The rare events at fixed target experiments

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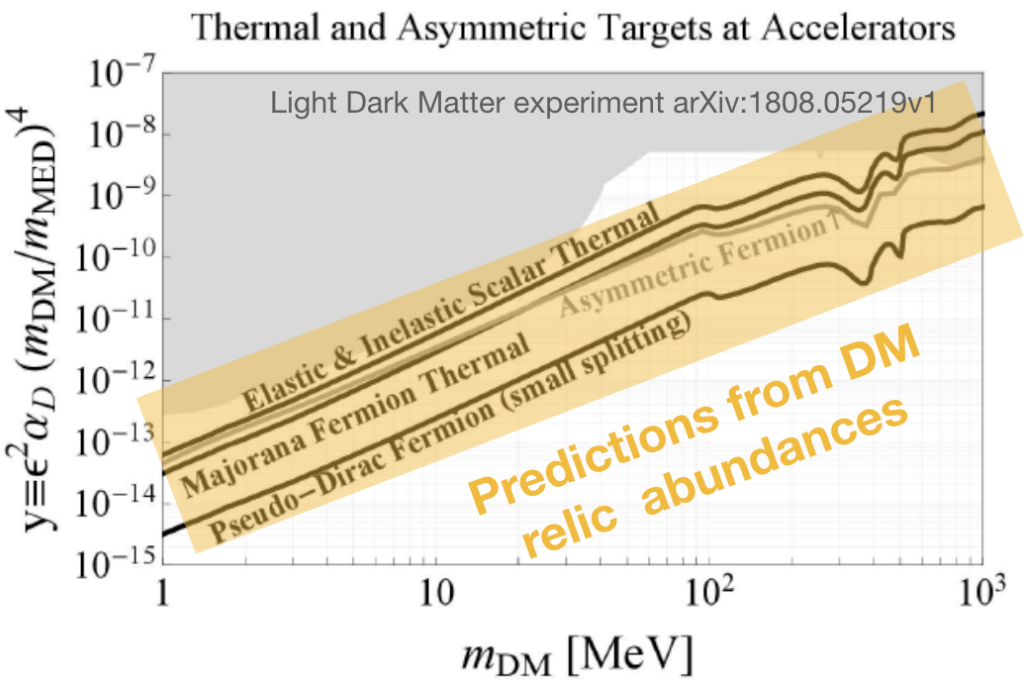
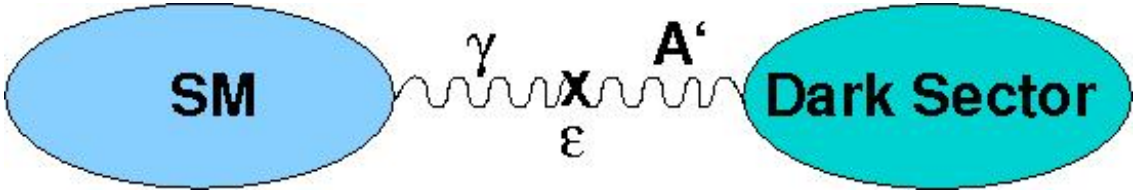
Motivations for searching for light DM mediators

- They are popular candidates for solution of experimental anomalies: $(g-2)_\mu$, MinoBooNE, ^{8}Be, KOTO, 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 presumably via gravity and possibly via a new interaction transmitted by the mediator.
  DARK MATTER $\longleftrightarrow$ MEDIATOR $\longleftrightarrow$ STANDARD MODEL
- The most popular models of Dark Matter χ: **Scalar Dark Matter, Majorana Dark Matter, Pseudo Dirac Dark Matter**



Vector Portal to Dark Sector

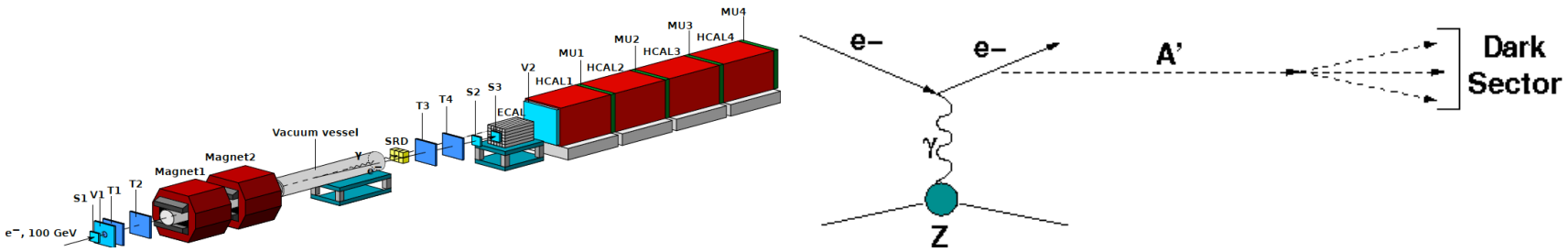


- **Okun, Holdom (1986)** $\alpha_D = e_D^2/(4\pi)$: new masssive boson A' (dark photon) which has kinetic mixing with ordinary photon ϵ:

$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}^2 + \frac{1}{4}\left(F'_{\mu\nu}\right)^2 + \frac{\epsilon}{2}F_{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_{A'}^2(A'_\mu)^2 + e\bar{\psi}_e\gamma_\mu A^\mu\psi_e + \mathcal{L}_{int}(A' - \mathrm{DM})$$

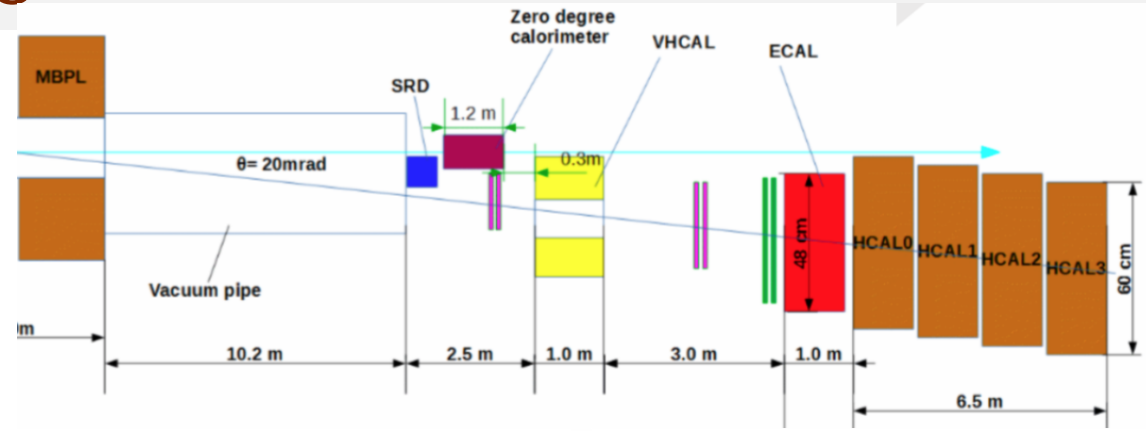
- Field redefinition $A_\mu \to A_\mu + \epsilon A'_\mu$ to get rid of kinetic mixing between Standard Model (SM) photon A and massive Dark Photon A'
- That implies the effective interaction of DP with electrons $\mathcal{L} \supset e\epsilon \cdot \bar{\psi}_e\gamma^\mu A'_\mu\psi_e$
- Production: A'-bremsstrahlung $e^- N \to e^- N A'$,
- Decays:
  – **Mostly Visible:** $A' \to e^+e^-$, $\mu^+\mu^-$, hadrons, assuming $m_{A'} > 2m_e$, $2m_\mu$...
  – **Mostly Invisible:** $A' \to \chi\chi$ if $m_{A'} > 2m_\chi$ assuming $\alpha_D \sim \alpha_{QED} \gg \epsilon$

