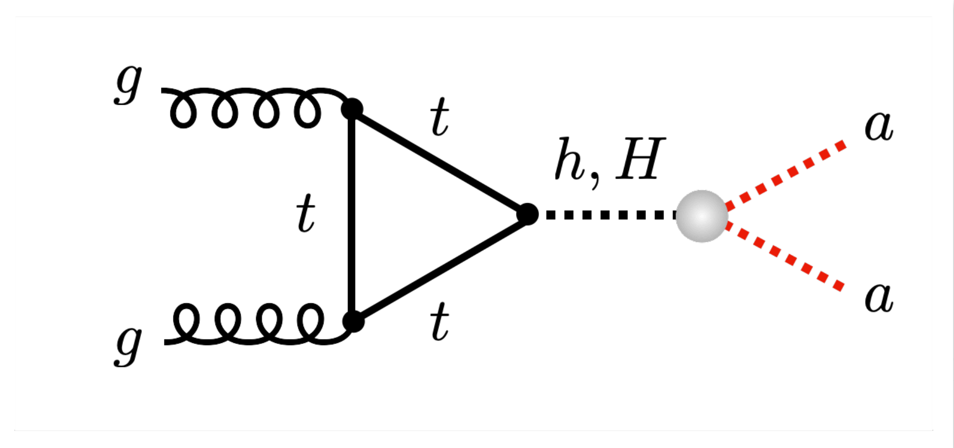
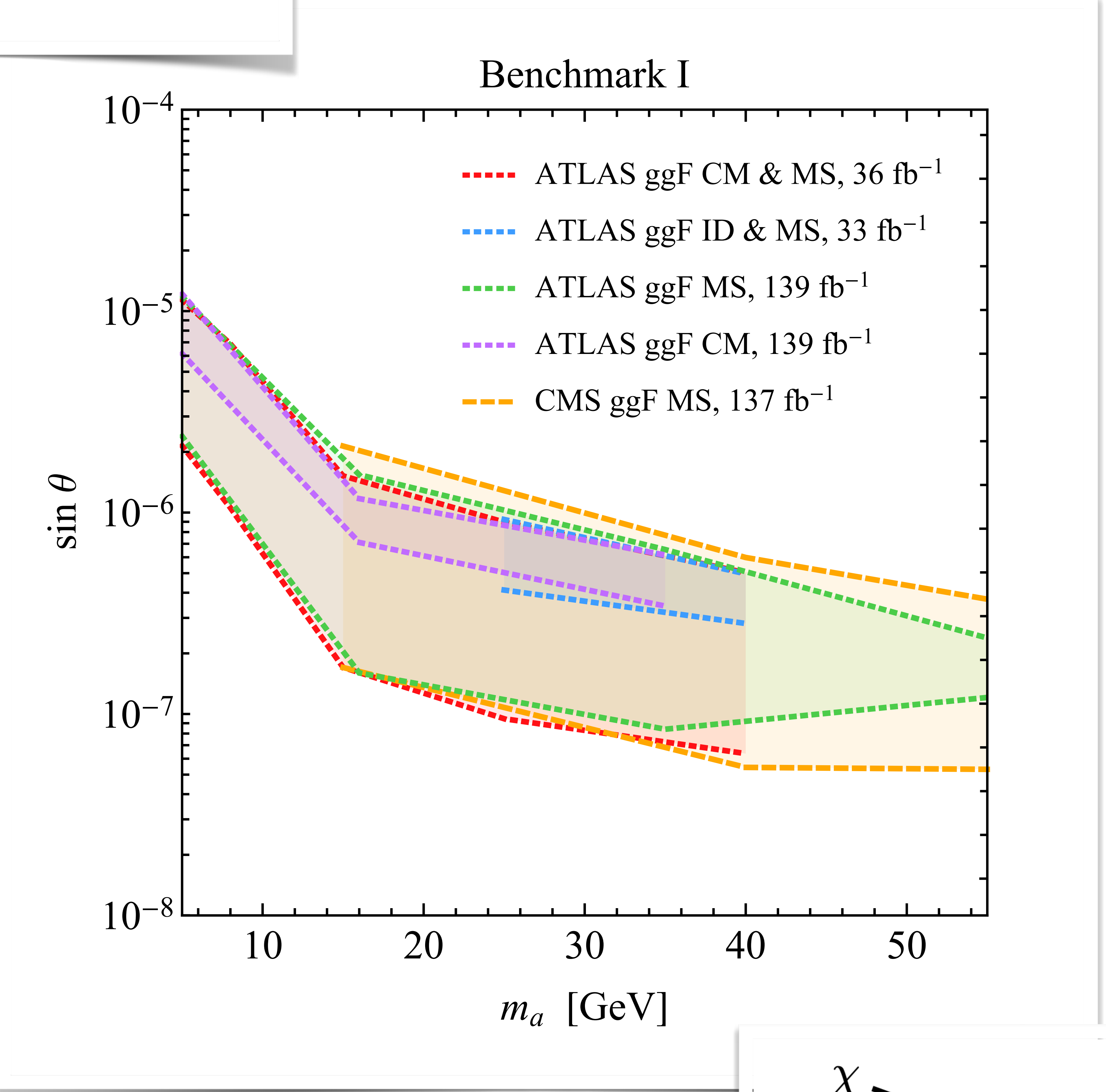
Based on ArXiv:2302.02735 (U. Haisch, LS)

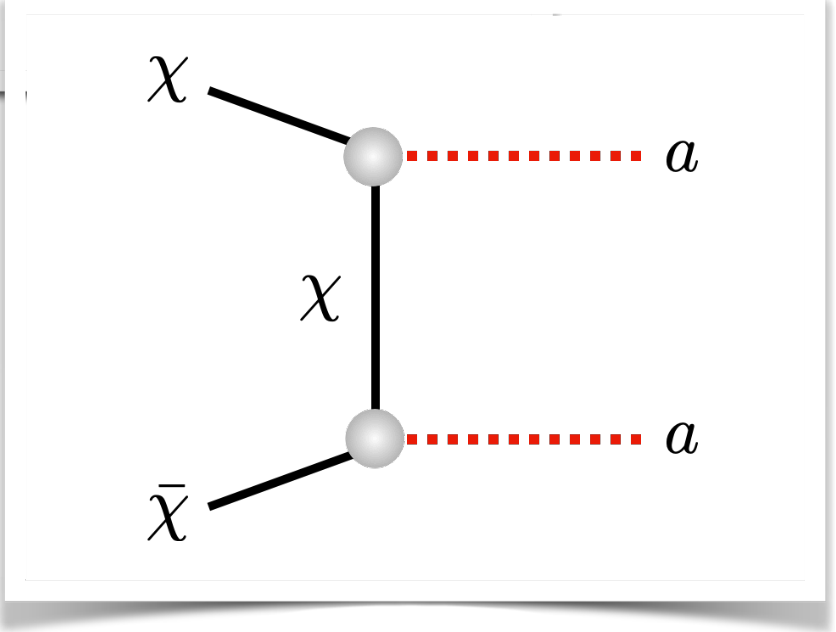
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

SFB 1258 Neutrinos Dark Matter Messengers

Technische Universität München







Long-lived particle phenomenology in the 2HDM+a model

Luc Schnell

13th Workshop of the Long-Lived Particle Community, CERN

June 20, 2023

1. Introduction

1.1 Motivation

1.2 2HDM+a in a nutshell

1.3 E_T^{miss} signatures

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UV-complete DM benchmarks

Sources: ArXiv:1510.02110 (F. Kahlhoefer, K. Schmidt-Hoberg, T. Schwetz, S. Vogl).

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UV-complete DM benchmarks

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Simplified models: e.g.
$$\mathscr{L} \supset - g_q^A Z'^{\mu} (\bar{q}\gamma_\mu\gamma^5 q) - g_{DM}^A Z'^{\mu} (\bar{\chi}\gamma_\mu\gamma^5 \chi)$$

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- **Mixing of a DM mediator with the (extended) scalar sector** leads to a rich and interesting collider phenomenology.

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2HDM+a model

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2HDM scalar potential

$$V_H = \mu_1 H_1^\dagger H_1 + \mu_2 H_2^\dagger H_2 + \left(\mu_3 H_1^\dagger H_2 + \text{h.c.}\right) + \lambda_1 \left(H_1^\dagger H_1\right)^2 + \lambda_2 \left(H_2^\dagger H_2\right)^2$$
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$$V_P = \frac{1}{2} m_P^2 P^2 + P \left(i b_P H_1^\dagger H_2 + \text{h.c.}\right) + P^2 \left(\lambda_{P1} H_1^\dagger H_1 + \lambda_{P2} H_2^\dagger H_2\right) ,$$

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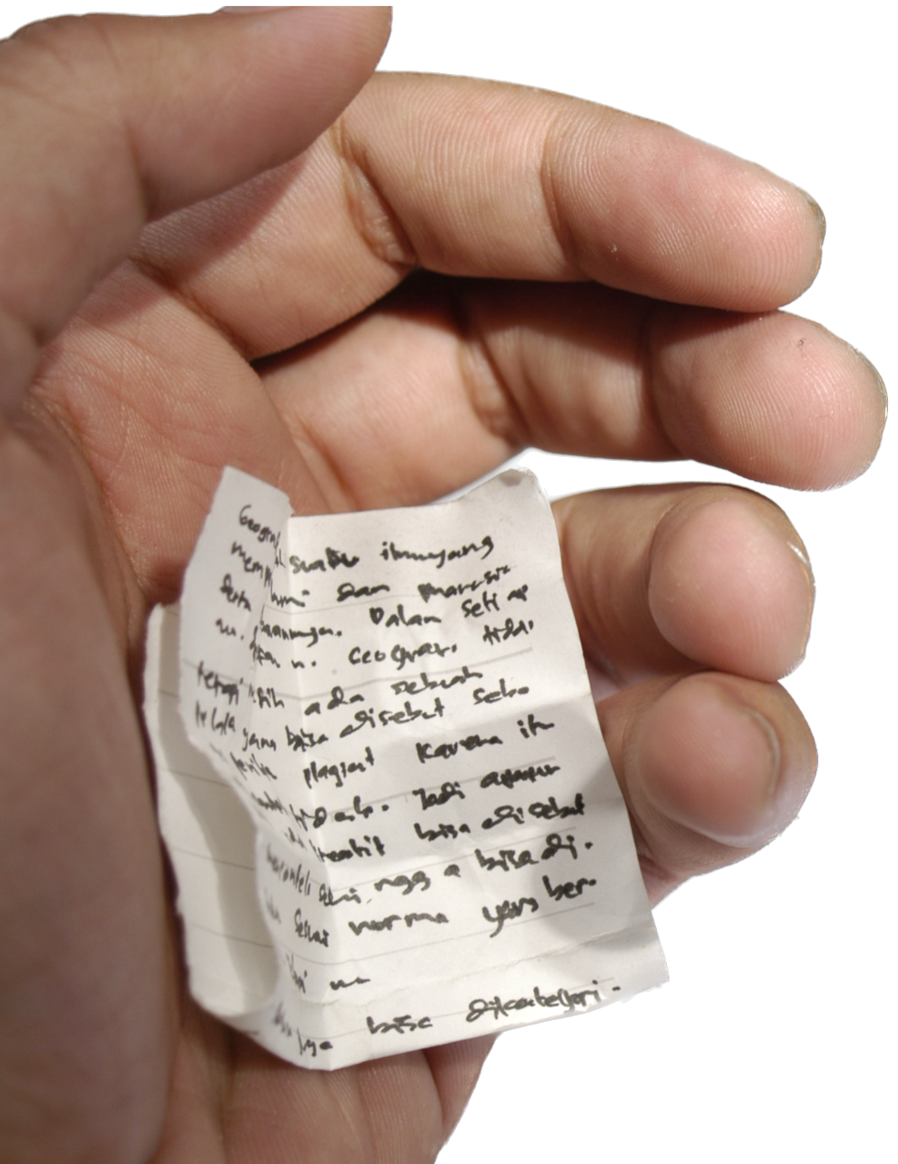

