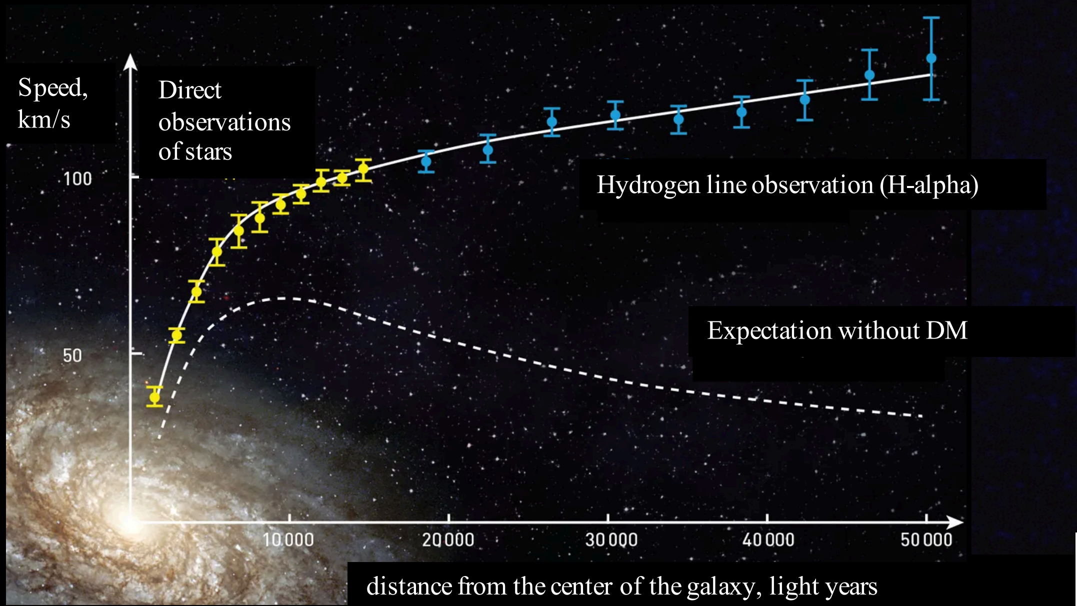
Latest results of the NA64 experiment at CERN

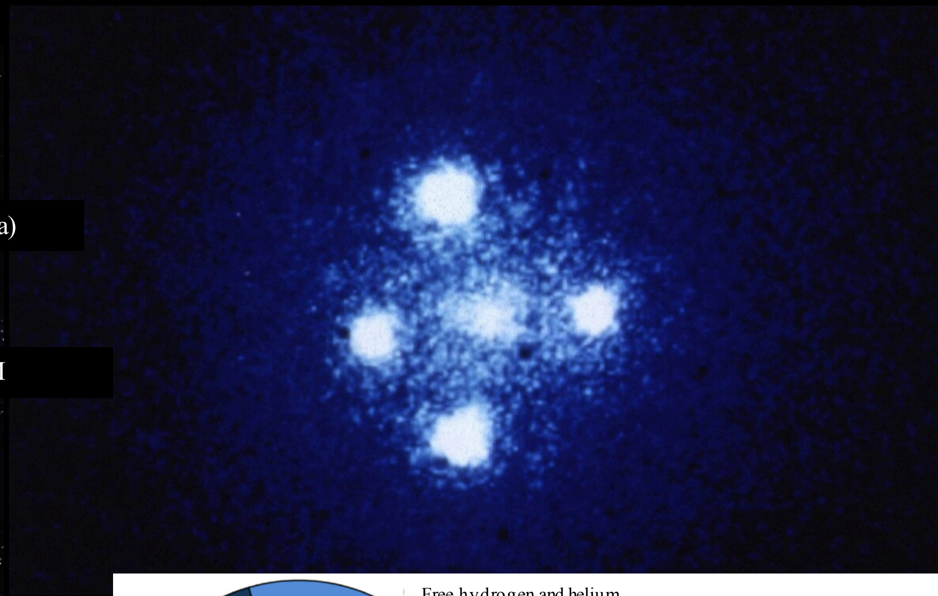
D.Peshekhonov, JINR, on behalf of the NA64 collaboration

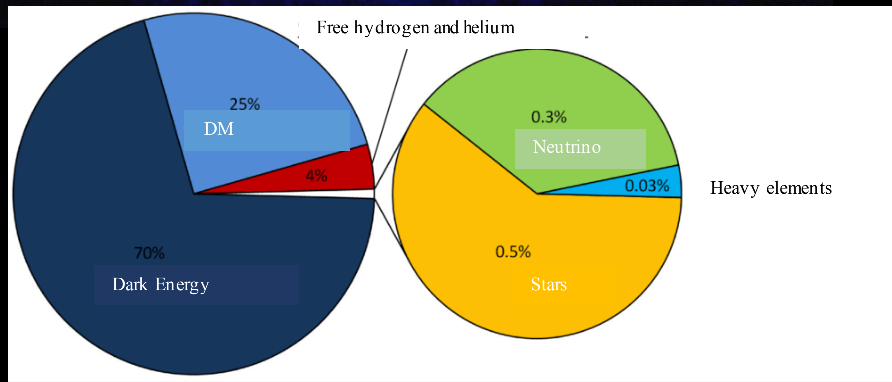
TWENTY- SECOND LOMONOSOV CONFERENCE ON ELEMENTARY PARTICLE PHYSICS

Dark Matter

- indirect evidence of existence (galaxy rotation rate, gravitational lensing, microwave background, structure of the Universe)



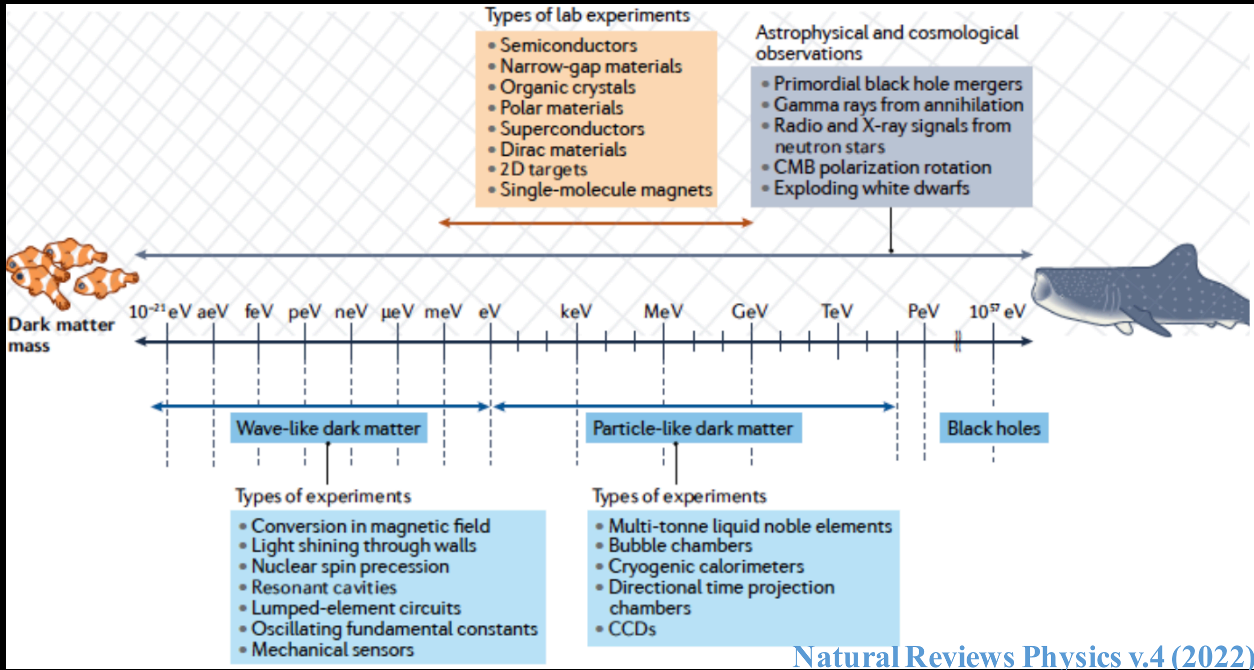




- is not involved in electromagnetic interaction
- is not baryonic
- makes up about 85% of the Universe mass

DM nature - ?

Dark Sector



Natural Reviews Physics v.4 (2022)

- “fuzzi DM” ~10^{-22} eV(de Broglie wavelength ~ galaxy size) - successfully explains the structure and features of galaxies motion; massive compact objects ("primordial" black holes, neutron stars);
- axions & ALP;
- Sterile neutrino;
- WIMP: massive particles, E-W scale;
- light dark matter

Dark sector (v<<c)

Direct search: gaseous detectors (XENON, PandaX, DarkSide, …); crystalls (CDMS, CRESST, EDELWEISS,..); bubble chambers (PICO)

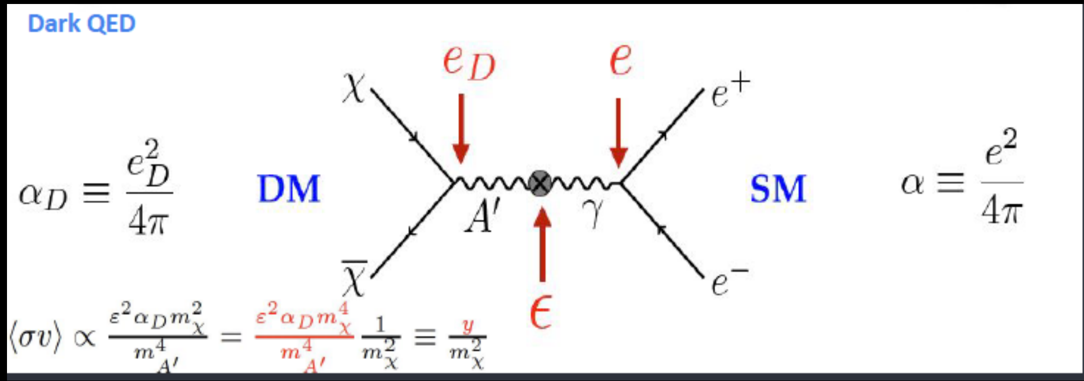
Indirect search: gamma/ neutrino/ radio telescopes; cosmic rays (IceCube, Baikal, AMS, MAGIC,…);

Search with accelerators:
- LHC (WIMP)
- extracted beams (LDM)

Light dark matter

Sub-GeV DS particles very weakly (ε) interacting with SM particles:

- Vector portal (mediator dark photon A')
- Scalar (Dark Higgs boson)
- Pseudo-scalar (axions)
- Fermion (Dark leptons)

