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

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

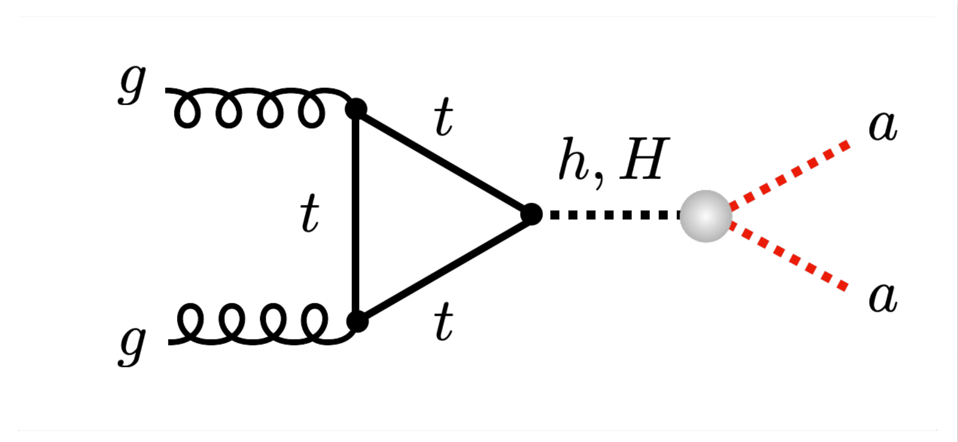
SFB 1258 Neutrinos Dark Matter Messengers

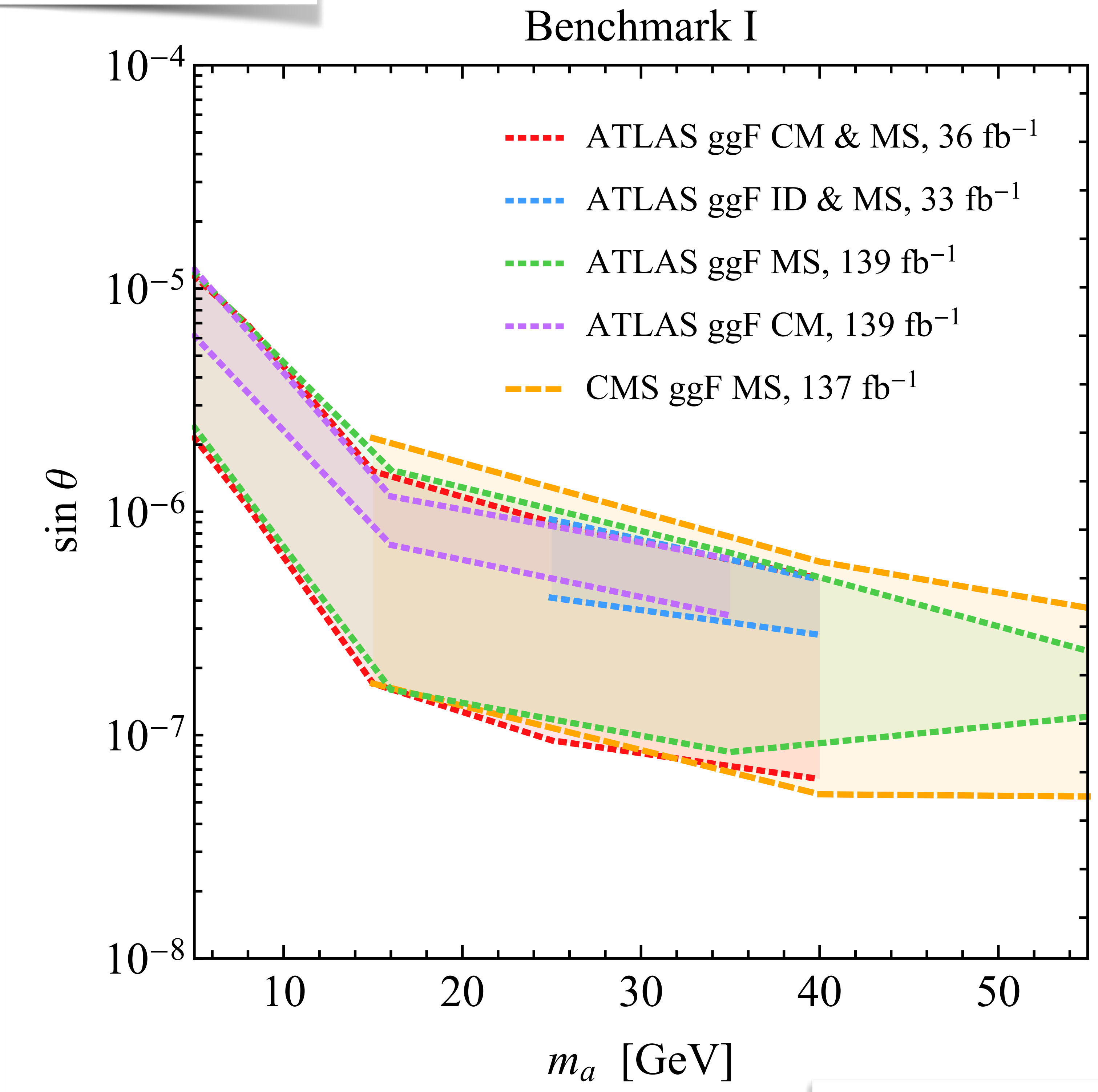
Technische Universität München

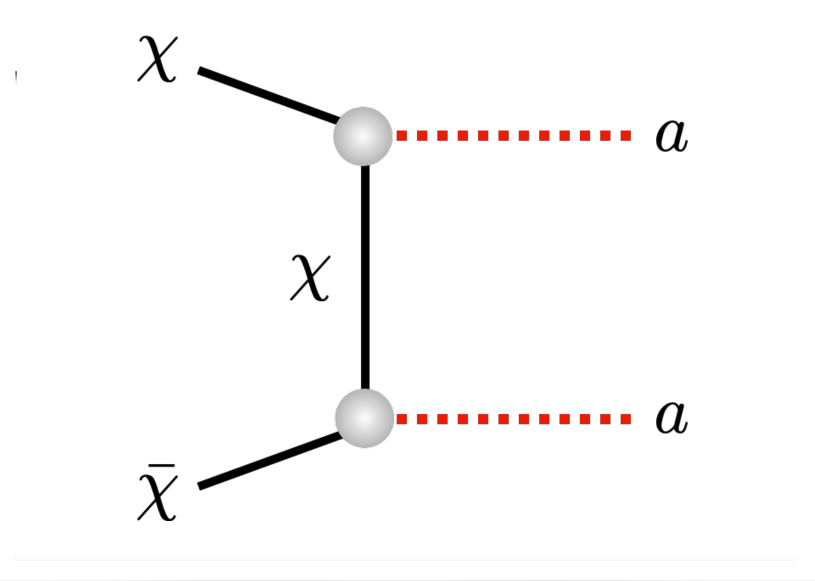
Long-lived particle phenomenology in the 2HDM+a model

Luc Schnell

Les Rencontres de Physique de la Vallée d'Aoste, La Thuile
March 10, 2023







1. Introduction

1.1 Motivation

1.2 2HDM+a in a nutshell

1.3 E_T^{miss} signatures

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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.

$$\begin{aligned}\mathscr{L} \supset &- g_q^A \, Z'^{\mu} \, (\bar{q}\gamma_\mu\gamma^5 q) \\ &- g_{DM}^A \, Z'^{\mu} \, (\bar{\chi}\gamma_\mu\gamma^5 \chi)\end{aligned}$$

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2HDM+a model

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2HDM scalar potential

$$\begin{aligned} V_H = {} & \mu_1 H_1^\dagger H_1 + \mu_2 H_2^\dagger H_2 + \left(\mu_3 H_1^\dagger H_2 + \text{h.c.}\right) + \lambda_1 \left(H_1^\dagger H_1\right)^2 + \lambda_2 \left(H_2^\dagger H_2\right)^2 \\ & + \lambda_3 \left(H_1^\dagger H_1\right)\left(H_2^\dagger H_2\right) + \lambda_4 \left(H_1^\dagger H_2\right)\left(H_2^\dagger H_1\right) + \left[\lambda_5 \left(H_1^\dagger H_2\right)^2 + \text{h.c.}\right] . \end{aligned}$$

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

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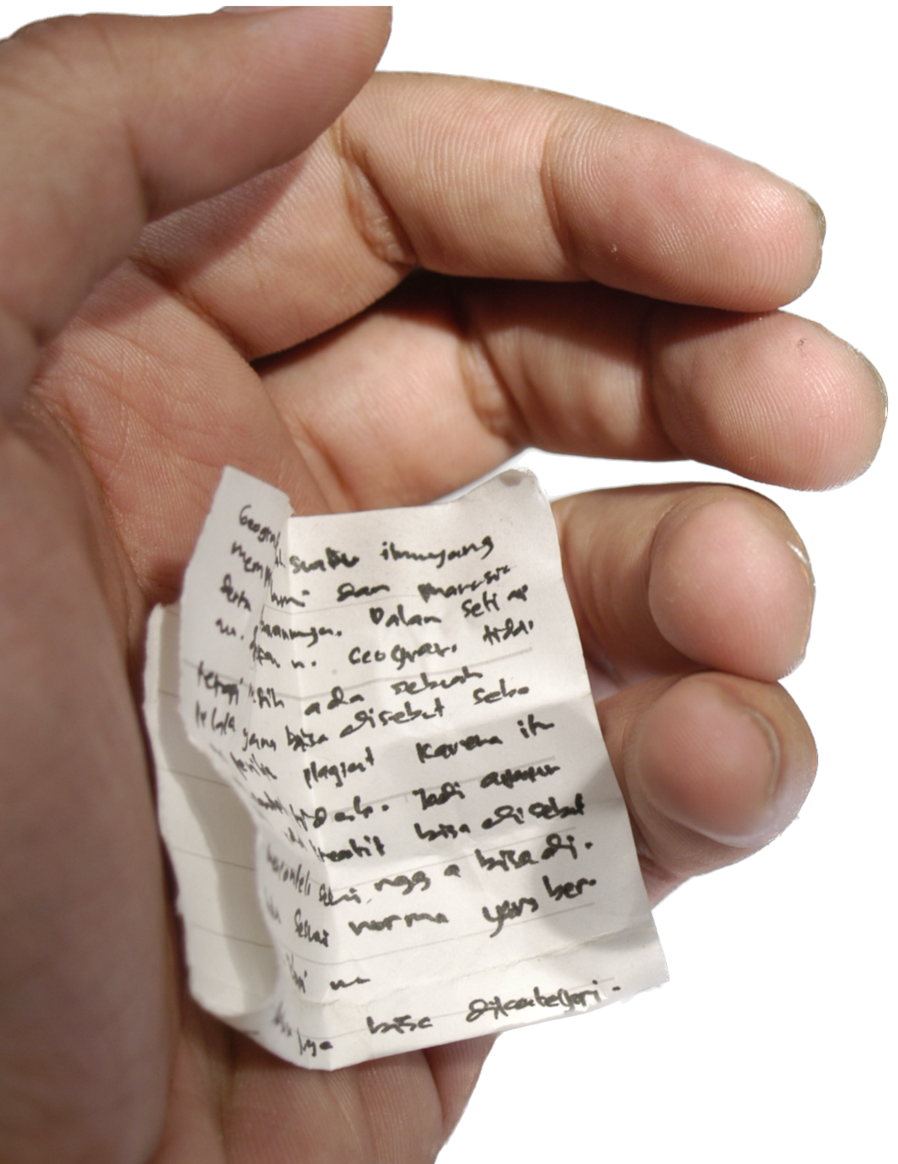

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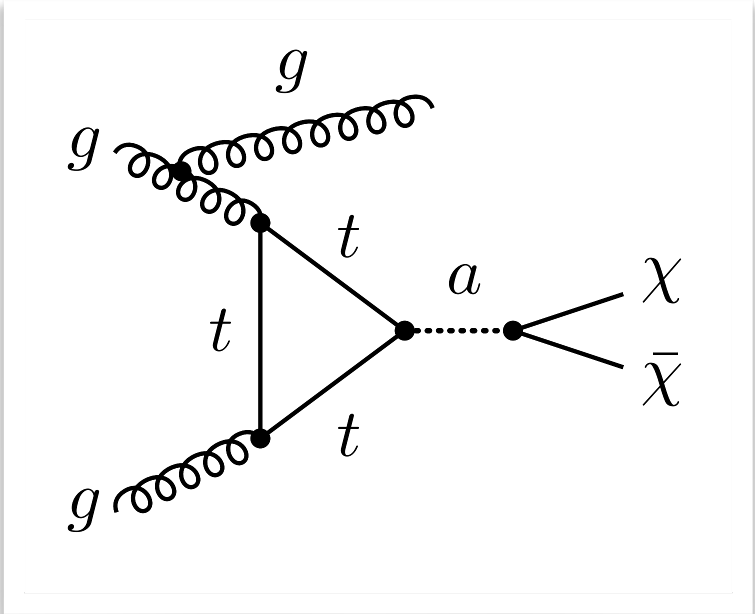

