Photoproduction of axion-like particles at NA64

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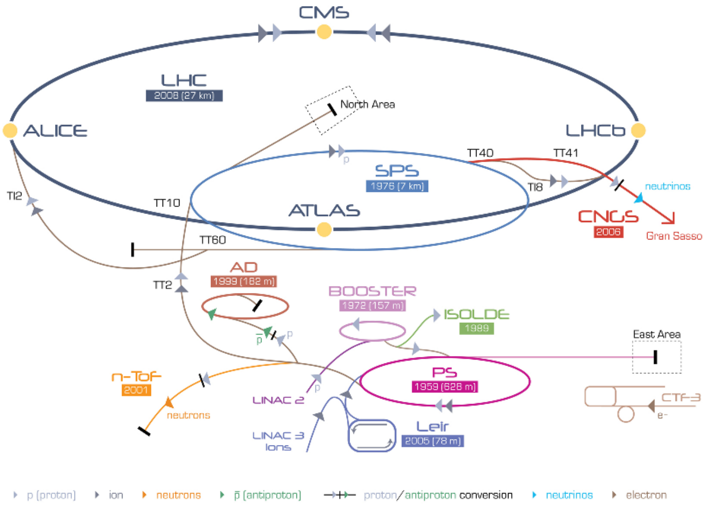
Outline

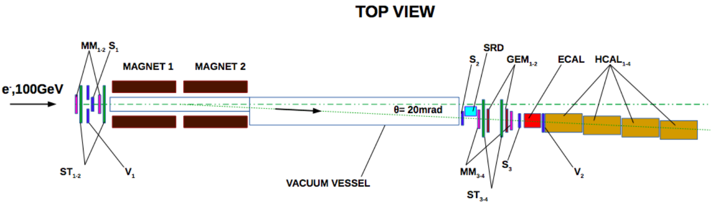
- Location of NA64 and its design
- Motivation of NA64
- **Axion-like particles**
- **Dark Photon**
- ETL vs IWW cross-section
- Visible mode setup: $X-$boson and $^*Be^8$ anomaly,
- **Millicharges**

NA64 location

Active target facility at **N**orth **A**rea (i.e. **NA**64) of SPS CERN



NA64



- Primary electrons of 100-GeV incident on lead shashlyk-like active target.
- Electron tagging by synchrotron radiation detector (SRD) and Micromega and GEM trackers around magnetic spectrometer (Magnet $1+2$), 1% momentum resolution.
- Electron missing energy process can be studied at NA64.
- **Axion-like particles** via Primakoff production: $\gamma N \to N a$.
- **Dark Photon** weakly coupled to electrons can be probed via bremsstrahlung-like processes $e^- N \to e^- N A'$ followed by invisible $A' \to \chi\bar{\chi}$ or visible decay $A' \to e^+ e^-$
- **Millicharged fermions:** $e^- N \to e^- N\gamma^* \to e^- N\chi\bar{\chi}$

ALP setup

Benchmark model for ALP and photon coupling:

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma}\, a F_{\mu\nu} \tilde{F}_{\mu\nu} + \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2} m_a^2 a^2$$

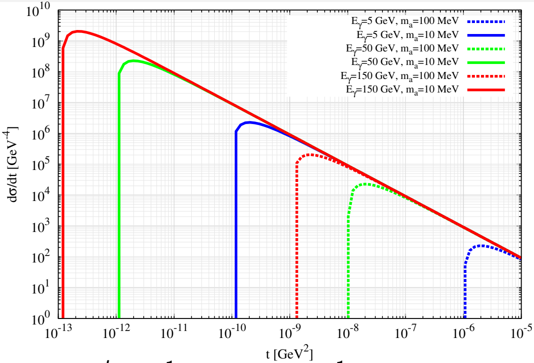
- We calculate yield of axion-like particles (ALP) via $\gamma_{brems.} + N \to a + N$ followed by decay $a \to \gamma\gamma$ outside HCAL1 module.
- m_a and $g_{a\gamma\gamma}$ are supposed to be independent parameters
- ALP has the following decay width

$$\Gamma_{a\to\gamma\gamma} = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}. \quad (1)$$

