Searching for the X17 particle with the NA64 experiment at CERN SPS

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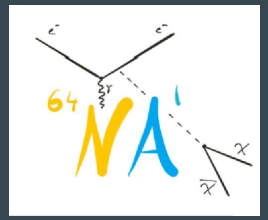
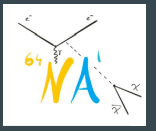
ECT*, Trento 24/3/2026



Summary



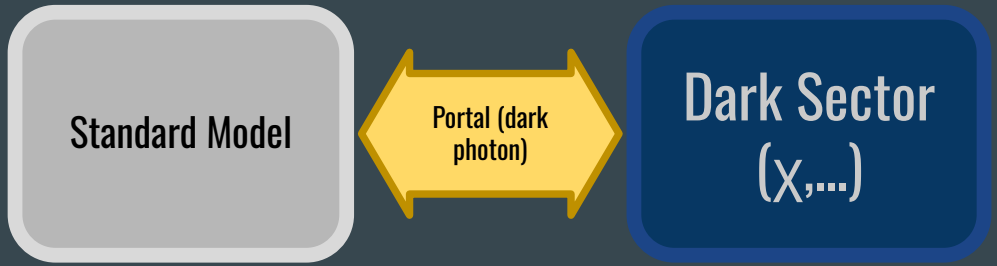
1. Introduction
2. Overview the experiment
   - The NA64-e detector and experimental technique
   - Results and future prospects in the search for light dark matter
3. X17 searches at NA64
   - Currents limits set by the experiment
   - Future prospects
4. Conclusions

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:

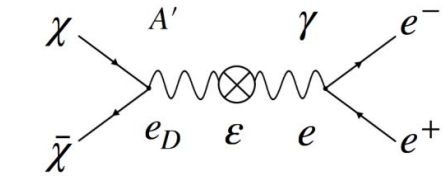
- DM and SM states in thermodynamic equilibrium in early Universe.
- DM relic abundance connected to the annihilation cross section $\chi\chi \rightarrow ll$ ("freeze-out" mechanism)
- **This sets a target in the LDM parameters space.**



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

$\alpha_D \equiv \frac{e_D^2}{4\pi}$



$\alpha \equiv \frac{e^2}{4\pi}$

DM SM

DM charged under new mediator
Small A'-photon mixing: $\varepsilon << 1$

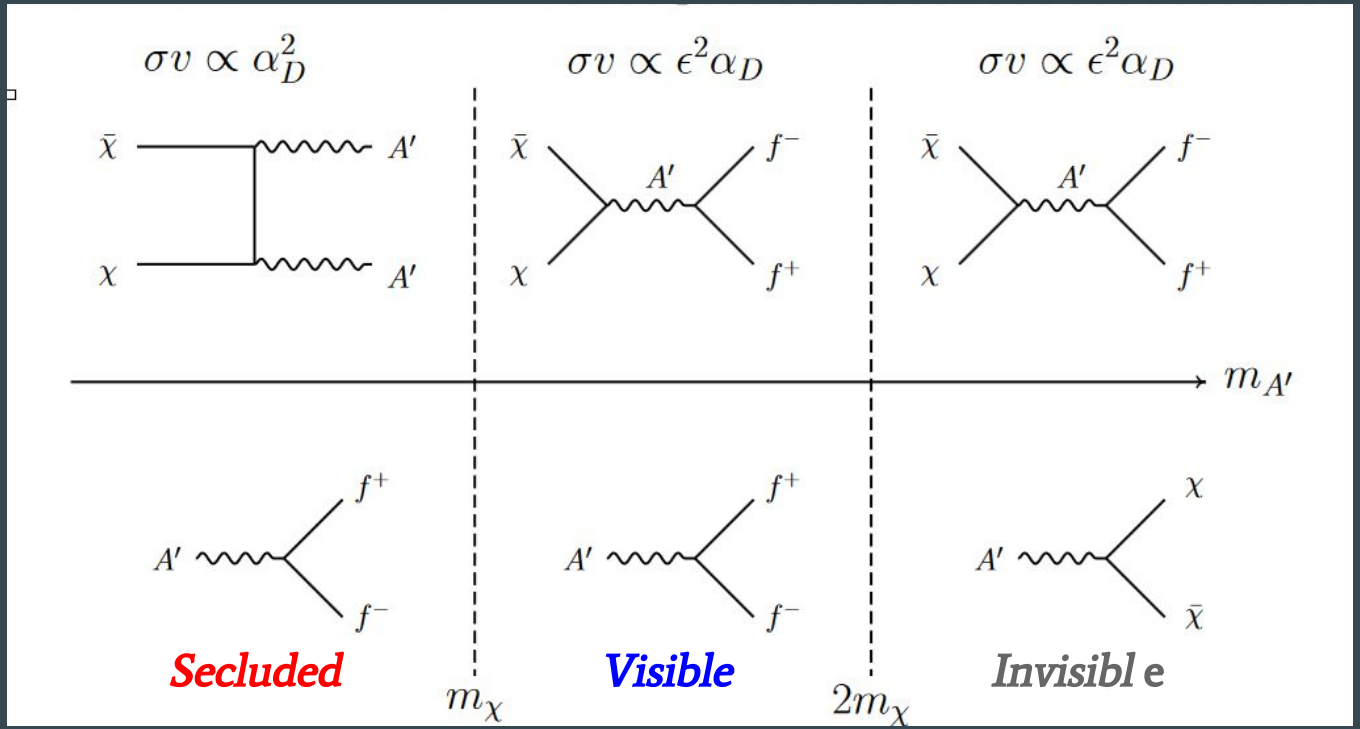
- By requiring that freeze-out mechanism reproduces today's relic abundance, a target in the parameters space can be derived:
- Define a new variable optimized for thermal targets:

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

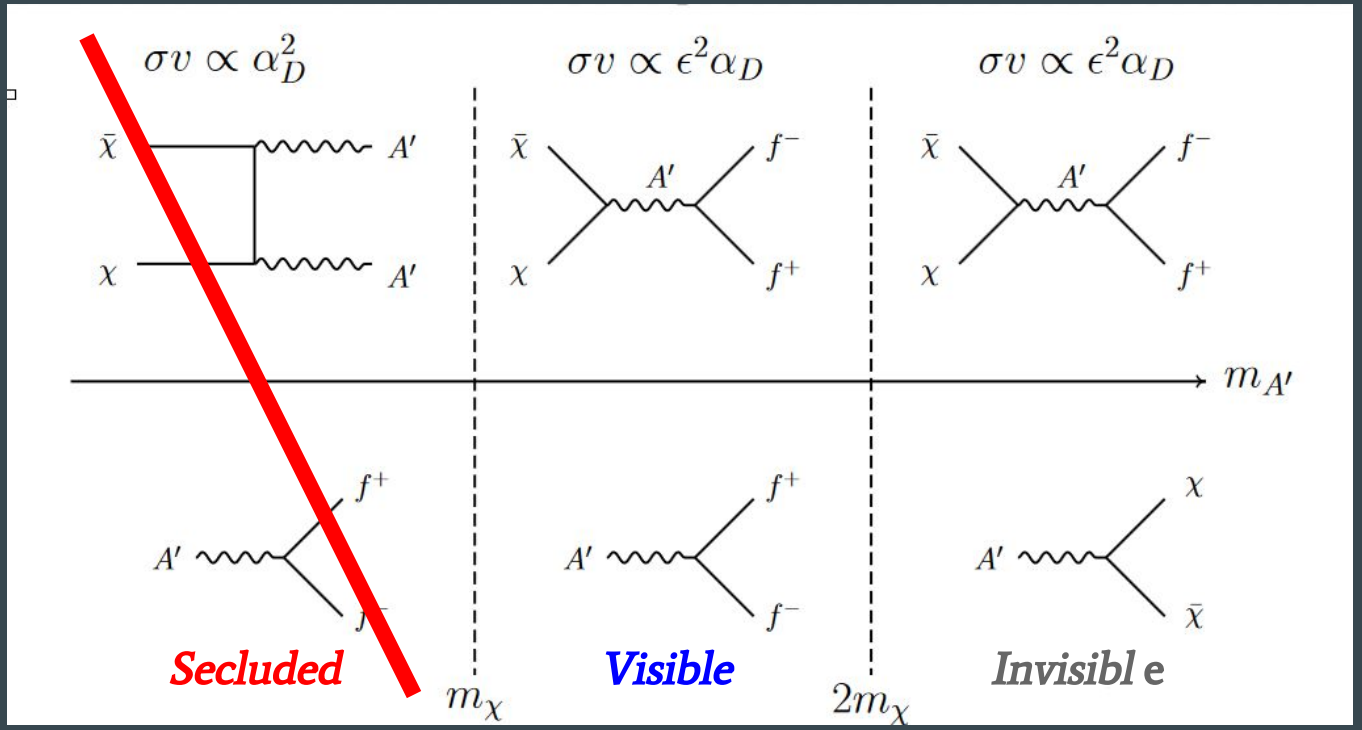
For a given value of m_χ, thermal origin imposes one value of y

1707.04591, 2005.01515, 2011.02157

LDM annihilation channels



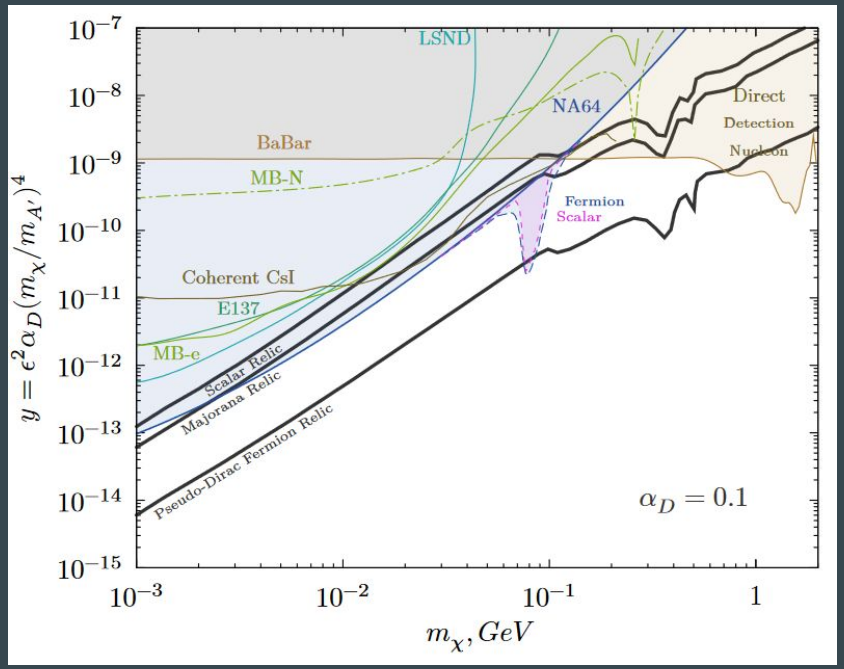
LDM annihilation channels



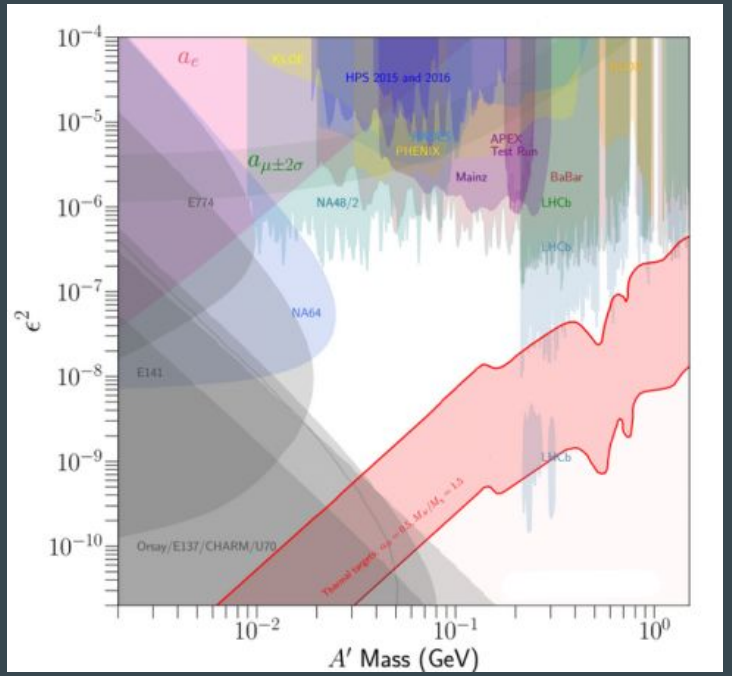
- Secluded scenario: provides no thermal target for accelerator-based experiments: any ε value is allowed

