

Exotic $h \rightarrow Za$ Higgs decays into τ leptons

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Why exotic Higgs decays (EHD)?

- EHD are among the most promising areas to search for new physics.
- Possible renormalizable interactions of the Higgs open space for its decay into BSM states.
Curtin et al [1312.4992], Cepeda et al [2111.12751]
- The HL-LHC would be able to constraint $BR(h \rightarrow X) \gtrsim 4\%$ through a global fit to Higgs data.
Blas et al [1905.03764]
- The symmetric decay $h \rightarrow aa$ ($h \rightarrow XX$) have received the most attention so far.
ATLAS [1505.01609, 1802.03388], CMS [1805.04865, 2005.08694]
- Although less explored, the asymmetric decay $h \rightarrow Za$ is being investigated, especially for $a \rightarrow \ell\ell$ and $a \rightarrow \gamma\gamma$ final states.
ATLAS[1802.03388, 2110.13673, 2111.01299, 2312.01942], LH [2002.12220]

Why $h \rightarrow Za, Z \rightarrow \mu\mu, a \rightarrow \tau\tau$?

- Experimental searches focus on $a \rightarrow \mu\mu$ since it is a cleaner final state.
ATLAS [1802.03388, 2110.13673], CMS [2111.01299],

- However, for concrete models like ALPs or 2HDM+a,
Bauer et al [1708.00443], Brivio et al [1701.05379]
Ipek et al [1404.3716], No [1509.01110], Goncalves et al [1611.04593], Bauer et al [1701.07427]

$$\frac{BR(a \rightarrow \mu\mu)}{BR(a \rightarrow \tau\tau)} \approx \frac{m_\mu^2}{m_\tau^2} \approx 3.6 \times 10^{-3}$$

- Even considering that the $\tau\tau$ final state is less clean, it could yield a larger sensitivity.
- $a \rightarrow \tau\tau$ is then a highly relevant channel for $3.5 \text{ GeV} \lesssim m_a \lesssim 33 \text{ GeV}$.
- A (very) preliminary study has been done for LH 2019.*

LH [2002.12220]

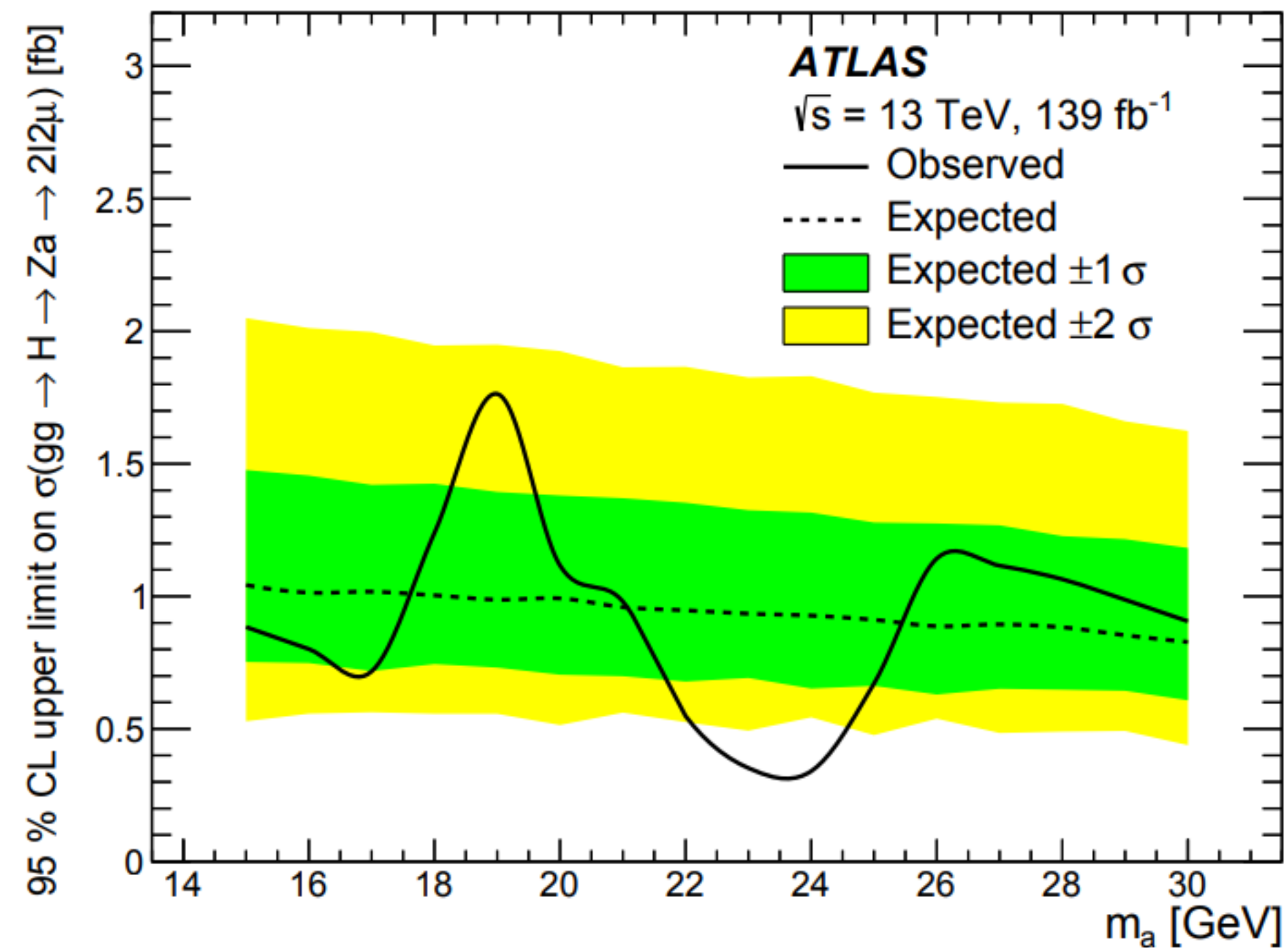
* Work done by A. Bharucha, J. M. Butterworth, N. Desai, S. Gascon-Shotkin, S. Jain, A. Lesauvage, G. Moreau, S. Mutzel, J. M. No, J. Quevillon, C. Smith, K. Tobioka, N. Vignaroli, S. L. Williamson, and J. Zurita.

Related experimental searches

To better understand the proposed process, we first study two searches involving similar features:

ATLAS at 13 TeV for $h \rightarrow Za \rightarrow \mu\mu\ell\ell$

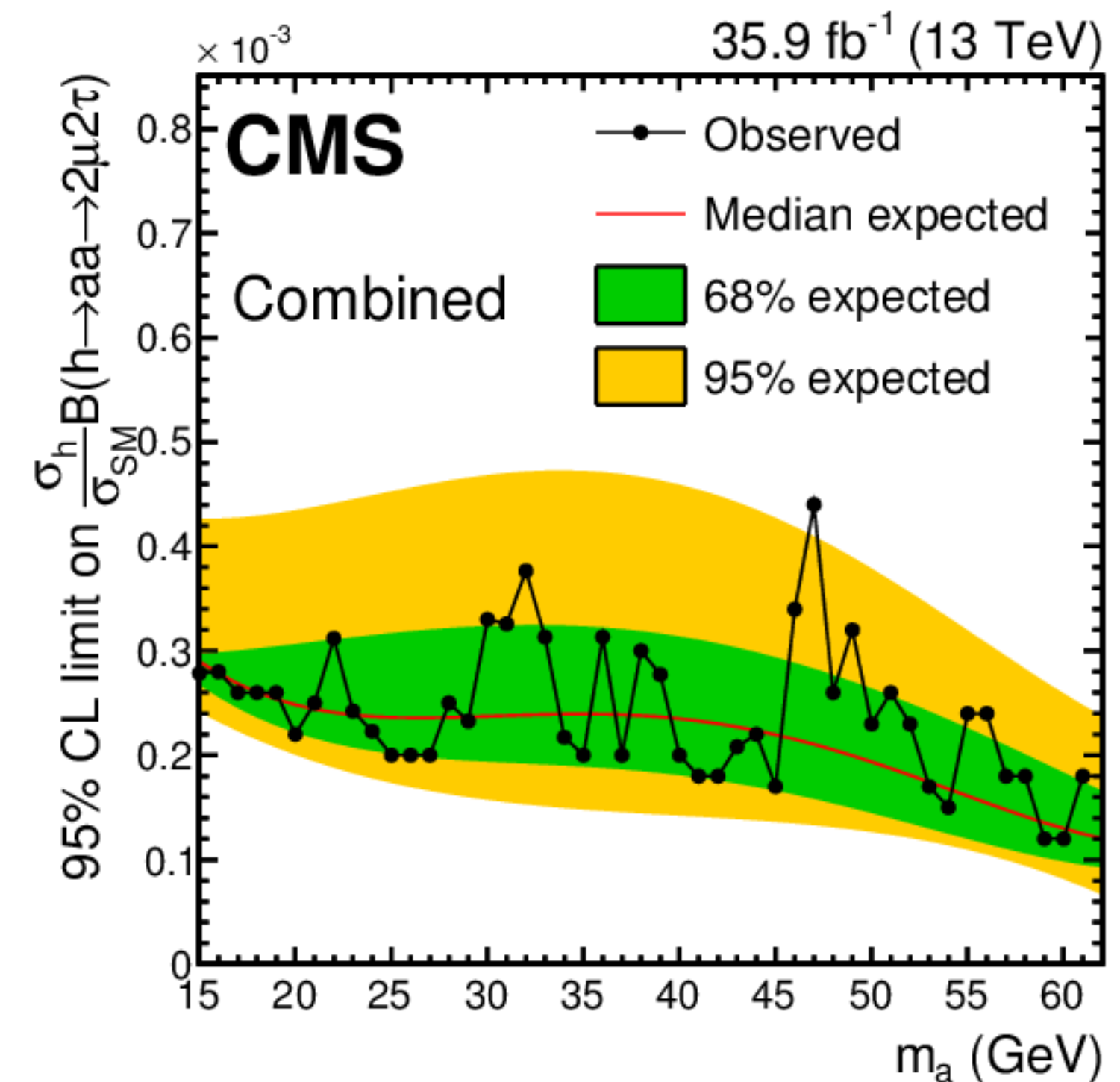
Limits on total cross section:



