



The NA64 Experiment at the CERN SPS

Accelerating LDM, bctp, Bonn, 01.10.2026

Paolo Crivelli, ETH Zurich, Institute for Particle Physics and Astrophysics on behalf of NA64 collaboration

Motivation to search for dark sectors

- Light, weakly coupled particles provide an alternative to heavy new physics and can address several open questions beyond the Standard Model.

$$\mathcal{L}_{\text{EFT}} = m_H^2 H^\dagger H + \mathcal{L}_{\text{SM}, \dim 4}(A, \psi, H) + \sum_{n \geq 5} \frac{1}{\Lambda^{n-4}} \mathcal{O}_{\text{SM}, \dim n}^{(n)}(A, \psi, H) + \mathcal{L}_{\text{portals}}(\psi, A, H; \varphi_{\text{DS}}) + \mathcal{L}_{\text{DS}}(\varphi_{\text{DS}}).$$

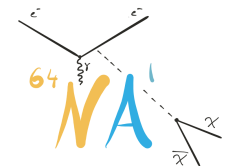
Heavy new physics

Light new fields

$$\mathcal{L}_{\text{portal}} = \sum \mathcal{O}_{\text{SM}} \times \mathcal{O}_{\text{DS}}$$

φ_{DS}	Portal	Coupling
Vector: Dark Photon, A'		$-\frac{\varepsilon}{2 \cos \theta_W} F'_{\mu\nu} B^{\mu\nu}$
Scalar: Dark Higgs, S		$(\mu S + \lambda_{\text{HS}} S^2) H^\dagger H$
Fermion: Heavy Neutral Lepton, N		$y_N L H N$
Pseudo-scalar: Axion, a		$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}, \frac{a}{f_a} G_{i,\mu\nu} \tilde{G}_i^{\mu\nu}, \frac{\partial_\mu a}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi$

For more details see excellent talks from Kai and Patrick



10th anniversary of NA64

CERN COURIER | Reporting on international high-energy physics

Physics ▾

Technology ▾

Community ▾

Magazine

DARK UNIVERSE | FEATURE

Ten years at the missing-energy frontier

23 July 2026

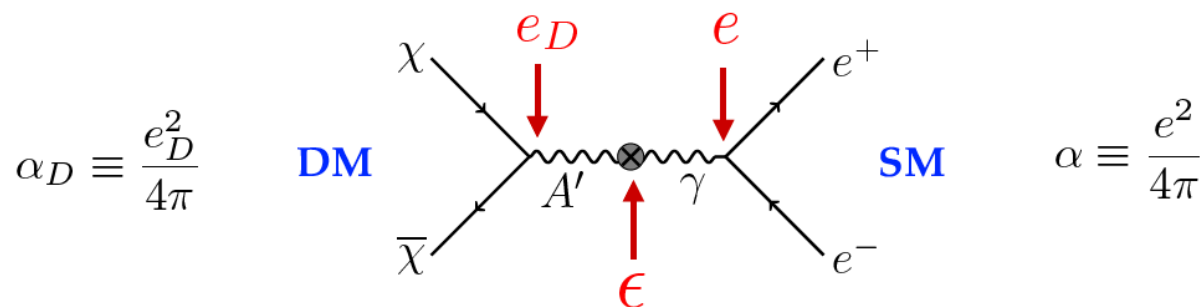
If dark matter couples feebly enough to evade direct detection, it may still betray itself by stealing energy from a beam. Paolo Crivelli, Laura Molina-Bueno and Sergei Gninenko look back on 10 years of NA64, the CERN experiment that puts this principle to work.

NA64 timeline

- Proposal submitted to arXiv 2013
- Proposal to CERN SPSC 2014
- First test beam 2015
- Approval CERN RB March 2016 as the 64th experiment in the North Area



10 years searching for the vector portal & Light Dark Matter at NA64



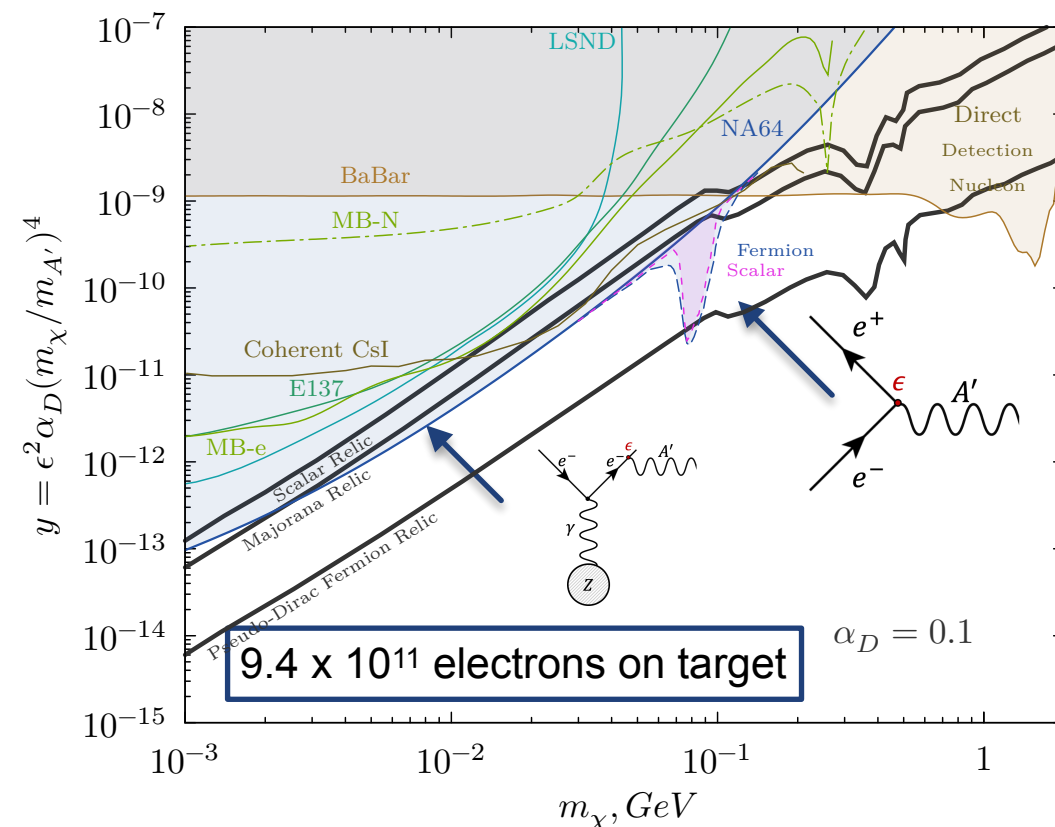
In this framework DM can be produced thermally in the early Universe

OBSERVED **AMOUNT OF DARK MATTER** TODAY $\Omega_X \propto \frac{1}{\langle v\sigma \rangle} \sim \frac{m_X^2}{y}$

WHERE $y = \epsilon^2 \alpha_D \left(\frac{m_X}{m_{A'}} \right)^4$

y parameter

NA64 latest results on LDM



MASS OF DARK MATTER

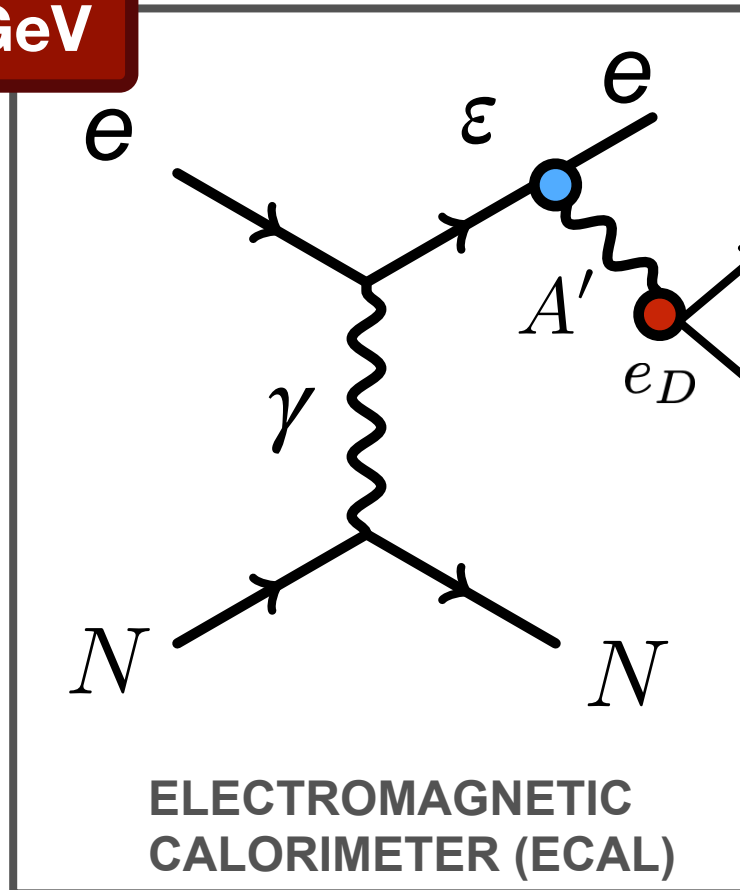
NA64 collaboration, Phys. Rev. Lett. 131, 161801 (2023), editor suggestion

J. Feng and J. Kumar Phys.Rev.Lett.101:231301,2008

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

TAGGED 100 GeV

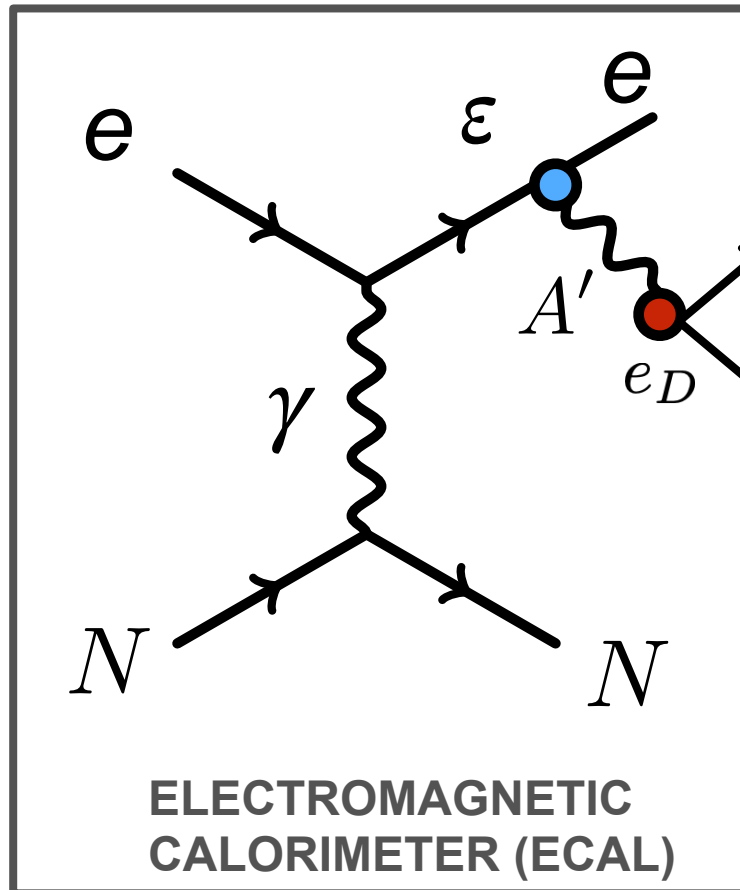
Active Dump



Requested ECAL ENERGY < 50 GeV

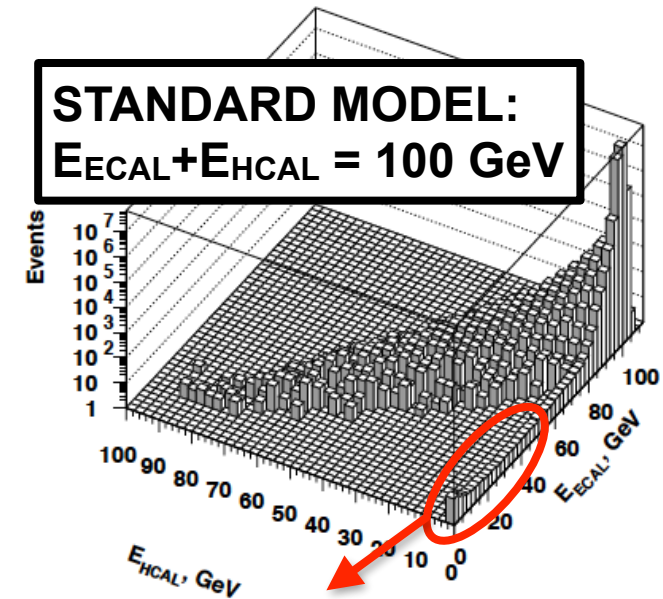
“BREMSSTRAHLUNG” OF A'

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



HADRONIC CALORIMETER (HCAL)

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

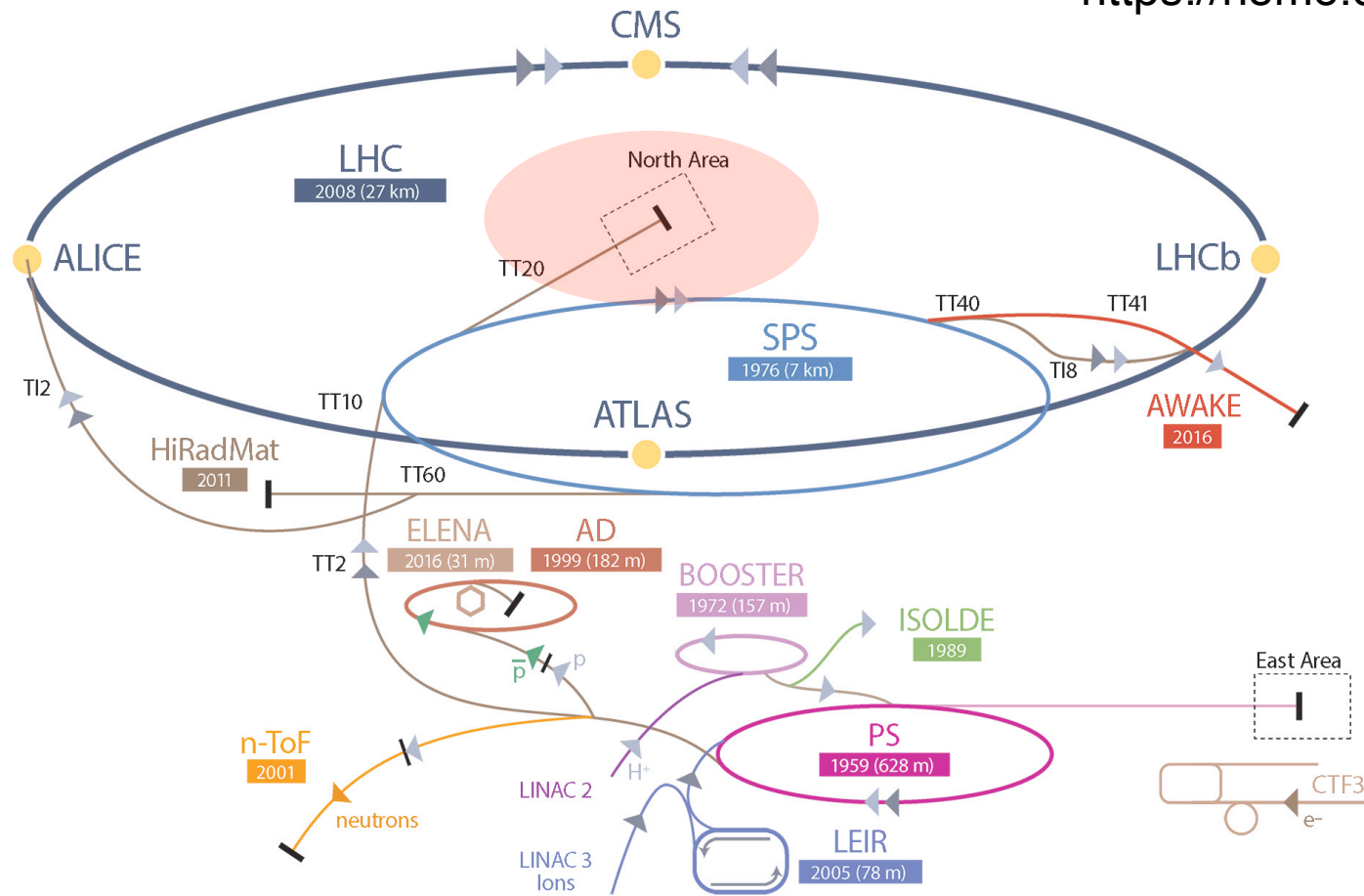


$A' \rightarrow$ MISSING ENERGY:
 $E_{\text{ECAL}} < 50 \text{ GeV}$
 $E_{\text{HCAL}} < 2 \text{ GeV}$

Where do we get 100 GeV particles?

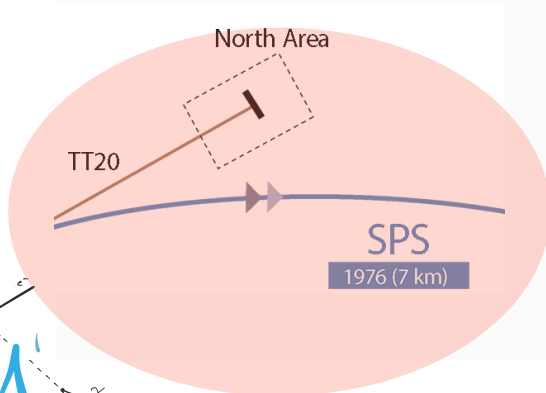
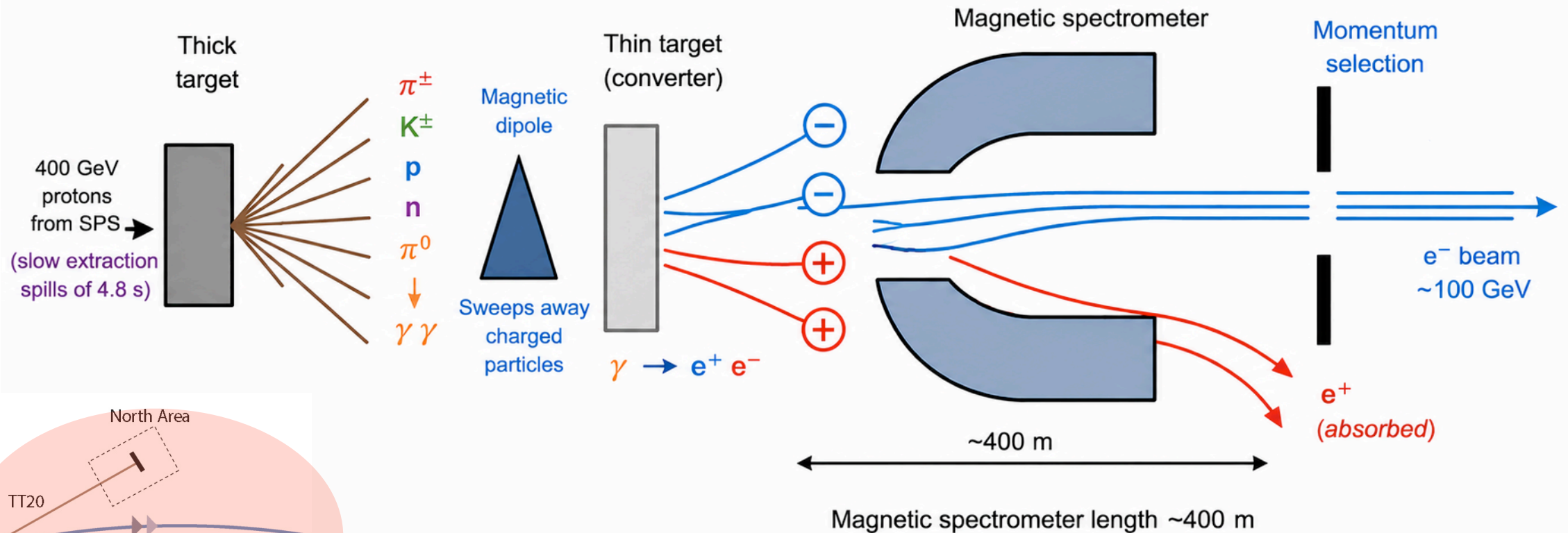
CERN's Accelerator Complex

<https://home.cern/science/accelerators>

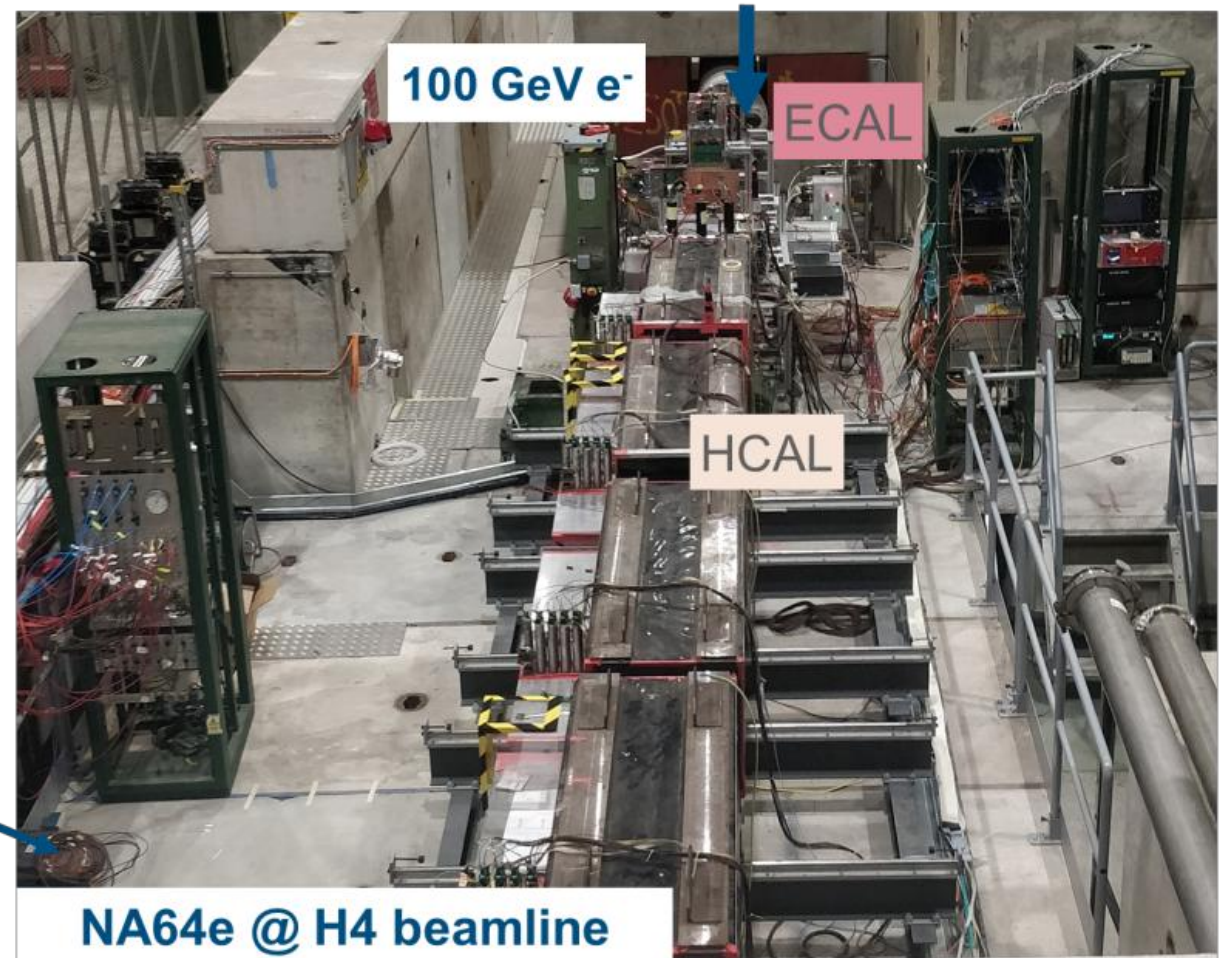
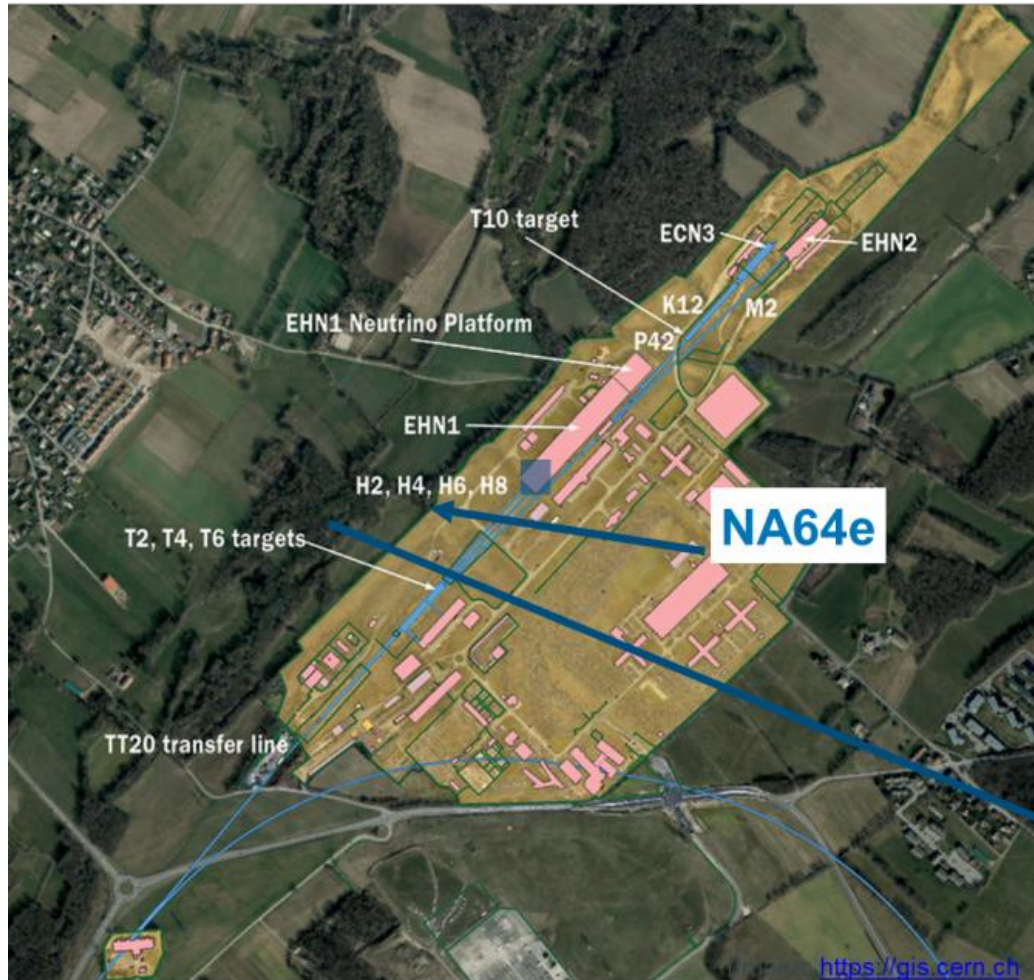


► p (proton) ► ion ► neutrons ► $\bar{p}$ (antiproton) ► electron ► $\leftrightarrow$ proton/antiproton conversion

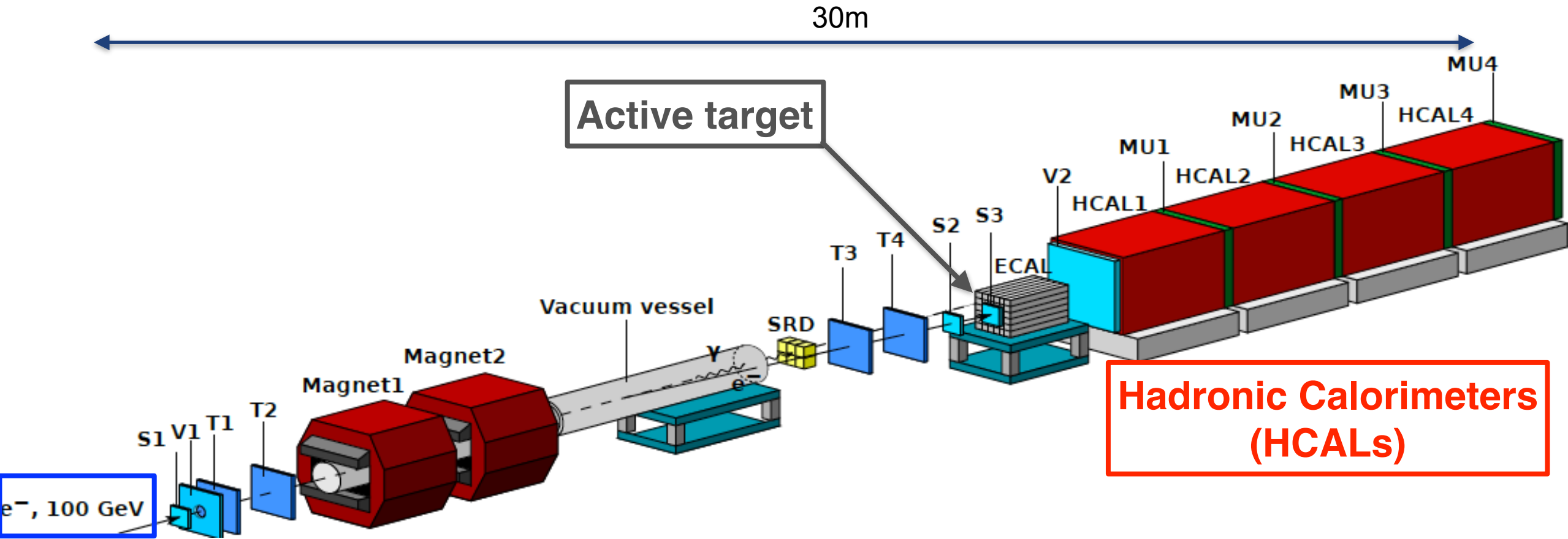
The high energy (50-150 GeV) SPS secondary beam lines in the CERN North Area



The NA64 experiment at the H4 beam line



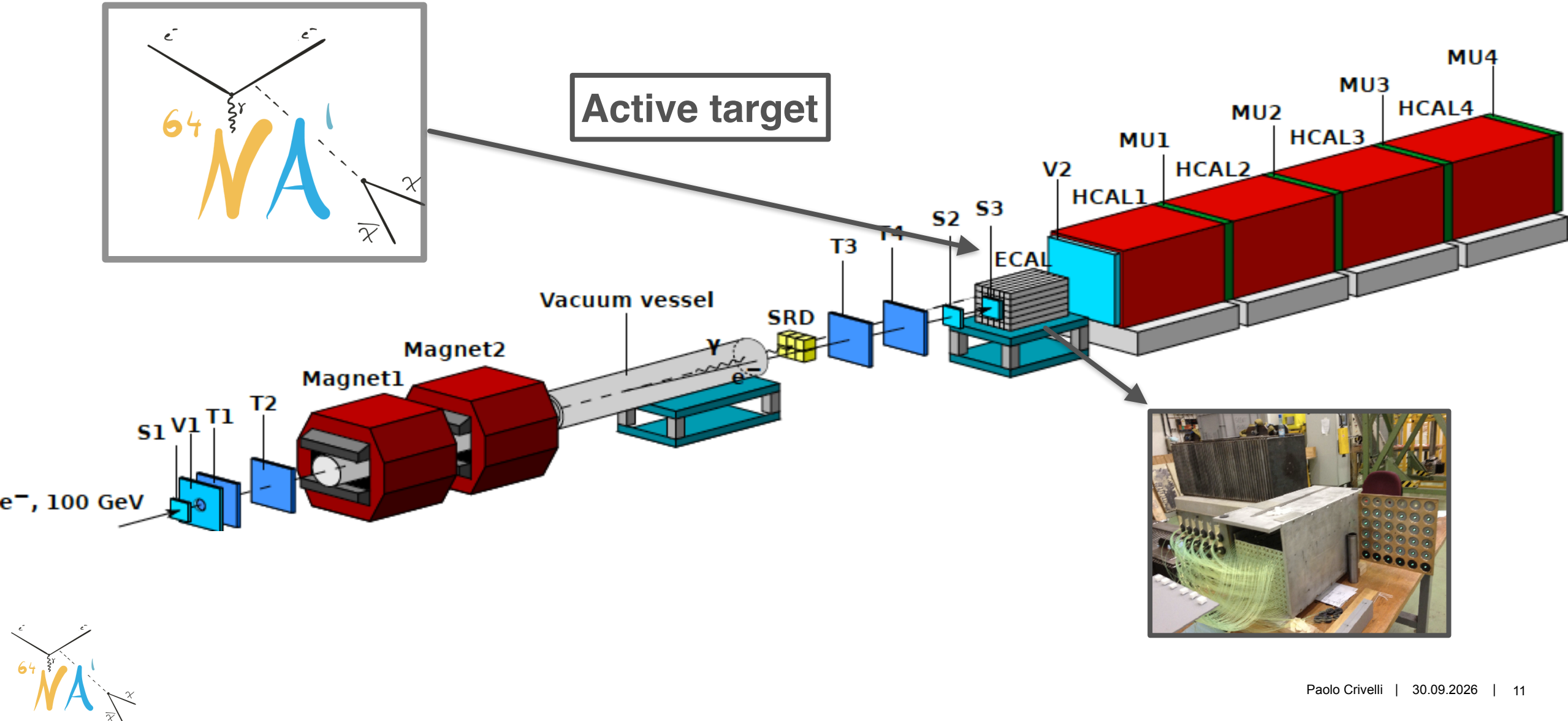
The NA64 detector



Hadronic Calorimeters (HCALs)

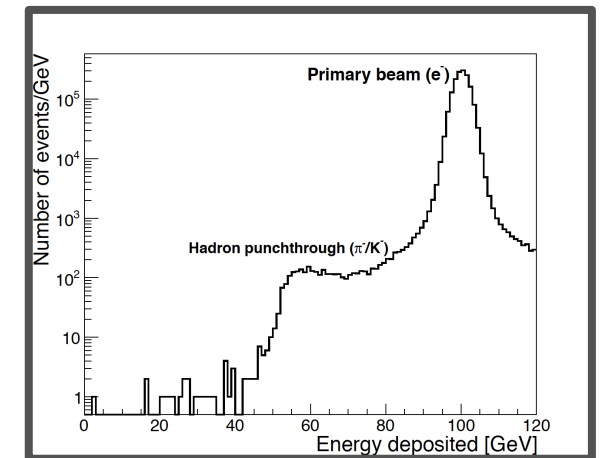
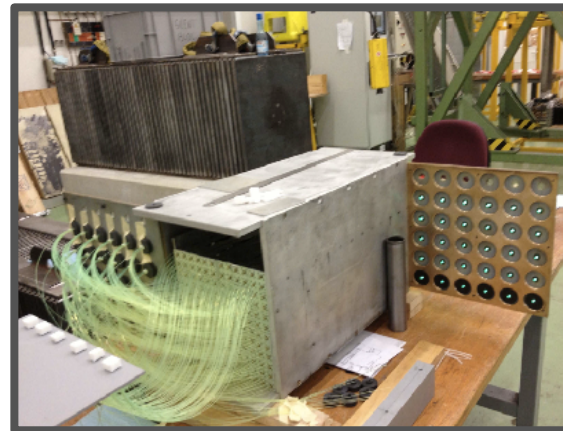
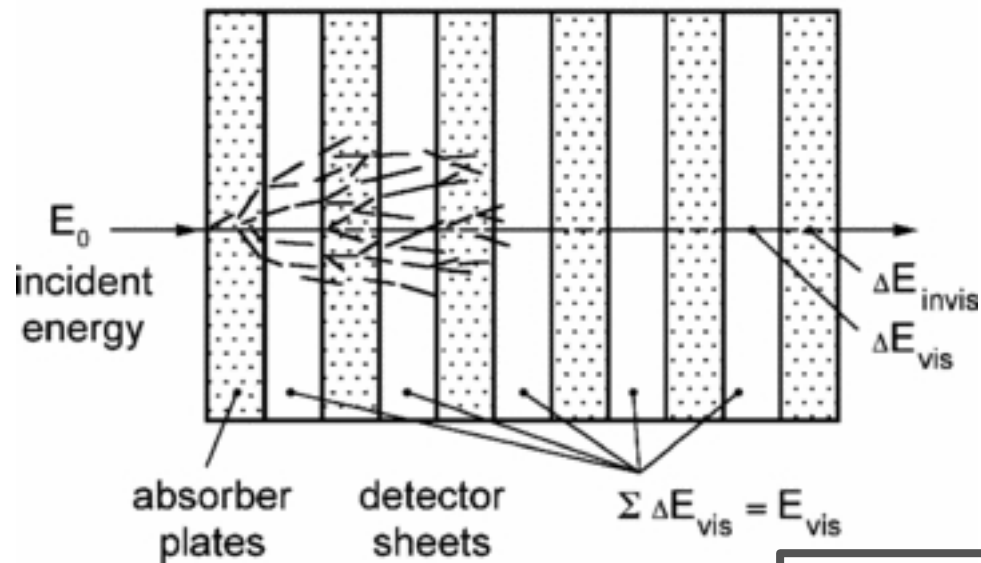
Tagged 100 GeV electrons

The Electromagnetic Calorimeter (ECAL)



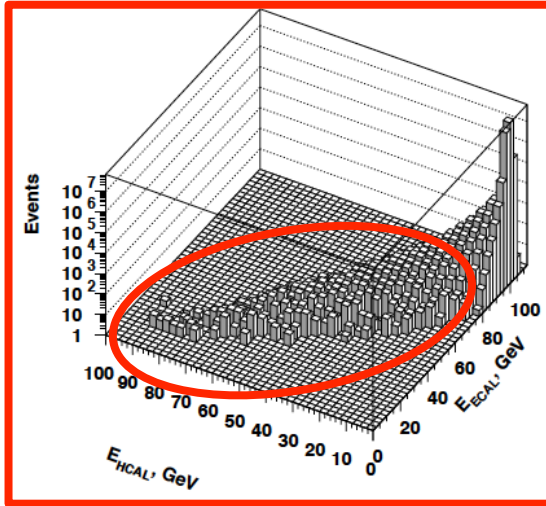
The Electromagnetic Calorimeter (ECAL)

$$\Sigma \Delta E_{\text{invis}} + \Sigma \Delta E_{\text{vis}} = E_{\text{invis}} + E_{\text{vis}} = E_{\text{absorbed}}$$

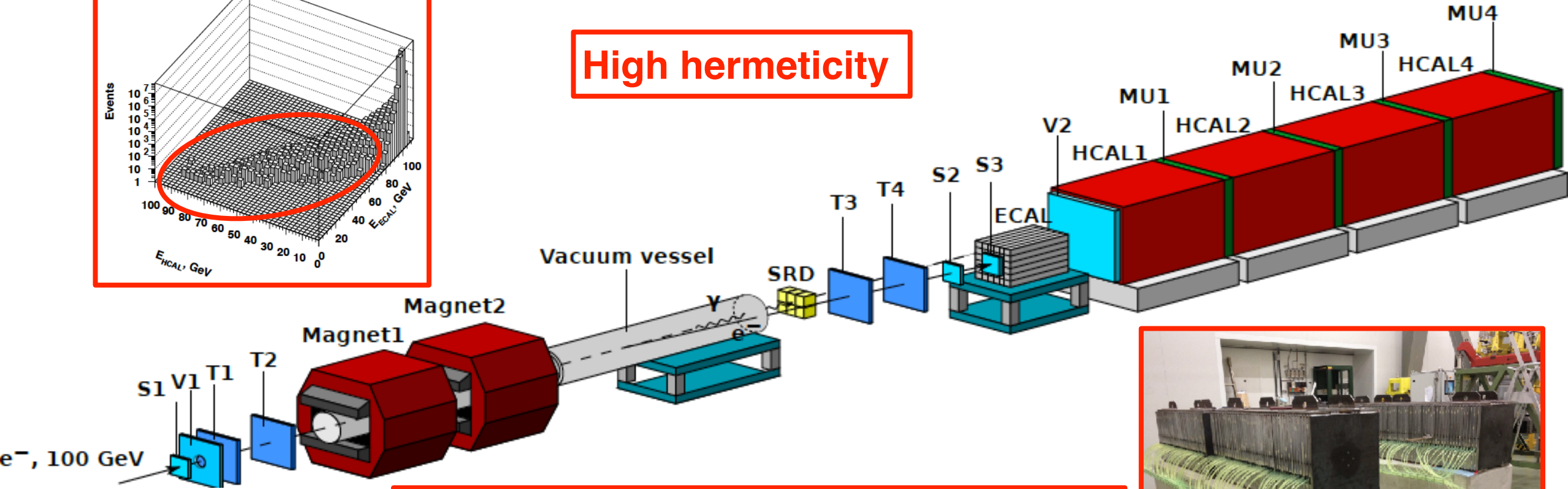


- ♦ High hermeticity ($\sim 40 X_0$)
- ♦ PbSc sandwich, 6x6 matrix, cells 38x38x490 mm³
- ♦ WLS fibers in spiral $\rightarrow$ suppress energy leaks
- ♦ Energy resolution $\sim 9\%/\sqrt{E[\text{GeV}]}$
- ♦ Longitudinal (Pre-shower) and lateral segmentation $\rightarrow$ shower profiles (hadron rejection)

The Hadronic Calorimeter (HCAL)



High hermeticity



- ♦ High hermeticity : 4 HCAL ($\sim 7 \lambda$ /module)
- ♦ FeSc sandwich 3x3 matrix, cells $19.4 \times 19.2 \times 150 \text{ cm}^3$
- ♦ WLS fibers in spiral $\rightarrow$ suppress energy leaks
- ♦ Energy resolution $\sim 60\%/\sqrt{E[\text{GeV}]}$

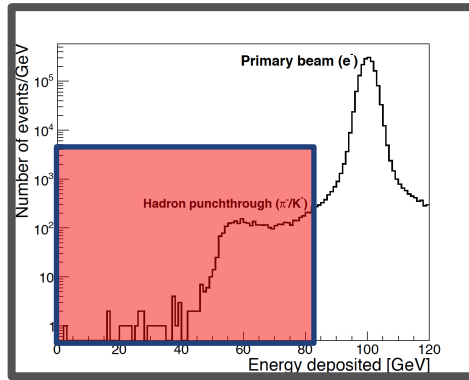
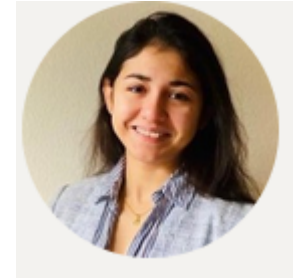


The magnetic spectrometer

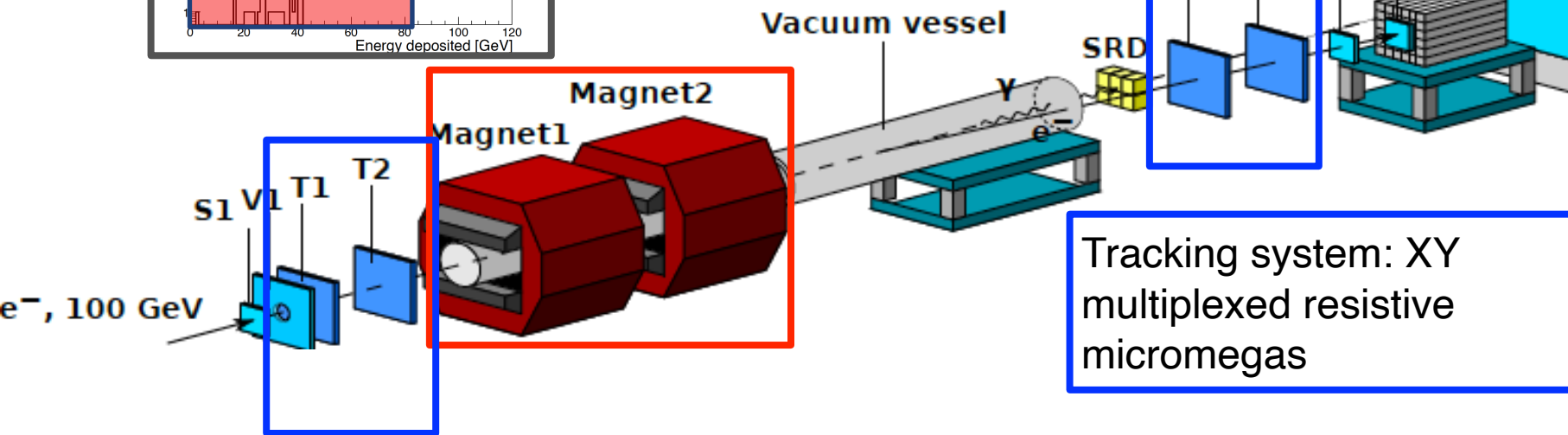
D. Banerjee et al., Advances in HEP, 105730 (2015)

D. Banerjee, PhD Thesis, ETH Zurich (2017)

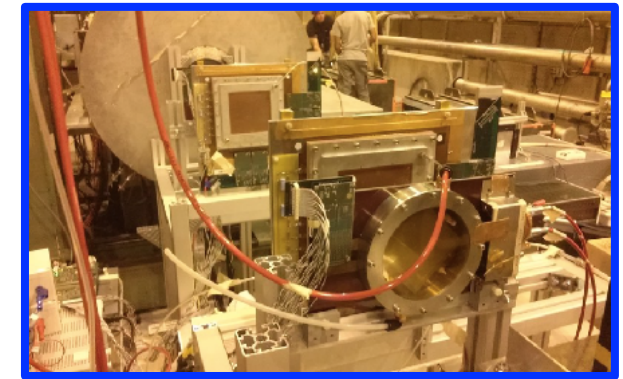
D. Banerjee et al., NIMA881 72-81 (2018)



Reconstruction of e^- incoming momentum

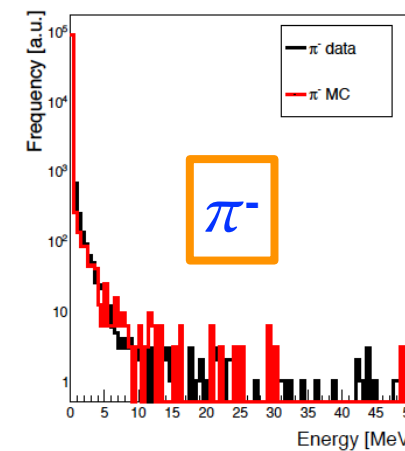
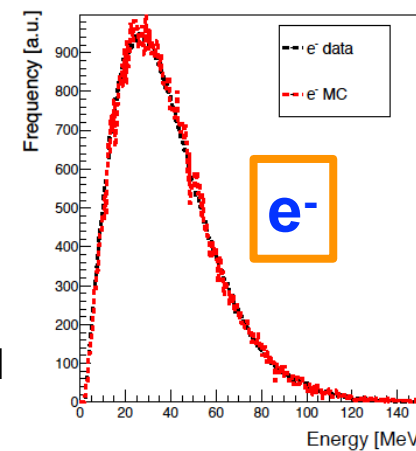
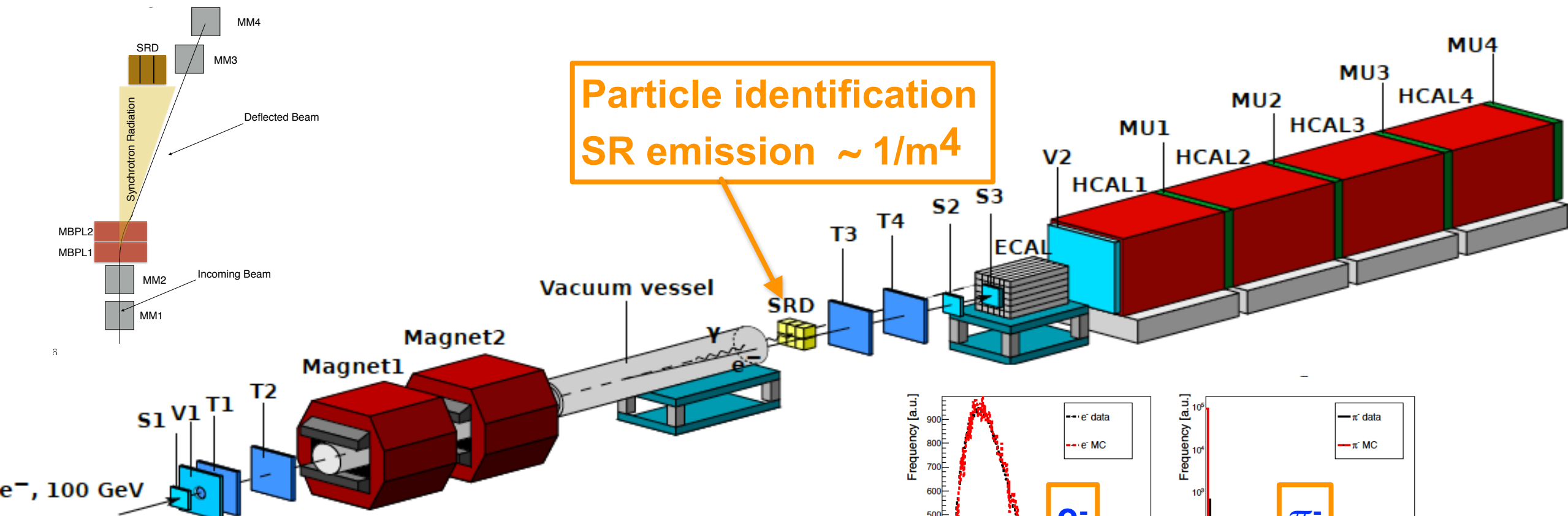


Tracking system: XY multiplexed resistive micromegas



Two bending magnets in series $\rightarrow$ 7 T.m field

The Synchrotron Radiation (SR) detector

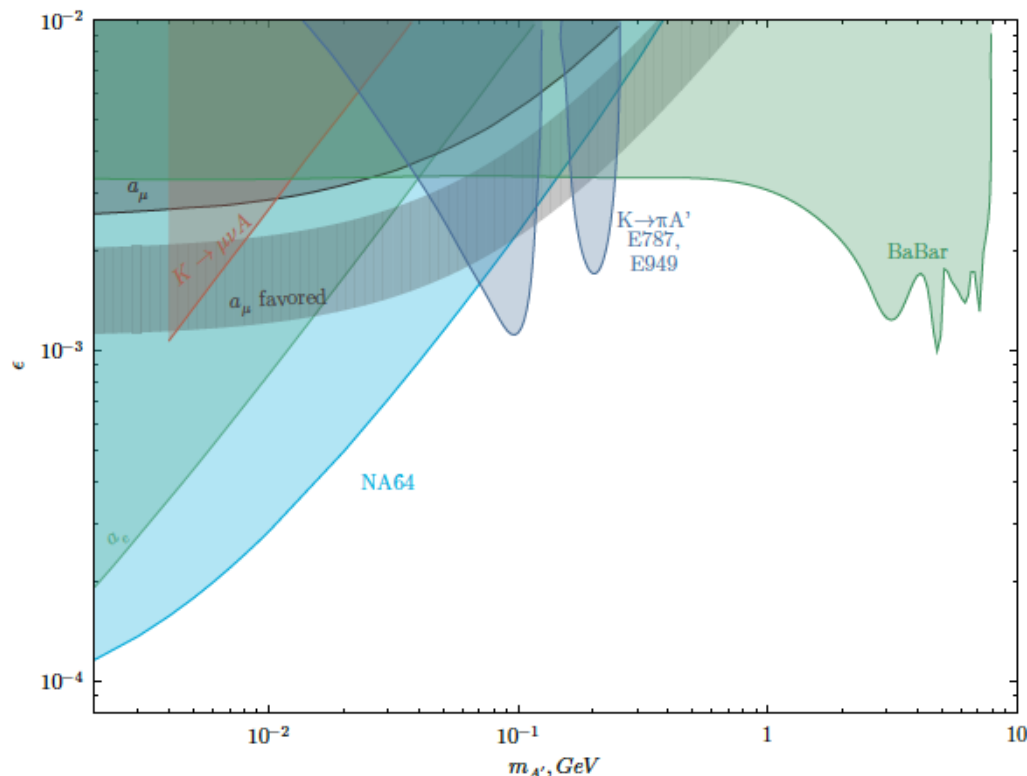


E. Depero et al., NIMA 866 (2017) 196-201 and
E. Depero, PhD thesis, ETH Zurich (2020).

Our first result $A' \rightarrow \chi\bar{\chi}$ - results (July 2016, 2 weeks)

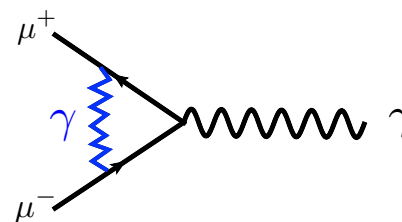
2.75 x 10⁹ electrons on target

COUPLING ϵ



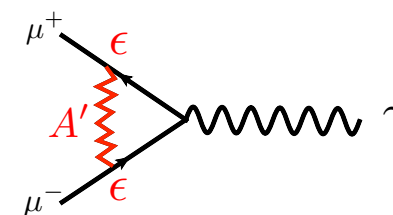
MASS OF THE DARK PHOTON

SM



$$(g_s - 2)_\mu^\gamma \simeq \frac{\alpha}{2\pi} \simeq 10^{-3}$$

DM



$$(g_s - 2)_\mu^{A'} \simeq \frac{\alpha}{2\pi} \times \epsilon^2 \quad (m_{A'} \ll m_\mu) \simeq 10^{-3} \times \epsilon^2$$

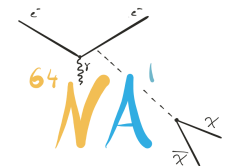
M. Pospelov, A. Ritz and M. B. Voloshin, PLB 662, 53 (2008)

After unblinding no event in the signal region
→ exclusion of most of g-2 muon favored region

NA64 collaboration, Phys. Rev. Lett. 118, 011802 (2017)

g-2 closed completely by BABAR results

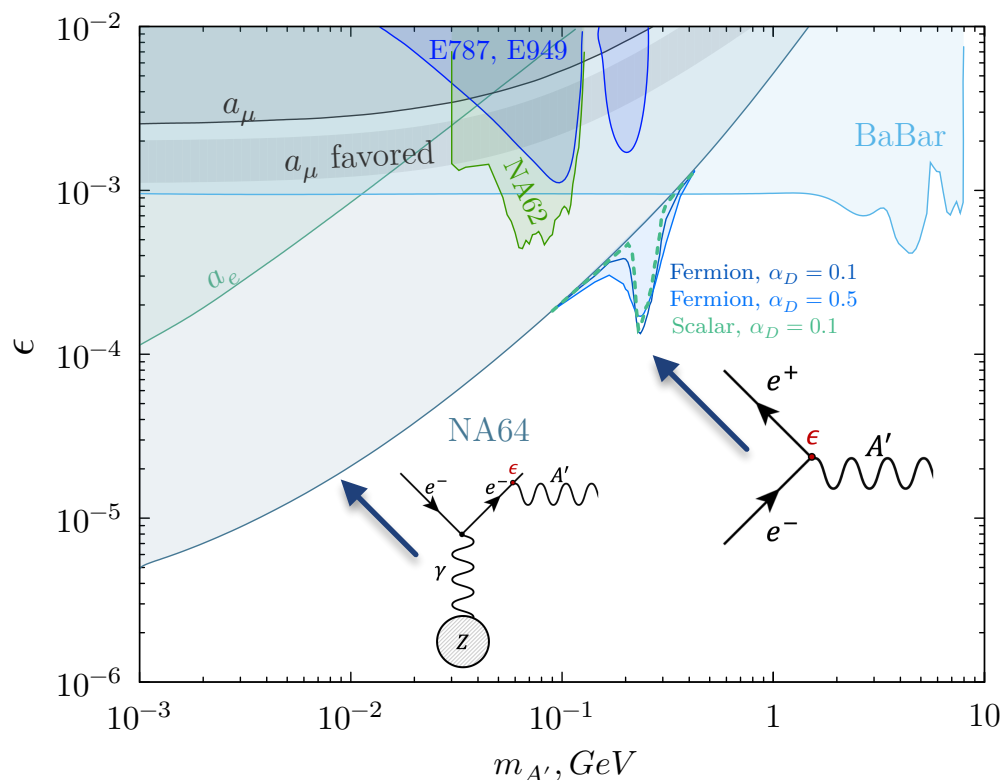
BABAR collaboration, Phys. Rev. Lett. 119, 131804 (2017)



NA64 LDM latest results (2016-2022)

9.4 x 10¹¹ electrons on target

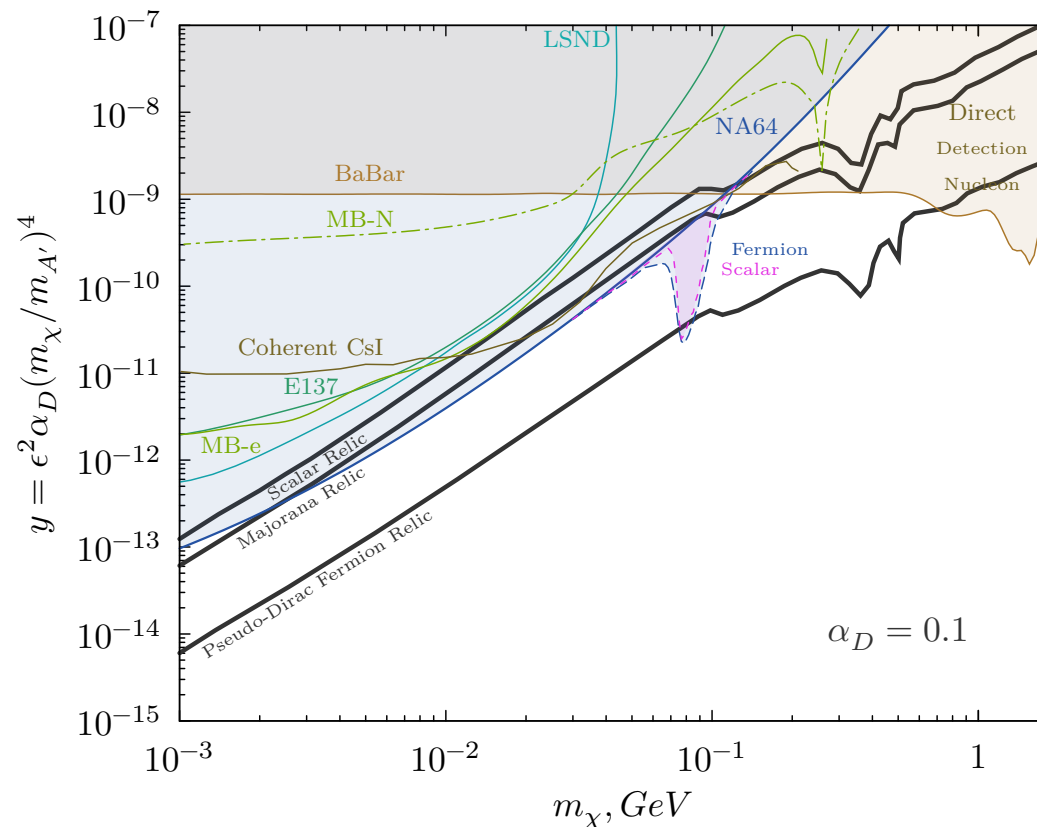
COUPLING ϵ



MASS OF THE DARK PHOTON

y parameter

NA64 results on LDM



MASS OF DARK MATTER

NA64 collaboration, Phys. Rev. Lett. 131, 161801 (2023), editor suggestion

NA64 from electrons to positrons, muons and hadrons

Multi-pronged approach possible due to the unique SPS versatility!

■ NA64e, NA64e+ (H4 beamline)

Search for vector-mediated (A') Light Dark Matter using electrons and positrons at H4

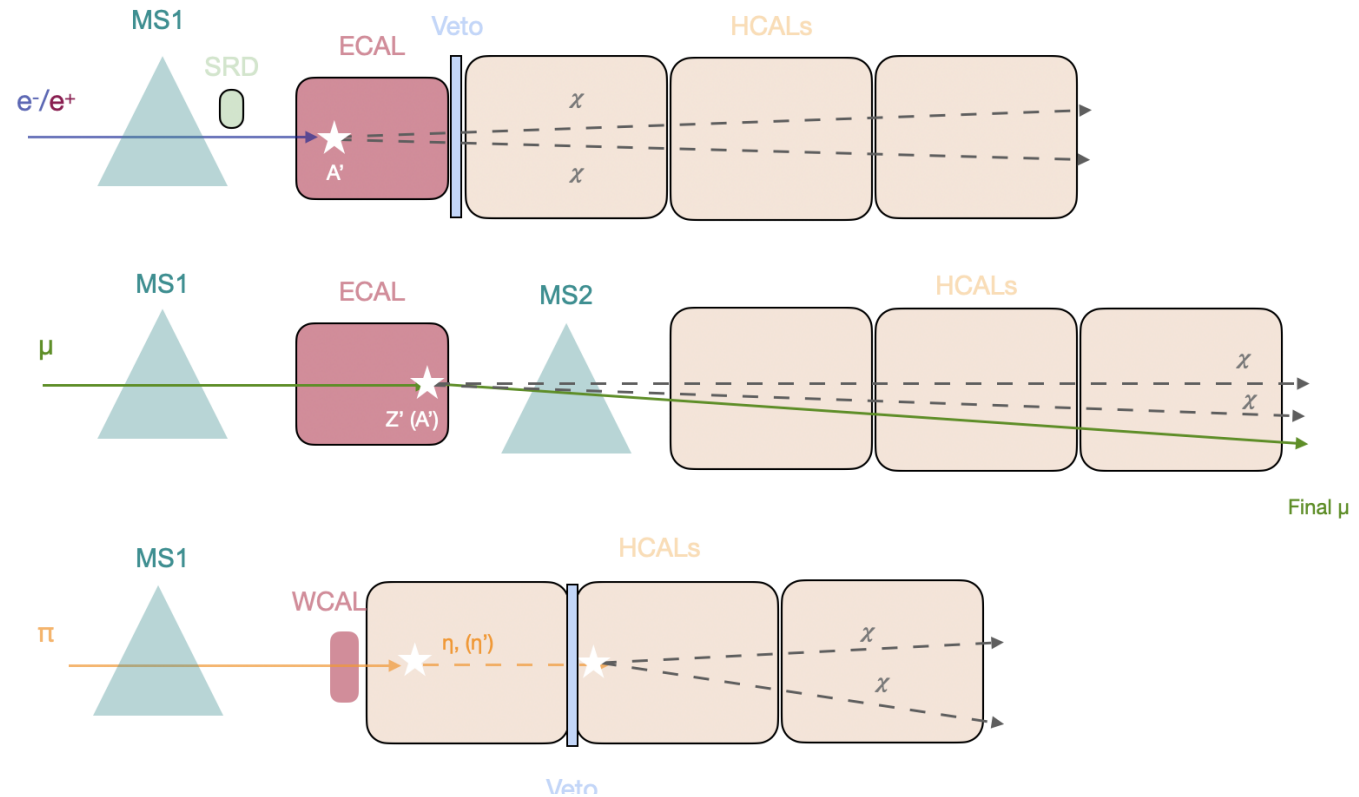
■ NA64mu: (M2 beamline)

Phase 1: test $L_\mu - L_\tau$, Z' motivated by the muon (g-2) anomaly and LDM

Phase 2: Complementary LDM, ALPs millicharged particles searches

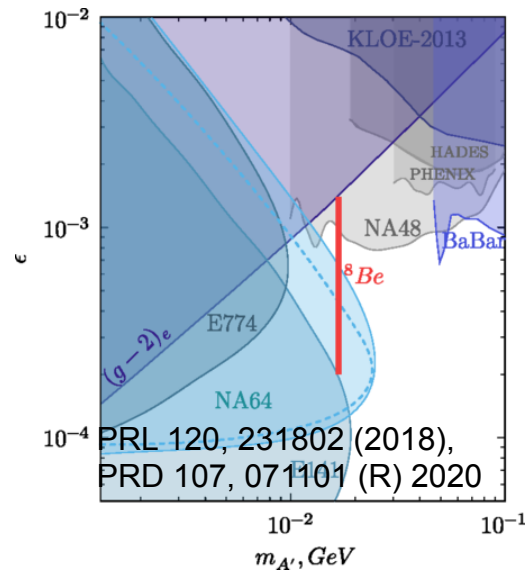
■ NA64h (H4 beamline)

Search for leptophobic DS coupled to light SM quarks

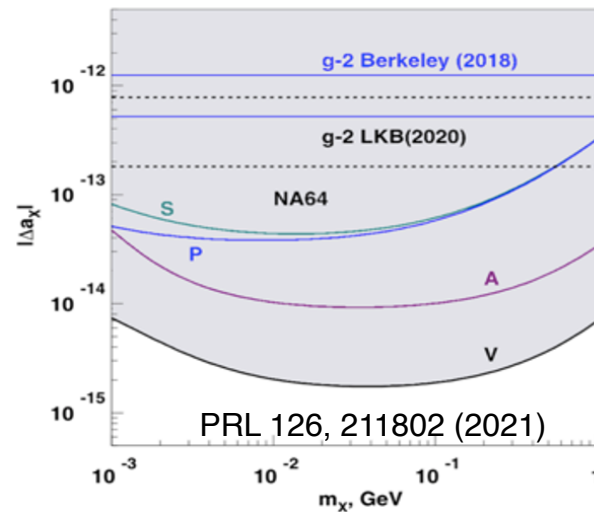


Some examples of NA64 sensitivity to additional BSM scenarios

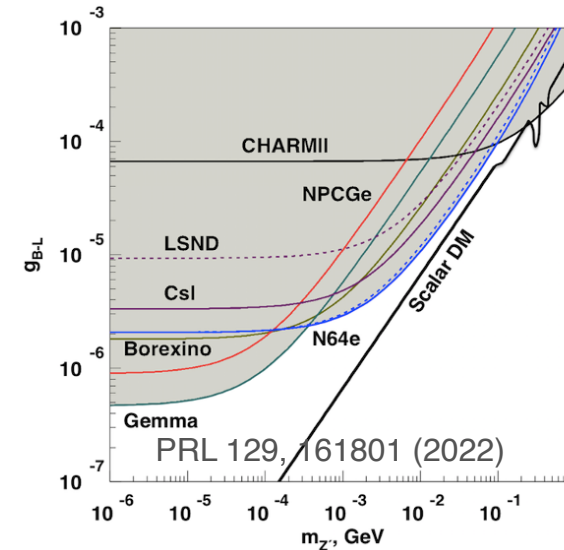
A' -> visible and X17



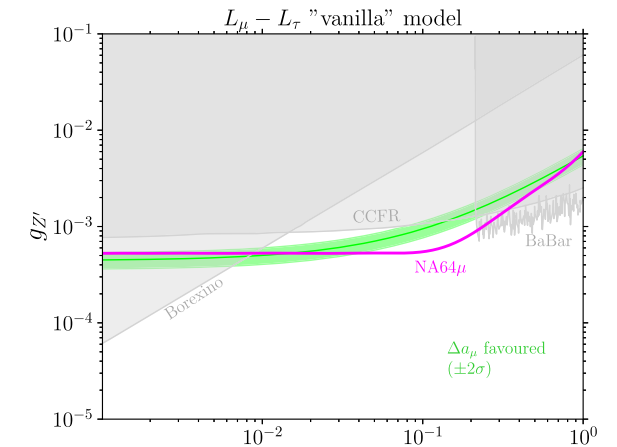
$e^-Z \rightarrow e^-ZX; X \rightarrow \text{invisible}$



B-L Z' vs neutrino scattering

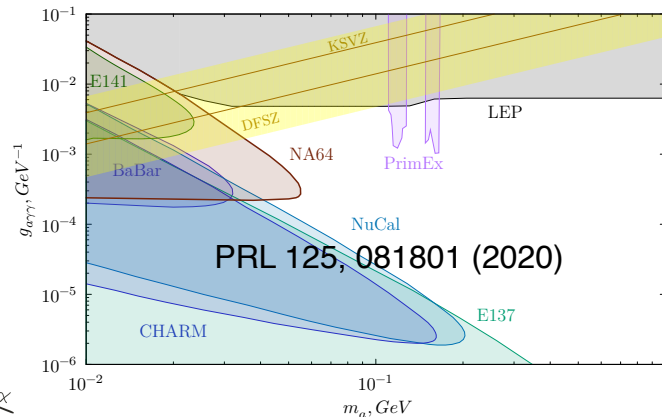


Lmu-Ltau Z'



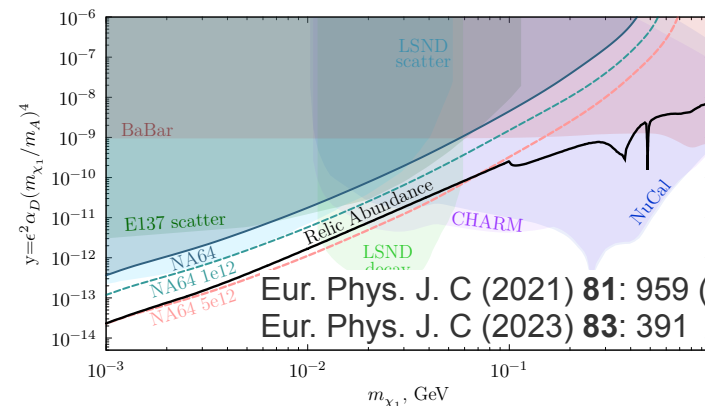
NA64, PRL 132, 21, 211803, (2024),
Featured in Physics

QCD axion and ALPs



Thermal iDM

Thermal iDM, $\Delta = 0.1 m_{\chi_1}, m_A = 3 m_{\chi_1}, \alpha_D = 0.1$



Dark sectors coupled to quarks

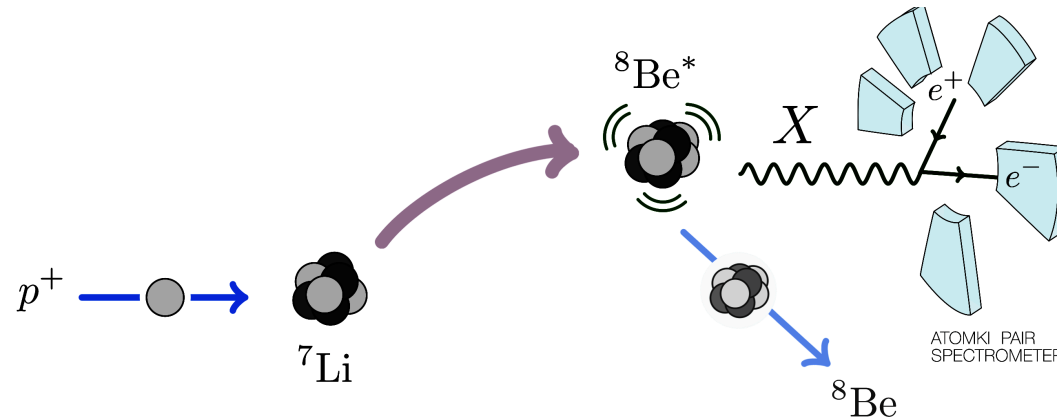
$$\text{Br}(\eta \rightarrow \text{invisible}) < 1.1 \times 10^{-4},$$

$$\text{Br}(\eta' \rightarrow \text{invisible}) < 2.1 \times 10^{-4},$$

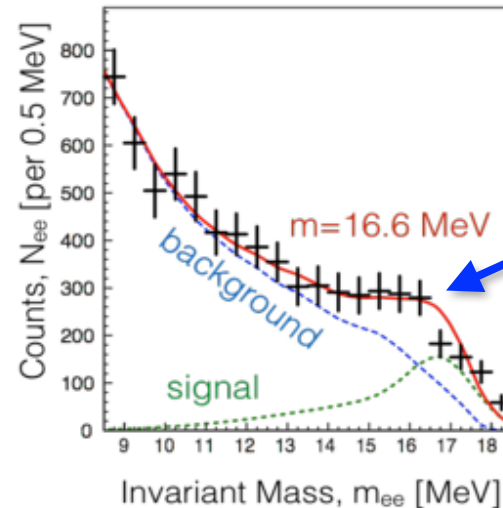
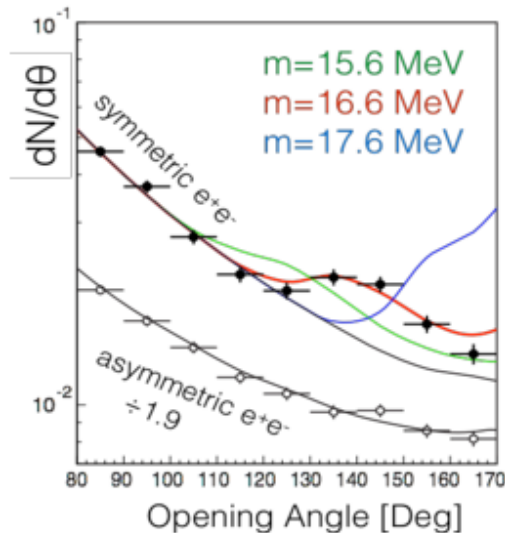
NA64, PRL 133 (2024) 12, 121803



The ^8Be anomaly and X17 boson



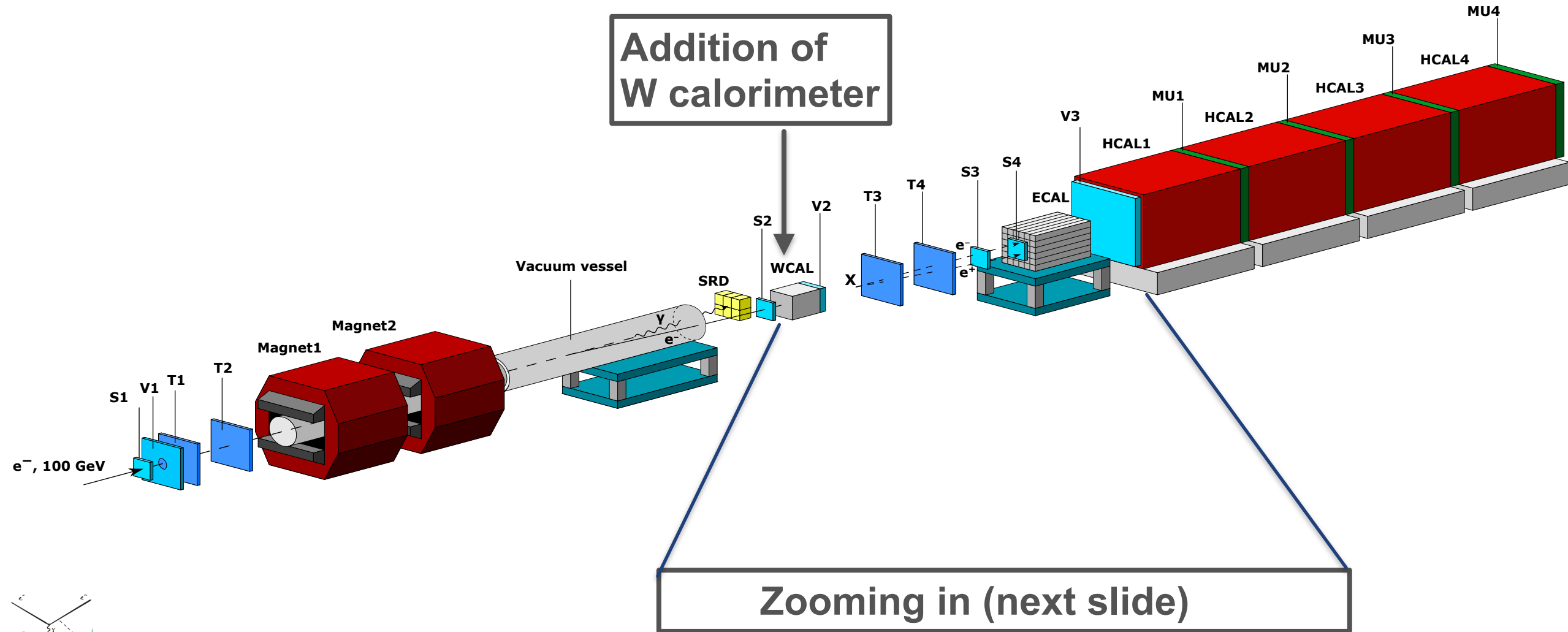
A. J. Krasznahorkay et al. Phys. Rev. Lett. 116, 042501 (2015)
and results for 4He arXiv:1910.10459



Could be explained by new
'protophobic' gauge boson X
with mass around 17 MeV

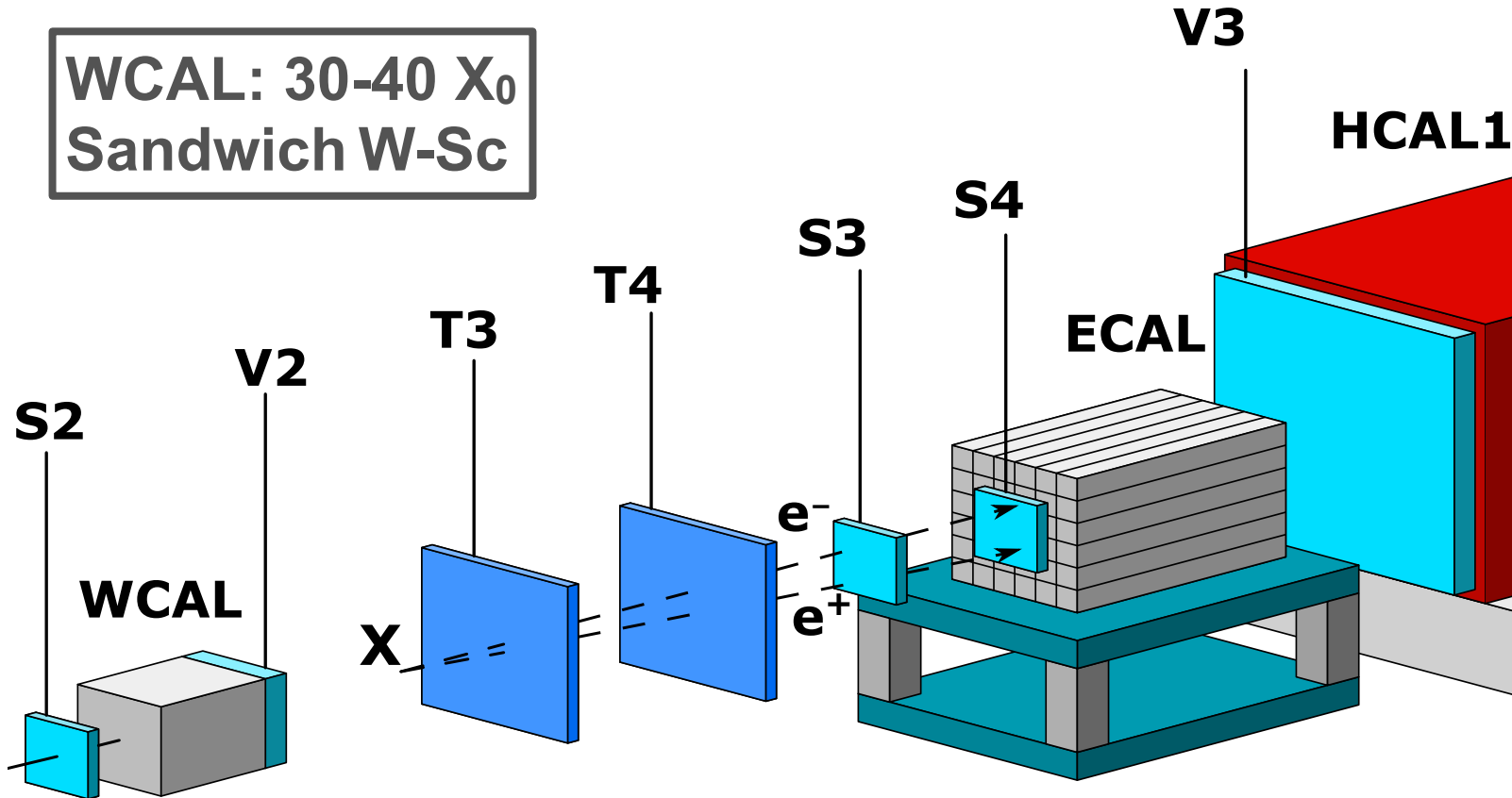
J. L. Feng et al. Phys. Rev. D95, 035017 (2017)

The NA64 search for $A'/X17 \rightarrow e^+e^-$ - experimental setup



The NA64 search for $A'/X17 \rightarrow e^+e^-$ - experimental signature

WCAL: 30-40 X_0
Sandwich W-Sc

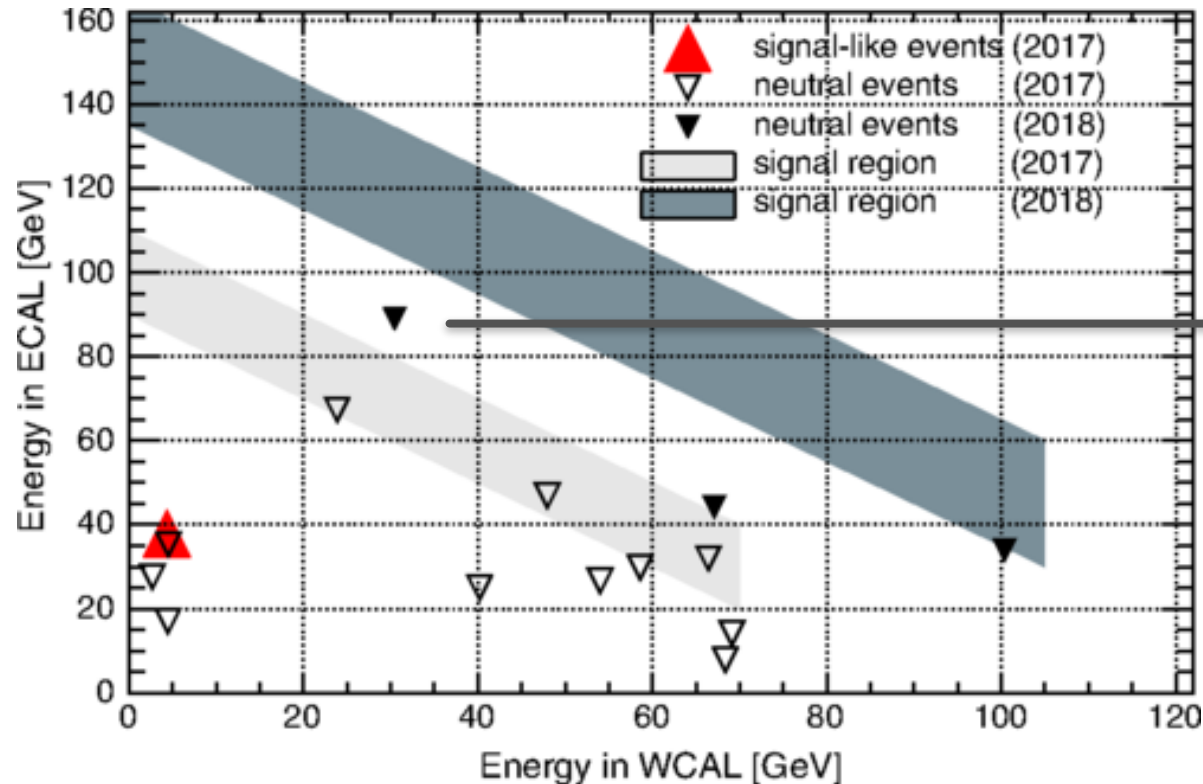


Signature:

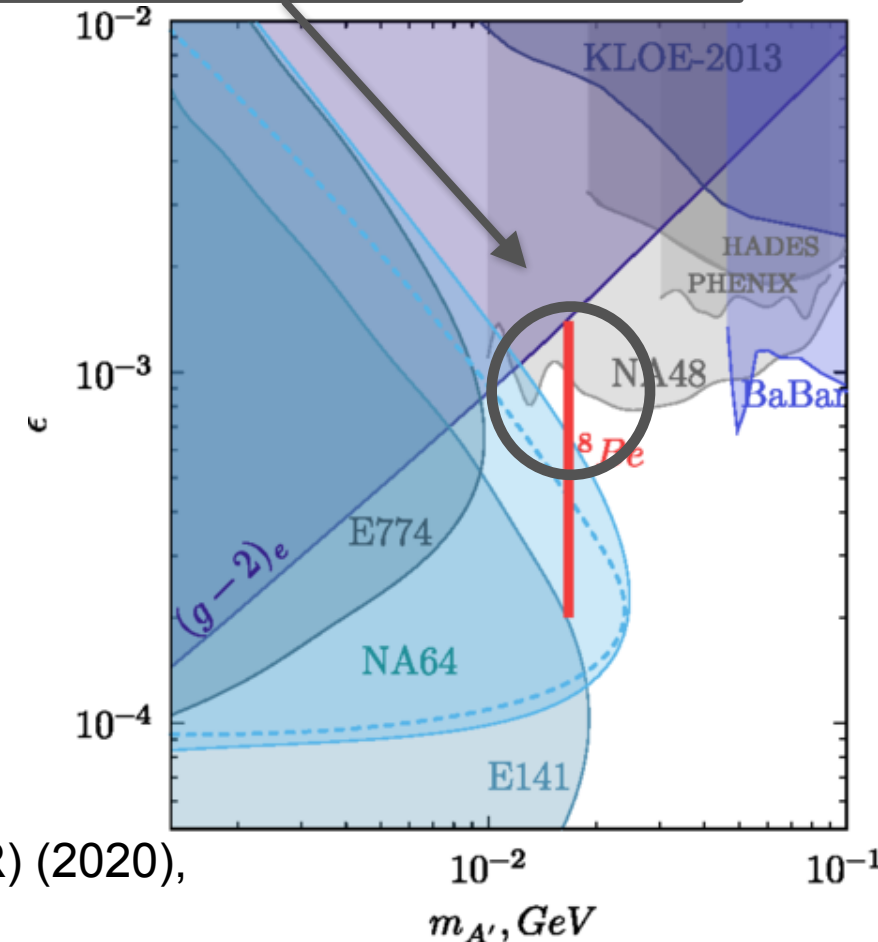
- 1) $E_{WCAL} + E_{ECAL} = 100 \text{ GeV}$
- 2) No activity in $V_{2,3}$ and HCAL
- 3) Signal in S3, S4
- 4) e-m shower in ECAL

The NA64 search for $A'/X17 \rightarrow e^+e^-$ - results (2017-2018)

X17 very short lived $< 10^{-13}$ s



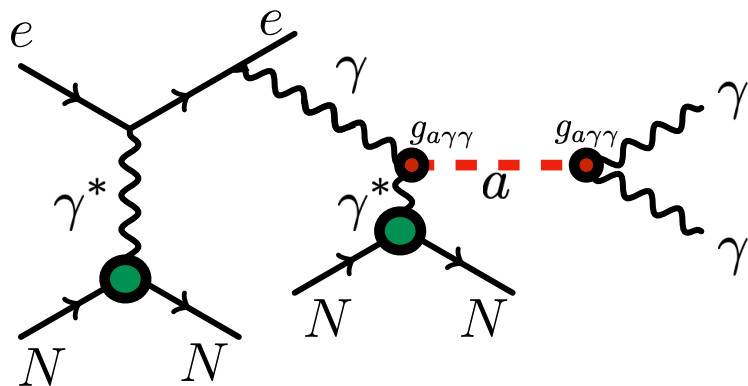
COUPLING ϵ



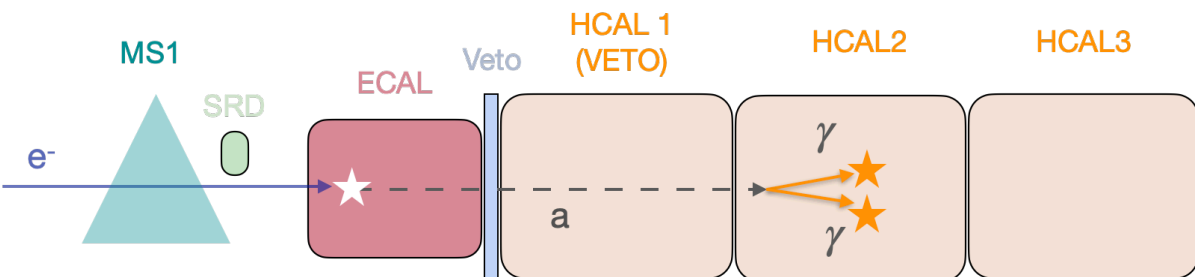
NA64 collaboration, PRL 120, 231802 (2018), PRD 107, 071101 (R) (2020),
 Eur. Phys. J. C (2020) 80:1159, PRD104, L111102 (2021)
 E. Depero, PhD thesis, ETH Zurich (2020).

The search for axions and axion-like-particles (ALPs) in NA64

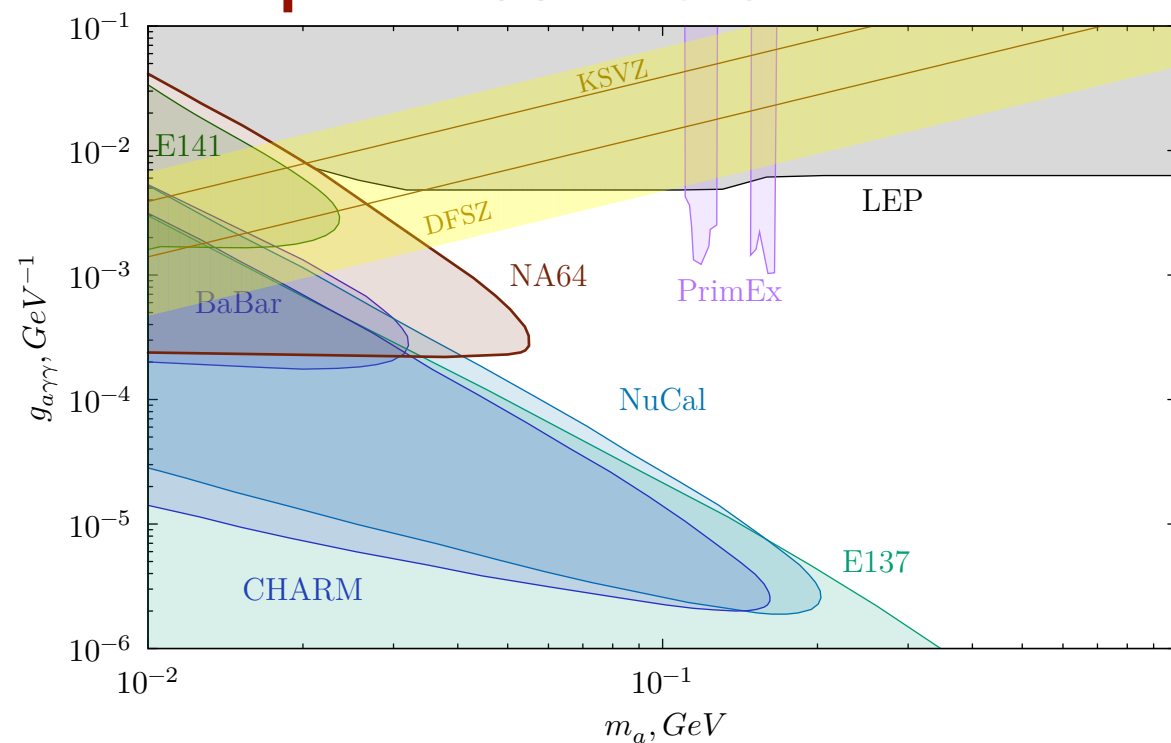
Production via Primakoff effect



$$e^- Z \rightarrow e^- Z \gamma; \gamma Z \rightarrow a Z; a \rightarrow \gamma \gamma$$

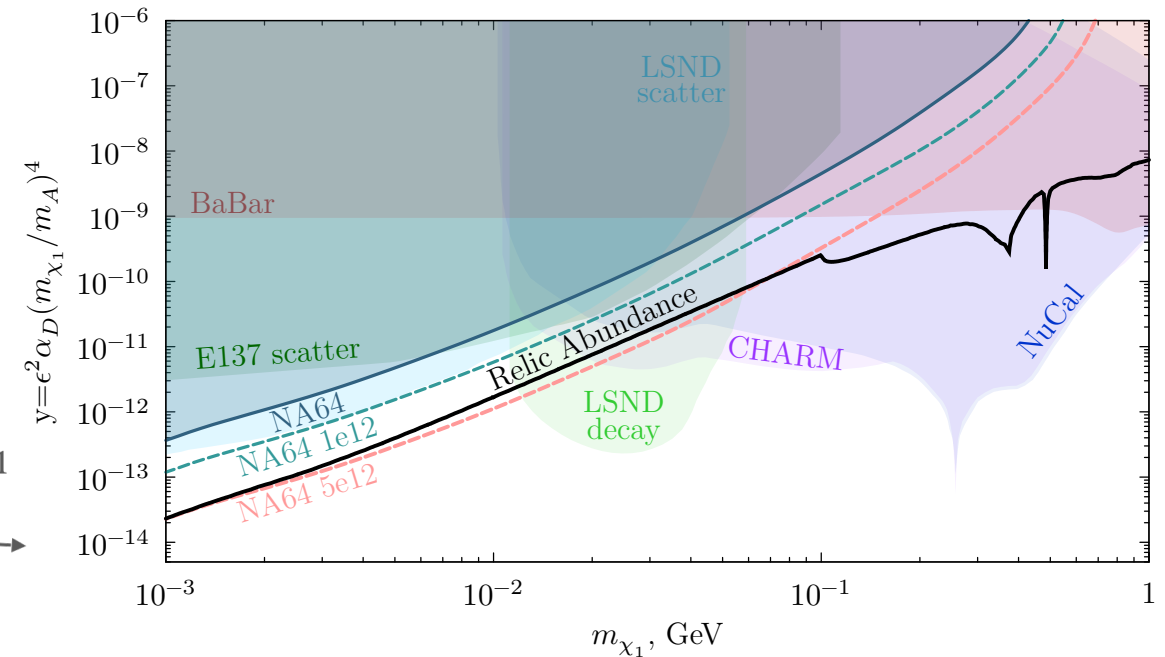


Closing the gap between beam dump and colliders



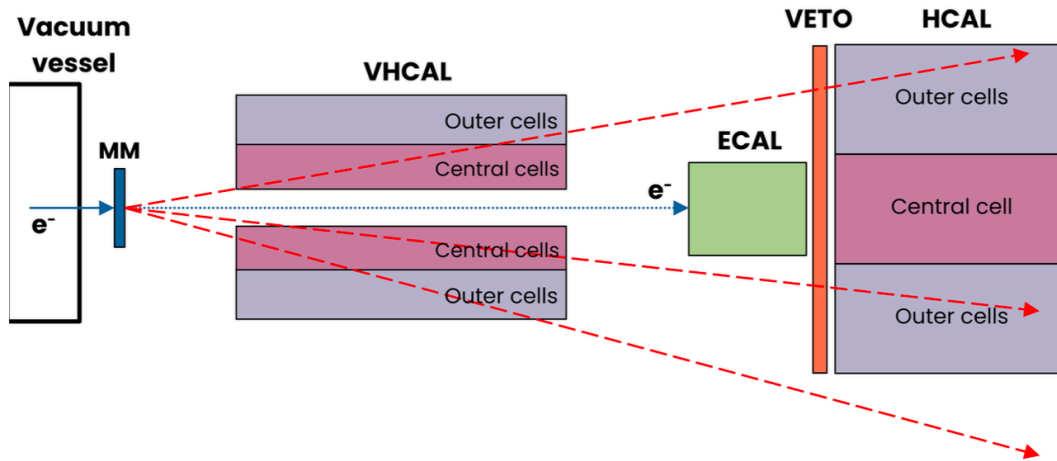
NA64 collaboration PRL 125, 081801 (2020)

Dr. Anna Kozłowska

Thermal iDM, $\Delta = 0.1m_{\chi_1}, m_A = 3m_{\chi_1}, \alpha_D = 0.1$ 

Background study and detector upgrade

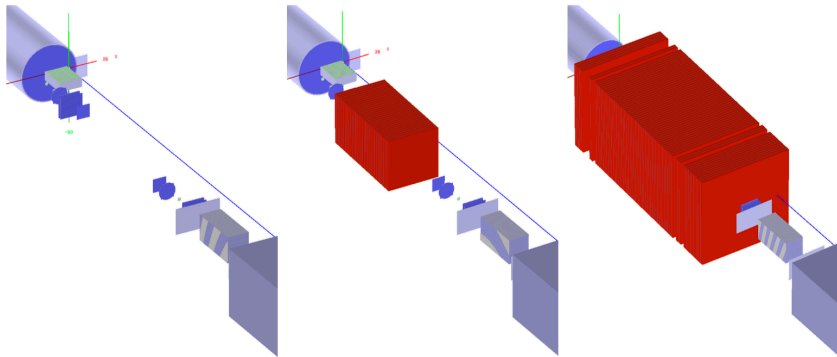
Large pt secondaries from electro-nuclear and photo-nuclear interactions along the beamline



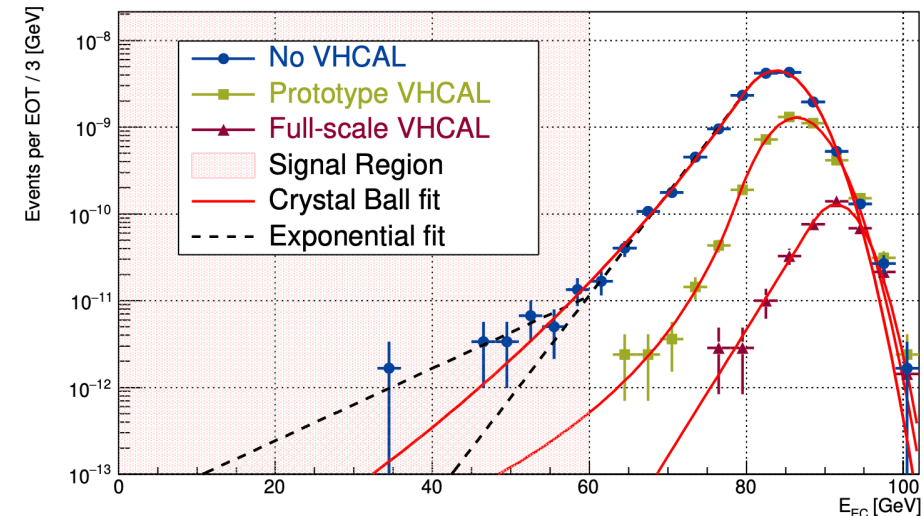
B. Banto-Oberhauser, PhD thesis, ETH Zurich (2025),
NIM A 1081, 170830 (2026)

Prototype VHCAL (2023)

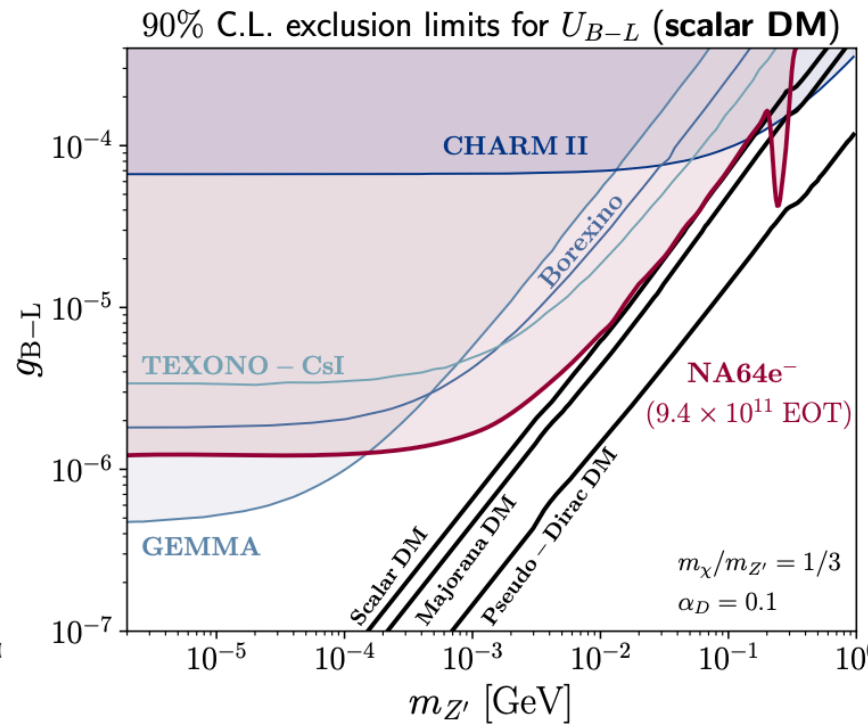
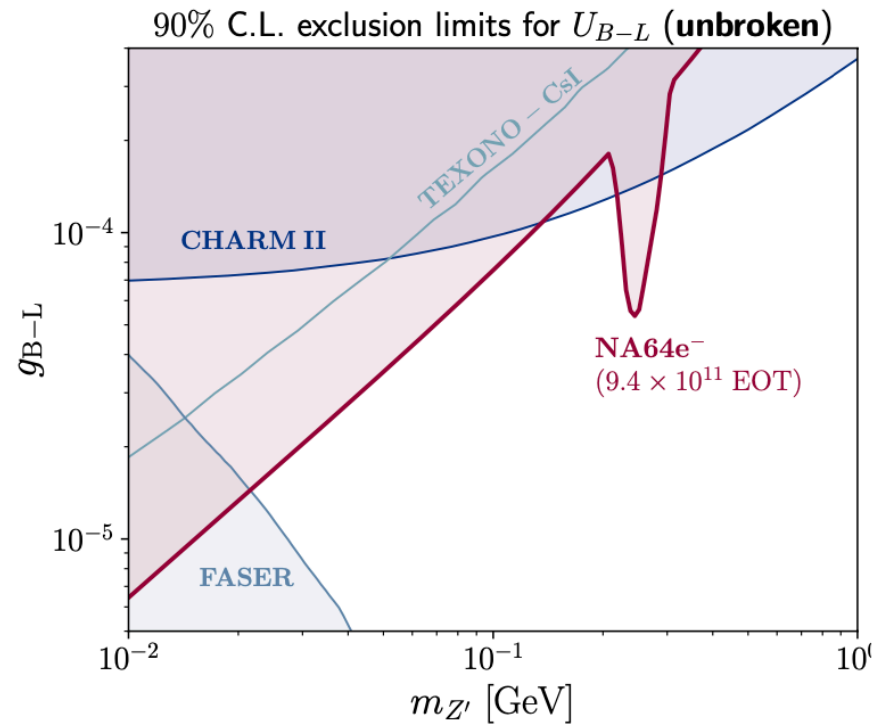
No VHCAL



Full-scale VHCAL



NA64 latest results- Search for a (B-L) Z' boson - (2016-2022)



arXiv:2606.17320

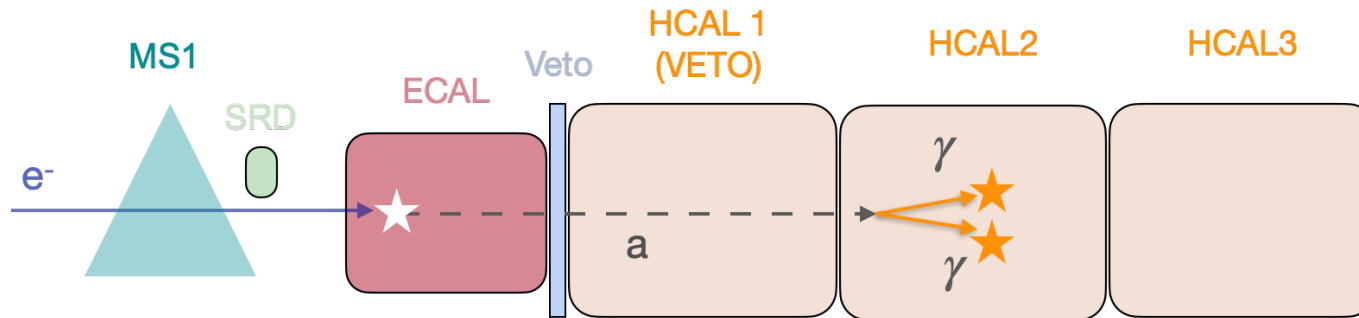
Dataset collected between 2016 and 2022: 9.37×10^{11} electrons on target.

Our **limits exceed** those from dedicated **neutrino-scattering experiments**.

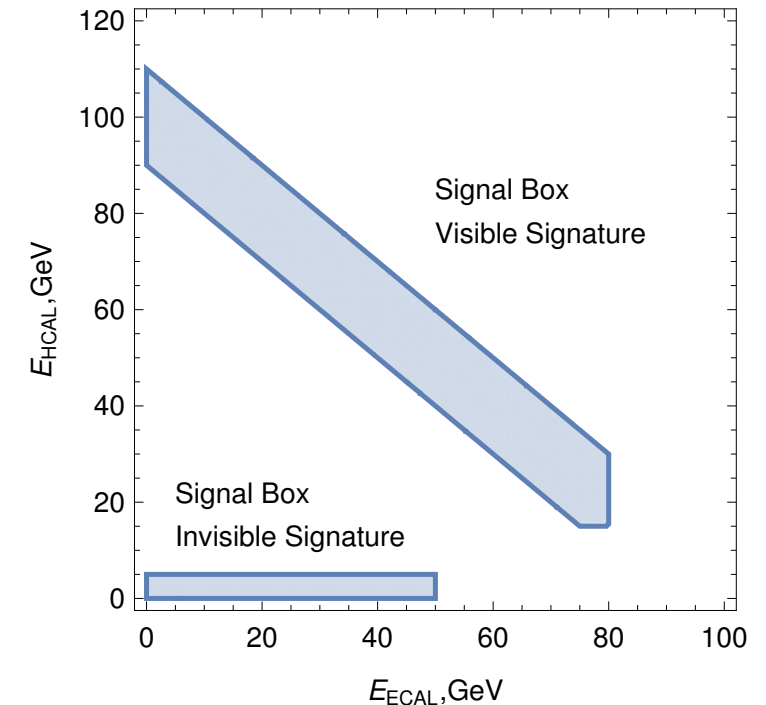
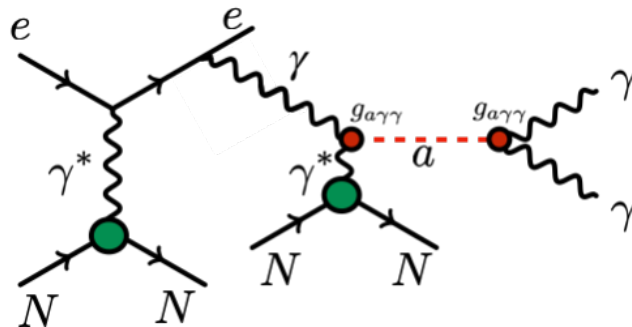


NA64 latest results - Search for ALPs (2016-2023)

Dataset collected between 2016 and 2023: 1.31×10^{12} electrons on target.



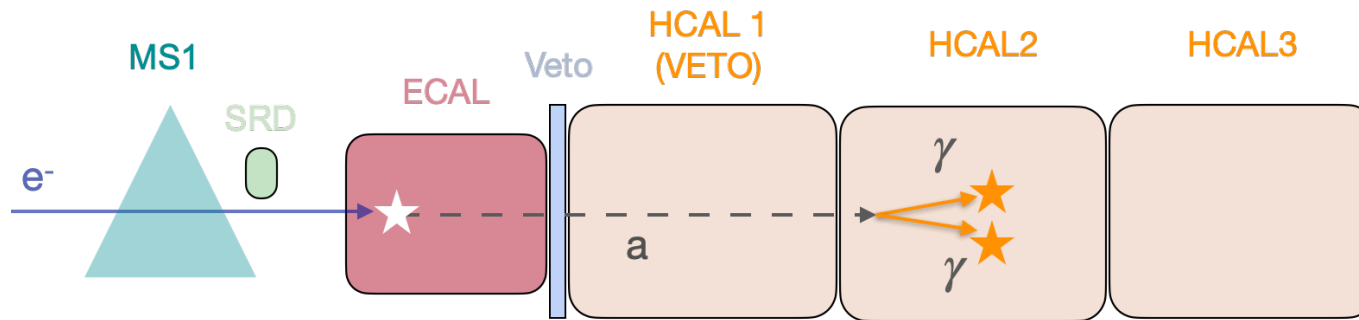
**Primakoff
production**



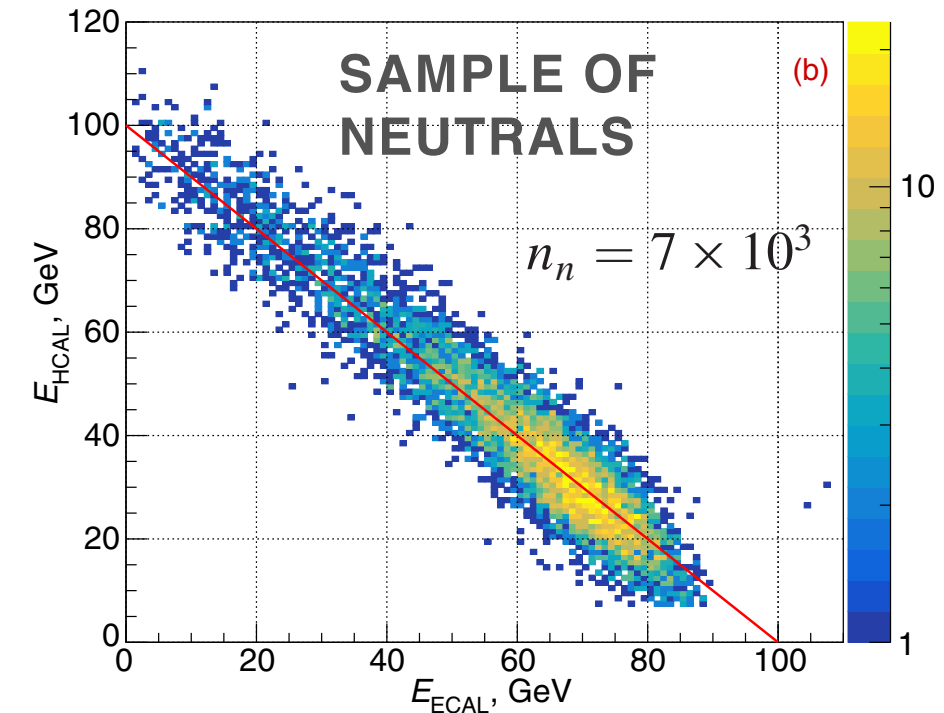
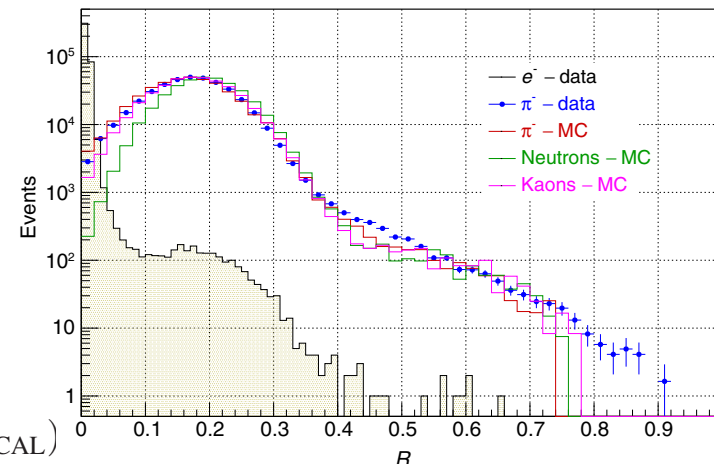
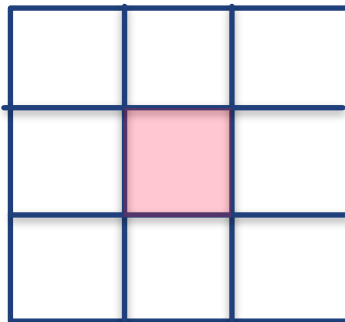
Expected background: 0.15 ± 0.04

NA64 latest results - Search for ALPs (2016-2023)

Dataset collected between 2016 and 2023: 1.31×10^{12} electrons on target.

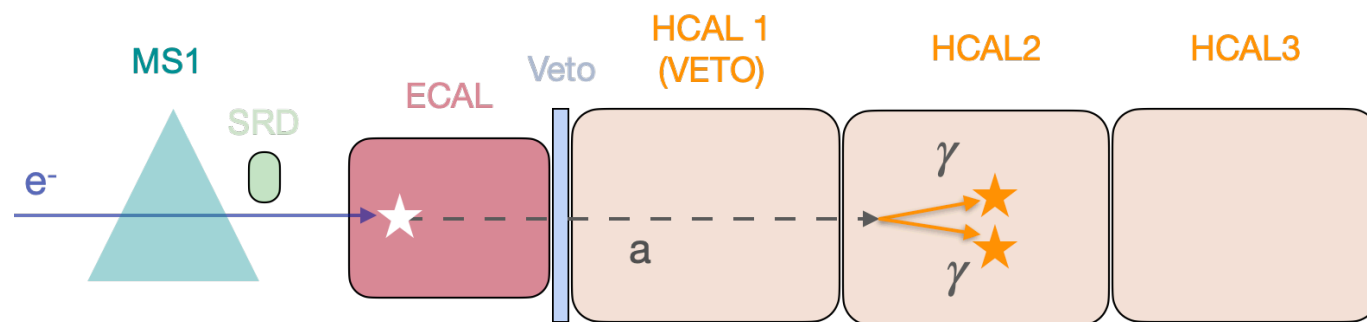


HCAL FRONT VIEW

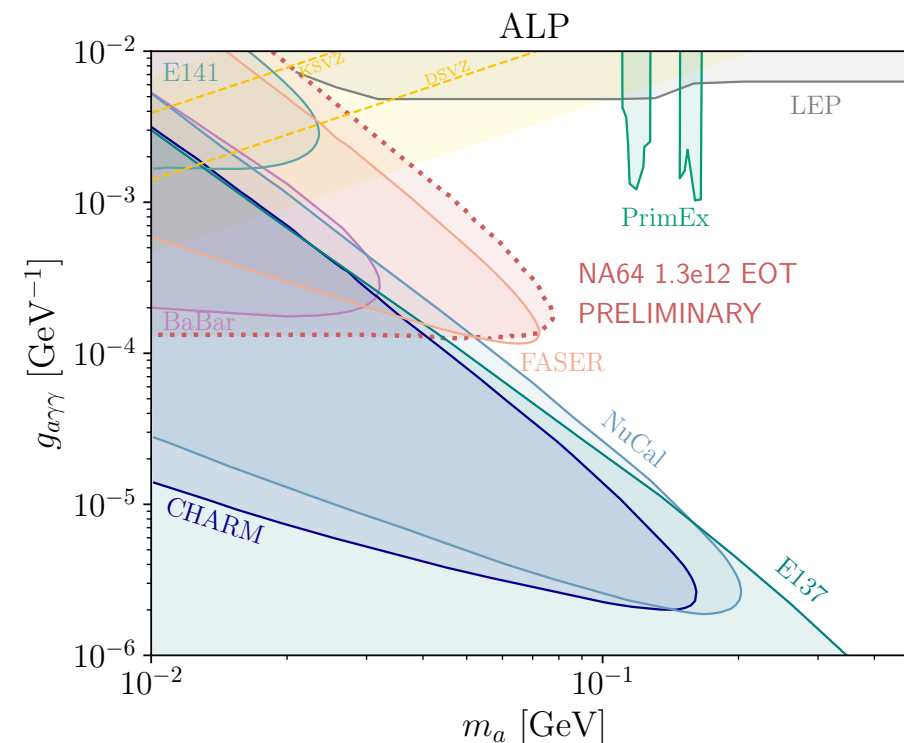
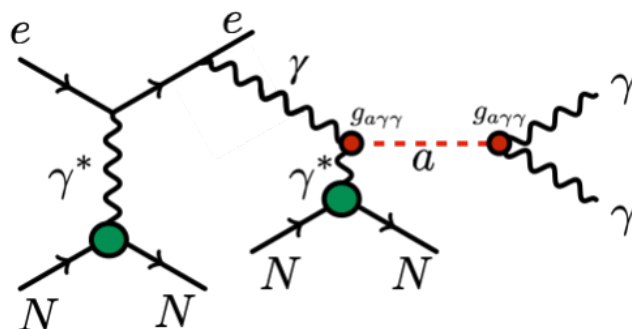


NA64 latest results - Search for ALPs (2016-2023)

Dataset collected between 2016 and 2023: 1.31×10^{12} electrons on target.



**Primakoff
production**

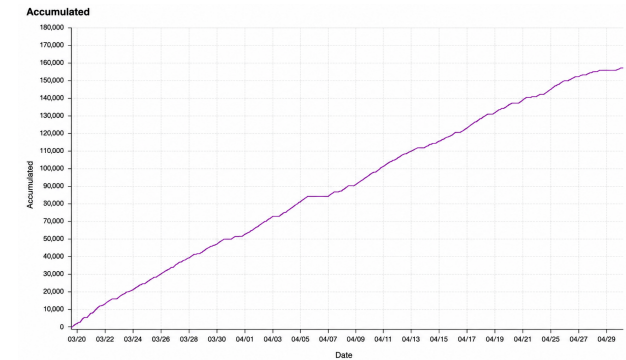


Expected background: 0.15 ± 0.04

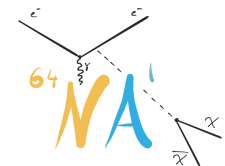
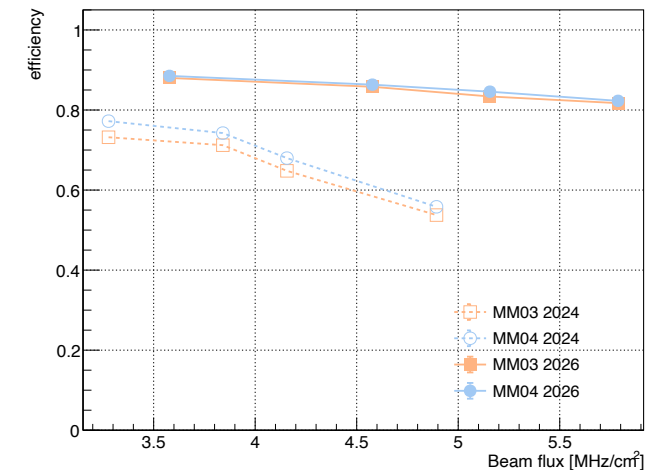
Upgrades already started in preparation for Run 4 (2029-2033)

- **Higher-rate DAQ:** Waveboard digitizers already deployed, with fit-based waveform reconstruction and improved pile-up handling
- **Tracking for high intensity:** new **Micromegas** built and operated in 2026, improving hit reconstruction and high-occupancy performance
- **Improved e⁻/e⁺ identification:** prototype LYSO-based SRD successfully operated in 2025–2026
- **Improved detector hermeticity:** second **VHCAL** installed and tested in 2025–2026, yielding about an order-of-magnitude suppression of upstream-interaction background
- **High-intensity running tests:** dedicated periods at up to 10^7 electrons/spill used to validate operation under Run-4-like conditions

Accumulated number of spills (2026)

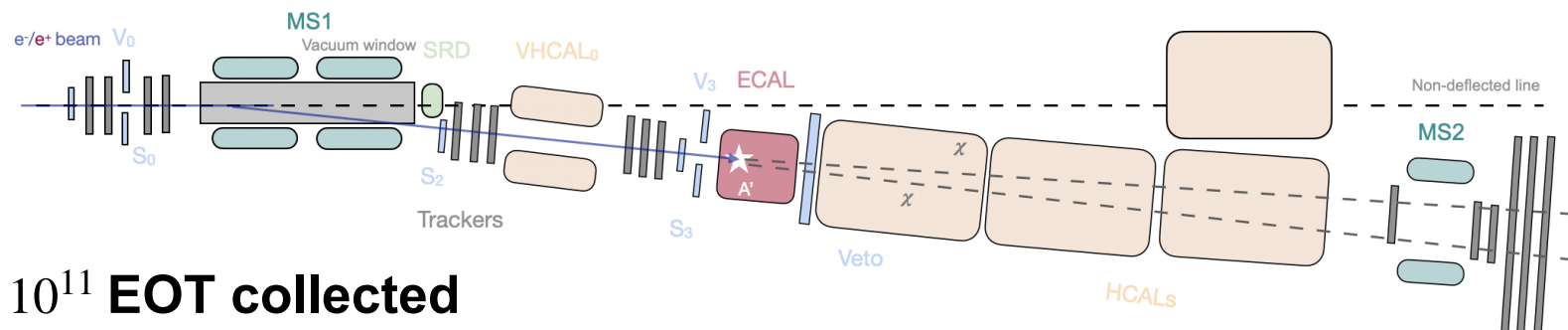


MM03/MM04 good hit efficiency vs flux, 2024 vs 2026



NA64e setup

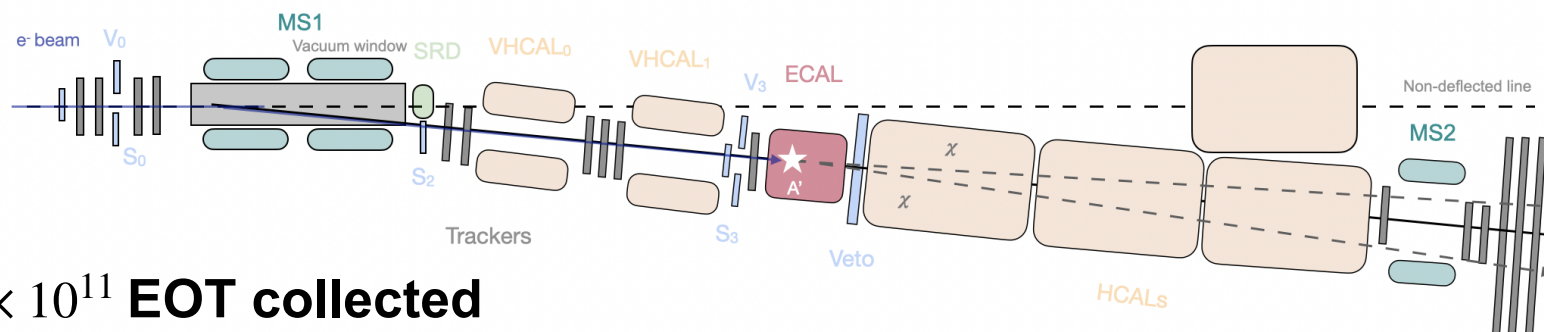
2023/2024



1 VHCAL
was added
to the setup

$4.4 \times 10^{11} / 4.8 \times 10^{11}$ EOT collected

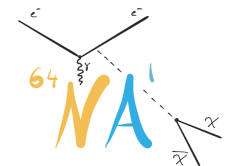
2025/2026



2 VHCALs +
new faster
electronics;
SRD, new MM

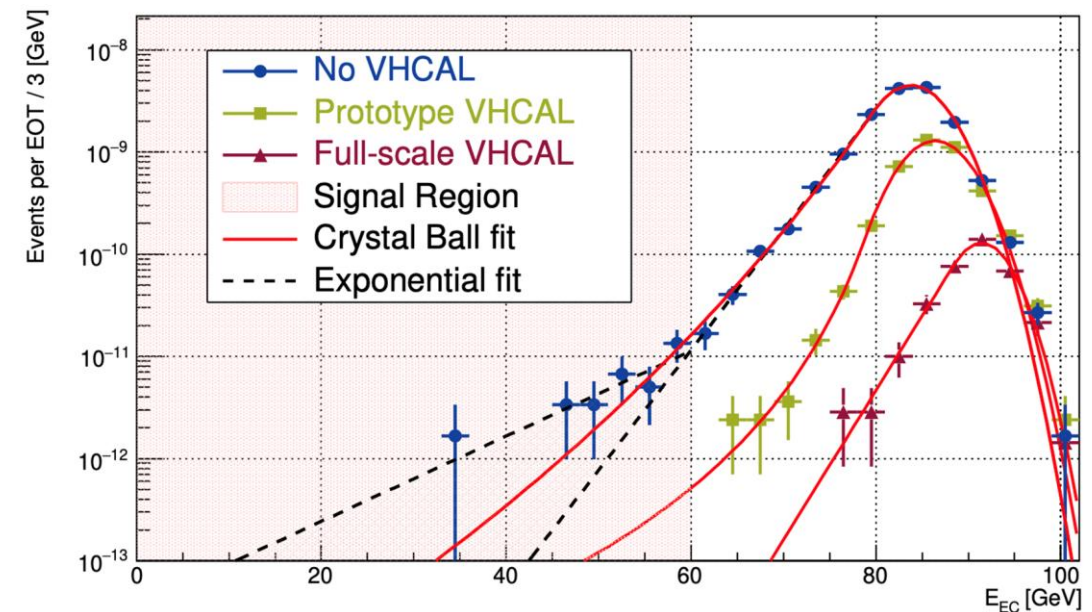
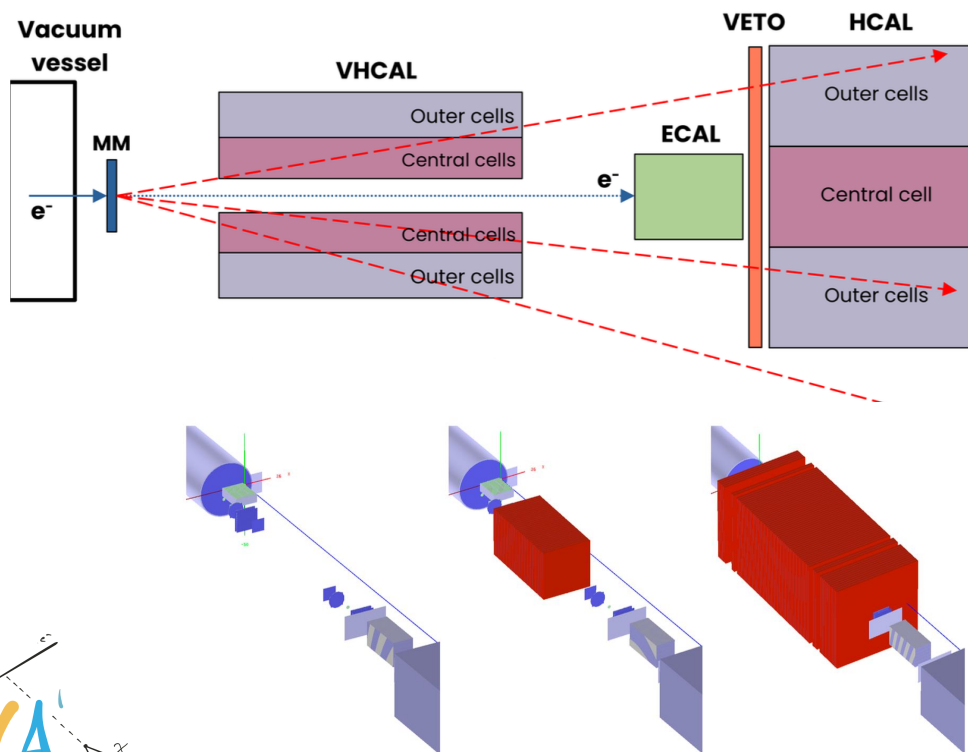
$3.8 \times 10^{11} / 5.6 \times 10^{11}$ EOT collected

2023–2026 combined analysis in progress

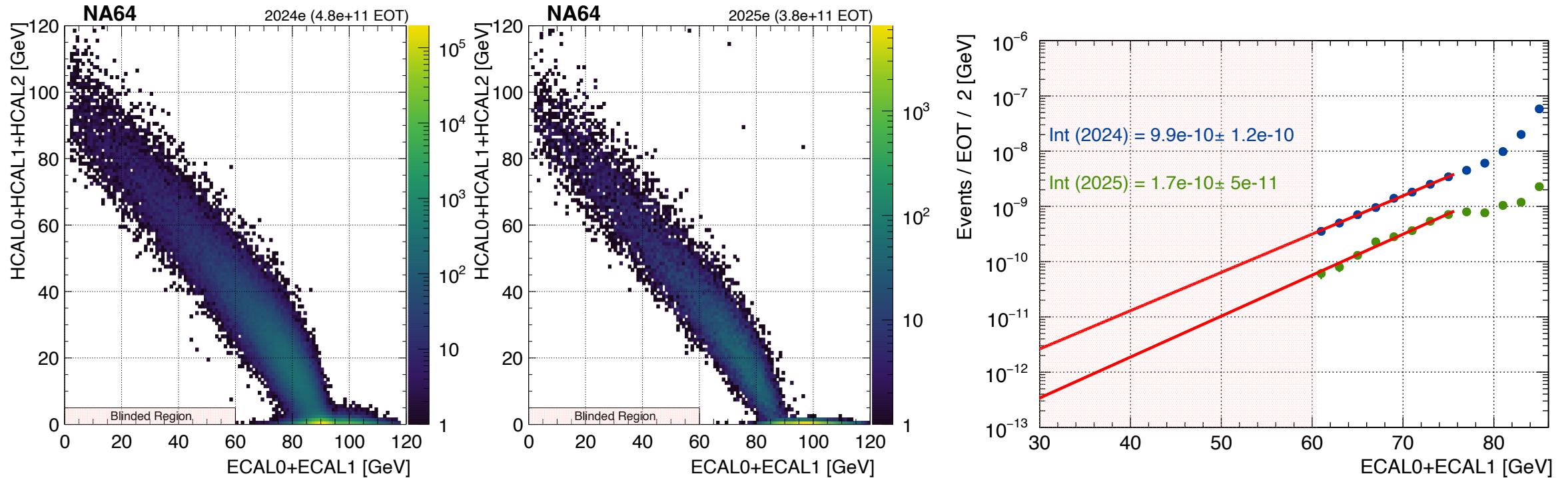


Main background: upstream hadron electro-production

- Comparison of data and MC demonstrated our understanding of **electro-nuclear and photo-nuclear** (NIM A 1081 (2026), 170830).
- Results driving the design of the final VHCAL to be implemented during LS3



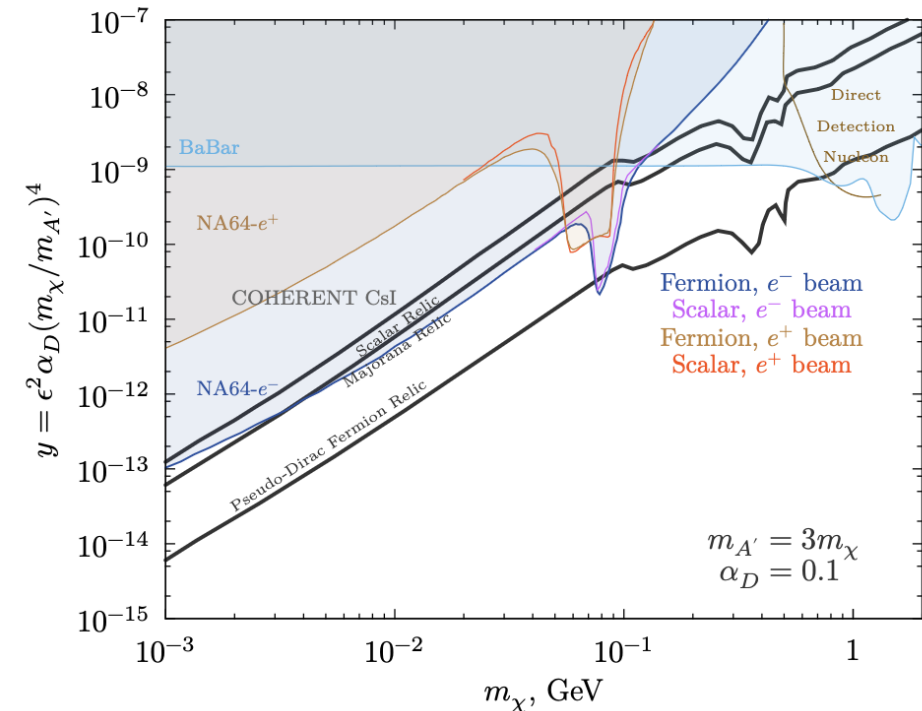
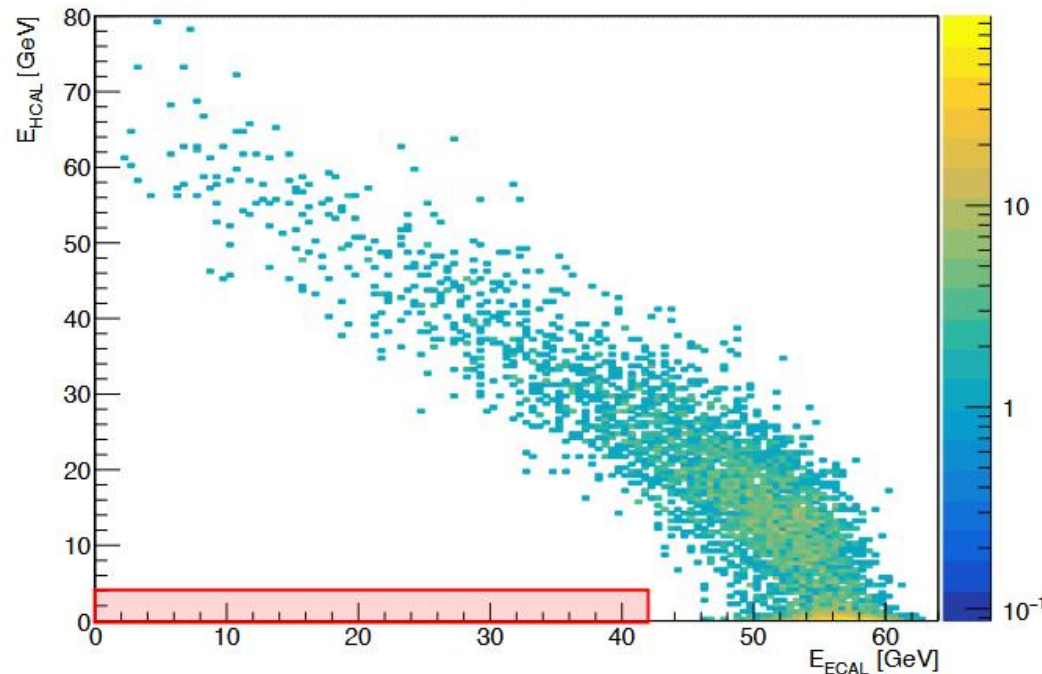
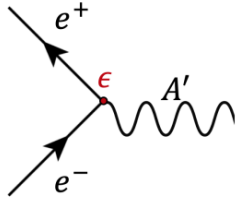
Comparison 2024 vs 2025 (still preliminary)



The **second VHCAL reduces** the number of **events in the tails** by approximately **one order of magnitude** as predicted by the MC.

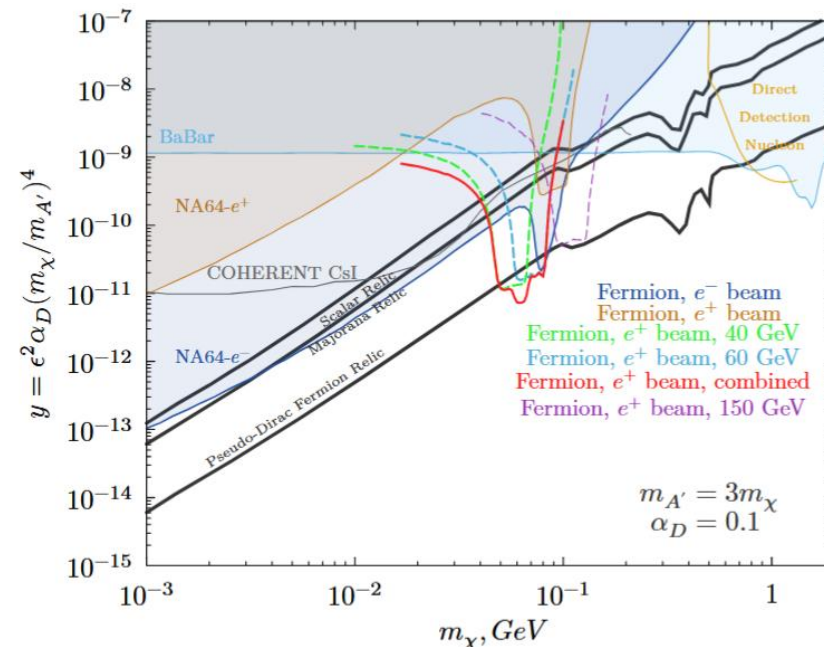
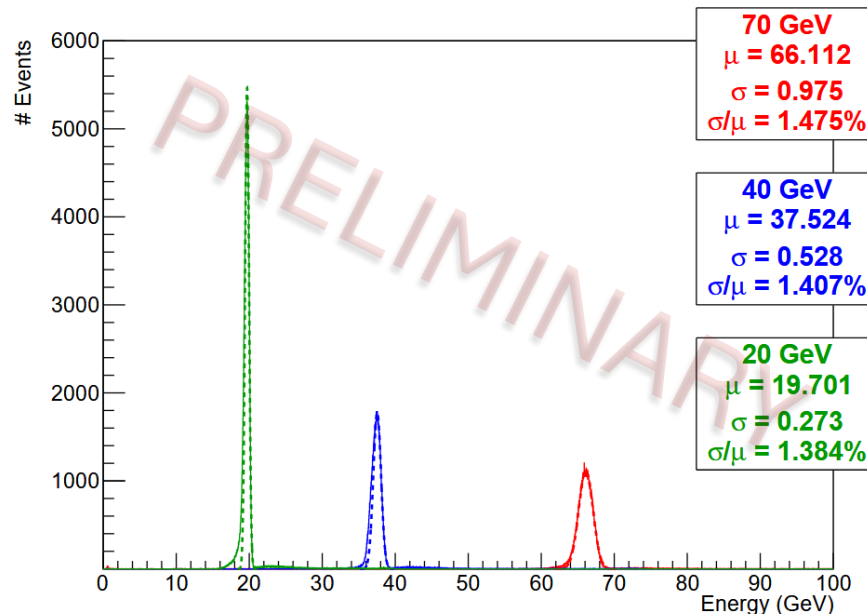
NA64e⁺ - result with 70 GeV positron beam

- **Resonant e⁺e⁻ annihilation** enhances LDM production for A' masses above ~ 100 MeV. First search using 100 GeV e⁺ published in Phys. Rev. D 109 (2024) 031103.
- Analysis of **1.6x10¹⁰ e⁺OT with 70 GeV beam energy** collected in 2023 has been recently published in JHEP 06 (2025), 256:

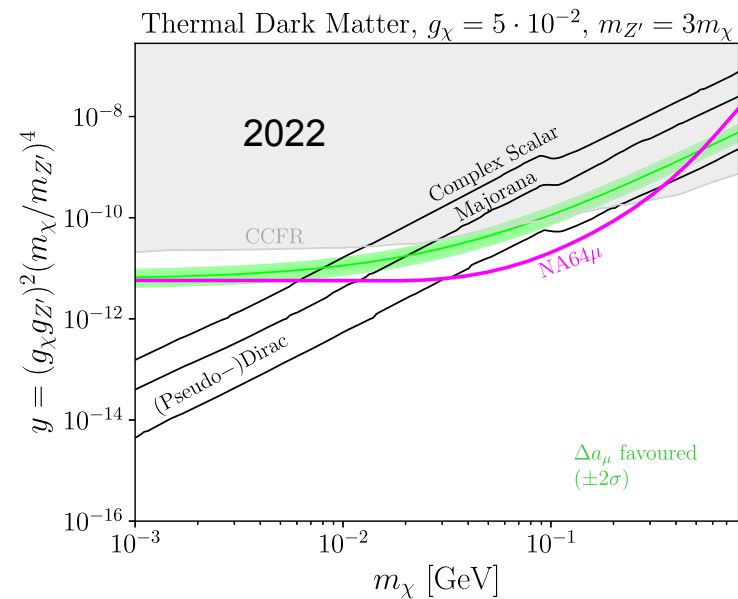


NA64e⁺ with 40 GeV and 45 GeV

- 2025: collected data at **40 GeV and 45 GeV** to demonstrate the feasibility of running at different initial energies to “scan” the A' mass region ($\sim 10^{10}$ e⁺OT collected)
- New **high-resolution PbWO₄ “POKER” calorimeter** used as an active target
- New **LYSO-based synchrotron radiation detector** for better incoming e⁻ /e⁺ ID at low energy



Status and results of NA64mu at M2 beamline



Background source

Background, n_b

(I) Momentum misreconstruction

0.05 ± 0.03

(II) $K \rightarrow \mu + \nu, \dots$ in-flight decays

0.010 ± 0.001

(III) Calorimeter non-Hermiticity

< 0.01

Total nb (conservatively)

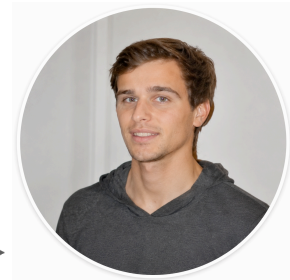
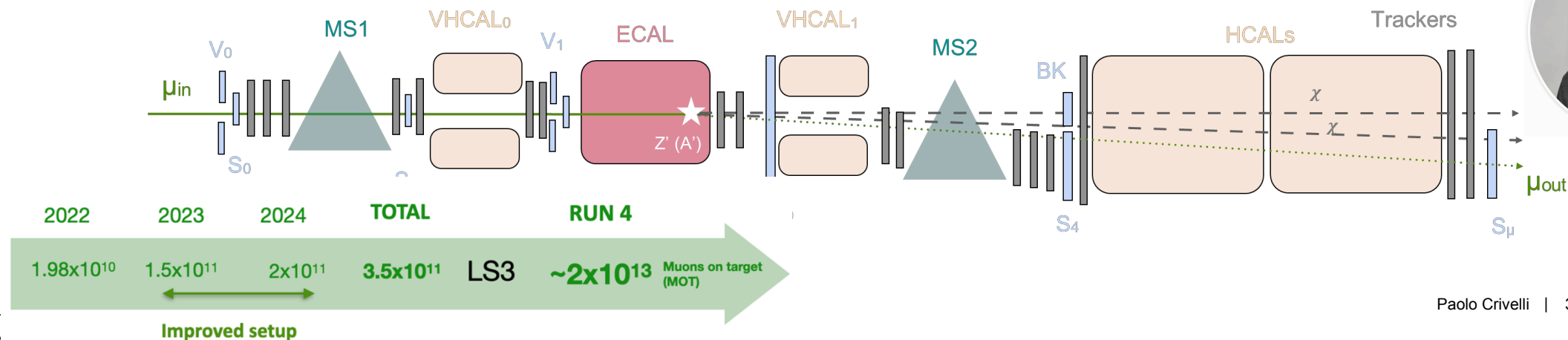
0.07 ± 0.03

NA64, PRL132 (2024) 21, 211803,

PRD 110, 112015 (2024)

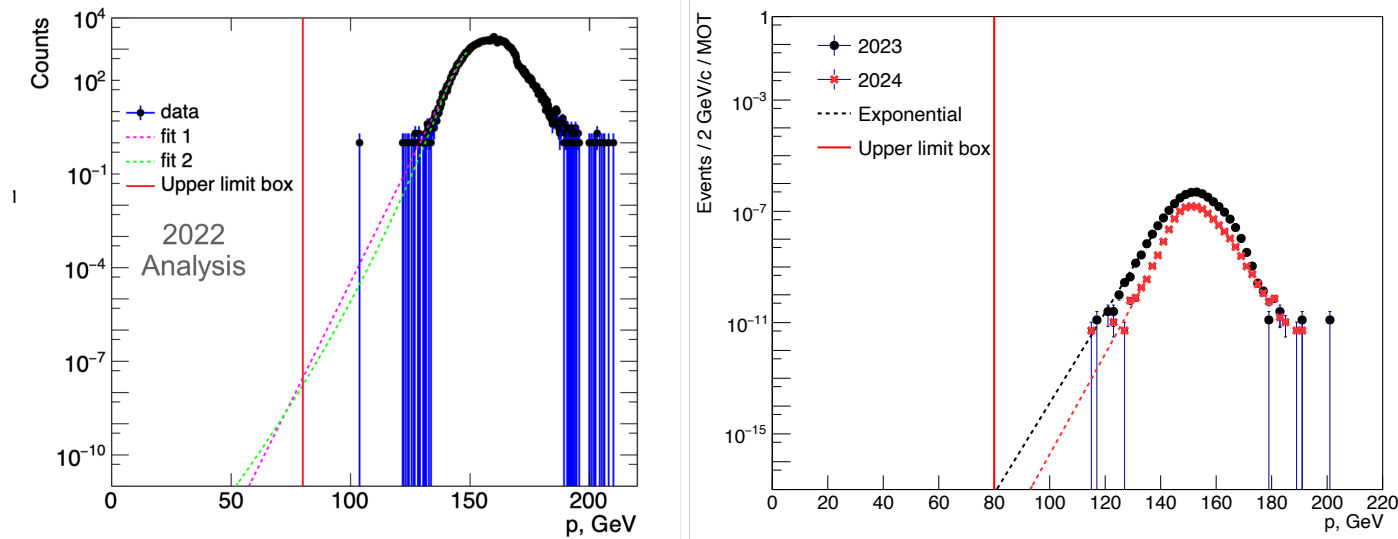
H Sieber, PhD thesis, ETH Zurich (2024)

IMPROVED SETUP FOR 2023-2024 (NEW MS1, VHCALs, VETO, trackers)



NA64mu - 2023 analysis (completed), 2024 (ongoing)

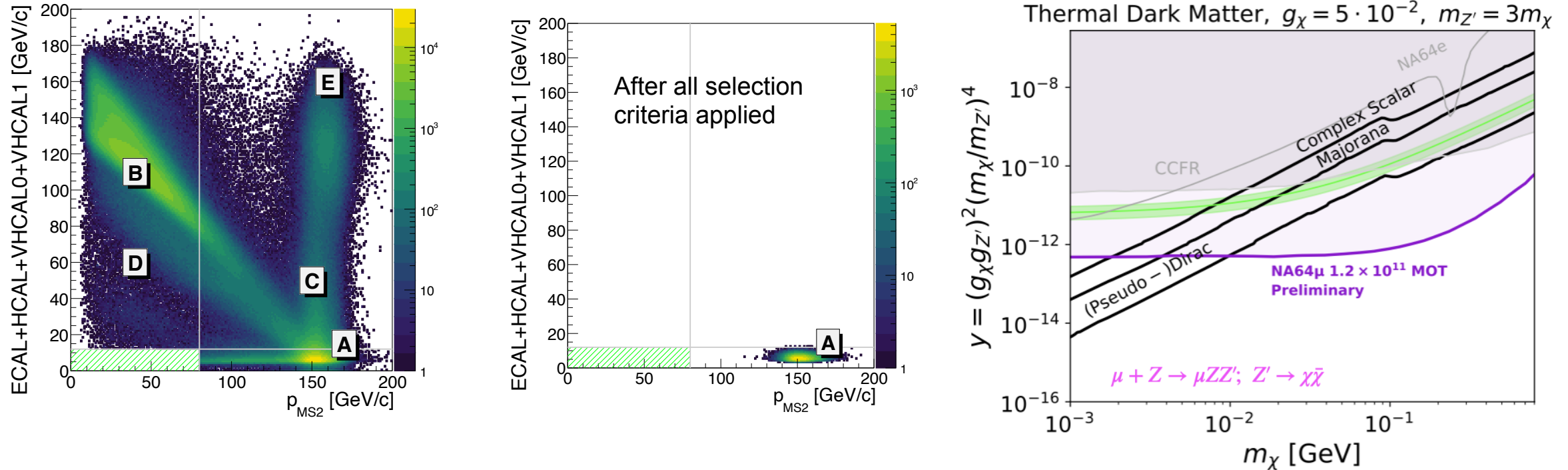
Background from the scattered muon track misreconstruction reduced by 2 orders of magnitude,



campaign	ϵ_{MS2}	ϵ_{MS1}	$\epsilon_{\text{MS1+2}}$
2023	0.52	0.42	0.22
2024	0.67	0.67	0.45

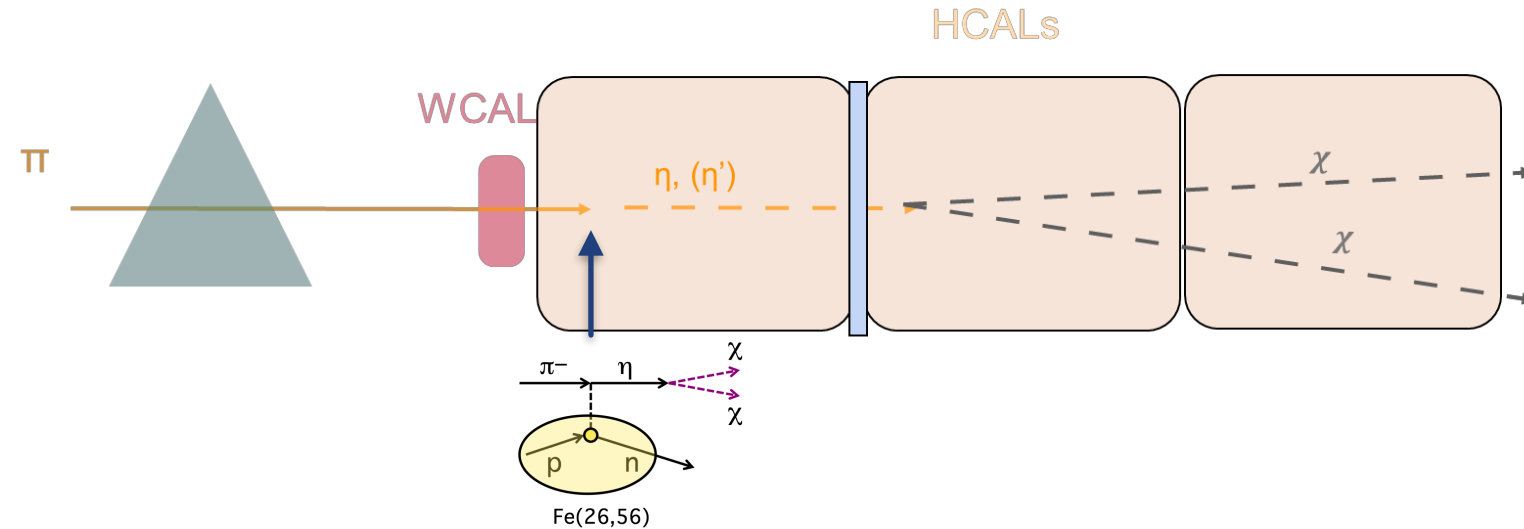
Overall tracking efficiency improved by a factor of ~ 2 in 2023 relative to 2022

NA64mu - 2023 analysis (completed), 2024 (ongoing)



- Preliminary results exclude the $\mathbf{L}_\mu - \mathbf{L}_\tau \mathbf{Z}'$ explanation of the muon g-2 anomaly.
- **Background extrapolation from $\sim 3.5 \times 10^{11}$ MOT** indicates background-free sensitivity up to 10^{13} MOT, to be validated with more data.

NA64h: Search for Dark Sector predominantly coupled to quarks



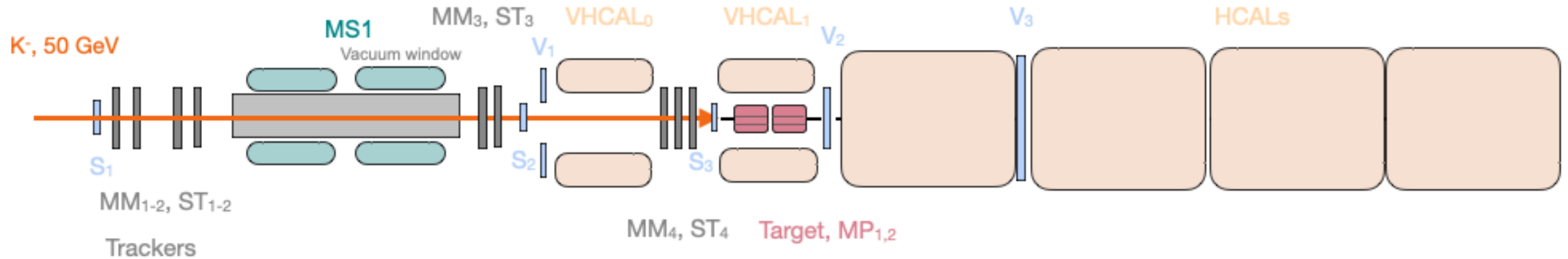
- Sensitive to **several models via missing-energy technique** (invisible decays of $\eta, \eta', \omega, \rho$ mesons, oscillations of neutral kaon into its “dark” partner, production of leptophobic LDM states)
- **First proof-of-concept results from the analysis of 2.9×10^9 π OT (1 day in 2022)**
- Set **stringent constraints on η, η' invisible decay**

$$\text{Br}(\eta \rightarrow \text{invisible}) < 1.1 \times 10^{-4}, \quad \text{Br}(\eta' \rightarrow \text{invisible}) < 2.1 \times 10^{-4}, \quad \text{NA64, PRL 133 (2024) 12, 121803}$$

≈ 3 . better than the bound from the BESIII



NA64h - 2025 run



NA64h analysis ongoing: expected to improve the $\eta, \eta' \rightarrow \text{invisible}$ sensitivity and to provide the first direct bounds on neutral-kaon oscillations into the dark/mirror sector, approaching the region constrained by cosmology.

An addendum to the SPSC with our future plans after LS3 is in preparation

Plans during LS3: analysis + upgrades

- **Complete analysis of the full pre-LS3 data set**

2023–2026 NA64e⁻, combined 2023/24 NA64μ, NA64e⁺ with 40-45 GeV, new generic boson, ALPs, B–L, LFV and hadron/kaon searches

- **Improve hermeticity and particle identification**

Maintain essentially background-free operation at higher SPS intensities

- **H4 upgrades:** upgraded VHCAL, ECAL refurbishment, LYSO SRD, HCAL segmentation/new PMTs, laser monitoring, new Micromegas, digital trigger/DAQ

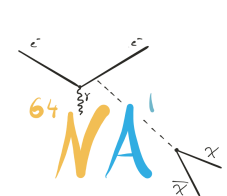
- **M2 upgrades:** additional tracking/veto detectors, extra HCAL modules and new trackers (Micromegas and large straw), independent high-rate trigger/DAQ

- **PS programme during LS3**

Detector and DAQ tests, hadron charge-exchange measurements

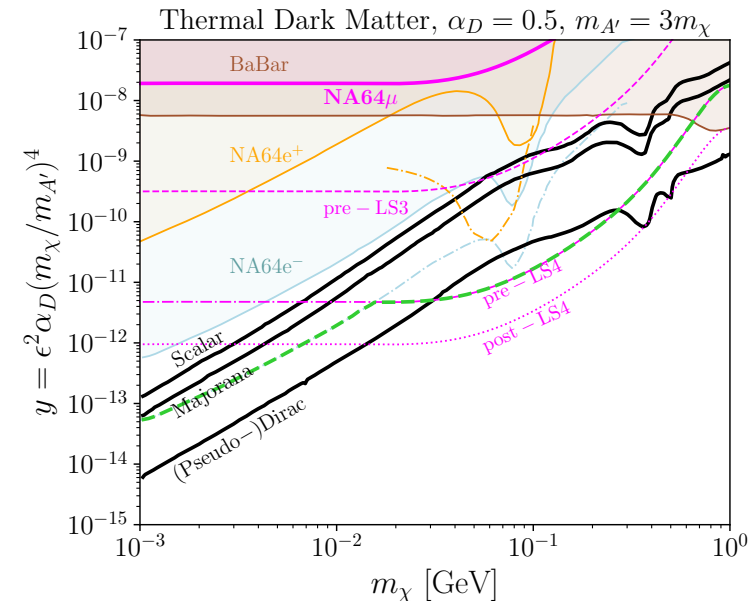
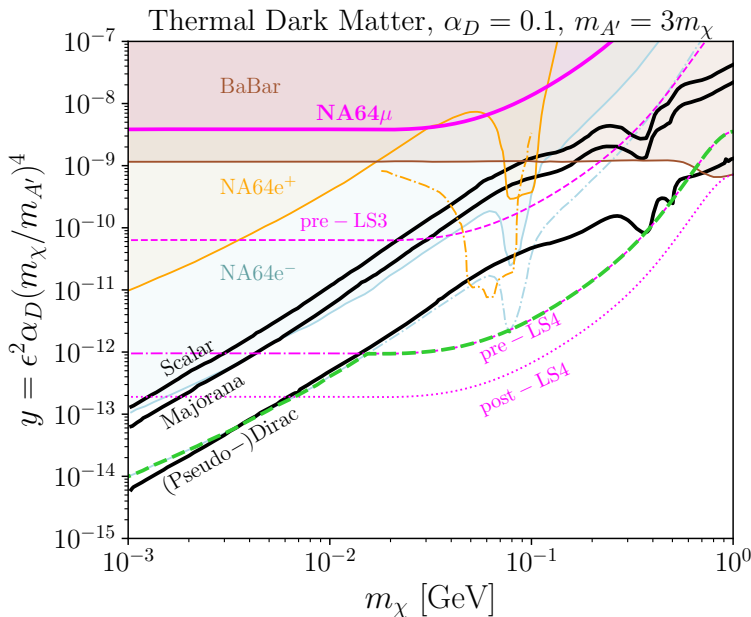
- **Prepare for Run 4**

Higher beam intensities and extended e⁻, e⁺, μ and hadron dark-sector programme

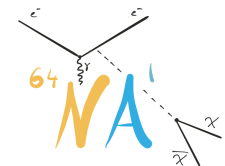


Post-LS3 NA64 programme and Run 4 physics reach

- e^- : pre-LS3 $\sim 2 \times 10^{12}$ EOT $\rightarrow$ Run 4: $\sim 10^{13}$ EOT
- e^+ : pre-LS3 $\mathcal{O}(10^{10})$ e^+ OT $\rightarrow$ Run 4: $> 10^{11}$ at several beam energies
- μ : pre-LS3 $\sim 3.5 \times 10^{11}$ MOT $\rightarrow$ Run 4: $> 10^{13}$ MOT
- h : pre-LS3 9.5×10^9 π OT $\rightarrow$ Run 4: programme to be defined in LS3



Run 4 statistics will allow NA64 to probe most of the remaining benchmark thermal-LDM parameter space.



Acknowledgments

NA64 collaboration and in particular S. Gninenko and L. Molina-Bueno



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Beam department: D. Banerjee, J. Bernhard, N. Charitonidis, G. Del Maso, L. Gattignon, M. Brugger

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