Searching for light Dark Matter with NA64 and POKER at CERN

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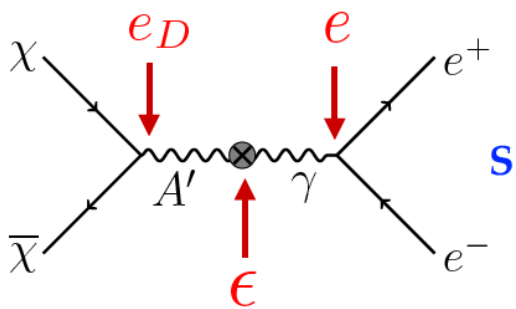
NA64 main physics case: vector-mediated light dark matter

"Light Dark Matter" hypothesis: DM made of sub-GeV particles χ, part of a new "dark sector". LDM-SM interaction mediated by a new massive U(1) gauge boson, the dark photon.

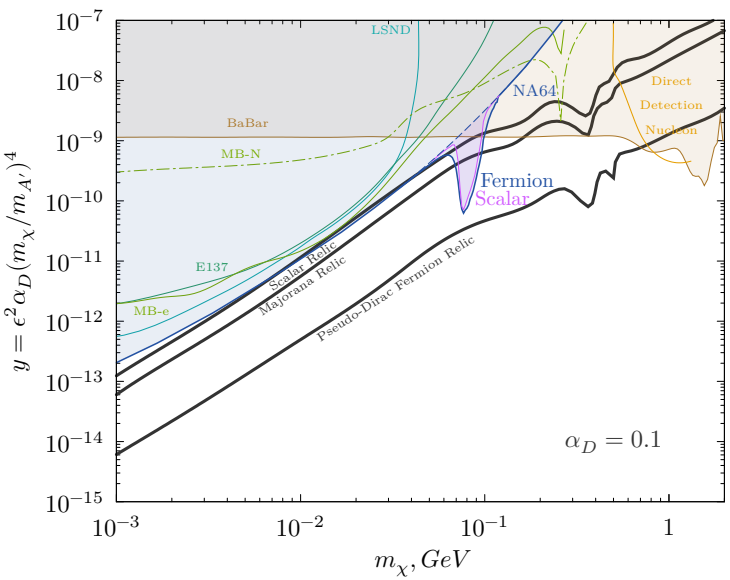
$$\alpha_D \equiv \frac{e_D^2}{4\pi}$$



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

- "Dark Photon" (A') portal, parameters:
  - A' and LDM masses
  - $A' - \chi$ coupling: $e_D \simeq 1$
  - $A' - \gamma$ kinetic mixing, $\varepsilon \ll 1$
- Annihilation cross section:

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



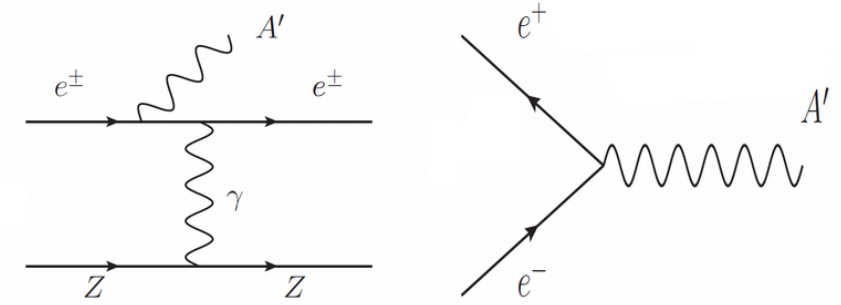
For a given m_χ value, y value is fixed by cosmology - $\mathcal{O}(1)$ variations depending on the fine details of the model.

The *missing energy* technique

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

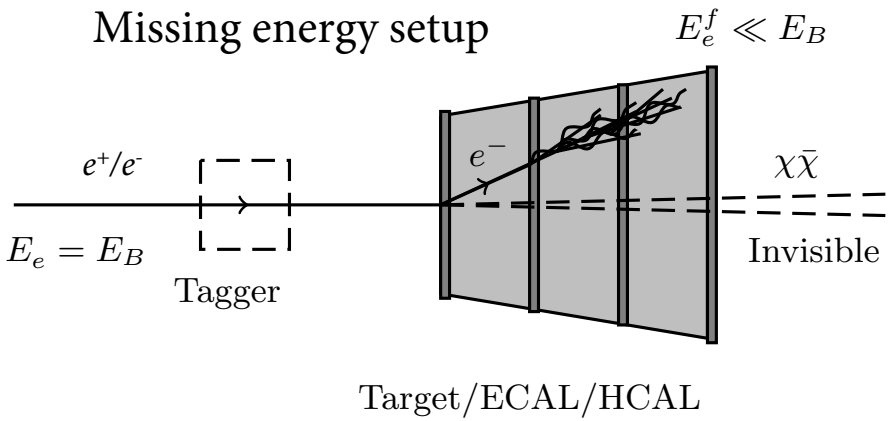
1. High intensity e^+/e^- beam impinging on thick active target $\rightarrow$ EM shower is initiated
2. A' are produced from e^+/e^- in the shower and promptly decay to χ particles - **"invisible decay"**
3. χs escape the detector without interacting

Main A' production mechanisms:



Missing Energy Signature

- 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 $E_{miss} = E_B - E_{dep}$
- Backgrounds: events with ν / long-lived (K_L) / highly penetrating (μ) particles escaping the detector