ATLAS [2110.13673]

CMS at 13 TeV with $h \rightarrow aa \rightarrow \mu\mu\tau\tau$

Limits on BR for symmetric Higgs decay:



CMS [1805.04865]

Proposal

Study $pp \rightarrow h \rightarrow Za \rightarrow \mu\mu\tau\tau$ for $m_a \lesssim 33$ GeV (on-shell region) in four possible reco-level final states (same ones as the CMS search in $pp \rightarrow h \rightarrow aa \rightarrow \mu\mu\tau\tau$):

- $\mu\mu + e\mu$:

- $\mu\mu + e\tau_h$

- $\mu\mu + \mu\tau_h$

- $\mu\mu + \tau_h\tau_h$

Model-independent simplified interpretation considering as free parameters m_a and $BR(h \rightarrow Za, a \rightarrow \tau\tau)$:

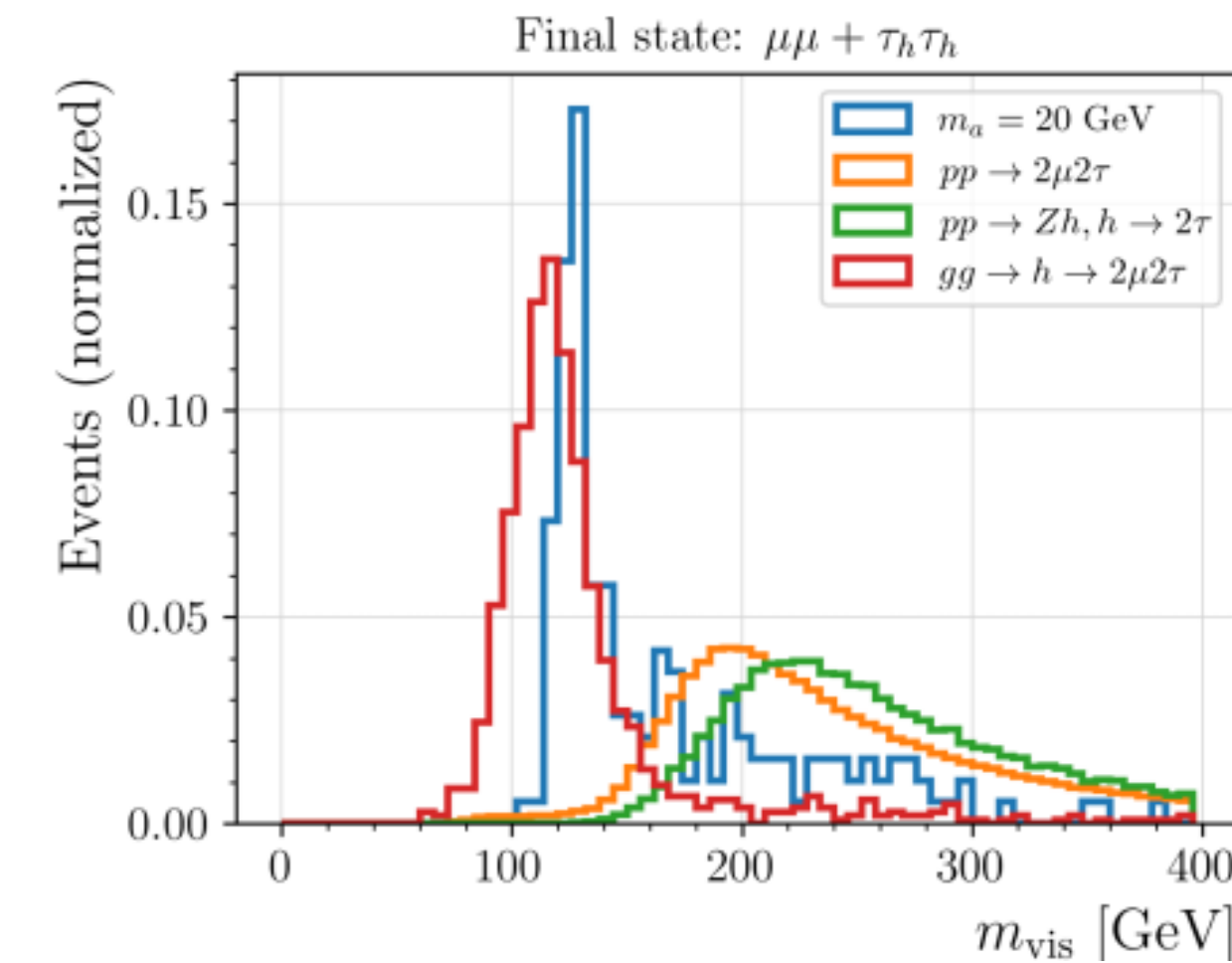
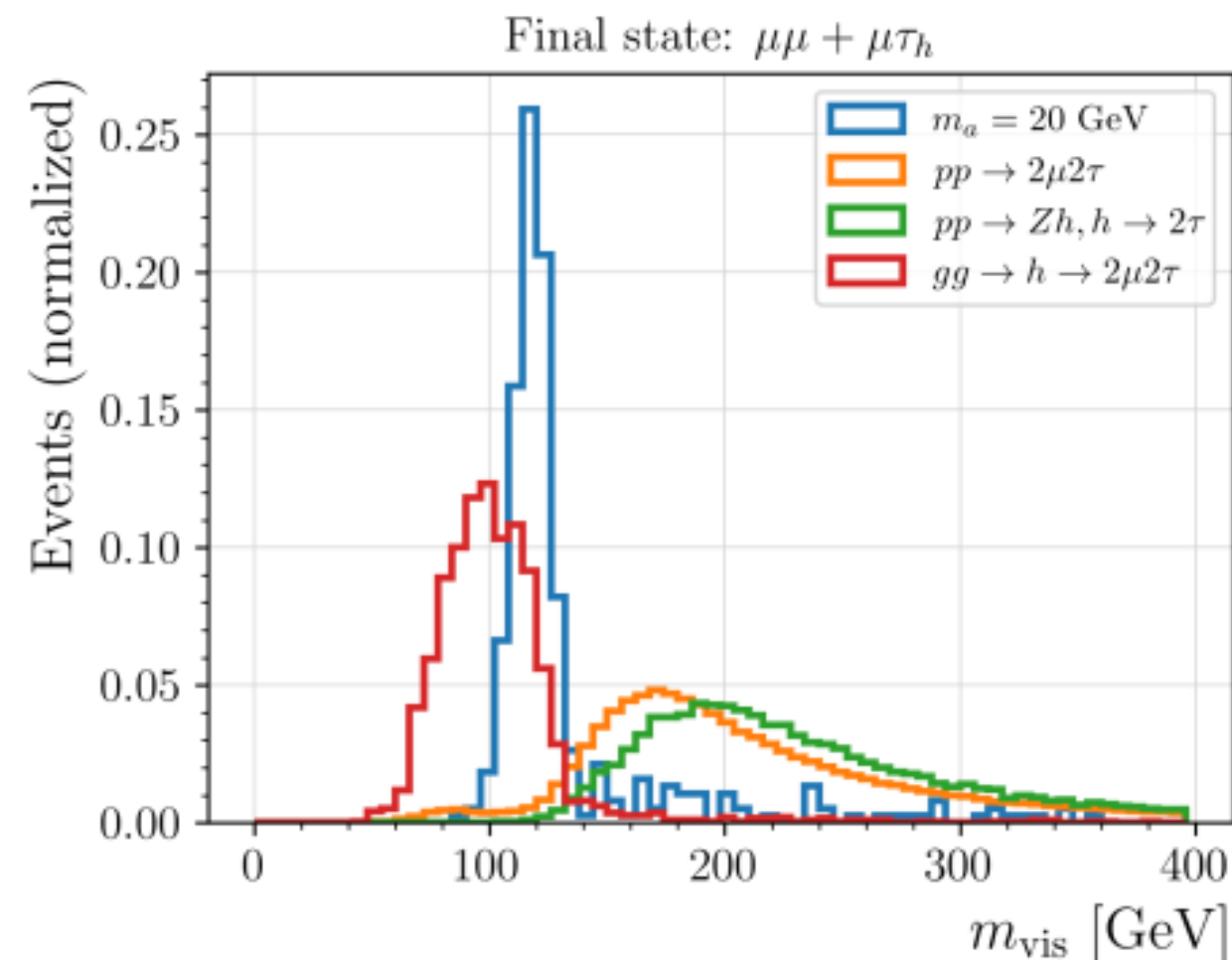
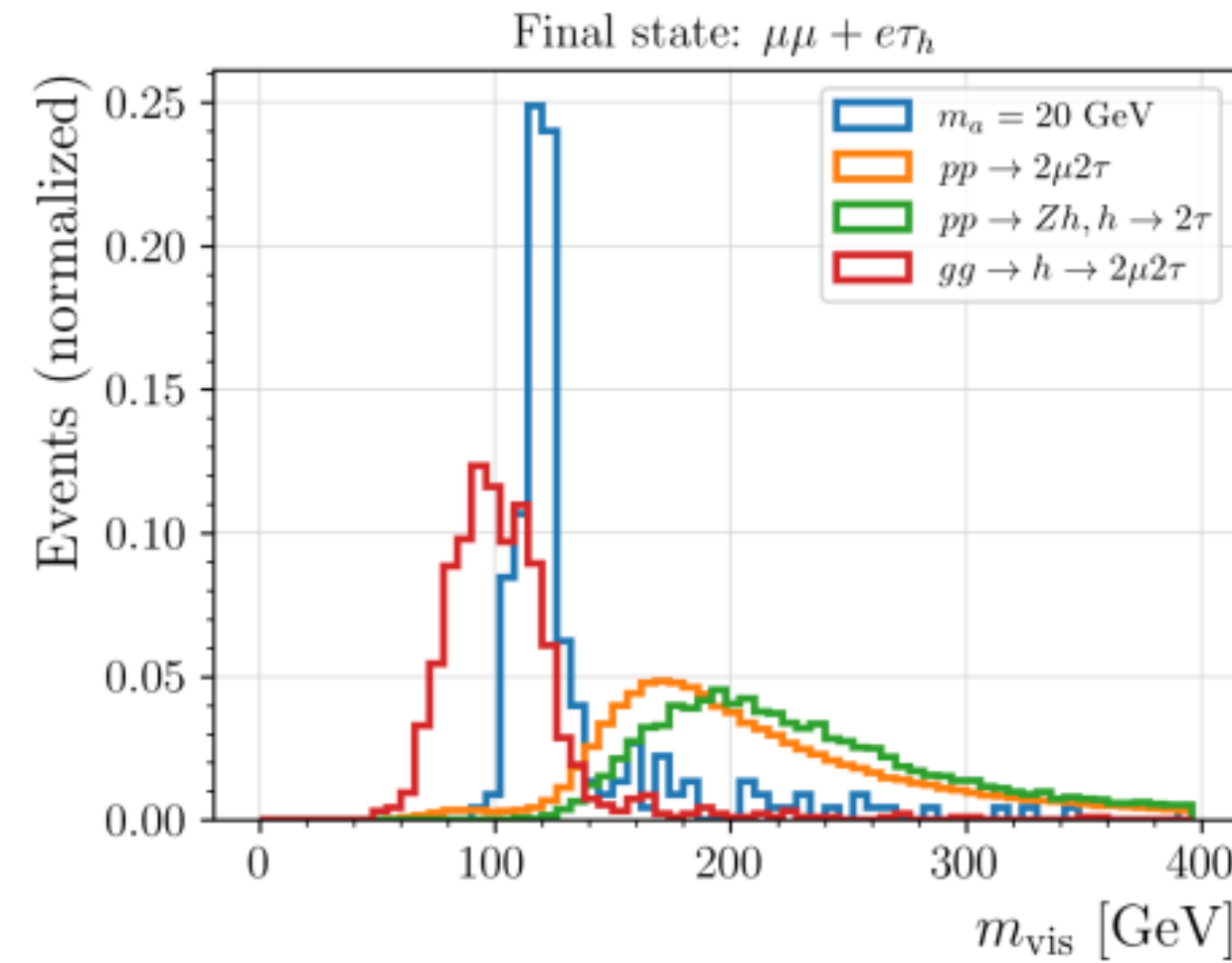
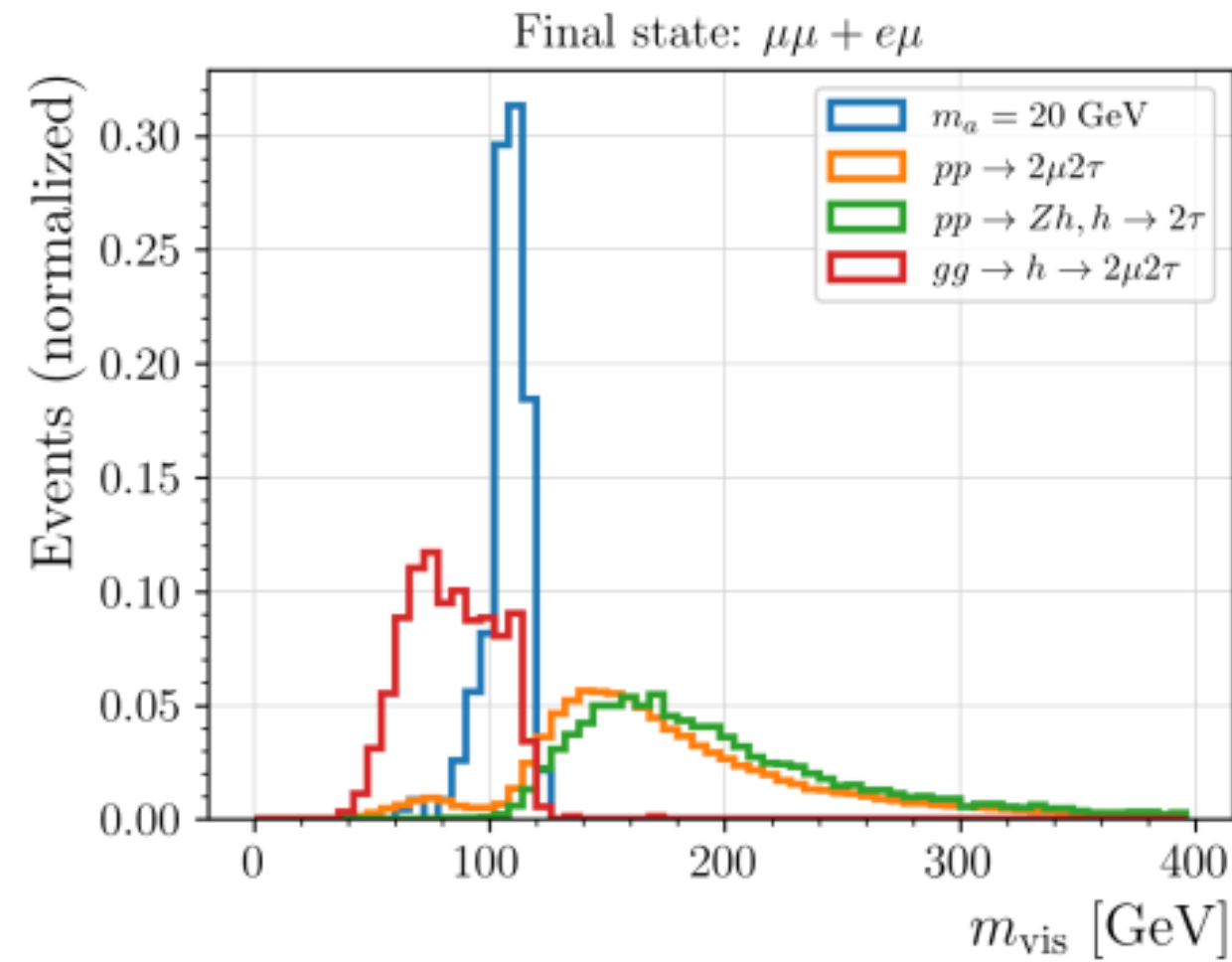
$$N_s = \sigma(pp \rightarrow h) \times BR(Z \rightarrow \mu\mu) \times BR(h \rightarrow Za, a \rightarrow \tau\tau) \times \mathcal{L} \times \epsilon(m_a)$$

