Current status and prospects of NA64 experiment

D. V. Kirpichnikov

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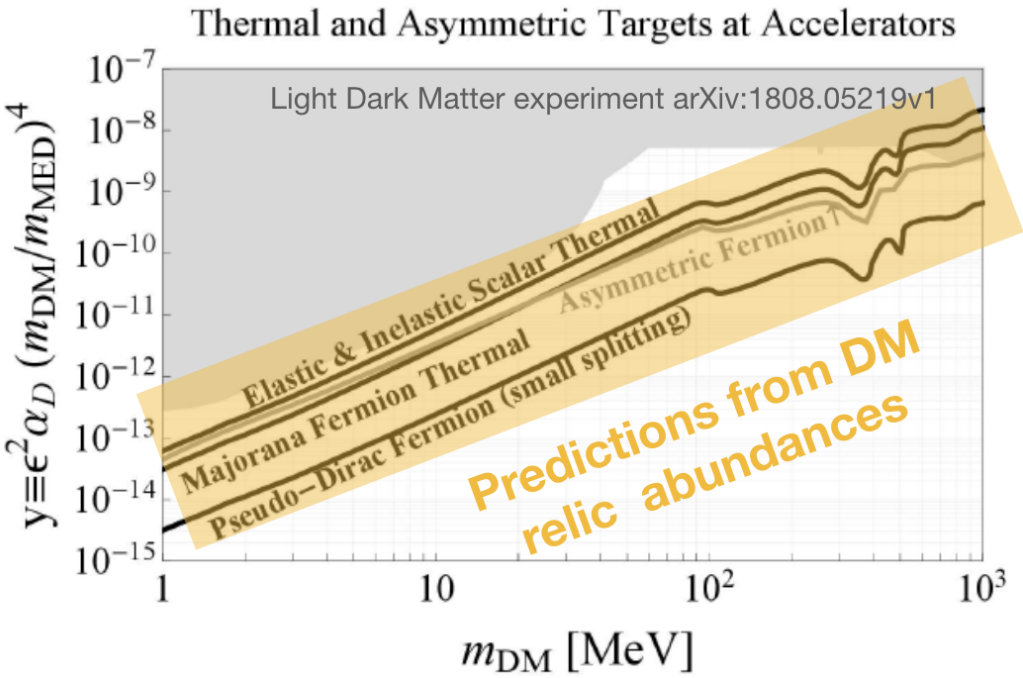
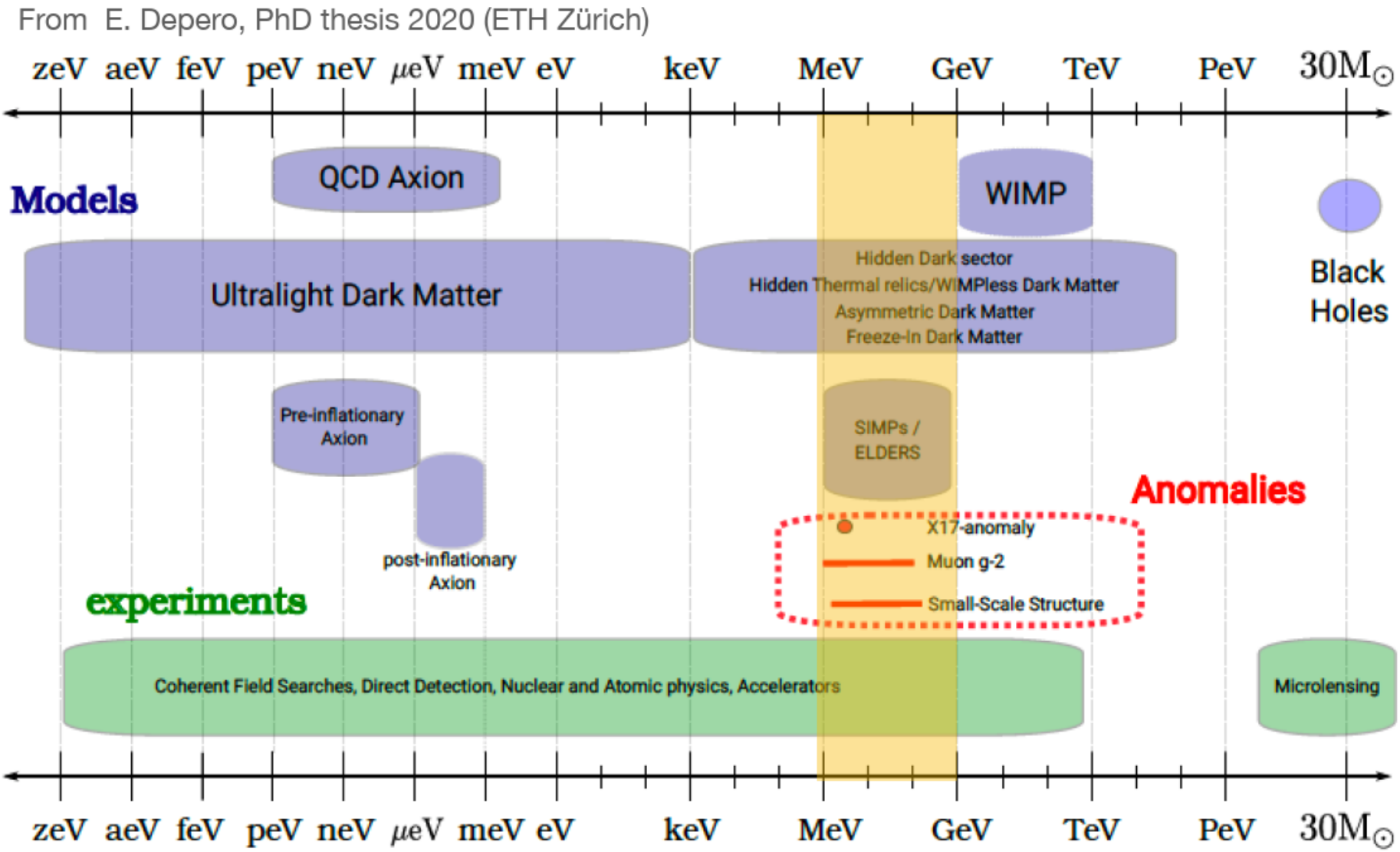
Motivations for searching for light vectors and ALPs

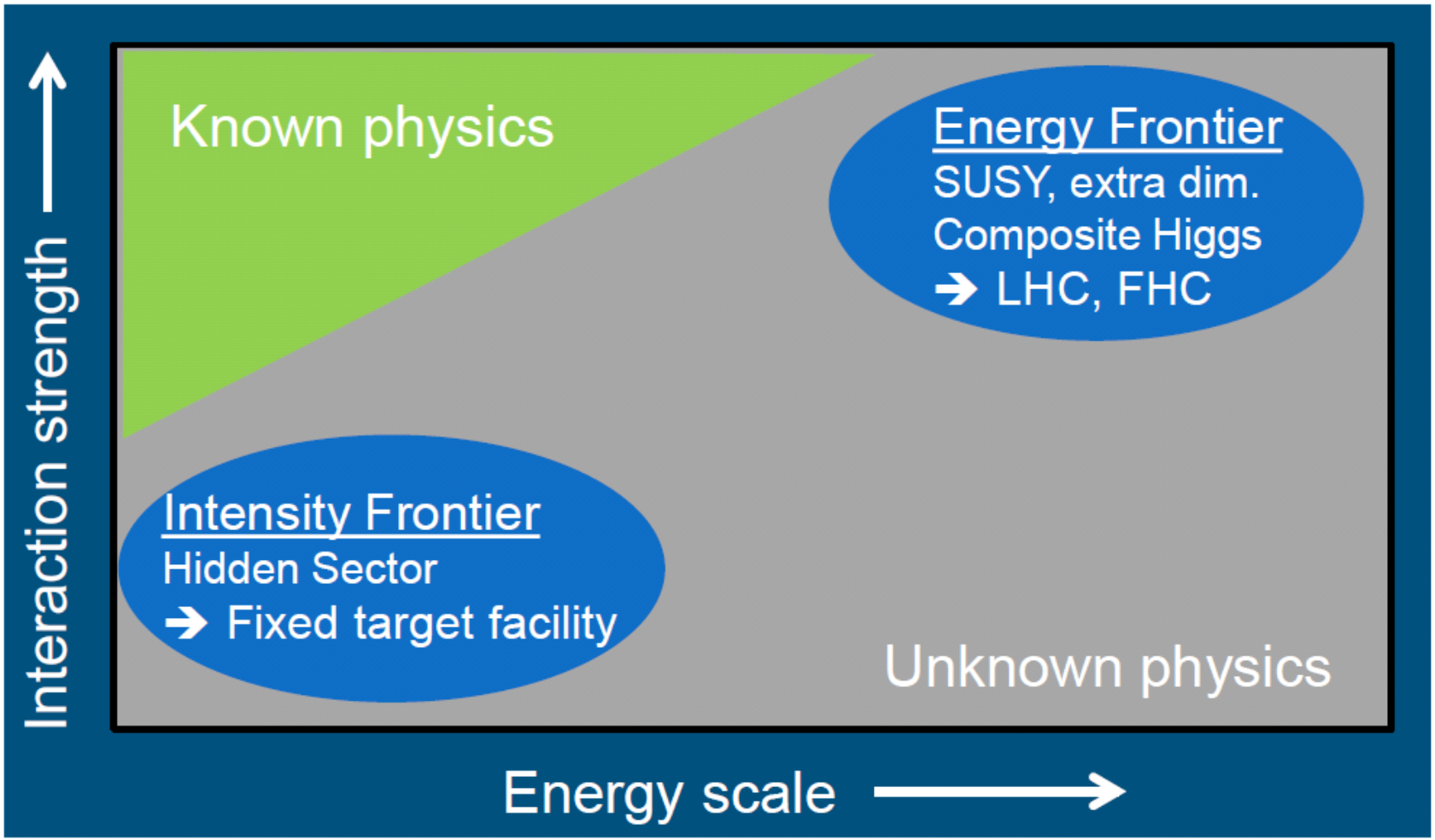
- They are popular candidates for solution of experimental anomalies: $(g-2)_\mu$, MinoBooNE, ^{8}Be, KOTO, XENON1T
- They could act as a mediator to a Dark Dector (DS). DS consists of particles and fields which are singlets with respect to the gauge group of the SM. It interacts with the SM presumably 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 χ: **Scalar Dark Matter, Majorana Dark Matter, Pseudo Dirac Dark Matter**

