Exotic Higgs decays: Present Status and Future Prospects at the LHC

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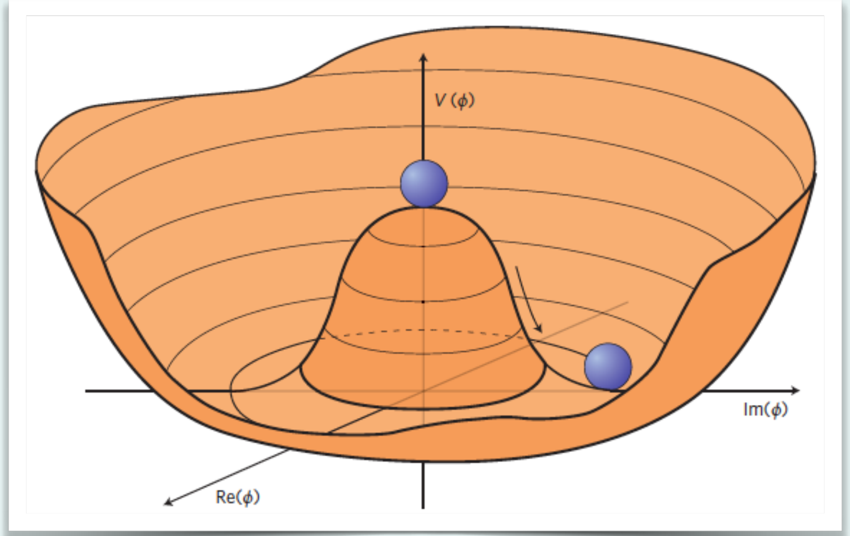
Higgs mechanism in SM

The Standard Model (SM) particles has mass but a mass term in the Lagrangian violates gauge symmetry. This problem is solved by the Higgs mechanism. The Lagrangian with the complex scalar field Φ is,

$$\mathscr{L} = (D_\mu\Phi)^\dagger(D_\mu\Phi) - V(\Phi)\,, \quad D_\mu = \partial_\mu - ieA_\mu\,, \quad V(\Phi) = \mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$

The symmetry breaking pattern is, $SU(2)_L \times U(1)_Y \rightarrow U(1)_{e.m.}$.



Masses:

Mass of W boson, $m_{W^\pm} = \frac{1}{2}gv$.

Mass of Z boson, $m_Z = \frac{1}{2}v\sqrt{g^2 + g'^2}$.

Mass of Higgs boson, $m_h = \sqrt{2\lambda v^2}$.

Mass of fermions, $m_f = \frac{y_f}{\sqrt{2}}v$

For $\mu^2 < 0$ and $\lambda > 0$: $\Phi^\dagger\Phi = -\frac{\mu^2}{2\lambda} \equiv \frac{v^2}{2}$