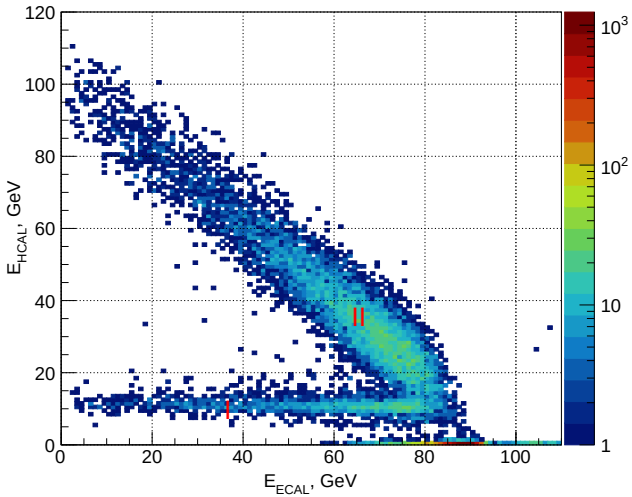
NA64 experiment setup (invisible mode): Proposed by S.Gninenko Phys.Rev.D 89 (2014) 7, 07500 (INR Moscow)

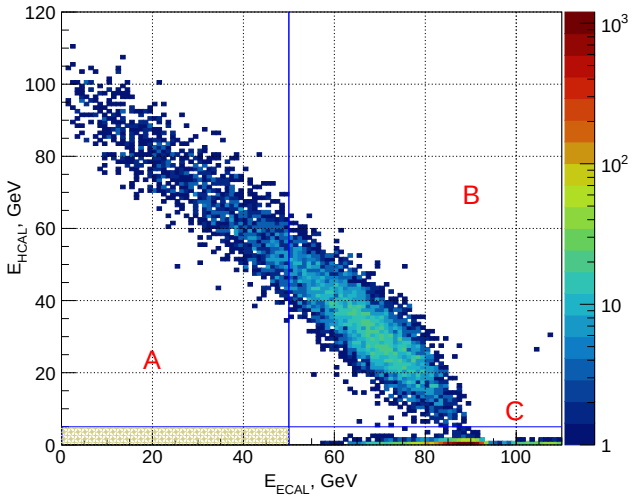


- **NA64** is designed to search for dark sector physics in missing-energy events with $e^{\pm}, \mu, \pi, K, p$ beams.
- **Main Components:** a) clean $E_0 = 100$ GeV e^- beam; b) e^- tagging system: tracker+SRD; c) hermetic ECAL+HCAL;
- **Signature:**
  a) in: 100 GeV e^- track; b) out: $E_{ECAL} 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

NA64e design for invisible mode

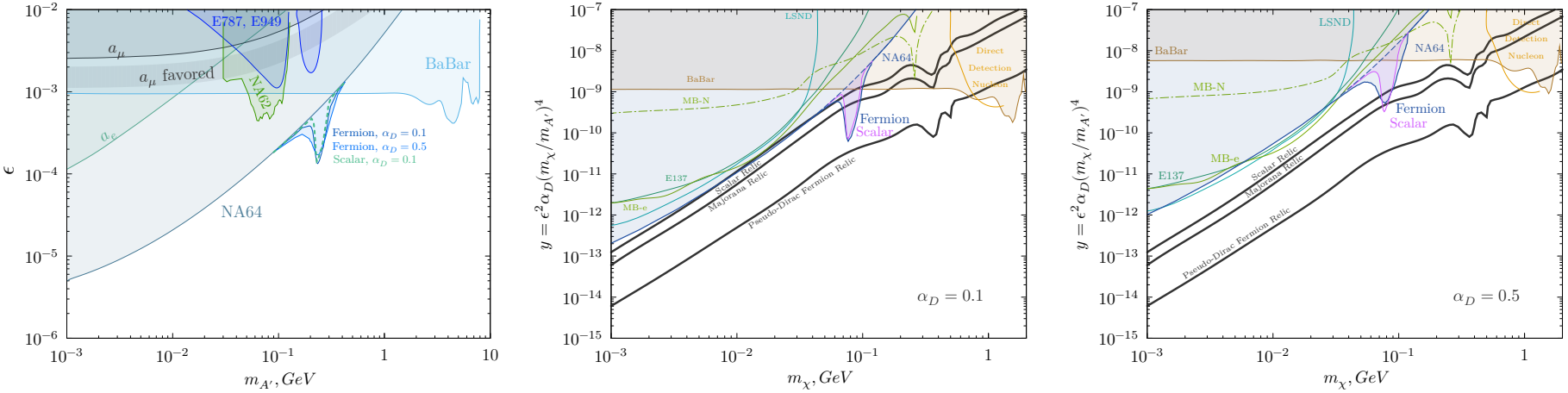






- $E_{beam} \simeq E_{HCAL} + E_{ECAL}$ **is the energy conservation for the experimental facility**
- **NA64e allows to probe invisible decays of Dark Matter mediators:** $eN \to eNX(X \to \chi\bar{\chi})$**, where** X **is a general hidden boson (spin 0, spin 1, spin 2) the mediator between SM and 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 production of A' by electron beam



- **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**

Millicharged particles (MCP)