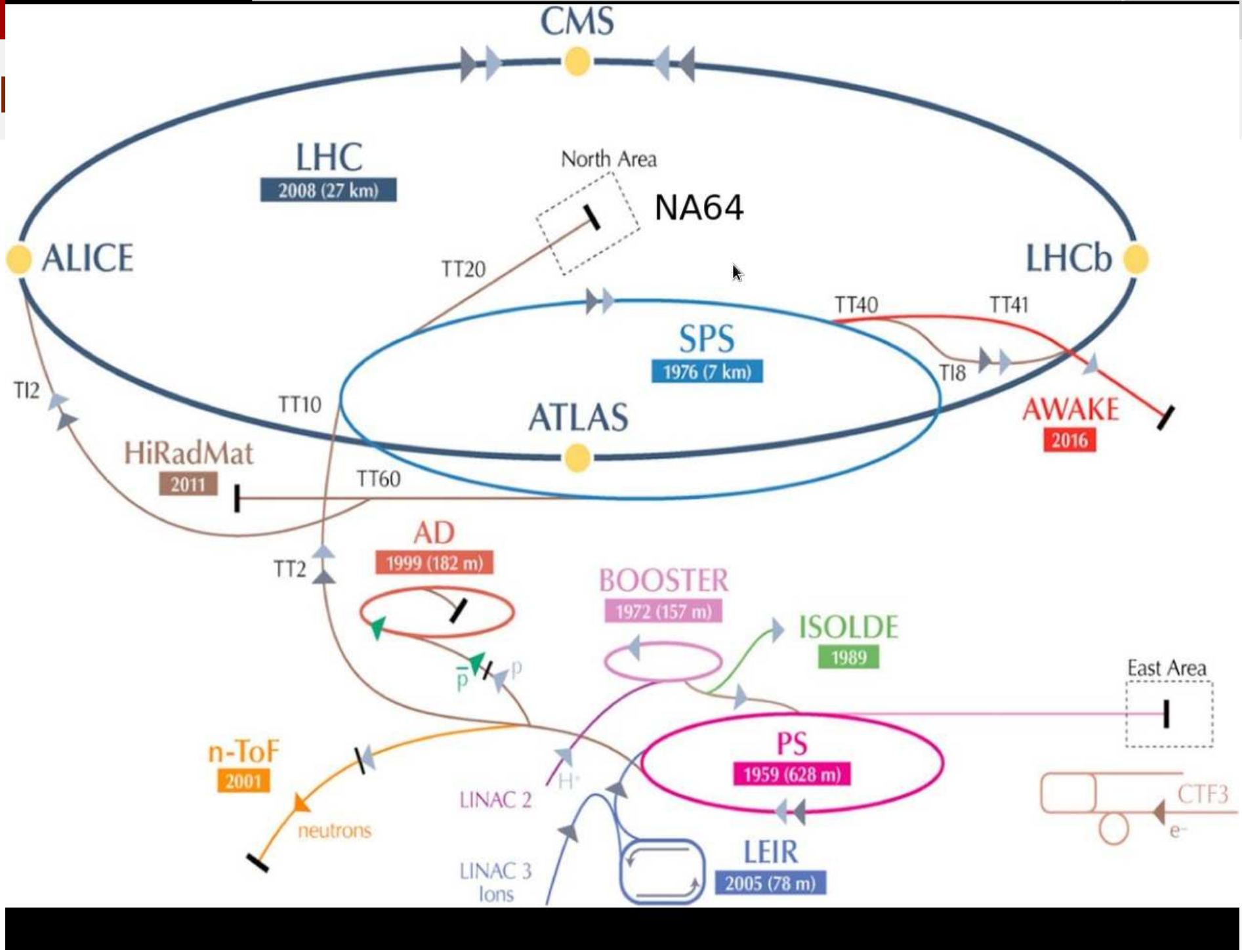


Intensity frontier



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
PS
1959 (628 m)
n-ToF
2001
neutrons
LINAC 2
LINAC 3
Ions
LEIR
2005 (78 m)
CTF3

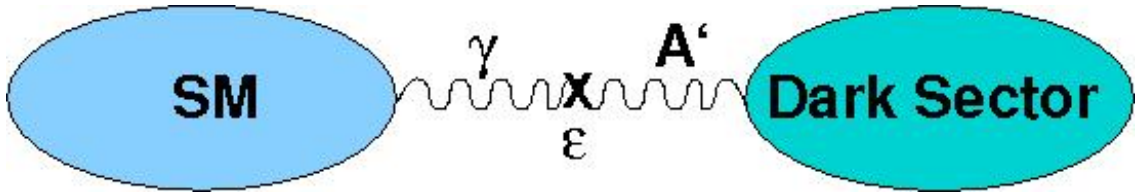
NA64 photograph

Yu. M. Andreev,[1] D. Banerjee,[2] B. Banto Oberhauser,[3] J. Bernhard,[2] P. Bisio,[4,5] V. E. Burtsev,[6] A. Celentano,[4] N. Charitonidis,[2] A. G. Chumakov,[7] D. Cooke,[8] P. Crivelli,[3] E. Depero,[3] A. V. Dermenev,[1] S. V. Donskov,[9] R. R. Dusaev,[7] T. Enik,[6] V. N. Frolov,[6] A. Gardikiotis,[10] S. G. Gerassimov,[11,12] S. N. Gninenko,[1,*] M. Hösgen,[13] M. Jeckel,[2] V. A. Kachanov,[9] A. E. Karneyeu,[1] G. Kekelidze,[6] B. Ketzer,[13] D. V. Kirpichnikov,[1] M. M. Kirsanov,[1] V. N. Kolosov,[9] S. G. Kovalenko,[14,15] V. A. Kramarenko,[6,16] L. V. Kravchuk,[1] N. V. Krasnikov,[6,1] S. V. Kuleshov,[14,15] V. E. Lyubovitskij,[7,15] V. Lysan,[6] L. Marsicano,[4] V. A. Matveev,[6] Yu. V. Mikhailov,[9] L. Molina Bueno,[3,17] D. V. Peshekhonov,[6] V. A. Polyakov,[9] B. Radics,[3] A. Rubbia,[3] K. M. Samalantin,[6] V. D. Samoylenko,[9] H. Sieber,[3] D. Shchukin,[12] O. Soto,[18,15] V. O. Tikhomirov,[12] I. V. Tlisova,[1] A. N. Toropin,[1] B. I. Vasilishin,[7] P. V. Volkov,[6,16] V. Yu. Volkov,[16] I. Voronchikhin,[7] and J. Zamora-Saá[14,15]

(NA64 Collaboration)

[1]*Institute for Nuclear Research, 117312 Moscow, Russia*
[2]*CERN, European Organization for Nuclear Research, CH-1211 Geneva, Switzerland*
[3]*ETH Zürich, Institute for Particle Physics and Astrophysics, CH-8093 Zürich, Switzerland*
[4]*INFN, Sezione di Genova, 16147 Genova, Italia*
[5]*Universitá degli Studi di Genova, 16126 Genova, Italy*
[6]*Joint Institute for Nuclear Research, 141980 Dubna, Russia*
[7]*Tomsk Polytechnic University, 634050 Tomsk, Russia*
[8]*UCL Departement of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, United Kingdom*
[9]*State Scientific Center of the Russian Federation Institute for High Energy Physics of National Research Center 'Kurchatov Institute' (IHEP), 142281 Protvino, Russia*
[10]*Physics Department, University of Patras, 265 04 Patras, Greece*
[11]*Technische Universität München, Physik Department, 85748 Garching, Germany*
[12]*P.N.Lebedev Physical Institute of the Russian Academy of Sciences, 119 991 Moscow, Russia*
[13]*Universität Bonn, Helmholtz-Institut für Strahlen-und Kernphysik, 53115 Bonn, Germany*
[14]*Center for Theoretical and Experimental Particle Physics, Facultad de Ciencias Exactas, Universidad Andres Bello, Fernandez Concha 700, Santiago, Chile*
[15]*Millennium Institute for Subatomic Physics at High-Energy Frontier (SAPHIR), Fernandez Concha 700, Santiago, Chile*
[16]*Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, 119991 Moscow, Russia*
[17]*Instituto de Fisica Corpuscular (CSIC/UV), Carrer del Catedrátic José Beltrán Martinez, 2, 46980 Paterna, Valencia*
[18]*Departamento de Física, Facultad de Ciencias, Universidad de La Serena, Avenida Cisternas 1200, La Serena, Chile*

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:

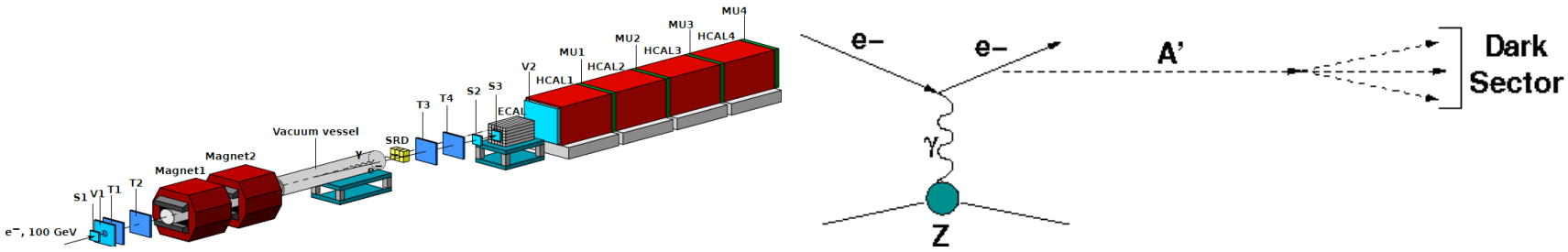
$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}^2 + \frac{1}{4}\left(F'_{\mu\nu}\right)^2 + \frac{\epsilon}{2}F_{\mu\nu}F'_{\mu\nu} + +e\bar{\psi}_e\gamma_\mu A^\mu\psi_e + \mathcal{L}_{int}(A' - \mathrm{DM})$$

- 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 $e^- N \to e^- NA'$,
- 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 $\alpha_D \sim \alpha_{QED} \gg \epsilon$

DM processes simulation: DMG4 toolkit

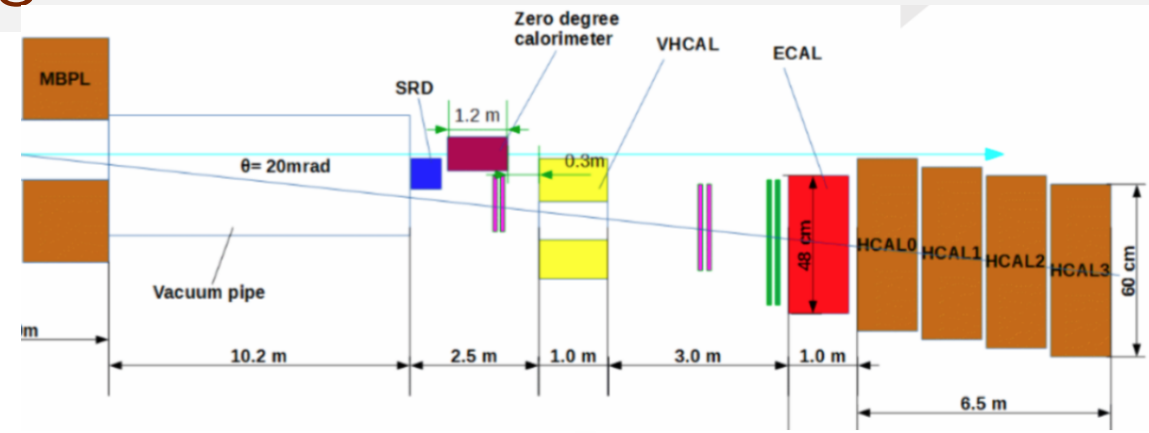
- Fully GEANT4 compatible package DMG4 is developed **(M. Kirsanov et al., 2021, Computer physics communication, 2102.12192)** . Can be used in any full simulation program based on GEANT4 toolkit
- Bremsstrahlung process of electrons and muons (like $eN \to eNA'$), gamma conversion to ALP ($\gamma N \to aN$), 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)**

