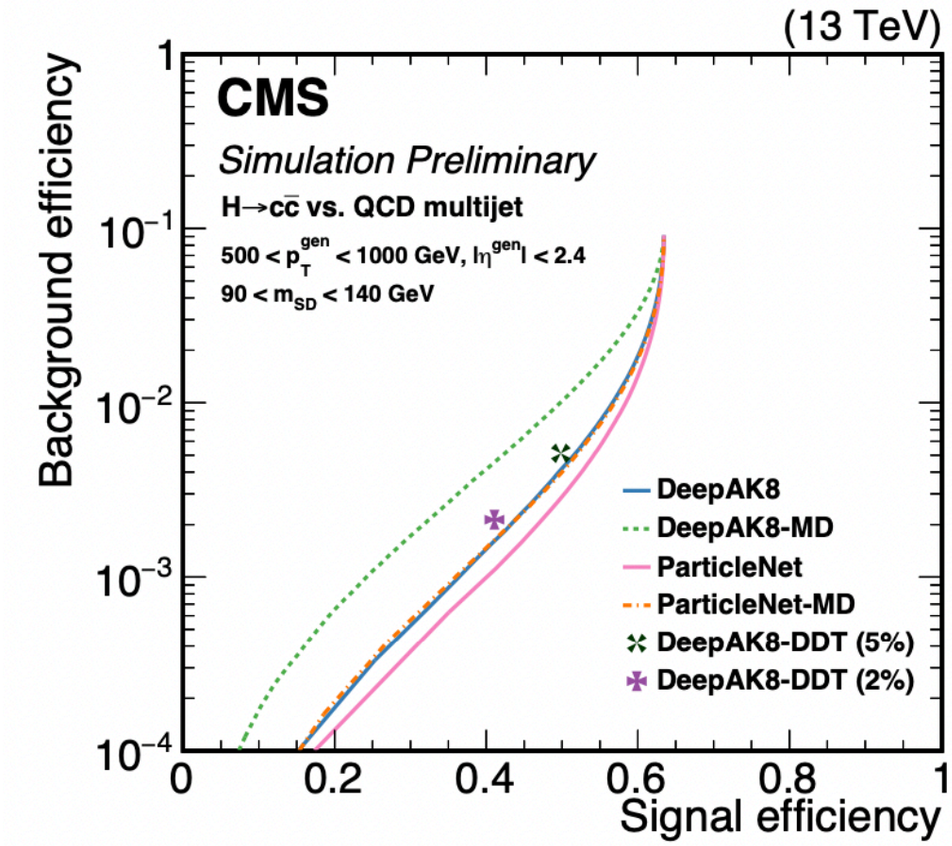


- Working on Run 3 analysis
  - hopefully observe the H→μμ decay with more than 5σ

H→cc̄ decay

- **H→cc̄ decay** is currently the main channel to probe Higgs coupling to c quarks
  - branching ratio in SM: 2.8%





CMS-DP2020/002

VH H→cc̄

- Tag leptonically decaying W/Z boson
- **Combine both resolved and boosted jet analyses**
- Boosted analysis benefits from Graph Neural Network based charm tagging (Phys. Rev. D 101, 056019 (2020), CMS-DP2020/002)
- Constraint on Higgs-charm Yukawa coupling modifier: **1.1 < |Kc| < 5.5**

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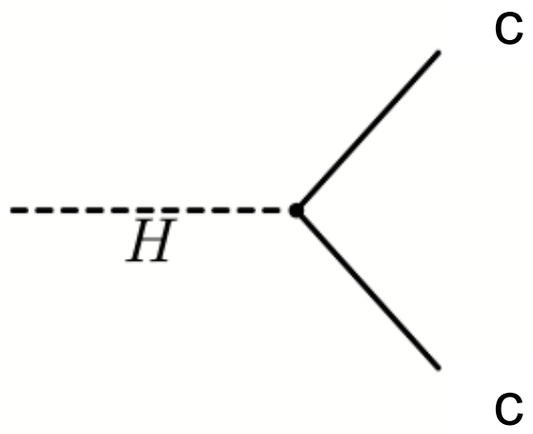
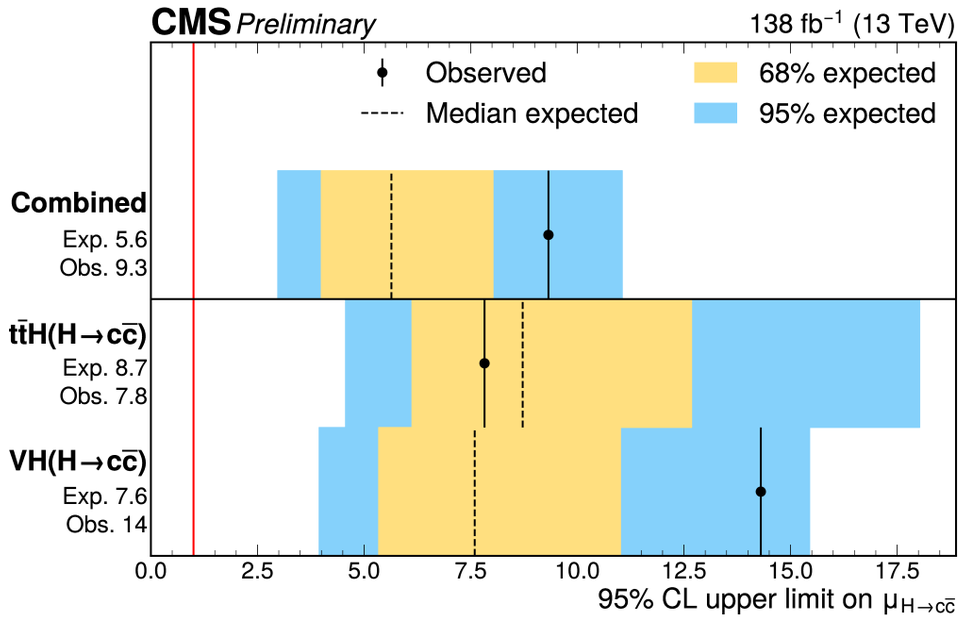




