Probing light Dark Matter with NA64e experiment

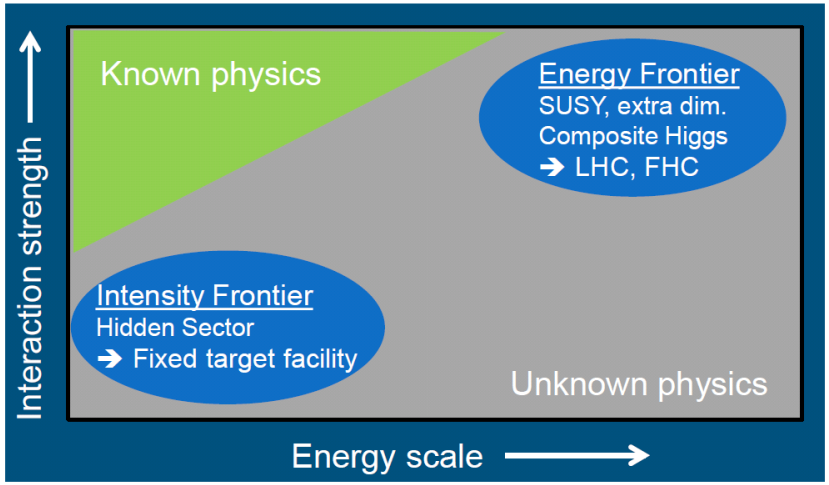
D. V. Kirpichnikov on behalf of NA64 collaboration

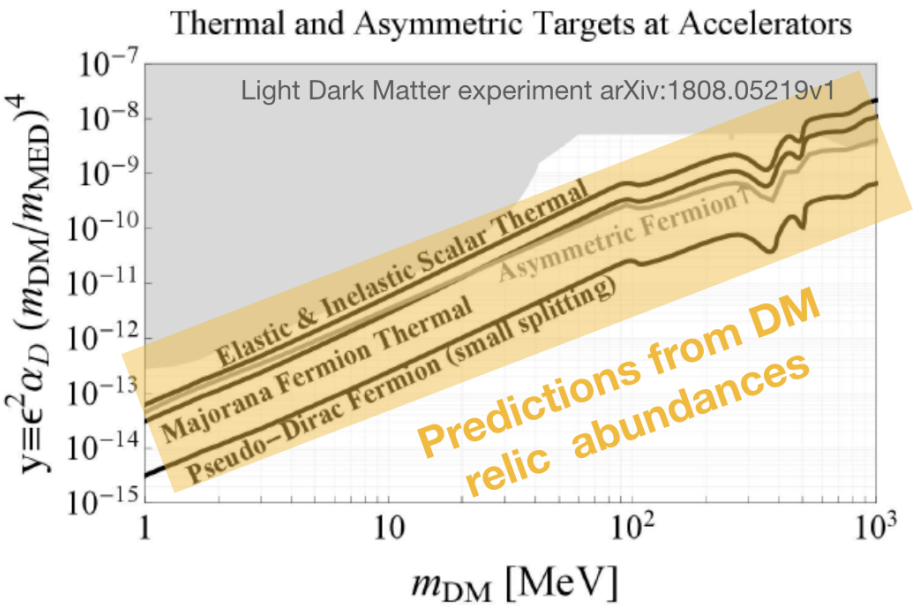
Nov 30 2022

6th International Conference on Particle Physics and Astrophysics, Moscow, Russia, Nov 29 - Dec 2

Motivations for searching for light vectors and ALPs

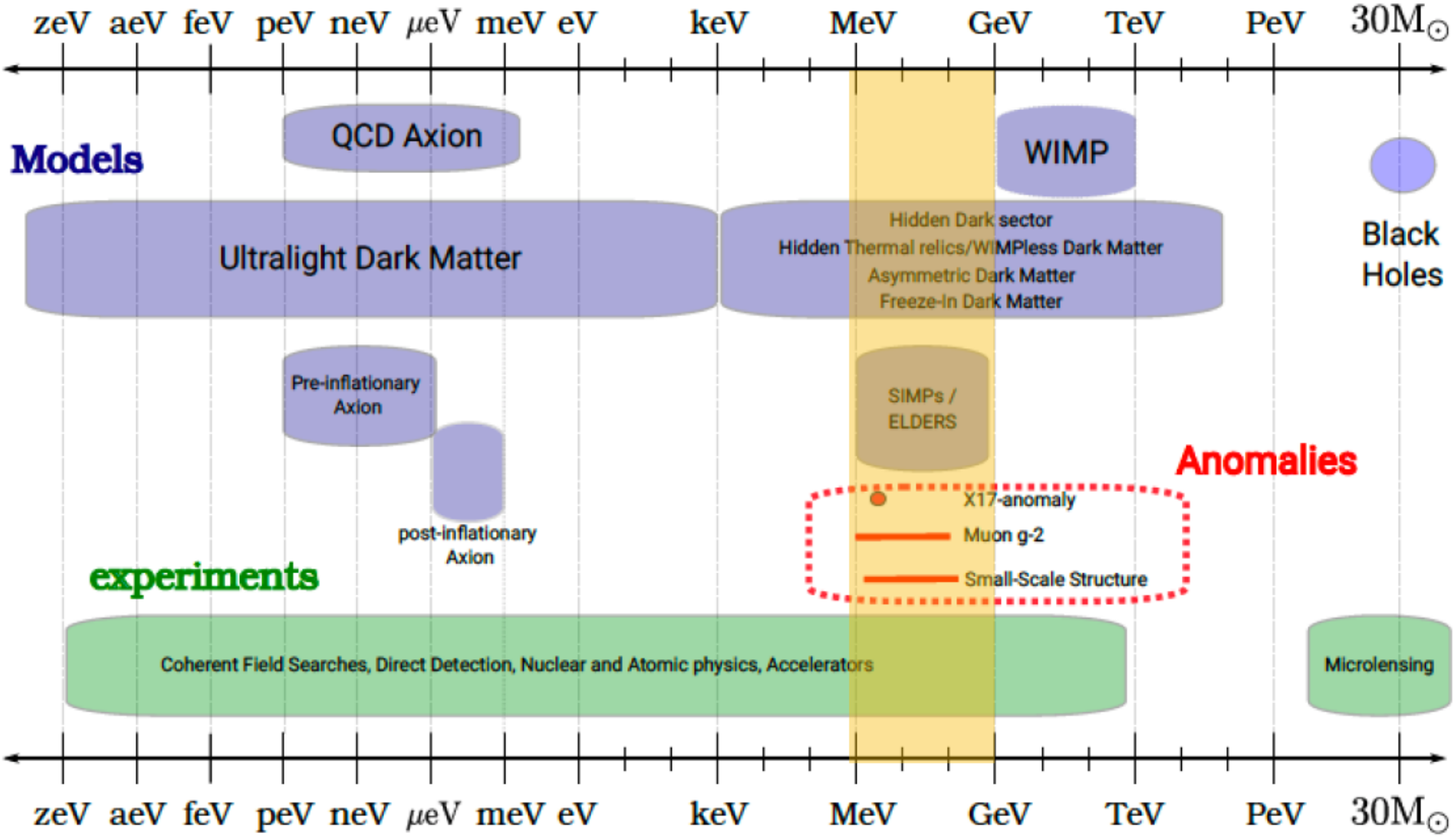
- They are popular candidates for solution of experimental anomalies: $(g-2)_\mu$, MiniBooNE, ^{8}Be, KOTO, XENON1T
- They could act as a mediator to a Dark Sector (DS). DS consists of particles and fields which are singlets with respect to the gauge group of the SM. It interacts with the SM presumably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

