Summary of (Recent) Exotic Higgs Decays Results

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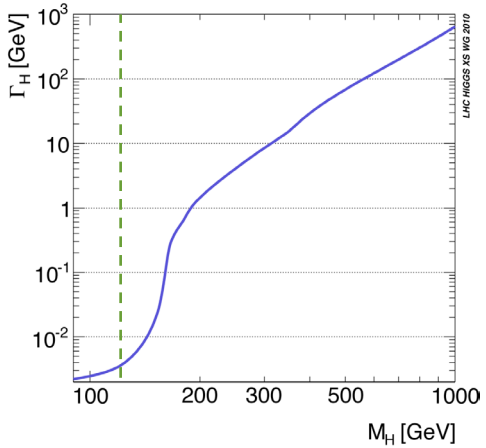
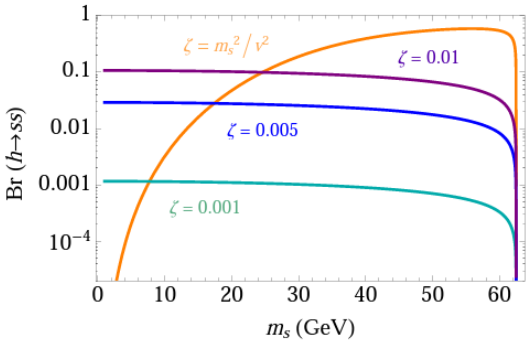
with inputs from **Brian Schuve, Alexis Kalogeropoulos** and **Verena Martinez**

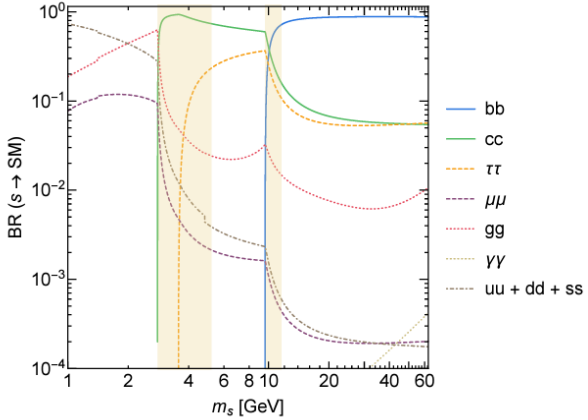
The 19th Workshop of the LHC Higgs Workshop Nov 28th, 2022

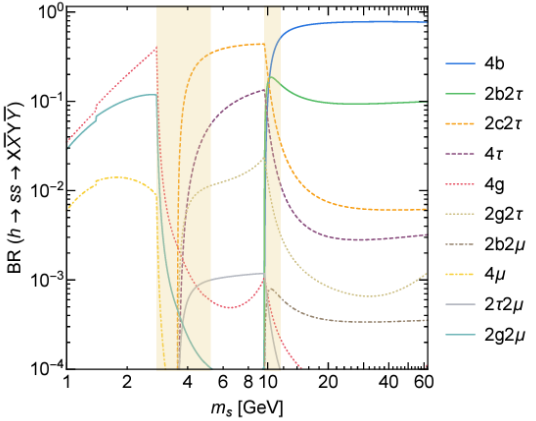
Exotic Higgs decays





- The Higgs boson has a very small total width.
- Even very weakly-coupled new particles can generate sizable $H \to ss$ branching ratios to **new low-mass particles**.
- Mixing with Higgs boson generates $H \to ss \to X\bar{X}Y\bar{Y}$ decays.
- Decays to CP-odd scalars $H \to aa$ common in ALP models.





Figures from Curtin D. et al., Exotic Decays of the 125 GeV Higgs Boson [Phys. Rev. D 90, 075004 (2014)]

The landscape of exotic Higgs decays

$H \to aa, a \to XX, a \to YY$

XX / YY	ee	$\mu\mu$	$\tau\tau$	bb	gg	$\gamma\gamma$
ee						
$\mu\mu$						
$\tau\tau$						
bb						
gg						
$\gamma\gamma$						

Many searches not available with full Run 2 dataset.

CMS	Full Run 2
	Partial Run 2
ATLAS EXPERIMENT	Full Run 2
	Partial Run 2

These tables are about Run 2 only. Many analyses also available with Run 1 data.

$H \to a + E_{\mathrm{T}}^{\mathrm{miss}}, a \to XX$

XX	$E_{\mathrm{T}}^{\mathrm{miss}}$	γ	bb

$H \to Za, a \to XX$

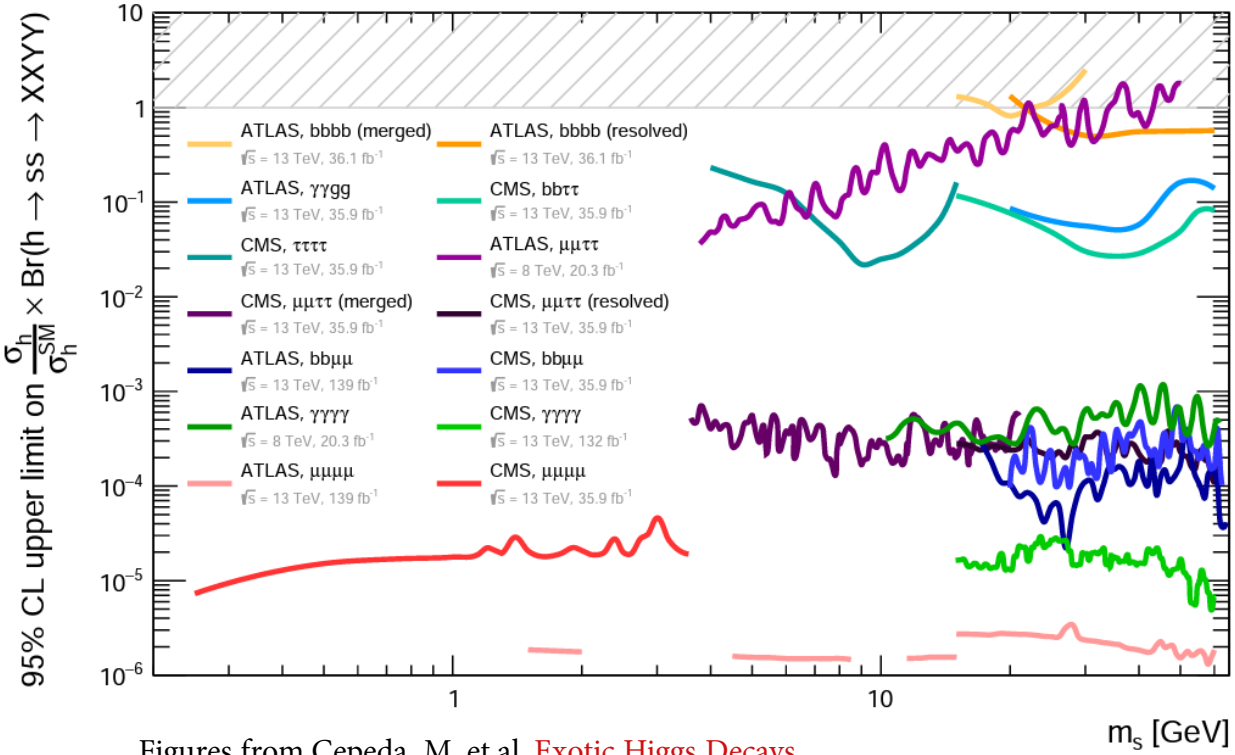
XX	ee	$\mu\mu$	gg	ss

And even when full analyses are available:

- Not all mass spectrum explored
- Not all production modes explored

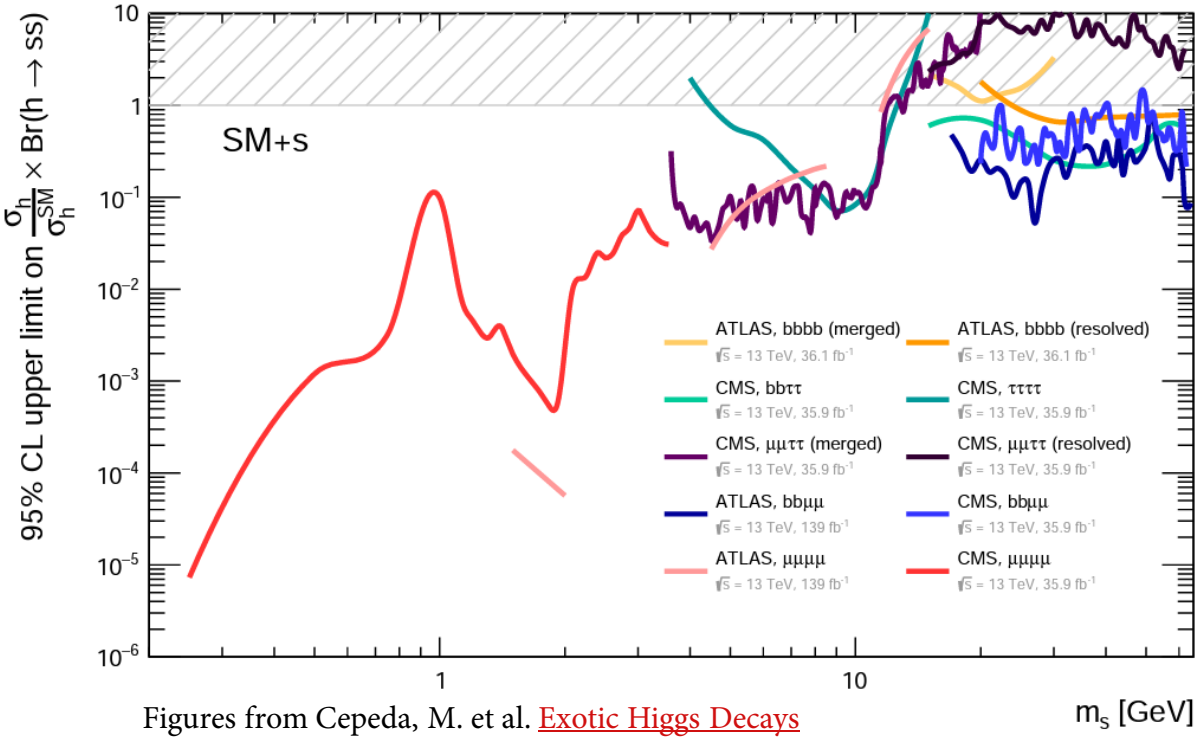
There is still a lot of power in Run 2 data that hasn't been explored yet!

Recent $H \rightarrow ss \rightarrow XXYY$ results



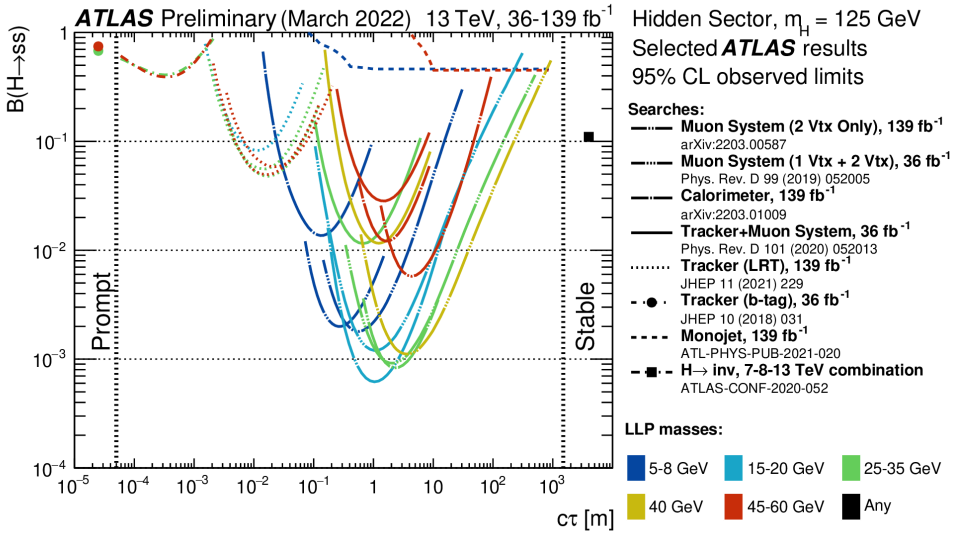
Figures from Cepeda, M. et al. Exotic Higgs Decays
[Annual Review of Nuclear and Particle Science, Volume 72, 2022]

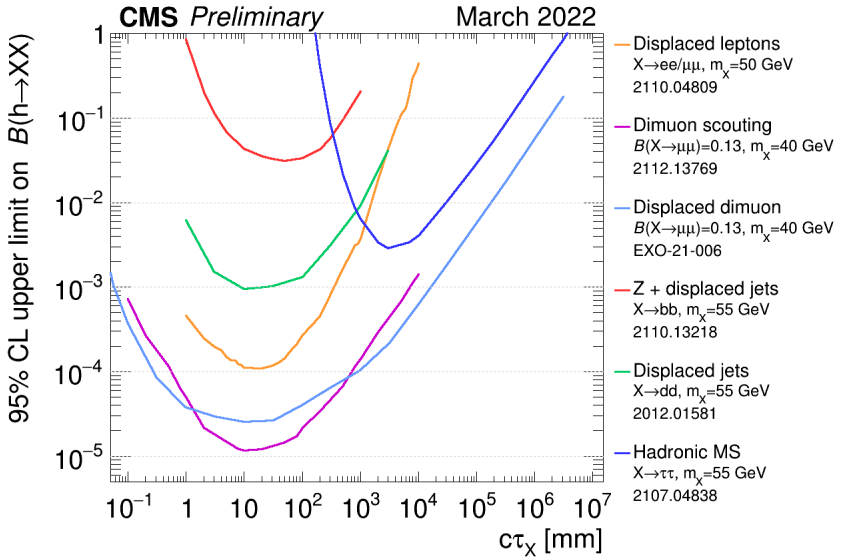
Interpreting result in SM+s model



Figures from Cepeda, M. et al. Exotic Higgs Decays
[Annual Review of Nuclear and Particle Science, Volume 72, 2022]

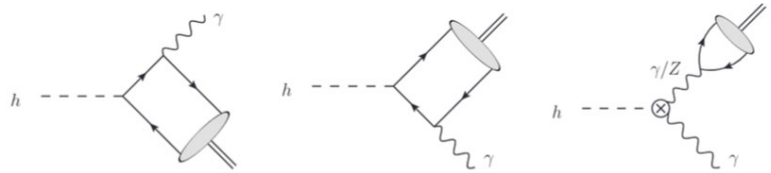
Exotic Higgs decays to long-lived particles





These analyses are more challenging to categorize.
Different final states can have similar signatures in the detectors.
Experimental searches rely on many different techniques depending on $c\tau$.