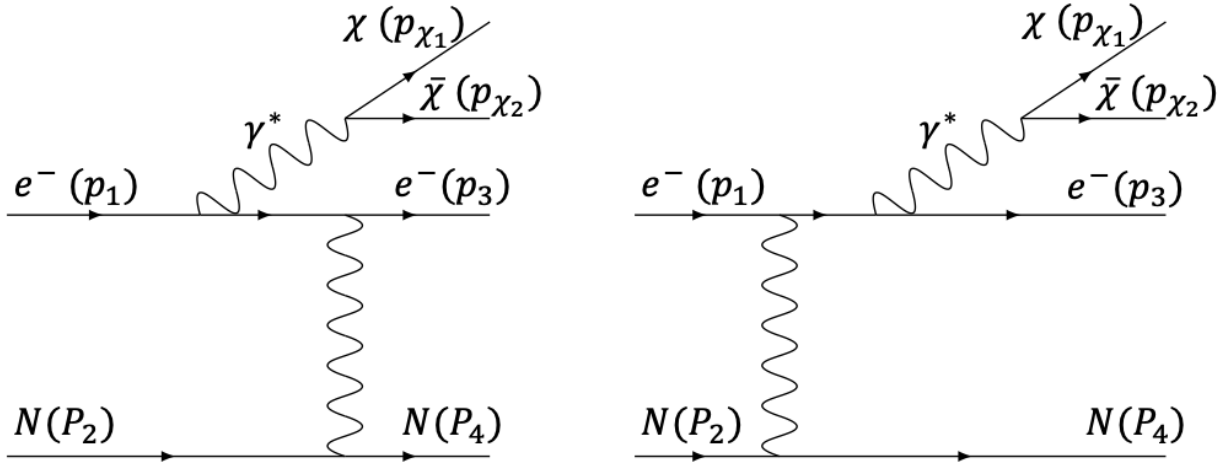
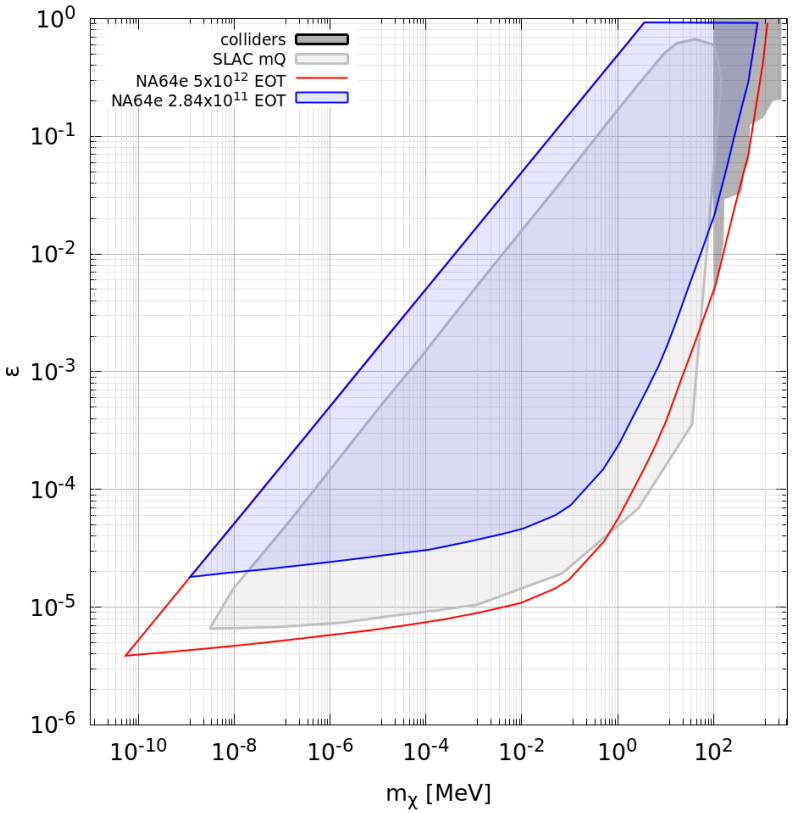


Figure: Feynman diagrams for MCP pair production process.

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.



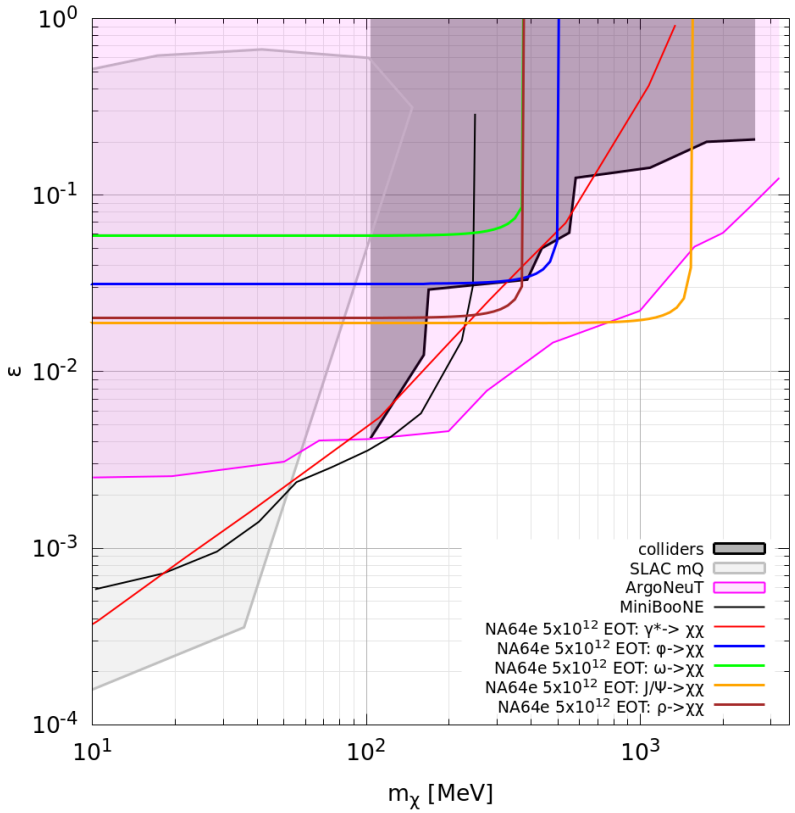
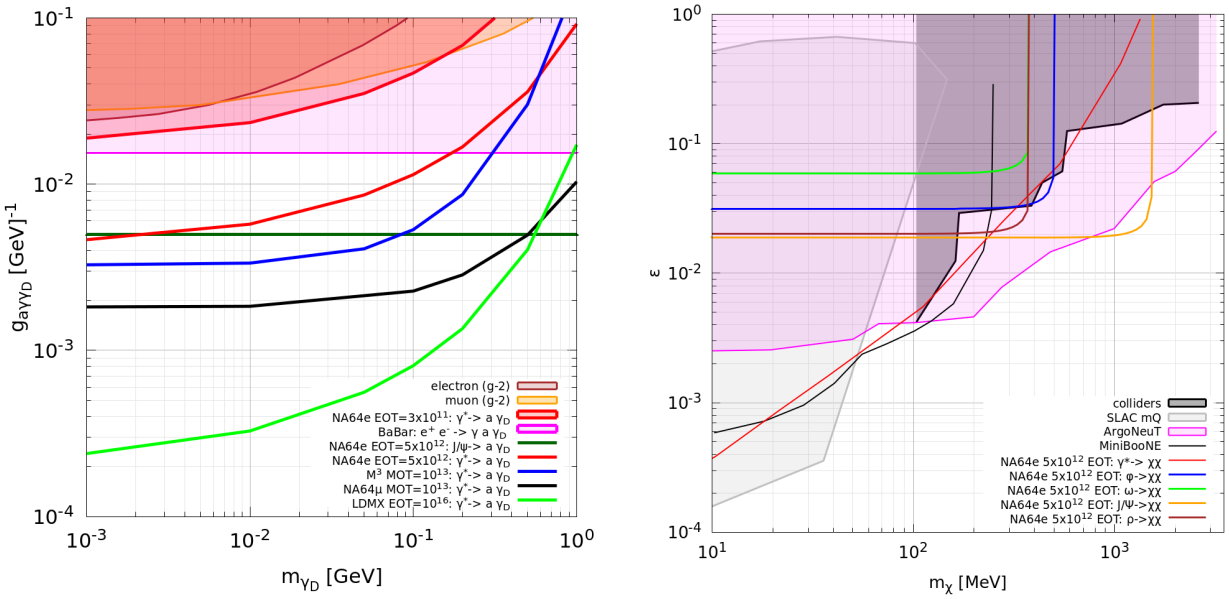
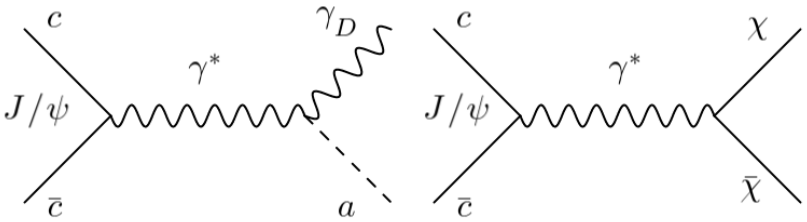


Figure: The expected sensitivity (90% C.L.) of NA64e in the (ϵ, m_χ) plane. We take into account invisible decays of vector mesons to the MCPs and MCP production by the energetic beam electrons via bremsstrahlung-like mode $\gamma^* \to \chi\bar{\chi}$ for the prospect statistics $N_{EOT} = 5 \times 10^{12}$ and MCP mass range $10\,\text{MeV} \leq m_\chi \leq 1.5$ GeV.

