# Probing Light Dark Matter with NA64

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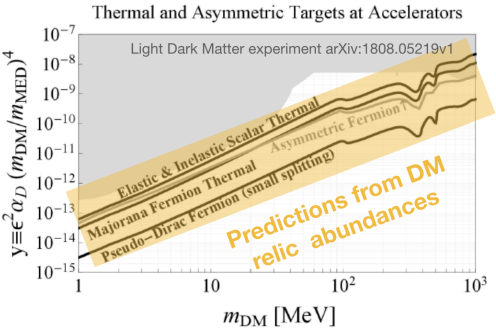
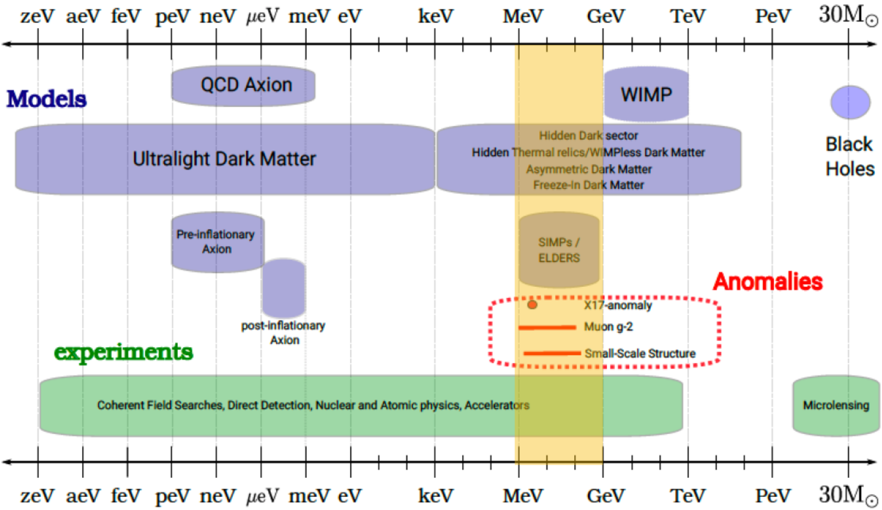
# Motivations for searching for light vectors and ALPs

- 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 $\chi$: **Scalar Dark Matter, Majorana Dark Matter, Pseudo Dirac Dark Matter**

