Search for light dark matter at accelerators

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Outline

1. 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. Spin of dark matter particles

2. Mass of dark matter particles

In SUSY with R-parity LSP is gaugino or Higgsino with $s = 1/2$ and $m = O(100\ \text{GeV})$ as a rule

3. ….

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

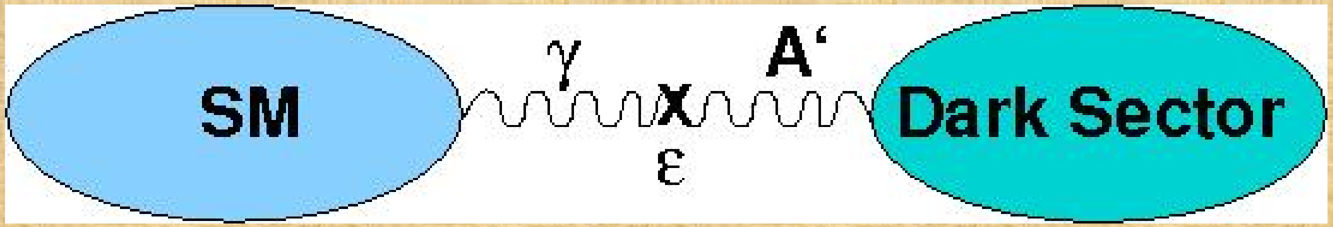
Renormalizable realization – additional interaction connects our world and dark particles world.

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

Also models with scalar mediator exist

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

THERMAL ORIGIN

If 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

See for example:

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

Thermal origin

During the Universe expansion the temperature decreases and at some temperature T_d the thermal decoupling of the dark matter starts to work[17, 18]. Namely, at some freeze-out temperature the annihilation cross-sections

$$DMparticles \rightarrow SMparticles$$

$$SMparticles \rightarrow DMparticles$$

become too small to obey the equilibrium of dark matter particles with the SM particles and dark matter decouples. To obtain quantitative estimates of the dark matter density [17, 18, 19] it is necessary to solve the Boltzmann equation

$$\frac{dn_d}{dt} + 3H(T)n_d = - < \sigma v_{rel} > (n_d^2 - n_{d,eq}^2) \,. \qquad (26)$$

The knowledge of dark matter density leads to prediction for the annihilation cross section

The dark matter relic density can be numerically estimated as [61]

$$\Omega_{DM}h^2 = 0.1(\frac{(n+1)x_f^{n+1}}{(g_{*s}/g_*^{1/2})})\frac{0.856 \cdot 10^{-9} GeV^{-2}}{\sigma_0}\,, \quad (10)$$

where $< \sigma v_{rel} >= \sigma_o x_f^{-n}$ and

$$x_f = c - (n + \frac{1}{2}) ln(c)\,, \quad (11)$$

$$c = ln(0.038(n+1)\frac{g}{\sqrt{g_*}} M_{Pl} m_{DM} \sigma_0)\,. \quad (12)$$

For scalar light dark matter and vector messenger one can find that the annihilation cross section

$$\sigma v_{rel} = \frac{8\pi}{3}\frac{\epsilon^2 \alpha \alpha_d m_{DM}^2 v_{rel}^2}{(m_{Z'}^2 - 4m_{DM}^2)^2},$$

Numerical estimates

For the case where dark matter consists of dark matter particles and dark matter antiparticles the $DM\bar{DM} \rightarrow SM\ particles$ annihilation cross sestion $\sigma_{an} = \frac{\sigma}{2}$. Numerically we find that

$$k(m_{DM}) \cdot 10^{-6} \cdot (\frac{m_{DM}}{GeV})^2 \cdot (\frac{m^2_{A'}}{m^2_{DM}} - 4)^2 = \epsilon^2 \alpha_D \,. \quad (13)$$

Here the coefficient $k(m_{DM})$ depends logarithmically on the dark matter mass m_{DM} and $k_{DM} \approx 0.5(0.9)$ for $m_{DM} = 1(100)\ MeV$. For instance, for $m_{A'} = 2.2\ m_d$ we have

$$0.71 k(m_{DM}) \cdot 10^{-6} \cdot (\frac{m_{DM}}{1\ \mathrm{GeV}})^2 = \epsilon^2 \alpha_d \,. \quad (14)$$

So the main features of light dark matter

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

2. The annihilation cross-section

$$\langle \sigma_{ann} v \rangle \approx 1\text{pbn} \times c$$

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

From the requirement of the absence of Landau pole singularity

H.Davoudiasl and W.Marciano,

arXiv:1502.07383

$$\alpha_D \lesssim 1$$

as a consequence

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

One loop estimates, arXiv:1502.07383

$$\alpha_d(q_0) \approx \frac{3\pi}{(2n_F + n_S/2)\ln(q^*/q_0)}.$$

for $q^* = 100$ GeV

$$\alpha_d(q_0) \lesssim 0.68/(n_F + n_S/4)$$

if $n_F = 1$ and $n_S = 1$

$$q_0 = 0.1 \text{ GeV}$$

$$\alpha_d(q_0) \lesssim 0.5$$

Other hint in favour of BSM is muon g-2 anomaly

Light vector boson contributes to muon g-2 at one loop level

$$\delta a = \frac{\alpha_\mu}{2\pi} F\left(\frac{m_{Z'}}{m_\mu}\right),$$

$$F(x) = \int_0^1 dz \frac{[2z(1-z)^2]}{[(1-z)^2 + x^2 z]}$$

Typical estimates

for $m_{Z'} \ll m_\mu$

$$\alpha_\mu = (1.8 \pm 0.5) \times 10^{-8}$$

$$m_{Z'} \gg m_\mu$$

$$\alpha_\mu = (2.7 \pm 0.7) \times 10^{-8} \times \frac{m_{Z'}^2}{m_\mu^2}$$

2.Search for light dark matter at accelerators

2a.Visible dark photon decays

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'

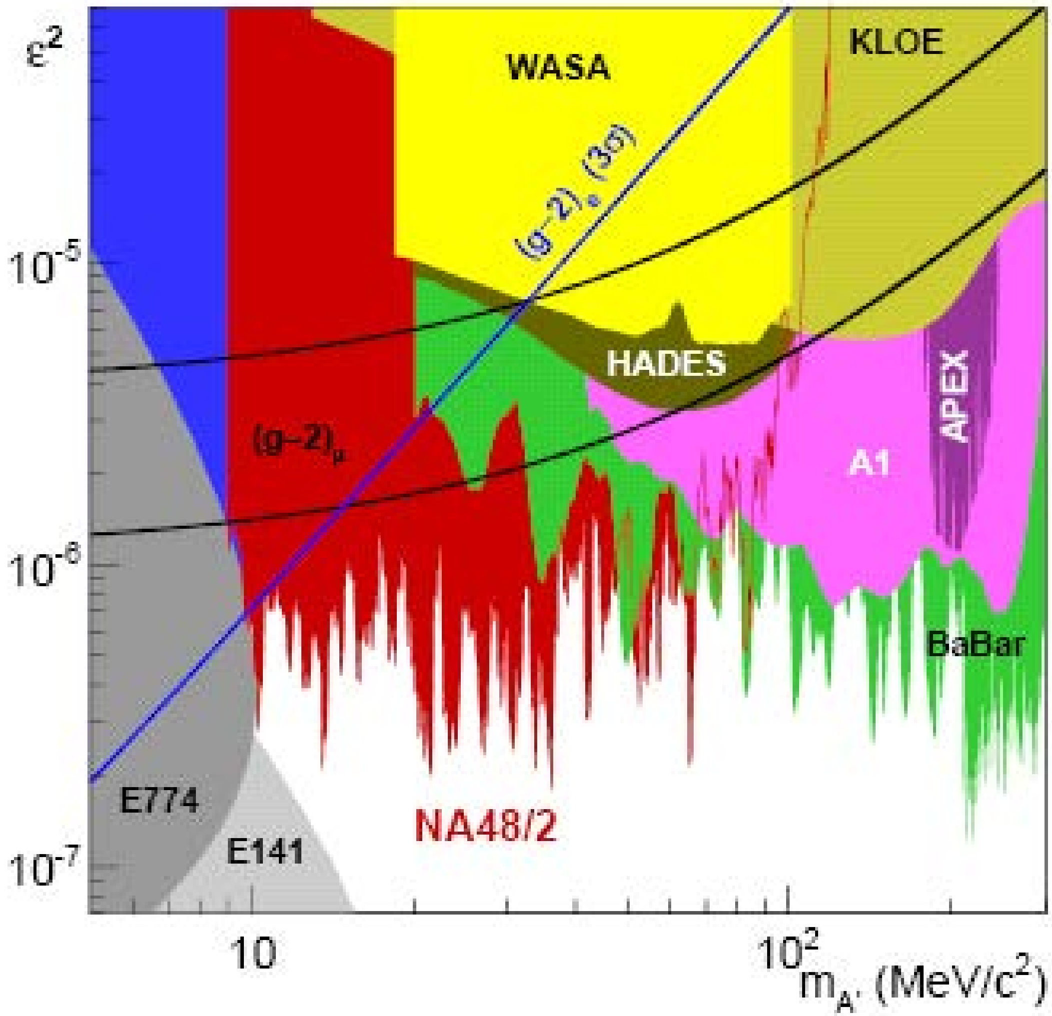
Current experimental bounds

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

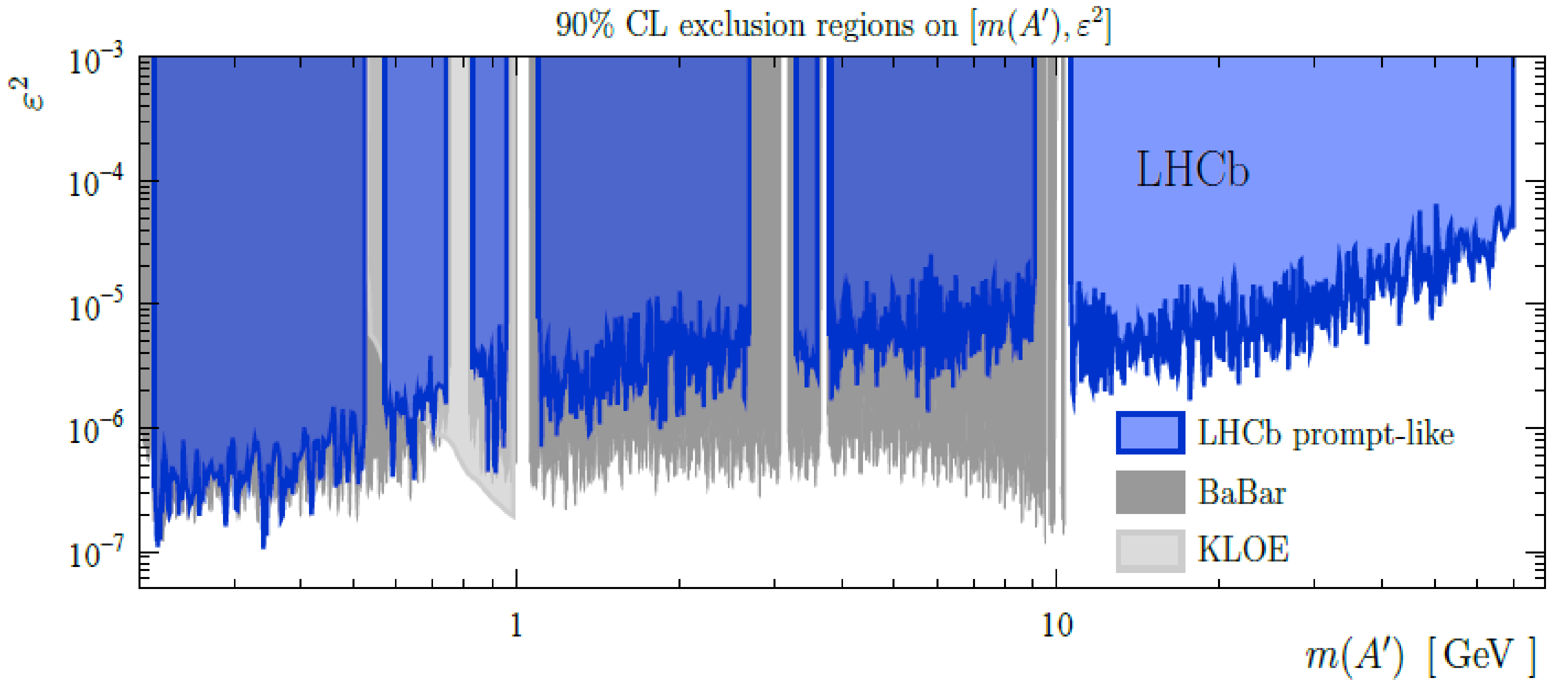
Current (2017) exclusion plot



LHCb bounds on visible decays

CERN-EP-2017-248

Phys.Rev.Lett. 2018

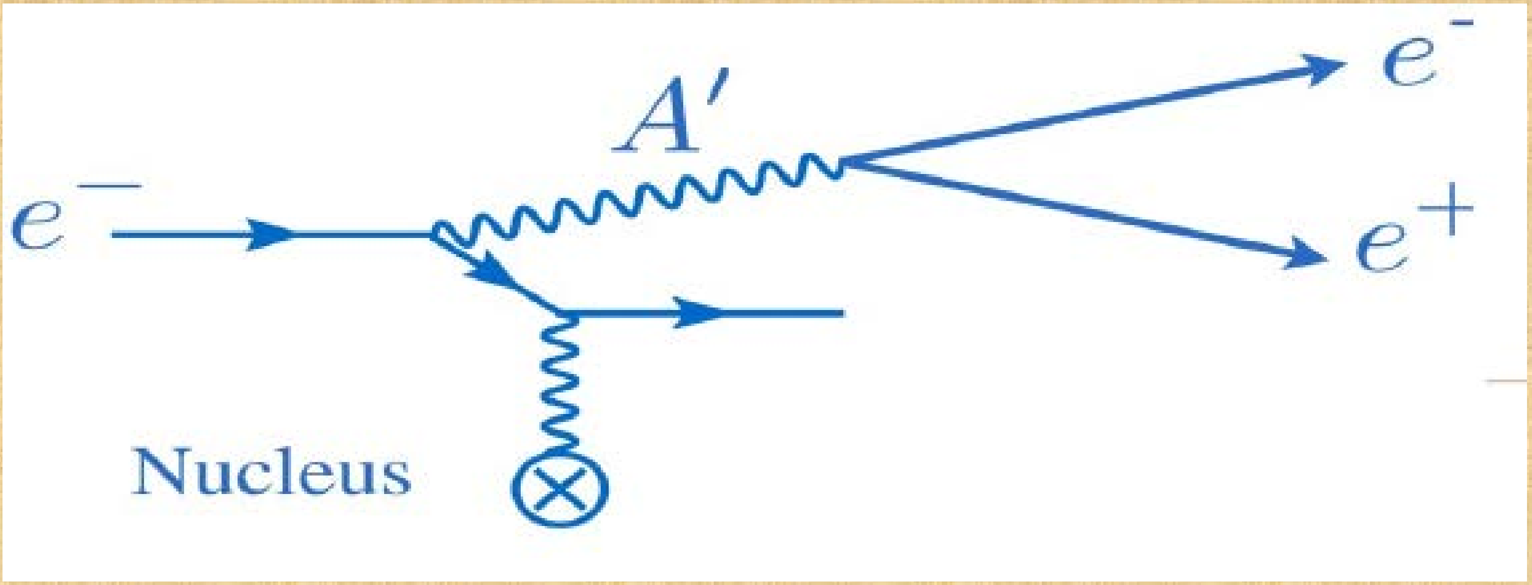


Future and current visible decays searches

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

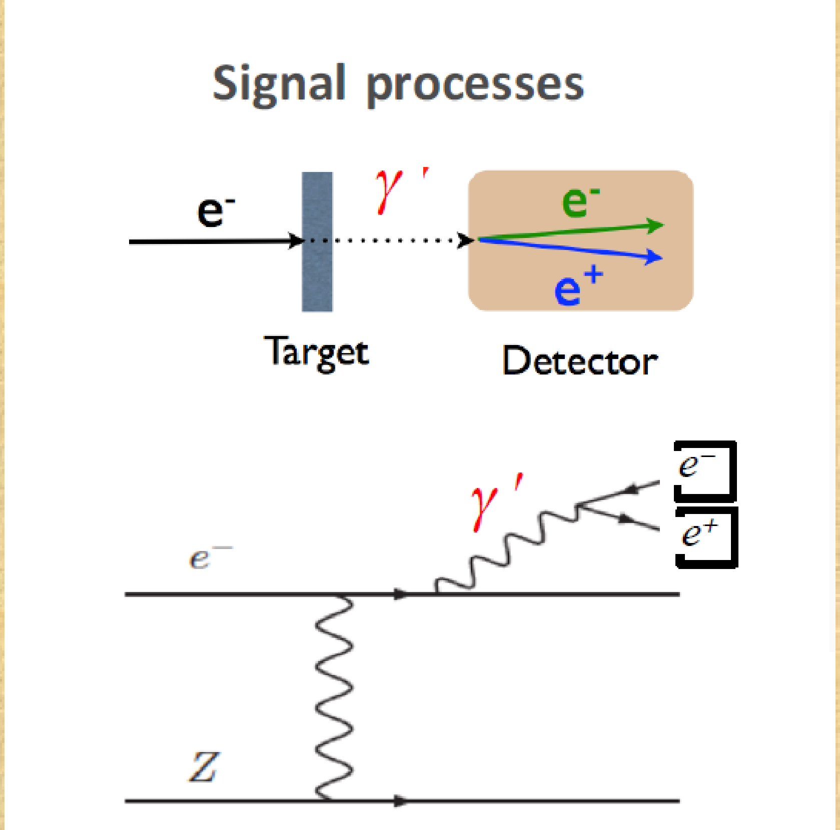


$$\frac{d\sigma(e^- Z \to e - Z(A' \to l^+ l^-))}{d\sigma(e^- Z \to e - Z(\gamma^* \to l^+ l^-))} = \frac{3\pi\epsilon^2}{2N_{eff}\alpha}\frac{m_{A'}}{\delta m}$$

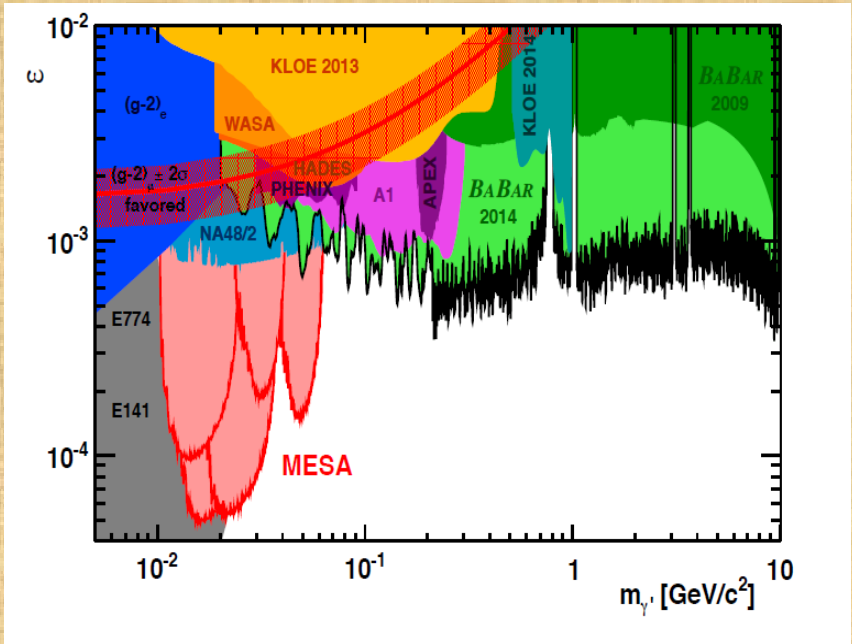
Prompt visible decays

The MAinz Gas Internal EXperiment

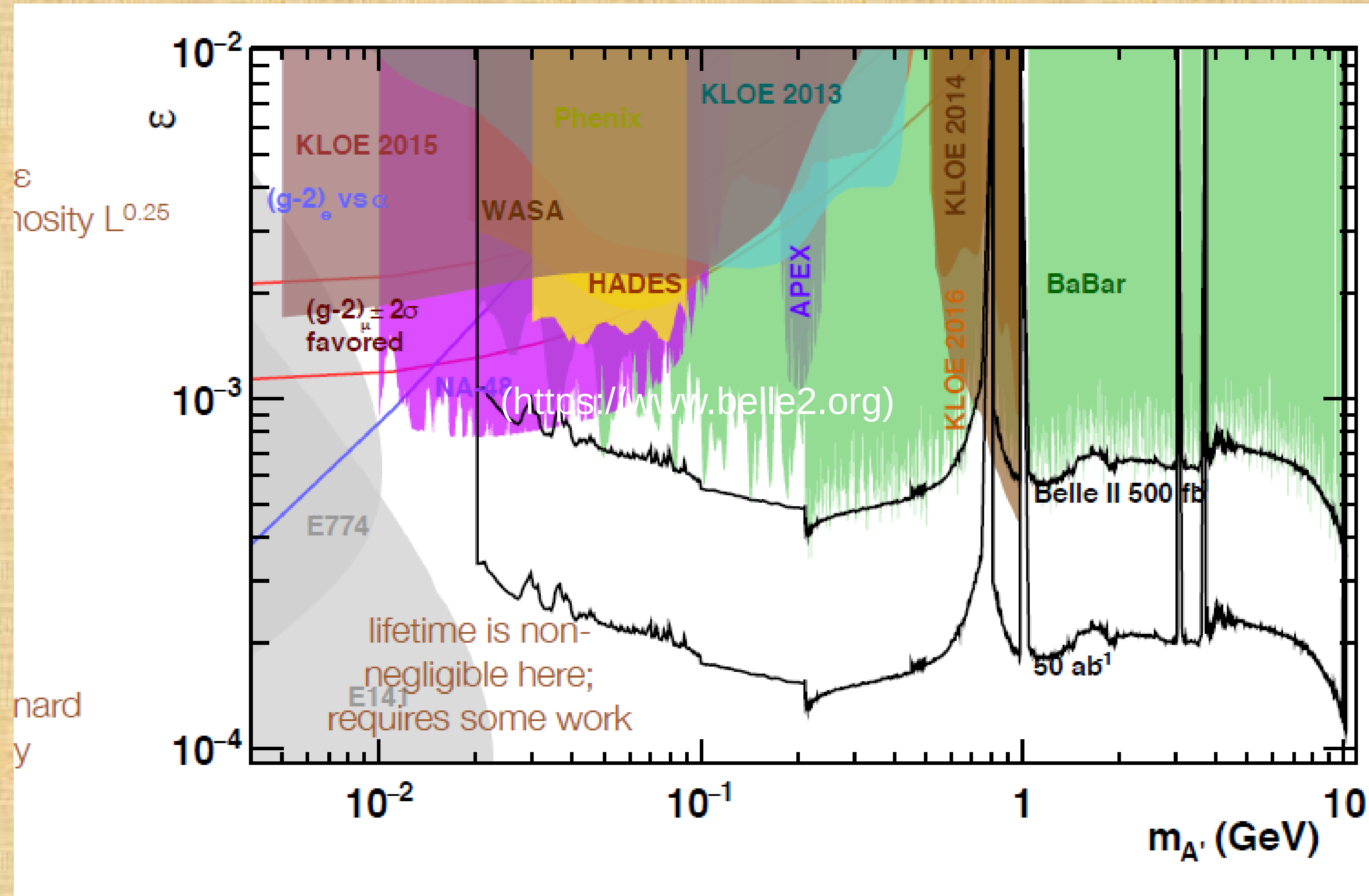
Experiment scheme



MAGIX Discovery potential (>2020)

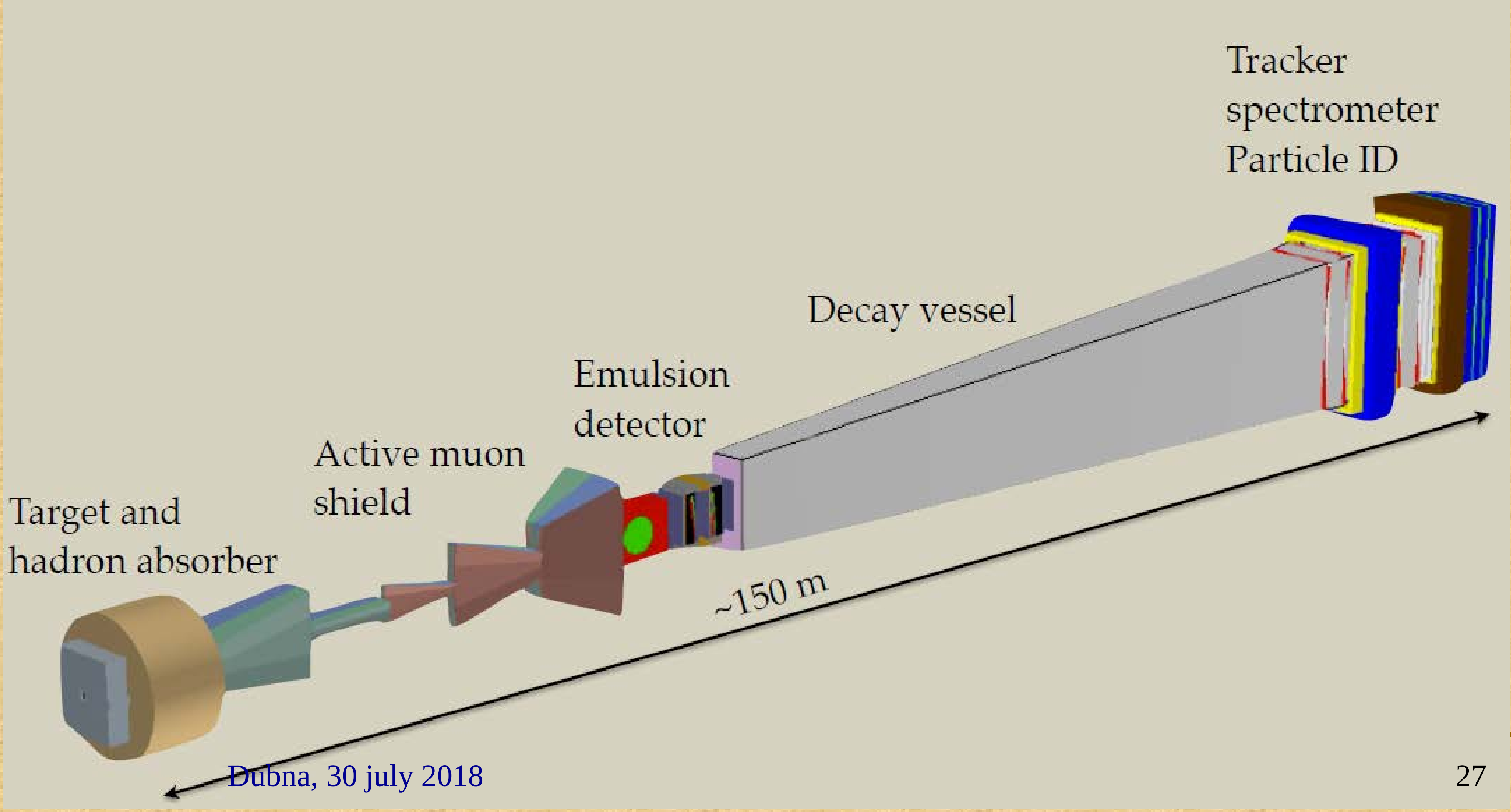


Belle || (>2018) expected bounds for visible decays, 50 ab^{-1}(https://www.belle2.org)



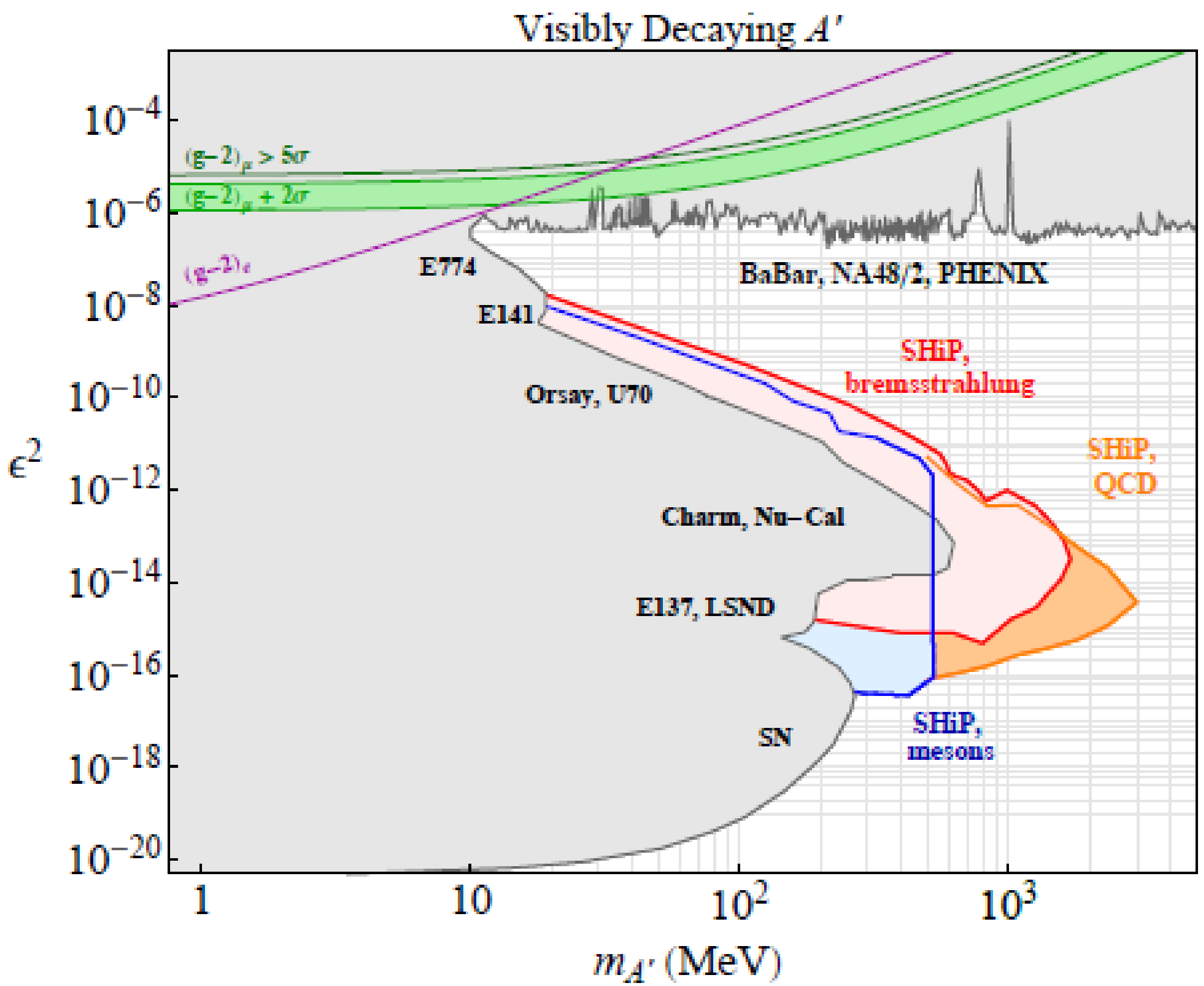
SHiP (>2026) experiment as an example of displaced decays

Rep. Prog. Phys. 79 (2016)
arXiv:1504.04855

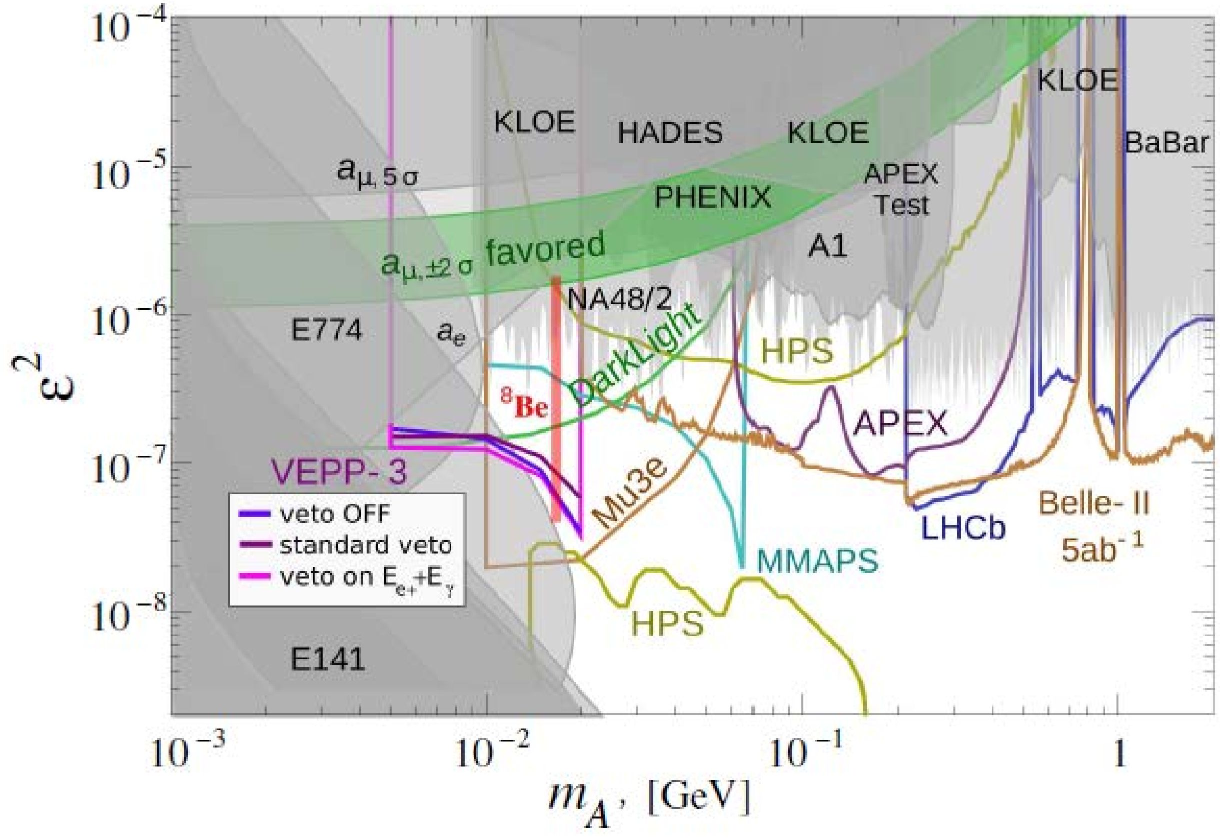


Expected SHiP bounds on visible decays for EPOT = $2*10^{20}$

Technical Proposal CERN-SPSC-2015-016



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



2b.Invisible decays

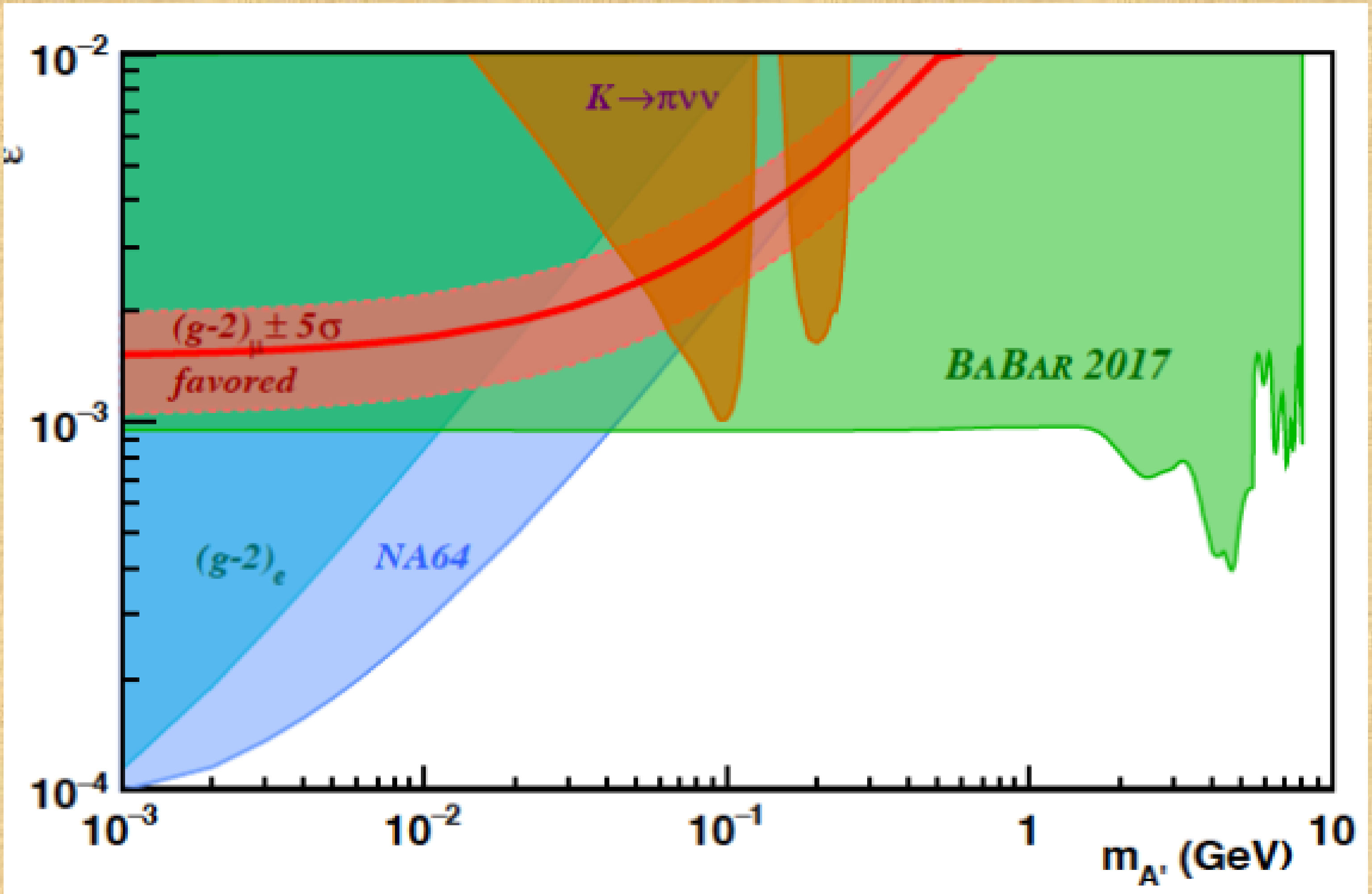
Invisible mode detection

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

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

Recent 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

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

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

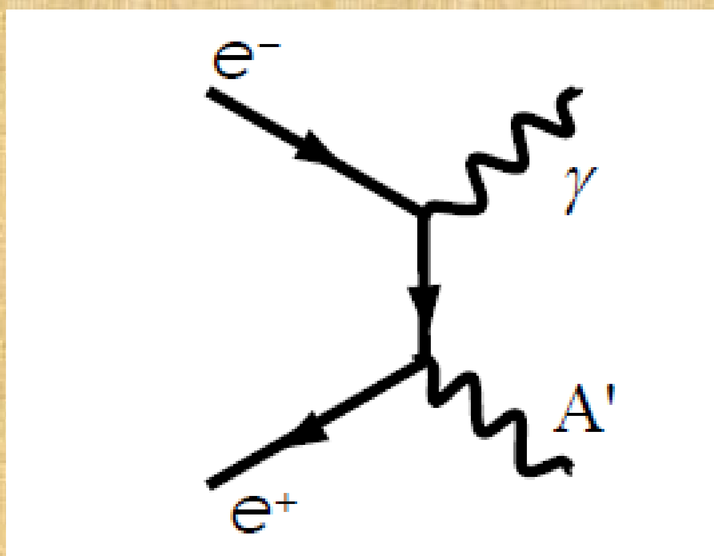
Future experiments missing mass searches

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

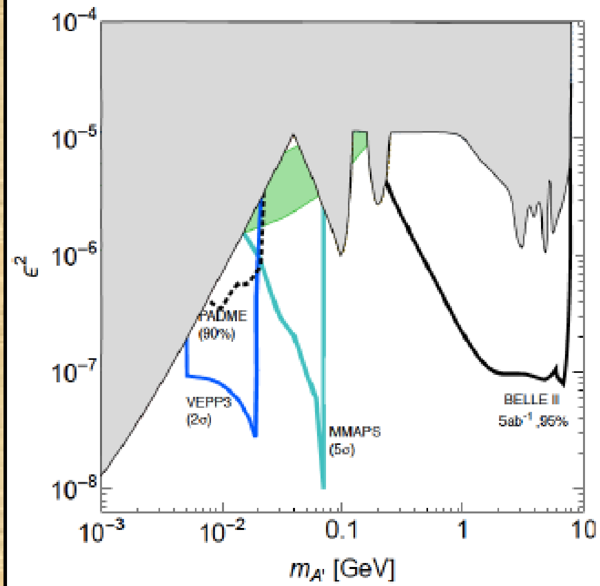
The knowledge of momenta e^+, e^- and γ allows to restore the A' mass – resonant distribution on invariant mass

PADME experiment

positron beam on “electron” target



Dark Photon arXiv:1608.08632v1



Invisible final state A’→χχ

Other future missing mass experiments

1. Russia(VEPP3 at BINP, Novosibirsk)

500 MeV positron beam, dark photon mass limit 22 MeV, ε^2 **limit** up to 10^{-7} , >2020

2. **USA(Cornell, MMAPS**), 6 GeV positron beam, dark photon mass limit 73 MeV,

ε^2 **limit** up to $10^{-6} – 10^{-7}$

Beam dump experiments

a. Electron beam dump

b. Proton beam dump

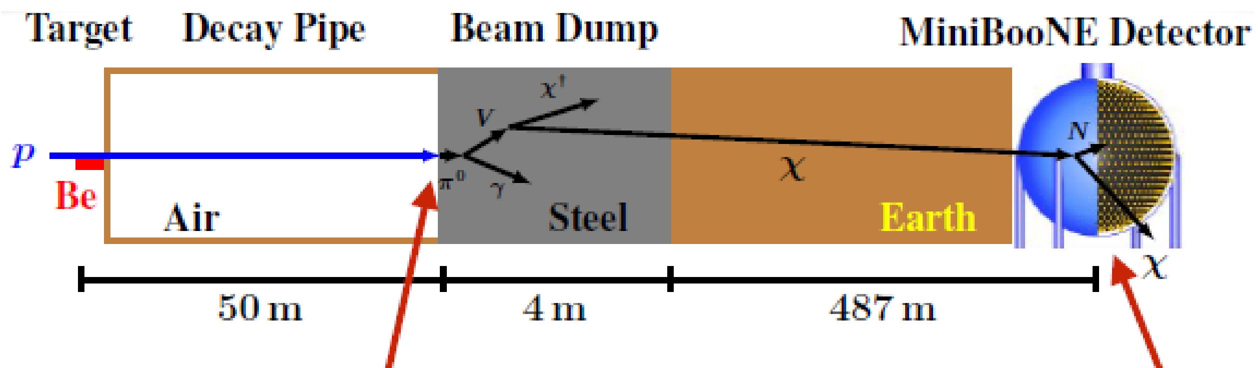
BDX(electron beam dump experiment) at JLAB (1607.01390)

Electron(E_e ~12 GeV) beam experiment for the search for light dark matter.

EOT $=10^{22}$ is assumed. The natural variable

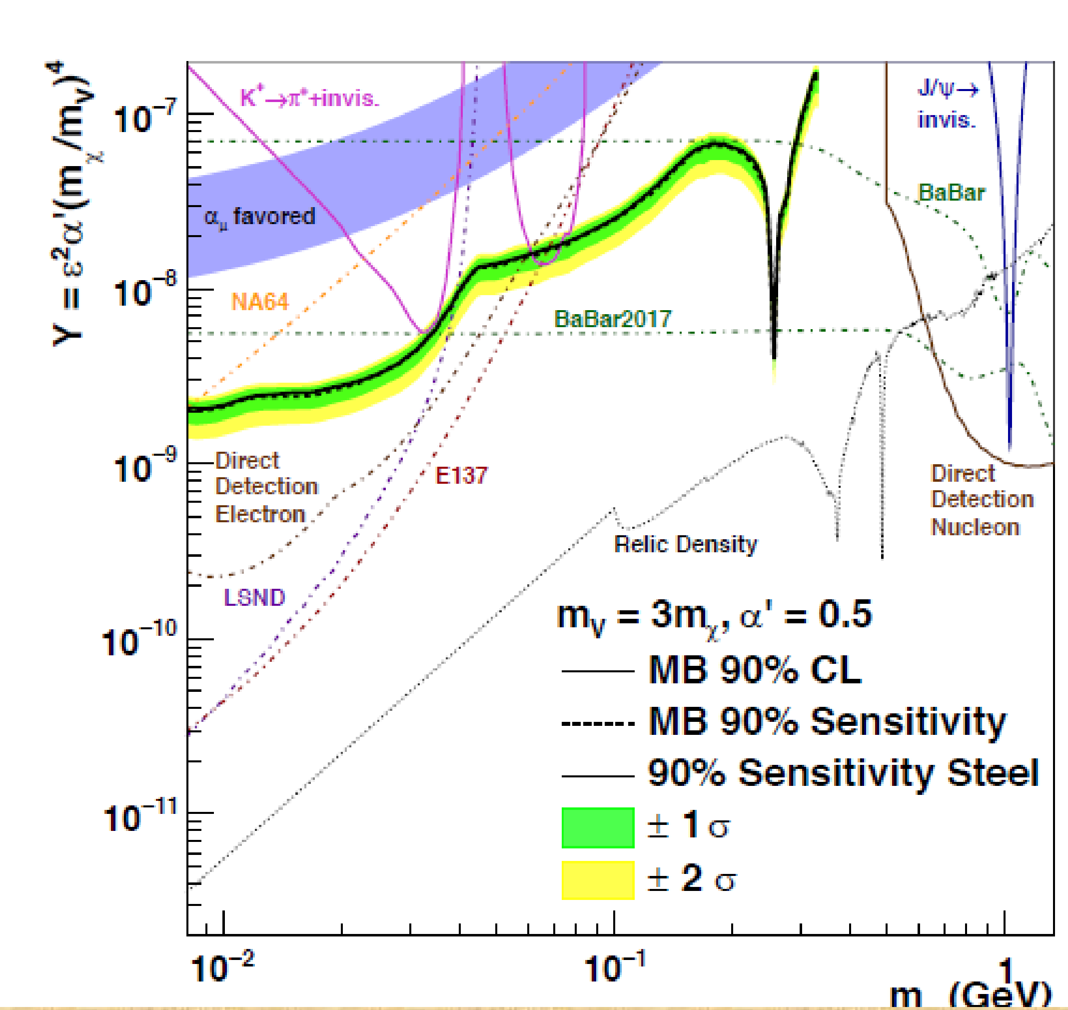
$$y \equiv \epsilon^2 \alpha_D \left(\frac{m_\chi}{m_{A'}} \right)^4$$

Example of proton beam dump. MiniBooNE



$$\sim \epsilon^4 \alpha_D$$

Last MiniBooNE bound arXiv:1702.02688



Future proton beam dumps at FNAL

SBND(Short Base Near Detector) –

factor 10 improvement in signal sensitivity relative to MiniBoone

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

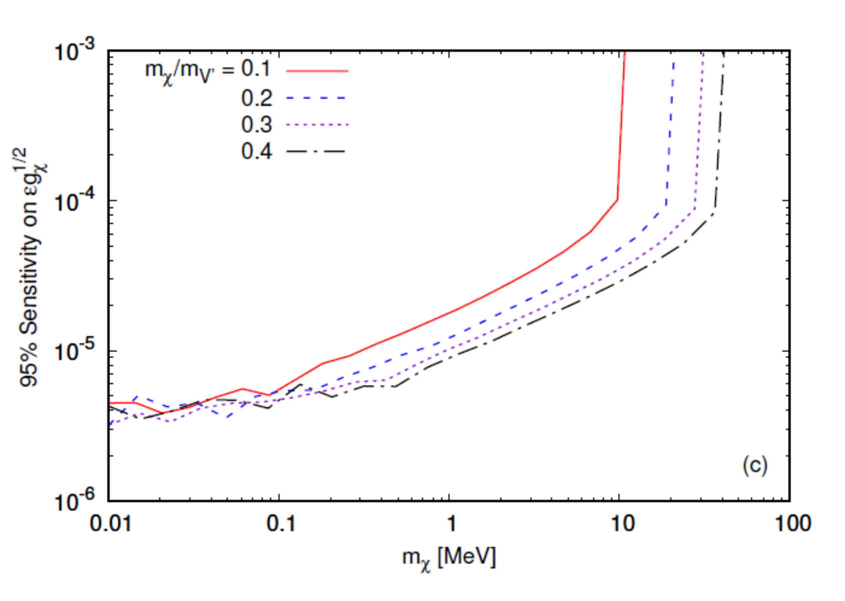
It is possible to extract bounds on A'

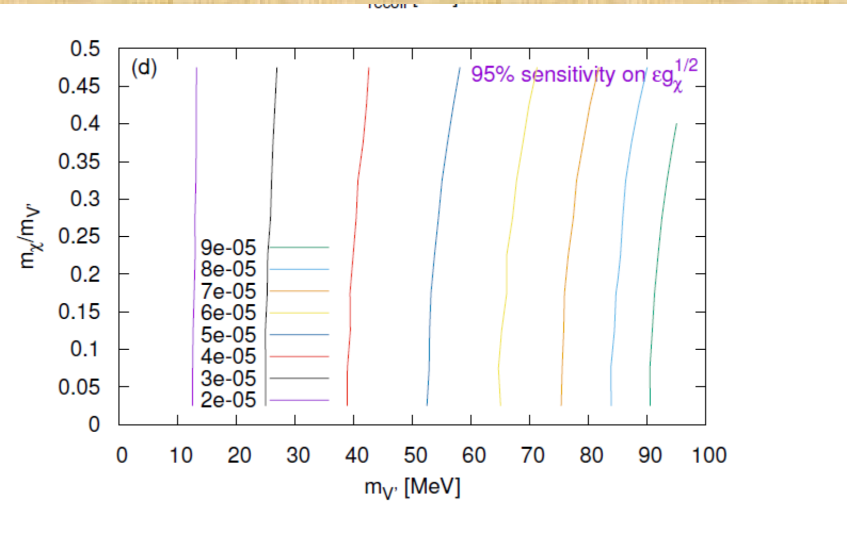
S.-F.Ge and I.N.Shoemaker, arXiv:1710.10889

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





Missing energy(momentum) reaction NA64 and LDMX1801.07867

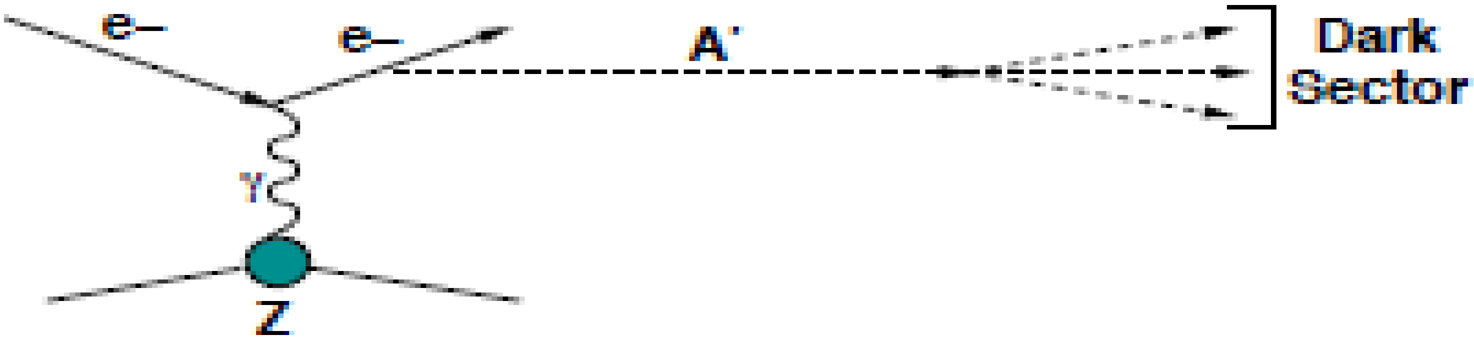
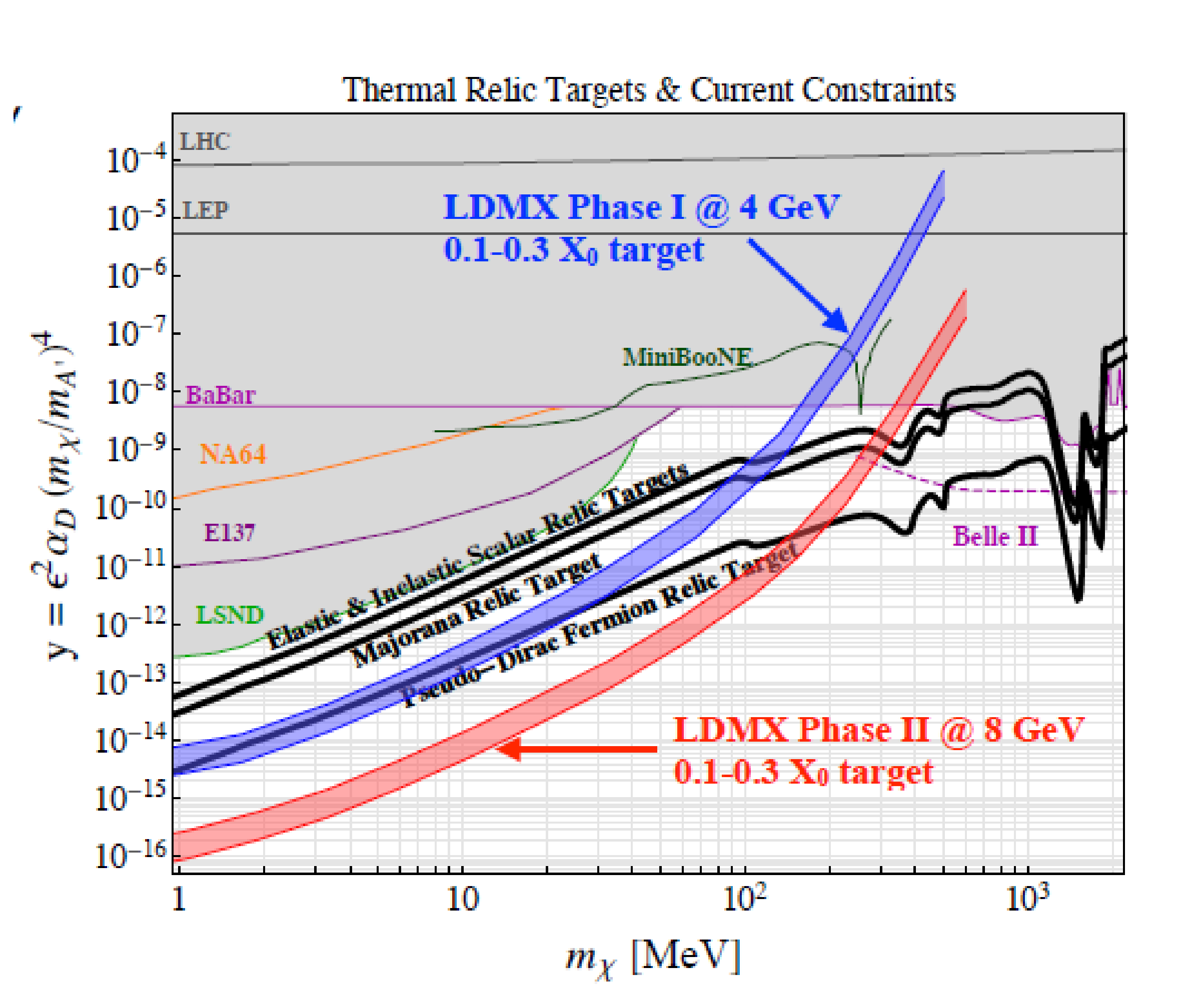
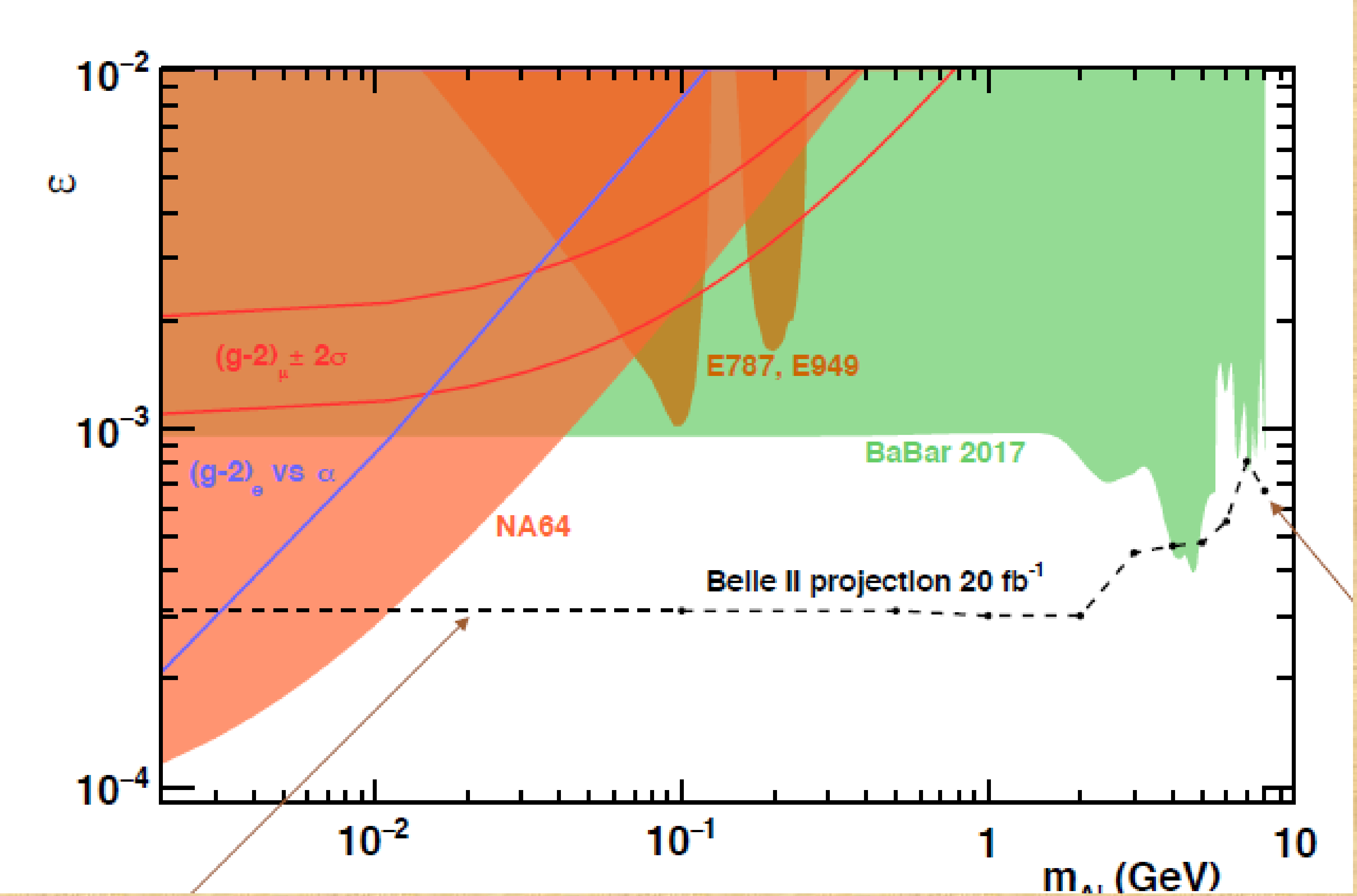


FIG. 1: Diagram contributing to the A' production in the reaction $e^-Z \to e^-ZA', A' \to$ *dark sector*. The produced A' decays invisibly into dark sector particles.

LDMX DISCOVERY POTENTIAL(180107867).



Expected Belle || discovery potential for invisible decays(https://www.belle2.org)



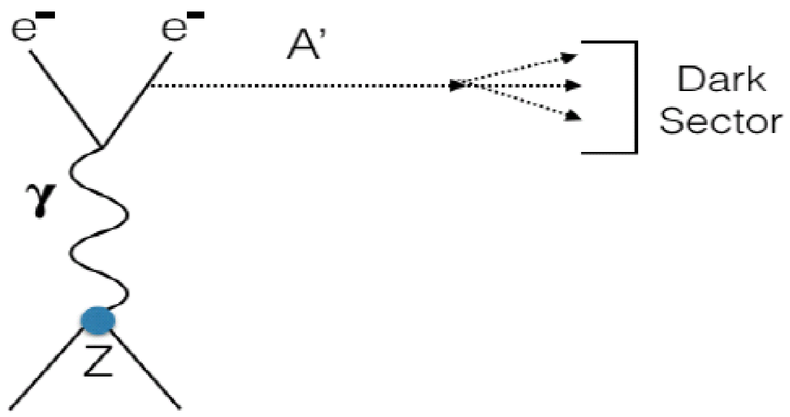
3. NA64 experiment

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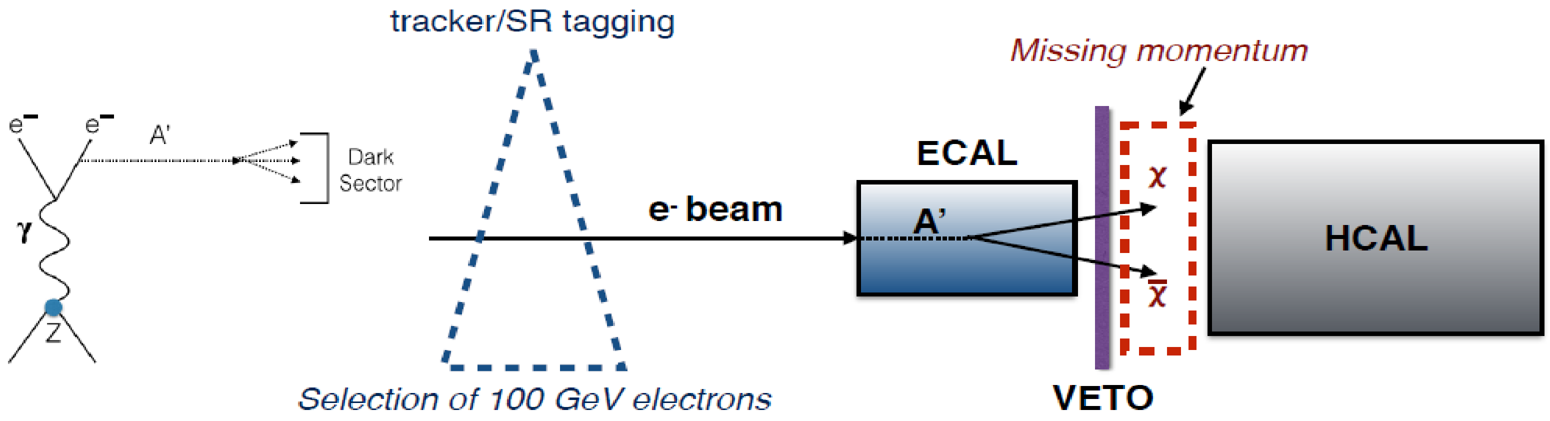
CERN-SPSC-2013-034 / SPSC-P-348
06/12/2013

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.

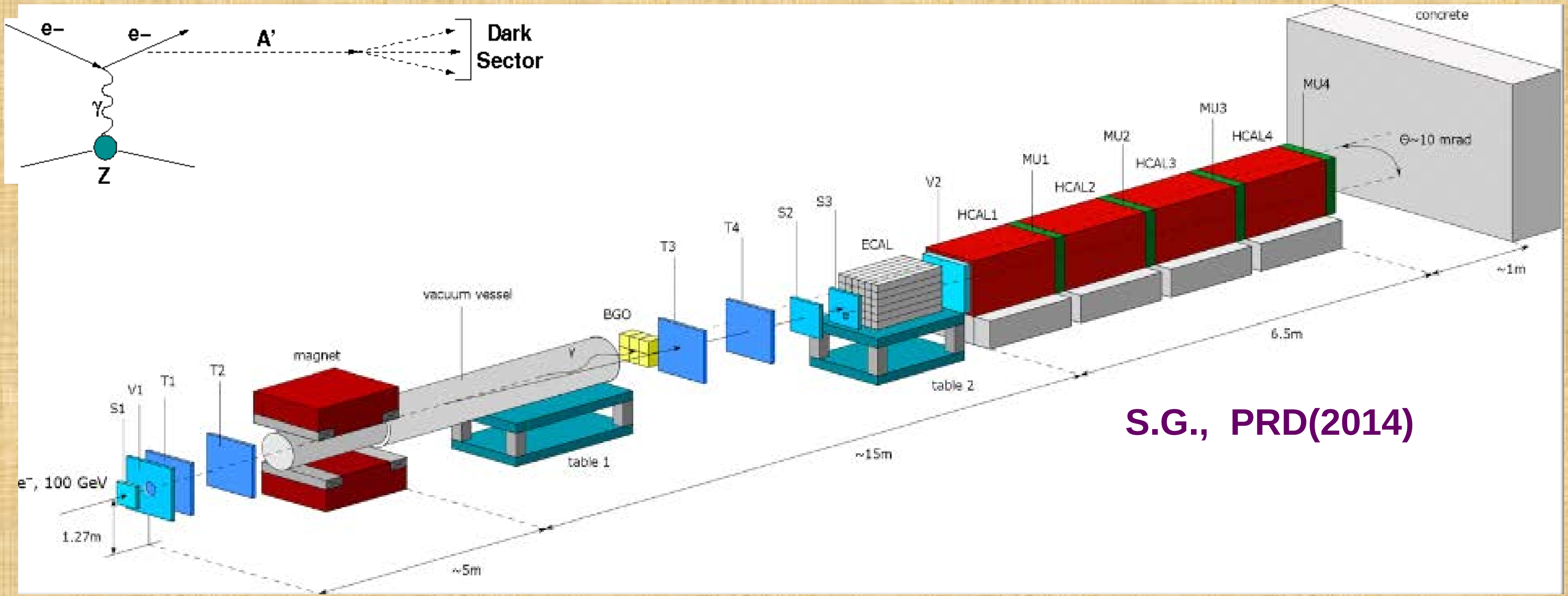
NA64 Research program

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)

3 main components :

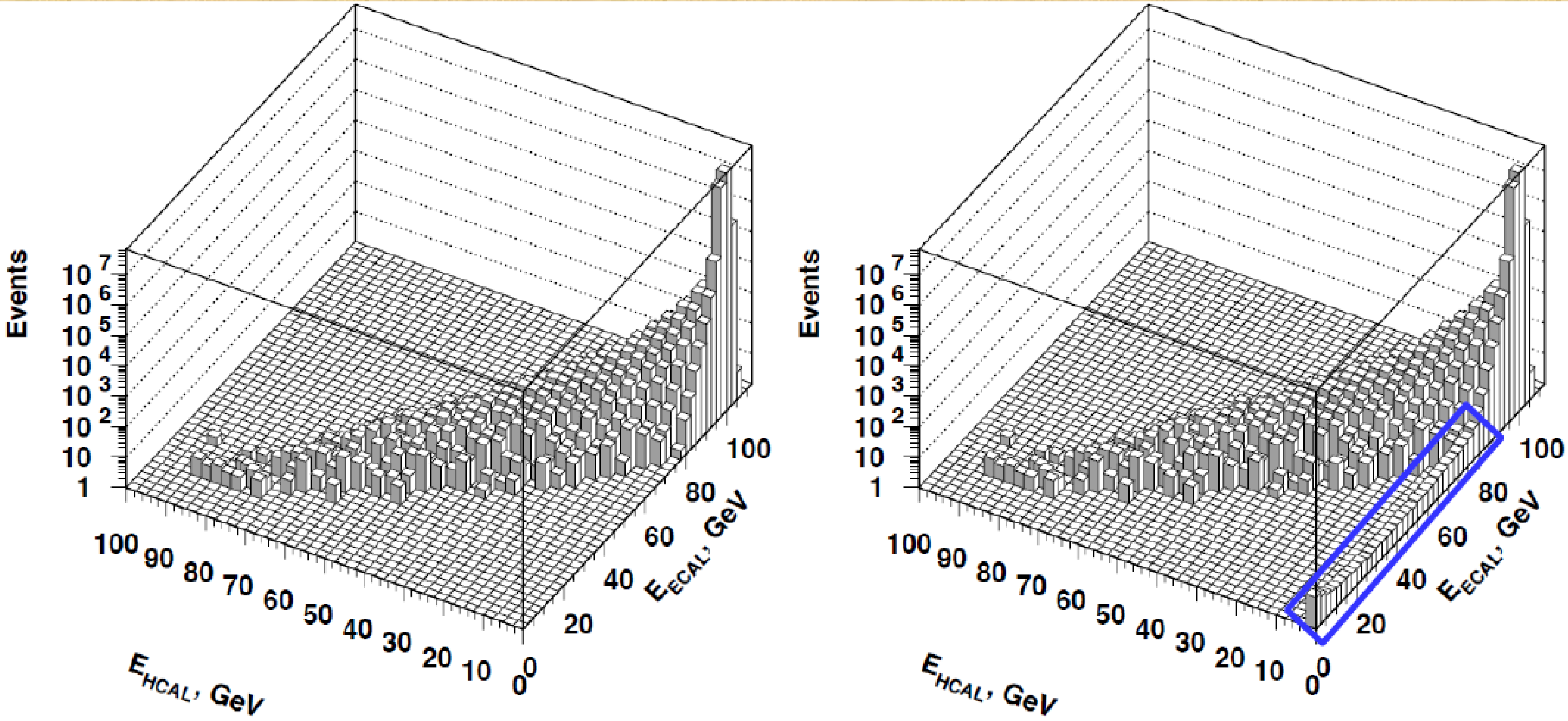
- clean, mono-energ. 100 GeV e- beam
- e- tagging system: MM tracker + SR
- 4π fully hermetic ECAL+ HCAL

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

Active target beam dump concept

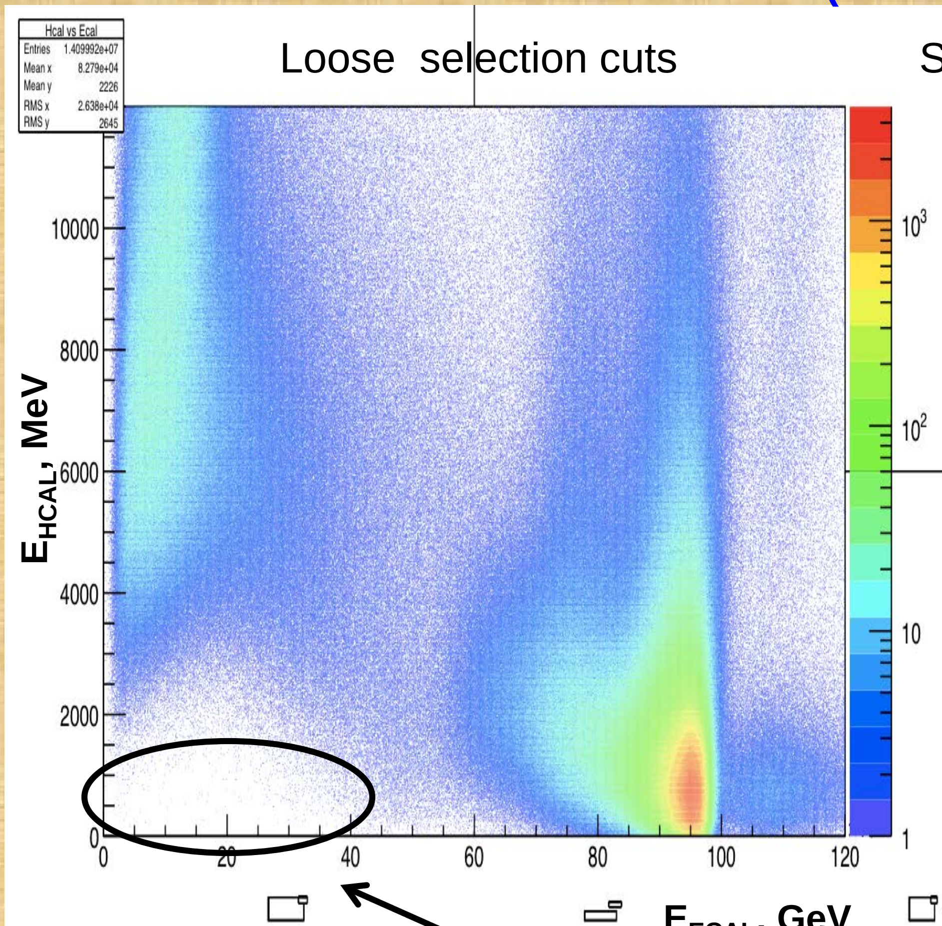


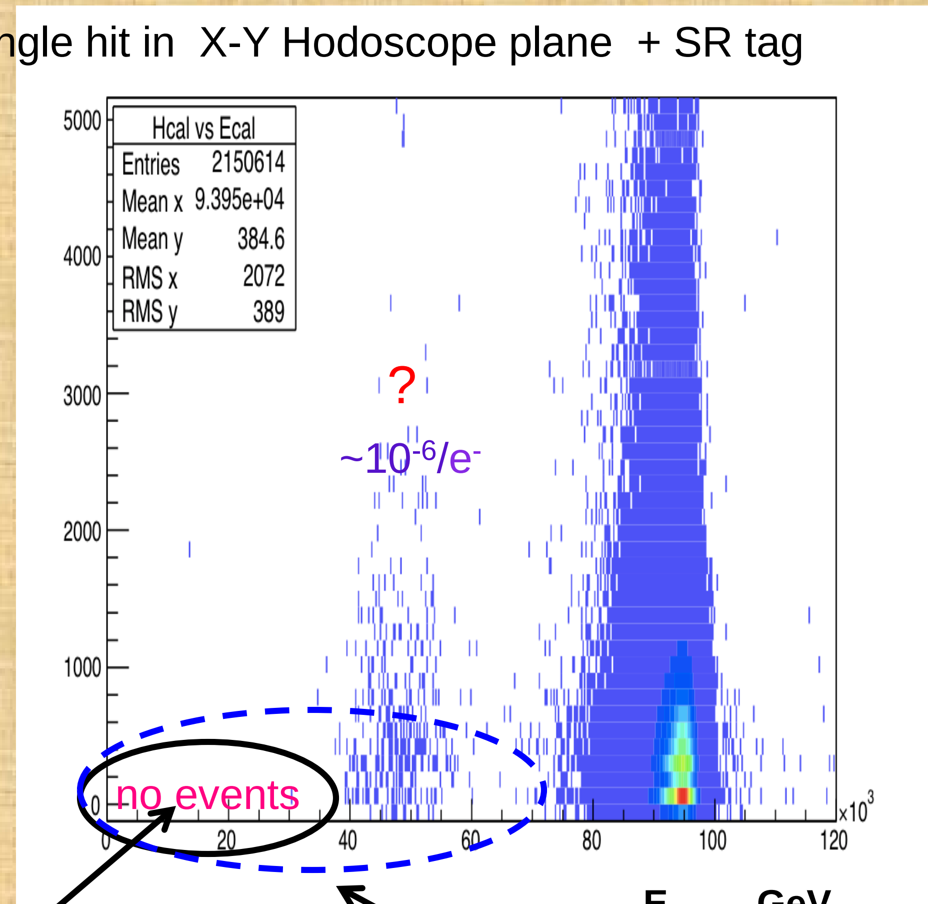
Dark Photon Signature for 100 GeV electron beam:

- 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

The NA64 first new result from July 2016 run

NA64 Collaboration,
Phys.Rev.Lett. 118, 011802(2017)

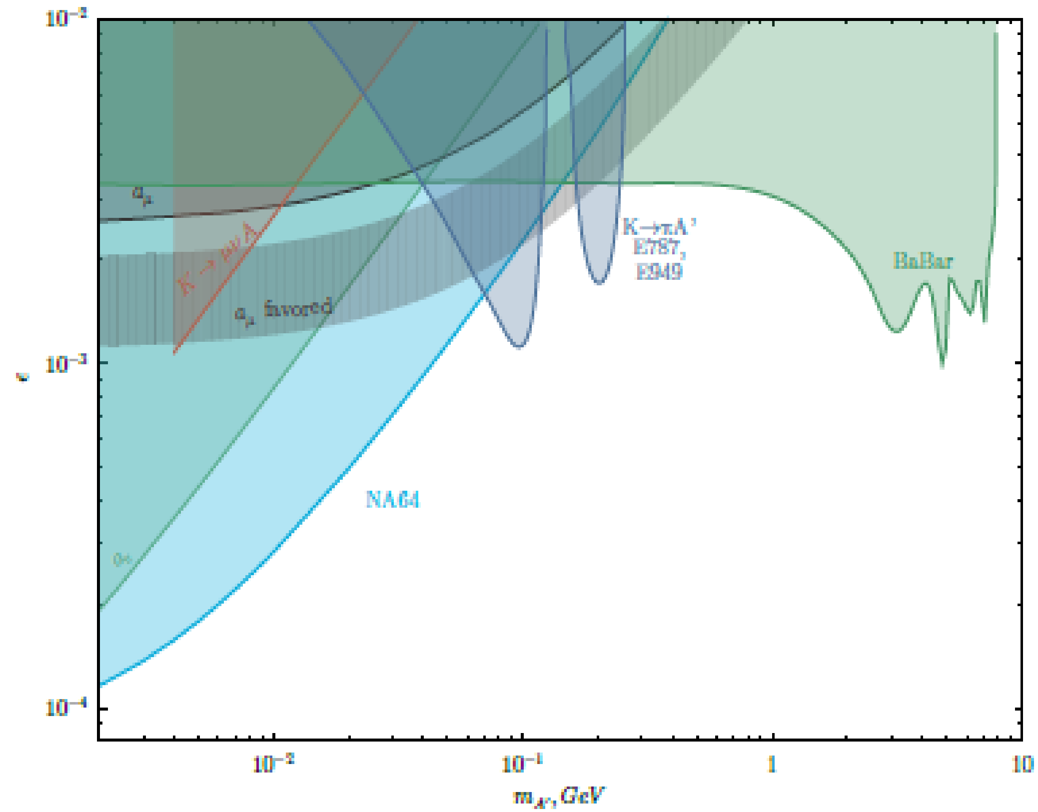
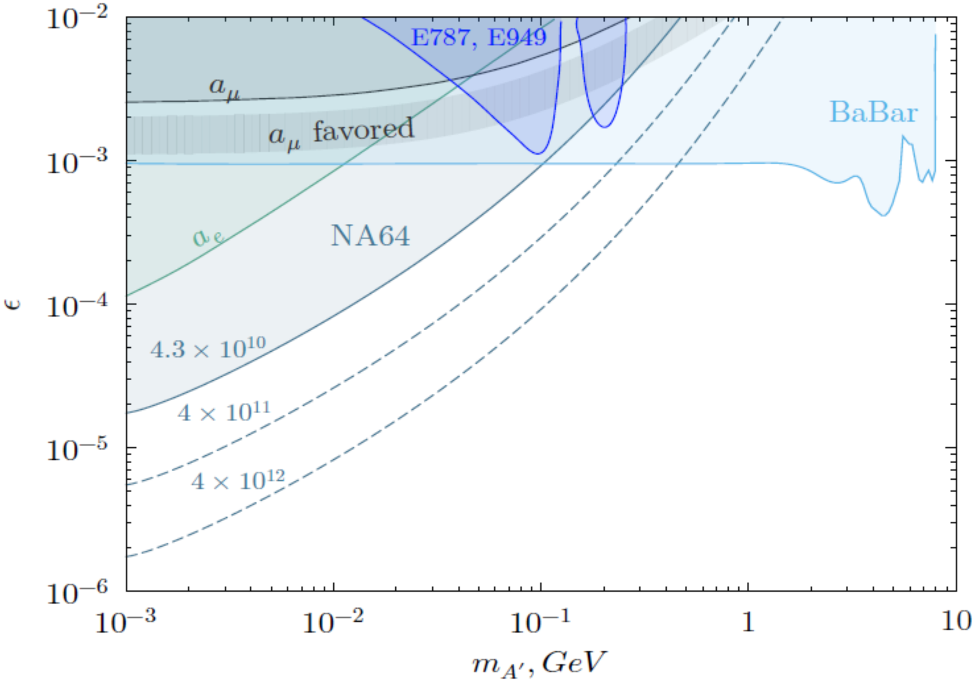


FIG. 3: The NA64 90 % C.L. exclusion region in the $(m_{A'}, \epsilon)$ plane. Constraints from the BaBar [48, 55], and E787+ E949 experiments [47, 56], as well as muon α_μ favored area are also shown. Here, $\alpha_\mu = \frac{g_\mu - 2}{2}$. For more limits obtained from indirect searches and planned measurements see e.g. Refs. [5].

LAST NA64 RESULT
July + October 2016 run(Phys.Rev.D, 2018)

arXiv: 1710.00971

Exact tree-level calculations of cross sections $\sigma(eZ\to eZA')$.
Large corrections to the WW approximation for $m_{A'} > \sim 100$ MeV.



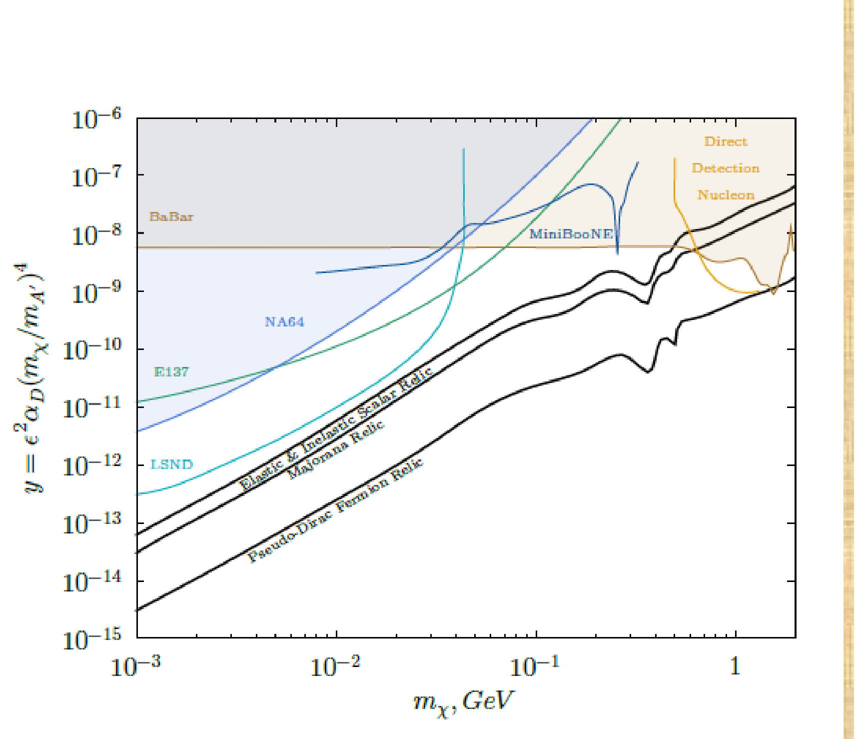
Plans to accumulate ~ 4×10^{12} EOT after LS2

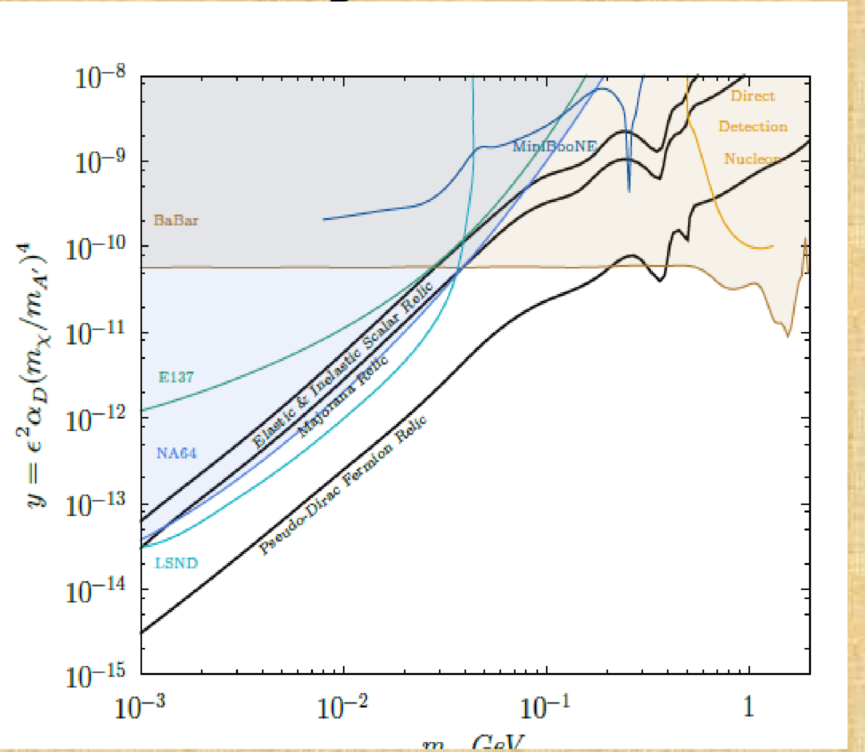
S.N. Gninenko – NA64++ report – PBC Workshop, CERN, November 21-22, 2017

NA64 bound for

$$y = \epsilon^2 \alpha_D \left(\frac{m_\chi}{m_{A'}}\right)^4$$

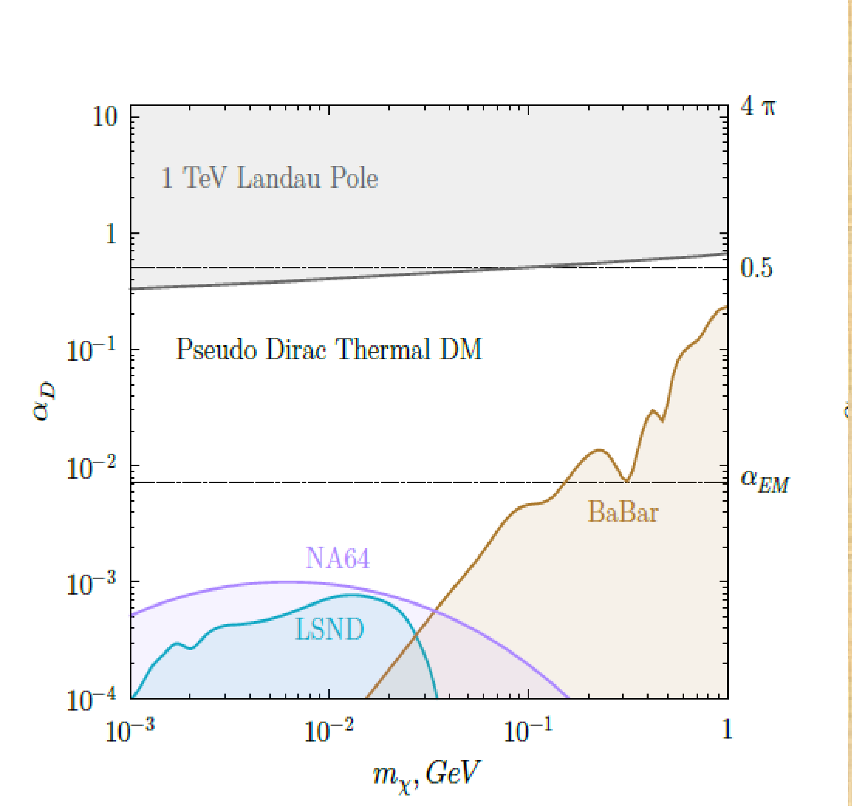
$\alpha_D = 0.5$ **$\alpha_D = 0.005$**



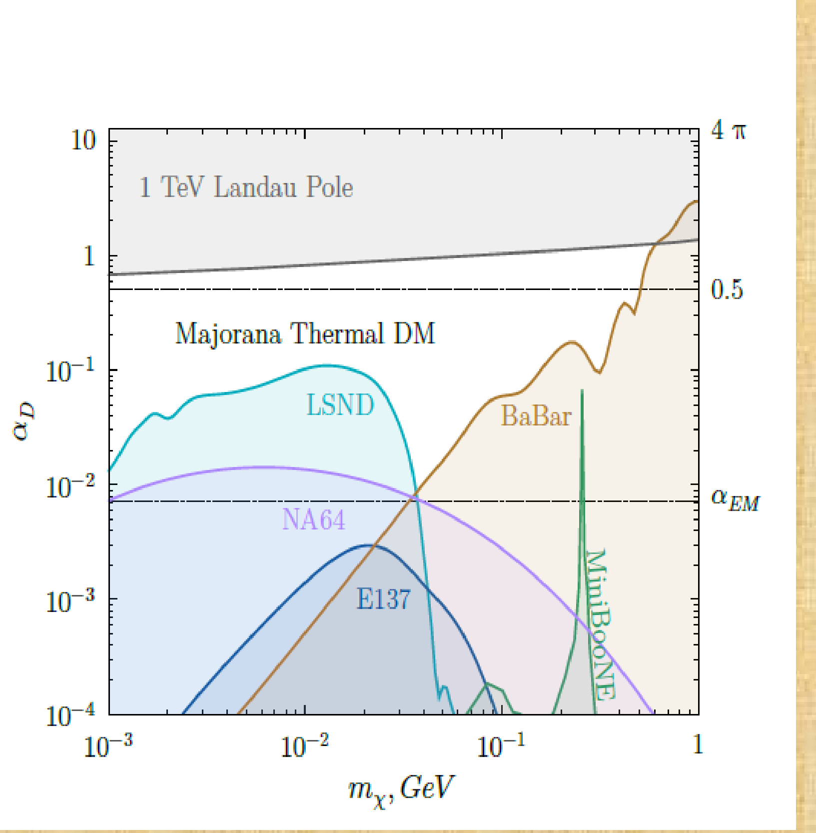


NA64 bound on α_D

Pseudo Dirac



Majorana



Expected NA64 bounds after 2018 run

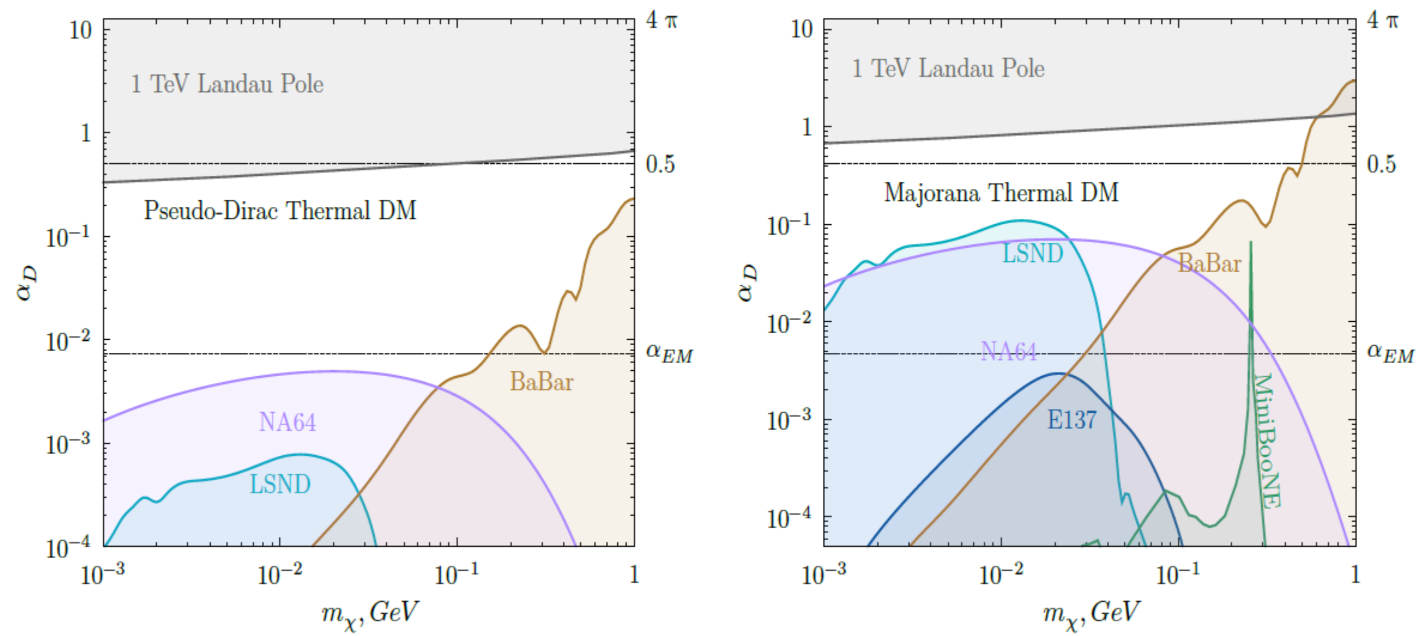


Figure 6: The provisional NA64 constraints in the (α_D;$m_{A'}$) plane on the pseudo-Dirac (the left panel) and Majorana (right panel) type light thermal DM obtained for 2×10^{11} EOT and shown in comparison with bounds from other experiments

Visible decays activity- the check of the ATOMKI experiment

10.

^{8}Be* 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
Institute for Nuclear Research, Hungarian Academy of Sciences (MTA Atomki), P.O. Box 51, H-4001 Debrecen, Hungary

T. J. Ketel
Nikhef National Institute for Subatomic Physics, Science Park 105, 1098 XG Amsterdam, Netherlands

A. Krasznahorkay
CERN, CH-1211 Geneva 23, Switzerland and Institute for Nuclear Research, Hungarian Academy of Sciences (MTA Atomki), P.O. Box 51, H-4001 Debrecen, Hungary
(Received 7 April 2015; published 26 January 2016)

^{7}Li(p, γ)^{8}Be, M_X =16.7 MeV

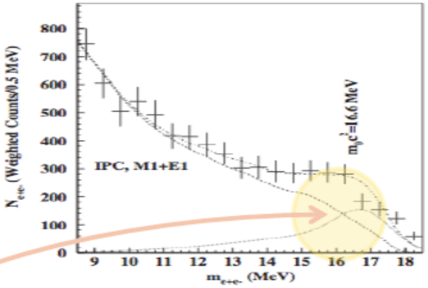
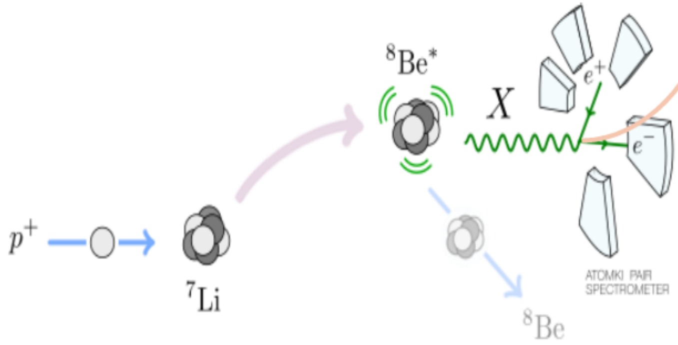
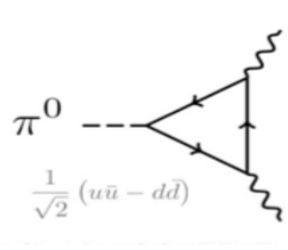


FIG. 5. Invariant mass distribution derived for the 18.15 MeV transition in ^{8}Be.



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



Feng et al, 2016

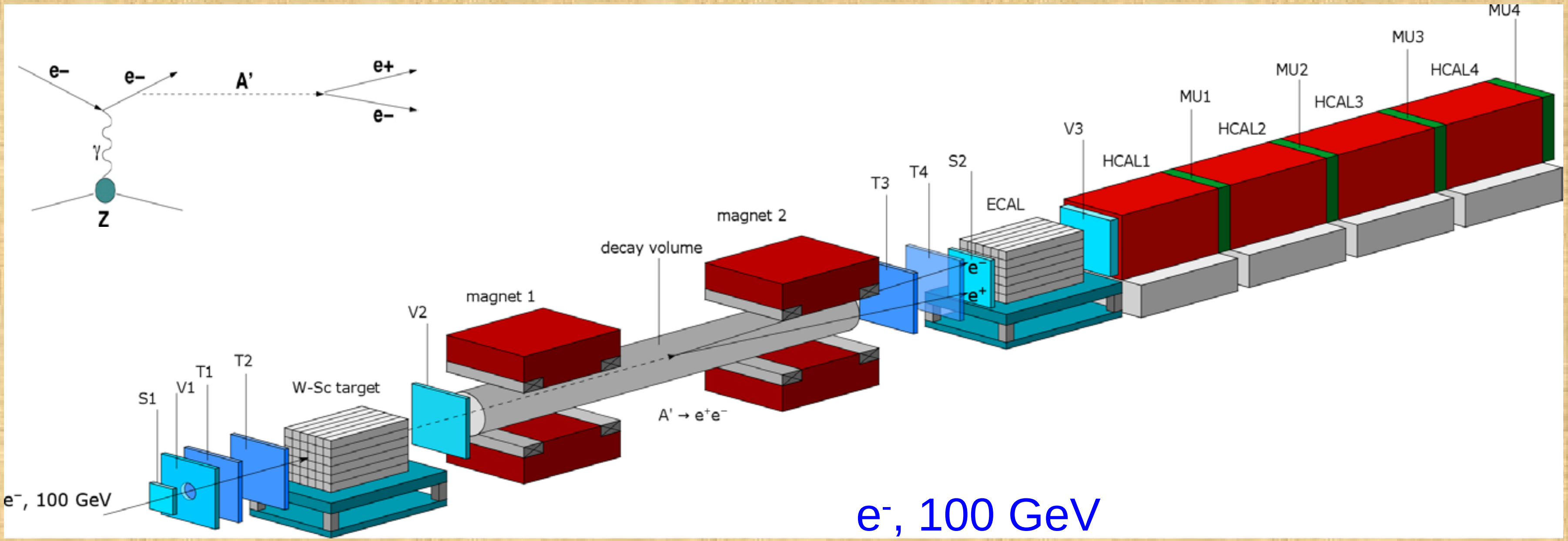
$2\times10^{-4} < \varepsilon_e < 1.4\times10^{-3}$

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

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

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

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



- 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

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)

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

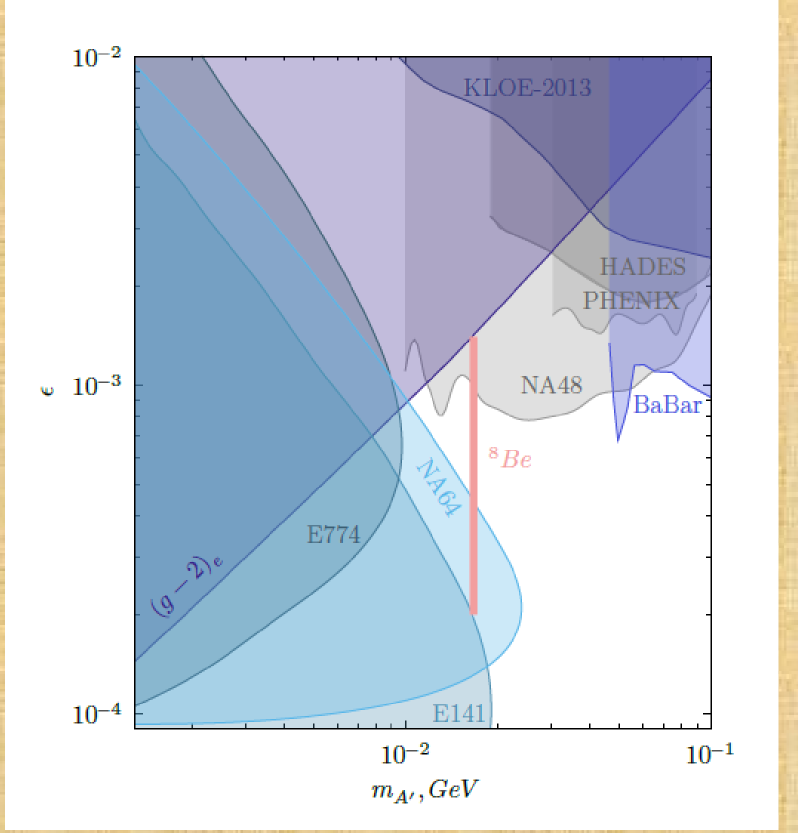
The part of this region is excluded , **namely:**

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

for

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

New NA64 result: arXiv:1803.07748(Phys.Rev.Lett. 2018)



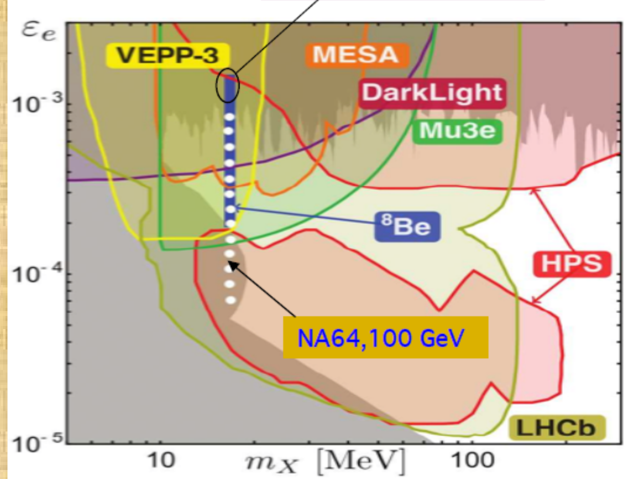
Visible decays activity

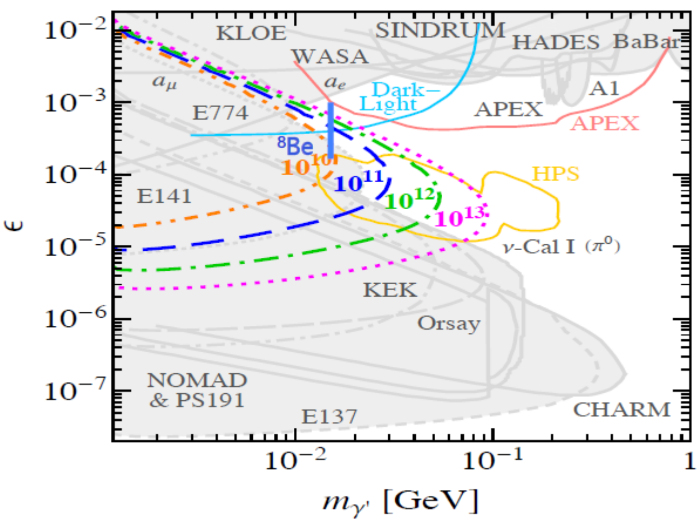
11.

Expected Bounds on X, A´ → e⁺e

Could be covered
by using Si pixels
Under study.

X, A´ → e⁺e⁻





2016 → test run

2017 → ~ 5×10^{10} EOT at 100 GeV. Analysis in progress.

2018 +.. → ~10^{11} EOT at 150 GeV required

S.N. Gninenko – NA64++ report – PBC Workshop, CERN, November 21-22, 2017

The experiment with muon **beam**

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

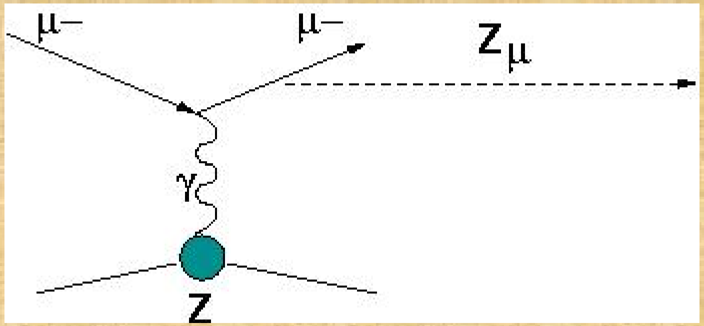
Phys.Rev. D91(2015)095015

Proposal to look for dark photon at collisions of

CERN SPS muon beams

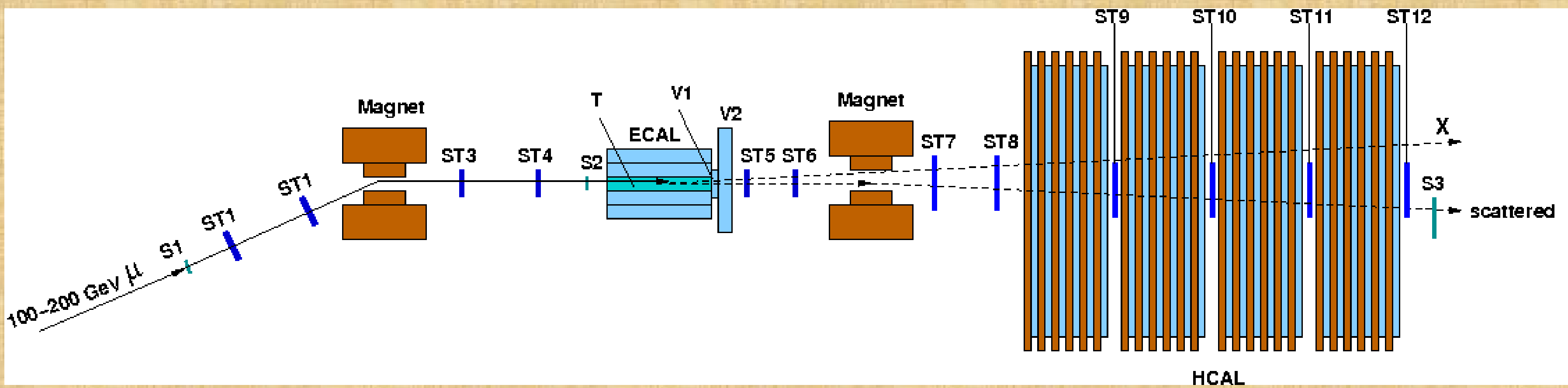
$$\mu(p) + Z(P) \to Z(P') + \mu(p') + Z_\mu(k)$$

The experiment at CERN SPS muon beam



T

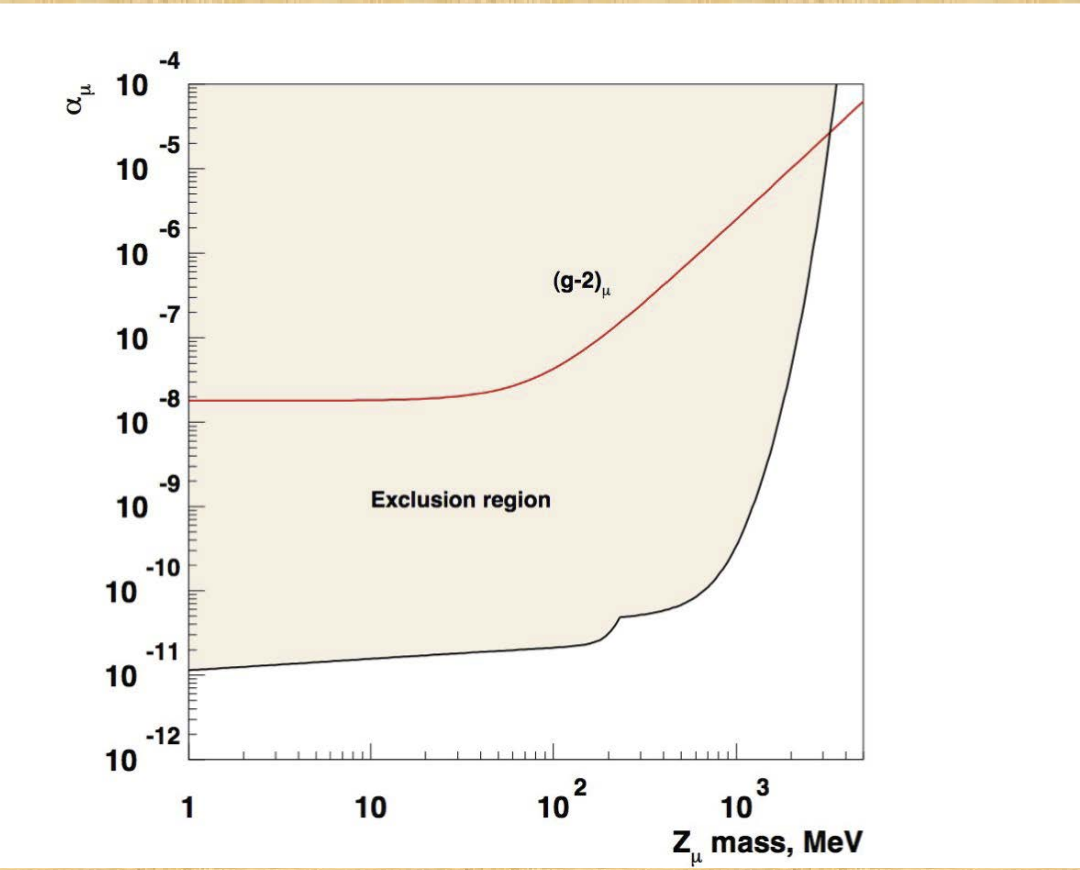
Schematic illustration of the setup to search for dark boson



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

Expected sensitivity for 10^{12} muons on target



Effect of one loop corrections

S.N.Gninenko an N.V.Krasnikov, Phys.Lett. B783, 24 (2018)

$$L_{Z'} = e_\mu Z'_\nu [\bar{\mu}\gamma^\nu \mu - \bar{\tau}\gamma^\nu \tau + \bar{\nu_\mu}\gamma^\nu \nu_\mu - \bar{\nu_\tau}\gamma^\nu \nu_\tau] \quad (1)$$

and it leads to additional contribution to the muon anomalous magnetic moment [44]

$$\delta a = \frac{\alpha_\mu}{2\pi} F(\frac{m_{Z'}}{m_\mu}), \quad (2)$$

where

$$F(x) = \int_0^1 dz \frac{[2z(1-z)^2]}{[(1-z)^2 + x^2 z]} \quad (3)$$

and $\alpha_\mu = \frac{e_\mu^2}{4\pi}$. The use of the formulae (2,3) allows to determine the coupling constant α_μ which explains the value of the $g_\mu - 2$ anomaly [16] - [29] and it does not contradict to existing experimental bounds for $m_{Z'} \leq 2m_\mu$ [29]. Namely, for $m_{Z'} \ll m_\mu$ [44]

$$\alpha_\mu = (1.8 \pm 0.5) \times 10^{-8}. \quad (4)$$

Let us now discuss the mixing between the Z' and ordinary photons. As it has been shown by Holdom [19] an account of one-loop diagrams, which is in our case propagator diagrams with virtual μ- and τ-leptons in the loop, leads to nonzero $\gamma - Z'$ kinetic mixing $\frac{\epsilon}{2} F^{\mu\nu} Z^{\mu\nu}$ where ϵ is the finite mixing strength given by

$$\epsilon = \frac{8}{3} \frac{e e_\mu}{16\pi^2} \ln(\frac{m_\tau}{m_\mu}) = 1.43 \cdot 10^{-2} \cdot e_\mu \, . \qquad (6)$$

$$\epsilon = (6.8 \pm 1.1) \cdot 10^{-6}$$

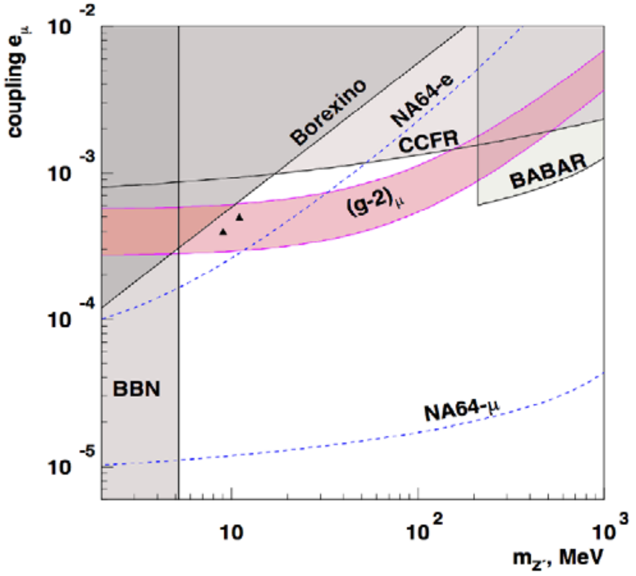


Figure 1: The NA64 90% C.L. expected exclusion regions in the $(m_{Z'}, e_\mu)$ plane (dashed curves) from the measurements with the election (NA64-e, $\simeq 5 \times 10^{12}$ EOT) [41, 42, 46] and muon (NA64-μ, $\simeq 10^{12}$ MOT) [45] beams. Constraints from the BOREXINO [36], CCFR [40], and BABAR [38] experiments, as well as the BBN excluded area [36, 47] are also shown. Two triangles indicate reference points corresponding to the mass $m_{Z'} = 9$ and 11 MeV, and coupling $e_\mu = 4 \times 10^{-4}$ and 5×10^{-4}, respectively, which are used to explain the IceCube results, see Ref.[36] for details.

Let us now show that an extension of the $L_\mu - L_\tau$ model is able to explain today DM density in the Universe. Indeed, let us consider the simplest SM extension with an additional complex scalar field[1] ϕ_d. The charged dark matter field ϕ_d interaction with the Z' field is

$$L_{\phi Z'} = (\partial^\mu \phi - i e_d Z'^\mu \phi)^* (\partial_\mu \phi - i e_d Z'_\mu \phi) - m_{DM}^2 \phi^* \phi - \lambda_\phi (\phi^* \phi)^2 \quad (8)$$

The annihilation cross section $\phi_d \bar{\phi}_d \to \nu_\mu \bar{\nu}_\mu, \nu_\tau \bar{\nu}_\tau$ for $s \approx 4m_{DM}^2$ has the form[2]

$$\sigma v_{rel} = \frac{8\pi}{3} \frac{\epsilon^2 \alpha \alpha_d m_{DM}^2 v_{rel}^2}{(m_{Z'}^2 - 4m_{DM}^2)^2}, \quad (9)$$

For the case where dark matter consists of dark matter particles and dark matter antiparticles the $DM\bar{DM} \to SM\ particles$ annihilation cross sestion $\sigma_{an} = \frac{\sigma}{2}$. Numerically we find that

$$k(m_{DM}) \cdot 10^{-6} \cdot (\frac{m_{DM}}{GeV})^2 \cdot (\frac{m^2_{A'}}{m^2_{DM}} - 4)^2 = \epsilon^2 \alpha_D \,. \quad (13)$$

Here the coefficient $k(m_{DM})$ depends logarithmically on the dark matter mass m_{DM} and $k_{DM} \approx 0.5(0.9)$ for $m_{DM} = 1(100)\ MeV$. For instance, for $m_{A'} = 2.2\ m_d$ we have

$$0.71k(m_{DM}) \cdot 10^{-6} \cdot (\frac{m_{DM}}{1\ \text{GeV}})^2 = \epsilon^2 \alpha_d \,. \quad (14)$$

As a consequence of (14) we find that for $m_{Z'} \ll m_\mu$ the values $\epsilon^2 = (2.5 \pm 0.7) \cdot 10^{-6}$ and

$$\alpha_d = (0.28 \pm 0.1) k(m_{DM}) \cdot (\frac{m_{DM}}{1 \text{ GeV}})^2 \tag{15}$$

explain both the $g_\mu - 2$ muon anomaly and today DM density. We can rewrite the equation (15) in the form

$$\frac{e_d^2}{e_\mu^2} = (16 \pm 5) k(m_{DM}) \cdot (\frac{m_{DM}}{1 \text{ MeV}})^2 \, . \tag{16}$$

So we see that for $m_{DM} \geq 1$ MeV we have $e_d \gg e_\mu$, i.e.the Z' must interact much more strongly with light DM than with the SM matter.

4.Conclusions

Light dark matter?

To be or not to be?

That's the question!

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

Thank You for your attention.

BACKUP

APEX(A-prime experiment) (1108.2750) 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

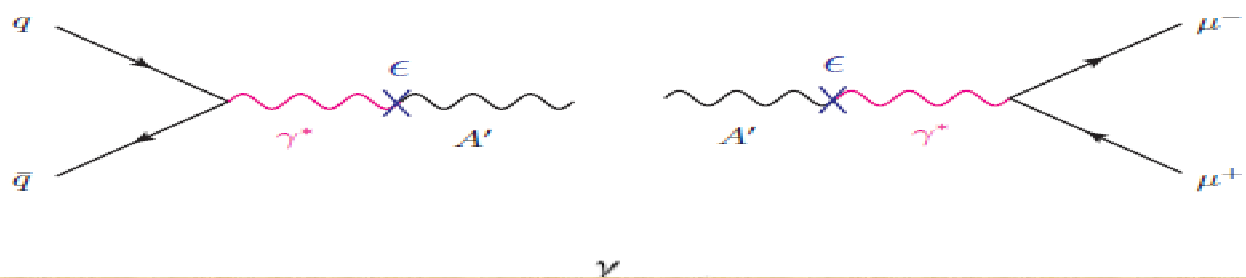
DarkLight at Jlab (1412.4717)

Both visible and invisible decays using the reaction pp $\rightarrow ppA'$, $A' \rightarrow e^+e^-$ - all visible final states momenta restoration

LERF accelerator with E_e ~170 MeV with high intensity electron beam

$\varepsilon^2 \gtrsim 10^{-6}$ for $10 < m_{A'} < 80$ MeV (>2020)

SeaQuest(FNAL,USA) prompt and displaced muon decay mode search



Visible dark photon decay searches at the muon spectrometer at the 120 GeV Main injector beamline at FNAL

$\varepsilon^2 \gtrsim 10^{-8}$ for $2m_\mu < m_{A'} < 9$ GeV (prompt decays)

$\varepsilon^2 \gtrsim 10^{-14}$ --- 10^{-8}

for $m_{A'} < 2$ GeV (displaced decays)

The knowledge of dark matter density leads to prediction for the annihilation cross section

The approximate solution of the Boltzmann equation can be represented in the form [20]

$$\Omega_d h^2 = 8.76 \times 10^{-11} GeV^{-2} [\int_{T_0}^{T_d} (g_*^{1/2} < \sigma v_{rel} >) \frac{dT}{m_d}]^{-1} \quad (27)$$

The ratio of dark particle mass m_d and freeze-out temperature T_d depends logarithmically on the m_d, $< \sigma v_{rel} >$, T_d, namely [21]

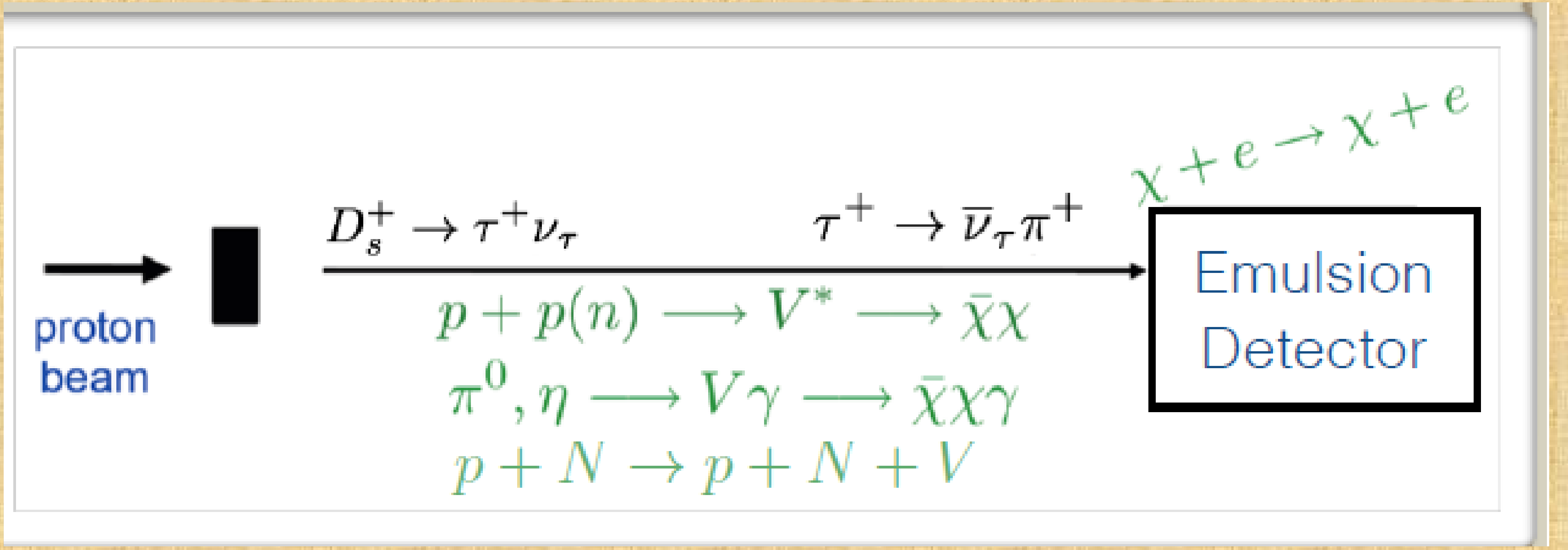
$$\frac{m_d}{T_d} \approx 17 + ln(< \sigma v_{rel} > /10^{-26} cm^3\ s^{-1}) + ln(m_d/GeV) + ln(\sqrt{m_d/T_d})\,. \quad (28)$$

Numerically $\frac{m_d}{T_d} \sim (12 - 20)$ and $g_*^{1/2} \approx 3.8$ for $10\ MeV < T_d < 100\ MeV$ [20]. Today dark matter density $\frac{\rho_d}{\rho_c} \approx 0.23$ [22] leads to the estimate[3]

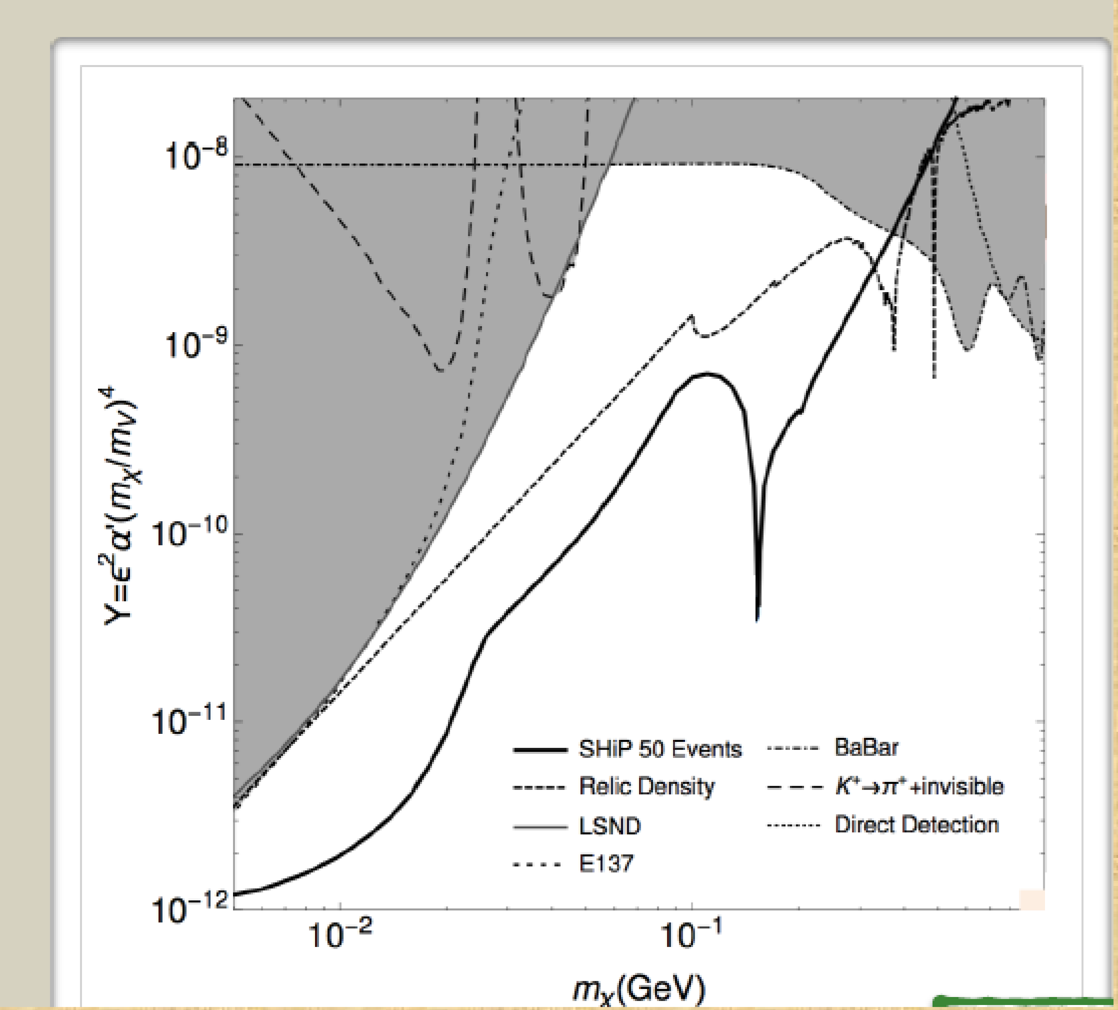
$$< \sigma_{an}(\psi_d \bar{\psi}_d \to f \bar{f}) v_{rel} > / < v_{rel}^2 >= 4.4 k_\psi \cdot 10^{-8}\ GeV^{-2}\,. \quad (29)$$

INVISIBLE DECAYS

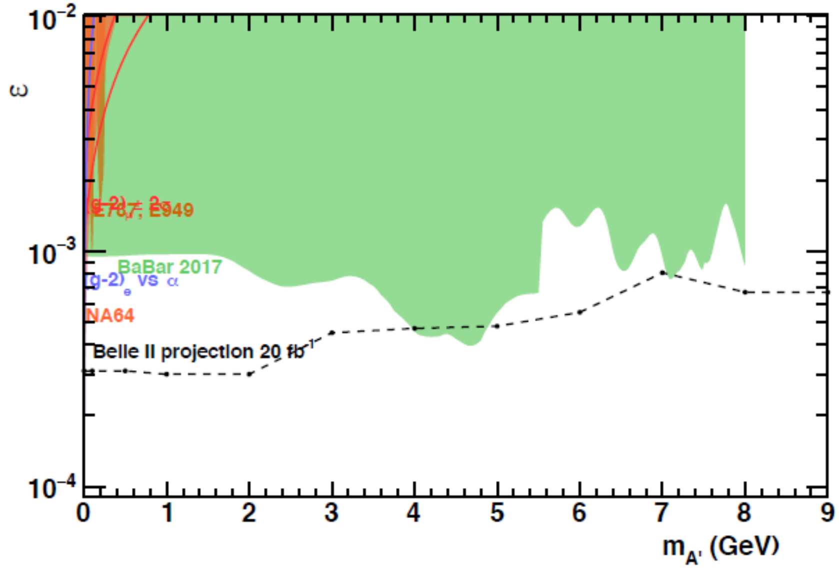
SHiP experiment can also search for invisible decays



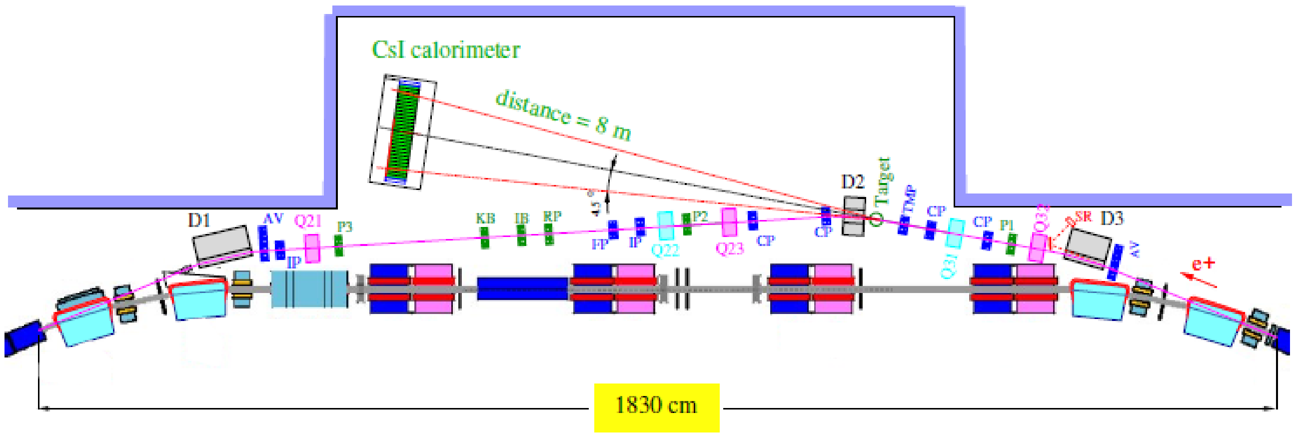
Expected SHiP sensitivity to invisible decays



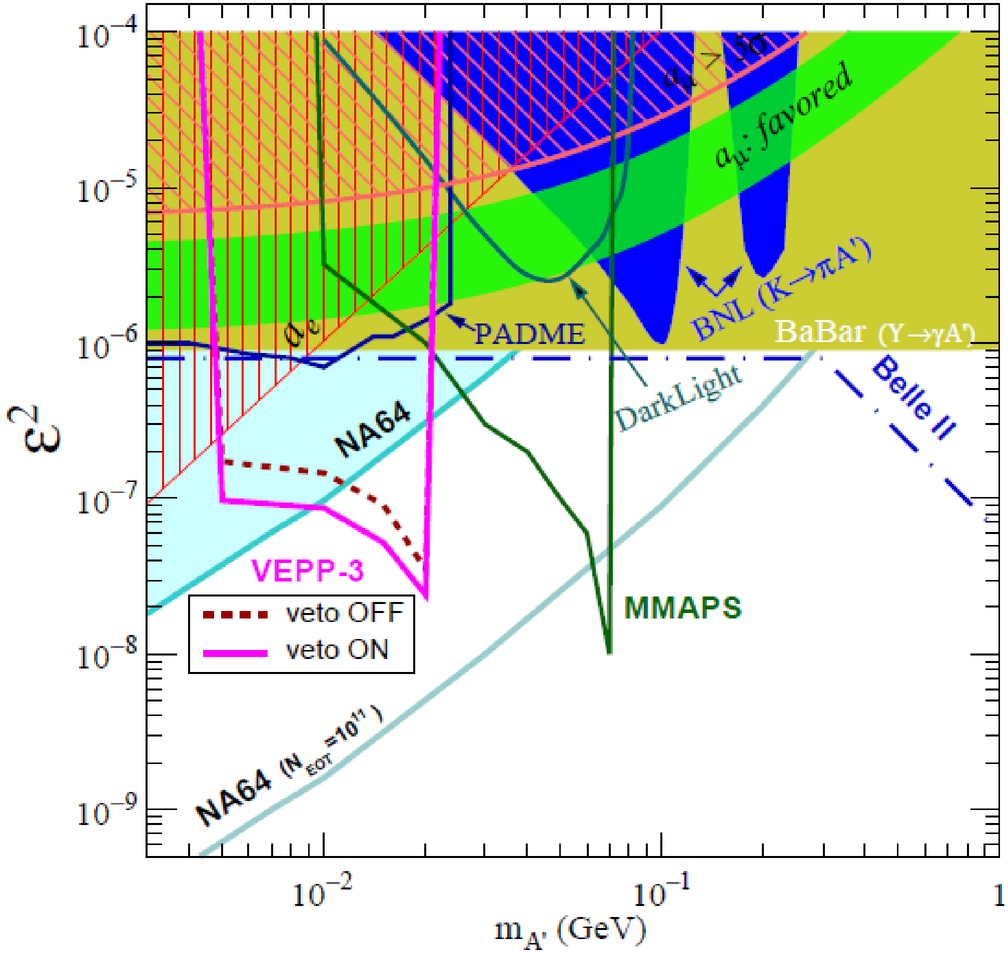
Projected Belle II exclusion region, 20 fb^{-1}



VEPP-3 LAYOUT

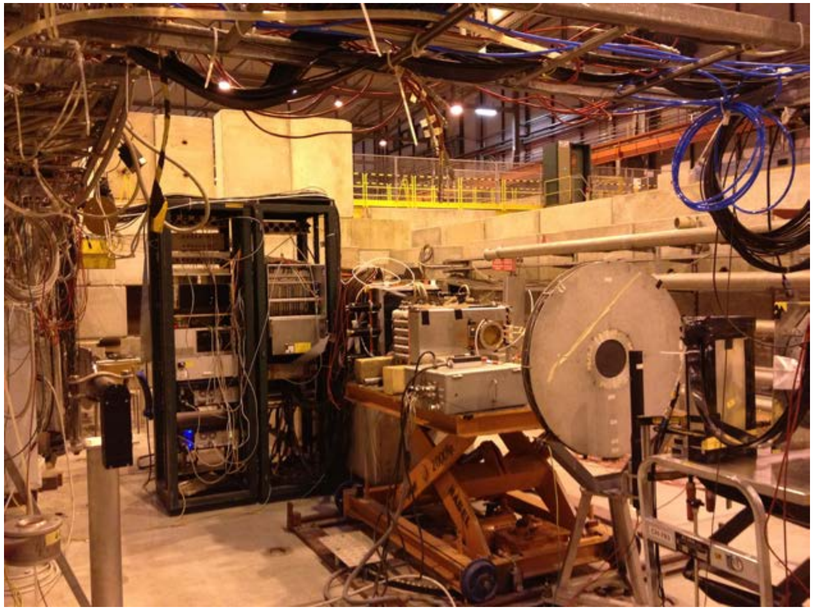


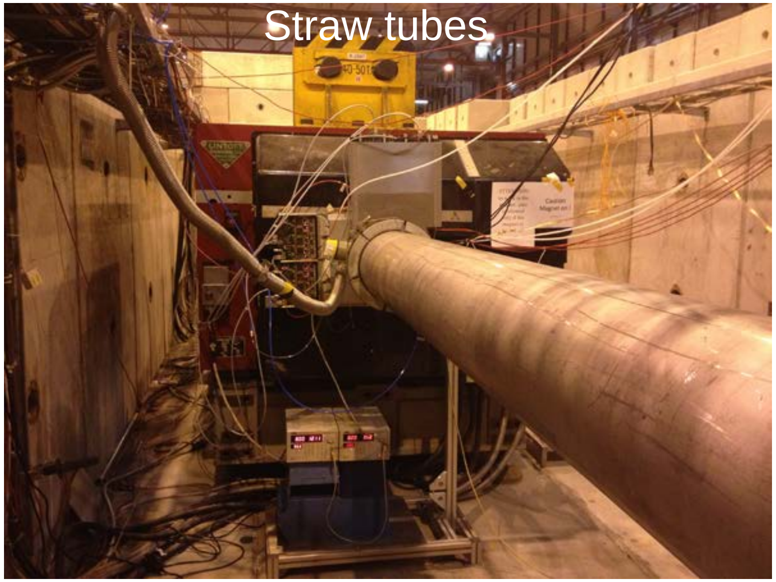
VEPP-3 PROJECTED SENSITIVITY




GOLIATH

BGOs, Micromegas, straws, hodoscopes, …





Background estimates

Background estimates

Source	Expected level	Comment
Beam contamination		
- π , p, μ reactions and punchthroughs,... - e^- low energy tail due to bremss., π , μ -decays in flight...	$< 10^{-13}$-10^{-12} $< 10^{-12}$	Impurity < 1% high precision MM tracker + e^- SR photon tag
Detector		
ECAL+HCAL energy resolution, transverse hermeticity, holes, dead material, cracks...	$<10^{-13}$	Full upstream coverage
Physical		
- hadron electroproduction, e.g. $e^-A \to e^-A^* + n,\pi,\rho,J/\psi$ – - n punchthrough, μ inefficiency - WI process: $e^- Z \to e^- Z\nu\nu$	$< 10^{-13}$ $< 10^{-13}$	HERA ep-data (H1 Collaboration) WI σ estimated.
Total	$< 10^{-12}$	

Limits on A' parameters

Average number of A' from Poisson distribution:

$$N_{A'} = n_{eot} \cdot n_{A'}(\epsilon, m_{A'}, \Delta E_{A'}) \cdot \varepsilon_{A'}(m_{A'}, \Delta E_{A'})$$

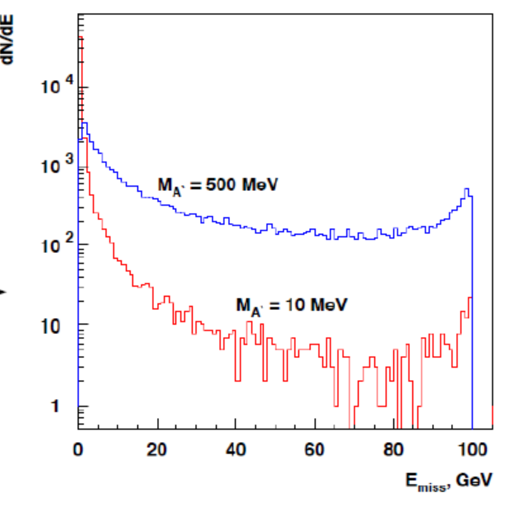
- A' yield depends on coupling, mass and missing energy
- Signal selection efficiency slightly depends on mass and Energy

$$N_{A'} = n_{eot} \cdot \frac{\rho N_A}{A_{Pb}} \cdot \varepsilon_{A'} \cdot \int \frac{d\,n}{d\,E_{A'}} d\,E_{A'}$$

With signal selection efficiency:

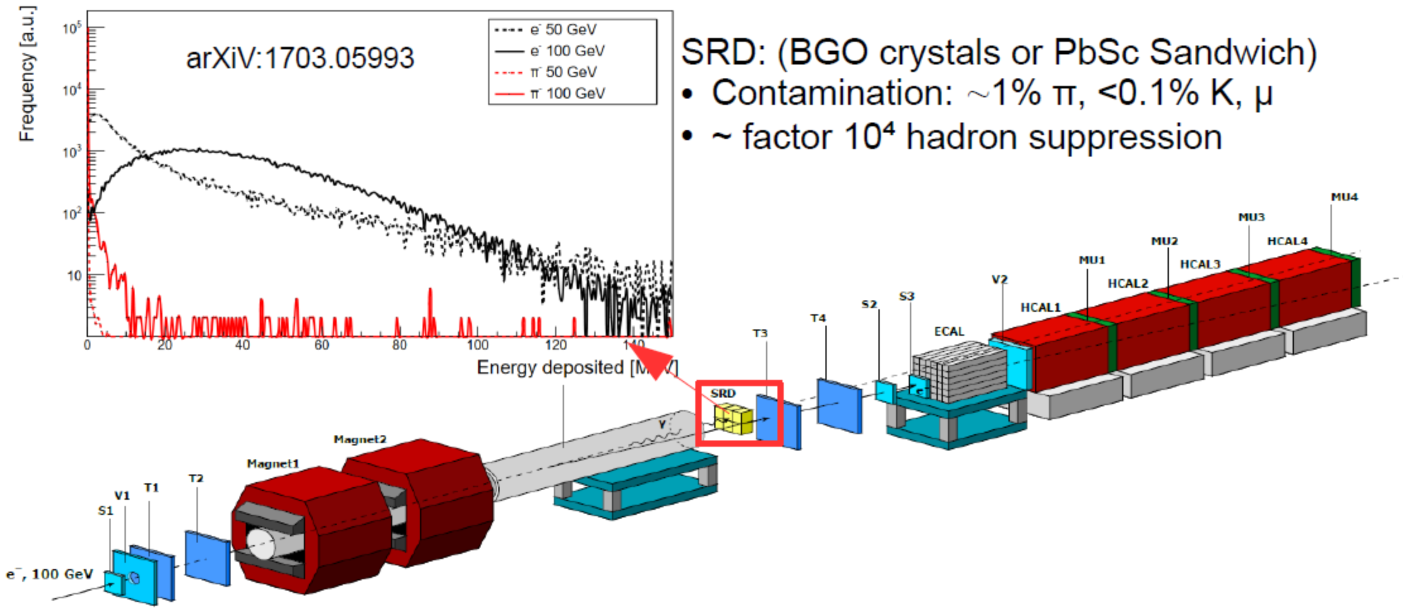
$$(0.69 \pm 0.09) \leq \varepsilon_{A'} \leq (0.55 \pm 0.07)$$

And yield predictions from MC →



$$N_{A'} = \frac{k \cdot n_{eot}}{10^{12}} \left(\frac{\epsilon}{10^{-5}}\right)^2 \left(\frac{10\,\text{MeV}}{M_{A'}}\right)^2$$

Background suppression



SRD: (BGO crystals or PbSc Sandwich)

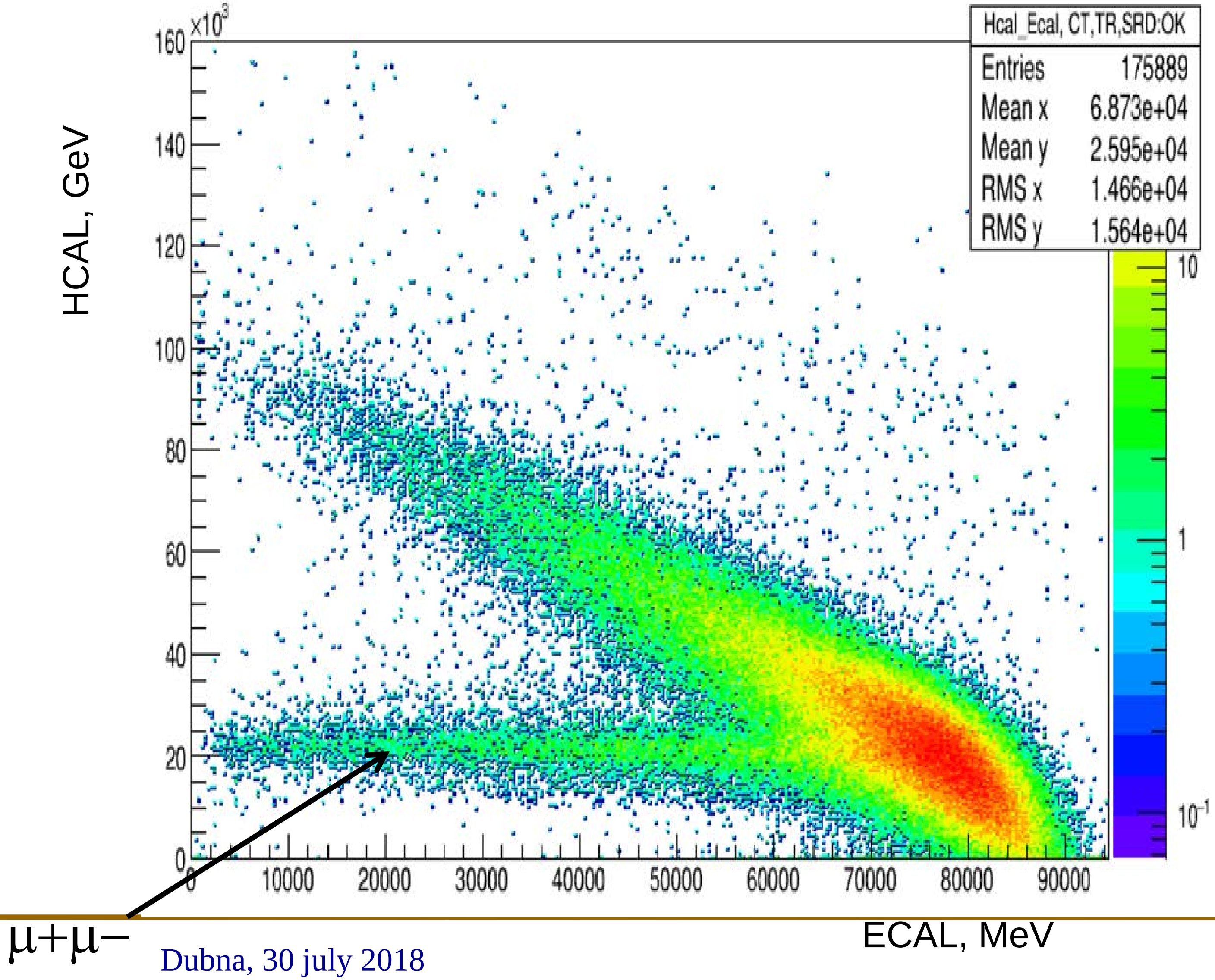
- Contamination: ~1% π, <0.1% K, μ
- ~ factor 10^4 hadron suppression

Requirements to the beam:

- Highest possible intensity (~5×10^6 e/spill of ~4.8 s)
- Lowest possible hadron/muon contamination
- Smallest possible low energy tails

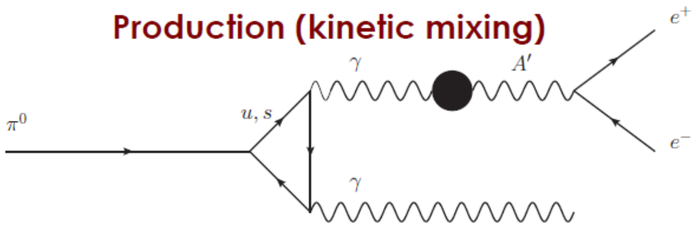
Dimuon production in the ECAL target by 100 GeV e-

Nice benchmark process similar to A´ production



Dark photon in π^0 decays

Production (kinetic mixing)

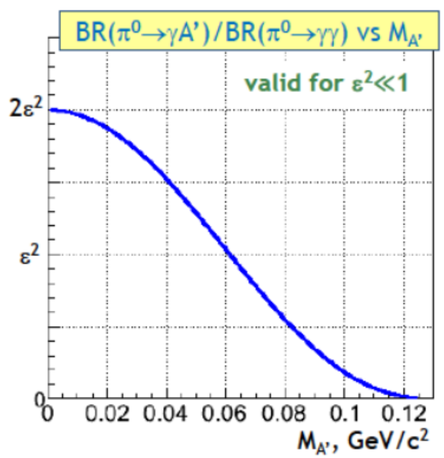


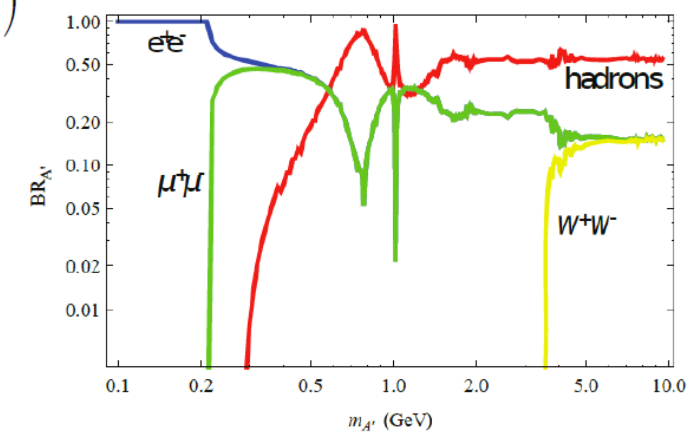
Decay (if no light dark sector)

$$\Gamma(A' \to e^+e^-) = \frac{\alpha}{3}\varepsilon^2 M_{A'}\sqrt{1-\frac{4m_e^2}{M_{A'}^2}}\left(1+\frac{2m_e^2}{M_{A'}^2}\right)$$

$$\frac{BR(\pi^0 \to \gamma A')}{BR(\pi^0 \to \gamma\gamma)} \approx 2\varepsilon^2 |F(M_{A'}^2)|^2 \left(1-\frac{M_{A'}^2}{M_\pi^2}\right)^3$$

Batell, Pospelov and Ritz, PHYS. REV. D 80, 095024 (2009)





$M_{A'} < M_{\pi 0}$ and no lighter wrt A' dark sector particles exist BR(A'→e^+e^-)=1

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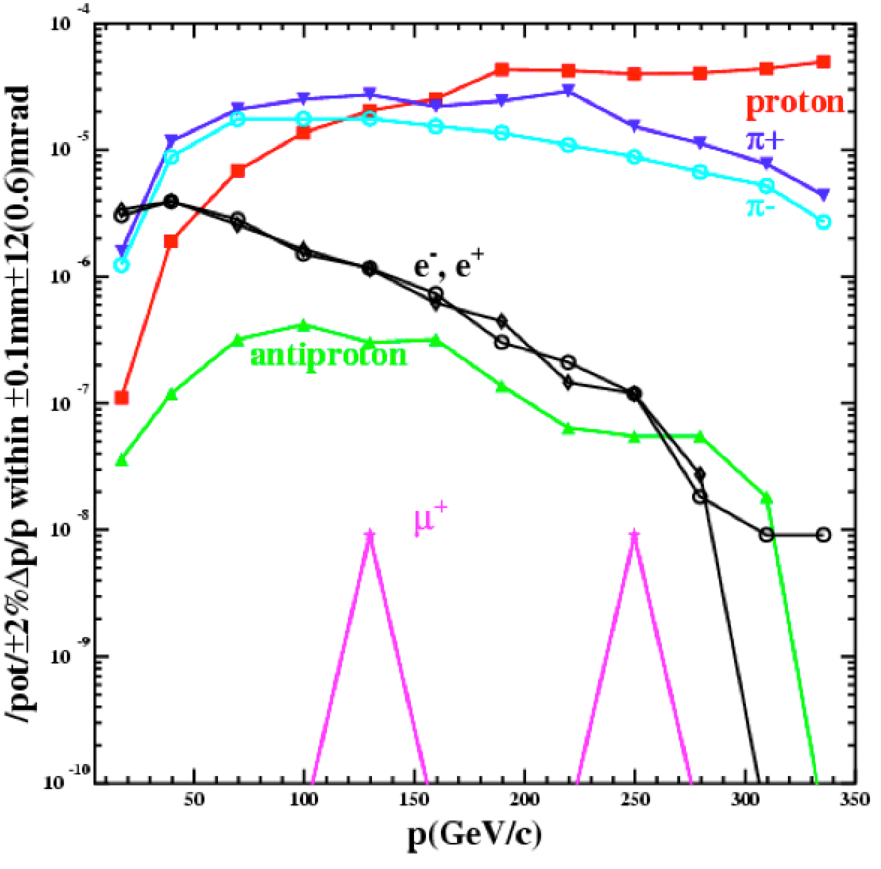
SPS e- beams

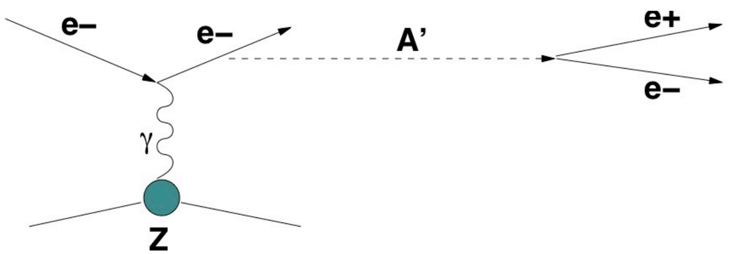


- H4, I_{max}~ 50 GeV e-
- 10^{12} pot per SPS spill,
- ~ $5x10^6$ e- per spill
- duty cycle is 0.25
- ~10^{12} e- / month

  additional tunning by

  a factor 2-3 ?
- beam spot ~ cm^2
- beam purity < 1 %

MeV A` production and decay



bremsstrahlung A`

- e Z->e Z A`cross section $\sigma_{A`} \sim \varepsilon^2 (m_e/M_{A`})^2 \sigma_\gamma$; Bjorken'09, Andreas'12
- decay rate $\Gamma(A` \to e^+e^-) \sim \alpha\varepsilon^2 M_{A`}/3$ is dominant for $M_{A`} < 2\, m_\mu$
- sensitivity $\sim\varepsilon^4$ for long-lived A`, typical for beam dump searches

For $10^{-5} < \varepsilon < 10^{-3}$, $M_{A`} < \sim 100$ MeV

- very short-lived A`: $10^{-14} < \tau_{A`} < 10^{-10}$ s
- very rare events: $\sigma_{A`}/\sigma_\gamma < 10^{-13}$-$10^{-9}$
- A`energy boost to displace decay vertex,

  $\varepsilon \sim 10^{-4}$, $M_{A`} \sim 50$ MeV, $E_{A`} \sim 100$ GeV, $L_d \sim 1$ m
- background suppression