The NA64-e Experiment at CERN

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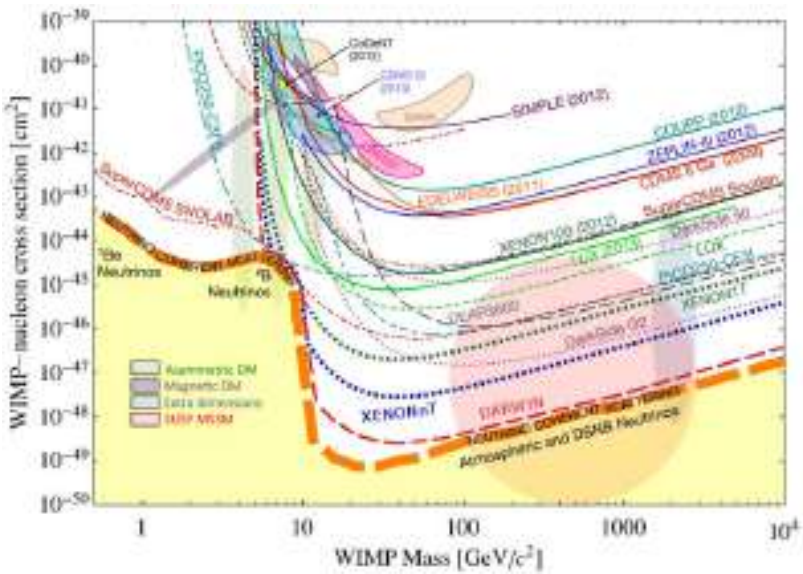
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 947715 (ERC Starting Grant POKER, 2020).

The Dark Sector - Introduction

Dark Matter: it is there, but very little is known about it! What is it? How does it interact with ordinary matter?

- "WIMP miracle:" electroweak scale masses ($\simeq$100 GeV) and DM annihilation cross sections (10^{-36} cm^2) give correct Dark Matter density / relic abundances. **No need for a new interaction!**
- Intense experimental program searching for a signal in this mass region. So far, no positive evidences have been found.
- What about **Light Dark Matter**, in the mass range 1 MeV $\div$ 1 GeV?

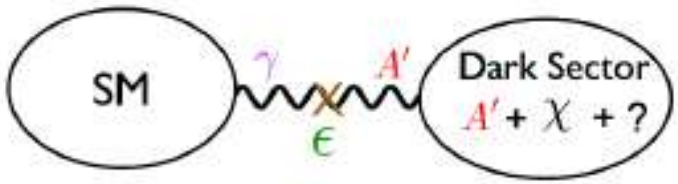
arXiv:1408.4371



Light Dark Matter

The Light Dark Matter hypothesis can explain the observed Dark Matter density, **provided a new interaction mechanism between SM and Dark Sector exists**[1].

- The "portal couplings" connecting SM to the Dark Sector are strongly constrained by Lorentz and SM gauge invariance.
- The full set of allowed renormalizable interactions:



Vector Portal	$\frac{1}{2}\epsilon_Y F^Y_{\mu\nu} F'^{\mu\nu}$	Coupling with SM hyper-charge
Higgs Portal	$A_h \lvert h \rvert^2 \phi$	Yukawa-like coupling
Neutrino Portal	$\epsilon_\nu (hL)\psi$	Fermion mixing with neutrino through Higgs

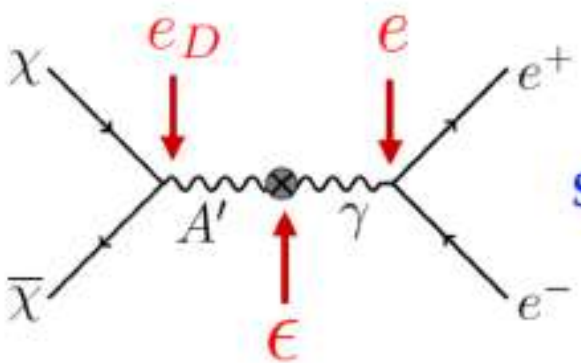
[1] For a comprehensive review: 1707.04591, 2005.01515, 2011.02157

The Dark Photon Model

Representative case: DM-SM interaction through a new massive U(1) gauge-boson (Dark Photon / A') coupled to electric charge.

"Dark – QED"

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



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

Model parameters:

- Dark Photon $m_{A'}$ and Dark Matter m_χ masses (sub-GeV)
- $A' - \chi$ coupling $e_D \simeq 1$
- $A' - \gamma$ coupling via kinetic mixing ε

Annihilation cross section ($\chi\bar{\chi} \to SM$) reads:

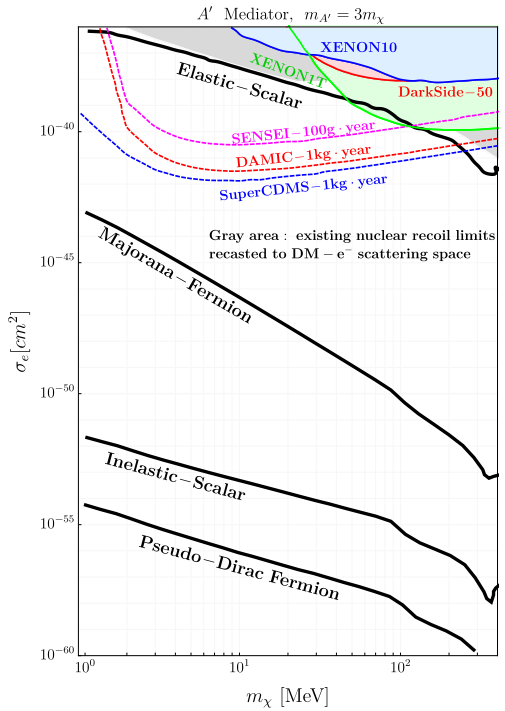
$$\langle \sigma v \rangle \propto \frac{\varepsilon^2 \alpha_D m_\chi^2}{m_{A'}^4} = \frac{\varepsilon^2 \alpha_D m_\chi^4}{m_{A'}^4} \frac{1}{m_\chi^2} \equiv \frac{y}{m_\chi^2}$$

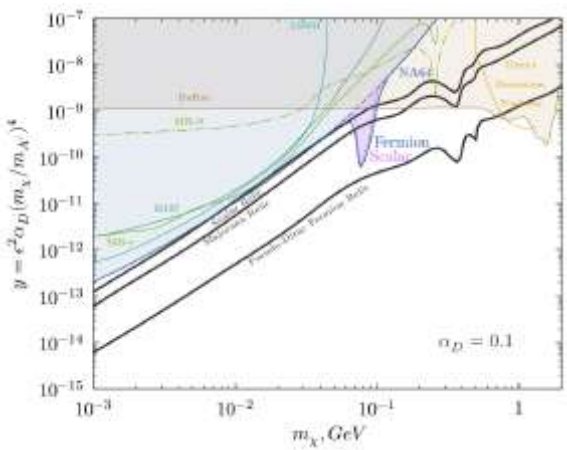
For a fixed m_χ value, the thermal origin hypothesis imposes a unique value of y.