Event Selection Criteria

Our event selection is based on both CMS and ATLAS analyses. We applied the following baseline criteria on generated events using MG5 + Pythia + Delphes:

- Muons: $p_T > 5$ GeV and $|\eta| < 2.4$
- Electrons: $p_T > 7$ GeV and $|\eta| < 2.5$
- Hadronically decaying taus (τ_h): $p_T > 18.5$ GeV and $|\eta| < 2.3$
- Additional cuts on p_T for μ fulfilling online and offline triggers in the related CMS search
- Events should have a pair of OS muons ($\mu\mu$) and a pair of OS tau candidates ($e\mu$, $e\tau_h$, $\mu\tau_h$, or $\tau_h\tau_h$)
- $\Delta R > 0.3$ (or $\Delta R > 0.4$ if the event has τ_h)

Signal + dominant background after baseline criteria:



Additional criteria:

- $\mu\mu + e\mu$: $m_{\text{vis}} < 110$ GeV
- $\mu\mu + e\tau_h$ or $\mu\mu + \mu\tau_h$: $m_{\text{vis}} < 120$ GeV
- $\mu\mu + \tau_h\tau_h$: $m_{\text{vis}} < 130$ GeV

The m_{vis} cut renders $pp \rightarrow Zh$ negligible

- $m_{34} < m_{12}$
- $50 \text{ GeV} < m_{12} < 106 \text{ GeV}$

Broad window to ensure sufficient background events for statistical robustness

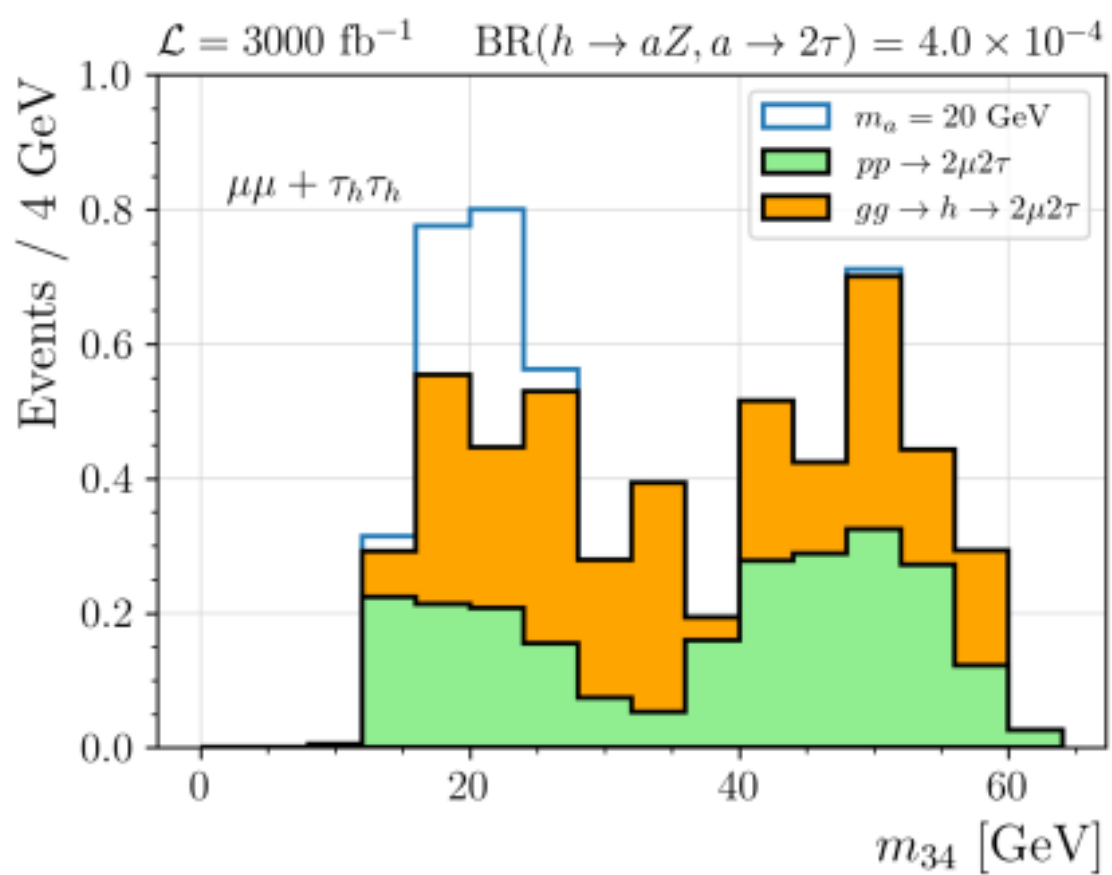
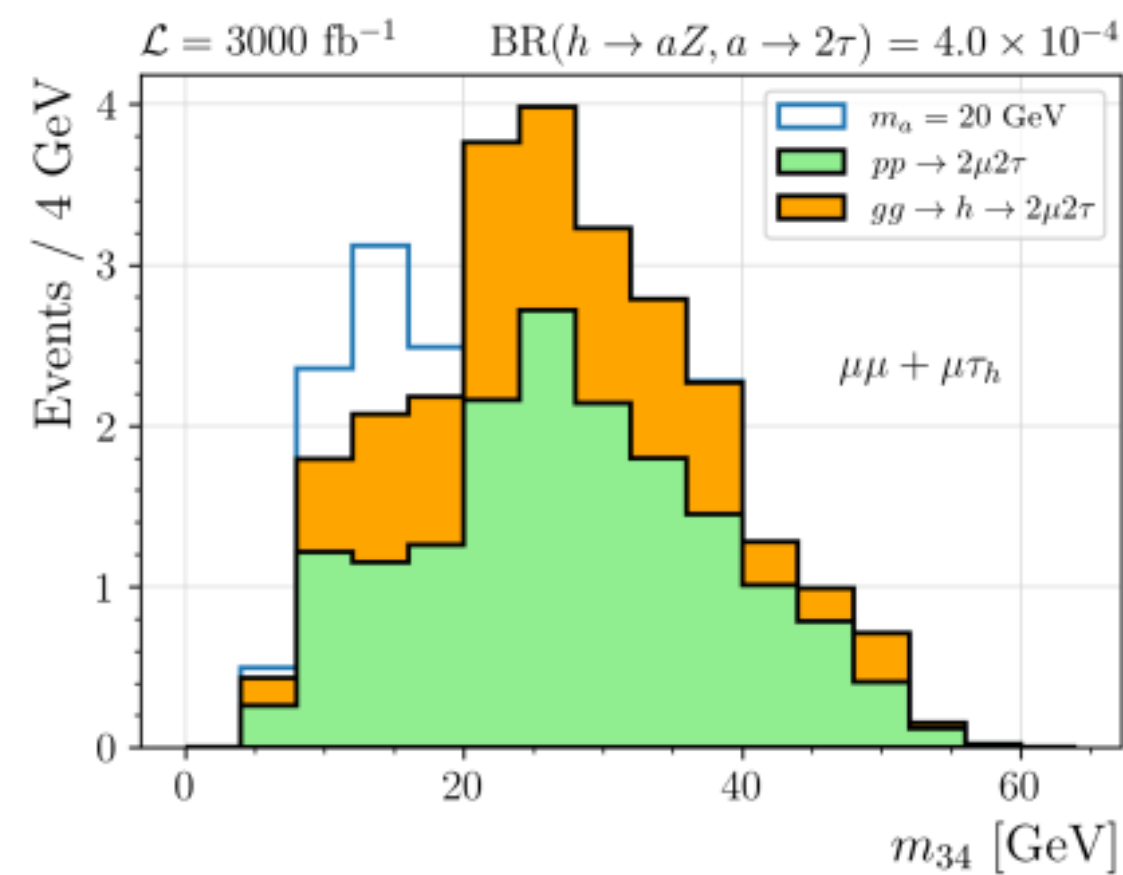
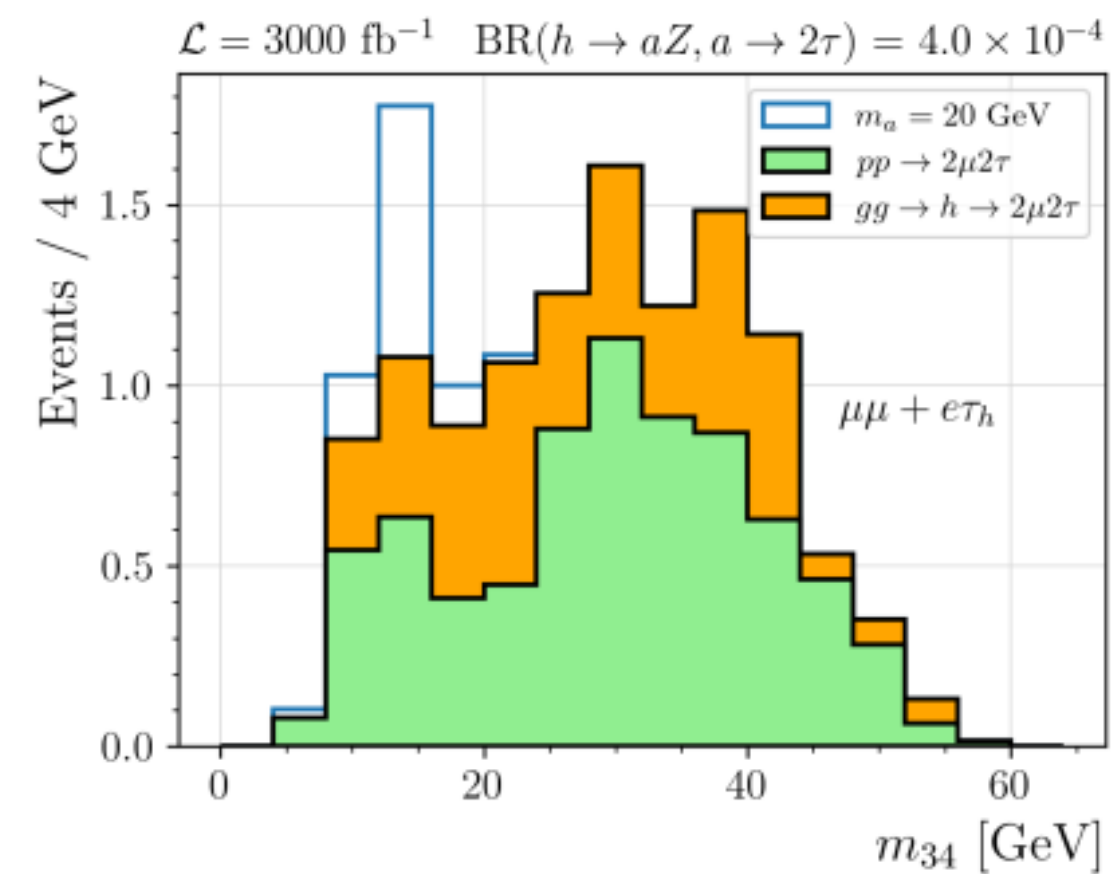
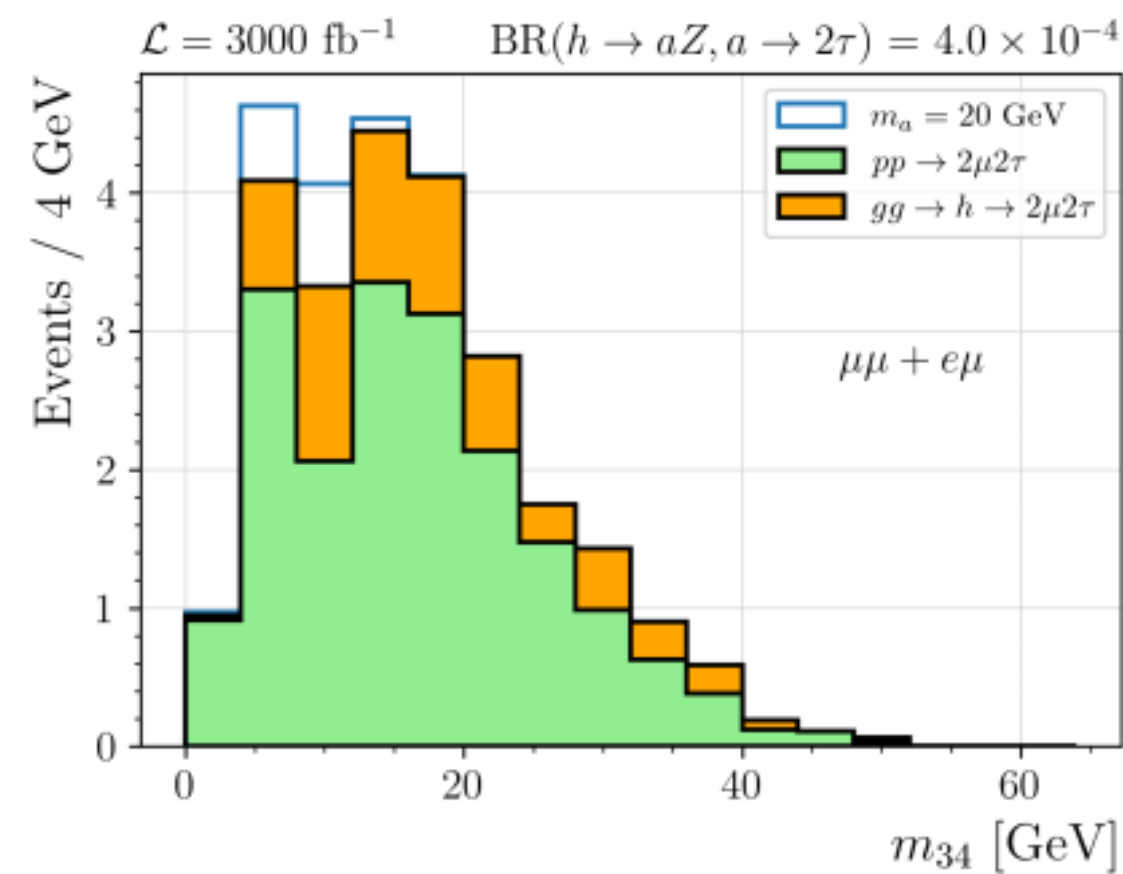
- b-jet veto ($p_T^j > 20 \text{ GeV}$)

