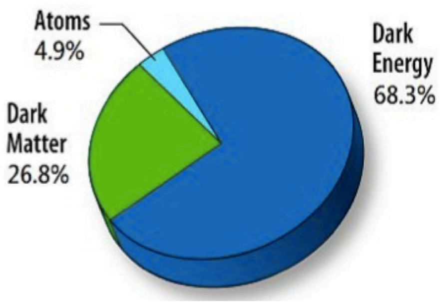
«The NA64 experiment - search for hidden sector at CERN SPS»

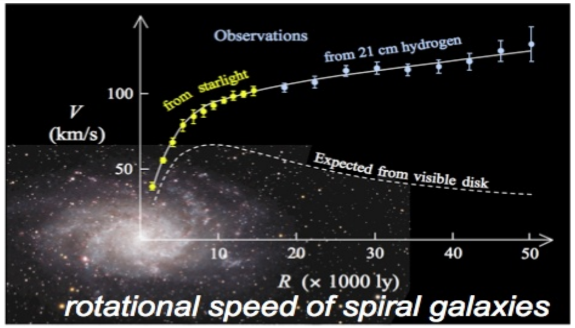
D.Peshekhonov

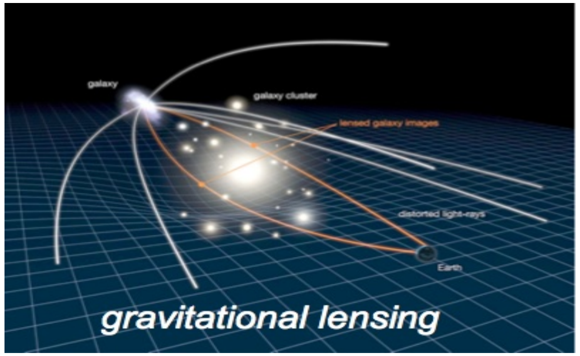
Motivation



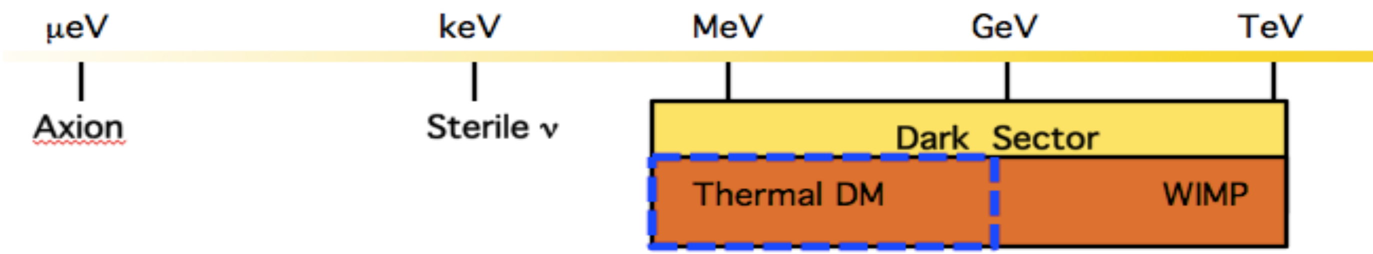
Existence of DM is firmly established:
rotational curves of galaxies, lensing, …

- Dark – doesn't couple to γ
- Cold/Warm – $v < c$
- DM relic density $\rho_{DM} \sim 10^{-6}$ GeV /cm^3





DM particles mass scale



WIMPs (χ) (m_χ, g_χ) ~ (m_{EW}, g_{EW}) - are not seen at LHC and in direct searches.
ρ_{DM}~ 0.3 GeV /cm^3 in Solar system => n_{WIMP} (~1 TeV) ~ 10^3/m^3, a very low counting rate.

Dark Matter (DM) from a Dark Sector (DS)

- DM is a part of DS
- DS consists of particles and fields which are singlet with respect to the SM gauge group, could be charged e.g. under a new U(1)′ gauge symmetry
- interacts with the SM via gravity and a new week interaction

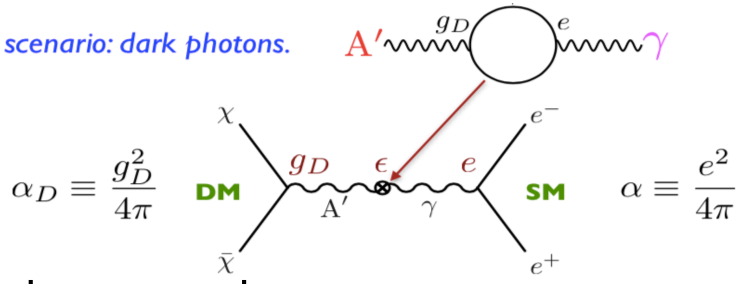
Portals between SM and Dark Sector

Several general extensions of the Standard Model (SM):

- Vector portal → Dark Photons (A')
- Scalar portal → Dark Scalars
- Neutrino portal → Heavy Neutral Leptons
- Axion portal → Axion-like particles

Vector portal to DS – Dark photon A’

Benchmark scenario: dark photons.



massive V, dark photon (A′)
- γ–A′ kinetic mixing: $\Delta L = \varepsilon/2\, F^{\mu\nu} A'_{\mu\nu}$
- coupling strength ~ εe
- $\varepsilon \sim 10^{-5} - 10^{-2}$, $m_{A'} \sim \varepsilon^{1/2} M_Z$

- A′decay modes:

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

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

- Useful variable to compare sensitivity. χ–SM annihilation:

  $n_\chi < \sigma v > \approx [\alpha_D\, \varepsilon^2 (m_\chi/m_{A'})^4]\alpha/m_\chi^2 = y\ \alpha/m_\chi^2$

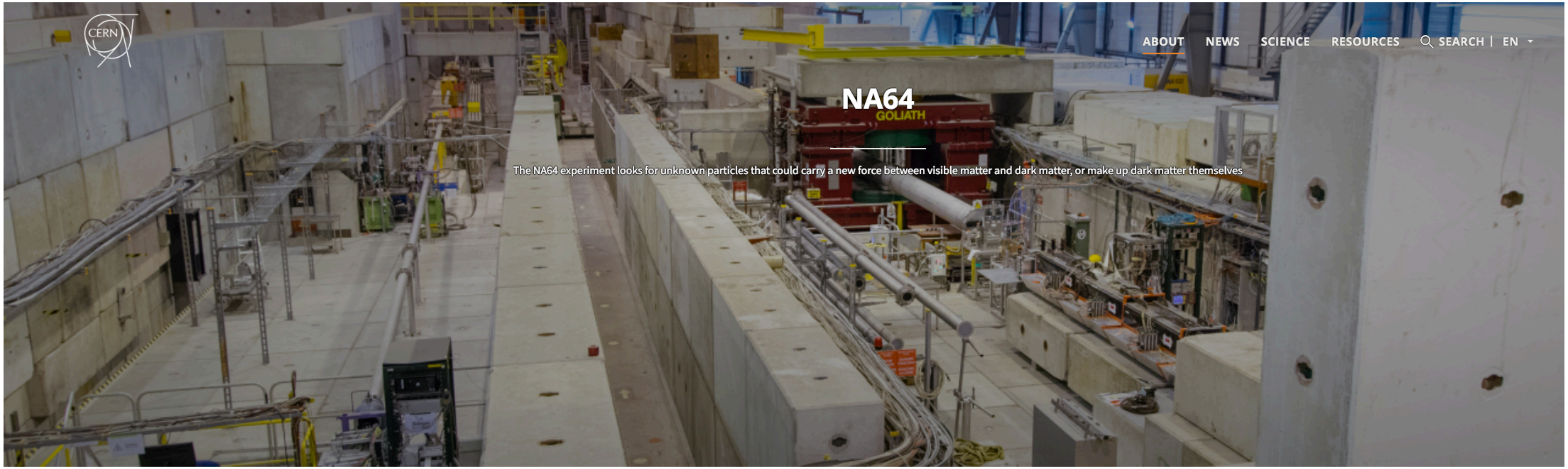
NA64 research program

- Thermal sub-GeV Dark Matter (LDM)
- ALP, S → γ γ decays
- S, P, V, and A dark portal particles, their invisible, visible, semi-visible decays
- SM expantion: Light **B-L** Z′ , ..
- ATOMKI anomaly: X17 (P, V, A′) → e+e- decays

NA64e: 50-150 GeV $e^\pm$ **NA64μ**: 100-160 GeV μ^- *NA64h: 50-200 GeV π-, K-, p*

NA64 collaboration

Collaboration: Univ. of Bonn (Bonn), JINR(Dubna), INFN (Genova), LPI, INR, SINP MSU (Moscow), IHEP (Protvino), TPU(Tomsk), SAPHIR(Chile), IFIC(Valencia), ETH(Zurich)) +recently York University (Canada)



The main aim of the NA64 experiment is to search for unknown particles from a hypothetical "dark sector". These particles could be dark photons, which would carry a new force between visible matter and dark matter, in addition to gravity, or they could make up dark matter themselves.

NA64 experiment in brief

Proposed as P348 in 2014

- Approved with e^- beam in March 2016 (NA64e)
- Proposal to run with M2 muon beam (NA64μ) in 2019.

