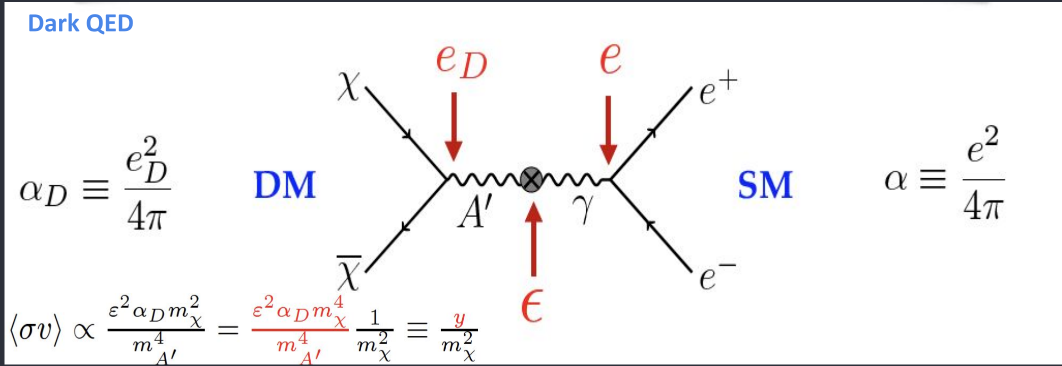
Status and plans of the NA64 experiment

A. Celentano (INFN-Genova), H. Sieber (ETH Zurich)

150th SPSC meeting
September 5th, 2023

NA64 physics case: the dark sector

Light Dark Matter hypothesis: DM is made of sub-GeV particles χ, part of a new "dark sector", feebly interacting with SM states through a new force in Nature. Representative case: **dark photon (A') model** -- the new force is mediated by a new massive U(1) gauge boson, whose coupling to SM electric charge reads εe, with ε<<1

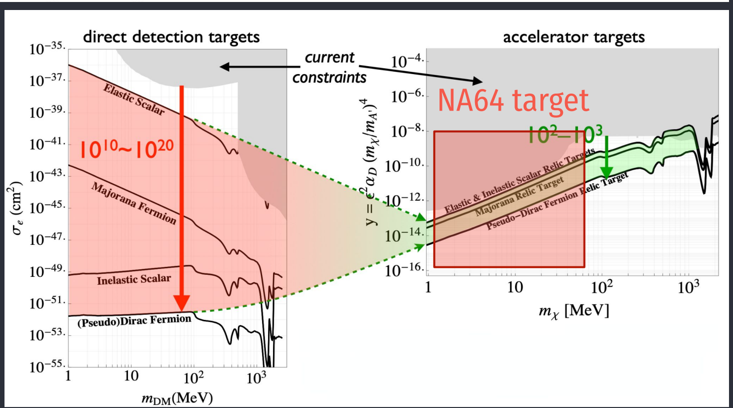


Cosmological prior

DM-SM thermal equilibrium in early Universe. Currently observed DM relic density is connected to χ+χ→SM+SM annihilation cross section ("freeze-out" mechanism).

Key observation: the DM relic density inferred from astrophysical/gravitational measurements provides a **target** in the LDM parameters space.

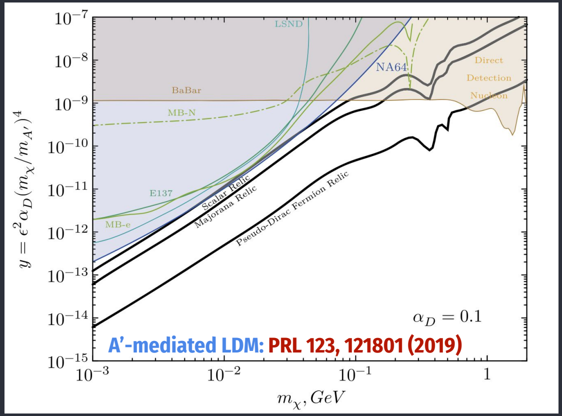
LDM searches at accelerators → large energy / q^2 regime: experiments are (almost) insensitive to DM spin and mass matrix



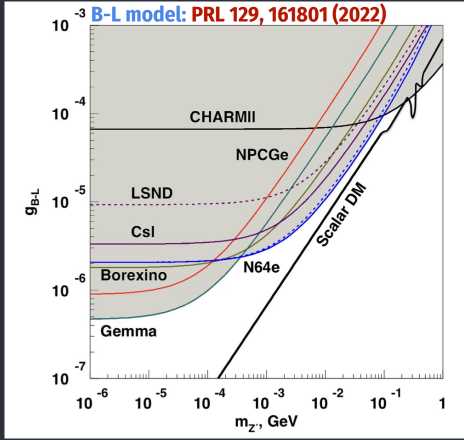
The NA64 physics program

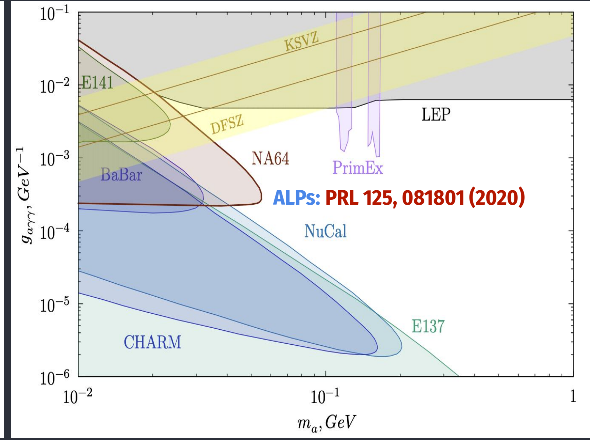
Comprehensive search for new physics with feebly interacting particles

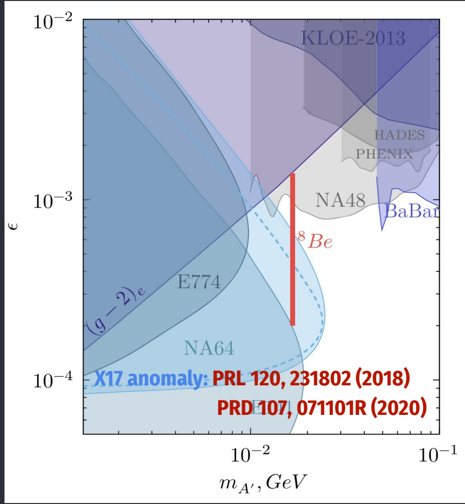
- A' - mediated LDM (scalar, Majorana, Pseudo-Dirac fermion)
- ALP particles, light scalars
- L_μ-L_τ models with light Z' →connection to muon g-2 anomaly
- B-L Z' models (complementary to dedicated ν-scattering experiments)
- Visible A' models
  - A' → $e^+ e^-$ decay, X17 anomaly from Atomki ^{8}Be measurement
- Semi-visible A' models
- New physics at the precision frontier in electron g-2



NA64 results set competitive or word-leading limits for all these scenarios





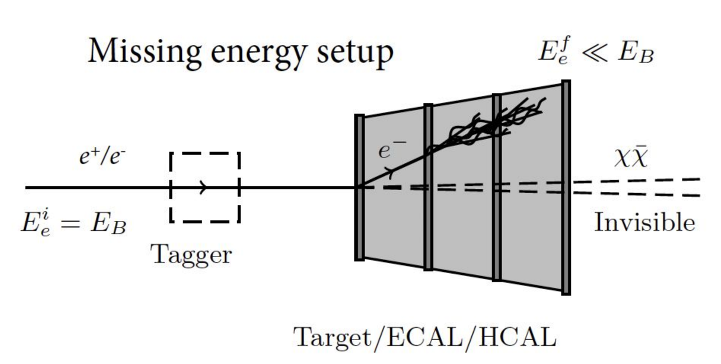


Electron beam missing energy experiment

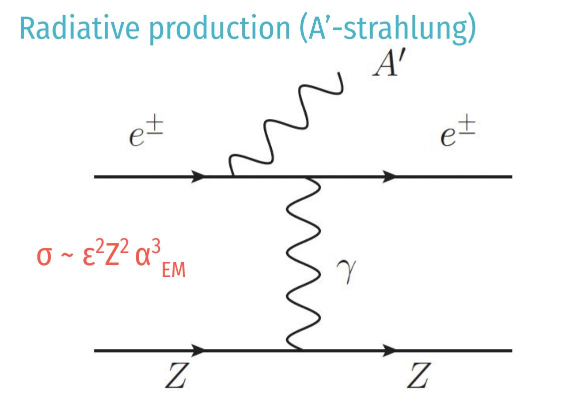
NA64-e: missing-energy measurement exploiting the high-purity 100 GeV e^- beam from SPS