Index 12: Z decayed particles

Index 34: a decayed particles

Considering for the signal: $N_s = \sigma(pp \rightarrow h) \times BR(Z \rightarrow \mu\mu) \times BR(h \rightarrow Za, a \rightarrow \tau\tau) \times \mathcal{L} \times \epsilon(m_a)$

Signal + (irreducible) background:



Fixed values:

N³LO gluon fusion production cross-section:

$$\sigma(pp \rightarrow h) = 54.67 \text{ pb}$$

Anastasiou et al [1602.00695]

Leptonic Z branching fraction:

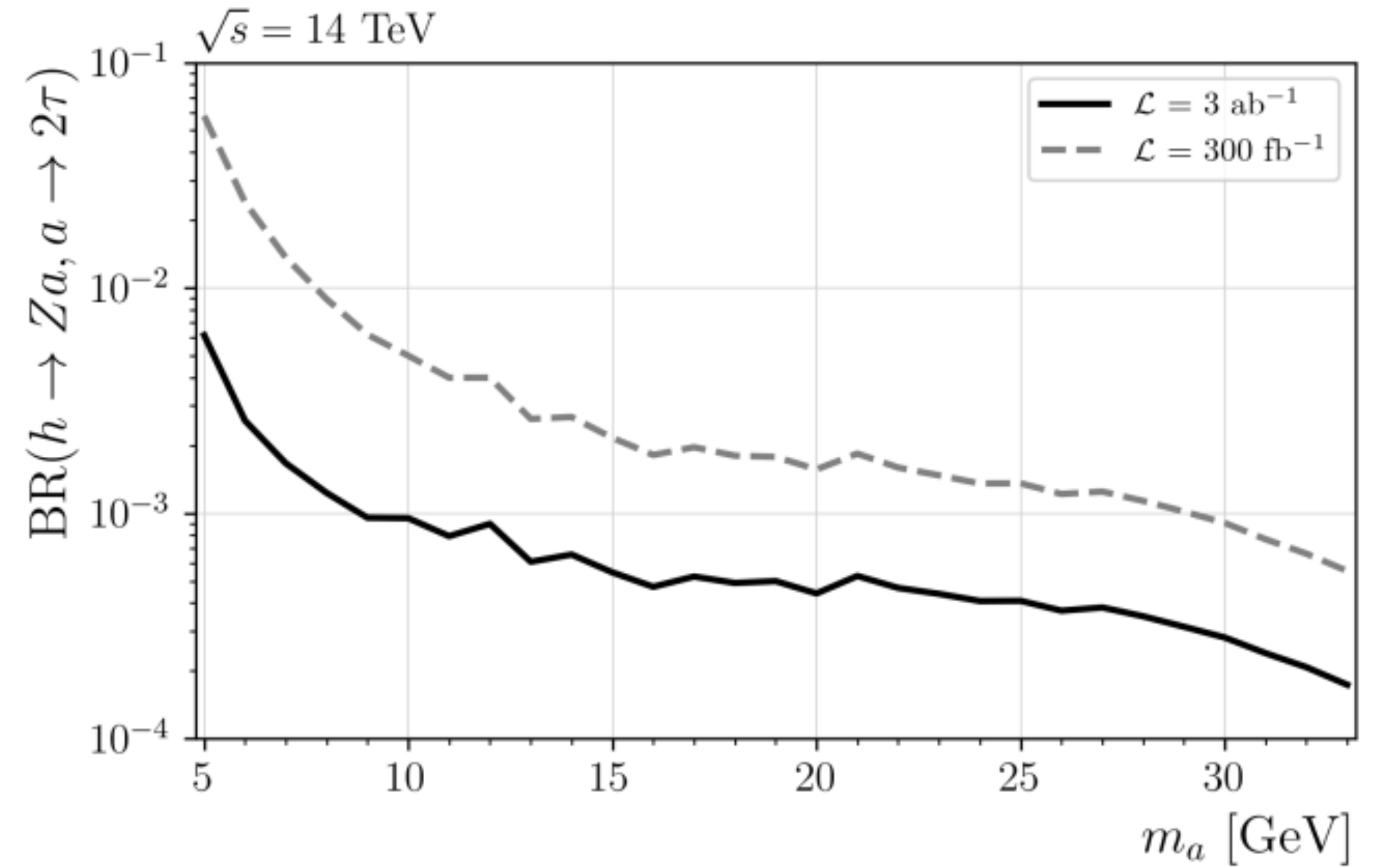
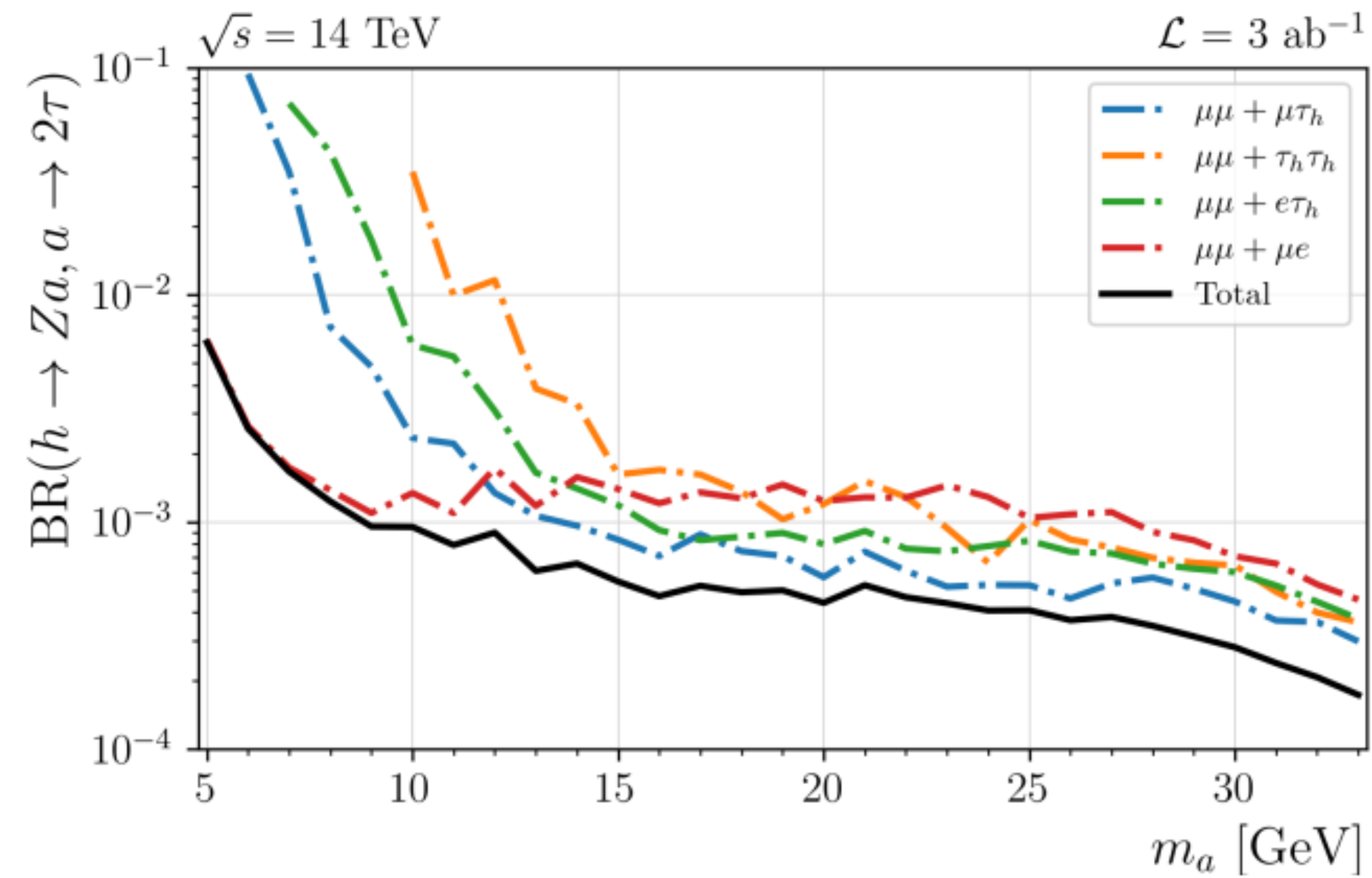
$$BR(Z \rightarrow \mu\mu) = 0.0337$$

PDG (2024)

Subdominant backgrounds $pp \rightarrow t\bar{t} + Z$ ($Z \rightarrow \mu\mu$), $pp \rightarrow \mu\mu\tau\tau + X$ ($X = \ell\ell, \nu\nu$) are negligible

