Study of dark matter physics using fixed target experiments.

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Based on work
which were done in collaboration with D. V. Kirpichnikov, V. E. Lyubovitskij, S. Kuleshov, S. Gninenko and NA64 Collaboration

Outline

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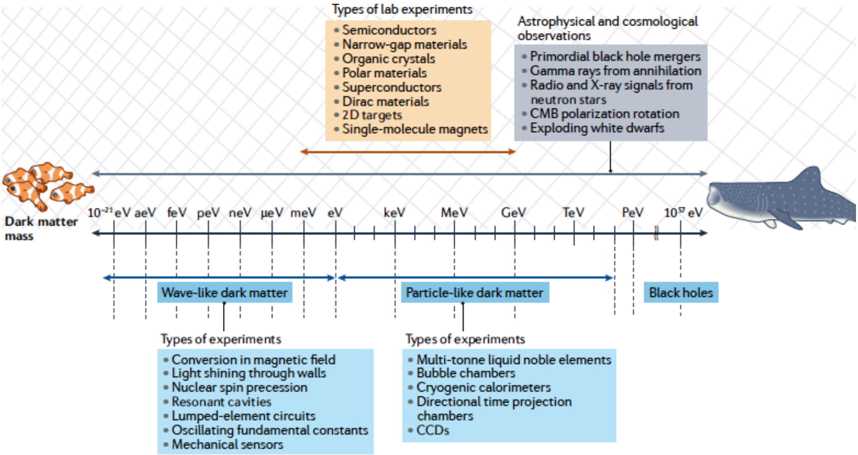
- Dark photon model
- $NA64_e$ or $NA64_\mu$
- Bounds for dark photon model - invisible mode
- Bounds from hadronic mode of $NA64_h$
- Conclusion

Dark matter puzzle



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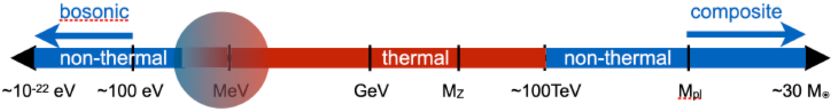
Dark matter puzzle



For the thermal DM in sub-GeV mass range, we have to assume the existence of a new feeble interaction between the ordinary and dark matter. One can stress several hidden sector scenarios that have been widely discussed in literature when such interaction is transmitted through the Higgs, tensor, vector or dark photon, sterile neutrino, and axion or axion-like (ALPs) portals.

Fixed target experiments

Three types of fixed target experiments to search DM:

- With missing energy or momentum technique (NA64e (eOT 5×10^{12}), NA64μ, NA64h, LDMX (eOT $10^{16}\div 10^{18}$), M^3 (μOT $10^{10}\div 10^{13}$), Dark-Shine (eOT 10^{14} for year)
- Search signal of interaction DM with detector (after wall) (NA62 (POT 1.4 $\times 10^{17}$), Coherent (POT 3.2 $\times 10^{23}$), ILC, SHIP)
- Rare decay study (REDTOP, HIAF (POT 10^{20} year))

Dark photon model

The most often studied mediator in recent times is the kinetically-mixed dark photon, owing to the appeal of a simple U(1) extension with a rich phenomenology and the absence of any flavor problems.

$$\mathcal{L} \supset -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}A'^{\mu\nu}A'_{\mu\nu} + \frac{\epsilon}{2}F^{\mu\nu}A'_{\mu\nu} + \frac{1}{2}m'^2_A A'_\mu A'^\mu + eA_\mu J^{mu}_{EM} + g_D A'_\mu J^{mu}_D \qquad (1)$$

where J^μ_{EM} is the electromagnetic current and J^{mu}_D is a dark current with gauge coupling g_D. From making the field redefinition $A_\mu = A_\mu - \epsilon A'_\mu$, which eliminates the kinetic mixing term

$$\mathcal{L} \supset -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}(1-\epsilon^2)A'^{\mu\nu}A'_{\mu\nu} + \frac{1}{2}m'^2_A A'_\mu A'^\mu + e(A_\mu + \epsilon A'_\mu)J^{mu}_{EM} + g_D A'_\mu J^{mu}_D \qquad (2)$$

where we see that dark photon mass eigenstate A' couples to SM charged particle.

Dark photon

The gauge invariant coupling of the dark photon A' and the SM photon A has the form

$$\mathcal{L}_{mix} = \frac{\epsilon}{2} F_{\mu\nu} A'^{\mu\nu} \tag{3}$$

where ϵ is the mixing parameter, $F_{\mu\nu}$ and $A'_{\mu\nu}$ are the stress tensors of the A and A' fields, respectively.
The interaction of the dark photon with the charged current of SM fermions and with dark fermion current has a form:

$$\mathcal{L} \supset \epsilon e A'_\mu J^\mu + g_D A'_\mu \bar{\chi} \gamma^\mu \chi \,, \tag{4}$$

where g_D is the coupling of the dark photon with dark fermions, e is the electric charge, and J_μ the electromagnetic current composed of the SM fermions.

$$\mathcal{L}^{\mathrm{A}'-\psi} \quad = \quad A'_\mu \sum_{ij} \bar{\psi}_i \gamma^\mu \left(g_{ij}^V + g_{ij}^A \gamma_5 \right) \psi_j \,. \tag{5}$$

The decay width of the A' to the dark fermions is

$$\Gamma_{A' \to \bar{\chi}\chi} = \frac{\alpha_D}{3} \, m_{A'} \, (1 + 2y_\chi^2) \, (1 - 4y_\chi^2)^{1/2} \,, \tag{6}$$

where $y_\chi = m_\chi / m_{A'}$, $\alpha_D = g_D^2 / 4\pi$, $m_{A'}$ and m_χ are masses of dark photon and dark fermions, respectively.