LDM parameter spaces

Invisible decay scenario

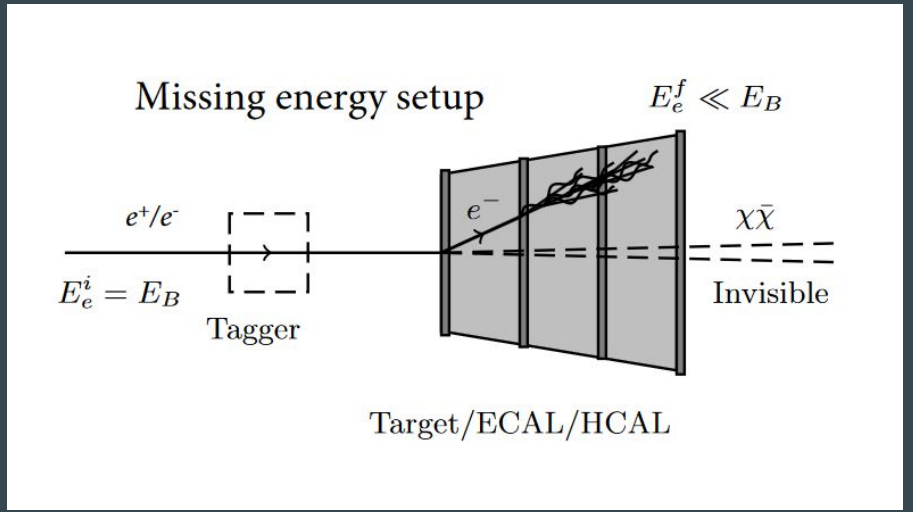


Visible decay scenario



NA64-e: the missing energy strategy

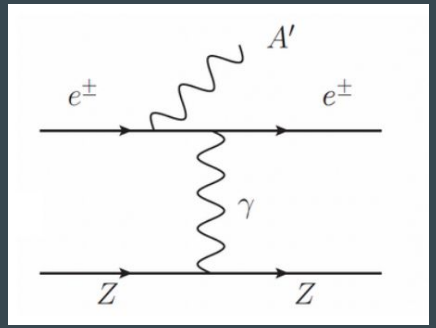
- Specific beam structure: particles impinging “one at a time” on the active target
- Deposited energy E_{dep} measured event-by-event
- **Signal:** events with large $E_{miss} = E_{Beam} - E_{dep}$
- **Backgrounds:** events with /long-lived (K_L) / highly penetrating (μ) particles escaping the detector,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

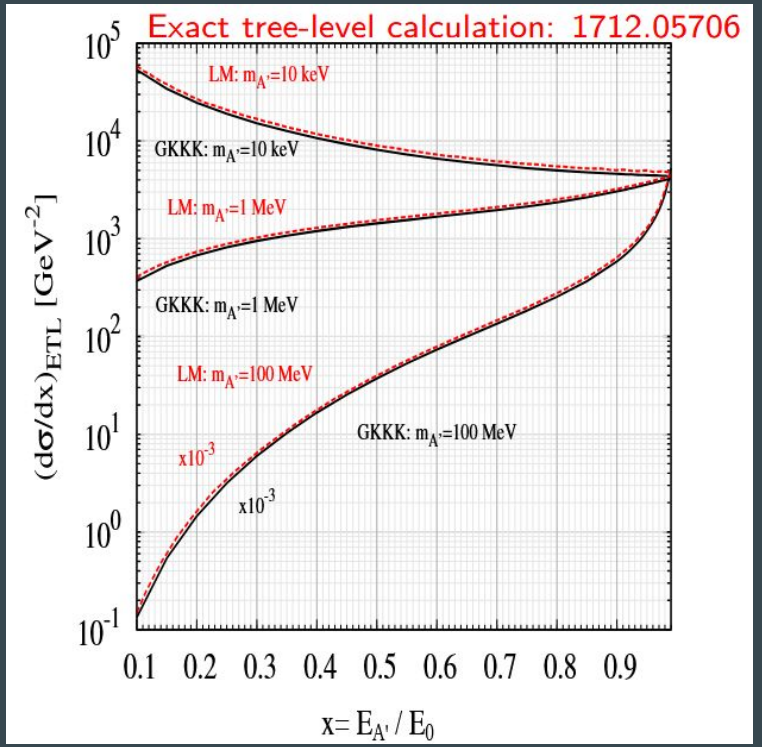


Signal scaling: $\propto \varepsilon^2$

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*

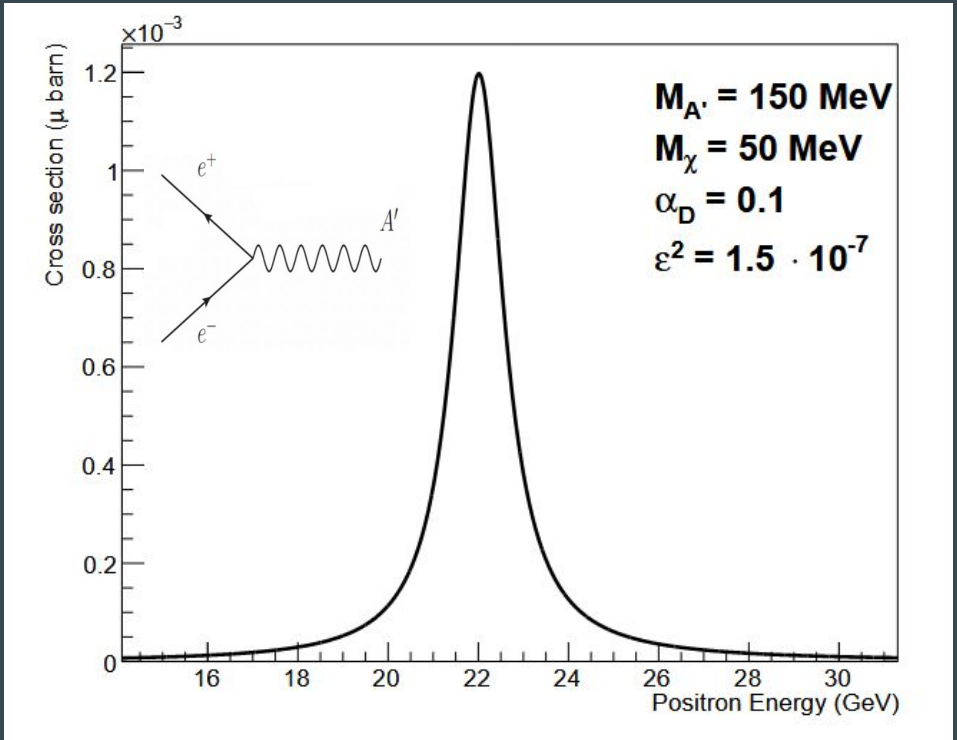
- Resonant annihilation followed by A' decay:

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

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

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

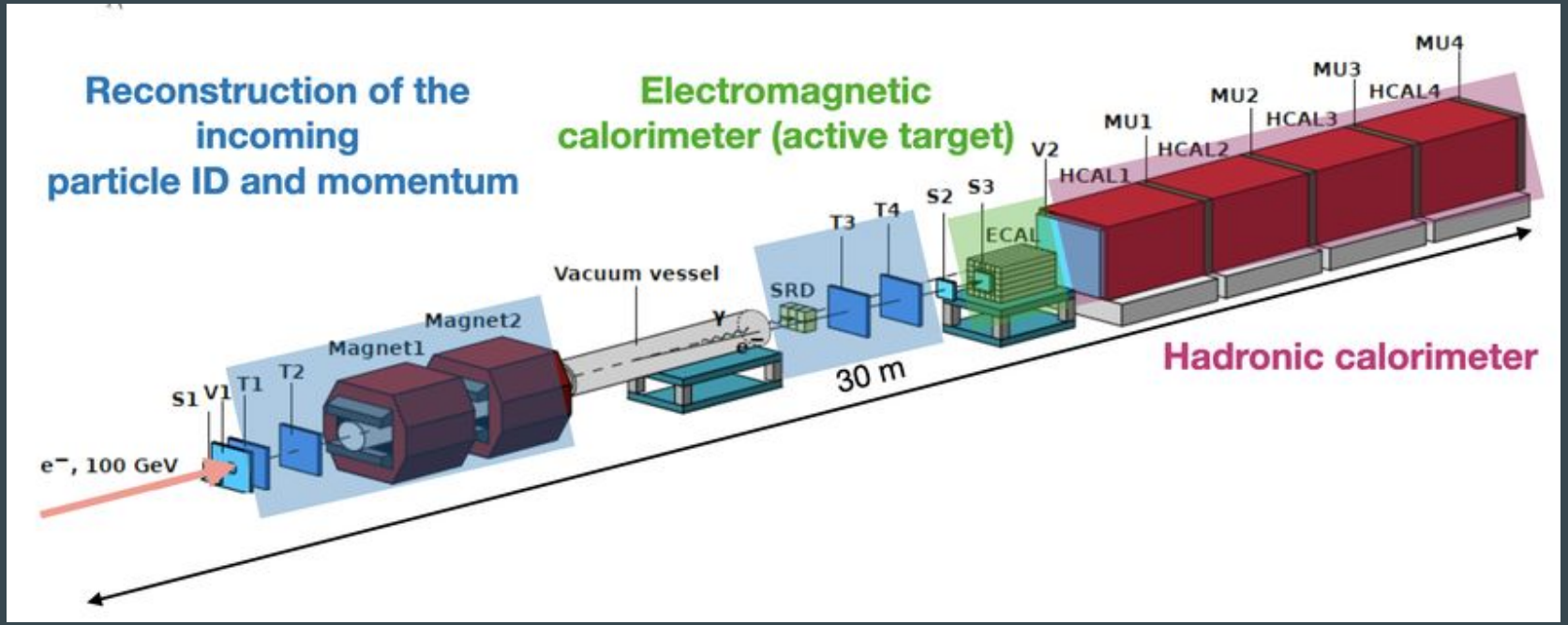
Relevant also with an e^- beam, due to secondary positrons in the target



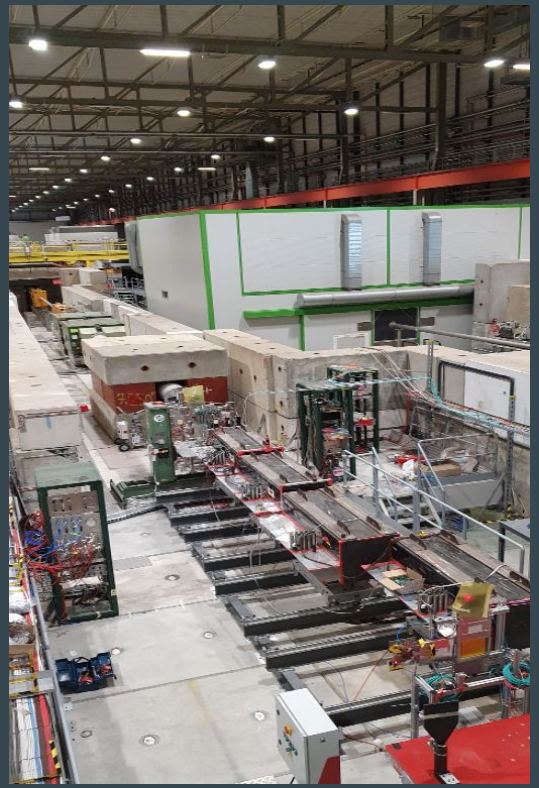
Phys. Rev. Lett. 121, 041802

The NA64-e experiment

Missing energy experiment at CERN SPS, H4 line (CERN North Area), operating since 2014

