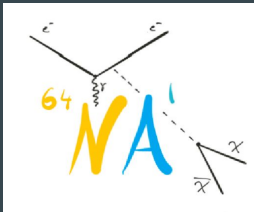


Light dark matter searches with the NA64 experiment at CERN



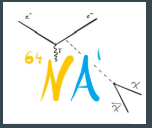
Luca Marsicano - INFN Sezione di Genova
1st BiCoQ Conference, Milan 16/6/2026



Summary



1. Introduction
2. Overview the NA64-e experiment
 - The NA64-e detector and experimental technique
 - The NA64-e results and broad physics program
3. The NA64- μ parallel effort at M2
4. Future prospects in the search for light dark matter at NA64
5. Conclusions



Light dark matter

Light Dark Matter: sub-GeV particles (χ), lightest stable state of a new “dark sector”. LDM particles interact with SM states via a new “portal” mediator (dark photon, A').

Hypothesis:

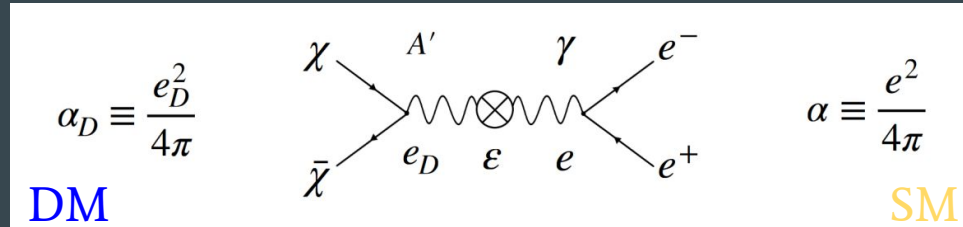
- ❖ DM and SM states in thermodynamic equilibrium in early Universe.
- ❖ DM relic abundance connected to the annihilation cross section $\chi\chi \rightarrow ll$ (“freeze-out” mechanism)
- ❖ **This sets a target in the LDM parameters space.**





Vector-mediated light dark matter

Simple, representative possibility: “vector-portal”. DM-SM interaction through a new U(1) gauge-boson (“dark-photon”) coupling to electric charge Dark QED



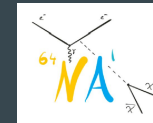
DM charged under new mediator
Small A' -photon mixing: $\epsilon \ll 1$

- ❖ By requiring that freeze-out mechanism reproduces today’s relic abundance, a target in the parameters space can be derived:
- ❖ Define a new variable optimized for thermal targets:

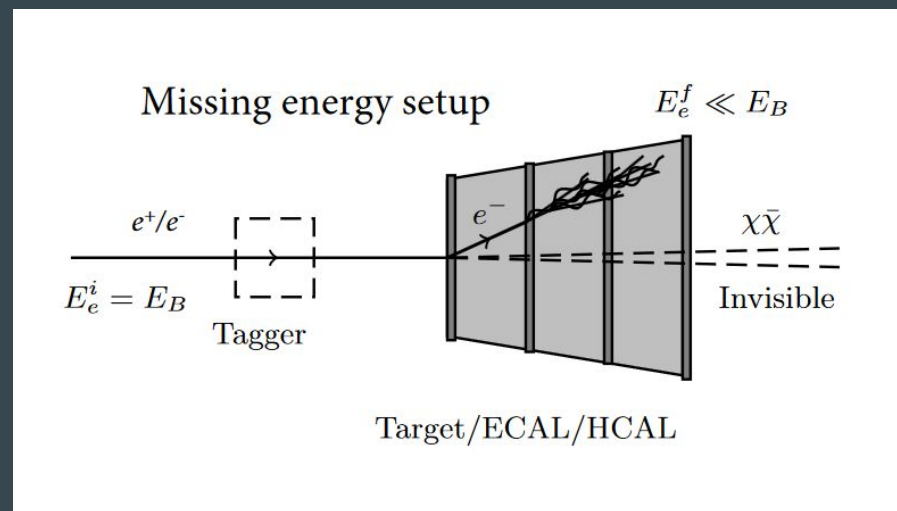
$$\langle \sigma v \rangle \propto \frac{\epsilon^2 \alpha_D m_\chi^2}{m_{A'}^4} = \alpha_D \epsilon^2 \left(\frac{m_\chi}{m_{A'}} \right)^4 \frac{1}{m_\chi^2} = \frac{y}{m_\chi^2}$$

For a given value of m_χ , thermal origin imposes one value of y

NA64-e: the missing energy strategy



- ❖ Specific beam structure: particles impinging “one at a time” on the active target
- ❖ Deposited energy E_{dep} measured event-by-event
- ❖ **Signal:** events with large $E_{\text{miss}} = E_{\text{beam}} - E_{\text{dep}}$
- ❖ **Backgrounds:** events with /long-lived (KL) / highly penetrating (μ) particles escaping the detector, beam contaminants

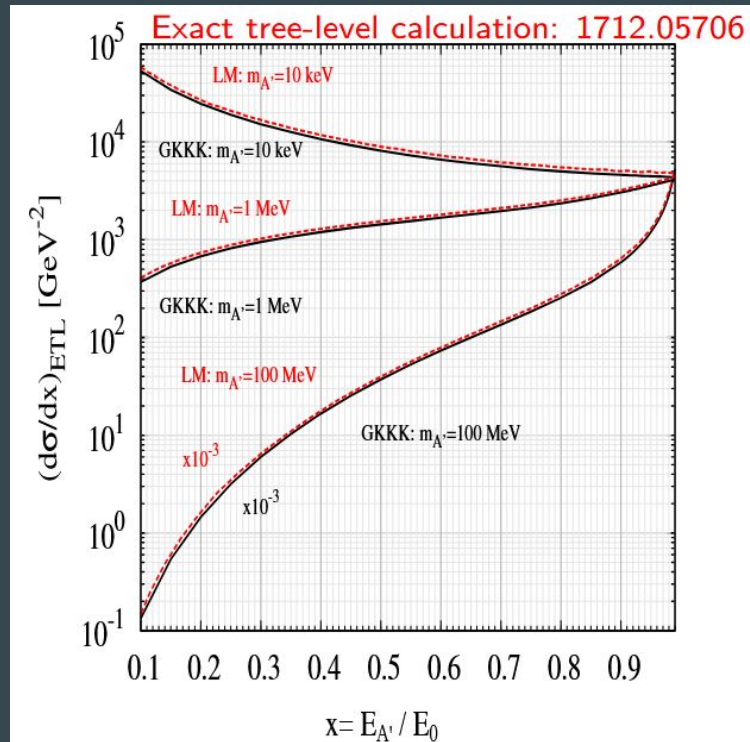
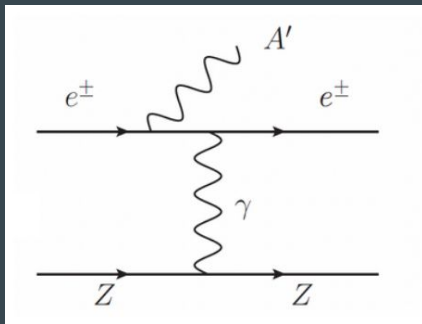


Signal scaling: $\propto \epsilon^2$

LDM production mechanisms - A' -strahlung



- ❖ Radiative A' emission followed by A' decay to LDM states
- ❖ Scaling: $Z^2 \alpha_{EM}^3$
- ❖ Forward boosted, high energy A' emission



