Exotic Higgs decay: $h \to Za$ into two muons and two taus

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Why exotic Higgs decays (EHD)?

- EHD are Higgs decays are among the most promising areas to search for new physics.

- The Higgs measurements of the Higgs opens 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 $BR(h \to X) \gtrsim 2.5\,\%$ through a global fit to Higgs data.
  Cepeda et al [1902.00134]

- The symmetric decay $h \to aa$ ($h \to XX$) have received the most attention so far.
  Draper et al [1204.1061], Davoudiasl et al [2105.05866], ATLAS [2110.13673, 1802.03388]

- 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.
  LH [2002.12220]

Why $h \to Za, Z \to 2\mu, a \to 2\tau$?

- Experimental searches focus on $a \to \mu\mu$ since it is a cleaner final state;

  CMS [2111.01299], ATLAS [2110.13673, 1802.03388]

- However, for concrete models like ALPs or 2HDM+a,

  Bauer et al [1701.07427], Brivio et al [1701.05379]

$$\frac{BR(a \to \mu\mu)}{BR(a \to \tau\tau)} \approx \frac{m_\mu^2}{m_\tau^2} \approx 3.6 \times 10^{-3} \,. \tag{1}$$

- Even considering that the τ 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 $\lesssim m_a \lesssim 33.9$ GeV.

- Vey preliminary study has been done for LH 2019*. LH [2002.12220]

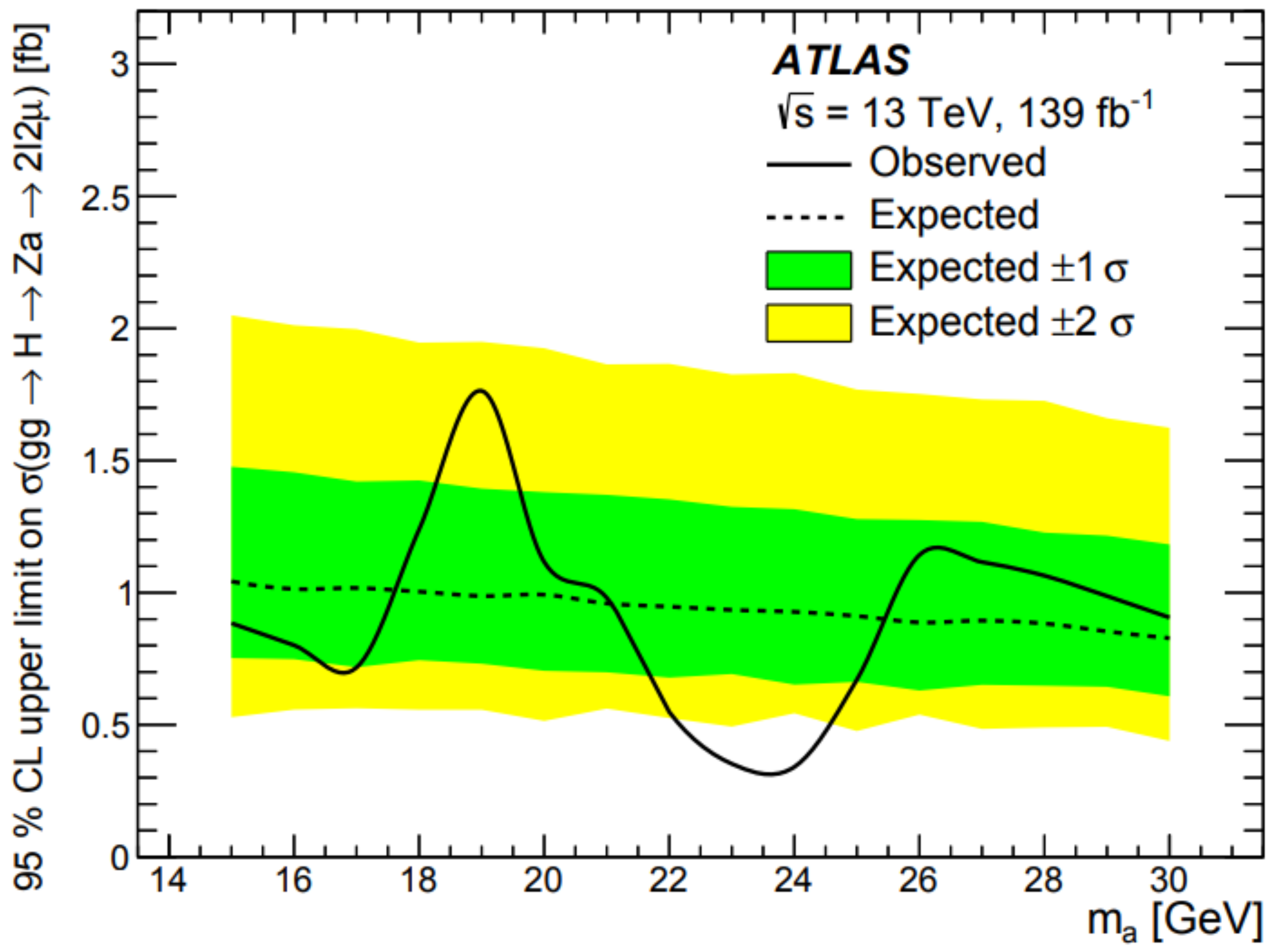
* Work done by A. Bharucha, J. M. Butterworth, N. Desai, S. Gascon-Shotkin, S. Jain, A. Lesauvage, G. Moreau, S. Mutzel, J. M. No, J. Quevillon, C. Smith, K. Tobioka, N. Vignaroli, S. L. Williamson, and J. Zurita.