v= vacuum expectation value = 246 GeV

Higgs boson production and decay

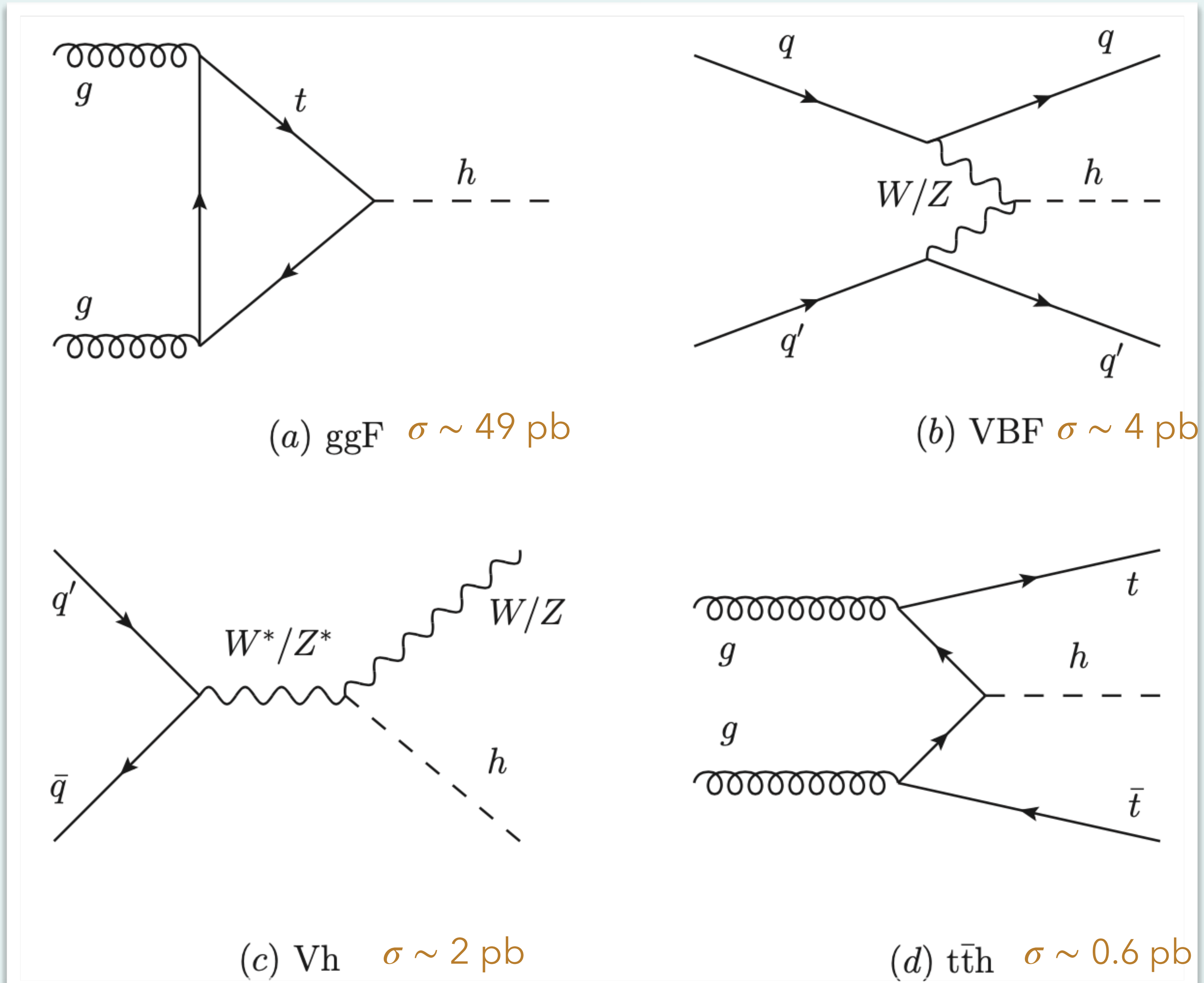


Fig: Higgs boson production modes at hadron collider

- $\sqrt{s} = 13$ TeV from CERN Twiki

$$Br(h \to b\bar{b}) = \frac{\Gamma(h \to b\bar{b})}{\Gamma_{\text{total}}}$$

Decay channel	Branching ratio
$H \to \gamma\gamma$	2.27×10^{-3}
$H \to ZZ$	2.62×10^{-2}
$H \to W^+W^-$	2.14×10^{-1}
$H \to \tau^+\tau^-$	6.27×10^{-2}
$H \to b\bar{b}$	5.84×10^{-1}
$H \to Z\gamma$	1.53×10^{-3}
$H \to \mu^+\mu^-$	2.18×10^{-4}

Higgs boson decay branching ratios for 125 GeV. [Ref. PDG]

Signal Strength parameter

Consider the process: $gg \to h \to \gamma\gamma$

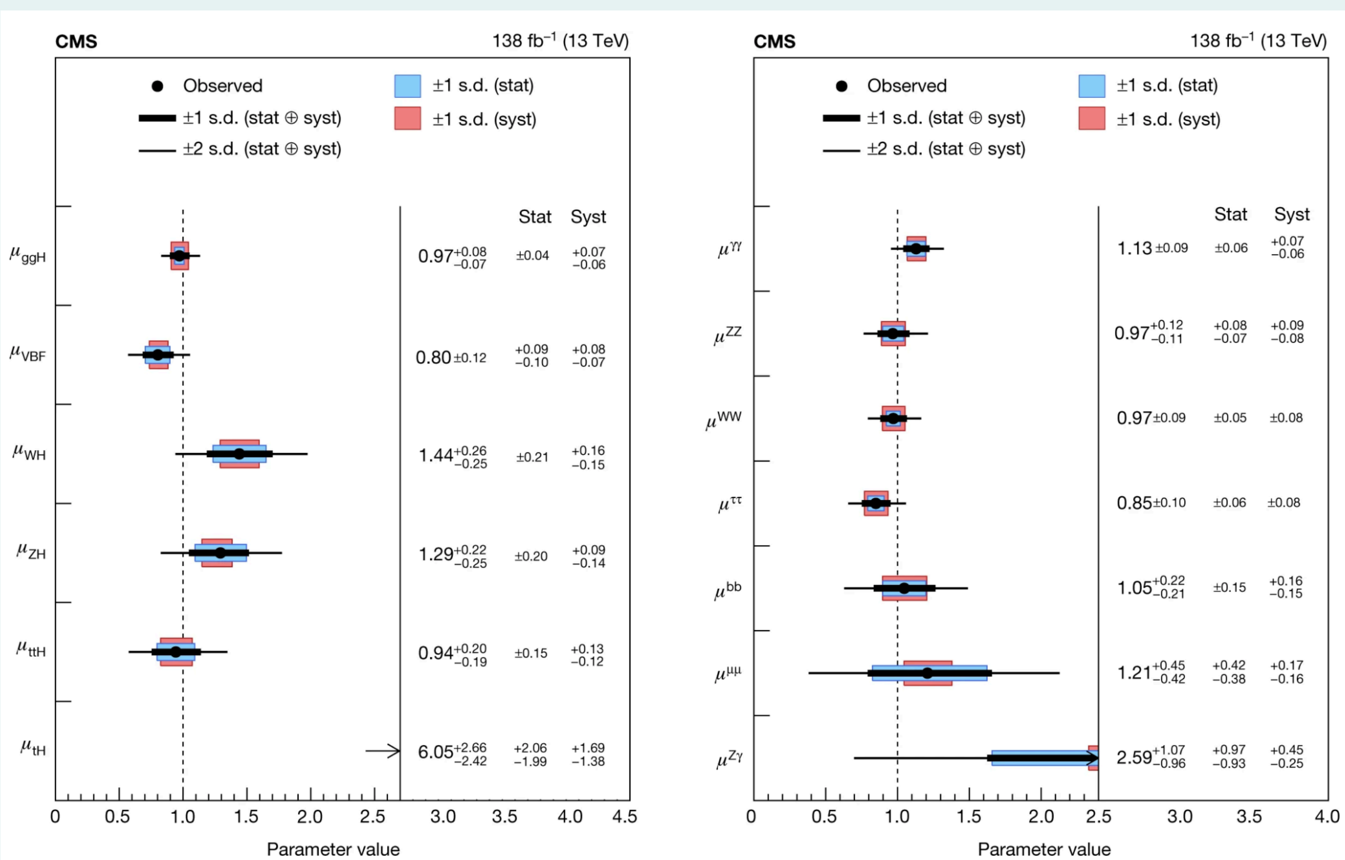
Signal strength parameter :

$$\mu = \frac{\sigma(gg \to h) \times Br(h \to \gamma\gamma)}{\sigma(gg \to h)_{SM} \times Br(h \to \gamma\gamma)_{SM}}$$

← Observed

← Expected

$\mu_{SM} = 1$



$Br = Br_{SM}$

$\sigma = \sigma_{SM}$

Overall

$\mu = 1.002 \pm 0.057$

CMS: Nature 607 (2022) 60-68

$\mu = 1.05 \pm 0.06$

ATLAS: Nature 607 (2022) 52-59

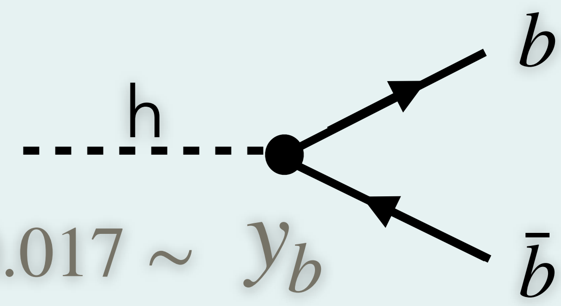
Consistent with SM!