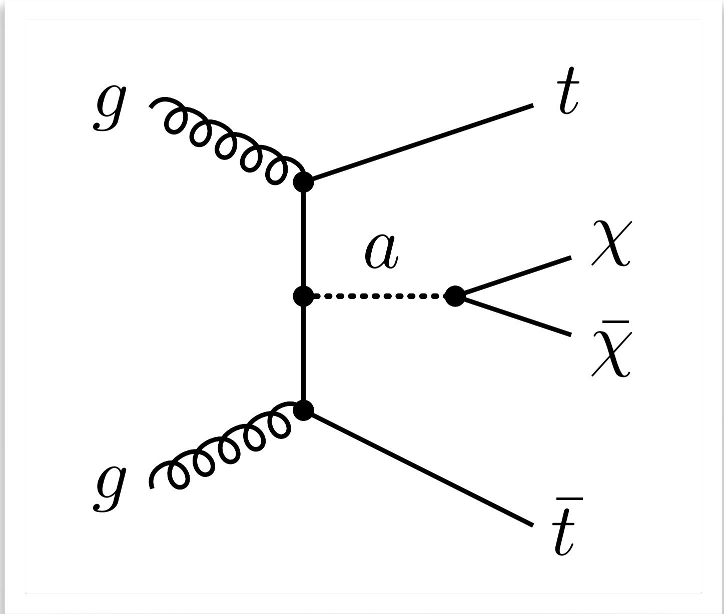

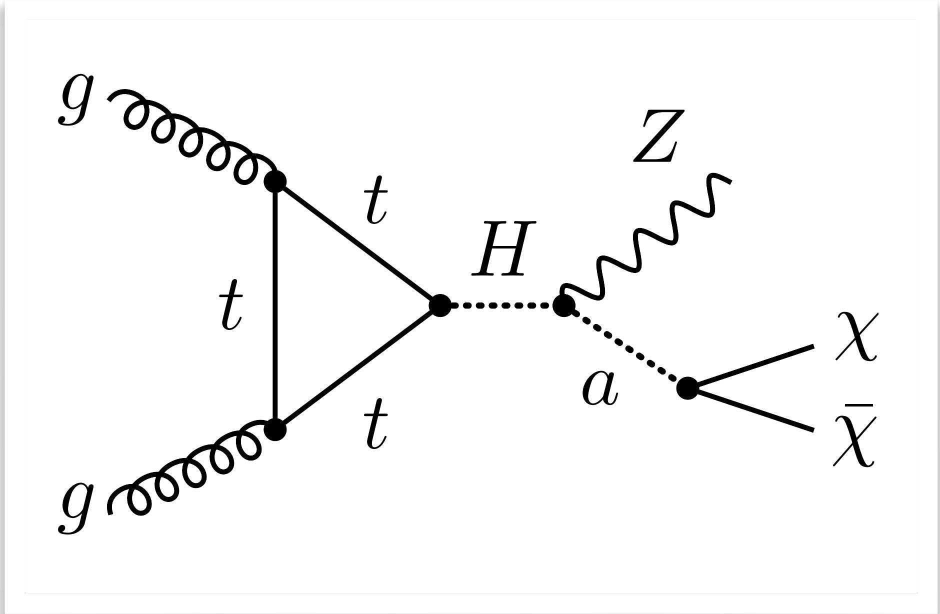

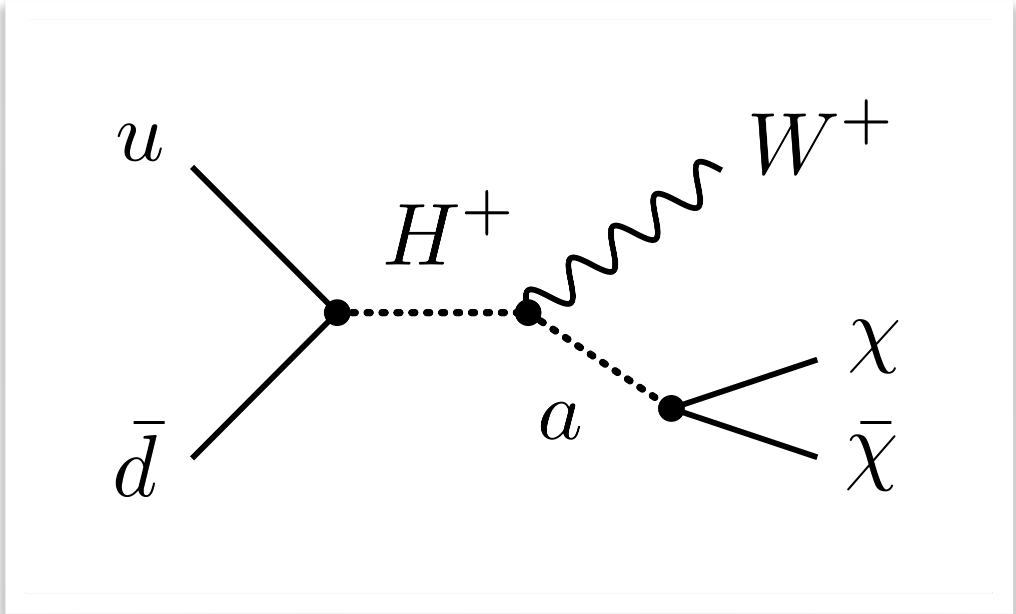

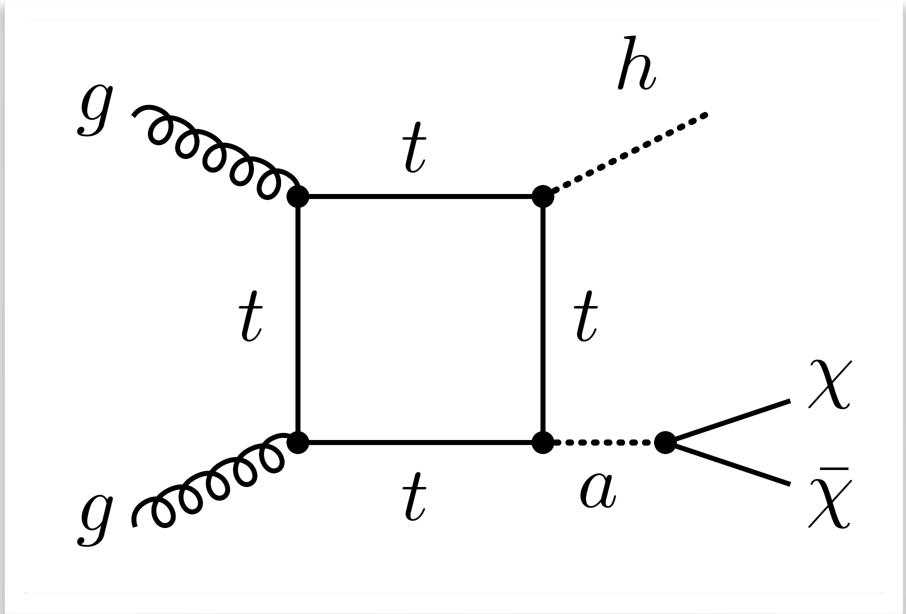

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$\mathbf{j + E_T^{miss}}$

$\mathbf{t\bar{t} + E_T^{miss}}$

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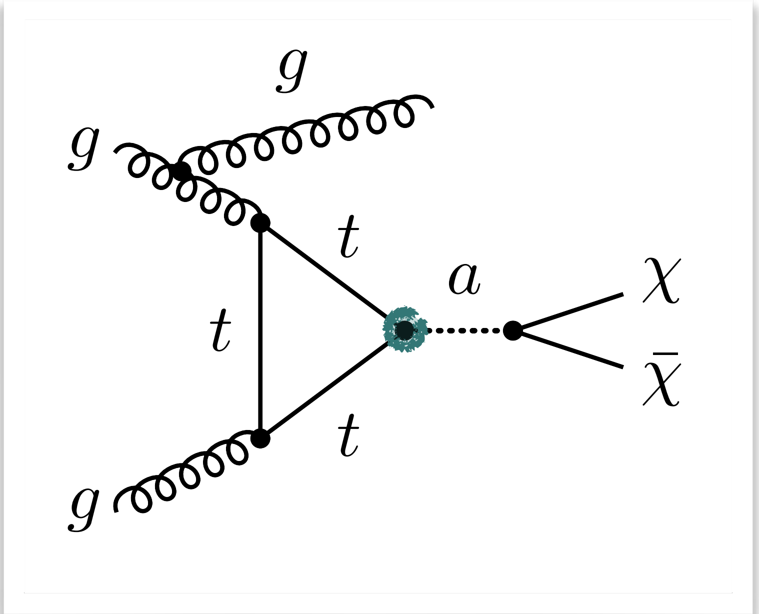

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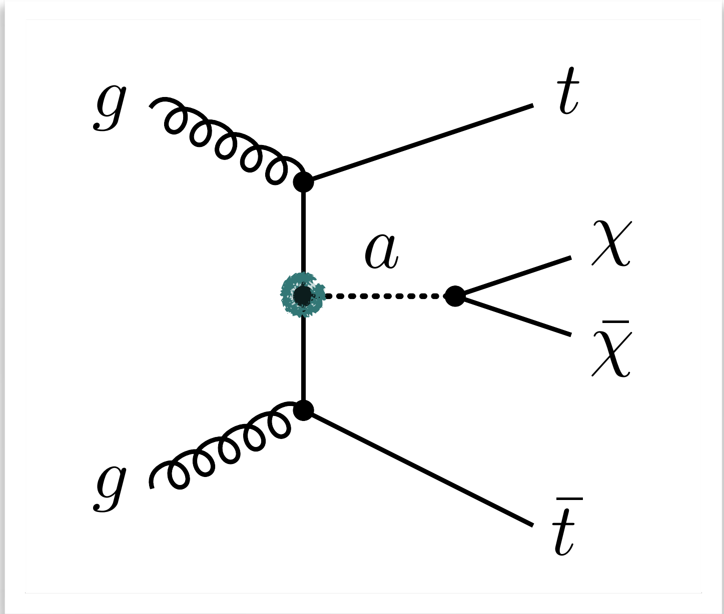

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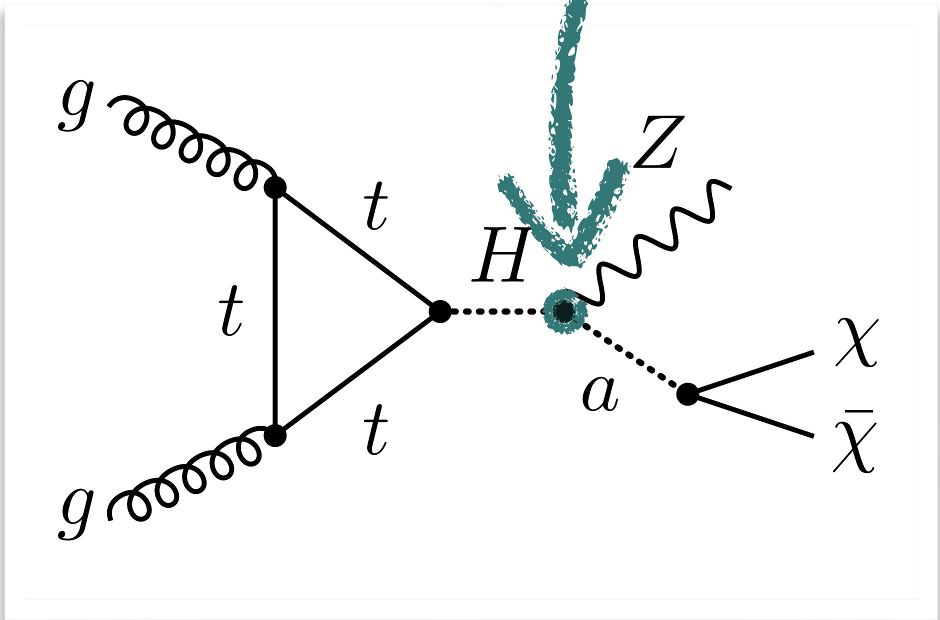
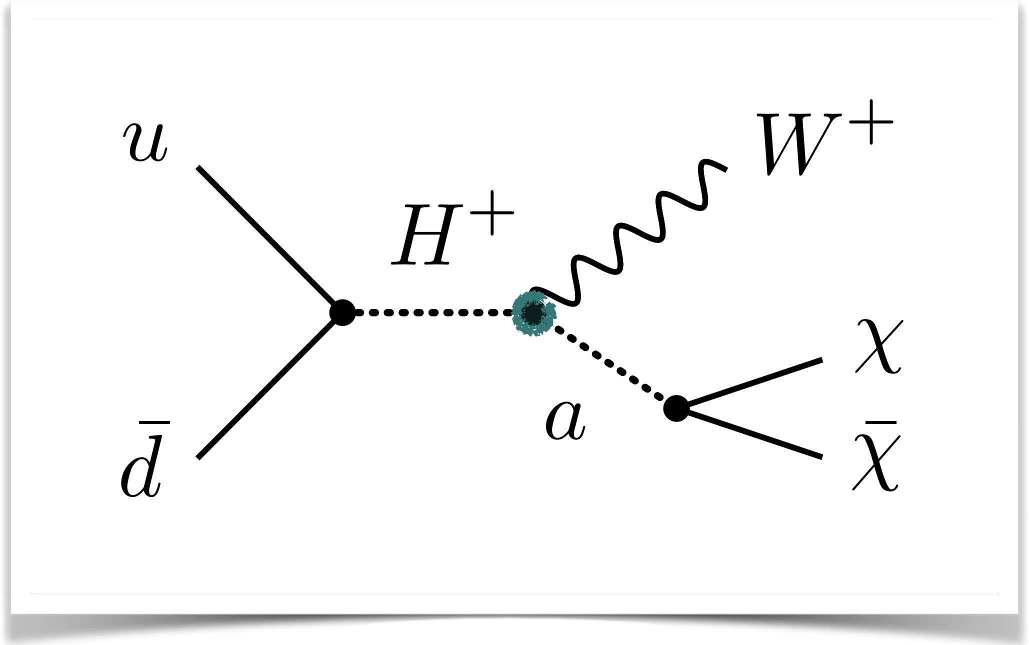
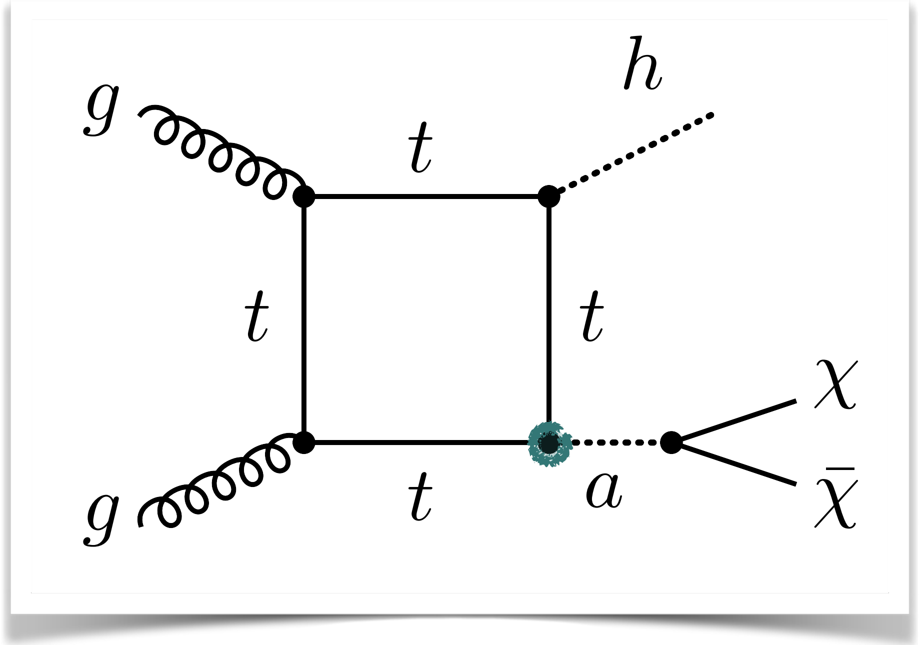