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1.3 E_T^{miss} signatures

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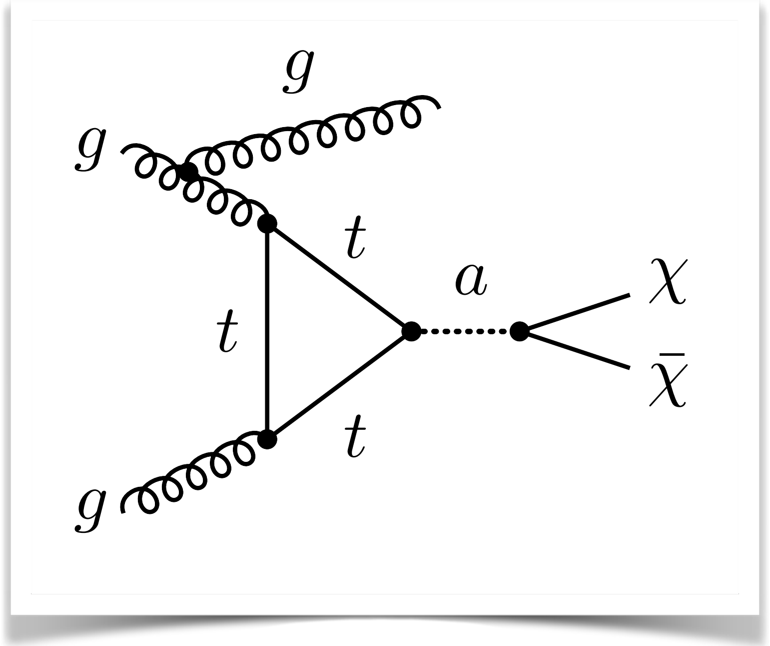
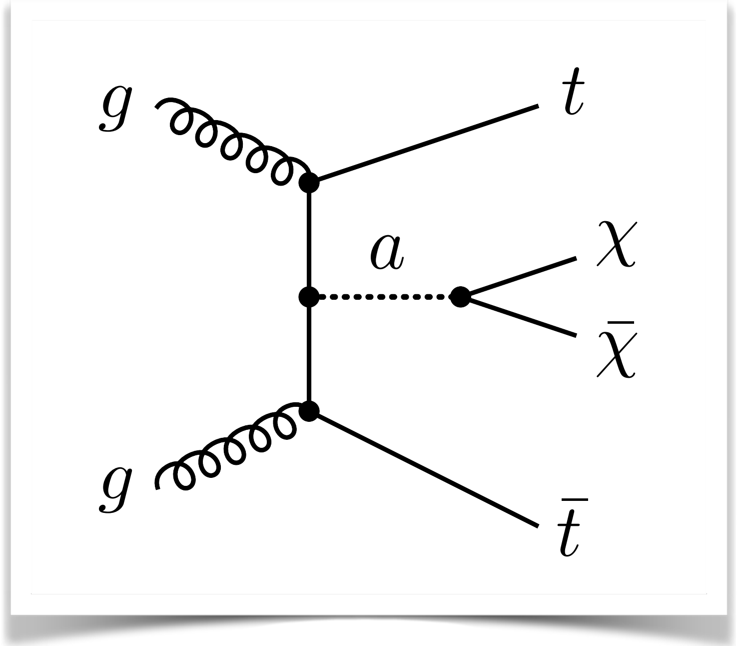
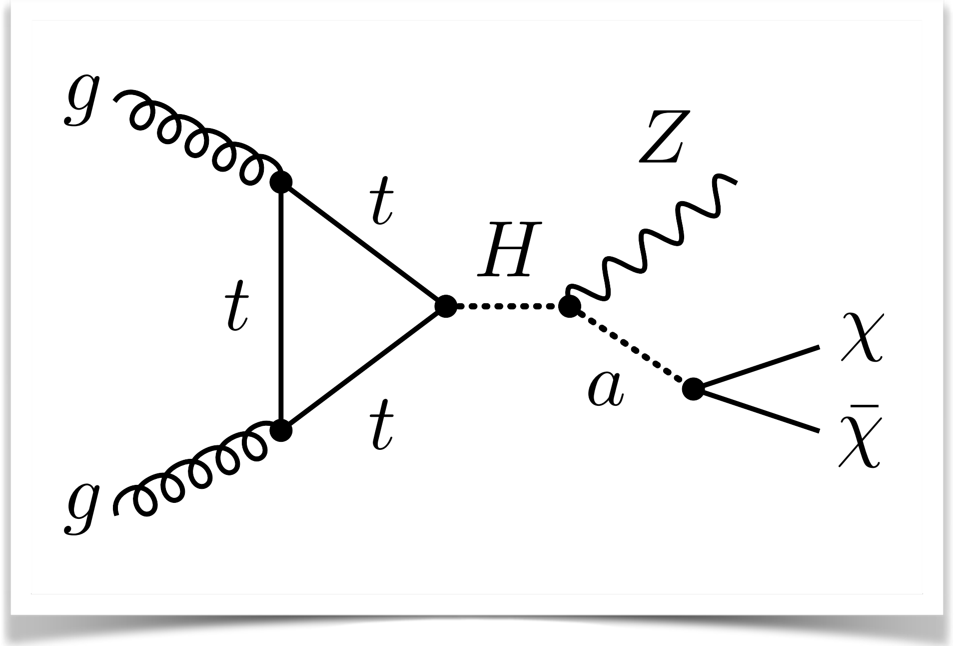
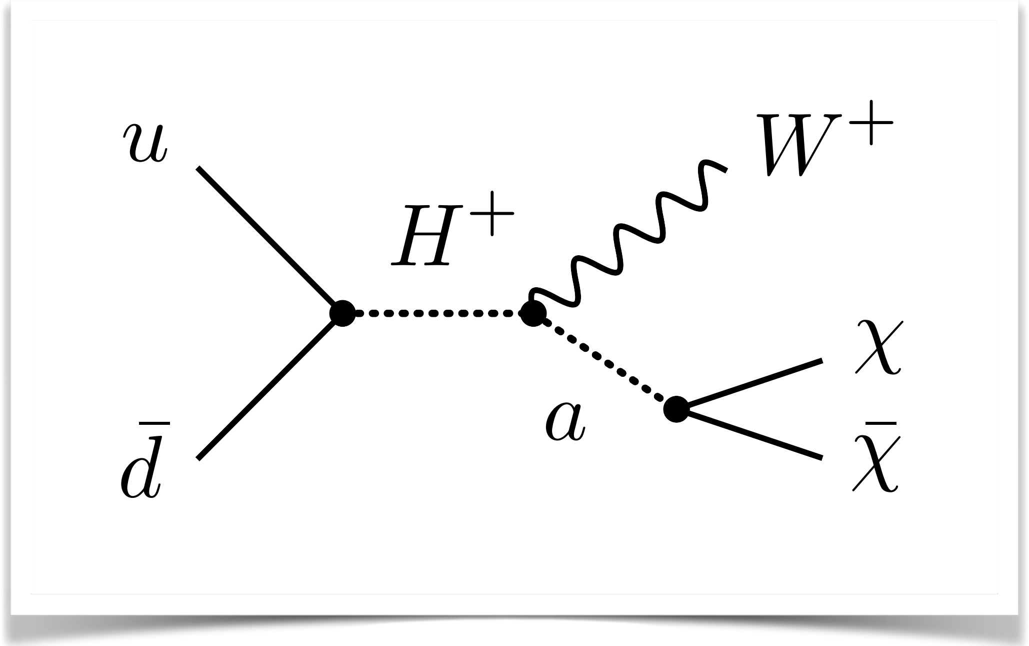
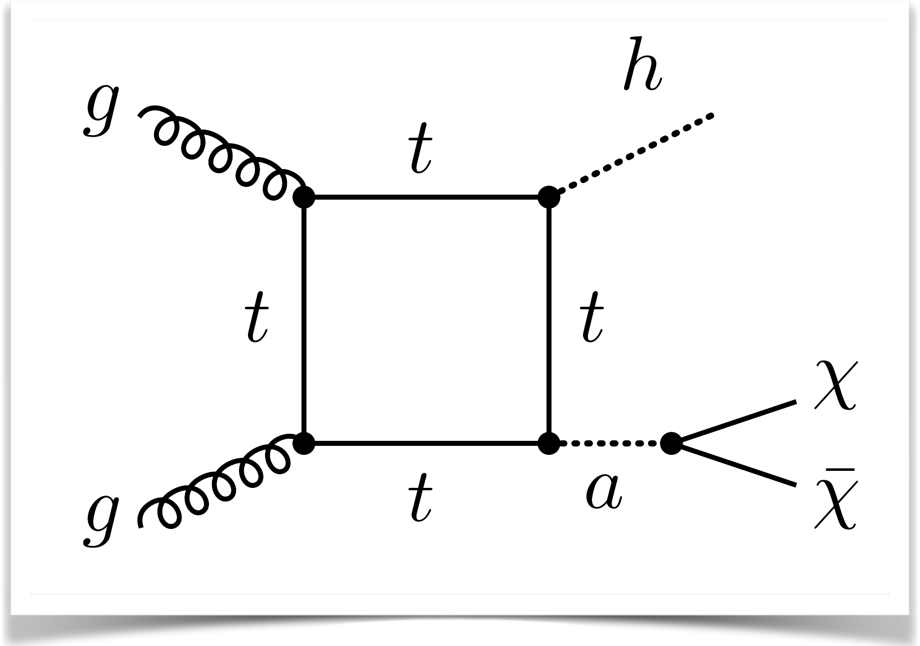
1.3 $\mathrm{E_T^{miss}}$ signatures











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$\mathbf{j + E_T^{miss}}$ | $\mathbf{t\bar{t} + E_T^{miss}}$ | $\mathbf{Z + E_T^{miss}}$ | $\mathbf{W + E_T^{miss}}$ | $\mathbf{h + E_T^{miss}}$

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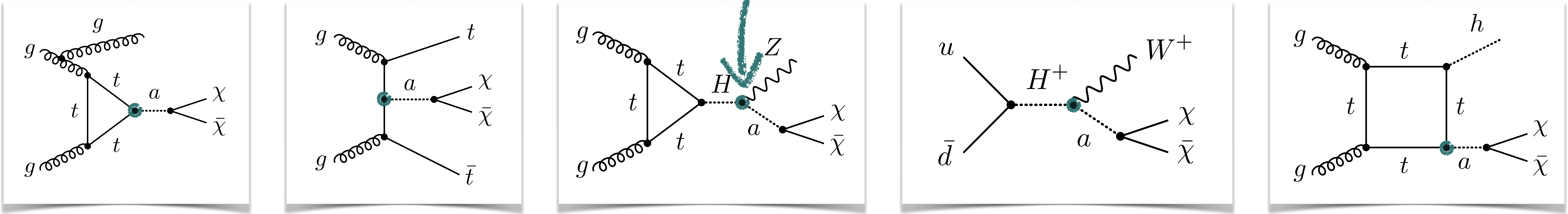
$\sim \sin\theta$



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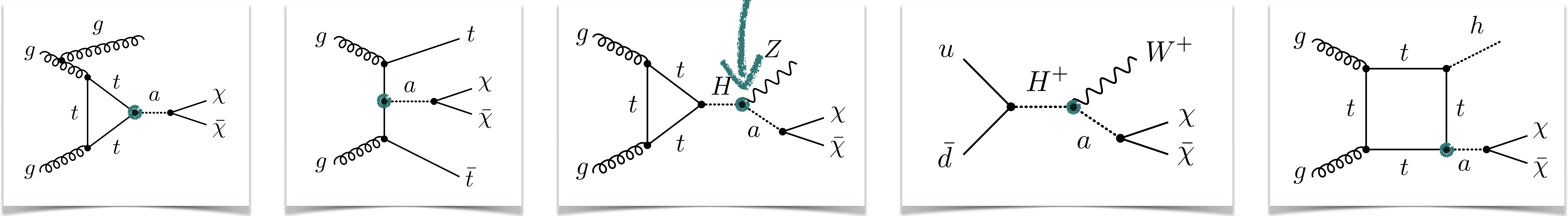

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- These E_T^{miss} signatures disappear for small mixing angles $\theta \simeq 0$ ($\rightarrow a \simeq P$).

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2. LLP Phenomenology

2.1 Model parameters

2.2 LLP constraints

2.3 Relic density

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- For small mixing angles θ, the pseudoscalar $a \simeq P$ can become **long-lived.**

Physical fields: $h, H, a, A, H^{\pm}$ and χ.

Physical parameters: $\alpha, \beta, \theta, v, \lambda_3, \lambda_{P1}, \lambda_{P2}, m_h, m_H, m_a, m_A, m_{H^{\pm}}$.

α: mixing angle for scalars (h, H)

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$$\Gamma\left(a \to gg\right) = \frac{\alpha_s^2}{32\pi^3 v^2} m_a^3 \left| \sum_{q=t,b,c} \eta_q f\left(\frac{4m_q^2}{m_a^2}\right)\right|^2 \sin^2\theta \,,$$

$$\Gamma\left(a \to \chi\bar{\chi}\right) = \frac{y_\chi^2}{8\pi} m_a \sqrt{1 - \frac{4m_\chi^2}{m_a^2}} \cos^2\theta \,,$$

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Source: ArXiv:1802.02156
(U. Haisch, J.F. Kemenik, A. Malinauskas, M. Spira).

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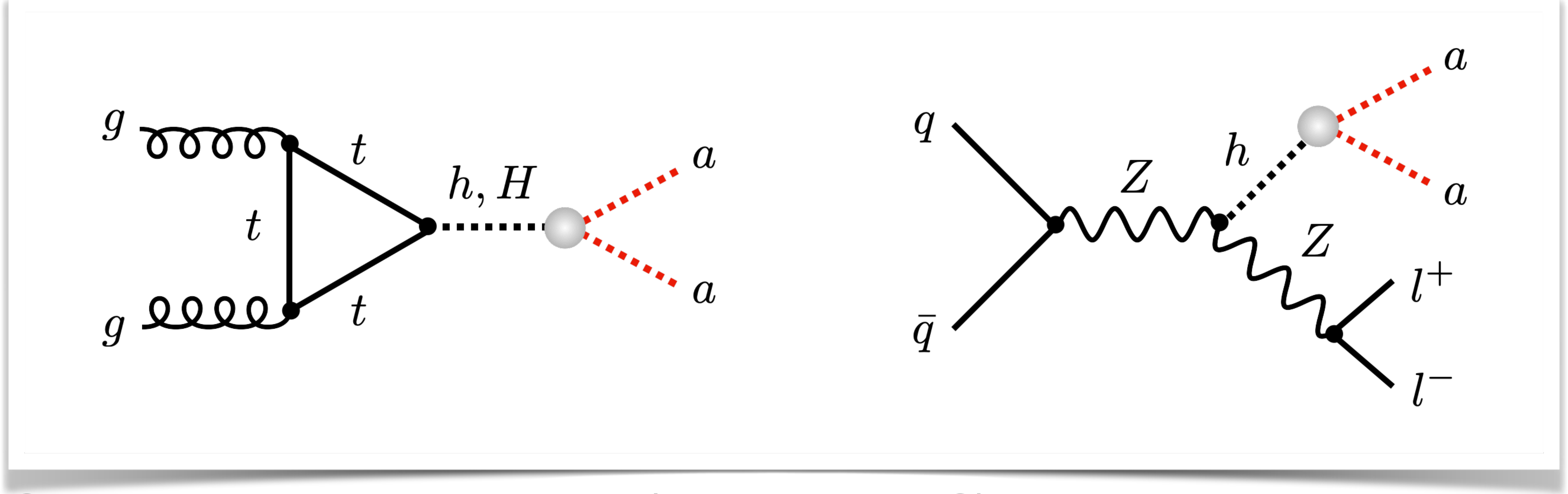
NLO + QCD corr.

- Production via the **decay of a heavier spin-0 state**:



Source: ArXiv:2302.02735 (U. Haisch, LS).

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NLO + QCD corr.

