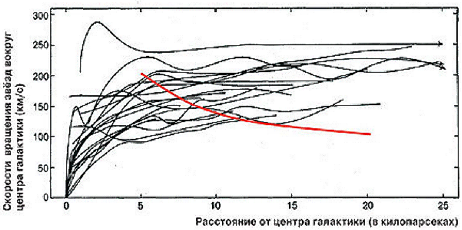
Constraints on dark matter from accelerator-based experiments and direct-detection searches

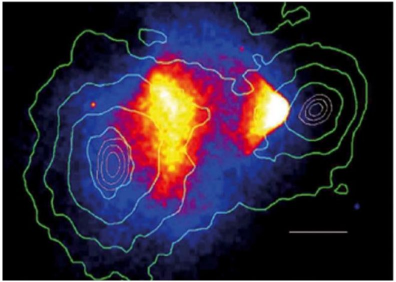
Voronchikhin I.V.,
INR RAS

22.05.2026

Introduction

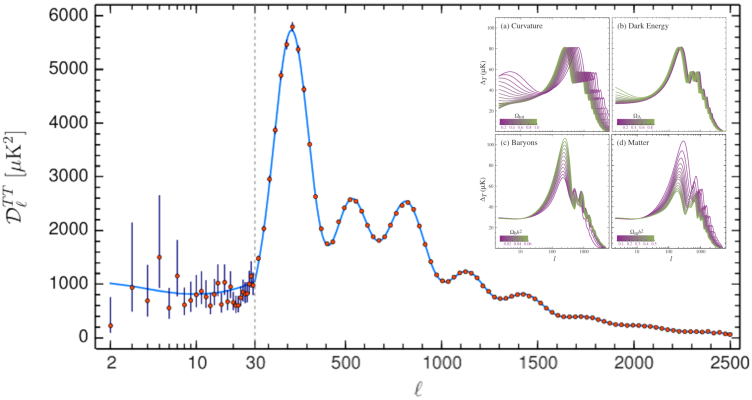
The impact of dark matter on the motion of visible matter

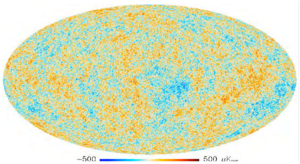


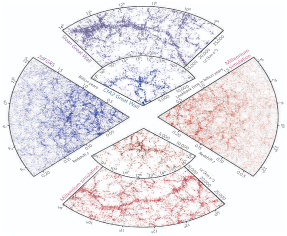


1. F. Zwicky On the Masses of Nebulae and of Clusters of Nebulae, Astrophys. J., vol. 86, p.217, 1937.
2. V. C. Rubin, N. Thonnard, and W. K. Ford, Jr. Rotational properties of 21 SC galaxies with a large range of luminosities and radii, from NGC 4605 R = 4kpc to UGC 2885 R = 122 kpc, Astrophys. J., 238:471, 1980.
3. D. Cloweet et al., A direct empirical proof of the existence of dark matter. Astrophys. J. Lett., 648:L109–L113, 2006, astro-ph/0608407

The impact of dark matter on the distribution of visible matter







1. W. Hu, S. Dodelson, Cosmic Microwave Background Anisotropies, Ann. Rev. Astron. Astrophys. T. 40. C. 171—216, 2002, astro-ph/0110414

2. G. R. Blumenthal, S. M. Faber, J. R. Primack, M. J. Rees, Formation of Galaxies and Large Scale Structure with Cold Dark Matter, Nature T. 311. C. 517—525, 1984

Dark matter

1. Density parameters for various components of the Universe [1]:

$$|\Omega_{\rm k}| < 0.01, \quad \Omega_{\rm r} = 9.4\times 10^{-5}, \quad \Omega_{\rm b} = 0.05, \quad \Omega_{\rm c} = 0.27, \quad \Omega_{\Lambda} = 0.68.$$

2. It is assumed that dark matter was in thermal equilibrium with particles of the visible sector in the early Universe.
3. The observed CMB anisotropy is sensitive to the injection of additional energy into the primordial plasma of the early Universe [2]:

$$\langle \sigma v\rangle^{\rm s-wave}_{\rm CMB} \lesssim \frac{3.6\times 10^{-27}\text{см}^3\text{с}^{-1}}{f(z, m_{\rm DM})}\left(\frac{m_{\rm DM}}{1\ \text{ГэВ}}\right),$$

4. For $m_e \lesssim m_{\rm DM} \lesssim \mathcal{O}(1)$ GeV, it is necessary to introduce a depletion mechanism to obtain its observed relic density [3].

