Exotic $h \to Za$ 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 $BR(h \to X) \gtrsim 4\,\%$ through a global fit to Higgs data.
  Blas et al [1905.03764]

- The symmetric decay $h \to aa$ $(h \to XX)$ have received the most attention so far.
  ATLAS [1505.01609, 1802.03388], CMS [1805.04865, 2005.08694]

- Although less explored, the asymmetric decay $h \to Za$ is being investigated, especially for $a \to \ell\ell$ and $a \to \gamma\gamma$ final states.
  ATLAS[1802.03388, 2110.13673, 2111.01299, 2312.01942], LH [2002.12220]

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

- Experimental searches focus on $a \to \mu\mu$ 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]

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

- Even considering that the $\tau\tau$ final state is less clean, it could yield a larger sensitivity.

- $a \to \tau\tau$ is then a highly relevant channel for 3.5 GeV $\lesssim m_a \lesssim 33$ GeV.

- A (very) preliminary study has been done for LH 2019.*

LH [2002.12220]

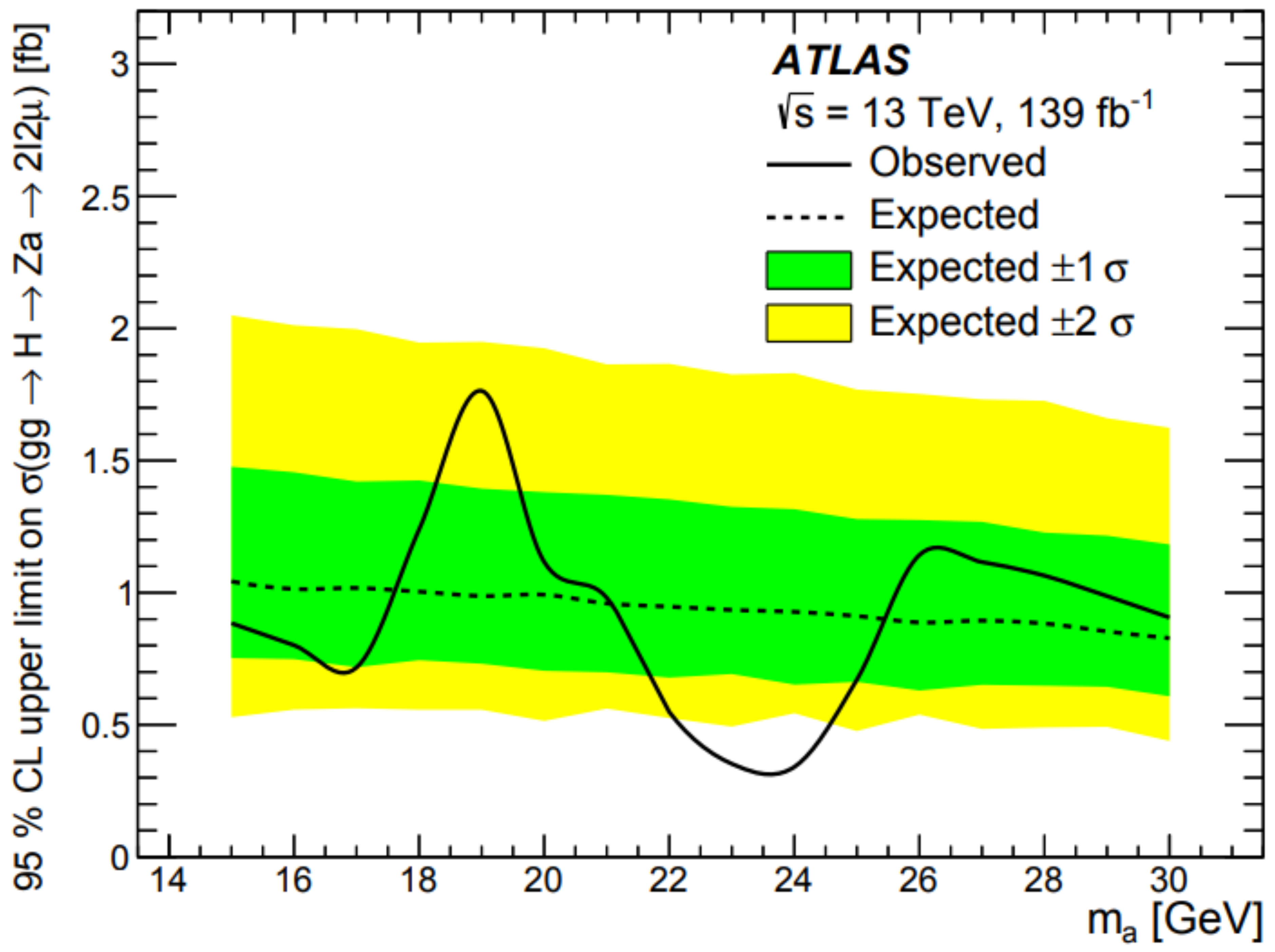
* Work done by A. Bharucha, J. M. Butterworth, N. Desai, S. Gascon-Shotkin, S. Jain, A. Lesauvage, G. Moreau, S. Mutzel, J. M. No, J. Quevillon, C. Smith, K. Tobioka, N. Vignaroli, S. L. Williamson, and J. Zurita.