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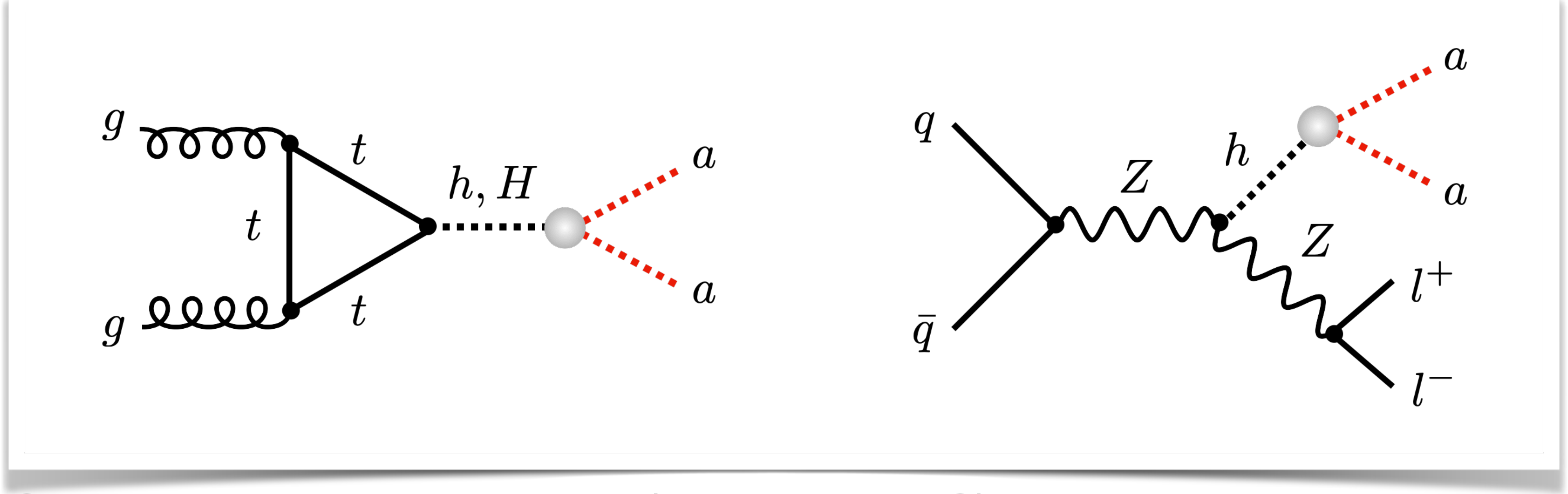

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NLO + QCD corr.

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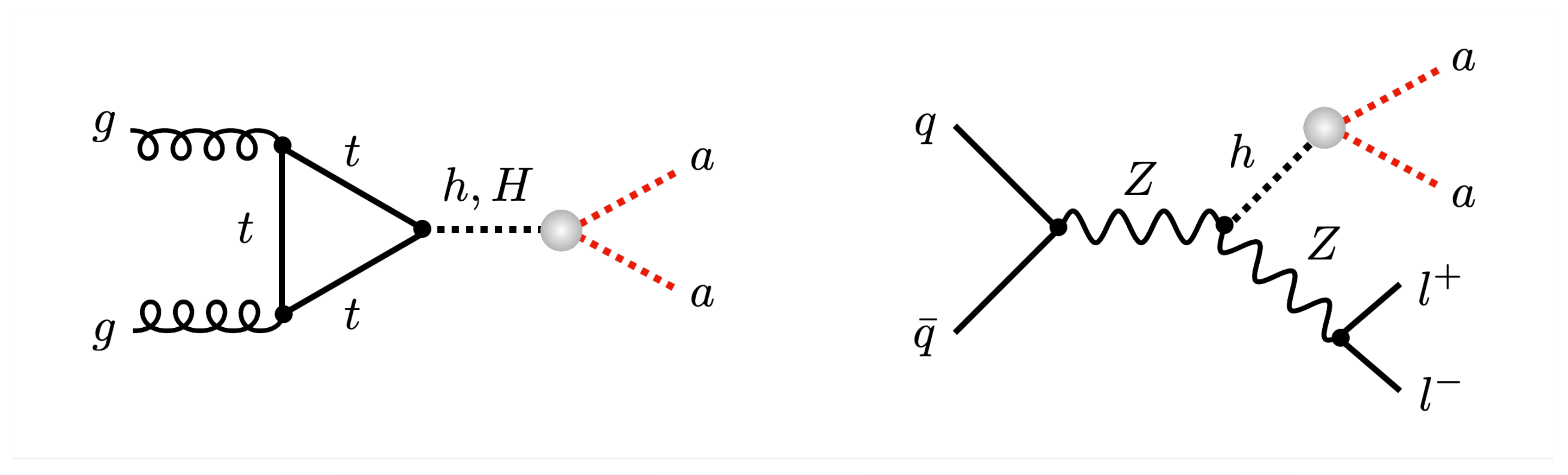

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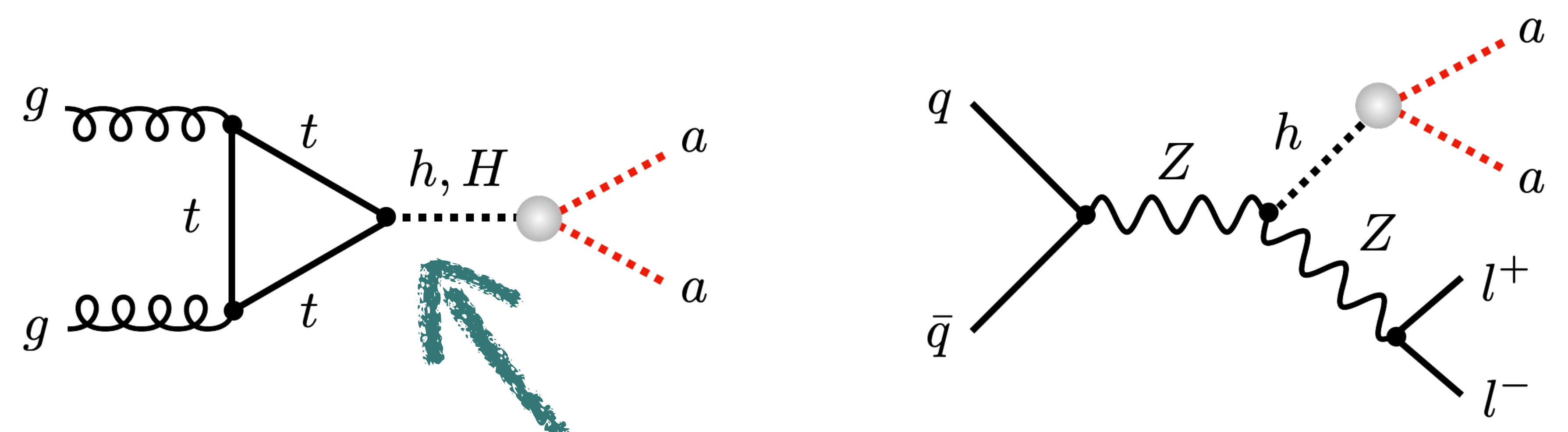

Source: ArXiv:2302.02735 (U. Haisch, LS).

BR$(h \to aa) \simeq 2\,\%$
(currently BR$(h \to$ inv.$) \lesssim 9\,\%$)

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2. LLP Phenomenology

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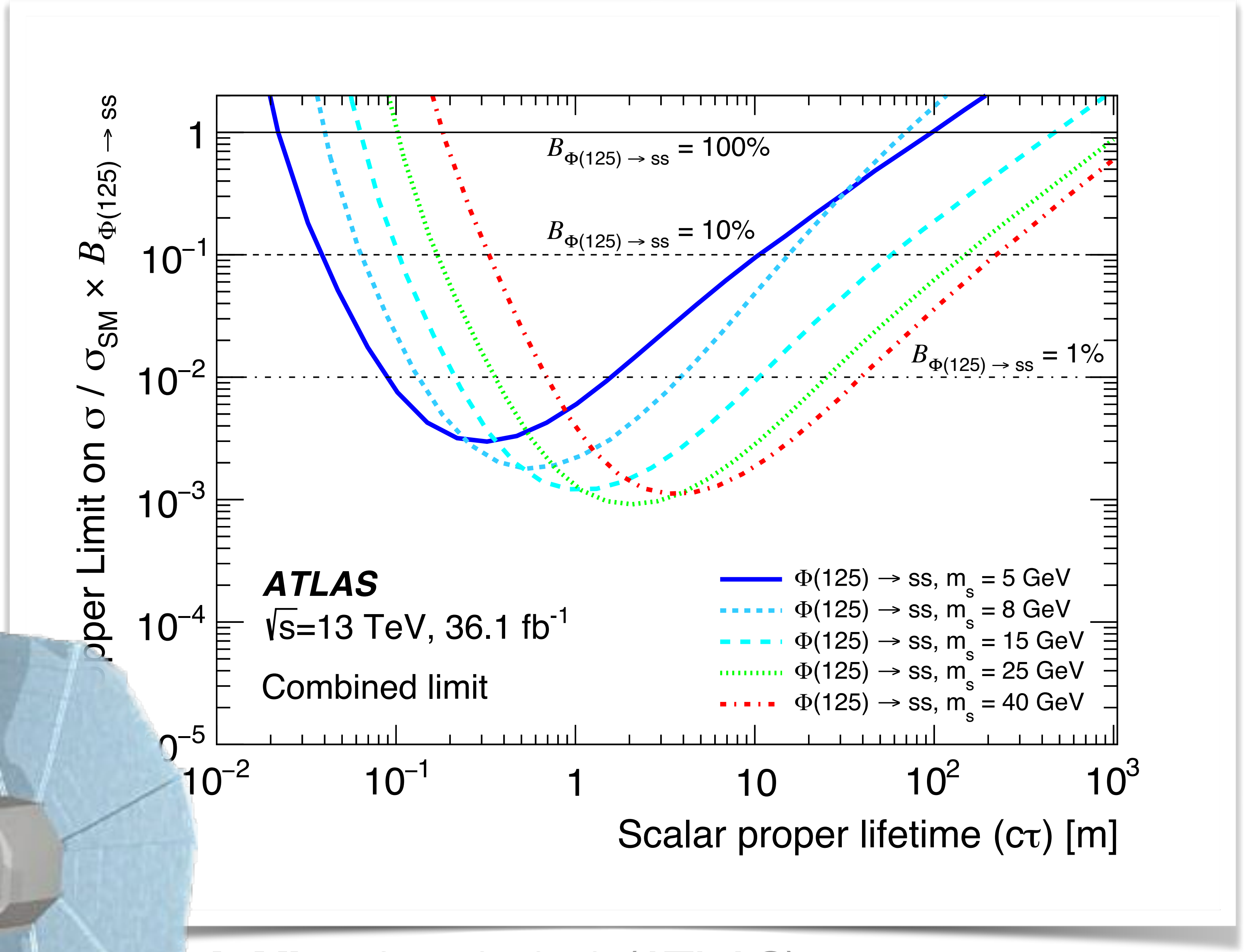

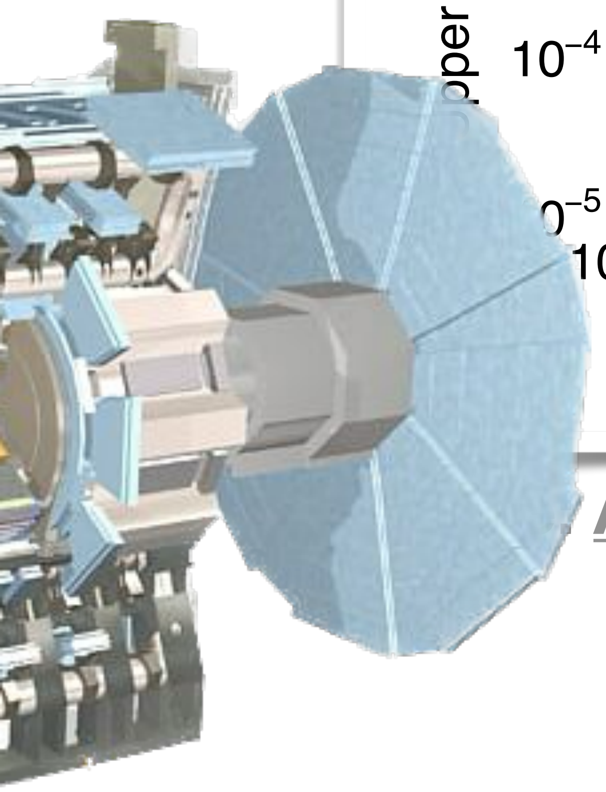

ArXiv:1811.07370 (ATLAS).

Physical fields: $h, H, a, A, H^{\pm}$ and χ.

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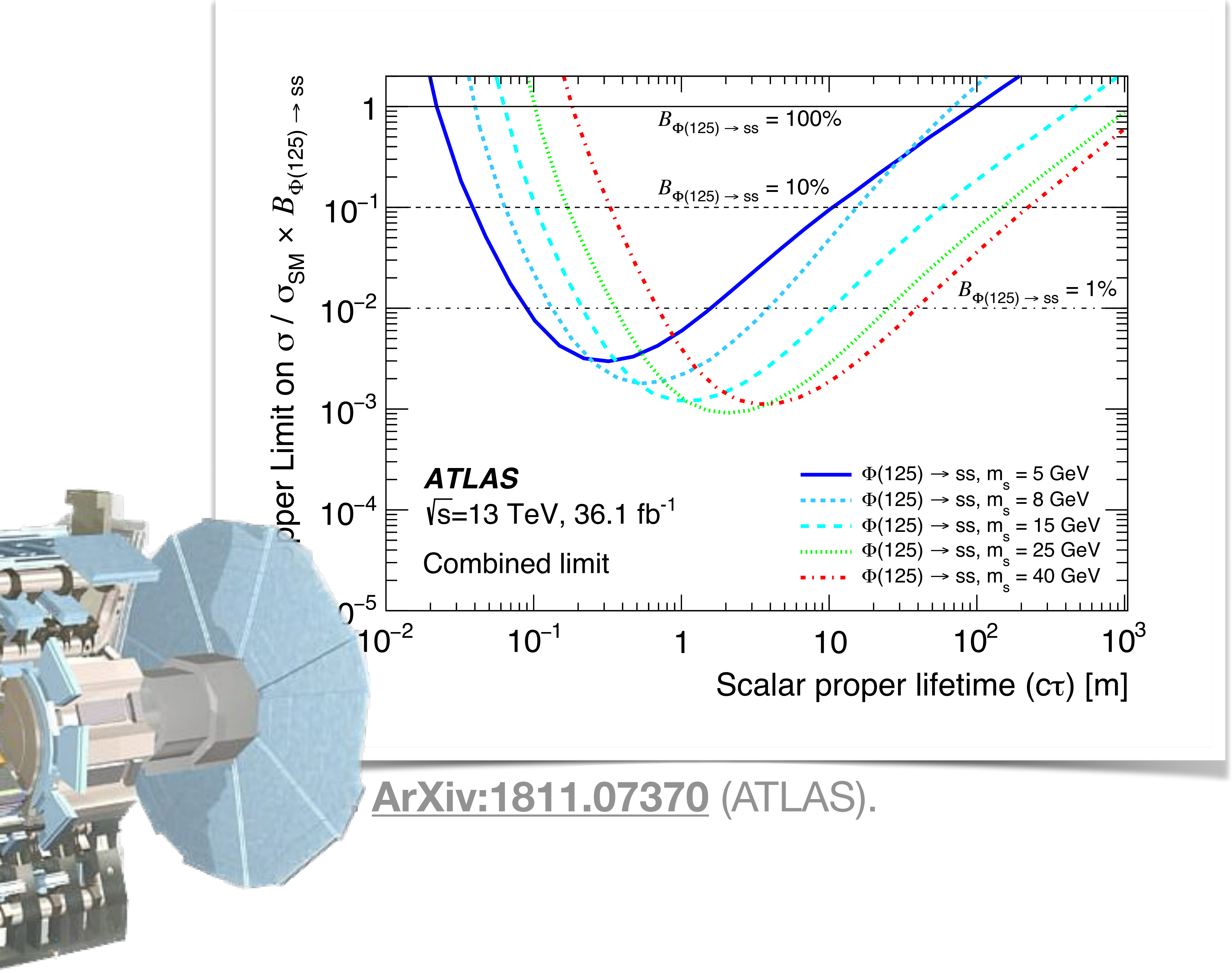