LDM Search at Accelerators

- DM direct detection experiments have a limited sensibility in the sub-GeV range: $E_R \propto m_\chi^2/m_N$.
- The LDM-SM interaction at low energies significantly depends on the details of the LDM theory.
- For some models, this results in strong suppression of cross sections.
- Relativistic scattering processes, on the contrary, are less affected by these effects.
- Accelerator experiments are particularly suited to explore the LDM hypothesis.

Complementarity is crucial!





Top figure: arXiv:1707.04591. Bottom figure: NA64 collaboration, Phys. Rev. D 104, L091701 (2021)

Dark Photon Production Mechanisms with Lepton Beams

Three main A' production mechanisms with $e^+ - e^-$ beams:

(a) **A'-strahlung**

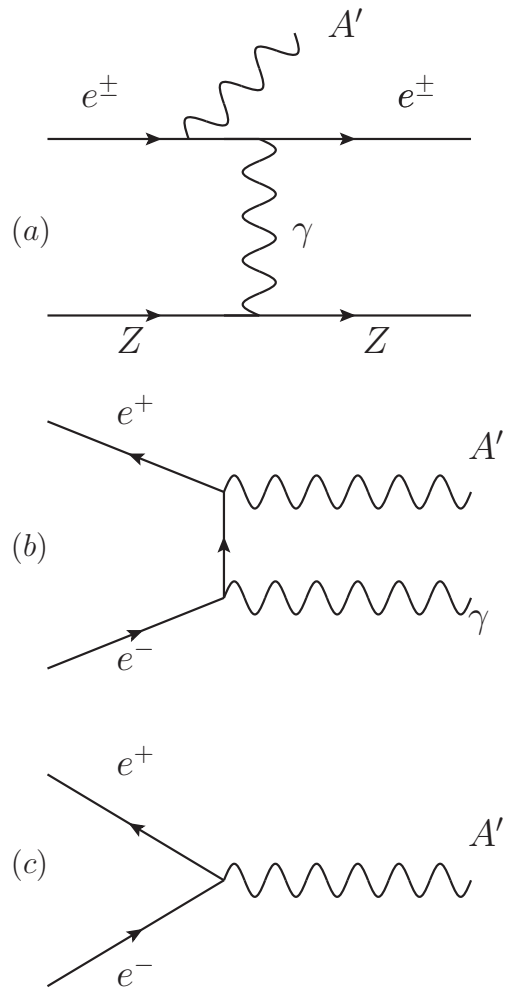
- Radiative A' emission in nucleus EM field
- Forward boosted, $Z^2\alpha_{EM}^3$ scaling

(b) **Non-resonant e^+e^- annihilation**

- Forward backward emission in the CM frame
- $Z\alpha_{EM}^2$ scaling

(c) **Resonant e^+e^- annihilation**

- Resonant, Breit-Wigner like cross section with $M_{A'} = \sqrt{2m_e E}$
- $Z\alpha_{EM}$ scaling
- Most efficient LDM production process for given kinematics[2]



[2] L. Marsicano et al., Phys. Rev. Lett. 121 (2018) 041802.

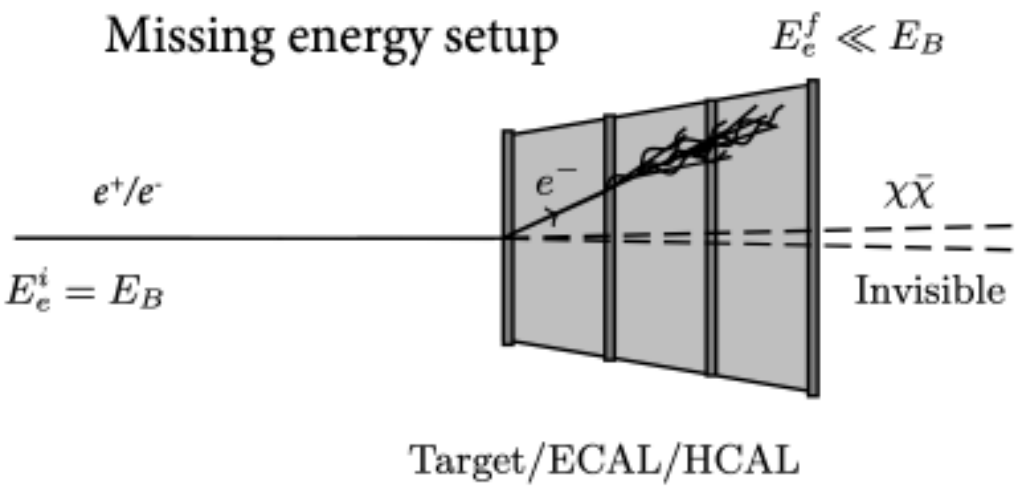
Fixed Active Thick-Target LDM Searches: Missing Energy Experiments

Missing energy approach - the *active thick target* is the detector

1. High intensity e^+/e^- beam impinging on thick active target $\rightarrow$ EM shower is initiated.
2. A' are produced from e^+/e^- in the shower and promptly decay to LDM particles χ. $(m_{A'} > 2m_\chi)$
3. χ particles escape the detector without interacting.