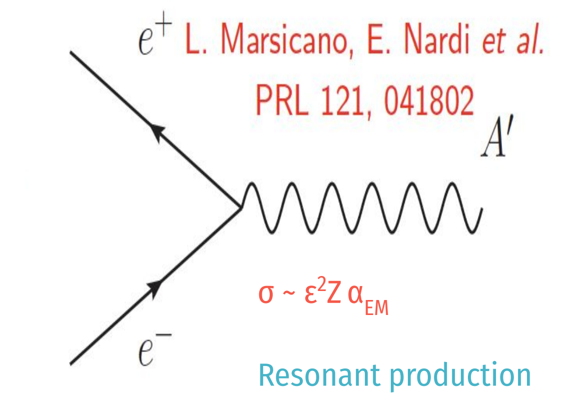
Key experiment element: **the active thick target (ECAL)**

- **Missing energy observable:** $E_{miss} = E_B - E_{dep}$
- **Beam time structure:** particles impinge on the detector "one at time", to be individually resolved → O (1 particle / us)
- **Signal:** any event from a clearly identified 100 GeV e^-, with large E_{miss} and no activity in the downstream detectors
- **Background:** production of highly penetrating / long lived particles escaping the ECAL



Main LDM production mechanisms with e^- beam:





Radiative production:
Bremmstrahlung-like process. High-energy, forward-focused A'.

Resonant production:
Breit-Wigner like cross section peaked at $M^2_{A'} = 2m_e E_{e+}$

Signal enhancement:

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

NA64 invisible mode: experimental setup (2022)

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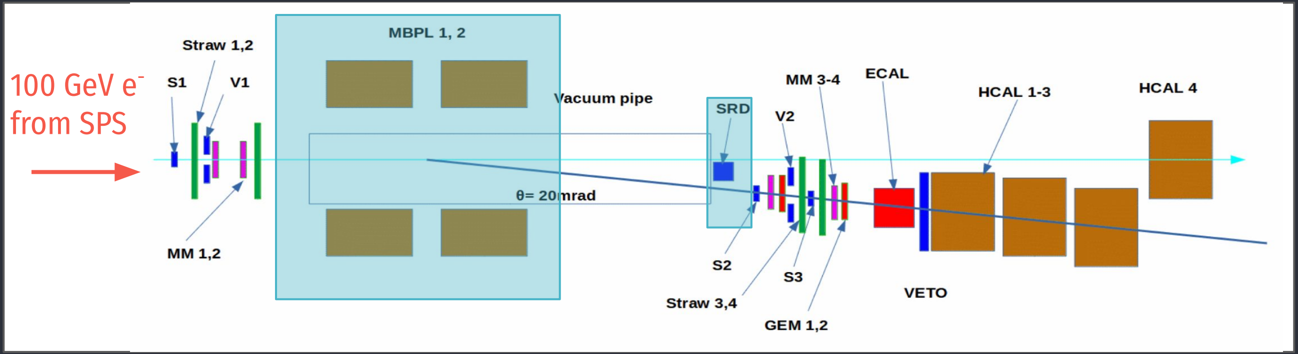
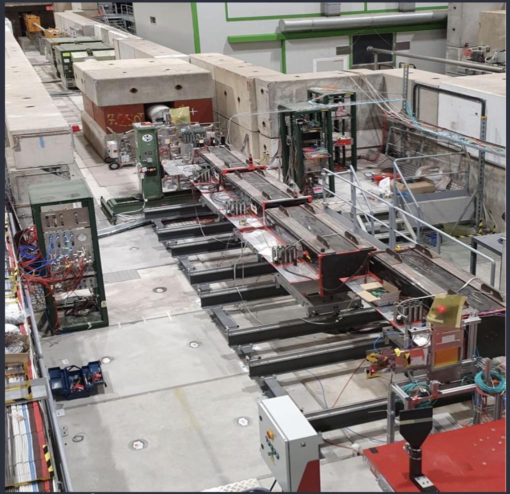




- High quality 100 GeV e^- beam from SPS (hadronic contamination ~ 0.4%)
- Impinging beam tagging and definition via plastic scintillator counters (S, V)
- Reconstruction of incoming particle ID and momentum: magnetic spectrometer + SRD detector
  - Tracking detectors: MM, GEM, Straw tubes
  - Total MBPL magnets field integral: 1.4 T·m. *Momentum resolution $\sigma_P / P \sim 1\%$*
- Active target: ECAL, 40 X_0 Pb/Sc Shashlik calorimeter with WLF+PMT readout, $\sigma_E / E \sim 10\%/\sqrt{E} \oplus 3\%$
  - First layers (4 X_0) acting as pre-shower detector with independent readout
  - Careful design to avoid any non-hermeticity effect (e.g. WLF fibers routed in a spiral to avoid leaks)
- HCAL: high-hermeticity (9 λ_I) Fe/Sc hadronic calorimeter, $\sigma_E / E \sim 60\%/\sqrt{E}$
  - Fourth module HCAL4 installed at zero degrees to detect neutral particles from upstream electro-nuclear interactions
- Production trigger: S+V+(E_{ECAL} < 90 GeV) + (E^{PRS} > 300 MeV)

NA64 results from 2021-2022 runs

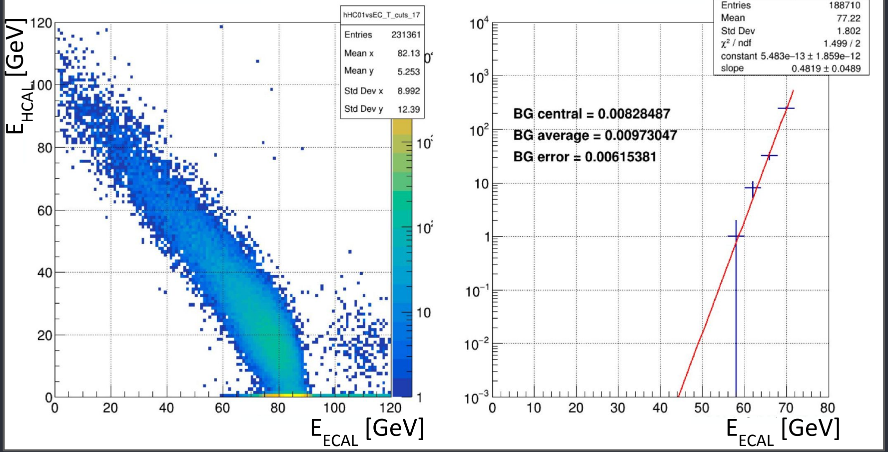
Accumulated statistics: $6{\cdot}10^{10}$ (2021) + $6.3{\cdot}10^{11}$ (2022) → in total, $9.37 \cdot 10^{11}$ EOT (2016-2022).