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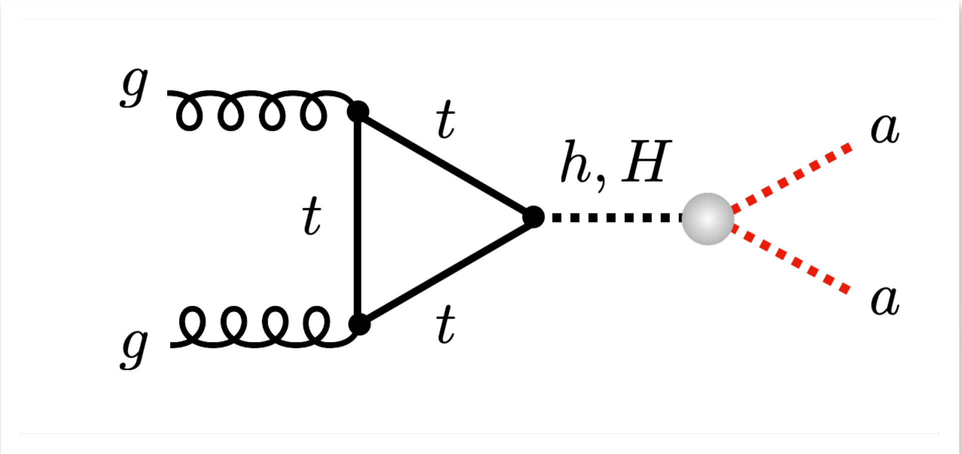

$$\frac{c\tau_a}{\mathrm{m}} \simeq 4.8 \cdot 10^{-12} \left(\frac{\mathrm{GeV}}{m_a}\right)^{0.9} \frac{1}{\sin^2\theta},$$

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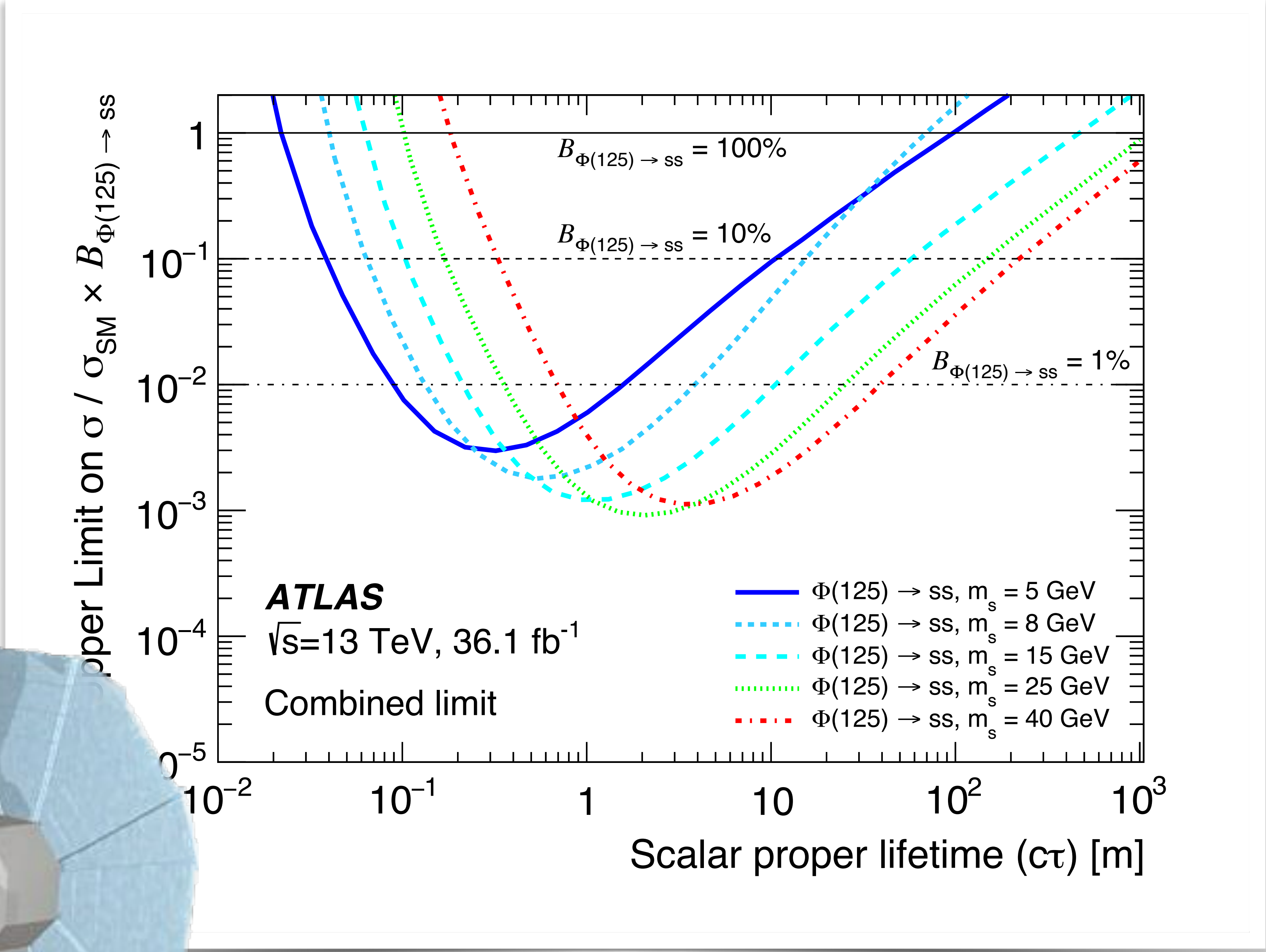

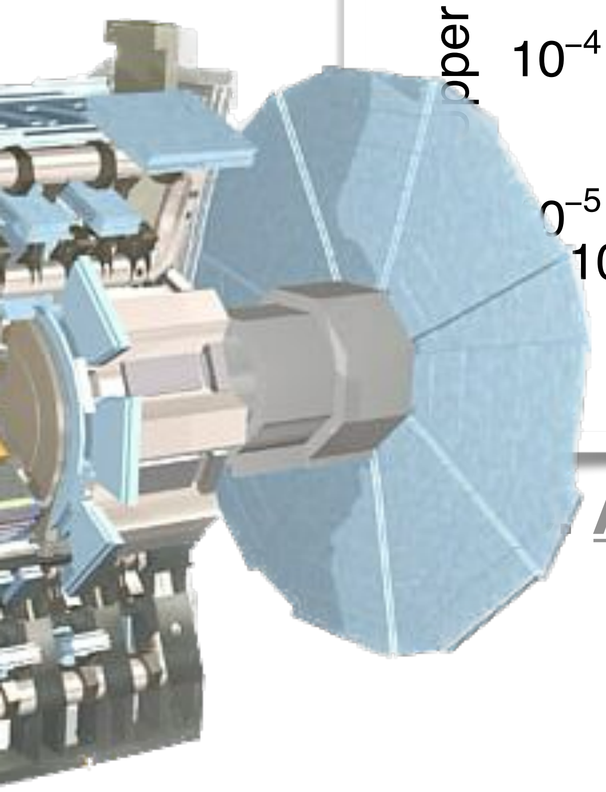

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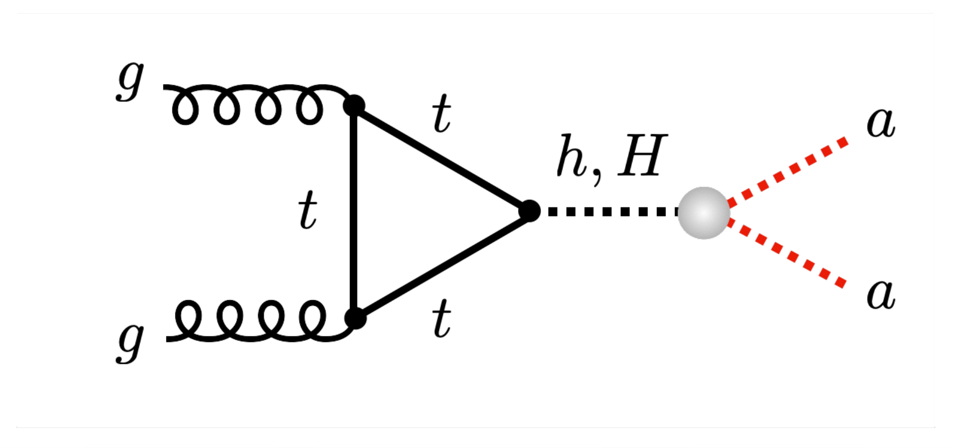

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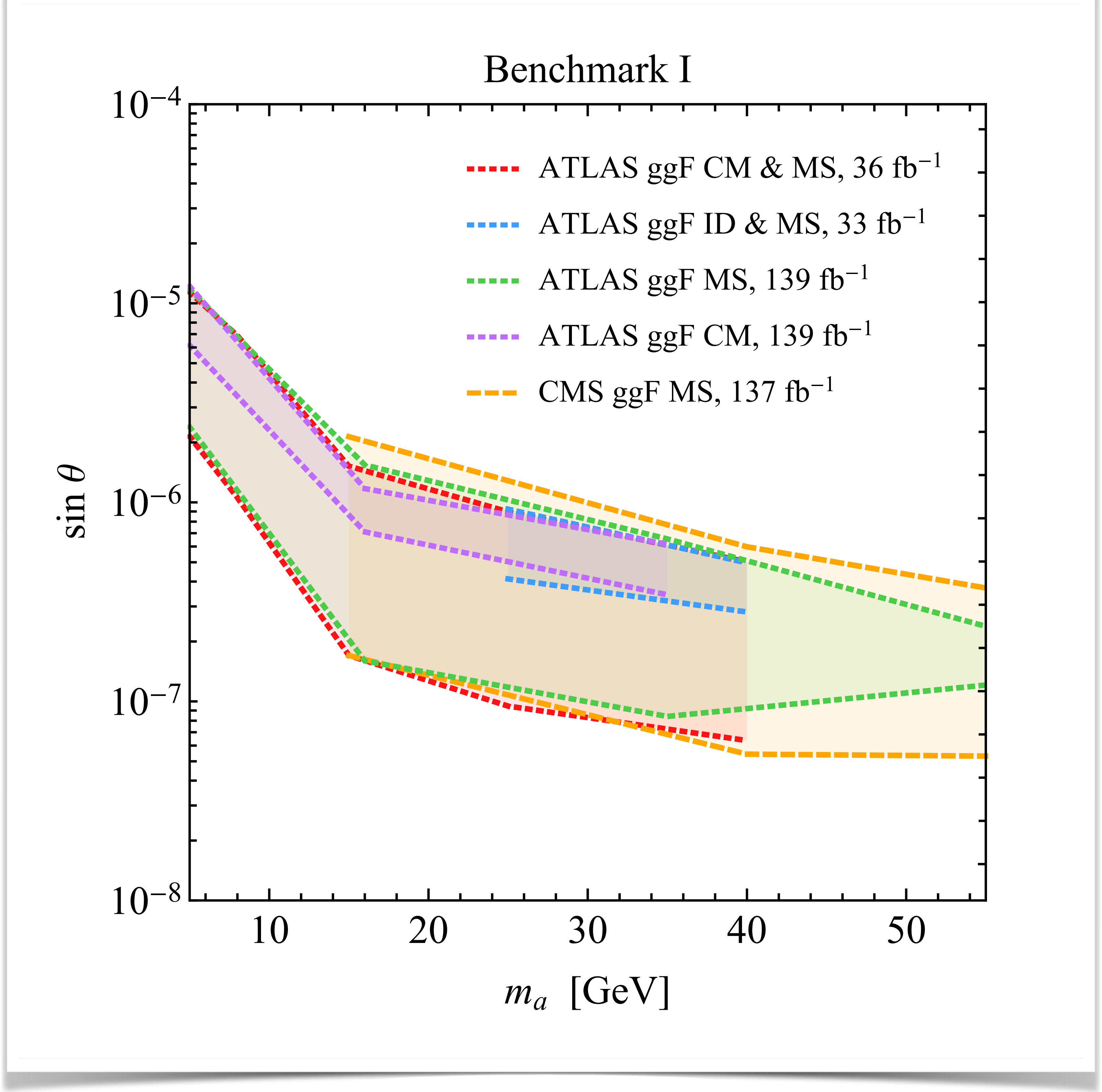

Source: ArXiv:2302.02735 (U. Haisch, LS).