Missing Energy Signature

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

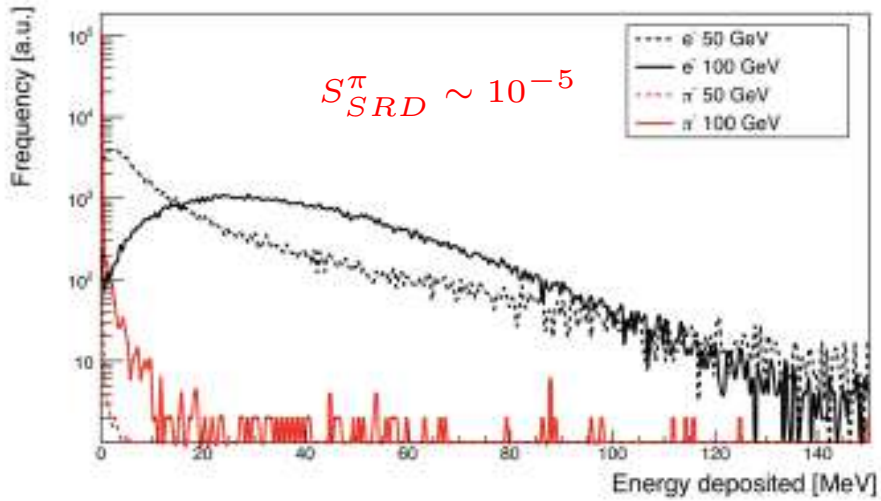


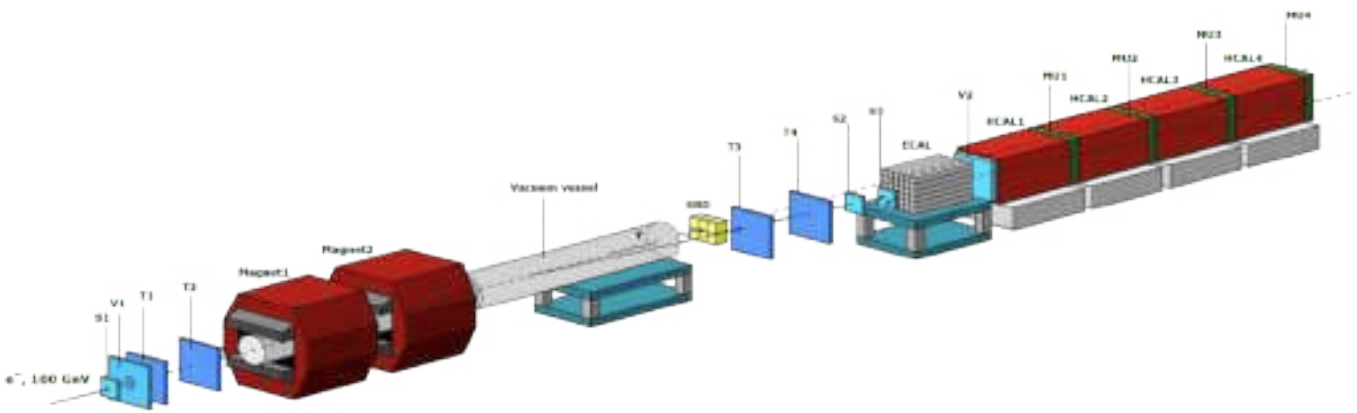
NA64-e Experiment

Missing energy experiment at CERN North Area H4 line - 100 GeV e^- beam
H4 line: few 10^7 e^-/spill. Energy resolution $< 1\%$ and hadron contamination $\sim 0.5\%$

Experiment Setup

- Beam identification system: magnetic spectrometer and SRD tagging (MBPL magnets)
- Target: $4X_0$ PS + $36X_0$ ECAL, Pb/Sc Shashlik
- Plastic scintillator VETO
- HCAL: 4 modules, $30\lambda_I$





D. Banerjee et al., PRL 123 (2019) 121801; D. Banerjee et al., NIMA881 (2018) 72-81; E. Depero et al., NIMA 866 (2017) 196-201

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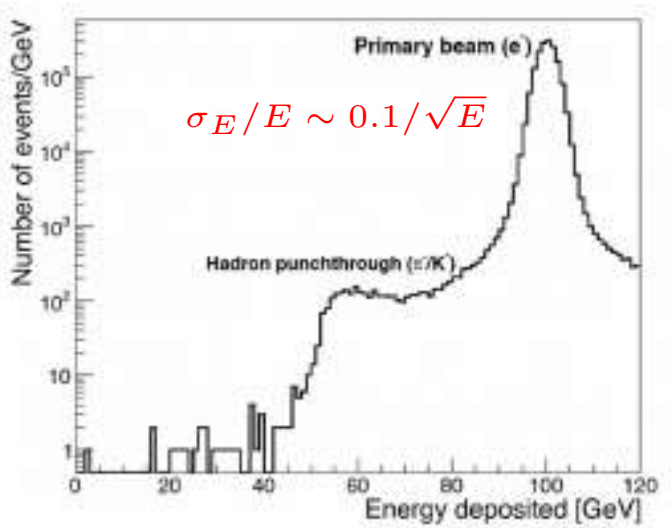

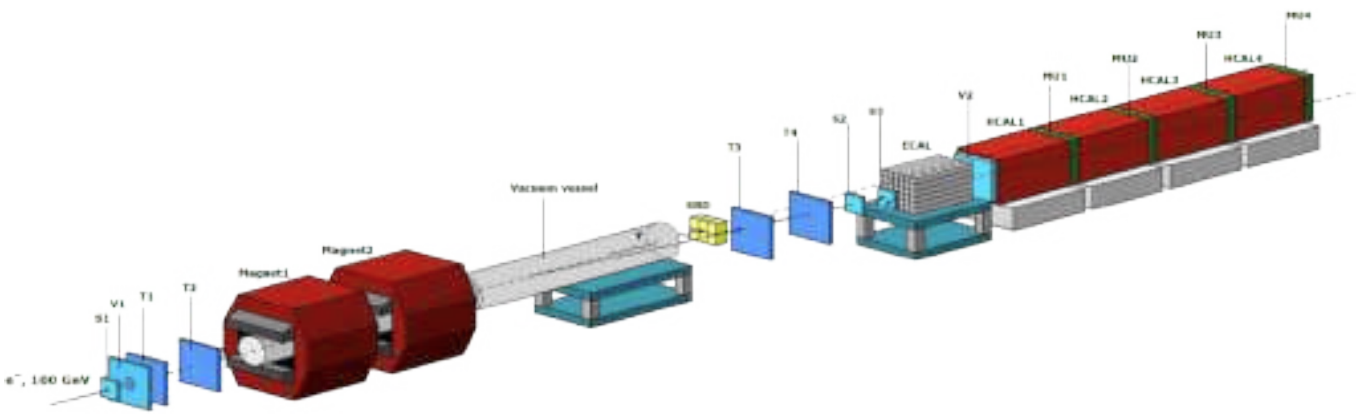

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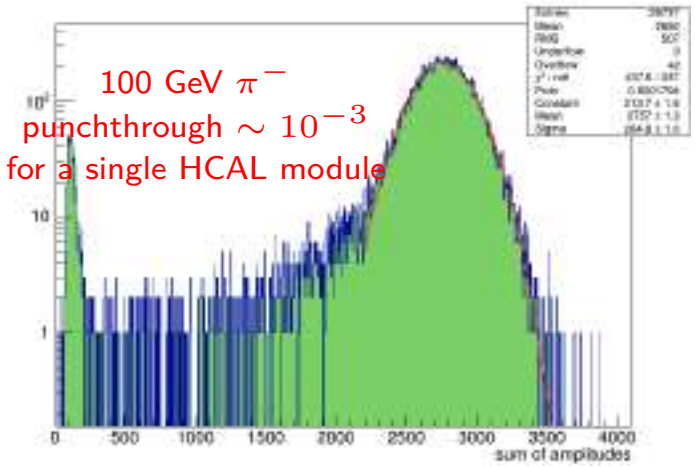

