



# BSM Higgs decay

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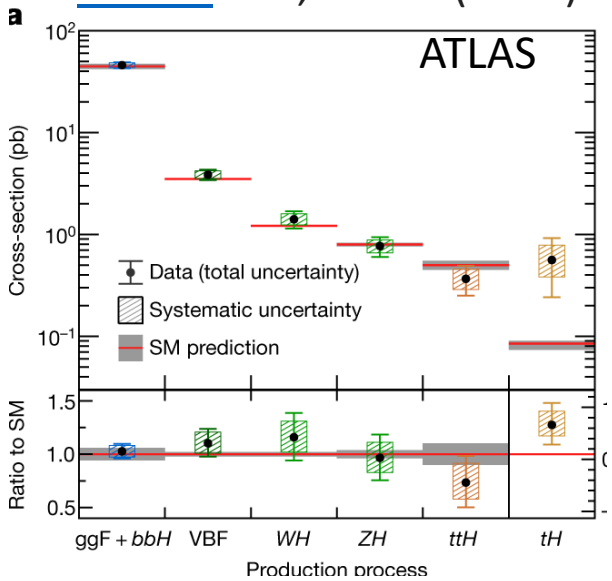
On behalf of the ATLAS, CMS, LHCb collaborations




# The SM Higgs(125) is a key to new physics

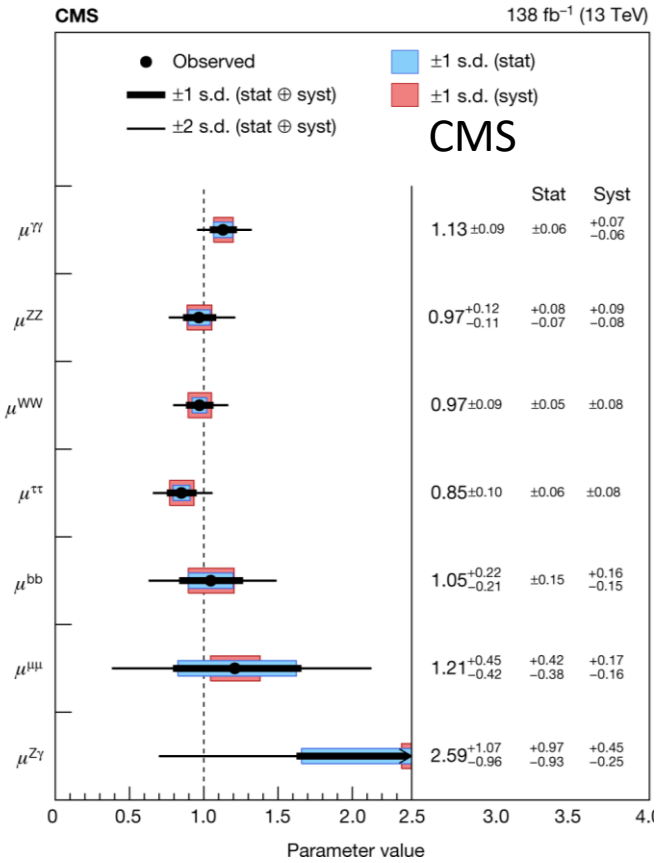
- SM H(125): discovered 11 years ago, production and decay have been precisely measured.
- BSM models predict exotic decays of the SM H(125): A bridge to new physics, discovery potential:
  - Decays to (pseudo) scalars (e.g. Axions).
  - Invisible decays (e.g. Dark Sectors).
  - Lepton Flavor Violation (LFV).
  - Decays to Long-Lived Particles (LLPs).

*Nature* **607**, 52–59 (2022)




Production

*Nature* **607**, 60–68 (2022)




Decay

# A selected list

**Invisible decays:**

$W/Z + (H \to inv)$,
$VBF + (H \to inv)$,
$t\bar{t}(H \to inv)$,

**Decays to (pseudo) scalars (e.g. ALPs):**

$H \to aa \to bbbb$,
$H \to aa(AA) \to 4\gamma$,
$H \to aa \to llbb$,
$H \to Za \to ll\gamma\gamma$

**Dark sector (e.g. dark photon):**

$H \to Z_d Z_d \to 4l$,
$H \to ZZ_d \to 4l$,
$Z(H \to \gamma\gamma_d)$

**Lepton Flavour Violation (LFV):**

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

**Decays to Long-Lived Particles (LLPs):**

$H -> LLPs$

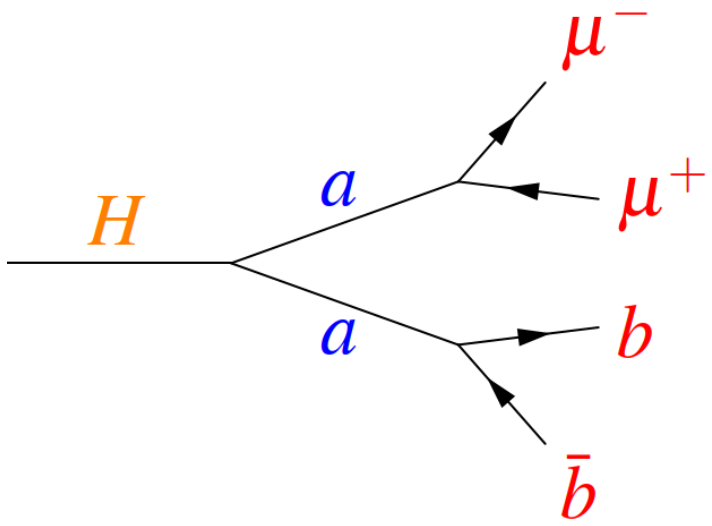
See dedicated talk by Shih-Chieh Hsu today.

This talk.

# Higgs to light (pseudo) scalars

- Several BSM extensions predict Higgs decays via a pair of on-shell light (pseudo) scalar bosons, noted as “a” or “A”, eg, in 2HDM+S or Axion-like particles (ALPs)

- The (pseudo) scalar “a” generally decays into fermions ($a \to bb$, $a \to \mu\mu$) but can also decay to bosons such as ($a \to \gamma\gamma$, $a \to gg$) depend on the model



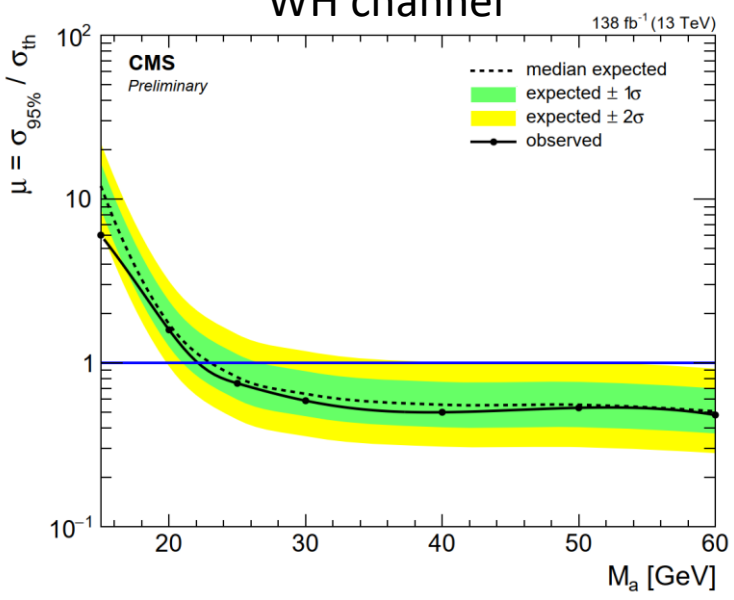
# $H \to aa \to bbbb$ at CMS

**CMS-PAPER-HIG-18-026**

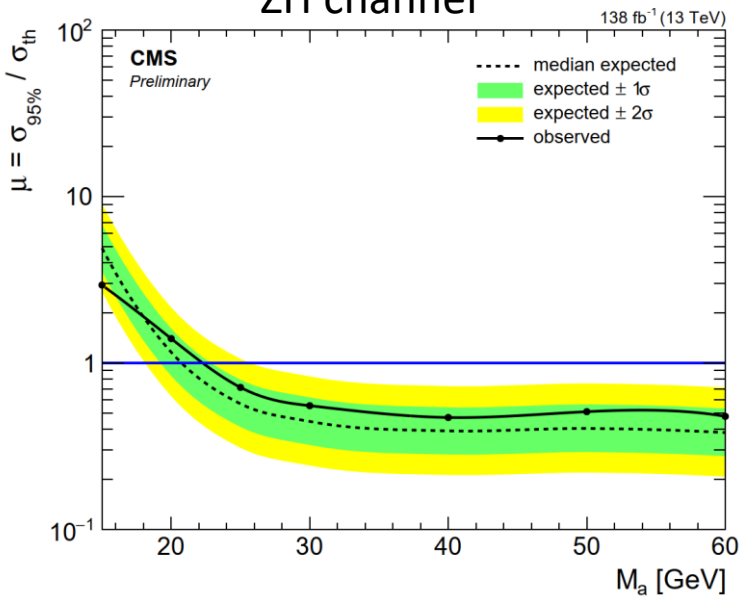
New

- Light pseudoscalar bosons (a) interpreted in 2HDM+S models, in mass range 15–60 GeV:
  - Higgs associated with leptonically decaying W or Z boson.
  - BDT used for signal-background separation.
- Set upper limits on the cross section of combined WH and ZH processes.