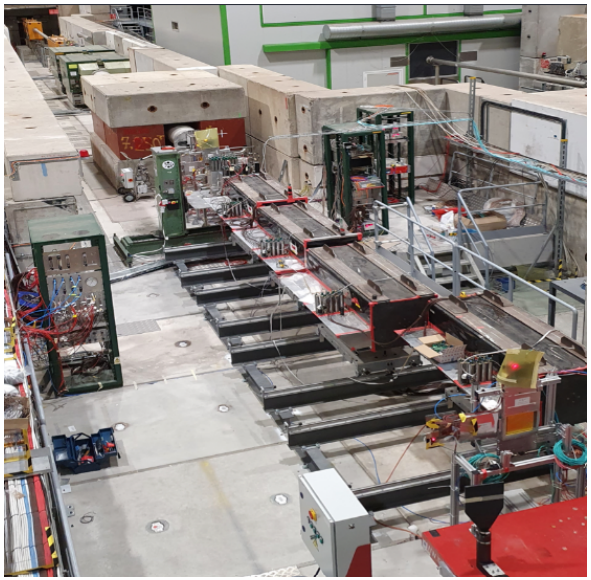


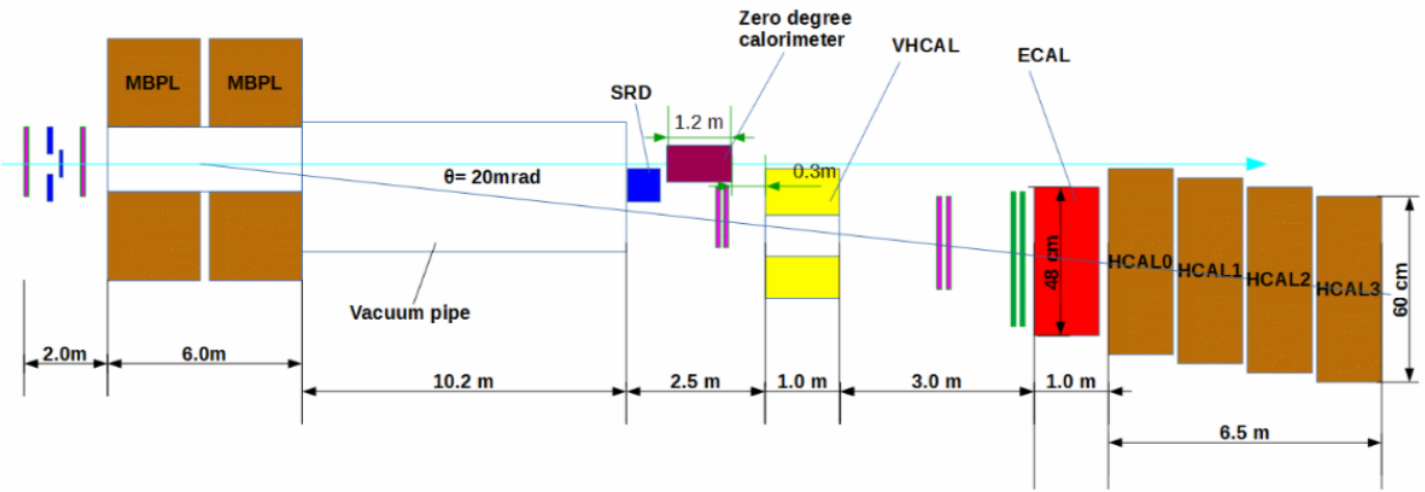
NA64 Experiment

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

Experiment Setup

- Beam identification system: magnetic spectrometer and SRD tagging (MBPL magnets)
- EM-Calorimeter: $40X_0$, Pb/Sc Shashlik
- Plastic scintillator VETO
- Hadron calorimeter: 4 m, 30 λ_I





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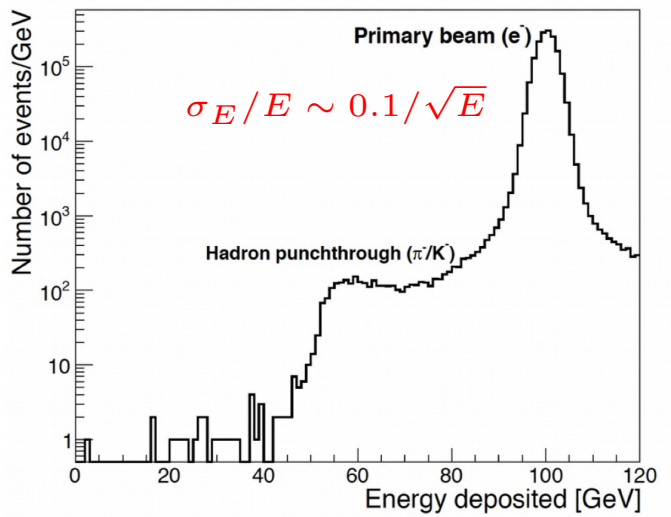

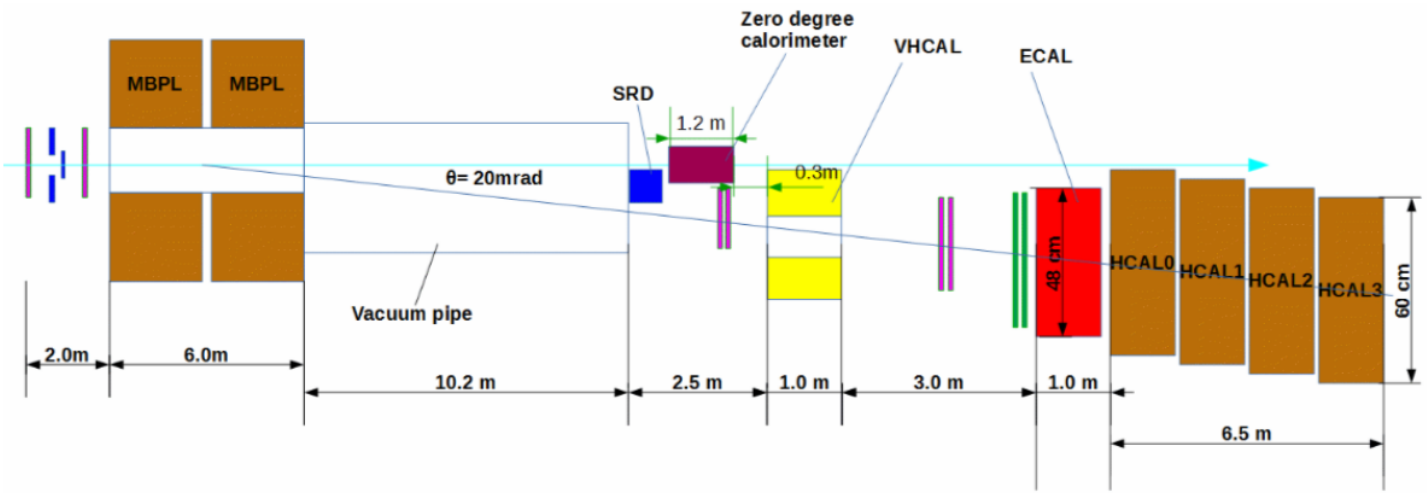

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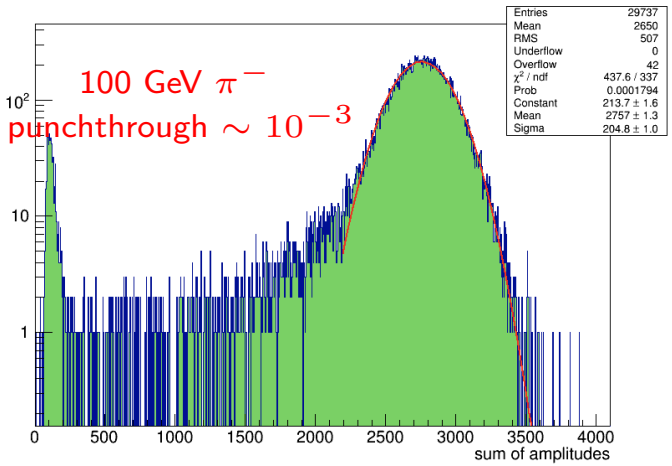
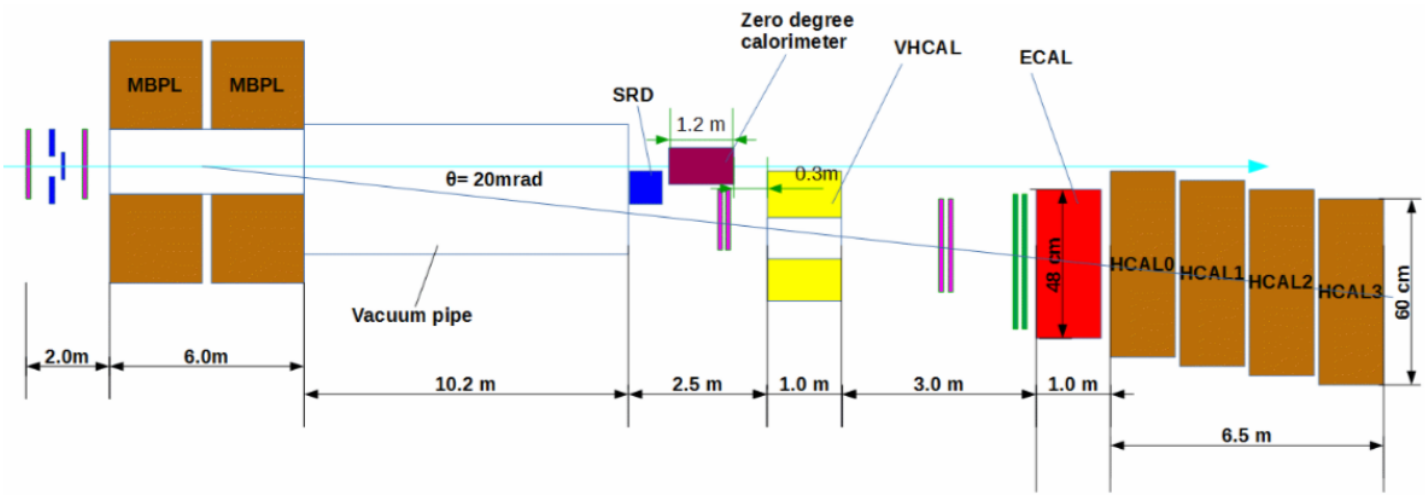




