Поиск легкой темной материи в эксперименте NA64

С.Н. Гниненко
ИЯИ

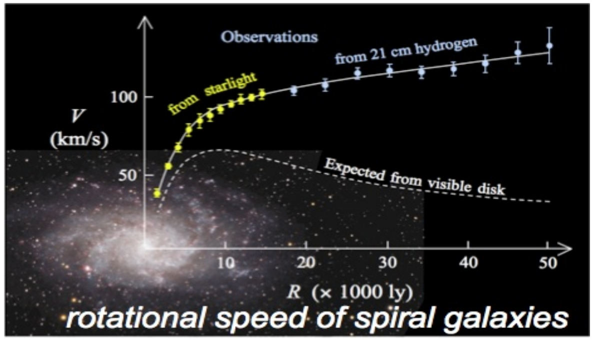
- Introduction.
- NA64e: 50-150 GeV e±
- NA64μ: 100-160 GeV μ-
- NA64h : 50 -200 GeV π-, K-, p
- Summary

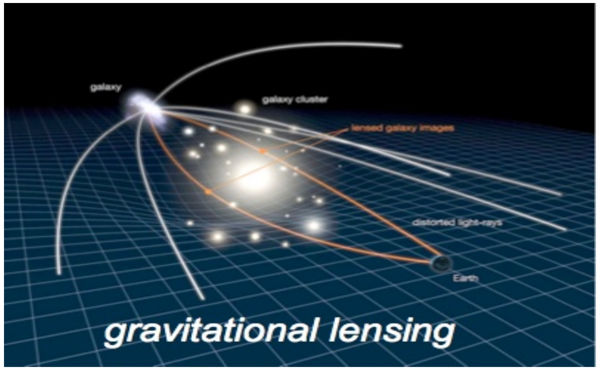
NA64e reserch program and recent results

- Thermal sub-GeV Dark Matter (LDM)
- axions, ALP, S → γ γ decays
- S, P, V, and A dark portal particles, their invisible, visible, semi-visible decays
- Light **B-L** Z′
- ATOMKI anomaly: X17 (P, V, A′) → e+e- decays
- MilliQ particles, etc…

Evidence for DM

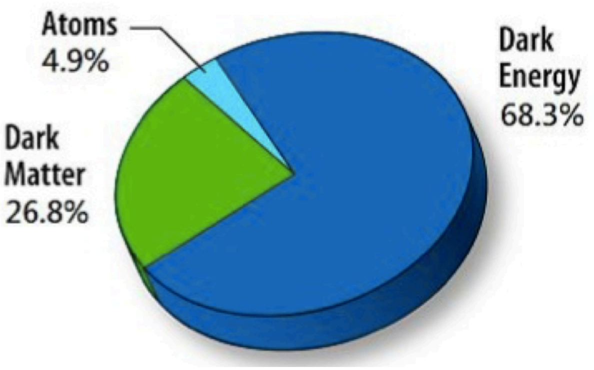
- Rotational curves of galaxies
- Galaxies in clusters
- Lensing
- CMB
- BBN



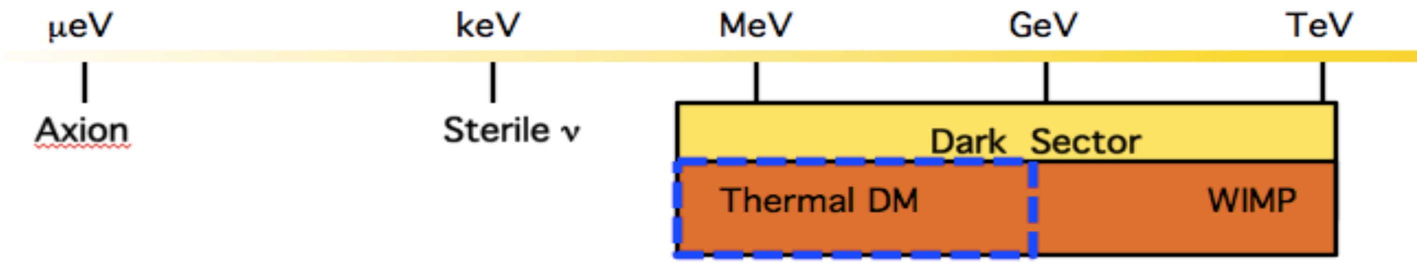


- Dark – doesn't couple to γ
- Cold/Warm – $v < c$
- Collisionless – $n_\chi \sigma v \tau \sim 1$
- Dark matter relic density

  $\rho_{DM} \sim 0.25\ \rho_C \sim\ 10^{-6}$ GeV /cm^3



Dark Sector



WIMPs (χ) $\rho_\chi \sim 1/\langle\sigma v\rangle \sim m^2_\chi / g^4_\chi$; $(m_\chi, g_\chi) \sim (m_{EW}, g_{EW})$ (WIMP miracle) are not seen at LHC and in direct searches.

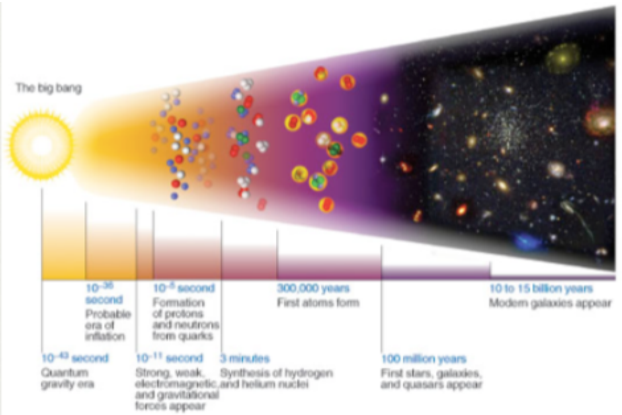
$\rho_{DM} \sim 0.3$ GeV /cm^3 in Solar system =>

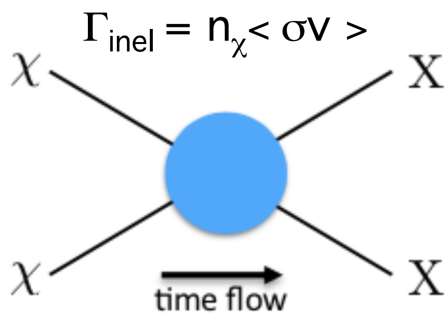
n_{WIMP} (~1 TeV) ~ $10^3/m^3$, a very low counting rate.

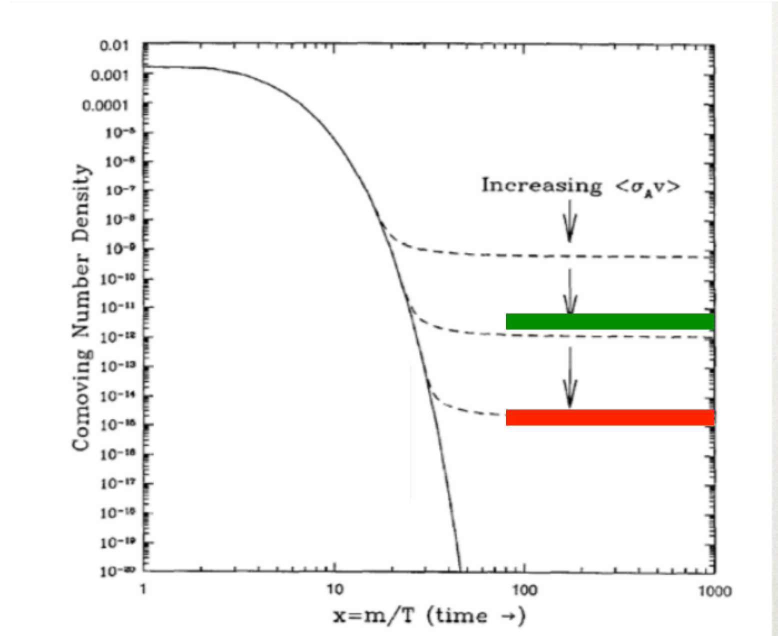
Dark Matter (DM) from a Dark Sector (DS)

- DM is a part of DS
- DS consists of particles and fields which are singlet with respect to the SM gauge group, could be charged e.g. under a new U(1)΄ gauge symmetry
- interacts with the SM via gravity and a new week interaction

Light Thermal Dark Matter ($m_\chi << 100$ GeV)







In this class of models:

- For $T >> m_\chi$, χχ-SM ann. is in equilibrium, $n_\chi \sim T^3$
- Hubble expansion, T & n_χ decrease
- For $T < m_\chi$ χχ-SM annihilation gets suppressed, $n_\chi \sim T^{3/2} e^{-m_\chi/T}$
- Finally χχ-SM annih. stops when $\Gamma_{inel} = n_\chi < \sigma v > < \sim H$, $n_\chi \sim$ frozen in time
- $\rho_\chi \sim 1/<\sigma v> \sim m^2_\chi / g^4_\chi$; $< \sigma v > \cong 3 \times 10^{-26}$ cm^3/s $\cong$ (1/20 TeV)^2
- Thermal freeze-out motivate new interaction to mediate DM-SM annihilation.

  New force in addition to gravity is required!

The SM Portals to Dark Sectors

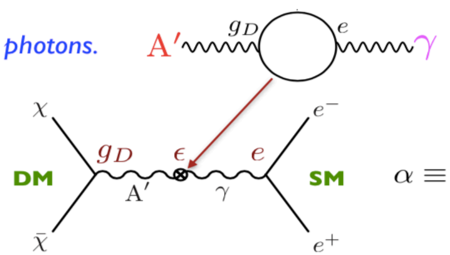
Several general extensions of the Standard Model (SM):

- Vector portal → Dark Photons (A')
- Scalar portal → Dark Scalars
- Neutrino portal → Heavy Neutral Leptons
- Axion portal → Axion-like particles

Vector portal to Dark Sector

Benchmark scenario: dark photons.

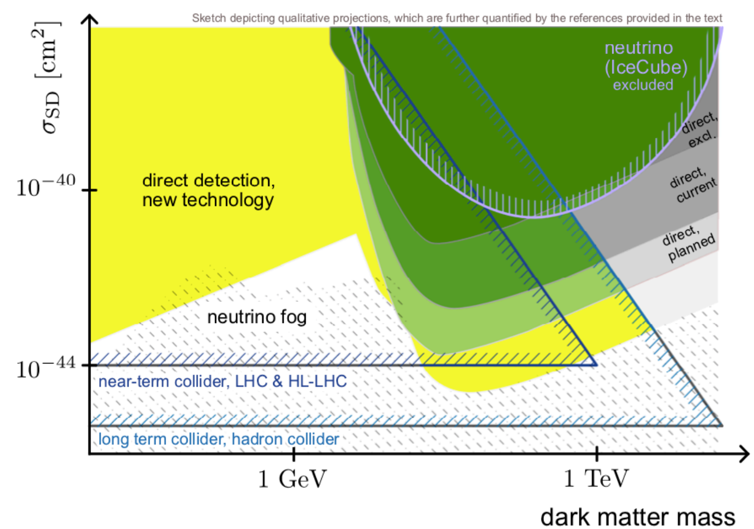
$\alpha_D \equiv \frac{g_D^2}{4\pi}$



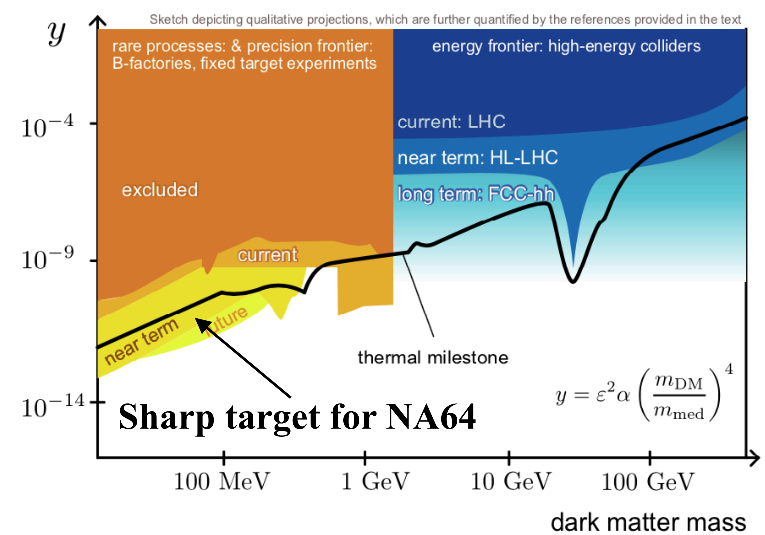
$\alpha \equiv \frac{e^2}{4\pi}$

- massive V, dark photon (A´)
- γ–A´ kinetic mixing: $\Delta L = \varepsilon/2\, F^{\mu\nu} A'_{\mu\nu}$
- coupling strength ~ εe
- $\varepsilon \sim 10^{-5}$ - 10^{-2}, $m_{A'} \sim \varepsilon^{1/2} M_Z$
- A´ decay modes:
  $m_{A'} < 2m_\chi$, $A' \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-$
  $m_{A'} > 2m_\chi$, $A' \to \chi\chi$
- popular DM candidates χ :
  S, Majorana, p-Dirac fermions
- TDM $(\varepsilon, \alpha_D, m_\chi, m_A)$ parameters can be probed at accelerators
- Useful variable to compare sensitivity χ–SM annihilation:
  $n_\chi < \sigma v > \approx [\alpha_D\, \varepsilon^2 (m_\chi/m_{A'})^4]\alpha/m_\chi^2 = y\, \alpha/m_\chi^2$

TDM targets for DM-e Scattering

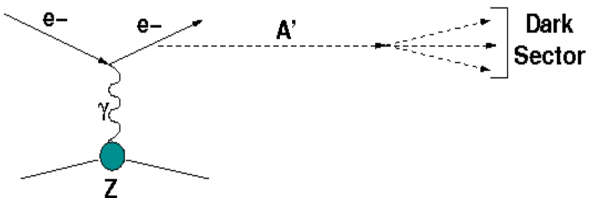


TDM targets for accelerator experiments

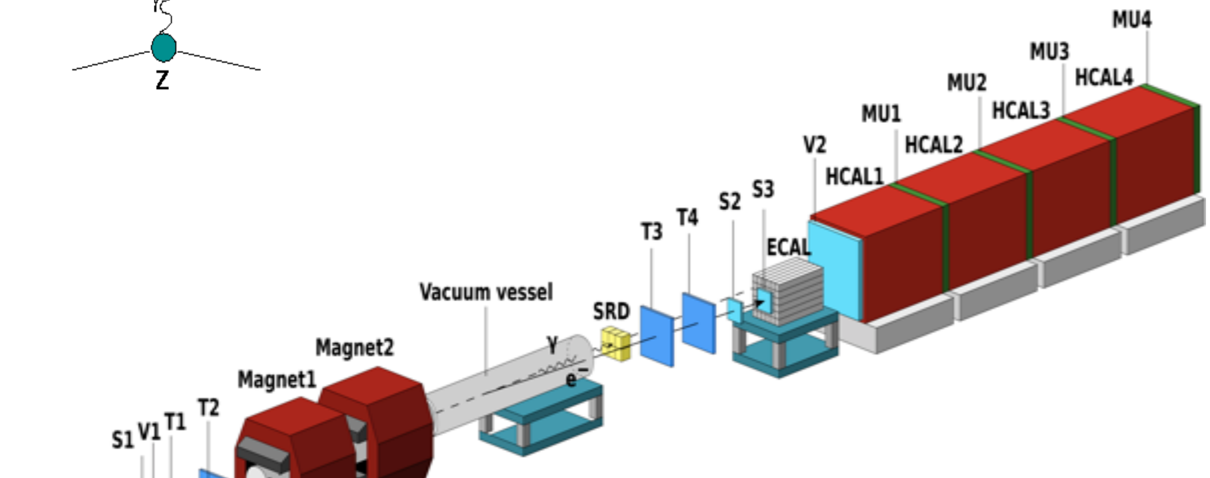


Na64e approach

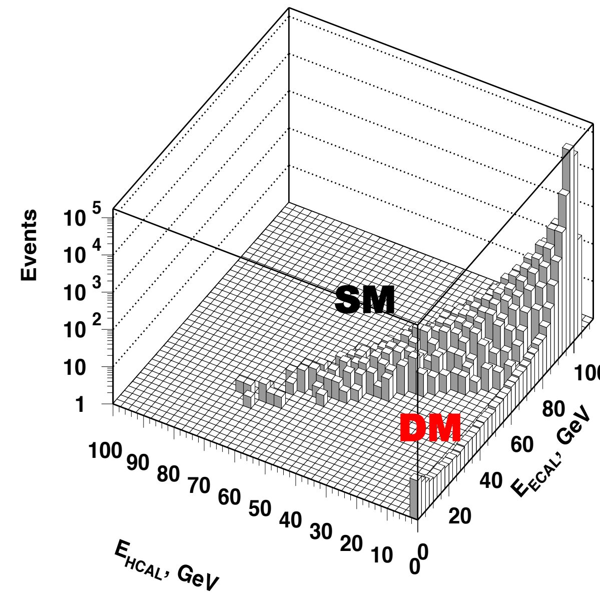
LDM produced in invisible decays of A´ mediator (recall Z)



$\sigma \sim \varepsilon^2 Z^2/m_{A'}^2$, $\Theta_{A'} \sim (m_{A'}/E_0)^{3/2}$, $\Theta_e \sim (m_{A'}/E_0)^{1/2}$



Required SES < 10^{-12}/EOT



Main components :

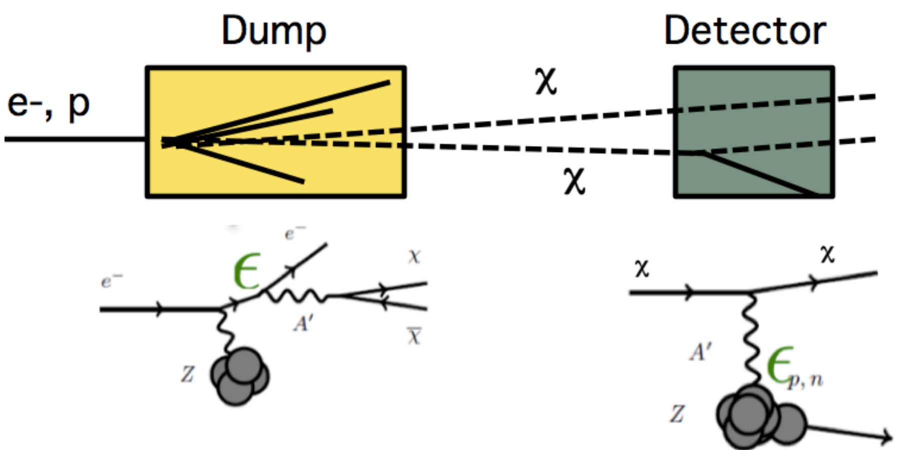
- clean 100 GeV e- beam
- e- tag: M-spectrometer+SRD
- fully hermetic ECAL+HCAL

Signature:

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

NA64 method vs beam-dump approach to probe LDM.

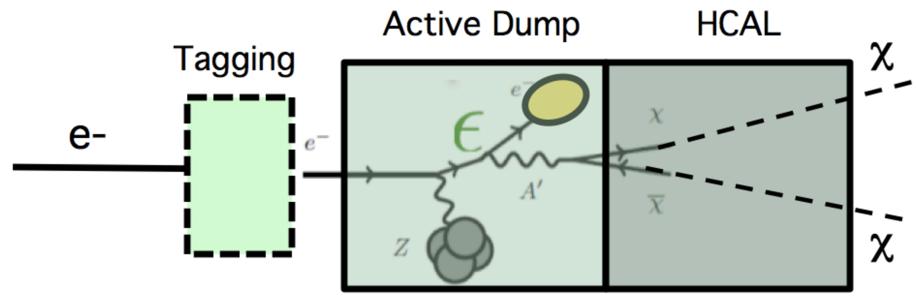
Beam-dump approach: Signal of χ scattering



Sensitivity

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

Active beam-dump+Missing energy



Sensitivity

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

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

Source of LDM (χ) any source of γ

- Bremsstrahlung $e^- Z \rightarrow e^- Z A'$; $A' \to \chi\chi$
- Meson decays π^0, η, η' … $\to \gamma A'$, $A' \to \chi\chi$, ee, μμ, ..

CERN RB (2019): NA64e permanent location at H4 after LS2

NA64 experiment in brief

Collaboration: ~50 participants; Univ. of Bonn (Bonn), JINR(Dubna), INFN (Genova), LPI, INR, SINP MSU (Moscow), IHEP (Protvino), TPU(Tomsk), SAPHIR(Chile), IFIC(Valencia), ETH(Zurich)+

Theory Collaboration: INR, SAPHIR, TPU, IFIC, INFN,

- Proposed as P348 in 2014
- Feasibility run in 2015
- Approved in March 2016.
- Proposal to run with M2 muon beam (NA64μ) in 2019.
- Runs taken

  2016 – 5 w at H4 (NA64e)

  2017 – 5 w at H4 (NA64e)

  2018 – 6 w at H4 (NA64e)

  2021 – 5 w at H4 (NA64e); 3 w pilot-run at M2 (NA64μ)

  2022 –10 w at H4 (NA64e, NA64h); 3 w pilot-run at M2 (NA64μ)
- Active member of PBC /FIPs since the beginning

DMG4 package (*Comput.Phys.Commun.* (2021))

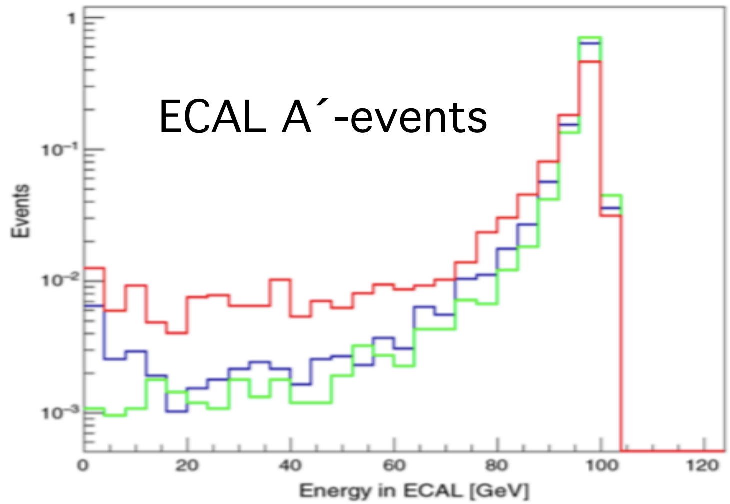
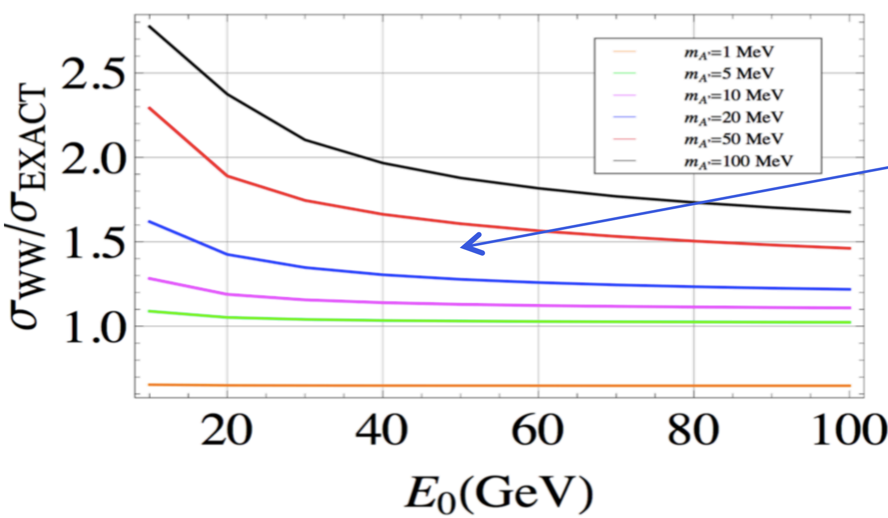


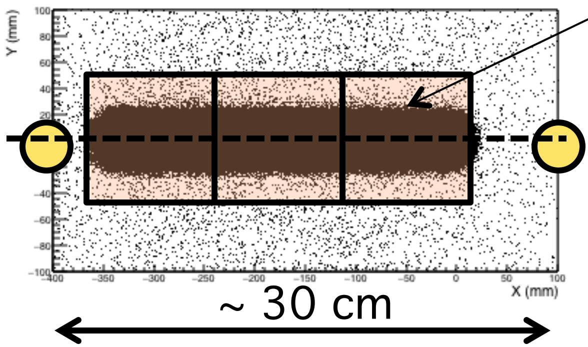
FIG. 6. The MC distributions of energy deposited in the ECAL target from the reaction $eZ \to eZA'$ induced by 100 GeV e^-s and accompanied by the emission of the bremsstrahlung A's with the mass 2 (green), 20(blue) and 200 (red) MeV.



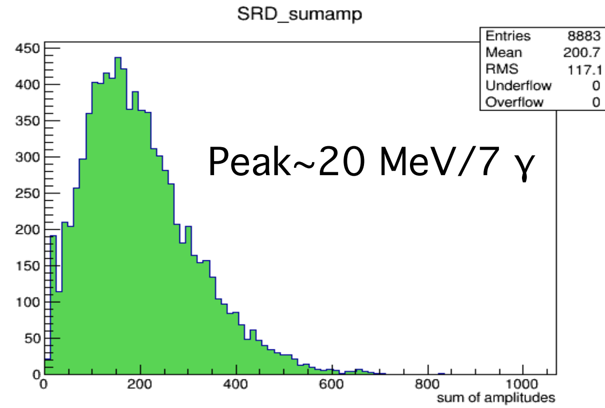
- Fully Geant4 compatible package for the simulation of Dark Matter in fixed target experiments DMG4 pakage
- **DMG4** is used for A´, ALP, S, A, V emission in theprocess of e-m shower development
- WW approximation for $\sigma(e^-Z\text{->}e^-ZA')$ (Bjorken et al.'09)
- Corrections (k-factors) to WW from exact tree-level (ETL) calculations: large for higher A´masses
- The shape of WW and ETL differential cross sections is quite similar: peaked at $x= E_{A'}/E_0 \sim 1$.
- Strong reduction for $m_{A'} >\sim m_\mu$

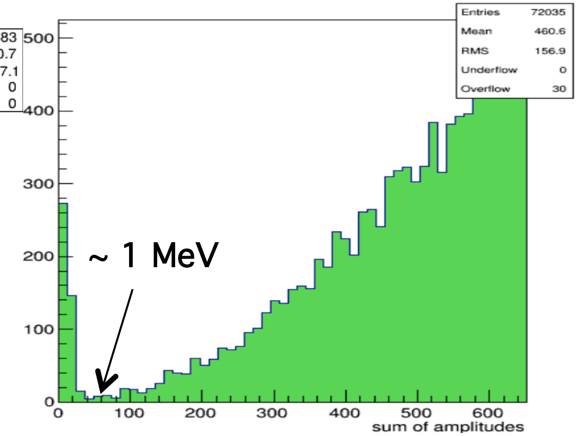
Electron tagging with synchrotron radiation (SR)

Deflected beam position



SRD: PbSc, 200 layers
0.08 mm Pb+1mm Sc +WLS

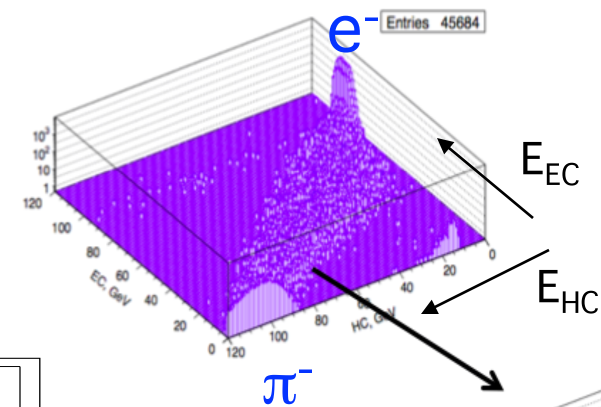


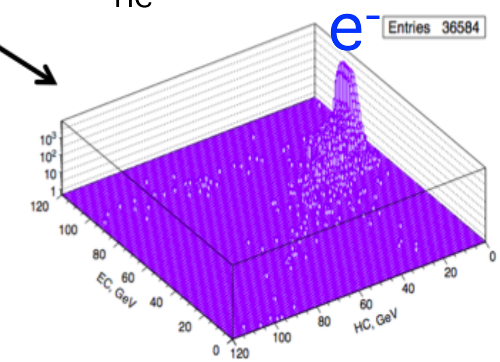


SRD selection:

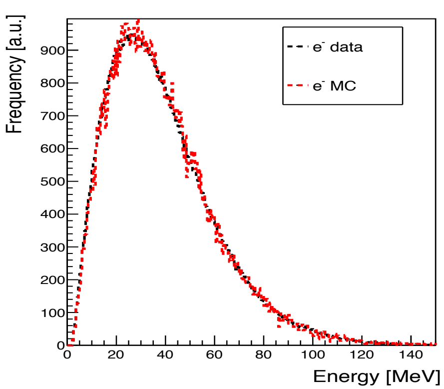
Amount of SR energy, γ's: $\Delta E \sim E_0^2/m^4$
$<E\gamma> \sim 2$ MeV, $<N\gamma> \sim 30$

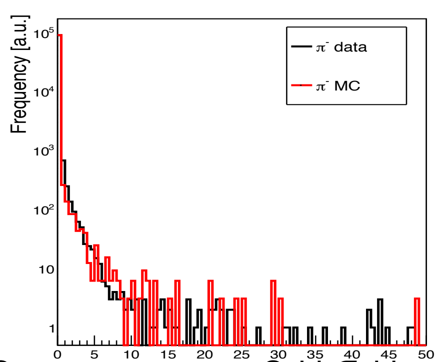
- $1 < SRD_i < 80$ MeV
- $\varepsilon_{SRD} > 0.95$, $\pi/e \sim 10^{-6}$, π reject.~10^4
- Background from π, K.. decays





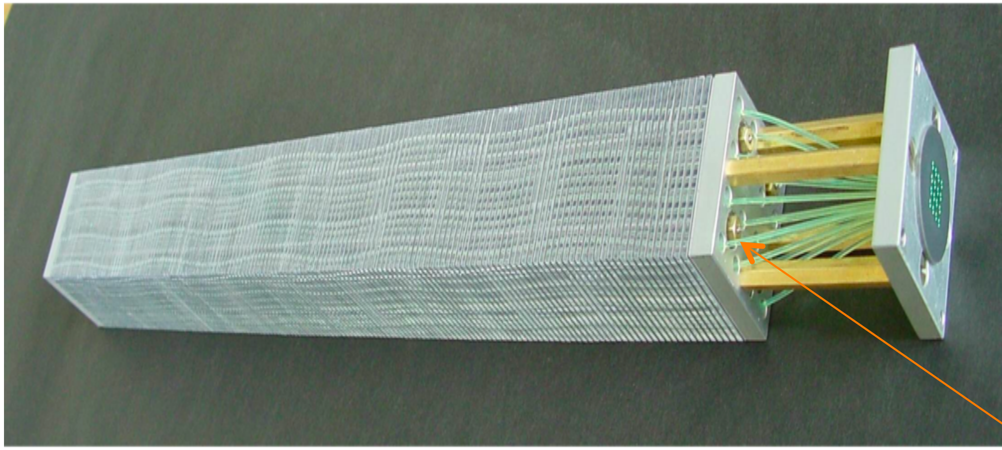
NIMA(2017)

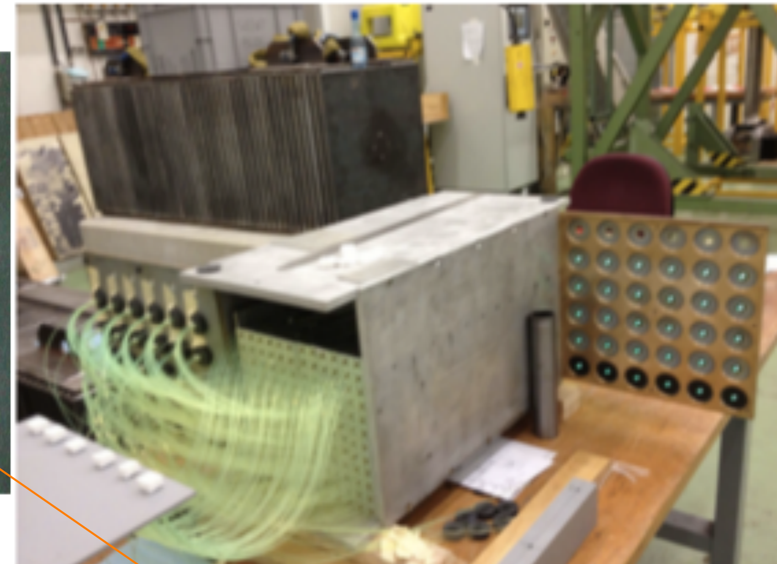




Active dump: shashlik ECAL

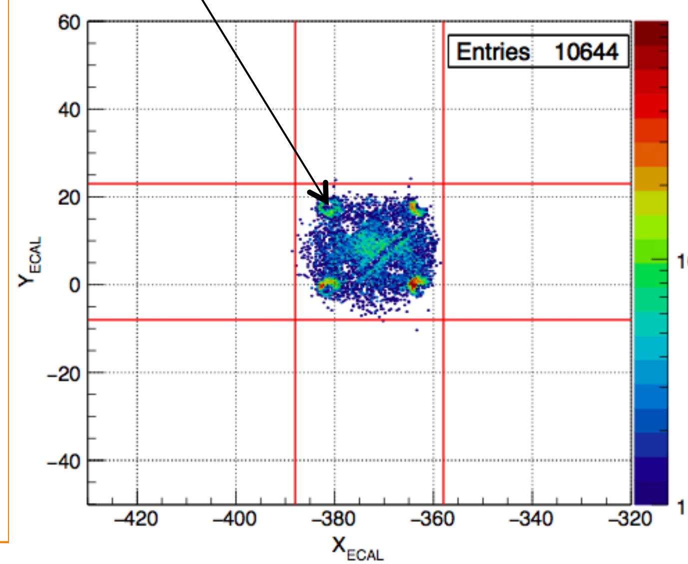
ECAL cell



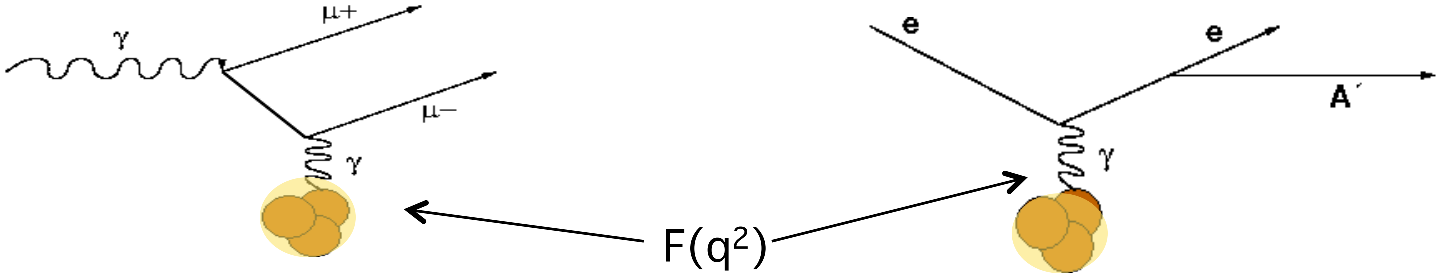


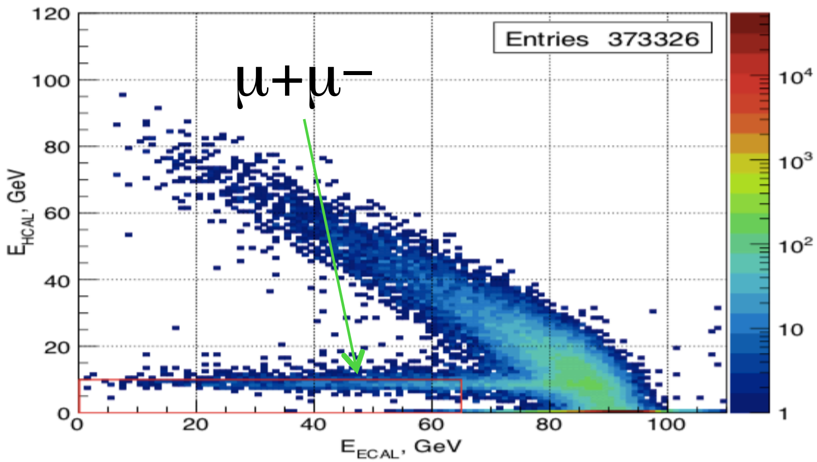
- Dump: rad.-hard, tight, fast, hodoscopic, good energy resolution
- Readout WLS fibers go in a spiral to avoid E-leak and dead zones
- Transverse X-Y scan showed non-uniformity in vicinity of fibers $\Delta E/E < 2$ %
- Variation of ECAL energy in vicinity of rods $\Delta E/E < 10$ %
- Resolution $\Delta E/E \sim 0.1/E^{0.5}$, ΔX, $\Delta Y \sim 1$-5mm
- Hermeticity scan: no potential source of background is found

e,γ punchthroughs

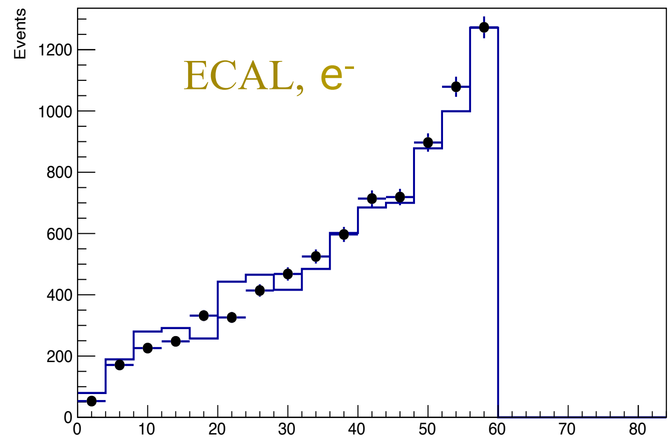


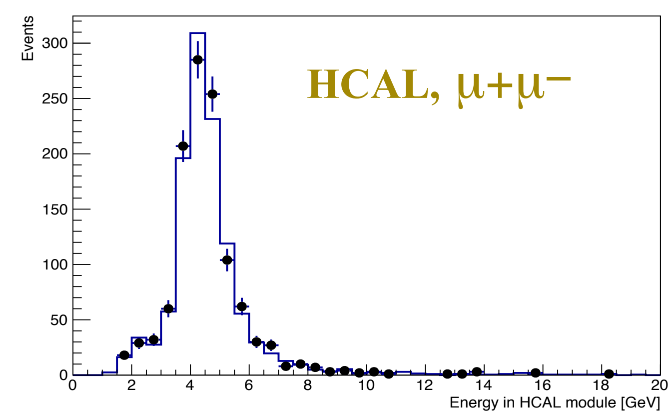
Reference process: dimuon production in eZ->eZγ, γ->μ⁺μ⁻





Dimuon Data vs MC



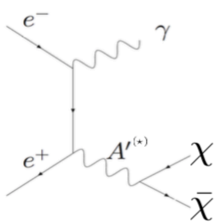


Rare QED reference process~10^{-5}/EOT:

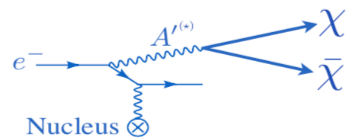
- similar to the A´ production
- same region of $q^2 \sim m^2_{A'}/E \sim m^2_{\mu\mu}/E$
- cross check of A´ yield, systematic errors
- background prediction from data
- cross check of overall efficiency

The A′explanation of g_μ-2 anomaly is ruled out by NA64 and BaBar

colliders



fixed target

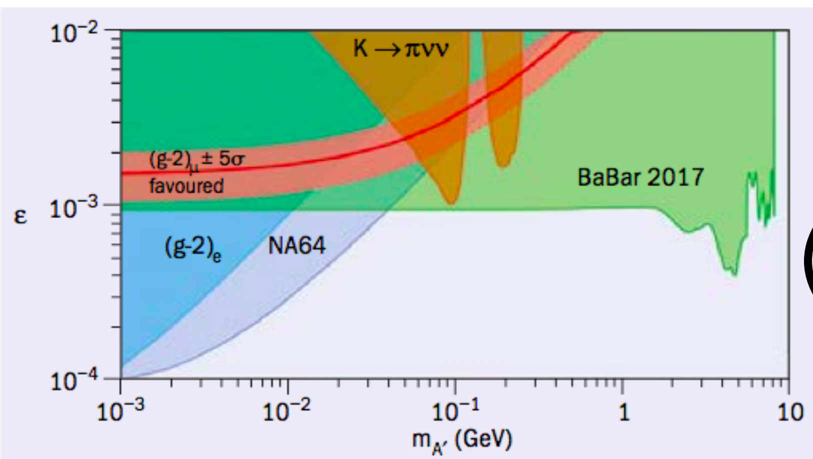


$$\sigma \propto \frac{\epsilon^2}{E_{cm}^2} \ll \sigma \propto \frac{Z^2\epsilon^2}{m_{A'}^2}$$

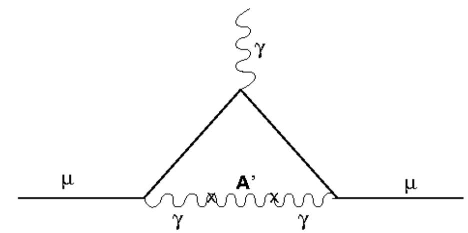
- BaBar $e^+ e^- \to \gamma A'$; $A' \to$ invisible
- NA64 $e^- Z \to e^- Z A'$; $A' \to$ invisible

CERN Courier April 2017

News



Regions of the dark-photon parameter space (mixing strength versus mass) excluded by BaBar (green) compared with the previous constraints. The new analysis rules out dark-photon coupling as the explanation for the muon (g-2) anomaly and places stringent constraints on dark-sector models.



of Caltech, who has worked on dark-photon models. "In contrast to massless dark photons, which are analogous to ordinary photons, this experiment constrains a slightly different idea of dark force-carrying particles that are associated with a broken symmetry, which therefore get a mass and then can decay. They are more like 'dark Z bosons' than dark photons."

Further reading

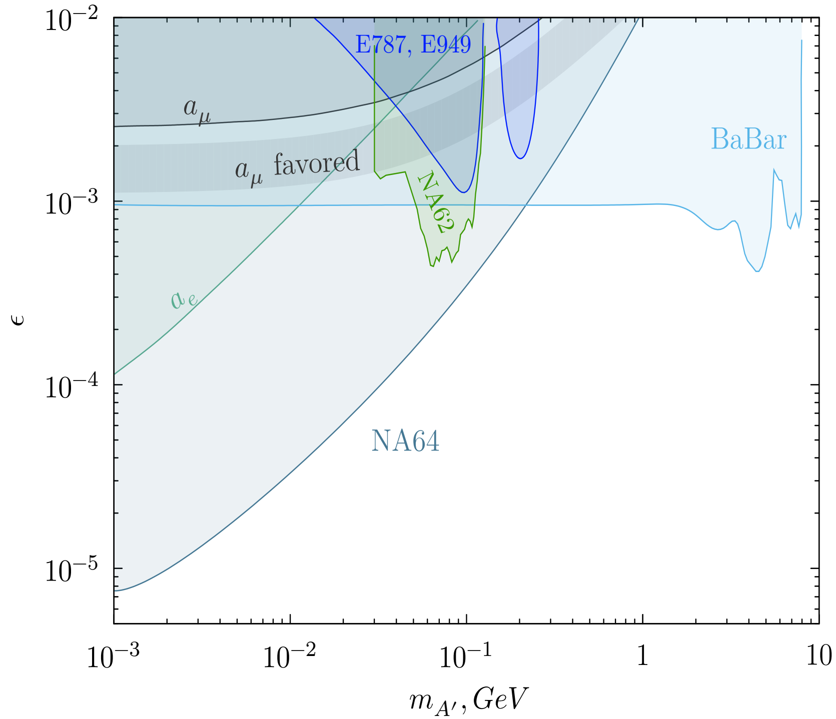
BaBar Collaboration 2017 arXiv:1702.03327.
NA64 Collaboration 2017 *Phys. Rev. Lett.* **118** 011802.

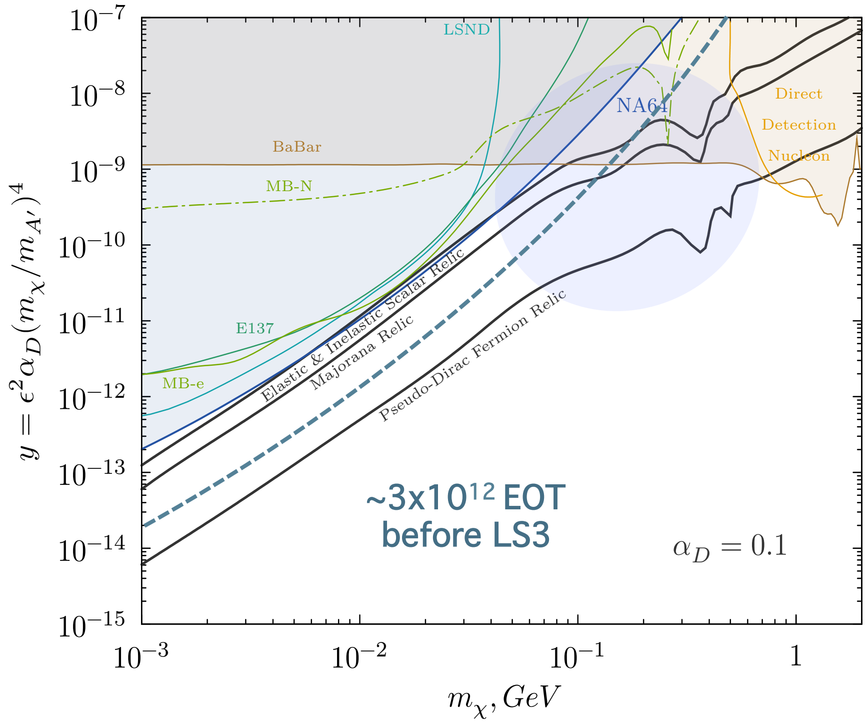
PHYSICAL REVIEW LETTERS **123**, 121801 (2019)

Editors' Suggestion

Dark Matter Search in Missing Energy Events with NA64

~$3\mathrm{x}10^{11}$ EOT

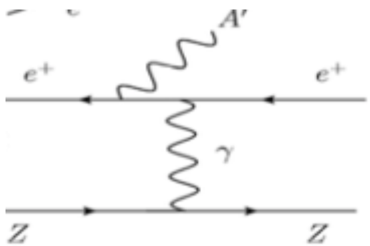




- Most stringent bounds compare to LSND, SLAC, MiniBooNE with~10^{20}-10^{22} POT. Sensitivity of NA64~ε^2, while for the beam-dump it's ~$\varepsilon^4\alpha_D$
- Plans to cover $m_{A'} \leq m_\mu$ area with ~ a few 10^{12} EOT at a new H4 location
- Challenge: high mass region $m_{A'} \geq \sim m_\mu$, as cross-section ~ $(1/m_{A'})^2$
- Ways out: i) resonance A′ production, and ii) high-energy muon beam ($NA64_\mu$)

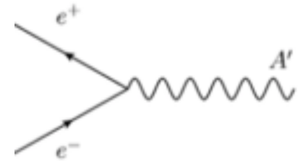
Resonant A′ production

L. Marsicano et al. PRL(2018)
NA64 Coll. PRD Lett. (2021)



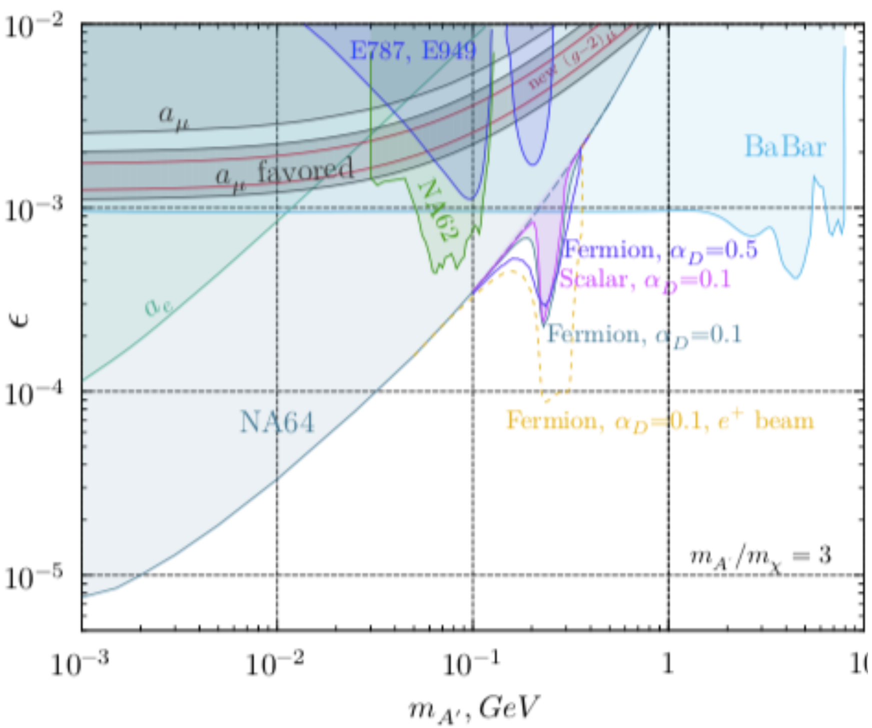
$\sigma \sim Z^2\alpha^3\varepsilon^2$ vs

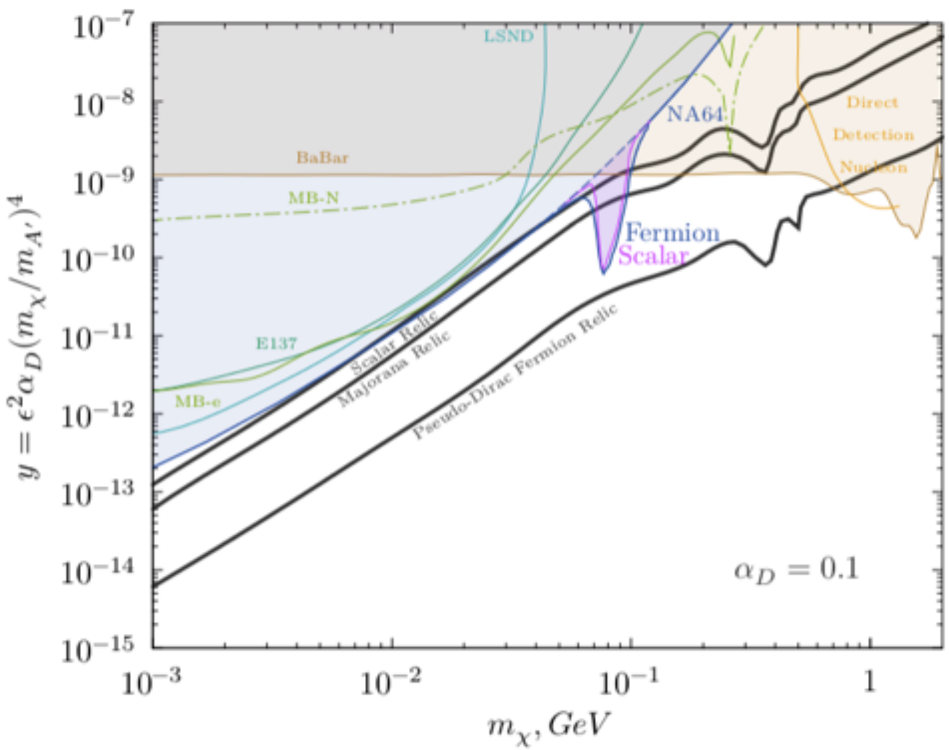
$m_{A'} \sim (2 m_e E_0)^{1/2}$



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

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

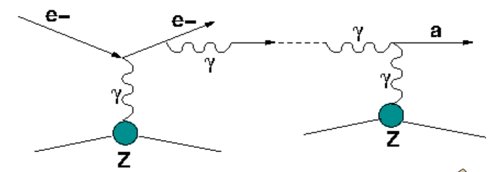


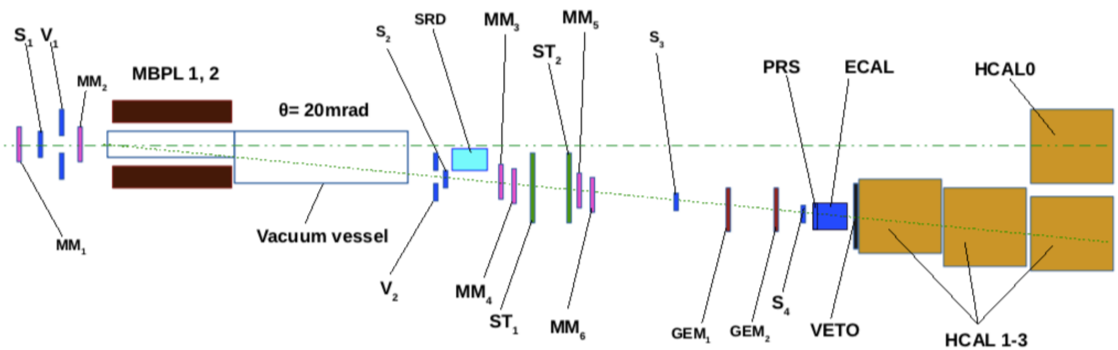


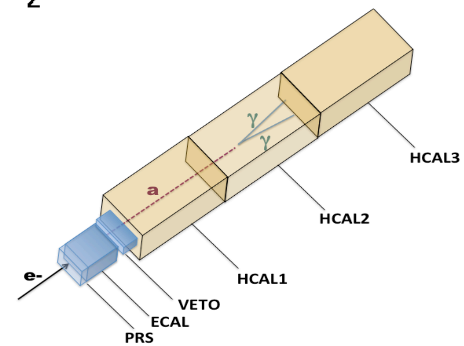
Exploiting NA64e potential:
Other searches for new physiscs

Search for the axion, ALP, S → $\gamma\gamma$ decays

- Dominant *a*-γ coupling, $L = - g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}/4$
- Primakoff production in the ECAL dump :







Signature:

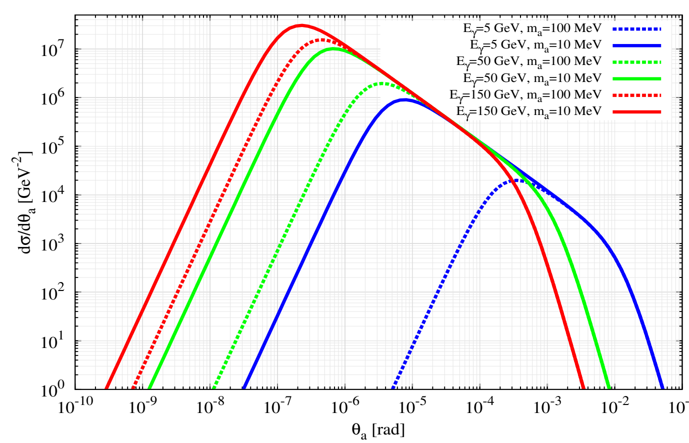
- 100 GeV e- track
- $E_{ECAL} < E_0$ shower in ECAL
- no activity in Veto and HCAL1
- Then, either

a) no activity in HCAL2 and HCAL3:
a decays outside HCAL, or

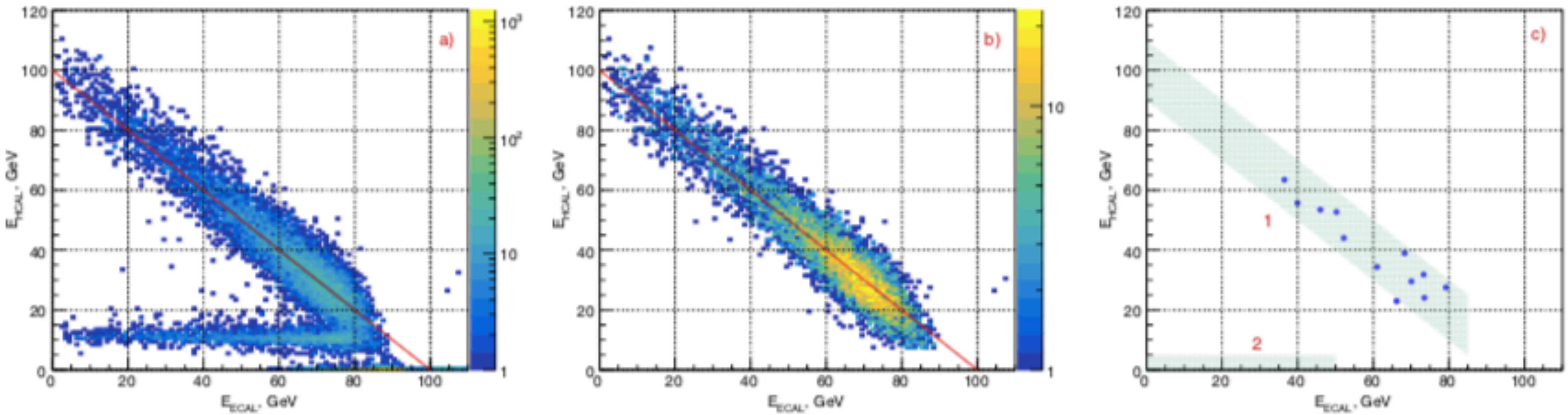
b) e-m like energy in HCAL2+HCAL3
a decays inside HCAL

Production cross-section:

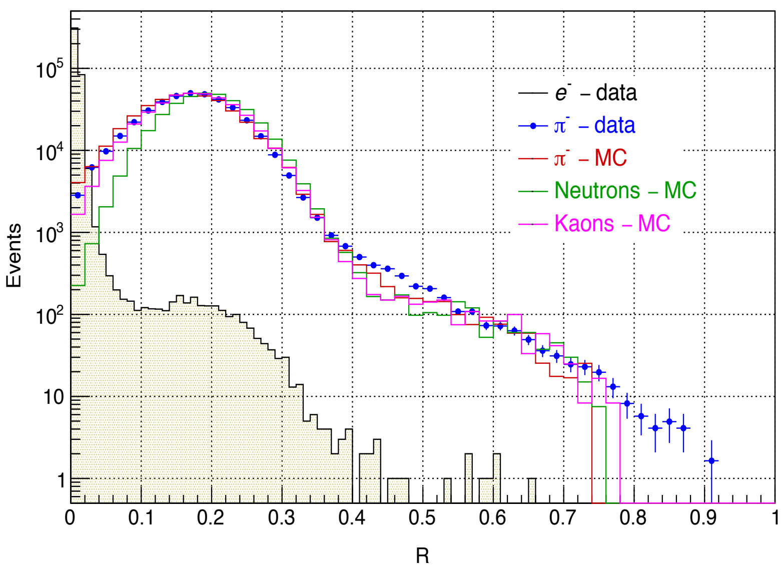
ETL full calculations,
e.g. the *a* emission angle



Event selections



Variable R:
lateral shower shape in the HCAL



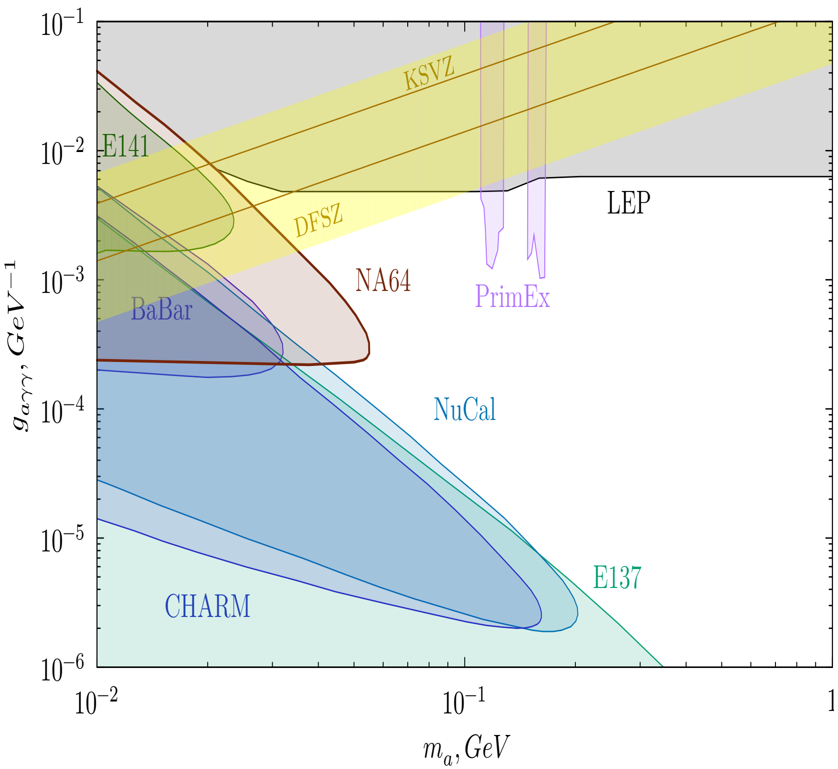
- Main bckg – punchthrough neutral secondaries (n,$K^0_{S,L}$)
- Well predicted from punchthrough charged hadrons

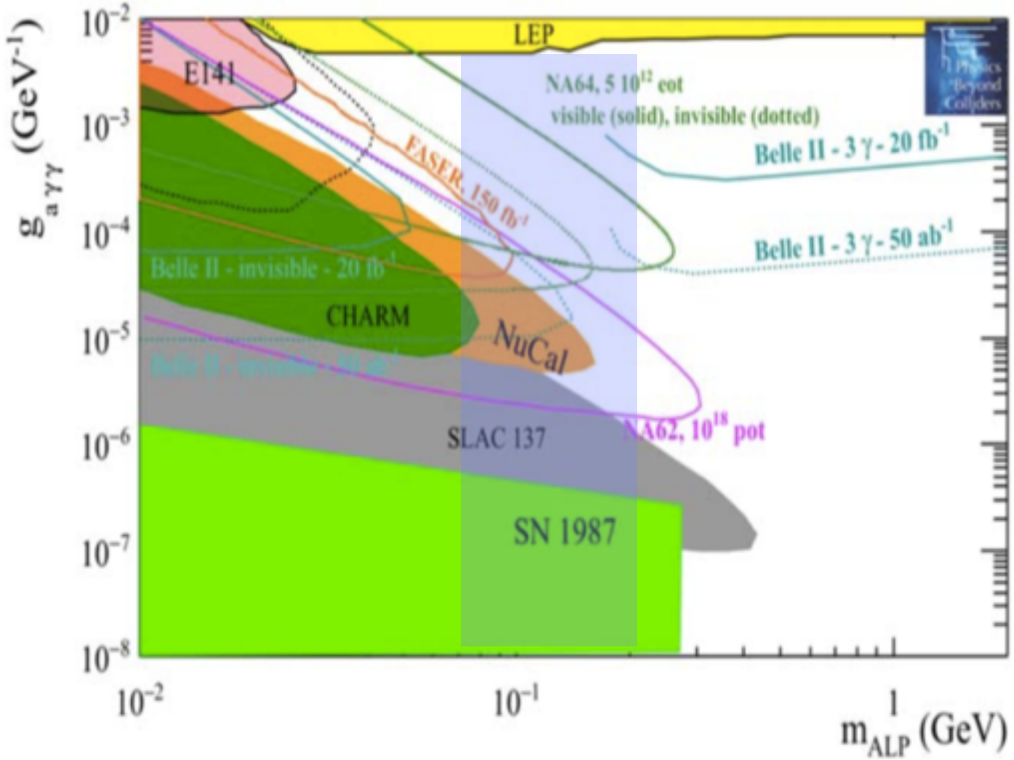
No events in the signal box after the cut on R

Results for ALP, S → γγ decays

NA64,Phys.Rev.Lett.(2020)

PBC BSM WG, J.Phys.G: Nucl.Part.Phys. 47(2020)





Plans to probe couplings $g_{a\gamma\gamma}$ in ~π^0 mass region (π^0 →γγ background).

Results on a →γγ decays are also applicable to long-lived A′→e^+e^- search.

Constraints on New Physics in $(g\text{-}2)_e$

NA64,Phys.Rev.Lett.(2021)

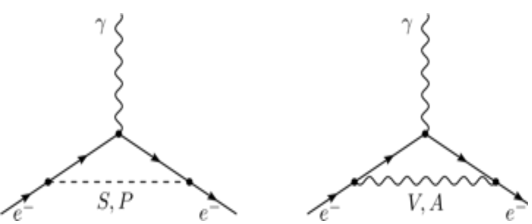
$(g\text{-}2)_e$ from high-precision measurements of α

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

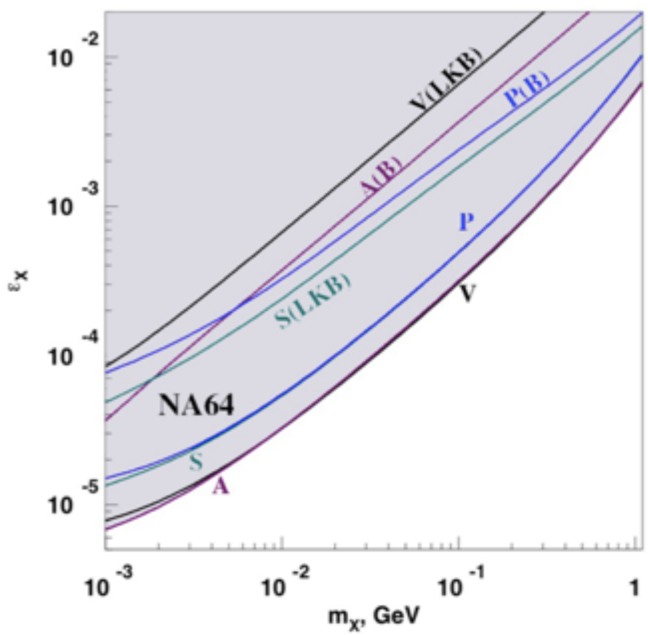
$$\Delta a_e = a_e^{exp} - a_e^{LKB} = (4.8 \pm 3.0) \times 10^{-13} \quad (1)$$

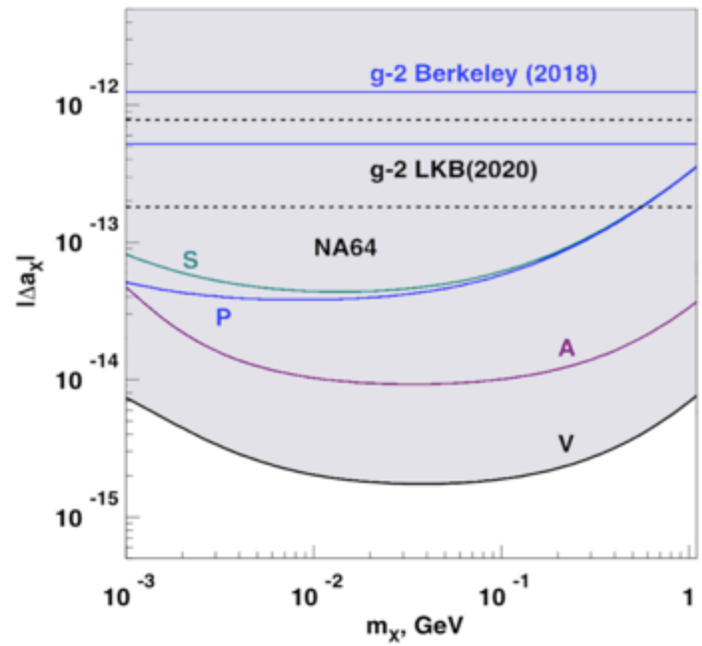
$$\Delta a_e = a_e^{exp} - a_e^{B} = (-8.8 \pm 3.6) \times 10^{-13} \quad (2)$$

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



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



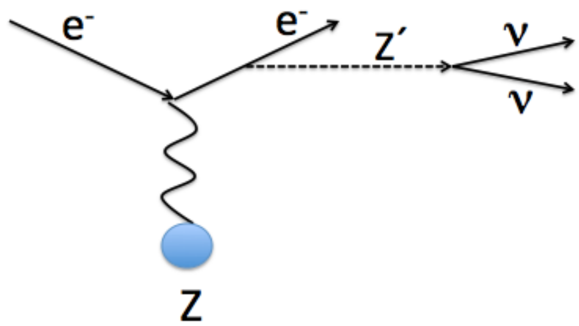


NA64 provided most stringent constraints on new physics contribution $\Delta a_X < 10^{-15} - 10^{-13}$ for $X=S, P, V,$ or A compared to LKB and Berkley high-precision measurements

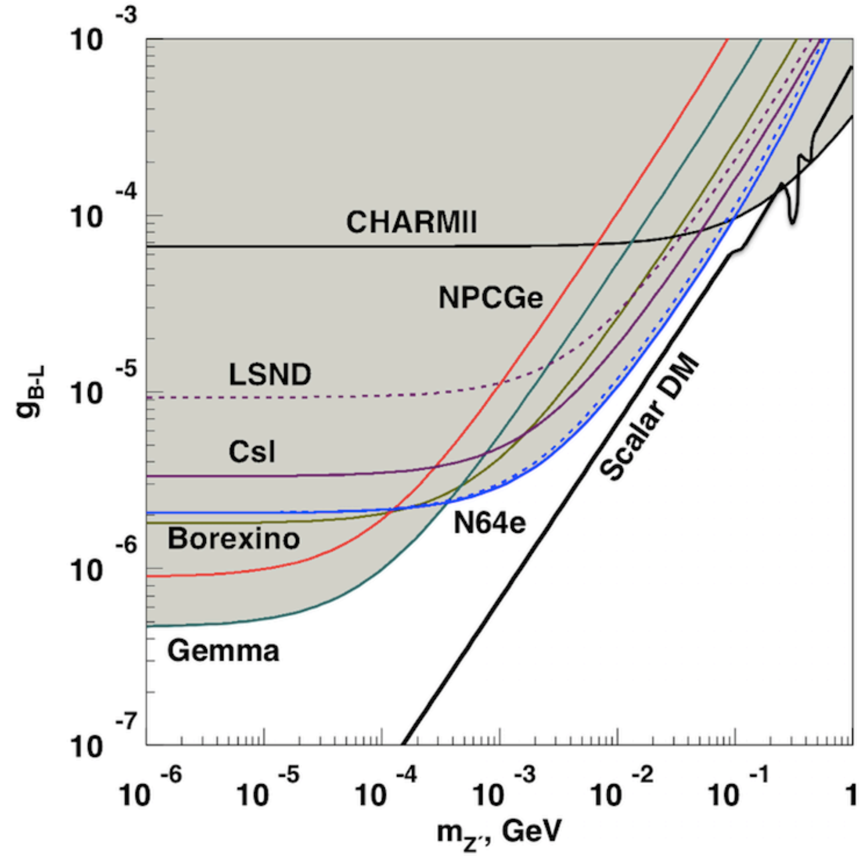
Search for B-L Z′

NA64, Phys.Rev.Lett.(2022)

3.2x10[11] EOT collected in 2016-2018, 2021 runs



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



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

^{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

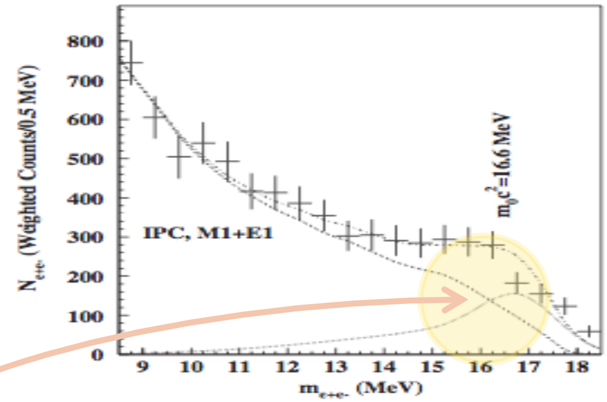
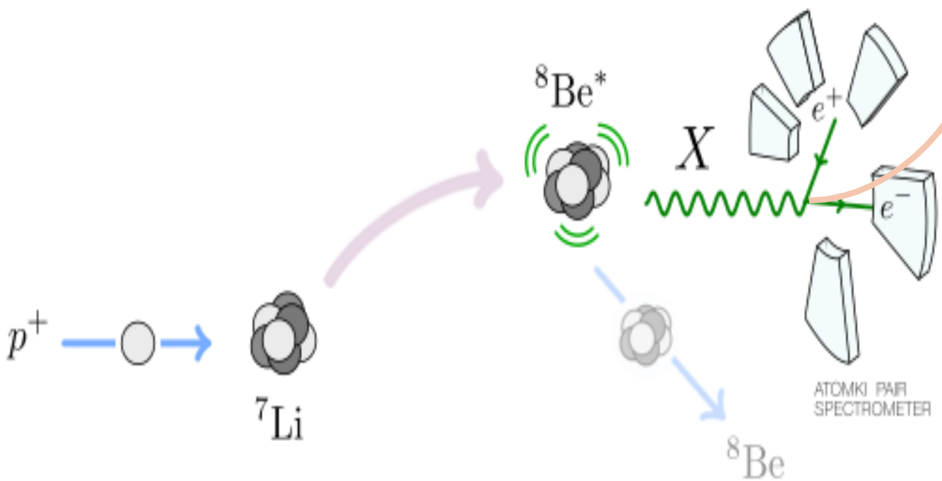
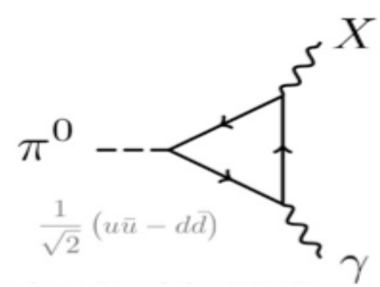


FIG. 5. Invariant mass distribution derived for the 18.15 MeV transition in ^{8}Be.



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



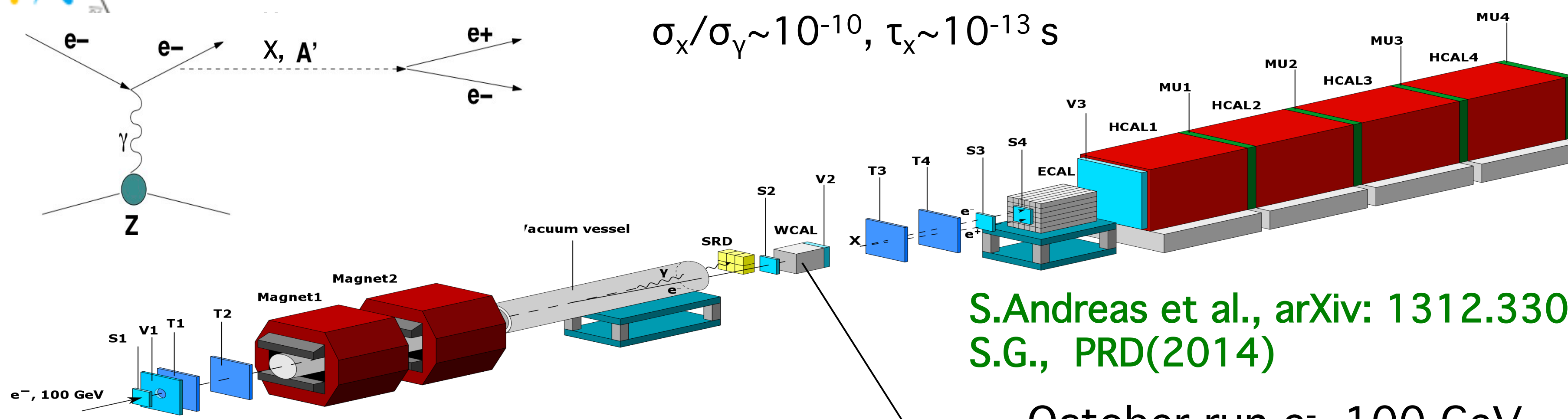
Feng et al, 2016

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

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

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

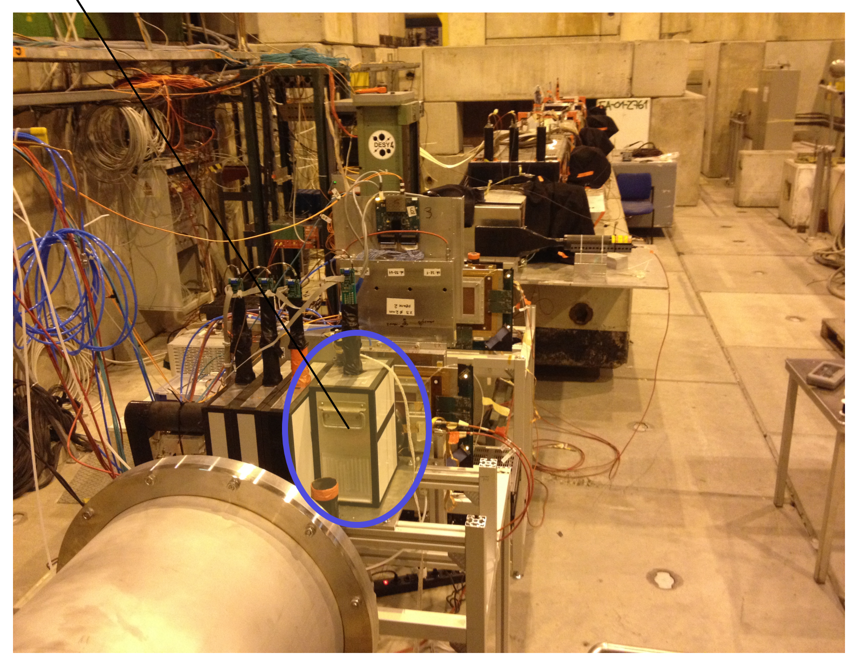
Feasibility test for the X(A´)->e$^+$e$^-$ decay



$\sigma_X/\sigma_\gamma \sim 10^{-10}$, $\tau_X \sim 10^{-13}$ s

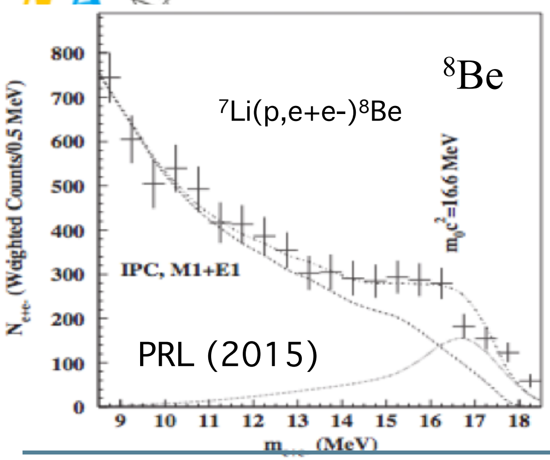
S.Andreas et al., arXiv: 1312.3309
S.G., PRD(2014)

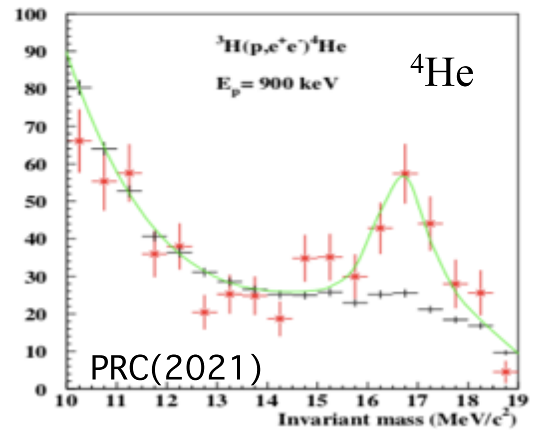
October run e$^-$, 100 GeV

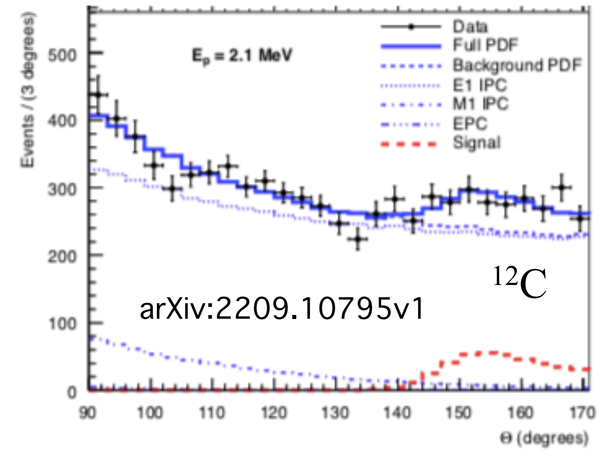


- X's decay mostly outside WCAL
- **Signature:** two separated showers from a single e-
- $E_{WC} < E_0$, and $E_0 = E_{WC} + E_{EC}$
- θ_{e+e-} too small to be resolved
- **Background** mainly from
- bremss γ punchthrough
- beam and secondary hadrons

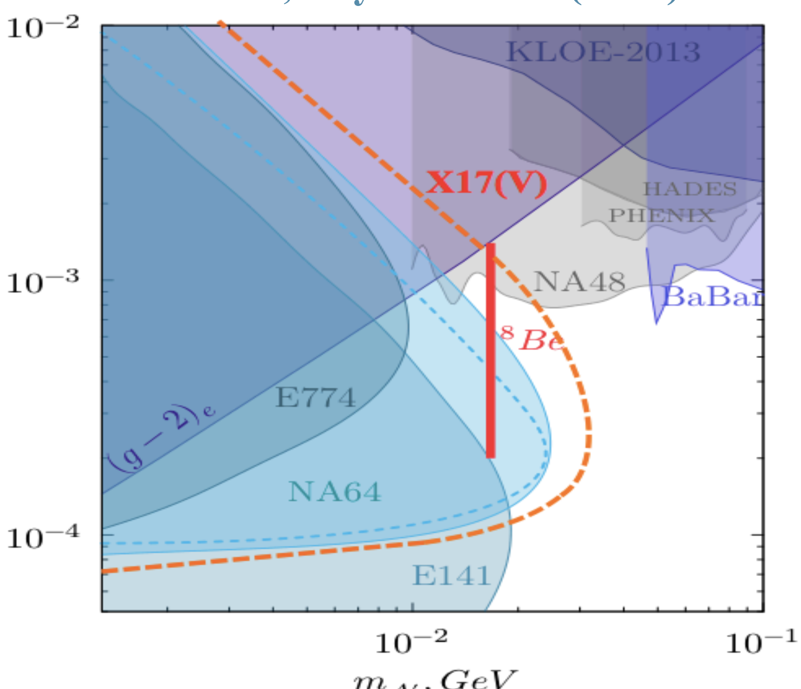
Results on A′, X17 -> e+e- decays



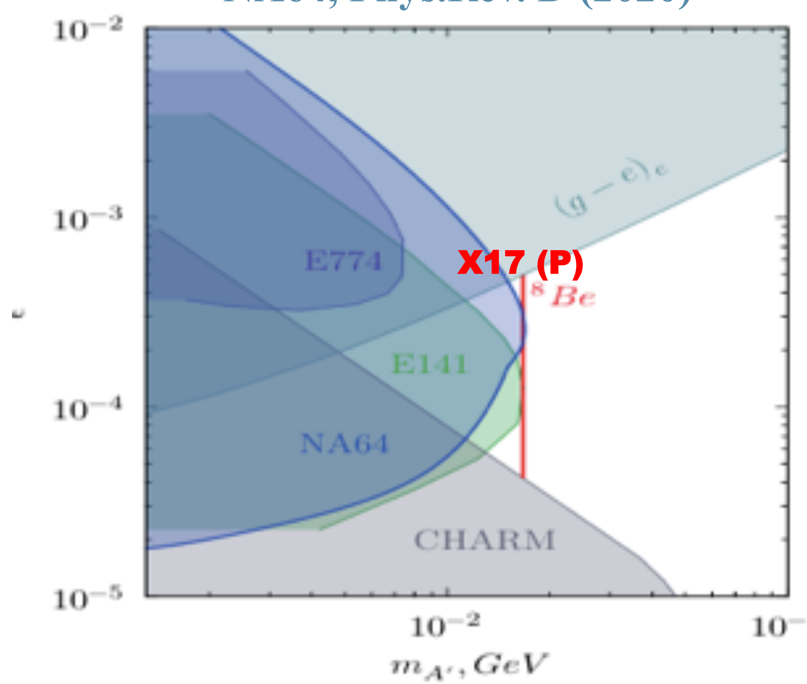




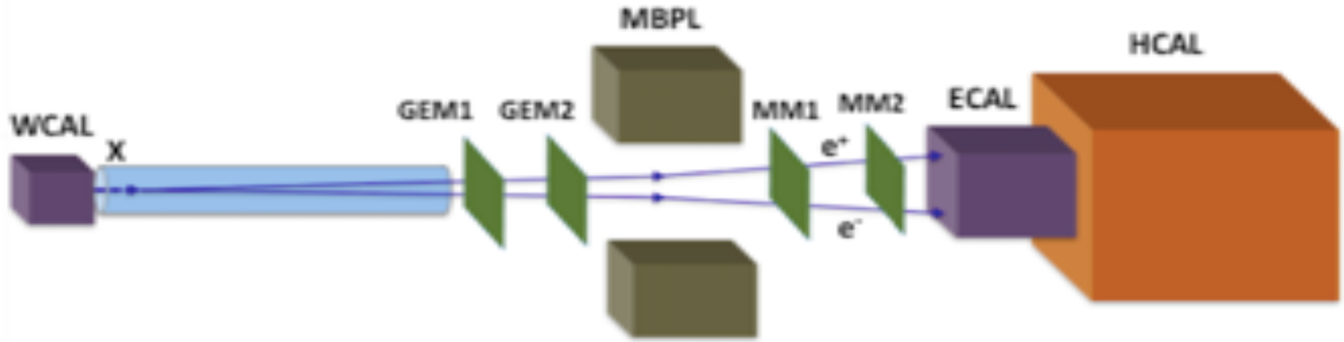
NA64, Phys.Rev.Lett.(2018)



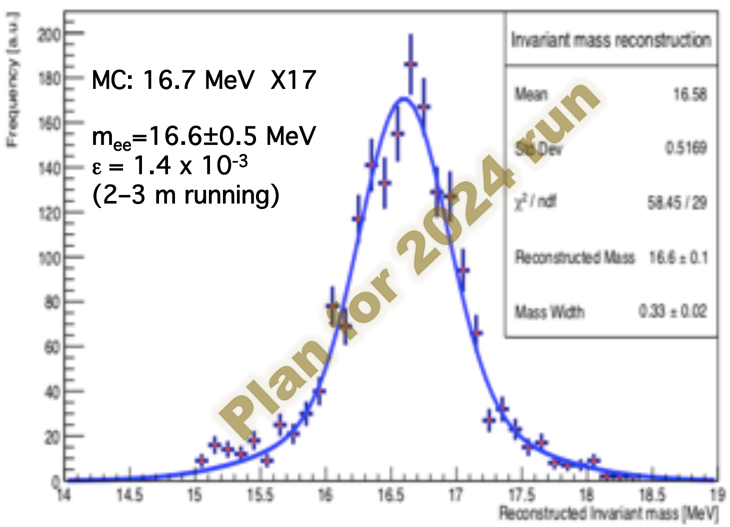
NA64, Phys.Rev. D (2020)



Plans for 2024: 150 GeV, ~ 2 x 10^{11} EOT



Good two-track resolution required.



A possibility: 2 мм Straw Tubes chambers

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 62, NO. 6, DECEMBER 2015 3283

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, and I. A. Zhukov

***Abstract*—A class of models of a “dark sector” of particles consider new very weak interaction between the ordinary and dark matter transmitted by U’(1) gauge bosons A’ (dark photons) mixing with ordinary photons. If such A’s exist, they could be searched for in a light-shining-through-a-wall experiment with a high energy electron beam from the CERN SPS. A proposed search project suggests detection of the e+e− pairs produced in the A′ -> e+e− decays with a very small opening angle. Coordinate detectors based on the thin-wall drift tubes with a minimal material budget and a two-hit resolution for e+ and e− tracks separated by more than 0.5 mm are considered as an option for detecting such events.**

***Index Terms*—Dark matter, e+e− pairs , gas detectors.**

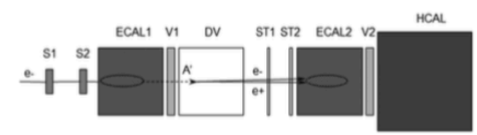
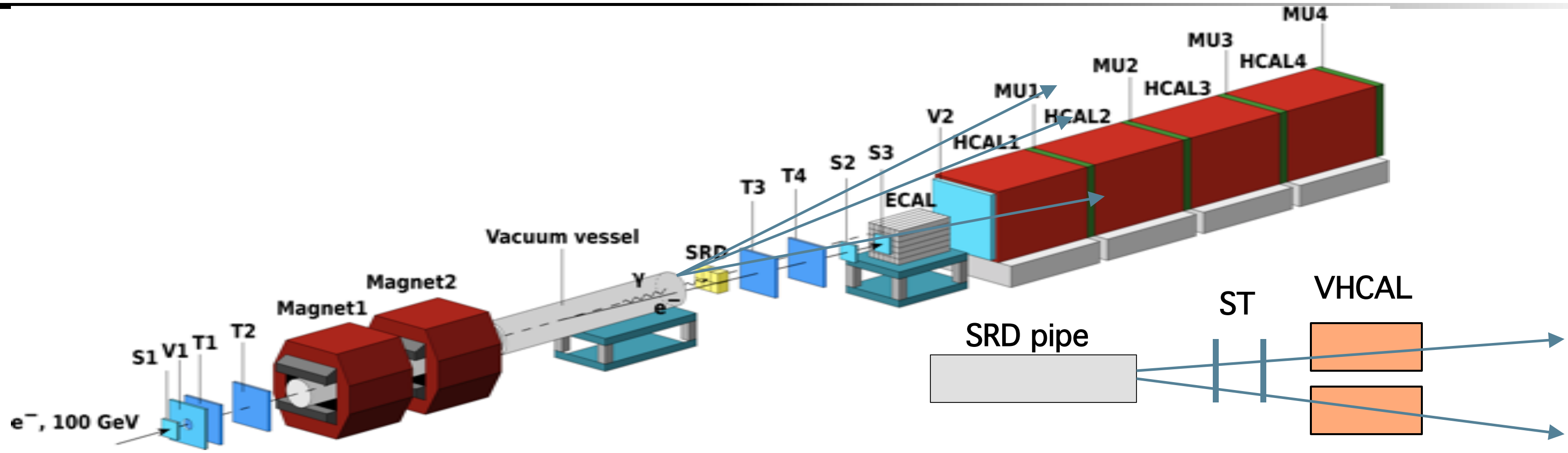


Fig. 1. Schematic layout of the setup to search for dark photons in a light-shining-through-a-wall type experiment at high energies. Shown are the scintillation counters S1 and S2 defining the primary electron beam, electromagnetic calorimeters ECAL1 and ECAL2, veto counters V1 and V2, decay volume DV, straw tube chambers ST1 and ST2, and the hadron calorimeter HCAL.

Background and upgrade for the runs after LS2 (2021->)



- By 2021 several world-leading NA64 dark sector results already completed. Further improvement in sensitivity required NA64 upgrade.
- Background due the insufficient detector hermeticity against charged and neutral hadrons produced in electron beam interactions in the beam material at large angles. It was supressed for charged secondaries by using large size beam Straw Tubes as a veto. While for neutrals a veto HCAL (VHCAL) has to be installed in the setup.
- For NA64e detector and NA64μ design and construction of a new detectors for New ECAL, HCAL and WCAL calorimeters, the SRD detector, new MM and Straw chambers for tracker, the trigger, electronics and DAQ has to be produced for the run after LS2.

Встреча с Д.А. Медведевым. ЦЕРН, 10 июня 2019 г.

С.Г. Вопрос о возможности поддержки NA64.

Г.В. Трубников: Дмитрий Анатольевич, вопрос правильный, поскольку, кроме самого Большого адронного коллайдера и физики на нём, есть ещё много очень интересных направлений, абсолютно точно прорывных и перспективных...

NA64 upgrade and 2021 runs

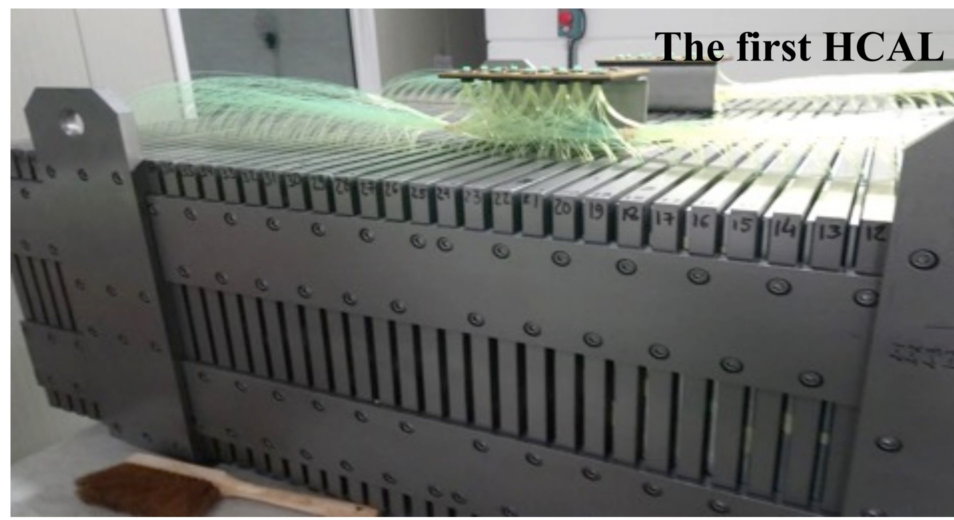
Contributions of INR and IHEP. Detectors were fabricated thanks to the grant of MSHE RF and help of JINR

- Veto HCAL - 3 modules
- HCAL - 4
- ECAL -2
- SRD -1
- WCAL -1

Contributions of JINR, ETHZ, BONN

- Straw Tube chambers – 7
- Micromegas - 8
- GEM - 4

Beginning of assembly in 887/R-Q11



Plan to complete the assembly ~ by the summer 2022

Straw Tube chambers for NA64e and NA64μ

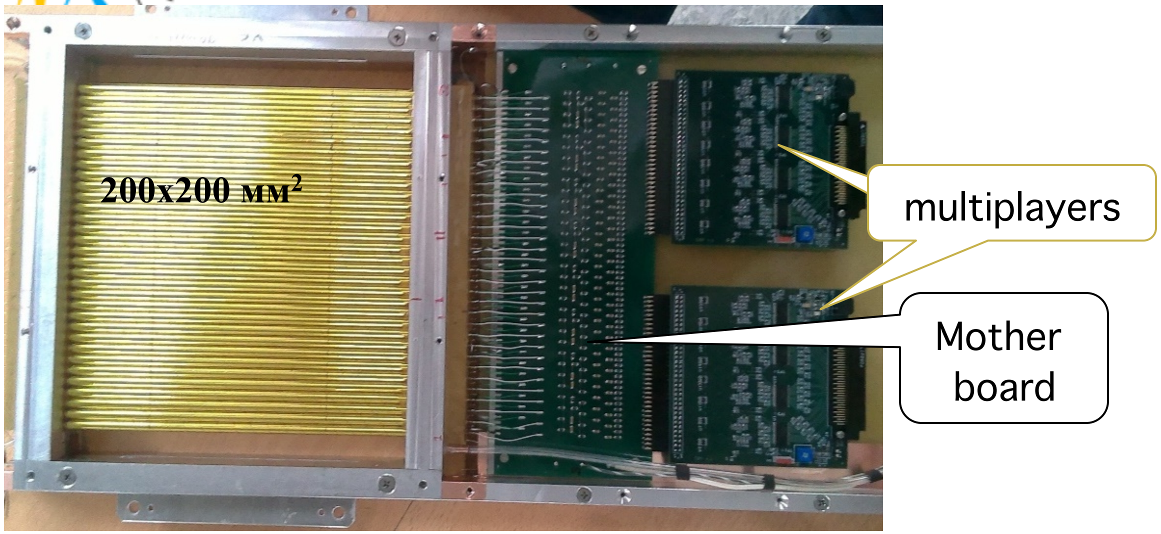
- Three types of two-layer Straw Tube chambers for NA64e/NA64μ have been developed.
- The total number of Straw tubes in the NA64 experiment is 6900. Total cost $160,000
- The integration work was done in the period 2018-2022

Size, X-Y mm^2	Diameter of drift tubes, mm	Number of tubes	Comments
200x200	6	768	12 chambers
1200x600	6	5376	7 chambers
200x200	2	768	2 prototypes, 25μm walls

ST have advantage over other Micromegas and GEM track detectors used in NA64 due to:

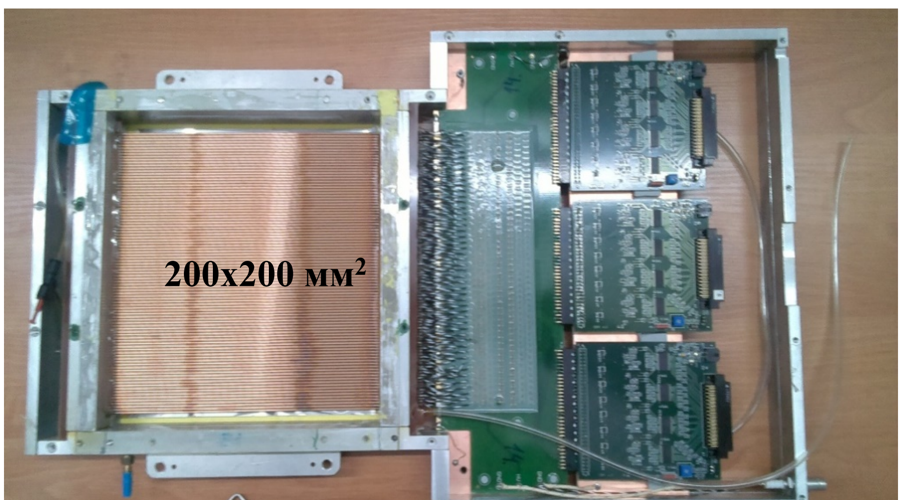
- a smaller dead material 0.0016 X/X_0
- higher efficiency at high intensity
- higher multitrack efficiency reco.
- better efficiency of track reconstruction

200x200 mm² Straw Tube chambers



Two-layer, 64x6 мм ST, 200 x 200 mm²

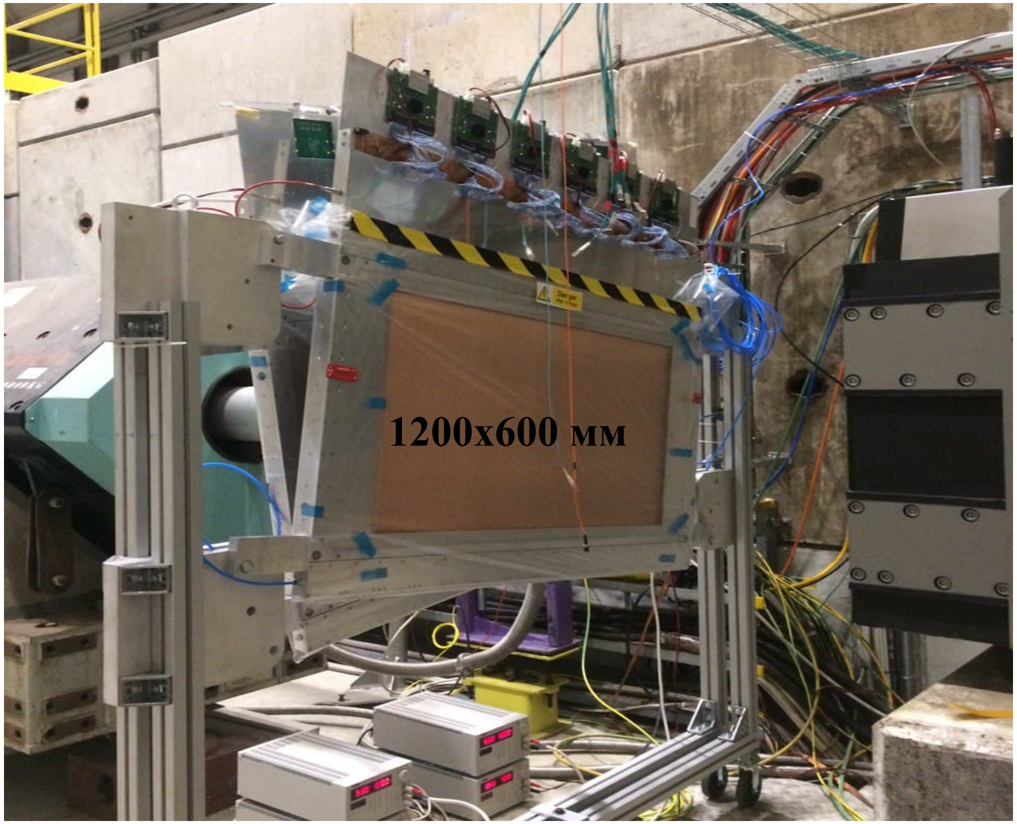
Allowed to suppress background from hadron electroproduction on beamline material upstream the ECAL.
Critical for 2018 run.



Prototypes of two-layer, 192x2 мм ST, 200 x 200 mm²

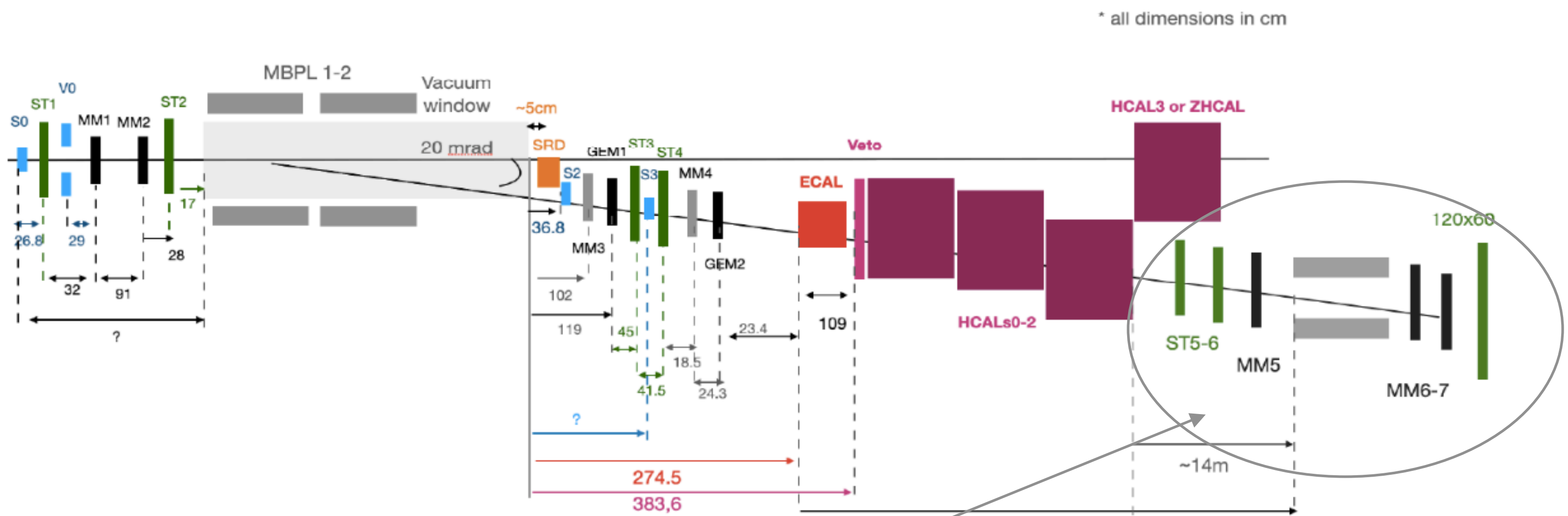
Good two-track resolution is expected for the X17 boson search in ~ 2024 run
Critical for X17 mass reconstruction.

1200x600 mm^2 Straw Tube chambers



Двухслойная камера с трубками диаметром 6 мм, размер 1200 х 600 мм
с усилителями. 384 Straw трубок

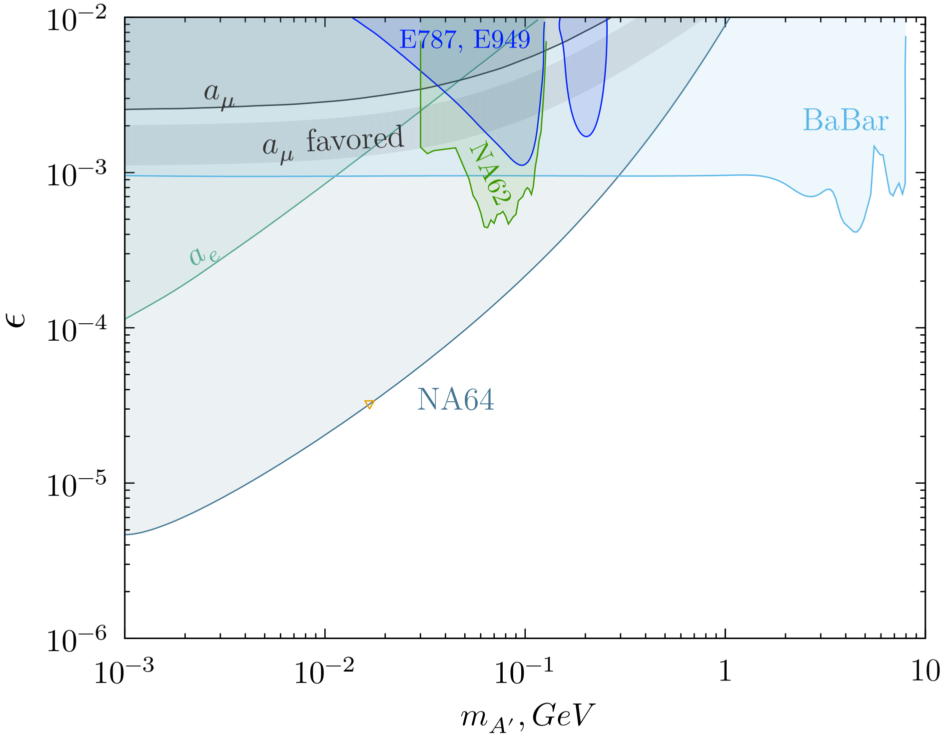
NA64e 2021-2022 runs. New Area at H4.

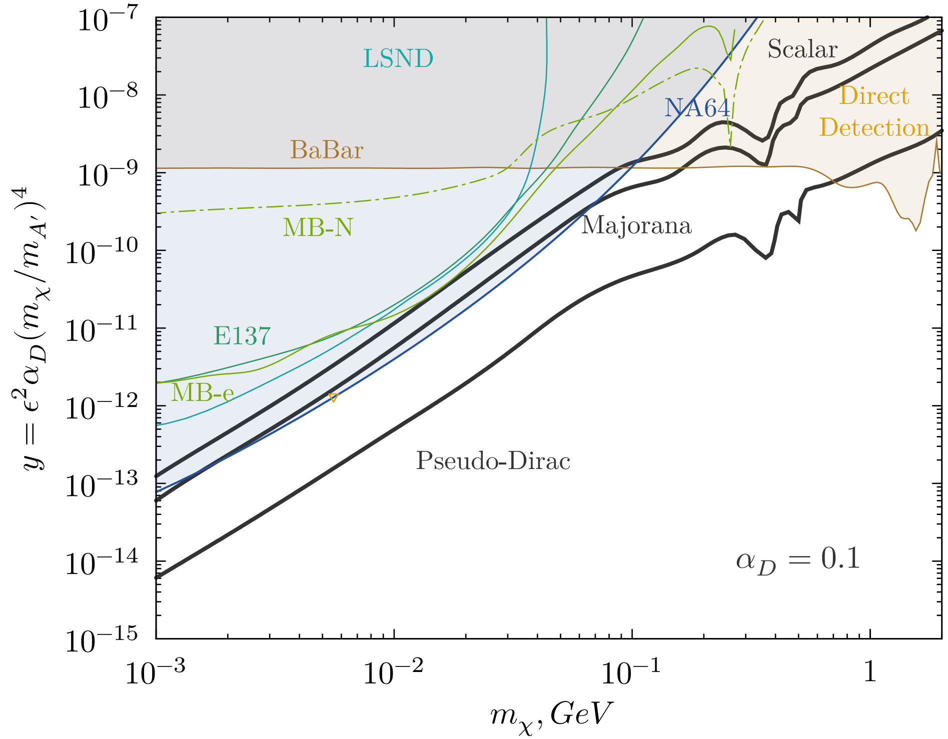


Setup 2022

- The whole calorimetry system is moved upstream by ~ 3 m.
- New magnetic spectrometer added for $eZ \to \mu^+ \mu^- Z$, and searching for $eN \to \mu N \phi$ conversion [NA64 Th.Coll. Leptonic scalar portal, PRD(2022)]
- Collected in 2022: 6.4 x10^{11} e-; 5 x10^{10} e+
- Total number accumulated during 2016-2022 Runs ~ 10^{12} EOT

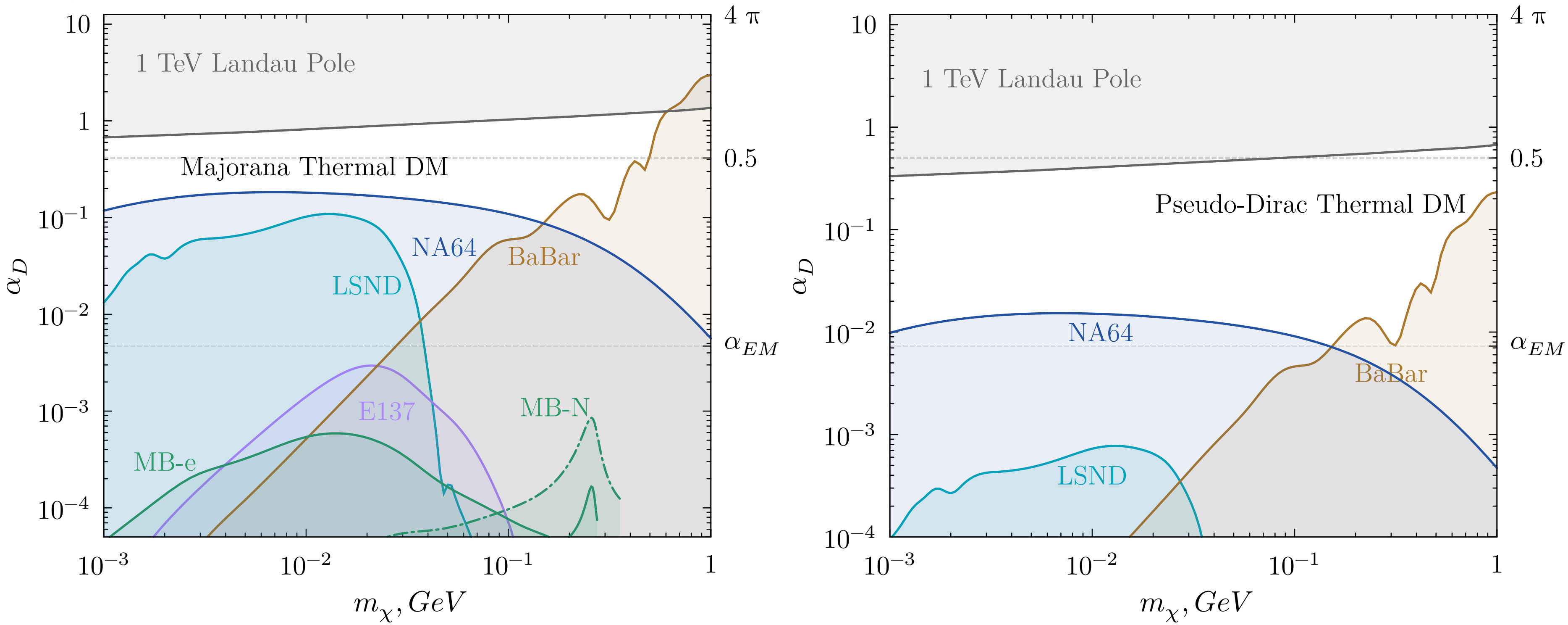
NA64e results from 2016-2022 runs with ~10^{12} EOT (I)





- World-leading constraints on parameters of LDM for $m_{A'}$ <~ m_μ
- First intervention into the most-motivated LDM parameter space
- It gets excitingly interesting! Plans to double statistics by LS3.

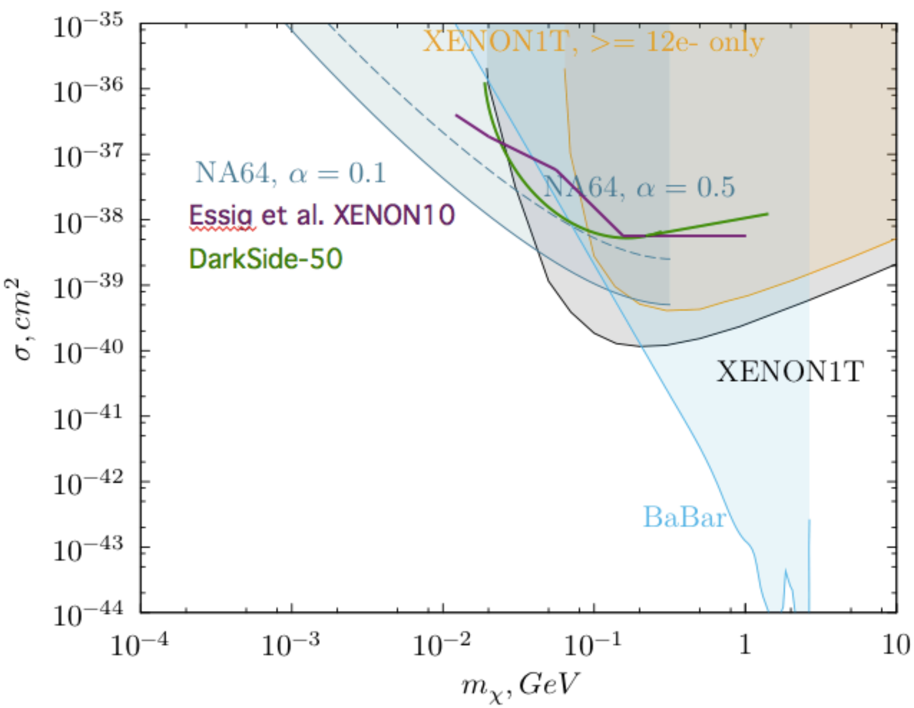
NA64e results from 2016-2022 runs with ~10^{12} EOT (II)

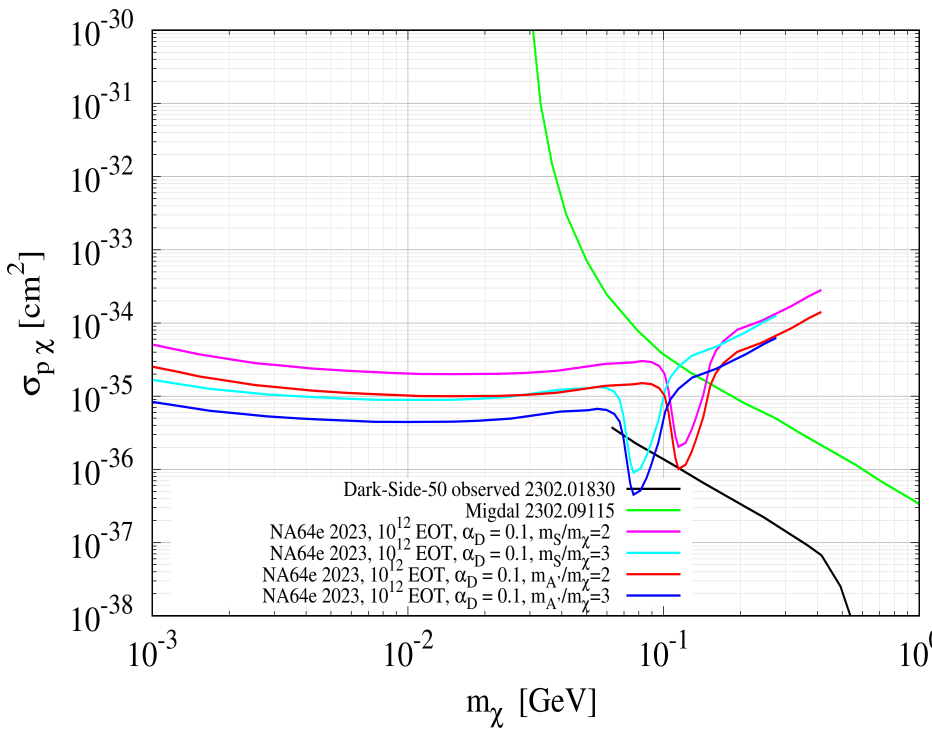


- World-leading constraints on parameters of LDM for $m_{A'} <\sim m_\mu$
- First intervention into the most-motivated LDM parameter space
- It gets exitingly interesting! Plans to double statistics by LS3.

Constraints on DM-electon cross-sections

Complementarity of NA64 and direct DM searches





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

D. Kirpichnikov (preliminary)

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

NA64μ: search for Dark Sector with muons at M2

S.G, N. Krasnikov, V. Matveev PRD(2015)

Prepared for submission to SPSC

CERN-SPSC-2019-002 / SPSC-P-359
14/01/2019

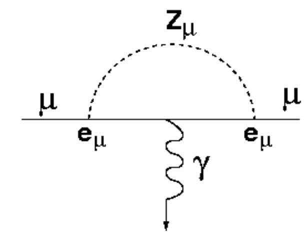
Proposal for an experiment to search for dark sector particles weakly coupled to muon at the SPS

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]

NA64μ: search for Dark Sector with muons at M2

E989 (FNAL) => $(g\text{-}2)_\mu$ anomaly at ~4.2σ
and DM relic abundance can be explained
by the existence of $\mathbf{L_\mu - L_\tau}$ Z_μ interacting to μ, τ and DM



- Searches for sub-GeV muonic S_μ, Z′
- LFV μ - τ conversion (e–τ (HERA))

New ideas for NA64μ-like experiment

- $\mathbf{L_\mu}$**-** $\mathbf{L_\tau}$ **Z′** M[3]@FNAL,**arXiv:1804.03144**
- Leptophilic TDM, arXiv:1807.03790
- Light scalars of DS, arXiv:1701.07437

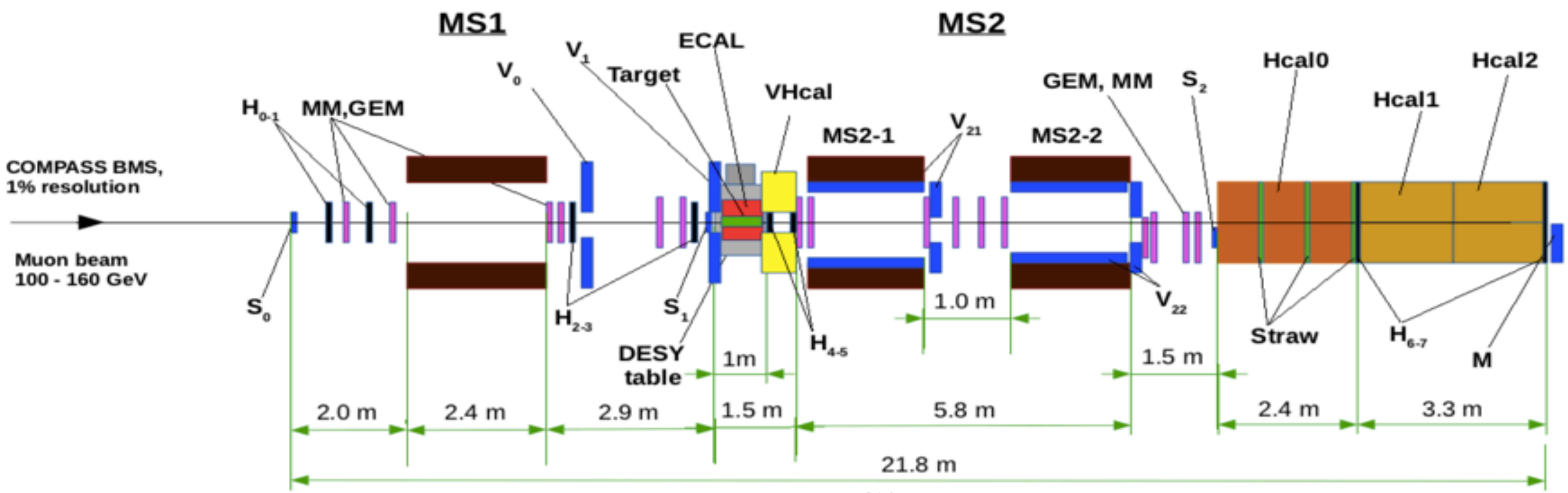
PHYSICAL REVIEW LETTERS **128,** 141802 (2022)

Simplest and Most Predictive Model of Muon g − 2 and Thermal Dark Matter

Ian Holst[1,2,*] Dan Hooper[1,2,3,†] and Gordan Krnjaic[1,2,3,‡]

[1]University of Chicago, Department of Astronomy and Astrophysics, Chicago, Illinois 60637, USA
[2]University of Chicago, Kavli Institute for Cosmological Physics, Chicago, Illinois 60637, USA
[3]Fermi National Accelerator Laboratory, Theoretical Astrophysics Group, Batavia, Illinois 60510, USA

Search for Z_μ (S_μ) in missing energy events



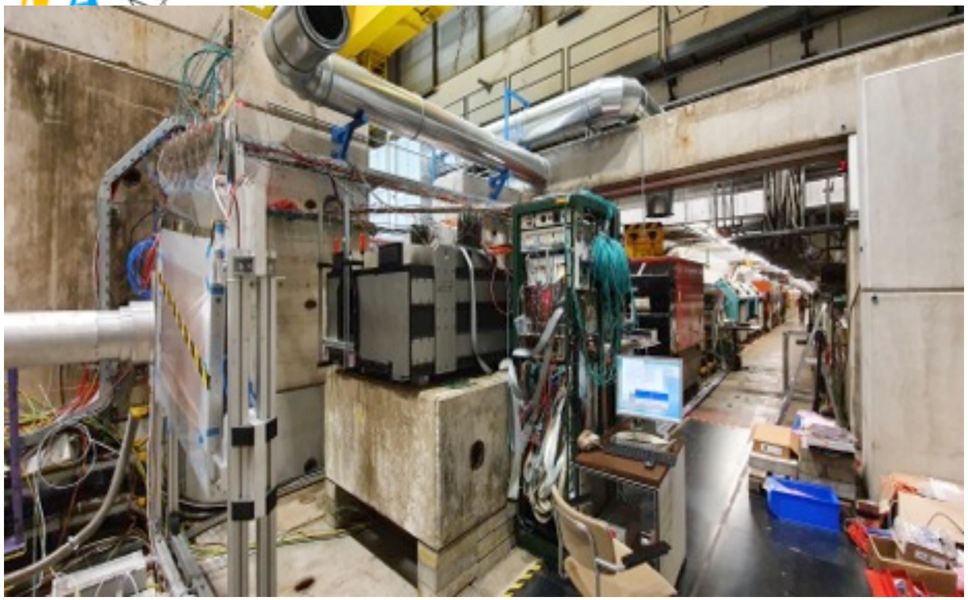
Main components :

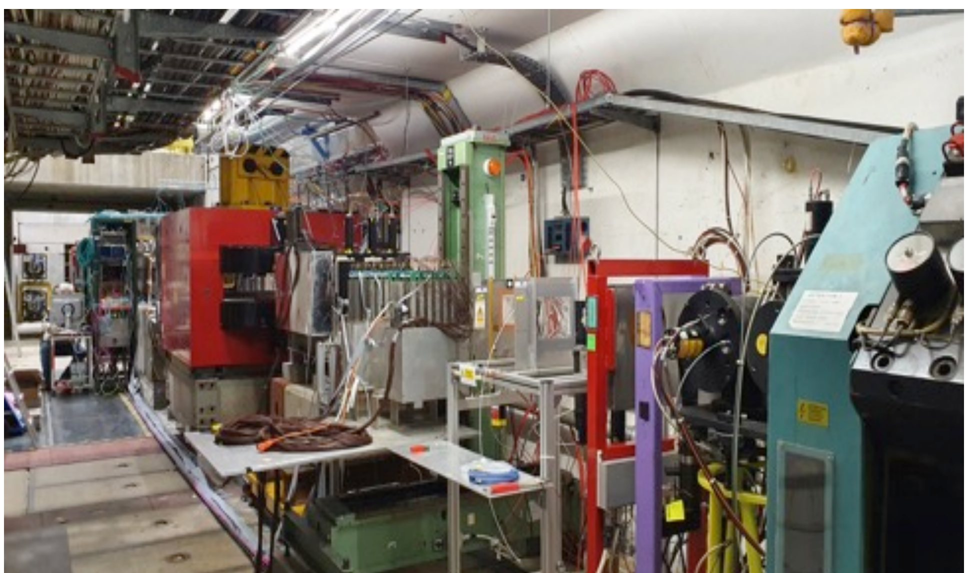
- 100-160 GeV μ- beam, $I_\mu \sim 10^7 \mu$/spill.
- in μ tagging: BMS+MS1(MBPL+tracker)
- out μ tagging: MS2 (2MBPL+tracker)
- 4 π fully hermetic ECAL+Veto+ HCAL

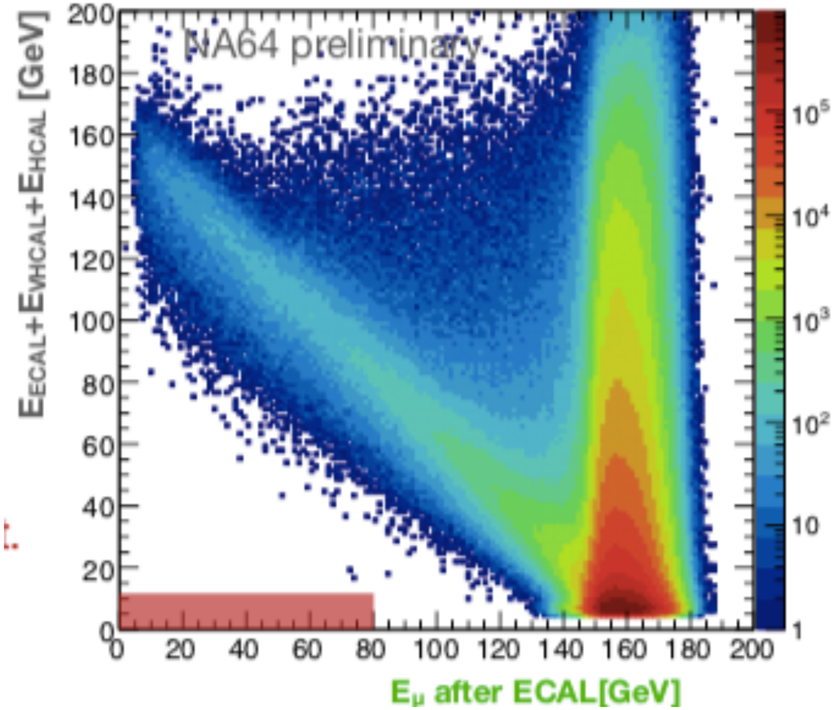
Signature:

- in: 160 GeV μ- track
- out: < ~100 GeV μ- track
- no energy in the ECAL, Veto, HCAL
- Sensitivity ~ g_μ^2

NA64μ – pilot run at M2 (2021)

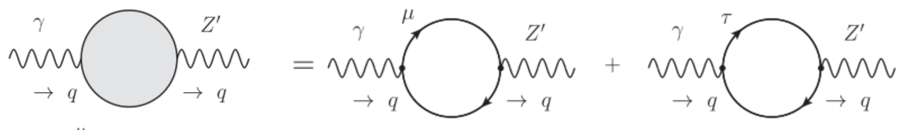




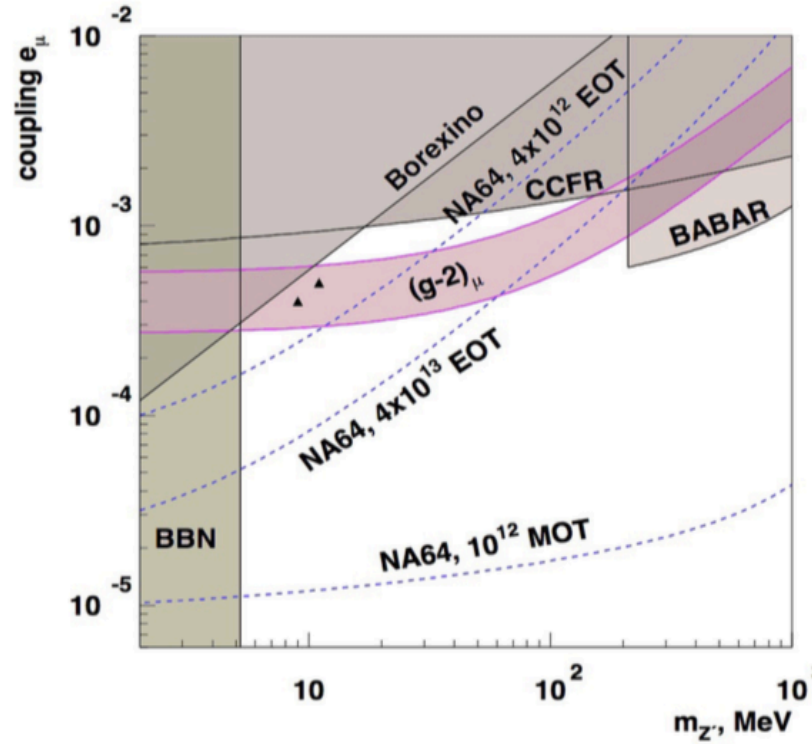


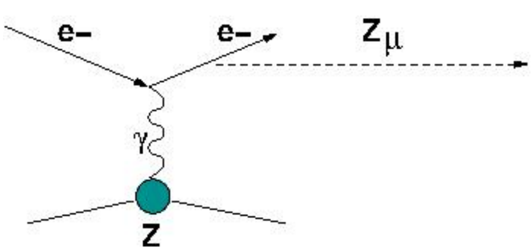
Analysis in progress

Complementarity of NA64e and NA64μ searches (I): $\gamma - Z_\mu$ mixing



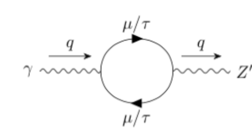
- $\gamma - Z_\mu$ kinetic mixing
- Mixing $\varepsilon \sim 3eg_\mu/16p^2 \ln(m_\tau/m_\mu)$
- $m_{Z'} < m_\mu$: $g_\mu = 4.8\times10^{-4}$, $\varepsilon = 6.8\times10^{-6}$
- **Loophole:** search for Z_μ with e- beams
  $e^- Z \to e^- Z Z_\mu$; $Z_\mu \to$ invisible (similar to A´)





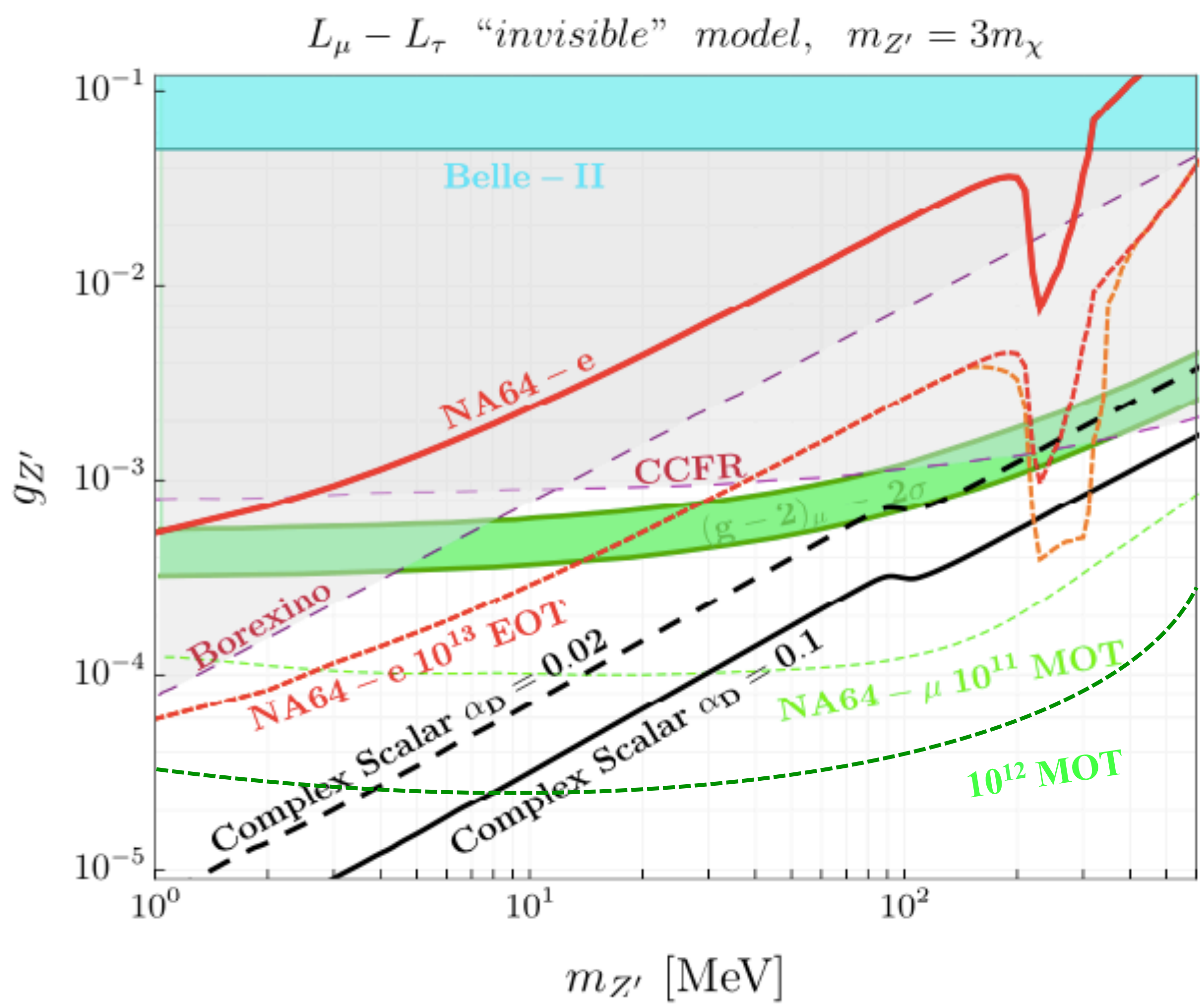
Complementarity of NA64e and NA64μ:
Z_μ < ~100 MeV should be also seen in NA64e

1801.10448



NA64μ / NA64e projections for L_μ-L_τ Z′

NA64 Collaboration, PRD(2022)



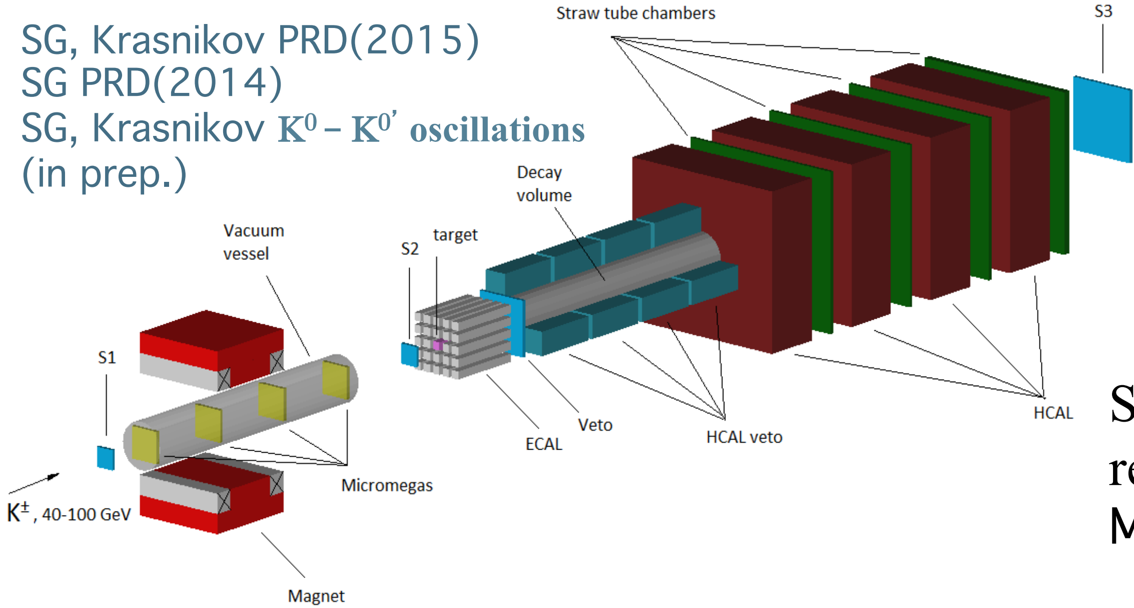
NA64h: Search for dark sector coupled to q's with π, K, p beams

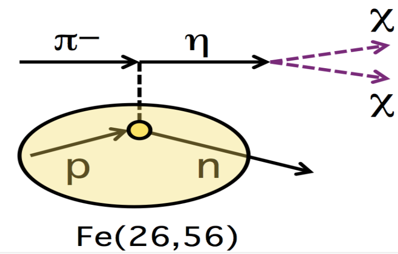
- π^0, η, η', K_S, $K_L \rightarrow$ invisible
- Leptophobic LDM in reactions pA->DM+X

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

K_L -> invisible: nothing in, nothing out

SG, Krasnikov PRD(2015)
SG PRD(2014)
SG, Krasnikov $K^0 - K^{0'}$ oscillations (in prep.)





Source of M^0: charge exchange reactions: π^-, $K^-+p \to M^0 + n$
$M^0=\pi^0, \eta, \eta', K_L, K_S$…

Main components :

- 20-50 GeV π,K- beam
- MM/GEM tracker, ECAL-Veto target
- 4π fully hermetic ECAL+ HCAL

Signature:

- in: 20-50 GeV π, K-track
- out: no energy in ECAL, Veto, HCAL

Complete disappearance of beam energy !

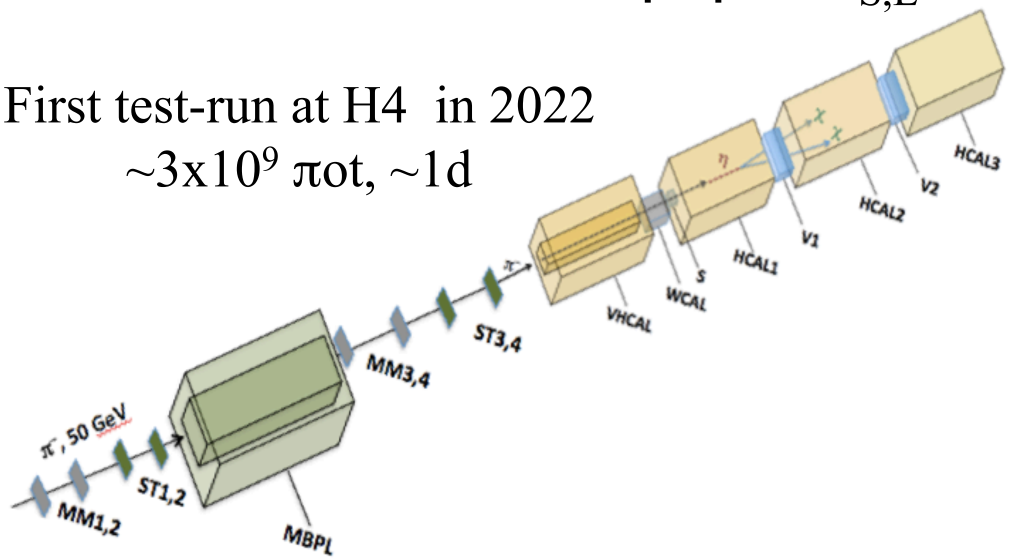
TABLE II. Expected upper limits on the branching ratios of different decays into invisible final states calculated for the total number of 10^{12} incident pions or kaons (see text for details).

Expected limits on the branching ratio	Present limit
$Br(K_S \to \text{invisible}) \lesssim 10^{-8}$	no
$Br(K_L \to \text{invisible}) \lesssim 10^{-6}$	no
$Br(\pi^0 \to \text{invisible}) \lesssim 10^{-8}$	$< 2.7 \times 10^{-7}$ [2]
$Br(\eta \to \text{invisible}) \lesssim 10^{-7}$	$< 1.0 \times 10^{-4}$ [3][a]
$Br(\eta' \to \text{invisible}) \lesssim 10^{-6}$	$< 5.2 \times 10^{-4}$ [3][a]

NA64h: Search for dark sector coupled to quarks

π^0, η, η', $K^0_{S,L}$,..→ inv decays

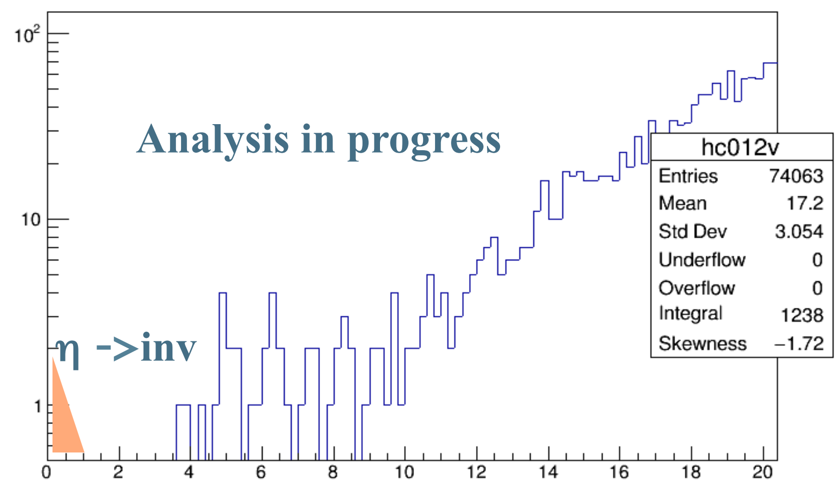
First test-run at H4 in 2022
~3x10^9 πot, ~1d



Signature of π(K) Z->η(K^0) (Z-1); η(K^0) ->inv

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

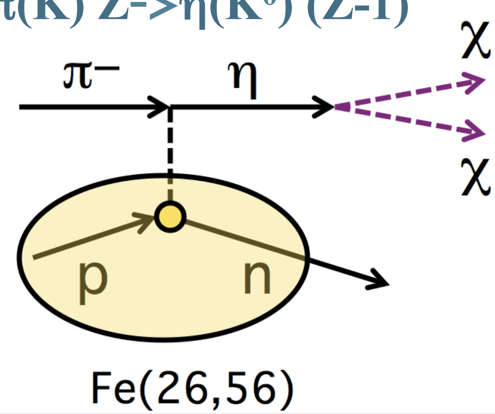
E(hadron), HCAL(0+1+2), VETO<Thr



Br(η -> inv) < 3x10^{-4} (~BaBar)

η, η', K0 – production:

π(K) Z->η(K^0) (Z-1)



NA64 research program: input to EPPS 2018.

Process	New Physics	Comments, Projections for limits
e^- **beam**		Required number of EOT: 5×10^{12}
$A' \to e^+e^-$, and	Dark photon	$10^{-5} < \epsilon < 10^{-2}$, $1 \lesssim m_{A'} \lesssim 100$ MeV
$A' \to invisible$		$2 \times 10^{-6} < \epsilon < 10^{-3}$, $10^{-3} \lesssim m_{A'} \lesssim 1$ GeV
$A' \to \chi\overline{\chi}$	sub-GeV Dark Matter (χ)	Scalar, Majorana, pseudo-Dirac DM
		$\alpha_D^{S,M} \lesssim 1$, $\alpha_D^{p-D} \lesssim 0.1$, for $m_\chi \lesssim 100$ MeV
$X \to e^+e^-$	new gauge X- boson	^{8}Be* anomaly, $\epsilon_e^{up} < 10^{-5}$; $\epsilon_e^{low} > 2 \times 10^{-3}$
milliQ particles	Dark Sector, charge quantisation	$10^{-4} < mQ < 0.1$ e, $10^{-3} < m_{mQ} < 1$ GeV
$a \to \gamma\gamma, invisible$	Axion-like particles	$g_{a\gamma\gamma}^{inv} \lesssim 2 \times 10^{-5}$, $m_a \lesssim 200$ MeV
μ^- **beam**		Required number of MOT: 10^{11} – 5×10^{13}
$Z_\mu \to \nu\nu$	gauge Z_μ-boson of $L_\mu - L_\tau$, $< 2m_\mu$	(g-2)$_\mu$ anomaly; $g_\mu^V \lesssim 10^{-4}$, with $\lesssim 10^{11}$ MOT
$Z_\mu \to \chi\overline{\chi}$	$L_\mu - L_\tau$ charged Dark Matter (χ)	$y \lesssim 10^{-12}$ for $m_\chi \lesssim 300$ MeV with $\simeq 10^{12}$ MOT
milliQ	Dark Sector, charge quantisation	$10^{-4} < mQ < 0.1$ e, $10^{-3} < m_{mQ} < 2.5$ GeV
$a_\mu \to invisible$	non-universal ALP coupling	$g_Y \lesssim 10^{-2}$, $m_{a_\mu} \lesssim 1$ GeV
$\mu - \tau$ conversion	Lepton Flavour Violation	$\sigma(\mu - \tau)/\sigma(\mu \to all) \lesssim 10^{-11}$
π^-, K^- **beams**	Current limits, PDG'2018	Required number of POT(KOT):$5 \times 10^{12}(5 \times 10^{11})$
$\pi^0 \to invisible$	$Br(\pi^0 \to invisible) < 2.7 \times 10^{-7}$	$Br(\pi^0 \to invisible) \lesssim 10^{-9}$
$\eta \to invisible$	$Br(\eta \to invisible) < 1.0 \times 10^{-4}$	$Br(\eta \to invisible) \lesssim 10^{-8}$
$\eta' \to invisible$	$Br(\eta' \to invisible) < 5 \times 10^{-4}$	$Br(\eta \to invisible) \lesssim 10^{-7}$
$K_S^0 \to invisible$	no limits	$Br(K_S^0 \to invisible) \lesssim 10^{-9}$
$K_L^0 \to invisible$	no limits	$Br(K_L^0 \to invisible) \lesssim 10^{-7}$
		complementary to $K^- \to \pi\nu\nu$

Summary

NA64e

- In 2022 NA64e has accumulated the milestone number of ~ 10^{12} EOT.
  World-leading results completed from the analysis 2016-2022 data on:
  - Light DM. First probing of LDM parameter space is very exiting.
  - S, P, V, and A and $(g-2)_e$; B-L Z′ → invisible; Lμ - Lτ Z′ → invisible

  Surprisingly, NA64e is highly competitive to high-precision frontier and high-intensity neutrino experiments.
- ~ 10^{10} e+OT are collected for the first time for the resonance A′ production. Projection sensitivity under study and looks very promising.

NA64μ

- The 2021-2022 runs were successful
  - commissioning of the detector,
  - ~4 x 10^{10} MOT accumulated
  - analysis of data sample is in progress

NA64h

- The 2022 run were successful
  - commissioning of the detector,
  - 3 x 10^{9} POT , 50 GeV accumulated
  - feasibility study is in progress

New physics below EW scale can effectively probed with the NA64 techniques.
We looking forward to further increase of sensitivity following detector upgrade.

The new results are expected to be rich, and might be unexpected

Backup Slides

Summary (contributions to PBC, schedule)

NA64e

- < LS3 ~5x10^{12} EOT
- LDM models
- A´,X17→e$^+$e$^-$ ATOMKI
- ALP(S) → $\gamma\gamma$ decays
- Dark *S, P, V, A,* milliQ
- Resonant A´ with e$^+$

NA64μ

- 2021 test run
- (g-2)$_\mu$ ~10^{11} MOT
- LDM, A´~10^{13} MOT
- μ - τ conversion

NA64h

- 2024–26 test run
- π^0,η,η´ →inv, 10^{12} POT
- K$^0_{S,L}$→ inv~10^{12} KOT
- pA→ X+E$_m$~10^{12} POT

NA64++ provisional time schedule

2016 I 2017 I 2018 I 2019 I 2020 I 2021 I 2022 I 2023 I 2024 I 2025 I 2026 I 2027 I

e$^-$, H4 → (g-2)$_\mu$, 8Be, Dark Sector | LS2 | 8Be, Dark Sector | LS3

μ^-, M2 → Proposal, Preparation | g$_\mu$-2, Dark sector, μ-τ | LS3

π^-, K$^-$, H2-H8,T9 → π^0,η,η´,K$_L$→inv | LS3