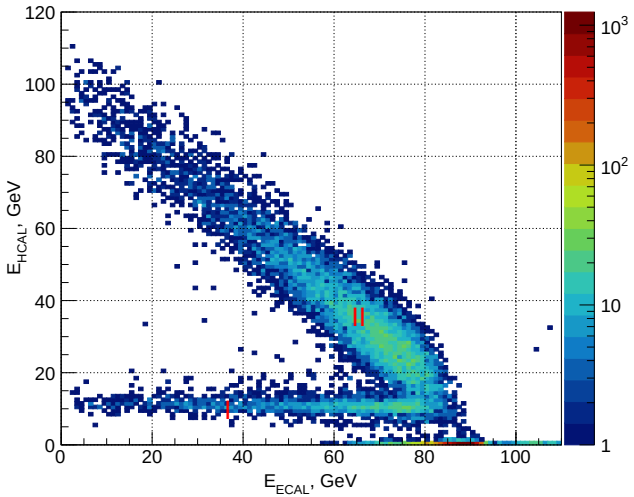
NA64 experiment setup (invisible mode): Proposed by S.Gninenko Phys.Rev.D 89 (2014) 7, 07500 (INR Moscow)

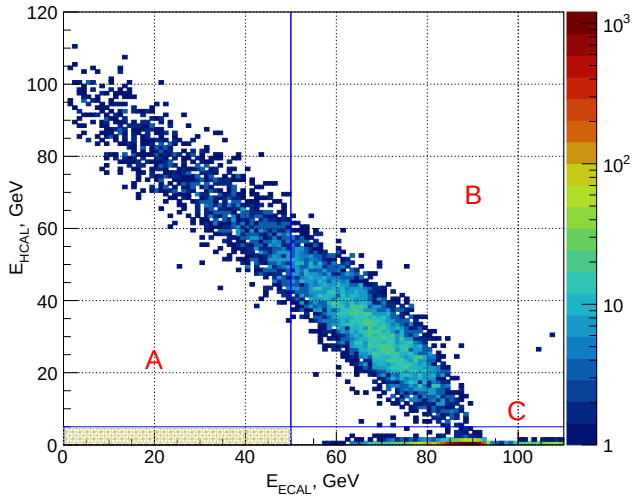


- **NA64** is designed to search for dark sector physics in missing-energy events with $e^{\pm}, \mu, \pi, K, p$ beams.
- **Main Components:** a) clean $E_0 = 100$ GeV e^- beam; b) e^- tagging system: tracker+SRD; c) hermetic ECAL+HCAL;
- **Signature:**
  a) in: 100 GeV e^- track; b) out: $E_{ECAL} 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

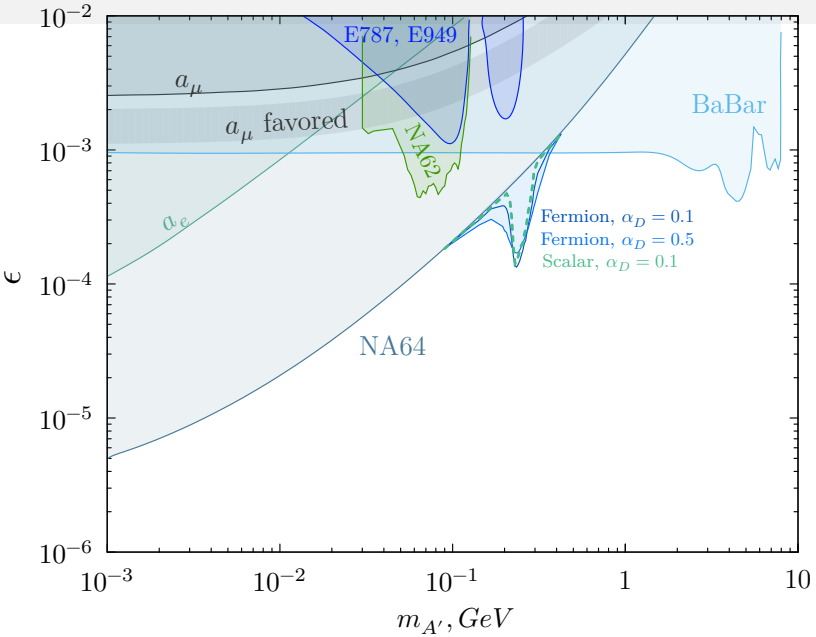


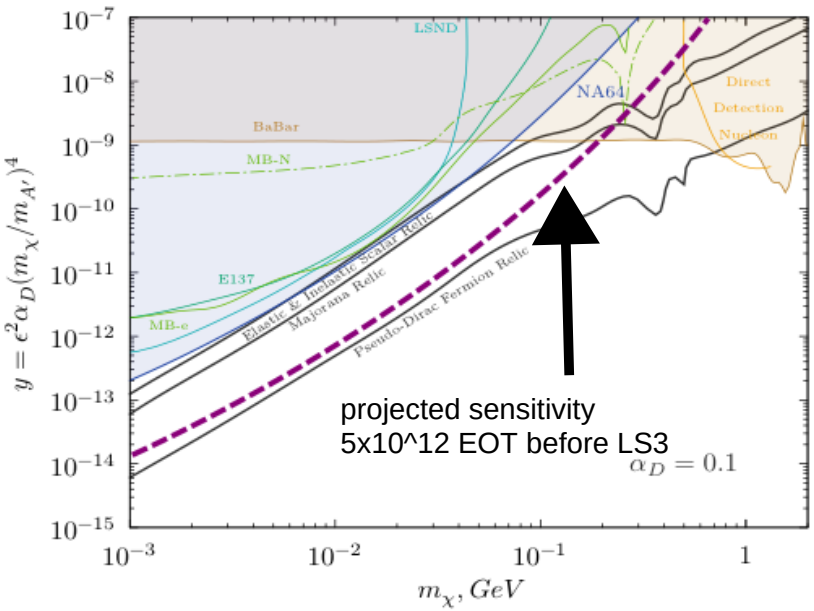




- $E_{beam} \simeq E_{HCAL} + E_{ECAL}$ **is the energy conservation for the experimental facility**
- **NA64e allows to probe invisible decays of Dark Matter mediators:** $eN \to eNX(X \to \chi\bar{\chi})$**, where** X **is a general hidden boson (spin 0, spin 1, spin 2) the mediator between SM and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

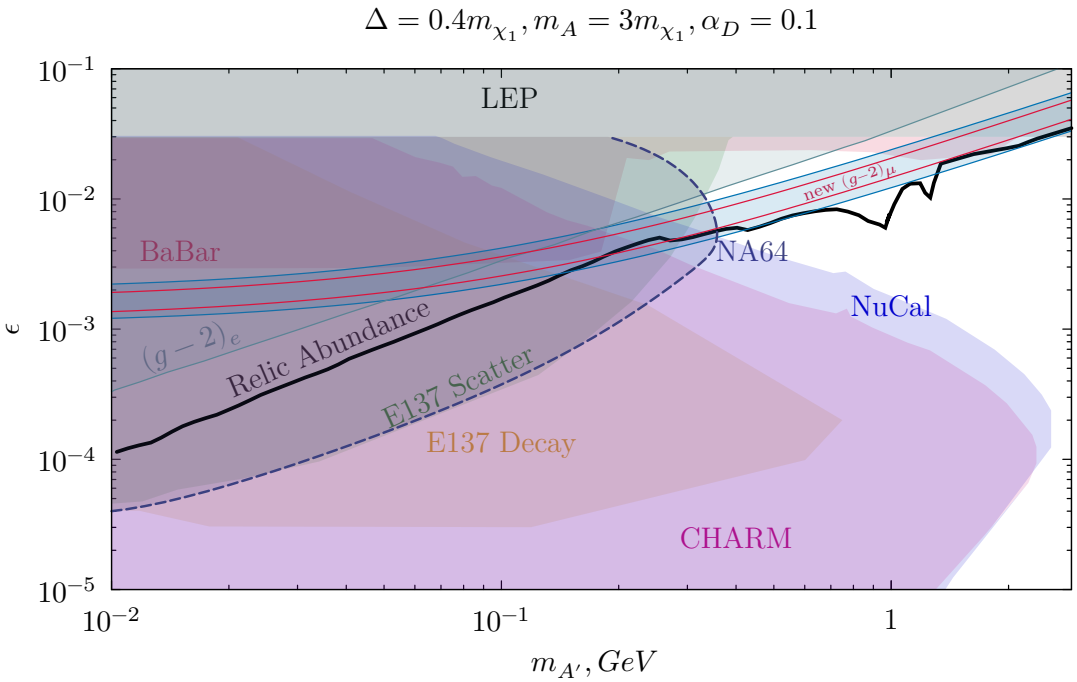
Current and future sensitivity to Dark Photon $(\epsilon, m_{A'})$ and (y, m_χ)

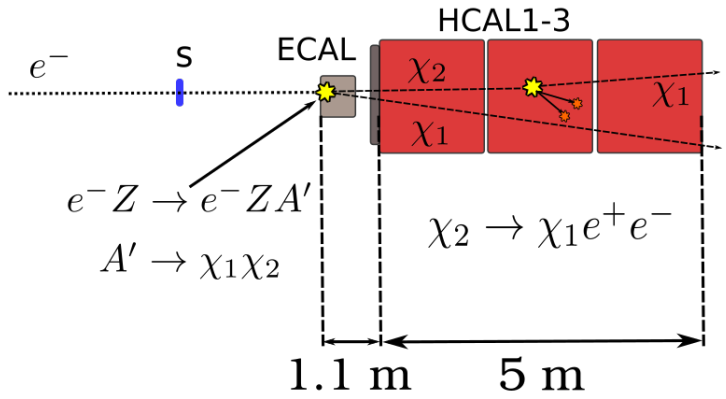




- **Invisible mode data taking: 2016-2017-2018 (combined analysis 2.84×10^{11} EOT)**
- **Long Shutdown 2: 2019-2020**
- **Data taking 11th August 2021 (5 weeks) $\simeq 10^{10}$ EOT**
- **Data taking in 2022 (combined analysis yields 9.37×10^{11} EOT)**
- **Data taking in 2023 (June -July for electron beam mode)**
- **GOAL: Beam setup and electronics upgrade $\rightarrow$ reduce background from electro nuclear interactions along the beam line.**
- **GOAL: to accumulate 5×10^{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:

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

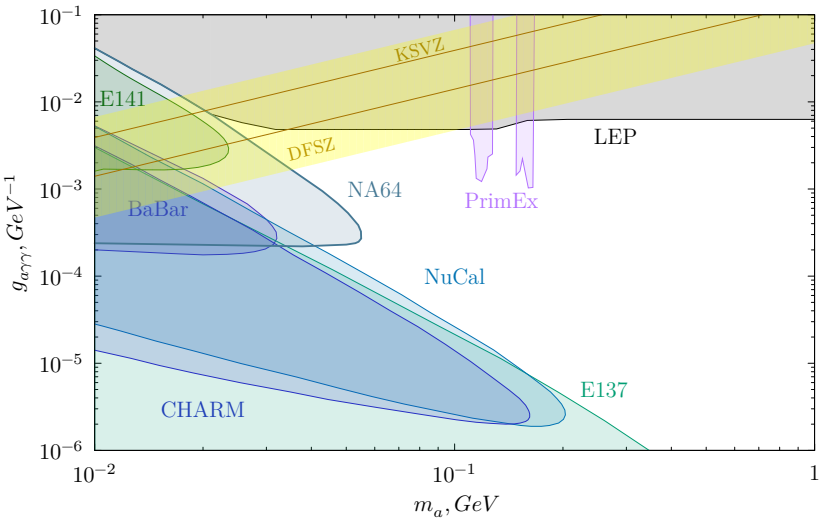
- Primakoff production: $\gamma_{brems.} + N \to a + N$
- followed by decay $a \to \gamma\gamma$
  – in the fiducial volume of NA64 in case of **visible mode setup** .
  – for **invisible mode setup** the ALP decays outside detectors
- Typical decay width