- The relevant typical decay length of ALP is given by

$$l_a = 4\text{m} \cdot \frac{E_a}{100\,\text{GeV}} \cdot \left(\frac{g_{a\gamma\gamma}}{10^{-4}\,\text{GeV}^{-1}}\right)^{-2} \cdot \left(\frac{m_a}{100\,\text{MeV}}\right)^{-4}. \quad (2)$$

ALP momentum distribution



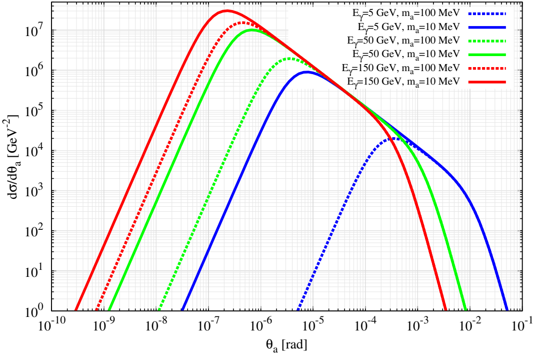
$$\frac{d\sigma}{dt} = \frac{1}{2^3} \cdot g^2_{a\gamma\gamma} \alpha F^2(t) \cdot \frac{1}{t^2} (t - t_{min}) \tag{3}$$

where elastic form-factor is

$$F(t) \approx Z \left(\frac{a^2 t}{1 + a^2 t} \right) \left(\frac{1}{1 + t/d} \right), \tag{4}$$

here $a = 111 Z^{-1/3}/m_e$ and $d = 0.164\,\mathbf{GeV}^2 A^{-2/3}$, here m_e is the mass of electron and A is the atomic weight and $t_{min} = m_a^4/(4E_\gamma^2)$.

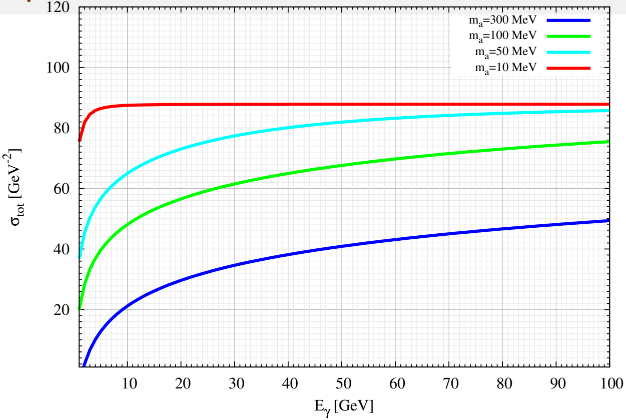
ALP angle distribution



$$d\sigma \approx \frac{1}{m_a^3} 16\pi\alpha F^2(t)\Gamma_{a\to\gamma\gamma}\frac{\theta_a^3 d\theta_a}{(\theta_a^2+\delta_a^2)^2}, \tag{5}$$

where $\delta_a \approx m_a^2/(2E_\gamma^2)$ is a parameter that characterizes a typical angle between the beam line and the ALP momentum.

ALP total production cross-sections



$$\sigma_{tot} = \frac{16\pi\alpha}{m_a^3} \cdot \Gamma_{a\to\gamma\gamma} \cdot \frac{Z^2}{2} \left(\ln \left[\frac{d}{1/a^2 + t_{min}} \right] - 2 \right). \tag{6}$$

Signal estimation

The number of ALP produced at i-th photon's step length in EMS is given by

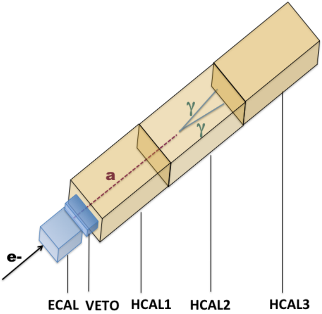
$$N_a^{(i)} = \textbf{EOT} \times \textbf{Photons\_per\_EOT}_i \times \frac{\rho N_A}{A} \times \sigma_{tot}(E_\gamma^i) \times l_i \qquad (7)$$