LDM production mechanisms - *Resonant annihilation*



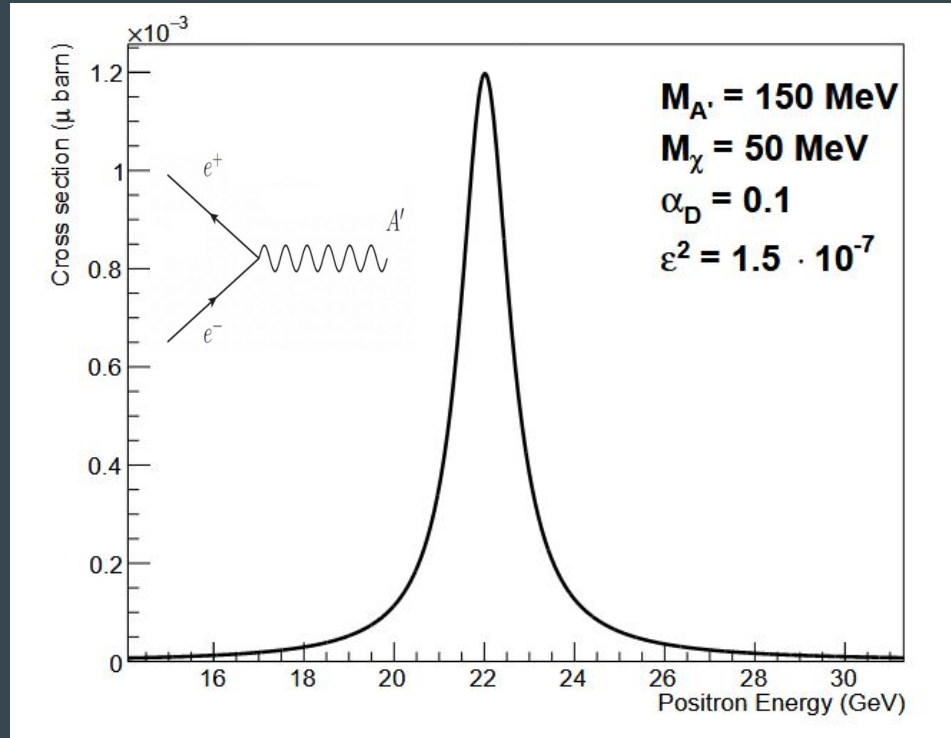
- ❖ Resonant annihilation followed by A' decay:

$$e^+e^- \rightarrow A' \rightarrow \chi\bar{\chi}$$

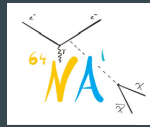
- ❖ Scales as $Z \alpha_{EM}$
- ❖ Resonant, Breit-Wigner like cross section with

$$m_{A'} = \sqrt{2m_e E_{e^+}}$$

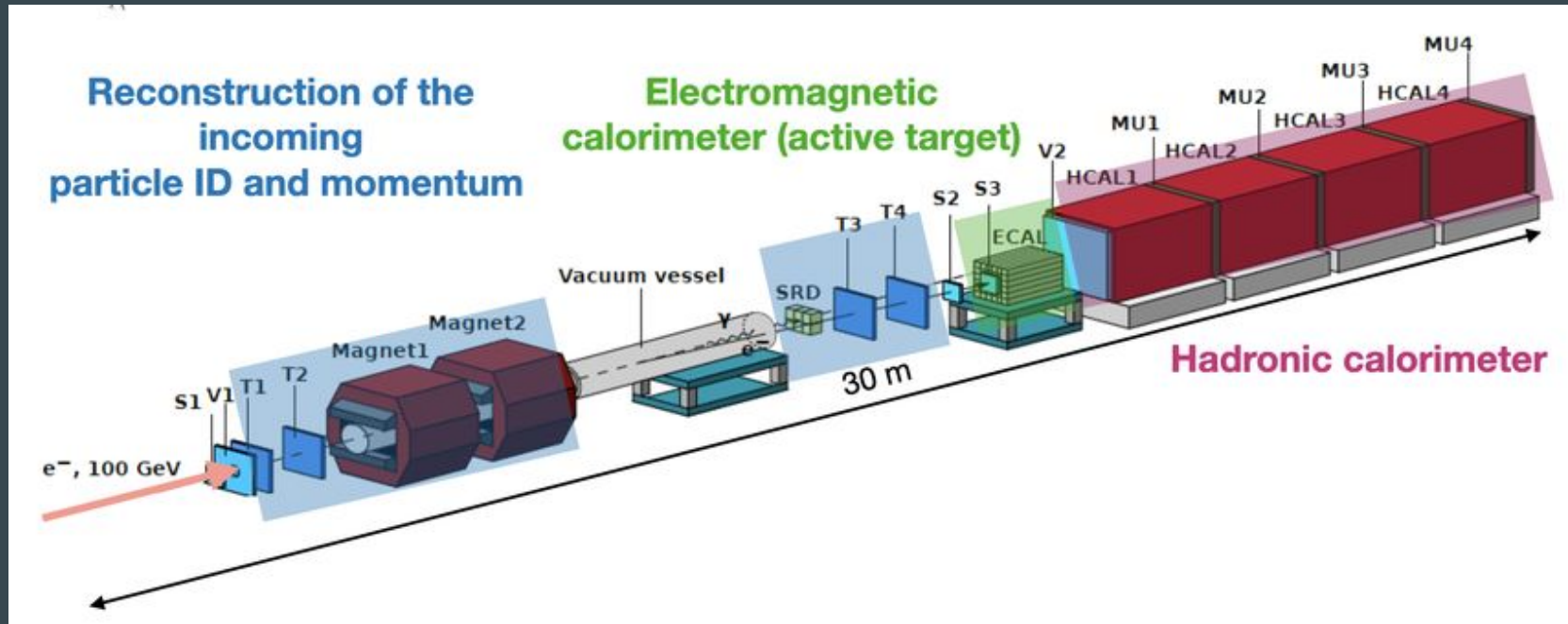
Relevant also with an e^- beam, due to secondary positrons in the target



The NA64-e experiment



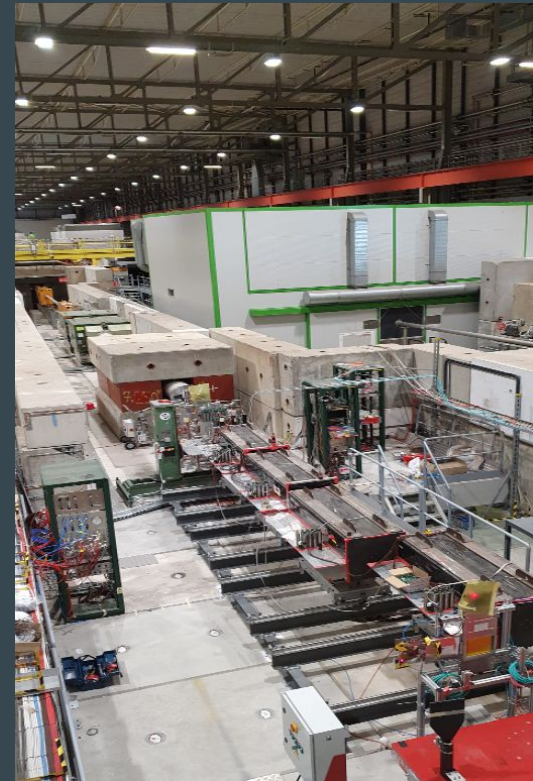
Missing energy experiment at CERN SPS, H4 line (CERN North Area), operating since 2016



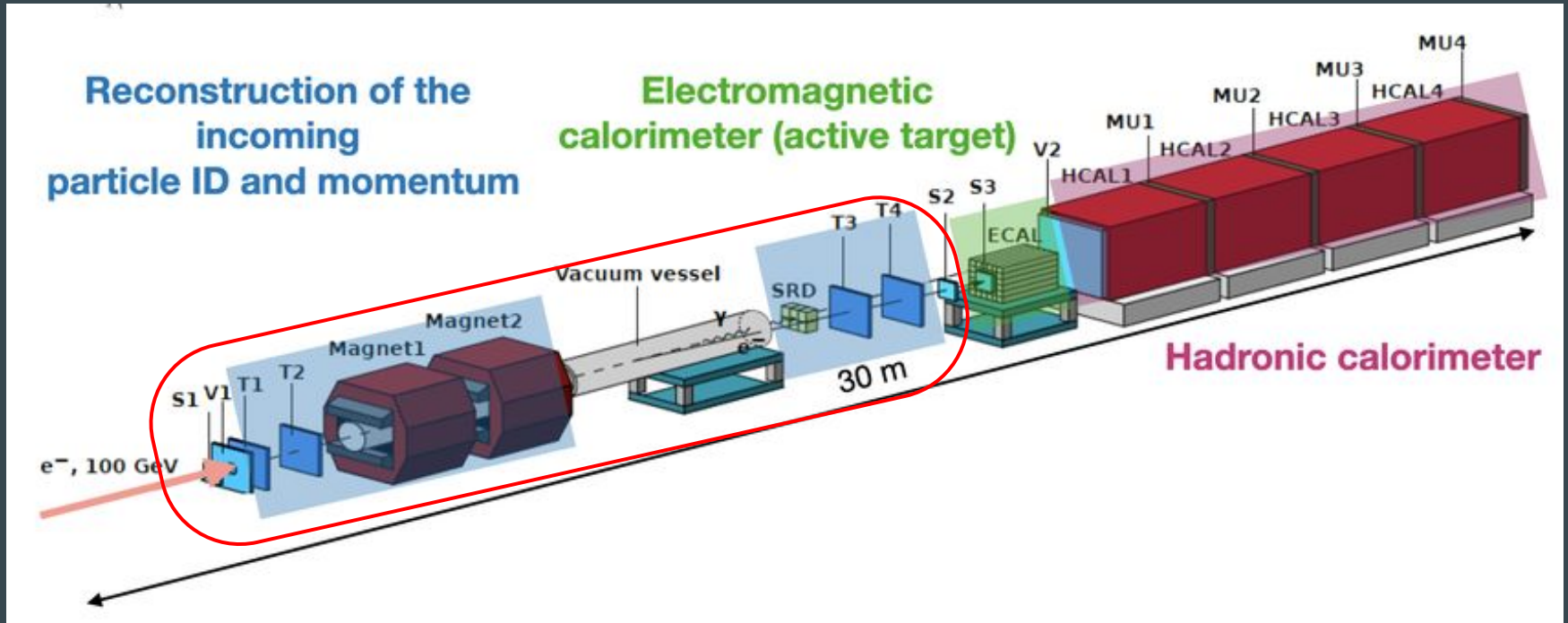
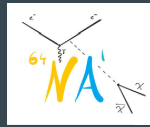
NA64-e at CERN SPS - H4 line



