Rare signatures at missing momentum experiments

D. V. Kirpichnikov

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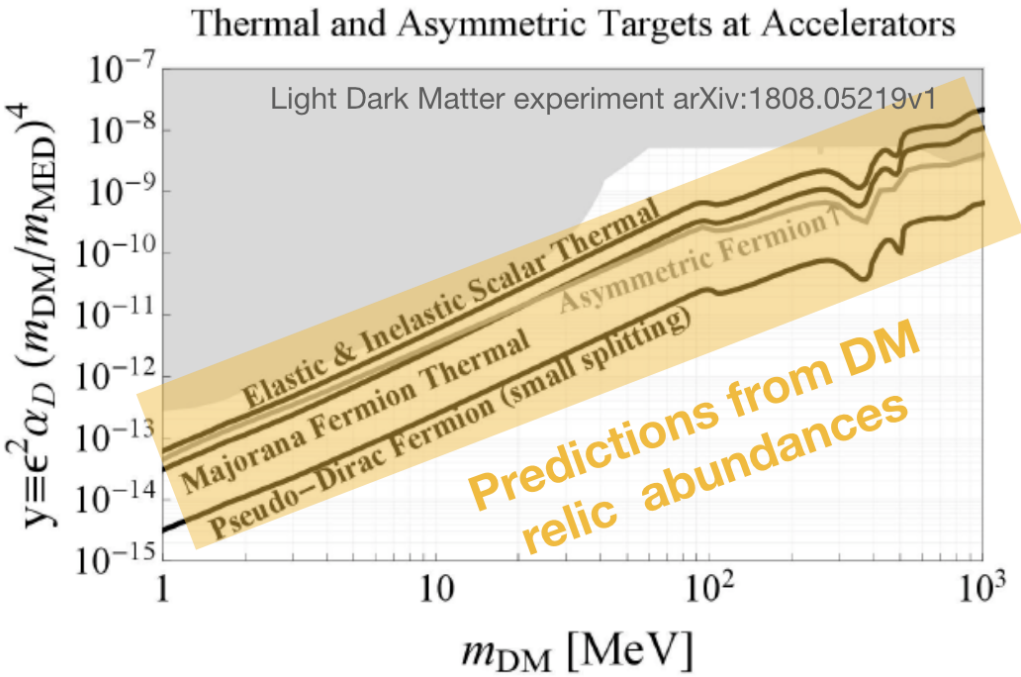
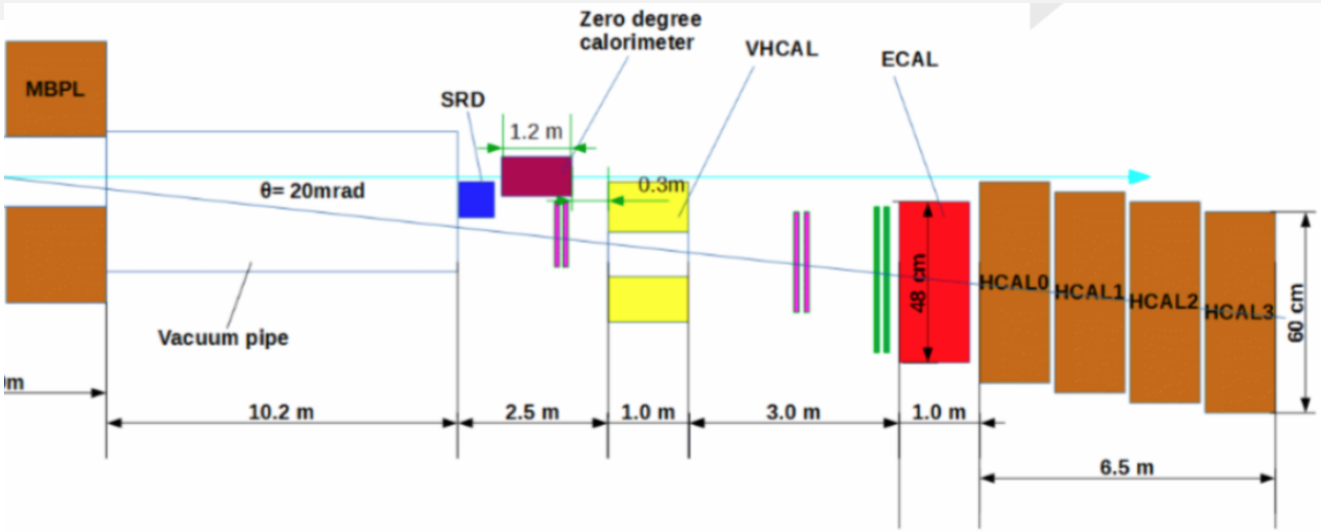
Motivations for searching for light DM mediators

- They are popular candidates for solution of experimental anomalies: MiniBooNE, ^{8}Be, XENON1T
- They could act as a mediator to a Dark Dector (DS). DS consists of particles and fields which are singlets with respect to the gauge group of the SM. It interacts with the SM possibly via a new interaction transmitted by the mediator.
  DARK MATTER $\longleftrightarrow$ MEDIATOR $\longleftrightarrow$ STANDARD MODEL
- The most popular models of Dark Matter χ mediated by vector: **Scalar Dark Matter, Majorana Dark Matter, Pseudo Dirac Dark Matter**

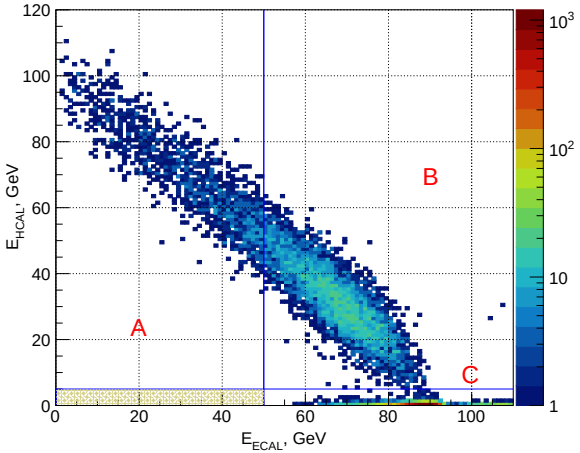


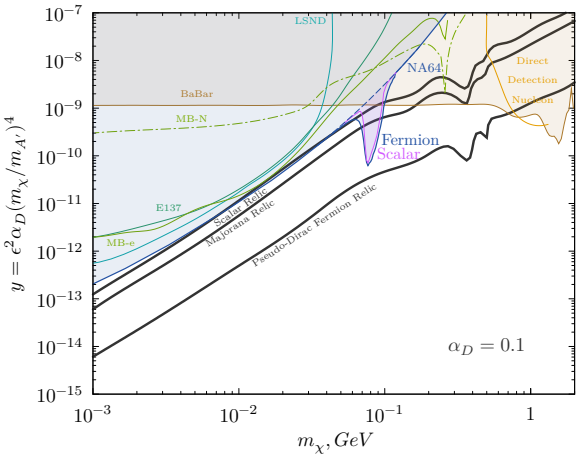
NA64e experiment setup (invisible mode): Proposed by S.Gninenko Phys.Rev.D 89 (2014) 7, 07500 (INR Moscow)

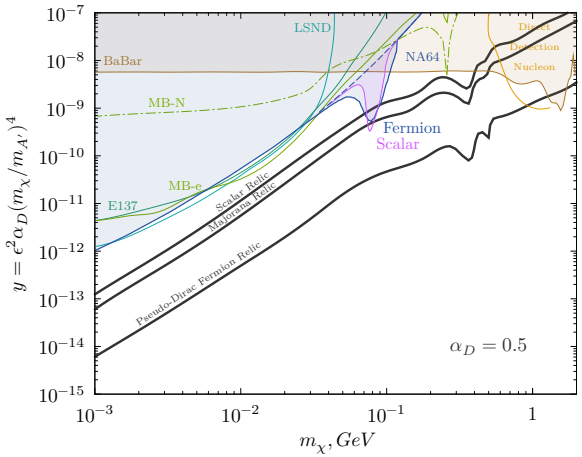


- **NA64** is designed to search for dark sector physics in missing-energy events with $e^{\pm}$, μ, π, K, p beams.
- **Main Components:** a) clean $E_0 = 100$ GeV e^- beam; b) e^- tagging system: tracker+SRD; c) hermetic ECAL+HCAL;
- **Signature:** a) in: 100 GeV e^- track; b) out: $E_{ECAL} < E_0/2$ 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