Operation

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

2017 – 5 weeks at H4 (NA64e) ~5,5x10^{10}eot,

2018 – 6 weeks at H4 (NA64e) ~2,0x10^{11}eot,

2017-18 in visible mode ~ 8,4x10^{10}eot,

2021 – 5 weeks at H4 (NA64e) ~ 5,2x10^{10}eot,

2022 –10 weeks at H4 (NA64e) ~ 6,4x10^{11}eot,

e^+ ~ 1,0x10^{10}eot

Total accumulated & analysed **~10^{12}eot, published ~3,4x10^{11}eot**

2021 – 3 weeks pilot-run at M2 (NA64μ)

2022 – 3 weeks pilot-run at M2 (NA64μ)

s Total accumulated ~4x10^{10}μot

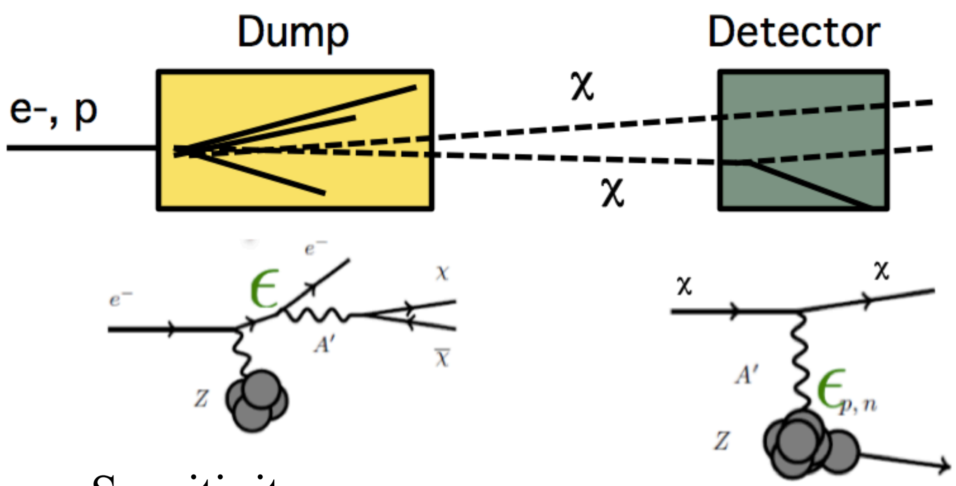
2023 – 8 weeks NA64e 5,1 x10^{11}eot with I~ 6,2 – 6,8 10^6 e^-/spill

1,6 x$10^{10}$$e^+$ot

& 4 weeks NA64μ 1,5 x 10^{11}μot

NA64 approach

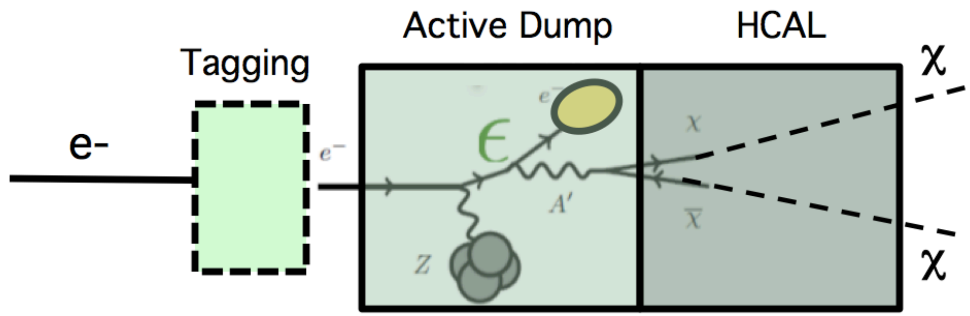
Beam-dump approach: Signal of χ scattering



Sensitivity

$n_S \sim \alpha_D \varepsilon^4 n_{pot}$

Active beam-dump+Missing energy



Sensitivity

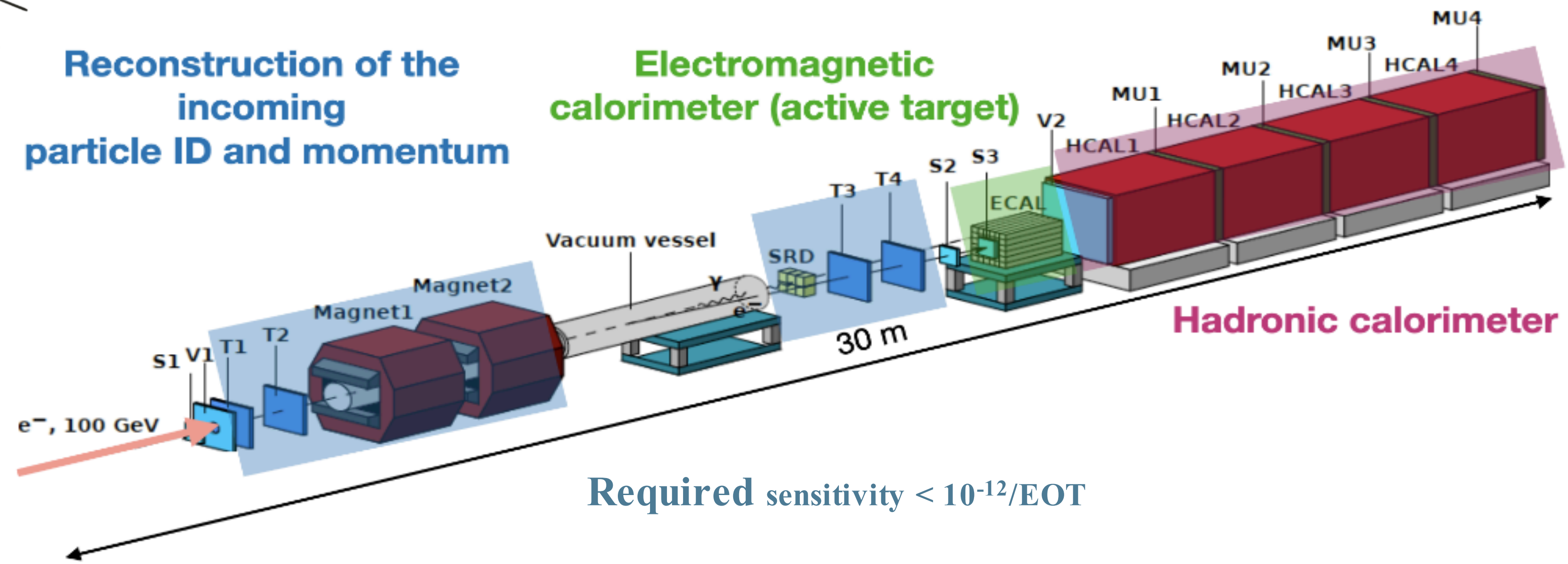
$n_S \sim \alpha_D \varepsilon^2 n_{eot}$

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

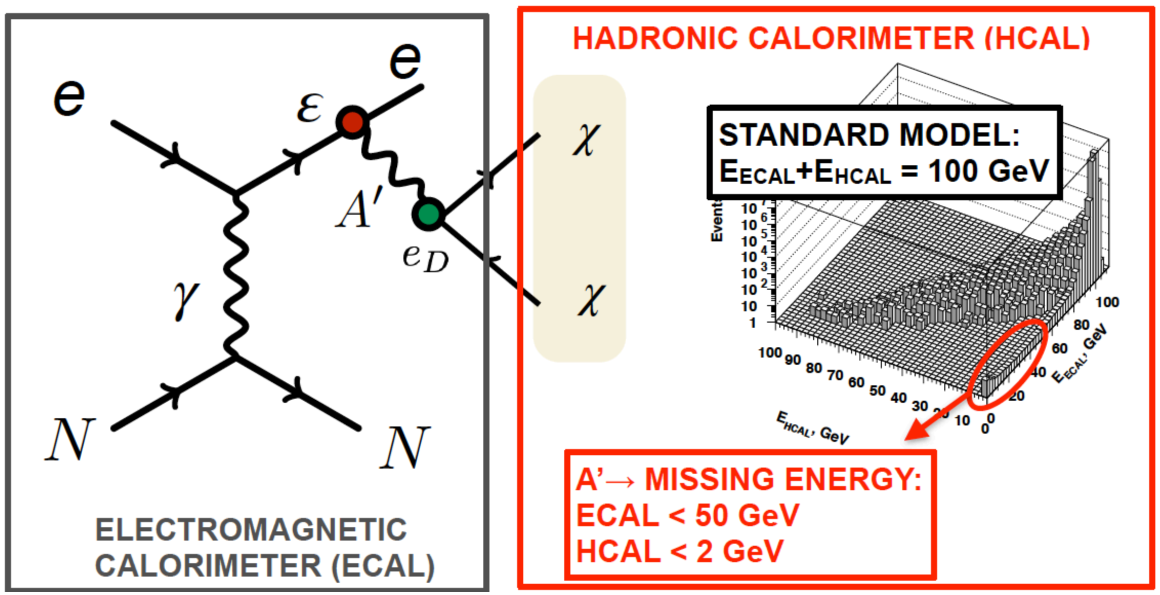
Source of LDM (χ) any source of γ

- Bremsstrahlung $e^- Z \rightarrow e^- Z A'$; A′->χχ
- Meson decays π^0,η,η′… ->γA′, A′->χχ, ee, μμ, ..

NA64 approach



Bremsstrahlung of A'



Main components :

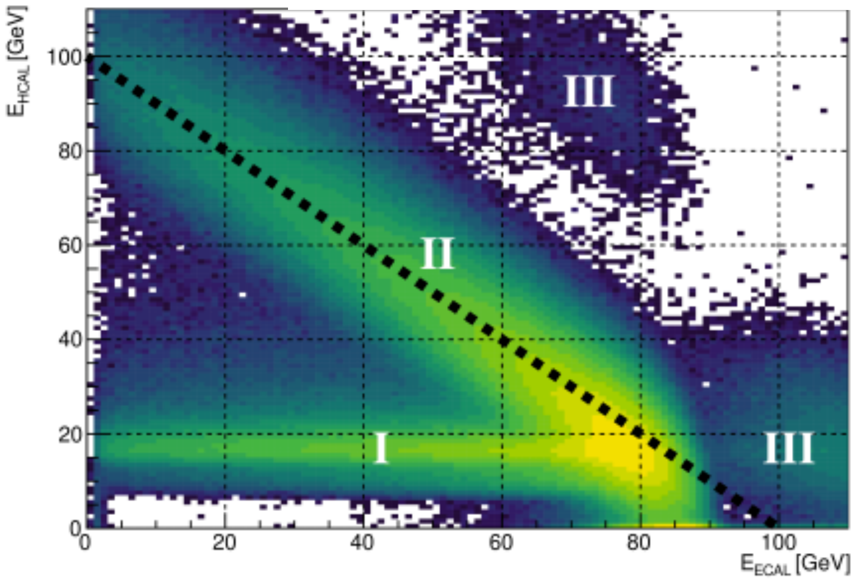
- clean 100 GeV e- beam
- e- tag: M-spectrometer+SRD
- fully hermetic ECAL+HCAL

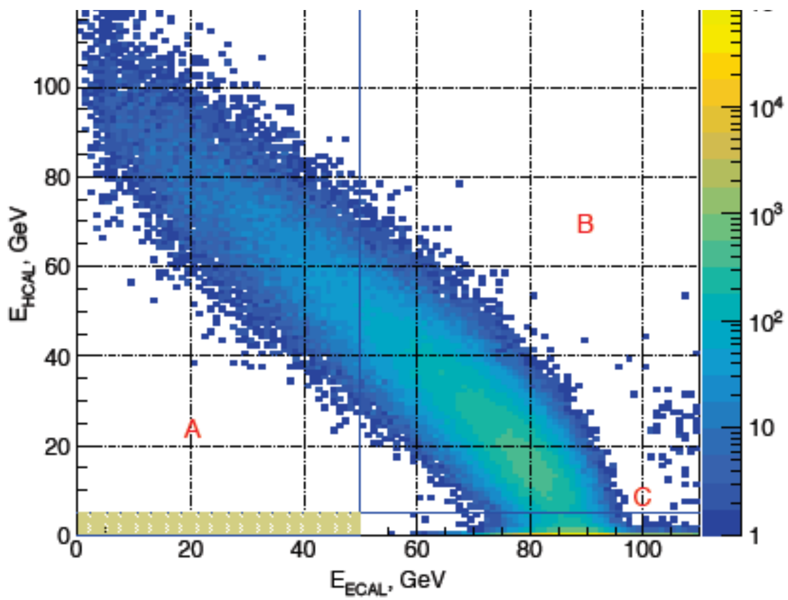
Signature:

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

NA64 approach

- *Region I: These events correspond to the rare QED di-muon production in the target used as a benchmark process to study the accuracy of our MC simulation.*
- *Region II: The diagonal along this region corresponds to the energy conservation line arising from SM events.*
- *Region III: The events visible in this region result from pile-up events.*



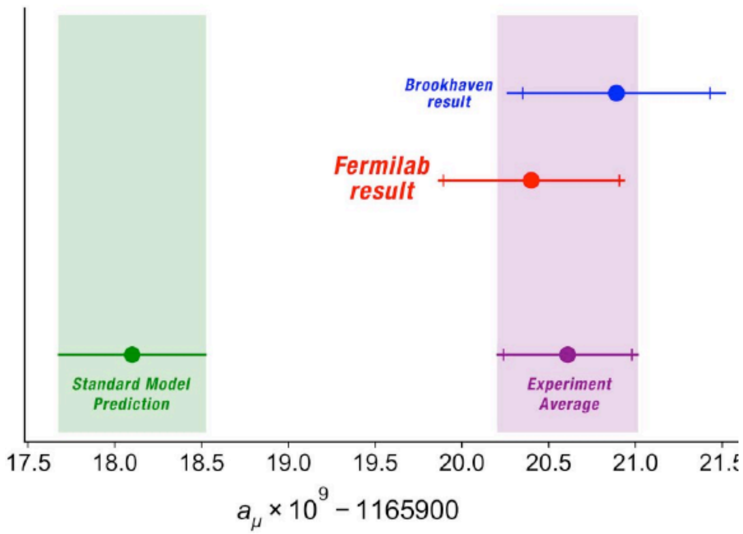


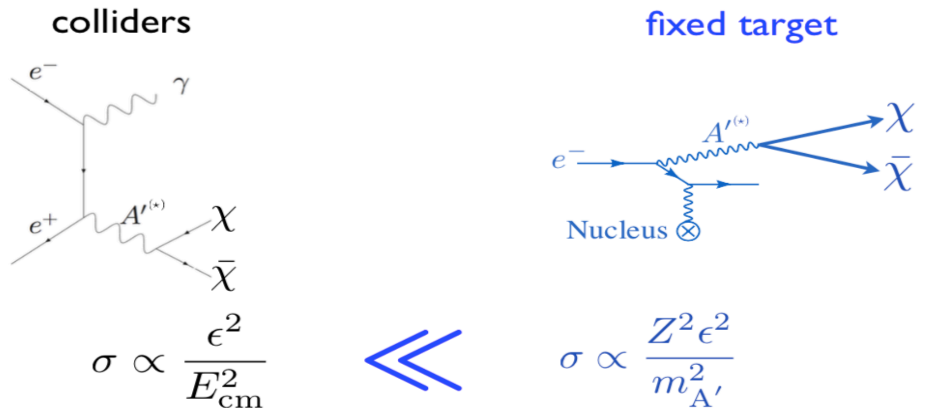
Selection criteria: single e^-track 100±10 GeV with angle to the beam axis within 3 mrad; PID from SRD (rejection ~ 2 10^{-5}); shape of the shower are consistent with e-m one; no background from hadron electroproduction (no signal in straw & veto)

The signal box: $E_{ECAL} < 50$ GeV and $E_{HCAL} < 1$ GeV. Energy in the HCAL is determined mostly by the noise of the read-out electronics

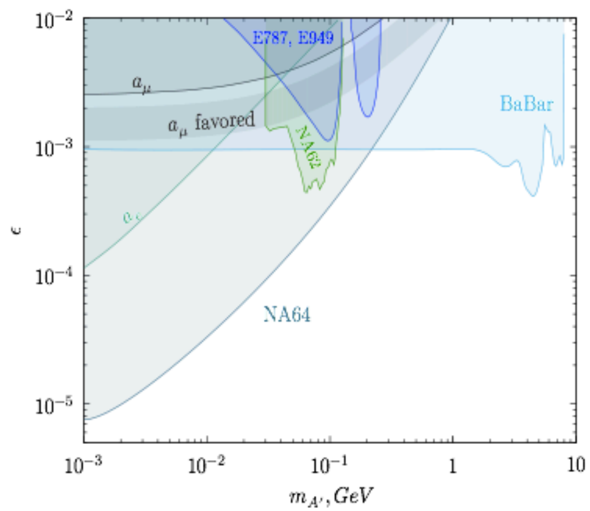
Muon (g-2): additional motivation to search for A’

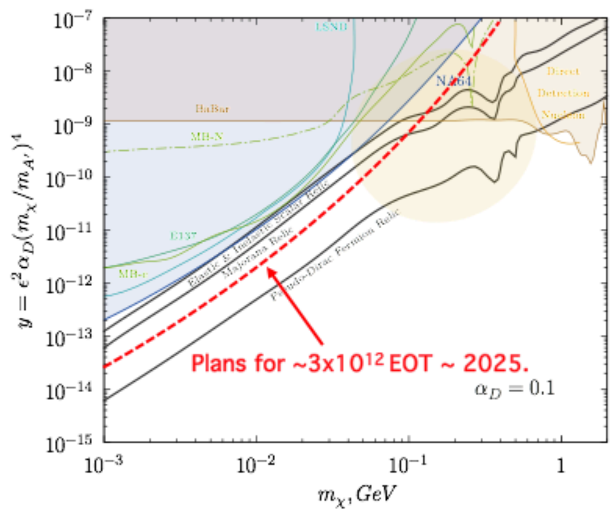
B. Abi, et al. Phys. Rev. Lett. 126, 141801 (2021)





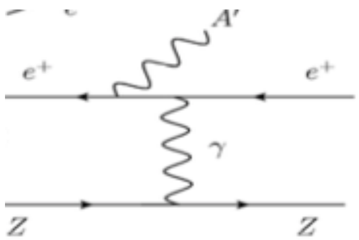
- BaBar $e^+e^- \to \gamma A'$; $A' \to$ invisible
- NA64 $e^- Z \to e^- Z A'$; $A' \to$ invisibl





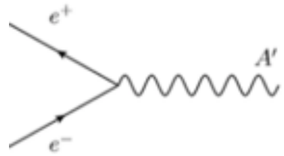
- Most stringent bounds compare to LSND, SLAC, MiniBooNE with $\sim 10^{20}$-10^{22} POT. Sensitivity of NA64$\sim\varepsilon^2$, while for the beam-dump it’s $\sim\varepsilon^4\alpha_D$
- Plans to cover $m_{A'} \leq m_\mu$ area with ~ a few 10^{12} EOT
- Challenge: high mass region $m_{A'} \geq \sim m_\mu$, as cross-section $\sim (1/m_{A'})^2$
- Ways out: i) resonance A′ production, and ii) high-energy muon beam ($NA64_\mu$)

Resonant A' production



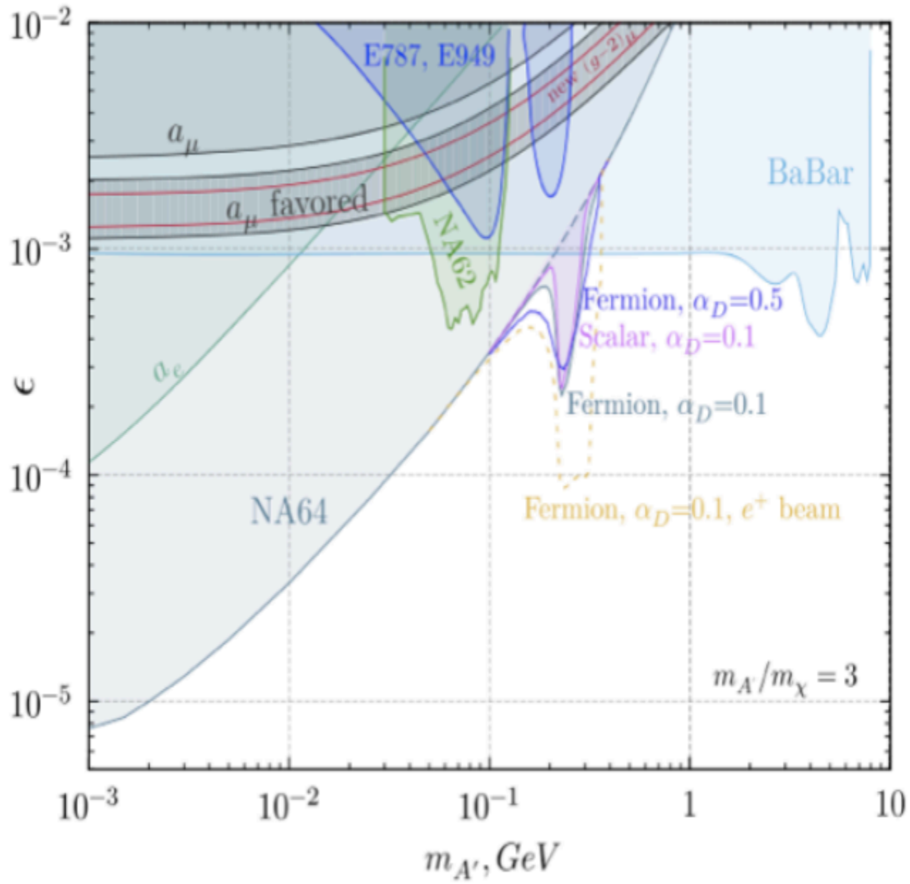
$\sigma \sim Z^2\alpha^3\varepsilon^2$ vs

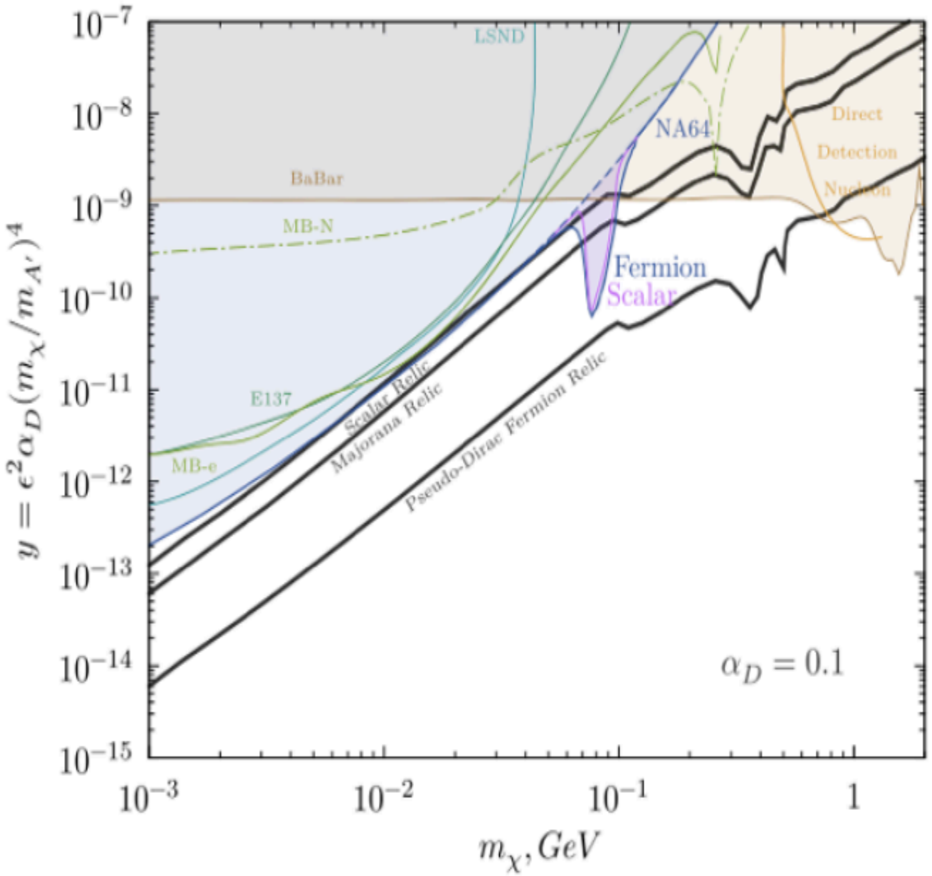
$m_{A'} \sim (2m_eE_0)^{1/2}$



$\sigma \sim Z\alpha\varepsilon^2$ x res.factor

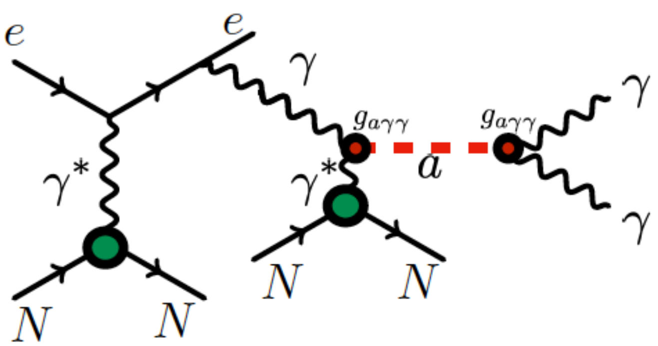
For masses $m_{A'} \sim$ 220-320 MeV a factor ~O(10) improvement in ε, and ~O(10^2) in y (~ε^2). Possibility to scan masses >100 MeV vs e+ energy



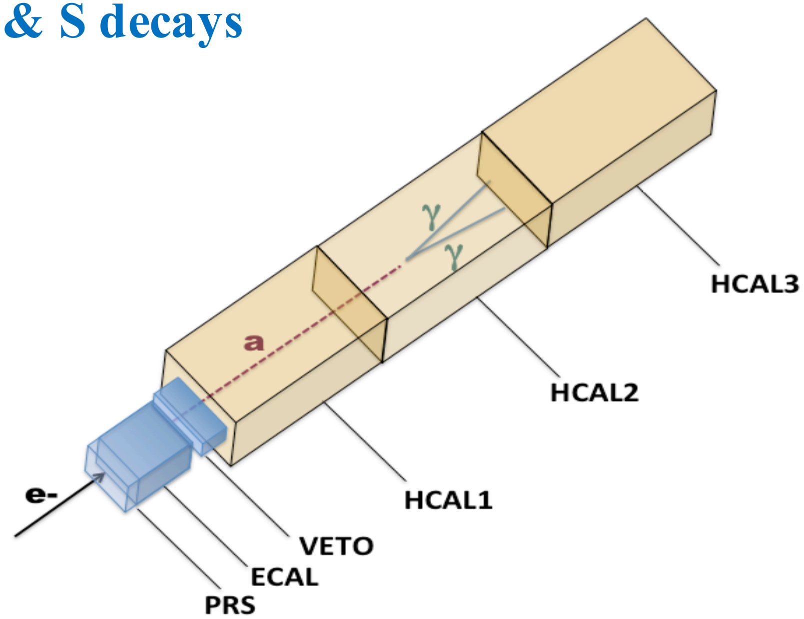


NA64e potential for new physics

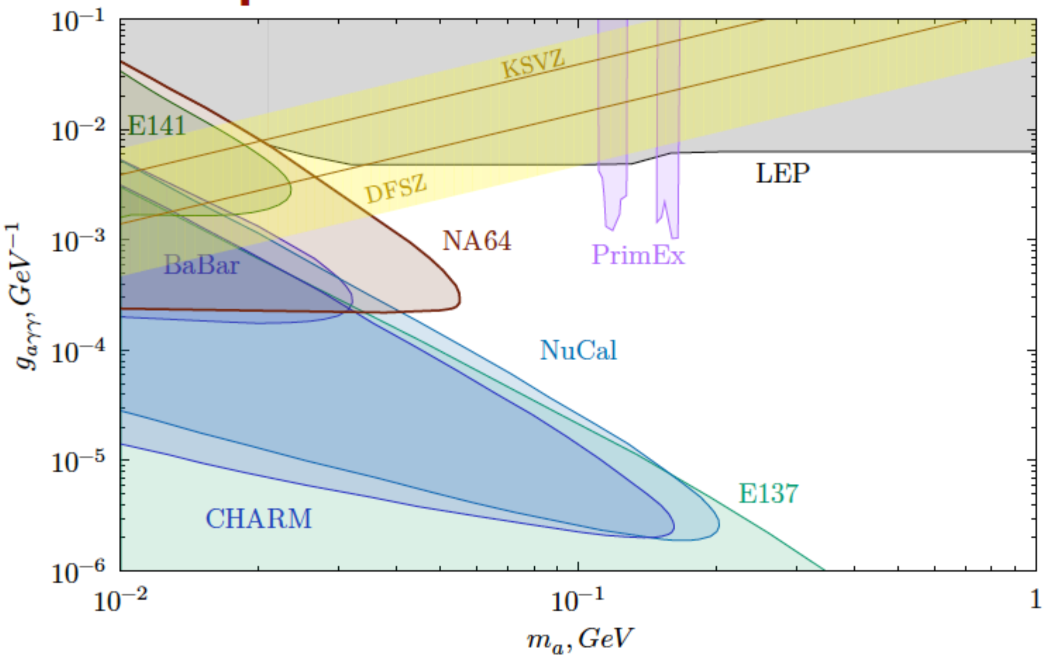
Search for axion, ALP & S decays



Production via Primakoff effect



Closing the gap between beam dump and colliders



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

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 bckg – punchthrough neutral secondaries ($n, K^0_{S,L}$)

NA64e potential for new physics

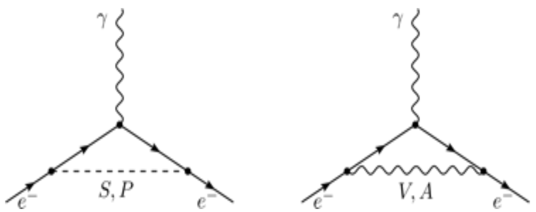
Constraints on dark S,P,V,A and $(g\text{-}2)_e$ from high-precision measurements of α

LKB(^{87}Rb): $\alpha^{-1} = 137.035999296(11)$. 2.5 more accurate, 5σ difference with Berkley(^{137}Cs)

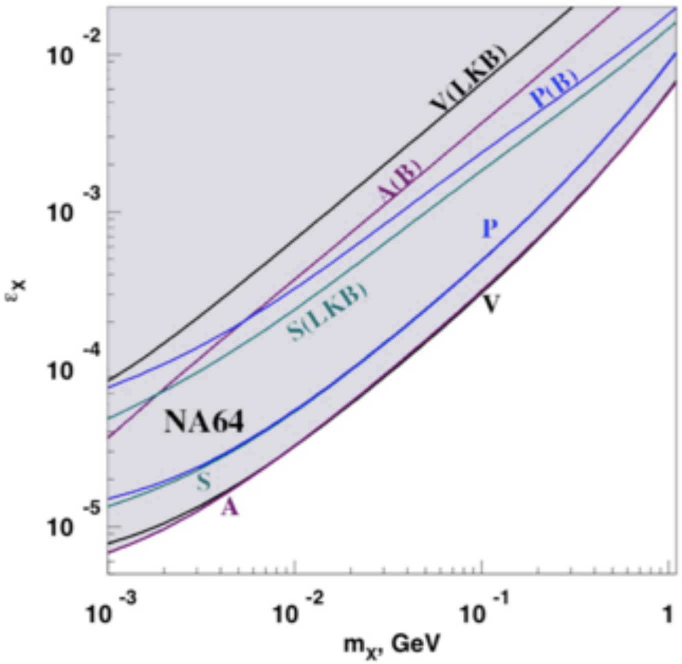
$$\Delta a_e = a_e^{exp} - a_e^{LKB} = (4.8 \pm 3.0) \times 10^{-13} \qquad (1)$$
$$\Delta a_e = a_e^{exp} - a_e^{B} = (-8.8 \pm 3.6) \times 10^{-13} \qquad (2)$$

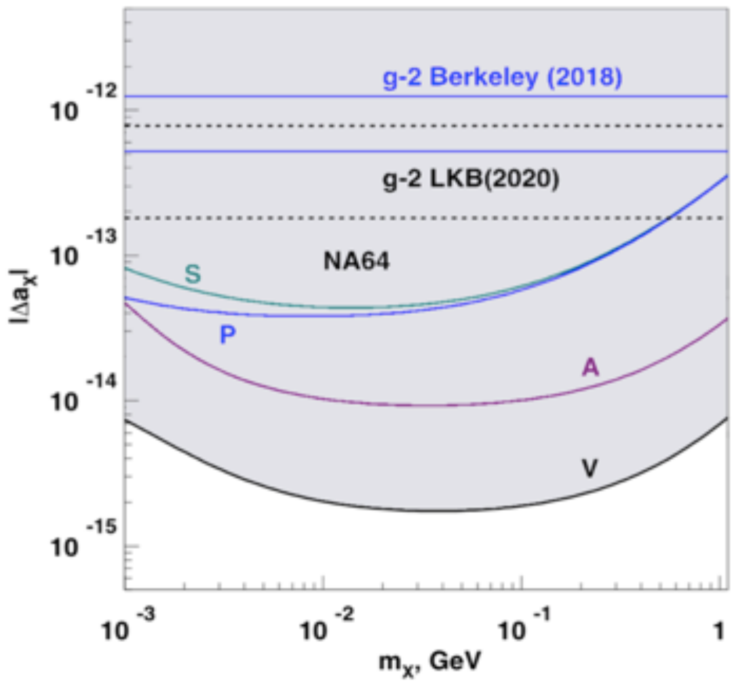
NA64,Phys.Rev.Lett.(2021)

Dark $X = S, P, V,$ or A



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



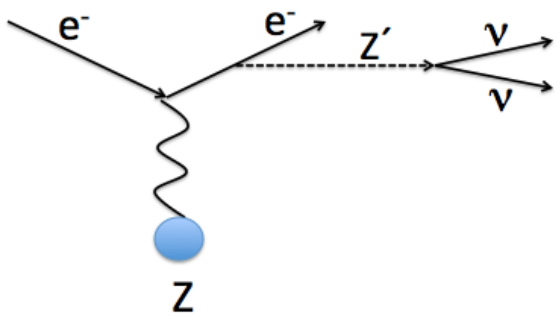


NA64 provided most stringent constraints on new physics contribution $\Delta a_X < 10^{-15} - 10^{-13}$ for $X = S, P, V,$ or A compared to LKB and Berkley high-precision measurements

NA64e potential for new physics

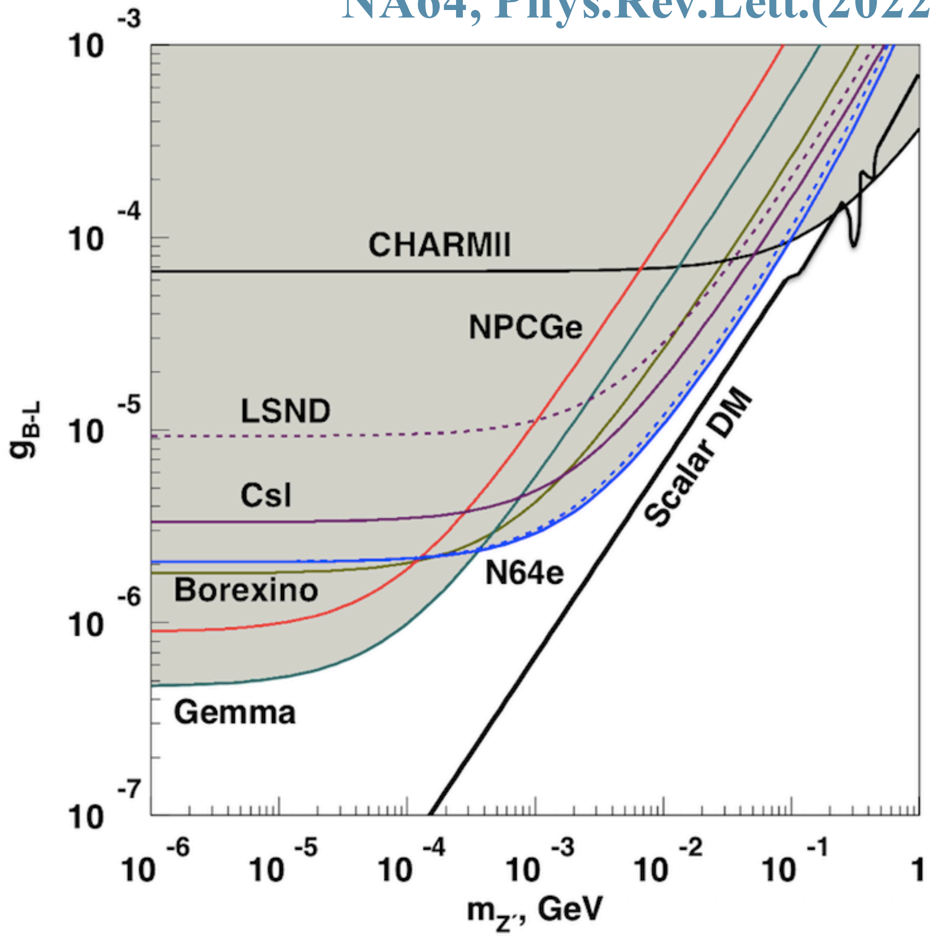
Search for new B-L Z' boson

3.2x10^{11} EOT collected in 2016-2018, 2021 runs



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

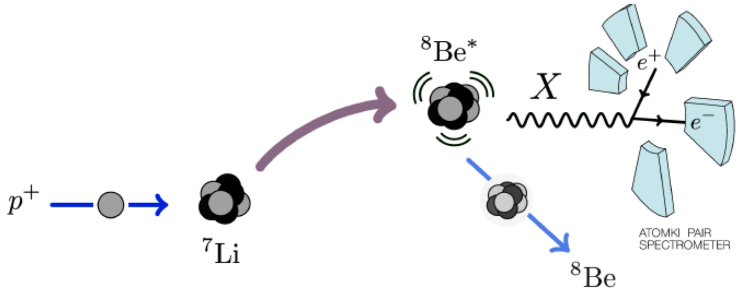
NA64, Phys.Rev.Lett.(2022)



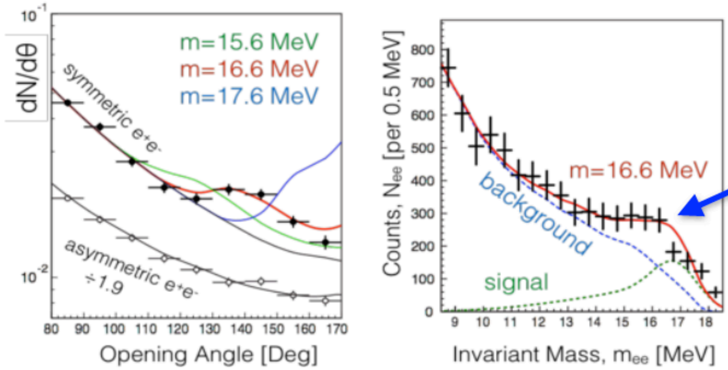
NA64 provided most stringent constraints on B-L Z´ compared to ν - e- scattering data

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

^{8}Be anomaly and X boson

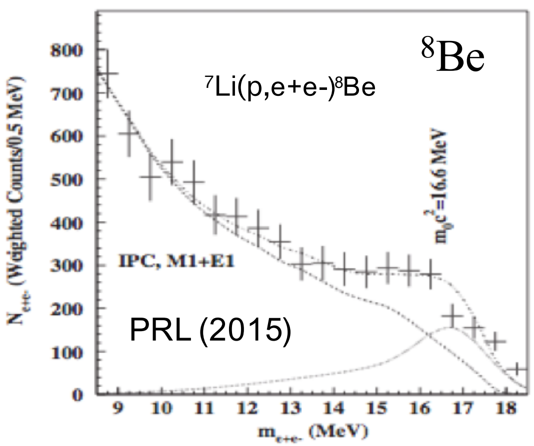


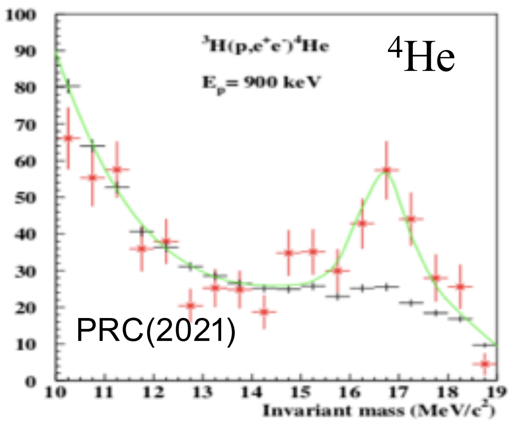
A. J. Krasznahorkay et al. Phys. Rev. Lett.116, 042501 (2015) and recent results for 4He arXiv:1910.10459

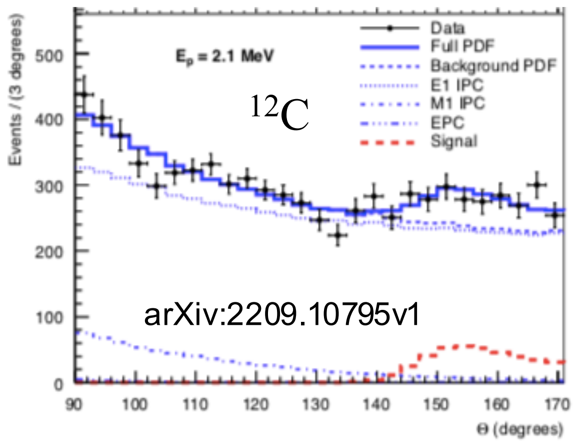


Could be explained by new 'protophobic' gauge boson X with mass around 17 MeV

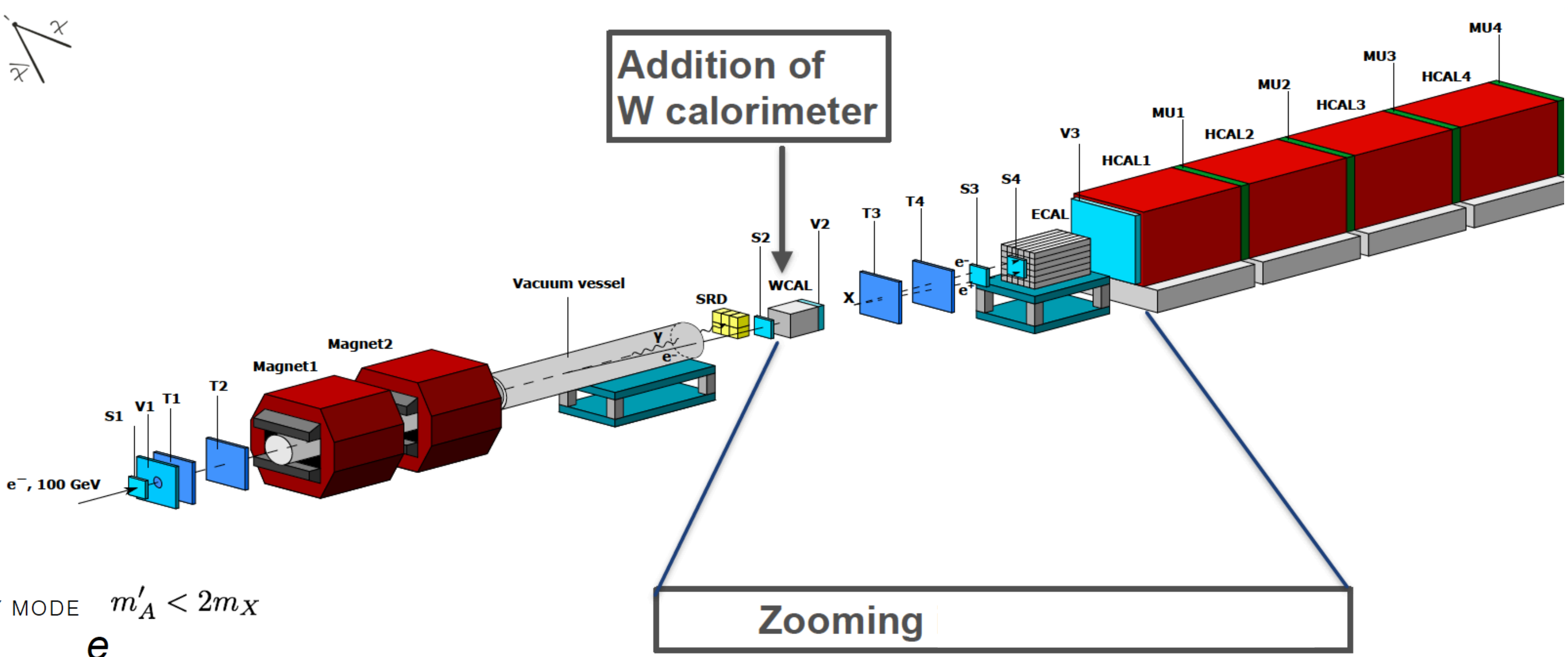
J. L. Feng et al. Phys. Rev. D95, 035017 (2017)



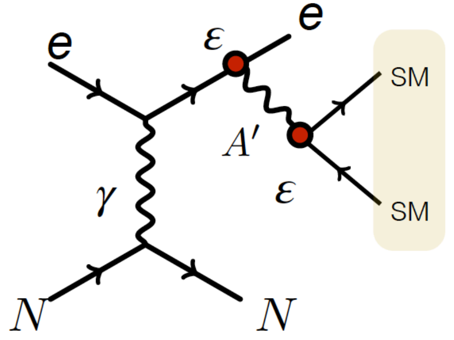




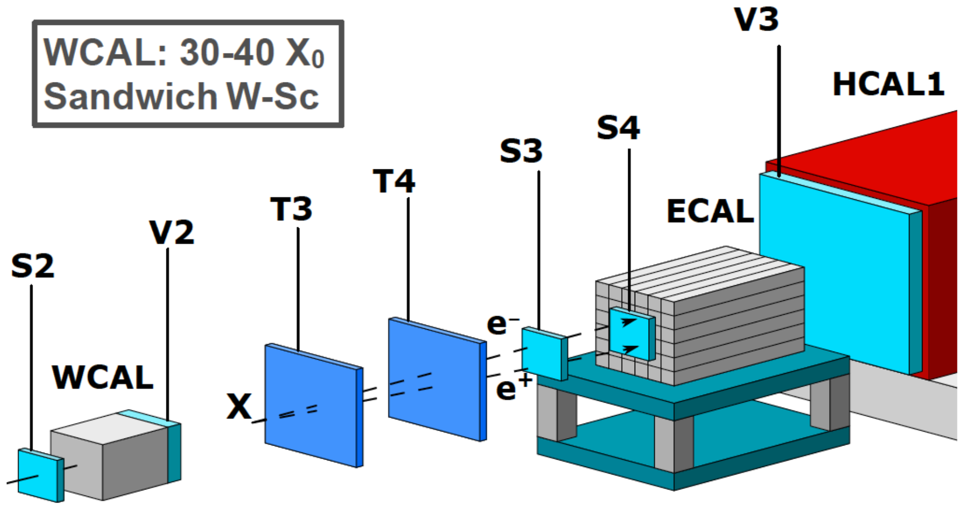
Visible mode: ^{8}Be* anomaly – new X boson?



VISIBLE DECAY MODE $m'_A < 2m_X$

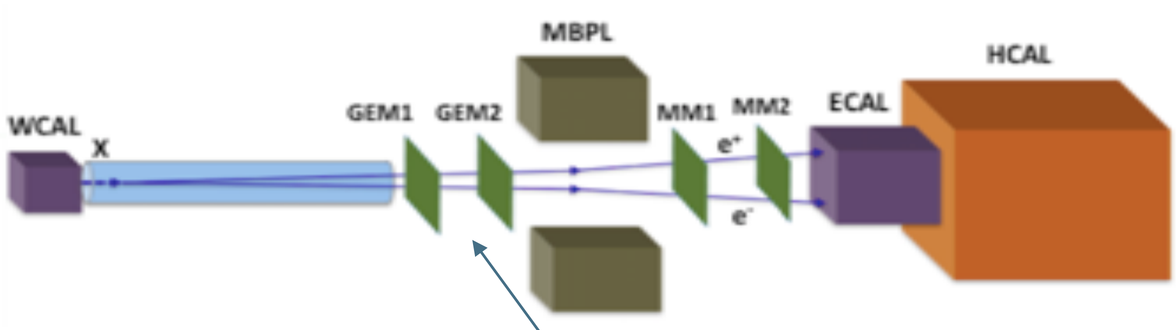


WCAL: 30-40 X_0
Sandwich W-Sc

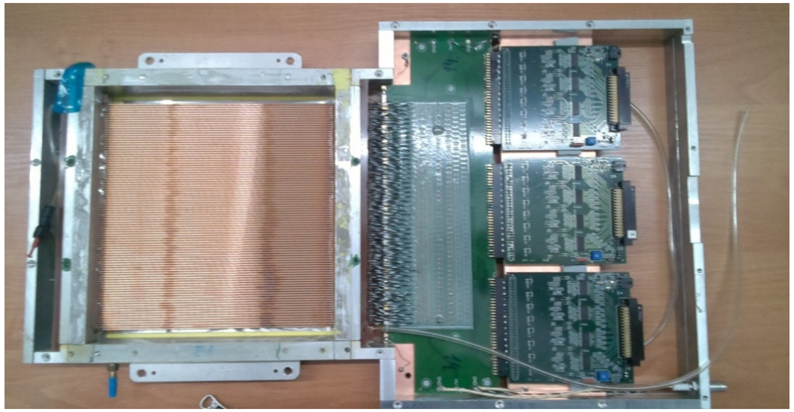


Signature:
1) $E_{WCAL}+E_{ECAL}$ = 100 GeV
2) No activity in $V_{2,3}$ and HCAL
3) Signal in S3, S4
4) e-m shower in ECAL

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

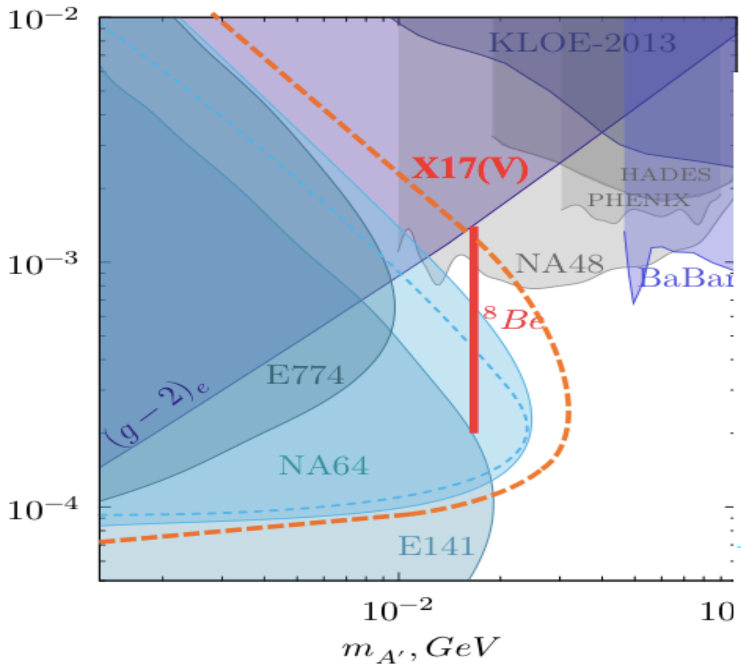


A possibility: 2 мм Straw Tubes chambers

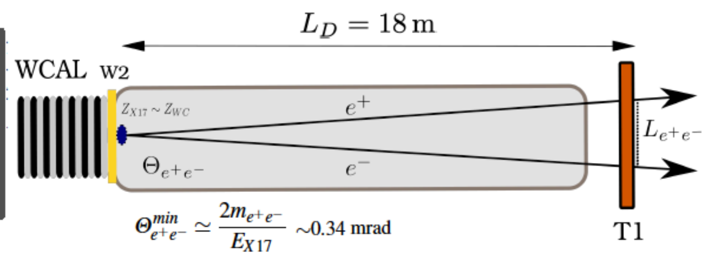


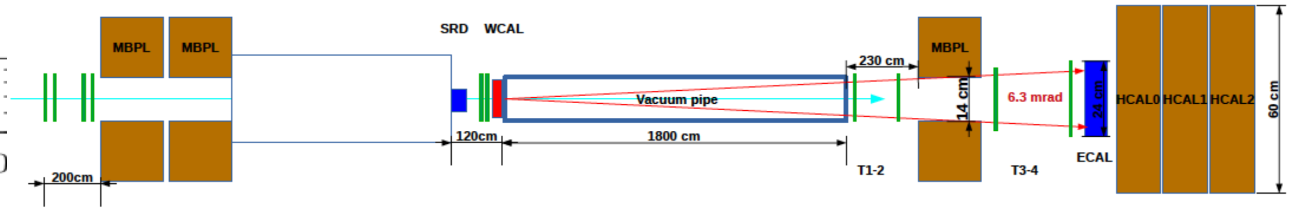
Prototypes of two-layer, 192x2 мм ST, 200 x 200 mm^2