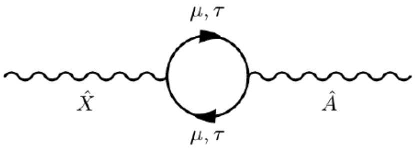
Dark photon

Besides we can construct other variant of gauge invariant theory, for example, for $U(1)_{L_i - L_j}$

$$J^{\mu}_{i-j} = \overline{L}_i \gamma^{\mu} L_i - \overline{L}_j \gamma^{\mu} L_j + \bar{l}_i \gamma^{\mu} l_i - \bar{l}_j \gamma^{\mu} l_j, \tag{7}$$

for $U(1)_{B-L}$

$$J^{\mu}_{B-L} = \overline{Q} \gamma^{\mu} Q + \overline{u}_R \gamma^{\mu} u_R + \overline{d}_R \gamma^{\mu} d_R - \overline{L} \gamma^{\mu} L + \bar{l} \gamma^{\mu} l, \tag{8}$$



$$\epsilon = \frac{e g_X}{2\pi^2} |f(m_{\mu}, m_{\tau}, q^2)|; \tag{9}$$

$$f(m_{\mu}, m_{\tau}, q^2) = \int_0^1 dx x(1-x) \ln \frac{m_{\mu}^2 - q^2 x(1-x)}{m_{\tau}^2 - q^2 x(1-x)}; \tag{10}$$

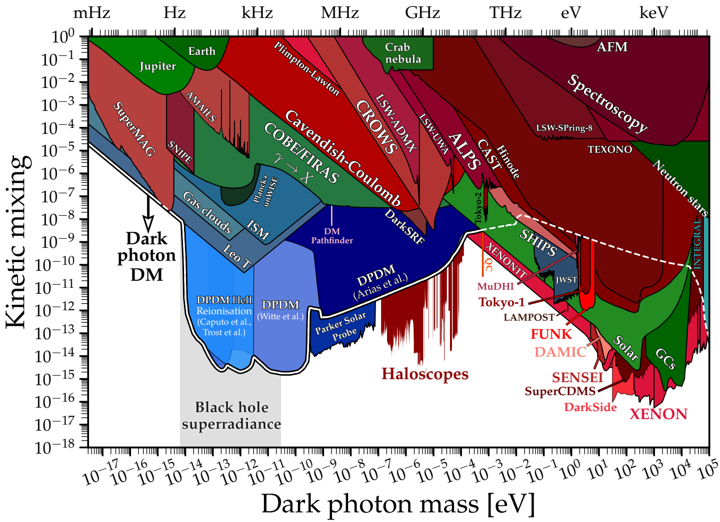
Dark matter and parameter space

The parameter space even for the minimal model is 4–dimensional $[m_{A'}, m_\chi, \epsilon, \alpha_D = \frac{g_D^2}{4\pi}]$, and it has become standard to compare the reach of accelerator experiments in a 2–dimensional subspace of coupling versus DM mass. A convenient coupling to use is the canonical parameter $y \equiv \epsilon^2 \alpha_D (m_\chi / m_{A'})^4$. This is motivated by considerations of DM production in the early universe. For $m_{A'} \geq O(few) m_\chi$, the DM annihilation rate near freeze–out is proportional to $< \sigma \nu > \propto \alpha_{EM} \frac{y}{m_\chi^2}$, implying that the cosmological abundance is in agreement with the observed DM energy density for

$$y \sim \frac{m_\chi^2}{\alpha_{EM} T_{eq} m_{pl}} \sim O(10^{-10}) \times \left(\frac{m_\chi}{100 MeV} \right)^2 \qquad (11)$$

where T_{eq} is the temperature at matter–radiation equality and m_{pl} is the Planck mass.

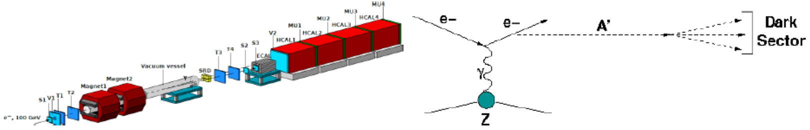
Dark photon


mHz
Hz
kHz
MHz
GHz
THz
eV
keV
Kinetic mixing
Dark photon mass [eV]
Jupiter
Earth
Crab nebula
AFM
Spectroscopy
Plimpton-Lawton
AMAILS
SuperMAG
SNIPE
Cavendish-Coulomb
COBE/FIRAS
CROWS
LSW-ADMX
LSW-UWA
ALPS
CAST
Hinode
LSW-SPring-8
TEXONO
Neutron stars
Planck+ unWISE
Gas clouds
ISM
Leo T
DM Pathfinder
DarkSRF
Tokyo-2
SHIPS
XENON1T
INTEGRAL
JWST
MuDHI
Tokyo-1
LAMPOST
FUNK
DAMIC
SENSEI
SuperCDMS
DarkSide
XENON
Solar
GCs
Dark photon DM
DPDM HeII Reionisation (Caputo et al., Trost et al.)
DPDM (Witte et al.)
DPDM (Arias et al.)
Parker Solar Probe
Haloscopes
Black hole superradiance

