# Inelastic Dark Matter and a Dark Higgs

**Camilo A. Garcia Cely**

Alexander von Humboldt Fellow

DESY.

Long-lived particles at Belle II
Online workshop

December 10, 2020

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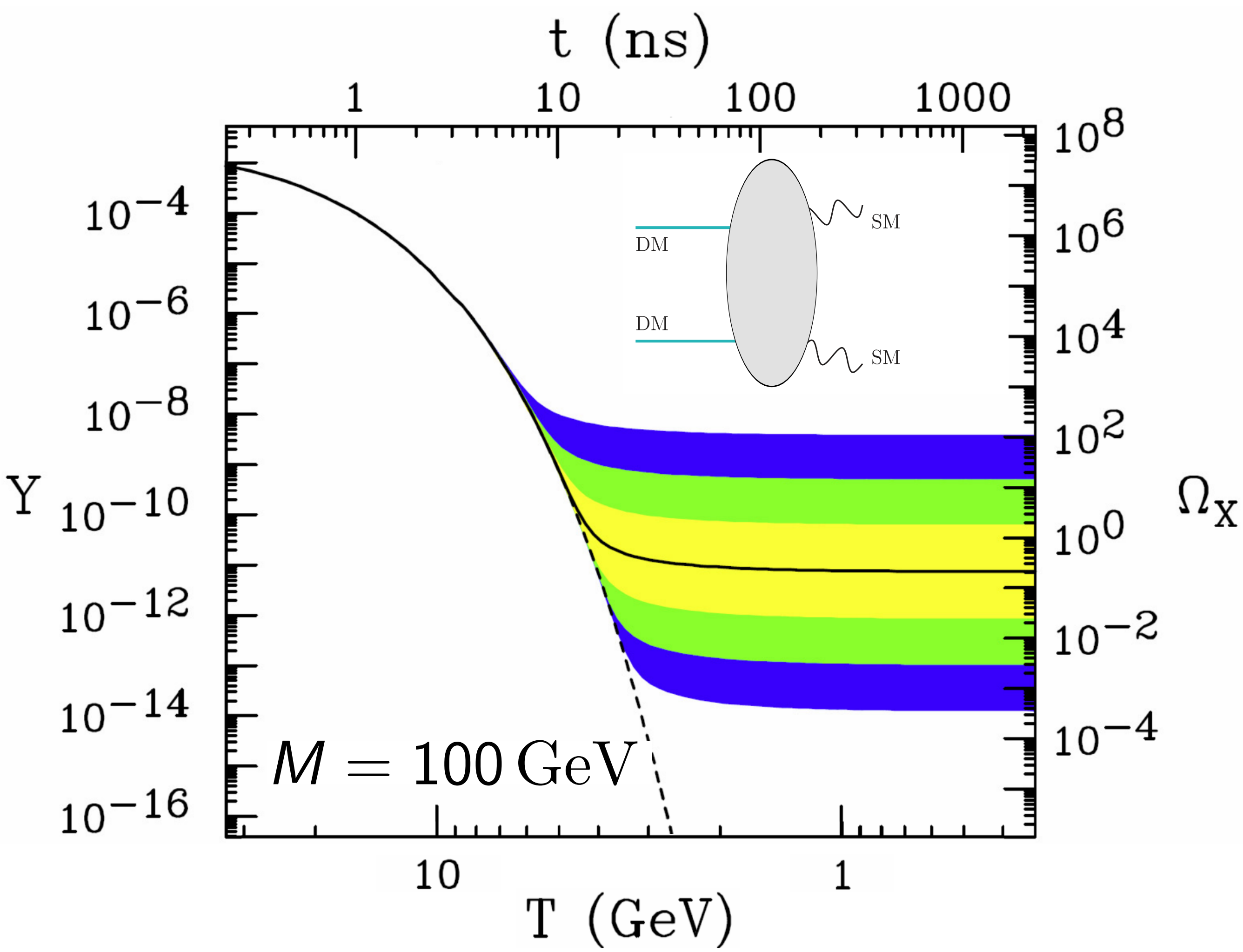
Preliminary

Duerr, Ferber, Garcia-Cely, Hearty, Schmidt-Hoberg

# Thermal Dark Matter Paradigm

Zel'dovich (1966)
Lee Weinberg (1977)
Dicus, Kolb, Teplitz (1977)




Feng et al. (2010)

Thermal dark matter is a well motivated and predictive scenario which can be probed with direct and indirect searches as well as with collider experiments

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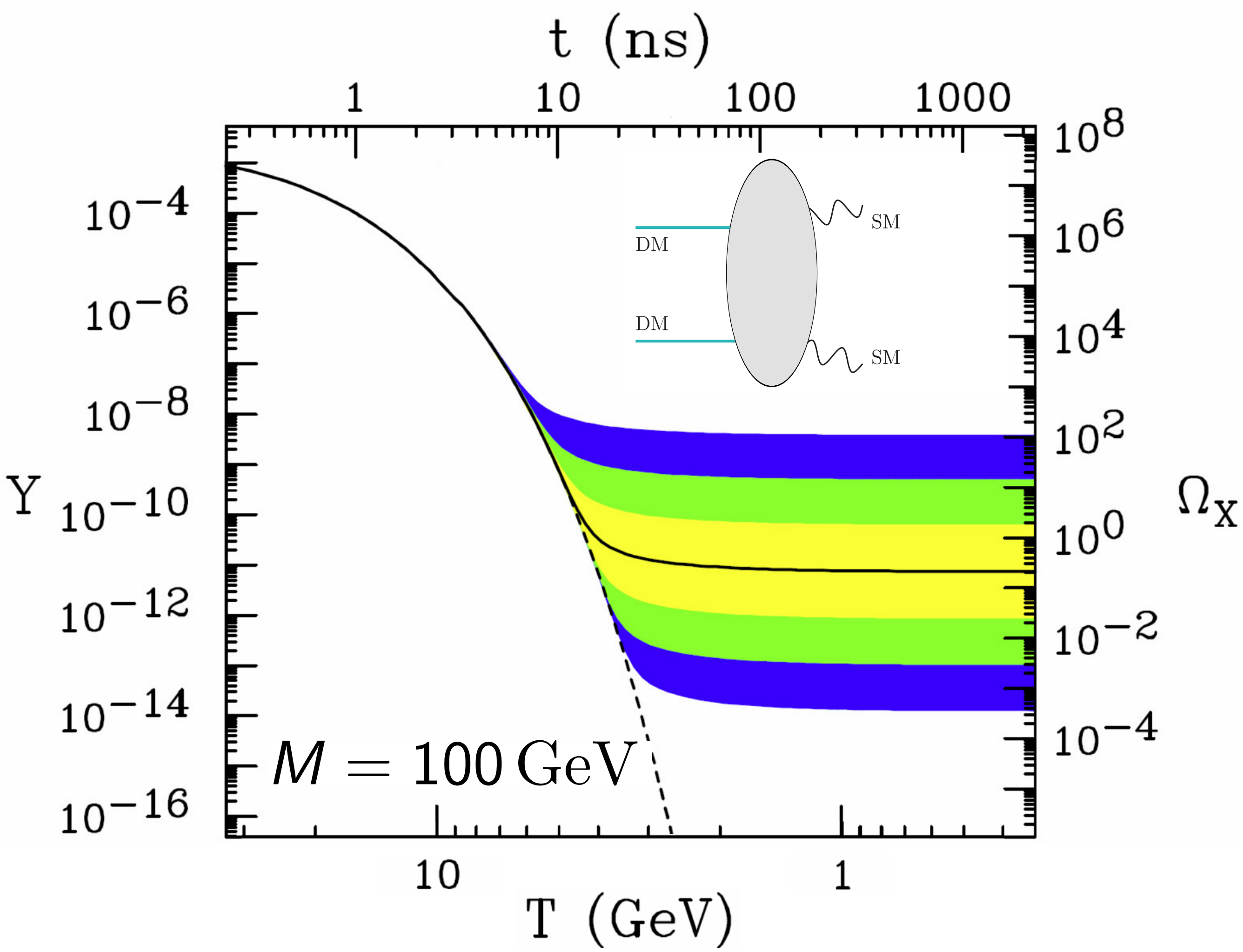



Feng et al. (2010)

$\sigma v \sim 10^{-26}\mathrm{cm}^3/s$

$\sigma \sim 1\mathrm{pb}$

$m$ from subGeV to $100$TeV

Griest and Kamionkowski (1990).

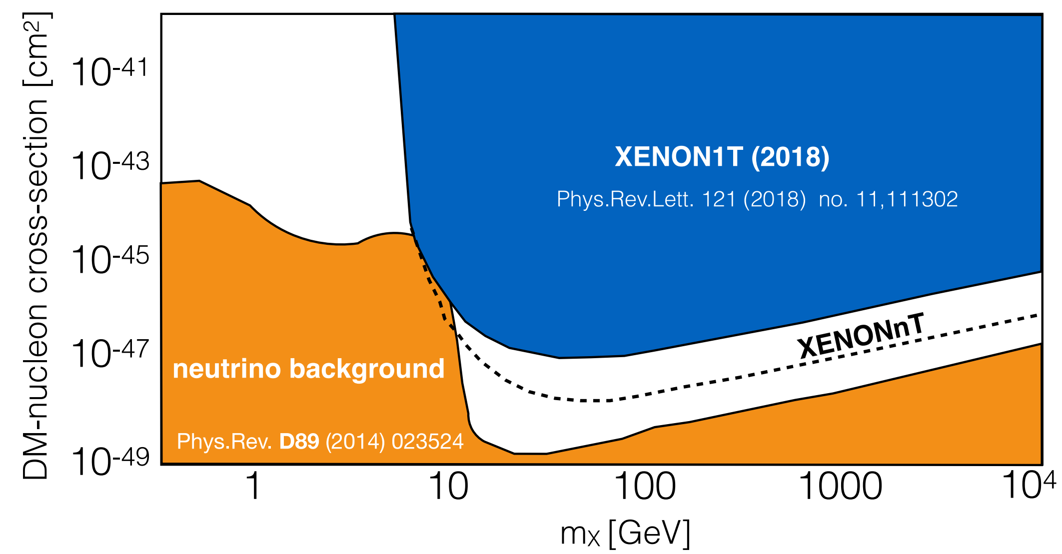
Thermal dark matter is a well motivated and predictive scenario which can be probed with direct and indirect searches as well as with collider experiments