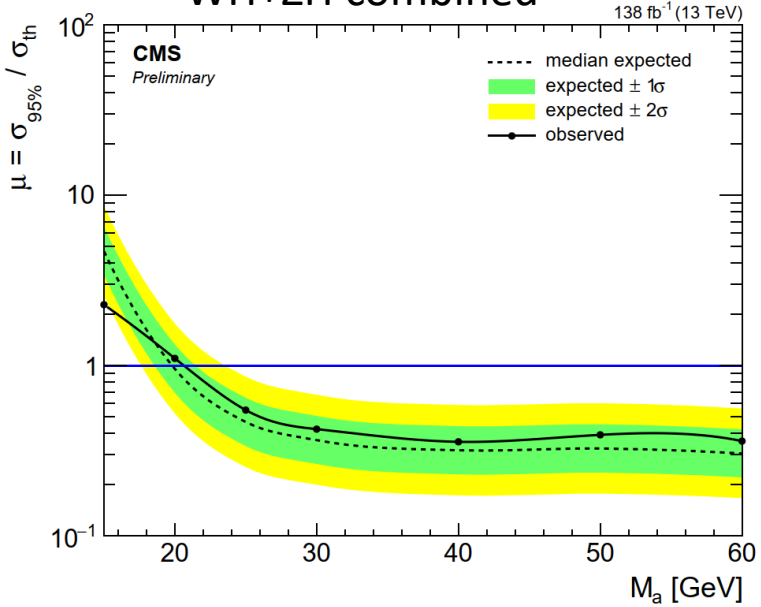
WH channel



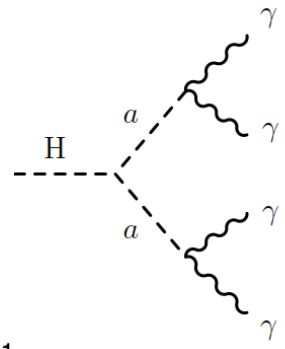

ZH channel




WH+ZH combined

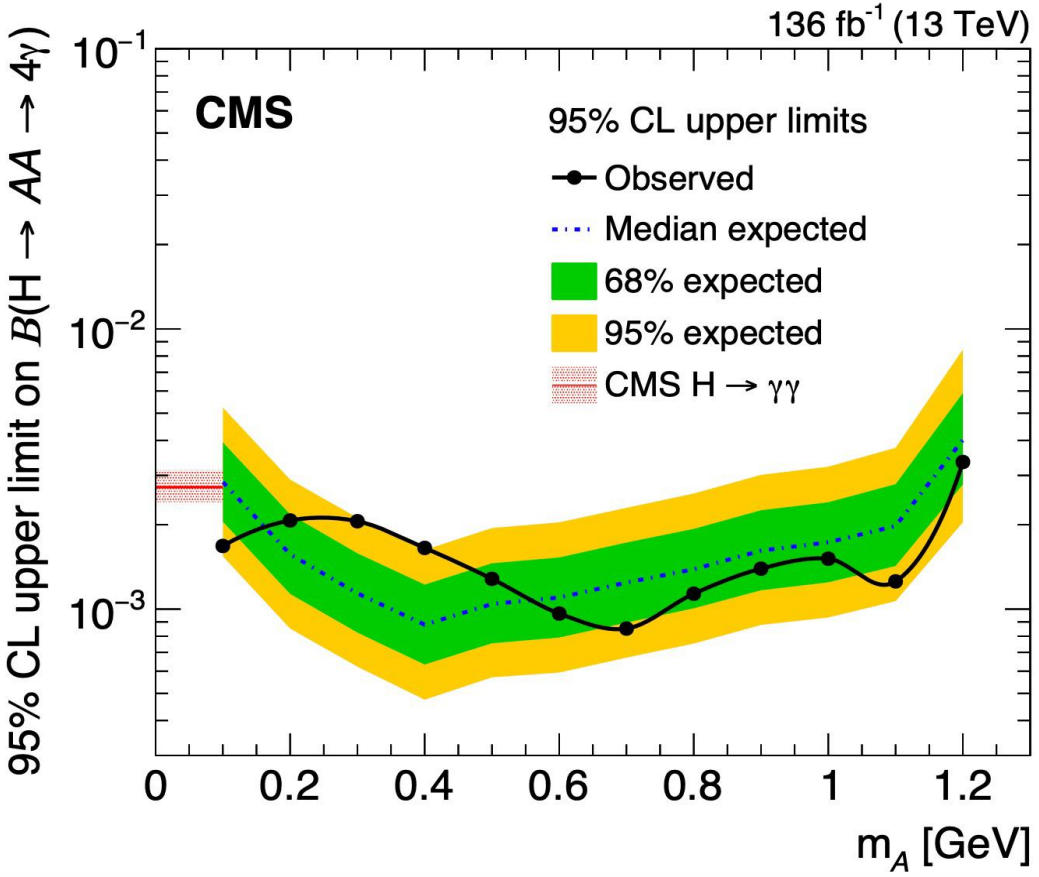


# $H \to AA \to 4\gamma$ at CMS



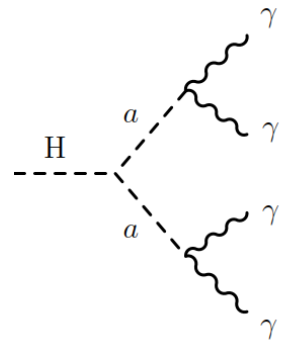

Phys. Rev. Lett. 131 (2023) 101801

- Low mass (0.1–1.2 GeV) ALP model search:
  - First direct search for Higgs exotic decay to ALPs with ALP to $2\gamma$, limits set on $B(H \to aa \to 4\gamma)$
  - Merged $\gamma\gamma$ reconstructed as a single photon-like object $\Gamma$, a regressor trained to predict $m(\Gamma)$ based on low-level detector information
  - Backgrounds $H \to \gamma\gamma$ and multijet processes

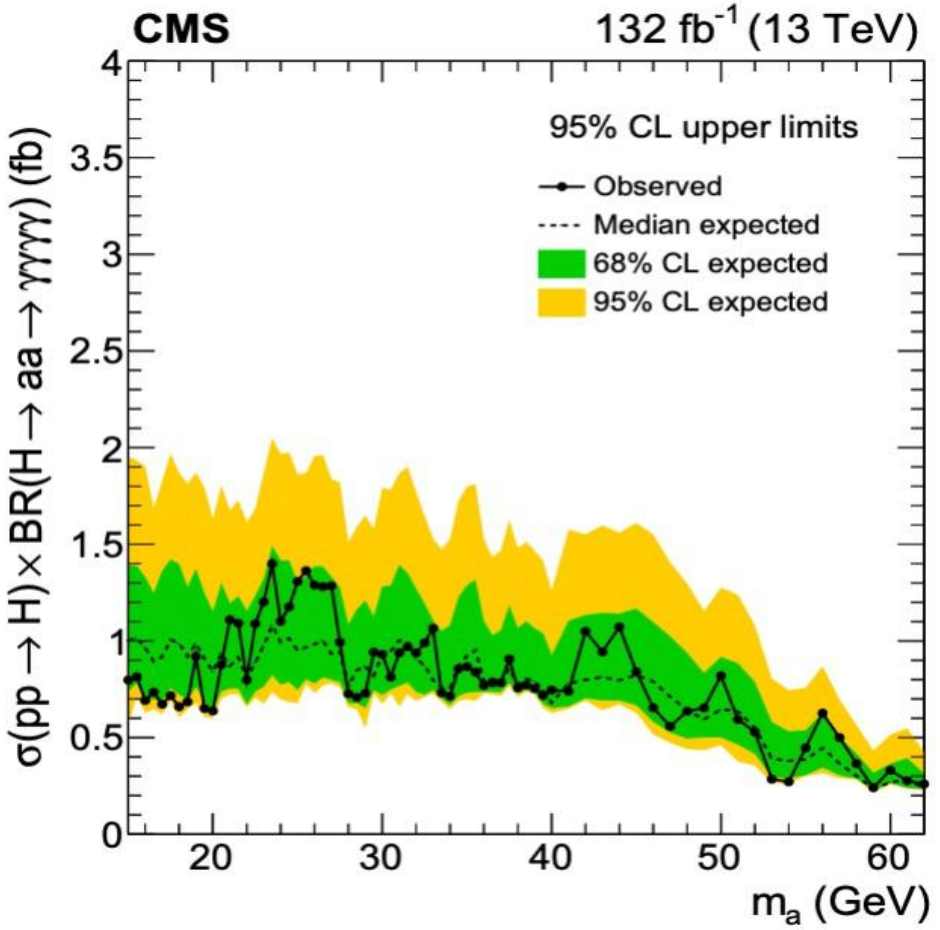


# $H \to aa \to 4\gamma$ at CMS

JHEP 07 (2023) 148

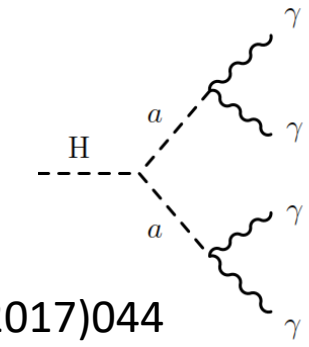



- Higher Mass (15–62 GeV) 2HDM+S pseudoscalar Search.
  - Well isolated and fully reconstructed photons, limits set on $\sigma(H) \times B(H \to aa \to 4\gamma)$
  - Backgrounds: $\gamma$+jets processes, estimated by data-driven method
  - Train a BDT parameterized in $m(a)$ for event categorization



# $H \to aa \to 4\gamma$ at ATLAS

**ATLAS-CONF-2023-040**



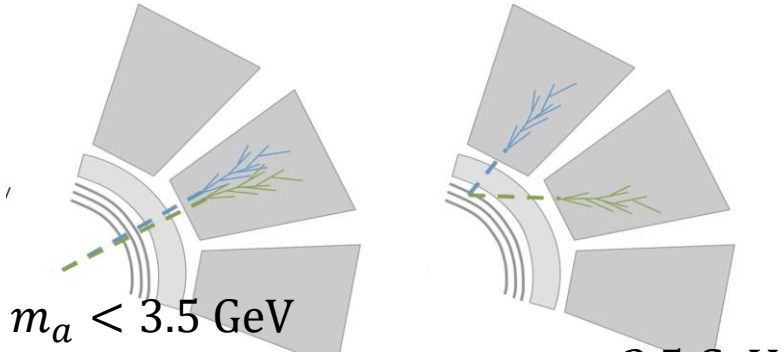

JHEP12(2017)044

- ALPs allows wider mass range than original Peccei-Quinn QCD axion.

$$\Gamma(a \to \gamma\gamma) \equiv \frac{4\pi\alpha^2 m_a^3}{\Lambda^2} \left| C_{\gamma\gamma}^{\text{eff}} \right|^2$$

  - Prompt (short-lived), large $\Gamma$:
    - $m_a > 5$ GeV and $C_{\gamma\gamma}/\Lambda > 0.1\text{TeV}^{-1}$
  - Long-lived, small $\Gamma$:
    - $m_a > 0.1$ GeV and $C_{\gamma\gamma}/\Lambda < 0.1\text{TeV}^{-1}$