Exotic Higgs decays

1312.4992
Curtin et. al.

- The SM Higgs decay width is extremely narrow. New light state with small coupling to Higgs → Sizable branching ratio.

$\Gamma_h \sim 4$ MeV



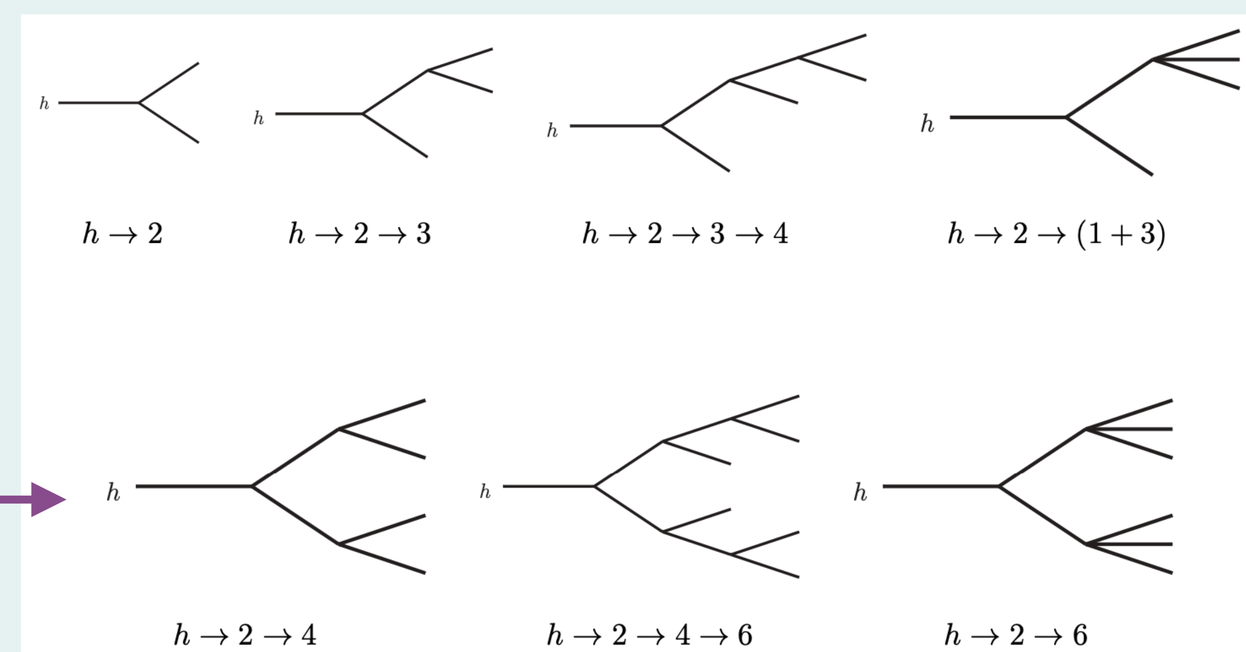
$0.017 \sim y_b$

- New physics (NP) can easily couple to Higgs boson, e.g. $\Delta\mathscr{L} = \frac{\zeta}{2} s^2 |H|^2$ or $\frac{\mu}{\Lambda^2} |H|^2 \bar{\psi}\psi$.

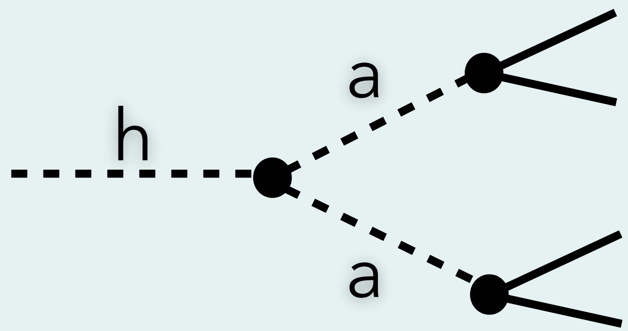
Br(h→ss) $\sim 10\,\% \Rightarrow \zeta \sim 0.01$ / Br(h→$\bar{\psi}\psi$) $\sim 1\,\% \Rightarrow \Lambda \gtrsim 1$ TeV ($\mu \sim m_\psi$)

- Br(h → BSM) $\lesssim$ 20 - 50 % from current data.
  Br(h → BSM) ~ (5 -10) % future projection.