CMS-PAS-HIG-24-018

ttH H→cc̄

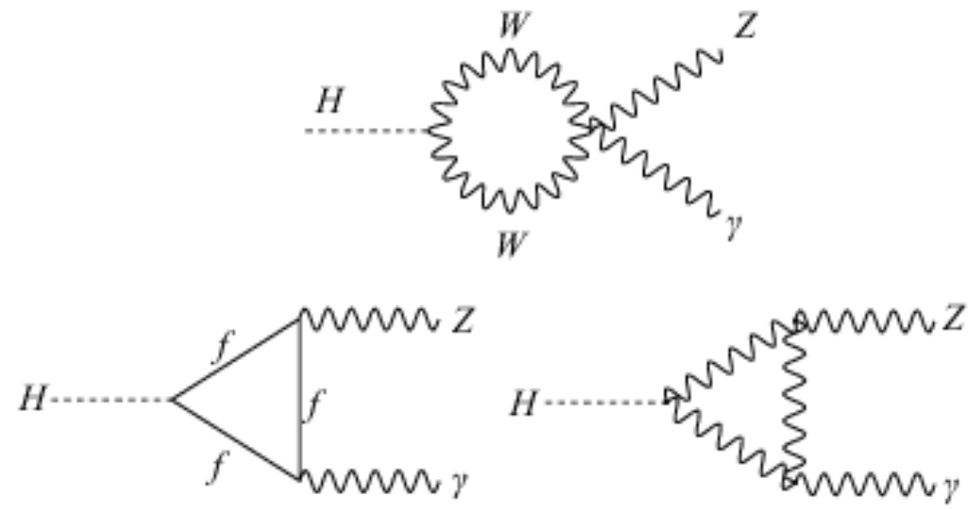
- First search for H→cc̄ in ttH production channel
  - Graph convolutional NN for simultaneous ID of b- and c-jets (PNet)
  - Multiclass event classifier-based (ParT)
- In combination with VH, most stringent constraint to date

$$|y_c/y_c^{SM}| \leq 3.5\ (2.7)\ \text{obs. (exp.)}$$

$H \to ll\gamma$

H→Zγ decay

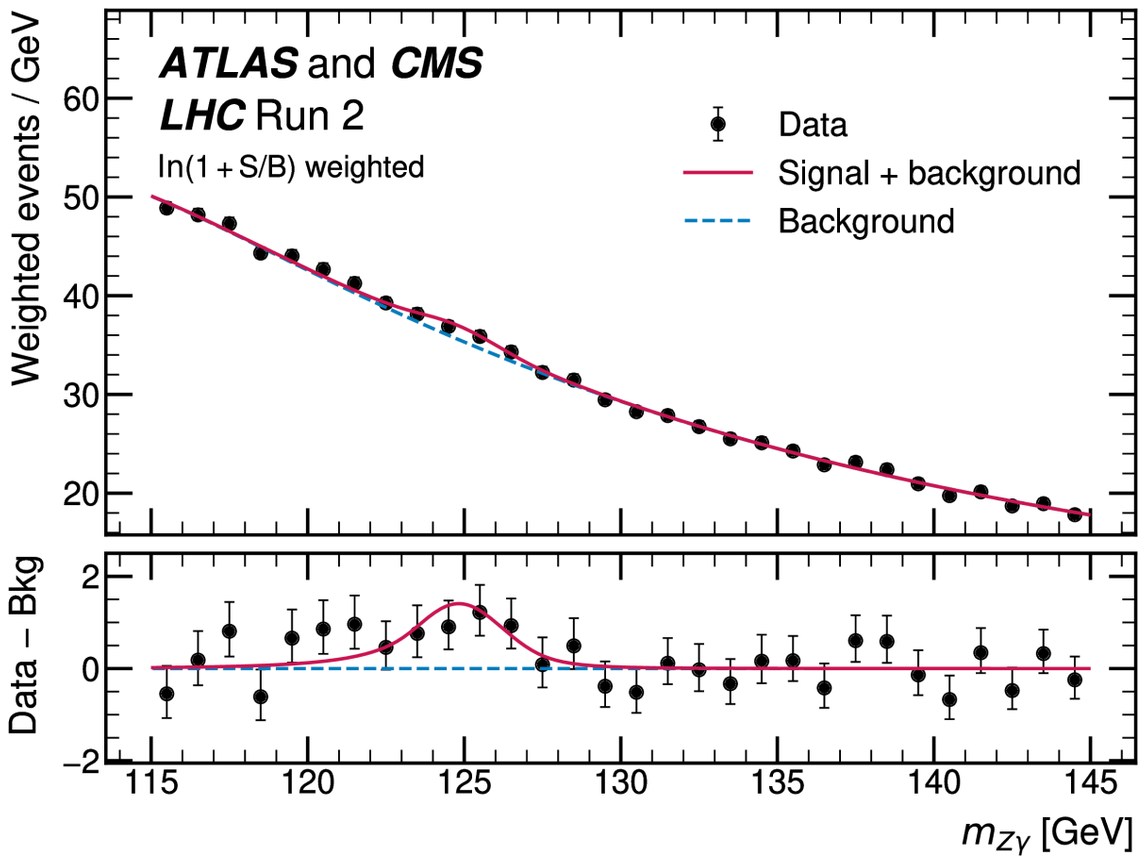
- BSM particles & couplings could be present in the quantum loops
- Difference between H→Zγ decay and H→γγ/H→ZZ decay sensitive to new physics
  - (e.g. Qing-Hong Cao et al. *Phys. Lett. B* 789 (2019) 233)
  - Small branching ratio in SM (1.6×10^{-3}); main bkg: non-Higgs Zγ, Z+jets

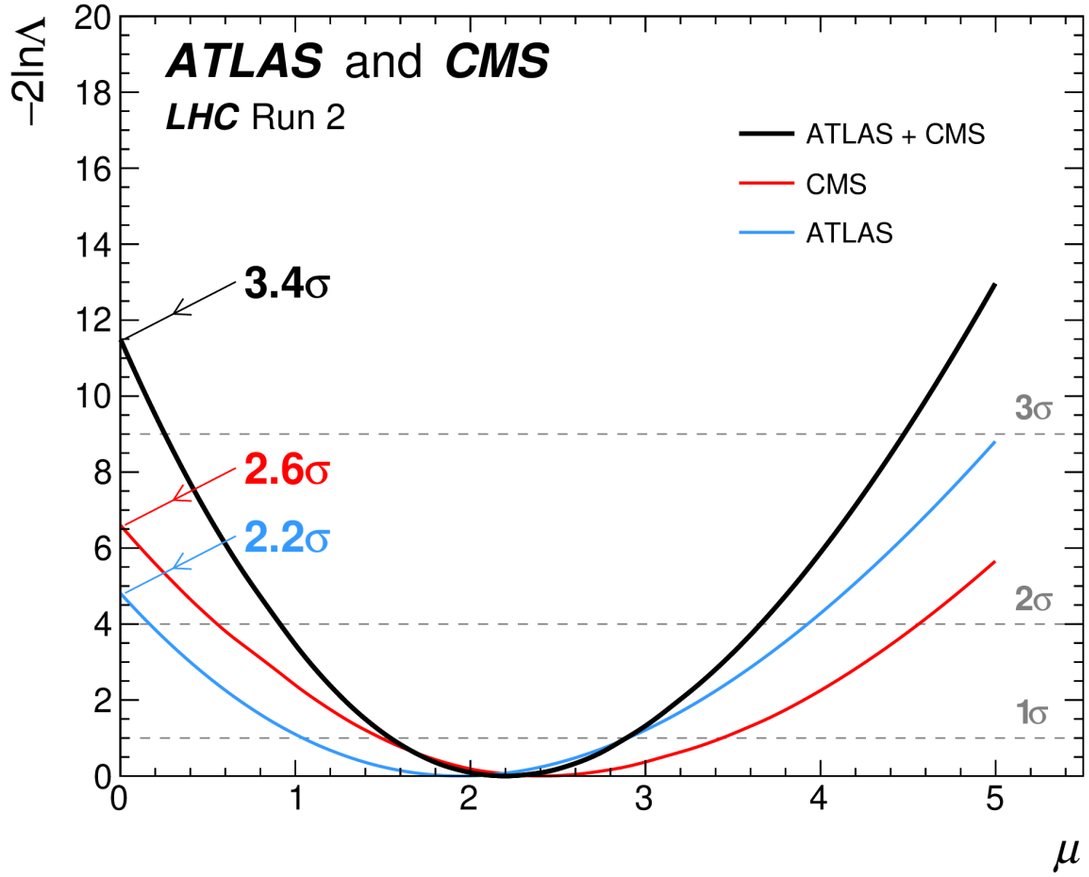


- Select events with two leptons (mll ~90 GeV) and one photon and separate them to multiple categories to target various production modes
- Fit in llγ mass distribution over all categories