Probing J/ψ vector meson photoproduction $\gamma N \to N J/\psi$ followed by its invisible decay into pair of ALP-Dark photon $J/\psi \to a\gamma_D$ and millicharged particles $J/\psi \to \bar{\chi}\chi$. The spectra of J/ψ for NA64e can be found in P. Schuster, N. Toro and K. Zhou, Phys. Rev. D **105**, no.3, 035036 (2022) [arXiv:2112.02104 [hep-ph]].

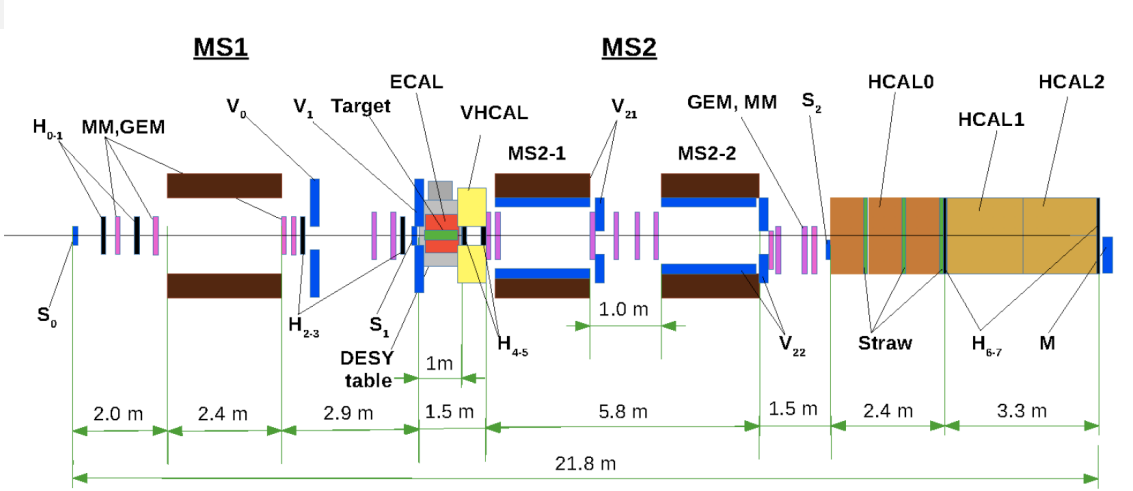




Right Panel (**PRELIMINARY:** PRD, 106 (2022) 3, 035029, Arefyeva, Gninenko, Gorbunov and Kirpichnikov): dark green solid line is the expected reach of NA64e for the dark axion portal coupling $\mathcal{L} \supset e\epsilon\bar{\chi}A_\mu\gamma^\mu\chi$

Left Panel (**PRELIMINARY:** PRD, 106 (2022) 3, 035018, Zhevlakov, Lyubovitskij and Kirpichnikov): the orange solid line is expected reach of NA64e for the millicharged coupling $\mathcal{L} \supset \frac{g_{a\gamma\gamma_D}}{2} aF_{\mu\nu}\tilde{F}'_{\mu\nu}$

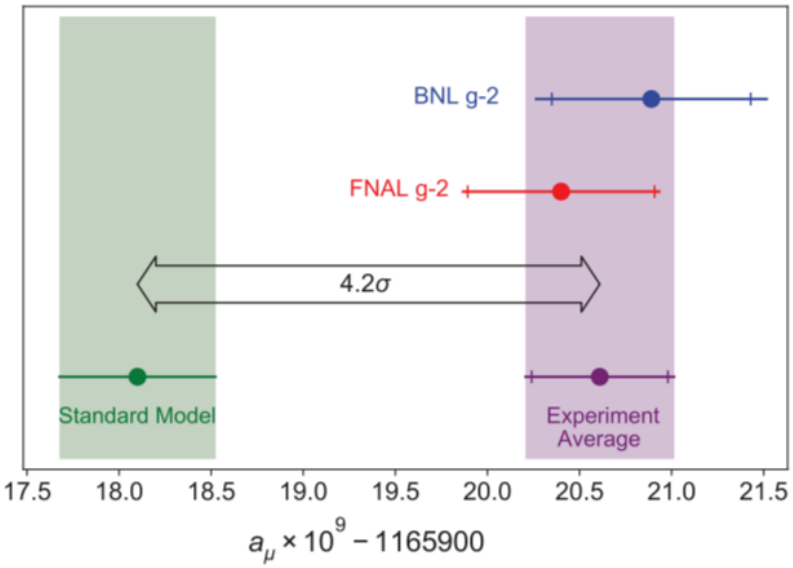
NA64μ

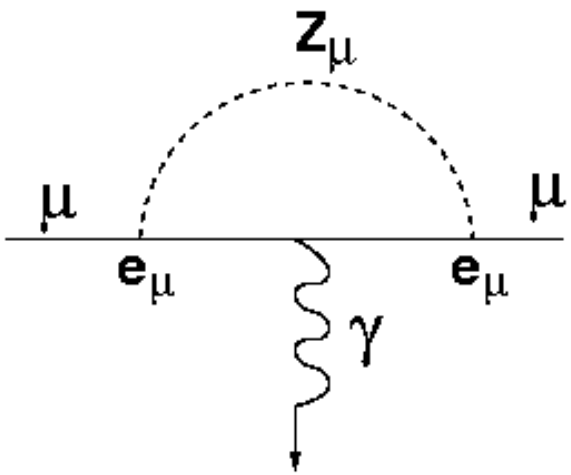


- **Open questions:**
  - **trigger rate, π, K contamination**
  - **purity of track reconstuction**
  - **detector hermeticity, optimal muon energy**
- **Experimental runs**
  - **3 w run at M2 in Oct.- Nov. 2021**
  - **3 w run in April 2022, 100-160 GeV μ,**
  - **3 w run in July + Aug 2023, 100-160 GeV μ,**
- **Plans: – Goal to probe for the first time $(g-2)_\mu$ parameter space for sub-GeV Z_μ: $\simeq$ a few 10^{10} MOT**

