NA64++

D. V. Kirpichnikov on behalf of NA64 collaboration

Nov 8 2022

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OUTLINE

- **NA64e$^{\pm}$**
- **NA64μ**
- **NA64h**

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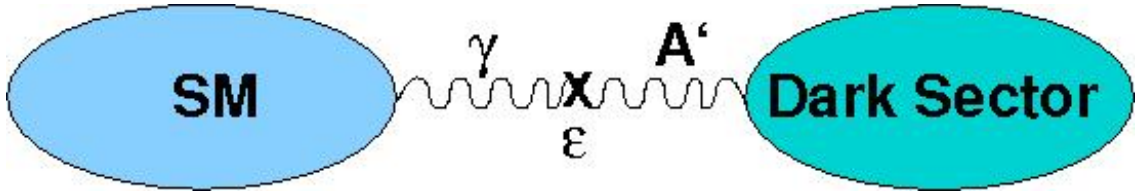
- NA64 collaboration ($\sim$ 50 researches from 18 institutes)
- **Proposed** in 2014 as **P348**, first test beam in 2015 (2 weeks);
- **Approved** by CERN SPS in March 2016 $\rightarrow$ **NA64**. 2016: 5 weeks; 2017: 5 weeks; 2018: 6 weeks.
- 2021/2022: 5/10 weeks in H4 and 3/3 weeks at M2

NA64e: Vector Portal to Dark Sector

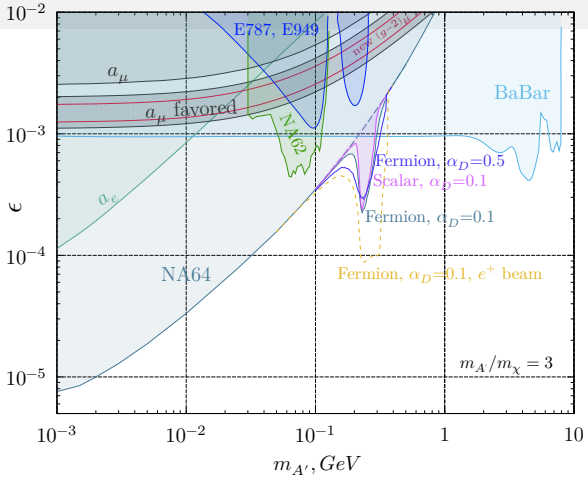


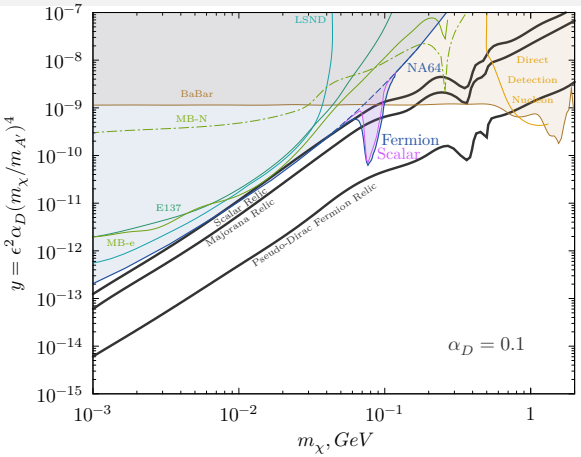
- **Okun, Holdom (1986)** $\alpha_D = e_D^2/(4\pi)$: new masssive boson A' (dark photon) which has kinetic mixing ϵ with ordinary photon A:

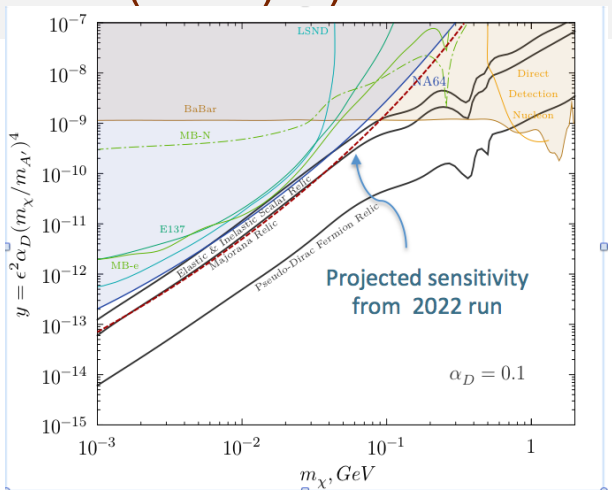
$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}^2 + \frac{1}{4}\left(F'_{\mu\nu}\right)^2 + \frac{\epsilon}{2}F_{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_{A'}^2(A'_\mu)^2 + e\bar{\psi}_e\gamma_\mu A^\mu\psi_e + \mathcal{L}_{int}(A' - \mathrm{DM})$$