1. Planck 2018 results. VI. Cosmological parameters // Astron. Astrophys. — 2020. — T. 641. — A6. 2. S. Galli, T. R. Slatyer, M. Valdes, F. Iocco., Systematic Uncertainties In Constraining Dark Matter Annihilation From The Cosmic Microwave Background, Phys.Rev.D 88 063502, 2013, 1306.0563 [astro-ph.CO]
3. B. W. Lee and S. Weinberg, Cosmological Lower Bound on Heavy-Neutrino Masses, Phys. Rev. Lett. 39, 165, 1977

Scalar mediator

Inelastic dark matter with a scalar mediator

For the scenario with a scalar leptonphilic mediator ϕ and inelastic Majorana dark matter, the effective Lagrangian as low-energy simplified EFT benchmark is [1,2]:

$$\mathcal{L}_{\text{eff.}} \supset c^{\phi}_{\chi_1\chi_2}\overline{\chi}_1\chi_2\phi - \sum_{l=e,\mu,\tau} c^{\phi}_{ll}\bar{l}l\phi,$$

$$c^{\phi}_{ee} : c^{\phi}_{\mu\mu} : c^{\phi}_{\tau\tau} = m_e : m_\mu : m_\tau .$$

$$\frac{m_{\chi_1}}{m_\phi} = \frac{1}{3}, \quad \Delta = \frac{m_{\chi_2} - m_{\chi_1}}{m_{\chi_1}}, \quad m_e \lesssim m_{\chi_1}, \quad \alpha_{\text{iDM}} = 0.5.$$

1. Herbi K. Dreiner, Howard E. Haber, and Stephen P. Martin, “Two-component spinor techniques and Feynman rules for quantum field theory and supersymmetry” Phys. Rept. 494, 1–196 (2010), 0812.1594 [hep-ph]
2. Chien-Yi Chen, Jonathan Kozaczuk, and Yi-Ming Zhong, “Exploring leptophilic dark matter with NA64-μ,” JHEP 10, 154 (2018), arXiv:1807.03790 [hep-ph]

Parameters of fixed-target experiments

The process of mediator radiation can be represented as:

$$l^{\pm}(p) + N(P_i) \to l^{\pm}(p') + N(P_f) + \mathrm{MED}(k),$$

	NA64e [1]	LDMX [2]	NA64μ [3]
Target material	Pb	Al	Pb
$x_{\mathrm{cut}} = E_{\phi}^{\mathrm{cut}}/E_l$	0.5	0.7	0.5
E_l, GeV, beam energy	100	16	160
Expected statistics	1.5×10^{12}	1×10^{15}	5×10^{13}
Expected background	$\mathrm{N}_{\mathrm{bckg.}} \lesssim 0.75$	$\mathrm{N}_{\mathrm{bckg.}} \ll 1$	$\mathrm{N}_{\mathrm{bckg.}} \lesssim 0.35$

1. Y. M. Andreev et al. (NA64 Collaboration), Search for Light Dark Matter with NA64 at CERN // Phys. Rev. Lett. 131, 161801, 2023
2.Akesson et al. (LDMX collaboration), A High Efficiency Photon Veto for the Light Dark Matter eXperiment // JHEP. - 2020 - T. 04. - C. 003.
3. H. Sieber, D. Banerjee, P. Crivelli, E. Depero, S.N. Gninenko, D.V. Kirpichnikov, M.M. Kirsanov, V. Poliakov, and L. Molina Bueno, Prospects in the search for a new light Z' boson with the NA64μ experiment at the CERN SPS // Phys. Rev. D 105, 052006, 2022