Data analysis of 2021-2022 runs

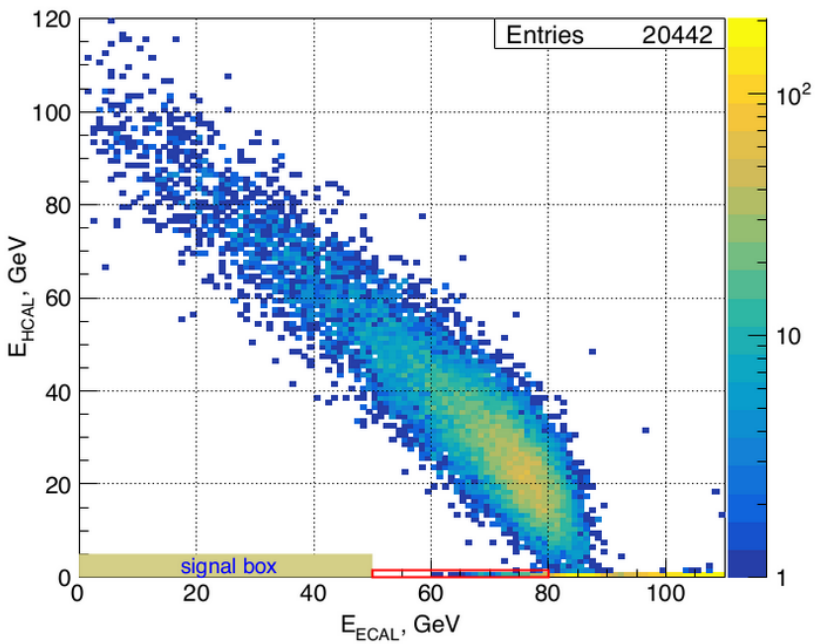
Accumulated statistics: 2.8×10^{11} (2016-2018) + 6.5×10^{11} (2022) + 5.2×10^{11} (2023) $\rightarrow$ $\sim$1.5 $\times 10^{12}$ e^- on target (EOT) . Target before LS3: $\sim 3 \times 10^{12}$ EOT

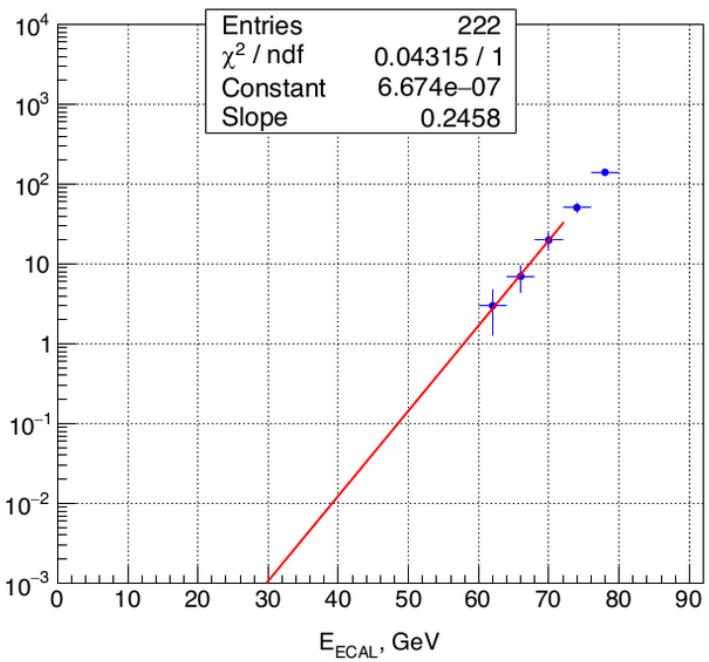
Selection cuts:

- Clean impinging 100 GeV e^-, no activity in VETO/HCAL,
- shower-shape compatible with e- induced one (data-driven shower shape χ^2 distribution)

Signal window: $E_{ECAL} <$ 47-50 GeV, $E_{HCAL} <$ 1 GeV, depending on the run conditions and detector performances

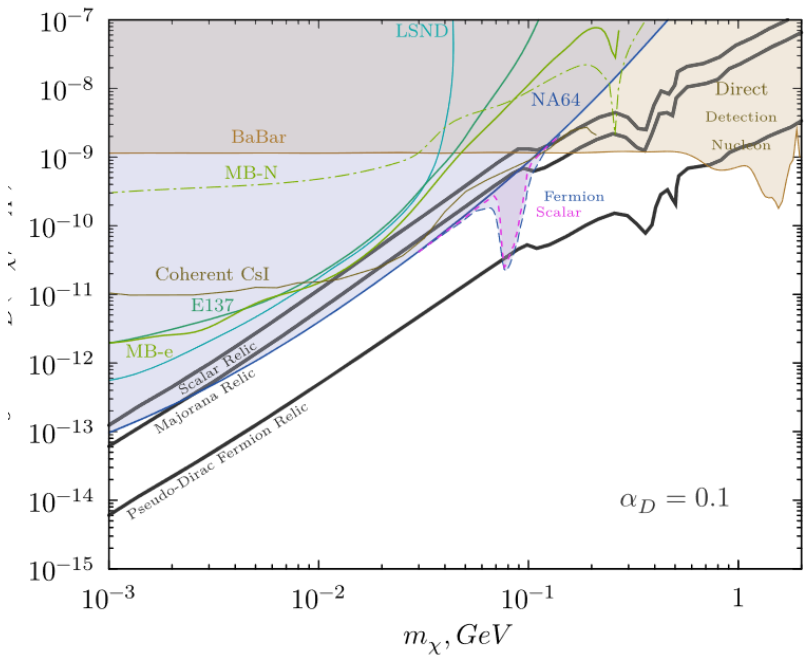
Expected background yield: $\sim$ 0.5 events (contribution of upstream electro-nuclear reactions extrapolated from data via sideband fit)