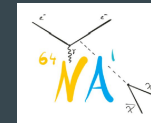
(Image: <https://ais.cern.ch>)



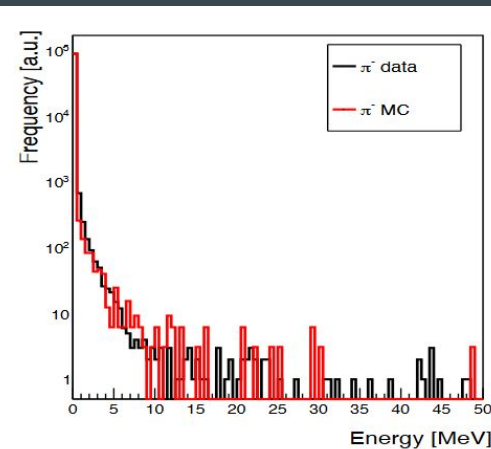
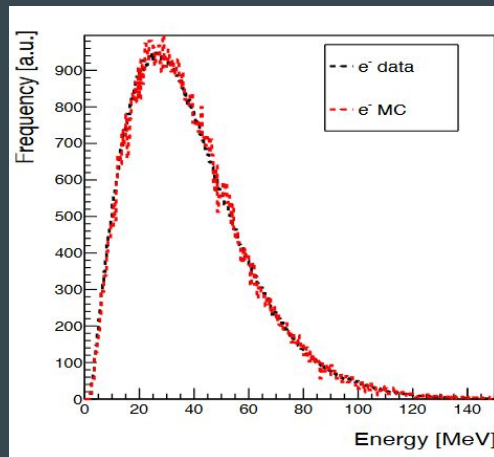
The NA64-e Detector- Upstream Tagger



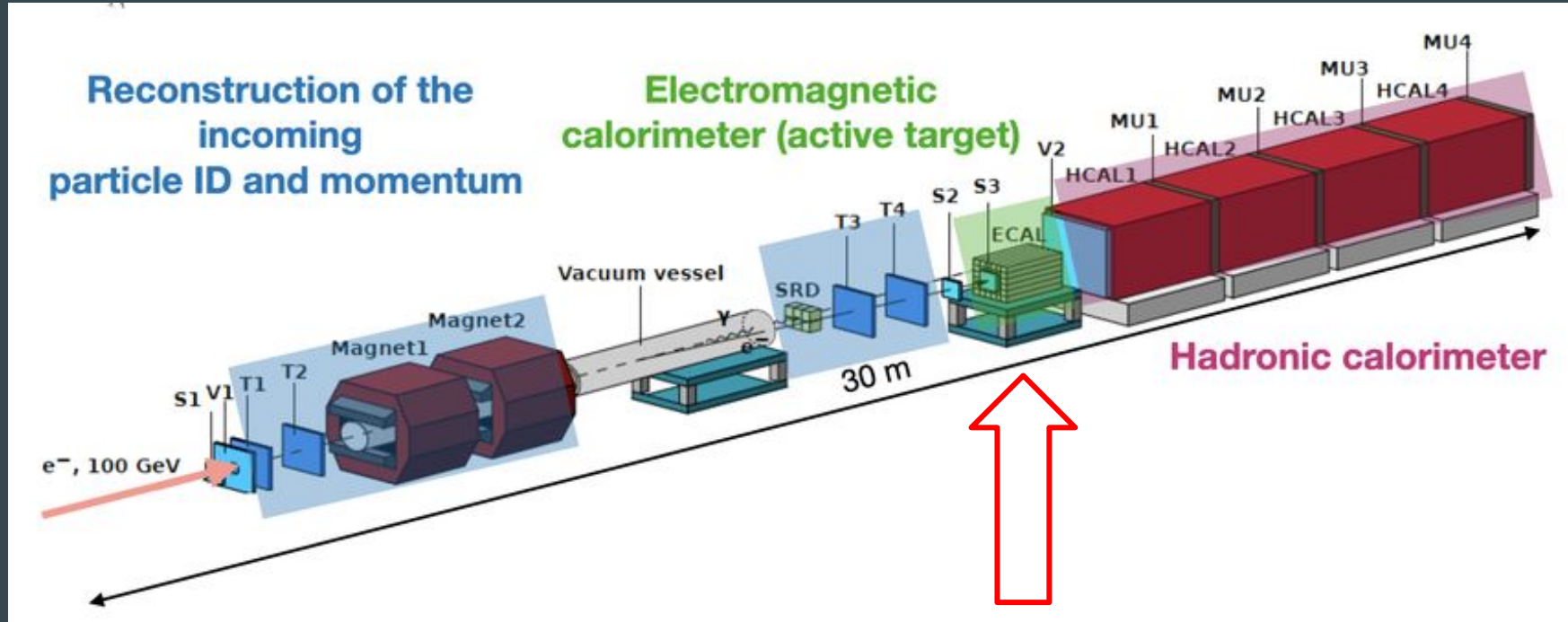
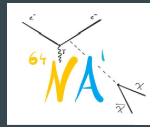
Tagging e^- with SRD detector



- ❖ Reject hadron contaminants with synchrotron radiation detector (SRD)
- ❖ Three modules: plastic scintillator + Pb layers, PMT readout (replaced with LYSO detector from 2024)
- ❖ Pion rejection inefficiency at 100 GeV: $10^{-4} - 10^{-5}$



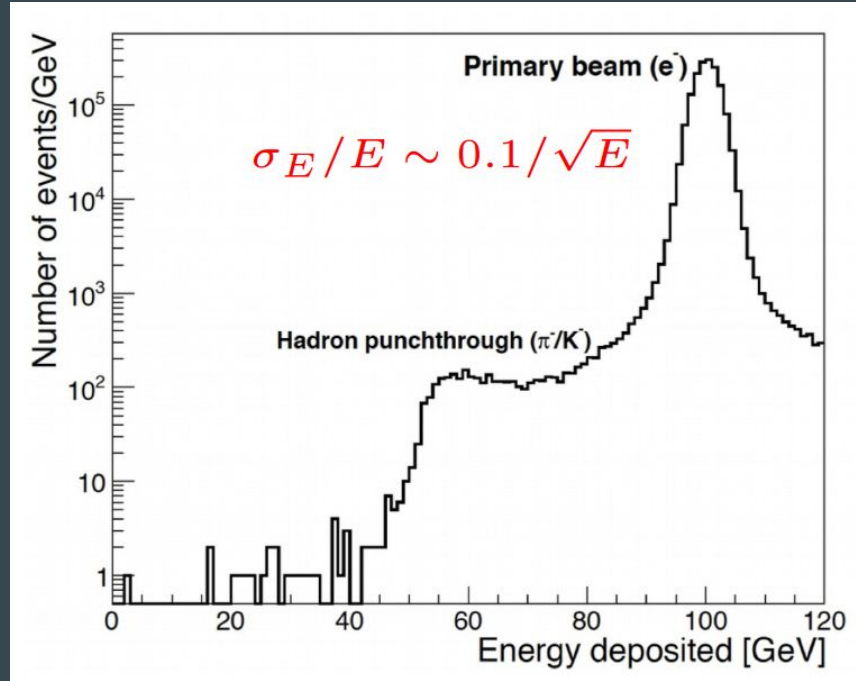
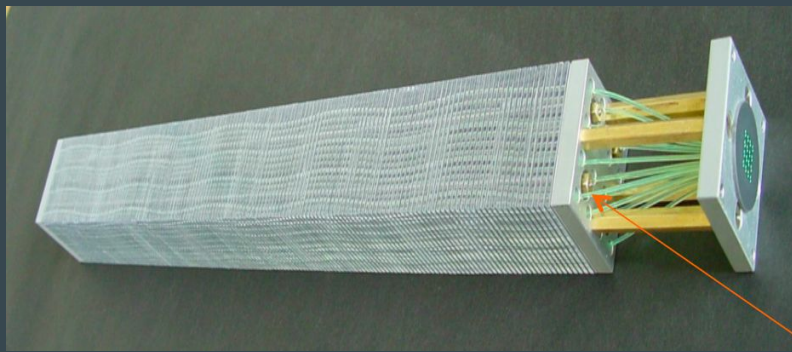
The NA64-e Detector - The Active Target



