Bounds to dark axion portal

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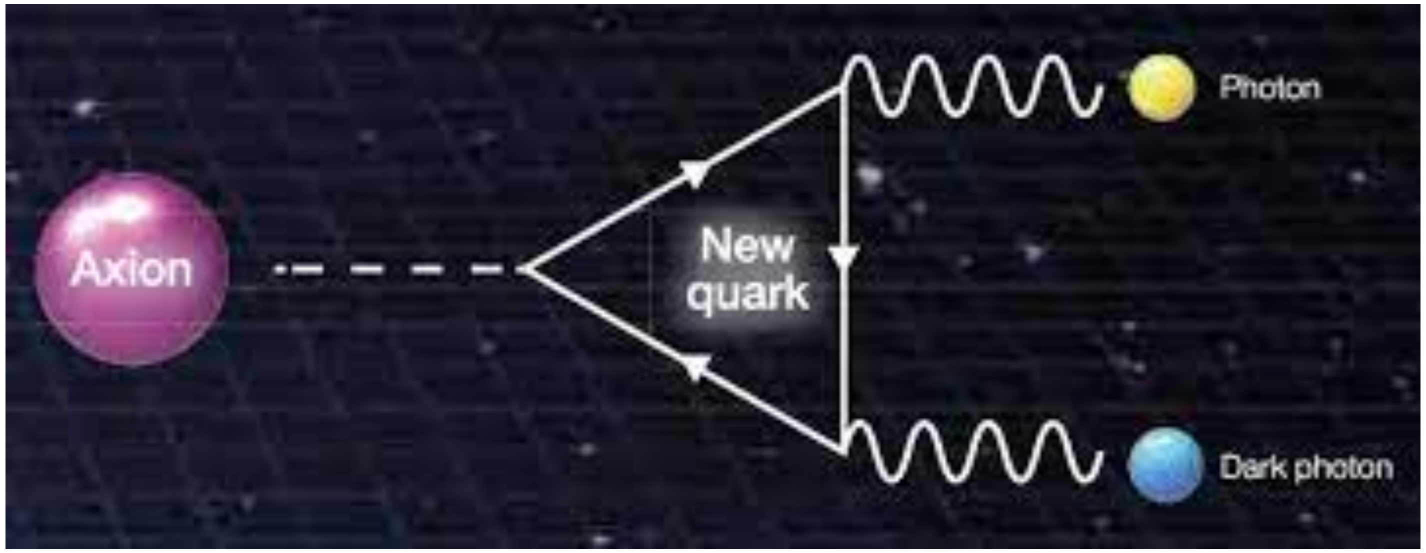

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Based on: 2204.09978 [hep-ph]

Plan:

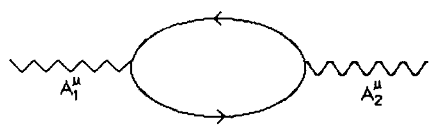
- Dark axion portal scenarios
- ALP and EDMs
- Minimal scenarios
- Non-minimal scenarios

Axion portal and dark axion portal:

$$\mathcal{L}_{\text{axion portal}} = \frac{G_{agg}}{4} a G_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{G_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} + \cdots$$

$$\mathcal{L}_{\text{dark axion portal}} = \frac{G_{a\gamma'\gamma'}}{4} a Z'_{\mu\nu}\tilde{Z}'^{\mu\nu} + \frac{G_{a\gamma\gamma'}}{2} a F_{\mu\nu}\tilde{Z}'^{\mu\nu}$$

The effective phenomenological Lagrangian
for vector portal is:



B. Holdom Phys.Letter 1986

$$\mathscr{L}_{\textbf{vector portal}} = \frac{\epsilon}{2} F_{\mu\nu} F^{'\mu\nu}$$

where ϵ is the kinetic mixing parameter between the two U(1) gauge symmetries, $F_{\mu\nu}$ and $F'_{\mu\nu}$ are the strength tensors of SM electromagnetic and DM dark gauge (dark photon) fields, respectively.

By shift SM photon field we can remove kinetic mixing term

$$A_\mu \to A_\mu - \epsilon A'_\mu$$

then, rescale the dark photon field

$$A'_\mu \to A'_\mu (1-\epsilon^2)^{1/2} \quad \longrightarrow \quad \mathscr{L}_{\text{mix}}^{\text{A}'-\psi} = e\,\epsilon_A\, A'_\mu\, \bar{\psi}\, \gamma^\mu\, T_Q\, \psi$$

The effective phenomenological Lagrangian for vector portal is:

$$\mathscr{L}_{\textbf{vector portal}} = \frac{\epsilon}{2} F_{\mu\nu} F^{'\mu\nu}$$

the minimal dark ALP portal scenario

For dark axion portal we have:

$$\mathscr{L}_{\textbf{dark axion portal}} = \frac{g_{a\gamma_D\gamma_D}}{4} a F'_{\mu\nu} \widetilde{F}^{'\mu\nu} + \frac{g_{a\gamma\gamma_D}}{2} a F_{\mu\nu} \widetilde{F}^{'\mu\nu}$$

+ dark fermions:

$$\mathscr{L} \supset \mathscr{L}_{\textbf{dark axion portal}} + \bar{\chi}(\gamma^\mu i\partial_\mu - g_D \gamma^\mu A'_\mu + m_\chi)\chi,$$

