Latest results of NA64 searching for Dark Sectors at CERN SPS

MEPA 2023

Benjamin Banto Oberhauser, Group Prof. Dr. Paolo Crivelli, on behalf of the NA64 collaboration

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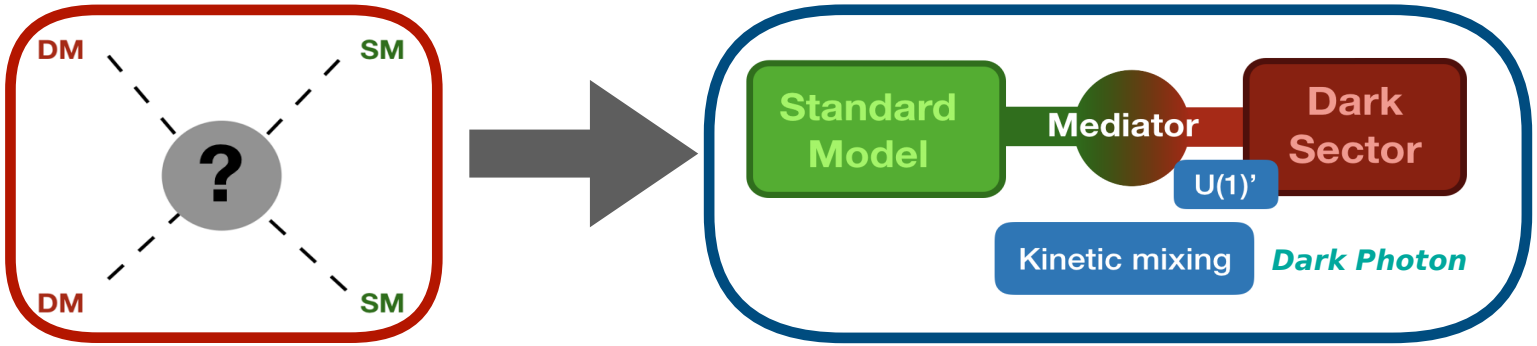
Motivation



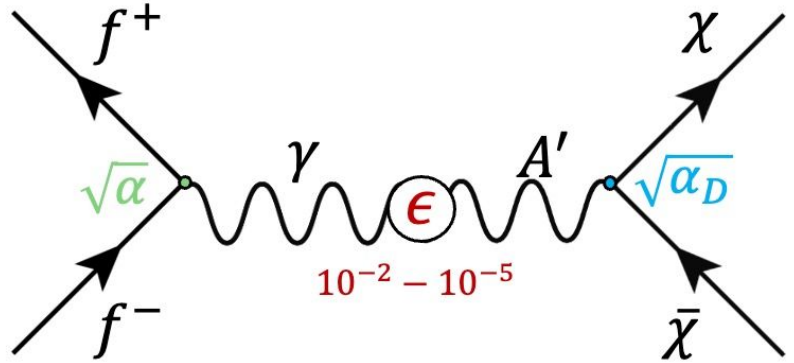
Dark particles could interact via **new feeble interactions**, generating portal connections with the SM

<u>Renormalizable portals:</u>

- **Vector portal** → **dark photon (A')**
- Scalar portal → dark Higgs
- Fermion portal → heavy neutral leptons

Vector portal: addition of new $U(1)_D$ symmetry to the SM gauge group

$$\mathcal{L}_{DP} = \frac{m_{A'}^2}{2} A'_\mu A'^\mu + A'_\mu \left(g_D \mathcal{J}^\mu_{DS} - e\varepsilon \mathcal{J}^\mu_{EM} \right)$$



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Motivation

Known gaps in SM + experimental anomalies:

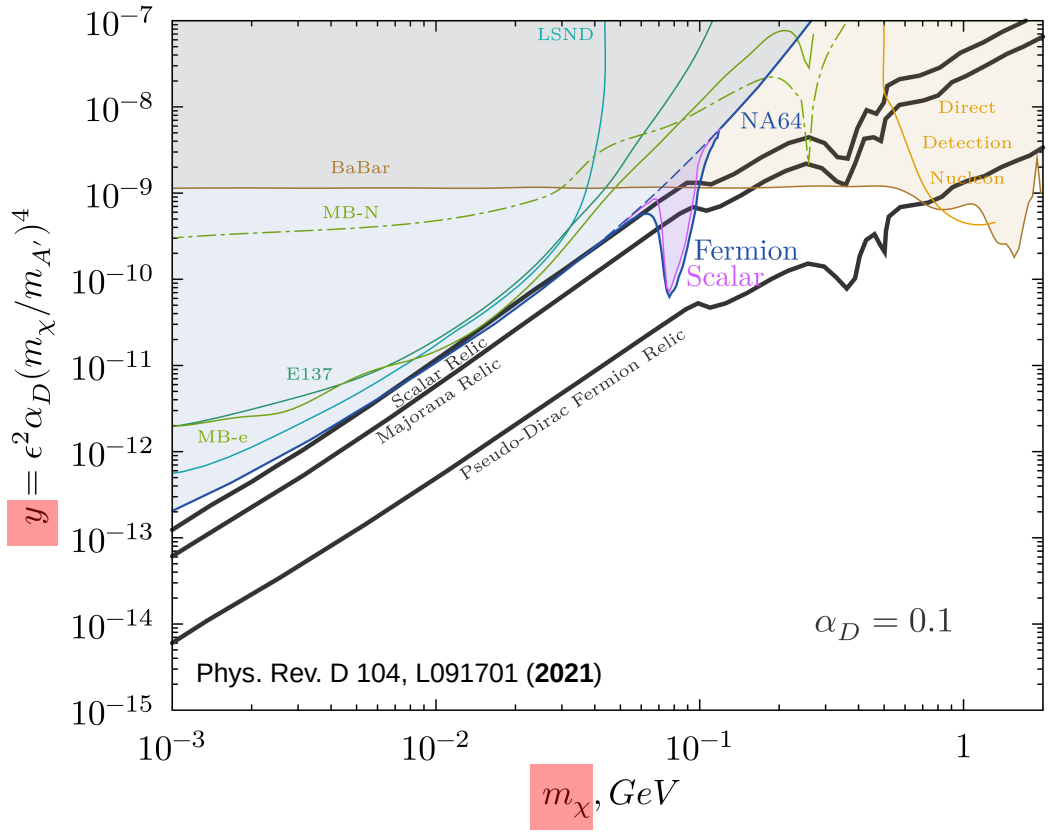
- **Sub-GeV thermal dark matter**
- Neutrino masses generation
- Muon $(g-2)_\mu$ anomaly

DM relic density

$$\Omega_\chi \propto \frac{1}{<\sigma v>} \sim \frac{m_\chi^2}{g_\chi^4}$$

$$\sigma v(\chi\chi \to A' \to ff) \propto \epsilon^2 \alpha_D \frac{m_\chi^2}{m_{A'}^4} = \frac{y}{m_\chi^2}$$

Target in LDM parameter space!



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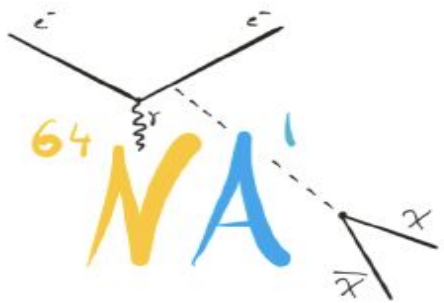
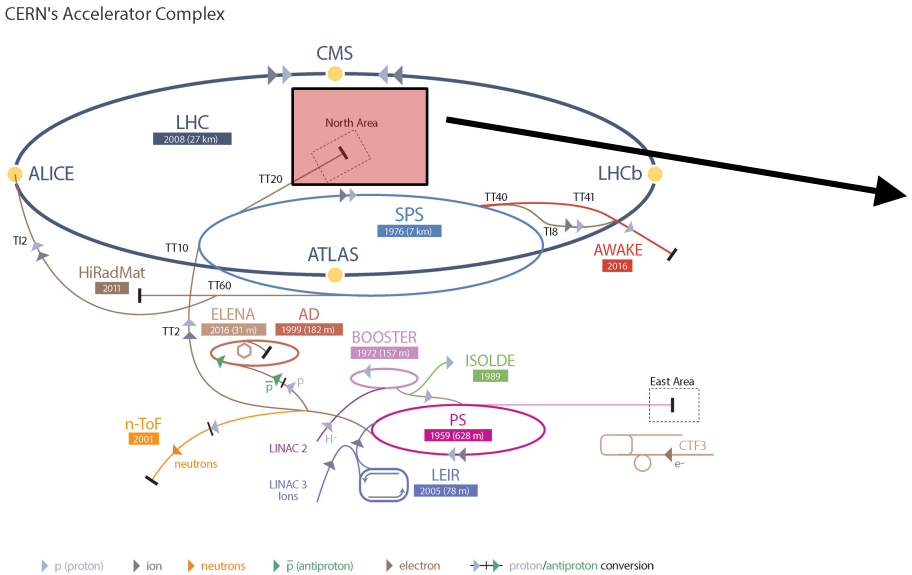
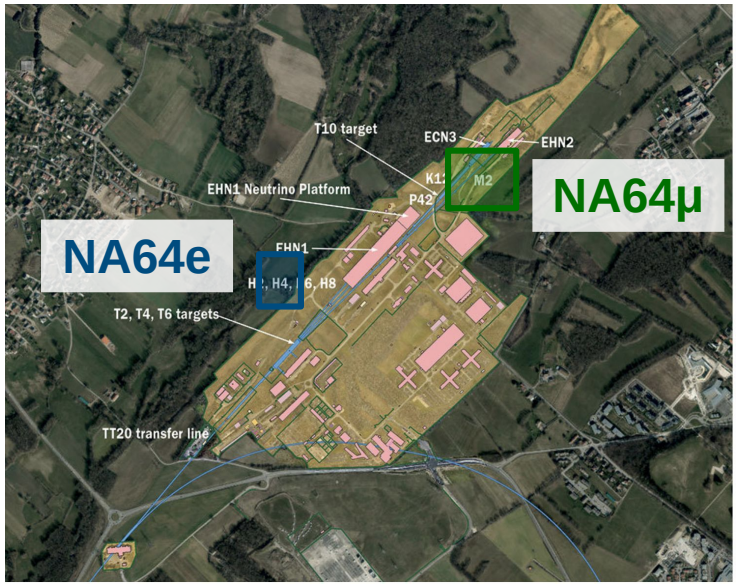
The NA64 experiment

Intensity-frontier, fixed-target experiment at the CERN SPS

- **High-purity e and μ beams** (H4 and M2 beam lines)
- Exploration of **Dark Sectors in MeV-GeV** scale
- **Active beam-dump** technique + **missing energy** search
  → Detection signal only relies on *A'* production $\propto \epsilon^2$







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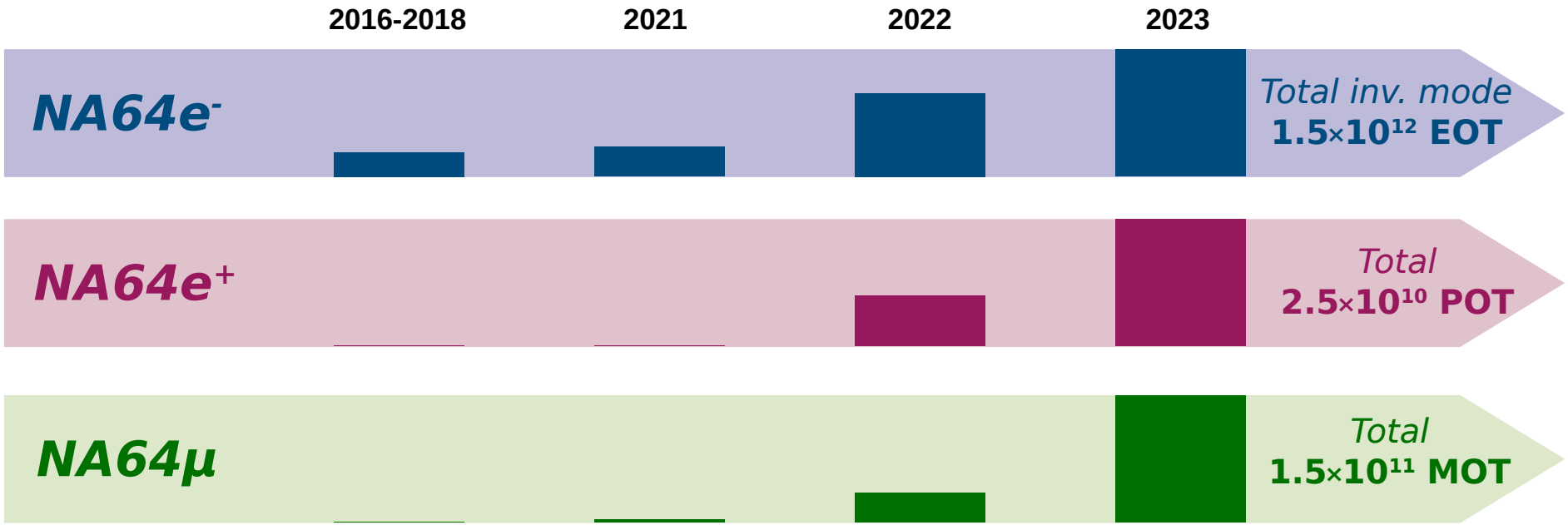
Overview of NA64 physics program



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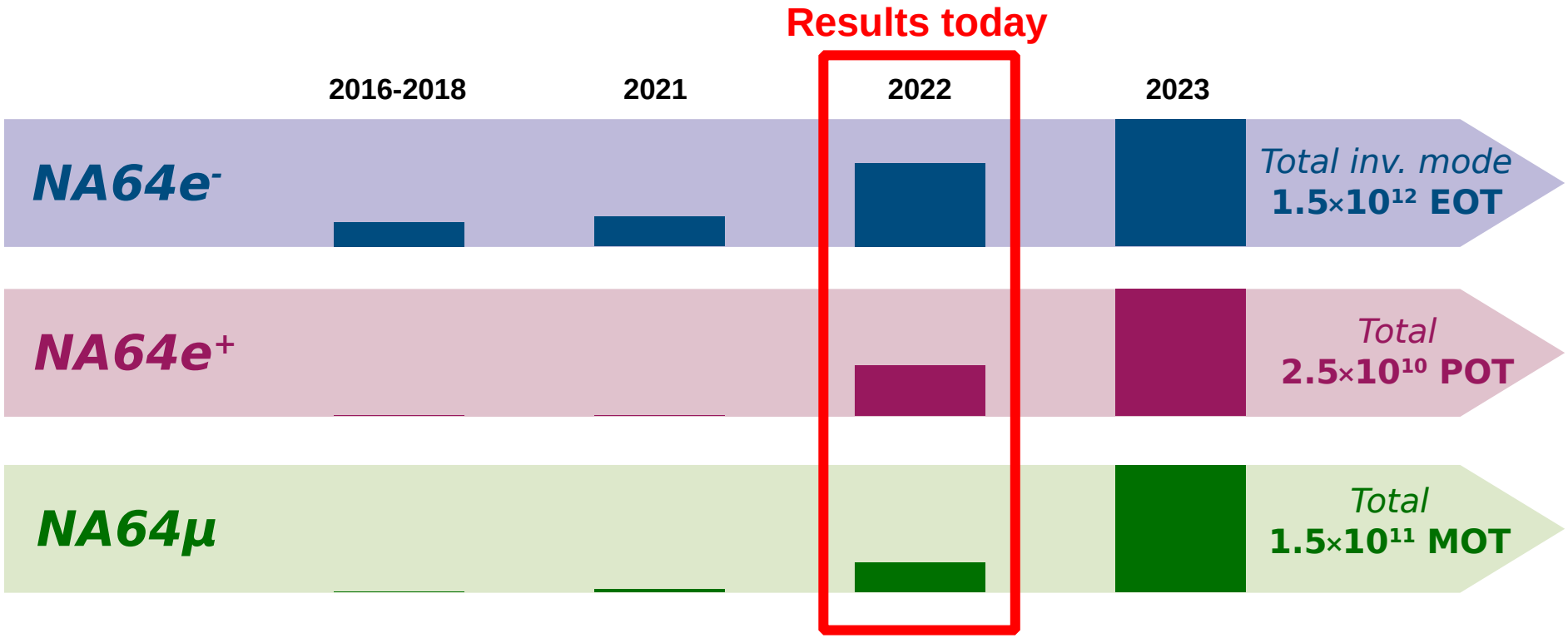


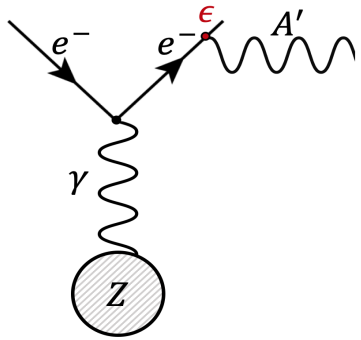
The NA64 technique

Active Dump + Fully hermetic detector

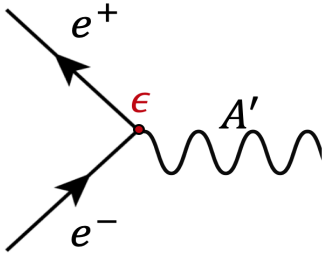
Initial well-defined beam

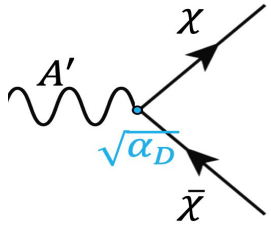
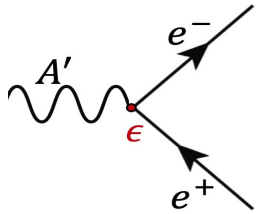
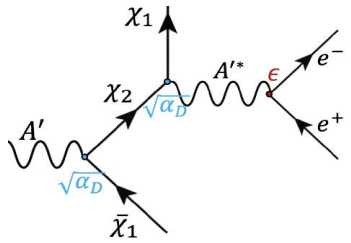
e^-, e^+, μ, π

A'-Bremsstrahlung

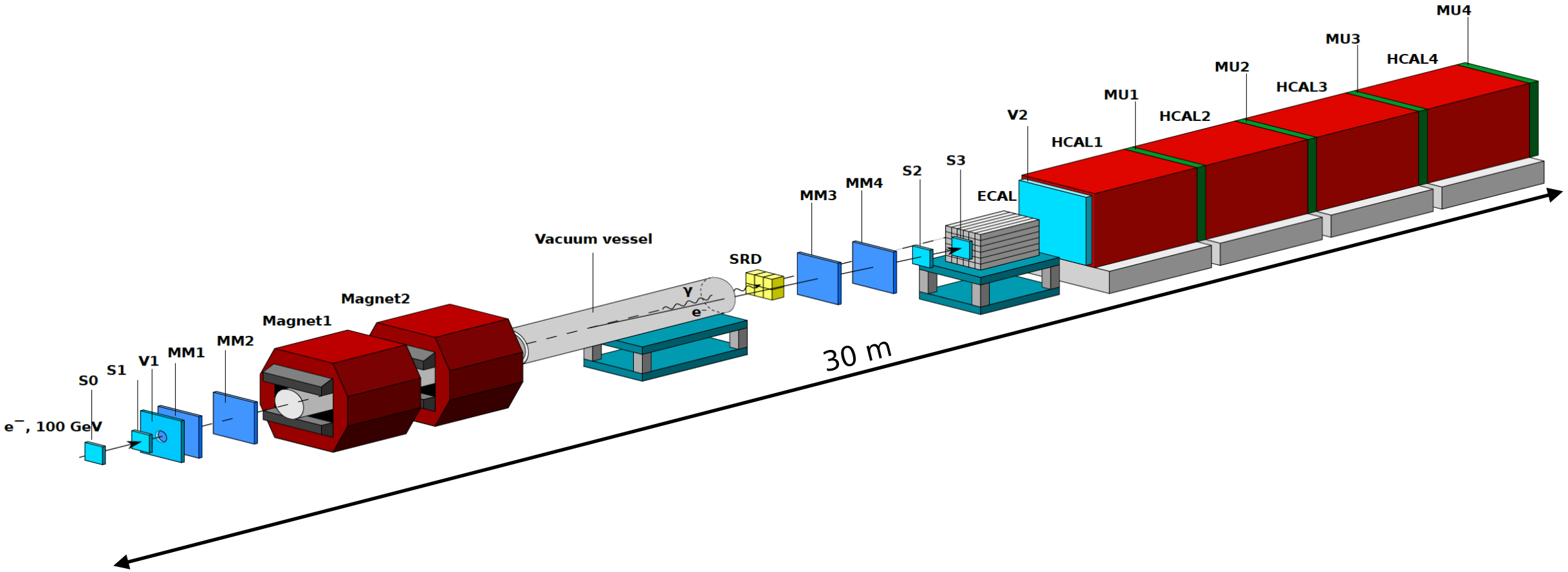


Resonant A' production



Decay		Signature
• *Invisible* $m_{A'} > 2m_\chi$		Missing energy
• *Visible* $m_{A'} < 2m_\chi$		SM pair particles
• *Semi-Visible* $m_{A'} > m_{\chi_1} >> m_e$		Missing energy + SM pair particles

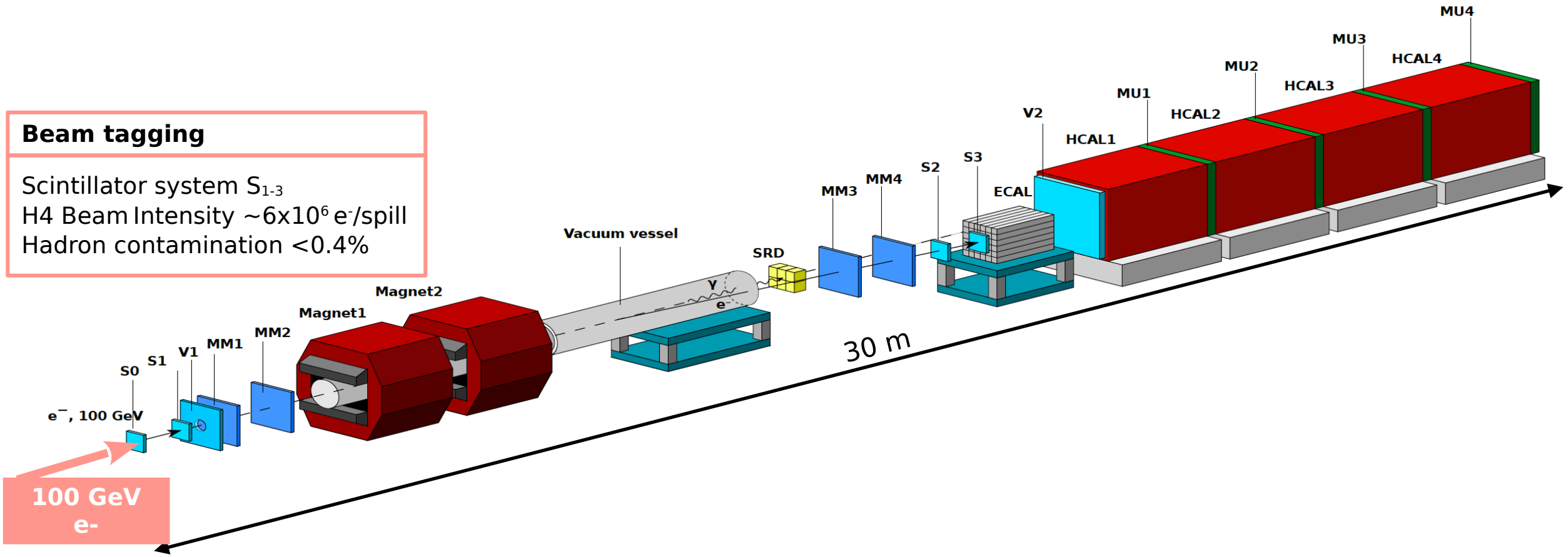
NA64 *invisible* mode: Experimental setup



NA64 *invisible* mode: Experimental setup

Beam tagging

Scintillator system $S_{1\text{-}3}$
H4 Beam Intensity ~$6x10^6$ e^-/spill
Hadron contamination <0.4%



NA64 *invisible* mode: Experimental setup

Momentum reconstruction

Tracking system
- 2 bending magnets (7 Tm)
- 4 Micromegas + 2 GEM detectors
- Momentum resolution ~1%

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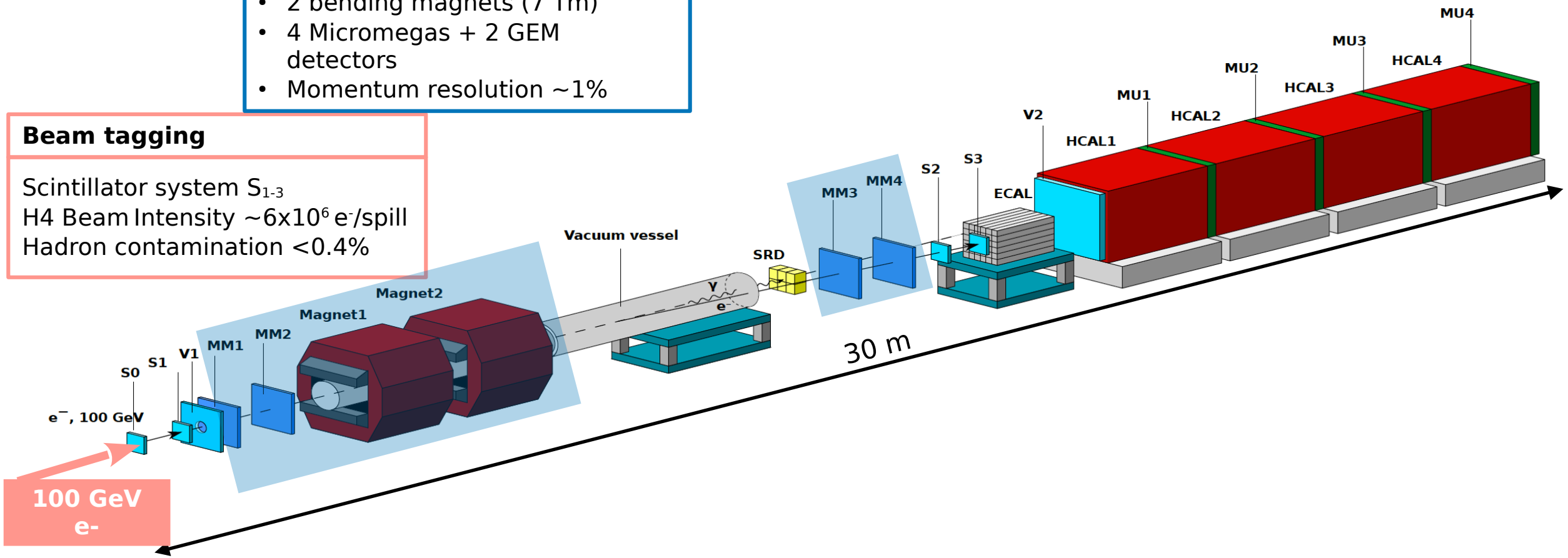

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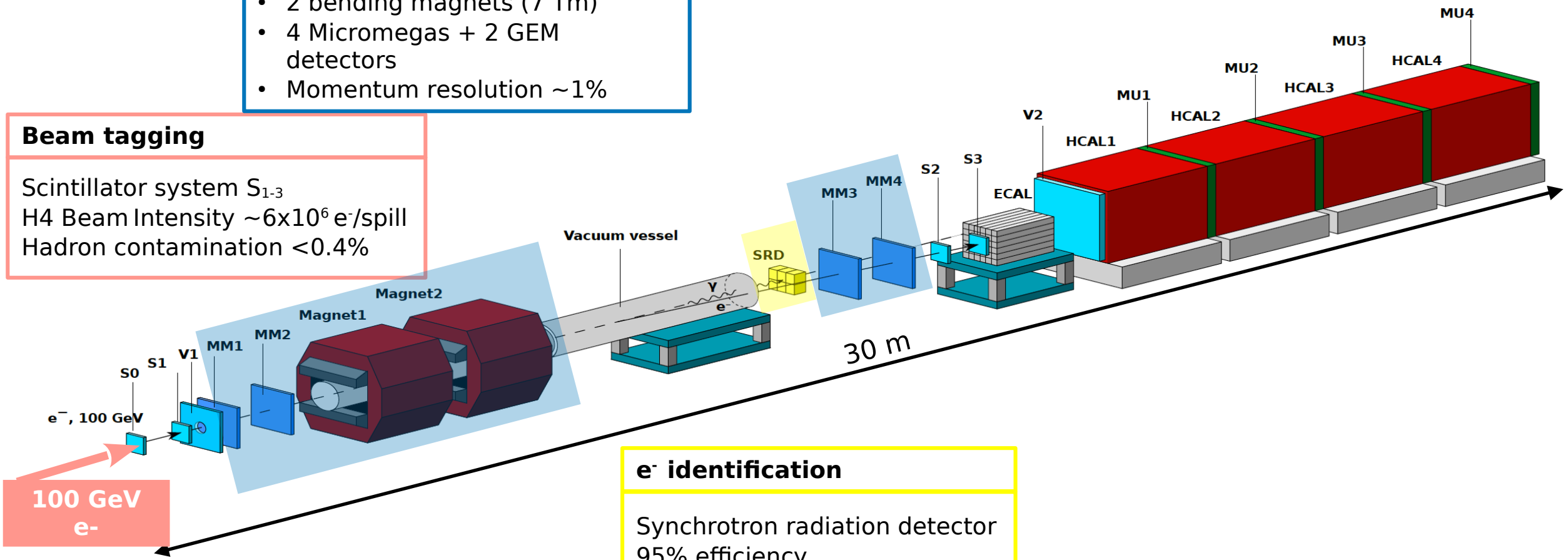

e^- identification

Synchrotron radiation detector
95% efficiency

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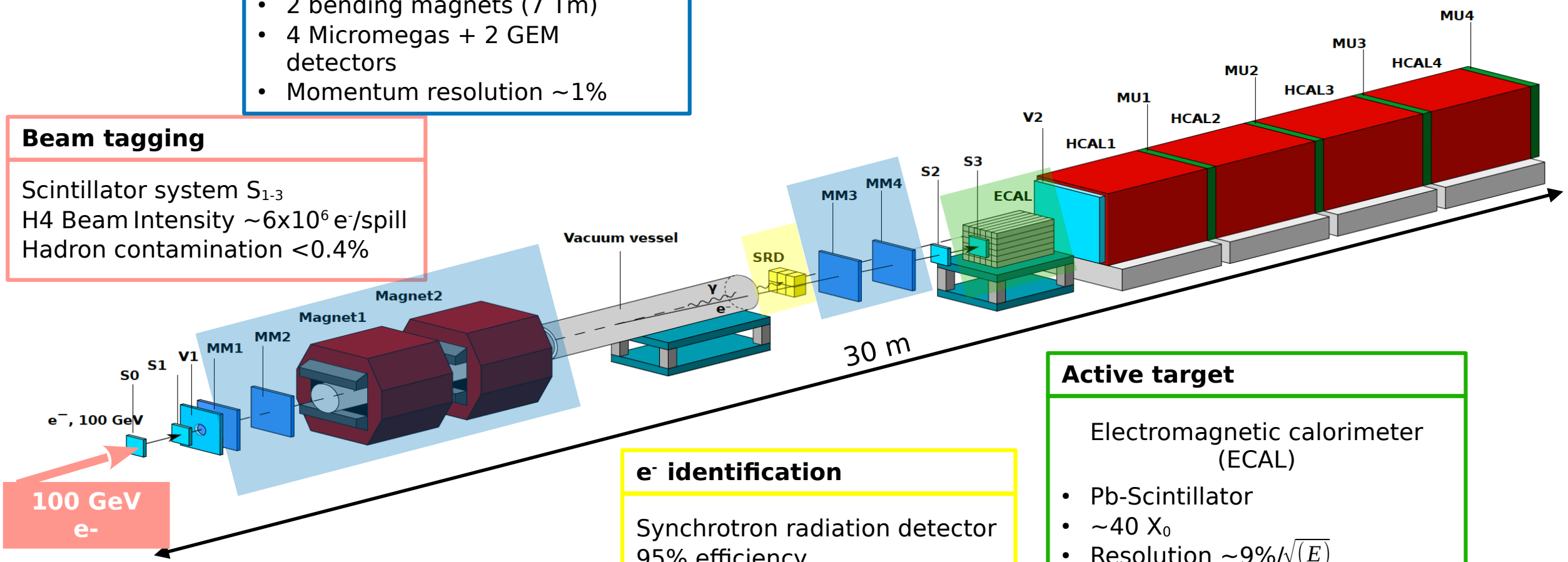

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95% efficiency

Active target

Electromagnetic calorimeter (ECAL)
- Pb-Scintillator
- ~40 X_0
- Resolution ~$9\%/\sqrt{(E)}$

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NA64 *invisible* mode: Experimental setup

Momentum reconstruction

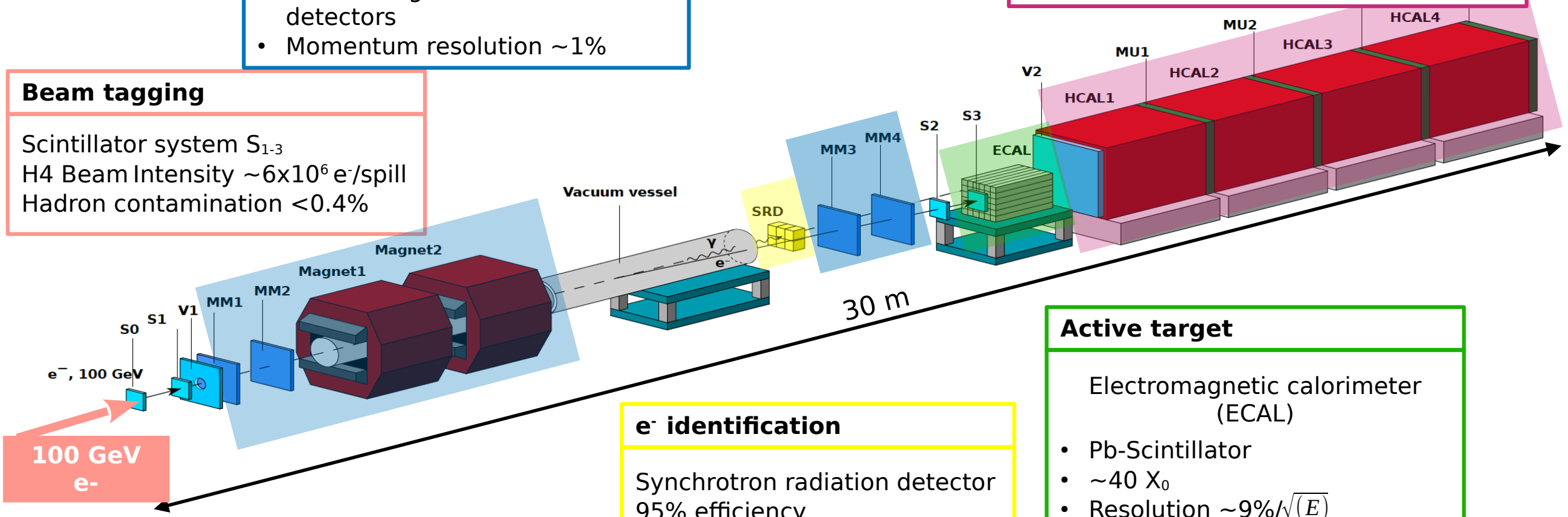
Tracking system
- 2 bending magnets (7 Tm)
- 4 Micromegas + 2 GEM detectors
- Momentum resolution ~1%

Hermeticity

Veto + Hadronic calorimeter (HCAL)
- Fe-Scintillator
- ~28 λ
- Resolution ~60%/$\sqrt{(E)}$

Beam tagging

Scintillator system $S_{1\text{-}3}$
H4 Beam Intensity ~6x10^6 e$^-$/spill
Hadron contamination <0.4%



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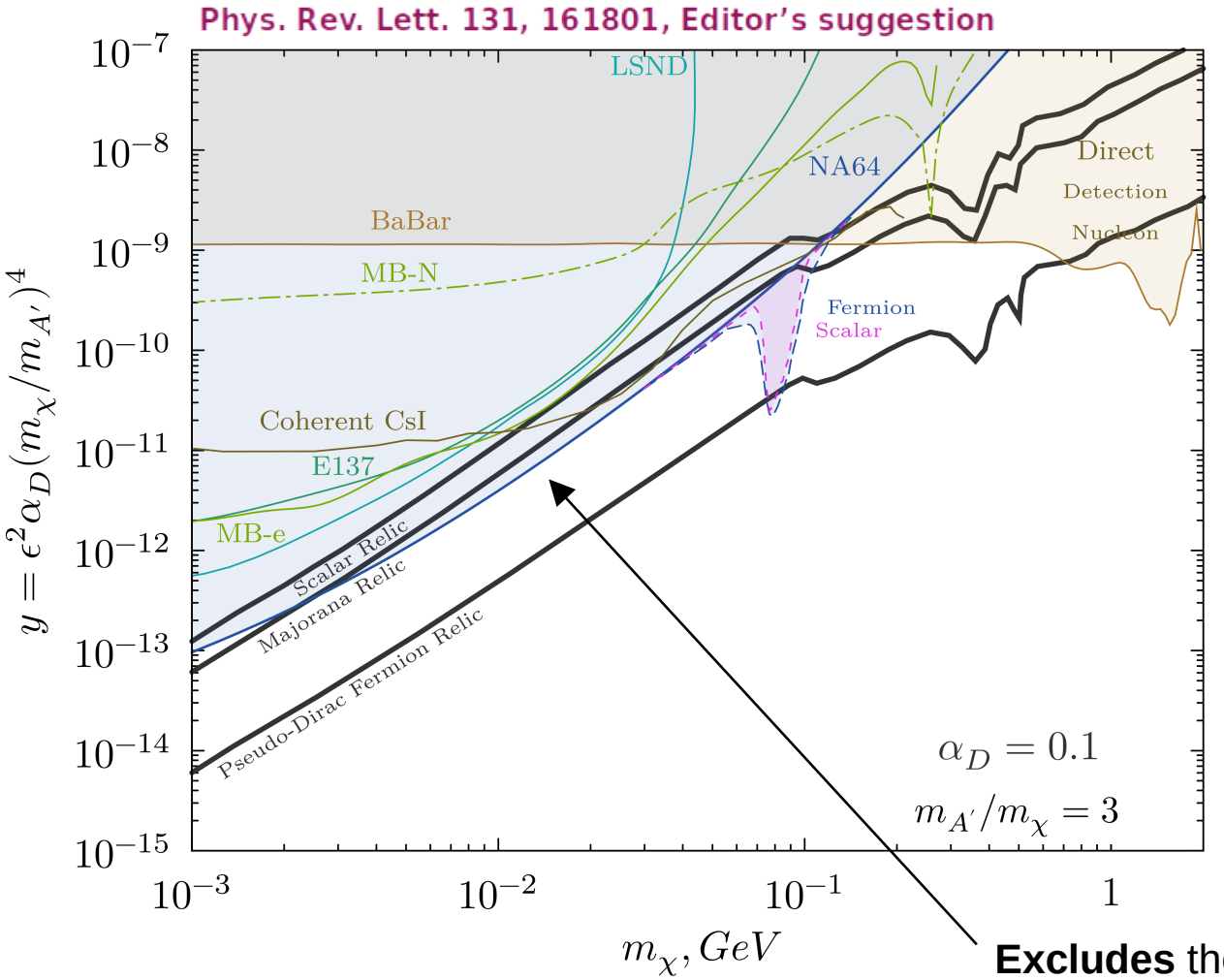
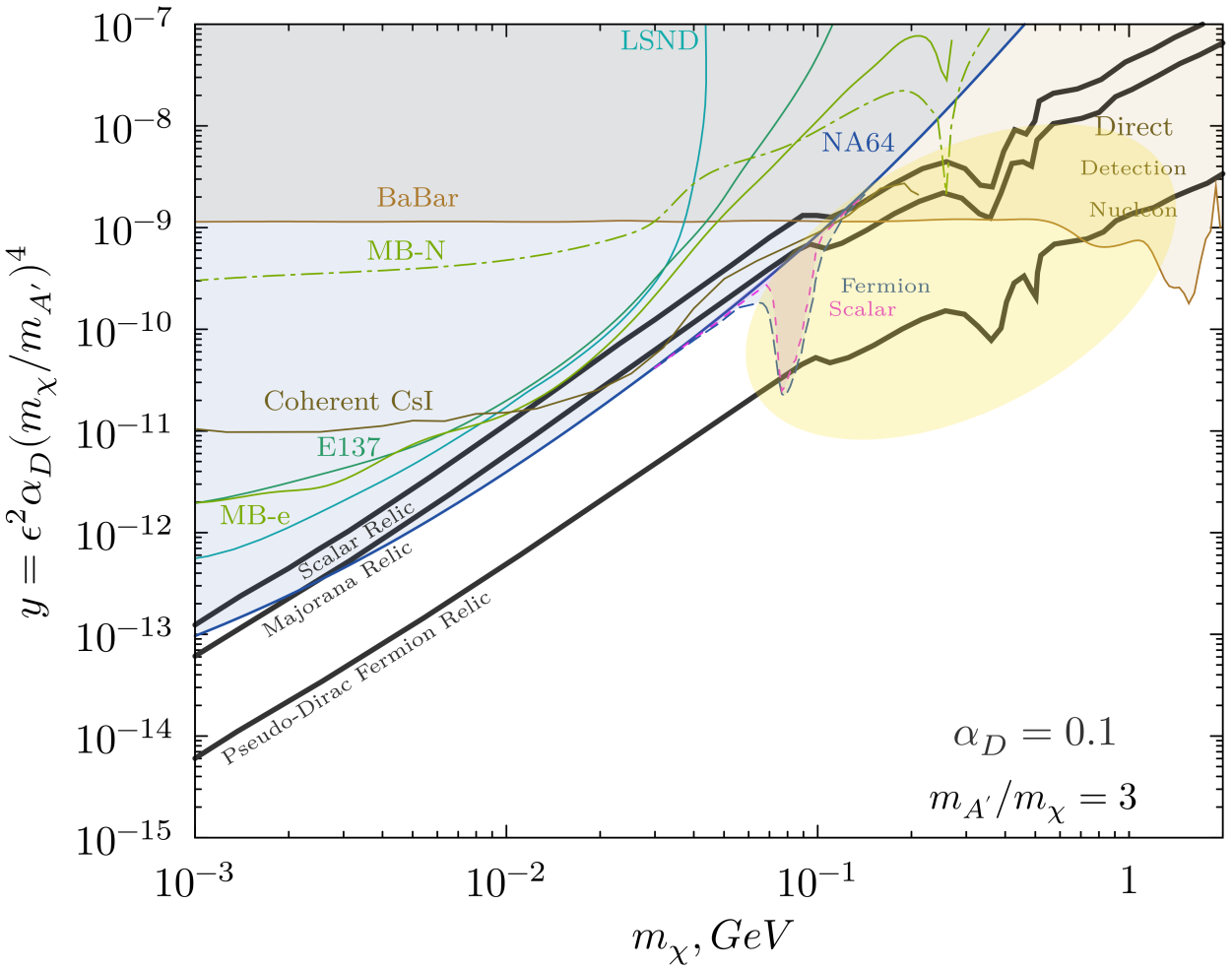
NA64e$^-$ results: combined 2016-2022 data, ~10^{12} EOT



- **No signal** found after unblinding
- Most stringent limits in the LDM parameter space!
- On-going extension these results to other physics cases:
  - L_μ-L_τ Z'
  - B-L Z'
  - Non-diagonal (inelastic) LDM
  - ALPs
  - ...

Excludes the Scalar and Majorana scenario

New complementary ideas



Bremsstrahlung A' emission **~1/m²$_{A'}$**

➡ signal yield suppressed at higher masses

How to enlarge the sensitivity at higher masses?

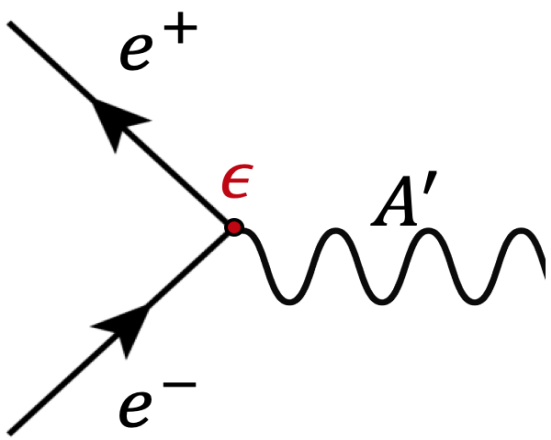
NA64 complementary searches

Use a **positron** beam: ***NA64e⁺***

L. Marsicano *et al.* Phys. Rev. Lett. 121, 041802

NA64 collaboration, Phys. Rev. D 104, L091701 (2021)

Resonant A' production

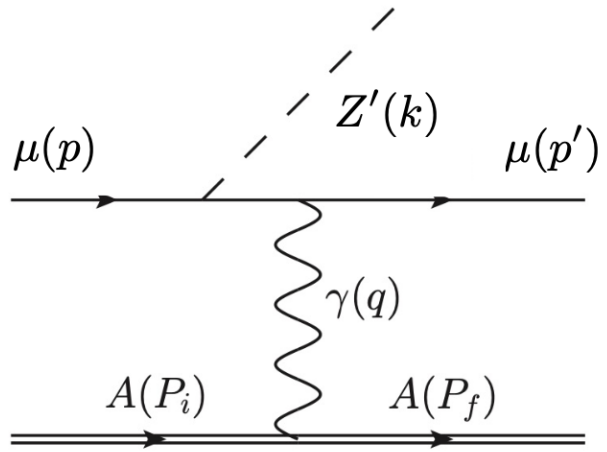


Use a **muon** beam: ***NA64μ***

S.Gninenko et al. PLB796, 117 (2019)

D. Banerjee et al. [NA64 Collaboration]. CERN-SPSC-2019-002 / SPSC-P-359, January 14, 2019.

Radiative Z’ production with muons



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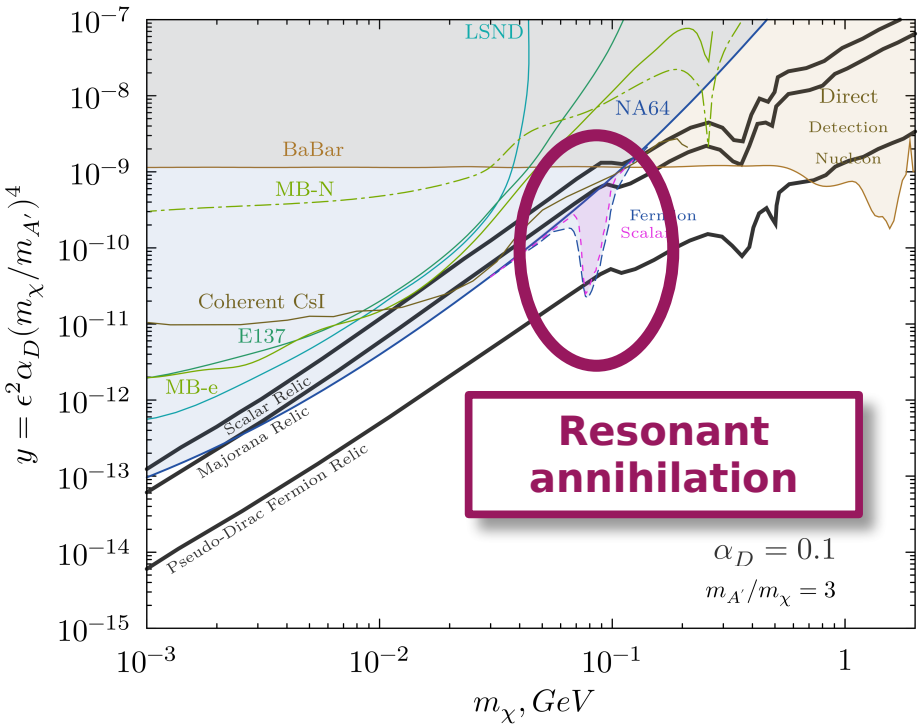

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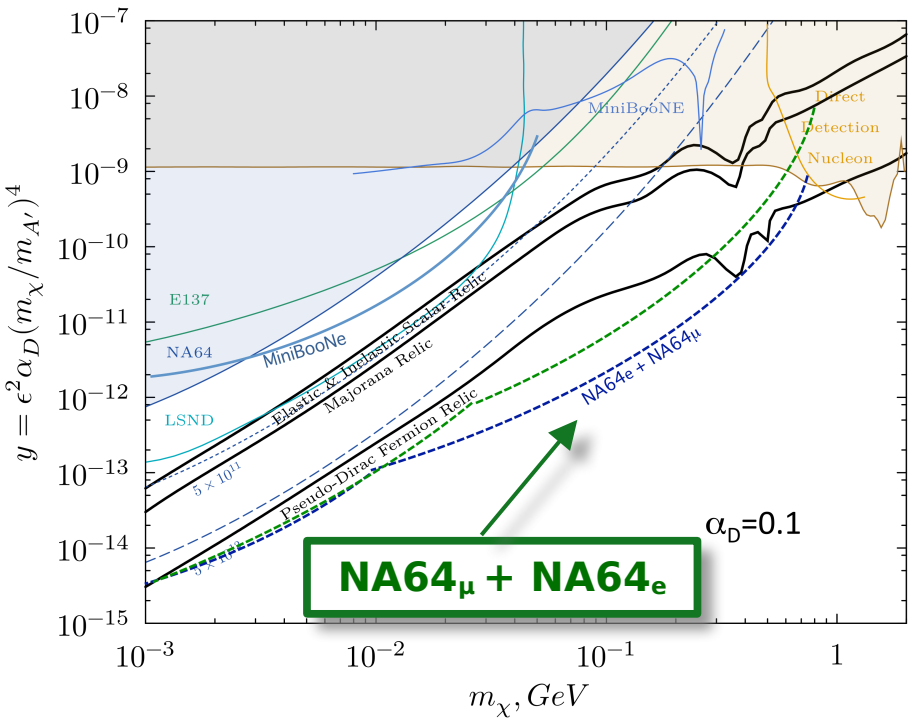

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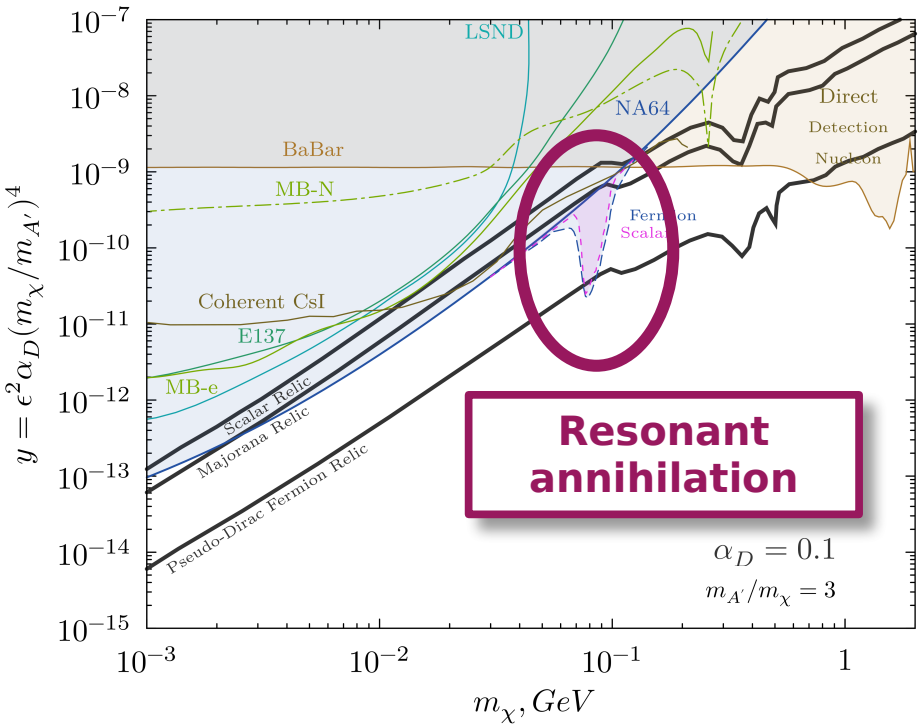

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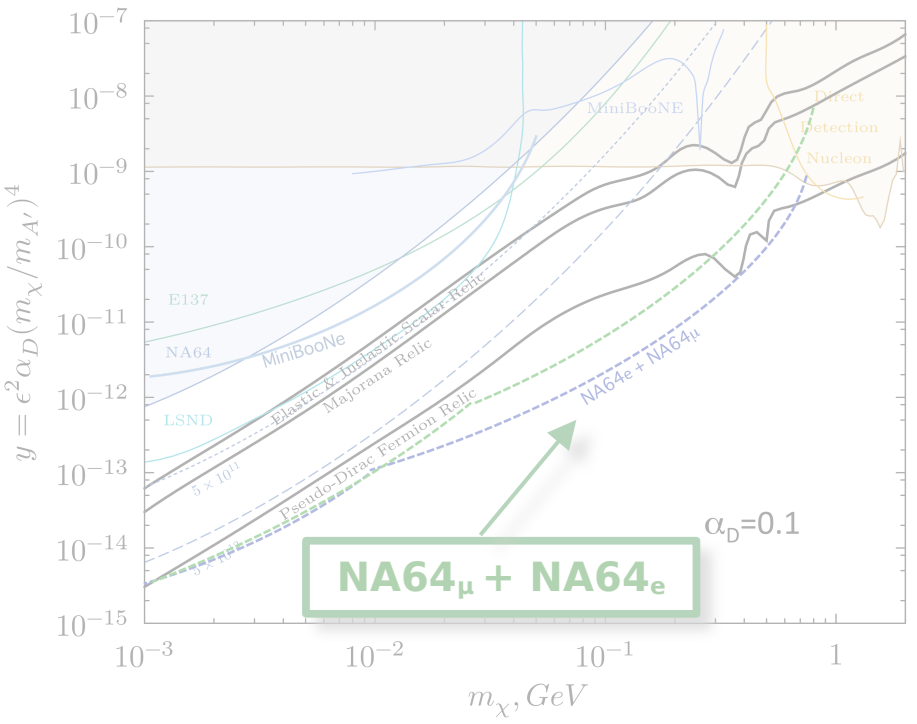

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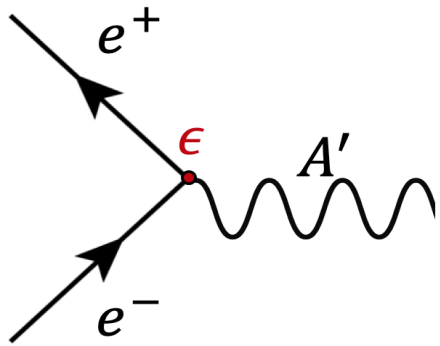
NA64 exploration with e⁺ beam



- Exploit resonant production:
  - Breit-Wigner-like cross section peaked at

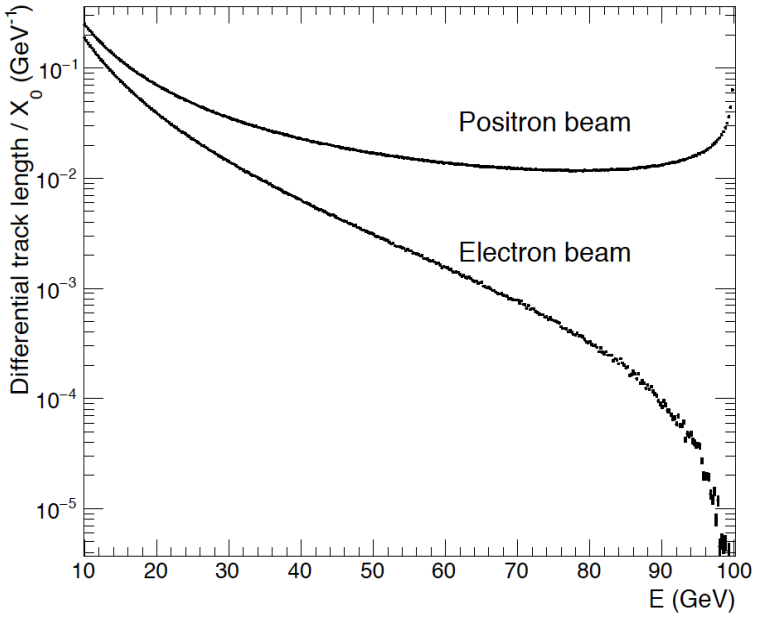
$$m^2_{A'} = 2 m_e E_e$$

- Signal enhancement in region:

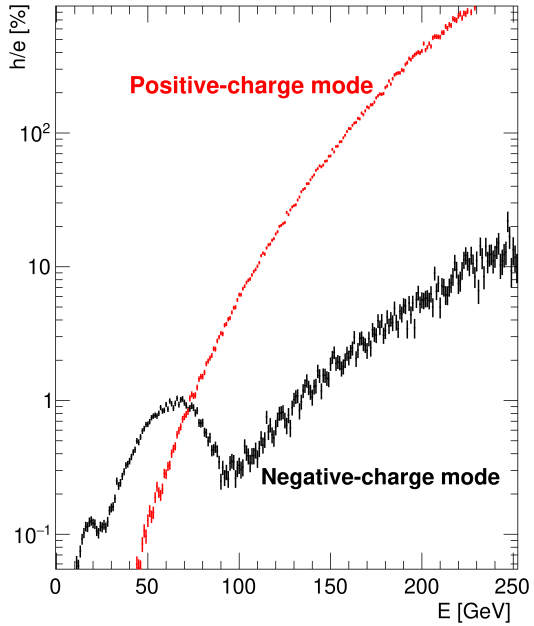
$$\sqrt{2 m_e E_{thr}} < m_{A'} < \sqrt{2 m_e E_0}$$

- Main challenge:
  - Hadronic background (4%)

Track length of secondary positrons in the thick target



h/e ratio at the T2 target (FLUKA)



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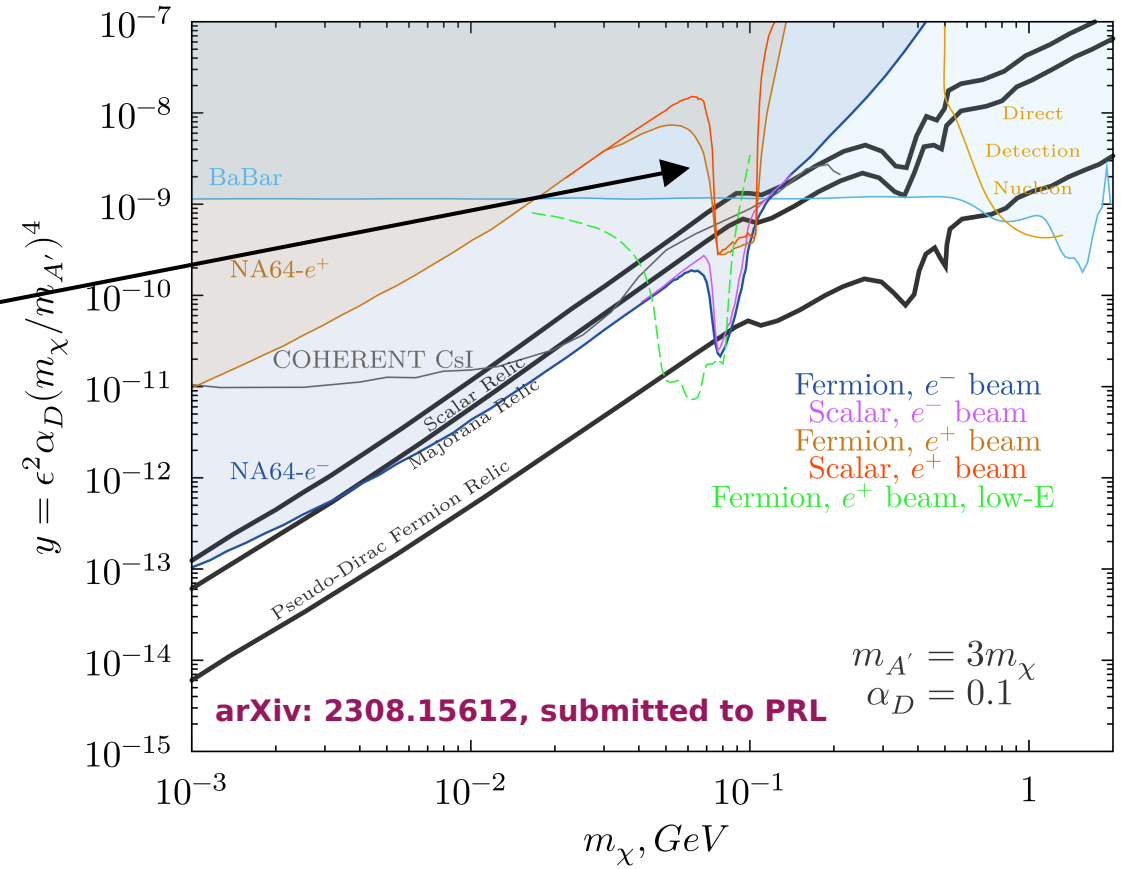
NA64 results with e⁺ beam

- A first pilot run in 2022
  - Collected **~10^{10} E⁺OT** with 100 GeV e⁺ beam
- **No signal** found after unblinding
  → Upper limits in LDM parameter space
- Enhanced sensitivity in resonant region, **despite x100 lower statistics**

- <u>Outlook:</u>
  Completed run at 70 GeV in 2023 to further explore the potential of e⁺ beam



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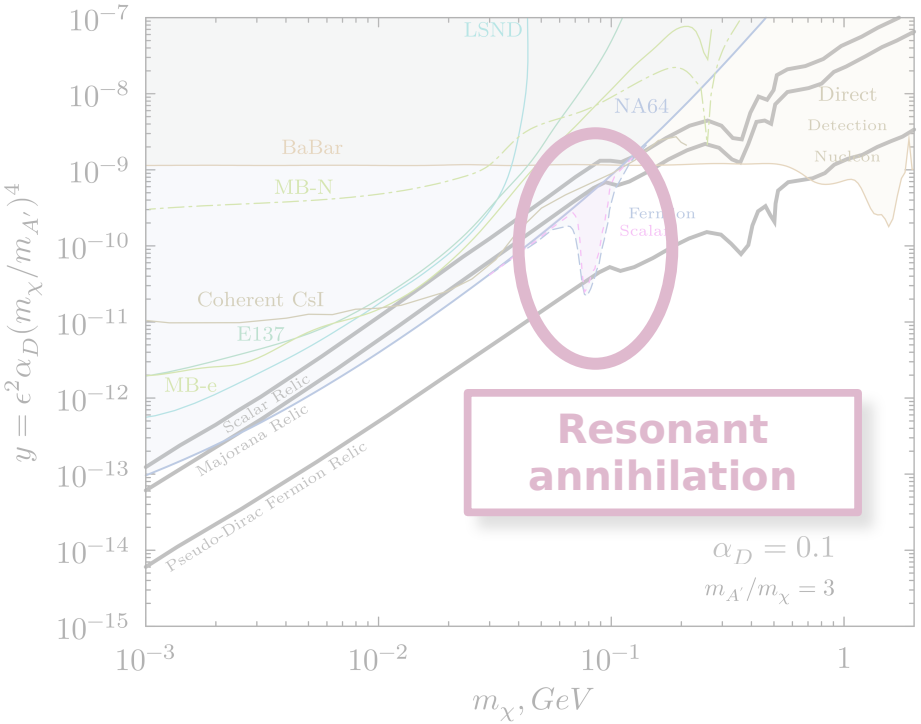

Use a **muon** beam: ***NA64μ***

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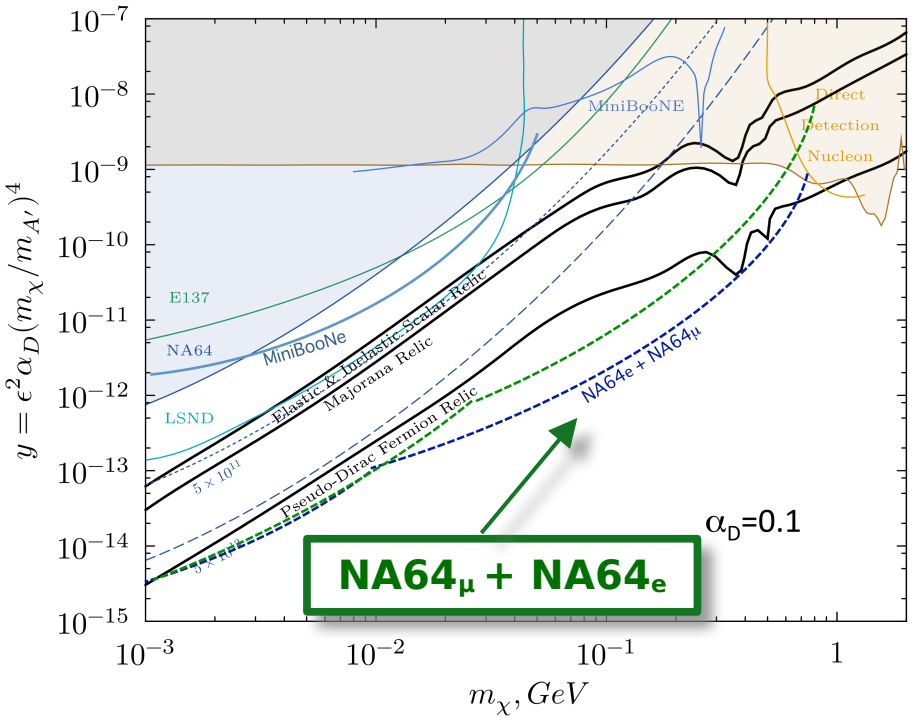

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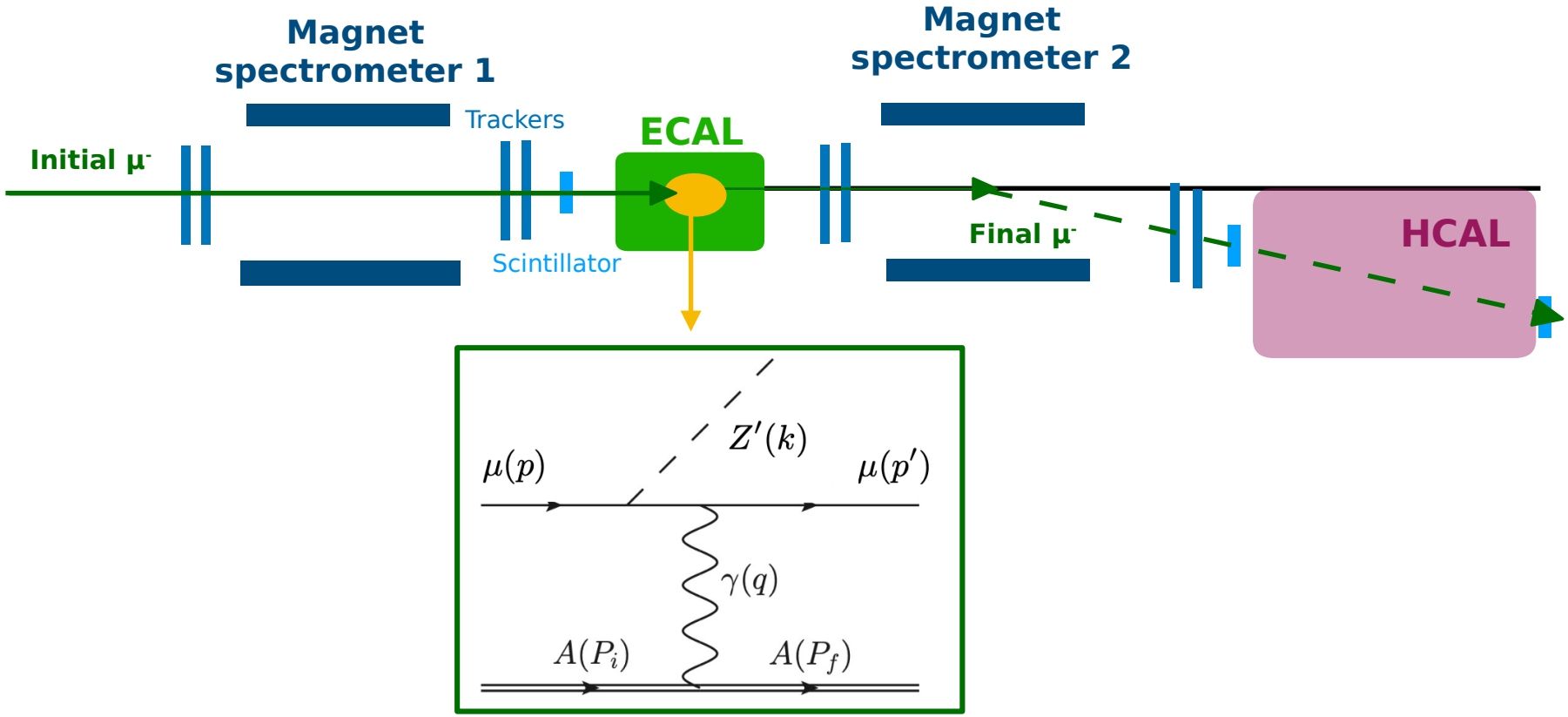
NA64μ experiment



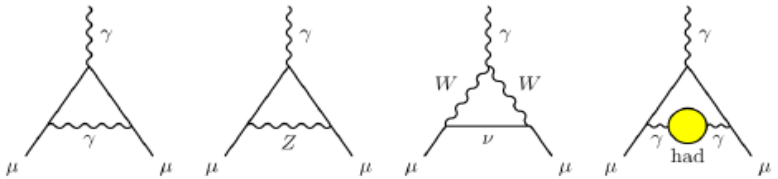
Signature

Missing energy + *missing momentum*

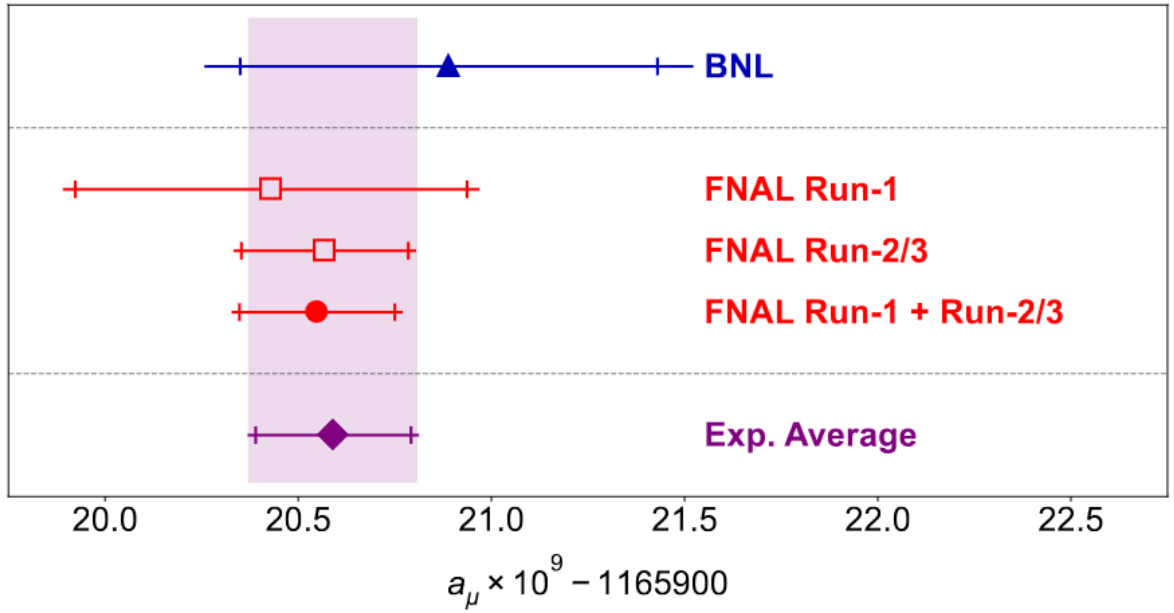
NA64μ: additional motivation, $(g-2)_\mu$

$$a_\mu = \frac{g_\mu - 2}{2}$$

$$a_\mu^{TH} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{HAD}$$



FNAL results from August 2023 reaffirm experimental measurements



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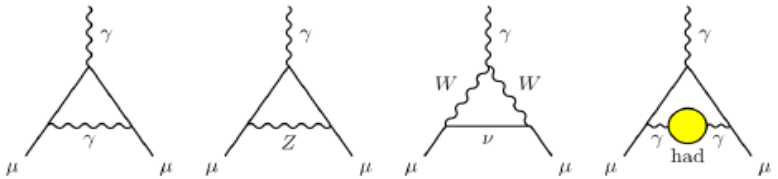
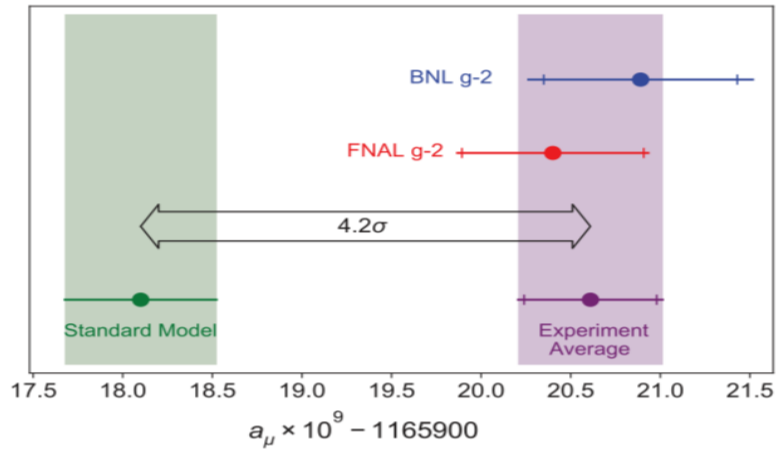
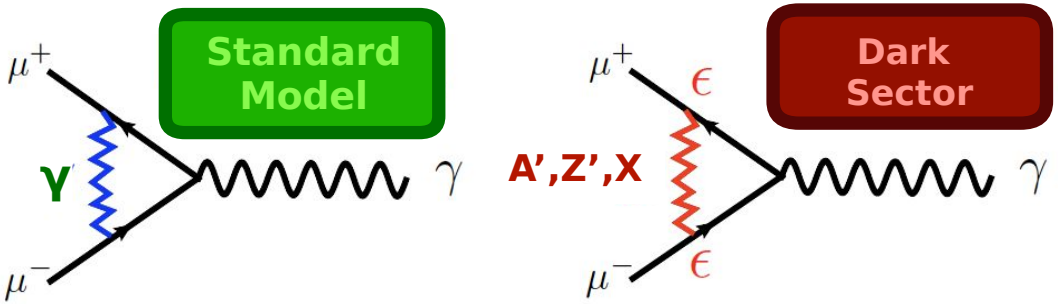


$$\Delta a_\mu = a_\mu^{EXP} - a_\mu^{TH} = (251 \pm 59) \cdot 10^{-11}$$



(Lattice QCD calculations are in better agreement)



Specific target for NA64

New physics?
1-loop contributions from dark sector bosons such as A', Z' or a generic X

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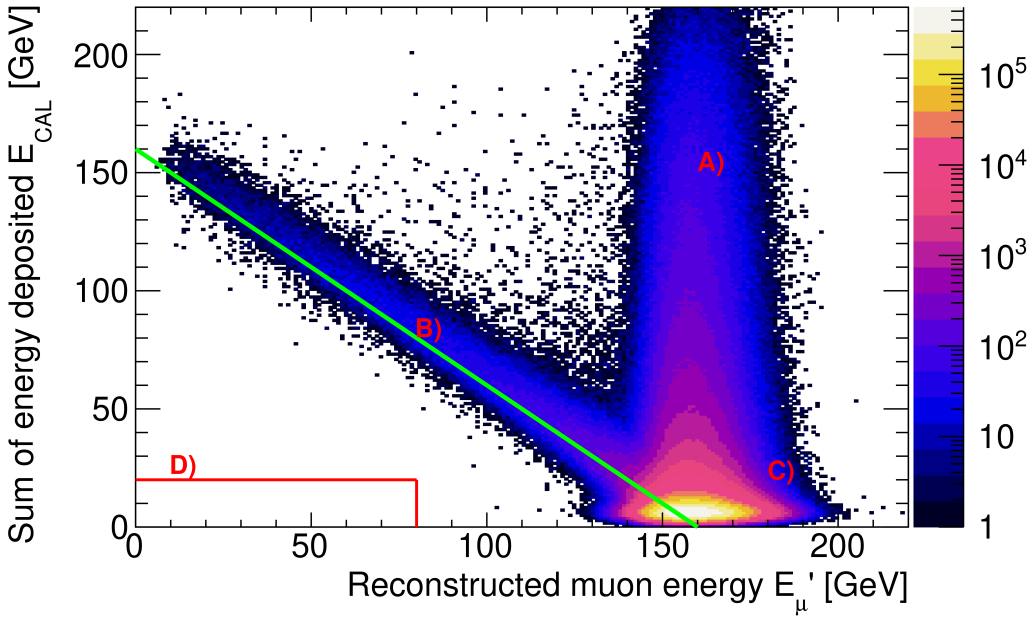
NA64μ experimental technique

- **Signature:**
  - Well-defined incoming μ with 160 GeV/c
  - Scattered μ with < 80 GeV/c
  - No activity in VHCAL and Vetos
  - MIP energy deposit in ECAL and HCAL

- **Main challenges:**
  - Fully hermetic detector
  - Initial and final μ momenta mis-measurements down to $<10^{-13}$
  - High beam intensities $>10^{6}$ μ/s



Background source	Background, n_b
Momentum mis-reconstruction	0.045 ± 0.031
Hadron in-flight decays	0.010 ± 0.001
Calorimeter non-hermeticity	< 0.01
Total (conservatively) n_b	0.07 ± 0.03

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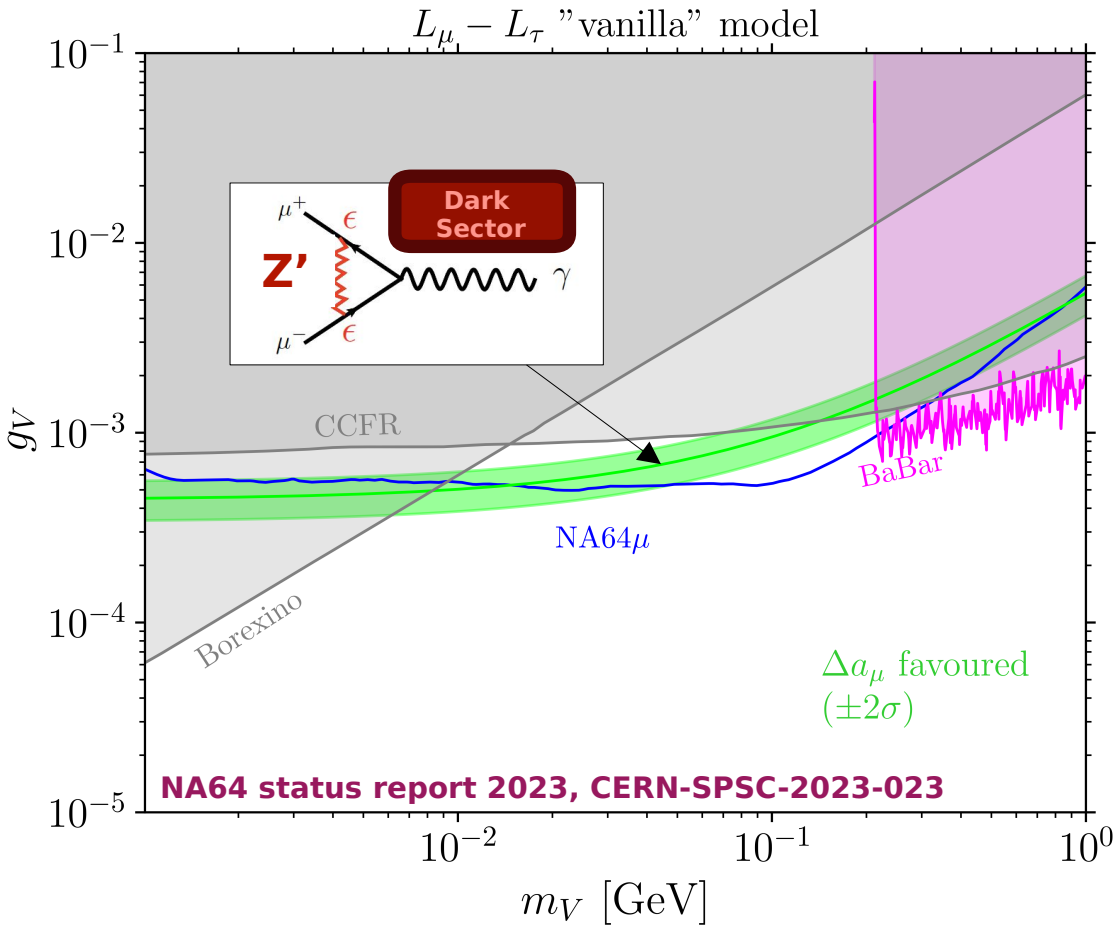
NA64μ analysis (still blinded)



- Blinded analysis with data and MC-driven background estimation
- Preliminary results at 90% C.L. assuming no signal suggest that a **significant part of the (g-2)$_\mu$ can be covered**

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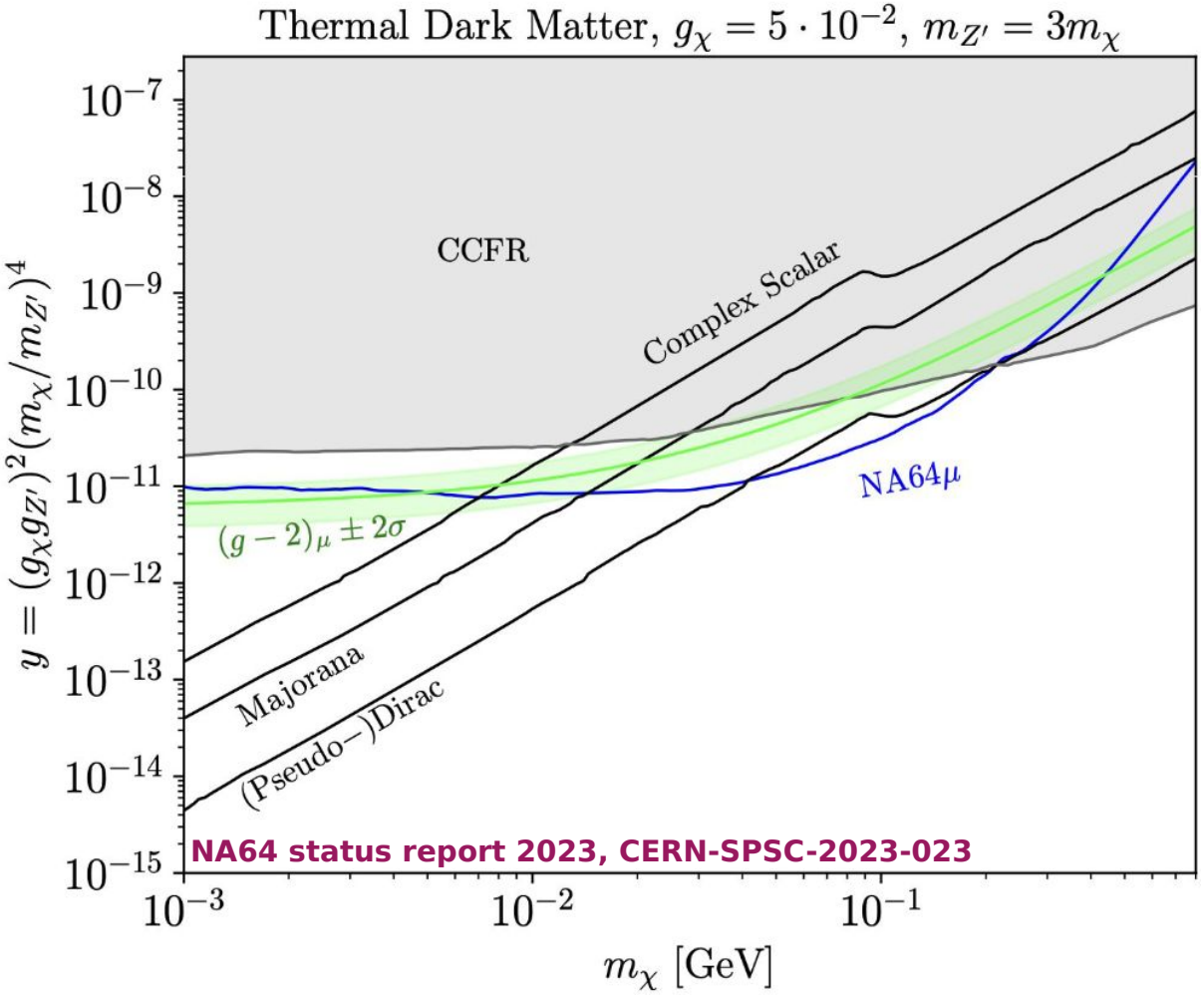
NA64μ complementary LDM results



- Additional results on **muon-philic scalar boson** and **LDM complementary searches to NA64e** will follow!

- <u>Outlook:</u>

  Run in 2023 with **improved setup** aiming to reduce background

Summary and outlook

NA64e⁻

- **Collected ~1.5×10¹² EOT** being background-free
- **Probing the LDM models** suggested parameter space
- Extend results to **other DS scenarios:**
  - L_μ-L_τ Z', B-L Z', ALPs, non-diagonal (inelastic) LDM.

NA64e⁺

- **Positron program successfully started in 2022 and continued in 2023!**
- **Confirmed feasibility**, complementing the electron results in the high-mass region

NA64μ

- **Pilot run in 2021** and **2022** (4x10¹⁰ MOT collected)
- Analysis (**to be unblinded**) → probe **$(g-2)_\mu$ parameter space** in **L_μ-L_τ Z'** mode
- **On-going analysis** of the recent **2023 run** (1.5x10¹¹ MOT)

The NA64 hunt for New Physics has just begun!

THANKS!

Acknowledgements

The NA64 Collaboration, in particular P. Crivelli and S. Gninenko

The ETH Zurich group, in particular P. Crivelli, H. Sieber, M. Mongillo, P. Blumer

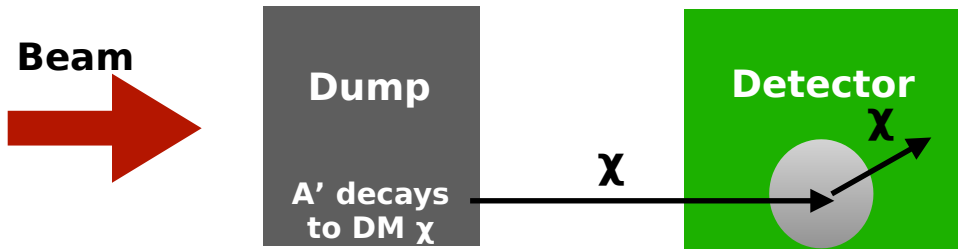
The IFIC group, in particular L. Molina Bueno and M. Tuzi

Funded by ETH Zürich Grant 22-2 ETH-031 and SNSF Grants No. 169133, 186181, 186158, 197346

Backup

NA64 *invisible* mode

1) BEAM DUMP APPROACH (MiniBooNE, LSND, NA62, SHIP, T2K, DUNE…)



$e^- \chi$ scattering

Flux of X generated by decays of A's produced in the dump.

Signal: X scattering in far detector

$$\sigma \propto \epsilon^4 \alpha_D$$

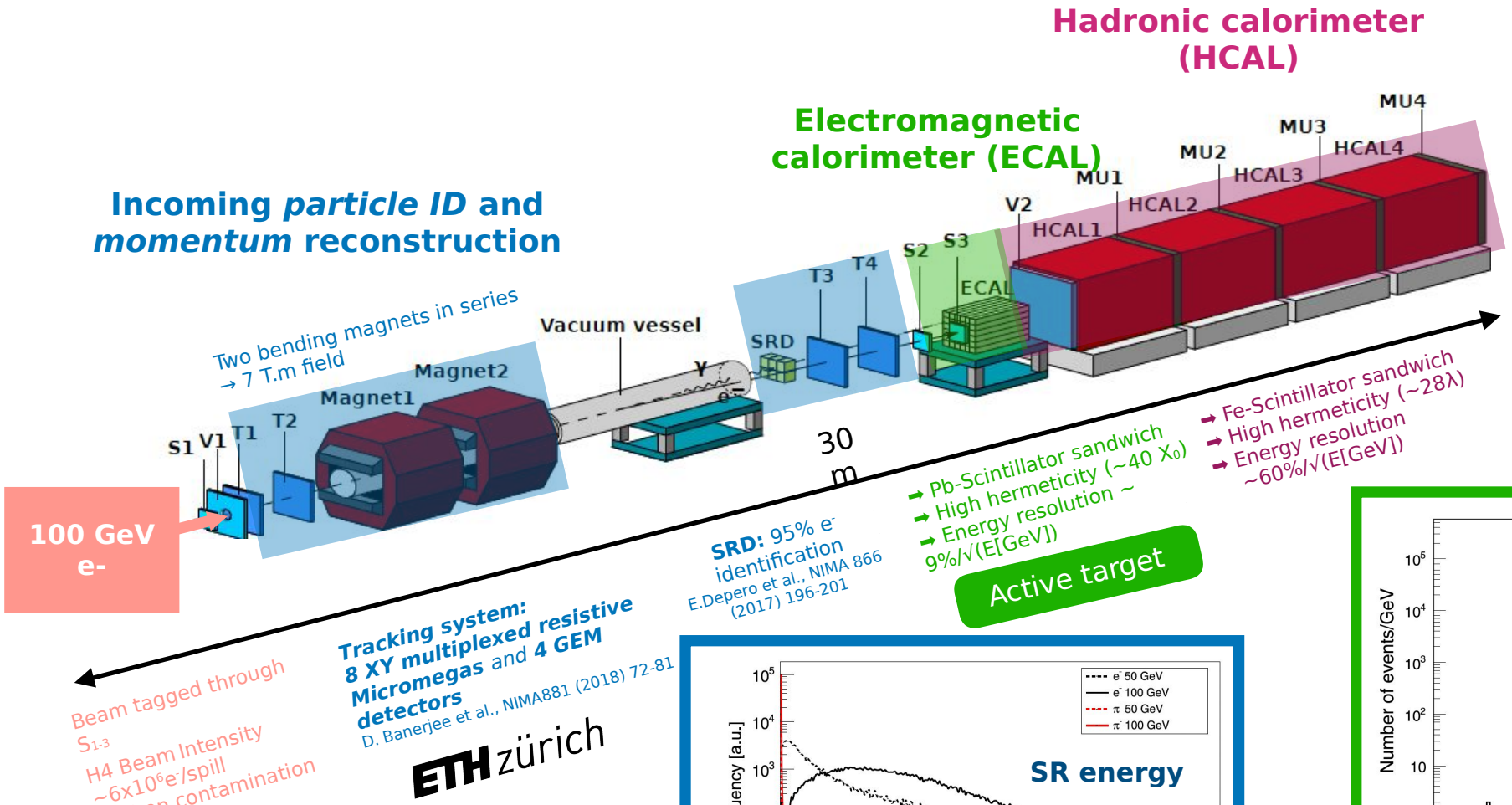
2) NA64/LDMX APPROACH

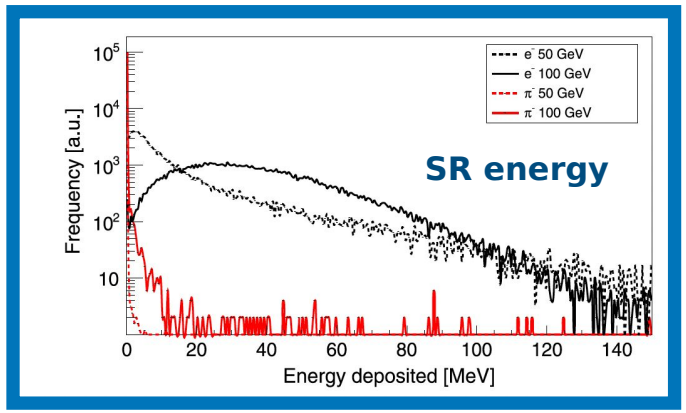
Produced A's carry away energy from the active dump.

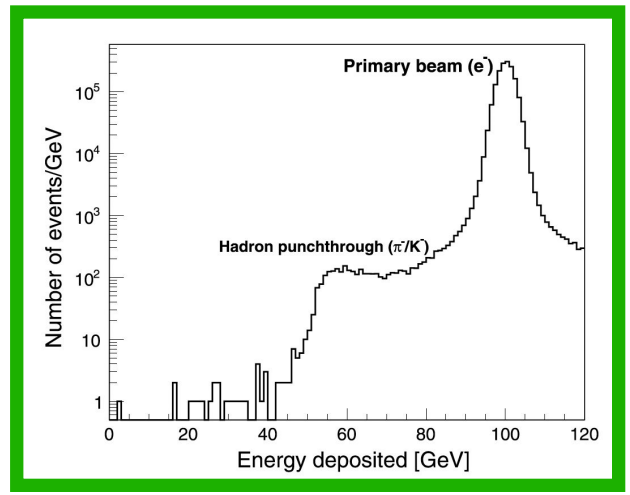
Signal: Missing energy/momentum

$$\sigma \propto \epsilon^2$$

NA64 *invisible* mode: Experimental setup







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NA64 *invisible* mode: Background for ~10^{12} EOT

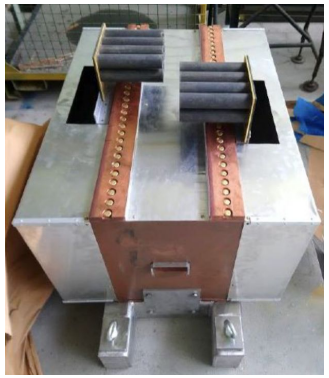
TABLE I. Expected background for 2021-2022 runs

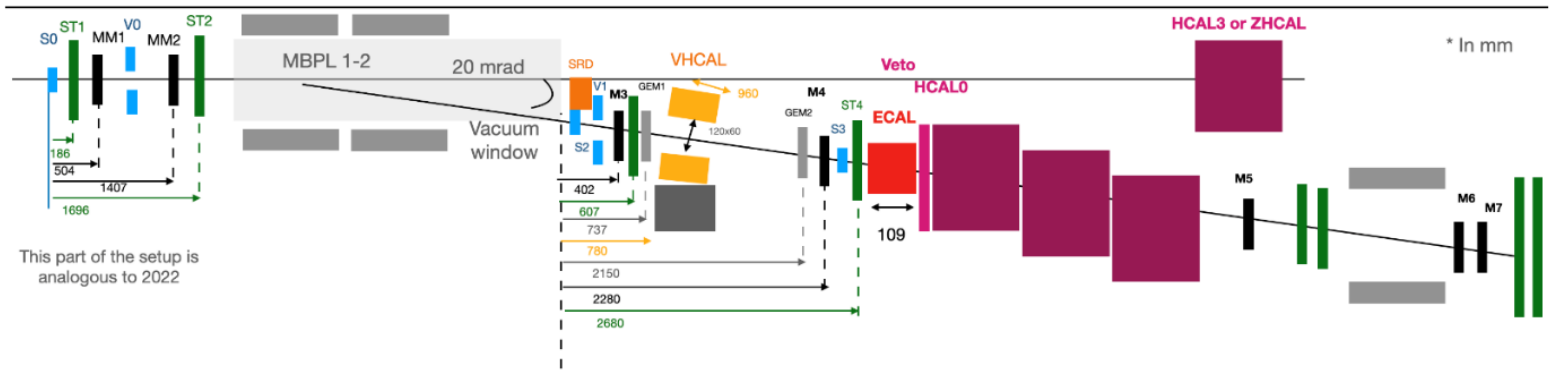
Background source	Background, n_b
(i) dimuons losses or decays in the target	0.04 ± 0.01
(ii) $\mu, \pi, K \to e + ...$ decays in the beam line	0.3 ± 0.05
(iii) lost γ, n, K^0 from upstream interactions	0.16 ± 0.12
(iv) Punch-through leading n, K_L^0	< 0.01
Total n_b (conservatively)	0.51 ± 0.13

NA64 *invisible* mode: 2023 run, 5.1×10^{11} EOT

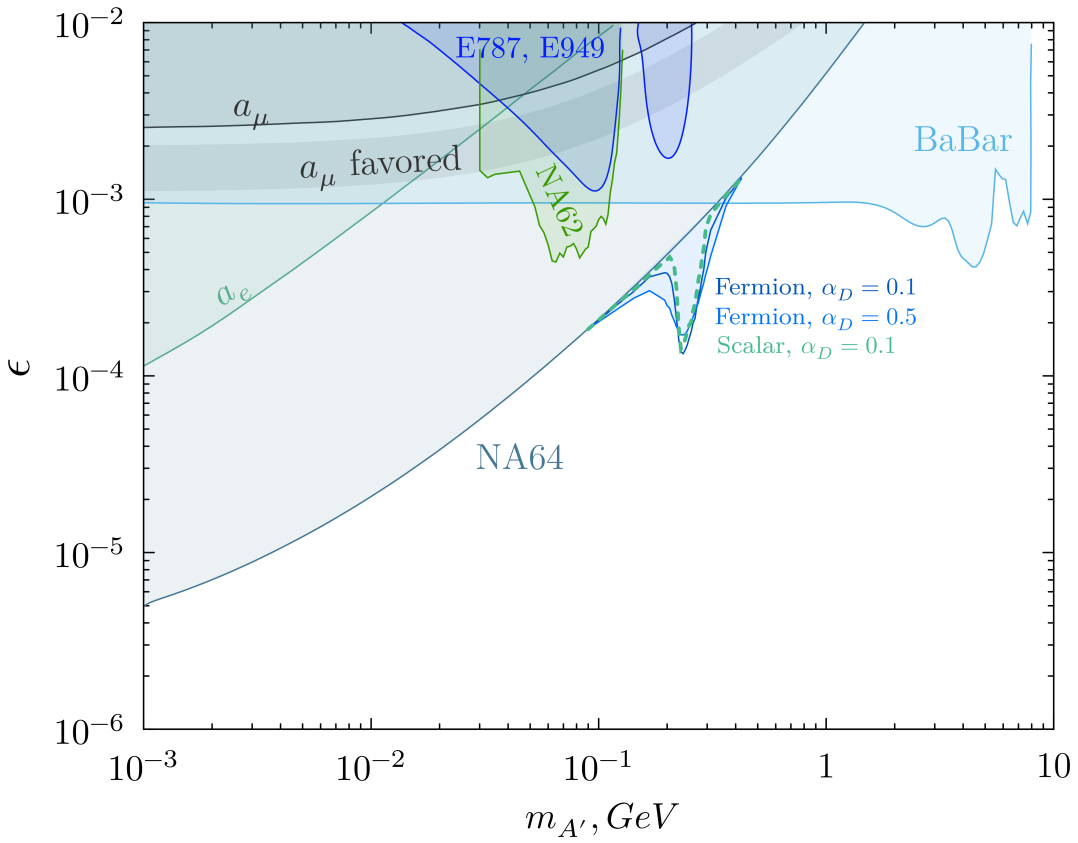
Experimental setup upgrades:

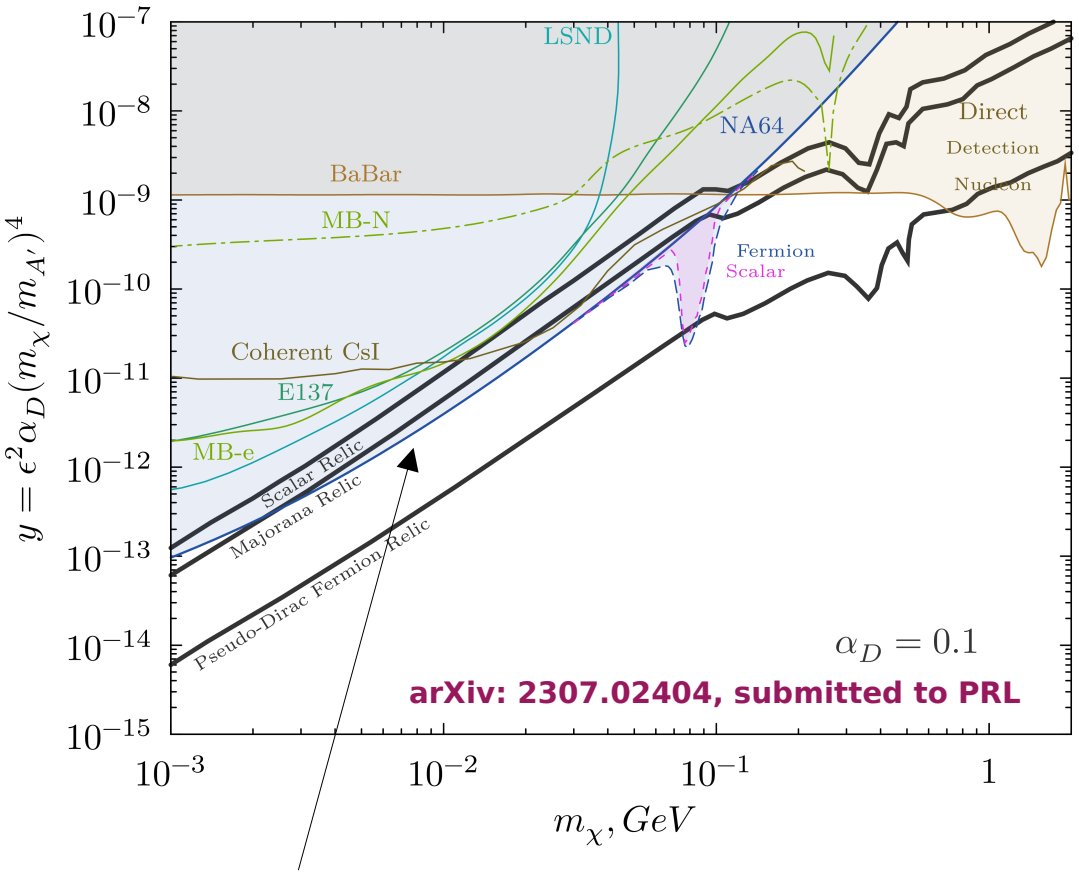
- New **Cu/Sc veto hadronic calorimeter** (VHCAL) installed to further suppress upstream electro-nuclear reactions
- Optimized DAQ system, including a programmable **trigger pre-scaler** to be able to acquire multiple event types in parallel
- Excellent beam quality: lower beam halo fraction and hadron contamination





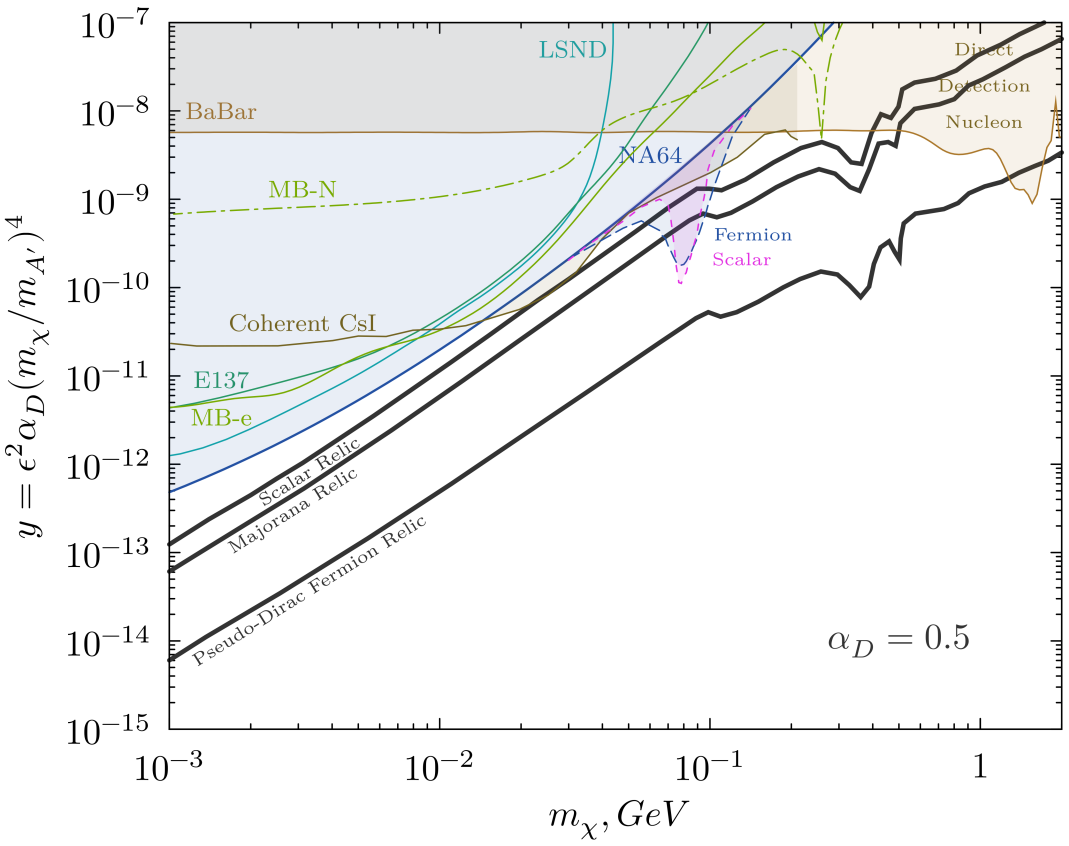
NA64e results: combined 2016-2022 data, ~10^{12} EOT

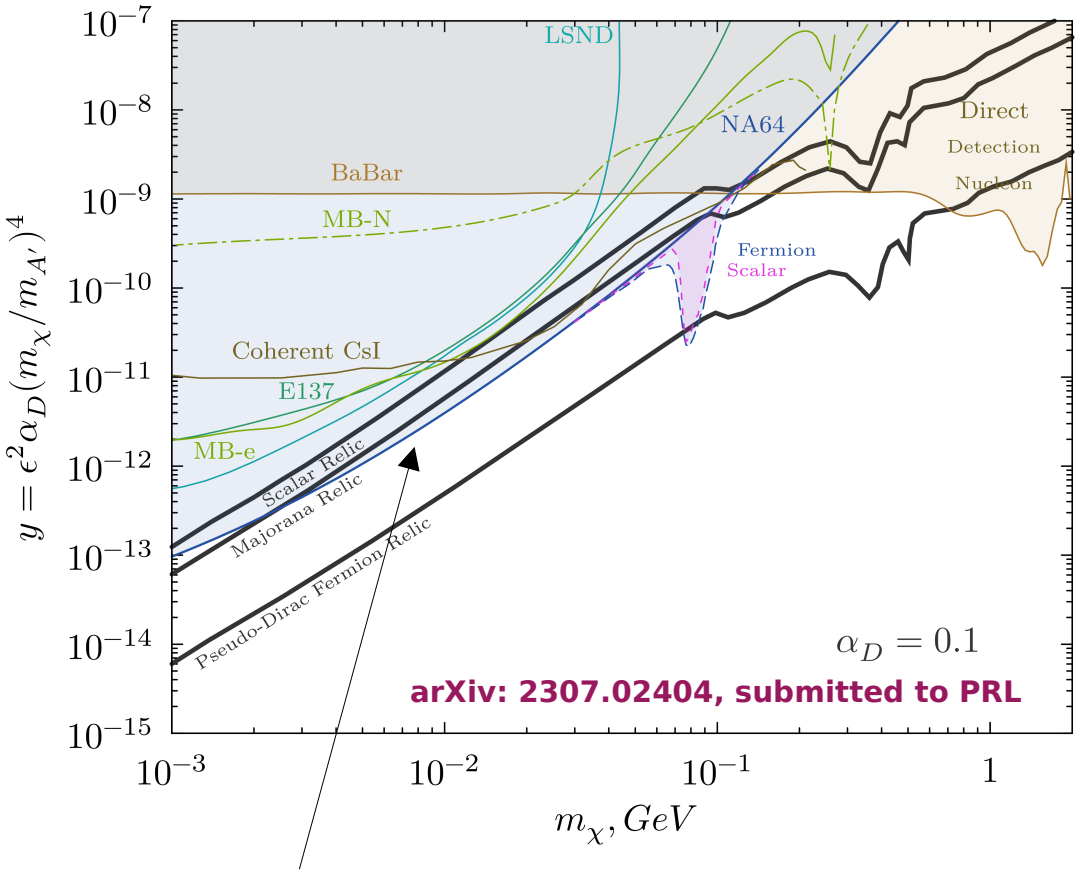




Excludes the Scalar and Majorana scenario

NA64e results: combined 2016-2022 data, ~10^{12} EOT





Excludes the Scalar and Majorana scenario

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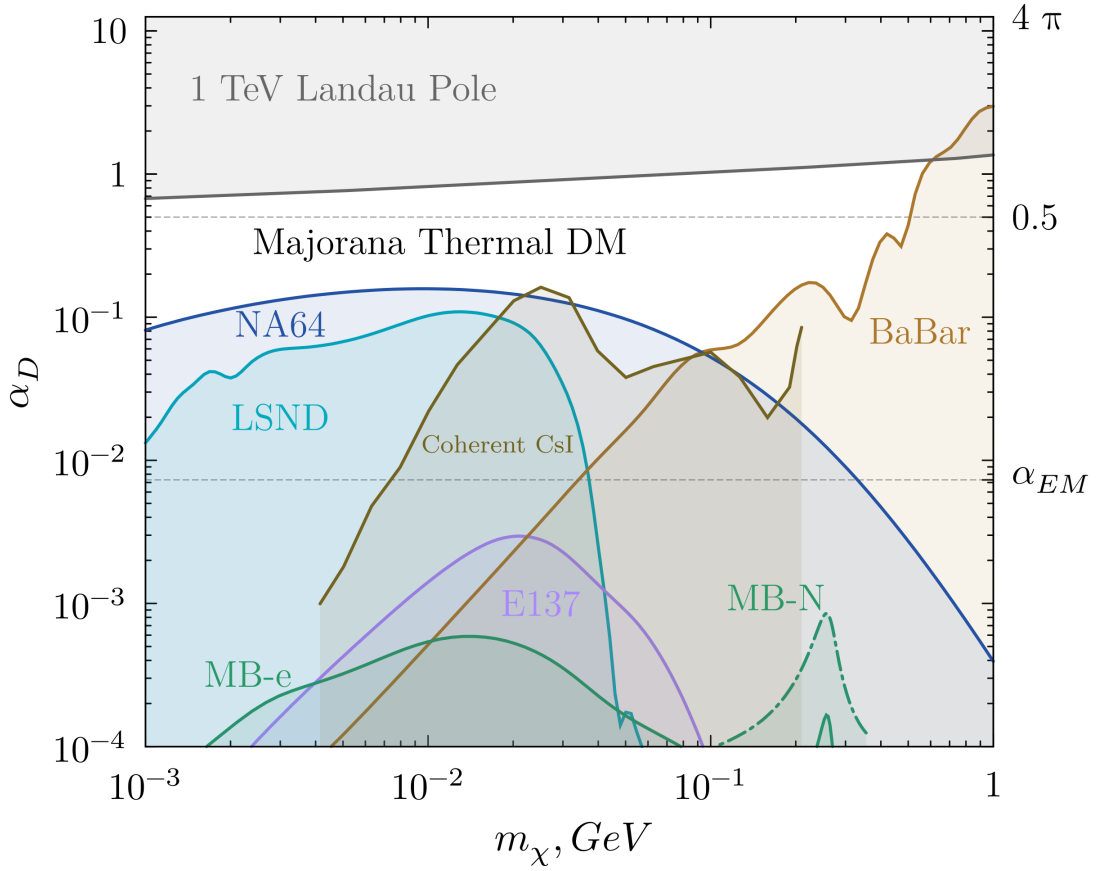
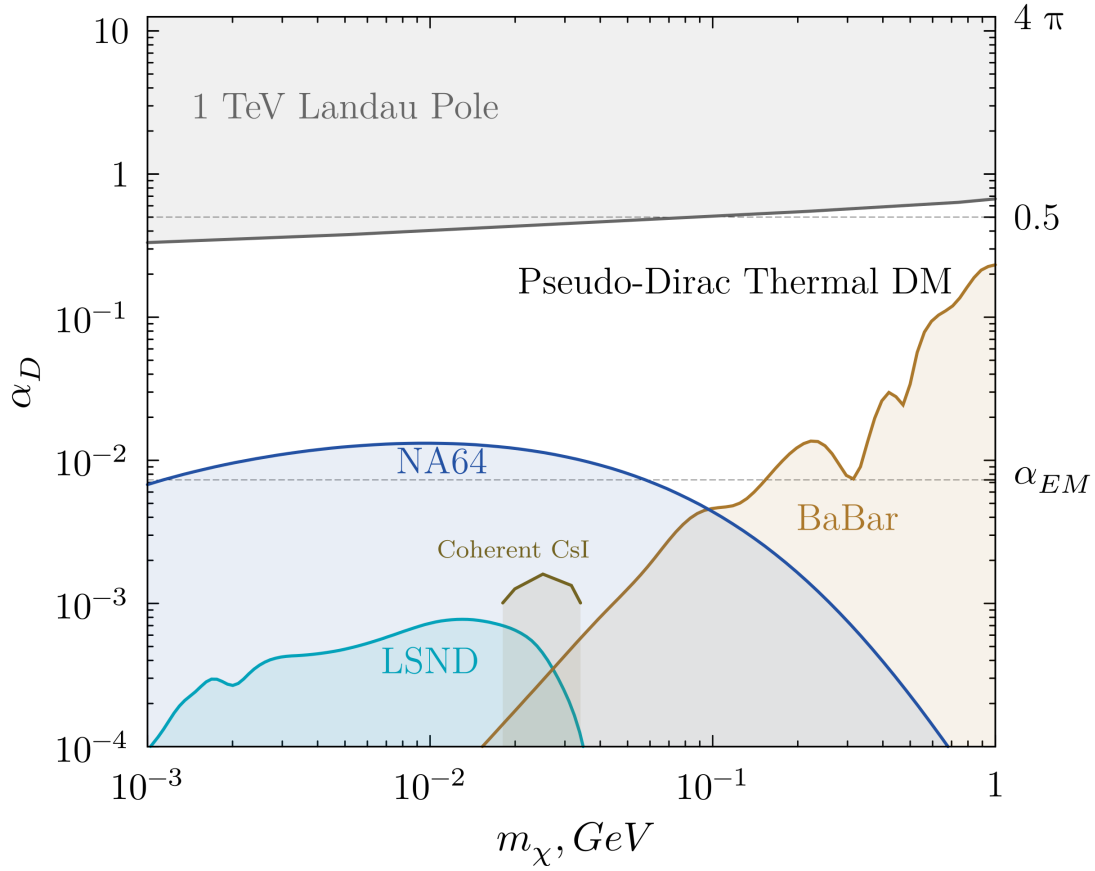
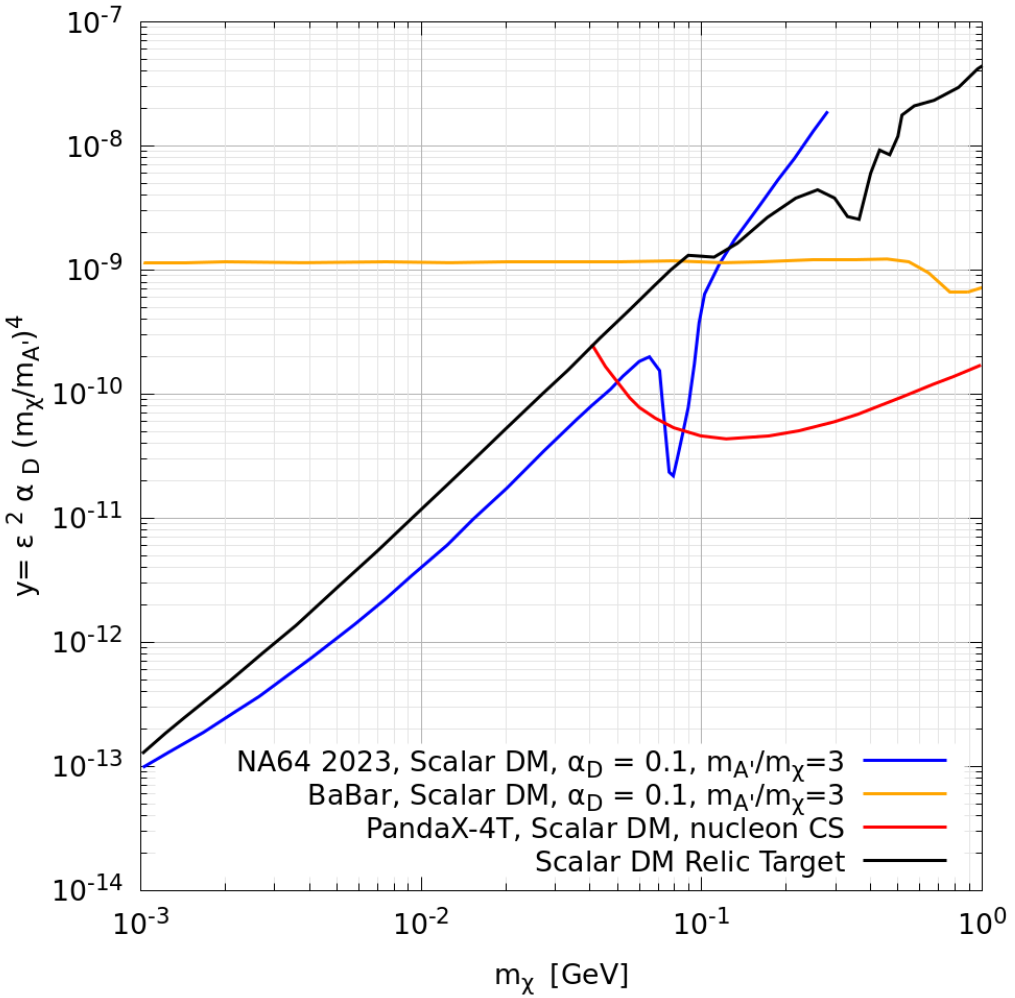
NA64e results: combined 2016-2022 data, ~10^{12} EOT





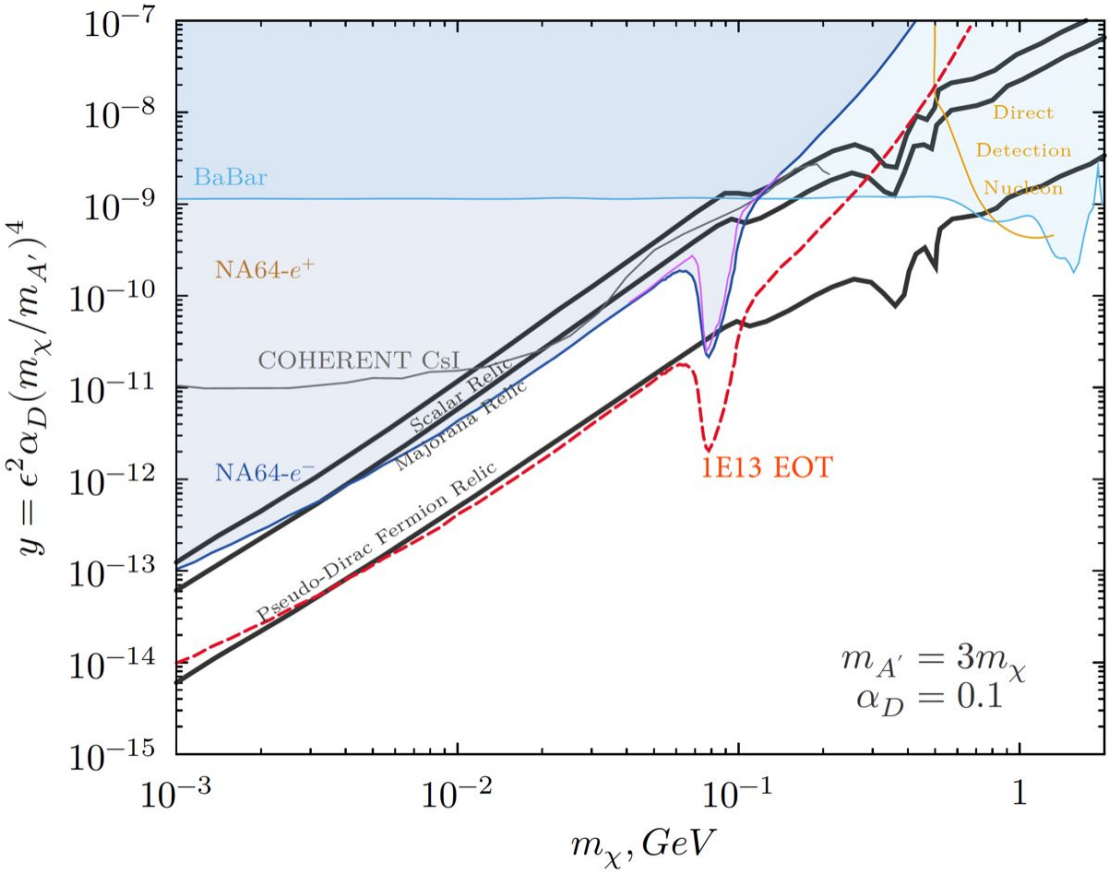
NA64e results: complementary with direct DM searches

Recent results presented by PandaX-4T in the case of **Scalar DM**

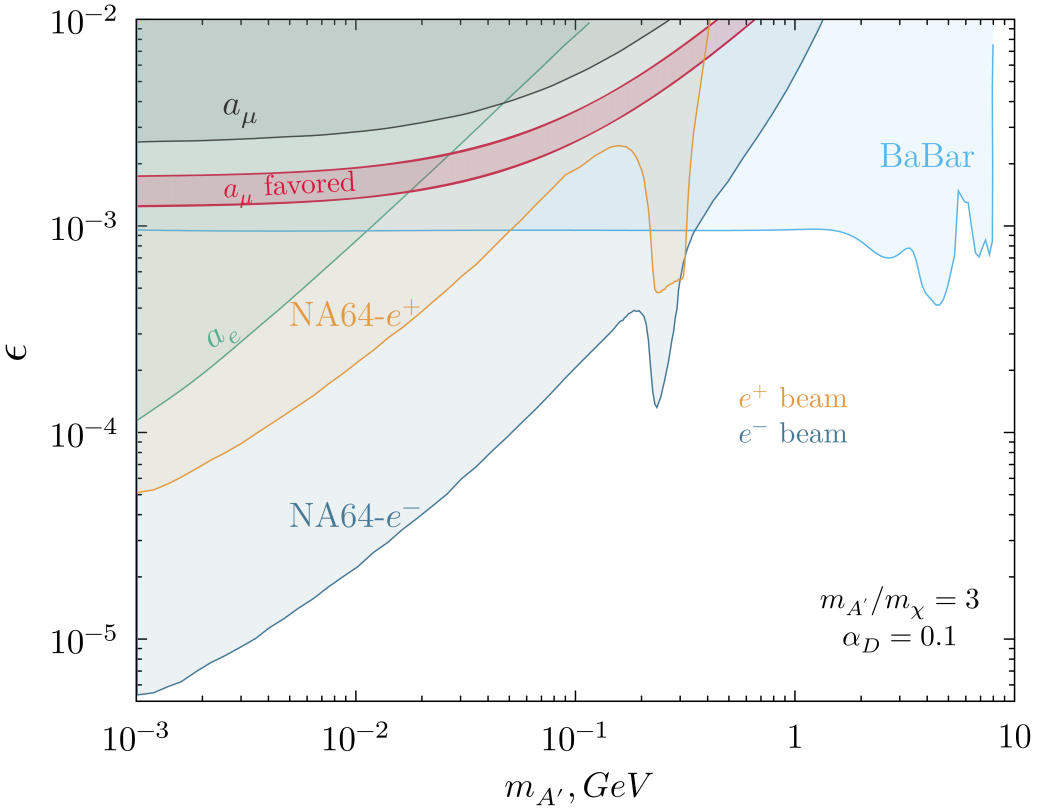


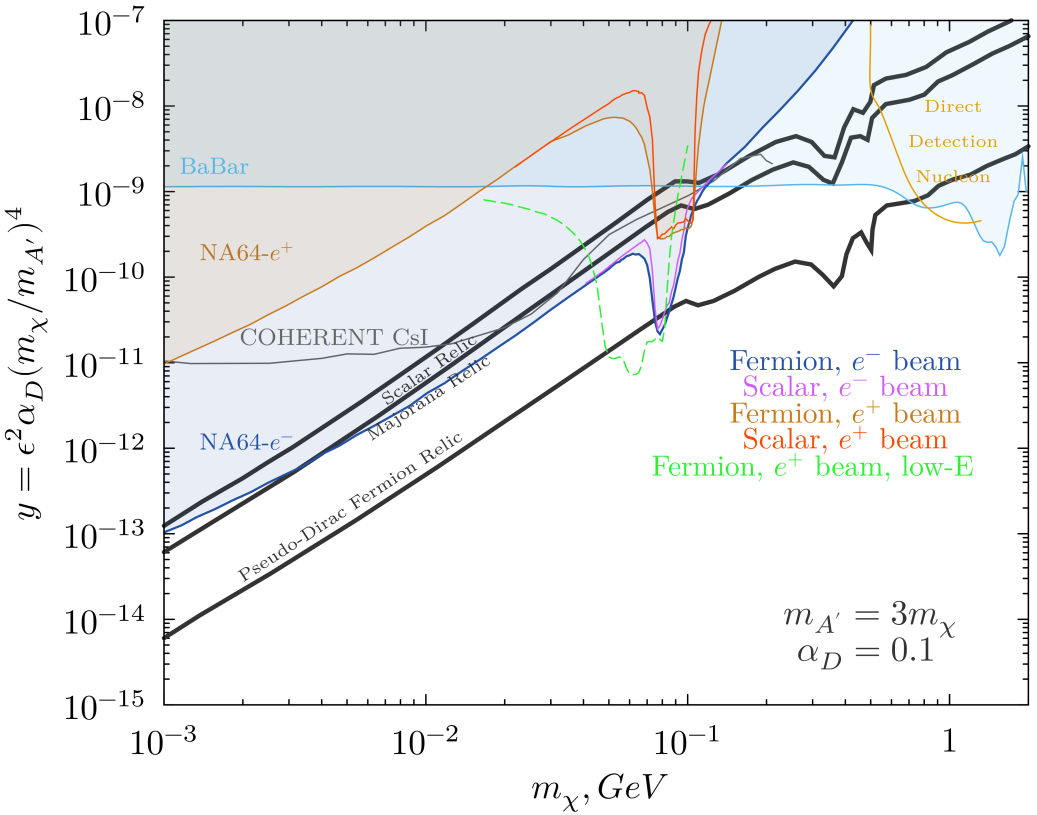
NA64e plans beyond LS3

- Complete setup upgrade to run at higher intensities
  - → Up to **1.5×10^7 EOT/spill**
  - → PMT-based detectors: develop faster MSADC readout
  - → Trackers: upgrade readout to VMM
- Collect **10^{13} EOT** and fully cover all thermal targets in the m_χ < 100 MeV region

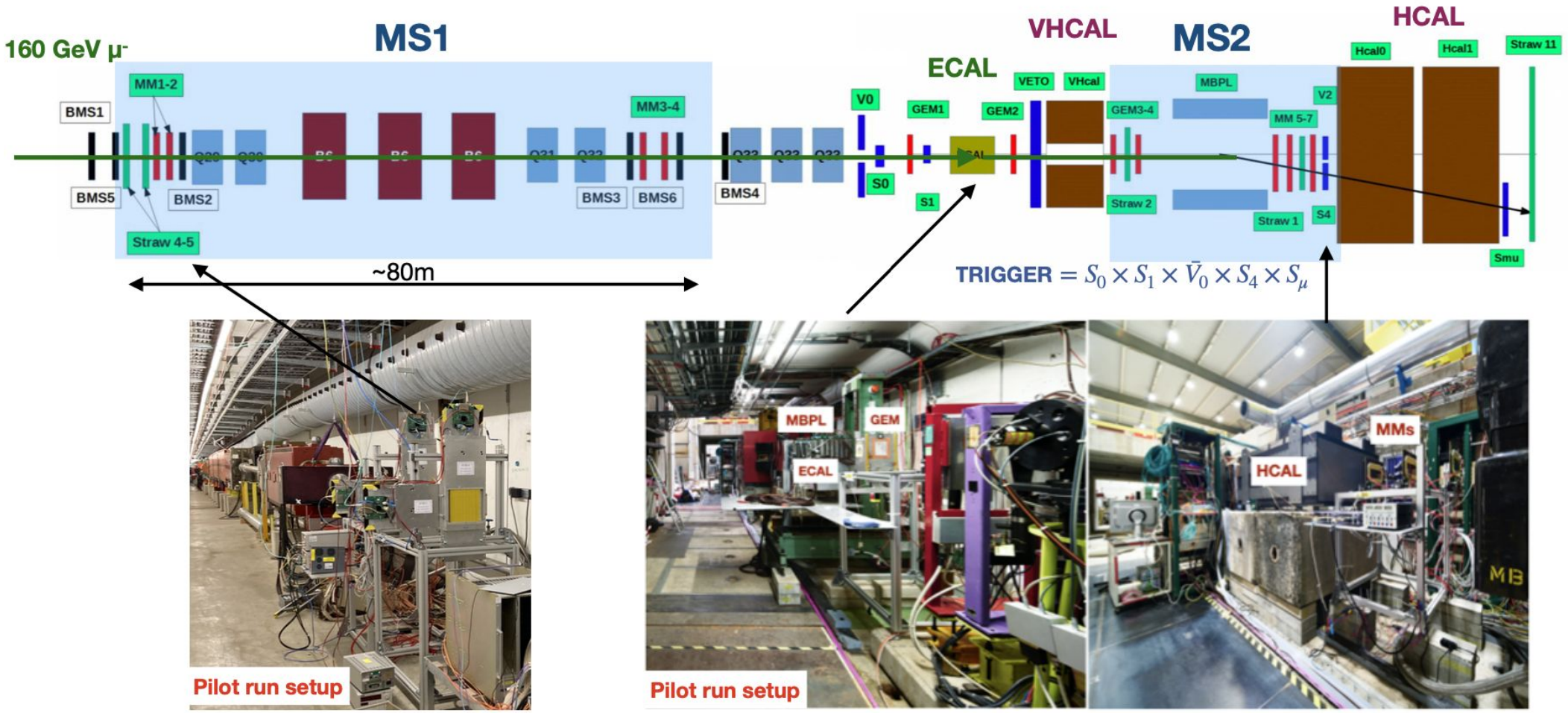


NA64 results with e⁺ beam





NA64μ experiment: setup in M2 during 2022 pilot run

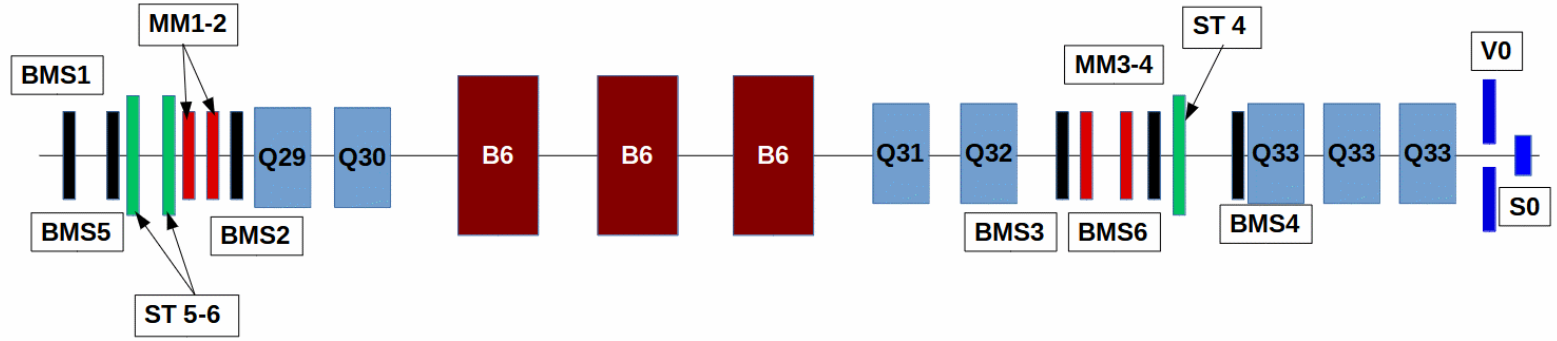


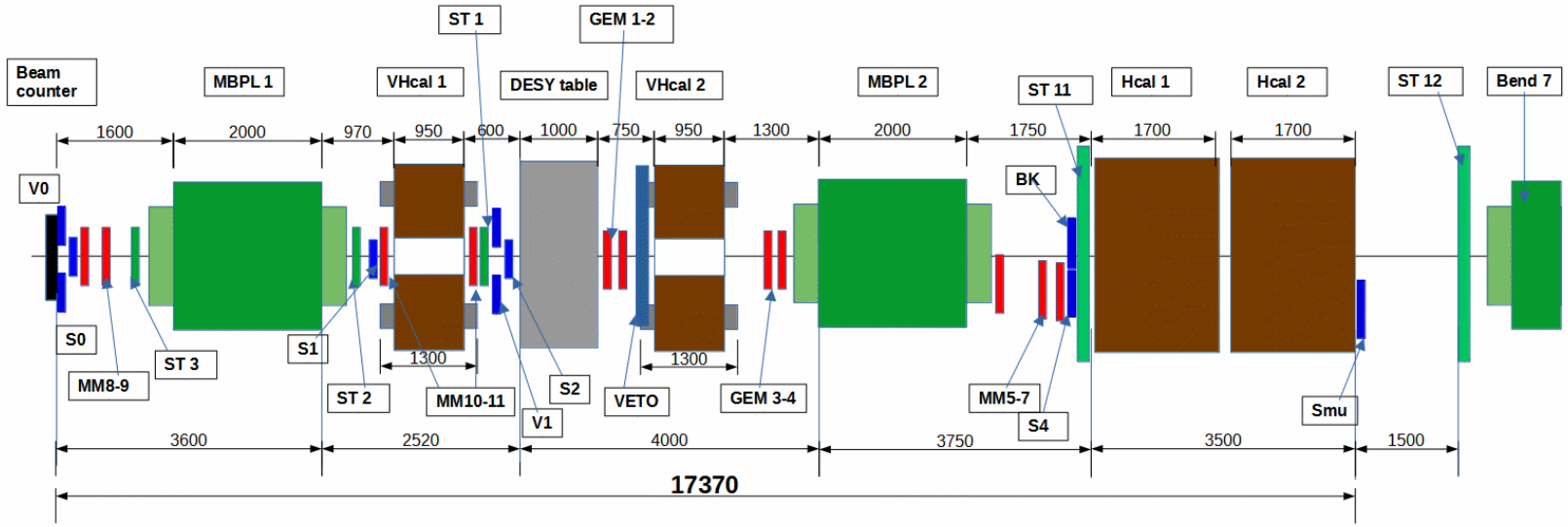
NA64μ prospects: 2023 run

Several improvements:

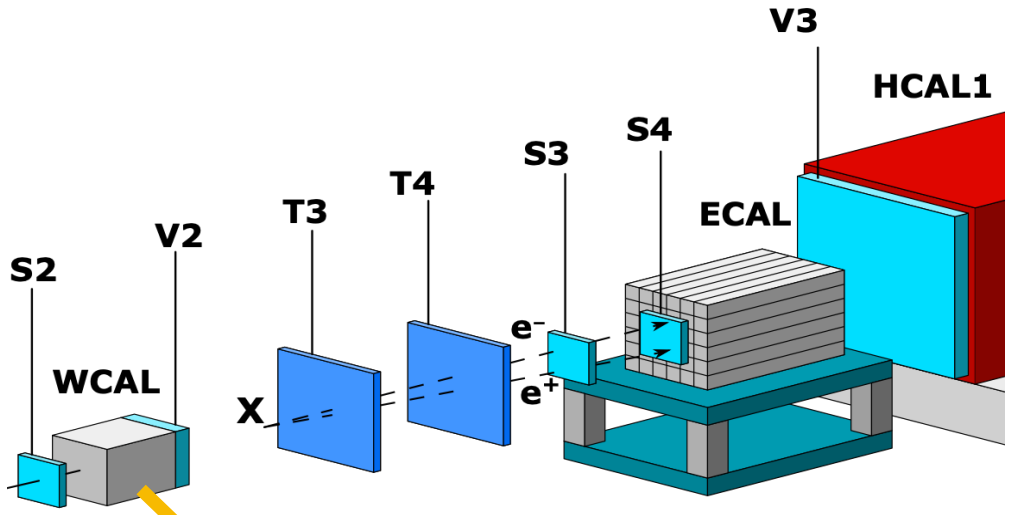
- Additional **magnet spectrometer** to minimize misreconstruction
  - 23 trackers in total
- **Veto hadronic calorimeters (VHCAL)** for improved background rejection
- **Scintillator counters** for clear beam definition

➡**Analysis just started!**

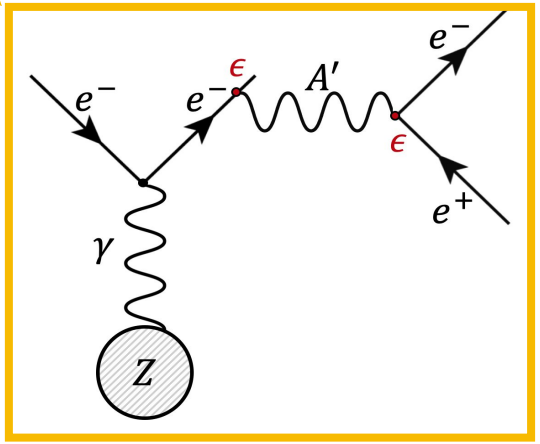




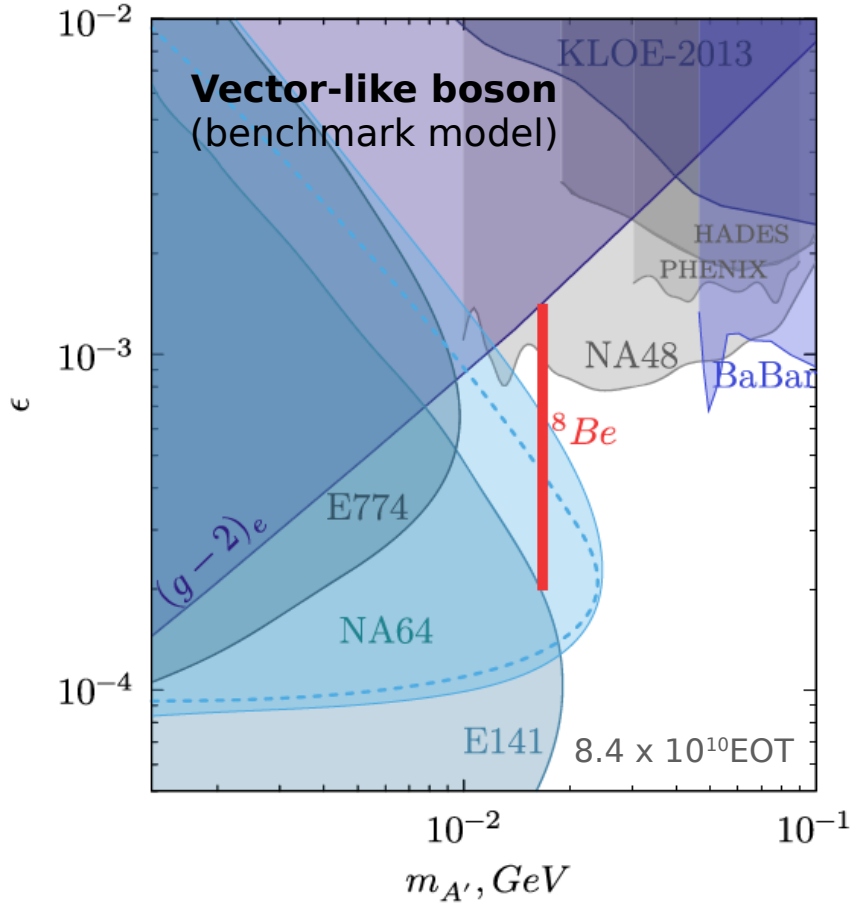
NA64 visible mode: 2017-2018 combined results



Compact Tungsten calorimeter



$e^-Z \to e^-ZX_{17}(A');\ X_{17}(A') \to e^+e^-$



NA64 collaboration,
PRL 120, 231802 (**2018**), PRD 107, 071101 (R) 2020

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