Related experimental searches

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

ATLAS at 13 TeV for $h \to Za \to 4\ell$

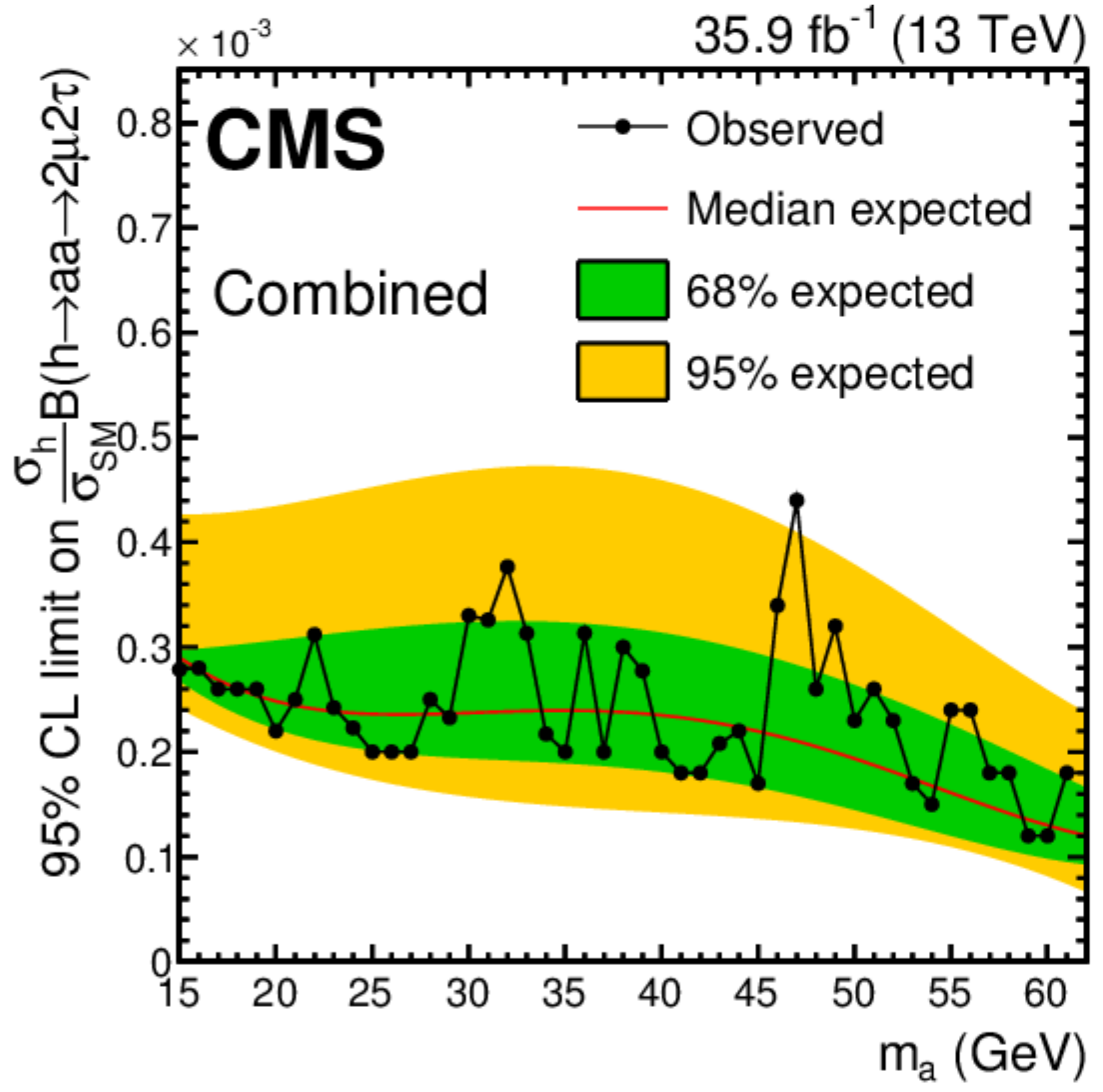
Limits on total cross section:



ATLAS [2110.13673]

CMS at 13 TeV with $h \to aa \to 2\mu 2\tau$.