Many other possibilities



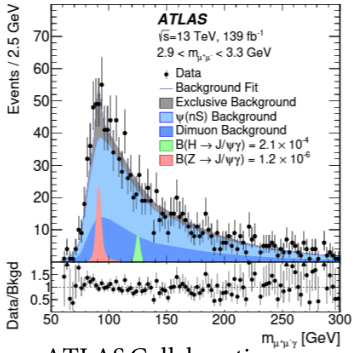
Decays to meson + photon

- $H \to J/\psi$ or $\Upsilon + \gamma$

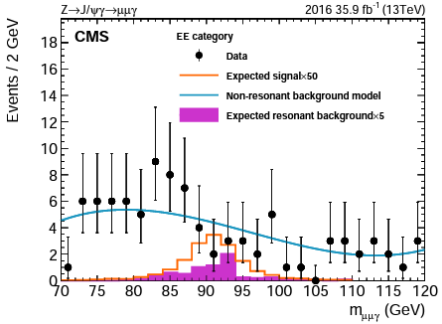
See talk by R. Ward

Other mesons can be probed, for instance:

- $H \to D$ or $K_s + \gamma$ (flavor violation)



ATLAS Collaboration,
Eur. Phys. J. C 79 (2019)94

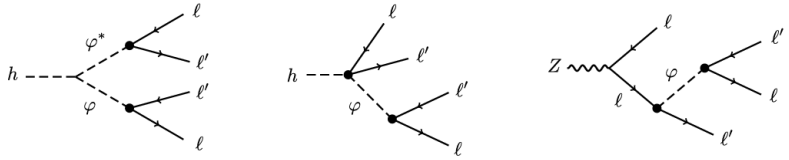


CMS Collaboration,
Eur. Phys. J. C 79 (2019)94

Flavor violating Higgs decays

- $H \to e\mu, H \to e\tau, H \to \mu\tau$
- $H \to cs$

We can also consider flavor-violating decays of the low-mass scalars [Evans et al, arXiv:1910.07533]:



The landscape of exotic Higgs decays is very vast and this talk will try to focus on the most recent results…

Snowmass 2021

- Several contributions related to exotic Higgs decays at Snowmass showing the continued interest in the field [link to contributions]
  - EF02: Higgs boson as a portal to new physics
  - EF10: Beyond the Standard Model: dark matter at colliders

Higgs portal vector dark matter interpretation: review of Effective Field Theory approach and ultraviolet complete models

Mohamed Zaazoua [1], Loan Truong [2], Kétévi A. Assamagan [3], Farida Fassi [1]

[1] *Mohammed V University in Rabat, Faculty of Science*
[2] *University of Johannesburg, Department of Mechanical Engineering Science*
[3] *Brookhaven National Laboratory (BNL)*

Study of Electroweak Phase Transition in Exotic Higgs Decays at the CEPC

Zhen Wang,[a,b,g] Xuliang Zhu,[a,b] Elham E Khoda,[f] Shih-Chieh Hsu,[f] Nikolaos Konstantinidis[h] Ke Li,[f] Shu Li,[a,b,e,i] Michael J. Ramsey-Musolf,[a,b,c,d] Yanda Wu,[a,b] Yuwen E. Zhang[h]

A short overview on low mass scalars at future lepton colliders - Snowmass White Paper

Tania Robens[1,2,*]

[1] *Ruder Boskovic Institute, Bijenicka cesta 54, 10000 Zagreb, Croatia*
[2] *Theoretical Physics Department, CERN, 1211 Geneva 23, Switzerland*

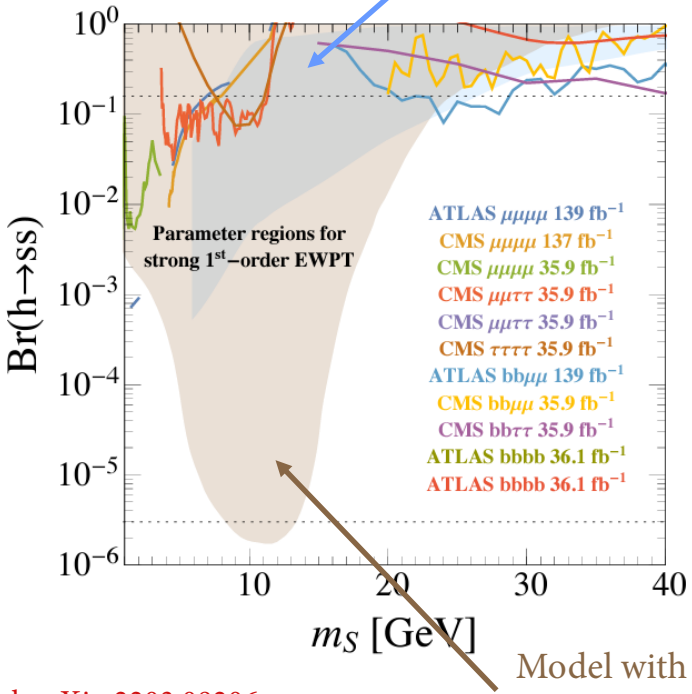
(Dated: March 17, 2022)

Probing the Electroweak Phase Transition with Exotic Higgs Decays

Marcela Carena,[1,2,3] Jonathan Kozaczuk,[4] Zhen Liu,[5] Tong Ou,[2] Michael J. Ramsey-Musolf,[6,7,8] Jessie Shelton,[9] Yikun Wang,[10] and Ke-Pan Xie[11]

Strong first order EW phase transition

Model with $s - H$ mixing with $\sin\theta = 0.01$ from Kozaczuk et al. [Phys. Rev. D 101, 115035 (2020)]



Probing the Electroweak Phase Transition with Exotic Higgs Decays

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- Models of SFOEWPT with $m_s > 25$ GeV are disfavored by LHC searches
- Region $10 < m_s < 25$ GeV can be probed with $H \to ss \to bbbb$ and $H \to ss \to bb\tau\tau$
- Region with $m_s < 10$ GeV can be probed with $H \to ss \to \tau\tau\tau\tau$ and $H \to ss \to \tau\tau\mu\mu$

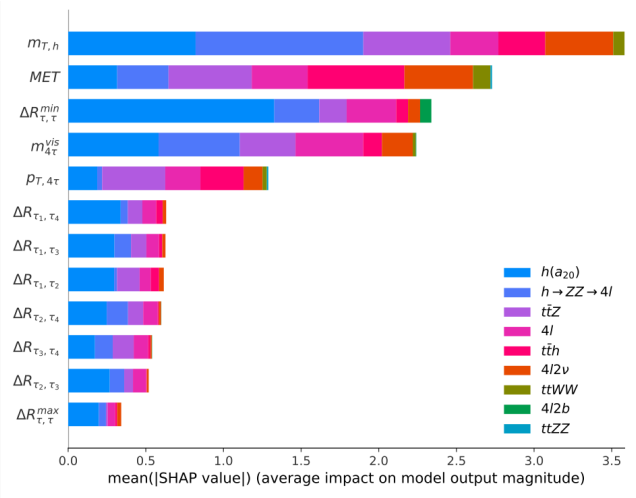
Carena, M. et al. arXiv:2203.08206

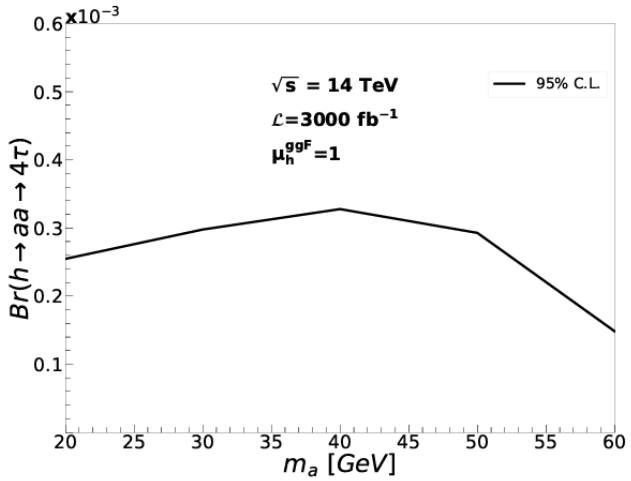
Model with Z_2 symmetry spontaneously broken by Carena et al. [arXiv:2210.14352]

