Production of dark photons in particle collisions

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New Physics: where?

- Observations – Standard Model is very good!
- Still we need some new physics:
  - neutrino oscillation
  - dark matter
  - matter-antimatter asymmetry
- Plenty of scenarios for New Physics
- No evidence!
- Where is it?

Models of New Physics – still a guesswork

- New particles at TeV scale?
- Motivations for New Physics at TeV scale (like SUSY): dark matter and quantum corrections to the Higgs boson mass
- Other possibilities should be explored!
- A hidden sector with new particles!
- Hidden-visible interactions:
  - Universal interaction – gravity
  - Renormalizable portals:

Higgs portal:	Neutrino portal:	Vector boson portal:
$\mathcal{L}_{int} \sim \phi^* \phi H^\dagger H$	$\mathcal{L}_{int} \sim L\tilde{H}N$	$\mathcal{L}_{int} \sim B_{\mu\nu}^{U(1)_Y} B_{\mu\nu}^{U(1)'}$
new scalar(s)	sterile neutrinos	new vectors

Vector boson portal

- Dark photon γ' with a mass $m_{A'}$
- "Kinetic" mixing between visible γ and dark photons γ'

$$\mathcal{L}_{mix} = -\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$$

- Dark photon interacts with e/m current

$$\mathcal{L}_{int} = \epsilon e A'_\mu J^\mu_{EM}$$

- Typically, the hidden sector include particles χ charged under $U(1)'$, i.e.

$$\mathcal{L}_{int} = g\bar{\chi}\gamma^\mu\chi A'_\mu \quad \longrightarrow \epsilon g\bar{\chi}\gamma^\mu\chi A_\mu$$

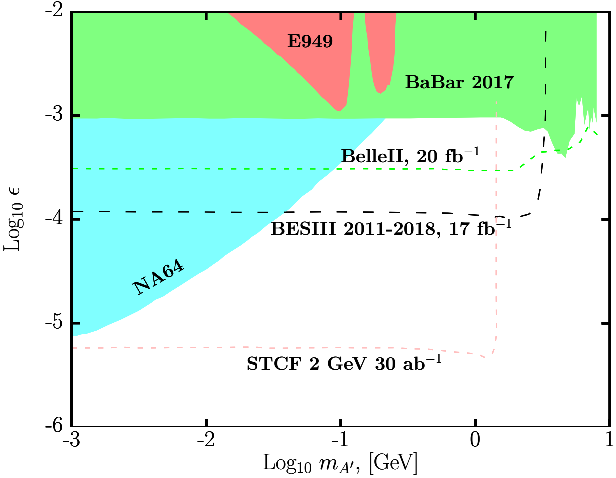
Vector portal: collider phenomenology of dark photon

- Decays of the dark photon:
  - Invisible decay channels $\gamma' \to \bar{\chi}\chi$
  - Visible decay channels $\gamma' \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-$ etc.
- Production mechanisms:
  - Direct production: $e^+e^- \to \gamma\gamma'$, $eZ \to eZ\gamma'$ or $q\bar{q} \to \gamma'$.
  - Production in decays: $\pi^0 \to \gamma\gamma'$, $J/\psi \to P\gamma'$ with $P = \pi^0, \eta, \eta'$.
- Search strategies:
  - Peak in e^+e^- (or $\mu^+\mu^-$ etc.) invariant mass distribution
  - Displaced vertices after a visible (i.e. $\gamma' \to e^+e^-$) decay
  - Missing energy signature (i.e. $e^+e^- \to \gamma\gamma'$ with $\gamma' \to$ invisible)

Collider searches

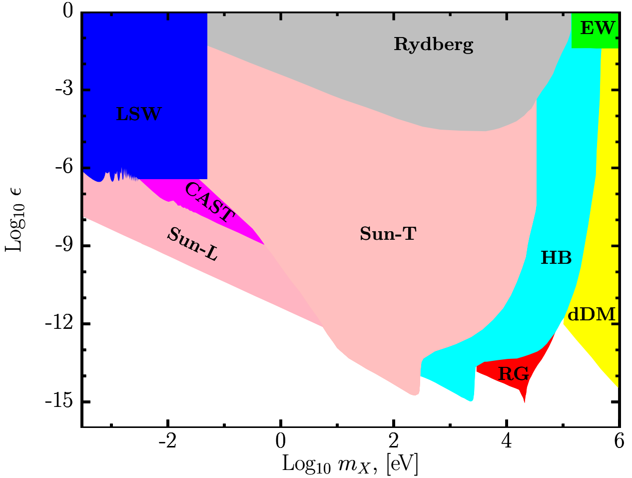
Invisible mode, selected results/expectations, $m_{A'} > 1$ MeV

1710.00971, 1901.09966, 1907.07046



Light dark photons: astrophysical/cosmological bounds

Region $m_{A'} < 1$ MeV



Can we extend collider bounds to smaller masses?