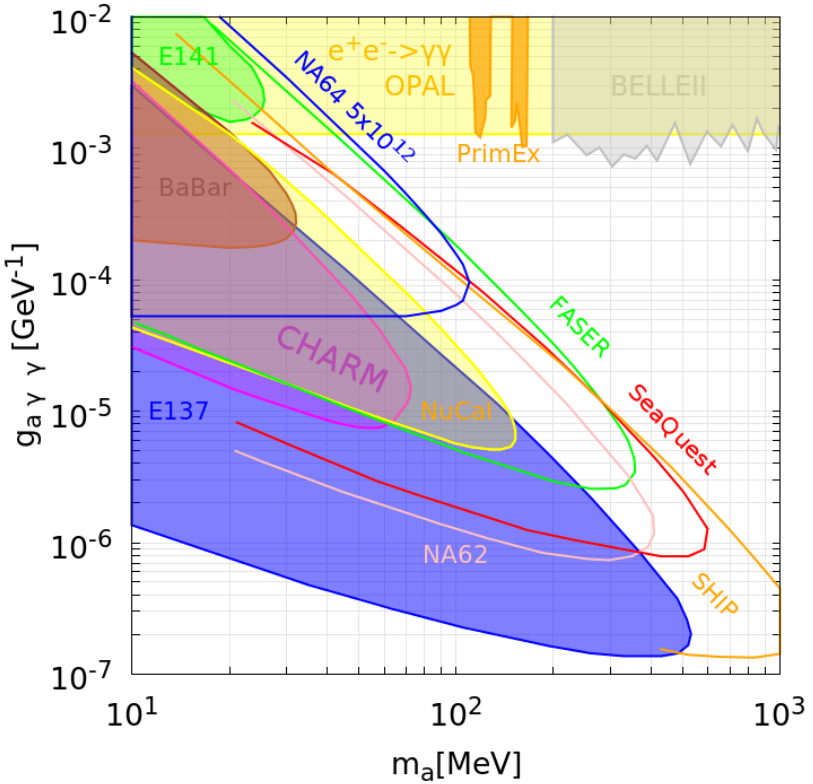
$$\Gamma_{a\to\gamma\gamma} = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}. \tag{1}$$

- Typical decay length

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

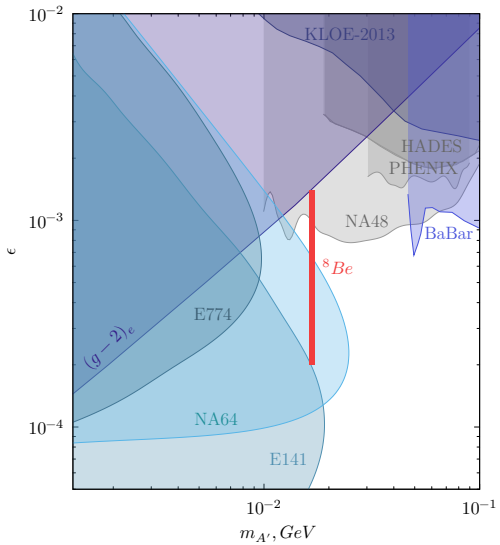
Current limits and projection for ALPs

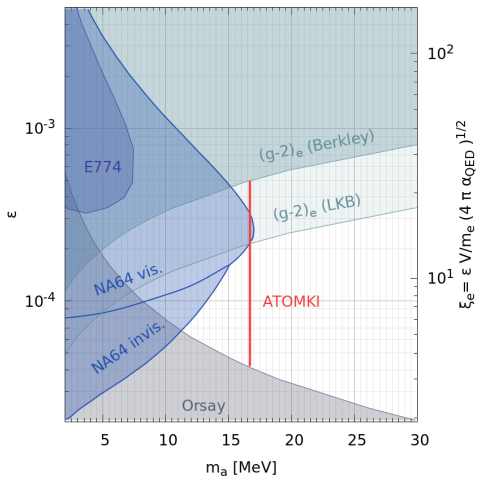




- **Left plot is a current limit for $EOT = 2.84 \cdot 10^{11}$ (PRL, 2020)**
- **Right plot is projected limit for $EOT = 5 \times 10^{12}$ (PRD, 2020)**
- **small $g_{a\gamma\gamma} \to$ long-lived ALPs, large $g_{a\gamma\gamma} \to$ short-lived ALPs**
- **Future Plans: to consider invisible decay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

Visible mode of Dark Photon and ALPs coupled mostly to electrons

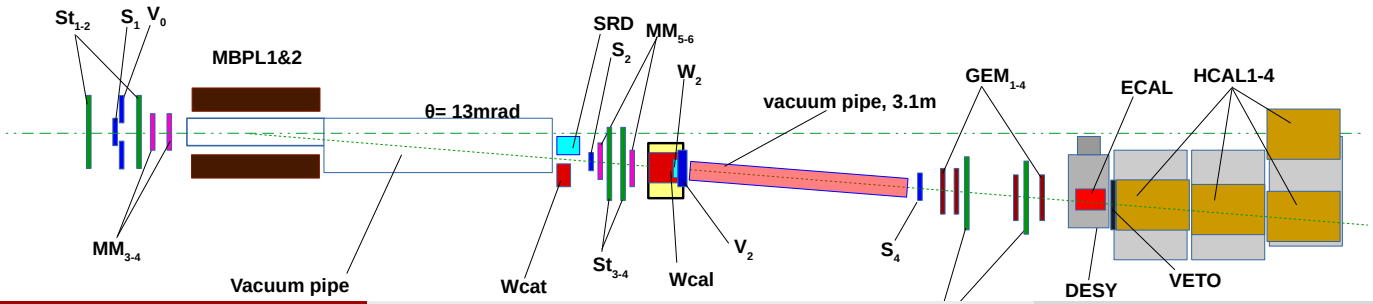




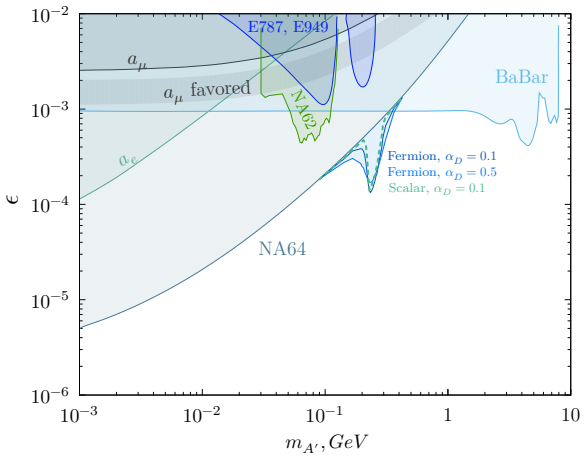
The ATOMKI experiment of (Krasznahorkay et al. 2016) has reported the observation of a 6.8 σ excess of events in the invariant mass distributions of e^+e^- pairs produced in the nuclear transitions of excited $^*Be^8$ and $^*He^4$ This anomaly can be associated with X-boson of $m_X = 16.7$ MeV.

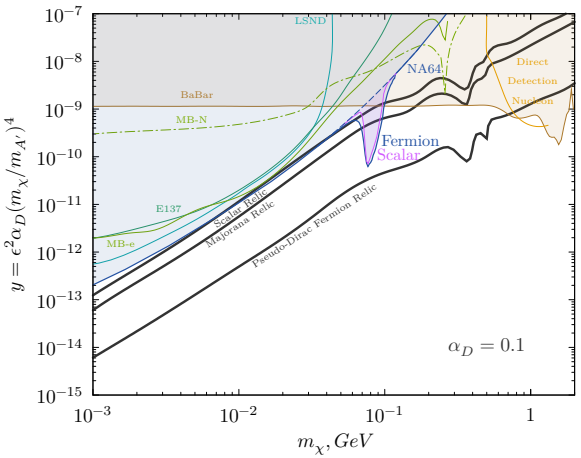
GOAL: to perform invariant mass reconstruction:

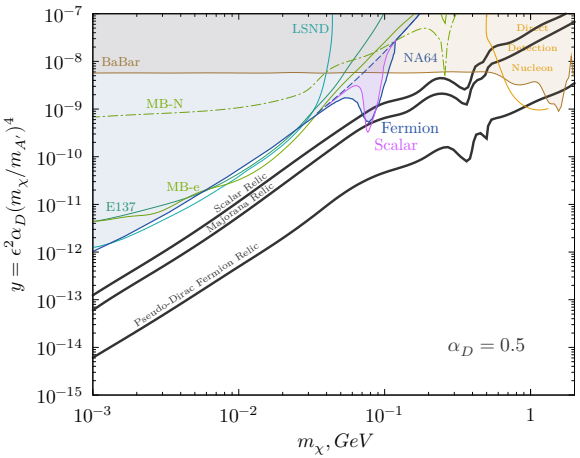
- **Increase the length of decay tube to resolve e^+e^- tracks.**
- **More compact WCAL**