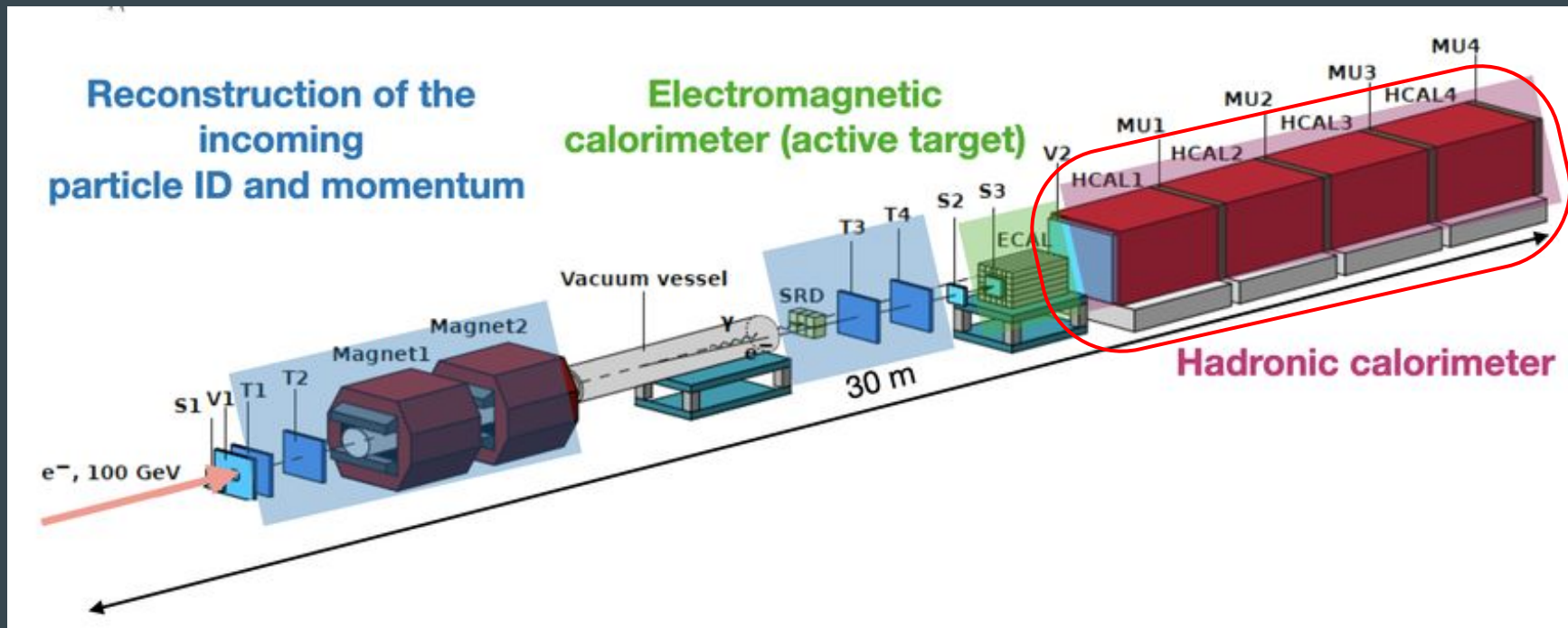
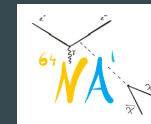
The Electromagnetic Calorimeter (ECal)



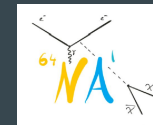
- ❖ EM-Calorimeter: $40 X_0$, Pb/Sc Shashlik, PMT readout
- ❖ Readout WLS fibers go in a spiral to avoid E-leak and dead zones
- ❖ Hermeticity scan: no potential source of background is found



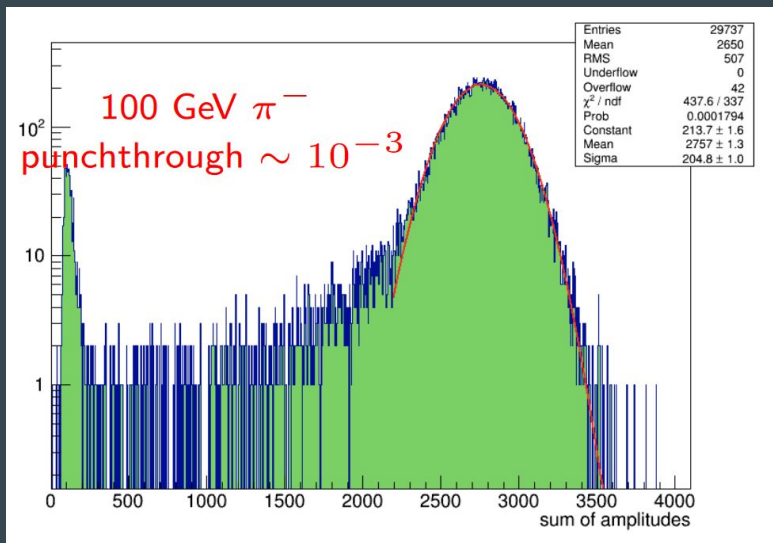
The NA64-e Detector - Downstream Section

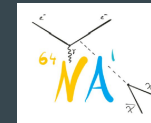


Hadronic Calorimeter (HCal)



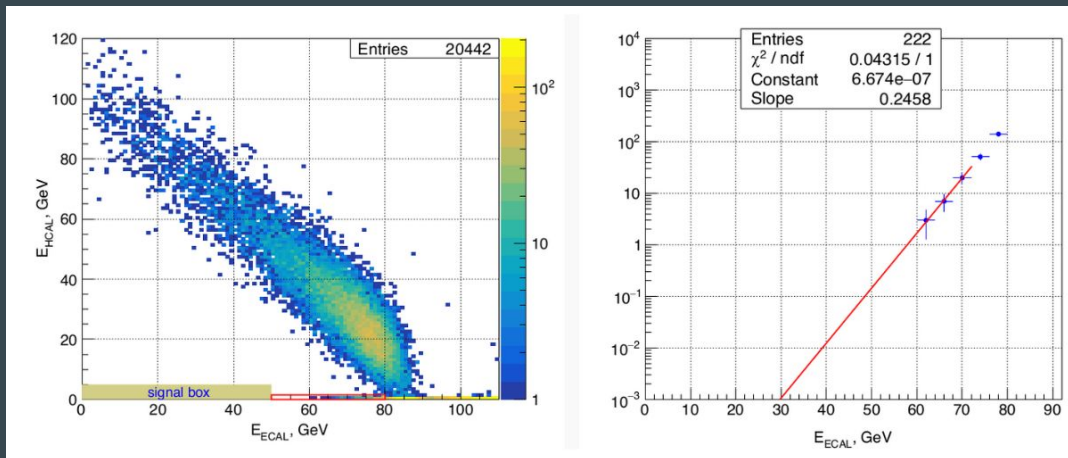
- ❖ 4× 1-m long sandwich modules ~ 30 nuclear interaction length
- ❖ Optical fibers + PMT readout
- ❖ Pion punchthrough probability: 10^{-3} per module





