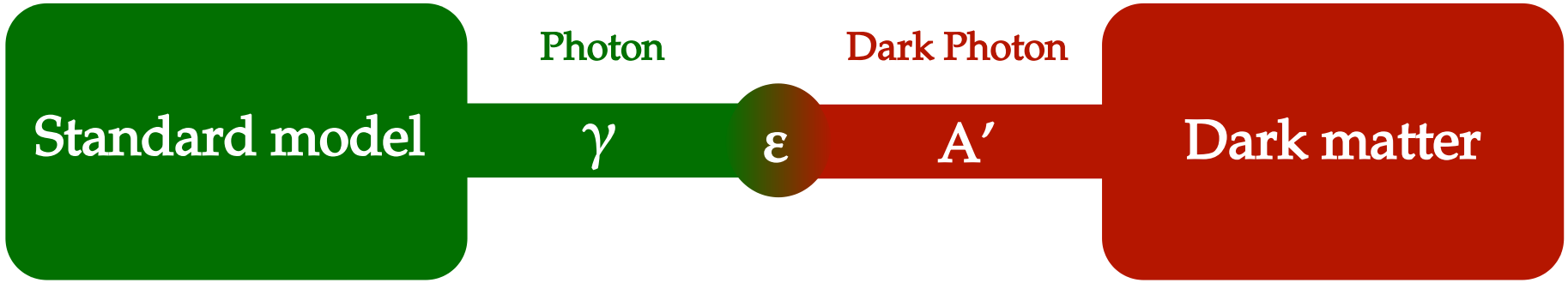
NA64 SEARCHING FOR HIDDEN SECTORS AT THE CERN SPS

Emilio Depero

This work is supported by SNSF under the grants 169133 and 186181 (PI: **Paolo Crivelli**)

Dark photon - motivation



$$L = L_{SM} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + m^2_{A'} A'_{\mu} A'^{\mu} + \frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu}$$

Standard Model Lagrangian

Additional U(1) symmetry describing the new force carried by a massive vector boson, ***the Dark photon A'***

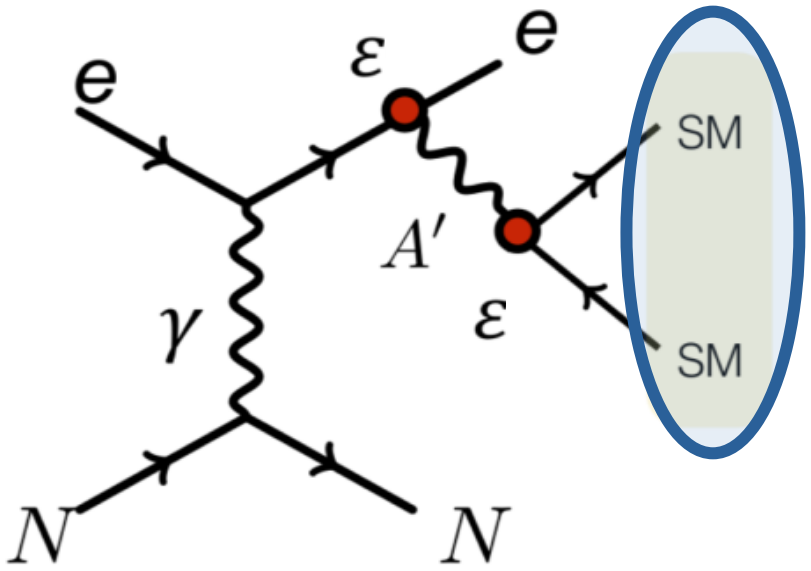
Kinetic mixing term with the ***standard photon γ***

$$\epsilon \sim 10^{-8} - 10^{-2}$$

Dark photons - signature at fixed target experiment

- The electron collides with heavy nuclei irradiating A′ (dark-bremstrahlung) which can decay to:

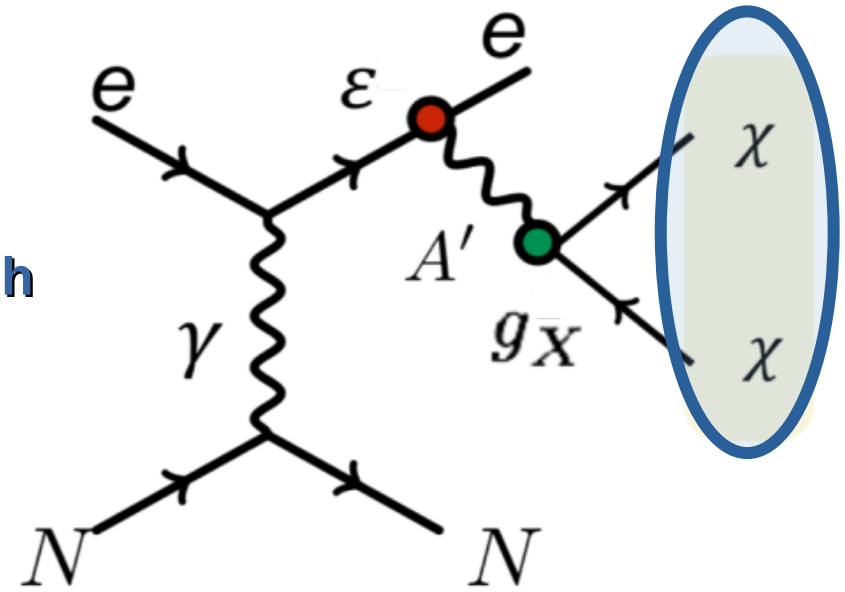
Visible mode



$m_{A'} < 2m_{\chi}$

Light shine through a wall

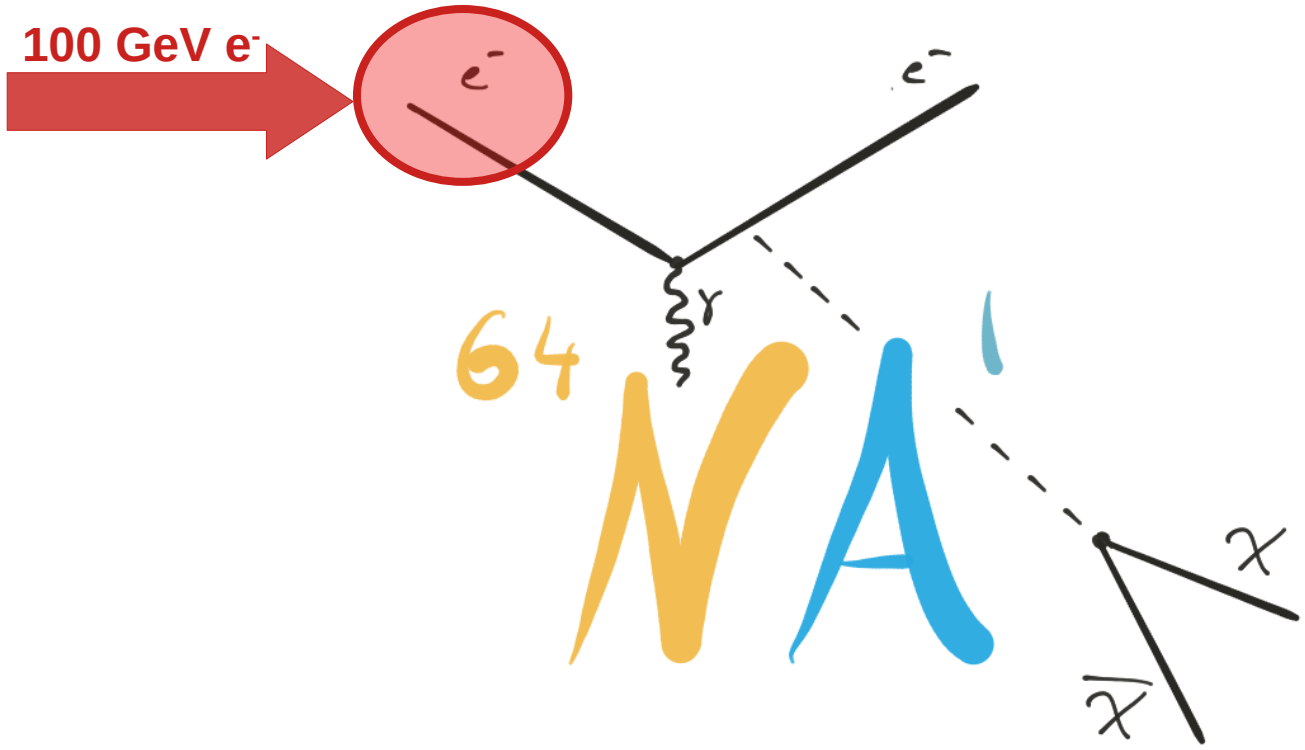
Invisible mode



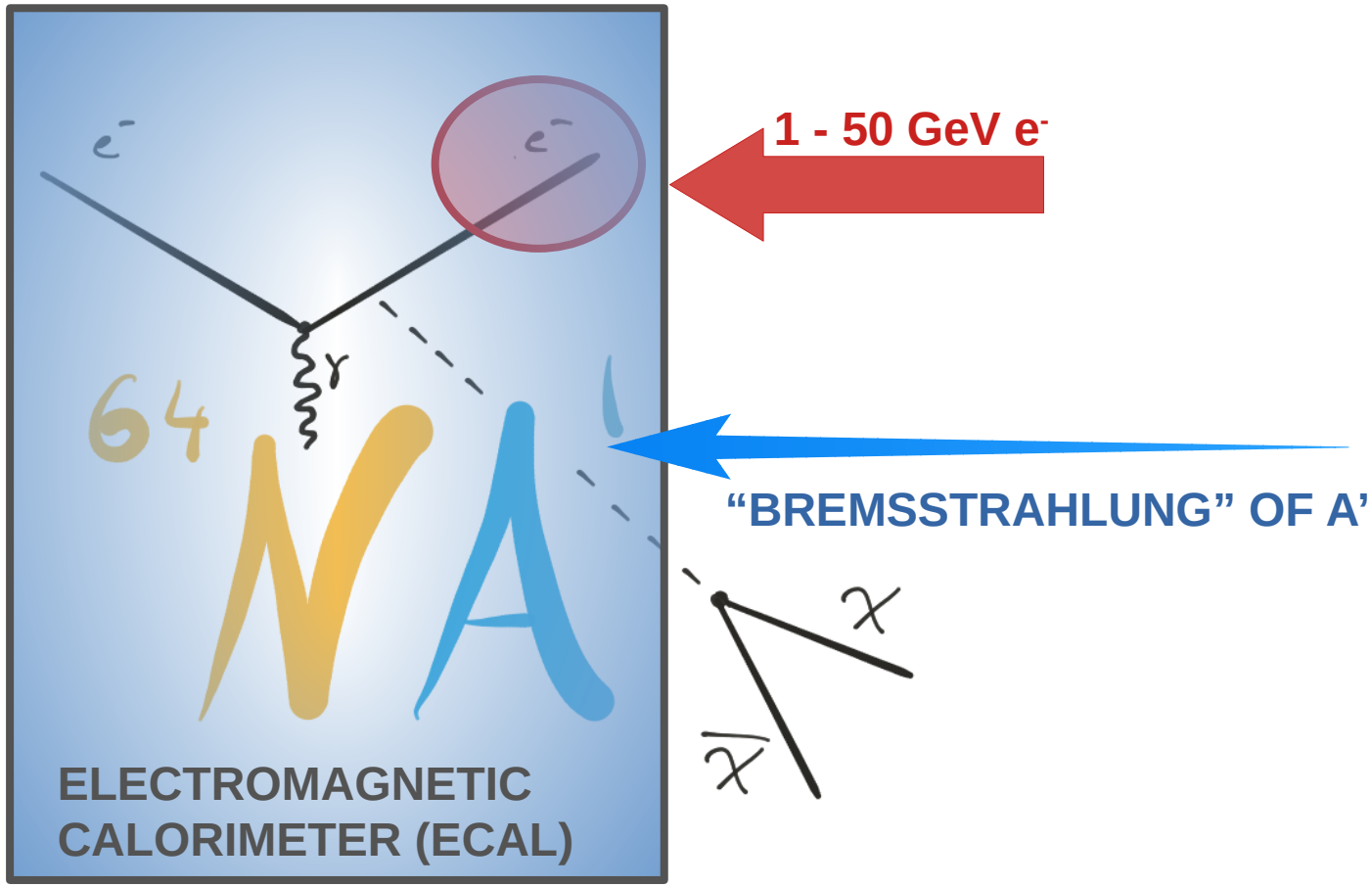
$m_{A'} > 2m_{\chi}$

Missing Energy search

The NA64 working principle to search for A' → invisible



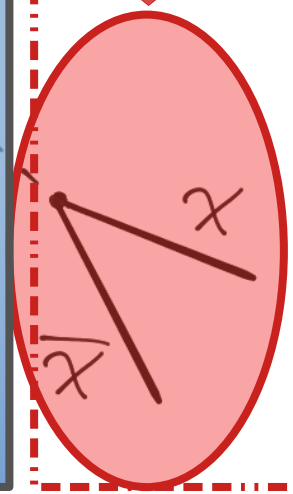
The NA64 working principle to search for A' → invisible



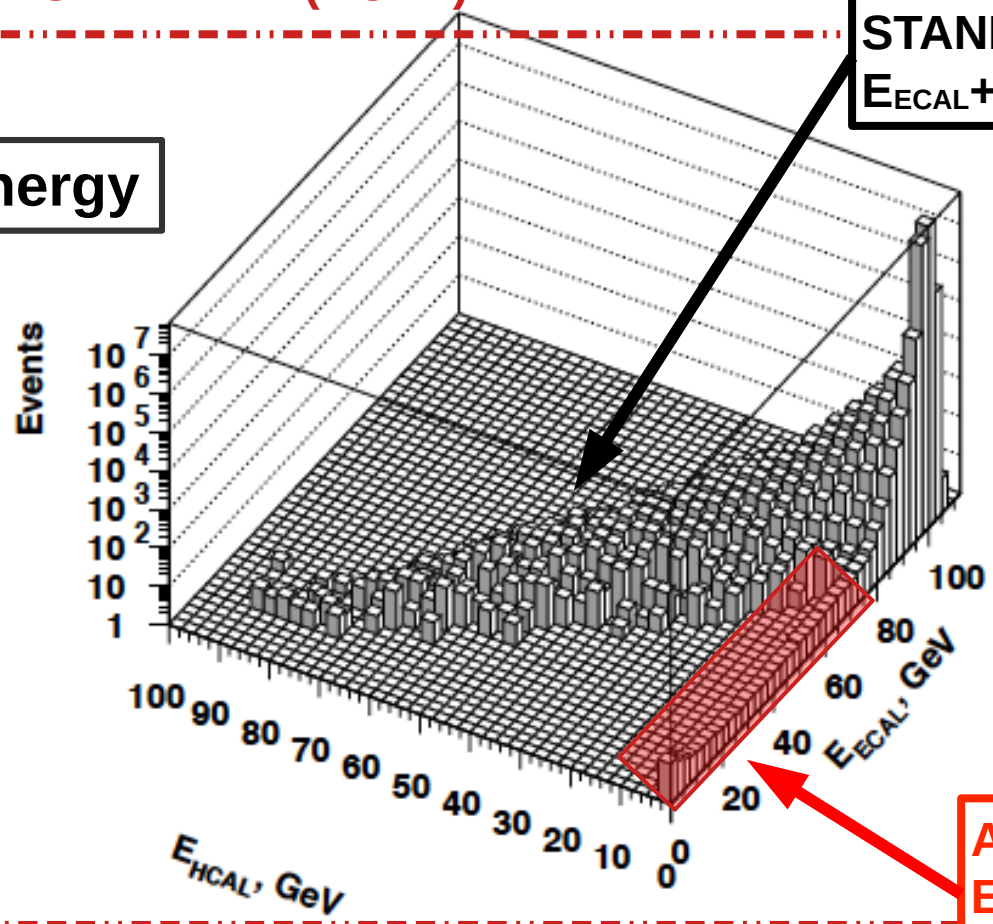
The NA64 working principle to search for A' → invisible

HADRONIC CALORIMETER (HCAL)

Missing energy



STANDARD MODEL:
$E_{ECAL}+E_{HCAL}$ = 100 GeV



A' Signal:
ECAL < 50 GeV
HCAL < 2 GeV

The NA64 collaboration

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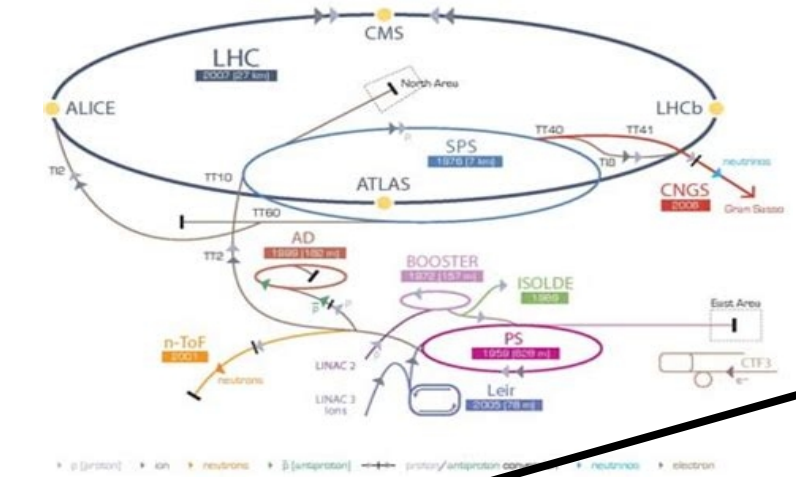
50 Researchers
(6 from ETH)
From
16 institutions!

Sergei Gninenko
spokesperson

Paolo Crivelli
Deputy

The NA64 setup – A' → invisible search – the beam



100 GeV e⁻ beam Produced at the CERN SPS

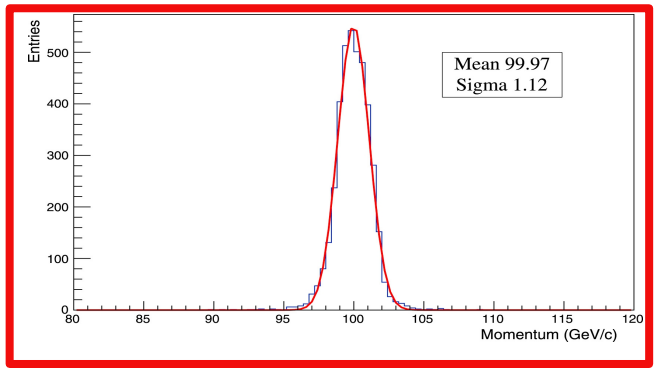
TRIGGER:
Three scintillator (S1-S2-S3) and one Veto to define the beam

BEAM:

- **Up to 10^7 e⁻/spill/min, 4.8s spill duration**
- **Low energy tails (<1%)**
- **Low contamination: π(<1%) K / μ (<0.1%)**
- **Beam spot of 1.2 cm (FWHM)**

The NA64 setup – A' → invisible search – the particle selection

- Energy of electron is selected using a tracking system. Impurities of the beam are rejected using a synchrotron radiation detector



Momentum reconstructed with 1% resolution

E. Depero et al., NIMA 866 (2017) 196-201

D. Banerjee et al., NIMA881 (2018) 72-81

7 T ·m integrated field

ETH group responsibility

Tracking Detectors:
- 8 XY multiplexed Micromegas
- 4 GEM stations

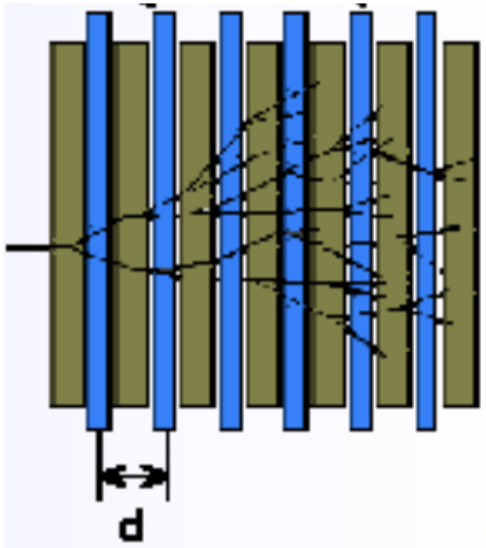
Characteristic:
- 1 GeV momentum resolution
- Capable of coping with high intensity

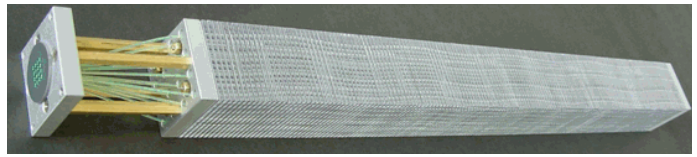
$P \sim E^4/m^4$

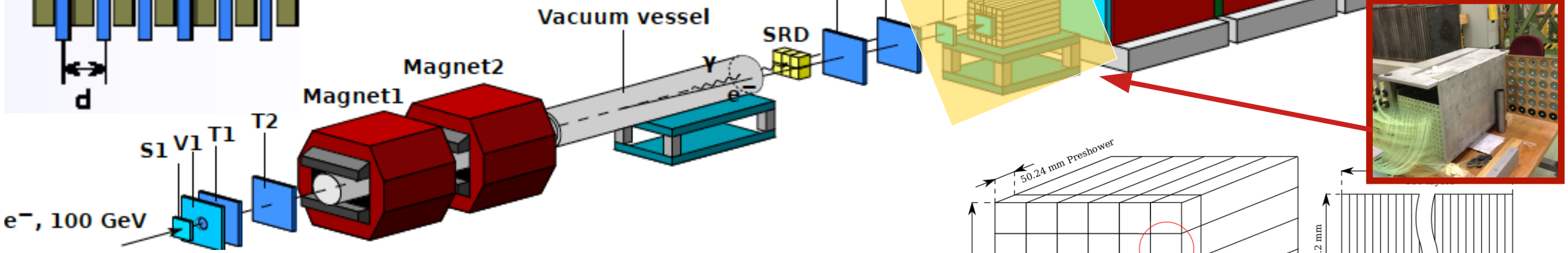
<10^{-5} achieved rejection

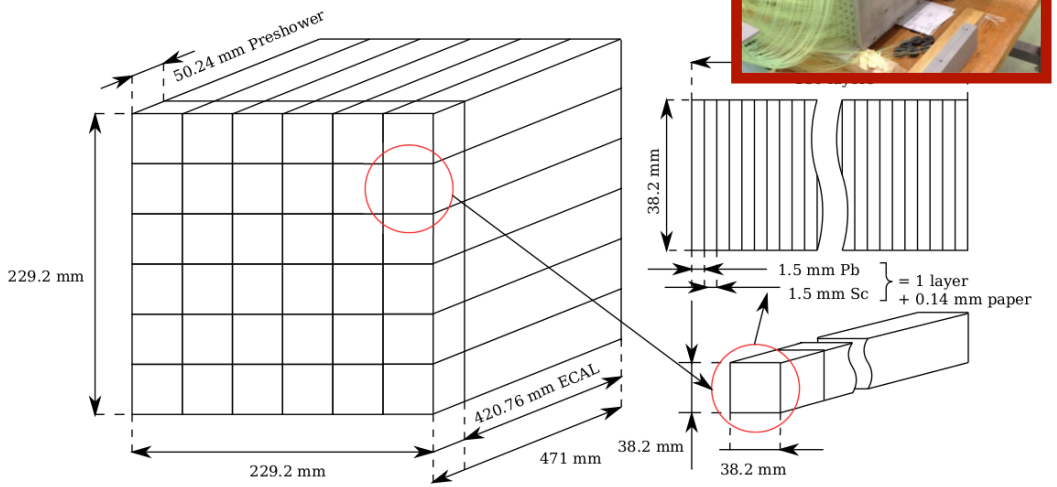
The NA64 setup – A' → invisible search – the ECAL

- ECAL: Lead scintillator sandwich calorimeter to measure incoming energy







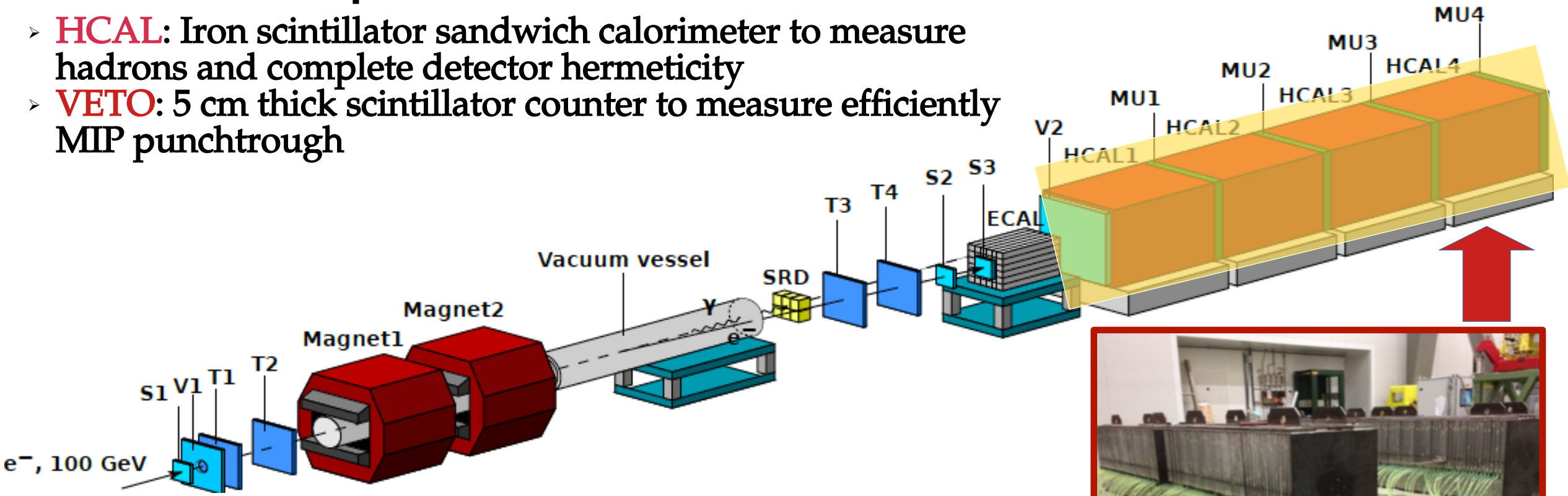


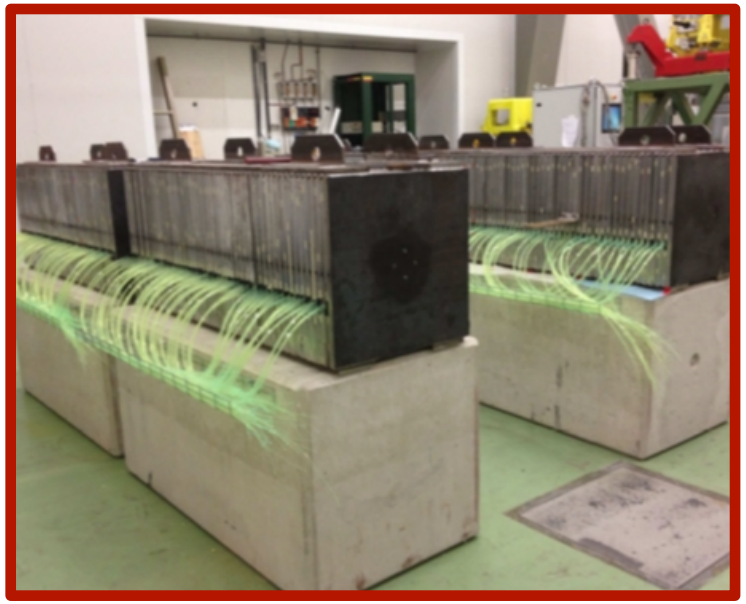
ECAL Characteristic

- High hermeticity ($40X_0$)
- Energy resolution ~9%/√(E[GeV])
- Longitudinal and lateral segmentation → shower profile (hadron rejection)
- WLS fiber inserted in spiral → suppress energy leak

The NA64 setup – A' → invisible search – the HCAL

- HCAL: Iron scintillator sandwich calorimeter to measure hadrons and complete detector hermeticity
- VETO: 5 cm thick scintillator counter to measure efficiently MIP punchtrough



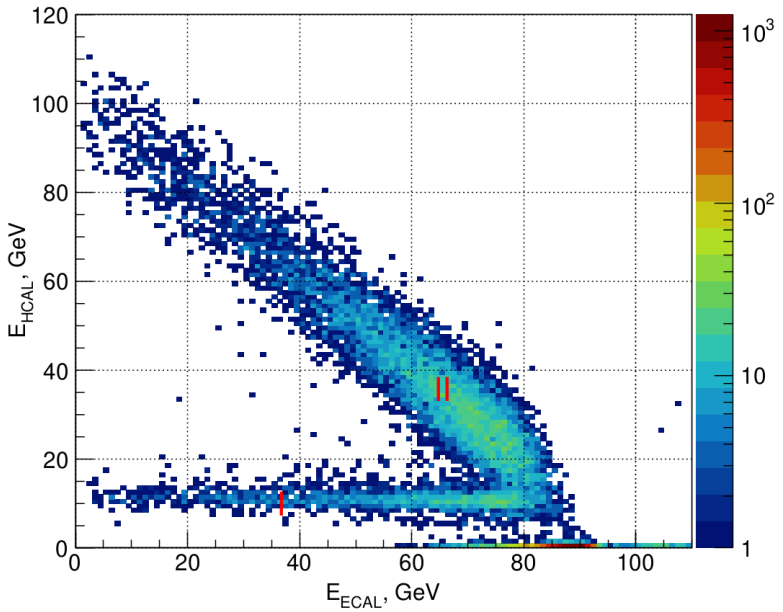


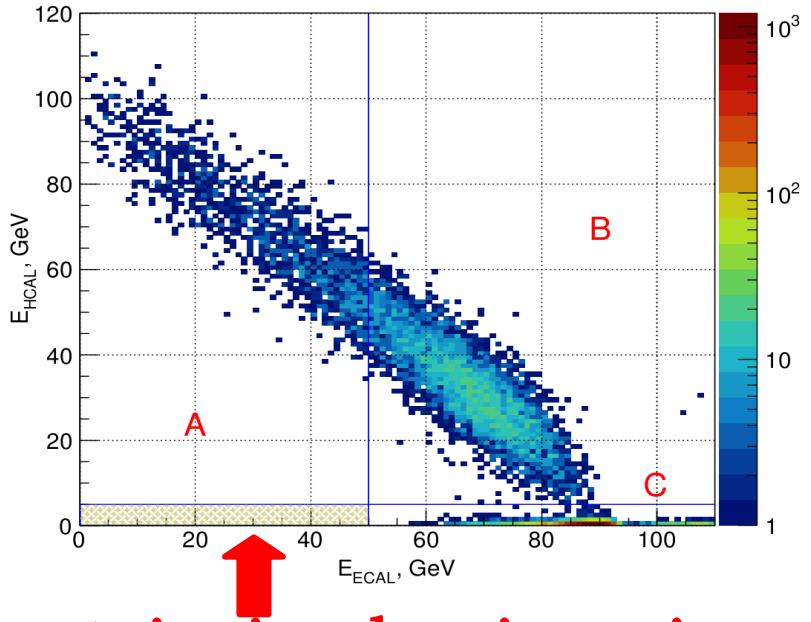
HCAL Characteristic

- High hermeticity 4λ/module
- Energy resolution ~50%/√(E[GeV])
- Lateral segmentation: 3x3 matrix, cells 19.4 x 19.2 x 150 cm^3

The NA64 setup – A' → invisible search – in real life

Invisible search – event selection and results





No events in signal region using the full 2016-2018 statistics (2.84×10^{11} EOT)

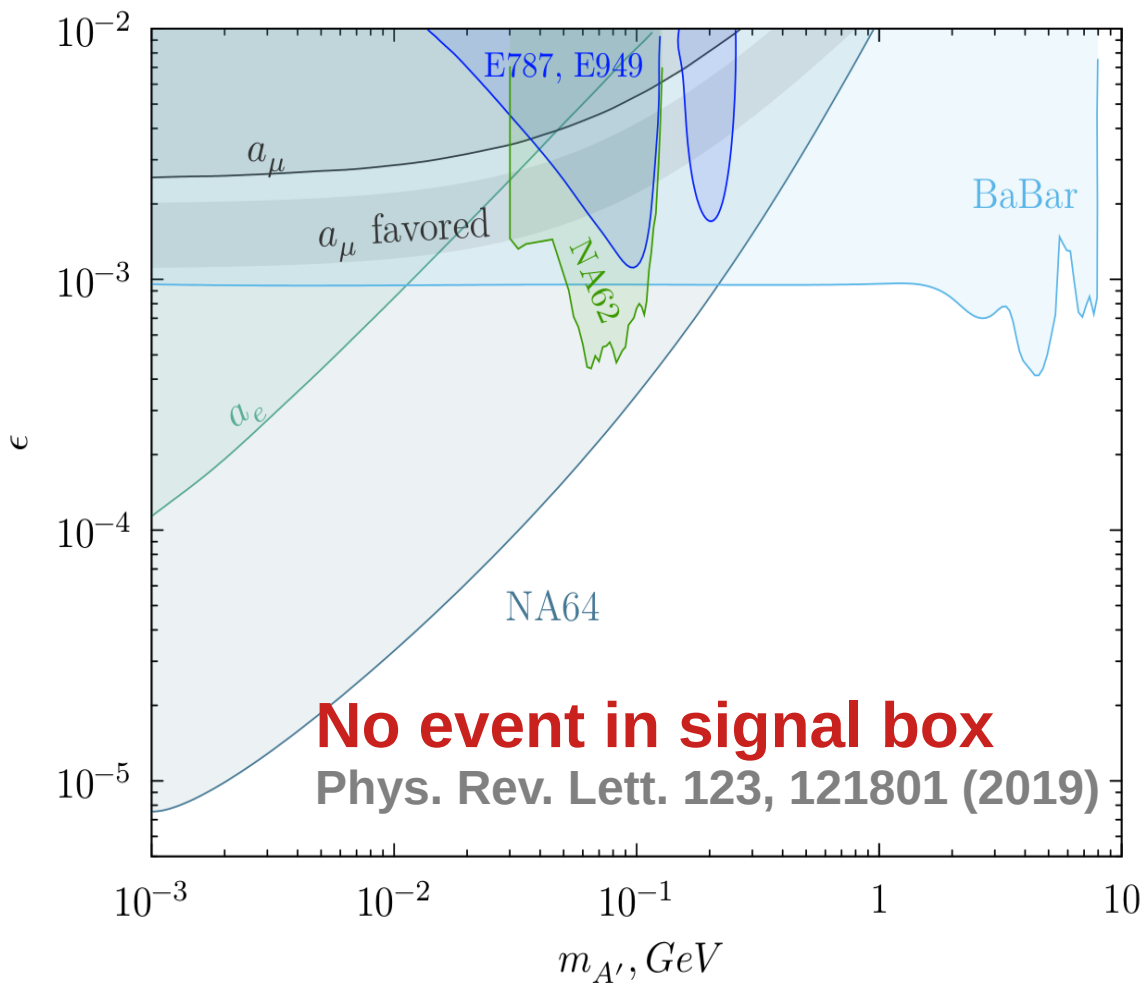
Control area:

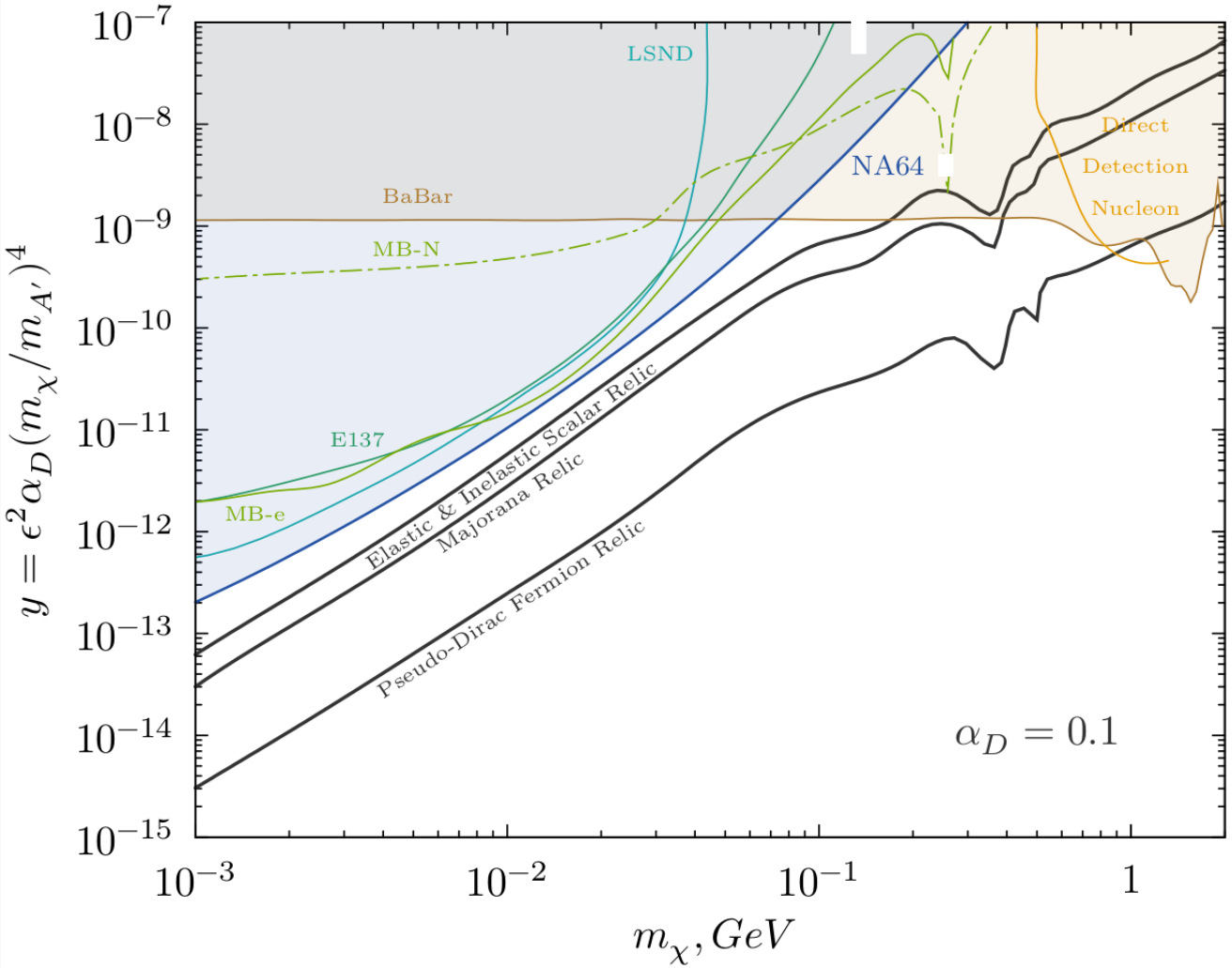
- **AREA I**: dimuon pair produced in ECAL shower (more on next slide)
- **AREA II**: Electron-hadron production

Event Selection:

- Timing information
  - pileup suppression
  - Noise suppression
- Clean incoming track:
  - Good incoming angle
  - No multiple hits
  - Momentum ~ 100 GeV
- Electron selected:
  - SRD detected
  - Shower profile compatible
- No punchtrough:
  - No activity in VETO
  - No activity in HCAL

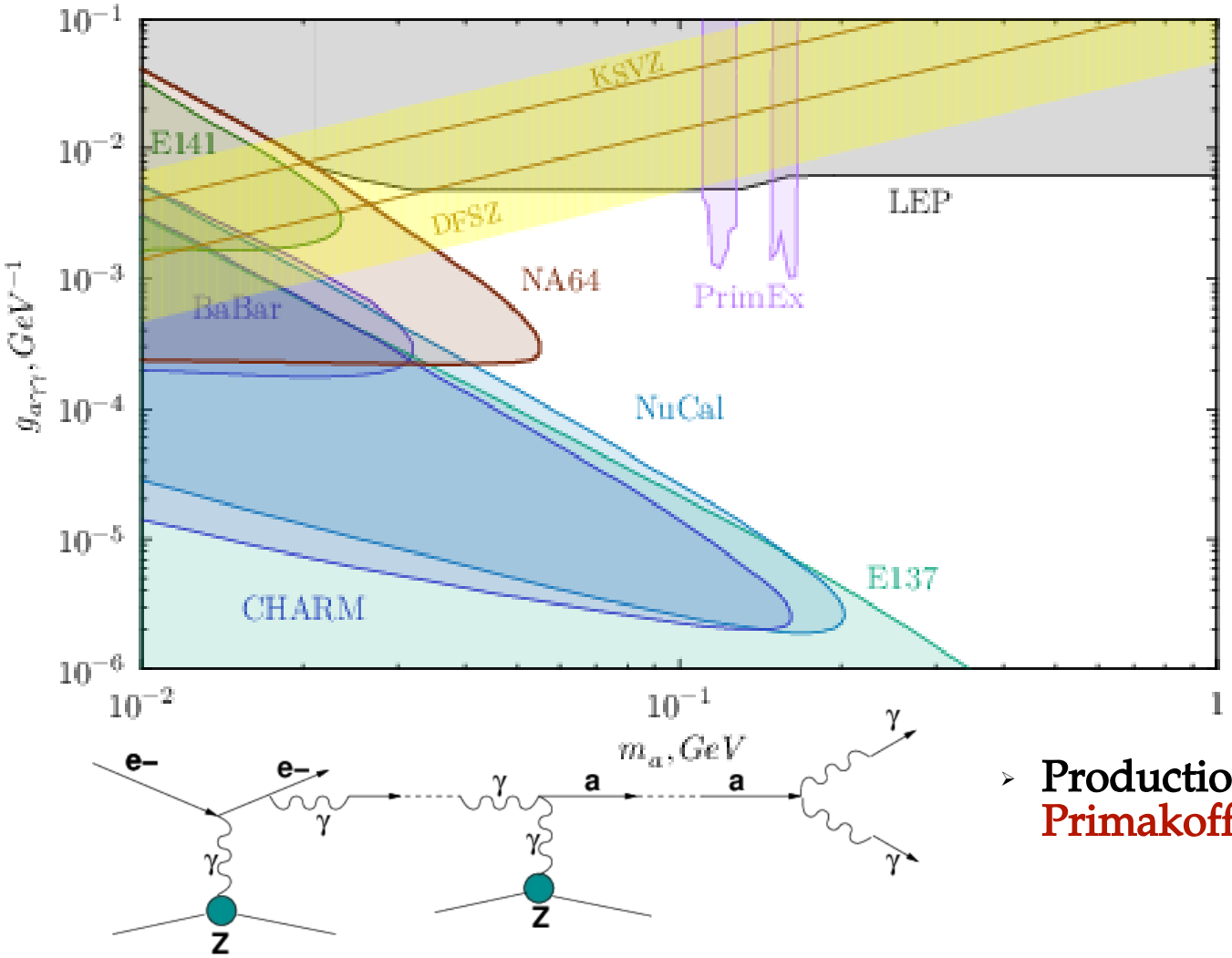
Invisible search – constraint on light thermal matter





- ***For the first time results better than previous beam dump experiments!***

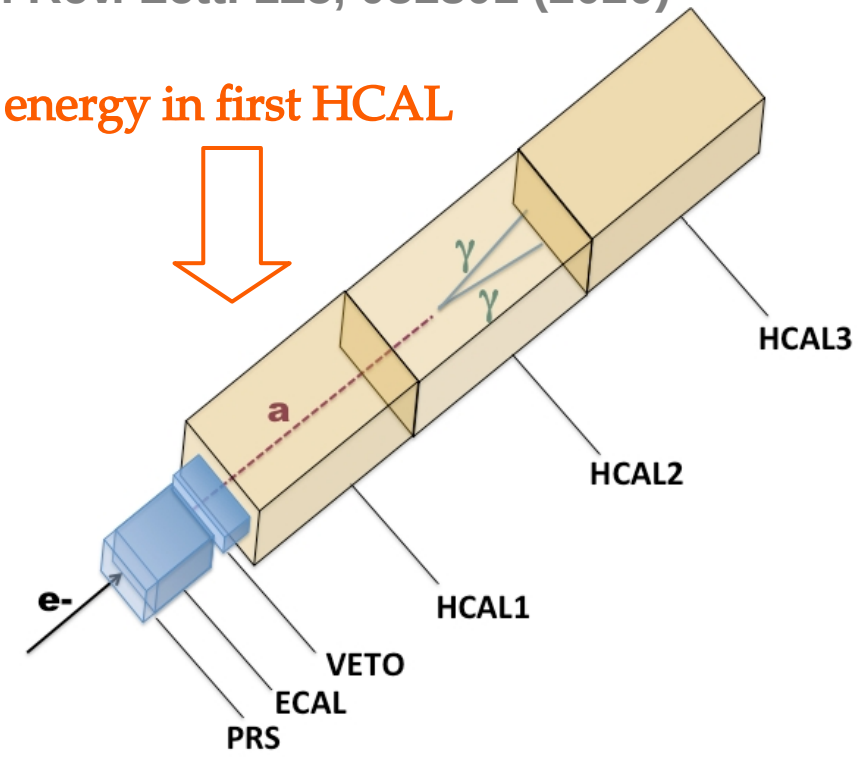
Search for Axionlike and Scalar particles



No event in signal box

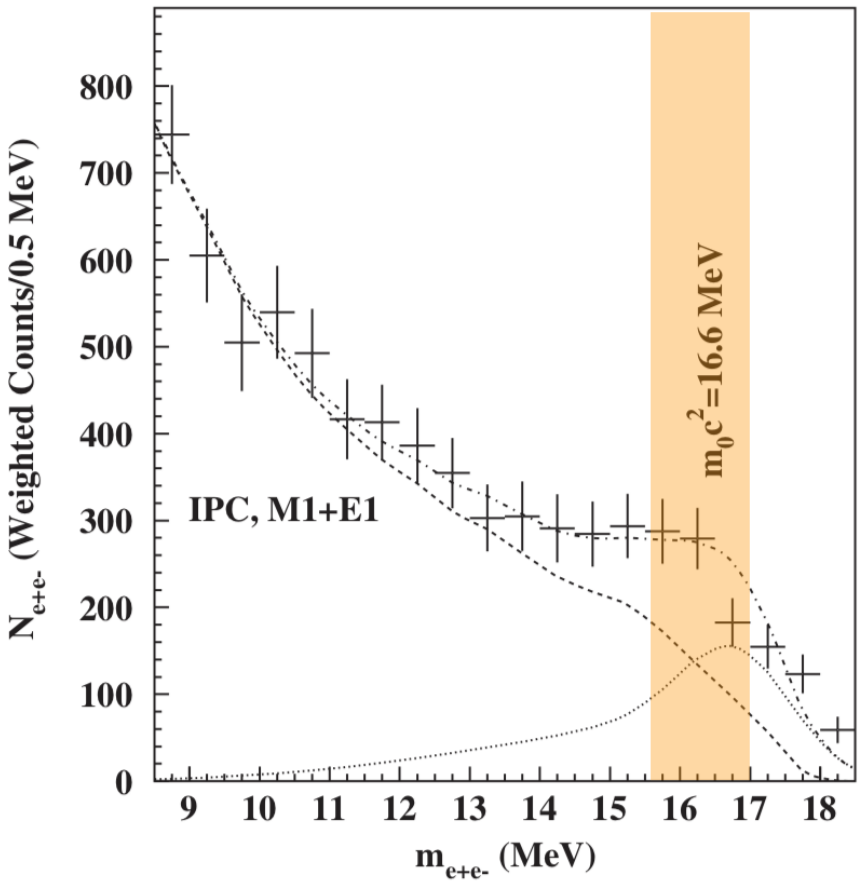
Phys. Rev. Lett. 125, 081801 (2020)

No energy in first HCAL



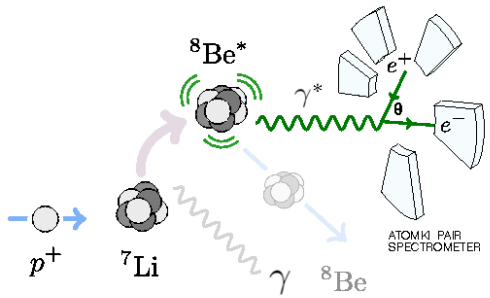
- Production of Axionlike via the Primakoff effect

Visible search – Light trough a wall experiment

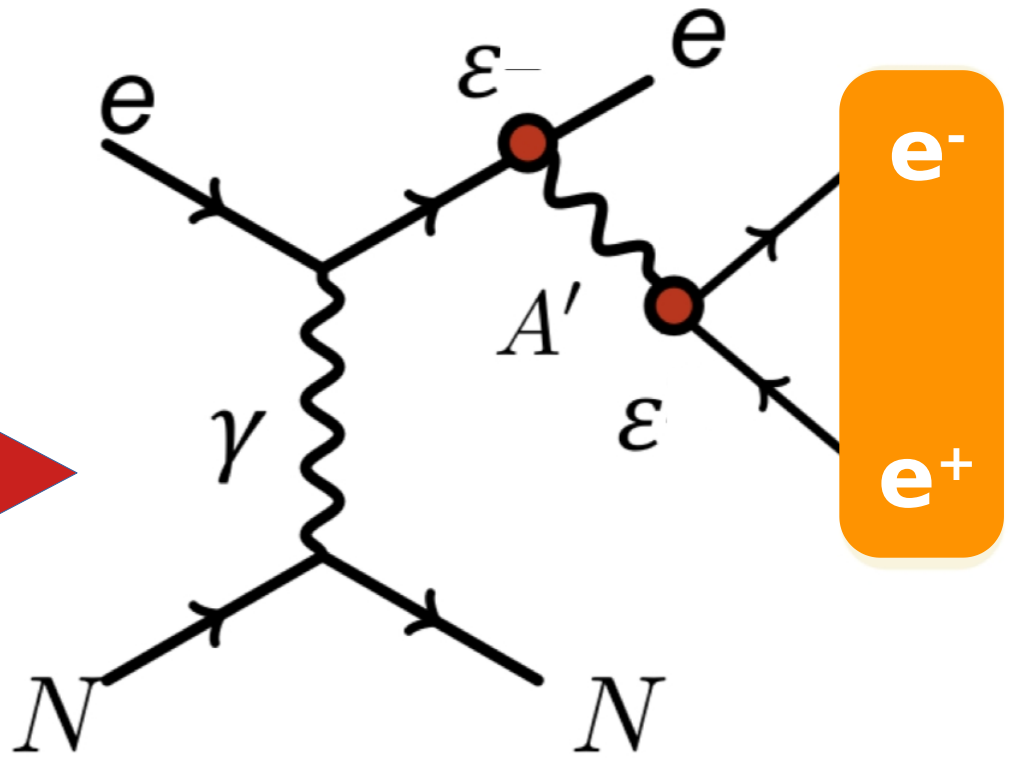


^{8}Be anomaly: a new 17 MeV X boson?

- NA64 visible mode setup has sensitivity over the anomaly



Visible mode



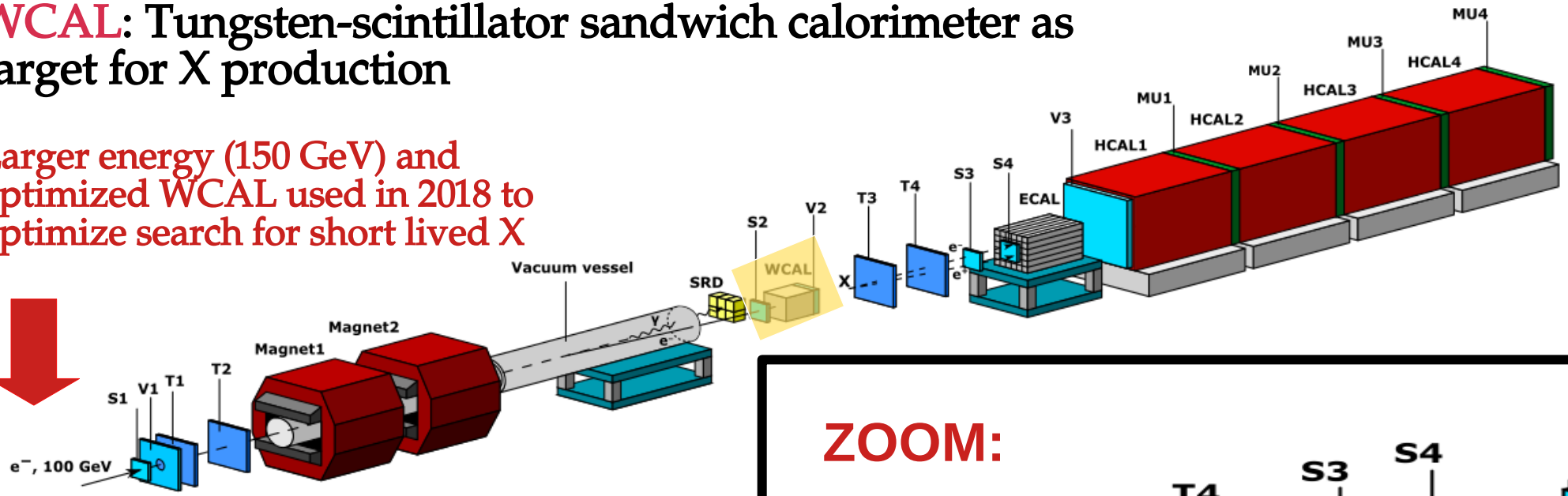
A. J. Krasznahorkay et al. Phys. Rev. Lett.116, 042501 (2015)

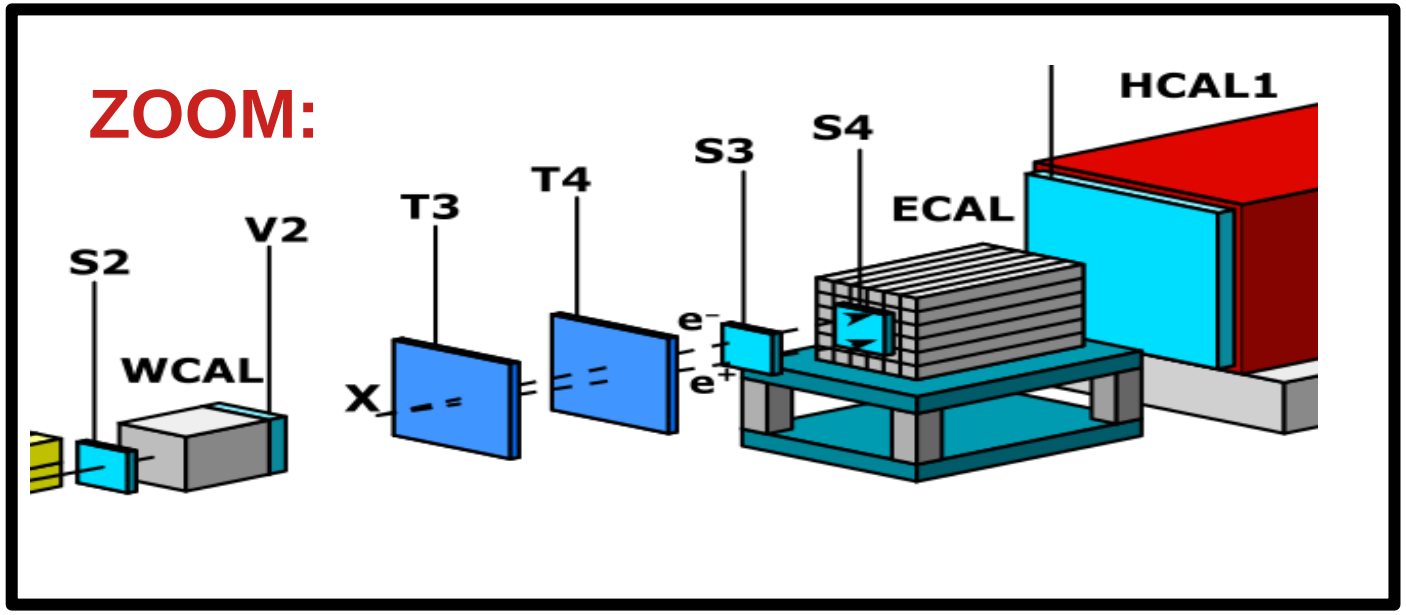
A. J. Krasznahorkay et al. arXiv:1910.10459 (2019)

Visible search – Light trough a wall experiment

- WCAL: Tungsten-scintillator sandwich calorimeter as target for X production

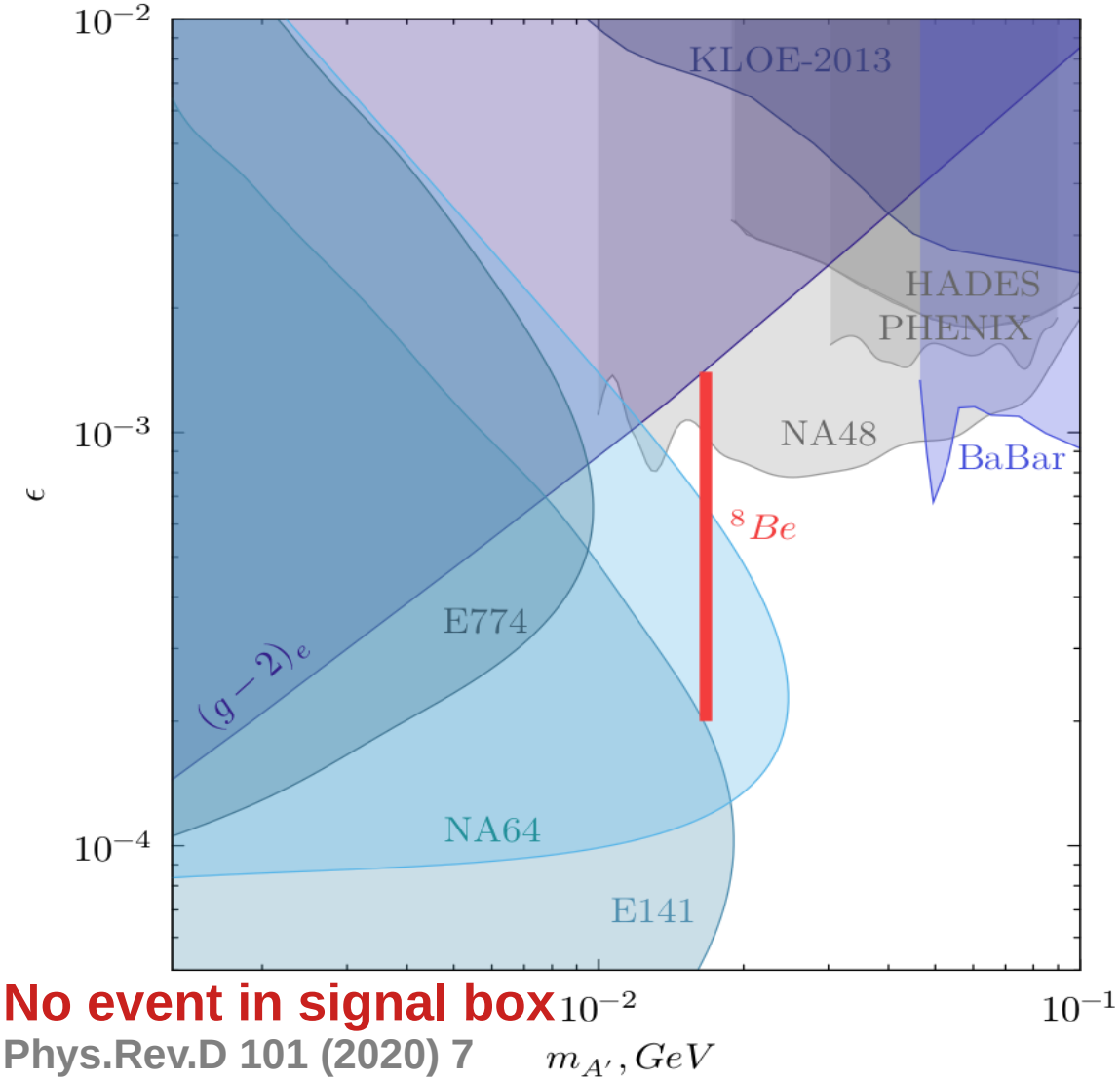
Larger energy (150 GeV) and optimized WCAL used in 2018 to optimize search for short lived X





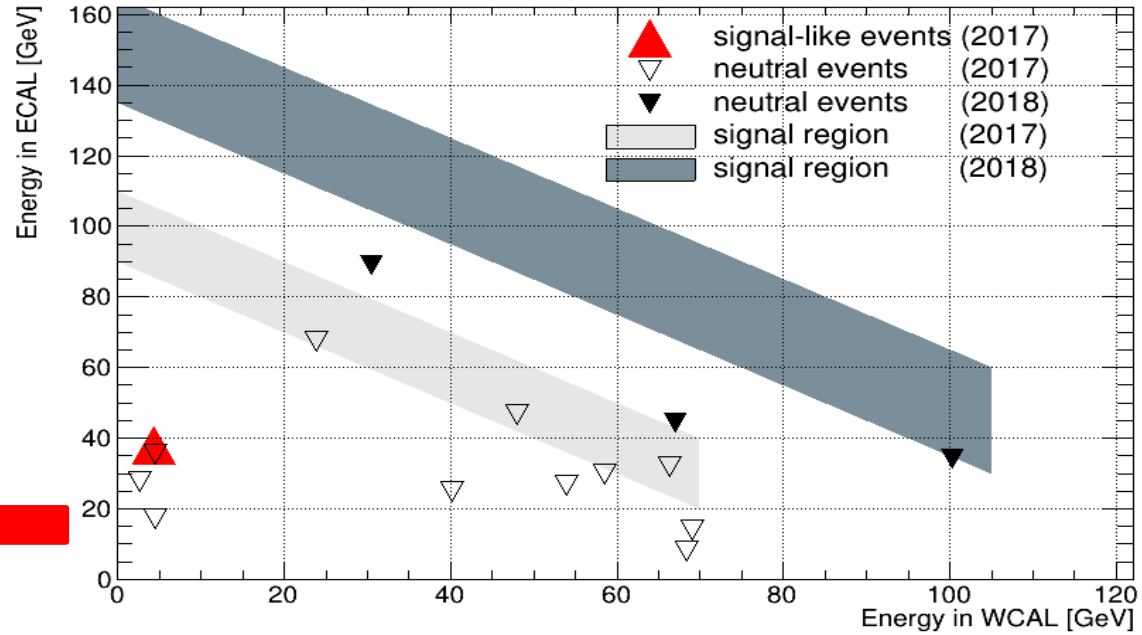
- Very compact ($30X_0$ in 17 cm) to allow detection of short lived X-boson
- V2 installed downstream to veto punchthrough
- 4 GEM station used for vertex reconstruction
- Vacuum pipe installed in 2018 to reduce background

Visible search – Results for 2016-2018 statistics



No event in signal box

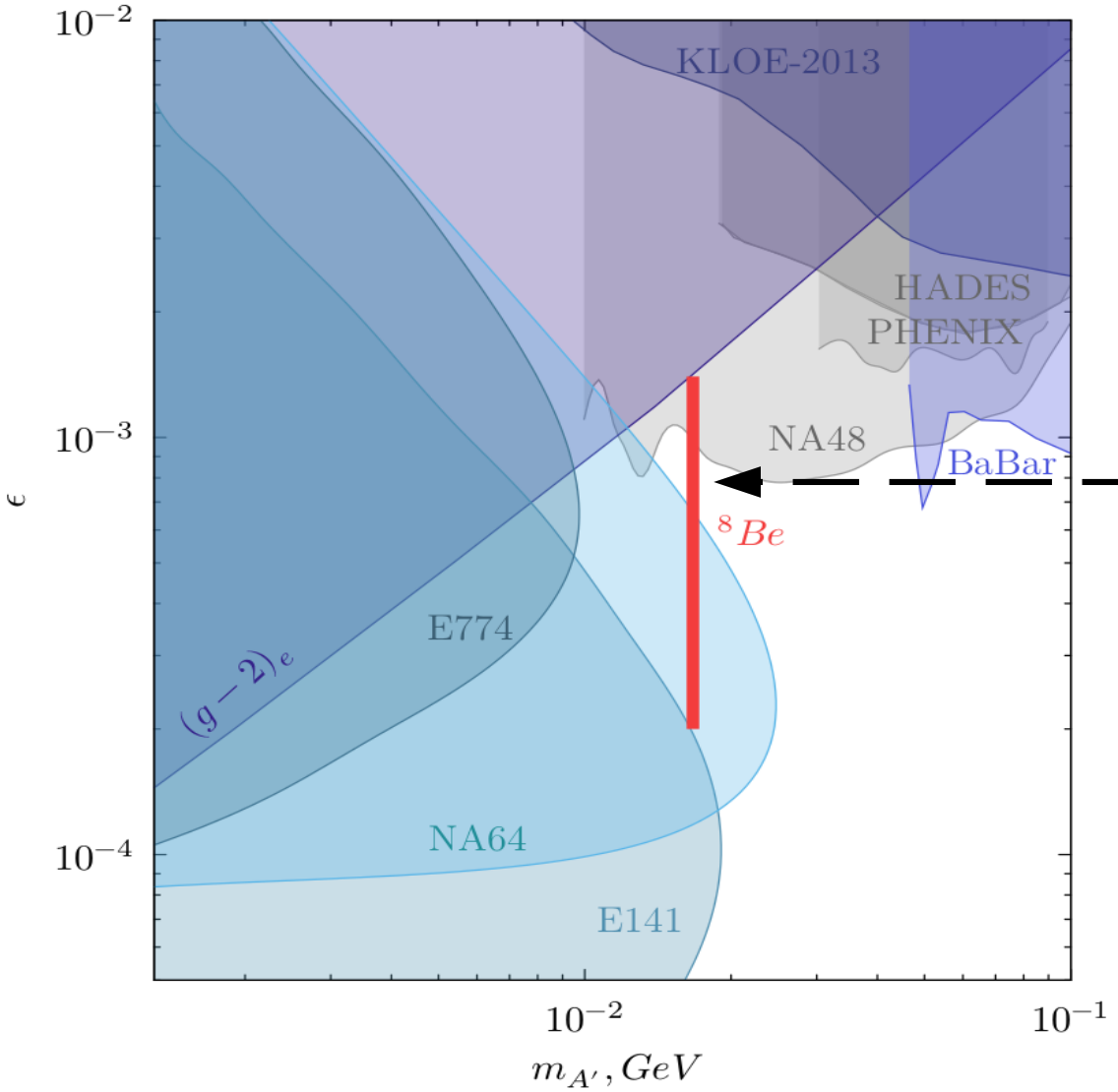
Phys.Rev.D 101 (2020) 7



Event Selection:

- Neutral exiting WCAL → No activity in V2
- Leaking in decay volume → single e-m shower in ECAL
- Charged particle in decay volume → signal in S4
- No hadron/large scattering → no activity in HCAL/VETO

Visible search – Improve limits



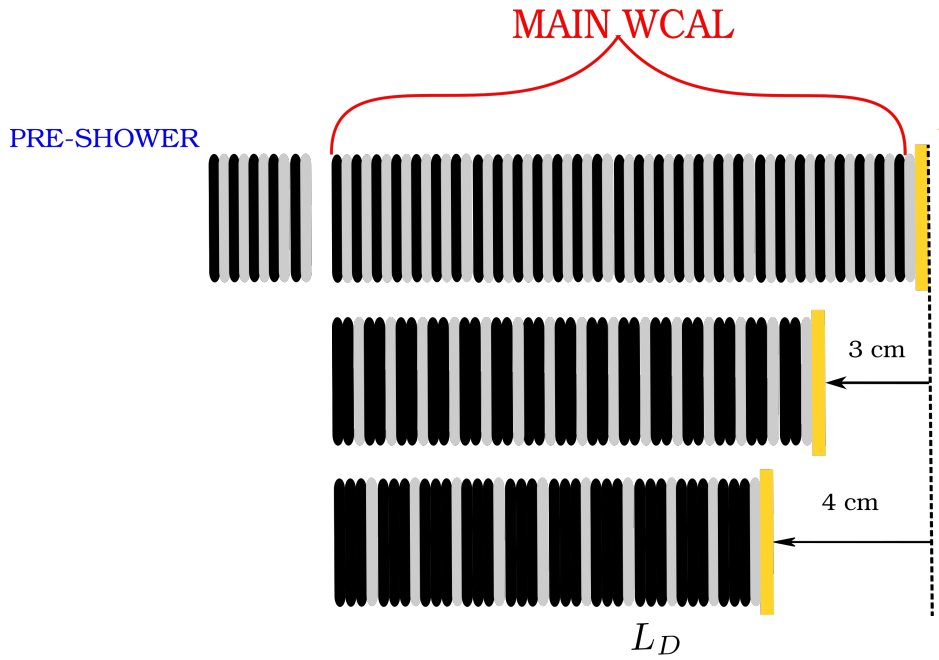
Limit improves only logarithmically
By adding statistics

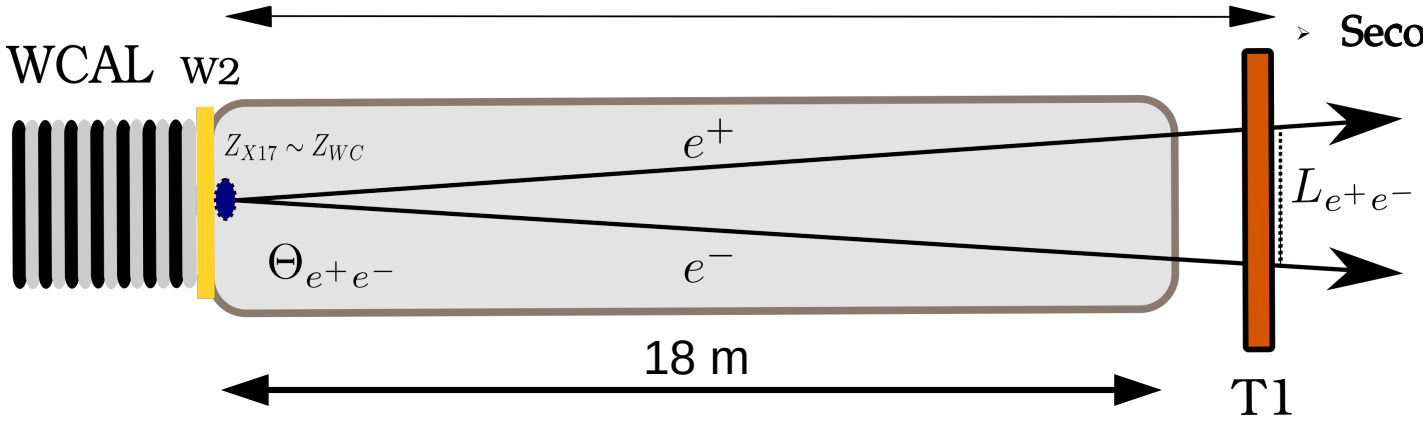
$$\epsilon_{up} \sim \frac{E_{beam}}{L_{dump}} \times \ln N_{EOT}$$

Remaining region of parameter space

$$6.8 \times 10^{-4} \lesssim \epsilon \lesssim 1.4 \times 10^{-3}$$

Visible search – New setup 2021





Decreasing the length of the WCAL to increase signal yield

- **Reshuffling WCAL converter tiles.**
  - WCAL is ~4 cm shorter, large improvement in signal yield
  - Worse energy resolution, but less relevant for X17
- **Invariant mass reconstruction of X17 decay**
  - **Long vacuum tube of 18 m with two trackers at the end**
    - Angle reconstructed from distance between decay products
  - **Second magnetic spectrometer to reconstruct momentum**
    - Momentum reconstructed at ~1%

Anomaly can be completely covered with 8×10^{11} EOT

Depero et al. arXiv:2009.02756 (2020)

Future prospects

Dark sector physics interesting framework to explain dark matter
NA64 ideal experiment to probe or rule out many candidates

Process	New Physics
e^- **beam**	
$A' \to e^+e^-$, and	Dark photon
$A' \to invisible$	
$A' \to \chi\overline{\chi}$	sub-GeV Dark Matter (χ)
$X \to e^+e^-$	new gauge X- boson
milliQ particles	Dark Sector, charge quantisation
$a \to \gamma\gamma, invisible$	Axion-like particles
μ^- **beam**	
$Z_\mu \to \nu\nu$	gauge Z_μ-boson of $L_\mu - L_\tau$, $< 2m_\mu$
$Z_\mu \to \chi\overline{\chi}$	$L_\mu - L_\tau$ charged Dark Matter (χ)
milliQ	Dark Sector, charge quantisation
$a_\mu \to invisible$	non-universal ALP coupling
$\mu - \tau$ conversion	Lepton Flavour Violation
π^-, K^- **beams**	Current limits, PDG'2018
$\pi^0 \to invisible$	$Br(\pi^0 \to invisible) < 2.7 \times 10^{-7}$
$\eta \to invisible$	$Br(\eta \to invisible) < 1.0 \times 10^{-4}$
$\eta' \to invisible$	$Br(\eta' \to invisible) < 5 \times 10^{-4}$
$K_S^0 \to invisible$	no limits
$K_L^0 \to invisible$	no limits

After long shutdown 2 in 2021:

- **Continue electron program, reach 5x10^{12} EOT for A'→ invisible to cover completely LDM Majorana and Pseudo-Dirac**
- **explore remaining parameter space for X → e$^+$ e$^-$**
- **Proposed searches of dark sector in NA64 leptonic and hadronic beams with unique sensitivites:**
  - Search for Z' coupled to muon with M2 beamline at CERN (160 GeV/c muon)

Acknowledgments

NA64 collaboration and in particular **P.Crivelli** and **S. Gninenko**

ETH Zurich group:
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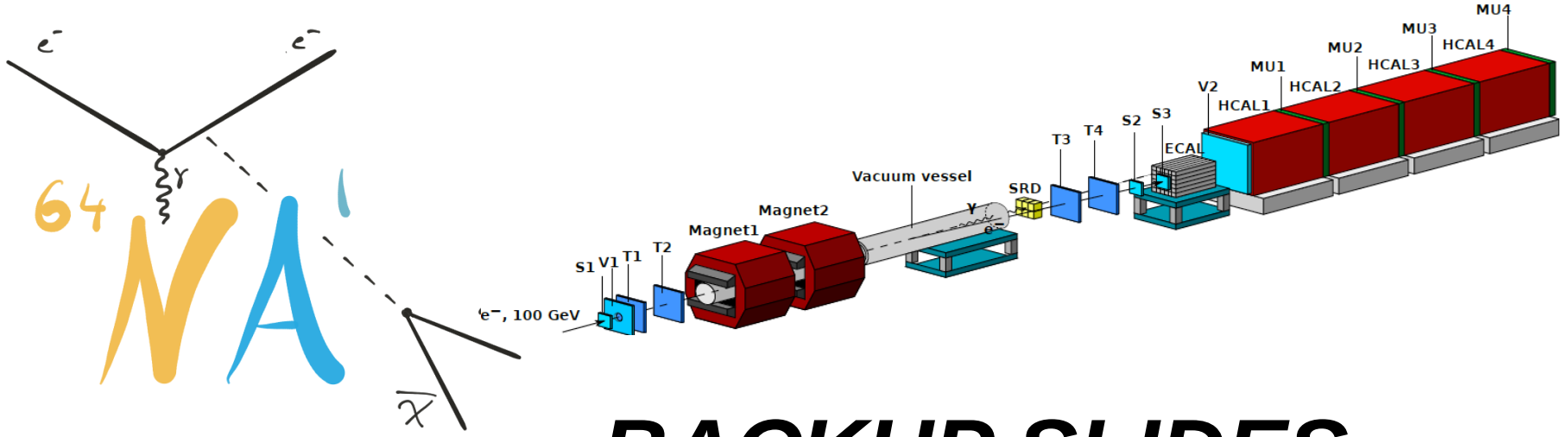
FNSNF
Swiss National Science Foundation

Signature of dark photons at fixed target experiment



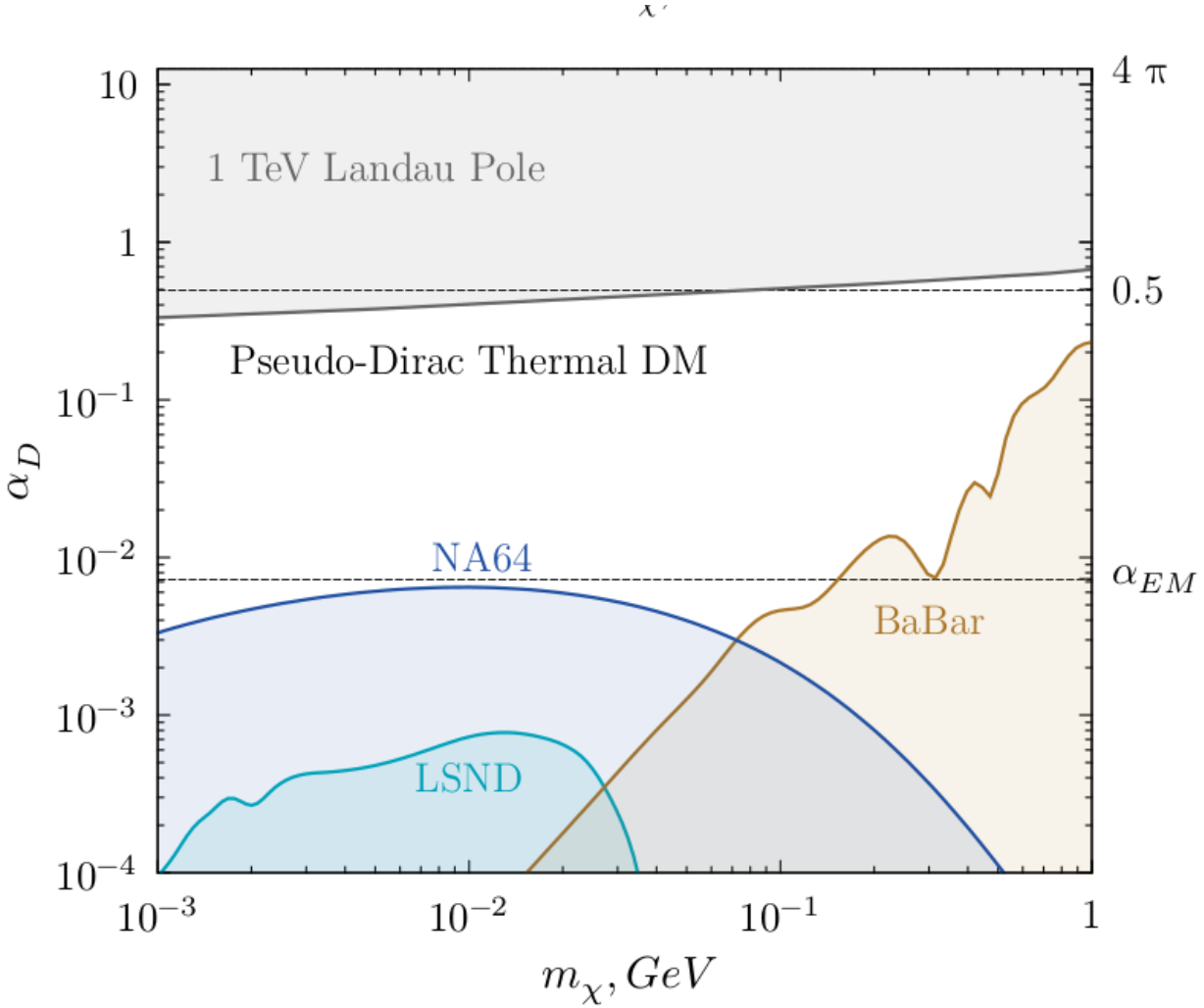
CERN

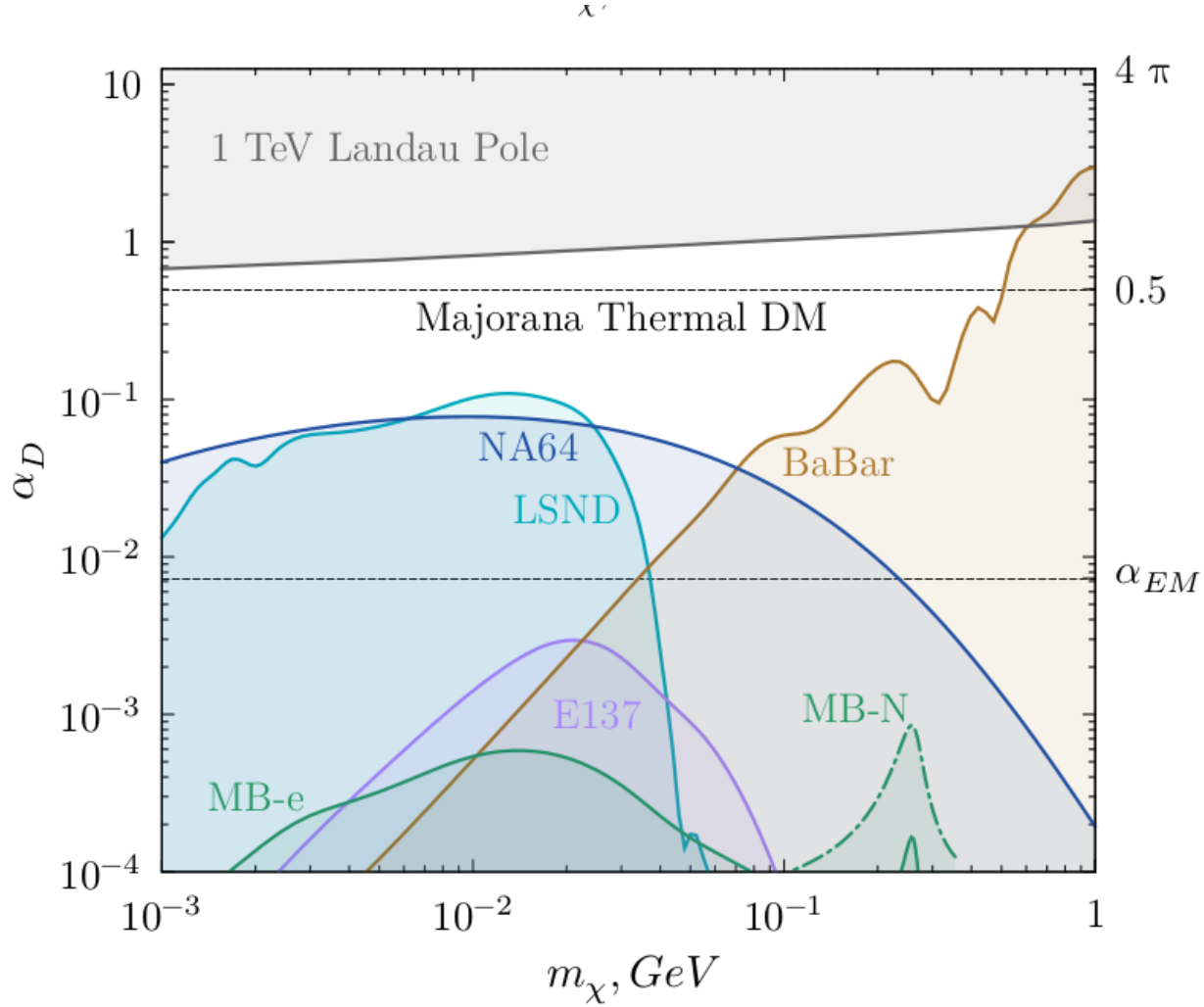
BACKUP SLIDES

IPA

ETH zürich

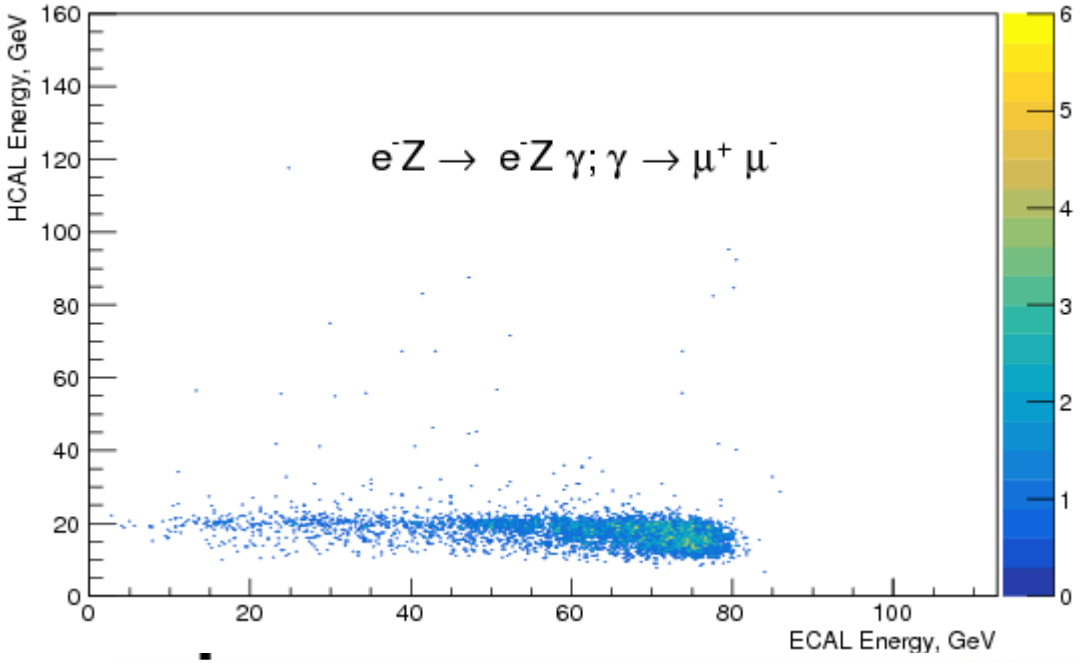
Pseudo-Dirac and Majorana Thermal Dark Matter





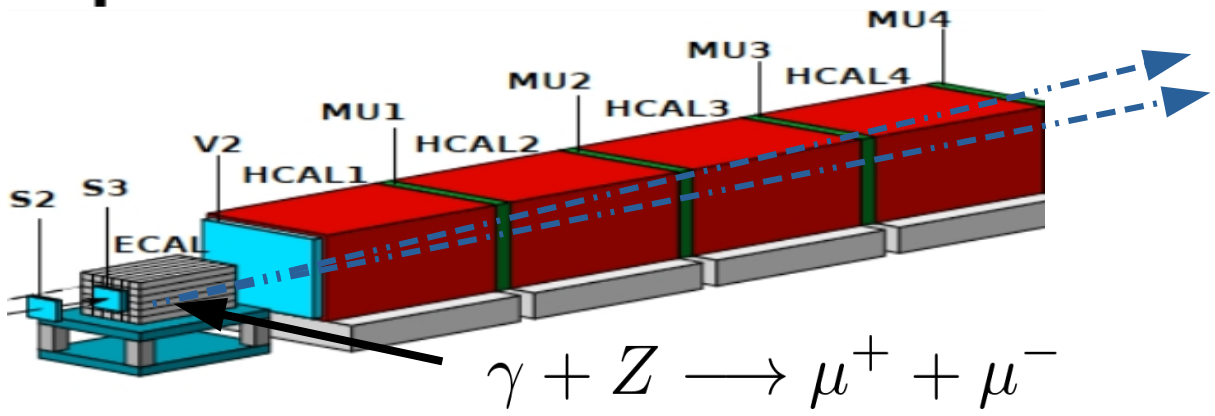
- ***For the first time results better than previous beam dump experiments!***

Invisible search – dimuon events

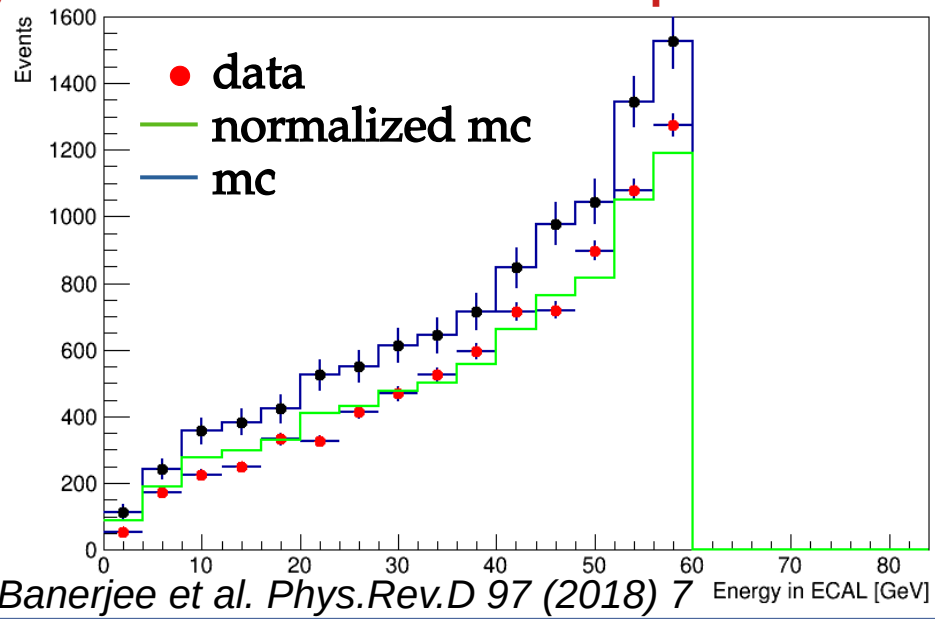


Dimuon events:

- Rare QED interaction visible in our setup
- Used to check reliability of MC simulation
- Similar to signal → used to correct the yield and take into account systematic uncertainty

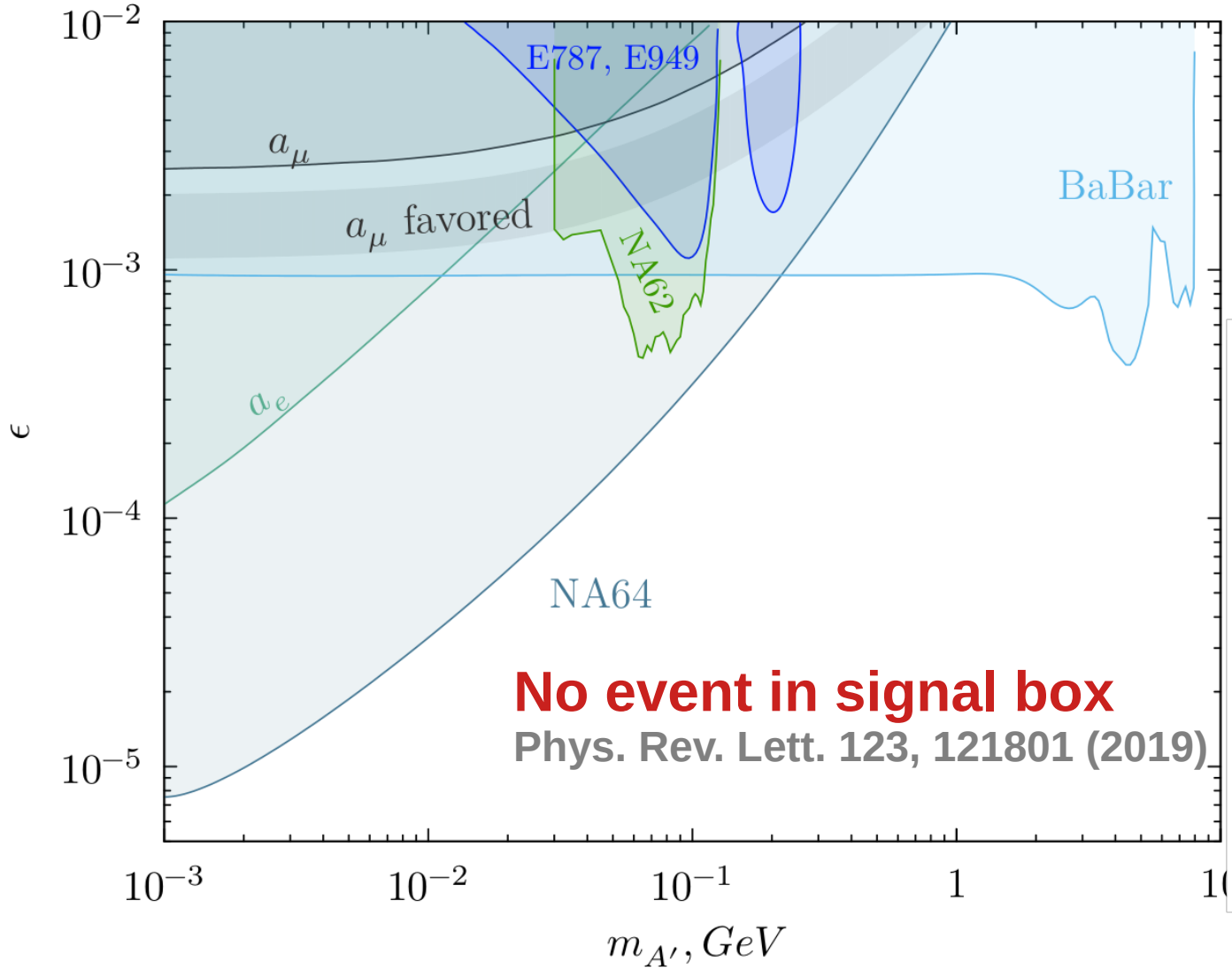


Excellent agreement with MC for ECAL spectrum



D. Banerjee et al. Phys.Rev.D 97 (2018) 7

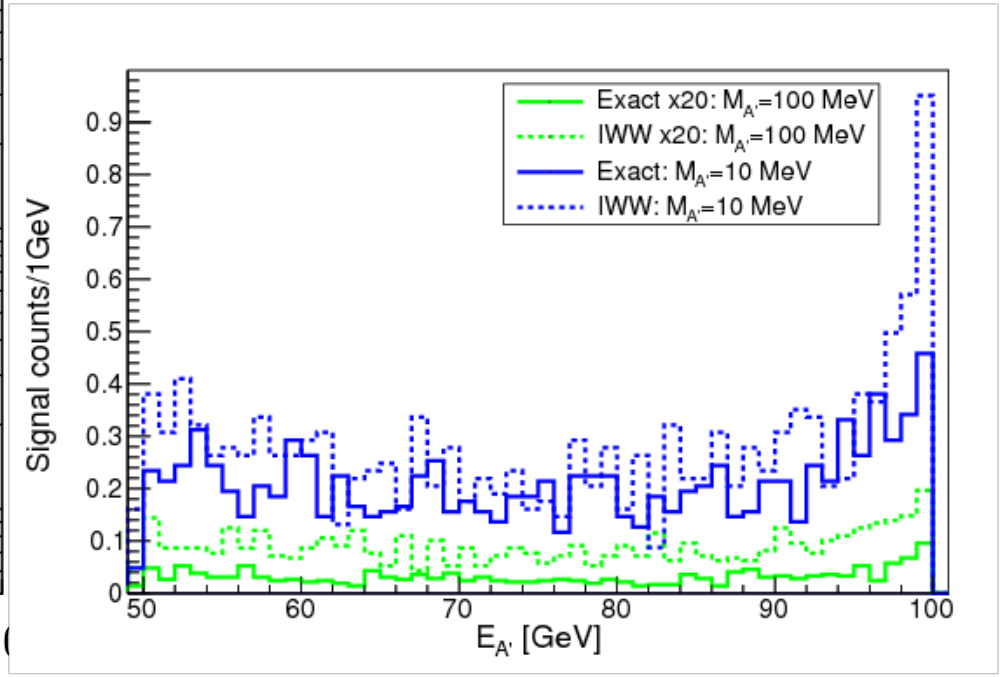
Invisible search – exclusion plot



No event in signal box

Phys. Rev. Lett. 123, 121801 (2019)

- Signal yield calculated using Exact Tree Level integration of the cross section!



S. Gninenko et al. Phys.Lett. B782 (2018) 406-411

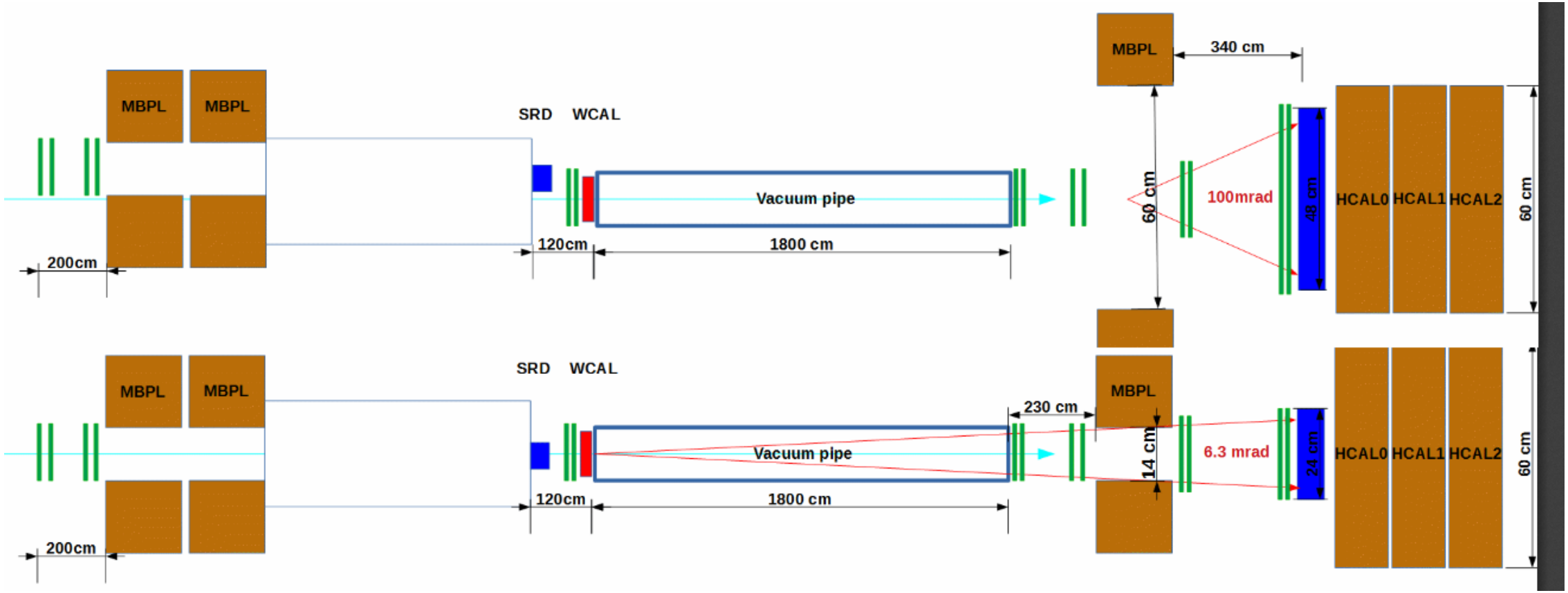
New invisible mode 2018 - background

Background source	Background, n_b
(i) Dimuons	0.024 ± 0.007
(ii) $\pi, K \to e\nu, K_{e3}$ decays	0.02 ± 0.01
(iii) e^- hadron interactions in the beam line	0.43 ± 0.16
(iv) e^- hadron interactions in the target	<0.044
(v) Punch-through γ's, cracks, holes	<0.01
Total n_b (conservatively)	0.53 ± 0.17

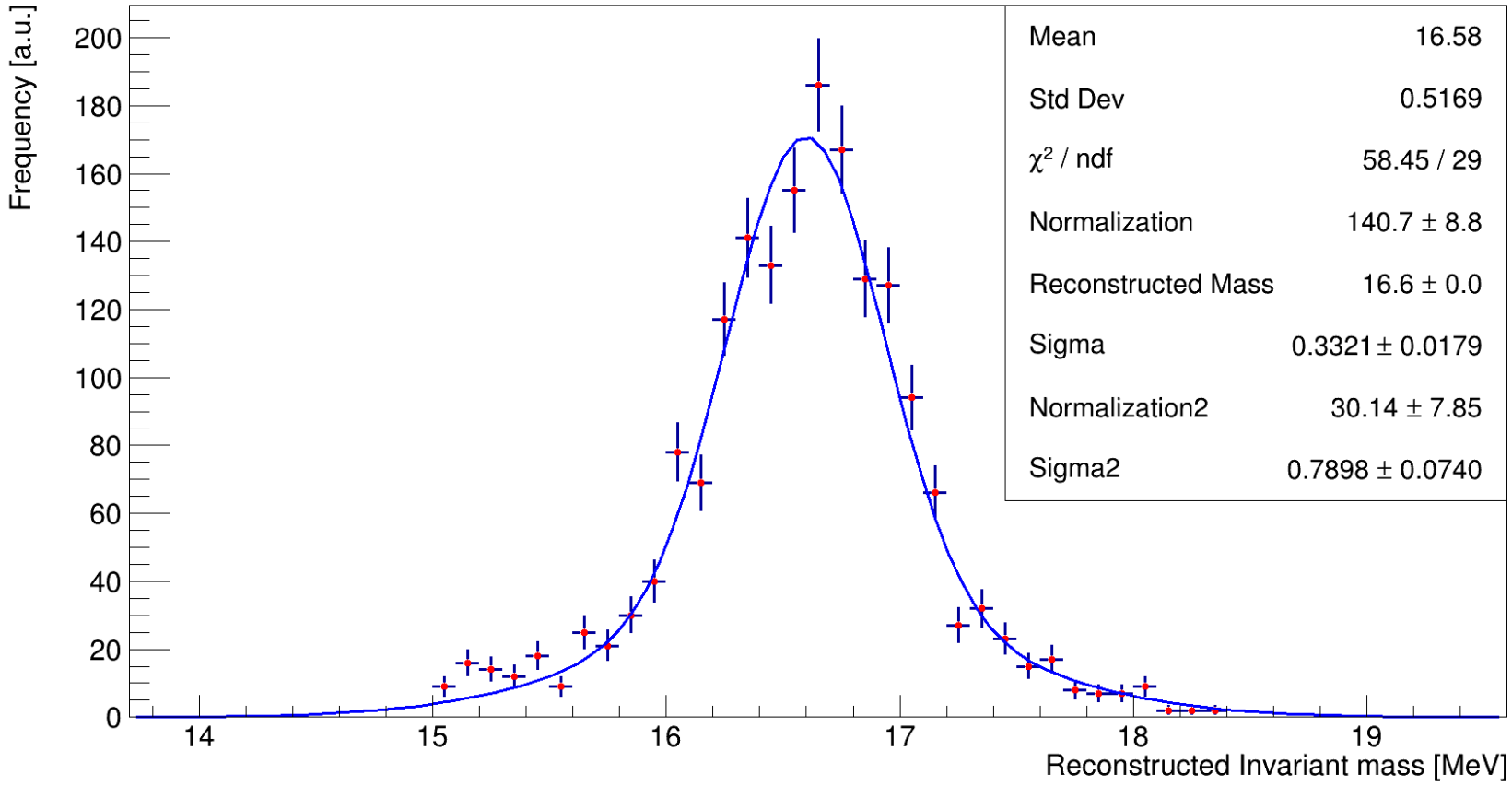
New visible mode 2018 - background

Background source	n_b (2017)	n_b (2018)	n_b (2018, new analysis)
π^- punch-through	0.0015±0.0008	0.0007±0.0004	0.0007±0.0004
$K_S^0 \to \pi^0\pi^0$	0.06±0.034	0.005±0.003	<0.001
e^-/hadron nuclear interaction	0.01±0.004	0.01±0.004	0.01±0.004
μ^- punch-through	< 0.001	< 0.001	< 0.001
$\pi^-, K^- \to e\nu\, K_{4e}$	<0.001	< 0.001	< 0.001
$eZ \to eZ\mu^+\mu^-; \mu^\pm \to e^\pm\nu\bar{\nu}$	<0.001	< 0.001	< 0.001
punch-through γ	<0.001	<0.0005	<0.001
Total (conservatively)	0.07 ± 0.035	0.006 ± 0.003	0.006 ± 0.003

New visible mode setup 2021



New visible mode setup 2021 – invariant mass reconstruction



ALPS search