- Field redefinition $A_\mu \to A_\mu + \epsilon A'_\mu$ to get rid of kinetic mixing between Standard Model (SM) photon A and massive Dark Photon A'
- That implies the effective interaction of DP with electrons $\mathcal{L} \supset e\epsilon \cdot \bar{\psi}_e\gamma^\mu A'_\mu\psi_e$
- Production:
  – A'-**bremsstrahlung** $e^- N \to e^- NA'$, $(A' \to \chi\chi)$
  – resonant pair **annihilation** $e^+e^- \to A' \to \chi\chi$
- Decays:
  – Mostly **Visible:** $A' \to e^+e^-$, $\mu^+\mu^-$, hadrons, assuming $m_{A'} > 2m_e$, $2m_\mu$...
  – Mostly **Invisible:** $A' \to \chi\chi$ if $m_{A'} > 2m_\chi$ assuming $\alpha_D \sim \alpha_{QED} \gg \epsilon$
- Relic DM abundance: $\Omega_\chi \propto \langle v\sigma\rangle^{-1} \propto m_\chi^2/y$, where $y = \epsilon^2\alpha_D(m_\chi/m_{A'})^4$

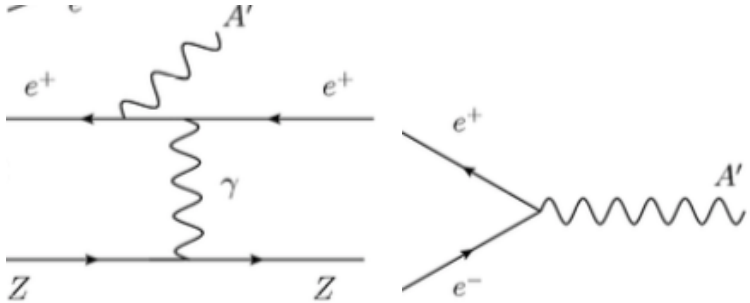
Probing Light Dark Matter with NA64++ (Phys.Rev.D 104 (2021) 9)

