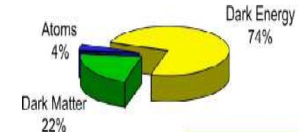
JINR participation in the NA64 project «Search for dark sectors in missing energy events»

Status report & prolongation

D.Peshekhonov on behalf of the team

Motivation



In spite of the fact that the SM is in great agreement with many taken measurements, it cannot be considered as a complete theory. Astrophysical and cosmological observations, obviously demonstrate the existence of the dark matter (DM) and dark energy which make about 25% and 70% of its full weight in the Universe. Thus, the SM actually describes only ~5% of the Universe matter.

Intensive search for major candidates for DM on the LHC (SUSY) and in underground laboratories (WIMPs) has not resulted. An essential problem is that the main sampler for DM properties study serves gravitational interaction. Therefore, attempts to detection of a new type of interaction between usual and DM are extremely interesting and important.

Recently the assumption that DM is a part of the so-called Hidden or Dark Sector consisting of families of new particles that are arranged as a visible part of the Universe was made.

It is supposed that the main (phenomenologically unobjectionable on F. Wilczek) interactions (portals) between Dark Sector and SM, which allow creation of the renormalized SM expansion, can occur due to mixing a) scalar fields (Higgs, F. Wilczek), b) vector fields (**photon - dark photon**, Okun, Glashow) c) neutrino (right-handed neutrino).

In such SM expansion, one of the most interesting is the model of the hidden sector which considers possible existence of "dark" electromagnetism by analogy with SM electromagnetism. In this model, interaction between the SM and hidden particles occurs due to the **exchange of the massive dark photon A' as a result of its mixing with SM photon**. If it is light, < 1 GeV, then search of such A' can be carried out at accelerators in experiments with high sensitivity.

If the A’ is the lightest state in the dark sector, then it would decay visibly, i.e., to SM leptons or hadrons. However, in the presence of lighter dark matter, with masses < $m_{A'}$, the A’ would predominantly decay invisibly into those particles.

NA64 experiment

The P348 experiment was proposed to the CERN SPSC in January 2014 with the primary goal to search for the A'->invisible and A'->e+e- decay modes.
In January 2016 P348 was recommended for approval **as a CERN SPS experiment for the search for the A'->invisible decays.**
The CERN Research Board officially approved the P348 experiment on March 9, 2016 with the reference number **NA64**.

JINR participation was approved by 46th PAC for PP in Jan. 2017

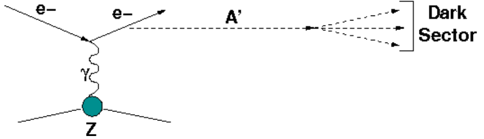
G.D. Kekelidze, V.Yu. Karjavine, V.A. Kramarenko, V. Lysan, V.A. Matveev,
D.V. Peshekhonov, A.A. Savenkov,, I.A. Zhukov, A.Festchenko, T.Enik
with FTE = 2,4 *(+ at least, 2 units for test of electronic & support in the analysis)*

JINR participation in 2019

G.Kekelidze (0,4), V.Karjavine (0,1), V.Kramarenko (0,4), V.Lysan (0,8), V.Matveev (0,1),
D.Peshekhonov (0,3), A.Savenkov (0,3), I.Zhukov (0,8), A.Festchenko (0,1), T.Enik (0,2),
P.Volkov (0,5), A.Ivanov(0,3), V.Burtsev(0,5), V.Frolov (0,2)

FTE = 5

NA64 goals and approach

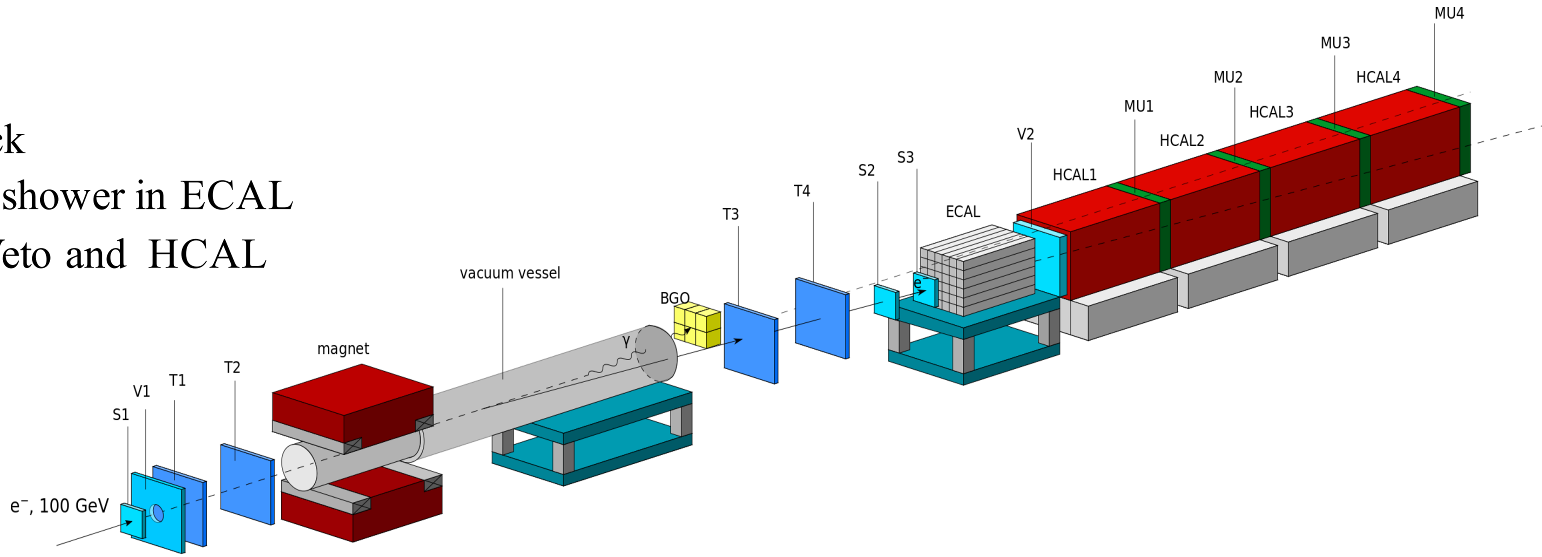


A' could have a mass $m_{A'} < 1$ GeV - associated with a spontaneously broken gauged $U(1)_D$ symmetry- and couple to the SM through kinetic mixing with the ordinary photon, $-\frac{1}{2}\epsilon F_{\mu\nu}A'^{\mu\nu}$ parameterized by the mixing strength $\epsilon \ll 1$.

The NA64 collaboration currently focuses on the search for the *A' -> invisible* decay with the H4 electron beam with the main goal to accumulate up to **5 * 10^{12} EOT** in total in order to probe most of the remaining $(\epsilon; m_{A'})$ parameter space and unexplored parameter regions of sub-GeV dark matter models.

Signature:

- in: 100 GeV e- track
- out: < 50 GeV e-m shower in ECAL
- no energy in the Veto and HCAL
- Sensitivity $\sim \varepsilon^2$

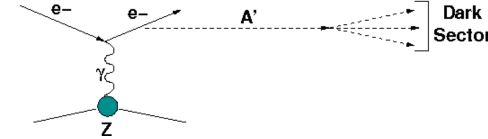


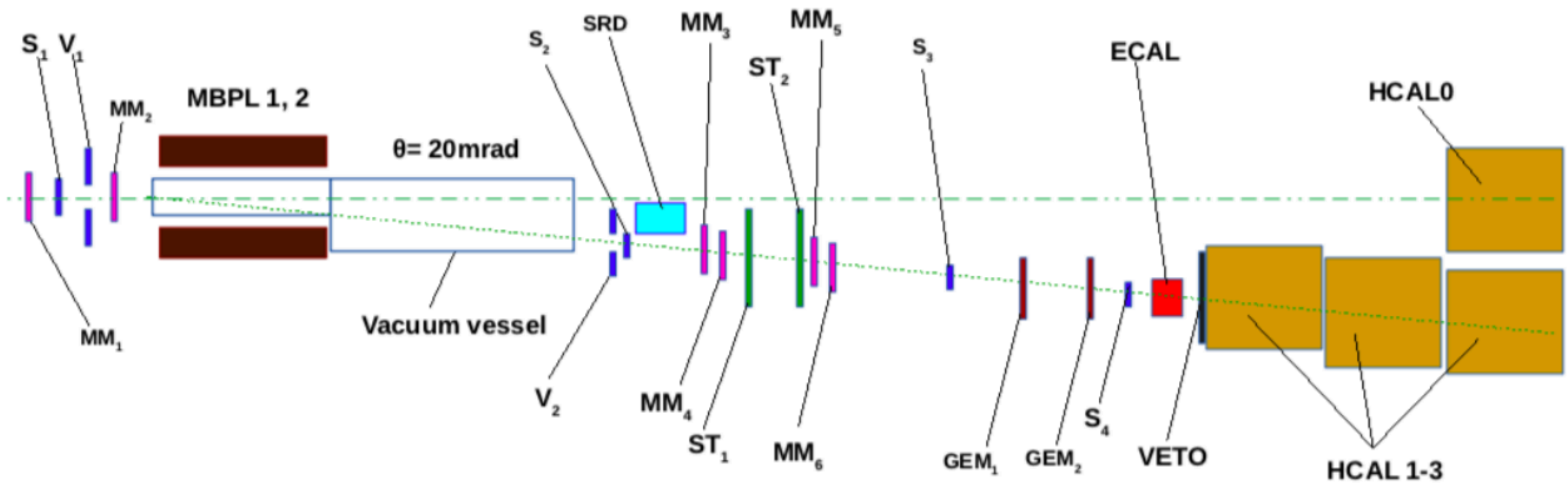
Requirements:

- high quality e- beam: monochromaticity, purity, intensity
- e^- tagging system: to suppress pion, kaon decays in flight
- calorimeter hermeticity: to avoid energy leak & high quality tracking

Expected sensitivity: single A´ event per $10^{10} - 10^{12}$ eot

NA64 spectrometer



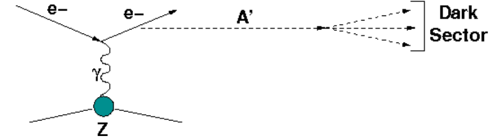


NA64 experiment uses H4 100 GeV electron beam. The maximum intensity is 10^7 per SPS spill of 4.8 s.

Detector utilizes the beam defining scintillator counters S_{1-4} and veto $V_{1,2}$, dipole magnets $MBPL_{1,2}$ (integral magnetic field of 7 T·m), and a low-material-budget tracker: upstream - $MM_{1,2}$ and downstream - MM_{3-6} Micromegas, straw-tube $ST_{1,2}$ and $GEM_{1,2}$ chambers (total precision $\delta p/p_{e-} \sim 1\%$).

To enhance the electrons identification their synchrotron radiation in the magnetic field is used – SRD is PbSc sandwich calorimeter of a very fine segmentation or BGO crystals. It suppresses the initial admixture of the hadron contamination in the beam ($\pi/e- < 10^{-2}$) by a factor $> 10^3$. The detector has an active dump target - ECAL, 6×6 Shashlik-type modules assembled from Pb and Sc plates for measurement of the electron energy E_e. Each module has ~ 40 X_0, first 4X_0 serves as a pre-shower. Also detector is equipped with a large veto counter VETO and massive, hermetic hadron calorimeter HCAL of ~30 nuclear interaction lengths in total. $HCAL_{1-3}$ serves as a veto to detect muons or hadrons produced in the e^--A interactions in the target, the zero-degree calorimeter $HCAL_0$ is used to reject events accompanied by hard neutrals from the upstream e^- interactions.

Data from 2016-2018 runs



Obtained statistics:

2016: $n_{EOT} = 4.3 \times 10^{10}$ EOT, beam intensity $(1.5\text{-}5) \times 10^{6}$ e^{-}/spill
2017: $n_{EOT} = 5.4 \times 10^{10}$ EOT, beam intensity $(5-6) \times 10^{6} e^{-}$/spill
2018: $n_{EOT} = 1.87 \times 10^{11}$ EOT, beam intensity $(8-9) \times 10^{6} e^{-}$/spill

In total **$n_{EOT} = 2.84 \times 10^{11}$ EOT** were analyzed with similar selection criteria.

Candidate events were requested to have the missing energy $E_{miss} > 50$ GeV.
The signal box was defined as $E_{ECAL} < 50$ GeV; $E_{HCAL} < 1$ GeV

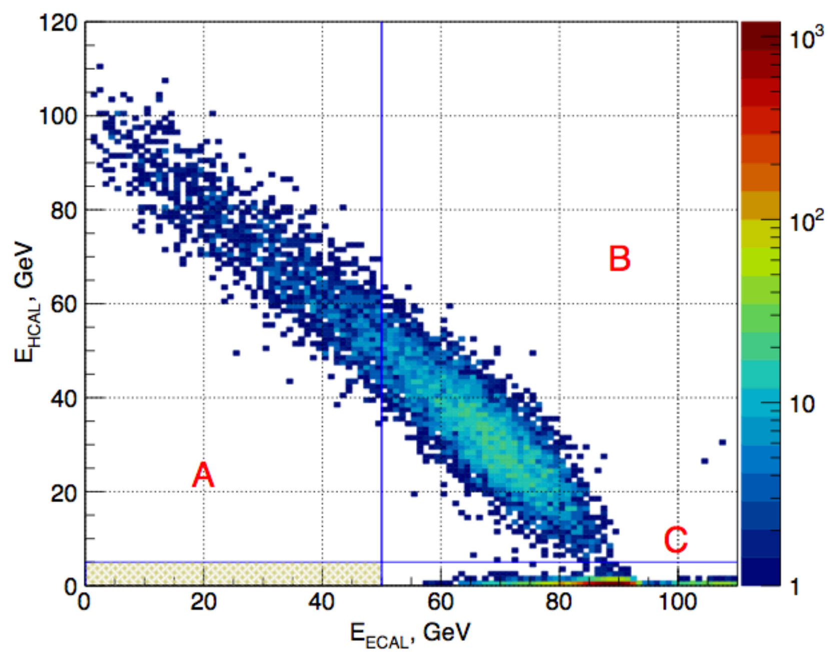
Selection criteria:

-incoming particle track should have the momentum 100 ± 3 GeV and a small angle with respect to the beam axis to reject tracks from the upstream e^{-} interactions;

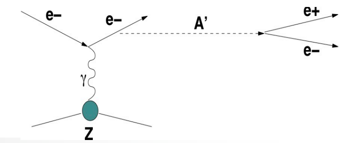
-energy deposited in the SRD detector should be within the SR range emitted by e^{-}s and in time with the trigger;

-lateral and longitudinal shape of the shower in the ECAL should be consistent with the one expected for the signal shower;

-no multiple hits in the Straw - an effective cut against hadron electro-production in the beam material upstream the dump; and no activity in VETO.



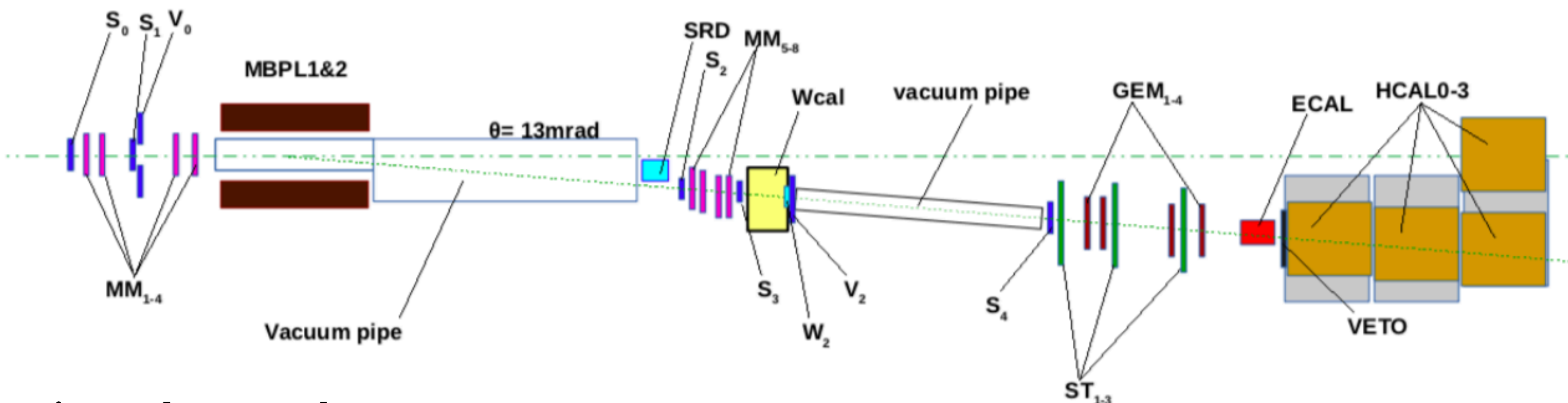
Search for the A´->e⁺e⁻ decay



Direct search for a new 16.7MeV boson (X)

The ATOMKI experiment has reported the observation of a 6.8σ excess of events in the invariant mass distributions of e^+e^- pairs produced in the nuclear transitions of excited $^8Be^*$ to its ground state via internal pair creation. Due to its coupling to electrons, the X could be produced in the bremsstrahlung reaction $e^-Z \rightarrow e^-ZX$ and observed through the subsequent decay into e^+e^- pair.

The data were collected in two runs in 2017 and 2018, total statistics is **8.4×10^{10} EOT** .



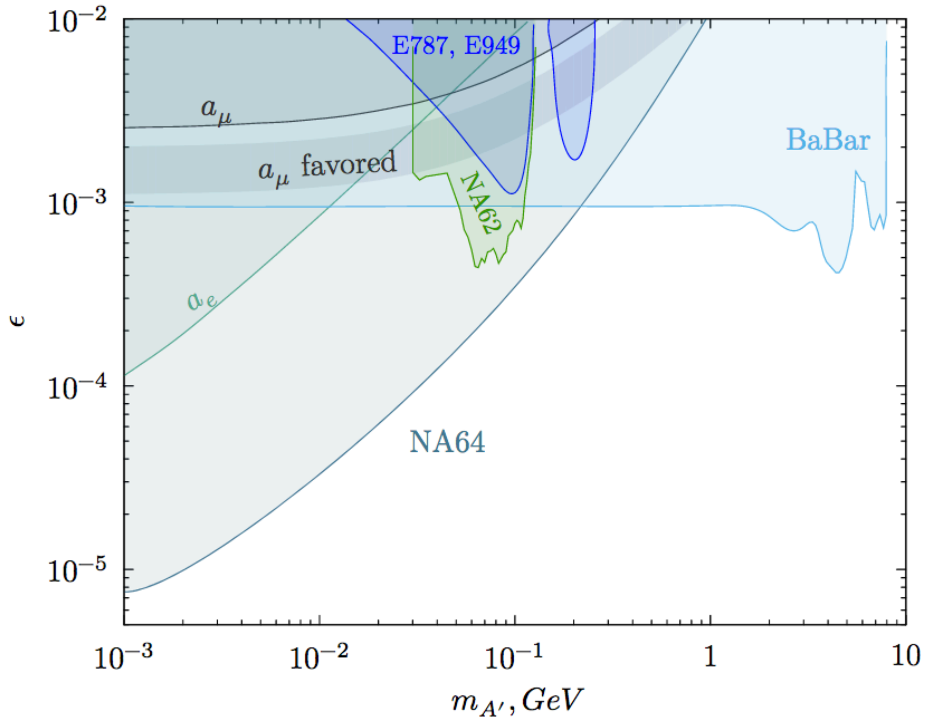
Experimental approach

WCAL was a target and served as a dump to absorb the e^- energy completely. The bremsstrahlung X(A′) decays in a flight into e^+e^- pair downstream the WCAL. A fraction (f) of the primary beam energy $E_1=fE_0$ is deposited in the WCAL. The remaining part of the primary electron energy $E_2=(1-f)E_0$ is transmitted by the A′ and deposited in the second downstream calorimeter ECAL. Signal event has two e-m showers in the detector: one in the WCAL and another one in the ECAL, with the total energy $E_{tot}=E_{WCAL}+E_{ECAL}=E_0$

Result from 2016-2018 runs

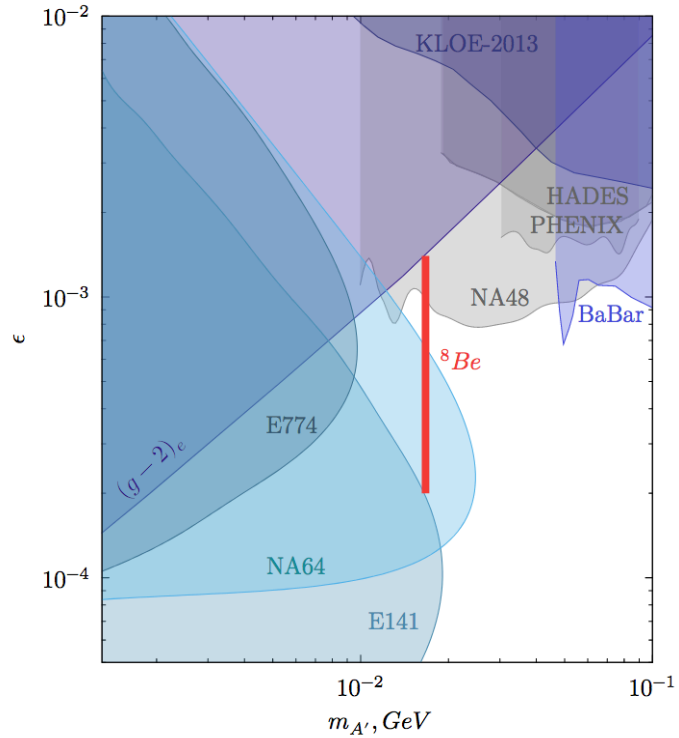
Background source	Background number, n_b
punchthrough γ's, cracks, holes	< 0.01
loss of dimuons	0.024 ± 0.007
$\mu \to e\nu\nu,\ \pi,\ K \to e\nu,\ K_{e3}$ decays	0.02 ± 0.01
e^- interactions in the beam line	0.43 ± 0.16
μ, π, K interactions in the target	0.044 ± 0.014
accidental SR tag and μ, π, K decays	< 0.01
Total n_b	0.53 ± 0.17

Source of background	2017 data	2018 data
punchthrough γ	< 0.001	< 0.0005
$K_S^0 \to 2\pi^0$	0.06 ± 0.034	0.005 ± 0.003
$\pi N \to (\geq 1)\pi^0 + n + ...$	0.01 ± 0.004	0.001 ± 0.0004
π^- hard brem. in the WCAL	< 0.0001	
$\pi, K \to e\nu,\ K_{e4}$ decays	< 0.001	
$eZ \to eZ\mu^+\mu^-; \mu^\pm \to e^\pm\nu\nu$	< 0.001	
Total	0.07 ± 0.035	0.006 ± 0.003



The NA64 90% C.L. exclusion region in the $(m_{A'}, \epsilon)$ plane.

CERN-SPSC-2019-024 / SPSC-SR-255
07/06/2019

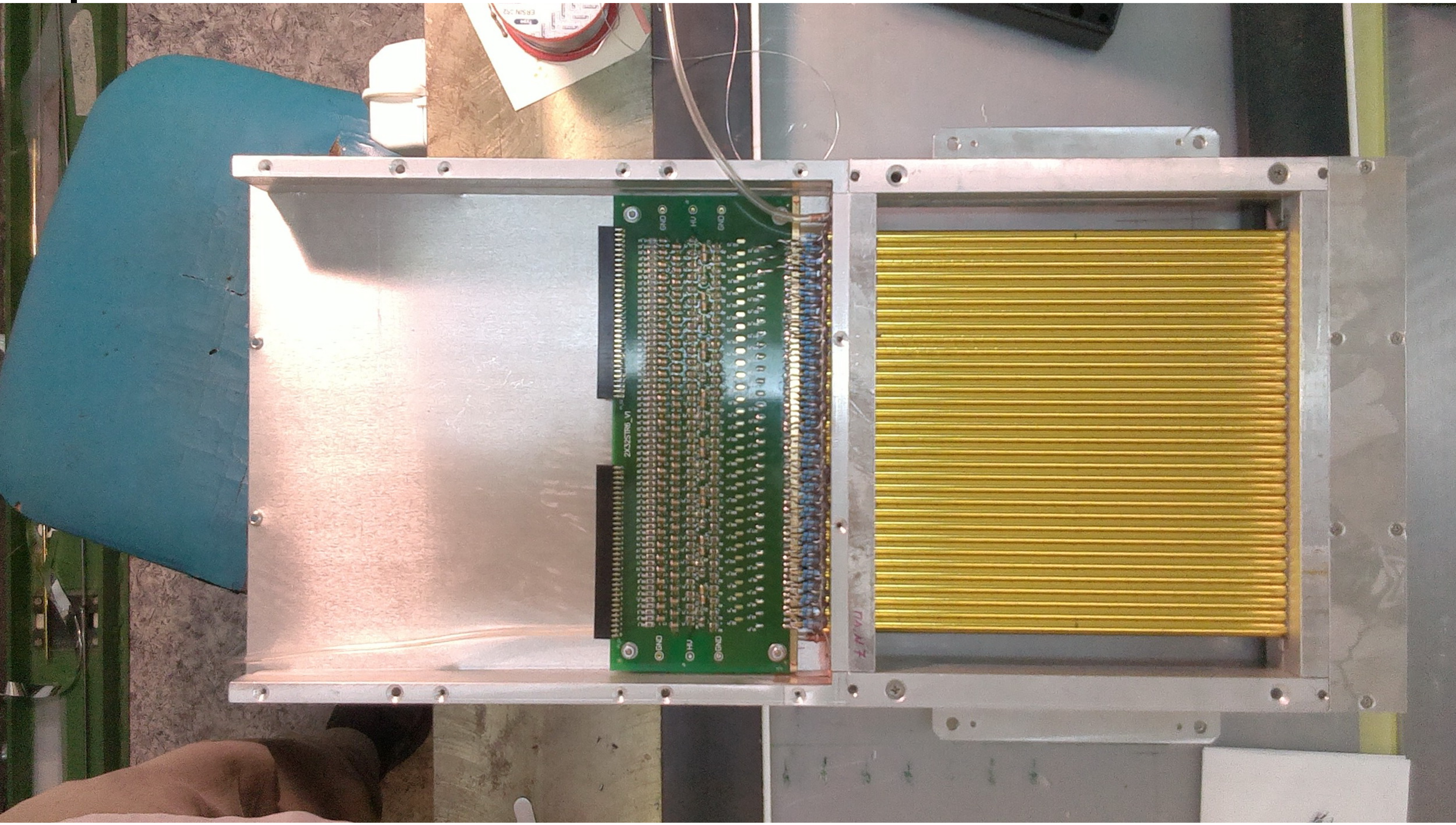


The preliminary 90% C.L. exclusion areas in the (m_X; ϵ_e) plane from the NA64 experiment (blue area).

Current JINR responsibilities

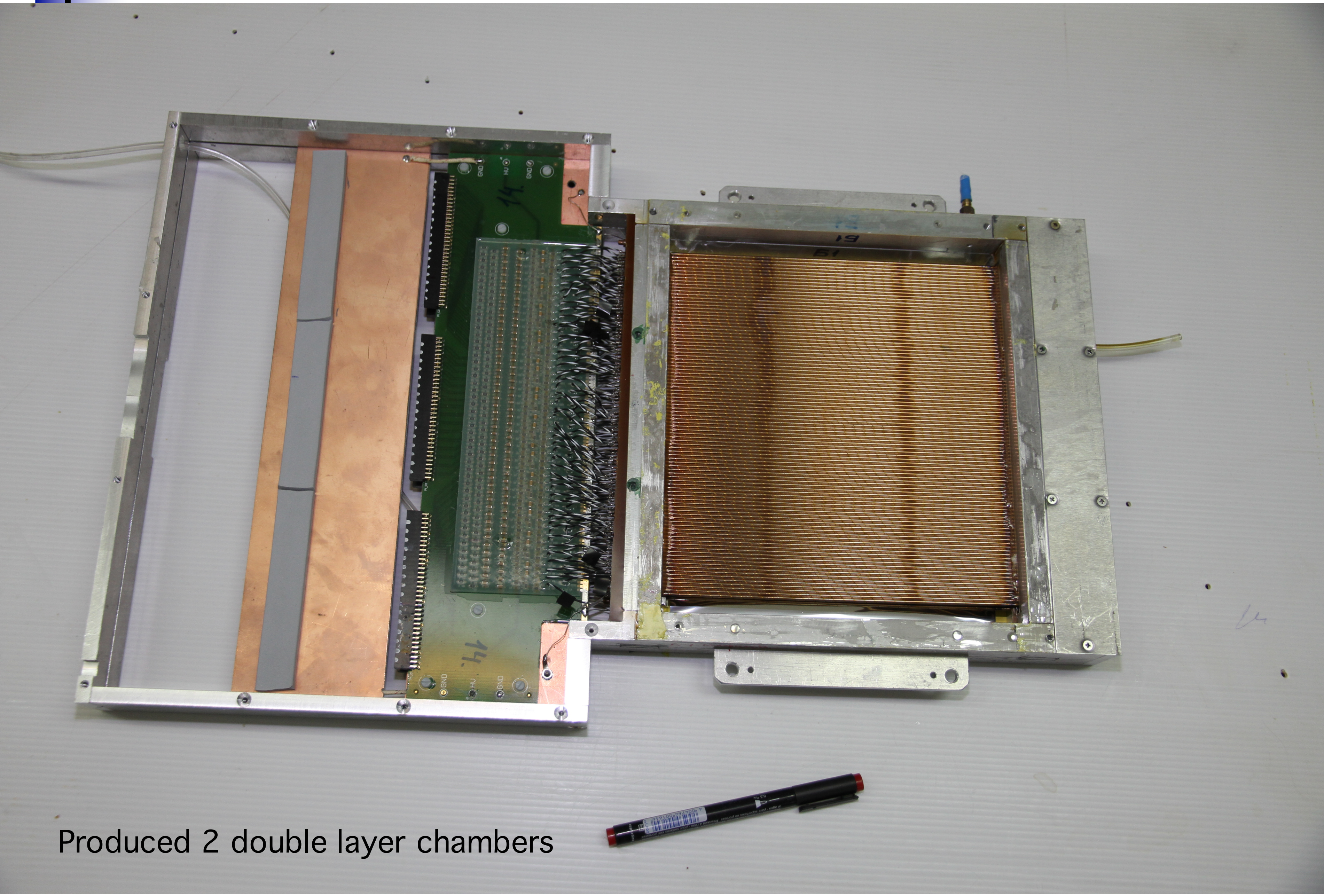
Responsibility	Deliverables	Institutions
Scintillators	Beam trigger counters	IHEP
	Veto counters	IHEP
Beam hodoscopes	Two modules	IHEP, TPU
Tracker system	Micromegas	ETHZ
	Straw tubes	JINR, LPI, SINP MSU
	GEMs	HISKP
ECAL	Preshower, ECAL, Photo-readout, WLS fibers, Trigger modules	IHEP, INR
HCAL	Four Fe-Sc modules, Photo-readout, WLS fibers	IHEP, INR, UTFSM
Synchrotron Radiation detector	BGO Crystals	ETHZ
	LYSO Crystals	UTFSM
	Shashlik	IHEP, INR
Theory	A′ and milli-Q production cross-sections, decay rate	INR
Slow control	Centralized slow control	IHEP, INR, all
DAQ	DAQ modules	IHEP, all
Electronics	Modules	All

6mm straw (double layer, 64ch)



Produced 12 double layer chambers

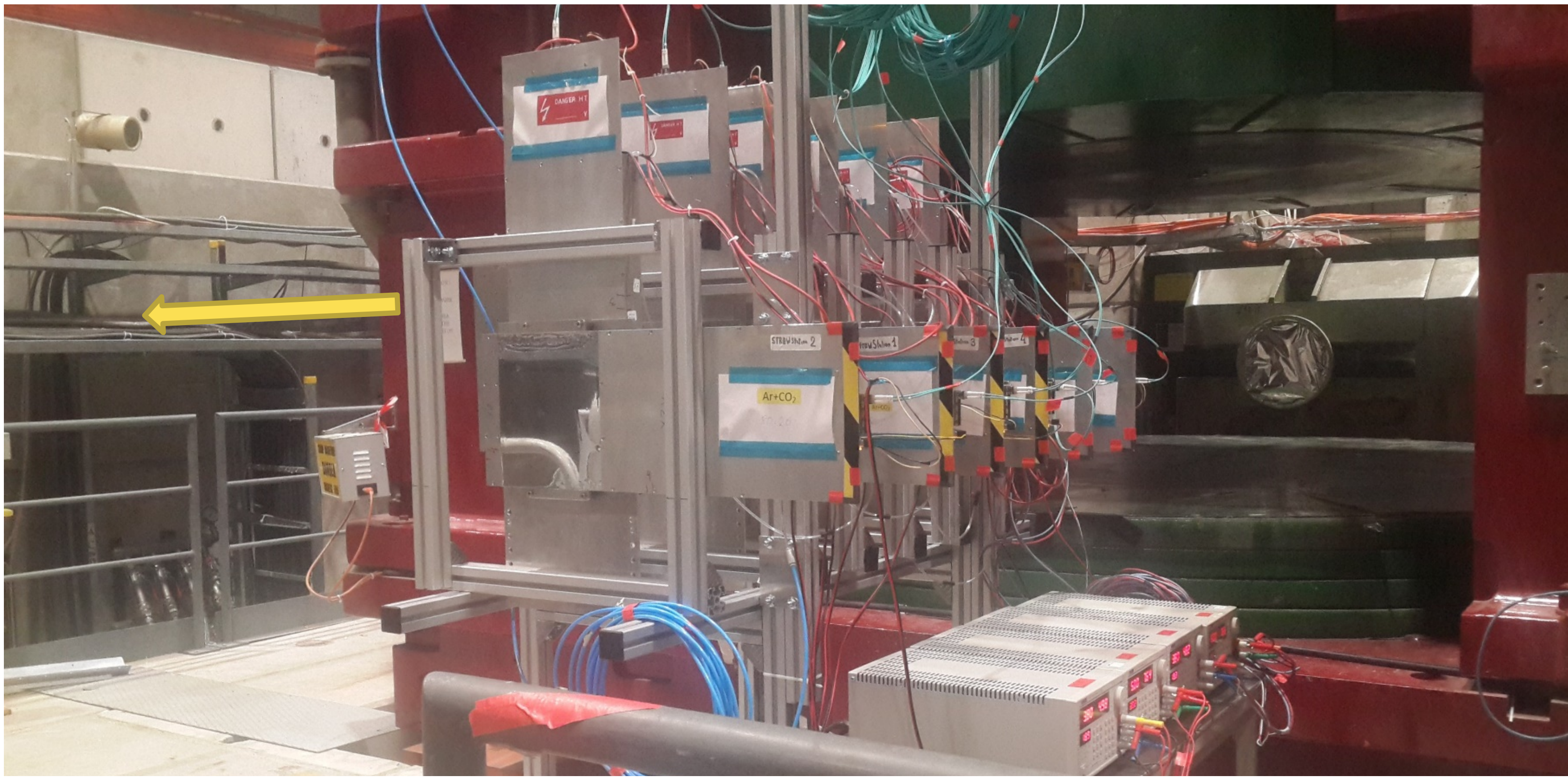
2mm straw (double layer, 192ch)



Produced 2 double layer chambers

Current JINR responsibilities

11 of May 2018 NA64 experimental zone.
Six stations (XXYY) of 6mm straw tube detectors set on the beam.



	Номер прошивки: 10.152.72. ...												
	126	127	124	125	122	123	120	121	118	119	116	117	108
Beam --->	X	Y	X	Y	X	Y	X	Y	X	Y	X	Y	T0
# порта мультипл	1	0	3	2	5	4	7	6	9	8	11	10	12
	ST2		ST1		ST3		ST4						

Current experiment status

Invisible decay

Data from years 2016 - 2018 have been processed and partially (2016-2017) published, the total statistics is **~3 * 10^{11}** events, candidates for the signal corresponding to the signature of the dark photon have not been detected.

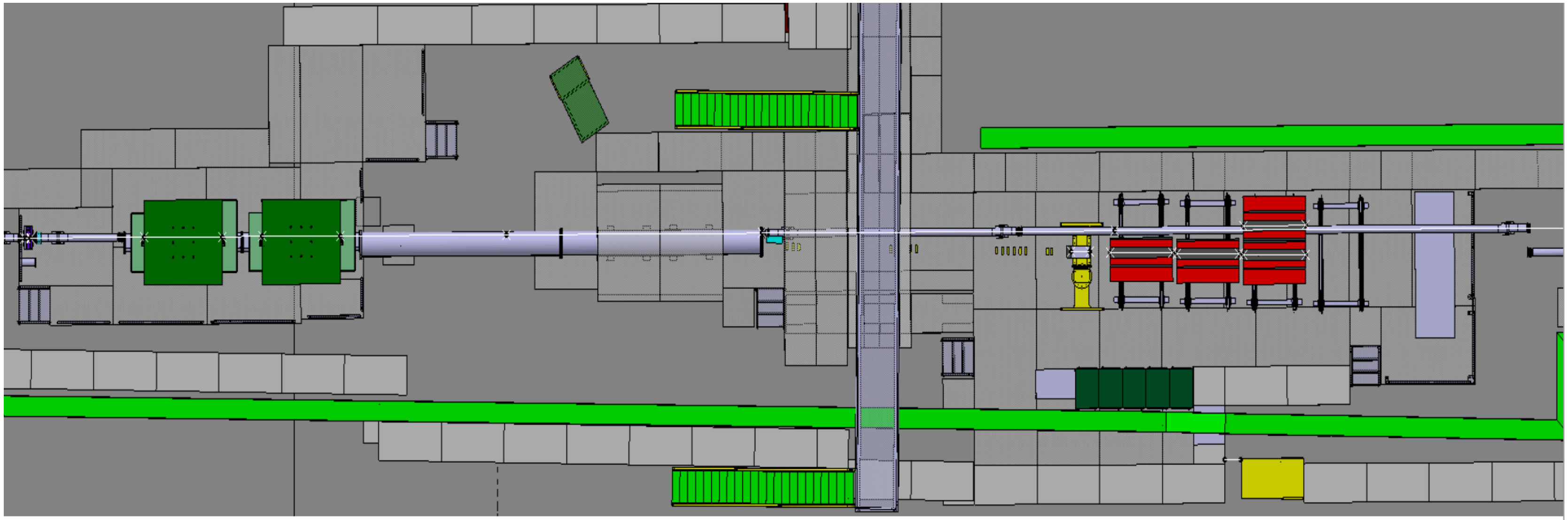
Visible decay

Part of 2017-2018 runs was devoted to the search for a new hypothetical X-boson with the mass of 16.7 MeV, which could explain the result on the anomalous production of e^+e^- pairs obtained in the ATOMKI experiment. **$8.4x10^{10}$** events were taken, hypothetical boson was not found, obtained data allowed significantly increase the limit on the coupling constant of the X-boson with an electron, as well as on the mixing parameter of the A´ with the conventional photon.

CERN-SPSC-2019-024 / SPSC-SR-255
07/06/2019

Experimental zone

Permanent experimental zone at CERN on the H4 channel was allocated for the experiment. Preparatory works on its arrangement started.



Upgrades for 2021-2024 runs

Existed facility has to be upgraded for more efficient operation with a high beam intensity.
In 2021 run collaboration plans significantly increase statistics by registering **~ $5*10^{11}$ - 10^{12}** events for further searches for A' and X-boson decays.

To increase the overall signal efficiency and improve background rejection the following upgrade of the setup is planned:
-produce and install additional number of the MM, GEM, ST stations. A possible use of Si pixels as the tracker for the $X \to e^+e^-$ decay search is also considered;
-install higher transversely segmented SRD detector with improved readout;
-install large Veto HCAL (VHCAL) in front of the ECAL to reject large angle neutral secondaries from the upstream e−hadron interactions

In order to probe the theoretically interesting parameter space $\epsilon \simeq 10^{-5} - 10^{-3}$ and $m_{A'} < 1$ GeV the number of accumulated electrons on the target is required to be around **$n_{eot} \sim 5 \times 10^{12}$** and a very low background rate. Assuming the beam rate $\sim 10^7$ e^-/spill and ~4000 good spills/day, about 6 months of data taken are required.

Request to the JINR group:

In order to increase detector hermetisity and improve signal/background separation it is proposed to produce 7 new double layer 6mm straw chambers with a size 1200x600 мм^2 and electronics (responsibility of SRI NP BSU, Belarus);

NA64 with muon beam

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]

4 The experiment to search for the $Z_\mu \to invisible$ decays

The experiment can to perform in two Phases:

- The main goal of the Phase 1 is to probe the muon $(g-2)_\mu$ parameter space, which would require accumulation of $\lesssim 10^{11}$ muons on target (MOT)
- The main goal of the Phase 2 is to cover the DM parameter space by collecting $\gtrsim 10^{13}$ MOT.

NA64 with muon beam

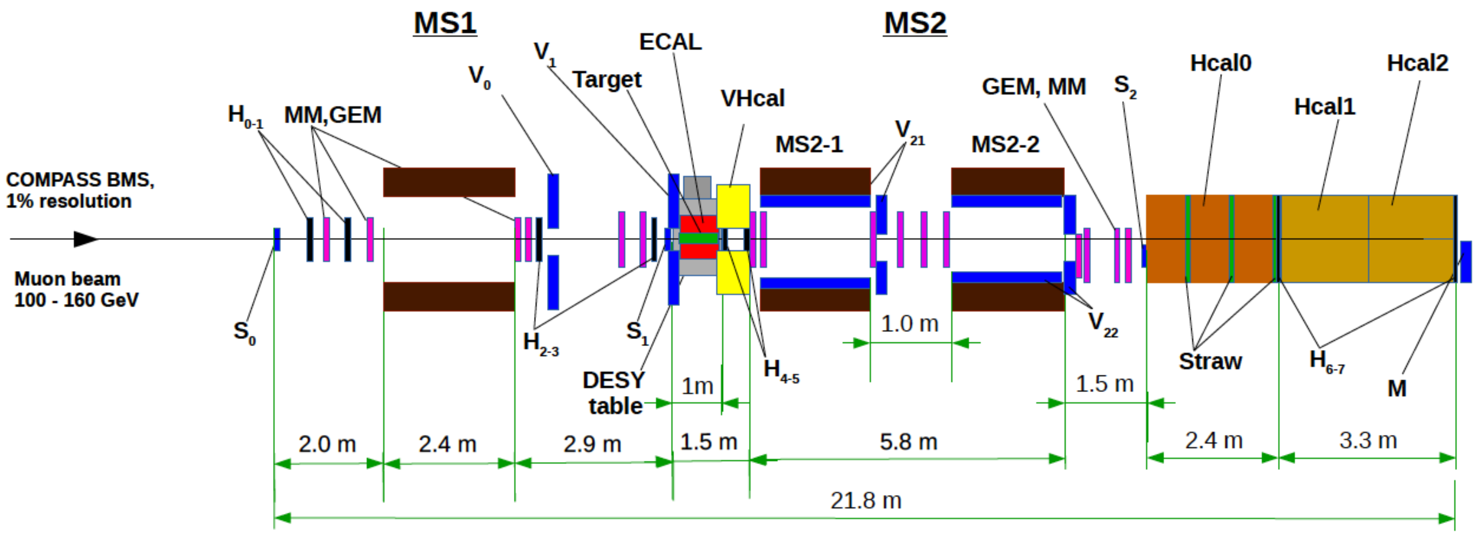


Figure 4. Schematic illustration of the setup to search for dark Z_μ. The bremsstrahlung Z_μs are produced in the forward direction in the reaction $\mu + Z \to \mu + Z + Z_\mu$ of a high-energy muon scattering off nuclei of an active target (see text for definition of colors).

The method of the search is as follows. The bremsstrahlung Z_μs are produced in the reaction (3.1) which occurs uniformly over the length of the target (T). A fraction (f) of the primary beam energy $E'_\mu = fE_\mu$ is carried away by the scattered muon which is detected by the second magnetic spectrometer, as shown in Fig. 4, tuned for the scattered muon momentum $p'_\mu \lesssim fp_\mu$. The remaining part of the primary muon energy $(1-f)E_\mu$ is carried away beyond all the subdetectors by the neutrinos from the prompt $Z_\mu \to \nu\nu$ decay resulting in the missing energy $E_{miss} = E_\mu - E'_\mu$.

Required resources

N	Purpose of expenses	1st year	2d year	3d year	Full cost
	Direct expenses				
	Accelerator				
	Design bureau				
	Computing				
	Materials	45	45	10	100
	Equipment	45	30	20	95
	Collaboration funds	15	15	15	45
	Contracts for R&D				
	Business trips	40	40	40	120
	a) non-rouble zone	40	40	40	120
	б) rouble zone				
	в) by protocols				
	Total:	**145** **50***	**130** **45***	**85** **10***	**360** **105***

Summary

- NA64 start data taking;
- JINR group successfully fulfills obligations corresponding to the straw tube detectors and also participates in development of on-line monitoring and analysis software, development and support of DAQ, electronics development, joint new participants - SRI NP BSU;
- SPSC approved data taking with electron beam on the period 2021-2024, new NA64 experimental area is in preparation (CERN investment 400к SFr);
- SPSC proposed to provide 30 days pilot run with the muon beam at the beginner of 2022, the Proposal of this experiment is under consideration.

SWOT analysis
Strengths – NA64 obtains unique data in unexplored region of $(\epsilon; m_{A'})$ parameter space
Weaknesses – human resources
Opportunities – at the moment the are no another experiment doing the same measurements
Threats – expected statistics will not be obtained due to - ???

Thank you

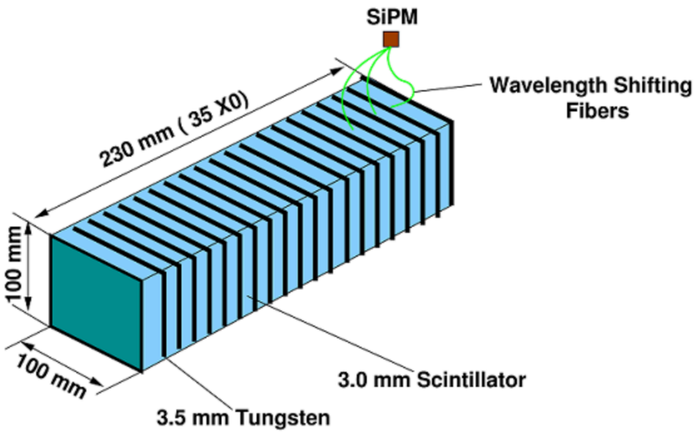


Figure 6. Schematic illustration of a scintillator-fiber-tungsten module consisting of a stack of tungsten and scintillator plates of the size 3.5 mm and 3 mm, respectively. Wavelength shifting fibers pass laterally through the plates and are read out at the side of the module with either SiPMs or APDs photodetector. The similar module with a lateral 2x2 (or 3x3) cells segmentation is also under design.

- Longitudinal segmentation → 4 modules
- Energy range → 0.5÷120 GeV
- Energy resolution → 65%/√E + 6%
- Full energy deposition, thickness → ~ 28 λ
- No crack, uniformity → 2÷3%
- Module size → 60x60 cm²
- Module length → 150 cm
- Number cells per modules → 9
- Cell size → 192x194 mm²
- Read out → PMT, FEU-84-3

1. Electromagnetic calorimeters ECAL + Preshower
- module design: (1.5 mm Pb + 1.5 mm Sc) × 150 layers
- purpose: energy measurements, shower profile measurements, e/π separation
- performance: energy resolution $\Delta E/E \simeq 0.18/\sqrt{E}$, X,Y resolution $\simeq$ 3 mm,$e/\pi \lesssim 10^{-2}$
- event rate: up to 10^6 e^- per spill, $10^{12} - 10^{13}$ e^- in total run

2. Hadronic Calorimeter HCAL, 4 modules
- module design: (25 mm Fe+ 4 mm Sc) × 48 layers
- purpose: secondary energy detection, π, p, n detection
- performance: energy resolution $\Delta E/E \simeq 0.62/\sqrt{E}$, π-hermeticity $\simeq 10^{-9}$
- event rate: up to 10^6 π per spill, $10^{10} - 10^{11}$ in total run

3. Beam counters S1,S2 and Hodoscopes H1,H2
- design: Sc 1mm hodoscopes
- purpose: e^-e^+ pair hits, track detection and T_0
- performance: spacial resolution $\simeq$ 1 mm, 2 tracks separation $\Delta R \gtrsim 1$ mm
- event rate: up to 10^6 e^- per spill

4. Veto counter
- design: plastic scintillator, 5 cm x 60x 60 cm^3
- purpose: low energy charged track detection
- performance: mip inefficiency $\lesssim 10^{-3}$
- event rate: up to 10^5 hits per spill

5. Synchrotron radiation counter, BGO array
- design: diam 60x200 mm thick BGO crystal
- purpose: γ ray energy mesurements in the range 1-30 MeV
- performance: energy resolution $\Delta E/E \simeq 3\%$ at 1 MeV, time resolution $\simeq$ 2 ns.
- event rate: up to 10^6 1-30 MeV γ per spill, $\simeq 10^{11}$ for full run

6. Decay volume
- design: diameter $\simeq$30 cm × 15 m length, filled with He or vacuum $\lesssim 10^{-5}$ Torr
- purpose: minimize secondary particles interactions

7. Micromegas tracker, 4 chambers
- design: diam 80 mm
- purpose: e- track measurement
- performance: momentum resolution at 100 GeV $\Delta P/P \simeq 2\%$.
- event rate: up to a few 10^5 per spill

8. Straw tube chambers, 4 chambers
- design: 200x200 mm^2, thickness $\simeq$ 200 μm thick, straw tube diameter 2 and 6 mm
- purpose: e- track measurement
- performance: momentum resolution at 100 GeV $\Delta P/P \simeq 2\%$.
- event rate: up to 10^6 per spill