Decay topologies →



Exotic Higgs decays - light scalars



- Theoretically well-motivated.
- $m_a \lesssim \frac{m_h}{2}$

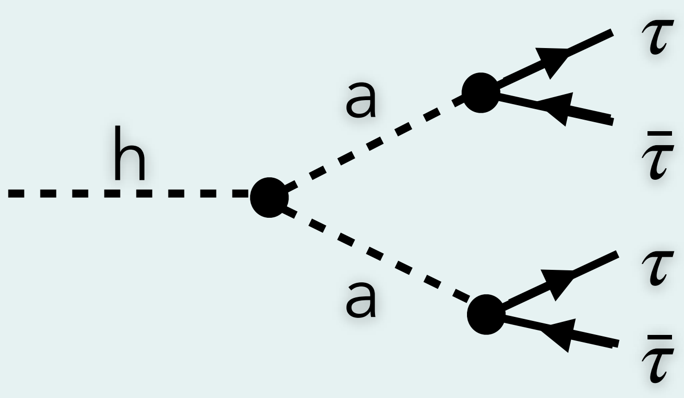
Channel (X)	Mass of a, m_a (GeV)	95% CL upper limit on $\sigma \times Br(h \to aa \to X)$ (fb)	95% CL upper limit on $Br(h \to aa \to X)$
$b\bar{b}b\bar{b}$ [16, 17]	$[20, 60]$	$[3000, 1300]$	–
$2b2\tau$ [18]	$[15, 60]$	–	$[0.03, 0.12]$
$2b2\mu$ [19]	$[20, 60]$	–	$(1.2 - 8.4) \times 10^{-4}$
$2b2\mu$ [20]	$[20, 62.5]$	–	$(1 - 7) \times 10^{-4}$
$2b2\mu$ [21]	$[16, 62]$	–	$(0.2 - 4) \times 10^{-4}$
4μ [22, 23]	$[0.25, 8.5]$	$[0.15, 0.39]$	–
4τ [31]	$[15, 60]$	$\mu^{\pm}\mu^{\pm}$ + SS τ-jet	$[0.30, 0.10]]$
$2\mu2\tau$ [24]	$[3.6, 21]$	–	upto 1.5×10^{-4}
$4\tau/2\mu2\tau$ [25]	$[4, 15]$ (9)	–	$[0.23, 0.16]$ (0.022)
$2\mu2\tau$ [26–28]	$[15, 62.5]$	–	upto 1.2×10^{-4}
4γ [29]	$[10, 62]$	$[3 \times 10^{-4}, 4 \times 10^{-4}] \times \sigma_{SM}$	–
$2\gamma2j$ [30]	$[20, 60]$	$[3100, 9000]$	–

Table 1: *Model-independent upper limits at 95% CL on the branching ratio of Higgs boson to pseudoscalars with a further decay into various four-particle final states.*

2211.07674, **A.A** et. al.

- Dominant decay mode, $a \to \tau\tau$.
- Weaker limits on this channel.
- Expected in single Higgs first, then di-Higgs channels.

Selected channels for $h \to 4\tau$ analysis



- Good signal rate.
- Rich phenomenology.
- Absence of dedicated study.

2211.07674

A.A, S. Banerjee, R.K. Barman, B. Batell, B. Bhattacherjee, C. Bose, Z. Qian, M. Spannowsky

- Single Higgs production : gluon fusion and vector boson fusion.

(a) $gg \to h \to aa \to 4\tau$, (b) $pp \to (h \to aa \to 4\tau)\ jj$

- Non-resonant di-Higgs process in the gluon fusion channel.

(a) $gg \to hh \to (h \to b\bar{b})(h \to aa \to 4\tau)$ (b) $pp \to Zh \to (Z \to b\bar{b})(h \to aa \to 4\tau)$

- Resonant di-Higgs production.

$pp \to H \to hh \to (h \to b\bar{b})(h \to aa \to 4\tau)$

Cut-based and XGBoost

$m_a = [20 : 60]$ GeV
$m_H = [200 : 1000]$ GeV

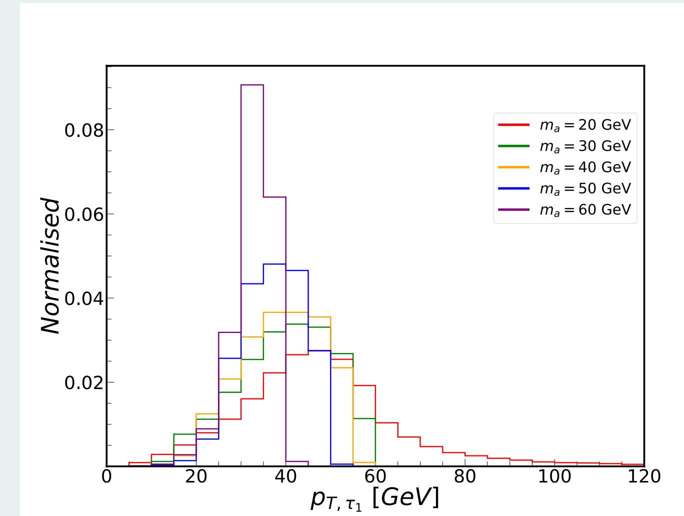
$gg \to h \to aa \to 4\tau$ final state

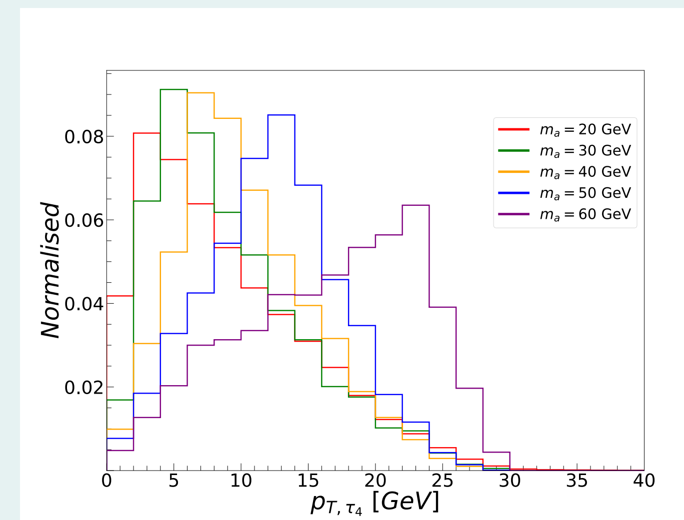
- Backgrounds : Inclusive $4l$, $h \to ZZ^* \to 4l$ (Major)
  $4l2\nu$, $4l2b$, $t\bar{t}Z$, $t\bar{t}h$, $t\bar{t}ZZ$, $t\bar{t}WW$ (Sub-dominant)