Related experimental searches

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

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

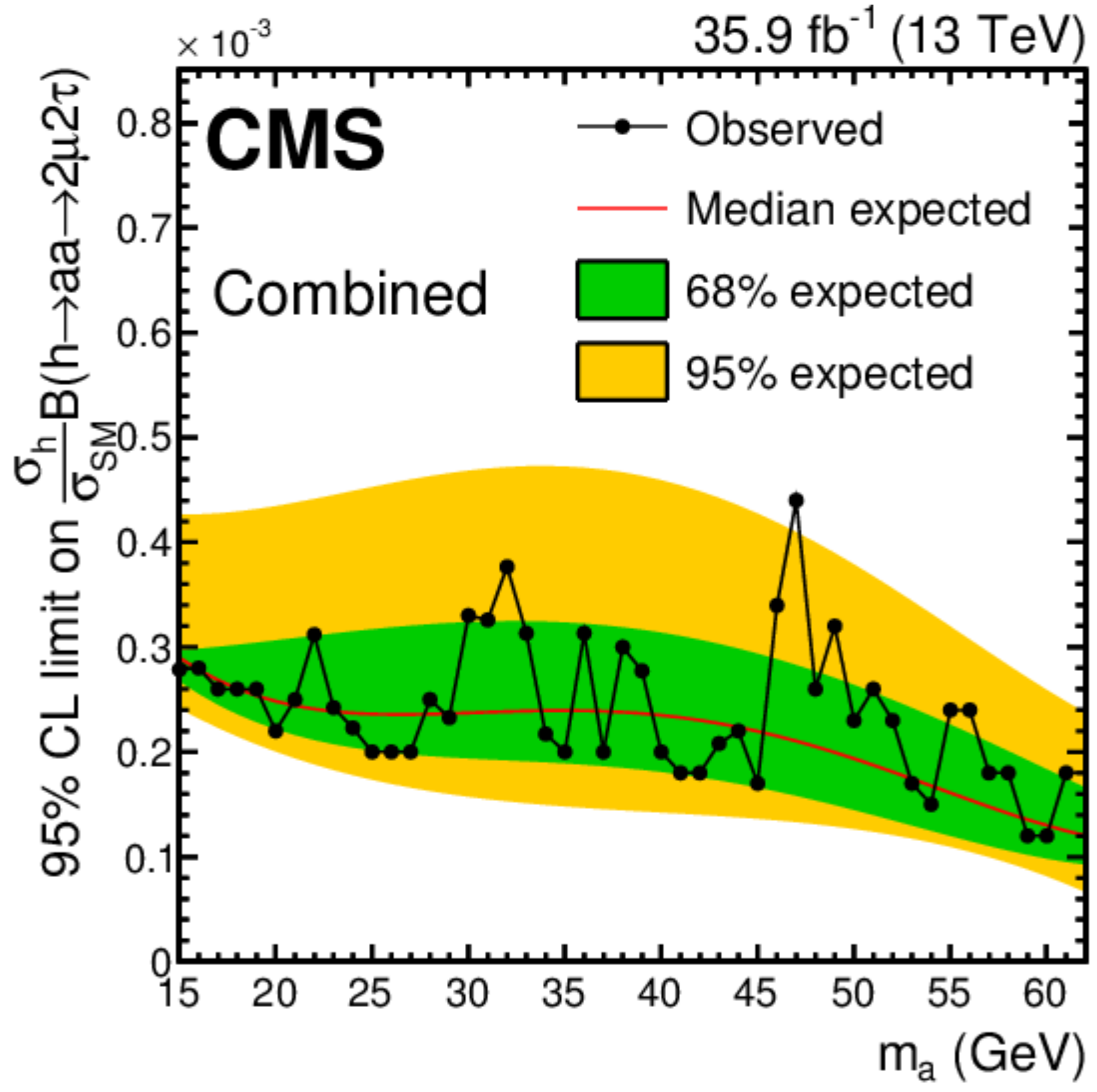
Limits on total cross section:



ATLAS [2110.13673]

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

Limits on BR for symmetric Higgs decay:



CMS [1805.04865]

Proposal

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

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

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

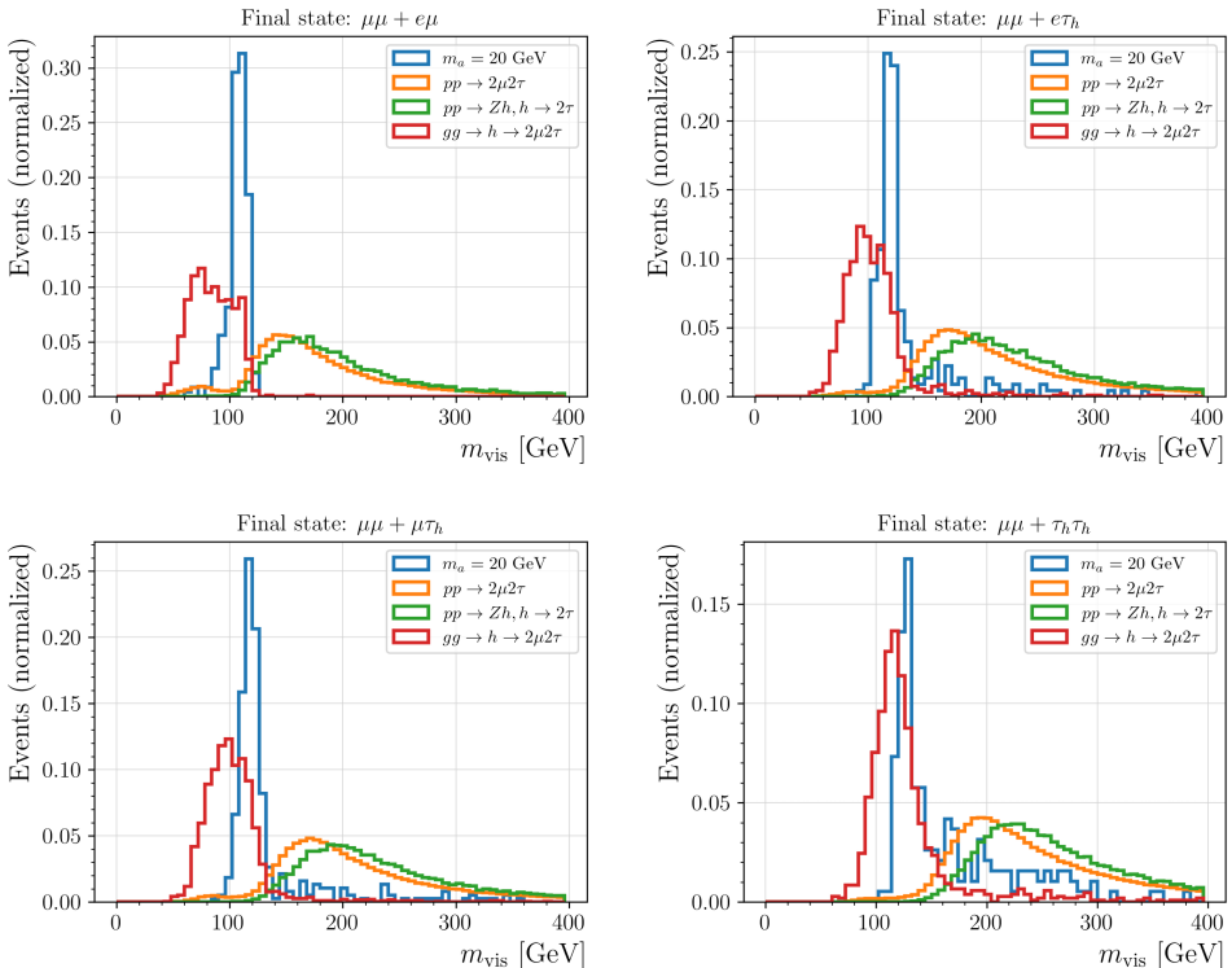
$$N_s = \sigma(pp \to h) \times BR(Z \to \mu\mu) \times BR(h \to Za, a \to \tau\tau) \times \mathscr{L} \times \epsilon(m_a)$$

