Light Dark Matter. NA64 experiment

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Outline

1. Introduction
2. Light dark matter
3. NA64 experiment
4. Conclusions

1.Introduction

A lot of references are contained in:

1. J. Alexander et al., arXiv:1608.08632;

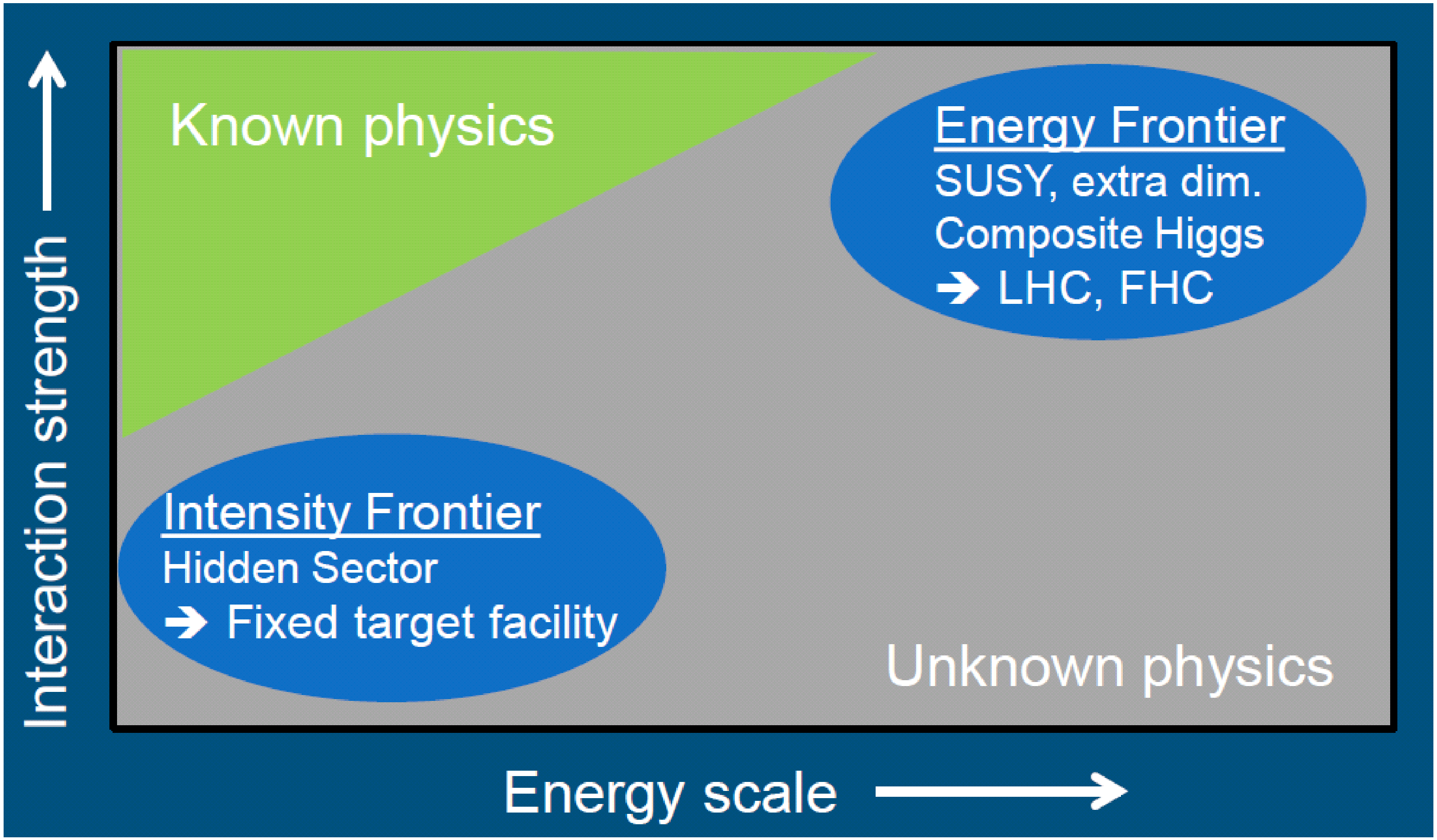
2. E.W.Kolb, M.S.Turner, Front.Phys. 69 1 (1990)

3. S.N.Gninenko, N.V.Krasnikov, V.A.Matveev, Phys.Part.Nucl. 51 829 (2020)

4. M. Battaglieri et al., arXiv:1707.04591

5. D.S.Gorbunov, V.A.Rubakov, Introduction to the Theory of early Universe, 2011

1.Introduction



1. Introduction

The main motivation in favor of BSM physics is dark matter

also probably some hints as:

1. (g-2)-muon anomaly

3. B-mesons semi leptonic decays

There are a lot of dark matter models

For many years SUSY with R-parity was

the most popular dark matter model

However LHC failed to discover SUSY

Other models became popular now

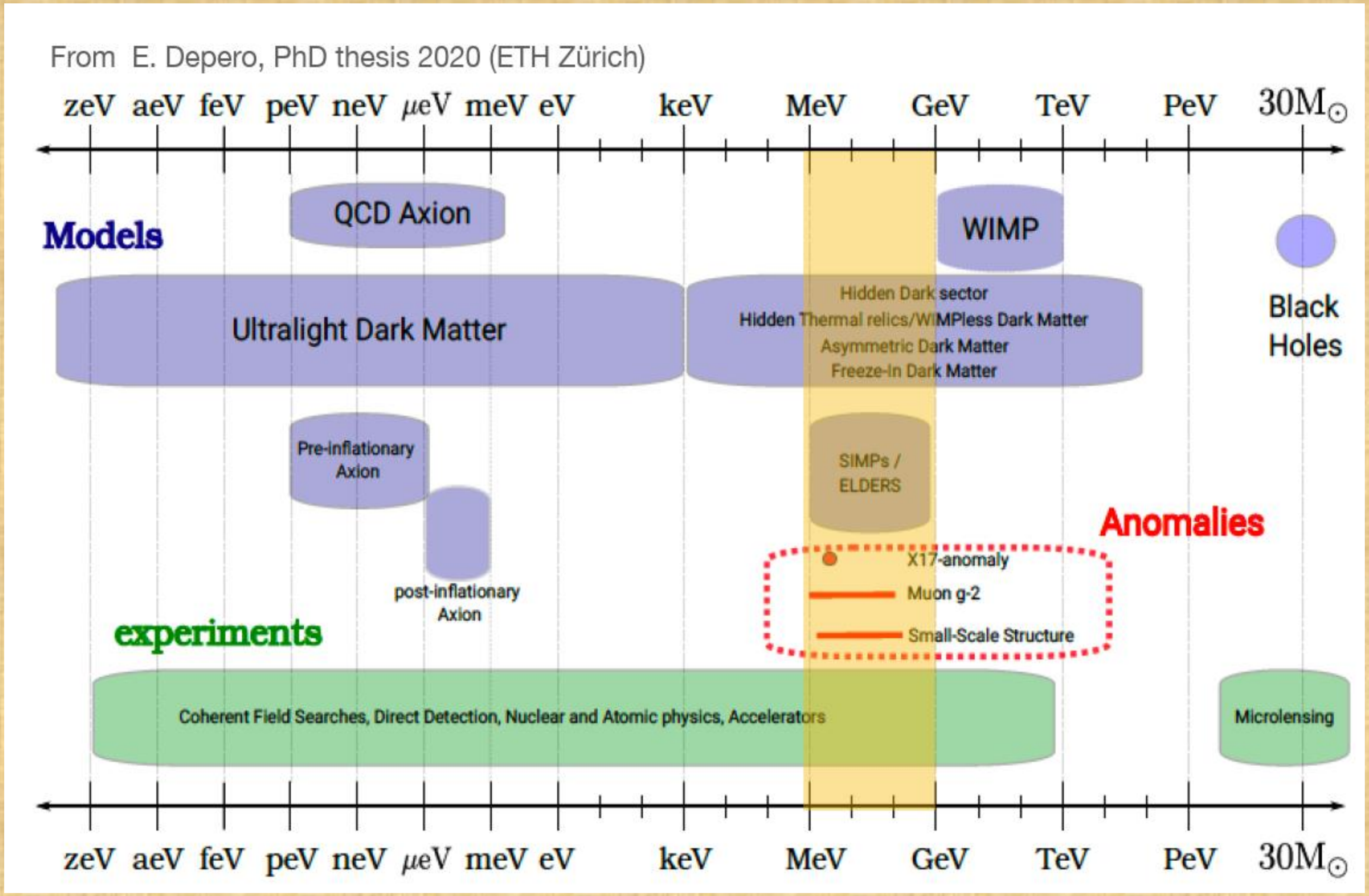
We know that dark matter exists and it is cold (nonrelativistic) or warm

But we don’t know:

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

In SUSY with R-parity LSP is gaugino with s = ½ and m = O(100 GeV) as a rule

Dark matter mass range



Dark matter constraints

1. Dark matter is nonrelativistic or warm

2. From PLANCK experiment (CMB bounds) data s-wave annihilation is

excluded for dark matter masses

$m_{\chi} \leq 10$ GeV

2.Light dark matter

It is possible that dark matter particles are relatively light with masses O(1 GeV) or less (C.Boehm, P.Fayet)

To avoid Lee-Weinberg "theorem"

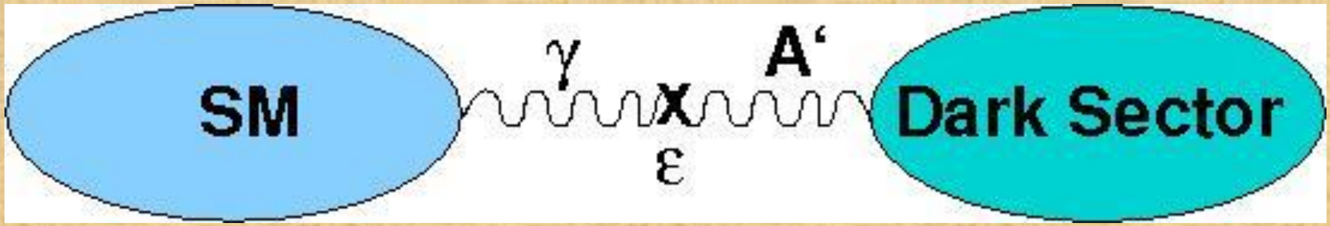
Renormalizable realization – additional interaction connects our world and dark world

The most popular scenario – model with vector messenger dark photon (B.Holdom, L.Okun).

Also models with scalar mediator exist

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, >500 papers /few last years, 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

The most popular light dark matter model – model with additional U(1) gauge field A' – dark photon model (Holdom, Okun)

Dark photon connects our world and dark matter world due to nonzero kinetic mixing between dark photon and ordinary photon

The Lagrangian is the sum of 3 terms

$L = L_{SM} + L_{SM,dark} + L_{dark}$

L_{SM} – the SM Lagrangian

L_{dark} - dark particles Lagrangian

$L_{SM,dark} = -(\varepsilon/2\cos(\theta_W))F'_{\mu\nu}B^{\mu\nu}$

$F'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'$

$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$

B_μ - U(1) gauge field of SM

SU(2)·U(1) – gauge fields

Scalar dark matter χ

$L_{dark,s} = (\partial_\mu \chi - i e_D A'_\mu \chi)^* \cdot (\partial_\mu \chi - i e_D A'_\mu \chi) - m^2_\chi \chi^* \chi - \lambda(\chi^* \chi)^2$
$-(1/4)F'_{\mu\nu}F'^{\mu\nu} + (m^2_{A'}/2)A_\mu' A'^\mu$

It is possible to use Higgs mechanism to create dark photon mass in a gauge invariant way

Also models with majorana fermion ($\chi = C\chi^*$) are often used

$L_M = (e_D/2)\chi^* \gamma_\mu \gamma_5 \chi A'^\mu$

THERMAL ORIGIN

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

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

Dark matter annihilation mechanism

Direct annihilation

$\chi\chi^{*}$--> $e^{+}e^{-}$, … ($m_\chi < m_{A'}$)

Secluded annihilation

$\chi\chi^{*}$--> A'A' ($m_\chi > m_A$

For dark photon model secluded annihilation is s-wave and for light

dark matter it is excluded . For scalar mediator secluded annihilation is

possible. Here we shall consider direct annihilation

To estimate DM density we have to solve Boltzmann equation

$$\frac{dn_d}{dt} + 3H(T)n_d = - < \sigma v_{rel} > (n_d^2 - n_{d,eq}^2) \, .$$

$$n_d(T) = \int \frac{d^3p}{2\pi^3} f_d(p,T)$$

The dark matter relic density can be numerically estimated as

$$\Omega_d h^2 = 8.76 \times 10^{-11} GeV^{-2} [\int_{T_0}^{T_d} (g_*^{1/2} < \sigma v >) \frac{dT}{m_d}]^{-1}$$

In nonrelativistic approximation with $< \sigma v_{rel} >= \sigma_o x_f^{-n}$ one can find that

$$\Omega_{DM} h^2 = 0.1 \Big(\frac{(n+1) x_f^{n+1}}{(g_{*s}/g_*^{1/2})} \Big) \frac{0.876 \cdot 10^{-9} GeV^{-2}}{\sigma_0}$$

$$x_f = c - (n + \frac{1}{2}) \ln(c) \, ,$$

$$c = \ln(0.038(n+1) \frac{g}{\sqrt{g_*}} M_{Pl} m_\chi \sigma_0)$$

Here g_*, g_{*s} are the effective relarivistic energy and entropy degrees of freedom and g is an internal number of freedom degree. If DM particles differ from DM antiparticles $\sigma_o = \frac{\sigma_{an}}{2}$.

For s-wave annihilation cross-section with $n = 0$

$$< \sigma v_{rel} >= 7.3 \cdot 10^{-10} GeV^{-2} \cdot \frac{1}{g_{*,av}^{1/2}} (\frac{m_d}{T_d})$$

$$\sigma(\chi\bar{\chi} \to e^- e^+) v_{rel} = \frac{16\pi\epsilon^2 \alpha_D m_\chi^2}{(m_{A'}^2 - 4m_\chi^2)^2}$$

$$\epsilon^2 \alpha_D = 2 \cdot 10^{-8} GeV^{-2} \frac{(m_{A'}^2 - 4m_\chi^2)^2}{m_\chi^2} \cdot \frac{2c_s}{g_{*,av}^{1/2}}$$

For $m_{A'}=3m_\chi$ we find that dark matter is nonrelativistic:
$(T_D/m_\chi) = (0.1 - 0.05)$ for
$1\ \mathrm{MeV} < m_\chi < 1\ \mathrm{GeV}$

Scalar dark matter (p-wave)

$$\epsilon^2 \alpha_D \sim 10^{-11} \cdot \left(\frac{m_\chi}{MeV}\right)^2$$

for Majorana dark matter additional factor 1/2

For fermion dark matter(s-wave)

$$\epsilon^2 \alpha_D \sim 0.4 \cdot 10^{-12} \cdot \left(\frac{m_\chi}{MeV}\right)^2$$

So the main features of light dark matter

1. p-wave annihilation(or annihilation shuts off before CMB) (Planck data)
2. The annihilation cross-section

$<\sigma_{an} \cdot v> = O(1)$ pbn → The main assumption at the early Universe dark matter is in equilibrium with our matter

However other scenario are possible

Freeze-in scenario

S.Dimopoulos and H.Georgi, 1981

L.J.Hall et al., 2010

R.Essig et al., 2012

Dark sector is never in thermal equilibrium with the SM, out-of-equilibrium scattering populates the dark matter. Couplings are very small.

$\alpha_D \varepsilon^2 = O(3 \cdot 10^{-24})$ for $m_{A'}$=100 MeV

Not very exciting from accelerator point of view

From the requirement of the absence of Landau pole singularity(H.Davoudiasl and W.J.Marciano, Phys.Rev. D92 035008 (2015)) upper bound on α_D

The concrete number depends on the Landau pole scale Λ and the model. For instance,

for $\Lambda = 1$ TeV

$\alpha_D \leq$ 0.8(0.2) for scalar(Majorana or pseudo Dirac)

for $\Lambda = M_{PL} = 1.2 \cdot 10^{19}$ GeV

$\alpha_D \leq$ 0.2(0.05) for scalar(Majorana or pseudo Dirac)

Visible and invisible A' decays

Visible A' decays A' → e^+e^- ,$\mu^+\mu^-$

1. Prompt decays – resonant behavior in invariant mass distribution

2. Displaced decays –long lived A' (NA64 exp.)

Invisible decays

3. Missing momentum(energy) from

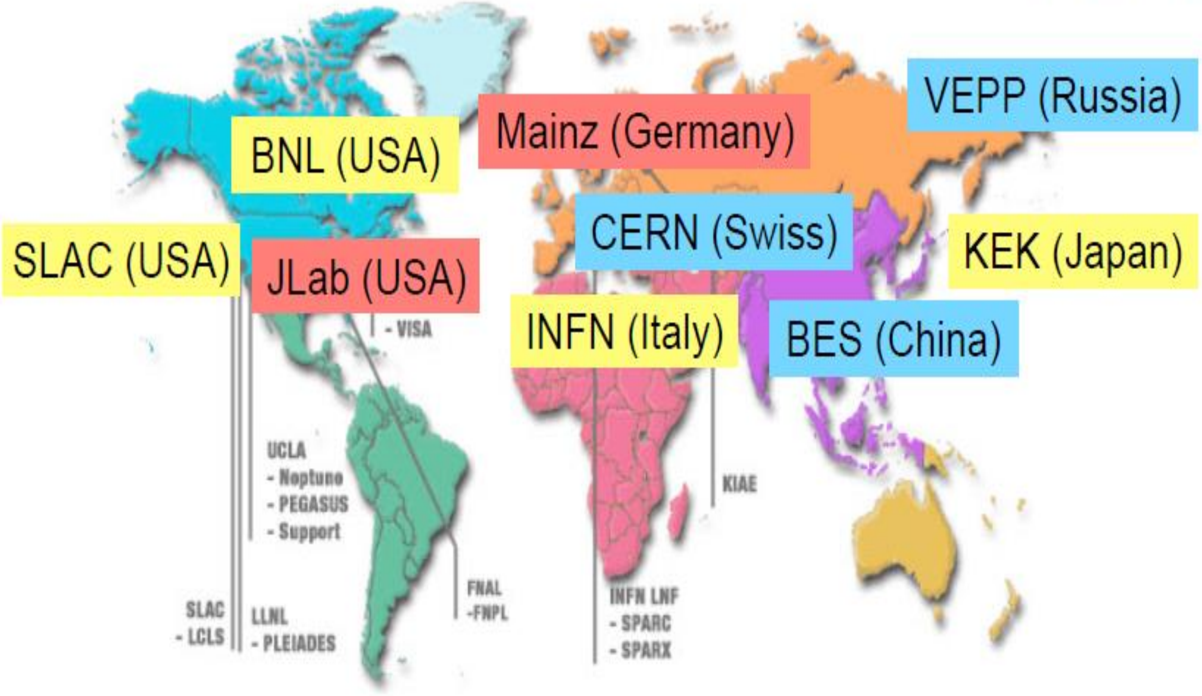
A' → χχ decays into dark matter particles

Invisible mode detection

1. Beam dump (SHiP, …)
2. Missing mass measurement – resonant distribution (PADME, …)
3. Missing energy measurement (NA64)
4. Missing momentum measurement (LDMX)

Dark Force searches in the Labs

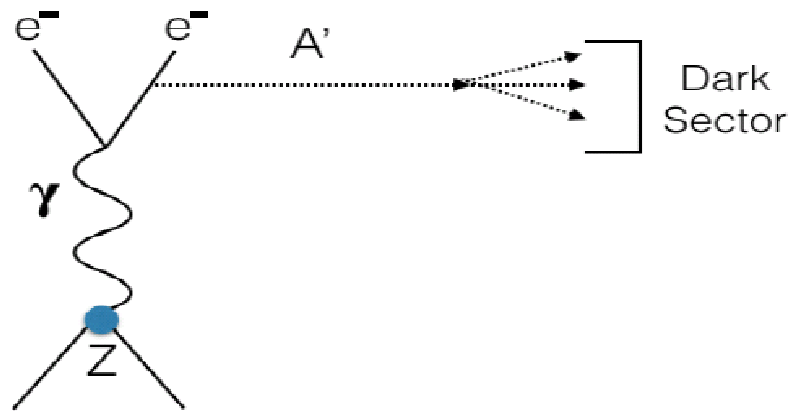
Many searches for Dark Force in the Labs around the world (ongoing/proposed).



3. 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.

The NA64 Collaboration

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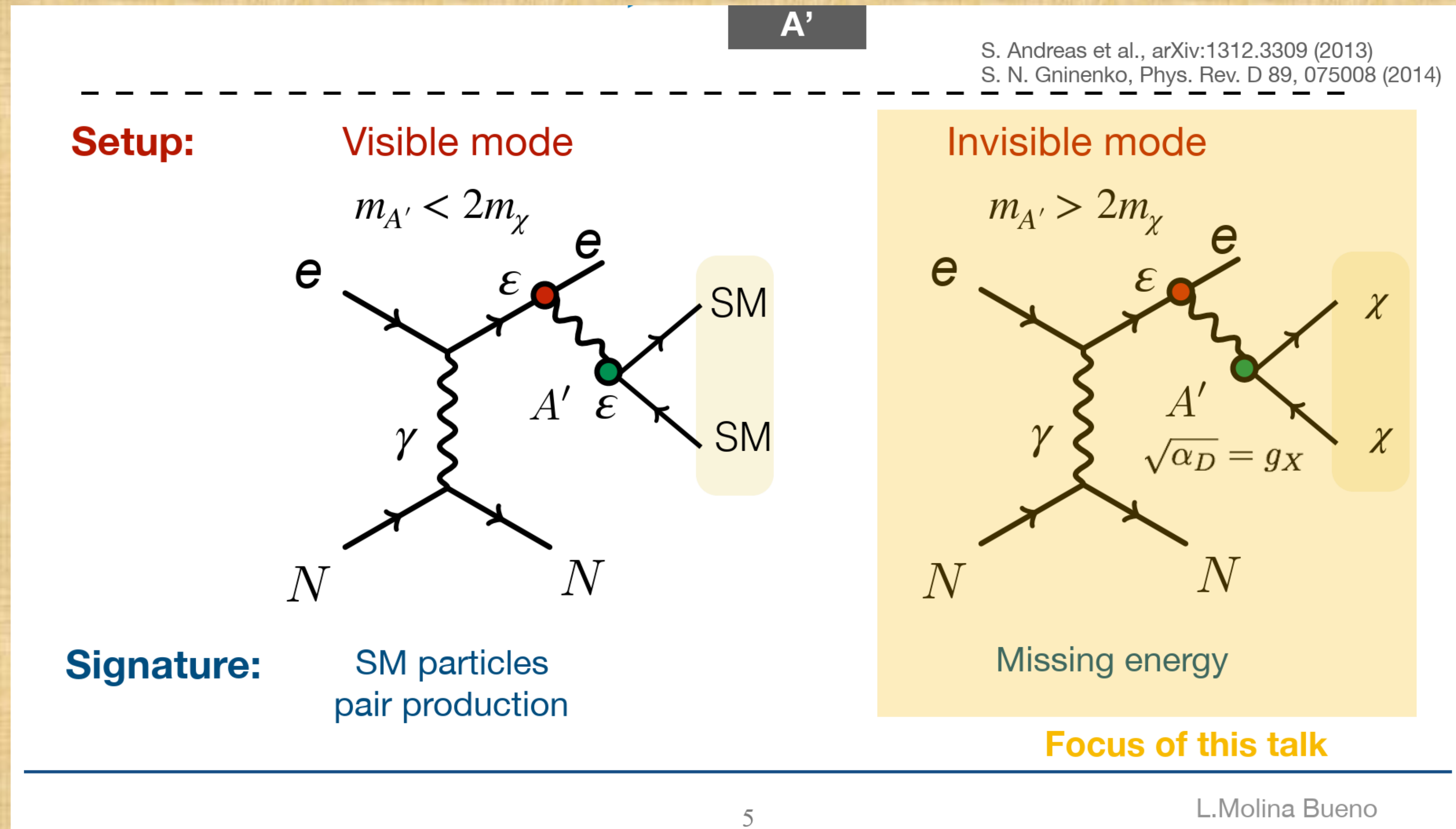
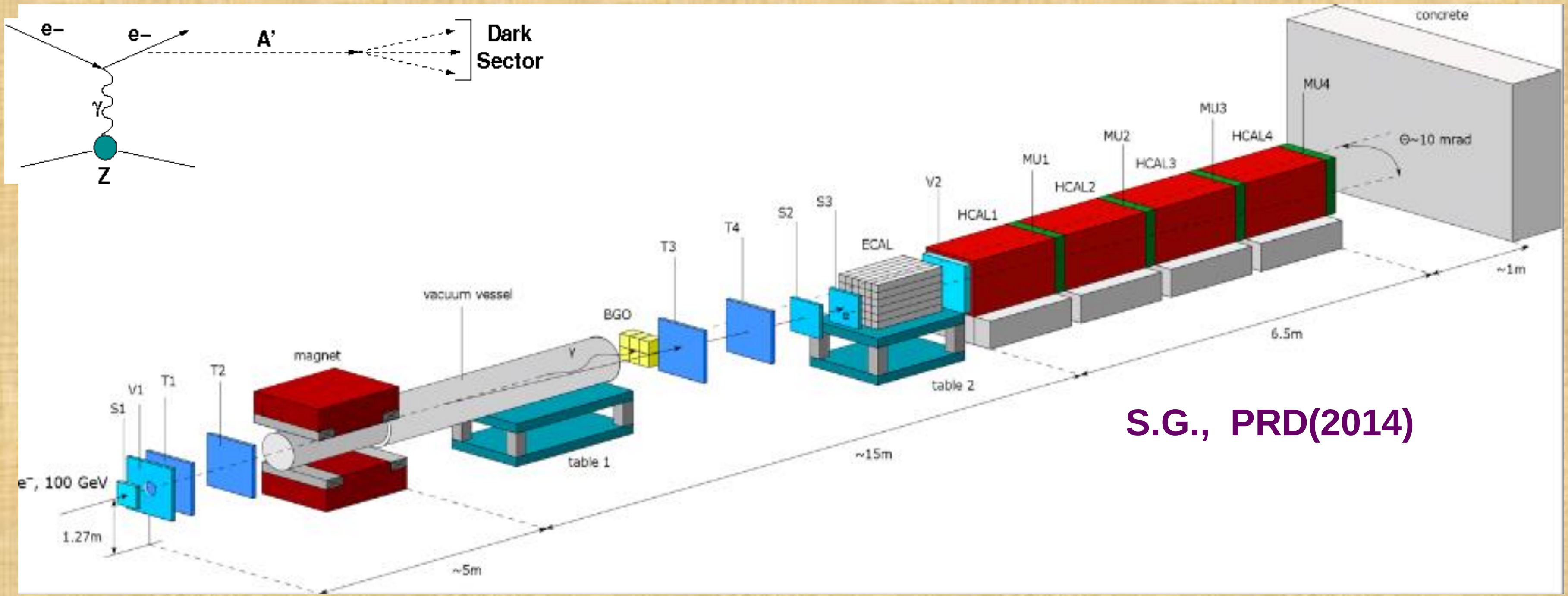
47 researchers from 12 institutes

Two main reactions



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

Invisible decay of Invisible State!



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


GOLIATH

NA64 dark photon detection

A' – production in ECAL, invisible decay

The A' production in electron nucleus interactions

$eZ \rightarrow eZA'$, $A' \rightarrow$ invisible

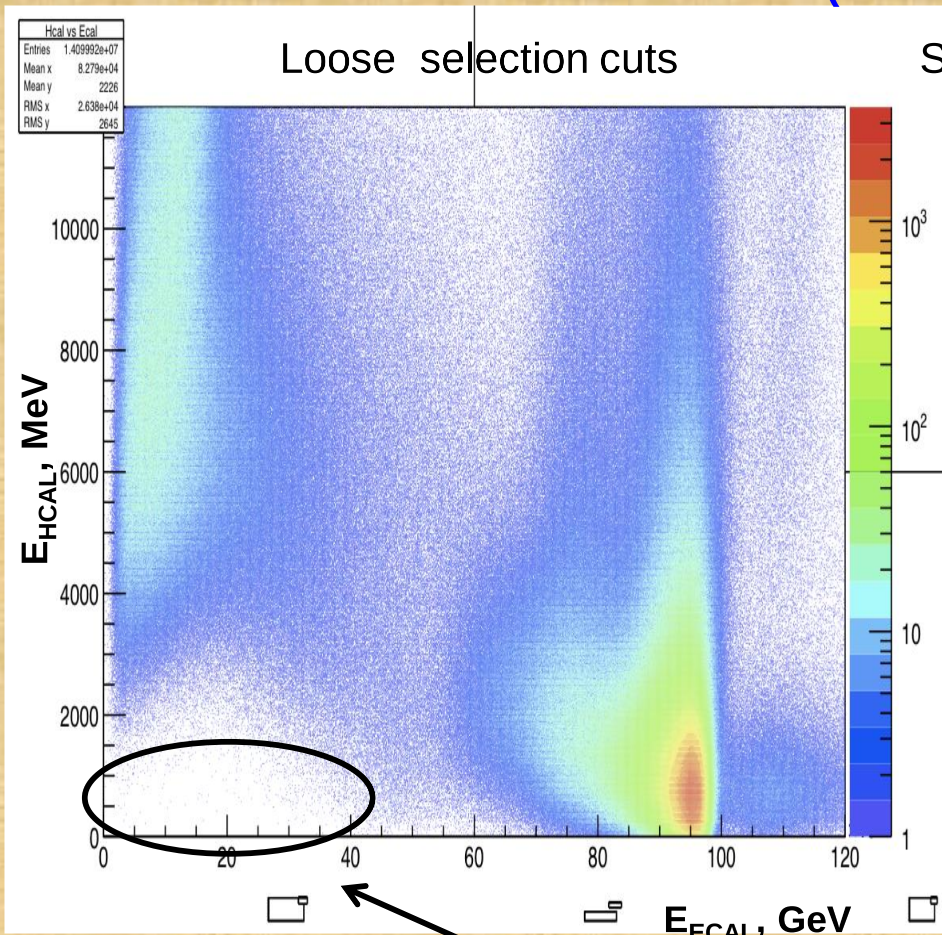
Signature: missing energy in ECAL + HCAL

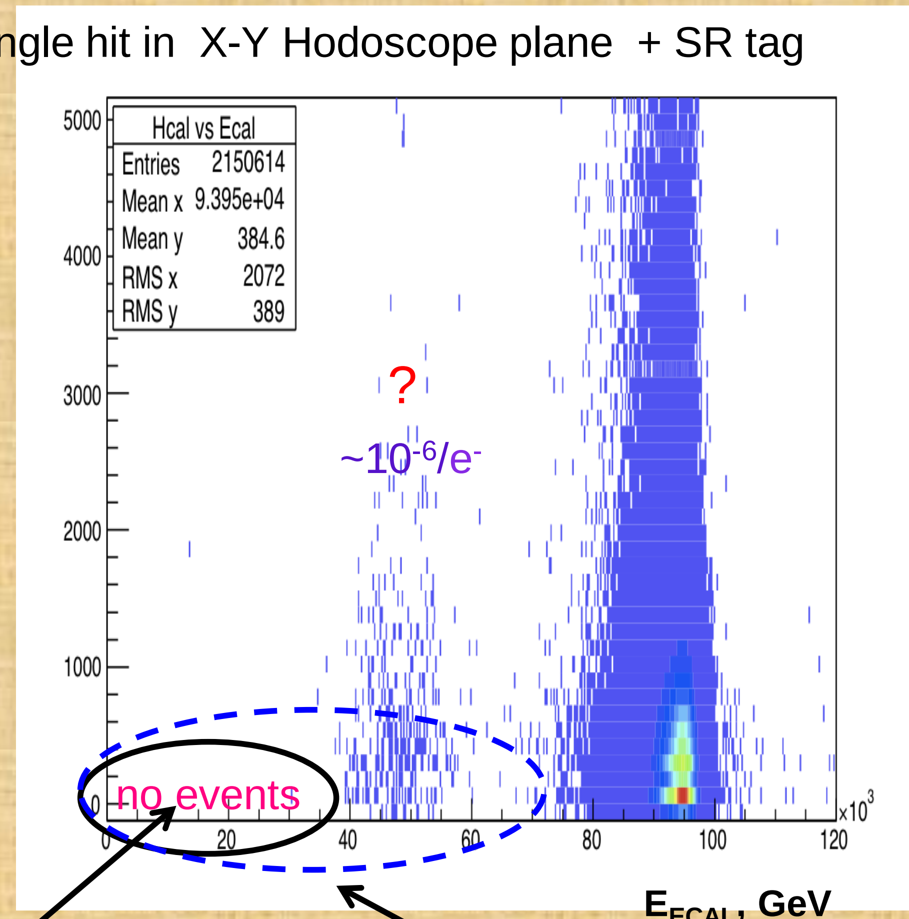
In comparison with initial 100 GeV electron

plus no essential activity in HCAL(E_{HCAL}<2 GeV)

A´ signal in (E_{HCAL}; E_{ECAL}) plaine

Tr = S0 x S1x PS(>2 GeV) x ECAL(< 95 GeV)



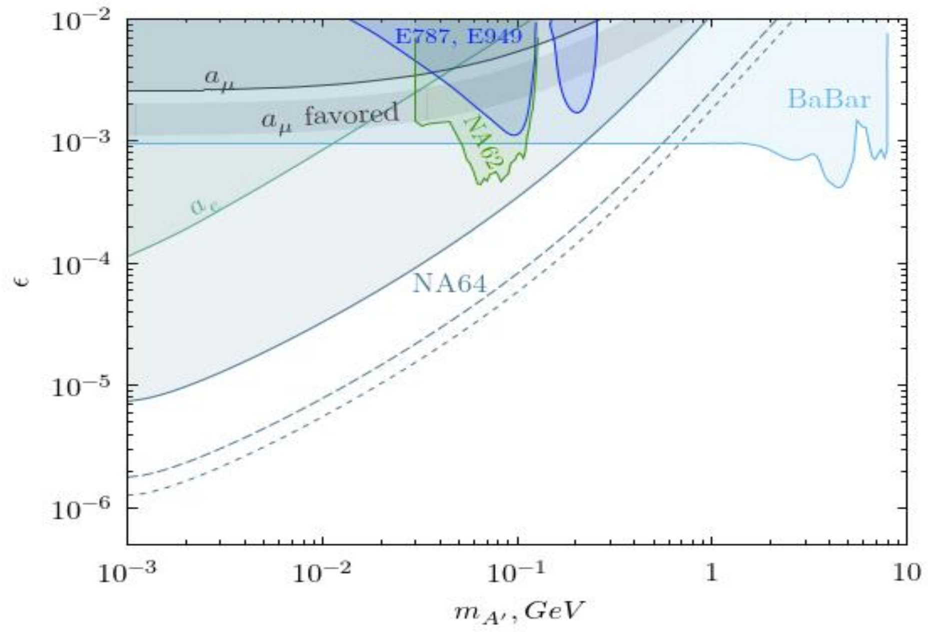


SIGNAL REGION

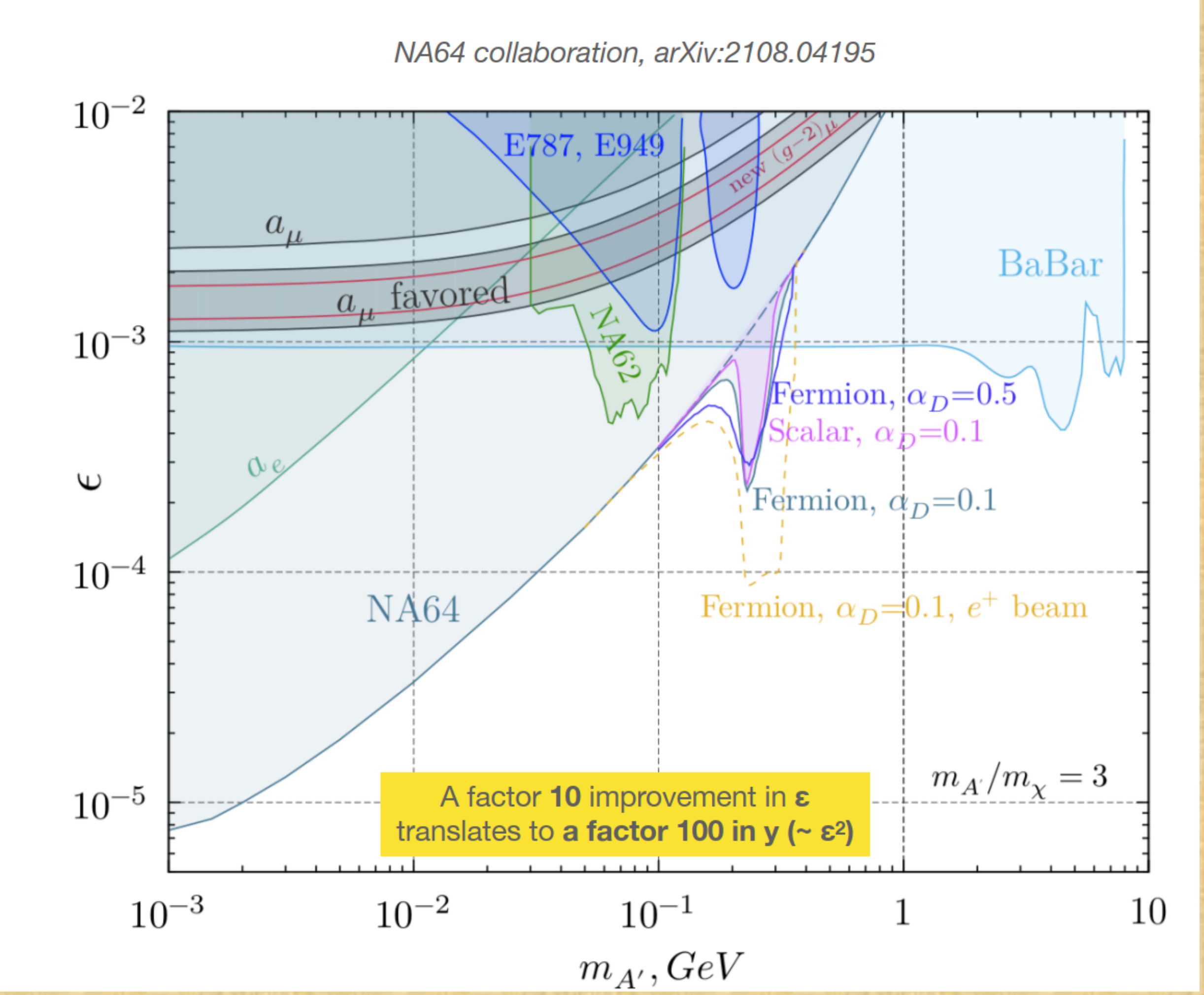
Background $< 10^{-8}/e^-$

Possible extension of signal region

Last NA64 result on ε parameter invisible dark photon decay Phys.Rev.Lett. 123 121801 (2019)



The use of $e^+e^- \rightarrow A'^* \dashrightarrow \chi\chi^*$
Positrons from $eZ \rightarrow eZe^+e^-$



New NA64 limit in comparison with predictions for light dark matter models

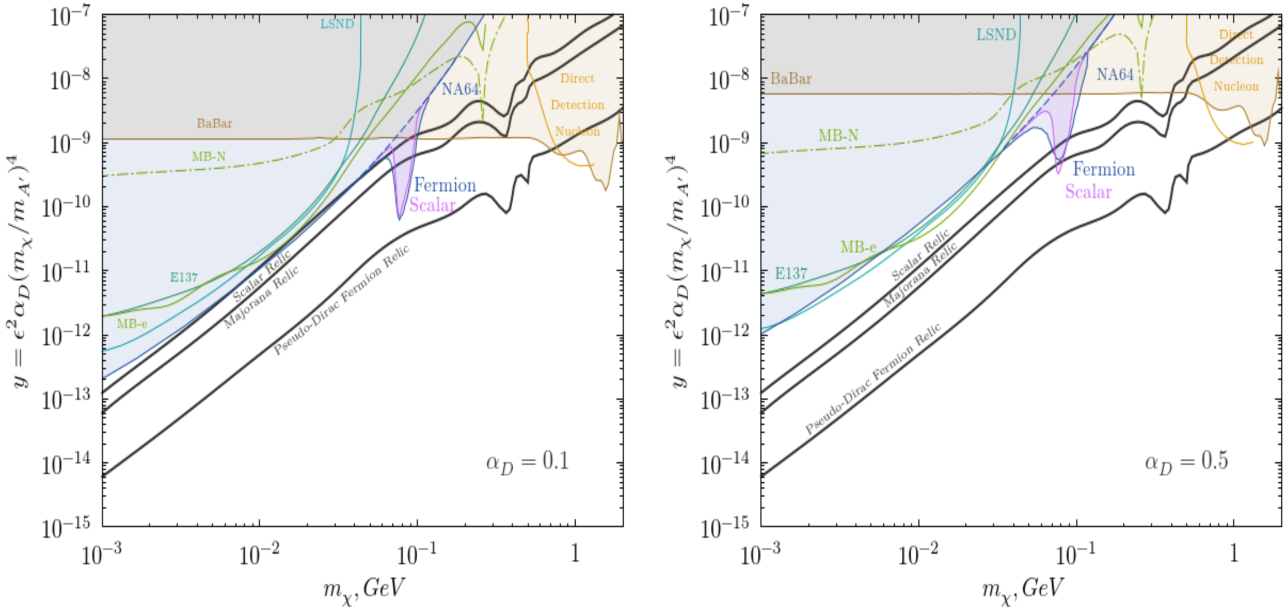
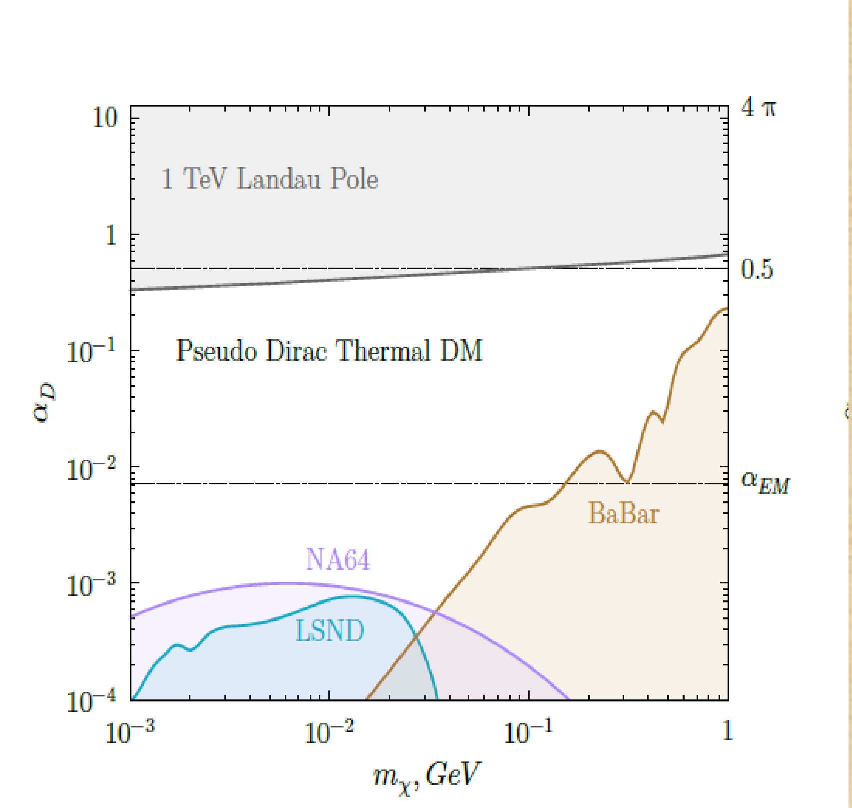


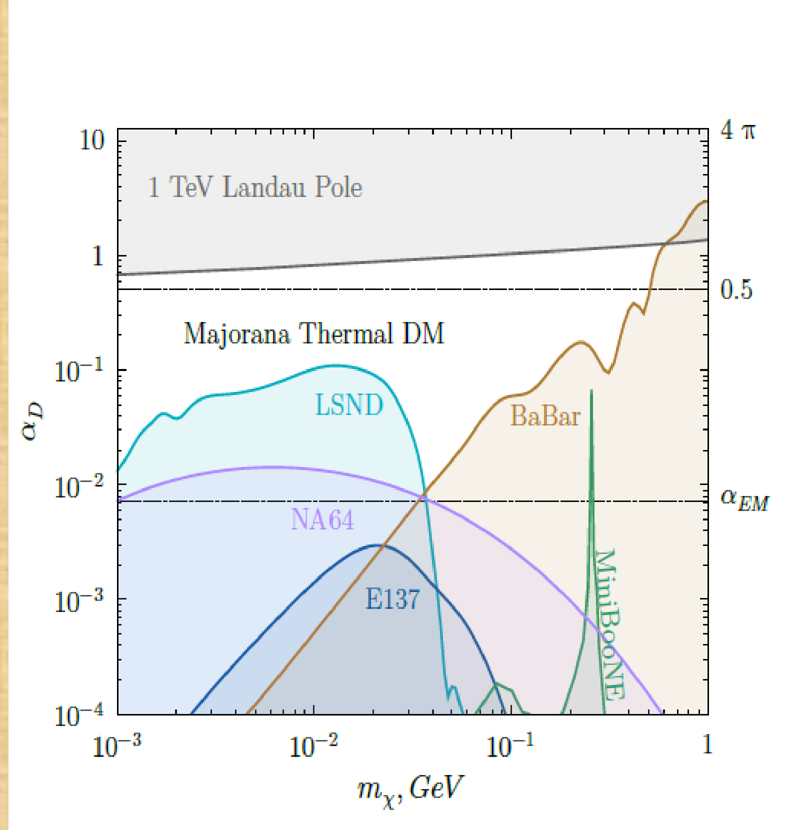
FIG. 4. The new NA64 exclusion limit in the (y, m_χ) plane, including the e^+e^- annihilation process, in the (m_χ, y) plane, for $\alpha_D = 0.1$ (left) and $\alpha_D = 0.5$ (right). The other curves and shaded areas report already-existing limits in the same parameters space from E137 [47], LSND [48, 49], MiniBoone [49], and BaBar [22]. The black lines show the favored parameter combinations for the observed dark matter relic density for different variations of the model.

NA64 bound on α_D

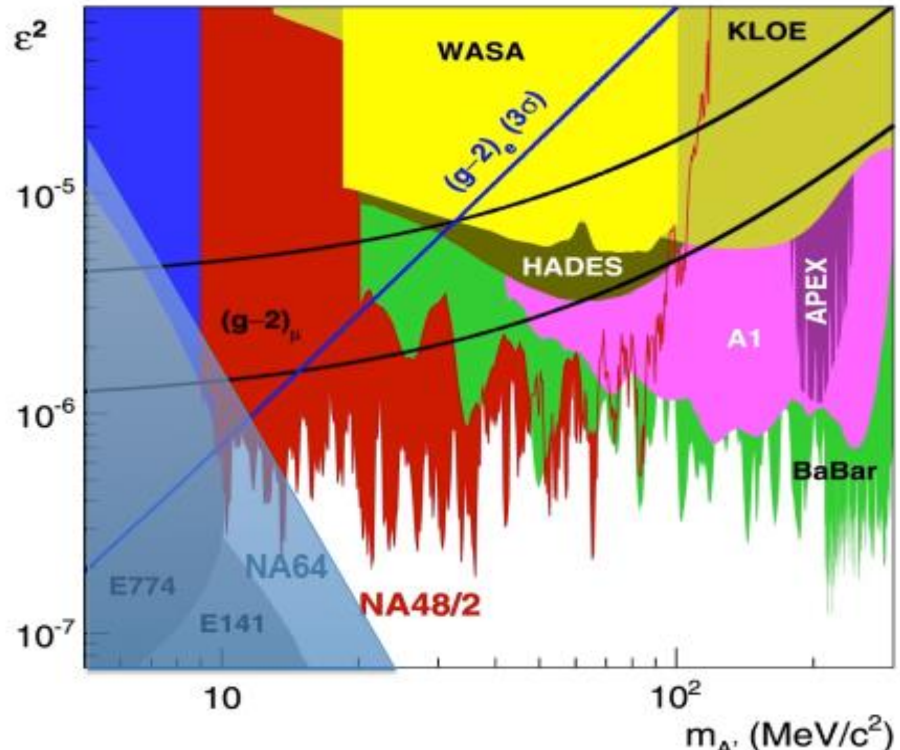
Pseudo Dirac



Majorana



Summary plot for visible A' decays

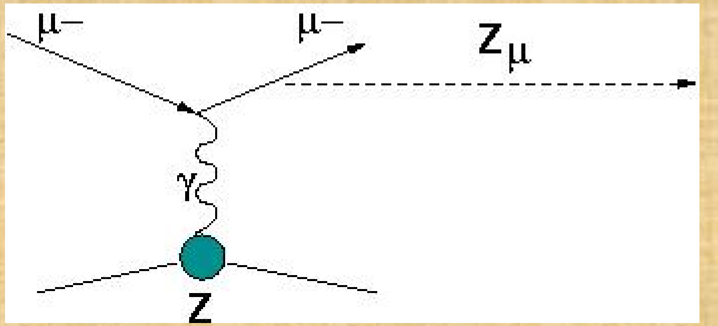


The NA64 experiment with muon beam

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 NA64 experiment at CERN with muon beam



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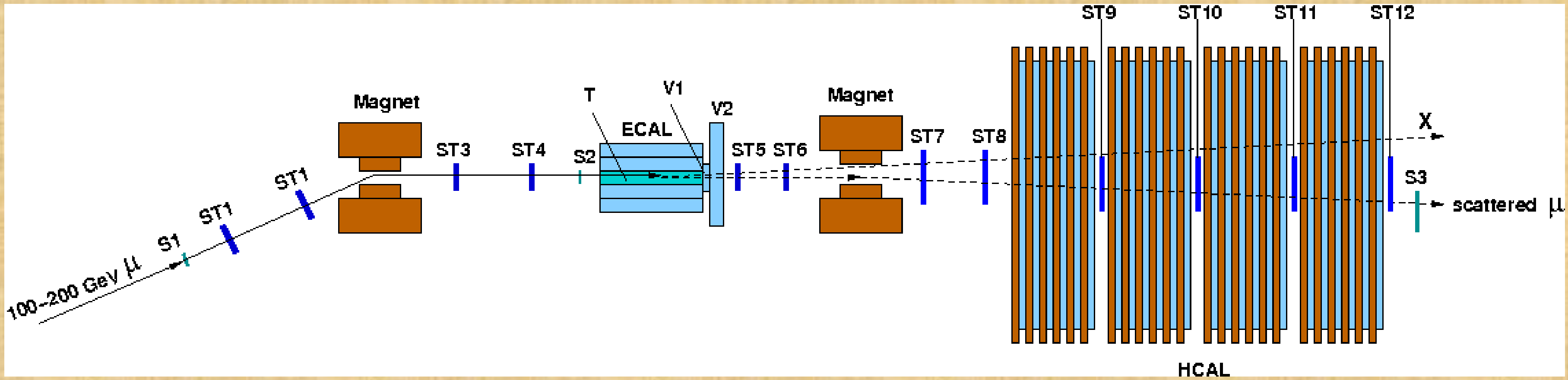
Schematic illustration of the setup to search for dark boson



NA64 at CERN SPS with muon beam

Coming muon produces dark boson at the target. Dark boson decays into neutrino or light dark matter and escapes the detection. So the signature is imbalance in energy for incoming and outcoming muons without big activity in HCAL and ECAL

Motivation for the muon beam use

There is possibility that new boson Z_μ interacts only with $L_\mu - L_\tau$ current

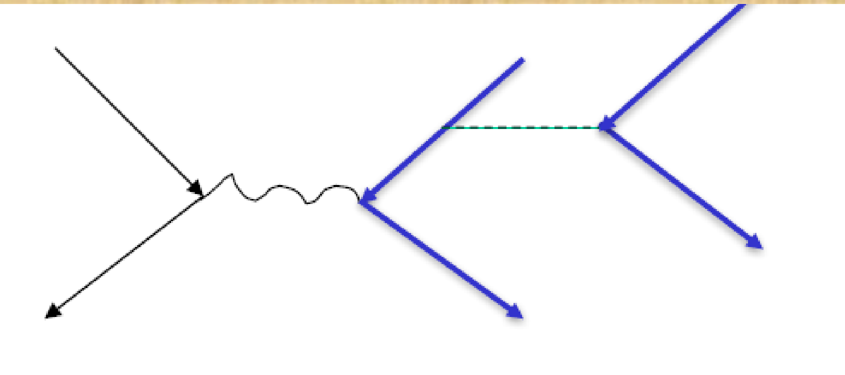
$$L_{Z_\mu} = e_\mu [\bar{\mu}\gamma_\nu \mu + \bar{\nu}_{\mu L}\gamma_\nu \nu_{\mu L} - \bar{\tau}\gamma_\nu \tau - \bar{\nu}_{\tau L}\gamma_\nu \nu_{\tau L}] Z_\mu^\nu$$

For this model the most nontrivial bound (W.Almannsofer et. al) comes from CCFR data on neutrino trident $\nu_\mu N \to \nu_\mu N + \mu^+ \mu^-$ production. Masses $m_{Z_\mu} \geq 400\ MeV$ are excluded

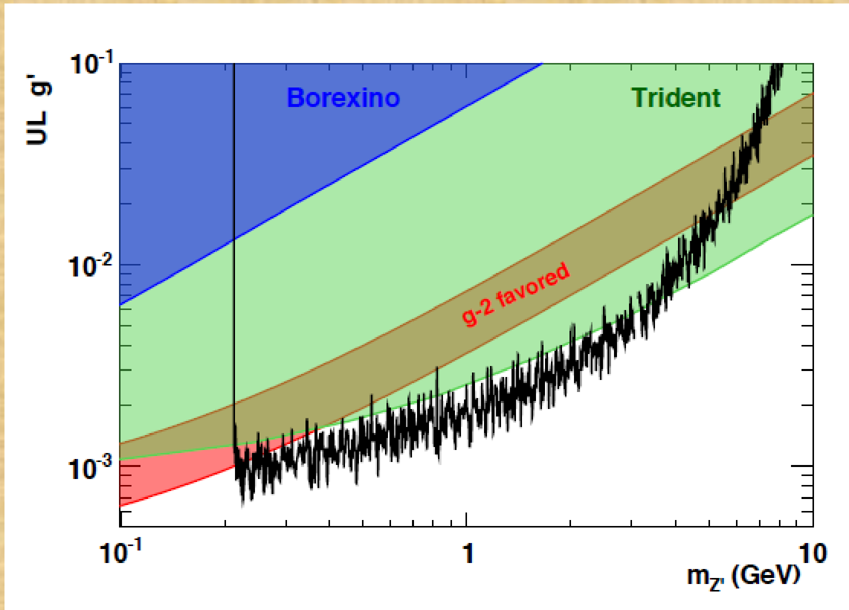
New BaBaR bound excludes m > 214 MeV

BaBar bound
Phys.Rev.D94,011102(R) (2016)

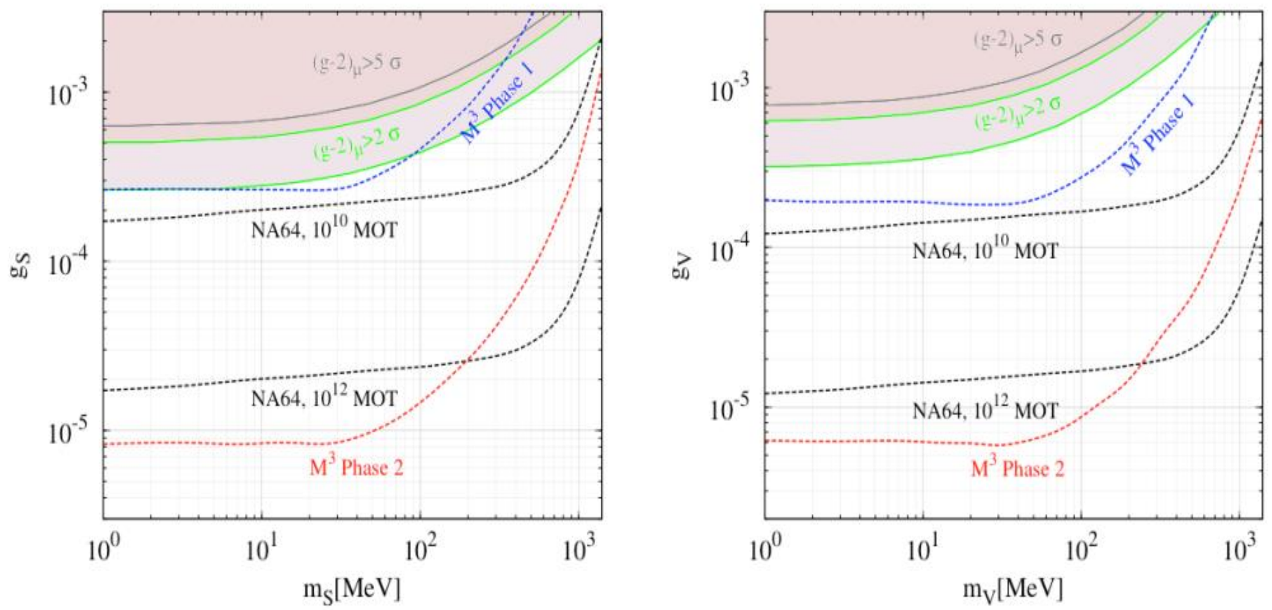
The main diagram



Only masses <214 MeV survive

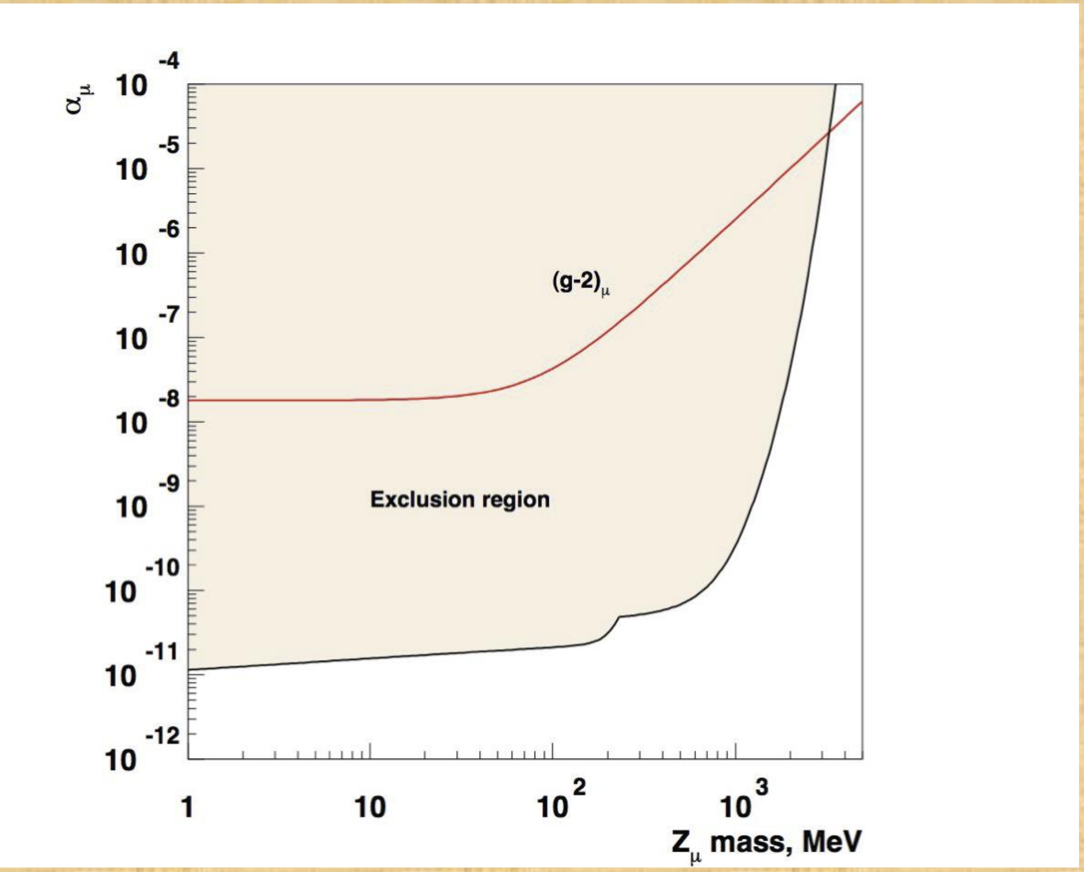


NA64 discovery potential for experiment with muon beam



Dubna, 13 october 2021

Expected sensitivity for 10^{12} muons on target



4.Conclusions

1. Light dark matter – good alternative to SUSY and other models (axions, sterile neutrino, …)

2. Dark photon model is the simplest

realization

3. Dark photon model predicts mixing interesting for experimental search

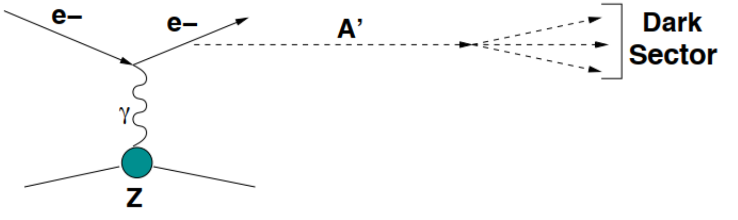
4. NA64 with future statistics $5 \cdot 10^{12}$ EOT will

be able to test the most interesting models

5. NA64μ has good perspectives to test L_μ-L_τ model

Thank You for your attention.

Additional slides


e–
e–
A'
Dark
Sector
γ
Z

2 Upper bound on α_D

One can obtain upper bound on α_D by the requirement of the absence of Landau pole singularity for the effective coupling constant $\bar{\alpha}_D(\mu)$ up to some scale Λ [16]. One loop β function for $\bar{\alpha}_D(\mu)$ is

$$\beta(\bar{\alpha}_D) = \frac{\bar{\alpha}_D^2}{2\pi}[\frac{4}{3}(Q_F^2 n_F + Q_S^2 \frac{n_S}{4})]\,. \quad (5)$$

Here $\beta(\bar{\alpha}_D) \equiv \mu\frac{d\bar{\alpha}_D}{d\mu}$ and n_F (n_s) is the number of fermions (scalars) with the $U^{`}(1)$ charge $Q_F(Q_S)$. For the model with pseudo Dirac fermion we must have additional scalar with $Q_d = 2$ to realize the splitting between fermion masses, so one loop β function is $\beta(\bar{\alpha}_D) = \frac{2\bar{\alpha}_D^2}{3\pi}$. For the model with Majorana fermions we also must have an additional scalar field with the charge $Q_S = 2$ and additional Majorana field to cancel γ_5 anomalies, so the β function coincides with the β function for the model with pseudo Dirac fermions. For the model with charged scalar matter in order to create nonzero dark photon mass we have to introduce additional scalar field with $Q_S = 1$ so one loop β function is $\beta = 2 * \alpha^2/12\pi¿$.

From the requirement that $\Lambda \geq 1\ TeV$ [16][2] we find that $\alpha_D \leq 0.2$ for pseudo Dirac and Majorana fermions and $\alpha_D \leq 0.8$ for charged scalars. Here α_D is an effective low energy coupling at scale $\mu \sim m_{A^{\backprime}}$, i.e. $\alpha_D = \bar{\alpha}_D(M_{A^{\backprime}})$. In our calculations we used the value $M_{A^{\backprime}} = 10\ MeV$. In the assumption that dark photon model is valid up to Planck scale, i.e. $\Lambda = M_{PL} = 1.2 \cdot 10^{19}\ GeV$, we find that for pseudo Dirac and Majorana fermions $\alpha_D \leq 0.05$ while for scalars $\alpha_D \leq 0.2$. In the SM the $SU_c(3)$, $SU_L(2)$ and $U(1)$ gauge coupling constants are equal to $\sim (1/30 - 1/50)$ at the Planck scale. It is natural to assume that the gauge coupling $\bar{\alpha}_D(\mu = M_{PL})$ also lies within the interval $\sim (1/30 - 1/50$. As a consequence we find that low energy coupling constant $\alpha_D \sim (0.014 - 0.02)$. So the values $\alpha_D \sim (0.014 - 0.02)$ are the the most natural for α_D. In the next section we shall use the values $\alpha_D = 0.2$, $\alpha_D = 0.05$ and $\alpha_D = 0.02$ for numerical estimates.

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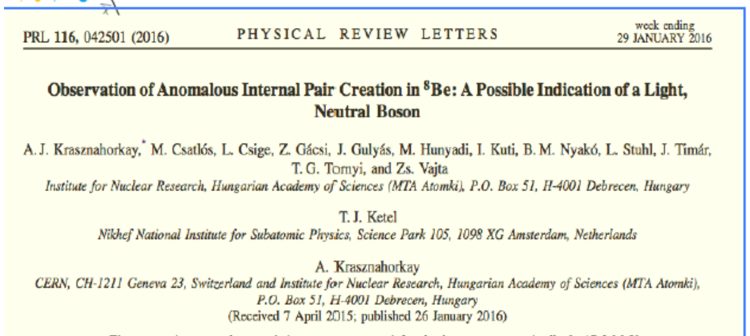
Visible decays activity- the check of the ATOMKI experiment

^{8}Be* anomaly: a new light X boson?

10.



PRL 116, 042501 (2016) PHYSICAL REVIEW LETTERS week ending 29 JANUARY 2016

Observation of Anomalous Internal Pair Creation in ^{8}Be: A Possible Indication of a Light, Neutral Boson

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^{7}Li(p, γ)^{8}Be, M_X =16.7 MeV

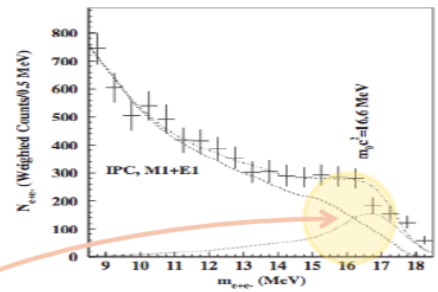
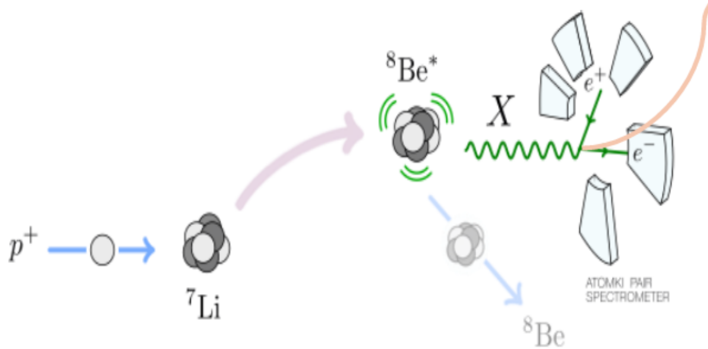
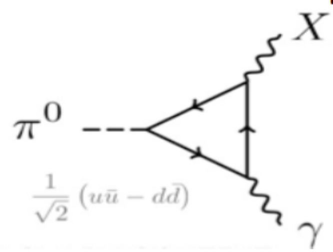


FIG. 5. Invariant mass distribution derived for the 18.15 MeV transition in ^{8}Be.



X cannot be A´due to constraints from $\pi^0 \to X\gamma$ decay:



Feng et al, 2016

$2 \times 10^{-4} < \varepsilon_e < 1.4 \times 10^{-3}$

$\Gamma(\pi^0 \to X\gamma) \sim (\varepsilon_u q_u - \varepsilon_d q_d)^2 \sim 0$

if $2\varepsilon_u = -\varepsilon_d$ -> protophobic X

S.N. Gninenko – NA64 Status Report, SPSC Open Meeting, CERN, June 20–21, 2017

Future and current visible decays searches

1. APEX at JLab(USA) –prompt decays
2. HPS at JLab – prompt decays
3. NA64 – displaced decays
4. Belle-|| at KEK(Japan) – prompt decays
4. MAGIX at MESA(Germany) –prompt decays
6. SHiP at CERN – displaced decays
7. VEPP3 at BINP(Russia) – prompt decays
8. SeaQuest(FNAL, USA) – dark photon decays into muons

Visible decays. New NA64 result-October 2017 run with 4.5*10^14 EOT

ALLOWED REGION,

J.Feng et al., Phys.Rev.Lett., 117, 071803 (2016)

$$10^{-4} \lesssim \epsilon_e \lesssim 10^{-3}$$

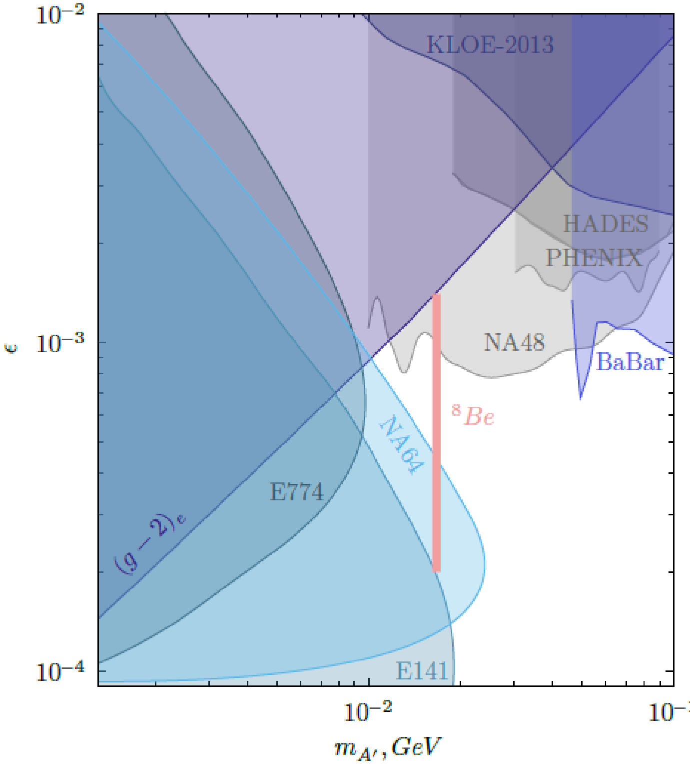
The part of this region is excluded , **namely:**

$$1.3 \times 10^{-4} \lesssim \epsilon_e \lesssim 4.2 \times 10^{-4}$$

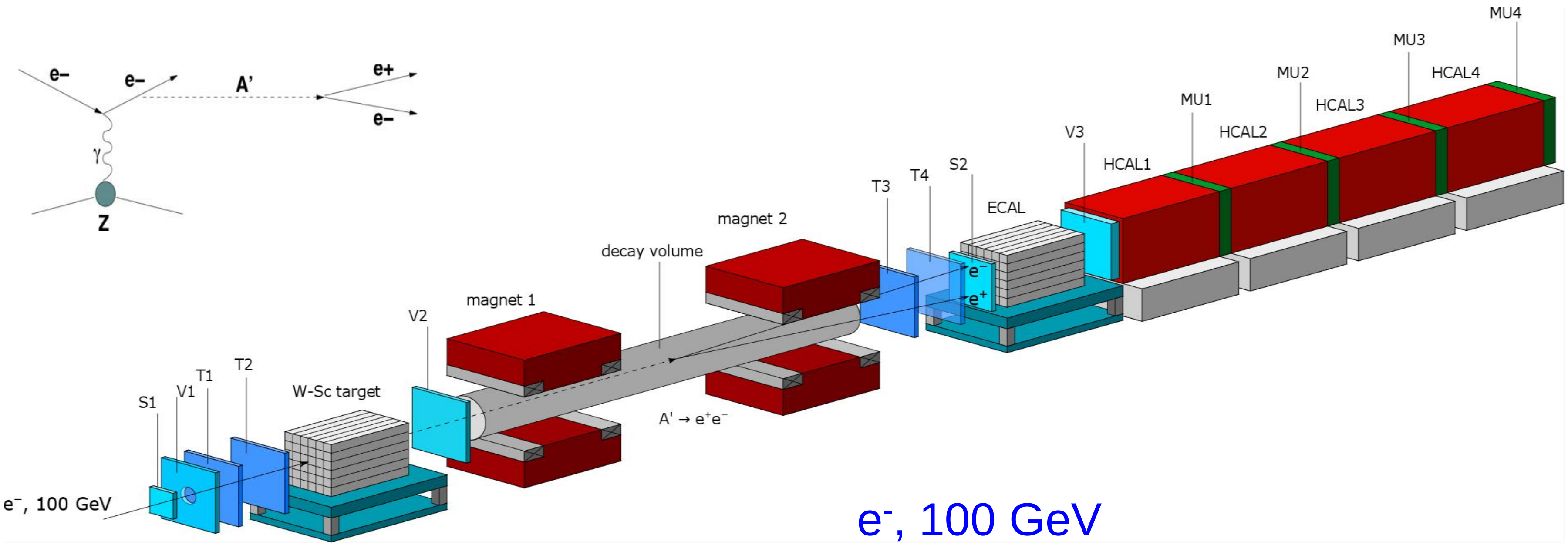
for

$$n_{EOT} = 5.4 \times 10^{10}\ \mathrm{EOT}$$

New NA64 result: arXiv:1803.07748



Search for $A' \to e^+e^-$



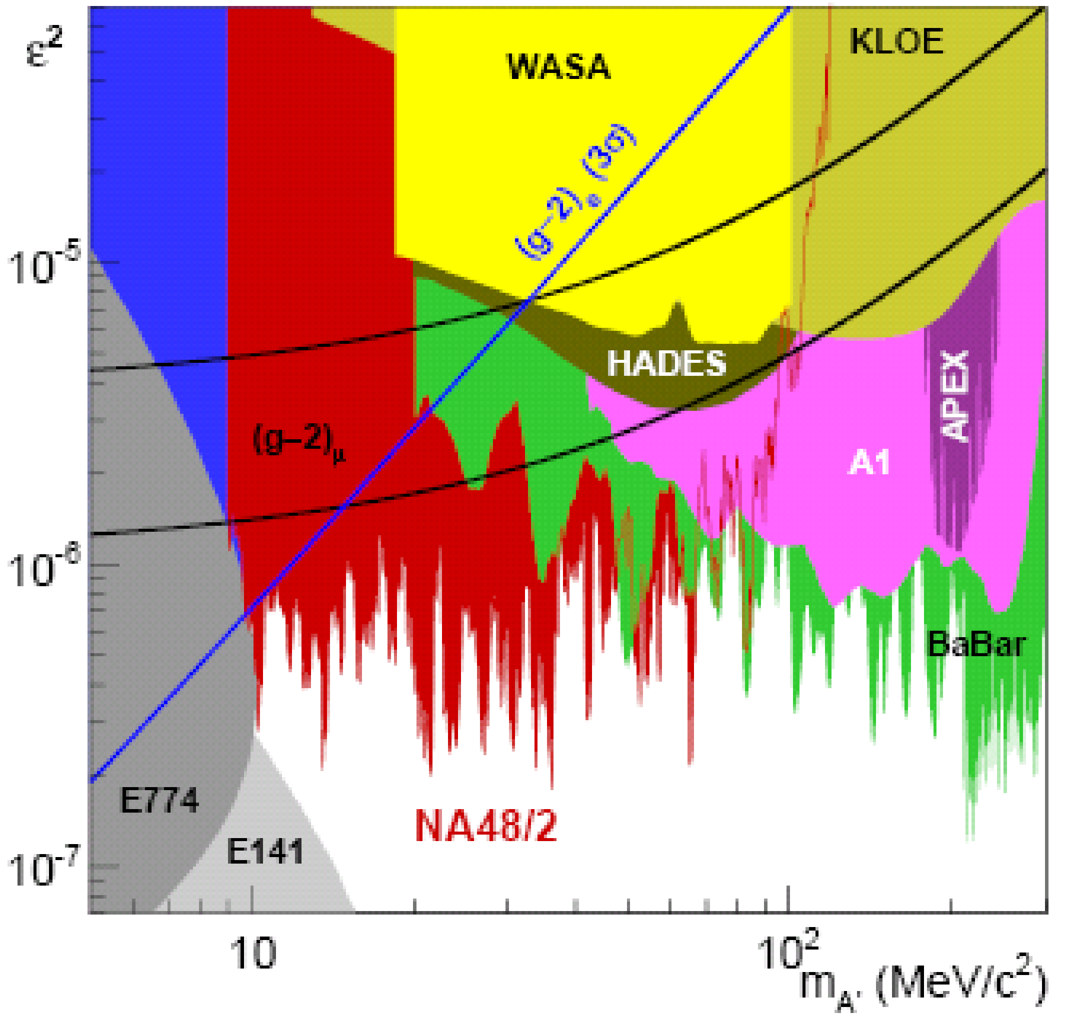
e^-, 100 GeV

- A´ decay outside W-Sc ECAL1
-
- Signature: two separated e-m showers from a single e^-

S= ECAL1xS1xS2x ECAL2 x$\overline{\text{V1xV2xHCAL}}$

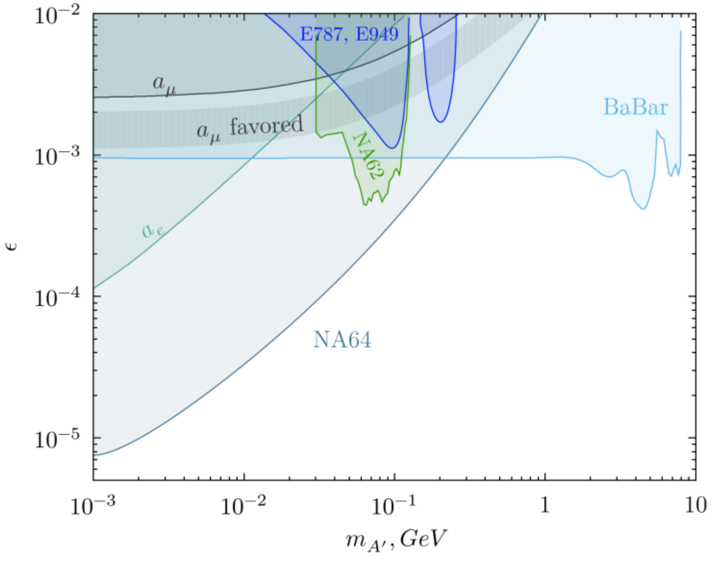
- $E_1 < E_0$, and $E_0 = E_1 + E_2$
- θ_{e+e-} is small to be resolved

Current (2017) exclusion plot



LAST NA64 RESULTS. INVISIBLE DARK PHOTON DECAY MODE(arXiv:1906.00176). BOUND ON ε PARAMETER OF DARK PHOTON MIXING WITH ORDINARY PHOTON

We have improved our last 2018 bound on ε parameter by factor ~3



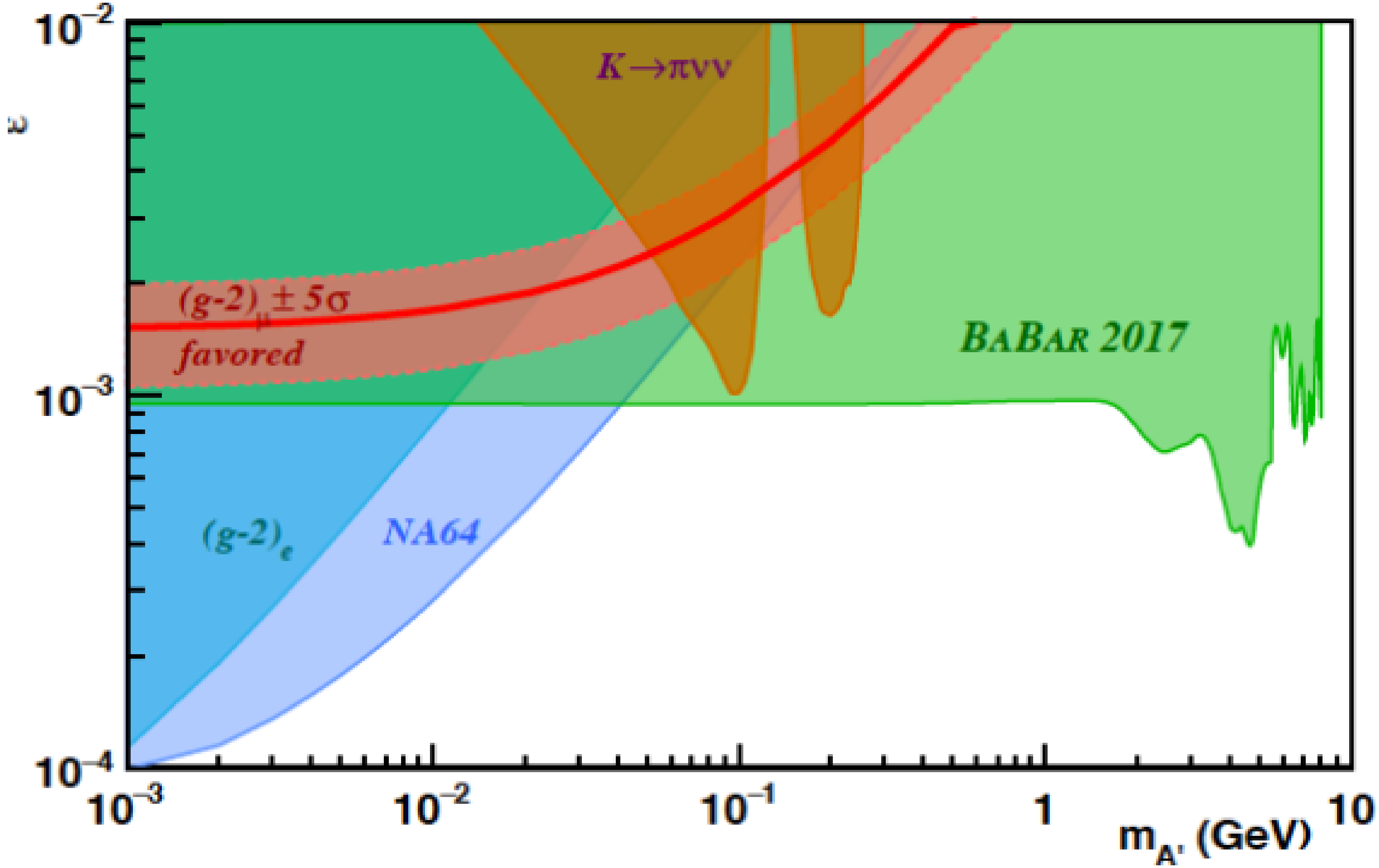
Current experimental bounds

1. The A1 and NA48 collaborations excluded masses between 30 MeV and 300 MeV as muon g-2 anomaly explanation.
2. BaBar collaboration excluded masses between 32 MeV and 10.2 GeV.

So the possibility of g-2 anomaly explanation in the model with visible A` decays is excluded.

Also beam dump experiments(electron beam dump – E137, E774, E141) exclude some regions in ε

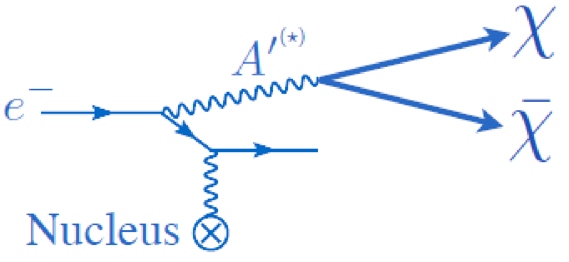
Recent experimental results from NA64 and BaBar exclude (g-2) anomaly explanation



Current and future invisible decays searches

1. NA64 – missing energy searches
2. PADME at LNF(Italy) – missing mass searches
3. VEPP3 at BINP(Russia) – missing mass searches
4. Belle-|| at KEK(Japan) – missing mass searches
5. DarkLight at JLab(USA) – missing mass searches
6. MMAPS at Cornell(USA) – missing mass searches
7. LDMX at SLAC(USA) – missing momentum searches
8. MiniBooNE at FNAL(USA) – proton beam-dump
9. SHiP at CERN – proton beam –dump
10. SBN at FNAL(USA) – proton beam-dump
11. COHERENT at ORNL(USA) – proton beam- dump

Missing energy(momentum) reaction NA64 and LDMX



$$\sigma \propto \frac{Z^2 \epsilon^2}{m_{\mathrm{A}'}^2}$$

LDMX DISCOVERY POTENTIAL