NA64e current results: brems. and annihilation channels

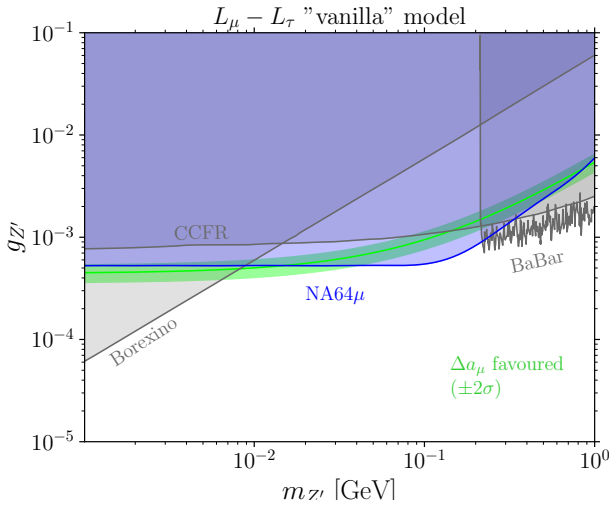


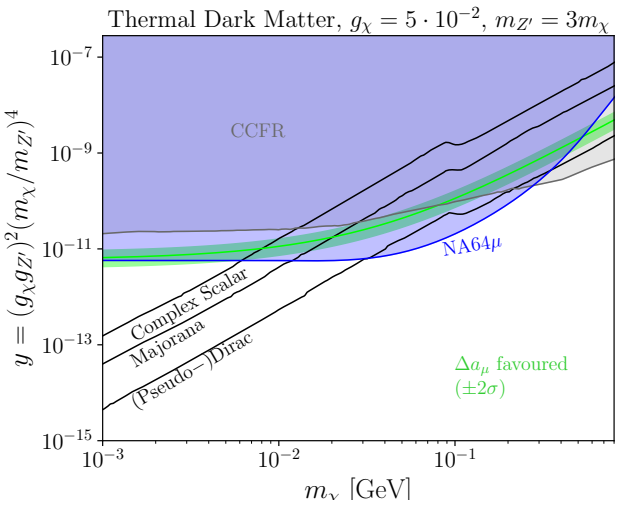


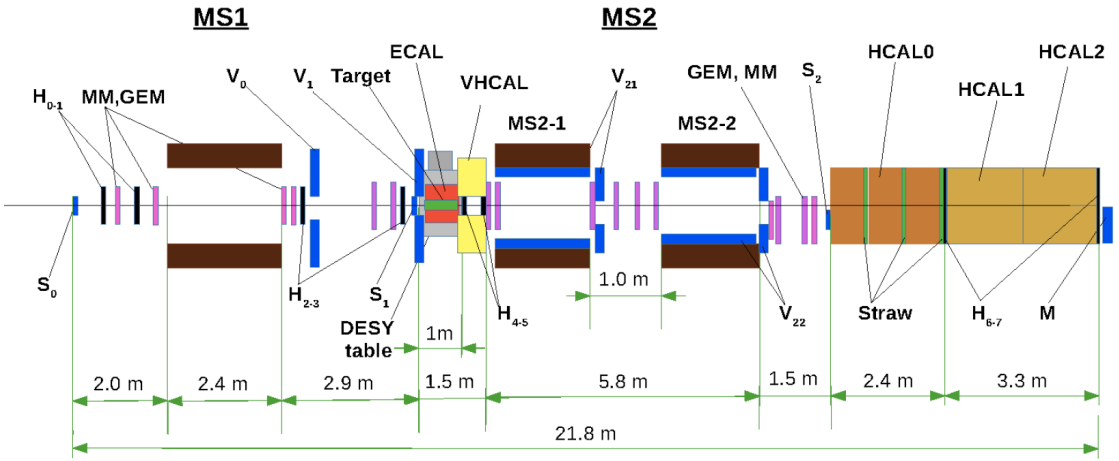


- $E_{beam} \simeq E_{HCAL} + E_{ECAL}$ **is the energy conservation for the experimental facility**
- **NA64e allows to probe invisible decays of Dark Matter mediators:** $eN \to eNX(X \to \chi\bar{\chi})$**, where** X **is a general hidden boson (spin 0, spin 1, spin 2) the mediator between SM and DM particle** χ **(Scalar, Dirac or Majorana).**
- **Signal box (A) of missing energy signature: no events in** $E_{ECAL} \lesssim 50$ **GeV &&** $E_{HCAL} \lesssim 1$ **GeV**
- **Resonance annihilation channel using the secondary positrons present in the EM shower in the target induced by the initial electron beam**
- **Improvement limit on** ϵ **up to factor** 10 **in the resonant region** $m_{A'} \simeq (2m_e E_{cut})^{1/2}$
- **Probing resonant** $e^+e^- \to A' \to \chi\chi$ **production by electron beam: Phys. Rev. D 104 (2021) 9 (2108.04195 [hep-ph])**
- **Current result for combined statistics** 9.37×10^{11}**: Phys.Rev.Lett. 131 (2023) 16, 161801**

NA64μ







- **Experimental runs**
  – 3 w run at M2 in Oct.- Nov. 2021
  – 3 w run in April 2022, 100-160 GeV μ,
  – 3 w run in July + Aug 2023, 100-160 GeV μ,
- **GOAL: probing $L_\mu - L_\tau$ scenario and some DM benchmark models with NA64μ Phys.Rev.D 104 (2021) 7, 076012, e-Print: 2107.13297 [hep-ph]**
- **Current result: Phys. Rev. Lett. 132 (2024) 21, 211803**
  PHYSICAL REVIEW D 110, 112015 (2024) $\rightarrow 1.98 \times 10^{10}$ MOT

Probing Millicharged particles (MCP) with NA64e

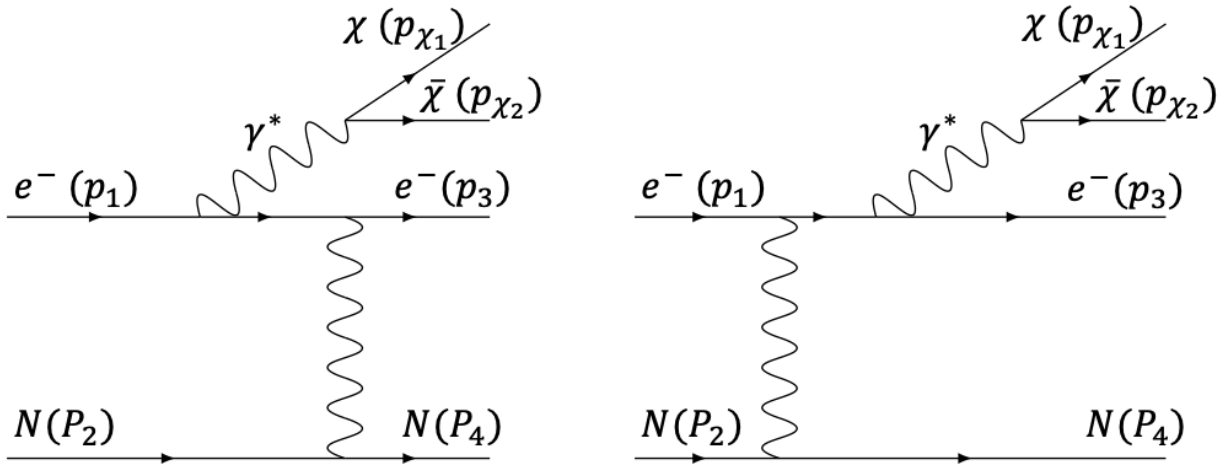
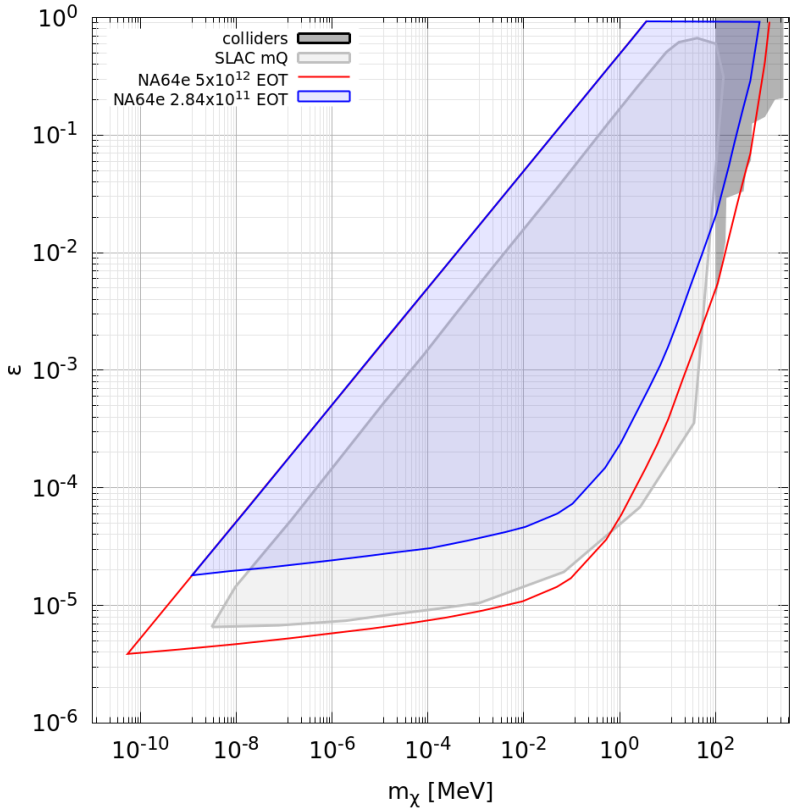