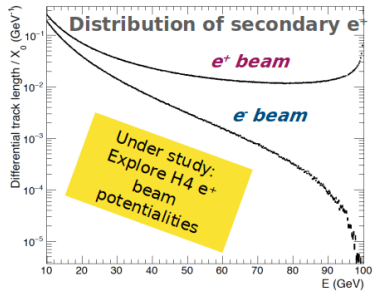




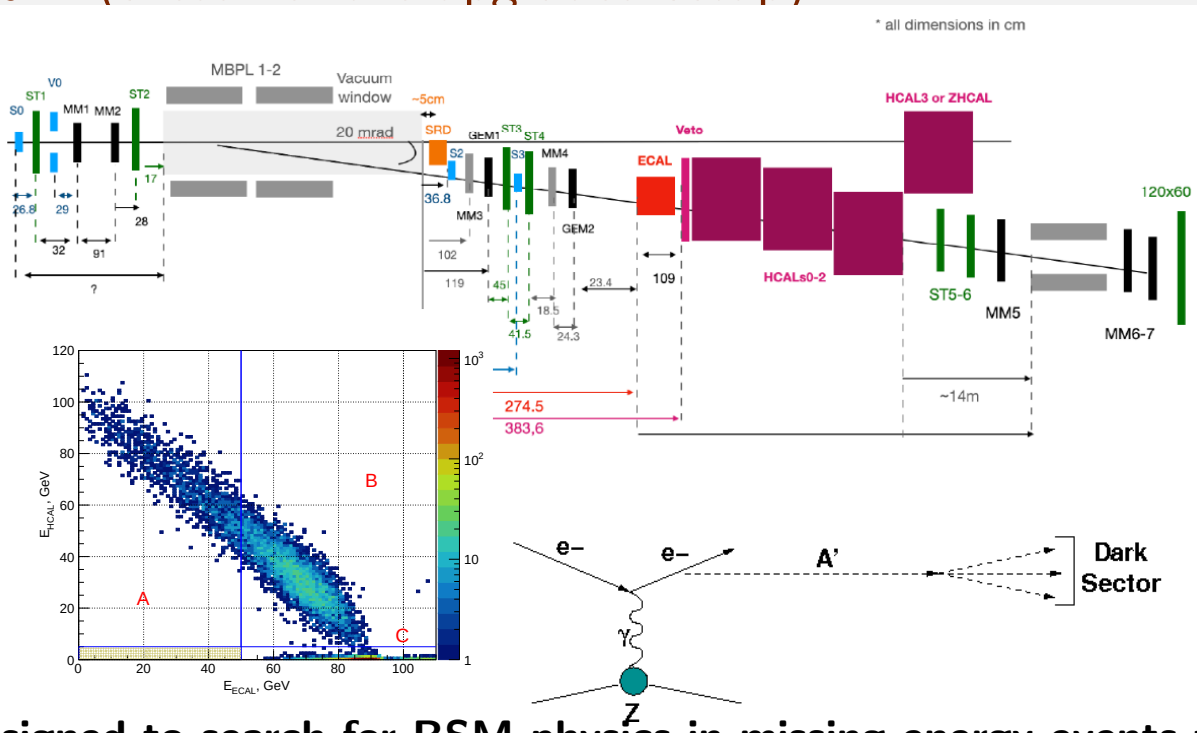


- **Combined 2016-2018 NA64 sensitivity ($N_{sign} \propto \epsilon^2$, EOT$\simeq 2.84 \times 10^{11}$) to light thermal DM exceeding constraints from beam dump experiments (suppressed $N_{sign} \propto \epsilon^4 \alpha_D$)**
- **In 2022 NA64e collected about 6.4×10^{11} EOT, thus the total amount of accumulated EOTs is 10^{12}; The data analysis is in progress**
- **Improved limit on ϵ up to factor 10 in the resonant region $m_{A'} \simeq (2 m_e E_{cut})^{1/2}$**
- **Advantage of using a positron beam $\rightarrow$ beam energy scanning method, 10$\times$bckgr. :(**
- **NA64++ target: SIGNIFICANT DM parameter space can be probed in Run 3 using unique CERN SPS electron and positron beams.**



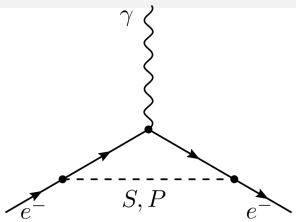


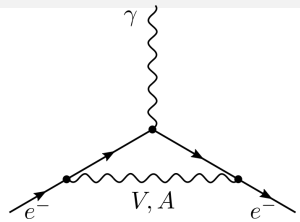
NA64e run in 2022 (sketch of the upgraded setup)

