Unveiling Time-Varying Signals of Ultralight Bosonic Dark Matter at Collider and Beam Dump Experiments

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JHG, Yuxuan He , Jia Liu, Xiao-Ping Wang and Ke-Pan Xie, *Commun.Phys.* 6 (2023) 225

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- Time-varying Mass of Dark Photon
- Experiments Recast and Reanalysis
- Time-dependent Method Analysis
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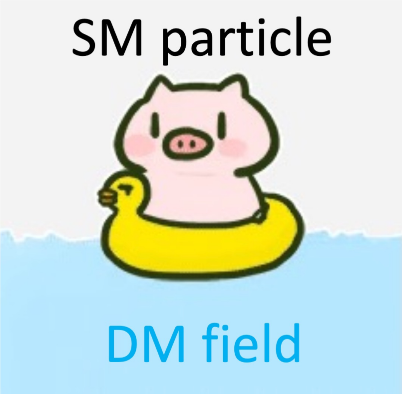
Introduction

- Time varying physical constants Dirac, Nature 139 (1937) 323
- Ultralight dark matter

  EOM: $$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2\phi = 0$$

  And misalignment mechanism

$$\phi(t) \approx \phi_0 \cos(m_\phi t) \qquad \rho_{\rm DM} = m_\phi^2 \phi_0^2/2$$



- Ultralight dark matter and varying constants Stadnik et al, 1412.7801, 1503.08540

$$\mathcal{L} \supset -\sum_{f=e,p,n} \frac{m_f}{\Lambda_f}\phi\bar{f}f + \frac{\phi}{4\Lambda_\gamma}F_{\mu\nu}F^{\mu\nu}$$

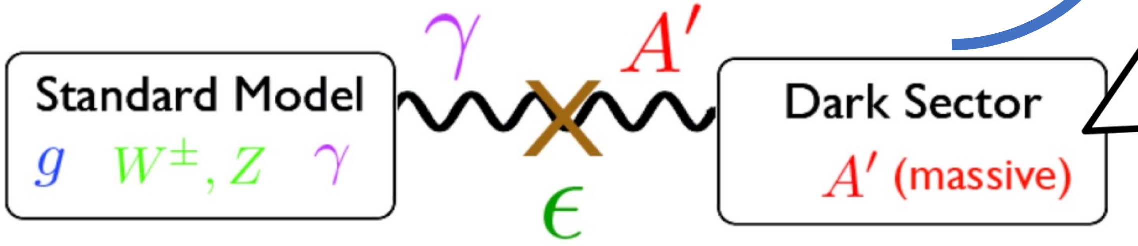
$$m_f \to m_f\left(1 + \frac{\phi_0\cos(m_\phi t)}{\Lambda_f}\right), \quad \alpha \to \frac{\alpha}{1 - \phi_0\cos(m_\phi t)/\Lambda_\gamma}$$

Introduction

Varying dark particle mass:

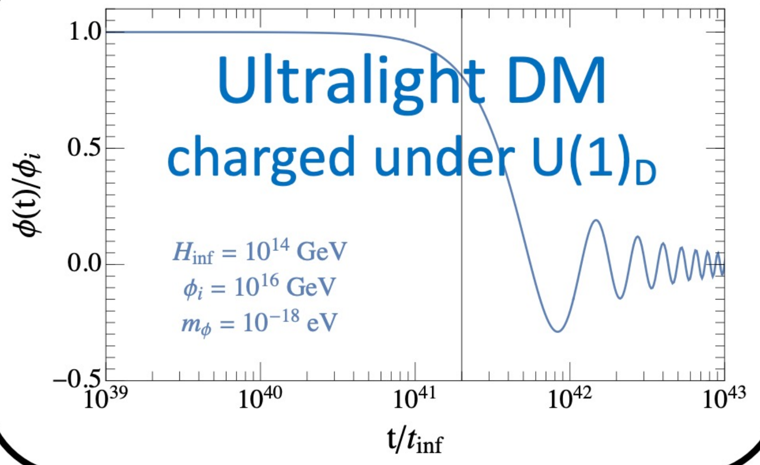
Solve the $g-2$ anomaly

The classic dark U(1)$_D$ model



$$\Delta\mathcal{L} = \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$

"Kinetic Mixing" Holdom; Galison, Manohar



$$\phi(t) \approx \phi_0 \cos(m_\phi t)$$

DM couples to A'

$$(D_\mu \phi)^* D^\mu \phi \supset (g' Q_\phi)^2 \phi^* \phi A'_\mu A'^\mu$$

Obtain a time varying mass:

$$m_{A'}(t) = \sqrt{m_0^2 + 2(g'Q_\phi)^2 |\phi_0|^2 \cos^2(m_\phi t)}$$

$$\equiv m_0 \sqrt{1 + \kappa \cos^2(m_\phi t)}$$

$$\kappa \equiv 2(g'Q_\phi)^2 \rho_{\rm DM} / \left(m_\phi^2 m_0^2\right) = 10 \left(\frac{\rho_{\rm DM}}{0.3\,{\rm GeV/cm^3}}\right) \times \left(\frac{g'Q_\phi}{1.5\times 10^{-8}} \frac{10^{-19}{\rm eV}}{m_\phi} \frac{0.1{\rm GeV}}{m_0}\right)^2,$$