H→Zγ decay

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





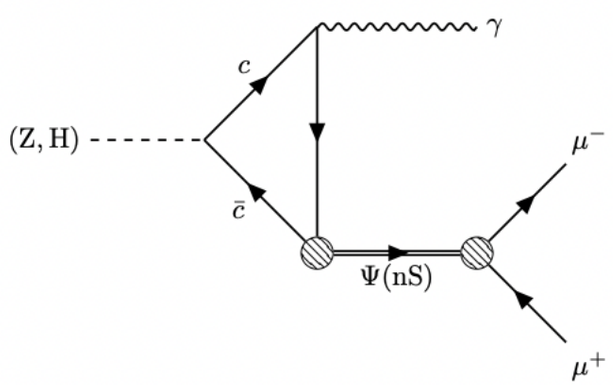
- In ATLAS+CMS combined result, the observed H→Zγ significance is **3.4σ** (expected 1.6σ)
  - **First evidence** of the H→Zγ decay
- Signal strength is 2.2 ± 0.7: agrees with theoretical expectation within **1.9σ**
- With the ongoing Run-3, we will be able to improve the precision of this rare Higgs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

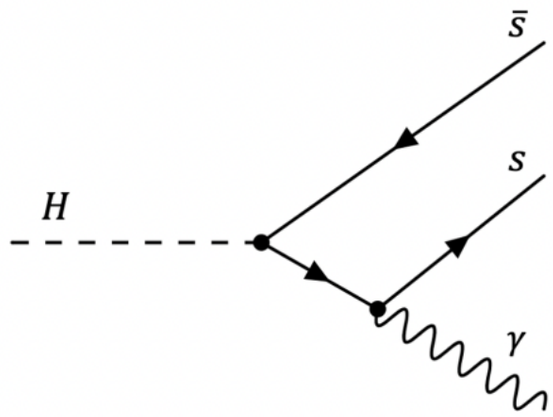
$H \to mesons$

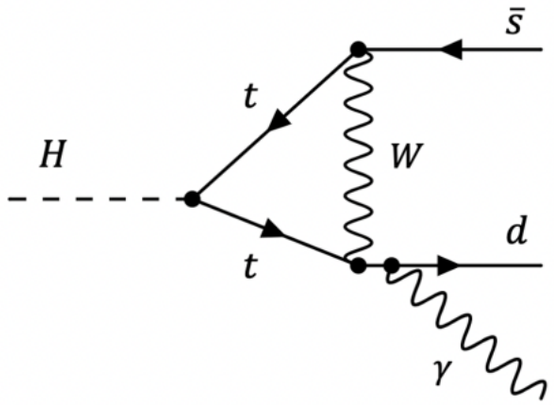
Higgs decays to mesons

- 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

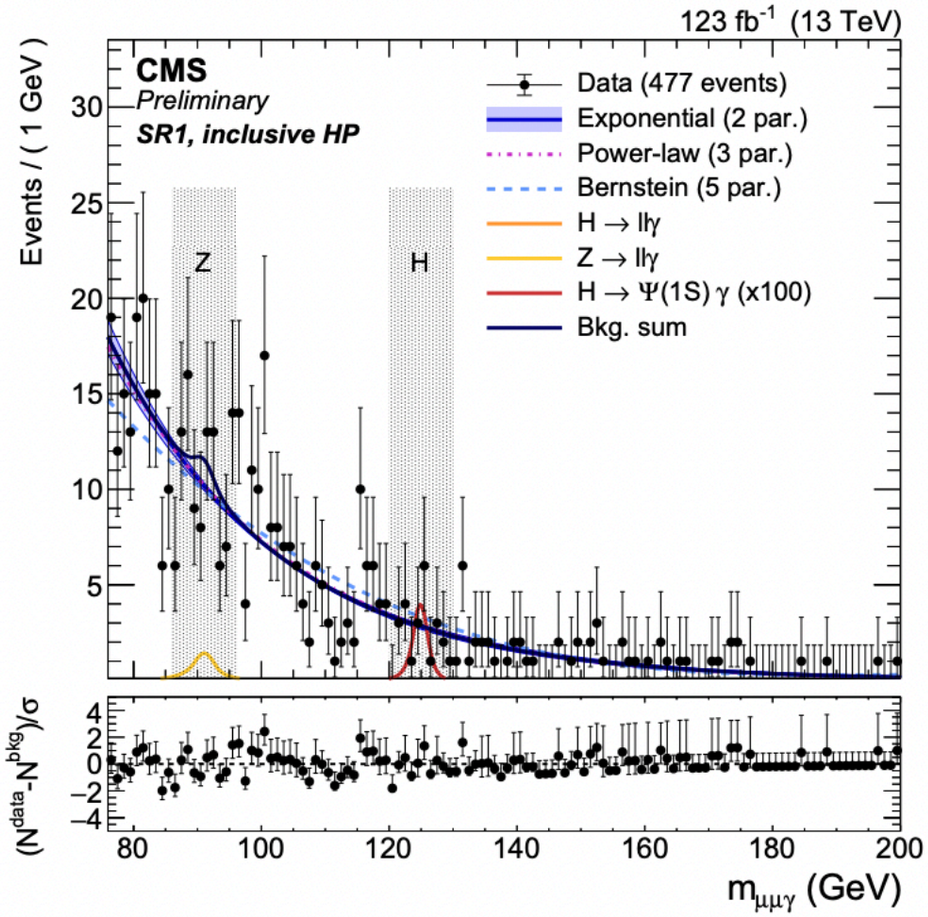






Higgs decays to heavy meson + photon

- Sensitive to Higgs boson couplings to charm quarks
- The quarkonium decays to two muons leave a clear signature inside the detectors