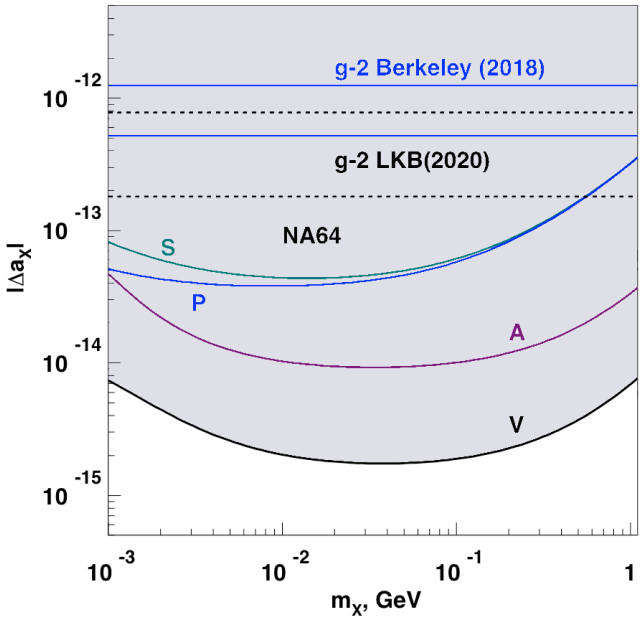


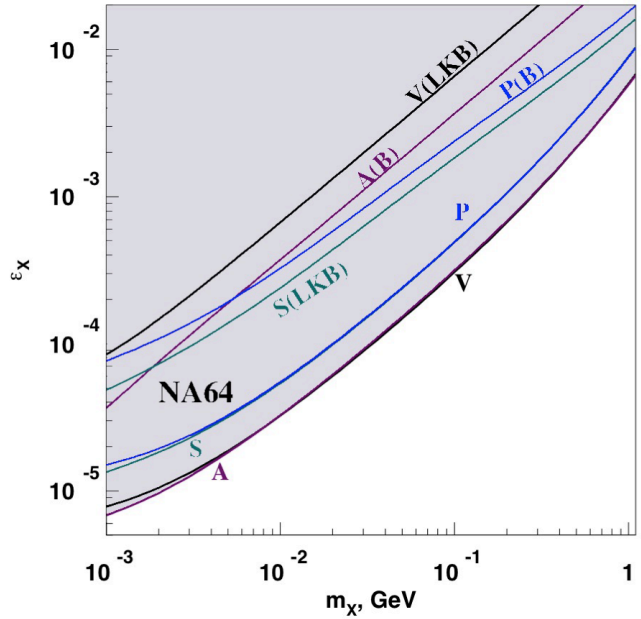
- **NA64 is designed to search for BSM physics in missing-energy events with $e^{\pm}, \mu, \pi, K, p$ beams.**
- **Main Components: a) clean $E_0 = 100$ GeV e^- beam; b) e^- tagging system: tracker+SRD; c) hermetic ECAL+HCAL;**
- **$E_{beam} \simeq E_{HCAL} + E_{ECAL}$ - main diagonal**
- **Signal Box (A):**
  a) in: 100 GeV e^- track; b) out: $E_{ECAL} < 0.5E_0$ electromagnetic shower in ECAL; c) no energy in Veto and HCAL;
- **Background:**
  a) μ, π, K decays in flight; b) upstream interaction; c) Tail < 50 GeV in the e^- beam; d) energy leak from ECAL+HCAL. Background free at the level of $\sim 10^{-12}$

Probing $(g-2)_e$ with NA64: $eN \to eNX, (X \to \chi\chi)$, where $X = (S, P, V, A)$



