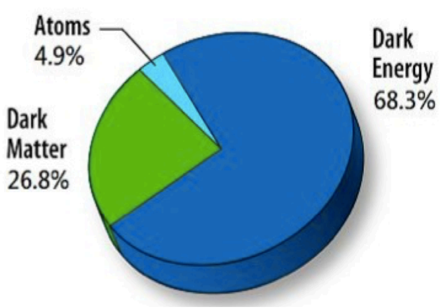
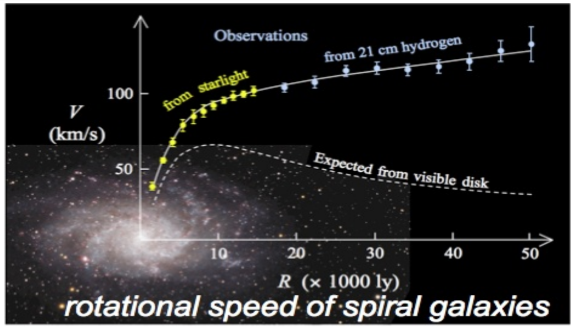
«Search for the dark sectors in missing energy events»

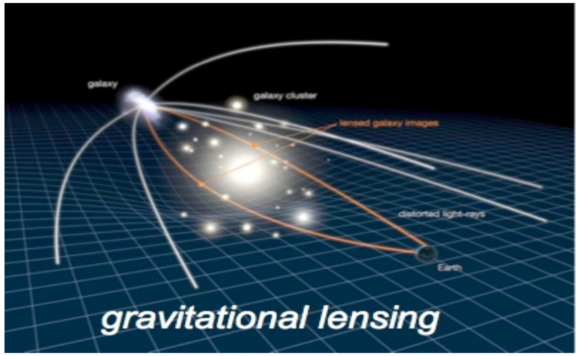
Motivation



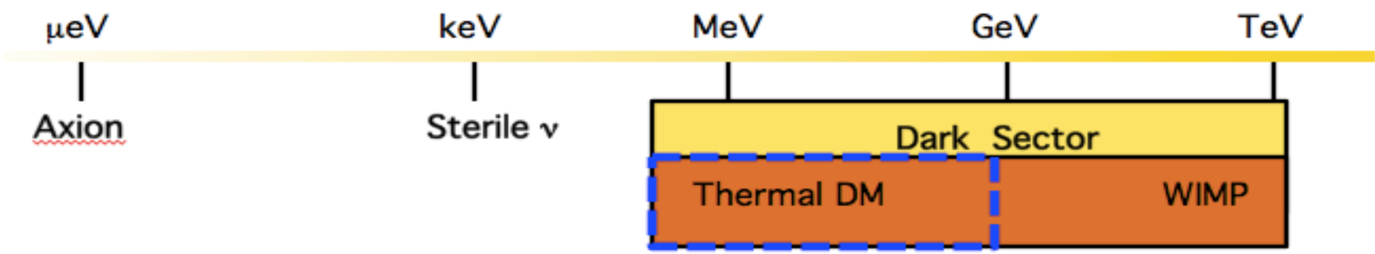
Existence of DM is firmly established:
rotational curves of galaxies, lensing, …

- 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



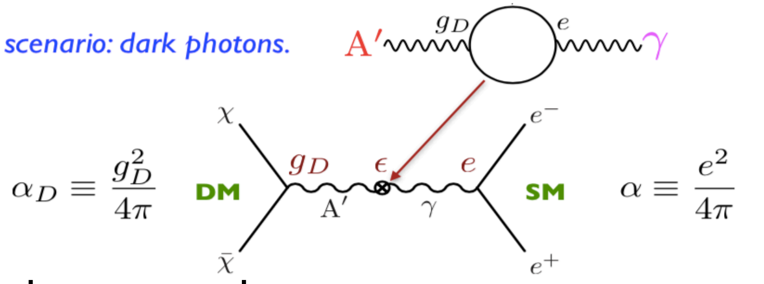
WIMPs (χ) (m_χ, g_χ) ~ (m_{EW}, g_{EW}) - are not seen at LHC and in direct searches.
ρ_{DM}~ 0.3 GeV /cm^3 in Solar system => n_{WIMP} (~1 TeV) ~ $10^3/m^3$, a very low counting rate.

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

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 → $\gamma\ \gamma$ 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*

JINR participation in the NA64 project

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)

LHEP: G.Kekelidze, V.Kramarenko, V.Lysan, I.Zhukov, T.Enik, K.Salamatin, I.Kambar, P.Volkov, D.Peshekhonov, E.Kasianova, S.Gertsenberger, A.Ivanov
LTP: V.A.Matveev, A.Zhevlakov
LNP: V.Frolov

FTE:

Detector operation & support - 3,0;
Analysis and MC simulation - 3,0;
Theory - 0,5

Young reseachers:

K.Salamatin (Ph.D.), I.Kambar, P.Volkov, E.Kasianova, S.Gertsenberger, A.Ivanov, A.Zhevlakov(Ph.D.)

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) ~$4{,}5 \times 10^{10}$eot,

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

2018 – 6 weeks at H4 (NA64e) ~$2{,}0 \times 10^{11}$eot,

2017-18 in visible mode ~ $8{,}4 \times 10^{10}$eot,

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

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

e^+ ~ $5{,}0 \times 10^{10}$eot

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

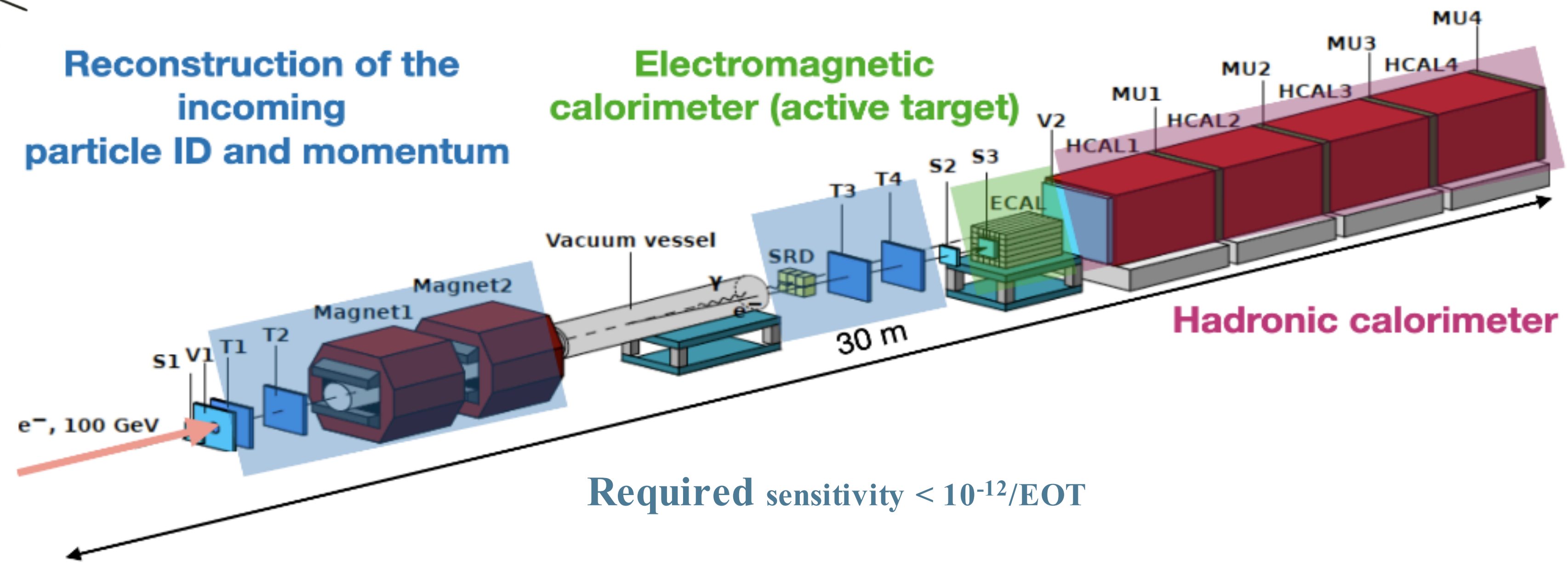
2021 – 3 weeks pilot-run at M2 (NA64μ)

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

Total accumulated ~4×10^{10}μot

2023 – 8 weeks NA64e & 3 weeks NA64μ

NA64 approach



Required sensitivity < 10^{-12}/EOT

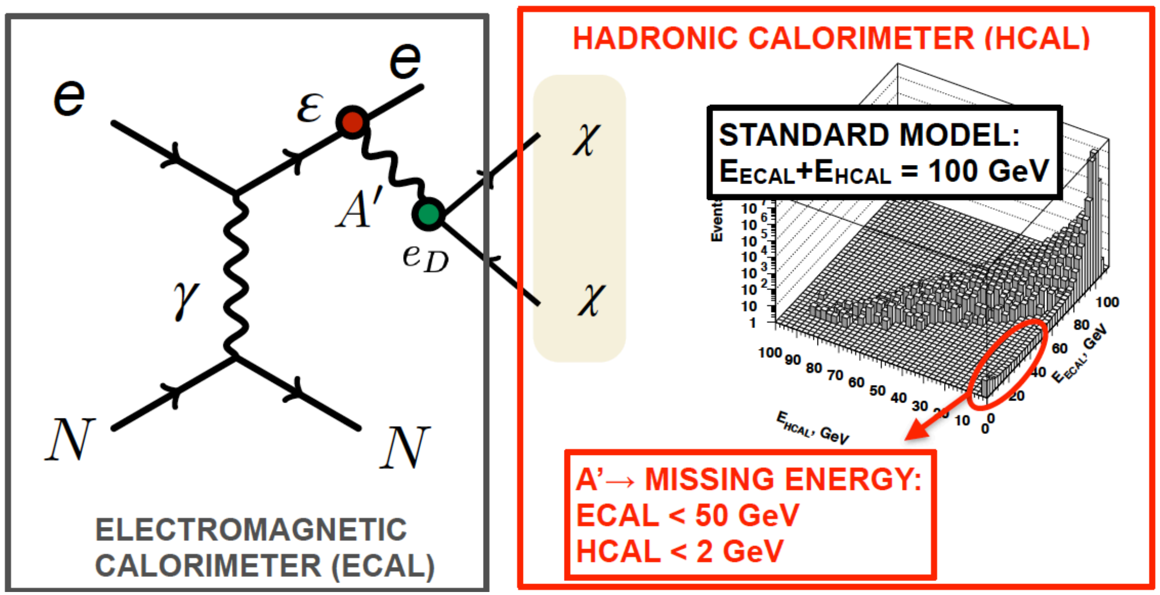
Main components :

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

Signature:

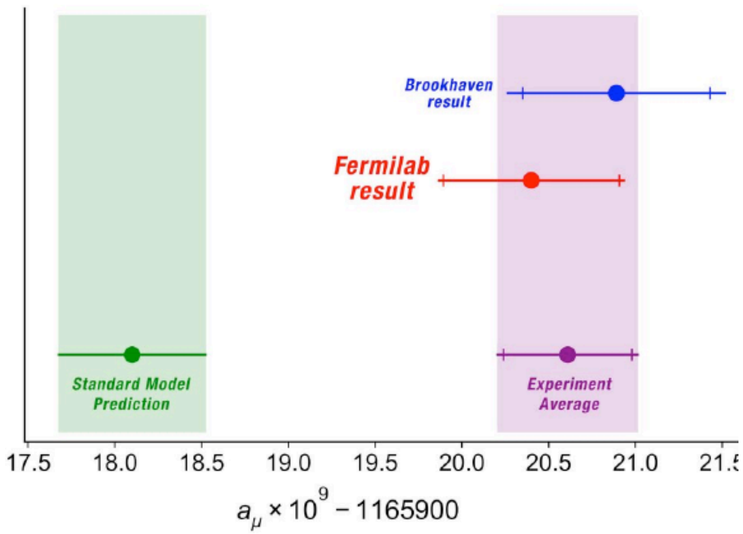
- in: 100 GeV e- track
- out: $E_{ECAL} < E_0$ shower in ECAL
- no energy in Veto and HCAL

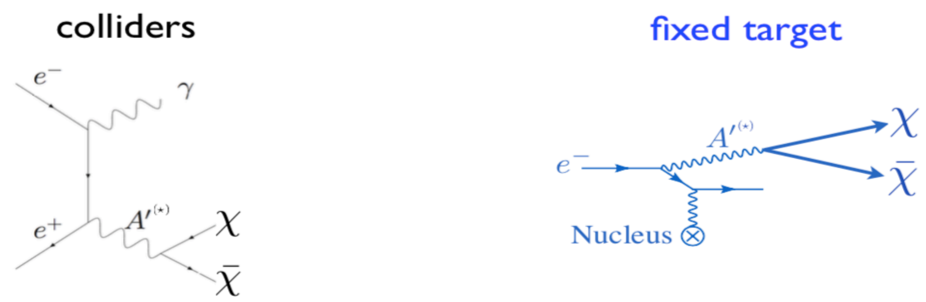
Bremsstrahlung of A'



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

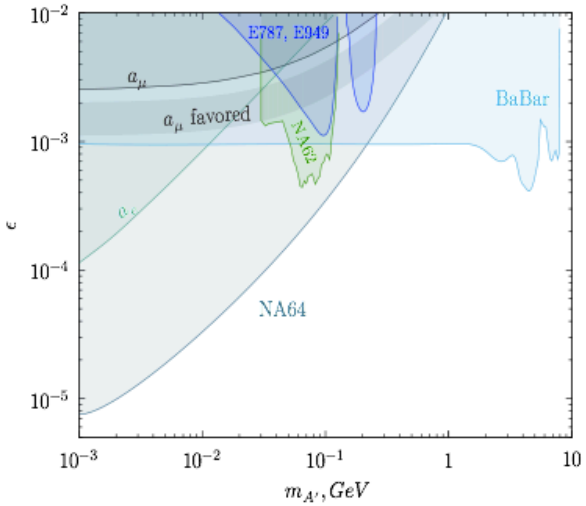
B. Abi, et al. Phys. Rev. Lett. 126, 141801 (2021)

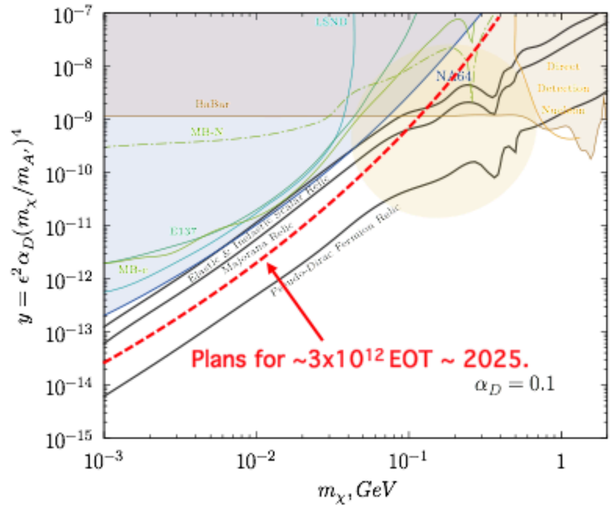




$$\sigma \propto \frac{\epsilon^2}{E_{\rm cm}^2} \ll \sigma \propto \frac{Z^2\epsilon^2}{m_{A'}^2}$$

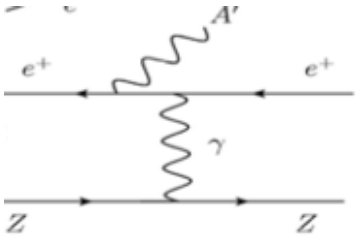
- BaBar $e^+e^- \to \gamma A'$; $A' \to$ invisible
- NA64 $e^- Z \to e^- Z A'$; $A' \to$ invisibl





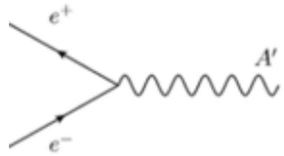
- Most stringent bounds compare to LSND, SLAC, MiniBooNE with $\sim 10^{20}$-10^{22} POT. Sensitivity of NA64 $\sim\varepsilon^2$, while for the beam-dump it’s $\sim\varepsilon^4\alpha_D$
- Plans to cover $m_{A'} \leq m_\mu$ area with ~ a few 10^{12} EOT
- Challenge: high mass region $m_{A'} \geq \sim m_\mu$, 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



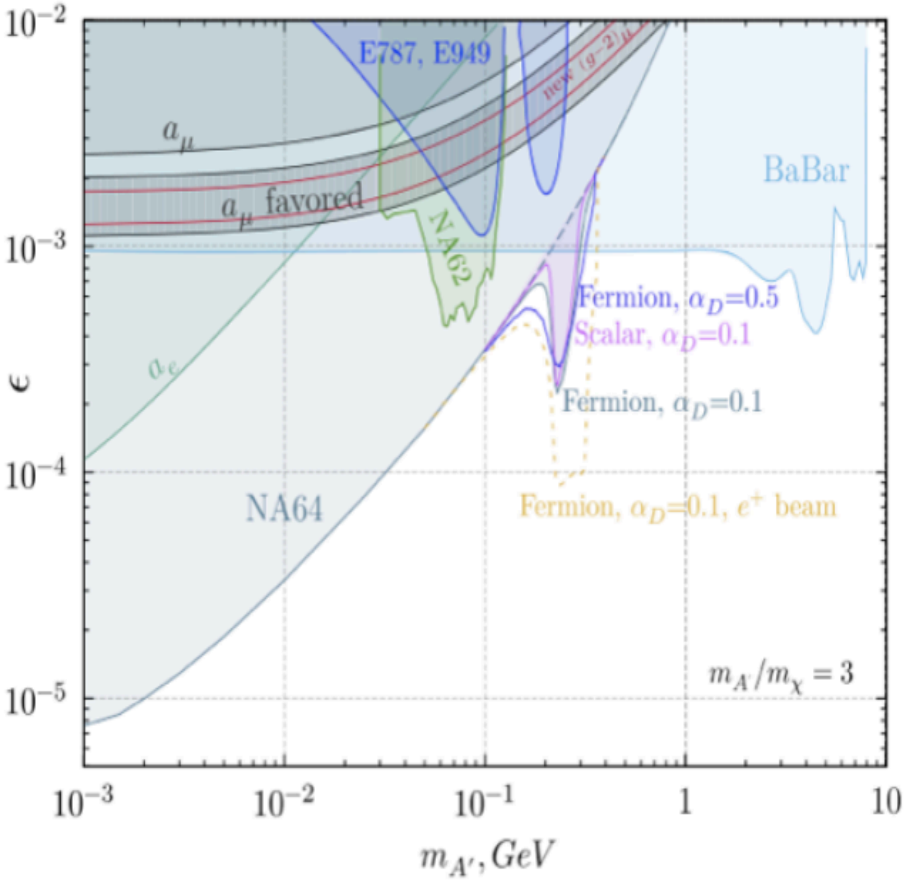
$\sigma \sim Z^2\alpha^3\varepsilon^2$ vs

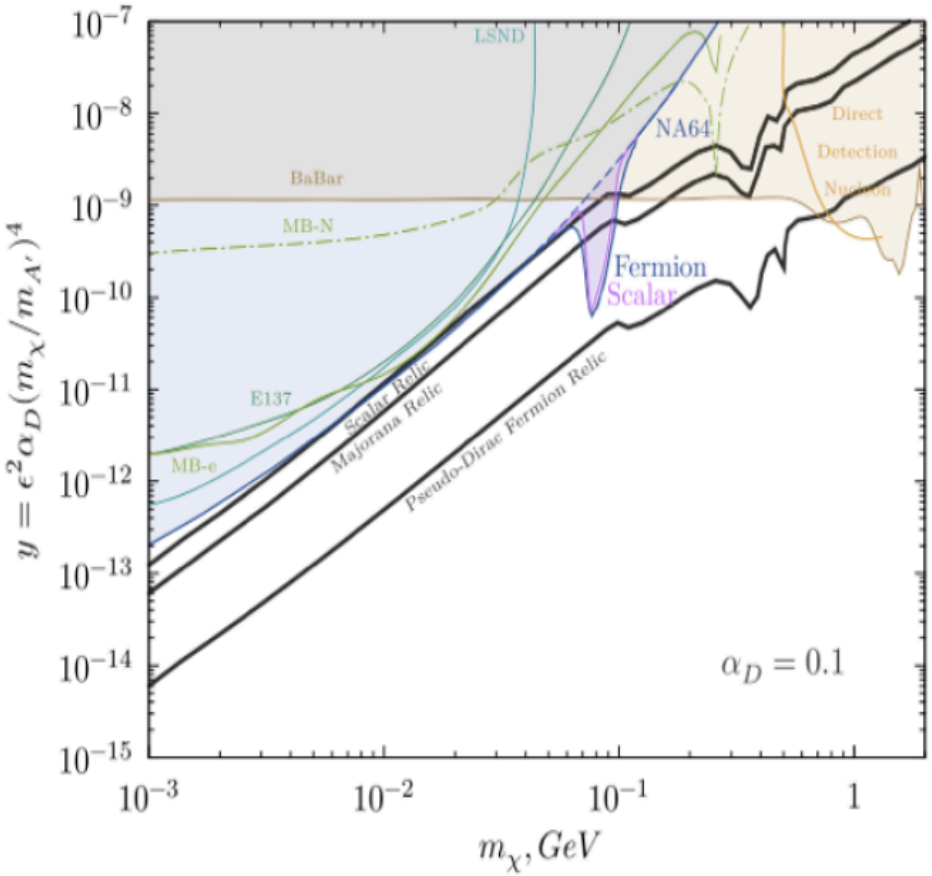
$m_{A'} \sim (2m_eE_0)^{1/2}$



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

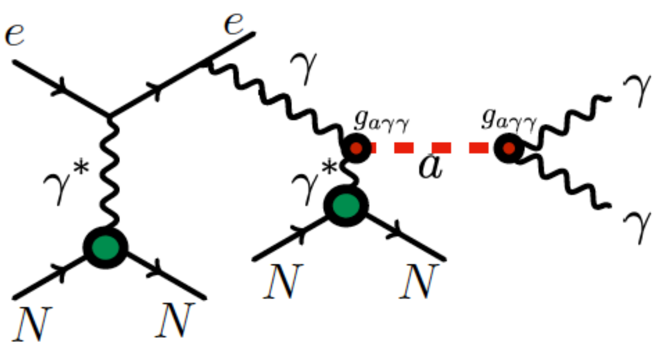
For masses $m_{A'} \sim$ 220-320 MeV a factor ~O(10) improvement in ε, and ~O(10^2) in y (~ε^2). Possibility to scan masses >100 MeV vs e+ energy



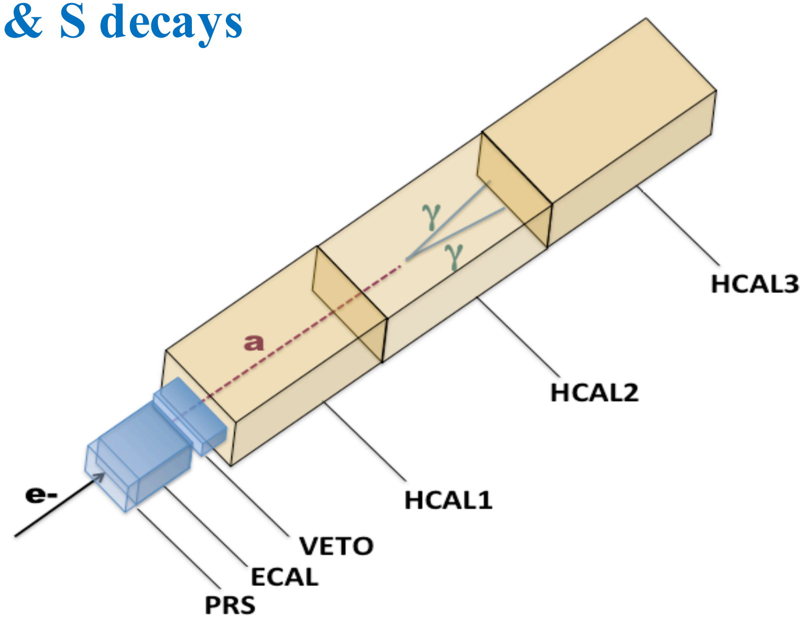


NA64e potential for new physics

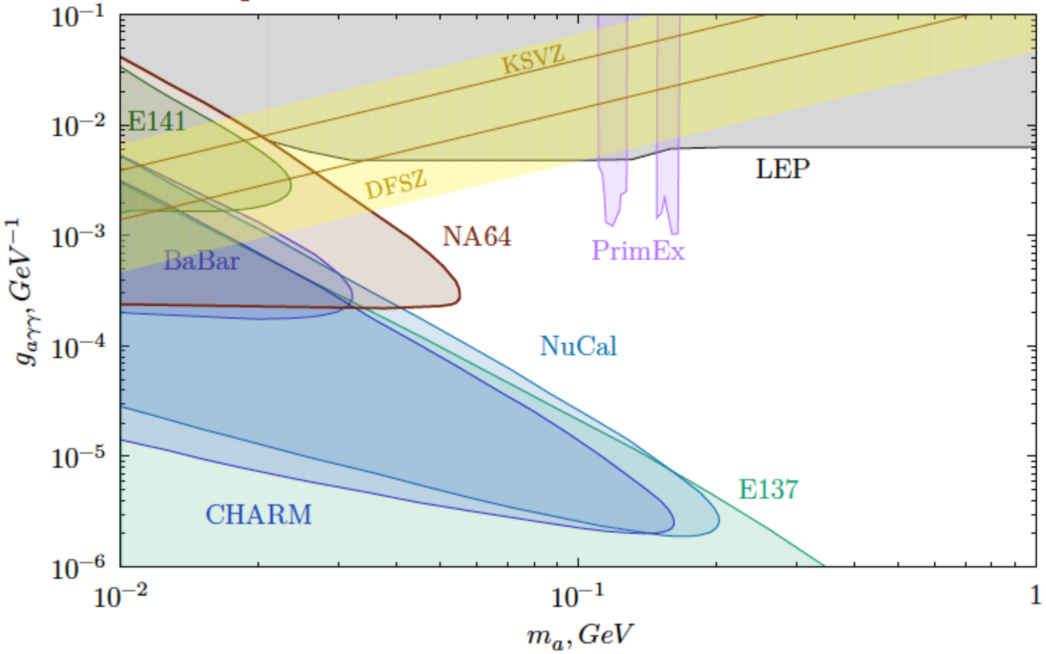
Search for axion, ALP & S decays



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

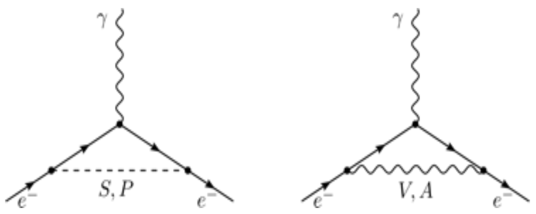
Constraints on dark S,P,V,A and $(g\text{-}2)_e$ from high-precision measurements of α

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

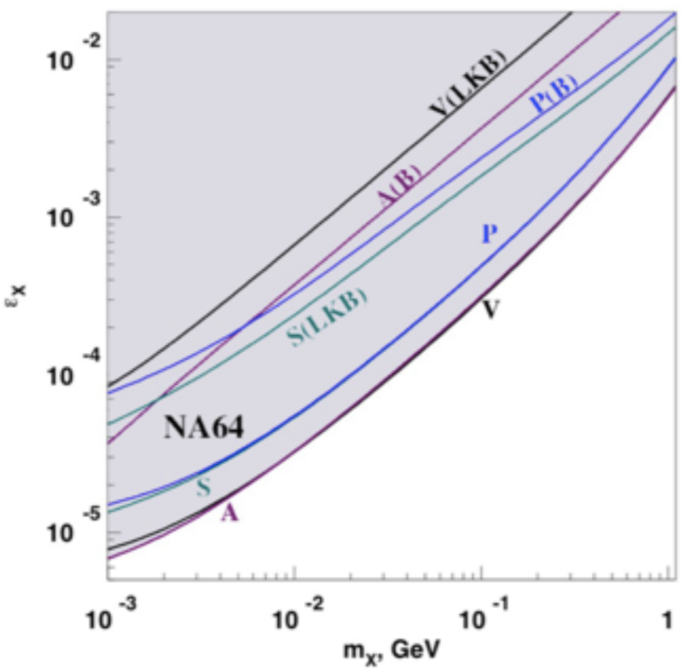
$$\Delta a_e = a_e^{exp} - a_e^{LKB} = (4.8 \pm 3.0) \times 10^{-13} \qquad (1)$$
$$\Delta a_e = a_e^{exp} - a_e^{B} = (-8.8 \pm 3.6) \times 10^{-13} \qquad (2)$$

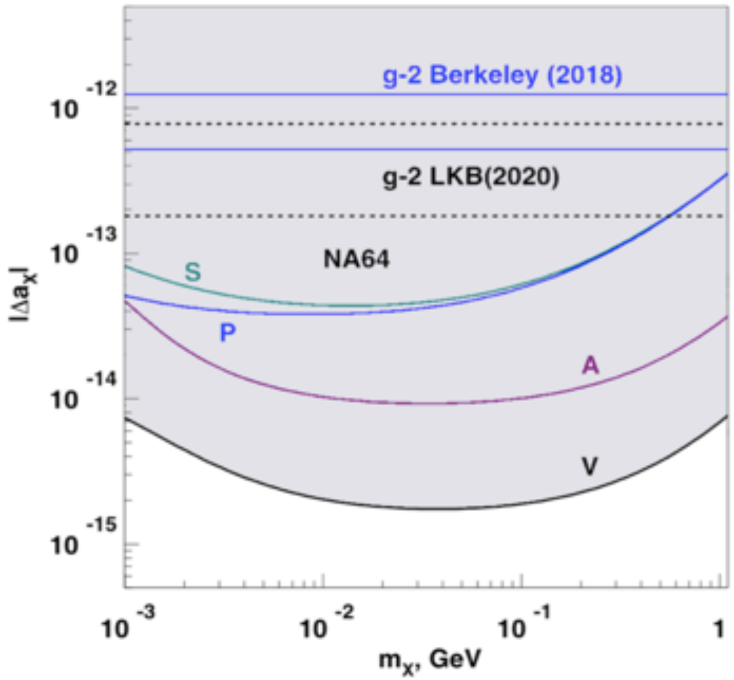
NA64,Phys.Rev.Lett.(2021)

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



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



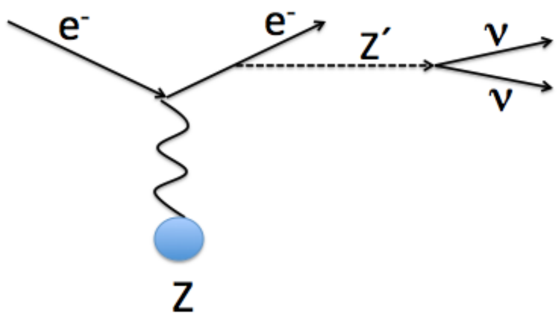


NA64 provided most stringent constraints on new physics contribution $\Delta a_X < 10^{-15} - 10^{-13}$ for X=$S, P, V,$ or A compared to LKB and Berkley high-precision measurements

NA64e potential for new physics

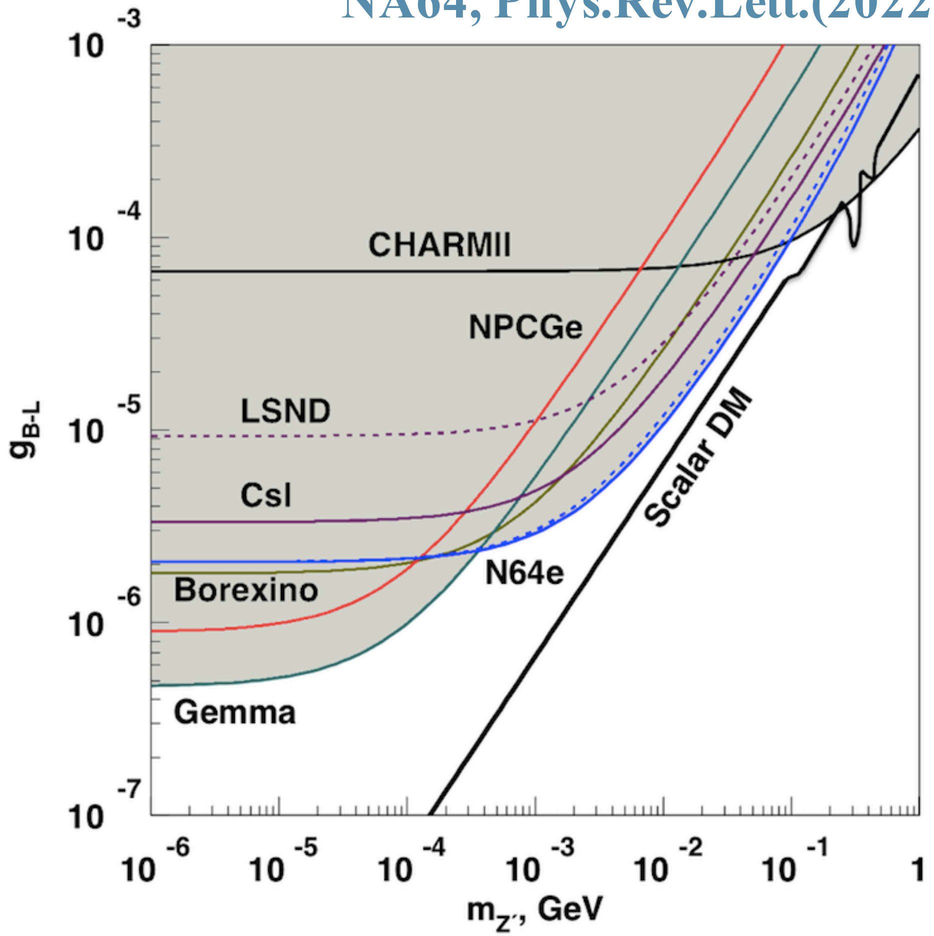
Search for new B-L Z' boson

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



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

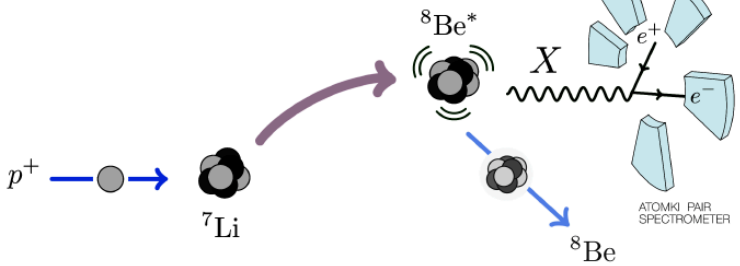
NA64, Phys.Rev.Lett.(2022)



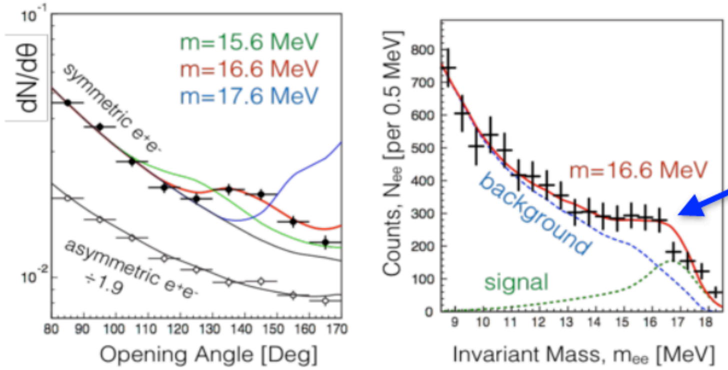
NA64 provided most stringent constraints on B-L Z′ compared to ν - e- scattering data

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

^{8}Be anomaly and X boson

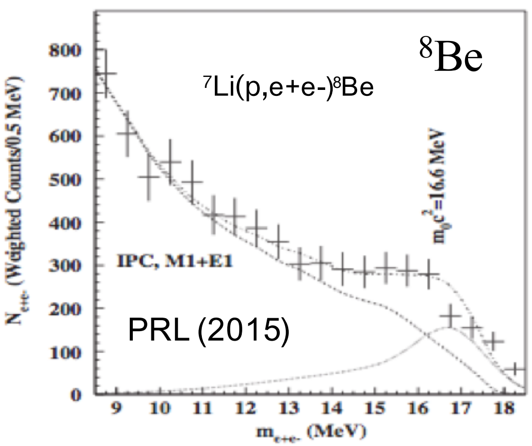


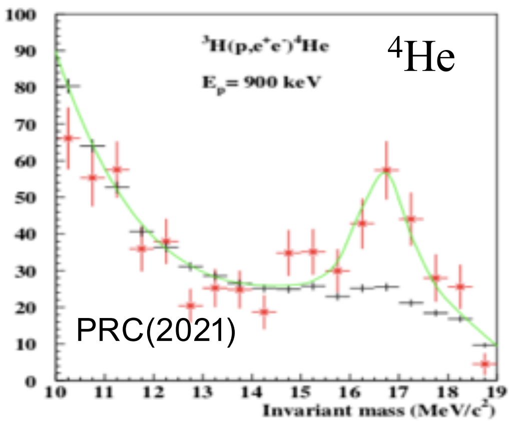
A. J. Krasznahorkay et al. Phys. Rev. Lett.116, 042501 (2015)
and recent results for 4He arXiv:1910.10459

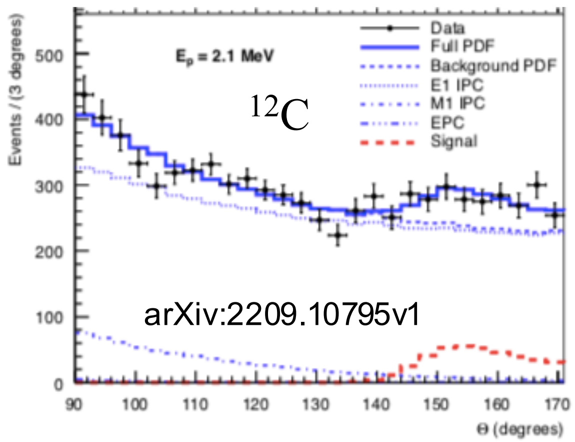


Could be explained by new 'protophobic' gauge boson X with mass around 17 MeV

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

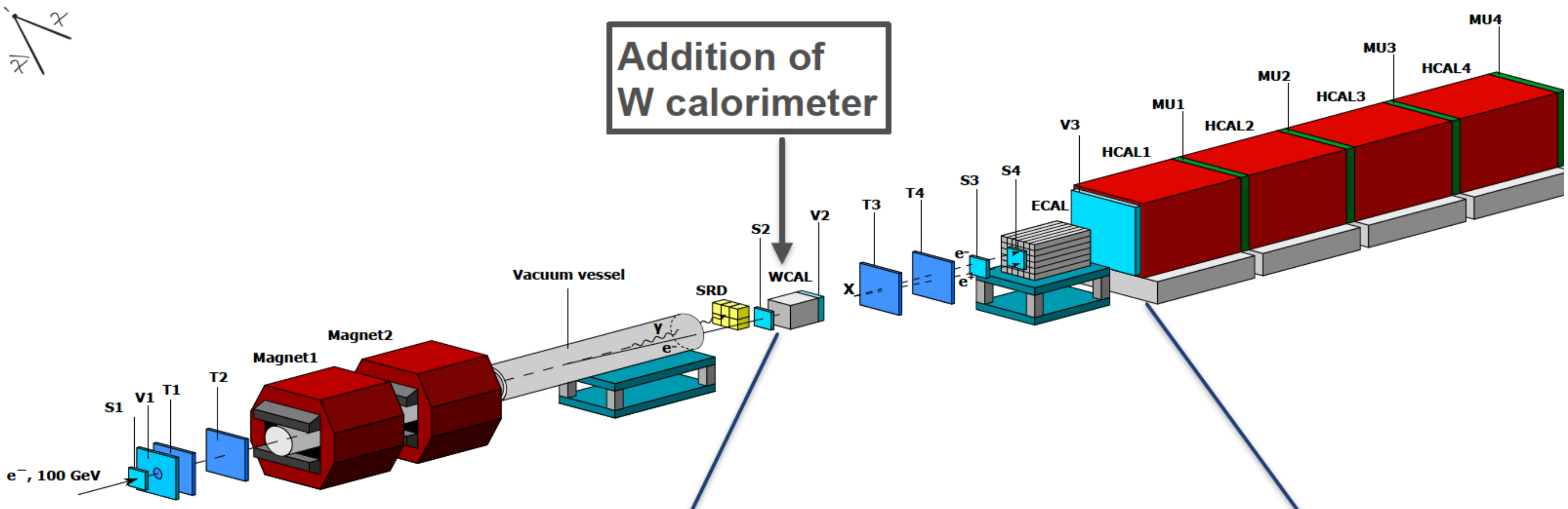






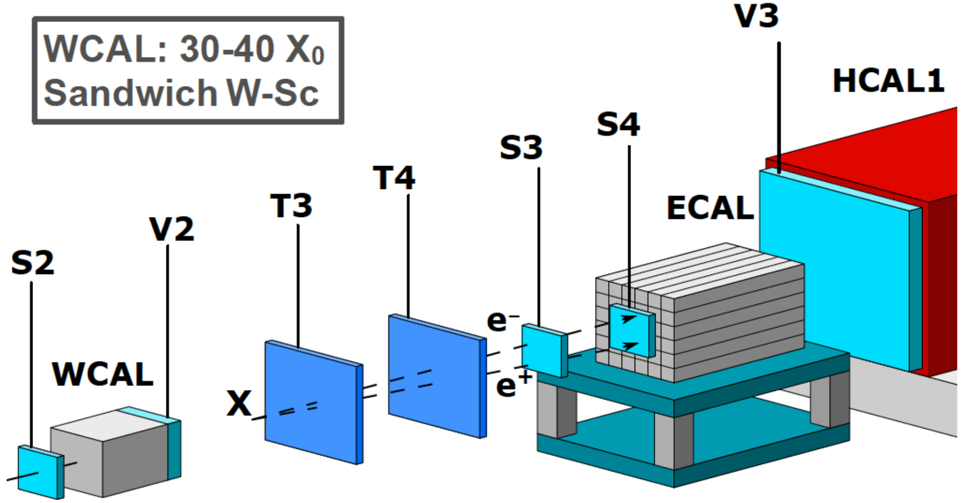
Visible mode: ^{8}Be* anomaly – new X boson?

Addition of W calorimeter



Zooming

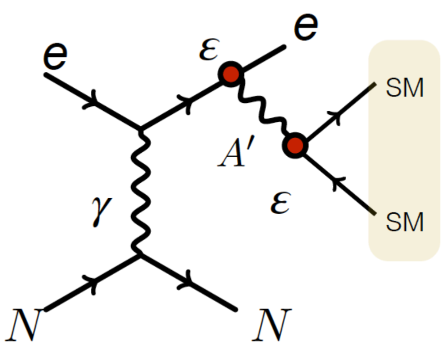
WCAL: 30-40 X_0
Sandwich W-Sc



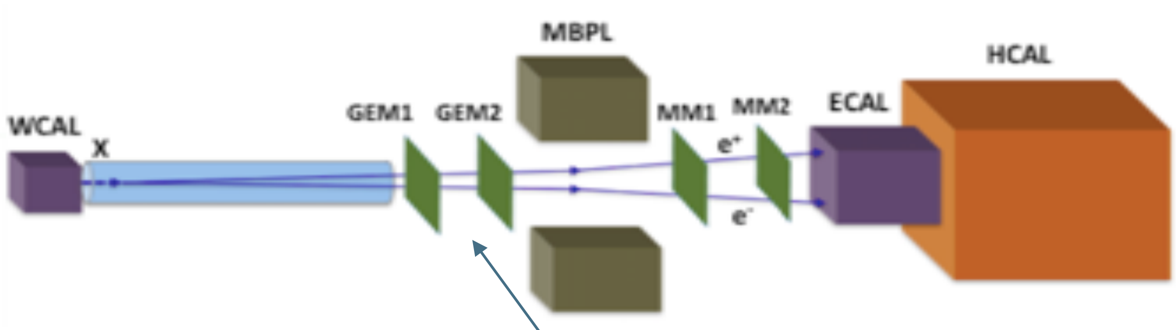
Signature:

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

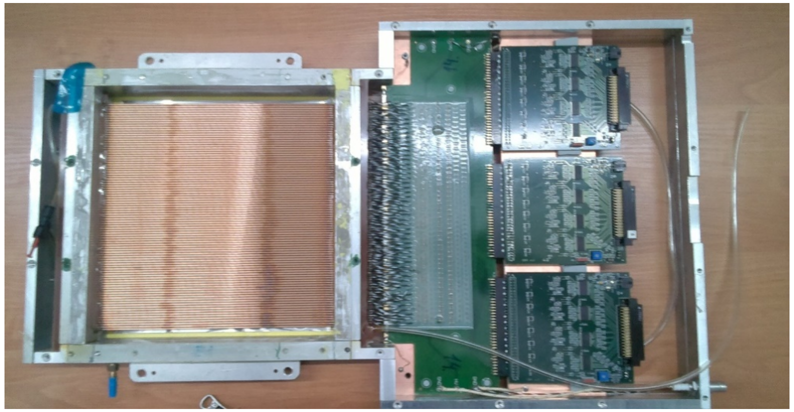
VISIBLE DECAY MODE $m'_A < 2m_X$



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

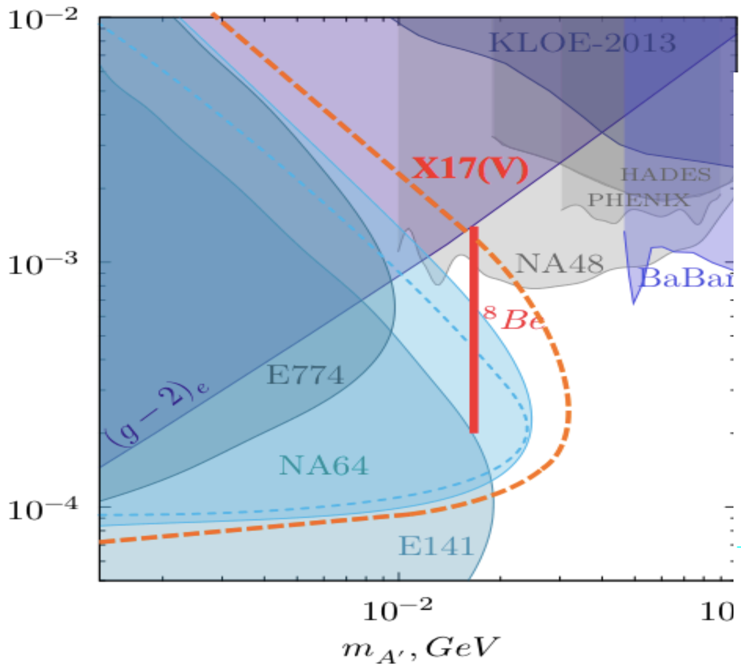


A possibility: 2 мм Straw Tubes chambers

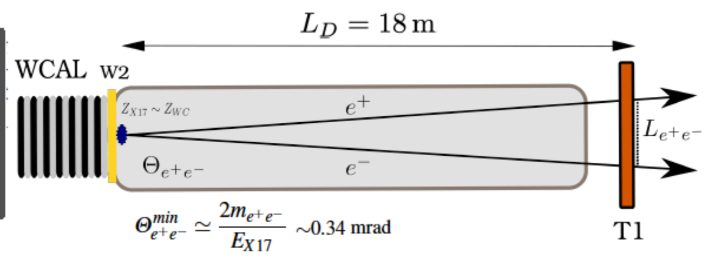


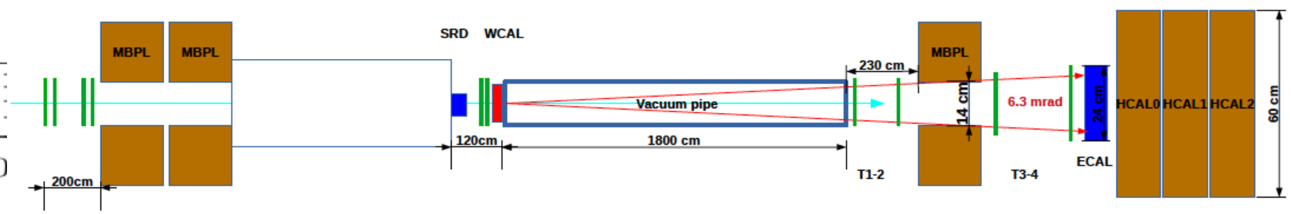
Prototypes of two-layer, 192x2 мм ST, 200 x 200 mm^2

2024: ~ 2 x 10^{11} EOT



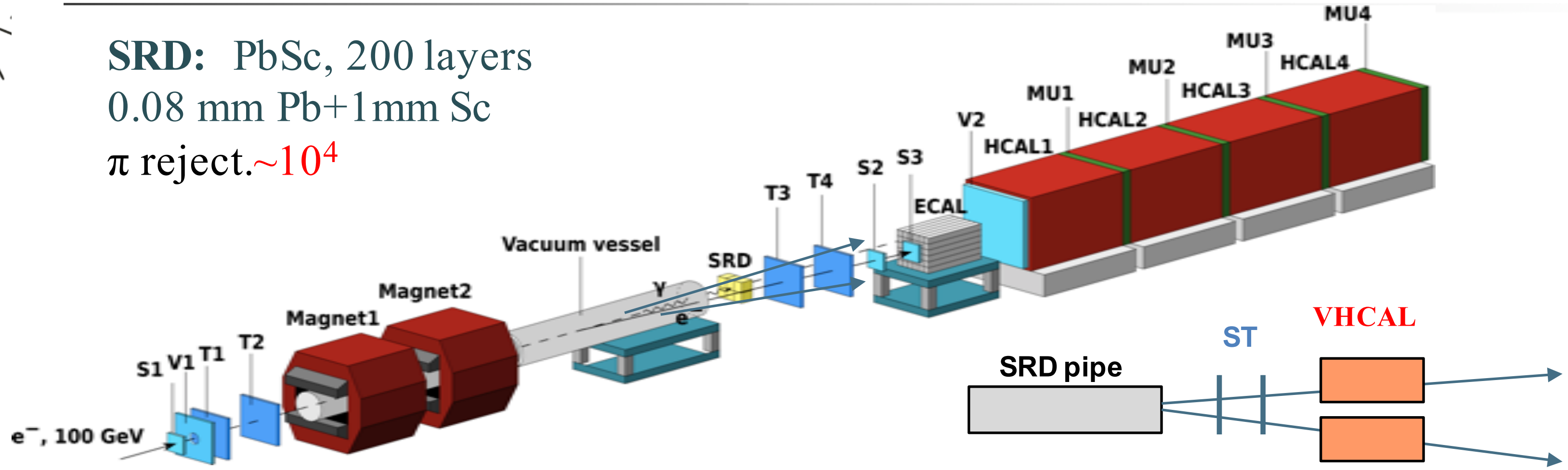
Optimization of WCAL: 20% shorter keeping 30X$_0$



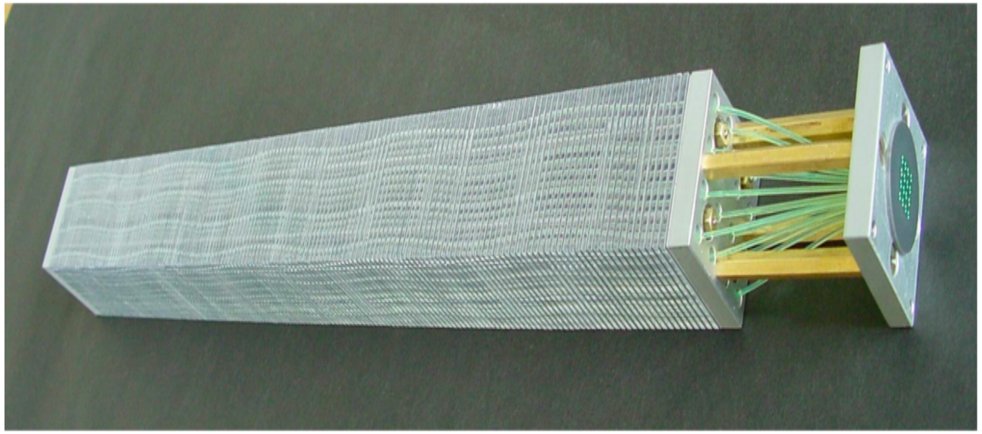


Background

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



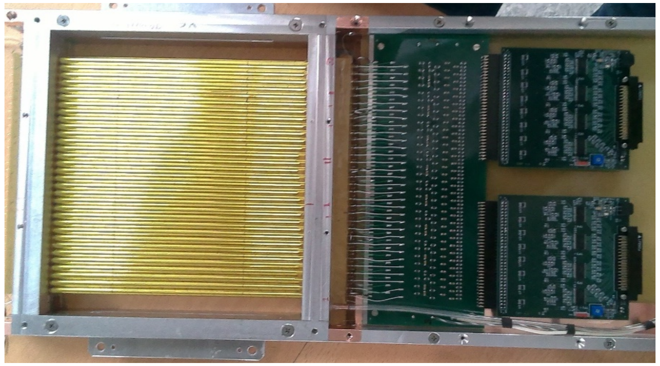
Active damp: shashlik type ECAL cell



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

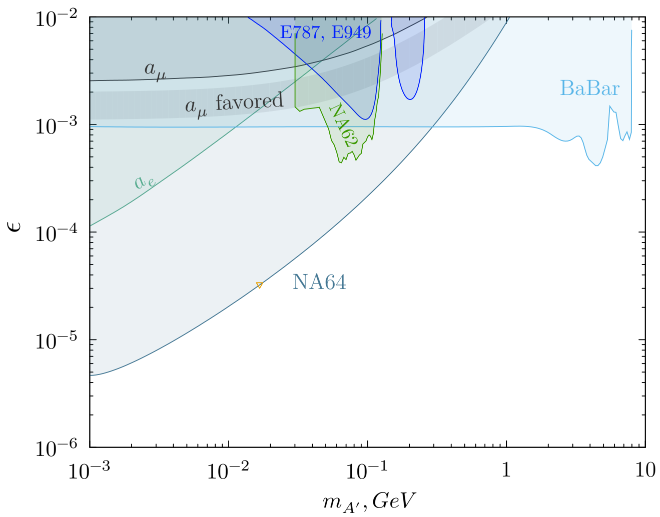
Hermeticity scan shows - **no leak and potential source of background**

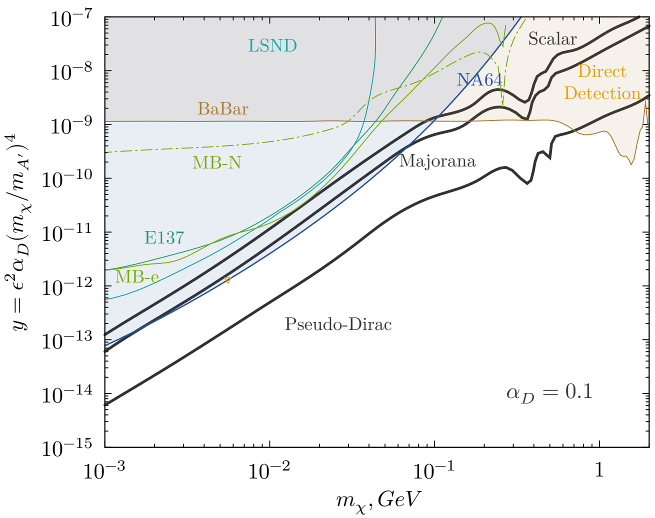
Background due to the insufficient detector hermeticity against charged and neutral hadrons produced in electron beam interactions in the beam material at large angles. It was supressed **for charged secondaries by using Straw Tubes** as a veto.



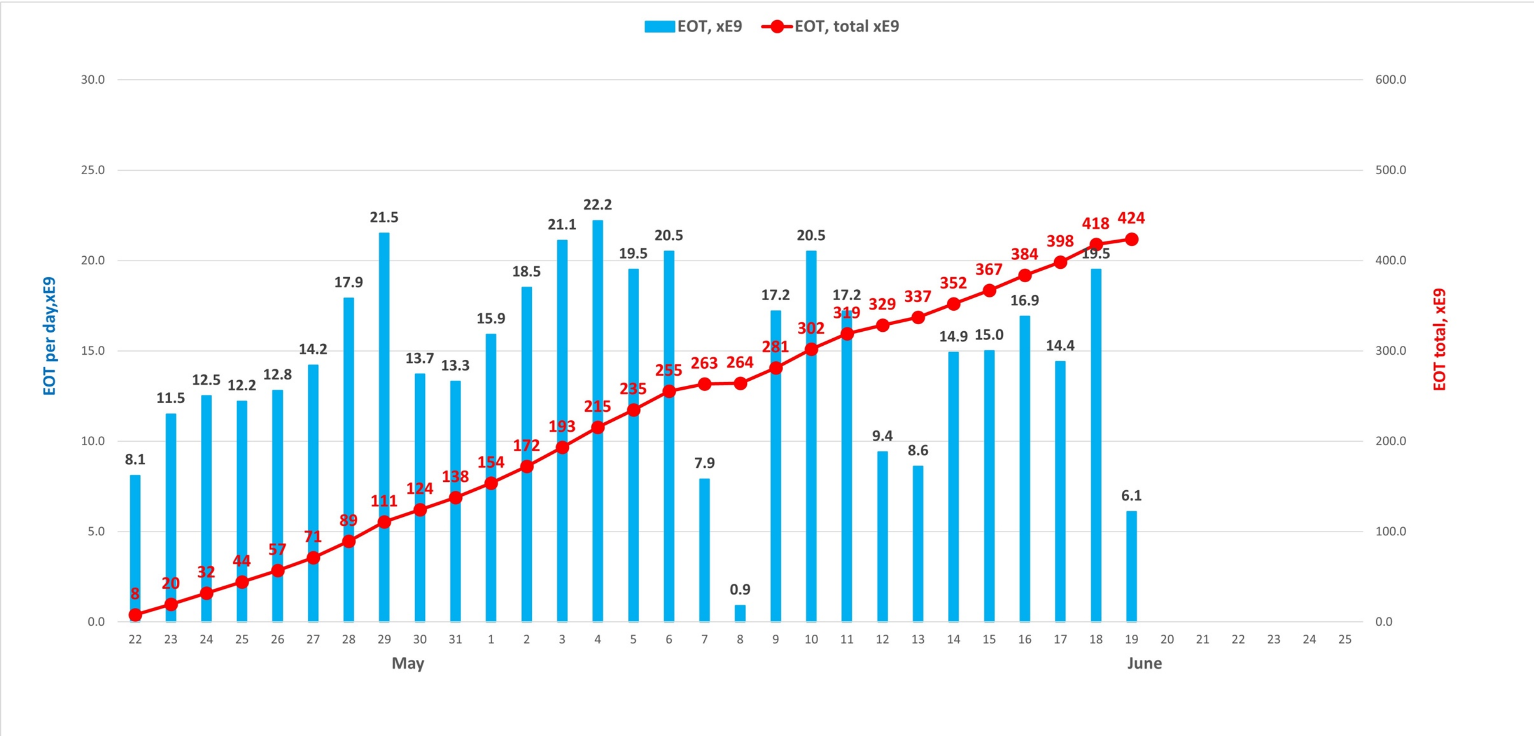
While for neutrals a veto HCAL (VHCAL) has to be installed in the setup (done in 2023).

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

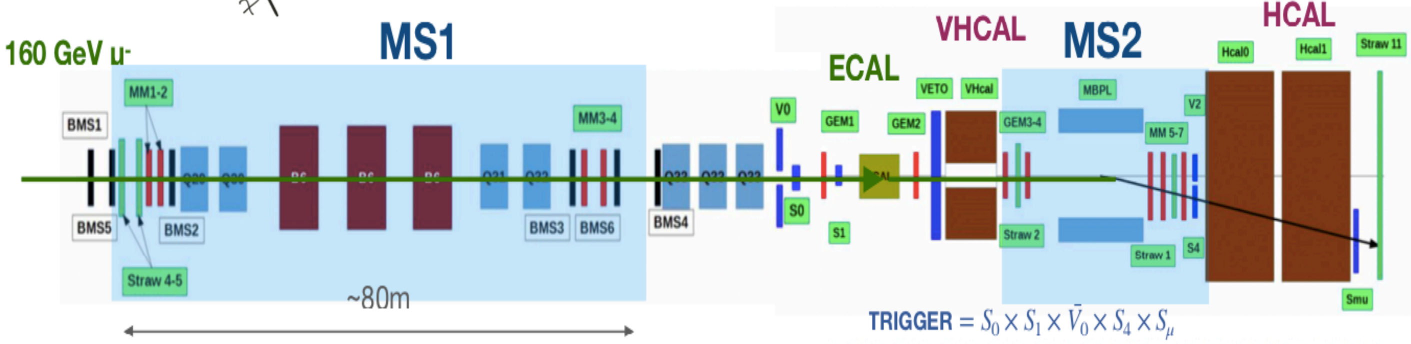




2023 data taking status



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

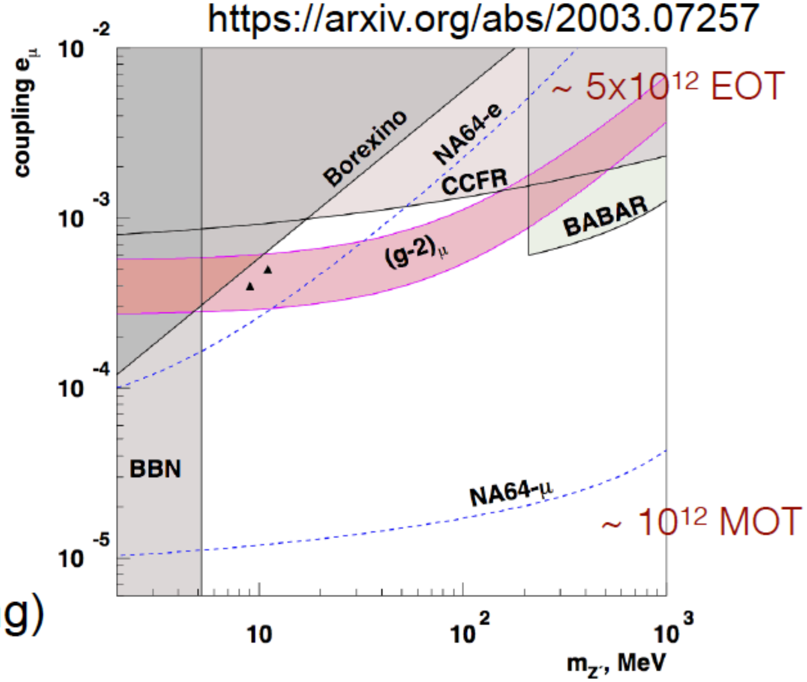
CERN SPS **M2 160 GeV muon beam** offers unique opportunities to further **searches for DS** of particles predominantly weakly-coupled to 2nd second and possibly 3rd generations of the SM.

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

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

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

https://arxiv.org/abs/2003.07257

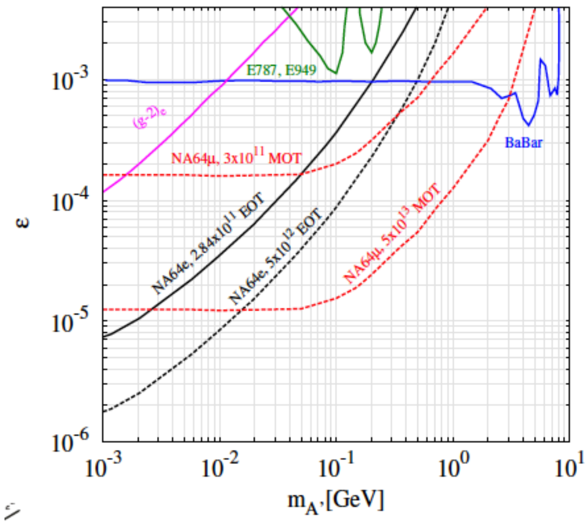


Muon mode: LDM search

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

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

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

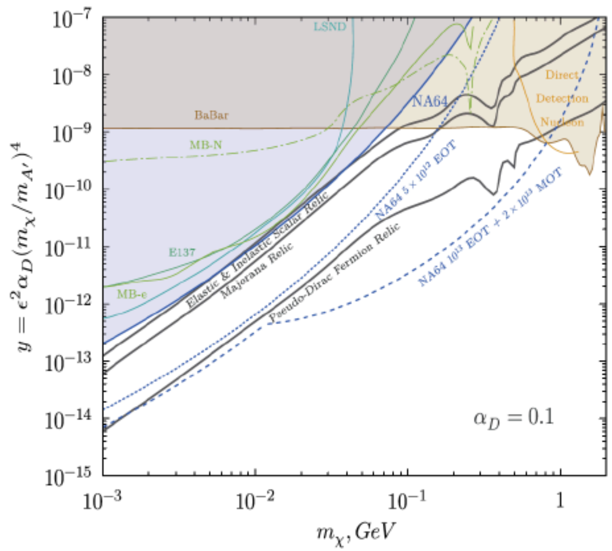


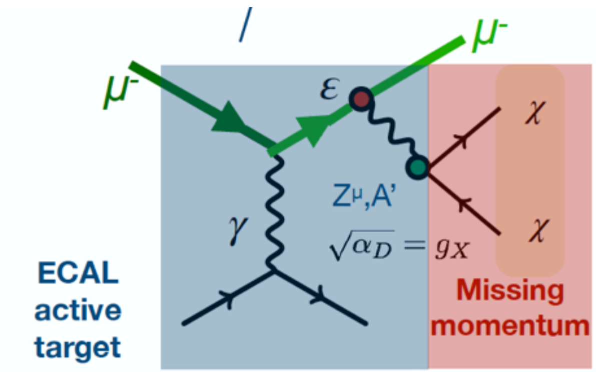
NA64$_e$

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

NA64$_\mu$

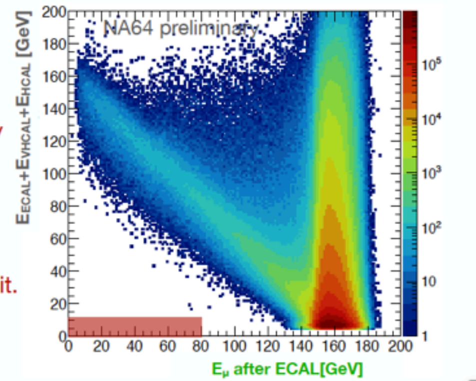
$$N^\mu_{A'} \sim L^\mu \sigma^\mu_{A'}$$
$$L^\mu \simeq 40X_0$$
$$\sigma^\mu_{A'} \sim \epsilon_\mu^2/m^2_\mu \qquad m_{A'} \lesssim m_\mu$$





Signature

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

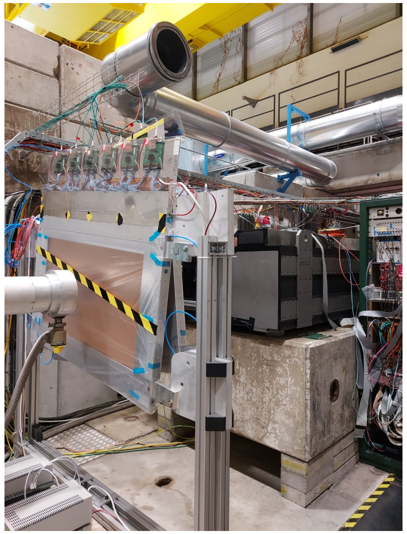
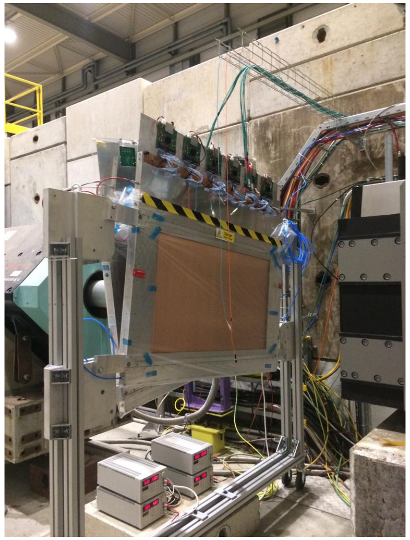


Zμ,A' decaying to DM particles

JINR contribution & obligations

electron setup *muon setup*



Size, X-Y mm^2	Diameter of drift tubes, mm	Number of tubes	Comments
200x200	6	768	12 chambers
1200x600	6	5376	7 chambers
200x200	2	768	2 prototypes,

- full support of the DAQ, straw chamber online-monitor
- theory, M-C simulation, reconstruction, data taking and analysis
- 2 PhDs in progress

Straw Tube have advantage over Micromegas and GEM track detectors used in NA64 due to:

- a smaller material buget 0.0016 X/X_0
- higher efficiency at high intensity & better multitrack reconstruction

Financial request

Schedule proposal and resources required for the implementation of the Project

Names of costs, resources, sources of funding	Cost (thousands of $) resource requirements	Cost, distribution by year				
		1st year	2nd year	3rd year	4th year	5th year
International cooperation (IC)		70	70	40		
Materials		15	15	15		
Equipment and third-party services (commissioning)		20+37	20+37	20+37		
Commissioning work						
Services of research organisations		10	10	10		

Outlook & conclusions

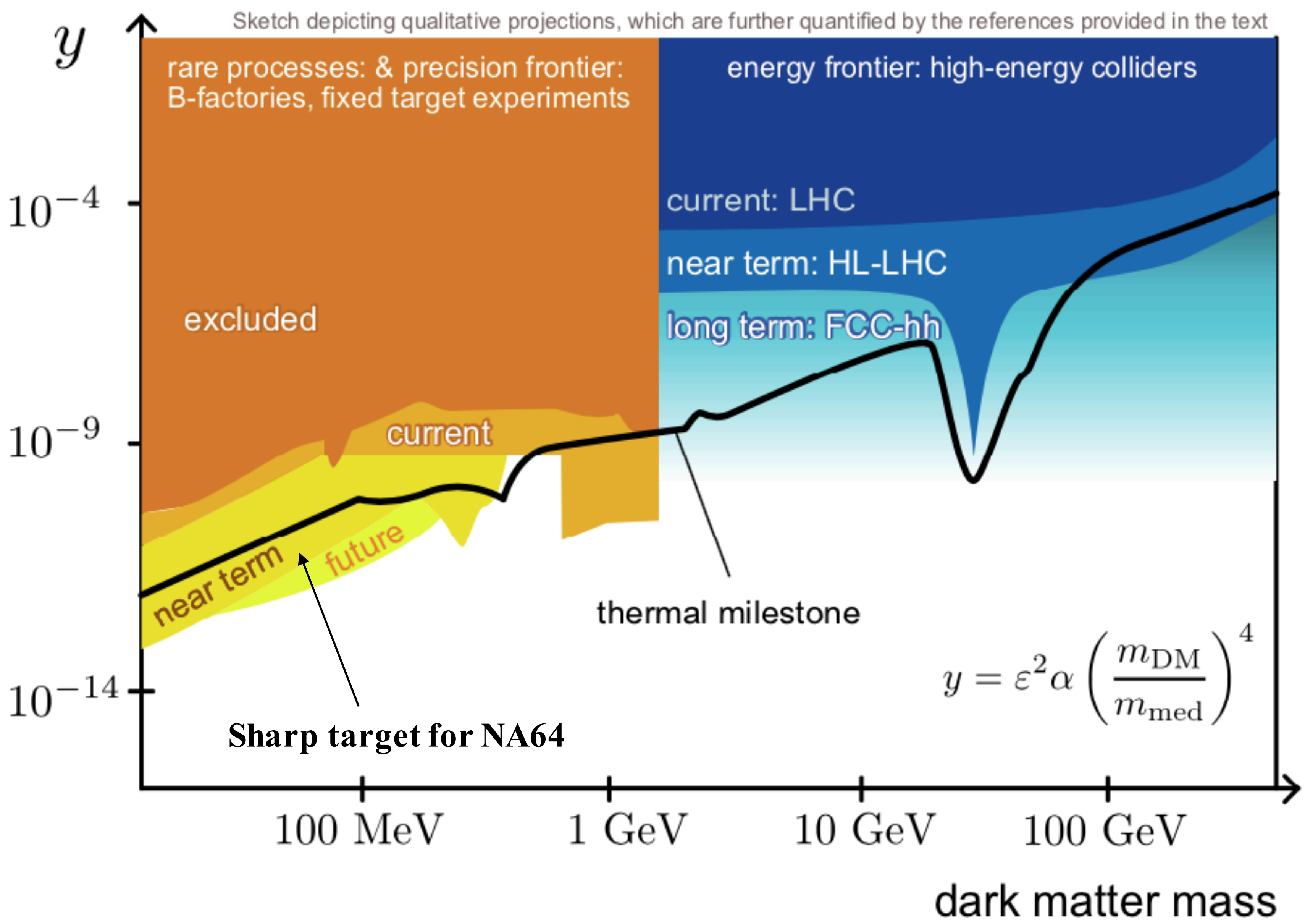
NA64 just reached a major milestone of accumulating ~ 10^{12} EOT which allows one to start probing very interesting LDM benchmark models. The analysis is ongoing and with the increased statistics we expect to improve the sensitivity for ALPs, Lμ-Lτ and B-L Z' bosons, ,....
The plan until LS3 is to accumulate 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. The results of the pilot runs show that with an optimized setup, one could collect > 10^{11} MOT before LS3 in order to check if an Lμ-Lτ 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.

In the 2022 beam-time, we also accumulated ~ 2×10^{9} pions on target in order to understand the potential of NA64 to explore dark sectors coupled predominantly to quarks using the missing energy technique. This will be further investigated and, if the feasibility would be demonstrated, a dedicated search will be performed after LS3.

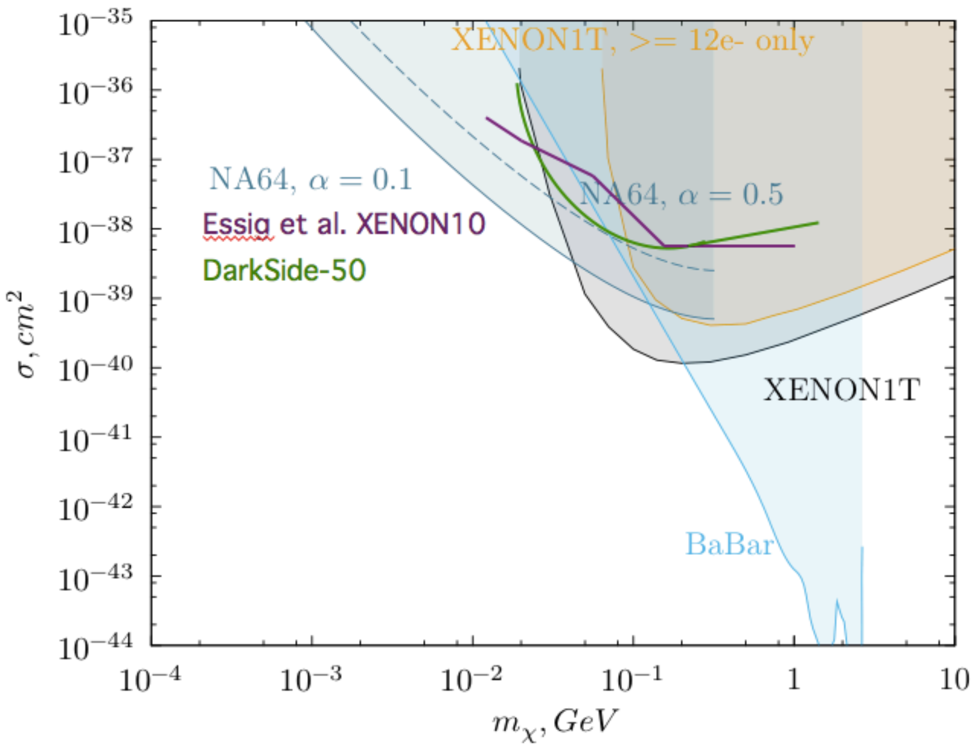
The exploration of the NA64 physics potential has just begun. Proposed searches with leptonic and hadronic beams provide unique sensitivities & highly complementary to similar projects.

Tnank you!

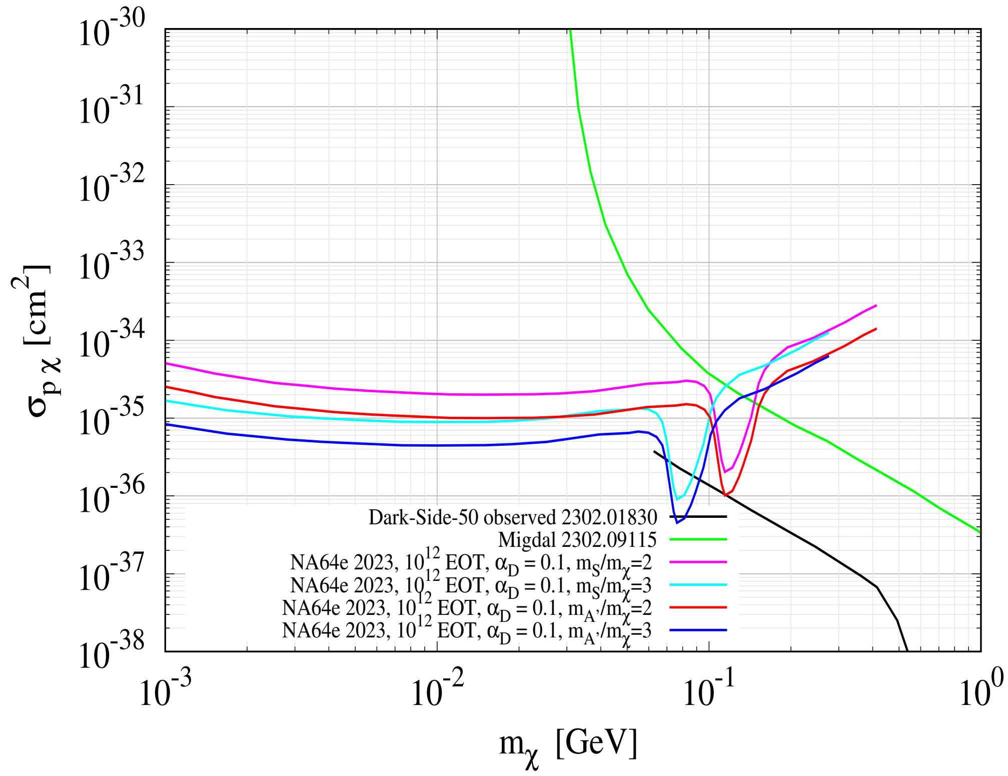

Sketch depicting qualitative projections, which are further quantified by the references provided in the text
y
rare processes: & precision frontier:
B-factories, fixed target experiments
energy frontier: high-energy colliders
current: LHC
near term: HL-LHC
long term: FCC-hh
excluded
current
future
near term
thermal milestone
10^{-4}
10^{-9}
10^{-14}
$y = \varepsilon^2 \alpha \left(\frac{m_{DM}}{m_{med}}\right)^4$
Sharp target for NA64
100 MeV
1 GeV
10 GeV
100 GeV
dark matter mass

Constraints on DM-electon cross-sections

Complementarity of NA64 and direct DM searches



XENON Coll. arXiv:1907.11485
SG,Krasnikov,Matveev arXiv:2003.07257



D. Kirpichnikov (preliminary)

The 90% C.L. upper limits on DM-electron scattering cross-sections
NA64: no assumptions on DM number density and velocity distribution

NA64h: Search for dark sector coupled to q's with π, K, p beams

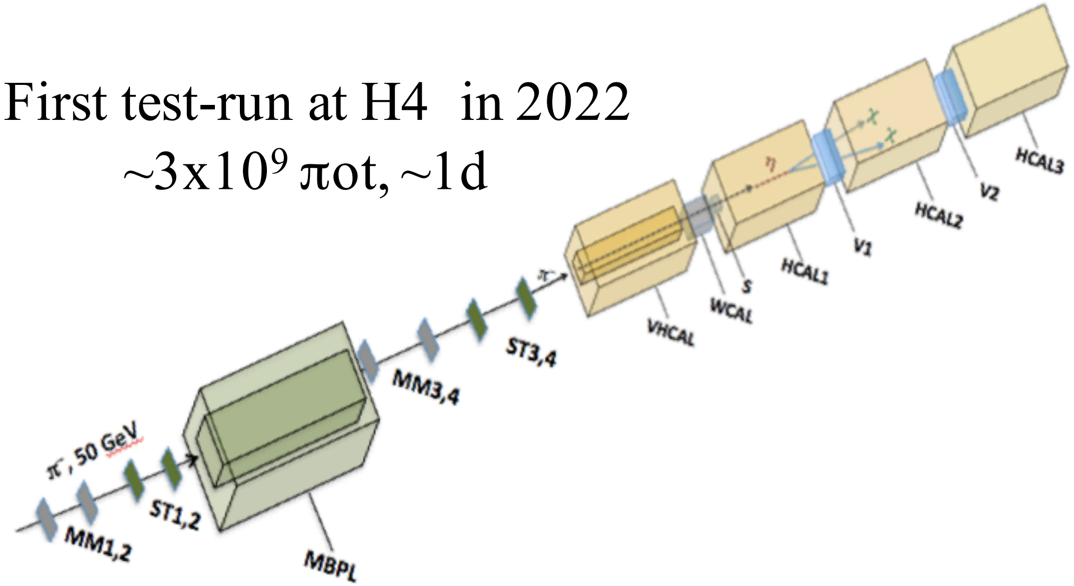
- π^0, η, η', K_S, $K_L \rightarrow$ invisible
- Leptophobic LDM in reactions pA->DM+X

- In SM π^0, η, η', $K^0 \to \nu\nu$ suppressed : $Br(K^0 \to \nu\nu) \sim 10^{-10}$ $m_\nu \sim 10$ MeV
- could occur in 2HDM, 2HDM+ light scalars, mirror model, ..
- in some scenarios could be at $Br(K^0 \rightarrow inv) \sim 10^{-8} - 10^{-6}$
  not constrained by $K \to \pi\nu\nu$.
- clean probe of NP scales above 100 TeV,
- Complementary to $K \to \pi\nu\nu$ (NA62)
- K^0 – mirrow K^0 oscillations

NA64h: Search for dark sector coupled to quarks

$\pi^0, \eta, \eta', K^0_{S,L}, .. \rightarrow$ inv decays

First test-run at H4 in 2022
~3x10^9 πot, ~1d

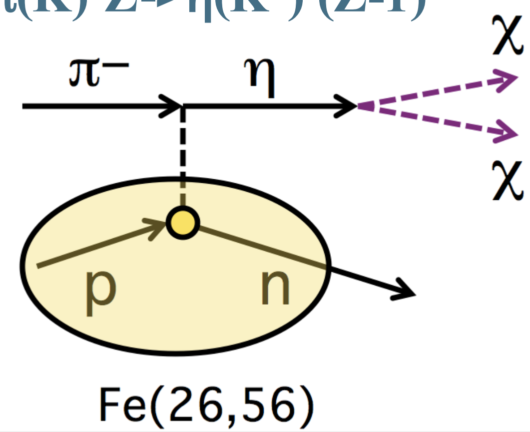


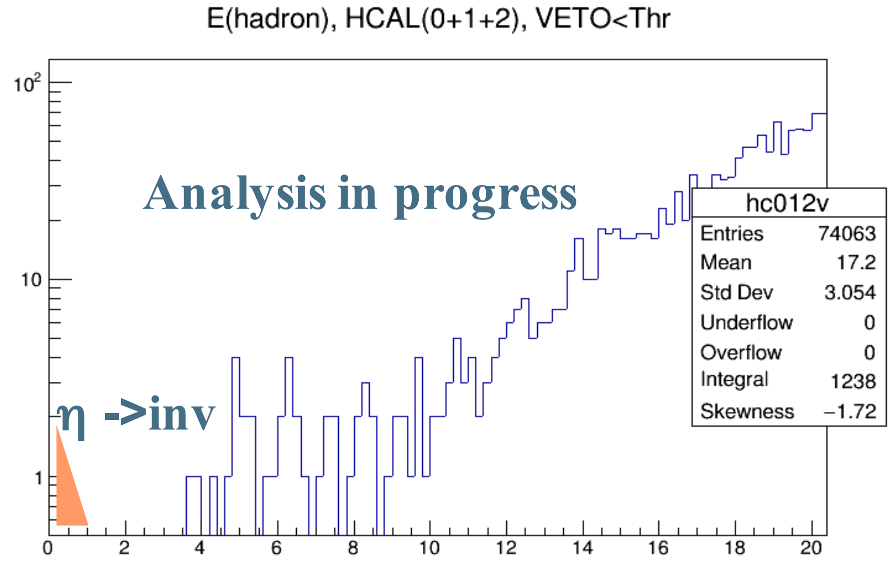
Signature of π(K) Z->η(K⁰) (Z-1); η(K⁰) ->inv

- Single track from 50 GeV p-
- MIP in WCAL and S
- N0 energy in HCAL: $E_{miss} \sim E_0$

η, η′, K0 – production:

π(K) Z->η(K⁰) (Z-1)

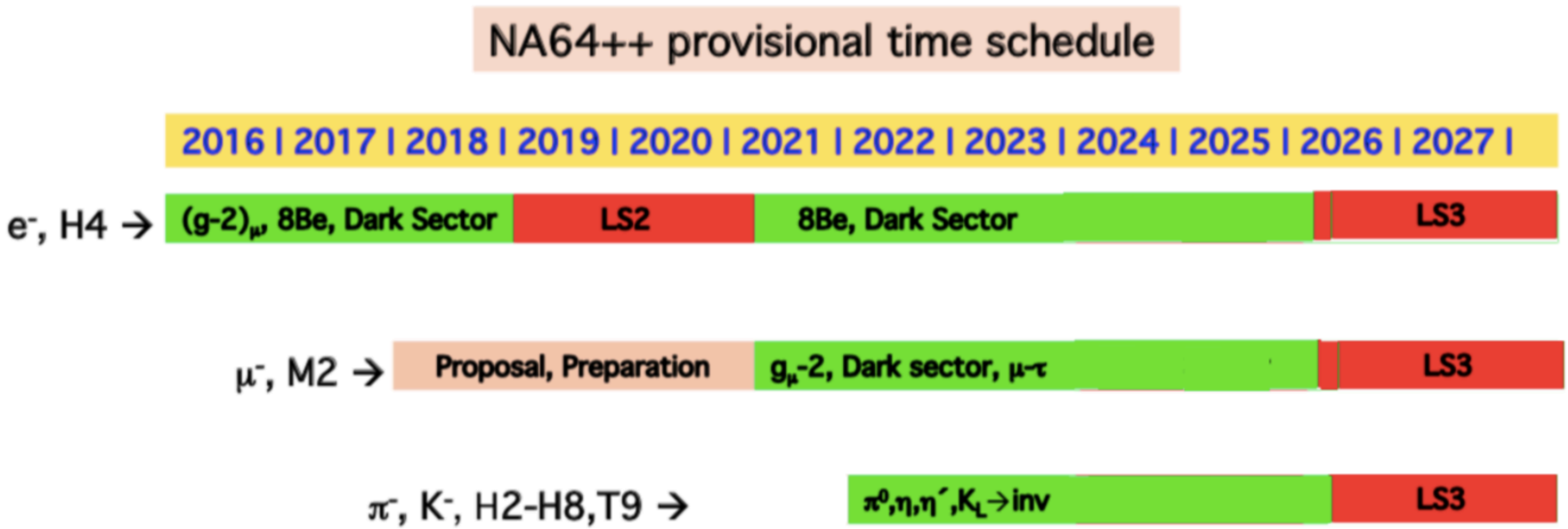




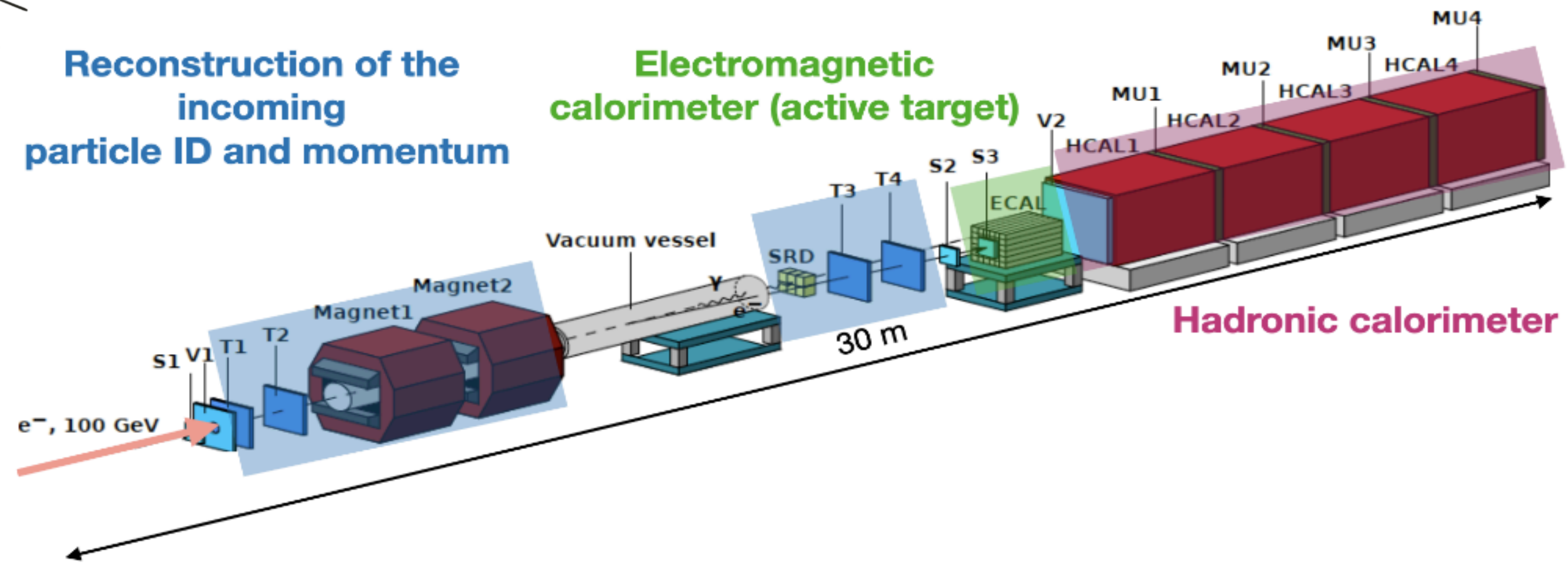
Br(η -> inv) < 3x10⁻⁴ (~BaBar)

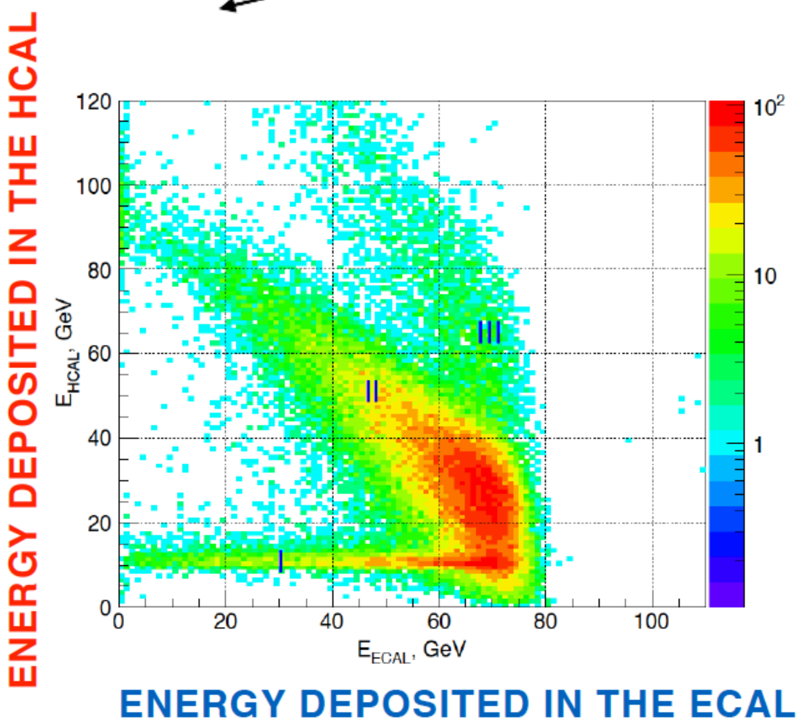
Summary (contributions to PBC, schedule)

NA64e	NA64μ	NA64h
- < LS3 ~5x10^{12} EOT	- 2021 test run	- 2024-26 test run
- LDM models	- $(g-2)_\mu$ ~10^{11} MOT	- $\pi^0,\eta,\eta' \rightarrow$ inv, 10^{12} POT
- $A', X17 \rightarrow e^+e^-$ ATOMKI	- LDM, A'~10^{13} MOT	- $K^0_{S,L} \rightarrow$ inv~10^{12} KOT
- ALP(S) $\rightarrow \gamma\gamma$ decays	- $\mu - \tau$ conversion	- pA$\rightarrow$ X+E_m~10^{12} POT
- Dark *S, P, V, A,* milliQ		
- Resonant A' with e^+		



NA64e approach





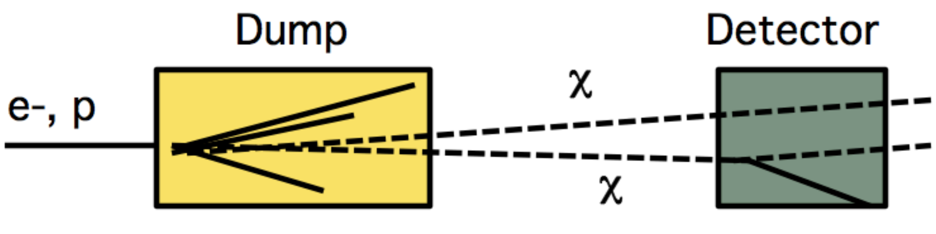
★ **Region I:** $e^- Z \to e^- Z\gamma;\ \gamma \to \mu^+\mu^-$
→ benchmark for MC

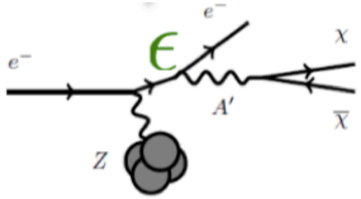
★ **Region II:** SM events
$E_{ECAL} + E_{HCAL} \simeq 100$ GeV

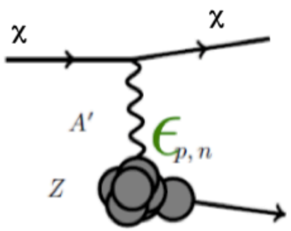
★ **Region III** —> pile-up events

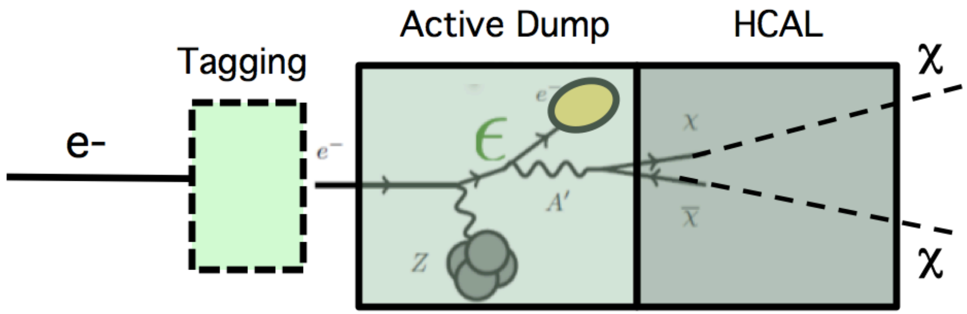
Research program

NA64 method vs beam-dump approach to probe LDM.









<u>Sensitivity</u>

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

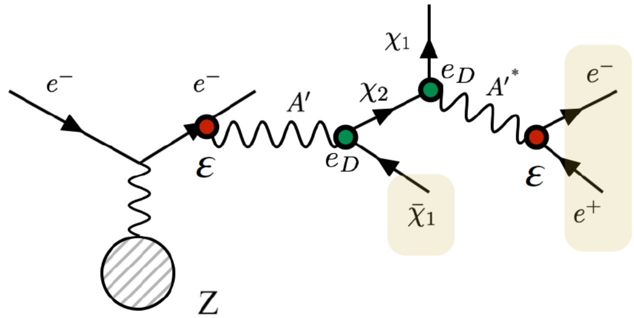
$n_S \sim \alpha_D \varepsilon^2 n_{eot}$

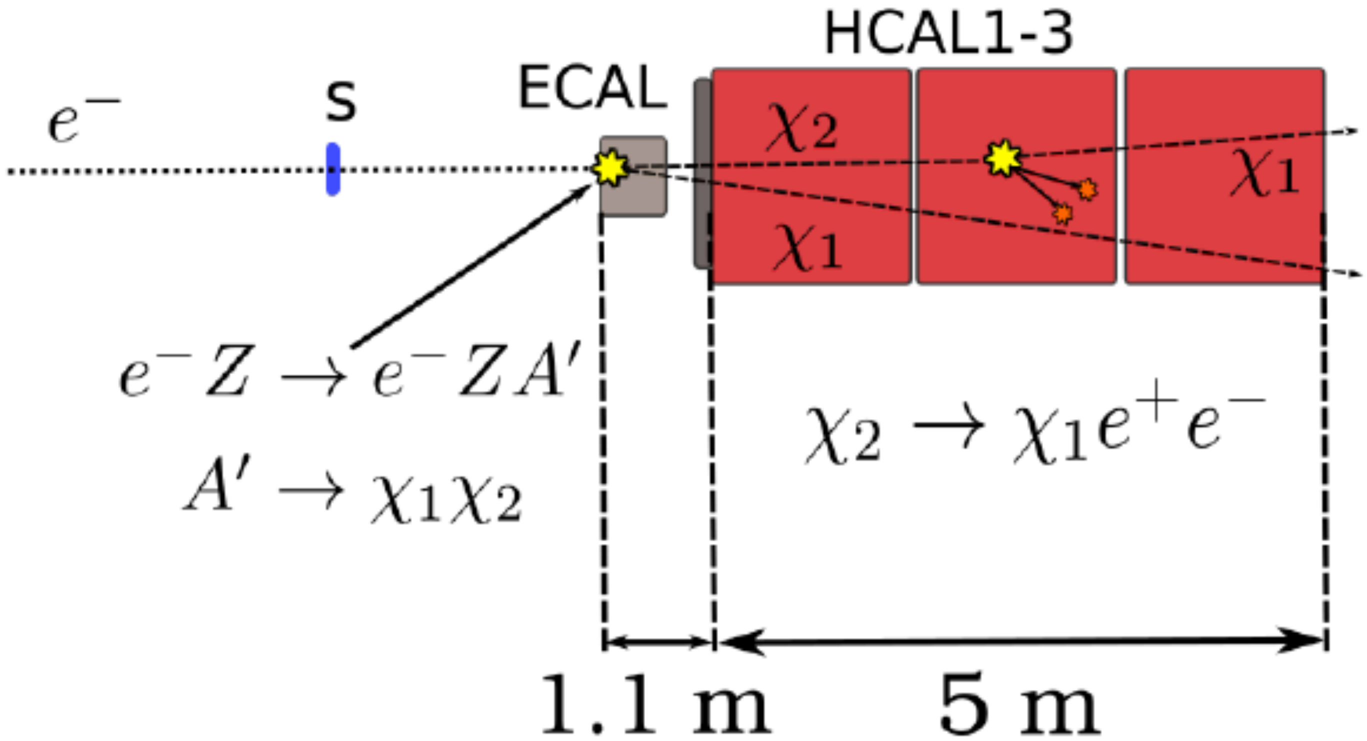
Advantage a factor ~ $1/\varepsilon^2$ ~10^{10}