Resonance production of A' by electron beam

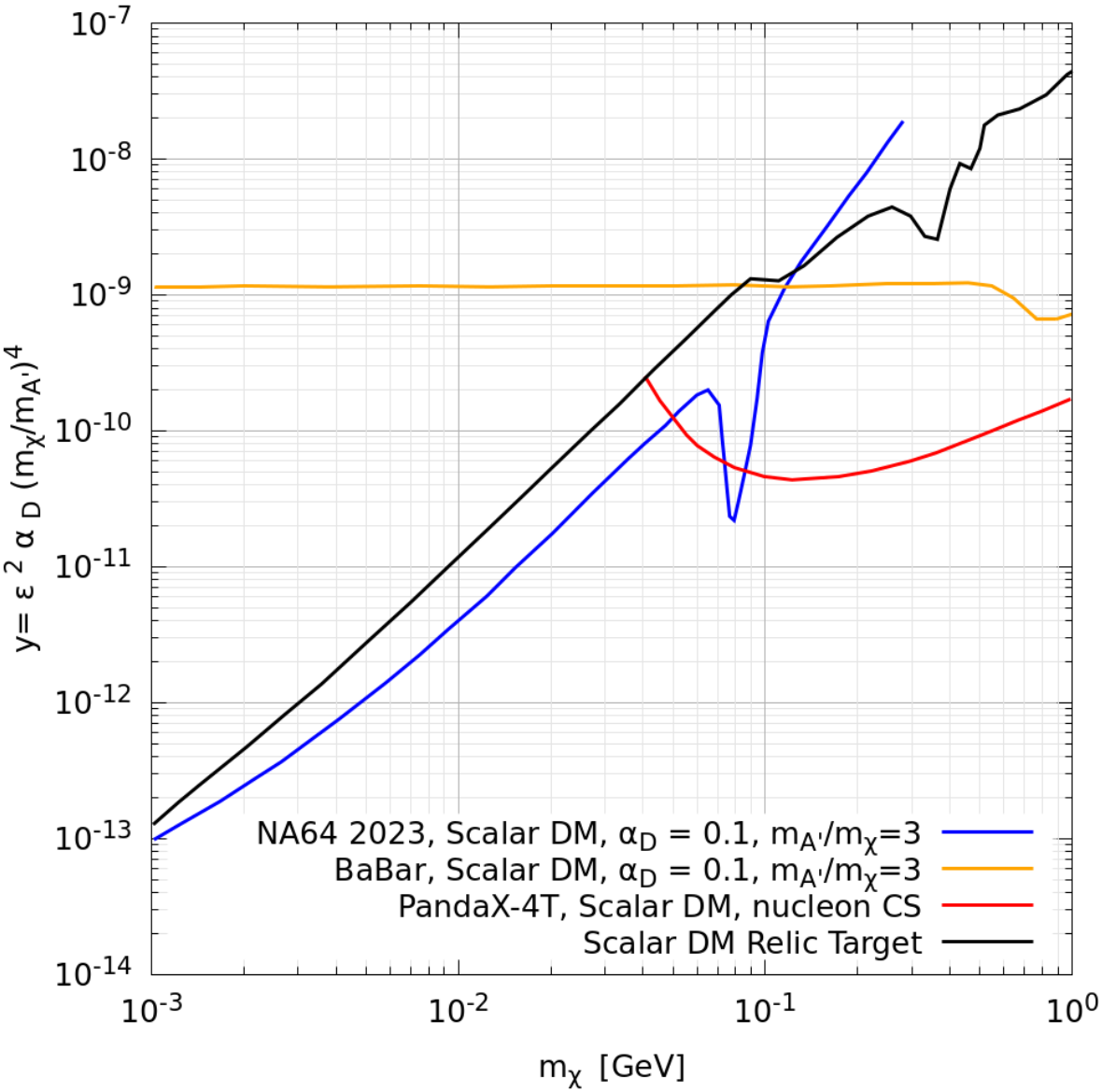




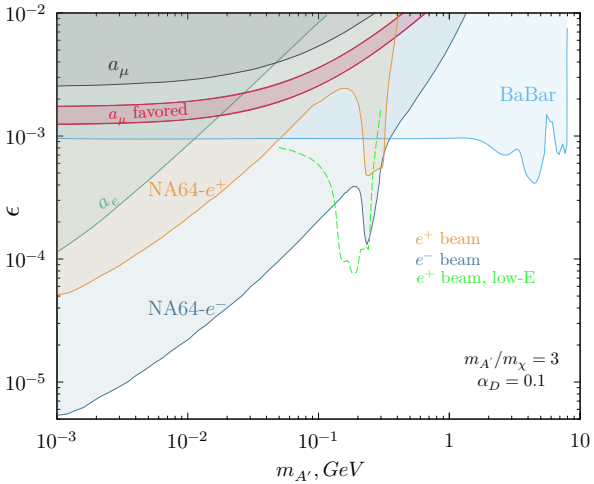


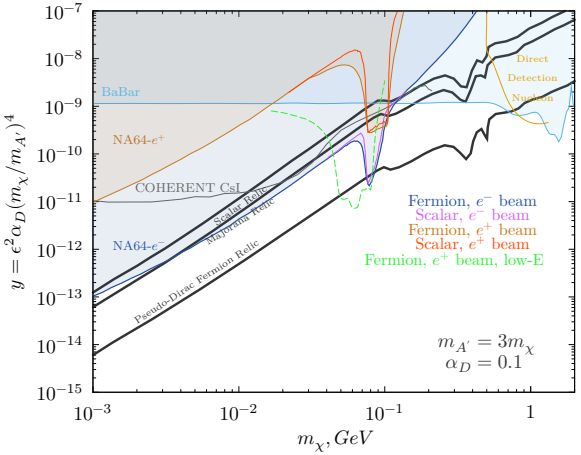
- **Resonance annihilation channel using the secondary positrons present in the EM shower in the target induced by the initial electron beam**
- **Improvement limit on ϵ up to factor 10 in the resonant region $m_{A'} \simeq (2 m_e E_{cut})^{1/2}$**
- **Probing resonant $e^+ e^- \to A' \to \chi\chi$ production by electron beam: Phys. Rev. D 104 (2021) 9 (2108.04195 [hep-ph])**
- **Preliminary result for combined statistics 9.37×10^{11}: 2307.02404**

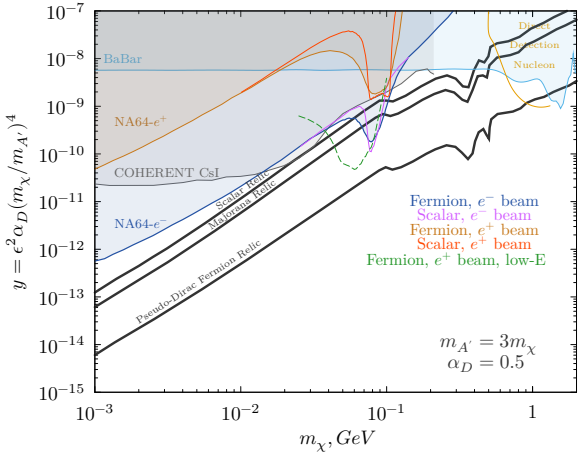
Comparison with Direct Detection Experiment PandaX-4T



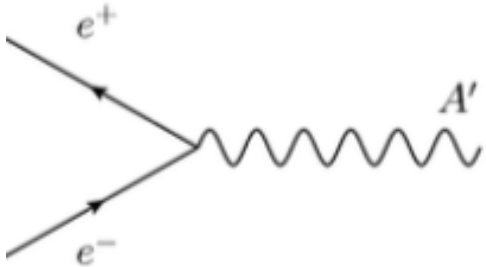
Resonance production of A' by positron beam

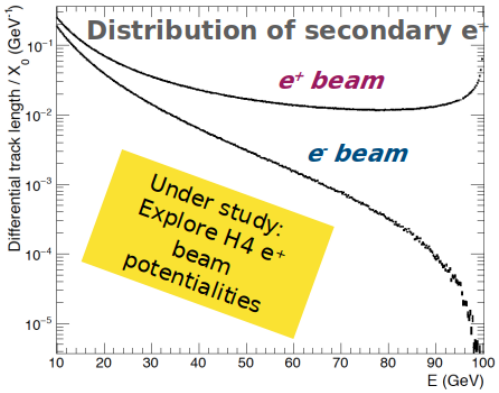






- **Preliminary: probing the resonance $e^+e^- \to A'$ by positron beam**





Millicharged particles (MCP)

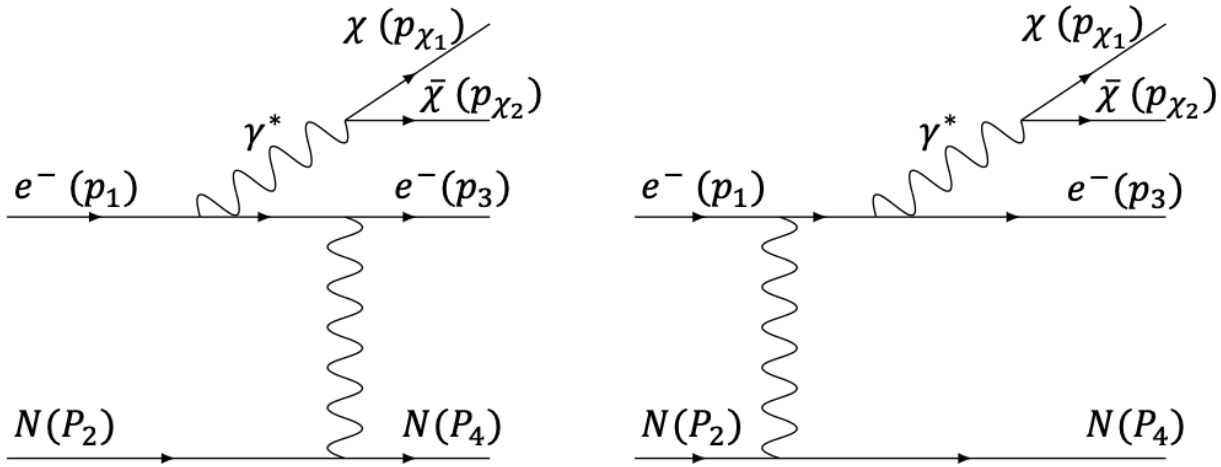
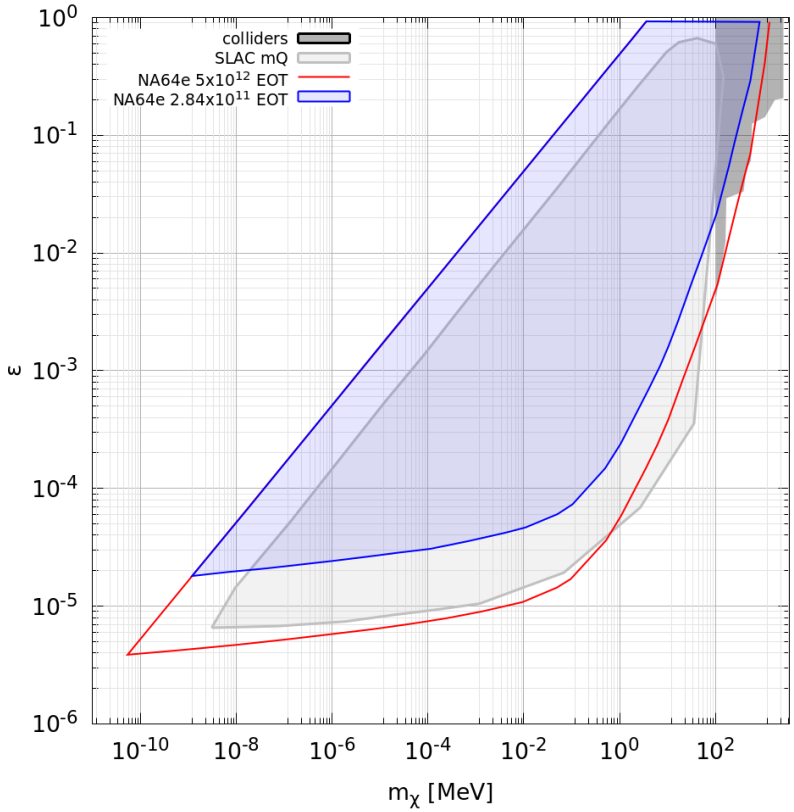


Figure: Feynman diagrams for MCP pair production process.

The Lagrangian can be written as follows

$$\mathcal{L} \supset i\bar{\chi}\gamma^\mu\partial_\mu\chi - m_\chi\bar{\chi}\chi + e\epsilon A_\mu\bar{\chi}\gamma^\mu\chi, \tag{3}$$

where m_χ is the Dirac mass of the hidden MCPs and A_μ is the SM photon.