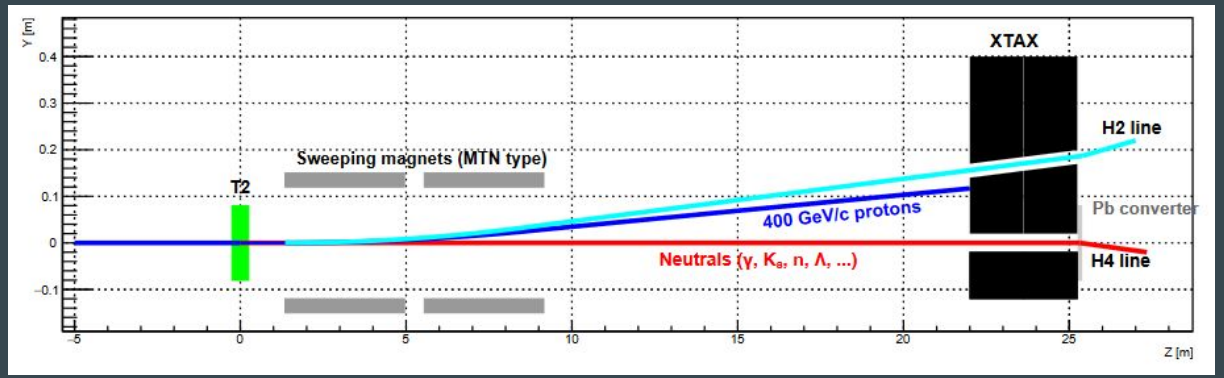


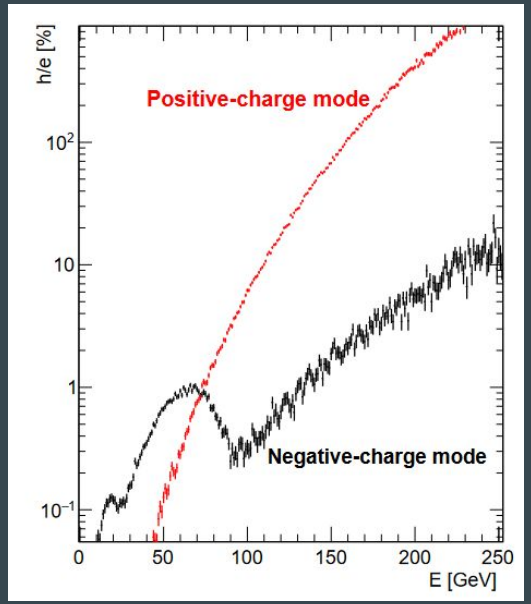
NA64-e at CERN SPS - H4 line



The H4 beam-line at Cern SPS

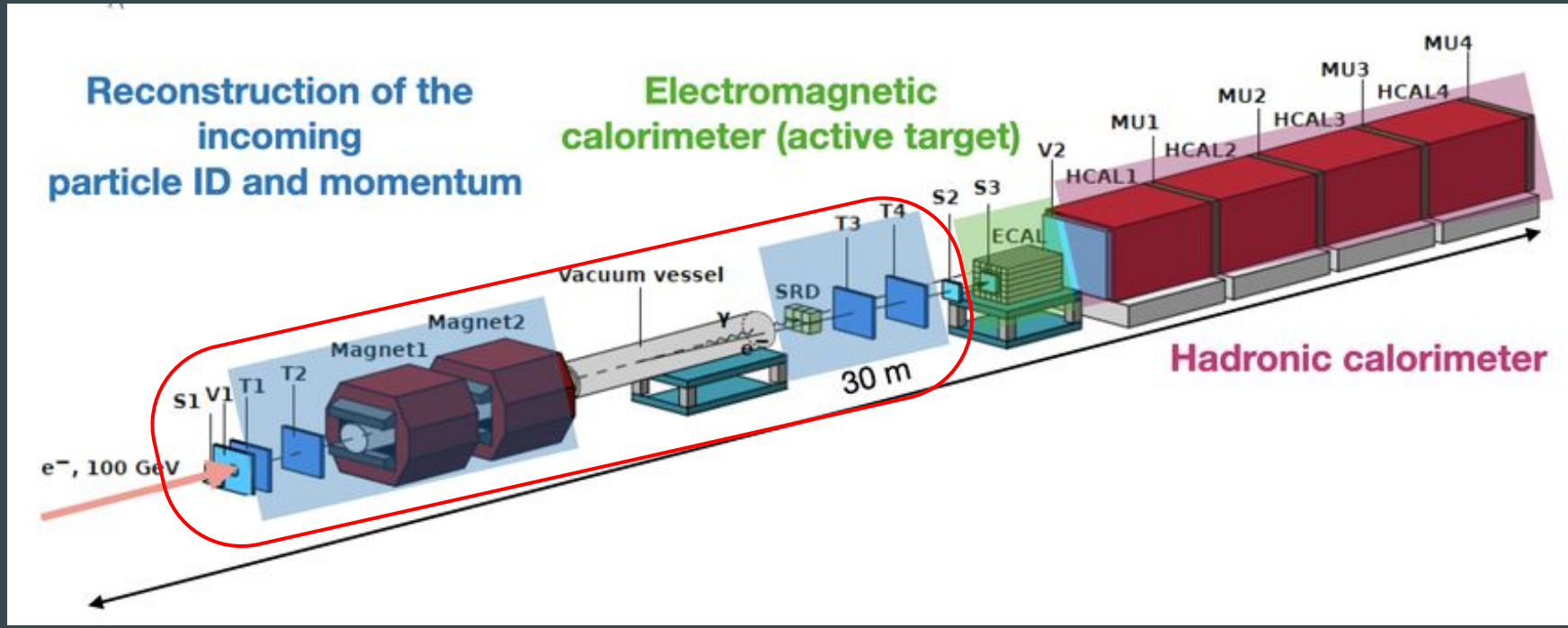
- e^- produced starting from the 400 GeV SPS proton beam, impinging on the beryllium T2 target
- Intensity on T2 target: 2–3 × 10^{12} protons per 4.8 s spill
- photons from T2 selected via XTAX absorber
- e^- obtained from photons converting on a downstream Pb target
- Intensity provided at NA64 target: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





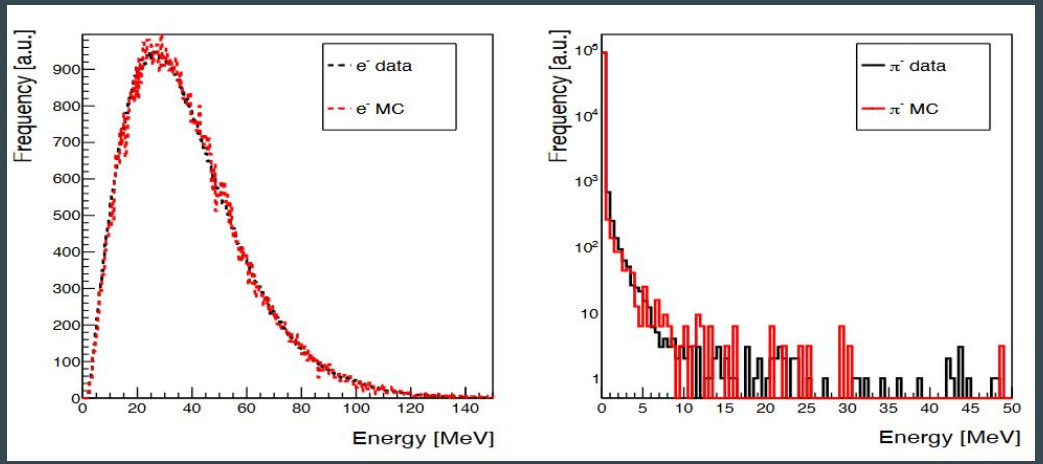
Hadron contamination at 100 GeV e^- mode: ~ 0.3%

The NA64-e Detector- Upstream Trackers

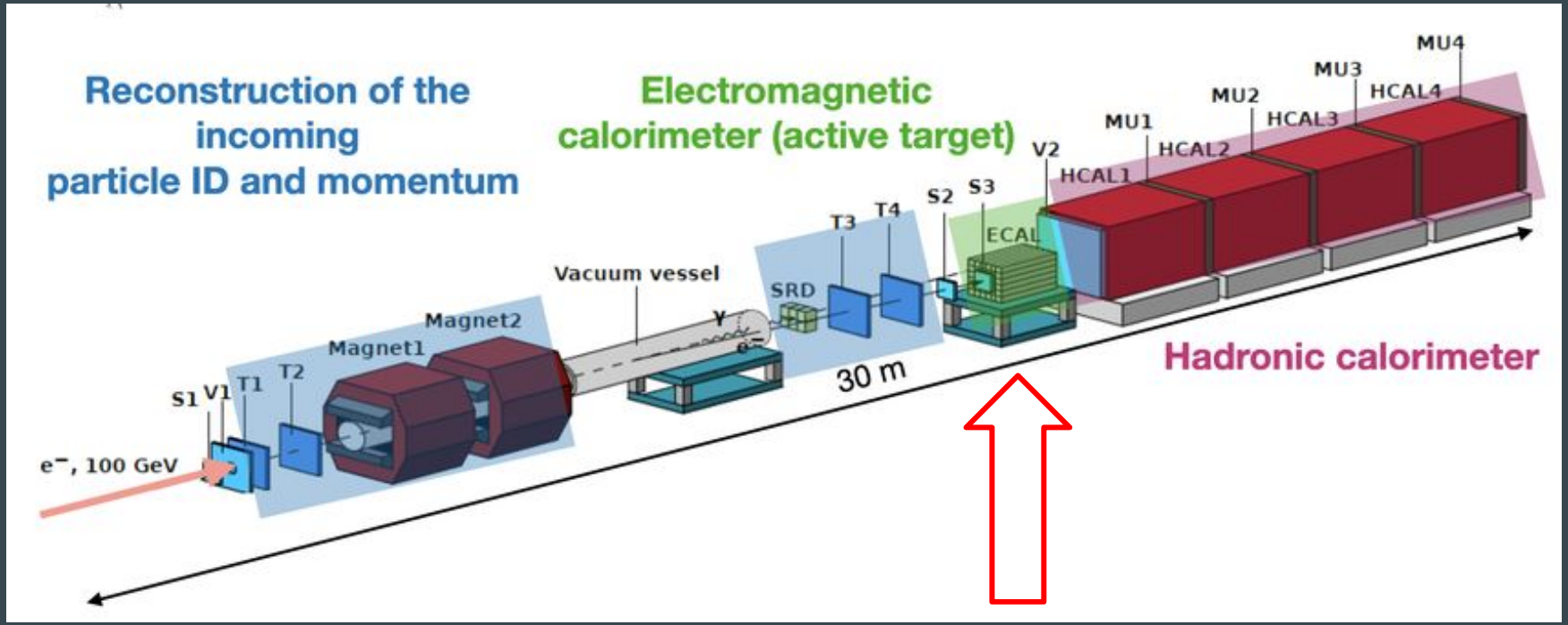


Tagging e^- with SRD detector

- Reject hadron 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}

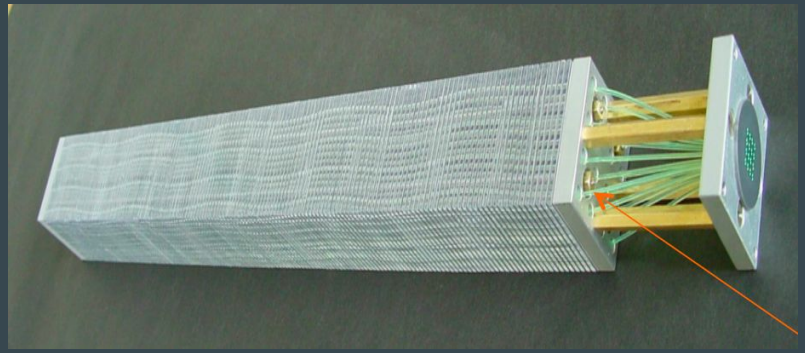


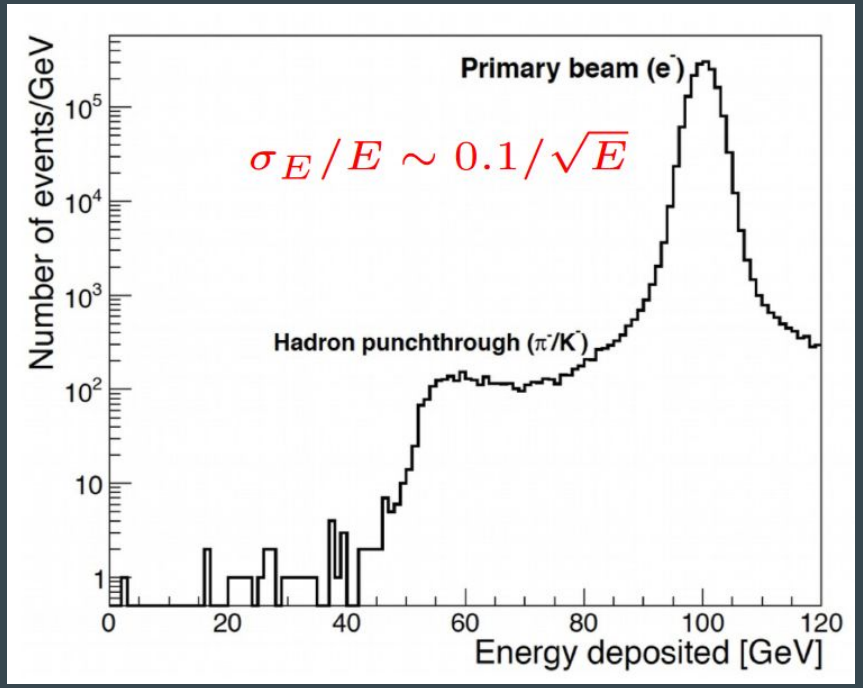
The NA64-e Detector - The Active Target



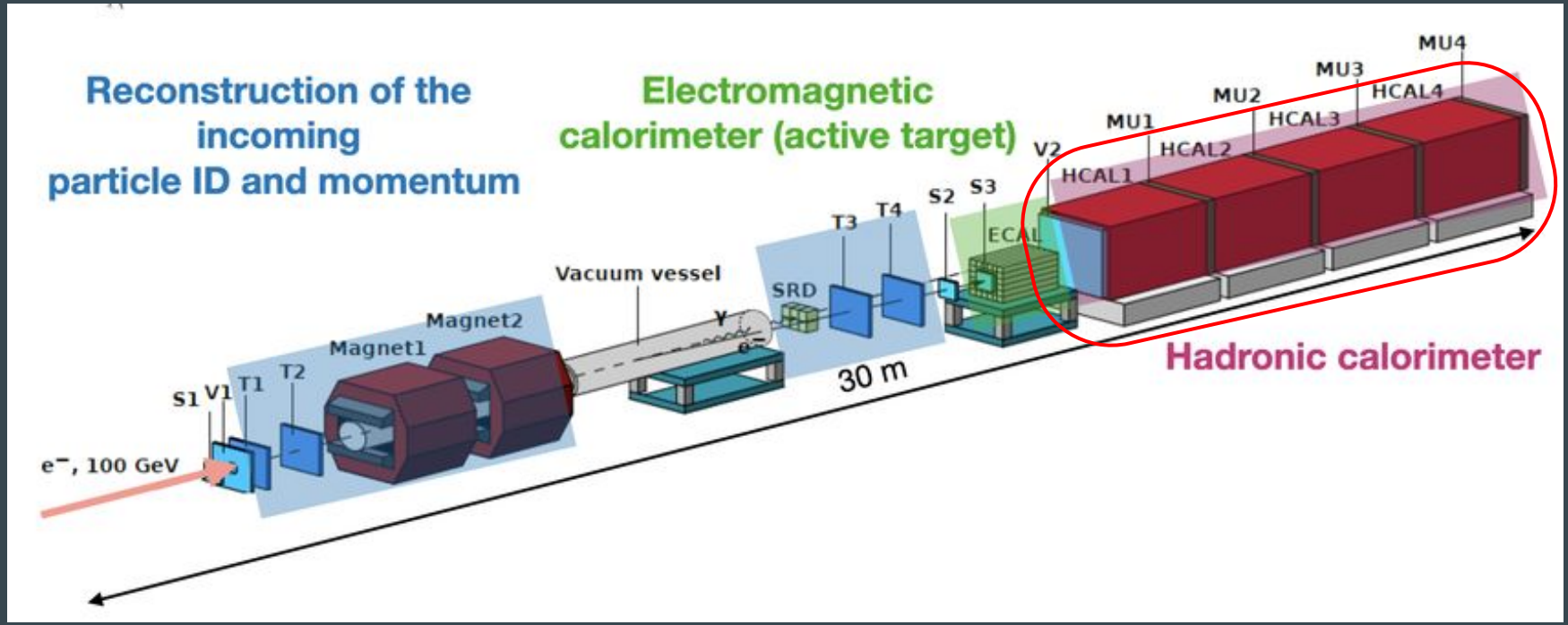
The Electromagnetic Calorimeter (ECal)