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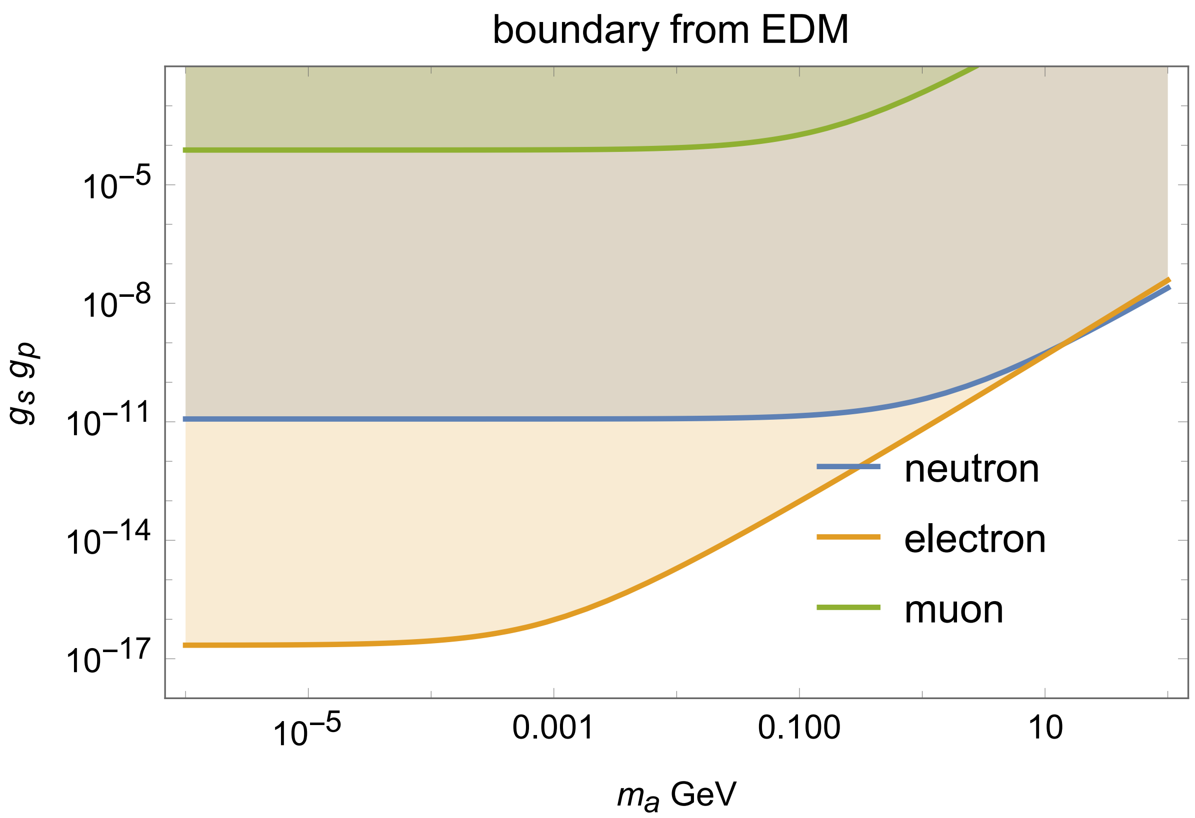
And

$$\mathcal{L} \supset \mathcal{L}_{\textbf{dark axion portal}} + \bar{\chi}(\gamma^\mu i \partial_\mu - g_D \gamma^\mu A'_\mu + m_\chi)\chi + \sum_\psi a \bar{\psi}(g^s_\psi + i g^p_\psi \gamma_5)\psi$$



ALP Lagrangian of interaction with matter:

$$\mathcal{L}_{aP} \supset \sum_{\psi} \bar{\psi} a (g^s_\psi + i g^p_\psi \gamma_5)\psi$$

$$d_\psi = \frac{e g^s_\psi g^p_\psi}{8\pi^2 m_\psi} g_i(y)$$

Bounds on |g^n_s g^n_p| from neutron EDM for light mass of ALPs are proportional to $\bar{\theta}$, parameter of CP-violation of vacuum in the quantum chromodynamics (QCD) which typical value is ~ 10^{-10}

For leptons:

$$g_1(y) = \int_0^1 dx \frac{x^2}{x^2 + y^2(1-x)}$$

$$y = m_a/m_\psi$$

For neutron:

$$g_2(y) = k_n \int_0^1 dx \frac{(1-x)(1-x^2)}{(1-x)^2 + y^2 x}$$

$$y = m_a/m_N$$

The dark photon can decay through the different channels in the dark ALP portal scenario.

$$\Gamma_{\gamma_D \to a\gamma} = \frac{g^2_{a\gamma\gamma_D}}{96\pi} m^3_{\gamma_D} \left(1 - \frac{m_a^2}{m^2_{\gamma_D}}\right)^3$$