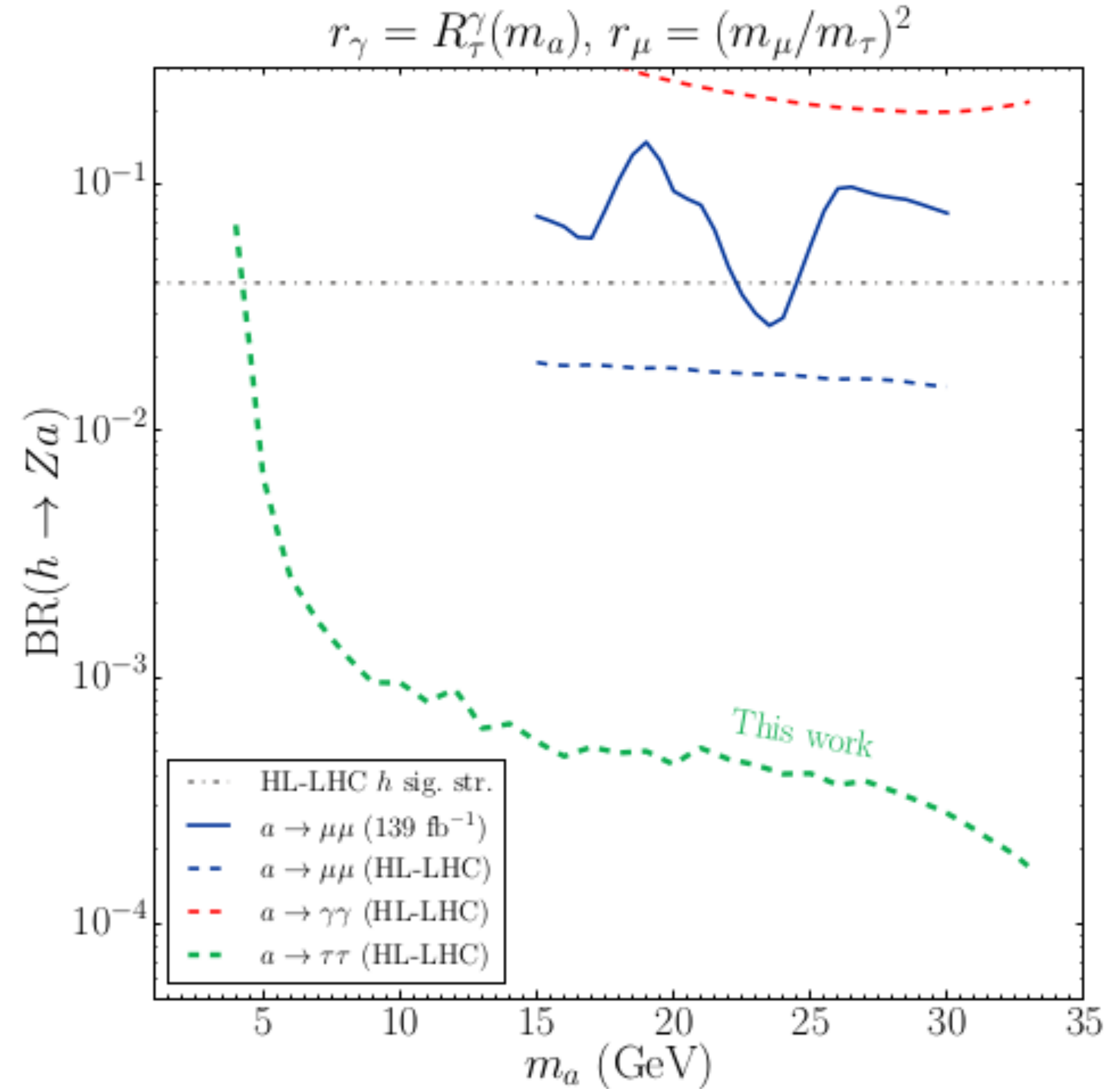
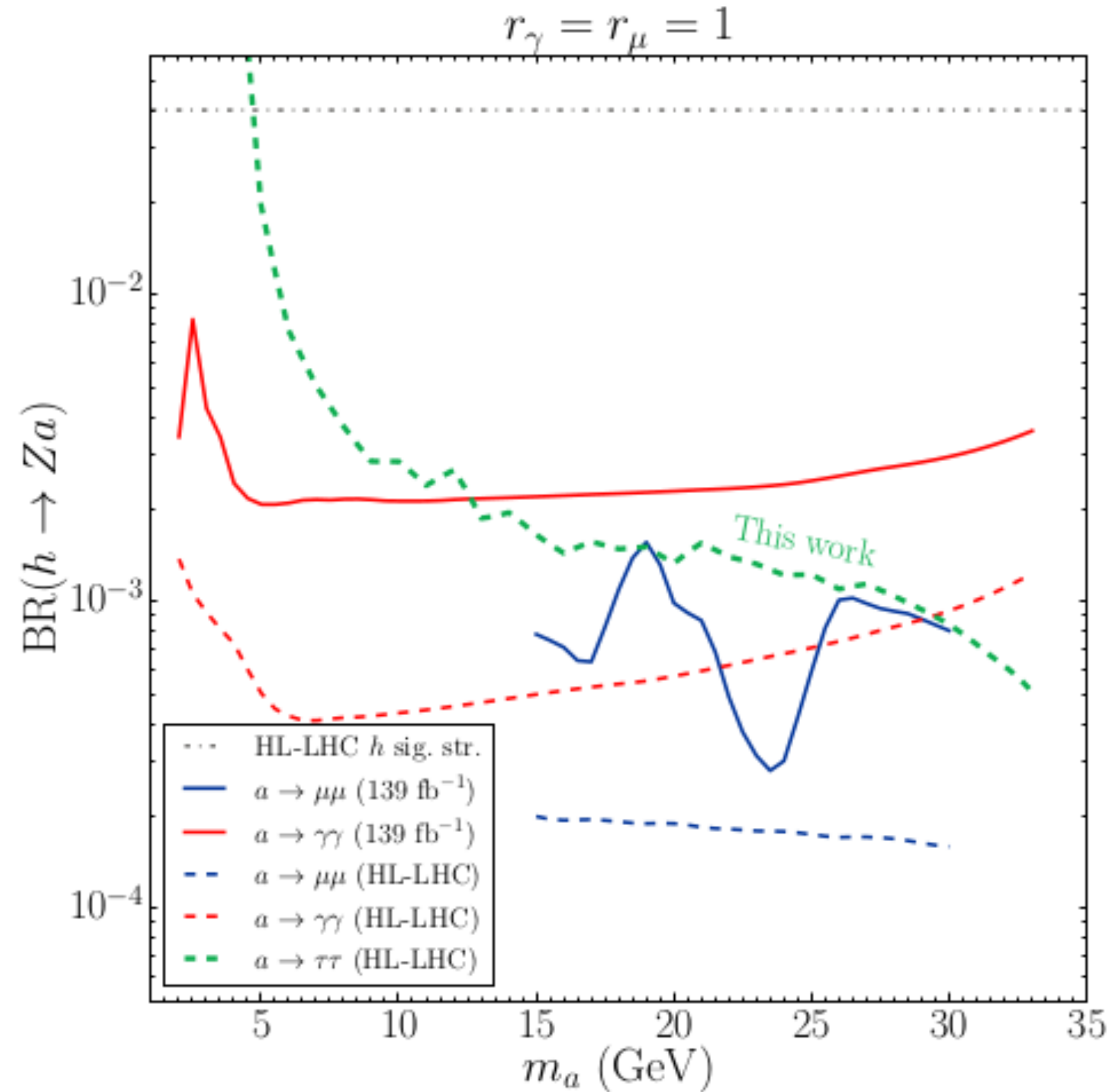
Results

Model-independent expected **95 % CL** exclusion limits (using m_{34} for Binned-Likelihood fit), and projected in m_a and $BR(h \rightarrow Za, a \rightarrow \tau\tau)$ parameter space:



Results

$$r_\gamma \equiv \frac{\text{BR}(a \rightarrow \gamma\gamma)}{\text{BR}(a \rightarrow \tau\tau)} \quad , \quad r_\mu \equiv \frac{\text{BR}(a \rightarrow \mu\mu)}{\text{BR}(a \rightarrow \tau\tau)}$$



ALPs: accessing the $(g - 2)_\mu$ parameter space

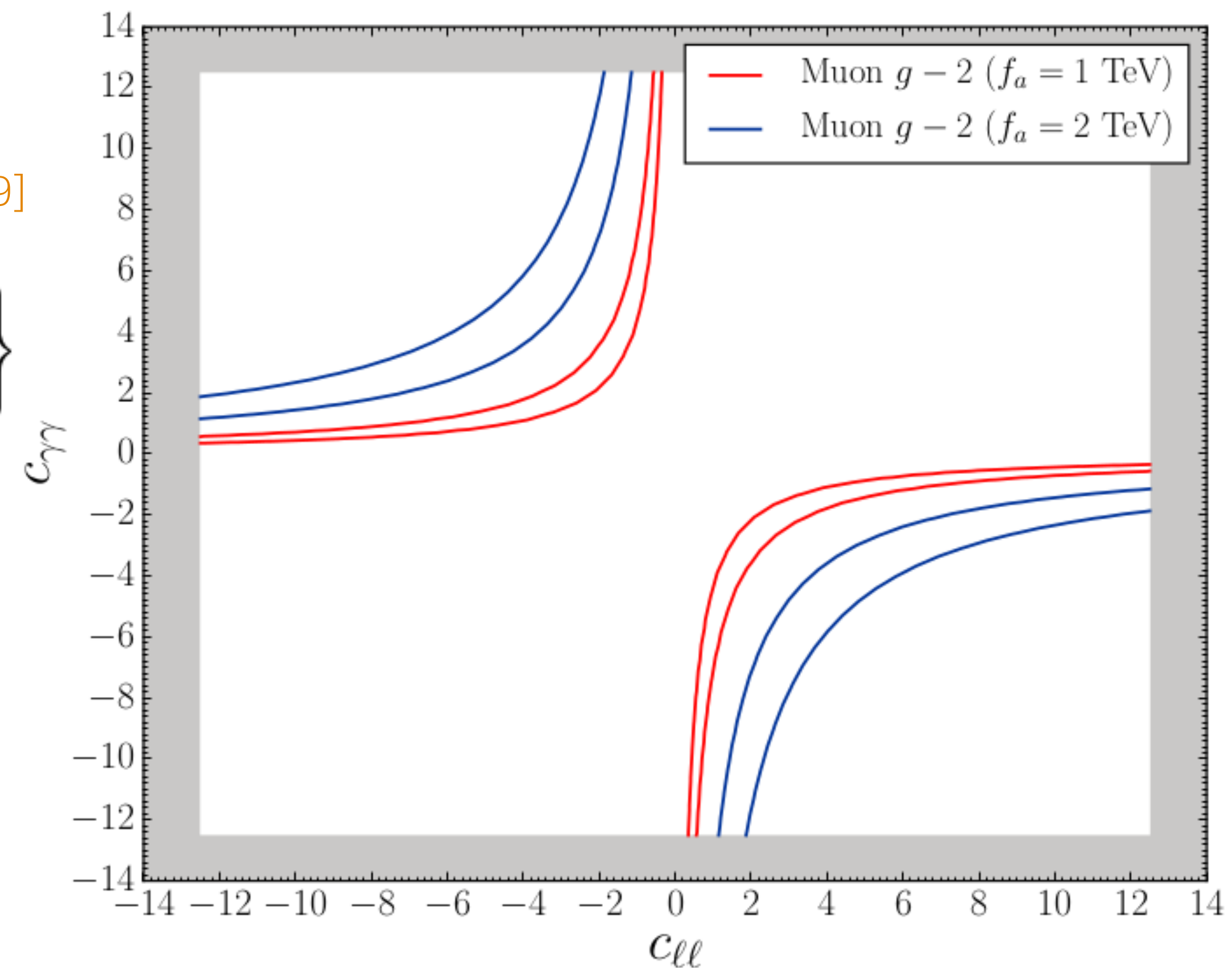
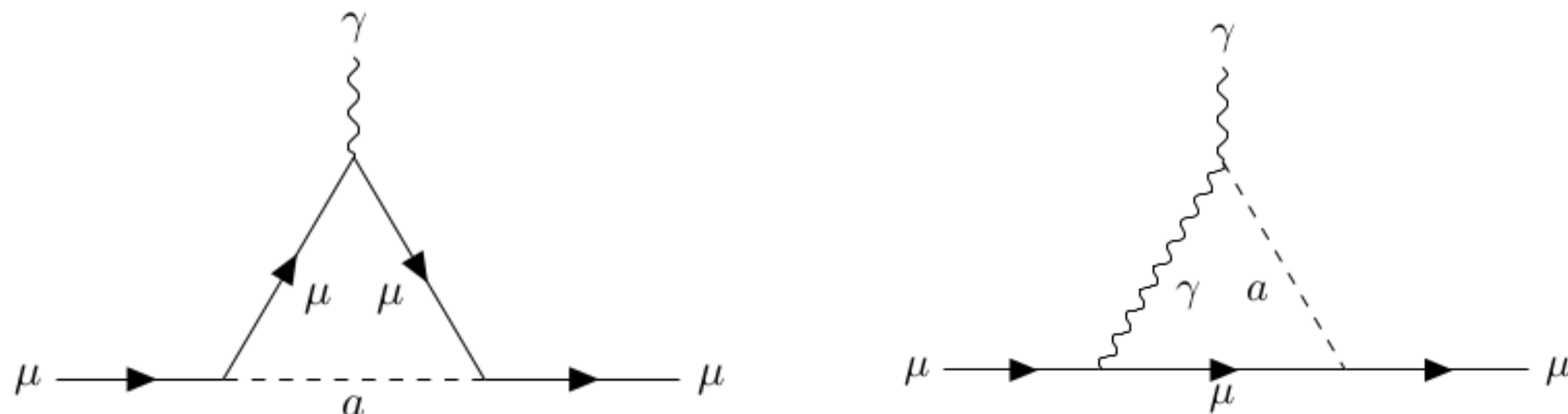
$$\delta a_\mu \equiv a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (24.9 \pm 4.8) \times 10^{-10} \quad \text{Muon } g-2 \text{ [2308.06230]}$$