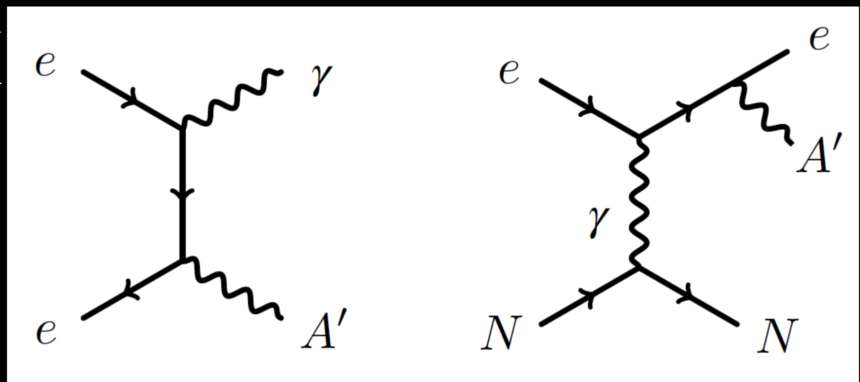


For A': ε, α_D, m_χ, $m_{A'}$

$y = \varepsilon^2 \alpha_D (m_\chi / m_{A'})^4$

Breit-Wigner cross section maximum at $M_{A'}^2 = 2 m_{e^-} E_{e^+}$

$\sigma \sim \varepsilon^2 Z \alpha_{EM}$



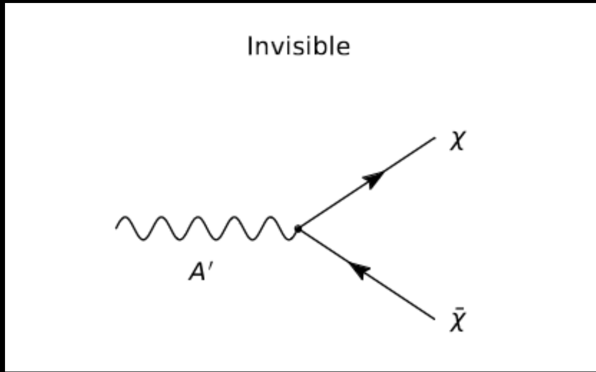
annihilation   bremsstrahlung

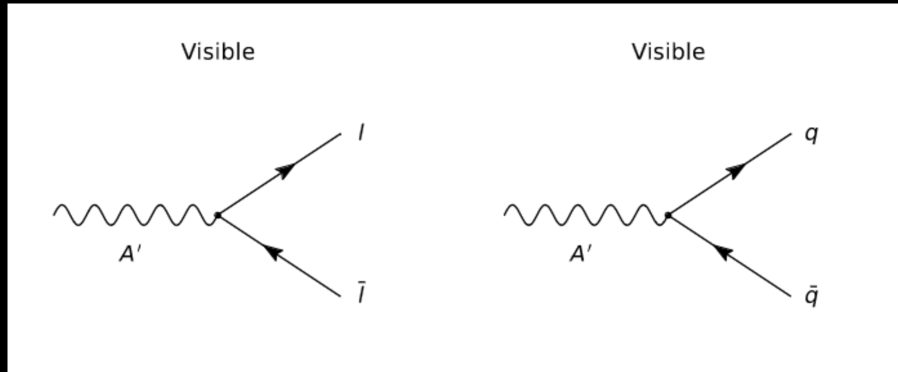
$\sigma \sim \varepsilon^2 Z^2 \alpha^3_{EM}$

Setting up the experiment

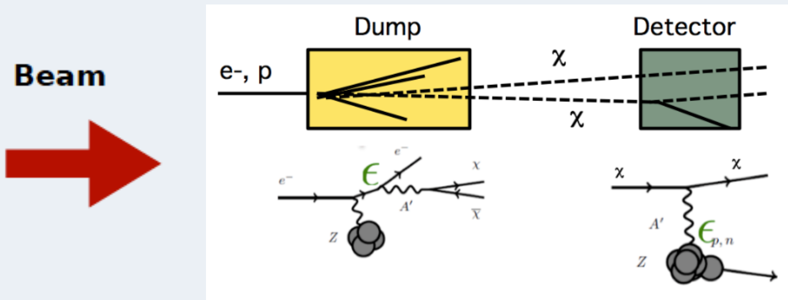
$m_{A'} > 2m_\chi$, $A' \rightarrow \chi\chi$

$m_{A'} < 2m_\chi$, $A' \rightarrow e^+e^-, \mu^+\mu^-, ..$

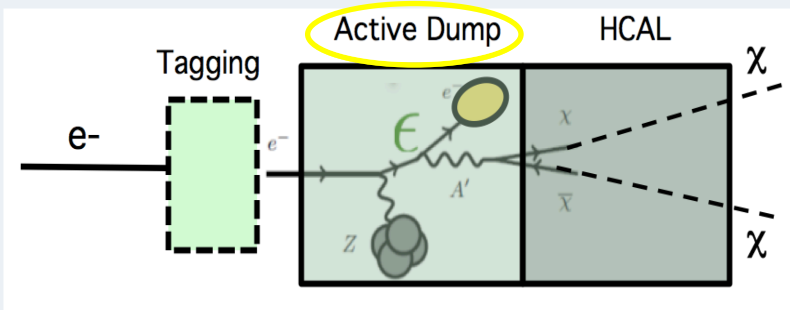




1) BEAM DUMP APPROACH
(MiniBooNE, LSND, NA62, SHIP, T2K, DUNE…)



2) NA64, LDMX APPROACH



$$\sigma \propto \epsilon^4 \alpha_D$$

$$\sigma \propto \epsilon^2$$

Signal:

DM particle in far detector

«missing energy»

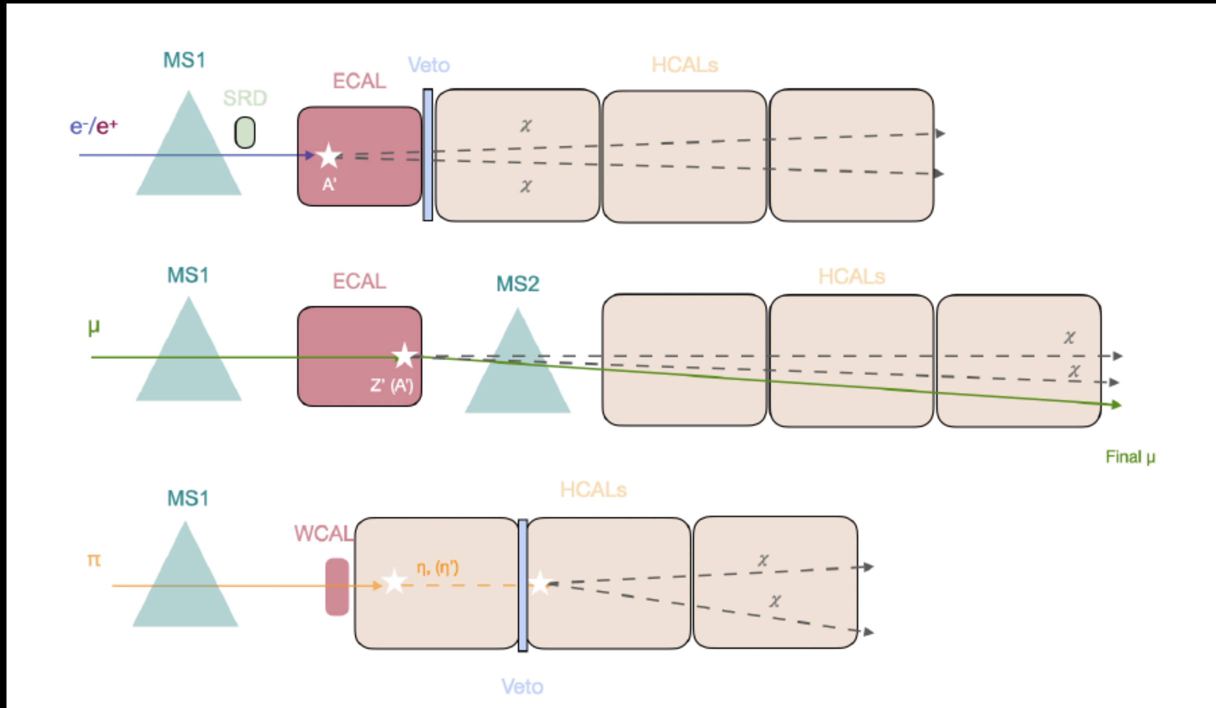
NA64 experiment

NA64 collaboration: ~ 60 researchers from JINR, Italy, Spain, Switzerland, Chile and Germany

2014 – P348 Proposal: search for the light DM (Sub-GeV) at CERN SPS using the «active dump» & «missing energy» techniques;

2016 – NA64e^- approved by SPSC;

2021 – NA64μ approved by SPSC

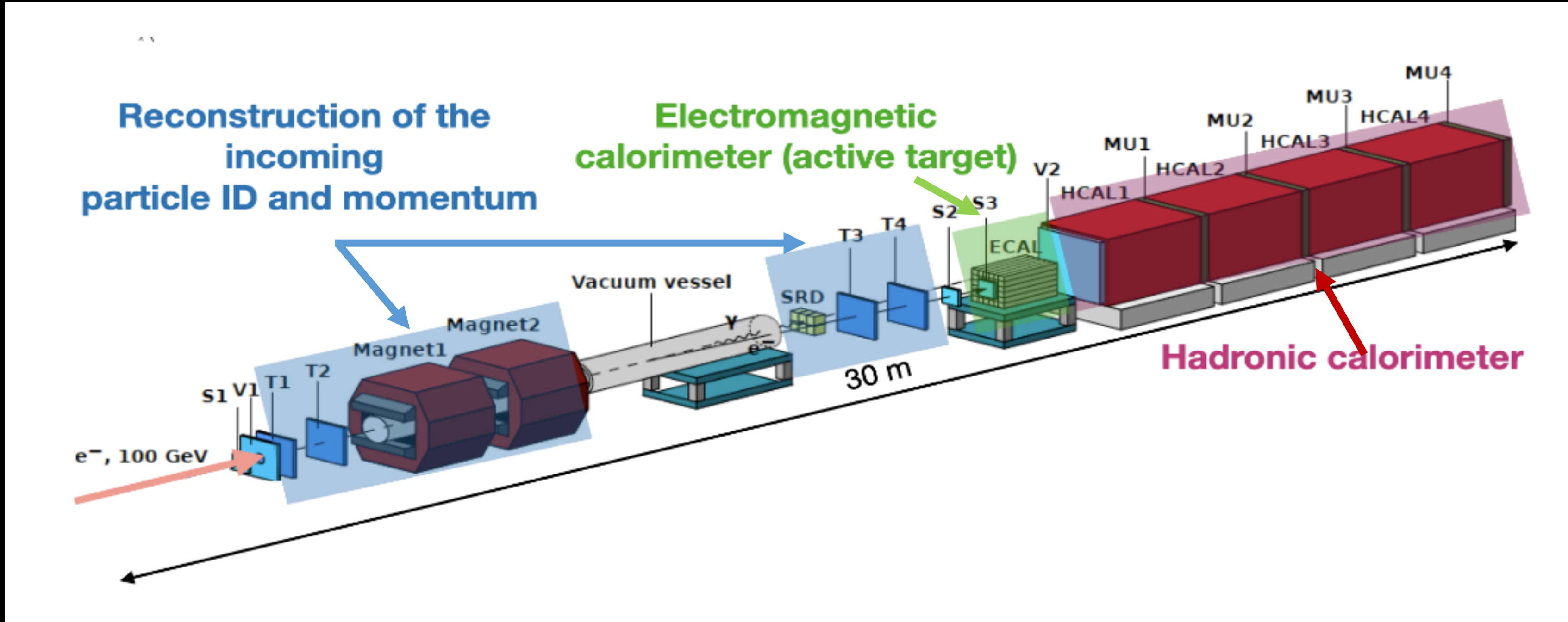


Schematics of the missing energy technique used by NA64 combining initial e^-, e^+, μ and π beams

NA64 research program address the three complementary issues in DS physics that are accessible at the SPS:

1. search for LDM and other BSM physics with masses below the electroweak scale combining the results from electron and positron beams at H4;
2. search for DS predominantly coupled to the second lepton generation and LDM with the M2 muon beam;
3. search for leptophobic DS predominantly coupled to light SM quarks with the SPS hadronic beams.

