Search for Dark Matter at NA62 and NA64 experiments

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Search for DM at NA62

NA62 experiment

NA62: fixed target experiment at CERN SPS

Technique:
Kaon decays in flight

Timeline:
- 2015: commissioning
- 2016-2018: physics runs

- 2021-2025: physics runs

Primary goal:
Measure BR($K^+ \to \pi^+ \nu\nu$)

ECN3 hall at CERN

NA62 collaboration: ~300 participants, ~30 institutions

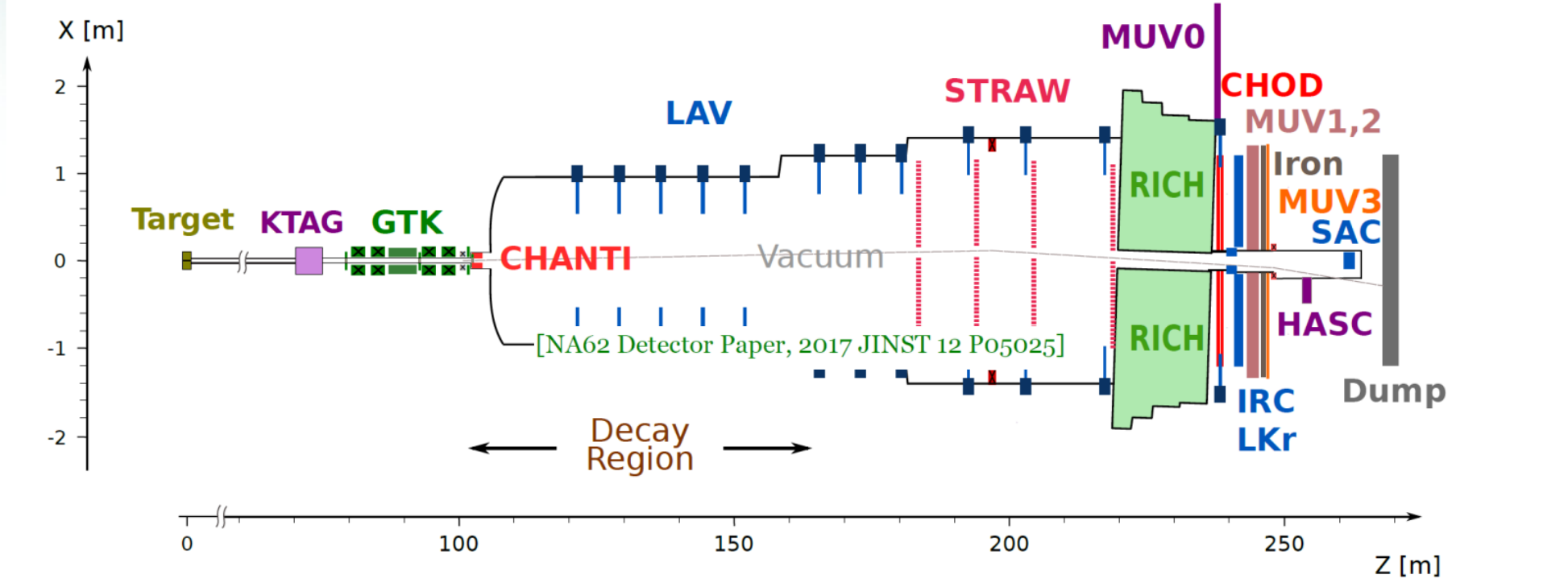
NA62 recent results

- $K^+ \to \pi^+ \nu \nu$ JHEP 06 (2021) 93; JHEP 03 (2021) 58
- Precision measurements
  - $K^+ \to \pi^+ \mu^+ \mu^-$ JHEP 11 (2022) 011
  - $K^+ \to \pi^+ \gamma \gamma$ Paper in preparation
- LFV/LNV decays
  - $K^+ \to \pi \mu e$ PRL 127 (2021) 131802
  - $K^+ \to \pi^- l^+ l^+$ PLB797 (2019) 134794; PLB830 (2022) 137172
  - $K^+ \to \pi^- \pi^0 e^+ e^+$ PLB830 (2022) 137172
  - $K^+ \to \mu^- \nu e^+ e^+$ PLB838 (2022) 137679
- Beam dump searches for DM
  - $A' \to \mu^+ \mu^-$ arXiv: 2303.08666
  - $A' \to e^+ e^-$ new

This talk

NA62 experimental setup

[NA62 Detector Paper, 2017 JINST 12 P05025]

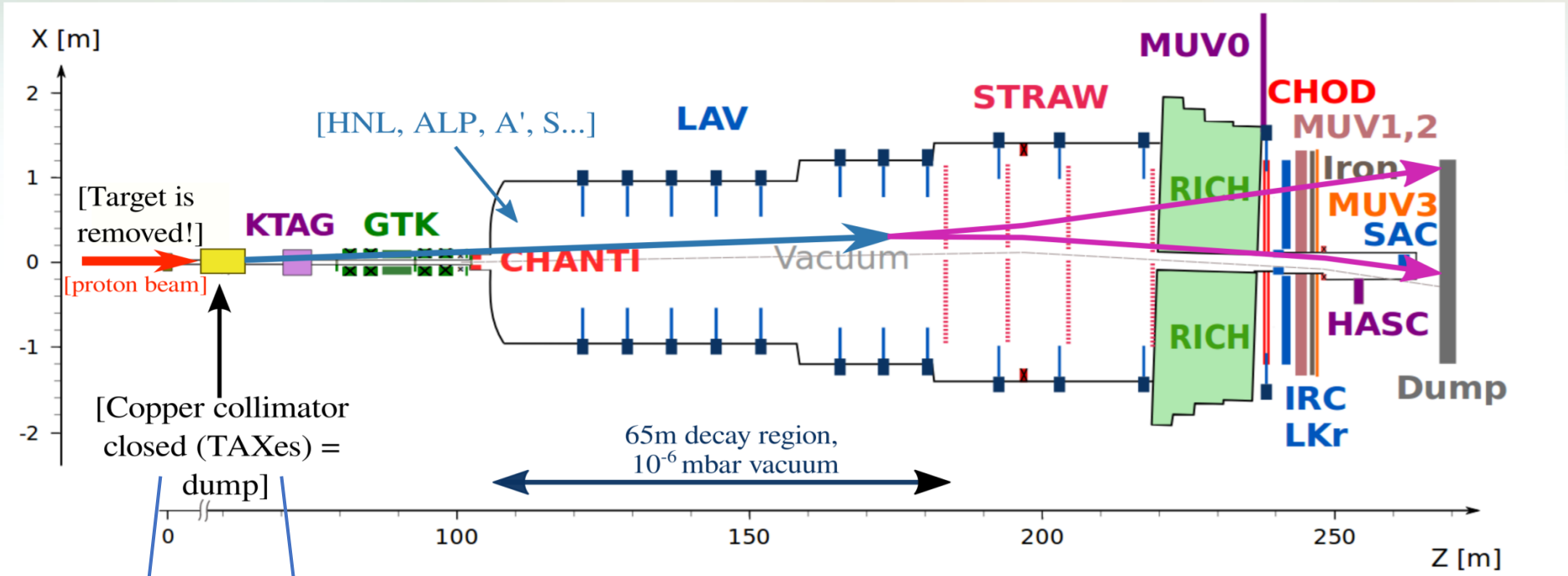


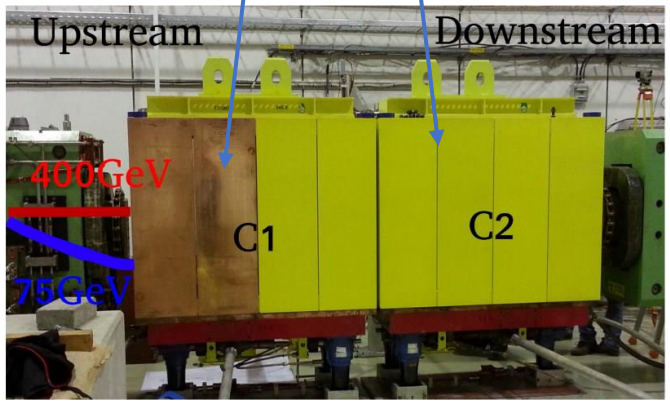
Primary beam:
- 400 GeV/c protons
- 3×10^{12} protons per spill

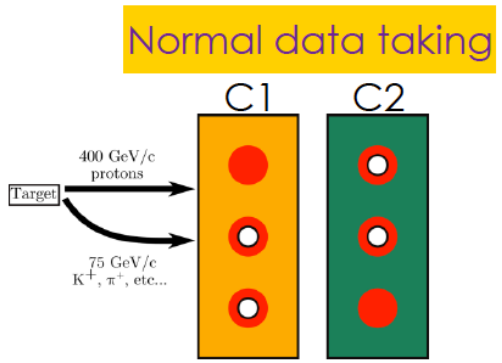
Secondary beam:
- 75 GeV/c (±1%)
- Divergency < 100 μrad
- 70% pions, **6% K^+**, 24% protons

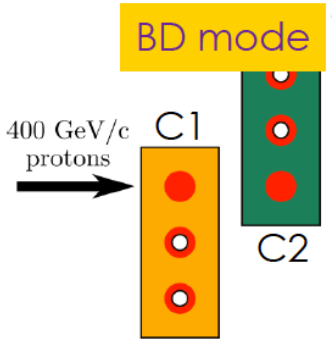
Key detectors:
- PID: KTAG, RICH, LKr, MUV1-2, MUV3
- Momentum: GTK, STRAW
- Time: GTK, KTAG, RICH, CHOD
- Photon veto: LAV, LKr, IRC, SAC