- the energy distribution of the electron beam after passing through a target medium is simulated by GEANT4.
- the emission of electron bremsstrahlung initiates the ALP production in a electromagnetic shower (EMS) via Primakoff process, $\gamma N \to aN$.
- total ALP production cross-section σ_{tot}^a depends rather weak on m_a in contrast to the Dark Photon case

$$\sigma_{tot}^{A'} \sim \epsilon^2/m_{A'}^2, \qquad \sigma_{tot}^a \sim g_{a\gamma\gamma}^2,$$

- the typical energy of ALP in Primakoff process is $E_a \approx E_\gamma$. Therefore, ALP spectra are associated with bremsstrahlung distribution in the target.

invisible mode design

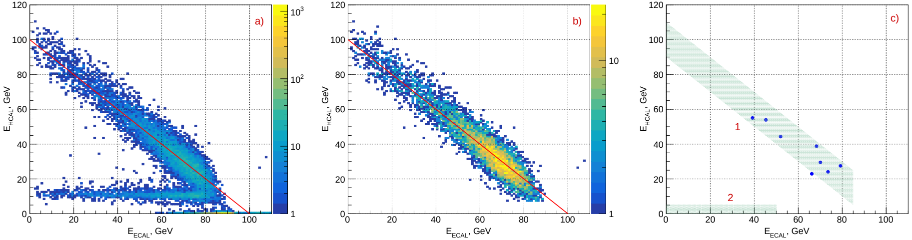


The signal of ALP decaying into photons can be written as

$$N_a = \sum_i N_a^{(i)} \exp\left(-\frac{L_D}{l_a^{(i)}}\right) \mathcal{B}(a \to \gamma\gamma), \tag{8}$$

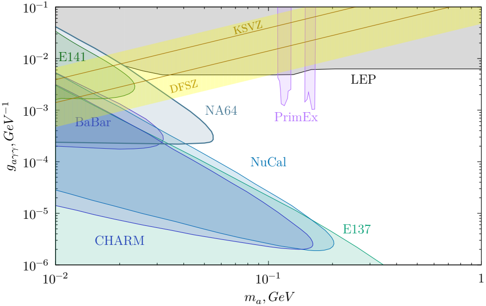
where L_D is the typical length between the ALP production point in ECAL and the its decay point for two distinctive signature

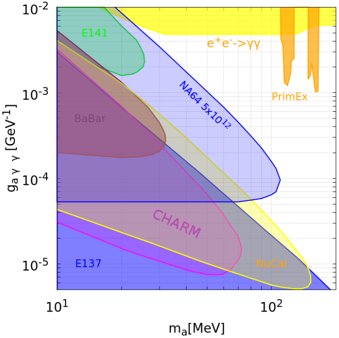
- 1) decay into 2γ inside the HCAL2 or HCAL3 modules
- 2) event with large missing energy if ALP decays down- stream of the HCAL2,3



Panel a) shows the measured distribution of all events in the $(E_{ECAL}; E_{HCAL})$ plane selected at the earlier phase of the analysis with the loose cuts. The distribution of pure neutral hadronic secondaries is illustrated in panel b). The shaded area shown in panel c) represents the signal boxes 1 and 2 in the $(E_{ECAL}; E_{HCAL})$ plane for the signatures 1 and 2 respectively, where no candidates for the signal events were found after applying all selection criteria. The blue squares represent events in the control region from leading neutral hadrons.