and

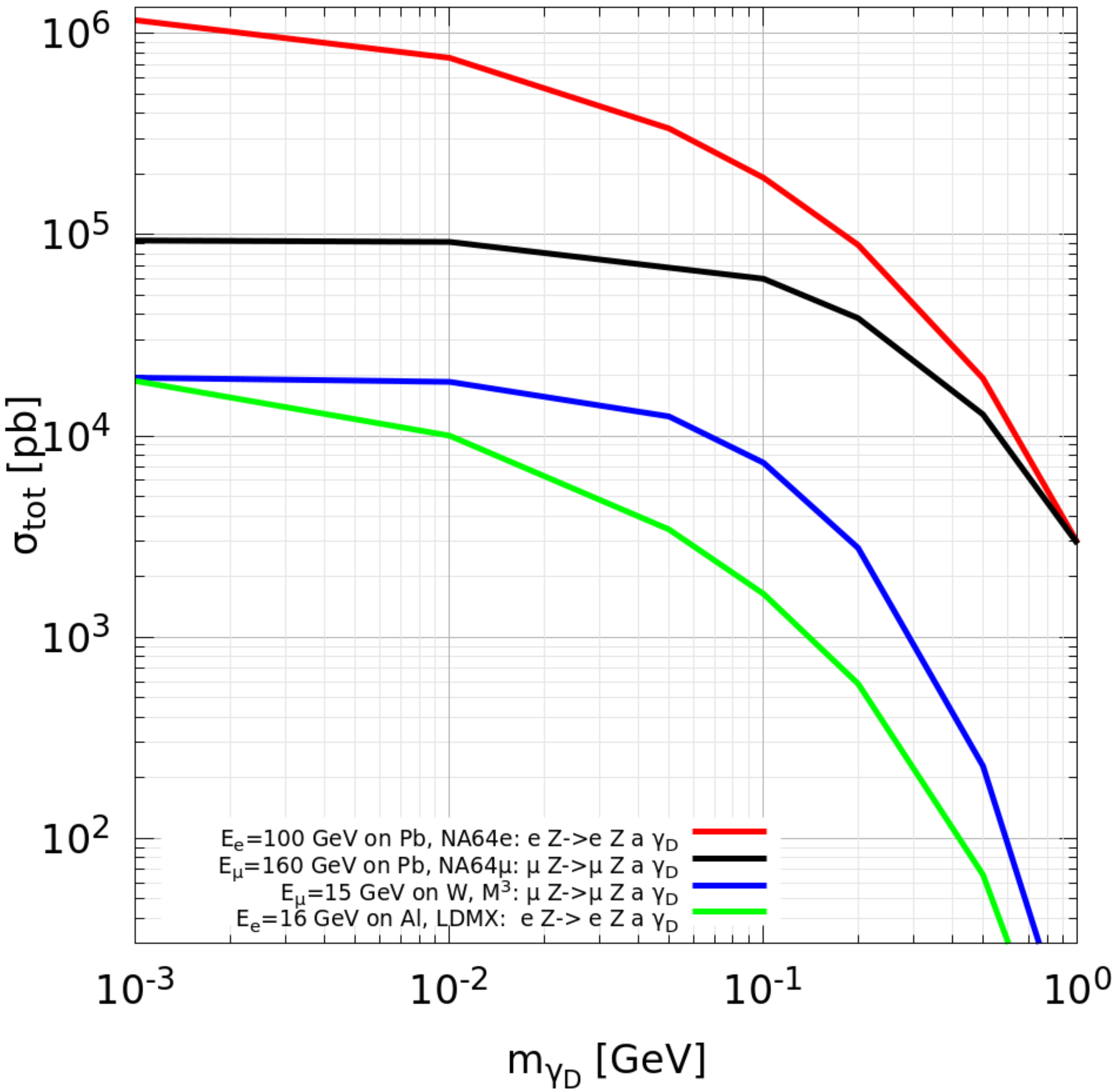
$$\Gamma_{\gamma_D \to \bar{\chi}\chi} = \frac{g_D^2}{12\pi} m_{\gamma_D} \left(1 + \frac{2m_\chi^2}{m^2_{\gamma_D}}\right) \left(1 - \frac{4m_\chi^2}{m^2_{\gamma_D}}\right)^{1/2}$$

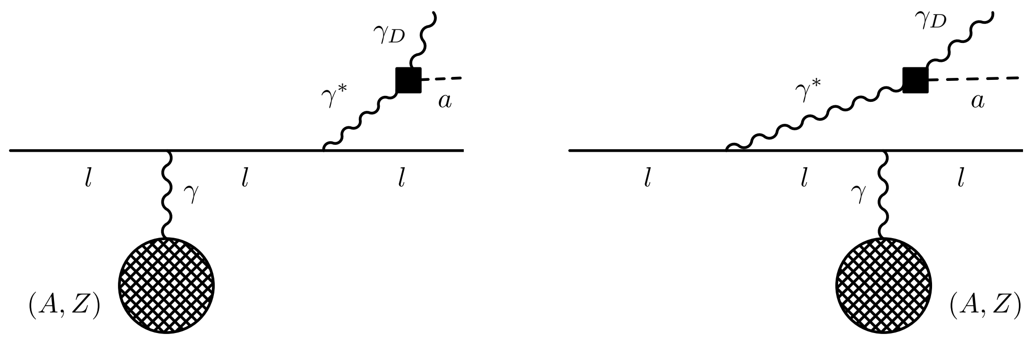
We focus on the process of invisible channel. In our analysis throughout the paper we keep the ALP mass m_a well below m_{γ_D}

We estimate the number of missing energy events for the lepton beam at fixed target as follows

$$N_{sign} \simeq \mathbf{LOT} \cdot \frac{\rho N_A}{A} L_T \int_{x_{min}}^{x_{max}} dx \frac{d\sigma(E_l)}{dx} \mathbf{Br}(\gamma_D \to \chi\bar{\chi})$$