Invisible mode

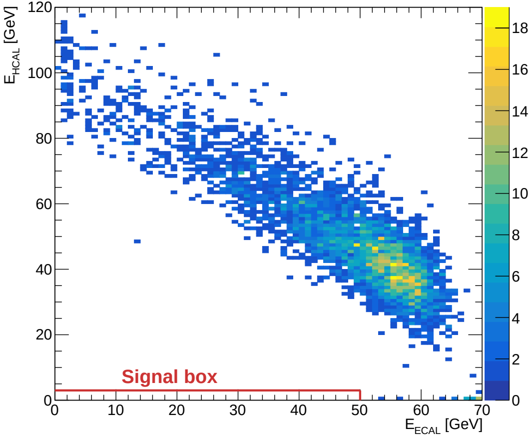
NA64

NA64 experiment setup (invisible mode): Proposed by S.Gninenko Phys.Rev.D 89 (2014) 7, 07500 (INR Moscow)



- NA64 is designed to search for dark sector physics in missing-energy events with $e^{\pm}$, μ, π,K, p beams.
- Main Components: a) clean E0 = 100 GeV e beam; b) e tagging system: tracker+SRD; c) hermetic ECAL+HCAL;
- Signature: a) in: 100 GeV e track; b) out: $E_{ECAL} < E_0/2$ electromagnetic shower in ECAL; c) no energy in Veto and HCAL;
- Background: a) μ, π,K decays in flight; b) upstream interaction; c) Tail < 50 GeV in the e beam; d) energy leak from ECAL+HCAL

NA64



The measured distribution of events in the (EECAL;EHCAL) plane after applying all selection criteria. The shaded area is the signal box, with the size along the EHCAL axis increased for illustration purposes. The side bands A and C are the ones used for the background estimate inside the signal region.

From fixed target experiments

$$N_{A'} \simeq \text{LOT} \cdot \frac{\rho N_A}{A} L_T \int\limits_{x_{min}}^{x_{max}} dx \frac{d\sigma_{2\to 3}}{dx}(E)\,, \tag{12}$$

where A is atomic weight number, N_A is the Avogadro's number, LOT is number of leptons accumulated on target, ρ is the target density, L_T is the effective interaction length of the lepton in the target, $d\sigma_{2\to 3}/dx$ is the differential cross section of the lepton conversion $lN \to l'NA'$, E is a initial lepton beam energy, $x = E_{A'}/E$ is the energy fraction that dark photon carries away, $x_{min} = E_{cut}/E$ and $x_{max} \simeq 1$ are the minimal and maximal fraction of dark photon energy respectively for the regarding experimental setup, E_{cut} is a detector missing energy cut that is determined by the specific facility.

From fixed target experiments

Differential cross section for $2 \to 3$ process, calculated in the framework of the Weizsäcker-Williams (WW) approximation [Budnev:1975poe, Tsai:1973py]. approximation is given by

$$\frac{d\sigma_{lZ \to l' Z A'}}{d(pk) d(k\mathcal{P}_i)} \simeq \frac{\alpha \gamma_Z}{\pi (p' \mathcal{P}_i)} \cdot \frac{d\sigma_{l\gamma^* \to l' A'}}{d(pk)}\Big|_{t=t_{min}}, \tag{13}$$

where t_{min} is a minimal momentum transfer that is provided below in Eq. (26), $\alpha \simeq 1/137.036$ is a fine structure constant, γ_Z is the effective photon flux from nucleus defined as

$$\gamma_Z = Z^2 \int_{t_{min}}^{t_{max}} dt \frac{t - t_{min}}{t^2} F^2(t). \tag{14}$$

where $\mathcal{P}_i$ is momentum of nuclear, p, p' and k are momenta of initial, finale leptons and dark photon (see definition in Fig. 2), t_{max} and t_{min} are kinematic bounds is obtained from the energy-conserving δ-function in the Lorentz-invariant phase space (details in Ref. [Liu:2017]). $F(t)$ has the form

$$F(t) = \frac{a^2 t}{(1 + a^2 t)} \frac{1}{(1 + t/d)}, \tag{15}$$

where $a = 111 Z^{-1/3}/m_e$ and $d = 0.164 A^{-2/3}\,\text{GeV}^2$ are the screening and nucleus size parameters, respectively [Bjorken:2009].

From fixed target experiments

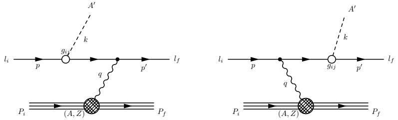


Figure: The dark photon A' bremsstrahlung process in lepton scattering on fixed atomic target.