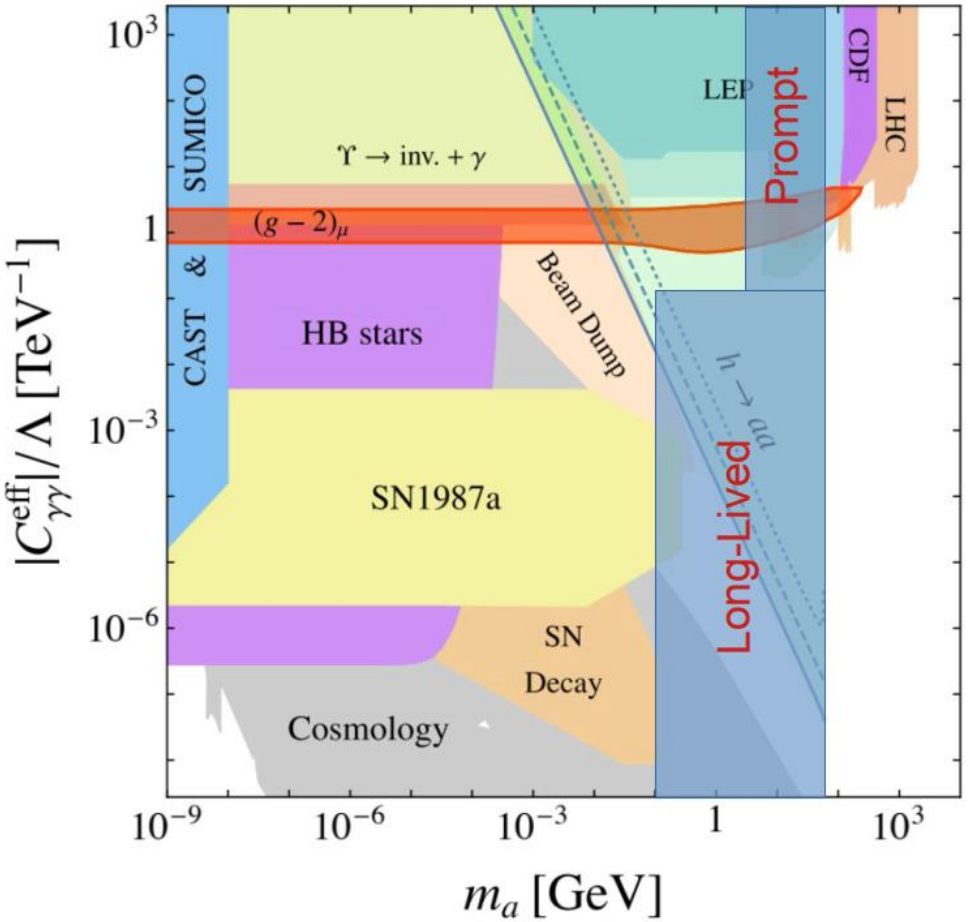
Dedicated MVA to identify calorimeter clusters with 2 merged photons.



$m_a < 3.5$ GeV

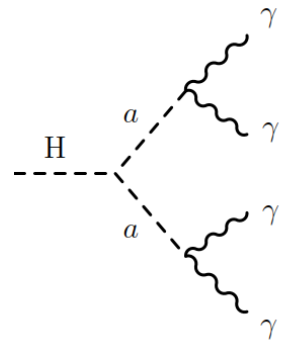
Only in the long lived search

$m_a > 3.5$ GeV



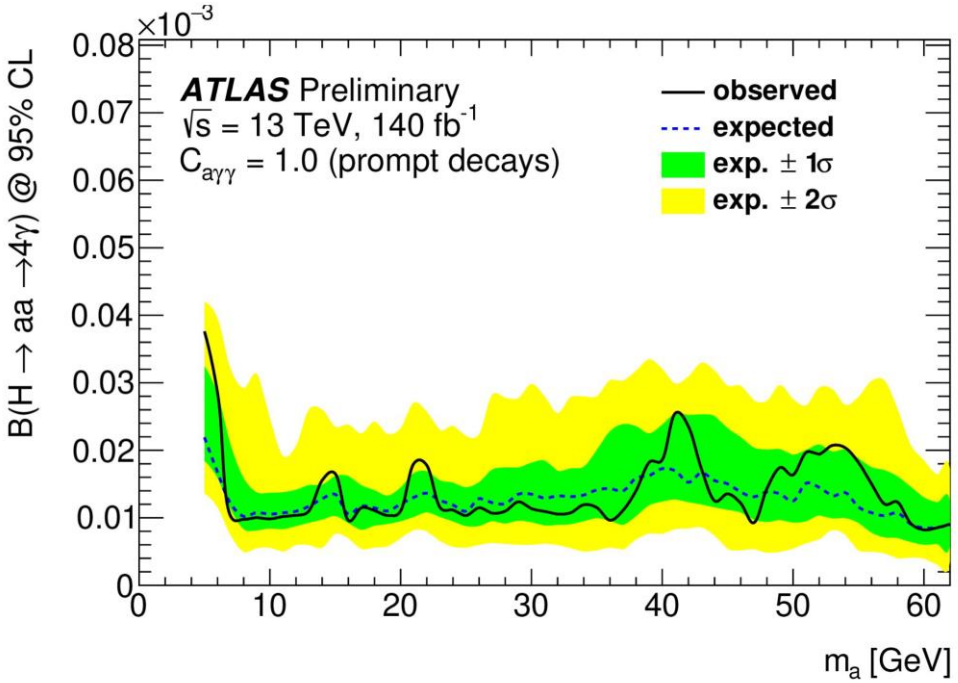
# $H \to aa \to 4\gamma$ at ATLAS

**ATLAS-CONF-2023-040**

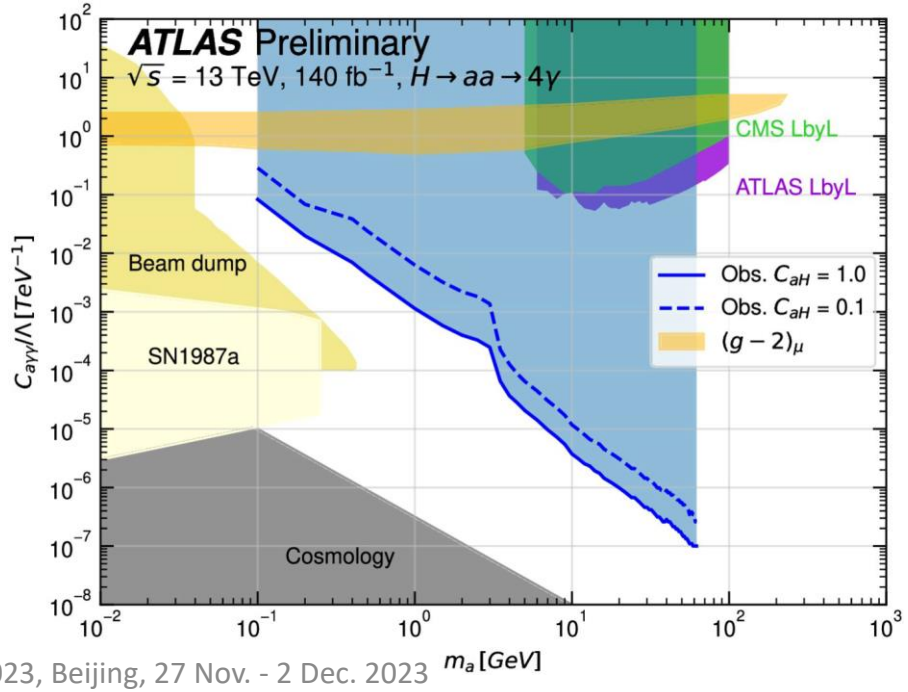



- Explored ALP masses from 100 MeV to 62 GeV.
- The most stringent limits to date, assuming $\frac{C_{aH}}{\Lambda^2} = 1.0\ \mathrm{TeV}^{-2}$

Upper limits on $B(H \to 4\gamma)$ at 95% CL



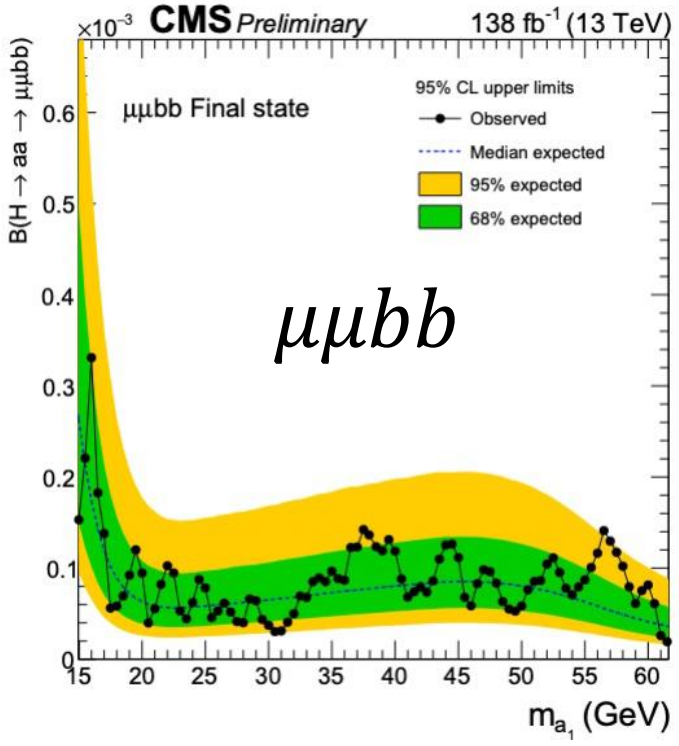

Limits on the ALP mass and coupling to photons at 95% CL

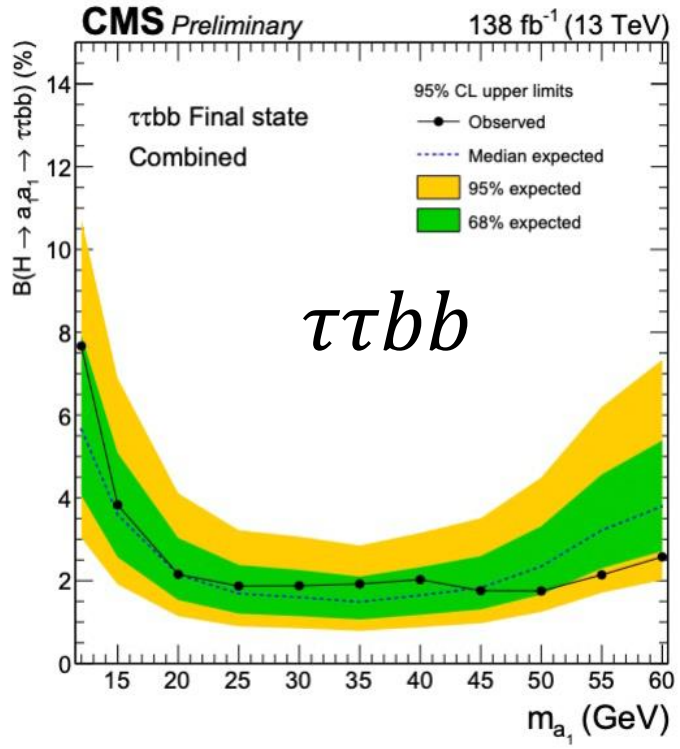


# $H \to aa \to \mu\mu bb/\tau\tau bb$ at CMS

CMS-PAS-HIG-22-007

- Interpretation under 2HDM+S model with $m_a > 15\ (12)$ GeV for $\mu$ ($\tau$) channel
  - Excellent resolution in $m(\mu\mu)$, and large $B(a \to bb)$
  - Three $\tau\tau$ decay channels: $\mu\tau_h$ (most sensitive) / $e\tau_h$ / $e\mu$
  - Major backgrounds are top-pair, $Z + jets$ and $jet \to \tau_h$ fakes, data-driven estimation
  - Limits sets on $B(H \to aa \to \tau\tau bb)$ and $B(H \to aa \to \mu\mu bb)$



