Time-varying resonant mass at collider and beam dump experiments

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2206.14221, Jinhui Guo, YXH , Jia Liu, Xiao-Ping Wang and Ke-Pan Xie

- **Introduction**
- **Time-varying mass of the particle**
- **Experiments recast**
- **Time dependent analysis**
- **Conclusion**

Introduction

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

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

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

  $$\rho_{\rm DM} = m_\phi^2 \phi_0^2 / 2$$

- Ultralight dark matter and varying constants

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

Stadnik et al, 1412.7801, 1503.08540

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

Time-varying mass of the particle

- **Model Setup**

Consider mixing between dark photon and photon

$$\mathcal{L} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_0^2 A'_\mu A'^\mu + \epsilon e A'_\mu J^\mu_{\rm em}$$

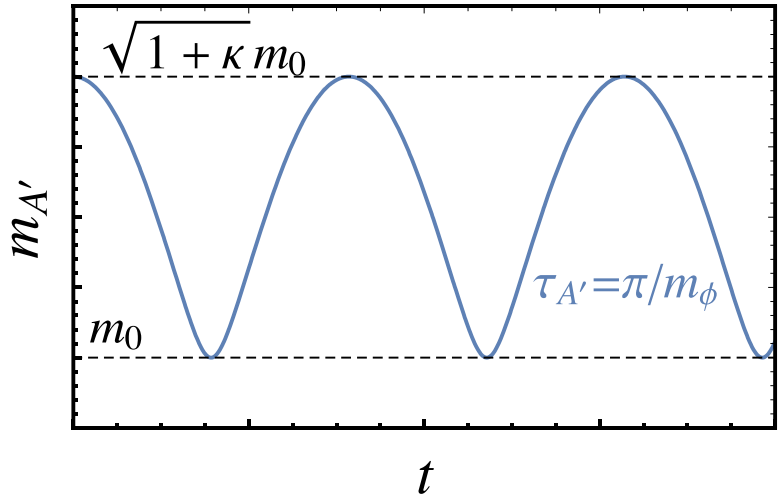
Consider ultralight complex scalar DM $\phi(t) \approx \phi_0 \cos(m_\phi t)$