Number of signal events in the invisible mode

The differential cross section for the production of a mediator in the nuclear field takes the form [1,2]:

$$\frac{d\sigma_{2\to 3}}{dx d\cos(\theta_{\mathrm{MED}})} = \frac{(c_{ll}^{\mathrm{MED}})^2 \alpha^3 Z^2}{4\pi} \frac{|\boldsymbol{k}| E_p}{|\boldsymbol{P}||\boldsymbol{k}-\boldsymbol{p}|} \int\limits_{t_{\min}}^{t_{\max}} dt \frac{F^2(t)}{t^2} \frac{1}{8M^2} \int\limits_{0}^{2\pi} \frac{d\phi}{2\pi} \left|\mathcal{A}_{2\to 3}^{\mathrm{MED}}\right|^2 ,$$

where $x = E_{\mathrm{MED}}/E_l$ is the fraction of the total energy of the mediator relative to the initial lepton.
The number of signal events in the thin-target approximation is [2]:

$$N_{\mathrm{MED}}^{\mathrm{brem.}} \simeq \mathrm{LOT} \cdot \frac{\rho N_A}{A} L_T \int\limits_{x_{min}}^{x_{max}} dx \frac{d\sigma_{2\to 3}(E_0)}{dx} .$$

1.Kwang Je Kim and Yung-Su Tsai. Improved Weizsacker-Williams Method and Its Application to Lepton and W-Boson Pair Production. Phys. Rev. D, 8:3109, 1973.
2. J. D. Bjorken, R. Essig, P. Schuster, and N. Toro, Phys. Rev. D 80, 075018 (2009), arXiv:0906.0580.

Relic curves of dark matter

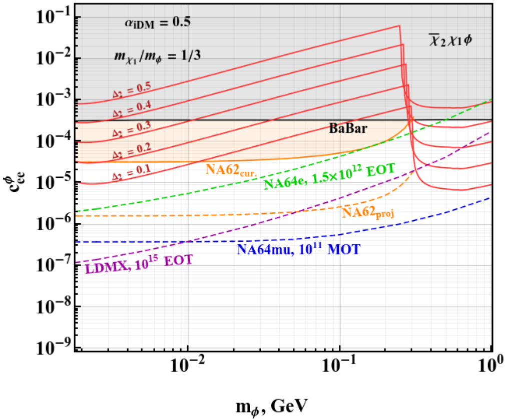
The Boltzmann equation for the total density of dark matter particles, n, leads to relate the interaction in the early Universe and the observed density of dark matter as [1-3]:

$$\dot{n} = -3Hn - \sum_{i,j,f} \langle \sigma_{ij} v_{ij} \rangle \left(n_i n_j - n_i^{\mathrm{eq}} n_j^{\mathrm{eq}} \right) \Rightarrow \Omega_c h^2 \propto \left(\int\limits_{x_f}^{\infty} \frac{\langle \sigma_{\mathrm{eff}} v \rangle}{x^2} dx \right)^{-1} ,$$

$$\langle \sigma_{ij} v_{ij} \rangle \simeq \left\langle \sum_{k=0}^{\infty} \frac{a_k v_-^{2k+1}}{k!} \right\rangle \simeq a_0 + \frac{3}{2} \left(\frac{2m}{\mu_{ij}} \right) a_1 \left(\frac{m}{T} \right)^{-1} + \frac{15}{8} \left(\frac{2m}{\mu_{ij}} \right)^2 a_2 \left(\frac{m}{T} \right)^{-2} .$$

1. Kim Griest and David Seckel, “Three exceptions in the calculation of relic abundances” Phys. Rev. D 43, 3191–3203 (1991)
2. Joakim Edsjo and Paolo Gondolo, “Neutralino relic density including coannihilations” Phys. Rev. D 56, 1879–1894 (1997), arXiv:hep-ph/9704361
3. Paolo Gondolo and Graciela Gelmini, “Cosmic abundances of stable particles: Improved analysis” Nucl.Phys. B 360, 145–179 (1991).