Figure: Feynman diagrams for MCP pair production process.

The Lagrangian can be written as follows

$$\mathcal{L} \supset i\bar{\chi}\gamma^{\mu}\partial_{\mu}\chi - m_{\chi}\bar{\chi}\chi + e\epsilon A_{\mu}\bar{\chi}\gamma^{\mu}\chi, \tag{1}$$

where m_{χ} is the Dirac mass of the hidden MCPs and A_{μ} is the SM photon.



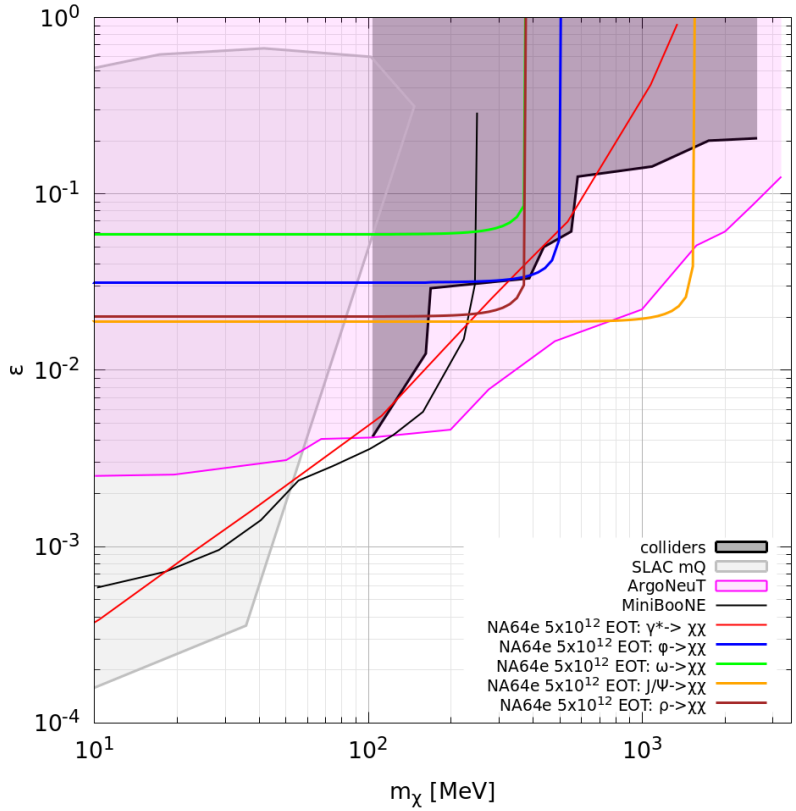
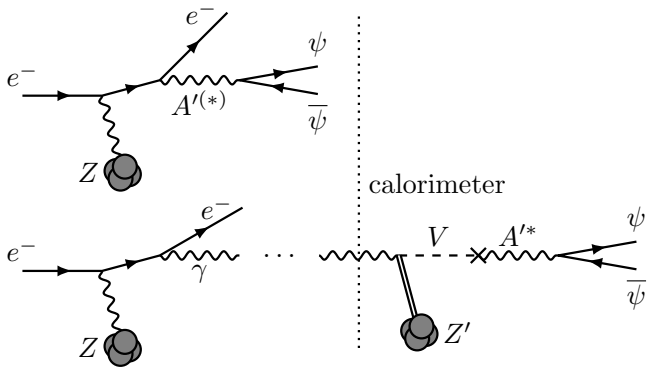
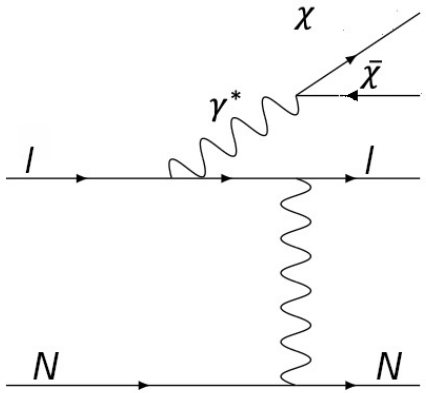
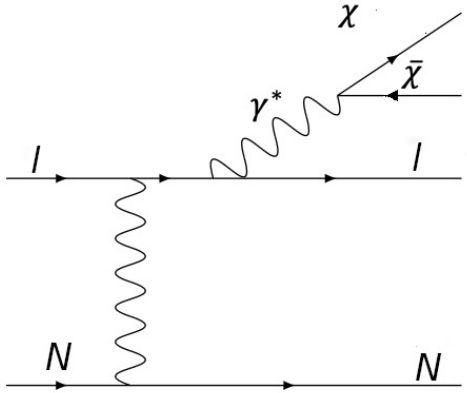


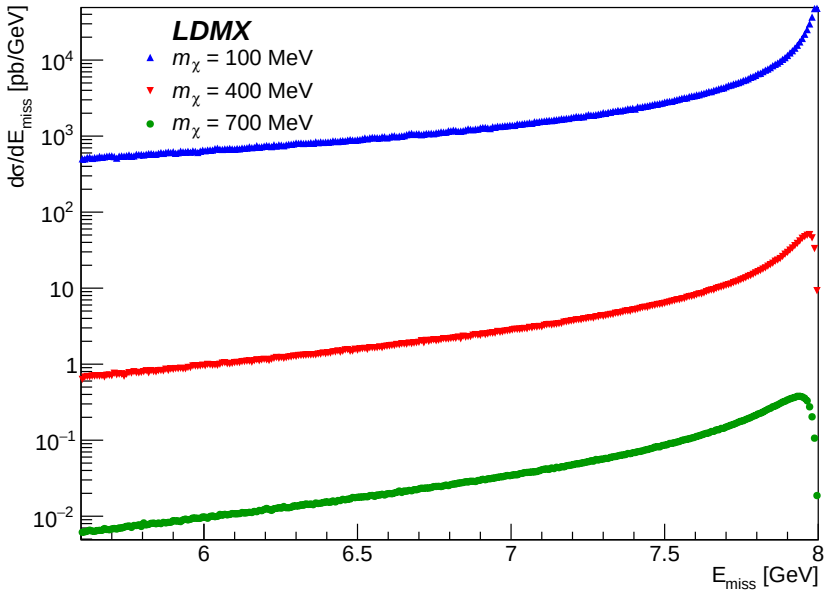
Figure: The expected sensitivity (90% C.L.) of NA64*e* in the (ϵ, m_χ) plane. We take into account invisible decays of vector mesons to the MCPs and MCP production by the energetic beam electrons via bremsstrahlung-like mode $\gamma^* \to \chi\bar{\chi}$ for the prospect statistics $N_{EOT} = 5 \times 10^{12}$ and MCP mass range $10\,\text{MeV} \leq m_\chi \leq 1.5$ GeV. The Sub-MeV limits are complementary to the CONNIE experiment.

