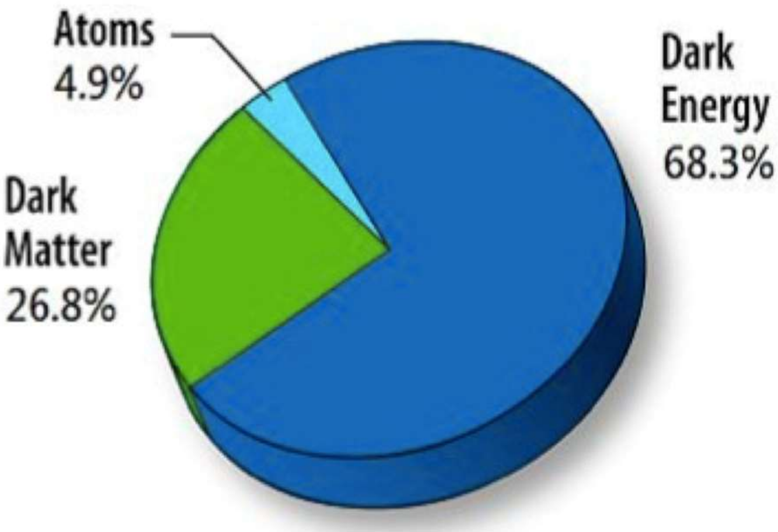
Latest results of the NA64 experiment at CERN
HSFI-2024, Gatchina

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

Dark Matter



Early Universe: **T>>m_χ**

equilibrium in Dark Matter - SM annihilation

Hubble expansion: **T decrease & <m_χ**

annihilation suppesed & stop

Dark Matter (DM) is cold/warm (v < c);

Relic density $\rho_{DM} \sim 10^{-6}$ GeV /cm^3

μeV. keV MeV GeV TeV

Axion sterile ν Thermal Dark Matter WIMP

For WIMPs (χ) **(m_χ, g_χ) ~ (m_{EW}, g_{EW})** - are not seen at LHC and in direct searches.

Complementary proposal:

Dark Matter — Mediator — Standard Model

Observed amount of DM $\mathbf{\Omega_\chi \sim m^2_\chi / g^4_\chi}$

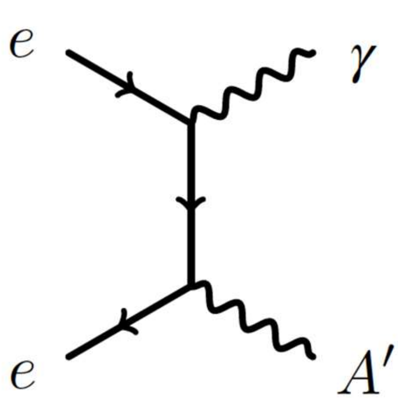
Dark Sector

Thermal freeze-out motivates new interaction to mediate DM-SM annihilation, very promising proposal is an existance of the Dark Sector (DS)

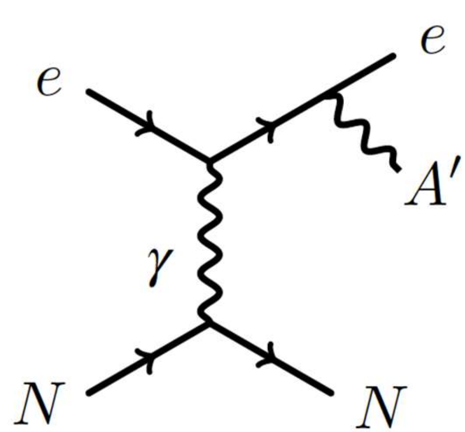
DS charged under new U(1)' gauge symmetry and interacts with the SM through kinetic mixing (ε) of massive vector mediator (A') with photon. DM with mass m_χ is a part of DS

Observed amount of DM $\Omega_\chi \sim m^2_\chi/y$ where $y = \alpha_D\, \varepsilon^2(m_\chi/m_{A'})^4$

A' production



Annihilation



Bremsstrahlung

Dark Photon A’

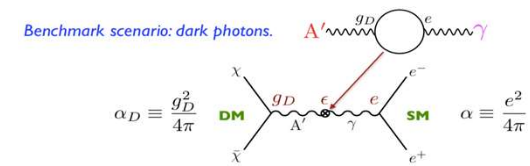
Dark Photon (A´) :

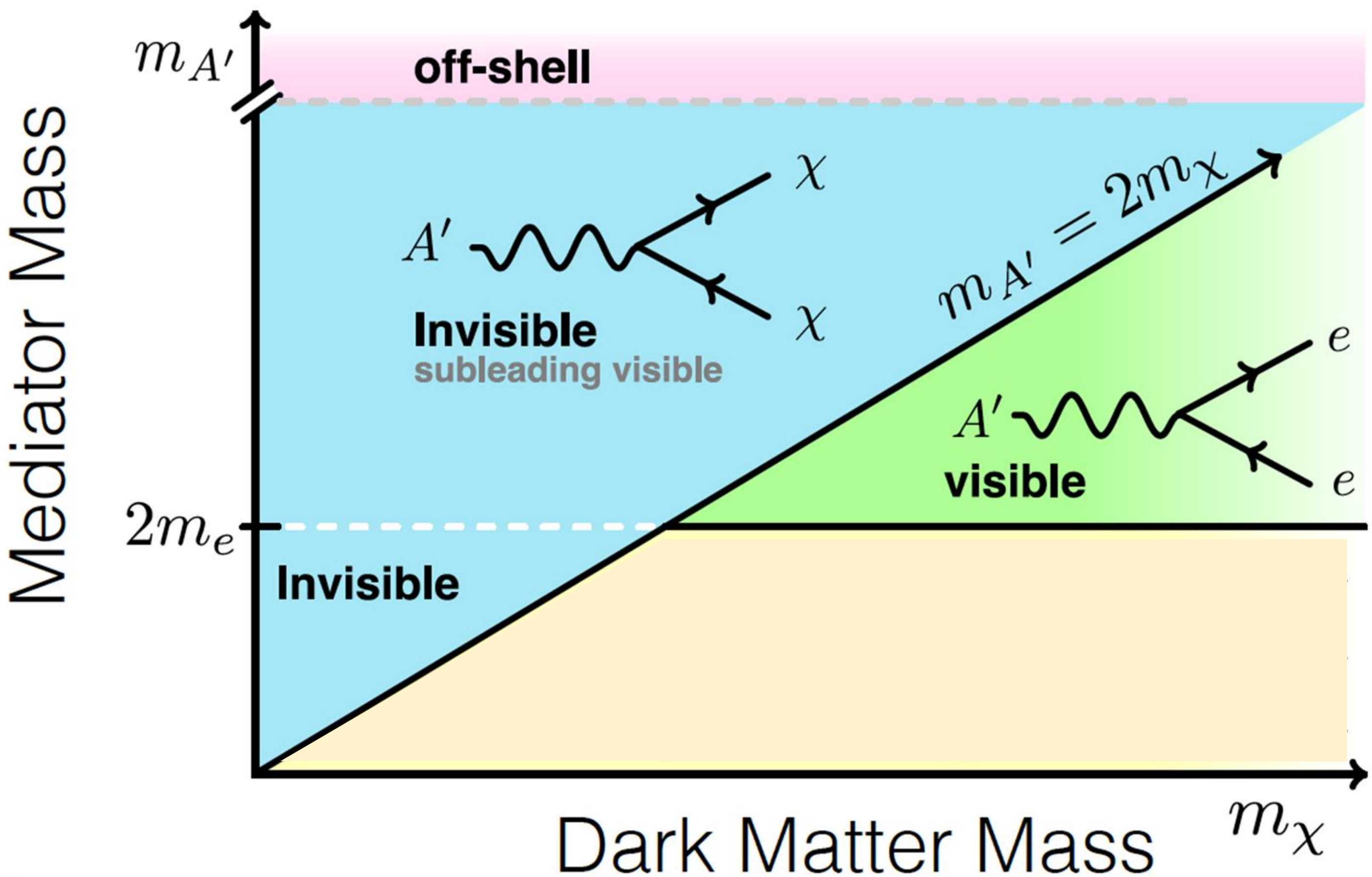
γ−A´ kinetic mixing: $\Delta L = \varepsilon/2\ F^{\mu\nu} A'_{\mu\nu}$

coupling strength ~ εe

$\varepsilon \sim 10^{-5}$ -10^{-2}, $m_{A'} \sim \varepsilon^{1/2} M_Z$

TDM (ε, α_D, m_χ, m_A) parameters can be probed at accelerators

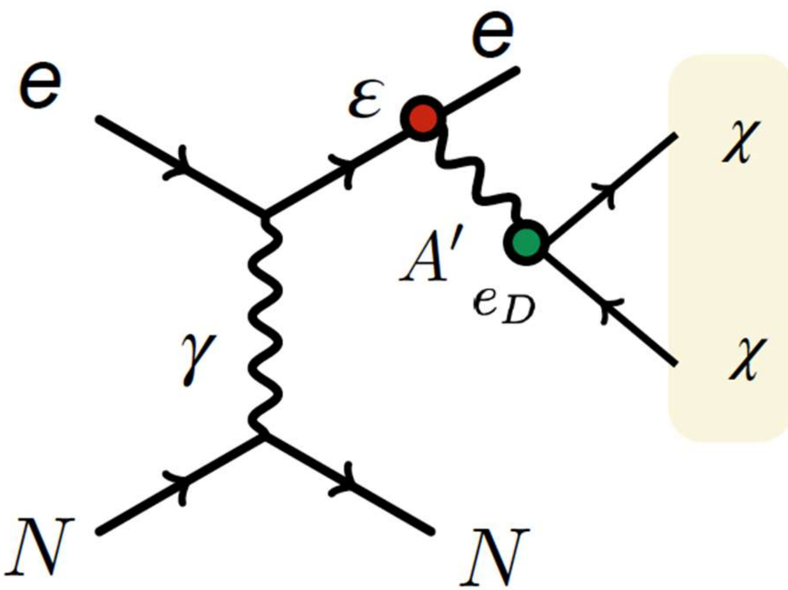


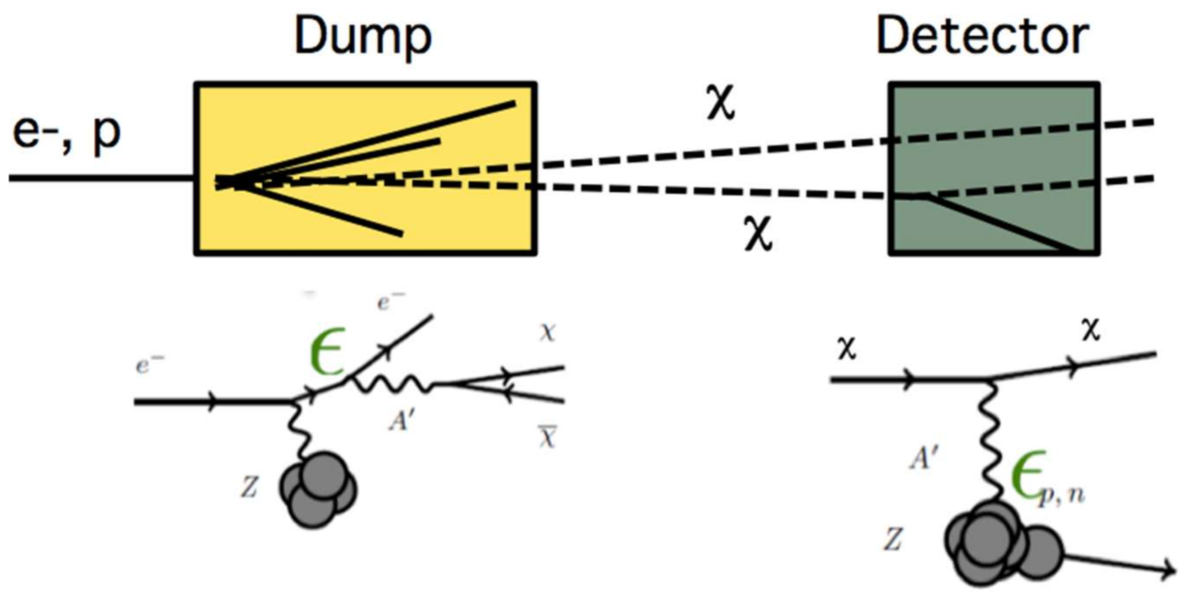


$m_{A'} < 2m_\chi$, $A' \rightarrow e^+e^-$, $\mu^+\mu^-$, .. $m_{A'} > 2m_\chi$, $A' \rightarrow \chi\chi$

Search for DM & DS at accelerator

1. Beam dump approach (MiniBooNE, LSND,…)



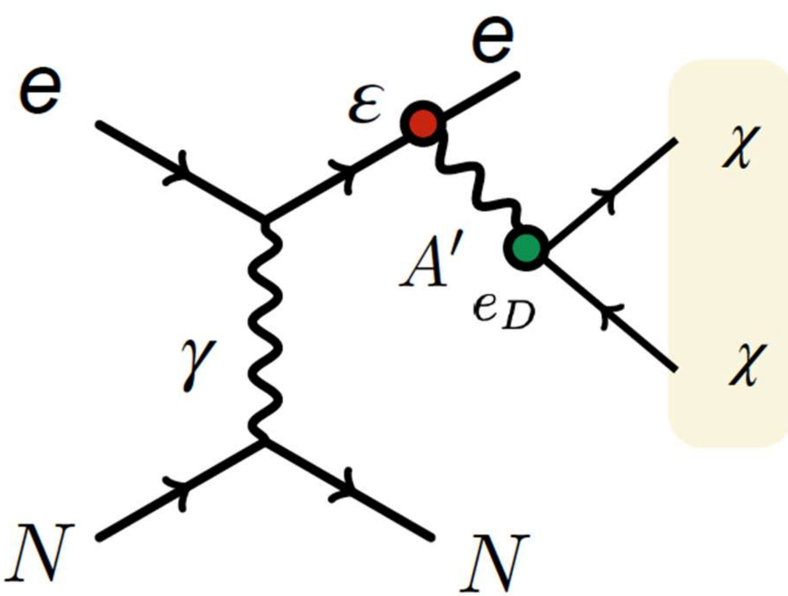


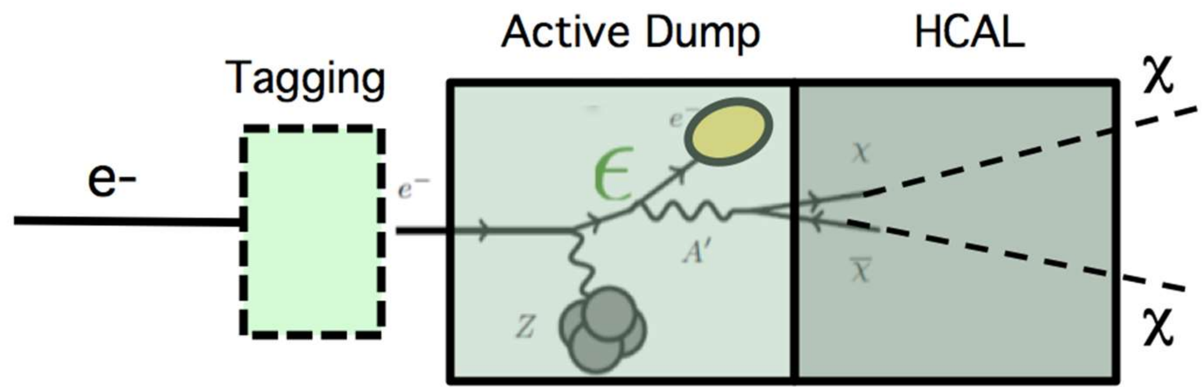
Signal: scattering in far detector DM particles generated by A’ decay