NA62 in beam dump mode

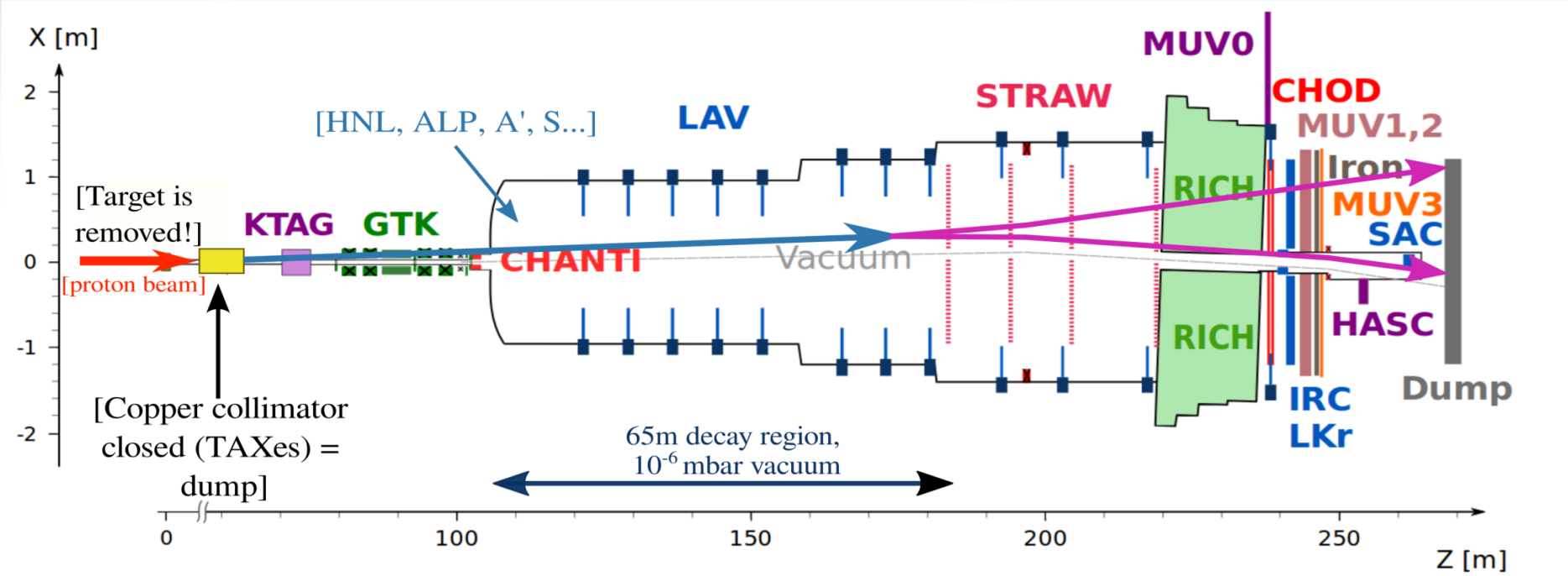








NA62 in beam dump mode



Beam dump prerequisites

- Beam line optimized in 2021 (improved sweeping, higher intensity)
- single and 2-track trigger based on CHOD
- Control trigger based on LKr

2021 run

- 10 days in beam dump mode
- 3.2 m Cu-Fe collimators (TAXes) used as target
- $(1.40 \pm 0.28) \times 10^{17}$ POT collected

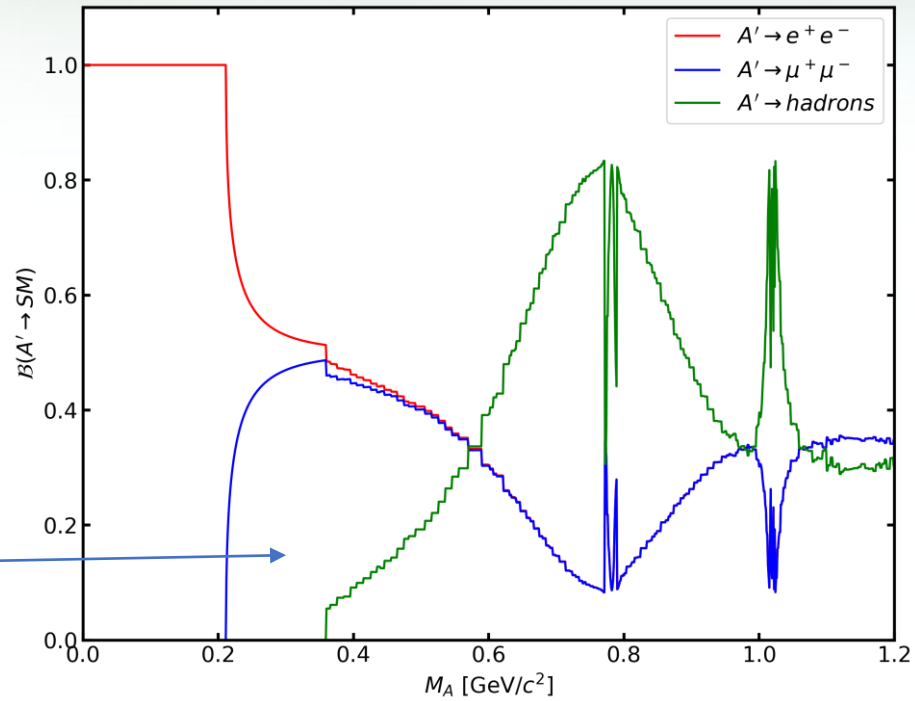
DM searches @ NA62

Dark sector portals and mediators

- Vector portal → dark photon
- Scalar portal → dark scalar
- Neutrino portal → HNL
- Axion portal → ALP

Dark photon (DP)

- New vector field $F'_{\mu\nu}$ feebly interacting with SM fields
- Kinetic mixing with the SM hypercharge $B_{\mu\nu}$ $\quad \mathcal{L} \supset -\epsilon \frac{1}{2cos\theta_W} F'_{\mu\nu} B_{\mu\nu}$
- Could decay to SM particles
- m < 600 MeV: decays to leptons dominate



DP searches @ NA62

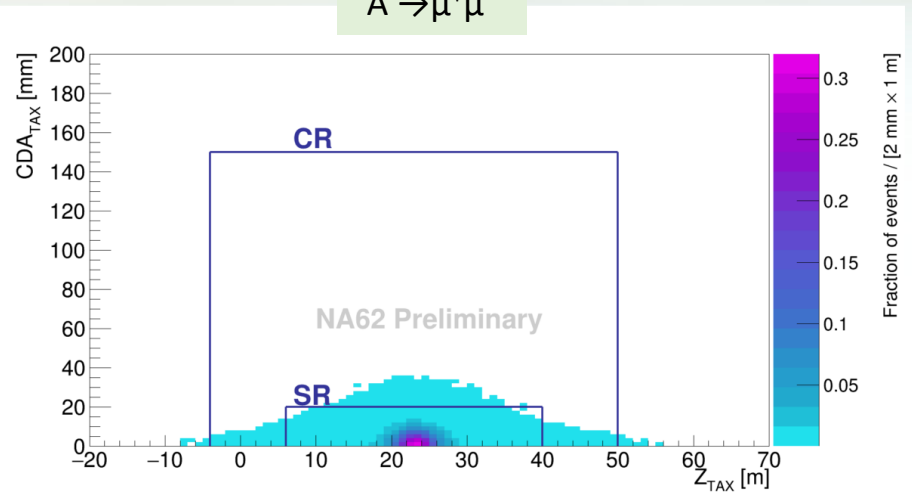
- DP produced in beam-TAX interactions (bremsstrahlung, decays of secondary mesons)
- **Search for DP in decays to a lepton pair**
- Two free parameters: mass and coupling ε
- Sensitive to **m < 600 MeV** (where decays to leptons dominate)

Dark photon search in A'→$\mu^+\mu^-$ and A'→e^+e^-

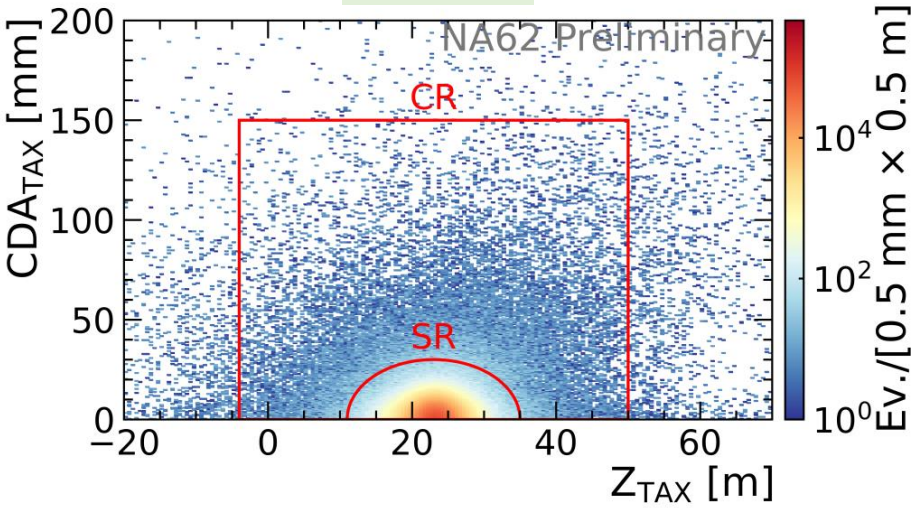
Analysis strategy

- Lepton-antilepton vertex in the NA62 decay region
- Dilepton momentum pointing back to taxes
- Kinematic variables: Z_{tax} and CDA_{tax}
- CDA_{tax}: closest distance of approach between beam and dimuon direction, σ_{CDA} = 7 mm
- Z_{tax}: Z coordinate of the beam-TAX interaction vertex (calculated using CDA), σ_Z = 5.5 m
- Signal region for A'→$\mu^+\mu^-$: 6 < Z_{tax} < 40 m & CDA_{tax} < 20 mm
- Signal region for A'→e^+e^- : ellipse centered around Z_{tax} = 23 m & CDA_{tax} = 0 mm

A'→$\mu^+\mu^-$



A'→e^+e^-



Expected DP yield

$$N_{exp} = \mathrm{POT} \times \chi(pp \to A') \times \mathrm{BR}(A' \to \mu\mu) \times P_{rd}(\epsilon) \times A_{acc} \times A_{trig}$$

- POT = (1.40 ± 0.28) x 10^{17}
- $\chi(pp \to A')$: DP production probability
- $\mathrm{BR}(A' \to \mu\mu)$: DP decay branching fraction
- $P_{rd}(\epsilon)$: probability to reach the NA62 decay volume and decay there
- A_{acc} : signal selection efficiency
- A_{trig} : trigger efficiency