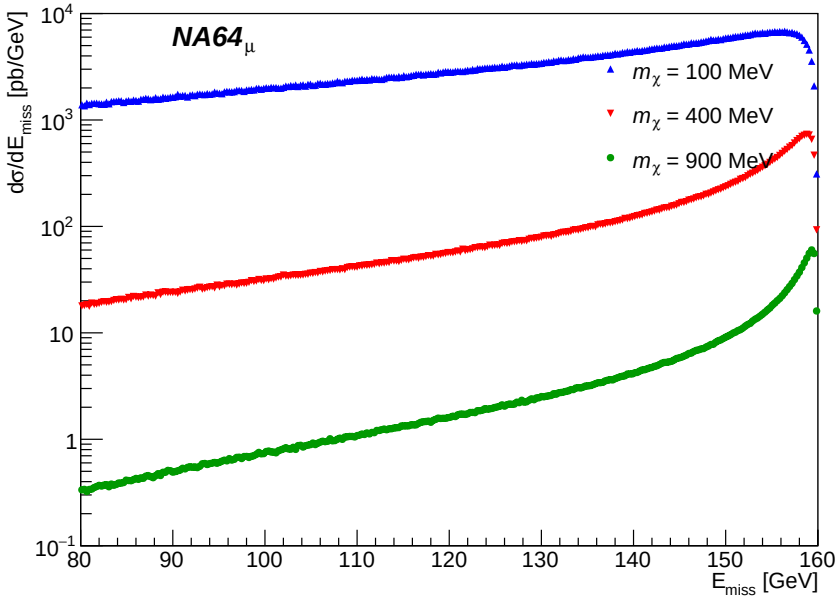
Probing MCP with NA64μ and LDMX



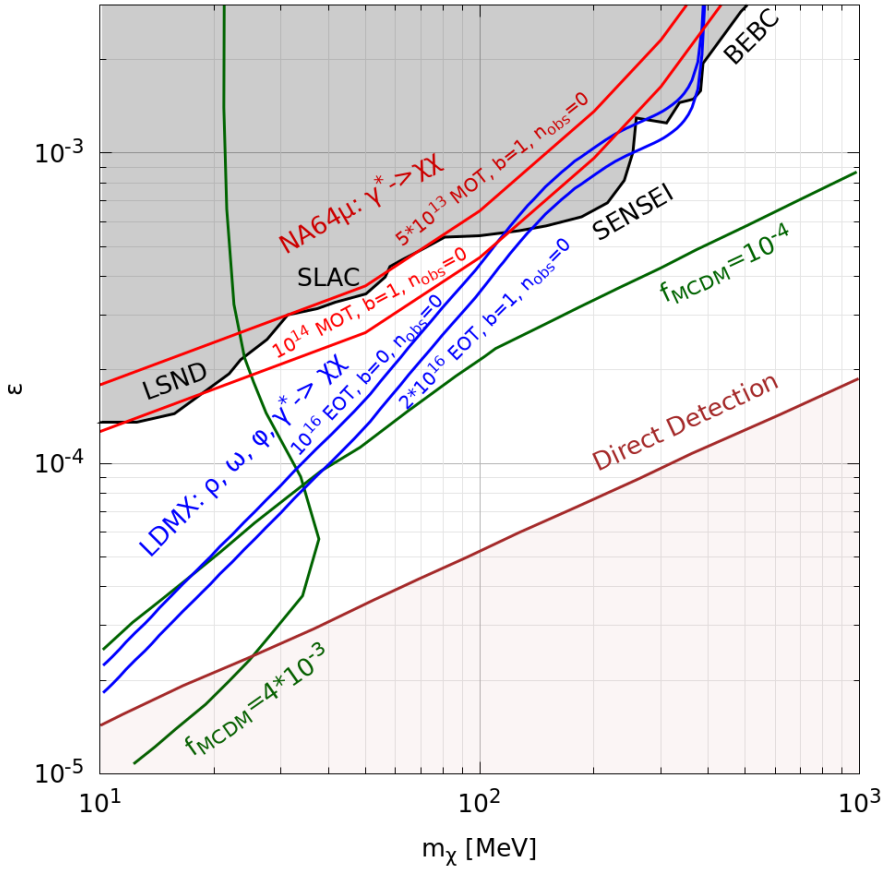


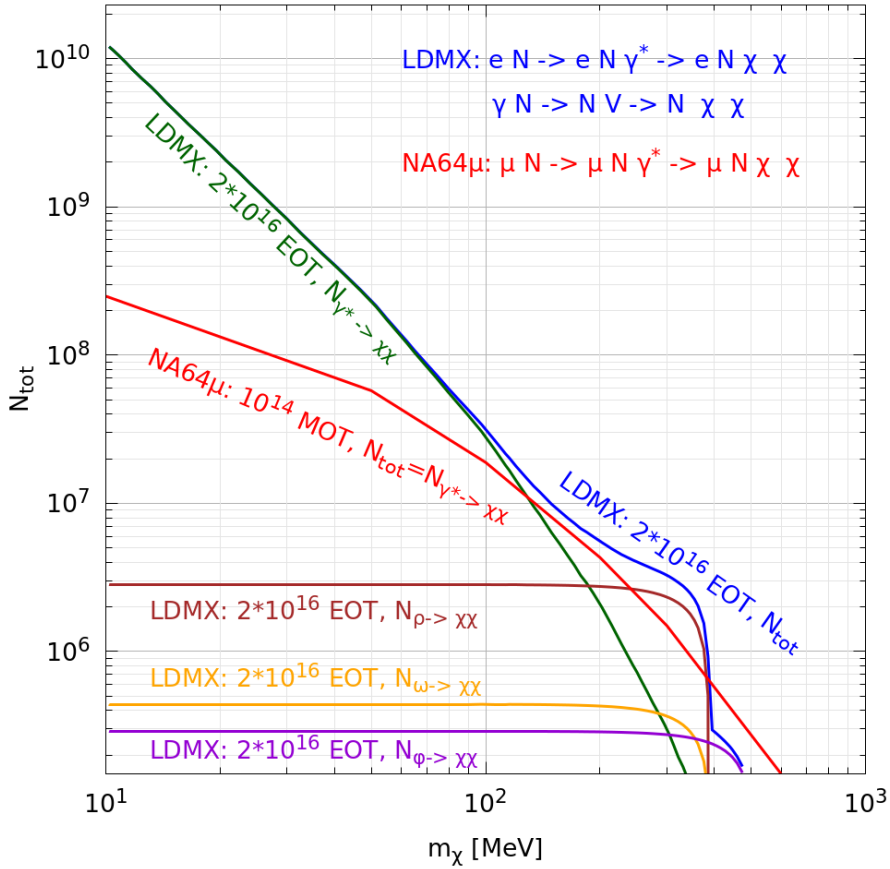




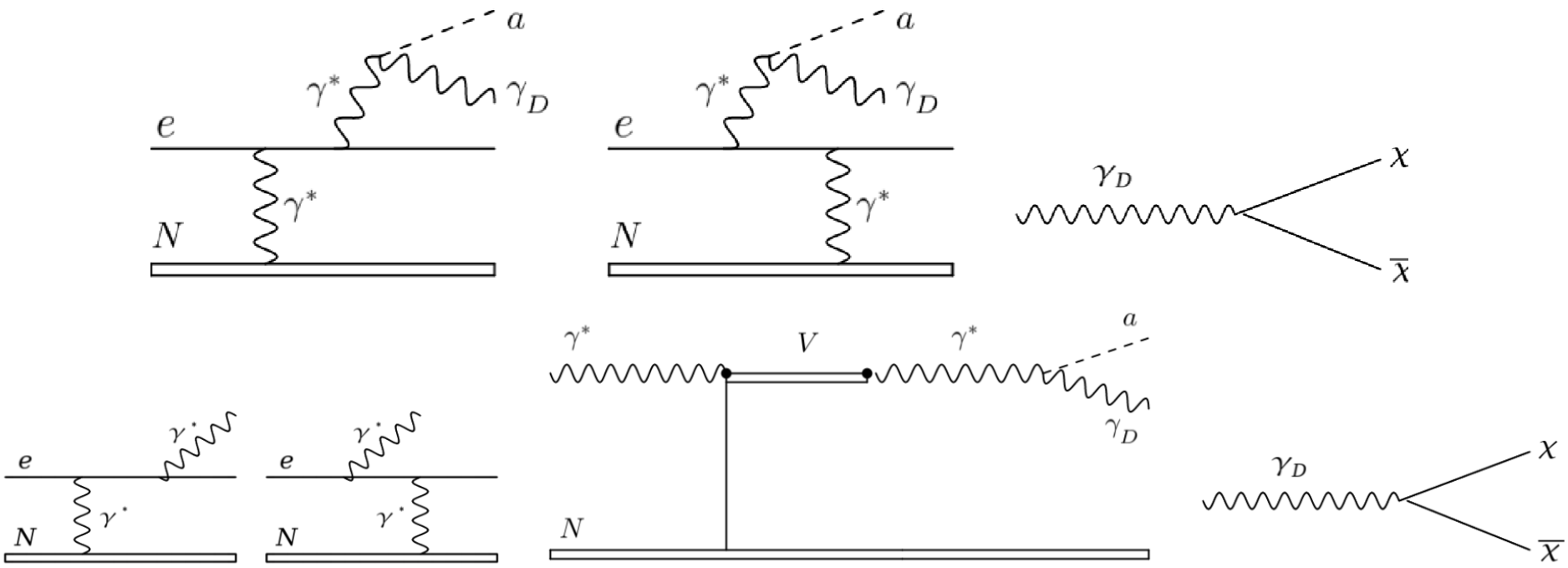


Probing MCP with NA64μ and LDMX: EPJC, 2505.04295





Probing Dark Axion Portal

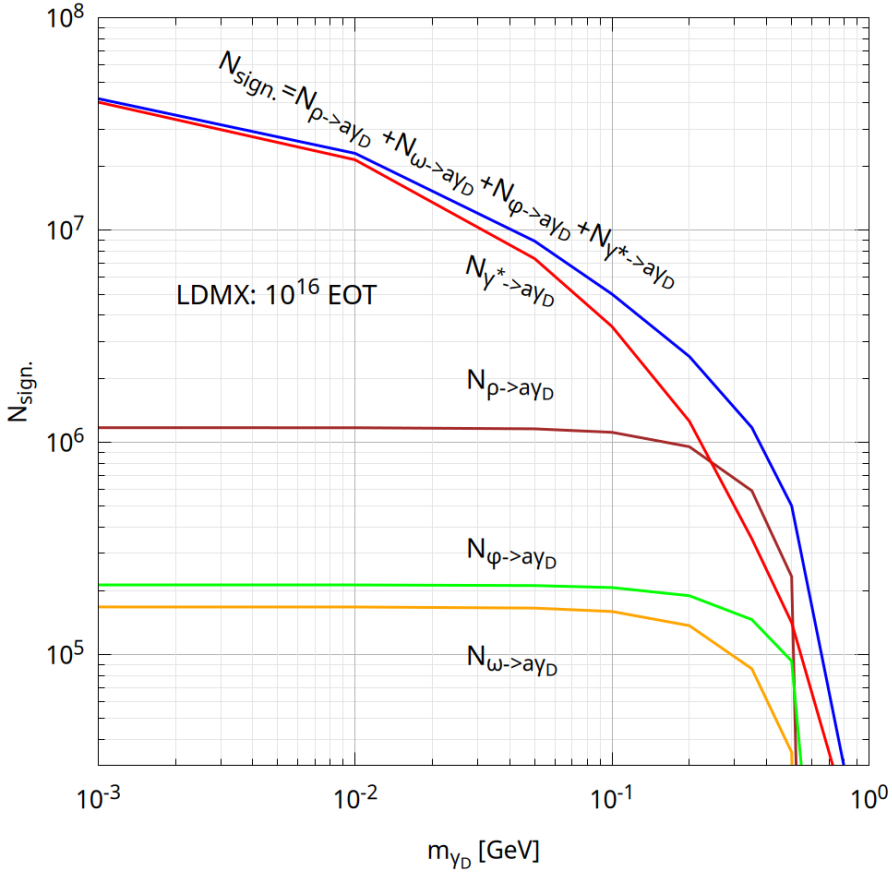


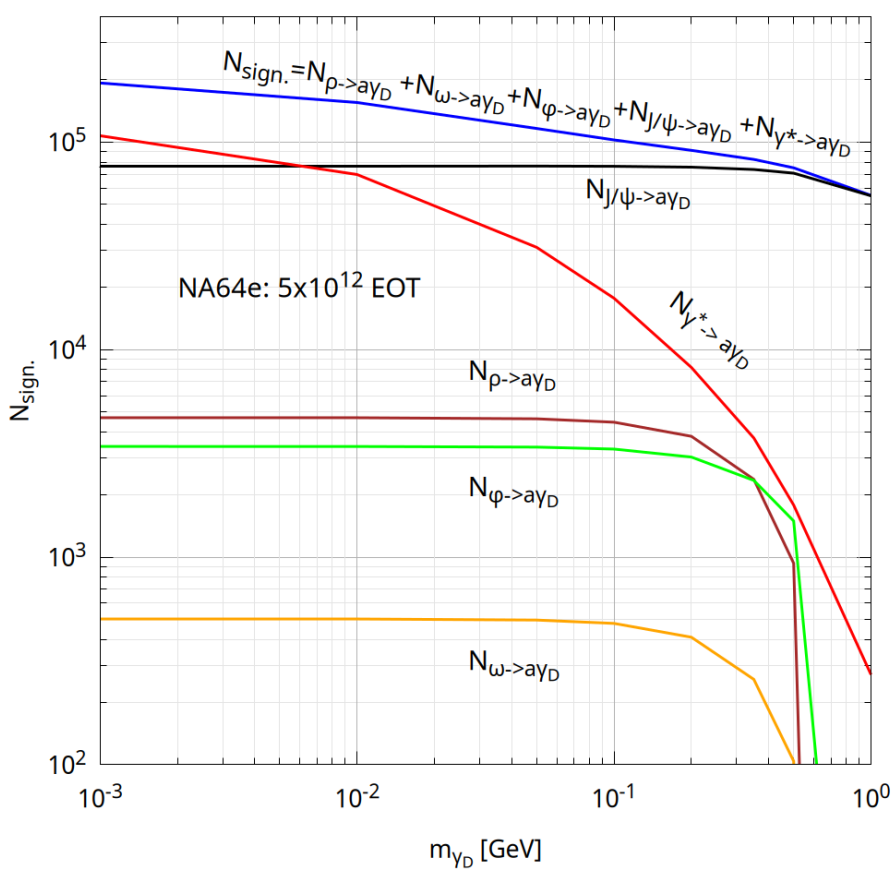
$$\mathcal{L}_{\text{dark axion portal}} \supset \frac{g_{a\gamma\gamma_D}}{2} a F_{\mu\nu} \widetilde{F}'^{\mu\nu}, \quad \mathcal{L}_{\text{DS}} \supset \bar{\chi} \left(i\gamma^\mu D_\mu - m_\chi \right) \chi, \tag{2}$$

$$N_{\gamma^* \to a\gamma_D} \simeq \text{EOT} \cdot \frac{\rho N_A}{A} L_T \int_{E_{\text{min}}}^{E_{\text{max}}} dE_{\text{miss}} \frac{d\sigma_{2\to 4}(E_e)}{dE_{\text{miss}}}, \quad N_{V\to a\gamma_D} \simeq N_V \times \text{Br}_{V\to a\gamma_D}, \tag{3}$$