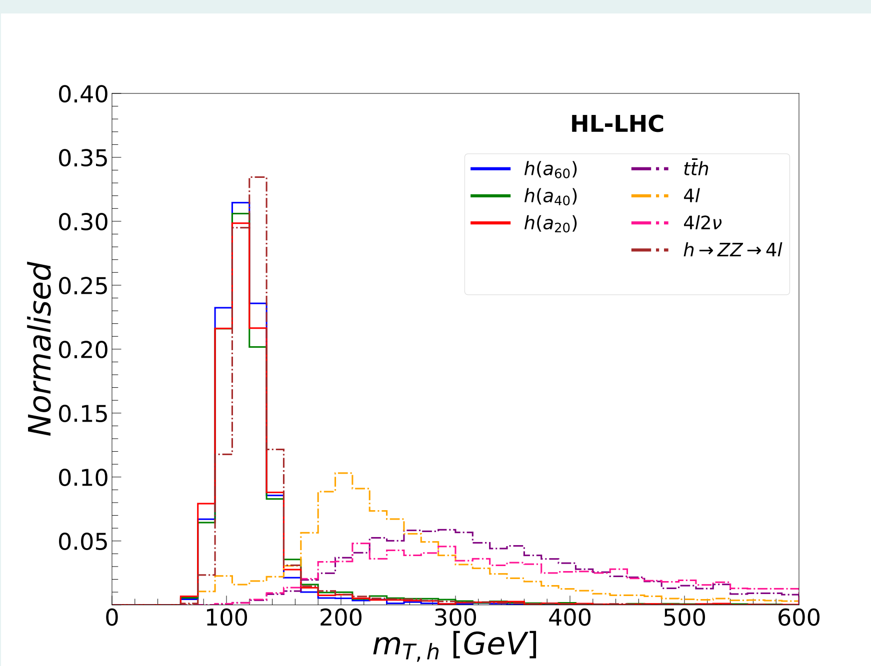
- $4\tau_h + 3\tau_h 1l + 2\tau_h 2l + 1\tau_h 3l$, $p_{T,\tau_h(l)} > 20\ (10)$ GeV
  $\Delta R(\tau_h, \tau_h) = \Delta R(\tau_h, l) = 0.4,\ \Delta R(l, l) = 0.1$
  b-veto

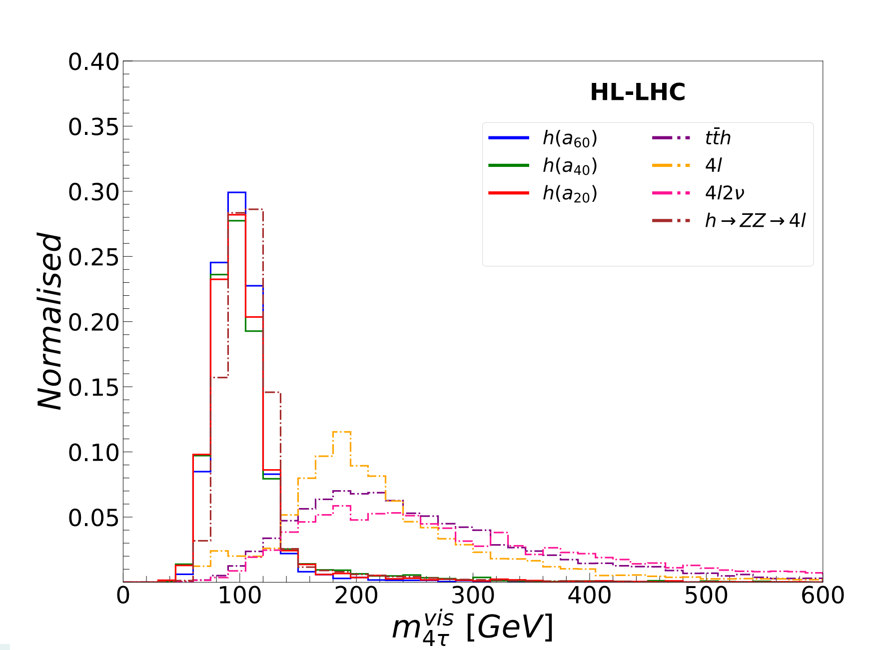
- Kinematic observables for XGBoost analysis :

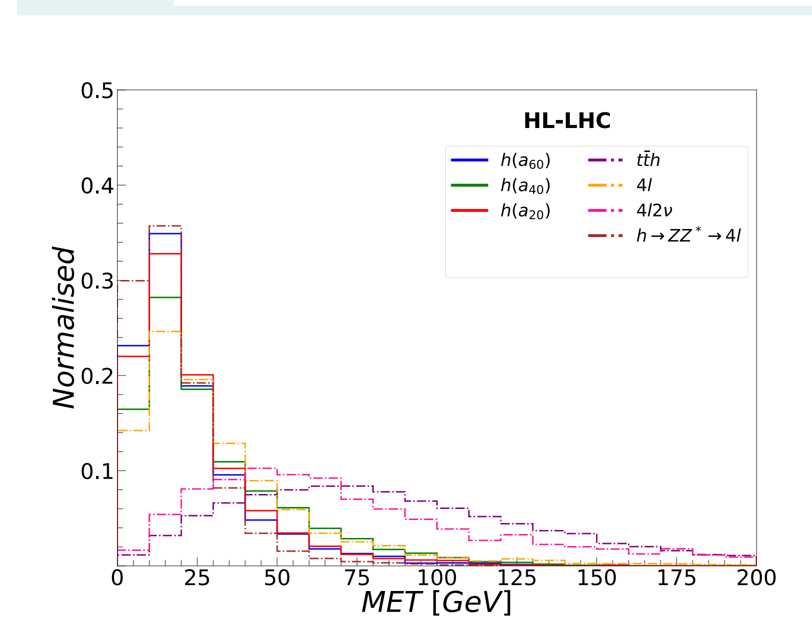
$$\Delta R_{\tau_i \tau_j}(i, j = 1-4; i \neq j),\ \Delta R^{min}_{\tau\tau},\ \Delta R^{max}_{\tau\tau},\ p_{T,4\tau},\ m^{vis}_{4\tau},\ m_{T,h},\ \not{E}_T.$$