NA64e$^-$



NA64e set up

Magnetic spectrometer:

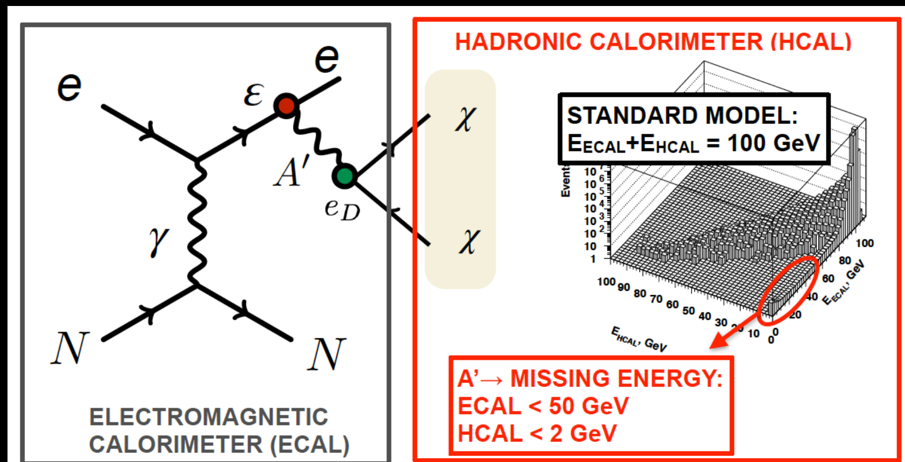
- MM, GEM, Straw, Field integral 6.8T, $\Delta p/p \sim 1\%$;

SRD:

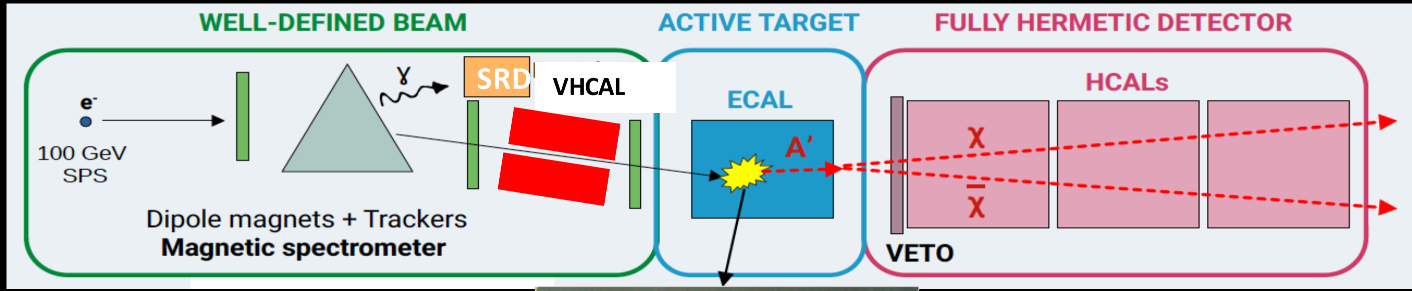
- LYSO crystalls 32x48x45 mm^3; $\langle N\gamma\rangle \sim 30$ γ's,
  $\langle E\gamma\rangle \sim$ MeV $\varepsilon_{SRD} > 0.95$, $\pi/e \sim 10^{-6}$

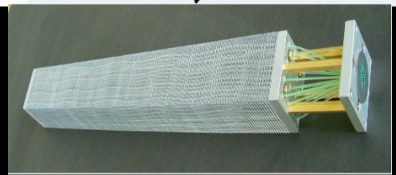
Active target: $40X_0$ Pb/Sc calorimeter, 20x24cm^2(5x6)
150x(1.5mm Pb+1.5mm Sc); $\sim 10\%/\sqrt{E} + 3\%$

Hadron calorimeter: 4x7,5λ; 48x(25mm Fe+4mm Sc)
~60x60cm^2 ;~ $60\%/\sqrt{E}$



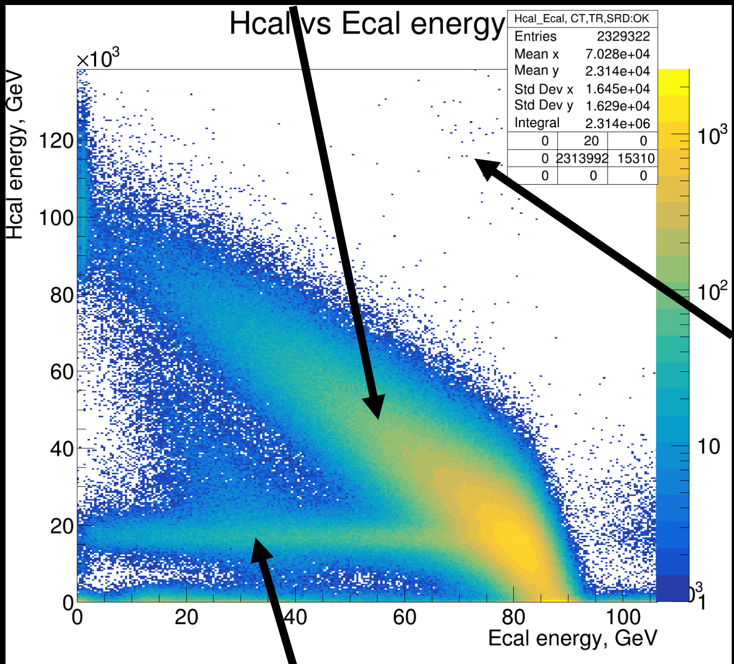
Signal selection (NA64e^-)





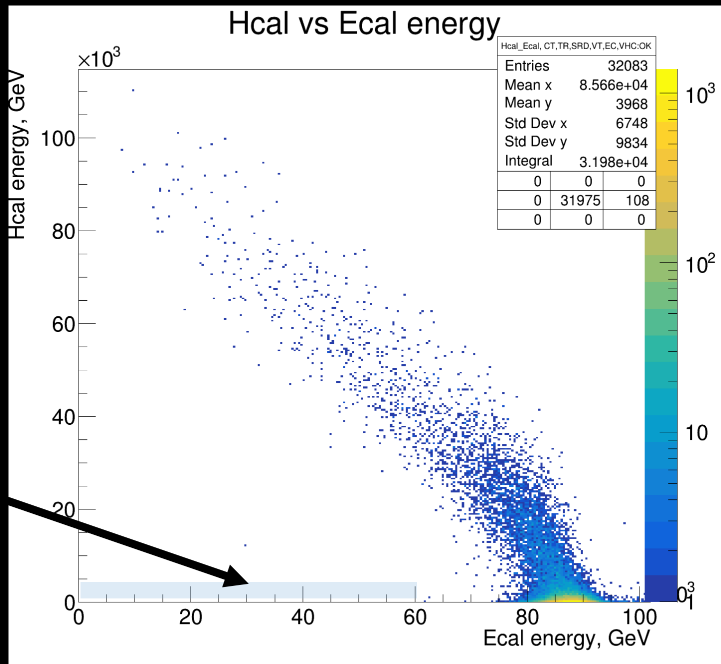
Signal selection criteria:
Timing (pile up suppression) + Clean e^- track (single hit, correct angle and momentum) + Synchrotron radiation signal for e^- ID + Shower in ECAL compatible with e^- + No activity in Veto&HCAL

Zone II: SM events
$E_{ECAL}+E_{HCAL}=$ 100 GeV



Zone III: pile up

Zone I: $e^-Z \rightarrow e^-Z\gamma$; $\gamma \rightarrow \mu^+\mu^-$ (reference)



Signal box

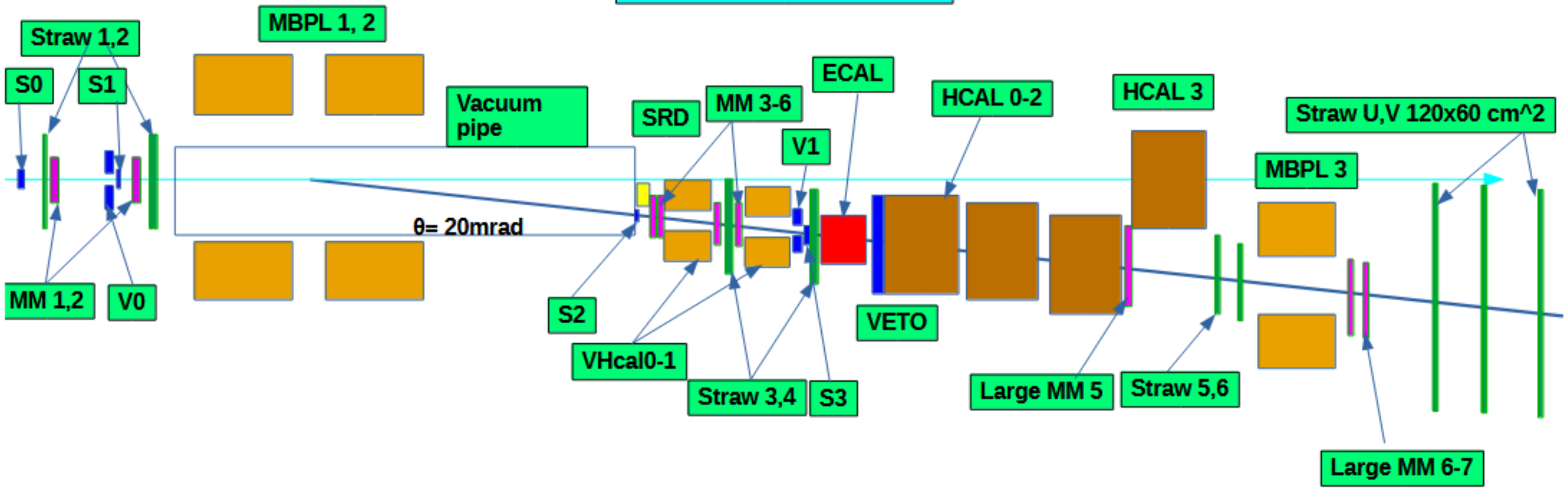
NA64 experiment

Summary, NA64 2025.