Constraint from fixed-target experiments



1. I. V. Voronchikhin and D. V. Kirpichnikov, “Examining scalar portal inelastic dark matter with lepton fixed-target experiments,” Phys. Rev. D 113, 015031 (2026), arXiv:2505.04290 [hep-ph]

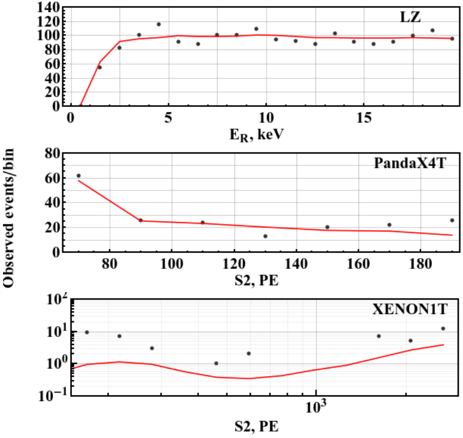
Parameters of direct-detection search experiments

Scattering of halo dark matter on atomic electrons of the detector:

$$\chi_i(p_i) + e^-(p_3) \to \chi_f(p_f) + e^-(p_4),$$

	XENON1T [1]	PandaX-4T [2]	LZ [3]
Z	54	54	54
E_d, keV	0.186 – 3	0.07 – 0.23	1 – 20
ε, t × day	356	200	1533

1. E. Aprile et al. (XENON), "Light Dark Matter Search with Ionization Signals in XENON1T," Phys. Rev. Lett. 123, 251801 (2019), 1907.11485 [hep-ex].
2. Shuaijie Li et al. (PandaX), "Search for Light Dark Matter with Ionization Signals in the PandaX-4T Experiment," Phys. Rev. Lett. 130, 261001 (2023), 2212.10067 [hep-ex].
3. D. S. Akerib et al. (LZ), "Search for New Physics via Low-Energy Electron Recoils with a 4.2 Tonne-Year Exposure from the LZ Experiment," (2025), 2511.17350 [hep-ex].



Number of signal events in direct-detection experiments

The thermally averaged differential cross section is [1]:

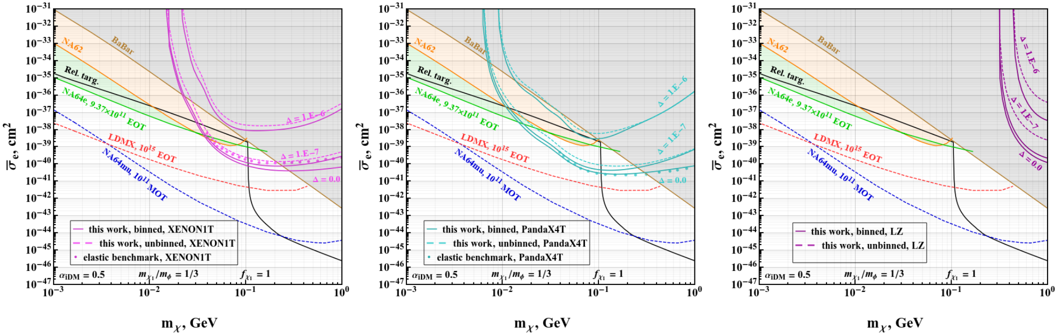
$$\frac{d\langle\sigma v\rangle}{dE_{\mathrm{d}}} = \frac{\bar{\sigma}_e}{2\mu_{\chi e}^2} \int\limits_{q_-(v_{\chi_1}^{\max})}^{q_+(v_{\chi_1}^{\max})} q \frac{K(E_{\mathrm{d}}, q)}{E_{\mathrm{H}}} \eta\left(v_{\min}\right) \left|F_{\mathrm{DM}}(q)\right|^2 dq,$$