# Thermal Dark Matter Paradigm

## Direct searches

Light dark matter does not have enough momentum to kick heavy nuclei

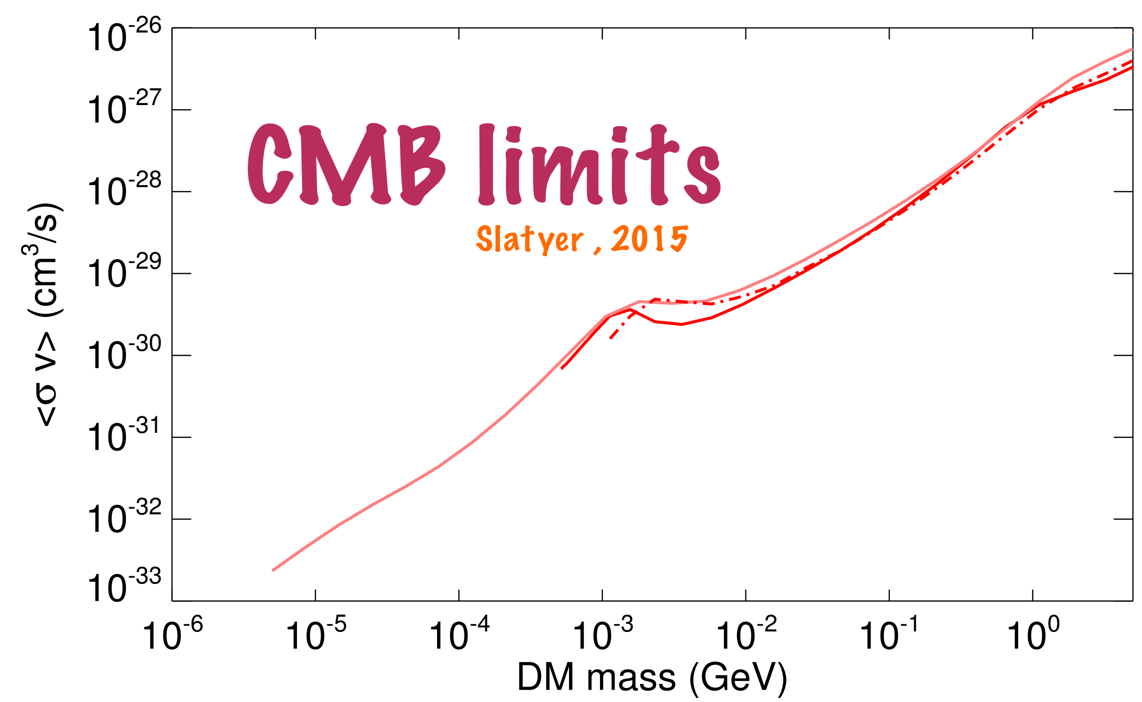
Loss of sensitivity mass for SubGeV masses.




Borrowed from Tien-Tien Yu

## Indirect searches

S-wave thermal cross sections are excluded by CMB observations



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# Inelastic Dark Matter

A simple scenario for light thermal dark matter which evades the strong CMB bounds is the case where DM couples inelastically to Standard Model.

Here a sufficiently large mass splitting between the DM particle $\chi 1$ and its heavier twin $\chi 2$ ensures that:

(i) direct detection limits are basically absent Smith, Weiner (2001)

(ii) residual DM annihilations are no longer efficient during the time of the CMB.



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start with $\psi$ a Dirac fermion charged under a $U(1)$ symmetry .

After $U(1)$ symmetry breaking

$$\chi_1 = \frac{\psi - \psi^c}{\sqrt{2}}\,, \qquad \text{and} \qquad \chi_2 = \frac{\psi + \psi^c}{\sqrt{2}}\,.$$

# Portals to the Standard Model

Wilczek (2006)

| | |
|---|---|
| $B_{\mu\nu} V_{\mu\nu}$ | "Kinetic mixing" with additional U(1)' group |
| $H^{+}H\,(\lambda\, S^2 + A\, S)$ | Higgs-singlet scalar interactions (scalar portal) |
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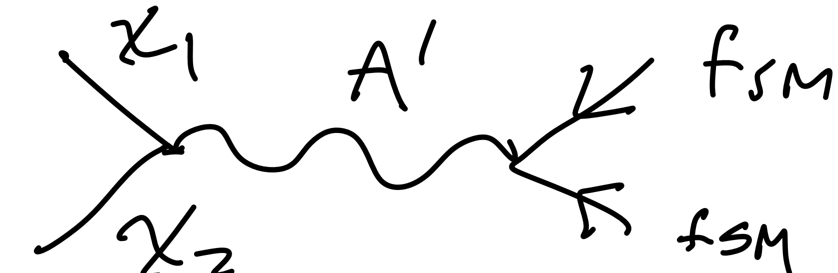
$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} - \frac{\epsilon}{2c_{\rm W}}\hat{X}_{\mu\nu}\hat{B}^{\mu\nu}$$

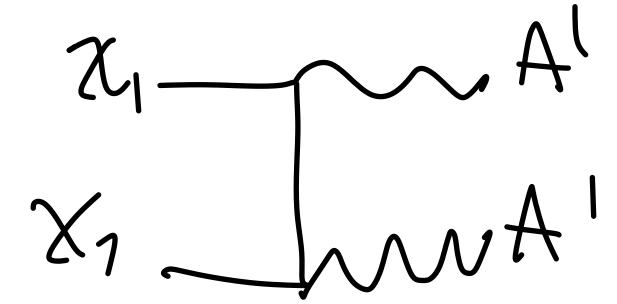



A' inherits the coupling structure of the photon to the SM fermions where the electric charge is multiplied by a common factor ε.

# Inelastic Dark Matter




Thermal process



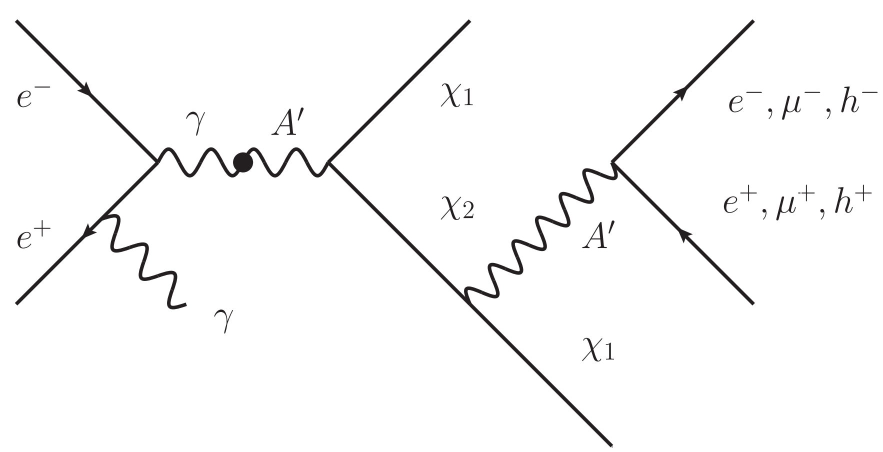

Take $m_{A'} > m_{\chi_1}$ to avoid CMB constraints

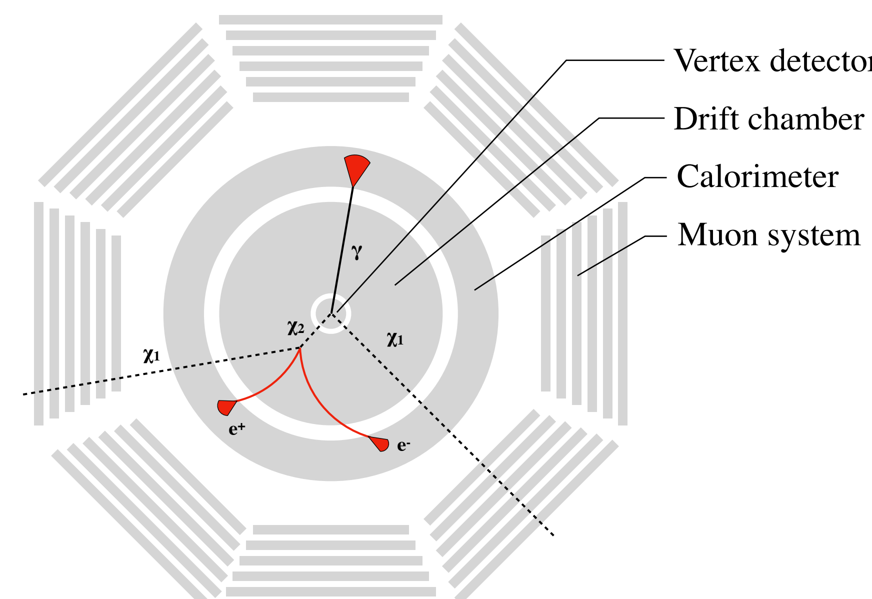
## Collider signatures

Izaguirre, Krnjaic, Shuve (2016)
Izaguirre, Kahn, Krnjaic, Moschella (2017)

## displaced vertices

Duerr, Ferber, Hearty, Kahlhoefer, Schmidt-Hoberg (2019)



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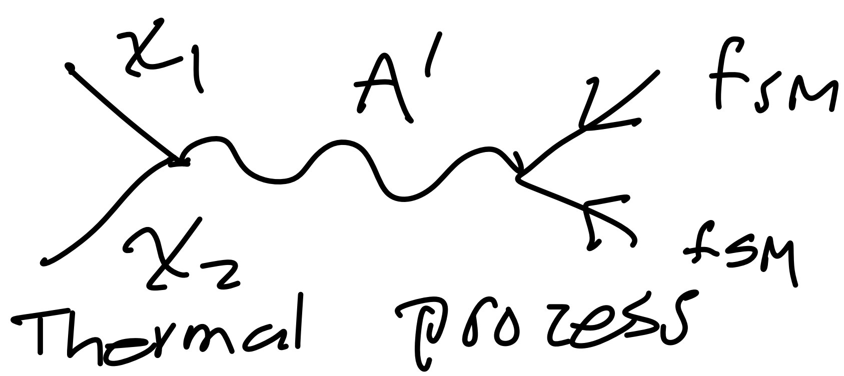


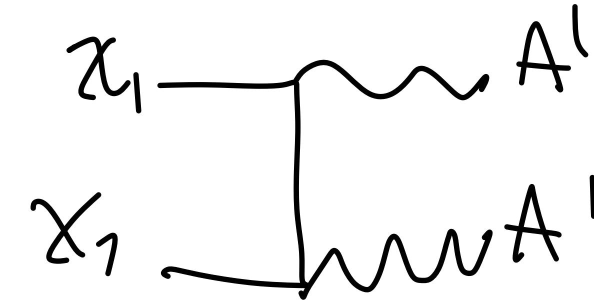


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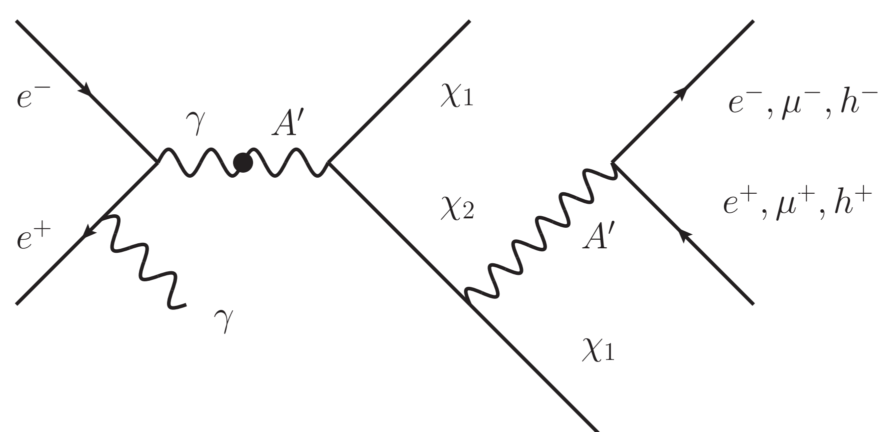