- 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



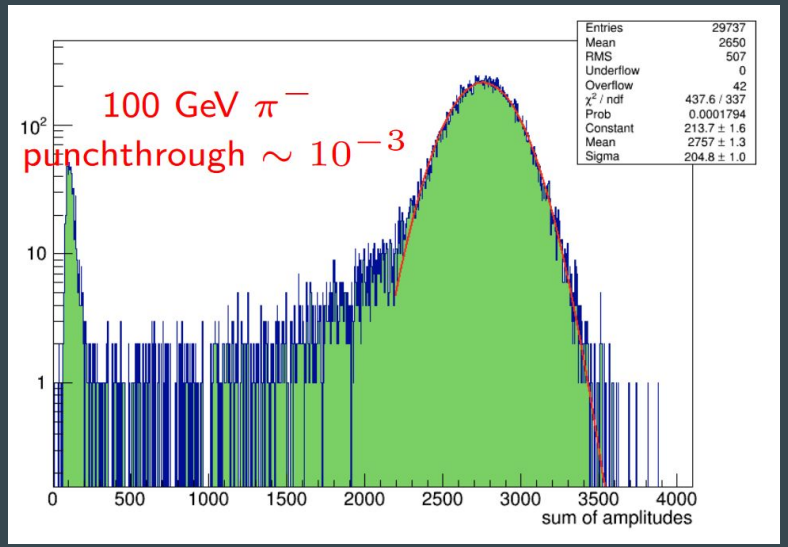


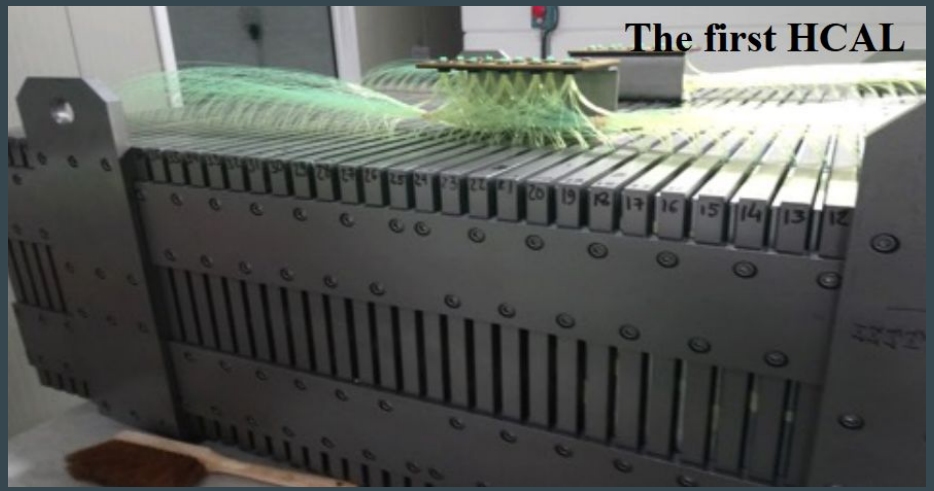
The NA64-e Detector - Downstream Section



Hadronic Calorimeter (HCal)

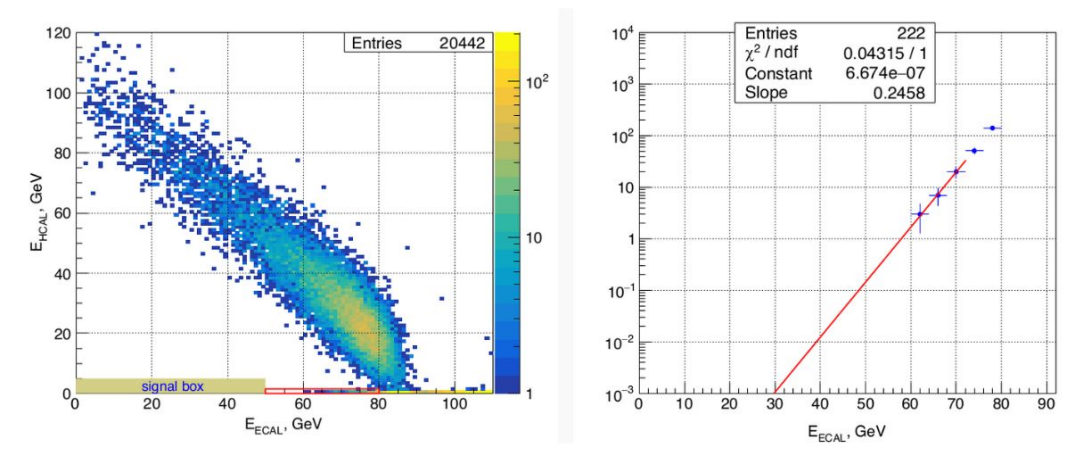
- 4× 1-m long sandwich modules ~ 30 nuclear interaction length
- Optical fibers + PMT readout
- Pion punchthrough probability: 10^{-3} per module





NA64-e analysis cut-flow

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



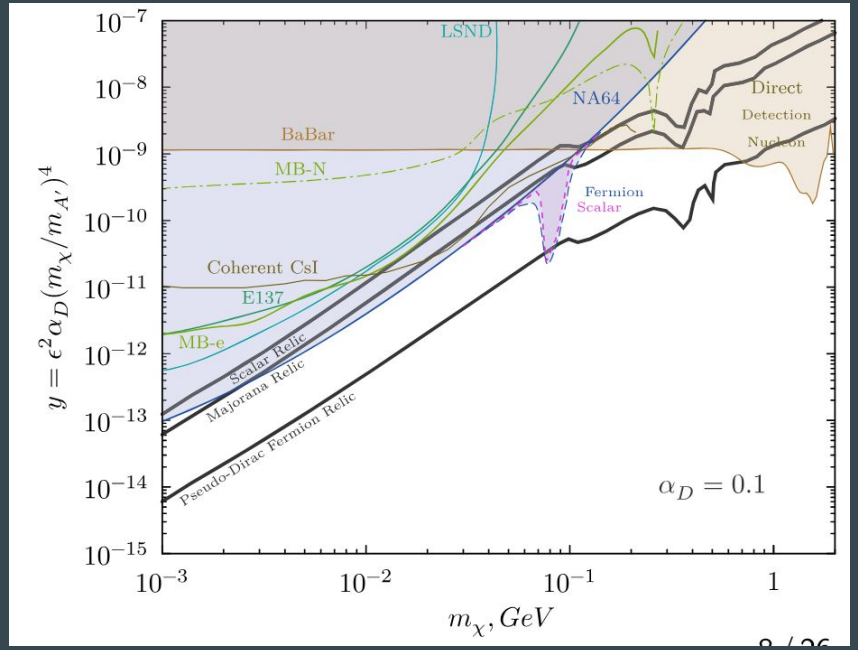
Main backgrounds:

- 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 ν_e final state.
- Electro- / photo-nuclear interactions with upstream beamline materials.

NA64-e limits in the LDM scenario

- Current published results based on ~ 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

Background source	Background, n_b
1. Di-muons losses or decays in the target	0.04 ± 0.01
2. μ, π, K $\rightarrow$ e +... 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

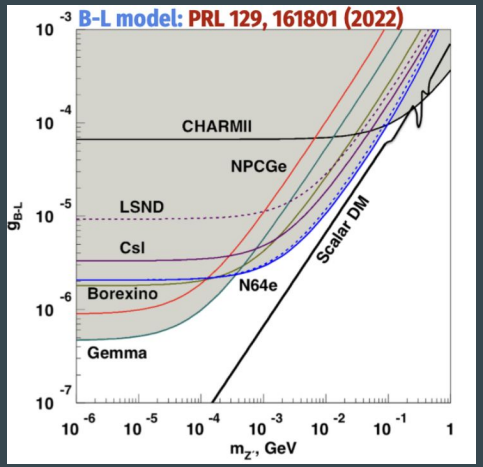


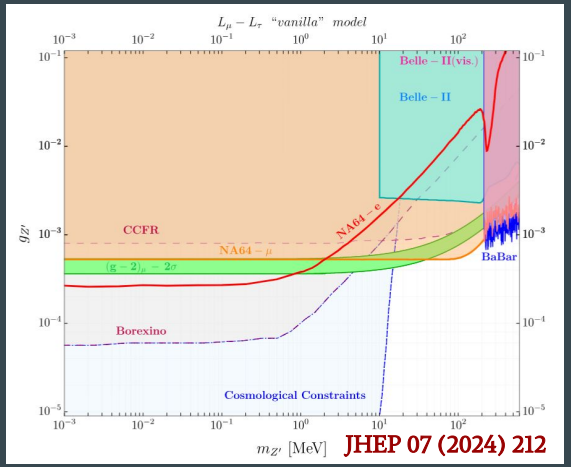
Phys. Rev. Lett. 131, 161801

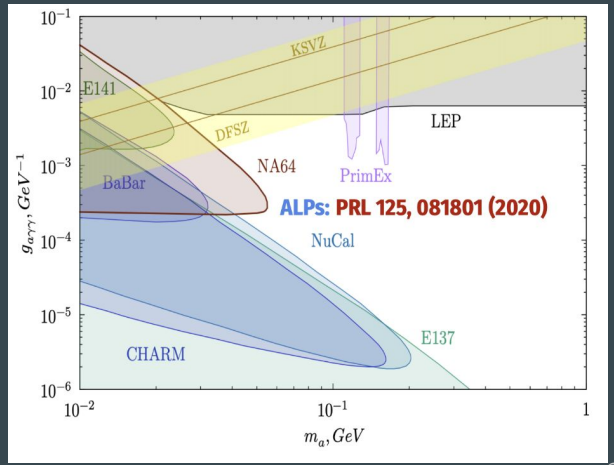
NA64-e broad physics program

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, $L_u - L_\tau$ models with light Z′ mediator
- Light Thermal Inelastic Dark Matter models with semi-visible decays