Limits on BR for symmetric Higgs decay:



CMS [1805.04865]

Proposal

Study $pp \to h \to Za, Z \to 2\mu, a \to 2\tau$ for $m_a \lesssim 30$ GeV (on-shell region) in four possible reco-level final states (same ones as the CMS search in $pp \to h \to aa \to 2\mu 2\tau$):

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

Model-independent simplified interpretation considering as free parameters m_a and $BR(h \to Za, a \to 2\tau)$:

$$N_s = \sigma(pp \to h) \times BR(Z \to 2\mu) \times BR(h \to Za, a \to 2\tau) \times \mathscr{L} \times \epsilon(m_a)$$

Event Selection Criteria

Our event selection is based on both CMS and ATLAS analyses. We applied the following cuts on generated events for $pp \to h \to Za \to 2\mu 2\tau$ 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 $|\eta| < 2.3$
- $\Delta R > 0.3$ (or $\Delta R > 0.4$ if the event has τ_h)
- Additional cuts on p_T fulfilling online and offline triggers in the related CMS search

Event Selection Criteria

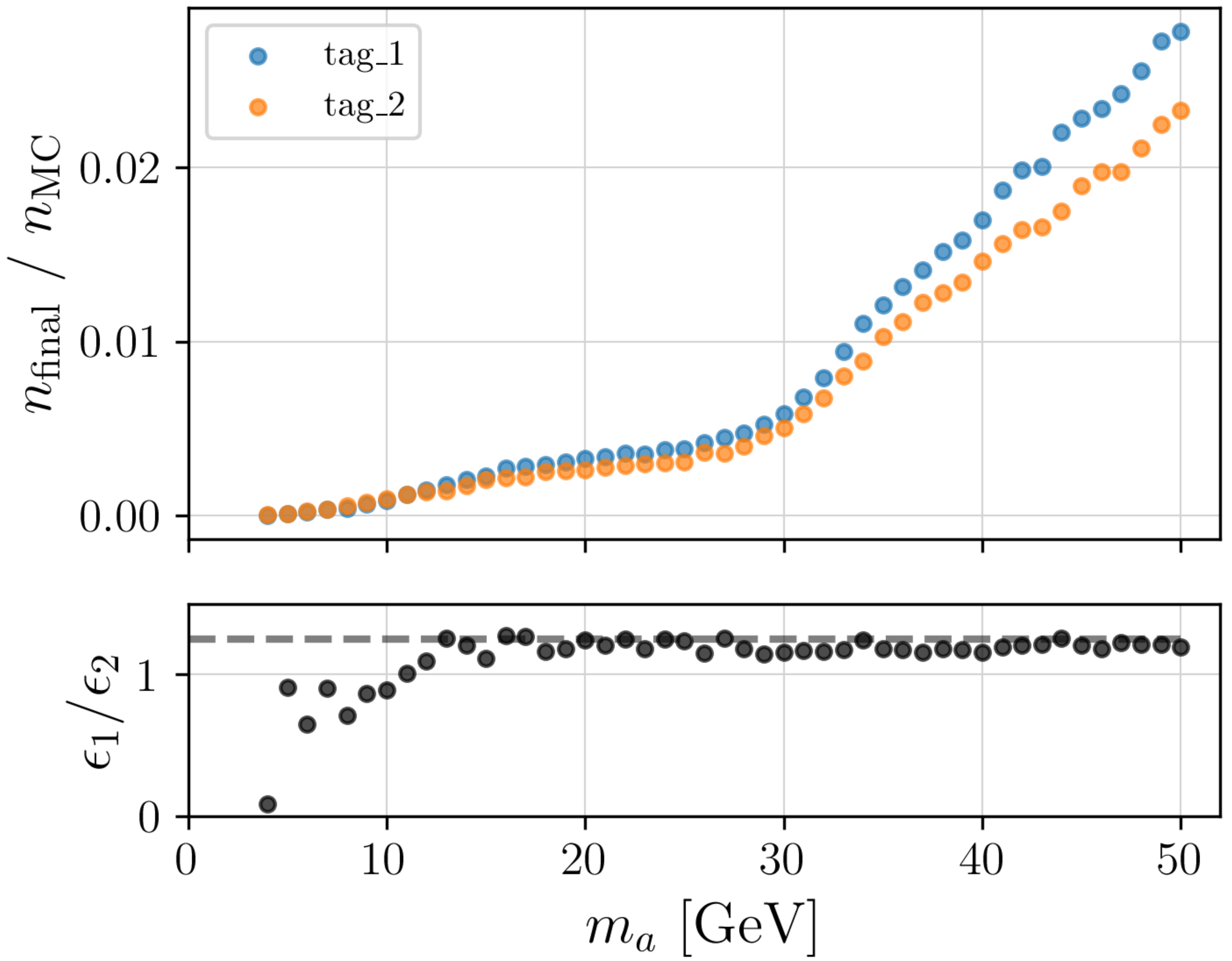
- Events should have a pair of OS muons ($\mu\mu$) and OS tau candidates ($e\mu, e\tau_h, \mu\tau_h,$ or $\tau_h\tau_h$);
- $2\mu + e\mu$: $m_{4\ell} < 110$ GeV
- $2\mu + e\tau_h$ or $2\mu + \tau_h\mu$: $m_{4\ell} < 120$ GeV
- $2\mu + 2\tau_h$: $m_{4\ell} < 130$ GeV
- $m_{34} < m_{12}$
- 50 GeV $< m_{12} < 106$ GeV ➡ Important to keep broad window for higher values of m_a