NA64-e analysis cut-flow

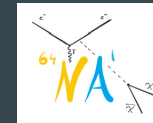
- ❖ **Selection cuts:**
 - Clean impinging 100 GeV/c e^- , $E_{\text{SRD}} < 1$ MeV
 - No activity in VETO/HCAL
 - EM shower-shape compatible with an e^- induced one (data-driven shower shape χ^2 distribution)
- ❖ **Signal window:** $E_{\text{ECAL}} < 50$ GeV, $E_{\text{HCAL}} < 1$ GeV



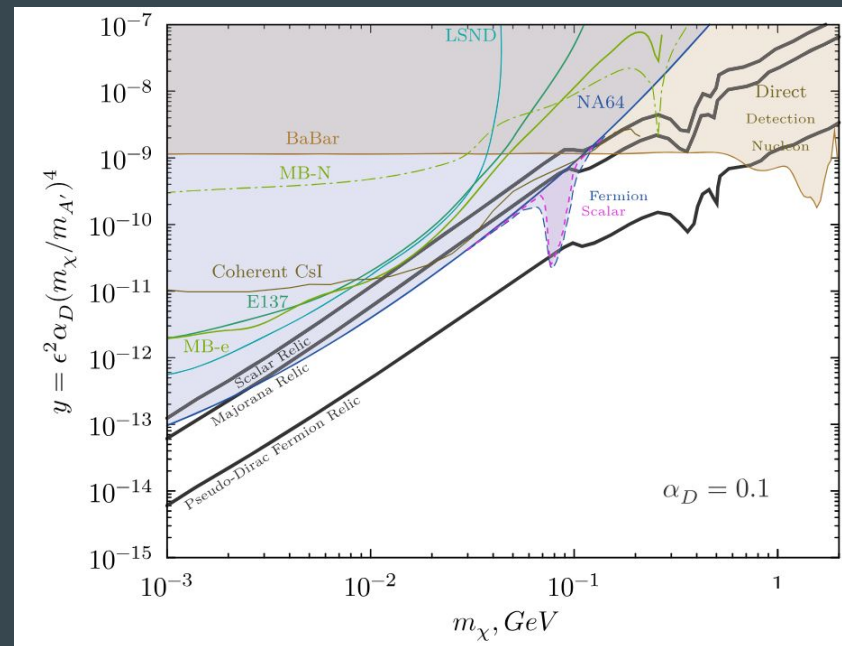
Main backgrounds:

- ❖ Di-muon events: $eZ \rightarrow eZ\mu^+\mu^-$, with one or both muons escaping without being detected by VETO/HCAL.
- ❖ Decay of mis-identified contaminating hadrons to $e\nu_e$ final state.
- ❖ **Electro- / photo-nuclear interactions with upstream beamline materials.**

NA64-e limits in the LDM scenario

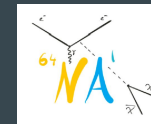


- ❖ Current published results based on $\sim 10^{12}$ e^-OT collected up to 2022
- ❖ No signal observed, in agreement with background predictions
- ❖ Set best limits in the A' invisible decay scenario for $m_{A'} < \sim 200$ MeV
- ❖ Reached the *pseudo-dirac fermion target* for $m_\chi \sim 100$ MeV thanks to secondary e^+ resonant annihilation

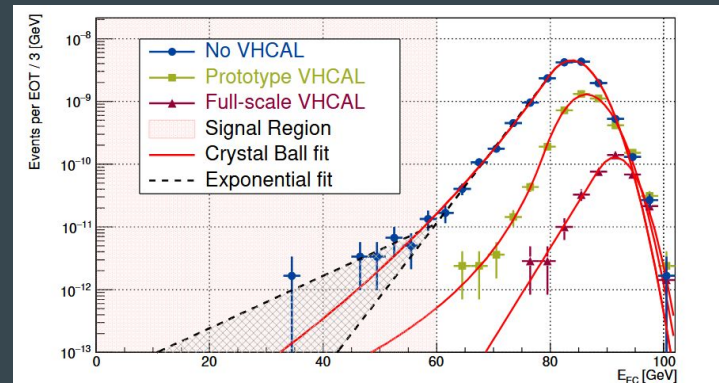


Background source	Background, n_b
1. Di-muons losses or decays in the target	0.04 ± 0.01
2. $\mu, \pi, K \rightarrow e + \dots$ decays in the beam line	0.3 ± 0.05
3. lost neutrals (γ, n, K^0) from upstream interactions	0.16 ± 0.12
4. Punch-through leading n, K_L^0	< 0.01
Total (conservatively) n_b	0.51 ± 0.13

NA64-e: 2023-2026 Runs

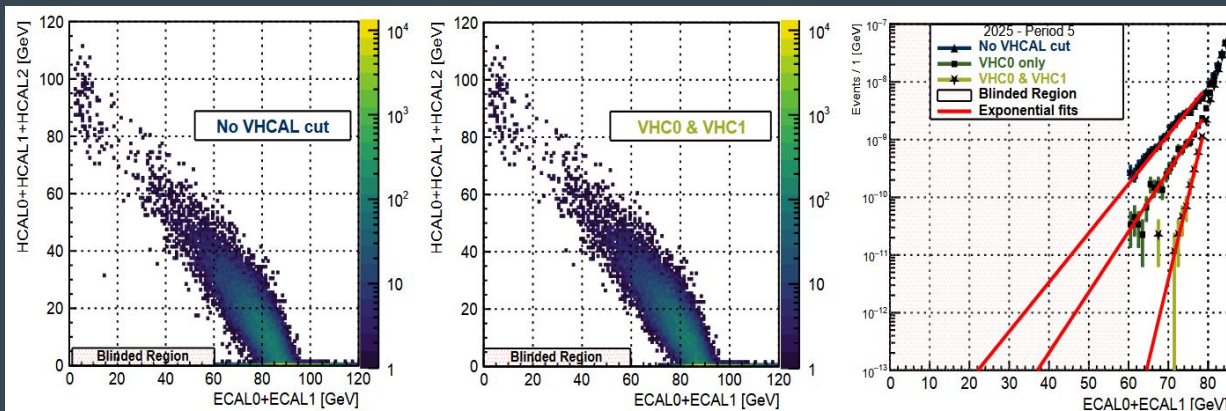


- ❖ Goal: improve statistics (1.6×10^{12} e^-OT collected between 2023-2024) and study backgrounds induced by upstream interactions; improve setup towards post-LS3.
- ❖ 2023-2024: **New veto hadron calorimeter (VHCAL)** implemented upstream the ECAL to improve detector hermeticity
- ❖ 2025-2026: further upgrade with **second VHCAL module**

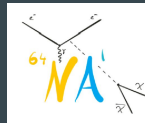


NIM A, 1081, 170830 (2026)

PRELIMINARY - 2025 RUN

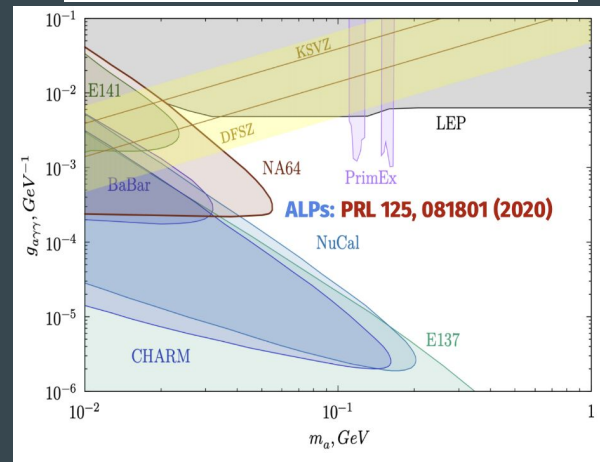
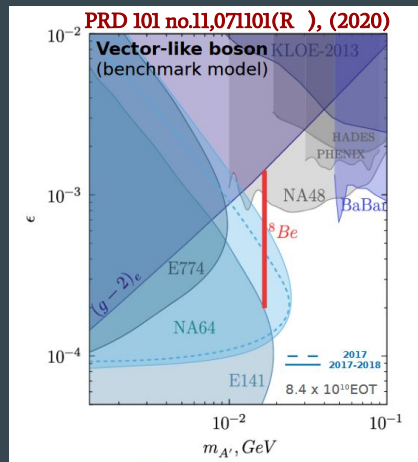
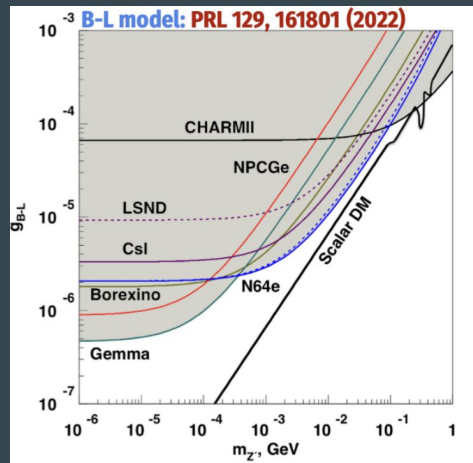
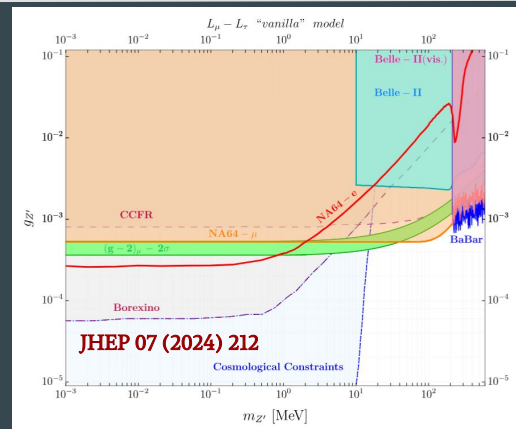