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:

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

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

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

Broad window to ensure sufficient background events for statistical robustness

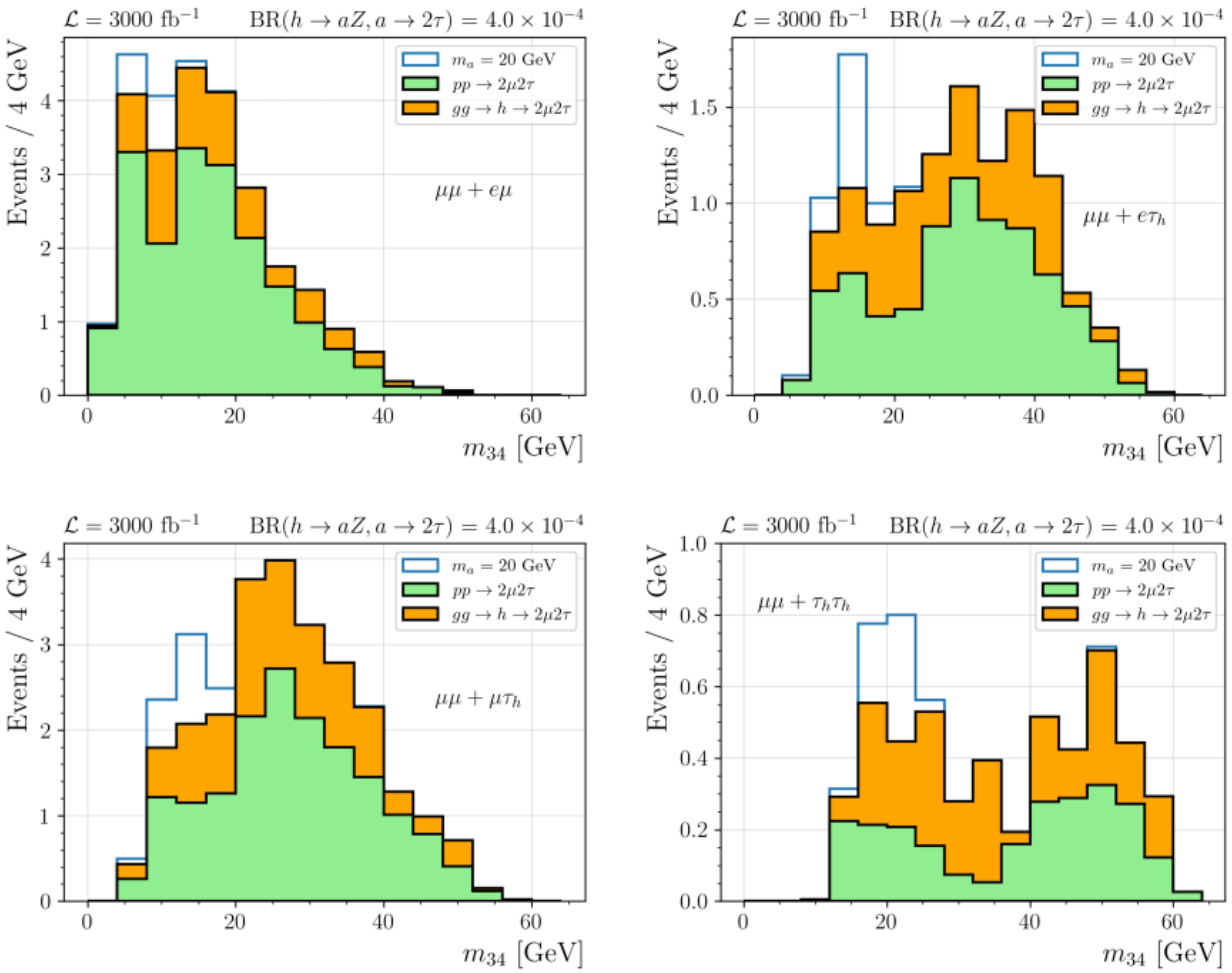
- b-jet veto ($p_T^j > 20$ GeV)

Index 12: Z decayed particles

Index 34: a decayed particles

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

Signal + (irreducible) background:



Fixed values:

N^3LO gluon fusion production cross-section:

$\sigma(pp \to h) = 54.67$ pb

Anastasiou et al [1602.00695]

Leptonic Z branching fraction:

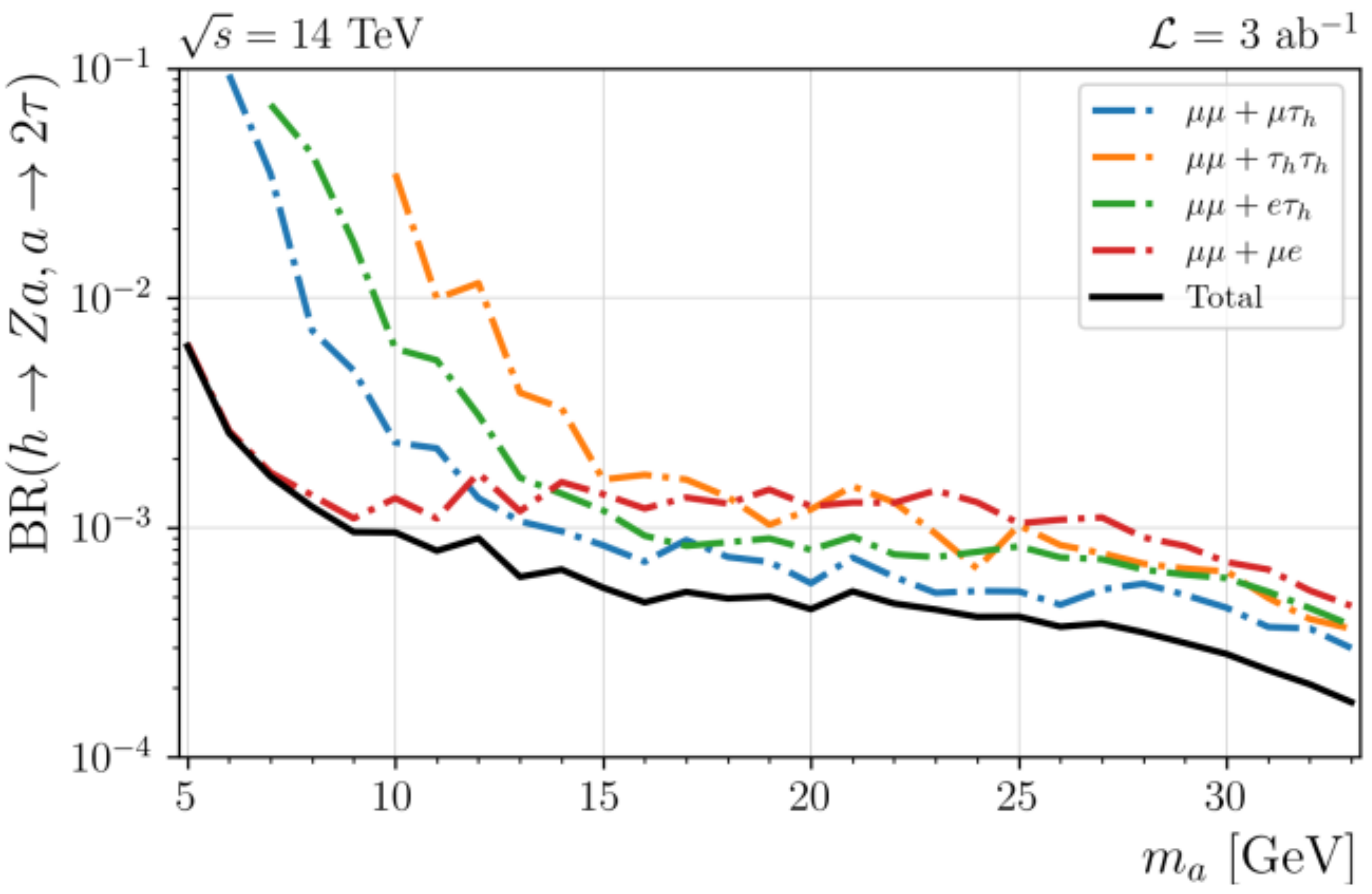
$BR(Z \to \mu\mu) = 0.0337$

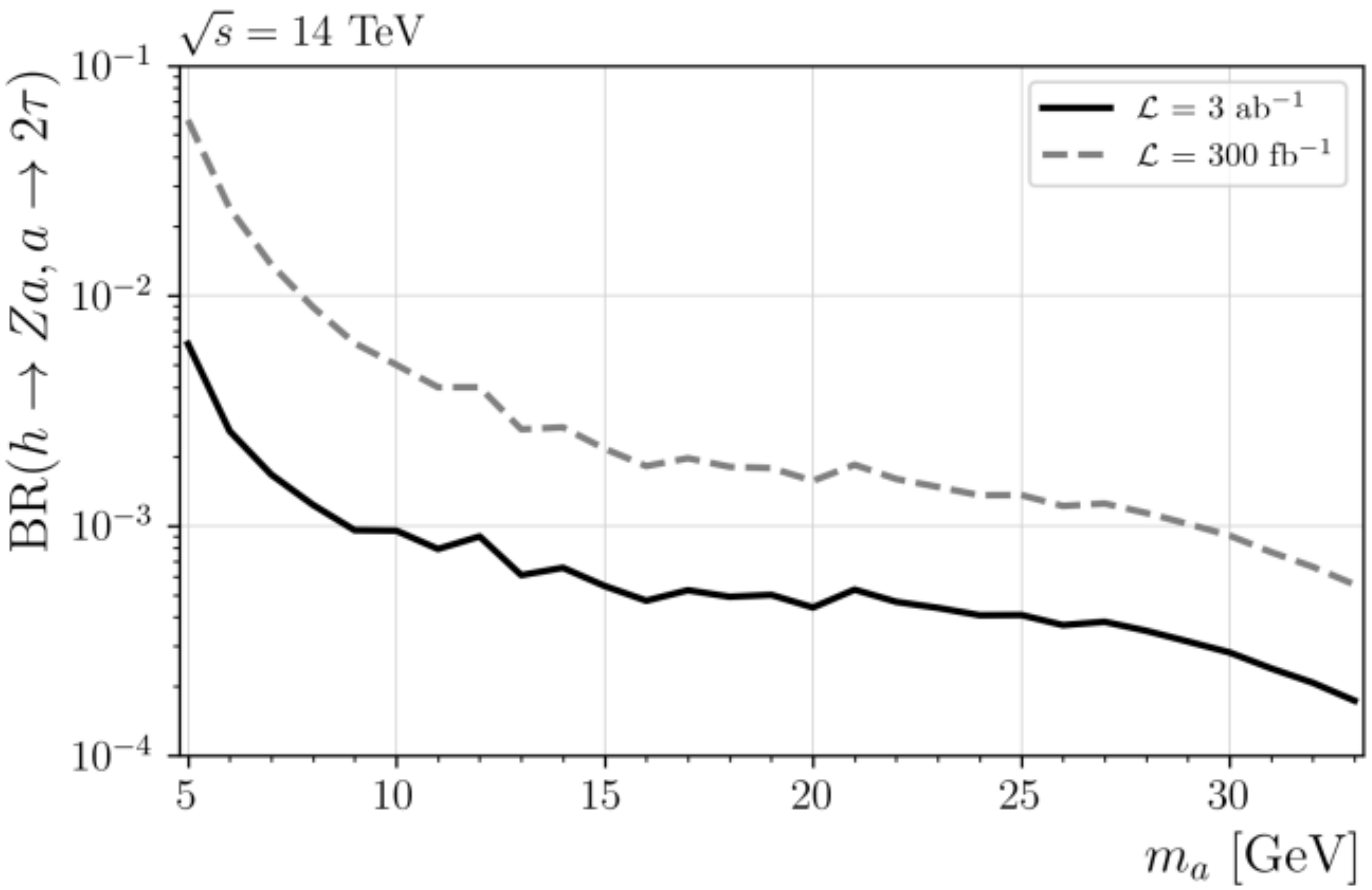
PDG (2024)