$\sim \sin\theta$

$\mathbf{Z + E_T^{miss}}$



$\mathbf{W + E_T^{miss}}$



$\mathbf{h + E_T^{miss}}$

Source: ArXiv:1701.07427 (M. Bauer, U. Haisch and F. Kahlhoefer).

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

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

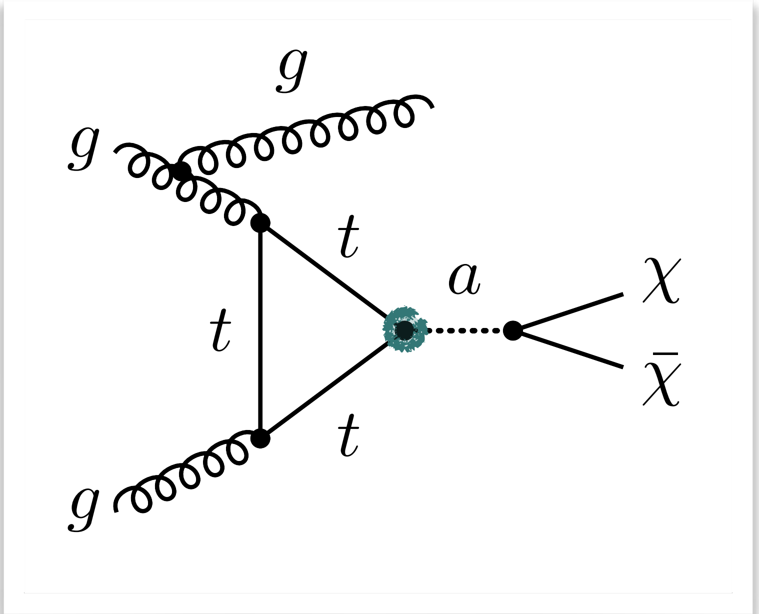
α: mixing angle for scalars (h, H)

θ: mixing angle for pseudo-scalars (a, A)

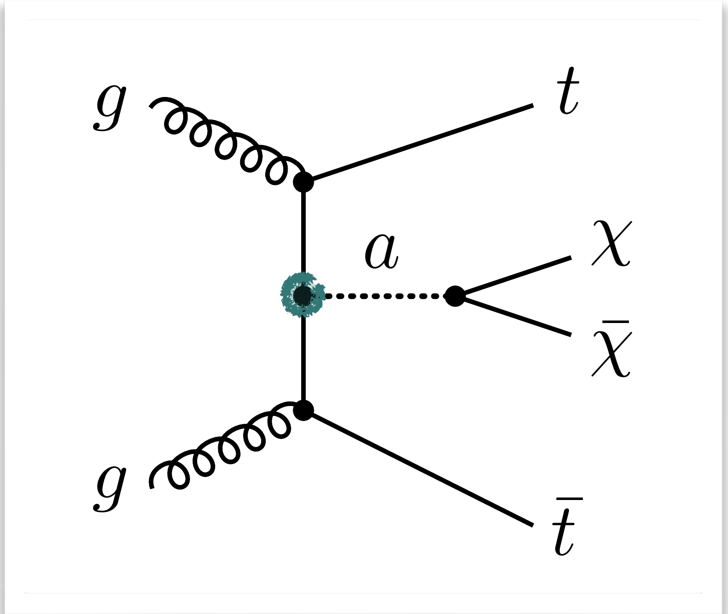
1. Introduction

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

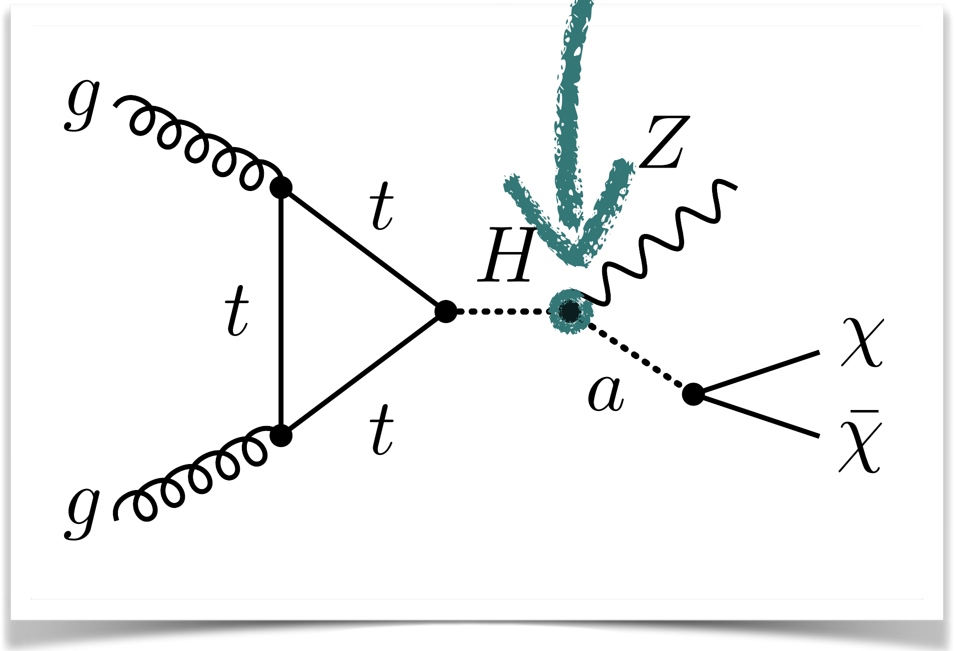
$\sim \sin\theta$



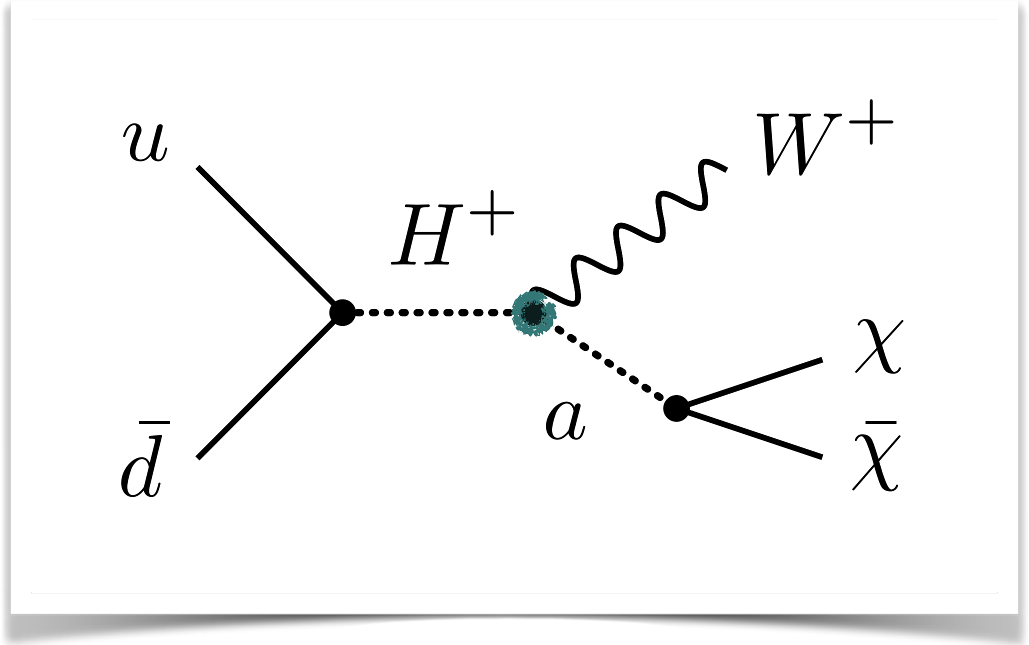
$\mathbf{j + E_T^{miss}}$



$\mathbf{t\bar{t} + E_T^{miss}}$



$\mathbf{Z + E_T^{miss}}$



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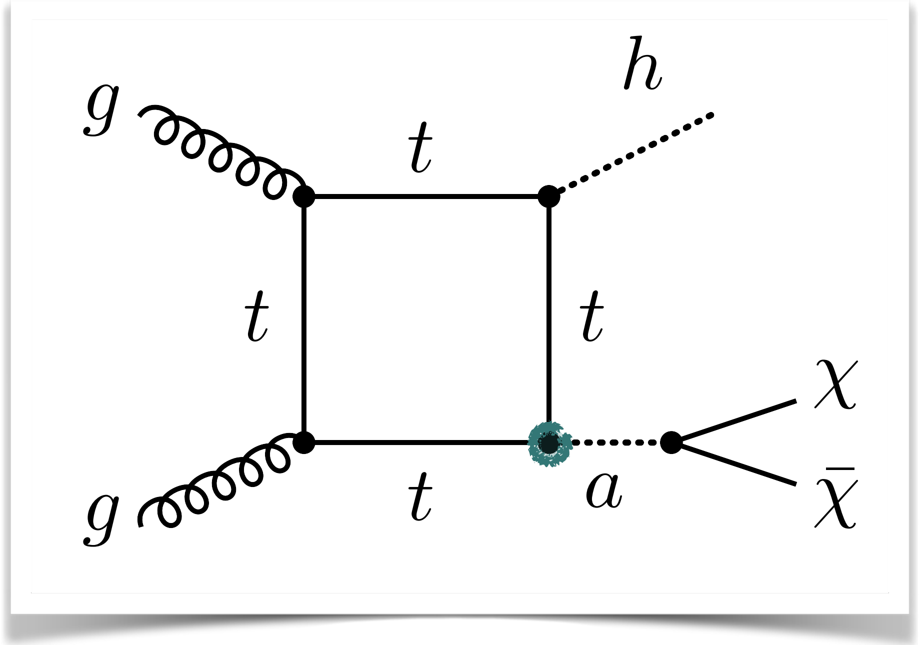

$\mathbf{h + E_T^{miss}}$

Source: ArXiv:1701.07427 (M. Bauer, U. Haisch and F. Kahlhoefer).

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

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

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

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2. LLP Phenomenology

2.1 Model parameters

2.2 LLP constraints

2.3 Relic density

2. LLP Phenomenology

2.1 Model parameters

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

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2. LLP Phenomenology

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

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

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2. LLP Phenomenology

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

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

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NLO + QCD corr.