Process	This analysis ($123\,\mathrm{fb}^{-1}$)		
	$\mu_{obs}(\mu_{exp})$	$\sigma_{obs}(\sigma_{exp})$ [pb]	$\mathcal{B}_{obs}(\mathcal{B}_{exp})$
$Z \to \Psi(1S)\gamma$	$7.2\ \left(8.6^{+4.1}_{-2.7}\right)$	$3.8\ \left(4.4^{+1.9}_{-1.3}\right) \times 10^{-2}$	$0.6\ \left(0.7^{+0.3}_{-0.2}\right) \times 10^{-6}$
$Z \to \Psi(2S)\gamma$	$29\ \left(68^{+36}_{-22}\right)$	$8\ \left(19^{+8}_{-6}\right) \times 10^{-2}$	$1.3\ \left(3.1^{+1.4}_{-0.9}\right) \times 10^{-6}$
$H \to \Psi(1S)\gamma$	$88\ \left(62^{+30}_{-19}\right)$	$1.4\ \left(1.0^{+0.5}_{-0.3}\right) \times 10^{-2}$	$2.6\ \left(1.8^{+0.9}_{-0.6}\right) \times 10^{-4}$
$H \to \Psi(2S)\gamma$	$970\ \left(781^{+417}_{-259}\right)$	$5.5\ \left(4.4^{+2.3}_{-1.5}\right) \times 10^{-2}$	$9.9\ \left(8.0^{+4.2}_{-2.6}\right) \times 10^{-4}$

Interpretation of results in κ-framework provides constraints on κ_c / κ_γ at 95% CL

$\kappa_c / \kappa_\gamma \in$ (-157, +199) (observed)

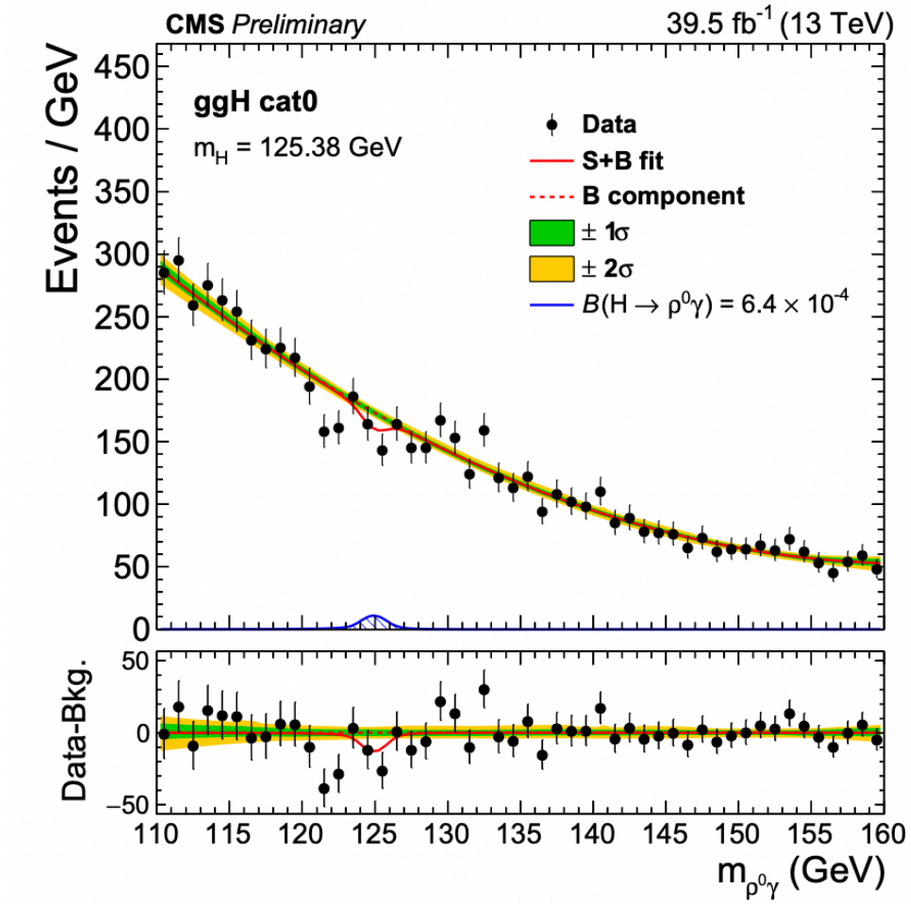
$\kappa_c / \kappa_\gamma \in$ (-121, +161) (expected)

no signal is observed

CMS-PAS-SMP-22-012

Higgs decays to light meson + photon

- Sensitive to Higgs boson couplings to light quarks and anomalous flavour-changing Higgs boson couplings
- The bounds states can decay into kaons and pions, which are reconstructed from tracks with vertex-constrained fit and have good mass resolution at low pT



	U.L. $\mathcal{B}(H \to \rho^0\gamma)$		U.L. $\mathcal{B}(H \to \phi\gamma)$		U.L. $\mathcal{B}(H \to K^{*0}\gamma)$	
category	Exp.(10^{-4})	Obs.(10^{-4})	Exp.(10^{-4})	Obs.(10^{-4})	Exp.(10^{-4})	Obs.(10^{-4})
VH	$62.3^{+25.6}_{-17.9}$	73.7	$37.3^{+16.9}_{-11.3}$	45.0	$25.3^{+11.4}_{-7.3}$	48.5
low-p_T^γ VBF	$49.6^{+22.5}_{-15.0}$	35.6	$33.1^{+18.7}_{-11.5}$	27.9	$18.8^{+8.90}_{-5.7}$	12.3
high-p_T^γ VBF	$22.9^{+10.5}_{-6.9}$	16.0	$16.0^{+9.0}_{-5.5}$	10.7	$9.13^{+4.25}_{-2.75}$	6.66
ggH	$6.01^{+2.53}_{-1.72}$	4.37	$3.08^{+1.33}_{-0.98}$	3.46	$2.20^{+0.94}_{-0.62}$	1.93
combined	$5.71^{+2.37}_{-1.63}$	3.74	$2.88^{+1.33}_{-0.83}$	2.97	$2.10^{+0.90}_{-0.58}$	1.71

Dedicated trigger for ggF category deployed in 2018, thus expected significance improvement from Run-3