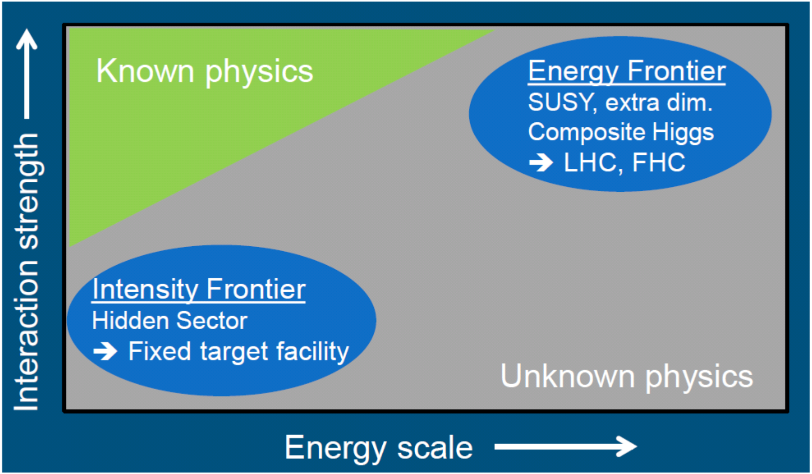


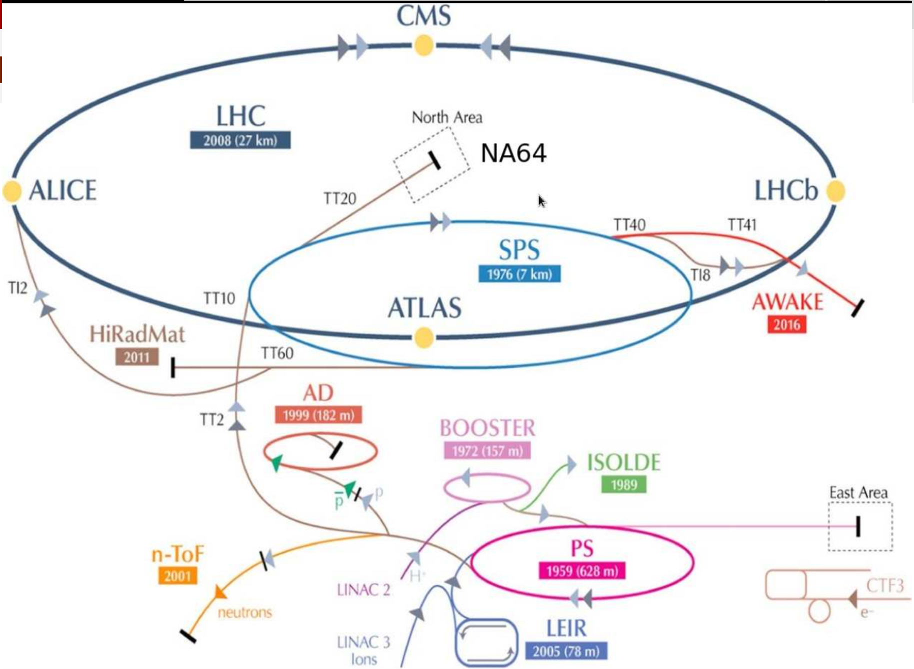
# Intensity frontier

From E. Depero, PhD thesis 2020 (ETH Zürich)



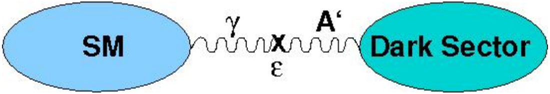
# Intensity frontier




CMS
LHC
2008 (27 km)
North Area
NA64
ALICE
LHCb
TT20
TT40
TT41
SPS
1976 (7 km)
TI8
TI2
TT10
ATLAS
AWAKE
2016
HiRadMat
2011
TT60
AD
1999 (182 m)
TT2
BOOSTER
1972 (157 m)
ISOLDE
1989
East Area
p̄
p
n-ToF
2001
PS
1959 (628 m)
CTF3
e−
H+
LINAC 2
neutrons
LINAC 3
Ions
LEIR
2005 (78 m)

# NA64 photograph

# Vector Portal to Dark Sector

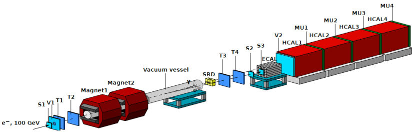


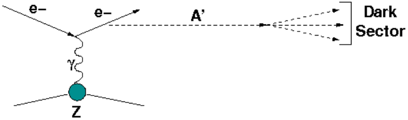

- **Okun, Holdom (1986)** $\alpha_D = e_D^2/(4\pi)$: new masssive boson $A'$ (dark photon) which has kinetic mixing with ordinary photon $\epsilon$:

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

- 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 $m_{A'} > 2m_e$, $2m_\mu \ldots$
  – **Mostly Invisible:** $A' \to \chi\chi$ if $m_{A'} > 2m_\chi$ assuming $\alpha_D \sim \alpha_{QED} \gg \epsilon$

# NA64 experiment setup (invisible mode)



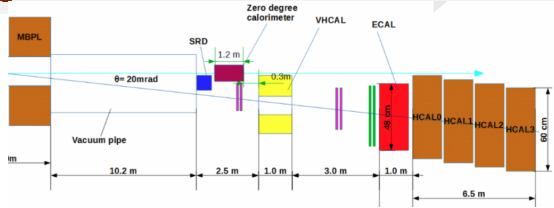



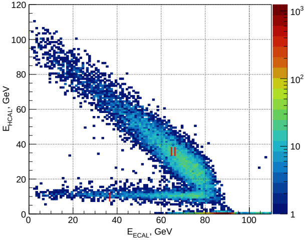

- **NA64** is designed to search for dark sector physics in missing-energy events with $e^{\pm}, \mu, \pi, K, p$ beams.
- **Main Components:** a) clean $E_0 = 100$ GeV $e^-$ beam; b) $e^-$ tagging system: tracker+SRD; c) hermetic ECAL+HCAL;
- **Signature:**
  a) in: 100 GeV $e^-$ track; b) out: $E_{ECAL}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

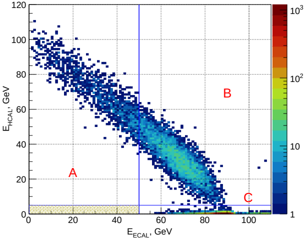
# DM processes simulation: DMG4 toolkit

- Fully GEANT4 compatible package DMG4 is developed **(M. Kirsanov et al., 2021, Computer physics communication, 2102.12192)** . Can be used in any full simulation program based on GEANT4 toolkit
- Bremsstrahlung process of electrons and muons (like $eN \to eNA'$), gamma conversion to ALP ($\gamma N \to aN$), annihilation processes (like $e^+e^- \to A' \to \chi\chi$)
- DM messengers: vector ($A'$), axial vector, scalar, pseudoscalar
- invisible, semivisible and visible (to SM particle) decays
- **For the total cross-section we use the full matrix element calculation (ETL)** (1712.06706) through K-factors applied to the IWW cross-section
- **We continue development the package (more exact WW differential cross-section)**