charged under $U(1)'$

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

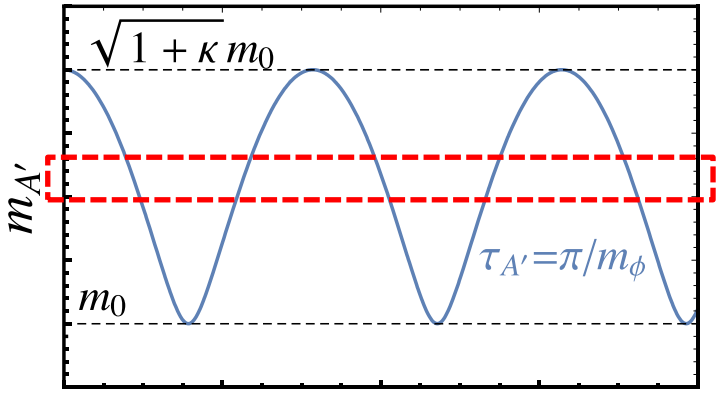
Obtain a time varying mass

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



Time-varying mass of the particle

- **Time varying resonant spectrum** $m_{\rm res}^2(t) = m_{\rm res}^2(t+\tau)$



$$m_\phi \gtrsim 2 \times 10^{-20}\ \text{eV}$$

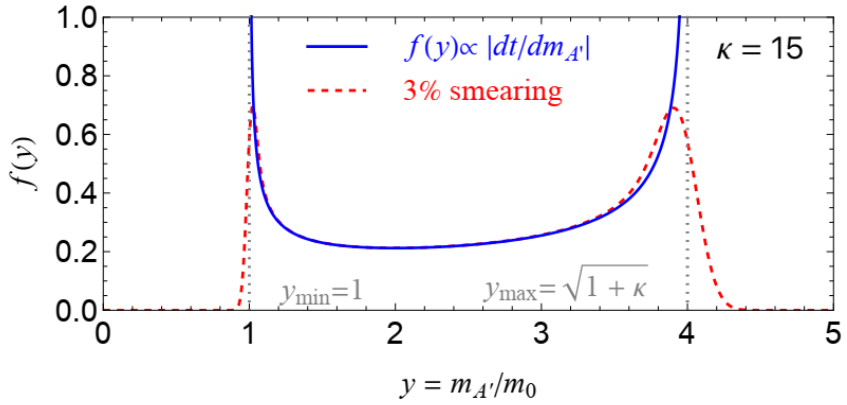
$$t_{\rm exp} \gg \tau$$

number of events per bin

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

mass probability density function

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

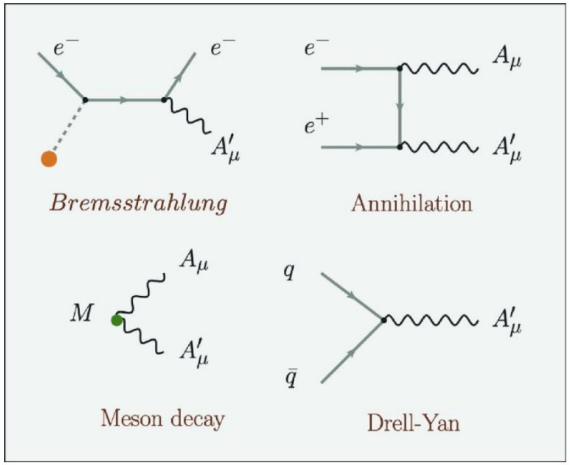


$$f(y) = \frac{2y}{\pi\sqrt{(y^2 - y_{\rm min}^2)\,(y_{\rm max}^2 - y^2)}}$$

double peak

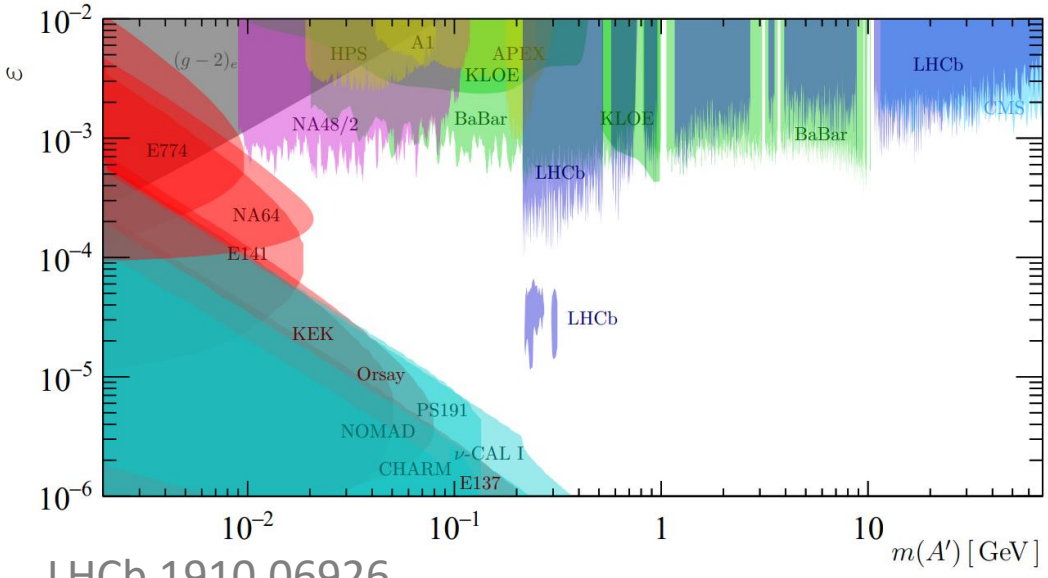
Time-varying mass of the particle

- **The Existing constraints on dark photon mixing**



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

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



LHCb 1910.06926

Experiments recast

- **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]	$e^-Z \to e^-ZA'$	$E_e \in [0.180, 0.855]$ 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