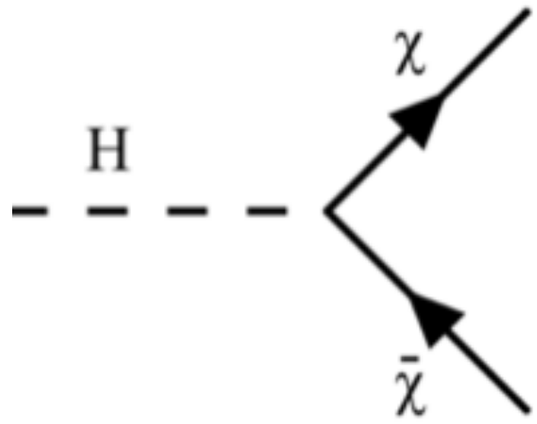
no signal is observed

CMS-PAS-HIG-23-005

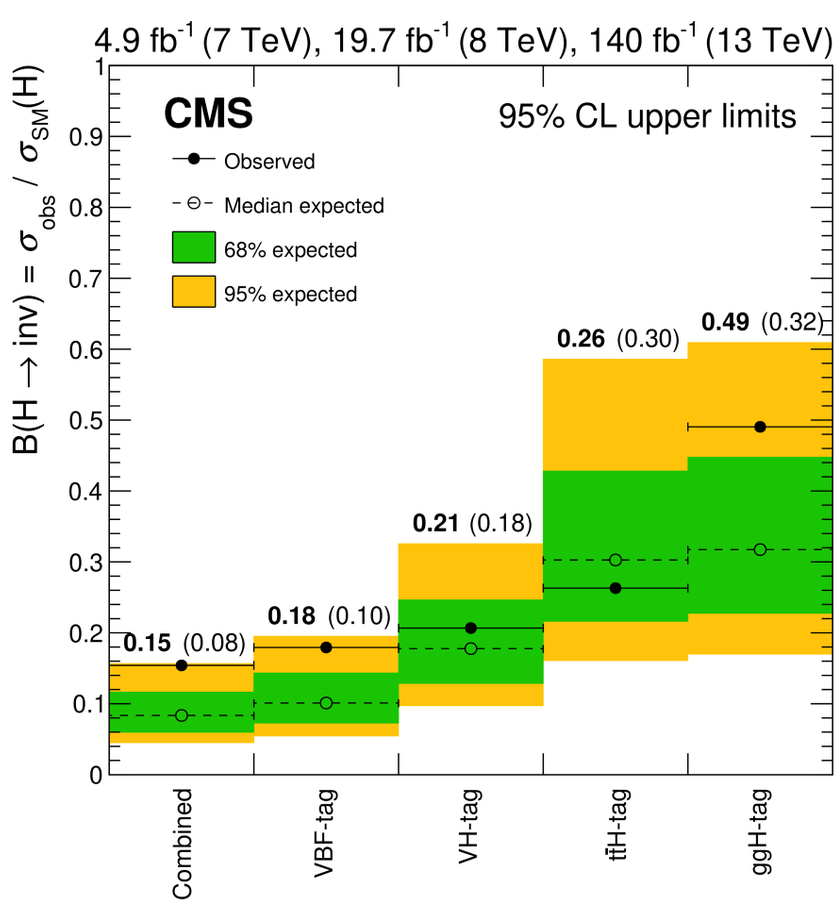
$H \to$ *invisible*

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:
  - 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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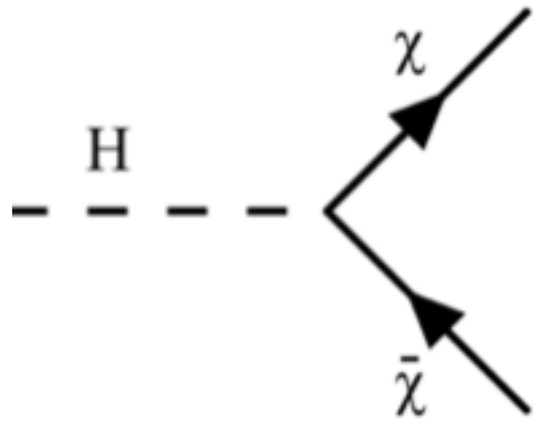

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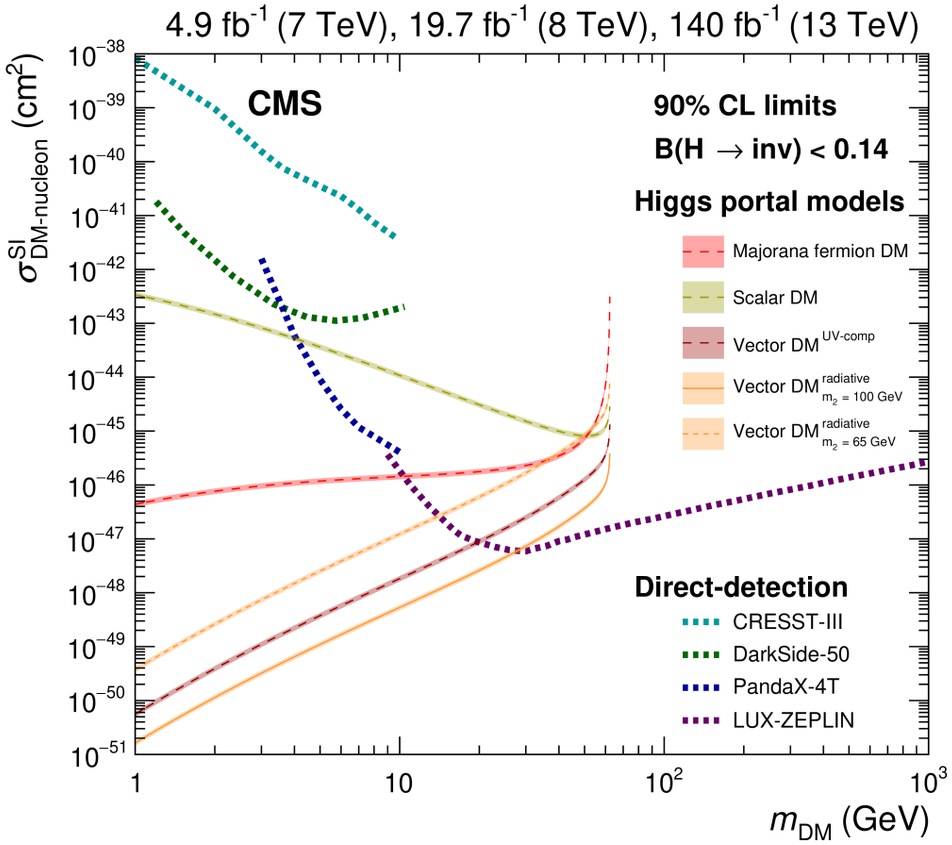
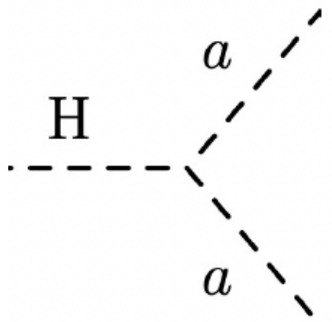