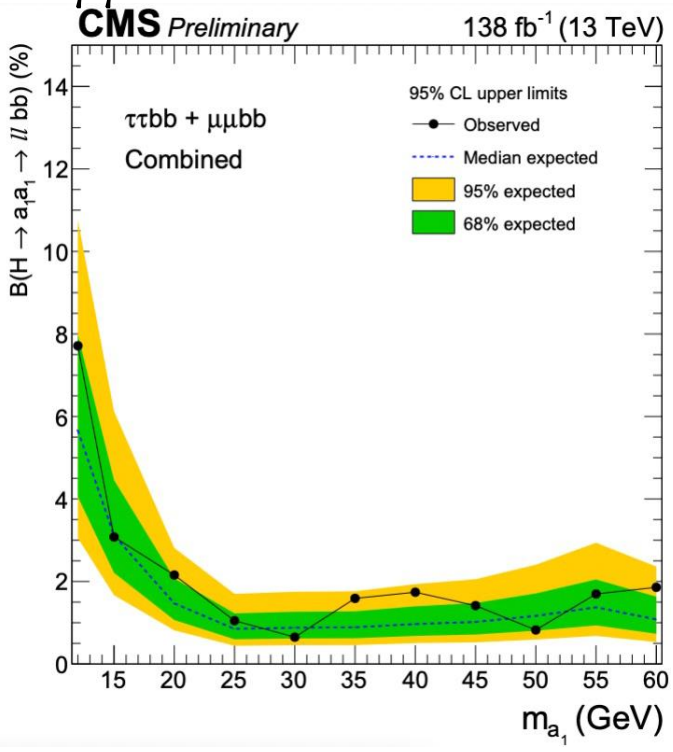



# $H \to aa \to \mu\mu bb/\tau\tau bb$ at CMS

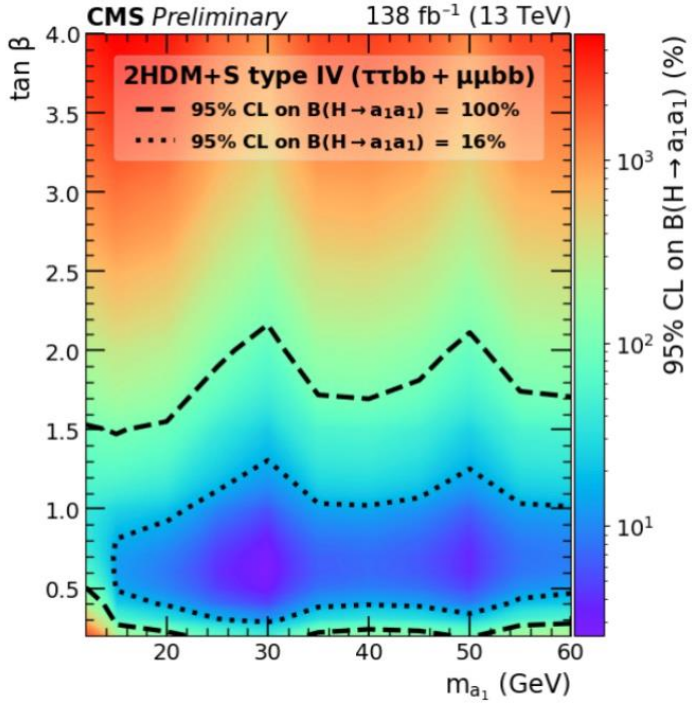
**CMS-PAS-HIG-22-007**

- Combination of $\mu\mu$bb and $\tau\tau$bb, most stringent limits in $12 < m_a < 60$ GeV
- Interpretation in 2HDM+S (four coupling types can avoid FCNC at LO)