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

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

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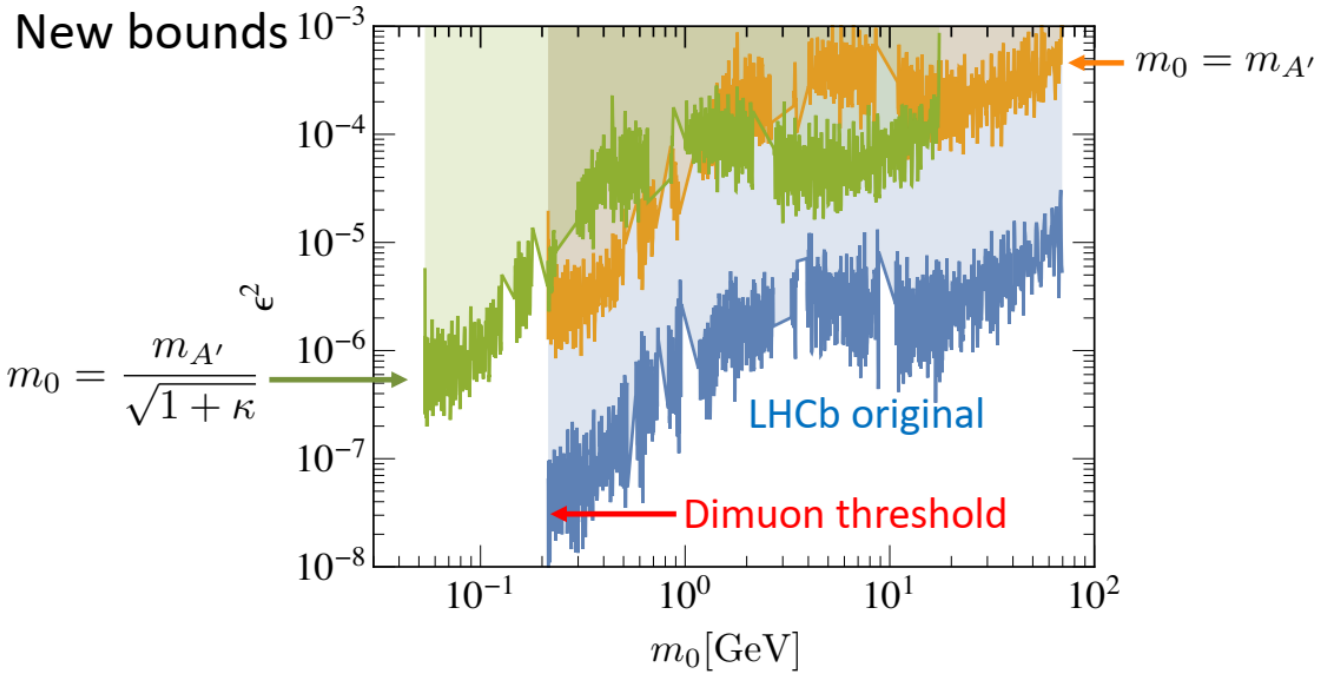
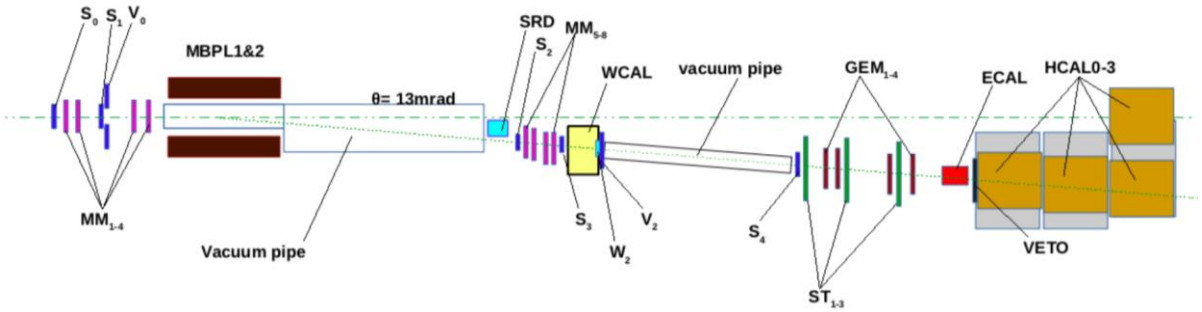