Motivation for NA64μ: $(g-2)_\mu$ anomaly

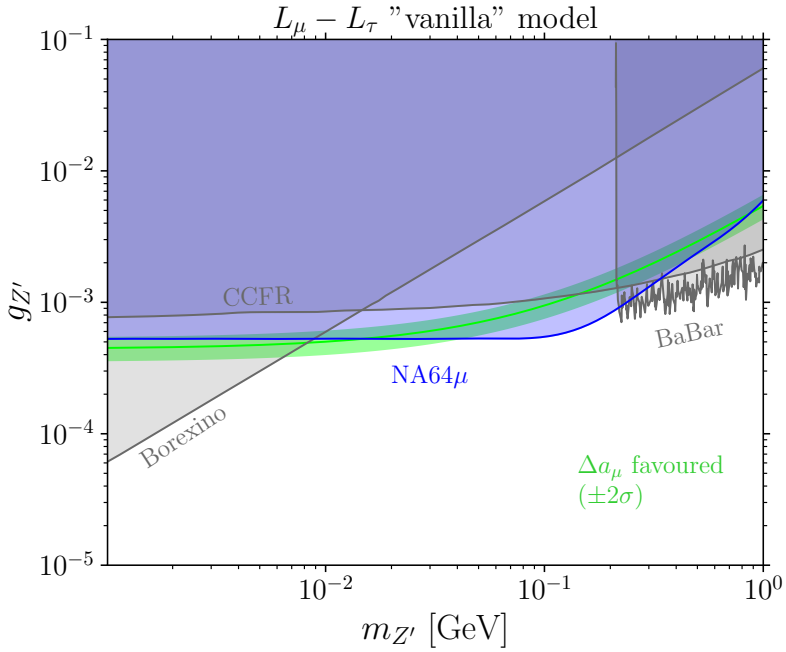
$$\text{FNAL:} \quad a_\mu = \frac{g_\mu - 2}{2}, \quad \Delta a_\mu = a_\mu^{exp} - a_\mu^{th} = (251 \pm 59) \cdot 10^{-11}$$

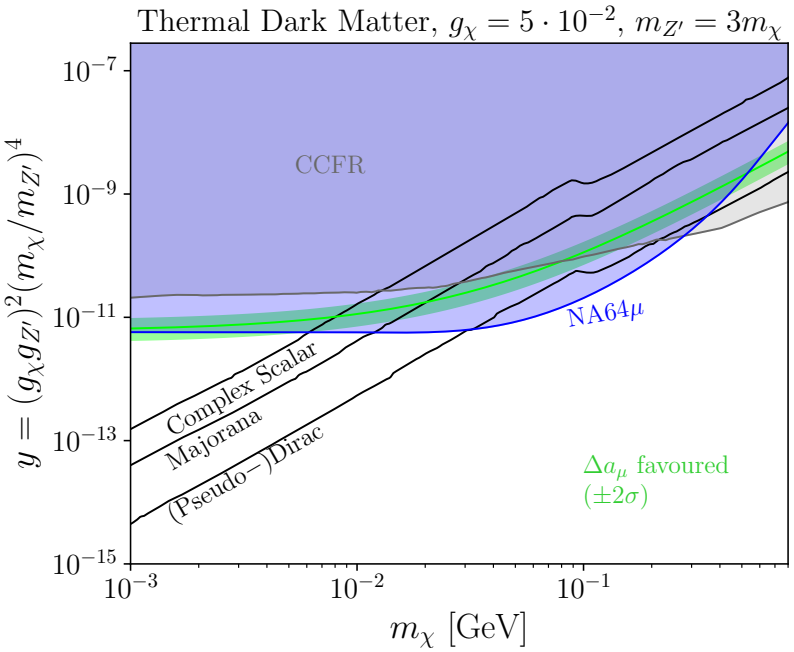




- B. Abi et al. Muon g-2 collaboration Phys. Rev. Lett. 126, 141801 (2021)
- T. Aoyama et al. Phys. Rept. 887 (2020) 1-166
- **NA64: 1-Loop contribution from Dark Sector. Sub-GeV range of $m_{Z'}$: $Z' \to \nu\nu$ for $m_{Z'} \lesssim 2m_\mu$**

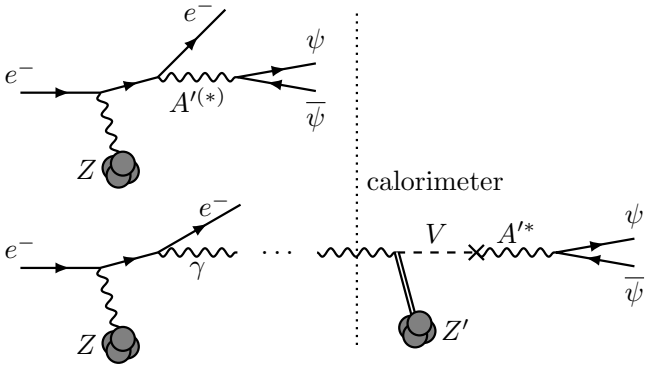
NA64μ

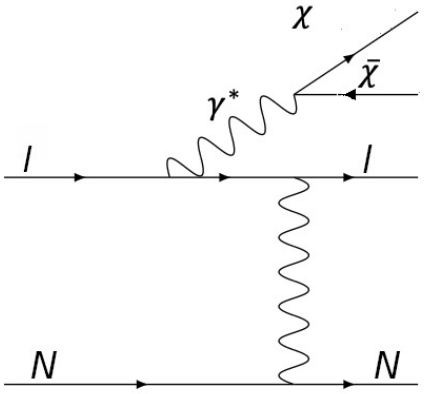


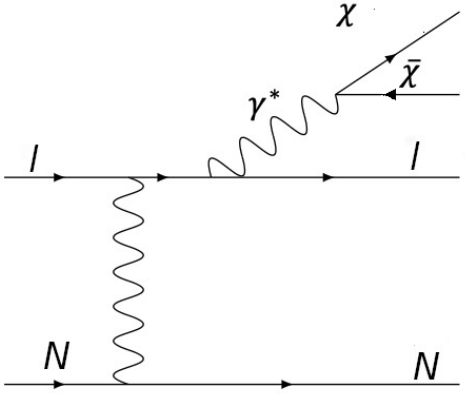


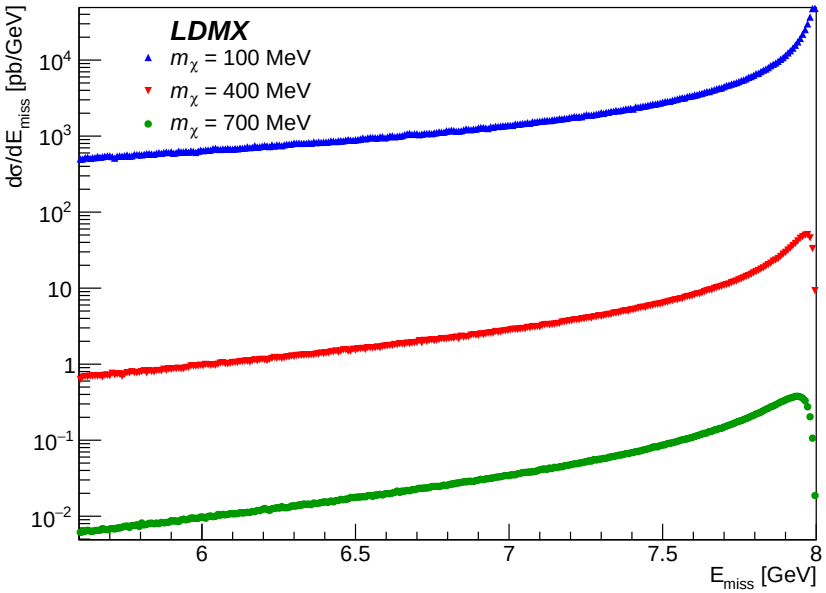
- **Pilot muon beam run (M2 channel) - November 2021 (MOT$\simeq 6 \times 10^9$ accumulated)**
- **GOAL: probing muon $(g-2)$ anomaly at NA64μ within $L_\mu - L_\tau$ anomaly free gauge extension Phys.Rev.D 104 (2021) 7, 076012, e-Print: 2107.13297 [hep-ph]**
- **Current result: Phys. Rev. Lett. 132 (2024) 21, 211803**