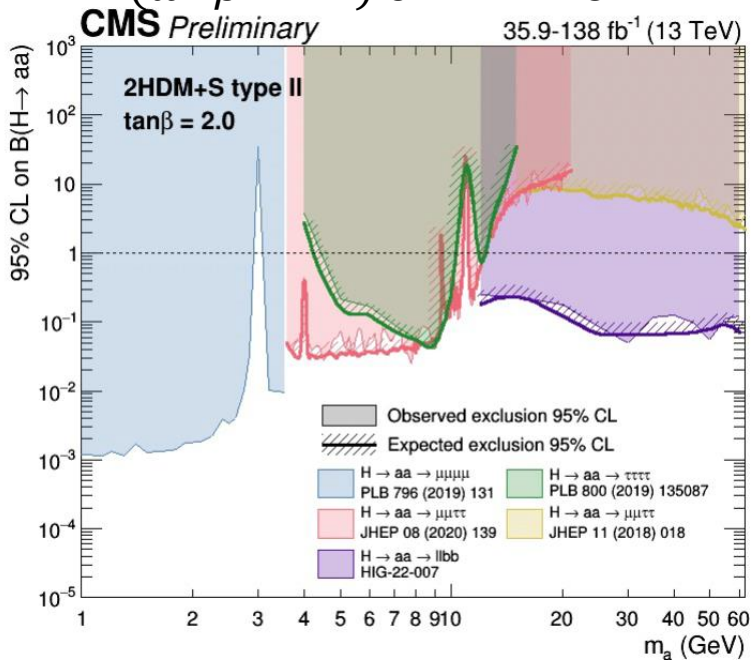
$\mu\mu bb + \tau\tau bb$ combined




Limits on $B(H \to aa)$ for type IV of 2HDM+S



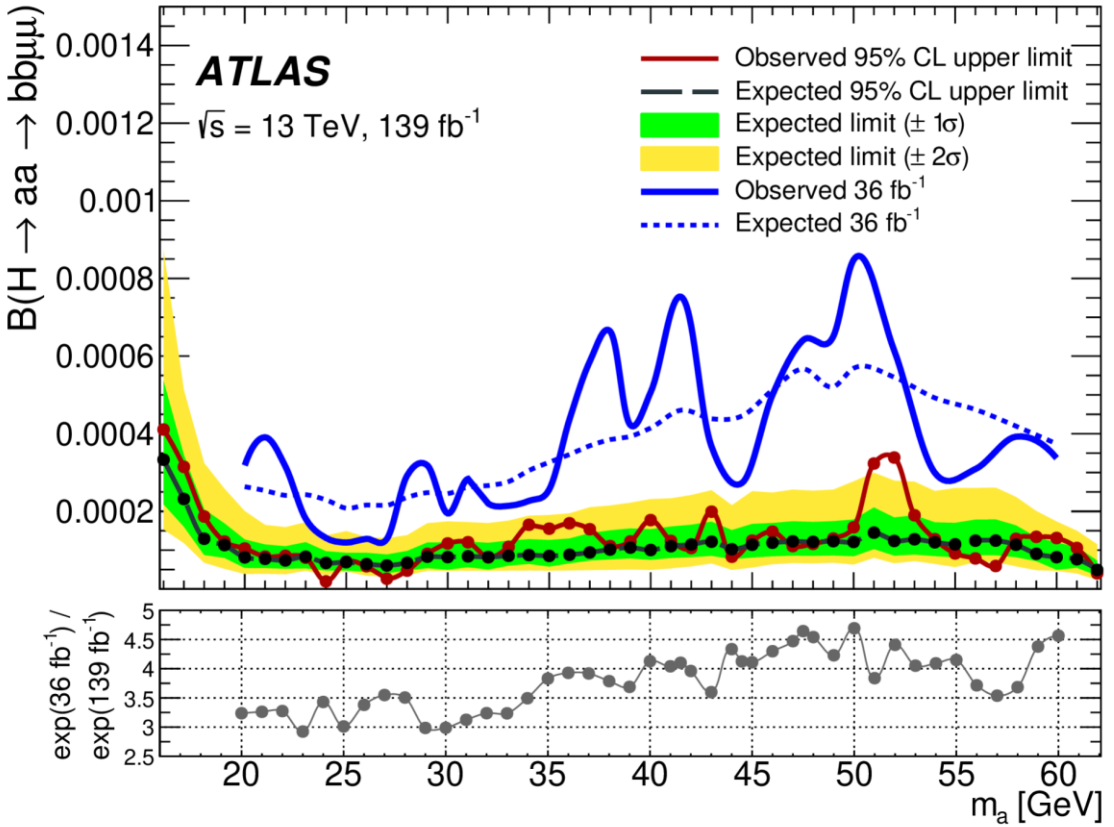

Limits on $B(h \to aa)$ for type II $(\tan\beta = 2)$ of 2HDM+S



# $H \to aa \to \mu\mu bb$ at ATLAS

Phys. Rev. D 105 (2022) 012006

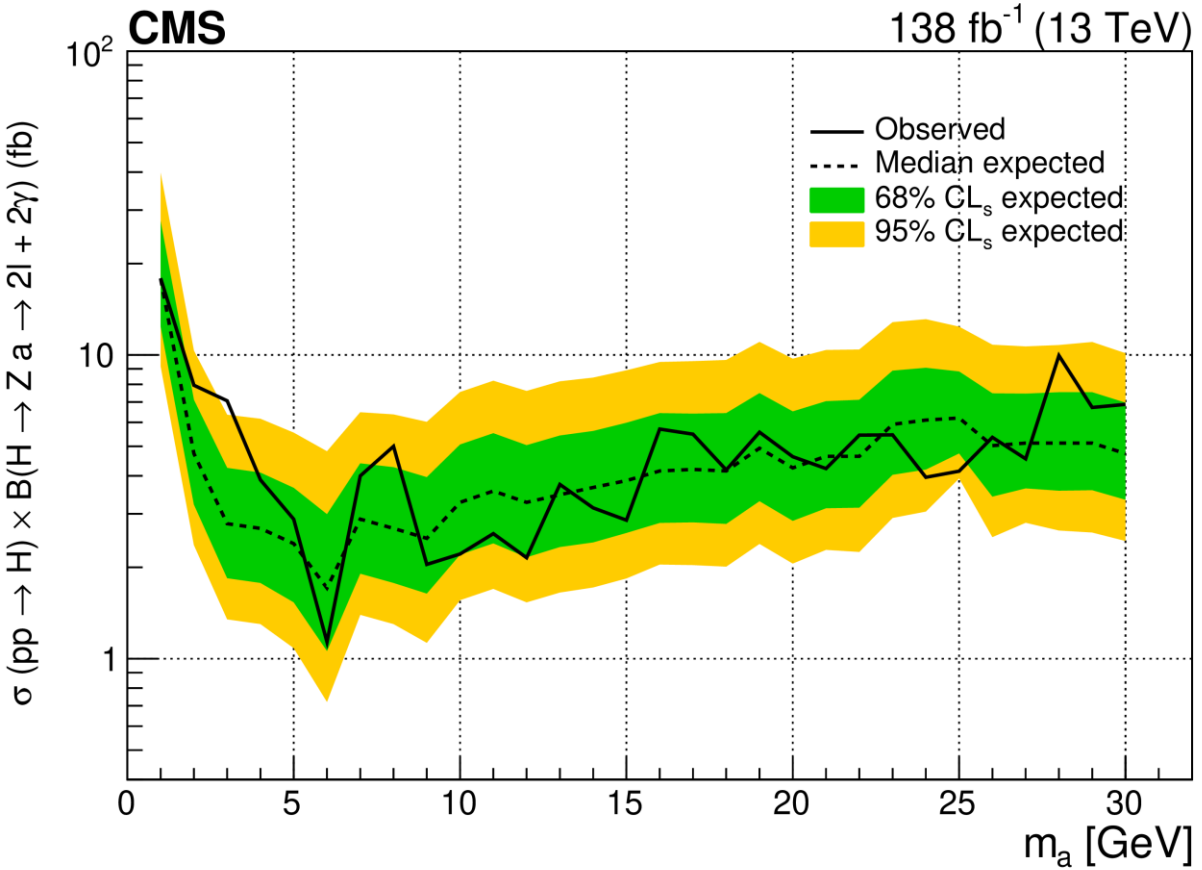
- Searched for resonance (2HDM models) in the range $16 < m_{\mu\mu} < 62$ GeV :
  - Assuming $m_{\mu\mu} = m_{bb}$ within resolution
  - BDT used to suppress major backgrounds (DY, $t\bar{t}$ ), modelled using control regions
- Upper limits are set on $Br(H \to aa \to bb\mu\mu)$:
  - **Results with BDT: Excess of $3.3\sigma$ $(1.7\sigma)$ local (global) observed at $m_a = 52$ GeV**
    - BDT selection significantly improve the sensitivity
  - Result without BDT, no excess is observed.



# $H \to Za \to ll\gamma\gamma$ at CMS

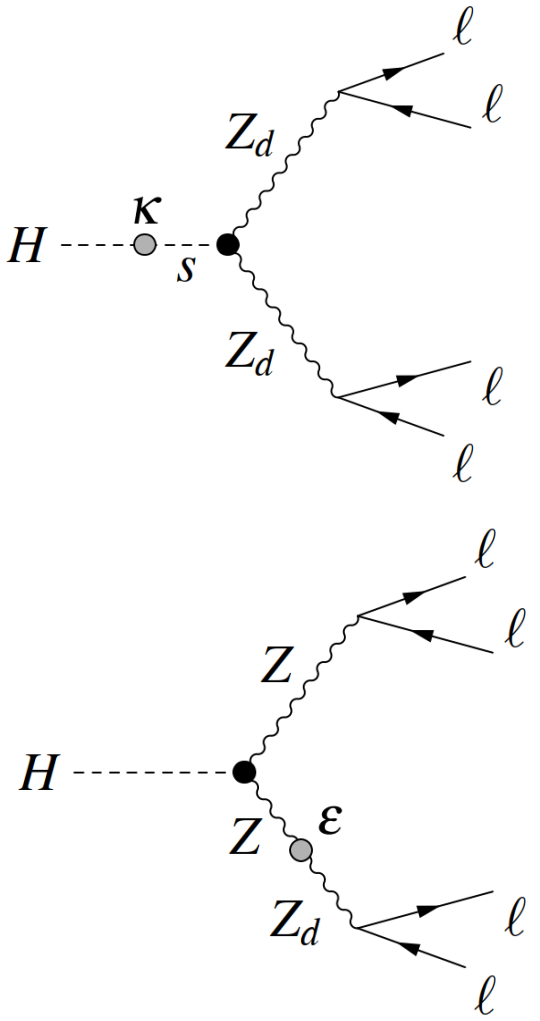
arXiv:2311.00130 (submitted to PLB)

- First search in LHC looking for the signature $Za \to ll\gamma\gamma$
  - Consider $1 < m_a < 30$ GeV
  - Backgrounds $Z(ll)$ with $jet \to \gamma$ fakes, data-driven method
  - BDT classifier parameterised in $m_a$ for event categorization
  - Limits set on $\sigma(H) \times B(H \to Za \to ll\gamma\gamma)$ and ALP models



# Higgs decay to dark photons

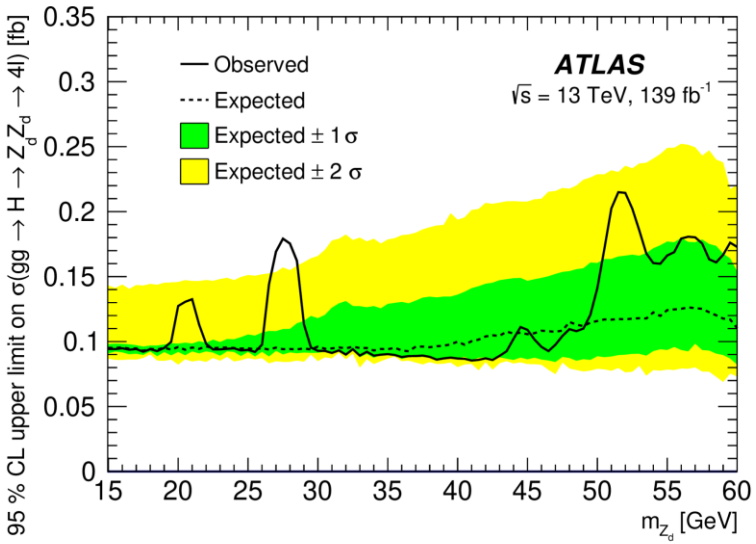
- Many SM extensions include a $U(1)$ dark gauge symmetry with gauge boson $Z_d$ mixing with SM Higgs via $\kappa$ and with hypercharge gauge boson via $\epsilon$.
- Gives rise to $H \to Z_d Z_d$ and $H \to Z Z_d$.
- $Z_d$ has significant decays to $ll$ ($\sim 20-30\%$).

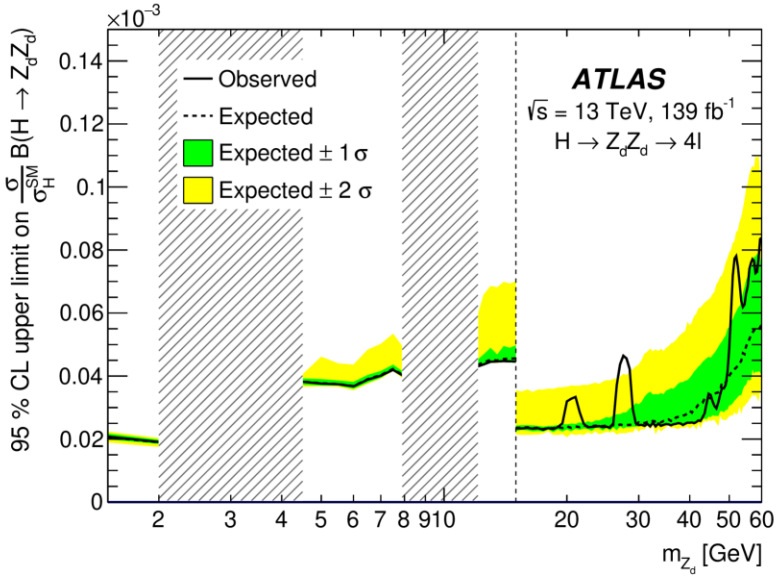


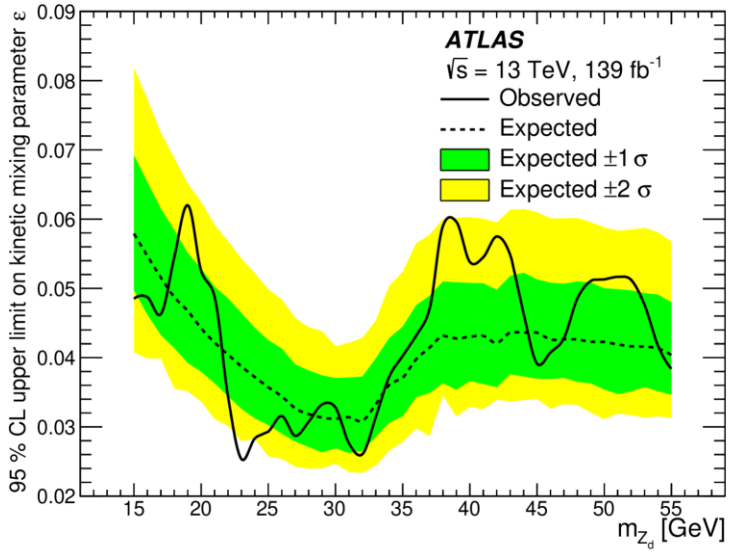
# $H \to Z_d Z_d \to 4l$ at ATLAS

**JHEP 03 (2022) 041**

- Search for exotic decays of the Higgs boson into four leptons through intermediate scalars or vector bosons, motivated by dark-sector models
- Main background are estimated from simulation : $H \to ZZ^* \to 4l$, $ZZ^* \to 4l$ and Heavy flavour jets faking leptons
- Limits set on signal cross-section, fiducial cross-section, Higgs branching ratios, and model parameters