Sensitivity ~ $\alpha_D \varepsilon^4 n_{eot}$

Search for DM & DS at accelerator

2. Active dump approach (NA64)





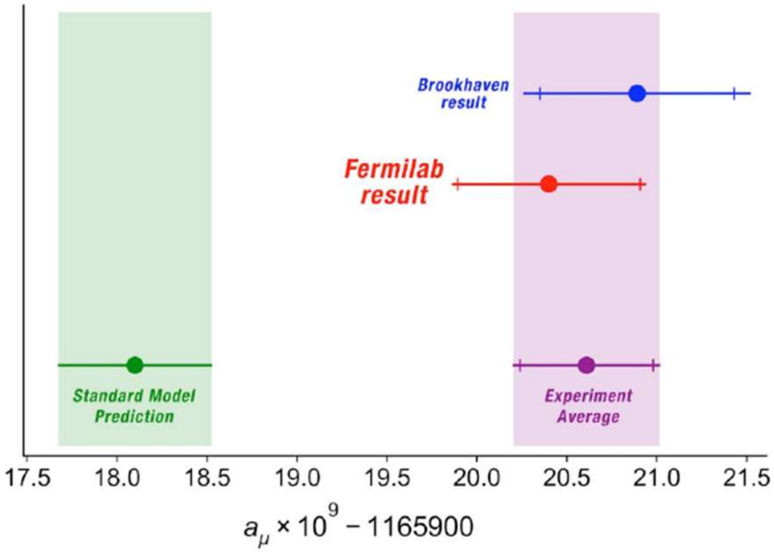
Signal: missing energy
A' pass away from the dump which measures recoil e^- energy

Sensitivity ~ $\alpha_D \varepsilon^2 n_{eot}$

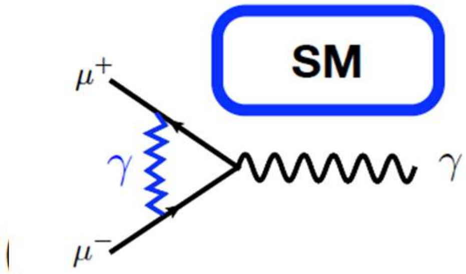
Advantage a factor ~ $1/\varepsilon^2$ (~10^{10})

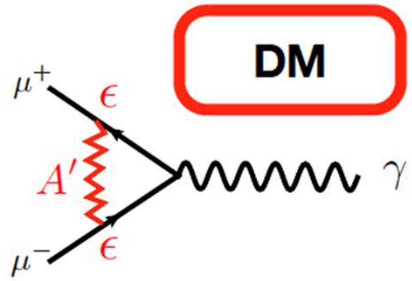
Muon (g-2) : additional motivation to search for A'

B. Abi, et al. Phys. Rev. Lett. 126, 141801 (2021)



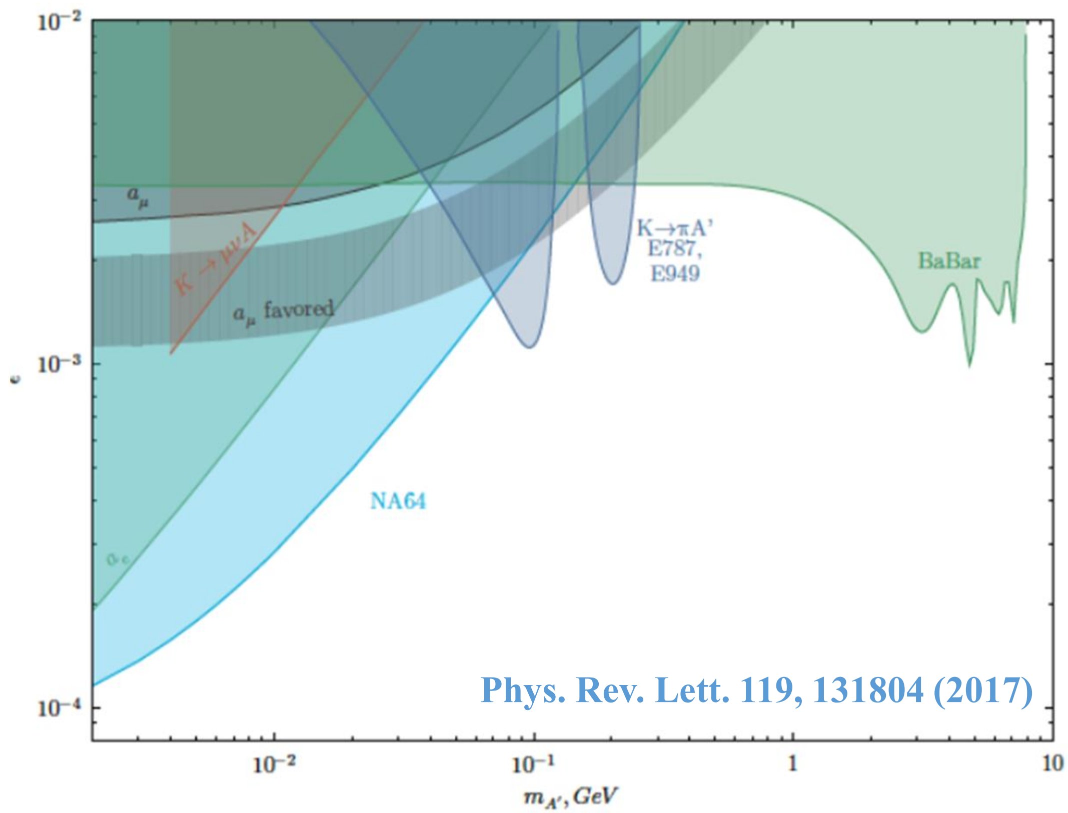
A' may explain observed anomaly





$$(g_s-2)^\gamma_\mu \simeq \frac{\alpha}{2\pi} \simeq 10^{-3}$$

$$(g_s-2)^{A'}_\mu \simeq \frac{\alpha}{2\pi}\times\epsilon^2 \simeq 10^{-3}\times\epsilon^2 \qquad (m_{A'} \ll m_\mu)$$



Phys. Rev. Lett. 119, 131804 (2017)

$(g\text{-}2)_\mu$ completely closed by BARBAR results

NA64 experiment

Proposed in 2014 (P348), first test beam in 2015 (2 weeks), approved by CERN SPSC in March 2016 as NA64 experiment.

NA64 collaboration includes ~60 researchers from 15 Institutions

FSMTU (Chile), IHEP (KI), INR (RAN), ETH(Switzerland), IFIC (Spain), JINR, MSU, MISPHEF (Chile), NRTPU, LIP(RAN), INFN (Genova, Italy), TSPU, UAB (Chile), Bonn Univ. (Germany), York Univ. (Canada)

Research program

1. Thermal sub-GeV (Light) Dark Matter (LDM)
2. ALP, S → $\gamma\gamma$ decays
3. S, P, V and A dark portal particles: invisible, visible and semi-visible decays
4. SM expansion: Light **B-L** Z′ , ..
5. ATOMKI anomaly: X17 (P, V, A′) → e+e- decays

NA64 experiment

Operation modes: **NA64e**: 50-150 GeV $e^{\pm}$ **NA64μ**: 100-160 GeV μ^{+}

__NA64h__: 50-200 GeV π-, K-, p

Data taking

2016 – 5 weeks at H4 (NA64e) ~4,5x10^{10}eot,

2017 – 5 weeks at H4 ~5,5x10^{10}eot,

2018 – 6 weeks at H4 ~2,0x10^{11}eot, *2017-18 in visible mode* ~ 8,4x10^{10}eot,

2021 – 5 weeks at H4 ~ 5,2x10^{10}eot, 3 weeks pilot-run at M2 (NA64μ),

2022–10 weeks at H4 ~ 6,4x10^{11}eot, e^{+} ~ 5,0x10^{10}eot, 3 weeks at M2 Total ~4x10^{10}μot

2023 – 8 weeks at H4 ~ 5,1x10^{11}eot, e^{+} ~ 1,6x10^{10}eot, 3 weeks at M2 ~ 1,6x10^{11} μot

2024 – 8 weeks at H4 ~ 5,2x10^{11}eot, e^{+} ~ 2,25x10^{10}eot (70 GeV) & soon 6 weeks at M2

Total accumulated: **~2 10^{12}eot , ~ 9 $10^{10}$$e^{+}$ot ,** ~ 2 10^{11} μot

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

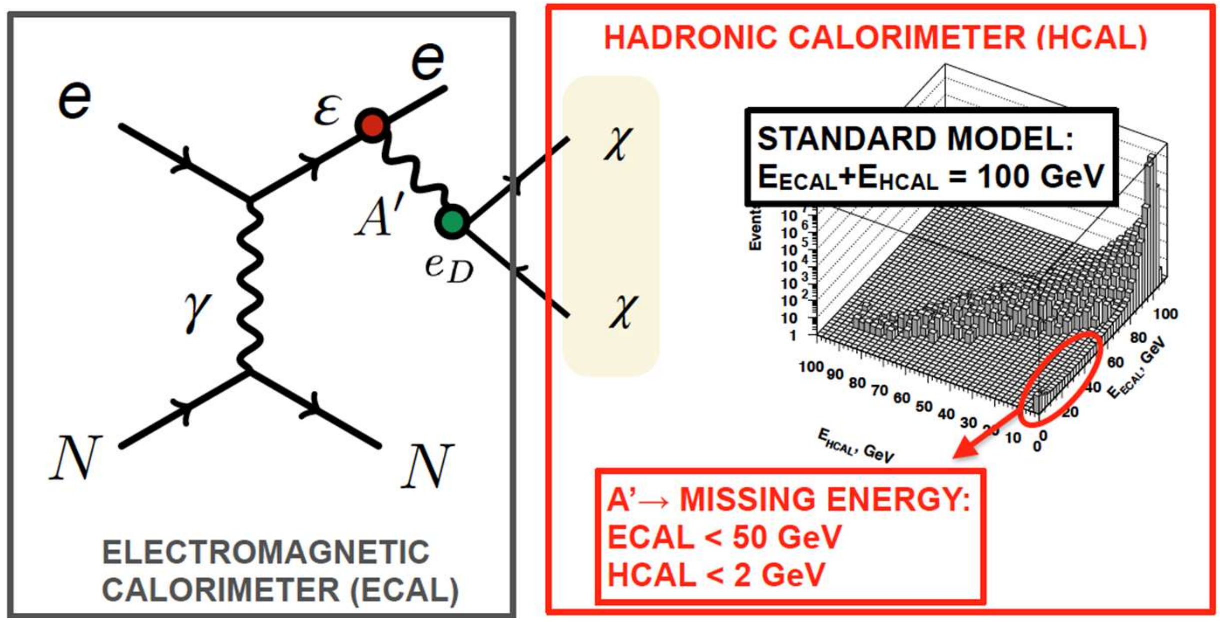
NA64 approach $A' \rightarrow \chi\bar{\chi}$

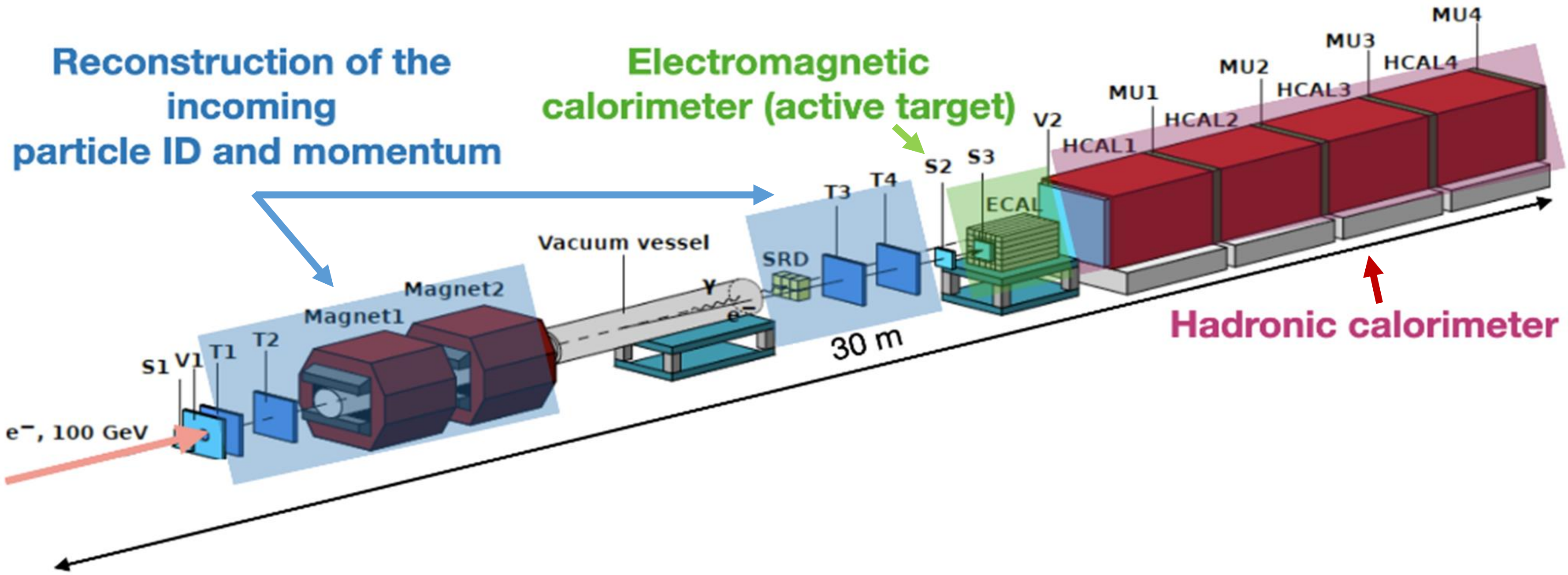
Requirements:

- clean 100 GeV e$^-$ beam
- e$^-$ tag: spectrometer & SRD
- full hermeticity ECAL+HCAL

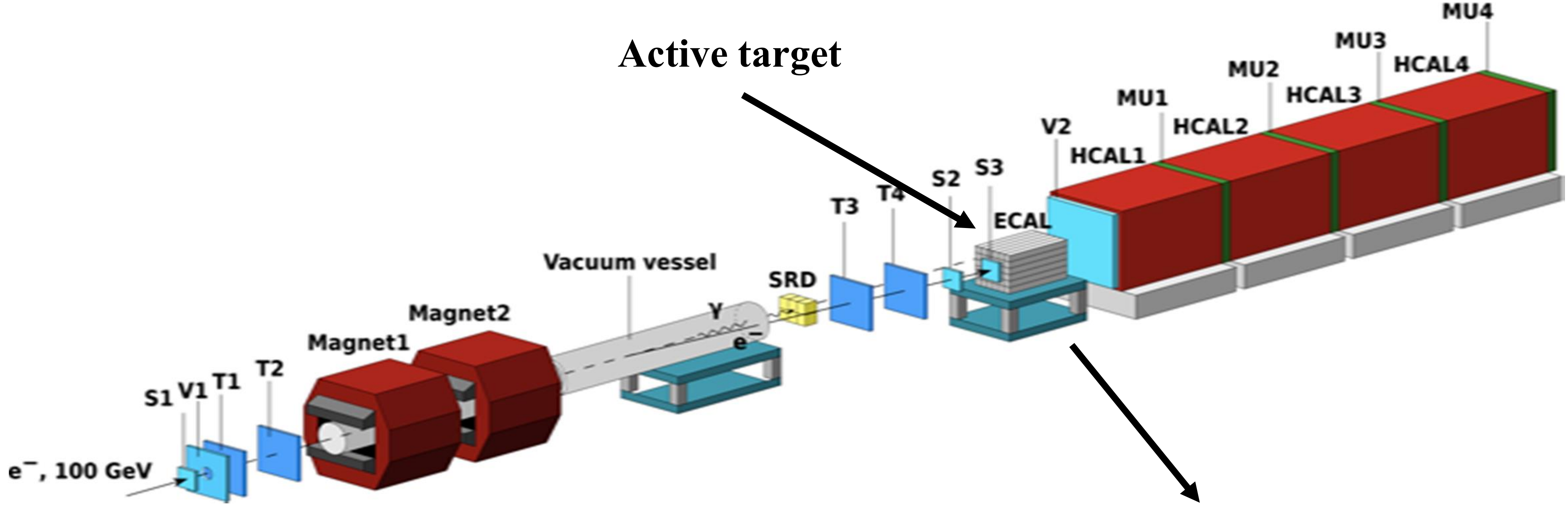
Signature:

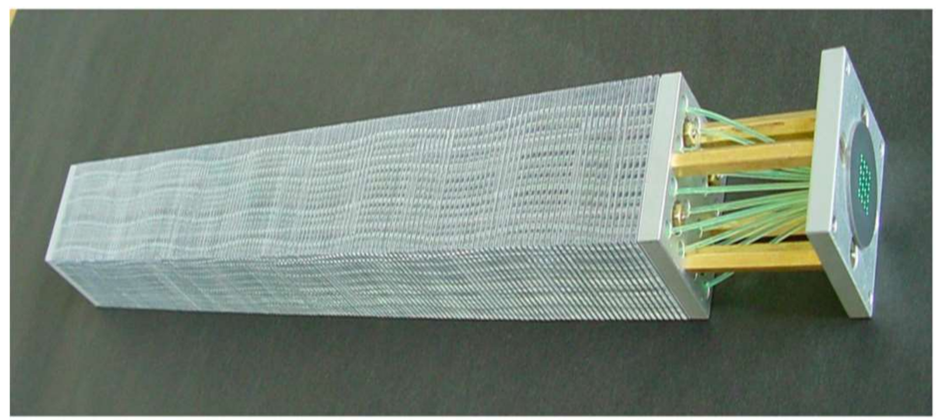
- **in:** 100 GeV e- track
- **out:** $E_{ECAL} < E_0$, shower in ECAL
- no energy in Veto and HCAL





Electromagnetic calorimeter (ECAL)





Shashlik type electromagnetic calorimeter:

Size ~48x20 cm^2, matrix$_{2021\text{->}}$ 12x5 counters,

~24x24 cm^2, matrix$_{2016\text{ - }2018}$ 6x6 counters,

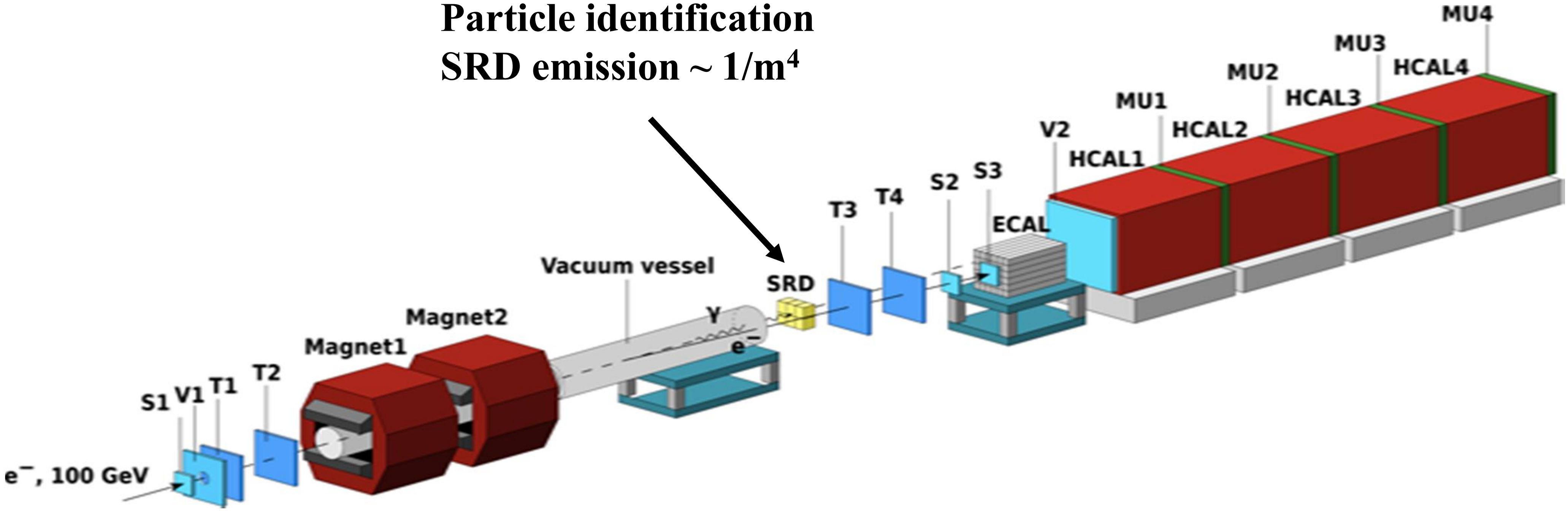
Length ~50cm or 40X$_0$, 150 layers,

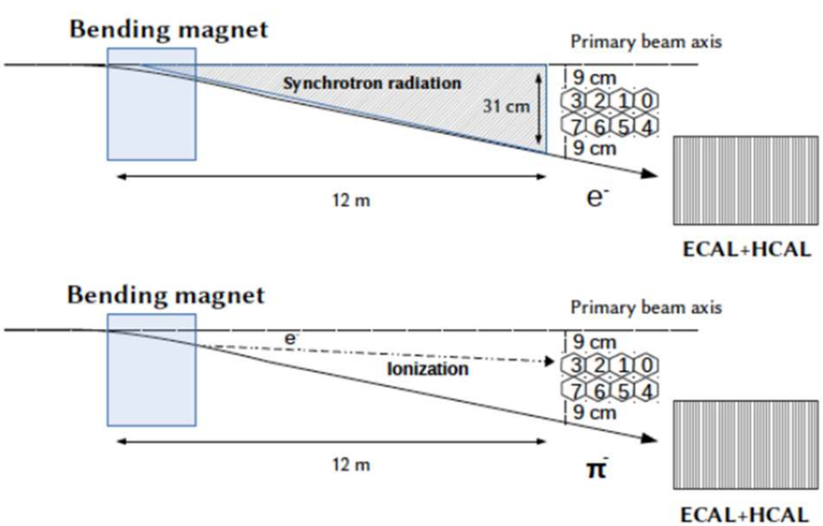
Layers 1.5 mm lead and 1.5 mm scintillator

Readout WLS fibers go in a spiral to avoid energy-leak and dead zones. Hermeticity scan shows no leak.

Synchrotron radiation detector SRD

Particle identification
SRD emission ~ $1/m^4$





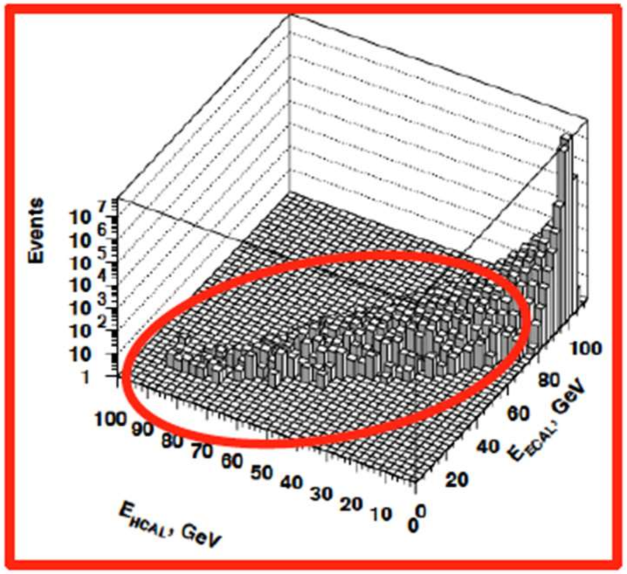
SRD: LYSO crystals 32x48x45 mm3

$\langle E\gamma \rangle \sim$ few MeV, $\langle N\gamma \rangle \sim 30$ γ's,

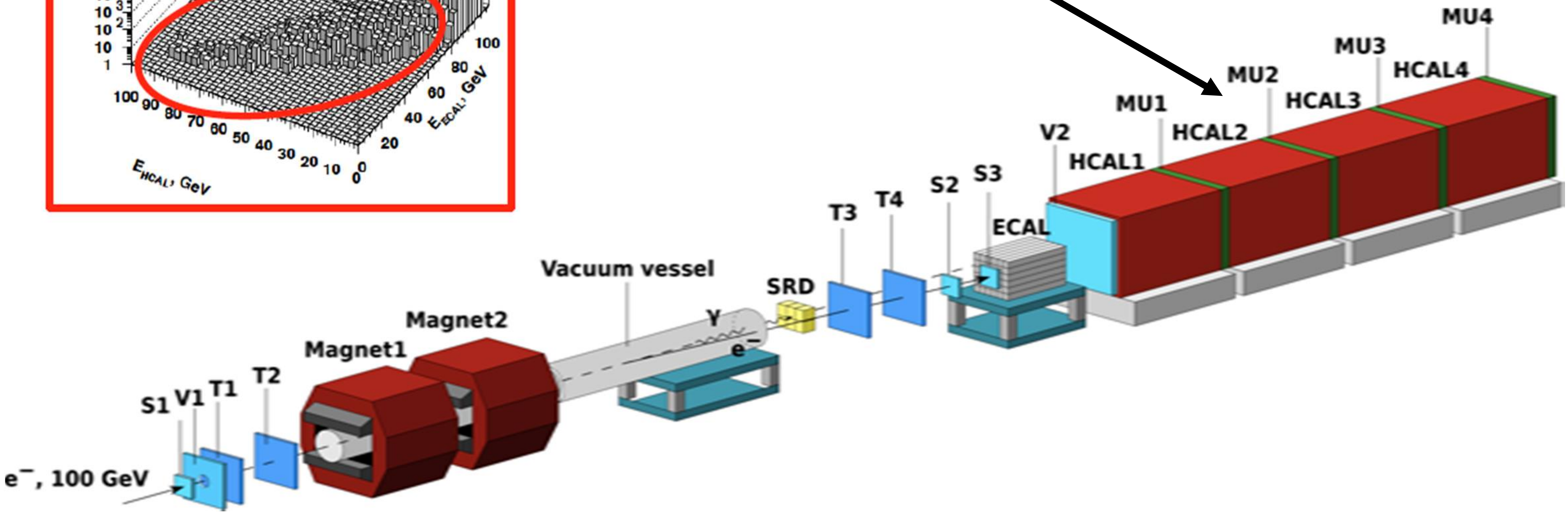
Efficiency $\varepsilon_{SRD} > 0.95$,

$\pi/e \sim 10^{-6}$,

Hadron calorimeter (HCAL)



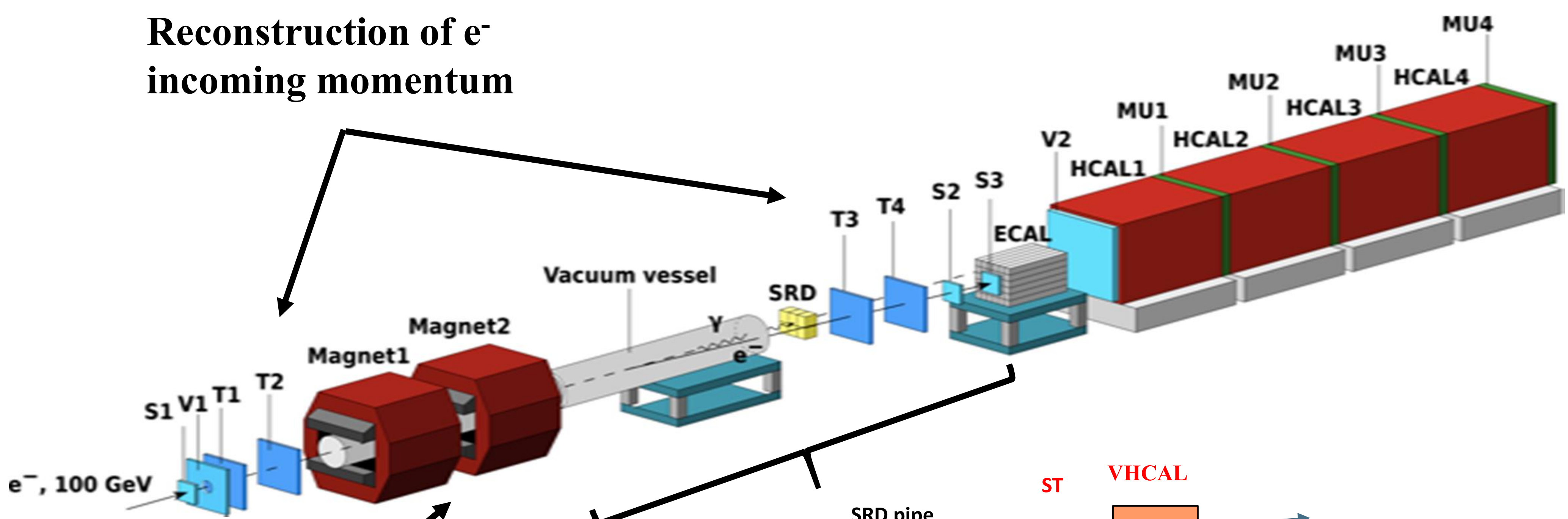
Hermeticity providing

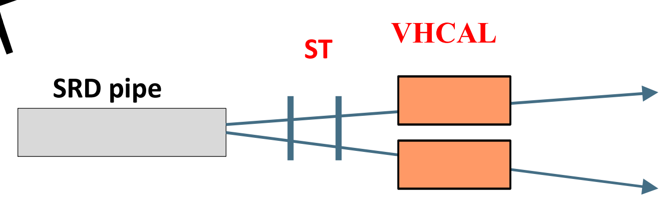


Shashlik type hadron calorimeters:
4 HCALs ~7 λ each,
sandwich: 48 x (25mm Fe + 4 mm Sc),
matrix 3x3, ~19x19x150 cm^3,
Energy resolution ~ $60\%/\sqrt{E[GeV]}$

Magnetic spectrometer

Reconstruction of e⁻ incoming momentum





Bending dipoles

Tracking system:

$S_{0\text{-}3}$ beam counters,1 mm Sc hodoscopes, e^-_{beam} tagging, T_0

XY Micromegas $MM_{1\text{-}4}$,

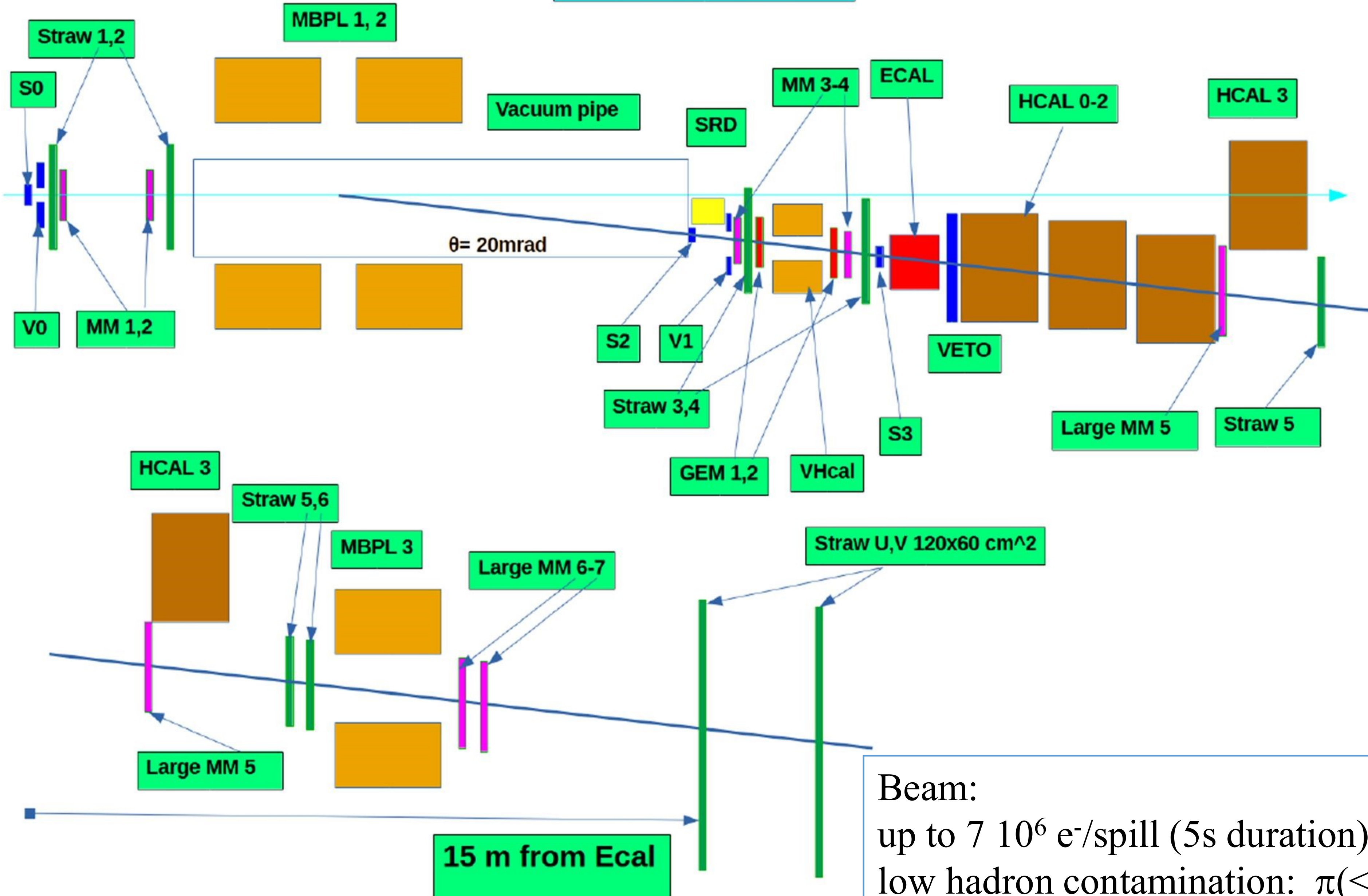
XY Straw tube stations $ST_{1\text{-}4}$,

$GEM_{1\text{-}2}$

Background due to the insufficient detector hermeticity against charged and neutral hadrons produced in electron beam interactions in the beam material at large angles. Suppressed for charged secondary by using Straw Tubes as a veto, for neutral - VHCAL

Experimental setup

2024 setup

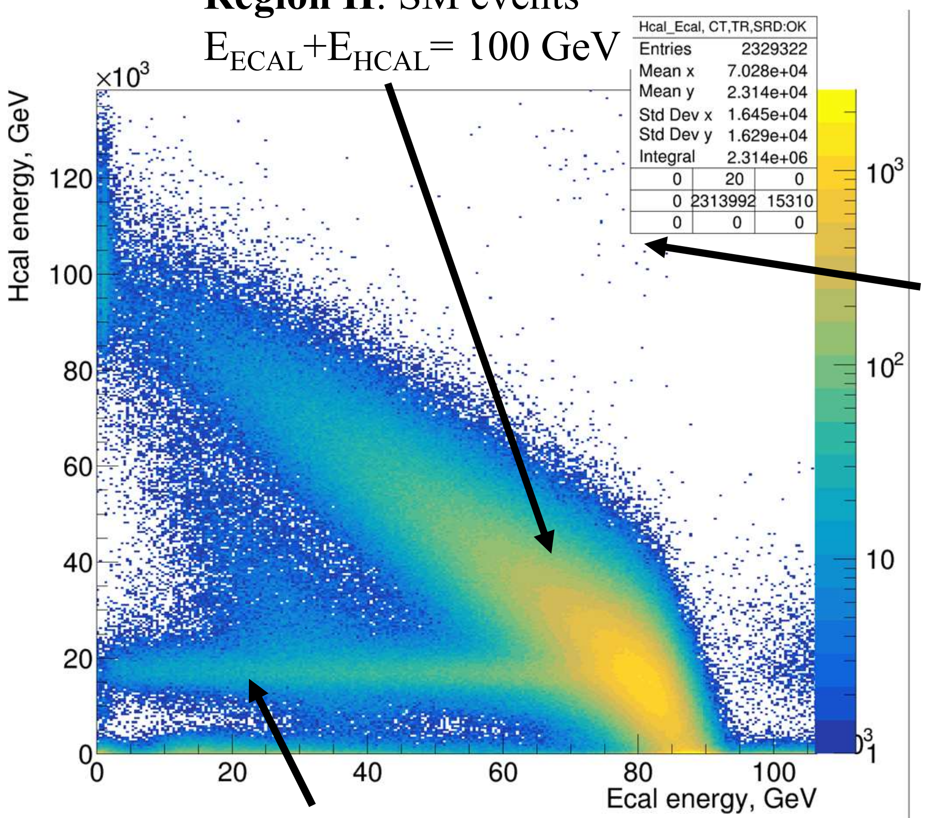


Beam:
up to 7 10^6 e^-/spill (5s duration)
low hadron contamination: π(<1%)
μ/K(<.1%)
low energy tails (<1%)

Experimental setup

Online analysis (2024 data $2.3\ 10^{10}$eot)

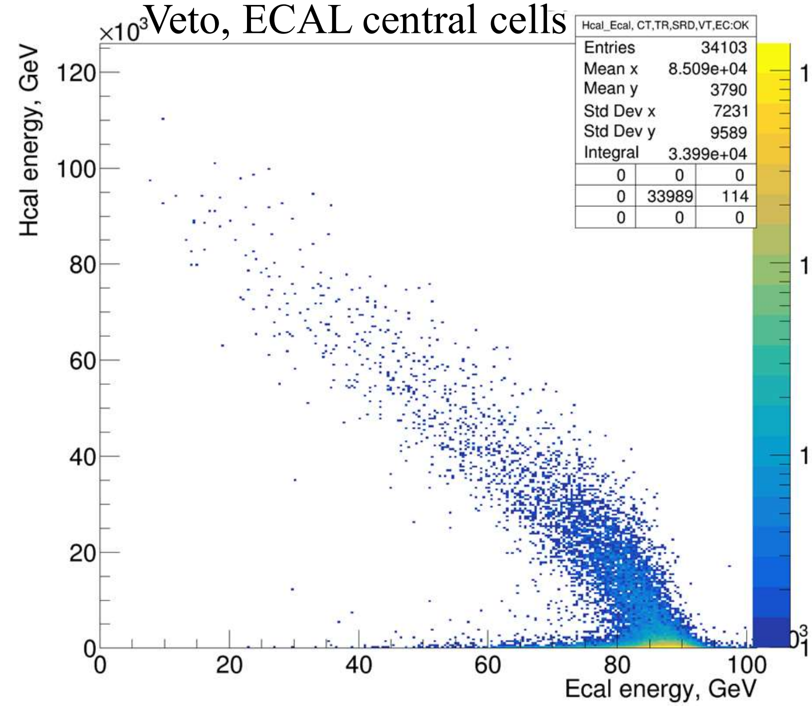
Region II: SM events
$E_{ECAL}+E_{HCAL}$= 100 GeV



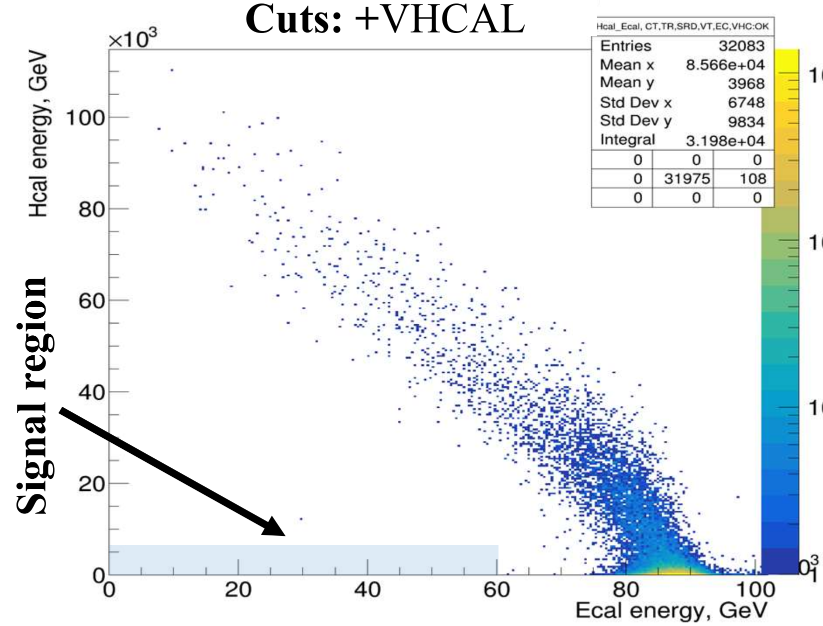
Region III: pile up events

Region I: $e^-Z \rightarrow e^-Z\gamma$; $\gamma \rightarrow \mu^+\mu^- \rightarrow$ benchmark for MC

Cuts: Time window, SRD, Veto, ECAL central cells



Cuts: +VHCAL



Selection criteria:

-Timing (pile up suppression)

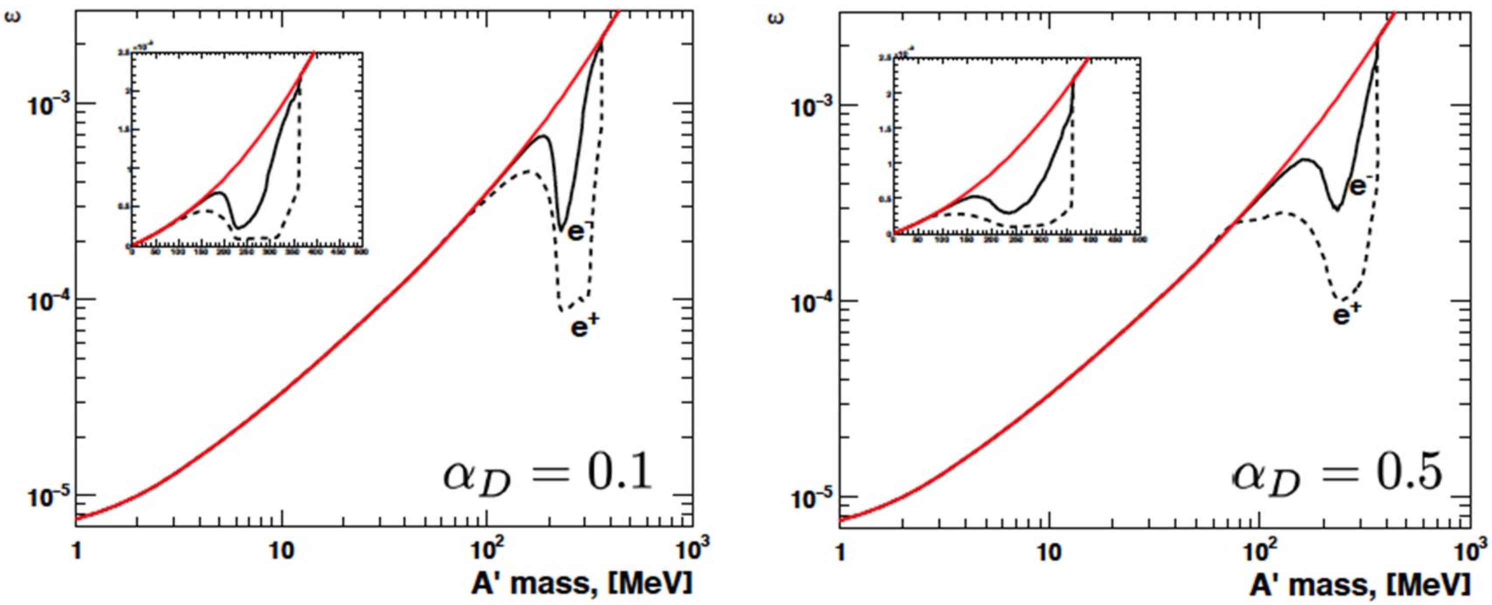
-Clean e^- track (sigle hit, correct angle and momentum)

-Synchrotron radiation signal

-Shower in ECAL compatible with e^-

-No activity in Veto

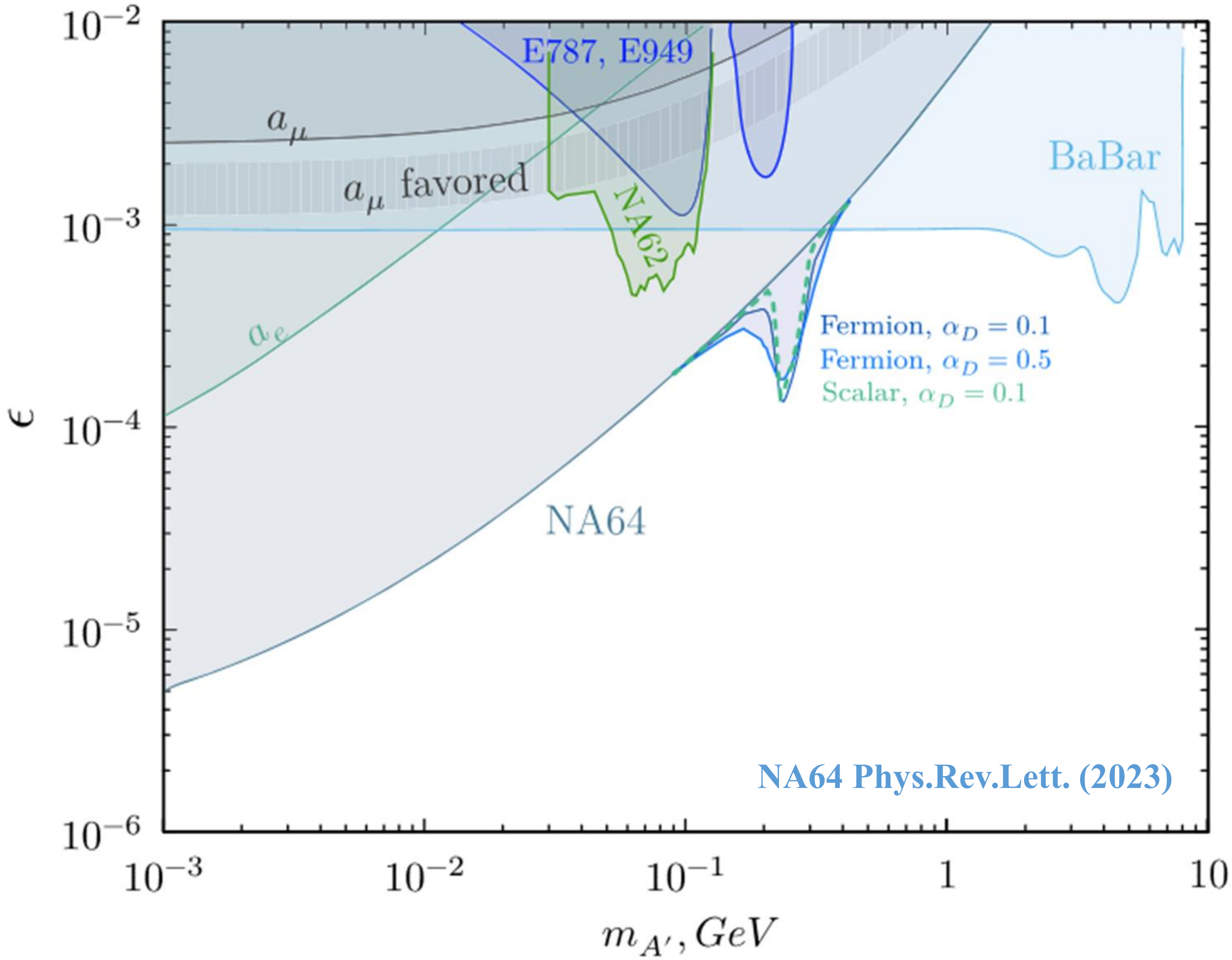
NA64 search with positron beam



Project NA64e^+
Search for A' with 100 GeV positron beam
For $m_{A'}$ ~ 200-300 MeV a factor **~10** improvement for ε
Enhancement **~10²** for **y**~ ε^2