One can calculate number of theoretical signal events by the expression [2]:

$$N_{\text{sign.}} = \epsilon \cdot \sum_i R_{ij} \frac{N_T \rho_\chi}{m_T m_\chi} \frac{d\langle\sigma v\rangle}{dE_{\mathrm{d}}}(E_{\mathrm{d}i}) dE_{\mathrm{d}i},$$

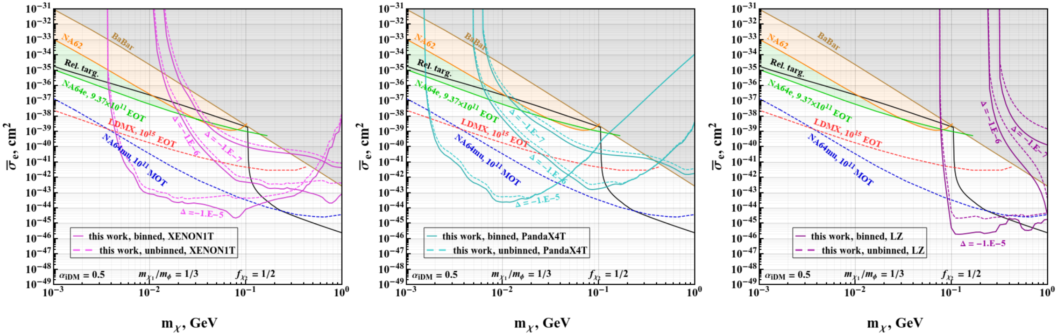
1. A. R. Caddell, V. V. Flambaum, and B. M. Roberts, "Accurate electron-recoil ionization factors for dark matter direct detection in xenon, krypton, and argon," Phys. Rev. D 108, 083030 (2023), arXiv:2305.05125 [hep-ph].
2. R. Essig, A. Manalaysay, J. Mardon, P. Sorensen, and T. Volansky, "First Direct Detection Limits on sub-GeV Dark Matter from XENON10," Phys. Rev. Lett. 109, 021301 (2012), arXiv:1206.2644 [astro-ph.CO].

Constraint for endothermic scenario



1. I. V. Voronchikhin and D. V. Kirpichnikov, "Direct-detection constraints on inelastic dark matter with a scalar mediator", 2604.06929 [hep-ph]

Constraint for exothermic scenarios



1. I. V. Voronchikhin and D. V. Kirpichnikov, “Direct-detection constraints on inelastic dark matter with a scalar mediator”, 2604.06929 [hep-ph]

Magnetic dipole dark matter

Semi-visible mode in the planned ILC-BDX experiment

Effective Lagrangian is [1]:

$$\mathcal{L} \supset \frac{1}{\Lambda_{\mathrm{M}}} \bar{\chi}_1 \sigma^{\mu\nu} \chi_0 F_{\mu\nu}, \qquad \Delta = \frac{m_{\chi_1} - m_{\chi_1}}{m_{\chi_0}}.$$

The dark matter production process is:

$$e^- N \to e^- N \gamma^* \to e^- N \bar{\chi}_0 \chi_1.$$

Boosted dark matter can subsequently scatter off detector electrons as:

$$\chi_i(p) + e(k) \to \chi_j(p') + e(k')$$

	ILC-BDX [2]
$Z_{\text{targ.}}$	8
E_0, ГэВ	125 (250)
$L_{\text{sh.}}$, м	70
$L_{\text{dec.}}$, м	50
$Z_{\text{det.}}$	56
$E_{\text{th.}}$ ГэВ	1
$\theta_\chi^{\max}$ ГэВ	0.874°
LOT(s$_{\text{up}}$)	$4.0 \times 10^{21}(3.8)$
LOT$_{\max}$(s$_{\text{up}}$)	$4.0 \times 10^{22}(7.3)$

1. Herbi K. Dreiner, Howard E. Haber, and Stephen P. Martin, “Two-component spinor techniques and Feynman rules for quantum field theory and supersymmetry” Phys. Rept. 494, 1–196 (2010), 0812.1594 [hep-ph]
2. Kento Asai, Sho Iwamoto, Yasuhito Sakaki, and Daiki Ueda, “New physics searches at the ILC positron and electron beam dumps,” JHEP 09, 183 (2021), arXiv:2105.13768 [hep-ph]