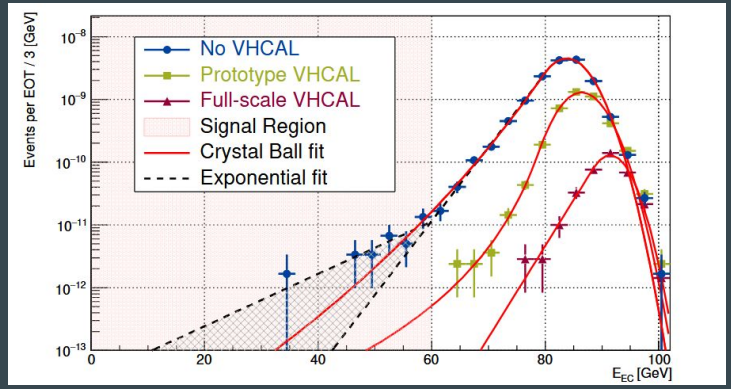




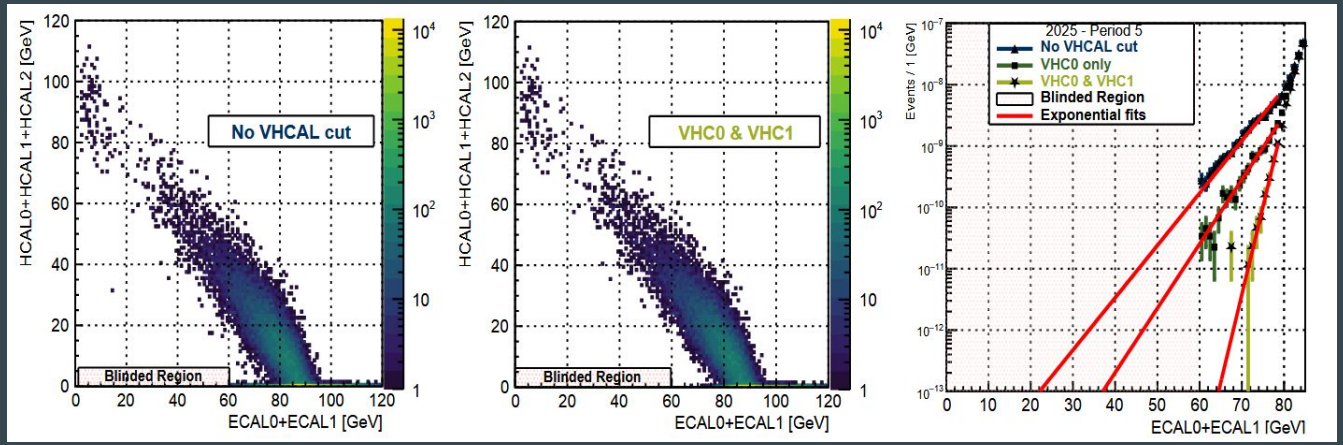


NA64-e: 2023-2025 Runs

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

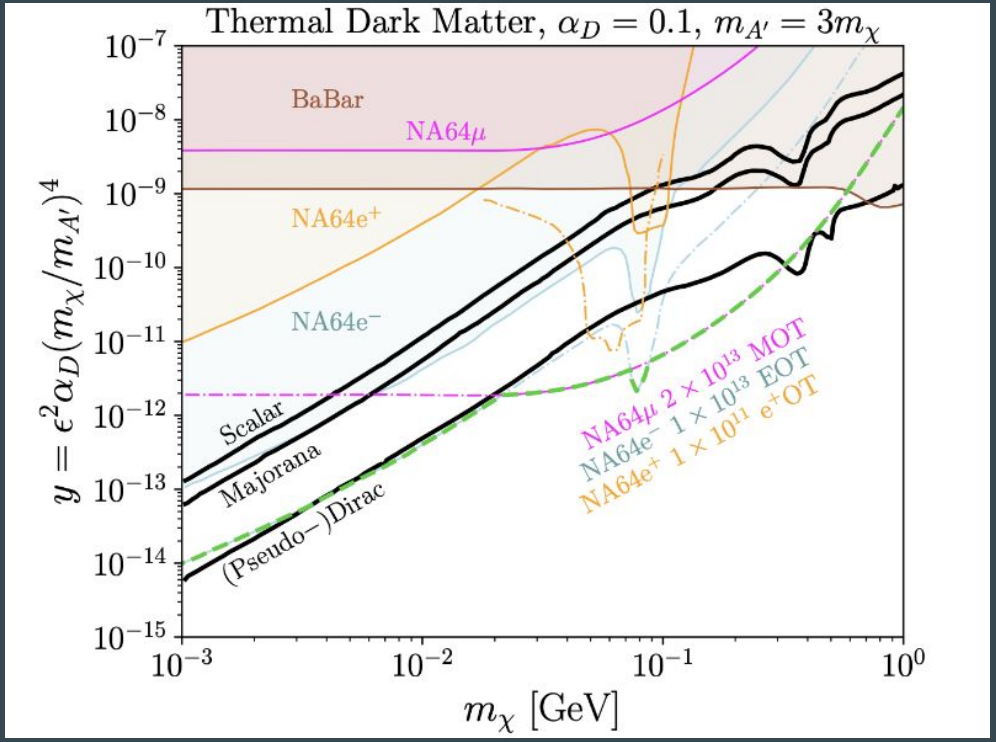


PRELIMINARY 2025 RUN

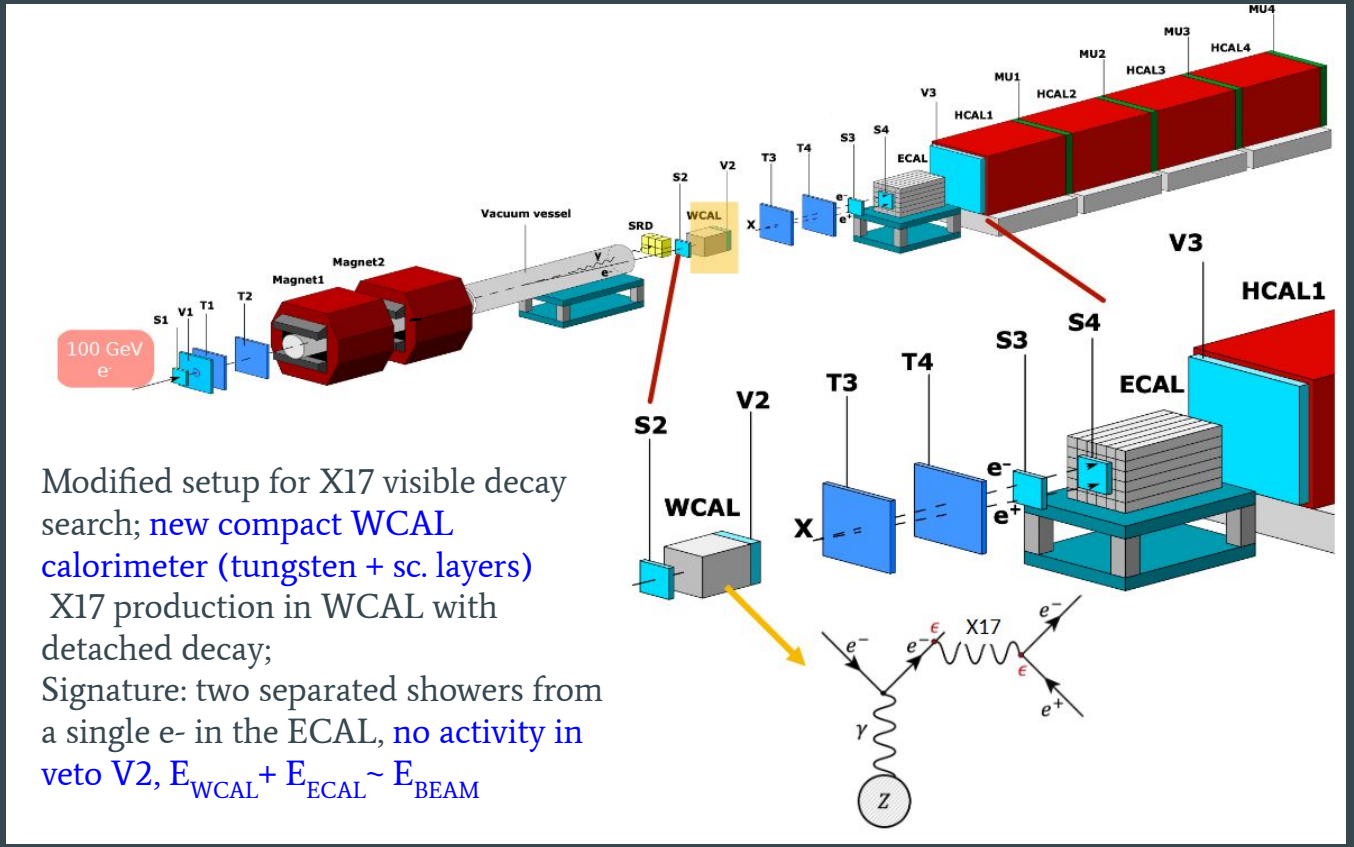


NA64 post LS3-program

NA64 goal for post-LS3 runs: accumulate 10^{13} e^-OT, 2×10^{13} MOT, 10^{11} e^+OT to probe the entire LDM parameters space down to the Pseudo-Dirac scenario



NA64 search for A' visible decay



Modified setup for X17 visible decay search; new compact WCAL calorimeter (tungsten + sc. layers)

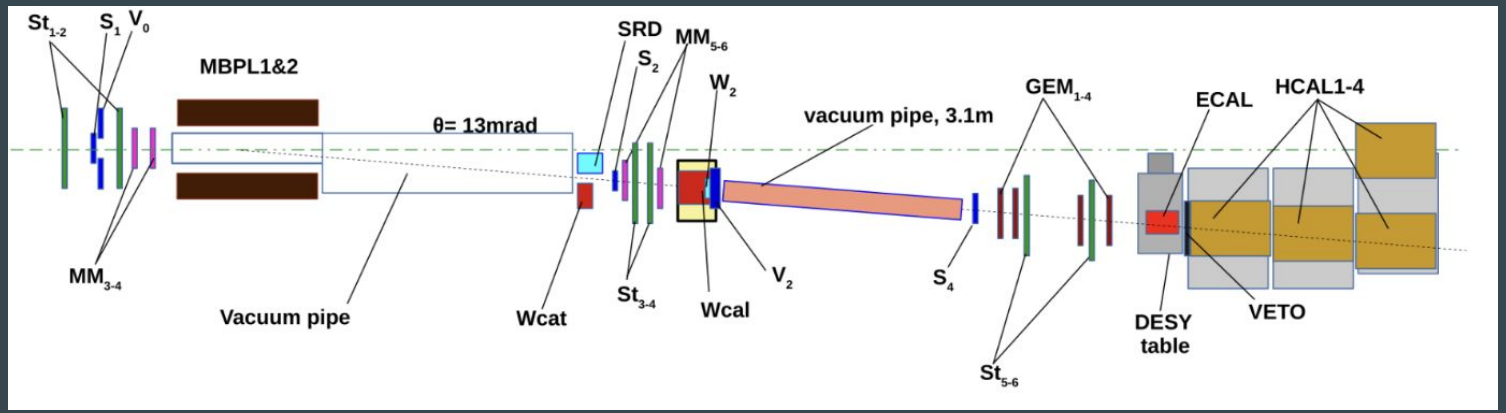
X17 production in WCAL with detached decay;

Signature: two separated showers from a single e- in the ECAL, no activity in veto V2, $E_{WCAL} + E_{ECAL} \sim E_{BEAM}$

Visible A' searches at NA64

Two data taking runs collected by NA64 in visible mode:

- **2017: 100-GeV beam, 5.4×10^{10} e⁻OT**
  - Baseline: NA64-e invisible-mode configuration (SRD, tracking, HCAL)
  - 30 X_0-WCAL installed after SRD, 3.5 m upstream
  - 2× segmented plastic scintillator counters installed in front of ECAL
- **2018: 150-GeV beam, 3.0×10^{10} e⁻OT**
  - New W2 VETO counter installed immediately after WCAL
  - Increased distance between WCAL and ECAL (6 m), with a 3-m vacuum tube in the first part
  - 4 GEM and 4 straw tube trackers in front of ECAL



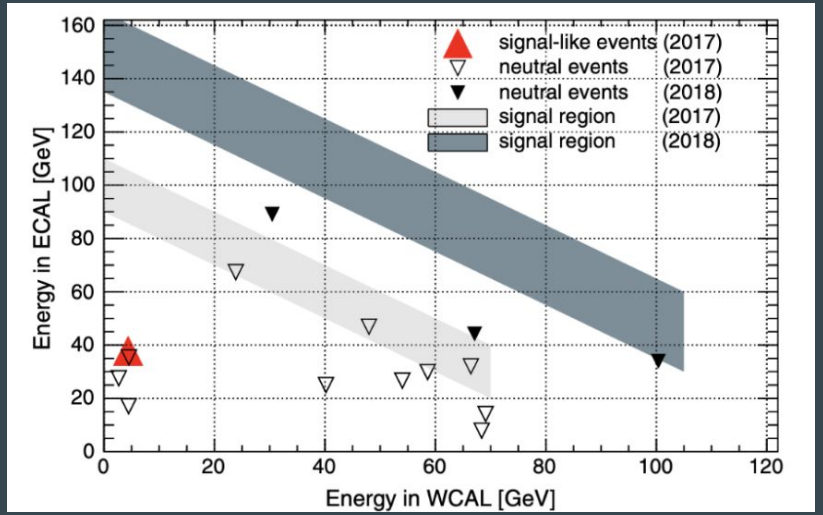
NA64 visible search: analysis of 2017-2018 data

Events selection:

- Clean impinging e^- with $E \simeq E_{beam}$
- No activity in W2 and V2 veto counters
- 2x MIP-like signature in S4 and trackers
- No activity in VETO, HCAL
- Total energy deposition in WCAL and ECAL compatible with E_{beam}

Backgrounds:

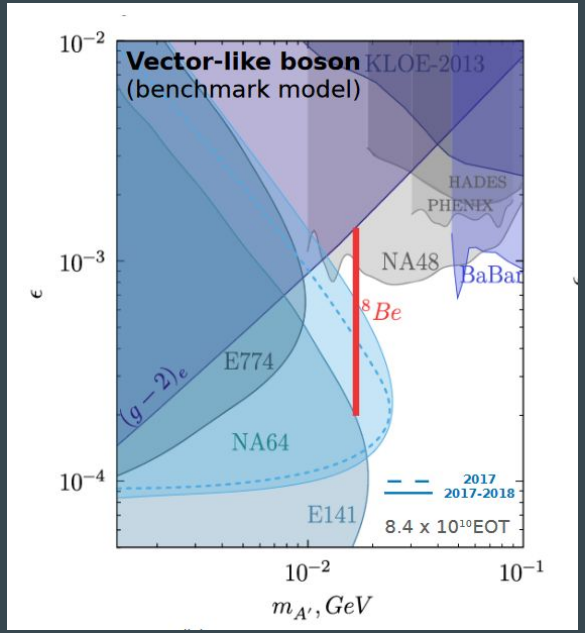
- Main background coming from the decay of pions downstream the WCAL, $\pi_0 \rightarrow e^+ e^- \gamma$ or $\pi_0 \rightarrow \gamma\gamma$, followed by $\gamma \rightarrow e^+e^-$
- Pions produced mainly via decay of K_0 arising from misidentified π^- interacting in the WCAL
- No signal events observed after unblinding