Future $H \to aa \to \tau\tau\tau\tau$ searches

- Renewed interest in the $H \to aa \to 4\tau$
- Phenomenology works trying to understand future reach of this channel

Adhikary, A. et al, arXiv:2211.07674





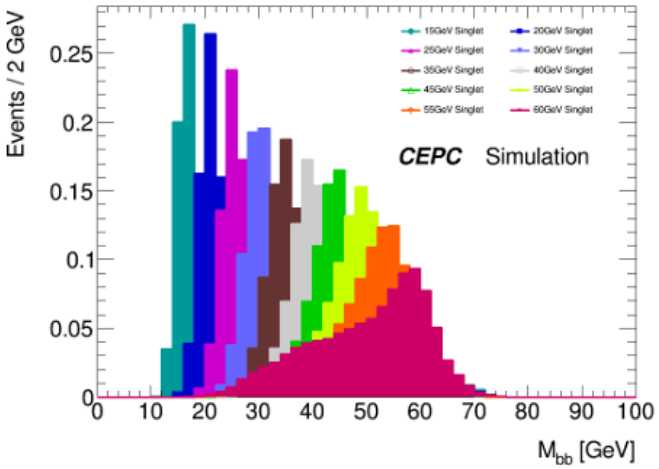
Caveats:

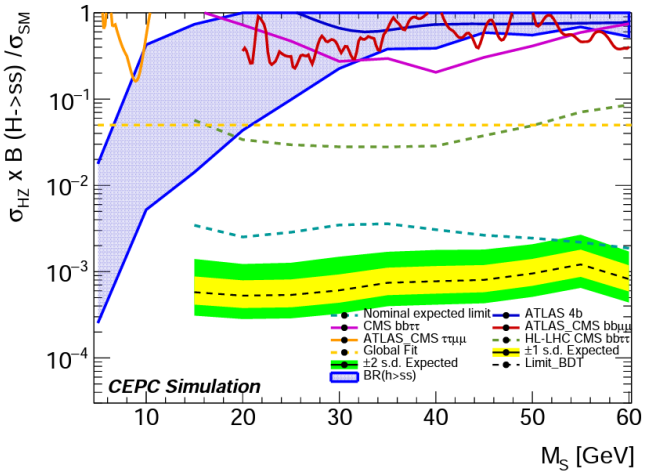
No fake background

Final state at low m_a becomes merged and require dedicated reconstruction

Future $H \rightarrow aa \rightarrow bbbb$ searches

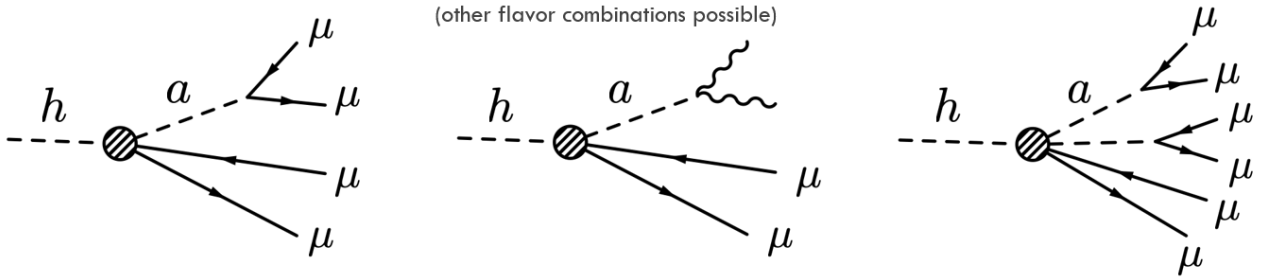
Wang, Z. et al. arXiv:2203.10184





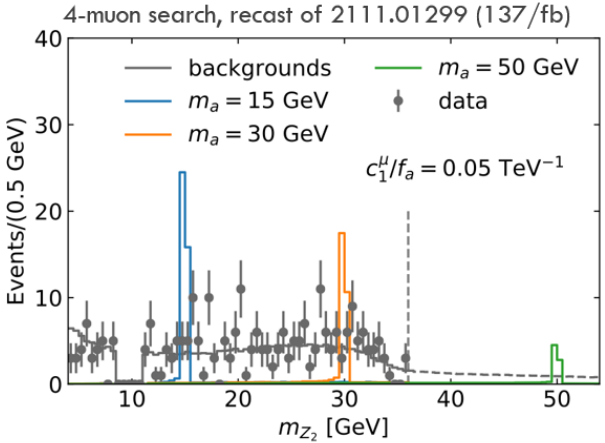
Exotic Higgs decay searches in future Higgs searches will be able to probe a very large region of the phase space favored by SFOEWPT.

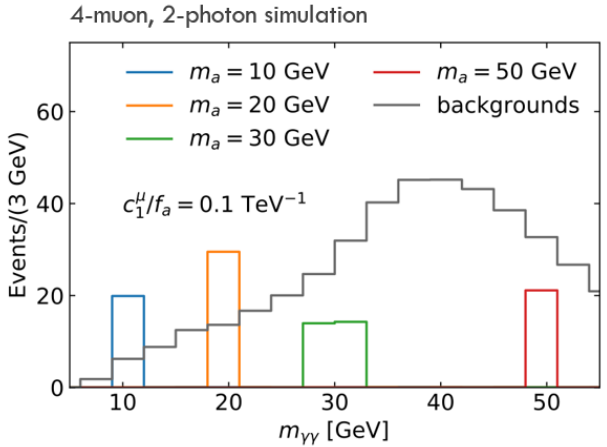
New exotic Higgs decays to ALP



Biekötter A. et al.
Phys.Lett.B 834 (2022) 137465

Higher dimension ALP operators can allow $H \to a\bar{f}f$ and $H \to aa\bar{f}f$
Signal can be probed via multi-lepton searches. Here a recast of the CMS $Z_d Z_d \to 4\ell$ search