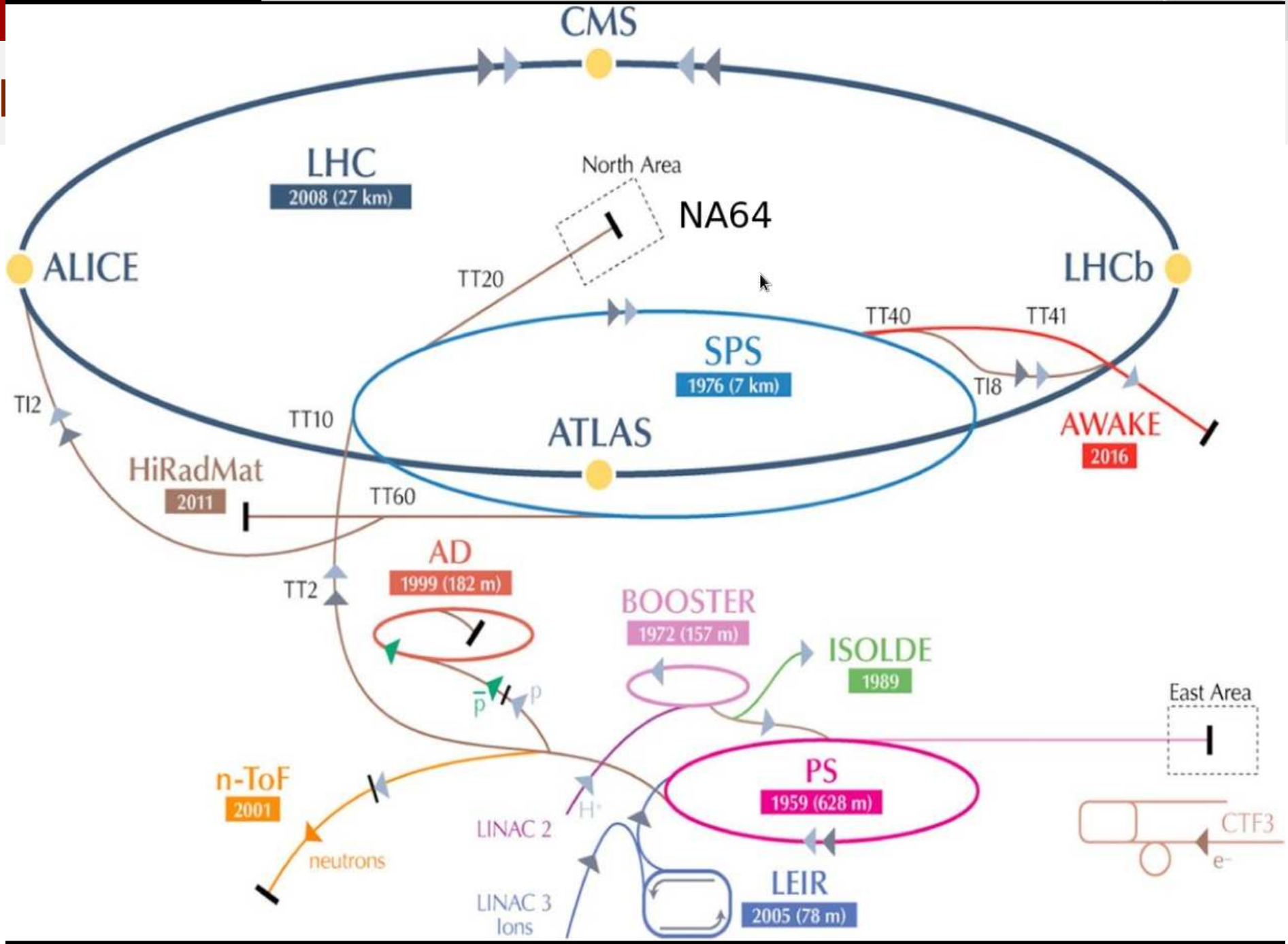




Intensity frontier

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




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

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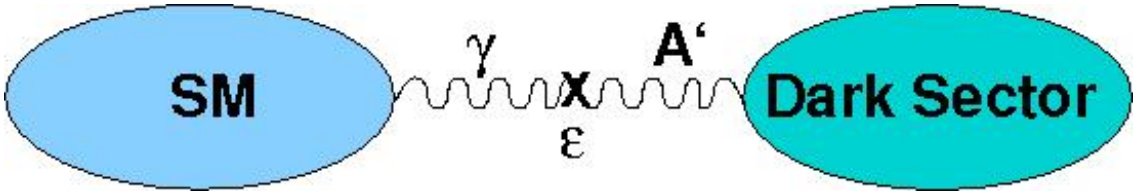
- NA64 collaboration ($\sim$ 50 researches from 18 institutes)
- **Proposed** in 2014 as **P348**, first test beam in 2015 (2 weeks);
- **Approved** by CERN SPS in March 2016 $\rightarrow$ **NA64**. 2016: 5 weeks; 2017: 5 weeks; 2018: 6 weeks.
- 2021/2022: 5/10 weeks in H4 and 3/3 weeks at M2

NA64e: Vector Portal to Dark Sector

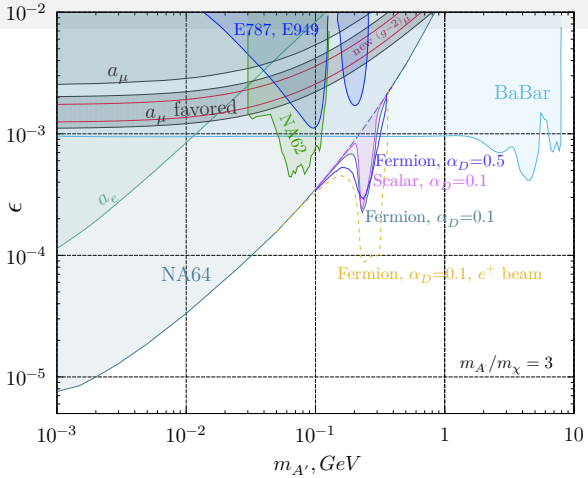


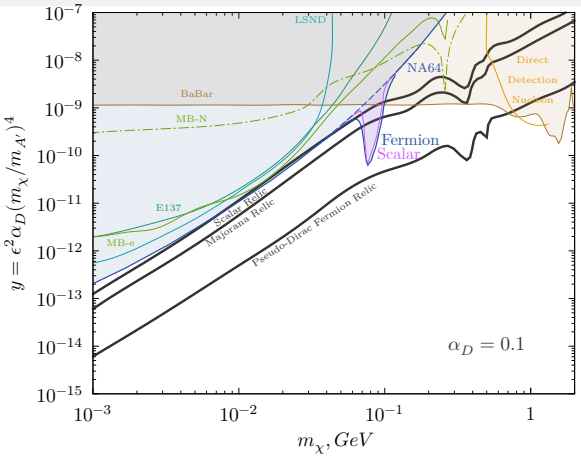
- **Okun, Holdom (1986)** $\alpha_D = e_D^2/(4\pi)$: new masssive boson A' (dark photon) which has kinetic mixing ϵ with ordinary photon A:

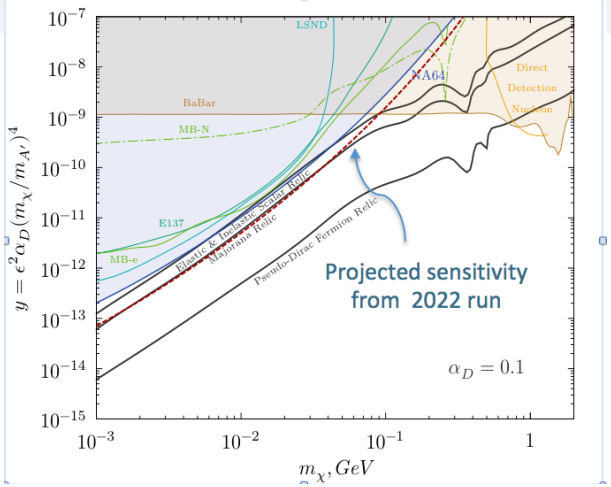