Index 12: Z decayed particles

Index 34: a decayed particles

Challenges

Extremely low efficiency to reconstruct τ candidates:



tag_1: detector simulation, after recasting of CMS search.

tag_2: adding CMS expected efficiency for tau-tagging for HL-LHC (special thanks to Maria Cepeda).

Cutflow for 200k MC events and $m_a = 20$ GeV (tag_2):

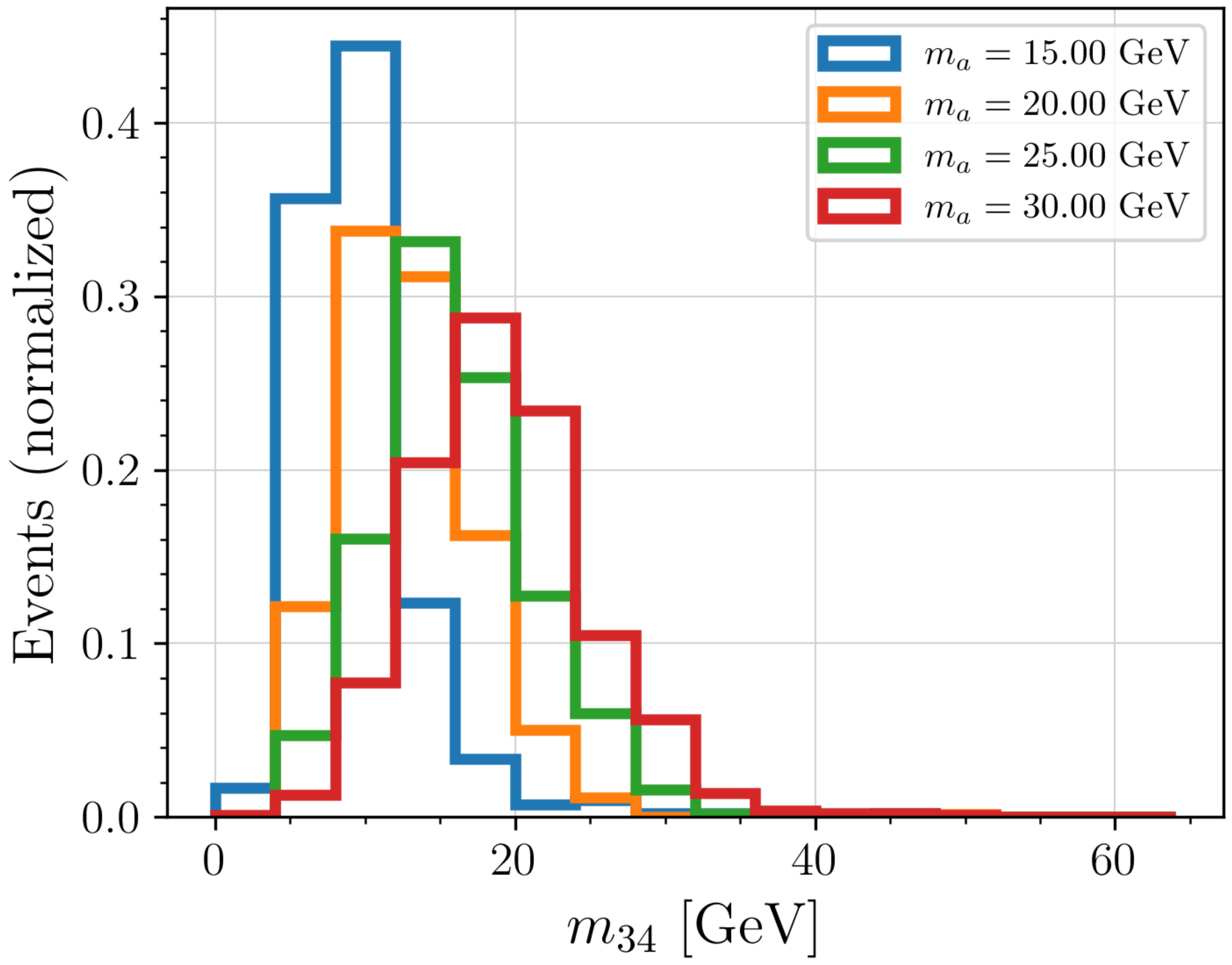
Cut	Events
OS pairs	1290
$\Delta R > 0.3(0.4)$	1116
$m_{4\ell} < 110/120/130$ GeV	547
$m_{34} < m_{12}$	537
$50 < m_{12} < 106$ GeV	523