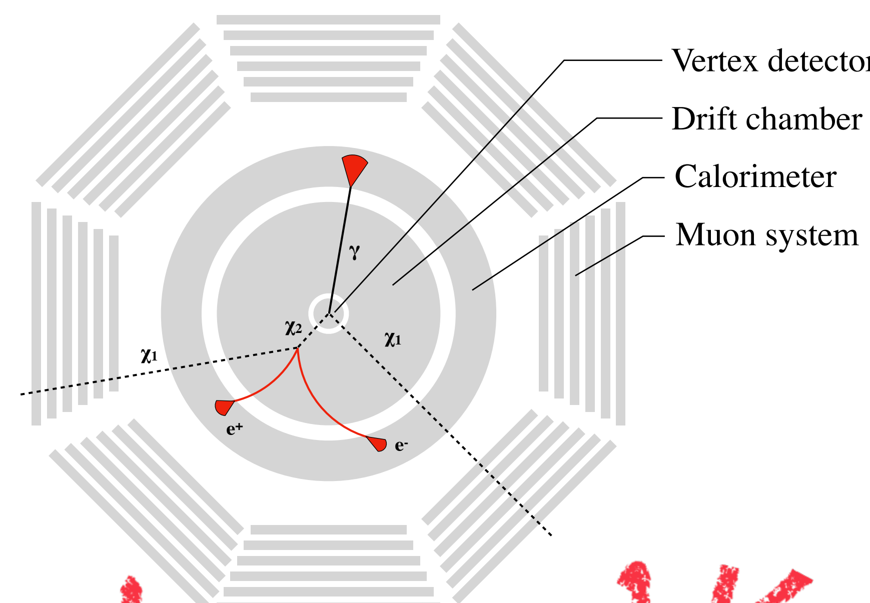


Saurnd's talk



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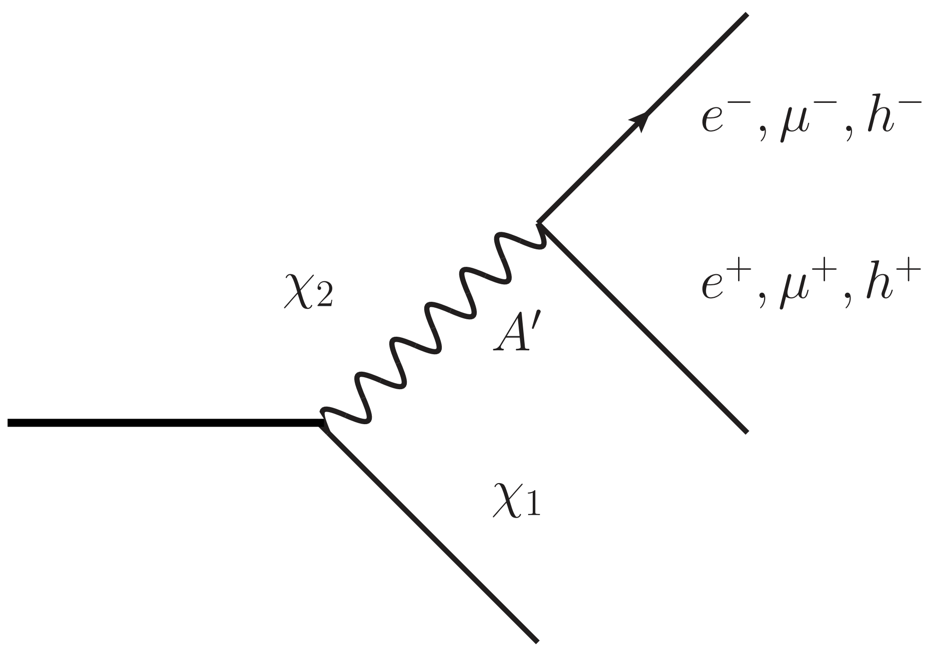
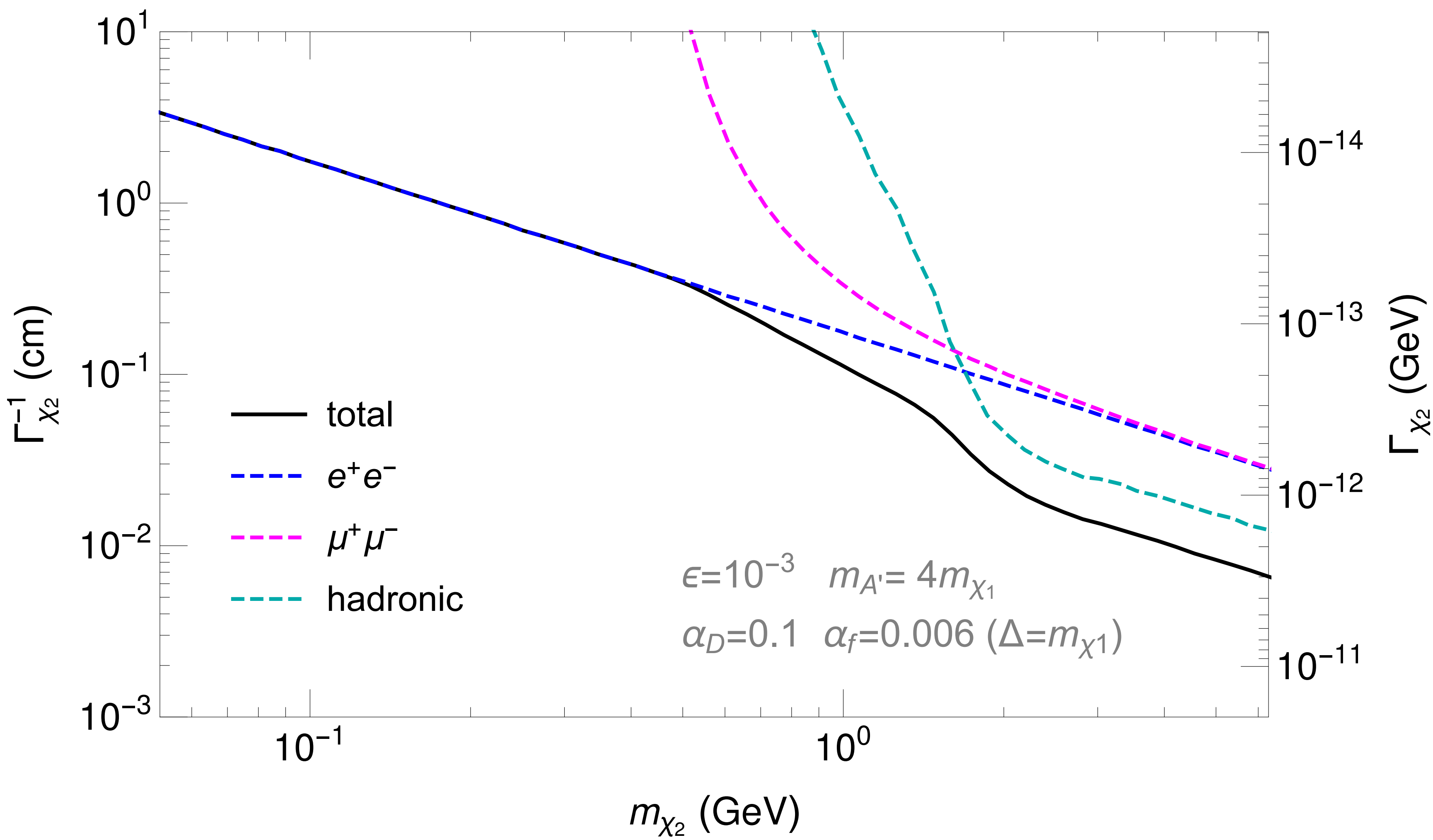
# Decay width

**Preliminary**

Duerr, Ferber, Garcia-Cely, Hearty, Schmidt-Hoberg



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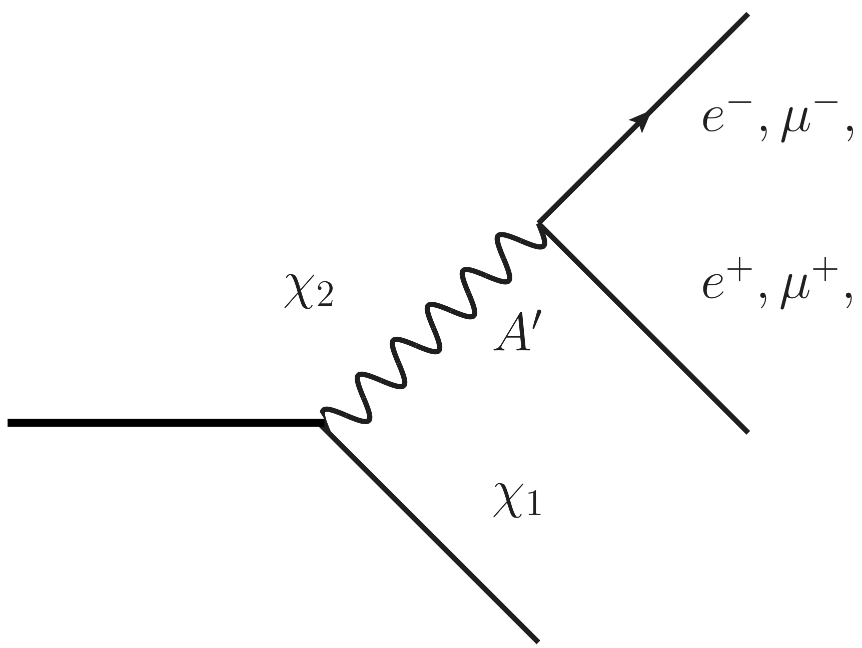