$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}^2 + \frac{1}{4}\left(F'_{\mu\nu}\right)^2 + \frac{\epsilon}{2}F_{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_{A'}^2(A'_\mu)^2 + e\bar{\psi}_e\gamma_\mu A^\mu\psi_e + \mathcal{L}_{int}(A' - \mathrm{DM})$$

- 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 A' with electrons $\mathcal{L} \supset e\epsilon \cdot \bar{\psi}_e\gamma^\mu A'_\mu\psi_e$
- Production:
  – A'-**bremsstrahlung** $e^- N \to e^- NA'$, $(A' \to \chi\chi)$
  – resonant pair **annihilation** $e^+e^- \to A' \to \chi\chi$
- 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 $\alpha_D \sim \alpha_{QED} \gg \epsilon$
- Relic DM abundance: $\Omega_\chi \propto \langle v\sigma\rangle^{-1} \propto m_\chi^2/y$, where $y = \epsilon^2\alpha_D(m_\chi/m_{A'})^4$

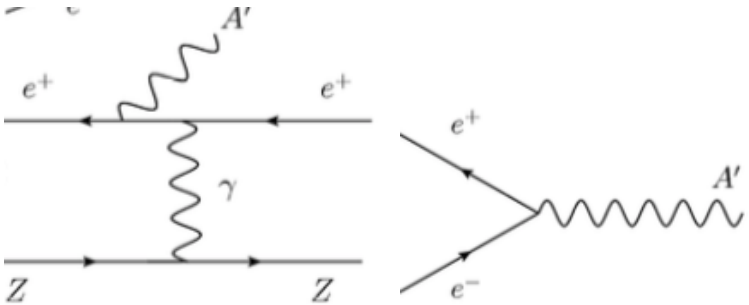
Probing Light Dark Matter with NA64++ (Phys.Rev.D 104 (2021) 9)