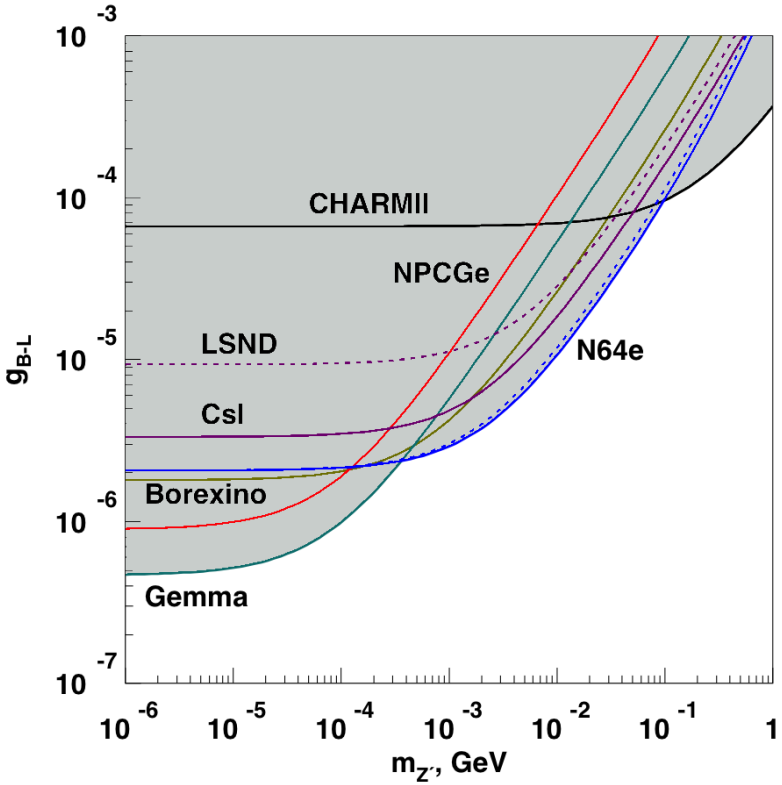


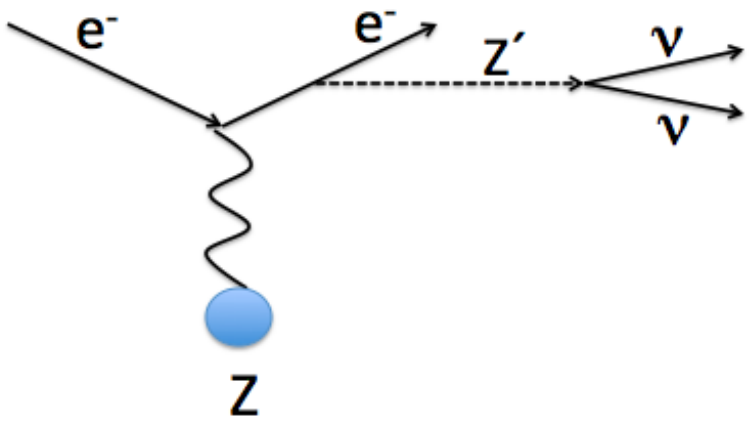




- $\Delta a_e^{LKB} = a_e^{exp} - a_e^{th} = (4.8 \pm 3.0) \cdot 10^{-13}$ LKB, L. Morel, Zh. Yao, P. Clade, and S. Guellati-Khelifa, Nature (London) 588, 61 (2020).
- $\Delta a_e^{B} = a_e^{exp} - a_e^{th} = (-8.8 \pm 3.6) \cdot 10^{-13}$ Berkeley, R. H. Parker, C. Yu, W. Zhong, B. Estey, and H. Muller, Science 360, 191 (2018)
- $X(J^P = 0^{\pm}, 1^{\pm}) \to$ invis.: **Motivation** is to check the explanation of $(g-2)_e$ puzzle due to X decaying invisibly.
- **NA64, Phys. Rev. Lett. 126, 211802 constraint is better than High Precision Table-top Experiments Berkeley**

Z' boson from B-L scenario: Phys.Rev.Lett. 129 (2022) 16, 161801

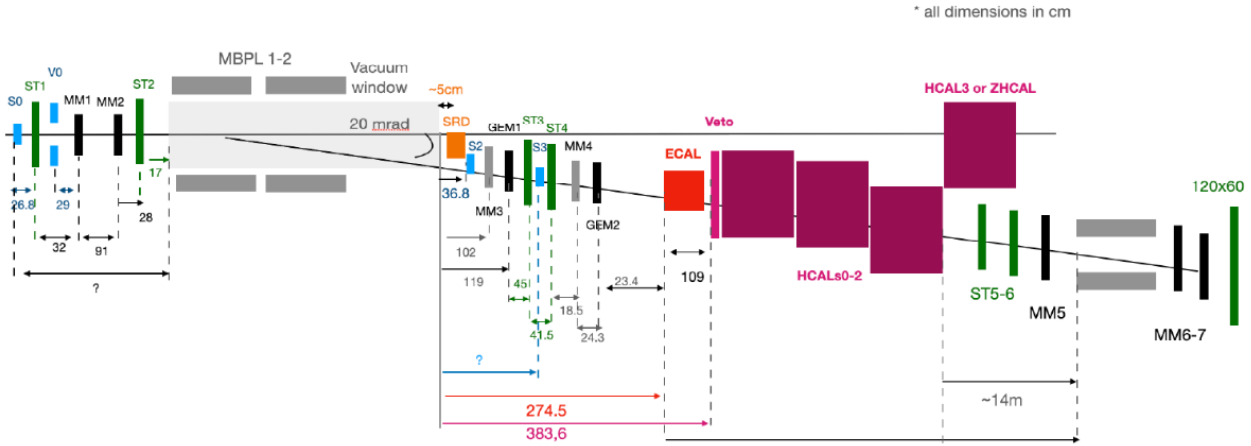


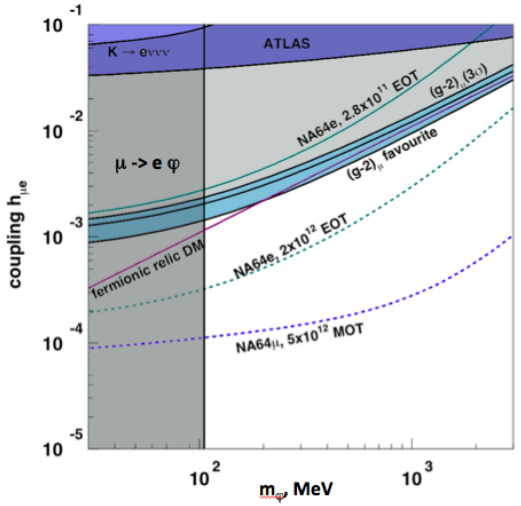


$$\mathcal{L} \supset g_{B-L} Z'_\mu \sum_{families} \left[\frac{1}{3} \bar{q} \gamma^\mu q - \bar{l} \gamma^\mu l - \bar{\nu} \gamma^\mu \nu \right]$$

- Mass range of interest $1\,\text{keV} \lesssim m_{Z'} \lesssim 1\,\text{GeV}$
- DATA: 3.2×10^{11} EOT collected during 2016-2018 and 2021 runs
- **NA64 RESULTS more stringent compared to those obtained from neutrino-electron scattering data in the mass range** $300\,\textbf{keV} \lesssim m_{Z'} \lesssim 100\,\textbf{MeV}$