Semivisible mode

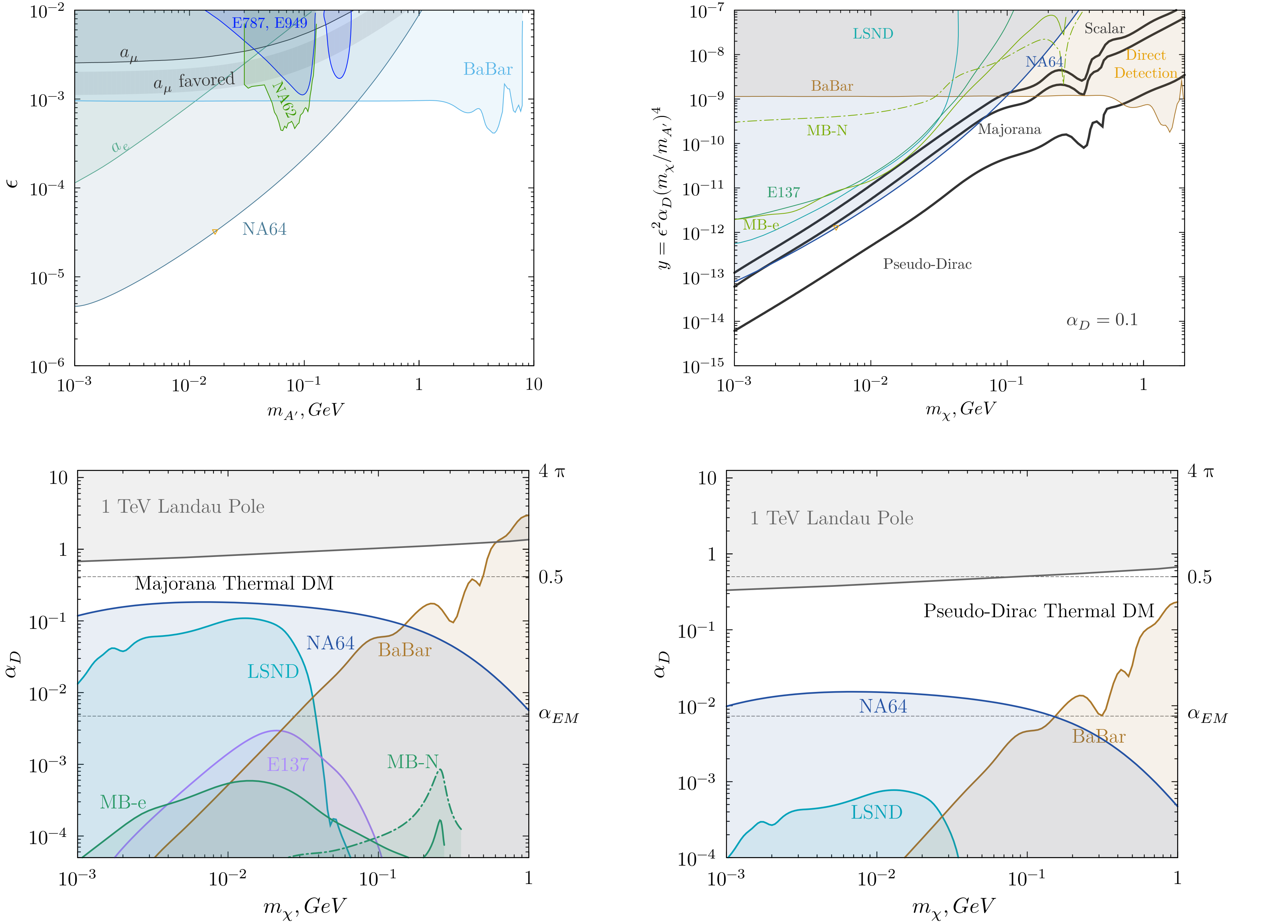
SEMIVISIBLE DECAY MODE

cascade of decays



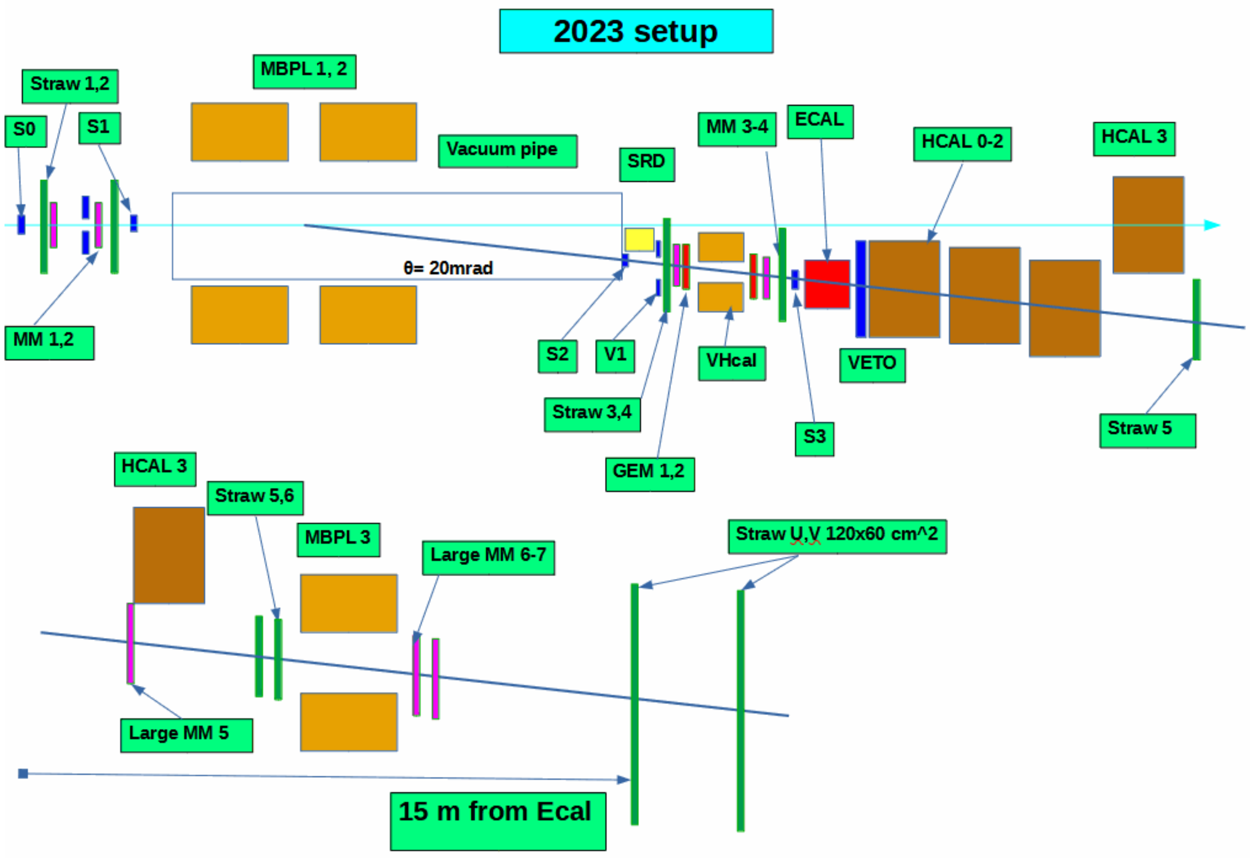


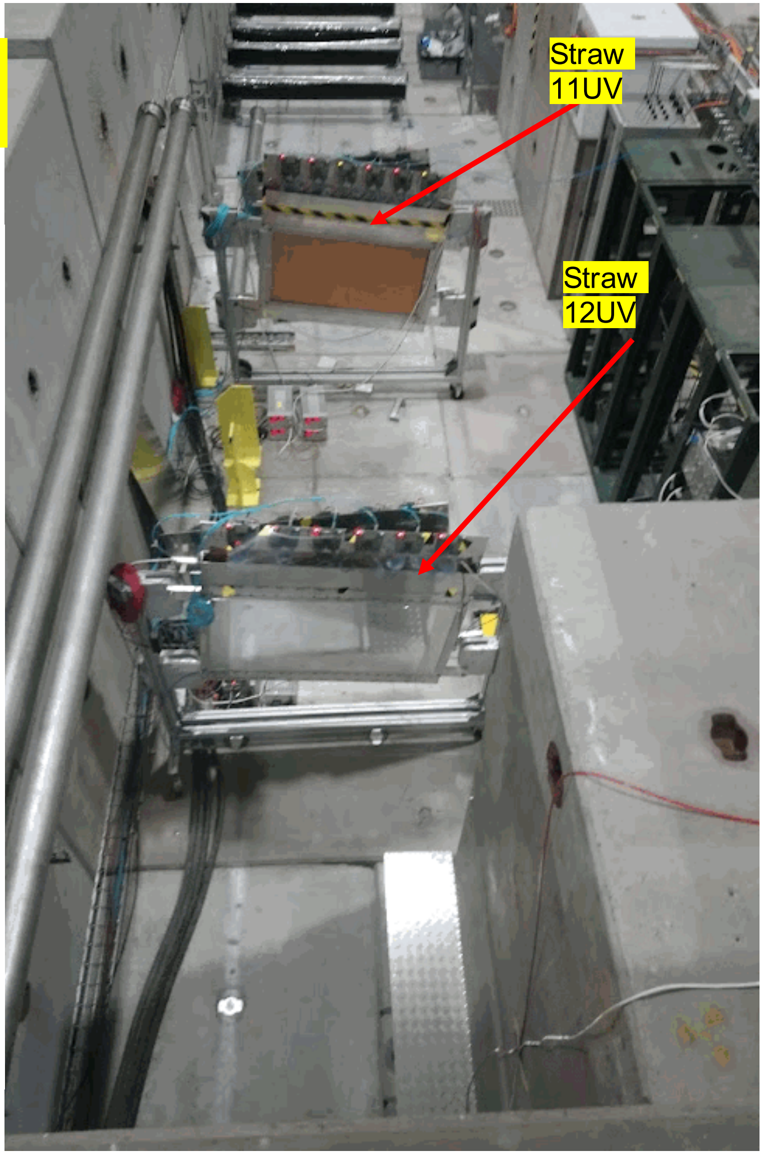
NA64 results from 2016-2022: ~10^{12}eot



2023

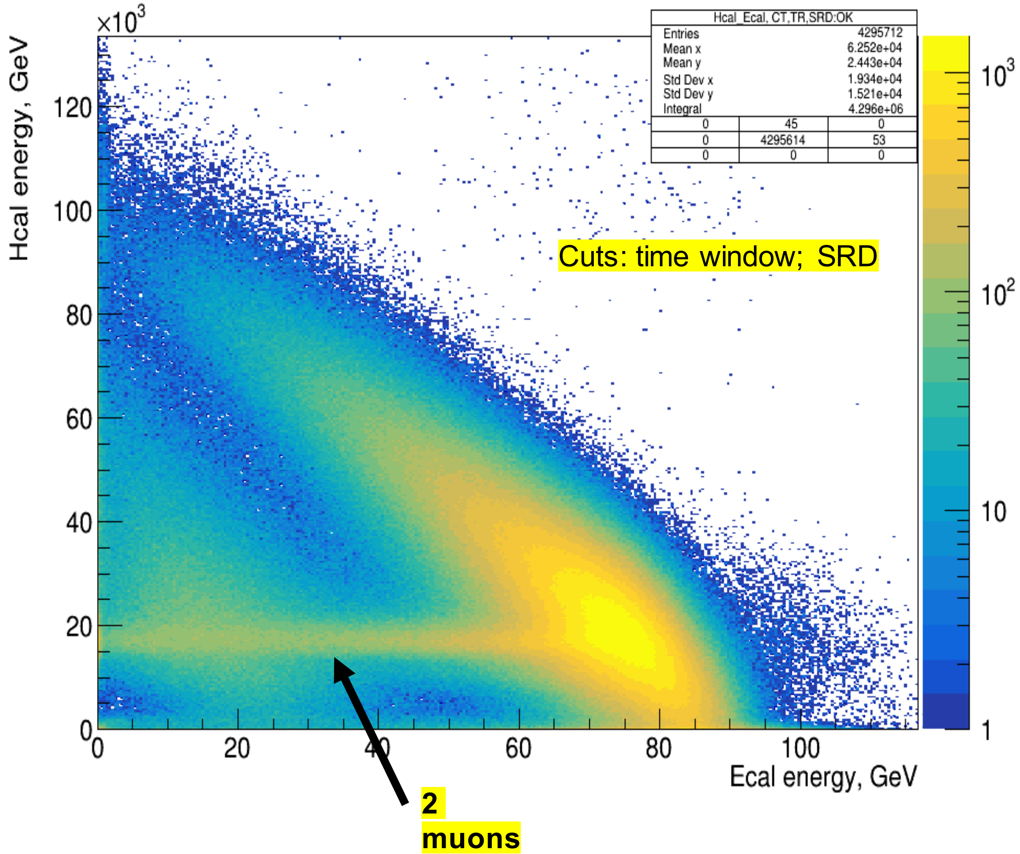
Two important modification in 2023, new Vhcal calorimeter and second magnetic spectrometer with two large Straw stations.

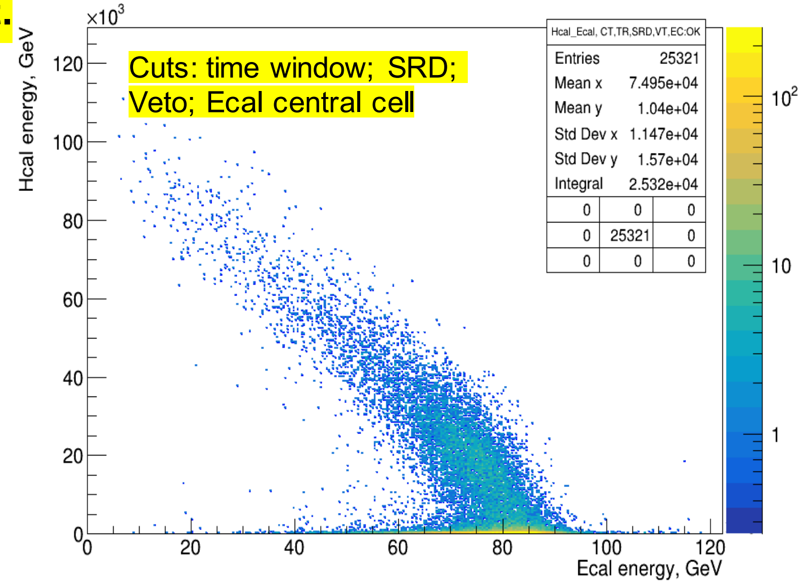


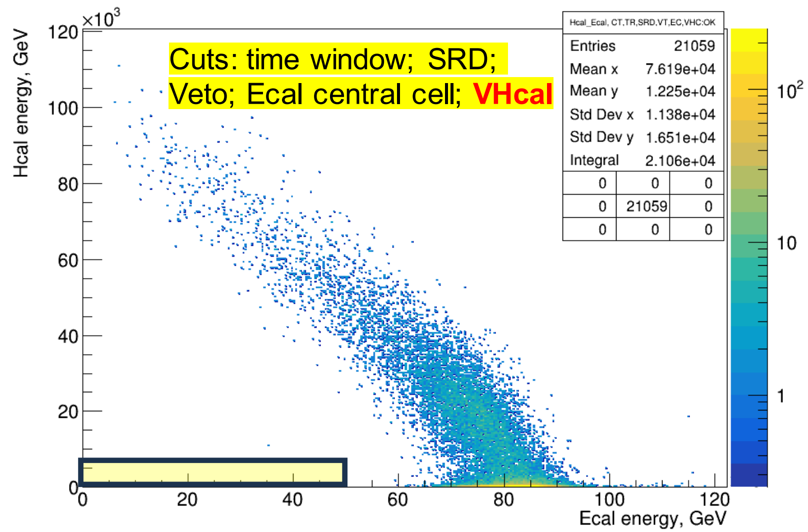


2023

Online analysis, preliminary results for 4.5x10^{10} electrons on target.







2023

Online analysis, preliminary results for 4.5x10^{10} electrons on target.