Search for light dark matter at accelerators. NA64 experiment

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and
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Useful references:

1. E.W.Kolb and M.S.Turner, The early Universe, Front.Phys. 69, 1-547, 1990

2. Direct Sectors Workshop:Community report

J.Alexander et al.,arXiv:1608.08632

3. NA64 collaboration:

arXiv:1906.00176;

Phys.Rev. D97, 07202, 2018

Outline

1. Long Introduction
2. Search for light dark matter at accelerators
    a. visible mode
    b. invisible mode
3. NA64 experiment
4. Conclusions

The main motivation in favor of BSM physics is dark matter

also probably some hints as:

1. (g-2)-muon anomaly

2. proton radius measured for electron and muon atoms

3. 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

$$O(1)\ \text{MeV} < m_d < O(10)\ \text{TeV}$$

O(10) TeV – tree level unitarity bound

O(1) MeV – BBN bound

Renormalizable models – spin 0, ½ and 1

Lee- Weinberg “theorem”:

$$m_d \gtrsim 10\ \mathrm{GeV}$$

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

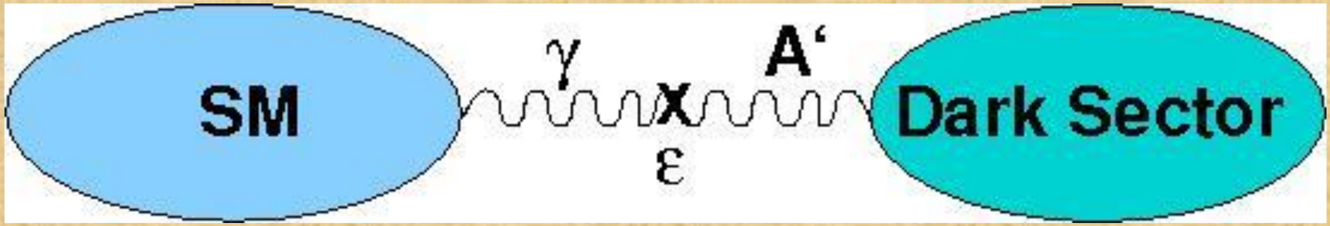
The kinetic mixing in low energy region leads to interaction of dark photon with the SM electromagnetic current J^{μ}_{SM}, namely

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

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:

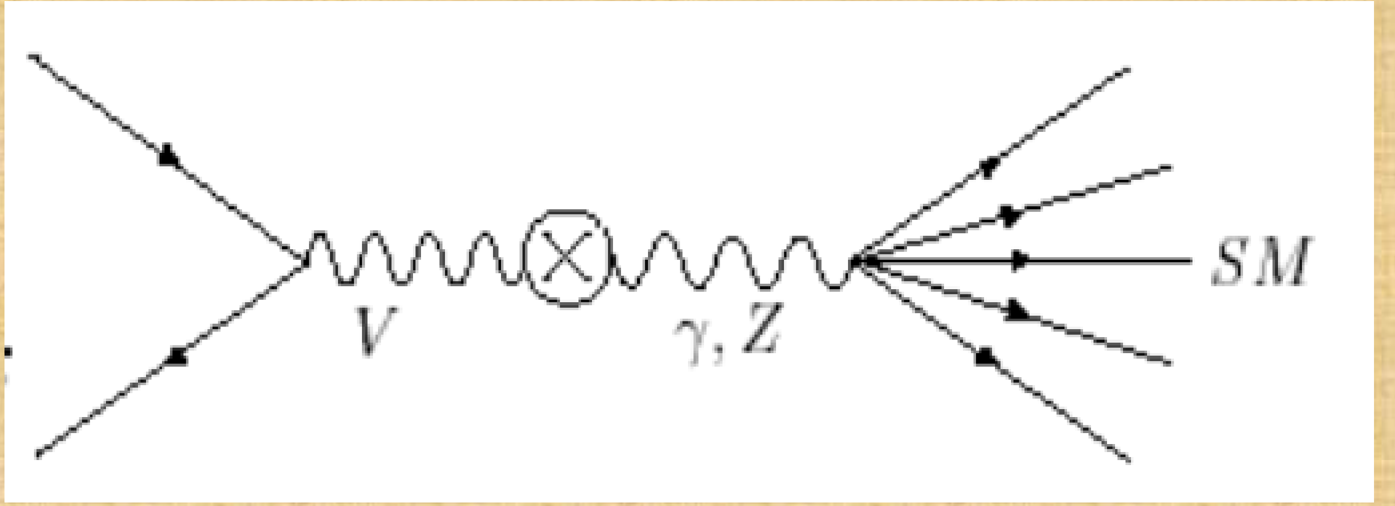
Direct

DM DM → A` → $e^+ e^-$, …

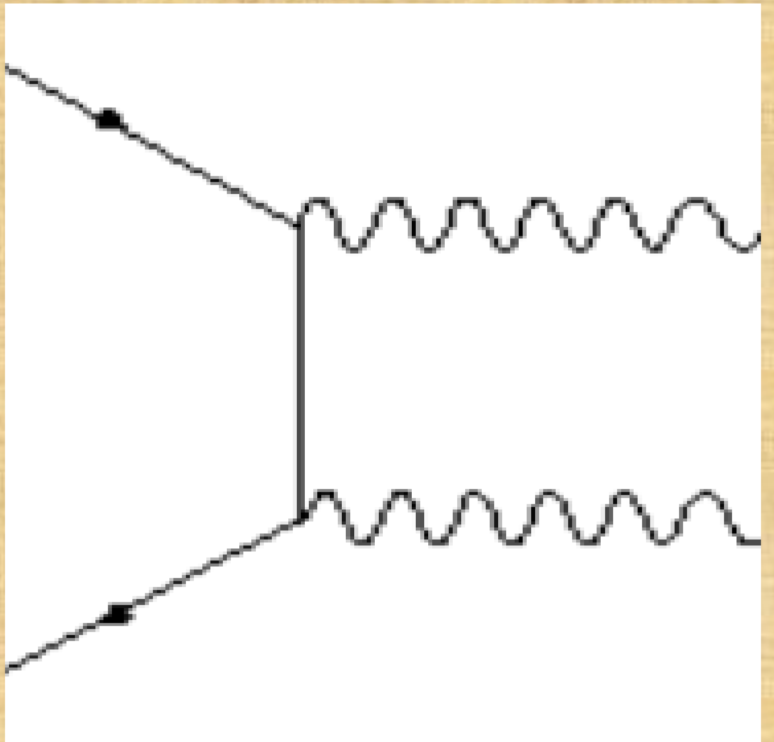
Secluded

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

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

Upper bound on α_D

From the requirement that the effective coupling constant does not have Landau pole singularity up to some scale Λ one can find upper on low energy coupling constant (H.Davoudiasl and W.J.Marciano, 2015)

In our estimates we used $\Lambda = 1$ TeV(M_{PL}) and for models with pseudo Dirac and Majorana we found $\alpha_D \lesssim 0.2(0.05)$

Direct light DM detection

Nuclear recoil detection

$E_{NR} \lesssim 2\mu^2_{DM,N} v^2_{DM} / m_N$, $v_{DM} \sim 10^{-3}$ c

Here $\mu_{DM,N} = m_{DM} m_N (m_{DM} + m_N)^{-1}$

is reduced DM nucleis mass

For a silicon nucleus and $m_{DM} = 100$ MeV

$E_{NR} \sim 1$ eV. Direct detection is extremely difficult. Probably electron recoil detection will help

2.Search for light dark matter at accelerators

Dark Photon Searches

Production Modes

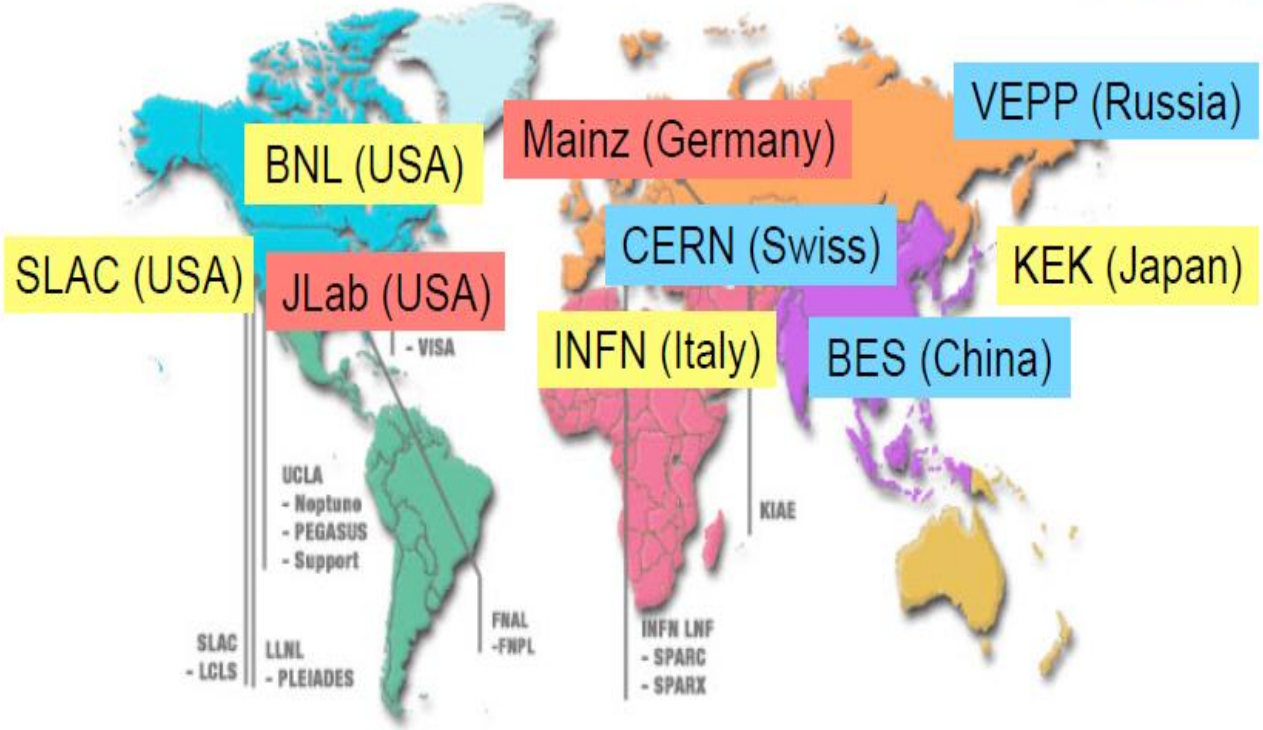
- Electron-positron annihilation
- Meson Decays
- Drell-Yan (collider or fixed target)
- Bremsstrahlung

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).



2a.Visible decays

2a. Visible decays

Mainly

$$A` \rightarrow e^+ e^-$$

Two ways of visible A' decay detection

Visible decays detection

1. Prompt decays – resonant behavior in invariant mass distribution
2. Displaced decays – long lived A'

Current experimental bounds

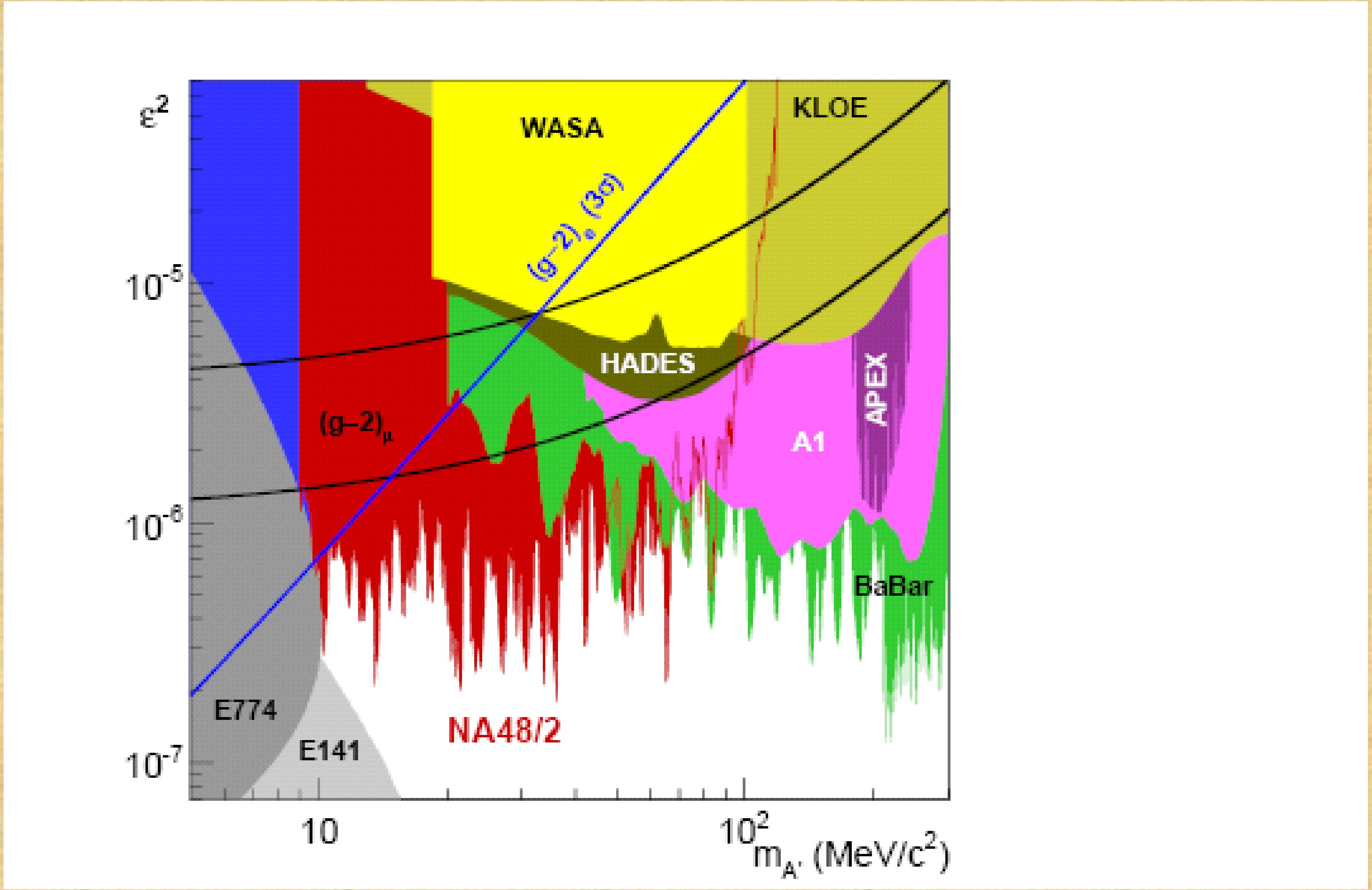
1. The A1 and NA48 collaborations excluded masses between 30 MeV and 300 MeV as muon g-2 anomaly explanation(There were speculations on dark photon contribution to g-2)

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.

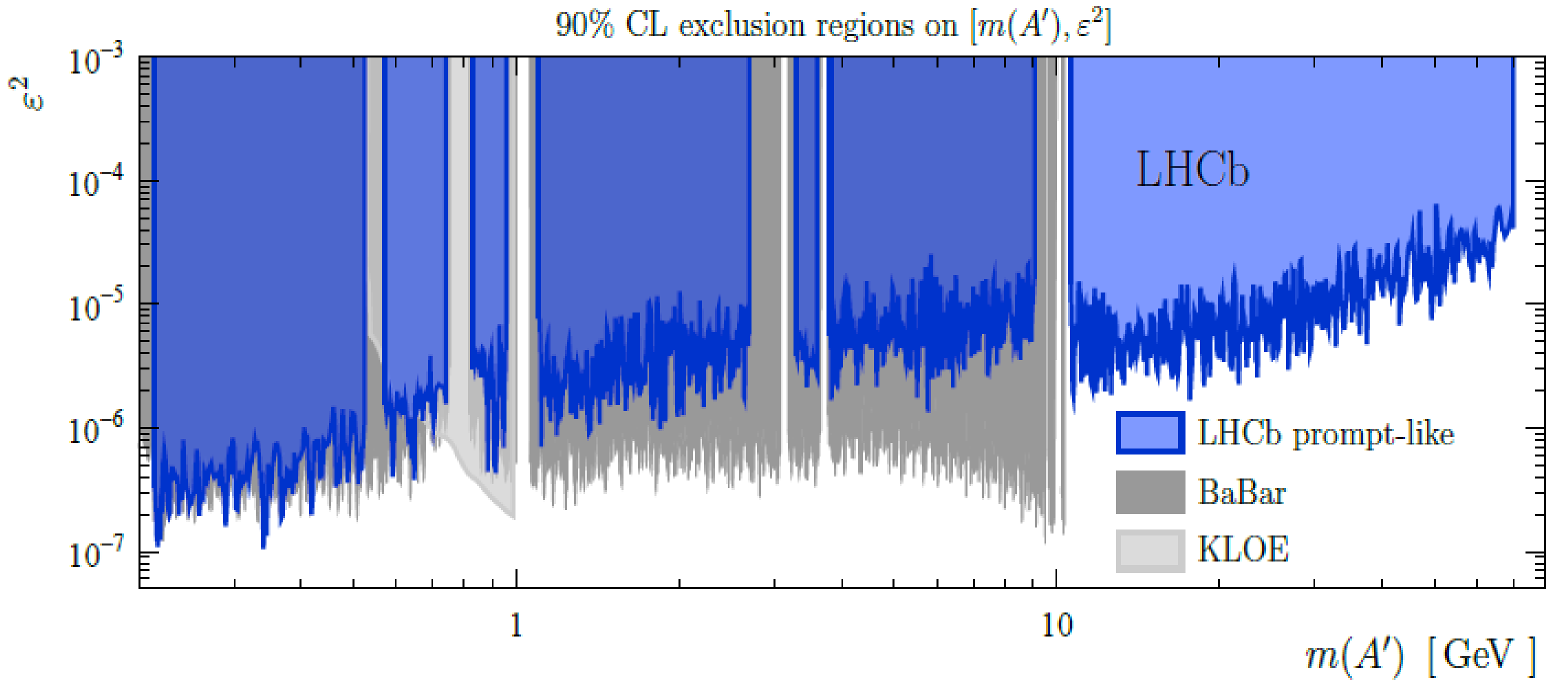
Also beam dump experiments(electron beam dump – E137, E774, E141) exclude some regions in ε

Current (2017) exclusion plot



LHCb bounds on visible decays

CERN-EP-2017-248
Phys.Rev.Lett. 2018

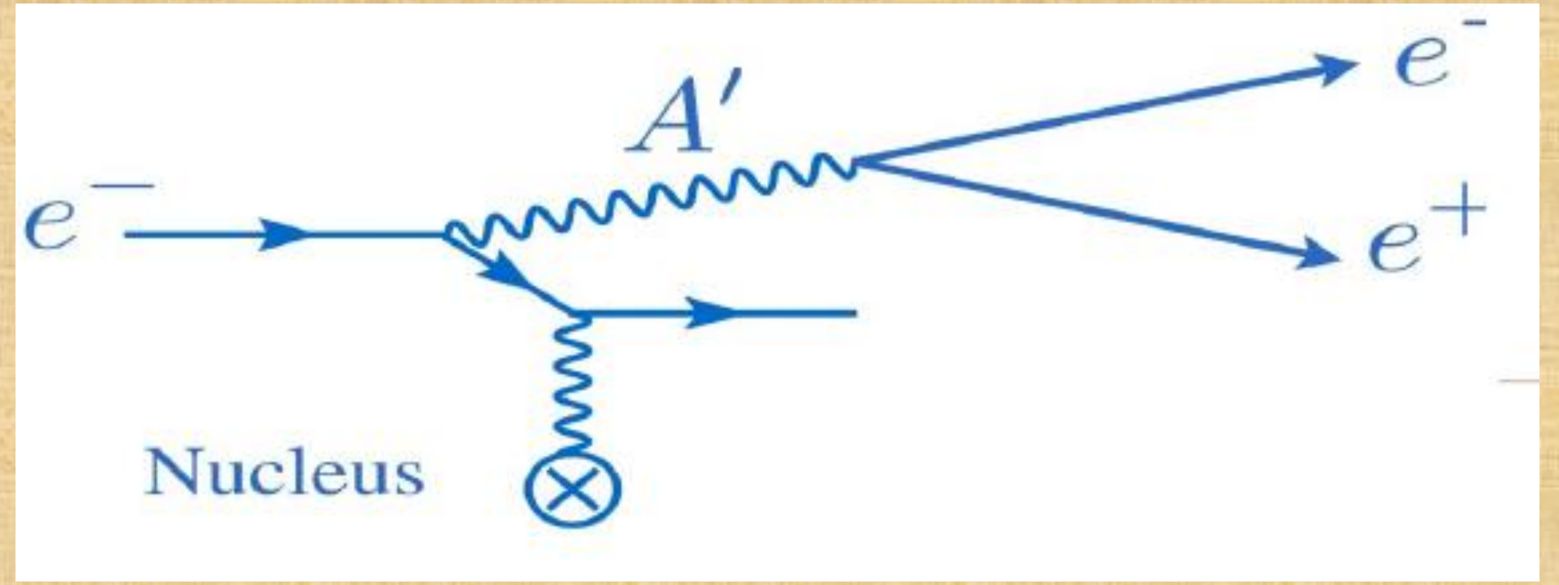


Future and current visible decays searches

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

APEX,HPS,MAGIX

The A’ bremsstrahlung production

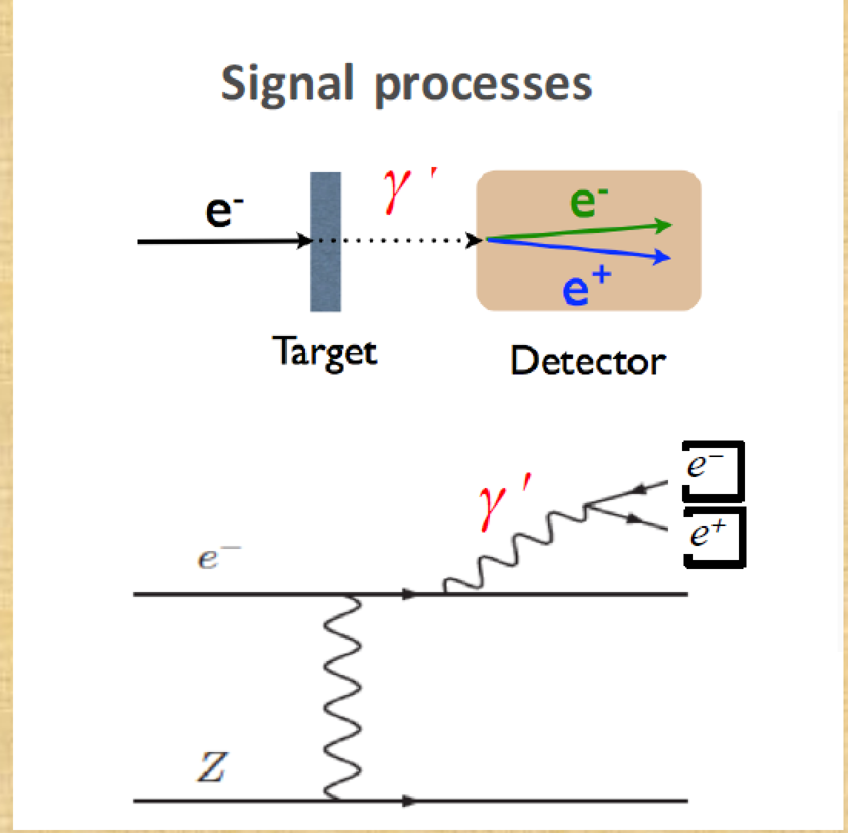


$$\frac{d\sigma(e^-Z \to e - Z(A' \to l^+l^-))}{d\sigma(e^-Z \to e - Z(\gamma^* \to l^+l^-))} = \frac{3\pi\epsilon^2}{2N_{eff}\alpha}\frac{m_{A'}}{\delta m}$$

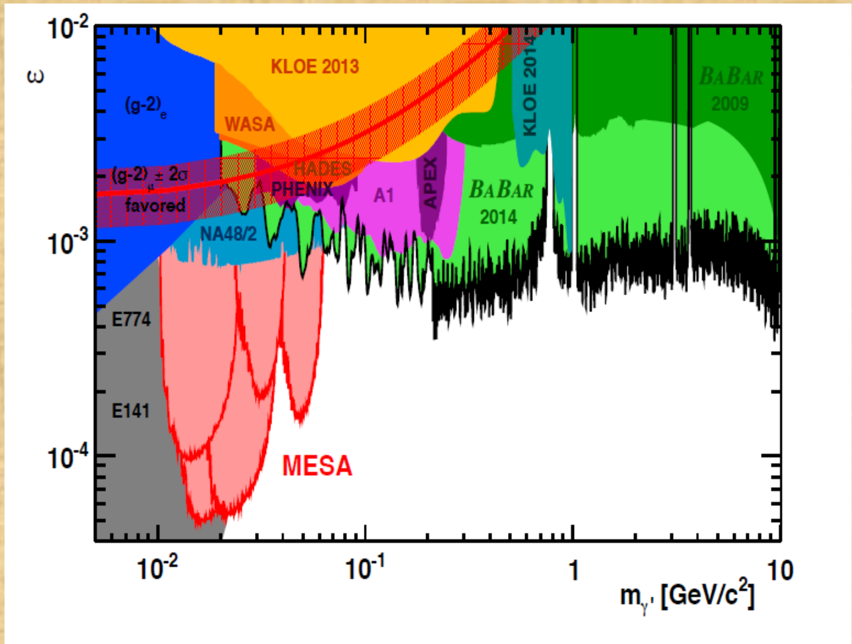
Prompt visible decays

The **MA**inz **G**as **I**nternal **EX**periment

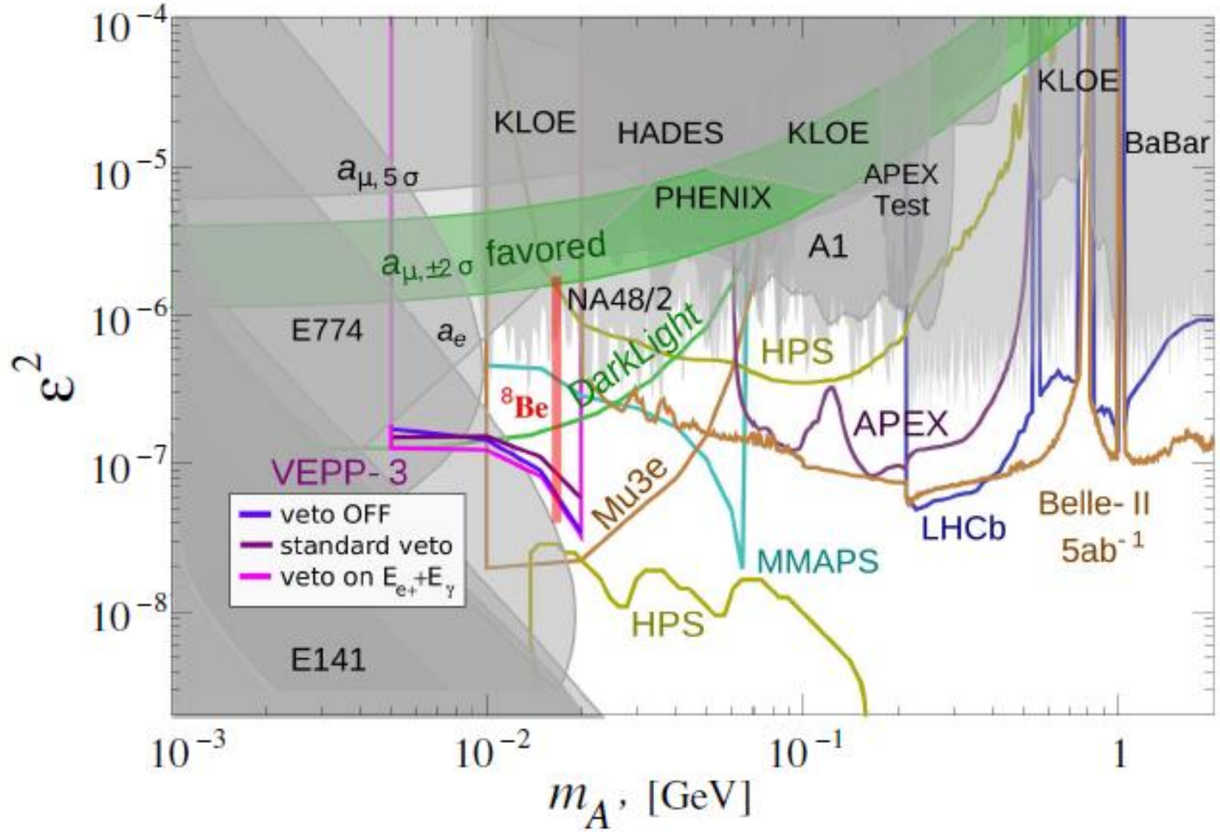
Experiment scheme



MAGIX Discovery potential (>2020)



Expected sensitivity for visible decays for ε^2 (J.P.Alexander et al., arXiv:1708.07901) for future experiments

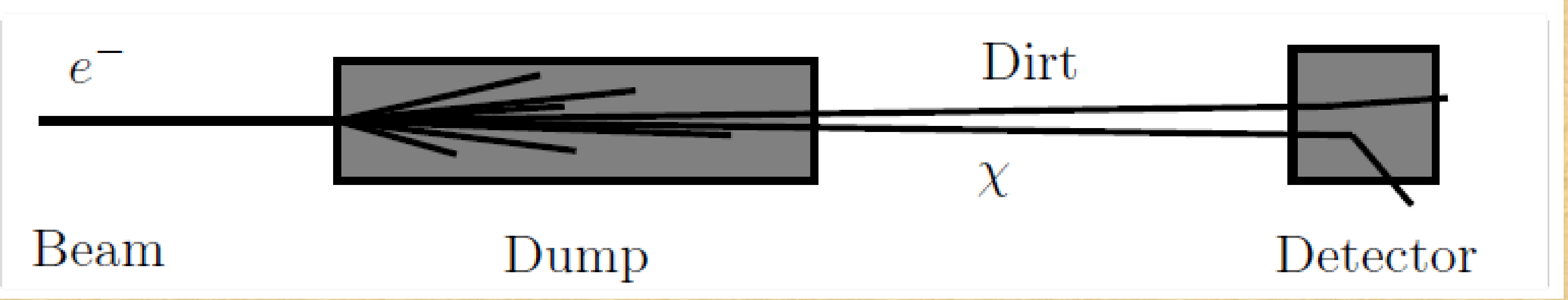


2b.Invisible decays

Invisible mode detection

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

Beam dump scheme



Invisible mode detection

Beam dump:

eZ ->eZA` ->eZ DM DM

DM e(Z) -> Dm e(Z)

The signal is proportional to

$$\varepsilon^2 \cdot \varepsilon^2 \alpha_D$$

while for active beam dump experiments like NA64 the signal(number of signal events) is proportional to ε^2

Future experiments missing mass searches

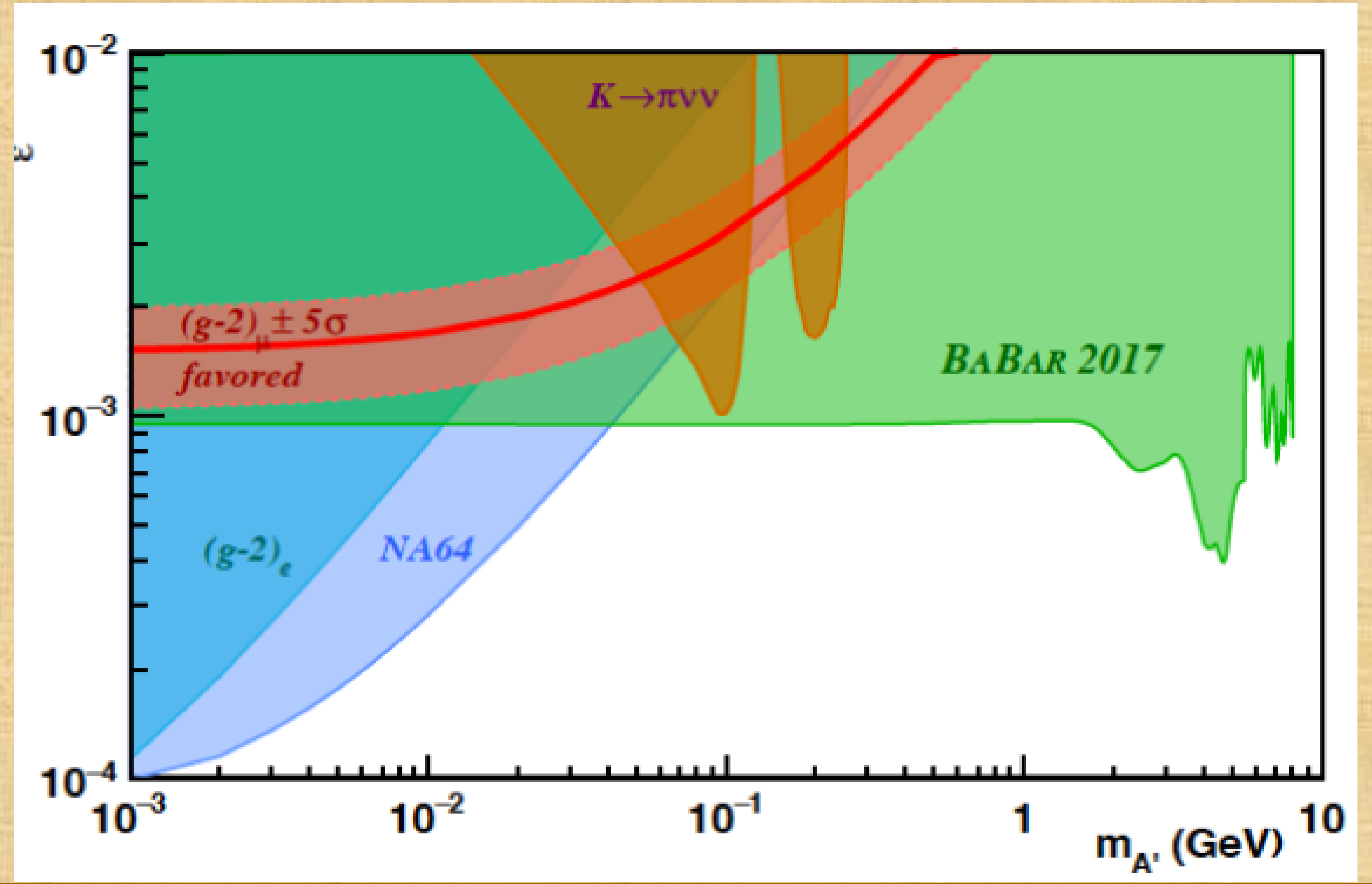
$$e^+ e^- \to e^+ e^- \gamma A'$$

The knowledge of momenta e^+, e^- and γ allows to restore the A' mass – resonant distribution on invariant mass

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

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



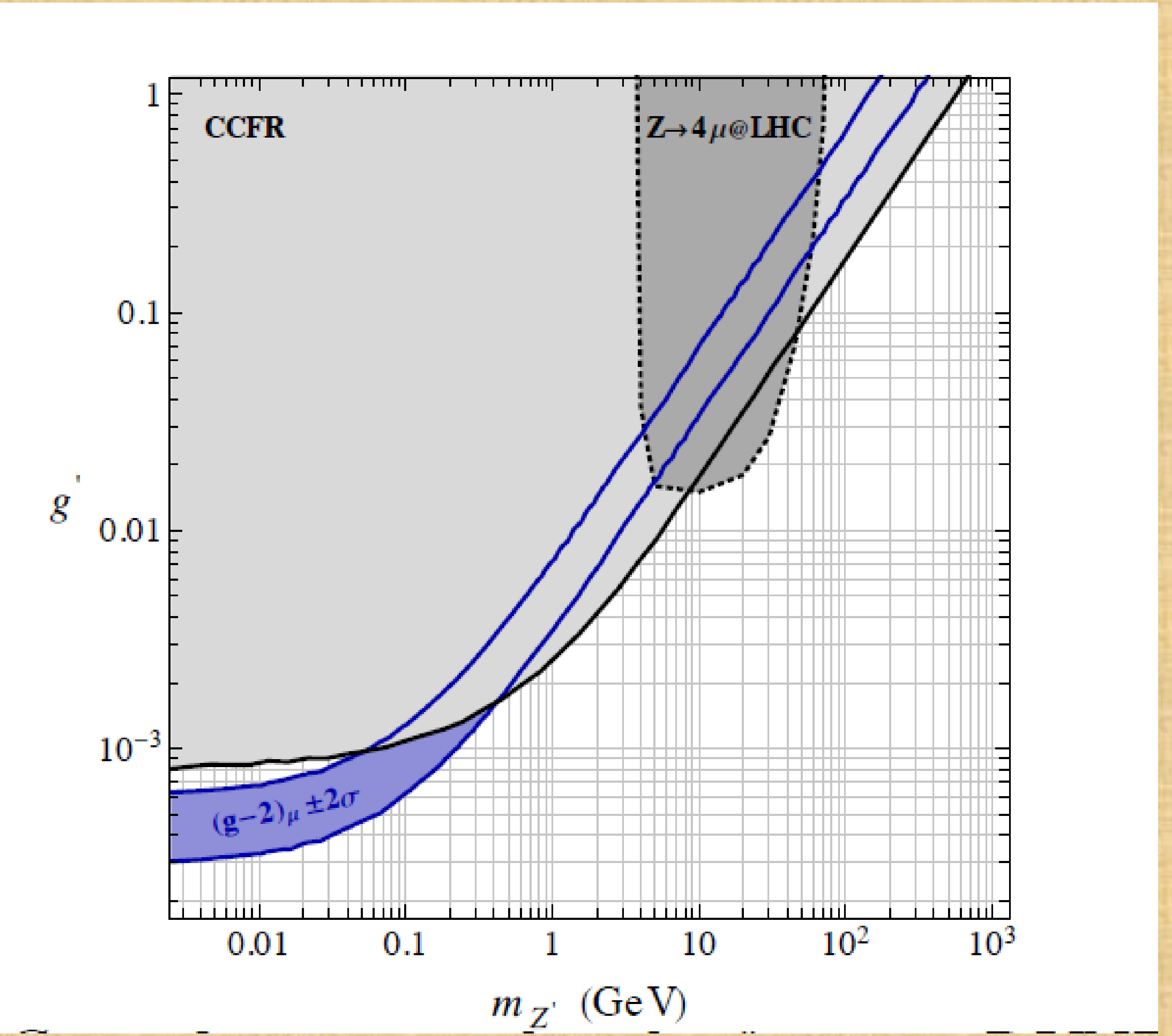
Experimental bounds for $L_\mu - L_\tau$ model

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

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

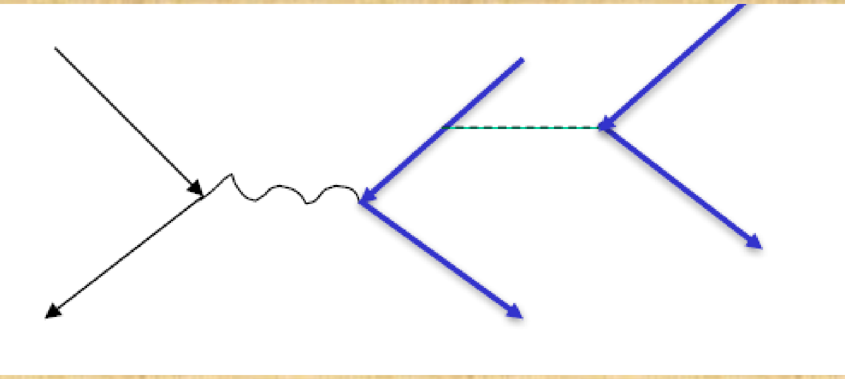
For this model the most nontrivial bound (W.Almannsofer et. al) comes from CCFR data on neutrino trident $\nu_\mu N \to \nu_\mu N + \mu^+\mu^-$ production. Masses $m_{Z_\mu} \geq 400\ MeV$ are excluded

New BaBaR bound excludes m > 214 MeV

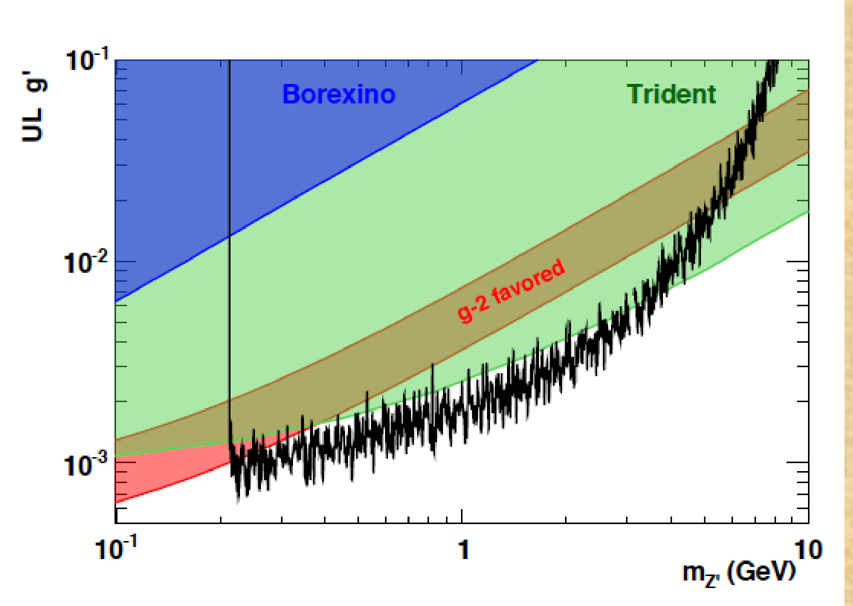

CCFR
Z→4μ@LHC
(g−2)μ ±2σ
1
0.1
0.01
10⁻³
g'
0.01
0.1
1
10
10²
10³
m_Z' (GeV)

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

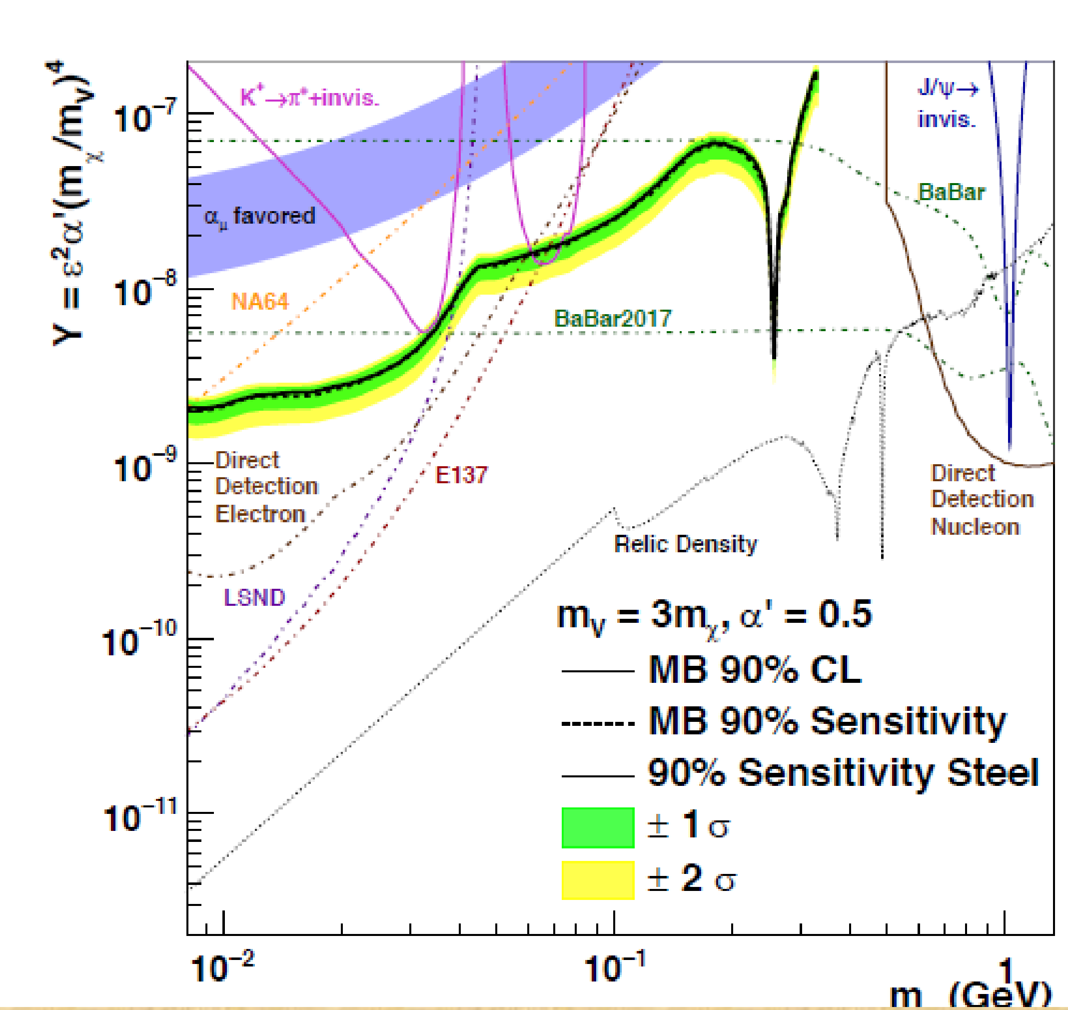
The main diagram



Only masses <214 MeV survive



Last MiniBooNE bound arXiv:1702.02688



3. NA64 experiment

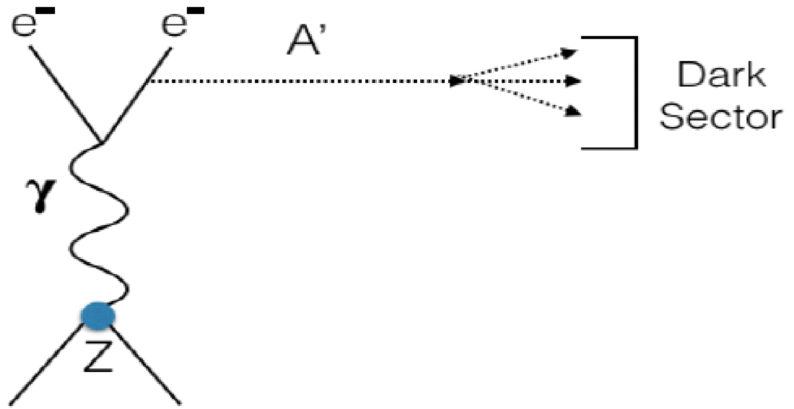
NA64 - Searches

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

PREPARED FOR SUBMISSION TO SPSC

Proposal for an Experiment to Search for Light Dark Matter at the SPS

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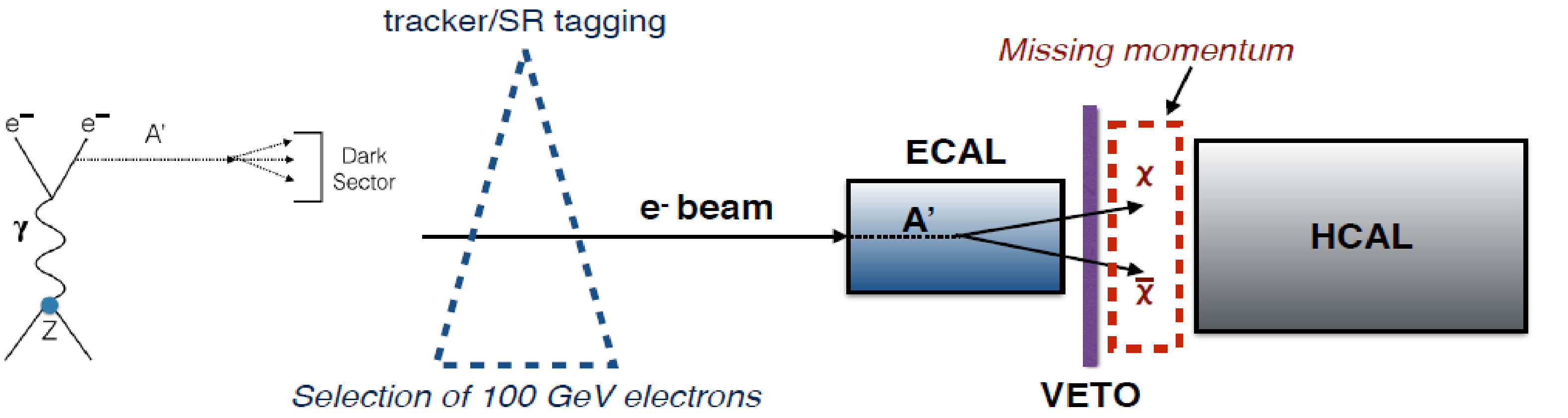
CERN-SPSC-2013-034 / SPSC-P-348
06/12/2013

December 6, 2013

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.

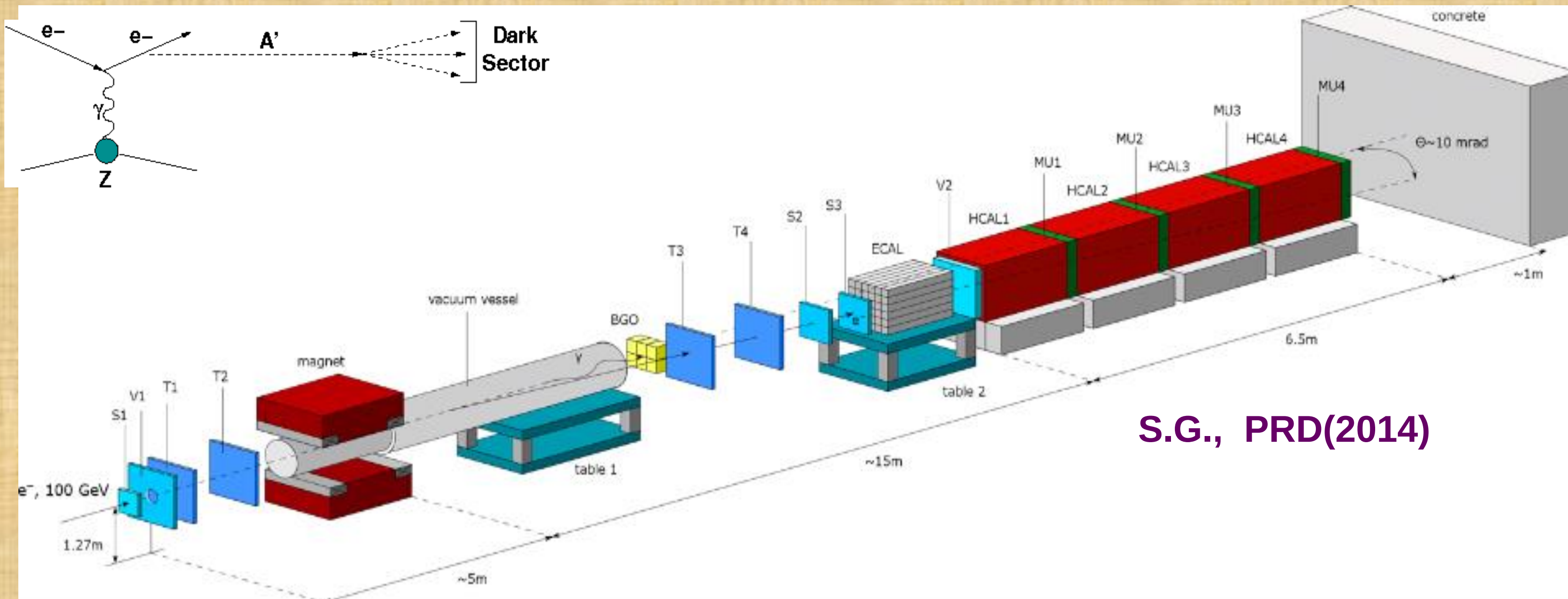
NA64 Research program

Reasearch program: Searches for sub-GeV Z`boson, NHL,… coupled to e, μ, q’s.
New method: Active beam dump combined with missing-energy technique

1. **Beam Purity for Light Dark Matter Search in Beam Dump Experiment**
   D. Banerjee, P. Crivelli, and A. Rubbia (Zurich, ETH) Adv.High Energy Phys. 2015(2015)105730
2. **On detection of narrow angle e+e- pairs from dark photon decays**
   A.V. Dermenev, S.V. Donskov, S.N. Gninenko, S.B. Kuleshov, V.A. Matveev, V.V. Myalkovskiy, V.D. Peshekhonov, V.A. Poliakov, A.A. Savenkov, V.O. Tikhomirov, I.A.Zhukov
   IEEE Trans.Nucl.Sc. 62 (2015) 3283;
3. **The K_L invisible decays as a probe of new physics**
   S.N. Gninenko and N.V. Krasnikov
   Phys. Rev. D92 (2015) 034009;
4. **Search for invisible decays of π0, η, η', K_S and K_L: A probe of new physics and test using the Bell-Steinberger relation**
   S.N. Gninenko,
   Phys. Rev. D91 (2015) 015004;
5. **Muon g-2 and searches for a new leptophobic sub-GeV dark boson in a missing-energy experiment at CERN**
   S.N. Gninenko, N.V. Krasnikov, V.A. Matveev,
   Phys. Rev. D91 (2015) 095015;
6. **Search for MeV dark photons in a light-shining-through-walls experiment at CERN**
   S.N. Gninenko,
   Phys. Rev. D89 (2014) 075008
7. **The Muon anomalous magnetic moment and a new light gauge boson,**
   S.N. Gninenko and N.V. Krasnikov,
   Phys. Lett. B420 (2000) 9;
8. **Proposal for an Experiment to Search for Light Dark Matter at the SPS**
   S. Andreas, D. Banerjee, S.V. Donskov, P. Crivelli, A. Gardikiotis, S.N. Gninenko, F. Guber et al.,
   arXiv:1312.3309[hep-ex]

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

Invisible decay of Invisible State!



S.G., PRD(2014)

Signature:

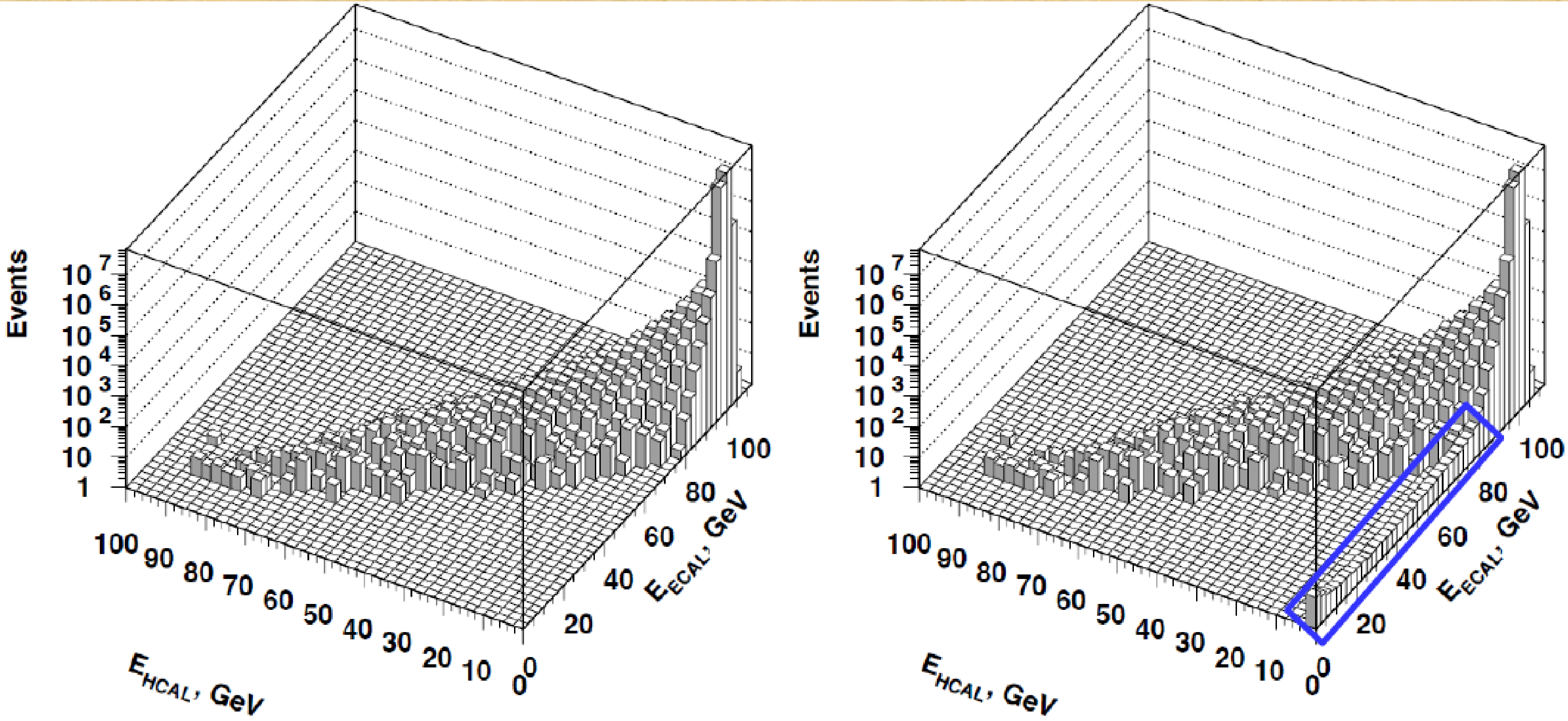
- in: 100 GeV e- track
- out: < 50 GeV e-m shower in ECAL
- no energy in the Veto and HCAL
- Sensitivity ~ ε^2

3 main components :

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


GOLIATH

Active target beam dump concept

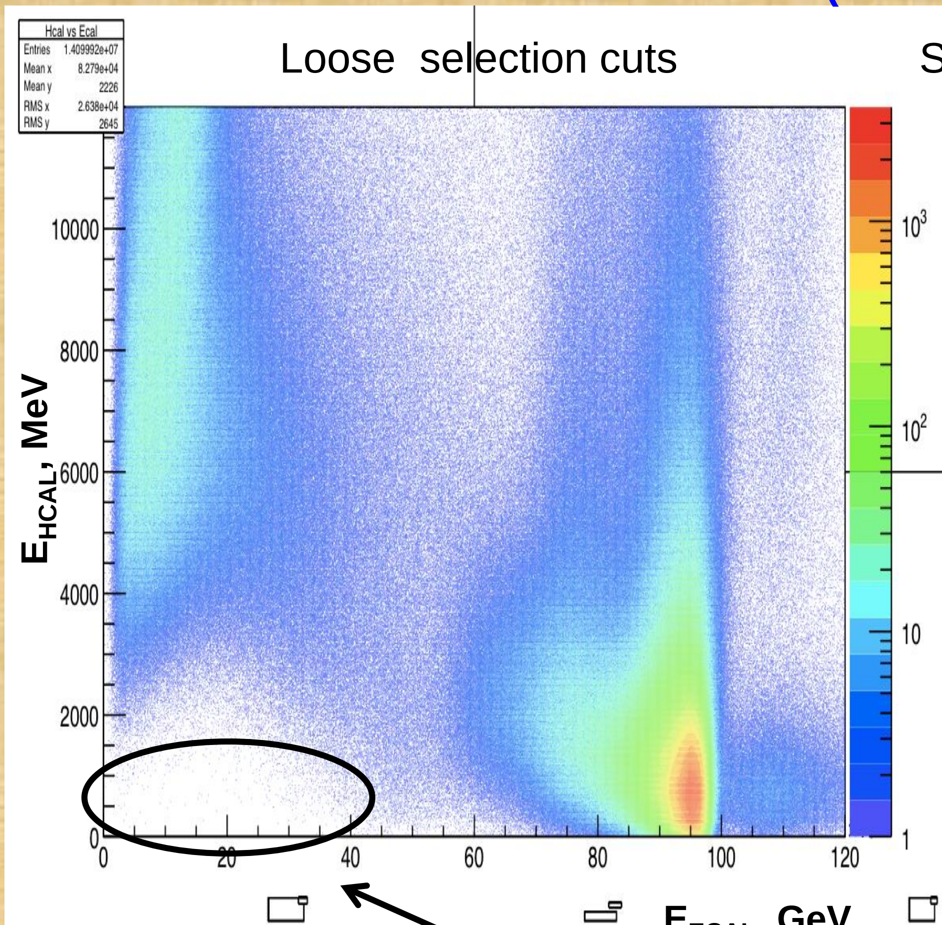


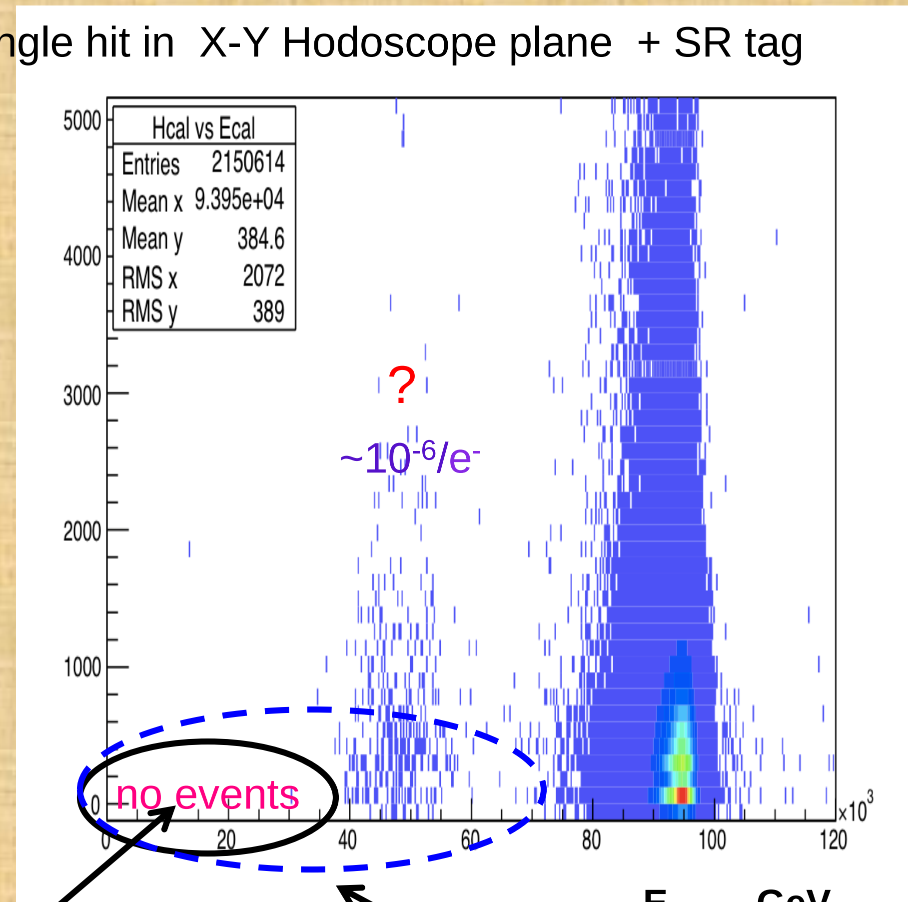
Dark Photon Signature for 100 GeV electron beam:

- Missing energy in ECAL (ECAL threshold < 50 GeV)
- No activity in Veto and HCAL

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$^-$

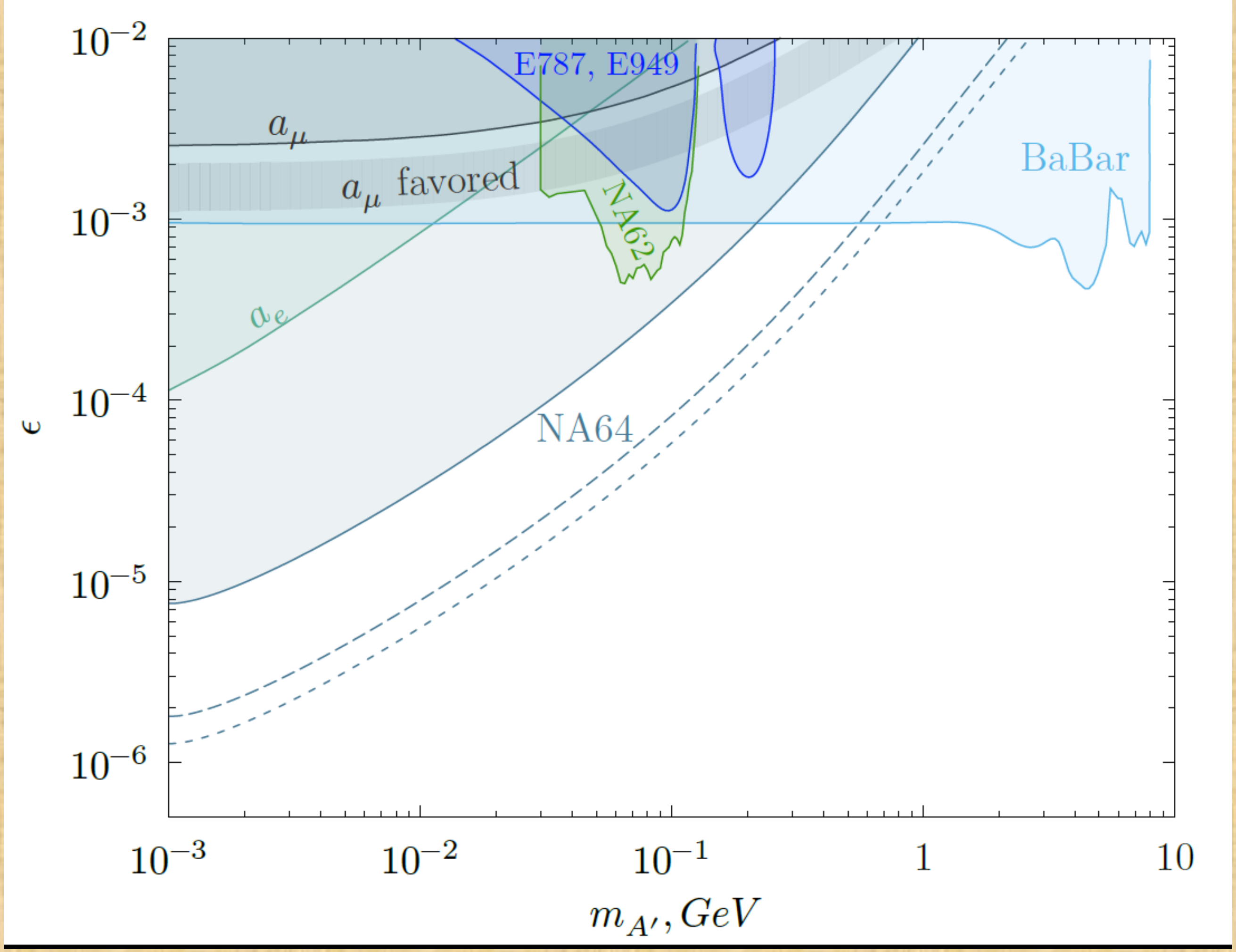
Possible extension of signal region

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



Implications for light DM

In our calculations for DM models we shall use three values

of $\alpha_D = 0.1$(red); 0.05(blue) ; 0.02(green) and

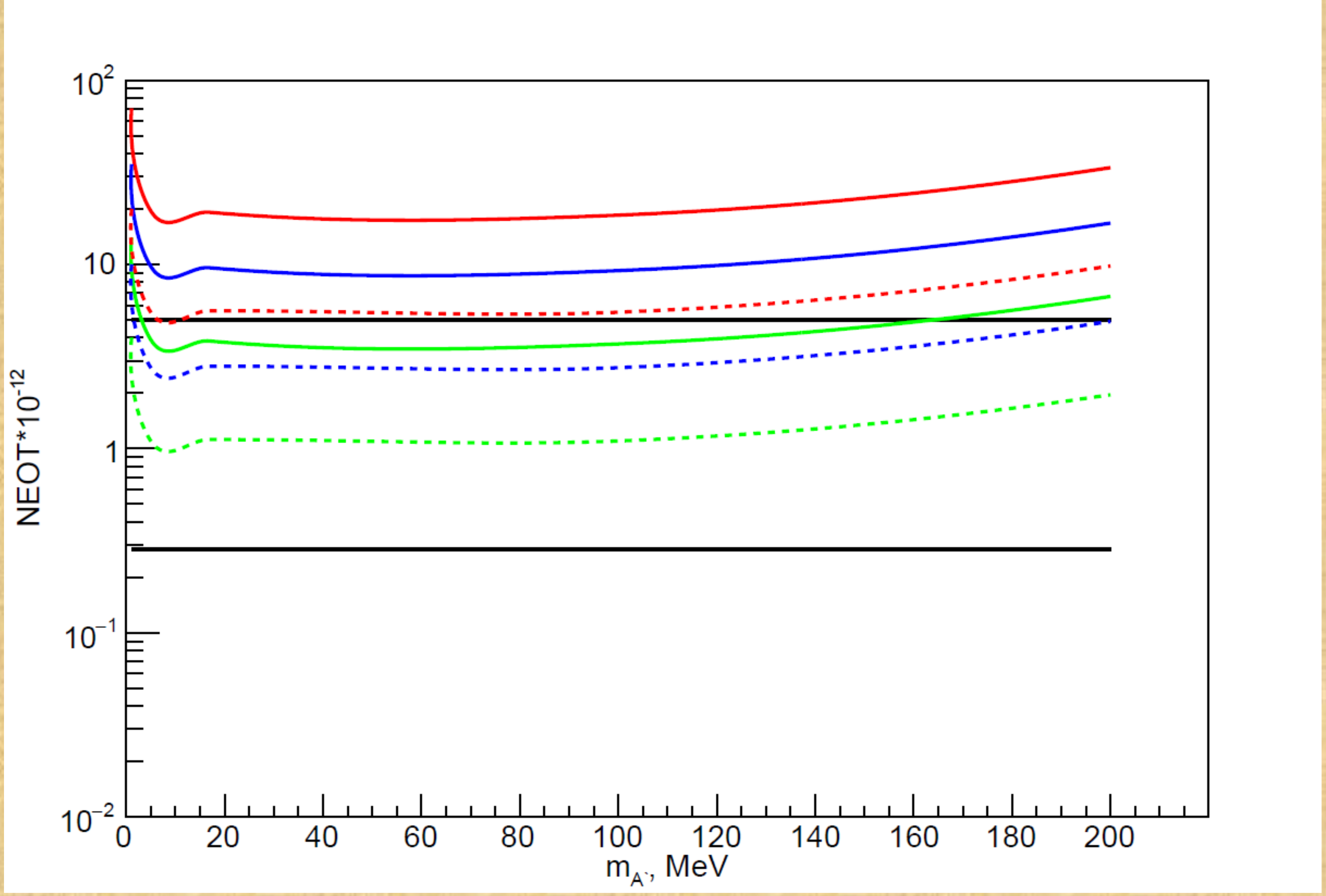
m_{A`}/m_{DM} =2.5(solid lines)

m_{A`}/m_{DM} =3(dotted lines)

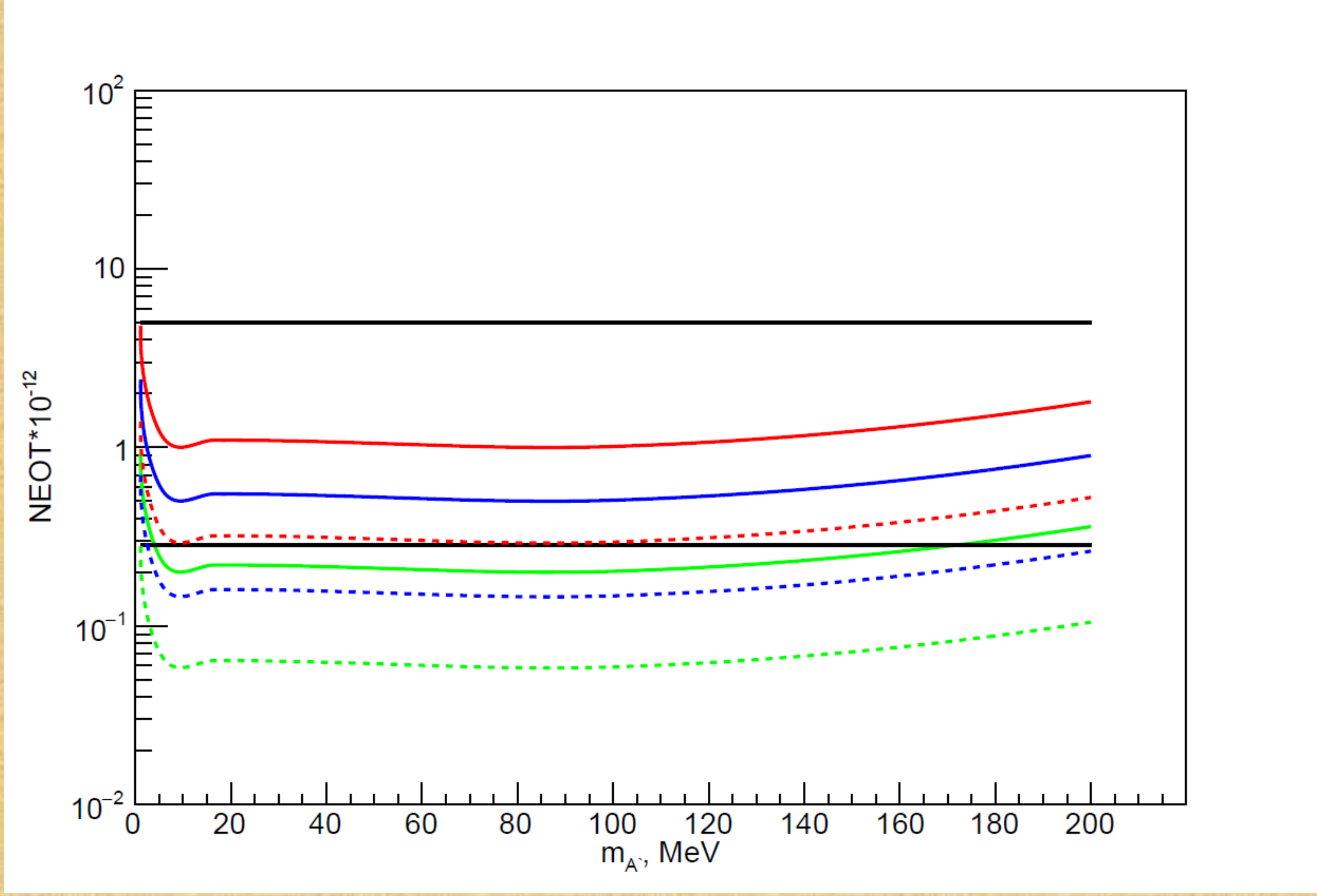
Also we assume that for electron mode

NEOT = $5*10^{12}$ will be realized

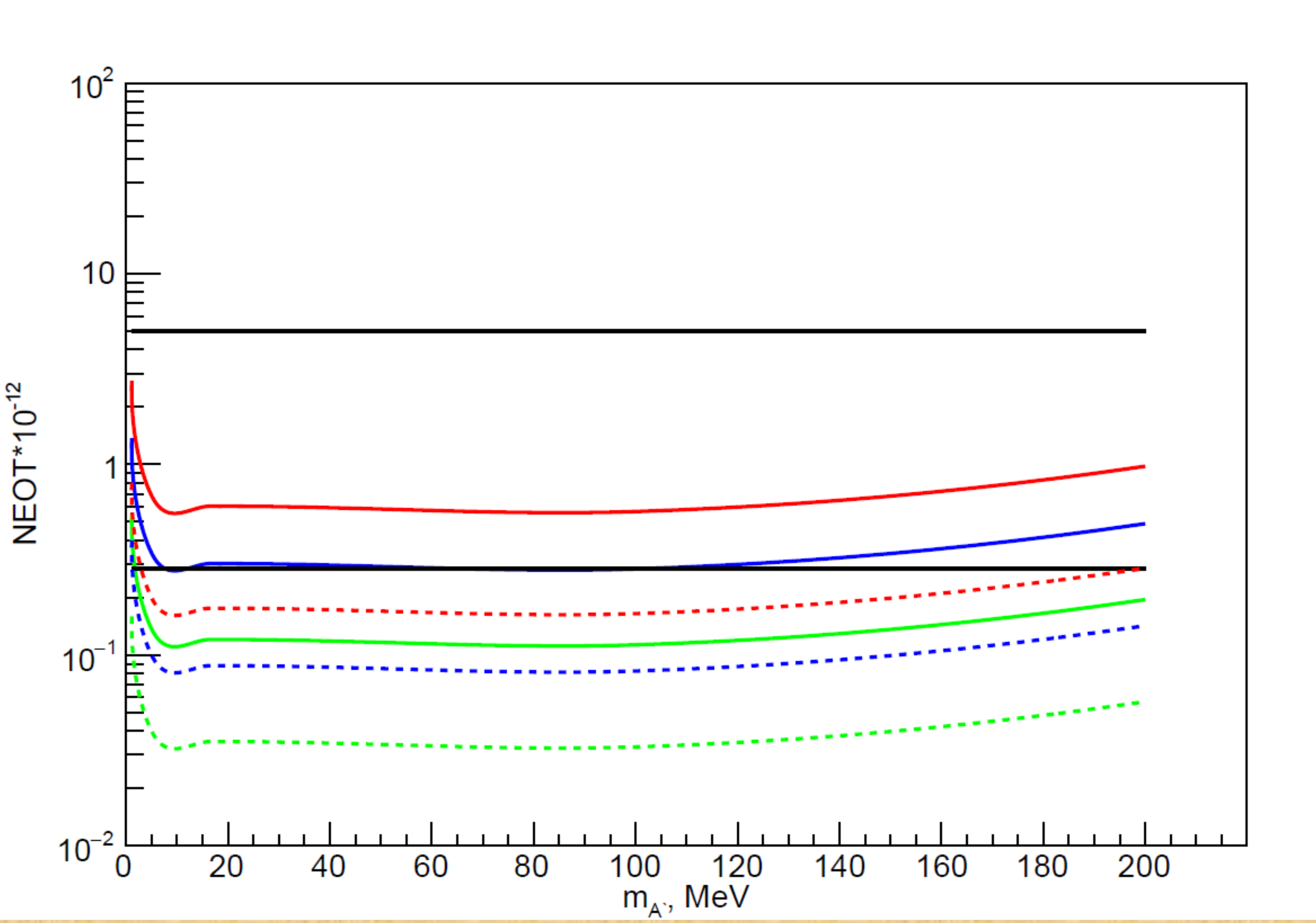
Pseudo Dirac DM for small mass splittings



Majorana light DM

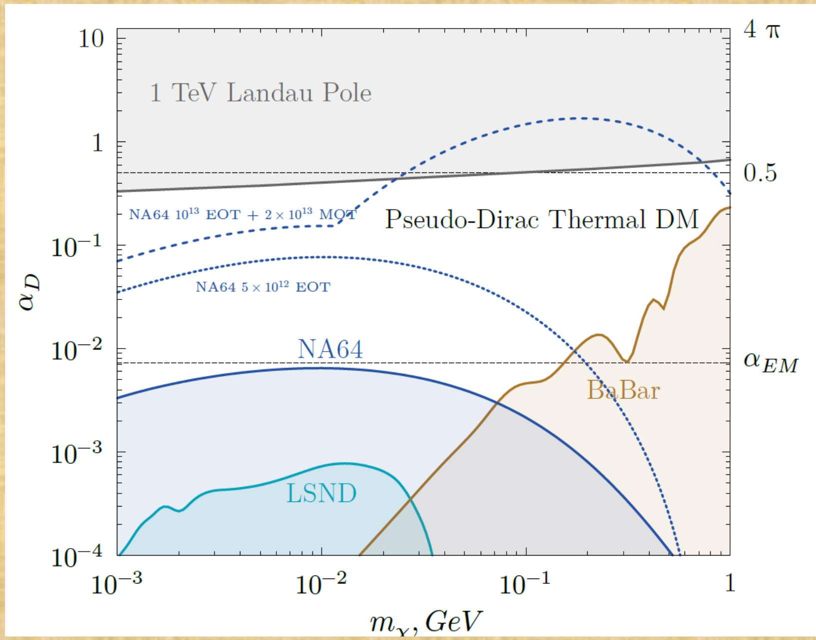


Scalar light DM

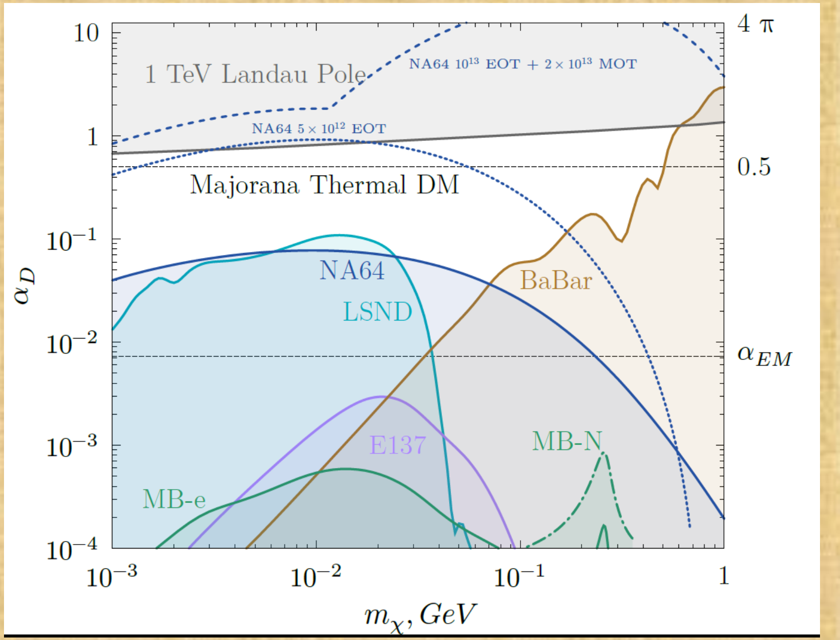


NA64 bound on α_D

Pseudo Dirac DM



Majorana DM



NA64 visible decays search

Displaced decays – long lived A`

Visible decays activity- the check of the ATOMKI experiment

10.

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

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

A. J. Krasznahorkay,* M. Csatlós, L. Csige, Z. Gácsi, J. Gulyás, M. Hunyadi, I. Kuti, B. M. Nyakó, L. Stuhl, J. Timár, T. G. Tornyi, and Zs. Vajta
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(Received 7 April 2015; published 26 January 2016)

^{7}Li(p, γ)^{8}Be, M_X =16.7 MeV

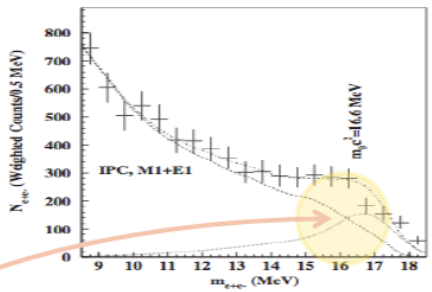
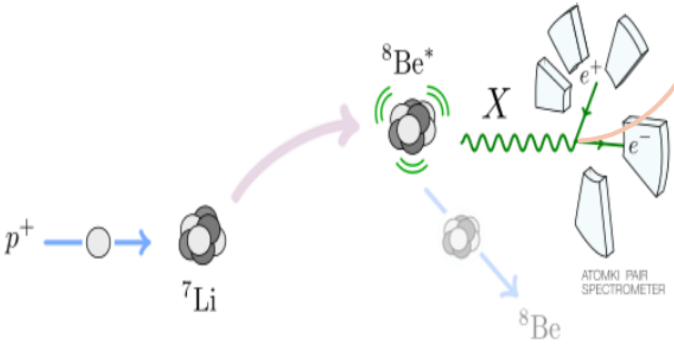
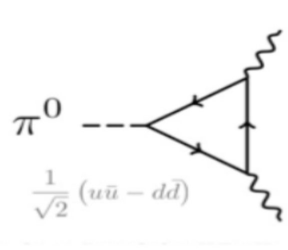


FIG. 5. Invariant mass distribution derived for the 18.15 MeV transition in ^{8}Be.



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



Feng et al, 2016

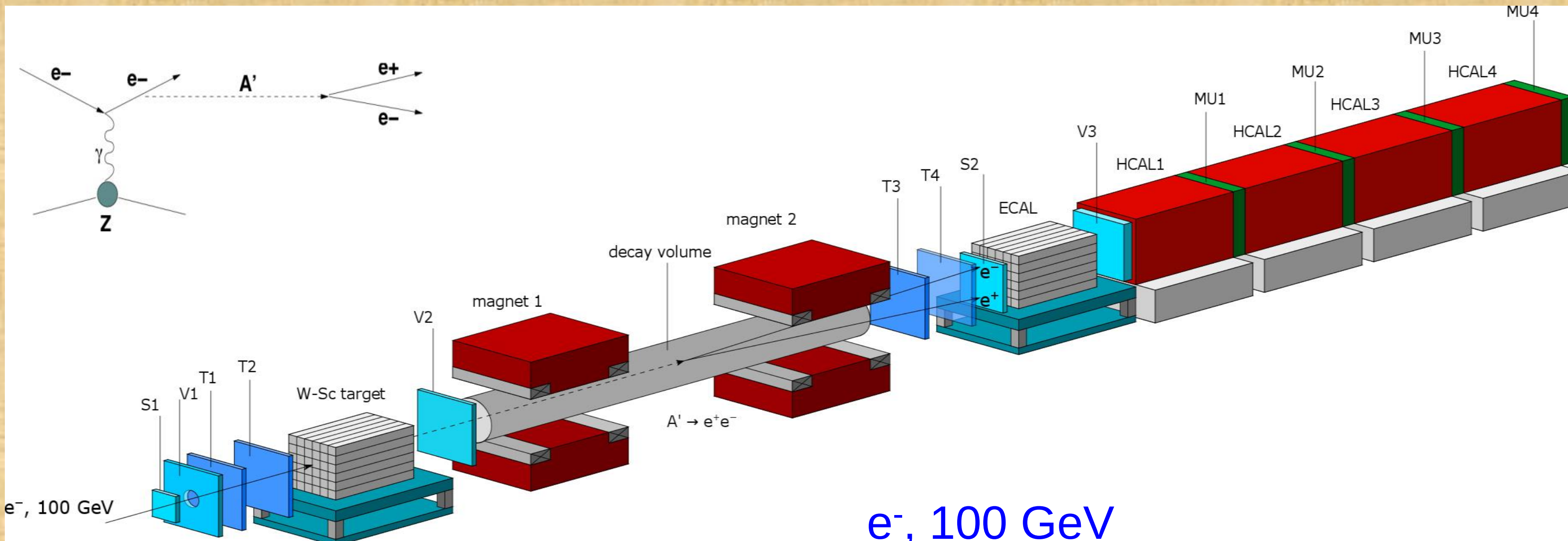
$2\times10^{-4} < \varepsilon_e < 1.4\times10^{-3}$

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

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

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

Search for *A´->e⁺e⁻*

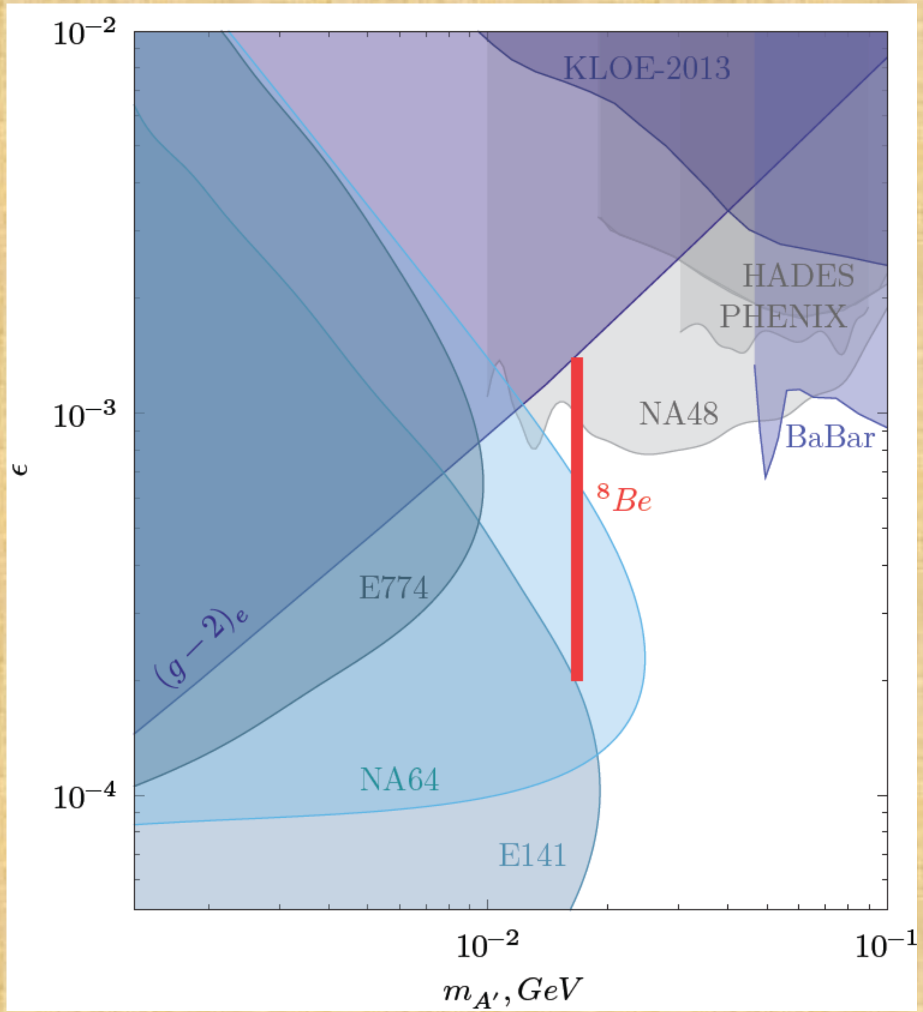


- A´ decay outside W-Sc ECAL1
- $10^{-14} < \tau_{A'} < 10^{-10}$ s, $\sigma_{A'}/\sigma_{\gamma} < 10^{-13}$-$10^{-9}$
- Signature: two separated e-m showers from a single e^-

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

Last NA64 bound on A` visible decays

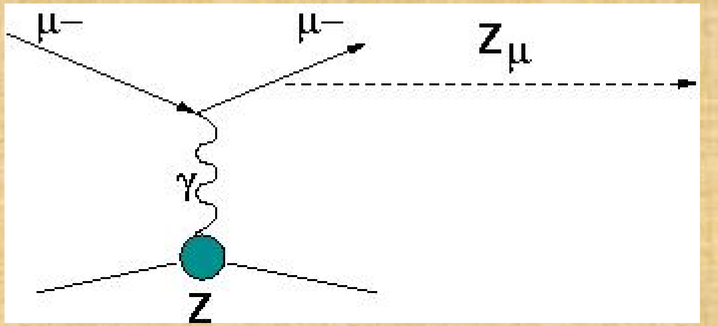


The experiment with muon **beam**

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

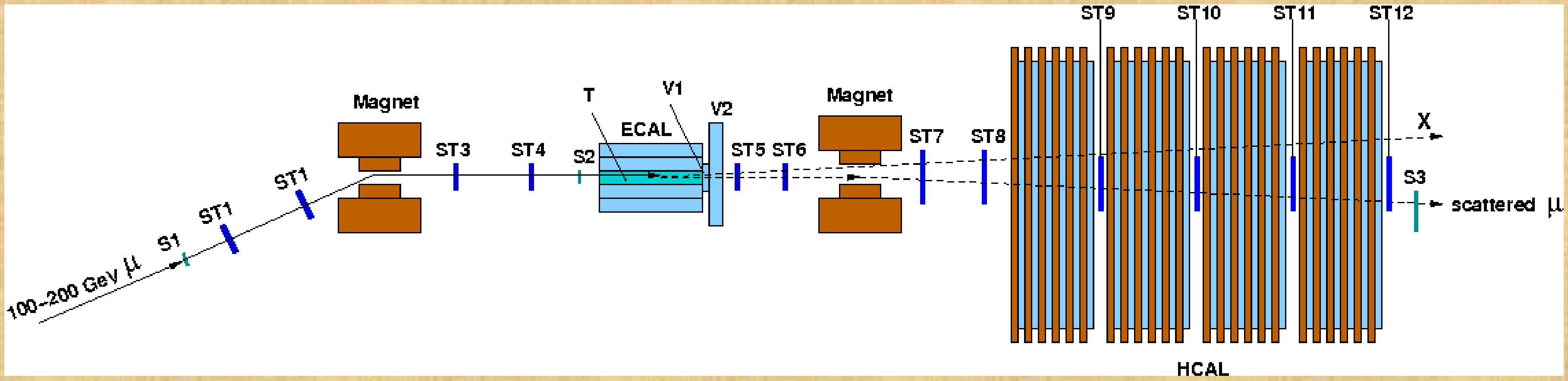
$$\mu(p) + Z(P) \to Z(P') + \mu(p') + Z_{\mu}(k)$$

The experiment at CERN SPS muon beam



T

Schematic illustration of the setup to search for dark boson



The experiment at CERN SPS 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

NA64μ proposal to the SPSC (Jan'19)

PREPARED FOR SUBMISSION TO SPSC

Proposal for an experiment to search for dark sector particles weakly coupled to muon at the SPS

D. Banerjee[k], J. Bernhard[d], V.E. Burtsev[j], A.G. Chumakov[j], P. Crivelli[m], E. Depero[m], A.V. Dermenev[e], S.V. Donskov[i], R. Dusaev[j], T. Enik[b], V. Frolov[b], A. Gardikiotis[h], S.N. Gninenko[e], M. Hösgen[a], A. Karneyeu[e], G.D. Kekelidze[b], B. Ketzer[a], D. Kirpichnikov[e], M.M. Kirsanov[e], S. Kovalenko[l], L.V. Kravchuk[e], V.A. Kramarenko[b,g], N.V. Krasnikov[e], S.V. Kuleshov[l], V.E. Lyubovitskij[j,l], V.M. Lysan[b], V.A. Matveev[b], Yu.V. Mikhailov[i],L. Molina-Bueno[m], D.V. Peshekhonov[b], V.A. Polyakov[i], B. Radics[m], A. Rubbia[m], V. Samoylenko[i], D. Shchukin[f], V.O. Tikhomirov[f], D.A. Tlisov[e], A.N. Toropin[e], A. Yu.Trifonov[j], P. Ulloa[l], B.I. Vasilishin[j], B.M. Veit[d], P.V. Volkov[b,g], and V.Yu. Volkov[g]

The NA64 Collaboration[1]

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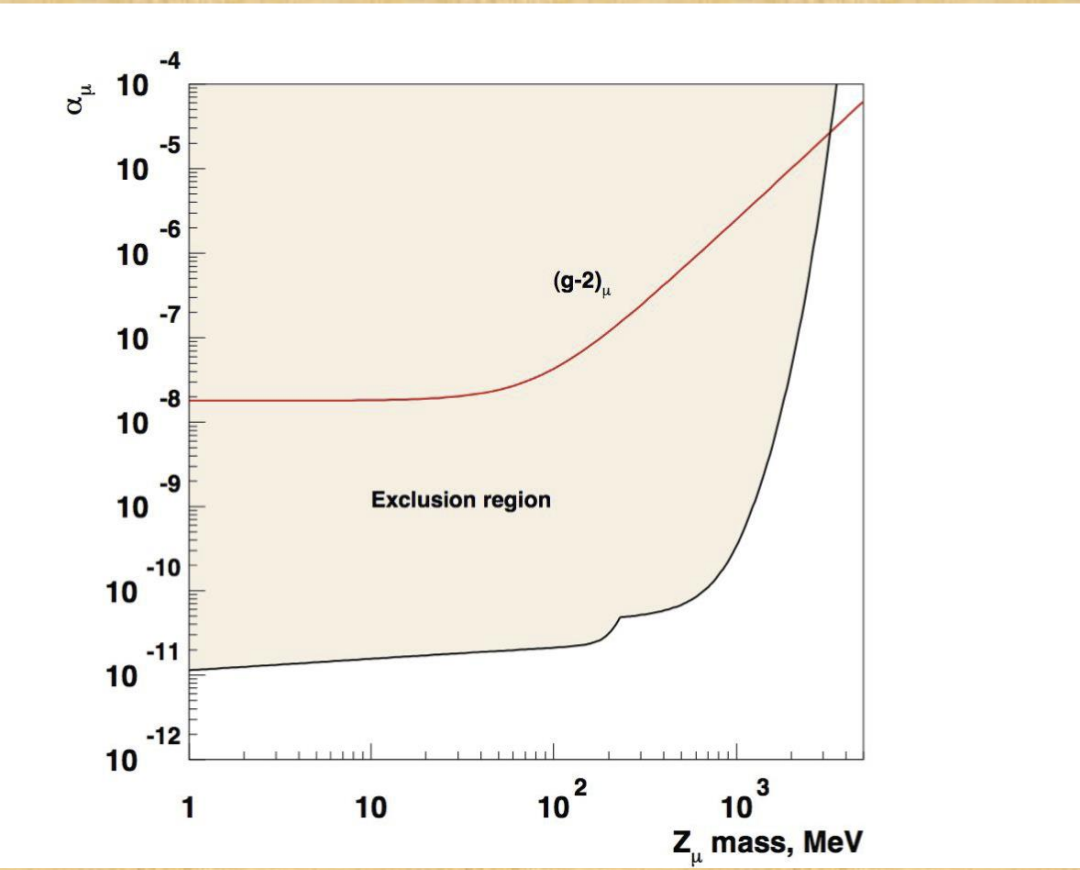
[j]*Tomsk State Pedagogical University, 634061 Tomsk, Russia*
[k]*University of Illinois, Urbana Champaign, Illinois, USA*
[l]*Universidad Técnica Federico Santa María, 2390123 Valparaíso, Chile*
[m]*ETH Zürich, Institute for Particle Physics, CH-8093 Zürich, Switzerland*

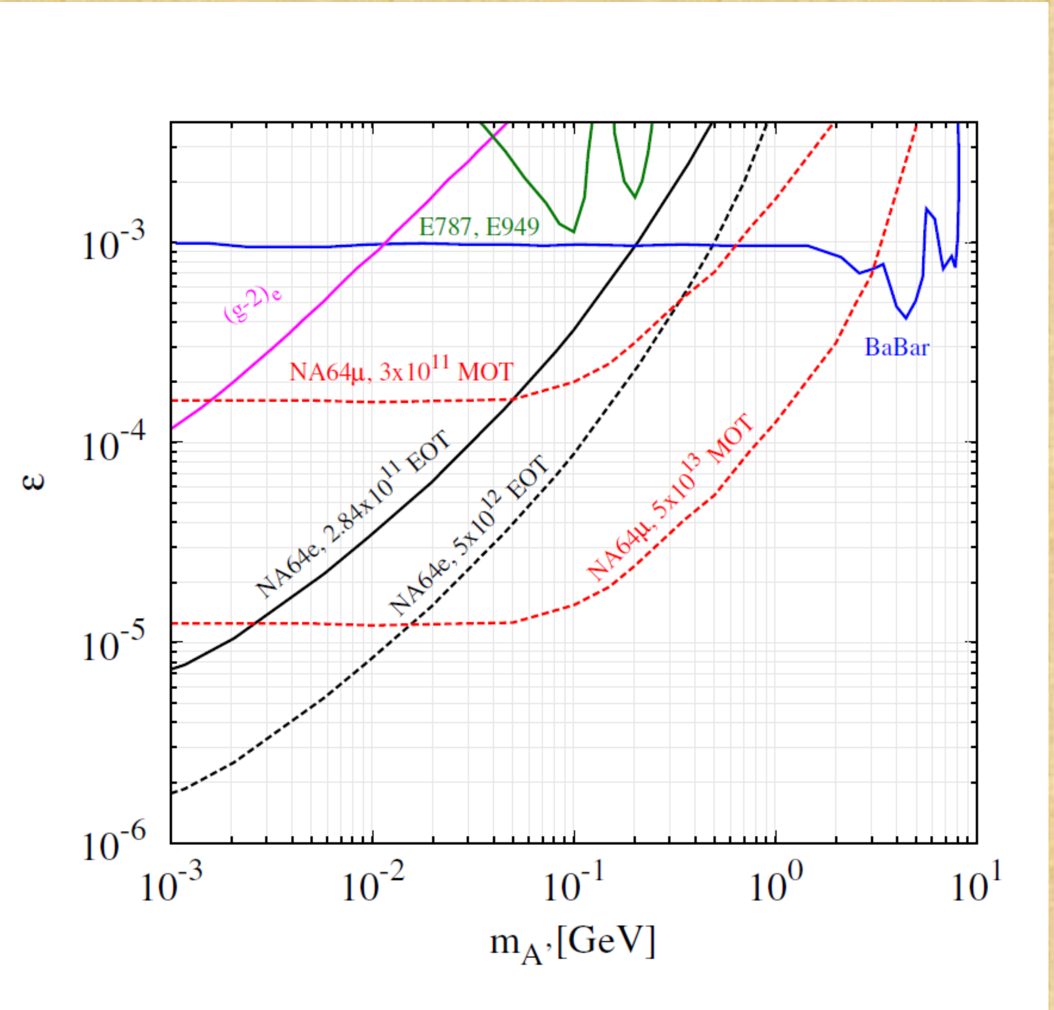
January 7, 2019

[1]http://webna64.cern.ch

Expected sensitivity for 10^{12} muons on target



The comparison of NA64e and NA64μ



Conclusions

NA64e with NEOT $=5*10^{12}$ electrons will allow to discover or exclude the most interesting scenarios. NA64μ with muon beam will be more powerful than NA64 with electron beam for dark photon masses bigger than 30~MeV.

Conclusions

Light dark matter?

To be or not to be?

That’s the question!

I hope the answer (positive? or negative?) will be known in 10 years.

Thank You for your attention.

BACKUP

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

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

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

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

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

COHERENT experiment

Spallation Neutron Source at Oak Ridge National Laboratory

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

"CEvNS":

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

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