Plans to cover $m_{A'} \leq m_\mu$ area with ~ a few 10^{12} eot
Challenge: high mass region $m_{A'} \geq m_\mu$, as cross-section ~ $(1/m_{A'})^2$
Ways out: i) resonance A′ production (NA64$_e{}^+$), and
ii) high-energy muon beam (NA64$_\mu$)

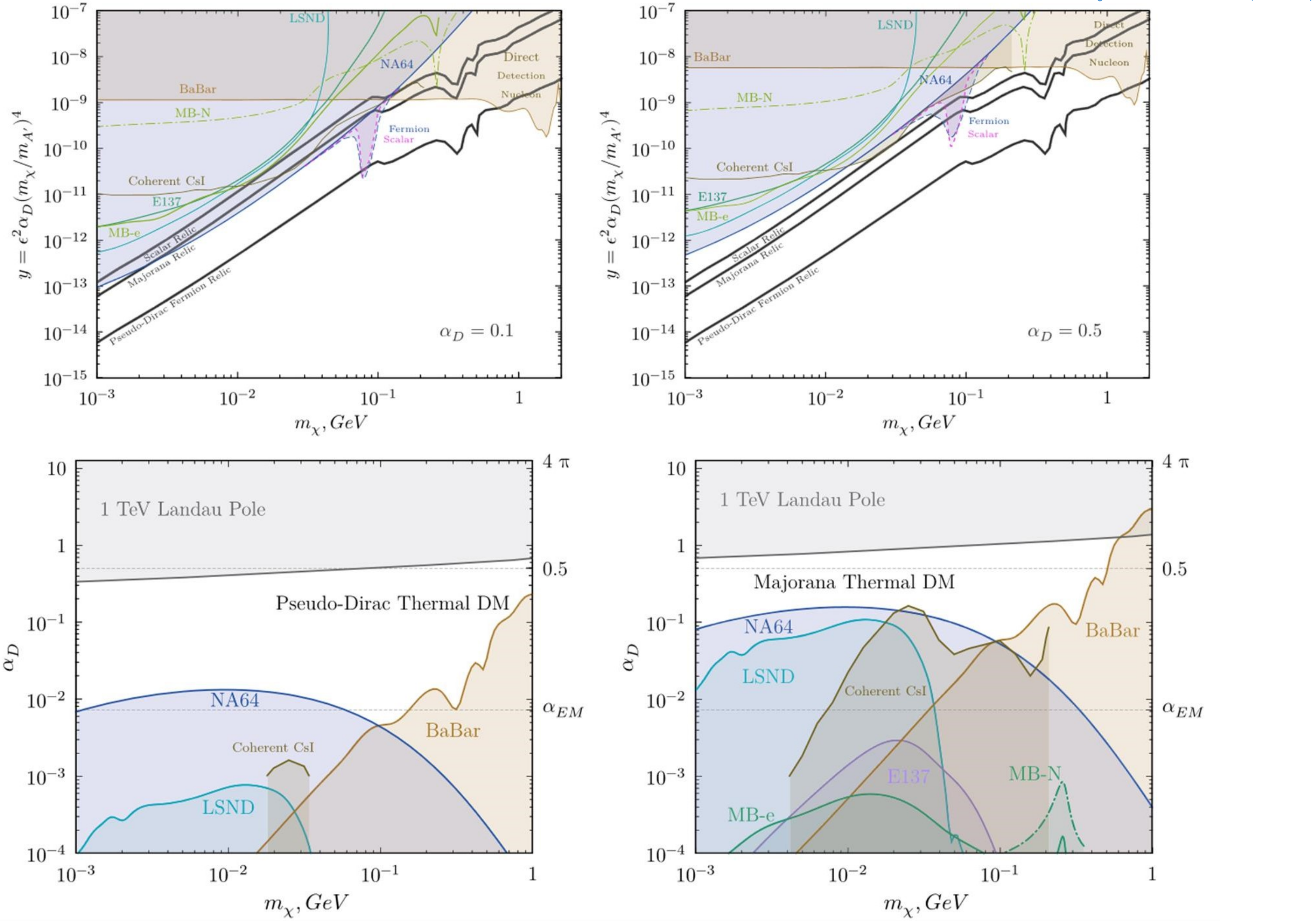
Search for Light Dark Matter with NA64



The NA64 90% C.L. exclusion region in the ($m_{A'}$,ϵ) plane. Constraints from the E787 and E949, BABAR and NA62 experiments, from the consideration of the anomalous magnetic moment of electron α_e, as well as the favored area explaining the α_μ anomaly with the A' contribution are also shown.

Search for Light Dark Matter with NA64

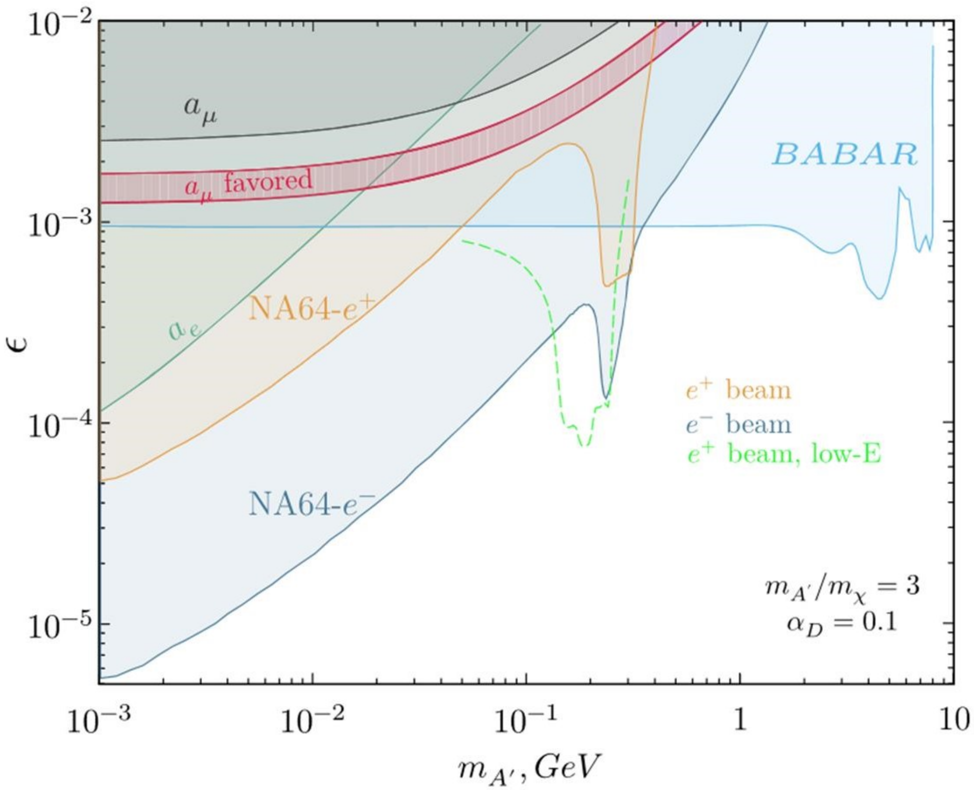
NA64 Phys.Rev.Lett. (2023)

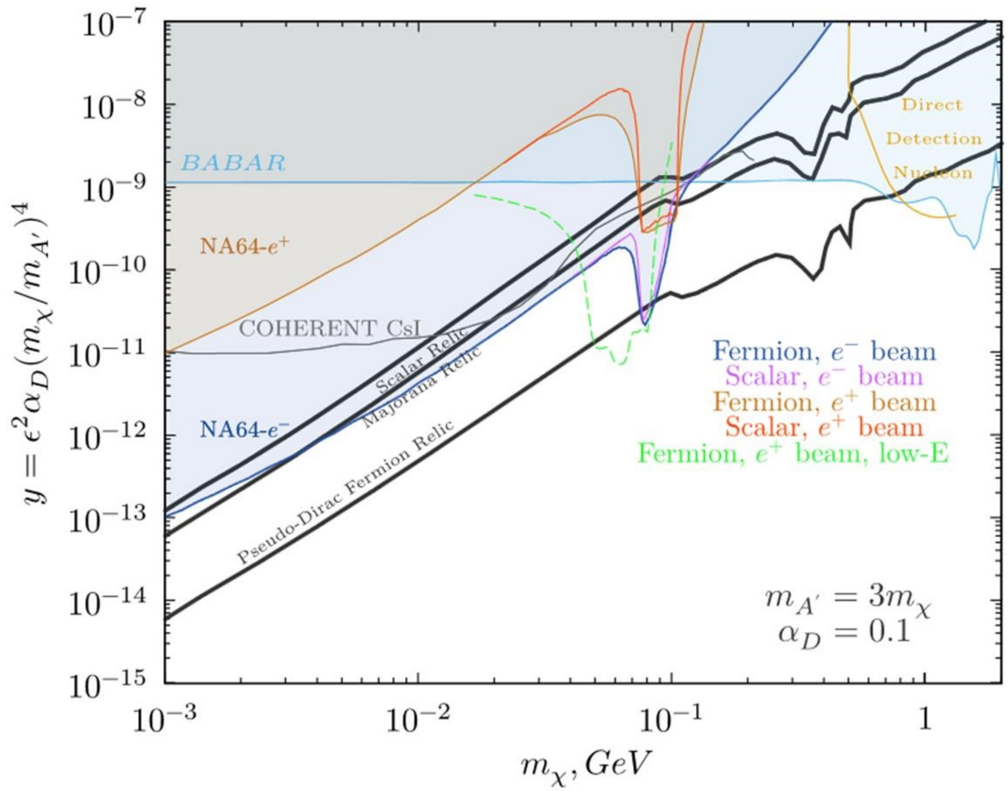


The top row shows the NA64 limits in the (y,m_χ) plane obtained for $\alpha_D = 0.1$(left) and $\alpha_D = 0.5$(right) assuming $m_{A'} = 3m_\chi$, from the full 2016–2022 dataset. The bottom row shows the NA64 constraints in the (α_D,m_χ) plane on the pseudo-Dirac(left) and Majorana(right) DM.

Search for Light Dark Matter with NA64

Phys. Rev. D (2024)

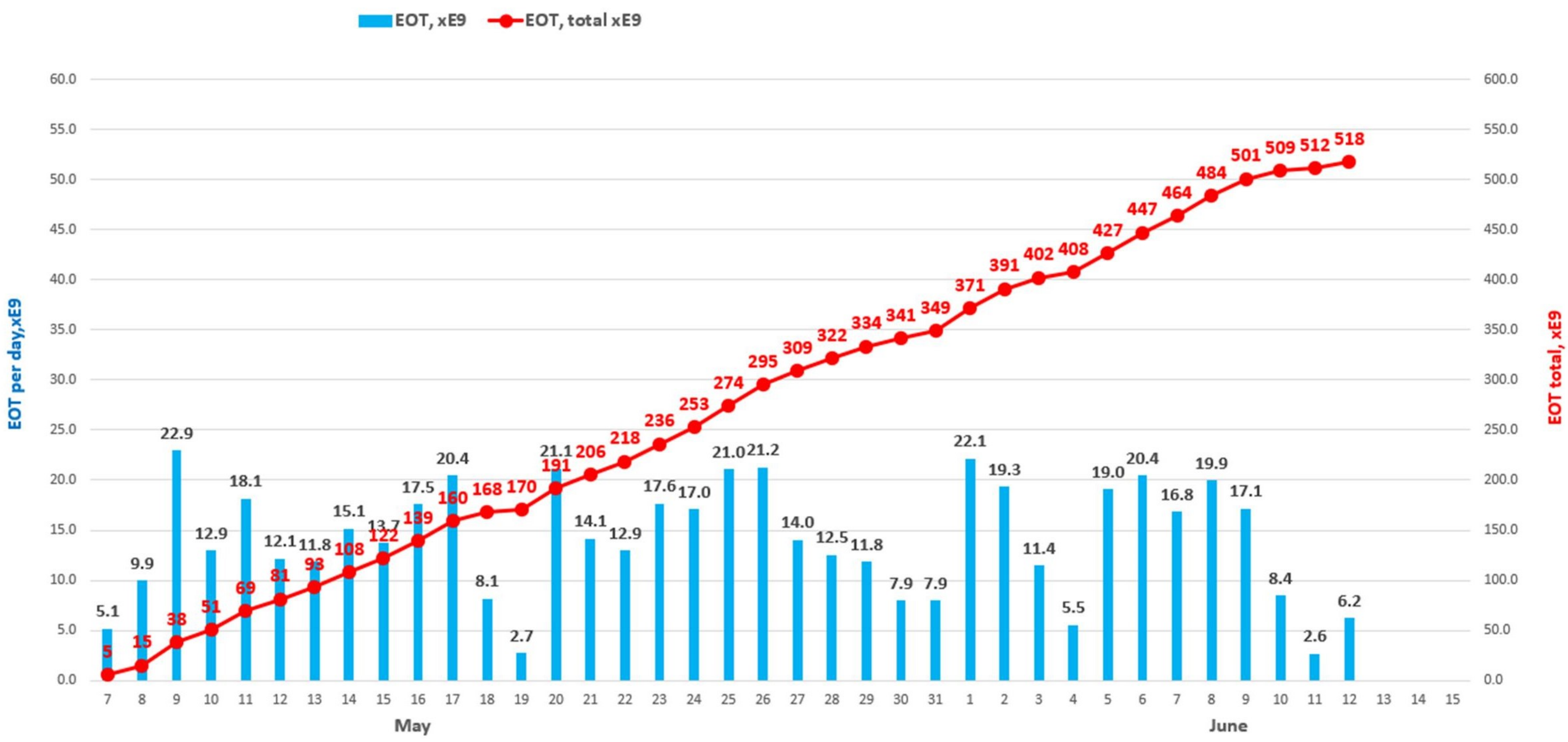




New exclusion limits from the e^+ beam, missing energy measurement presented in the ε vs $m_{A'}$ space, considering fermionic LDM for $\alpha_D = 0.1$. The most stringent LDM exclusion limits from BABAR and NA64 in e^- beam mode are also shown, as well as the favored area from the muon g − 2 anomaly (red lines). The green dashed lines reports the sensitivity for a future positron-beam effort at lower energy

The new NA64 e^+ beam exclusion limit in the (m_χ, y) plane, for $\alpha_D = 0.1$.
The black lines show the favored parameter combinations for the observed DM relic density for different model variations.