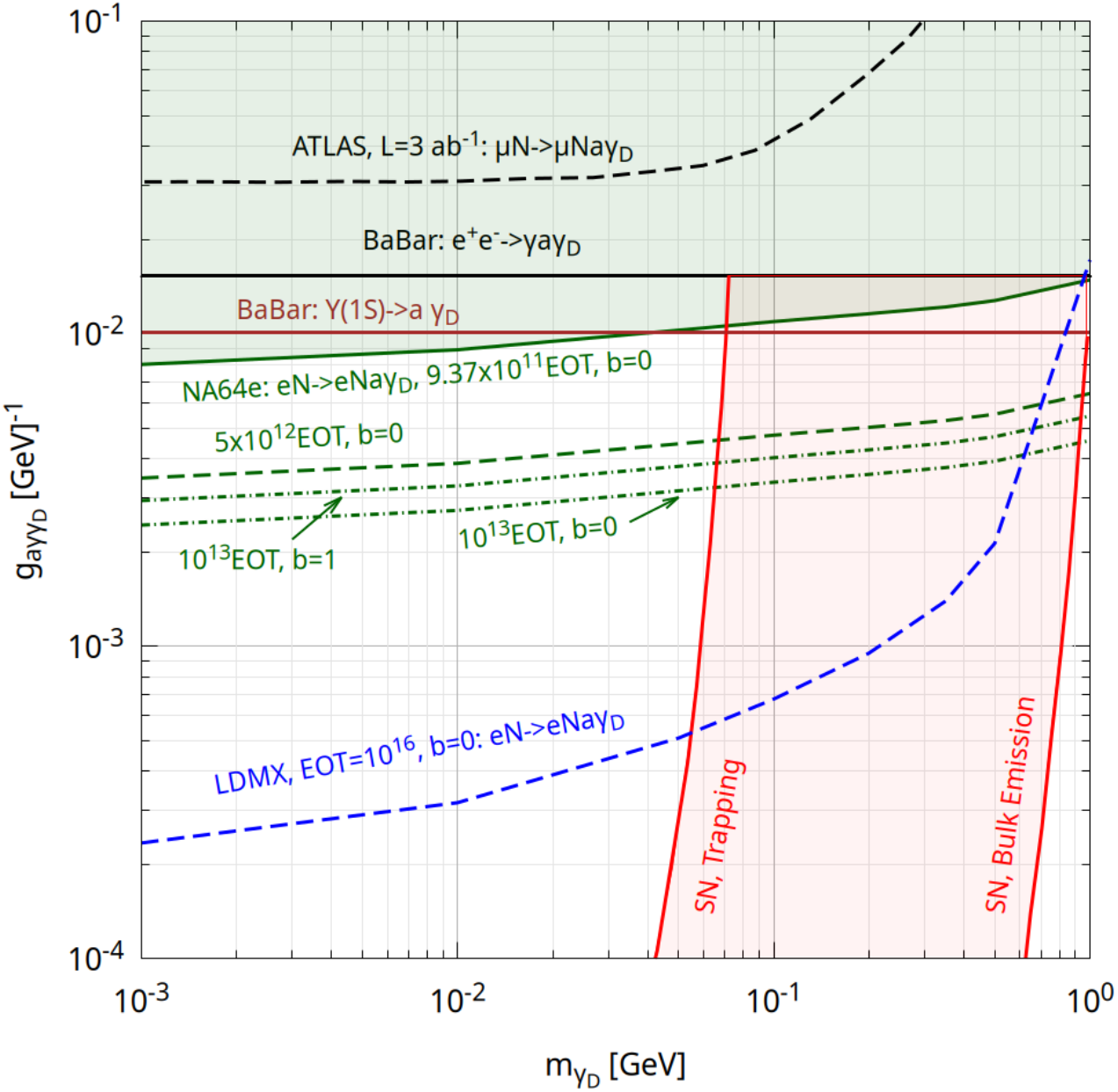
$$\mathcal{L}_{\text{VMD}} \supset -\sum_V \frac{e\, m_V^2}{g_V} A_\mu V^\mu, \quad \Gamma_{V\to a\gamma_D} = \frac{e^2 g_{a\gamma\gamma_D}^2}{96\pi} \frac{m_V^3}{g_V^2} \left(1 - \frac{m_{\gamma_D}^2}{m_V^2} \right)^3. \tag{4}$$

Probing Dark Axion Portal: number of signal events

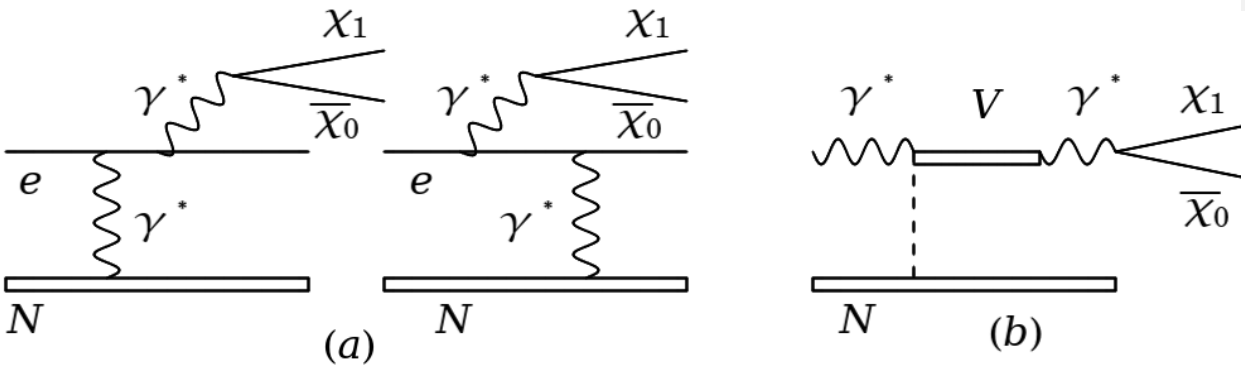


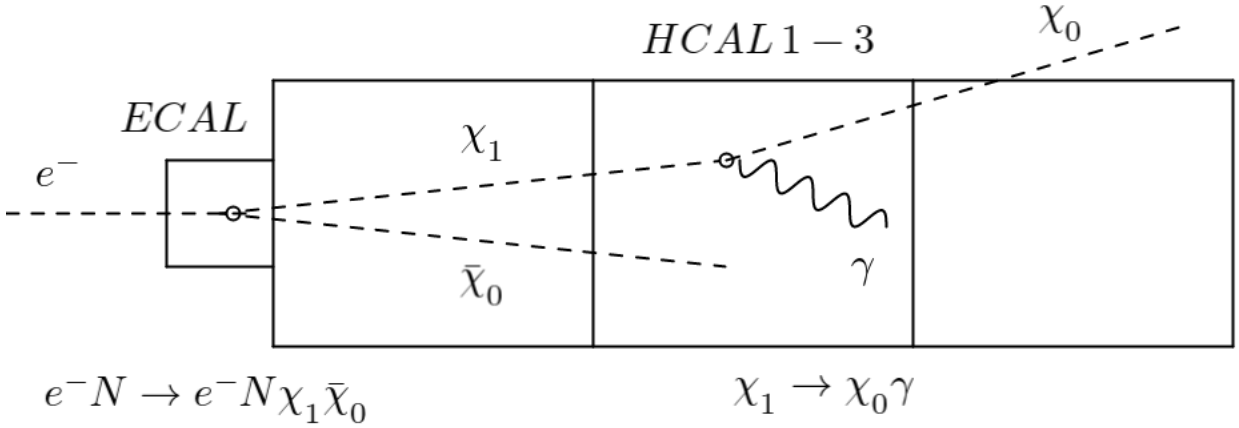


Probing Dark Axion Portal: exclusion plot (2602.11405, accepted for publication in PRD)



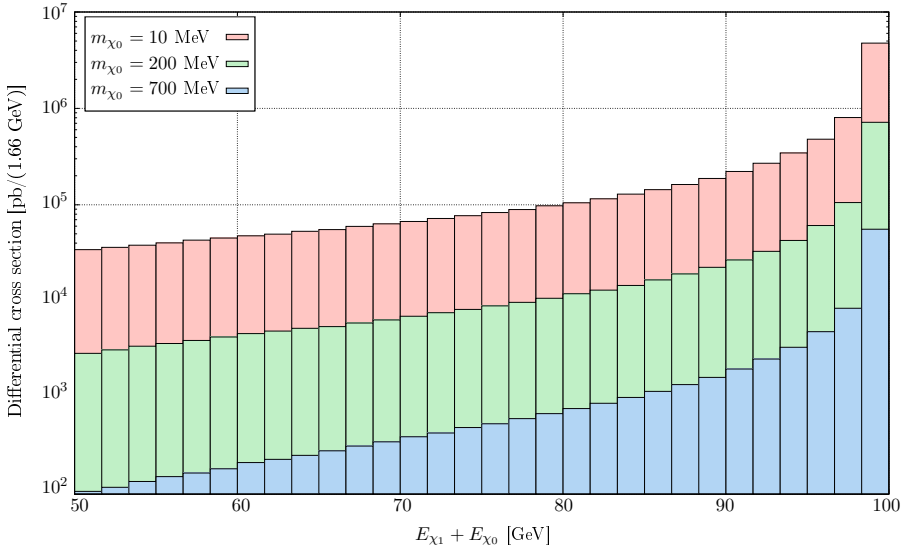
Probing magnetic dipole inelastic DM (MD iDM)