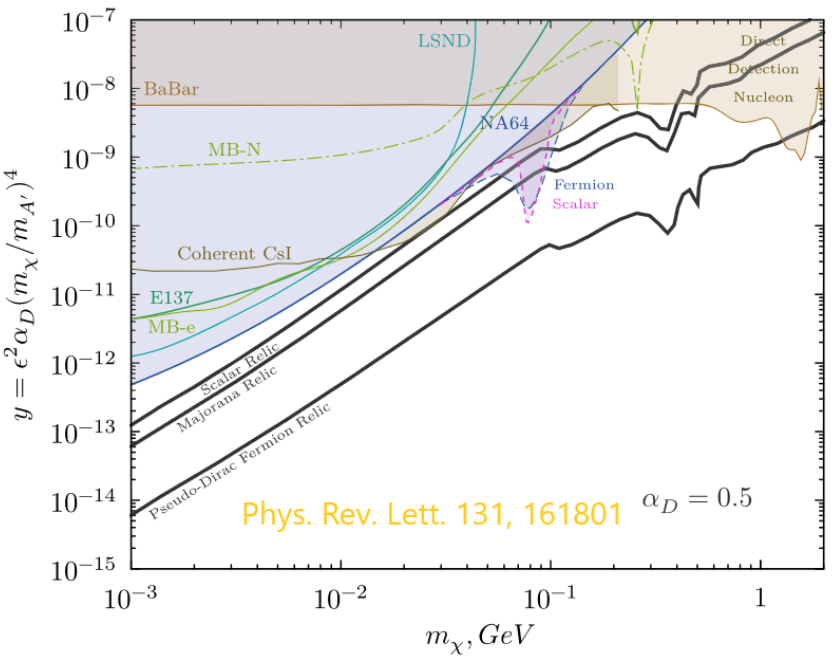




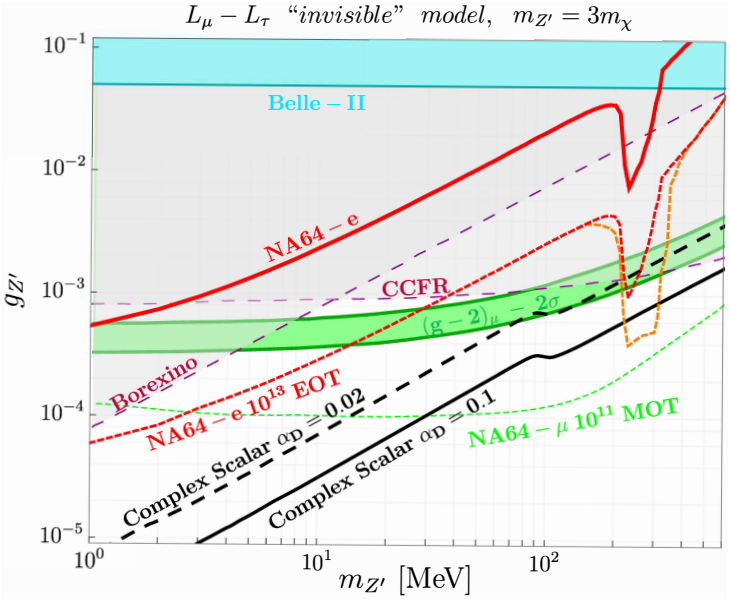
NA64 results

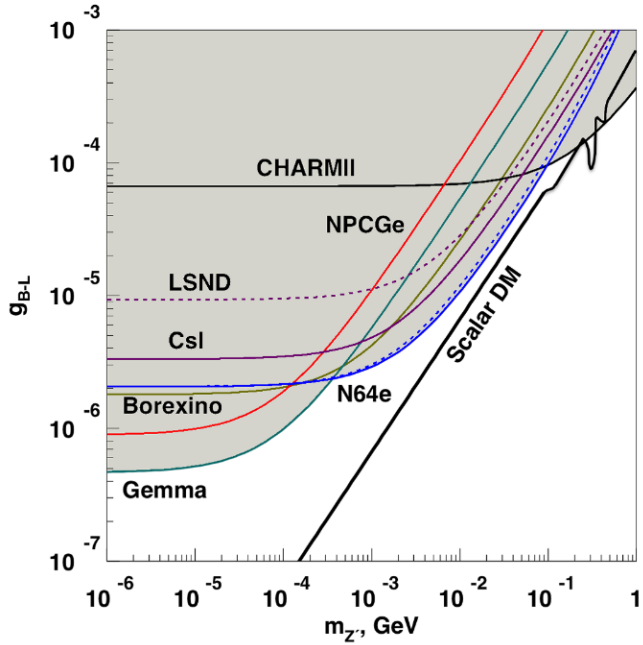
- Current published results are based on $\sim 10^{12}$ EOT (2016-2022) runs. **No signal observed after data unblinding.**
- For $\alpha_{\mathrm{D}} = 0.1$, NA64 excludes the Scalar and Majorana scenarios in a large m_χ interval.
- Thanks to e^+e^- resonant enhancement, the Pseudo-Dirac Fermion scenario is touched in a narrow m_χ region.
- Analysis of the 2023 data is currently ongoing...



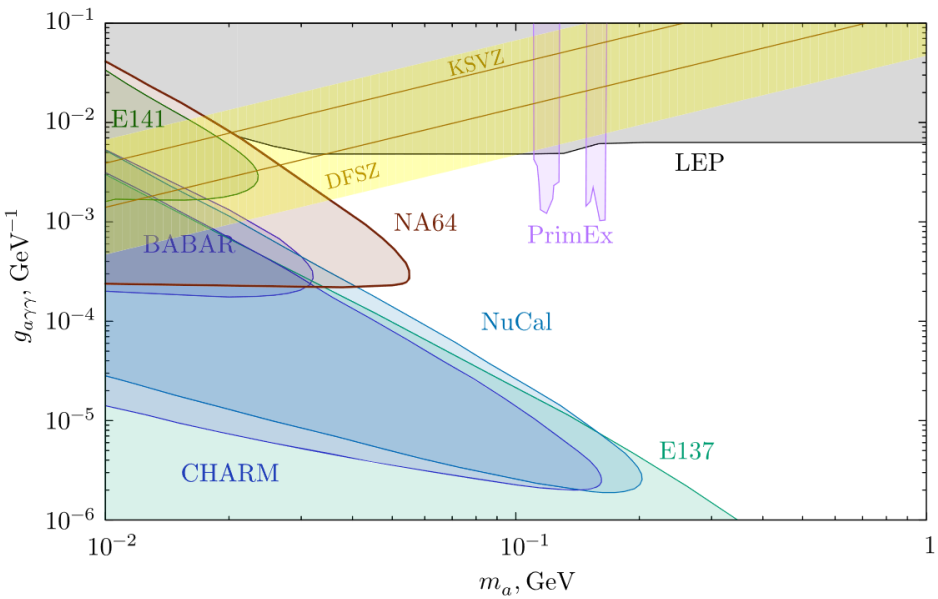


Exploring alternative BSM models, a quick (non-comprehensive) glance





- Data collected by NA64 has been re-analyzed to explore several SM extensions: $L_\mu - L_\tau$[a], $B - L$[b], ALPs[c]...



[a] Phys. Rev. D 106, 032015
[b] Phys. Rev. Lett. 129, 161801
[c] Phys. Rev. Lett. 125, 081801

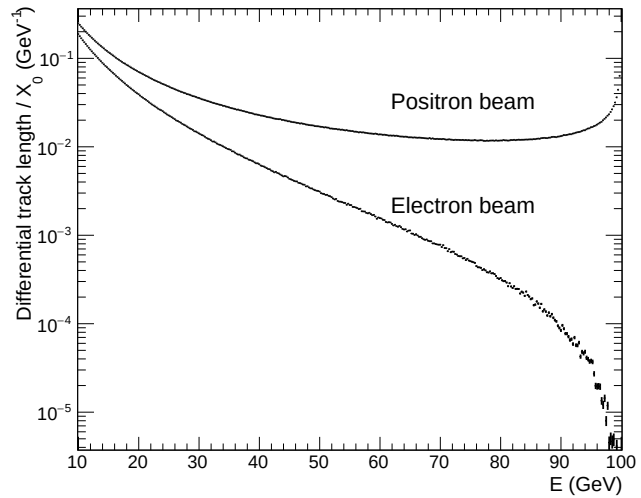
POKER: **PO**sitron resonant annihilation into dar**K** matt**ER**