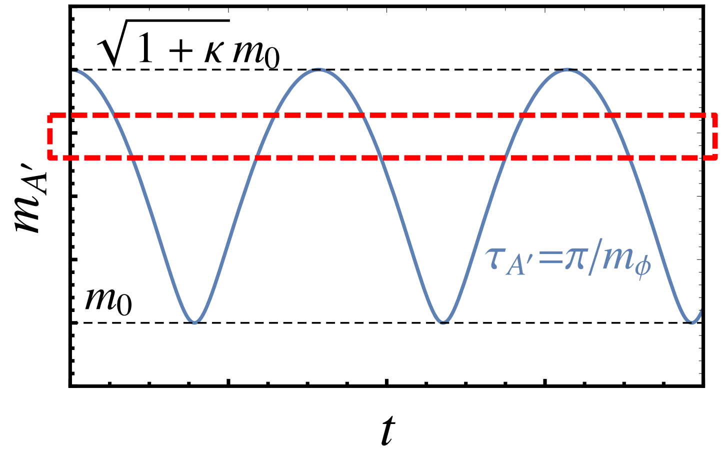
Time-varying Mass of Dark Photon

Varying dark particle mass:

$$m_{A'}(t) = \sqrt{m_0^2 + 2(g'Q_\phi)^2|\phi_0|^2\cos^2(m_\phi t)}$$
$$\equiv m_0\sqrt{1+\kappa\cos^2(m_\phi t)}$$

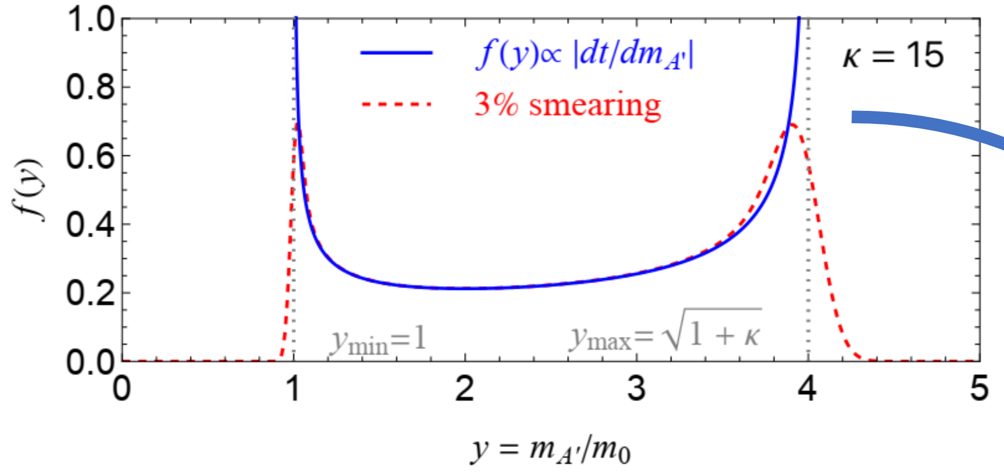
We focus on: $m_0 \sim \text{MeV}, \kappa \sim 10$

Time-varying resonant spectrum



$$m_{res}^2(t) = m_{res}^2(t+\tau)$$
$$m_\phi \gtrsim 2\times10^{-20}\ \text{eV}$$
$$t_{exp} \gg \tau$$

DP mass probability density function (pdf)



Number of events per bin:

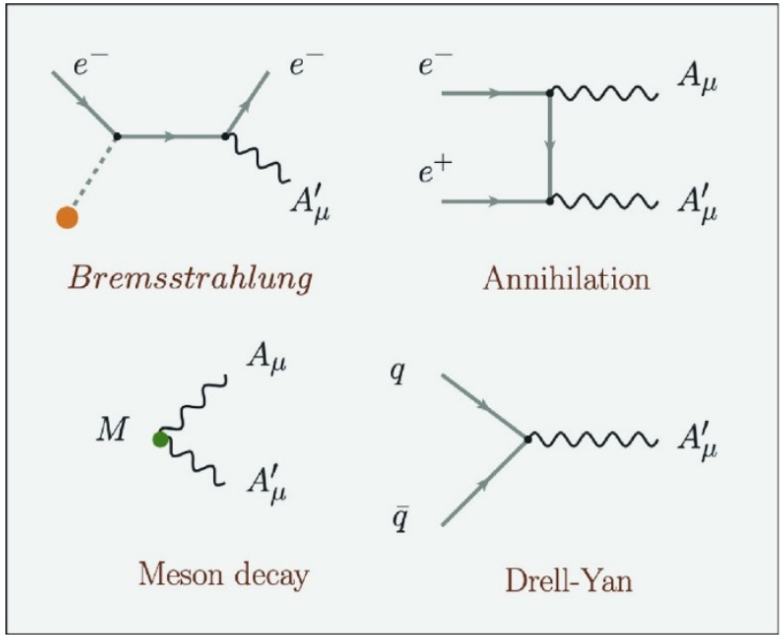
$$N_i = \sigma_{A'}^{(i)}\epsilon_i \text{L} \times \frac{1}{\tau_{A'}}\int_{m_i}^{m_{i+1}}\left|\frac{dt}{dm_{A'}}\right| dm_{A'}$$

$$\left|\frac{dt}{dm_{A'}}\right| = \frac{\tau}{m_0} f(y)$$

Double peak feature!!