- Selection cuts:
  - Clean impinging 100 GeV/c e^-, no activity in VETO/HCAL, including HCAL4
  - Multiplicity cut on STRAW detectors to further suppress background from upstream interactions
  - EM shower-shape compatible with e^- induced one (data-driven shower shape χ^2 distribution)
- Signal window: E_{ECAL} < 47-50 GeV, $E_{HCAL[1+2+3]}$ < 1 GeV, depending on the run conditions and detector performances
  - Signal window defined by maximizing the experiment sensitivity to LDM, including e^+e^- resonant contribution
- Expected background yield: ~ 0.5 events
  - Dominant contribution from in-flight decay of misidentified μ, π, K (MC estimate)
  - Contribution of upstream electro-nuclear reactions extrapolated from data via sideband fit
- No events observed in signal box after unblinding

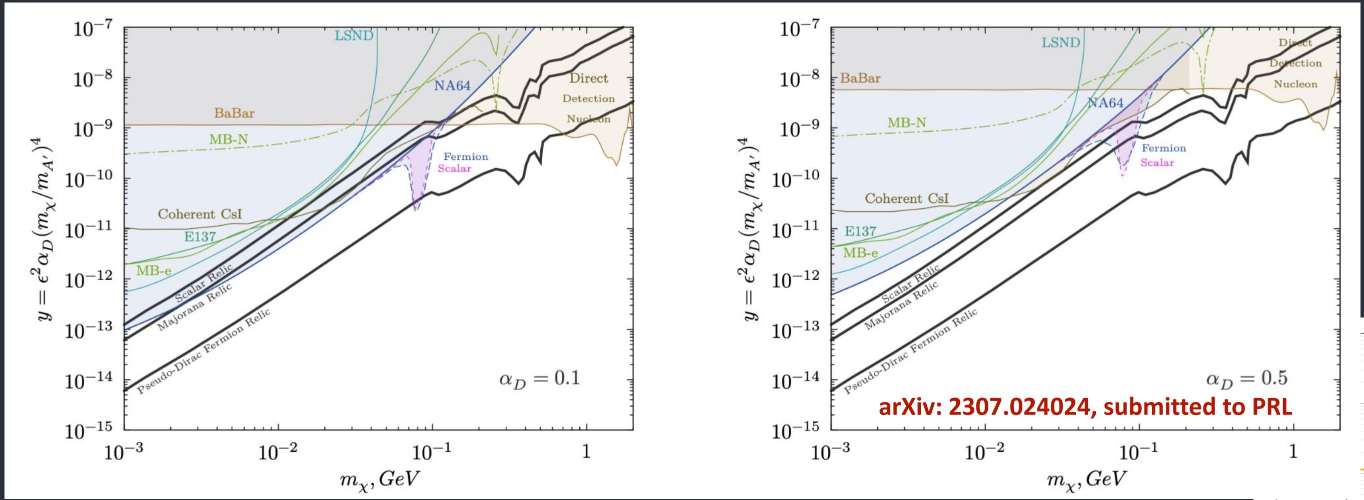
Estimated backgrounds for 2021-2022 runs

Background source	Background, n_b
1. Di-muons losses or decays in the target	0.04 ± 0.01
2. μ, π, K → 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

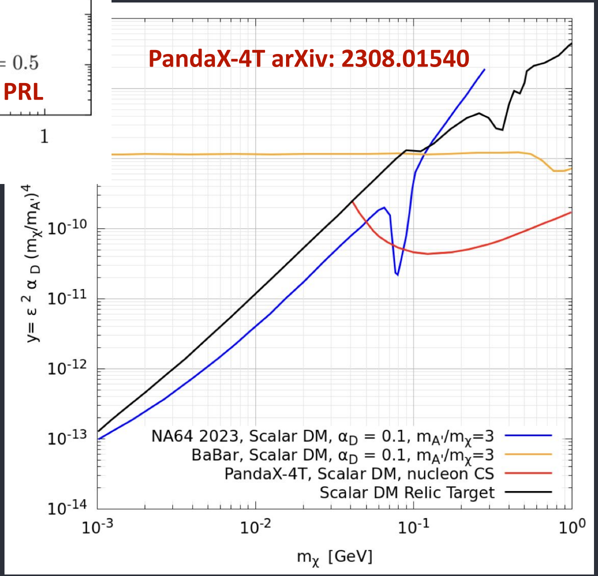
Sideband-fit example (2022 run, sub-run period #2)



NA64 results from all runs (~10^{12} EOT)



LDM production yield include resonant and radiative contributions.



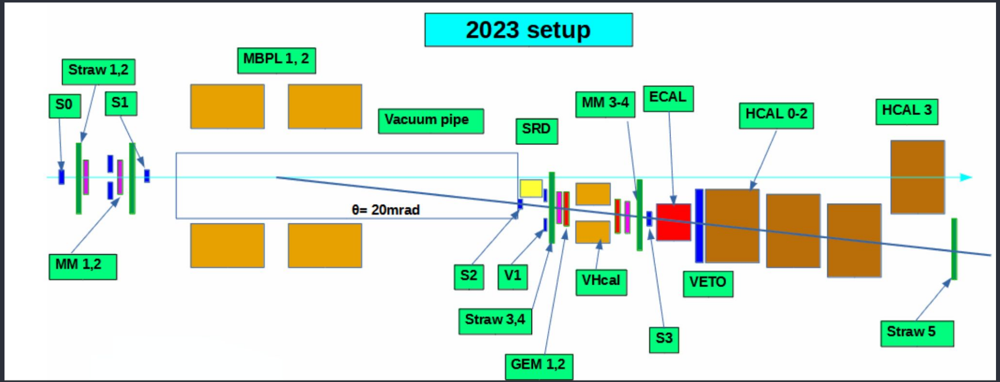
NA64 results represent the **most stringent limits in the LDM parameter space**

- For α_D=0.1, NA64 excludes the Scalar and Majorana scenarios for almost all m_χ values.
  - Scalar case also scrutinized by recent PandaX-4T result, insensitive to Majorana and Pseudo-Dirac scenarios → *Strong complementarity of NA64 and direct detection experiments.*
- Thanks to e^+e^- resonant enhancement, we also exclude the Pseudo-Dirac Fermion scenario for a narrow m_χ interval.
- We are already working to extend these results to other physics cases, such as L_μ-L_τ Z', B-L Z', non-diagonal (inelastic) LDM, ALPs, …

NA64 2023 run

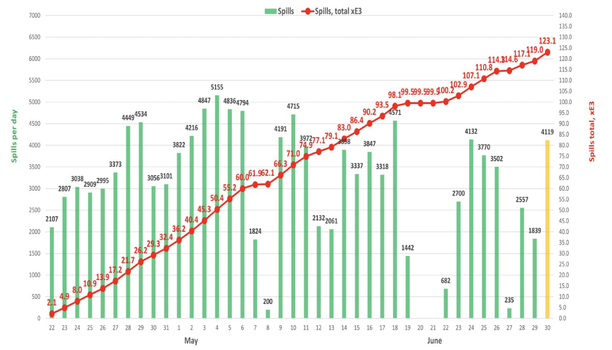
NA64 2023 run completed in July (8 weeks, May 10th - July 5th). Improved detector setup to further reduced backgrounds and improve sensitivity to LDM.

- New Cu/Sc veto hadronic calorimeter (VHCAL) installed in front of ECAL to further suppress upstream electro-nuclear reactions with large-angle neutral hadrons.
  - Detector geometry and setup optimized through high-statistics MC simulations based on Geant4 and FLUKA
- Optimized DAQ system, including a programmable trigger pre-scale to acquire full-energy e^- events in parallel to the main production trigger.
- Excellent beam quality in 2023! Beam halo ~ 3% (5% in 2022) and hadronic contamination ~ 0.3% even at large intensity. *Many thanks to BE-EA-LE: Nikos Charitonidis for the beam, and Sylvain Girod for setup assembly and installation*



6 weeks of prod. run with ~ $6.5 \cdot 10^6$ EOT/spill, and typically 3 spills/supercycle.

→ Total EOT ~ $5.1 \cdot 10^{11}$ EOT.
Data analysis just started.



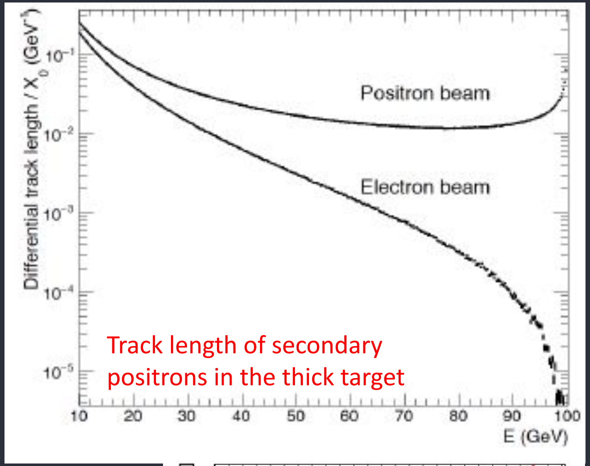
New VHCAL detector

NA64 dark sector exploration with e^+ beam

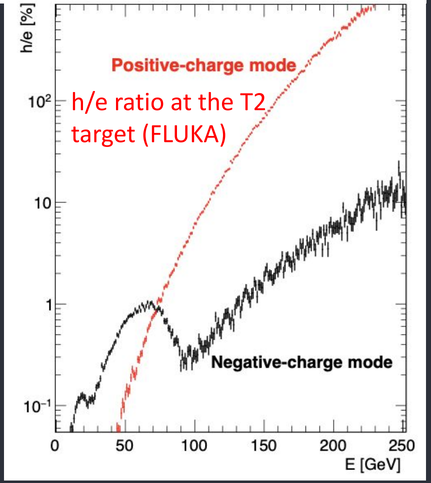
In the large-mass regime, the A'-strahlung production mechanism suffers a penalty from $\sigma \sim 1/m^2_{A'}$ dependency.