Amplitude of $2 \to 2$ process is given by

$$M^{2\to 2} = e^2 \epsilon\, \epsilon^{\mu}_{\lambda} \epsilon^{\alpha}_{\lambda'} \bar{u}_f(p', s') \left[\gamma_\mu \frac{\hat{p} - \hat{k} + m}{\tilde{u}} \gamma_\alpha + \gamma_\alpha \frac{\hat{p} + \hat{k} + m}{\tilde{s}} \gamma_\mu \right] \bar{u}_i(p, s), \qquad (16)$$

where g^V_{if} and g^A_{if} are the non-diagonal couplings of interaction of dark photon with leptons, ϵ is the polarization vector of photon or dark photon, m_i and m_f are the masses of initial and final leptons.

From fixed target experiments with different initial and finale lepton states

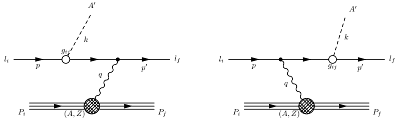


Figure: Lowest-order diagrams describing LFV emission of dark photon A' in lepton scattering on fixed atomic target.

Amplitude of $2 \to 2$ process is given by

$$M^{2\to 2} = ie\, \epsilon^{\mu}_{\lambda} \epsilon^{\alpha}_{\lambda'} \bar{u}_f(p', s') \left[\gamma_\mu \frac{\hat{p} - \hat{k} + m_f}{\tilde{u}} (\gamma_\alpha g^V_{if} + \gamma_5 \gamma_\alpha g^A_{if}) \right. \tag{17}$$

$$\left. + (\gamma_\alpha g^V_{if} + \gamma_5 \gamma_\alpha g^A_{if}) \frac{\hat{p} + \hat{k} + m_i}{\tilde{s}} \gamma_\mu \right] \bar{u}_i(p, s), \tag{18}$$

where g^V_{if} and g^A_{if} are the non-diagonal couplings of interaction of dark photon with leptons, ϵ is the polarization vector of photon or dark photon, m_i and m_f are the masses of initial and final leptons.

From fixed target experiments

In our calculation we will use the so-called modified Mandelstam variables:

$$\tilde{s} = (p' + k)^2 - m_f^2 = 2(p'k) + m_{A'}^2 , \quad (19)$$

$$\tilde{u} = (p - k)^2 - m_i^2 = -2(pk) + m_{A'}^2 , \quad (20)$$

$$t_2 = (p' - p)^2 = -2(p'p) + m_i^2 + m_f^2 , \quad (21)$$

$$t = q^2, \quad (22)$$

which satisfy the condition $\tilde{s} + t_2 + \tilde{u} = m_{A'}^2$.
In approximation of small angle of scattering, the modified Mandelstam variables are given by

$$U = -\tilde{u} \approx E^2 x\theta^2 + m_i^2 x + \frac{1-x}{x} m_{A'}^2, \quad (23)$$

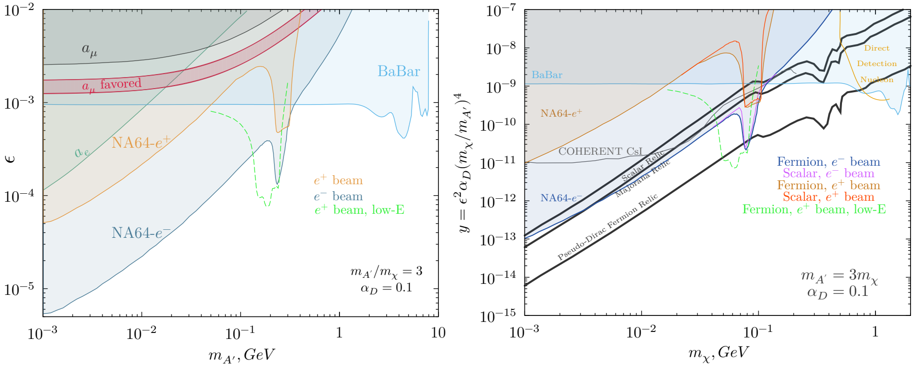
$$\tilde{s} \approx \frac{U + (m_f^2 - m_i^2)x}{1-x}, \quad (24)$$

$$t_2 \approx -\frac{x}{1-x}\left(U + (m_f^2 - m_i^2)\right) + m_{A'}^2, \quad (25)$$

$$t_{min} \approx \frac{(\tilde{s} + (m_f^2 - m_i^2))^2}{4E^2} . \quad (26)$$

Note that if we set $m_i = m_f$, then we reproduce formulas presented in Ref. [Bjorken:2009, Liu: 2017].

invisible mode A'



Bounds

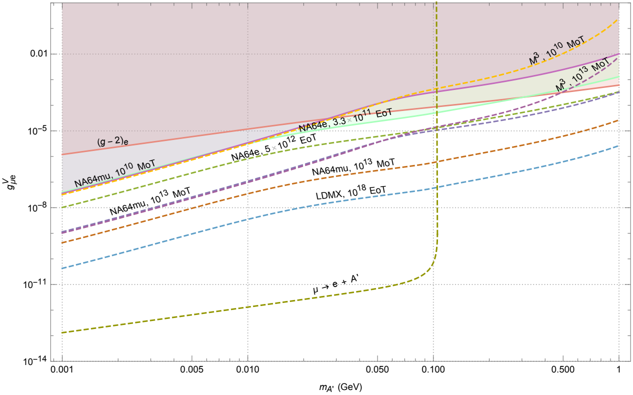


Figure: Bounds on vector non-diagonal coupling of dark photon with leptons using characteristics of running and proposed fixed-target experiments NA64e, NA64$_\mu$, LDMX, and M^3. Bounds from $g-2$ of leptons and invisible lepton LFV decay $l_i \to l_f + A'$ are included.