$0.27\,\%$ of the events passed all cuts for this BP

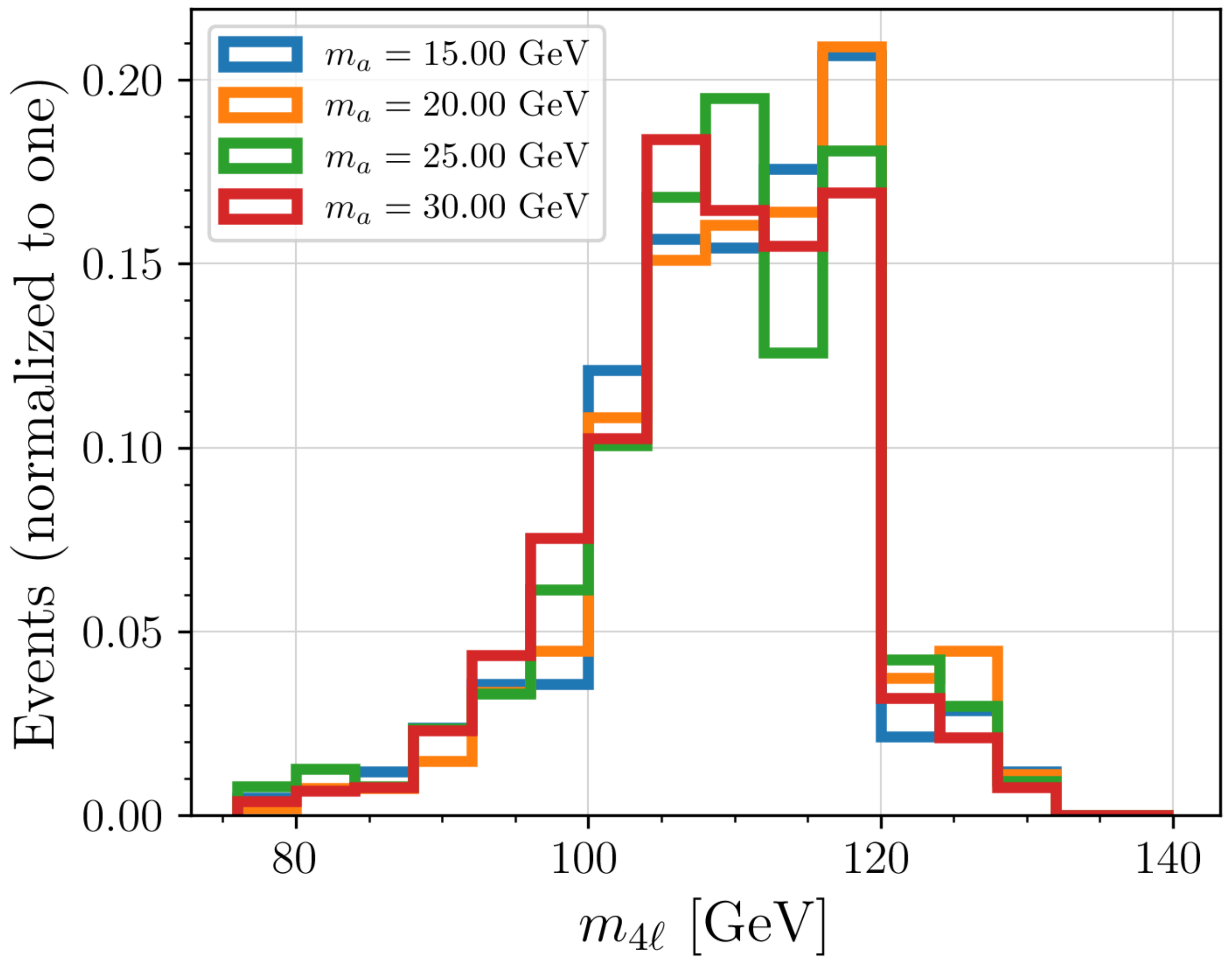
We are only able to reconstruct masses above ~ 14 GeV