Number of signal events in direct-detection experiments

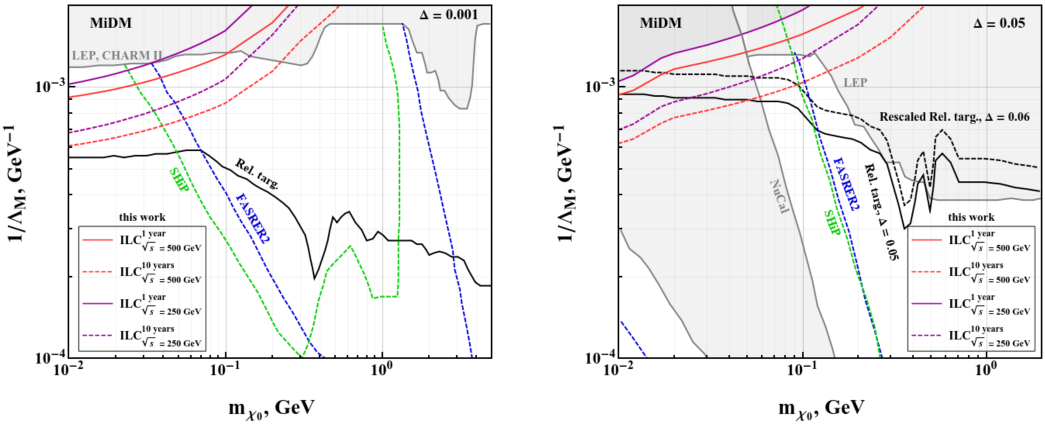
The electron-recoil event with the energy threshold $E_{\rm th} = 1$ GeV is:

$$N^{\chi_i}_{\rm det.} \simeq {\rm EOT} \times \frac{\rho N_A}{A} \times L_T \int\limits_{E_{\min}}^{E_{\max}} dE_{\chi_i} \int\limits_0^{\theta_{\max}} d\theta_{\chi_i} \frac{d\sigma_{2\to 4}}{dE_{\chi_i} d\theta_{\chi_i}} P^{\chi_i}_{\rm scat.}(E_{\chi_i}),$$

The probability of χ_0 and $\chi_1$scattering inside the detector is:

$$P^{\chi_0}_{\rm scat.} = n_{\rm det} l_{\rm det} \sigma^{\rm cut}_{2\to 2}(E_{\chi_0}), \qquad P^{\chi_1}_{\rm scat.} = n_{\rm det} l_{\rm det} \sigma^{\rm cut}_{2\to 2}(E_{\chi_1}) \exp\left(-\frac{L_{\rm sh} + L_{\rm dec.}}{d_{\chi_1}}\right),$$

Constraint of the ILC-BDX experiment



1. I. V. Voronchikhin and D. V. Kirpichnikov, “Prospects of boosted magnetic dipole inelastic fermion dark matter at ILC-BDX”, 2604.20385 [hep-ph]

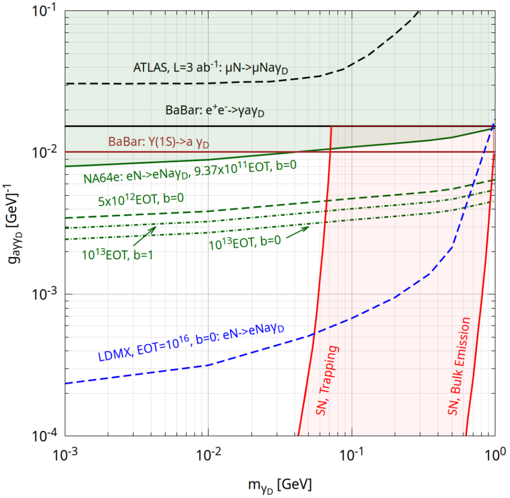
Dark axion portal

Constraint from the NA64e experiment

$$\mathcal{L}_{\text{dark axion portal}} \supset \frac{g_{a\gamma\gamma_D}}{2} a F_{\mu\nu} \widetilde{F}'^{\mu\nu}\,,$$