NA64e 2024 data taking



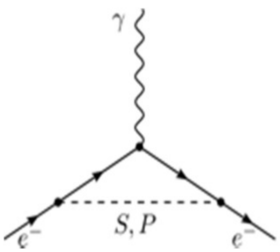
Search for new X boson and $(g\text{-}2)_e$

$e^- Z \rightarrow e^- Z X$; $X \rightarrow$ *invisible*
X: scalar (S), pseudoscalar (P), vector(V), axial (A)
$e^- X$: interaction with coupling strengh $g_X = \varepsilon_X e$

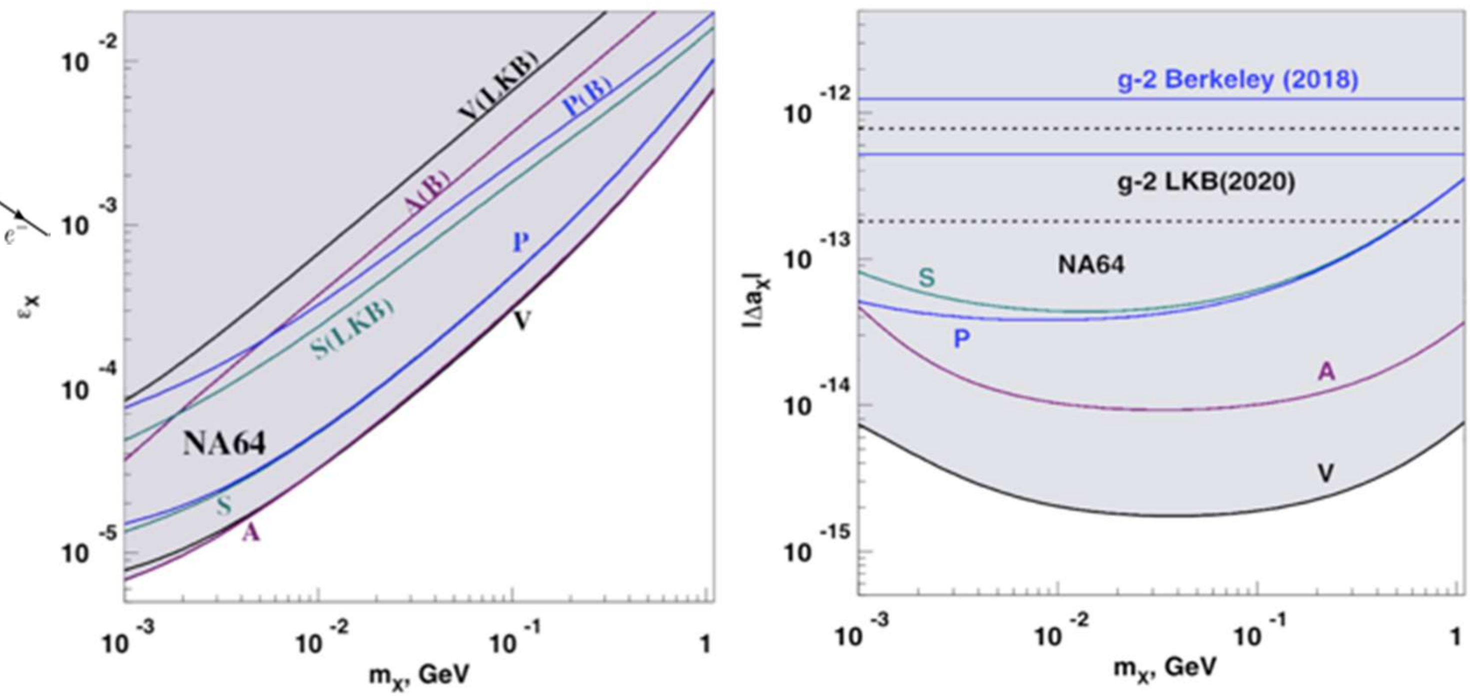
$$\mathcal{L}_S = g_S \bar{e} e S$$
$$\mathcal{L}_P = i g_P \bar{e} \gamma_5 e P$$
$$\mathcal{L}_V = g_V \bar{e} \gamma_\mu e V_\mu$$
$$\mathcal{L}_A = g_A \bar{e} \gamma_\mu \gamma_5 e A_\mu$$

$$\Delta a_e = a_e^{exp} - a_e^{LKB} = (4.8 \pm 3.0) \times 10^{-13} \quad (1)$$
$$\Delta a_e = a_e^{exp} - a_e^{B} = (-8.8 \pm 3.6) \times 10^{-13} \quad (2)$$

LKB(^{87}Rb) 5σ difference with Berkley(^{137}Cs)
$\alpha^{-1} = 137.035999296(11)$

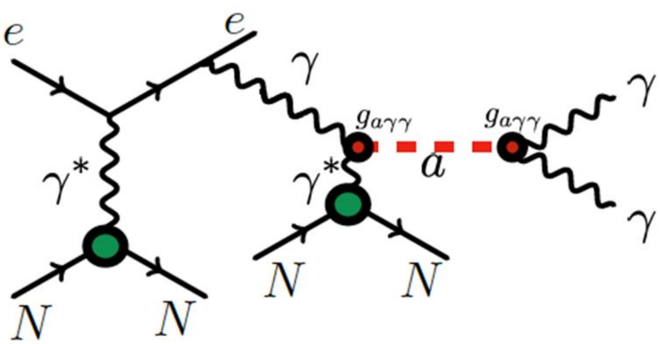


Dark $X = S, P, V,$ or A NA64,Phys.Rev.Lett.(2021)



NA64 provided most stringent constraints on new physics contribution $\Delta a_X < 10^{-15} - 10^{-13}$ for $X = S, P, V,$ or A compared to LKB and Berkley high-precision measurements

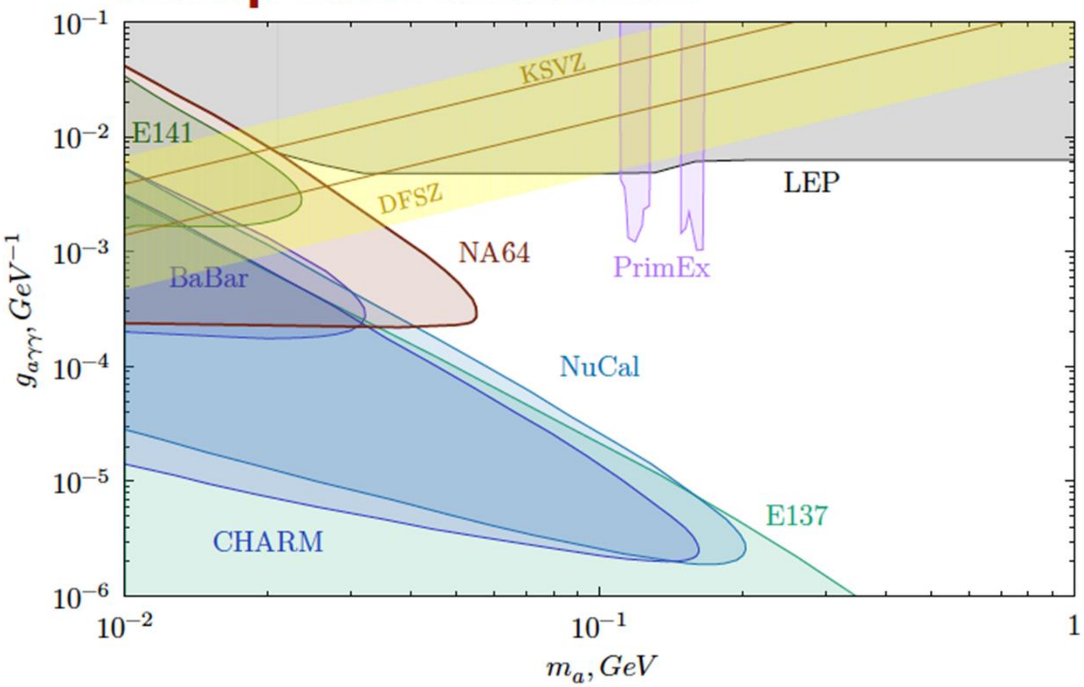
Search for ALP

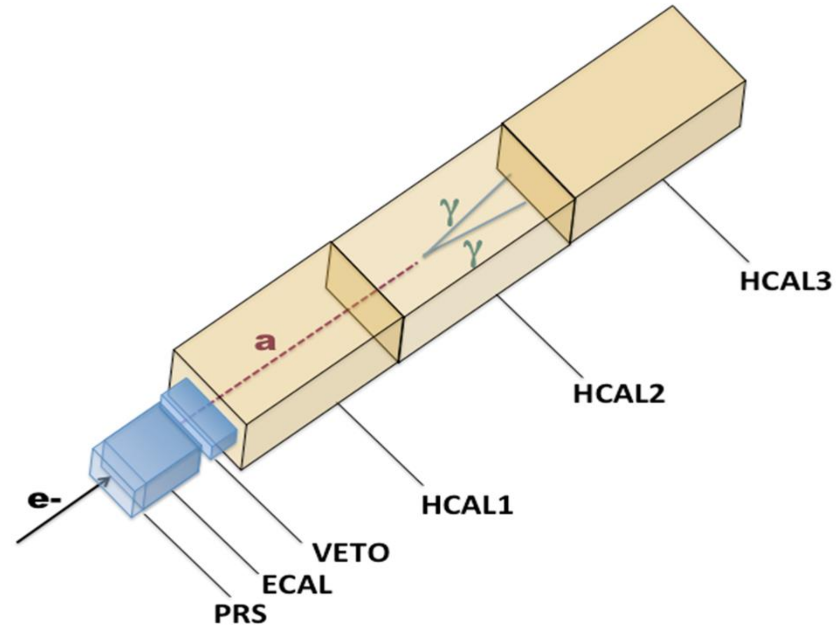


Production via Primakoff effect

$$e^- Z \to e^- Z\gamma; \gamma Z \to aZ; a \to \gamma\gamma$$

Closing the gap between beam dump and colliders





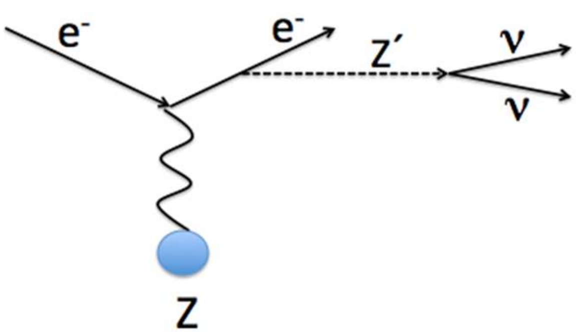
Signature:

- 100 GeV e- track
- $E_{ECAL} < E_0$ shower in ECAL
- no activity in Veto and HCAL1
- e-m like energy in HCAL2+HCAL3

Main background – punch through neutral secondaries (n,$K^0_{S,L}$)

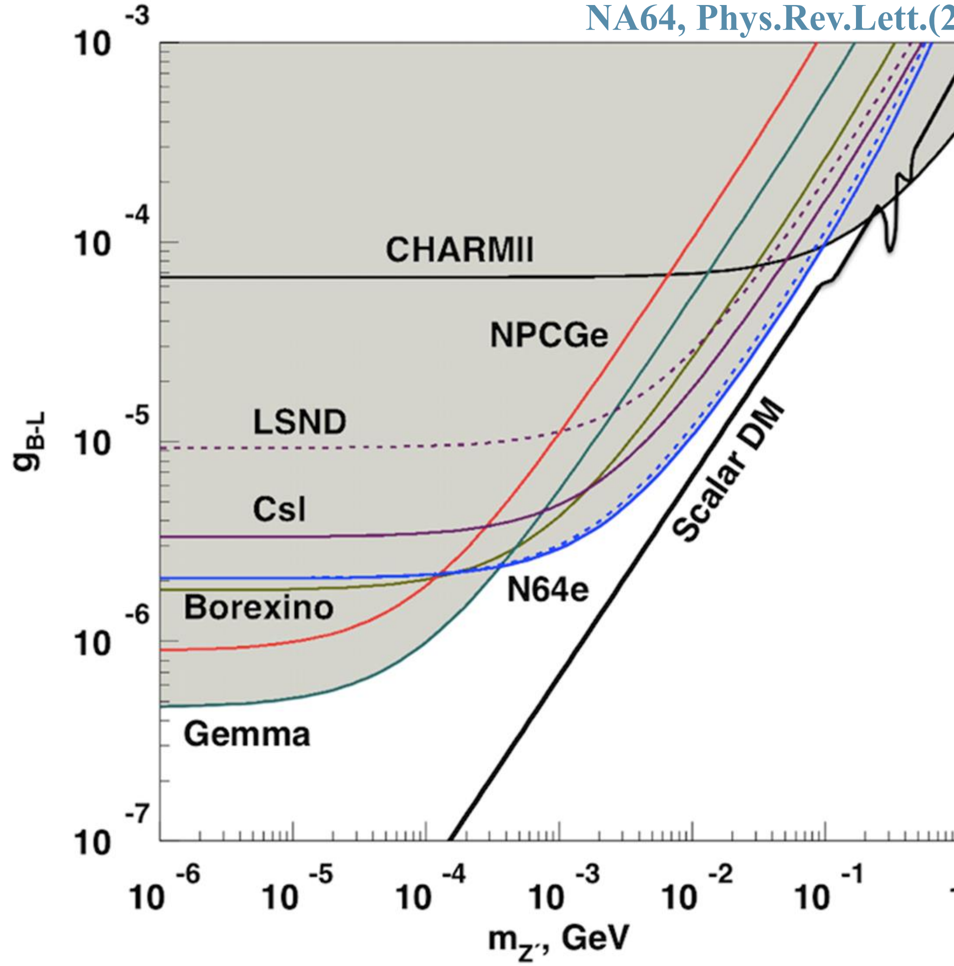
Search for new B-L Z' boson

3.2x10^{11} eot collected in 2016-2018 & 2021 runs



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

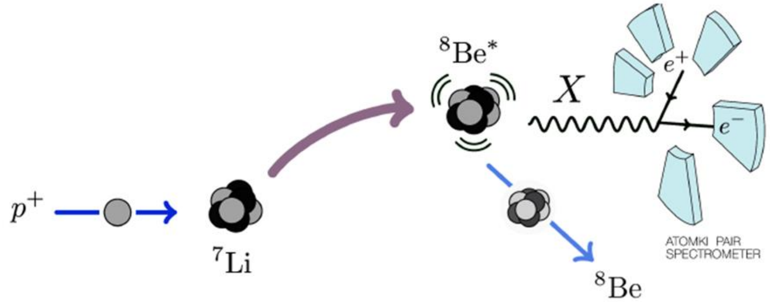
NA64, Phys.Rev.Lett.(2022)



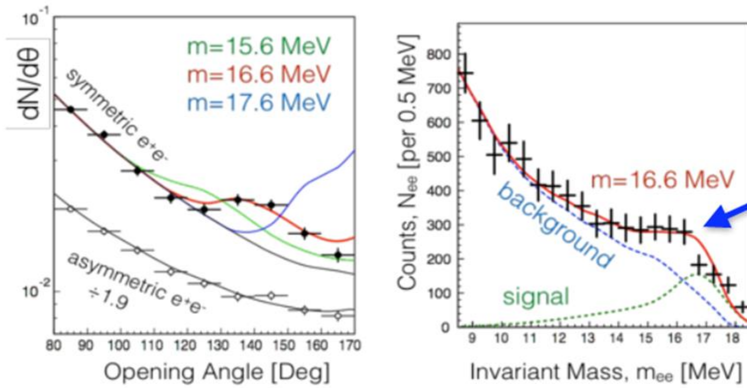
NA64 provided most stringent constraints
on B-L Z′ compared to ν - e- scattering data

Visible mode: ^{8}Be* anomaly – new X boson?