Kinematics

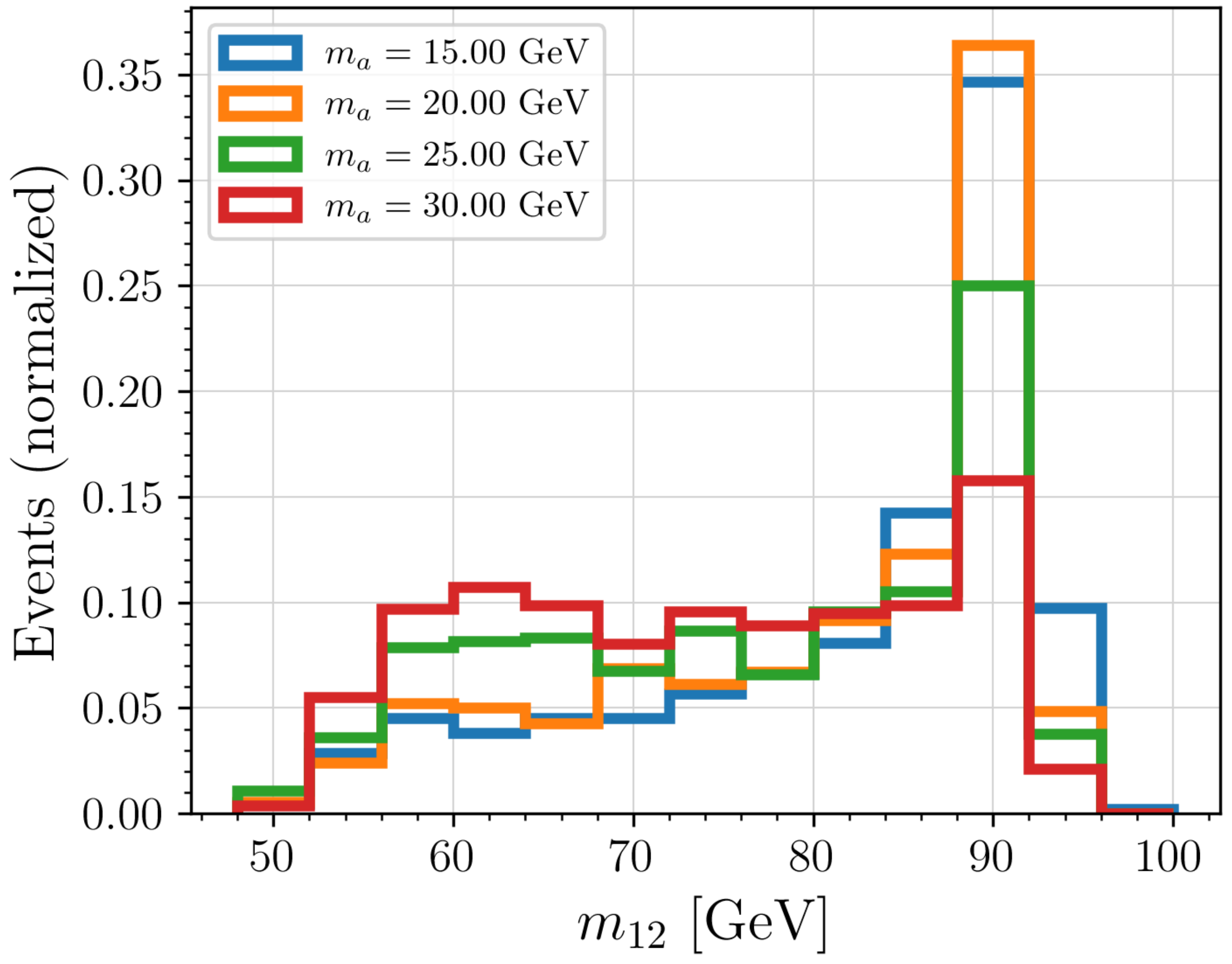
Invariant mass of the τ candidates (m_a):



Invariant mass of the final state (m_h):