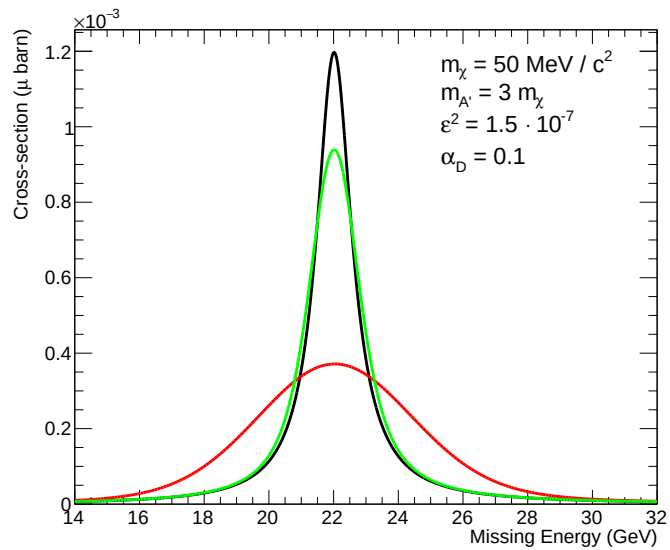
An optimized light dark matter search with positrons in the NA64 framework

Exploiting the LDM production process:

$$e^+e^- \rightarrow A' \rightarrow \chi\overline{\chi}$$ [1]

- 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 $E_R = \frac{M_{A'}^2}{2m_e}$ → **clear signal signature**





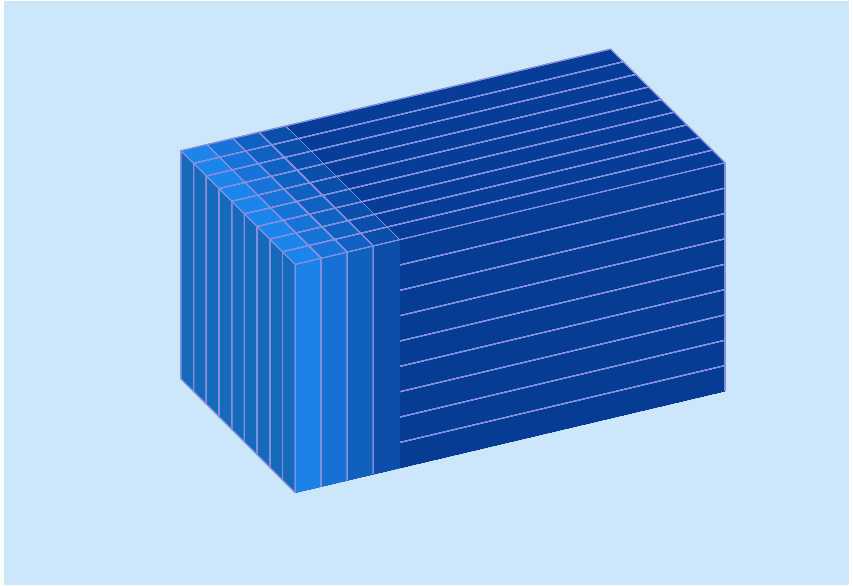
Project goal

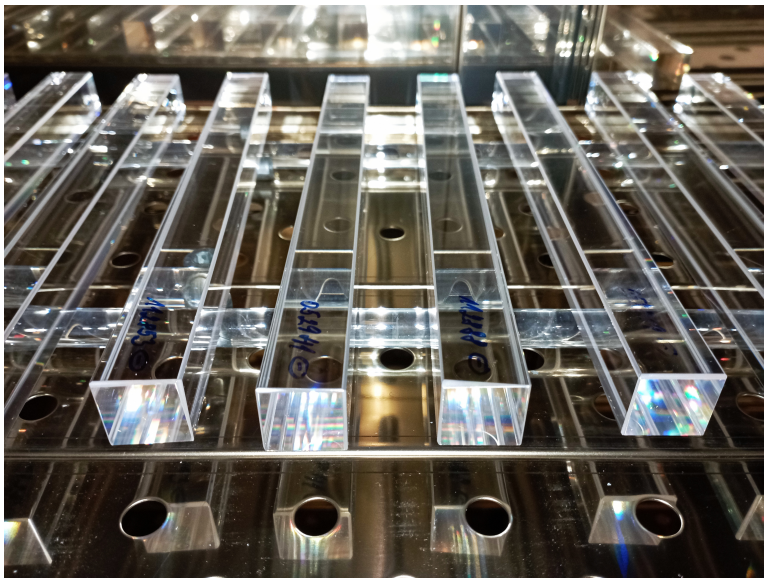
- Perform a dedicated missing energy measurement in NA64 with the SPS positron beam, replacing the existing NA64 ECAL with a new **high resolution detector ($PbWO_4$ calorimeter)**

[1] Phys. Rev. Lett. 121, 041802

The PKR-Cal Detector

- **Electromagnetic calorimeter**: 9×9 matrix of $2 \times 2 \times 20$ cm^3 $PbWO_4$ crystals + 4-layers pre-shower (total $\sim$ 120 crystals)
- **SiPM-based readout**: 4× 6×6 mm^2 Hamamatsu S14160-6010 SiPM per crystal (10 μm cell size)
- Expected resolution from MC simulations: $\sigma_E/E \sim 2.5\%/\sqrt{E} \oplus (0.5 \div 1)\%$





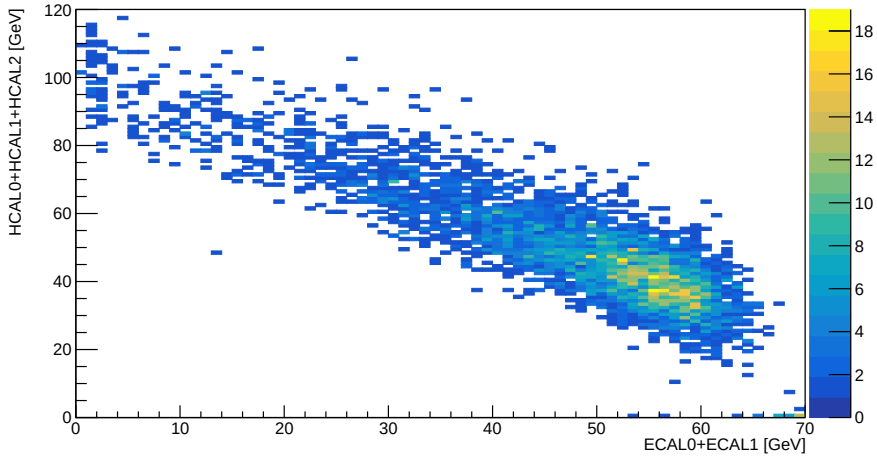
PKR-Cal R&D status:

- Crystals characterization (**light yield, light transmission, radiation hardness**) performed
- small-size (3X3 crystals) **prototype** built and tested at H8 line @CERN, to validate technical choices, further test foreseen in summer 2023
- PKR-Cal mechanical structure design ready
- detector assembly ongoing...