# NA64e design for invisible mode

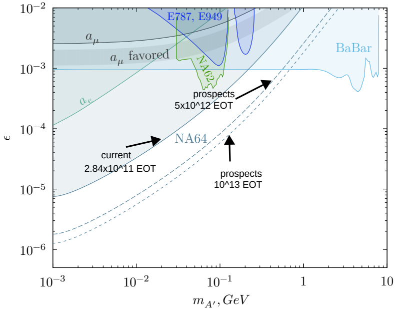


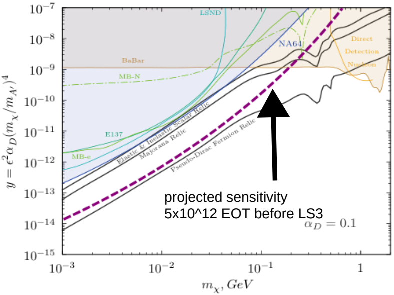




- $E_{beam} \simeq E_{HCAL} + E_{ECAL}$ **is the energy conservation for the experimental facility**
- **NA64e allows to probe invisible decays of Dark Matter mediators:** $eN \to eNX(X \to \chi\bar{\chi})$**, where** $X$ **is a general hidden boson (spin 0, spin 1, spin 2) the mediator between SM and DM particle** $\chi$ **(Scalar, Dirac or Majorana).**
- **Signal box (A) of missing energy signature: no events in** $E_{ECAL} \lesssim 50$ **GeV &&** $E_{HCAL} \lesssim 1$ **GeV**

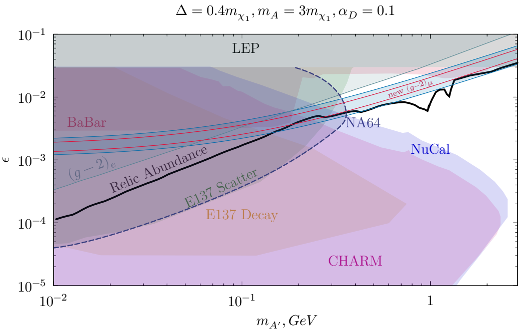
## Current and future sensitivity to Dark Photon $(\epsilon, m_{A'})$ and $(y, m_\chi)$

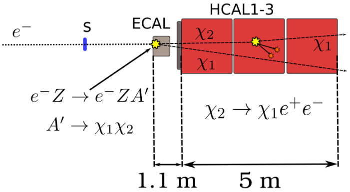



- **Invisible mode data taking: 2016-2017-2018 (combined analysis $2.84 \times 10^{11}$ EOT )**
- **Long Shutdown 2: 2019-2020**
- **Data taking 11th August 2021 (5 weeks)** $\simeq 10^{10}$ **EOT**
- **Planned data taking in 2022 (July 27 - October 12)**
- **GOAL: Beam setup and electronics upgrade $\rightarrow$ reduce background from electro nuclear interactions along the beam line.**
- **GOAL: to accumulate few $10^{11}$ EOT in 2022 and $5 \times 10^{12}$ EOT before LS3**

## Semivisible Decay of $A'$ in NA64




- **Signature:** Missing energy + SM particles pair
- **EPJC (2107.02021)**
- **Motivation:** $(g-2)_\mu$ anomaly and Light Dark Matter production
  E. Izaguirre, et al. PRD 96, 055007 (2017)
  G. Mohlabeng, PRD 99, 115001 (2019)
  Y. Tsai, et al., PRL126, 181801 (2021)

# ALP setup

Benchmark model for ALP and photon coupling:

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma}\, a F_{\mu\nu} \tilde{F}_{\mu\nu} + \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2} m_a^2 a^2$$

- Primakoff production: $\gamma_{brems.} + N \to a + N$
- followed by decay $a \to \gamma\gamma$
  - in the fiducial volume of NA64 in case of **visible mode setup** .
  - for **invisible mode setup** the ALP decays outside detectors
- Typical decay width

$$\Gamma_{a\to\gamma\gamma} = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}. \quad (1)$$

- Typical decay length

$$l_a = 4\text{m} \cdot \frac{E_a}{100\,\text{GeV}} \cdot \left(\frac{g_{a\gamma\gamma}}{10^{-4}\,\text{GeV}^{-1}}\right)^{-2} \cdot \left(\frac{m_a}{100\,\text{MeV}}\right)^{-4}. \quad (2)$$