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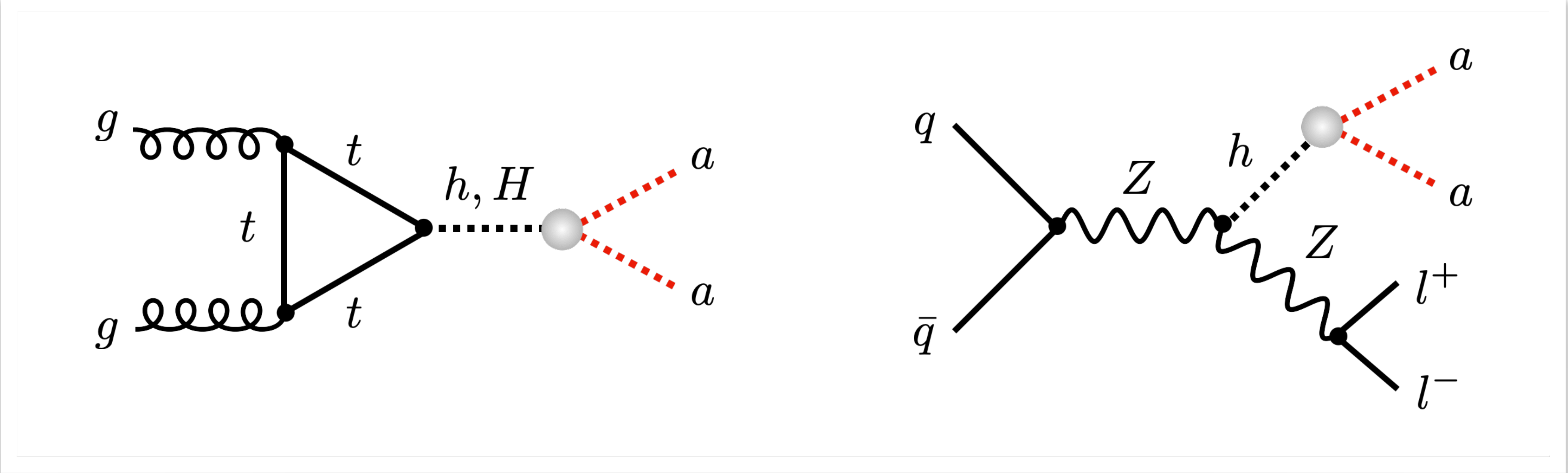
NLO + QCD corr.

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



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

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

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

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NLO + QCD corr.

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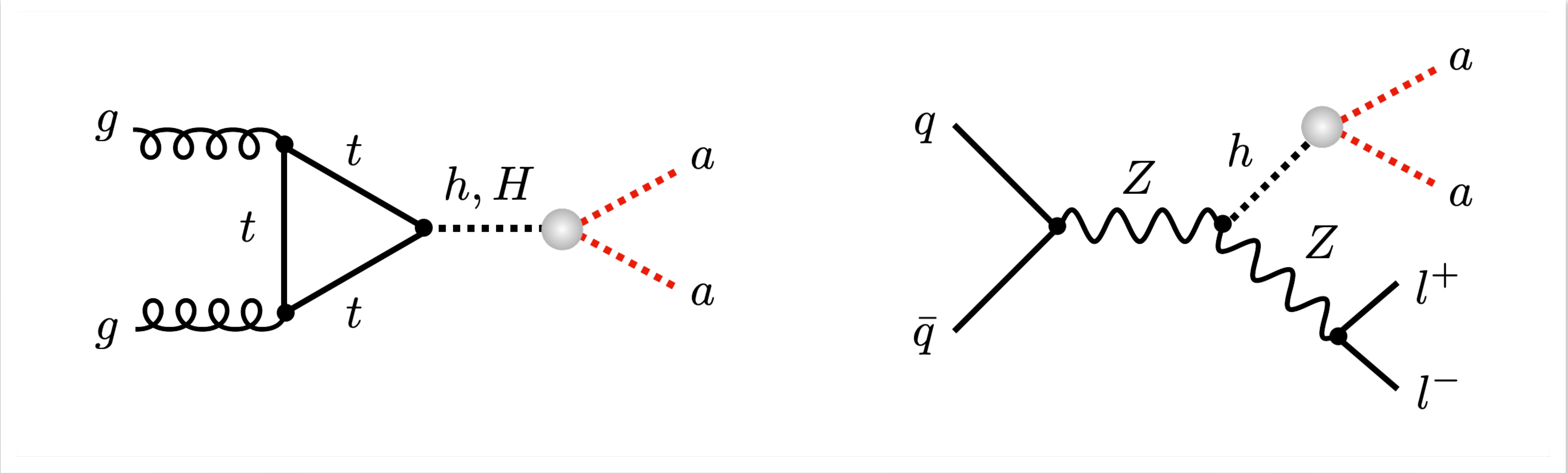
    - **Benchmark I:** $m_a < m_h/2$



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NLO + QCD corr.

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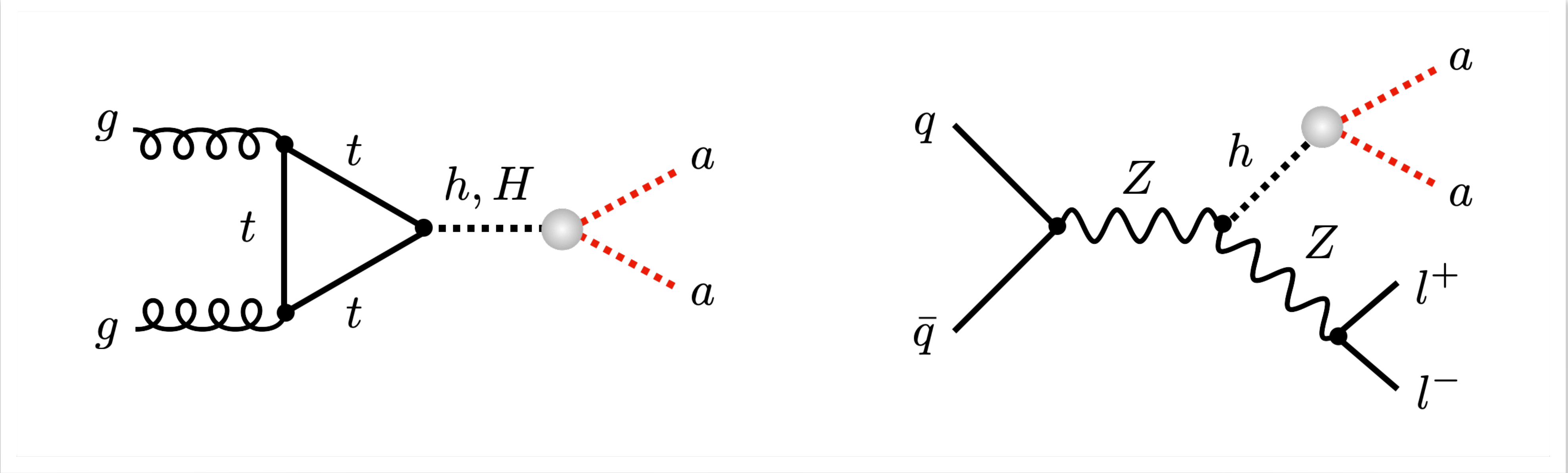
  - **Benchmark II:** $m_h/2 < m_a < m_H/2$



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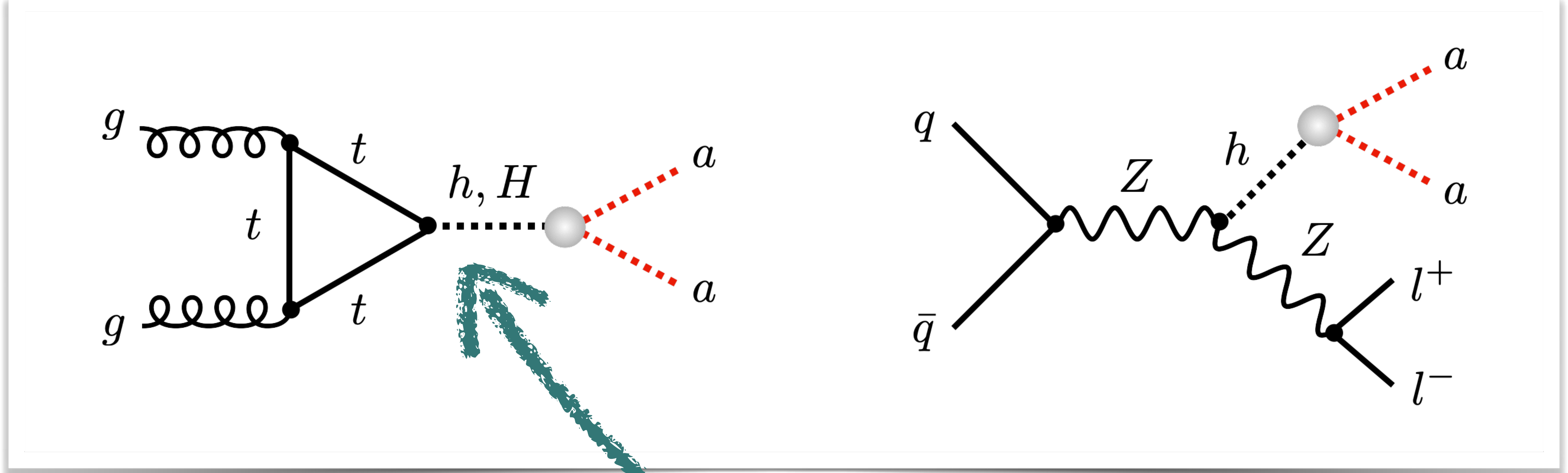

Source: ArXiv:2302.02735 (U. Haisch, LS).

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

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2. LLP Phenomenology

2.2 LLP constraints

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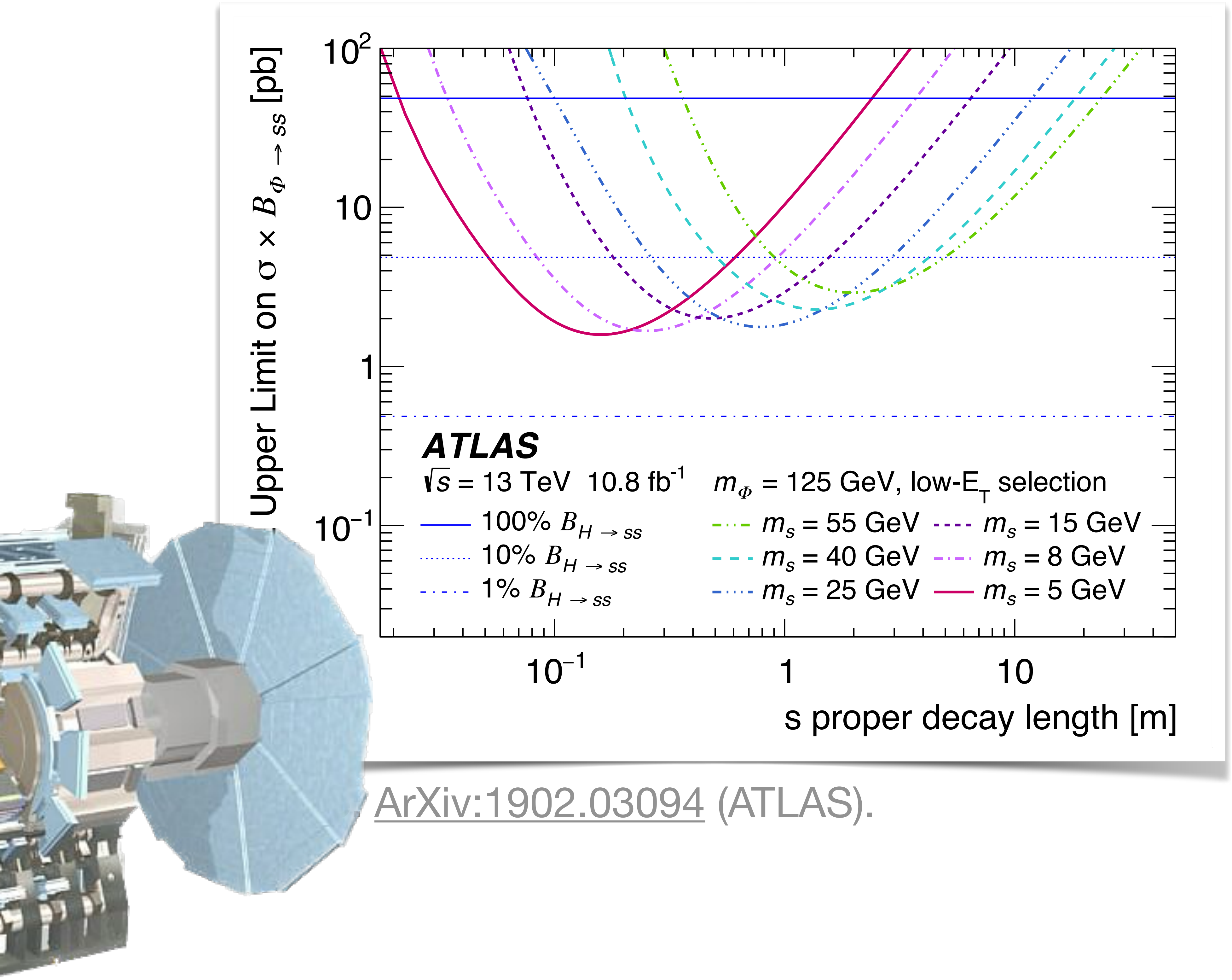

ArXiv:1902.03094 (ATLAS).

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

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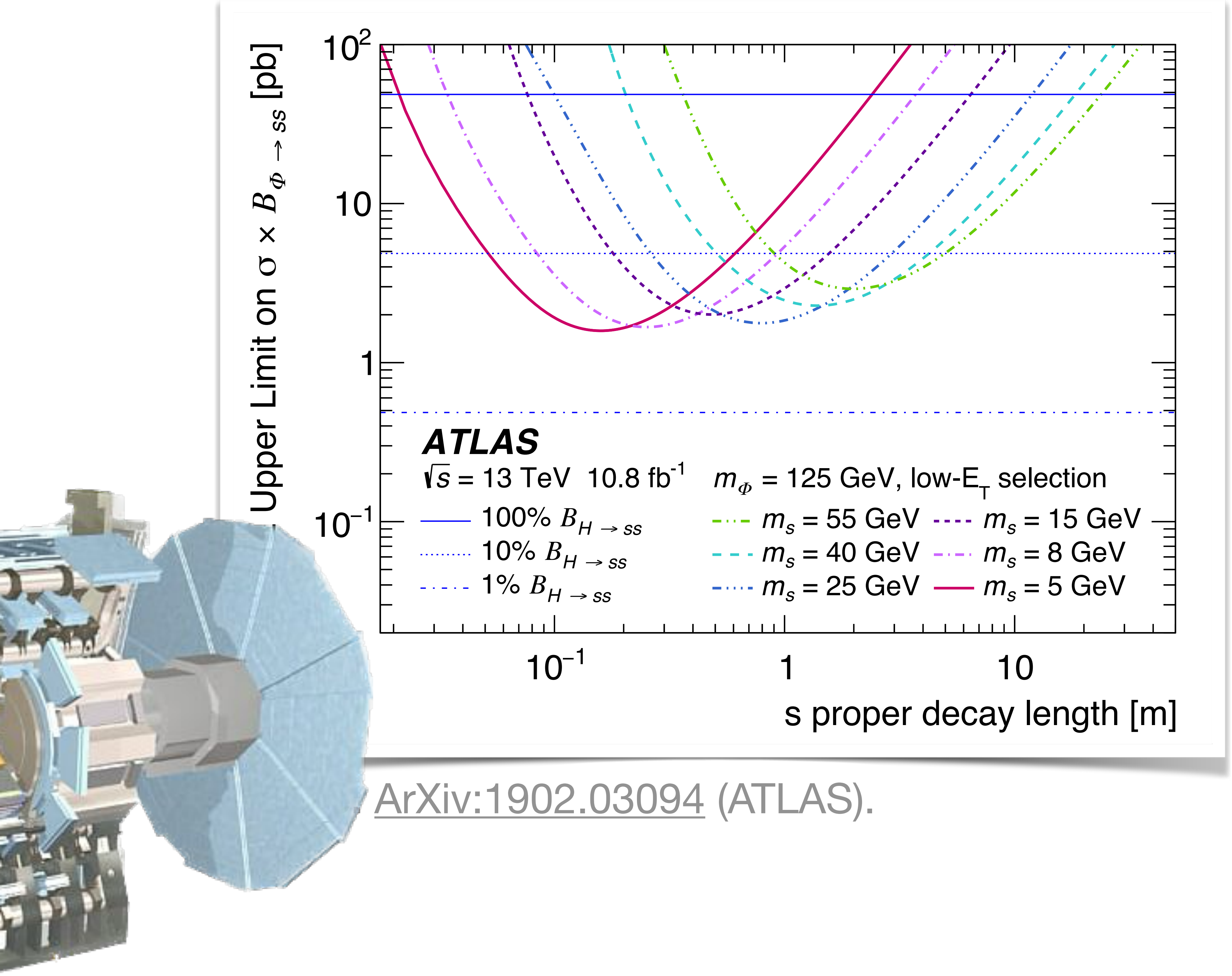

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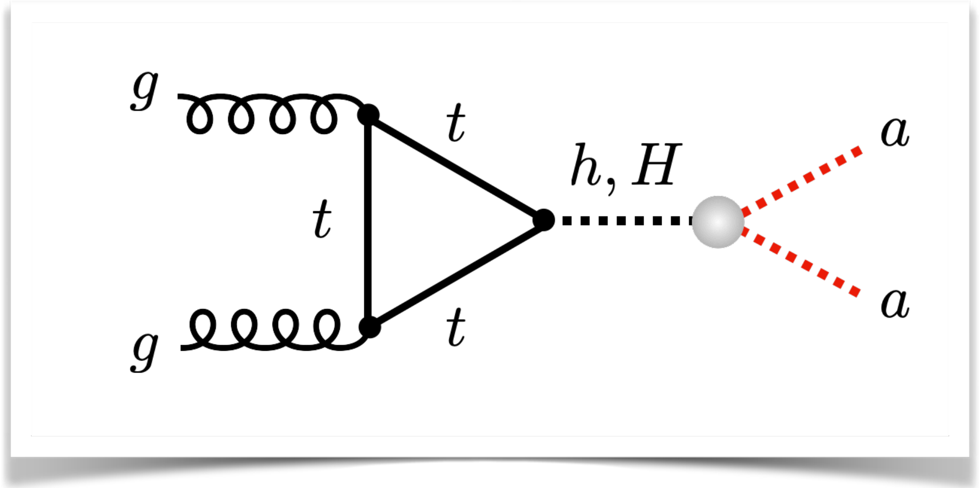

$$\frac{c\tau_a}{\mathrm{m}} \simeq 4.8 \cdot 10^{-12} \left(\frac{\mathrm{GeV}}{m_a}\right)^{0.9} \frac{1}{\sin^2\theta},$$

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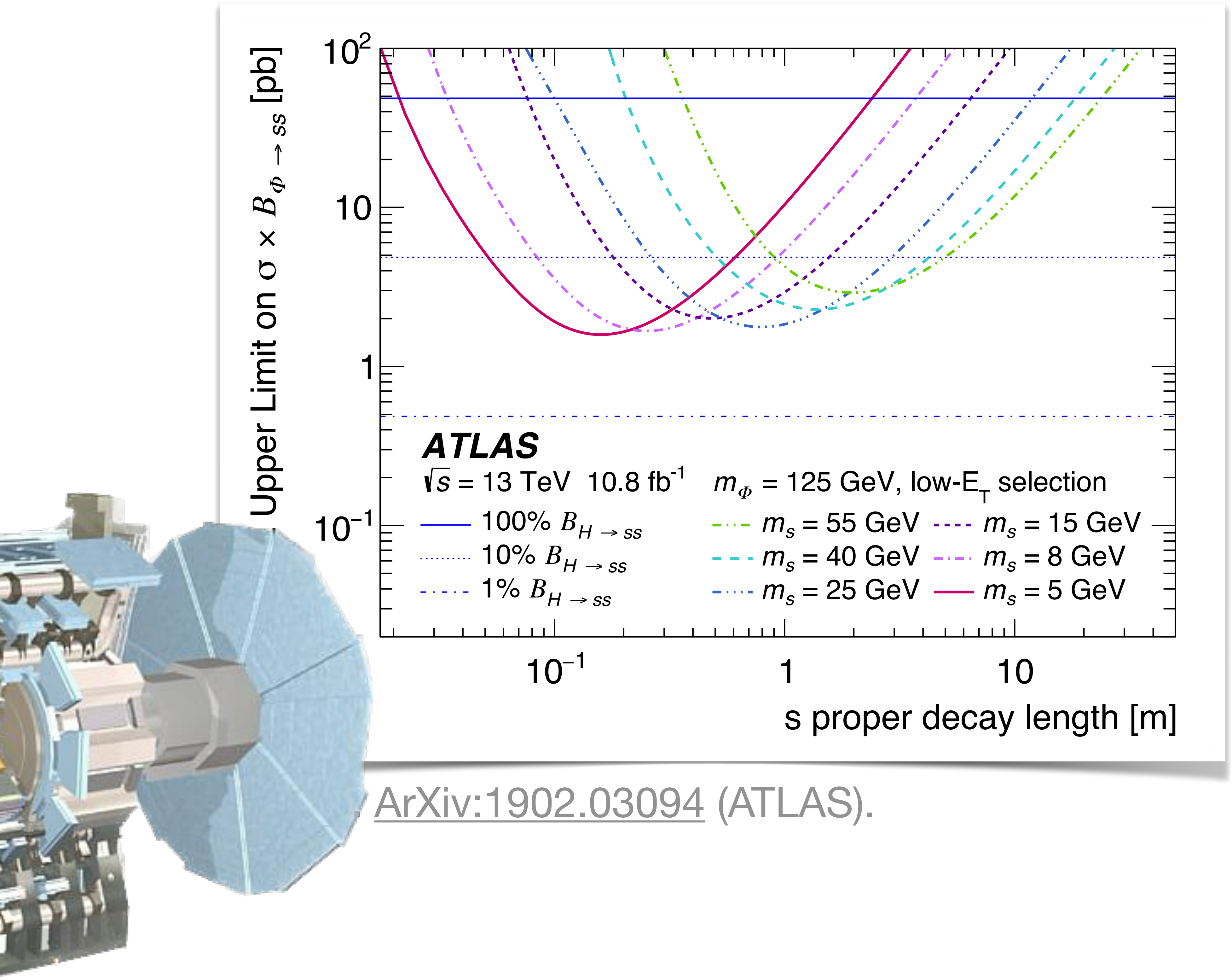

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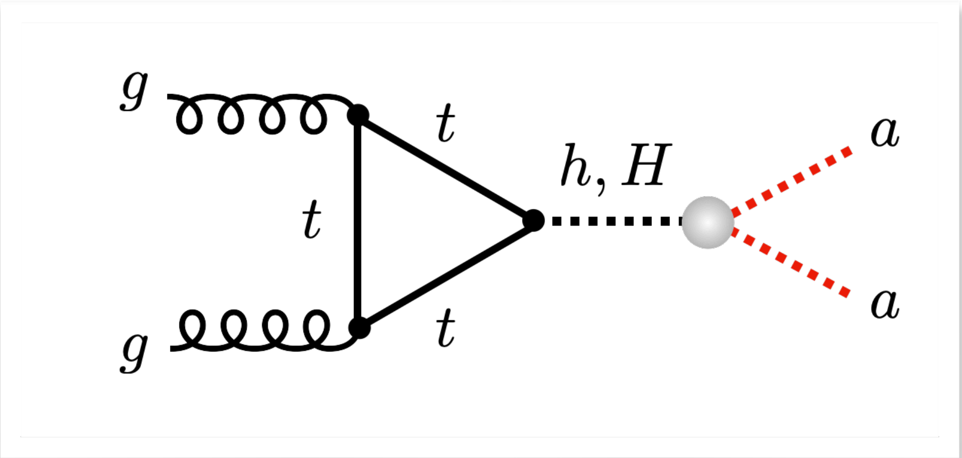

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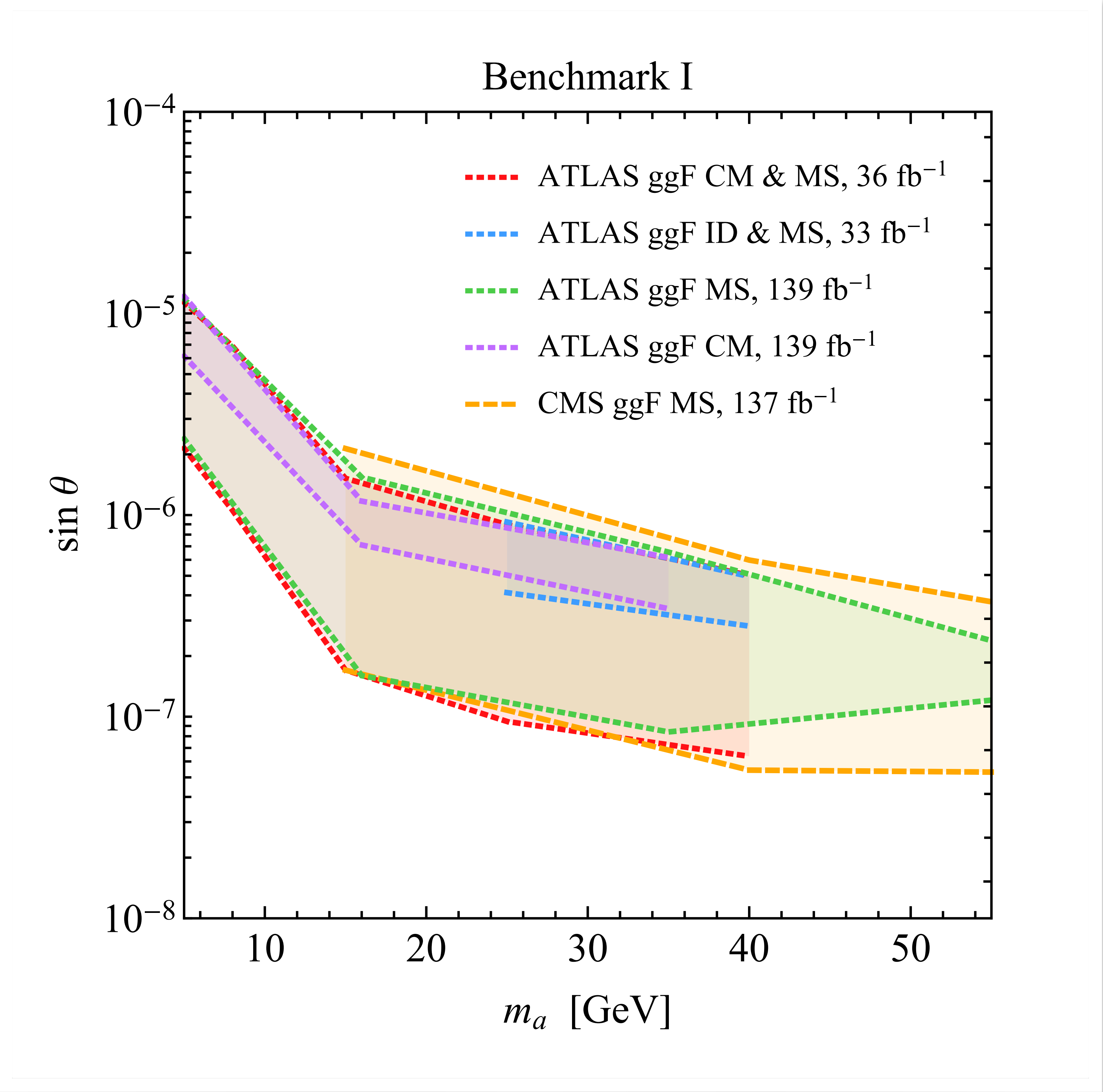

Source: ArXiv:2302.02735 (U. Haisch, LS).

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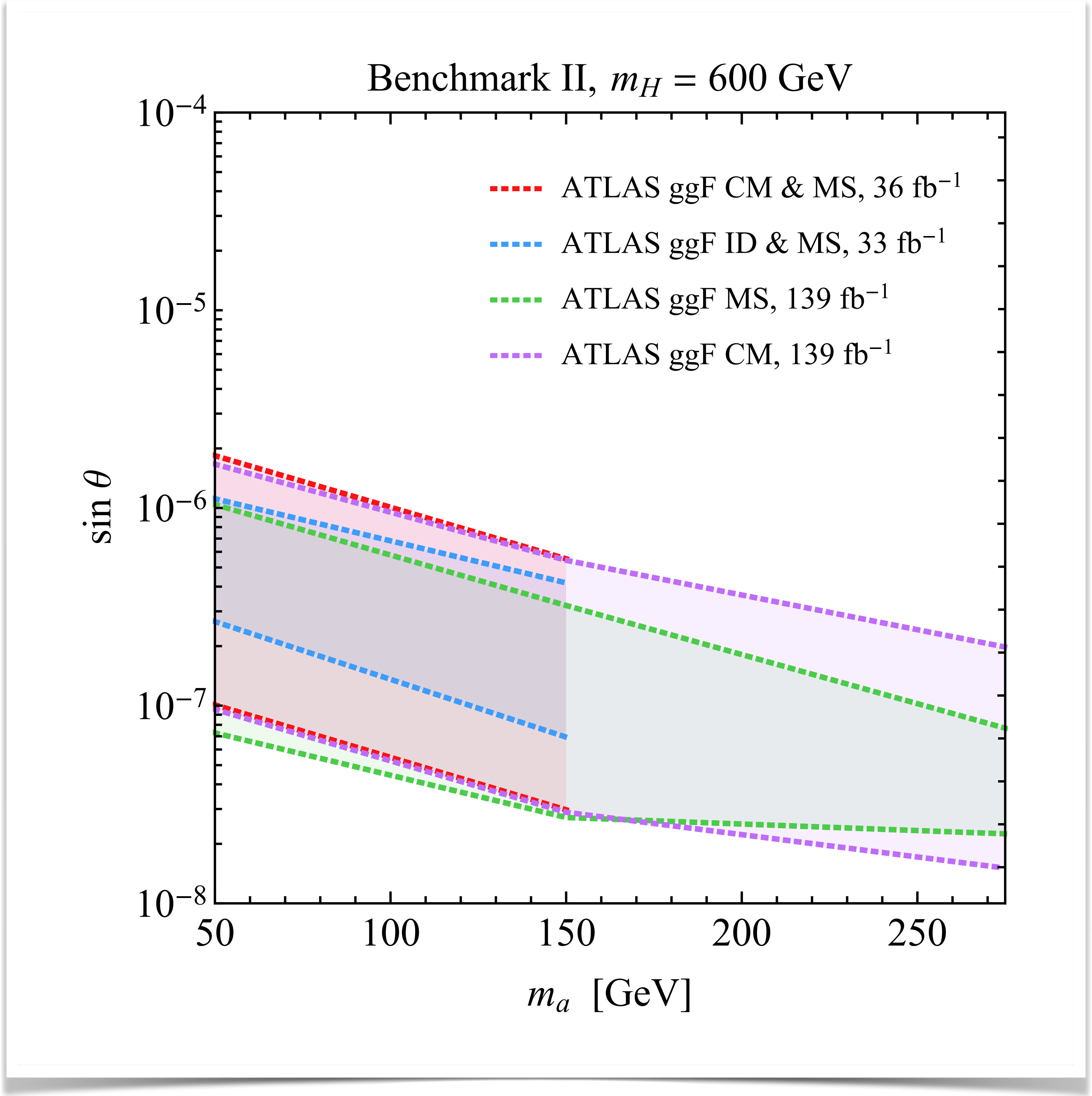

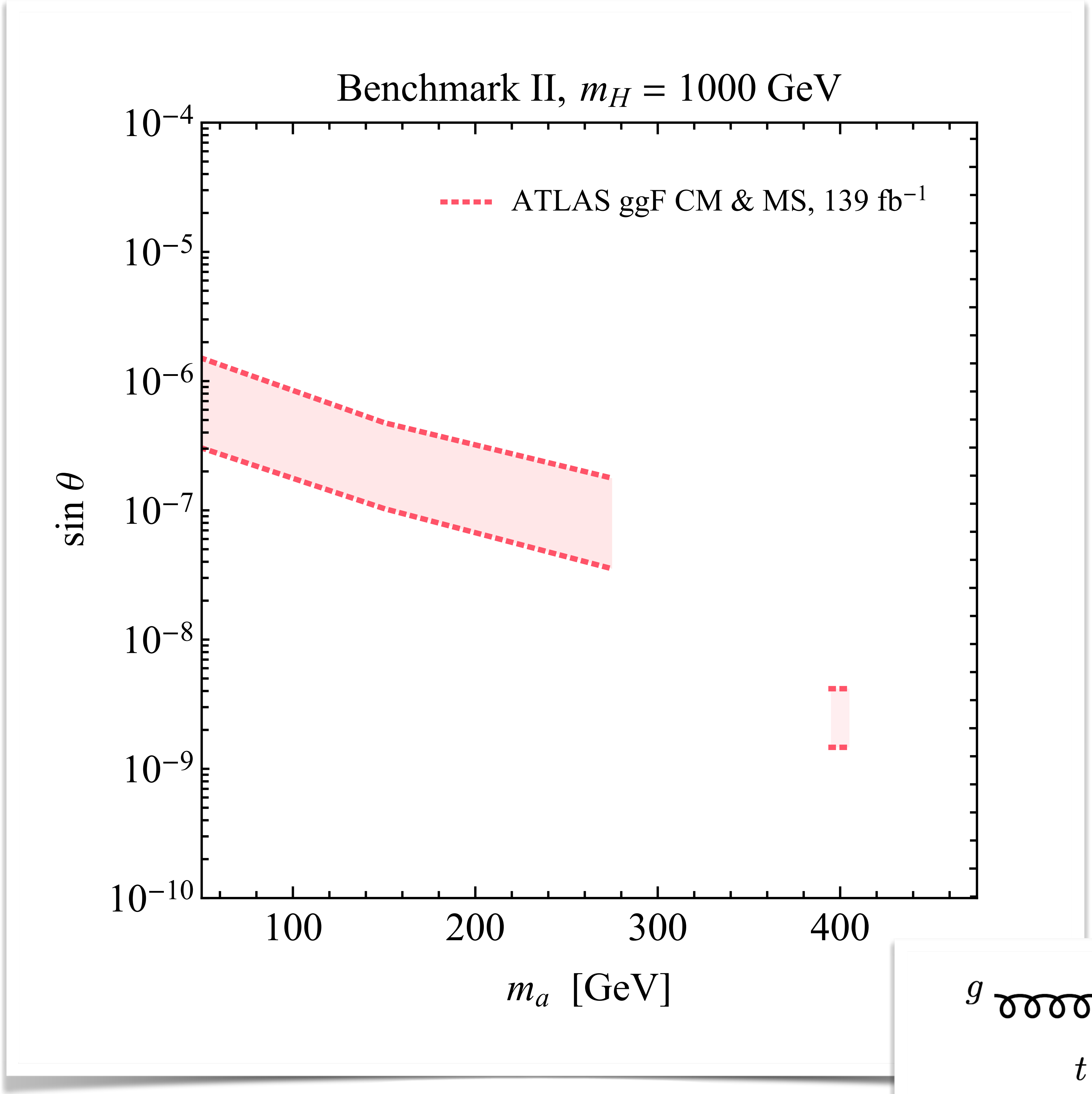

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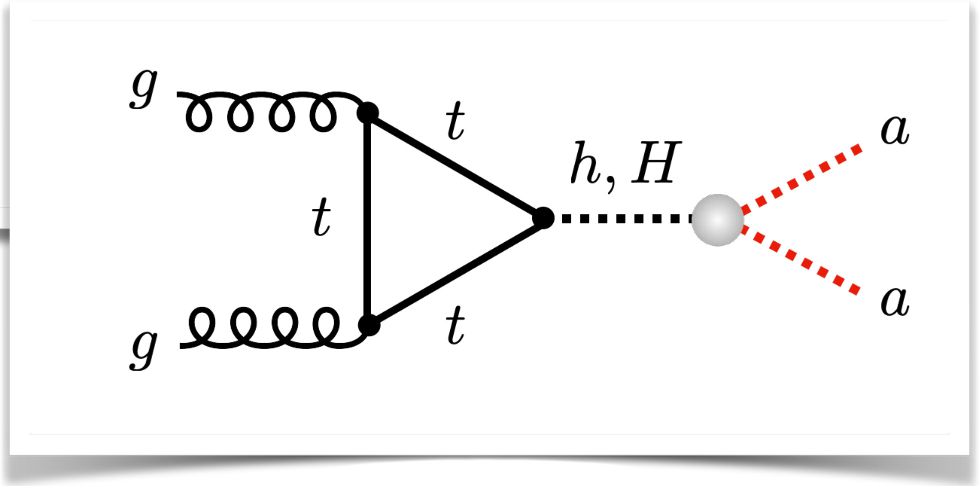