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Bounds

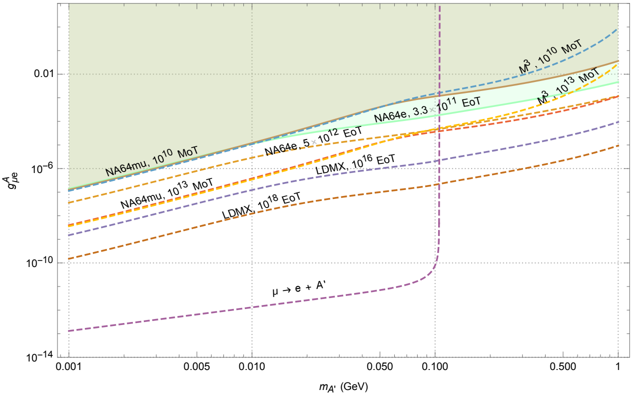

Figure: Bounds on vector non-diagonal coupling of dark photon with leptons using characteristics of running and proposed fixed-target experiments NA64e, NA64$_{\mu}$, LDMX, and M^3. Bounds from $g-2$ of leptons and invisible lepton LFV decay $l_i \to l_f + A'$ are included.

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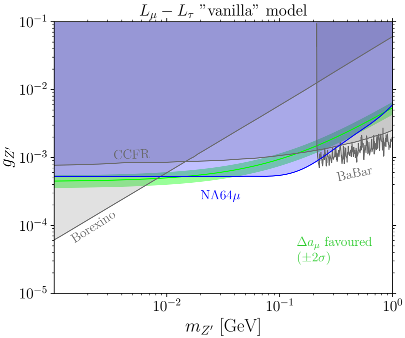
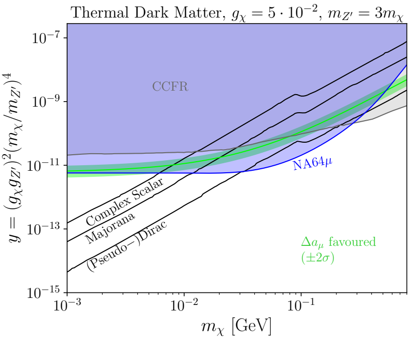
Bounds





NA64 90% CL exclusion limits on the coupling $g_{Z'}$ as a function of the Z' mass, $m_{Z'}$, for the vanilla L_μ - L_τ model.

- current limit from NA64 is more strict for dark photon model parameter space.
- The $\mathrm{NA64}_{\mu}$ fixed target experiment can provide a more stringent limit than the M^3 facility. Moreover, the expected reaches of the LDMX and $\mathrm{NA64}_{\mu}$ experiments at the masses of dark photon $m_{A'} \lesssim 1\,\mathrm{MeV}$ can be comparable with the current bounds from two-body LFV lepton decay, $\tau \to \mu(e)A'$.
- For non-diagonal coupling $g_{\mu e}$ strict limit from $\mu \to eA'$. For $g_{\tau e}$ and $g_{\tau\mu}$, LDMX future statistics can give more strict limit.
- Full analysis diagonal and non-diagonal couplings of dark photon in work.

Invisible mode for hadronic beam of NA64

Bounds from collider physics// pion beam

For pion beam we can generate pion from different processes.

- $\pi^- + (A, Z) \to \rho^0 + (A, Z-1)$
- Charge exchange reaction $\pi^- + (A, Z) \to M^0 + (A, Z-1)$

But we have a limit from experimental technology of search signal of DM.

The yield of meson in detector is

$$N_{M^0} \simeq \pi\mathrm{OT} \cdot \frac{\rho_T N_A}{A} L_T \, \sigma(\text{mesonproduction})\,, \tag{27}$$

$\mathrm{Br}(M^0 \to \text{inv.}) \leq 2.3/N_{M^0}$ for invisible
and
$\mathrm{Br}(M^0 \to \text{semi-inv.}) \leq 2.3/N_{M^0}$ for semi-invisible
at 90% confidence level (C.L.) assuming zero observed signal events and background-free case

Pion recharge process ($\pi^{\pm} + (A, Z) \to M^0 + (A, Z \pm 1)$)

Differential cross section in case of the proton target is parameterized by experimental groups of Serpukhov-CERN:

$$\frac{d\sigma_H(s,t)}{dt} = \frac{d\sigma_H(s,t)}{dt}\bigg|_{t=0} \Big[1 - g(s)c(s)t\Big] \; \exp[c(s)t]\,, \tag{28}$$

where

$$\frac{d\sigma_H(s,t)}{dt}\bigg|_{t=0} = A \left(\frac{s}{s_0}\right)^{2\alpha_r(0)-2}, \tag{29}$$