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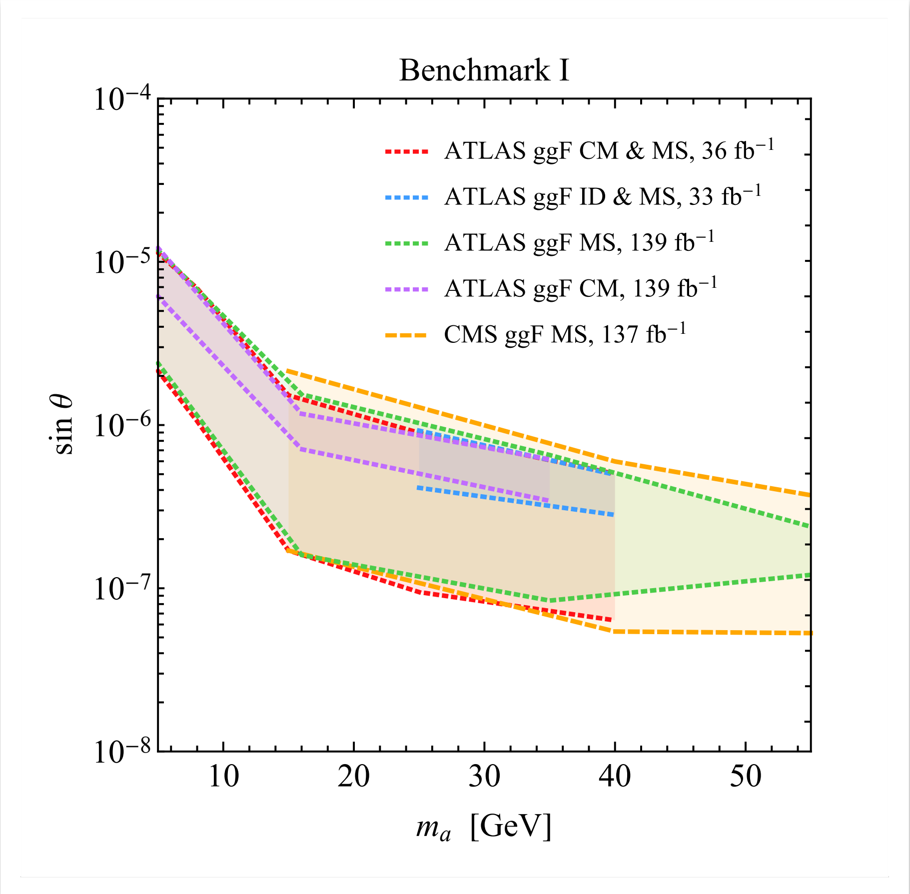

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2. LLP Phenomenology

2.2 LLP constraints

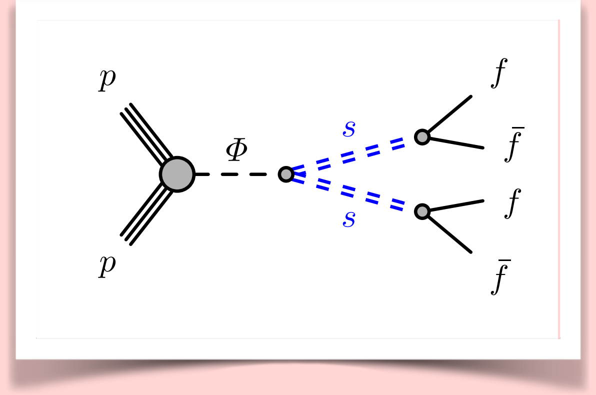
ArXiv:1811.07370 (ATLAS)

36.1 fb^{-1} of data.

Three benchmark models (one is scalar portal).

Narrow jets in **muon spectrometer (MS)**.

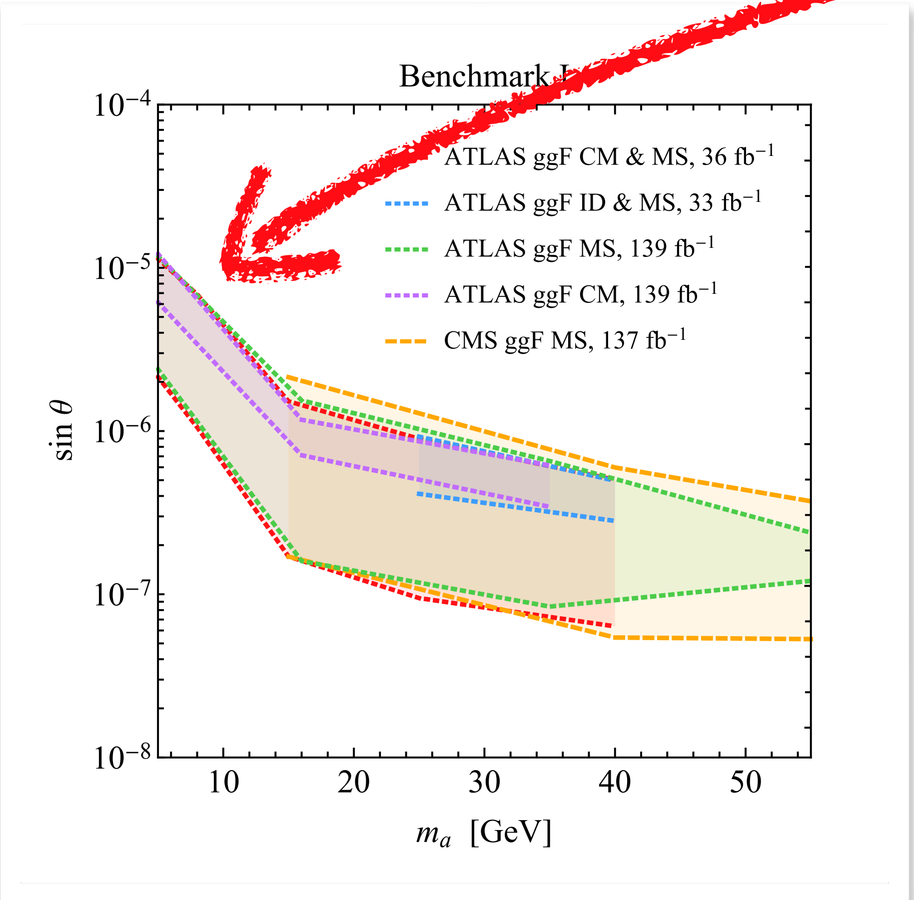
2 MS vertices, 1 MS vertex and $E_T^{miss} > 30$ GeV.



ArXiv:1902.03094 (ATLAS)

10.8 fb^{-1} of data.

Two narrow jets in **HCal** with no associated activity in tracker, high E_H/E_{EM} („$CalRatio$“).



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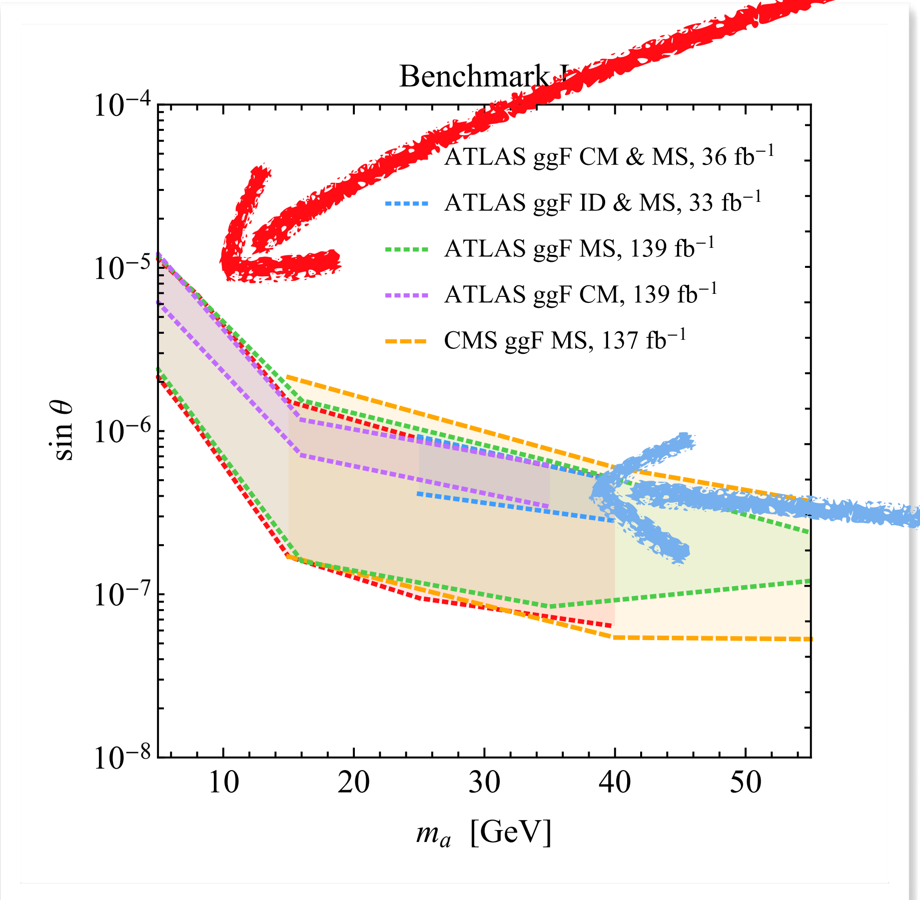

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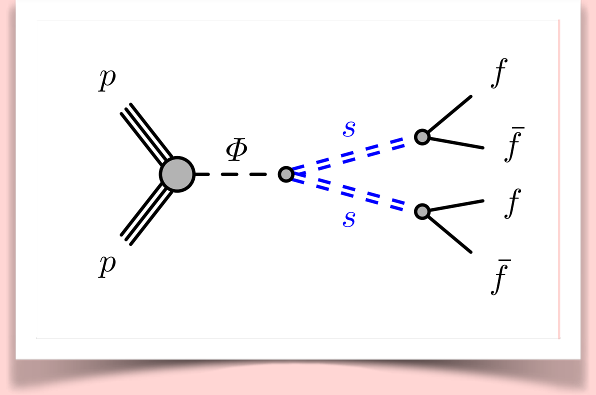

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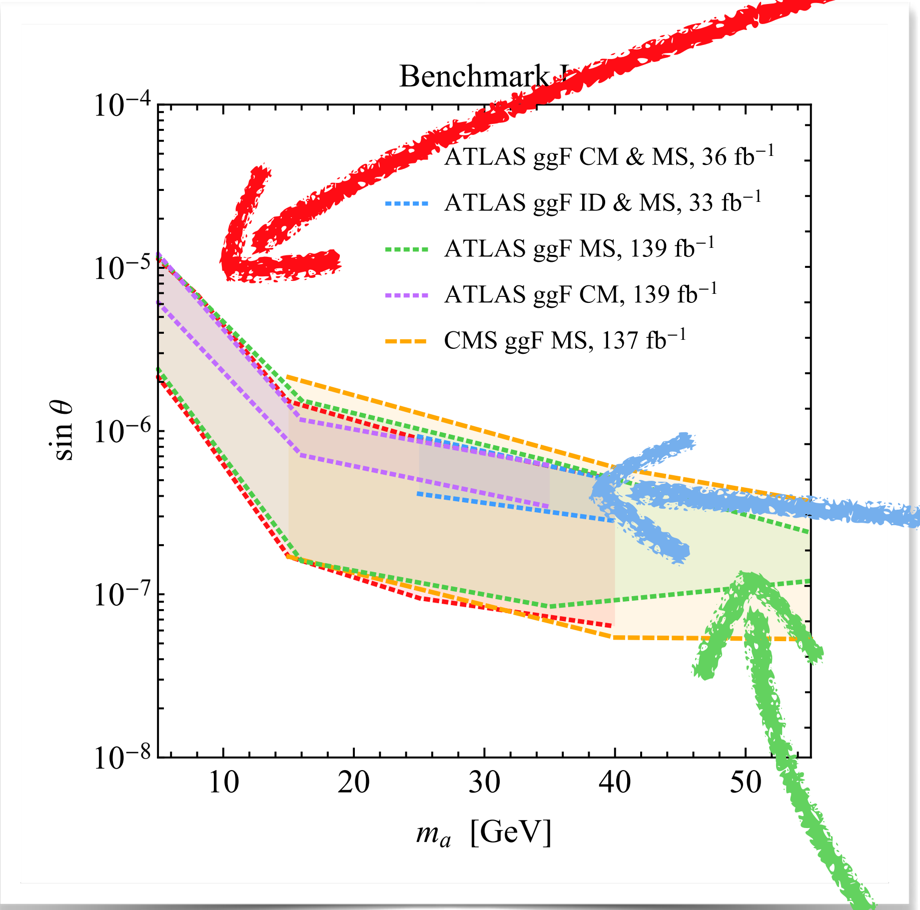
ArXiv:1911.12575 (ATLAS)

$33\ \mathrm{fb}^{-1}$ of data.
Narrow jet in **MS** and displaced track in **inner detector (ID)**.
Branching ratios $a \to b\bar{b} : c\bar{c} : \tau^+\tau^-$ assumed to be 85:5:8.

2. LLP Phenomenology

2.2 LLP constraints



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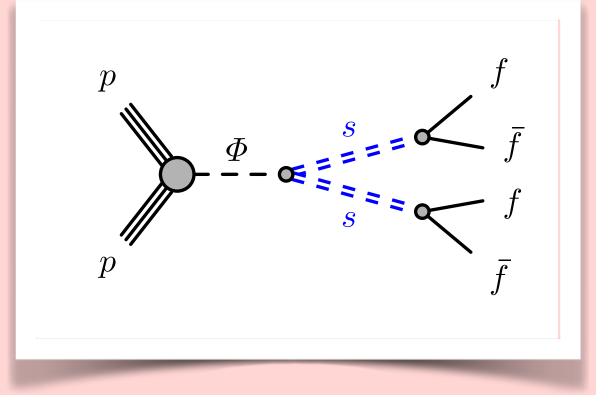
ArXiv:1811.07370 (ATLAS)



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ArXiv:1911.12575 (ATLAS)

33 fb^{-1} of data.
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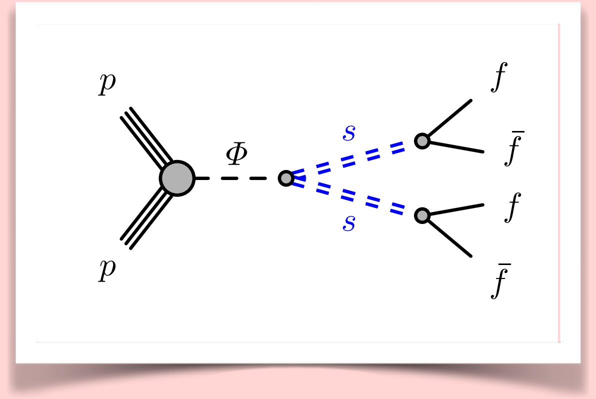
Branching ratios $a \to b\bar{b} : c\bar{c} : \tau^+\tau^-$ assumed to be 85:5:8.

ArXiv:2203.00587 (ATLAS)

139 fb^{-1} of data.
Two narrow, high-multiplicity jets in **MS**.
Background (punch-through jets, noncollision background) reduced by requiring two displaced vertices.