NA64-e broad physics program

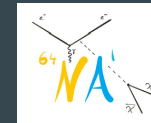


In addition to the main physics target of vector-mediated LDM, NA64-e set limits to several alternative BSM scenarios exploiting the missing-energy signature:

- ❖ ALPs, light scalars
- ❖ B - L, $L_\mu - L_\tau$ models with light Z' mediator
- ❖ Light Thermal Inelastic Dark Matter models with semi-visible decays
- ❖ Dark photon/X17/dark scalars with visible decays to electrons

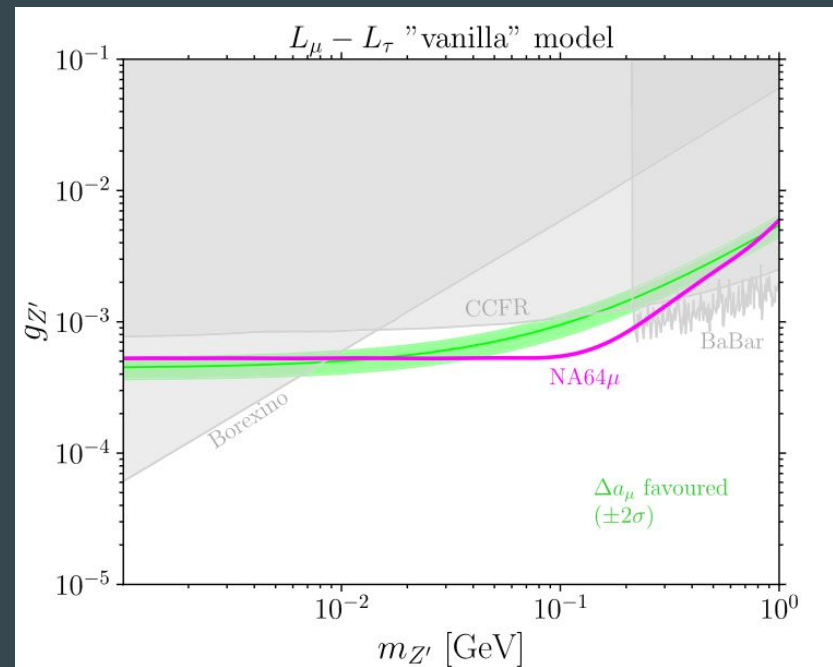


NA64- μ - Status



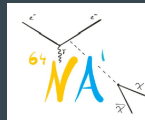
- ❖ Data collected up to 2022 - statistic of $(1.98 \pm 0.02) \times 10^{10}$ muons on target - published. **Almost completely excluded the explanation of the $(g-2)_\mu$ in this particular model.**
- ❖ Setup optimized in 2023-2024 to improve momentum reconstruction and increase intensity
 - Improved MS1 in 2024 (more efficient trackers)
- ❖ No data taking in 2025 –focus on analysis
 - Two independent blinded analysis ongoing (2023 and 2024 data samples)

Background source	Background, n_b
(I) Momentum mis-reconstruction	0.05 ± 0.03
(II) $K \rightarrow \mu + \nu, \dots$ in-flight decays	0.010 ± 0.001
(III) Calorimeter non-hermeticity	< 0.01
Total n_b (conservatively)	0.07 ± 0.03



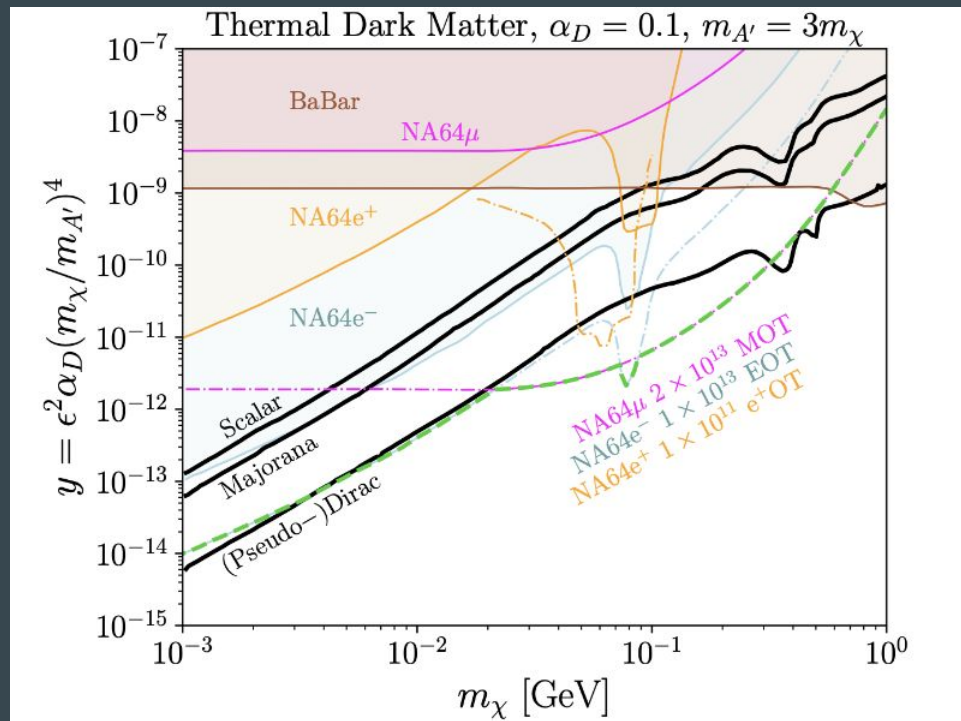
Phys. Rev. Lett. 132, 211803 (2024), Phys. Rev. D 101 (2020) no.11,071101(R)

NA64 post LS3-program



NA64 goals post CERN Long Shutdown 3

- ❖ Accumulate $10^{13} e^-OT$, $2 \times 10^{13} \mu OT$, $10^{11} e^+OT$ (exploit positron resonant annihilation enhancement) to probe the entire LDM parameters space down to the pseudo-dirac scenario
- ❖ Under study: NA64-h, missing energy search with hadron beam, to explore invisible meson decays/complementary DS scenarios



Conclusions



NA64: dark sector search experiment with multiple complementary measurements at CERN, based on the missing energy/missing momentum technique.

❖ **NA64-e: missing energy experiment at the H4 beamline**

- Run 2016-2022: $\approx 1 \times 10^{12}$ e⁻OT. Today, most stringent limits for LDM in a large region of the parameters space
- Run 2023-2025: accumulated further 1.6×10^{12} e⁻OT. Focus on setup optimization towards post-LS3 high-intensity runs.
- Final goal: Collect $\sim 10^{13}$ e⁻OT after LS3 to explore all the thermal targets in the vector-mediated LDM scenario

❖ **NA64- μ : missing momentum experiment at the M2 beamline**

- Analysis of data collected up to 2022 ($\sim 2 \times 10^{10}$ μ OT) has been published
- Setup optimized in 2023-2024 to improve momentum reconstruction and increase intensity (3.5×10^{10} μ OT collected in total)
- Final Goal: Collect 2×10^{13} μ OT after LS3 (complementary to the electron effort)

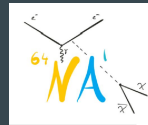
❖ **NA64-h: missing energy experiment with hadron beam**

- First results of the analysis of 2.9×10^9 π OT (1 day in 2022) published
- Further data collected in 2025, analysis ongoing. Post-LS3 strategy under discussion.