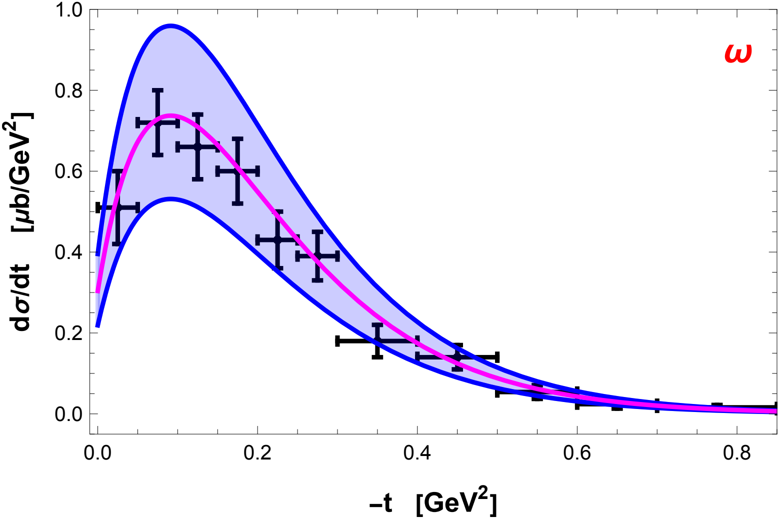
A is the normalization factor, $g(s) = g_0 + g_1 \log(s/s_0)$ and $c(s) = c_0 + c_1 \log(s/s_0)$ are the s-running couplings.
For the integral cross section in case of the proton target we get

$$\sigma_H(s) = A \left(\frac{s}{s_0}\right)^{2\alpha_r(0)-2} \frac{1 + g(s)}{c(s)}\,. \tag{30}$$

Extension to arbitrary nuclei N with charge Z is normally done by multiplying with factor $Z^{2/3}$. However, we found that this behavior should be slightly corrected as $Z^{2/3-0.15Z^{-2/3}}$. I.e. the integral cross section for the neutral meson production at nuclei with charge Z reads:

$$\sigma_N(s) = \sigma_H(s)\, Z^{2/3-0.15Z^{-2/3}}\,. \tag{31}$$

fit for ω production



Predictions for the integral cross sections for the $\pi^- + (A, Z) \to M^0 + (A, Z-1)$ reactions at beam momentum $P = 50$ GeV in μb units.

Meson	H	Li	Be	C	Al	Fe
π^0	8.1 ± 1.4	15.6 ± 2.6	18.8 ± 3.1	24.7 ± 4.1	41.9 ± 6.8	67.4 ± 11
η	2.6 ± 0.9	5.1 ± 1.7	6.1 ± 2.1	8.0 ± 2.8	13.6 ± 4.7	21.9 ± 7.5
η'	1.3 ± 0.4	2.4 ± 0.8	2.9 ± 1.0	3.8 ± 1.3	6.5 ± 2.1	10.4 ± 3.5
ω	2.0 ± 0.7	3.9 ± 1.2	4.7 ± 1.5	6.2 ± 1.9	10.5 ± 3.2	16.9 ± 5.1

Predictions for the integral cross sections for the $\pi^- + (A, Z) \to P^0(\to 2\gamma) + (A, Z-1)$, $\pi^- + (A, Z) \to \omega(\to \pi^0\gamma) + (A, Z-1)$, and $\pi^- + (A, Z) \to f_2(\to 2\pi^0) + (A, Z-1)$, reactions at beam momentum $P = 50$ GeV in μb units. Here $P^0 = \pi^0, \eta, \eta'$.

Meson	H	Li	Be	C	Al	Fe
π^0	8.1 ± 1.4	15.6 ± 2.6	18.8 ± 3.1	24.7 ± 4.1	41.9 ± 6.8	67.4 ± 11
η	1.0 ± 0.4	2.0 ± 0.7	2.4 ± 0.8	3.2 ± 1.0	5.4 ± 1.8	8.6 ± 3.0
η'	0.03 ± 0.01	0.06 ± 0.01	0.07 ± 0.03	0.09 ± 0.03	0.15 ± 0.05	0.24 ± 0.08
ω	0.17 ± 0.05	0.33 ± 0.10	0.39 ± 0.12	0.52 ± 0.15	0.87 ± 0.27	1.41 ± 0.43

Yields N_{M^0} of mesons in the reaction of charge exchange at the scattering of negative pion beam onto the Fe target at the beam E$\sim$ 50 GeV.

	N_{π^0}	N_η	$N_{\eta'}$	N_ω	N_{f_2}
$(3 \times 10^9 \quad \pi OT)$	0.35×10^6	0.089×10^6	0.054×10^6	0.088×10^6	0.089×10^6
$(5 \times 10^{12} \quad \pi OT)$	5.86×10^8	1.48×10^8	0.9×10^8	1.47×10^8	1.48×10^8

Vector meson decay into dark

We derive effective Lagrangian describing transition of neutral vector meson to dark photon

$$\mathcal{L}_{V-A'} = e\epsilon g_V m_V V_\mu A'^\mu, \tag{32}$$

The width of the decay of vector meson into the dark fermion pair $V \to \bar{\chi}\chi$ is given by

$$\Gamma(V \to \bar{\chi}\chi) = \frac{\alpha_D(\epsilon e)^2}{3} g_V^2 \frac{(m_V^2 + 2m_\chi^2)\sqrt{m_V^2 - 4m_\chi^2}}{(m_{A'}^2 - m_V^2)^2 + \Gamma^2_{A' \to \bar{\chi}\chi} m_{A'}^2}, \tag{33}$$

where $m_{A'}$ and m_χ are the masses of intermediate dark photon and DM fermion, respectively, m_V is the mass of vector meson [Schuster:2021]. Here we use the Breit-Wigner propagator for the dark photon A' assuming that its total width is dominated by the $A' \to \bar{\chi}\chi$ mode.