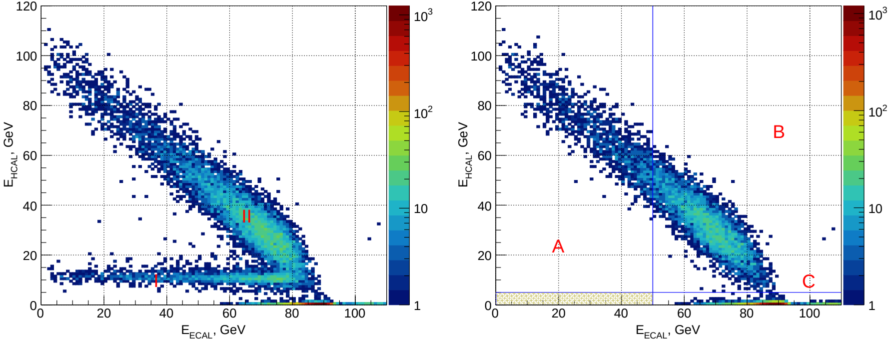
NA64 limits and sensitivity of past experiments





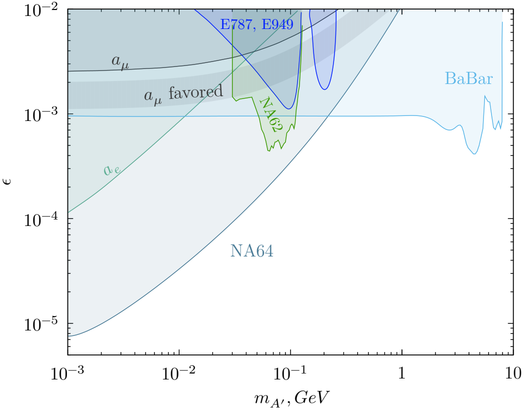
- Left panel is a current ALP limit from NA64 for $EOT = 2.86 \times 10^{11}$, arXiv:2005.02710, submitted to PRL
- Right panel is a prospect of NA64 to probe ALP with $EOT = 5 \times 10^{12}$, arXiv:2004.04469, submitted to PRD

Dark Photon signature: $e^- N \to e^- N A' (A' \to \bar{\chi}\chi)$



- primary electron beam with $E_0 = 100$ GeV, $E_0 = E_{miss} + E_{recoil}$
- no events in the signal region of ECAL: $E_{A'} \equiv E_{miss} > 50 GeV$
- no energy deposition in HCAL: $E_{HCAL} < 5$ GeV
- upper 95% CL limit on average number of signal events, $N_{signal} < 2.3$
- given MC simulation events one can obtain bounds on $(\epsilon, m_{A'})$ parameter space

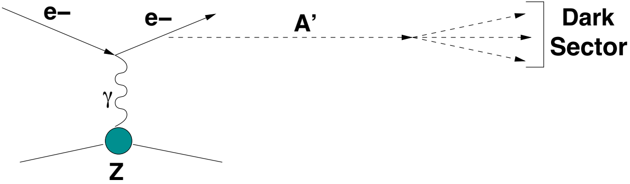
Recent limits of NA64 from invisible mode of Dark Photon



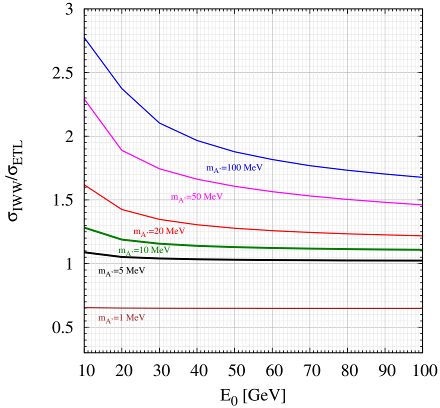
$EOT = 2.84 \times 10^{11}$, Phys.Rev.Lett. 123 (2019) no.12, 121801, arXiv:1906.00176

Simulation of $e^- Z \to e^- Z A'$

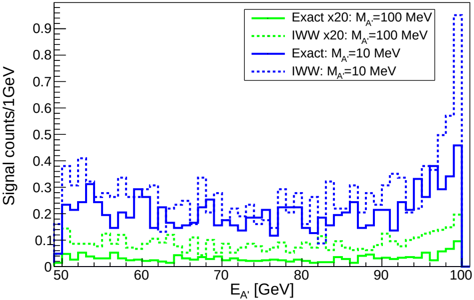
- GEANT4 + code for A' emission in the process of electromagnetic shower development in ECAL, $e^- Z \to e^- Z A'$, $\sigma \sim Z^2 \epsilon^2 / m_{A'}^2$
- The signal process events are simulated using simplified Weizsaecker-Williams (WW) approximation (Bjorken et al., 2009)
- Correction to A' production cross-section in WW approach appears to be large (Liu et al., 2017)
- **For the total cross section we use the full matrix element calculations (Gninenko et al. 2018) through the K-factors applied to the WW cross sections**