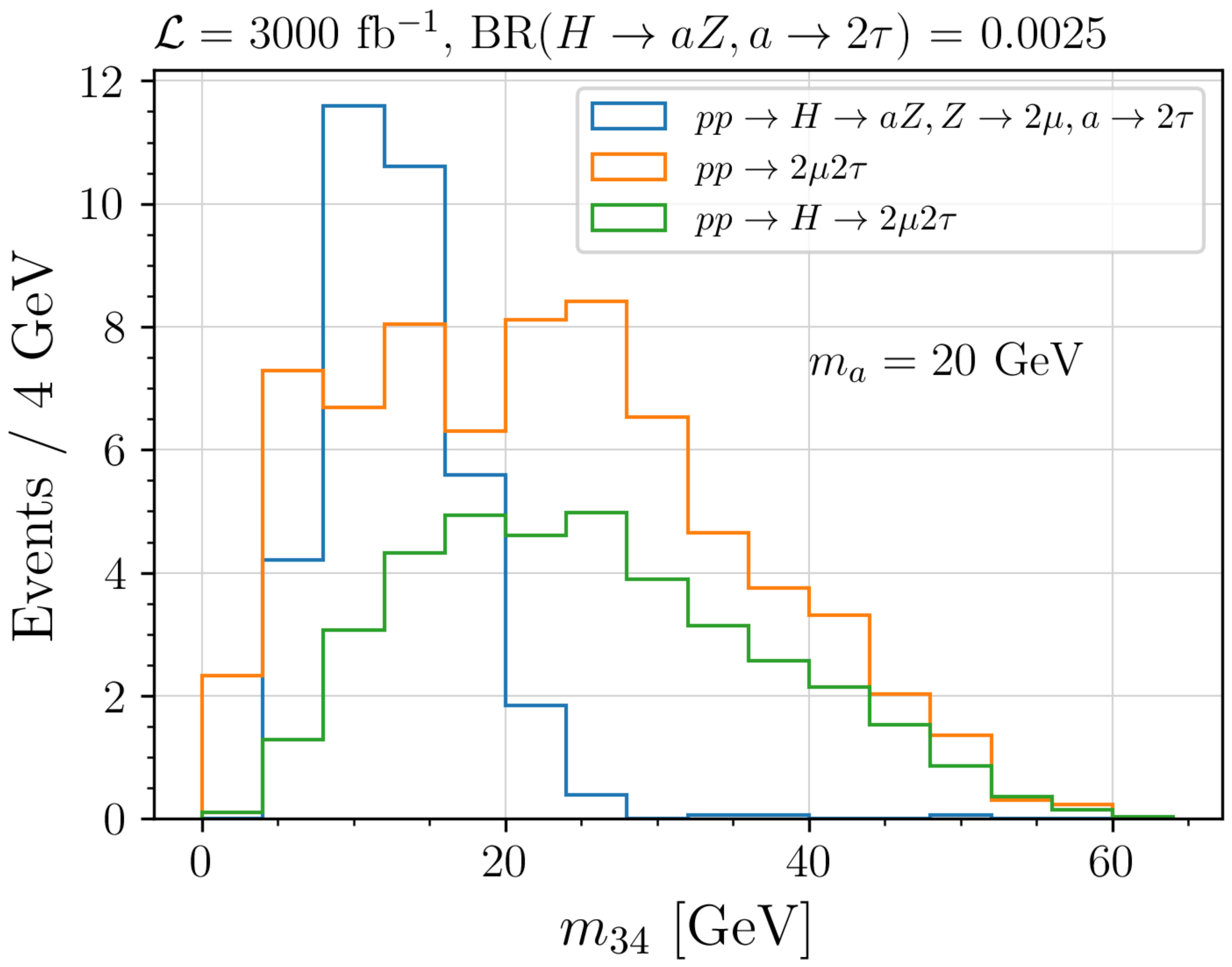


Invariant mass of the OS pair of muons (m_Z):



Considering for the signal: $N_s = \sigma(pp \to h) \times BR(Z \to 2\mu) \times BR(h \to Za, a \to 2\tau) \times \mathscr{L} \times \epsilon(m_a)$

Signal + (irreducible) background:



Fixed values:

$\sigma(pp \to h) = 52.17$ pb (from HWG)

$BR(Z \to 2\mu) = 0.0337$ (SM)

% of MC events after cuts:

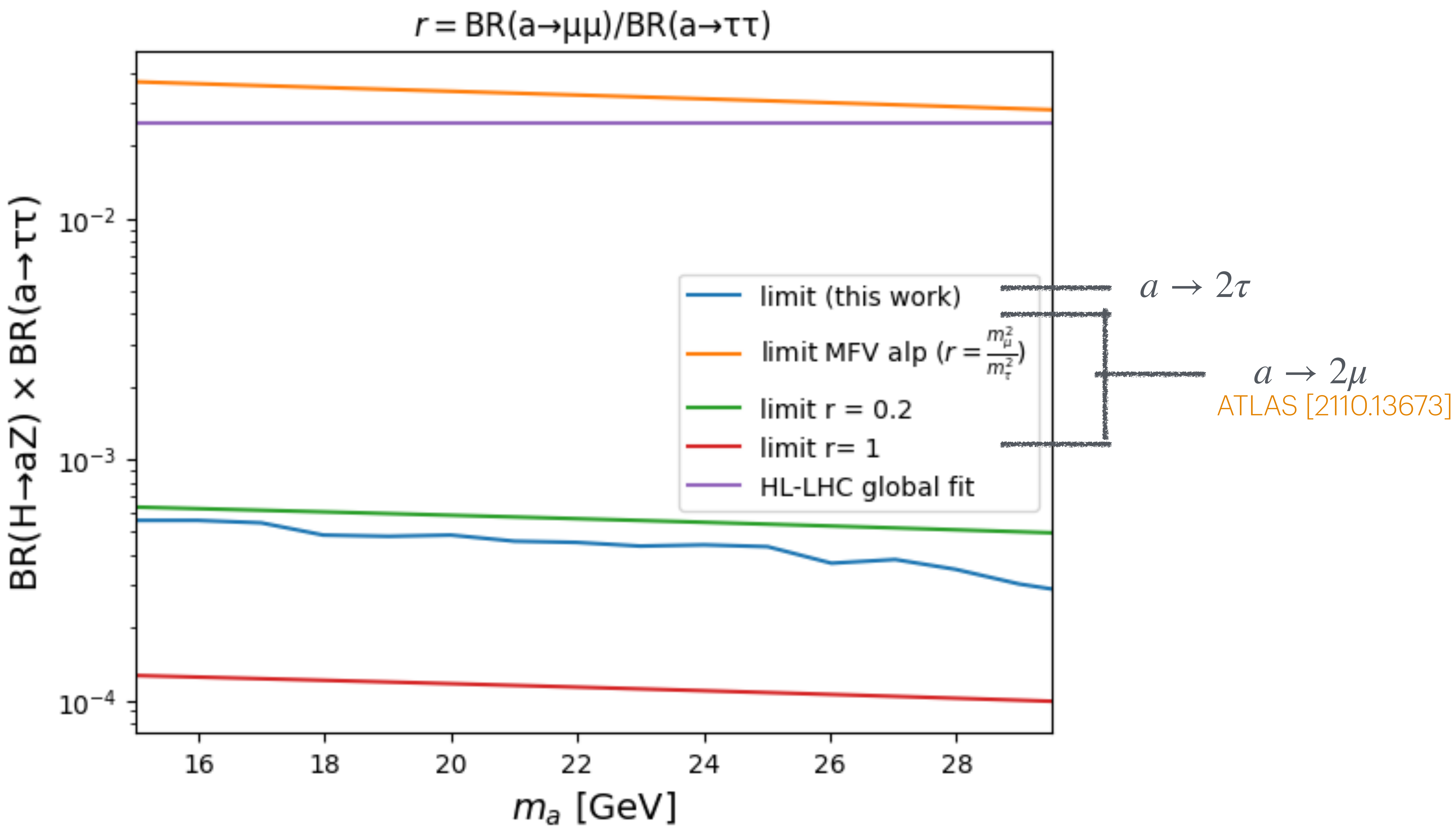
$pp \to 2\mu 2\tau : 0.01\,\%$

$pp \to h \to 2\mu 2\tau : 0.14\,\%$

Reducible backgrounds ($t\bar{t} + Z, Z + j, t\bar{t}, WZ, VVV$) are not expected to contribute much (to check).

Results

Model-independent expected $95\,\%$ CL exclusion limits (using m_{34} for Binned-Likelihood fit), and projected in m_a and $BR(h \to Za, a \to 2\tau)$ parameter space:



Conclusions

$pp \to h \to Za, Z \to 2\mu, a \to 2\tau$ is a very promising channel for $m_a \lesssim 30$ GeV

- We successfully defined signal regions based in related CMS and ATLAS searches.
- We are only able to explore $m_a \gtrsim 14$ GeV due to reconstruction limitations.
- We set limits in a model-independent approach for $BR(h \to Za, a \to 2\tau)$ (bellow the expected limit for the global fit to all Higgs data, and more sensitive than $a \to 2\mu$ in most expected scenarios).

Next steps

- Verify reducible backgrounds ($t\bar{t}+Z, Z+j, t\bar{t}, WZ, VVV$).
- Try small variations in event selection criteria.
- Explore ML techniques to enhance discrimination between signal and background and improve sensitivity.
- Model-dependent interpretation (ALP framework and 2HDM+a).

Thank you

Extra

Expected contribution from each final state: