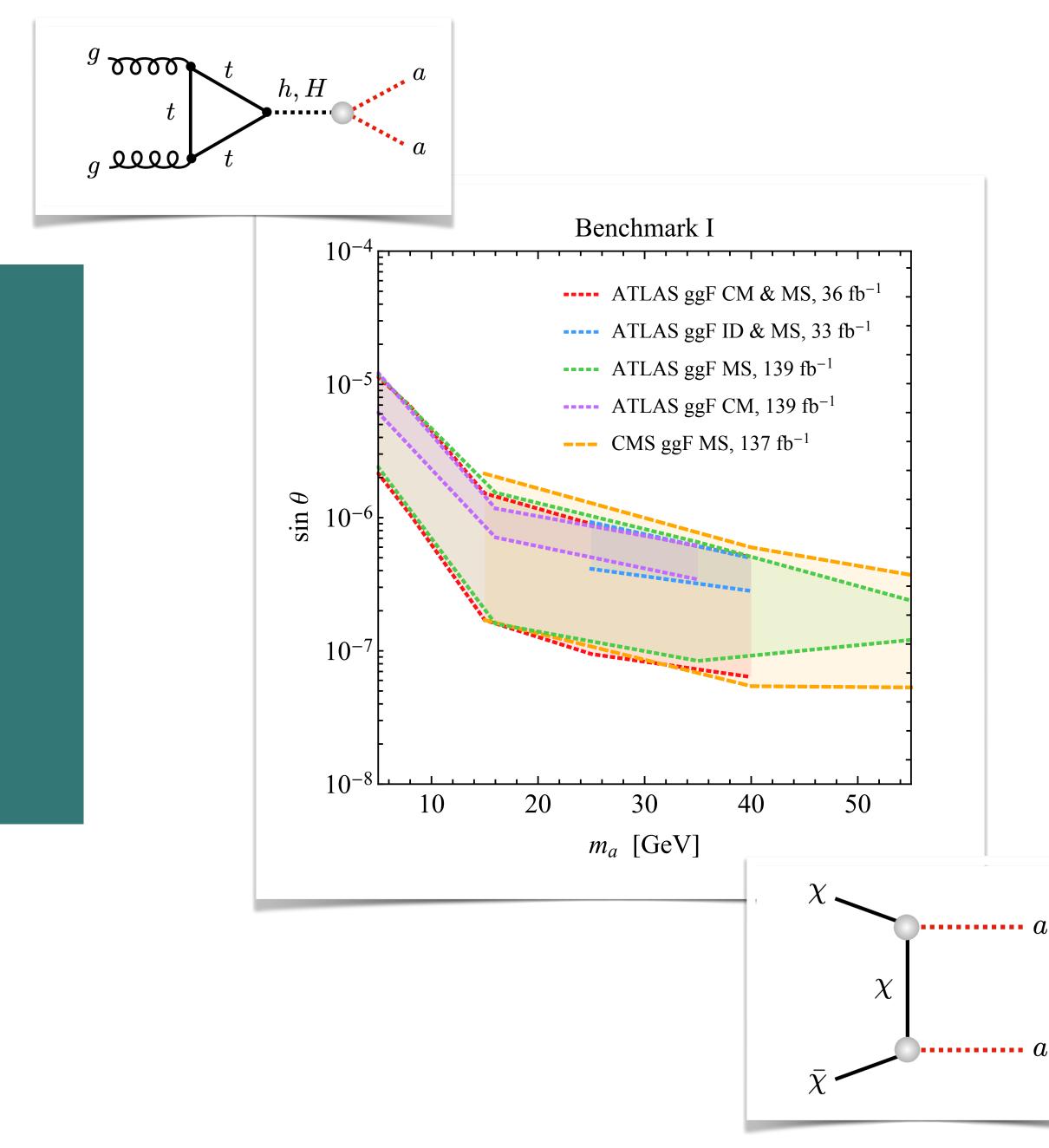


#### Long-lived particle phenomenology in the 2HDM+*a* model

#### Luc Schnell

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

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







# 1. Introduction

- **1.1 Motivation**
- **1.2 2HDM+**a in a nutshell
- **1.3**  $E_T^{miss}$  signatures



# **1. Introduction**

#### **1.1 Motivation**



**UV-complete DM benchmarks** 

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



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Simplified models: e.g.

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 $-g^{A}_{DM}Z^{\prime\mu}(\bar{\chi}\gamma_{\mu}\gamma^{5}\chi)$ 



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#### Mixing with scalar sector

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



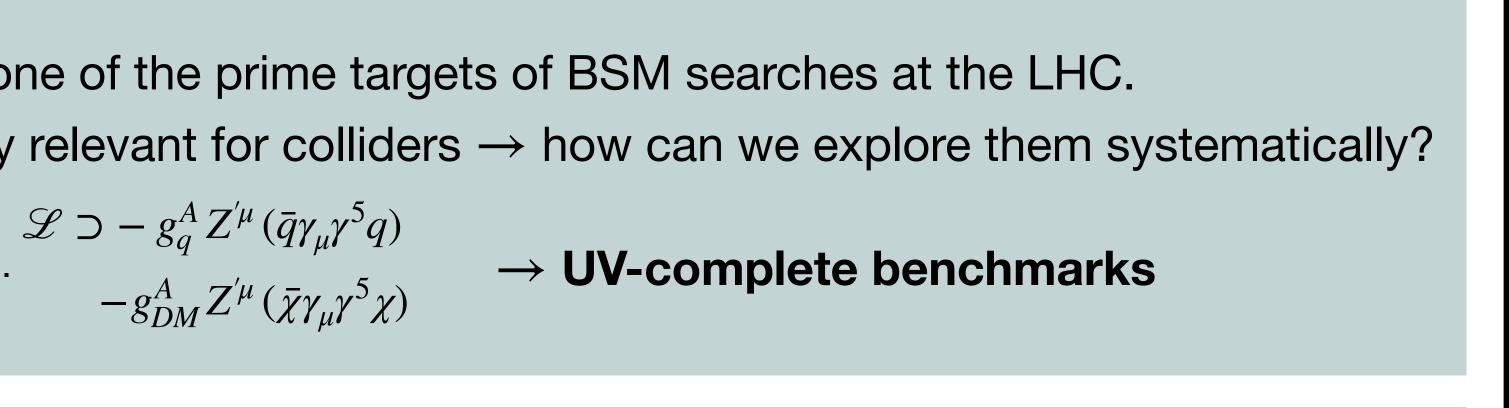
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2HDM scalar potential  $V_{H} = \mu_{1}H_{1}^{\dagger}H_{1} + \mu_{2}H_{2}^{\dagger}H_{2} + \left(\mu_{3}H_{1}^{\dagger}H_{2} + \text{h.c.}\right) + \lambda_{1}\left(H_{1}^{\dagger}H_{1}\right)^{2} + \lambda_{2}\left(H_{2}^{\dagger}H_{2}\right)^{2} + \lambda_{3}\left(H_{1}^{\dagger}H_{1}\right)\left(H_{2}^{\dagger}H_{2}\right) + \lambda_{4}\left(H_{1}^{\dagger}H_{2}\right)\left(H_{2}^{\dagger}H_{1}\right) + \left[\lambda_{5}\left(H_{1}^{\dagger}H_{2}\right)^{2} + \text{h.c.}\right].$ 



2HDM scalar potential

HD 1  

$$V_H = \mu_1 H_1^{\dagger} H_1 + \mu_2 H_2^{\dagger} H_2 + (\mu_3 + \lambda_3 (H_1^{\dagger} H_1) (H_2^{\dagger} H_2) + \lambda_4$$

 ${}_{3}H_{1}^{\dagger}H_{2} + \text{h.c.} + \lambda_{1} \left(H_{1}^{\dagger}H_{1}\right)^{2} + \lambda_{2} \left(H_{2}^{\dagger}H_{2}\right)^{2}$  ${}_{4} \left(H_{1}^{\dagger}H_{2}\right) \left(H_{2}^{\dagger}H_{1}\right) + \left[\lambda_{5} \left(H_{1}^{\dagger}H_{2}\right)^{2} + \text{h.c.}\right].$ 



2HDM scalar potential

$$HD 1 HD 2$$
$$V_{H} = \mu_{1}H_{1}^{\dagger}H_{1} + \mu_{2}H_{2}^{\dagger}H_{2} + (\mu_{3} + \lambda_{3}(H_{1}^{\dagger}H_{1})(H_{2}^{\dagger}H_{2}) + \lambda_{4}$$

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2HDM scalar potential

$$\begin{aligned} \mathbf{HD} \ \mathbf{I} \quad \mathbf{HD} \ \mathbf{2} \\ V_{H} &= \mu_{1} H_{1}^{\dagger} H_{1} + \mu_{2} H_{2}^{\dagger} H_{2} + \left( \mu_{3} H_{1}^{\dagger} H_{2} + \text{h.c.} \right) + \lambda_{1} \left( H_{1}^{\dagger} H_{1} \right)^{2} + \lambda_{2} \left( H_{2}^{\dagger} H_{2} \right)^{2} \\ &+ \lambda_{3} \left( H_{1}^{\dagger} H_{1} \right) \left( H_{2}^{\dagger} H_{2} \right) + \lambda_{4} \left( H_{1}^{\dagger} H_{2} \right) \left( H_{2}^{\dagger} H_{1} \right) + \left[ \lambda_{5} \left( H_{1}^{\dagger} H_{2} \right)^{2} + \text{h.c.} \right] . \end{aligned}$$

Pseudoscalar mediator

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



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$$\begin{aligned} \mathbf{HD 1} \quad \mathbf{HD 2} \\ V_{H} &= \mu_{1} H_{1}^{\dagger} H_{1} + \mu_{2} H_{2}^{\dagger} H_{2} + \left( \mu_{3} H_{1}^{\dagger} H_{2} + \text{h.c.} \right) + \lambda_{1} \left( H_{1}^{\dagger} H_{1} \right)^{2} + \lambda_{2} \left( H_{2}^{\dagger} H_{2} \right)^{2} \\ &+ \lambda_{3} \left( H_{1}^{\dagger} H_{1} \right) \left( H_{2}^{\dagger} H_{2} \right) + \lambda_{4} \left( H_{1}^{\dagger} H_{2} \right) \left( H_{2}^{\dagger} H_{1} \right) + \left[ \lambda_{5} \left( H_{1}^{\dagger} H_{2} \right)^{2} + \text{h.c.} \right] . \end{aligned}$$

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**2HDM scalar** potential

$$HD 1 HD 2$$
  

$$V_{H} = \mu_{1}H_{1}^{\dagger}H_{1} + \mu_{2}H_{2}^{\dagger}H_{2} + (\mu_{3}H_{1}^{\dagger}H_{2} + \text{h.c.}) + \lambda_{1}(H_{1}^{\dagger}H_{1})^{2} + \lambda_{2}(H_{2}^{\dagger}H_{2})^{2}$$
  

$$+ \lambda_{3}(H_{1}^{\dagger}H_{1})(H_{2}^{\dagger}H_{2}) + \lambda_{4}(H_{1}^{\dagger}H_{2})(H_{2}^{\dagger}H_{1}) + [\lambda_{5}(H_{1}^{\dagger}H_{2})^{2} + \text{h.c.}].$$

**Pseudo**scalar mediator

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

$$\mathcal{L}_{\chi} = -i y_{\chi} P \, \bar{\chi} \gamma_5 \chi \,,$$

Fermionic DM





2HDM s pote

$$\begin{aligned} & \mathsf{HD} \ \mathbf{1} \quad \mathsf{HD} \ \mathbf{2} \\ V_{H} &= \mu_{1} H_{1}^{\dagger} H_{1} + \mu_{2} H_{2}^{\dagger} H_{2} + \left(\mu_{3} H_{1}^{\dagger} H_{2} + \mathrm{h.c.}\right) + \lambda_{1} \left(H_{1}^{\dagger} H_{1}\right)^{2} + \lambda_{2} \left(H_{2}^{\dagger} H_{2}\right)^{2} \\ &+ \lambda_{3} \left(H_{1}^{\dagger} H_{1}\right) \left(H_{2}^{\dagger} H_{2}\right) + \lambda_{4} \left(H_{1}^{\dagger} H_{2}\right) \left(H_{2}^{\dagger} H_{1}\right) + \left[\lambda_{5} \left(H_{1}^{\dagger} H_{2}\right)^{2} + \mathrm{h.c.}\right] . \end{aligned}$$

$$h_{P}^{2} P^{2} + P\left(i b_{P} H_{1}^{\dagger} H_{2} + \mathrm{h.c.}\right) + P^{2} \left(\lambda_{P1} H_{1}^{\dagger} H_{1} + \lambda_{P2} H_{2}^{\dagger} H_{2}\right) , \qquad \mathcal{L}_{\chi} = -i y_{\chi} P \, \bar{\chi} \gamma_{5} \chi, \qquad \mathsf{Fermion} \\ \mathsf{DM} \end{aligned}$$

**Pseudo**scalar mediator

Scalar  
ential  
$$V_{H} = \mu_{1}H_{1}H_{1} + \mu_{2}H_{2}H_{2} + (\mu_{3}H_{1}H_{2} + \text{h.c.}) + \lambda_{1}(H_{1}H_{1}) + \lambda_{2}(H_{2}H_{2}) + \lambda_{2}(H_{2}H_{2}) + \lambda_{3}(H_{1}^{\dagger}H_{1})(H_{2}^{\dagger}H_{2}) + \lambda_{4}(H_{1}^{\dagger}H_{2})(H_{2}^{\dagger}H_{1}) + [\lambda_{5}(H_{1}^{\dagger}H_{2})^{2} + \text{h.c.}] .$$
$$V_{P} = \frac{1}{2}m_{P}^{2}P^{2} + P(ib_{P}H_{1}^{\dagger}H_{2} + \text{h.c.}) + P^{2}(\lambda_{P1}H_{1}^{\dagger}H_{1} + \lambda_{P2}H_{2}^{\dagger}H_{2}) , \qquad \mathcal{L}_{\chi} = -iy_{\chi}P\bar{\chi}\gamma_{5}\chi, \qquad \text{Fermion}$$





2HDM s pote

$$HD 1 HD 2$$

$$V_{H} = \mu_{1}H_{1}^{\dagger}H_{1} + \mu_{2}H_{2}^{\dagger}H_{2} + (\mu_{3}$$

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**Pseudo**scalar mediator

$$V_{H} = \mu_{1}H_{1}^{\dagger}H_{1} + \mu_{2}H_{2}^{\dagger}H_{2} + (\mu_{3}H_{1}^{\dagger}H_{2} + h.c.) + \lambda_{1}(H_{1}^{\dagger}H_{1})^{2} + \lambda_{2}(H_{2}^{\dagger}H_{2})^{2} + \lambda_{3}(H_{1}^{\dagger}H_{1})(H_{2}^{\dagger}H_{2}) + \lambda_{4}(H_{1}^{\dagger}H_{2})(H_{2}^{\dagger}H_{1}) + [\lambda_{5}(H_{1}^{\dagger}H_{2})^{2} + h.c.] .$$

$$V_{P} = \frac{1}{2}m_{P}^{2}P^{2} + P(ib_{P}H_{1}^{\dagger}H_{2} + h.c.) + P^{2}(\lambda_{P1}H_{1}^{\dagger}H_{1} + \lambda_{P2}H_{2}^{\dagger}H_{2}) , \qquad \mathcal{L}_{\chi} = -iy_{\chi}P\bar{\chi}\gamma_{5}\chi, \qquad \text{Fermion} DM$$





2HDM s pote

**Pseudo**scalar mediator

$$V_{H} = \mu_{1}H_{1}^{\dagger}H_{1} + \mu_{2}H_{2}^{\dagger}H_{2} + (\mu_{3}H_{1}^{\dagger}H_{2} + h.c.) + \lambda_{1}(H_{1}^{\dagger}H_{1})^{2} + \lambda_{2}(H_{2}^{\dagger}H_{2})^{2} + \lambda_{3}(H_{1}^{\dagger}H_{1})(H_{2}^{\dagger}H_{2}) + \lambda_{4}(H_{1}^{\dagger}H_{2})(H_{2}^{\dagger}H_{1}) + [\lambda_{5}(H_{1}^{\dagger}H_{2})^{2} + h.c.].$$

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Fermion DM







2HDM s pote

$$\begin{array}{c} \text{HD 1} \quad \text{HD 2} \\ V_{H} = \mu_{1}H_{1}^{\dagger}H_{1} + \mu_{2}H_{2}^{\dagger}H_{2} + \left(\mu_{3}H_{1}^{\dagger}H_{2} + \text{h.c.}\right) + \lambda_{1}\left(H_{1}^{\dagger}H_{1}\right)^{2} + \lambda_{2}\left(H_{2}^{\dagger}H_{2}\right)^{2} \\ + \lambda_{3}\left(H_{1}^{\dagger}H_{1}\right)\left(H_{2}^{\dagger}H_{2}\right) + \lambda_{4}\left(H_{1}^{\dagger}H_{2}\right)\left(H_{2}^{\dagger}H_{1}\right) + \left[\lambda_{5}\left(H_{1}^{\dagger}H_{2}\right)^{2} + \text{h.c.}\right]. \end{array} \right) \\ pseudoscal coupling \\ i^{2}_{P}P^{2} + P\left(ib_{P}H_{1}^{\dagger}H_{2} + \text{h.c.}\right) + P^{2}\left(\lambda_{P1}H_{1}^{\dagger}H_{1} + \lambda_{P2}H_{2}^{\dagger}H_{2}\right), \qquad \qquad \mathcal{L}_{\chi} = -iy_{\chi}P\bar{\chi}\gamma_{5}\chi, \qquad \begin{array}{c} \text{Fermion} \\ DM \end{array} \right)$$

**Pseudo**scalar mediator

$$V_{H} = \mu_{1}H_{1}^{\dagger}H_{1} + \mu_{2}H_{2}^{\dagger}H_{2} + (\mu_{3}H_{1}^{\dagger}H_{2} + h.c.) + \lambda_{1}(H_{1}^{\dagger}H_{1})^{2} + \lambda_{2}(H_{2}^{\dagger}H_{2})^{2} + \lambda_{3}(H_{1}^{\dagger}H_{1})(H_{2}^{\dagger}H_{2}) + \lambda_{4}(H_{1}^{\dagger}H_{2})(H_{2}^{\dagger}H_{1}) + [\lambda_{5}(H_{1}^{\dagger}H_{2})^{2} + h.c.].$$

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Fermion DM

**SSB:** 
$$\langle H_i \rangle = (0, v_i/\sqrt{2})^T$$
 with  $v = \sqrt{v_1^2 + v_2^2} \simeq 246 \,\text{GeV}$ 







2HDM s pote

**Pseudo**scalar mediator

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

**Physical fields:**  $h, H, a, A, H^{\pm}$  (three d.o.f. eaten by  $Z, W^{\pm}$ ) and  $\chi$ . **Physical parameters:**  $\alpha$ ,  $\beta$ ,  $\theta$ , v,  $\lambda_3$ ,  $\lambda_{P1}$ ,  $\lambda_{P2}$ ,  $m_h$ ,  $m_H$ ,  $m_a$ ,  $m_A$ ,  $m_{H^{\pm}}$ .

 $\alpha$ : mixing angle for scalars (*h*, *H*)

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 $\theta$ : mixing angle for pseudo-scalars (a, A)







2HDM s pote

$$\begin{array}{c} \text{HD 1} \quad \text{HD 2} \\ V_{H} = \mu_{1}H_{1}^{\dagger}H_{1} + \mu_{2}H_{2}^{\dagger}H_{2} + \left(\mu_{3}H_{1}^{\dagger}H_{2} + \text{h.c.}\right) + \lambda_{1}\left(H_{1}^{\dagger}H_{1}\right)^{2} + \lambda_{2}\left(H_{2}^{\dagger}H_{2}\right)^{2} \\ + \lambda_{3}\left(H_{1}^{\dagger}H_{1}\right)\left(H_{2}^{\dagger}H_{2}\right) + \lambda_{4}\left(H_{1}^{\dagger}H_{2}\right)\left(H_{2}^{\dagger}H_{1}\right) + \left[\lambda_{5}\left(H_{1}^{\dagger}H_{2}\right)^{2} + \text{h.c.}\right]. \end{array} \right) \\ pseudoscal coupling \\ h_{P}^{2}P^{2} + P\left(ib_{P}H_{1}^{\dagger}H_{2} + \text{h.c.}\right) + P^{2}\left(\lambda_{P1}H_{1}^{\dagger}H_{1} + \lambda_{P2}H_{2}^{\dagger}H_{2}\right), \qquad \qquad \mathcal{L}_{\chi} = -iy_{\chi}P\bar{\chi}\gamma_{5}\chi, \qquad \begin{array}{c} \text{Fermionized on the set of the set of$$

Pseudoscalar mediator

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$$V_{H} = \mu_{1}H_{1}^{\dagger}H_{1} + \mu_{2}H_{2}^{\dagger}H_{2} + (\mu_{3}H_{1}^{\dagger}H_{2} + h.c.) + \lambda_{1}(H_{1}^{\dagger}H_{1})^{2} + \lambda_{2}(H_{2}^{\dagger}H_{2})^{2}$$

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 $\alpha$ : mixing angle for scalars (h, H)

**SSB:** 
$$\langle H_i \rangle = (0, v_i/\sqrt{2})^T$$
 with  $v = \sqrt{v_1^2 + v_2^2} \simeq 246 \,\mathrm{GeV}$ 

 $\theta$ : mixing angle for pseudo-scalars (a, A)







### **1. Introduction 1.3** $E_{T}^{miss}$ signatures

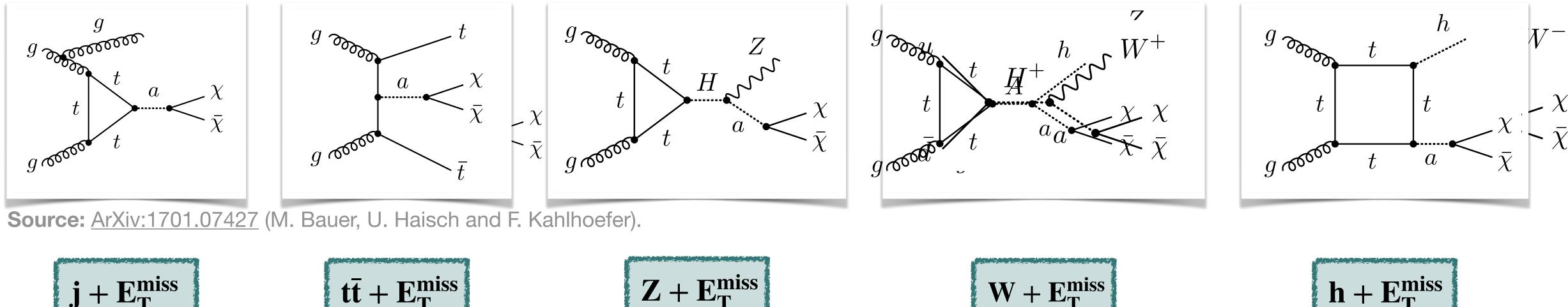
Physical fields:  $h, H, a, A, H^{\pm}$  and  $\chi$ .Physical parameters:  $\alpha, \beta, \theta, v, \lambda_3, \lambda_{P1}, \lambda_{P2}, m_h, m_H, m_a, m_A, m_{H^{\pm n}}$  $\alpha$ : mixing angle for scalars (h, H) $\theta$ : mixing angle for pseudo-scalars (a, A)

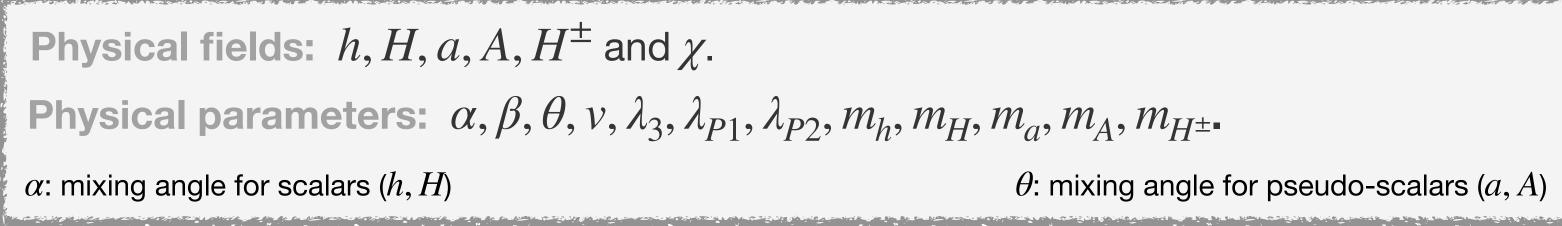
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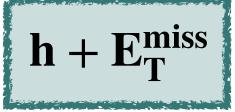
### 1. Introduction **1.3** E<sup>miss</sup> signatures





 $Z + E_{T}^{miss}$ 

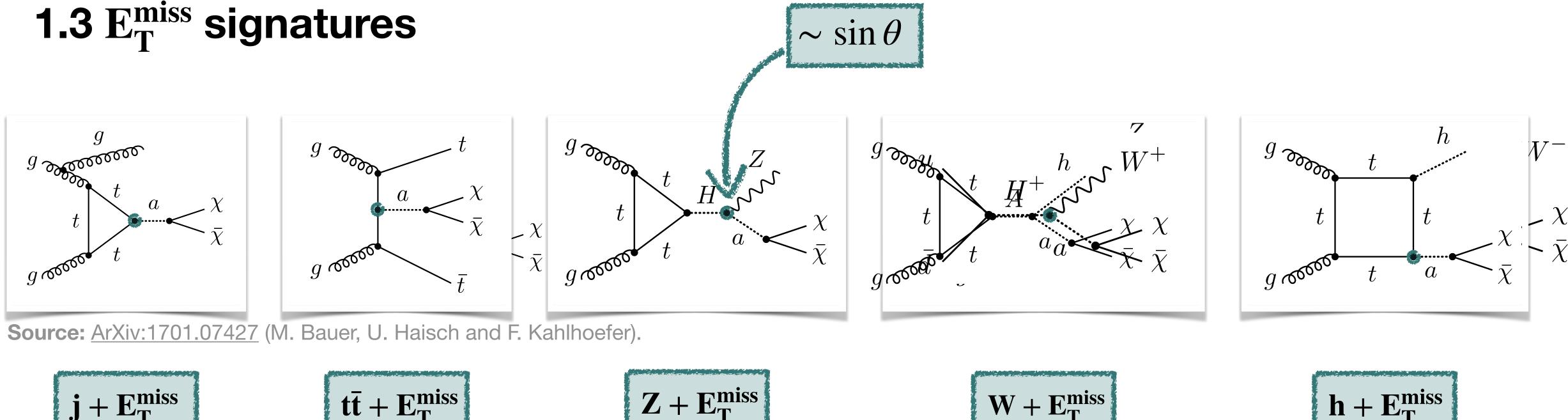
 $W + E_T^{miss}$ 

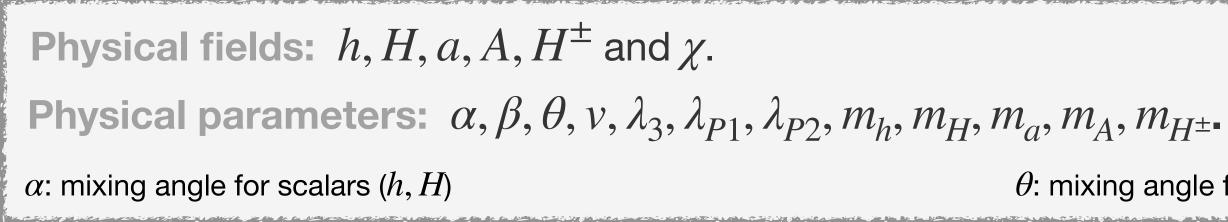


 $\theta$ : mixing angle for pseudo-scalars (a, A)



# **1. Introduction 1.3** E<sup>miss</sup><sub>T</sub> signatures

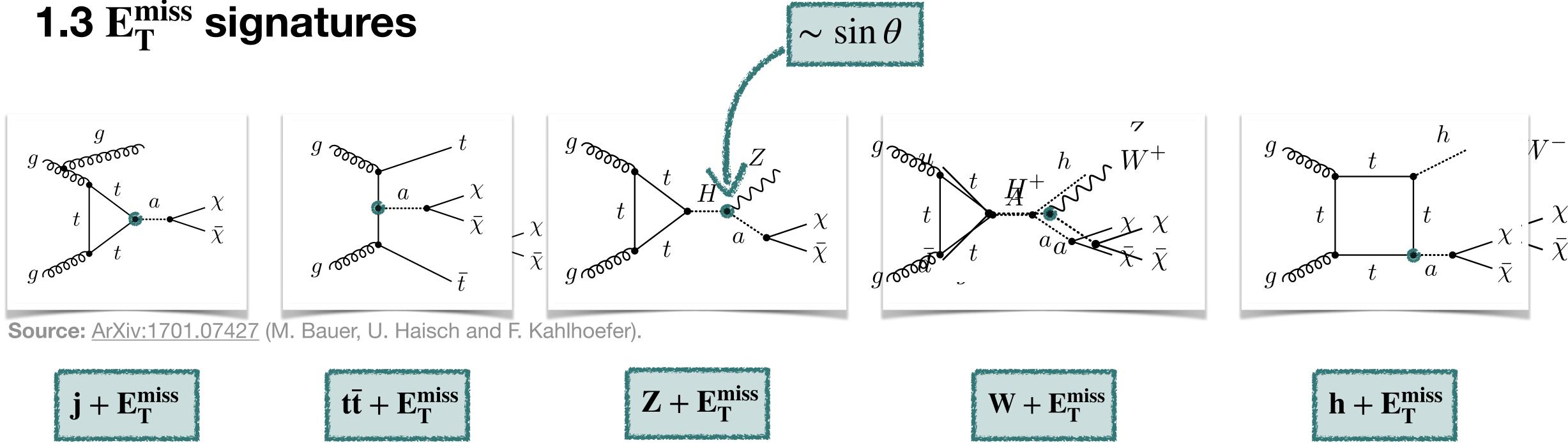




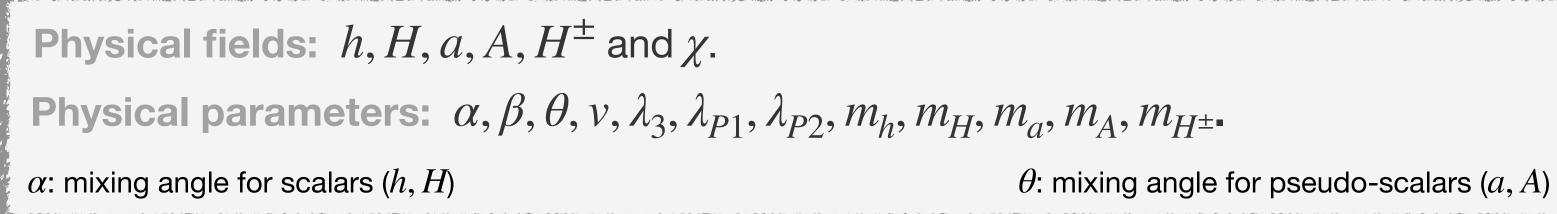
 $m_a, m_A, m_{H^{\pm \bullet}}$ heta: mixing angle for pseudo-scalars (a, A)



### 1. Introduction **1.3** $E_{T}^{miss}$ signatures



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





# 2. LLP Phenomenology

2.1 Model parameters2.2 LLP constraints2.3 Relic density



# 2.1 Model parameters

Physical fields:  $h, H, a, A, H^{\pm}$  and  $\chi$ .Physical parameters:  $\alpha, \beta, \theta, v, \lambda_3, \lambda_{P1}, \lambda_{P2}, m_h, m_H, m_a, m_A, m_{H^{\pm}}$ . $\alpha$ : mixing angle for scalars (h, H) $\theta$ : mixing angle for pseudo-scalars (a, A)

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

**Physical fields:**  $h, H, a, A, H^{\pm}$  and  $\chi$ . **Physical parameters:**  $\alpha, \beta, \theta, \nu, \lambda_3, \lambda_{P1}, \lambda_{P2}, m_h, m_H, m_a, m_A, m_{H^{\pm \bullet}}$  $\alpha$ : mixing angle for scalars (h, H)  $\theta$ : mixing angle for pseudo-scalars (a, A)



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

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

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

**Physical fields:**  $h, H, a, A, H^{\pm}$  and  $\chi$ . **Physical parameters:**  $\alpha, \beta, \theta, \nu, \lambda_3, \lambda_{P1}, \lambda_{P2}, m_h, m_H, m_a, m_A, m_A$  $\theta$ : mixing ang  $\alpha$ : mixing angle for scalars (h, H)

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$$n_{H^{\pm \bullet}}$$
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• For small mixing angles  $\theta$ , the pseudoscalar  $a \simeq P$  can become long-lived.

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

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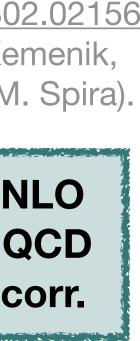
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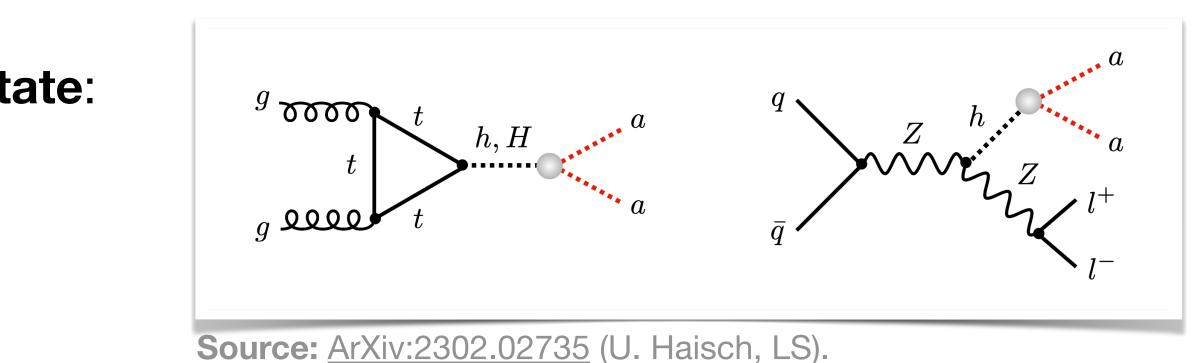




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Production via the decay of a heavier spin-0 state:

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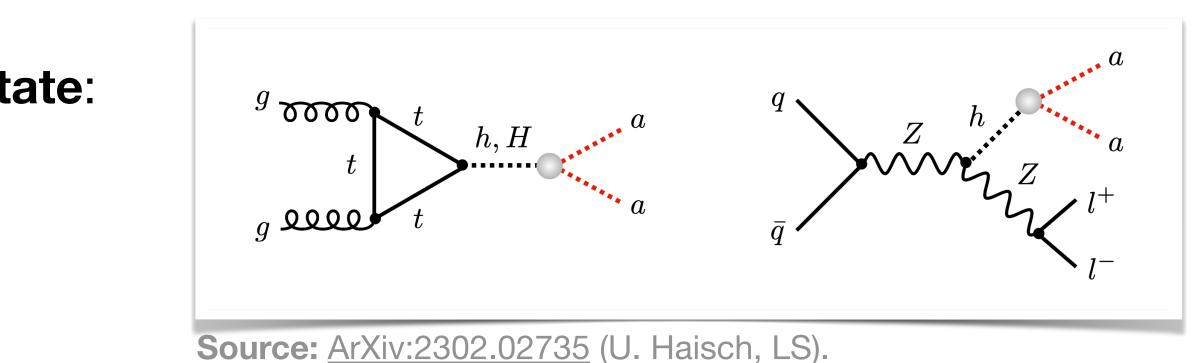


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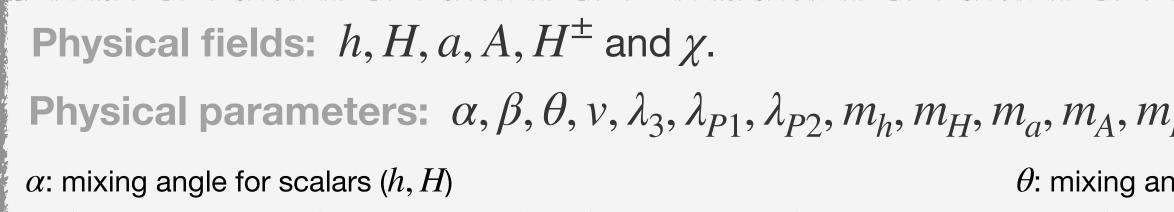


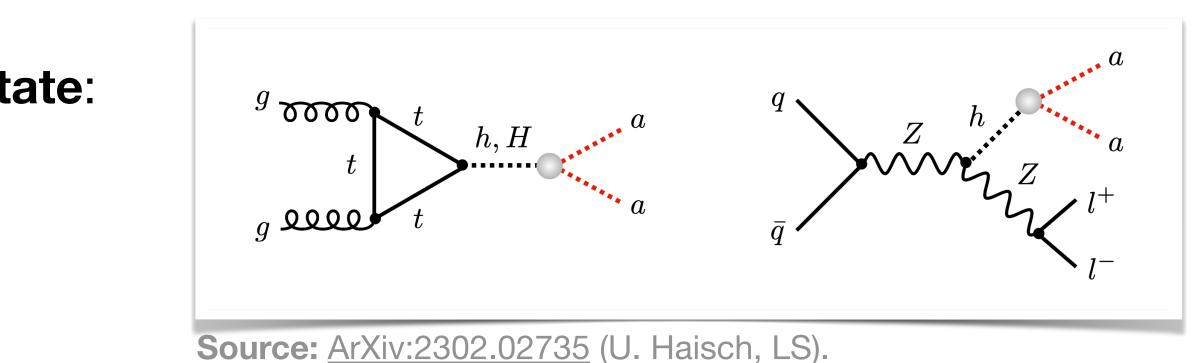
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Production via the decay of a heavier spin-0 state:

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



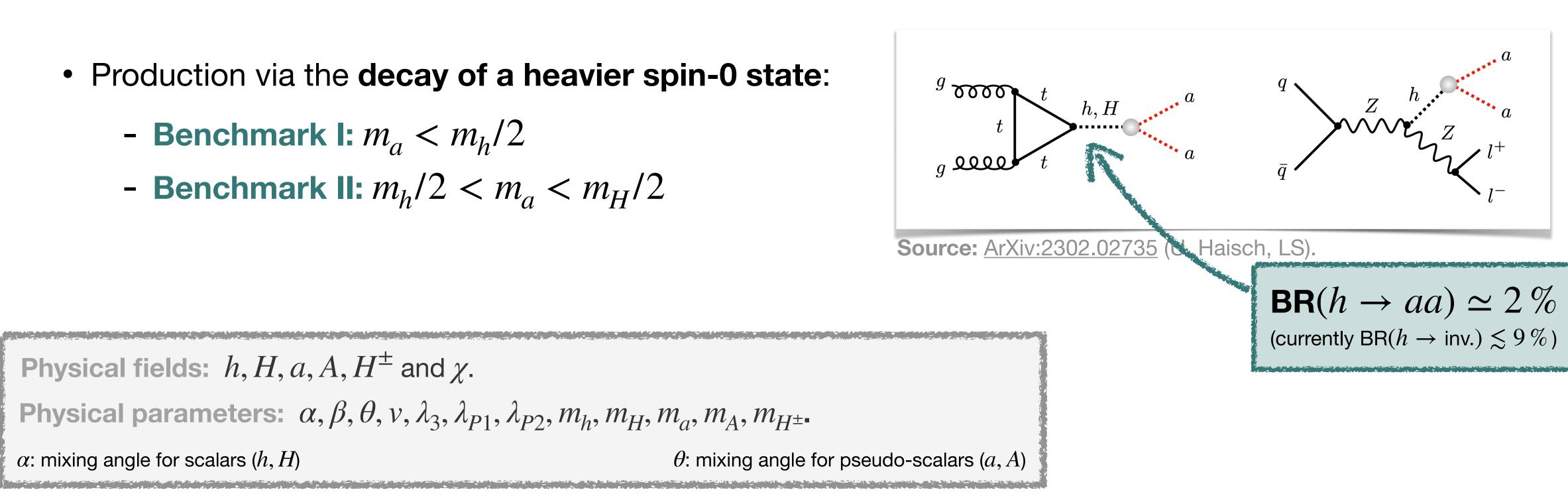


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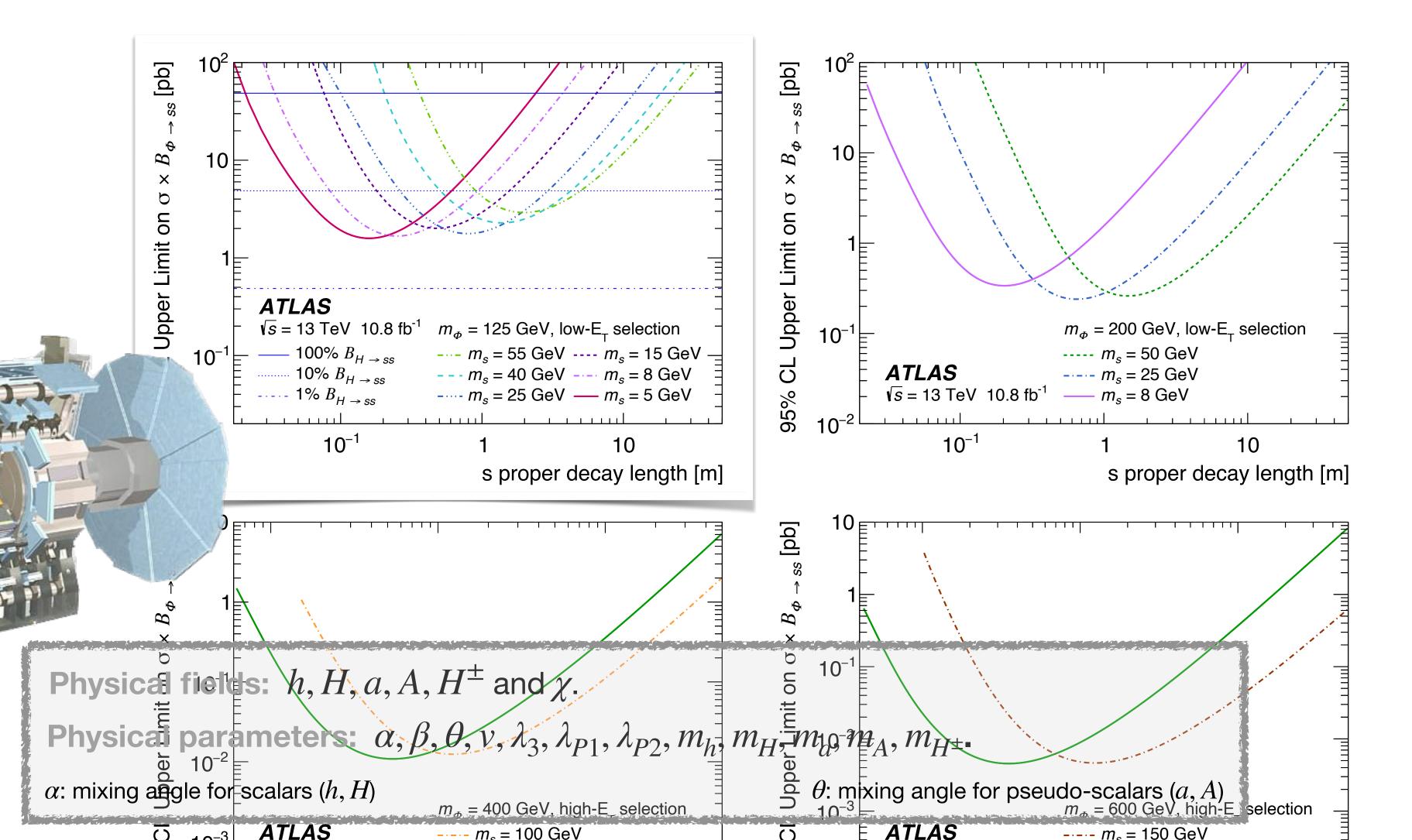


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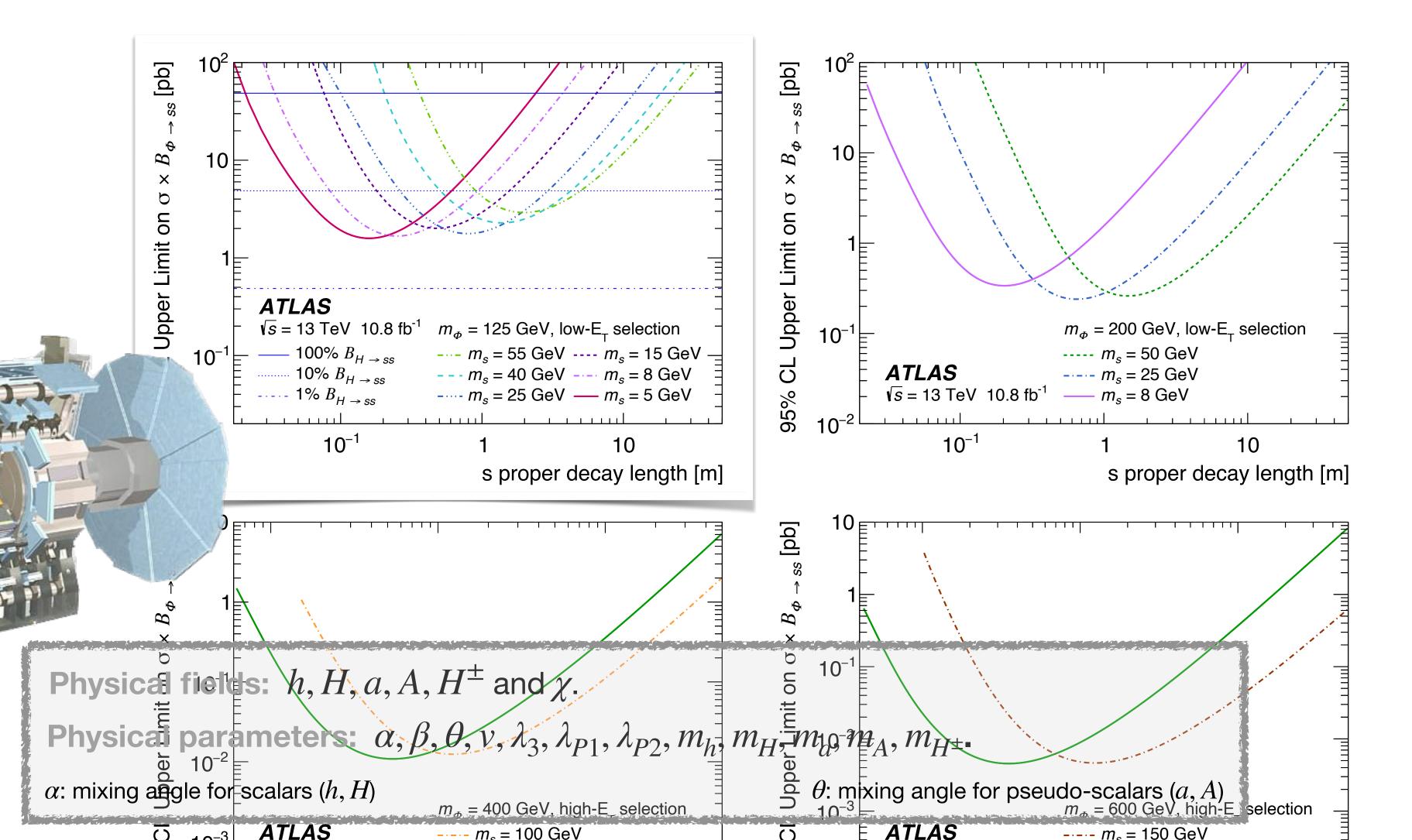
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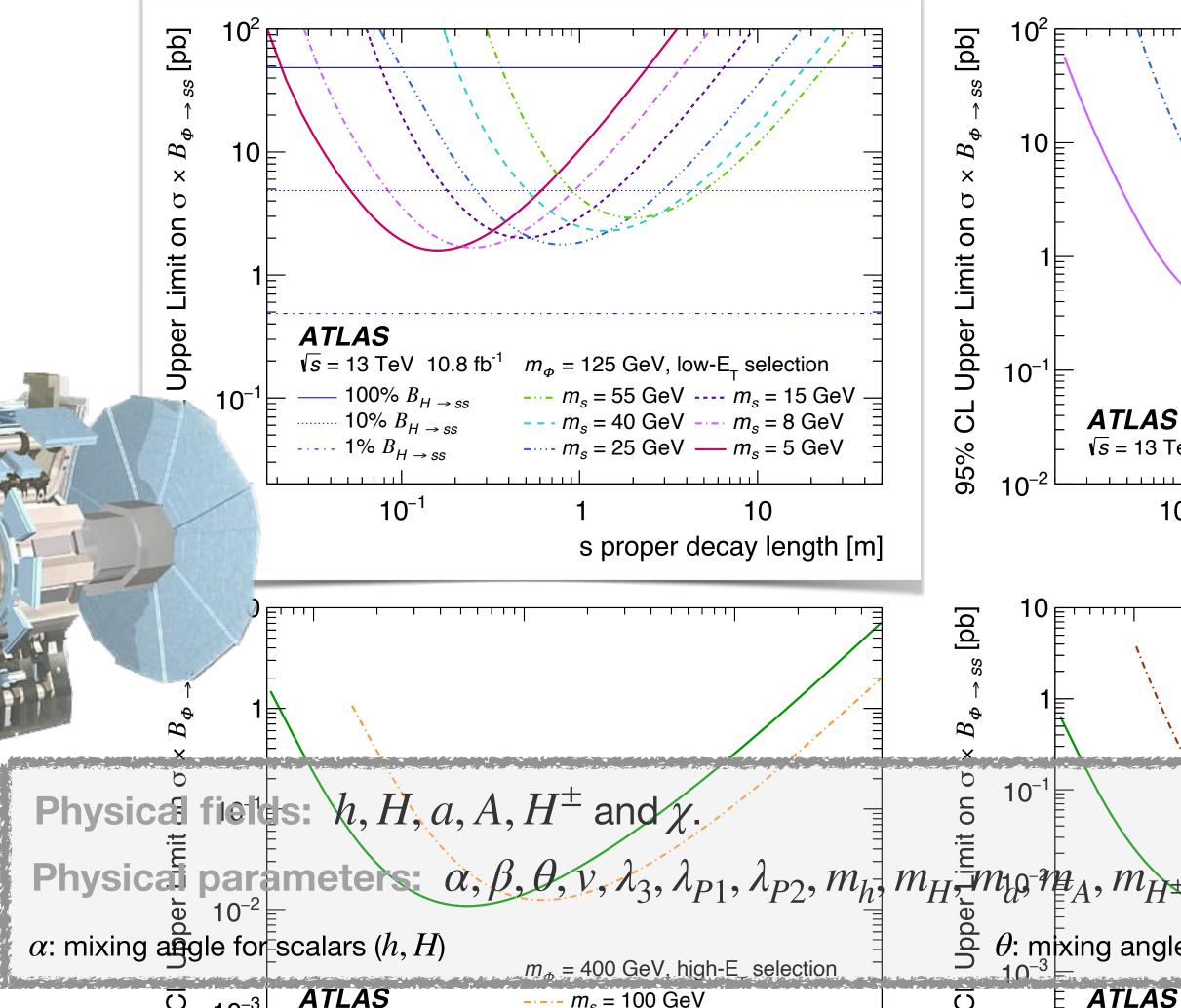


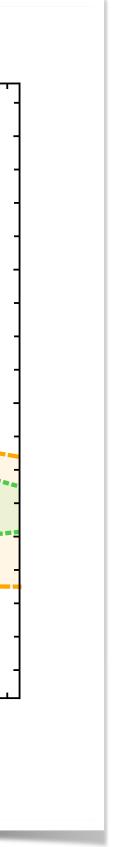






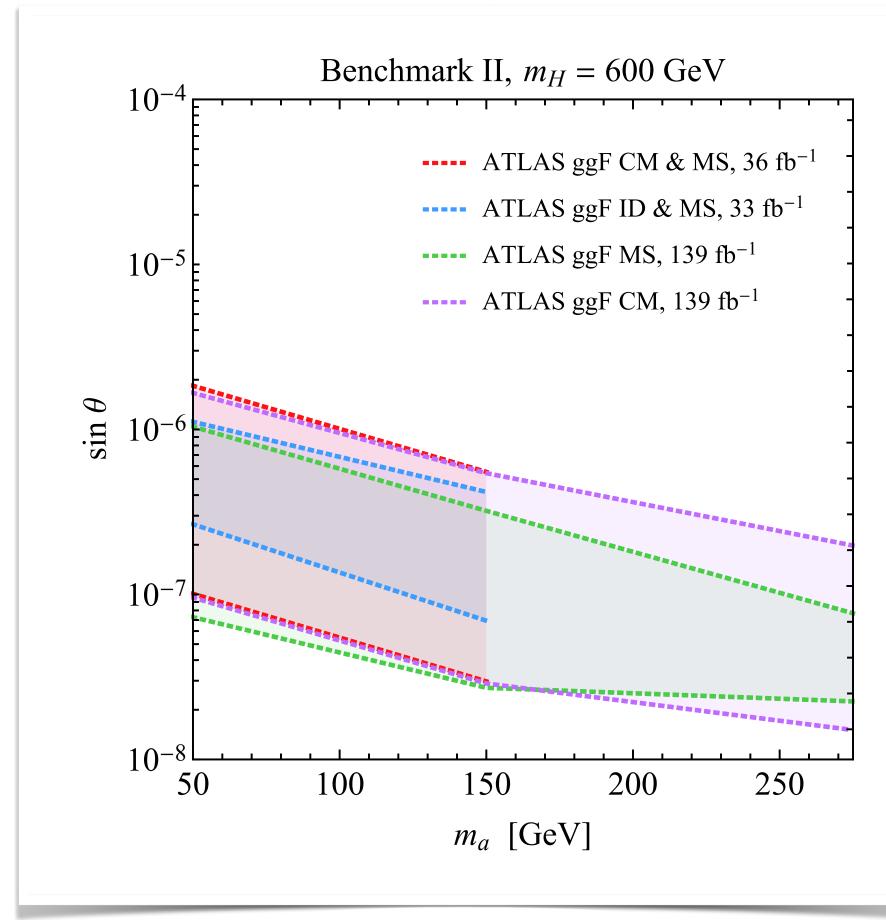
### 2. LLP Phenomenology **2.2 LLP constraints** Benchmark I $10^{-2}$ ----- ATLAS ggF CM & MS, 36 $fb^{-1}$ 10<sup>2</sup> ss [pb] [dd] ----- ATLAS ggF ID & MS, 33 $fb^{-1}$ SS ----- ATLAS ggF MS, 139 $fb^{-1}$ ----- ATLAS ggF CM, 139 $fb^{-1}$ $B_{{\Phi}}$ Φ 10E 10 B ---- CMS ggF MS, 137 fb<sup>-1</sup> Х X р р Upper Limit on Upper Limit on ATLAS $m_{\phi}$ = 125 GeV, low-E<sub>T</sub> selection $\sqrt{s} = 13 \text{ TeV} \ 10.8 \text{ fb}^{-1}$ $m_{\phi}$ = 200 GeV, low-E<sub>T</sub> selection 10 100% $B_{H \rightarrow ss}$ ---- $m_s = 55 \text{ GeV} ---- m_s = 15 \text{ GeV} -----$ ----- $m_s = 50 \text{ GeV}$ $10^{-1}$ CL ATLAS $--m_s = 40 \text{ GeV} - -m_s = 8 \text{ GeV}$ 10% $B_{H \rightarrow ss}$ ---- $m_s = 25 \text{ GeV}$ - 1% $B_{H \rightarrow ss}$ $\sqrt{s}$ = 13 TeV 10.8 fb<sup>-1</sup> ----- $m_s = 25 \text{ GeV} - m_s = 5 \text{ GeV}$ ----- *m<sub>s</sub>* = 8 GeV 95% $10^{-10}$ $10^{-1}$ $10^{-1}$ 10 10 s proper decay length [m] s proper decay length [m] 20 10 30 40 50 10 FT [dd] $m_a$ [GeV] SS θ : <u>ArXiv:2302.02735</u> (U. Haisch, LS). B $10^{-2}$ Upp $\theta$ : mixing angle for pseudo-scalars (a, A) $m_{\phi} = 600 \text{ GeV}$ , high-E selection $m_{\phi} = 400 \text{ GeV}, \text{ high-E} \text{ selection}$ $----m_{e} = 150 \text{ GeV}$



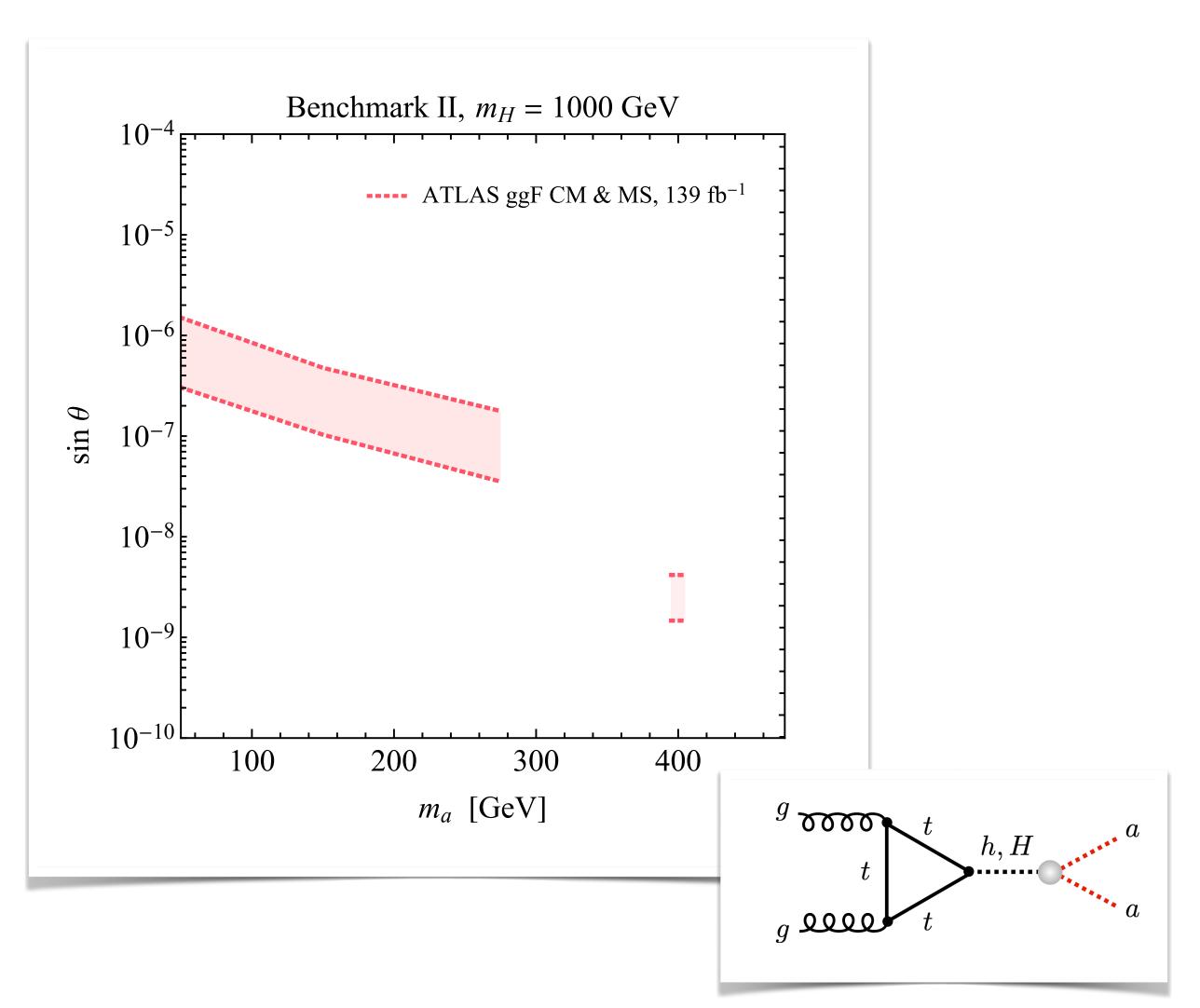




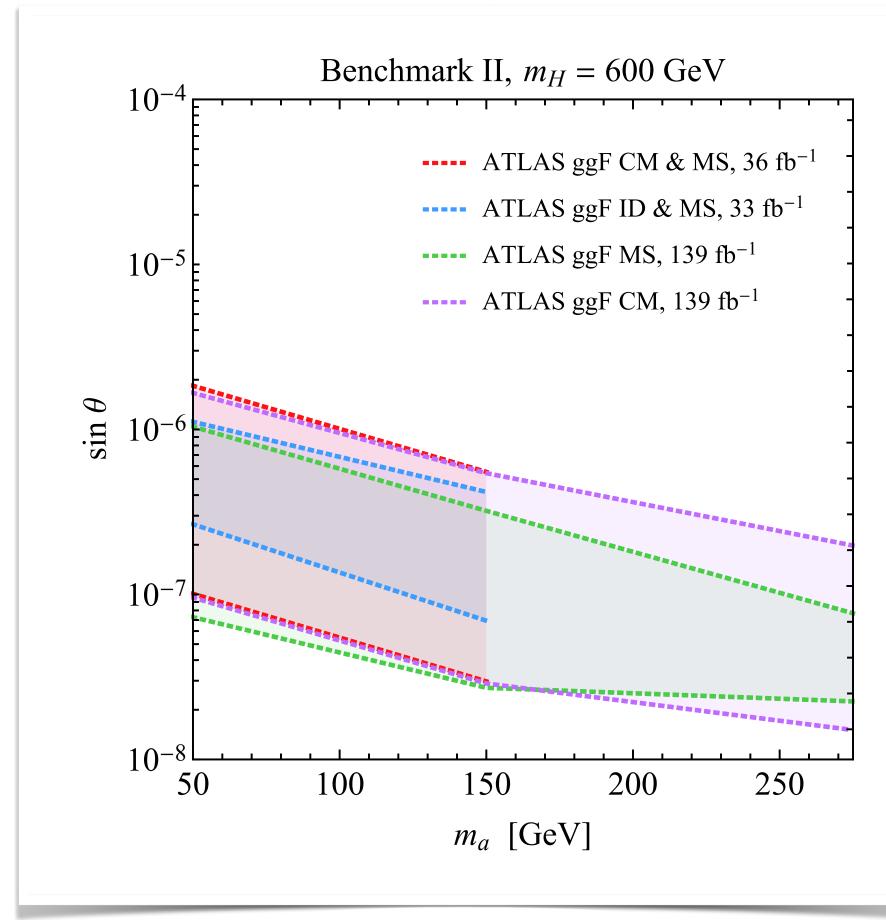




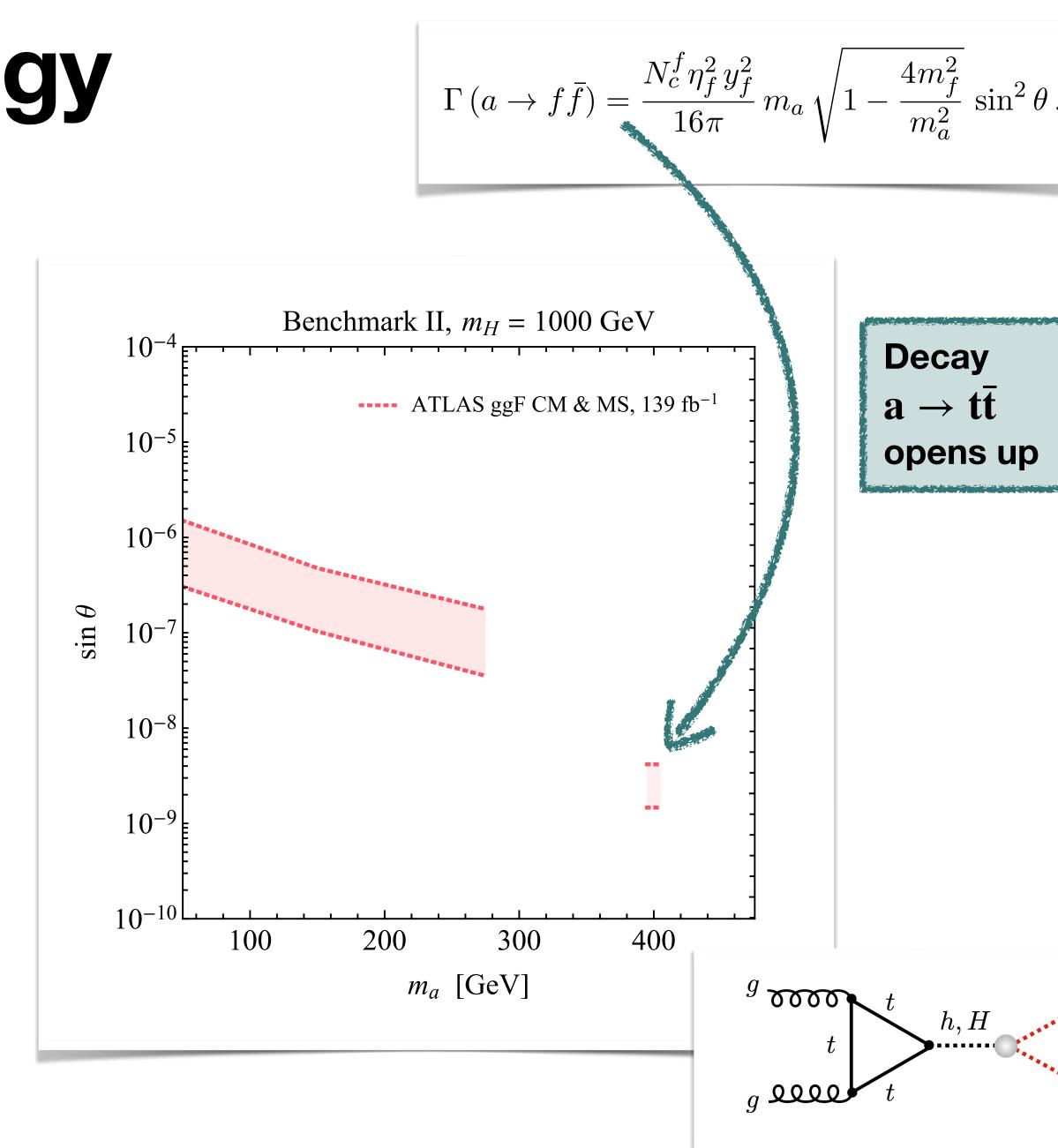
Source: <u>ArXiv:2302.02735</u> (U. Haisch, LS).







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Physical fields:  $h, H, a, A, H^{\pm}$  and  $\chi$ .Physical parameters:  $\alpha, \beta, \theta, v, \lambda_3, \lambda_{P1}, \lambda_{P2}, m_h, m_H, m_a, m_A, m_{H^{\pm}}$ . $\alpha$ : mixing angle for scalars (h, H) $\theta$ : mixing angle for pseudo-scalars (a, A)

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

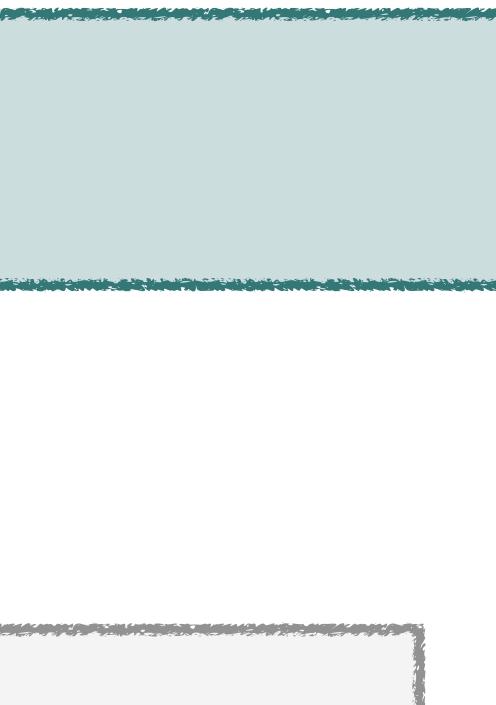
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- DM density evolution ("freeze-out"):

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

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$$\frac{dn_{\chi}}{dt} + 3Hn_{\chi} = -\left\langle \sigma v_{rel} \right\rangle \left( n_{\chi}^2 - n_{\chi}^{(eq)2} \right) \qquad \begin{array}{l} n_{\chi}/T^3 \sim \exp(-m_{\chi}/T) \\ \rightarrow \text{freeze-out:} n_{\chi} \left\langle \sigma v_{rel} \right\rangle \sim H \\ n_{\chi}/T^3 \equiv \text{const.} \end{array}$$

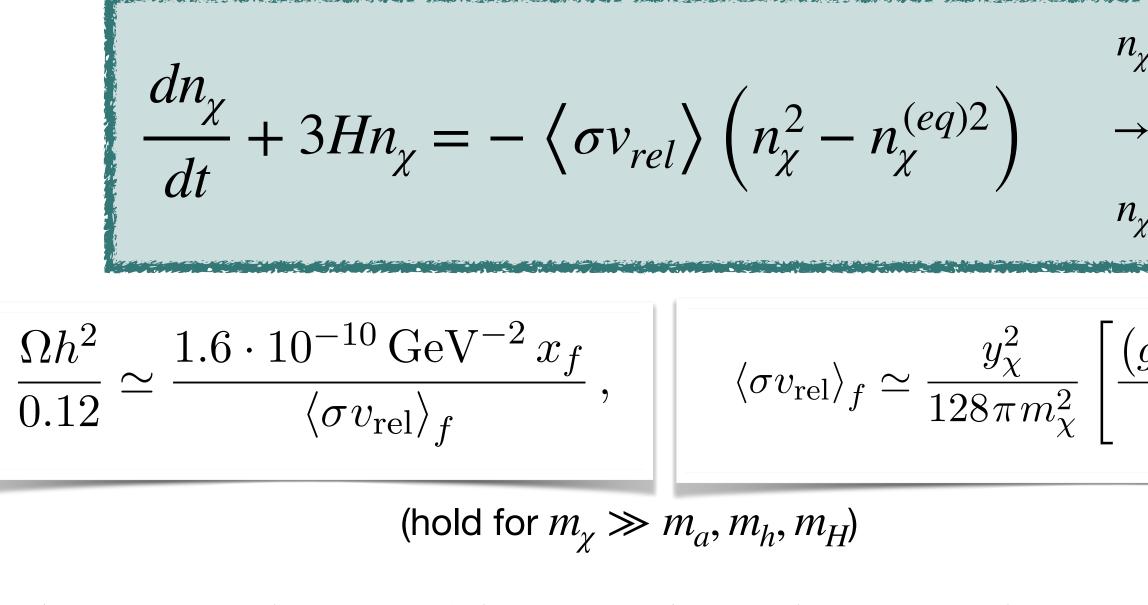
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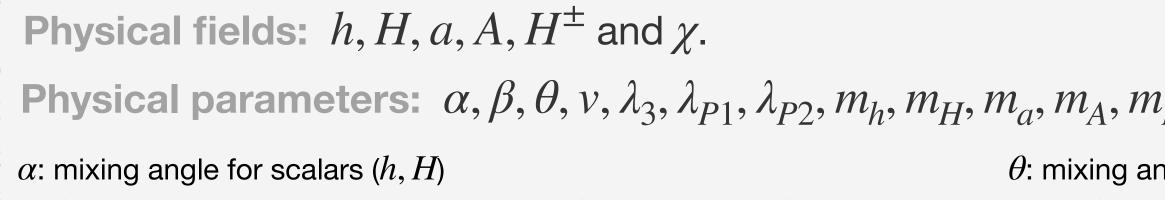
$$n_{H^{\pm \bullet}}$$
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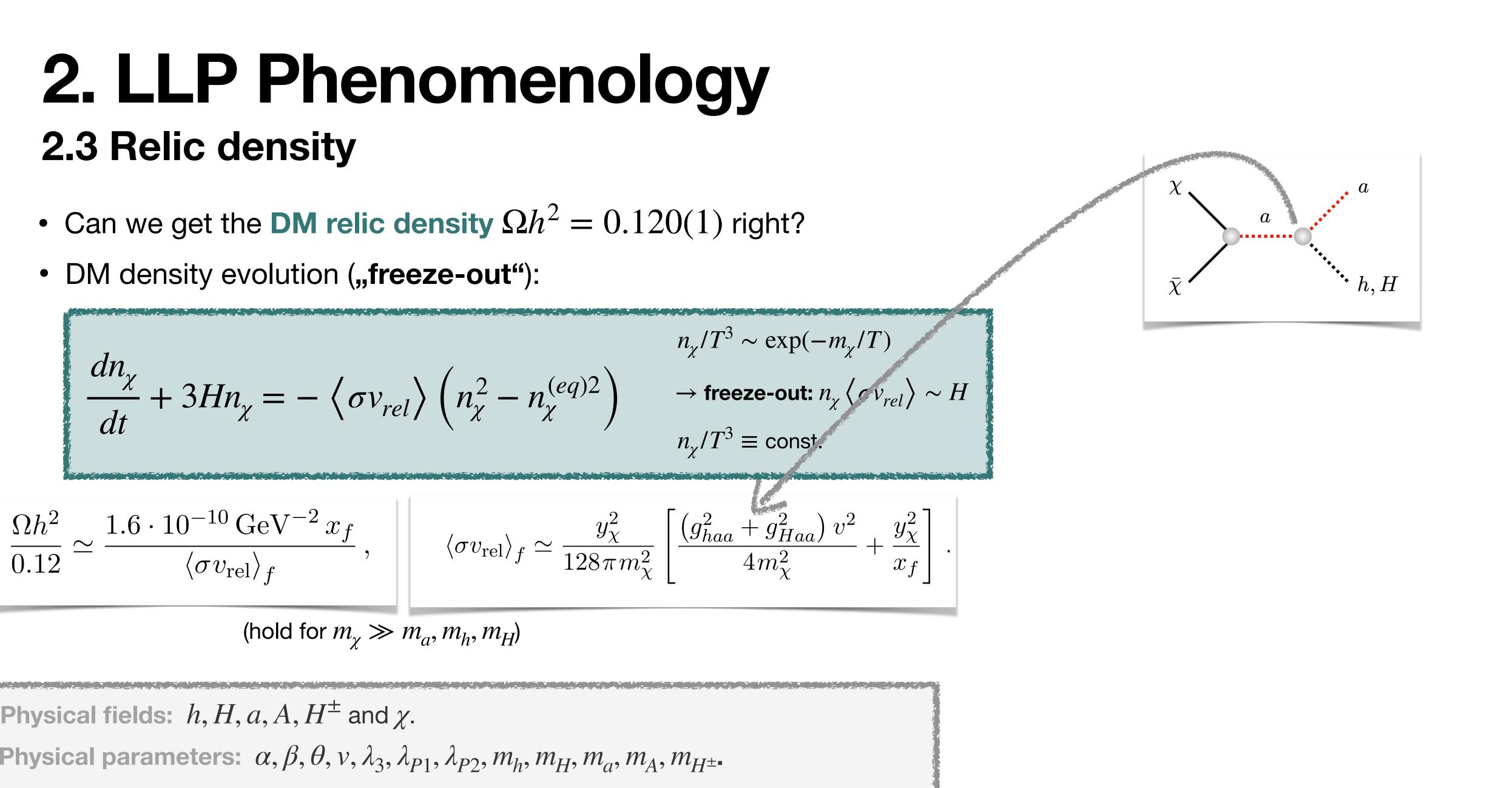


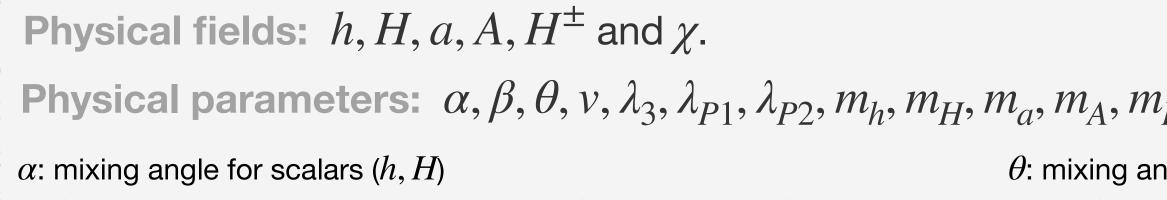
$$f_{\chi}/T^3 \sim \exp(-m_{\chi}/T)$$
  
 $\Rightarrow$  freeze-out:  $n_{\chi} \langle \sigma v_{rel} \rangle \sim H$   
 $f_{\chi}/T^3 \equiv \text{const.}$ 

$$\frac{\left(g_{haa}^2 + g_{Haa}^2\right)v^2}{4m_{\chi}^2} + \frac{y_{\chi}^2}{x_f}\right]$$

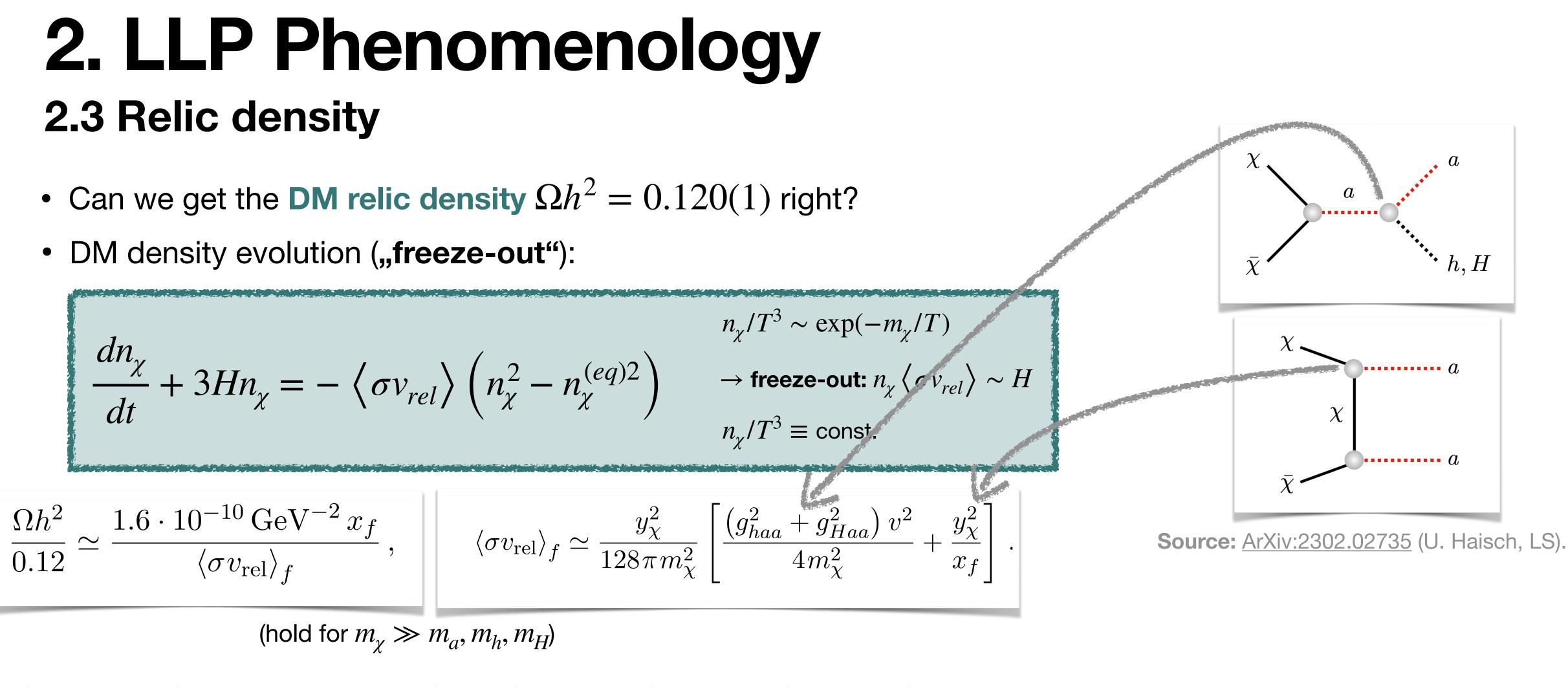
$$p_{H^{\pm \bullet}}$$
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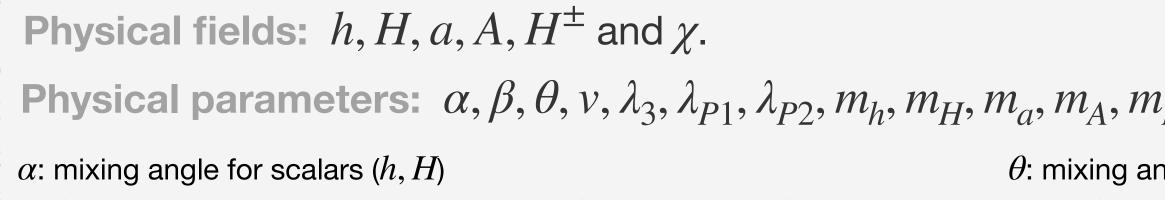






 $\theta$ : mixing angle for pseudo-scalars (a, A)





$$m_a, m_A, m_{H^{\pm ullet}}$$
 $heta$ : mixing angle for pseudo-scalars ( $a, A$ 





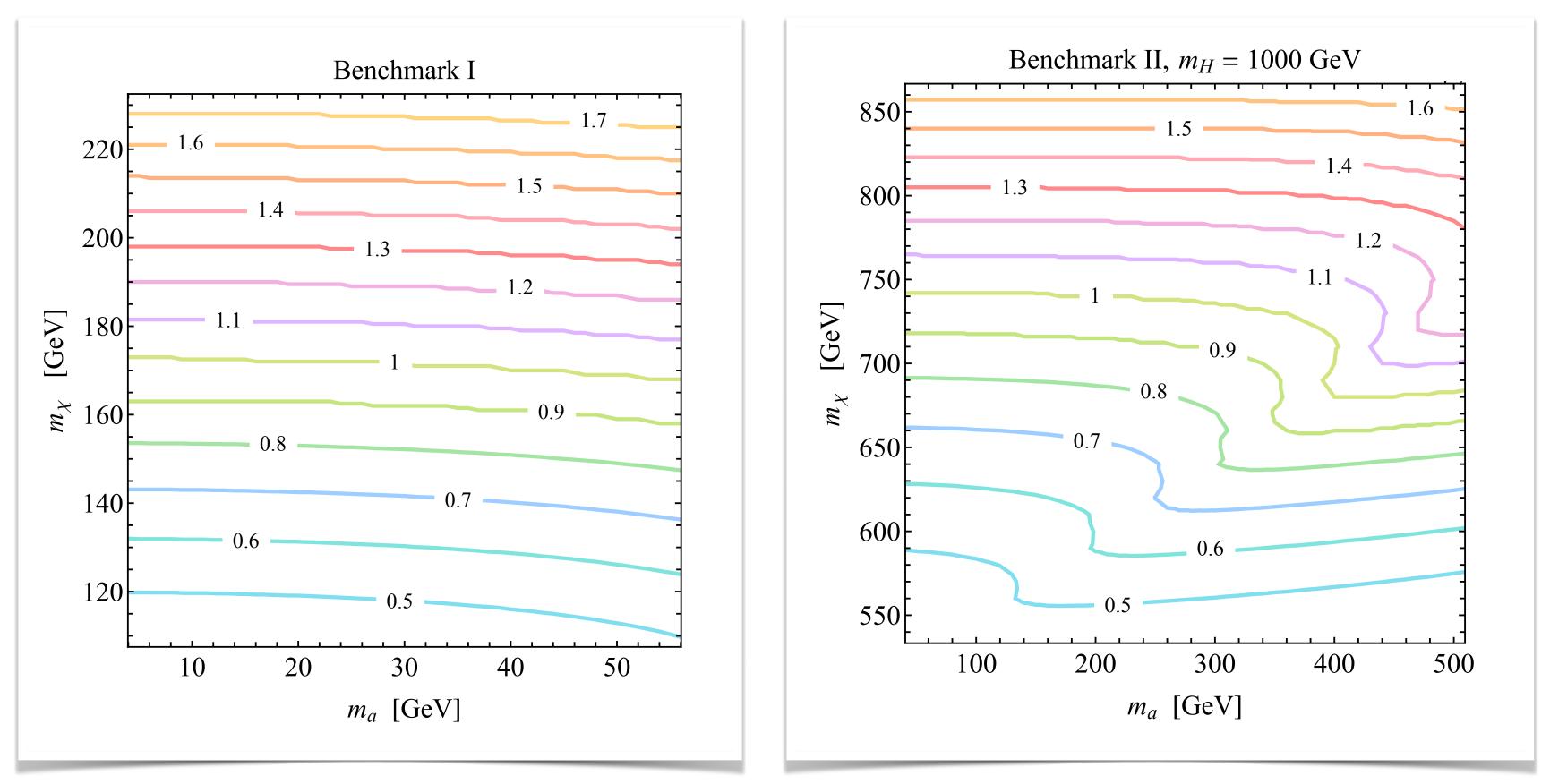
# 2.3 Relic density

Sources: <u>ArXiv:1505.04190</u> (M. Backovic, A. Martini), <u>ArXiv:2302.02735</u> (U. Haisch, LS).

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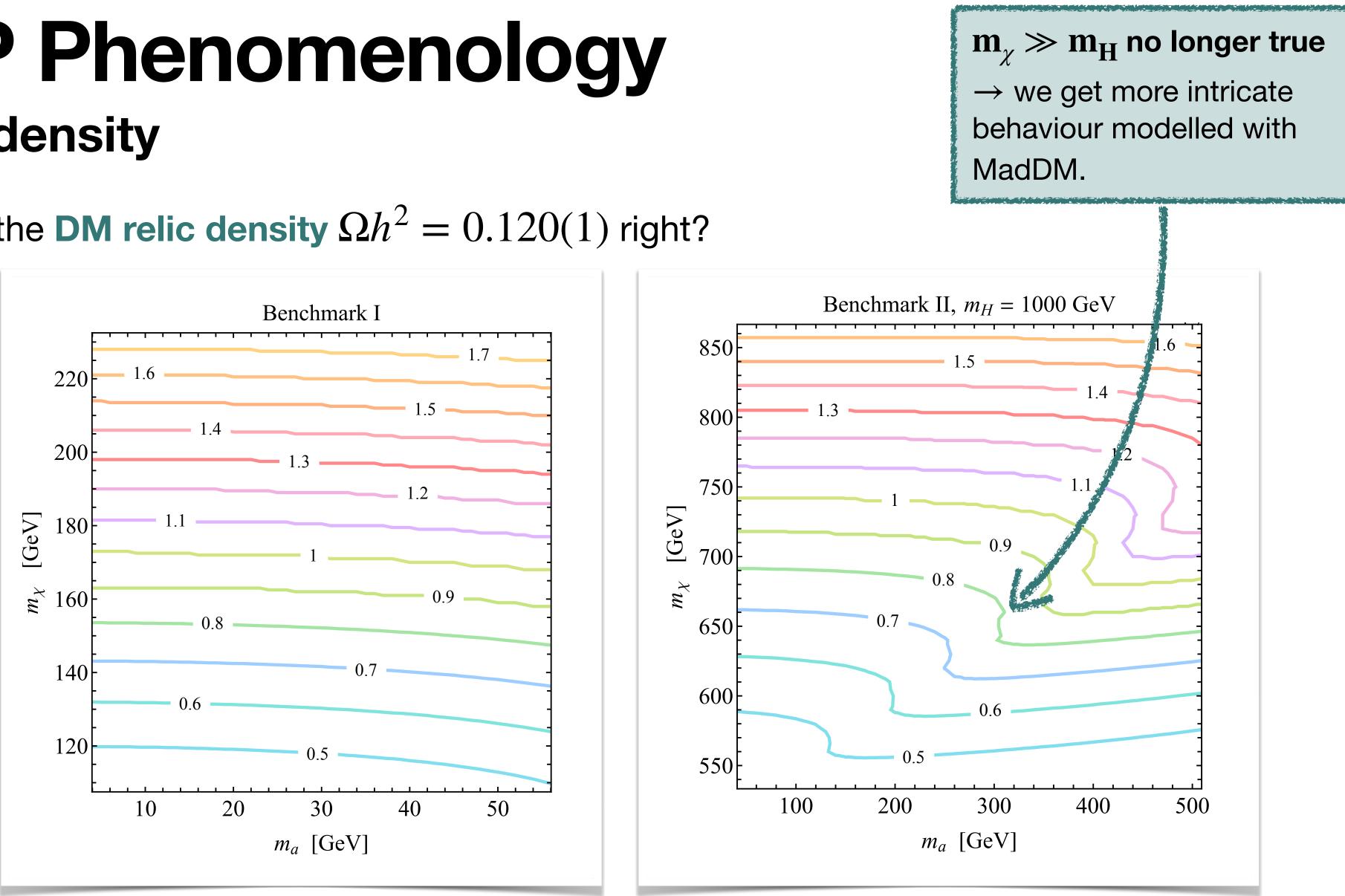
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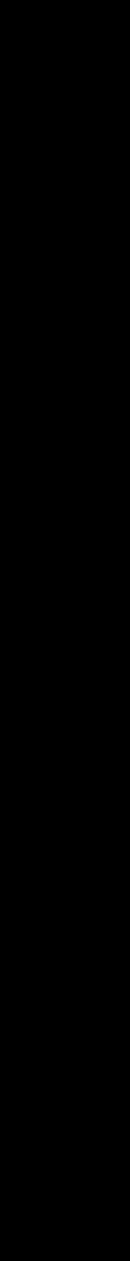


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This leads to an interesting collider phenomenology  $\rightarrow$  important benchmark.



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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  $\theta$ .
  - Interesting LLP signatures that can be probed for at colliders.
  - This scenario is compatible with current relic density measurements.



### Thank you for your attention!