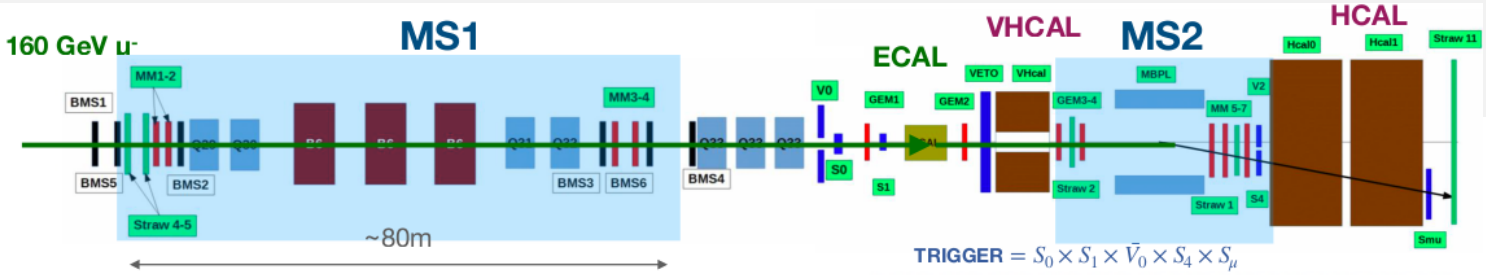
NEW ideas for NA64++ and resuming data taking after LS2

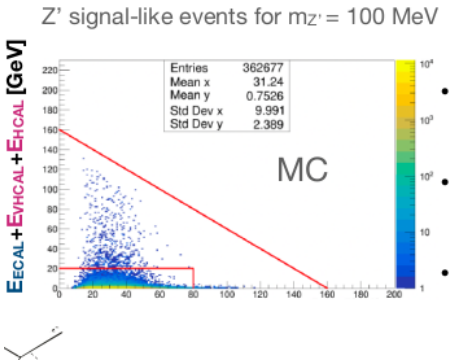




- NA64 theoretical group developments: Phys. Rev. D 106 (2022) 1, - lepton flavour violation
- NA64e design in 2022: new MBPL magnet was added to probe $eN \to \mu N\phi$ conversion (leptonic scalar)
- Total number of electrons accumulated during 2016-2022 Runs is close to $\sim 10^{12}$

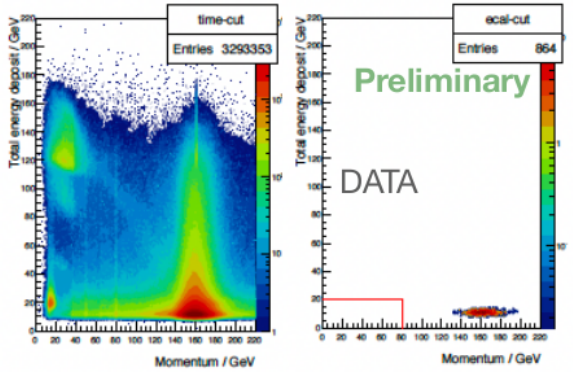
NA64μ:



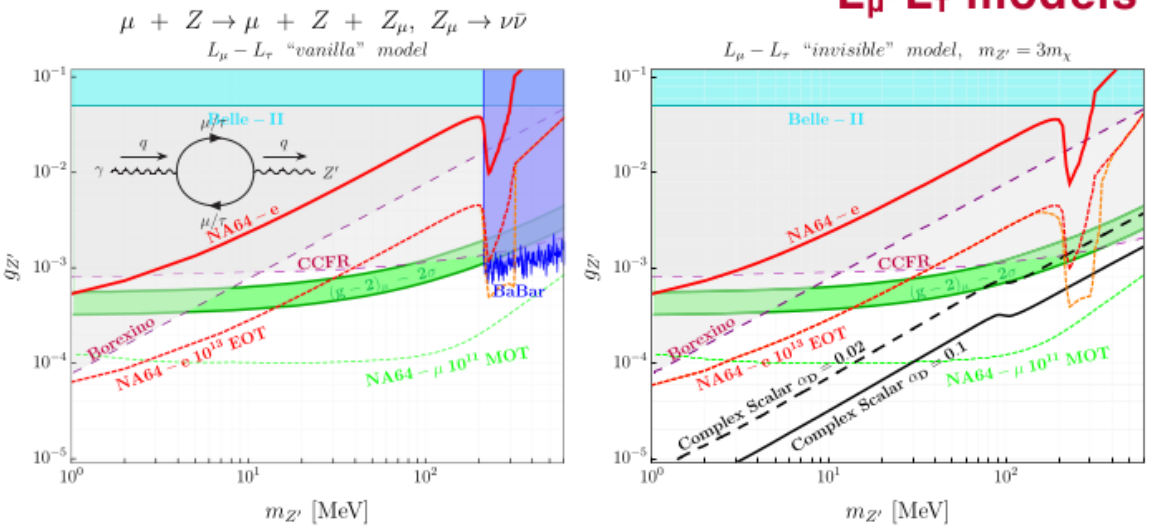


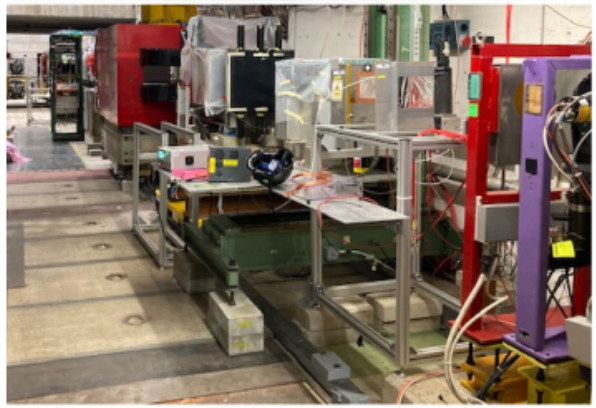
Signature

- 160 GeV initial μ-momenta (@MS1)
- Scattered μ-momenta < 80 GeV (@MS2)
- Energy deposit compatible with a MIP in ECAL, HCAL and in VETO