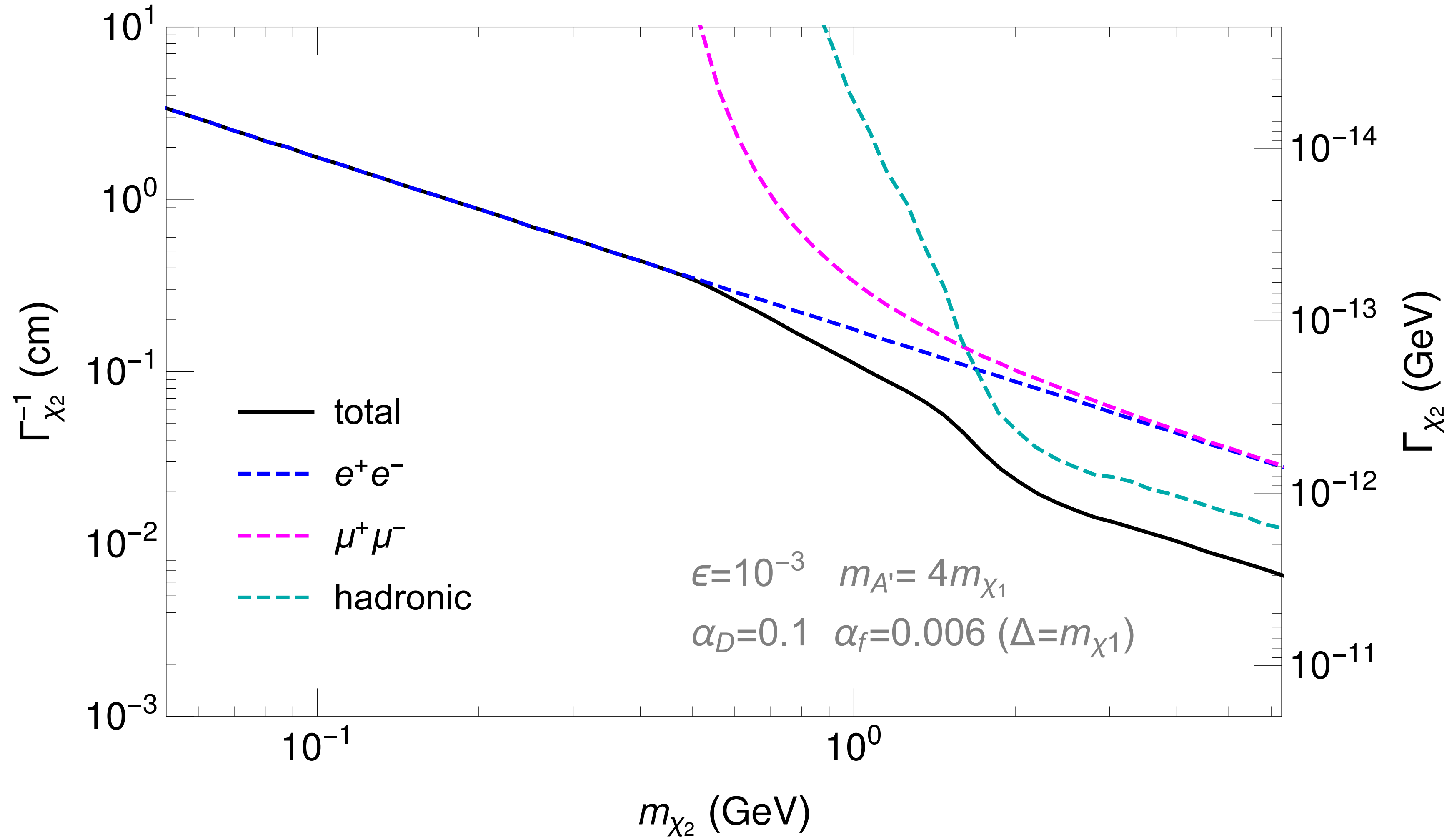


$$\Gamma_{\chi_2\to\chi_1 l^+l^-} = \alpha\alpha_D\epsilon^2\int_{4m_l^2}^{\Delta^2} ds \frac{|\vec{p}_{\chi_1}|(s-\Delta^2)\left(2s+(2m_{\chi_1}+\Delta)^2\right)(s+2m_l^2)(s-4m_l^2)^{1/2}}{6\pi m_{\chi_2}^2 s^{3/2}\left(s-m_{A'}^2\right)^2}$$

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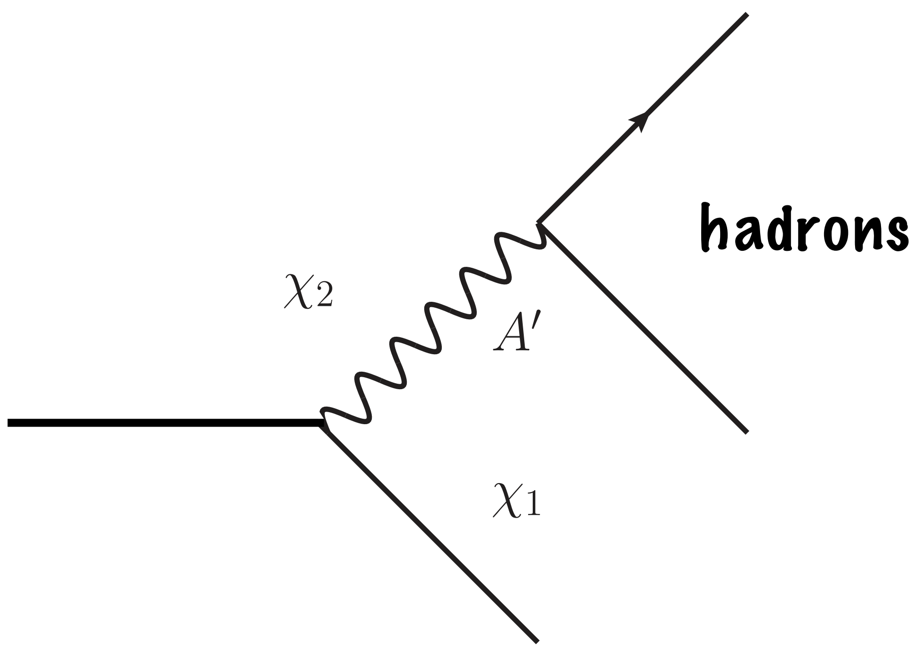