Background studies

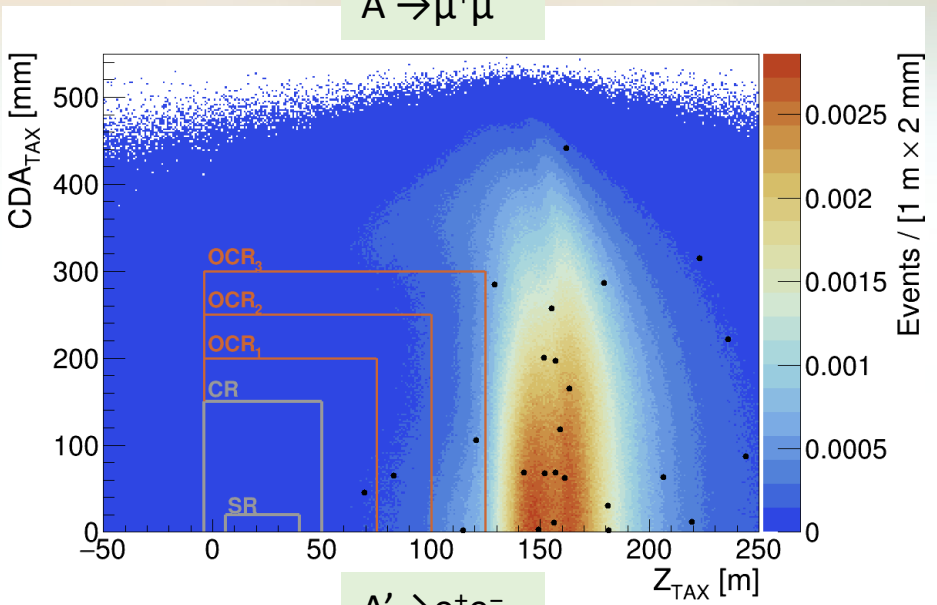
Combinatorial bkg

- Two uncorrelated “halo” muons
- Dominant for A’→μ⁺μ⁻

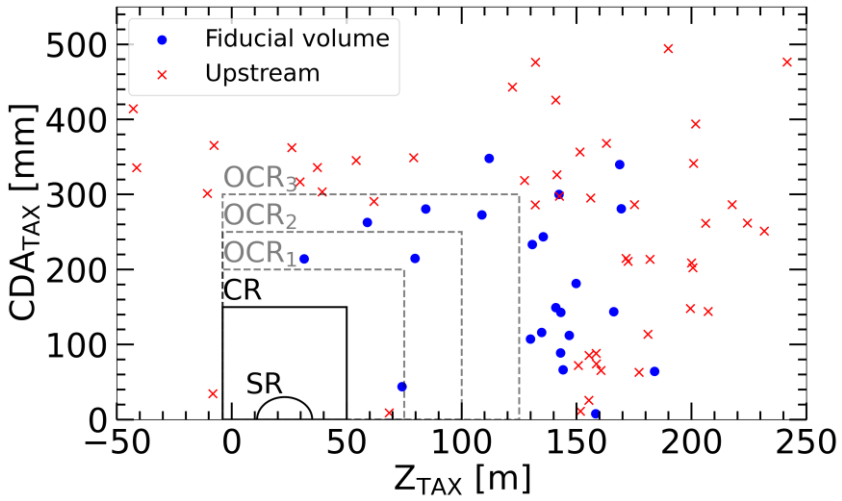
Prompt bkg

- Secondaries of a muon interaction with the traversed material
- Dominant for A’→e⁺e⁻

A’→μ⁺μ⁻



A’→e⁺e⁻



Expected bkg for A’→μ⁺μ⁻

	Combinatorial	Prompt@90% CL	Upstream prompt@ 90%CL
CR	0.17 ± 0.02	< 0.033	< 0.052
SR	0.016 ± 0.002	< 0.003	< 0.005

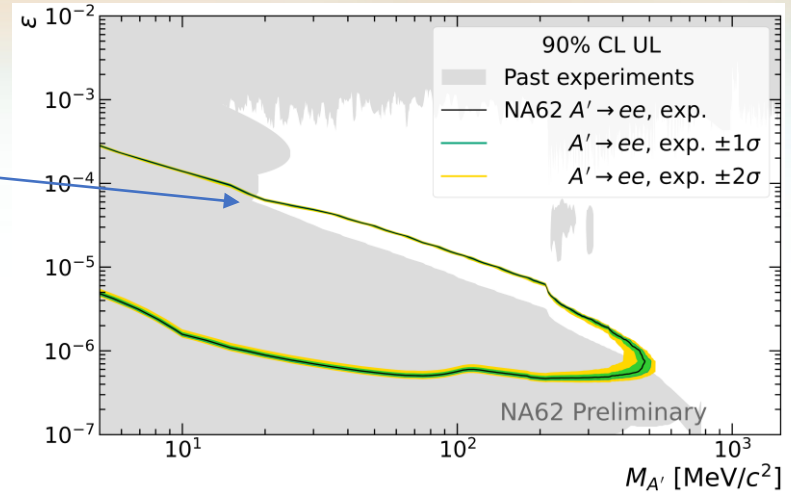
Expected bkg for A’→e⁺e⁻

$$N_{bkg}^{CR} = 0.0097^{+0.049}_{-0.009} \; @ \; 90\% \; CL$$
$$N_{bkg}^{SR} = 0.0094^{+0.049}_{-0.009} \; @ \; 90\% \; CL$$

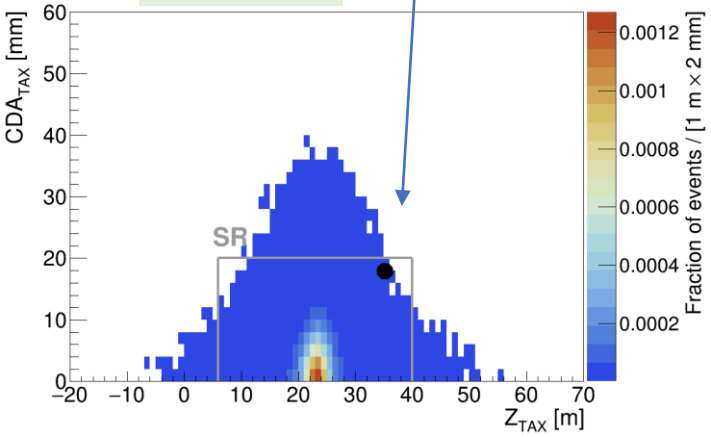
Results on DP search in A'→l^+l^-

A'→e^+e^- : N_{obs} = 0

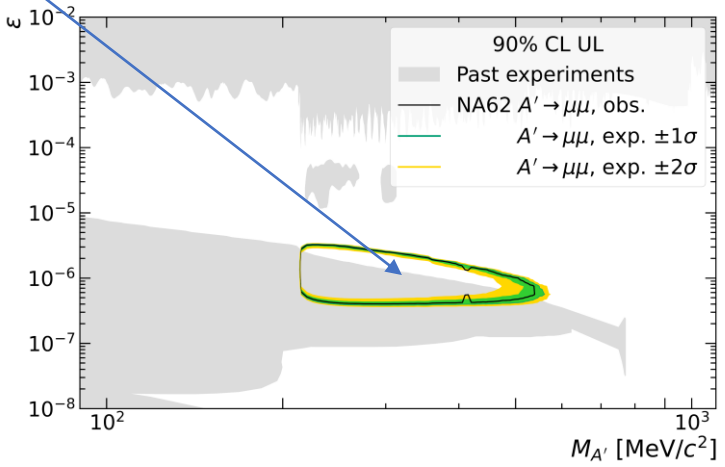
A'→$\mu^+\mu^-$: N_{obs} = 1 (2.4σ significance)

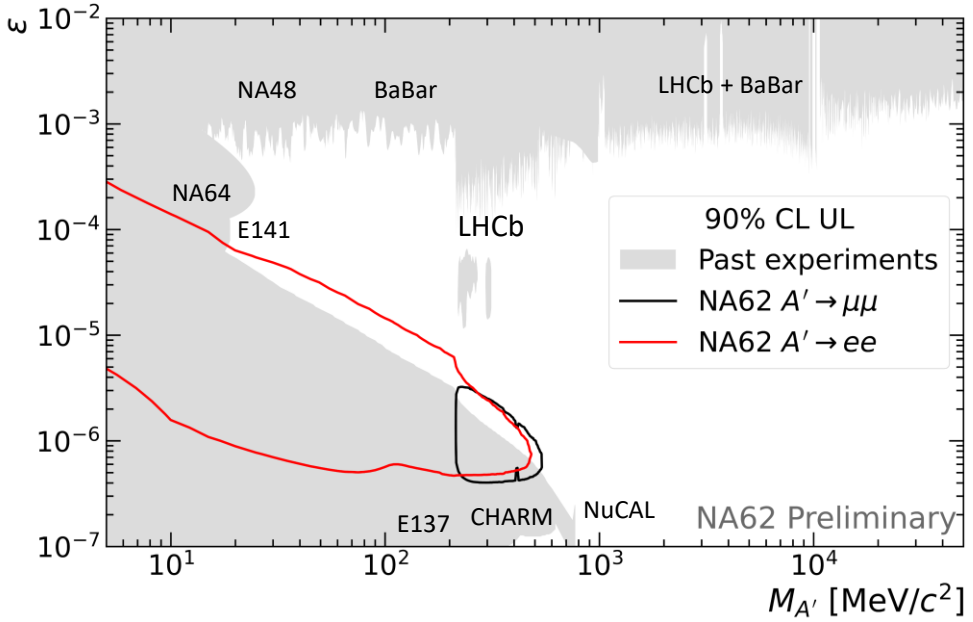


A'→$\mu^+\mu^-$



arXiv: 2303.08666





a→ $\mu^+\mu^-$

- ALP interpretation also possible
- See spare slides

Conclusions (NA62)