# Signal estimation

The number of ALP produced at $i$-th photon's step length in EMS is given by

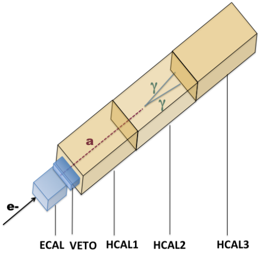
$$N_a^{(i)} = \mathbf{EOT} \times \mathbf{Photons\_per\_EOT}_i \times \frac{\rho N_A}{A} \times \sigma_{tot}(E_\gamma^i) \times l_i \qquad (3)$$

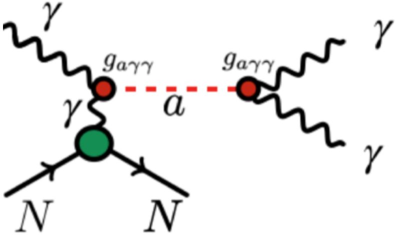
- the energy distribution of the electron beam after passing through a target medium is simulated by `GEANT4`.
- the emission of electron bremsstrahlung initiates the ALP production in a electromagnetic shower (EMS) via Primakoff process, $\gamma N \to aN$.
- total ALP production cross-section $\sigma_{tot}^a$ depends rather weakly on $m_a$ in contrast to the Dark Photon case

$$\sigma_{tot}^{A'} \sim \epsilon^2/m_{A'}^2, \qquad \sigma_{tot}^a \sim g_{a\gamma\gamma}^2,$$

- the typical energy of ALP in Primakoff process is $E_a \approx E_\gamma$. Therefore, ALP spectra are associated with bremsstrahlung distribution in the target.

# NA64 semivisible modes: ALPs



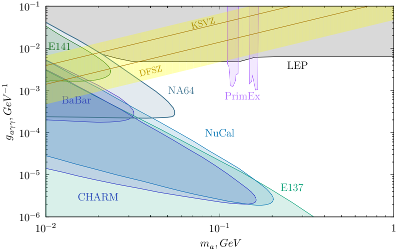



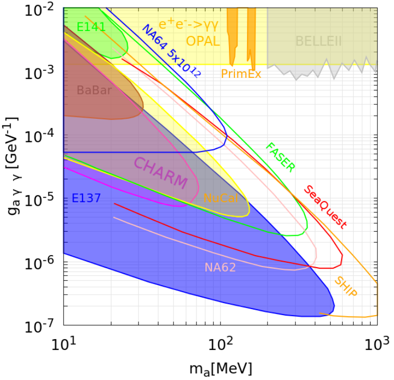

- ALPs predominantly coupled to photons produced via Primakoff effect

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}_{\mu\nu}$$

- **Signature:**
  - No signal in veto and HCAL1
  - **A: visible decay** into $\gamma\gamma$ on HCAL2 || HCAL3
  - **B: Decays after HCAL3** No activity in HCAL2 and HCAL3

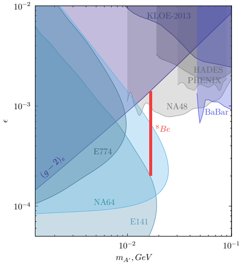
# Current limits and projection for ALPs

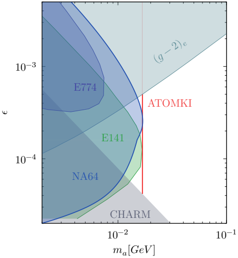



- **Left plot is a current limit for $EOT = 2.84 \cdot 10^{11}$ (PRL, 2020)**
- **Right plot is projected limit for $EOT = 5 \times 10^{12}$ (PRD, 2020)**
- **small $g_{a\gamma\gamma}$ $\to$ long-lived ALPs, large $g_{a\gamma\gamma}$ $\to$ short-lived ALPs**
- **Future Plans: to consider invisible decay into DM,**

# Visible mode of Dark Photon and ALPs coupled mostly to electrons

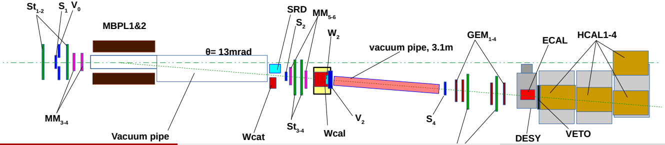


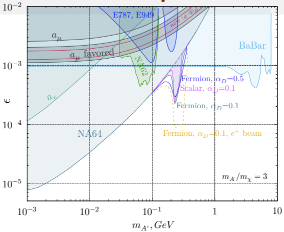

The ATOMKI experiment of (Krasznahorkay et al. 2016) has reported the observation of a 6.8 $\sigma$ excess of events in the invariant mass distributions of $e^+e^-$ pairs produced in the nuclear transitions of excited $^*Be^8$ and $^*He^4$ This anomaly can be associated with X-boson of $m_X = 16.7$ MeV.