Pseudoscalar meson decay into dark

The decay widths of the π^0 into $\gamma\gamma$, $\gamma A'$, and $A'A'$ are given by

$$\Gamma(\pi^0 \to \gamma\gamma) = \frac{\alpha^2}{64\pi^3}\frac{m_\pi^3}{F_\pi^2}, \quad (34)$$

$$\Gamma(\pi^0 \to \gamma A') = \frac{\alpha^2\epsilon^2}{32\pi^3}\frac{m_\pi^3}{F_\pi^2}\left(1-\frac{m_{A'}^2}{m_\pi^2}\right)^3, \quad (35)$$

$$\Gamma(\pi^0 \to A'A') = \frac{\alpha^2\epsilon^4}{64\pi^3}\frac{m_\pi^3}{F_\pi^2}\left(1-\frac{4m_{A'}^2}{m_\pi^2}\right)^{3/2}. \quad (36)$$

and for η and η' mesons

$$\Gamma(\eta \to \gamma A') = \frac{9\alpha^2\epsilon^2}{16\pi^3}\, m_\eta^3\left(1-\frac{m_{A'}^2}{m_\eta^2}\right)^3\left[\frac{C_8\cos\theta_0}{f_8\cos(\theta_8-\theta_0)}-\frac{(1-\Lambda_3)C_0\sin\theta_8}{f_0\cos(\theta_8-\theta_0)}\right]^2, \quad (37)$$

$$\Gamma(\eta' \to \gamma A') = \frac{9\alpha^2\epsilon^2}{16\pi^3}\, m_{\eta'}^3\left(1-\frac{m_{A'}^2}{m_{\eta'}^2}\right)^3\left[\frac{C_8\sin\theta_0}{f_8\cos(\theta_8-\theta_0)}+\frac{(1-\Lambda_3)C_0\cos\theta_8}{f_0\cos(\theta_8-\theta_0)}\right]^2, \quad (38)$$

η/η' meson decays

Eur. Phys. J. C 31, 525–547 (2003) [M. Benayoun, P. David, L. DelBuono, Ph. Leruste, H.B. O'Connell]

Decay with intermediate vector meson:

$$\Gamma(\eta' \to (\rho^0 \to A')\gamma) = \frac{\alpha\epsilon^2}{8m_{\eta'}^3} g_{\eta'\rho\gamma}^2 (m_{\eta'}^2 - m_{A'}^2)^3$$

$$\times \frac{g_\rho^2}{(m_\rho^2 - m_{A'}^2)^2 + \Gamma_\rho^2 m_\rho^2}. \quad (39)$$

M. Benayoun et al.: Anomalous η/η' decays: the triangle and box anomalies

Table 3. η/η' Partial widths as predicted by the HLS model when switching on/off the box anomaly contribution. The significance is computed using an error obtained by adding in quadrature the experimental error and the relevant model error computed by Monte Carlo sampling (using information in Table 1)

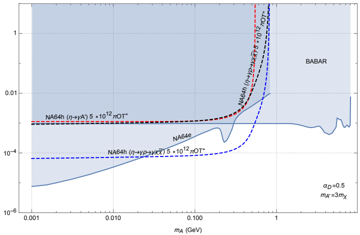
Decay	PDG 2002	Prediction with box anomaly	Prediction without box anomaly
$\eta \to \pi^+\pi^-\gamma$ (eV)	55 ± 5	56.3 ± 1.7	100.9 ± 2.8
Significance (n σ)		$0.25\ \sigma$	$8\ \sigma$
$\eta' \to \pi^+\pi^-\gamma$ (keV)	60 ± 5	48.9 ± 3.9	57.5 ± 4.0
Significance (n σ)		$1.75\ \sigma$	$0.39\ \sigma$

The differential decay width of $\eta' \to \gamma\chi\bar{\chi}$ with ρ meson resonance transition is

$$d\Gamma(\eta' \to (\rho^0 \to A' \to \chi\bar{\chi})\gamma) =$$

$$\frac{\alpha^2\epsilon^2\alpha_D}{6m_{\eta'}^3}(q^2 - m_{\eta'}^2)^3(q^2 + 2m_\chi^2)(q^2 - 4m_\chi^2)^{\frac{1}{2}} \quad (40)$$

$$\times \left[\frac{g_\rho^2}{(m_{A'}^2 - q^2)^2 + \Gamma_{A' \to \bar{\chi}\chi}^2 m_{A'}^2} \; \frac{g_{\eta'\rho\gamma}^2}{(m_\rho^2 - q^2)^2 + \Gamma_\rho^2 m_\rho^2}\right] \frac{dq^2}{\sqrt{q^2}}.$$