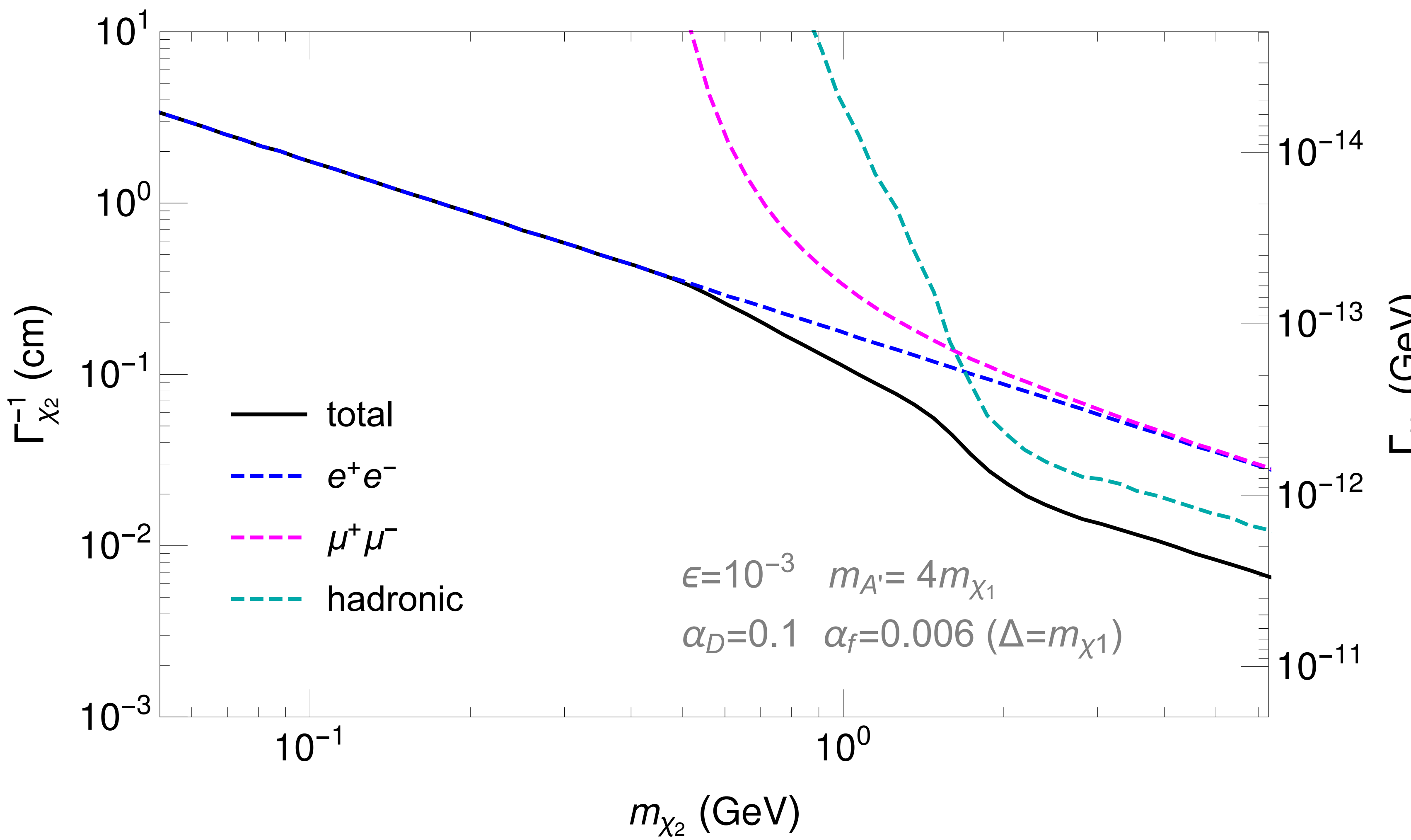


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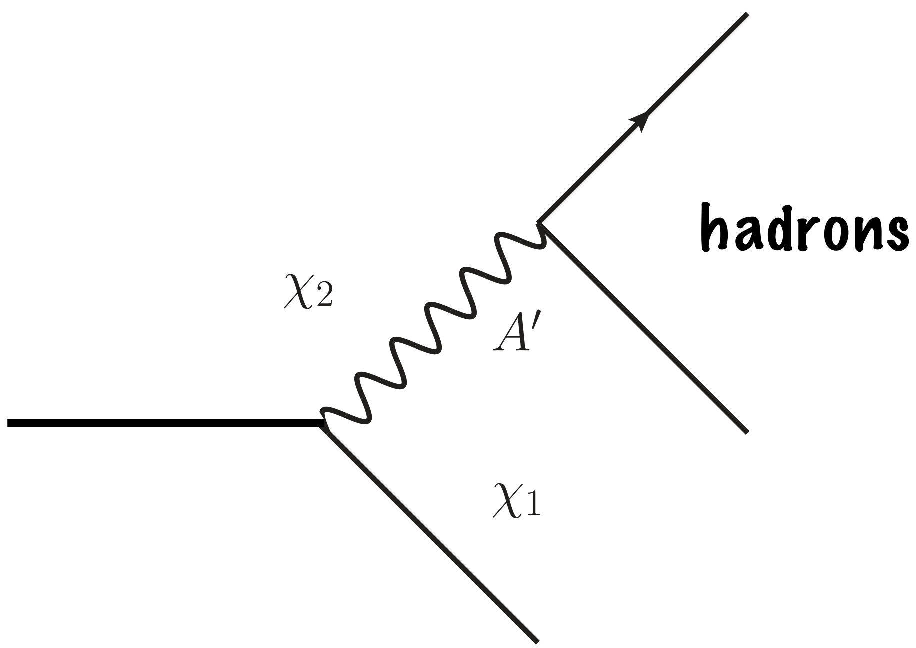
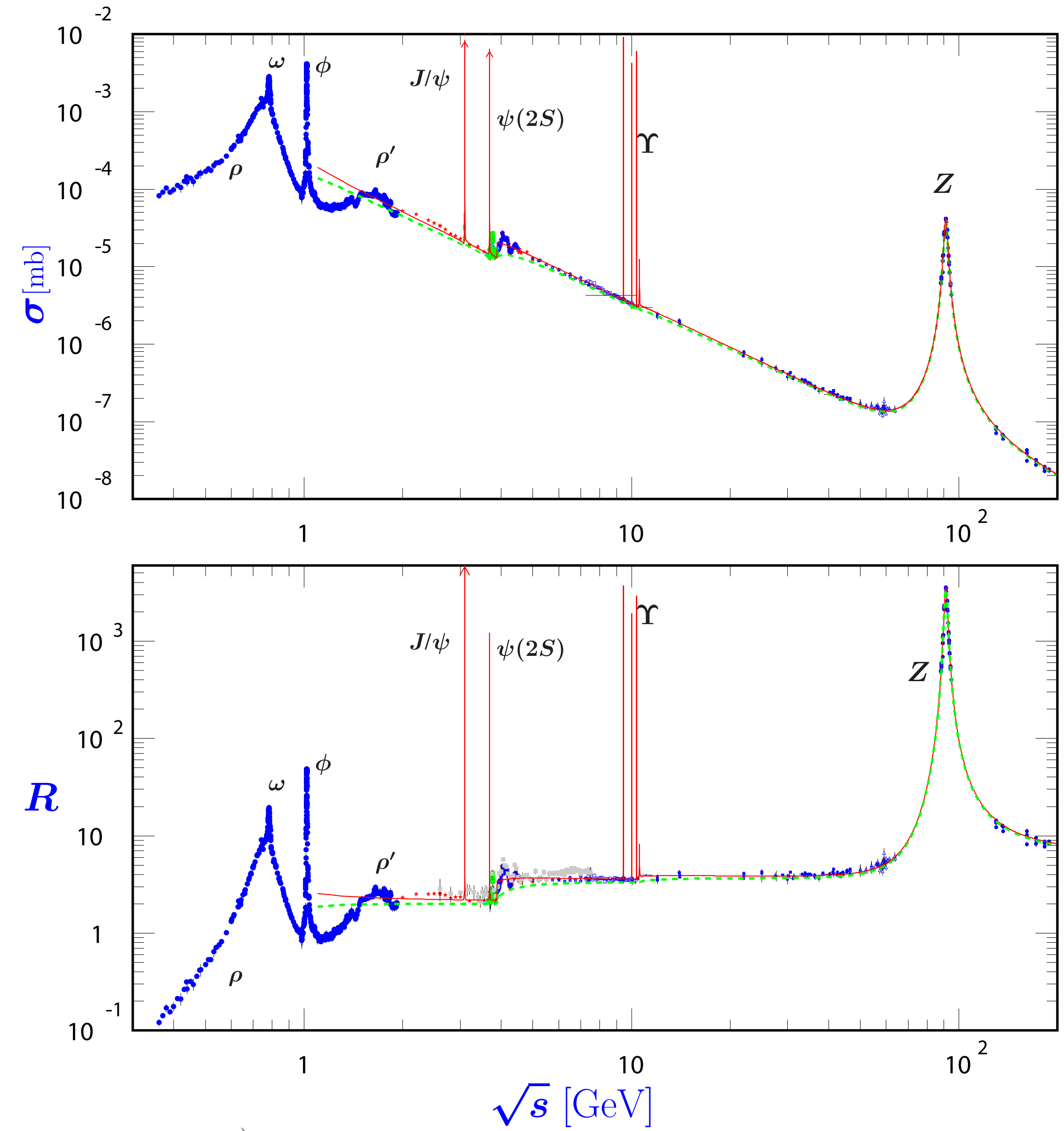
Duerr, Ferber, Garcia-Cely, Hearty, Schmidt-Hoberg




Particle Data Group

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# Open questions

This talk

Duerr, Ferber, Garcia-Cely, Hearty, Schmidt-Hoberg

Preliminary

What process generates the dark photon mass?

What induces the mass splitting $\Delta = m_{\chi_2} - m_{\chi_1}$?

Does it affect the phenomenology?

Invoke the dark Higgs mechanism:

$$V(\phi, H) = \lambda_H \left(H^\dagger H - \frac{v_H^2}{2}\right)^2 + \lambda_\phi \left(\phi^* \phi - \frac{v_\phi^2}{2}\right)^2 + \lambda_{\phi H} \left(H^\dagger H - \frac{v_H^2}{2}\right)\left(\phi^* \phi - \frac{v_\phi^2}{2}\right)$$

$$\phi = \frac{v_\phi + \hat{h}'}{\sqrt{2}}, \qquad H = \left(0 \;\; (v_H + \hat{h})/\sqrt{2}\right)^T$$

$\phi$ has two units of charge

# Portals to the Standard Model

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## two portal model

$$\mathcal{L}_\psi = \frac{1}{2}\left(i\overline{\chi_1}\partial\!\!\!/\chi_1 + i\overline{\chi_2}\partial\!\!\!/\chi_2 - m_{\chi_1}\overline{\chi_1}\chi_1 - m_{\chi_2}\overline{\chi_2}\chi_2\right) + \frac{i}{2} g_X \hat{X}_\mu (\overline{\chi_2}\gamma^\mu\chi_1 - \overline{\chi_1}\gamma^\mu\chi_2) + \frac{f}{2}\hat{h}'(\overline{\chi_1}\chi_1 - \overline{\chi_2}\chi_2)\,,$$

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scalar mixing angle

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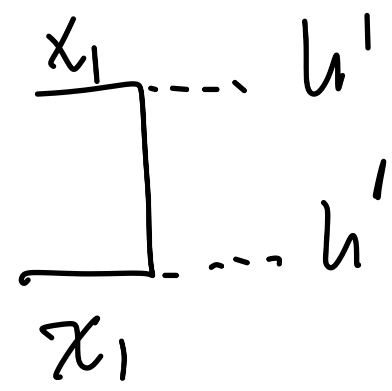
Inelastic interactions  Elastic interactions

# Inelastic Dark Matter and a Dark Higgs

Relic density via thermal processes




p-wave



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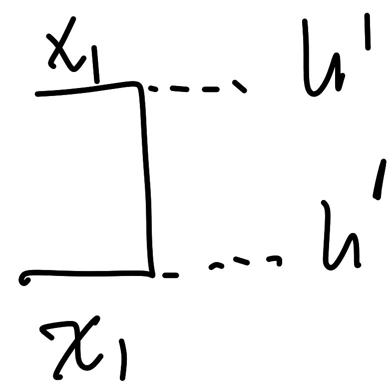


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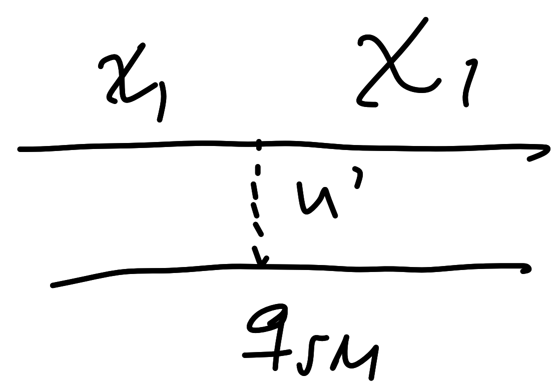
Elastic Scattering

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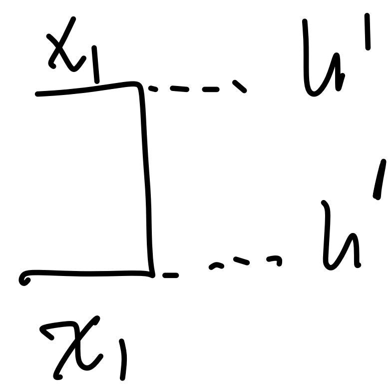


p-wave

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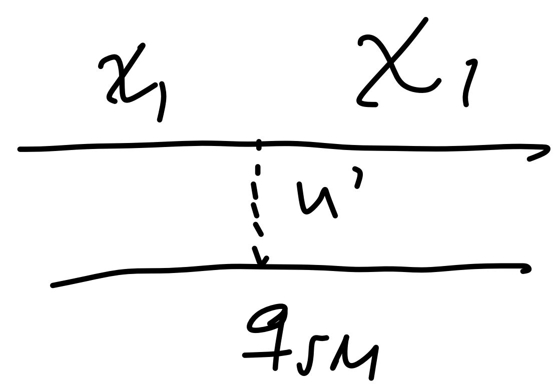