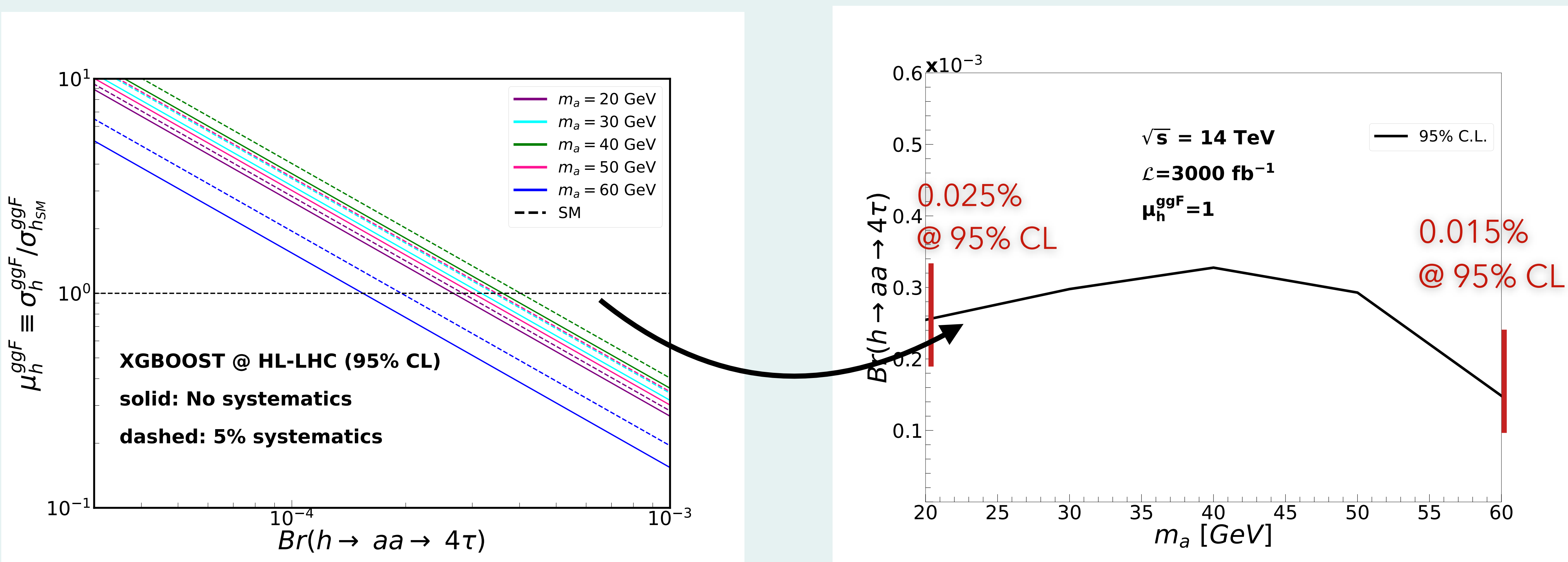
$gg \to h \to aa \to 4\tau$ final state

- Assuming Br($h \to aa \to 4\tau$) = 0.1%,

$$\sigma_s = 6.0\,(10.3) \text{ for } m_a = 20\,(60) \text{ GeV.}$$

$$5.8\,(9.0) \text{ for } m_a = 20\,(60) \text{ GeV with 5\% systematic.}$$

Upper limits



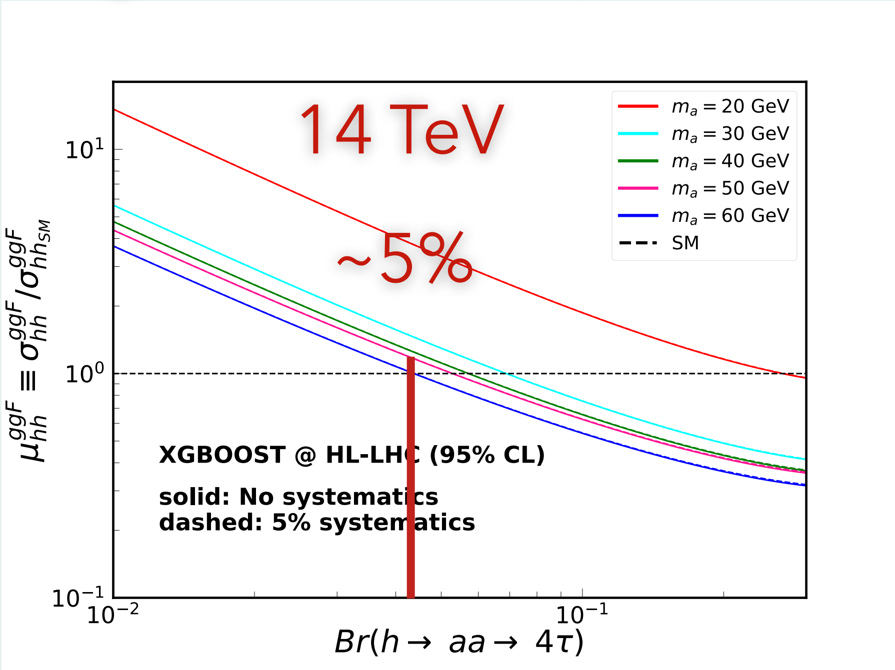
$gg \to hh \to (h \to b\bar{b})(h \to aa \to 4\tau)$ final state