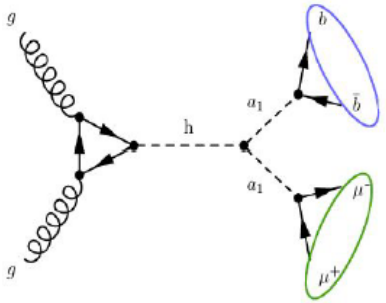




Recast of
CMS Collaboration,
Eur. Phys. J. C 82 (2022) 290

Search for $H \to aa \to bb\mu\mu$

See talk by E. Khazaie

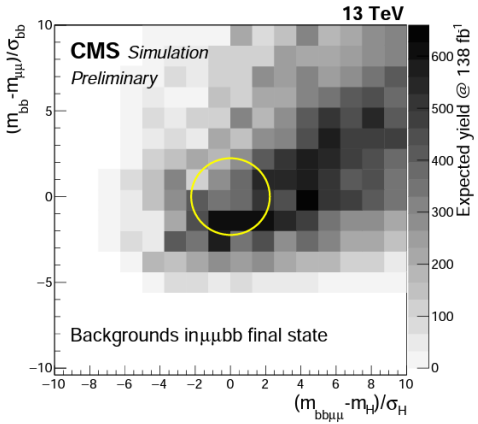


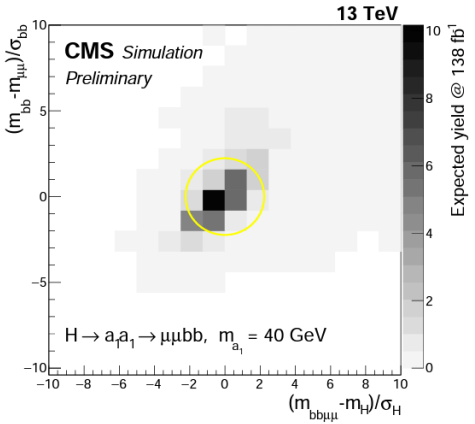
$a \to \mu\mu$: Benefit from excellent μ mass resolution

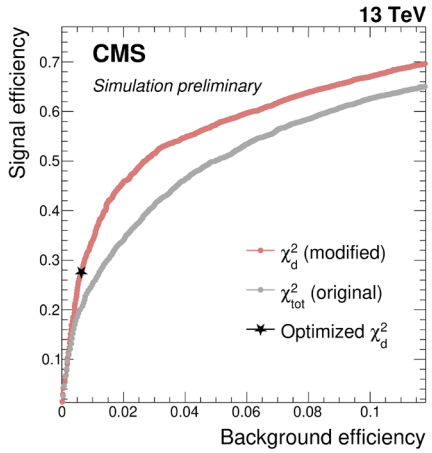
$a \to bb$: large BR in many parts of the parameter space

Use low p_T jets ($p_T > 15$ GeV) to increase acceptance.

CMS Collaboration, CMS-PAS-HIG-21-021







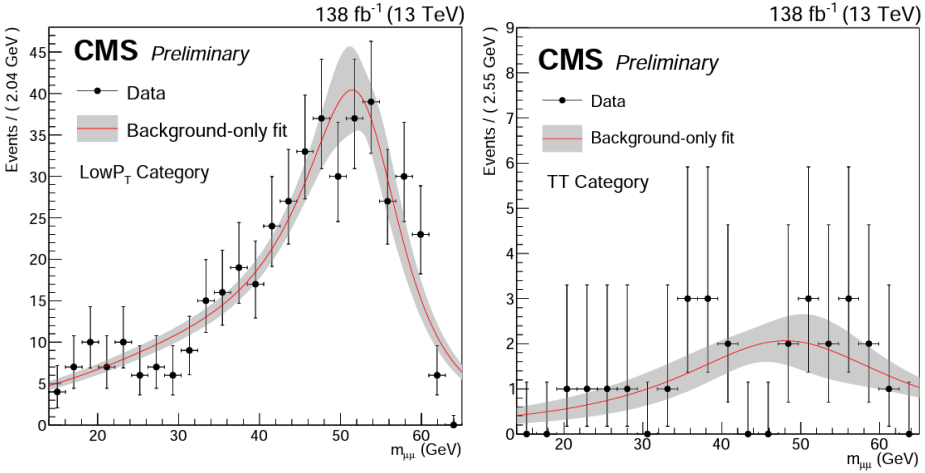
Select events based on mass compatibility

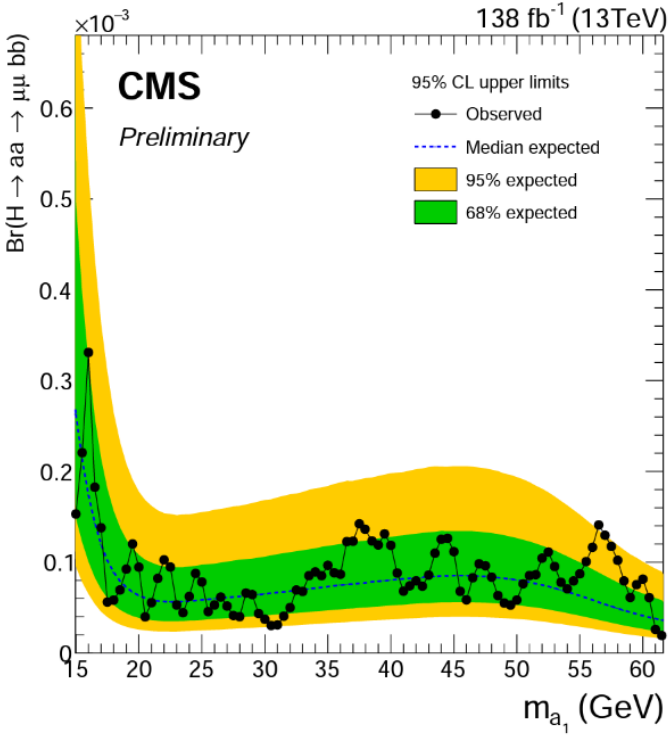
$$\chi^2_{bb} = (m_{bb} - m_{\mu\mu})/\sigma_{bb}$$

$$\chi^2_H = (m_{bb\mu\mu} - m_H)/\sigma_H$$

after decorrelating the two variables.

Search for $H \rightarrow aa \rightarrow bb\mu\mu$



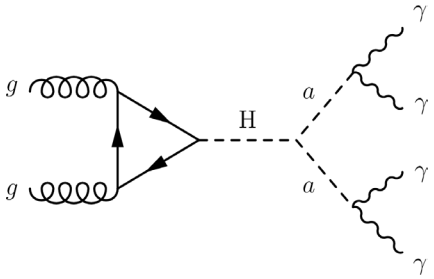


Search for a narrow peak in the $m_{\mu\mu}$ distribution

Signal categorization: LowPt, VBF, TT, TM, TL

Compatible with ATLAS result, no excesses.

Search for $H \to aa \to 4\gamma$

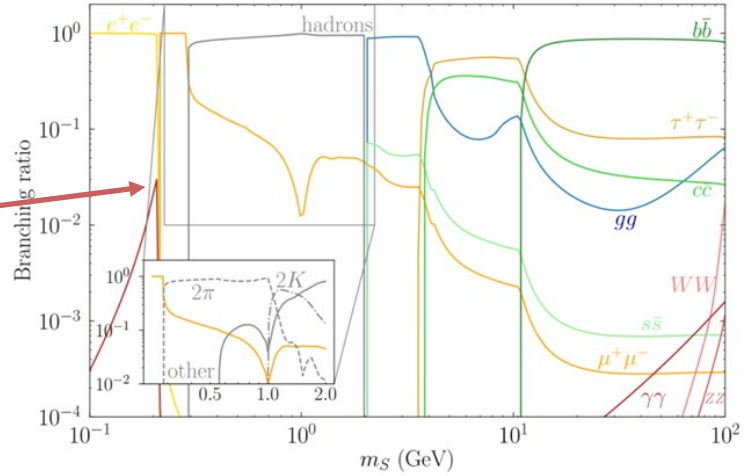


Fully resolved: $15 < m_a < 62$ GeV
CMS Collaboration, CMS-HIG-21-003, Accepted by JHEP