Experiments recast

- **Beam Dump Experiments**

E774 E141 NA64

PRL67(1991)2942 PRL59(1987)755 1912.11389

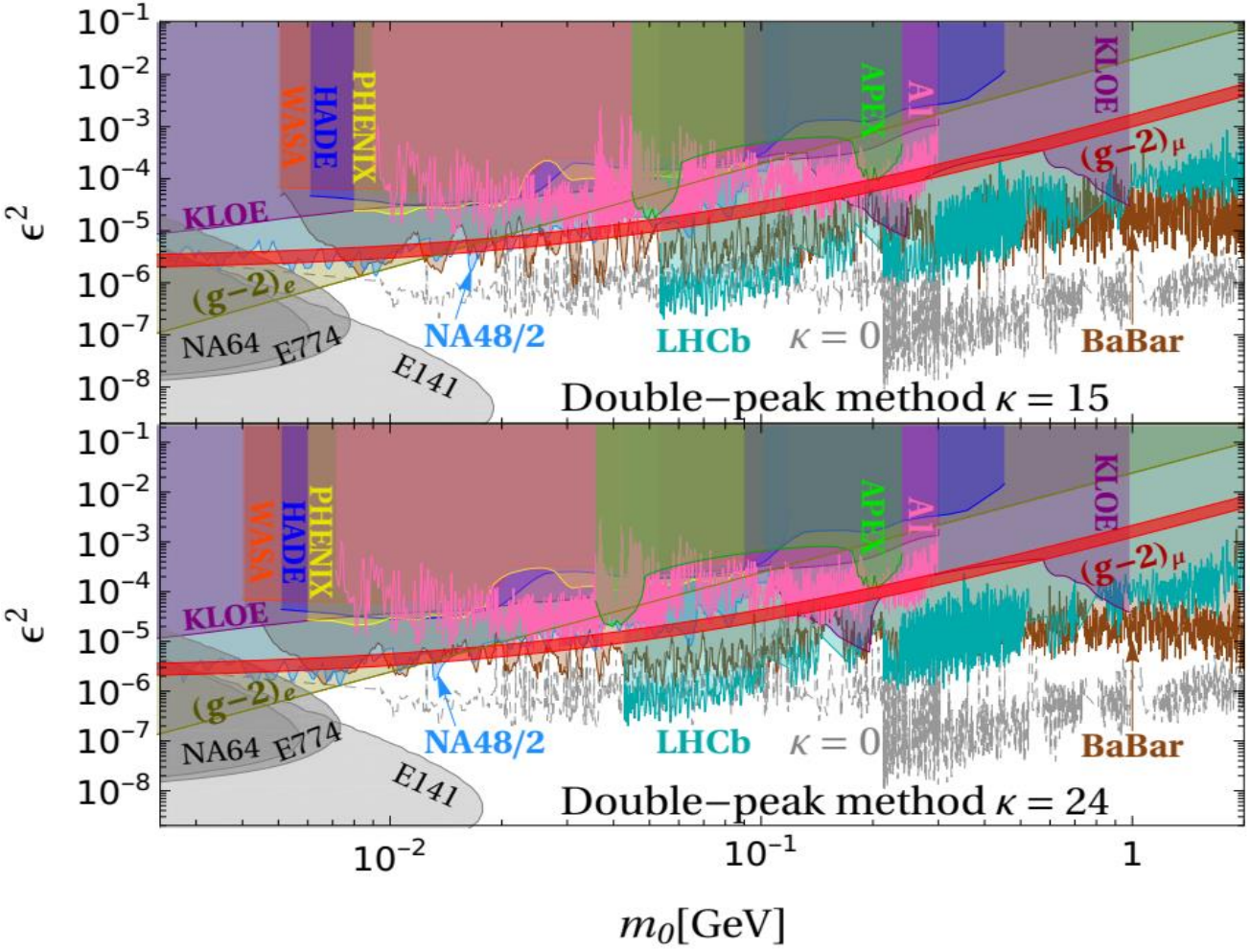


Production process in NA64 $e^- Z \to e^- Z A'$

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

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

Experiments recast

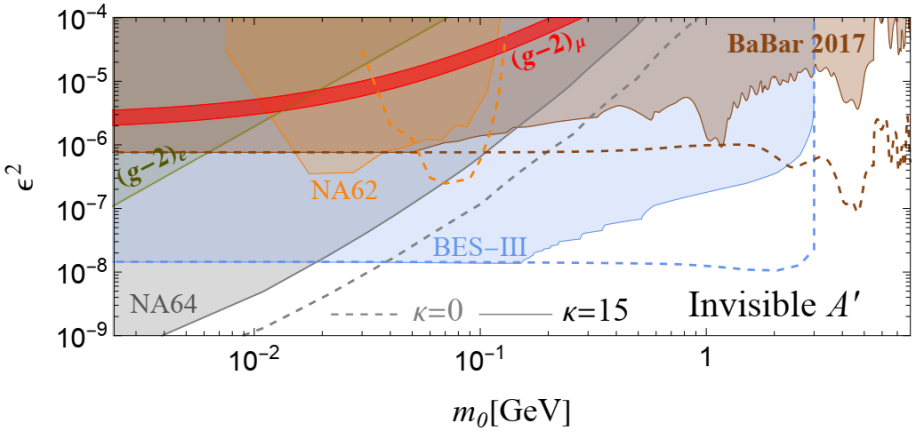


g-2 in time varying case: $\frac{1}{\tau}\int_0^\tau dt\ \Delta a_\mu\left(m_{A'}(t)\right)$