Laura Molina Bueno and Vladimir Poliakov

H4: start - April 23, end June 25; 7 days after ion run from July 7;
Electron beam, 100 GeV → April 23 to June 18
Positron beam, 40 and 45 GeV → June 18 to June 23
Hadron beam, 50 GeV → July 7 to July 14

2025 setup



IFIC CSIC Consejo Superior de Investigaciones Científicas · Universitat de València · Millennium Institute for Subatomic Physics at High-Energy Frontier SAPHIR · Joint Institute for Nuclear Research, International Intergovernmental Organization

NA64h

NA64h plans to perform a comprehensive study of leptophobic models predicting

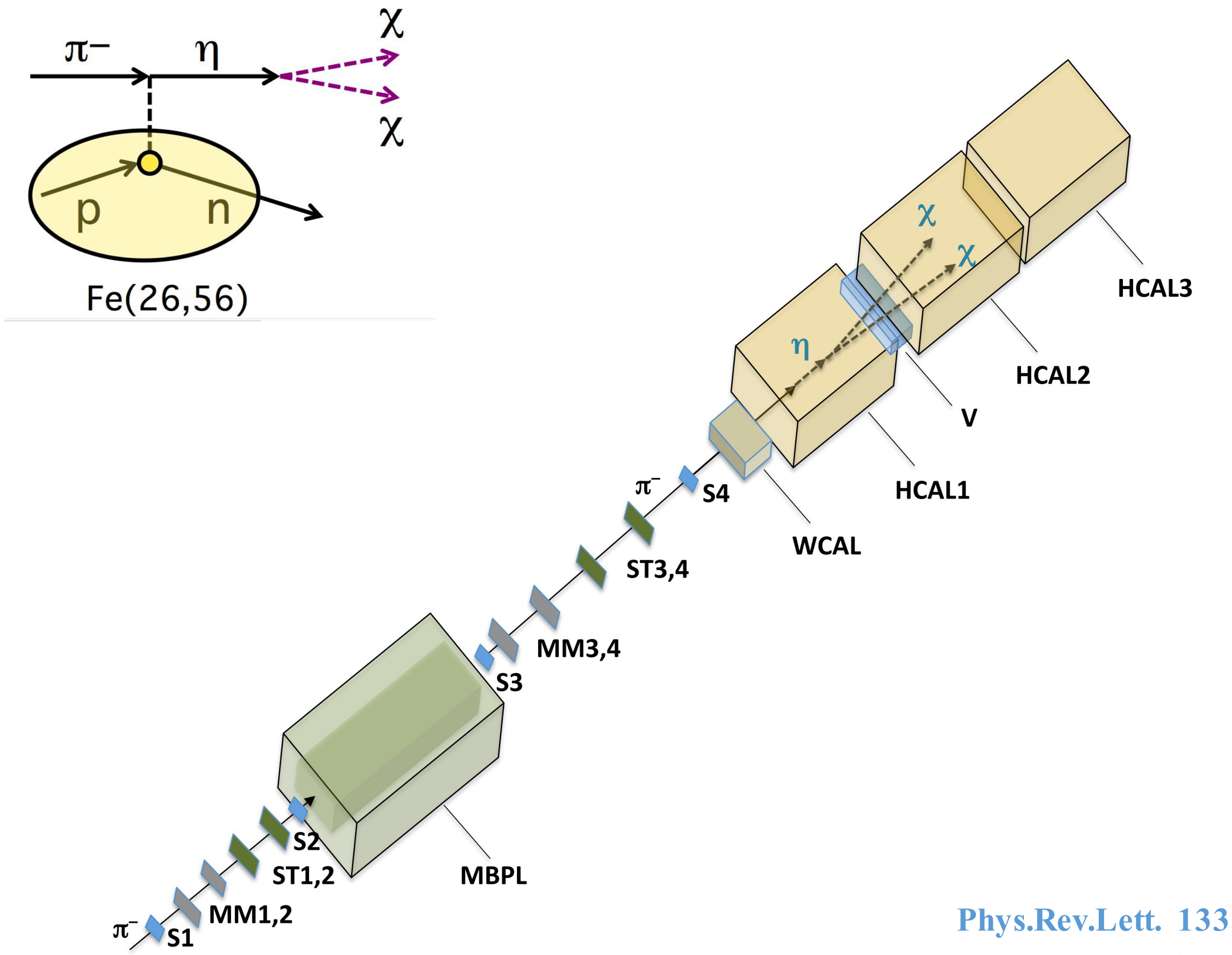
- a new U′(1) gauge bosons or scalars coupled to LDM
- invisible or semi-visible decays of neutral and vector mesons η, η′, ω, ρ, ..., and, in particular, $K_{S,L} \to$ invisible decays of neutral kaons, which have never been probed. The later is highly complementary to searches for $K^{+,0} \to \pi +$ invisible decays.
- $K^0 - K'^0$ oscillations of neutral K^0 into its dark partner, e.g., in the Mirror Matter model. This search is complementary to experiments looking for n − n′ oscillations.
- a class of dark sector models with a heavy neutral lepton can also be tested.

In 2024, we published the first results from a proof-of-concept search for DS via invisible decays of pseudoscalar η and η′ mesons. Our technique uses the charge-exchange reaction of 50 GeV π^- on nuclei of an active target as the source of neutral mesons. The η, η′ → invisible events would exhibit themselves via a signature - the complete disappearance of the incoming beam energy in the detector.
No evidence for such events has been found with $2.9\text{x}10^9$ pions on target. This allows us to set a stringent limit on the branching ratio Br(η′ → invisible) < $2.1\text{x}10^{-4}$, improving the current bound by a factor of ≃ 3. We also set a limit on Br(η → invisible) < $1.1\text{x}10^{-4}$ comparable with the existing one.

In 2025, we accumulate $\sim 9{,}5\text{x}10^9 \pi ot$ (50 GeV)

We are currently considering the possibility of performing this program at the CERN PS T9 beamline. The first 2 weeks of test beam at T9 are foreseen from the 24th of September until October 8th. An addendum to the SPSC with our future plans after LS3 is in preparation.

NA64h

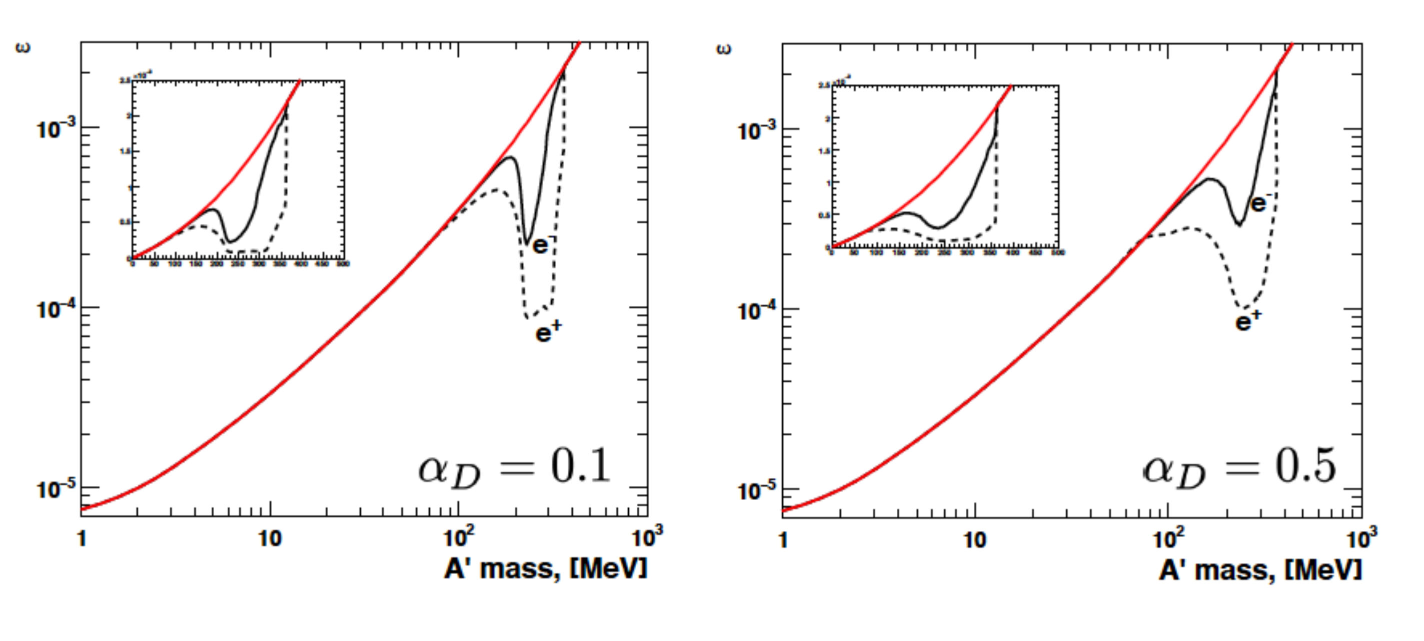


Phys.Rev.Lett. 133, 12 (2024)
Natural Science Review 1 5 (2024)

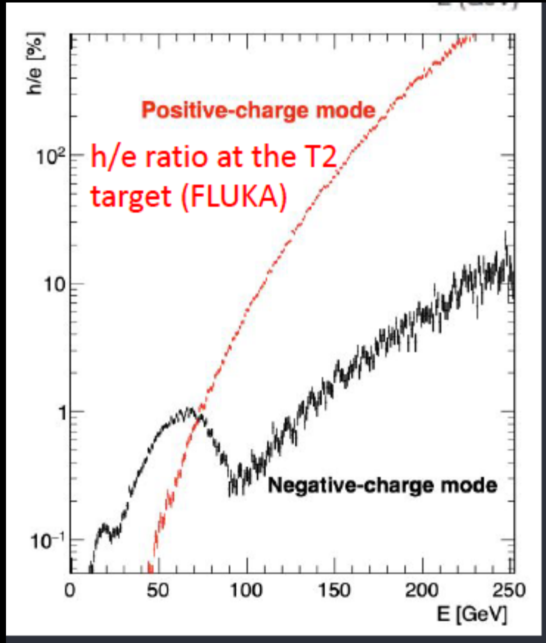
50 GeV π^-, MIP in WCAL, no signal in HCALs

NA64e$^+$

Advantages



Weaknesses



A' search with 100 GeV e$^+$ c beam
At range $m_{A'}$ ~ 200-300 MeV enhancement in **ε ~10,**
or ~10^2 for **y~ ε^2**

At 100 GeV, hadron impurity of the beam for e$^-$ is ~0,3%, which is 10 times less than for e$^+$, and the difference increases with energy