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More parameter space

Rich phenomenology



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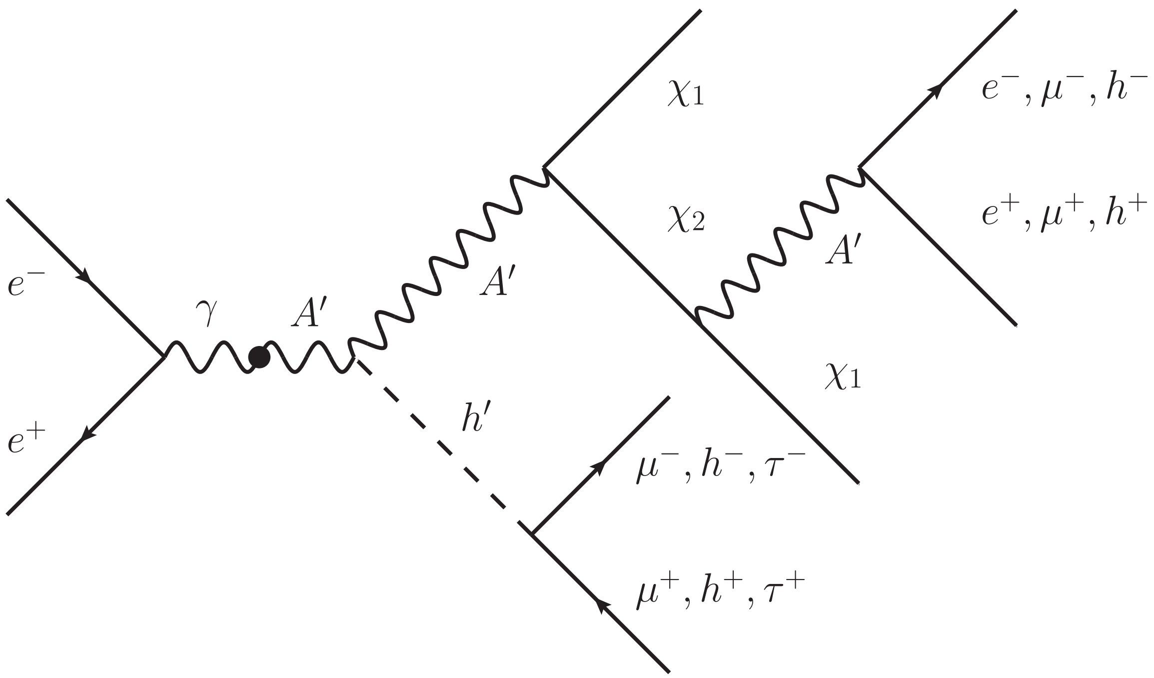
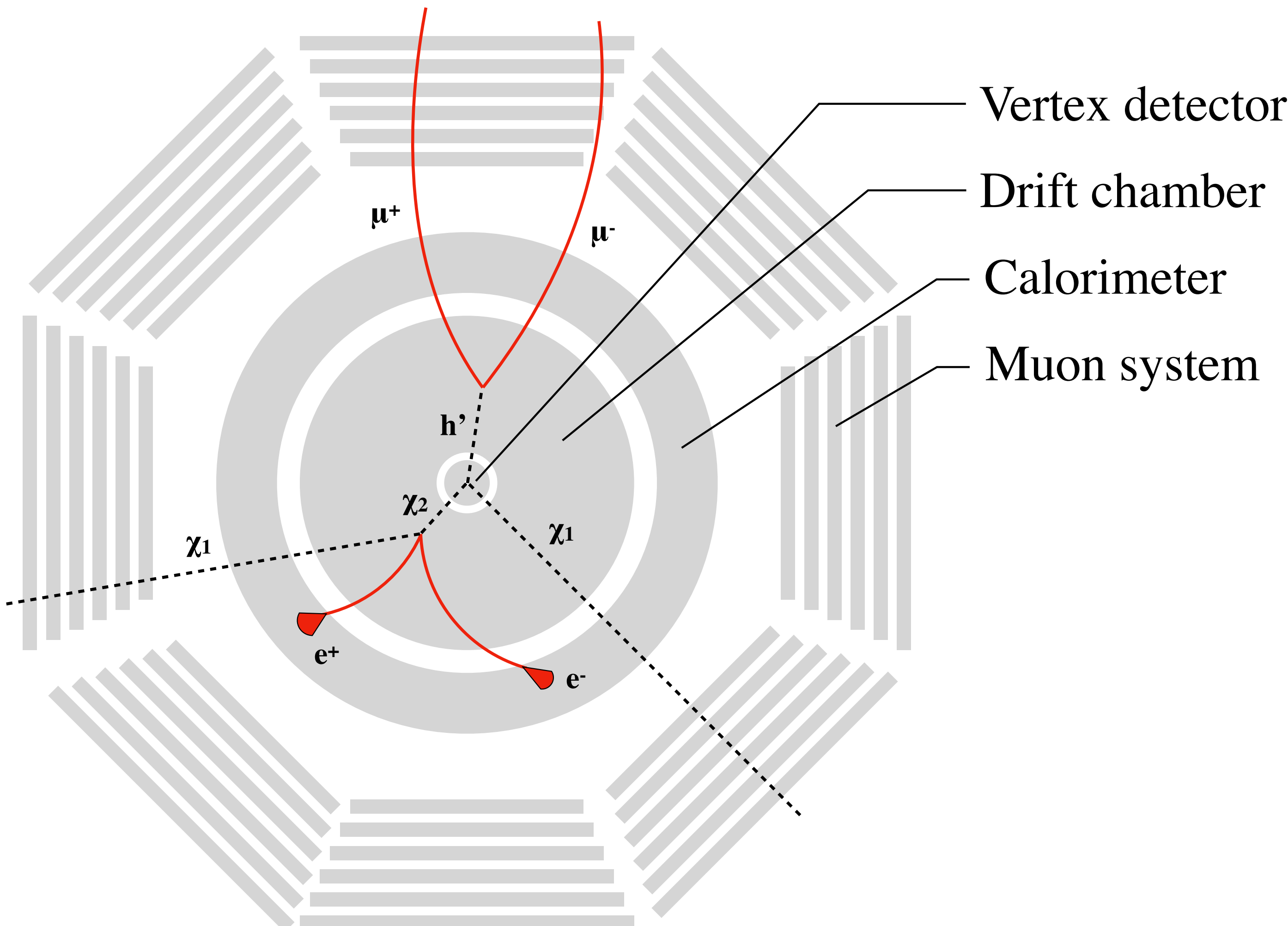
# Displaced Vertices involving the Higgs

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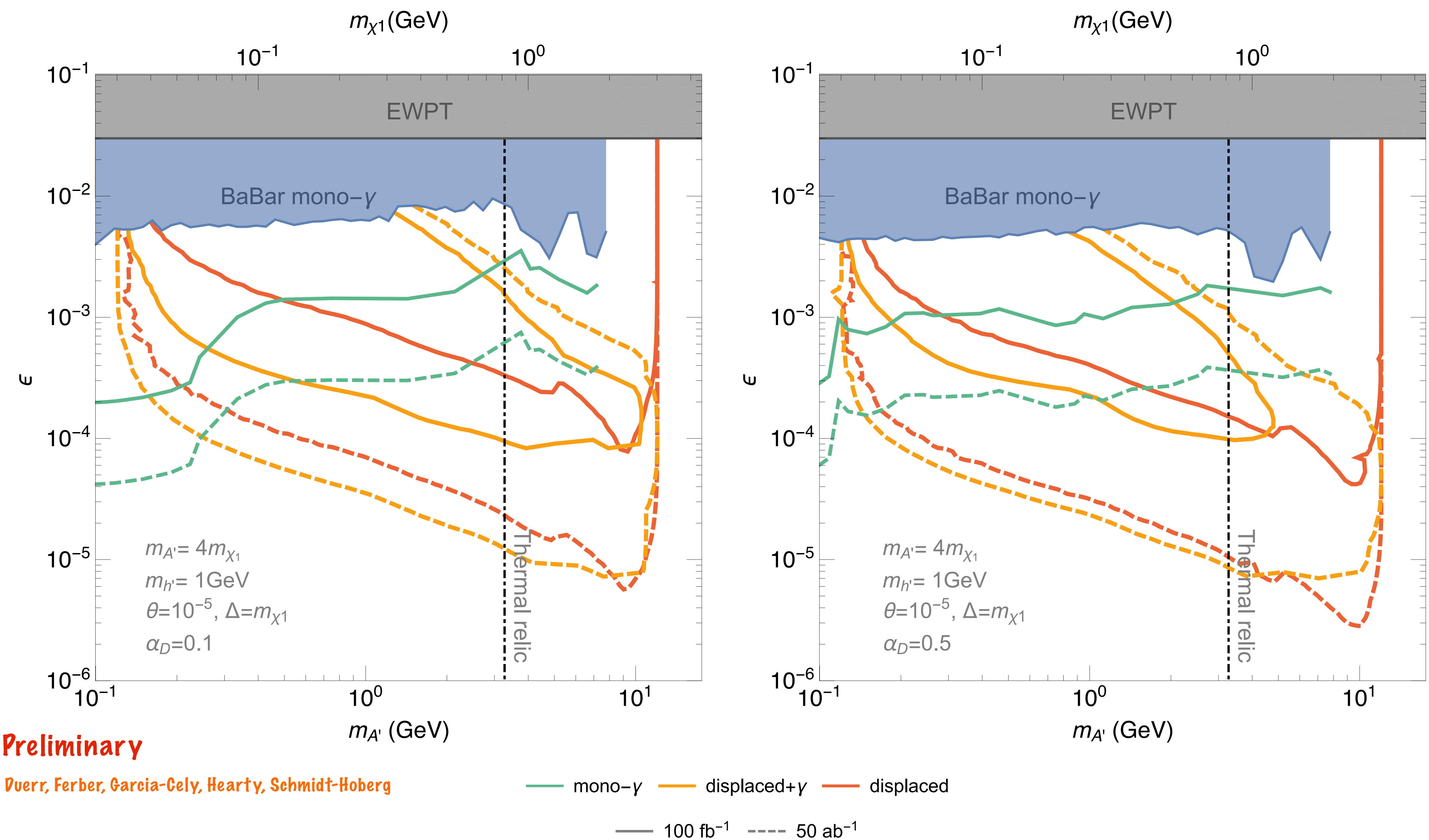
# Dark Photon Plane