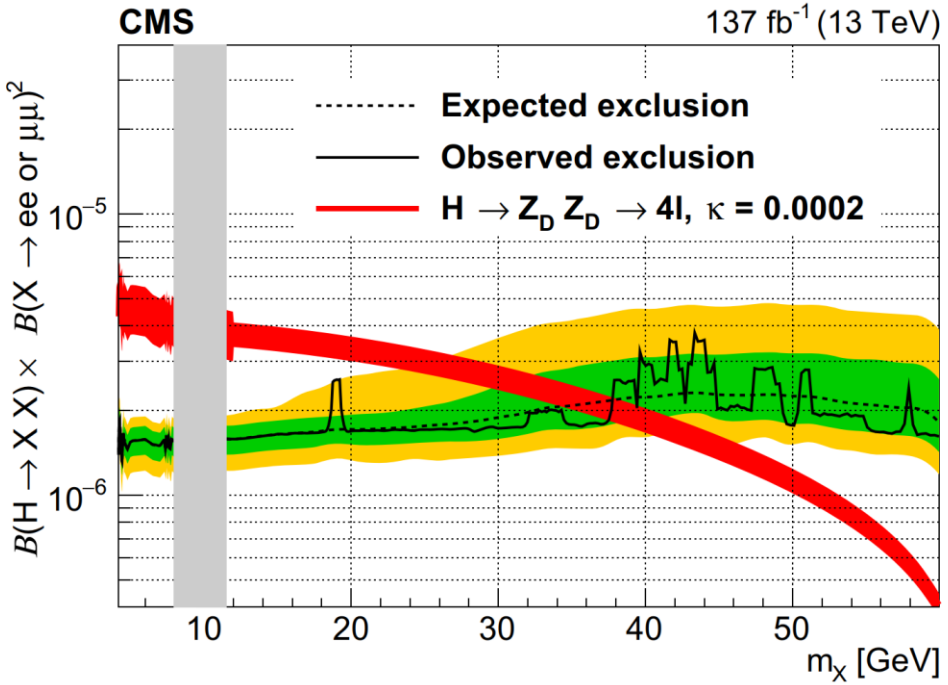



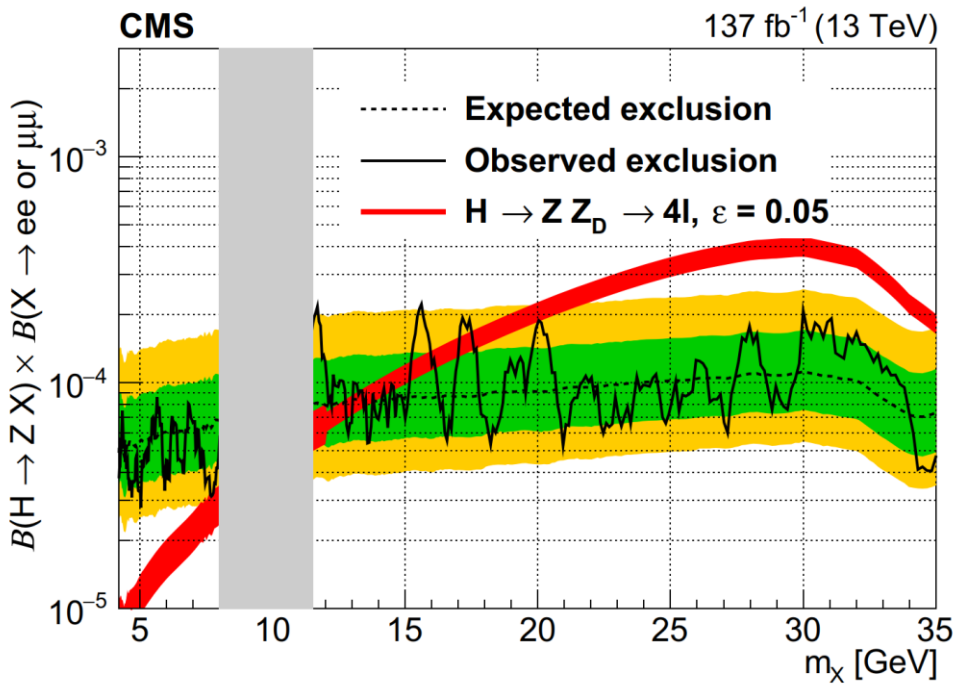



# $H \to Z_d Z_d / Z Z_d \to 4l$ at CMS

EPJC 82 (2022) 290

- Equivalent CMS analysis, sets limits on $B(H \to XX) \cdot B(X \to ee\ or\ \mu\mu)$ for both $H \to Z_d Z_d$ and $H \to Z Z_d$

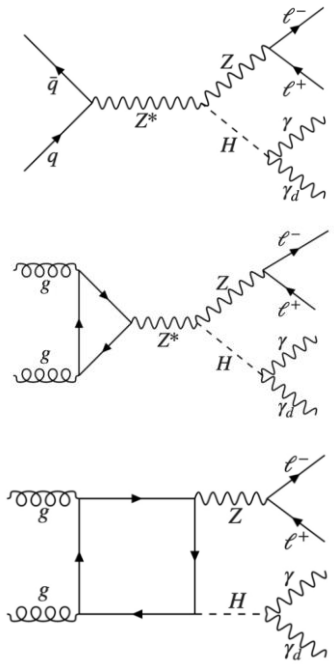


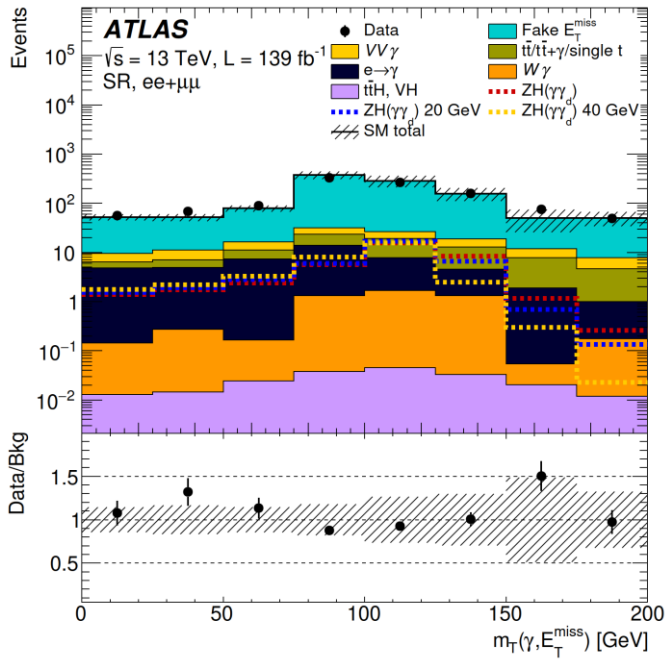



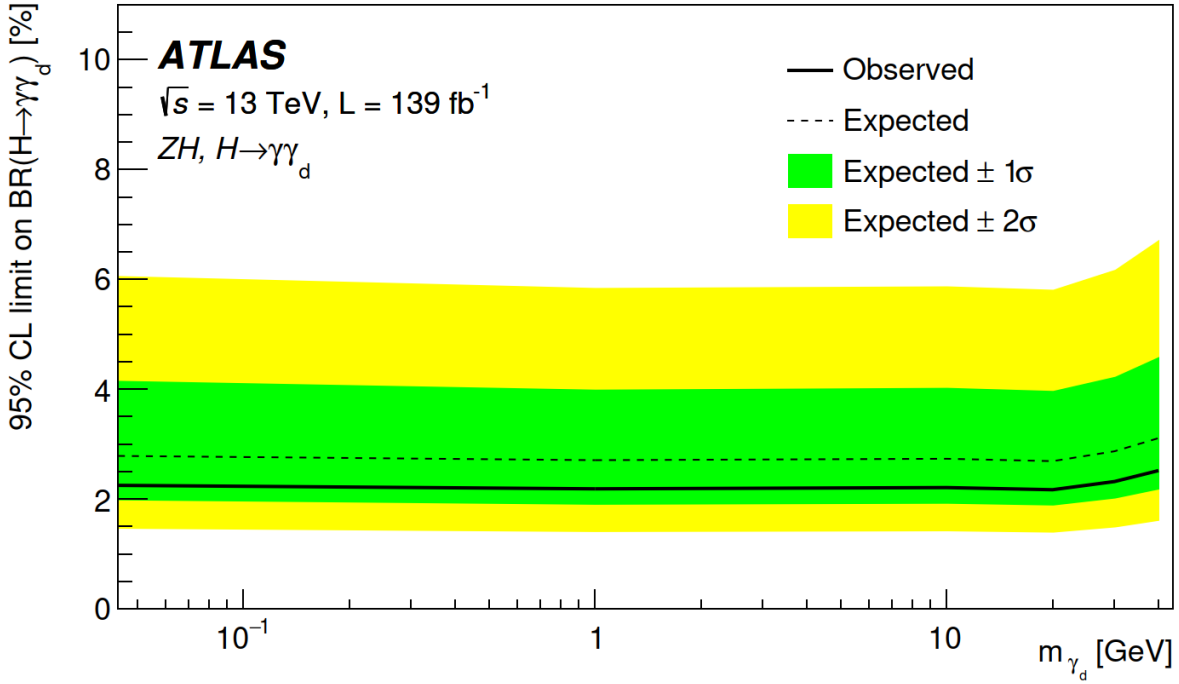
# $H \to \gamma\gamma_d$ in $ZH$ at ATLAS

**JHEP 07 (2023) 133**

- Search for Hidden Valley scenario $H \to \gamma\gamma_d$ for dark photon mass 0-40 GeV. Setting 95% CL limits on $BR(H \to \gamma\gamma_d)$ for varied $\gamma_d$ masses.
- Backgrounds characterized by fake $E_T^{miss}$ and misidentified photons, BDT kinematic discriminants for signal selection, data-driven + MC for background modelling.



# Lepton flavour violation (LFV)

- $H \to e\mu, e\tau, \mu\tau$ violate lepton flavour conservation
  - Accidental symmetry in SM, already broken by neutrino oscillations.
- In various BSM theories, such LFV processes can occur, and the Higgs boson can play a key role in these transitions.
  - SUSY, composite Higgs, Randall-Sundrum, 2HDM, models with heavy neutrinos, etc.