ETL vs IWW

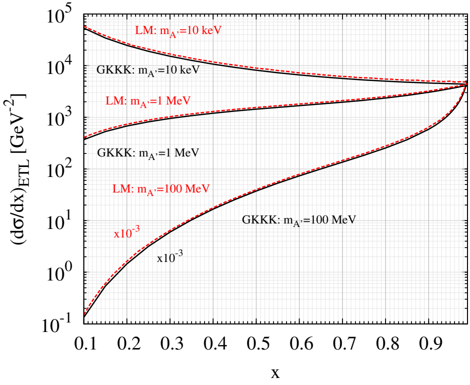


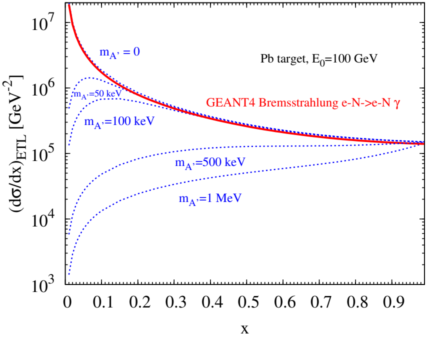
3
2.5
2
1.5
1
0.5
10 20 30 40 50 60 70 80 90 100
$\sigma_{IWW}/\sigma_{ETL}$
E_0 [GeV]
$m_{A'}$=100 MeV
$m_{A'}$=50 MeV
$m_{A'}$=20 MeV
$m_{A'}$=10 MeV
$m_{A'}$=5 MeV
$m_{A'}$=1 MeV



Exact x20: $M_{A'}$=100 MeV
IWW x20: $M_{A'}$=100 MeV
Exact: $M_{A'}$=10 MeV
IWW: $M_{A'}$=10 MeV
Signal counts/1GeV
$E_{A'}$ [GeV]
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9
50 60 70 80 90 100

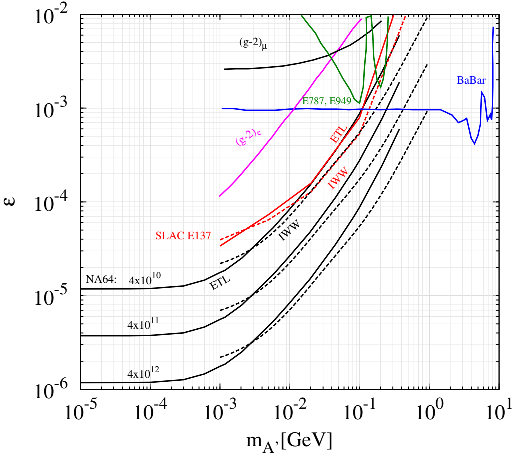
ETL vs IWW





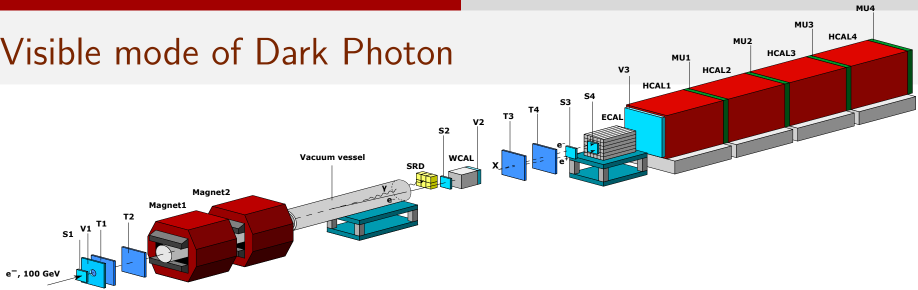
where $x = E_{A'}/E_0$ is a fraction of missing energy