Experiments recast

- **Invisible Dark Photon**

For dark photon decay to dark matter dominantly monophoton search



$$e^+e^- \to A'\gamma$$

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

Time varying photon energy spectrum

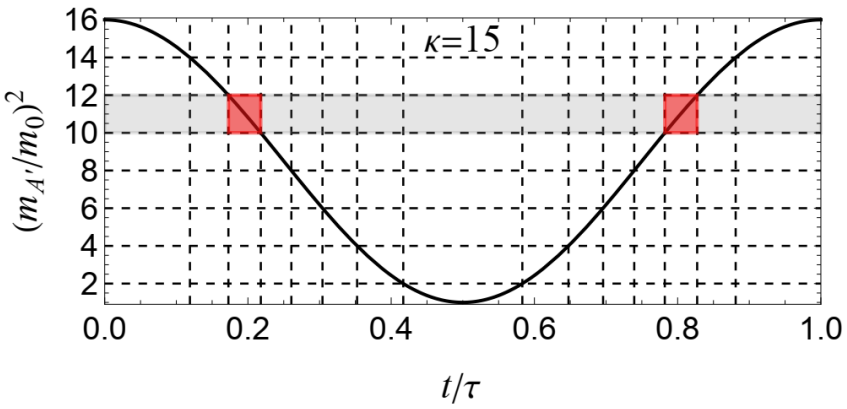
$$\left|\frac{dt}{dE_\gamma}\right| = \frac{\tau}{\pi\sqrt{(E_\gamma - E_{\min})\,(E_{\max} - E_\gamma)}}$$