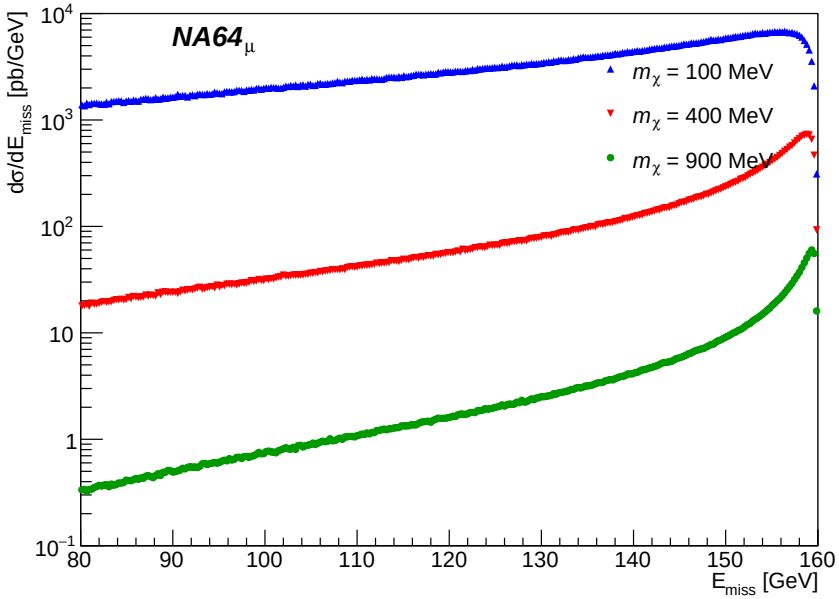
Probing MCP with NA64μ and LDMX



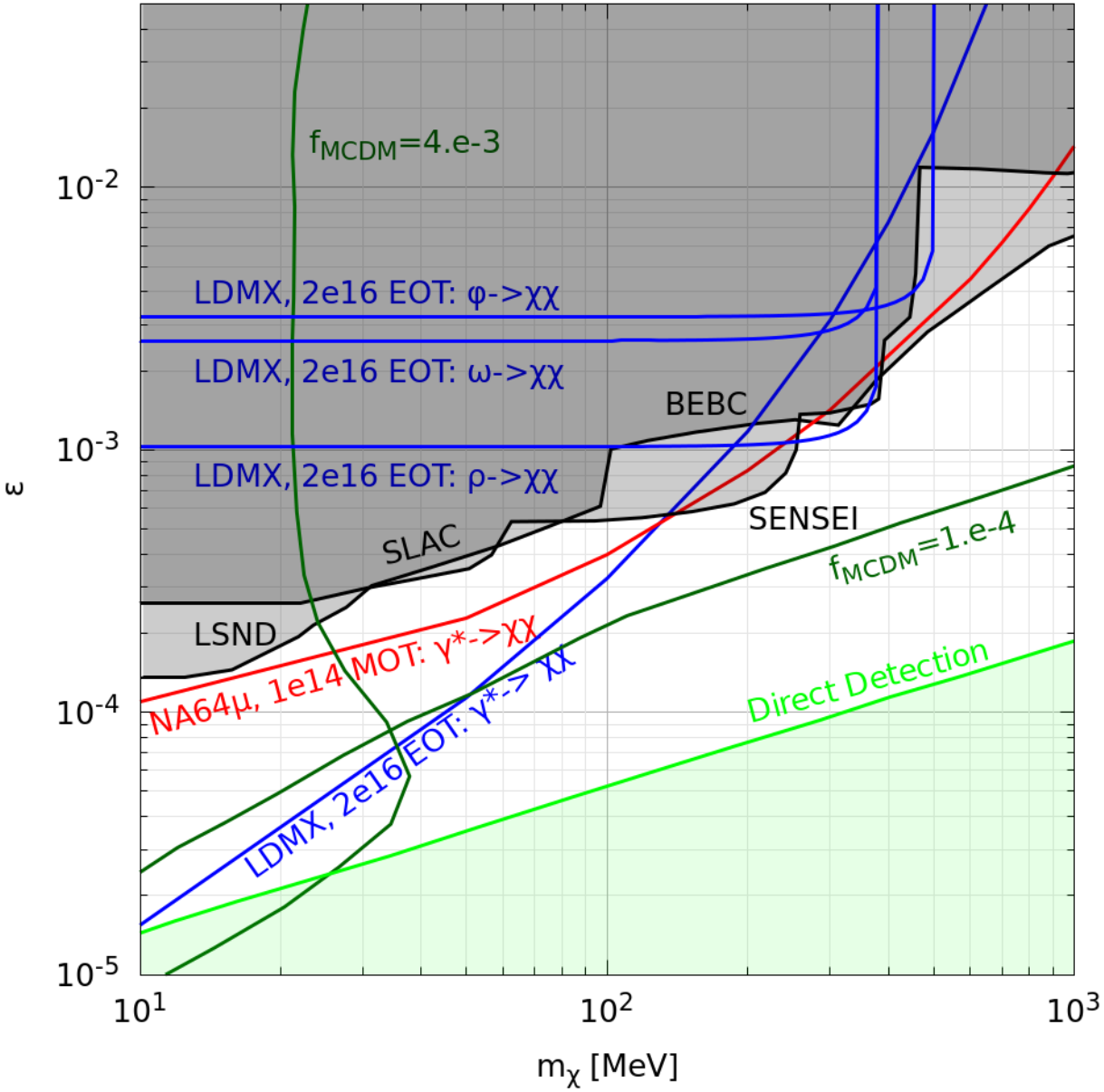








Probing MCP with NA64μ and LDMX: 2505.04295



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

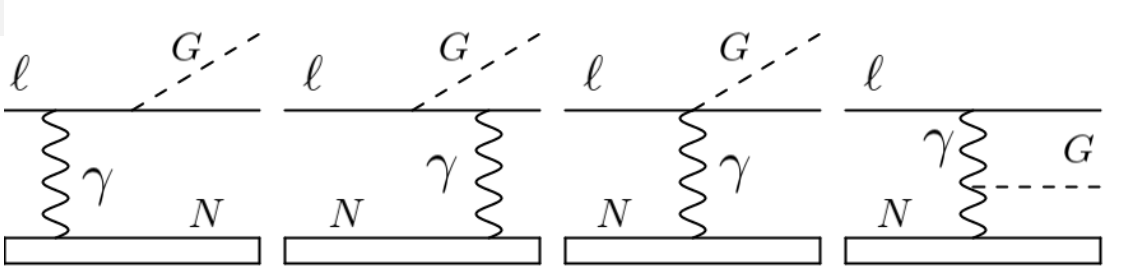
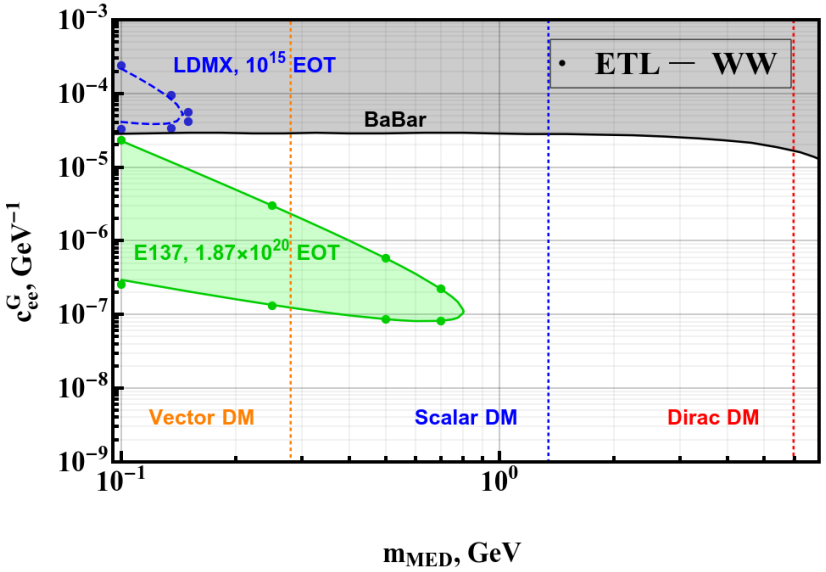