2. LLP Phenomenology

2.2 LLP constraints



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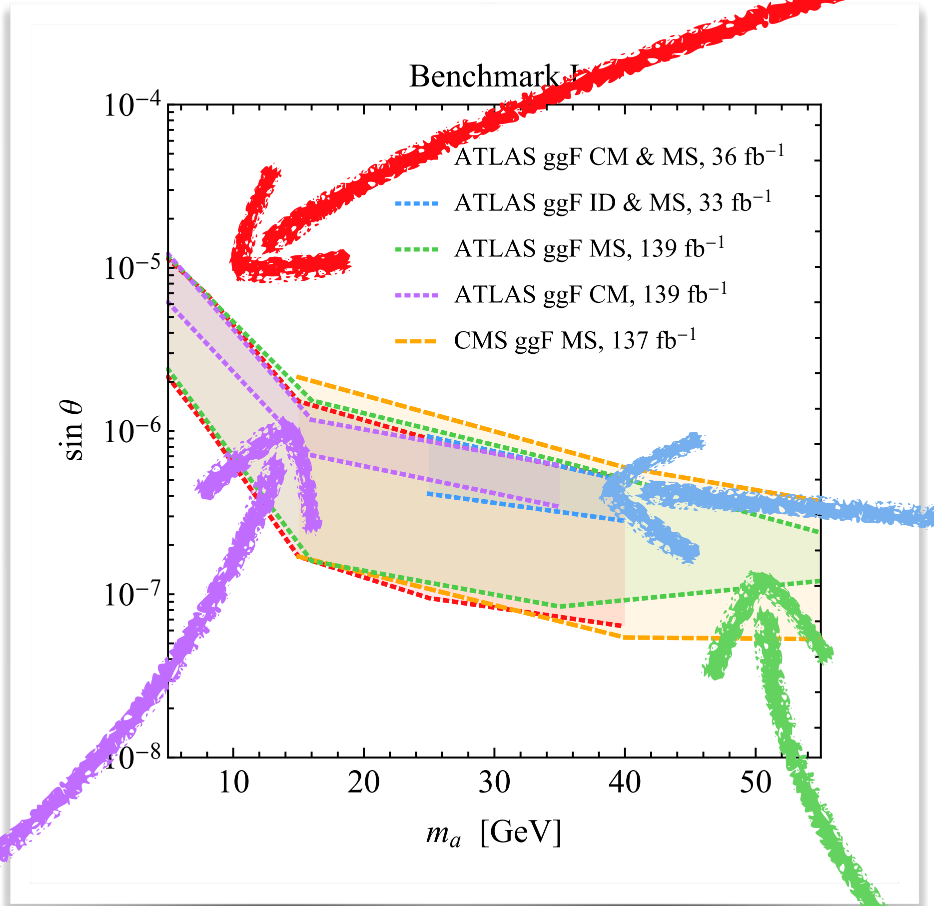
Narrow jet in **MS** and displaced track in **inner detector (ID)**.
Branching ratios $a \to b\bar{b} : c\bar{c} : \tau^+\tau^-$ assumed to be 85:5:8.



Source: ArXiv:2302.02735 (U. Haisch, LS).

ArXiv:2203.01009 (ATLAS)

139 fb^{-1} of data.
Two narrow jets in **HCal** with no associated activity in tracker, high E_H/E_{EM} („$CalRatio$“).
Improved displaced-jet identification (NN).

ArXiv:2203.00587 (ATLAS)

139 fb^{-1} of data.
Two narrow, high-multiplicity jets in **MS**.
Background (punch-through jets, noncollision background) reduced by requiring two displaced vertices.

2. LLP Phenomenology

2.2 LLP constraints

ArXiv:2107.04838 (CMS)

137 fb^{-1} of data.
One particle shower in **endcap muon detectors (EMD)** and $p_T^{miss} > 200$ GeV.
Sufficient level of shielding in front of the EMD makes background low enough to only search for one shower.

ArXiv:2203.01009 (ATLAS)

139 fb^{-1} of data.
Two narrow jets in **HCal** with no associated activity in tracker, high E_H/E_{EM} („$CalRatio$“).
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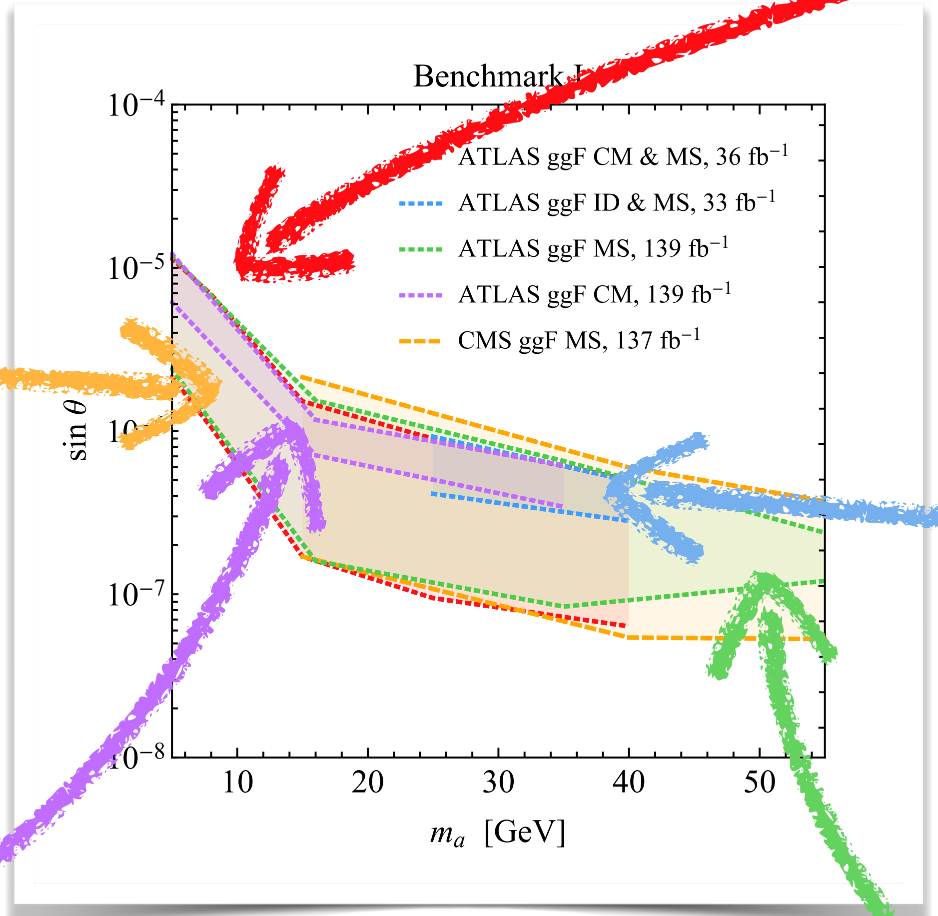
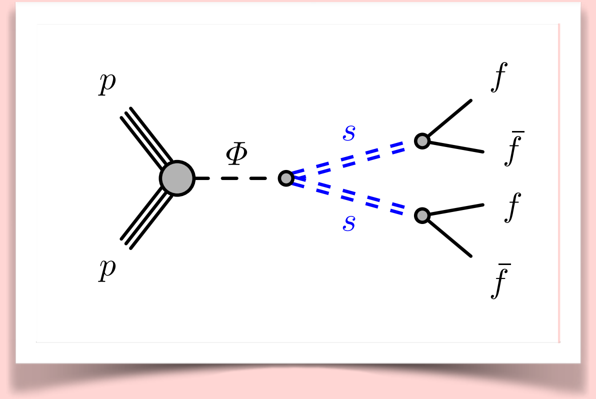


Source: ArXiv:2302.02735 (U. Haisch, LS).

ArXiv:1811.07370 (ATLAS)



36.1 fb^{-1} of data.
Three benchmark models (one is scalar portal).
Narrow jets in **muon spectrometer (MS)**.
2 MS vertices, 1 MS vertex and $E_T^{miss} > 30$ GeV.

ArXiv:1902.03094 (ATLAS)

10.8 fb^{-1} of data.
Two narrow jets in **HCal** with no associated activity in tracker, high E_H/E_{EM} („$CalRatio$“).

ArXiv:1911.12575 (ATLAS)

33 fb^{-1} of data.
Narrow jet in **MS** and displaced track in **inner detector (ID)**.
Branching ratios $a \to b\bar{b} : c\bar{c} : \tau^+\tau^-$ assumed to be 85:5:8.

ArXiv:2203.00587 (ATLAS)

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2. LLP Phenomenology

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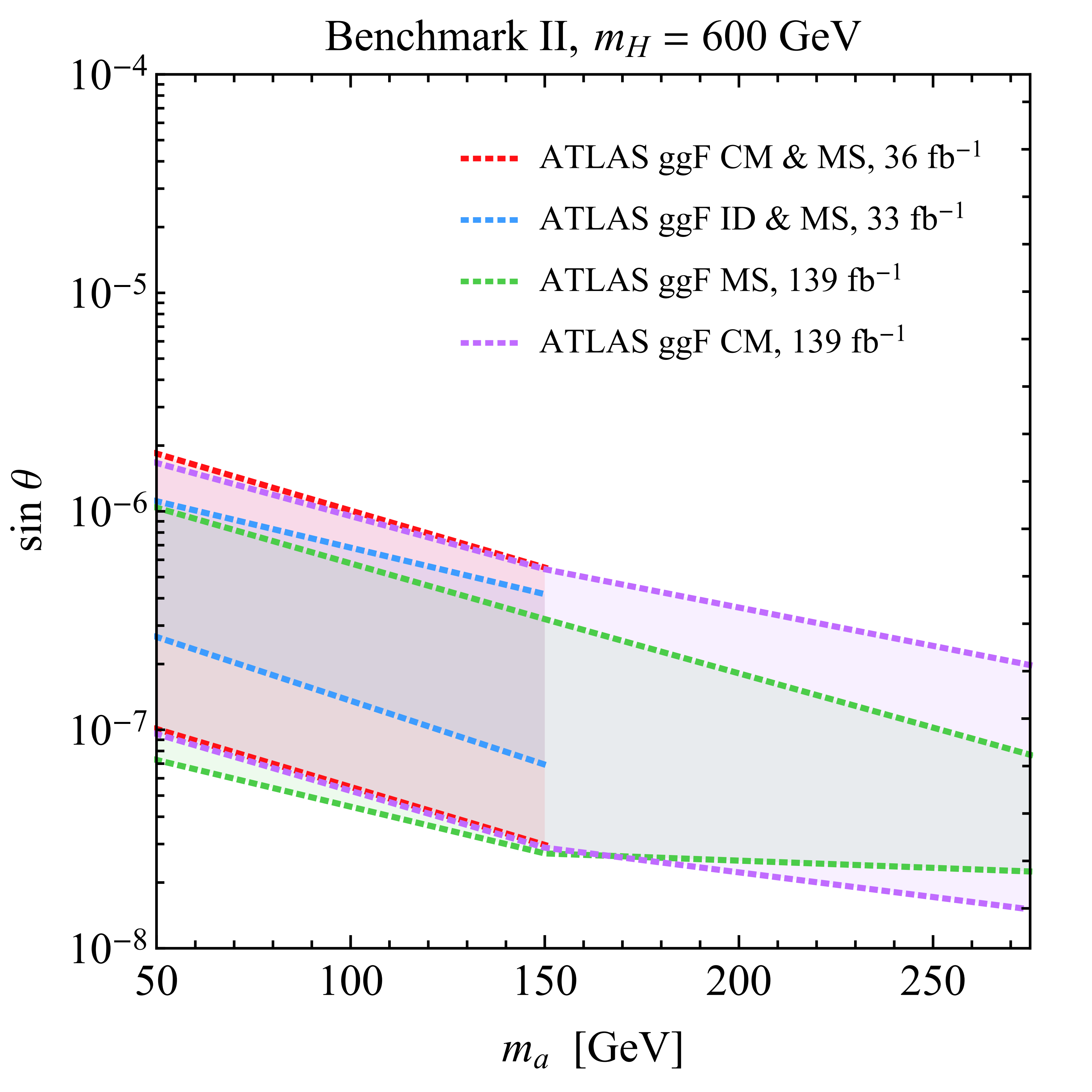