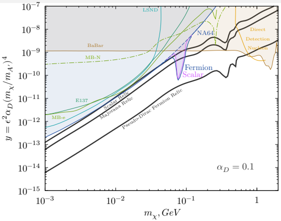
**GOAL: to perform invariant mass reconstruction:**

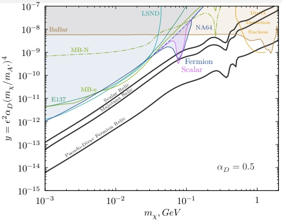
- **Increase the length of decay tube to resolve $e^+e^-$ tracks.**
- **More compact WCAL**



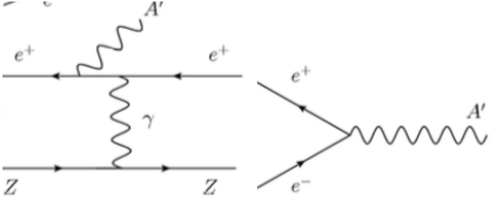
# Resonance production of $A'$ by (positron) electron beam

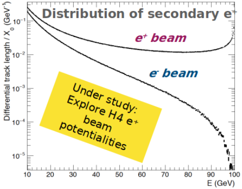


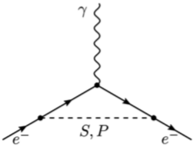

- **Resonance annihilation channel using the secondary positrons present in the EM shower in the target induced by the initial electron beam**
- **Improvement limit on $\epsilon$ up to factor 10 in the resonant region $m_{A'} \simeq (2m_e E_0)^{1/2}$**
- **FIRST RESULT: probing resonant $e^+e^- \to A' \to \chi\chi$ production by electron beam: Phys.Rev.D 104 (2021) 9 (2108.04195 [hep-ph])**
- **NEXT STEP: is to probe the resonance $e^+e^- \to A'$ by positron beam (SPS proposal)**

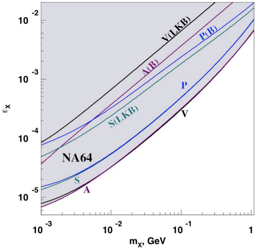


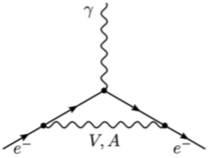



# Probing $(g-2)_e$ with NA64

- $\Delta a_e^{LKB} = a_e^{exp} - a_e^{th} = (4.8 \pm 3.0) \cdot 10^{-13}$ LKB, L. Morel, Zh. Yao, P. Clade, and S. Guellati-Khelifa, Nature (London) 588, 61 (2020).
- $\Delta a_e^{B} = a_e^{exp} - a_e^{th} = (-8.8 \pm 3.6) \cdot 10^{-13}$ Berkley, R. H. Parker, C. Yu, W. Zhong, B. Estey, and H. Muller, Science 360, 191 (2018)




- $X(J^P = 0^\pm, 1^\pm) \to$ invis.: **Motivation** is to exclude the explanation of $(g-2)_e$ puzzle due to $X$ decaying invisibly.
- **NA64, Phys. Rev. Lett. 126, 211802**

# Millicharged particles (MCP)

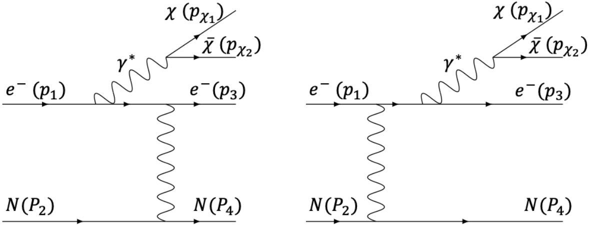



Figure: Feynman diagrams for MCP pair production process.

The Lagrangian can be written as follows

$$\mathcal{L} \supset i\bar{\chi}\gamma^\mu\partial_\mu\chi - m_\chi\bar{\chi}\chi + e\epsilon A_\mu\bar{\chi}\gamma^\mu\chi, \quad (4)$$

where $m_\chi$ is the Dirac mass of the hidden MCPs and $A_\mu$ is the SM photon.