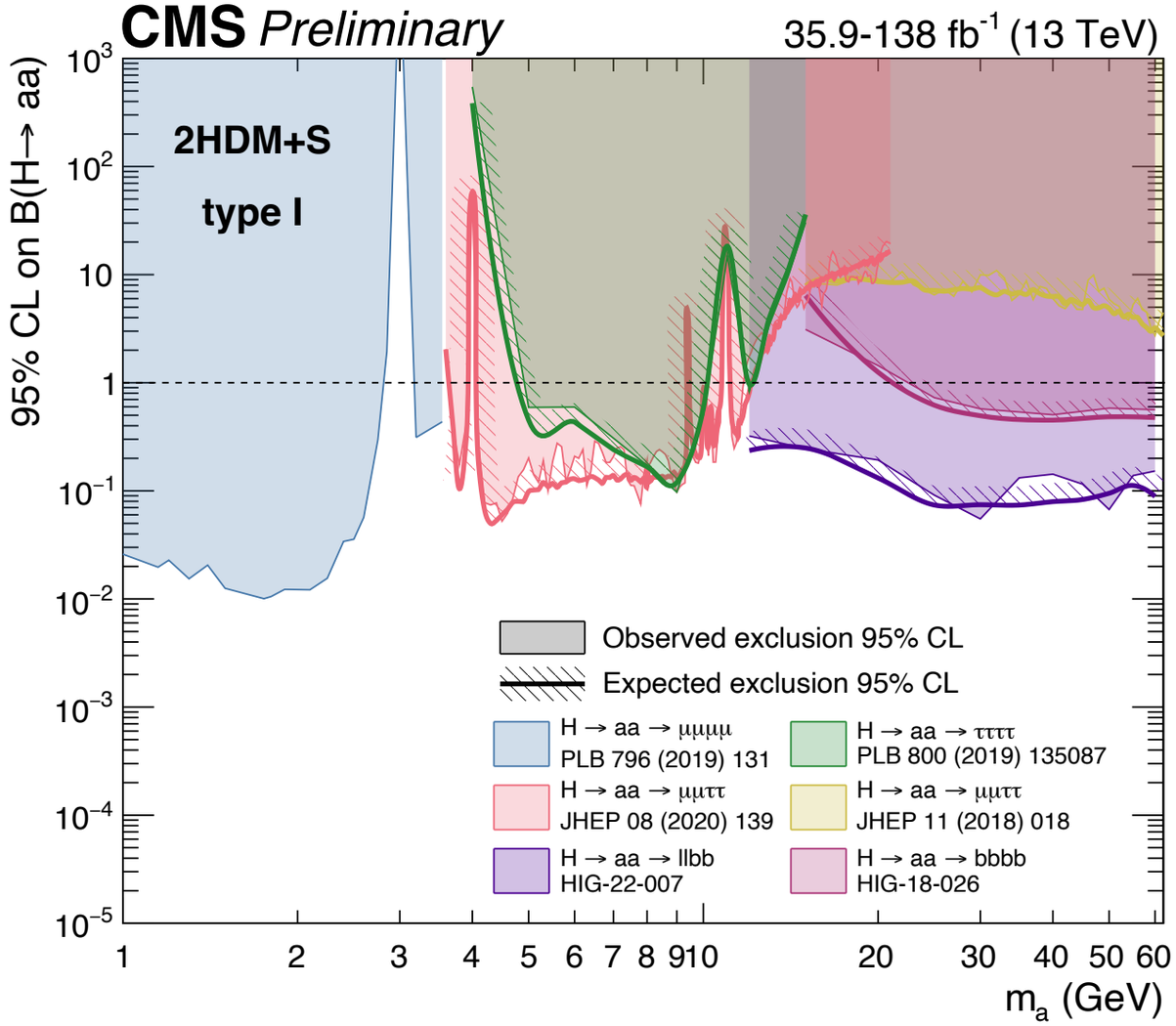
$H \to$ *pseudoscalars*

H→pseudoscalars



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

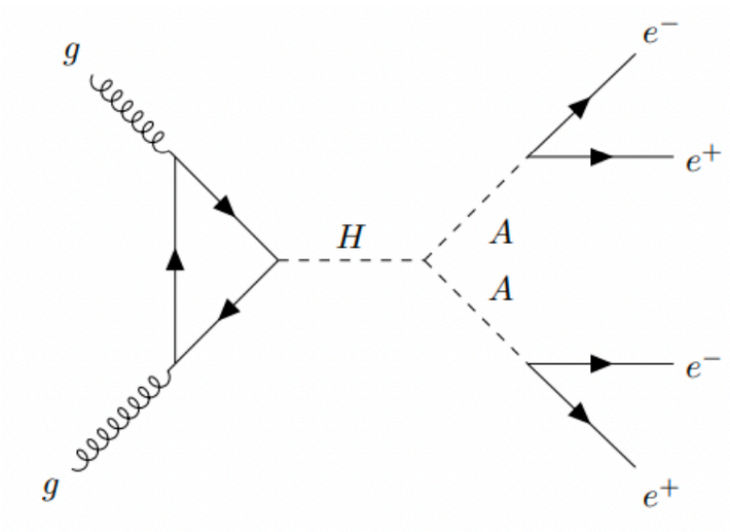
Many final states are analyzed: bbbb, bbll, llll, …