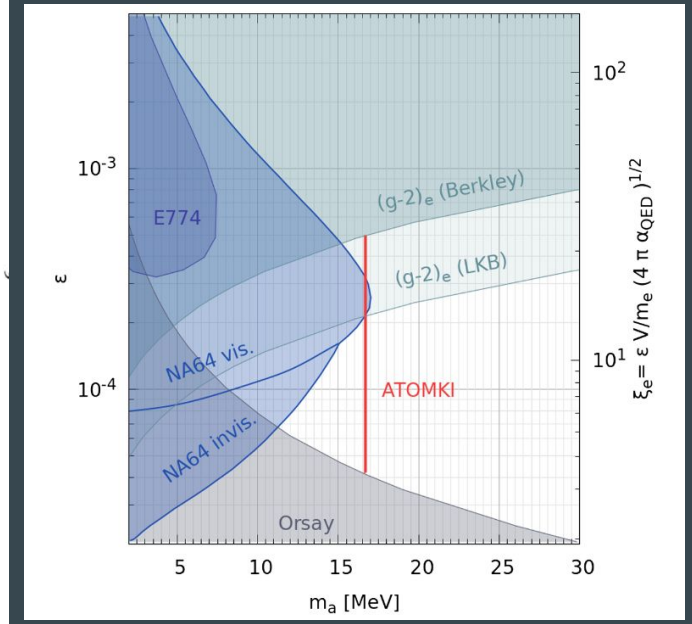
Source of background	2017 data	2018 data
$K_S^0 \rightarrow 2\pi^0$	0.06 ± 0.034	0.005 ± 0.003
$\pi N \rightarrow (\geq 1)\pi^0 + n + ...$	0.01 ± 0.004	0.001 ± 0.0004
punchthrough π^-	0.0015 ± 0.0008	0.0007 ± 0.0004
punchthrough γ	< 0.001	< 0.0005
$\pi, K \rightarrow e\nu$, K_{e4} decays	< 0.001	
$eZ \rightarrow eZ\mu^+\mu^-; \mu^\pm \rightarrow e^\pm\nu\bar{\nu}$	< 0.001	
Total	0.07 ± 0.035	0.006 ± 0.003

Results form 2017-2018 runs

The null result allowed to set stringent limit in the vector boson scenario, later re-interpreted in the pseudo-scalar model



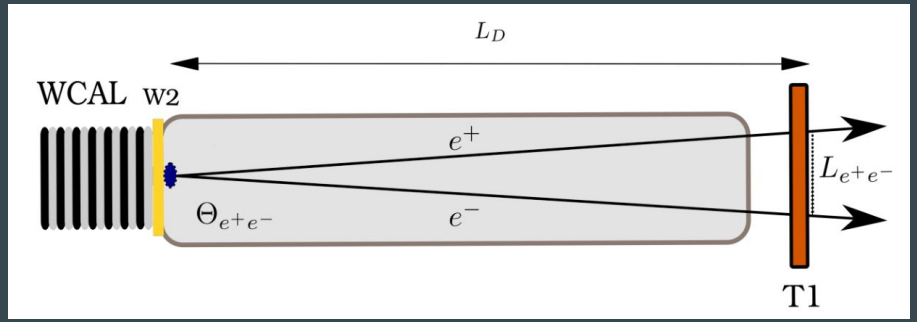
Phys. Rev. D 101 (2020) no.11,071101(R)

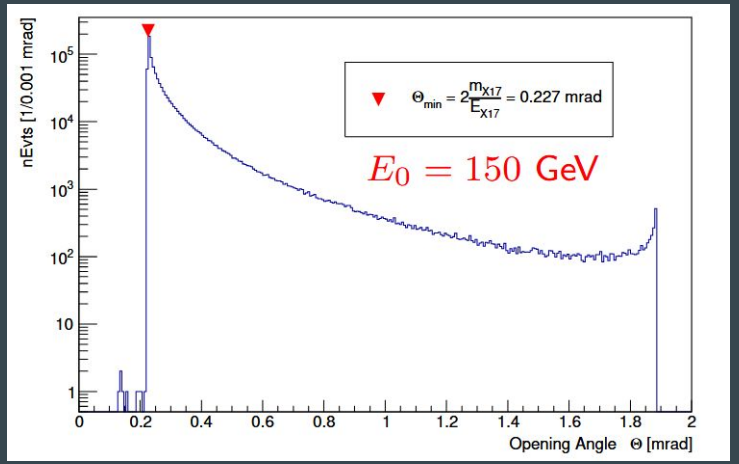


Phys. Rev. D 104, L111102 (2021)

NA64-e upgrades for the X17 search

- The sensitivity to the X17 in the NA64 visible mode is limited by the WCAL length ($\gamma c\tau_{X17}$ ~ 30 mm) and the capability to separate the very close tracks of the X17 → e^+e^- decay → new setup under consideration
- New WCAL geometry for improved signal efficiency (14 cm, 30 X_0 length)
- Dipole magnet + ~ 18 m vacuum pipe for tracks separation
- GEM trackers + ECAL for invariant mass measurement (10% invariant mass resolution)

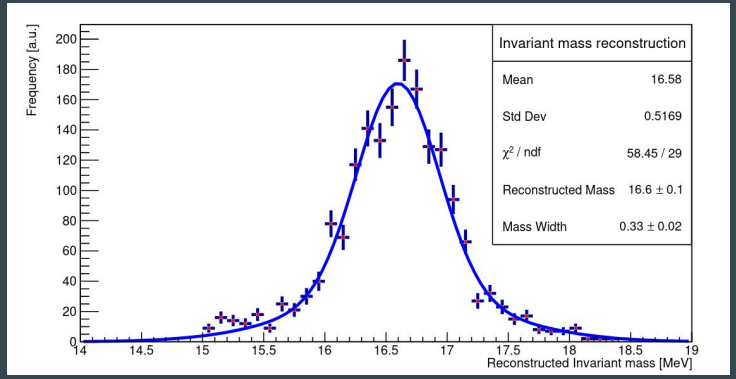


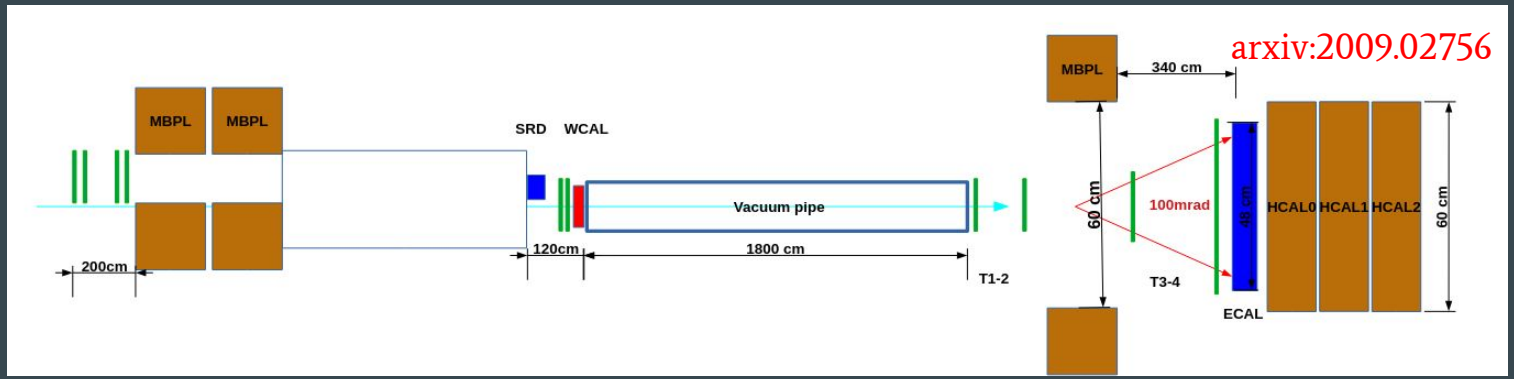


New setup for the exploration of the X17 at NA64-e

The measurement of the invariant mass of the e^+e^- pair would allow to suppress backgrounds and to obtain an unambiguous X17 signal proof of positive observation

- The invariant mass is measured from the energies of the e^+e^- pair and opening angle: $M_{ee} \sim \sqrt{E_+ E_- \theta}$
- The distance L_D between the WCAL and the first tracking station is a critical parameter for a precise measurement of ϑ
- To achieve the necessary invariant mass resolution: $L_D > 10$ m

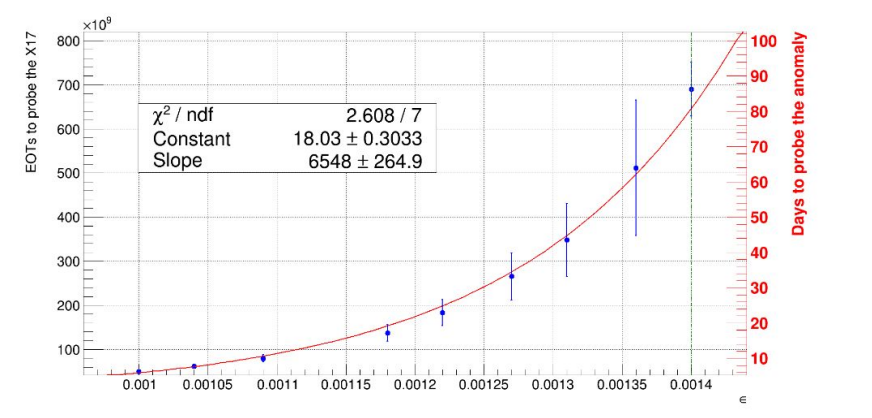


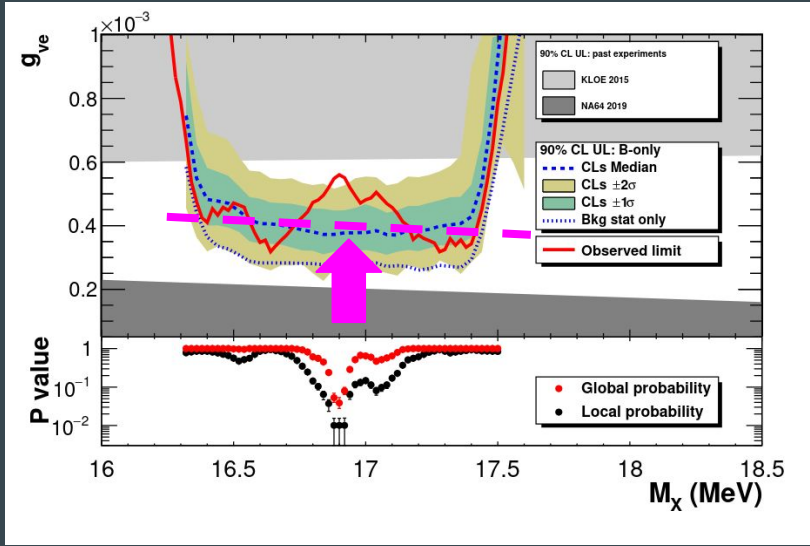


arxiv:2009.02756

NA64 projected sensitivity with optimized setup

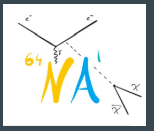
- The X17 detection efficiency is strongly dependent on the WCAL length L_W : $S \propto (1 - \exp(-\gamma c\tau X / L_W))$
- Optimized WCAL solution- 12 layers, 9 mm W + 2 mm Sc: 30 X_0 in 140 mm
- With such setup, NA64 can probe decay lengths down to ~3 cm





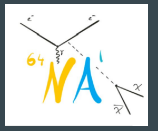
In the assumption of 0 background, NA64-e can explore ε values up to ~1.4×10^{-3} with a ~90 days run

Conclusions

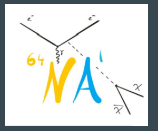


NA64: dark sector search experiment with multiple complementary measurements at CERN, based on the missing energy/missing momentum technique.

- **NA64-e** : missing energy experiment at the H4 beamline
  - Run 2016-2022: ≃ 1×10^{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.
- **X17 searches at NA64** : dedicated "visible" setup with two active targets (WCAL and ECAL).
  - Run 2017-2018: 8.4×10^{10} e^-OT. accumulated (100 GeV / 150 GeV). Null results used to exclude the X17 existence for $1.2 \times 10^{-4} < \varepsilon < 6.8 \times 10^{-4}$
  - A new improved setup is required to probe the $\varepsilon \simeq 10^{-3}$ region (short-lived X17): compact WCAL and invariant mass measurement.
  - With the new setup, in ≃ 3 months NA64 can reach up to $\varepsilon \simeq 1.4 \times 10^{-4}$.
- **Collaboration plans for post-LS3 run (≳ 2029) will be defined during the forthcoming CERN LS3 stop.**



Thanks for the attention!