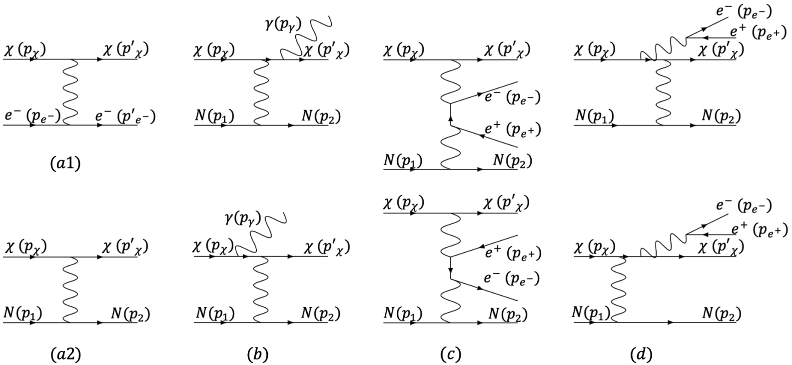



Figure: Feynman diagrams for MCPs energy loss in matter, (a) scattering off atomic nucleus and electrons, (b) bremsstrahlung, (c,d) $e^+e^-$ pair production.

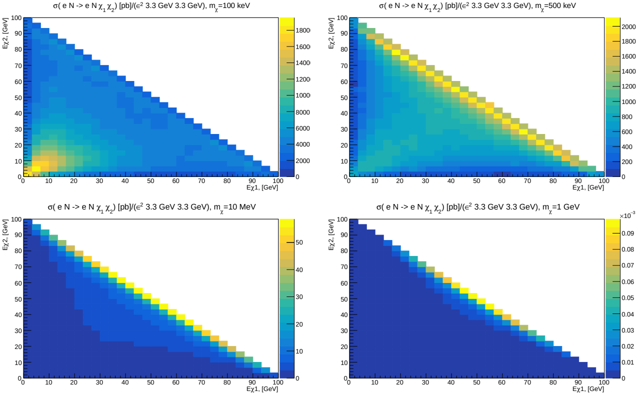



Figure: Double-differential cross section of the MCP pair production as a function of MCP energies $E_{\chi 1}$ and $E_{\chi 2}$ for a set of MCP masses $m_\chi$ and energy of incident electron $E_{beam} = 100\,\text{GeV}$.

The total number of MC pairs produced in the process $eN \to eN\chi\bar{\chi}$ can be calculated as follows

$$N_{\chi\bar{\chi}} = \frac{\rho N_A}{M_A} N_{EOT} X_0 \int_{\text{s.b.}} dE_{\chi 1} dE_{\chi 2} \frac{d\sigma(E_{beam})}{dE_{\chi 1} dE_{\chi 2}} \,. \tag{5}$$

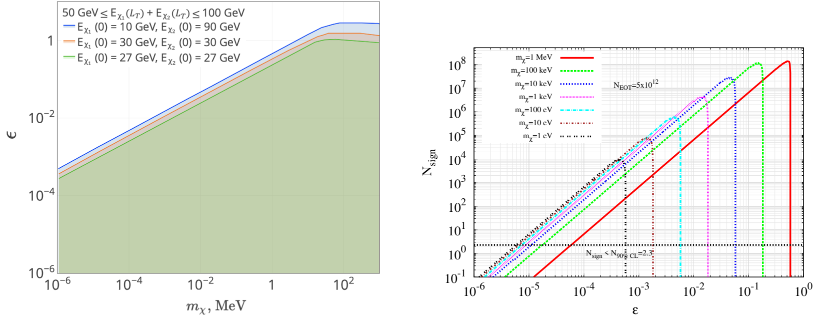



Figure: Left: The MCP pairs with a chosen initial energies do not contribute to the signal events for parameters above the corresponding lines. Right: Number of signal events as function of $\epsilon$

The integration over $E_{\chi 1}$ and $E_{\chi 2}$ in (5) is performed inside the signal box (s. b.) as follows

$$E_{miss}^{th} \lesssim E_{\chi 1} + E_{\chi 2} - \Delta E_{\chi 1} - \Delta E_{\chi 2} \lesssim E_{beam}, \quad (6)$$

where $\Delta E_{\chi_1}$ and $\Delta E_{\chi_2}$ are the total energy depositions of the millichrged particles in the ECAL due to possible electromagnetic rescattering on their way out.