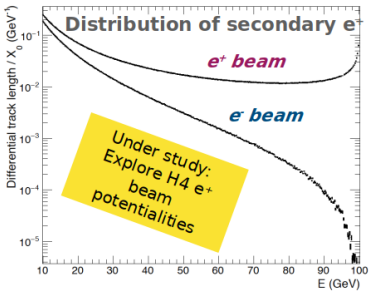




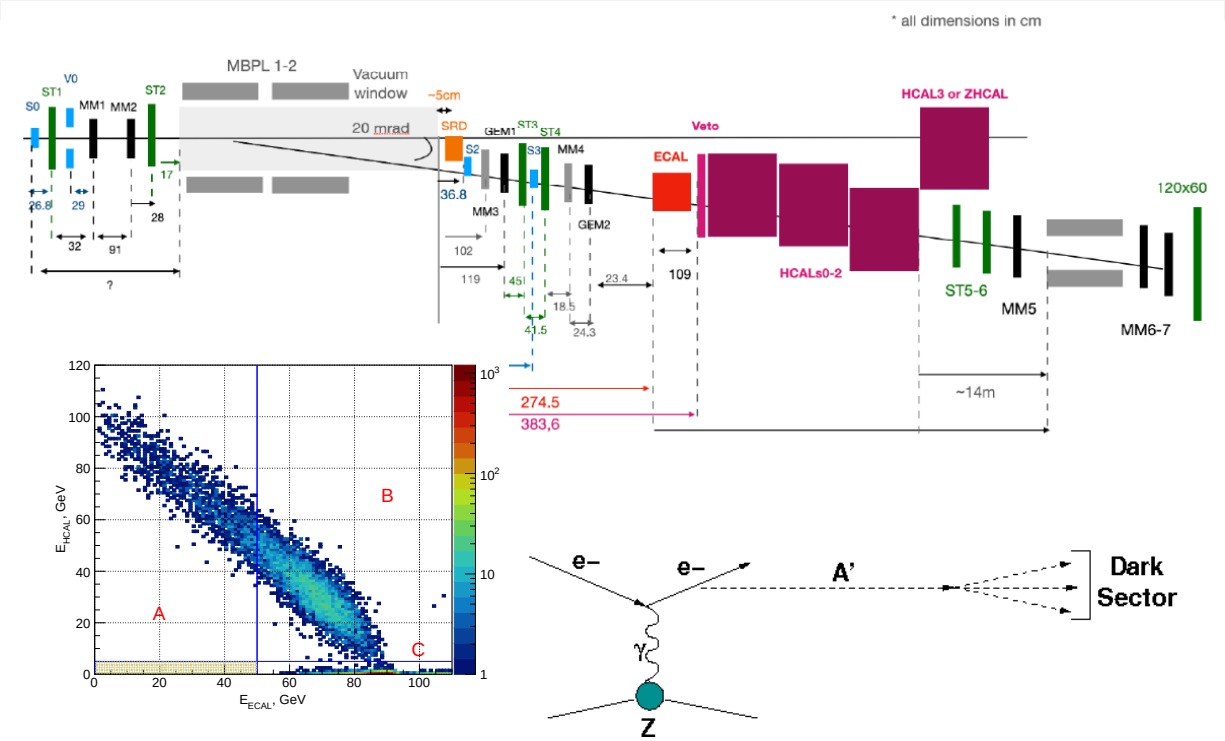


- **Combined 2016-2018 NA64 sensitivity ($N_{sign} \propto \epsilon^2$, EOT$\simeq 2.84 \times 10^{11}$) to light thermal DM exceeding constraints from beam dump experiments (suppressed $N_{sign} \propto \epsilon^4 \alpha_D$)**
- **In 2022 NA64e collected about 6.4×10^{11} EOT, thus the total amount of accumulated EOTs is 10^{12}; The data analysis is in progress**
- **Improved limit on ϵ up to factor 10 in the resonant region $m_{A'} \simeq (2m_e E_{cut})^{1/2}$**
- **Advantage of using a e^+-beam $\rightarrow$ beam energy scanning. Under study: $10\times$bckgr**
- **NA64++ target: SIGNIFICANT DM parameter space can be probed in Run 3 using unique CERN SPS electron and positron beams.**



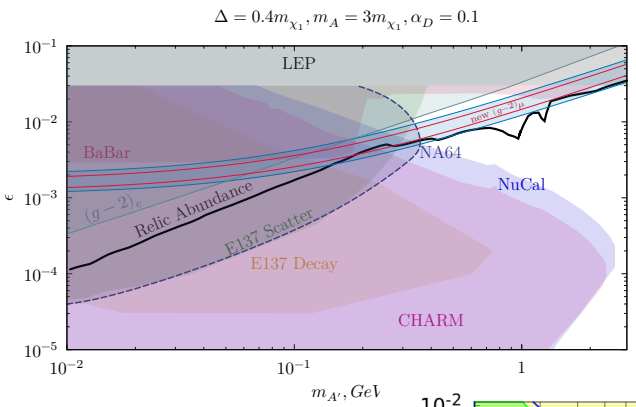


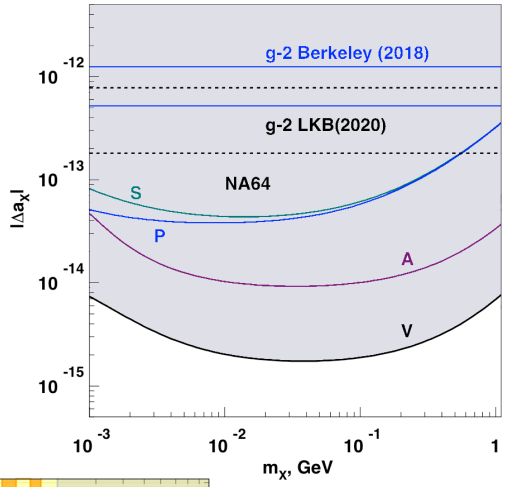
NA64e run in 2022 (sketch of the upgraded setup)