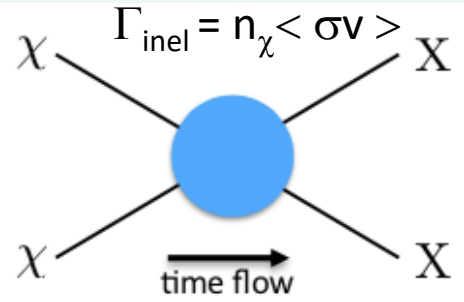
- NA62 collected (1.40 ± 0.28) x 10^{17} POT in the beam dump mode in 2021
- Dark photon search performed in $A' \to \mu^+\mu^-$ and $A' \to e^+e^-$ decays arXiv: 2303.08666
- Obtained upper limits exclude new regions in the (ε, m) parameter space

Future plans

- 2021 data analysis: search for exotic particles decaying to ($\gamma\,\gamma$), ($\pi^+\,\pi^-\,\gamma$) states
- Collect 10^{18} POT in 2022-2025

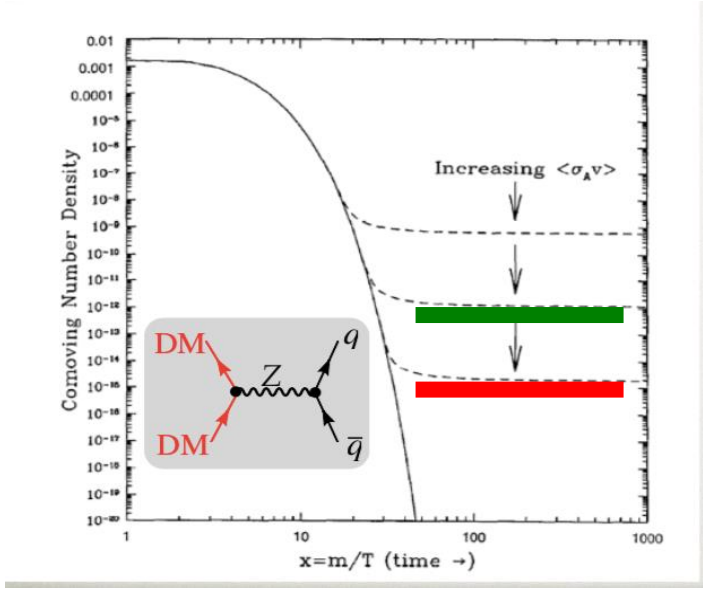
Search for DM at NA64

Light Thermal Dark Matter (m_χ << 100 GeV)



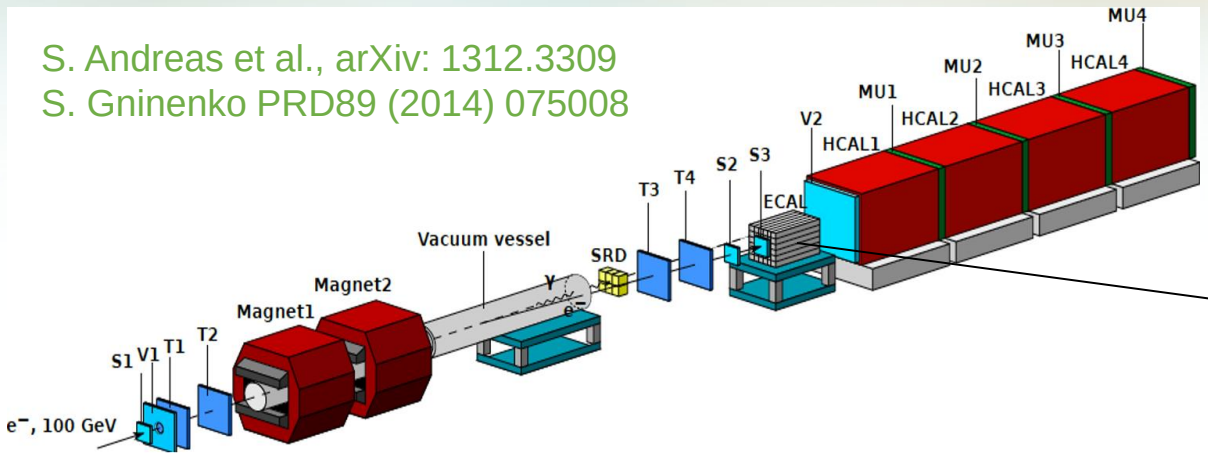
Dark Matter freeze out

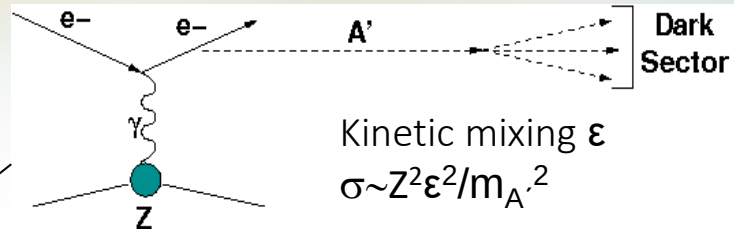
- Cross section of $\chi\chi \leftrightarrow$SM reactions: $\sigma v \sim [\alpha_D\, \varepsilon^2 (m_\chi/m_{A'})^4]\, \alpha/m_\chi^2$
- For $T >> m_\chi$, $\chi\chi \rightarrow$SM and SM$\rightarrow\chi\chi$ are in equilibrium, $n_\chi \sim T^3$
- Hubble expansion, T & n_χ decrease
- For $T < m_\chi$ SM$\rightarrow\chi\chi$ gets kinematically suppressed, $n_\chi \sim T^{3/2} e^{-m\chi/T}$
- Finally $\chi\chi \rightarrow$SM annihilation stops when $\Gamma_{inel} = n_\chi < \sigma v > < \sim H$, n_χ~ frozen in time
- DM abundance: $\rho_\chi \sim 1/<\sigma v> \sim m^2_\chi/g^4_\chi$; $< \sigma v > \cong 3\text{x}10^{-26}$ cm^3/s $\cong$ (1/20 TeV)^2
- Thermal freeze-out motivates new interaction to mediate DM$\leftrightarrow$SM annihilation. New force in addition to gravity is required!
- Dark Matter χ can be: Scalar, Majorana, Pseudo Dirac



NA64: search for A´→invisible decays at CERN SPS

S. Andreas et al., arXiv: 1312.3309
S. Gninenko PRD89 (2014) 075008





DP production @ NA64
- A' emission in the em shower development
- Annihilation production also possible: e^+e^-→ A´→ χχ

Main components :
- clean 100 GeV e^- beam
- e^- tagging system: MS+SRD
- hermetic ECAL+HCAL
- Signal rate: $N_{evt} \sim \varepsilon^2$(beam-dump: ε^4)

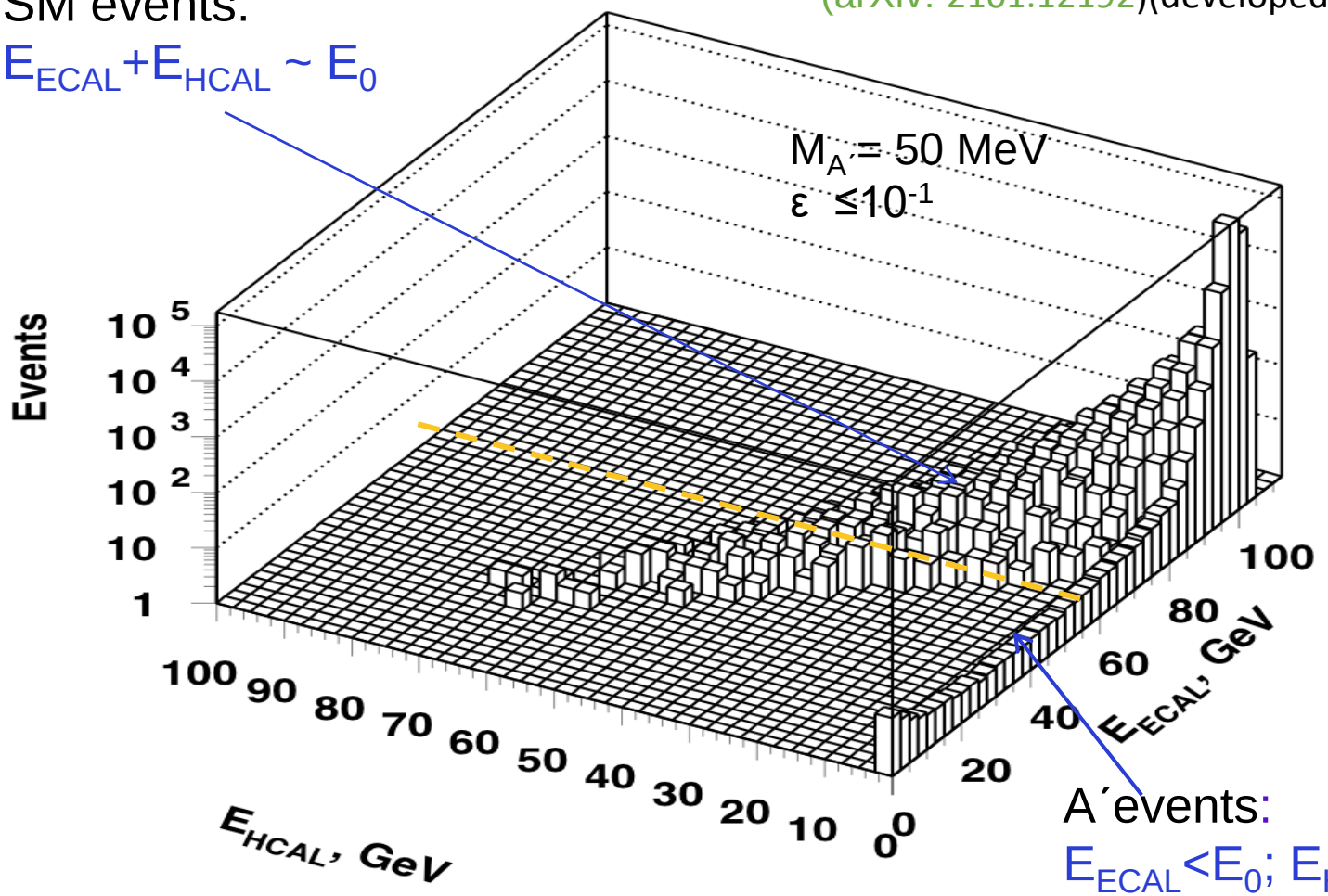
Signal signature:
- in: 100 GeV e^- track
- out: $E_{ECAL} < E_0$ shower in ECAL
- no energy in Veto and HCAL