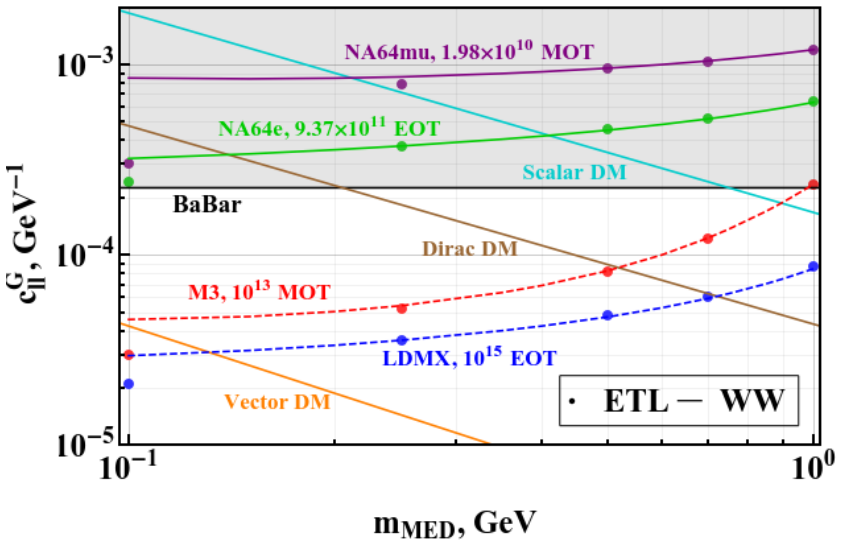
Figure: Feynman diagrams describing bremsstrahlung-like signature for the tensor mediator.

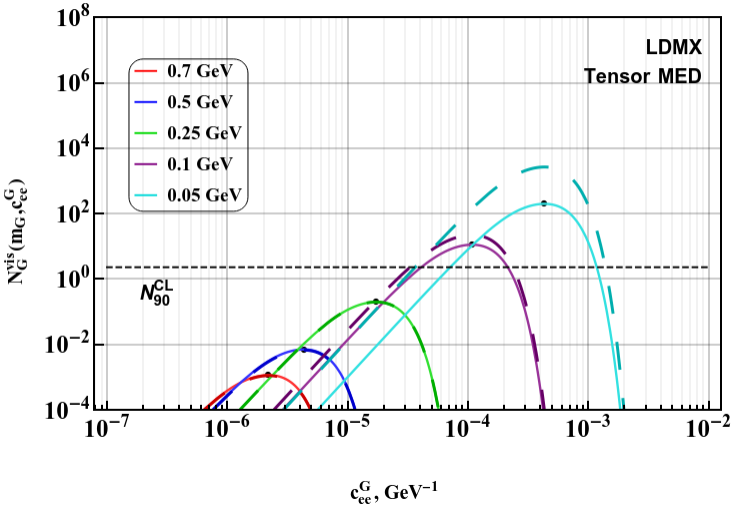
	NA64e	LDMX	NA64μ	M^3	E137
target material	Pb	Al	Pb	W	Al
Z, atomic number	82	13	82	74	13
A, g $\cdot$ mole^{-1}	207	27	207	184	27
$x_{\rm cut} = E_{\rm G}^{\rm cut}/E_l$	0.5	0.7	0.5	0.4	0.1
$l^\pm$, primary beam	$e^\pm$	e^-	$\mu^\pm$	$\mu^\pm$	e^-
E_l, GeV, beam energy	100	16	160	15	20
vis. mode, G$\to$SM+SM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

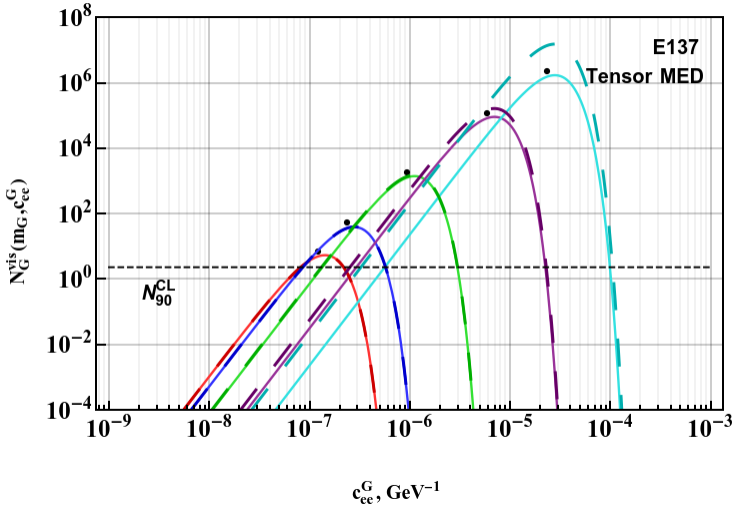
Table: The benchmark parameters for the spin-2 mediator production cross section $l^\pm N \to l^\pm N + \mathrm{G}$ at the lepton fixed-target experiments.