The anomaly at face value can be explained via a light ALP that couples to SM leptons, photons and the 125 GeV Higgs boson:

$$\mathcal{L}_{\text{ALP}} \supset \frac{c_{\gamma\gamma}}{f_a} a F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{c_{\ell\ell}}{f_a} \sum_\ell (\partial^\mu a) \bar{\ell} \gamma_\mu \gamma_5 \ell$$

Bauer et al [1708.00443], Brivio et al [1701.05379]

$$\delta a_\mu \simeq -m_\mu^2 \left\{ \left(\frac{c_{\ell\ell}}{4\pi f_a} \right)^2 F_1 \left(\frac{m_a^2}{m_\mu^2} \right) + \frac{2 \alpha_{\text{EM}}}{\pi} \frac{c_{\ell\ell} c_{\gamma\gamma}}{f_a^2} \left[\ln \left(\frac{Q^2}{m_\mu^2} \right) + \delta_2 + 3 - F_2 \left(\frac{m_a^2}{m_\mu^2} \right) \right] \right\}$$

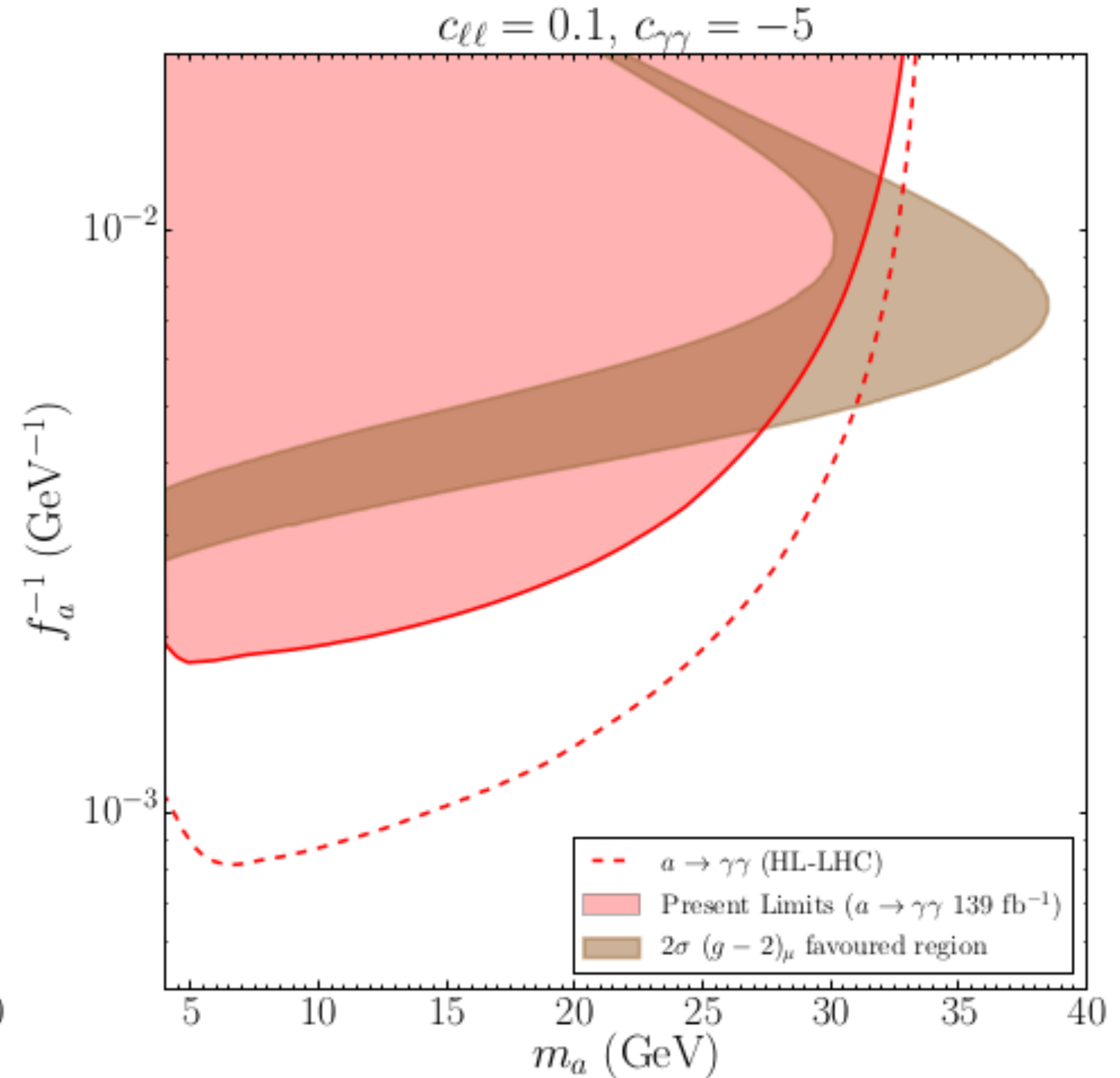
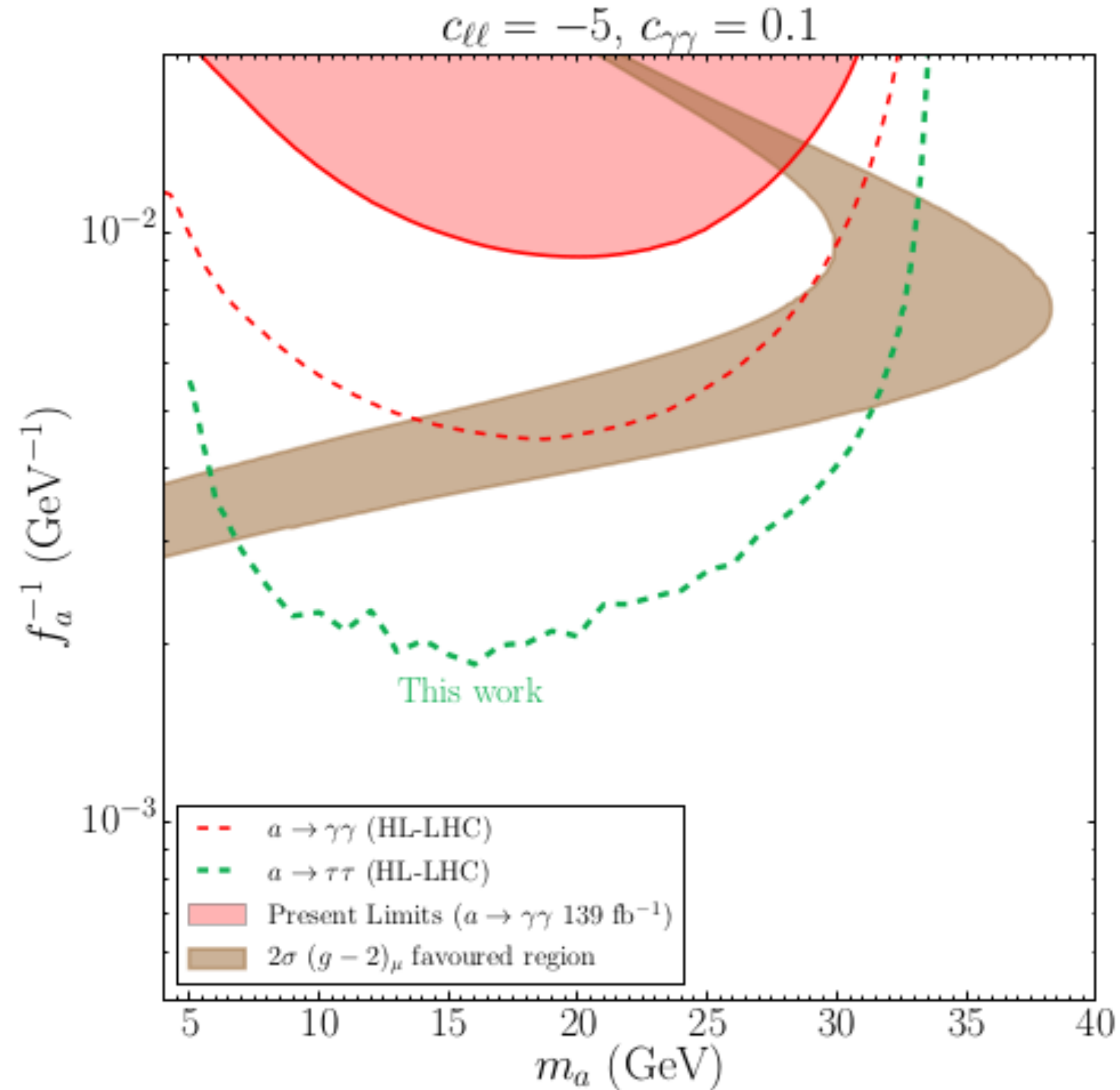