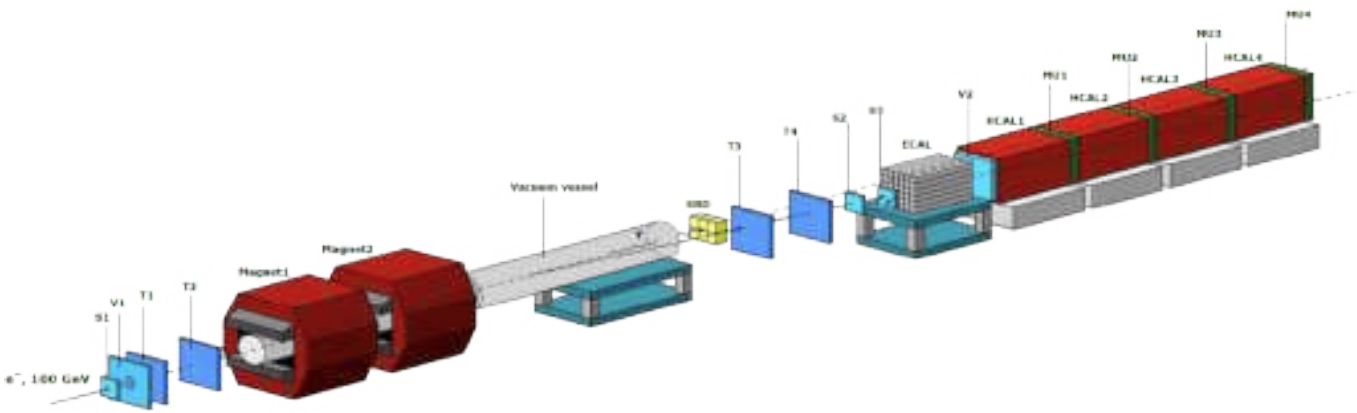

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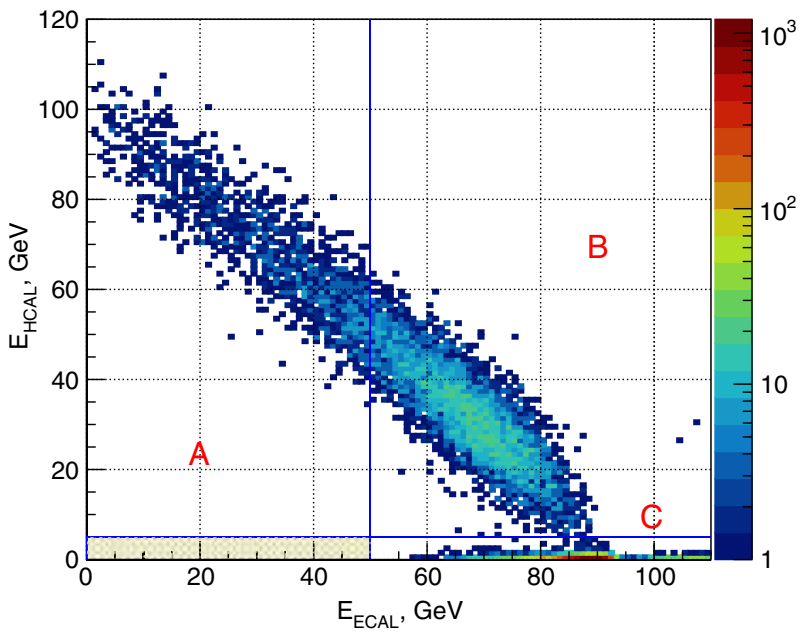
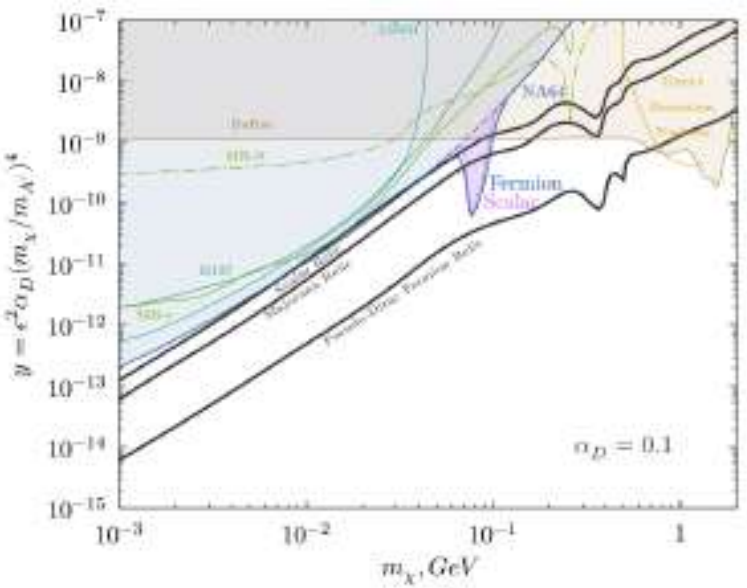
NA64 Results

- NA64 results based on $2.84 \cdot 10^{11}$ EOT collected during 2016-2018.
- After applying all selection cuts, no events observed in the signal region $E_{ECAL} < 50$ GeV, $E_{HCAL} < 1$ GeV.
- Expected number of background events ~ 0.5 compatible with null observation.
- **Most competitive exclusion limits** in large portion of the LDM parameters space.
- Secondary positron annihilation contribution included in recent analysis.
- An optimised LDM search with positron in the NA64 framework (POKER project) is ongoing.



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

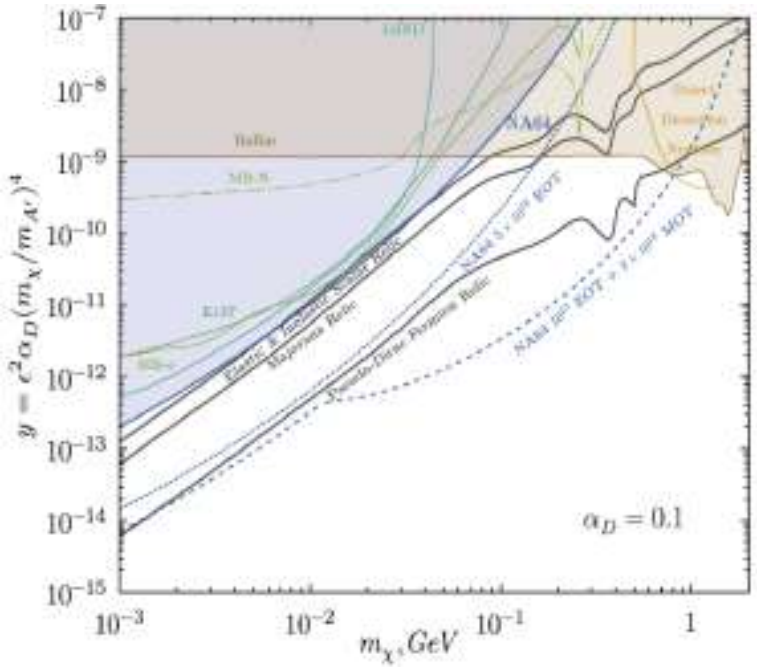


Conclusions

- Light Dark Matter scenario (MeV-to-GeV range) is largely unexplored.
  - Can efficiently explain the correct Dark Matter density.
  - Theoretically well grounded assuming a new DM-SM interaction mechanism exists.
  - Accelerator-based experiments are uniquely suited to explore it.
  - NA64 is an electron-beam missing-energy experiment at CERN, investigating the Dark Sector.