Complementary strategy to explore the large-mass regime: use a positron beam to maximally exploit the e^+e^- resonant annihilation.

A first pilot e^+ beam missing-energy measurement was performed in 2022 with a 100 GeV beam ($E^+OT \sim 10^{10}$)



- Due to the much higher (~4%) hadronic contamination, the missing energy trigger threshold was increased to E_{ECAL} ~< 60 GeV. Similarly, the pre-shower threshold was increased to ~ 400 MeV
- Data analysis similar to the e^- beam measurement; selection cuts tuned by maximizing the experiment sensitivity.
  - Signal region: E_{ECAL} < 50 GeV, E_{HCAL}<1 GeV
- Main background source: in-flight decay of misidentified π^+ and K^+.
  - Yield evaluated from MC, after ad-hoc experimental measurement of the hadronic contamination (arXiv: 2305.19411)



Supported by the ERC Starting Grant 2020 project: POKER "POsitron annihilation into darK mattER"

POKER
POsitron resonant annihilation into darK mattER

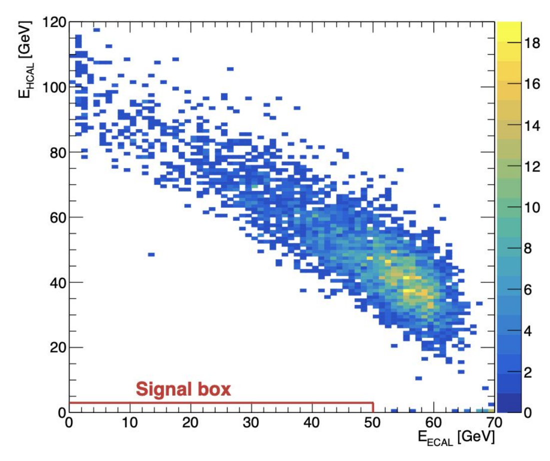
NA64 dark sector exploration with e^+ beam

No events were observed in the signal region after unblinding

- Expected background yield ~ 0.5 events.

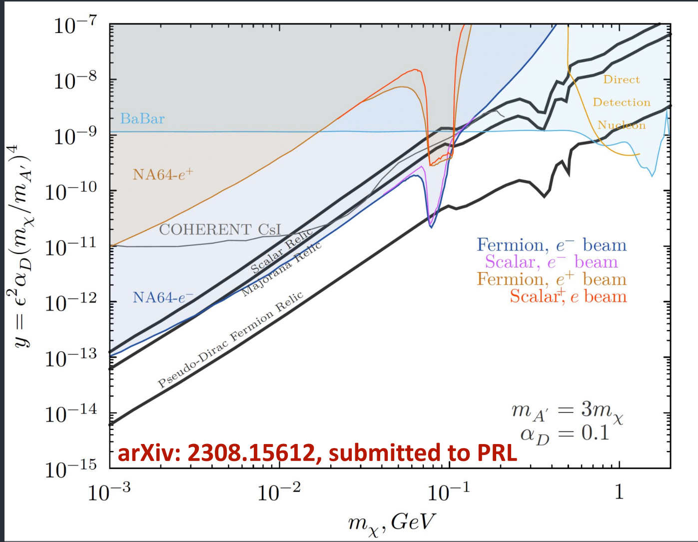
An upper limit was set in the LDM parameters space.

- Despite the x100 lower statistics, thanks to the increased e^+ contribution the results touch the e^- beam limits in the ~ 100 MeV mass region
- This proves the feasibility and the potential of a dedicated positron program at NA64. To further explore this, a dedicated test at 70 GeV was run in 2023, accumulating ~ 1.5 $\cdot 10^{10}$ E^+OT.



We foresee to submit a **proposal addendum** to the SPSC in the near future to start a dedicated experimental program with positrons beam, at different energies.

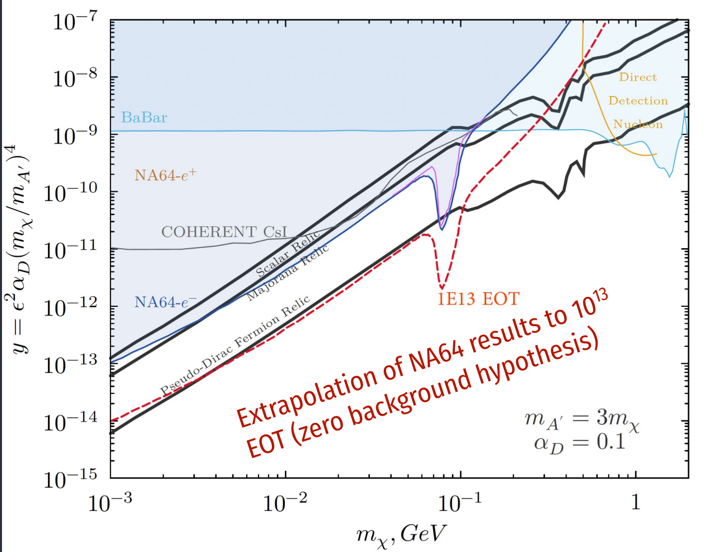
The goal of this program is to explore the LDM parameter space exploiting the resonant production mechanism at masses where higher sensitivity compared to the electron mode can be achieved.



NA64e to and beyond LS3

Plans before the next long shutdown (LS3):

- Extend the analysis of current dataset to other Dark Sector models
- Reach up to ~ $3 \cdot 10^{12}$ EOT and continue to lead the LDM searches in the low mass region
  - In 2024, we plan to request 10 weeks of beam time
- Finalize the detector upgrade to run at higher intensity
  - *New MSADC development:* hardware ready, firmware expected to be completed in Fall 2023, test during 2024 run.
  - *New MM readout:* on-going study and tests to upgrade the current MM readout to VMM chips



Plans beyond LS3:

- Complete the setup upgrade to run with up to $1.5 \cdot 10^7$ EOT/spill
- **Ultimate goal:** collect ~10^{13} EOT and fully scrutiny all thermal targets in the m_χ < 100 MeV region

The NA64μ experiment

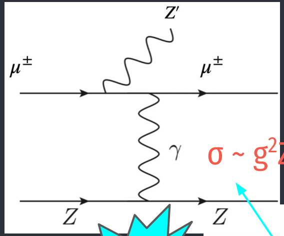
A. Celentano (INFN-Genova) / H. Sieber (ETH Zurich), 150th SPSC meeting, September 5th, 2023

- anomaly-free L_μ-L_τ models with light Z': the simplest and most predictive solution to $(g-2)_\mu$ and LDM

Phys. Rev. Lett. 128 (2022) 14, 141802

Initial state:
well-defined incoming muon with 160 GeV/c

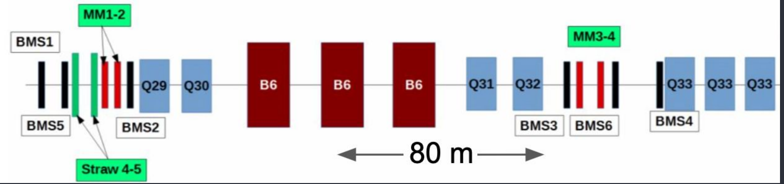
Radiative production



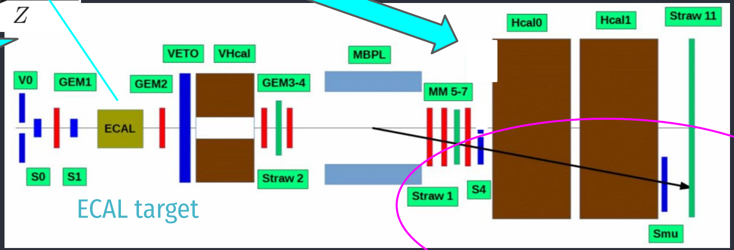
$\sigma \sim g^2 Z^2 \alpha^2_{EM} / m^2$