Background:
- μ, π, K decays in flight
- upstream interactions
- Tail < 50 GeV in the e^- beam spectrum
- Energy leak from ECAL+HCAL

Simulation of eZ→eZA´; A´→ invisible & bkg

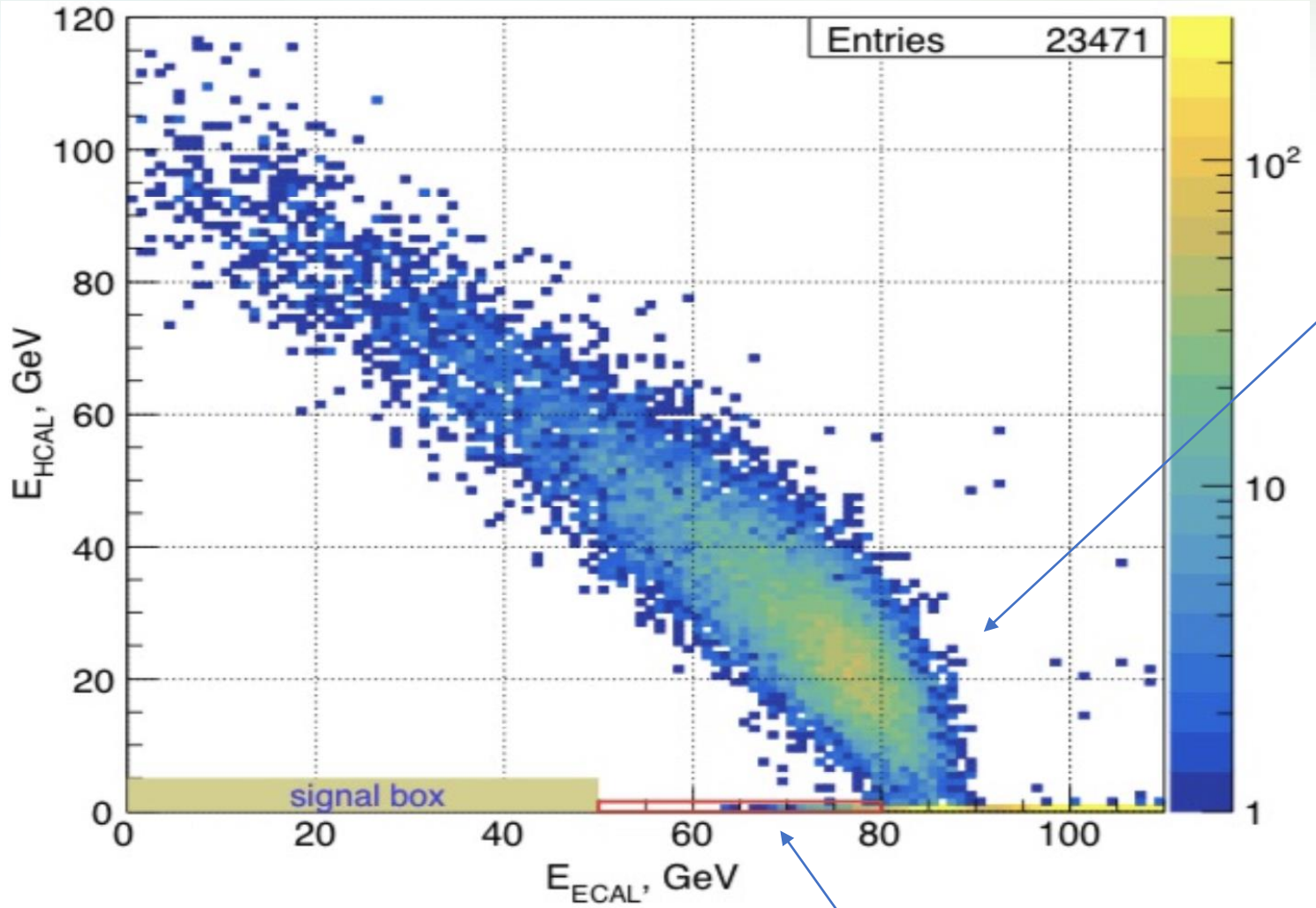
A´emission in the process of e-m shower development.
Simulated by universal G4 compatible package DMG4 (arXiv: 2101.12192)(developed by collaboration members)

SM events:
$E_{ECAL}+E_{HCAL} \sim E_0$



A´events:
$E_{ECAL}<E_0$; $E_{HCAL}=0$

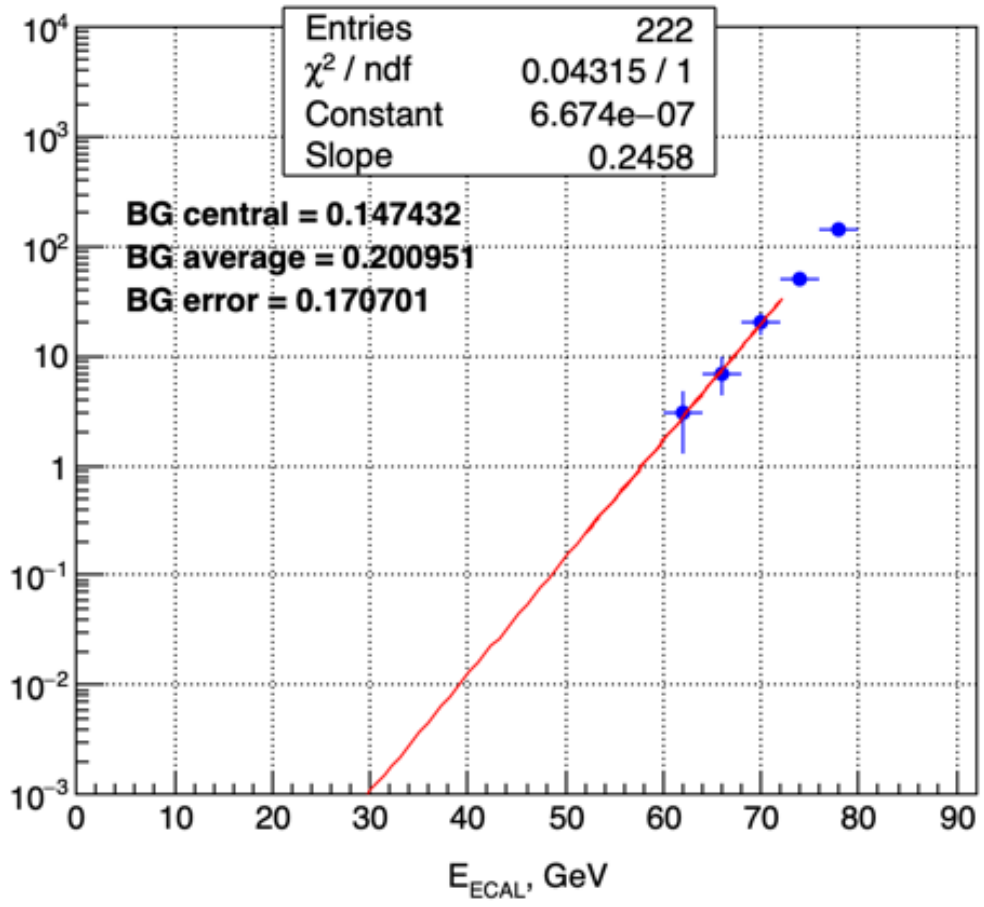
2D plot, part of data 2022



The peak at E_{ECAL} ~100 GeV
is cut off by trigger: threshold ~85 GeV

Control region for bkg evaluation

Backgrounds and example of extrapolation



Main backgrounds:

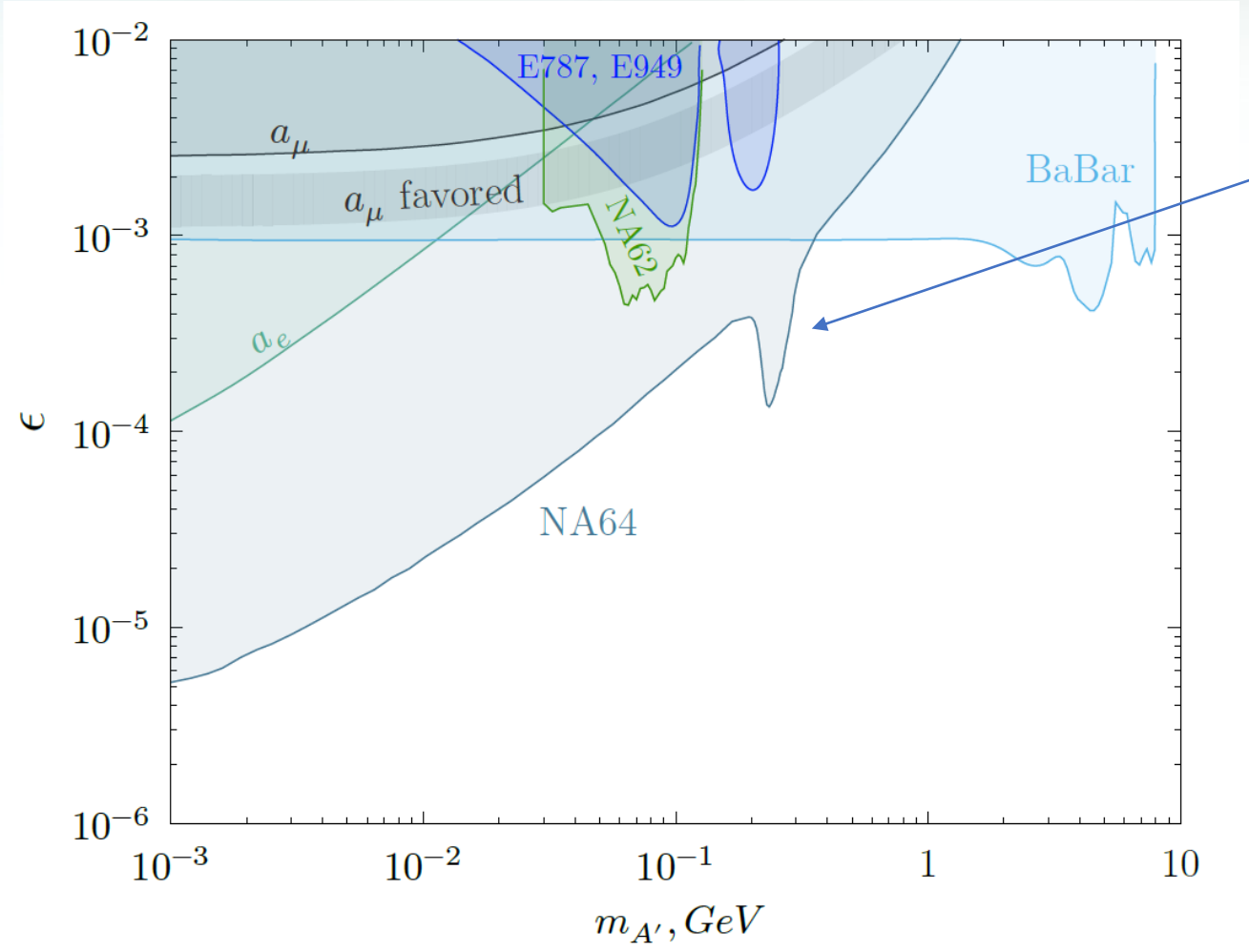
- e^- interactions in the beam line, (mainly neutral component), predicted from data with extrapolation
- Decays of muons misidentified by SRD