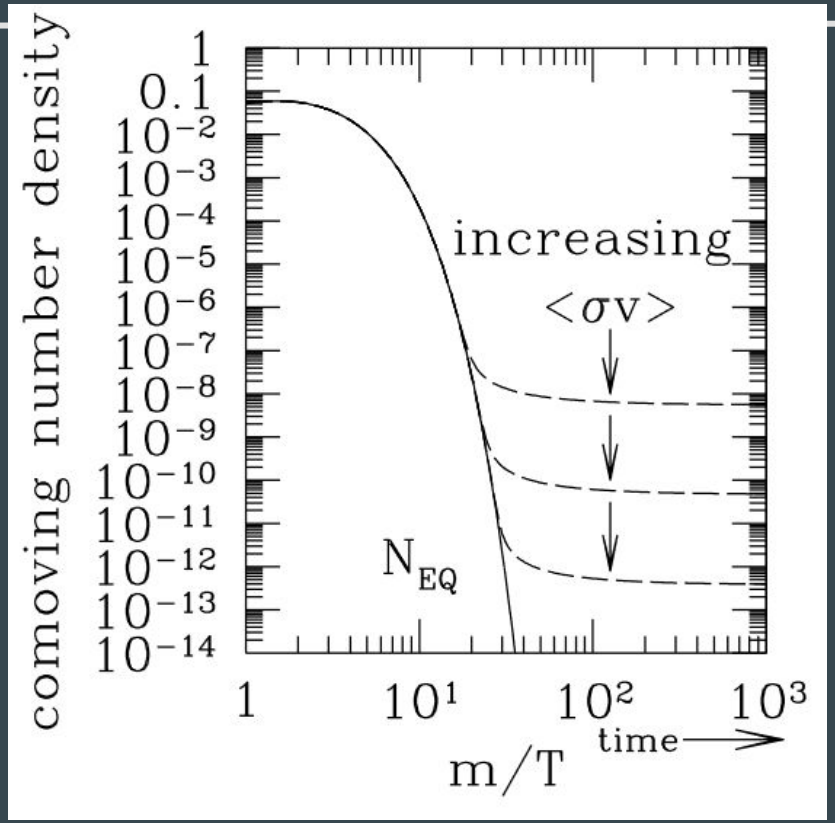


Backup

Thermal DM Hypothesis

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

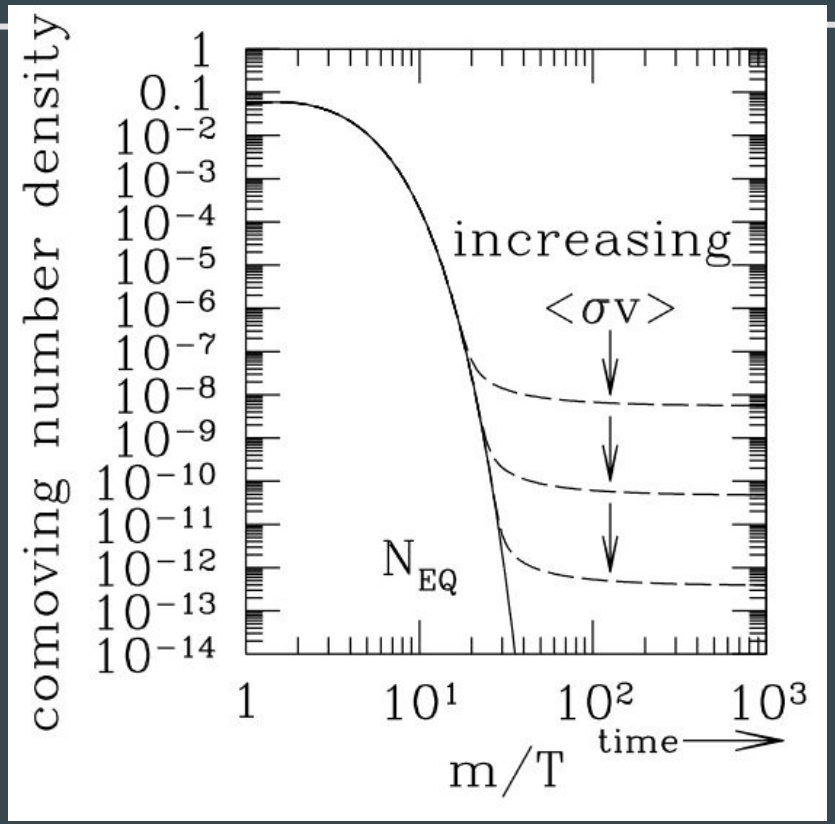
- Early universe: high-T, relativistic regime. Both reactions ($\leftarrow$ and $\rightarrow$) permitted
- As Universe expands and cools down below χ mass, only $\rightarrow$ reaction occurs. DM number density is exponentially suppressed: Boltzmann regime
- Eventually, DM number density is too low for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



Thermal DM Hypothesis

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

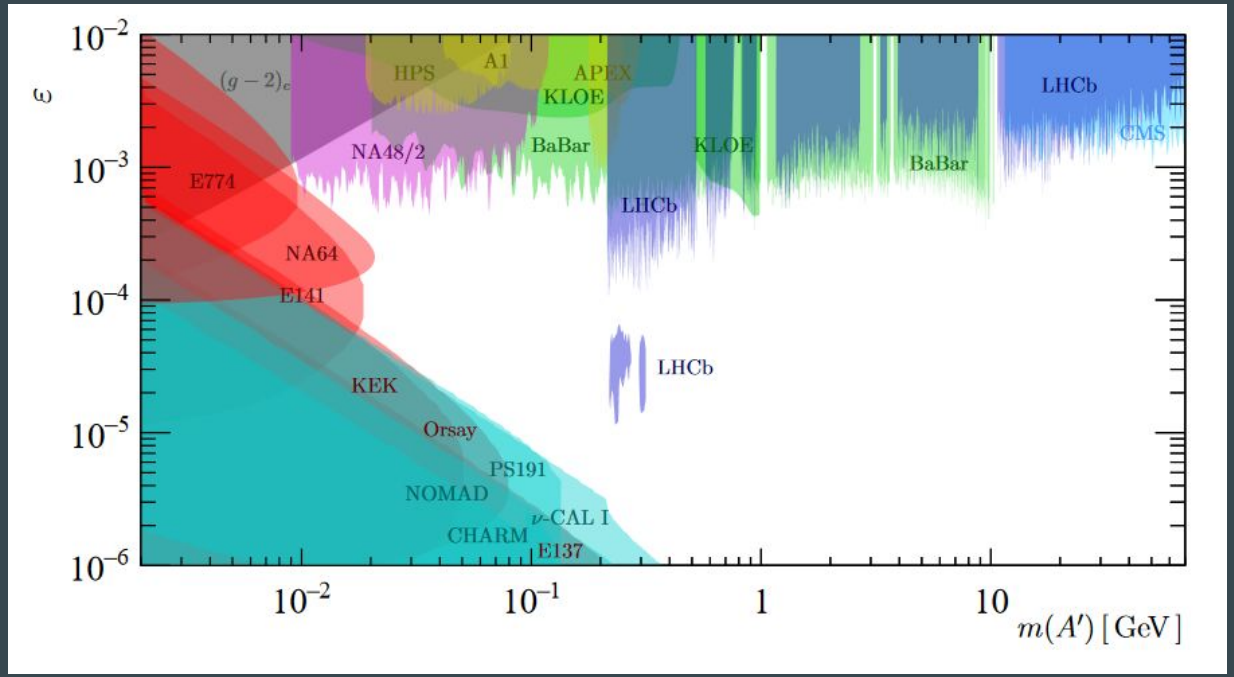
- If annihilation-cross section is too high (small), DM particles would stay longer in equilibrium in the Boltzmann regime, resulting in a lower (higher) number density at present
- DM particle mass and annihilation cross-section are bound
- If $m_\chi \sim 100$ GeV → typical weak Interaction cross section: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



Visible scenario phenomenology

- High ε regions dominated by fixed thin-target experiments (low mass) and colliders (large mass)
- Faint ε regions dominated by fixed thick-target searches (beam-dumps)

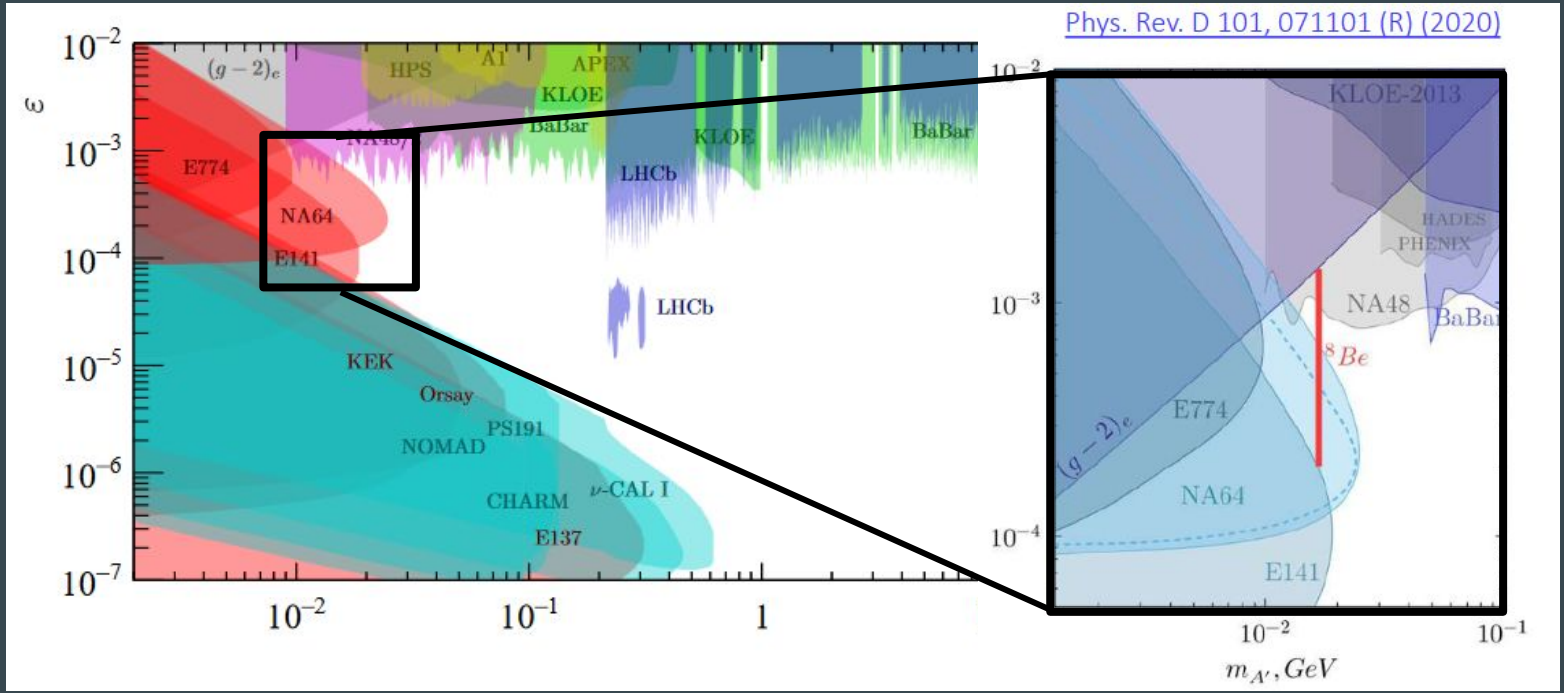
large cross-section



long-lived

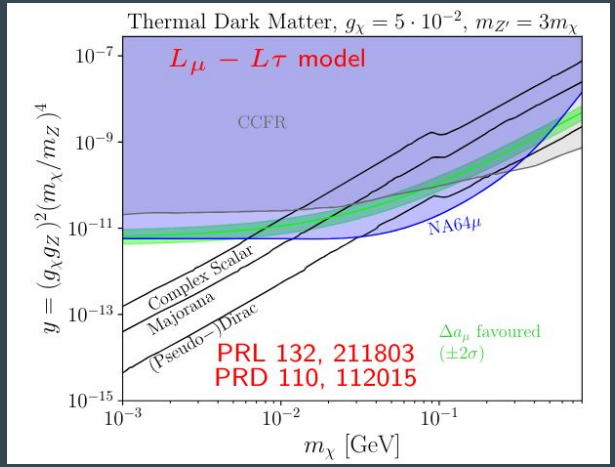
Experimental constraints on new vector boson

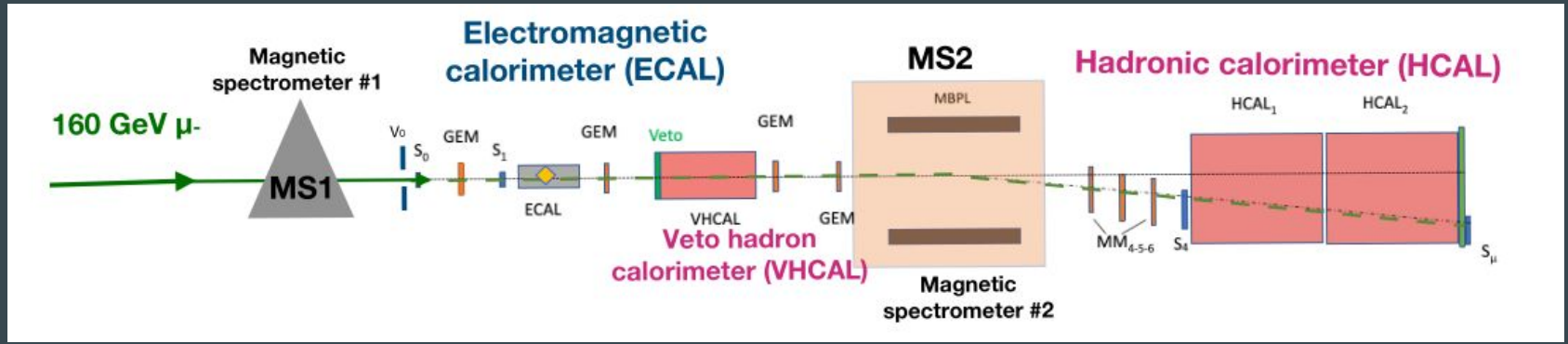
- Some free space to be explored
- Challenging region at the boundary between the sensitivity of colliders and beam dumps



NA64-μ exploring the $L_\mu - L_\tau$ scenario

- Parallel effort to NA64-e: missing-momentum experiment with a 160-GeV muon beam at the M2 line at CERN SPS
- Complementary to NA64-e searches in the $L_\mu - L_\tau$ scenario and for large Dark Photon masses