# $H \to e\tau/\mu\tau$ at ATLAS

**JHEP 07 (2023) 166**

- $H \to e\tau$ and $H \to \mu\tau$, Leptonic and hadronic decays of the tau lepton
- Backgrounds: $Z \to \tau\tau$ ; W + jets, multi-jet events: BDT and NN to suppress background
- Both $e\tau/\mu\tau$ independent and simultaneous fits are performed

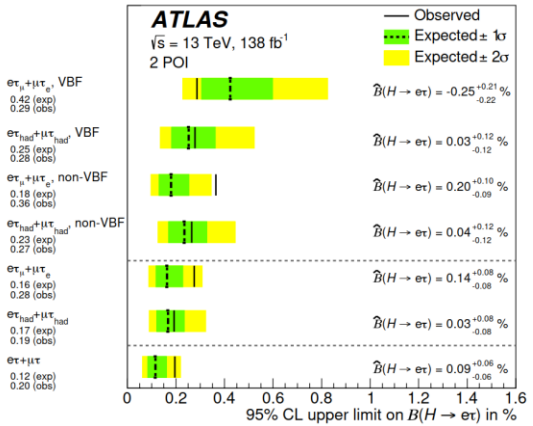
  Yukawa coupling:

simultaneous fits results are shown on this slide

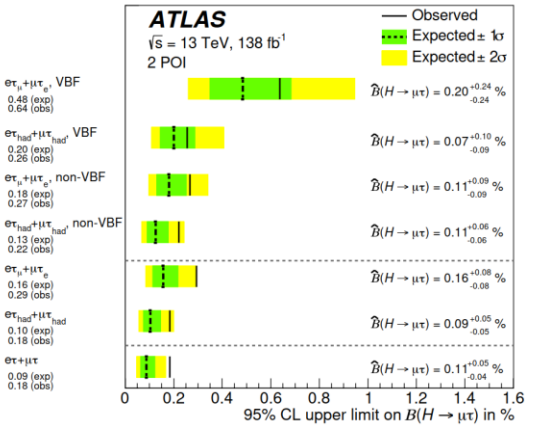
$$\sqrt{|Y_{\tau e}|^2 + |Y_{e\tau}|^2} < 0.0013$$

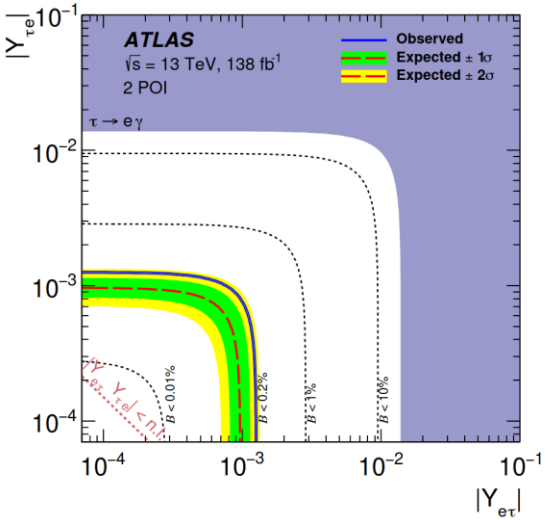
$$\sqrt{|Y_{\tau\mu}|^2 + |Y_{\mu\tau}|^2} < 0.0012$$

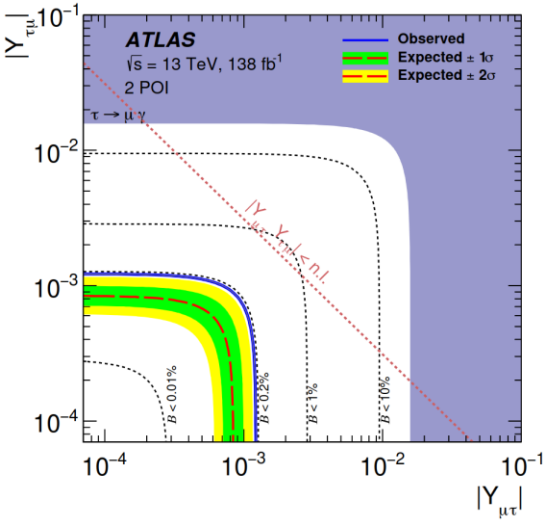
$H \to e\tau$




$H \to \mu\tau$



# $H \to e\tau/\mu\tau$ at CMS

*Phys.Rev.D* **104 (2021) 3, 032013**

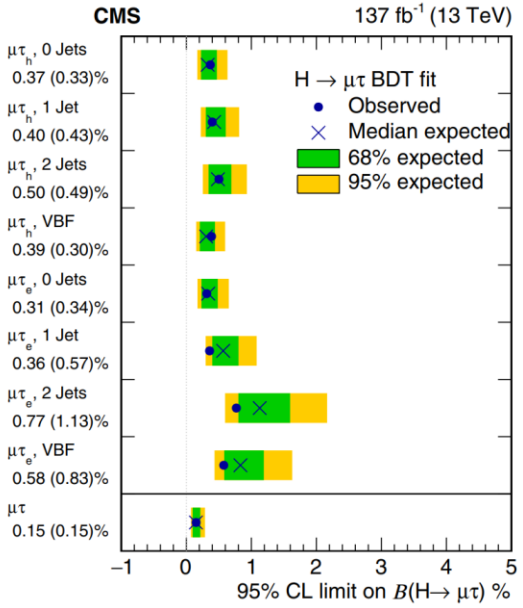
- The corresponding CMS results published earlier:

Yukawa coupling:

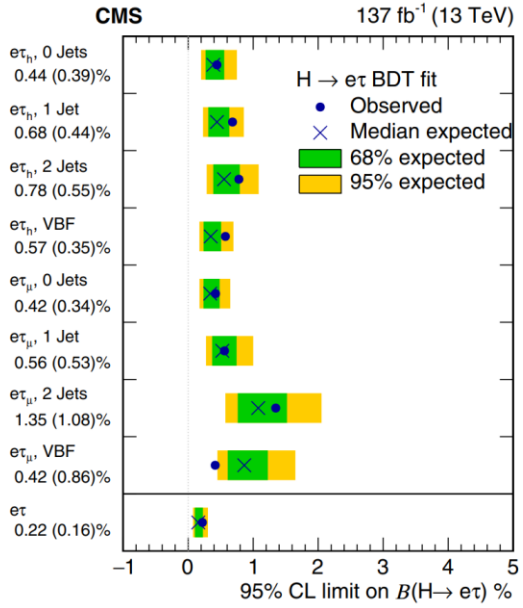
$$\sqrt{|Y_{\tau e}|^2 + |Y_{e\tau}|^2} < 0.00135$$