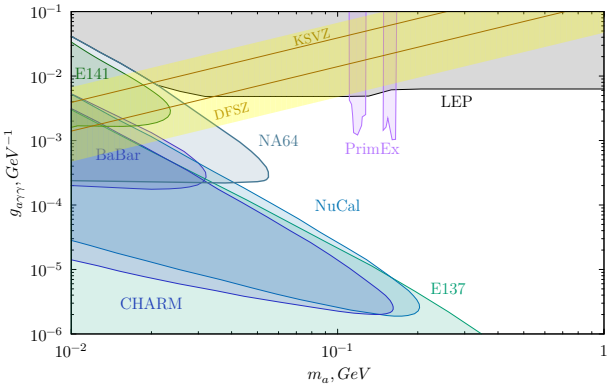


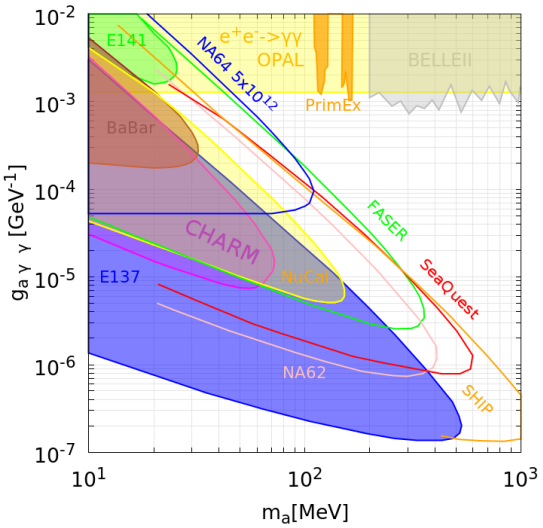
- **NA64 is designed to search for BSM physics in missing-energy events with $e^{\pm}, \mu, \pi, K, p$ beams.**
- **Main Components: a) clean $E_0 = 100$ GeV e^- beam; b) e^- tagging system: tracker+SRD; c) hermetic ECAL+HCAL;**
- $E_{beam} \simeq E_{HCAL} + E_{ECAL}$ **- main diagonal**
- **Signal Box (A): a) in: 100 GeV e^- track; b) out: $E_{ECAL} < 0.5E_0$ 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. Background free at the level $\sim 10^{-12}$**

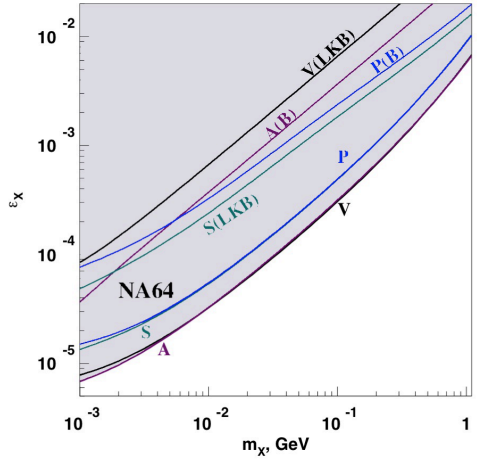
ALPs, semivisible decays of Dark Photon and $(g-2)_{e,\mu}$