NA64e^+

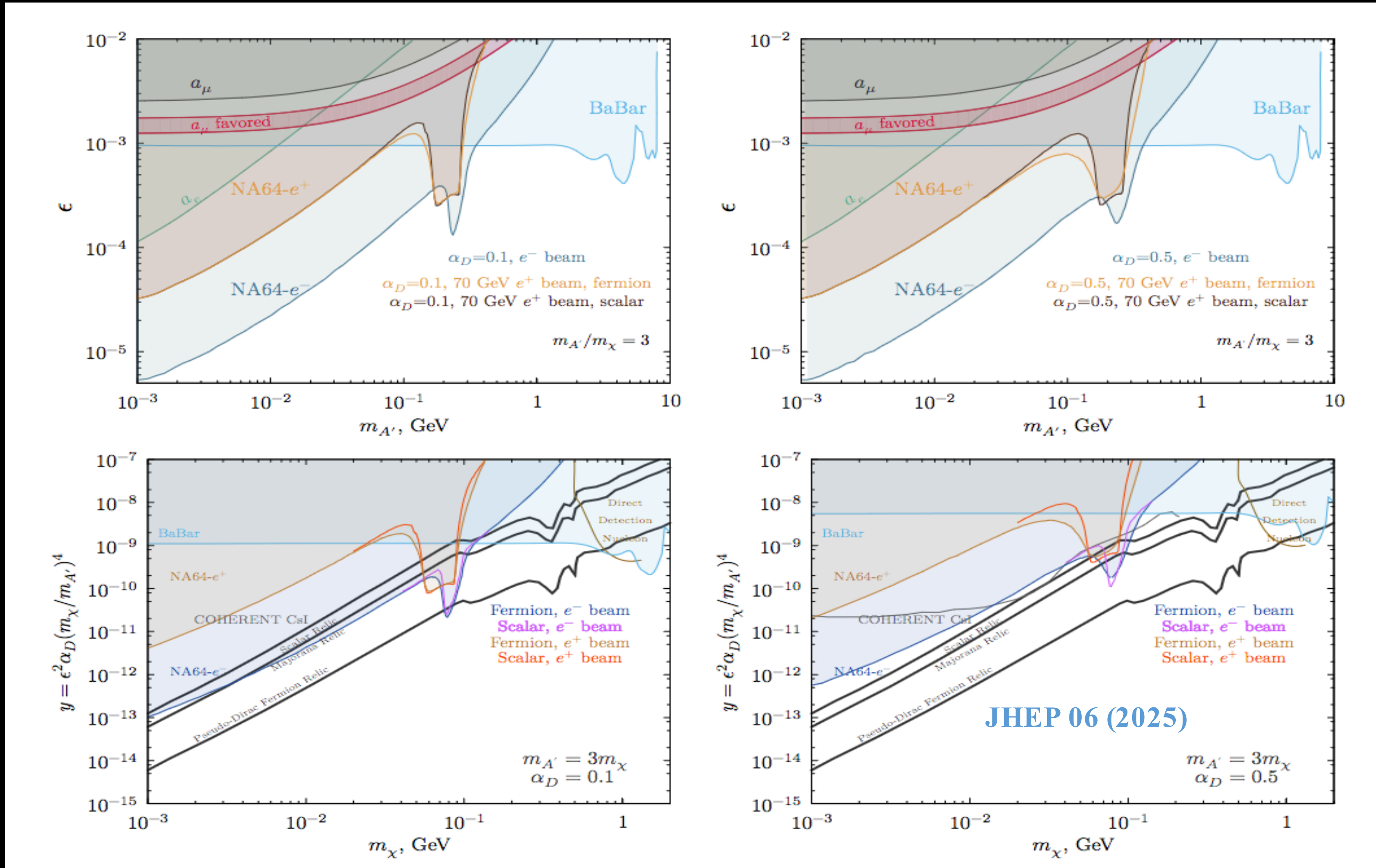
After the successful pilot measurement performed with a 100 GeV/c positron beam during the 2022 run, we continued the experimental program with e^+ beams. In 2023, we dedicated one week of beam-time to execute a new e^+ measurement, lowering the beam energy to 70 GeV. The primary goal was to characterize the main background sources in this low-energy configuration, as well as to assess the detector performances. The total accumulated statistics was 1.6×10^{10} e^+OT.

Specifically, our results exclude the existence of vector-mediated light dark matter in the mass range $165 < m_{A'} < 220$ MeV, for ε values down to 2.5×10^{-4} and $\alpha_D = 0.1$, and confirmes the already-observed exclusion contours for $\alpha_D = 0.5$ in the same window by the NA64-e^- run, with a factor ~ 100 larger accumulated statistics.

The success of the 70 GeV/c e^+ beam measurement confirmed the feasibility of conducting a low-energy program with NA64 using positron beams. The collaboration is now looking toward the post-LS3 period to run high-statistic, multiple energy e^+ measurements to probe the $mA' \simeq 100$ MeV region. At the same time, these promising results motivated in 2024 and 2025 two new positron beam runs at even lower beam energy (40 GeV), to complete the R&D activities supporting the future runs. The corresponding data analysis is currently in progress.

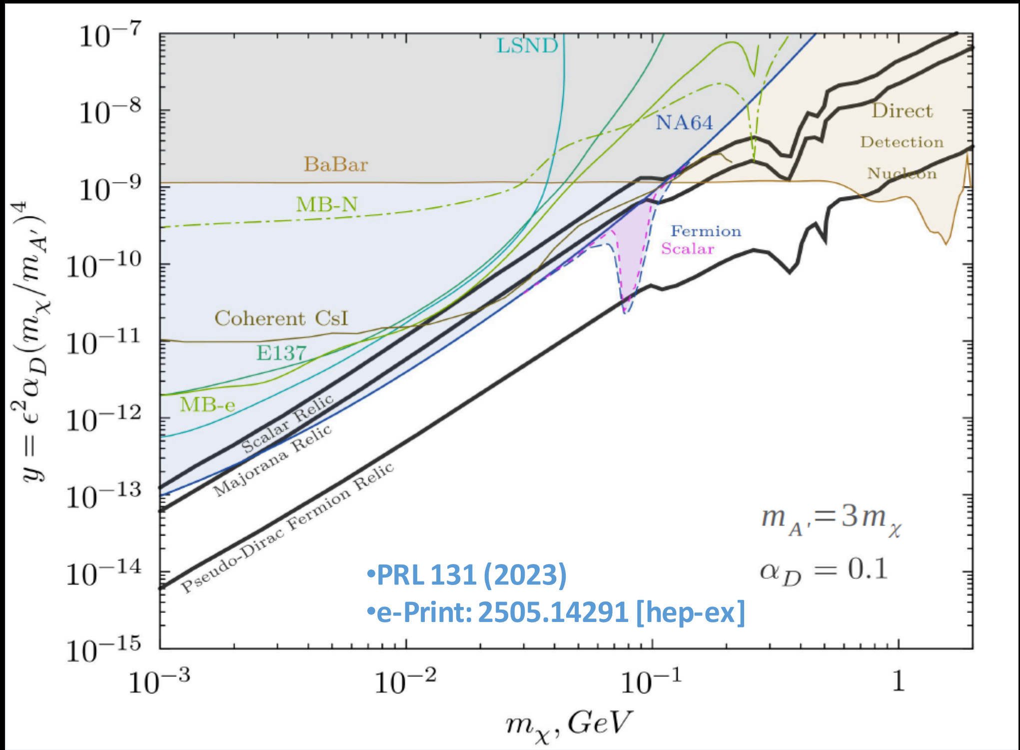
Already accumulated ~ 10^{11} e^+
Scheduled statistics are a few 10^{12} including

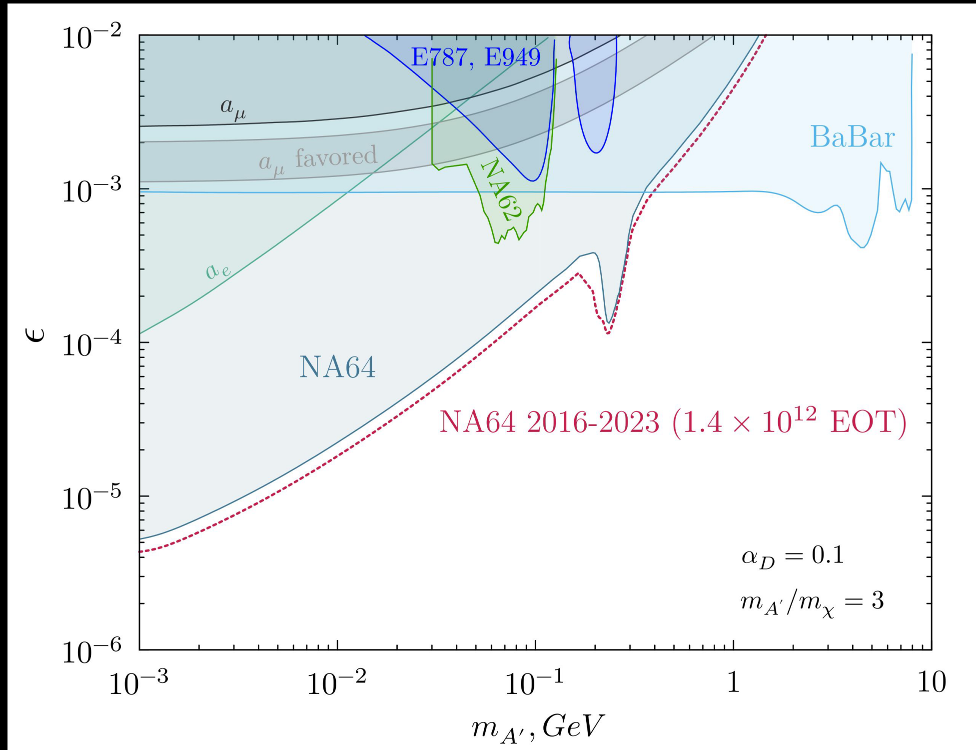
NA64e+



Exclusion limits at 90% confidence level derived from the 70 GeV/c positron-beam missing energy measurement. Top (bottom): exclusion limits — brown and orange curves- in the [$m_{A'}$, ε] ([m_χ, α_D]) plane, for $\alpha_D = 0.1$ (left) and $\alpha_D = 0.5$ (right). The other curves and shaded areas report already-existing limits in the same parameters space from NA64 in electron-beam mode (blue and violet), COHERENT (grey), and BaBar (light blue). In the bottom plots, the black lines show the favored parameter combinations for the observed dark matter relic density for different variations of the models.

NA64e$^-$

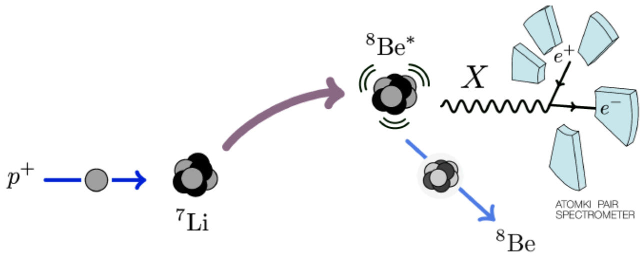




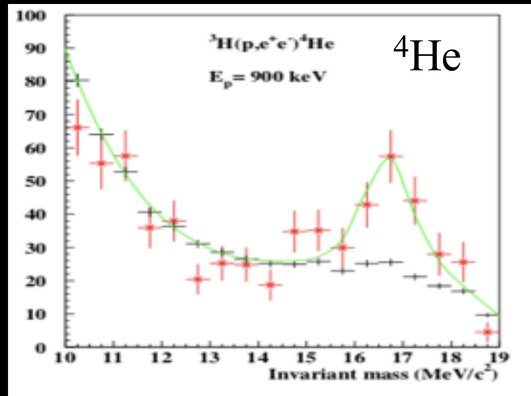
	2016-2022	2023	2024	2025	TOTAL
NA64e	9.7×10^{11} EOT	4.4×10^{11} EOT	5.2×10^{11} EOT	$\sim 5 \times 10^{11}$ EOT	$\sim 2.5 \times 10^{12}$ EOT

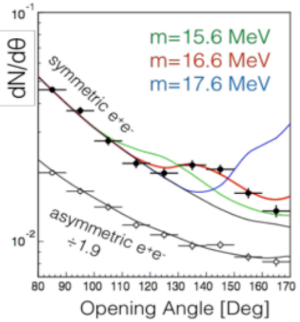
NA64e$^-$ - what else?