the minimal dark ALP portal scenario





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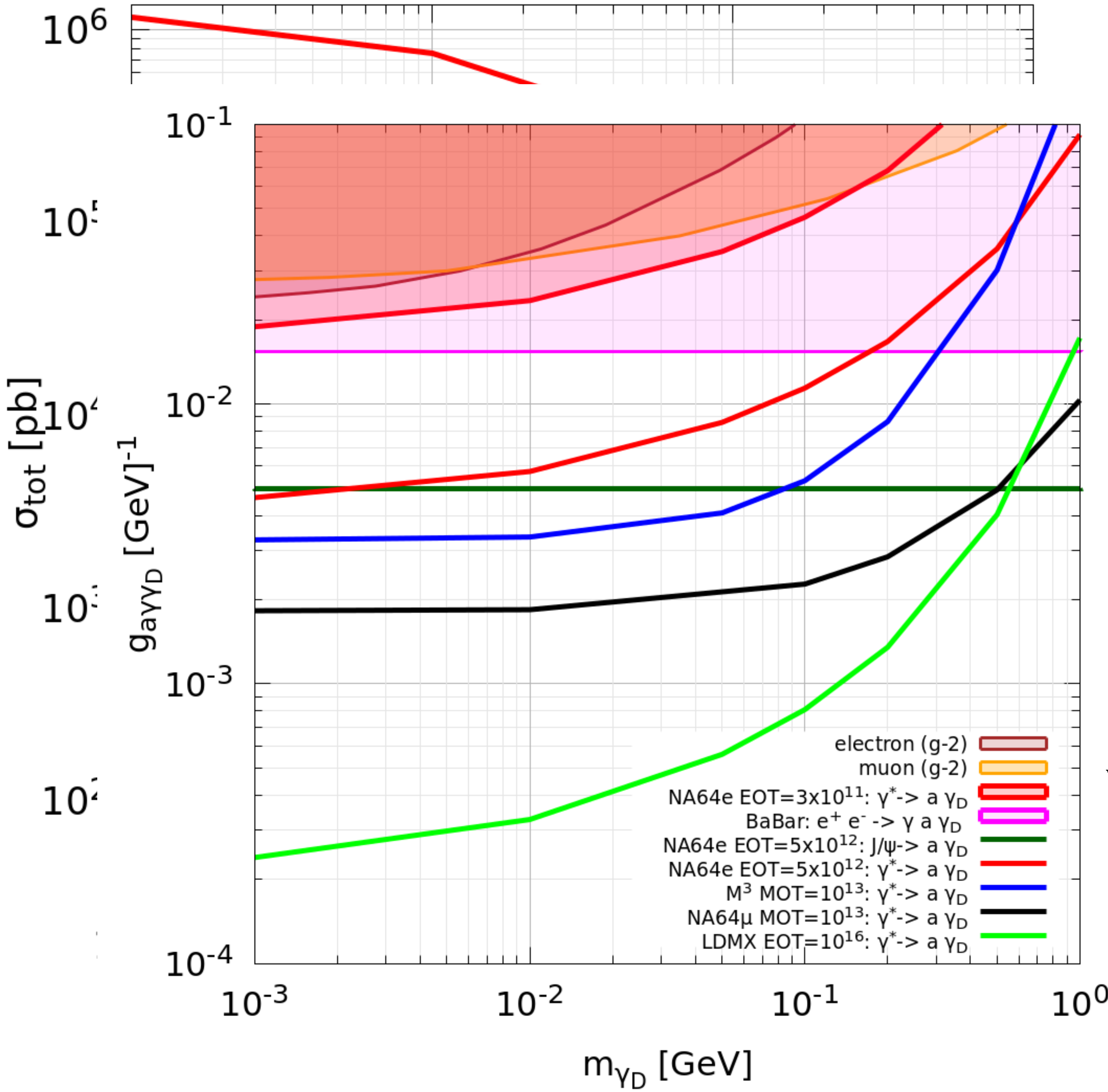

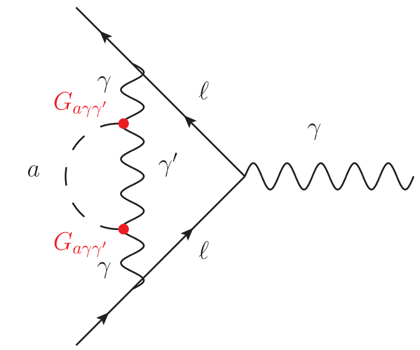

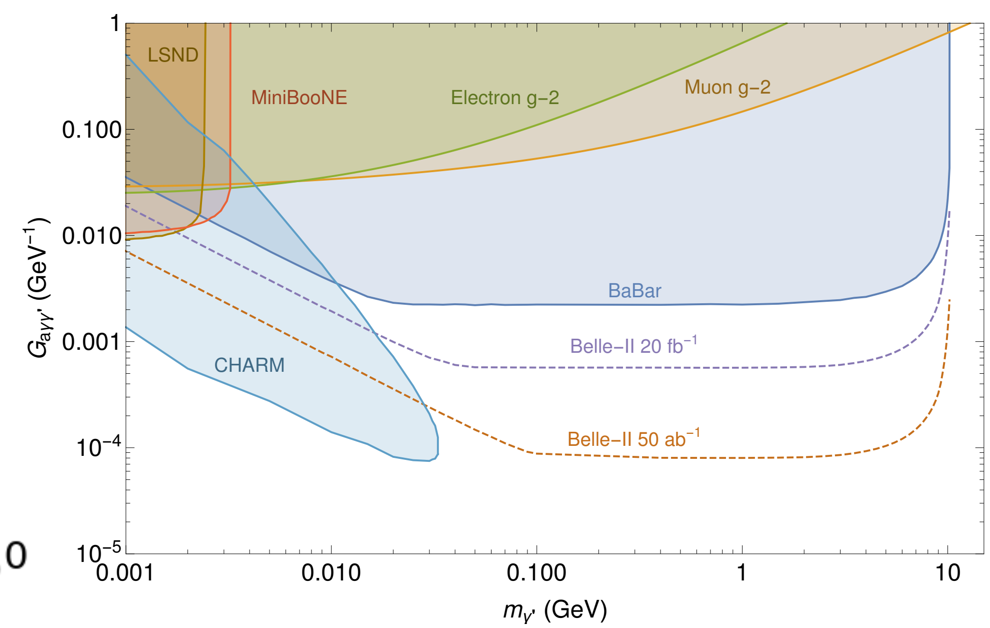

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the hadrophilic dark ALP portal scenario