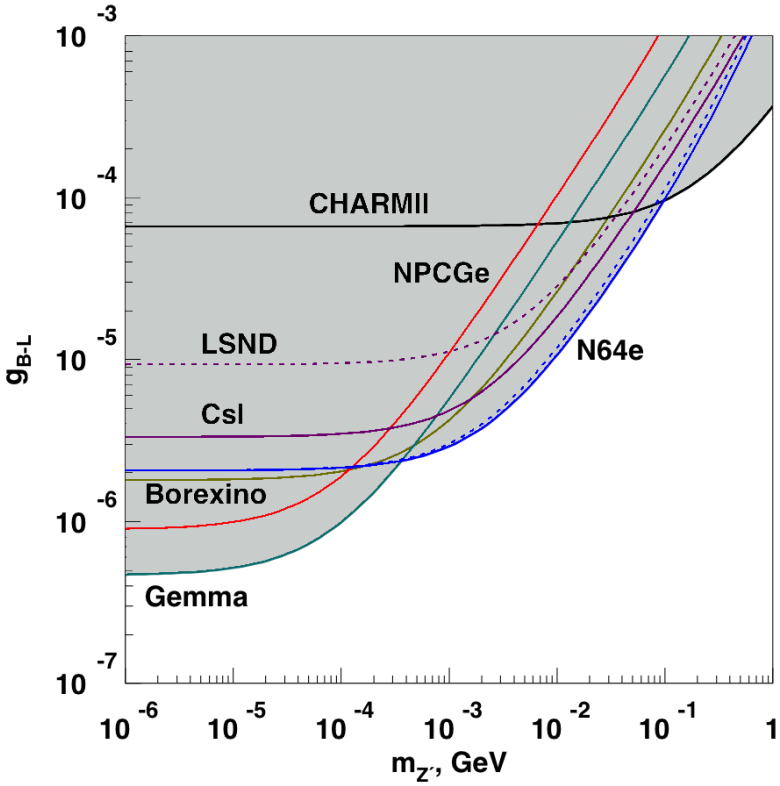


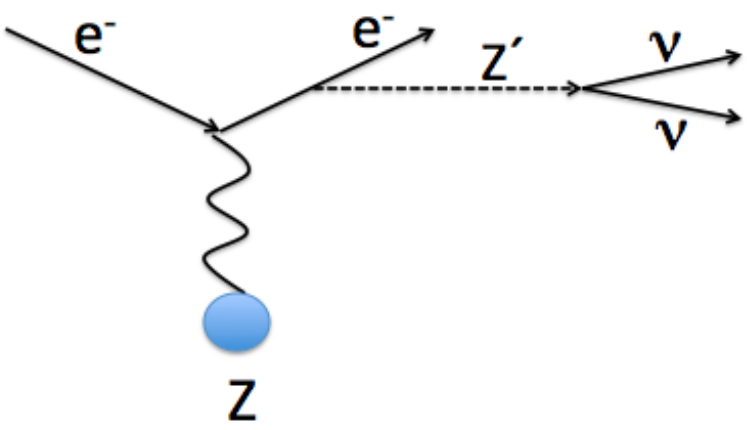




- A': **Motivation** $\to$ $(g-2)_\mu$ anomaly and light DM; **Signature** $\to$ missing energy + SM pair production
- ALPs: **Signature** $\to$ two photon pair production in HCAL; **Projection ALP-DM channel**: $\mathrm{Br}(a \to \chi\bar{\chi}) \simeq 1$
- $X(J^P = 0^\pm, 1^\pm) \to$ invis.: **Motivation** is to exclude the explanation of $(g-2)_e$ puzzle due to X decaying invisibly.
- **NA64, Phys. Rev. Lett. 126, 211802 constraint is better than High Precision Table-top Experiments Berkeley**

Z' boson from B-L scenario: Phys.Rev.Lett. 129 (2022) 16, 161801

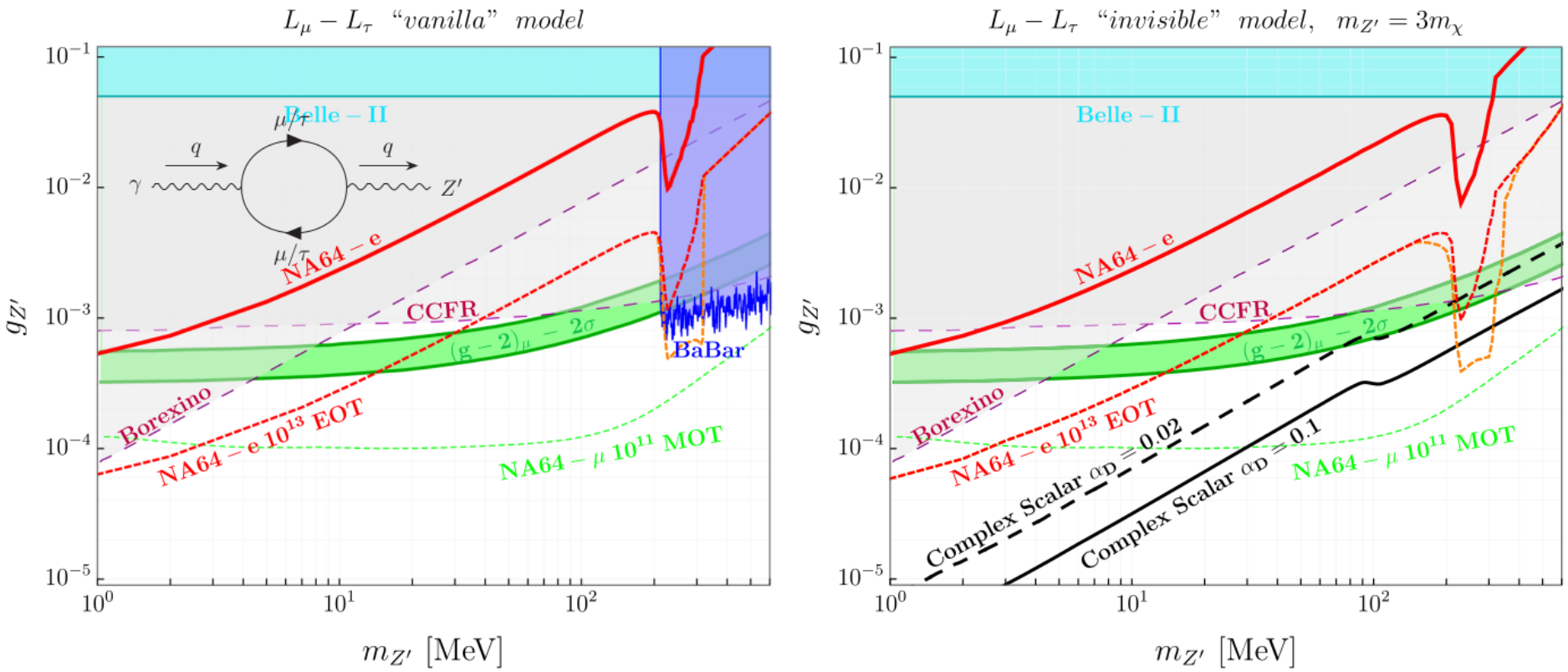




$$\mathcal{L} \supset g_{B-L} Z'_\mu \sum_{families} \left[\frac{1}{3} \bar{q}\gamma^\mu q - \bar{l}\gamma^\mu l - \bar{\nu}\gamma^\mu \nu \right]$$

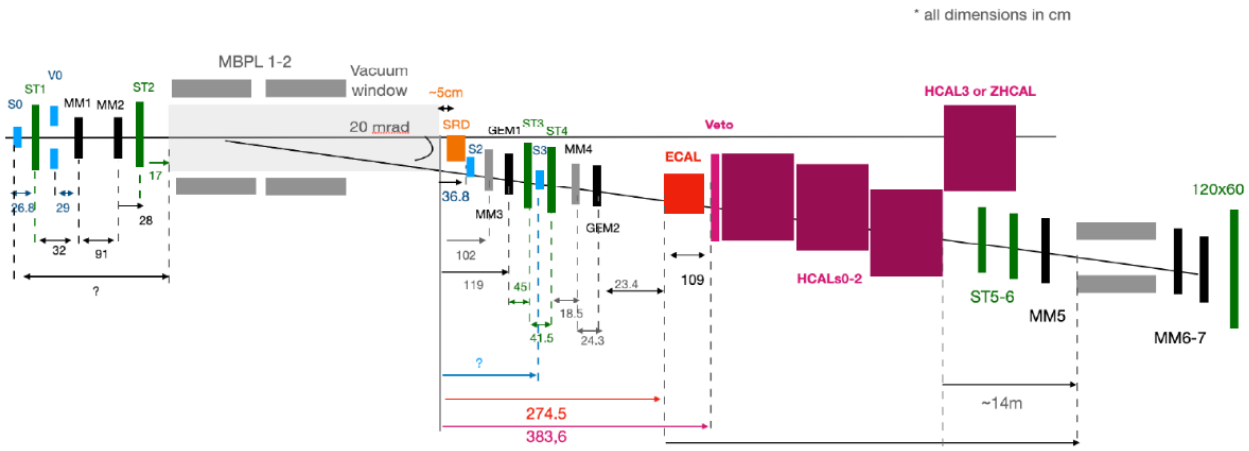
- Mass range of interest $1\,\text{keV} \lesssim m_{Z'} \lesssim 1\,\text{GeV}$
- DATA: 3.2×10^{11} EOT collected during 2016-2018 and 2021 runs
- **NA64 RESULTS more stringent compared to those obtained from neutrino-electron scattering data in the mass range** $300\,\textbf{keV} \lesssim m_{Z'} \lesssim 100\,\textbf{MeV}$