- NA64 produced several important results in the search for LDM.
- In 2022 we reached the 10^{12} EOT milestone and we plan to increace statistics as much as possible before CERN LS3.
- The experiment sensitivity will be further improved by collecting more e^- data and for high mass range by using a positron beam.

PLB796, 117 (2019)



Backup Slides

NA64 program

Electron Beam:

- NA64-e: 2.84×10^{11} EOT already measured
- Additional $\sim 6 \times 10^{10}$ EOT collected in 2021 (data analysis ongoing), after detector upgrade (electronics, straw detectors and veto hadron calorimeter)
- High statistic run in 2022: 10^{12} EOT. **Probe significant part of the A' invisible parameter space up to the thermal relic targets**

Muon Beam:

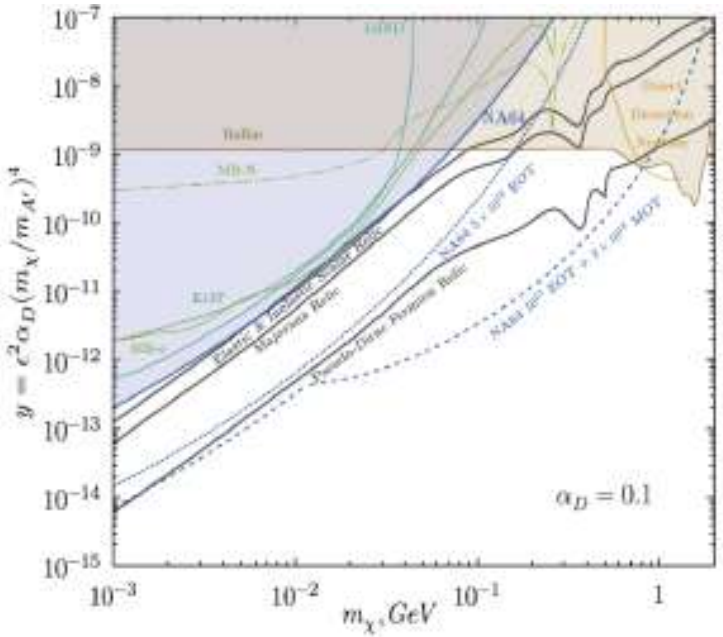
- NA64-μ: missing momentum and energy experiment with a muon beam
- Ongoing parallel effort of the NA64 collaboration

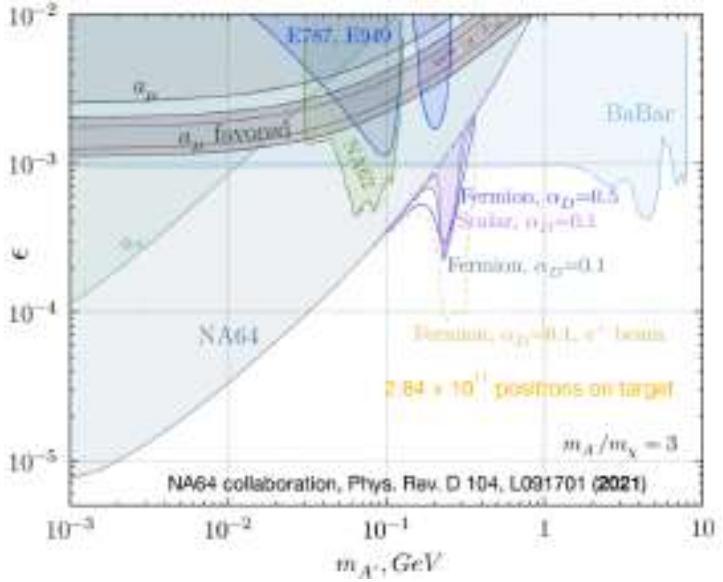
Positron Beam:

- Primary e^+ beam allows to exploit the enhanced resonant annihilation cross section $\rightarrow$ **high sensitivity to large A' masses**
- **Dedicated short e^+ run in 2022**: 10^{10} e^+OT accumulated
- **POKER run** foreseen in 2024

Hadron Beam

- Explore light mesons fully invisible decay modes
- First ideas are currently being developed

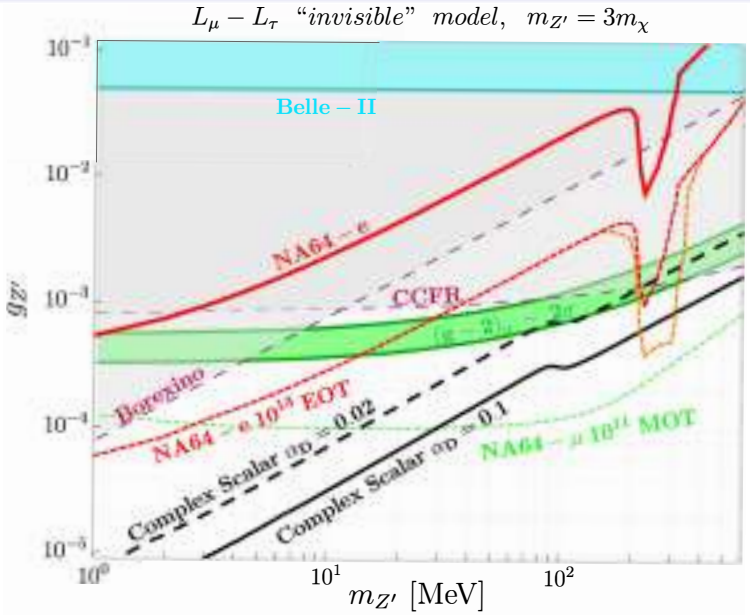




NA64-e at CERN - further recent results

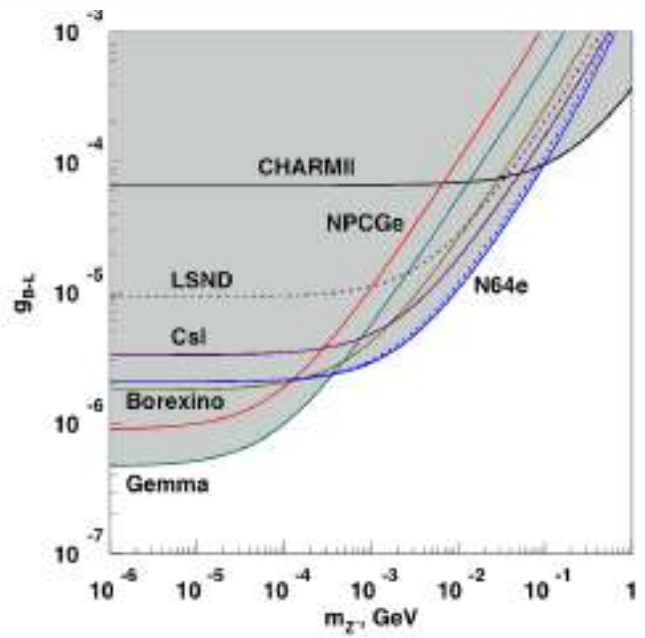
Light Z' search in the $L_\mu - L_\tau$ scenario

