Light dark matter

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Useful references:

1. S.N.Gninenko, N.V.Krasnikov, V.A,Matveev, Physics of Particles and Nuclei, 51(5)829-858 (2020).

2. Direct Sectors Workshop:Community report

J.Alexander et al.,arXiv:1608.08632

3. NA64 collaboration:

arXiv:1906.00176;

Phys.Rev. D97, 07202, 2018

The main motivation in favor of BSM physics is dark matter

also probably some hints as:

1. (g-2)-muon anomaly
2. B-mesons semi leptonic decays

We know that dark matter exists

But we don’t know:

1. Thermal DM ?
2. Non thermal DM ? (axion,sterile neutrino)

Here we shall assume thermal DM

We don’t know also :

1. Spin of dark matter particles
2. Mass of dark matter particles

$$O(5)\ \mathrm{MeV} < m_{DM} < O(10)\ \mathrm{TeV}$$

O(10) TeV – tree level unitarity bound

O(5) MeV – BBN bound

Renormalizable models – spin 0, ½ and 1

Lee- Weinberg “theorem”:

$$m_{DM} \gtrsim 10\ \mathrm{GeV}$$

However It is possible to avoid Lee-Weinberg Theorem and to have models with DM particles lighter O(1 GeV)

C.Boehm, P.Fayet, Nucl.Phys. B683,219,2004

Renormalizable realization – additional interaction connects our world and dark particles world.

The most popular scenario – model with vector messenger (dark photon).

Also models with scalar mediator exist

Dark photon model (B.Holdom)

Additional vector boson A` interacts with SM fields due to nonzero mixing of kinetic terms

$$\delta L = -\varepsilon(2\cos\theta_W)^{-1} B^{\mu\nu}F`_{\mu\nu}$$

Here

$B^{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$ SM U(1) field strength

$F`_{\mu\nu} = \partial_\mu A`_\nu - \partial_\nu A`_\mu$ Dark photon field strength

Dark photon

The kinetic mixing in low energy region leads to interaction of dark photon with the SM electromagnetic current $J^{\mu}{}_{SM}$, namely

$$\delta L` = \varepsilon J^{\mu}{}_{SM} A`_{\mu}$$

Dark photon interacts with DM particles - messenger between our world and DM world

An example of dark mediator A`

Holdom'86, earlier work by Okun, ..

- extra U`(1), new gauge boson A`(dark or hidden photon,…)
- $2\Delta L = \varepsilon F^{\mu\nu} A`_{\mu\nu}$ - kinetic mixing
- γ-A` mixing, ε - strength of coupling to SM
- A` could be light: e.g. $M_{A`} \sim \varepsilon^{1/2} M_Z$
- new phenomena: γ-A`oscillations, LSW effect, A`decays,..
- A`decay modes: e+e-, μ+μ-, hadrons,.. or A`-> DM particles, i.e. A`-> invisible decays

Large literature, >100 papers /few last years, many new theoretical and experimental results

Three most popular light dark models

1. Scalar dark matter
2. Majorana dark matter
3. Pseudo Dirac dark matter

The main assumption – in the early Universe dark matter is in equilibrium with observable matter. At some temperature dark matter decouples.

Observable dark matter density allows to predict the annihilation cross section

THERMAL ORIGIN

Here we assume that in the early Universe dark matter is in equilibrium with the SM matter

DM density today tells us about annihilation cross-section. Correct DM density corresponds to $<\sigma_{an} v> \sim O(1)$ pbn (solution of the Boltzmann equation)

Planck CMB data restrictions

Planck CMB data(arXiv:1303.5076) exclude s-wave annihilation DM with masses less than 10 GeV

So there are two possibilities:

1. p-wave annihilation(scalar, Majorana)
2. annihilation shuts of before CMB(pseudoDirac)

Two types of DM annihilation:

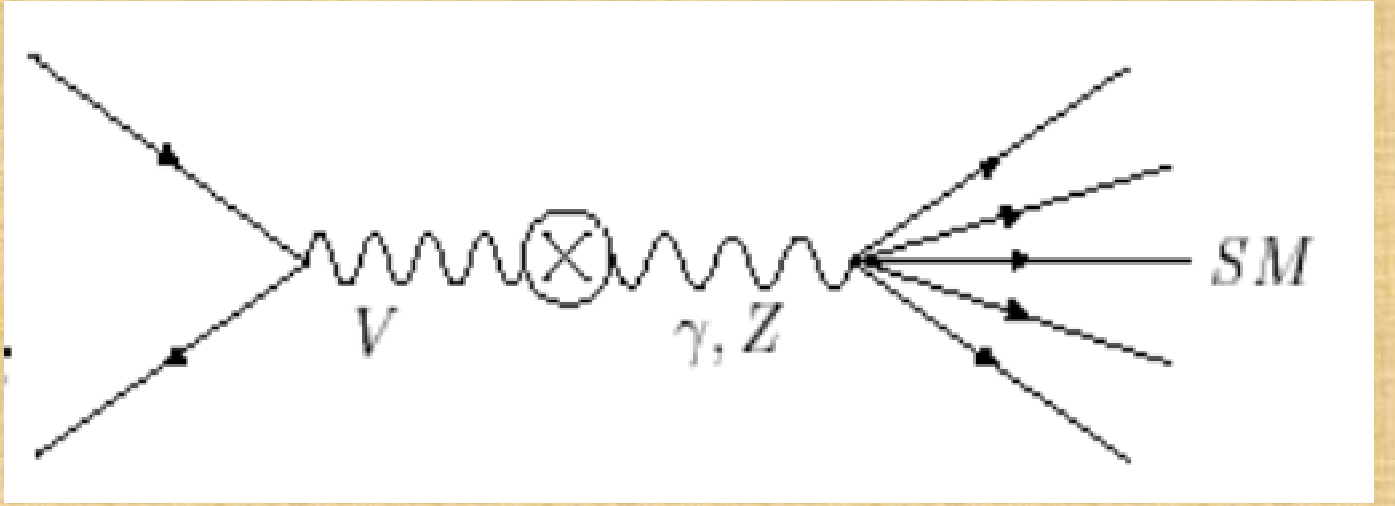
Direct

DM DM → A` → $e^+ e^-$, …

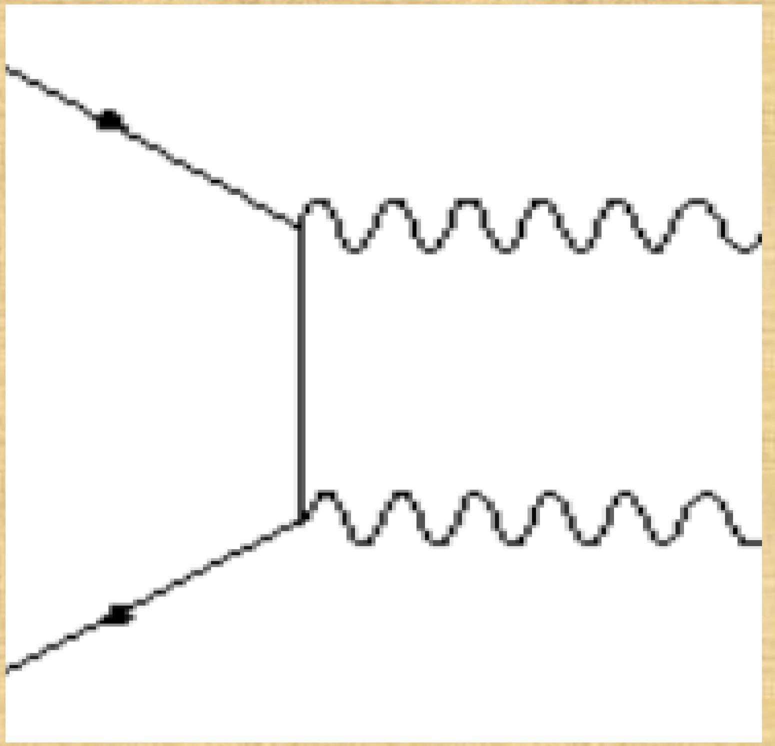
Secluded

DM DM → A` A` with subsequent decays of dark photon into SM particles Secluded annihilation for dark photon is s-wave, excluded(for scalar messenger –possible)

Direct annihilation
DM DM → SM



Secluded annihilation



So the main features of light dark matter

1. p-wave annihilation(or annihilation shuts off before CMB)

2. The annihilation cross-section

$$<\sigma_{an} v> \sim 1 \text{ pbn} \cdot c$$

As a consequence, crude estimate (E.Izaguirre, et al., Phys.Rev. D91, 094026 (2015)

$$\alpha_D \simeq 0.02 f \left(\frac{10^{-3}}{\epsilon}\right)^2 \left(\frac{m_{A'}}{100\ MeV}\right)^4 \left(\frac{10\ MeV}{m_\chi}\right)^2$$

f =O(1) –fermions, f = O(10) - scalars

As an example consider charged scalar DM. The nonrelativistic annihilation cross section

$$\sigma_{an} v_{rel} = \frac{8\pi}{3} \frac{\epsilon^2 \alpha \alpha_D m_{DM}^2 v_{rel}^2}{(m_{A'}^2 - 4m_{DM}^2)^2}$$

For fixed values of dark photon and DM masses from thermal prediction $<\sigma v> \sim 1$ pbn

we can calculate only the product $\varepsilon^2 \alpha_D$ while

accelerators (NA64) give upper bound on

ε^2 To test light dark matter models we must

have upper on α_D

Here $\alpha_D = e^2{}_D/4\pi$ - analog of $\alpha = 1/137$ for DM world

From the requirement of the absence of Landau pole singularity

H.Davoudiasl and W.J.Marciano, Phys.Rev. D92, 035008,2015.

$$\alpha_D \lesssim 1$$

as a consequence

$$\varepsilon \gtrsim F(m_\chi, m_{A`})$$

Dark Photon Searches

Production Modes

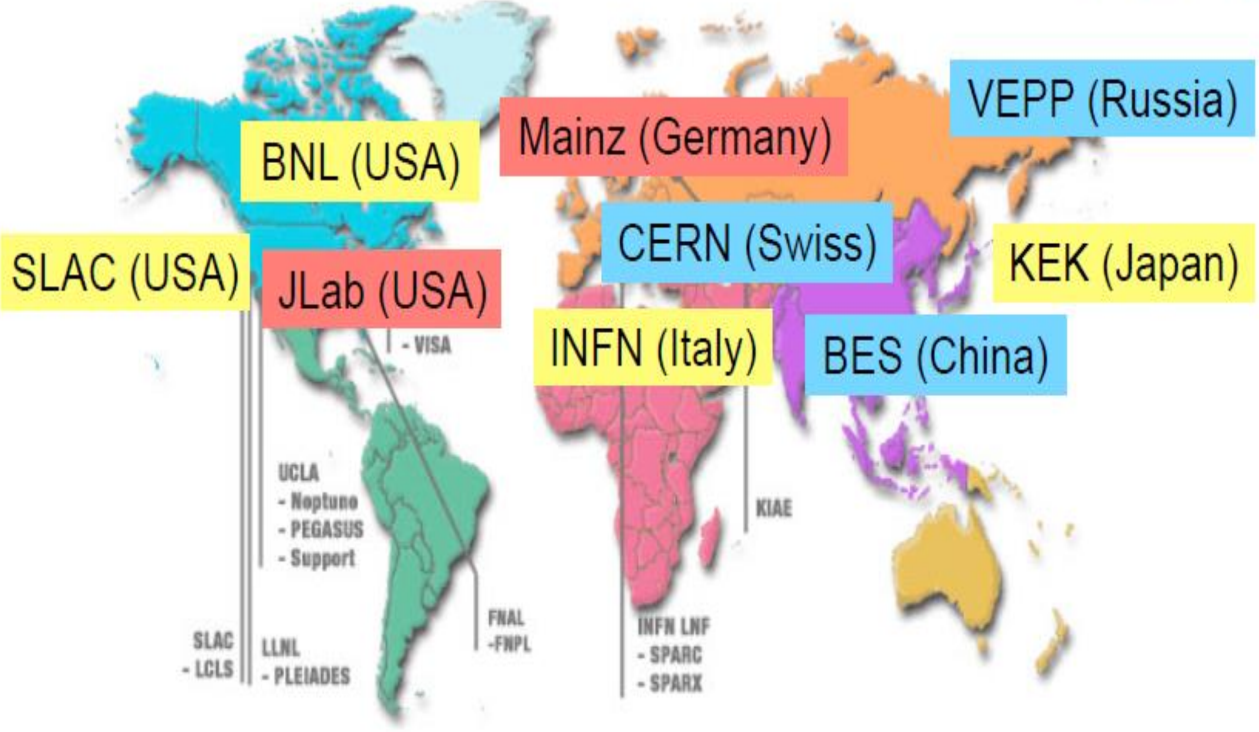
- Electron-positron annihilation
- Meson Decays
- Drell-Yan (collider or fixed target)
- Bremsstrahlung

Detection Signatures

- Pair resonance
- Beam-dump late decay
- Inclusive missing mass
- Reconstructed displaced vertex

Dark Force searches in the Labs

Many searches for Dark Force in the Labs around the world (ongoing/proposed).



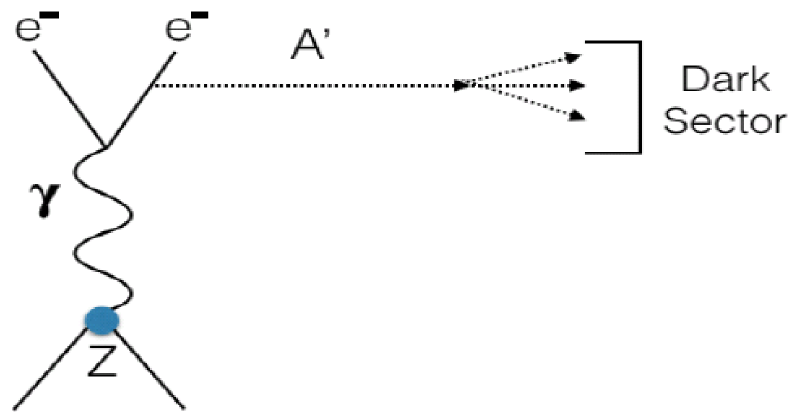
NA64 experiment

NA64 - Searches

A´-> invisible, *A´->* e^+e^-

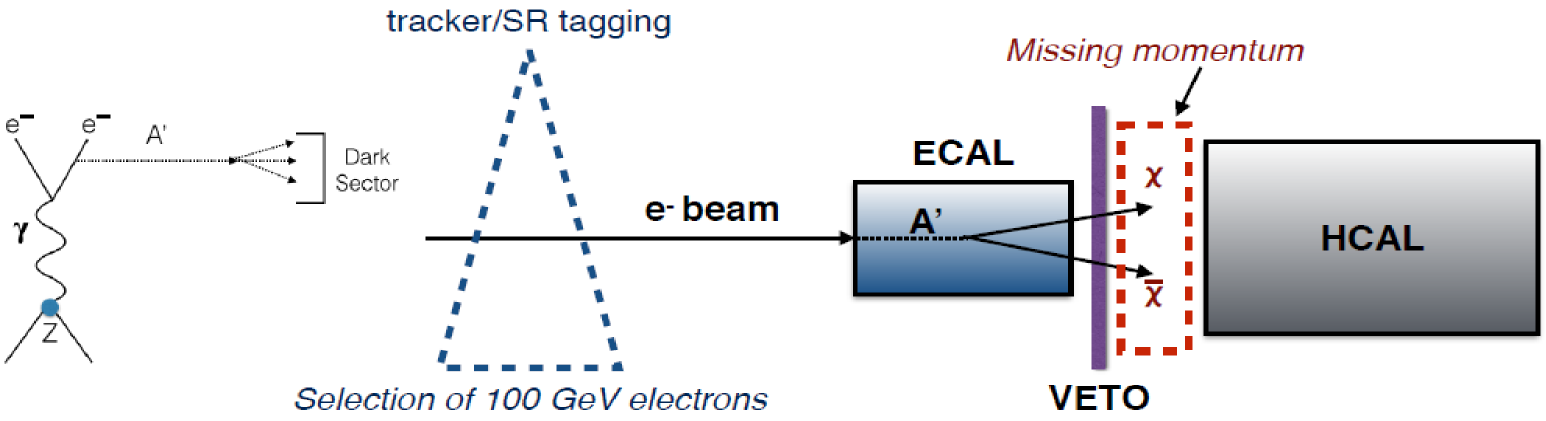
at SPS CERN

NA64 Experiment



NA64 is a fixed target experiment combining the active beam dump technique with missing energy measurement searching for invisible decays of massive A' produced in the reaction eZ—> eZA' of electrons scattering off a nuclei (A,Z), with a mixing strength $10^{-5} < \varepsilon < 10^{-3}$ and masses $M_{A'} < 100$ MeV.

NA64 Experiment



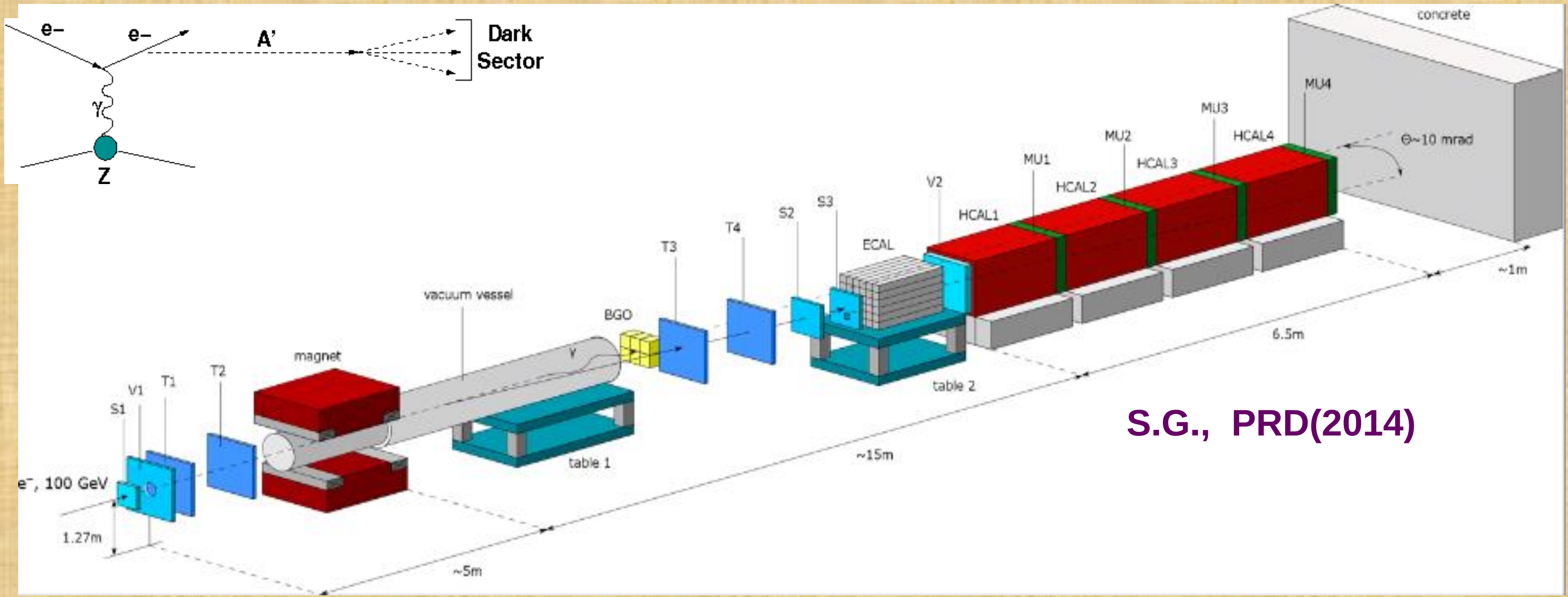
For NA64 a beam of ***100 GeV electrons*** *will be dumped against an ECAL, a sandwich of lead and scintillators (34 X_0), to produce massive A' through scattering with the heavy nuclei.*

A typical signature for a signal will be ***missing energy in the ECAL*** *and no activity in the the VETO and HCAL.*

Background from hadrons, muons and low energy electrons must be rejected upstream.

search for *A´->invisible* at CERN SPS

Invisible decay of Invisible State!



S.G., PRD(2014)

3 main components :

- clean, mono-energ. 100 GeV e- beam
- e- tagging system: MM tracker + SR
- 4π fully hermetic ECAL+ HCAL

Signature:

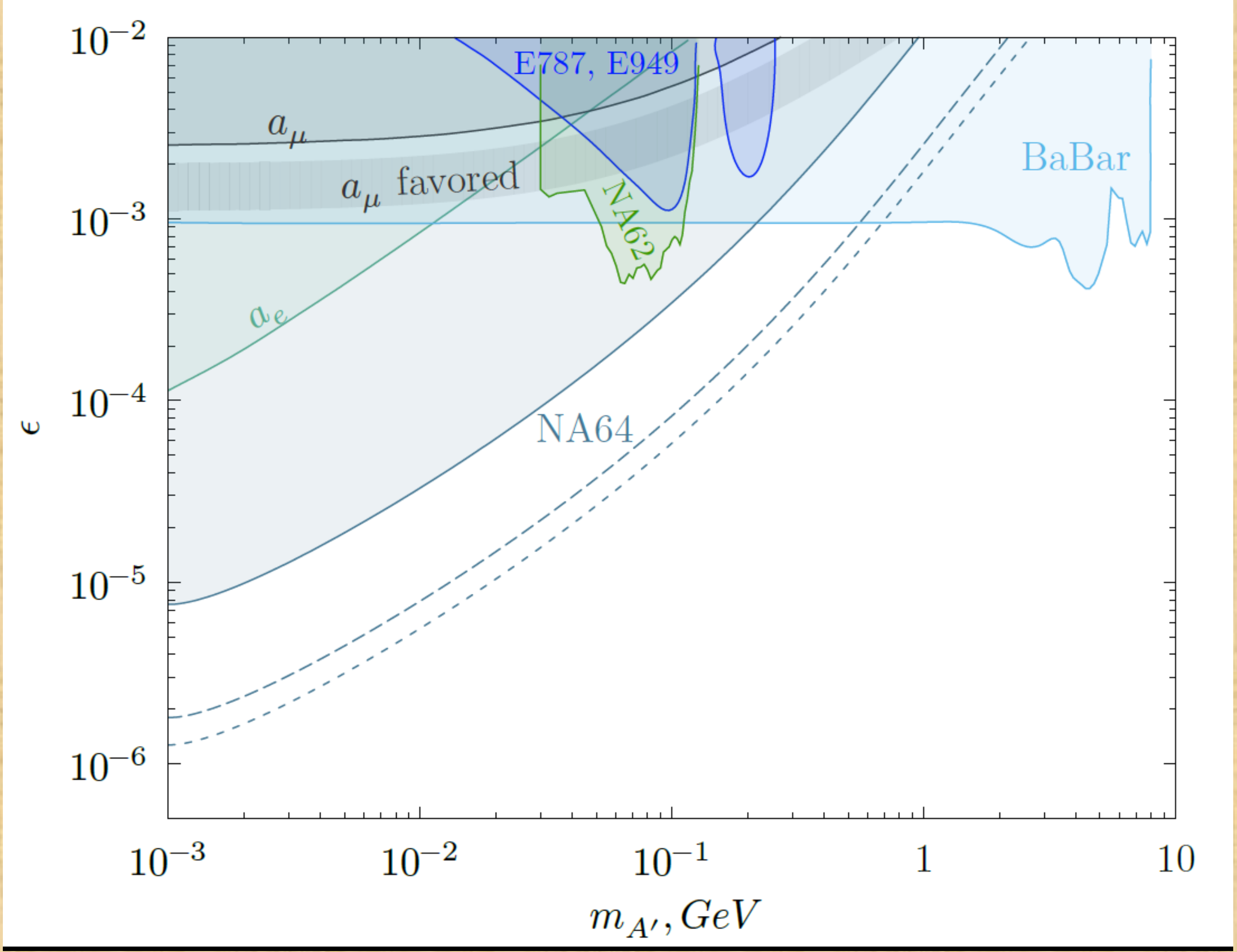
- in: 100 GeV e- track
- out: < 50 GeV e-m shower in ECAL
- no energy in the Veto and HCAL
- Sensitivity ~ ε^2

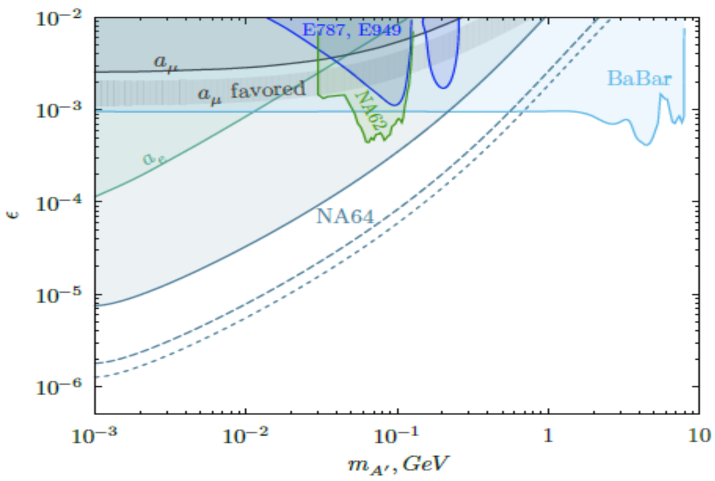
NA64 last results

We have published results (NA64 collaboration, arXiv:1906.00176) based on the use of $2.84*10^{11}$NEOT

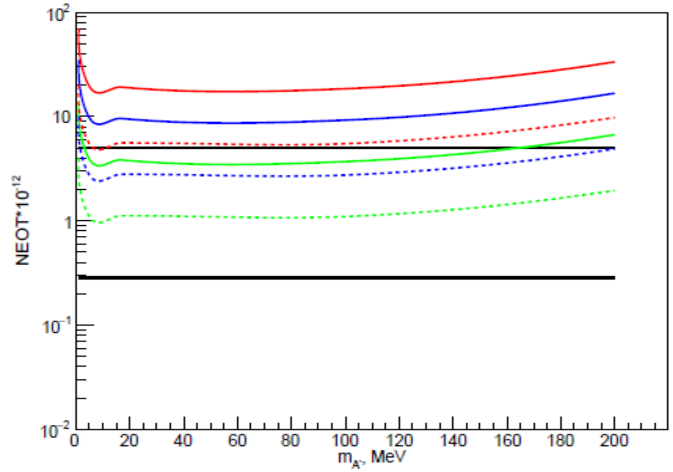
Our goal: to collect $5*10^{12}$ NEOT during 2021-2023 run at CERN.

Last NA64 result with NEOT = $2.88*10^{11}$ arXiv:1906.0176

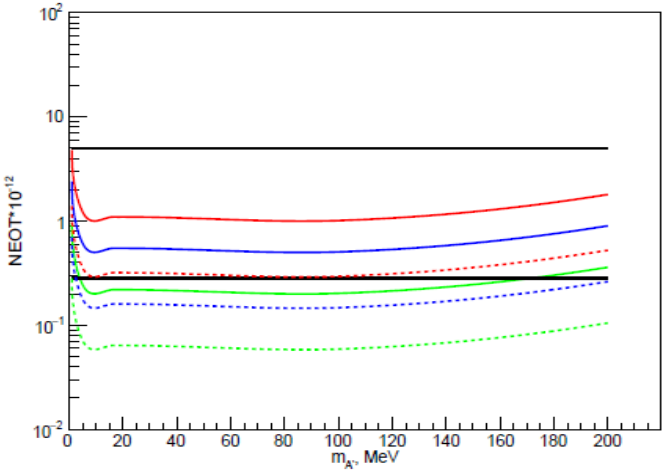




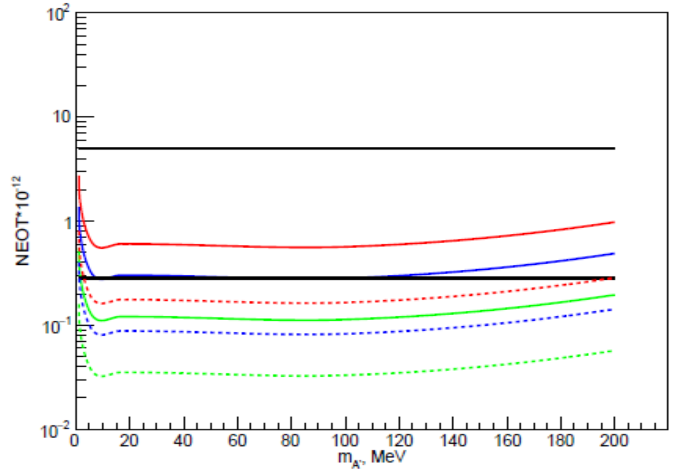
E787, E949
a_μ
a_μ favored
NA62
a_e
BaBar
NA64
ϵ
$m_{A'}, GeV$



NEOT*10^{-12}
$m_{A'}$, MeV



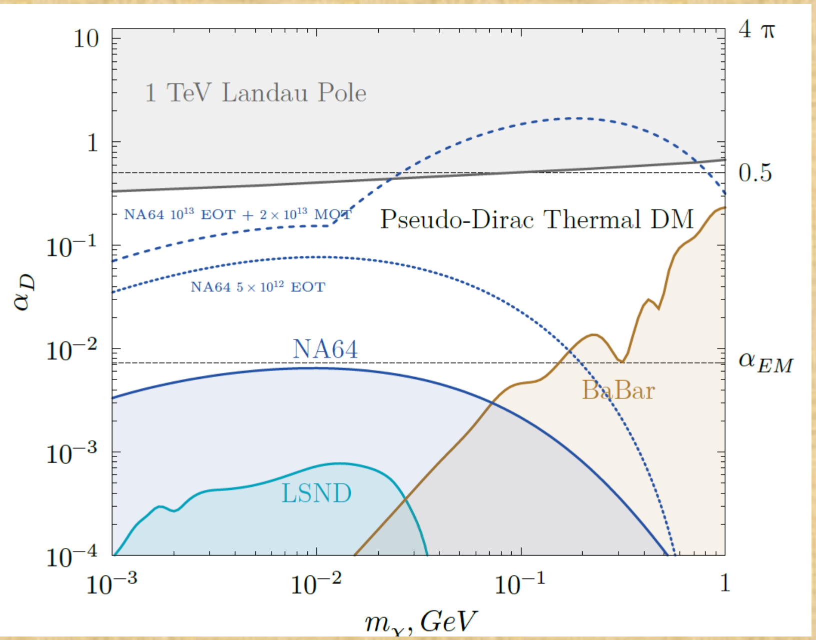
NEOT*10^{-12}
$m_{A'}$, MeV



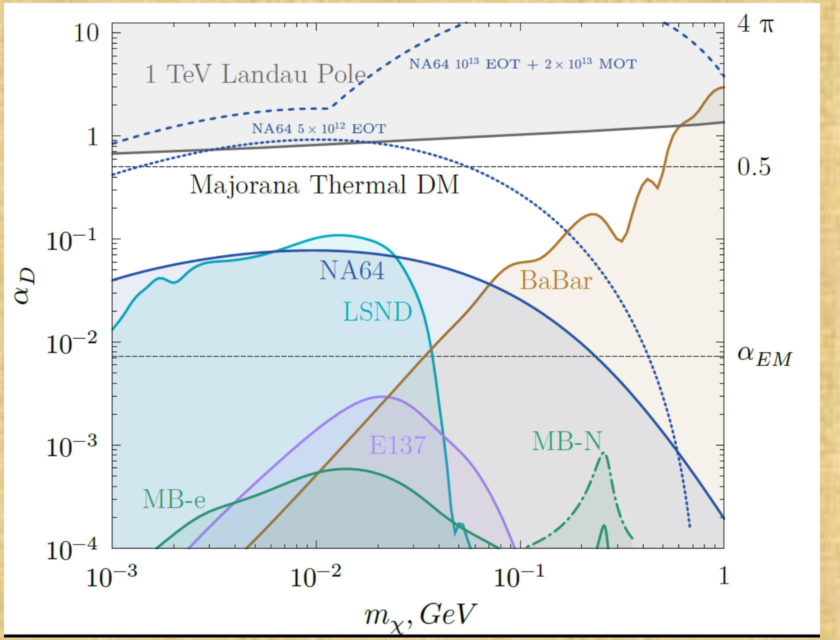
NEOT*10^{-12}
$m_{A'}$, MeV

NA64 bound on α_D

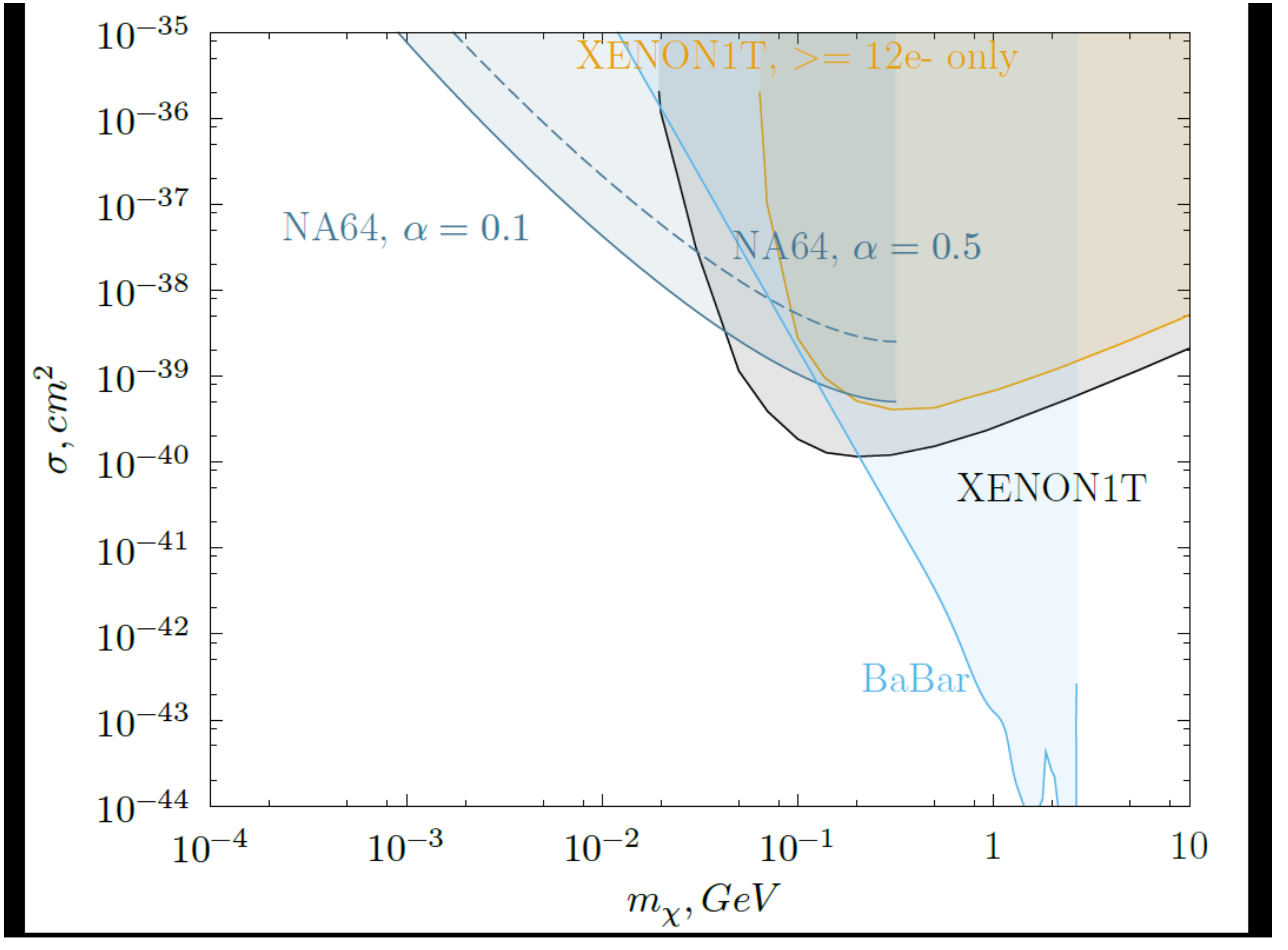
Pseudo Dirac DM



Majorana DM



Direct DM detection : the use of electon DM elastic scattering. Xenon1T results



The experiment with muon **beam**

S.Gninenko, N.Krasnikov and V.Matveev,

Phys.Rev. D91(2015)095015

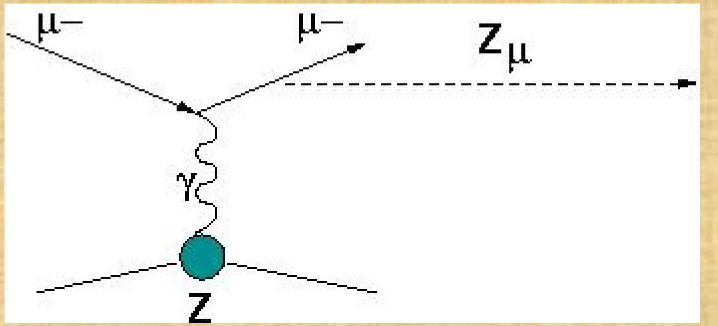
Proposal to look for dark photon at

collisions of

CERN SPS muon beams

$$\mu(p) + Z(P) \to Z(P^{'}) + \mu(p^{'}) + Z_{\mu}(k)$$

The experiment at CERN SPS muon beam



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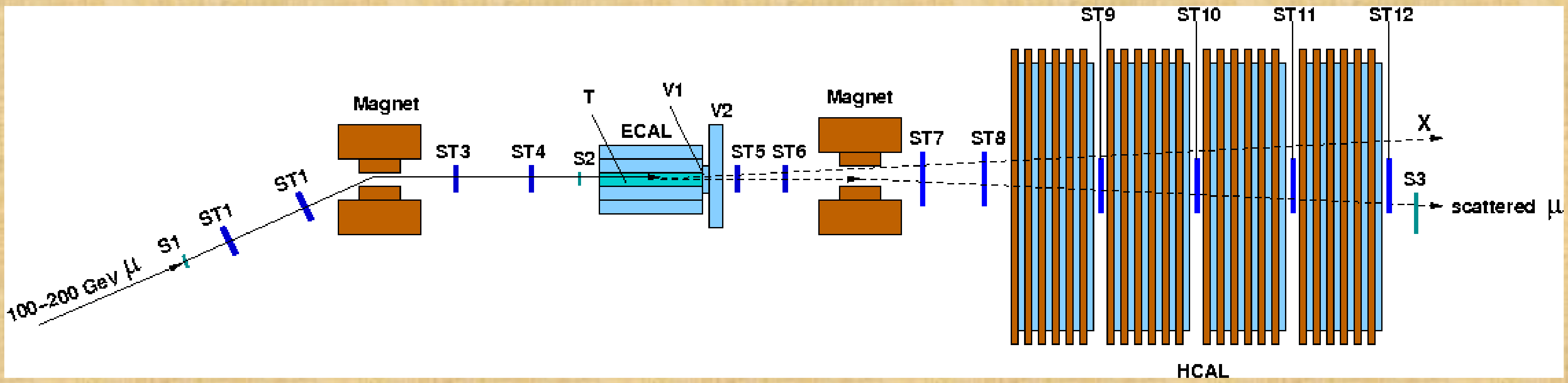
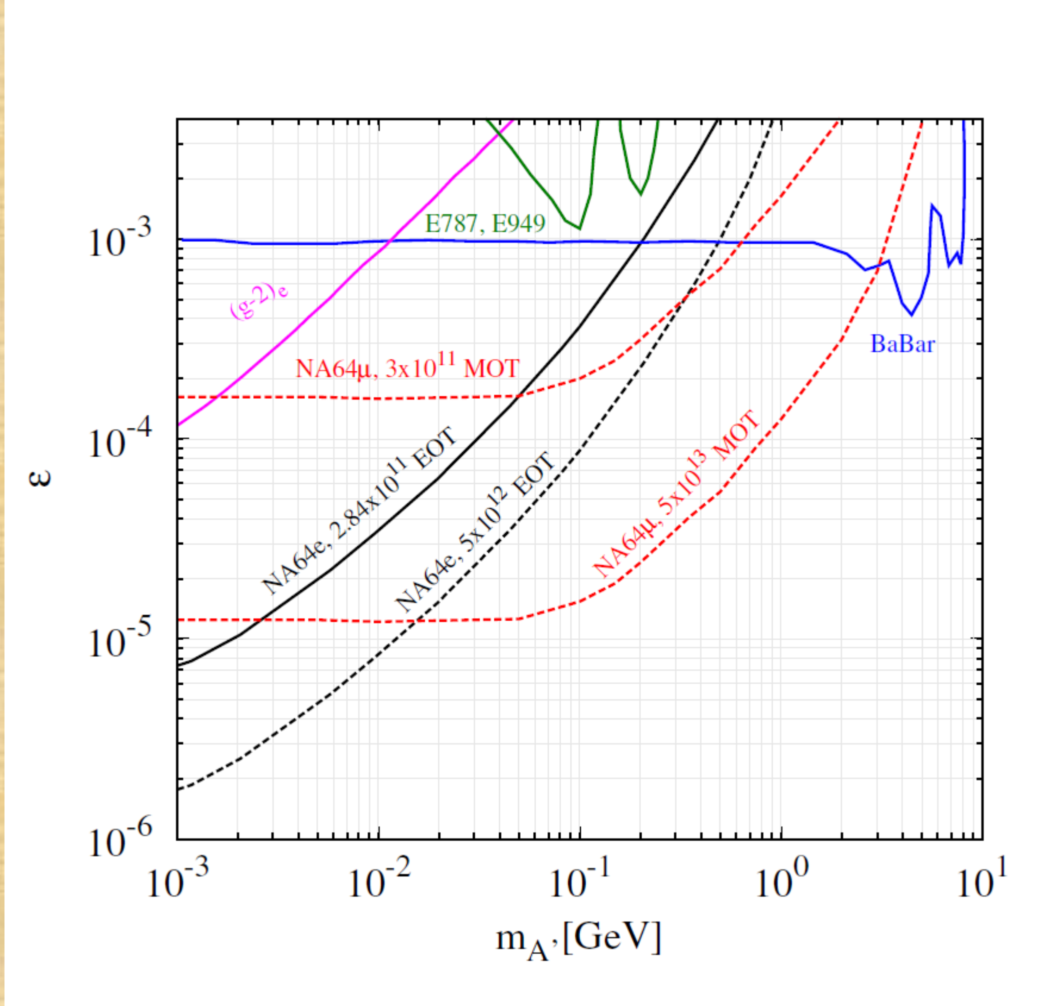
Schematic illustration of the setup to search for dark boson



The comparison of NA64e and NA64μ



Conclusions

NA64 will be able in next 5 years to test the most natural parameters of LDM models

Light dark matter

To be or not to be?

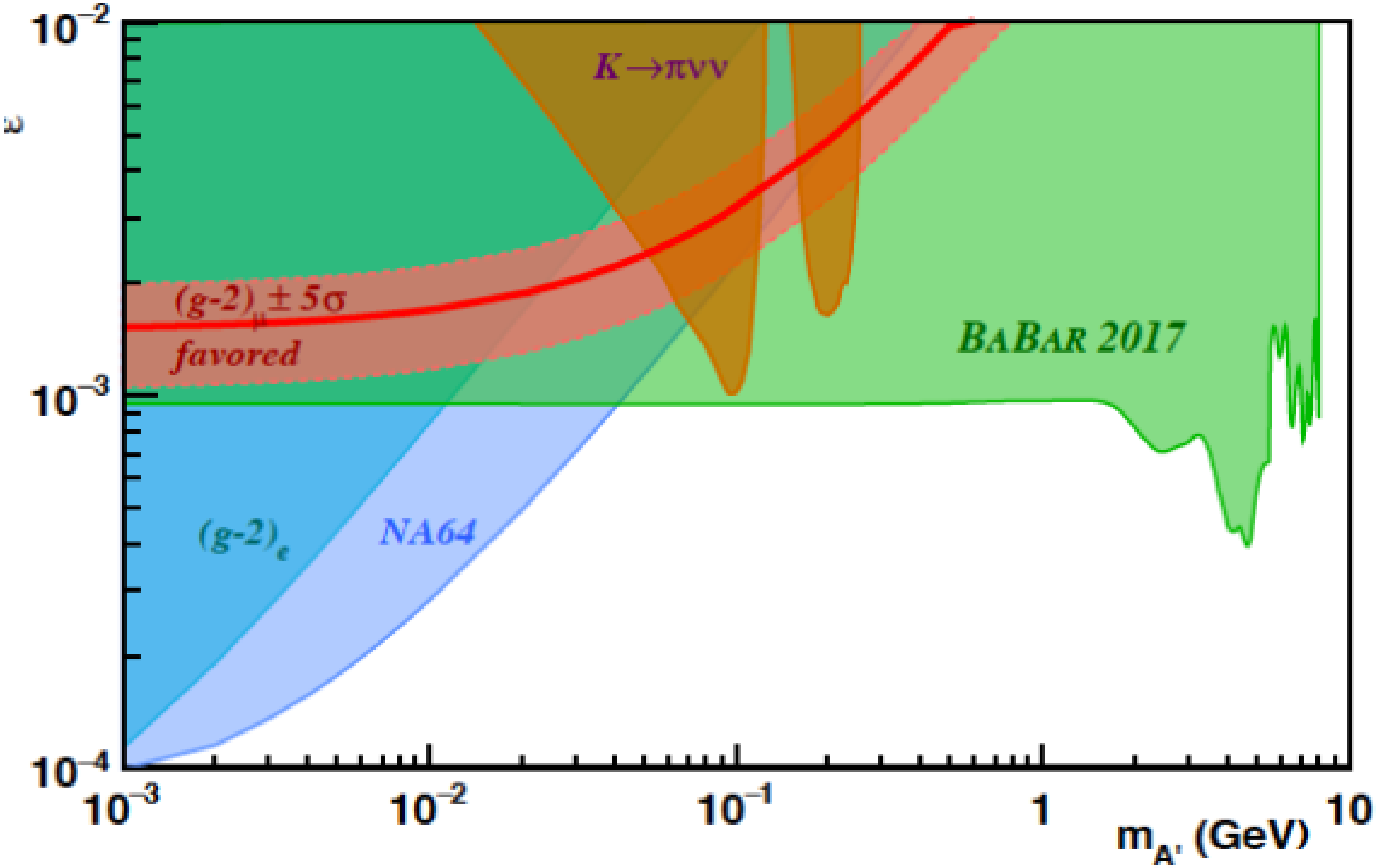
I hope the answer (positive? or negative?)

will be known in 5 years.

Thank You for your attention.

BACKUP

2017 experimental results from NA64 and BaBar exclude (g-2) anomaly explanation



VISIBLE A` DECAYS

APEX(A-prime experiment) and HPS(Heavy Photon Search) at JLAB(USA)

11 GeV electron beam from CEBAF.

APEX $\rightarrow \varepsilon^2 \gtrsim 10^{-7}$ for $60 < m_{A'} < 550$~MeV

after 2018

HPS $\rightarrow \varepsilon^2 \gtrsim 10^{-6}$ for $18 < m_{A'} < 500$ MeV

after 2019

Decays used in NA48/2

$K^{\pm} \longrightarrow \pi^{\pm}\pi^{0} \quad \pi^{0} \longrightarrow \gamma A' \quad A' \longrightarrow e{+}e{-}$:

$K^{\pm} \longrightarrow \pi^{\pm} A' \quad A' \longrightarrow \ell^{+}\ell^{-}$

decay chain $\pi^{0} \rightarrow \gamma A'$, $A' \rightarrow e^{+}e^{-}$

NA62 decays

$$K^{\pm} \rightarrow \pi^{\pm}\pi^{0} \rightarrow \pi^{\pm}\gamma A' \rightarrow \pi^{\pm}\gamma\chi\chi$$

Assuming BR(A' $\rightarrow \chi\chi$)=1

$$\mathrm{BR}\left(\pi^{0} \rightarrow A'\gamma\right) = 2\epsilon^{2}\left(1 - \frac{m_{A}^{2}}{m_{\pi^{0}}^{2}}\right)^{3} \times \mathrm{BR}\left(\pi^{0} \rightarrow \gamma\gamma\right)$$

COHERENT experiment

Spallation Neutron Source at Oak Ridge National Laboratory

The main goal – measurement of elastic coherent neutrino-nucleus scattering

"CEνNS":

Coherent Elastic ν-Nucleus Scattering: $\nu A \rightarrow \nu A$

The first result – arXiv:1708.01294

It is possible to extract bounds on A'

S.-F.Ge and I.N.Shoemaker, arXiv:1710.10889

Extracted bounds on $\varepsilon g_D^{1/2}$ from COHERENT results

bound on $\varepsilon g_D^{1/2}$ 1.76×10^{23} protons on target