^{8}Be anomaly and X boson

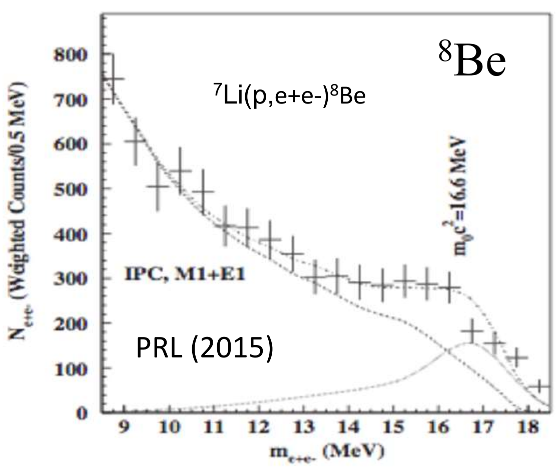


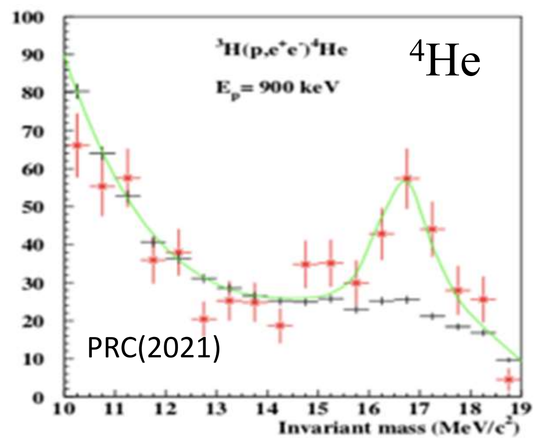
A. J. Krasznahorkay et al. Phys. Rev. Lett.116, 042501 (2015) and recent results for 4He arXiv:1910.10459

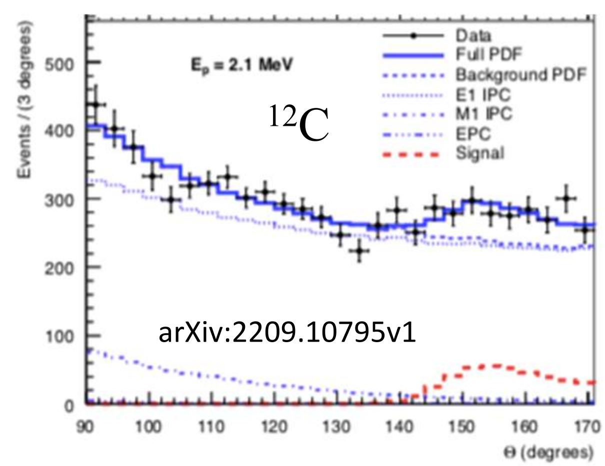


Could be explained by new ‘protophobic’ gauge boson X with mass around 17 MeV

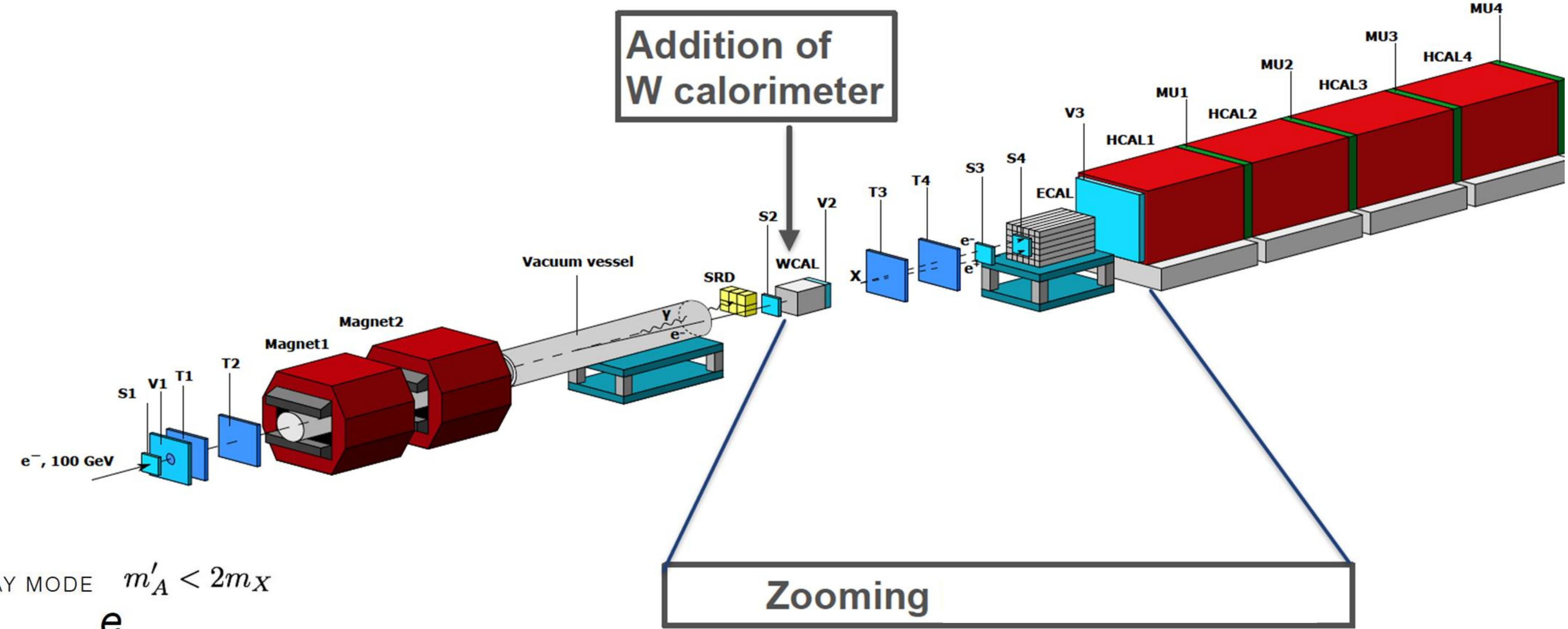
J. L. Feng et al. Phys. Rev. D95, 035017 (2017)

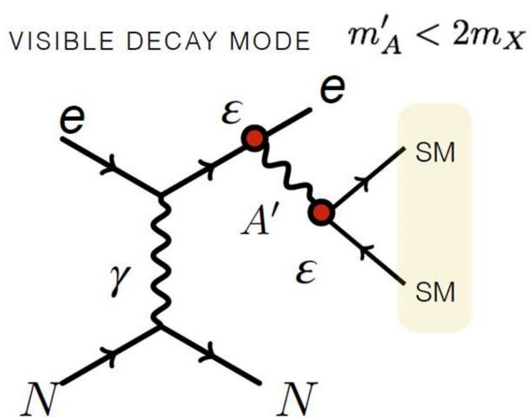




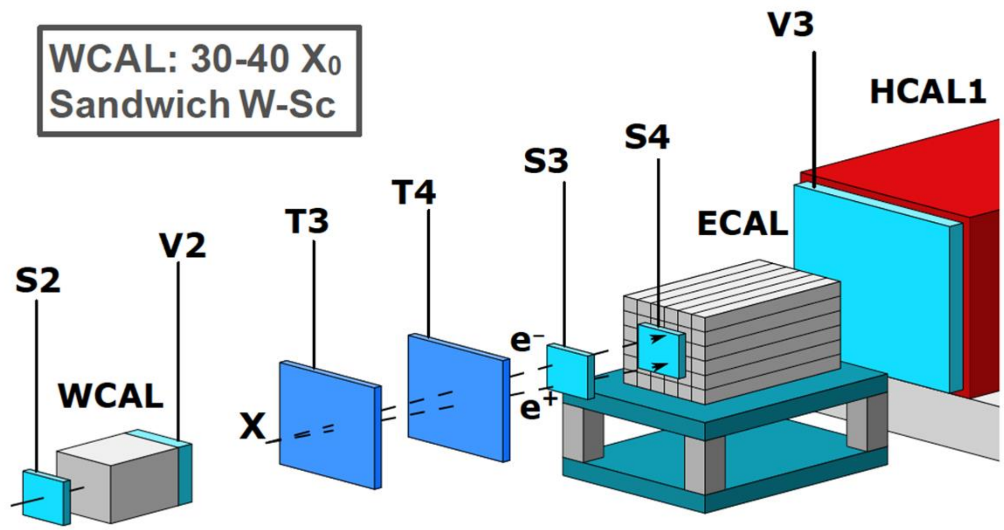


Visible mode: ^{8}Be* anomaly – new X boson?



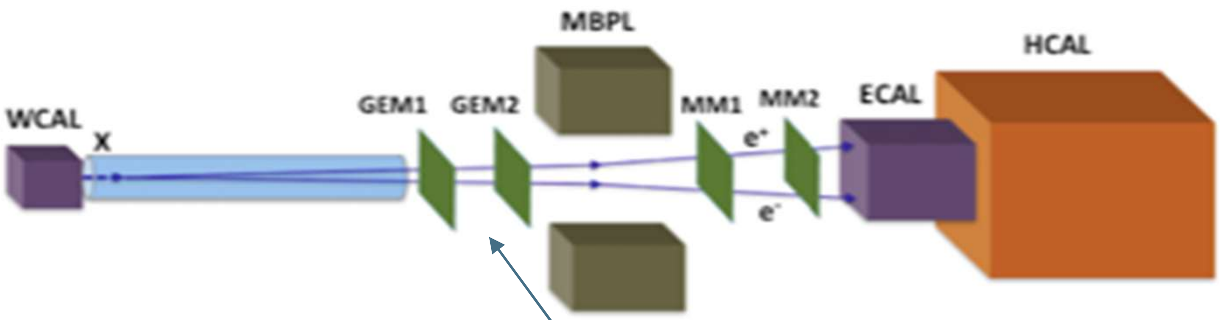


WCAL: 30-40 X_0
Sandwich W-Sc

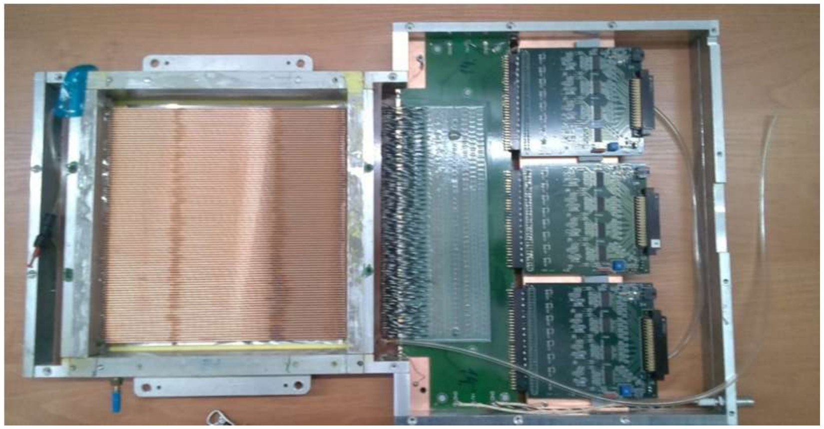


Signature:
1) $E_{WCAL}+E_{ECAL}$ = 100 GeV
2) No activity in $V_{2,3}$ and HCAL
3) Signal in S3, S4
4) e-m shower in ECAL

Visible mode: ^{8}Be* anomaly – new X boson?

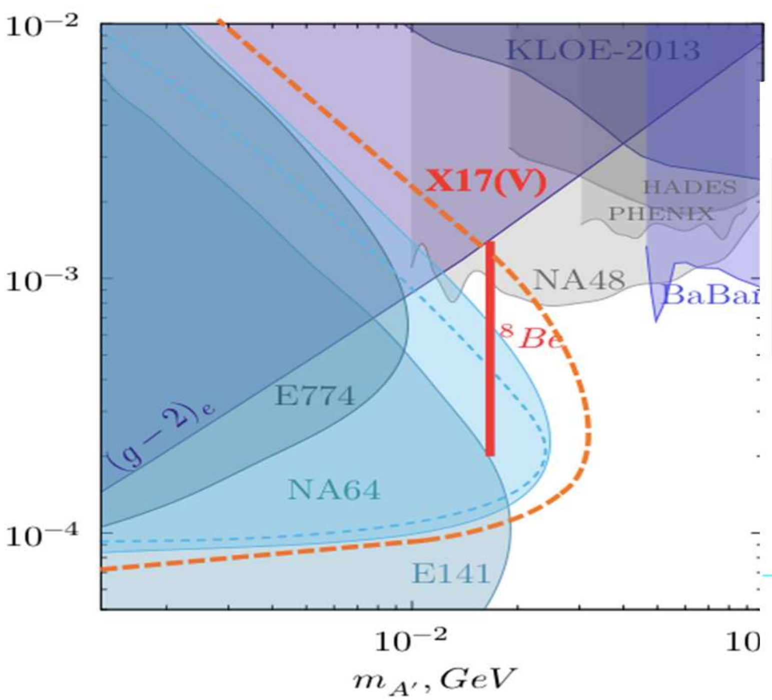


A possibility: 2 мм Straw Tubes chambers

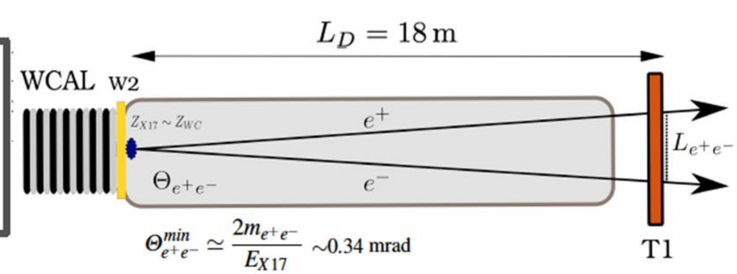


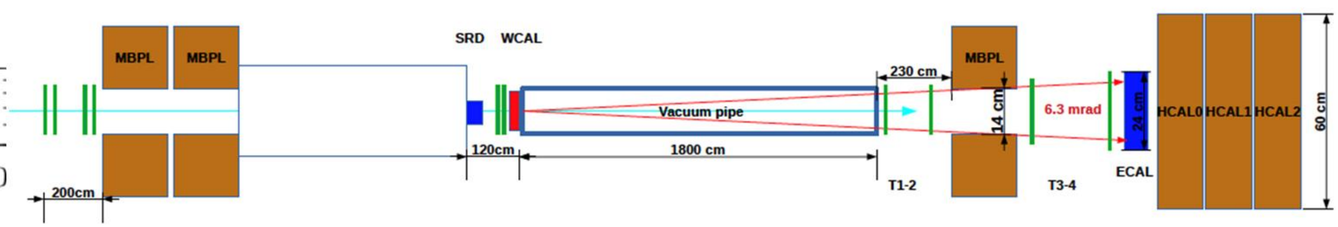
Prototypes of two-layer, 192x2 мм ST, 200 x 200 mm^2

in 202? ~ 2 10^{11} eot

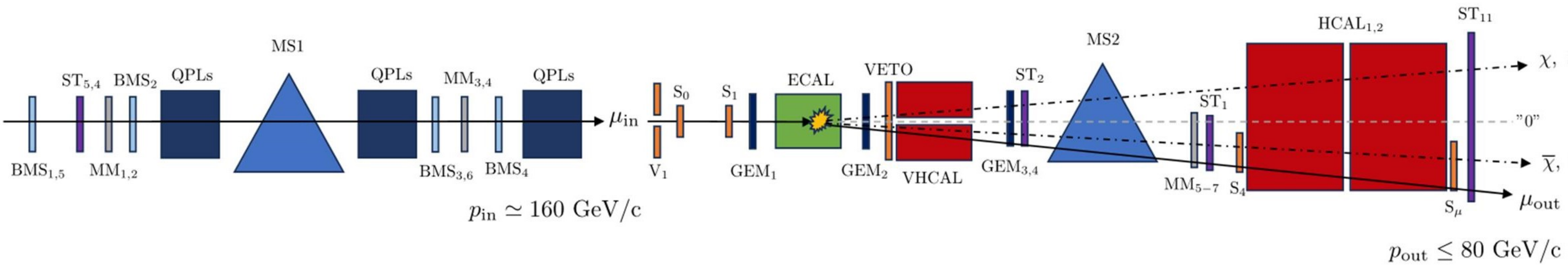


Optimization of WCAL: 20% shorter keeping 30X$_0$





$NA64_\mu$ (approved in 2021)

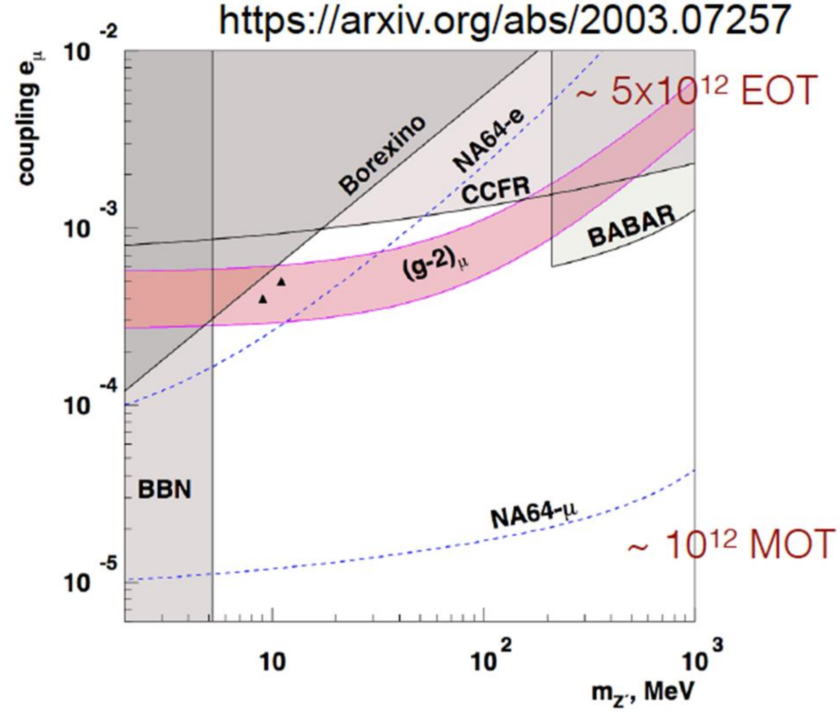


CERN SPS **M2 160 GeV muon beam** offers unique opportunities to further **searches for DS** of particles predominantly weakly-coupled to 2nd second and possibly 3rd generations of the SM.