$$\sqrt{|Y_{\tau\mu}|^2 + |Y_{\mu\tau}|^2} < 0.00111$$

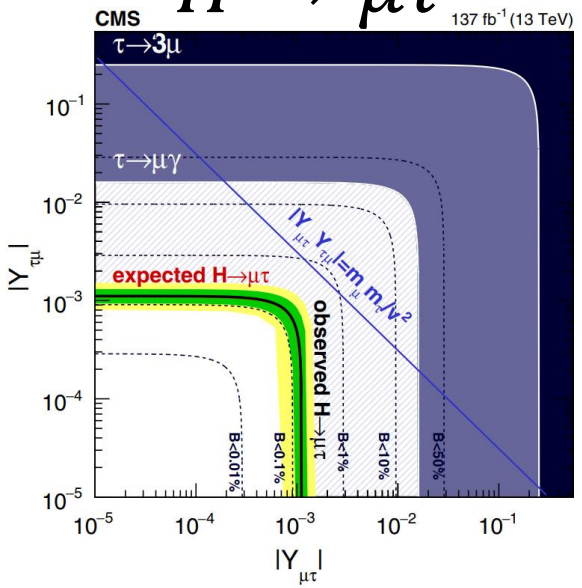
$H \to \mu\tau$



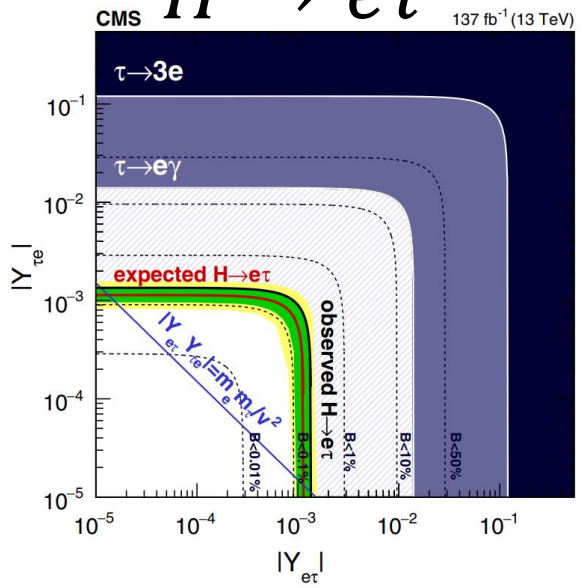

$H \to e\tau$




$H \to \mu\tau$



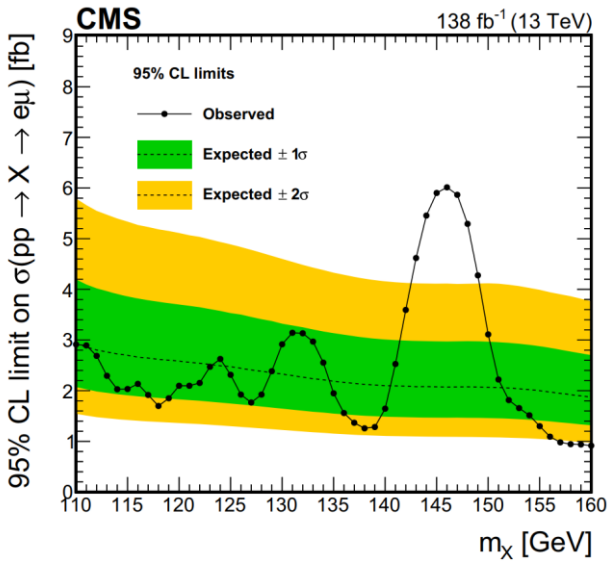

$H \to e\tau$

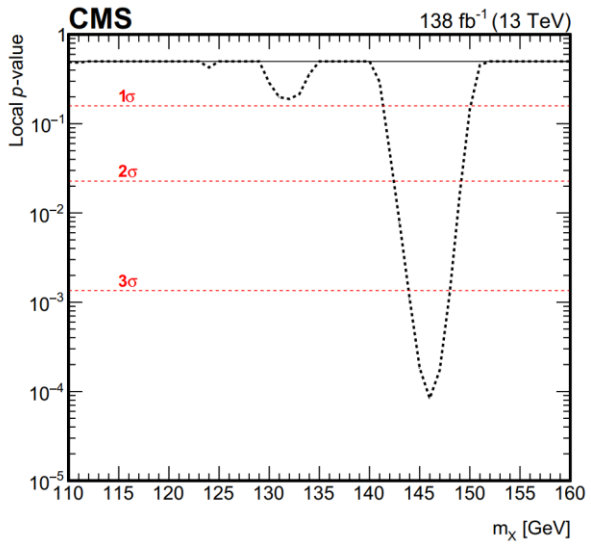


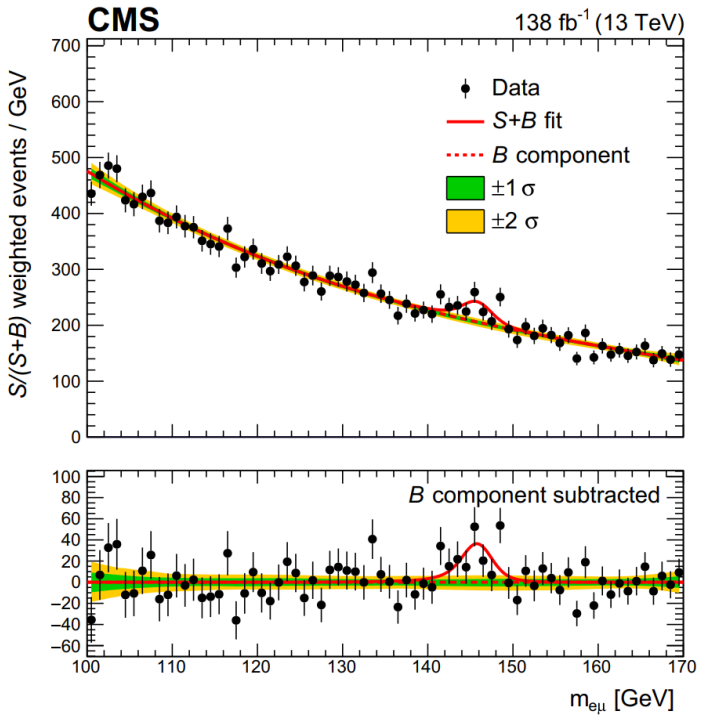
# $H \rightarrow e\mu$ at CMS

**Phys.Rev.D 108 (2023) 7, 072004**

- Searched H → eμ decay; no excess, set $4.4 \times 10^{-5}$ upper limit at 95% CL.
- Focused on ggH and VBF; targeted prompt $e\mu$ pairs.
- $m_{e\mu}$ distribution analysis confirms data-background alignment; CLs criterion used for branching fraction limits.

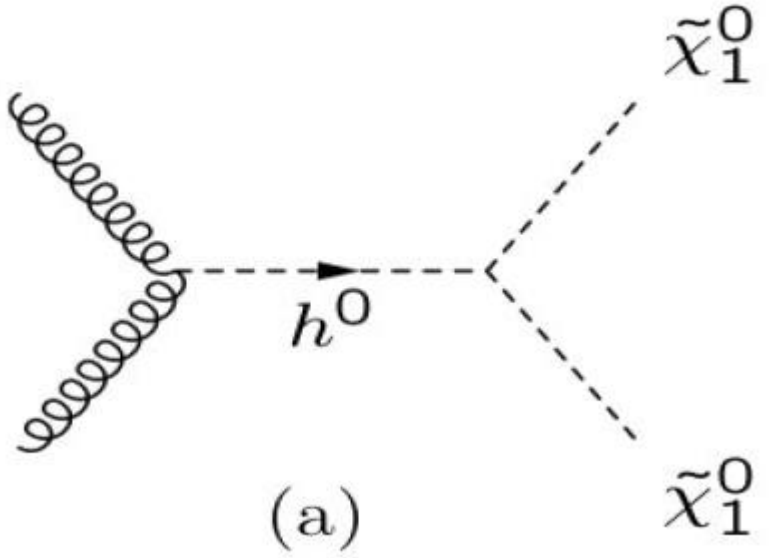


# Higgs decays to long-lived particles (H → LLPs)

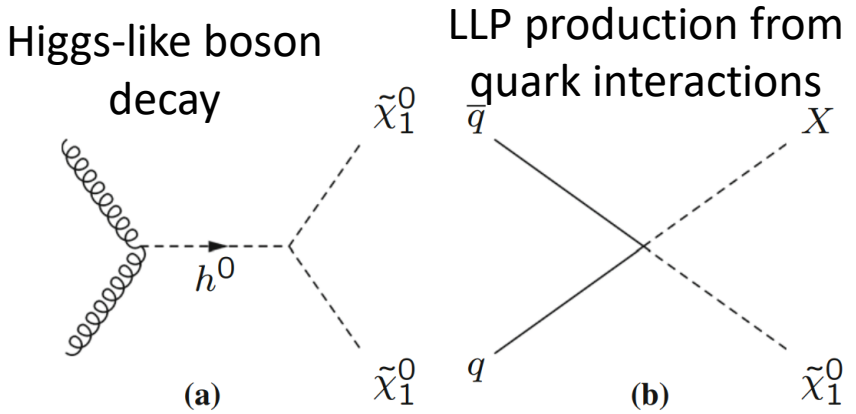
- Suppose a new massive, long-lived particle exists: it would be a clear sign for new physics
- Long-lived particles (LLPs) appear in many BSM scenarios:
  - Compressed SUSY, AMSB (Anomaly Mediated Supersymmetry Breaking), heavy neutral leptons, etc

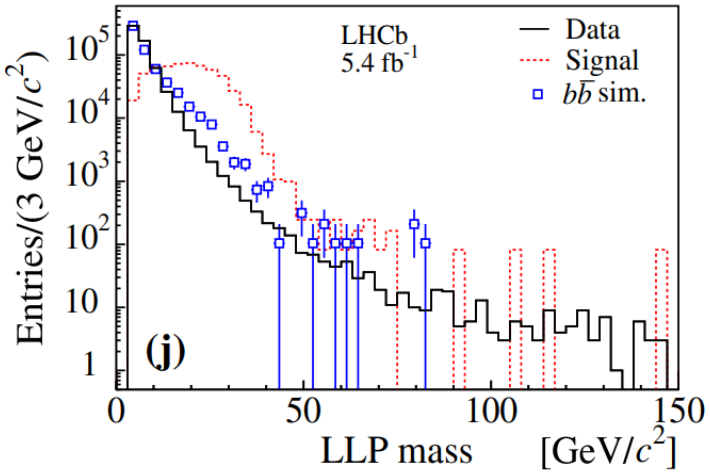


# $H \rightarrow LLPs$ at LHCb

***Eur.Phys.J.C* 82 (2022) 4, 373**

- Two LLP production processes:
  - (a) A Higgs-like boson (mass 30 to 200 GeV/c²) decaying into LLPs and
  - (b) Direct LLP production from quark interactions (LLP masses 10 to 90 GeV/c²).
- The LLP ($\tilde{\chi}_1^0$) decays into a muon and two quarks.
- Signal events selected based on displaced vertex containing a high-pT muon; MVA for background suppression, a data-driven approach for background modelling.



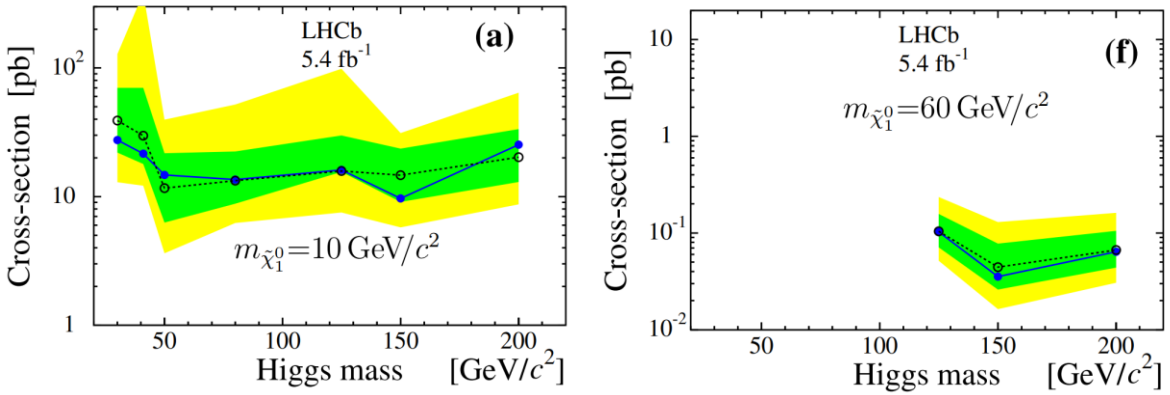



# $H \rightarrow LLPs$ at LHCb

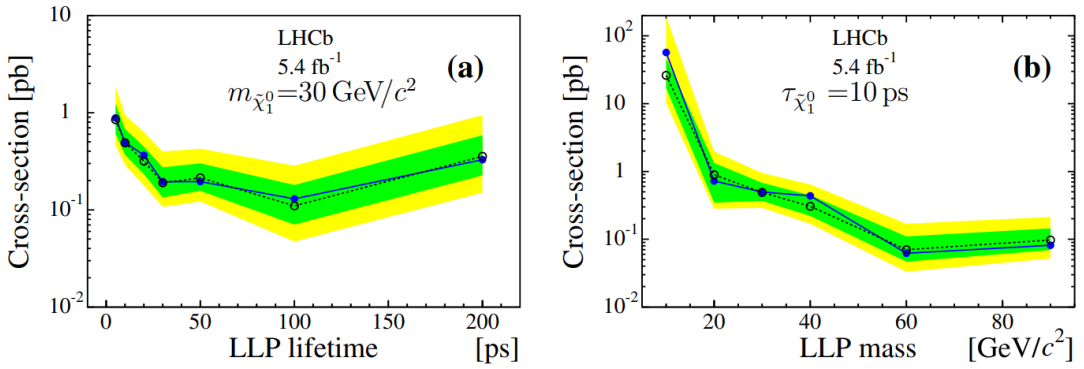
*Eur.Phys.J.C* **82 (2022) 4, 373**

- No evidence of these long-lived states was observed.
- Set upper limits on the production cross-section times branching ratio for each model considered.

Upper limits for LLPs via a Higgs-like boson decay




Upper limits for direct, non-resonant, LLP production



# Summary and outlook

- The SM Higgs, discovered 11 years ago, has well-studied production and decay patterns.
- BSM theories predict exotic Higgs decays, hinting at new physics.
- Focus on light (pseudo) scalars, invisible decays (dark sector), Lepton Flavor Violation (LFV), and Long-Lived Particles (LLPs), studies conducted using data from CMS, ATLAS, and LHCb.
- No significant excess found in exotic decay channels. Results led to stringent limits on branching ratios and cross-sections for these decays.
- Ongoing research to explore Higgs boson's role in uncovering new physics.
- Eager anticipation for new insights in upcoming LHC Run 3.

# Backup slides

# $H \to e\mu$ at ATLAS

***Phys.Lett.B* 801 (2020) 135148**

- $H \to e\mu$ decay search;
- Analysis involved $ee$ and $e\mu$ channels;
- No significant signal, observed upper limit $6.2 \times 10^{-5}$ at 95% CL.