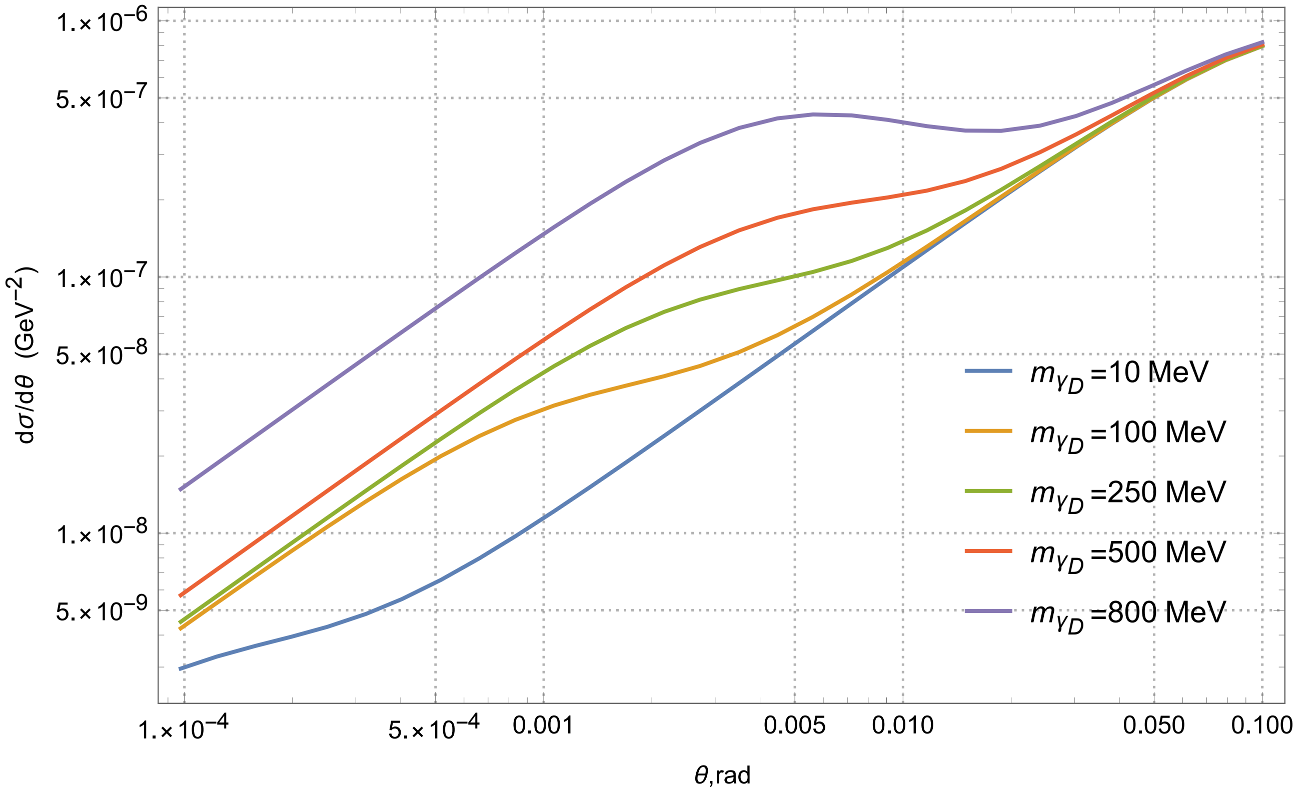
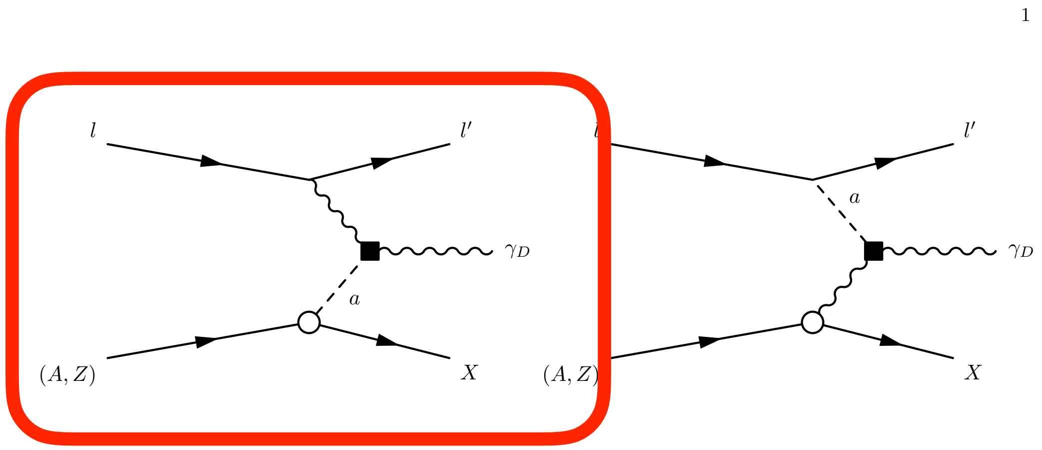


FIG. 12. The differential cross–section by angle of dark photon production at fixed target of NA64e in hadrophilic-ALP portal for various dark photon masses m_{γ_D} and for small values of angle θ between dark photon and photons from beam. We set parameters as $m_a = 10$ keV, $g^s = g^p = 1$, $g_{a\gamma\gamma_D} = 1$ GeV^{-1}, $E_e = 100$ GeV.



$$\sigma_{lZ\to lZ\gamma_D} = \int dx\, dq_\perp^2 \gamma_l(x_\gamma, q_\perp^2) \int dt \frac{d\sigma_{\gamma Z\to Z\gamma_D}}{dt}$$