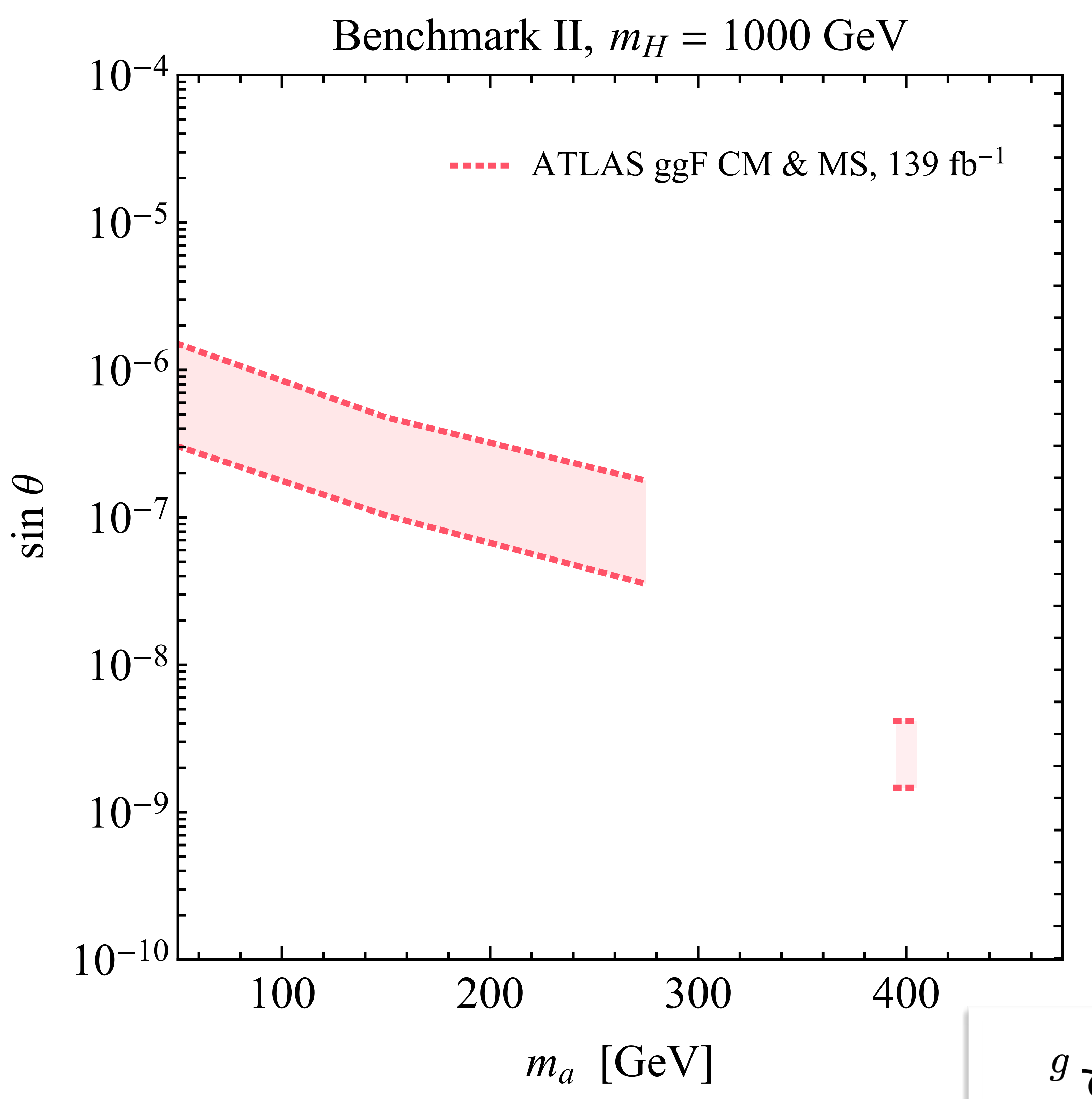

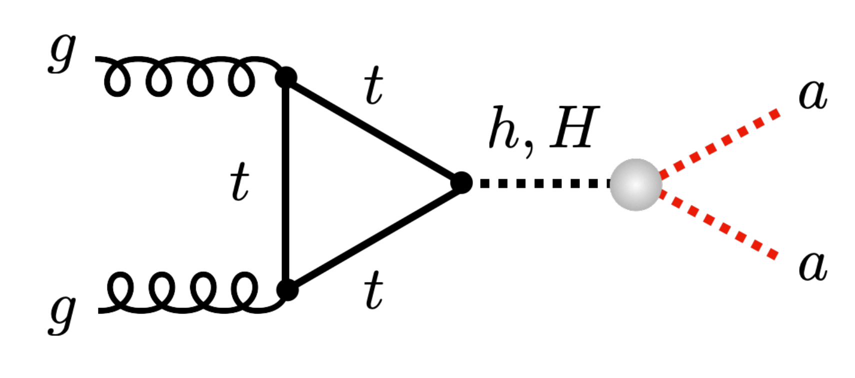

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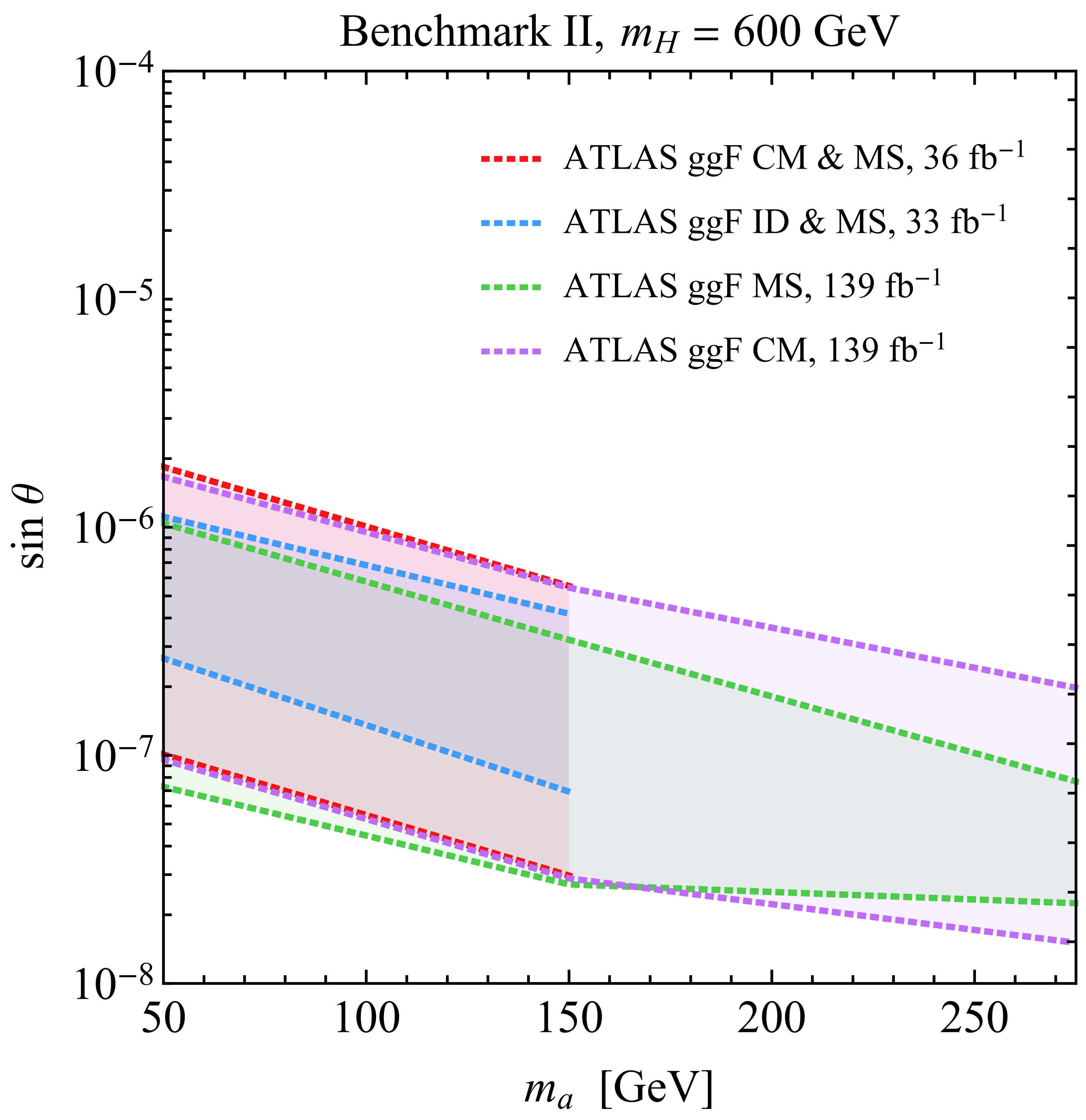
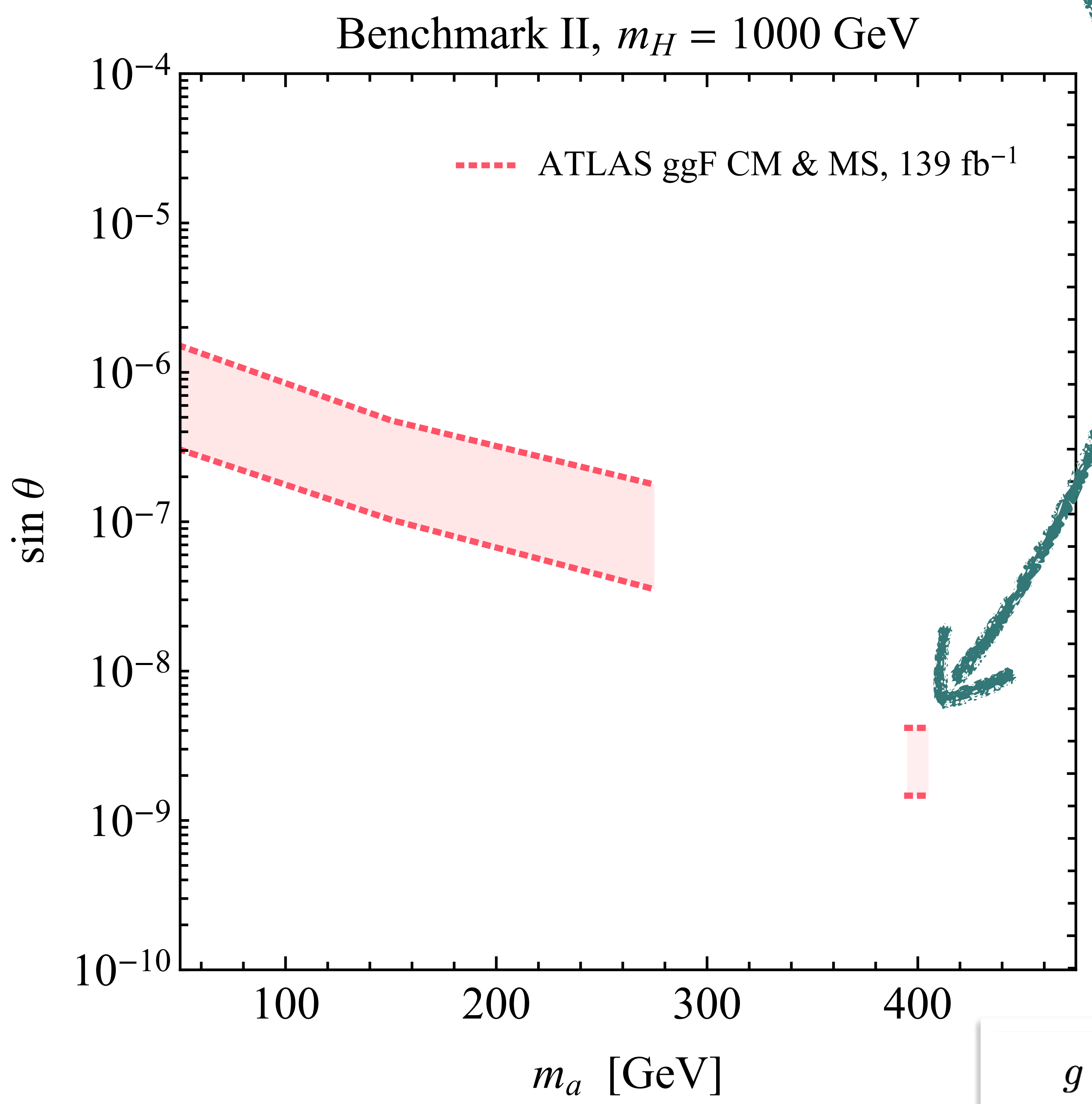
2. LLP Phenomenology

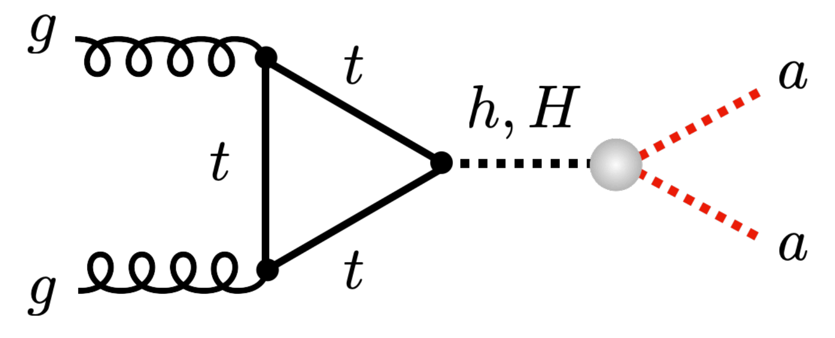
2.2 LLP constraints

$$\Gamma(a \to f\bar{f}) = \frac{N_c^f \eta_f^2 y_f^2}{16\pi} m_a \sqrt{1 - \frac{4m_f^2}{m_a^2}} \sin^2\theta \, .$$





Decay
$a \to t\bar{t}$
opens up



Source: ArXiv:2302.02735 (U. Haisch, LS).

2. LLP Phenomenology

2.3 Relic density

Physical fields: $h, H, a, A, H^{\pm}$ and χ.

Physical parameters: $\alpha, \beta, \theta, v, \lambda_3, \lambda_{P1}, \lambda_{P2}, m_h, m_H, m_a, m_A, m_{H^{\pm}}$.

α: mixing angle for scalars (h, H)

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- Can we get the **DM relic density** $\Omega h^2 = 0.120(1)$ right?

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$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v_{rel} \rangle \left(n_\chi^2 - n_\chi^{(eq)2} \right)$$

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$$\frac{\Omega h^2}{0.12} \simeq \frac{1.6 \cdot 10^{-10}\,\mathrm{GeV}^{-2}\, x_f}{\langle \sigma v_{\mathrm{rel}} \rangle_f},$$

$$\langle \sigma v_{\mathrm{rel}} \rangle_f \simeq \frac{y_\chi^2}{128\pi m_\chi^2} \left[\frac{\left(g_{haa}^2 + g_{Haa}^2 \right) v^2}{4 m_\chi^2} + \frac{y_\chi^2}{x_f} \right].$$

(hold for $m_\chi \gg m_a, m_h, m_H$)

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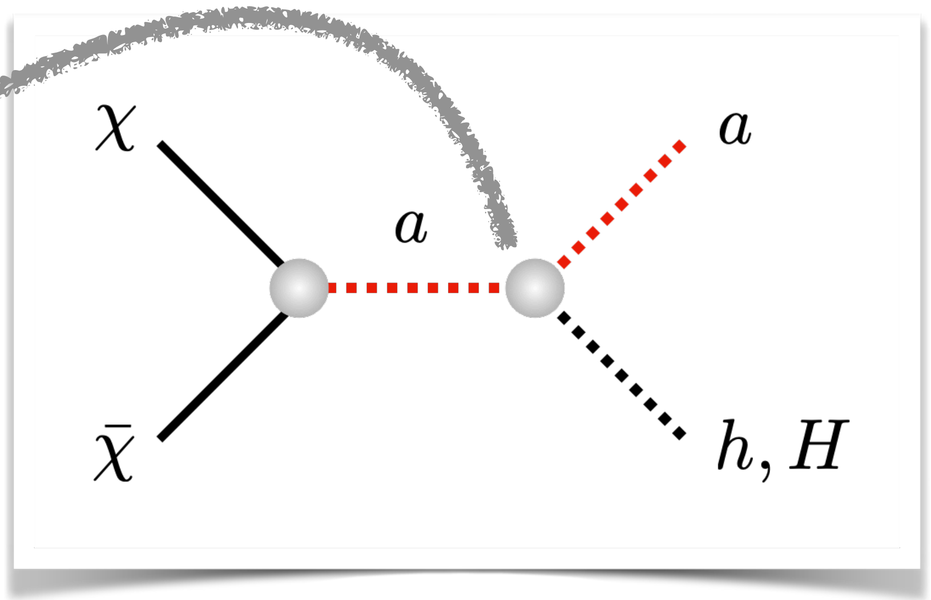