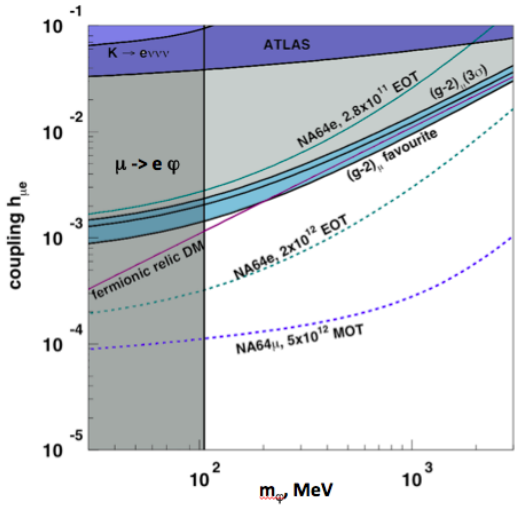
$L_\mu - L_\tau$ models could explain (g-2) muon anomaly



D. V. Kirpichnikov, Phys. Rev. D 104, 076012 (2021),
H. Sieber et al. ,Phys. Rev. D 105, 052006 (2022)
NA64 collaboration, Phys. Rev. D 106, 032015 (2022)

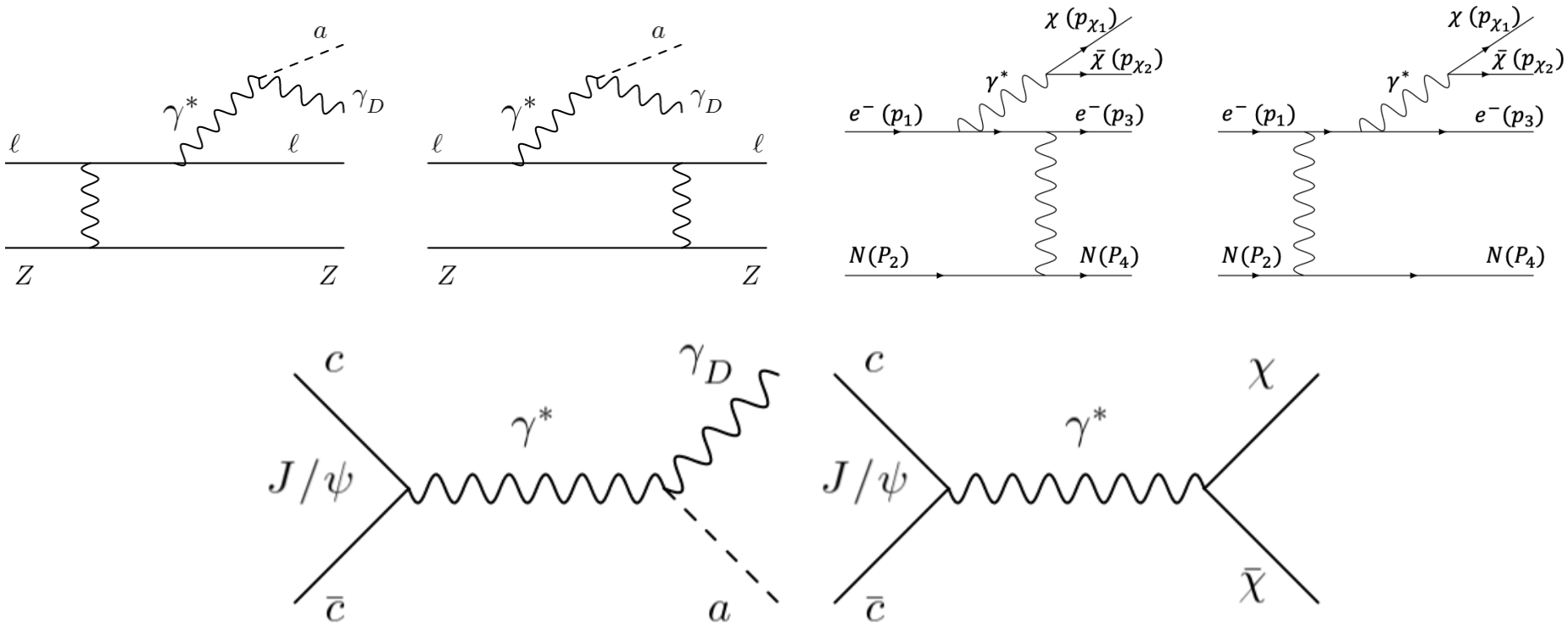
NEW ideas for NA64e and resuming data taking after LS2