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

Results

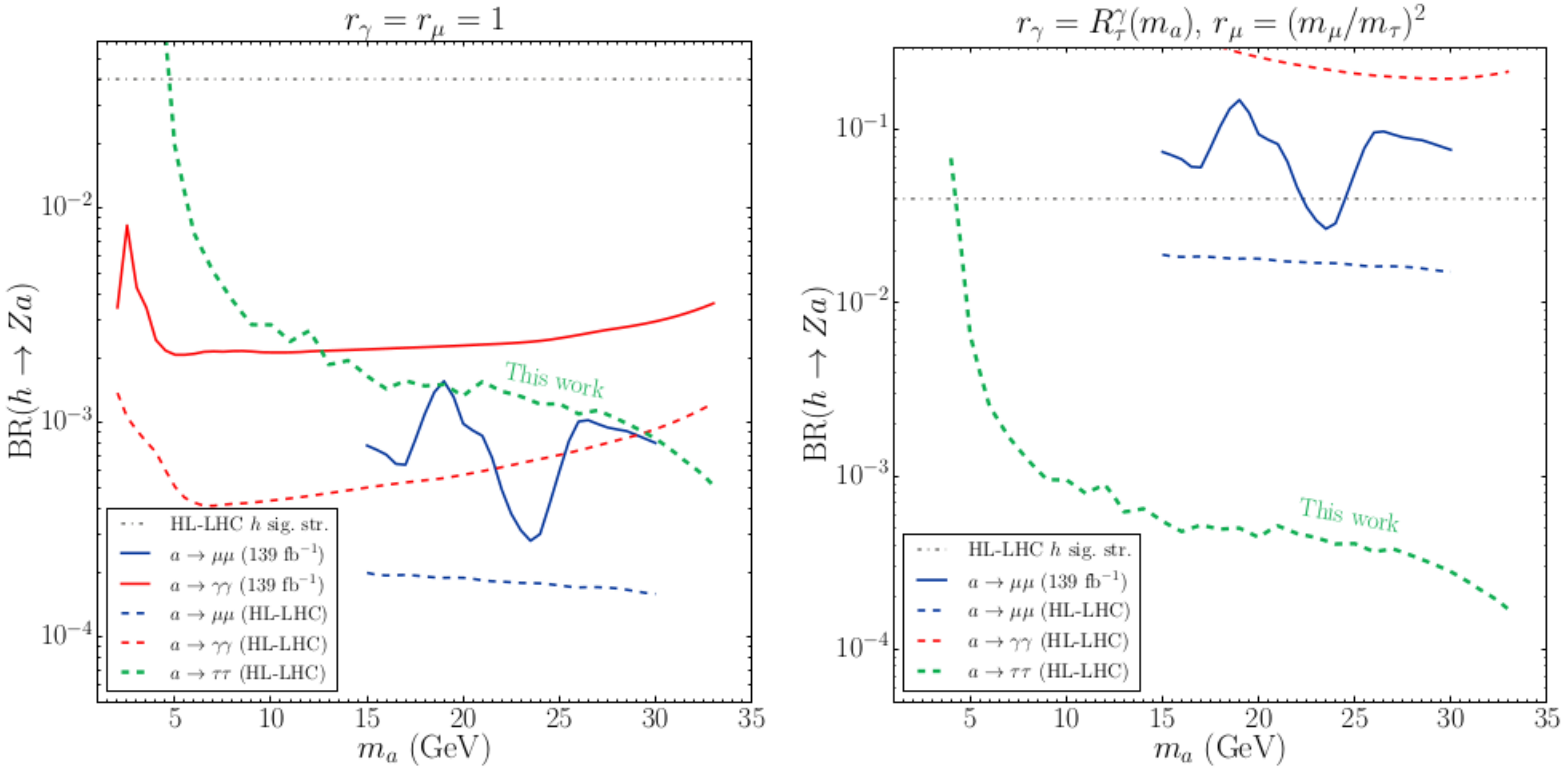
Model-independent expected $95\,\%$ CL exclusion limits (using m_{34} for Binned-Likelihood fit), and projected in m_a and $BR(h \to Za, a \to \tau\tau)$ parameter space:





Results

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



Data and extrapolation for HL-LHC from ATLAS [2110.13673] ($a \to \ell\ell$), ATLAS [2312,01942] ($a \to \gamma\gamma$)

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

$$\delta a_\mu \equiv a_\mu^{\rm exp} - a_\mu^{\rm SM} = (24.9 \pm 4.8) \times 10^{-10}$$