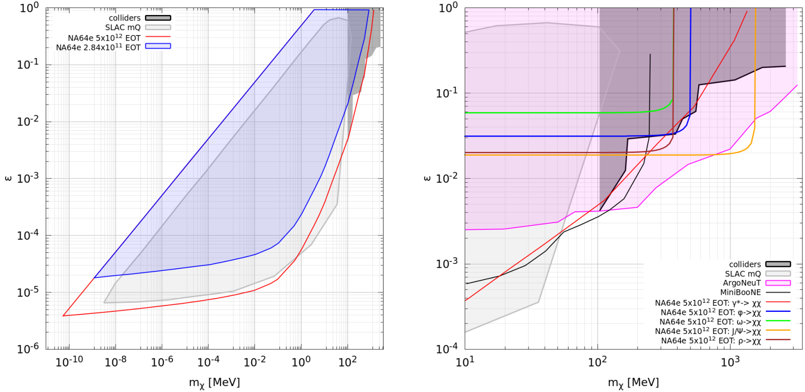
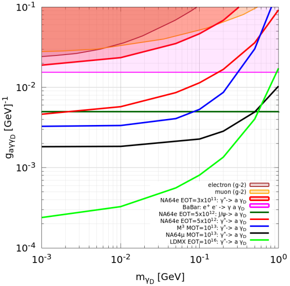
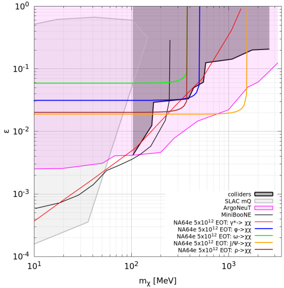
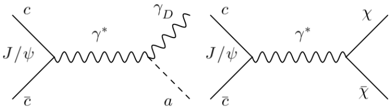



Figure: The expected sensitivity (90% C.L.) of NA64$e$ in the $(\epsilon, m_\chi)$ plane. We take into account invisible decays of vector mesons to the MCPs and MCP production by the energetic beam electrons via bremsstrahlung-like mode $\gamma^* \to \chi\bar{\chi}$ for the prospect statistics $N_{EOT}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

Probing $J/\psi$ vector meson photoproduction $\gamma N \to NJ/\psi$ 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 $J/\psi$ 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]].



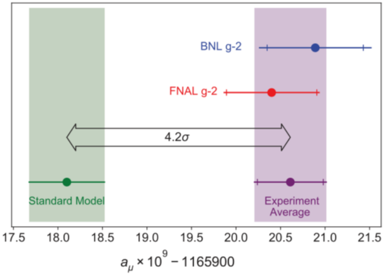



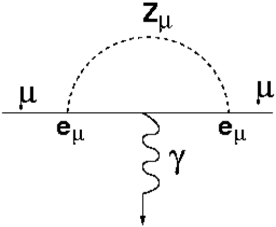
Left Panel (**PRELIMINARY** 2204.09978, Arefyeva, Gninenko, Gorbunov and Kirpichnikov): dark green solid line is the expected reach of NA64e for the dark axion portal coupling $\mathcal{L} \supset e\epsilon\bar{\chi}A_\mu\gamma^\mu\chi$

Right Panel (**PRELIMINARY** 2204.09978, Zhevlakov, Lyubovitskij and Kirpichnikov): the orange solid line is expected reach of NA64e for the millicharged coupling $\mathcal{L} \supset \frac{g_{a\gamma\gamma_D}}{2} aF_{\mu\nu}\tilde{F}'_{\mu\nu}$ (see A. Zhevlakov's talk)

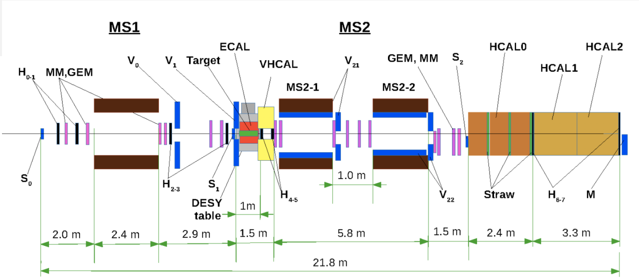
# Motivation for NA64$\mu$: $(g-2)_\mu$ anomaly

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



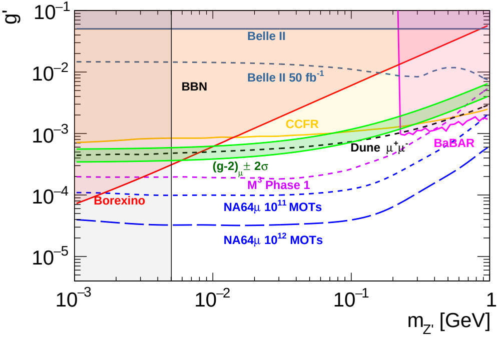



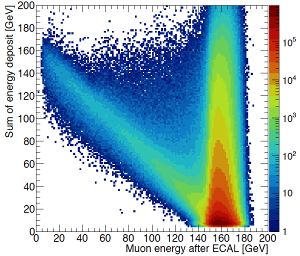

- B. Abi et al. Muon g-2 collaboration Phys. Rev. Lett. 126, 141801 (2021)
- T. Aoyama et al. Phys. Rept. 887 (2020) 1-166
- Sz. Borsanyi et al Nature volume 593, pages 5155 (2021)
- **NA64: 1-Loop contribution from Dark Sector. Sub-GeV range of $m_{Z'}$: $Z' \to \nu\nu$ for $m_{Z'} \lesssim 2m_\mu$**