Final state:
- no activity in the veto and VHCAL
- MIP in ECAL and HCAL
- scattered muon < 80 GeV

Upstream



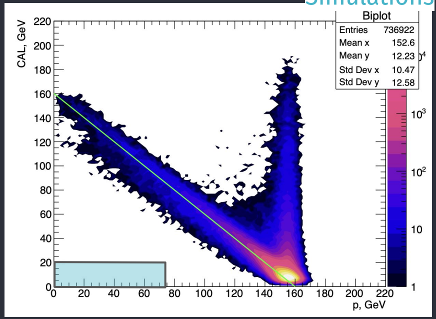
Downstream



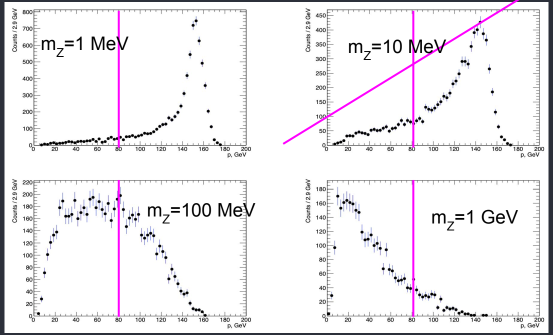
ECAL target

experimental signature

Simulations



optimisation of trigger configuration



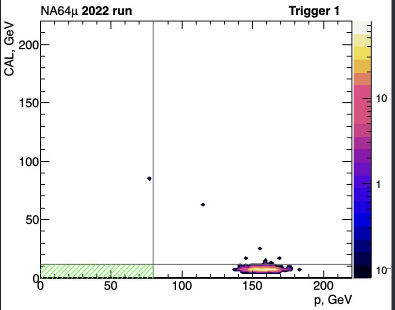
- acceptable DAQ rate
- coverage of the full Z' mass range
  - $m_{Z'}$< 100 MeV: low acceptance, high σ
  - $m_{Z'}$≥ 100 MeV: high acceptance, low σ

- Phys. Rev. D 104 (2021) 076012
- arXiv.2305.09015 (2023) accepted in Phys. Rev. D
- Eur. Phys. J. C 83 (2023) 775

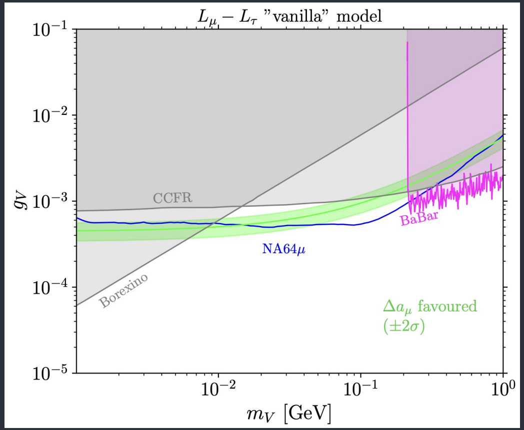
Analysis (still blinded) results of the 2022 run

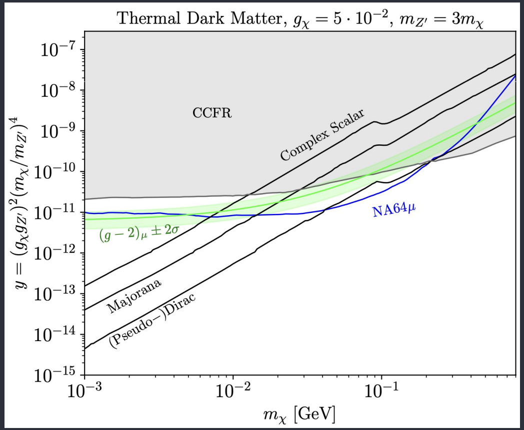
A. Celentano (INFN-Genova) / H. Sieber (ETH Zurich), 150th SPSC meeting, September 5th, 2023

Analysis of the physics statistics **(1.98±0.02) · 10^{10} MOT** at 2.8x10^6 **μ**/spill



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





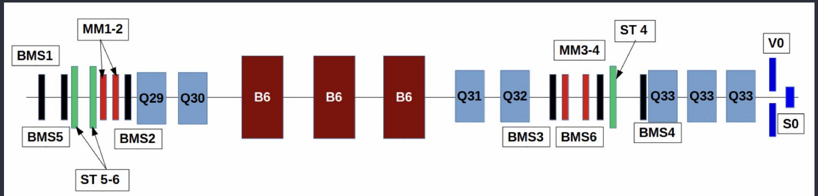
- **Blinded analysis** (p < 80 GeV/c, E < 12 GeV) with main selection criterion
  - (i) incoming momentum in the range 160±20 GeV/c, (ii) single reconstructed track in the set-up, (iii) MIP compatible energy deposit in the calorimeters (ECAL, VHCAL and HCAL) and veto

- Background estimated from both data and MC → ~0.07 events
  - (i) momentum mis-reconstruction - calibration runs, (ii) kaons decays - Monte Carlo, (iii) non-hermeticity - extrapolation of the control regions in the hermeticity plane

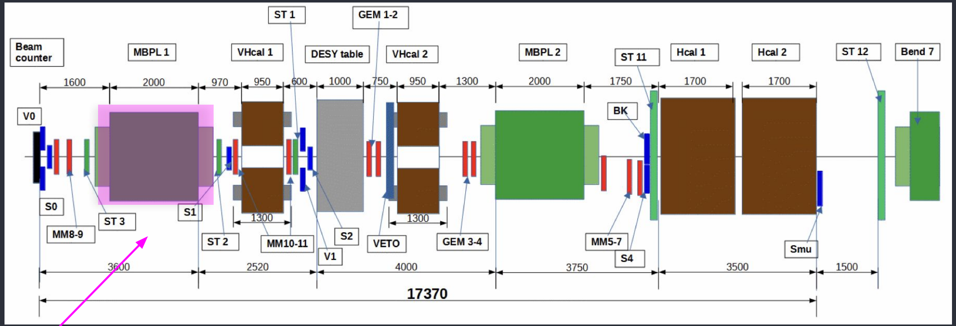
- Results at 90% C.L. suggest that part of the remaining **$(g\text{-}2)_\mu$ parameter space** compatible with a light Z' vector boson can be covered.
- Additional results on **muon-philic scalar** boson and complementary searches to NA64$e^\pm$ for **invisible *A'* decay**.

The 2023 muon run

Upstream



Downstream



July 12th - August 9th (28 days), **(1.50±0.02) · 10^{11} MOT**
→ **Main goal:** minimise momentum mis-reconstruction and run at higher intensity

Experimental set-up **upgrades**

- Magnet spectrometer system: additional **magnet spectrometer (MBPL)** at the entrance of the set-up
- Tracking detectors: additional **Micromegas** (+4) and **Straw detectors** (+3), total of 23 trackers
- Calorimetry: additional **veto hadronic calorimeter (VHCAL)** before the ECAL
- Trigger system: additional **scintillator counters** (S_2 and beam killer, BK)

Complementary **measurements**

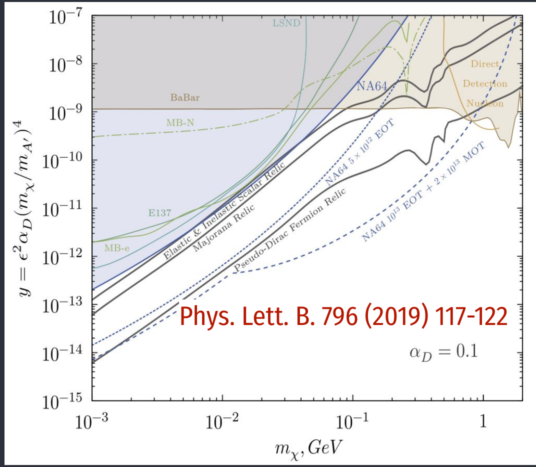
- **Hadron contamination in the beam-line**: measurements with 3-9 absorbers
- **Empty-target**: measurements with 160 GeV/c muons and 160 and 80 GeV/c hadrons
- **Beam intensity**: 2.8 · 10^6 μ/spill, 4.6 · 10^6 μ/spill and 10^7 μ/spill

→Improvement of the momentum reconstruction, background suppression, ...