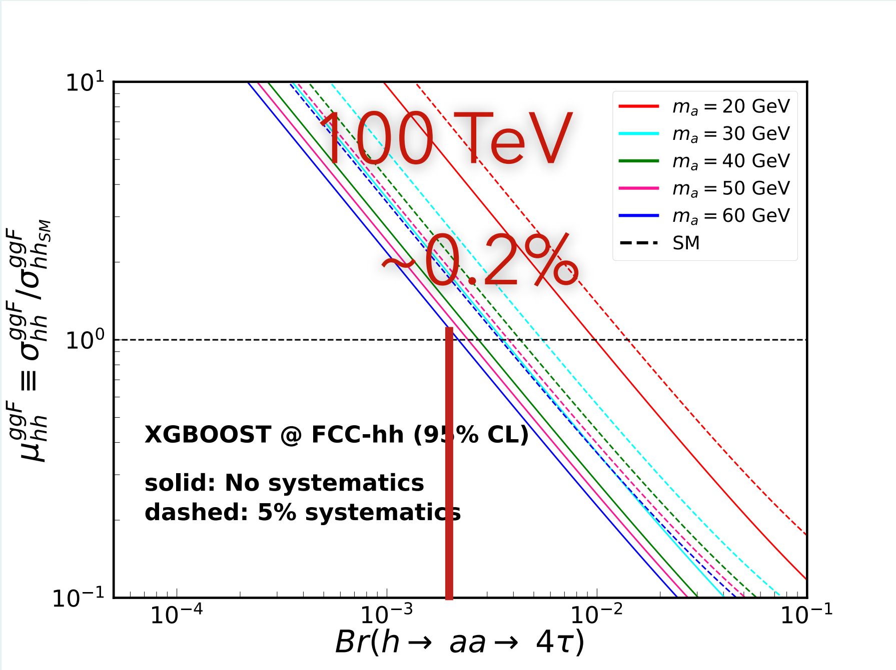
- Backgrounds : $t\bar{t}h$, $t\bar{t}Z$, $Zh \to (Z \to b\bar{b})(h \to aa \to 4\tau)$ (Major)
  $4l2b$, $t\bar{t}ZZ$, $t\bar{t}WW$ (Sub-dominant)

- Kinematic observables for XGBoost analysis :

$$m_{hh}^{vis},\ p_{T,hh}^{vis},\ \Delta R_{hh}^{vis},\ m_{T2},\ m_{T,h},\ m_{eff},\ p_{T,bb},\ m_{bb},\ \Delta R_{bb},\ m_{4\tau}^{vis},$$
$$\Delta R_{\tau1,\tau2},\ \Delta R_{\tau1,\tau3},\ \Delta R_{\tau1,\tau4},\ \Delta R_{\tau2,\tau3},\ \Delta R_{\tau2,\tau4},\ \Delta R_{\tau3,\tau4},\ \Delta R_{\tau\tau}^{min},\ \Delta R_{\tau\tau}^{max}.$$

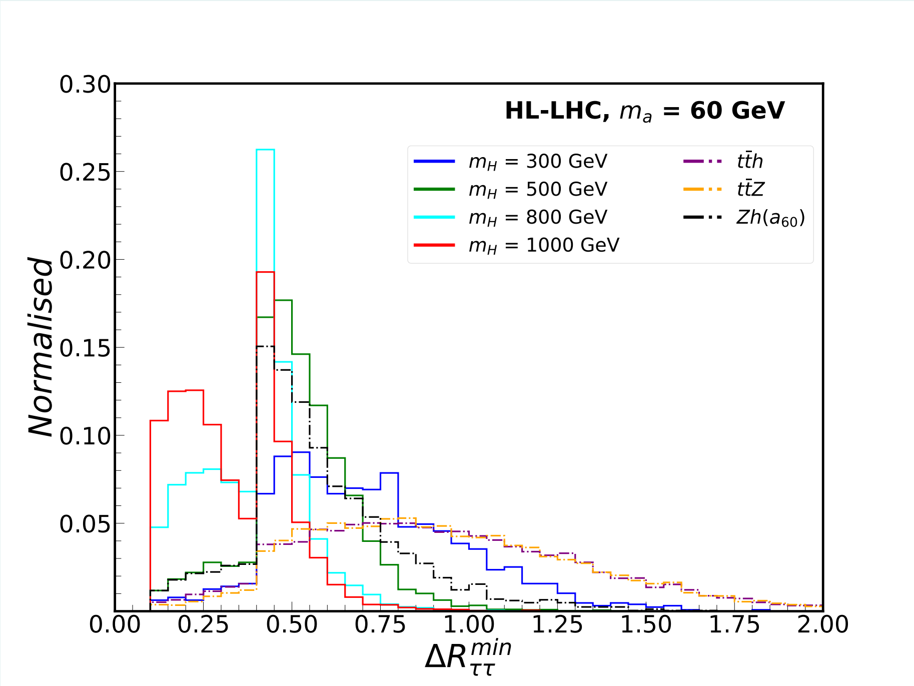
- Signal strength factor vs Br($h \to aa \to 4\tau$) :