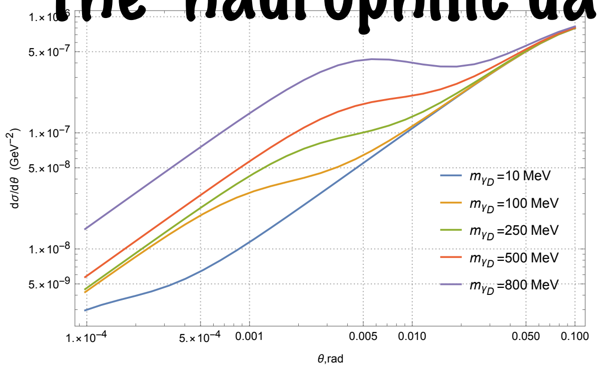
Where the photons following a distribution

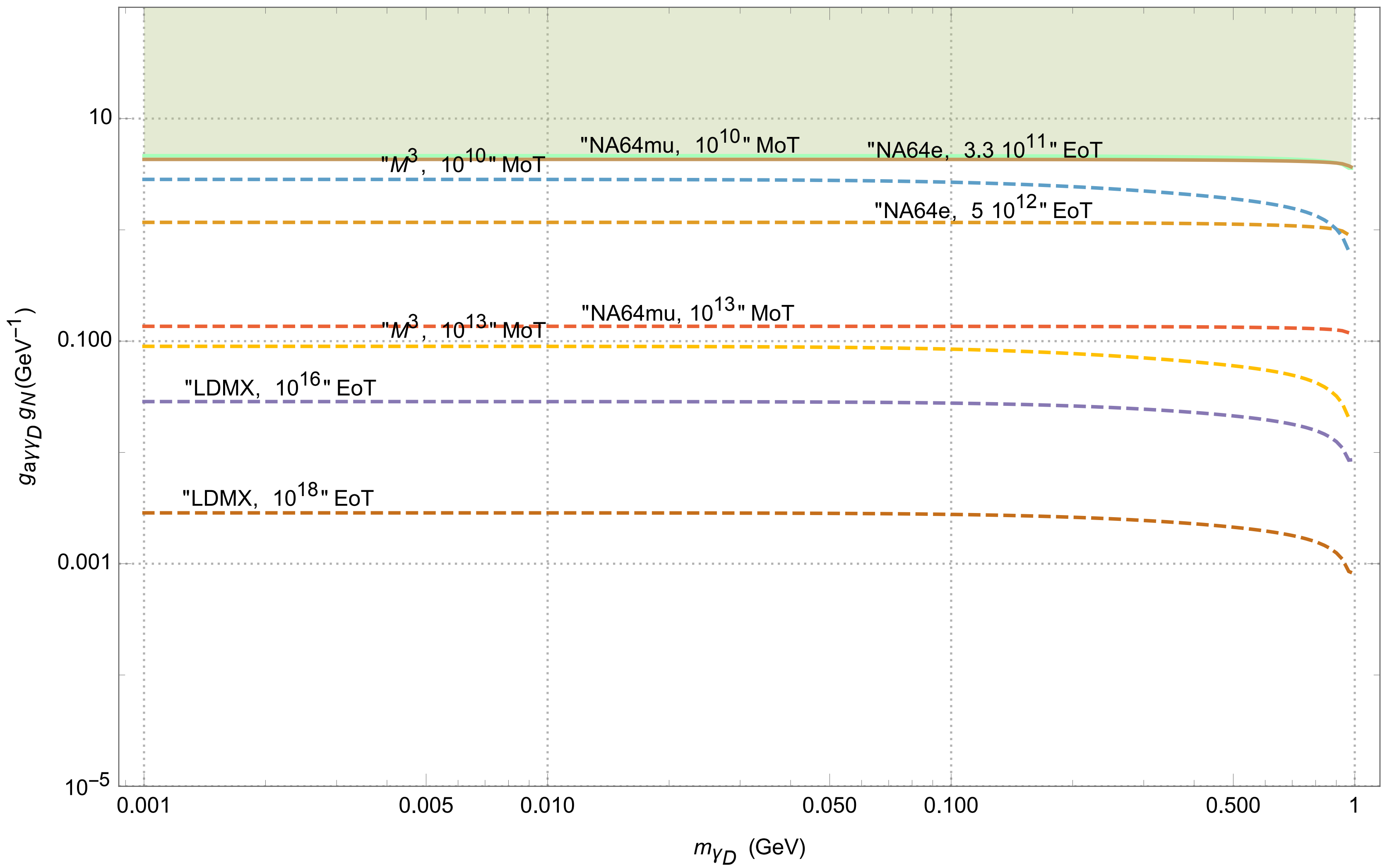
$$\gamma_l(x_\gamma, q_\perp^2) \simeq \frac{\alpha}{2\pi} \frac{1+(1-x_\gamma)^2}{x_\gamma} \frac{q_\perp^2}{(q_\perp^2 + x_\gamma^2 m_l^2)^2}$$

$$\frac{d\sigma_{\gamma Z\to Z\gamma_D}}{dt} = A \frac{\frac{1}{4}\sum_{\text{pol}} |M_{\gamma N}|^2}{16\pi\lambda(s, m_N^2, 0)},$$

$$|M_{\gamma N}|^2 \simeq \frac{g_{a\gamma\gamma_D}^2}{2} \frac{(t-m_{\gamma_D}^2)^2}{(t-m_a^2)^2} m_N^2 \times \left[g_s^2 - g_p^2 + (g_s^2+g_p^2)\frac{E_{2N}}{m_N}\right]$$

the hadrophilic dark ALP portal scenario





Bounds on combination of couplings ALPs with gauge fields $g_{a\gamma\gamma_D}$ and ALP couplings with nucleons $g^s = g^p = g_N$ for hadrophilic channel from current and proposal statistics of the experiments NA64e, NA64μ, LDMX and M^3. We set here $\mathrm{Br}(\gamma_D \to \chi\bar{\chi}) \simeq 1$ and m_a=10 keV.

