Recent results from the NA64 experiment at CERN SPS

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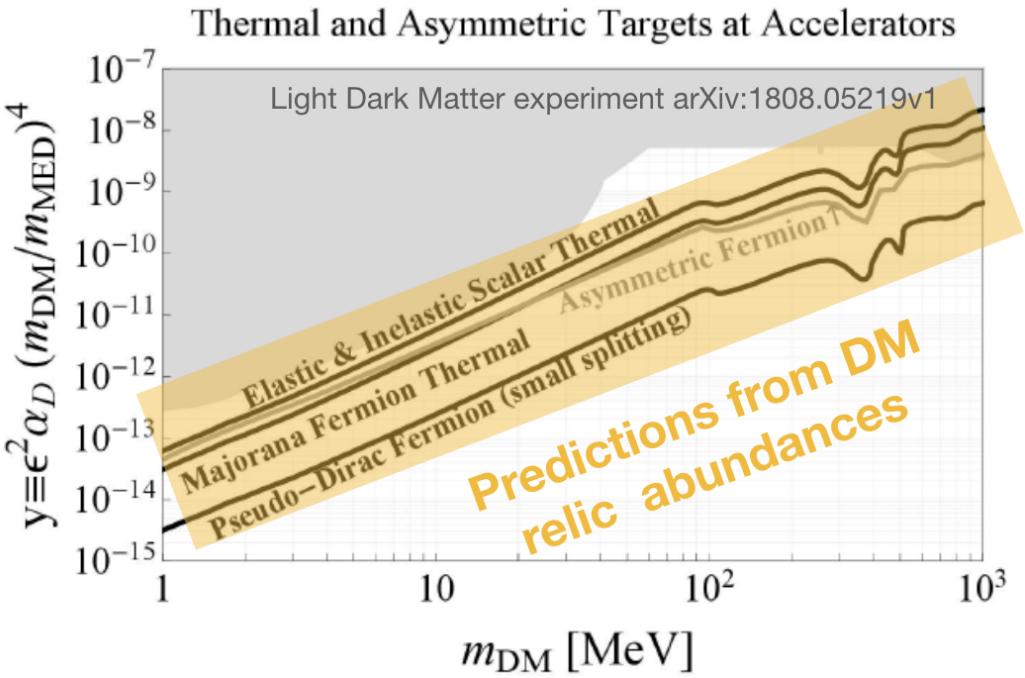
Outline

- Motivation: Light Dark Matter, $(g-2)_\mu$ anomaly
- Vector Portal to Dark Sector
- **NA64e (invisible mode setup)**
- Prospects for Light Dark Matter (invisible and semi-visible decay mode)
- prospect for ALPs (visible and invisible decays)
- **NA64e (visible mode setup)**
- Prospects for visible decays and ATOMKI anomaly
- **Probing $(g-2)_e$ with NA64**
- e^+**-beam,** e^-**beam: resonant DP production,** $e^+e^- \to A'$
- **NA64μ**
- moun beam: prospects for $(g-2)_\mu$ anomaly, Z' and millicharges
- **Combined NA64e and NA64μ projection**
- **Conclusion**

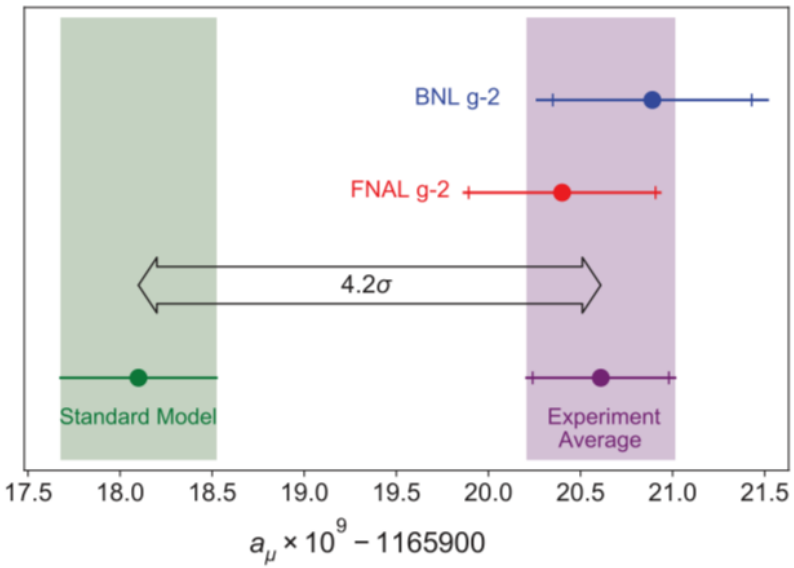
Motivations for searching for light vectors and ALPs

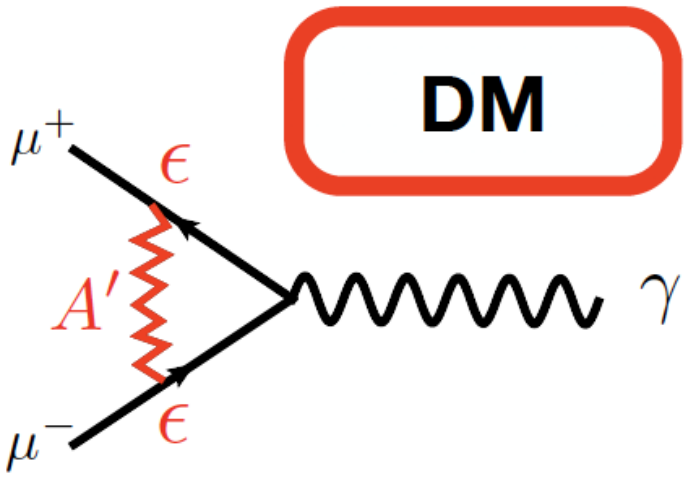
- They are popular candidates for solution of experimental anomalies: $(g-2)_\mu$, MinoBooNE, ^{8}Be, KOTO, XENON1T
- They could act as a mediator to a Dark Dector (DS). DS consists of particles and fields which are singlets with respect to the gauge group of the SM. It interacts with the SM presumably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



Additional motivation for NA64 is $(g-2)_\mu$ anomaly

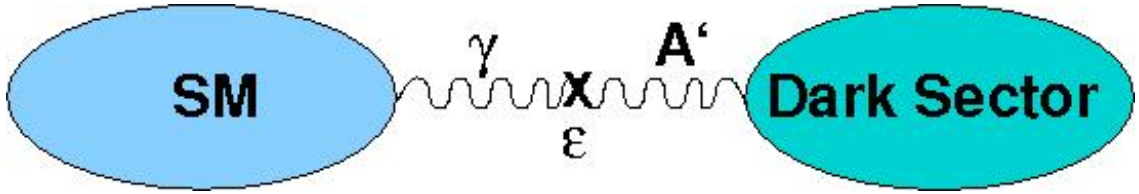
$$a_\mu = \frac{g_\mu - 2}{2}, \quad \Delta a_\mu = a_\mu^{exp} - a_\mu^{th} = (251 \pm 59) \cdot 10^{-11}$$