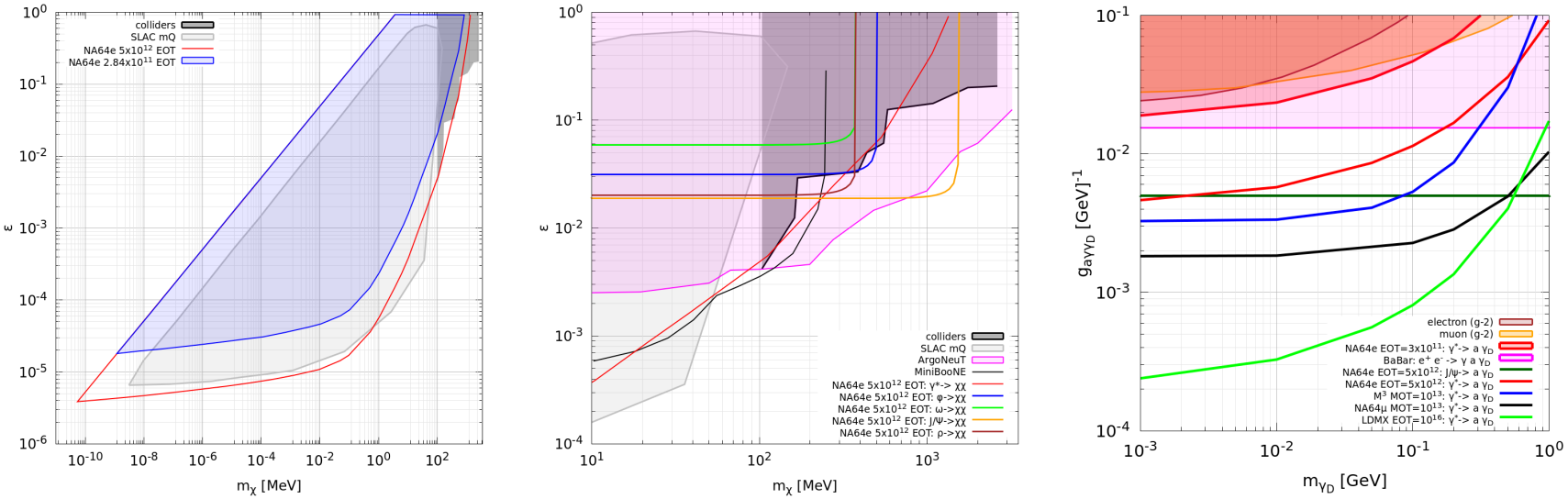
- NA64 theoretical group developments: Phys. Rev. D 106 (2022) 1, - lepton flavour violation
- NA64e design in 2022: new MBPL magnet was added to probe $eN \to \mu N \phi$ conversion (leptonic scalar)
- Total number of electrons accumulated during 2016-2022 Runs is close to $\sim 10^{12}$

New ideas for NA64e: Millicharged particles (MCP) and Dark Axion portal



$$\mathcal{L} \supset \frac{g_{a\gamma\gamma_D}}{2} a F_{\mu\nu} \tilde{F}'_{\mu\nu} \qquad \mathcal{L} \supset e\epsilon \bar{\chi} A_\mu \gamma^\mu \chi$$

New ideas for NA64e: Millicharged particles (MCP) and Dark Axion portal

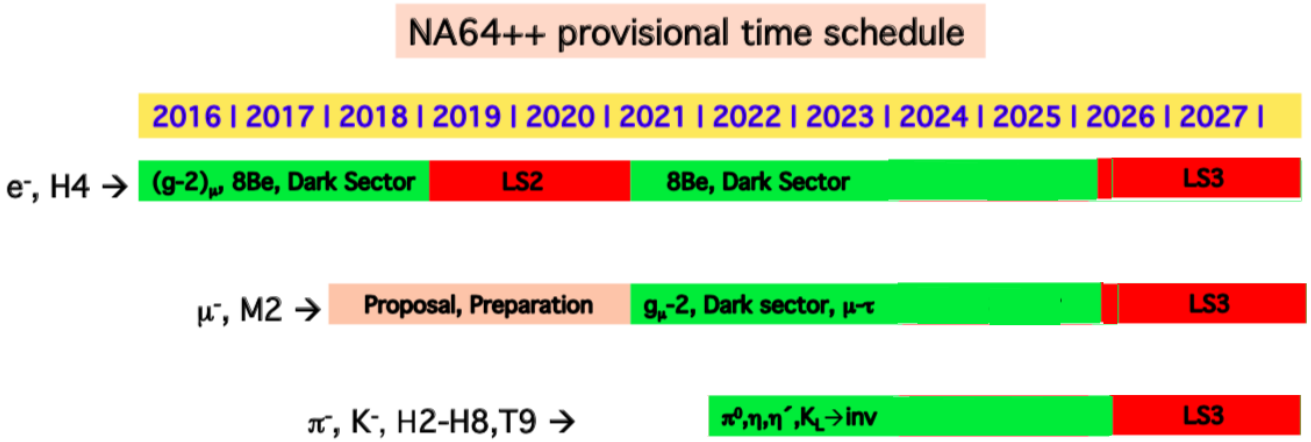


PRELIMINARY- PRD, 106 (2022) 3, 035029, Arefyeva, Gninenko, Gorbunov and Kirpichnikov: dark green solid line is the expected reach of NA64e for the millicharged coupling $\mathcal{L} \supset e\epsilon\bar{\chi}A_\mu\gamma^\mu\chi$

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

Summary and plans

- **NA64e±**: **Beamtime 2022** just finished milestone of $\sim 10^{12}$ EOT, $\rightarrow$ start probing **LDM benchmark models.**
- **Plan until LS3 increase statistics as much as possible**.
- **Beamtime 2022** (2 days) 10^{10} positrons on target collected; impact of $10\times$ larger hadron contamination than in electron mode (expected) under study



Aknowledgements: special thanks to N. Krasnikov, S. Gninenko, P. Crivelli, A. Celentano, M. Kirsanov, H. Sieber, L. Molina Bueno, A. Zhevlakov, V. Lyubovitskij, D. Gorbunov, N. Arefyeva. NA64e+ program is supported by a dedicated ERC Grant (POKER, Grant Agreement n. 947715). This work is supported by RSF grant 21-12-00379.