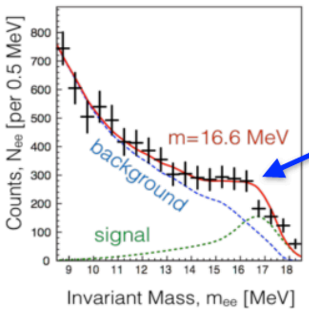
^{8}Be anomaly and X boson



A. J. Krasznahorkay et al. Phys. Rev. Lett.116, 042501 (2015) and recent results for 4He arXiv:1910.10459

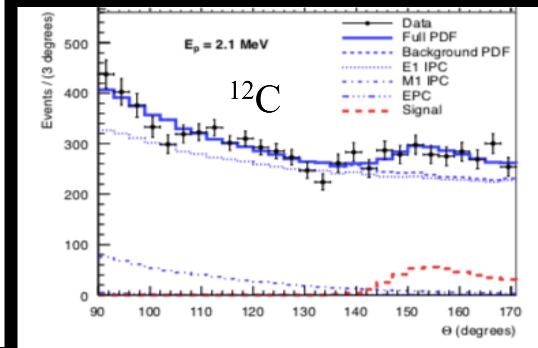




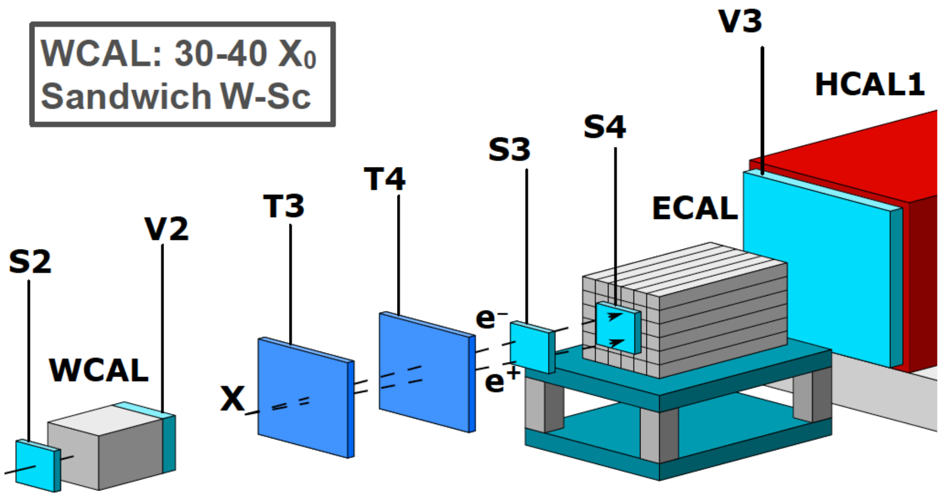


Could be explained by new 'protophobic' gauge boson X with mass around 17 MeV

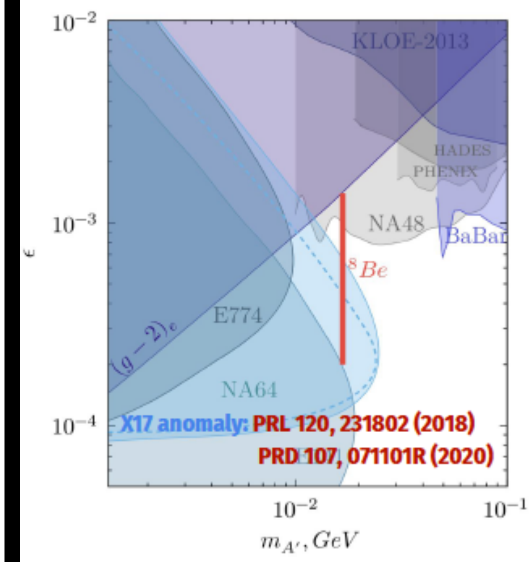
J. L. Feng et al. Phys. Rev. D95, 035017 (2017)



WCAL: 30-40 X_0
Sandwich W-Sc

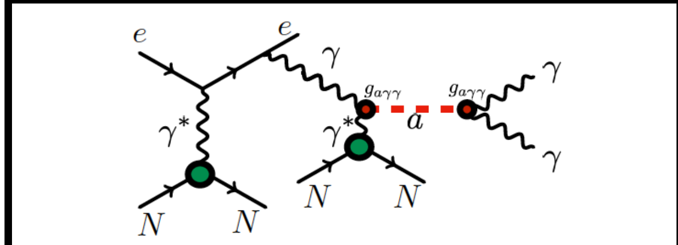


Signature:
1) $E_{WCAL}+E_{ECAL}$ = 100 GeV
2) No activity in $V_{2,3}$ and HCAL
3) Signal in S3, S4
4) e-m shower in ECAL

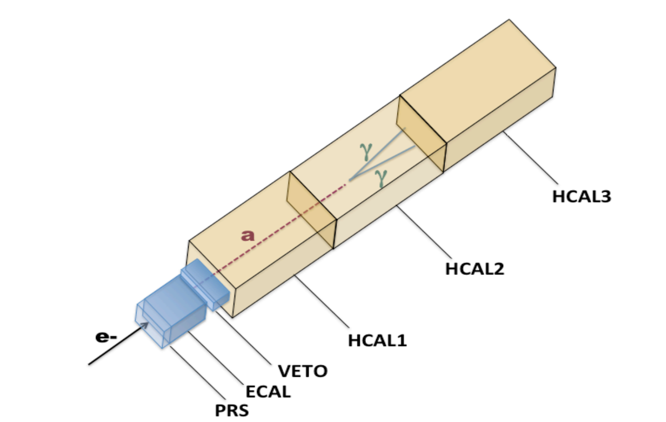


NA64e$^-$ - what else?

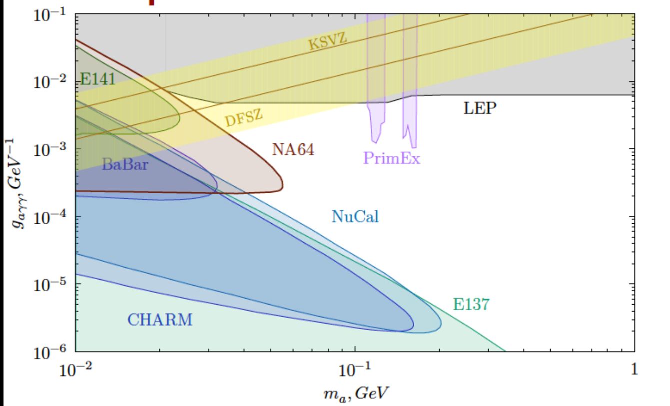
ALP



Production via Primakoff effect



Closing the gap between beam dump and colliders



$e^-Z \rightarrow e^-ZX$; $X \rightarrow$ *invisible*

X: scalar (S), pseudoscalar (P), vector(V), axial (A)

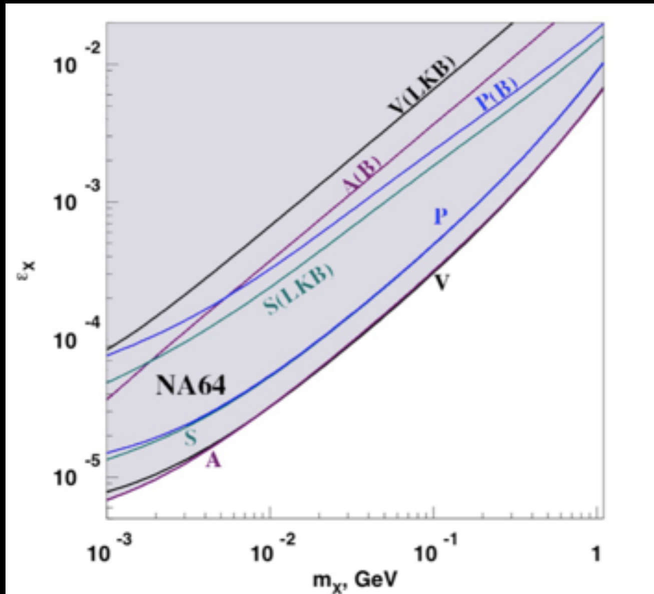
e^-X: interaction with coupling strength $g_X = \varepsilon_X e$

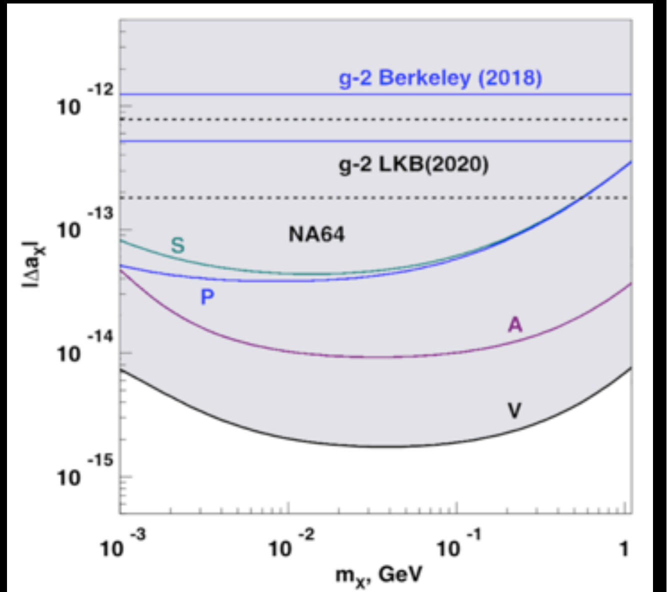
$$\Delta a_e = a_e^{exp} - a_e^{LKB} = (4.8 \pm 3.0) \times 10^{-13} \quad (1)$$

$$\Delta a_e = a_e^{exp} - a_e^{B} = (-8.8 \pm 3.6) \times 10^{-13} \quad (2)$$

$$\mathcal{L}_S = g_S \bar{e} e S$$
$$\mathcal{L}_P = i g_P \bar{e} \gamma_5 e P$$
$$\mathcal{L}_V = g_V \bar{e} \gamma_\mu e V_\mu$$
$$\mathcal{L}_A = g_A \bar{e} \gamma_\mu \gamma_5 e A_\mu$$

NA64,Phys.Rev.Lett.(2021)