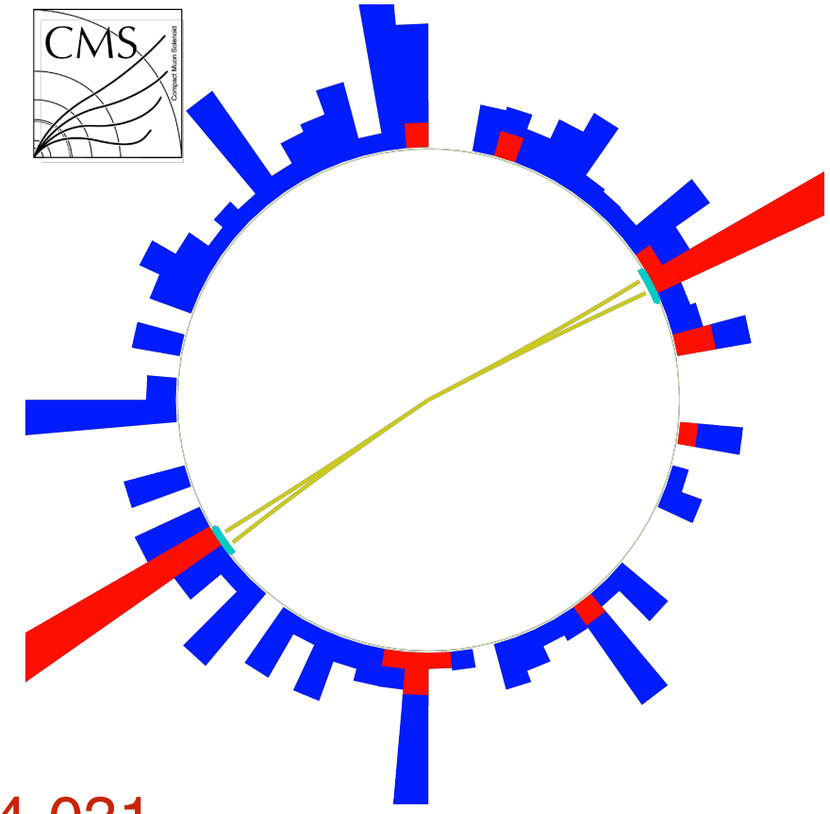


CMS Summary Plots

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





CMS-PAS-EXO-24-031

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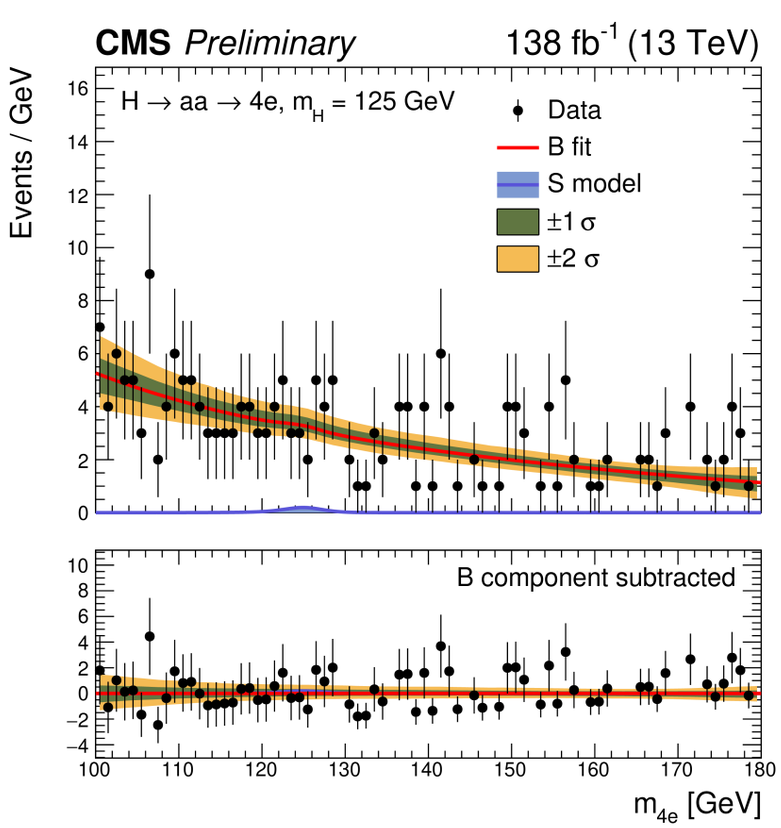
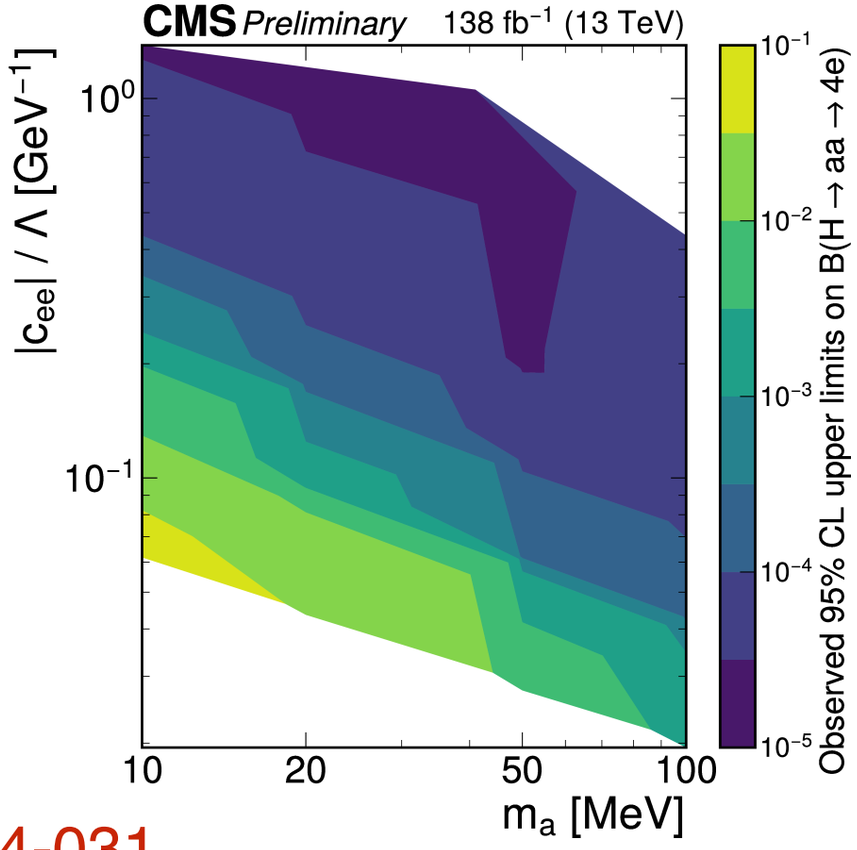
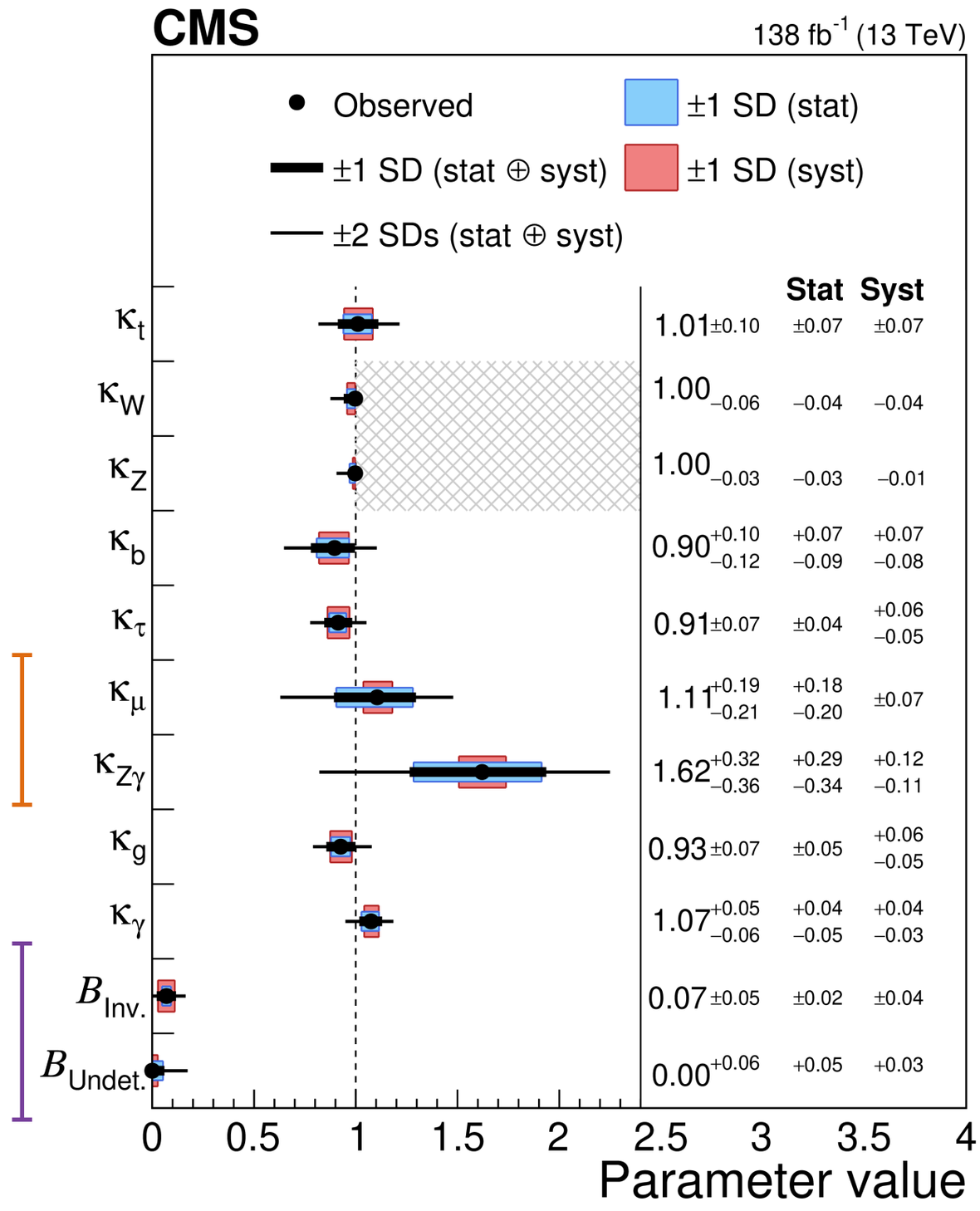