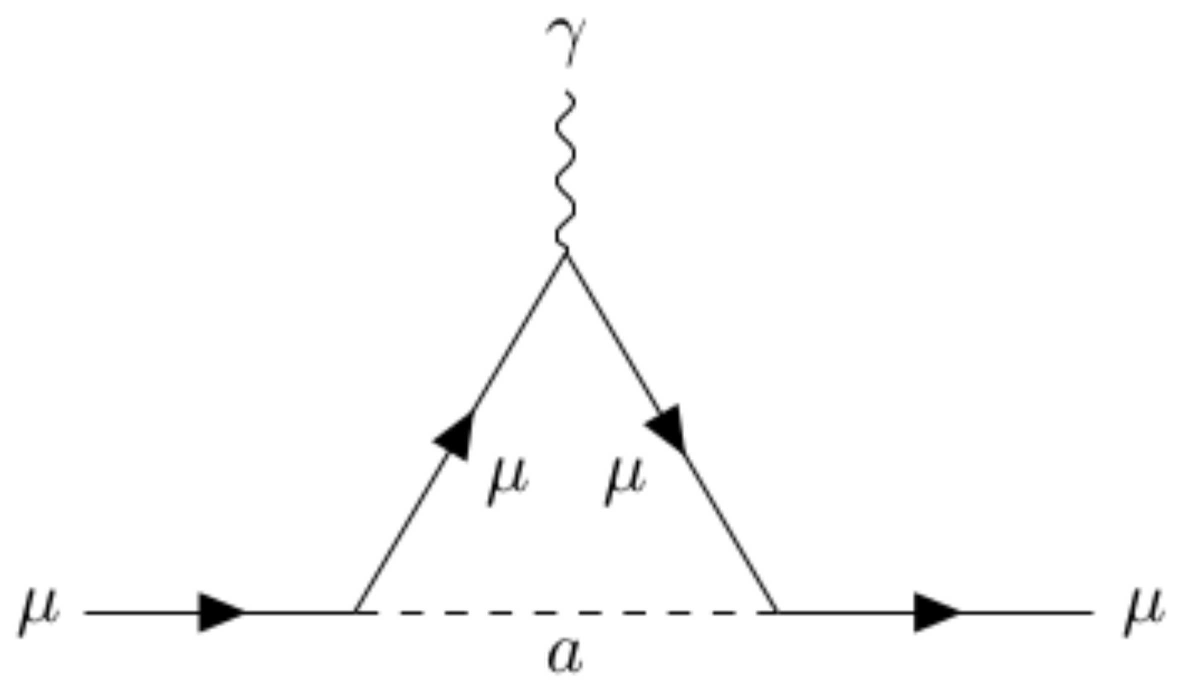
Muon g-2 [2308.06230]

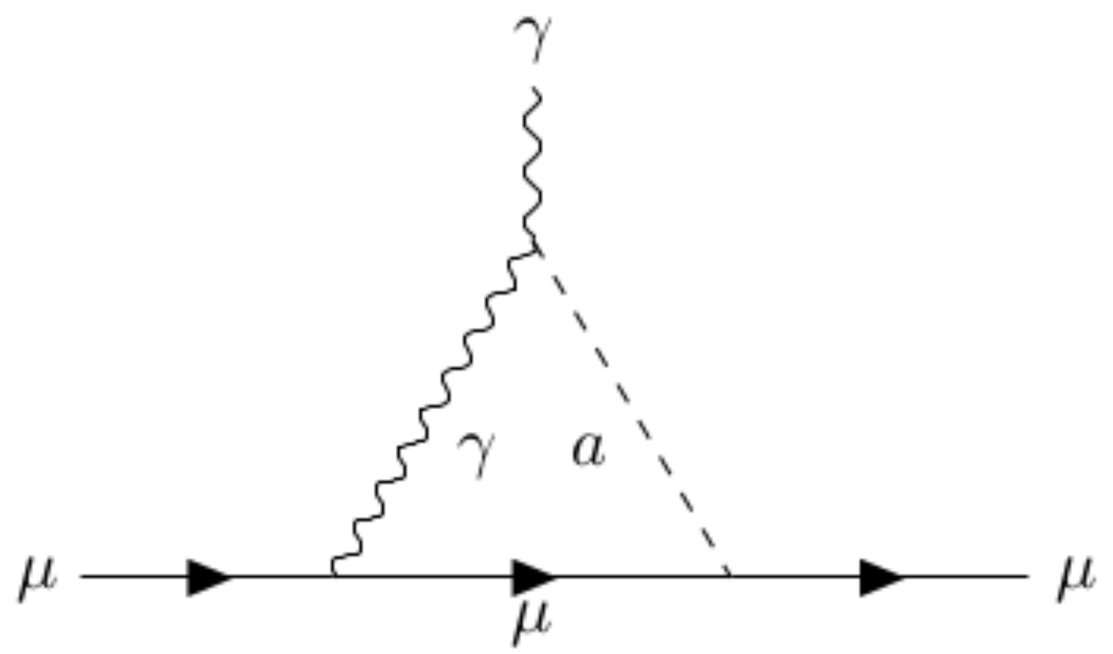
The anomaly at face value can be explained via a light ALP that couples to SM leptons, photons and the 125 GeV Higgs boson:

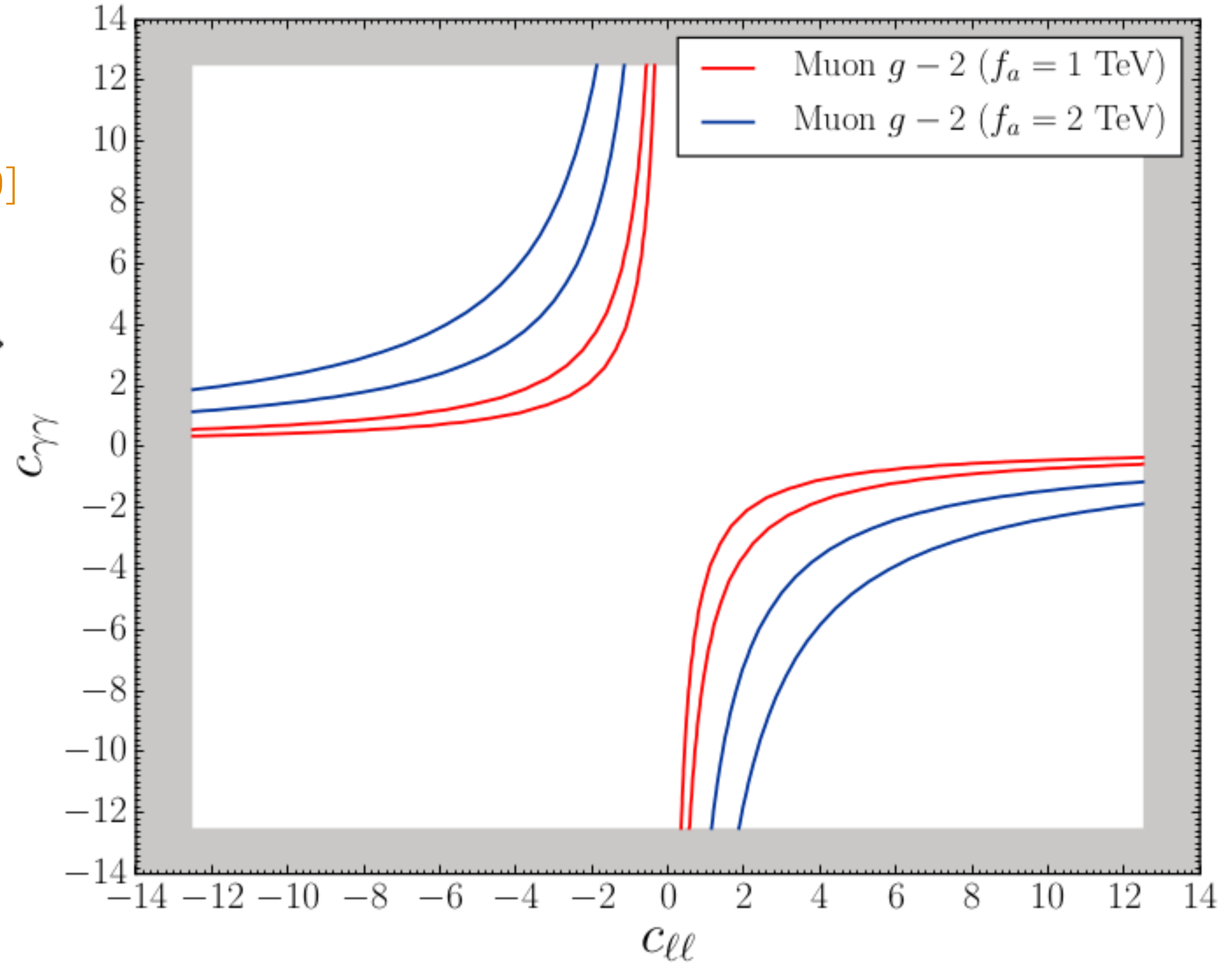
$$\mathcal{L}_{\rm ALP} \supset \frac{c_{\gamma\gamma}}{f_a} a\, F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{c_{\ell\ell}}{f_a}\sum_\ell (\partial^\mu a)\, \bar{\ell}\gamma_\mu\gamma_5\ell$$