Time-varying Mass of Dark Photon

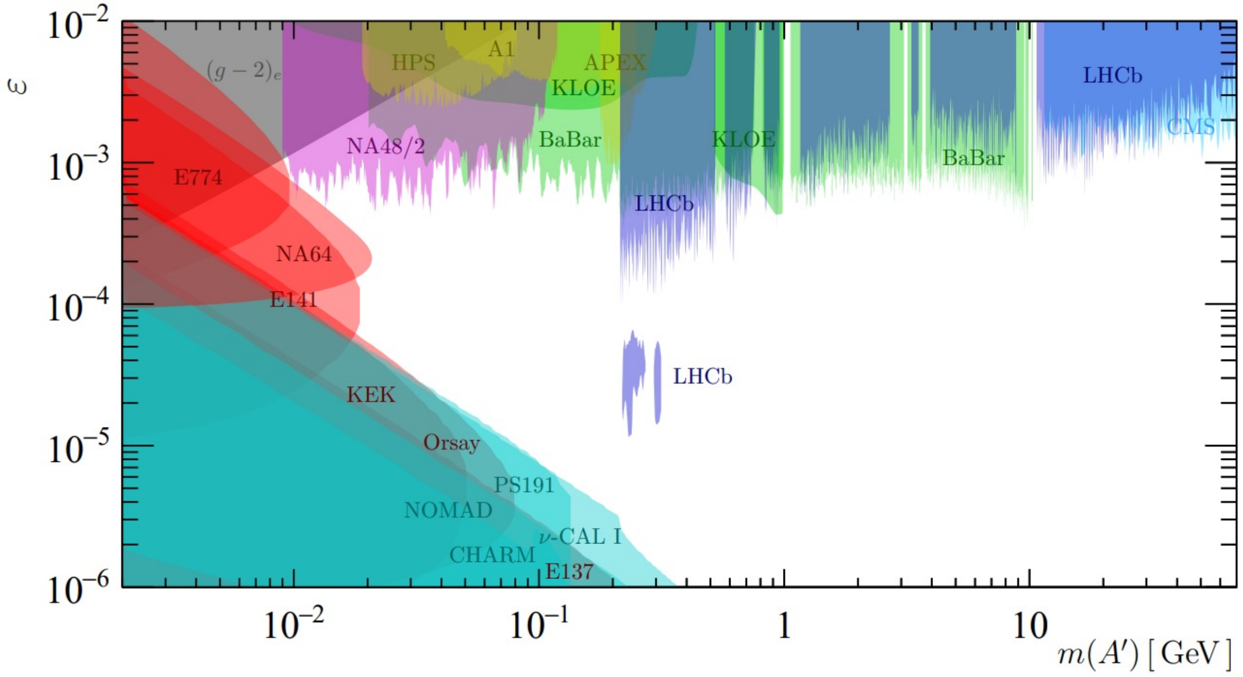
The existing constraints on dark photon mixing



$$\mathcal{L} \supset \epsilon e A'_\mu J^\mu_{\rm em}$$

Constraints on mixing

$$\sigma_{\rm production} \propto \epsilon^2$$



LHCb 1910.06926

Experiments Recast and Reanalysis

- Reanalyzing of existing experiments

Collaboration	Production mode	Experimental environment	Spectrum	Resolution $\sigma_{\rm re}$	Fit window
BaBar [1406.2980]	$e^+e^- \to \gamma A'$	$\sqrt{s} \approx 10$ GeV, 514 fb^{-1}	m_{ee}, $m_{\mu\mu}$	[1.5, 8] MeV	$m_{A'} \pm 10\,\sigma_{\rm re}$
LHCb [1910.06926]	$pp \to A'$	$\sqrt{s} = 13$ TeV, ~ 5 fb^{-1}	$m_{\mu\mu}$	[0.12, 380] MeV	$m_{A'} \pm 12.5\,\sigma_{\rm re}$
A1 [1404.5502]	$e^- Z \to e^- Z A'$	$E_e \in [0.180, 0.855]$ GeV	m_{ee}	0.5 MeV	$m_{A'} \pm 3\,\sigma_{\rm re}$
NA48/2 [1504.00607]	$\pi^0 \to \gamma A'$	1.69×10^7 $\pi^0 \to \gamma e^+ e^-$ events	m_{ee}	[0.16, 1.33] MeV	single bin

- Log likelihood ratio (LLR)

$$-2\log\left[\frac{\mathrm{Max}_{\vec{a}'}\prod_i \mathcal{N}(B_i - B(m_i,\vec{a}') - S f_G(m_i)|B_i)}{\mathrm{Max}_{\vec{a}}\prod_i \mathcal{N}(B_i - B(m_i,\vec{a})|B_i)}\right]$$

- Background fit by $B(m_i,\vec{a}) = a_0 + a_1 m_i + a_2 m_i^2$
- Constraints obtained by $\mathcal{S} \equiv -2\ln(\mathcal{L}/\mathcal{L}_0) = 3.84$