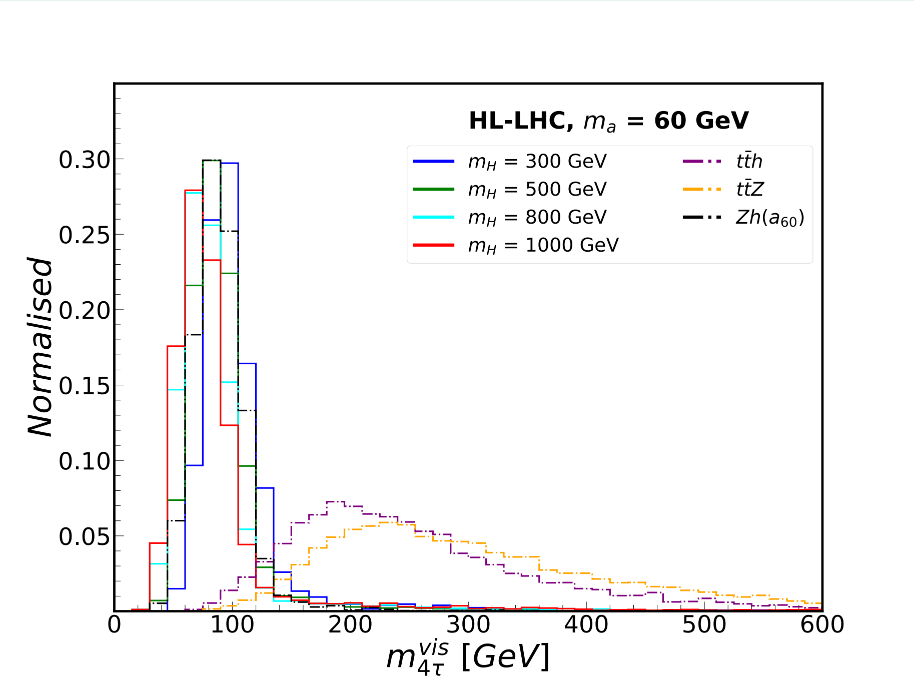




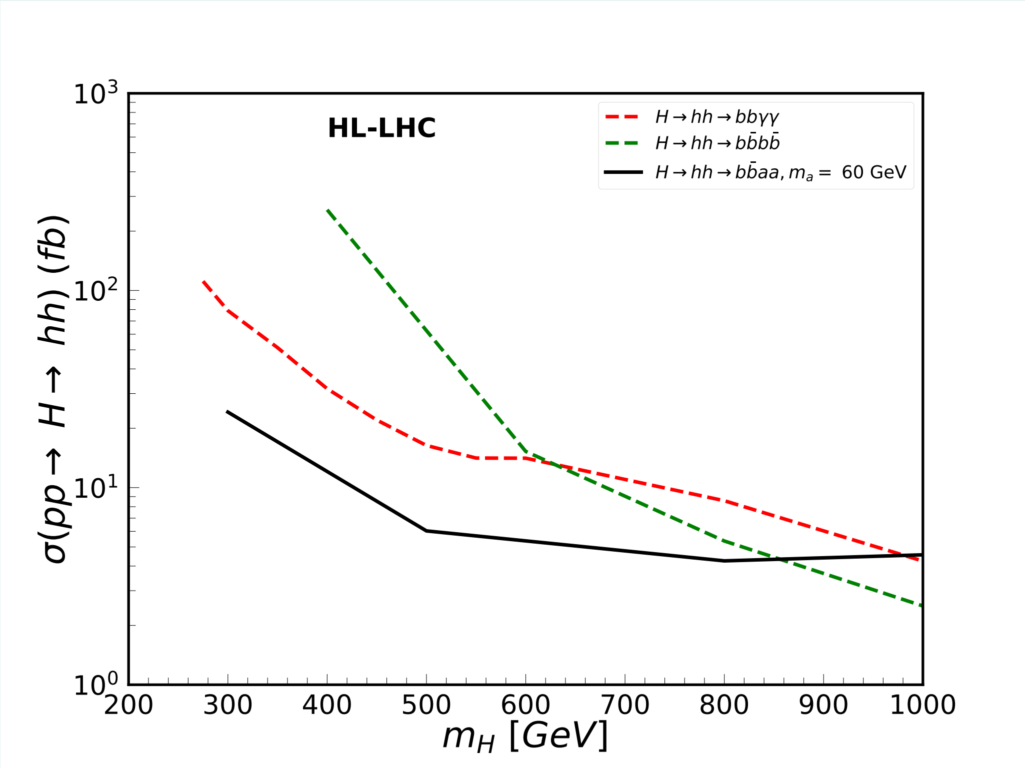
$pp \to H \to hh \to (h \to b\bar{b})(h \to aa \to 4\tau)$ final state

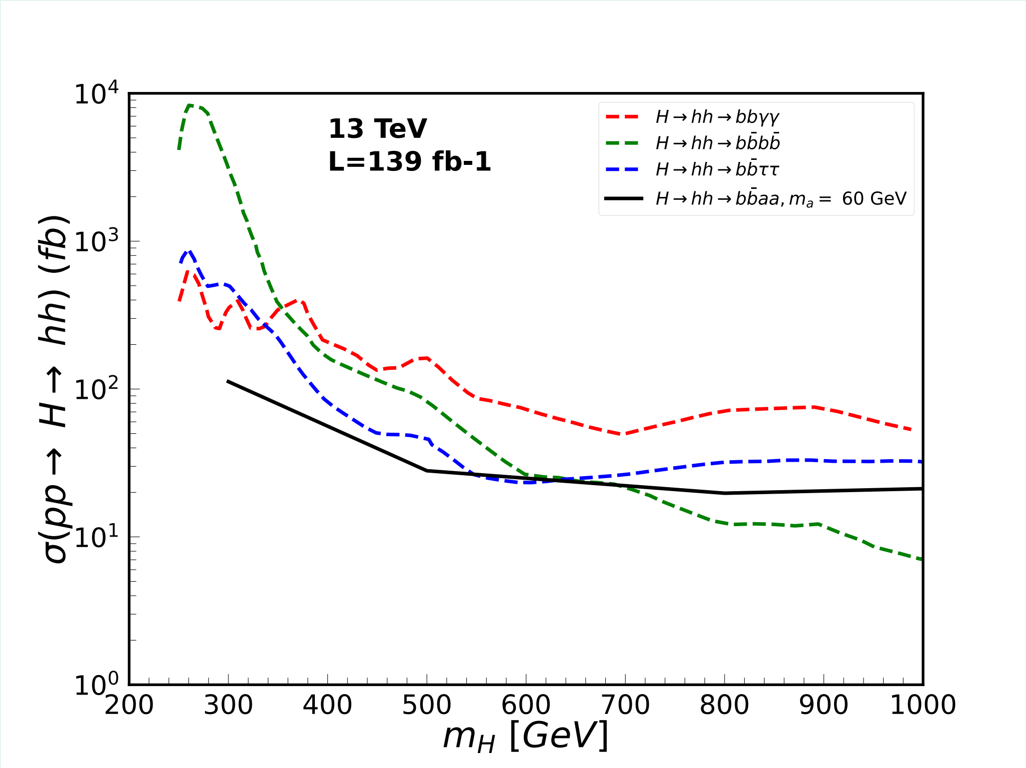
- Kinematic observables:





Upper limit on $\sigma(pp \to H \to hh)$





Summary and Outlook

- Searches for exotic Higgs decays are interesting probe for new physics: new light scalar states/sensitivity to high energy scales.
- $h \to aa \to 4\tau$ final state is well motivated and provide rich phenomenology, requires dedicated search strategies.
- The single Higgs production gives stringent constraint on Br($h \to aa \to 4\tau$).
- Complimentary to single Higgs, $gg \to hh$ can offer competitive sensitivity.
- Upper limits on resonant di-Higgs production are comparable to standard decay modes of Higgs boson.

Thank you