Thanks for your attention!

...

Backup

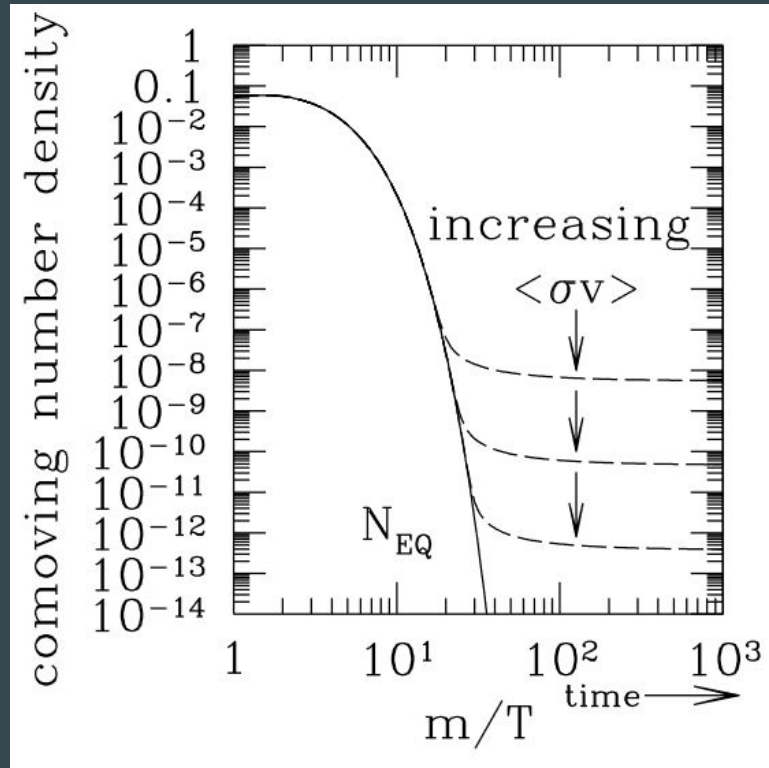




Thermal DM Hypothesis

Cosmological Hypothesis: DM particles were in equilibrium with primordial thermal bath in early universe $\chi + \chi \leftrightarrow f + f$

- ❖ Early universe: high-T, relativistic regime. Both reactions (\leftarrow and \rightarrow) permitted
- ❖ As Universe expands and cools down below χ mass, only \rightarrow reaction occurs. DM number density is exponentially suppressed: Boltzmann regime
- ❖ Eventually, DM number density is too low for χ to find each other \rightarrow annihilation stops \rightarrow **Freeze Out**



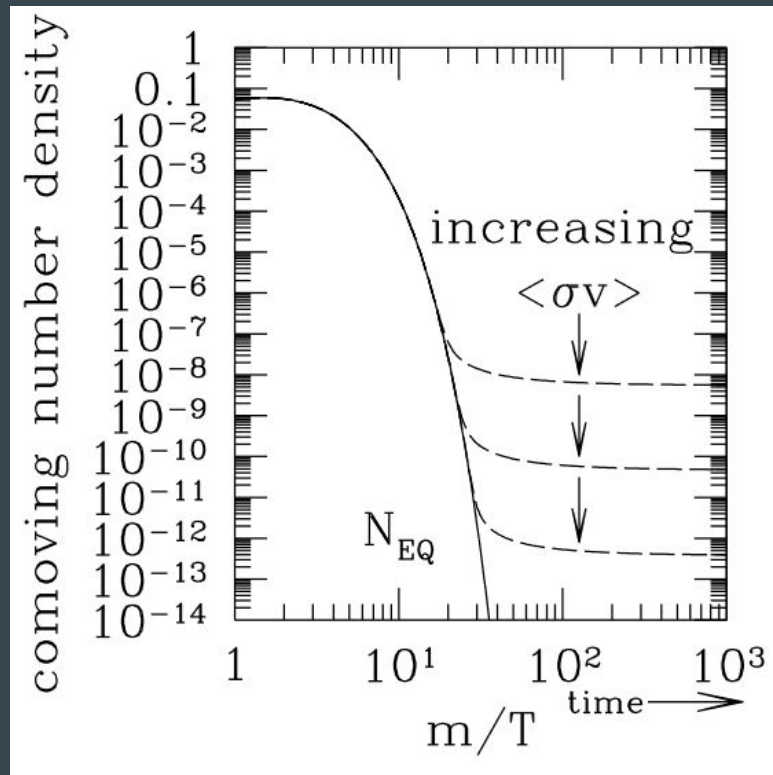


Thermal DM Hypothesis

L. Marsicano - Light dark matter searches with the NA64 experiment at CERN - 1st BiCoQ Conference

In the thermal DM scenario, DM density today can tell us about DM \rightarrow SM model annihilation cross-section: $\chi + \chi \leftrightarrow f + f$

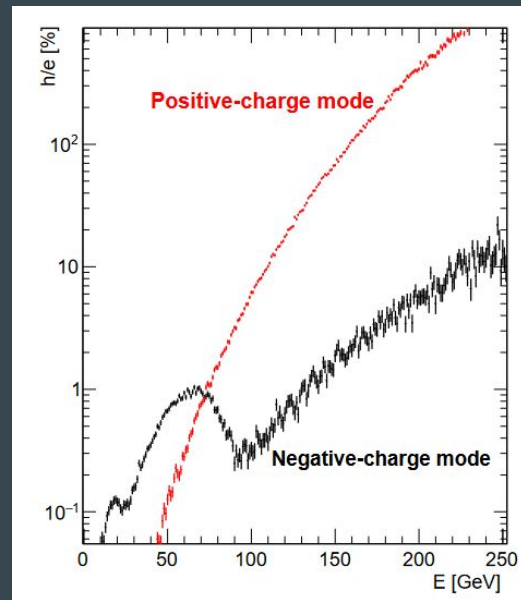
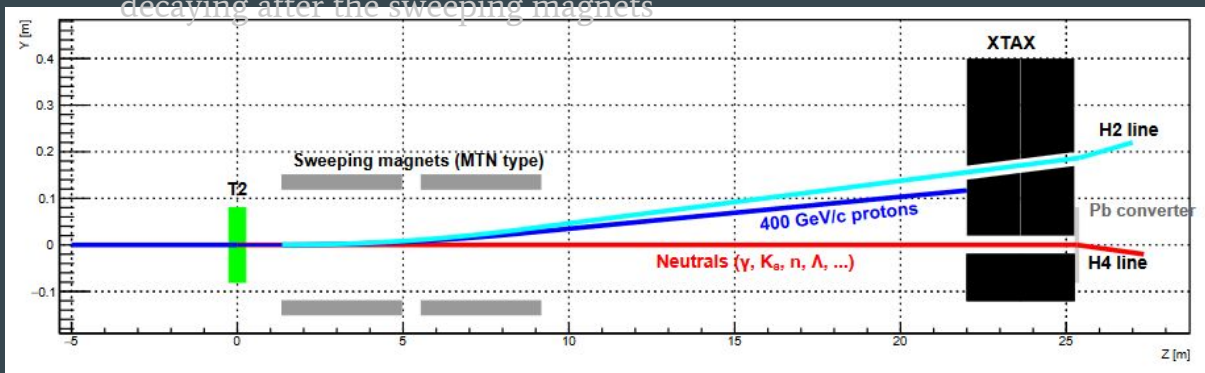
- ❖ If annihilation-cross section is too high (small), DM particles would stay longer in equilibrium in the Boltzmann regime, resulting in a lower (higher) number density at present
- ❖ DM particle mass and annihilation cross-section are bound
- ❖ If $m_\chi \sim 100$ GeV \rightarrow typical weak Interaction cross section: **WIMP Miracle**
- ❖ **But what if DM is lighter?**