ETL vs IWW



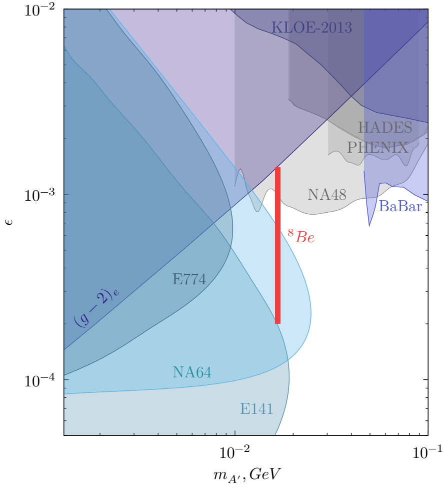
Phys.Lett. B 782 (2018) 406-411, arXiv:1712.05706

Visible mode of Dark Photon



- Let us consider A' visible mode setup of NA64
- being produced via $e^- Z \to e^- Z A'$ Dark Photon decays into e^+e^- pair
- NA64 is sensitive to short lived Dark Photons due to its short base line.

Visible mode of Dark Photon



The ATOMKI experiment of (Krasznahorkay et al. 2016) has reported the observation of a 6.8 σ excess of events in the invariant mass distributions of e^+e^- pairs produced in the nuclear transitions of excited $^*Be^8$

This anomaly can be associated with X-boson of $m_X = 16.7$ MeV.

Millicharge searches at NA64

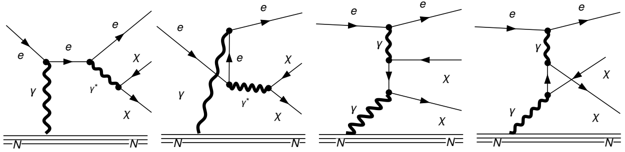
mQ intro:

- Millicharge coupling to photon is

$$\mathcal{L} = Q_\chi A_\mu \bar{\chi}\gamma_\mu \chi$$

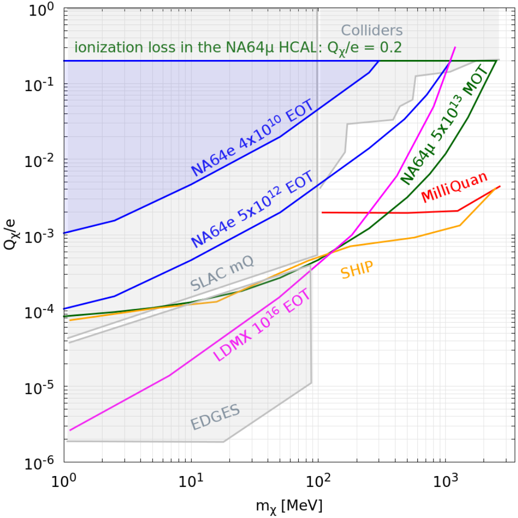
  with Q_χ being a small fraction of electron charge $Q_\chi/e \ll 1$
- Missing energy signature $e^- N \to e^- N\gamma^* \to e^- N\chi\bar{\chi}$ is $2 \to 4$ emission process which is the $\alpha^3 Q_\chi^2$ in the leading order.

Interference $\alpha^{5/2} Q_\chi^3$ -term



leading $\alpha^3 Q_\chi^2$ - order term; subleading $\alpha^2 Q_\chi^4$ -order term

mQ current limits and prospects



Phys.Rev. D100 (2019) no.3, 035003, arXiv:1810.06856

Conclusion

- NA64 is sensitive to wide range of well motivated models of Dark Sector (Dark Photons, millicharges, axion-like particle)
- NA64 has a great opportunity to cover parameter space of hidden sector after LS2
- Related experiments (dark sector searches):
  current: BELLE, BESIII, NA48/2, NA62.
  future: FASER, MATHUSLA, SHIP, LDMX.