the leptophilic dark ALP portal scenario

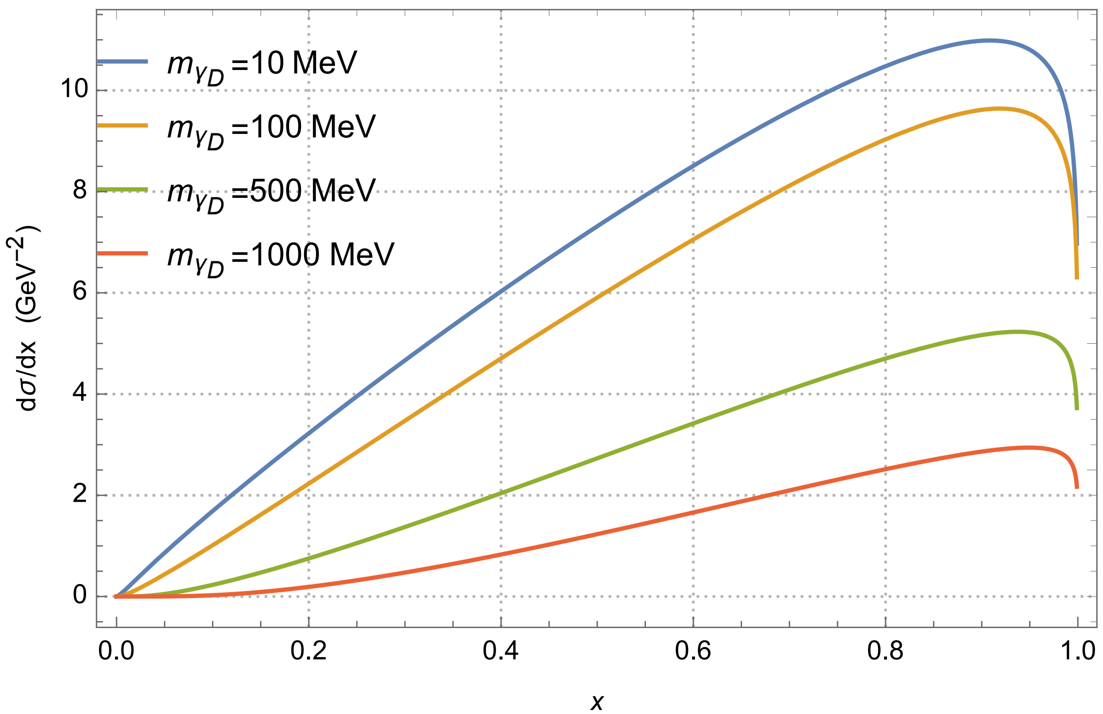
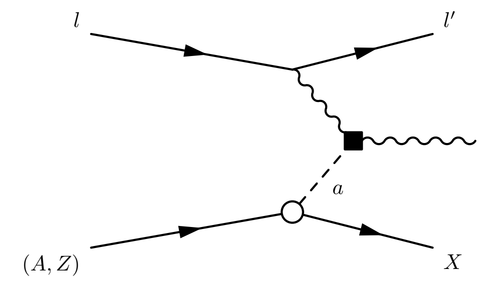


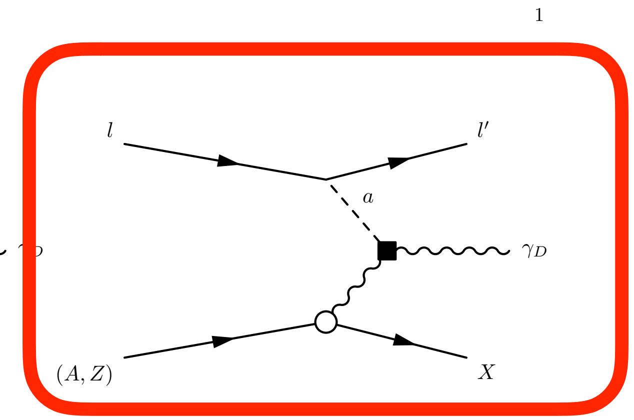
FIG. 13. The differential cross–section of dark photon production at NA64e as a function of fraction energy $x = E_{\gamma_D}/E_l$ for the ALP-leptophilic scenario and for various masses m_{γ_D}. We set $m_a = 10\,\mathrm{keV}$, $g_l^p = 1$, $g_{a\gamma\gamma_D} = 1\,\mathrm{GeV}^{-1}$ and $E_e = 100\,\mathrm{GeV}$.

$$\frac{d\sigma_{2\to3}}{dx\,d\cos\theta_{\gamma_D}} \simeq \frac{\alpha\chi}{32\pi^2} E_l^2 \beta_{\gamma_D} (g_l^p)^2 g^2_{a\gamma\gamma_D} \frac{x^3\left[xU - m^2_{\gamma_D}(1-x)\right]}{\left[xU - (1-x)(m^2_{\gamma_D} - m_a^2)\right]^2}$$

$$U \equiv -\tilde{u} \simeq E_l^2\theta^2_{\gamma_D} x + m^2_{\gamma_D}(1-x)/x + m_l^2 x$$

$$\chi(t) = \int_{t_{min}}^{t_{max}} \frac{t - t_{min}}{t^2}\left(G_2^{el}(t) + G_2^{in}(t)\right) dt$$





Atomic electric form factors:

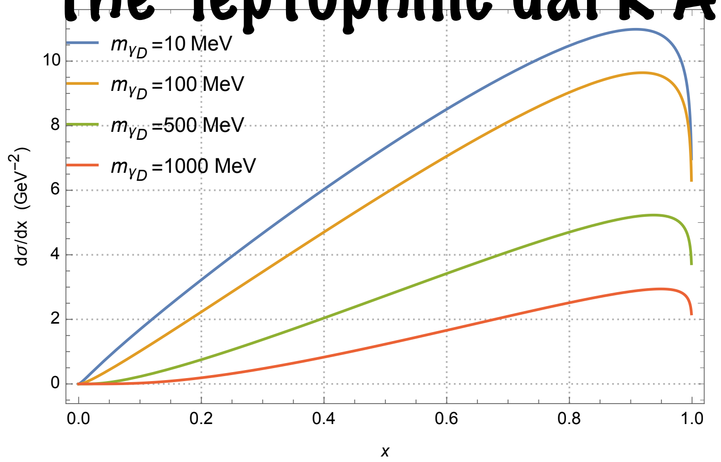
Elastic:

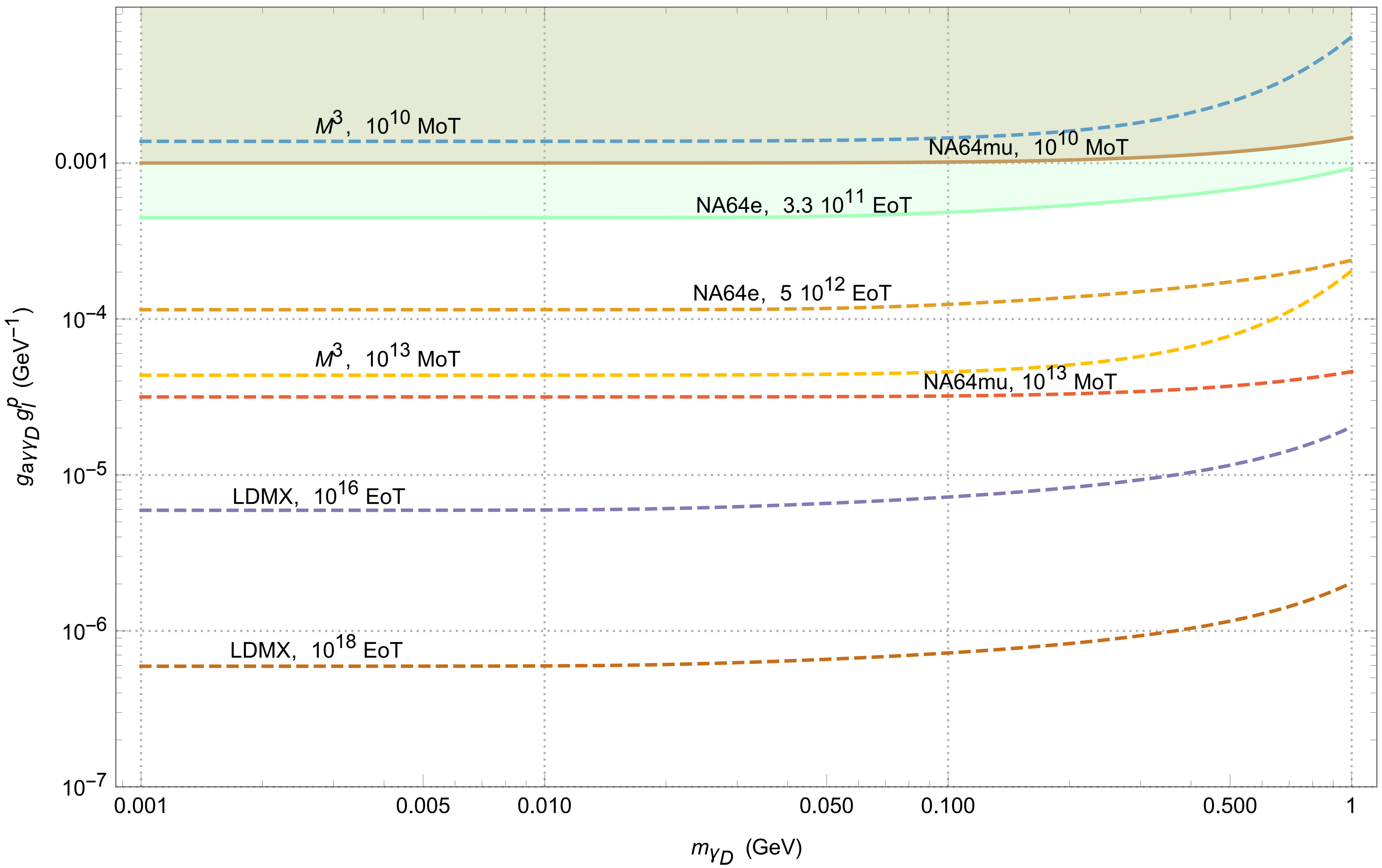
$$G_{2,el} = \left(\frac{a^2 t}{1 + a^2 t}\right)^2 \left(\frac{1}{1 + \frac{t}{d}}\right)^2 Z^2$$

Inelastic:

$$G_{2,in} = \left(\frac{a'^2 t}{1 + a'^2 t}\right)^2 \left(\frac{1 + \frac{t}{4m_p^2(\mu_p^2 - 1)}}{\left(1 + \frac{t}{0.71 GeV^2}\right)^4}\right)^2 Z$$

the leptophilic dark ALP portal scenario





Bounds for the combination of ALP couplings with leptons g_l^p and with gauge fields $g_{a\gamma\gamma_D}$ for the leptophilic scenario from current and proposal statistics of the NA64e, NA64μ, LDMX and M^3 experiments. We set here m_a=10 keV and $\mathrm{Br}(\gamma_D \to \chi\bar{\chi}) \simeq 1$.

Outlook:

1. Dark axion portal is a one of possible mechanisms of dark photon production in case where ε mixing parameter is very suppressed

3. We considered dark axion portal and obtain bounds to invisible mode in different scenarios.

3. Visible mode of dark axion portal is next step.

Thank you for attention