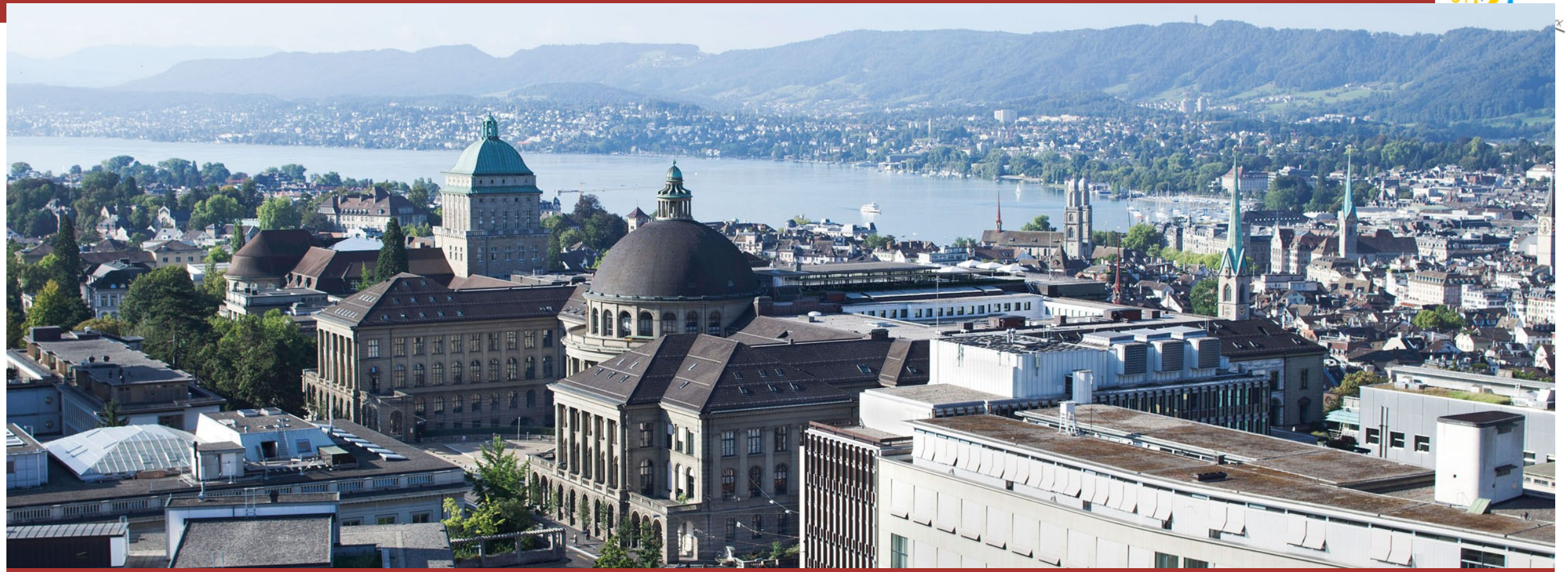
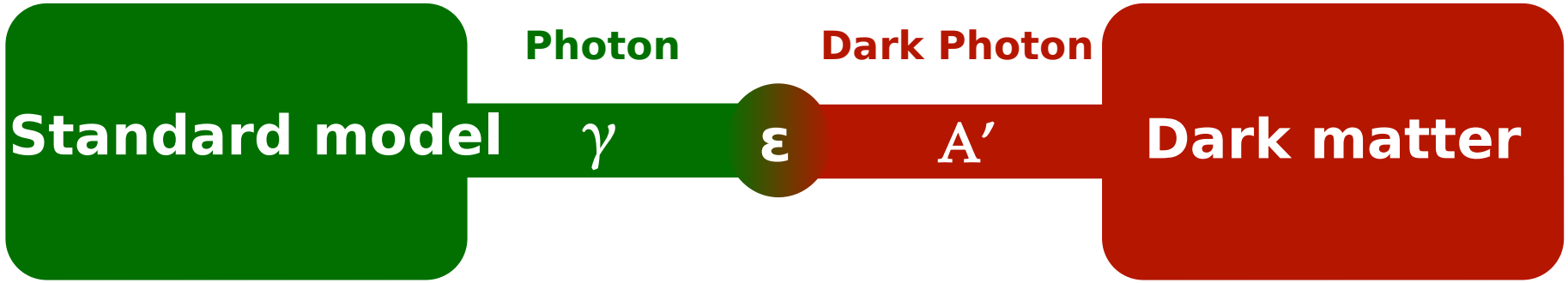


NA64 SEARCHING FOR HIDDEN SECTORS AT THE CERN SPS

Emilio Depero, ETH Zurich, Institute for Particle Physics and Astrophysics on behalf of the NA64 collaboration

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'***

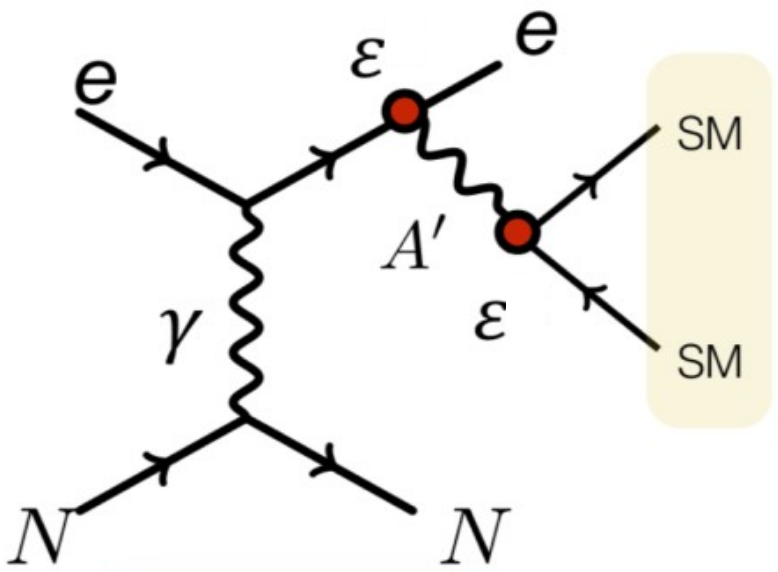
Kinetic mixing term with the ***standard photon γ***

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

Dark photons - signature at fixed target experiment

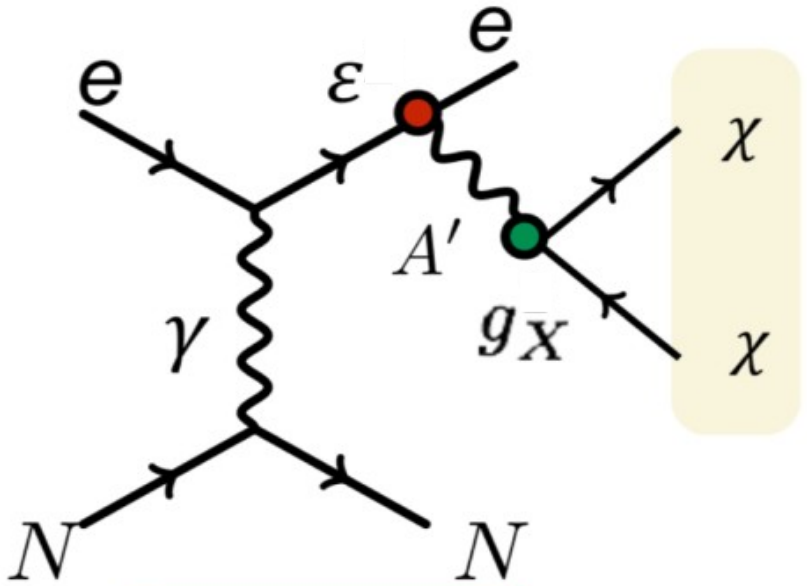
- The electron collides with heavy nuclei irradiating A′ (dark-bremstrahlung) which can decay to:

Visible mode



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

Invisible mode



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

Dark photons - signature at fixed target experiment

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

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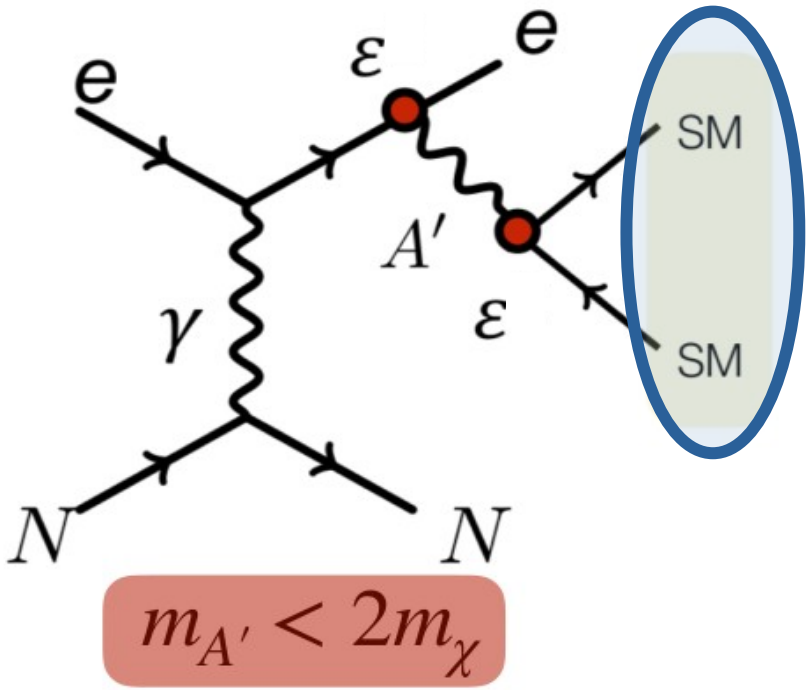
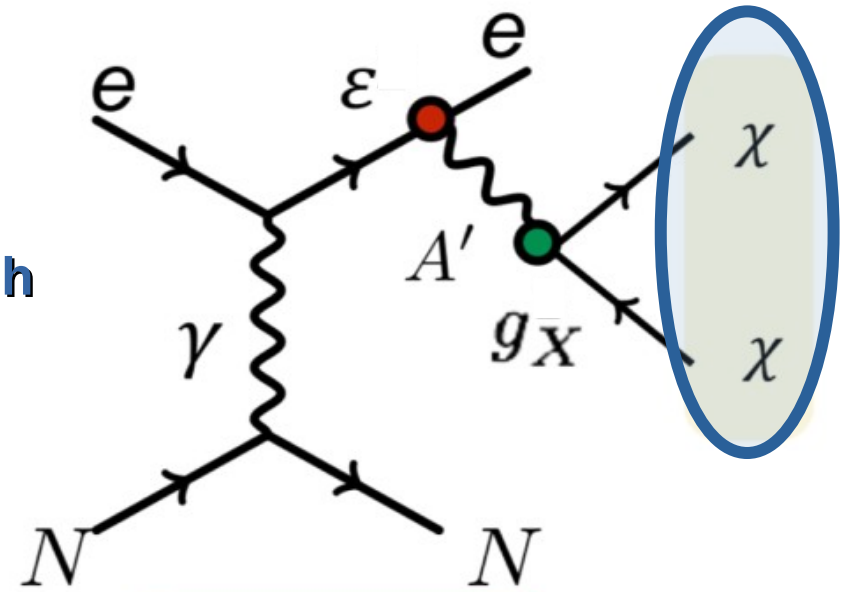


$m_{A'} < 2m_{\chi}$

Light shine through a wall

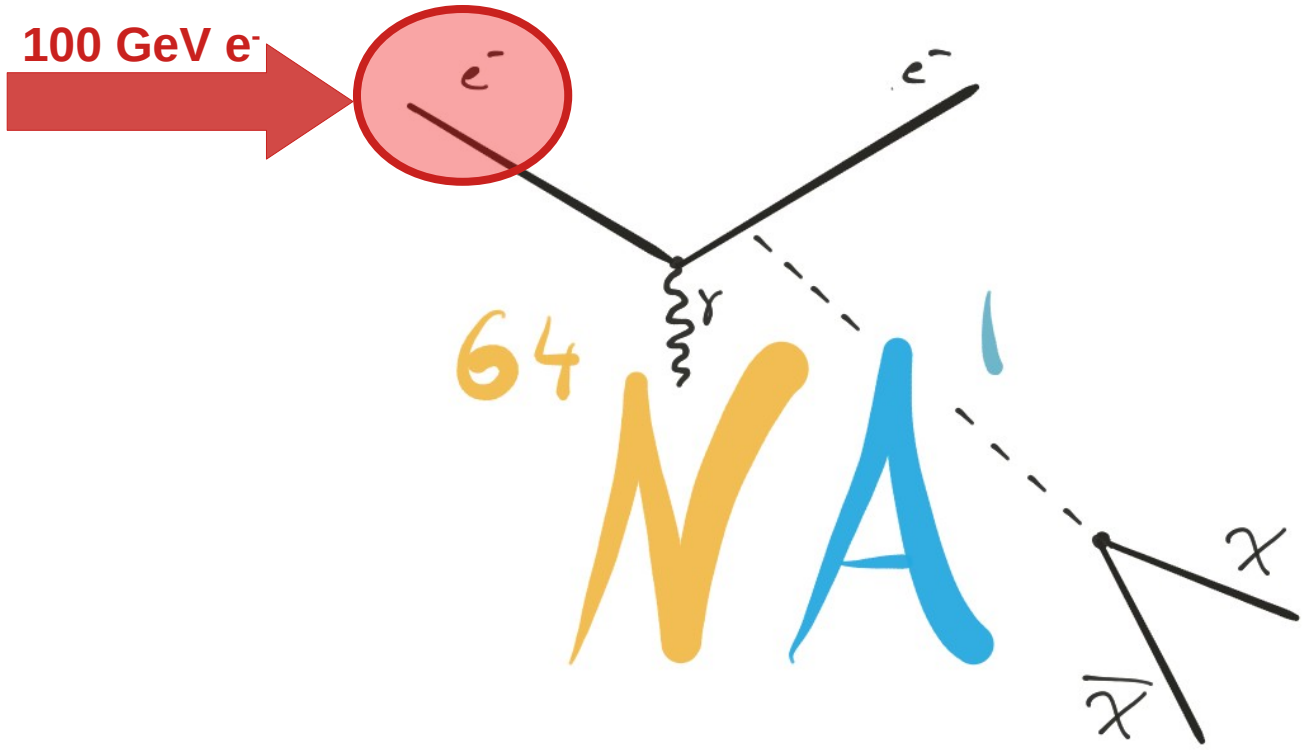
Invisible mode



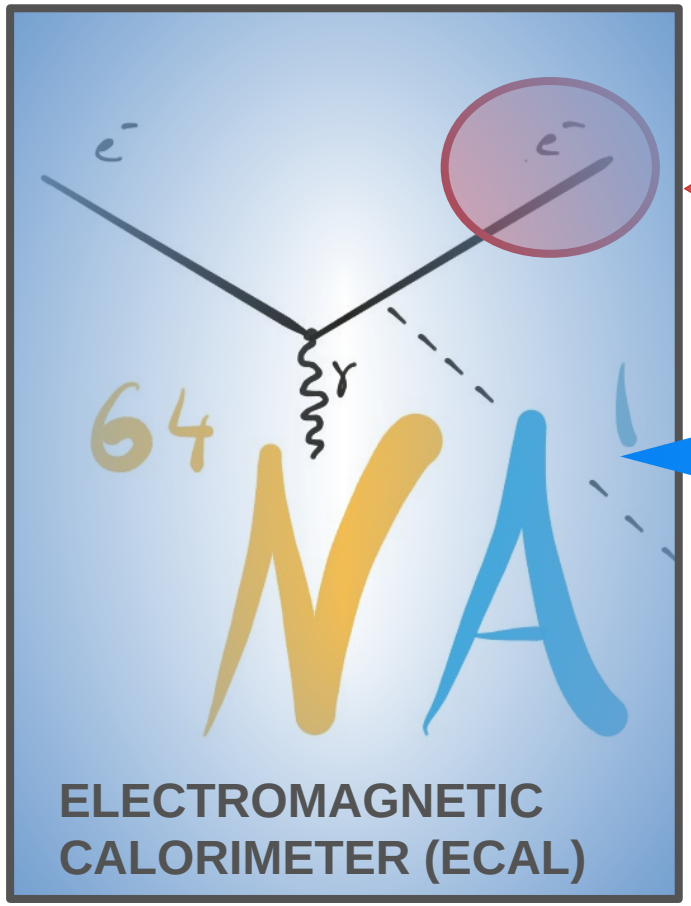
$m_{A'} > 2m_{\chi}$

Missing Energy search

The NA64 working principle to search for A' → $\chi\bar{\chi}$

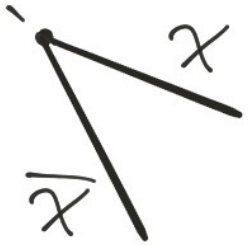


The NA64 working principle to search for A' $\rightarrow \chi\bar{\chi}$



1 - 50 GeV e⁻

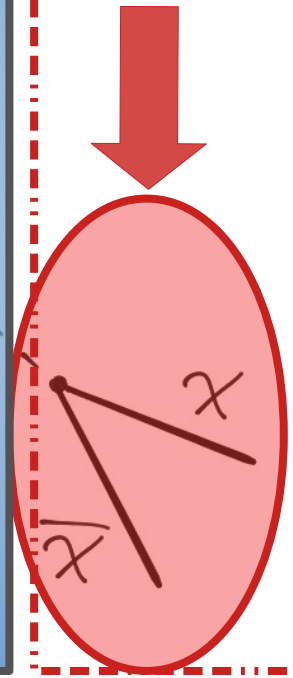
"BREMSSTRAHLUNG" OF A'



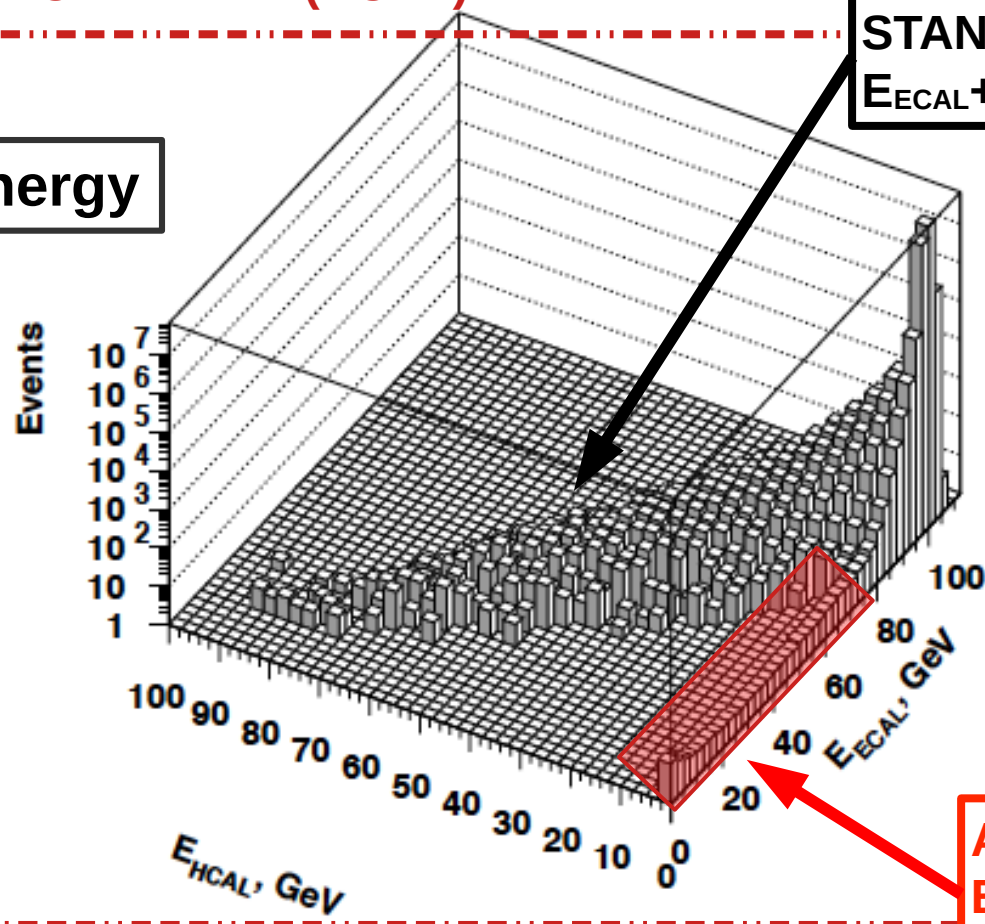
The NA64 working principle to search for A' → $\chi\bar{\chi}$

HADRONIC CALORIMETER (HCAL)

Missing energy



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



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

The NA64 collaboration

D. Banerjee,[12] V. E. Burtsev,[10] A. G. Chumakov,[10] D. Cooke,[12] P. Crivelli,[12] E. Depero,[12] A. V. Dermenev,[4] S. V. Donskov,[9] F. Dubinin,[5] R. R. Dusaev,[10] S. Emmenegger,[12] A. Fabich,[3] V. N. Frolov,[2] A. Gardikiotis,[8] S. G. Gerassimov,[5,7] S. N. Gninenko,[4,*] M. Hösgen,[1] A. E. Karneyeu,[4] B. Ketzer,[1] D. V. Kirpichnikov,[4] M. M. Kirsanov,[4] I. V. Konorov,[5,7] S. G. Kovalenko,[11] V. A. Kramarenko,[2,6] L. V. Kravchuk,[4] N. V. Krasnikov,[4] S. V. Kuleshov,[11] V. E. Lyubovitskij,[10,11] V. Lysan,[2] V. A. Matveev,[2] Yu. V. Mikhailov,[9] D. V. Peshekhonov,[2] V. A. Polyakov,[9] B. Radics,[12] R. Rojas,[11] A. Rubbia,[12] V. D. Samoylenko,[9] V. O. Tikhomirov,[5] D. A. Tlisov,[4] A. N. Toropin,[4] A. Yu. Trifonov,[10] B. I. Vasilishin,[10] G. Vasquez Arenas,[11] and P. Ulloa[11]

(The NA64 Collaboration)

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46 Researchers From 13 institutions!

Sergei Gninenko
NA64 spokesperson

The NA64 collaboration

D. Banerjee,[12] V. E. Burtsev,[10] A. G. Chumakov,[10] D. Cooke,[12] P. Crivelli,[12] E. Depero,[12] A. V. Dermenev,[4] S. V. Donskov,[9] F. Dubinin,[5] R. R. Dusaev,[10] S. Emmenegger,[12] A. Fabich,[3] V. N. Frolov,[2] A. Gardikiotis,[8] S. G. Gerassimov,[5,7] S. N. Gninenko,[4,*] M. Hösgen,[1] A. E. Karneyeu,[4] B. Ketzer,[1] D. V. Kirpichnikov,[4] M. M. Kirsanov,[4] I. V. Konorov,[5,7] S. G. Kovalenko,[11] V. A. Kramarenko,[2,6] L. V. Kravchuk,[4] N. V. Krasnikov,[4] S. V. Kuleshov,[11] V. E. Lyubovitskij,[10,11] V. Lysan,[2] V. A. Matveev,[2] Yu. V. Mikhailov,[9] D. V. Peshekhonov,[2] V. A. Polyakov,[9] B. Radics,[12] R. Rojas,[11] A. Rubbia,[12] V. D. Samoylenko,[9] V. O. Tikhomirov,[5] D. A. Tlisov,[4] A. N. Toropin,[4] A. Yu. Trifonov,[10] B. I. Vasilishin,[10] G. Vasquez Arenas,[11] and P. Ulloa[11]

(The NA64 Collaboration)

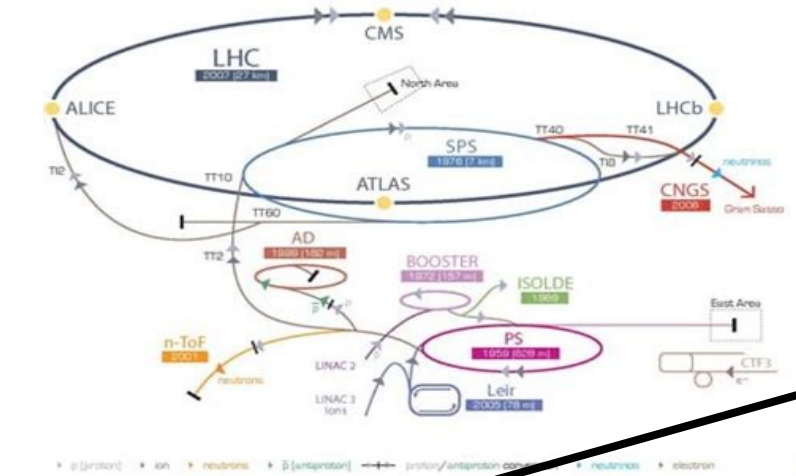
46 Researchers From 13 institutions!

Timeline

- Proposed in 2014
- 2015→ First test beam
- March 2016→ approved by CERN SPS as NA64
- Beam time:
  - 2016: 5 weeks
  - 2017: 5 weeks
  - 2018: 6 weeks

Sergei Gninenko
NA64 spokesperson

The NA64 setup – A' → $\chi\bar{\chi}$ search – the beam



100 GeV e^- beam Produced at the CERN SPS

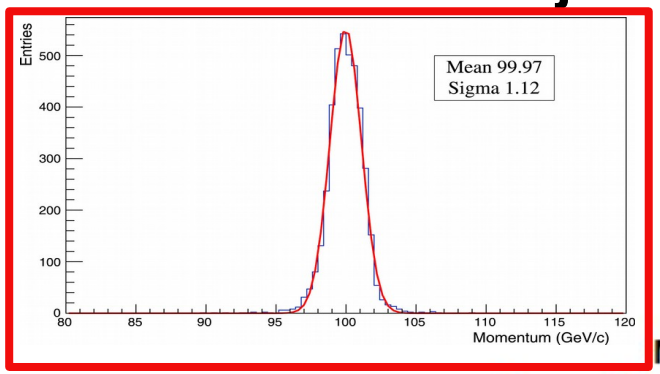
TRIGGER:
Three scintillator (S1-S2-S3) And one Veto to define the beam

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' → $\chi\bar{\chi}$ 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

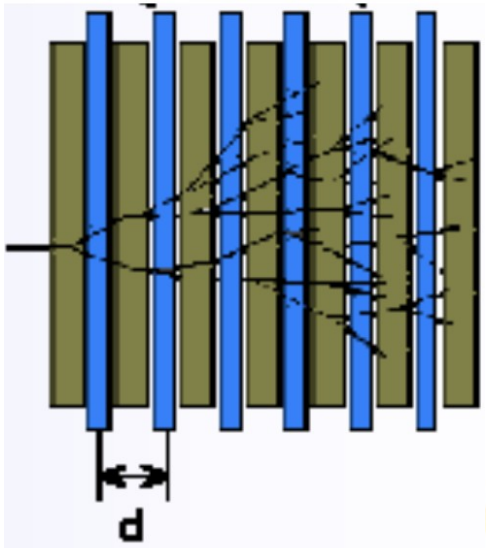
Tracking Detectors:
- 8 XY multiplexed Micromegas
- 4 GEM stations

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

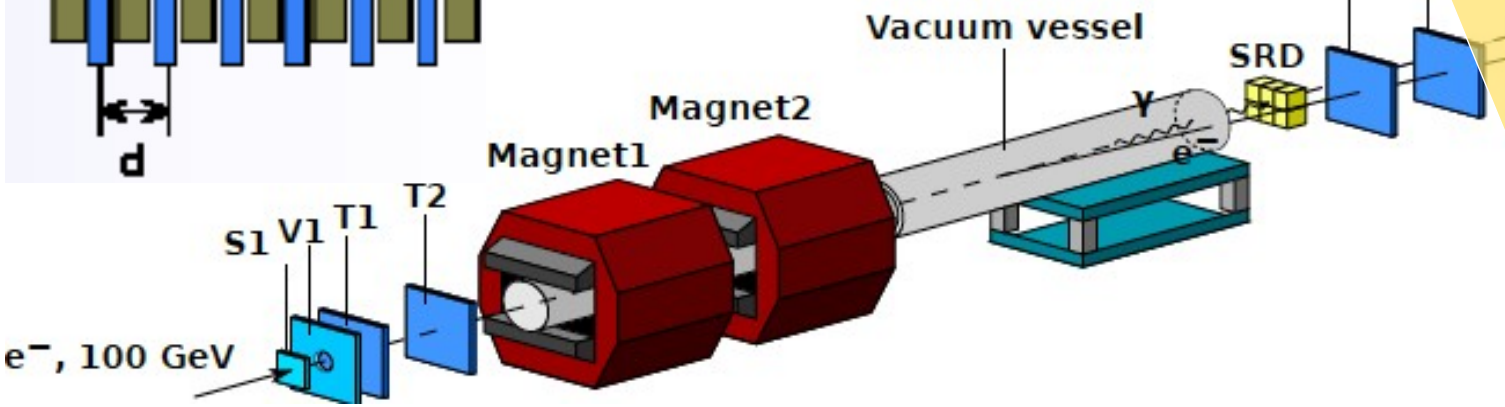
$$P \sim E^4/m^4$$

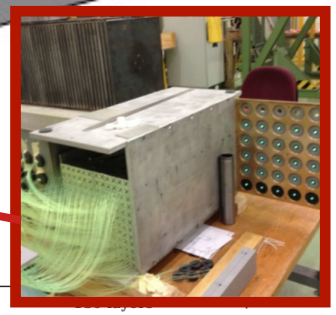
<10^{-5} achieved rejection

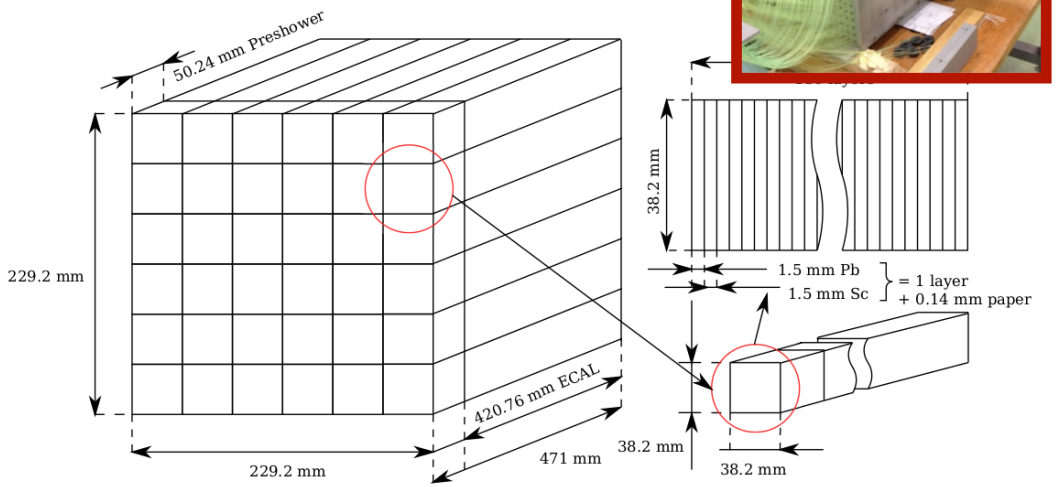
The NA64 setup – A' → χχ̄ search – the ECAL



- **ECAL**: Lead scintillator sandwich calorimeter to measure incoming energy





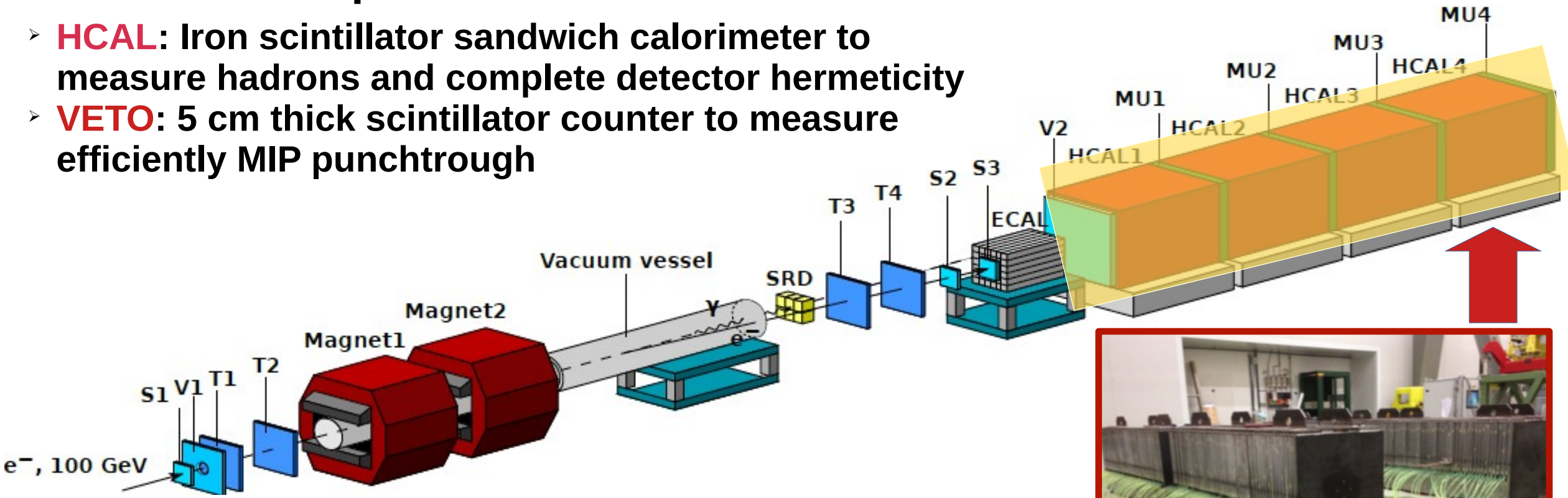


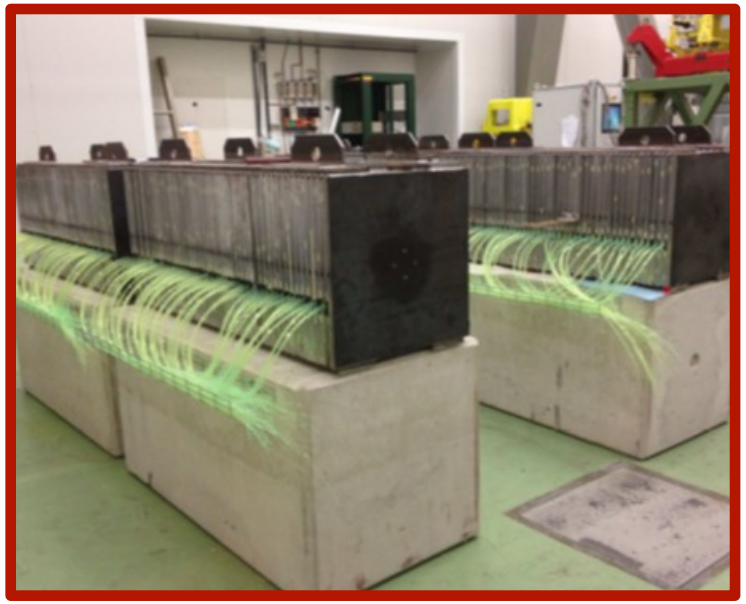
ECAL Characteristic

- 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' → $\chi\bar{\chi}$ 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



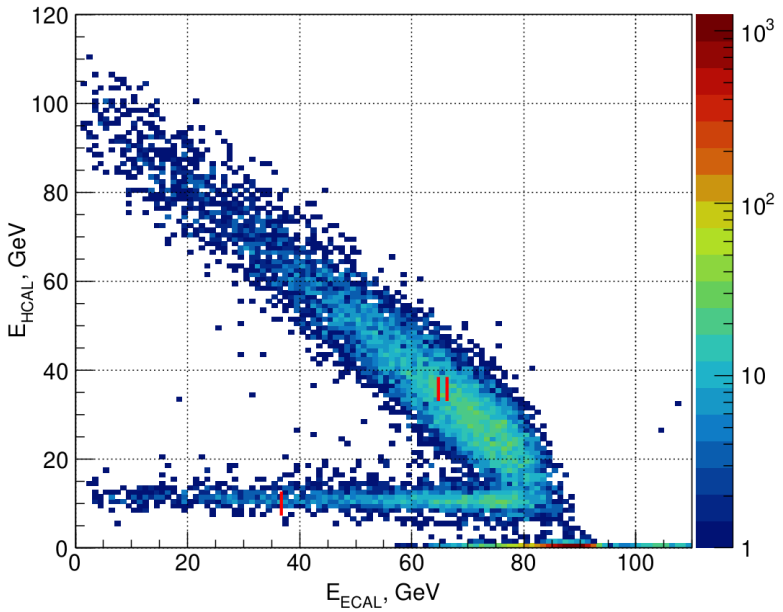


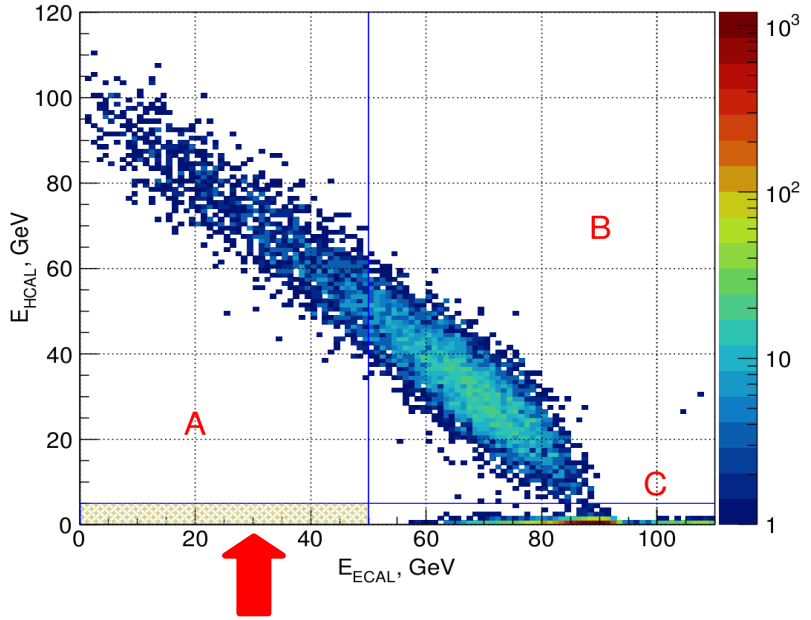
HCAL Characteristic

- 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' → $\chi\bar{\chi}$ search – in real life

Invisible searches – event selection and results





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

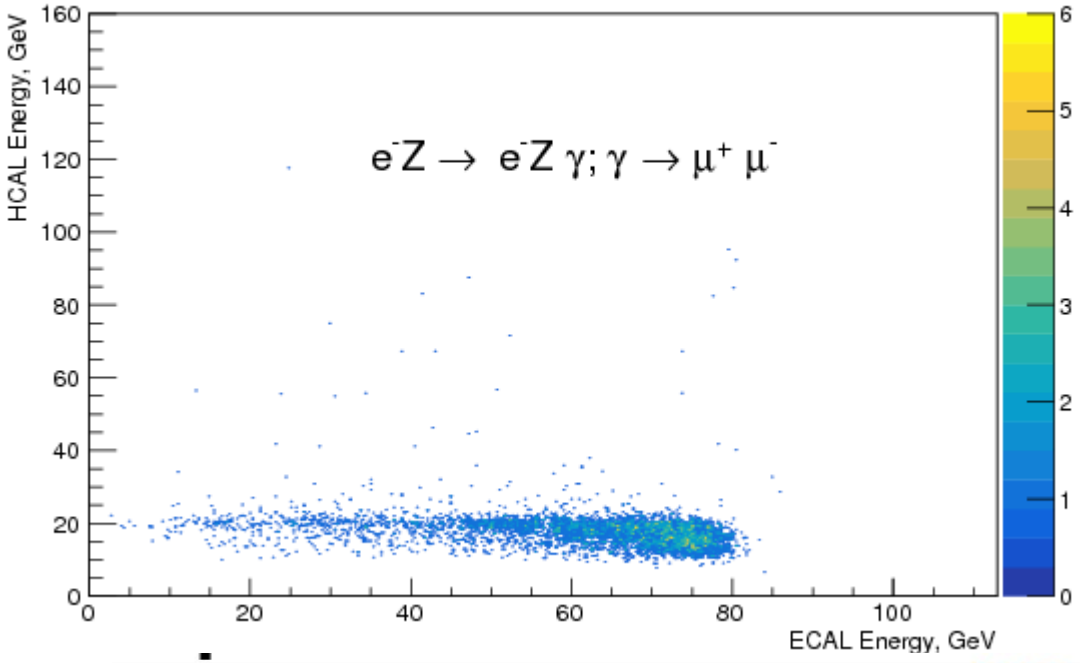
Control area:

- **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

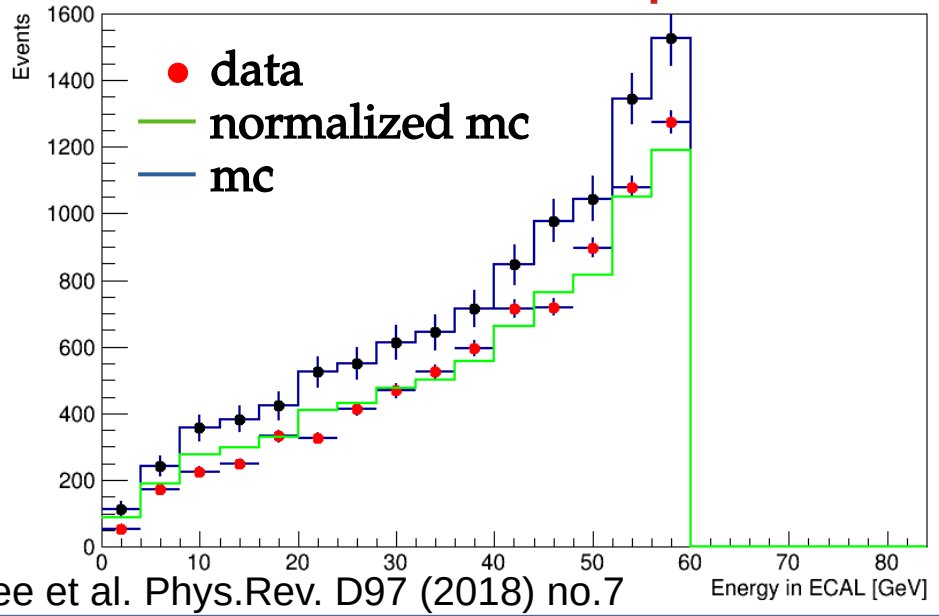
Invisible searches – dimuon events

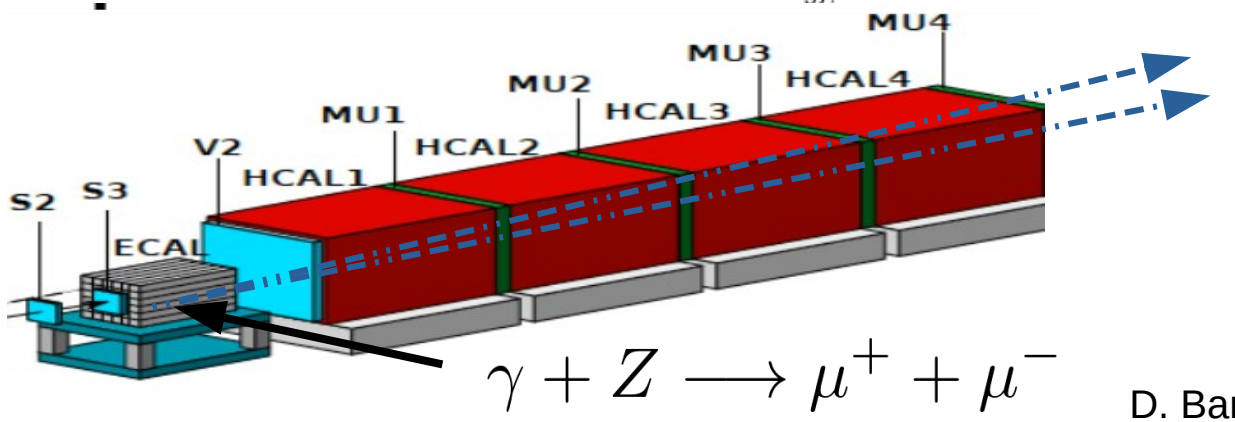


Dimuon events:

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

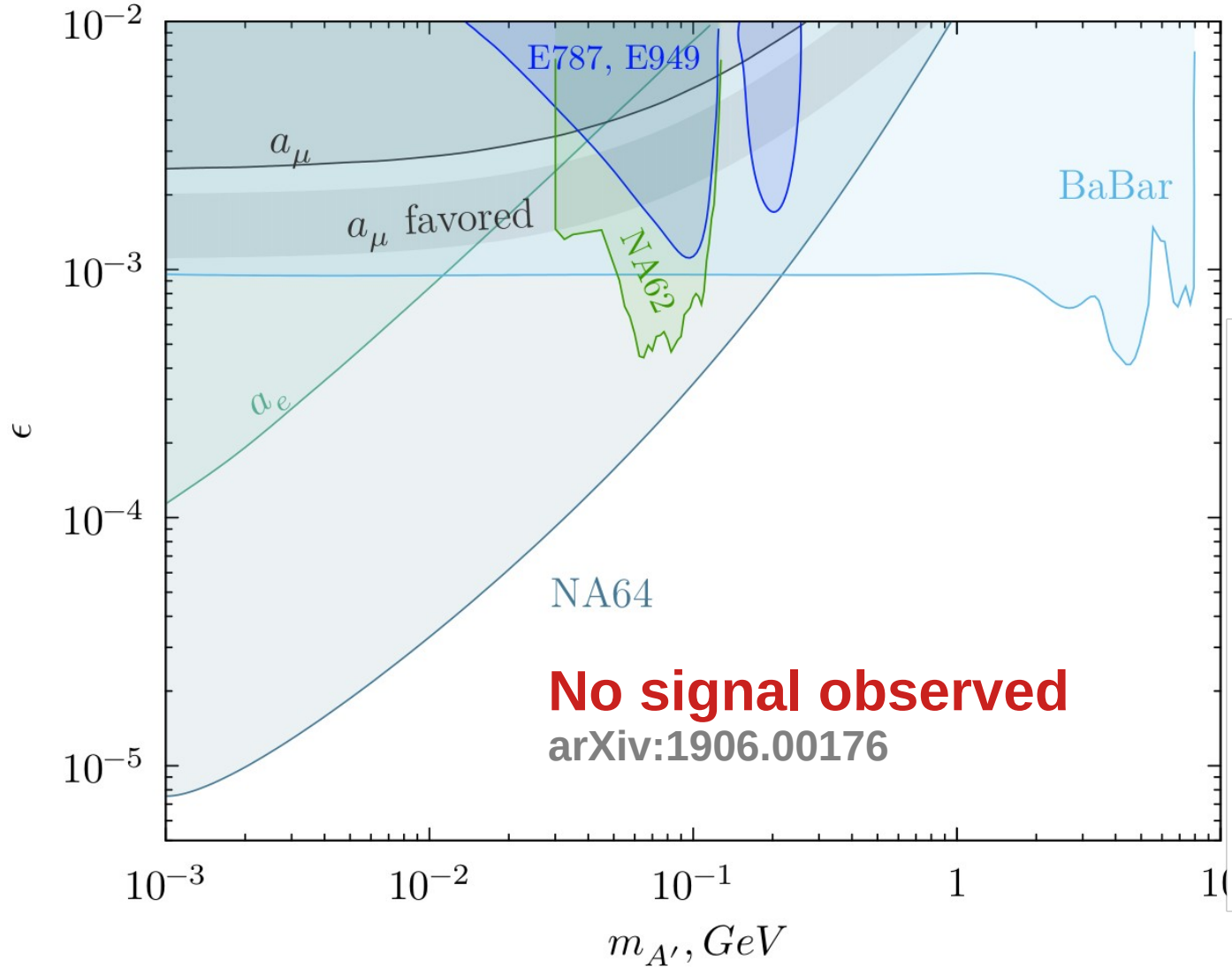
Excellent agreement with MC for ECAL spectrum



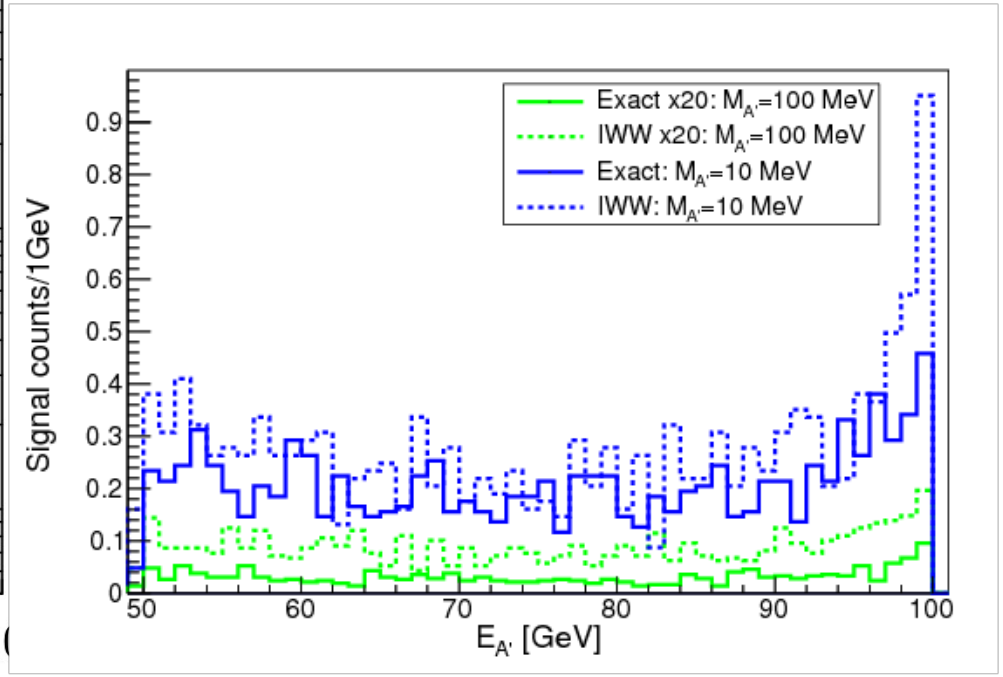


D. Banerjee et al. Phys.Rev. D97 (2018) no.7

Invisible searches – exclusion plot

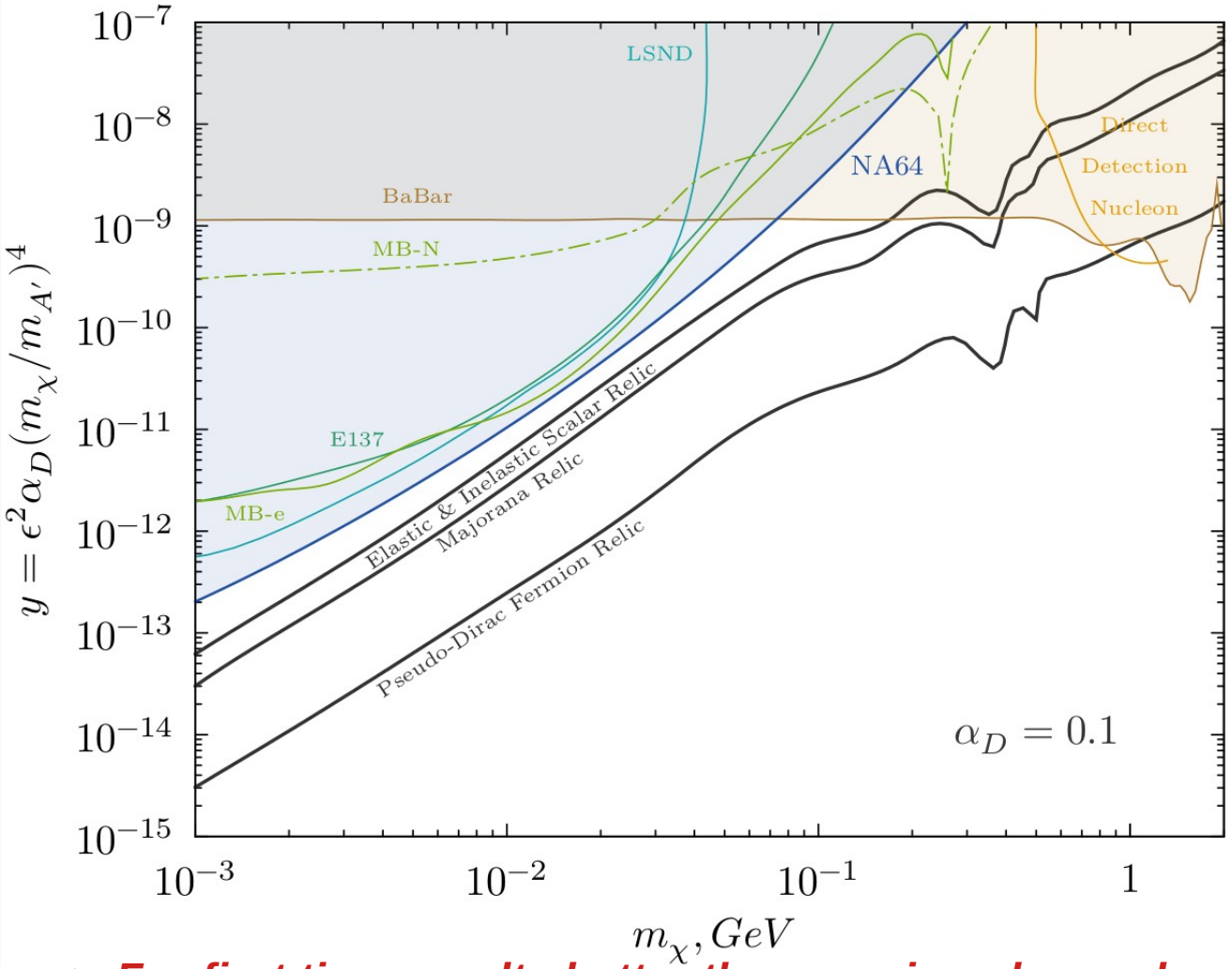


- **Signal yield calculated using Exact Tree Level integration of the cross section!**

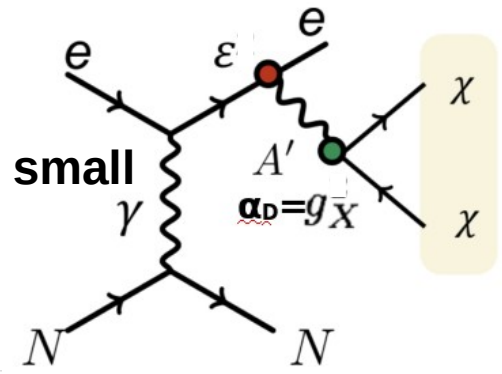


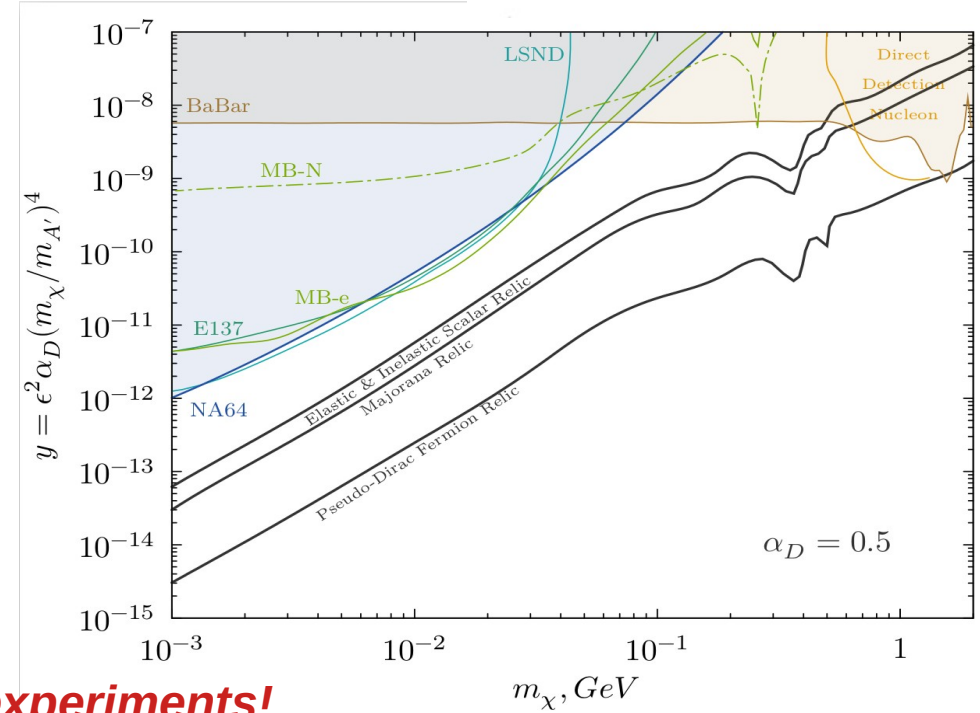
S. Gninenko et al. Phys.Lett. B782 (2018) 406-411

Invisible searches – constraint on light thermal matter



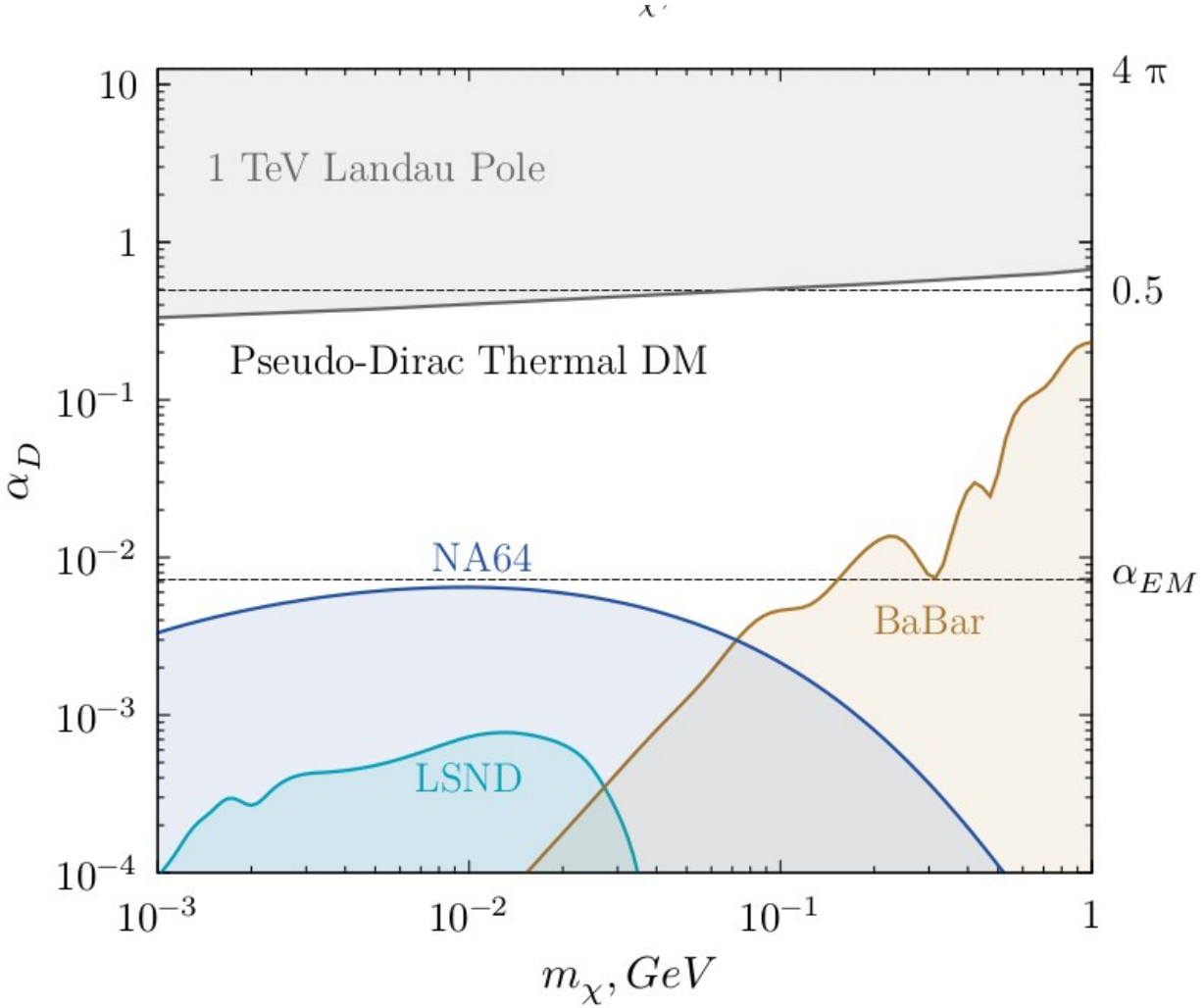
- Not dependent on g_x
- → Strong coverage for small coupling: scales as ε^2

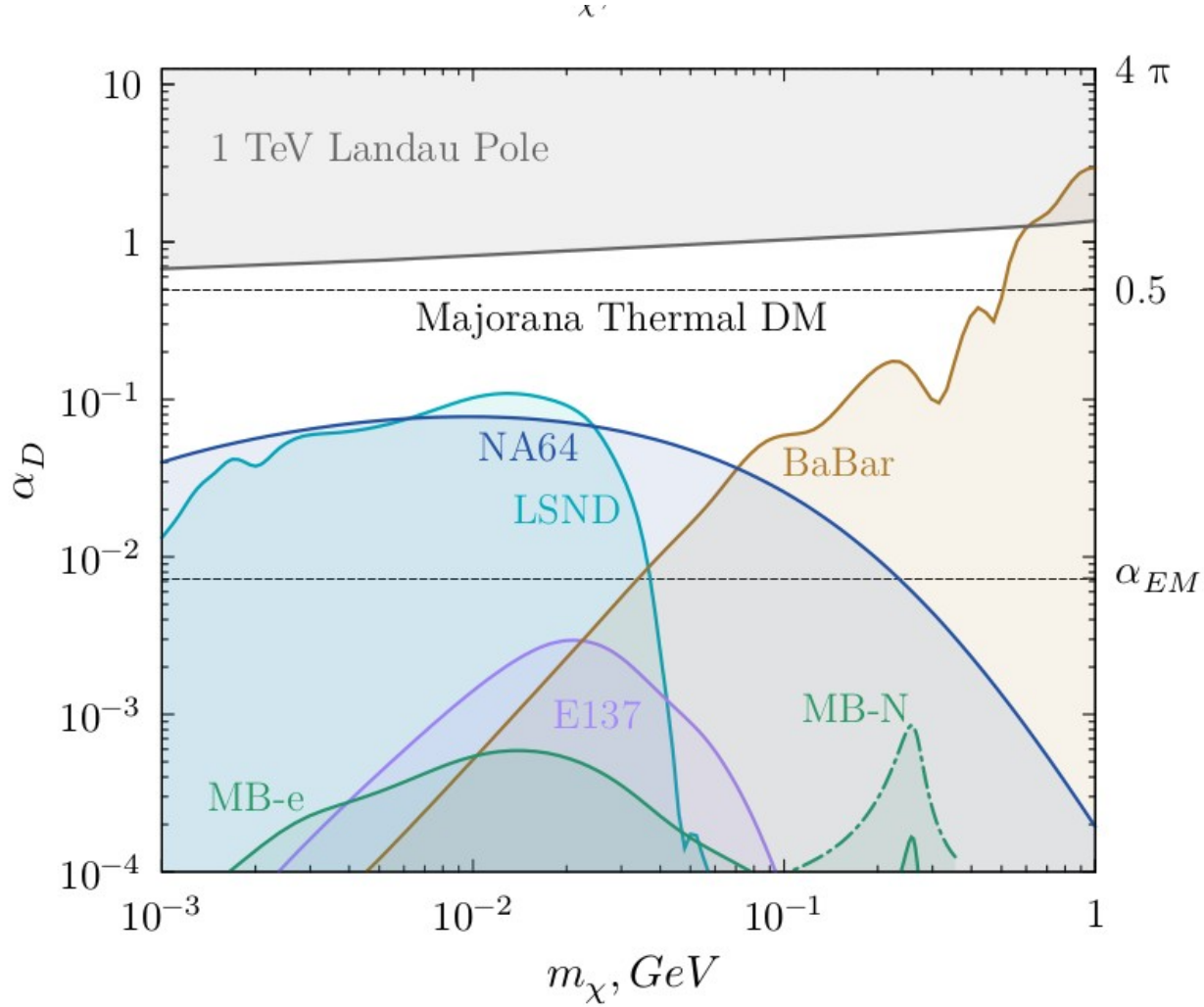




- ***For first time results better than previous beam dump experiments!***

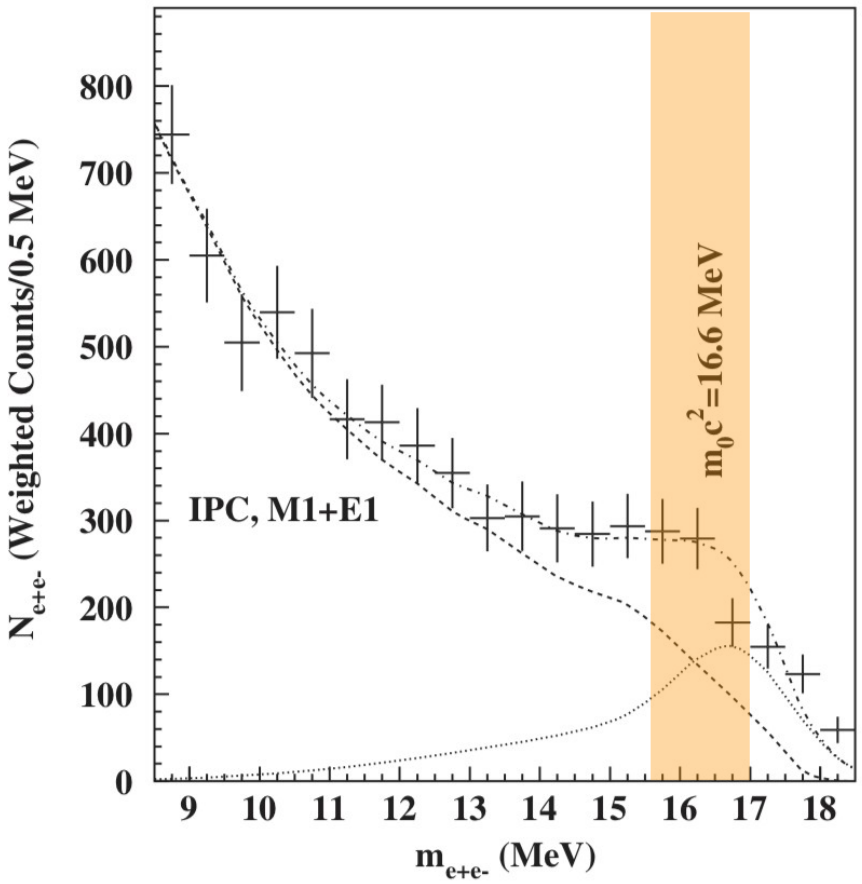
Pseudo-Dirac and Majorana Thermal Dark Matter





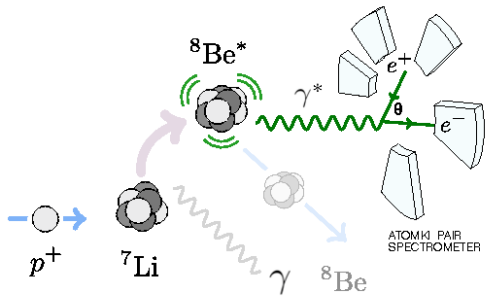
- ***For first time results better than previous beam dump experiments!***

Visible search – Light trough a wall experiment

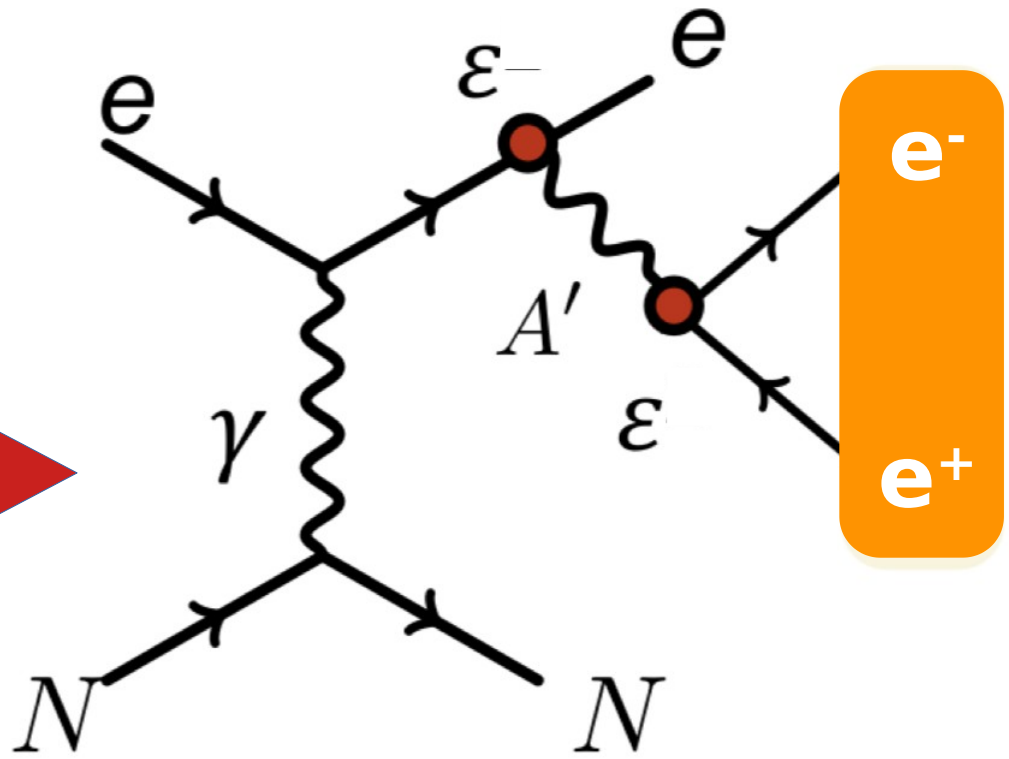


^{8}Be anomaly: a new 17 MeV X boson?

- NA64 visible mode setup has sensitivity over the anomaly



Visible mode

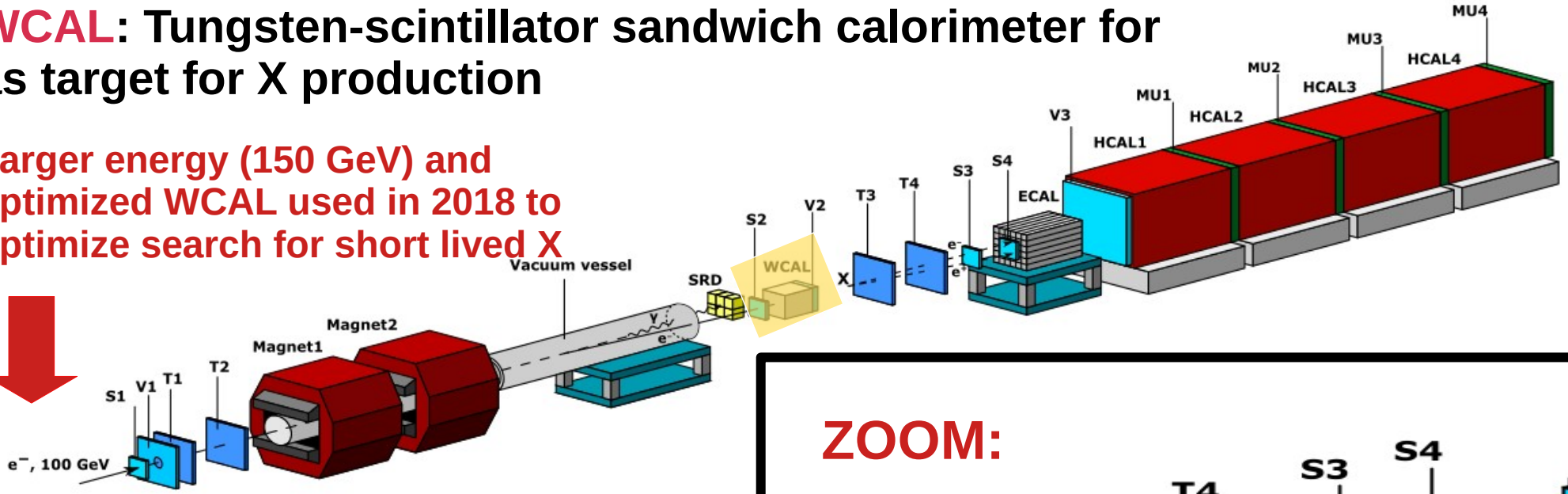


A. J. Krasznahorkay et al. Phys. Rev. Lett.116, 042501 (2015)

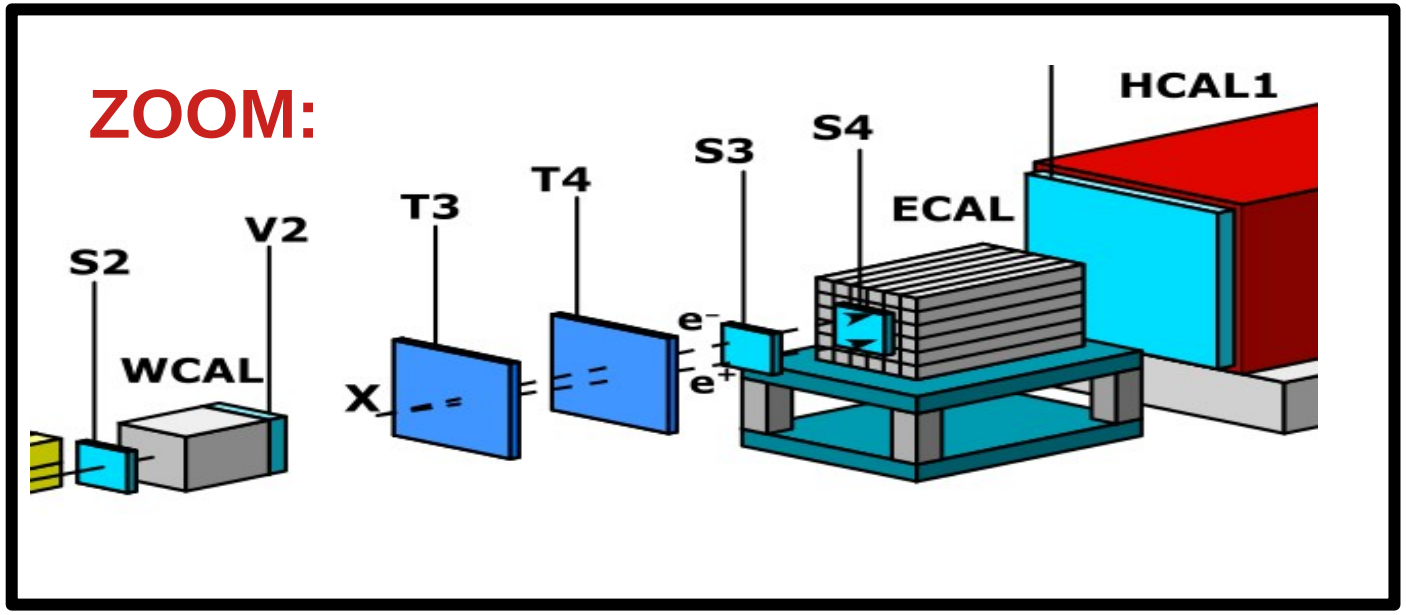
Visible search – Light trough a wall experiment

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

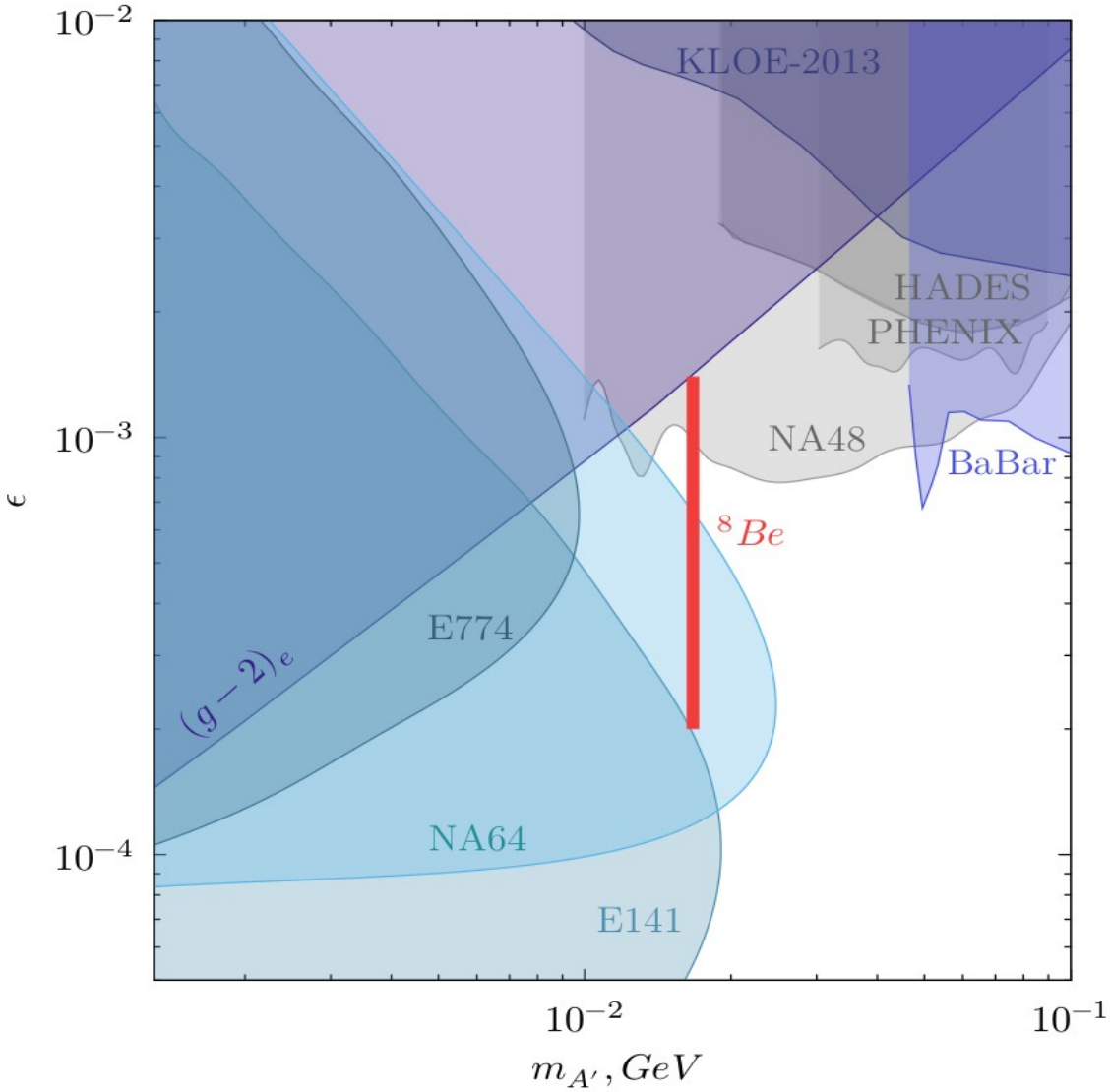
Larger energy (150 GeV) and optimized WCAL used in 2018 to optimize search for short lived X

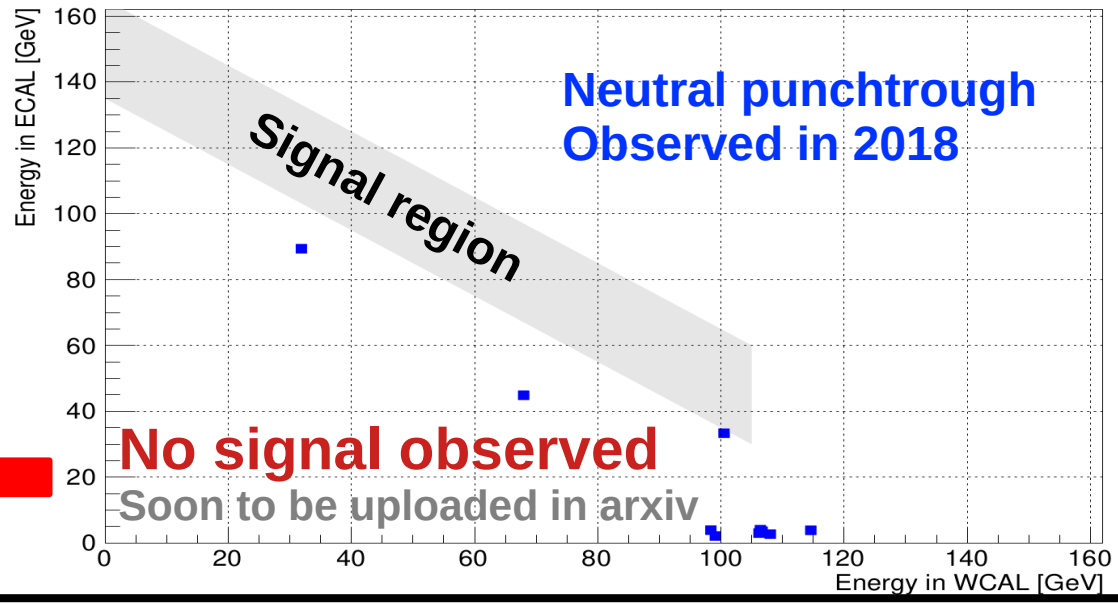


- Very compact ($30X_0$ in 17 cm) to allow detection of short lived X-boson
- V2 installed downstream to veto punchthrough
- 4 GEM station used for vertex reconstruction
- Vacuum pipe installed in 2018 to reduce background



Visible search – Results for 2016-2018 statistics





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

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)

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CERN

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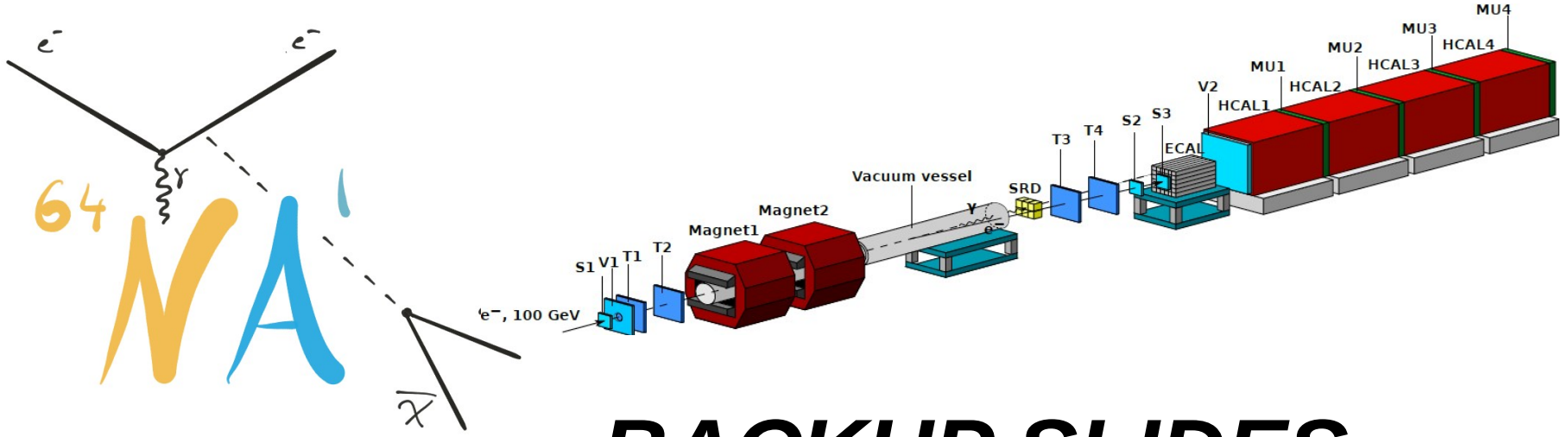
Signature of dark photons at fixed target experiment



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BACKUP SLIDES

IPA

ETH zürich

Constraint on ALPS

$10^{-4} < g_{ayy} < 10^{-2}$

$10 < m_a < 500$ MeV