- bkg from the interaction with beam elements is suppressed by multiplicity cuts in MM and Straw tubes

Total expected bkg: <1 event

Unblinding: $N_{obs} = 0$

Results on A’ search, 2016 – 2022 data

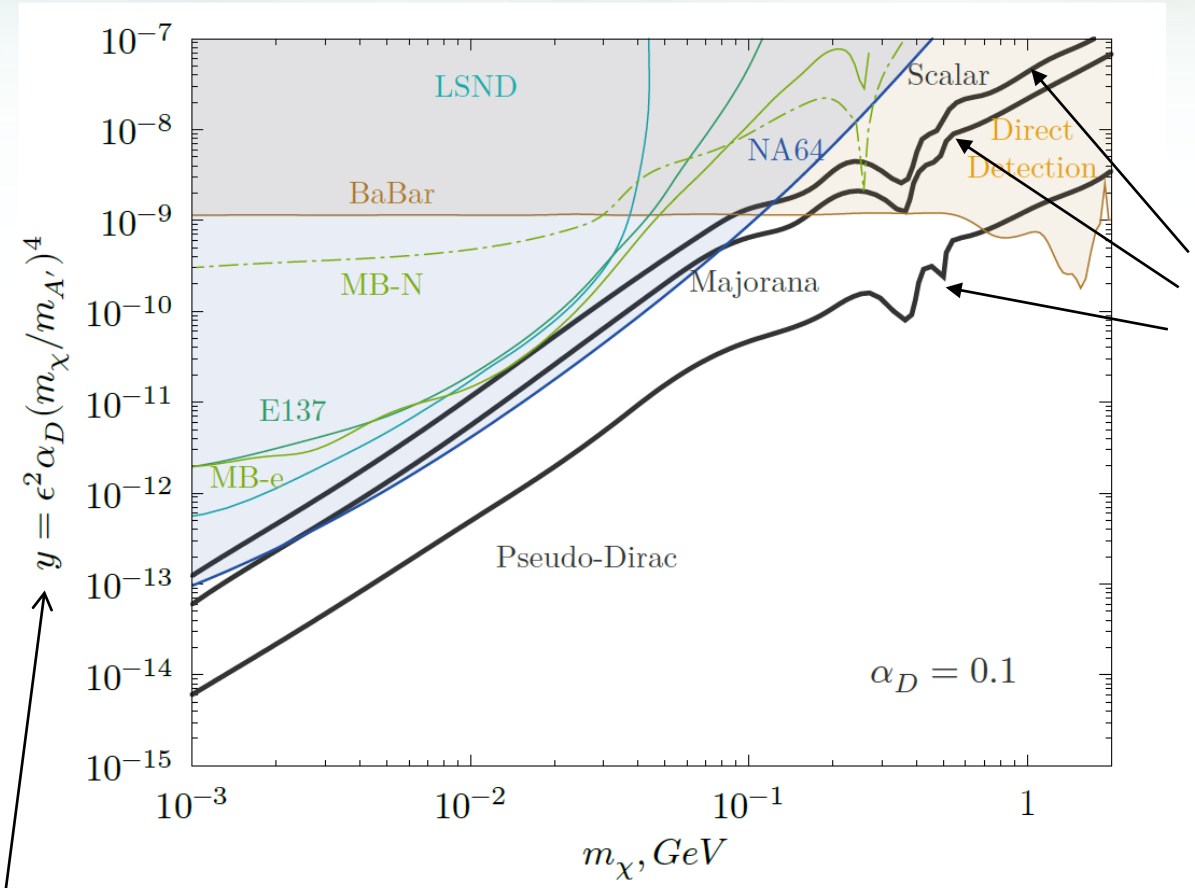


Bump at ~250 MeV is from e^+e^- annihilation contribution

- e^+ from em shower, e^- from the ECAL matter
- Shown for $\alpha_D = 0.1$ (preliminary)
- Possible enhancement: positron beam (POKER project)

Limits on Thermal Dark Matter, 2016-2022 data

Limits without e^+e^- annihilation contribution



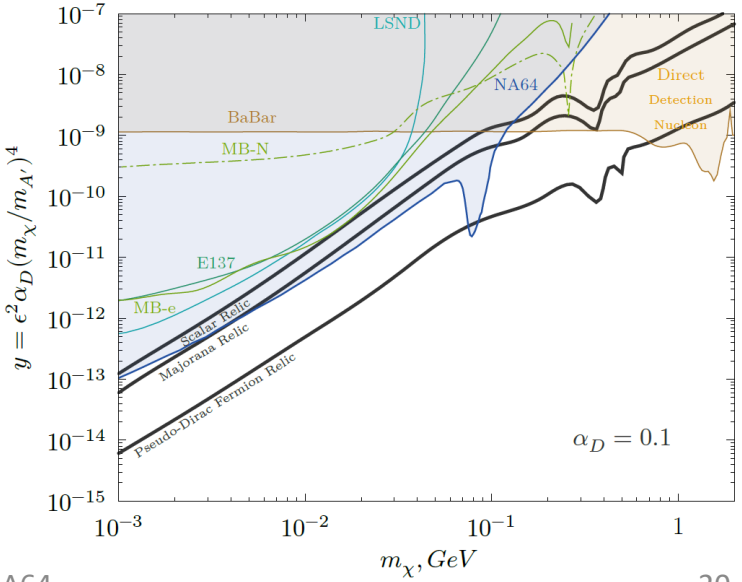
predictions from subGeV TDM models

factor in the DM<->SM annihilation cross section

Theory assumptions

- $\alpha_D = 0.1$, $m_{A'} = 3m_\chi$
- Less strict limits for $\alpha_D > 0.1$

Limits with e^+e^- annihilation contribution (preliminary)



NA64: world leader in sensitivity

First probes in the TDM region $m_\chi < 0.1$ GeV

Conclusions (NA64)

- The NA64 produced several important results in the search for light Dark Matter (m < 1 GeV) coupled to electrons. For example, the explanation of the $(g-2)_\mu$ anomaly by light A' is excluded (NA64+BaBar) PRL 123, 121801 (2019)
- New results probe the TDM region for m_χ < 100 MeV
- Searches for other FIP (Feebly Interacting Particles) performed: Axion-Like particles (ALP), X boson decaying to e^+e^-, light Z' of the B-L models PRD 101 (2020) 071101 PRL 125, 081801 (2020) PRD 104 (2021) L111102

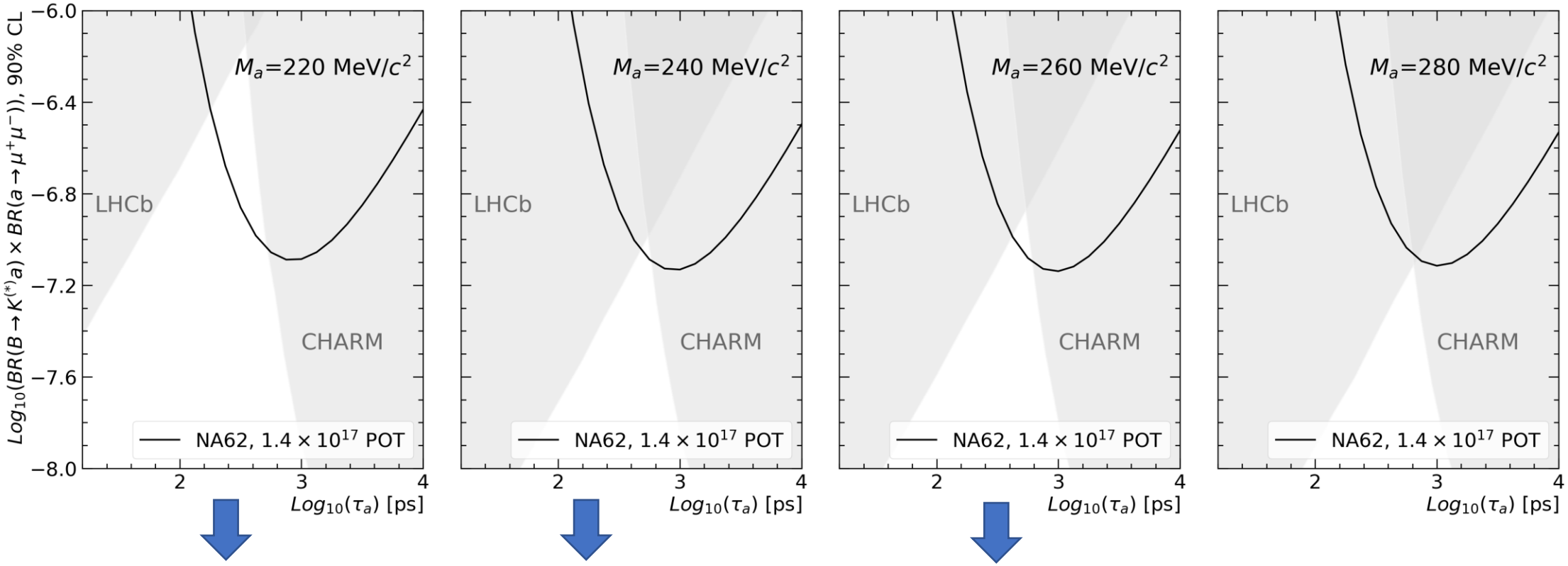
Future plans

- Data taking ongoing, plan to maximally cover TDM regions
- The NA64μ experiment at the CERN muon beam M2 started in 2021 (search for A' and light Z' of the $L_\mu - L_\tau$ model => remaining possibility to explain $(g-2)_\mu$ anomaly). Obtained data analysis in progress, run in 2023 is planned
- Searches for invisible decays of η, η', K^0 produced in charge exchange reaction in the hadron beam, limited pilot run in 2022, data are being analysed