Experiments Recast and Reanalysis

➢Reanalyzing of existing experiments

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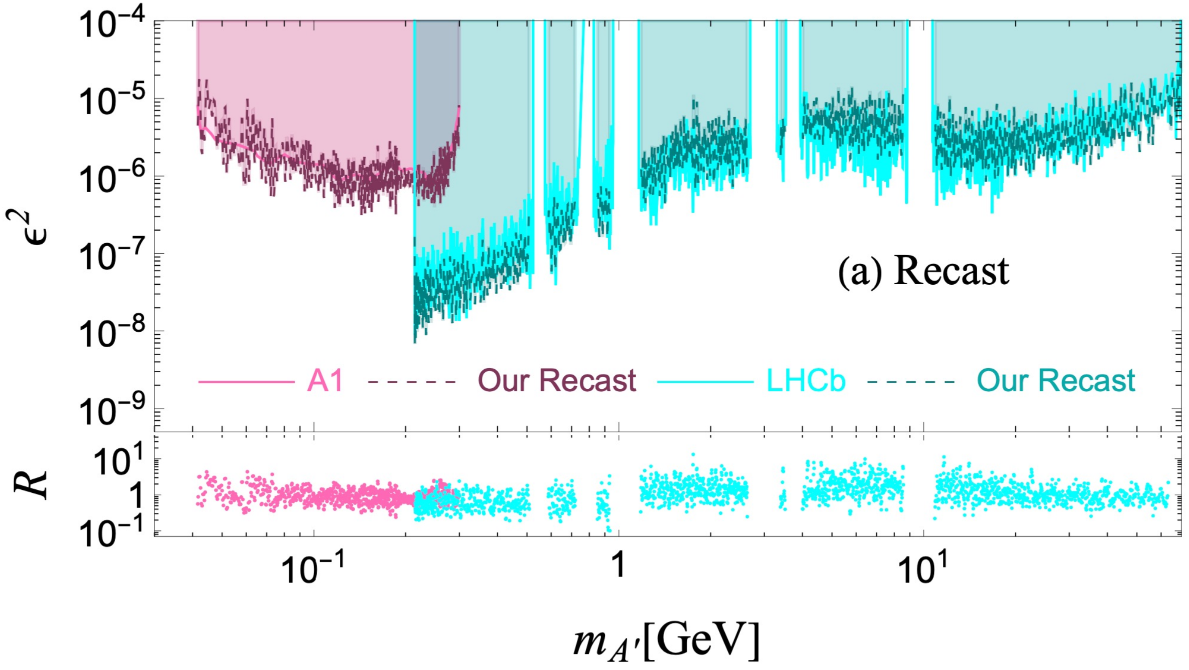
First, repeat the existing bounds with the single-peak signal



Experiments Recast and Reanalysis

- Reanalyzing of existing experiments

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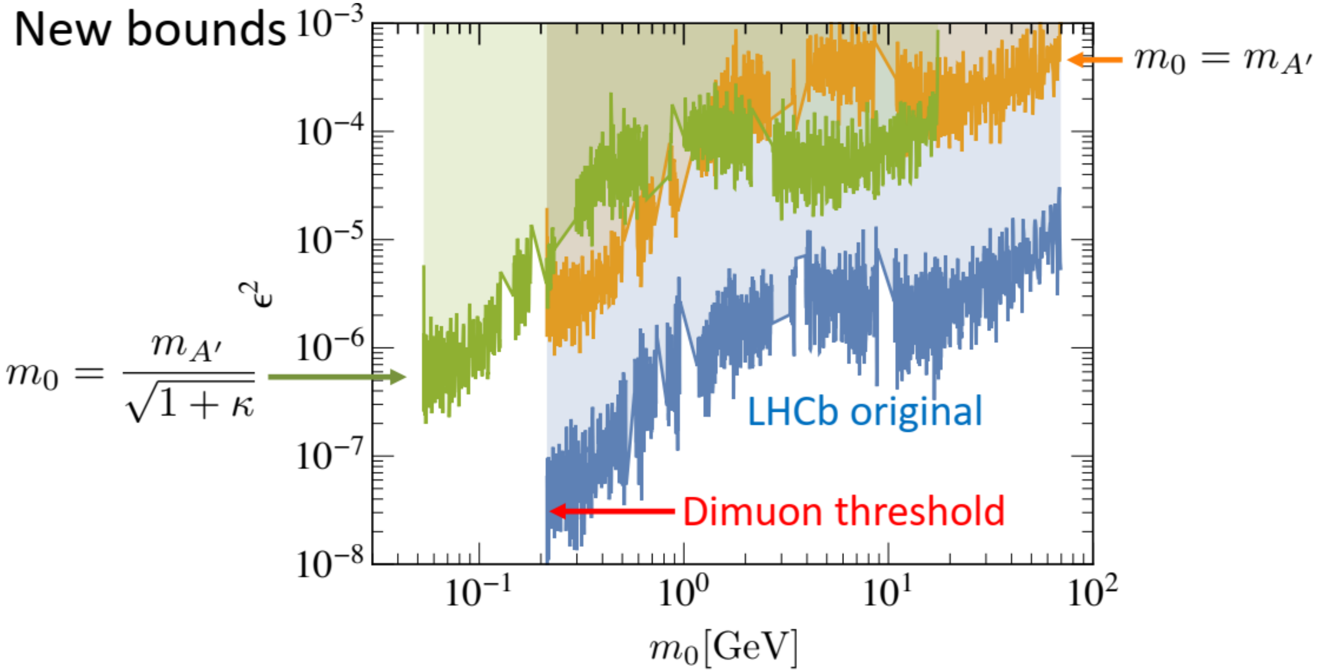
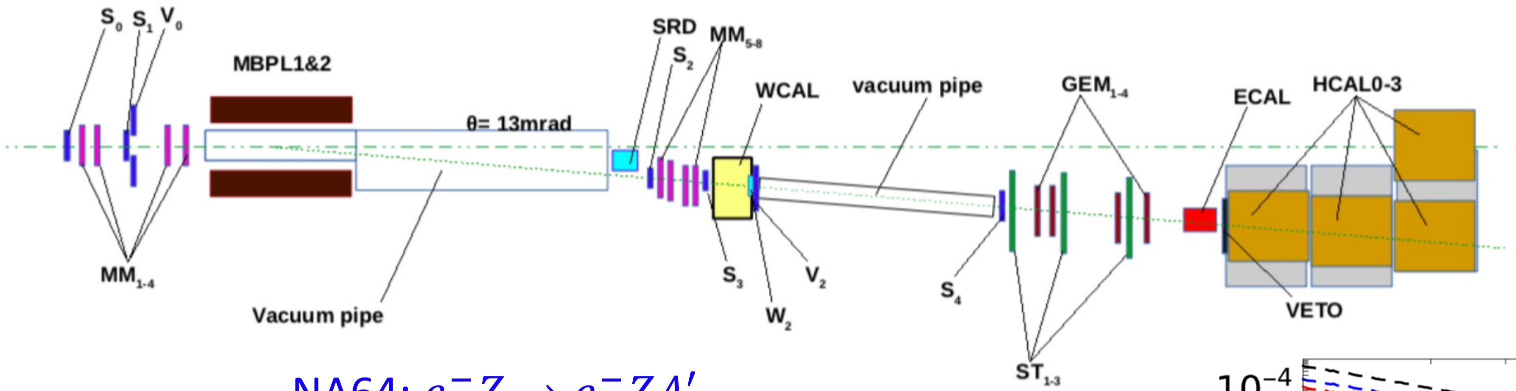
Then, obtain the new bounds:



Experiments Recast and Reanalysis

➢Reanalyzing the beam dump experiments

E774 [PRL67(1991)2942] E141 [PRL59(1987)755] NA64 [1912.11839]



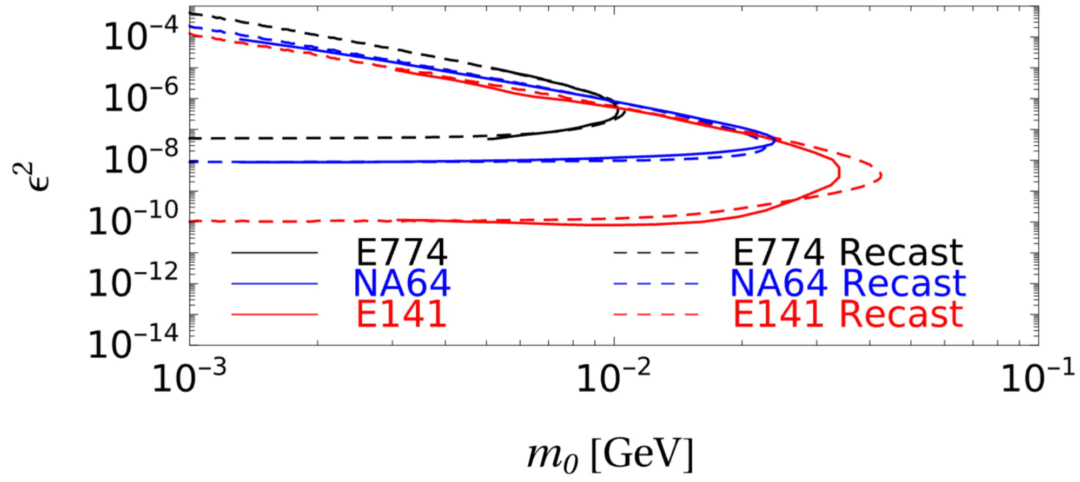
NA64: $e^-Z \to e^-ZA'$

Event number:

$$N(\epsilon, m_{A'}) = N_e \mathcal{C}' \epsilon^2 \frac{m_e^2}{m_{A'}^2} e^{-a_1 L_{\rm sh}\Gamma_{A'}} \times \left(1 - e^{-a_2 L_{\rm dec}\Gamma_{A'}}\right),$$

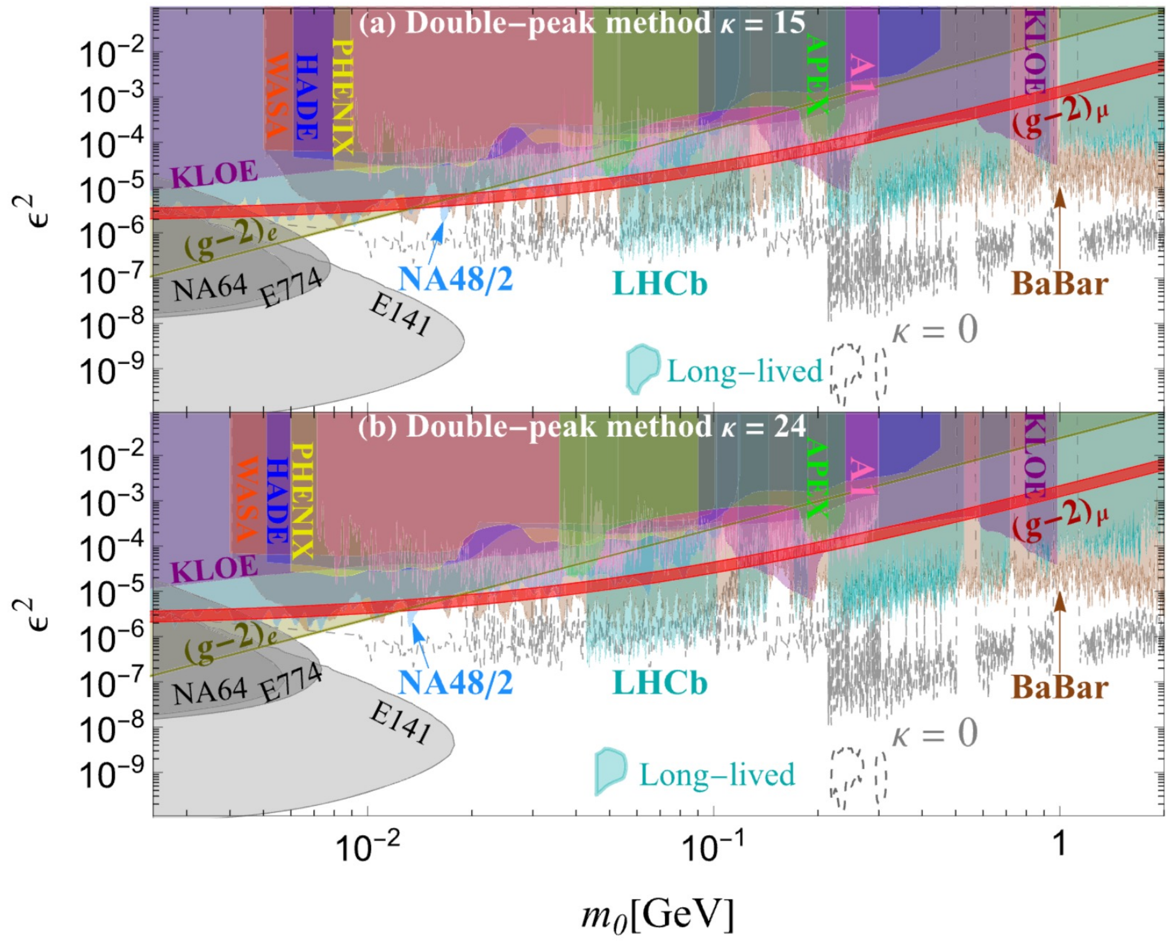
For our signals:

$$N(\epsilon, m_0, \kappa) = \frac{1}{\tau_{A'}} \int_{m_0}^{\sqrt{1+\kappa}m_0} N(\epsilon, m_{A'}) \left|\frac{dt}{dm_{A'}}\right| dm_{A'}.$$



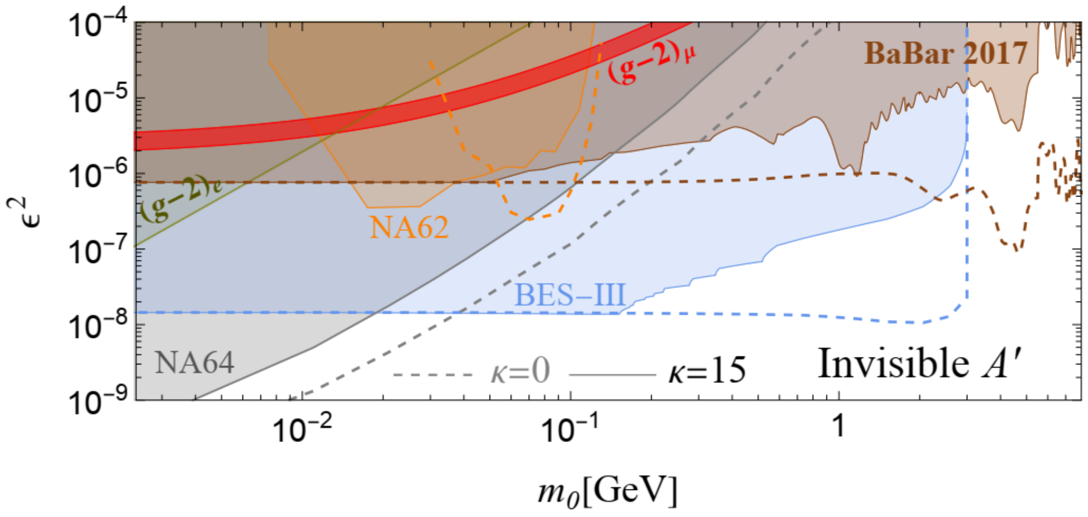
Experiments Recast and Reanalysis

➢Obtain the new constraints:



And the $g-2$: $\frac{1}{\tau}\int_0^\tau dt\ \Delta a_\mu\left(m_{A'}(t)\right)$

➢Invisible Dark Photon Searchesm ($A' \to \chi\bar{\chi}$)



- Monophoton search ($e^+e^- \to A'\gamma$):

$$E_\gamma = \frac{s - m_{A'}^2}{2\sqrt{s}}$$

- Time-varying photon energy spectrum:

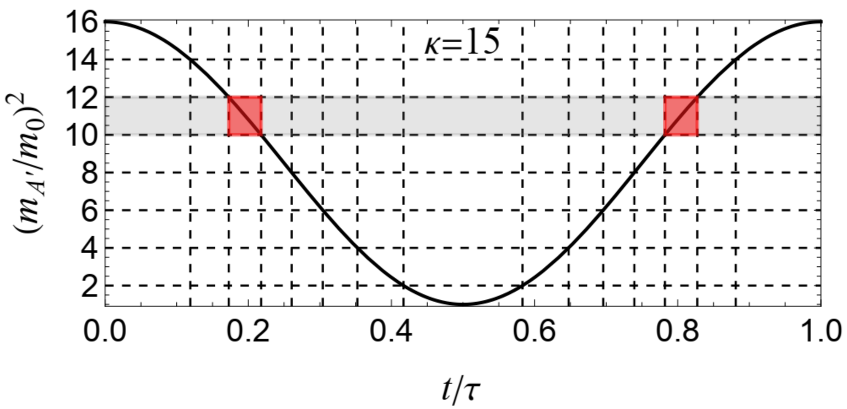
$$\left|\frac{dt}{dE_\gamma}\right| = \frac{\tau}{\pi\sqrt{\left(E_\gamma - E_{\min}\right)\left(E_{\max} - E_\gamma\right)}}$$