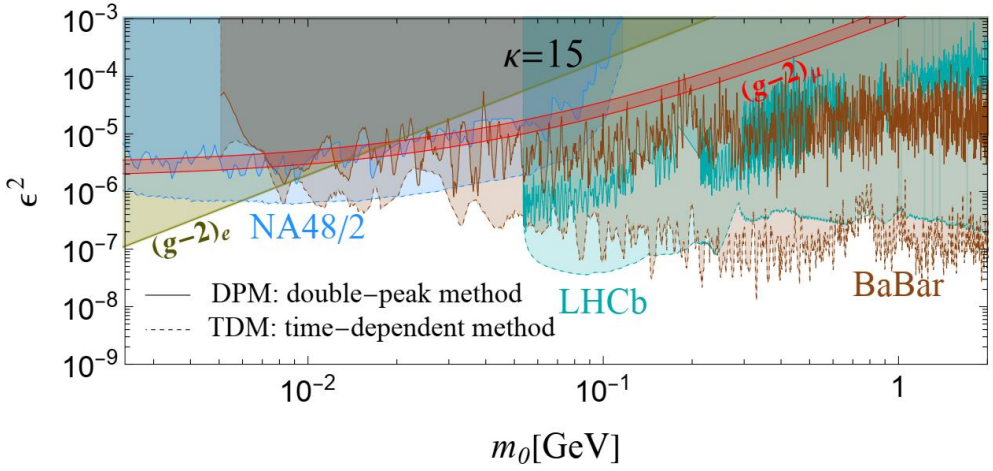
Time dependent analysis

- Using 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

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

Thank You

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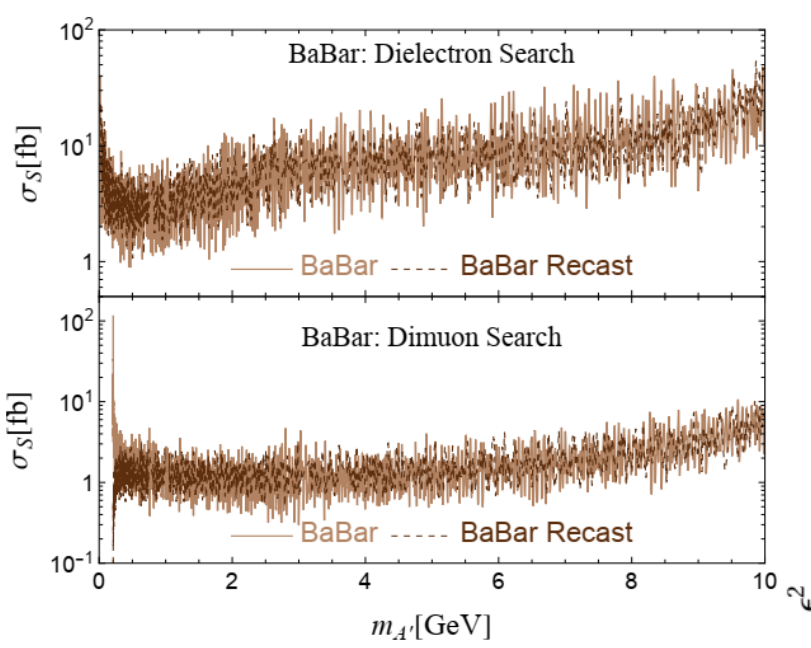
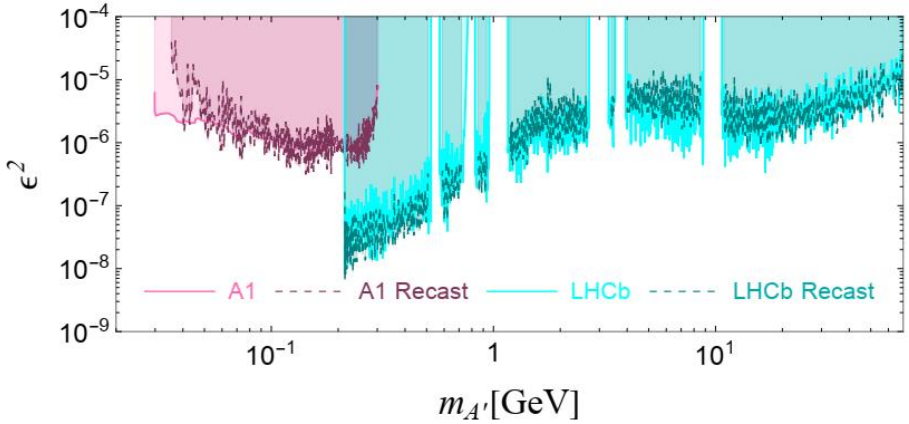
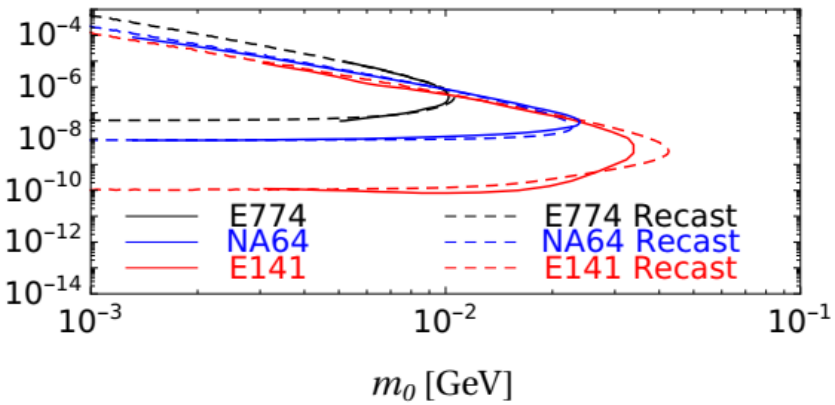
- Repeating of existing constraints







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- 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 constraints