Spare (NA62)

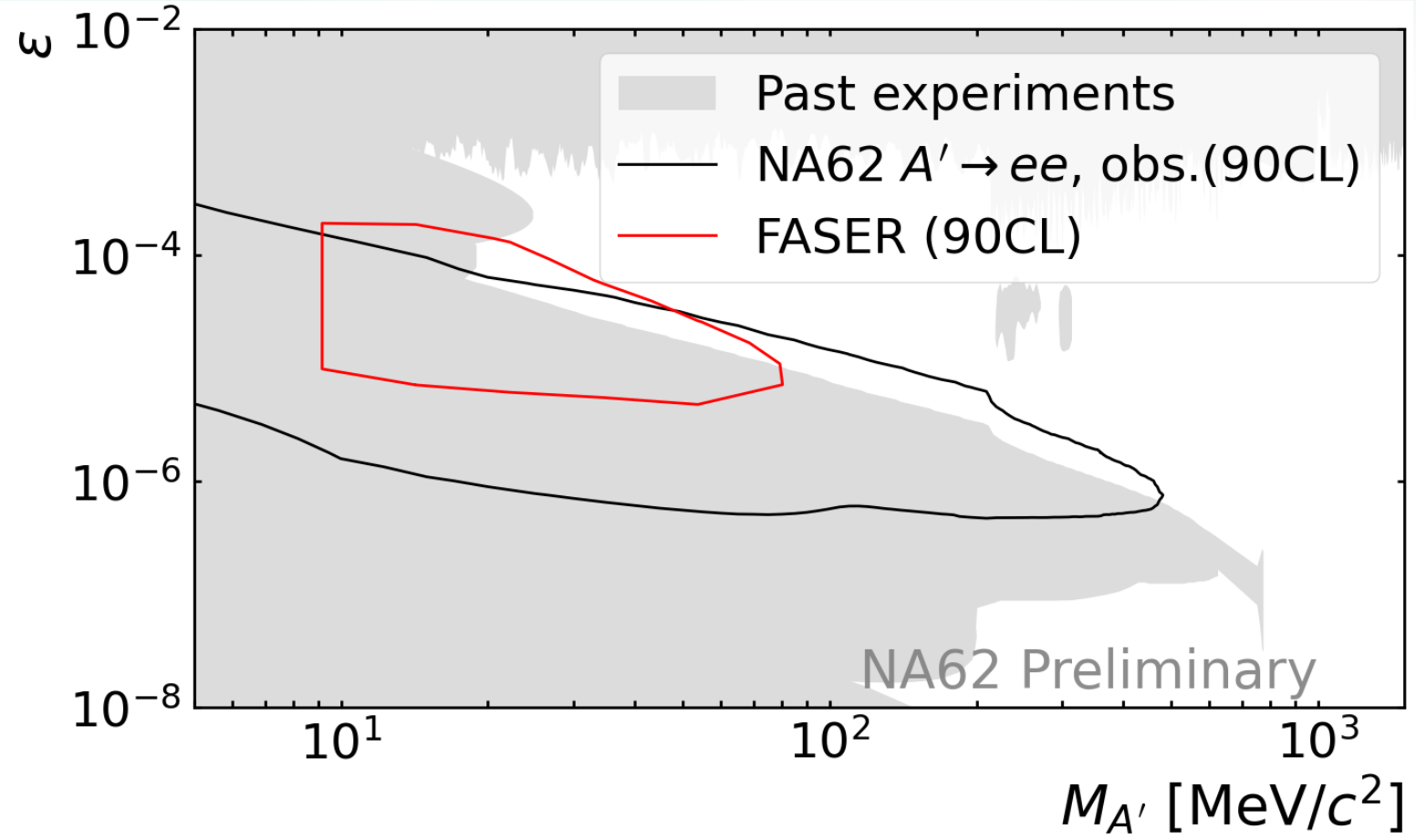
ALP interpretation of $a \to \mu^+ \mu^-$

- a: (pseudo)scalar produced in B decays
- free parameters: m, τ, coupling
- Set model-independent UL on BR(B→K a)xBR(a→$\mu^+\mu^-$) for each (m, τ) combination