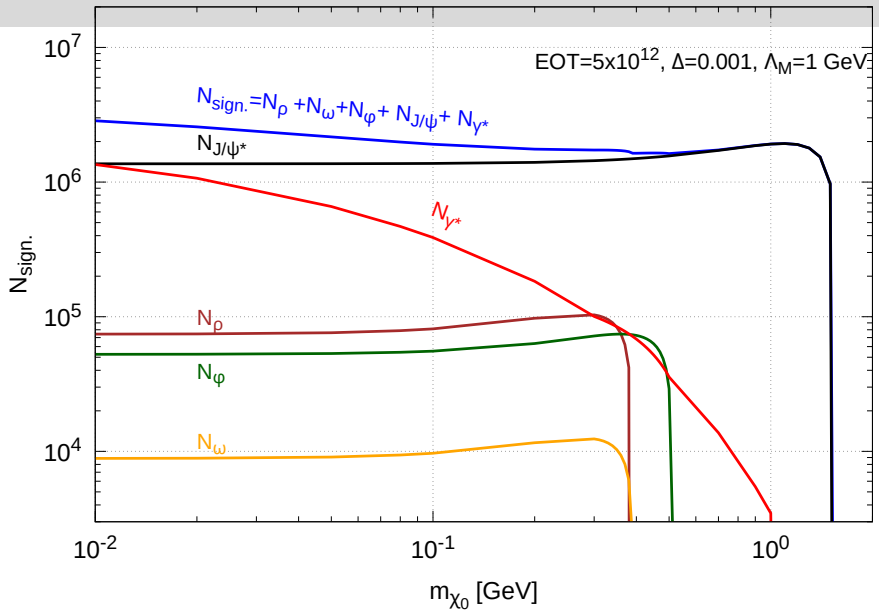




$$\mathcal{L} \supset \frac{1}{\Lambda_M}\bar{\chi}_1\sigma^{\mu\nu}\chi_0 F_{\mu\nu}, \quad \Delta = (m_{\chi_1} - m_{\chi_0})/m_{\chi_0} \ll 1, \tag{5}$$

$$E_\gamma \simeq \gamma_{\chi_1} m_{\chi_0}\Delta \lesssim \mathcal{O}(10^{-2})\ \text{GeV} \tag{6}$$



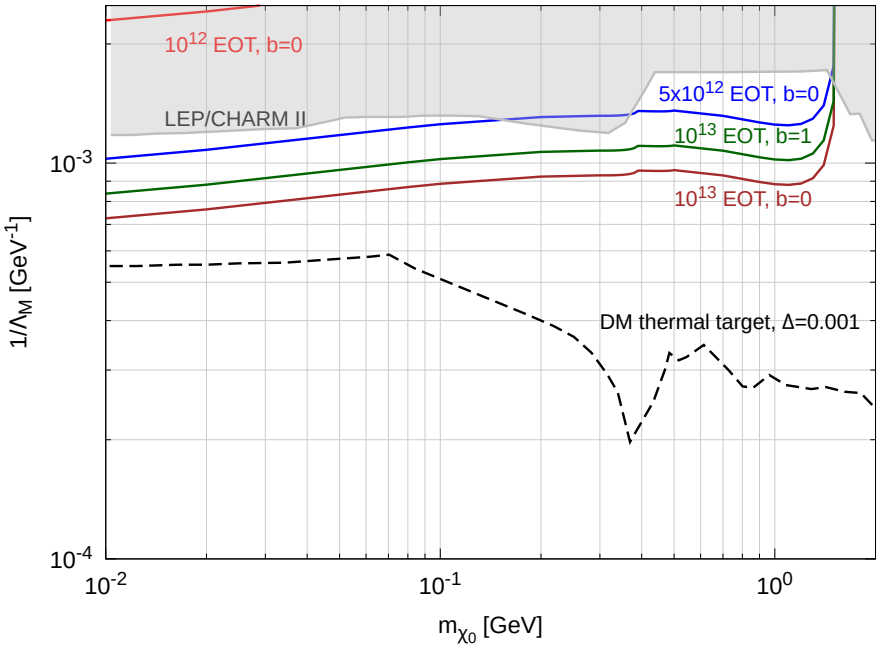


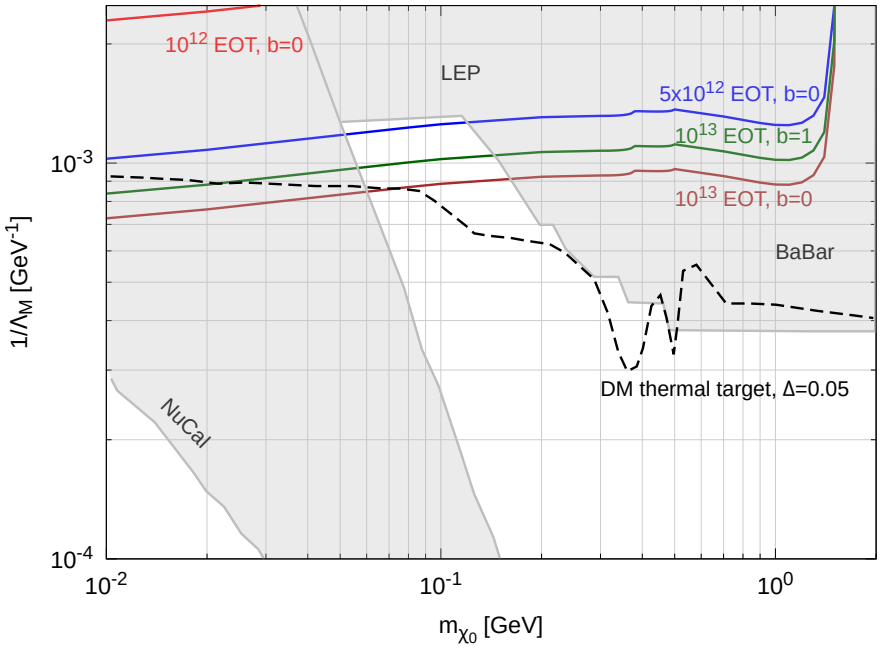
$$N_{\gamma^* \to \chi_1 \bar{\chi}_0} \simeq \text{EOT} \cdot \frac{\rho N_A}{A} L_T \int_{E_{\min}}^{E_{\max}} dE_{\text{miss}} \frac{d\sigma_{2\to 4}(E_e)}{dE_{\text{miss}}}, \quad N_{V\to\chi_1\bar{\chi}_0} \propto N_V \times \text{Br}_{V\to e^+e^-} \times M_V^2/\Lambda_{\text{M}}^2.$$

$$N_{\text{sign.}} \simeq N_{\gamma^* \to \chi_1 \bar{\chi}_0} + \sum_V N_{V\to\chi_1\bar{\chi}_0}. \tag{7}$$

V	M_V (MeV)	N_V	$\text{Br}_{V\to e^+e^-}$
ρ	775	1.2×10^8	4.7×10^{-5}
ω	782	9×10^6	7.3×10^{-5}
ϕ	1019	8×10^6	2.9×10^{-4}
J/ψ	3097	1.1×10^5	5.9×10^{-2}

Probing MD iDM: expected reach of NA64e (2603.28278, submitted to PRD)





We show that by accounting for heavy vector mesons decays, $\gamma^* N \to NV(\to \chi_1\bar{\chi}_0)$ along with bremsstrahlung-like emission of iDM pairs, $e^- N \to e^- N\gamma^*(\to \chi_1\bar{\chi}_0)$, will allow NA64e to probe still unexplored region of iDM parameter space with sufficiently small splittings, $\Delta = 5 \times 10^{-2}$, and relatively light masses $m_{\chi_0} \lesssim 100$ MeV. To achieve the required sensitivity an upgrade of the NA64e setup is currently in progress.