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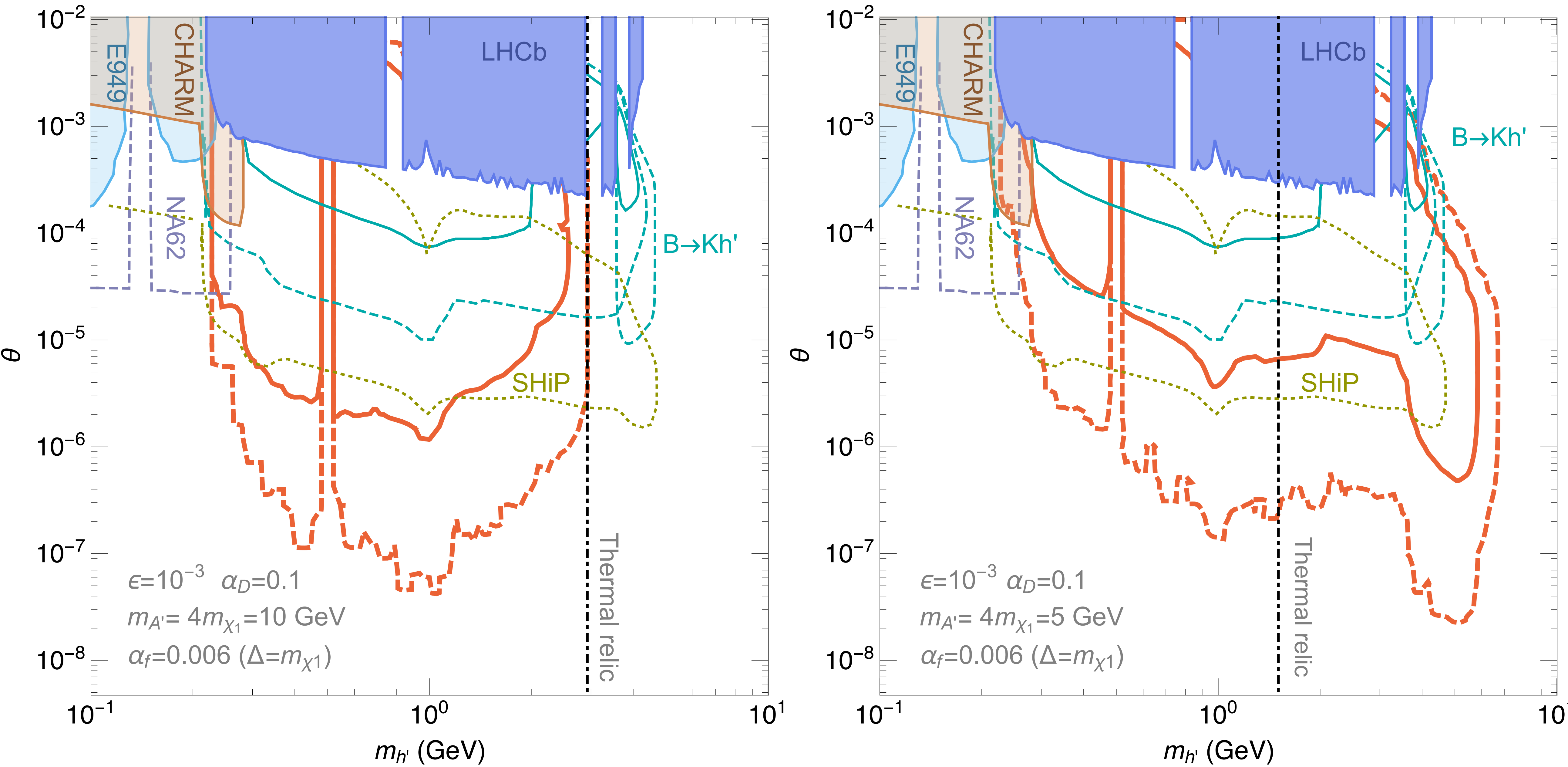


**Preliminary**

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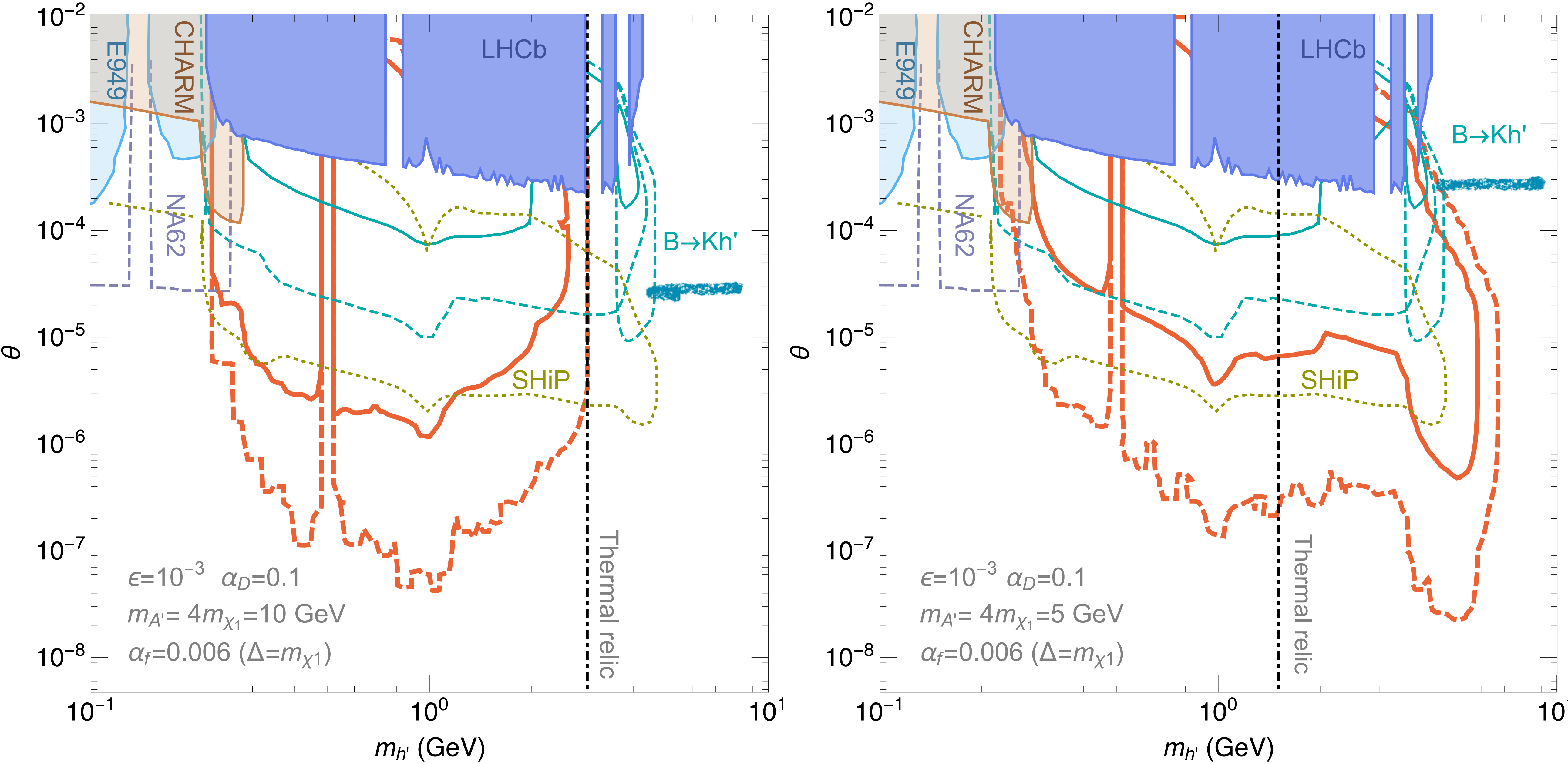
# Dark Higgs Plane

Anastasio's talk

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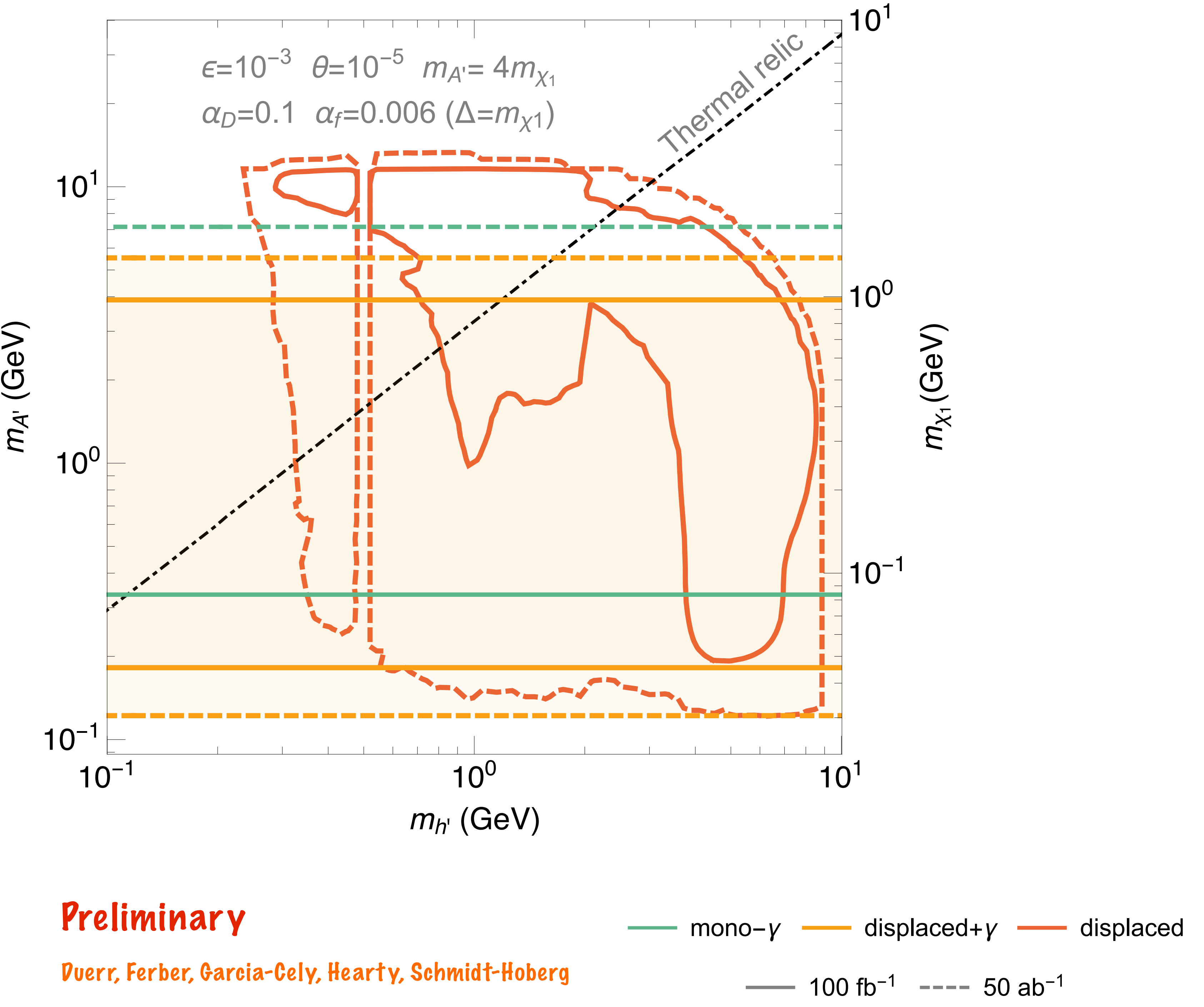