$$\Gamma_{\gamma\gamma} = \frac{m_a^3}{4\pi f_a^2} (c_{\gamma\gamma}^{\text{eff}})^2, \quad \Gamma_{\ell\ell} = \frac{m_a m_\ell^2}{8\pi f_a^2} (c_{\ell\ell}^{\text{eff}})^2 \sqrt{1 - \left(\frac{2m_\ell}{m_a}\right)^2}$$

Bonilla et al [2107.11392]

$$\Gamma_{h \rightarrow Z a} = \frac{m_h^3}{16\pi f_a^2} c_{hZa}^2 \lambda^{3/2}$$

$$\lambda = (1 - (m_Z^2 - m_a^2)/m_h^2)^2 - 4 m_Z^2 m_a^2 / m_h^4$$



For $|c_{\ell\ell}| \gg |c_{\gamma\gamma}|$ the $a \rightarrow \tau\tau$ search yields the strongest sensitivity

Conclusions

$pp \rightarrow h \rightarrow Za \rightarrow \mu\mu\tau\tau$ is a very promising search channel for $m_a \lesssim 33$ GeV:

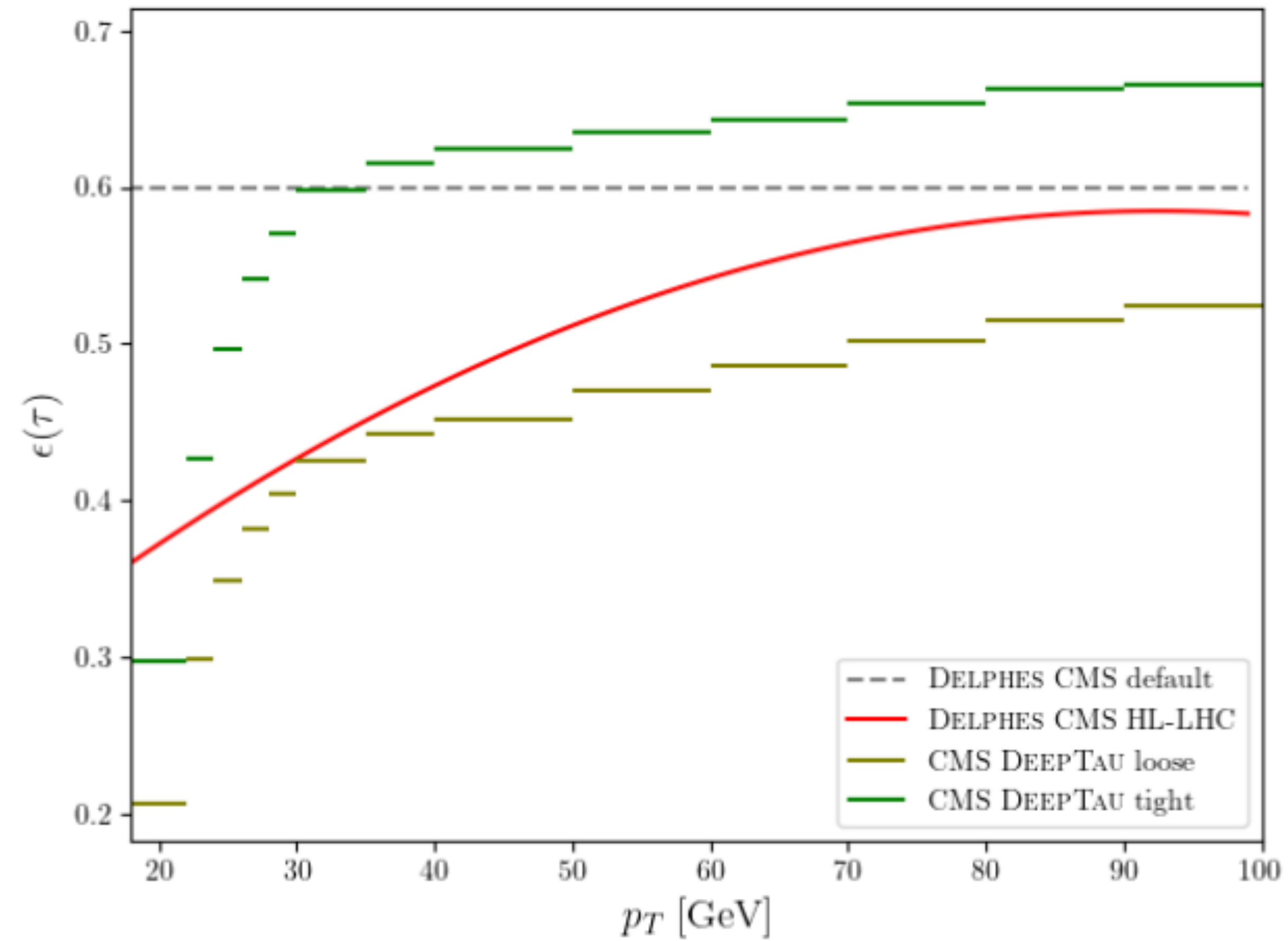
- We successfully defined a signal region based in related and validated ATLAS and CMS searches.
- We set limits in a model-independent approach for m_a and $BR(h \rightarrow Za, a \rightarrow \tau\tau)$, below the expected limit for the global fit to all Higgs data, and more sensitive than the asymmetric searches with $a \rightarrow \mu\mu$ and $a \rightarrow \gamma\gamma$ in most expected scenarios ([WG1](#)).
- Model-dependent interpretation (ALP scenario) compatible with muon $g - 2$ anomaly.
- Future: explore ML supervised techniques ([WG2!](#)) to enhance discrimination between signal and background and improve sensitivity.

Thank you

Extra

τ_h -tagging efficiencies Run 2 vs projection HL-LHC:

CMS [2201.08458]



Extra

Cutflow for signal and dominant backgrounds:

Selection	Signal ($m_a = 20$ GeV)	$pp \rightarrow 2\mu 2\tau$ (0, 1 j matched)	$gg \rightarrow h \rightarrow 2\mu 2\tau$	$pp \rightarrow Zh$ ($h \rightarrow \tau\tau$)
Inclusive σ (fb)	0.74	22.5	9.57	0.83
Online μ -trigger	0.62	20.8	2.98	0.71
Offline μ -trigger	0.41	17.4	1.63	0.48
OS $\mu\mu$ pair + τ -candidate pair + ΔR isolation	0.0037	2.72	0.052	0.083
m_{vis} selection	0.0018	0.087	0.043	1.43×10^{-4}
$m_{\tau\tau}^{\text{vis}} < m_{\mu\mu}$	0.0018	0.036	0.018	1.03×10^{-4}
$m_{\mu\mu}$ selection	0.0017	0.015	0.0075	8.01×10^{-5}
b -jet veto	0.0016	0.015	0.0071	7.84×10^{-5}

Extra

More information about the ALP model:

$$\delta a_\mu \simeq -m_\mu^2 \left\{ \left(\frac{c_{\ell\ell}}{4\pi f_a} \right)^2 F_1 \left(\frac{m_a^2}{m_\mu^2} \right) + \frac{2\alpha_{\text{EM}} c_{\ell\ell} c_{\gamma\gamma}}{\pi f_a^2} \left[\ln \left(\frac{Q^2}{m_\mu^2} \right) + \delta_2 + 3 - F_2 \left(\frac{m_a^2}{m_\mu^2} \right) \right] \right\}$$

$$F_1(x) = 1 + 2x + x(1-x)\ln(x) - 2x(3-x)\sqrt{\frac{x}{4-x}} \arccos(\sqrt{x}/2)$$

Bauer et al [1708.00443]

$$F_2(x) = 1 - \frac{x}{3} + \frac{x^2}{6}\ln(x) + \frac{2+x}{3}\sqrt{x(4-x)} \arccos(\sqrt{x}/2)$$

$$\Gamma_{\gamma\gamma} = \frac{m_a^3}{4\pi f_a^2} (c_{\gamma\gamma}^{\text{eff}})^2 \quad , \quad \Gamma_{\ell\ell} = \frac{m_a m_\ell^2}{8\pi f_a^2} (c_{\ell\ell}^{\text{eff}})^2 \sqrt{1 - \left(\frac{2m_\ell}{m_a} \right)^2}$$

Bonilla et al [2107.11392]

$$c_{\gamma\gamma}^{\text{eff}} \simeq c_{\gamma\gamma} + \frac{\alpha_{\text{EM}} c_{\ell\ell}}{4\pi} \left[B_1 \left(\frac{4m_\tau^2}{m_a^2} \right) + B_1 \left(\frac{4m_\mu^2}{m_a^2} \right) \right]$$

$$c_{\ell\ell}^{\text{eff}} \simeq c_{\ell\ell} + \frac{\alpha_{\text{EM}} c_{\gamma\gamma}}{\pi} \left[3 \log \left(\frac{f_a^2}{m_\ell^2} \right) - 4 - \frac{2\pi^2}{3} - \frac{1}{2} \left(\log \left(\frac{m_\ell^2}{m_a^2} \right) + i\pi \right)^2 \right]$$