Time-dependent Method Analysis

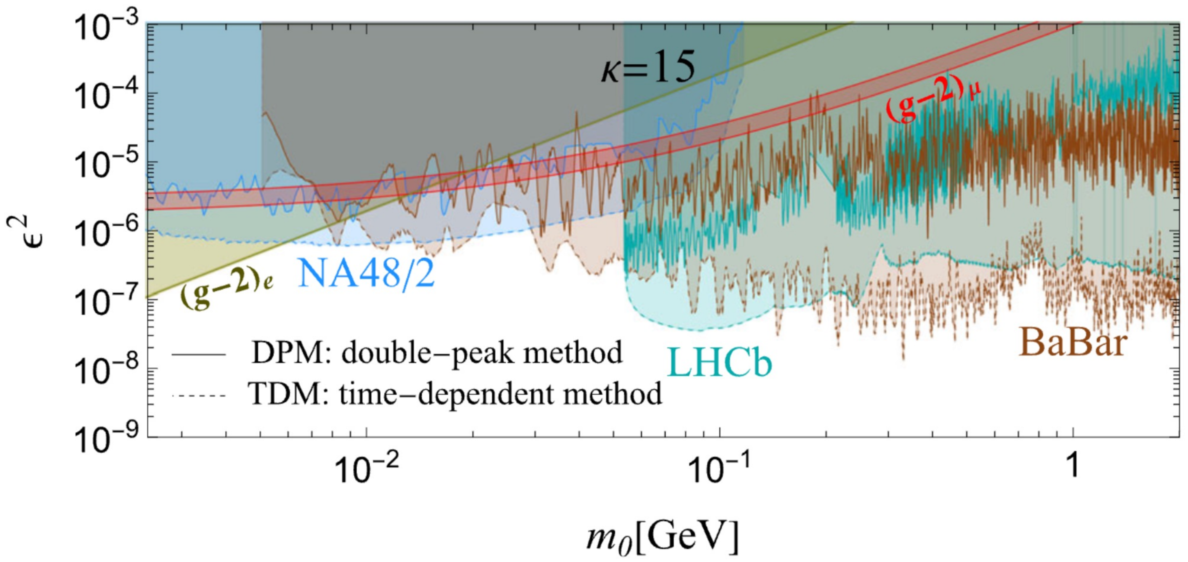
➢Using the time information:

$$N_i^{\rm red} = N_i \frac{1}{\tau} \int_{m_i}^{m_{i+1}} \left| \frac{dt}{dm_{A'}} \right| dm_{A'}$$

$$N_{i,j} = N_i \Delta t_j / \tau$$



- Signal not changed, while background suppressed!



TDM has better constraint than DPM

Time-dependent Method Analysis

➢Analyzing CMS Open Data

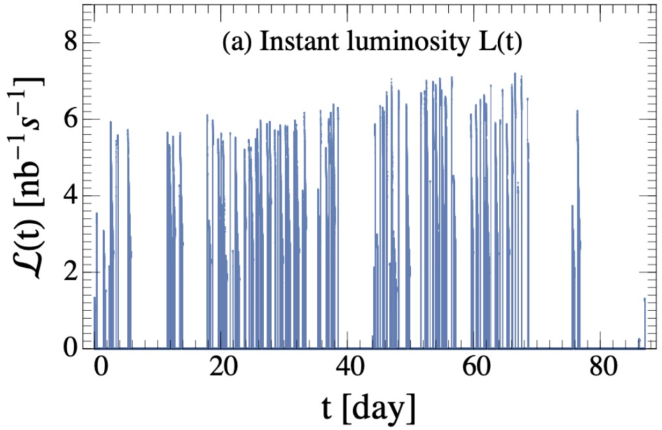
We choose 2012 dimuon events from CMS Open Data to verify the two methods: DPM and TDM

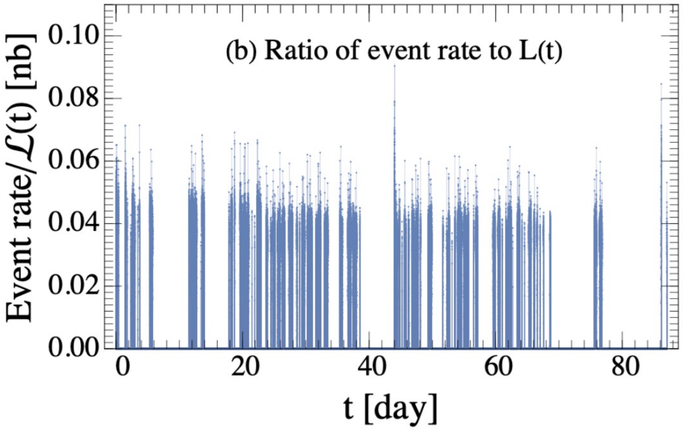
$$\frac{dN_S}{dm_{\ell\ell}} = \int_{t_1}^{t_2} dt\mathcal{L}(t)\frac{d\sigma_S}{dm_{\ell\ell}}$$