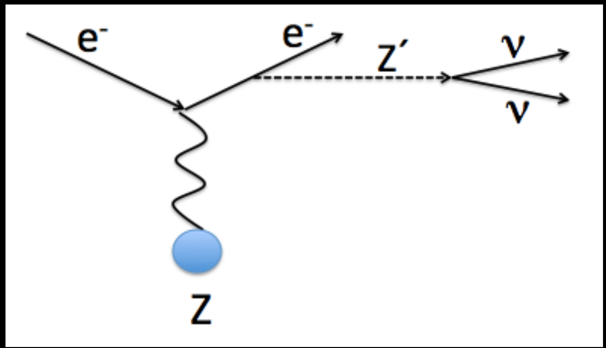


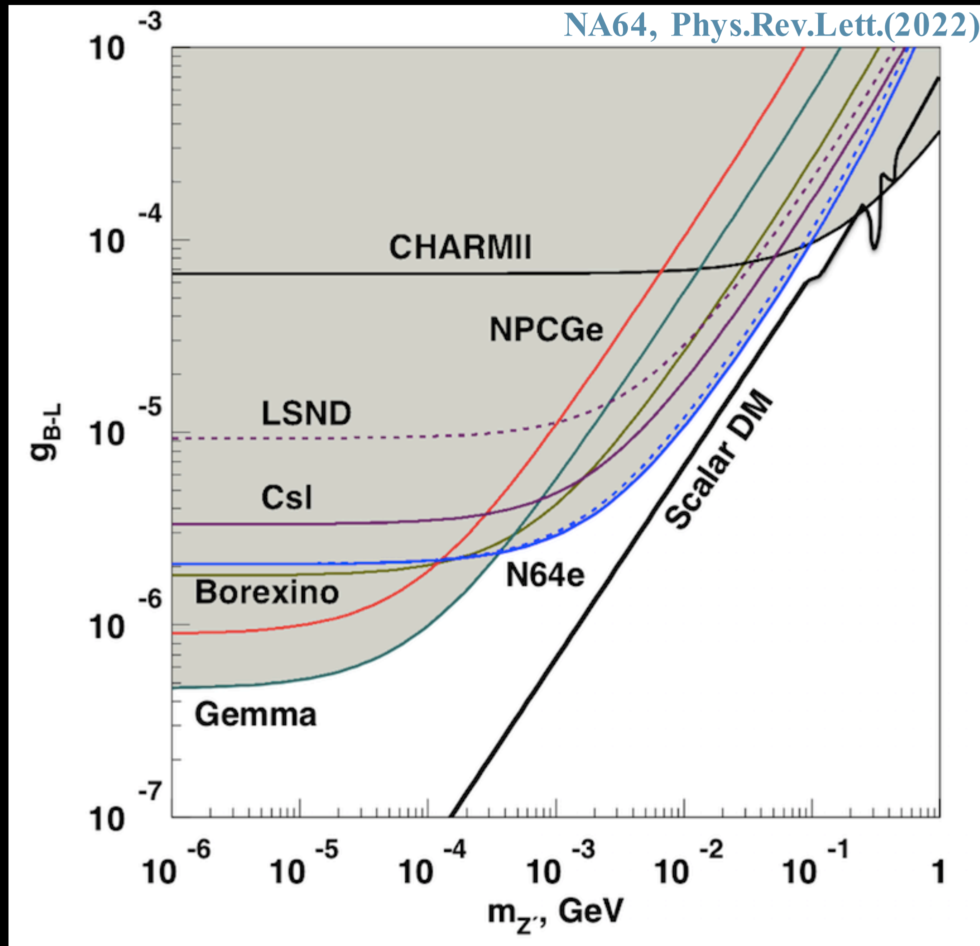
NA64e data give exclusion limits competing with precise measurements of Δa by LKB and Berkley

NA64e$^-$ - what else?

Search for B-L Z' bozon

3.2x10^{11} eot. 2016-2018 & 2021 data





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

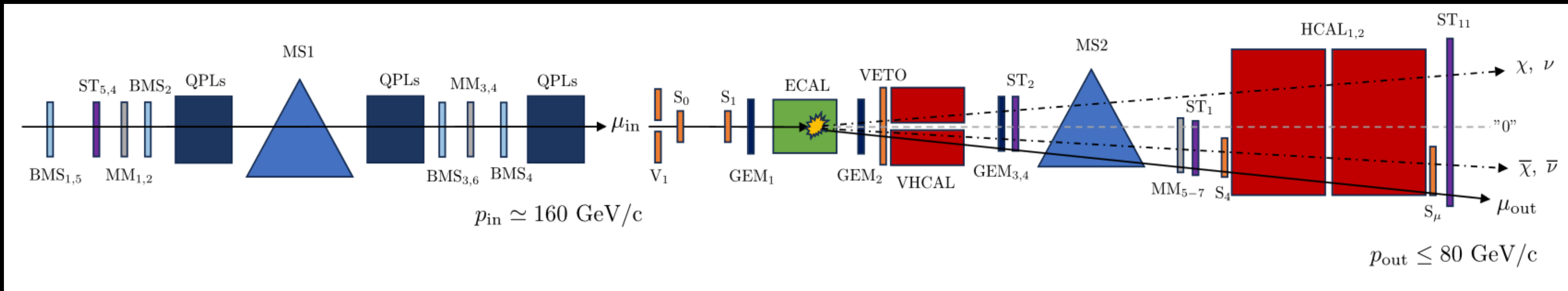
NA64 exclusion limits on B-L Z′ compared with the results of ν - e$^-$ scattering experiments

NA64μ

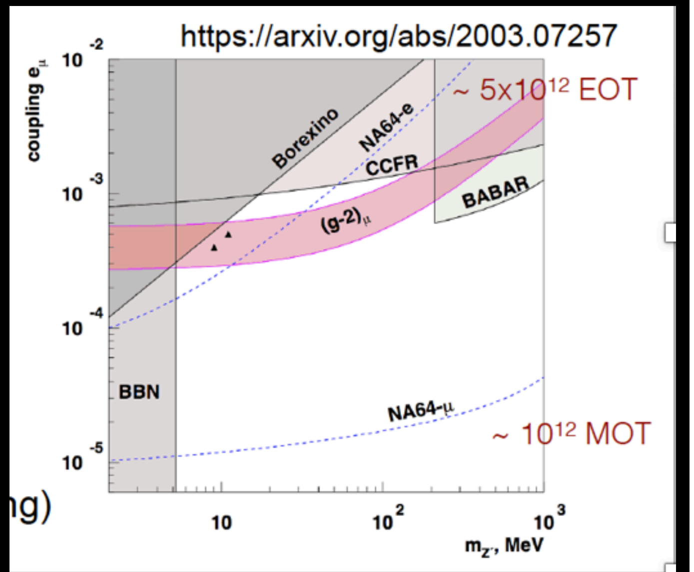
CERN SPS 160 GeV muon beam offers unique opportunities to further search for DS of particles predominantly weakly-coupled to 2nd and 3rd generations of the SM

$$\mu + Z \to \mu + Z + Z_\mu, \; Z_\mu \to \nu\bar{\nu}$$

LDM, high mass A', LFV, new Z'

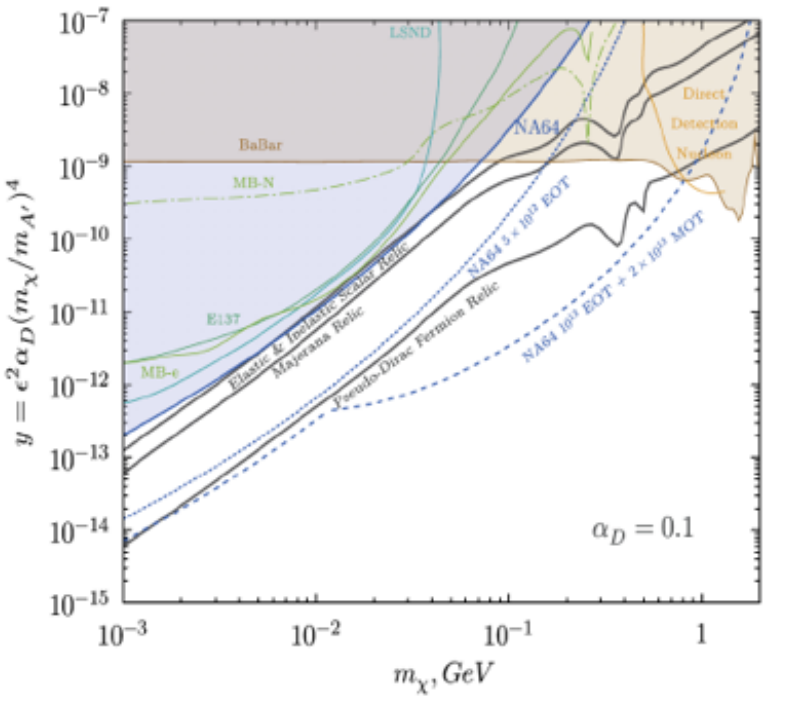


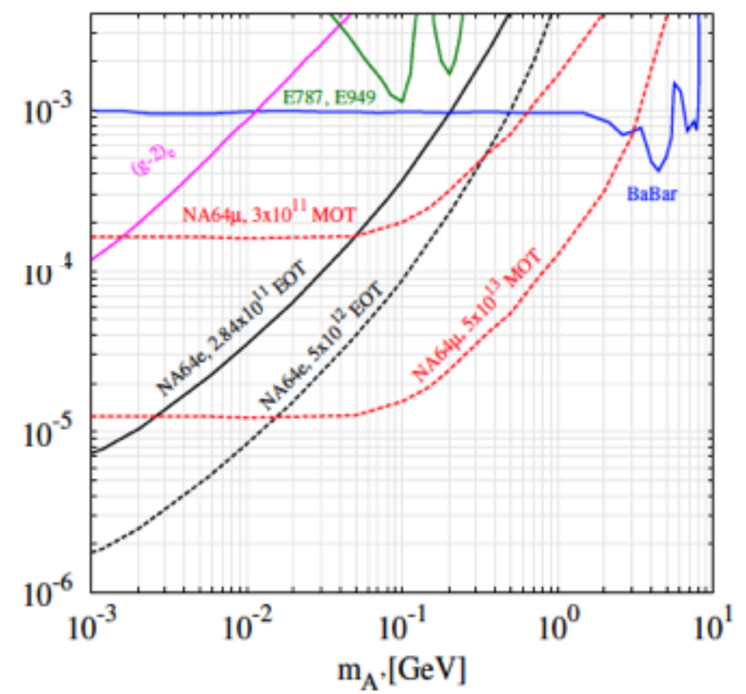
	2022	2023	2024	TOTAL
NA64μ	2.0×10^{10} MOT	1.5×10^{11} MOT	1.5×10^{11} MOT	3.2×10^{11} MOT

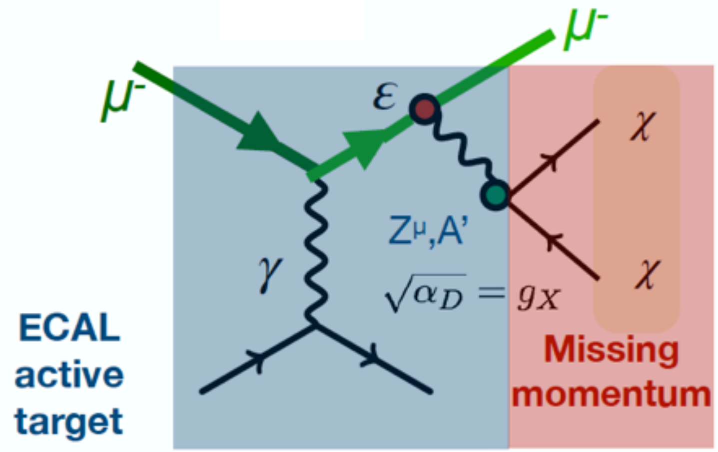


The current limit is not yet competitive compared to the other experiments but demonstrates our capability to probe masses above 100 MeV with higher statistics after LS3.