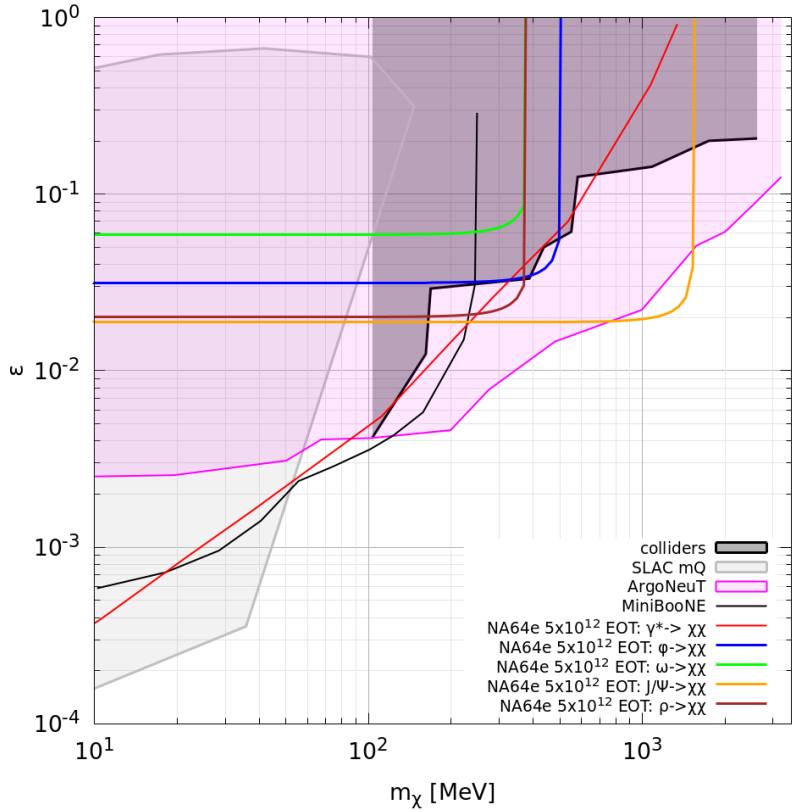
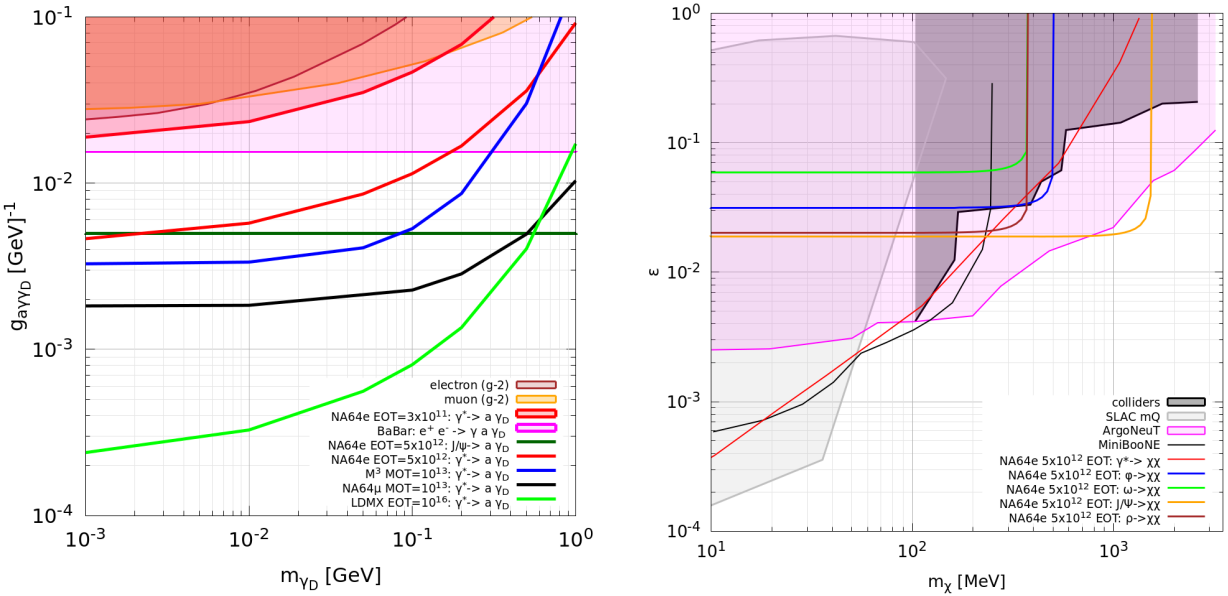
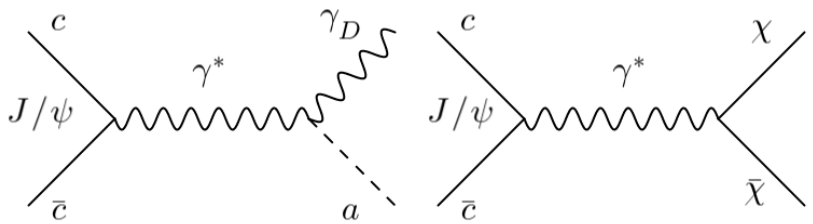


Figure: The expected sensitivity (90% C.L.) of NA64e in the (ϵ, m_χ) plane. We take into account invisible decays of vector mesons to the MCPs and MCP production by the energetic beam electrons via bremsstrahlung-like mode $\gamma^* \to \chi\bar{\chi}$ for the prospect statistics $N_{EOT} = 5 \times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



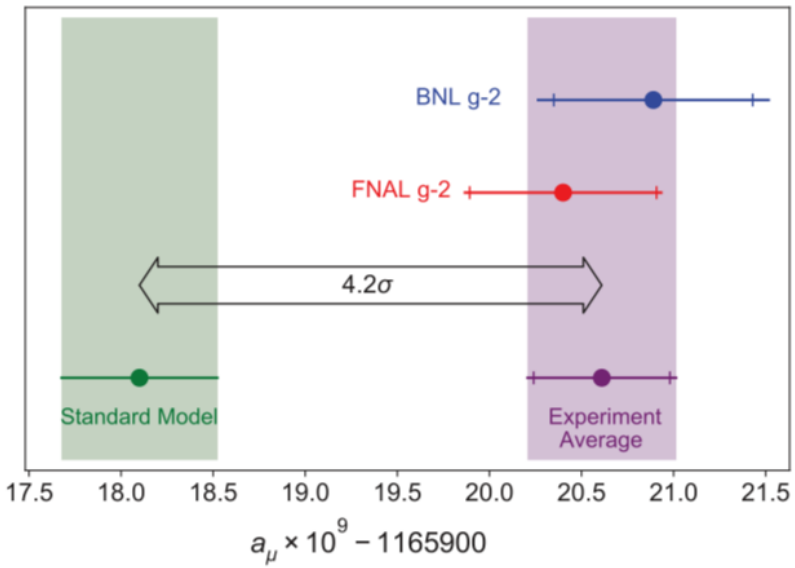


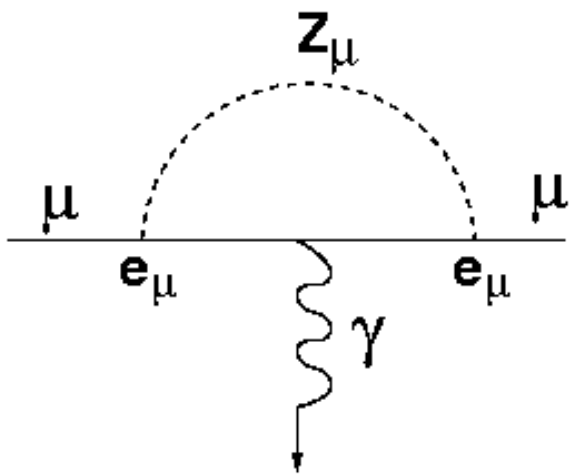
Right Panel (**PRELIMINARY:** PRD, 106 (2022) 3, 035029, Arefyeva, Gninenko, Gorbunov and Kirpichnikov): dark green solid line is the expected reach of NA64e for the dark axion portal coupling $\mathcal{L} \supset e\epsilon\bar{\chi}A_\mu\gamma^\mu\chi$

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 $\mathcal{L} \supset \frac{g_{a\gamma\gamma_D}}{2} aF_{\mu\nu}\tilde{F}'_{\mu\nu}$

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

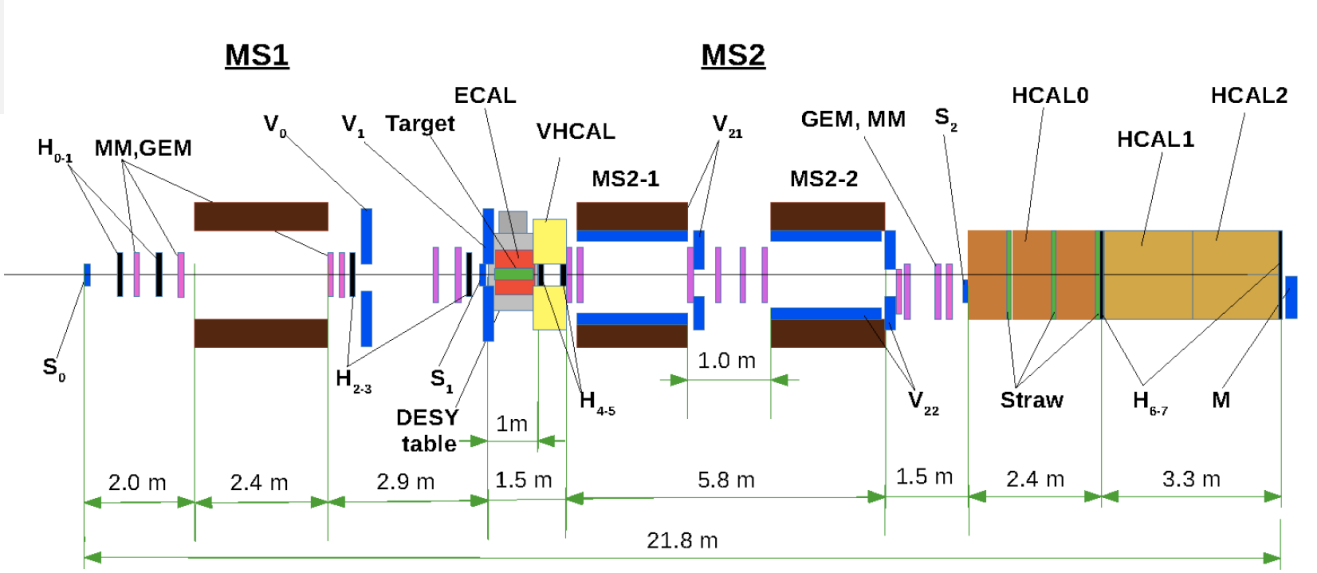
FNAL: $a_\mu = \dfrac{g_\mu - 2}{2}$, $\Delta a_\mu = a_\mu^{exp} - a_\mu^{th} = (251 \pm 59) \cdot 10^{-11}$