Limits of previous experiments extended for m < 280 MeV

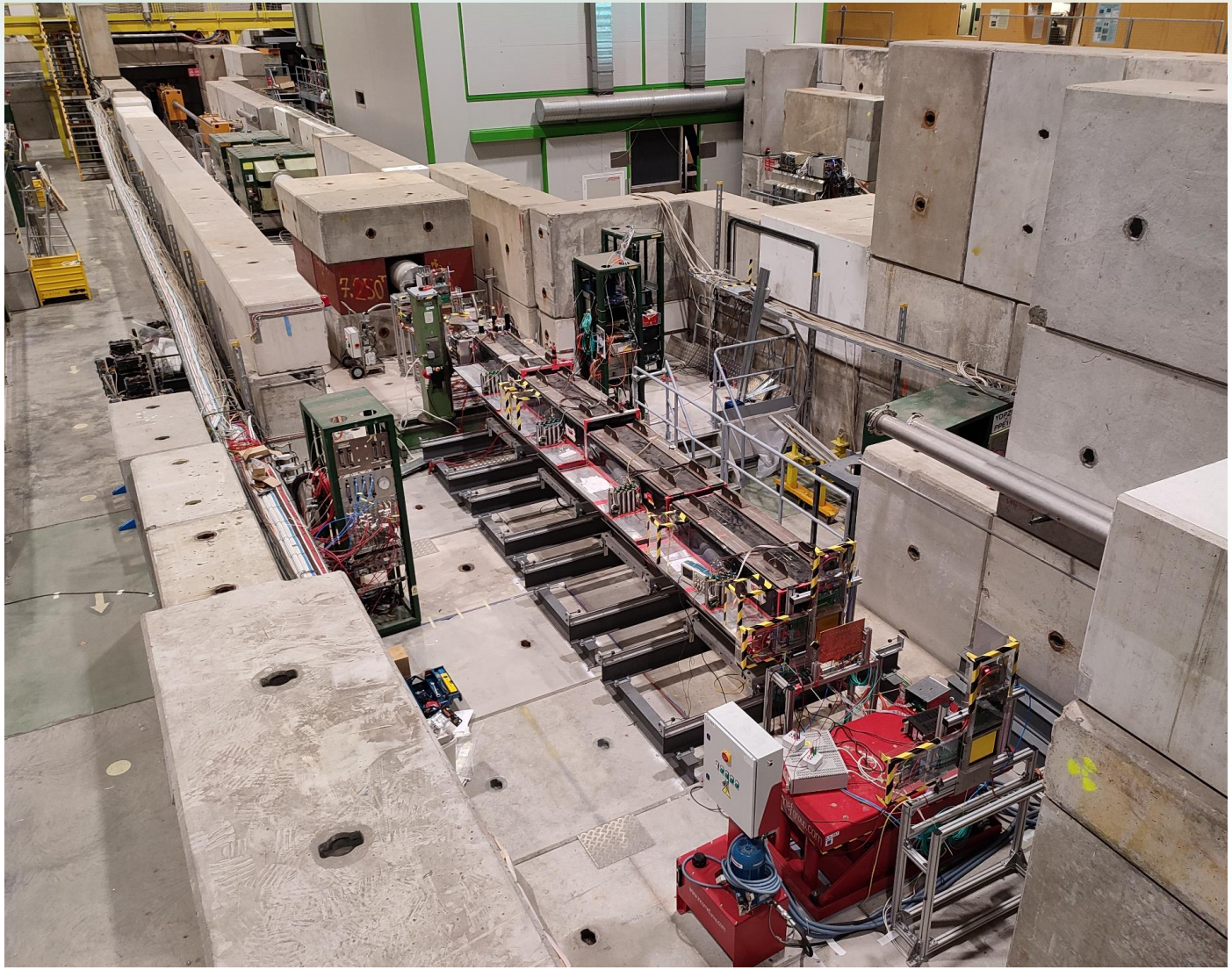
NA62 and FASER



- FASER more sensitive for m < 50 MeV
- NA62 more sensitive for higher m

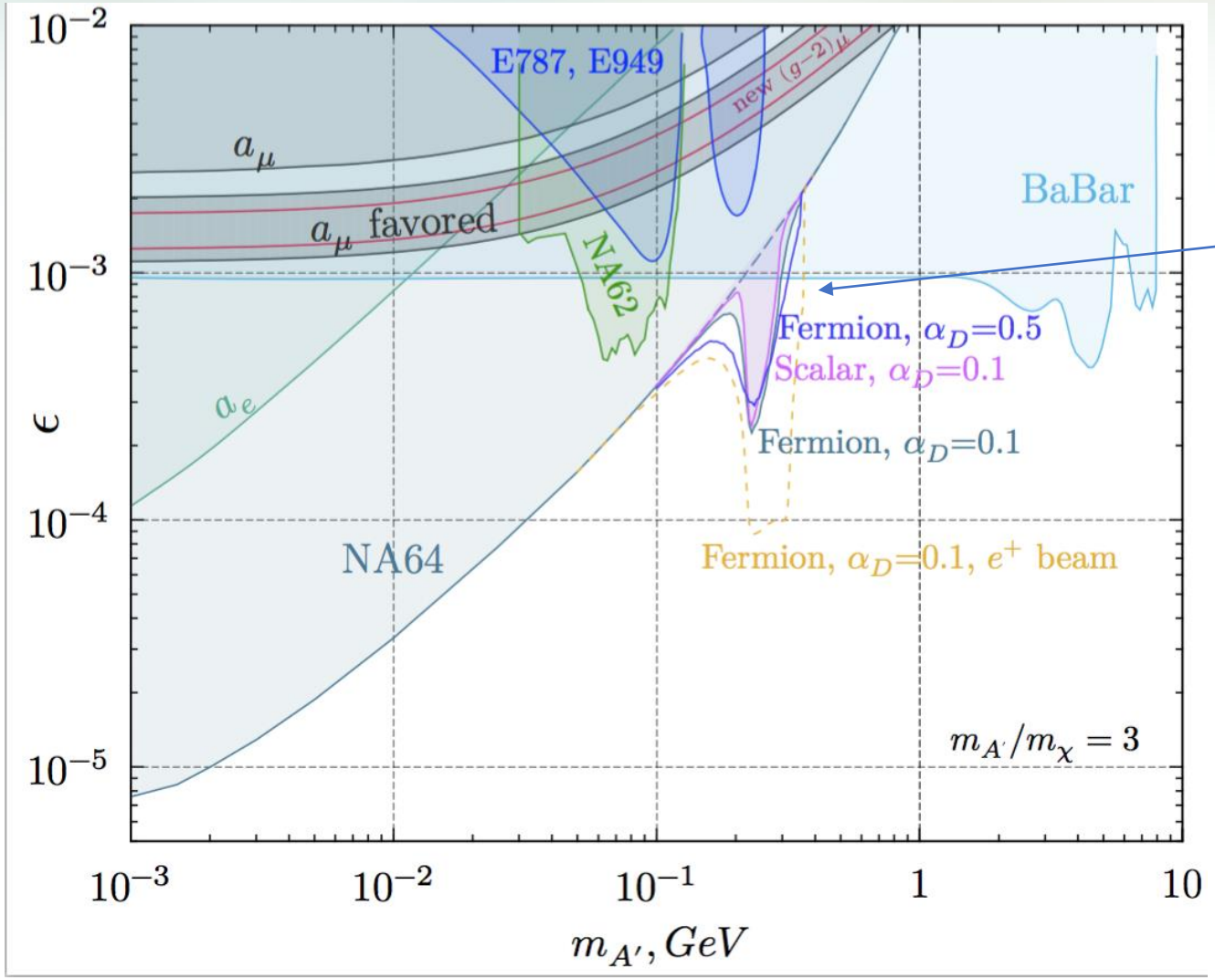
Spare (NA64)

NA64 in 2021-2022



- Permanent place@ H4 beamline prepared by the CERN beam division

NA64 published results



Banerjee et. al.
PRL 123, 121801 (2019)

Resonant e^+e^- annihilation added:
shower positrons on
electrons of the target
$e^+e^- \rightarrow A' \rightarrow \chi\chi$
Phys. Rev. D 104, L091701 (2021)

Future plans:

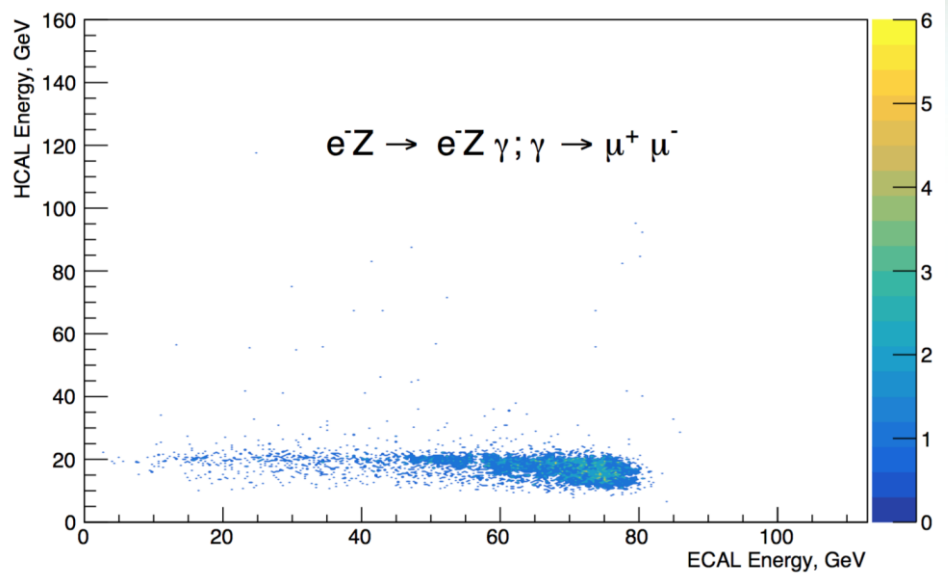
- Larger sensitivity region

can be obtained with a positron beam

Dimuon production as a reference process

reference process: gamma conversion to muons

- rather rare
- many similarities with the signal
- O(10^4) dimuon pairs with both muons reaching all HCAL modules collected in 2016

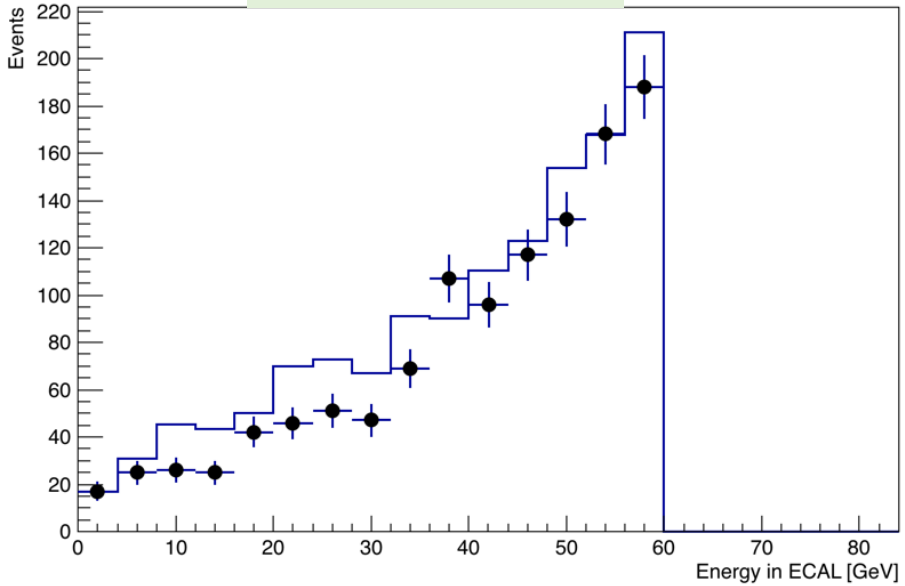


Simulation

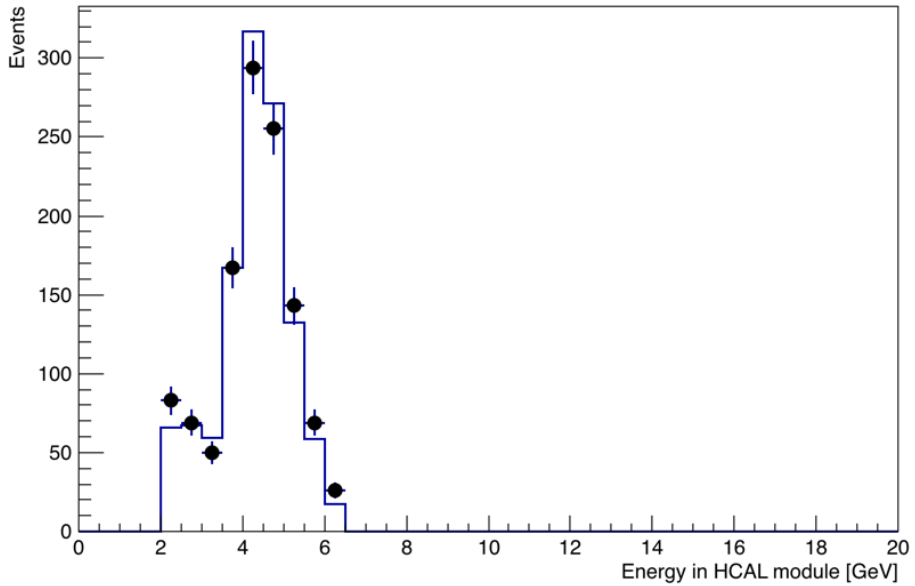
- The process is available in GEANT4, off by default
- cross section in GEANT4 increased by a factor of 200 in order to have good statistics with reasonable CPU time.
- Reasonable Data/MC agreement observed

Dimuon reconstruction

E_{ECAL} for dimuons



E_{HCAL} (module 3) for dimuons



Left plot: number of dimuons in DATA/MC ~0.92, slightly smaller at high intensity -> efficiency correction

Dimuon selection:

- $E_{ECAL} < 60$ GeV
- $2.5 < E_{HCAL1} < 6.35$ GeV
- $2 < E_{HCAL3} < 6.35$ GeV

NA64μ

NA64μ experiment

- started in 2021 at the CERN muon beam M2

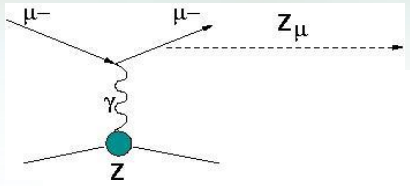
Goals

- obtain more direct answer to the question about the $(g-2)_\mu$ explanation by Dark Matter (search for light Z' of the $L_\mu - L_\tau$ model)
- improve sensitivity to A' for the masses > 100 MeV

Search for Z_μ in missing energy events on M2 beam

Motivated by $(g-2)_\mu$ measurements

Proposal NA64μ (2019)



Main components :

- 100-160 GeV μ- beam, $I_\mu \sim 10^7 \mu$/spill.
- in μ tagging: BMS+MS1(MBPL+tracker)
- out μ tagging: MS2 (2MBPL+tracker)
- 4π fully hermetic ECAL+Veto+ HCAL

Signature:

- in: 160 GeV μ^- track
- out: < 80 GeV μ^- track (recoil)
- small energy in the ECAL, Veto, HCAL
- Sensitivity ~ g_μ^2

Other searches and future plans

New project to search for X(17) particle (currently suspended)

- X(17) could explain ATOMKI anomaly

Other planned searches

- μ - τ conversion
- True Muonium

Spare