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

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





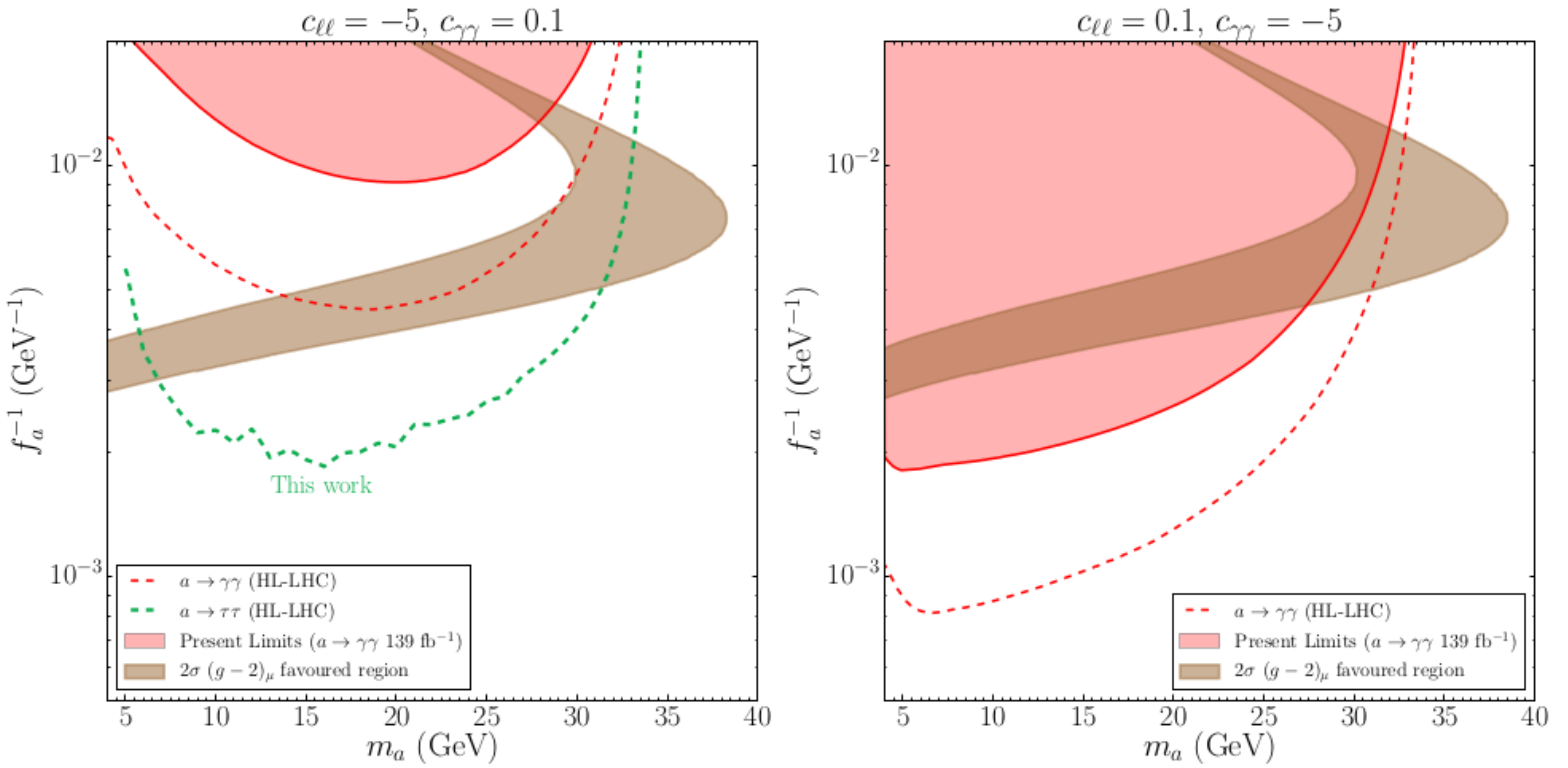


$$\Gamma_{\gamma\gamma} = \frac{m_a^3}{4\,\pi\, f_a^2}\,(c_{\gamma\gamma}^{\rm eff})^2 \quad , \quad \Gamma_{\ell\ell} = \frac{m_a\, m_\ell^2}{8\,\pi\, f_a^2}\,(c_{\ell\ell}^{\rm eff})^2 \sqrt{1-\left(\frac{2\,m_\ell}{m_a}\right)^2}$$

$$\Gamma_{h\to Za} = \frac{m_h^3}{16\pi f_a^2} c_{hZa}^2 \lambda^{3/2}$$

Bonilla et al [2107.11392]

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



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

Conclusions

$pp \to h \to Za \to \mu\mu\tau\tau$ 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 $BR(h \to Za, a \to \tau\tau)$, bellow the expected limit for the global fit to all Higgs data, and more sensitive than the asymmetric searches with $a \to \mu\mu$ and $a \to \gamma\gamma$ in most expected scenarios.

- Model-dependent interpretation (ALP scenario) compatible with muon $g - 2$ anomaly (if taken face value).

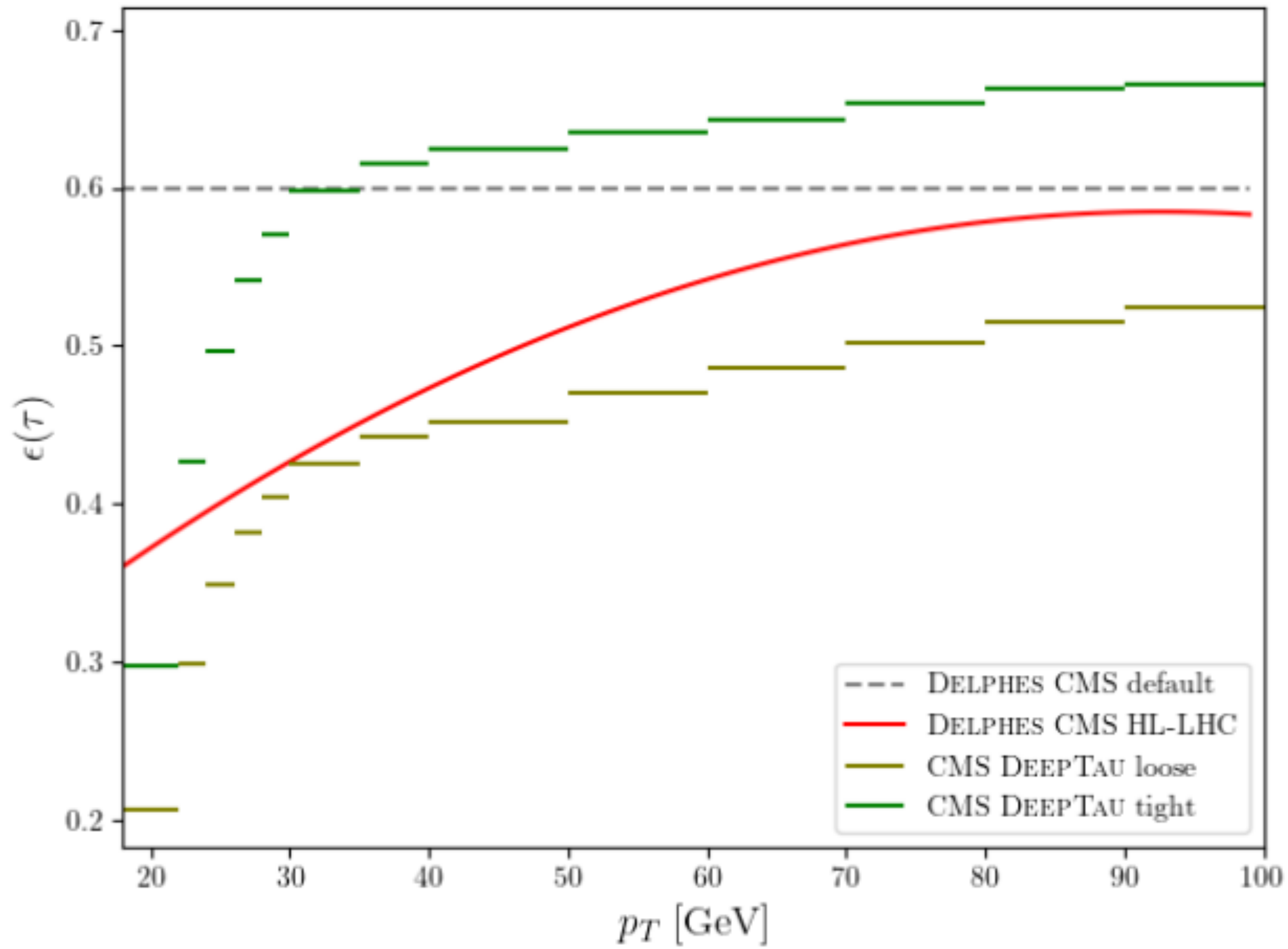
- Future: explore ML supervised techniques to enhance discrimination between signal and backgrounds and improve sensitivity.

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)	$pp \to 2\mu 2\tau$ ($0, 1\ j$ matched)	$gg \to h \to 2\mu 2\tau$	$pp \to Zh$ ($h \to \tau\tau$)
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:

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

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

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

Bauer et al [1708.00443]

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

Bonilla et al [2107.11392]

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

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