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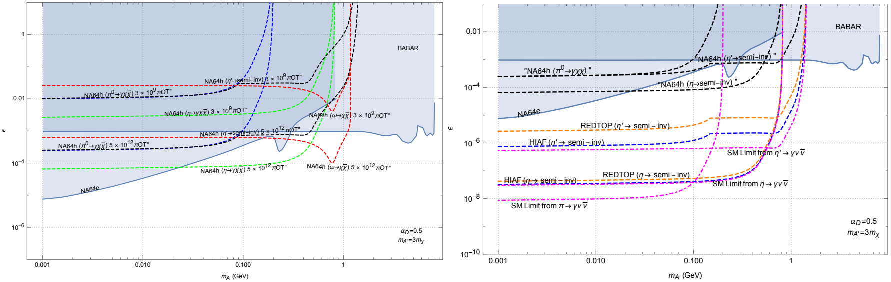
Bound to dark photon / ϵ mixing parameter



Bounds for dark photon ϵ parameter mixing obtained for 90% C.L. and for case where $m_{A'} = 3m_\chi$ and $\alpha_D = 0.5$. At both panels, we show existed limit from current data of NA64$_e$ experiment and constraints from production of DM in e^+e^- collision at BABAR. Top panel: Bounds from semi-invisible pseudoscalar decays ($\pi^0 \to \gamma\chi\bar{\chi}$, $\eta \to \gamma\chi\bar{\chi}$, $\eta' \to semi - inv$) and invisible decay ($\omega \to \chi\bar{\chi}$) for statistics 3×10^9 πOT (few days of data taking) and for 5×10^{12} πOT as proposal statistics for NA64$_h$ experiment. Bottom panel: Bounds from semi-invisible pseudoscalar decays ($\pi^0 \to \gamma\chi\bar{\chi}$, $\eta \to \gamma\chi\bar{\chi}$, $\eta' \to \gamma\chi\bar{\chi}$) for proposal/projected statistics of NA64$_h$, REDTOP and HIAF experiments. The dot-dashed lines show limit of neutrino floor from decay light pseudoscalar mesons to $\gamma\nu\bar{\nu}$ predicted in the framework of SM.

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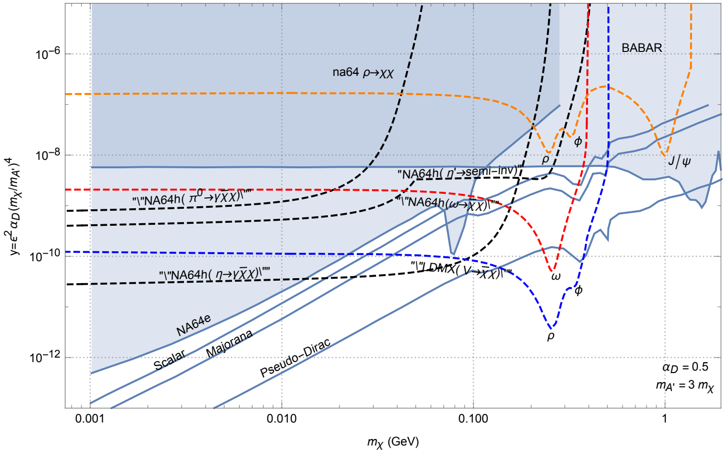
Bound to dark photon / $y = \alpha_D \epsilon^2 (m_\chi / m_{A'})^4$



Limits for the same decays for 5×10^{12} πOT of NA64$_h$ experiment in comparison with bound from invisible vector meson decays obtained for NA64$_e$ and LDMX experiments [Schuster:2021] and shifted after analysis of NA64 group for rho meson production in Geant4.

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outline for hadronic search

- Meson charge exchange reaction on of possible processes which can be used for analysis DM model parameter space by using missing energy/momentum technique.
- Intermediate vector state should take into account for analyze of decay of η and η' mesons into dark.
- Using projected statistics for the neutral meson yield in the NA64, we can predict the typical bound on the semi-invisible on the invisible branching ratio

$$\begin{aligned} \mathrm{Br}(\pi^0 \to \gamma + A') &< 3.16 \times 10^{-9} \quad (\text{from NA64}_h); \quad (41) \\ \mathrm{Br}(\eta \to semi - inv) &< 9.4 \times 10^{-9} \quad (\text{from NA64}_h); \quad (42) \\ \mathrm{Br}(\eta' \to semi - inv) &< 4.7 \times 10^{-9} \quad (\text{from NA64}_h); \quad (43) \\ \mathrm{Br}(\omega \to \text{inv.}) &< 8.1 \times 10^{-9} \quad (\text{from NA64}_h); \quad (44) \end{aligned}$$

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- Low energy pion beams are more suitable for test of DM physics by missing energy experimental search technique from light meson decays.
- And experimental results for full invisible decays from

$$\mathrm{Br}(\eta \to invisible) < 1.1 \times 10^{-4} \quad (45)$$

$$\mathrm{Br}(\eta' \to invisible) < 2.1 \times 10^{-4} \quad (46)$$

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Summary

Experimental

- Prolongation NA64+++, including the hadron mode
- Start new experiment (M^3, LDMX, HIAF, REDTOP, Dark-Shine)

Theory

- New ideas and check of model:
  1. dark axion portal
  2. spin-dependent interaction of DM and SM
  3. different general model for portals ideas
  4. ...