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{4}F_{\mu\nu}'^2 - \frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu} + \frac{m_{A'}^2}{2}A_\mu'^2 - eA_\mu J^\mu_{em}$$

Let us diagonalize the kinetic terms by $A'_\mu \to A'_\mu + \epsilon A_\mu$, $(\epsilon \ll 1)$.

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{4}F_{\mu\nu}'^2 + \frac{m_{A'}^2}{2}(A'_\mu + \epsilon A_\mu)^2 - eA_\mu J^\mu_{em} + \mathcal{O}(\epsilon^2)$$

where the field A'_μ is still sterile under electromagnetic interactions.
Interaction eigenstates are not mass eigenstates – like for neutrinos!

$$H = \frac{1}{2E}\begin{pmatrix} 0 & -\epsilon m_{A'}^2 \\ -\epsilon m_{A'}^2 & m_{A'}^2 \end{pmatrix}, \quad \text{for } E \gg m_{A'}\,.$$

γ–γ' oscillations: amplitude $4\epsilon^2$, oscillation length $L_{osc} = \frac{4\pi E}{m_{A'}^2}$

$$P(\gamma \to \gamma') = 4\epsilon^2 \sin^2\left(\frac{m_{A'}^2 L}{4E}\right)$$

Oscillations: coherence issues

- Size of the wave packet σ_x is important
- For production in a scattering process: $\sigma_x \sim \frac{1}{q}$
- For production in a decay: $\sigma_x \sim \gamma\tau$

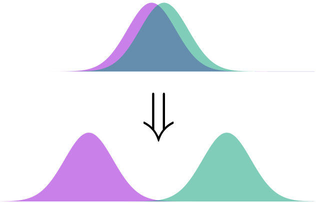
Validity of the oscillation picture requires:

- Small size of initial wave packet:

$$\sigma_x < L_{osc}$$

- Wave packets overlap:

$$L < l_{coh} \approx \frac{\sigma_x}{\Delta v} = \frac{2\sigma_x E^2}{\delta m^2}$$



Coherence is lost – no oscillations!

Note: here we discuss transverse polarizations only, production of longitudinal polarization is suppressed by $\frac{m_{A'}^2}{E^2}$ (see 1302.3884)

Matter effects

- Loss of coherence due to interactions (absorption and scattering) at $L > 1/\Gamma$
- Media results in change of the photon dispersion relation (effective mass)

$$m_\gamma^2 = 4\pi\alpha \frac{n_e}{m_e} \ ,$$

For typical media $m_\gamma \sim 20 - 60$ eV

- Conversion probability $(\epsilon m_{A'}^2 \ll |m_{A'}^2 - m_\gamma^2| \equiv \Delta m^2)$

$$P(\gamma \to \gamma') \approx \frac{\epsilon^2 m_{A'}^4}{(\Delta m^2)^2 + E^2\Gamma^2} \left(1 + \mathrm{e}^{-\Gamma L} - 2\mathrm{e}^{-\frac{\Gamma L}{2}} \cos\left(\frac{\Delta m^2 L}{2E}\right)\right)$$

where $\Delta m^2 = m_{A'}^2 - m_\gamma^2$.

Visible-to-hidden photon conversion

Large propagation distances, $\Gamma L \gg 1$: $P(\gamma \to \gamma') \approx \frac{\epsilon^2 m_{A'}^4}{(\Delta m^2)^2 + E^2\Gamma^2}$

- Very heavy dark photons $m_{A'}^2 \gg m_\gamma^2, E\Gamma$: $P(\gamma \to \gamma') \approx \epsilon^2$
- High absorption $|\Delta m^2| \ll E\Gamma$: $P(\gamma \to \gamma') \approx \epsilon^2 \frac{m_{A'}^4}{E^2\Gamma^2}$
- Low absorption $|\Delta m^2| \gg E\Gamma$: $P(\gamma \to \gamma') \approx \epsilon^2 \frac{m_{A'}^4}{m_\gamma^4}$

Production probability is additionally suppressed by a factor $\sim \frac{m_{A'}^4}{m_0^4}$.