$$eN \to eNa\gamma_D,$$

1. S. N. Gninenko, N. V. Krasnikov, V. E. Lyubovitskij, S. Kuleshov, A. S. Zhevlakov, I. V. Voronchikhin, and D. V. Kirpichnikov, "Constraints on dark axion portal: missing energy and fermion EDMs," (2026), arXiv:2602.11405 [hep-ph]



Results

The results are:

1. Constraints on the parameter space of inelastic dark matter models with a scalar mediator from the invisible mode of experiments with a lepton primary beam scattered on a fixed target.
2. Relic curves for a model of inelastic dark matter with a scalar mediator interacting with the lepton sector.
3. Constraints on the parameter space of inelastic dark matter models with a scalar mediator from direct search experiments.
4. Constraints on the parameter space of the magnetic dipole dark matter model from fixed-target experiments in semi-visible mode.
5. Constraints on the parameter space of the dark axion portal model from fixed-target experiments.

The work was supported by grant RSF-25-12-00309.

Thank you for your attention!

Рождение медиатора в экспериментах с фиксированной мишенью в приближении Вайцзеккера-Вильямса

Метод Вайцзеккера-Вильямса

Формула Вайцзеккера-Вильямса для дифференциального сечения [1,2]:

$$\left.\frac{d\sigma(p+P_i\to p'+P_f+k)}{dx\,d\cos(\theta_{\mathrm{MED}})}\right|_{\mathrm{WW}}=\frac{\alpha\chi}{\pi}\,\frac{E_l^2x\beta_{\mathrm{MED}}}{1-x}\,\left.\frac{d\sigma(p+q\to k+p')}{d(pk)}\right|_{t=t_{\min}},$$

поток виртуальных фотонов χ выражается через упругий форм-фактор $F(t)$ и выражение для $t_{\min}$ принимают вид:

$$\chi=Z^2\int\limits_{t_{\min}}^{t_{\max}}\frac{t-t_{\min}}{t^2}F^2(t)dt,$$

$$t_{\min}(x,\theta_{\mathrm{MED}})\simeq(E_l^2\theta_{\mathrm{MED}}^2x+m_{\mathrm{MED}}^2(1-x)/x+m_l^2x)^2/(4E_l^2(1-x)^2)>t_{\min}^{\mathrm{IWW}}=m_{\mathrm{MED}}^4/(4E_0^2).$$

1.Kwang Je Kim and Yung-Su Tsai. Improved Weizsacker-Williams Method and Its Application to Lepton and W-Boson Pair Production. Phys. Rev. D, 8:3109, 1973.
2. J. D. Bjorken, R. Essig, P. Schuster, and N. Toro, Phys. Rev. D 80, 075018 (2009), arXiv:0906.0580.

Форм-фактор

Атомный форм-фактор Тсаи-Шиффа, Хельма и экспоненциальный, в следующем виде, соответственно [1, 2, 3]:

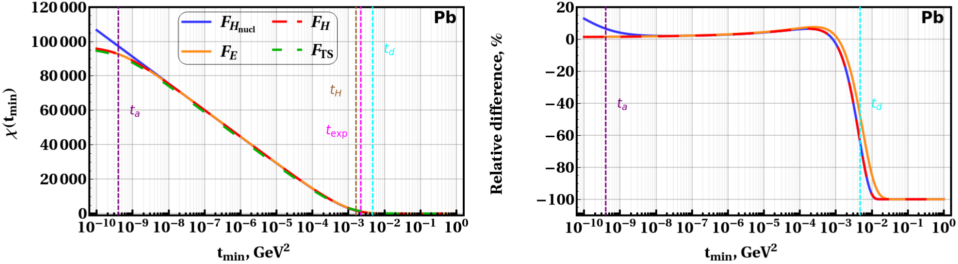
$$F_{\mathrm{TS}}(t) = F_{\mathrm{scr}}(t)\frac{1}{(1+t/t_{\mathrm{d}})}, \quad F_{\mathrm{H}}(t) = F_{\mathrm{scr}}(t)\frac{3j_1(\sqrt{t}R_{\mathrm{H}})}{\sqrt{t}R_{\mathrm{H}}}e^{-s_{\mathrm{H}}^2 t/2},$$