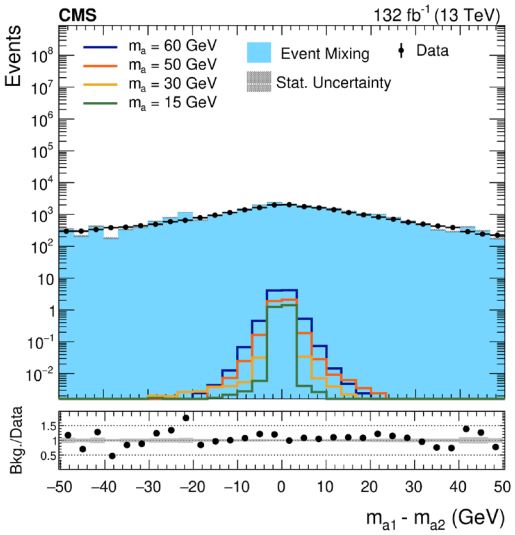
Fully merged: $0.1 < m_a < 1.2$ GeV
CMS Collaboration, CMS-HIG-21-016, Submitted to PRL

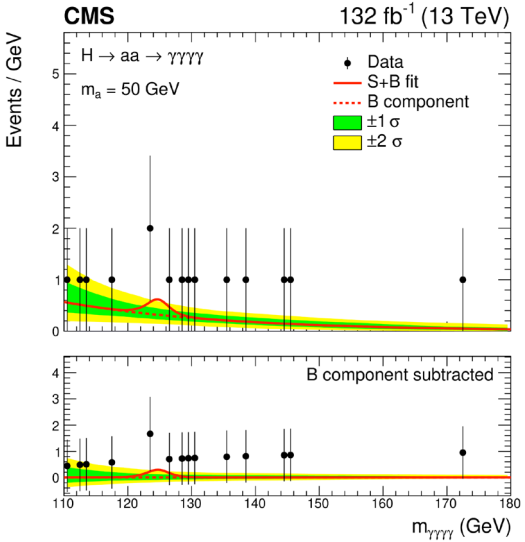
See talk by B. Marzocchi

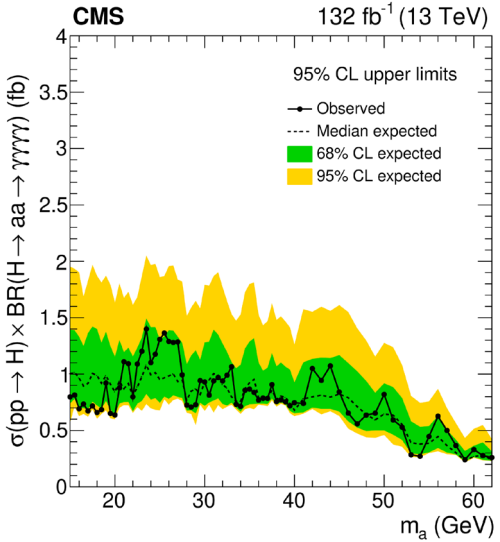
- Coupling is subdominant in most of the mass range.
- Branching ratio enhanced for very low mass $m_a < 2m_\mu$.
- Final state with very low background.



Search for $H \to aa \to 4\gamma$ (resolved)



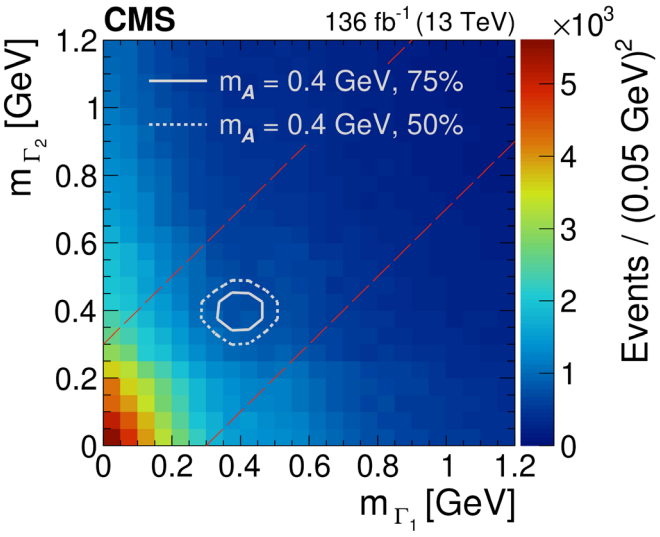


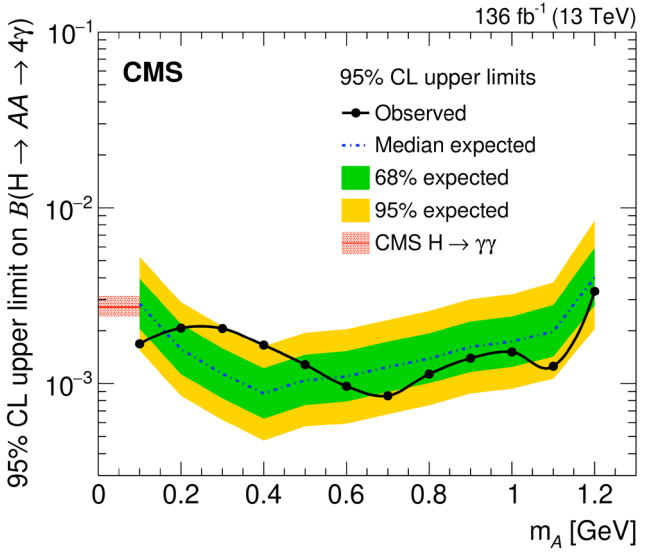


- Vertex selection has impact on $m_{\gamma\gamma\gamma\gamma}$ resolution. Vertex ID BDT assign scores to all vertex choices.
- Background estimated used event mixing: data events are mixed without any preselection applied.

- BDT trained in data sidebands to improve background description around m_H.
- Another BDT trained to discriminate signal and background.
- Search for narrow peak in $m_{\gamma\gamma\gamma\gamma}$ distribution.

Search for $H \to aa \to 4\gamma$ (merged)



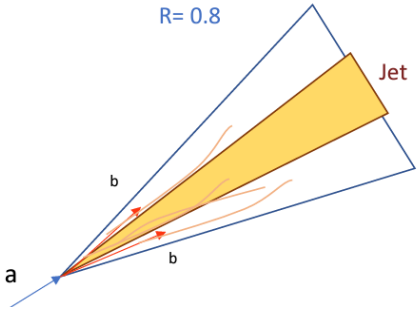


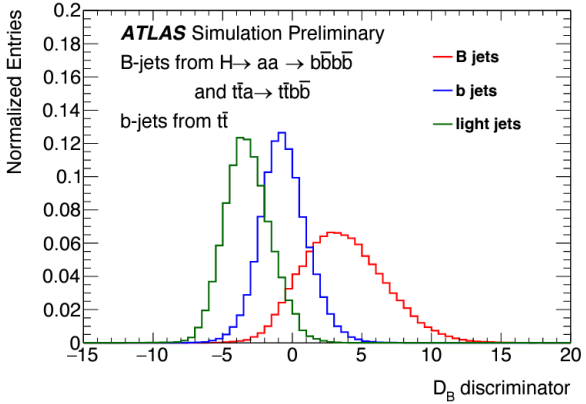
Deep learning technique used to estimate mass of merged diphoton Γ object.
Define SR along diagonal $m_{\Gamma_1} \simeq m_{\Gamma_2}$ and $m_{\Gamma_1\Gamma_2} \simeq m_H$
Mass sidebands are used to estimate background.

Other dedicated algorithms

DeXTer: Deep Set $X \rightarrow bb$ Tagger

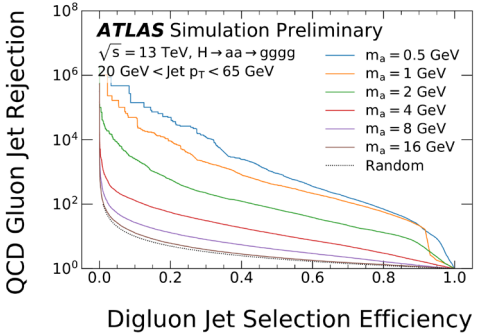
ATL-PHYS-PUB-2022-042

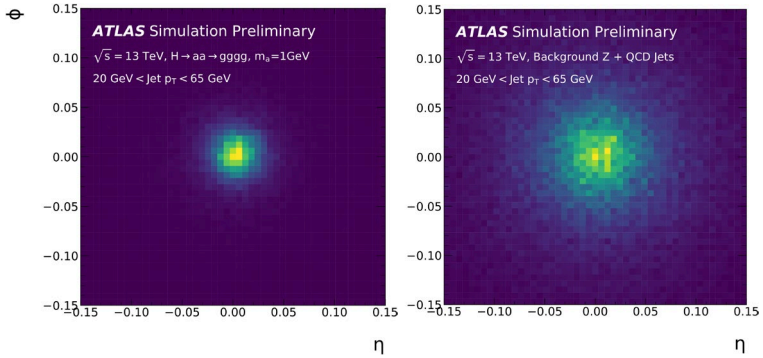




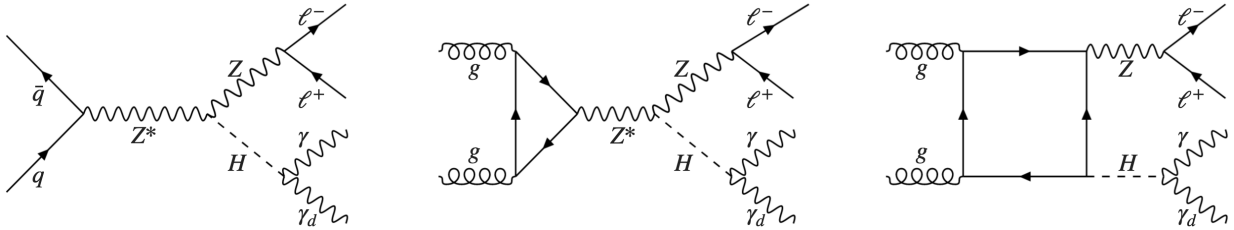
Di-gluon Tagger

ATL-PHYS-PUB-2021-027



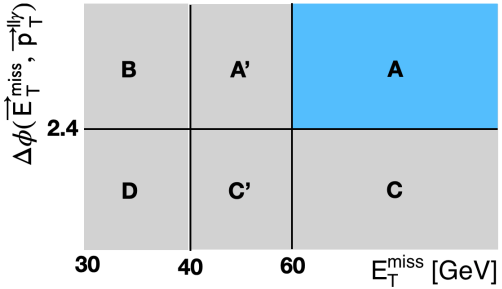


Search for $ZH, H \to \gamma\gamma_D$

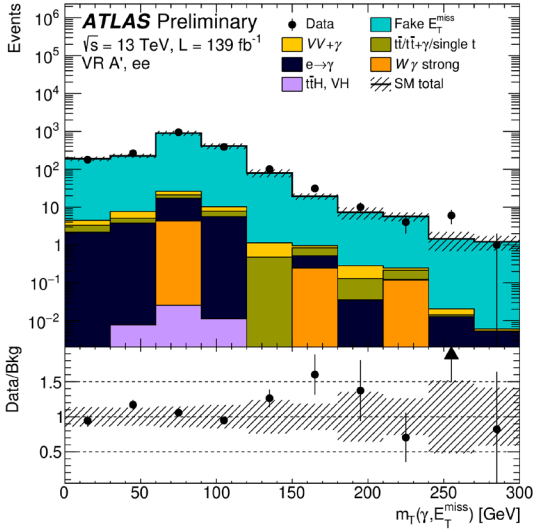


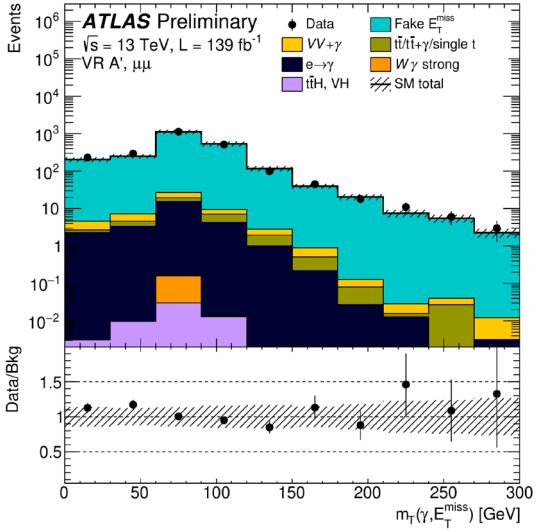
ATLAS EXPERIMENT

ATLAS Collaboration
ATLAS-CONF-2022-064

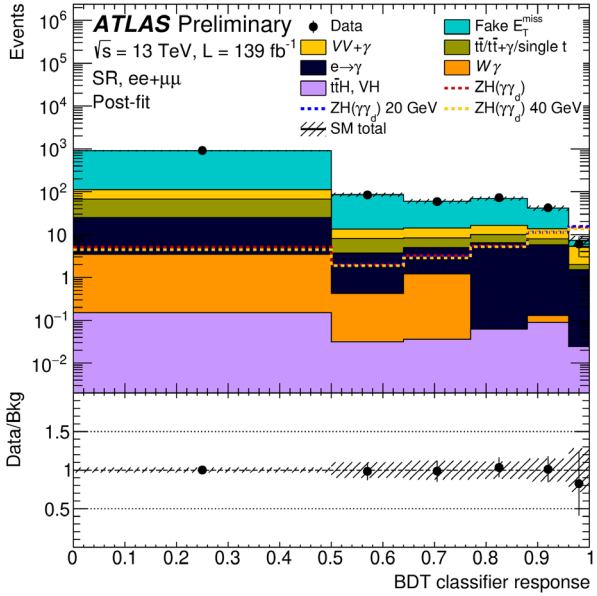


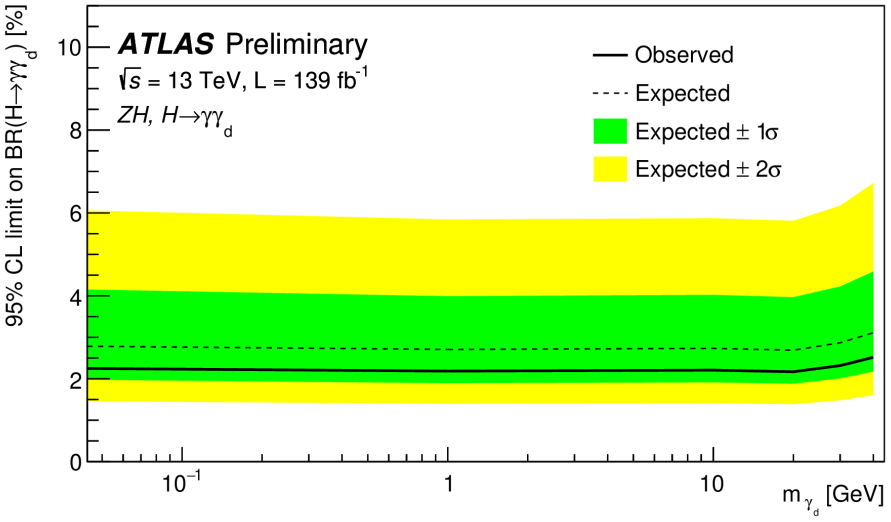
Leading source of background are $Z\gamma$ events with instrumental E_T^{miss}. Estimated with ABCD method.