CMS-PAS-EXO-24-031

Summary

- **CMS experiment has a large program to study Higgs boson rare and exotic decays and keep improving sensitivities**
  - Results are so far consistent with the SM predictions
  - First evidence of H→μμ and H→Zγ
  - etc.
- **Run 3 is ongoing and HL-LHC is coming. Stay tune for the new results!**



Nature 607 (2022) 60-68

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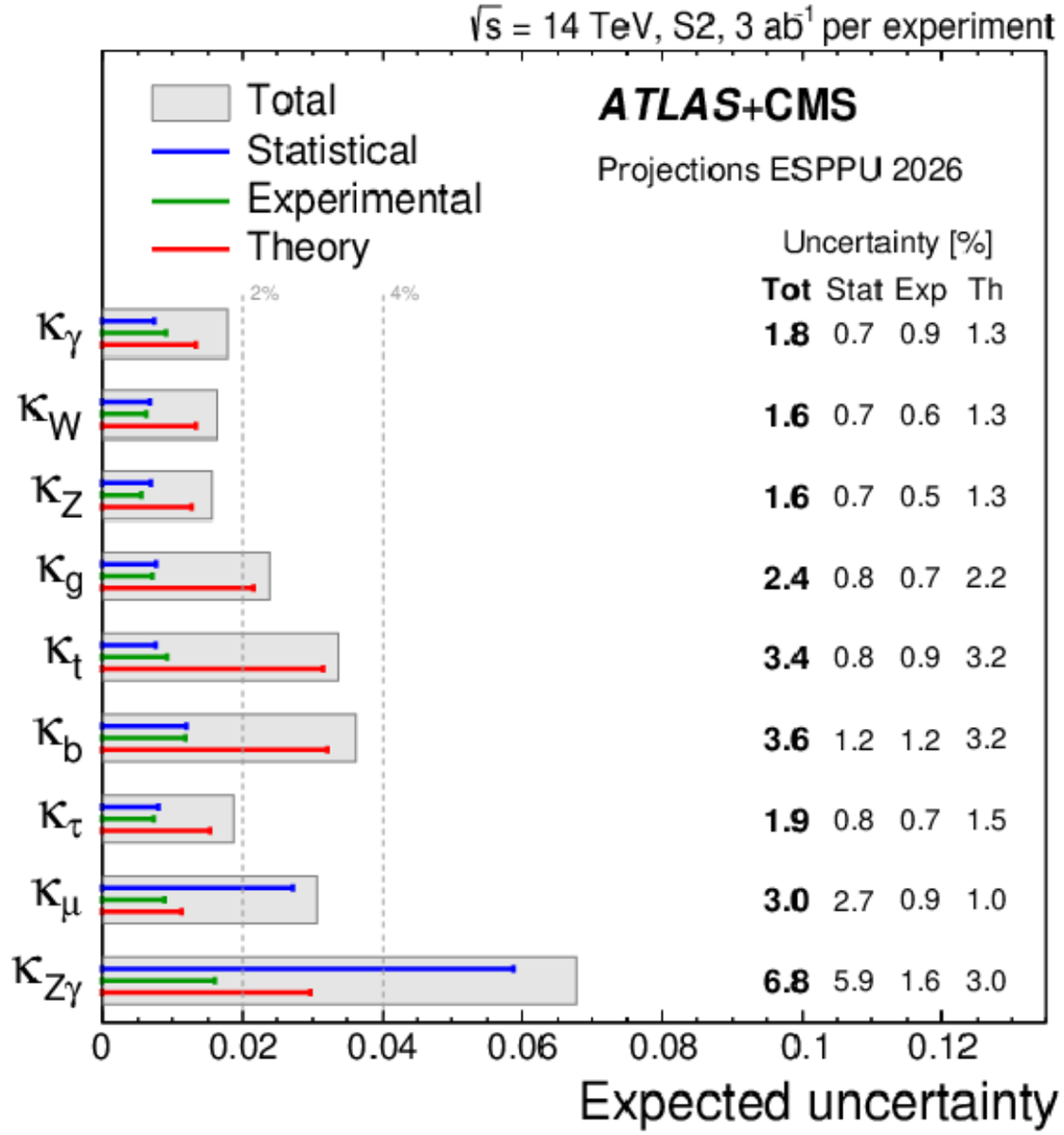


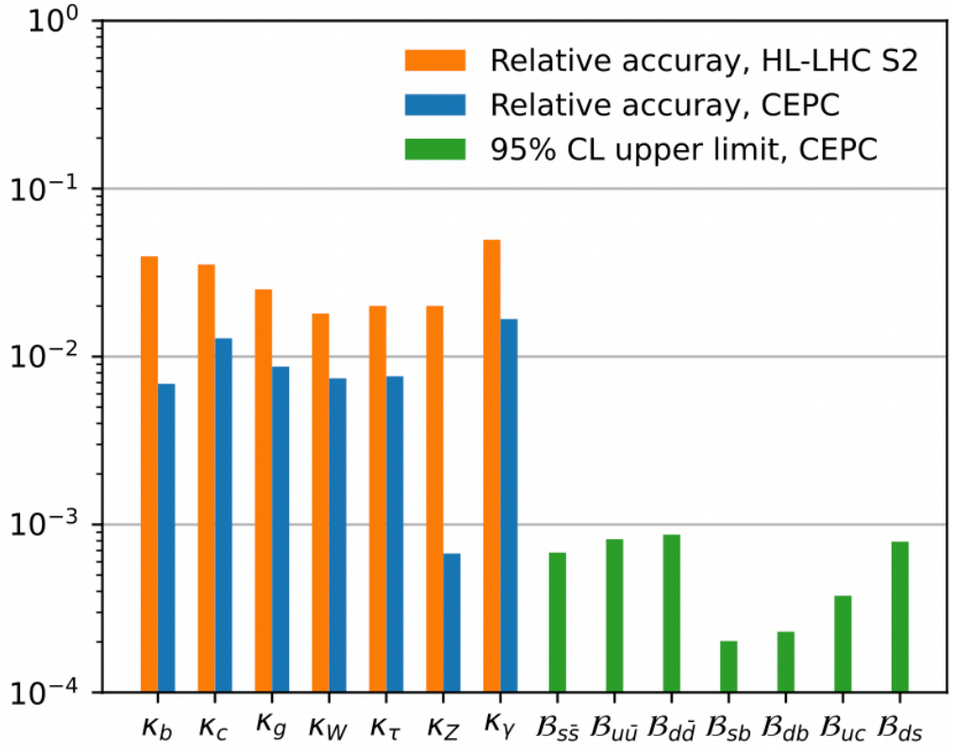
arxiv:2504.00672

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



Phys. Rev. Lett. 132 (2024) 221802

Thank you!