- B. Abi et al. Muon g-2 collaboration Phys. Rev. Lett. 126, 141801
- 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 (A', Z')**

Vector Portal to Dark Sector

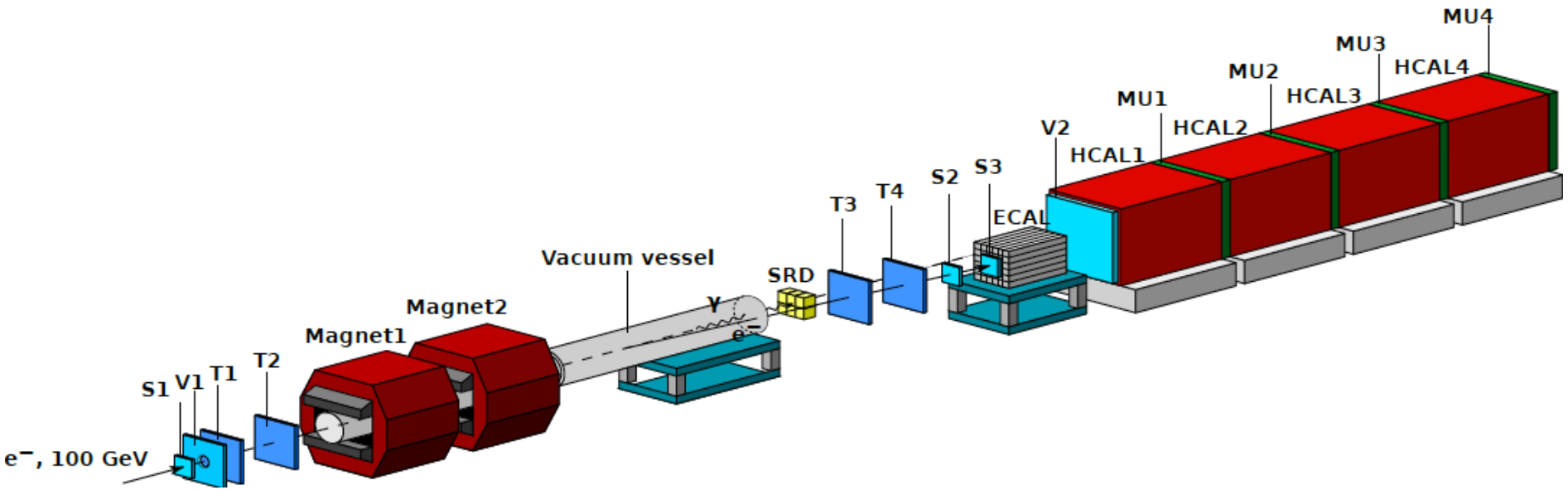


- **Okun, Holdom (1986)** $\alpha_D = e_D^2/(4\pi)$: new masssive boson A' (dark photon) which has kinetic mixing with ordinary photon ϵ:

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

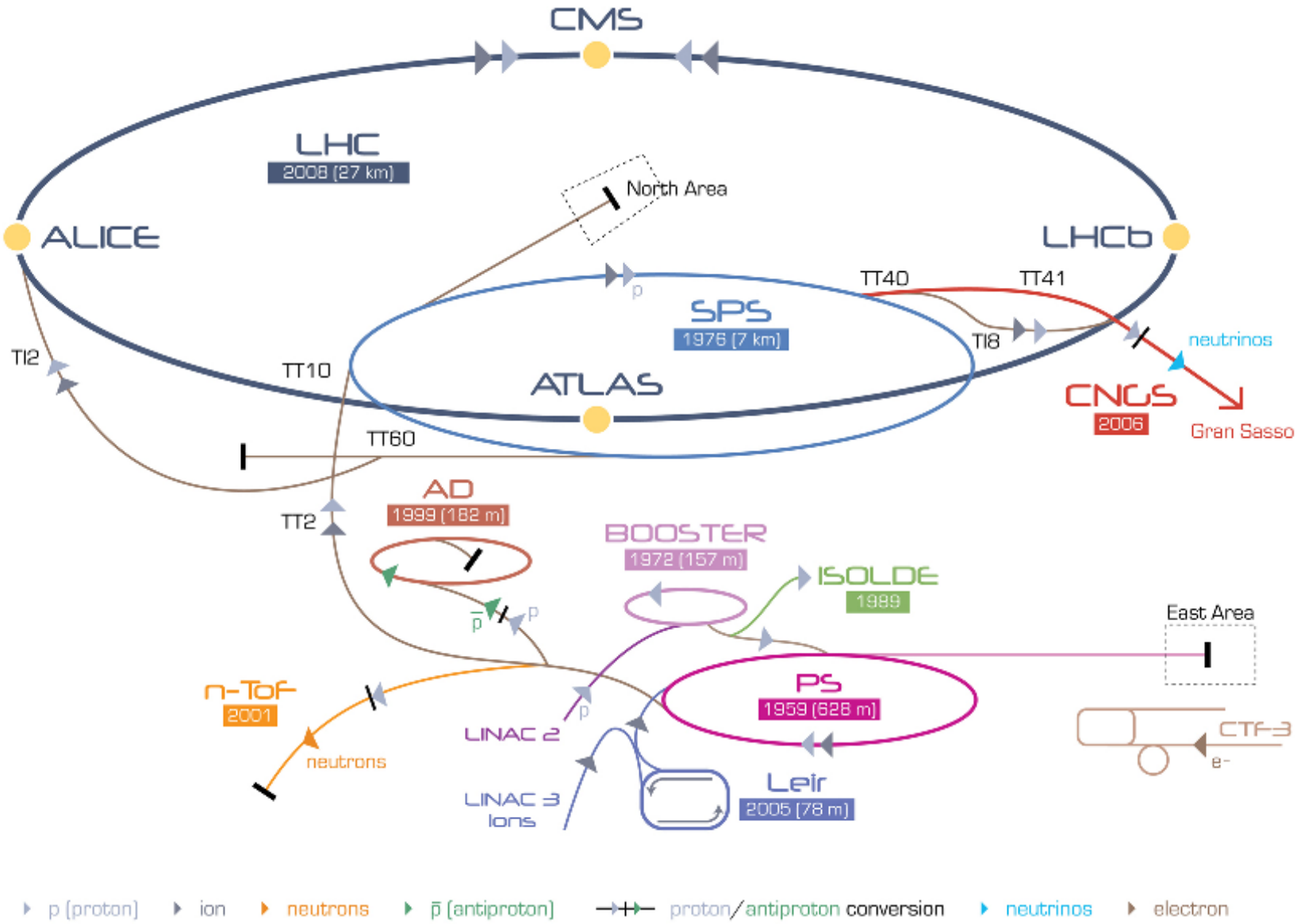
- Production: A'-bremsstrahlung $e^- N \to e^- N A'$,
- Decays:
  – **Mostly Visible:** $A' \to e^+e^-$, $\mu^+\mu^-$, hadrons, assuming $m_{A'} > 2m_e$, $2m_\mu$...
  – **Mostly Invisible:** $A' \to \chi\chi$ if $m_{A'} > 2m_\chi$ assuming $\alpha_D \sim \alpha_{QED} \gg \epsilon$

NA64 experiment setup (invisible mode)



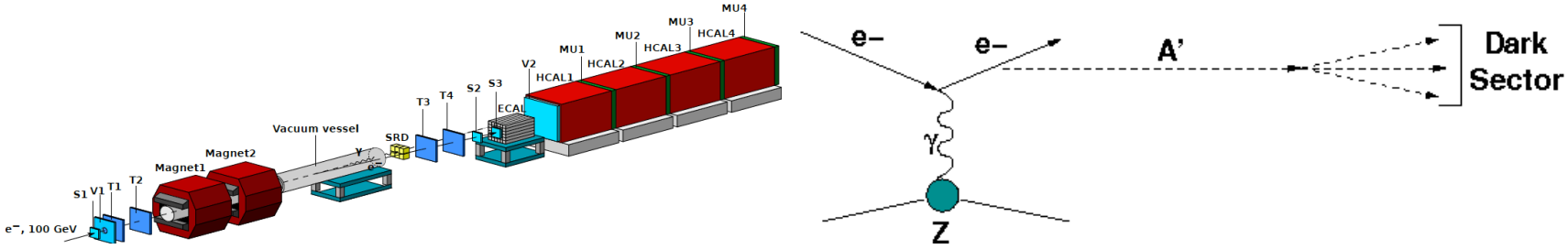
$\sim$ 50 researchers from 12 institutes.
Proposed in 2014, first test runs in 2015

NA64 location



NA64 photograph

NA64 experiment setup (invisible mode)



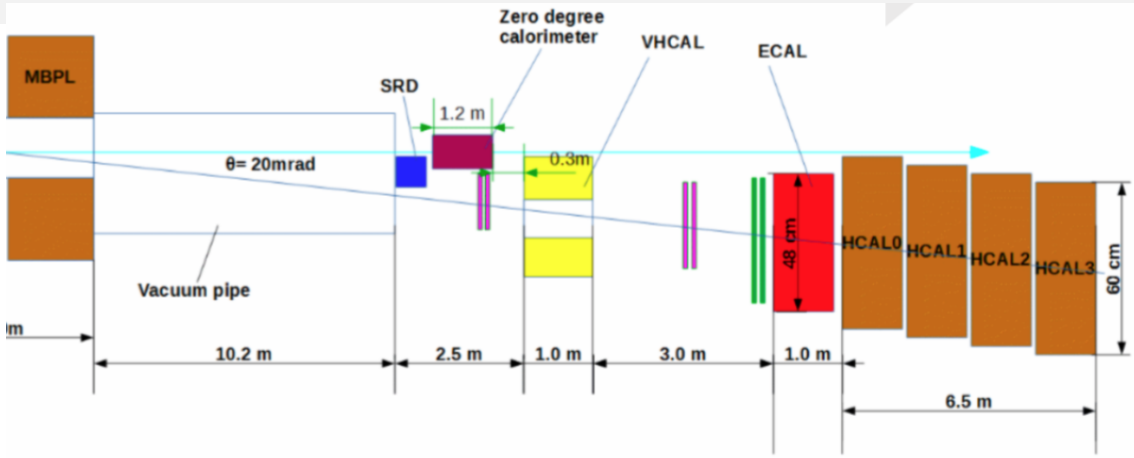
S.Andreas et al., arXiv: 1312.3309 S.G., PRD(2014)

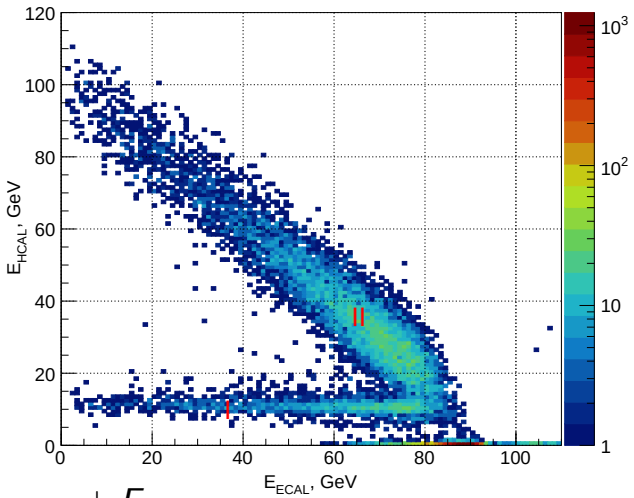
- **Main Components:** a) clean $E_0 = 100$ GeV e^- beam; b) e^- tagging system: tracker+SRD; c) hermetic ECAL+HCAL;
- **Signature:**
  a) in: 100 GeV e^- track; b) out: $E_{ECAL} < E_0$ shower in ECAL; c) no energy in Veto and HCAL;
- **Background**:
  a) μ, π, K decays in flight; b) upstream interaction; c) Tail < 50 GeV in the e^- beam; d) energy leack from ECAL+HCAL

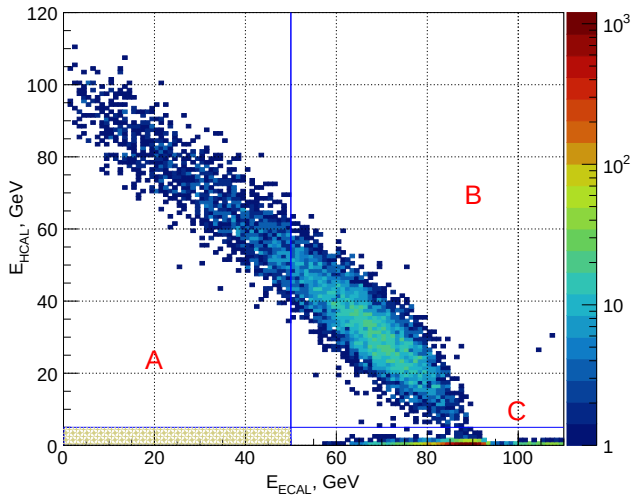
DM processes simulation: DMG4 toolkit

- Fully GEANT4 compatible package DMG4 is developed **(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, annihilation processes (like $e^+e^- \to A' \to \chi\chi$)
- DM messengers: vector (A'), axial vector, scalar, pseudoscalar
- invisible 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

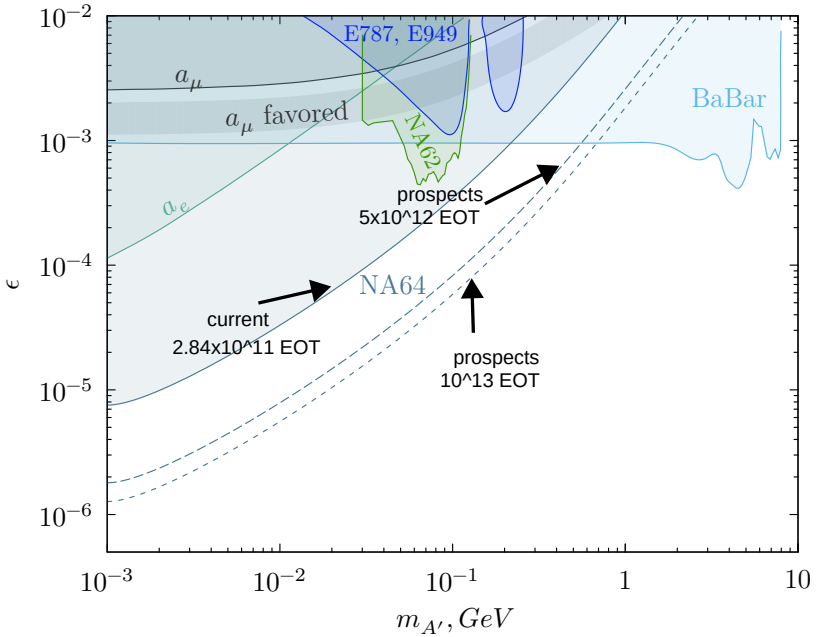


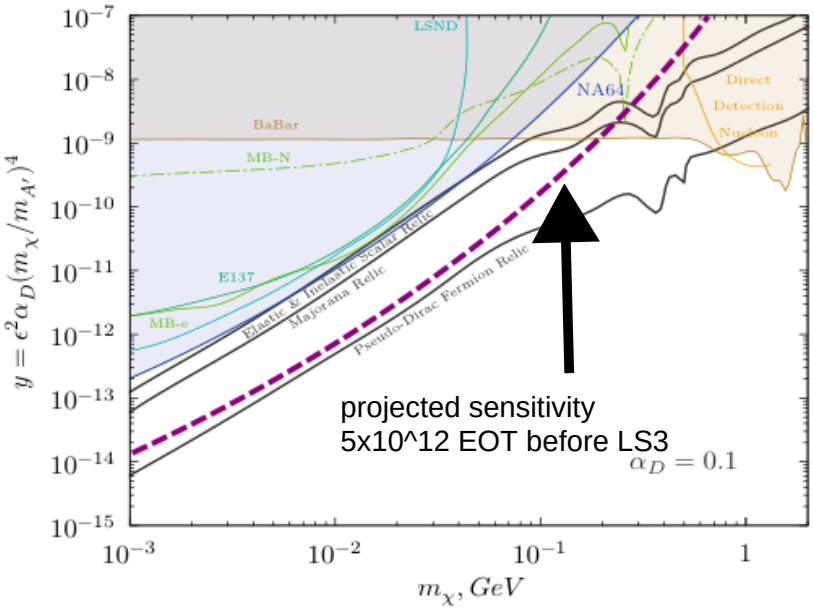




- $E_{beam} \simeq E_{HCAL} + E_{ECAL}$
- **NA64e allows to probe invisible decays of Dark Matter mediators: $eN \to eNX(X \to \chi\bar{\chi})$, where X is a general hidden boson (spin 0, spin 1, spin 2) the mediator between SM and DM particle χ (Scalar, Dirac or Majorana).**
- **Signal box (A) of missing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

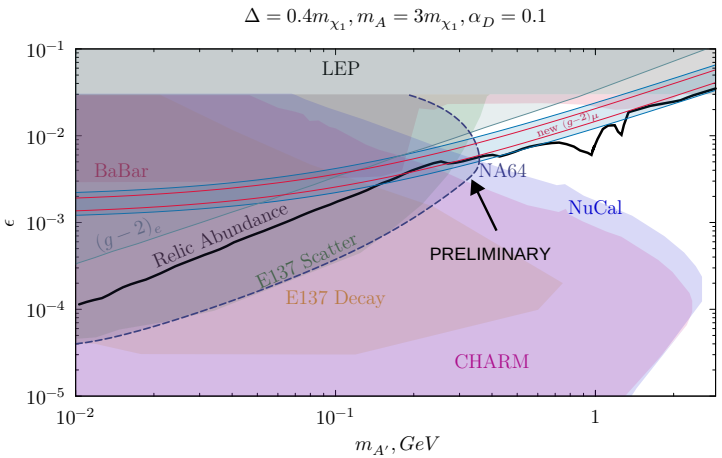
Current and future sensitivity to Dark Photon $(\epsilon, m_{A'})$ and (y, m_χ)

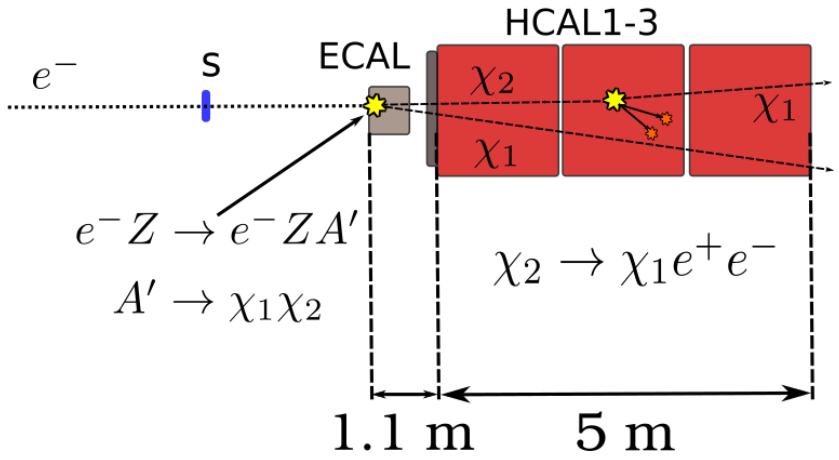




- **Invisible mode data taking: 2016-2017-2018 (combined analysis 2.84×10^{11} EOT)**
- **Long Shutdown 2: 2019-2020**
- **data taking 11th August 2021 (5 weeks)**
- **GOAL: Beam setup and electronics upgrade $\rightarrow$ reduce background from electro nuclear interactions along the beam line.**
- **GOAL: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