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

L_μ-L_τ models Z_μ could explain $(g-2)_\mu$

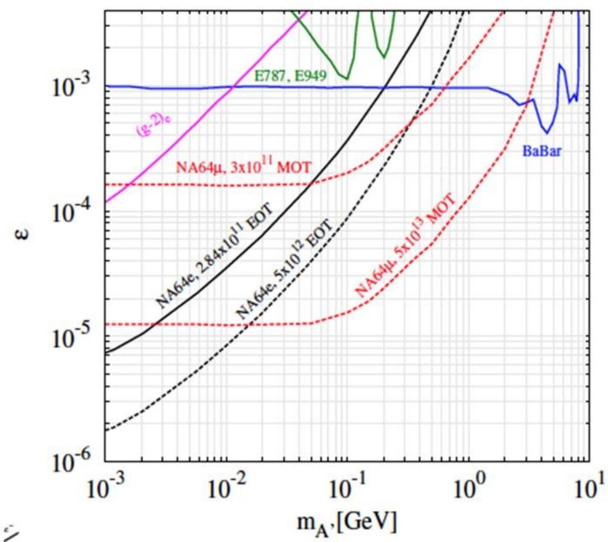
https://arxiv.org/abs/2003.07257



NA64$_\mu$ - search for LDM

Search for **Dark photons** complementary to NA64e in mass region $m_{A'} > 0.1$ GeV

$$\mu + Z \to \mu + Z + A', A' \to \chi\bar{\chi}$$



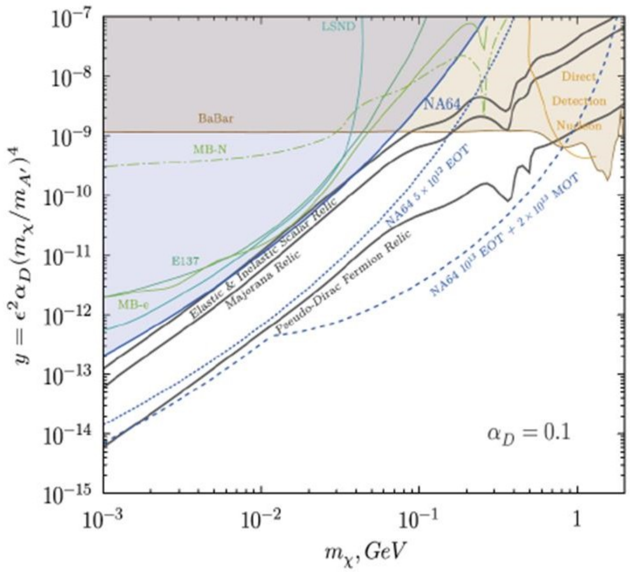
NA64$_e$

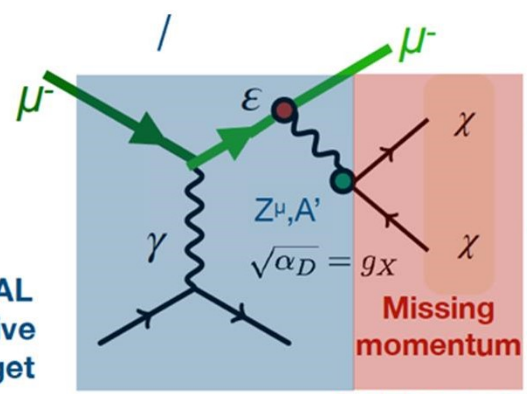
$$N^e_{A'} \sim L^e \sigma^e_{A'}$$
$$L^e \simeq X_0$$
$$\sigma^e_{A'} \sim \epsilon_e^2/m_{A'}^2$$

NA64$_\mu$

$$N^\mu_{A'} \sim L^\mu \sigma^\mu_{A'}$$
$$L^\mu \simeq 40X_0$$
$$\sigma^\mu_{A'} \sim \epsilon_\mu^2/m_\mu^2 \quad m_{A'} \lesssim m_\mu$$

Combined LDM sensitivity of NA64$_e$ -NA64$_\mu$

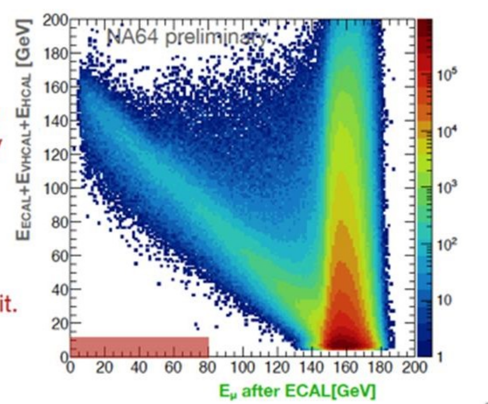




Signature

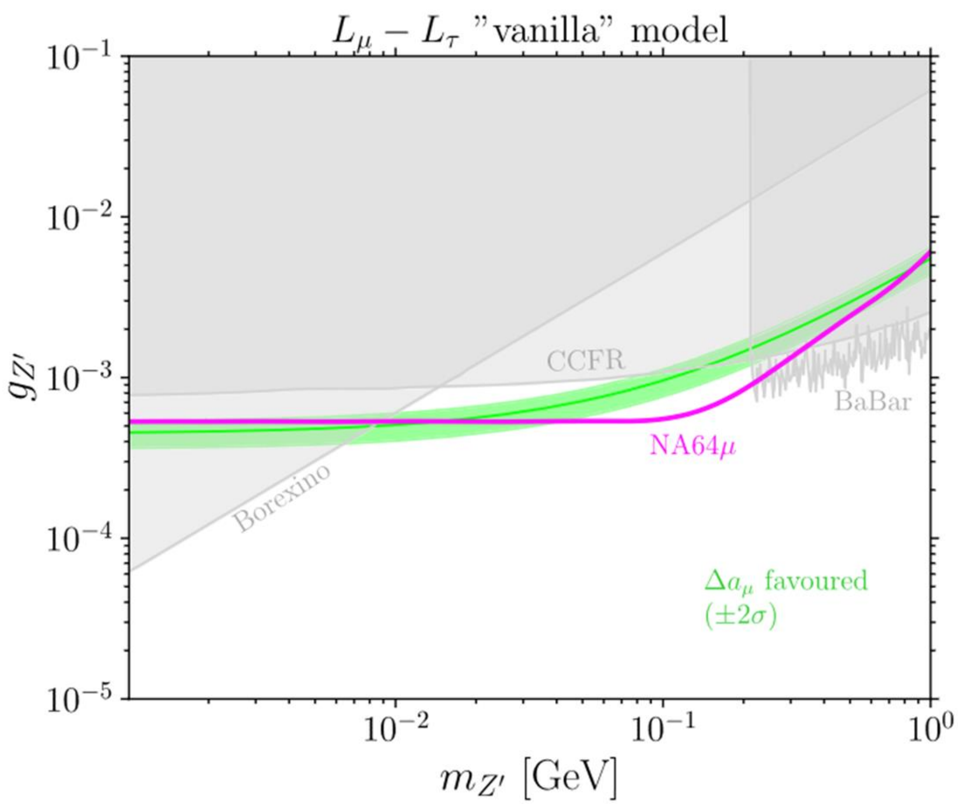
- Missing momentum (Deflected μ- energy <80 GeV).
- Energy on ECAL, VHCAL and HCAL compatible with a muon energy deposit.

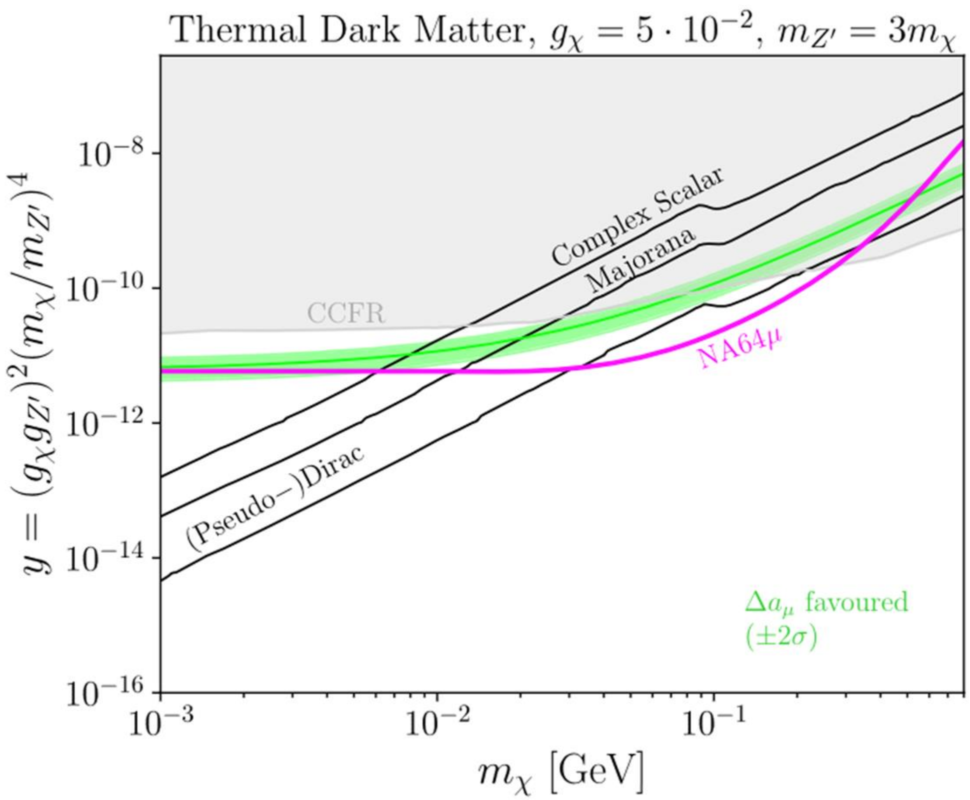
Z$^\mu$,A' decaying to DM particles



NA64$_\mu$ first results

Phys. Rev. Lett 132, 211803 (2024)





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.

NA64e & NA64$_\mu$ results

Accepted by JHEP, arXiv:2404.06982v5 [hep-ex] 22 Jun 2024

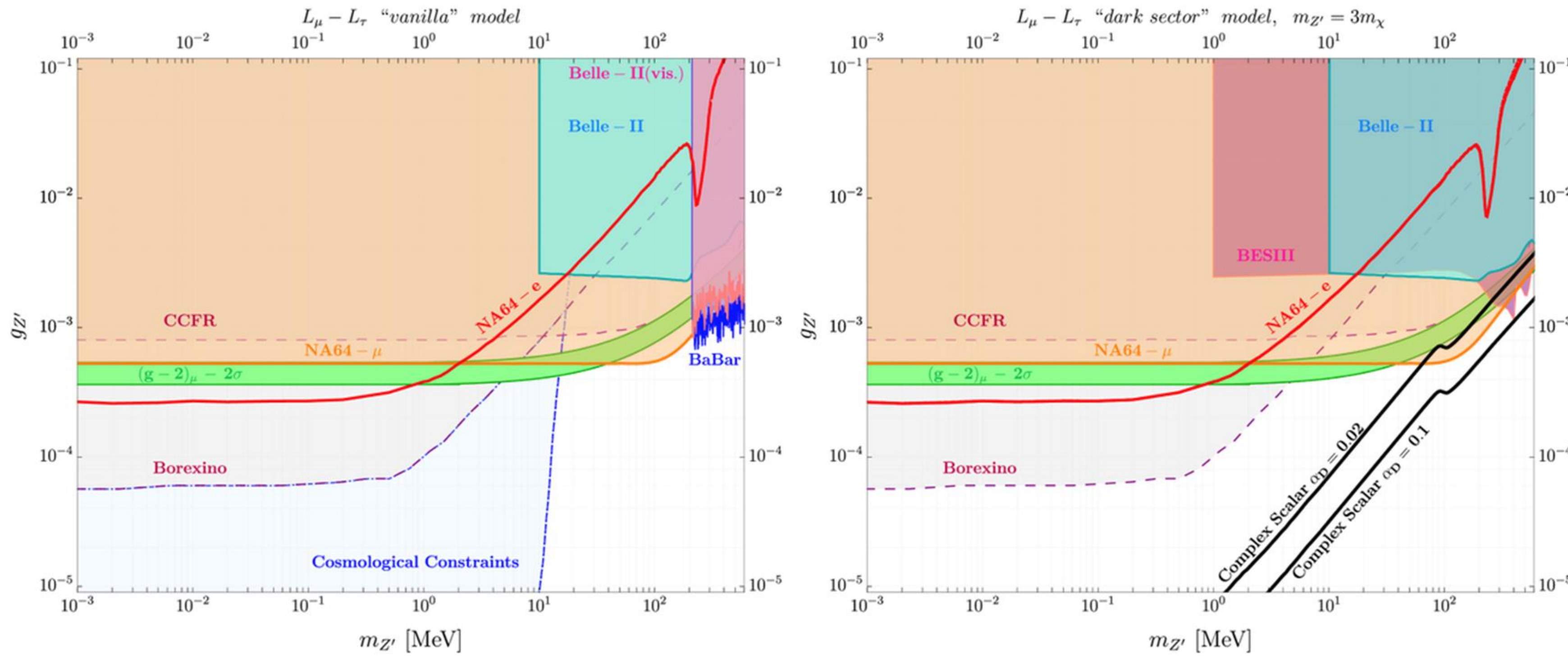


Figure 4: The new exclusion limits from the NA64−e experiment in the $(g_{Z'}, m_{Z'})$ parameter space for the $L_\mu - L_\tau$ model, considering the "vanilla" scenario without any DS coupling (left) and the full "dark sector one" (right), for $\alpha_D = 0.1$ (continuous curve) and $\alpha_D = 0.02$ (dashed curve). The most competitive bounds reported by other experiments are also shown (see text for further details). The green band correspond to preferred combination of the model parameters that would solve the muon $g-2$ tension. The blue dashed line defines the region excluded by cosmological and astrophysical considerations. Finally, the black curves in the right plot are the preferred combination of the parameters to explain the observed dark matter relic density (so-called "thermal target").

Outlook & conclusions

NA64 accumulated **~ 2 10^{12} eot** it allows to start probing very interesting LDM benchmark models.

We plan until LS3 accumulate as many as possible **eot** and also use the positron mode to enhance the sensitivity in the higher $m_{A'}$ region. After LS3 the experiment plan continue data taking to accumulate ~10^{13} eot

NA64 started program with high intensity 160 GeV μ beam to explore dark sectors weakly coupled to μ. We plan to collect **> 5 10^{11} μot** before LS3 in order to check if an L_{μ}-L_{τ} Z′ boson as the explanation of the $(g-2)_{\mu}$ anomaly and complement the searches with electrons.

After LS3 the experiment plan continue data taking to accumulate ~10^{13} μot to explore the A′ higher mass region and $\mu \rightarrow \tau$ and $\mu \rightarrow e$ LFV processes.

The exploration of the NA64 physics potential just begun. Proposed searches with leptonic and hadronic beams provide unique sensitivities & highly complementary to other projects.

Thank you!