2. LLP Phenomenology

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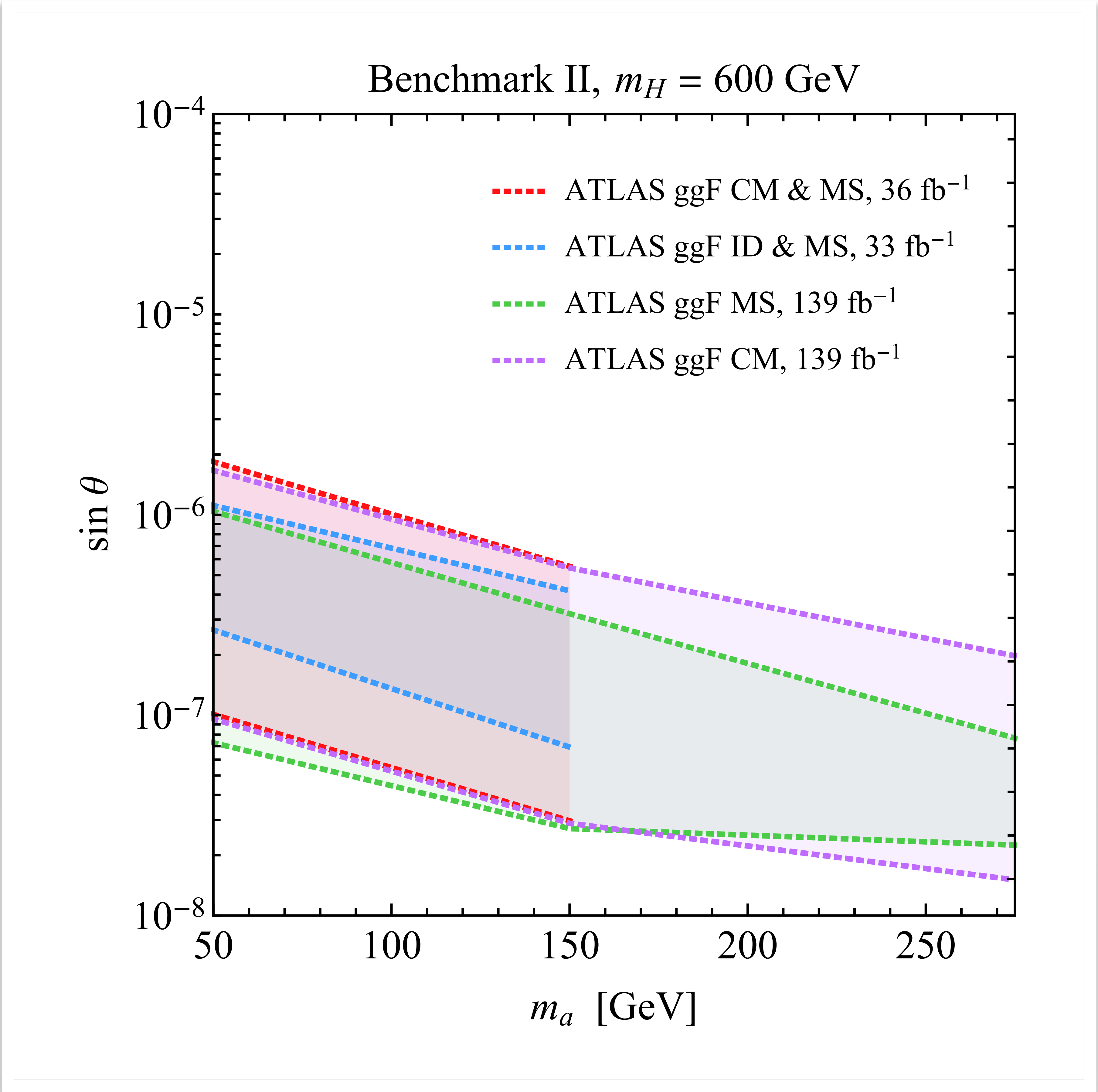
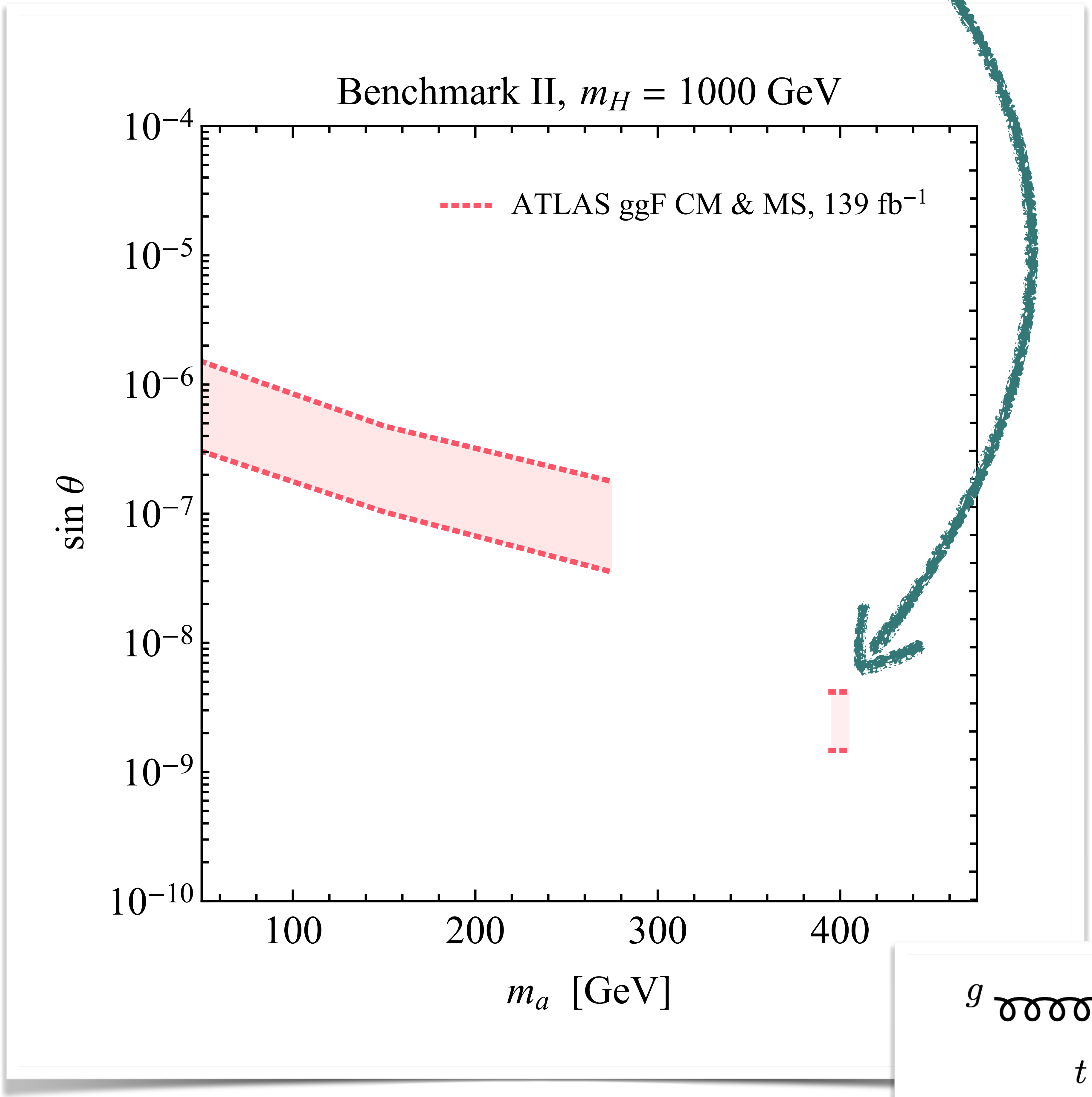
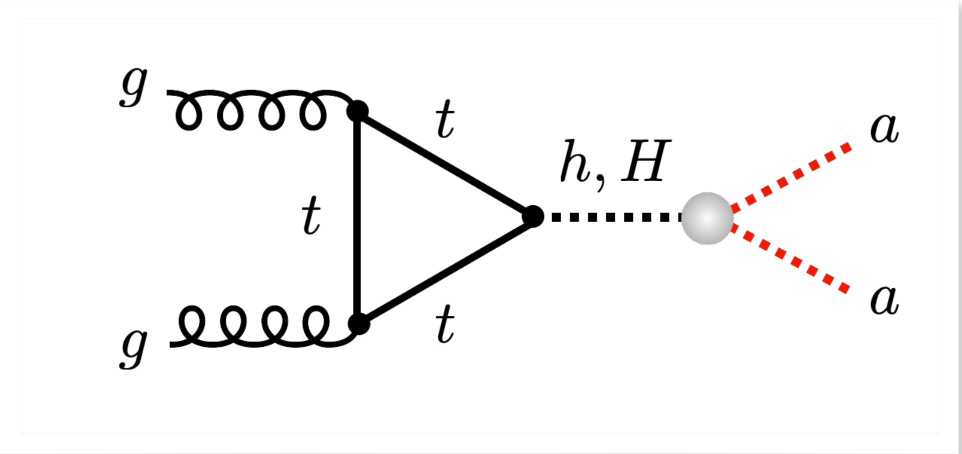




Decay
$a \to t\bar{t}$
opens up

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



2. LLP Phenomenology

2.3 Relic density

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

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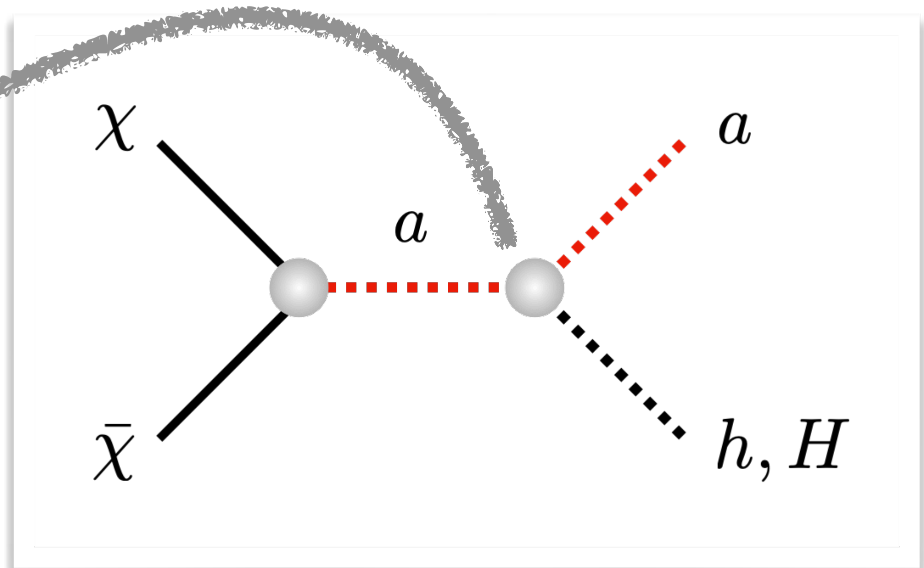

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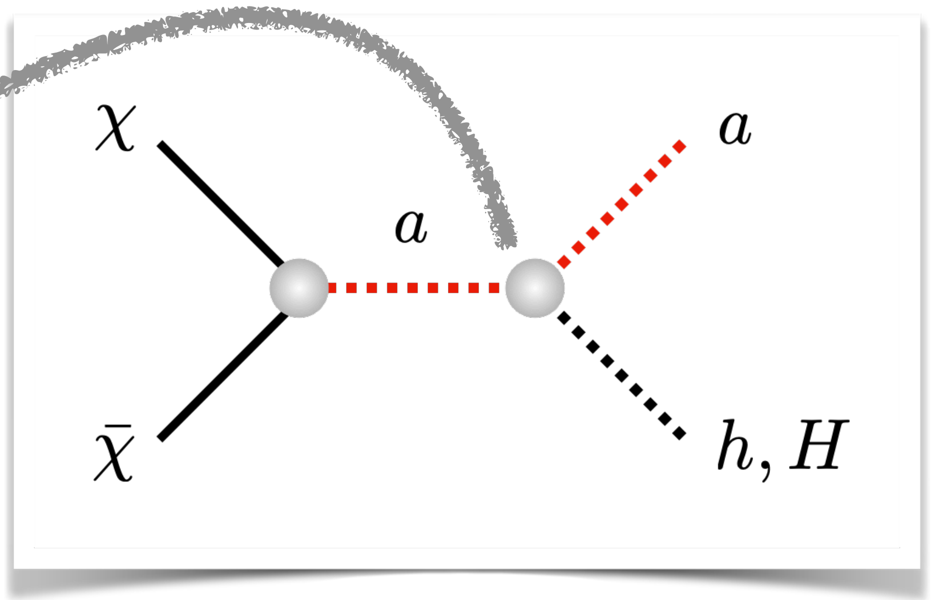

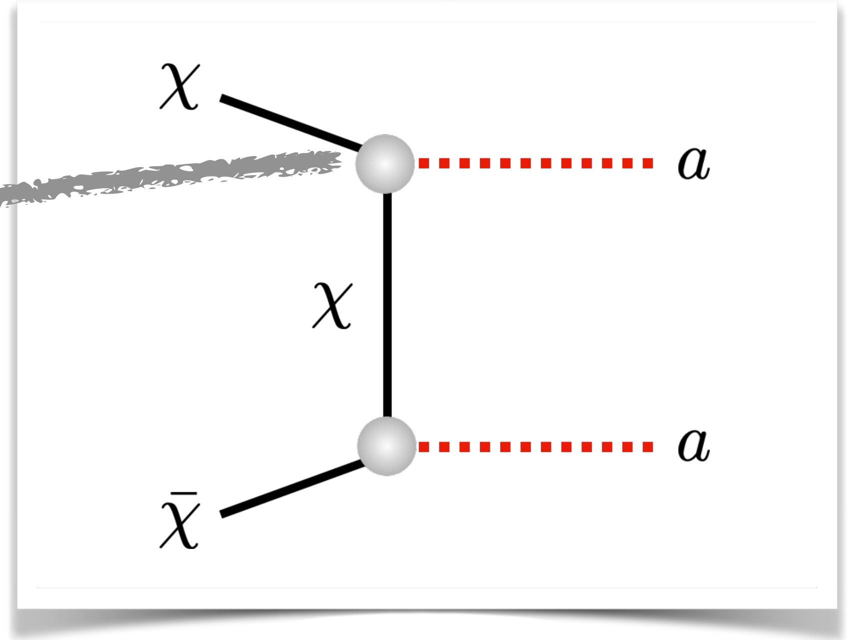

Source: ArXiv:2302.02735 (U. Haisch, LS).

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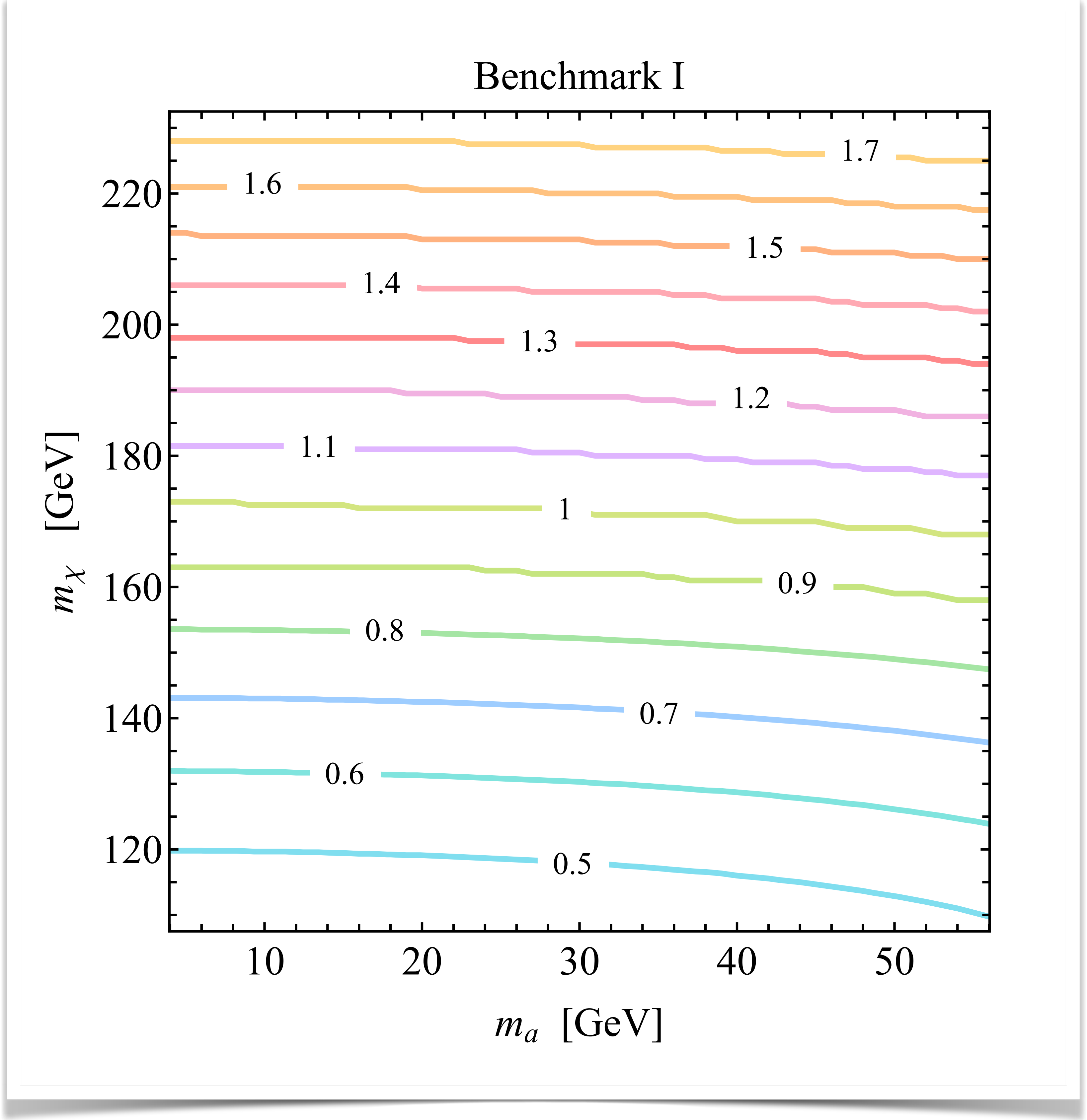