NA64μ to and beyond LS3

- Plans before the long shutdown (LS3)
  - Pursue the 2022 analysis with the treatment of other scenarios such as LFC, to be also explored in the 2023 analysis
  - Finalise the 2022 analysis by unblinding the data
  - Cover the remaining parameter space compatible with the $(g\text{-}2)_\mu$ anomaly by accumulating ~10^{12} MOT
  - Complement NA64e in the high mass region in the search for light dark matter

- Plans beyond LS3
  - Upgrade the experiment to exploit the M2 beam-line capabilities by running at beam intensity ~10^7 μ/spill
  - Cover the high-mass region of the thermal target with ~$2 \cdot 10^{13}$ MOT
  - Explore scenarios involving LFC, ALPs, ...



Summary and outlook

NA64 at CERN SPS is an experiment which has unique sensitivity to Dark Sector physics.
In the next years we expect either to unambiguously discover or reject nearly all benchmark thermal LDM models

Electron beam:

- Collected so far $1.5 \cdot 10^{12}$ EOT (2016-2023), aiming to reach ~ $3 \cdot 10^{12}$ EOT before LS3.
  - Most of statistics accumulated with improved NA64 detector installed in the new permanent experimental zone.
- Background-free results from 2016-2022 statistics (~ 10^{12} EOT) allowed to probe for the first time the **scalar** and the **Majorana** thermal targets - excluded by NA64 for $\alpha_D<0.1$.
  - Results currently being exploited to probe other representative Dark Sector scenarios (L_μ-L_τ Z', B-L Z', non-diagonal (inelastic) LDM, ALPs, ...)

Positron beam:

- Complementary high-sensitivity probe to explore the large A' mass region exploiting the e^+e^- annihilation channel.
  - First results from 2022 pilot run (10^{10} E^+OT at 100 GeV) confirm the feasibility of this approach at NA64. Thanks to resonant enhancement, the results touch the latest limits from the full electron-beam statistics.
- We foresee to submit a **proposal addendum** to the SPSC in the near future to start a dedicated experimental program in a strong collaboration with BE-EA

Muon beam:

- Total statistics accumulated during 2021-2023 runs is **$1.9 \cdot 10^{11}$ MOT**, aiming at reaching ~10^{12} MOT by LS3
- Analysis results from the 2022 data set (~$2 \cdot 10^{10}$ MOT) indicate part of the remaining **$(g-2)_\mu$ parameter space** can be probed
  - Additional results for muon-philic **scalar boson** and **light dark matter**
- On-going analysis of the recent 2023 statistics with preliminary analysis planned by the end of the year

Thanks!

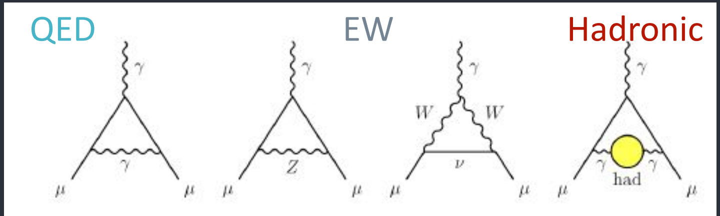
We gratefully acknowledge CERN management and staff for their excellent support in preparing and running the NA64 experiment, in particular D. Banerjee, N. Charitonidis, and S. Girod from BE-EA group

Spare slides

The NA64 physics program: muon g-2 anomaly

Muon anomalous magnetic momentum $a_\mu=(g_\mu-2)/2$

SM contributions to a_μ:



> 4 σ discrepancy between exp. and theo. results!

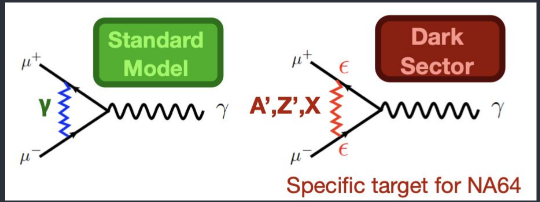
$$\Delta a_\mu = a_\mu^{EXP} - a_\mu^{TH} = (251 \pm 59) \cdot 10^{-11}$$

Theoretical uncertainty dominated by hadronic term. If the hadronic term is computed through lQCD instead of using traditional dispersive techniques, the discrepancy reduces significantly

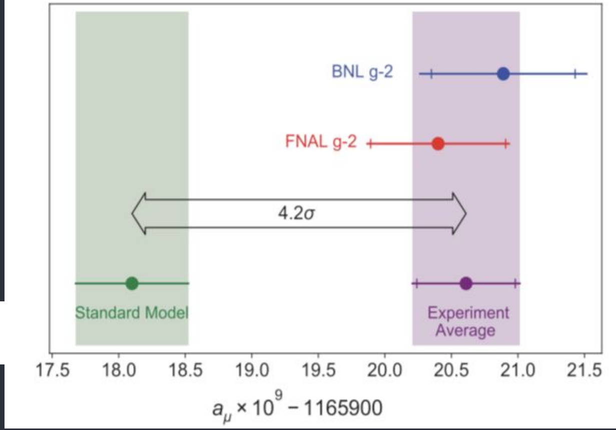
- Dedicated measurements are necessary to further explore this → MUONE experiment

Hint of new physics? Contribution to a_μ from feebly interactive massive particles coupled to muons

- Vanilla A' scenario already excluded
- Room for muon-philic Z' scenarios



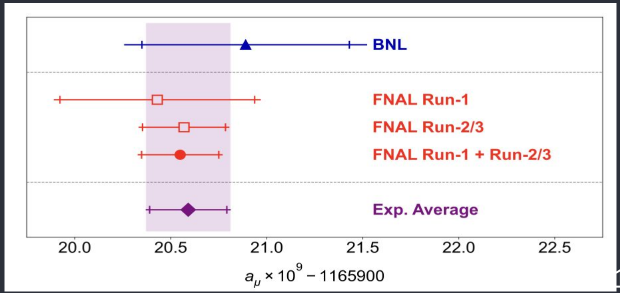
Does not include latest FNAL results



Experiment: B. Abi *et al.* Phys. Rev. Lett. 126, 141801

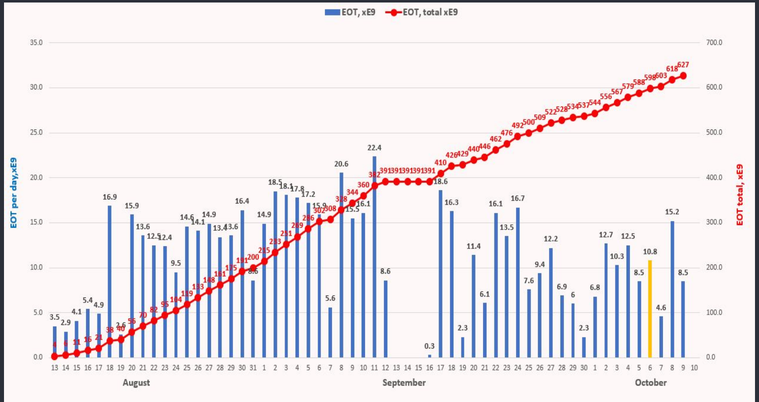
Theory: T. Aoyama *et al.* Phys. Rept. 887 (2020) 1-166

FNAL results from August 2023: experimental result confirmed with ~ x2 lower uncertainty



NA64 2021-2022 runs

- NA64 after LS2: detector installed at the new permanent location
  - Minimize installation time and optimize the use of the allocated beam-time.
- 2021 run: 4 weeks allocated (11th August - 8th September)
  - 2 weeks for new detector installation and commissioning, 1 week lost for SPS instabilities
  - $6 \cdot 10^{10}$ EOT accumulated in one week of production run
- 2022 run: 12 weeks allocated (27th July - 12th October)
  - *Same detector configuration as in 2021 to maximize production run time (predicted BGK from 2021 data: $5 \cdot 10^{-13}$ / EOT)*
  - ~2 weeks for detector installation and commissioning
  - ~1 week lost due to long MD
  - Accumulated $6.3 \cdot 10^{11}$ EOT (beam intensity ~ 6E6 e^-/ spill), *twice that from 2016-2021!*
  - *Looking forward to future NA64 activities*, few days at run end were dedicated to e^+ beam and hadron beam studies.
- Total NA64 statistics: $9.37 \cdot 10^{11}$ EOT