- Re-analysis of the 2016-2018 dataset searching for a new gauge boson coupling predominantly to muons and taus
- Ad-hoc calculation of the loop-induced coupling to photons (kinetic mixing)
- Results are more stringent than Belle-II limits, and compatible with exclusion contours from the re-analysis of neutrino experiments



Search for a new B-L Z' gauge boson

- First NA64 analysis using the 2021 dataset
- New constraints on the Z' parameters space, more stringent compared to those obtained from the neutrino-electron scattering data for the 0.3-100 MeV mass range
- Results can be re-casted to A' space via $g_{B-L} \leftrightarrow \varepsilon e$.



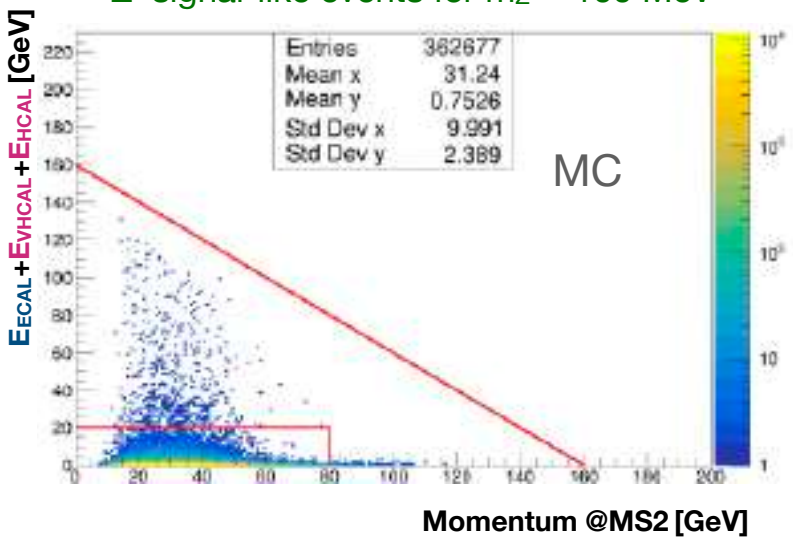
NA64-μ experiment: muon beam missing energy + momentum search

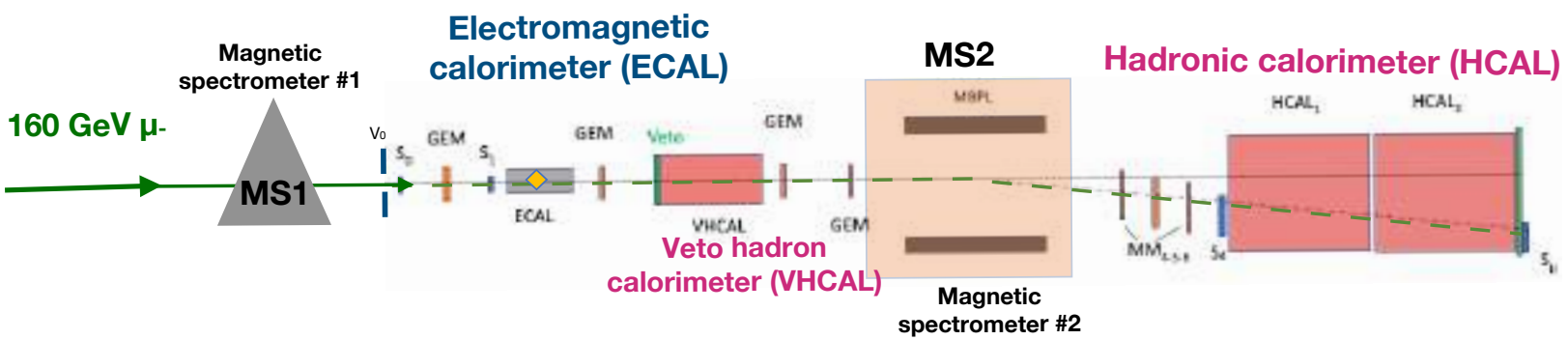
Beam: M2 beamline at CERN SPS, 160 GeV μ^-, $10^5 - 10^7$ μ/s.
Detector:

- Two magnetic spectrometers, MS1 (impinging μ) / MS2 (scattered μ)
- Three calorimeters: ECAL (active target), VHCAL, HCAL
- Beam-defining plastic scintillator counters

Signal signature: $P_1 \simeq 160$ GeV, $P_2 < 80$ GeV, $E_{CAL} \simeq$MIP.