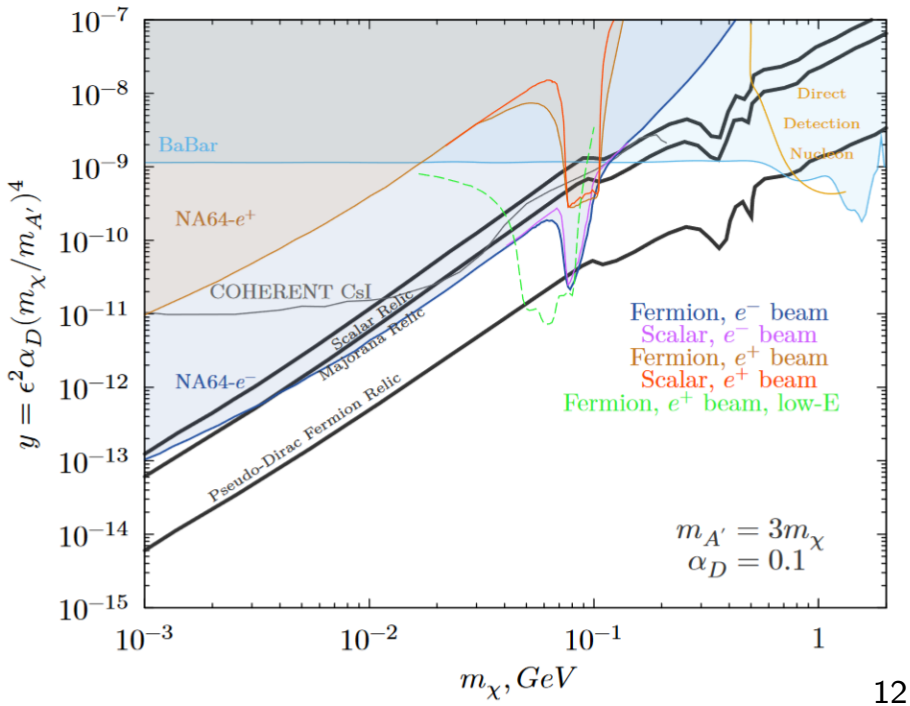
First e^+ measurement at NA64

While the POKER active target is being built, a first measurement with a 100 GeV e^+ beam, using the current NA64 setup has been performed in 2022

- **Goals:** background studies, first upper limit optimized for resonant A' production
- $\sim 10^{10}$ e^+OT collected
- **Blind-analysis approach**: signal region $E_{ECAL} < 50$ GeV, $E_{HCAL} < 1$ GeV
- **Main expected background source**: decay of misidentified K and π contaminants in the beam
- No events in the signal region after data unblinding



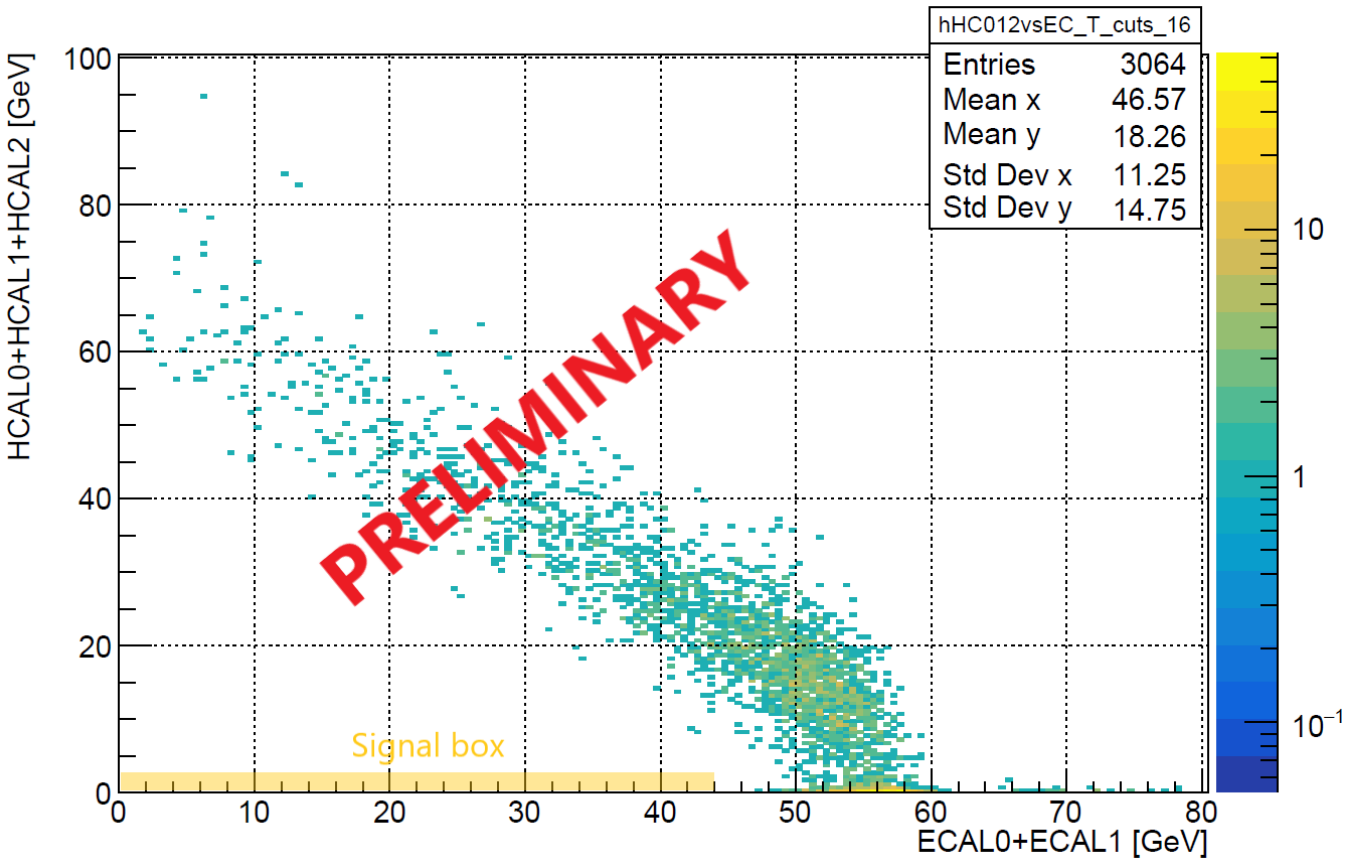
Phys. Rev. D 109, L031103



70-GeV positron run - preliminary analysis results

First measurement with a 70-GeV e^+ beam performed in 2023

- $\sim 1.6 \times 10^{10}$ e^+OT collected
- Critical aspects to address: detector **hermeticity** and **SRD tagging efficiency** at lower beam energy
- Analysis ongoing: first results are encouraging...