- **Main components:**
  - **100-160 GeV $\mu$-beam $\simeq 10^7 \mu/$spill**
  - **in $\mu$ tagging: BMS+MS1(MBPL+tracker)**
  - **out $\mu$ tagging: MS2 (2MBPL+tracker)**
  - **$4\pi$ fully hermetic ECAL+Veto+ HCAL**
- **Signature:**
  - **in: 160 GeV $\mu$ track**
  - **out: $\lesssim 80 GeV \mu$ track**
  - **no energy in the ECAL, Veto, HCAL**
  - **sensitivity on $\sim g_\mu^2$**

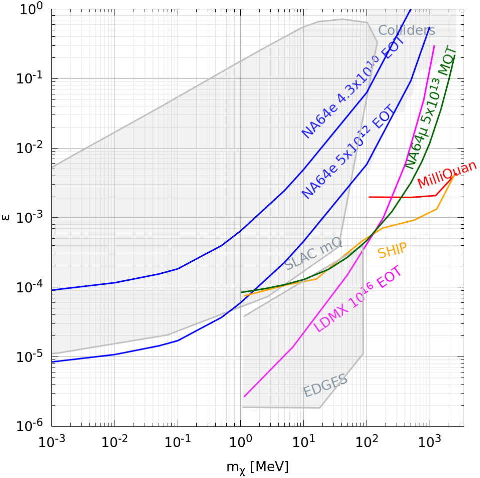
# NA64$\mu$



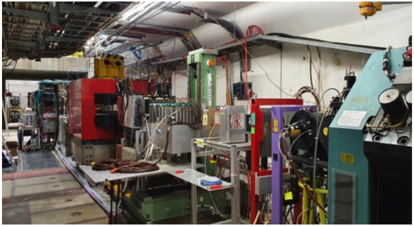
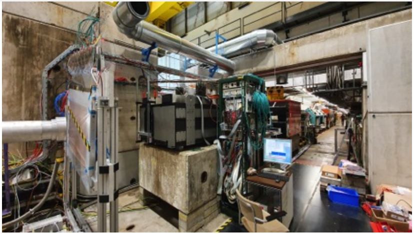

- **Pilot muon beam run (M2 channel) - November 2021 (MOT$\simeq 6\times 10^9$ accumulated)**
- **GOAL: probing muon $(g-2)$ anomaly at NA64$\mu$ within $L_\mu - L_\tau$ anomaly free gauge extension (exact tree level cross-section $\mu N \to \mu N Z'$ without relaying on widely used IWW approach) Phys.Rev.D 104 (2021) 7, 076012, e-Print: 2107.13297 [hep-ph]**

# Millicharged particles with NA64$e$ and NA64$\mu$




- **Pilot muon beam run (M2 channel) - November 2021**
- **NA64$\mu$ GOAL: millicharged particles more effective production in Na64$\mu$ than in NA64$e$ for the masses $m_\chi \gtrsim 100$ MeV due to $X_0^\mu \gg X_0^e$ and increased intesity of muon beam.**
- **NA64$e$ GOAL: millicharged particles more effective production in Na64$e$ than in NA64$\mu$ for the masses $m_\chi \lesssim 1$ MeV**

# NA64$\mu$

- **Open questions:**
  – **trigger rate, $\pi$, $K$ 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 $\mu$,**
- **Plans: – Goal to probe for the first time $(g-2)_\mu$ parameter space for sub-GeV $Z_\mu$: $\simeq$ a few $10^{10}$ MOT**

# Summary and plans

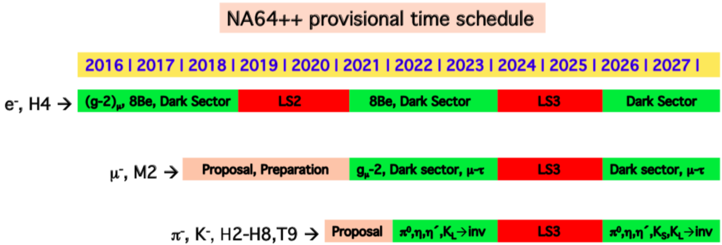
**Prospects of NA64++ before LS3:**

– 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. **Subject of proposal to SPS next year**

– **Main goal** to explore **LDM parameter space** with $\gtrsim 5 \times 10^{12}$ EOT

– We have started **searches of dark sectors weakly coupled to muons with NA64$\mu$:** $(g-2)_\mu$ and $L_\mu - L_\tau \to Z'$: **pilot run at M2**

– **Feasibility study for invisible decays of neutral meson** $\pi, K_S, K_L, \eta, \eta' \to$ **invisible (in progress)**

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