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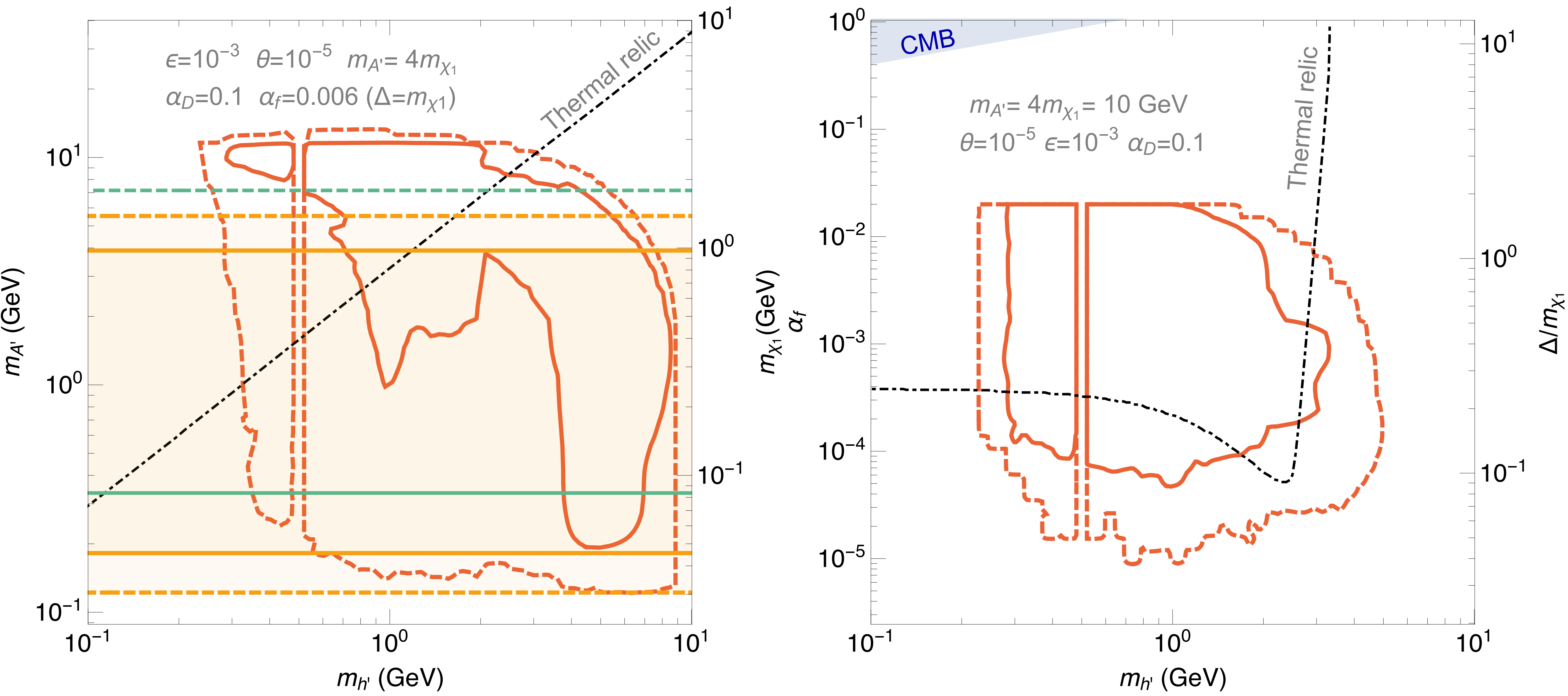


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mono−$\gamma$ displaced+$\gamma$ displaced

100 $fb^{-1}$ 50 $ab^{-1}$

# Conclusions

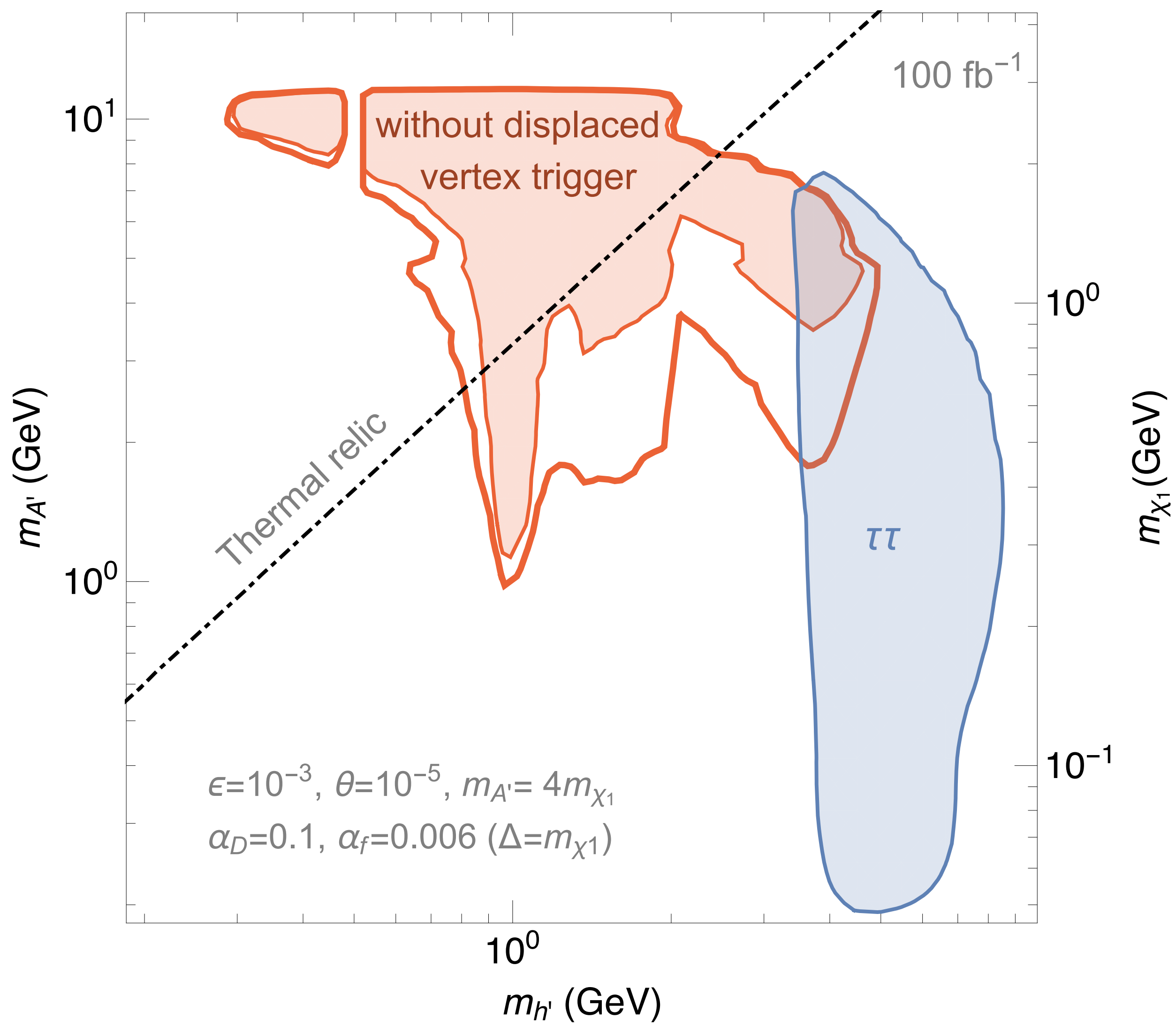
Inelastic DM is a well-motivated thermal DM candidate at the subGeV scale, in which a mass splitting between dark matter and its excited state allows to evade stringent CMB bounds and direct detection limits.

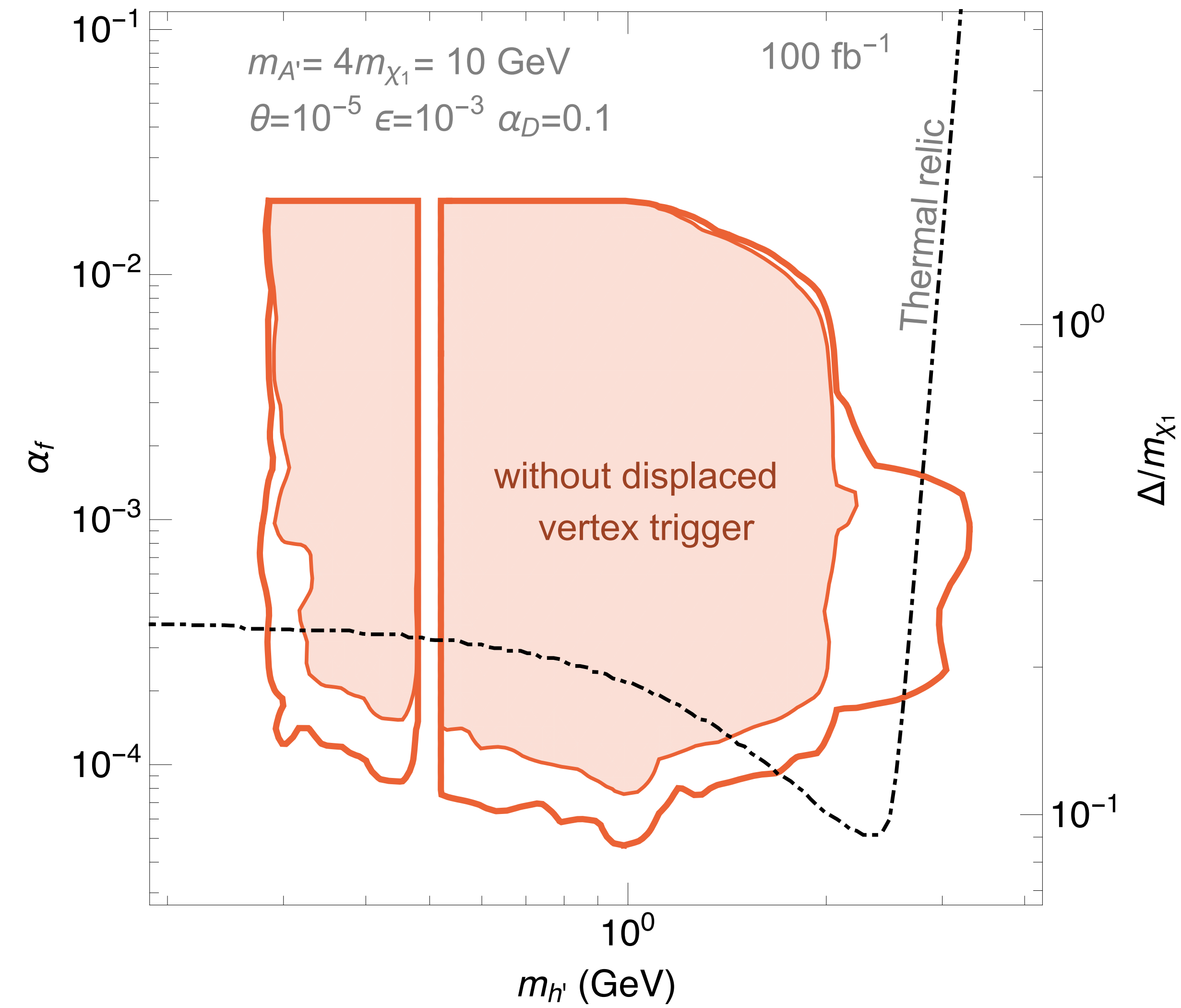
I discussed the phenomenological impact of including a dark Higgs to generate the mass splitting and the dark photon mass.

I have investigated the sensitivity of Belle II for the key signature of this model: a lepton pair originating from a displaced vertex in association with a single photon as well as with a dark Higgs.

Preliminary Duerr, Ferber, Garcia-Cely, Hearty, Schmidt-Hoberg

# The effect of the displaced vertex trigger

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