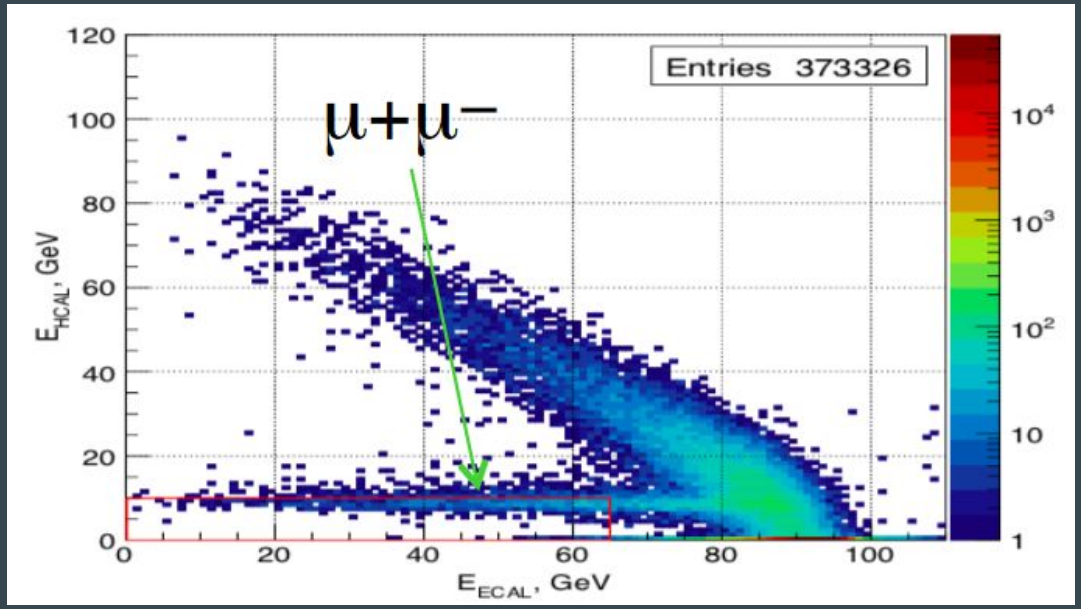


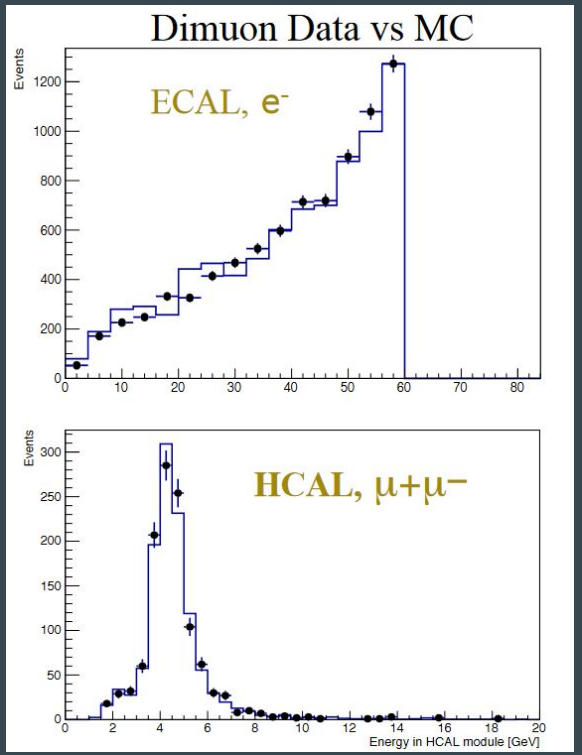


Di-muon events analysis

Rare QED process ~10-5/EOT:

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

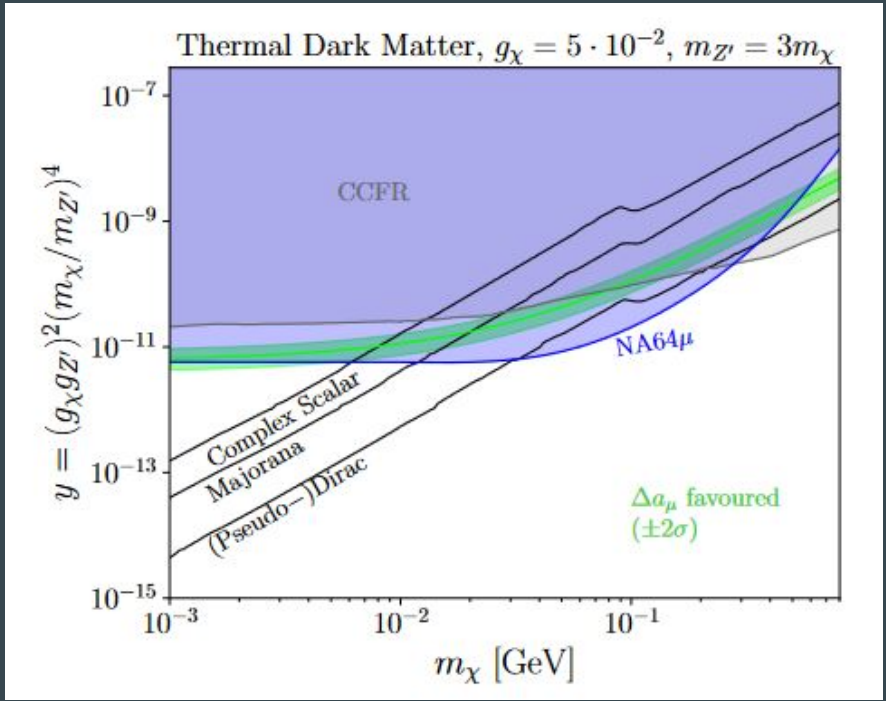




NA64-μ limits

- Total statistic of $(1.98 \pm 0.02) \times 10^{10}$ muons on target
- No events observed
- Almost completely excluded the explanation of the (g-2)μ in this particular model

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



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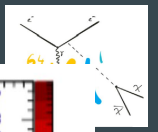
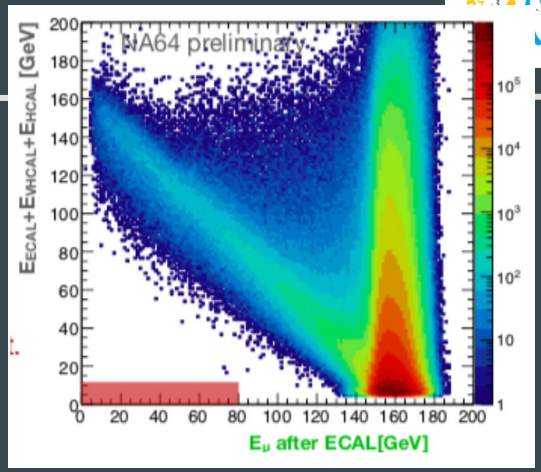
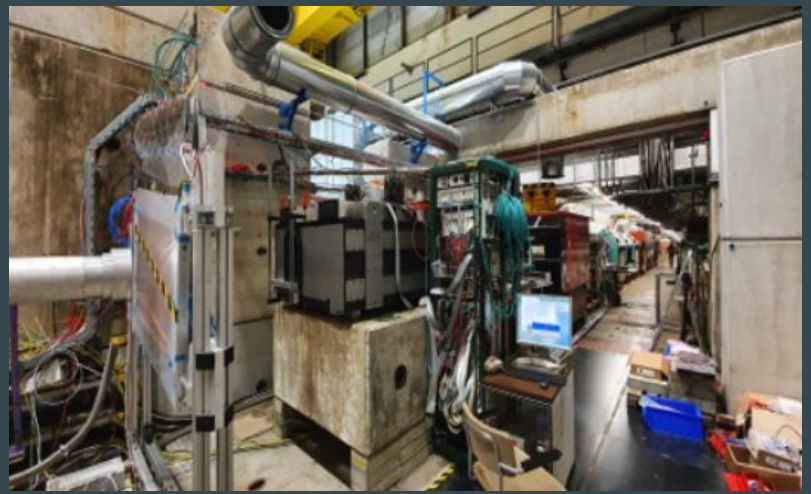
NA64-μ

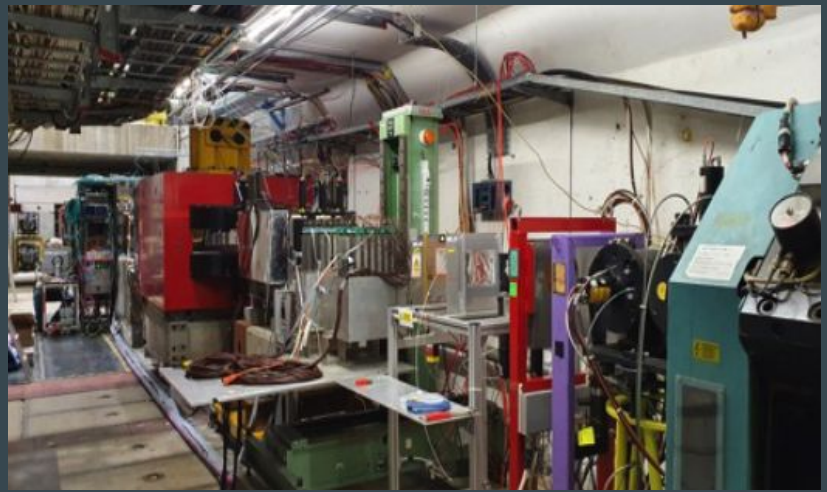




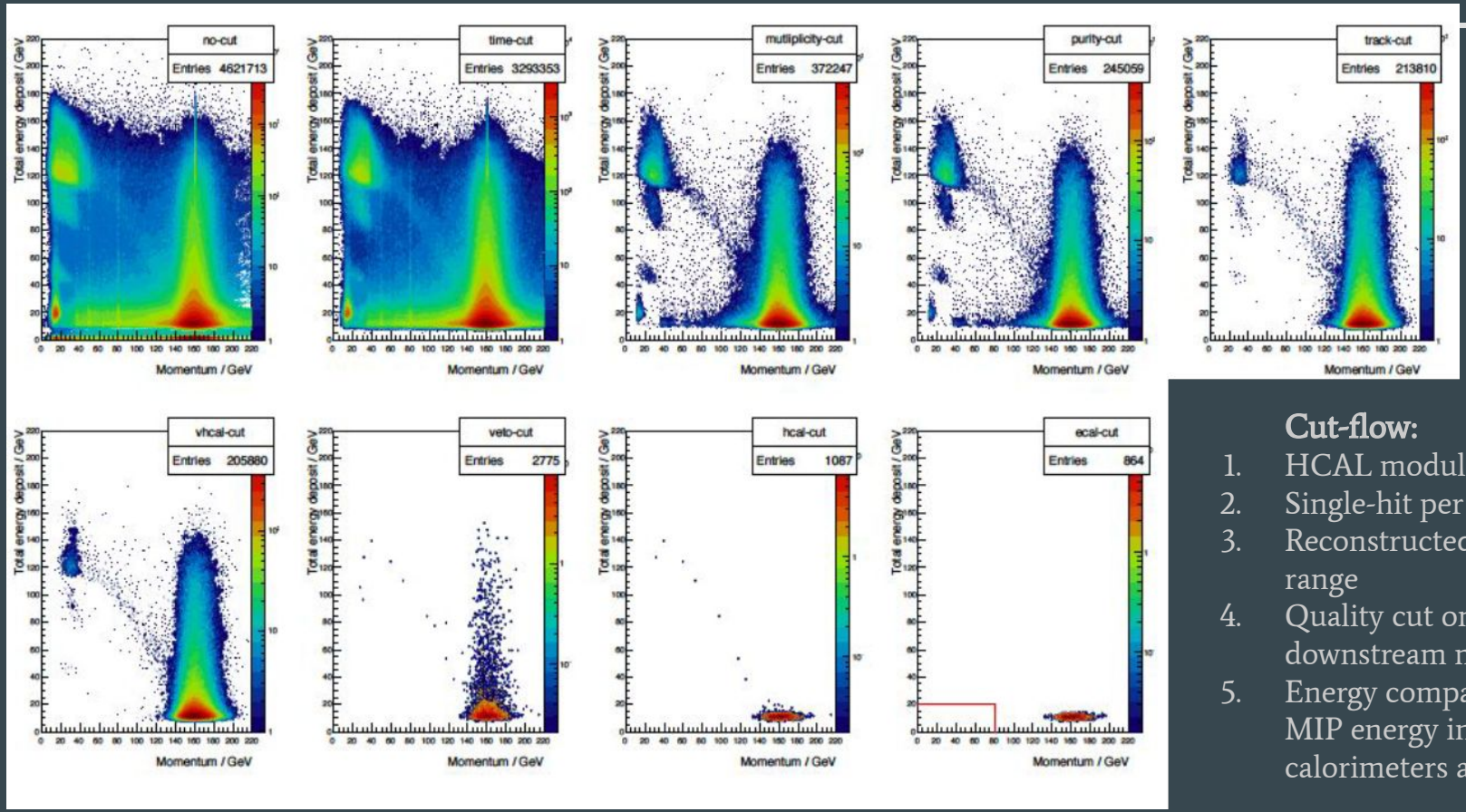
Signal Signature:

- in: clean 160 GeV μ- track
- out: < ~80 GeV μ- track
- no energy in the ECAL, Veto, HCAL





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