Probing spin-2 DM mediators with NA64e, NA64μ, M^3, E137, and LDMX (EPJC, 2412.10150)

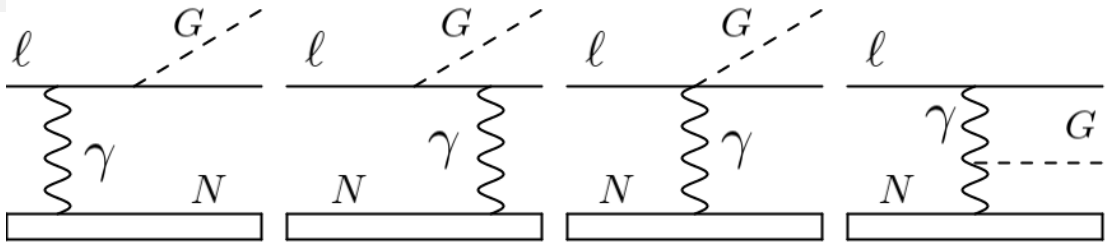
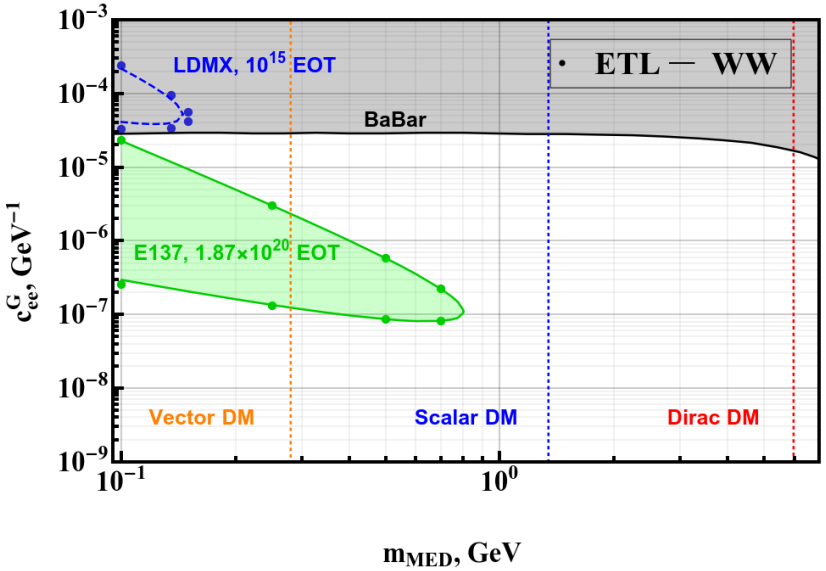


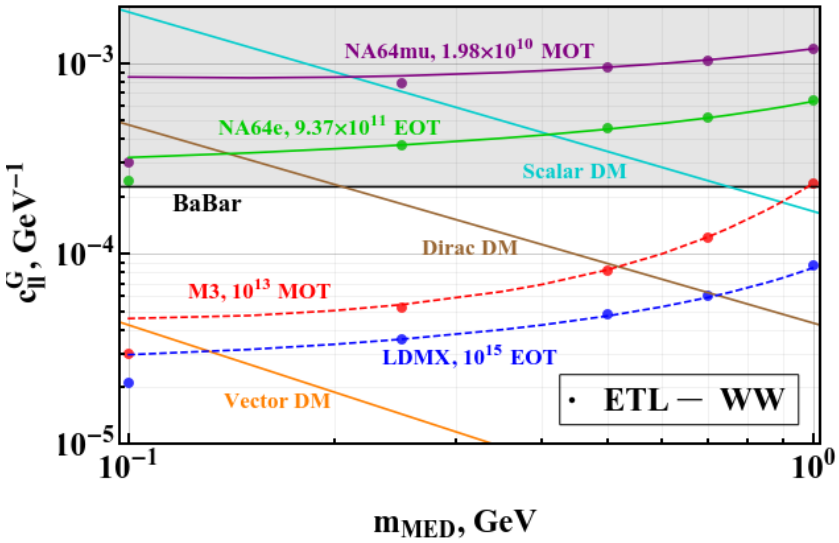
Figure: Feynman diagrams describing bremsstrahlung-like signature for the tensor mediator.

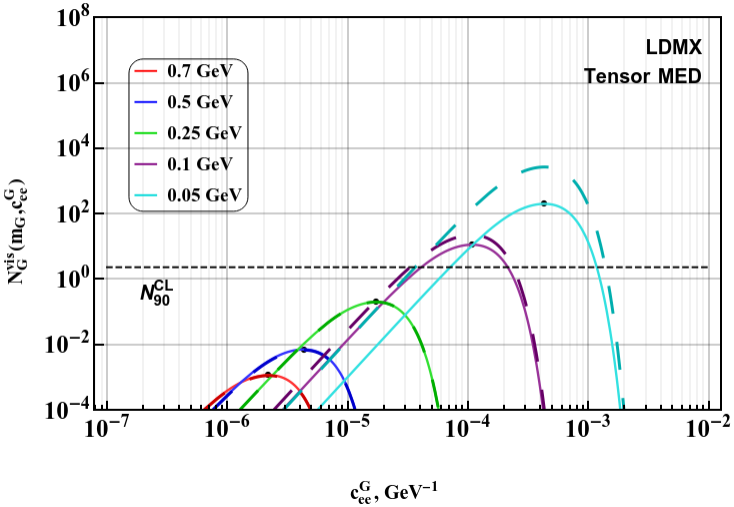
	NA64e	LDMX	NA64μ	M^3	E137
target material	Pb	Al	Pb	W	Al
Z, atomic number	82	13	82	74	13
A, g $\cdot$ mole^{-1}	207	27	207	184	27
$x_{\rm cut} = E_{\rm G}^{\rm cut}/E_l$	0.5	0.7	0.5	0.4	0.1
$l^{\pm}$, primary beam	$e^{\pm}$	e^-	$\mu^{\pm}$	$\mu^{\pm}$	e^-
E_l, GeV, beam energy	100	16	160	15	20
vis. mode, G$\to$SM+SM	+	+	$-$	$-$	+
inv. mode, G$\to$DM+DM	+	+	+	+	$-$
$\rm LOT_{current}$	9.37×10^{11}	-	1.98×10^{10}	-	1.87×10^{20}
$\rm LOT_{expected}$	5×10^{12}	10^{15}	5×10^{13}	1×10^{13}	-

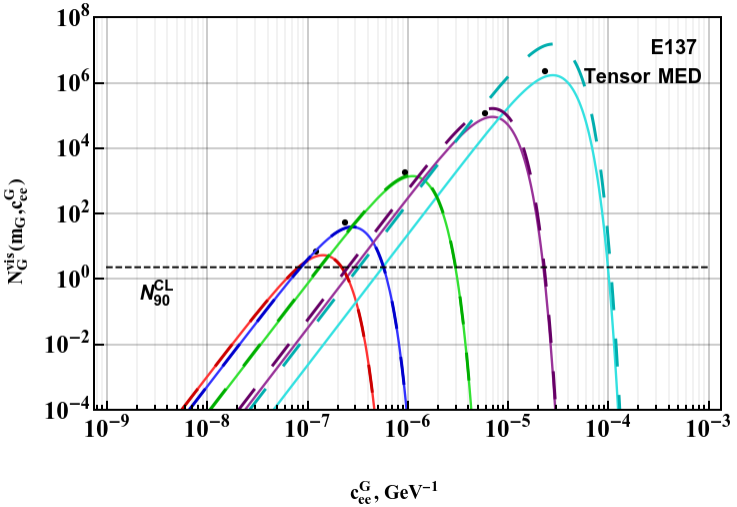
Table: The benchmark parameters for the spin-2 mediator production cross section $l^{\pm}N \to l^{\pm}N + {\rm G}$ at the lepton fixed-target experiments.

Probing spin-2 DM mediators with NA64e, NA64μ, M^3, E137, and LDMX (EPJC, 2412.10150)









Conclusion

Prospects of NA64++ before LS3:
– New area at H4 and setup upgrade to run at high intensity with $e^{\pm}$-beam. Probing light dark matter parameter space for $m_{A'} > 100$ MeV with resonant A' production.
– Main goal to explore LDM parameter space with $\gtrsim 5 \times 10^{12}$ EOT
– We have probed dark sectors weakly coupled to muons with NA64μ: $L_\mu - L_\tau \to Z'$: data collected in 2022-2024
Prospects for fixed target:
– NA64e and NA64μ can be sensitive to the unexplored region of the Millicharged Partilces, the Dark Axion Portal scenario, Magnetic Dipole inelastic DM.
– NA64e, NA64μ, M^3, LDMX: variety scenarios involving spin-1 and spin-2 DM mediators can be tested
– the typical signature is $l + N \to l + N + \mathrm{MED}$, followed by $\mathrm{MED} \to \mathrm{DM} + \mathrm{DM}$
This work is supported by the the Russian Science Foundation grant No. 25-12-00309