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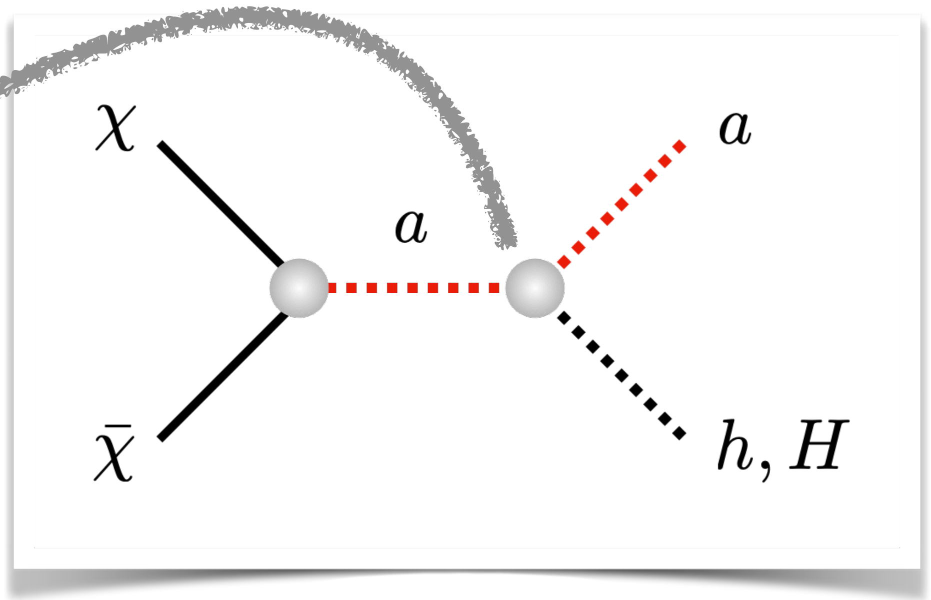

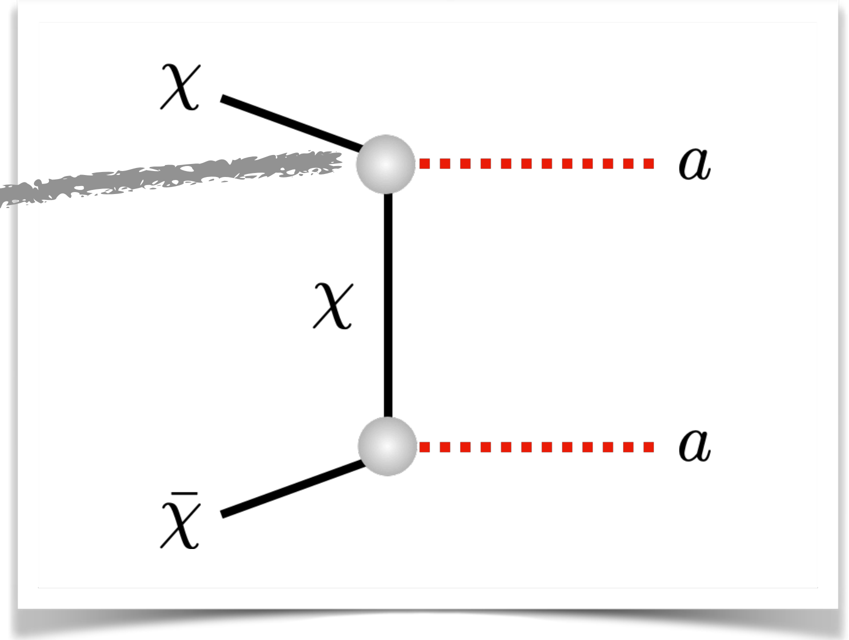

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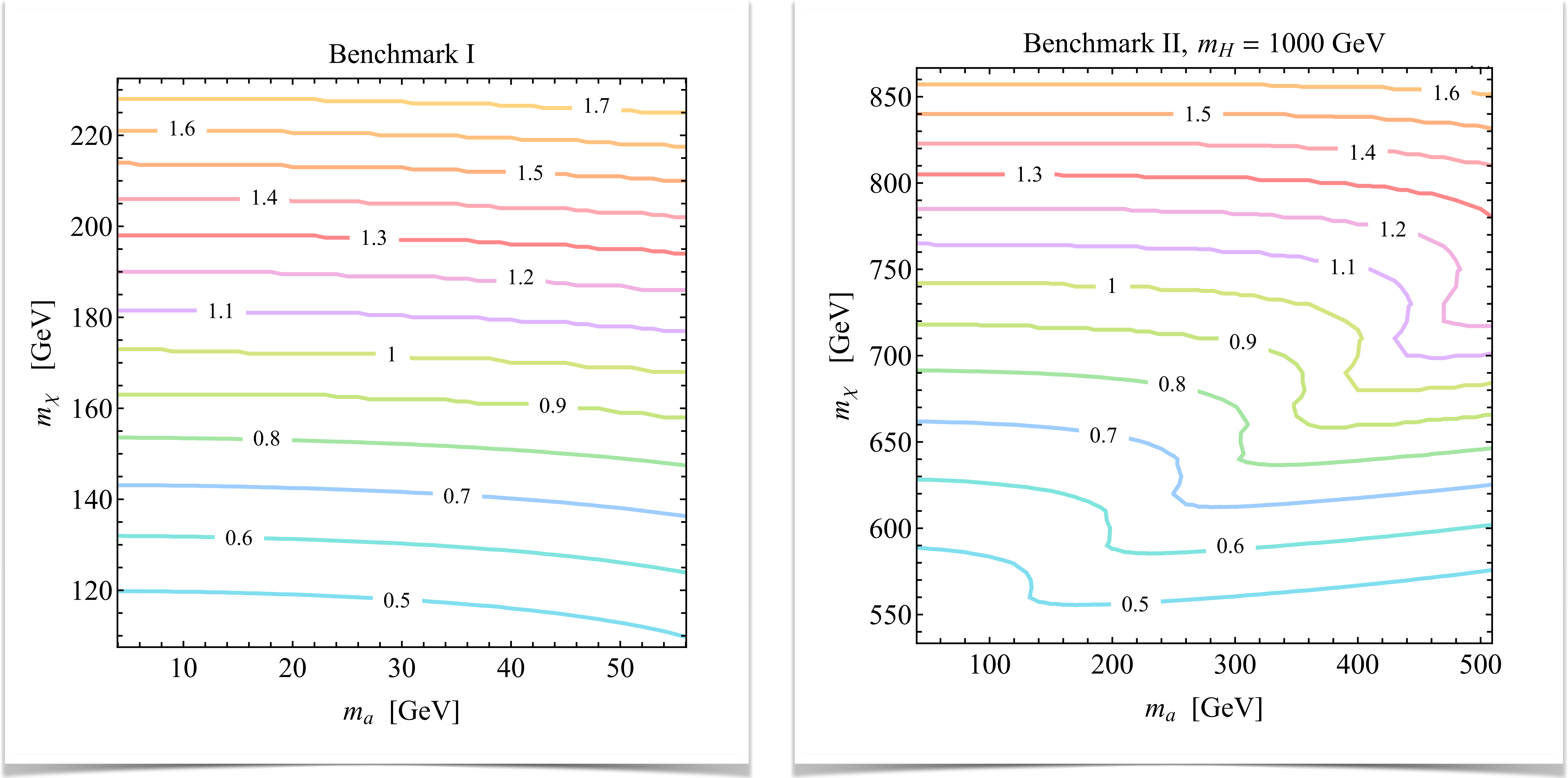

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2. LLP Phenomenology

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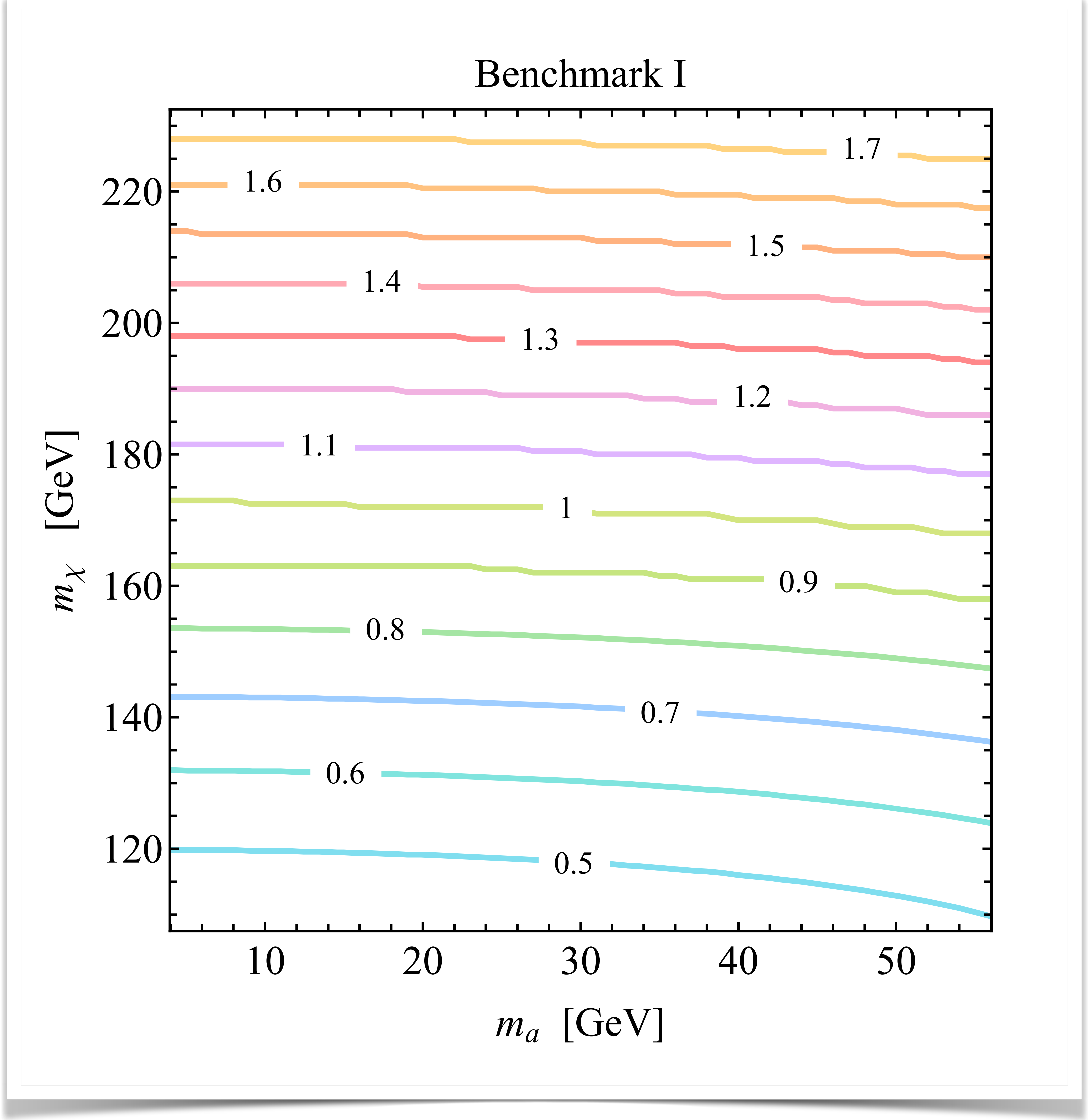
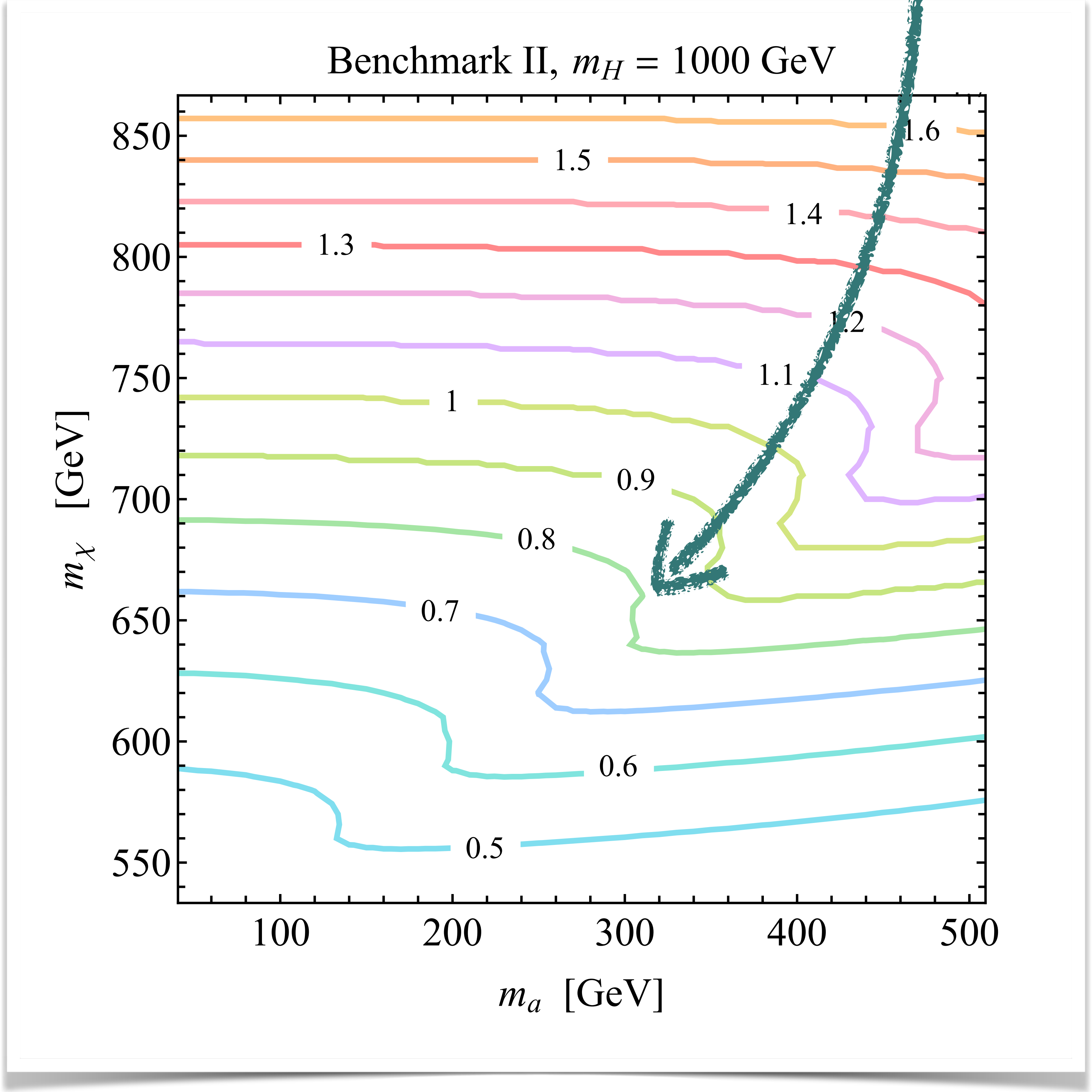
$\mathbf{m}_\chi \gg \mathbf{m_H}$ **no longer true**
→ we get more intricate behaviour modelled with MadDM.





3. Conclusions

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  This leads to an **interesting collider phenomenology** $\rightarrow$ **important benchmark**.

- The additional pseudo-scalar a can become **long-lived** for small mixing angles θ.
  - **Interesting LLP signatures** that can be probed for at colliders.
  - This scenario is **compatible with current relic density measurements**.

Thank you for your attention!