Z' signal-like events for $m_{Z'}$ = 100 MeV

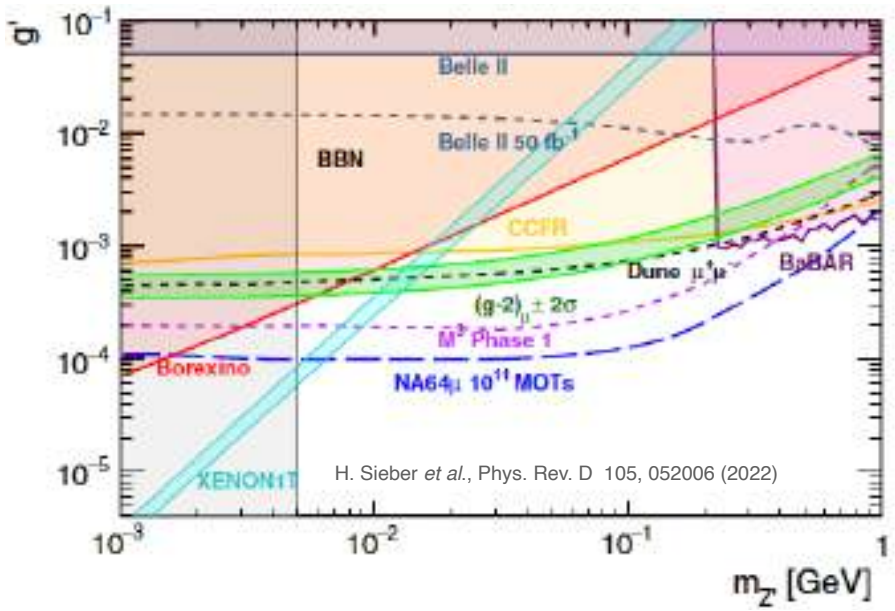




NA64$-\mu$ Physics cases

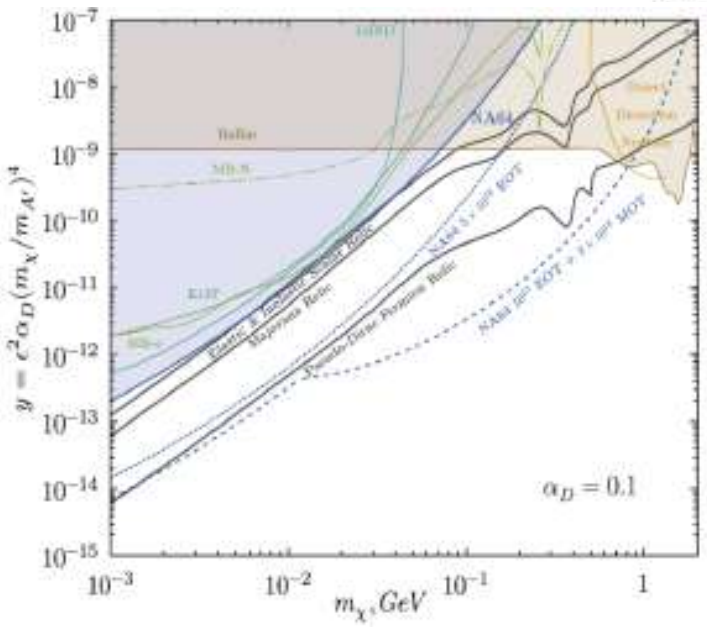
Sub-GeV Z' predominantly coupled to muons

- New gauge boson associated to $L_\mu - L_\tau$ symmetry
- Main motivation: muon $g-2$ anomaly.
- In extended models, can also explain DM as a thermal freeze-out relic.



Light dark matter

- Radiative A' emission, followed by A' decay to LDM
- Complementary to $e^\pm$ searches in the high-mass region.
  - Future sensitivity quoted for 10^{13} EOT$+2\cdot 10^{13}$ MOT.



NA64−μ Status

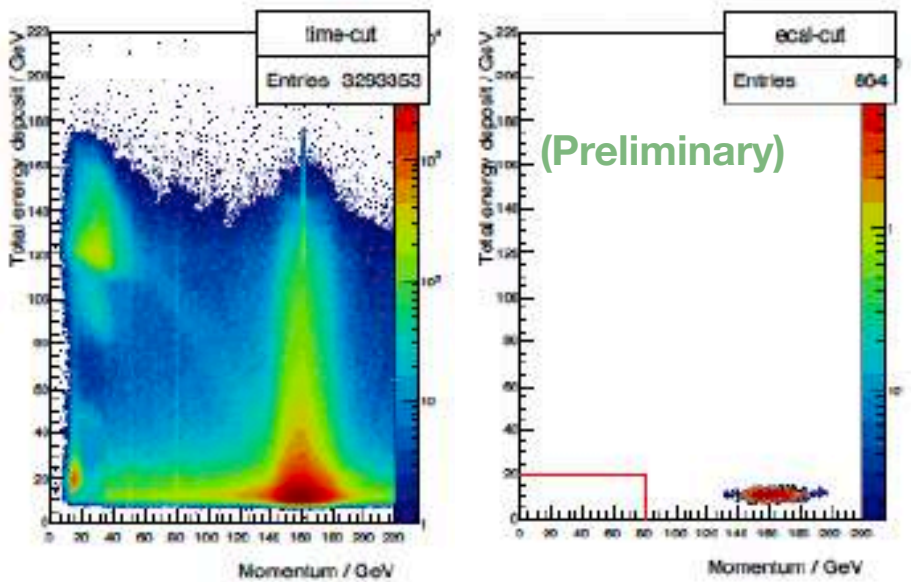
Two test runs have already been performed in 2021 (5x10^9 MOT) and 2022 (5x10^{10} MOT)

- First results from 2021 data analysis: less than 10^{-11} background events expected per MOT. No events observed in the signal region.
- 2022 data analysis in progress.

First physics run foreseen at the end of 2023 or beginning of 2024

- Detector optimization in progress.
- Final goal: 10^{11} MOT.

Source of background	Level per MOT
Hadron in-flight decay	$\lesssim 10^{-11}$
Momentum mismatch	$\lesssim 10^{-12}$
Detector non-hermeticity	$\lesssim 10^{-12}$
Single-hadron punch through	$\lesssim 10^{-12}$
Dimuon production	$< 10^{-12}$
Total (conservatively)	$\lesssim 10^{-11}$

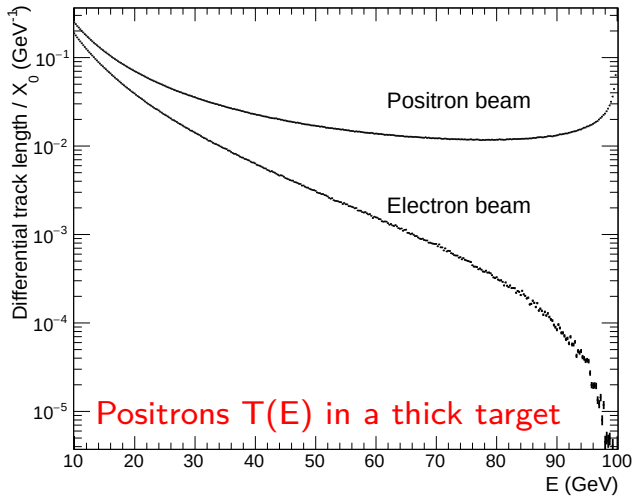


POKER: **PO**sitron resonant annihilation into dar**K** matt**ER**

An optimized light dark matter search with positrons in the NA64 framework[3]

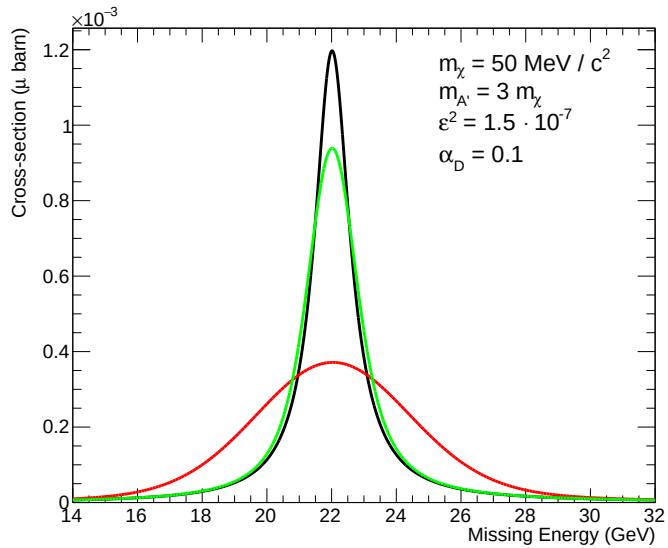
Signal production reaction: $e^+e^- \to A' \to \chi\overline{\chi}$