NA64 published results from 2016-2018 runs

Published results from 2016-2018 runs, $2.84 \cdot 10^{11}$ EOT

- Different beam intensities, from 10^6 to 10^7 EOT/spill
- Selection cuts:
  - Clean impinging e⁻ (single hit in all trackers, SRD energy deposition, reconstructed momentum $|P-P_0|<3$ GeV)
  - No downstream activity in VETO / HCAL
  - ECAL shower shape compatible with e⁻ - induced shower
- No events observed in the signal window $E_{ECAL} < 50$ GeV, $E_{HCAL}<1$ GeV
  - Background in the signal region extrapolated from sidebands (C)
  - Expected background yield ~ 0.5 events, dominated by upstream electro-nuclear events with neutral secondaries
- Most stringent exclusion limits in the LDM space
  - The result includes the contribution to the signal yield from the resonant $e^+ e^-$ annihilation of secondary positrons in the EM shower

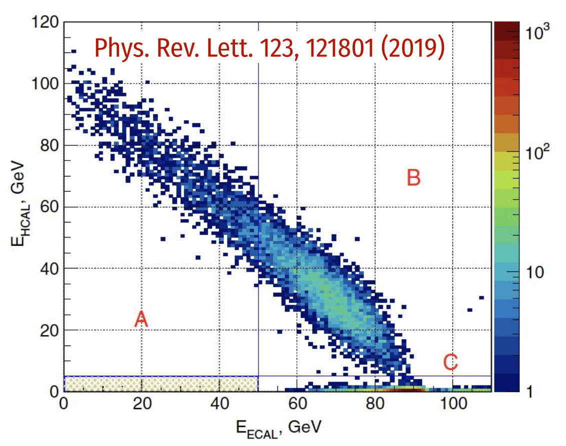
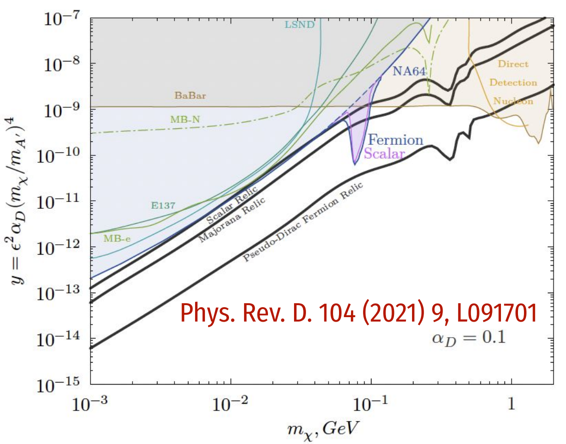


TABLE I: Expected background for 2.84×10^{11} EOT.

Background source	Background number, n_b
punchthrough γ's, cracks, holes	< 0.01
loss of dimuons	0.024 ± 0.007
$\mu \to e\nu\nu$, π, $K \to e\nu$, K_{e3} decays	0.02 ± 0.01
e^- interactions in the beam line	0.43 ± 0.16
μ, π, K interactions in the target	0.044 ± 0.014
accidental SR tag and μ, π, K decays	< 0.01
Total n_b	0.53 ± 0.17



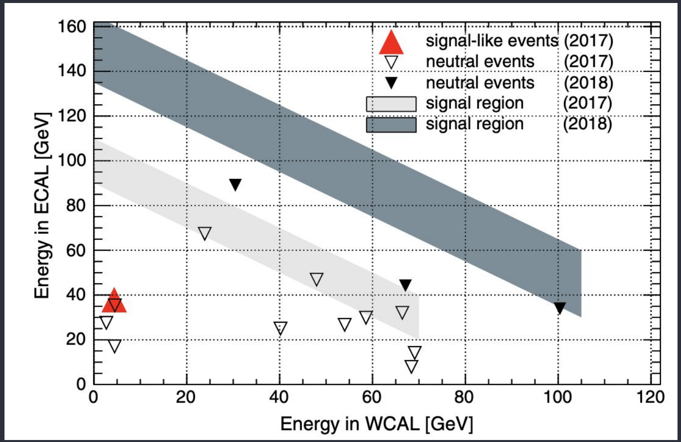
NA64e - visible A’ decay search

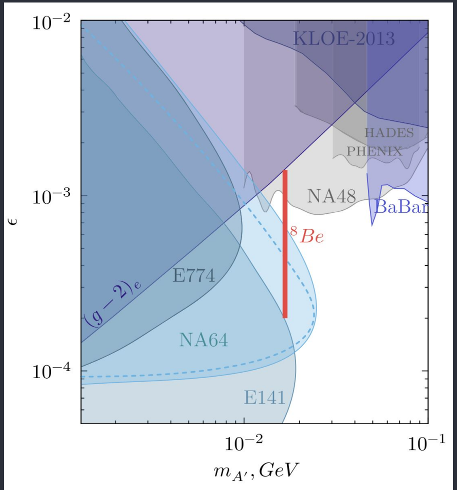
Search for A’ → $e^+ e^-$ decay with slightly modified setup with respect to invisible-mode measurement.
A’ production by radiative emission in compact WCAL active target and decay to e^+e^- in vacuum pipe.

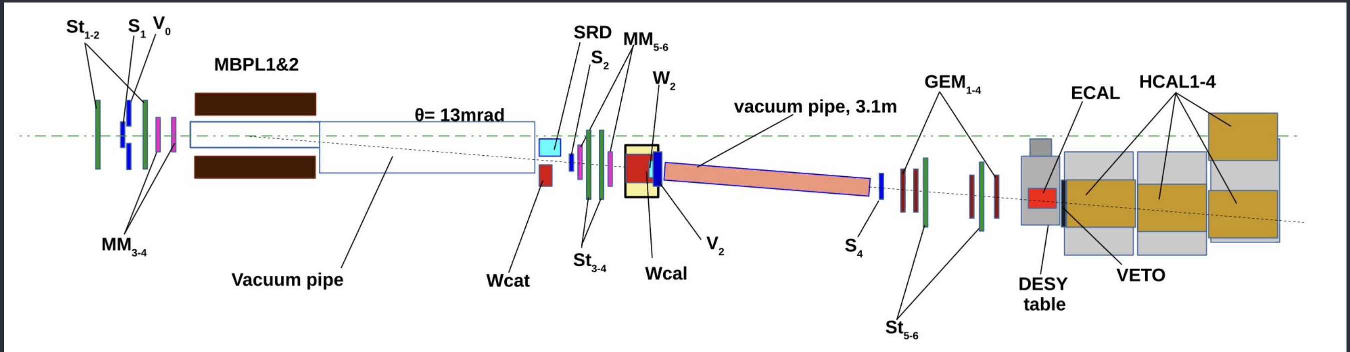
Signal signature (2018 run):

- Clean impinging e^- at nominal beam momentum
- No activity in W2 and V2 veto counters
- MIP-like signature in S4, signals in trackers
- No activity in VETO and HCAL
- Energy deposition in Wcal and ECAL, with $E_{WCAL}+E_{ECAL}=E_0$

Result from combined analysis of 2017 ($5.4\cdot10^{10}$ EOT @ 100 GeV/c) and 2018 ($3\cdot10^{10}$ EOT @ 150 GeV/c) data: no signal-like events observed in the signal region