NA64μ (estimation)

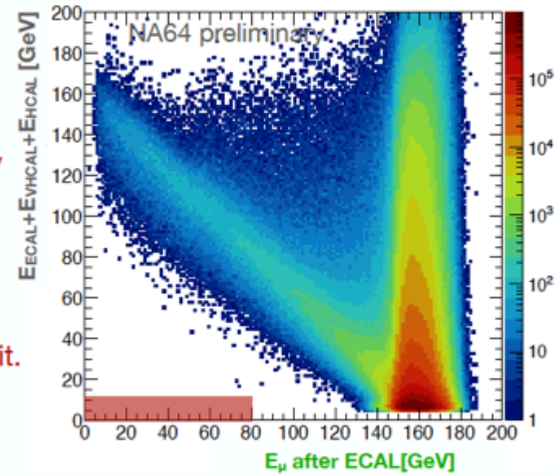






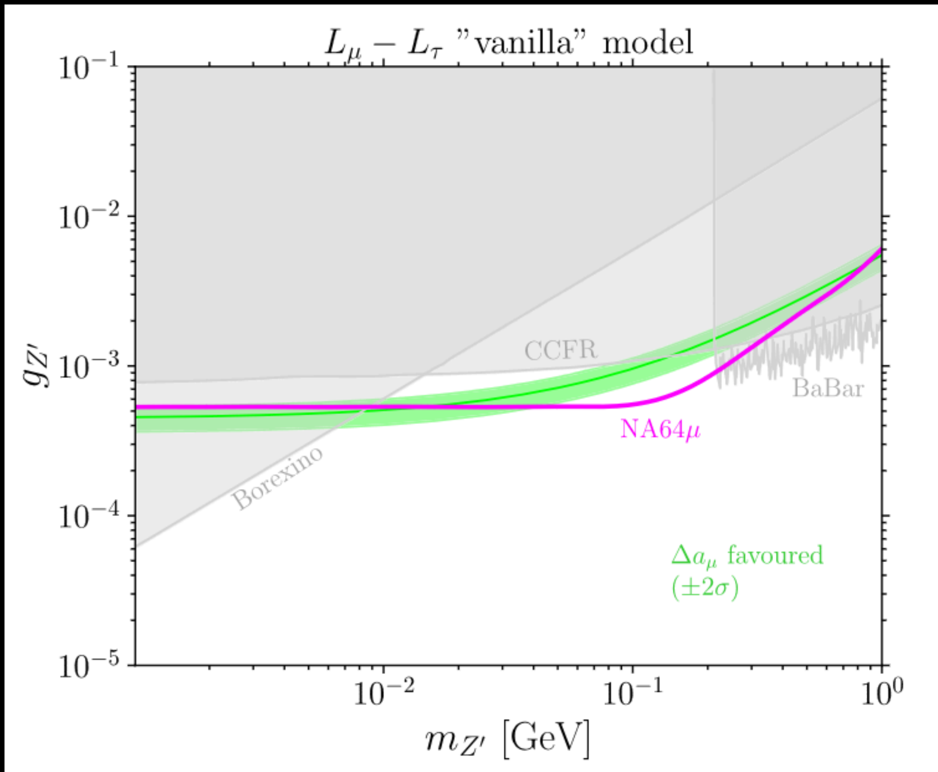
Signature

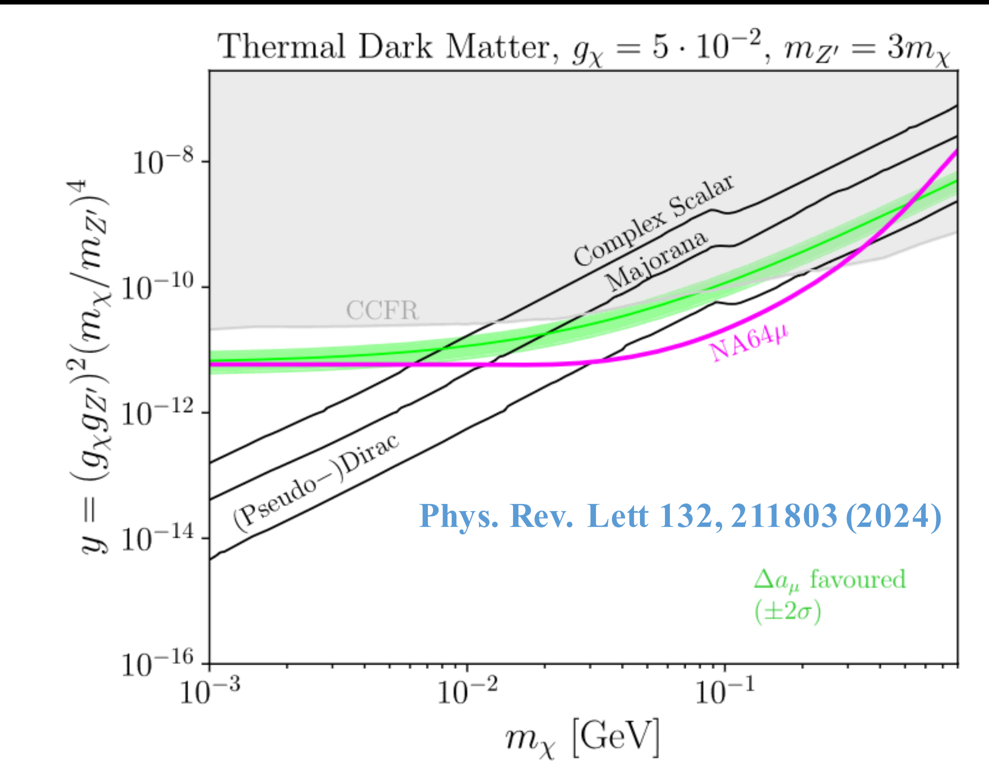
- Missing momentum (Deflected μ- energy <80 GeV).
- Energy on ECAL, VHCAL and HCAL compatible with a muon energy deposit.



Zμ,A' decaying to DM particles

NA64μ (1^{st} results)





Left: NA64μ 90% C.L. exclusion limits on the coupling $g_{Z'}$ as a function of the $m_{Z'}$, for the vanilla $L_\mu - L_\tau$ model. The 2σ band for the Z' contribution to the $(g-2)_\mu$ discrepancy is also shown. Existing constraints from BABAR and from neutrino experiments such as BOREXINO and CCFR are plotted. Right: The 90% C.L. exclusion limits obtained by the NA64μ experiment in the (m_χ, y) parameters space for thermal dark matter charged under $U(1)_{L\mu-L\tau}$ with $m_{Z'} = 3m_\chi$ and the coupling $g_\chi = 5 \times 10^{-2}$ for 2×10^{10} μot.

Current status of data taking

Operation modes: **NA64e**: 40-150 GeV $e^{\pm}$ **NA64μ**: 100-160 GeV μ^{+}

***NA64h**: 50-200 GeV π-, K-, p*

Data taking

2016 – 5 weeks at H4 (NA64e) ~$4,5\text{x}10^{10}$eot,

2017 – 5 weeks at H4 ~$5,5\text{x}10^{10}$eot,

2018 – 6 weeks at H4 ~$2,0\text{x}10^{11}$eot, *2017-18 in visible mode* ~ $8,4\text{x}10^{10}$eot,

2021 – 5 weeks at H4 ~ $5,2\text{x}10^{10}$eot, 3 weeks pilot-run at M2 (NA64μ),

2022–10 weeks at H4 ~ $6,4\text{x}10^{11}$eot, e^{+} ~ $5,0\text{x}10^{10}$eot, 3 weeks at M2 Total ~$4\text{x}10^{10}$μot

2023 – 8 weeks at H4 ~ $5,1\text{x}10^{11}$eot, e^{+} ~ $1,6\text{x}10^{10}$eot, 3 weeks at M2 ~ $1,6\text{x}10^{11}$ μot

2024 – 8 weeks at H4 ~ $5,2\text{x}10^{11}$eot, e^{+} ~ $2,25\text{x}10^{10}$eot (70 GeV) & soon 6 weeks at M2

2025 – 8 weeks at H4 ~ $5,3\text{x}10^{11}$eot, e^{+} ~ $9,25\text{x}10^{9}$eot (40/45 GeV),

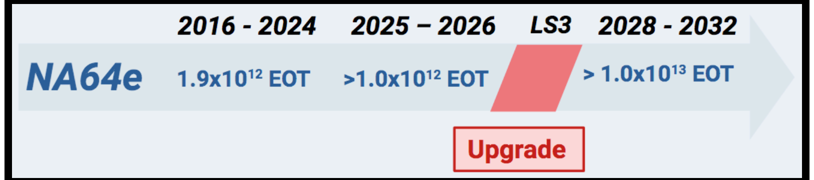
π^{-} ~ $9,5\text{x}10^{9}$eot (50 GeV),

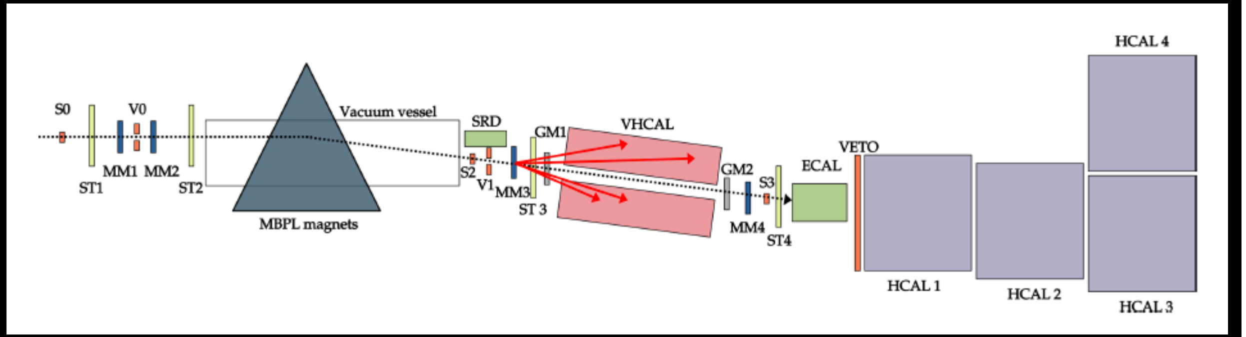
Total accumulated: **~$2,5\ 10^{12}$eot , ~ $10^{11}$$e^{+}$ot** , ~ $2\ 10^{11}$ μot, ~ 10^{10} **πot**

Published: **~10^{12}eot & ~$2\ 10^{10}$ μot**

CONCLUSION

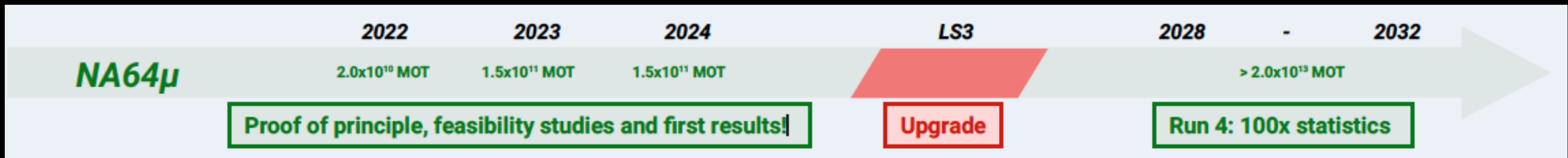
NA64e accumulated **~ 2.5 10^{12} eot;** in 2025, the calorimeters were equipped with new fast ADC electronics (250 MHz/14 bit), and the setup hermeticity was improved by installing an additional veto VHCAL.





Visible mode in 2026?

NA64μ with 160 GeV μ beam aims to search for the L_μ-L_τ Z′; LDM, high mass A′, and $\mu \to \tau$ and $\mu \to e$ LFV processes. We plan to collect **~2** 10^{13} μot .



NA64h – proposal is under preparation

Thank you for attention!