- Large event yield:
  $N_s^{annihil} \propto Z\alpha_{EM}$ vs
  $N_s^{brem} \propto Z^2\alpha_{EM}^3$
- Missing energy distribution shows a **peak** around $E_R = \frac{M_{A'}^2}{2m_e}$ $\to$ **clear signal signature**



Project goal

- Perform a preliminary missing energy measurement with a positron beam, using a new **high resolution detector ($PbWO_4$ calorimeter)** replacing the existing NA64 ECAL
- Demonstrate the technique and set the basis of the first **optimized** light dark matter search at a positron-beam facility



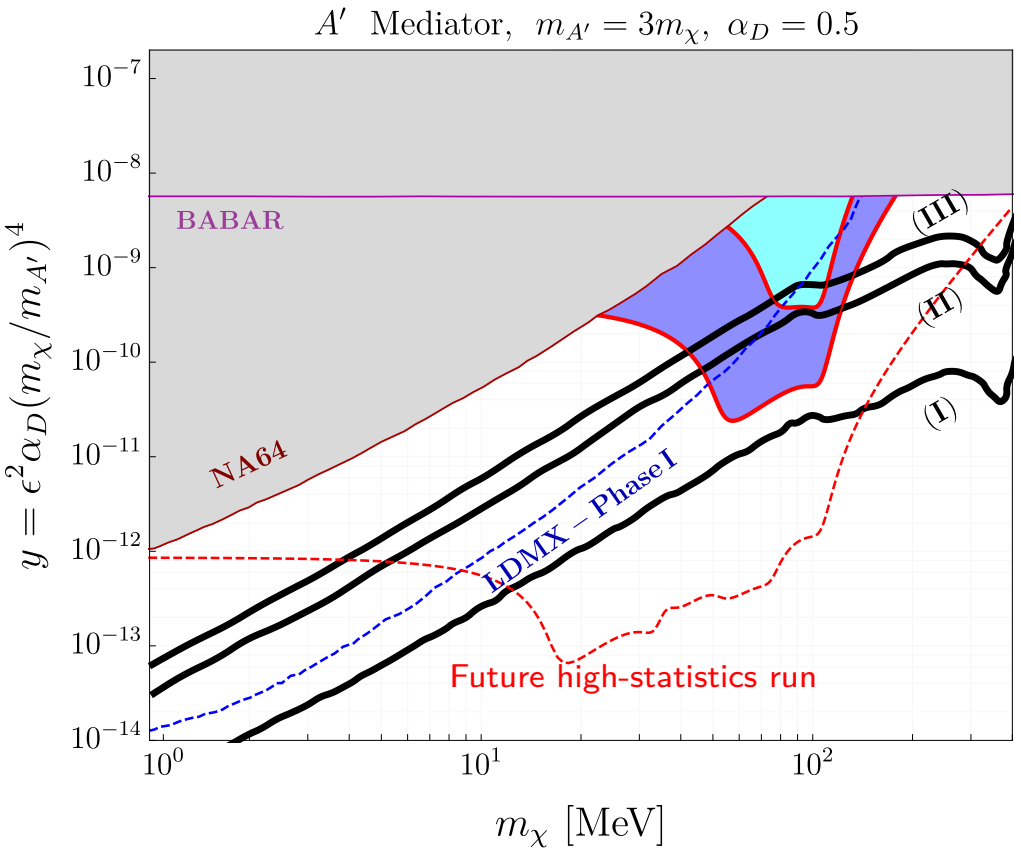
[3] Project funded by ERC grant

POKER sensitivity to LDM

Pilot run sensitivity - 0 bck

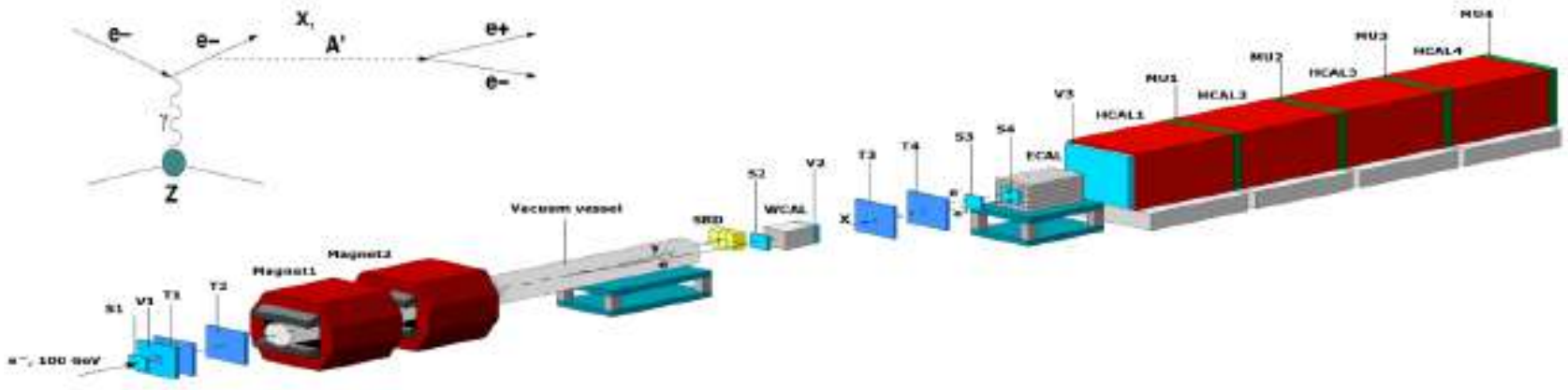
Pilot measurement at the H4 beamline with 100 GeV e^+ beam[4]

- **Baseline scenario:** $5 \cdot 10^{10}$ e^+OT, 50 GeV missing energy threshold
- **Aggressive scenario:** $3 \cdot 10^{11}$ e^+OT, 25 GeV missing energy threshold
- Future experimental program with multiple 10^{13} e^+OT runs at different energies



[4] Currently discussing within NA64 and SPSC to possibly run the pilot measurement in 2024

NA64 - visible mode



NA64 collaboration, Phys. Rev. D 101 (2020) no.11, 071101(R)

- Interest has recently grown towards A' **visible decay** $A' \to e^+e^-$ in the ~ 17 MeV mass region (X17 anomaly)
- NA64 visible mode: A' produced in **WCAL** detector (plastic and tungsten calorimeter). Search for decay products in **ECAL**
- 8.4×10^{10} EOT collected in visible mode: ruled out part of the available X17 parameter space