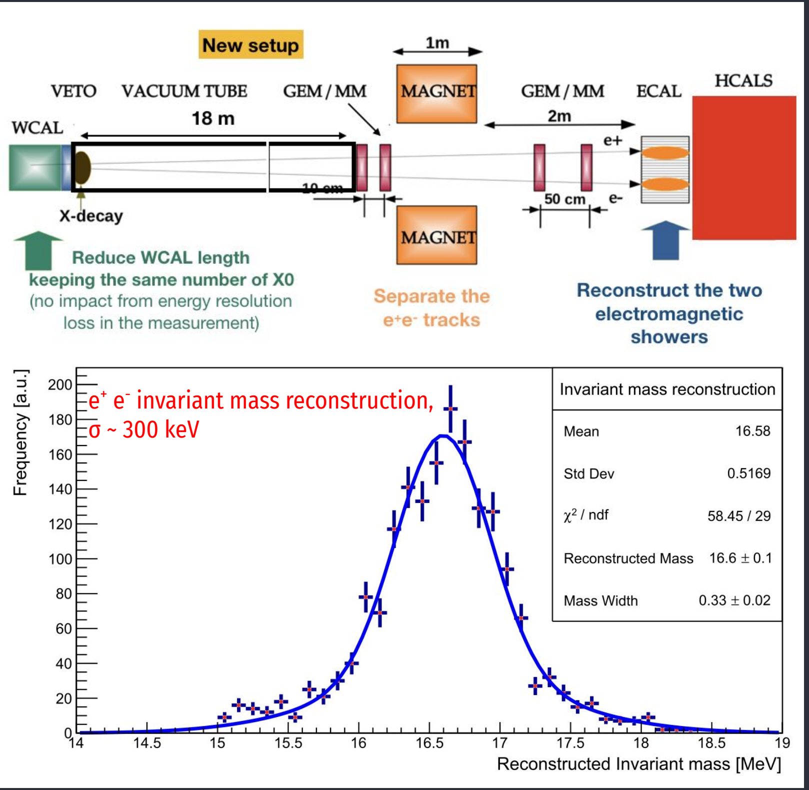
NA64e - visible A’ decay search

Future prospects for post-2023 run: improved setup with $e^+ e^-$ invariant mass reconstruction.

Detector upgrades:

- New compact tungsten calorimeter (same X_0) to measure short-leaved A’ and improve sensitivity to large ε
- New SRD optimized for 150 GeV beam energy
- New larger transverse size MM (same design as NA64μ)
- New ECAL with larger transverse dimensions (already used for 2022 and 2023 NA64e run)

With these modifications, ~ 20 days of beam time at 150 GeV/c will be required to fully scrutinize the still-unexplored X17 parameters space.



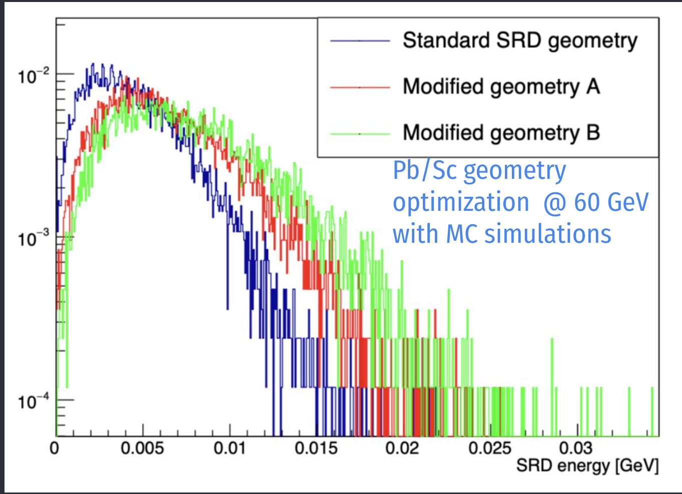
NA64e with e^+ beam

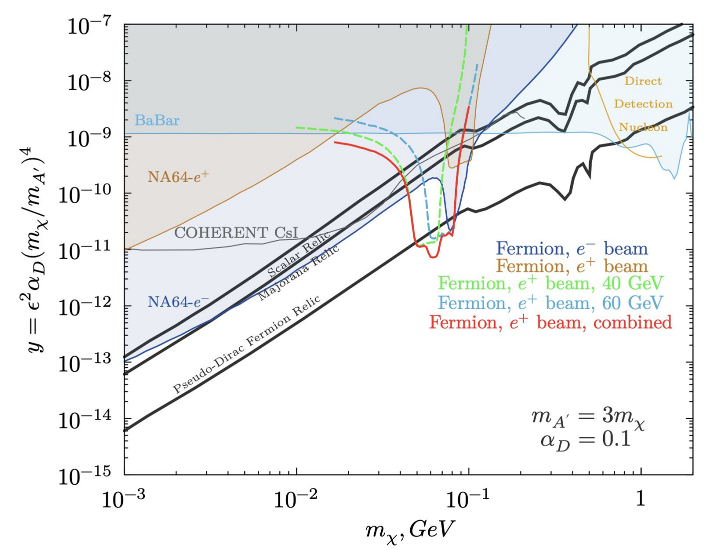
We are looking forward to start a dedicated experimental program with e^+ beam to explore the $M_{A'}$ ~ 100-300 MeV mass region exploiting the LDM resonant production mechanism via e^+e^- annihilation.

Tentative program (under study): two runs at 60 GeV and 40 GeV beam energy, 10^{11} E^+OT for each measurement.

Possible upgrades to the existing setup:

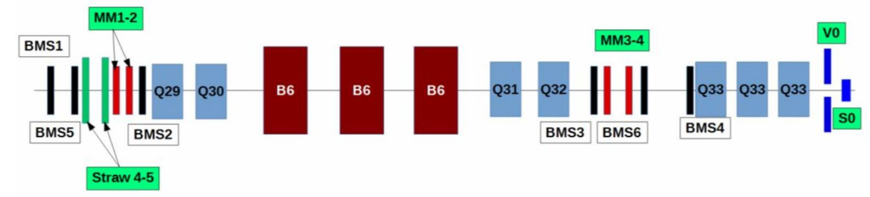
- New SRD detector to cope with lower synchrotron radiation emission (under investigation: new Pb/Sc geometry - LYSO option)
- For 40 GeV measurement, new ECAL detector with higher resolution at very low energy (under investigation: $PbWO_4$ option)



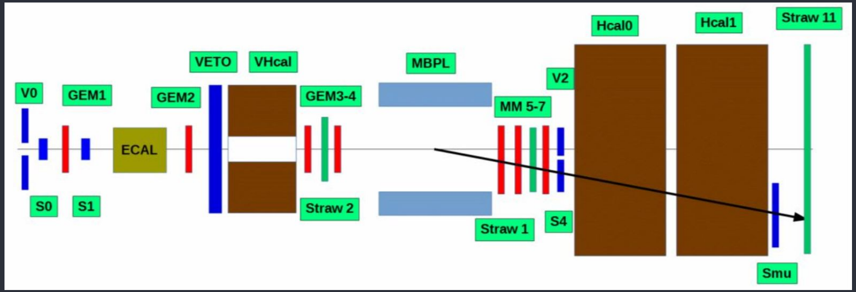


Overview of the 2021-2022 pilot runs

Upstream

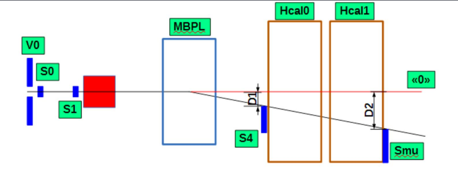


Downstream



- First pilot run in 2021 to validate the feasibility of the search method (October 27th - November 11th)
  - Total accumulated statistics ~**$3 \cdot 10^9$** muons on target (MOT) at beam intensity of 10^6 **μ**/spill
  - Study of the **beam profiles**, set-up **hermeticity** and **momenta reconstruction**, **trigger rate**, **accidentals**

- Second pilot run in 2022 (April 22nd - May 11th)
  - Total accumulated statistics (calibration runs, trigger 1+2, ECAL out, ...) ~**$4 \cdot 10^{10}$ MOT** at beam intensity of $2.8 \cdot 10^6$ **μ**/spill
  - Improvements in **trigger system** (10x10 cm^2 veto V_0 with a hole, larger counters with 42 mm diameters)
  - Additional study of the **trigger rate** with different configurations from the *zero-line* with relative efficiency of 0.02% and 0.07% of calibration configuration $S_0 x S_1 x V_0$
  - Improvements in **track-reconstruction** with more tracking chambers (+2 20x20 cm^2 Straw detectors) and Beam Momentum Stations (BMS, +6), σ/p ~ 4%
  - Validation of the detailed **M2 beam line simulations** provided by the CERN BE-EA group



/	Trigger1	Trigger 2
S_4 [mm]	-65	-65
S_μ [mm]	-152	-117