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

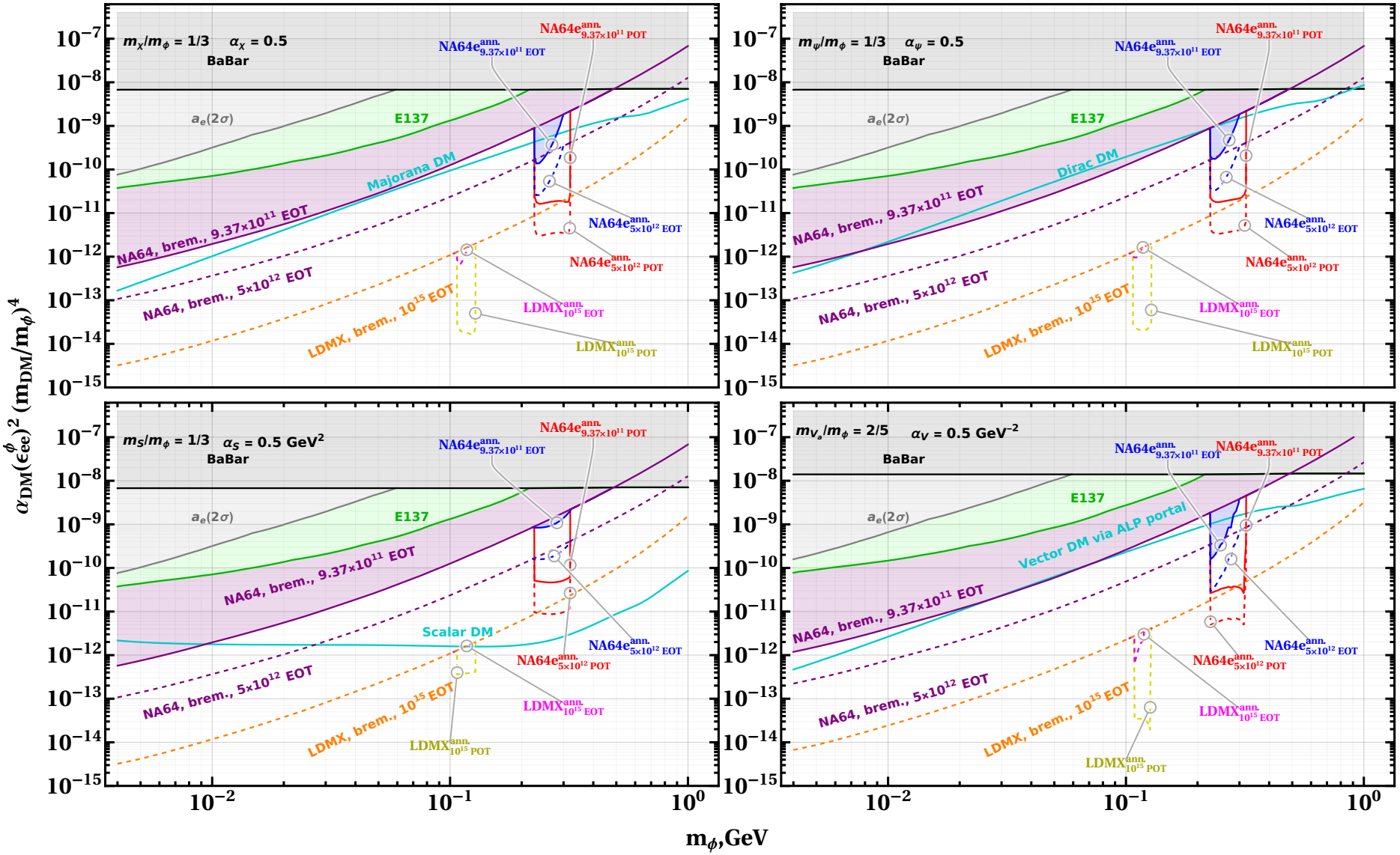




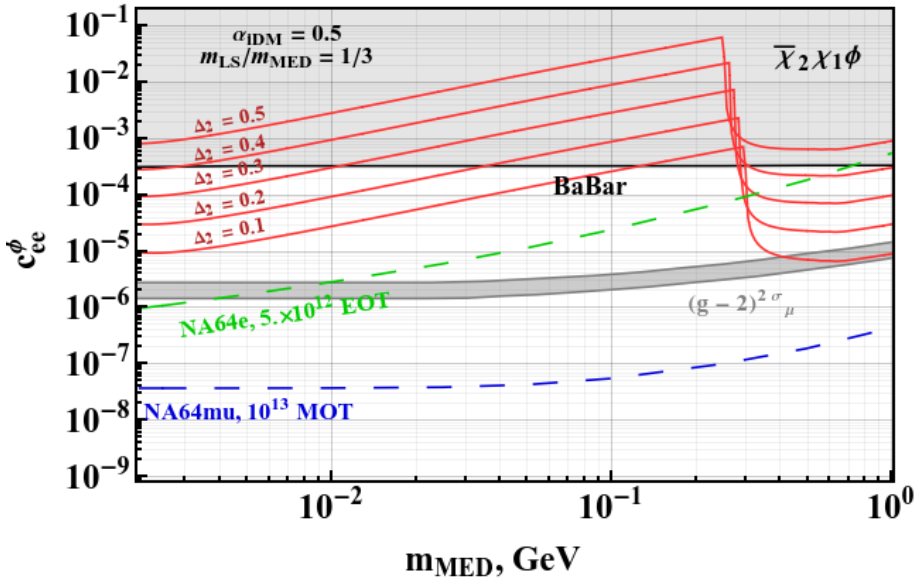


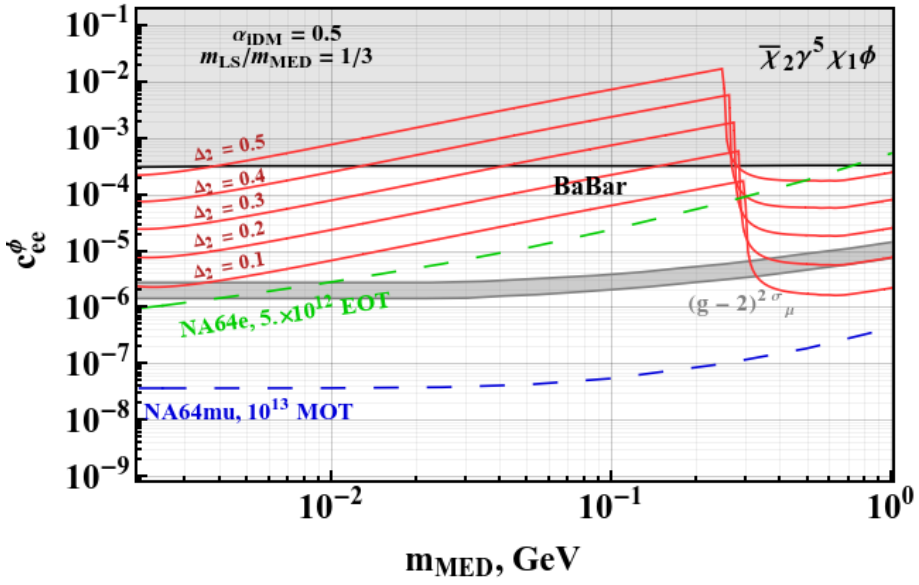


Thermal Target and Scalar Mediator: NA64e and LDMX



Scalar Portal iDM for NA64e and NA64μ: 2505.04290





Missing energy signatures for NA64e and NA64μ experiments in association with $IN \to IN\phi(\to \chi_1\chi_2)$, followed by $\chi_2 \to \chi_1 e^+ e^-$ decays

$$\mathcal{L} \supset \sum_{i=e,\mu,\tau} \frac{c^{\phi}_{ii}}{\Lambda}\phi\overline{L}_i H E_i, \quad c^{\phi}_{ee} : c^{\phi}_{\mu\mu} : c^{\phi}_{\tau\tau} = m_e : m_\mu : m_\tau, \quad \Delta_2 = \frac{(m_{\chi_2} - m_{\chi_1})}{m_{\chi_1}}$$

Conclusion

Prospects of NA64++ before LS3:
– New area at H4 and setup upgrade to run at high intensity with e^+-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:** $(g-2)_\mu$ and $L_\mu - L_\tau \to Z'$: **data collected in 2022-2024**
Prospects for fixed target:
– NA64e, NA64μ, M^3, LDMX: variety scenarios involving spin-0, spin-1, and spin-2 DM mediators can be tested
– the typical signature is $l + N \to l + N + \mathrm{MED}$, followed by $\mathrm{MED} \to \mathrm{DM} + \mathrm{DM}$ $(\mathrm{MED} \to \mathrm{SM} + \mathrm{SM})$