Recent results and plans of the NA64 experiment at the CERN SPS

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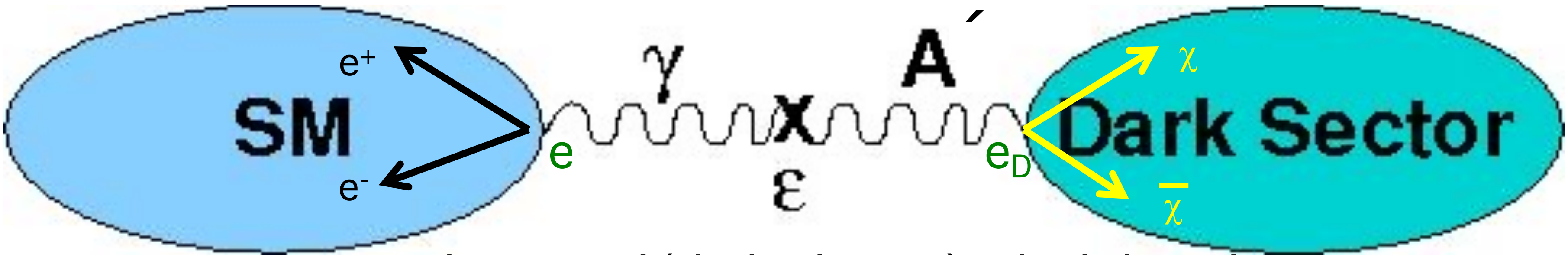
Outline

- 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
- ALP search in invisible mode configuration
- Visible mode: X-boson, motivation, results, new project
- $(g\text{-}2)_\mu$ and NA64μ
- NA64h: searches in hadron beams

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

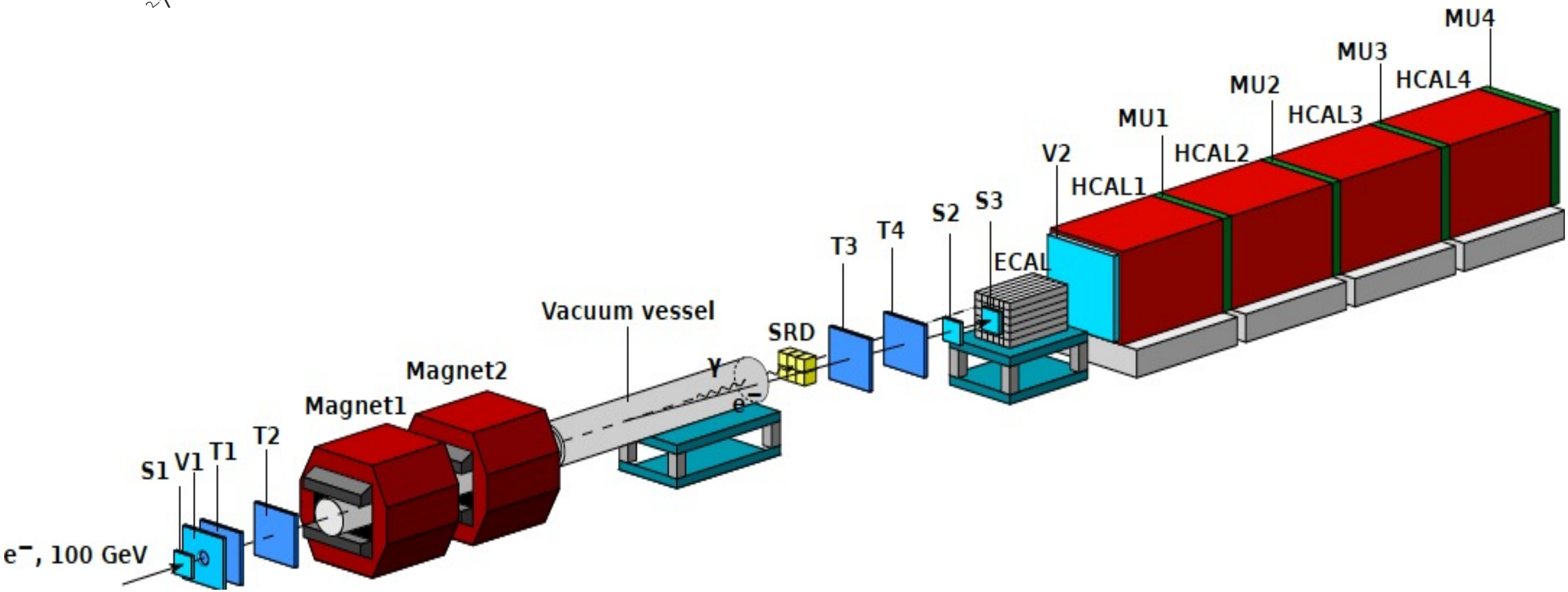
- Decays:
  - Visible: $A' \rightarrow e^+e^-, \mu^+\mu^-$, hadrons,..
  - Invisible: $A' \rightarrow \chi\chi$ if $m_{A'} \geq 2m_\chi$ assuming $\alpha_{DM} \sim \alpha >> \varepsilon$.

  Can explain $(g\text{-}2)_\mu$, astrophys. observations
  - Cross section for χ–DM annihilation: $\sigma v \sim \underbrace{[\alpha_{DM}\, \varepsilon^2 (m_\chi/m_{A'})^4]}_{y}\, \alpha/m_\chi^2$

Thermal dark matter

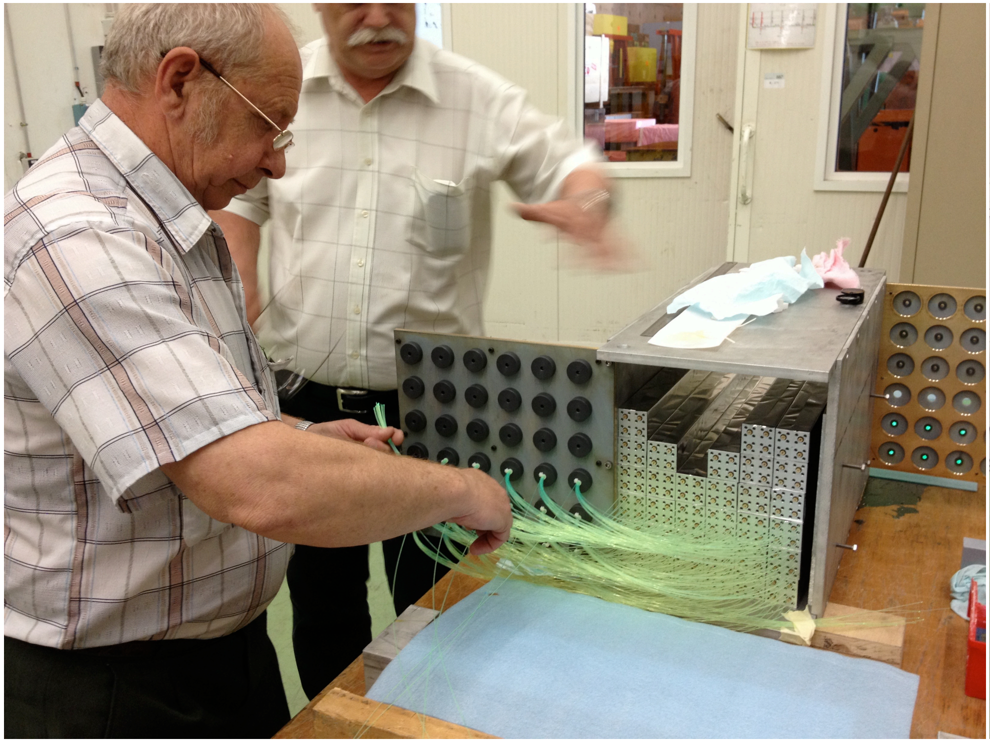
- Assume that in the early Universe dark matter is in equilibrium with the SM matter. At some temperature the dark matter decouples
- DM density today tells us about the annihilation cross-section. Correct DM density corresponds to $<\sigma_{an}v> \sim O(1)$ pbn
- Most popular models of light (sub-GeV)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

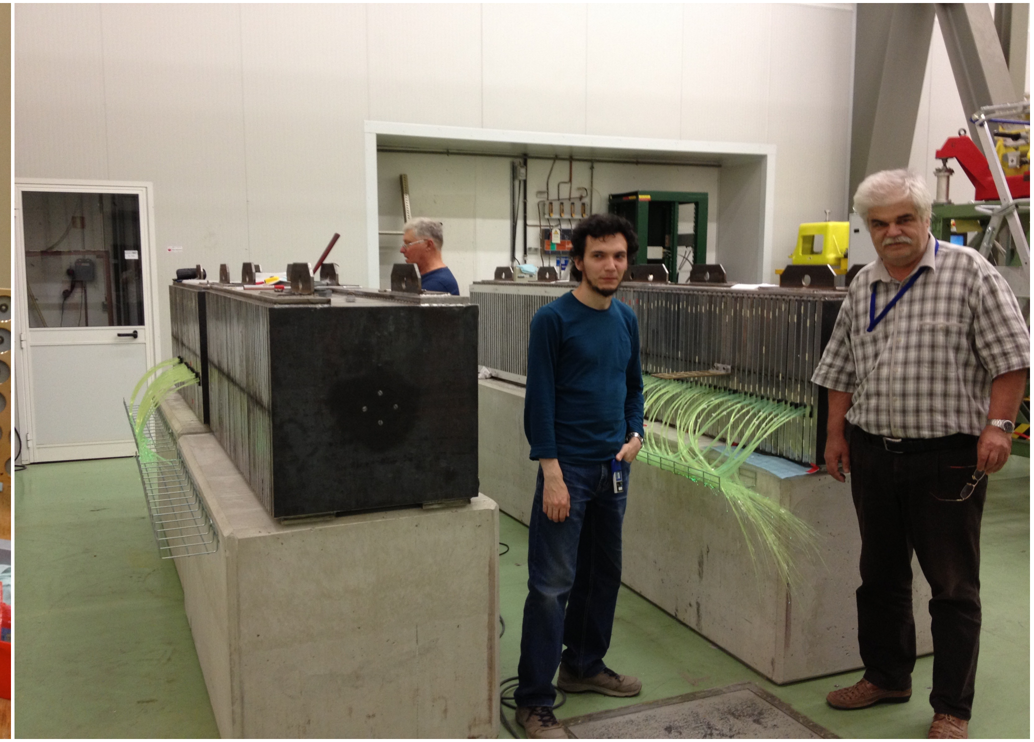
NA64 experiment setup (invisible mode)



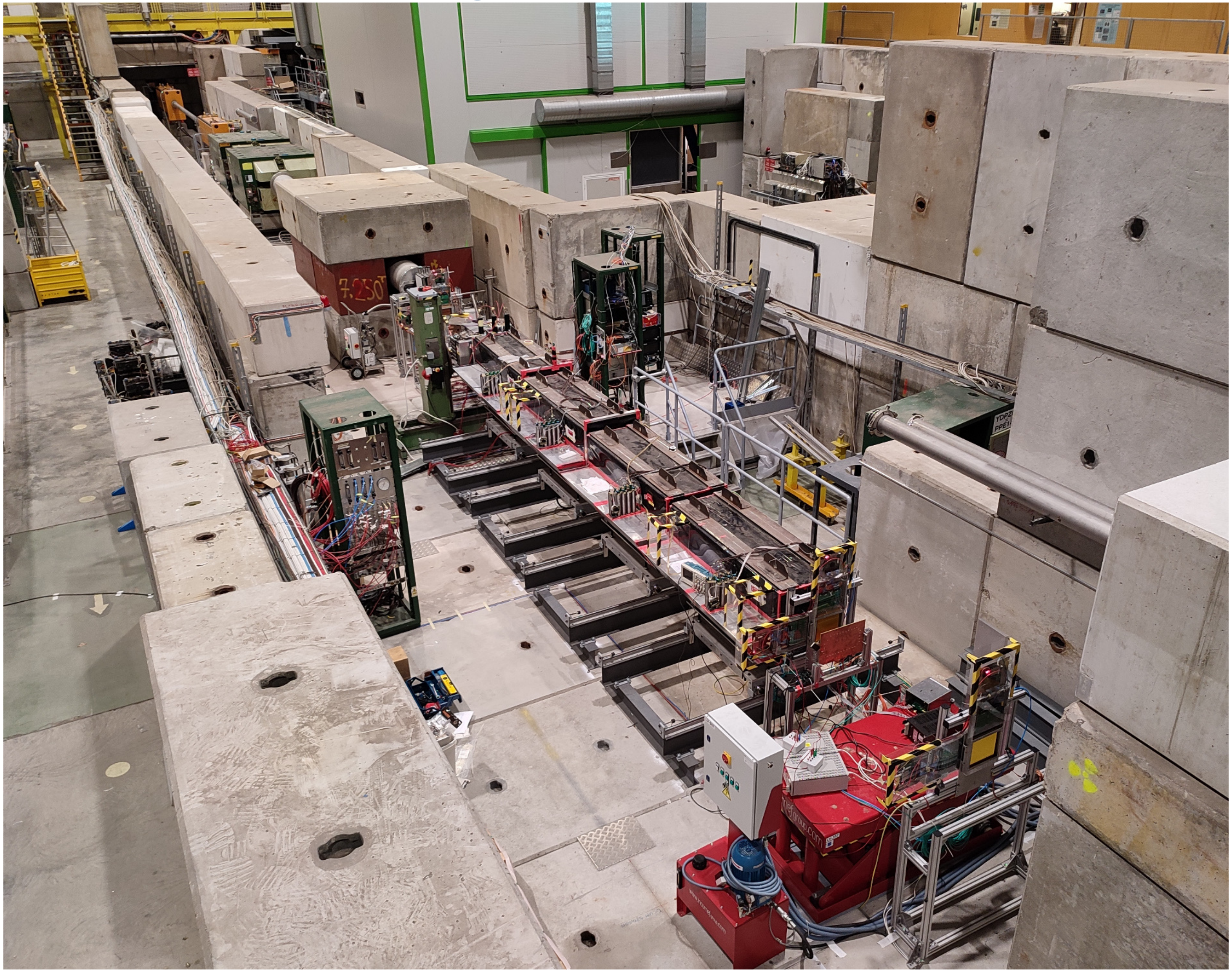
~50 researchers from 12 institutes, >50% from RF inst. + JINR
Proposed in 2014, first test runs in 2015, approved as NA64 2016

Assembling NA64 subdetectors (2015)

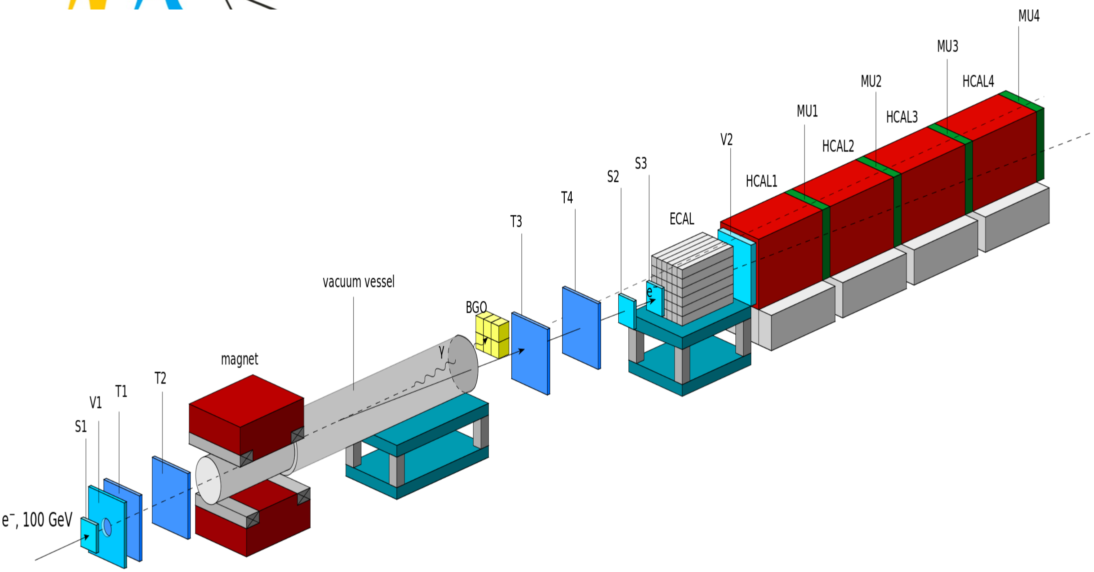


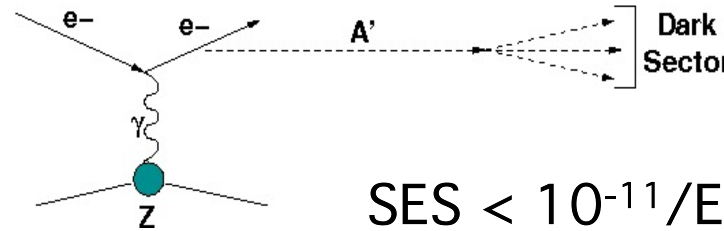


NA64 in 2021-2022, permanent place at H4 prepared by the CERN Beam Division



Search for A´->invisible decays at CERN SPS





SES < 10^{-11}/EOT

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

Signature:

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

Main components :

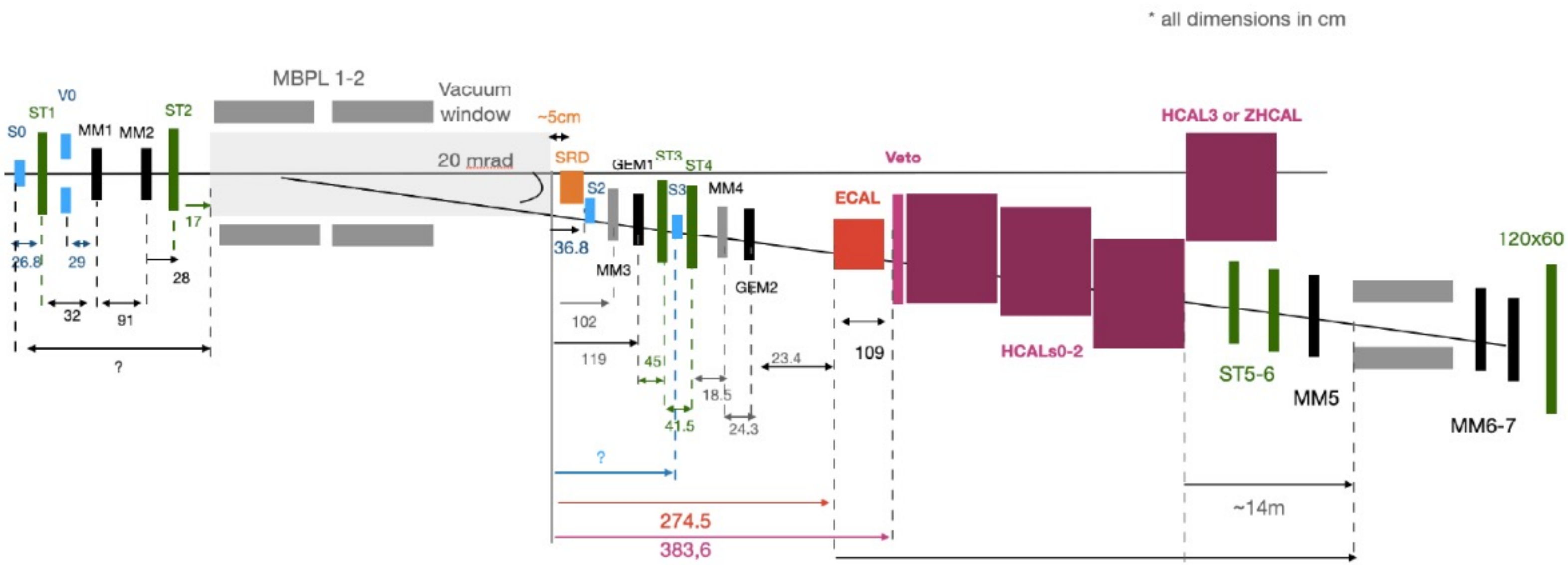
- clean 100 GeV e- beam
- e- tagging system: MS+SRD
- hermetic ECAL+HCAL

Background:

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

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

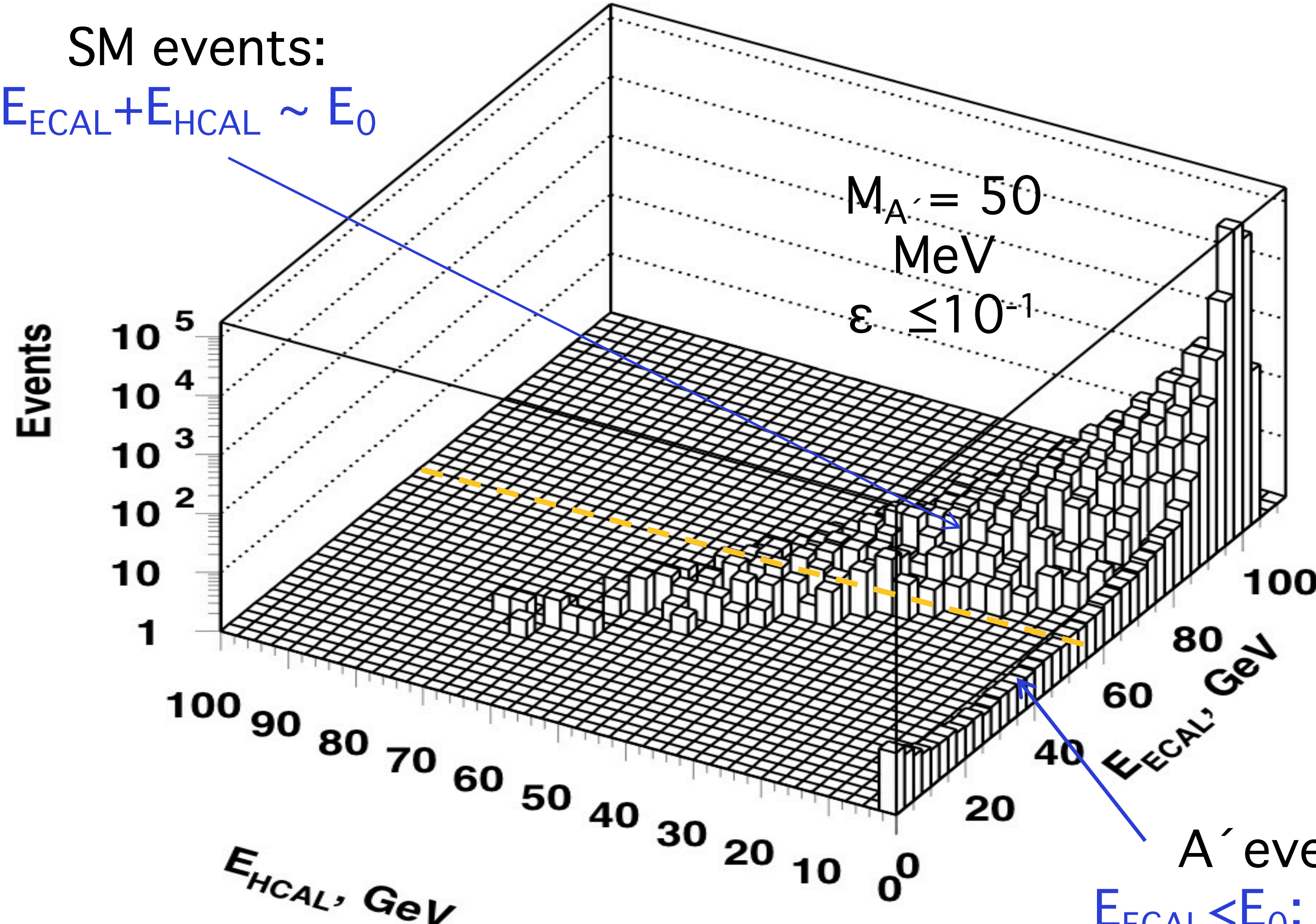
- **Invisible mode** configuration, first run 12.10-09.11 2016
  - Run 2016 EOT ~ $4.5\text{x}10^{10}$, S_0 rate $2\div4\text{x}10^6$;
  - Run 2017 EOT ~ $5.4\text{x}10^{10}$, S_0 rate $4\div6\text{x}10^6$
  - Run 2018 EOT ~ $1.9\text{x}10^{11}$, S_0 rate $6\div8\text{x}10^6$
  - Run 2021 EOT ~ $5.2\text{x}10^{10}$, S_0 rate $4\div5\text{x}10^6$
  - Run 2022 EOT ~ $6.4\text{x}10^{11}$, S_0 rate $5\div7\text{x}10^6$
  - Run e^+ 2022 EOT ~ $1.0\text{x}10^{10}$, S_0 rate $5\div7\text{x}10^6$
  - Run 2023 EOT ~ $6.0\text{x}10^{11}$, S_0 rate $5\div7\text{x}10^6$
  - Total analysed electrons (2016 – 2022) ~ $9.37\text{x}10^{11}$ eot
  - Total accumulated (2016 – 2023) ~$1.5\text{x}10^{12}$ eot

- **Visible mode** configuration first run 22.09-01.10 2017
  - Subrun 1 WCAL 40X0 EOT ~ $2.4\text{x}10^{10}$, S_0 rate ~$3\text{x}10^6$
  - Subrun 2 WCAL 30X0 EOT ~ $3\text{x}10^{10}$, S_0 rate $4\text{-}5\text{x}10^6$
  - Run 2018 S4 in WCAL EOT ~ $3\text{x}10^{10}$, beam 150 GeV
  - Total EOT ~ $8.4\text{x}10^{10}$

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

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

SM events:
$E_{ECAL}+E_{HCAL} \sim E_0$



$M_{A'} = 50$ MeV
$\varepsilon \leq 10^{-1}$

A´events:
$E_{ECAL}<E_0$; $E_{HCAL}=0$

DM processes simulation: DMG4

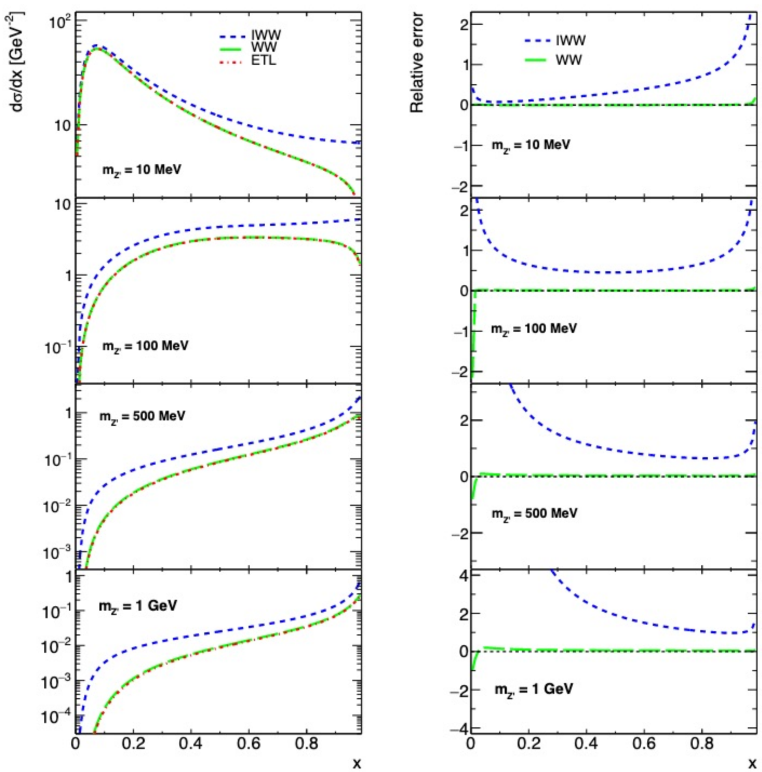
- Fully Geant4 compatible package DMG4 is developed arXiv:2101.12192 [hep-ph]. Can be used in any full simulation program based on the Geant4 toolkit
- Bremsstrahlung processes off electrons and muons (like $eZ \rightarrow eZA'$), gamma conversion to ALP, annihilation processes (like $e^+e^- \rightarrow A' \rightarrow \chi\chi$) can be simulated
- DM messengers: vector (A'), axial vector, scalar, pseudoscalar, spin 2 (graviton), 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)

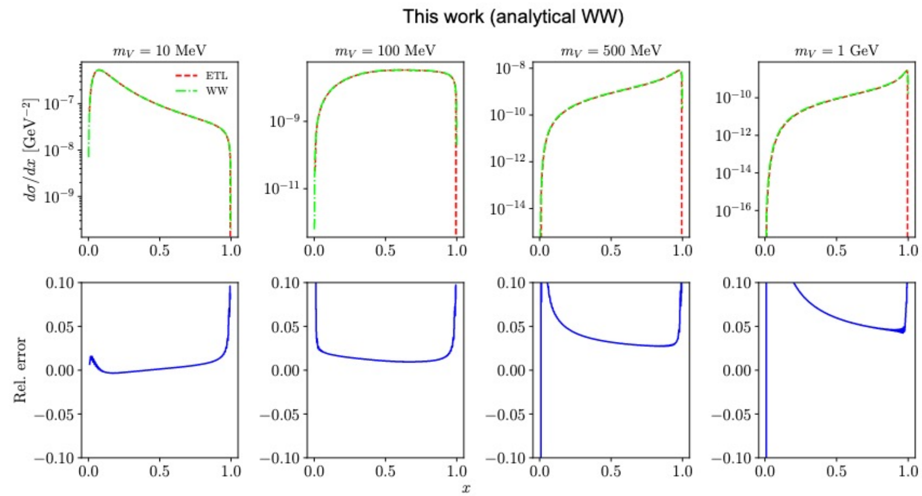
- Simplified IWW approximation in e^{-+} beams for differential cross sections (messenger masses > 1 MeV), sufficient accuracy. Messenger energy and angle are sampled
- Tabulated e^{-+} beams differential cross section for masses < 1 MeV
- Recently implemented WW approximation in muon beams Complicated 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)



Vector (V)

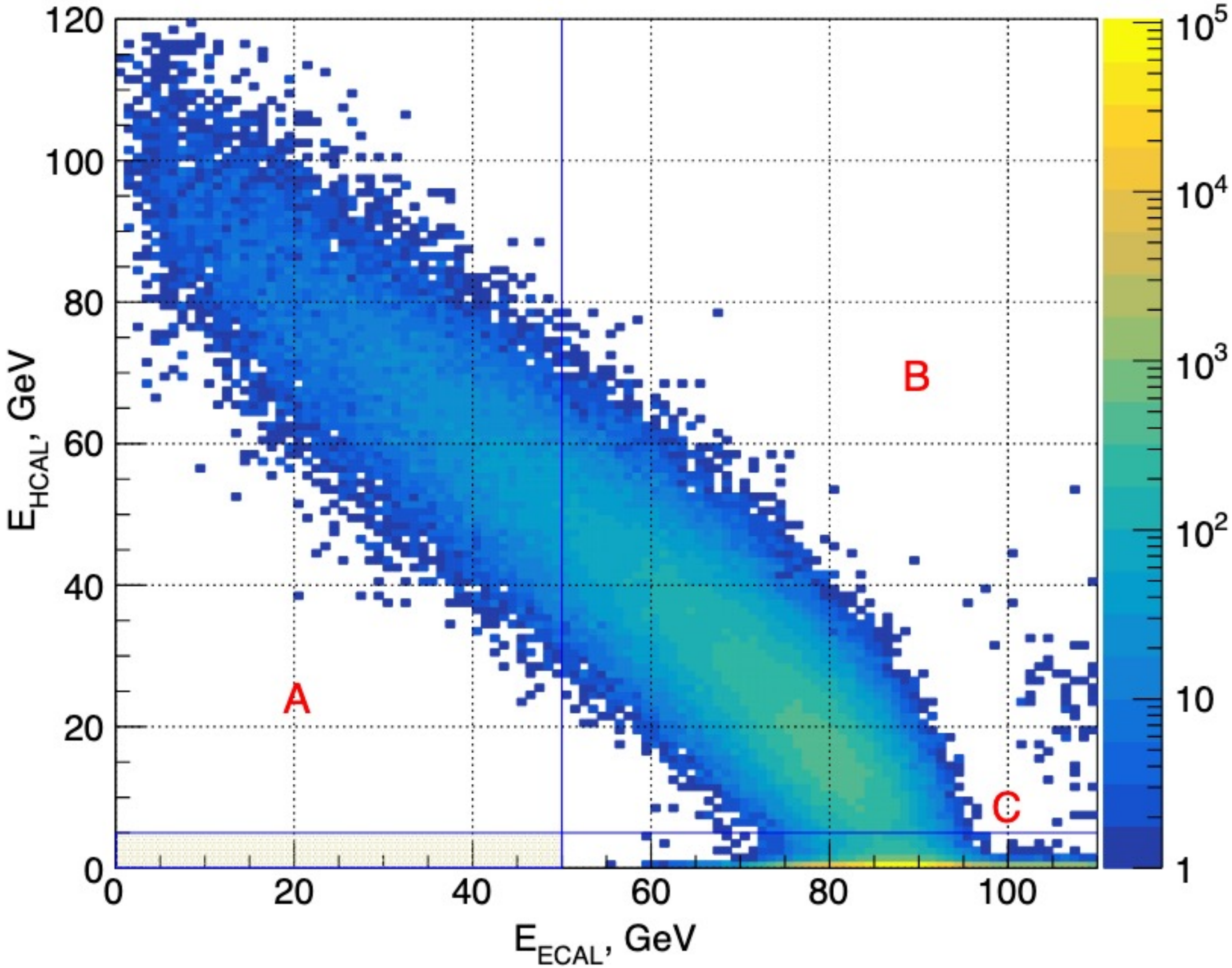
σ@160 GeV

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

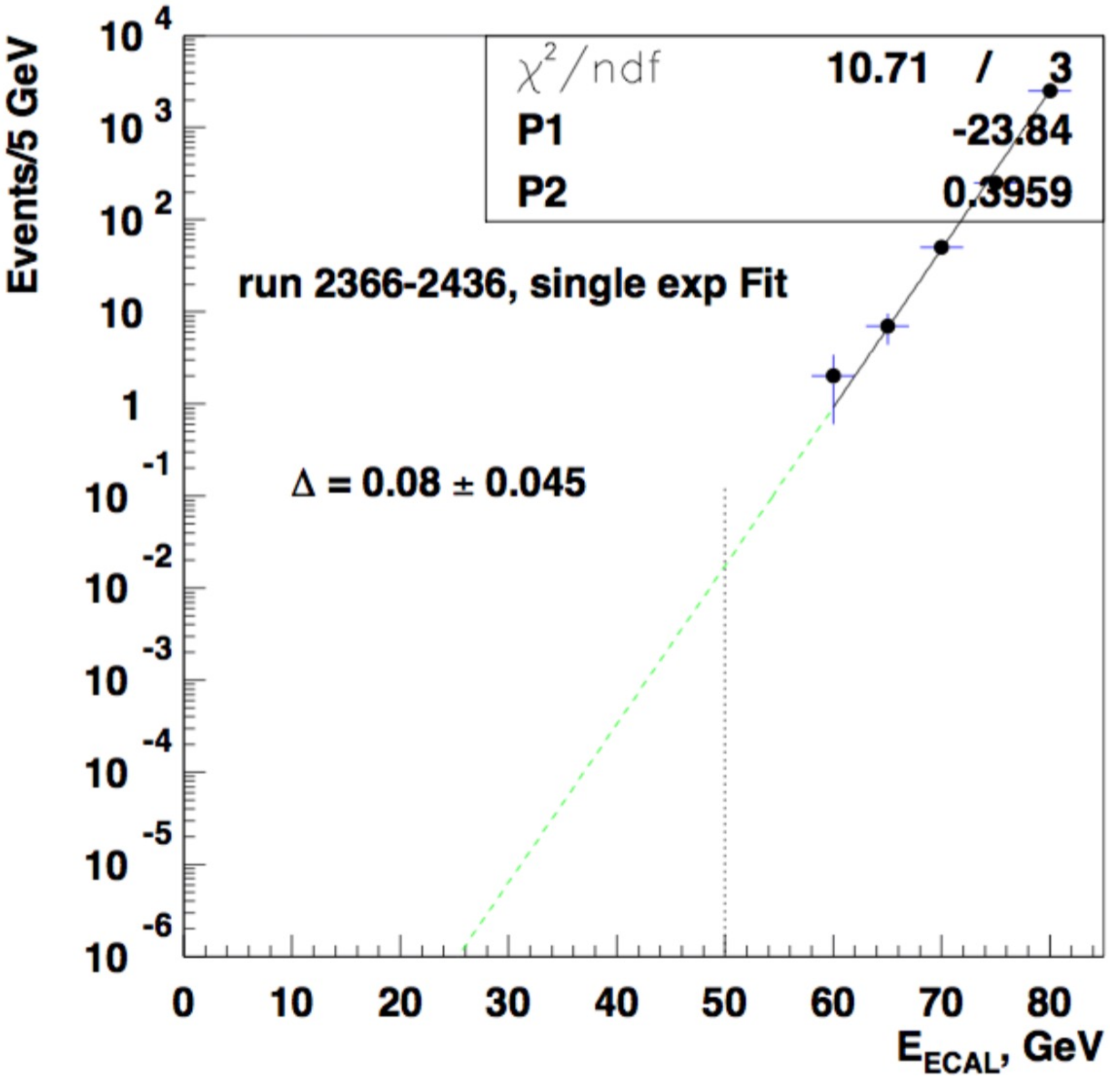
Analysis of data 2022

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

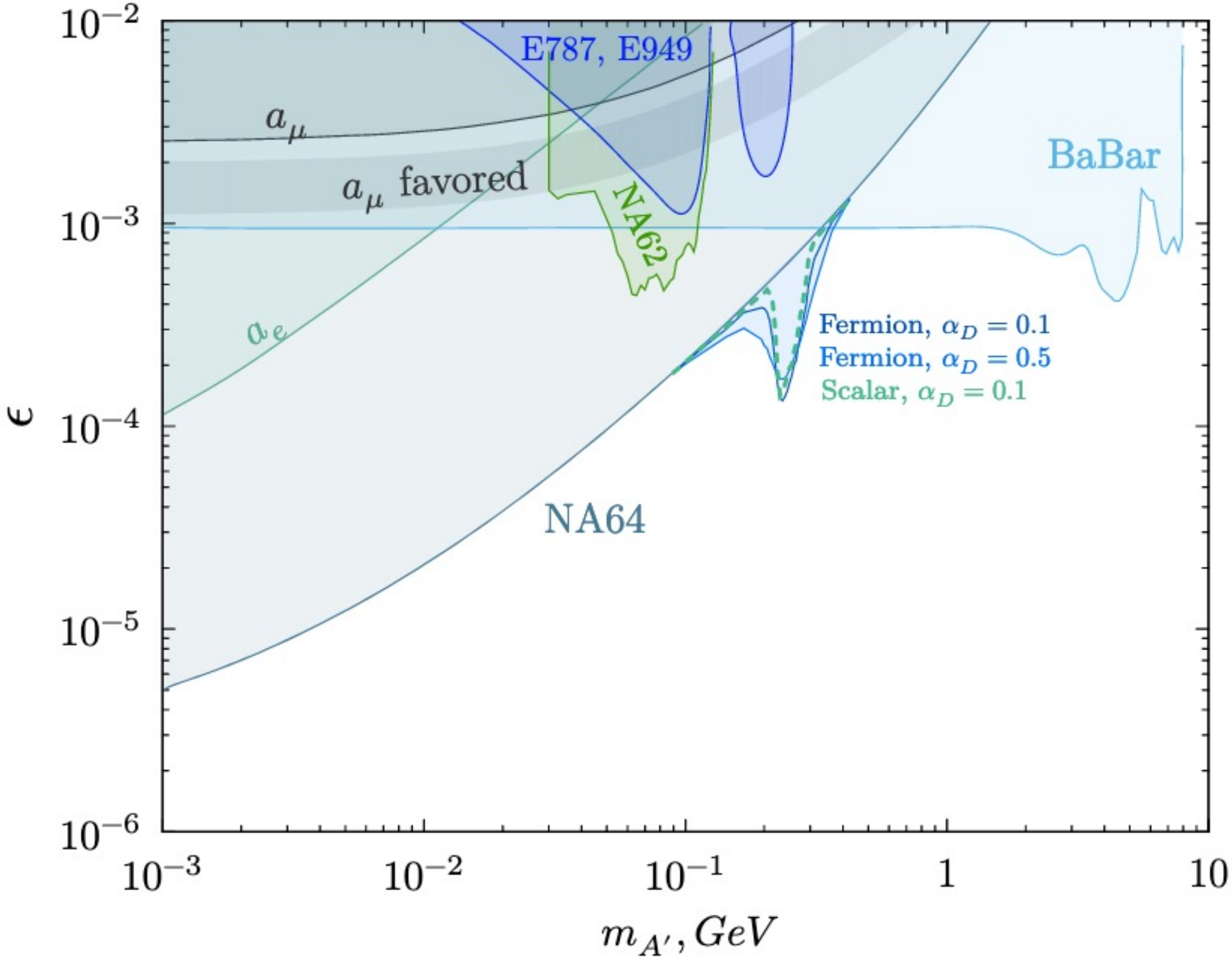


Background sources runs 2021 - 2022

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

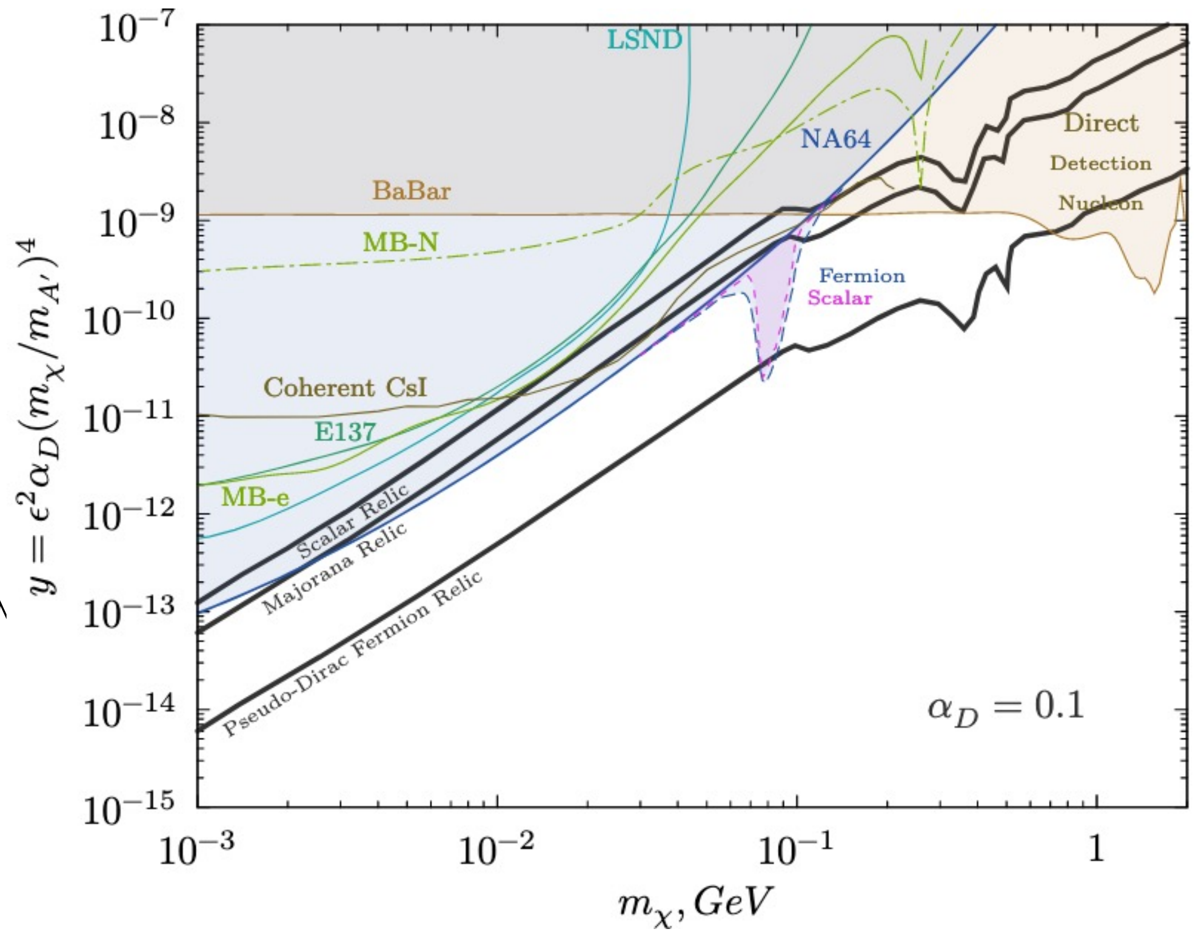
+ Resonant process: shower positrons on electrons of the target

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

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



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

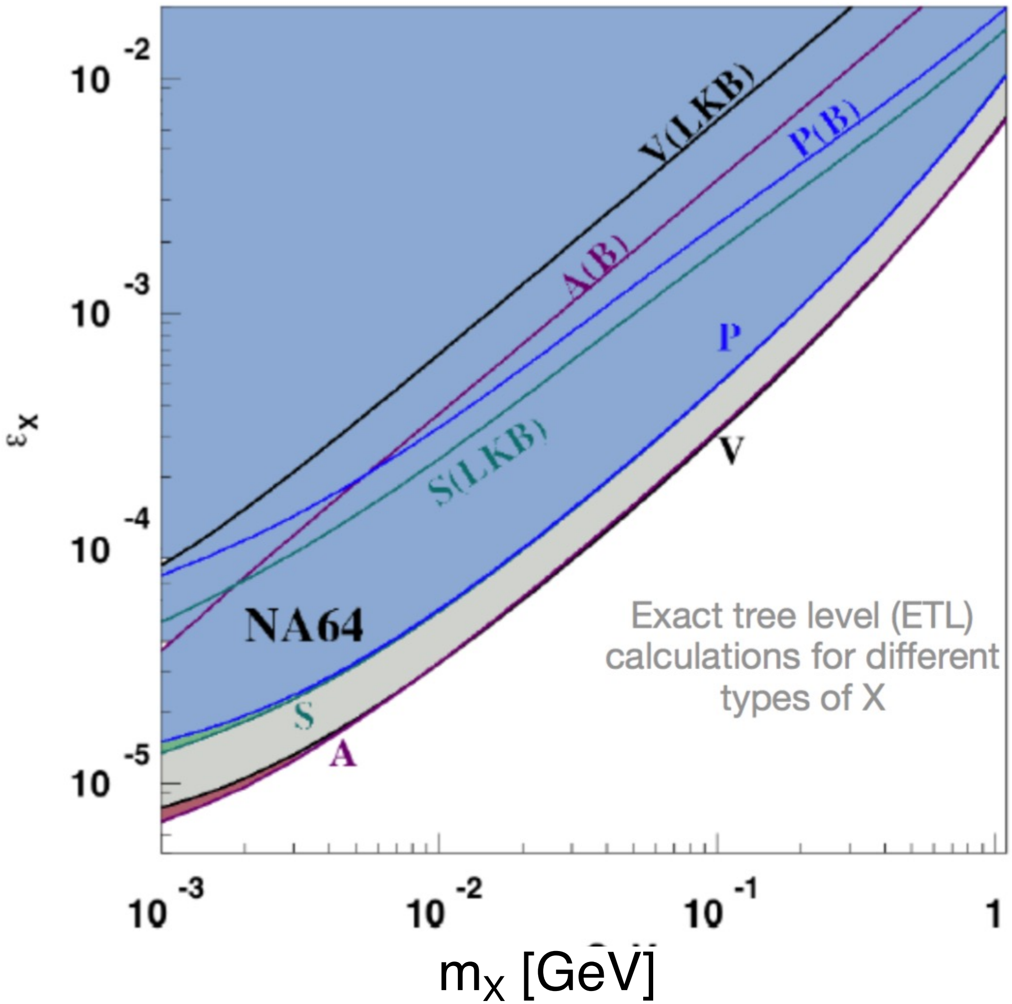
For $\alpha_D = 0.1$ we cover two models and touch the third

Less strict limits for $\alpha_D > 0.1$

proportional to DM<->SM annihilation cross section

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

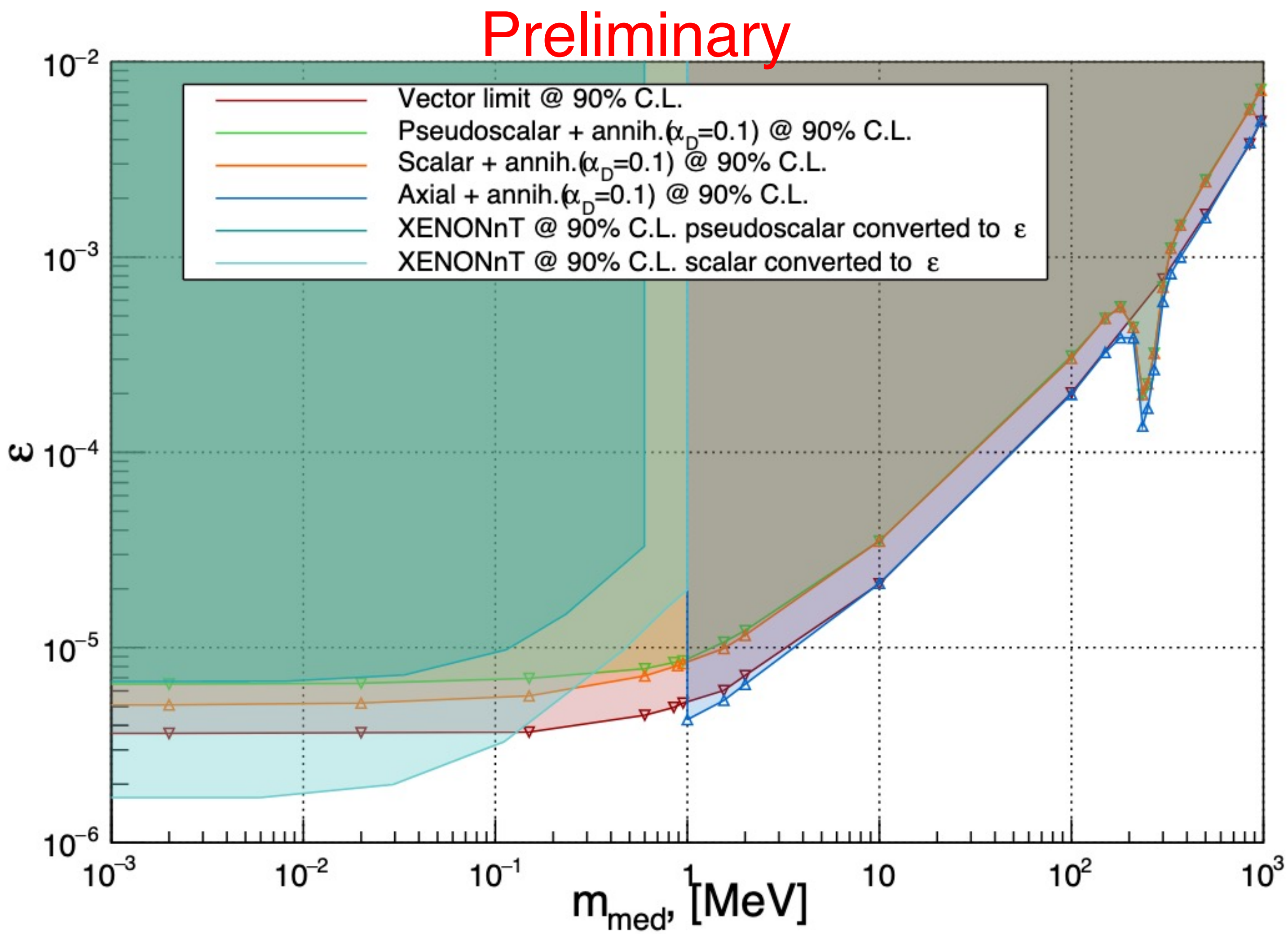
$e^- Z \rightarrow e^- Z X; X \rightarrow$ **invisible**



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

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

Limits on generic boson, new analysis

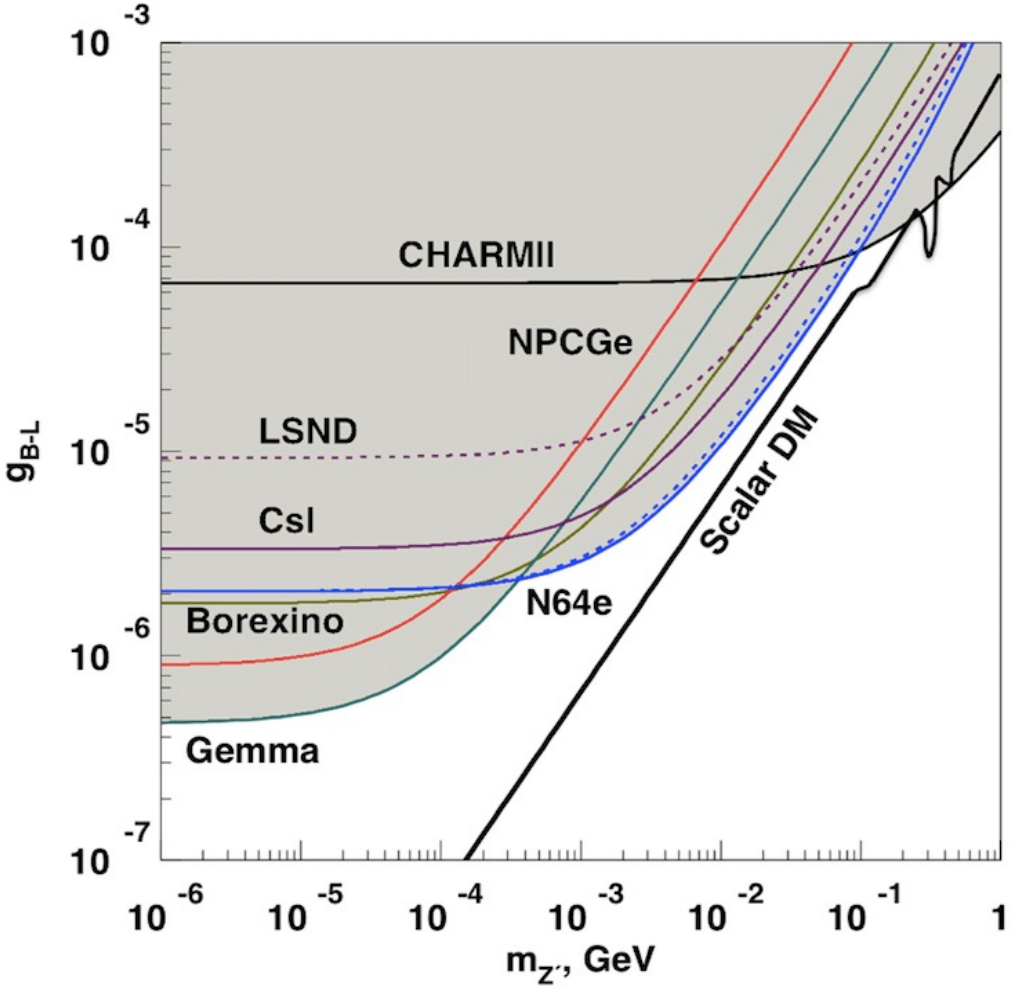


Consider also
Scalar,
Pseudoscalar,
Axial vector

+Annihilation

Extend to 1 KeV

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

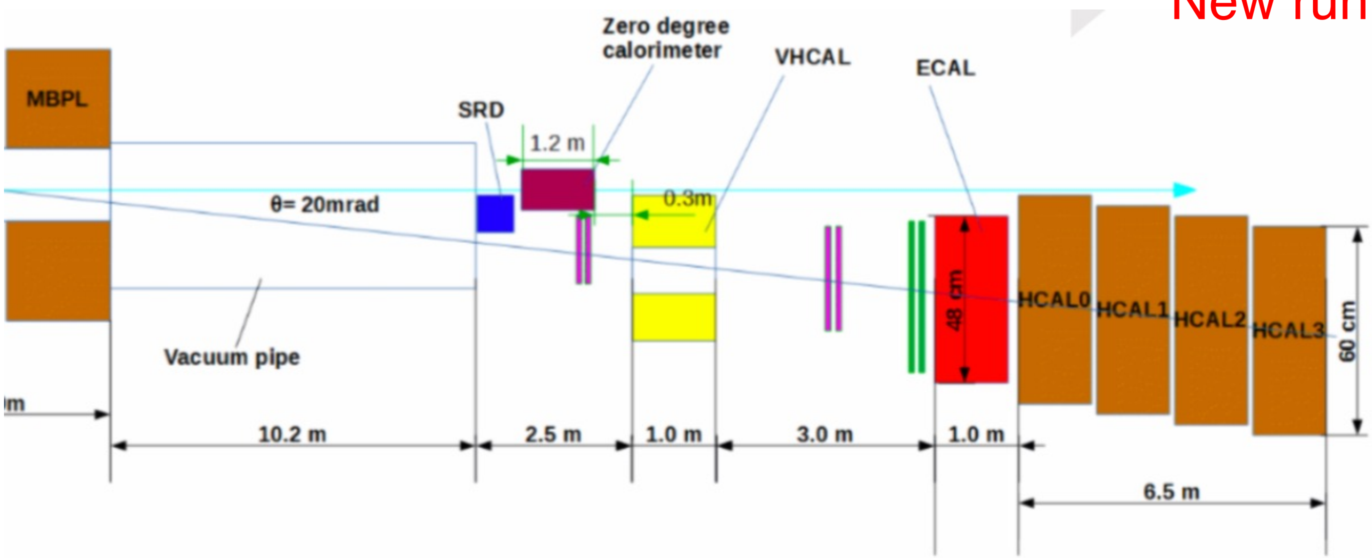


Better sensitivity than neutrino experiments!

Phys. Rev. Lett. (2022)

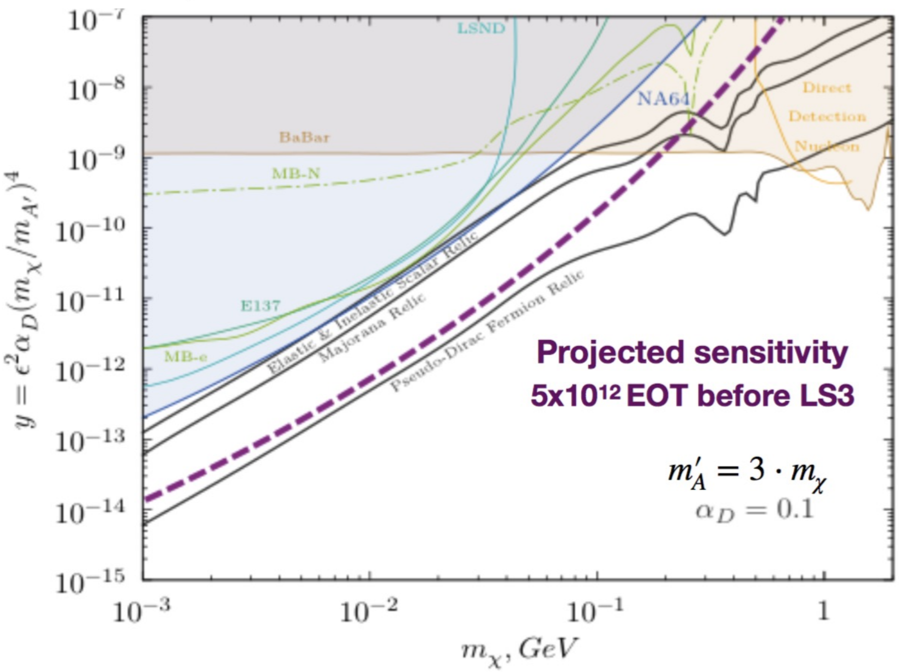
Continue searches in invisible mode

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

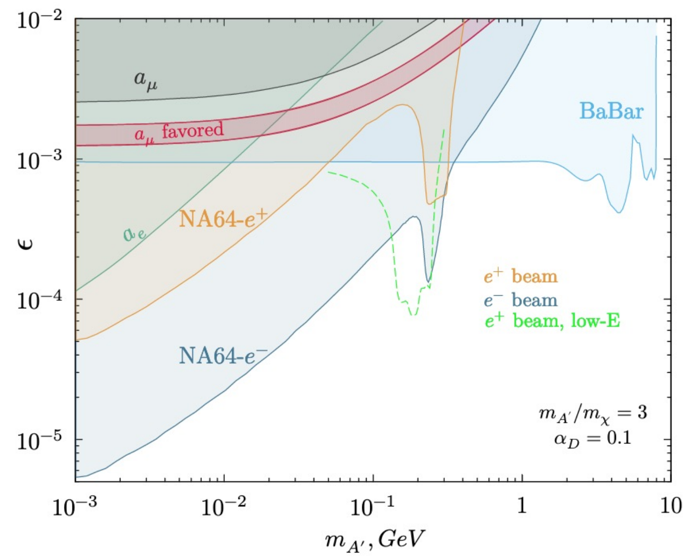


How to improve sensitivity above 100 MeV?

- Annihilation. Additional positron run in 2022 (already analysed), positron run at 70 GeV in 2023, 60, 40 GeV planned
- NA64μ at the muon beam M2, later in this talk.

Analysed positron data 2022, green dashed – expected from 40 - 70 GeV positrons with ~10^{11} POT

Additional region in positron beam is larger



To obtain or improve results in the positron beam: POKER!

POsitron resonant annihilation into dar**K** matt**ER**

Effort led by the group of INFN Genova: A. Celentano

At 100 GeV hadron BG is higher in positron beams
At lower energies the SRD tagging performance drops significantly (E^4)

- New LYSO-based SR detector, homogenious, with high light yield. Prototyping and simulations are in progress
- New active target: PKR-CAL calorimeter. Baseline design: 33.5 *X*0 PbWO4 calorimeter with SiPM readout, 9x9 matrix of 20x20x220 mm crystals, 4 layers

To obtain or improve results in the positron beam: POKER!

POsitron resonant annihilation into darK mattER

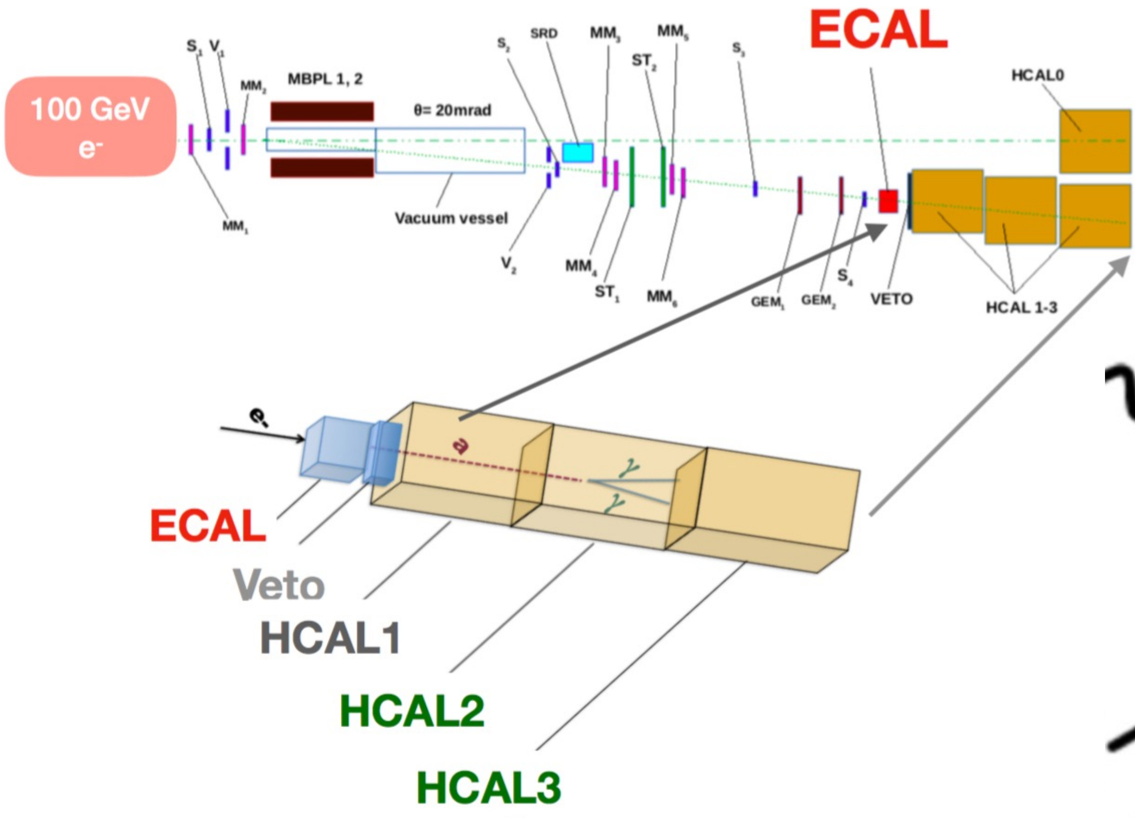
Progress in PKR-CAL development

- Goal: $\sigma / E \sim 2.5\% / E \oplus 0.5\%$
- High radiation doses
- POKERINO prototype tested on H4 beam line this year, analysis in progress, first results promising

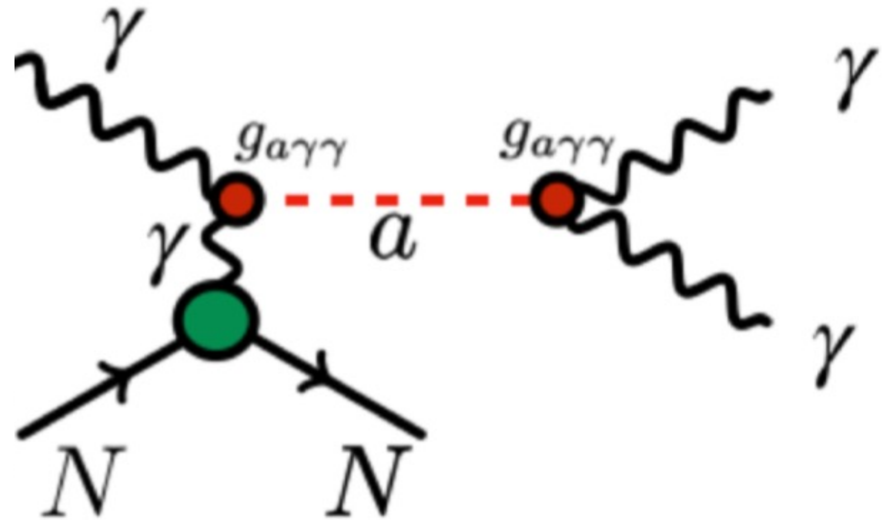
Axion-like particles (ALP) coupled to photons

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

Produced via Primakoff effect of gamma conversion on nuclei



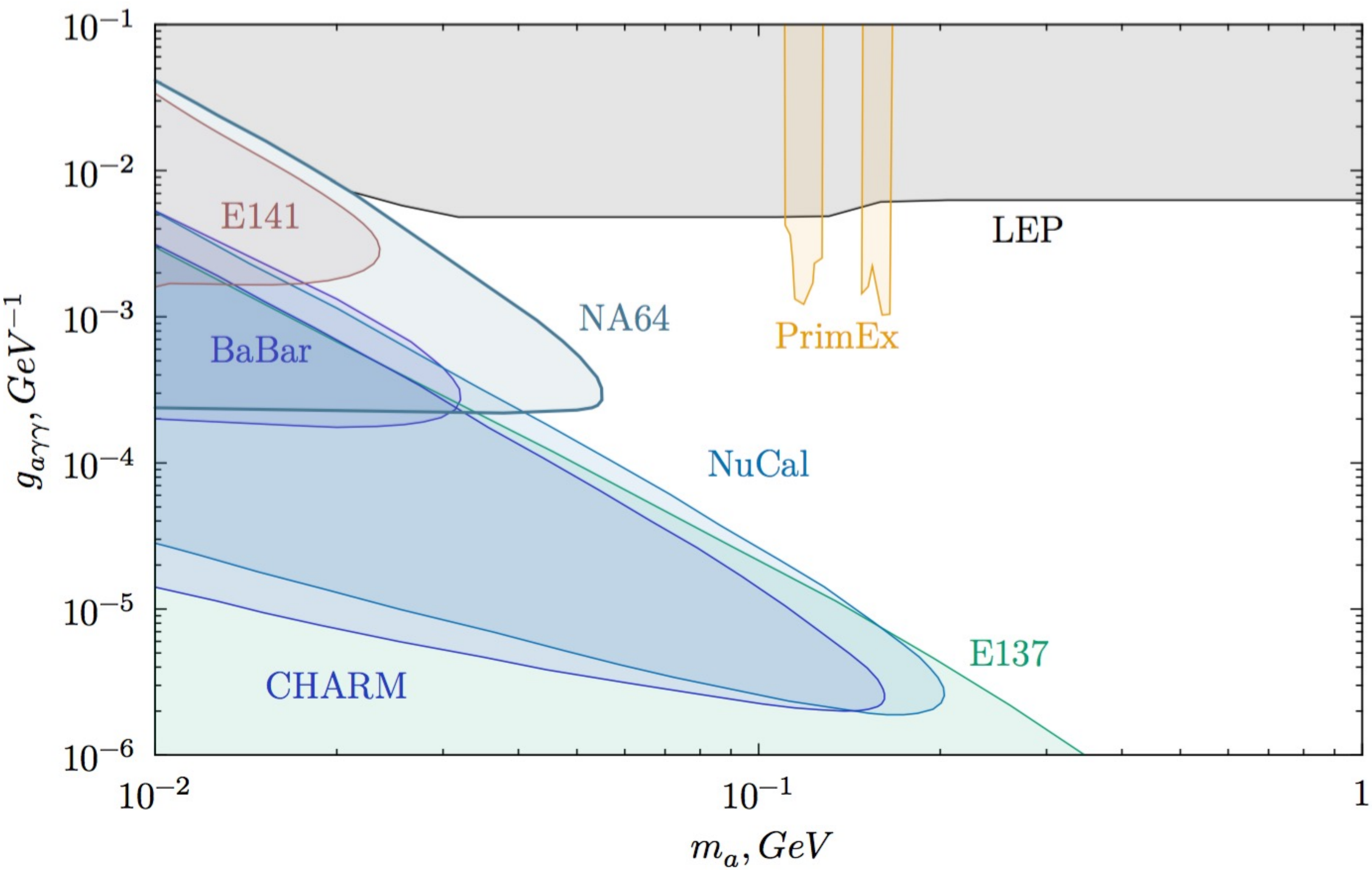
$$L_{int} = -\frac{1}{4} g_{a\gamma\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a$$



ALP search strategy

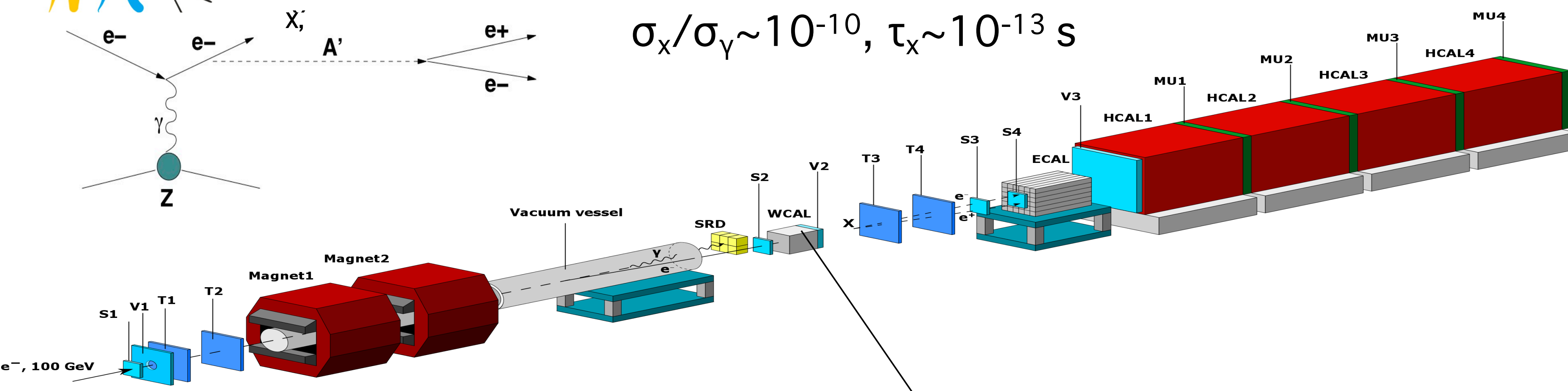
- In addition to invisible decays beyond the detector (missing energy signature) look for decays in HCAL2, HCAL3 with HCAL1 as a veto
- Allows softer cuts on energy deposition in ECAL
- Background: punch-through neutrons and K^0
- Final cut on R = (periphery cells)/(central cell), strong suppression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

ALP search results (data 2016 – 2018)

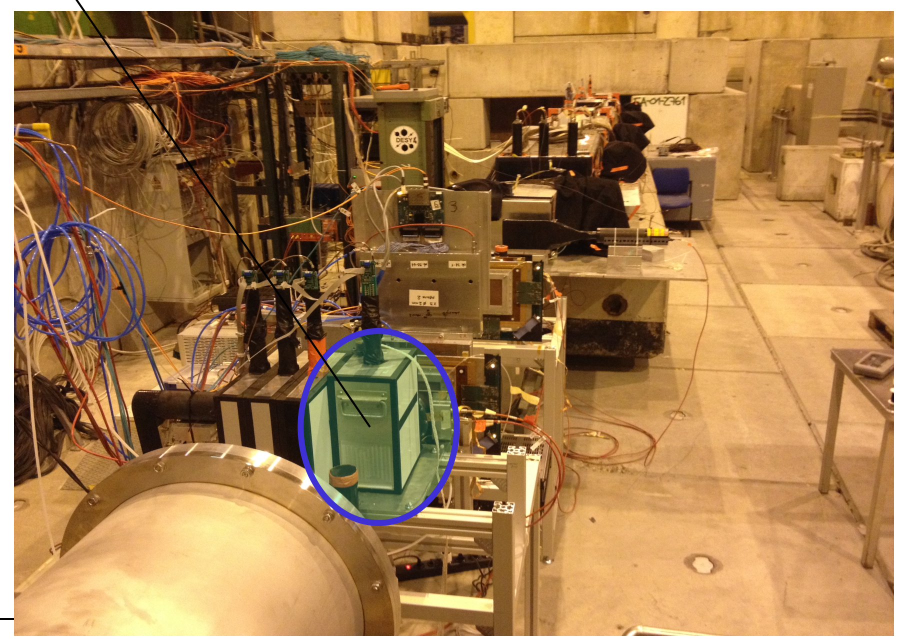


Search for X(A´)->e+e- decays

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

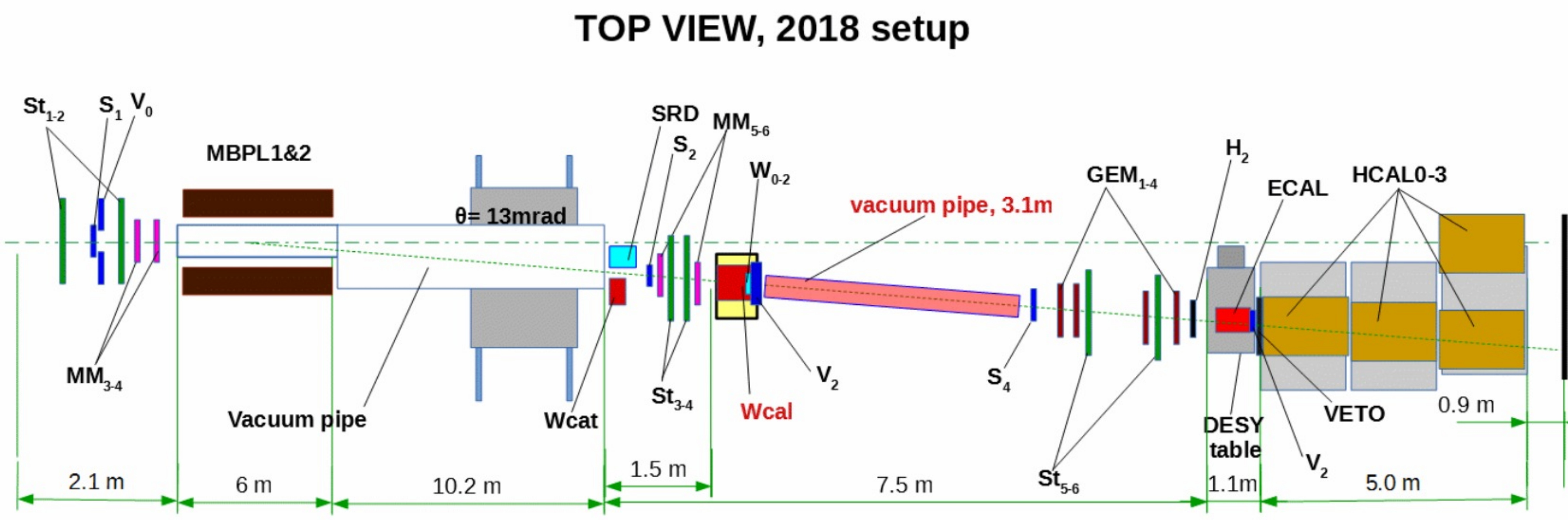


- Compact tungsten calorimeter WCAL
  - X decays outside WCAL dump
- Signature: two separated showers from a single e-
  - $E_{WC} < E_0$, and $E_0 = E_{WC} + E_{EC}$
  - θ_{e+e-} too small to be resolved



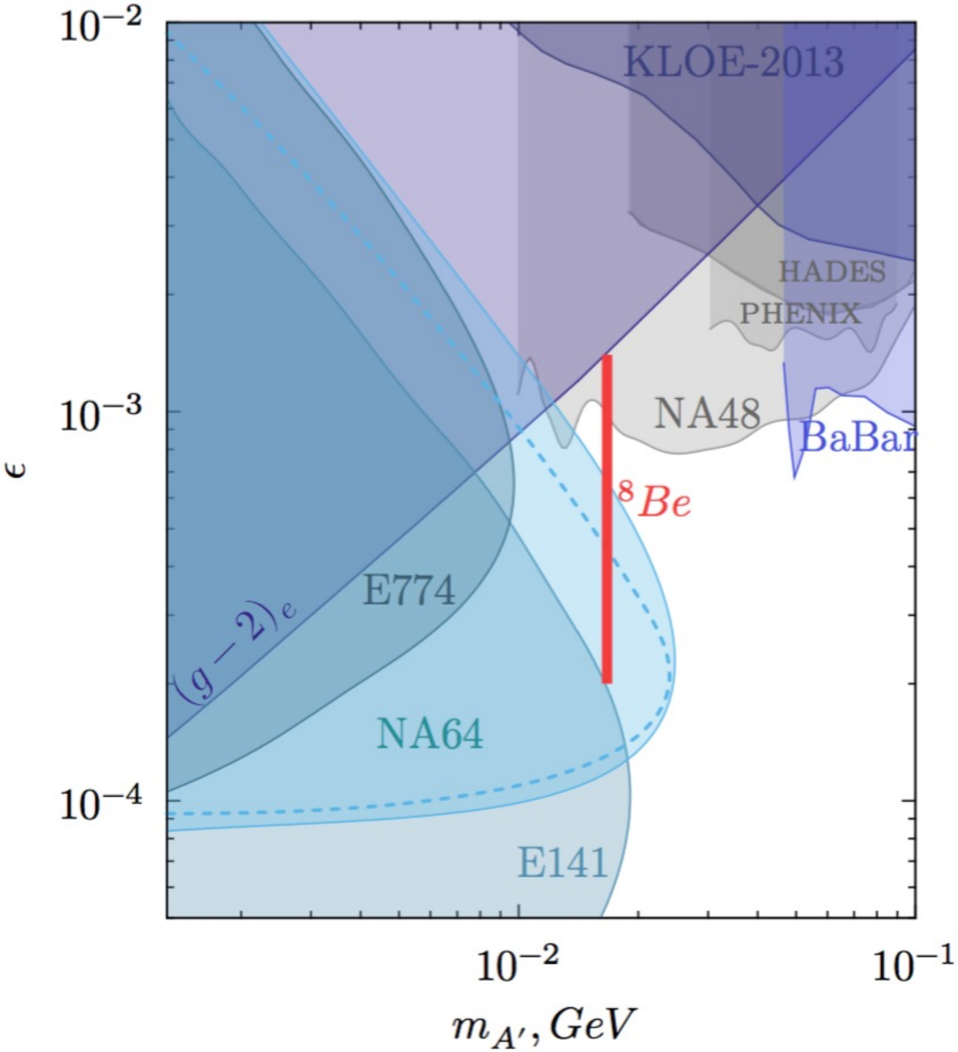
Setup optimization

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

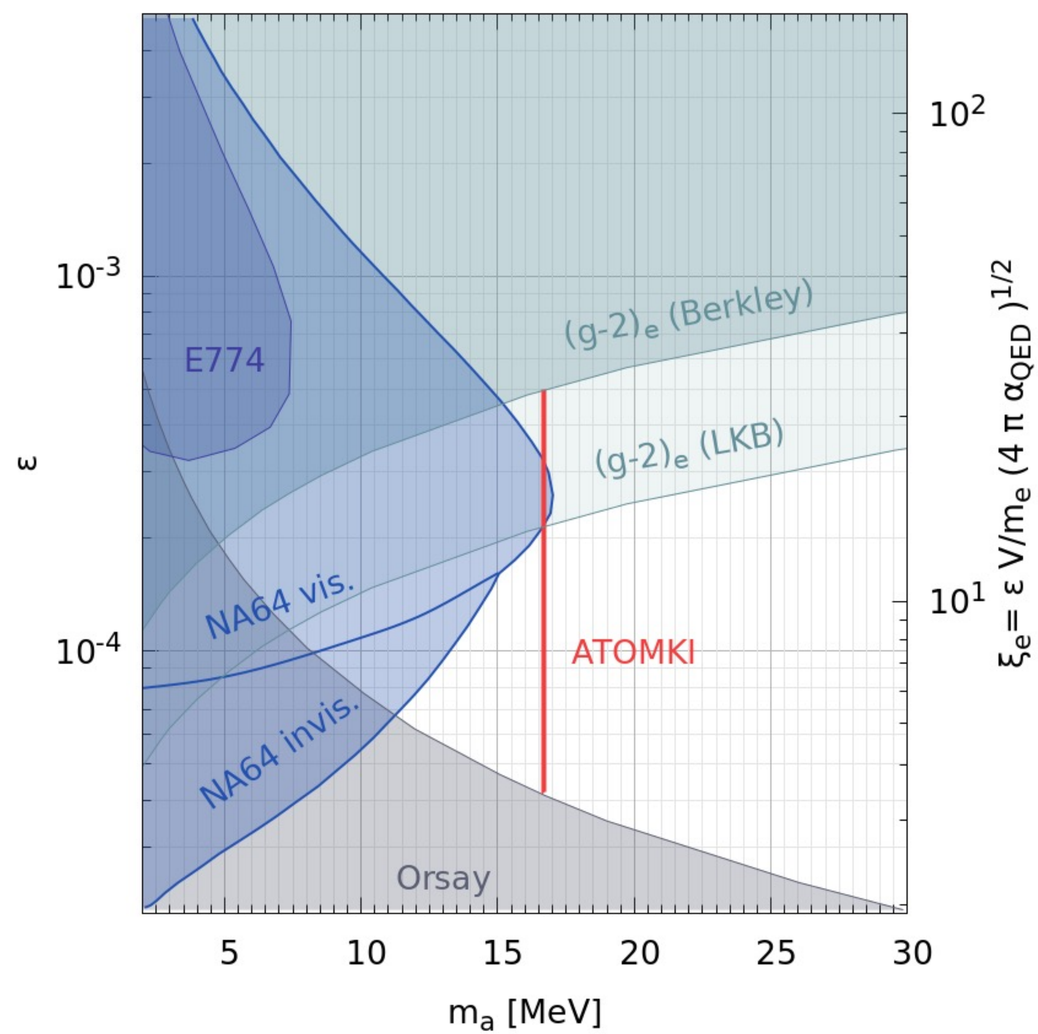


Results with 8.4 x 10^{10} EOT (+invis. mode data for pseudoscalar)

Vector, PRD 107, 071101 (R) 2020

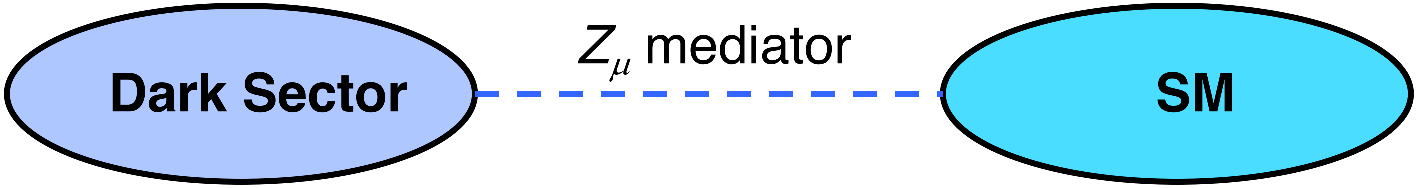


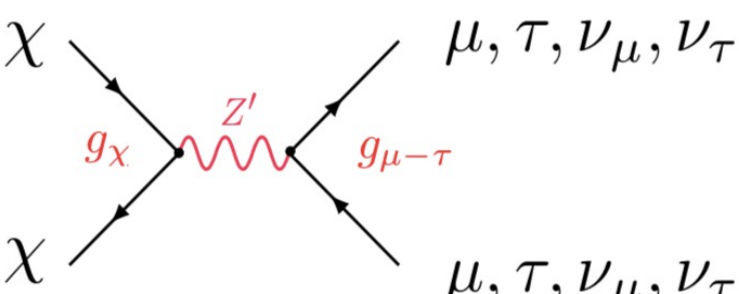
New: Pseudoscalar, arXiv: 2104.13342 [hep-ex]



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 $m_\chi, m_{Z\mu}, g_\chi, g_\mu$
    - Z_μ decays:

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

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

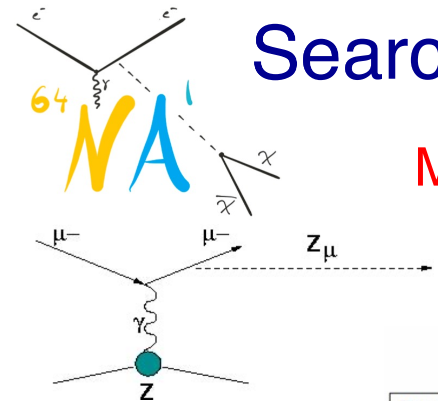
- Cross section for χ–DM annihilation:

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

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

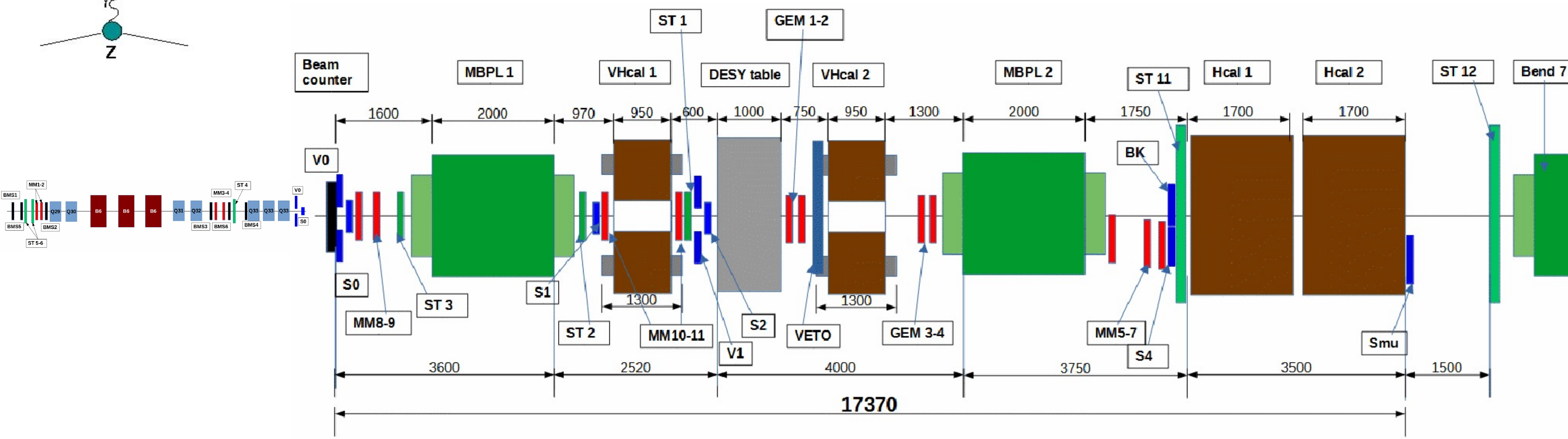
$y=[(g_\chi g_\mu)^2(m_\chi/m_{A'})^4]$ - useful variable to compare FTE sensitivities

Search for Z_μ in missing energy events on M2 beam



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

Proposal NA64μ
(2019)



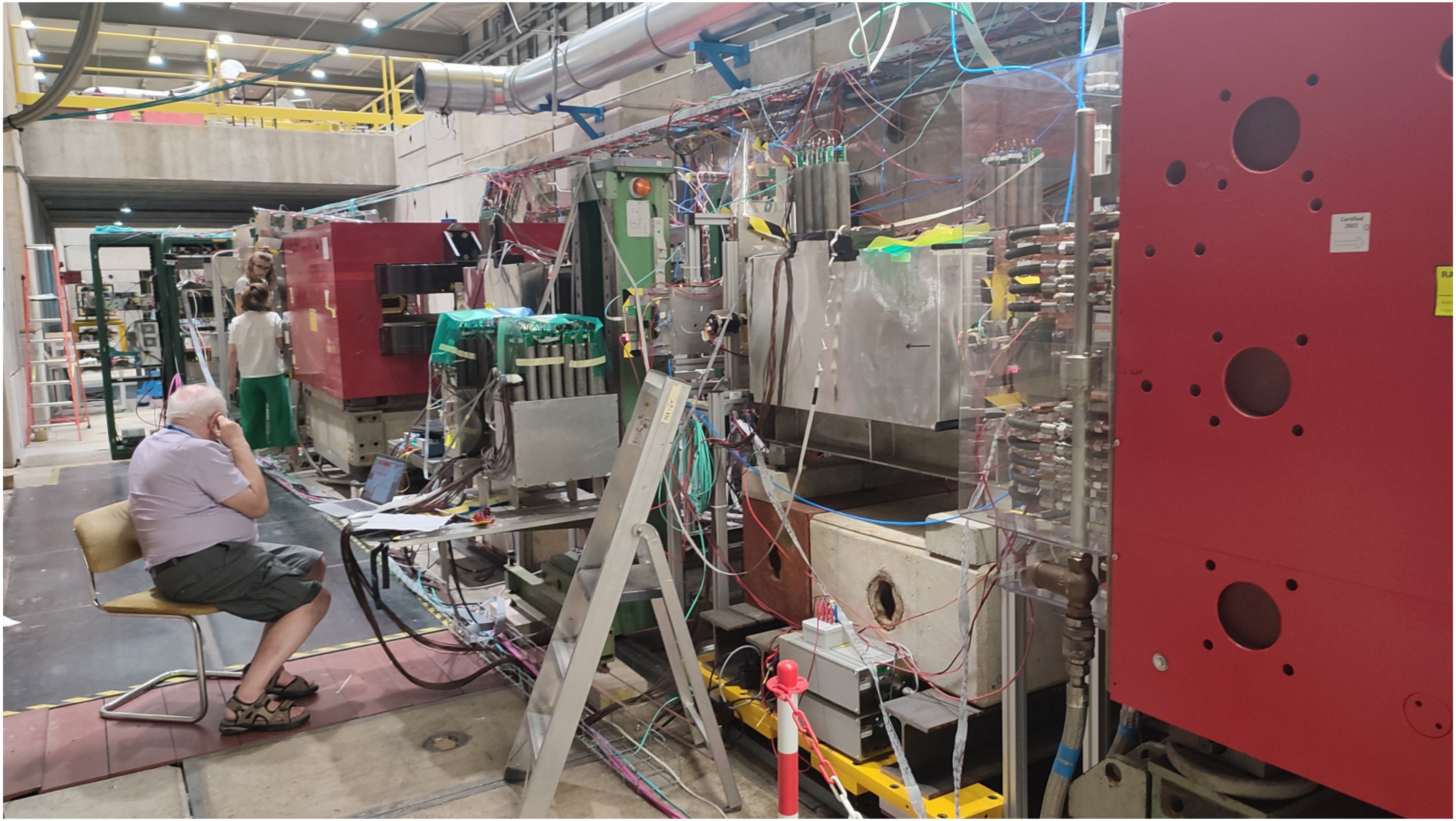
Main components :

- 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

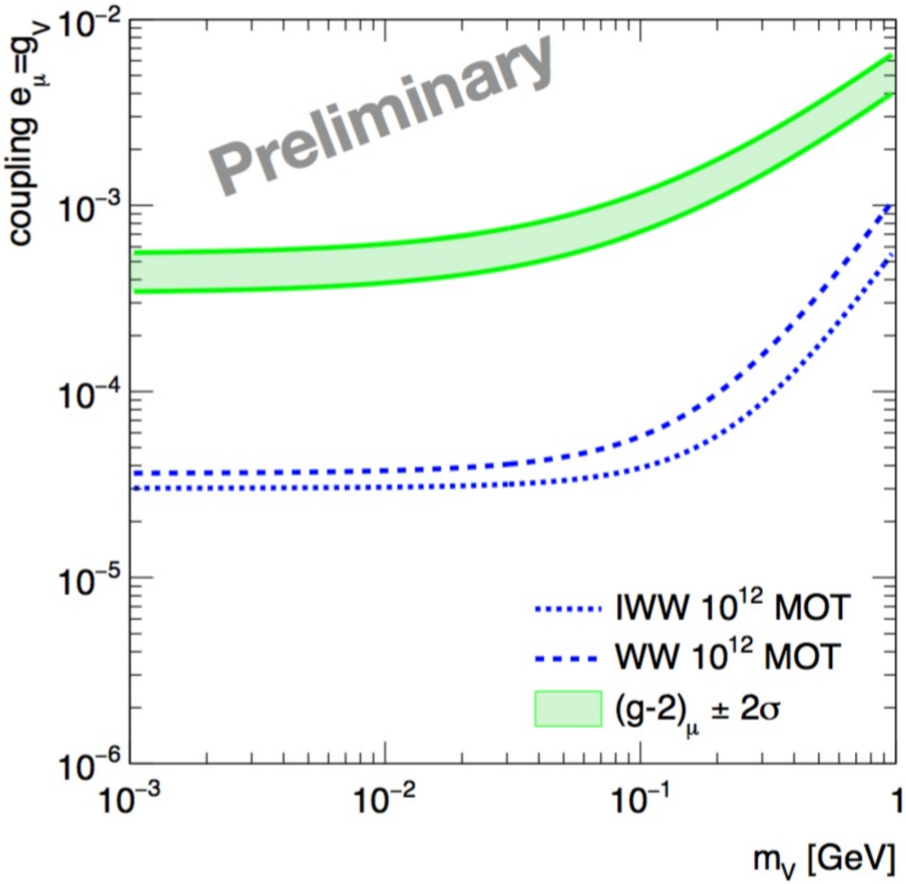
Signature:

- 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

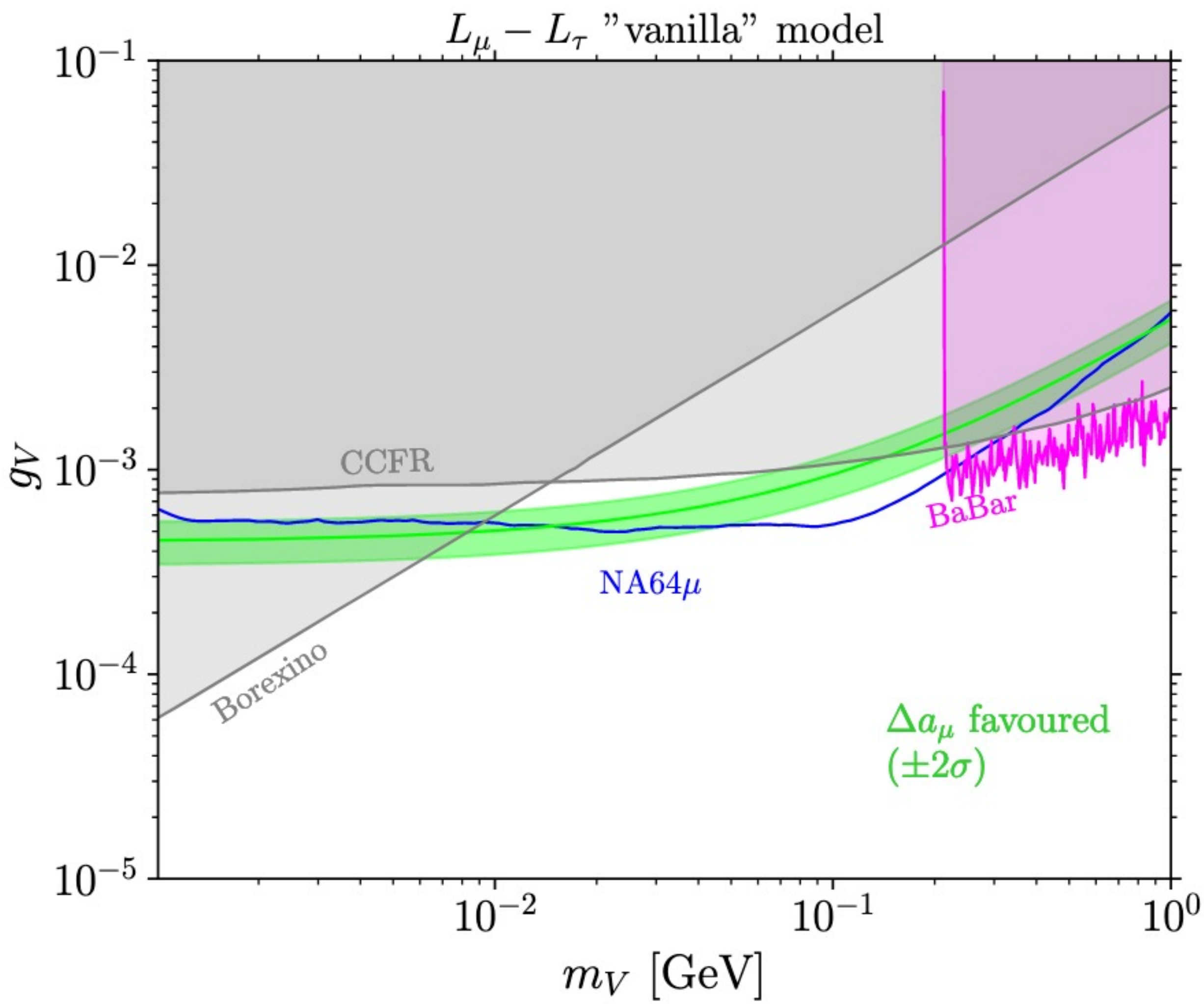
Pilot runs to check
trigger rate and
noise conditions
$\sim 4 \times 10^{10}$ MOT

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

- New wide HCAL
- New special ECAL

Physical analysis of the 2022 NA64mu data

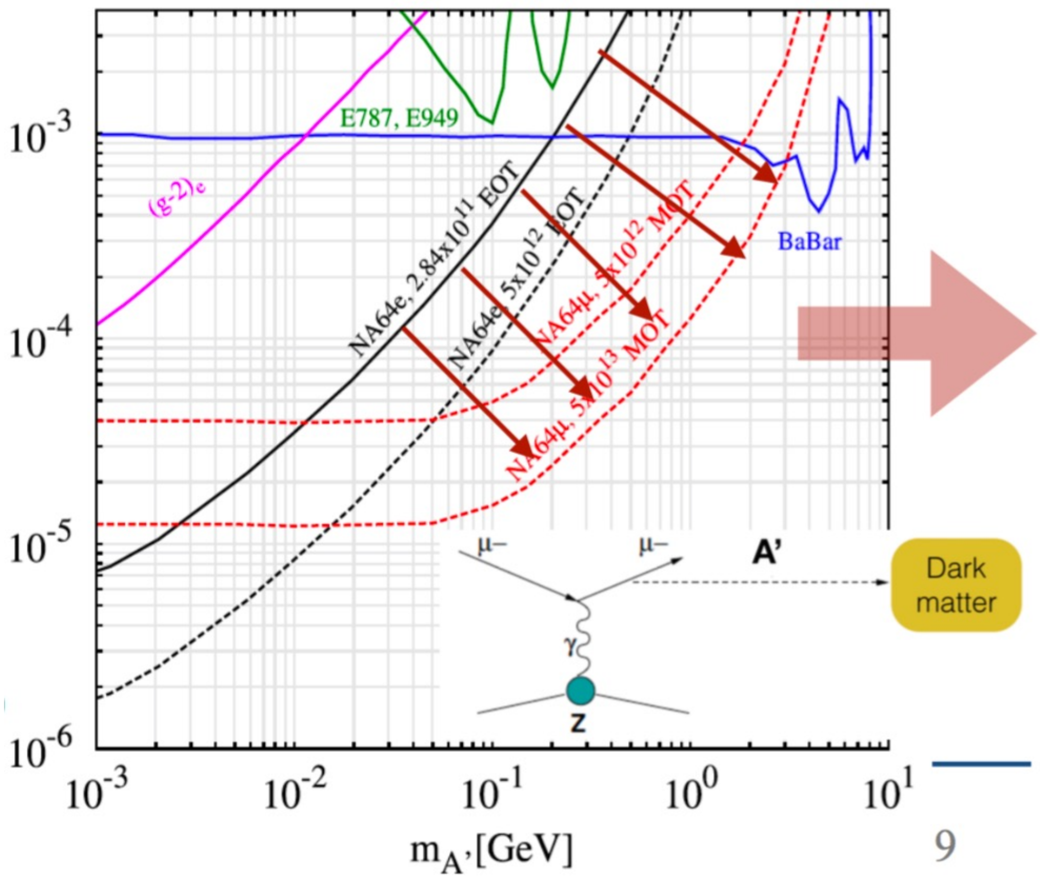
Preliminary

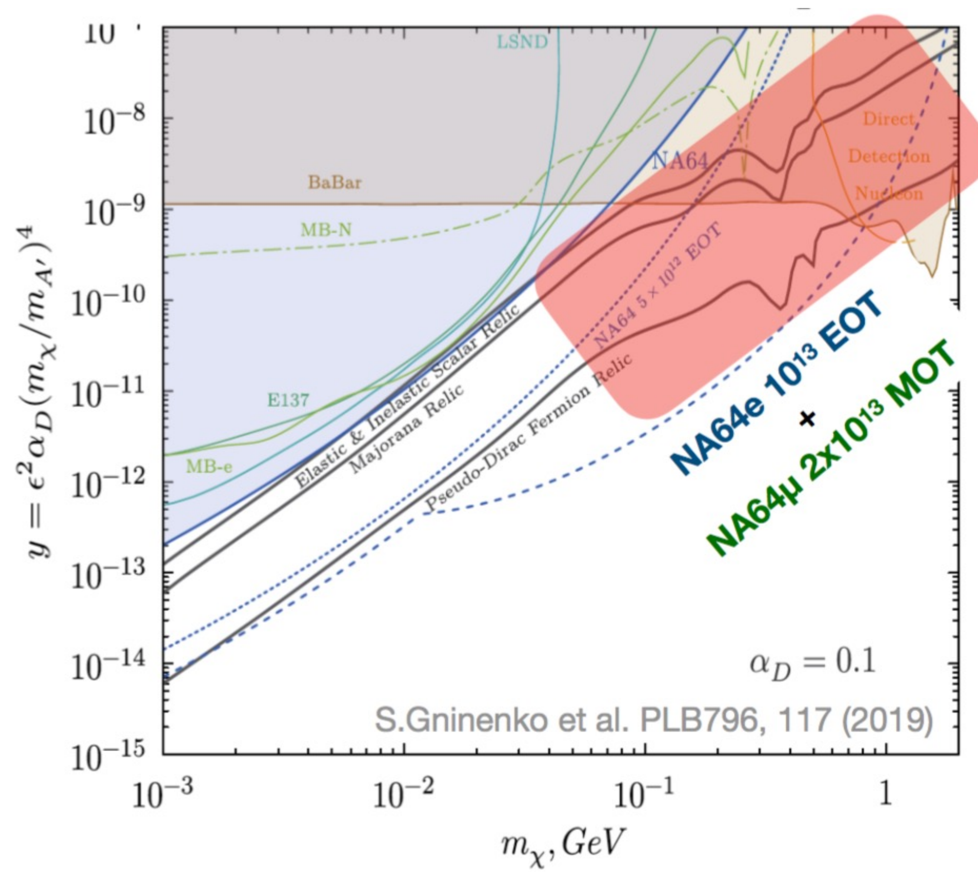


~$2\text{x}10^{10}$ MOT

Searches for A’ with NA64μ

Better sensitivity to heavy A’ (>100 MeV)



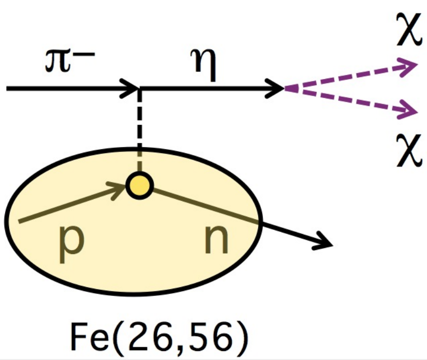


NA64h: Search for dark sector coupled mainly to quarks

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

Motivation: Instead of focusing on the DM coupled universally to SM particles probe also models with leptophobic (hadrophilic) mediators.

Method: search for invisible decays of pseudoscalar and vector mesons Their invisible SM decays are highly suppressed



Analysys, one of important uncertainties is the charge exchange cross sections (~30%)

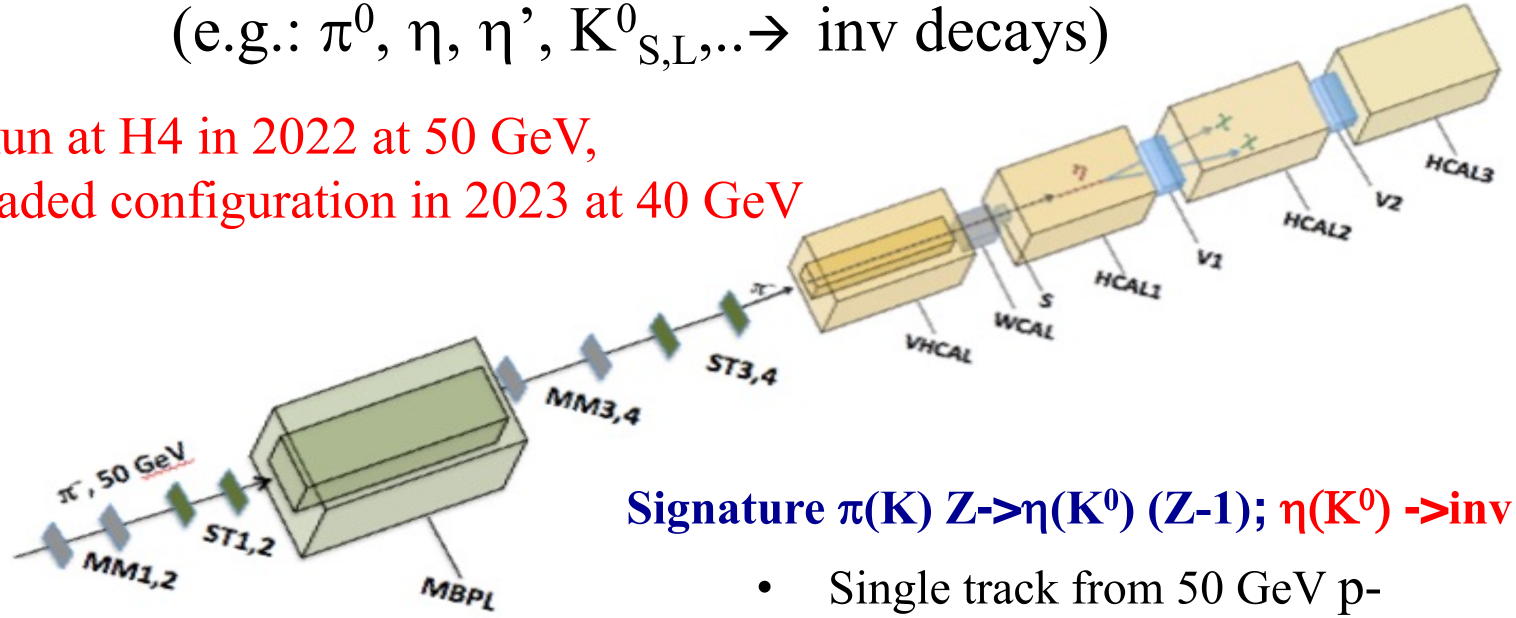
We prepared a review of experimental measurements and fits to them in order to interpolate to other targets (our target is iron), the publication in preparation

Based on this, the charge exchange reactions are implemented in Geant4, will be available in the end of this year

NA64h: Search for dark sector coupled mainly 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



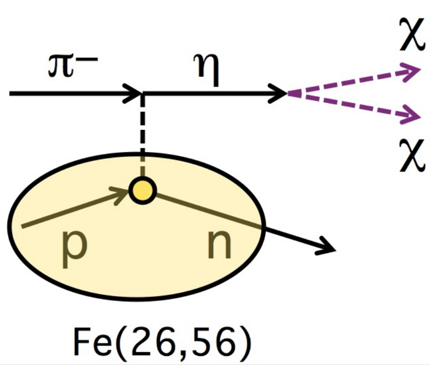
Signature $\pi(K)$ Z->$\eta(K^0)$ (Z-1); $\eta(K^0)$ ->inv

- 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(η -> inv) < ~ 10^{-5}-10^{-4} (BaBar/BESIII)

Analysis in progress

η, η', K0 – production:

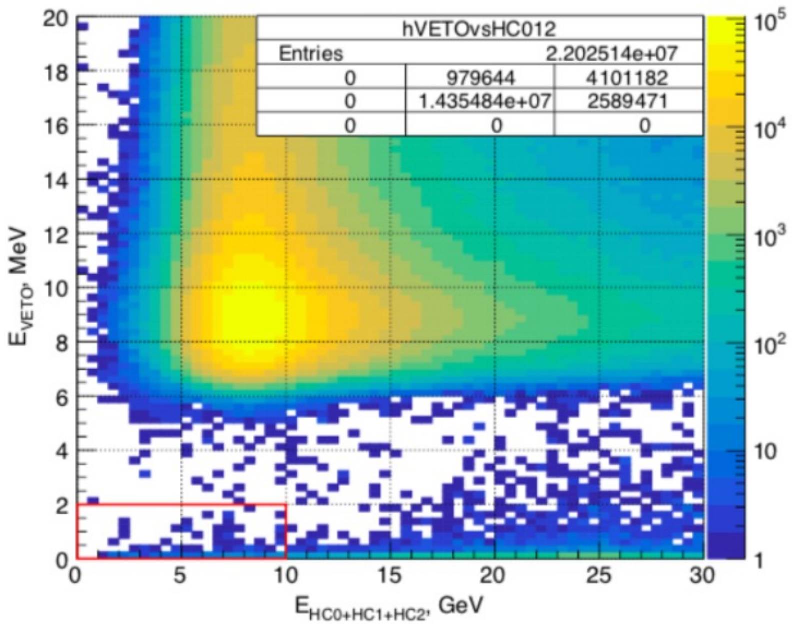
$\pi(K)$ Z->$\eta(K^0)$ (Z-1)



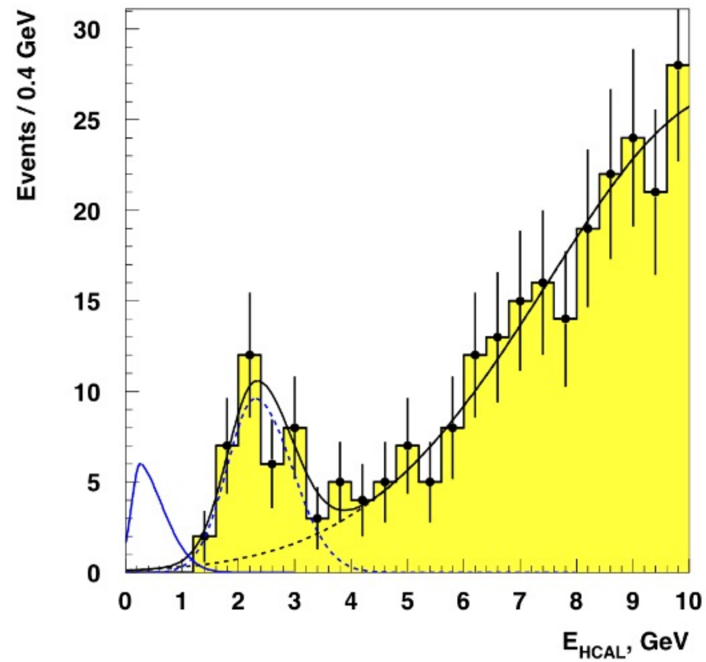
NA64h: Search for dark sector coupled mainly to quarks

Preliminary

E_{VETO} cut from random trigger



Preliminary



Yellow – BG. Peak at ~2.5 GeV is from K^- decays

Blue curve – signal + noise (from random trigger)

NA64h: Search for dark sector coupled mainly to quarks Results:

Preliminary results on Γ/Γtot: $\eta : < 1.1 * 10^{-4}$ existing: 1×10^{-4} (BESIII)

Preliminary results on Γ/Γtot: $\eta' : < 2.3 * 10^{-4}$ existing: 6×10^{-4} (BESIII)

The results are dominated by the uncertainty on the production reaction cross section (charge exchange process).

The measurement in the closest region, on Al, Cu at 20 – 48 GeV, is performed in IHEP Protvino

We plan a number of improvements, such as:

- ✓ the K^- identification,
- ✓ better segmented target,
- ✓ slightly lower energy

Summary

- The NA64 experiment produced several important results in the search for light Dark Matter (LDM, sub-GeV mass range) coupled universally to leptons and quarks. With the milestone statistics of $\sim 10^{12}$ EOT it provides the world-leading constraints on the benchmark LDM models
- The plan is to significantly increase the sensitivity and maximally cover the regions of predictive thermal Dark Matter models
- 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
- NA64h: the proof-of-concept in 2022 (1 day run) was rather successful. Preliminarily, the sensitivity to invisible decays of η' is several times better than from BESIII
- Other planned searches are μ - τ conversion, LFV DM production etc.

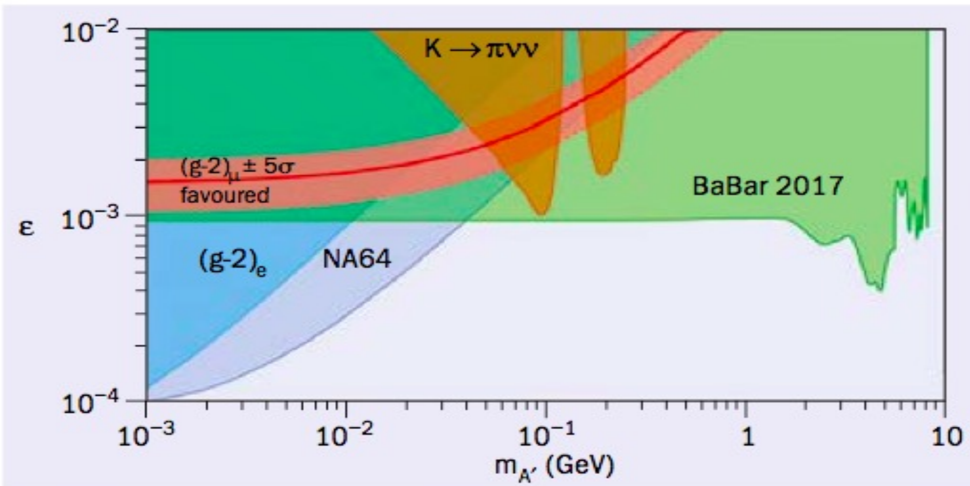
Backup slides

Backup

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

CERN Courier **April 2017**

News



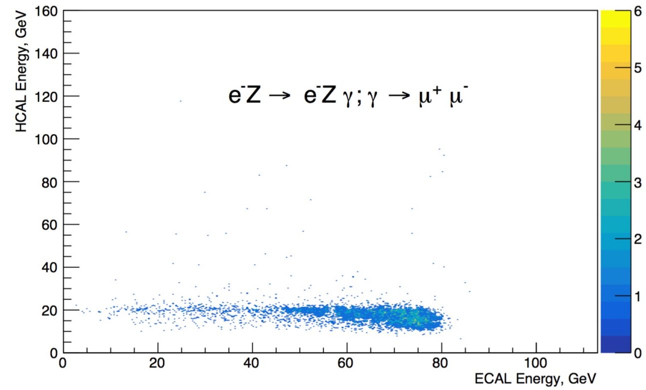
Regions of the dark-photon parameter space (mixing strength versus mass) excluded by BaBar (green) compared with the previous constraints. The new analysis rules out dark-photon coupling as the explanation for the muon (g-2) anomaly and places stringent constraints on dark-sector models.

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

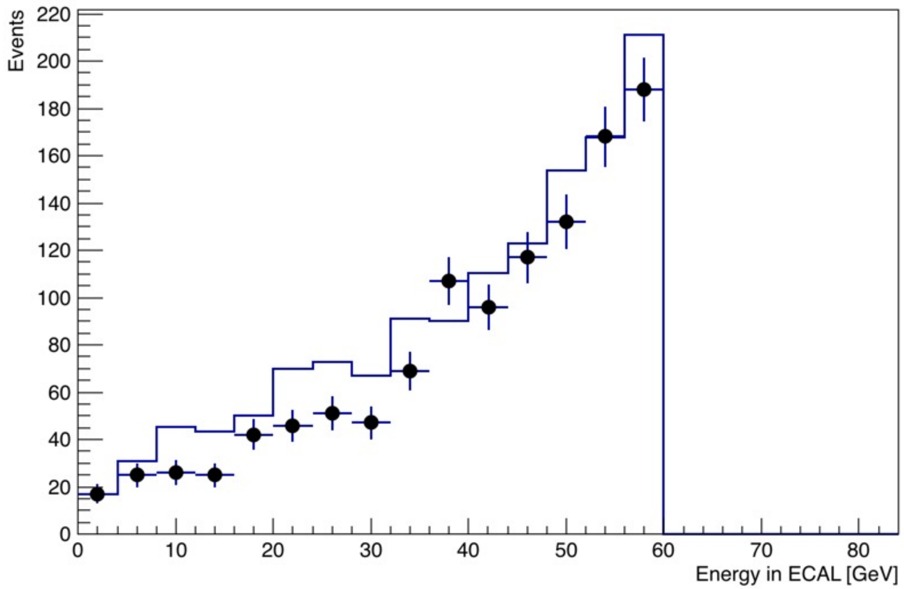
BaBar Collaboration 2017 arXiv:1702.03327.
NA64 Collaboration 2017 *Phys. Rev. Lett.* **118** 011802.

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
- Millions of dimuon pairs with both muons reaching all HCAL modules are registered in NA64
- 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



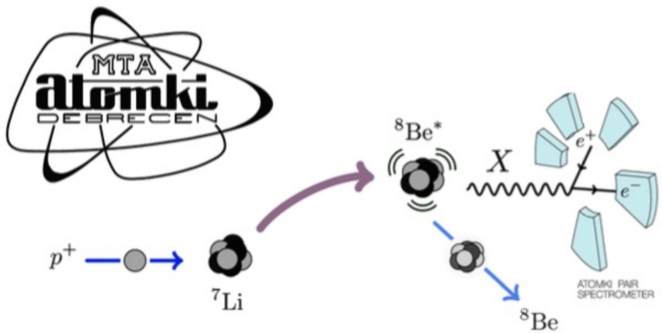
Dimuons selection: $E_{ECAL} < 60$ GeV

$3 < E_{HCAL1} < 7$

$3 < E_{HCAL2} < 7$

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

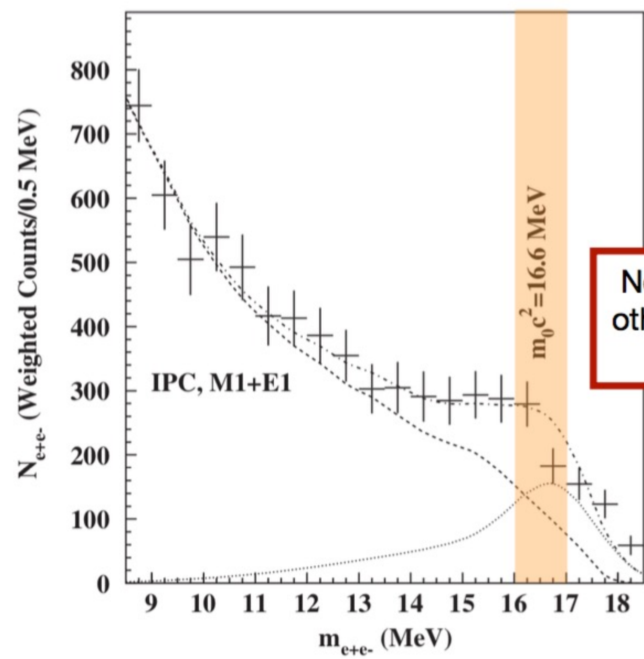
ATOMKI anomaly



- *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.

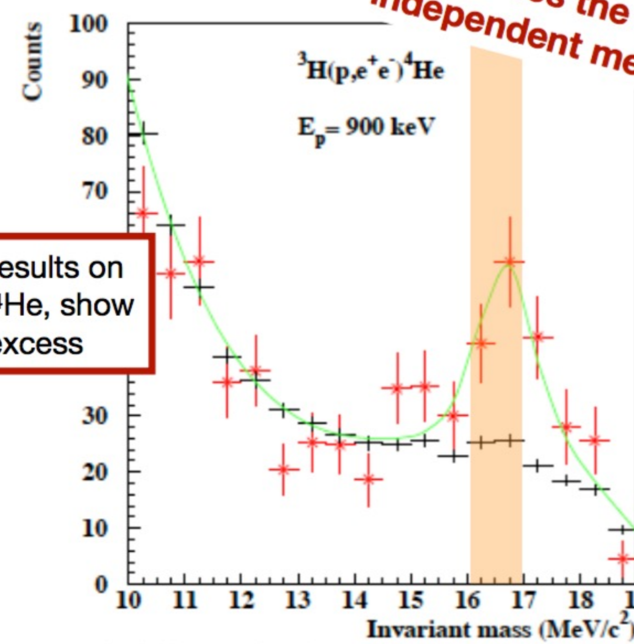
$$e^-Z \rightarrow e^-ZX_{17};\ X_{17} \rightarrow e^+e^-$$

Motivates the need of an independent measurement



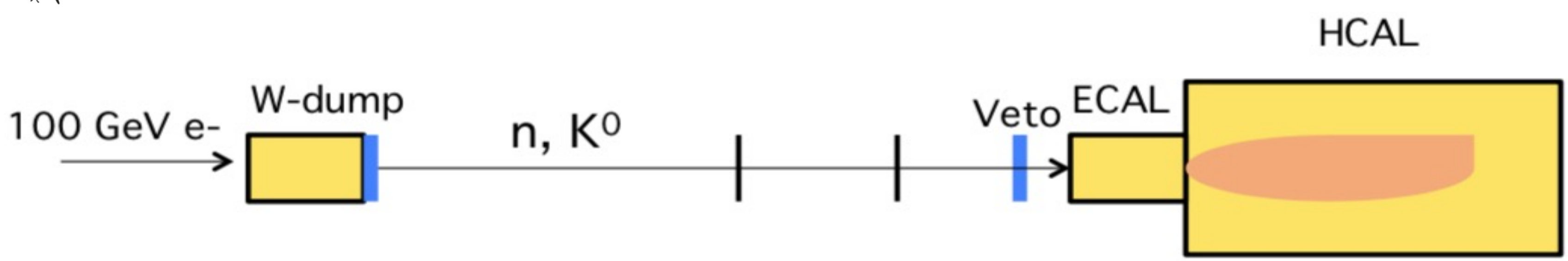
A.J. Krasznahorkay et al. Phys. Rev. Lett.116, 042501 (2015)

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



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

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

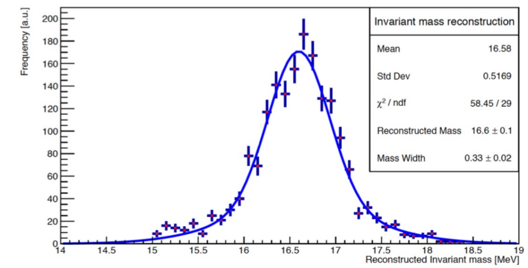


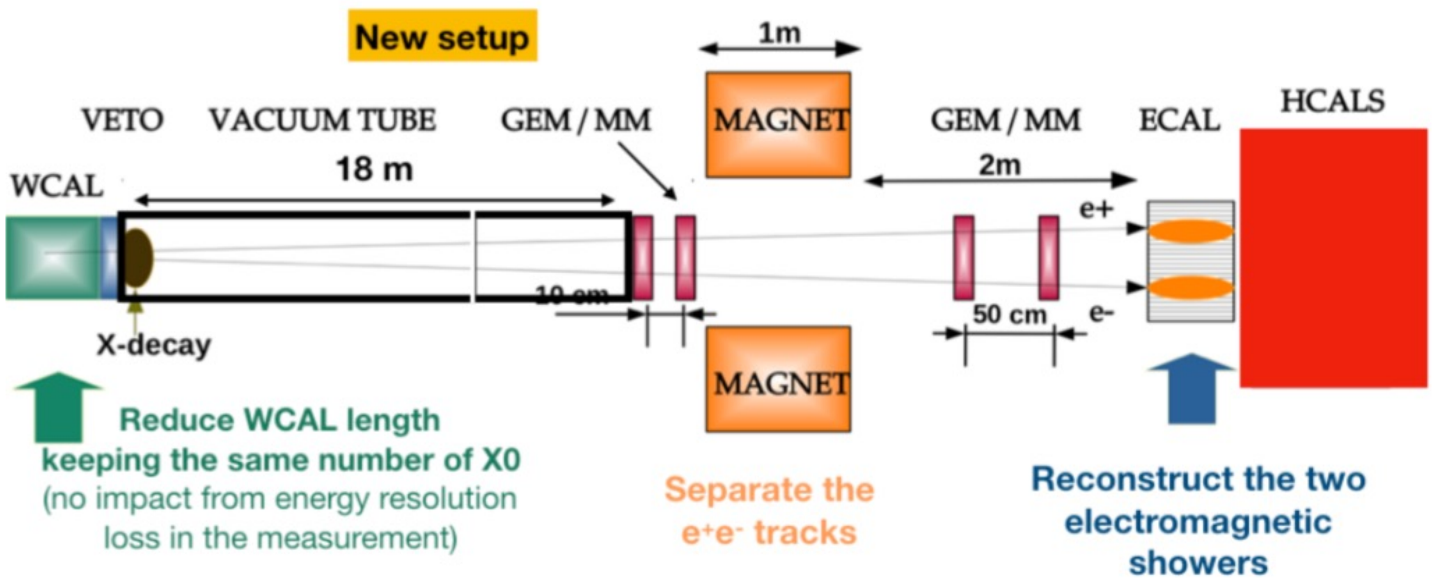
We used control sample to estimate this BG: fully neutral events

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

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)