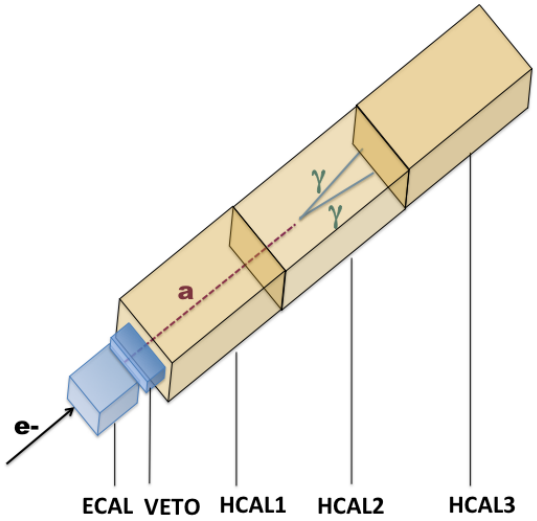
Semivisible Decay of A' in NA64: update 2107.02021 [hep-ph]

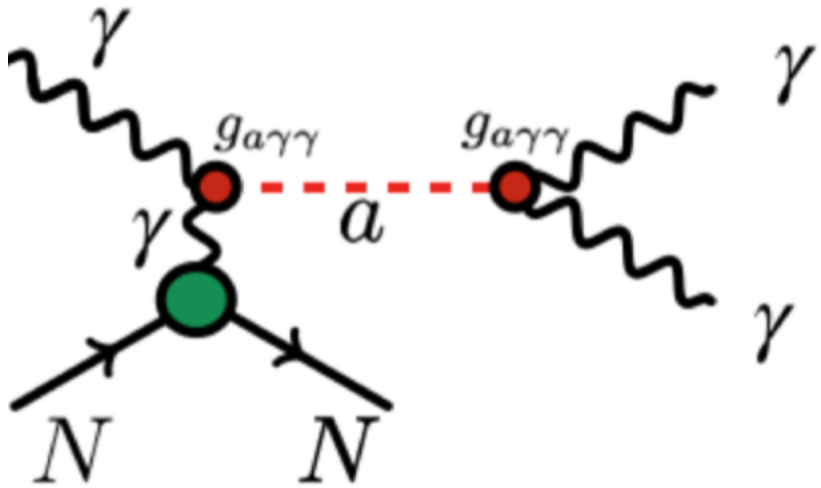




- **Motivation:** $(g-2)_\mu$ anomaly and Light Dark Matter production
  E. Izaguirre, et al. PRD 96, 055007 (2017)
  G. Mohlabeng, PRD 99, 115001 (2019)
  Y. Tsai, et al., PRL126, 181801 (2021)
- **Signature:** Missing energy + SM particles pair

NA64 semivisible modes: ALPs



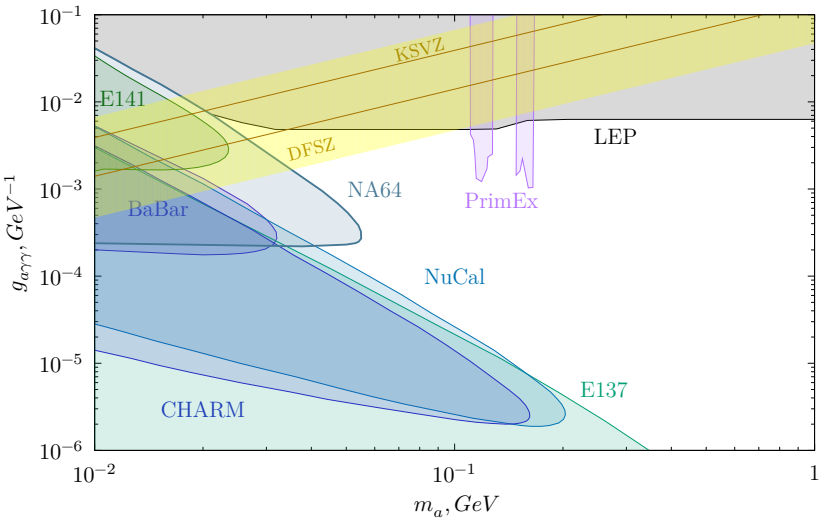


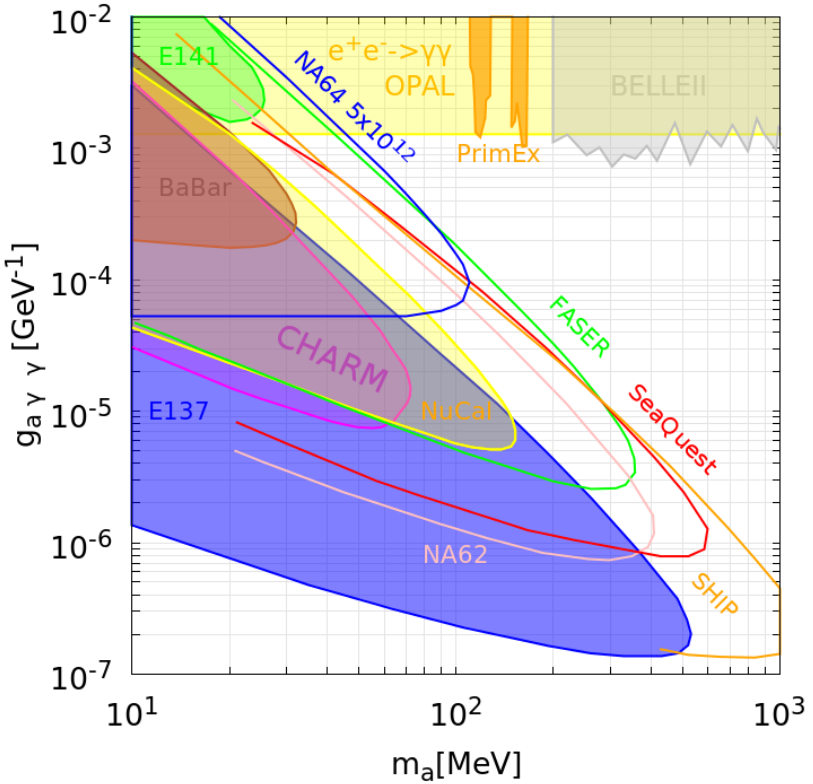
- ALPs predominantly coupled to photons produced via Primakoff effect

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

- **Signature:**
  - No signal on 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