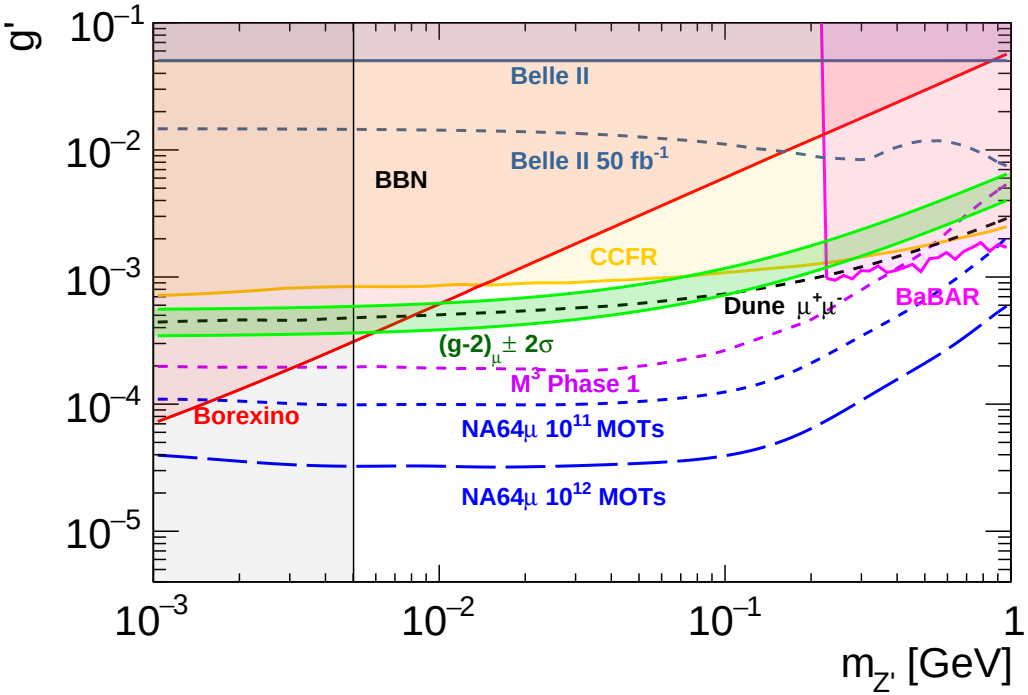
- B. Abi et al. Muon g-2 collaboration Phys. Rev. Lett. 126, 141801 (2021)
- T. Aoyama et al. Phys. Rept. 887 (2020) 1-166
- Sz. Borsanyi et al Nature volume 593, pages 5155 (2021)
- **NA64: 1-Loop contribution from Dark Sector. Sub-GeV range of $m_{Z'}$: $Z' \to \nu\nu$ for $m_{Z'} \lesssim 2m_\mu$**

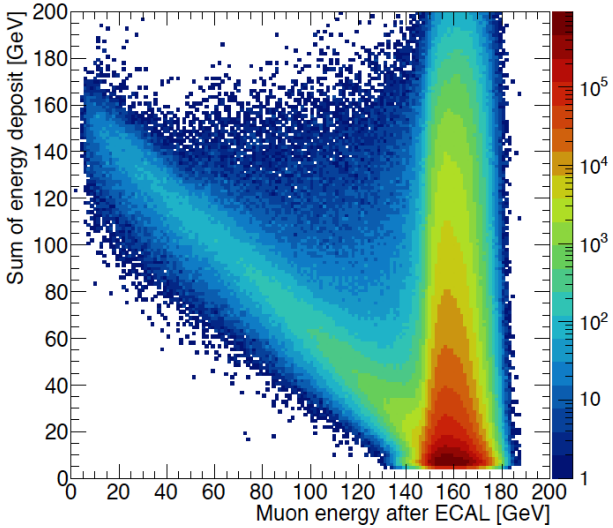
NA64μ



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

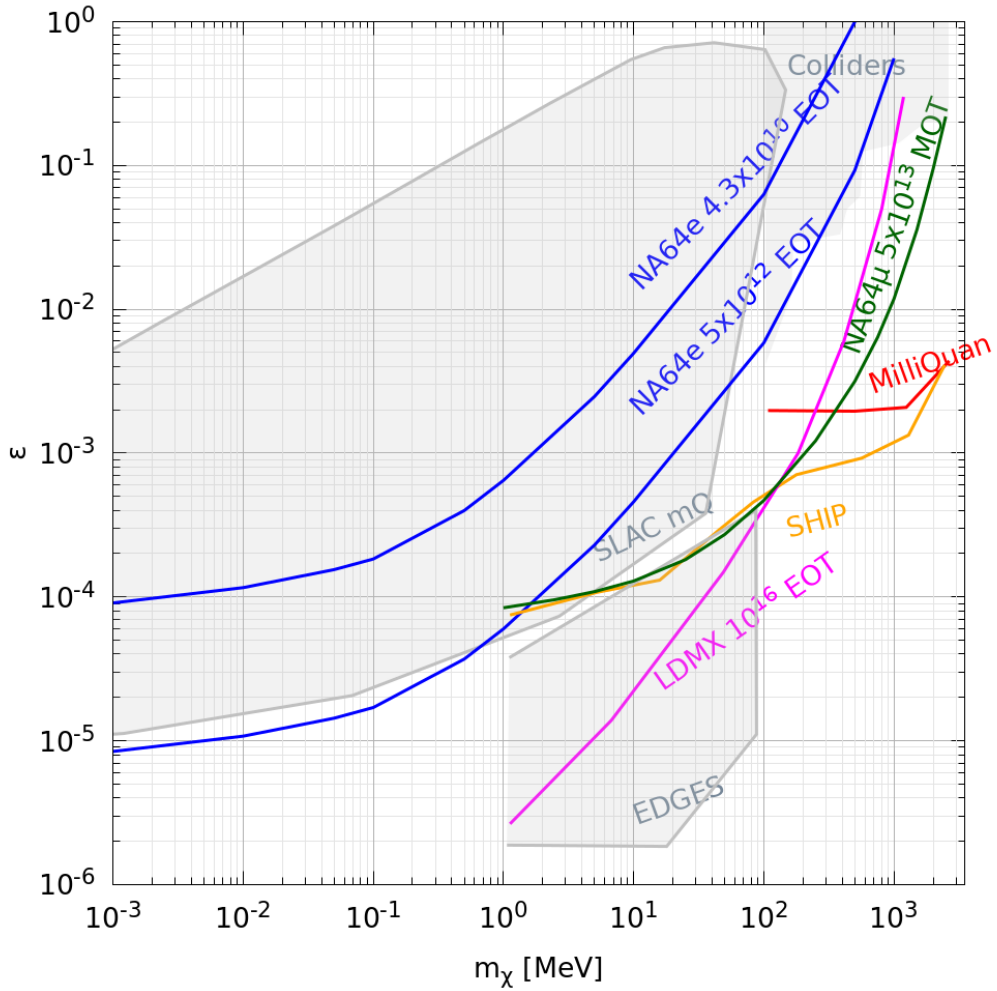
NA64μ





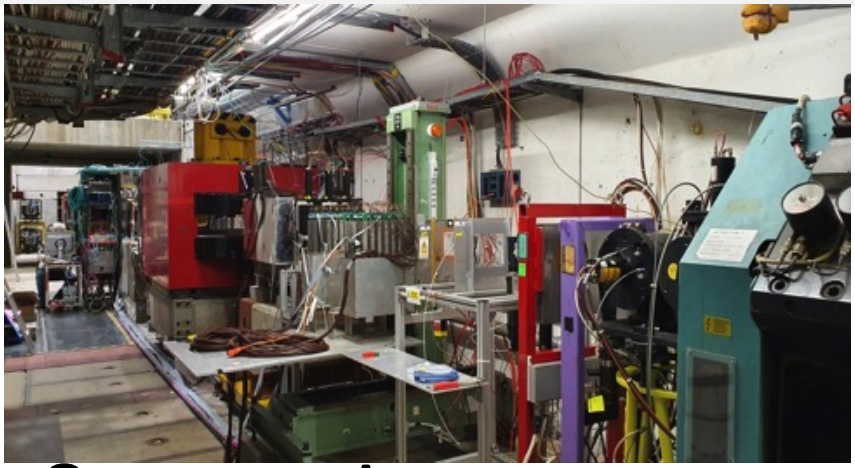
- **Pilot muon beam run (M2 channel) - November 2021 (MOT$\simeq 6 \times 10^9$ accumulated)**
- **GOAL: probing muon $(g-2)$ anomaly at NA64μ within $L_\mu - L_\tau$ anomaly free gauge extension (exact tree level cross-section $\mu N \to \mu N Z'$ without relaying on widely used IWW approach) Phys.Rev.D 104 (2021) 7, 076012, e-Print: 2107.13297 [hep-ph]**

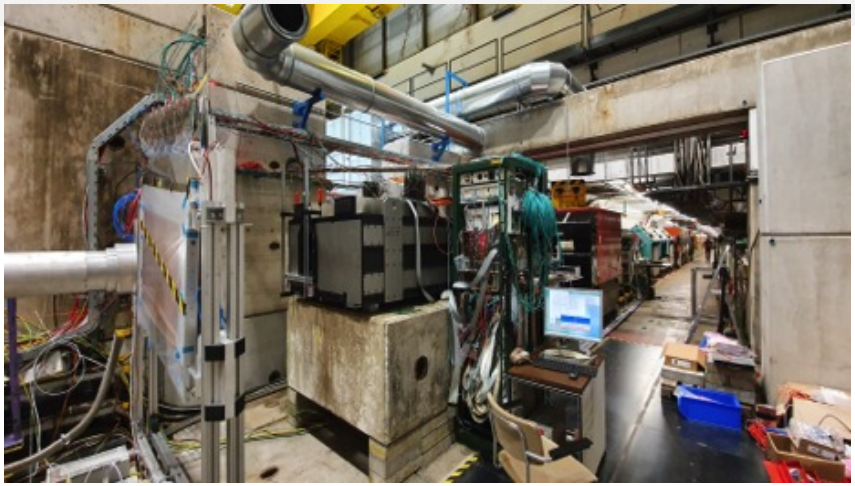
Millicharged particles with NA64e and NA64μ



- **Pilot muon beam run (M2 channel) - November 2021**
- **NA64μ GOAL: millicharged particles more effective production in Na64μ than in NA64e for the masses $m_\chi \gtrsim 100$ MeV due to $X_0^\mu \gg X_0^e$ and increased intesity of muon beam.**
- **NA64e GOAL: millicharged particles more effective production in Na64e than in NA64μ for the masses $m_\chi \lesssim 1$ MeV**