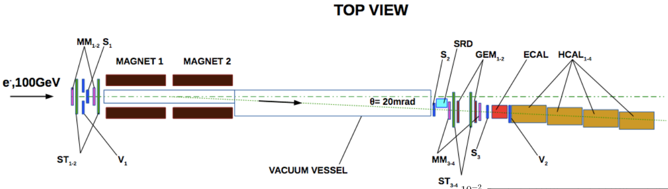
One expects decrease of experimental sensitivity of direct experiments to very light dark photons

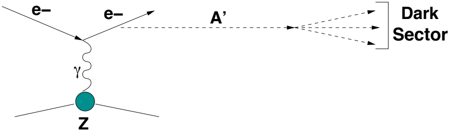
Possible setups:

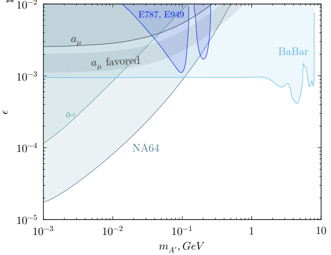
- "Appearance" type: $\gamma \to \gamma' \to \gamma$, $P \sim \epsilon^4$
- "Disappearance" type: $\gamma \to \gamma'$, $P \sim \epsilon^2$

1710.00971

Search for the hidden photon in NA64 – missing energy signature
Beam dump, electrons $E = 100$ GeV







Production of light dark photons in ECAL of NA64

1812.02719

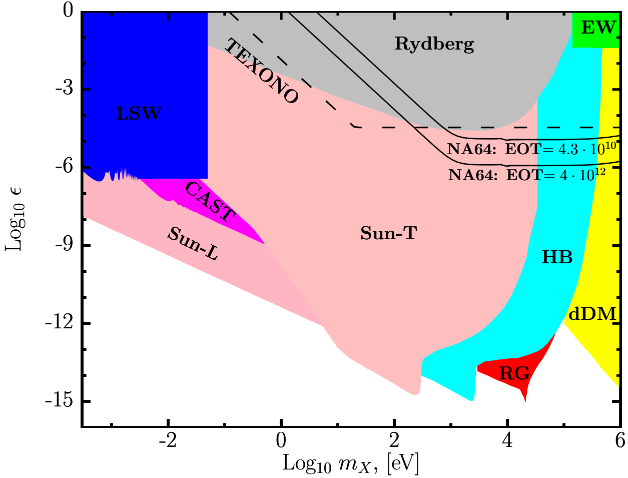
- Oscillation picture $e + Z \to e + Z + \gamma$, $\gamma \to \gamma'$
- Estimates: for $E_\gamma \sim 50 - 100$ GeV, $m_{A'} \lesssim 1$ keV, we have sufficiently large $l_{coh} \gtrsim 10$ cm
- Alternating layers (1.5mm) of lead (Pb) and scintillator (Sc); $m_{\gamma,Pb} \approx 60$ eV, $m_{\gamma,Sc} \approx 20$ eV
- We calculate probability of hidden photon production
- Limiting cases:
  - $m_{A'} \gtrsim 1$ keV, $P(\gamma \to \gamma') \approx \epsilon^2$
  - $m_{A'} \lesssim 100$ eV – high absorption in both layers

$$P(\gamma \to \gamma') \approx \epsilon^2 \frac{m_{A'}^4}{1\ \text{keV}^4},$$

- Neglect secondary photons at $E \sim 50 - 100$ GeV

NA64: expected limits for light dark photons

1804.10777, 1812.02719



Light dark photons at e^+e^- colliders

- e^+e^-, $\sqrt{s} \sim$ several GeVs
- Production of very light dark photons through oscillations: $e^+e^- \to \gamma\gamma$, $\gamma \to \gamma'$

Naive estimates:

- $\sigma_x \sim \frac{1}{E} \sim 10^{-14}$ cm.
- Coherence length $l_{coh} \sim \frac{2E^2}{m_{A'}^2}\sigma_x \lesssim 1$ m for $m_{A'} > 10$ eV
- Flat bound on ϵ till $m_{A'} \sim 10$ eV
- At $m_{A'} \lesssim 10$ eV one expects that the bounds weaken

Requires further study ...

Conclusions

- Direct searches for dark photons can be extended to small masses $m_{A'} \lesssim 1$ MeV
- Production of very light hidden photons is typically suppressed

$$P(\gamma \to \gamma') = \epsilon^2 \Rightarrow \epsilon^2 \left(\frac{m_{A'}}{m_0}\right)^4$$

due to interaction of photons with media and sensitivity is lost
- The value m_0 depends on the experiment

Thank you!