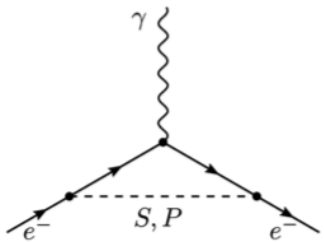


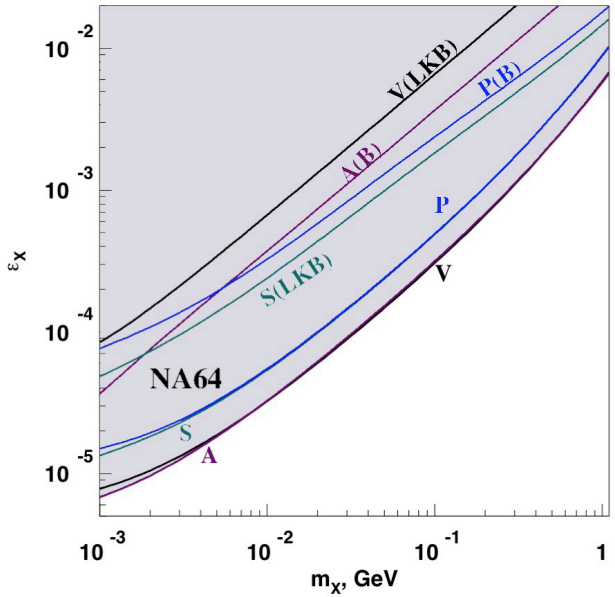


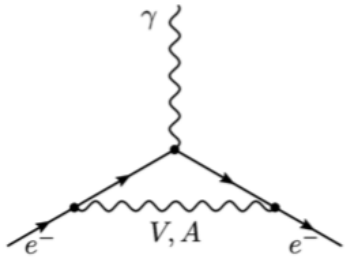
- **Left plot is a current limit for $EOT = 2.84 \cdot 10^{11}$ (PRL, 2020)**
- **Right plot is projected limit for $EOT = 5 \times 10^{12}$ (PRD, 2020)**
- **Future Plans: to consider invisible decay into DM, $Br(a \to \chi\chi) \simeq 1$**

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).
- $a_e^B = a_e^{exp} - a_e^{th} = (-8.8 \pm 3.6) \cdot 10^{-13}$ Berkley, R. H. Parker, C. Yu, W. Zhong, B. Estey, and H. Muller, Science 360, 191 (2018)

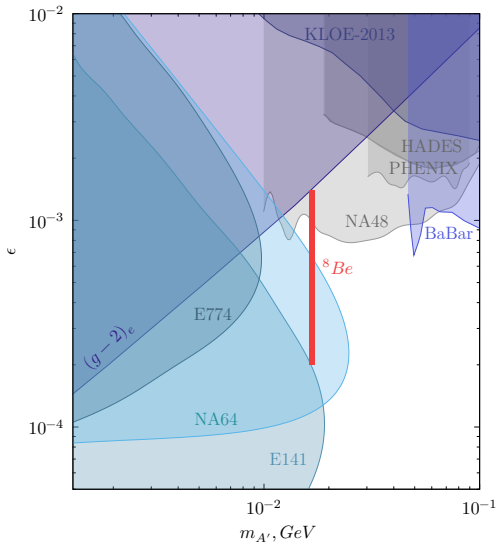


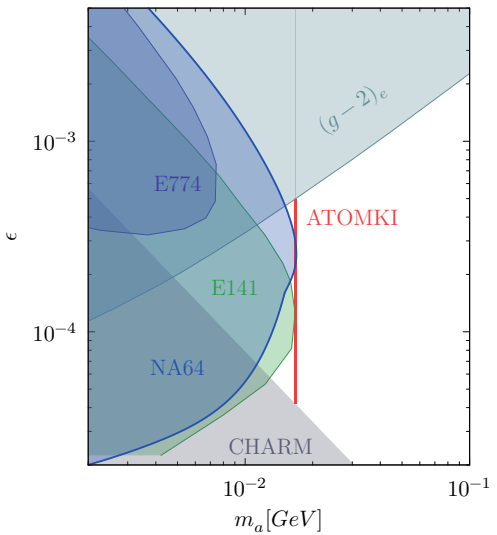




- $X(J^P = 0^{\pm}, 1^{\pm}) \to$ invis.: **Motivation** is to exclude the explanation of $(g-2)_e$ puzzle due to X decaying invisibly.
- NA64 collaboration, Phys. Rev. Lett. 126, 211802

Visible mode of Dark Photon and ALPs coupled mostly to electrons

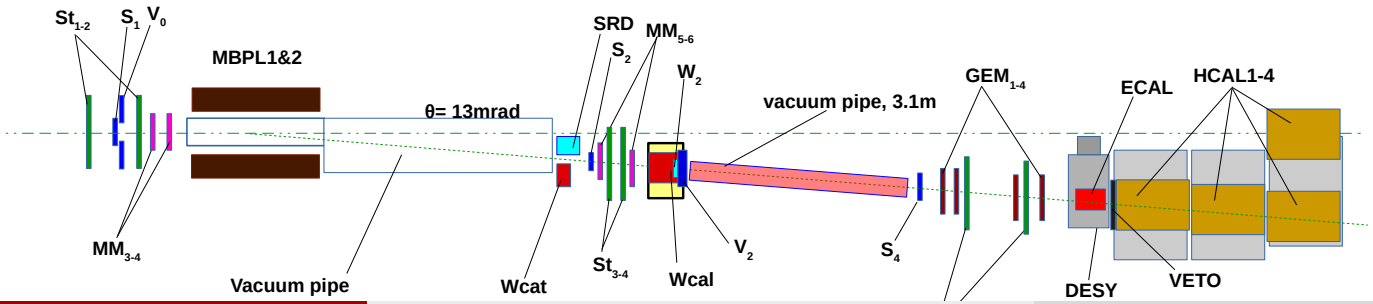




The ATOMKI experiment of (Krasznahorkay et al. 2016) has reported the observation of a 6.8 σ excess of events in the invariant mass distributions of e^+e^- pairs produced in the nuclear transitions of excited $^*Be^8$ and $^*He^4$ This anomaly can be associated with X-boson of $m_X = 16.7$ MeV.

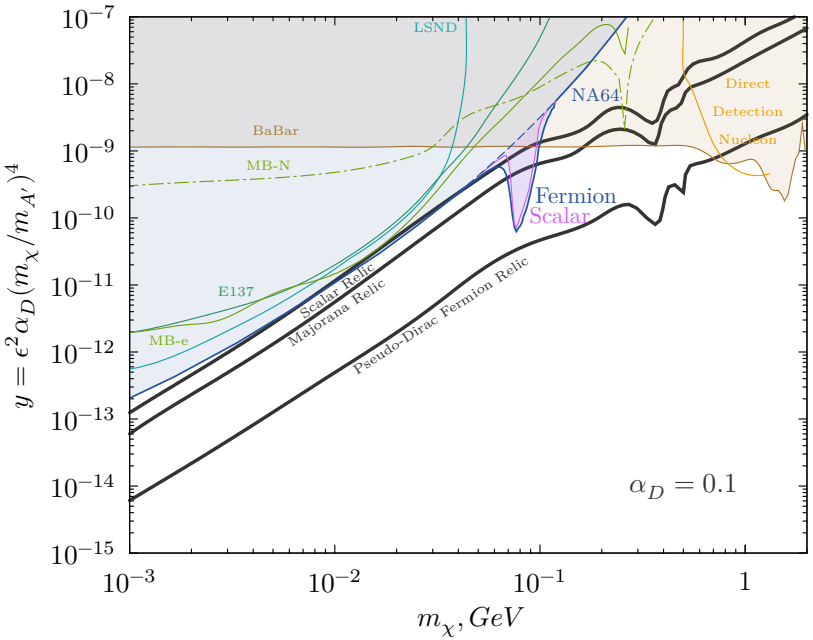
GOAL: to perform invariant mass reconstruction:

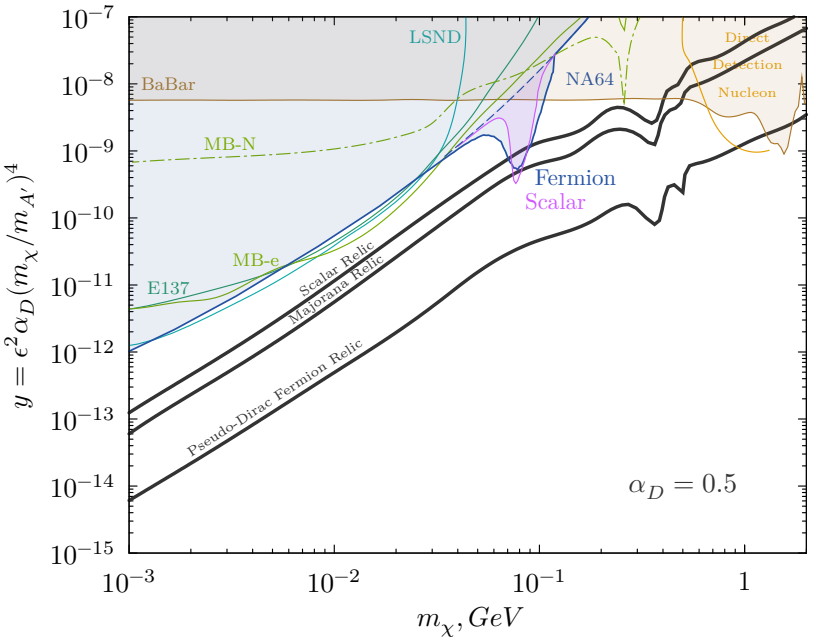
- **Increase the length of decay tube to resolve e^+e^- tracks.**
- **More compact WCAL**



New result!

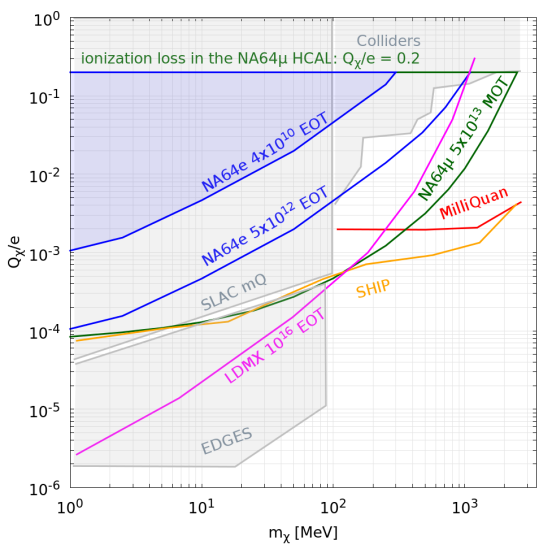
- **Resonance annihilation channel using the secondary positrons present in the EM shower in the target induced by the initial electron beam**
- **Improvement limit on ϵ up to factor 10 in the resonant region**

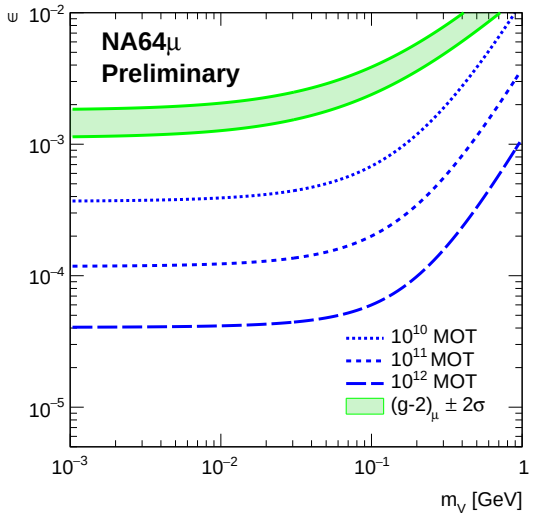




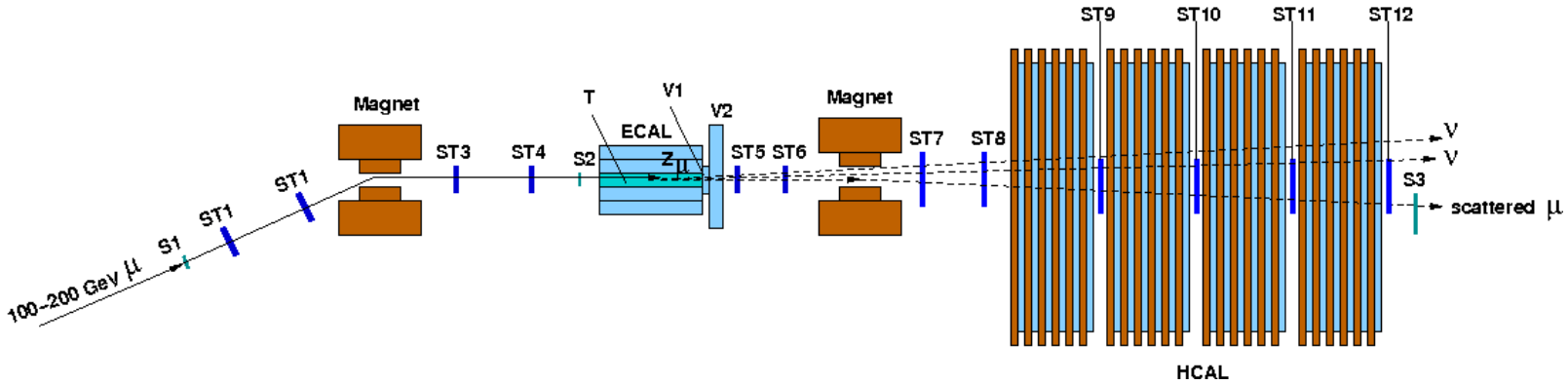
- **PRELIMINARY: probing resonant $e^+e^- \to A' \to \chi\chi$ production with electron beam (2108.04195 [hep-ph])**
- **NEXT STEP is to probe the resonance $e^+e^- \to A'$ with positron beam**