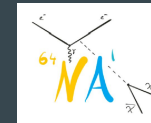
The H4 beam-line at Cern SPS

- ❖ e^- produced starting from the 400 GeV SPS proton beam, impinging on the beryllium T2 target
- ❖ Intensity on T2 target: $2-3 \times 10^{12}$ protons per 4.8 s spill
- ❖ photons from T2 selected via XTAX absorber
- ❖ e^- obtained from photons converting on a downstream Pb target
- ❖ Intensity provided at NA64 target: $\sim 10^7$ particles/spill, 3000 spills/day
- ❖ hadron contaminants arise from neutrals produced in the T2, and decaying after the sweeping magnets



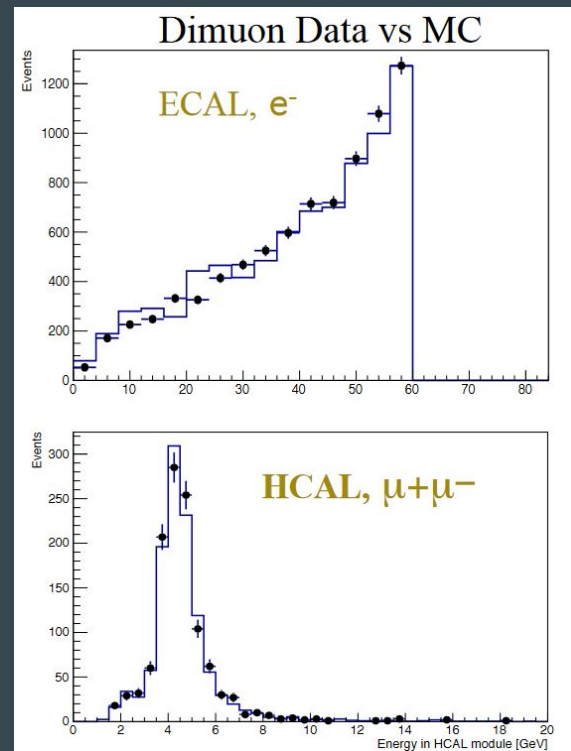
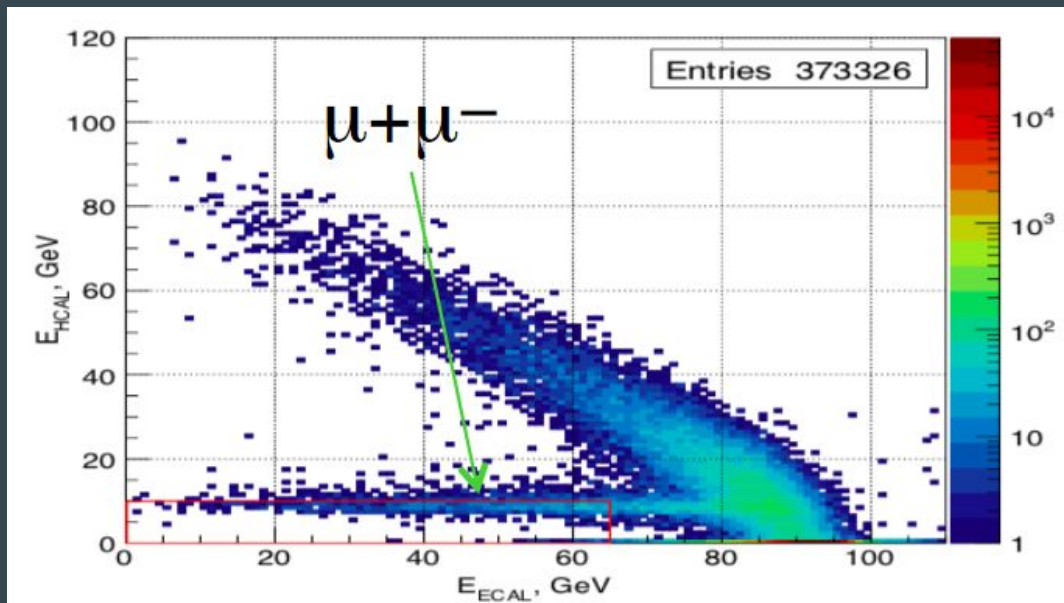
Hadron contamination at 100 GeV e^- mode: $\sim 0.3\%$

Di-muon events analysis

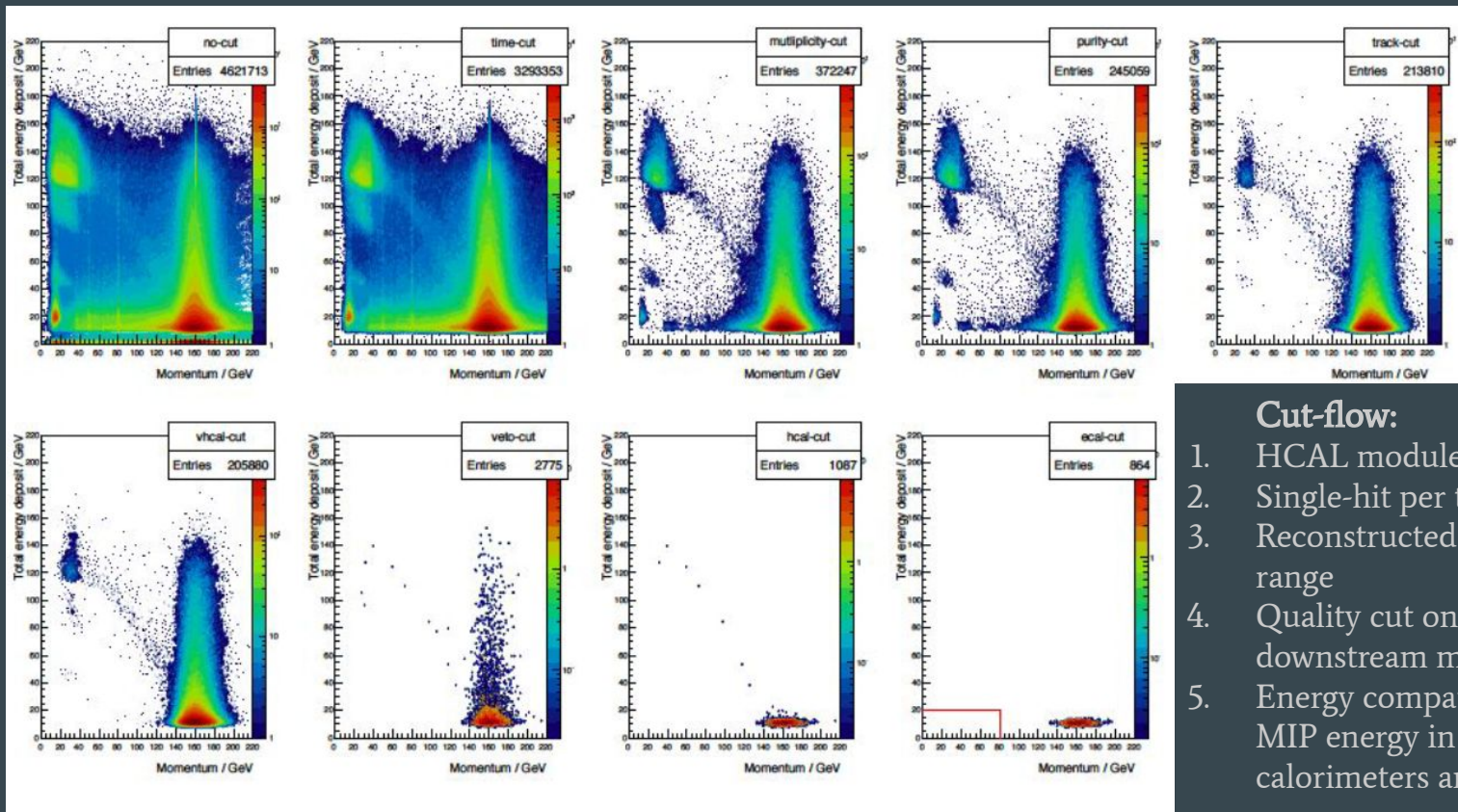
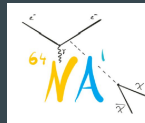


Rare QED process $\sim 10^{-5}/\text{EOT}$:

- ❖ similar to the A' production
- ❖ cross check of A' yield, systematic errors
- ❖ background prediction from data
- ❖ cross check of overall efficiency



NA64- μ analysis cut-flow



Cut-flow:

1. HCAL modules in-time
2. Single-hit per tracker
3. Reconstructed momenta range
4. Quality cut on downstream momenta
5. Energy compatible with MIP energy in calorimeters and veto

NA64 search for A' visible decay