$$F_{\mathrm{E}}(t) = F_{\mathrm{scr}}(t)\exp\left(-tR_{\mathrm{exp}}^2/6\right),$$

где $F_{\mathrm{scr}}(t) = t/(t_{\mathrm{a}}(Z)+t)$ - форм-фактор, соответствующий экранированию атомными электронами [1].

1.Yung-Su Tsai. Pair production and bremsstrahlung of charged leptons. Rev. Mod. Phys., 46:815, 1974.
2.Herbi K. Dreiner, Howard E. Haber, and Stephen P. Martin. Two-component spinor techniques and Feynman rules for quantum field theory and supersymmetry. Phys.Rept., 494:1–196, 2010,
3.Katherine Freese, Joshua A. Frieman, and Andrew Gould. Signal Modulation in Cold Dark Matter Detection. Phys. Rev. D, 37:3388–3405, 1988

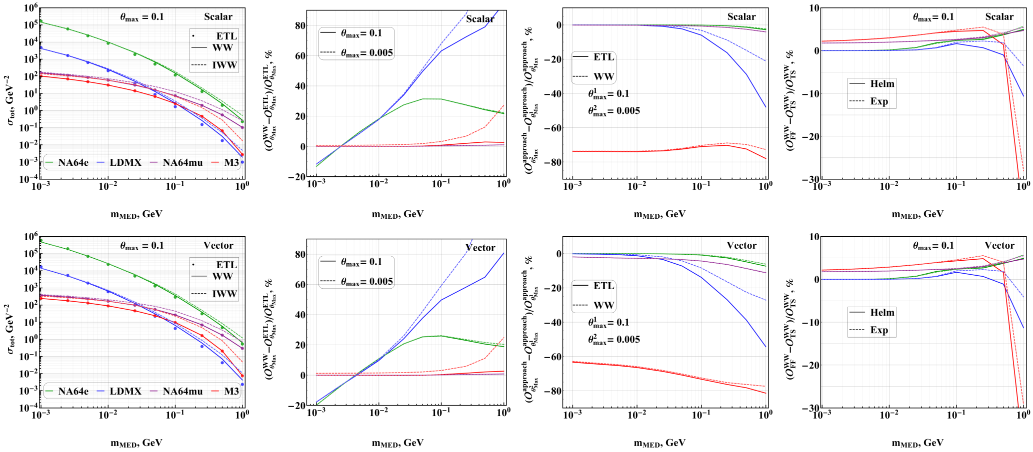
Поток виртуальных фотонов



(Слева) виртуальный поток фотонов как функция нижнего предела $t_{\min}$ при массе медиатора 1 ГэВ для форм-факторов Тсаи-Шиффа F_{TS}, ядерного Хелма $F_{\mathrm{H_{nucl}}}$, атомного Хелма F_H и атомного экспоненциального F_{E}. (Справа) относительная разница между потоком виртуальных фотонов с форм-фактором Тсаи-Шиффа и другими форм-факторами [1].

1. I. V. Voronchikhin and D. V. Kirpichnikov. Probing hidden spin-2 mediator of dark matter with NA64e, LDMX, NA64μ, and M3. Phys. Rev. D, 106(11):115041, 2022

Полное сечение рождения скалярного и векторного медиаторов



Полное сечение рождения скалярного и векторного медиаторов [1].

1. Voronchikhin I. V., Kirpichnikov D. V. Implication of the Weizsacker-Williams approximation for the dark matter mediator production //Physical Review D. – 2025. – Т. 111. – №. 3. – С. 035034.