Conclusions

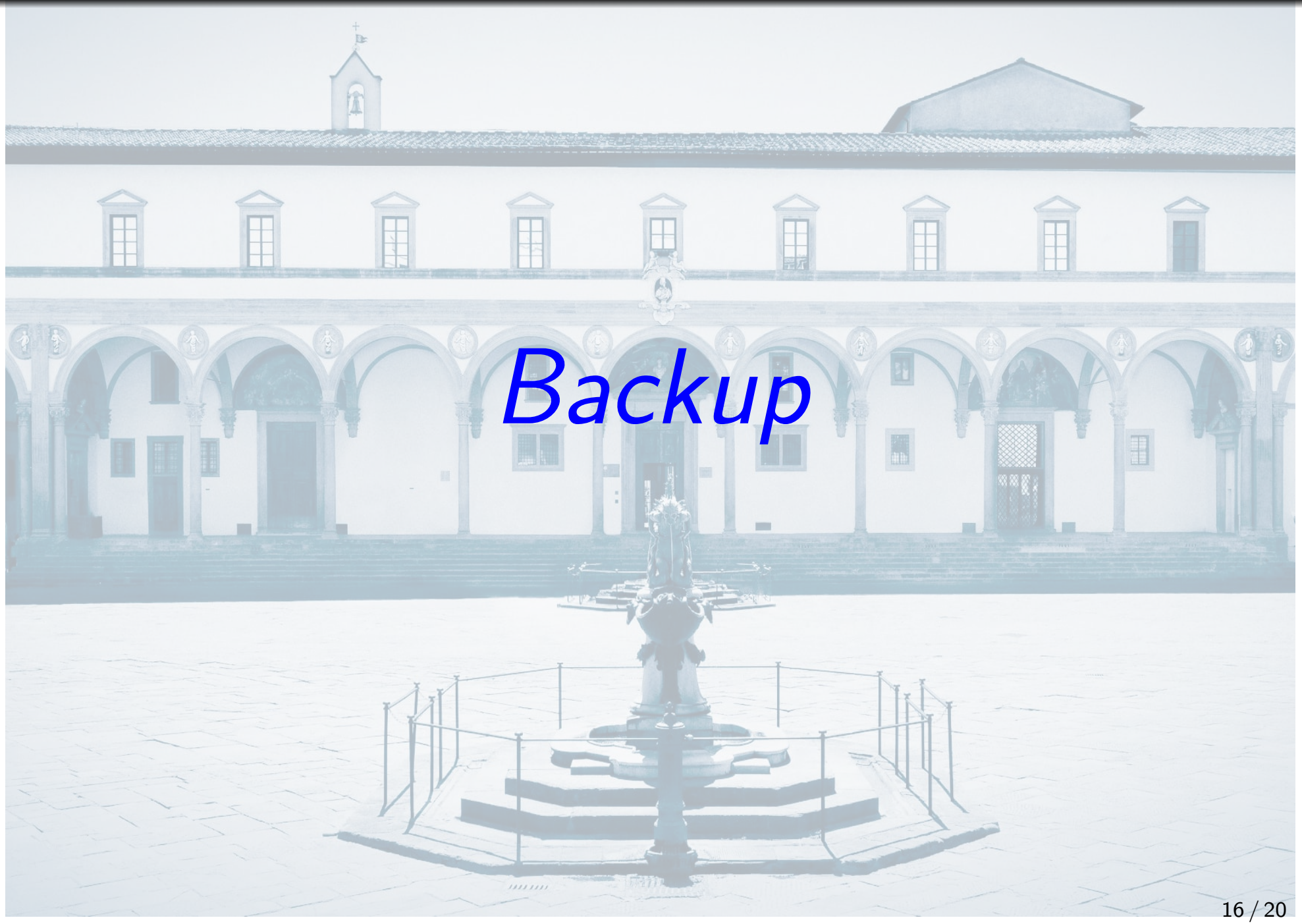
NA64 is an electron-beam missing-energy experiment at CERN searching for LDM particles in the dark photon paradigm

- The analysis of data collected up to 2022 allowed the collaboration to set stringent limits in the "invisible decay" dark photon parameter space ($A' \to \chi\bar{\chi}$)
- In addition to the A' "invisible decay" scenario, NA64 set limits on ALPs, Z', visible A' decay and B-L scenarios.
- The analysis of the 2023 data-sample is currently ongoing,

POKER is an ERC funded project, aiming to perform an optimized missing energy measurement with a positron beam

- The project includes the realization of a high-resolution active target ($\mathrm{PbWO_4}$ calorimeter) to be implemented in the NA64 setup.
- First test run with a positron beam performed in 2022, with the original NA64 setup. Results published on PRD.
- Second e^+ run collected in 2023 with a 70-GeV beam. Analysis is ongoing, data unblinded soon.
- POKER detector is being built - possibility to run the pilot measurement within 2025 currently discussed within the collaboration

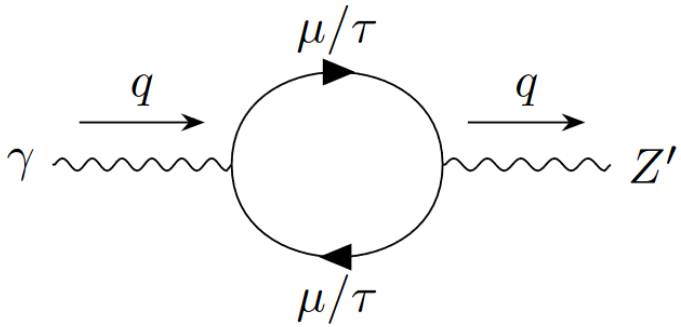
Grazie per l'attenzione!



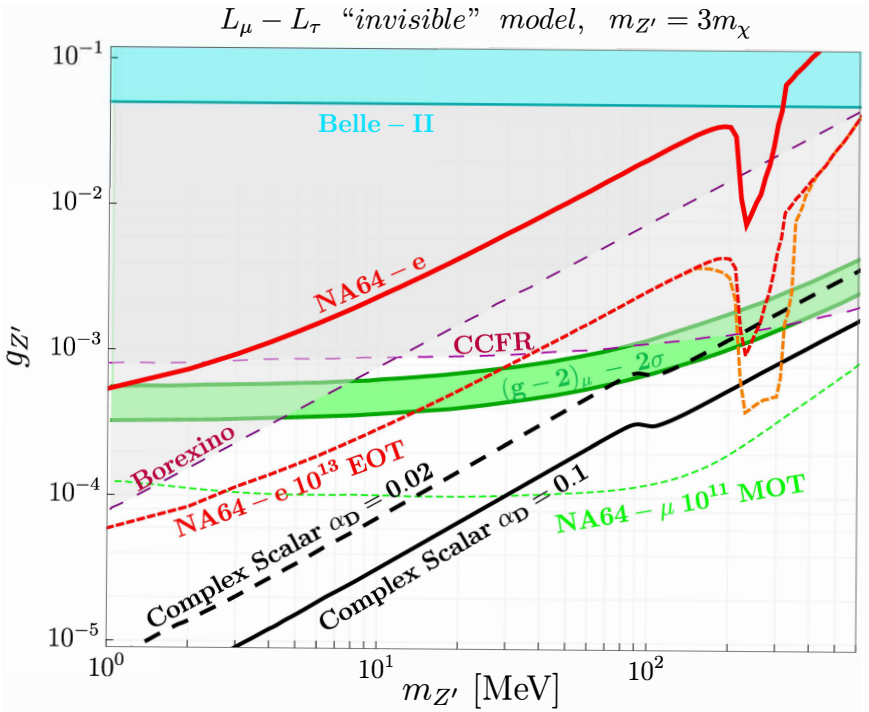
Backup

Search for Z' with NA64

- Dark Sector - SM interaction mediated by a light Z' boson with dominant coupling to μ and τ
- Data collected in 2016-2018 re-analyzed for the Z' search ($\sim 3 \times 10^{11}$ EOT)
- Loop-induced mixing between the SM photon and Z' - effective coupling implemented in signal simulation (MadGraph5)
- Resulting limits touch the preferred $g-2$ region for $m_{Z'}$ 1 MeV. Collecting 10^{13} EOT would allow to explore a significant part of the $g-2$ band.