2024 or later: ~ 2 x 10^{11} EOT



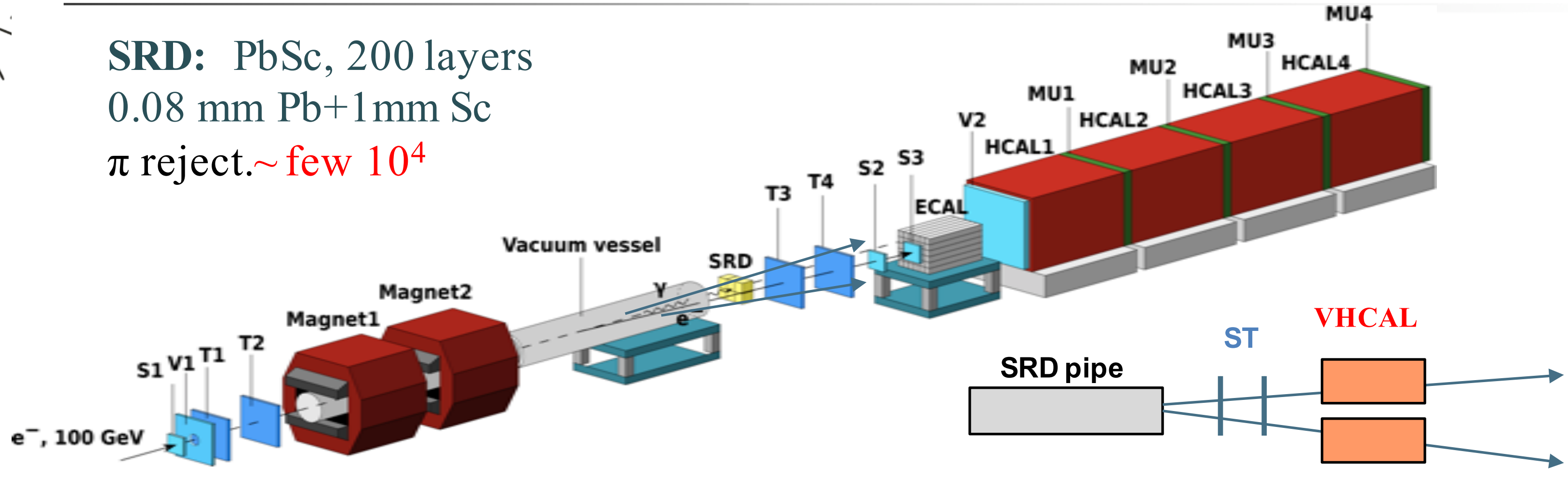
Optimization of WCAL: 20% shorter keeping 30X₀



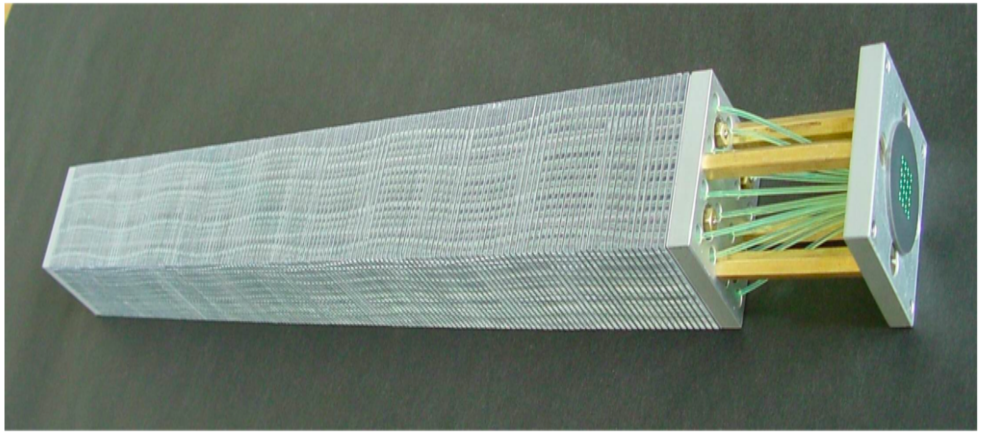


Background

SRD: PbSc, 200 layers
0.08 mm Pb+1mm Sc
π reject.~ few 10^4



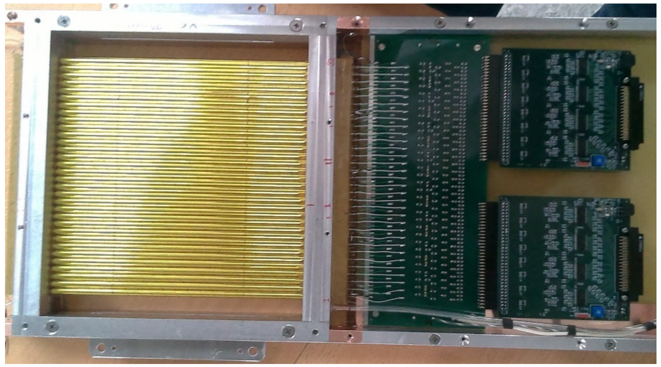
Active damp: shashlik type ECAL cell



Readout WLS fibers go in a spiral to avoid E-leak and dead zones

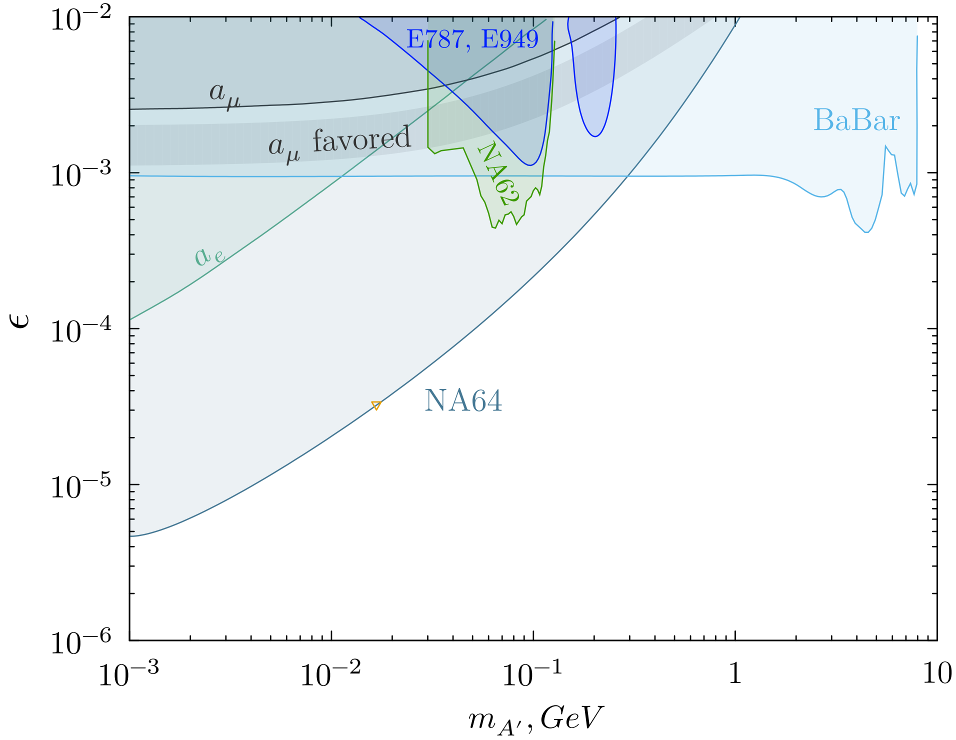
Hermeticity scan shows - **no leak and potential source of background**

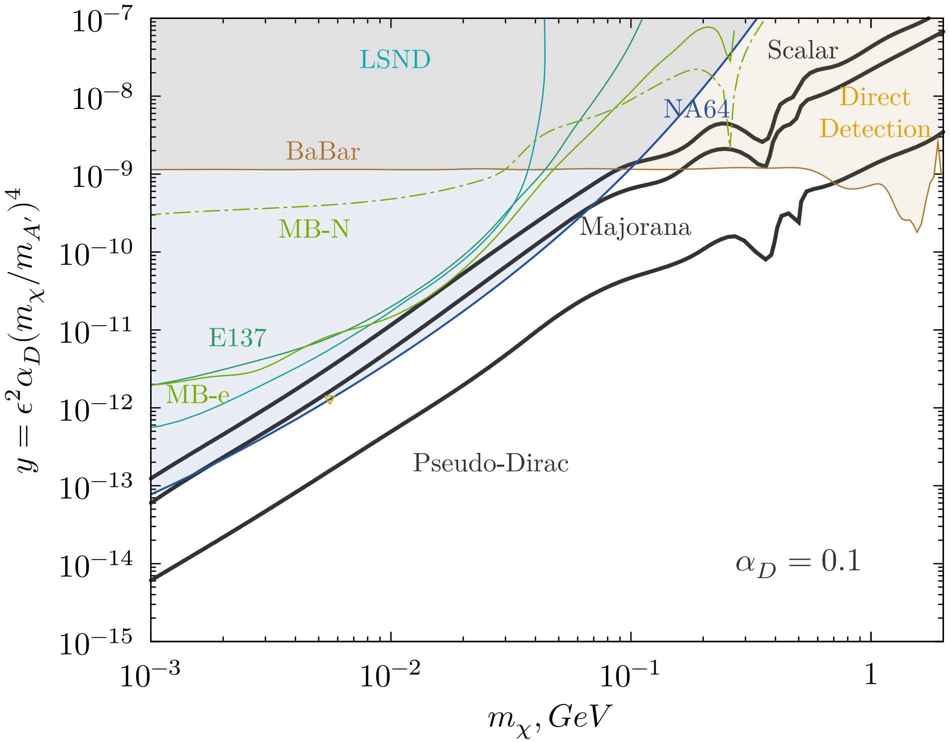
Background due to the insufficient detector hermeticity against charged and neutral hadrons produced in electron beam interactions in the beam material at large angles. It was supressed **for charged secondaries by using Straw Tubes** as a veto.



