Search for Light Dark Matter in the experiment NA64 at the CERN SPS

Mikhail Kirsanov

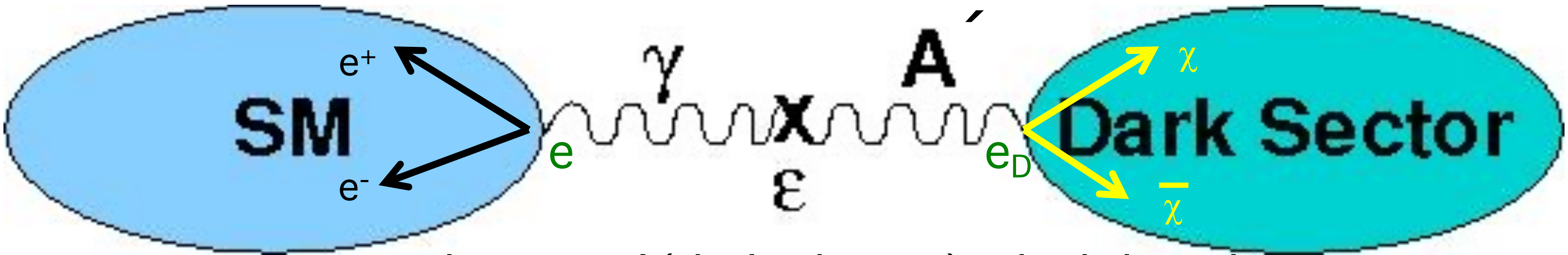
INR Moscow

Outline

- Motivation
- The NA64 experiment (setup, runs)
- Simulation of the Dark Matter production: DMG4 package
- Results on A' in invisible mode, new analyses
- Plans for the invisible mode
- NA64h: searches in hadron beams
- ALP search in invisible mode configuration
- Visible mode: X-boson, motivation, results, new project
- $(g-2)_\mu$ and NA64μ

Vector portal to Dark Sector

Okun, Holdom'86 .. $\alpha_D = e_D^2/4\pi$



- new massive boson A´ (dark photon) which has kinetic mixing with ordinary photon: $\Delta L = \varepsilon/2\ F^{\mu\nu} A'_{\mu\nu}$

- Production: A´ - bremsstrahlung $e^- Z \rightarrow e^- Z A'$, $\sigma \sim Z^2 \varepsilon^2 / m_{A'}^2$

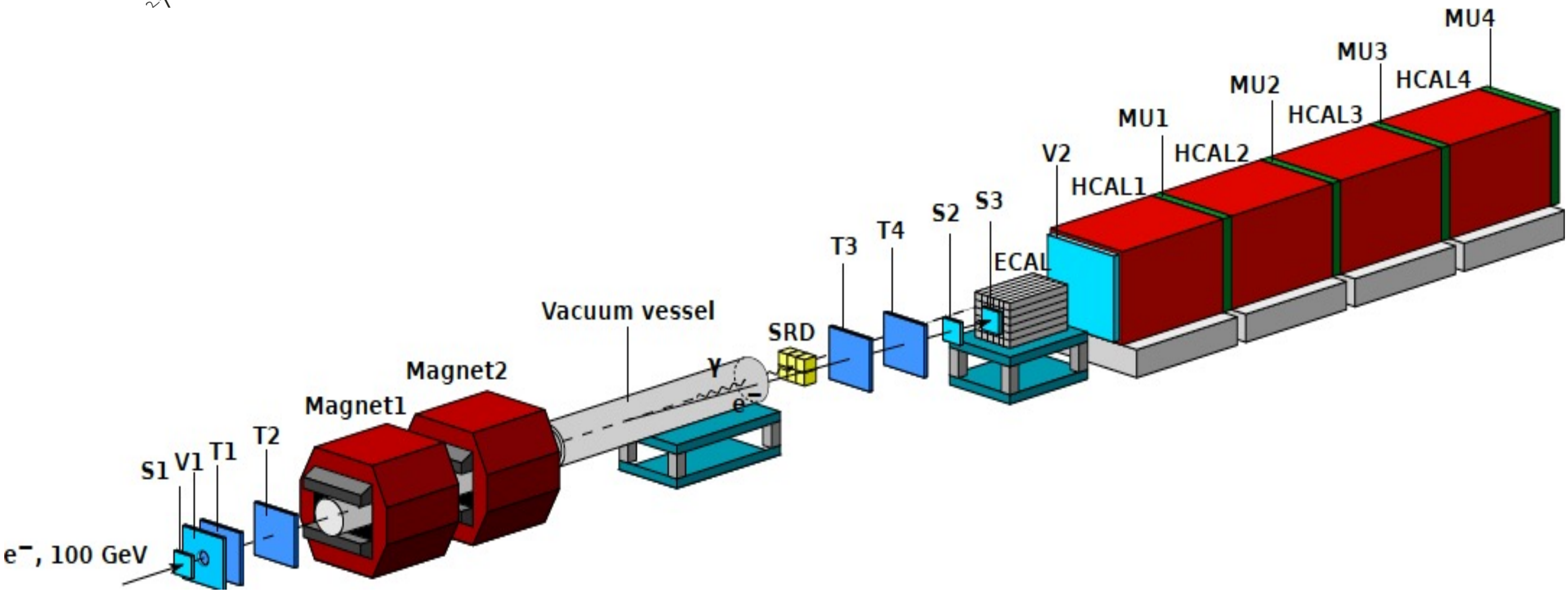
- Decays:

  - Visible: $A' \rightarrow e^+e^-, \mu^+\mu^-$, hadrons,..
  - Invisible: $A' \rightarrow \chi\chi$ if $m_{A'} \geq 2m_\chi$ assuming $\alpha_{DM} \sim \alpha \gg \varepsilon$.
    Can explain $(g-2)_\mu$, astrophys. observations
    - Cross section for χ–DM annihilation: $\sigma v \sim \overbrace{[\alpha_{DM}\, \varepsilon^2 (m_\chi/m_{A'})^4]}^{y}\ \alpha/m_\chi^2$

Thermal dark matter

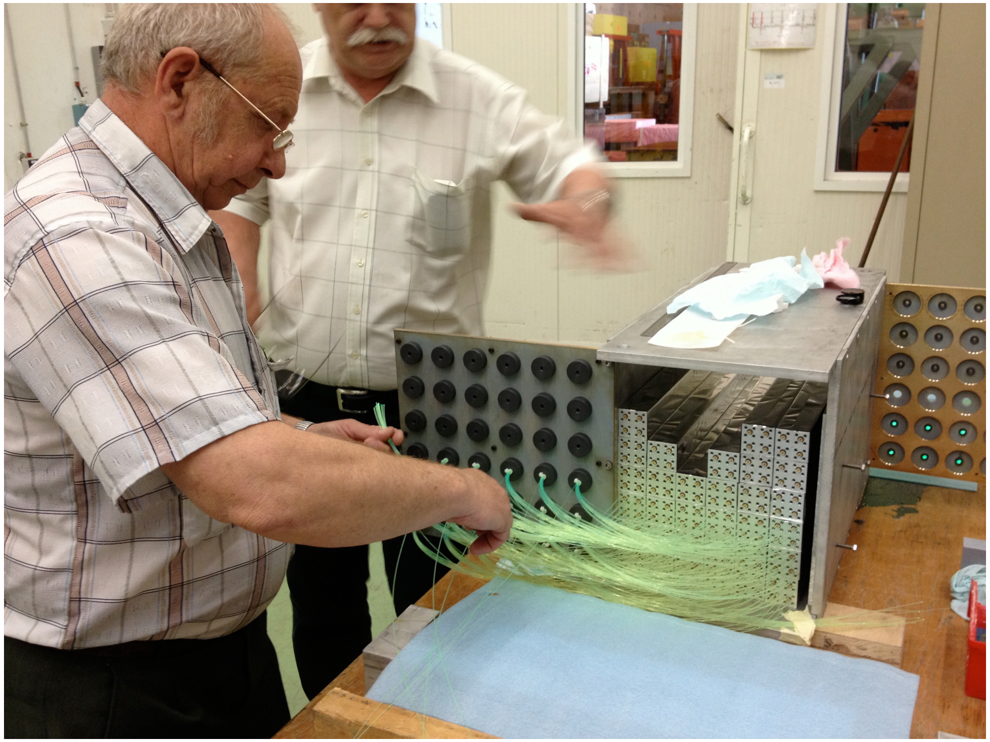
- Assume that in the early Universe dark matter is in equilibrium with the SM matter. At some temperature the dark matter decouples
- DM density today tells us about the annihilation cross-section. Correct DM density corresponds to $<\sigma_{an}v> \sim O(1)$ pbn
- Most popular models of light (sub-GeV) dark matter χ:
  - Scalar dark matter
  - Majorana dark matter
  - Pseudo Dirac dark matter

NA64 experiment setup (invisible mode)

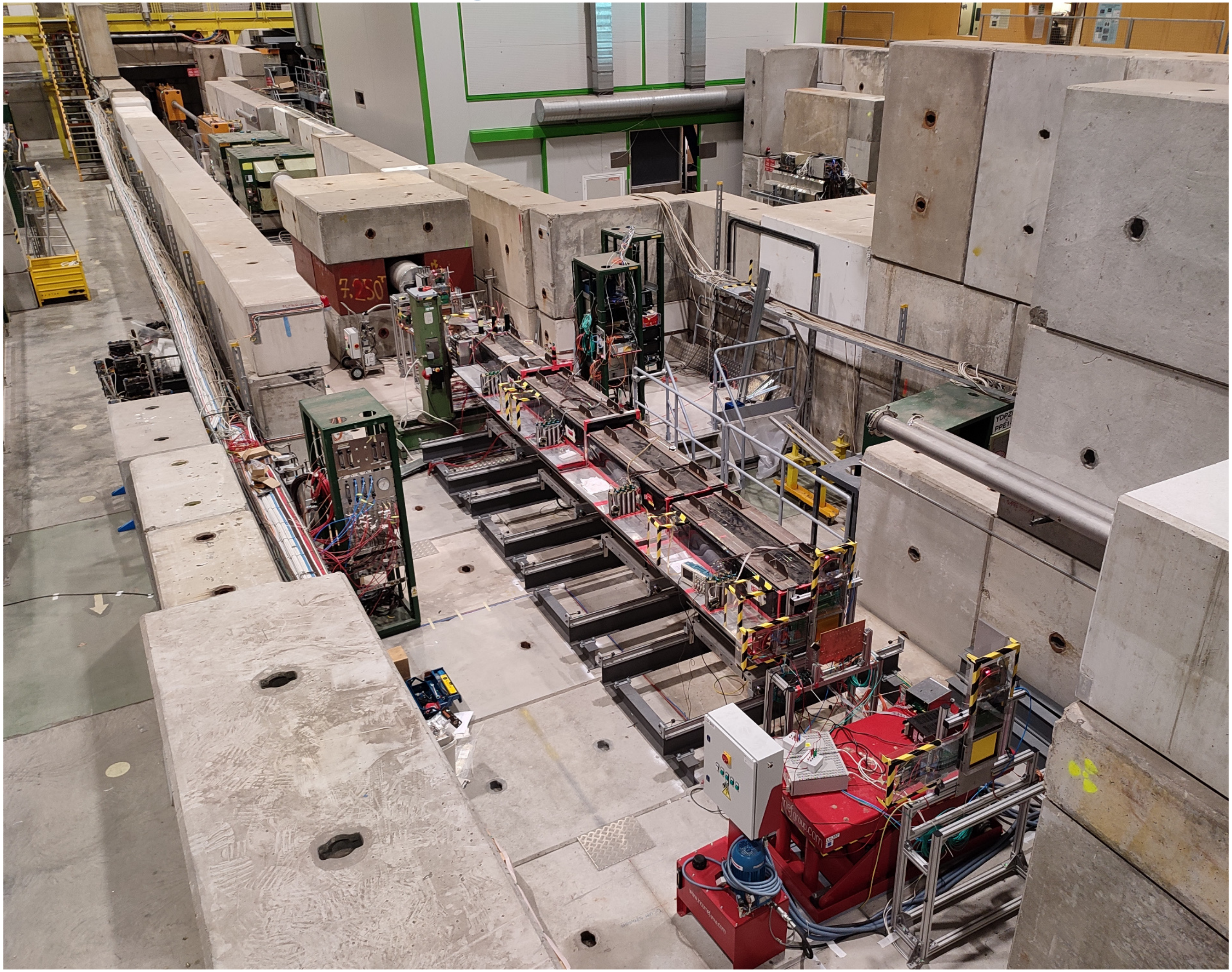


~50 researchers from 12 institutes, >50% from RF inst. + JINR
Proposed in 2014, first test runs in 2015, approved as NA64 2016

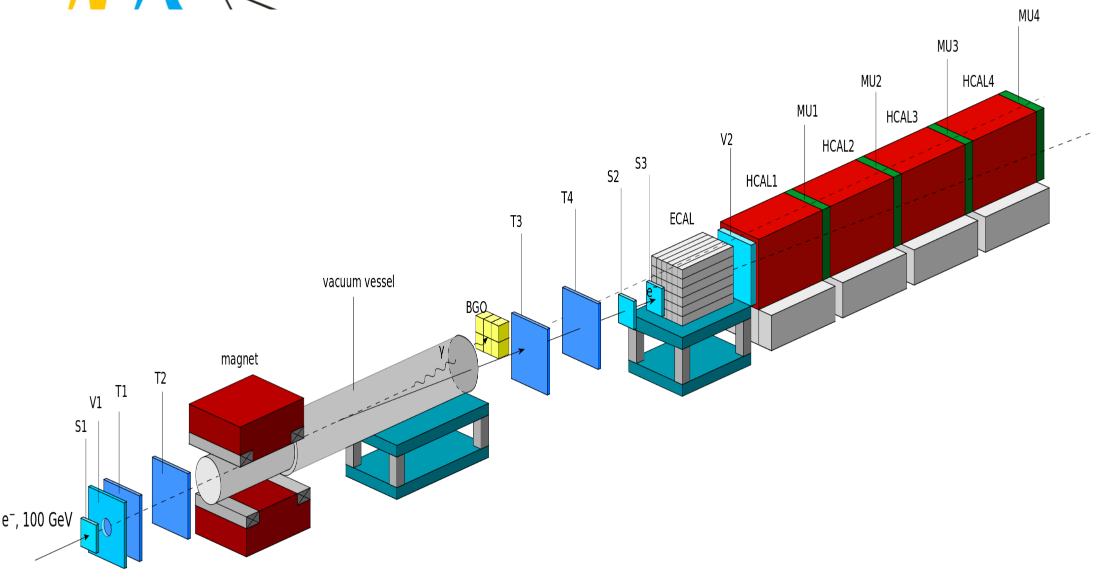
Assembling NA64 subdetectors (2015)



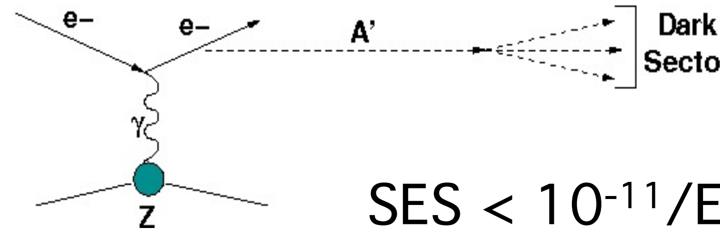
NA64 in 2021-2022, permanent place at H4 prepared by the CERN Beam Division



Search for A´->invisible decays at CERN SPS



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



SES < 10^{-11}/EOT

Signature:

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

Main components :

- clean 100 GeV e- beam
- e- tagging system: MS+SRD
- hermetic ECAL+HCAL

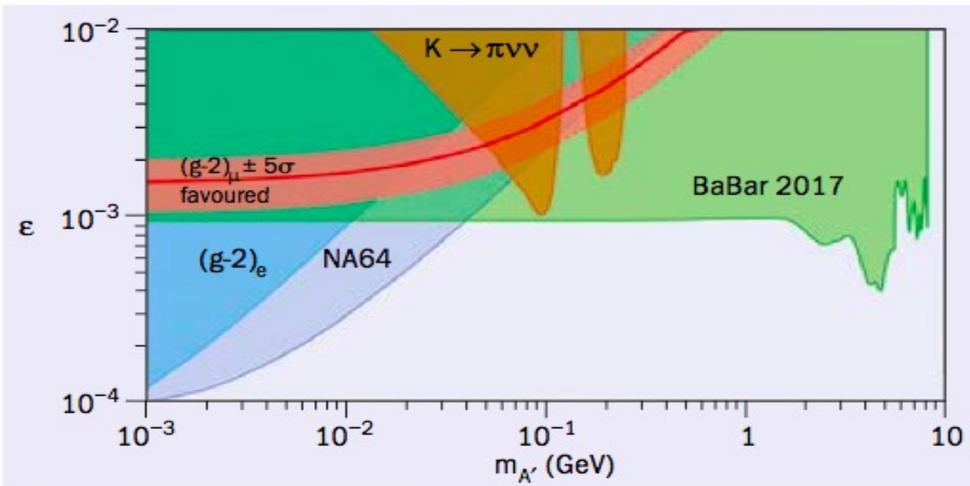
Background:

- μ, π, K decays in flight
- upstream interactions
- Tail < 50 GeV in the e- beam
- Energy leak from ECAL+HCAL

One of the first important results of NA64: A´explanation of $(g\text{-}2)_\mu$ anomaly is ruled out

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.

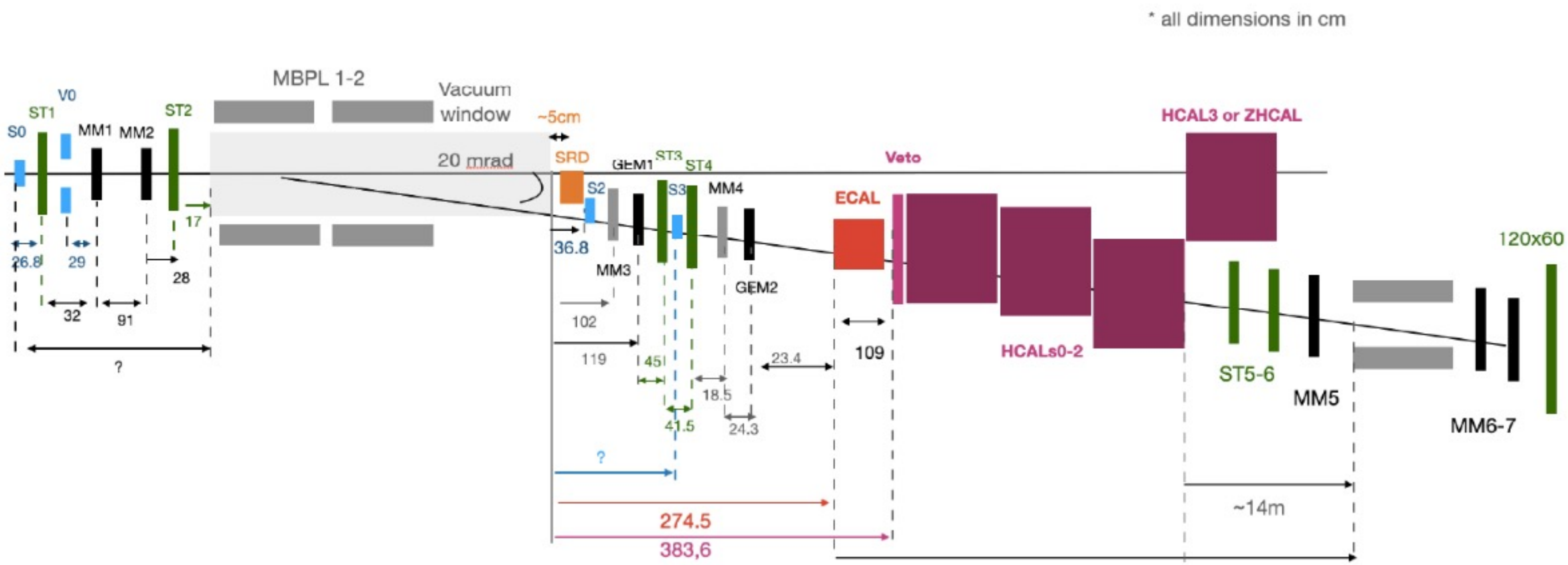
of Caltech, who has worked on dark-photon models. "In contrast to massless dark photons, which are analogous to ordinary photons, this experiment constrains a slightly different idea of dark force-carrying particles that are associated with a broken symmetry, which therefore get a mass and then can decay.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

NA64 in 2022

Run August – October 2022
10 weeks



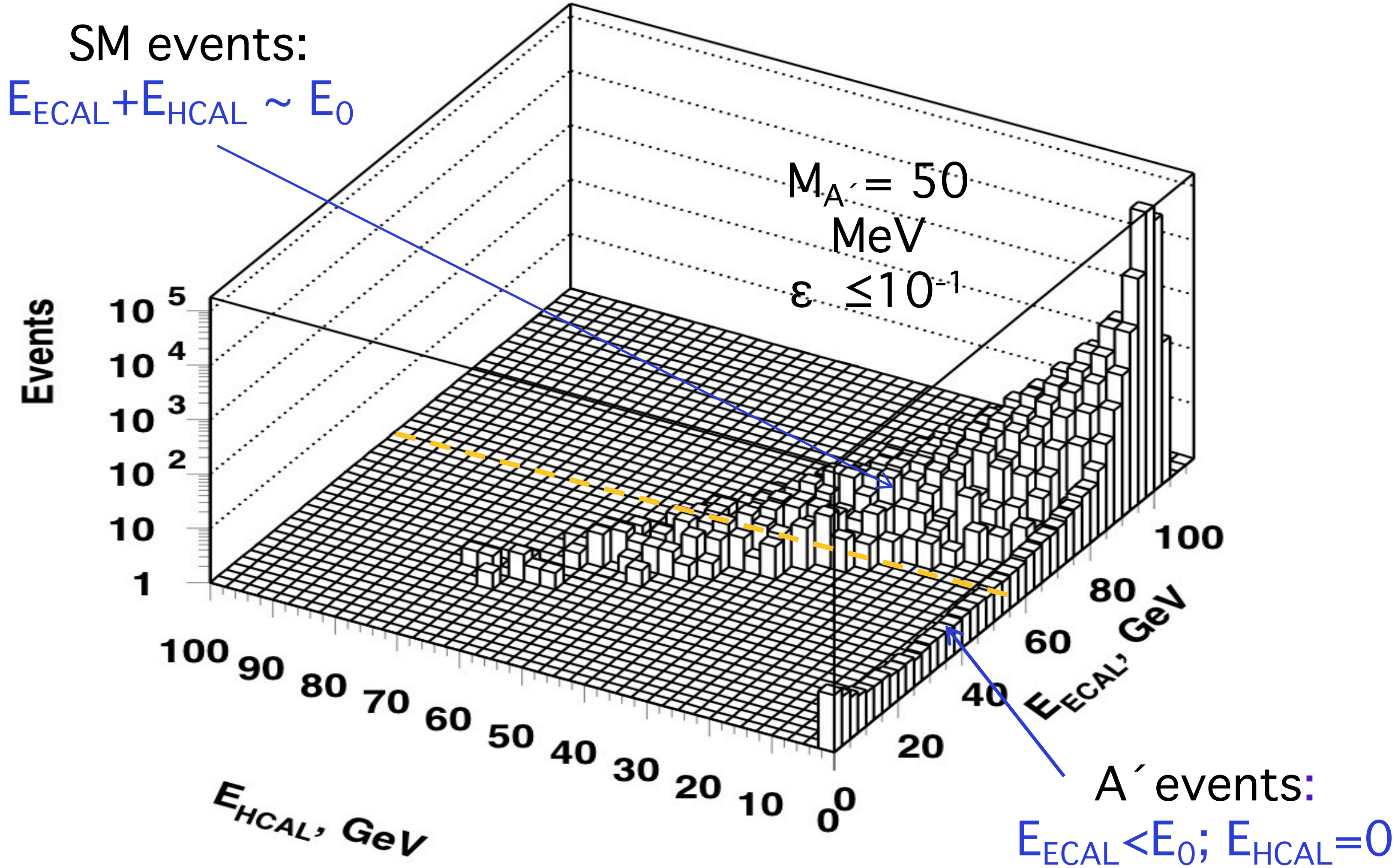
- New ECAL +
- New low material budget MM +
- Upgrade of the electronics --+
- Added end spectrometer to study dimuons and possibly new physics
- Permanent place in NA since 2021

Summary of the NA64 runs at H4

- **Invisible mode** configuration, first run 12.10-09.11 2016
  - Run 2016 EOT ~ $4.5x10^{10}$, S_0 rate $2÷4x10^6$;
  - Run 2017 EOT ~ $5.4x10^{10}$, S_0 rate $4÷6x10^6$
  - Run 2018 EOT ~ $1.9x10^{11}$, S_0 rate $6÷8x10^6$
  - Run 2021 EOT ~ $5.2x10^{10}$, S_0 rate $4÷5x10^6$
  - Run 2022 EOT ~ $6.4x10^{11}$, S_0 rate $5÷7x10^6$
  - Run e^+ 2022 EOT ~ $1.0x10^{10}$, S_0 rate $5÷7x10^6$
  - Run 2023 EOT ~ $6.0x10^{11}$, S_0 rate $5÷7x10^6$
  - Total analysed electrons (2016 – 2022) ~ $9.37x10^{11}$ eot
  - Total accumulated (2016 – 2023) ~$1.5x10^{12}$ eot
- **Visible mode** configuration first run 22.09-01.10 2017
  - Subrun 1 WCAL 40X0 EOT ~ $2.4x10^{10}$, S_0 rate ~$3x10^6$
  - Subrun 2 WCAL 30X0 EOT ~ $3x10^{10}$, S_0 rate $4\text{-}5x10^6$
  - Run 2018 S4 in WCAL EOT ~ $3x10^{10}$, beam 150 GeV
  - Total EOT ~ $8.4x10^{10}$

Simulation of eZ->eZA´; A´-> invisible @ BG

A´ emission in the process of e-m shower development.
$\sigma(e^-Z \to e^-ZA')$ (Bjorken et al. 2009)



DM processes simulation: DMG4

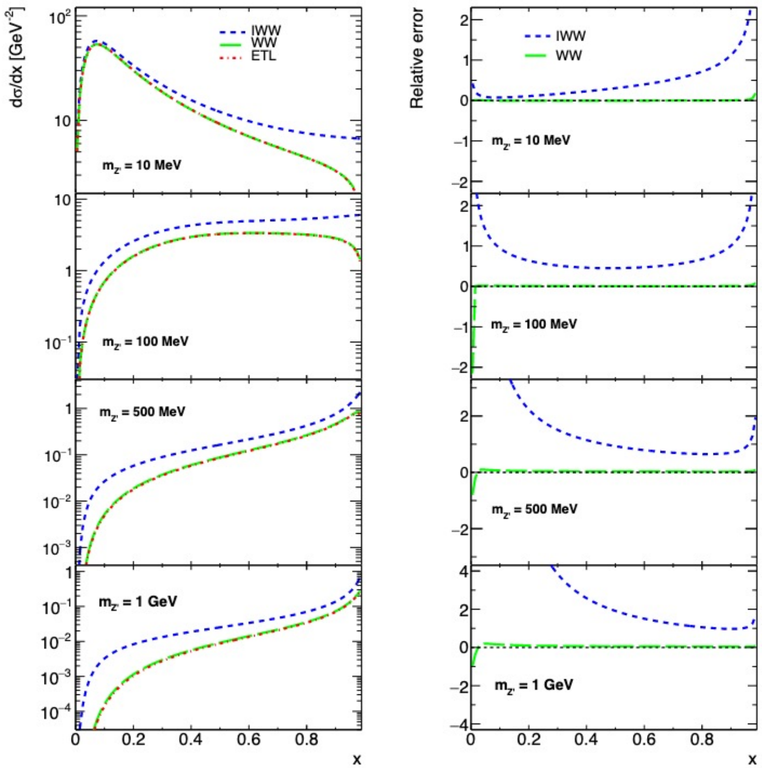
- Fully Geant4 compatible package DMG4 is developed arXiv:2101.12192 [hep-ph]. Can be used in any full simulation program based on the Geant4 toolkit
- Bremsstrahlung processes off electrons and muons (like $eZ \rightarrow eZA'$), gamma conversion to ALP, annihilation processes (like $e^+e^- \rightarrow A' \rightarrow \chi\chi$) can be simulated
- DM messengers: vector (A'), axial vector, scalar, pseudoscalar, masses up to 3 GeV
- Invisible and visible (to SM particles) decays
- For the total cross section we use the full matrix element calculations (ETL) (arXiV:1712.05706 [hep-ph]) through the K-factors applied to the IWW cross sections. These K-factors can be as small as 1/15 for electrons at $M_A \sim 1$ GeV

DM processes simulation: DMG4(2)

- Simplified IWW approximation in e^{-+} beams for differential cross sections (messenger masses > 1 MeV), sufficient accuracy. Messenger energy and angle are sampled
- Tabulated e^{-+} beams differential cross section for masses < 1 MeV
- Recently implemented WW approximation in muon beams Complicated analytical integration. Messenger energy and recoil muon angle are sampled by default (needed in analysis, see below)
- WW formulas are now extended to scalar mediators
- Recently implemented: spin 2 messengers
- Recently implemented: semivisible decays of DM
- Presented at ACAT-2021 and ACAT-2022
- We continue to develop the package (convenience, new processes)

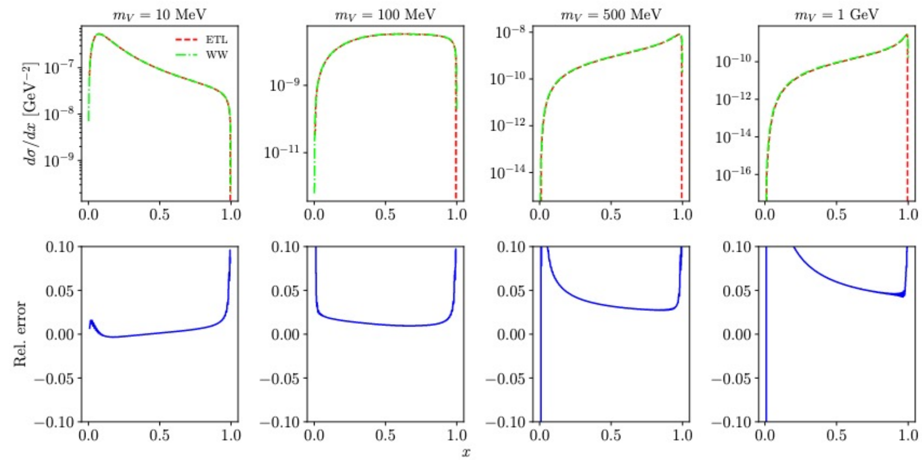
DMG4 muon beams: WW vs ETL

Single-differential cross-sections: vector case cross-check



Our previous work, Phys. Rev. D 104,076012
(numerical WW)

This work (analytical WW)



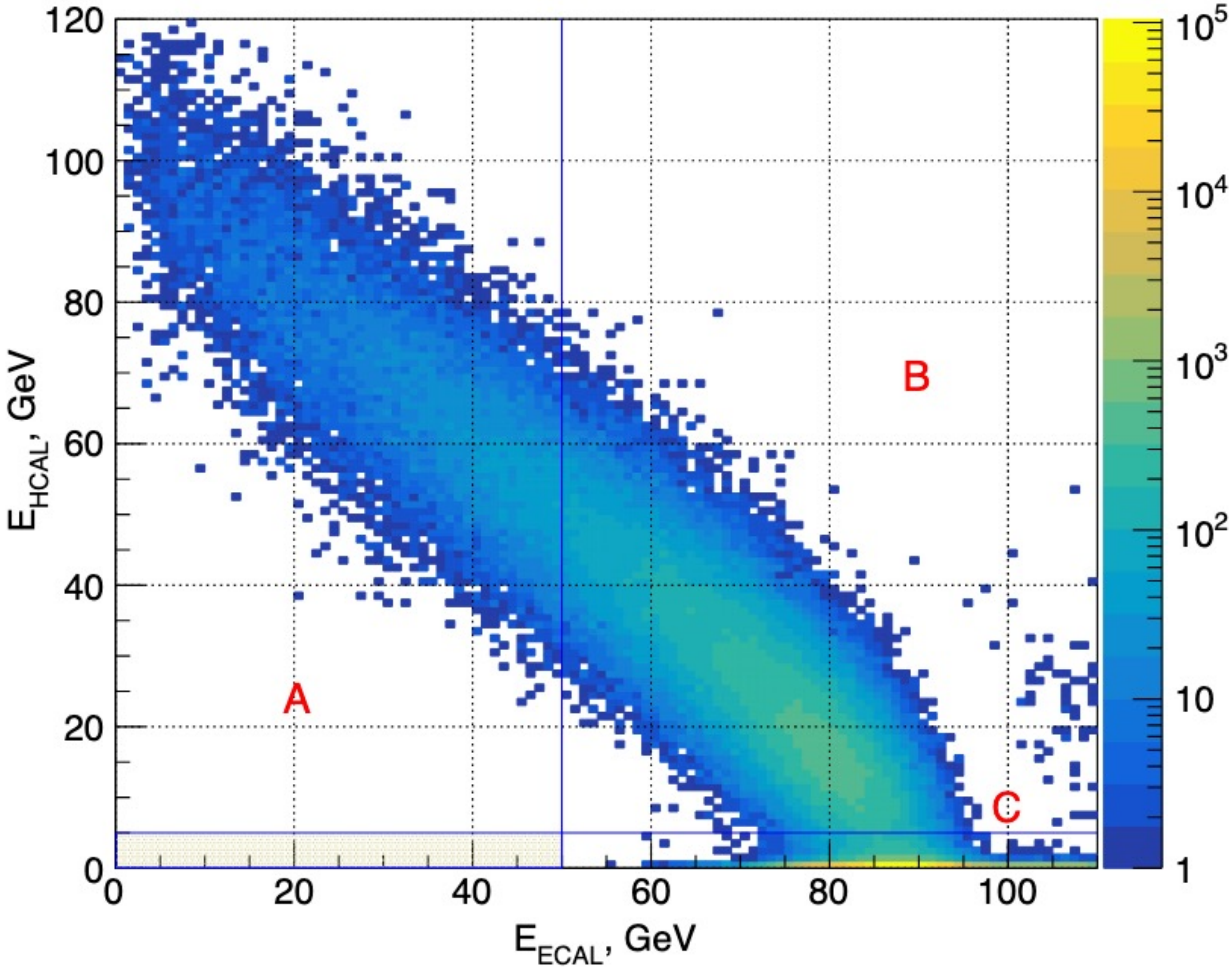
Vector (V) **σ@160 GeV**

Mass [MeV]	ETL [GeV^{-2}]	WW [GeV^{-2}]	|rel. err.| [%]
10	1.55e-07	1.56e-07	~0.2
100	2.42e-08	2.45e-08	~1
500	1.57e-09	1.62e-09	~4
1000	2.58e-10	2.74e-10	~6

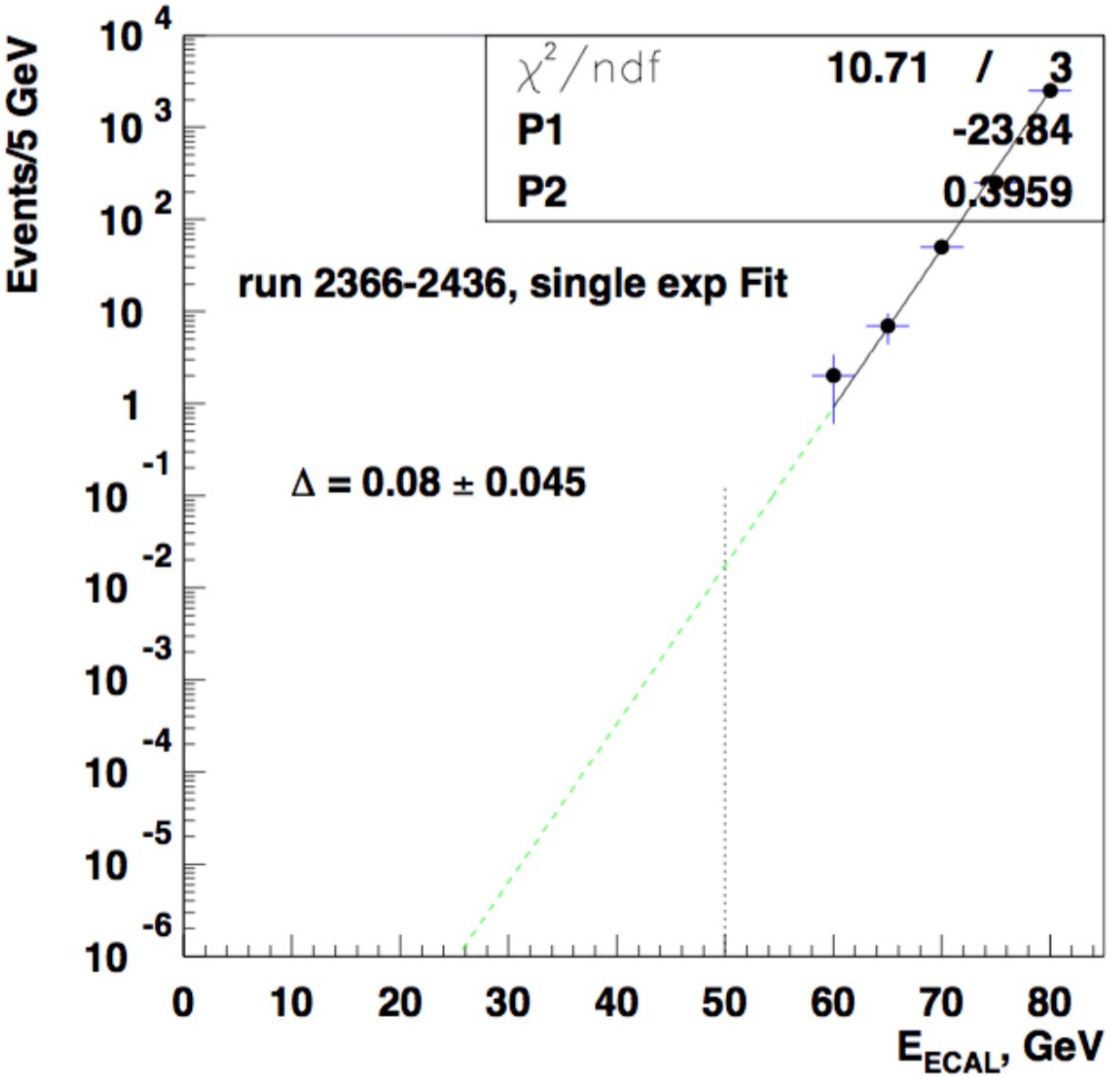
Analysis of data 2022

How is this shape formed?

- Electron – nuclear and gamma – nuclear interactions
- The main peak is cut off by trigger requirement $E_{ECAL} < 85$GeV



Background: example of extrapolation

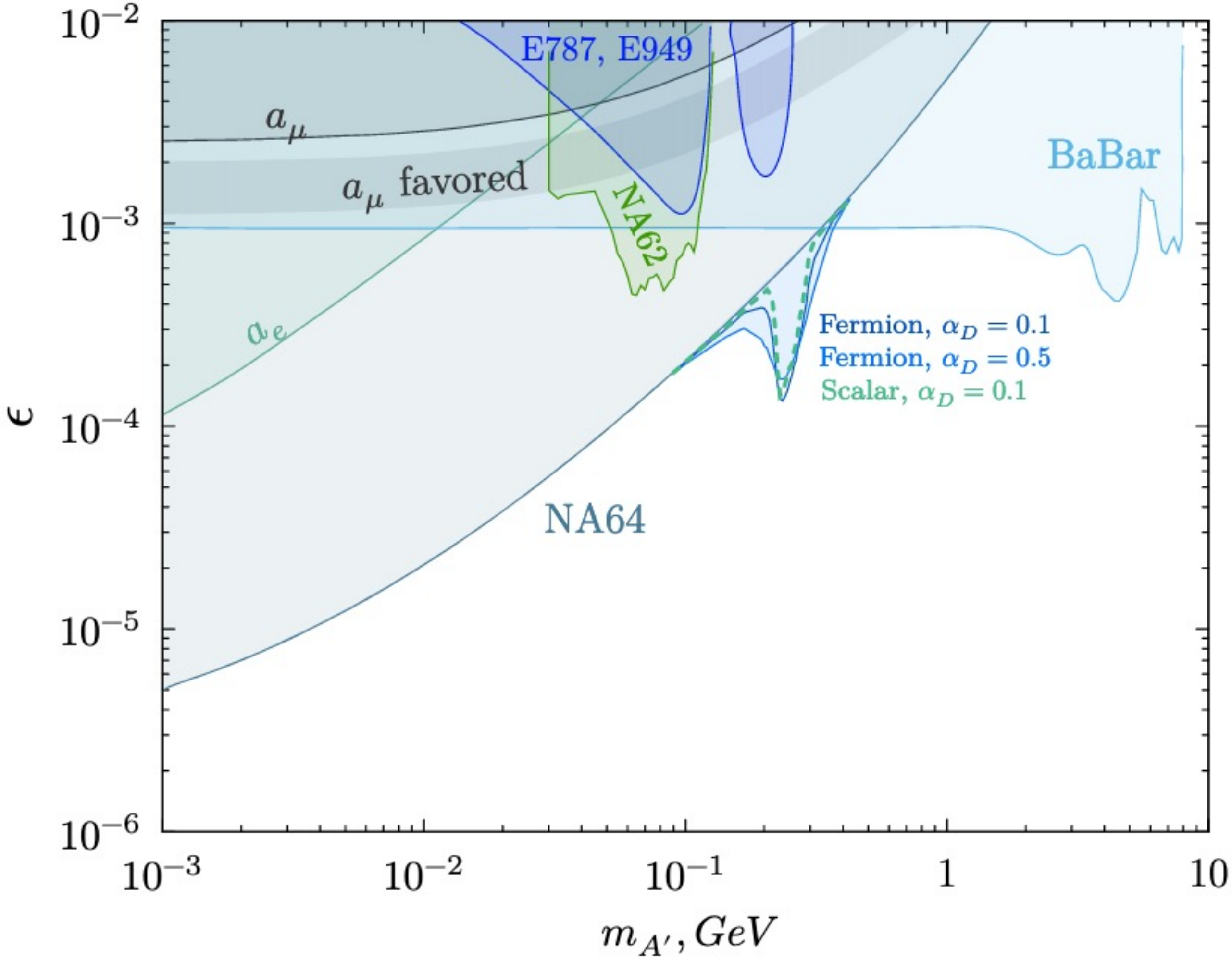


Background sources runs 2021 - 2022

Background source	Background, n_b
(i) dimuons losses or decays in the target	0.04 ± 0.01
(ii) $\mu, \pi, K \to e + ...$ decays in the beam line	0.3 ± 0.05
(iii) lost γ, n, K^0 from upstream interactions	0.16 ± 0.12
(iv) Punch-through leading n, K_L^0	< 0.01
Total n_b (conservatively)	0.51 ± 0.13

BG from the beam elements (iii) is suppressed by multiplicity cuts in MM and Straw tubes and by HCAL Topo cuts. Estimated from extrapolation

Results. Most recent on A'.



arXiv 2307.02404

+ Resonant process: shower positrons on electrons of the target

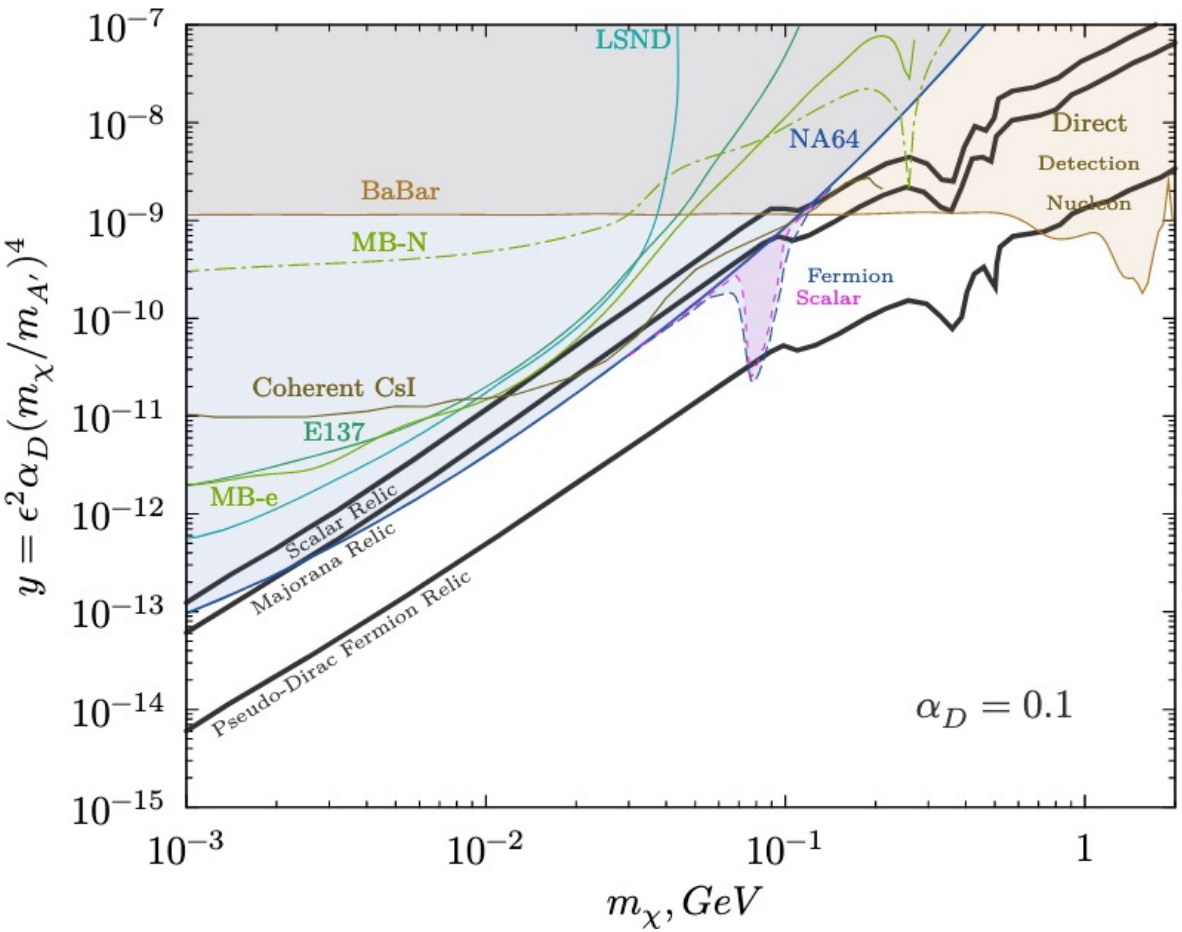
$e^+e^- \rightarrow A' \rightarrow \chi\chi$

First addition to the analysis:

Phys. Rev. D 104, L091701

(2021)

Limits in “cosmological” variables with 2022 data and sub-GeV Thermal Dark Matter models



proportional to DM<->SM annihilation cross section

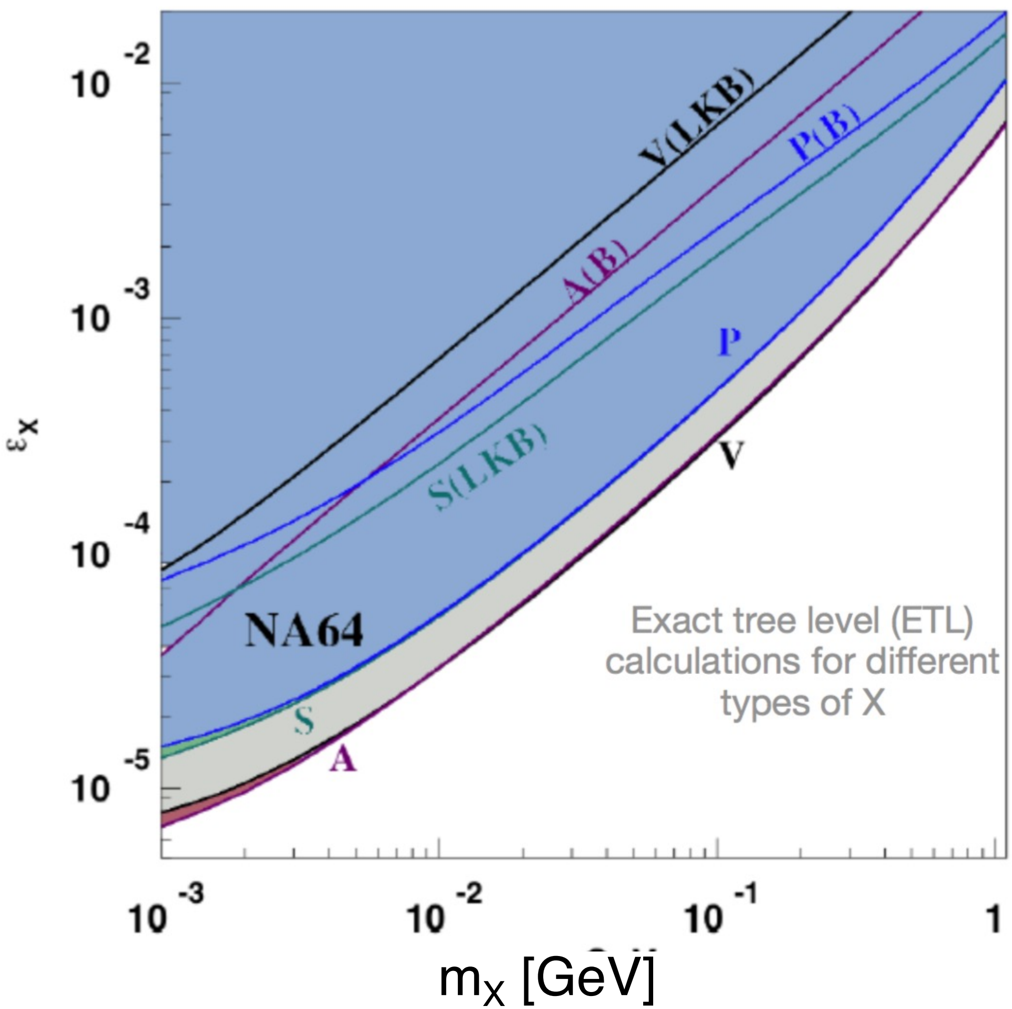
$\alpha_D = 0.1$, $m_{A\times} = 3m_\chi$

For $\alpha_D = 0.1$ we cover two models and touch the third

Less strict limits for $\alpha_D > 0.1$

Limits on generic boson and $(g\text{-}2)_e$

$e^- Z \rightarrow e^- Z X; X \rightarrow$ **invisible**

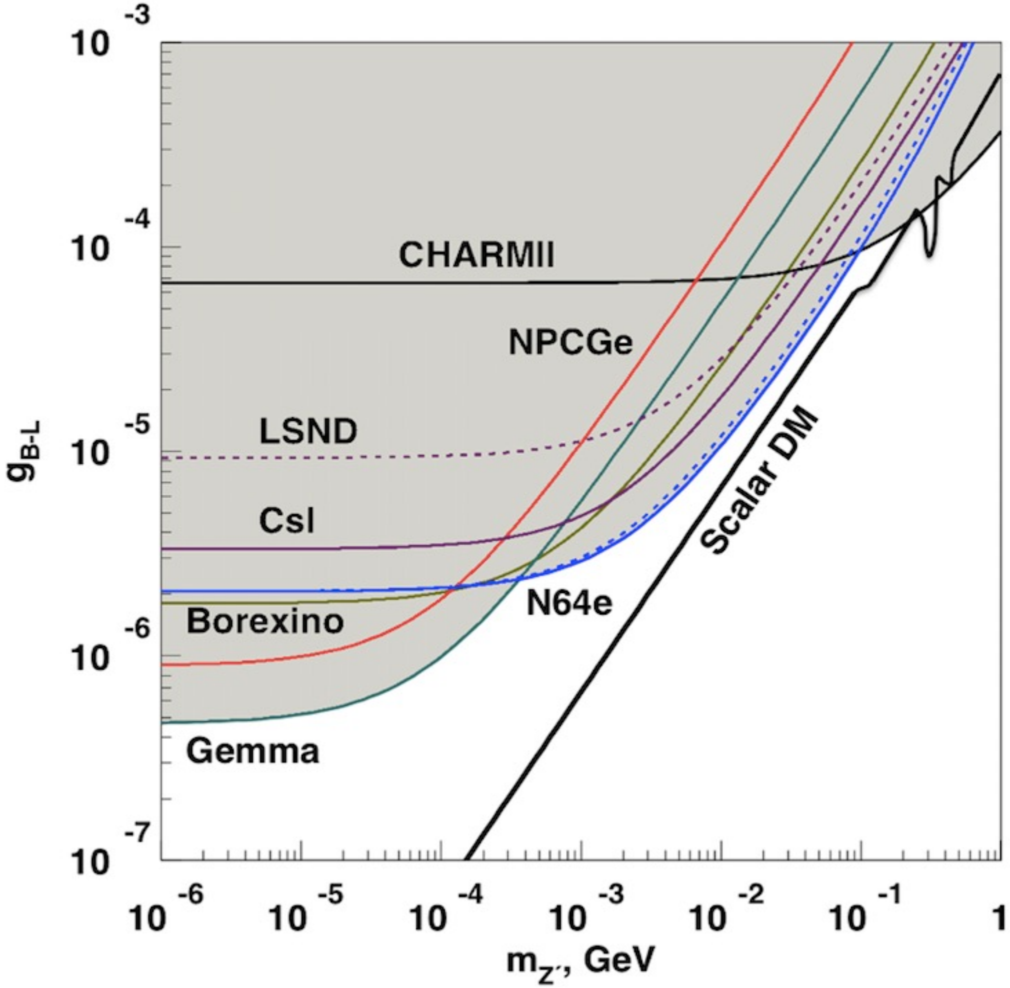


Consider also Scalar, Pseudoscalar, Axial vector
Andreev et al.
PRL 126, 211802 (2021)

Results (tension) on Δa_e :
LKB +1.6σ,
Berkley -2.4σ

New analysis,
including the masses down to 1 KeV,
Is in progress

Constraints on B-L Z' (decaying to SM particles)

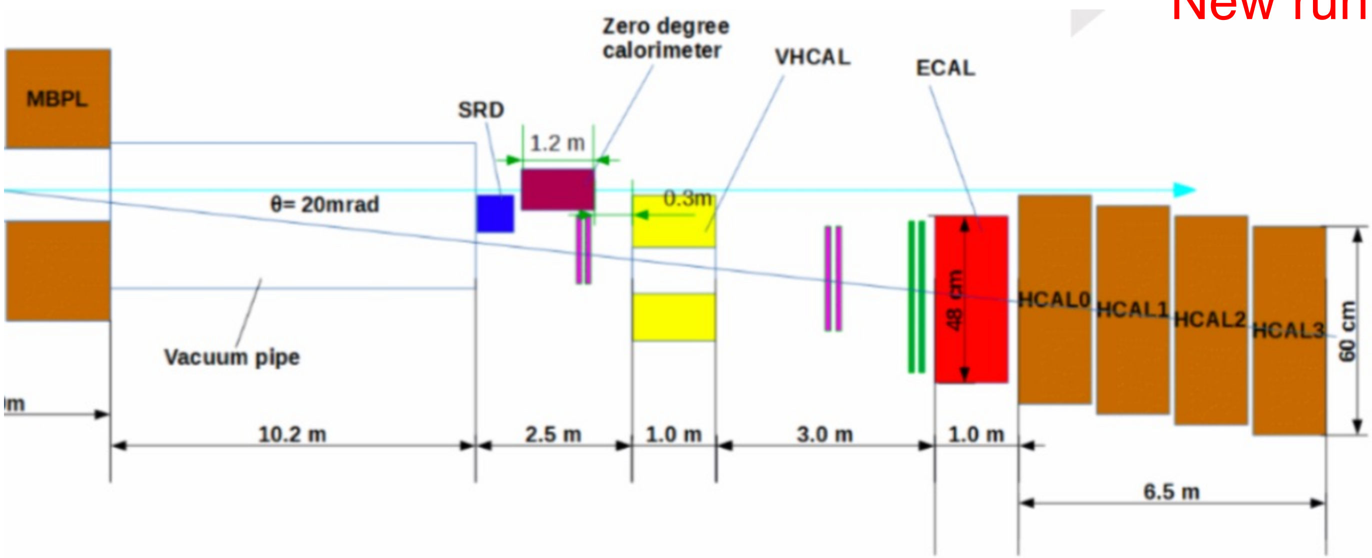


Better sensitivity than neutrino experiments!

Phys. Rev. Lett. (2022)

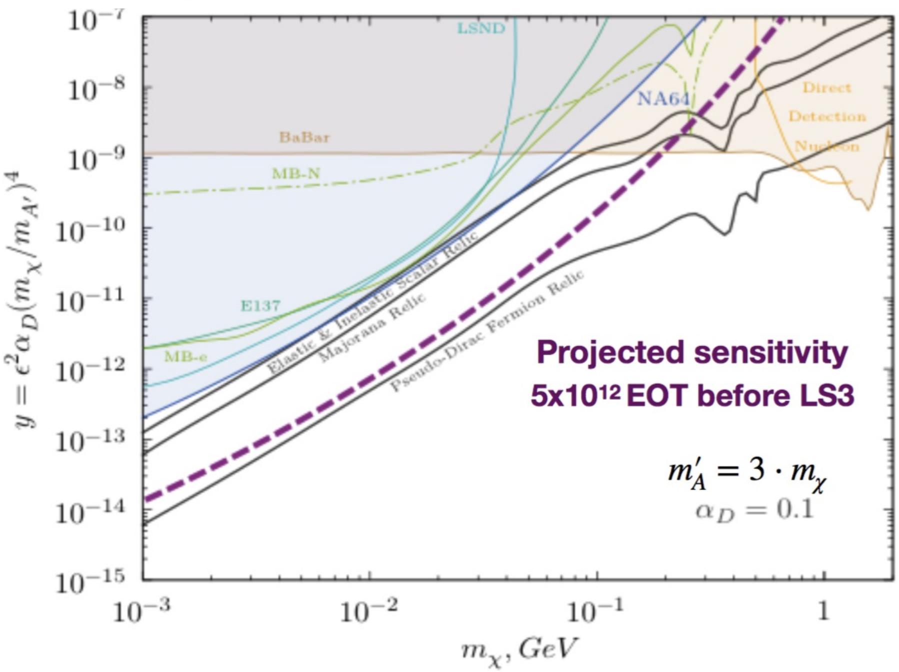
Continue searches in invisible mode

New run May – June 2023



- New subdetector VHCAL to suppress BG from beam elements and tracker
- Upgrade of DAQ
- Upgrade of electronics
- Upgrade of ECAL

Sensitivity to y and some popular sub-GeV Thermal Dark Matter models

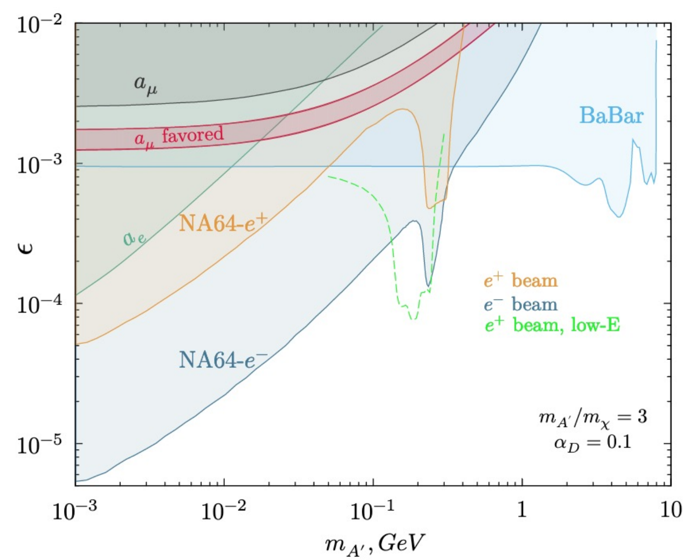


How to improve sensitivity above 100 MeV?

- Annihilation. Additional positron run in 2022 (already analysed), two positron runs at 40 and 70 GeV in 2023
- NA64μ at the muon beam M2, later in this talk.

Analysed positron data 2022 preliminary, green dashed – expected from 2023 positrons

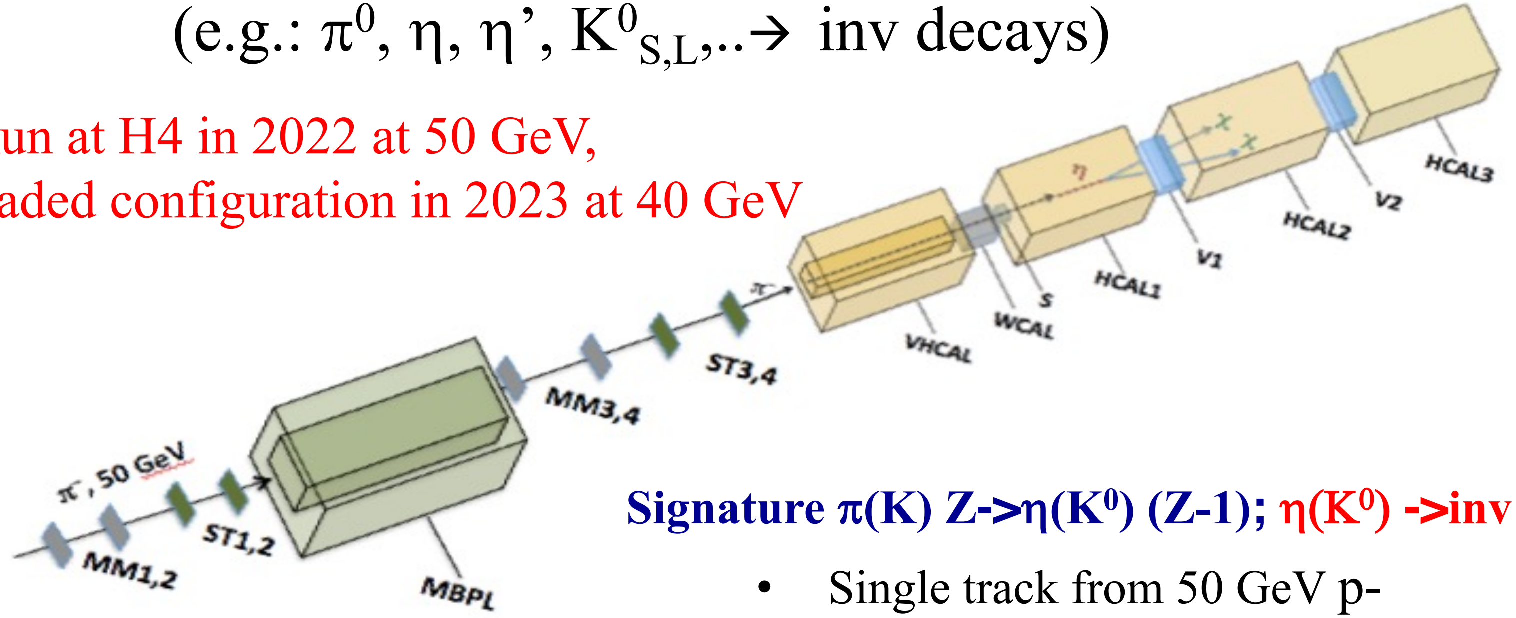
Additional region in positron beam is larger



NA64h: Search for dark sector coupled to quarks

(e.g.: π^0, η, η', $K^0_{S,L}$,..→ inv decays)

Run at H4 in 2022 at 50 GeV,
run in upgraded configuration in 2023 at 40 GeV

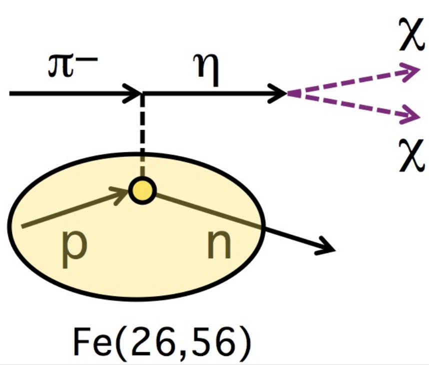


Signature $\pi(K)\ Z \to \eta(K^0)\ (Z-1)$; $\eta(K^0) \to inv$

- Single track from 50 GeV p-
- Events with $E_{HC} \approx E_0$ - test NA64mu
- MIP in WCAL and S
- Almost no energy in HCAL: $E_{miss} \sim E_0$
- BG: π, μ decays ~ 10^{-11}/pot
- ~2×10^9 pot (~1d, 2022),
- $Br(\eta \to inv) < \sim 10^{-5}$-$10^{-4}$ (BaBar/BESIII)

Analysis in progress

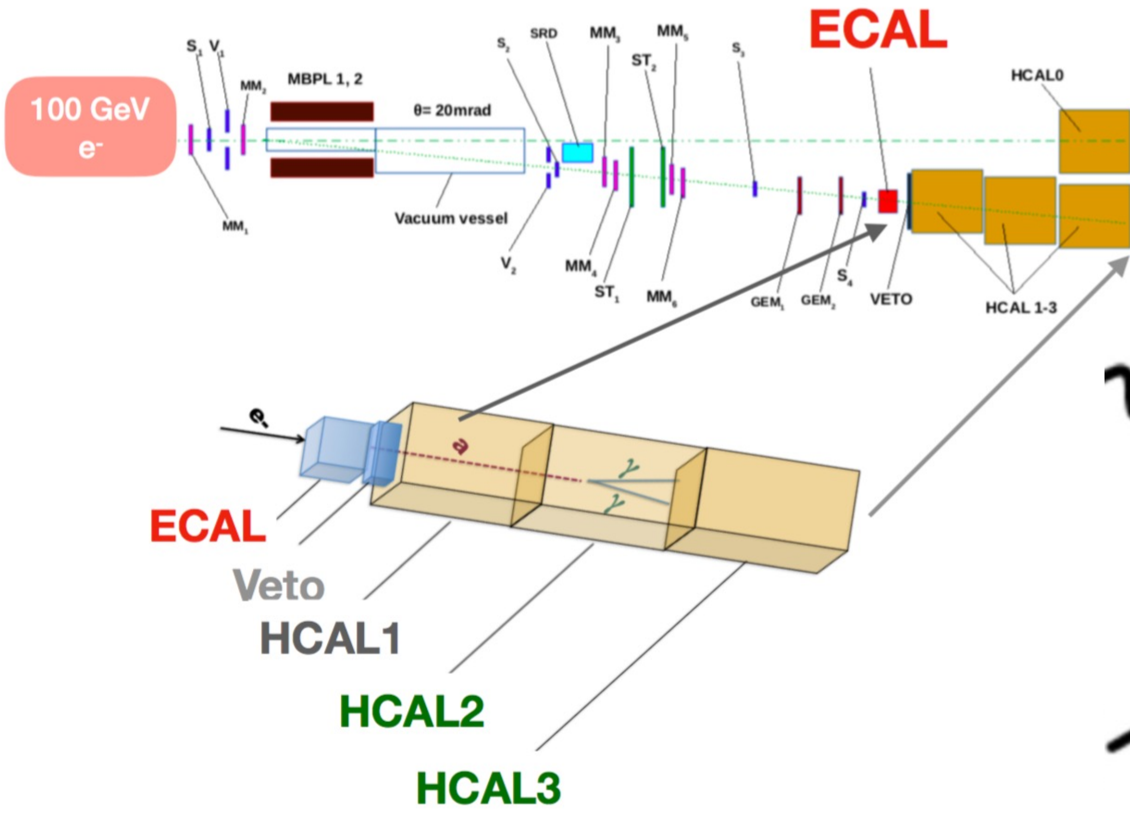
η, η', K0 – production:
$\pi(K)\ Z \to \eta(K^0)\ (Z-1)$



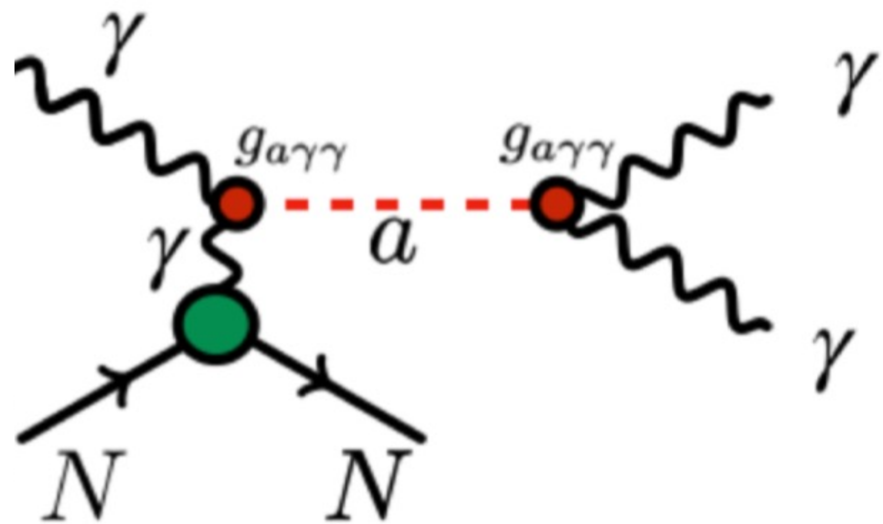
Axion-like particles (ALP) coupled to photons

New way of using the invisible mode geometry: visible decays!

Produced via Primakoff effect of gamma conversion on nuclei



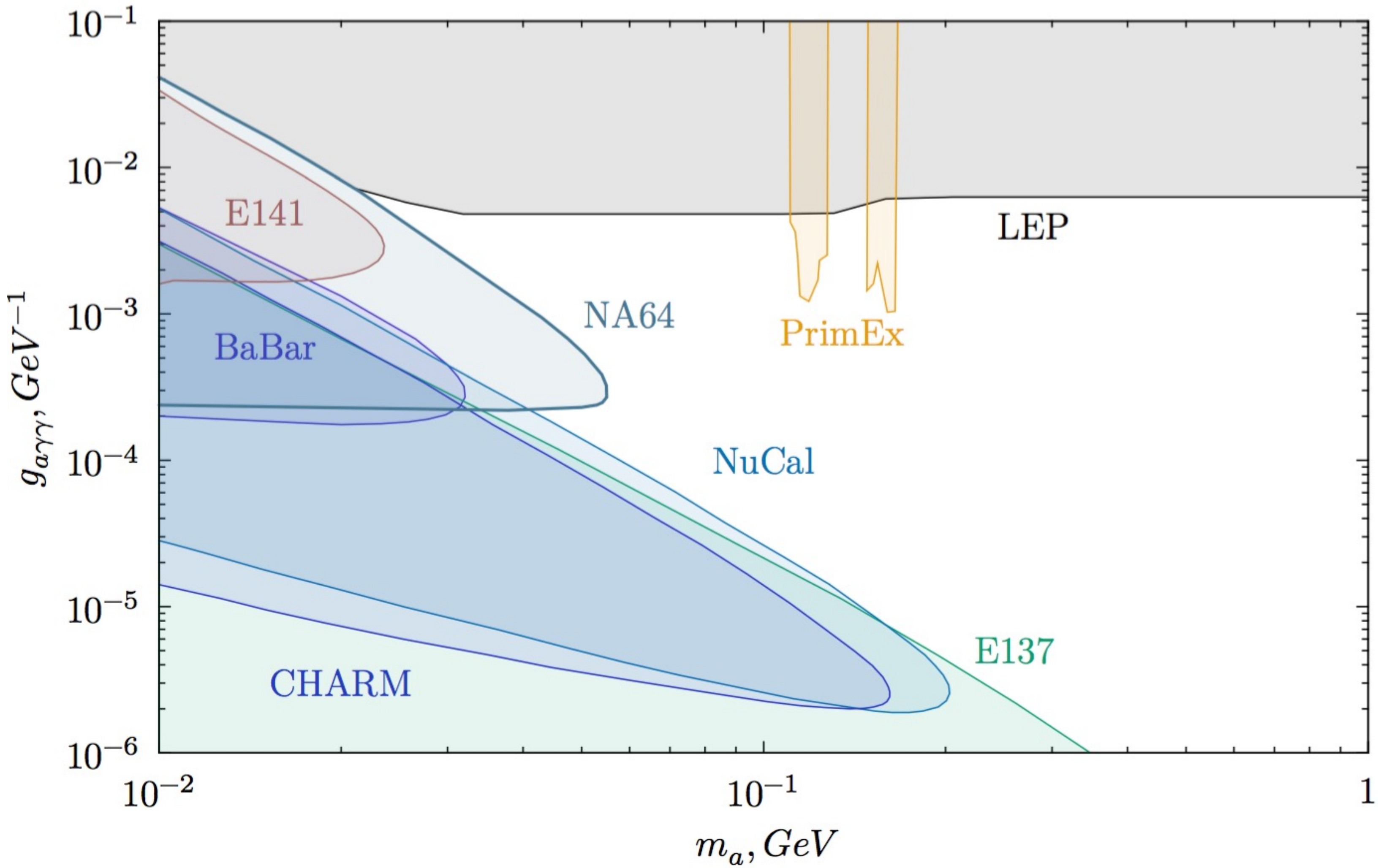
$$L_{int} = -\frac{1}{4} g_{a\gamma\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a$$



ALP search strategy

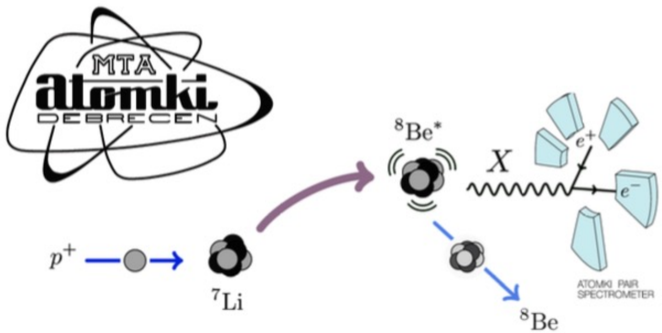
- In addition to invisible decays beyond the detector (missing energy signature) look for decays in HCAL2, HCAL3 with HCAL1 as a veto
- Allows softer cuts on energy deposition in ECAL
- Background: punch-through neutrons and K^0
- Final cut on R = (periphery cells)/(central cell), strong suppression of hadrons

ALP search results (data 2016 – 2018)



Search for new X-bosons and Dark Photons decaying to e^+e^-

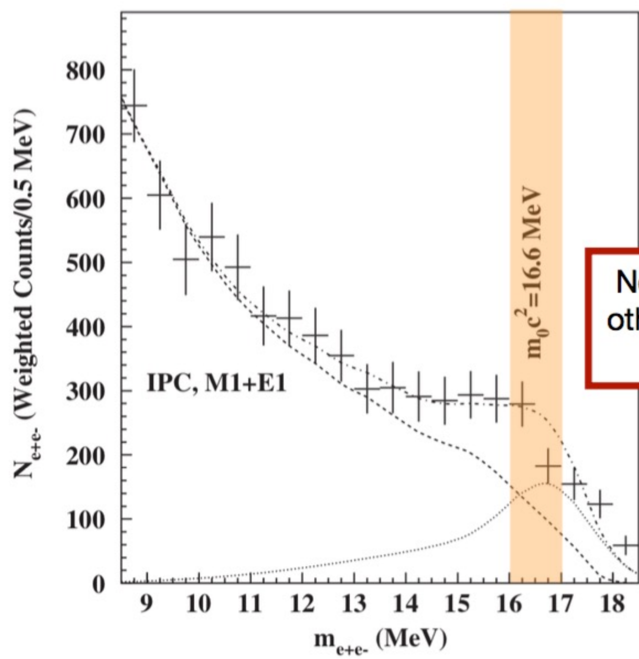
ATOMKI anomaly



- *Scalar, pseudo-scalar, vector, axial-vector* models could explain the anomaly (large literature)
- NA64 addresses the search for X17 in a model independent way, just assuming its non-zero coupling with electrons.
- Vector model used as benchmark.

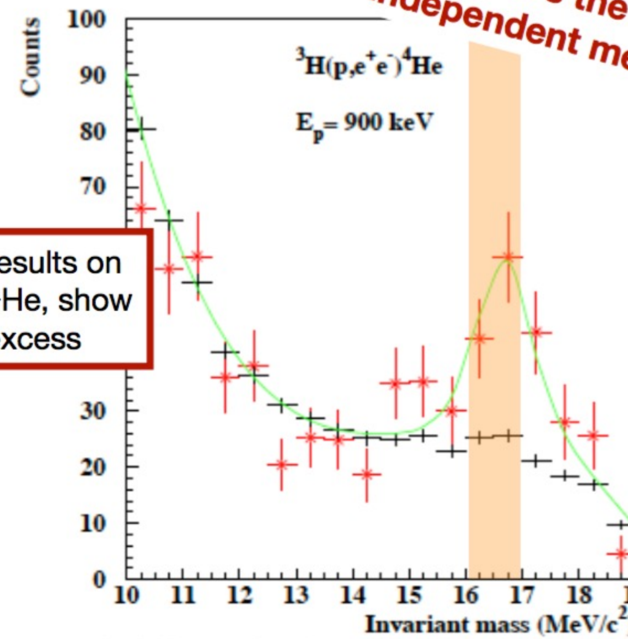
$$e^-Z \rightarrow e^-ZX_{17};\ X_{17} \rightarrow e^+e^-$$

Motivates the need of an independent measurement



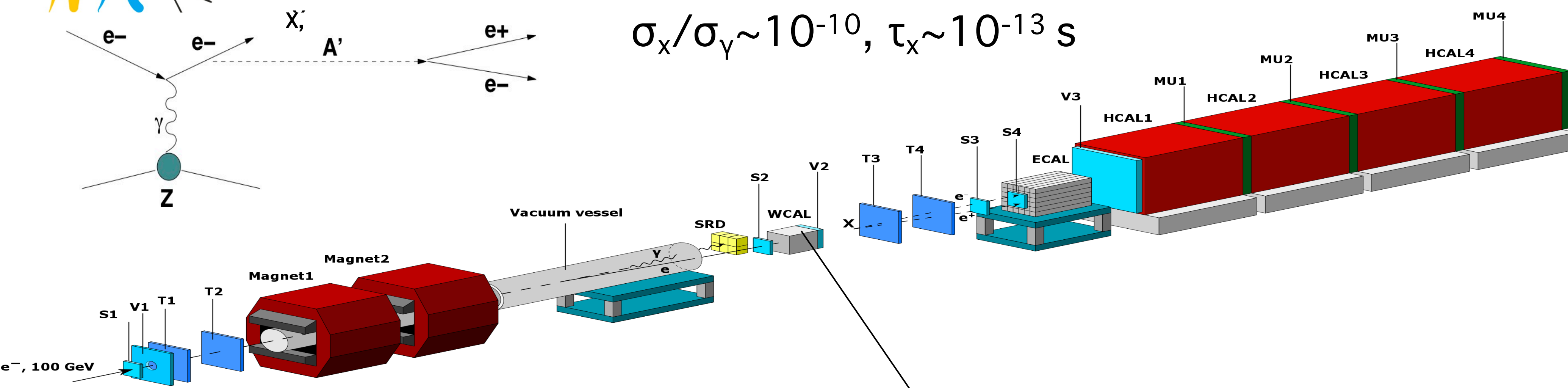
A.J. Krasznahorkay et al. Phys. Rev. Lett.116, 042501 (2015)

New recent results on other nuclei, ^{4}He, show a similar excess



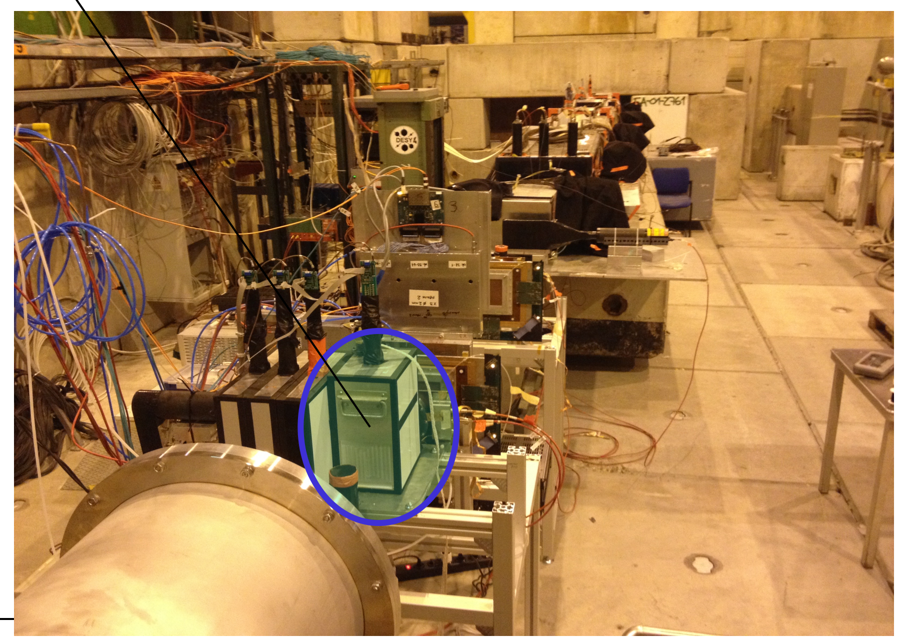
A. J. Krasznahaorkay et. Al Arxiv:1910.10459 (2019)

Search for X(A´)->e⁺e⁻ decays



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

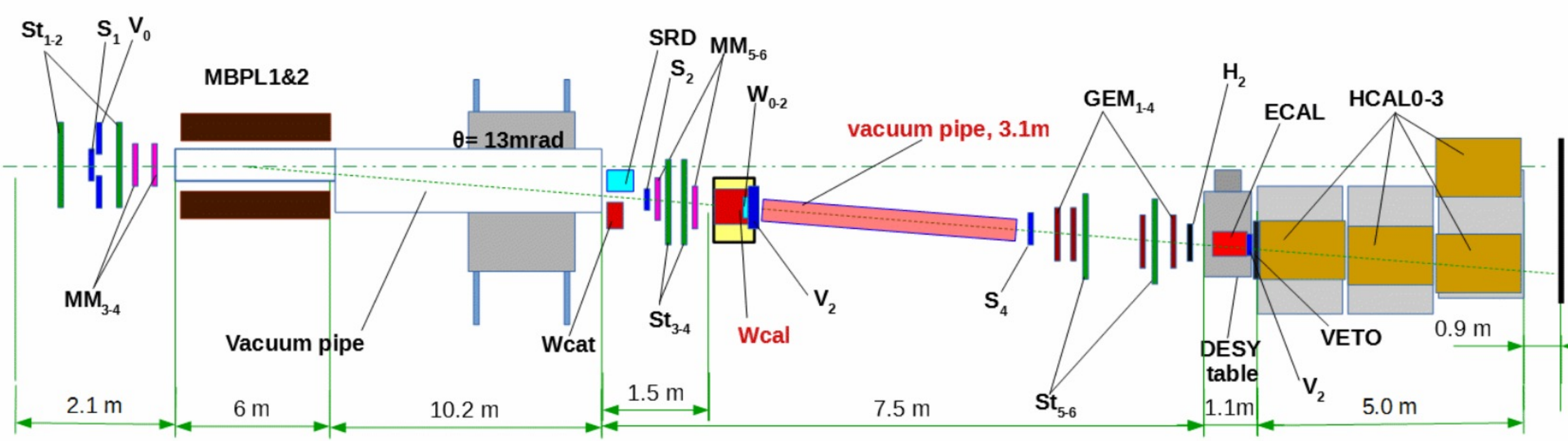
- Compact tungsten calorimeter WCAL
  - X decays outside WCAL dump
- Signature: two separated showers from a single e-
  - $E_{WC} < E_0$, and $E_0 = E_{WC} + E_{EC}$
  - θ_{e+e-} too small to be resolved



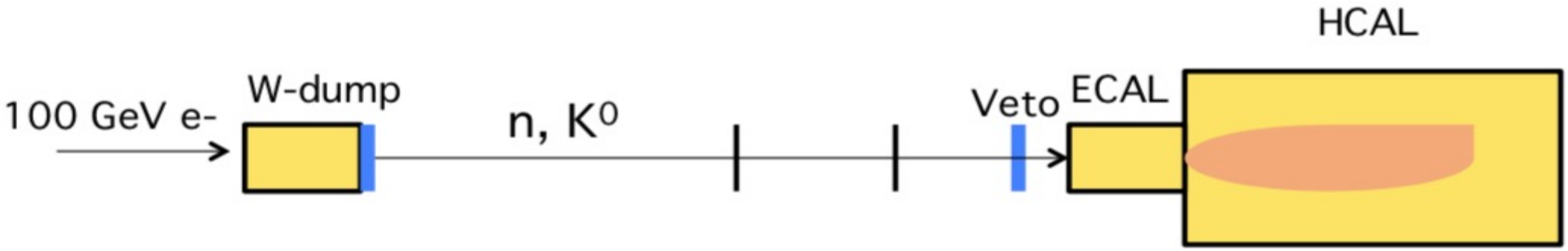
Setup optimization

Second run (2018), with $3x10^{10}$ EOT was performed with the visible mode configuration optimized for bigger ε (short-lived X) and better background suppression: 150 GeV beam, veto counter inside WCAL box, vacuum decay tube, larger distance WCAL - ECAL

TOP VIEW, 2018 setup



Main background from $K^0_S \to \pi^0 \pi^0 \to \gamma$'s $\to e^+e^-$ decay chain

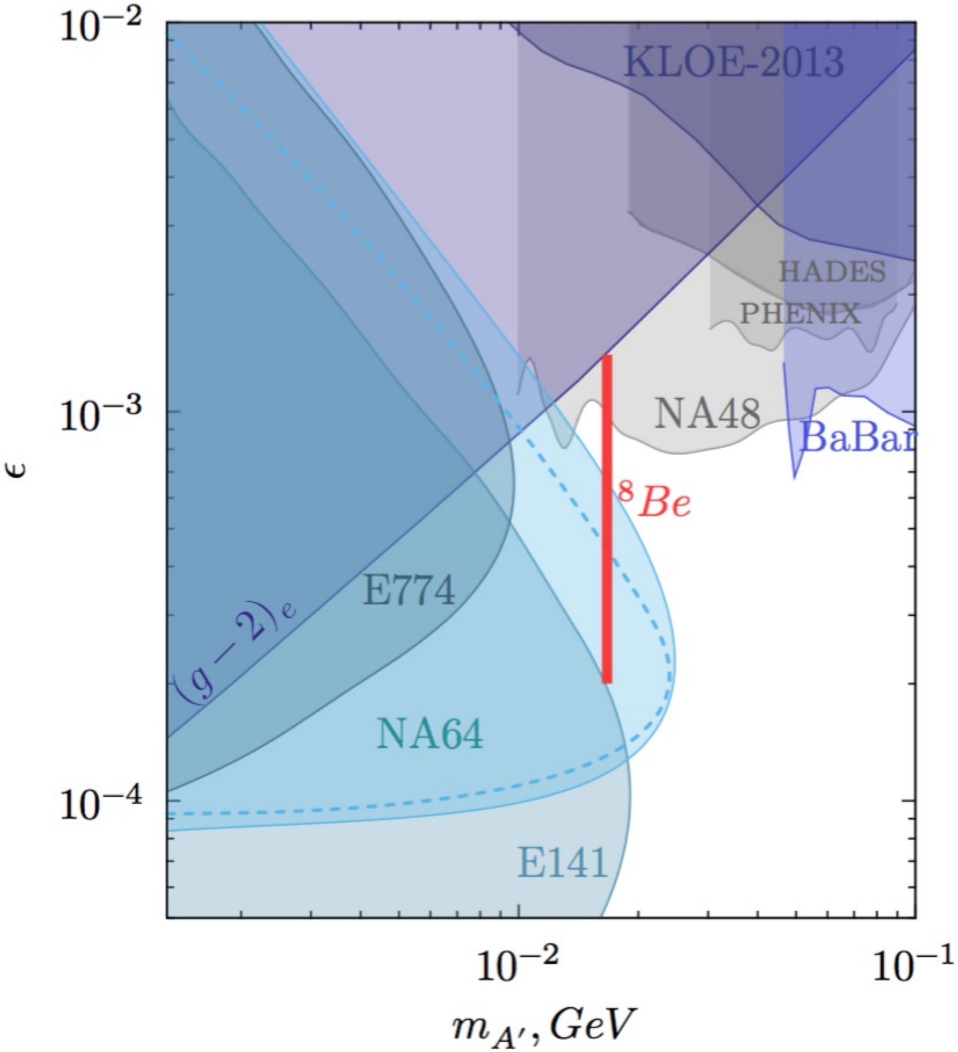


We used control sample to estimate this BG: fully neutral events

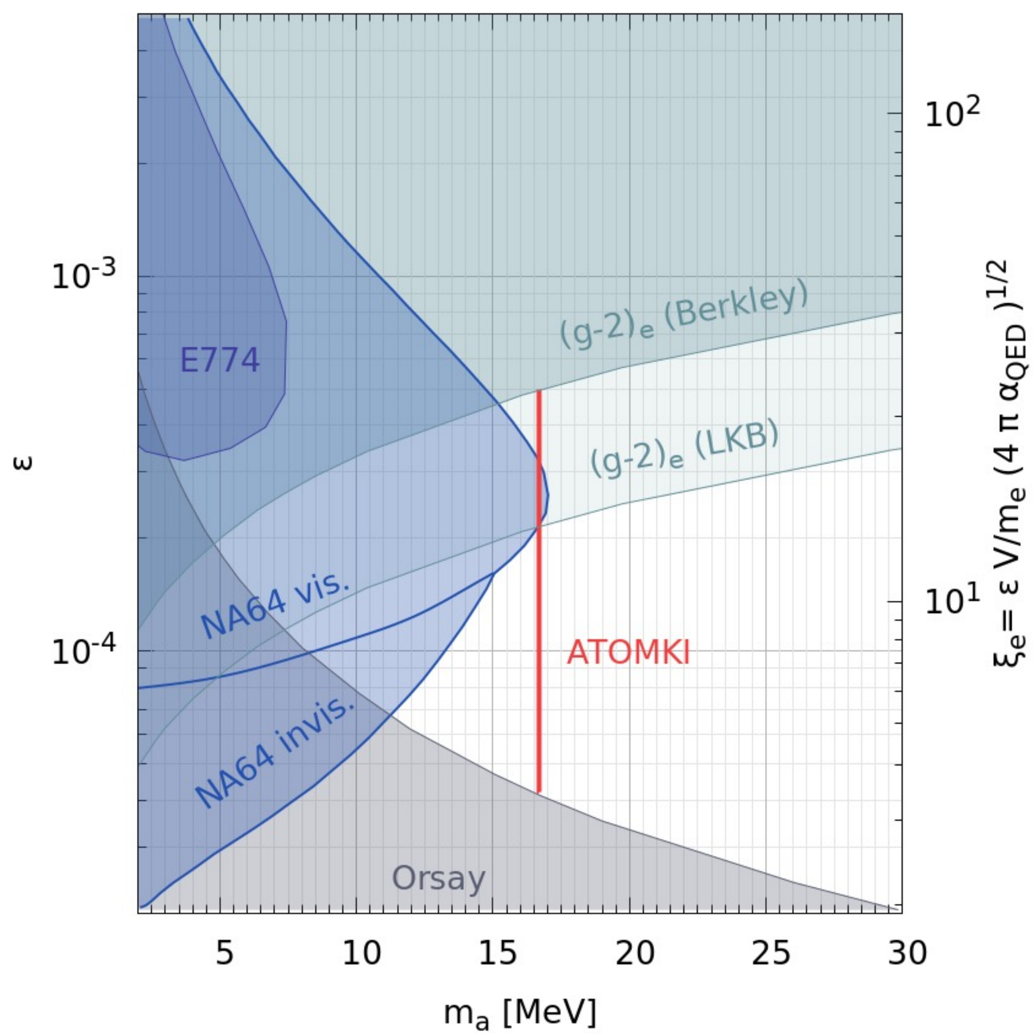
We performed also a search for pseudoscalar bosons. Here, we used also data collected in the invisible mode configuration, similarly to the ALP search

Results with 8.4 x 10^{10} EOT (+invis. mode data for pseudoscalar)

Vector, PRD 107, 071101 (R) 2020

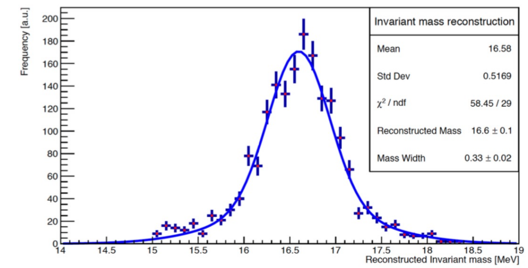


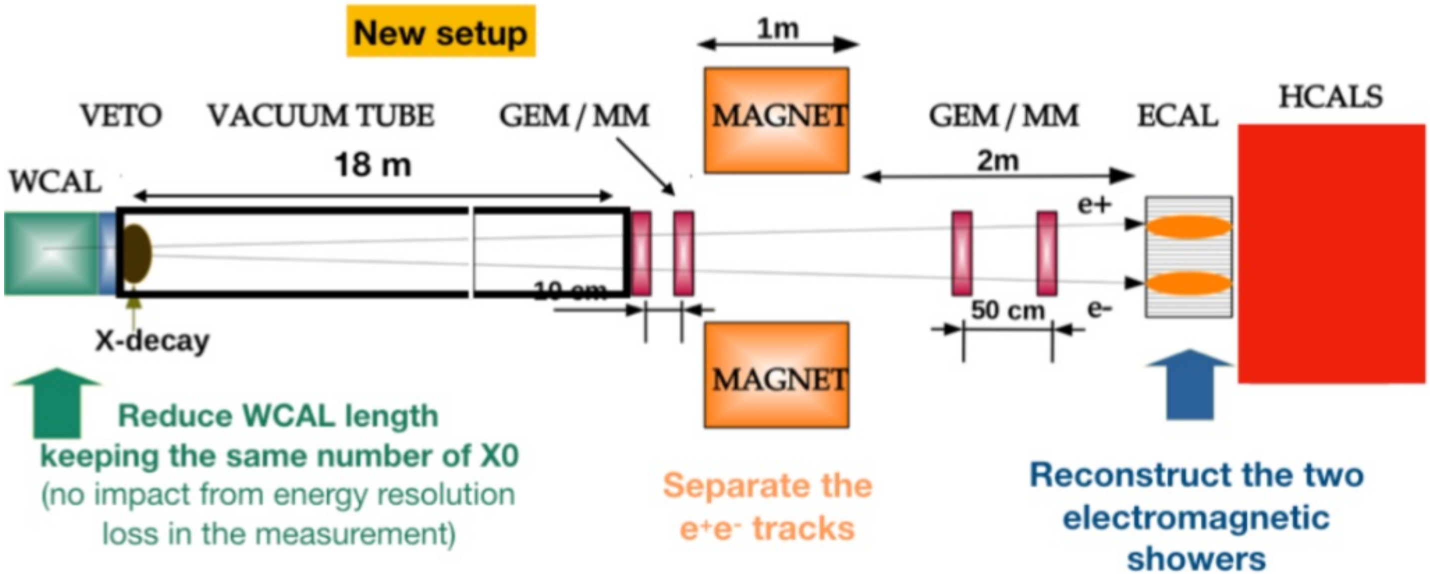
New: Pseudoscalar, arXiv: 2104.13342 [hep-ex]



Plans for the visible mode (2024?)

Full parameter space
Invariant mass reconstruction





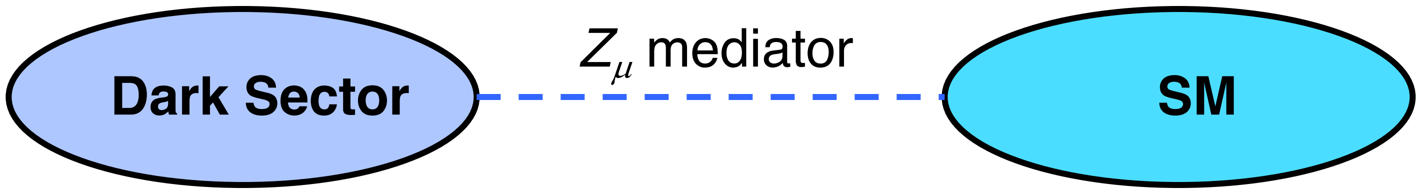
For vector:
cover ε up to
1.3×10^{-3}
with 10^{12} EOT

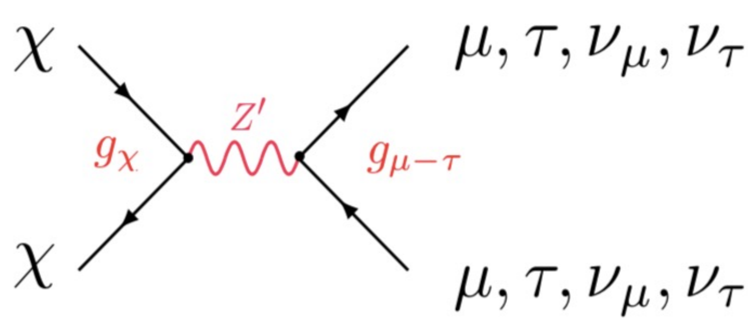
- New further optimized tungsten calorimeter WCAL
- Long decay tube
- Large area M
- Wide ECAL

Project described in
EPJ C 80 12 1159 (2020)

NA64μ

L_μ-L_τ Charged Dark Matter and Z_μ mediator





$$J^\mu_\chi = g_\chi \times \begin{cases} i\chi^*\partial_\mu\chi + h.c. & \text{Complex Scalar} \\ \overline{\chi}_1\gamma^\mu\chi_2 + h.c. & \text{Pseudo–Dirac Fermion} \\ \frac{1}{2}\overline{\chi}\gamma^\mu\gamma^5\chi & \text{Majorana Fermion} \\ \overline{\chi}\gamma^\mu\chi & \text{Dirac Fermion} \end{cases}$$

Gninenko, Krasnikov 1801.10448

Kahn, Krnjaic, Tran, Whitbeck 1804.03144

- LDM coupled predomimantly to generations 2,3
  - free parameters m_χ, m_{Z_μ}, g_χ, g_μ
    - Z_μ decays:

- $m_{Z_\mu} < 2m_\chi$-decays into SM, $Z_\mu \to \nu\nu, \mu^+\mu^-, \tau^+\tau^-$
- $m_{Z_\mu} > 2m_\chi$- invisible decays into DM: $Z_\mu \to \chi\chi, \nu\nu,$

$\alpha_D >> \alpha_{SM}$, $\alpha_D = g_\chi^2/4\pi$, $\alpha_{SM} = g_\mu^2/4\pi$

- Cross section for χ–DM annihilation:

$\Gamma_{inel} = n_\chi < \sigma v >$

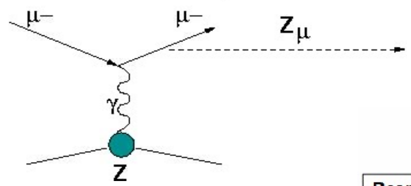
$\sigma v \approx [(g_\chi g_\mu)^2 (m_\chi/m_{A'})^4]/m_\chi^2 = y/m_\chi^2$;

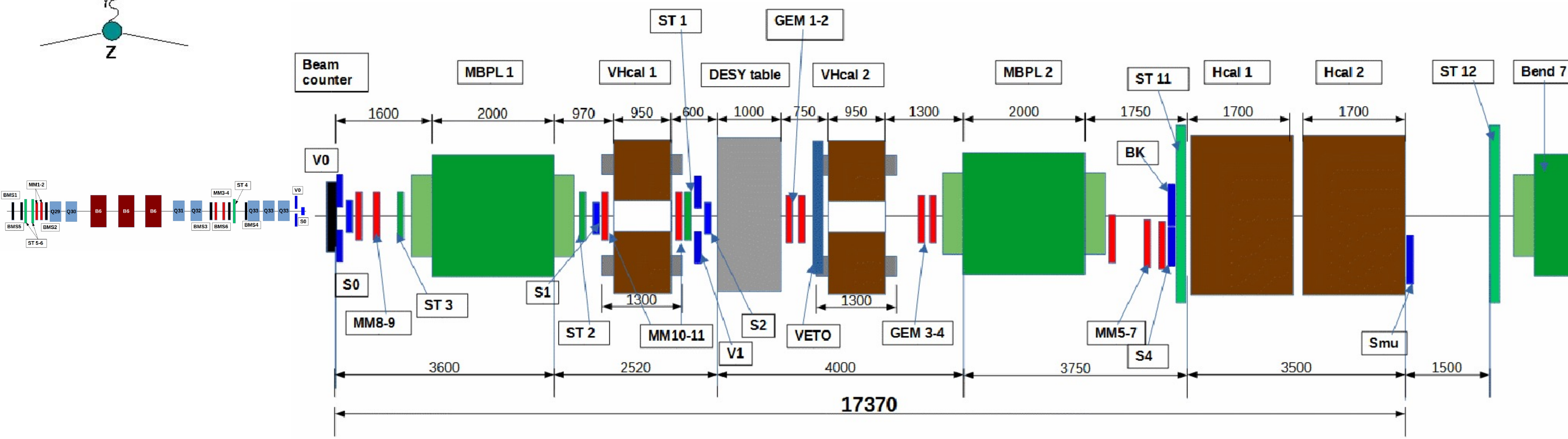
$y = [(g_\chi g_\mu)^2 (m_\chi/m_{A'})^4]$ - useful variable to compare FTE sensitivities

Search for Z_μ in missing energy events on M2 beam

Motivated by $(g-2)_\mu$ measurements

Proposal NA64μ (2019)





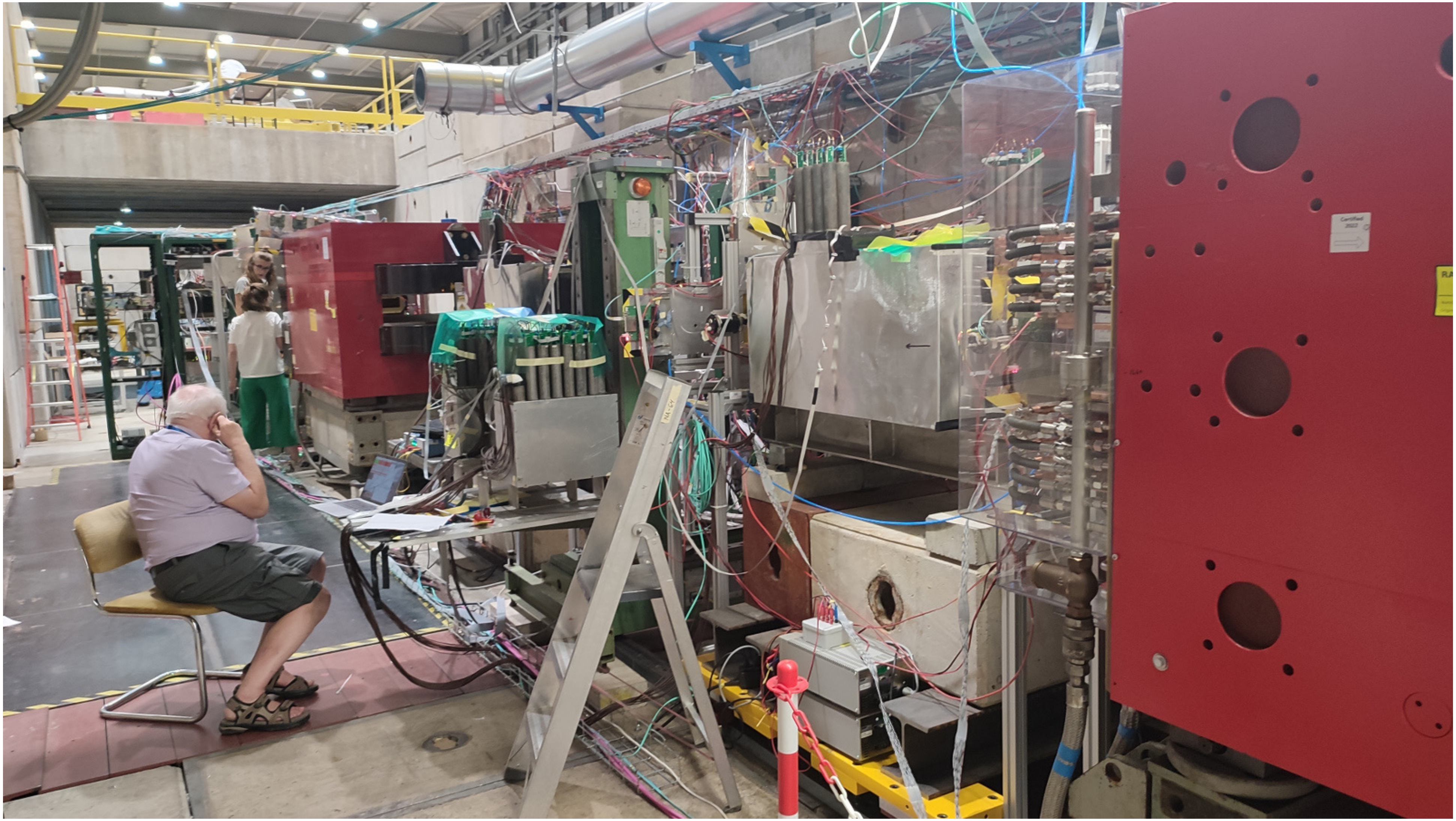
Main components :

- 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)
- 4π fully hermetic ECAL+Veto+ HCAL

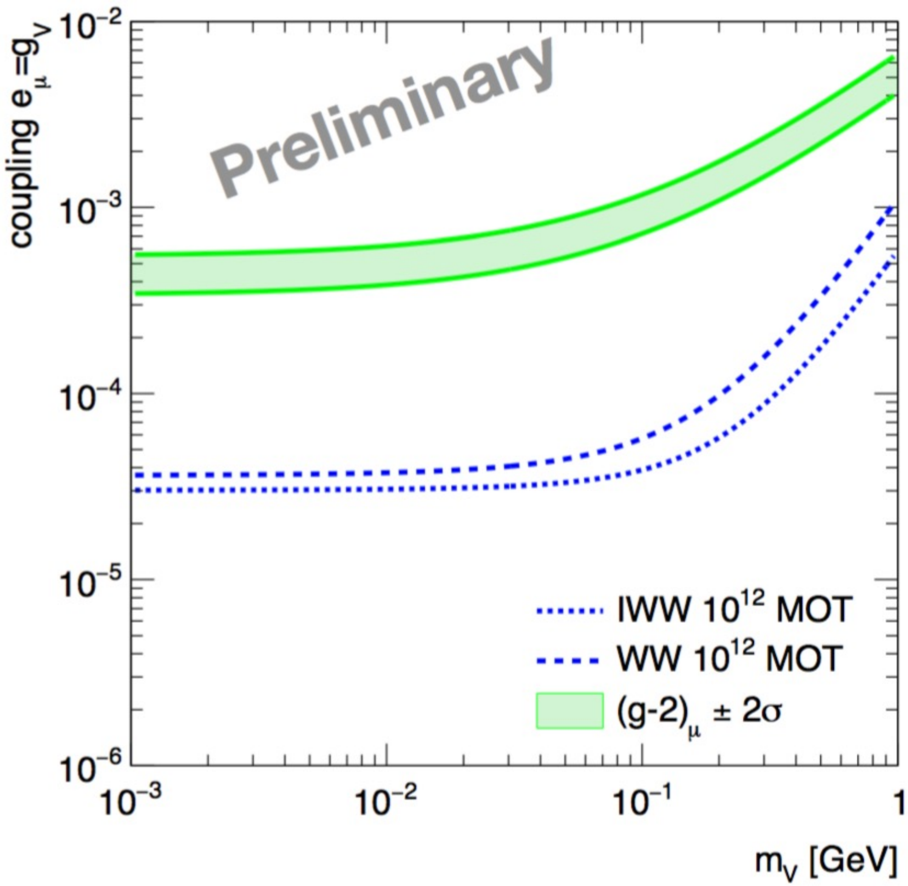
Signature:

- in: 160 GeV μ- track
- out: < 80 GeV μ- track (recoil)
- small energy in the ECAL, Veto, HCAL
- Sensitivity $\sim g_\mu^2$

NA64μ experiment setup, physics run 2023



Pilot runs on M2 in November 2021 and May 2022



DMG4 simulation: we moved recently to WW cross sections, they are close to ETL, σ_{tot} and $d\sigma/dXd\psi$, Ψ – recoil muon angle

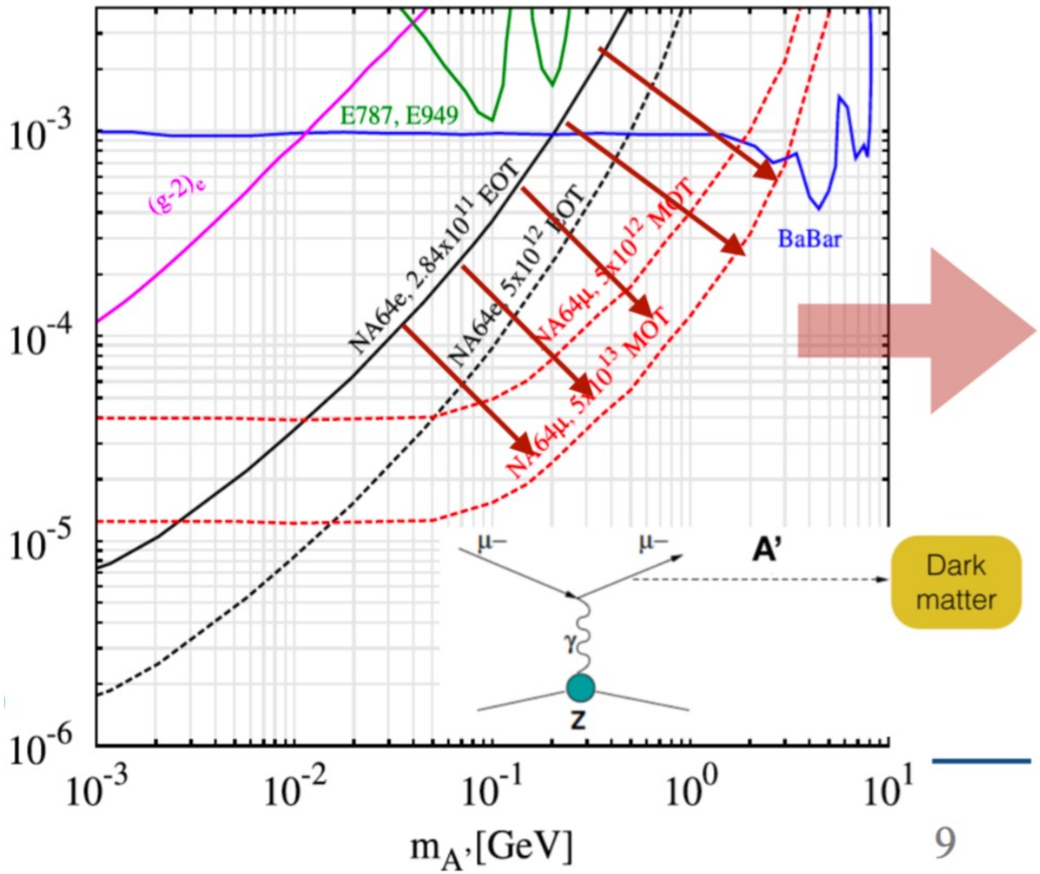
Pilot runs to check trigger rate and noise conditions ~$4\text{x}10^{10}$ MOT

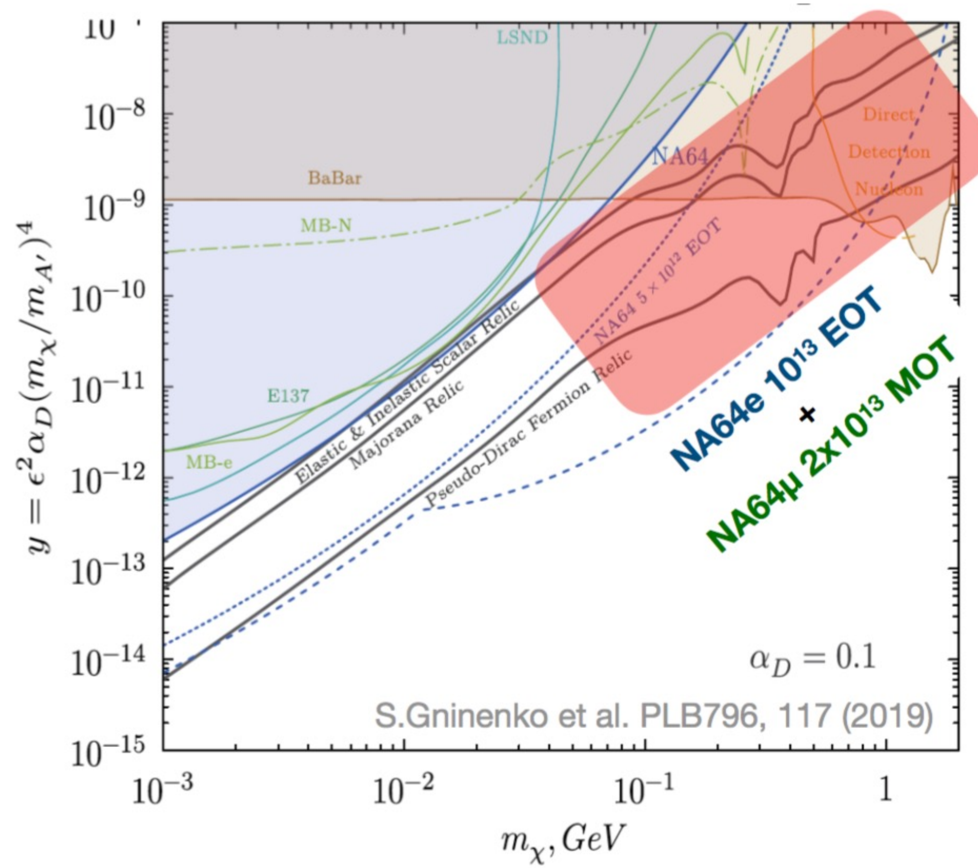
Using the experience from pilot runs we upgraded tracker and performed a physics run in 2023: ~$2\text{x}10^{11}$ MOT

- New wide HCAL
- New special ECAL

Searches for A’ with NA64μ

Better sensitivity to heavy A’ (>100 MeV)





Summary

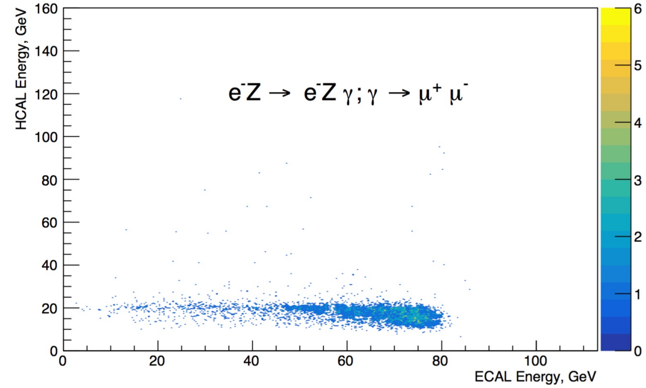
- The NA64 experiment produced several important results in the search for light Dark Matter (mass less than ~1 GeV) coupled to electrons. For example, the explanation of the $(g\text{-}2)_\mu$ anomaly by A' is excluded
- These searches will be continued, the plan is to significantly increase the sensitivity and maximally cover the regions of thermal Dark Matter.
- One of the possibilities to improve sensitivity is to use positron beam (POKER project)
- The NA64μ experiment started in 2021. The purpose is to obtain more direct answer to the question about the $(g\text{-}2)_\mu$ explanation by Dark Matter and to improve sensitivity to A' for the masses > 100 MeV.
- The searches for X(17) particle that could explain ATOMKI anomaly : new project ready, suspended for the time being
- Other planned searches are μ - τ conversion, NA64h etc.

Backup slides

Backup

Dimuon production as a reference process

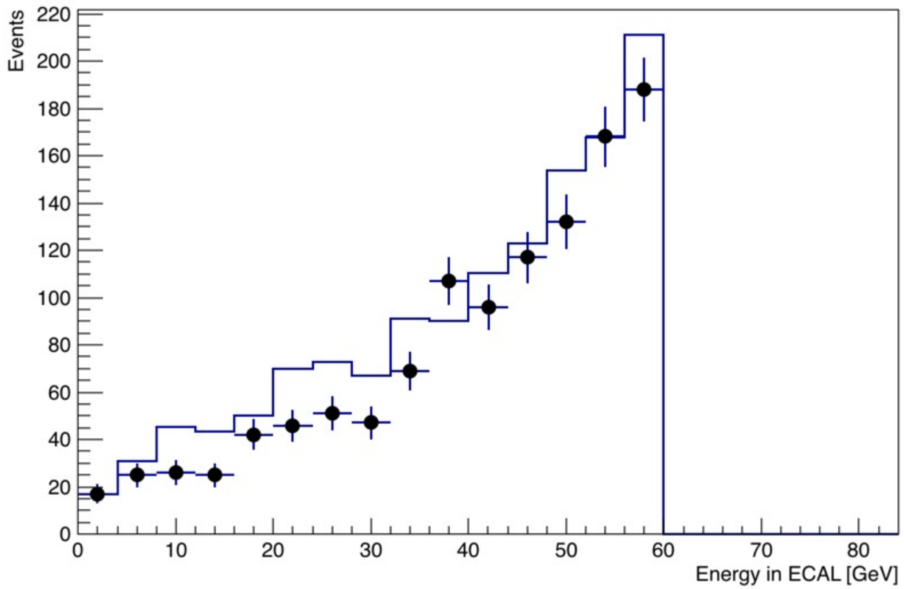
- There is an excellent reference process: gamma to muons conversion. It is rather rare and has many similarities with our signal

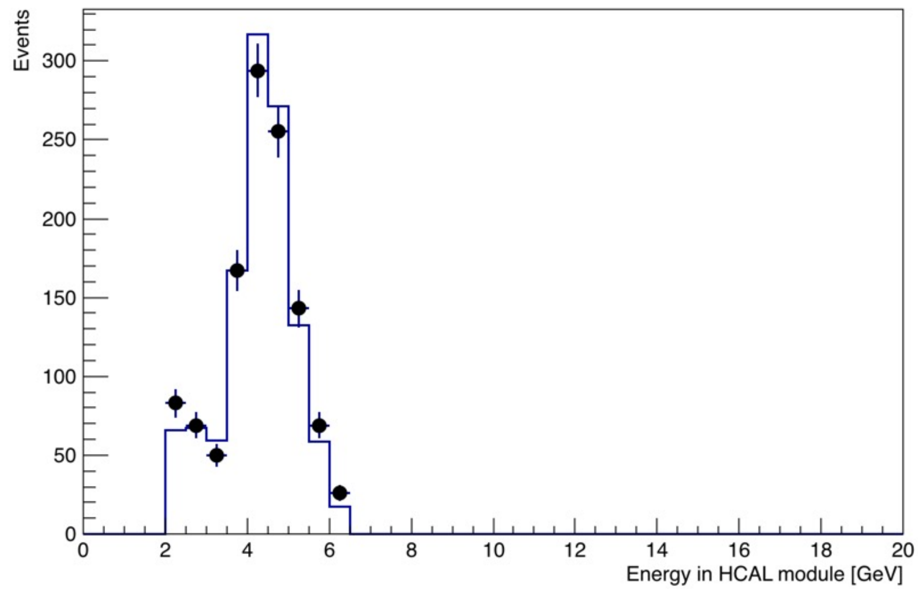


- Several 10^4 dimuon pairs with both muons reaching all HCAL modules are registered in the 2016 runs
- The process is available in GEANT4, off by default
- We bias the cross section in GEANT4 by a factor of 200 in order to have good statistics with reasonable CPU time.
- Reasonable agreement DATA - MC

Dimuon reconstruction

HCAL module 3





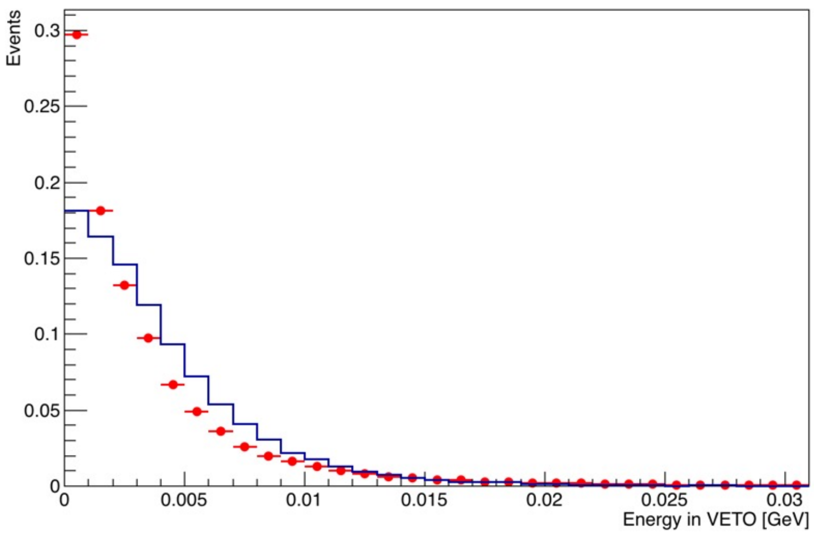
Dimuons selection: $E_{ECAL} < 60$ GeV
$2.5 < E_{HCAL1} < 6.35$
$2 < E_{HCAL3} < 6.35$

Left plot: number of dimuons in DATA ~ 0.92 of MC prediction, slightly smaller at high intensity -> efficiency correction

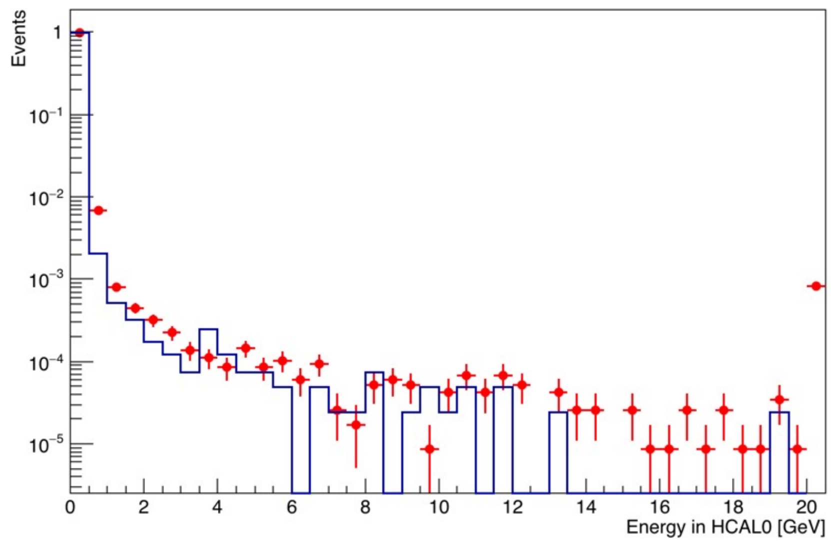
Analysis: efficiency corrections and uncertainties

Efficiency type	Method	Efficiency	uncertainty
Trigger and SRD selection, DAQ	Dimuons analysis	0.91	10%
VETO cut	Comparison MC - data in calib. runs	1	5%
HCAL cut	Comparison MC - data in calib. runs	0.99	5%

Veto: cut at 0.01 GeV



HCAL0: cut at 1 GeV



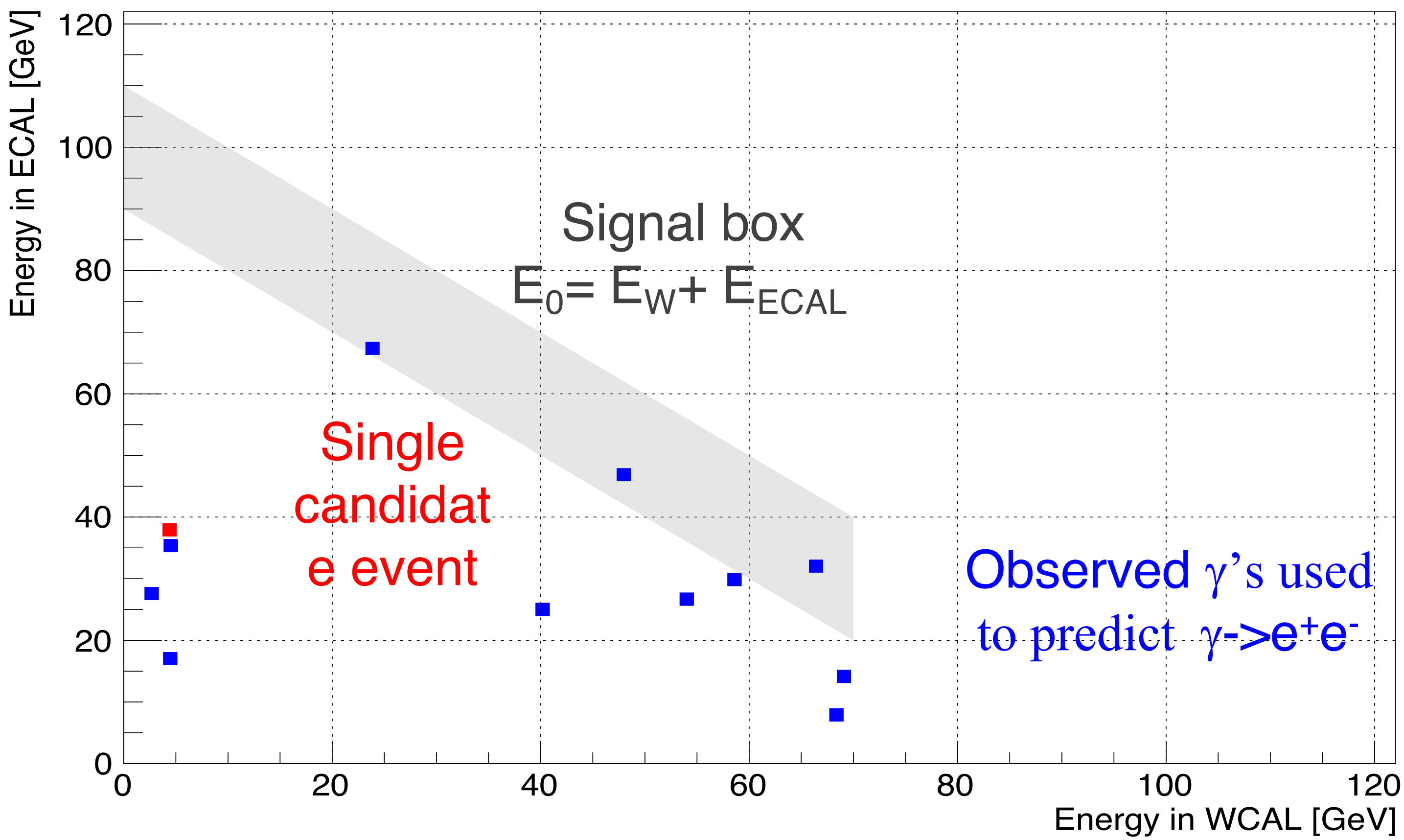
Analysis

- Data collected in the automn 2016 run are divided in 3 bins: low, medium and high intensity
- For each bin the background, efficiency corrections and their uncertainties are estimated
- The expected sensitivity was calculated with ProfileLikelihood method
- The limits are calculated with CL_S method

Final estimate of the background

Source of background	Events
e^+e^- pair production by punchthrough γ	< 0.001
$K^0_S \to 2\pi^0; \pi^0 \to \gamma e^+e^-$ or $\gamma \to e^+e^-$; $K^0_S \to \pi^+\pi^-$	0.06 ± 0.034
$\pi N \to (\geq 1)\pi^0 + n + ...; \pi^0 \to \gamma e^+e^-$ or $\gamma \to e^+e^-$	0.01 ± 0.004
π^- hard bremsstrahlung in the WCAL , $\gamma \to e^+e^-$	< 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
punchthrough π	< 0.003
Total	0.07 ± 0.035

Results from 2017 run, 5.4×10^{10} EOT



Event selection 2018 at 150 GeV: criteria

- SRD tag (with only 2 modules because of smaller bend)
- E_{WCAL} < 105 GeV (preliminary trigger selection
  E_{WCAL}< ~110 GeV)
- E_{V2} < 0.6 MIP (no charged particles after WCAL).
- E_{S4} > 1.5 MIP (two charged particles in ECAL).
  Control region for neutrals: E_{S4} < 0.7 MIP
- E_{WCAL} + E_{ECAL} > 125 GeV
- Shower profile in ECAL compatible with electron (or with two very close electrons)
- Small energy in VETO and HCAL