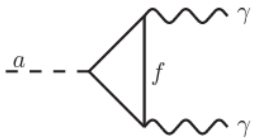
Search for $ZH, H \to \gamma\gamma_D$

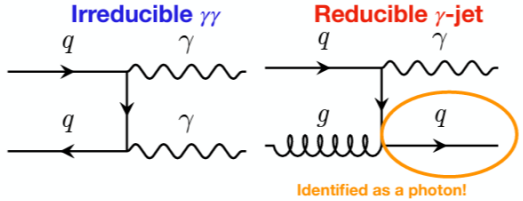




Dedicated BDT trained to improve signal discrimination with respect to dominant background sources.

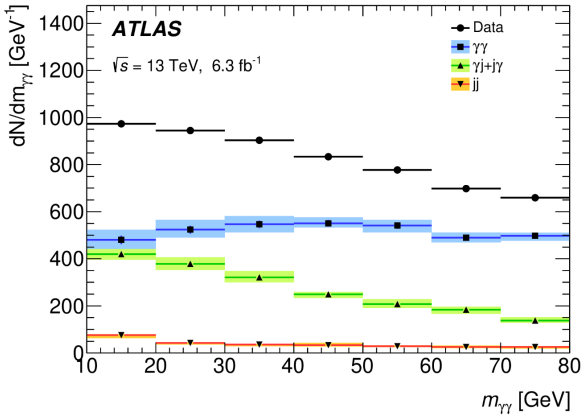
Search for low mass $a \to \gamma\gamma$

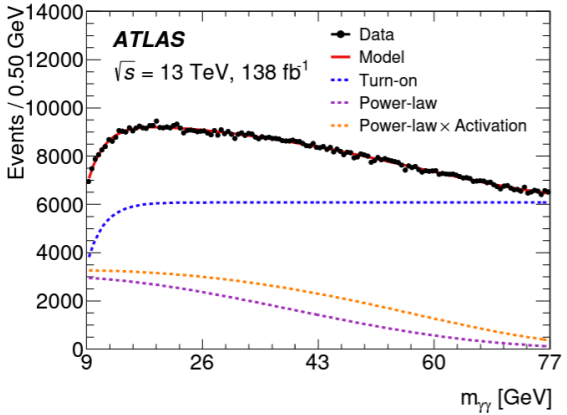




ATLAS EXPERIMENT

ATLAS Collaboration
arXiv:2211.04172

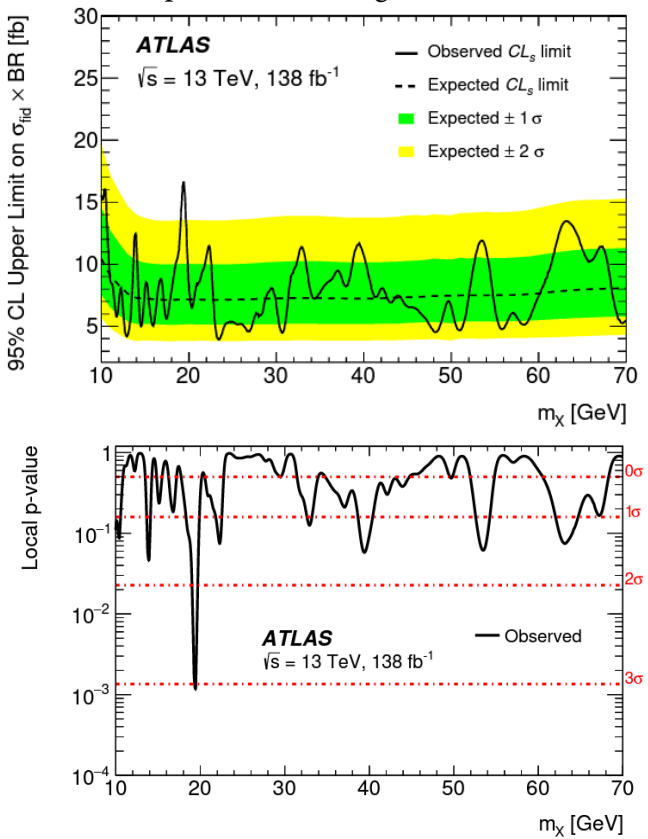


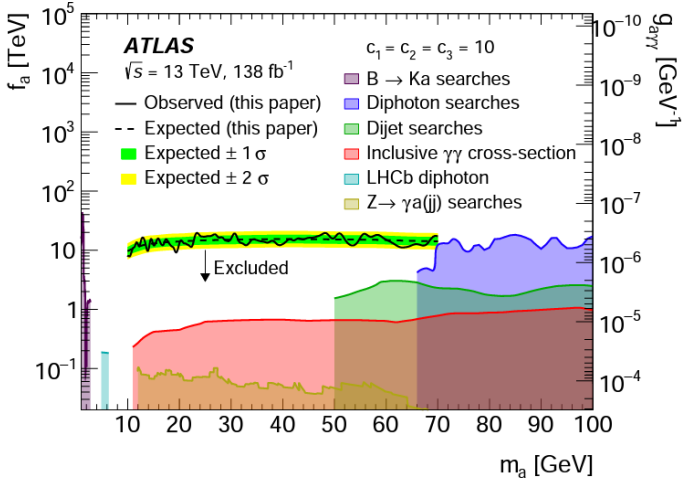


- Background model based on templates built from irreducible ($\gamma\gamma$) simulation and data control regions to measure fraction of reducible ($\gamma j + j\gamma, jj$) and irreducible components.
- Extending the background modeling to lower masses requires a more flexible function than the one use for analyses at higher $m_{\gamma\gamma}$.

Search for low mass $a \to \gamma\gamma$

Interpretation for a signal in the NWA





Interpretation in an ALP model

$$\frac{a}{4\pi f_a}\left[\alpha_3 c_3 G^a \tilde{G}^a + \alpha_2 c_2 W^i \tilde{W}^i + \alpha_1 c_1 B\tilde{B}\right] + \frac{1}{2}m_a^2 a^2$$

(with $c_1 = c_2 = c_3 = 10$)

Conclusion

- Exotic Higgs decays is a research area with a very vast landscape
- Many different ways to look for new decays of the Higgs boson and new low-mass states.
- Widespread interest in the field, with many contributions to Snowmass.
- Recent theory results show that LHC can probe a large fraction of the parameter space that can generate strong first-order EW phase transition.
- We reviewed recent results from ATLAS and CMS searching for new low-mass states.
- But many final-states are either unexplored or have results with only partial Run 2 dataset.
- New dedicated identification algorithms are being developed to close these gaps.