While for neutrals a veto HCAL (VHCAL) has to be installed in the setup (done in 2023).

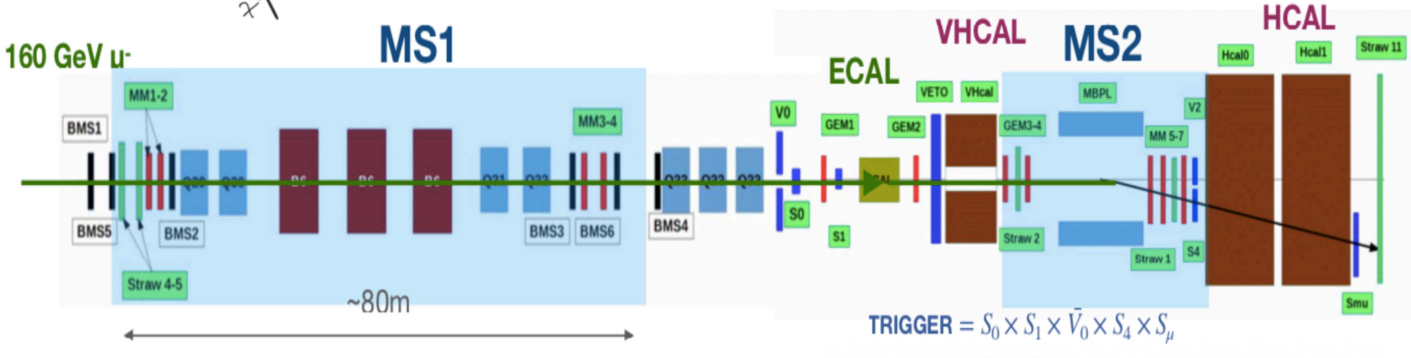
NA64 results from 2016-2022: ~10^{12}eot





Background source	Background, n_b
1. Di-muons losses or decays in the target	0.04 ± 0.01
2. μ, π, K $\rightarrow$ e +... decays in the beam line	0.3 ± 0.05
3. lost neutrals (γ, n, K^0) from upstream interactions	0.16 ± 0.12
4. Punch-through leading n, K_L^0	< 0.01
Total (conservatively) n_b	0.51 ± 0.13

NA64 in muon mode (approved & started in 2021)



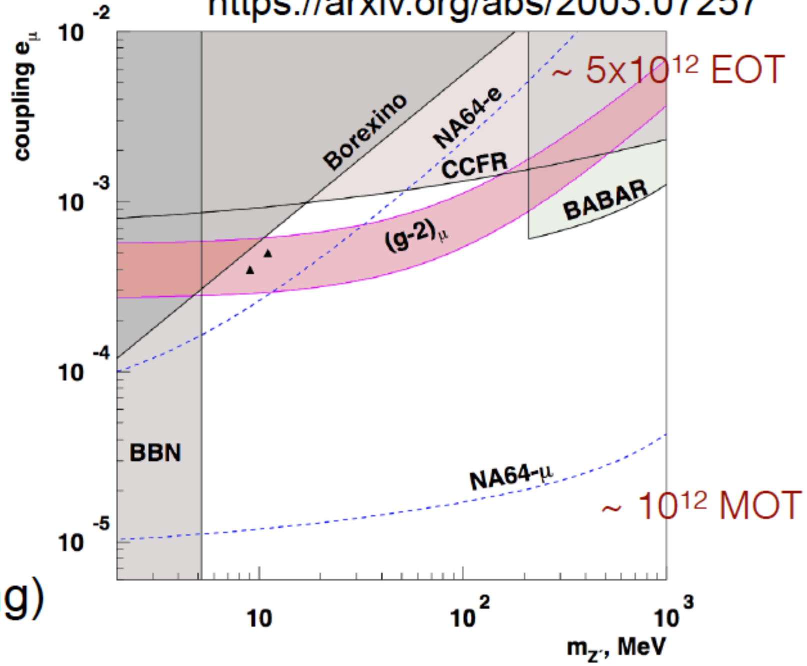
Signature:
1) Tagged 160 GeV incoming muon
2) Scattered muon with <80 GeV
3) No activity in HCAL

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

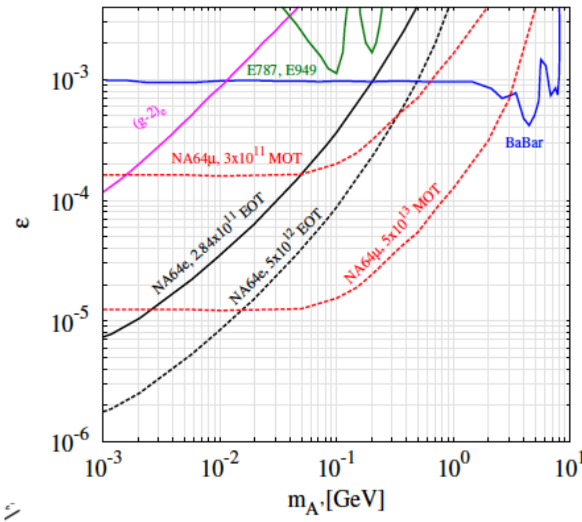


Sensitivity to be update with exact tree level calculations (ongoing)

Muon mode: LDM search

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

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



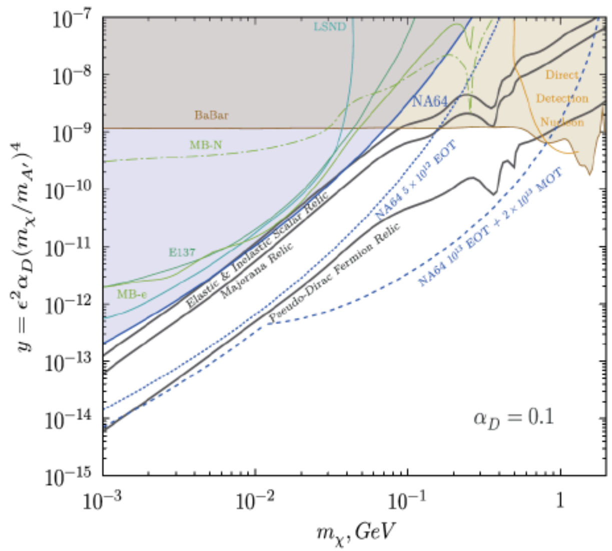
NA64e

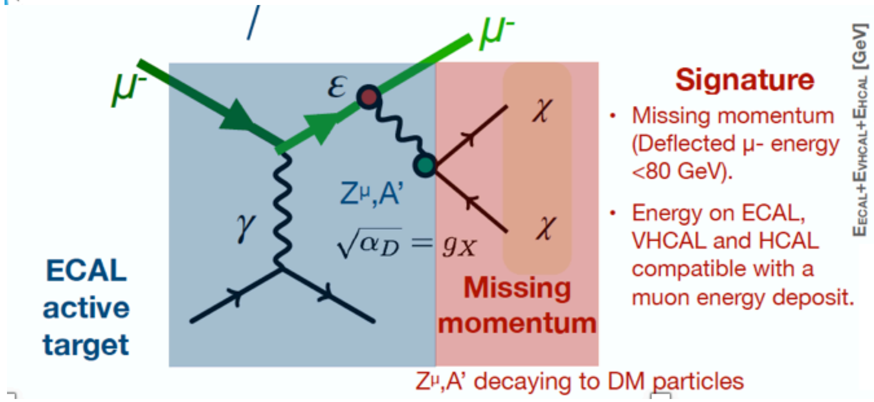
$$N^e_{A'} \sim L^e \sigma^e_{A'}$$
$$L^e \simeq X_0$$
$$\sigma^e_{A'} \sim \epsilon_e^2 / m^2_{A'}$$

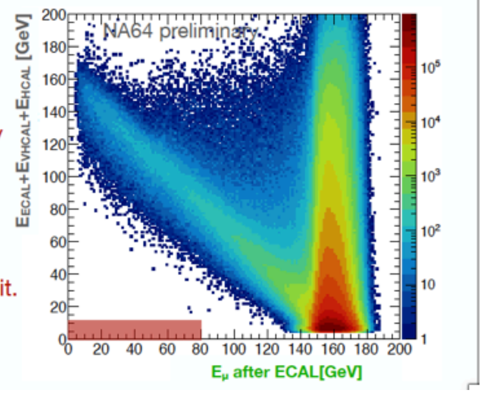
NA64μ

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

Combined LDM sensitivity of NA64e -NA64μ







Signal like event comprises: E_{init}=160 GeV, E_{out}<80 GeV, the total MIP energy in calorimeters E_{CAL}<12 GeV

Muon mode: LDM search

The selection criteria:

- *single muon* transversing the set up
- *initial muon* E_{init} = 160 GeV , momentim window 140-180 GeV
- *beam spot* criteria: ensured it is not muon from the beam halo
- initial *muon* impinges target (ECAL) central cell with one MIP ~1 GeV
- single track after the target compatible with MIPs (~2.5 GeV) in HCALs
- no secondaries in VHCAL and in the tracking detectors after VHCAL

Expected background for 2022 pilot run with 2 10^{10} mot

Background source	Background, n_b
Momentum mis-reconstruction	0.045 ± 0.031
Hadron in-flight decays	0.010 ± 0.001
Calorimeter non-hermeticity	< 0.01
Total (conservatively) n_b	0.065 ± 0.032

Outlook & conclusions

NA64 reached and exeeded a major milestone of accumulating ~ 1.5 10^{12} EOT which allows one to start probing very interesting LDM benchmark models. The analysis is ongoing and with the increased statistics we expect to improve the sensitivity for ALPs, $L\mu$-$L\tau$ and B-L Z' bosons, ,....
The plan until LS3 is to accumulate as many as possible electrons on target (up to 5 10^{12}) and also use the positron mode to enhance the sensitivity in the higher A' mass region.

NA64 started its program at the M2 beam-line providing unique high intensity 160 GeV muons to explore dark sectors weakly coupled to muons. 1.5 10^{11} mot were collected. The results of the pilot runs show that with an optimized setup, we can collect 6 10^{11} MOT before LS3 in order to check if an $L\mu$-$L\tau$ Z' boson as the explanation of the g-2 muon anomaly and complement the searches with electrons.

After LS3 the experiment would then continue data taking to accumulate ~ 10^{13} MOT to explore the A' higher mass region and $\mu \to \tau$ and $\mu \to e$ LFV processes.

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

Tnank you!