L_μ-L_τ models Z_μ could explain $(g-2)_\mu$



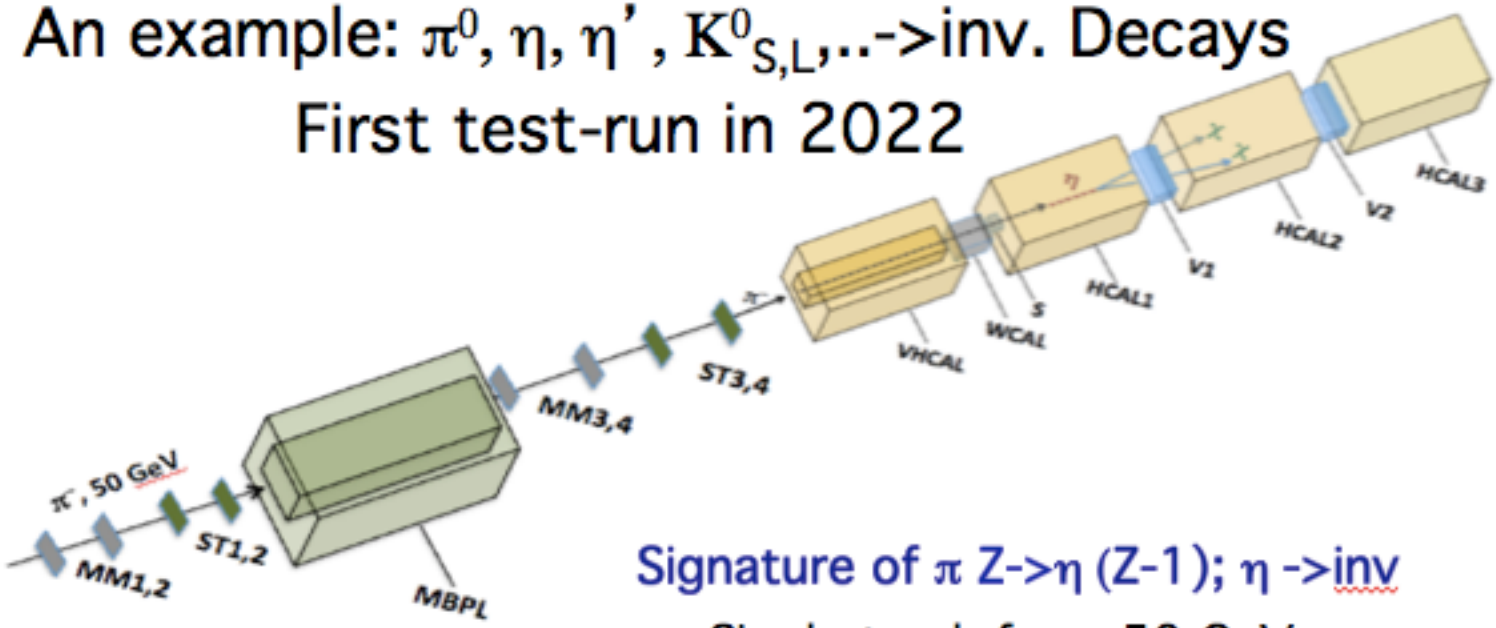


Pilot run 2021: 5x10⁹ MOT
Pilot run 2022: 4x10¹⁰ MOT

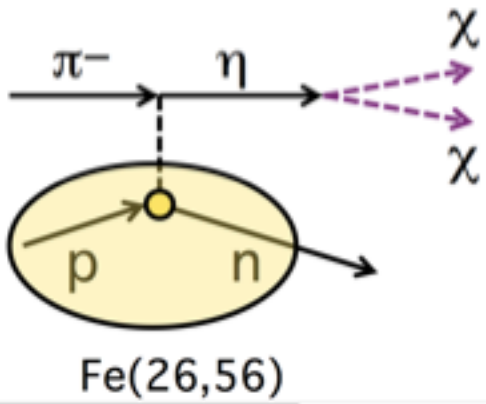
D. V. Kirpichnikov, Phys. Rev. D 104, 076012 (2021),
H. Sieber et al. ,Phys. Rev. D 105, 052006 (2022)
NA64 collaboration, Phys. Rev. D 106, 032015 (2022)

NA64h: Search for FIPs coupled to quarks

An example: π^0, η, η', $K^0_{S,L}$,..->inv. Decays
First test-run in 2022



η,,η', K0 – production:
π(K) Z->η(K^0) (Z-1)

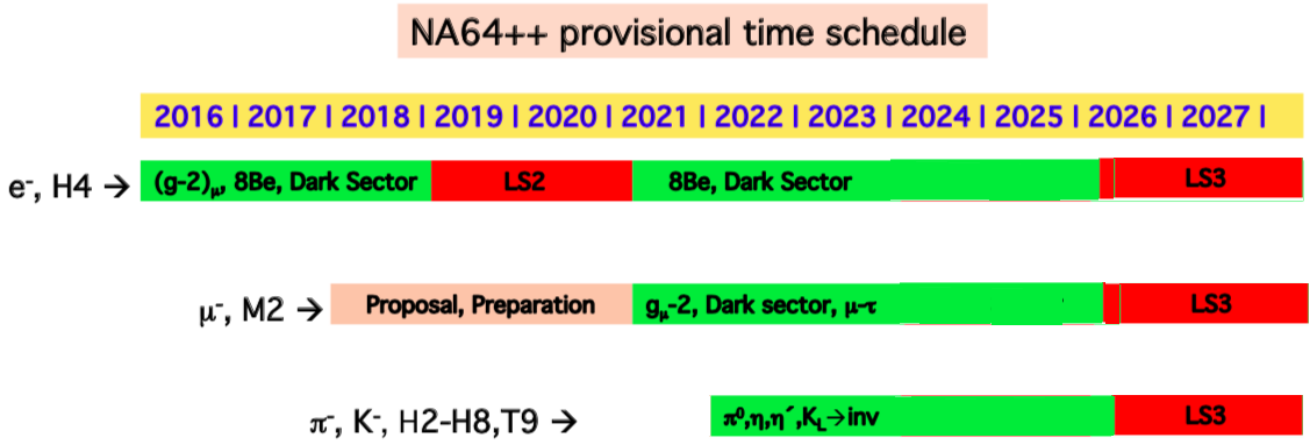


Signature of π Z->η (Z-1); η ->inv

- Single track from 50 GeV π-
- Events with $E_{HC} \approx E_0$ – test NA64mu
- MIP in WCAL and S
- N0 energy in HCAL: $E_{miss} \sim E_0$
- Bckg: π- ->e(μ)ν decays ~ 10^{-11}/pot
- ~2x10^9 pot (~1d, 2022),
- Br(η-> inv) < ~ 10^{-5}-10^{-4} (BaBar/BESIII)

Summary and plans

- **NA64e±**: **Beamtime 2022** just finished milestone of $\sim 10^{12}$ EOT, $\rightarrow$ start probing **LDM benchmark models. Plan until LS3 increase statistics as much as possible**. **Beamtime 2022** (2 days) 10^{10} positrons on target collected; impact of $10\times$ larger hadron contamination than in electron mode (expected) under study
- **NA64μ**: **Searches for dark sectors weakly coupled to muons at M2 beam-line**
  – pilot runs in 2021 and 2022 (4×10^{10} MOT collected). Start probing $(g-2)_\mu$ and Z'
  – Analysis ongoing, setup optimisation to collect before LS3 $\gtrsim 10^{11}$ MOT
- **NA64h**: Beamtime 2022 $\sim 2 \times 10^9$ pions (1 day) to understand potential of NA64 to explore dark sector coupled predominantly to quarks exploiting missing energy.
  Letter Of Intent was submitted to the **Moore Foundation** call for "Small scale experiments"



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