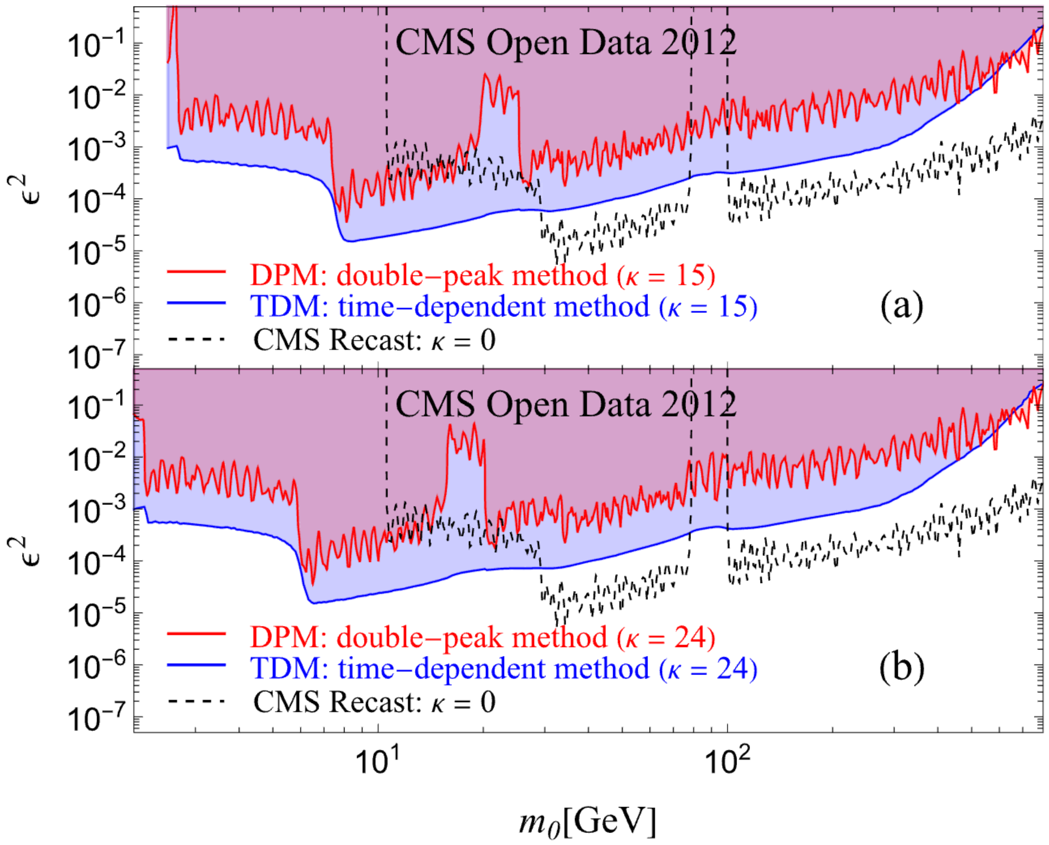
$$= \epsilon_S(m_{\ell\ell})\sigma_0(m_{\ell\ell})\frac{f(y)}{m_0}\frac{\tau}{2}\left[\sum_i \mathcal{L}(t_i^+) + \mathcal{L}(t_i^-)\right],$$

$$\bar{f}(m_{\ell\ell}/m_0) \equiv \frac{1}{\mathrm{L}\epsilon_S(m_{\ell\ell})\sigma_0(m_{\ell\ell})}\frac{dN_S}{d(m_{\ell\ell}/m_0)}$$

$$= f(y)\frac{\tau}{2\mathrm{L}}\left[\sum_i \mathcal{L}(t_i^+) + \mathcal{L}(t_i^-)\right].$$







Conclusion

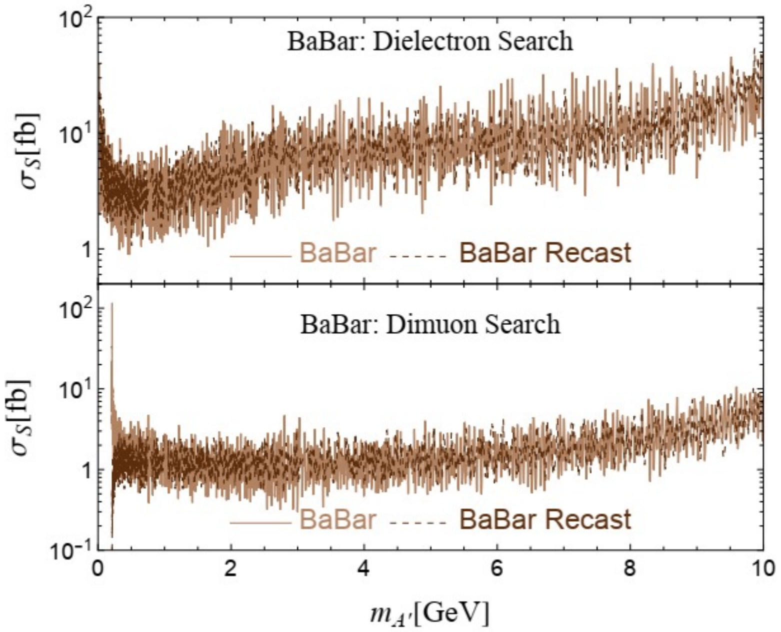
Dark photon can have a time varying mass by coupling with ultralight scalar DM:

- The existing bounds are significantly weakened;
- The muon g-2 solution becomes viable again;
- Including time information of experiments can improve sensitivity;
- CMS Open Data shows the validity of these two methods;
- If we find this time-varying signature, it can be used to unveil the ultralight DM.

Thank You

Backup

➢Repeating of existing constraints



Backup

➢Other constraints

Varying SM fermion mass

$$\frac{\Delta m_f}{m_f} \simeq \frac{3\left(e\epsilon Q_f\right)^2}{16\pi^2}\log\left(\frac{m_0^2+2(g'Q_\phi)^2\phi^*\phi}{m_0^2}\right)$$

Early universe:

1. Thermalization: small coupling $g'Q_\phi \sim 10^{-6} - 10^{-10}$, $m_\phi \sim 10^{-20} - 10^{-17}\text{eV}$, $\kappa \sim 10$; frozen scalar field gives a large DP mass;
2. Black hole super-radiance.