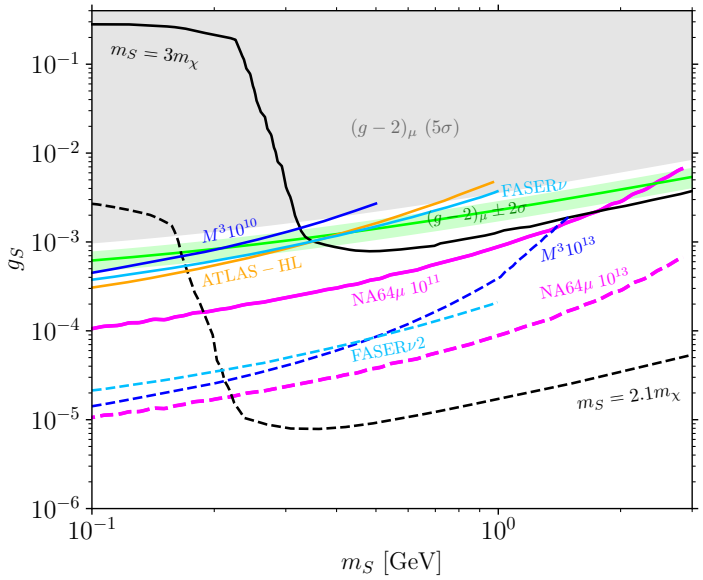
NA64μ

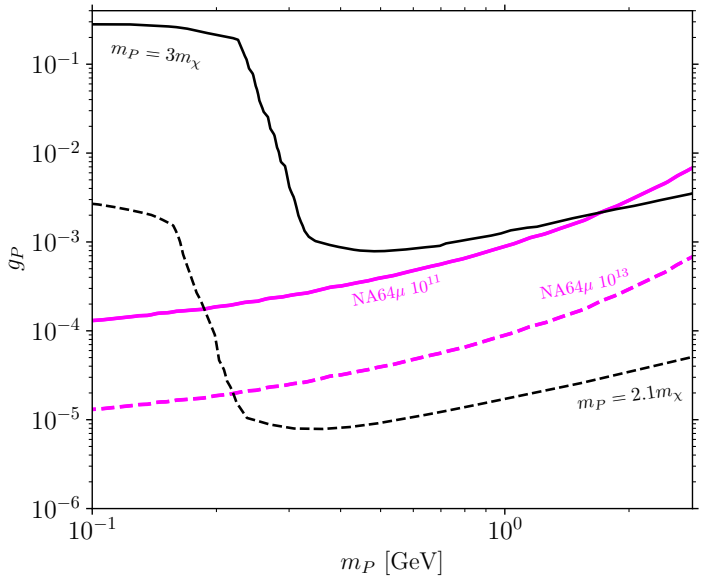


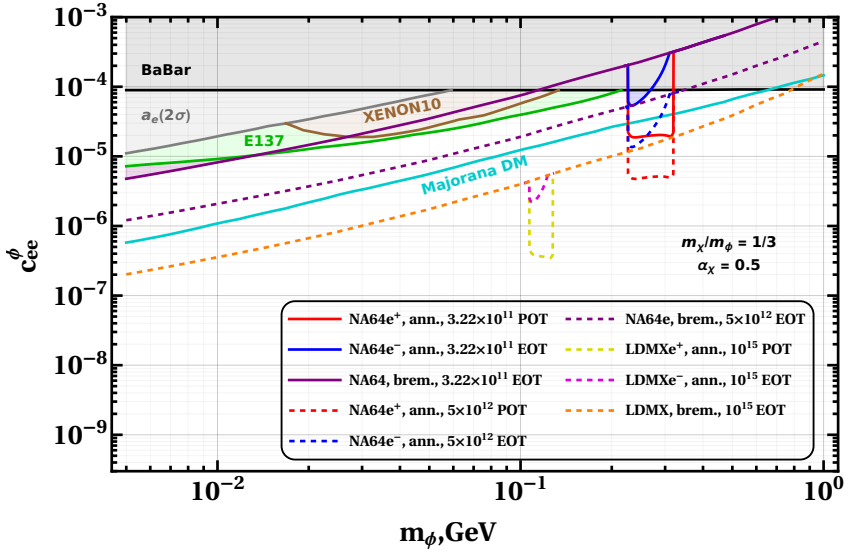


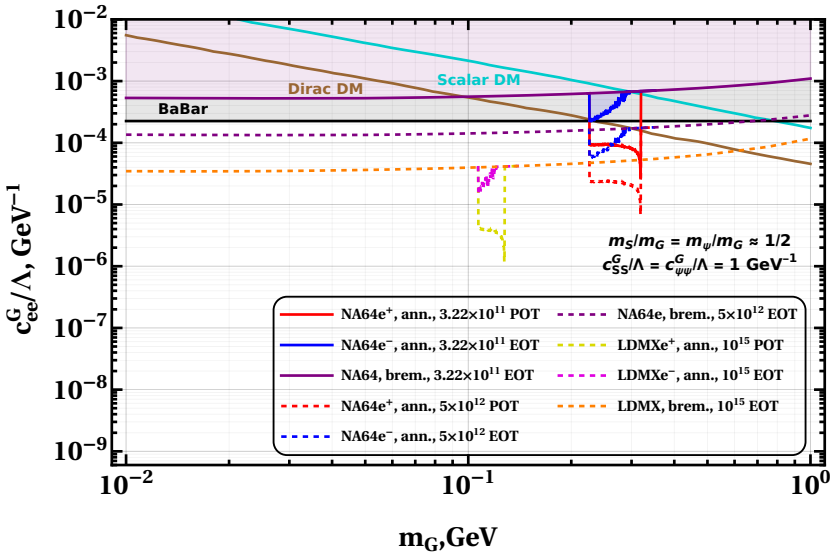
- **Open questions:**
  - **– trigger rate, π, K contamination**
  - **– purity of track reconstuction**
  - **– detector hermeticity, optimal muon energy**
- **Experimental runs**
  - **– 3 w run at M2 in Oct.- Nov. 2021**
  - **– 3 w run in April 2022, 100-160 GeV μ,**
  - **– 3 w run in July + Aug 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**

Probing spin-0 and spin-2 DM mediators

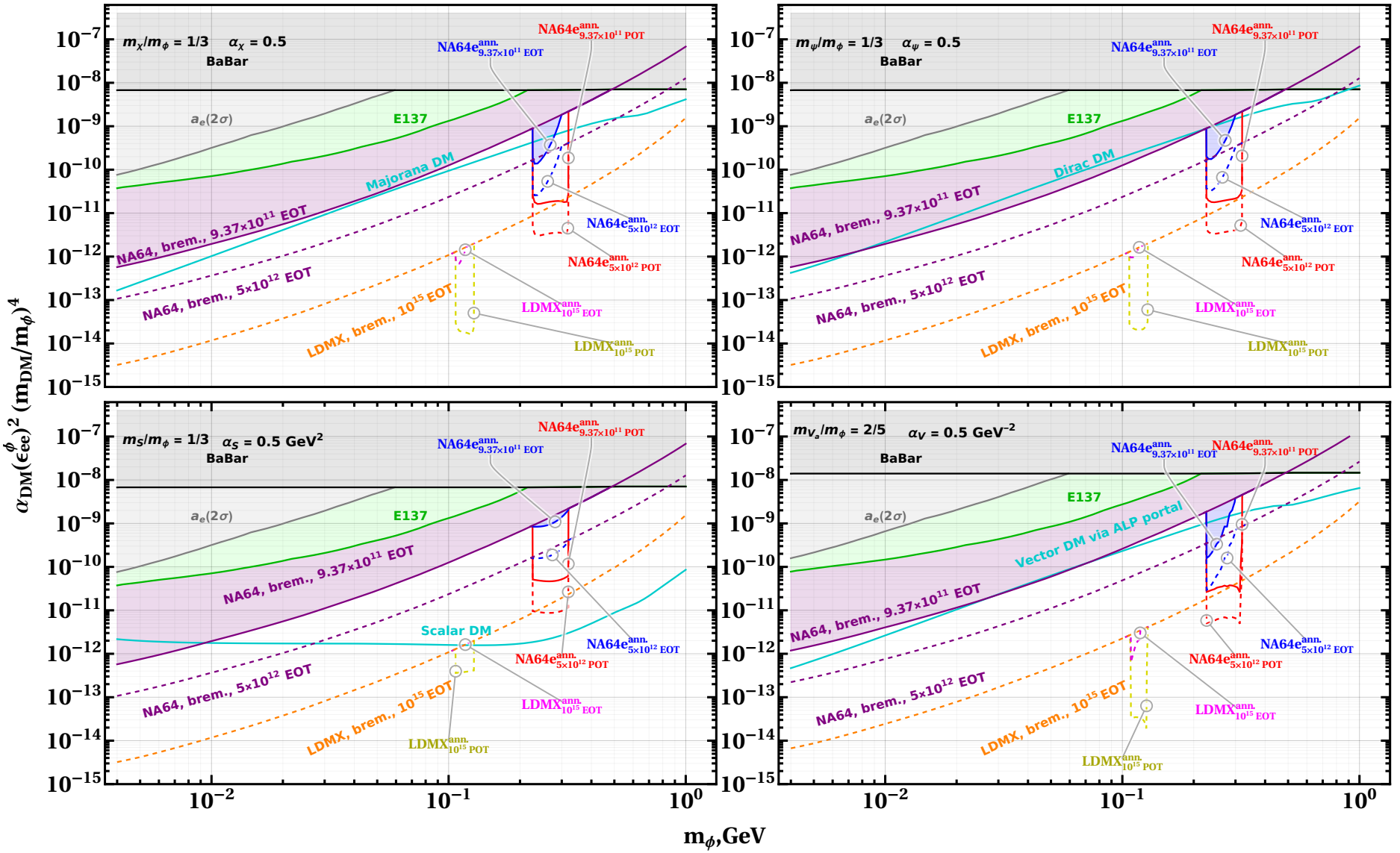






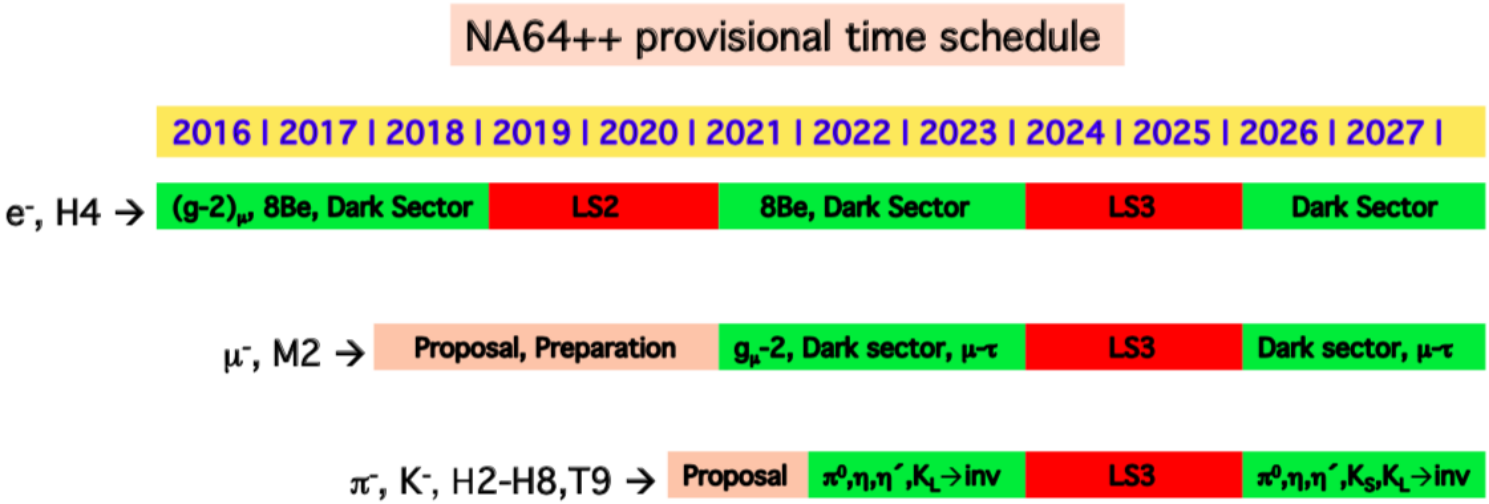


Thermal Target and Scalar Mediator



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 NA64μ:** $(g-2)_\mu$ 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)**



Aknowledgements: Russian Science Foundation RSF grant 21-12-00379