NA64e and NA64μ for large mass region $m_X \sim 1$ GeV

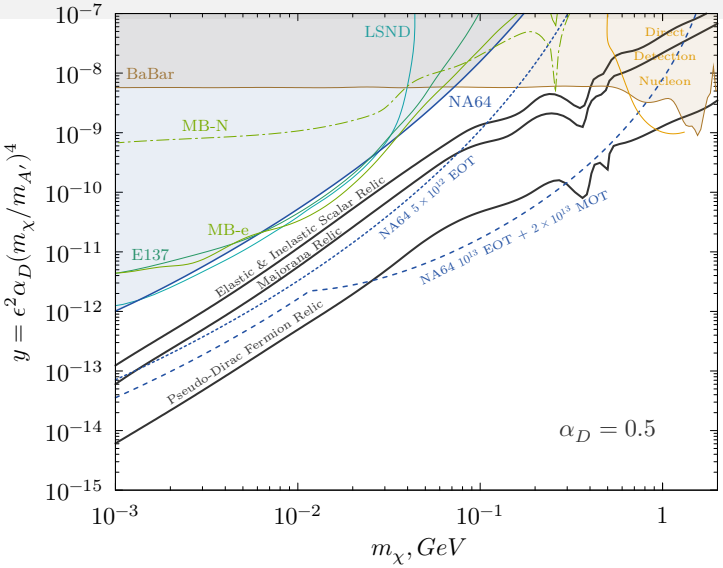


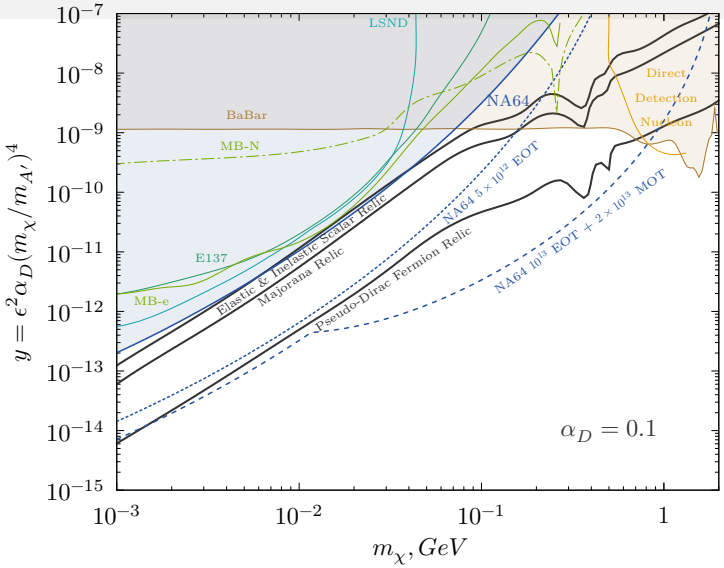


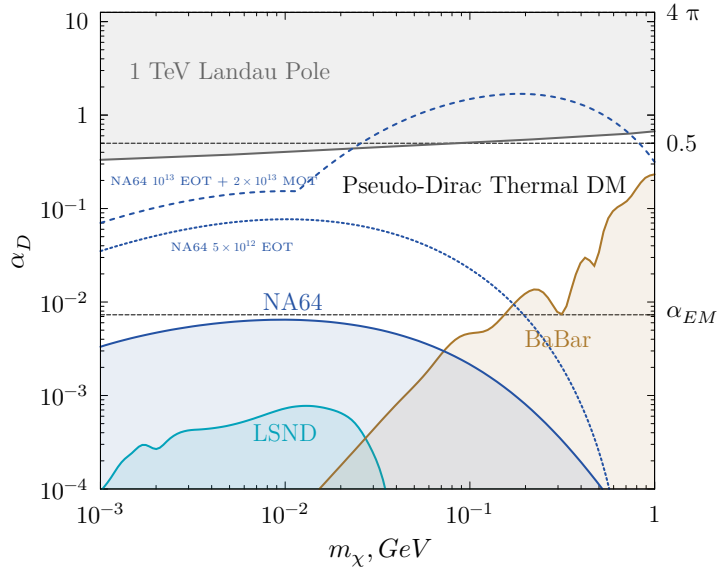
- **APPROVED: pilot muon beam run (M2 channel) - November 2021**
- **GOAL: millicharged particles (more effective production in Na64μ than in NA64e)**
- **GOAL: probing muon $(g-2)$ anomaly at NA64μ within $L_\mu - L_\tau$ anomaly free gauge extension (exact tree level cross-section $\mu N \to \mu N Z'$ without relaying on widely used IWW approach)**

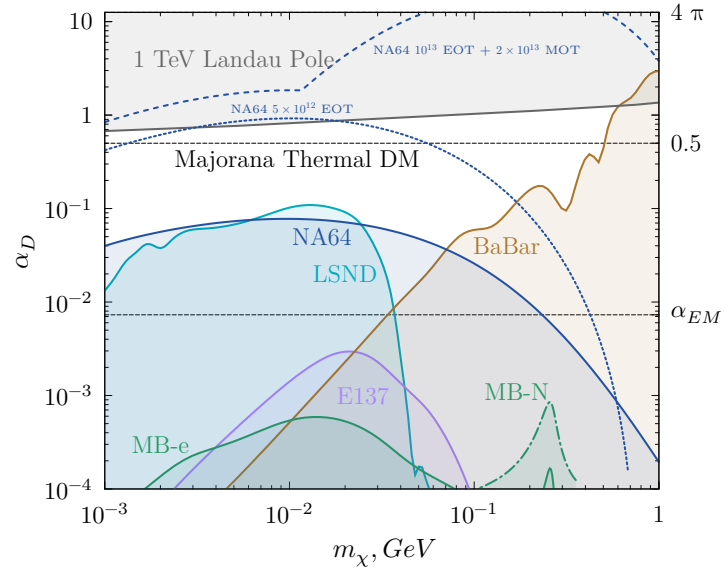


Combined *NA64e* and *NA64*μ limits









Summary

- Dark sector physics interesting framework to explain dark matter
- NA64 is an ideal experiment for testing benchmark scalar, Majorana and pseudo-Dirac thermal sub-GeV dark matter models
- **Prospects before LS3:**
- New area at H4 and setup upgrade to run at high intensity
- **Main goal** to explore **LDM parameter space** with goal $\gtrsim 5 \times 10^{12}$ EOT
- Start **searches of dark sectors weakly coupled to muons with NA64μ:** $(g-2)_\mu$ and $L_\mu - L_\tau \to Z'$: **pilot run at M2**
  Probing light dark matter parameter space for $m_{A'} > 100$ MeV
- **Increase sensitivity to** $A' \to e^+e^-$ **decays and explore** $X17 \to e^+e^-$ **remaining parameter space in 2022:** in case of signal-like events reconstruct the invariant mass with precision at few percent level.
- All DM physics is simulated by the newly developed DMG4 package
- **Exploration of LDM with NA64 has just began. Full physics potential to be exploited in the coming years!**