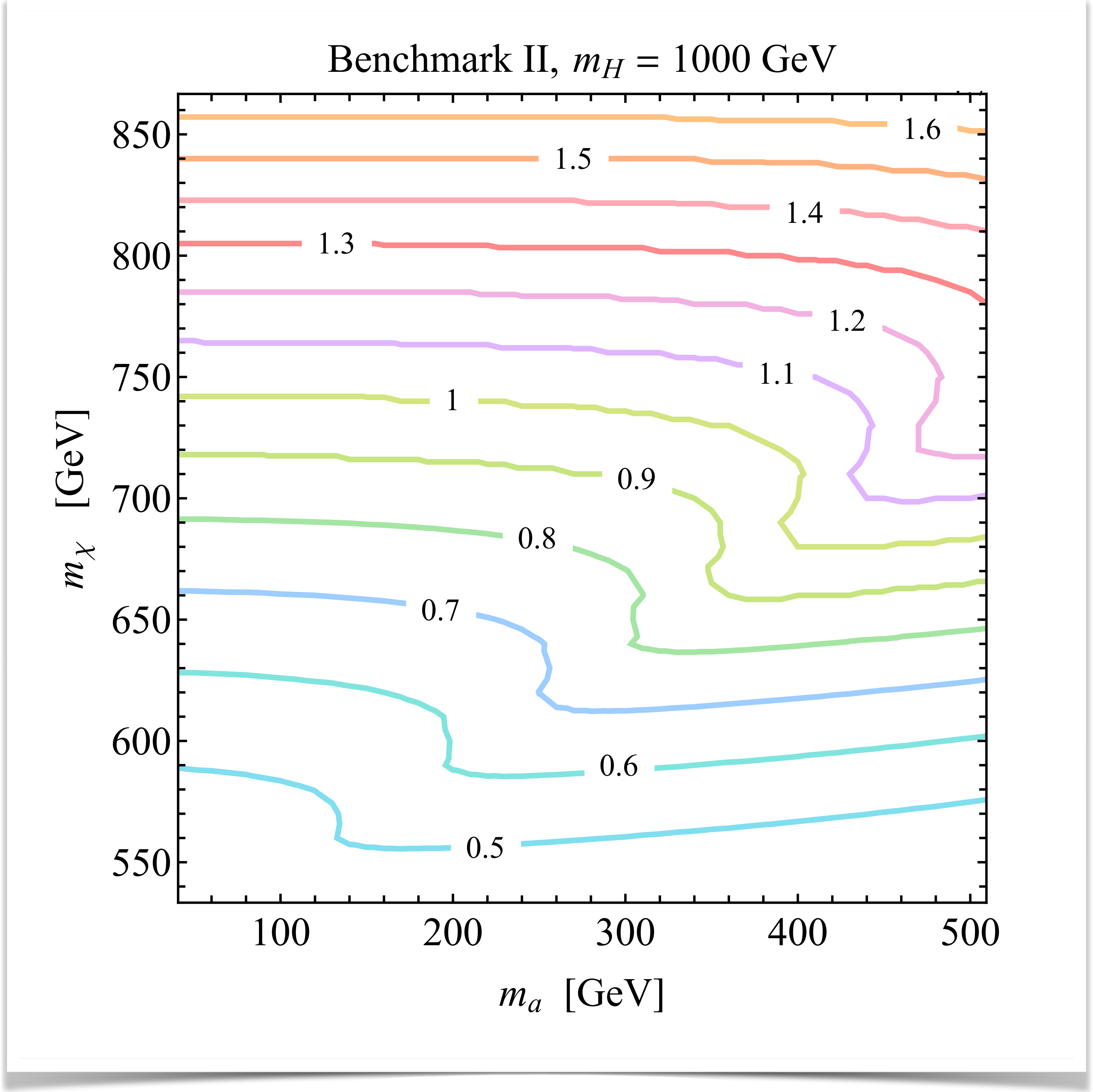

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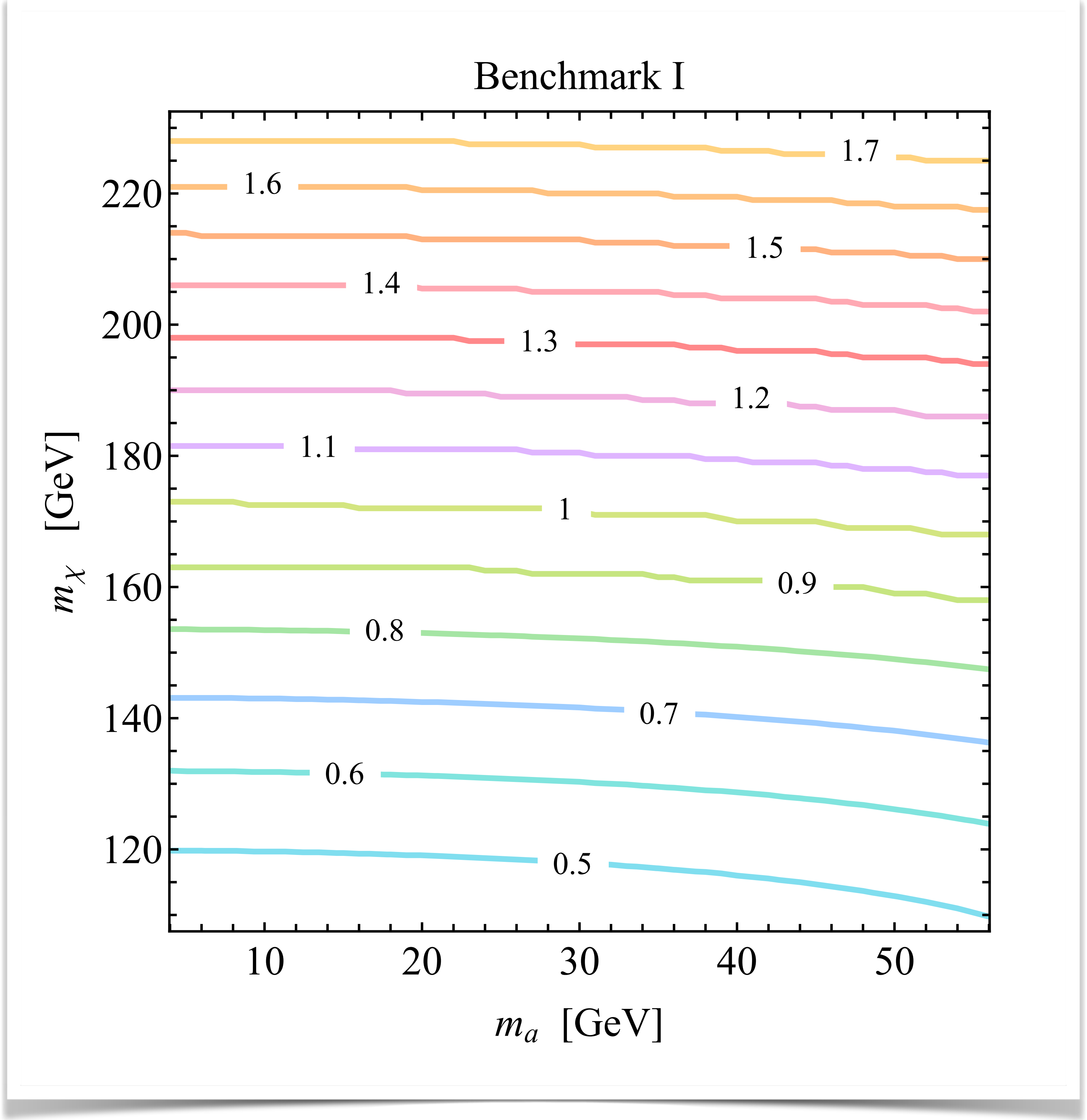
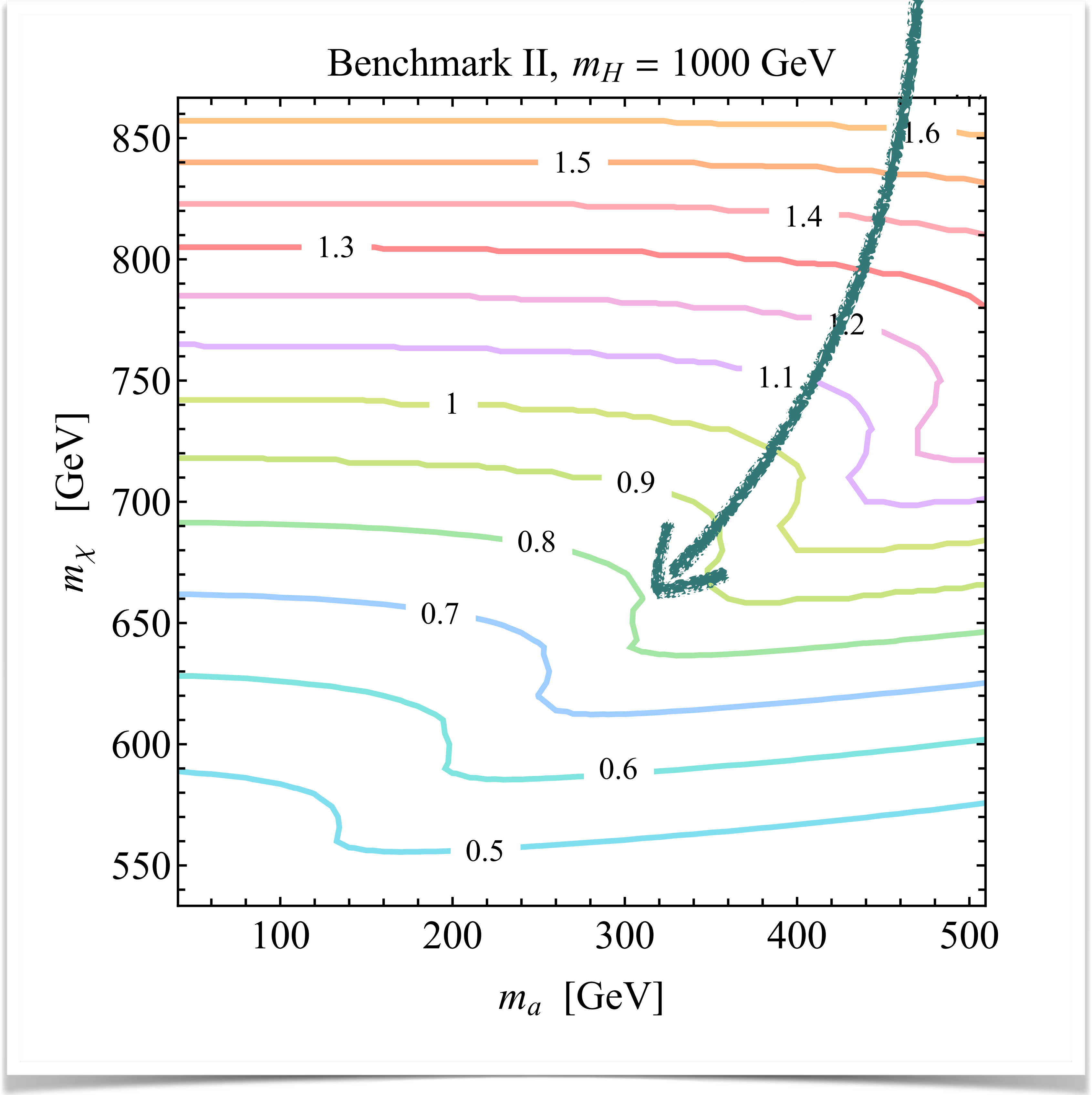
$m_\chi \gg m_H$ no longer true

→ we get more intricate behaviour modelled with MadDM.





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- 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!