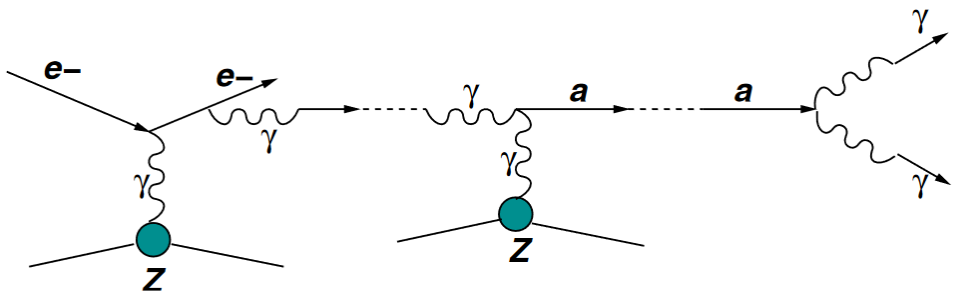


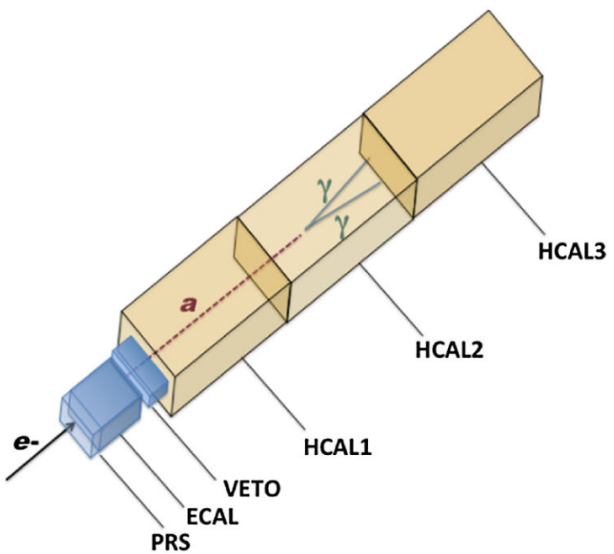
The NA64 Collaboration, Phys. Rev. D 106, 032015



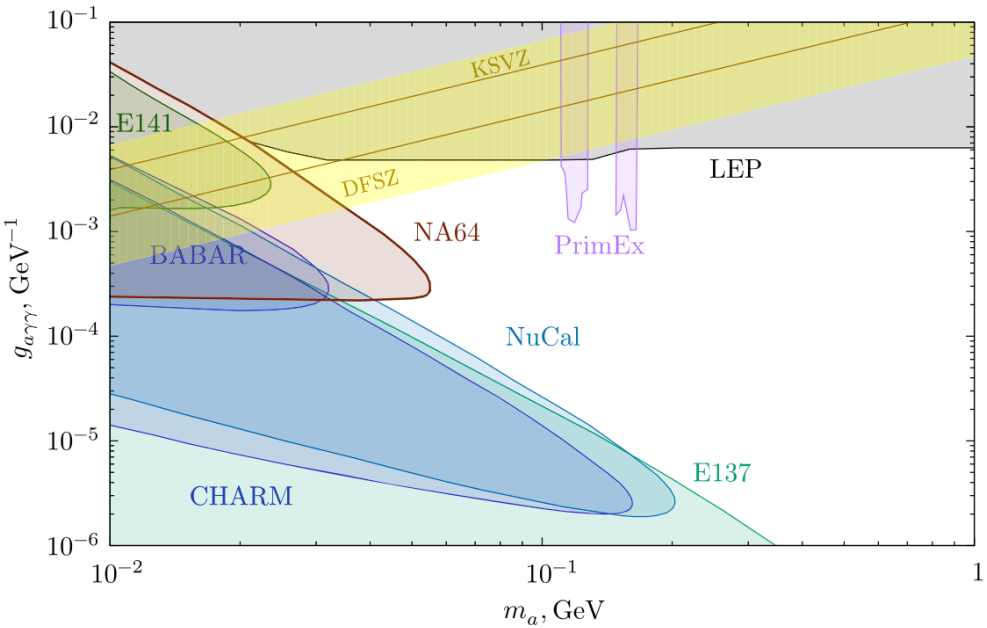
Search for ALPs and scalars

- ALPs produced via Primakoff effect from hard bremsstrahlung photons in the ECAL
- **HCAL fist module used as a veto**
- signal defined as: 1) $E_{ECAL} < 85$ GeV, $\mathrm{E_{HCAL23}} > 15$ GeV or 2) $\mathrm{E_{ECAL}} < 50$ GeV, $E_{HCAL23} \simeq 0$ GeV
- NO events observed in 2016-2018 data (compatible with expected background B $\simeq$ 0.17)

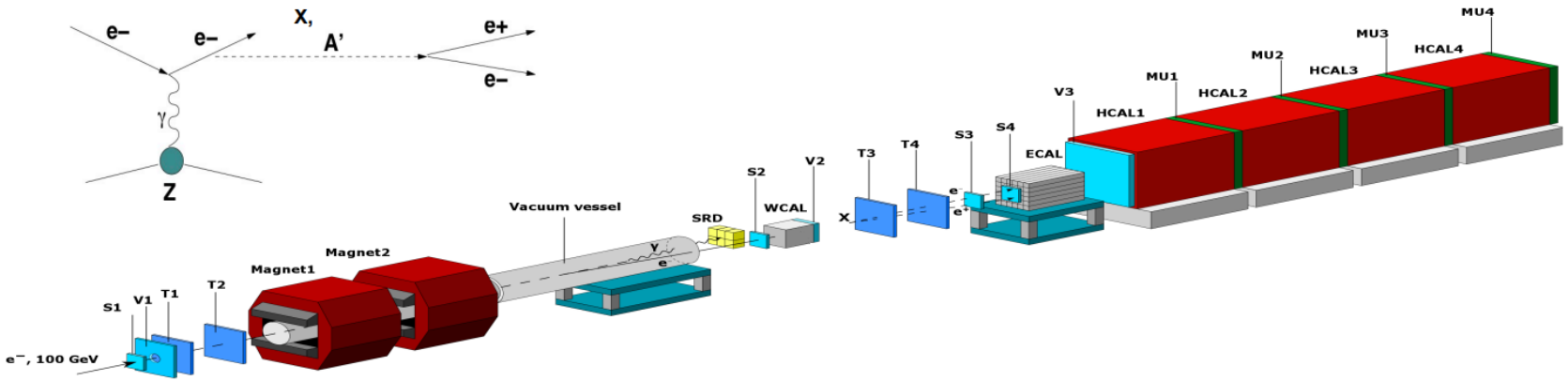




The NA64 collaboration Phys. Rev. Lett. 125, 081801 (2020)

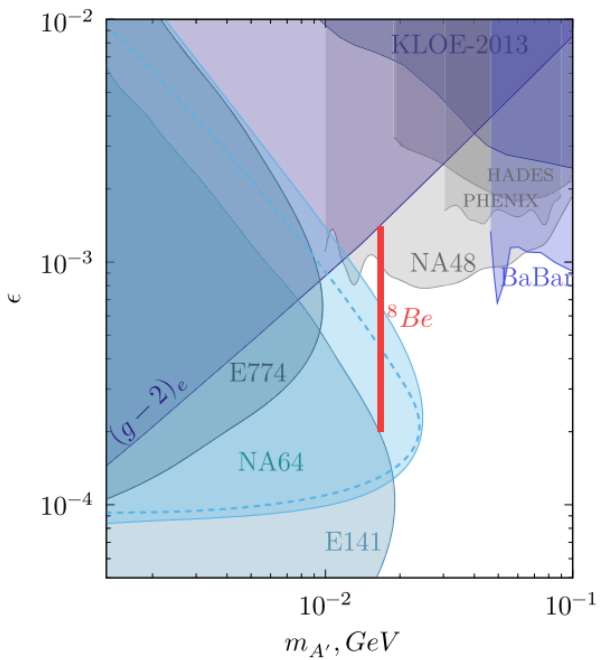


NA64 - visible mode



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
- **WCAL** detector upgrade necessary to improve reach



NA64 visible - future upgrade

The sensitivity to the X17 in the NA64 visible mode is limited by the WCAL length ($\gamma c\tau_{X17} \sim 30$ mm) and the capability to separate the very close tracks of the $X17 \to e^+e^-$ decay

→ **new setup under consideration**

- New WCAL geometry for improved signal efficiency
- Dipole magnet + ~ 18 m vacuum pipe for tracks separation
- GEM trackers + ECAL for invariant mass measurement (10% invariant mass resolution)
- Possible to probe significant part of the X17 parameter space in a ~ 20 days run