



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

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

$$\text{misalignment mechanism} \quad \phi(t) \approx \phi_0 \cos(m_\phi t)$$

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

- 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

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

Time-varying mass of the particle

- **Model Setup**

Consider mixing between **dark photon** and photon

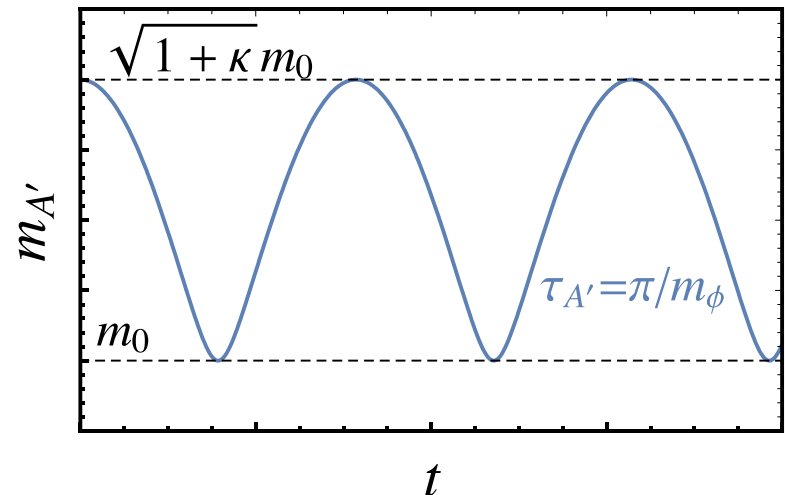
$$\mathcal{L} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_0^2 A'_\mu A'^\mu + \epsilon e A'_\mu J_{\text{em}}^\mu$$

Consider ultralight **complex scalar DM** $\phi(t) \approx \phi_0 \cos(m_\phi t)$
charged under $U(1)'$

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

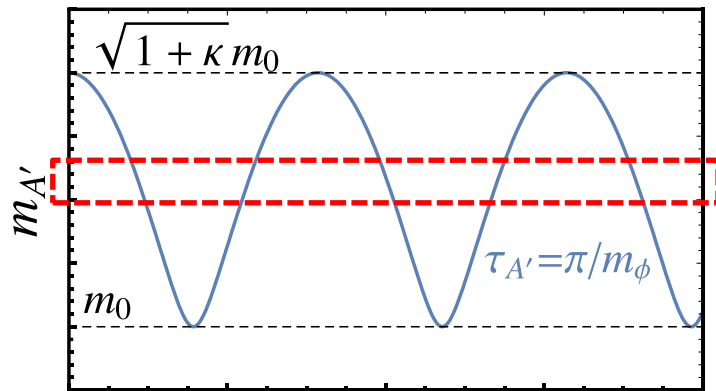
Obtain a time varying mass

$$\begin{aligned} m_{A'}(t) &= \sqrt{m_0^2 + 2(g' Q_\phi)^2 |\phi_0|^2 \cos^2(m_\phi t)} \\ &\equiv m_0 \sqrt{1 + \kappa \cos^2(m_\phi t)} \\ \kappa &\equiv 2(g' Q_\phi)^2 \rho_{\text{DM}} / (m_\phi^2 m_0^2) \end{aligned}$$



Time-varying mass of the particle

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



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

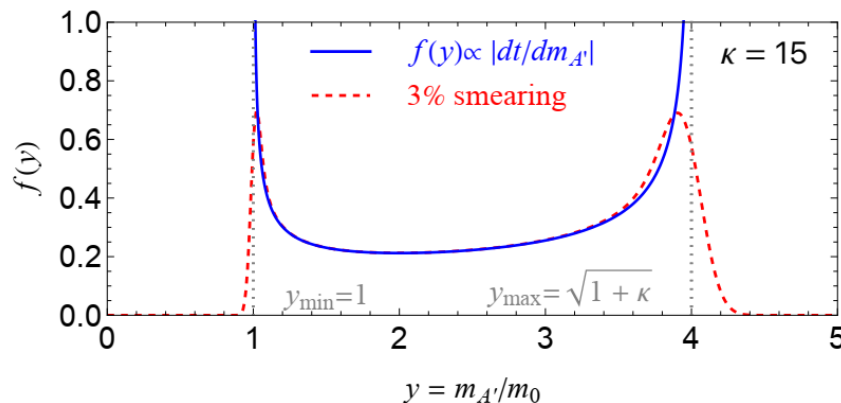
$$t_{\text{exp}} \gg \tau$$

number of events per bin

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

mass probability density function

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

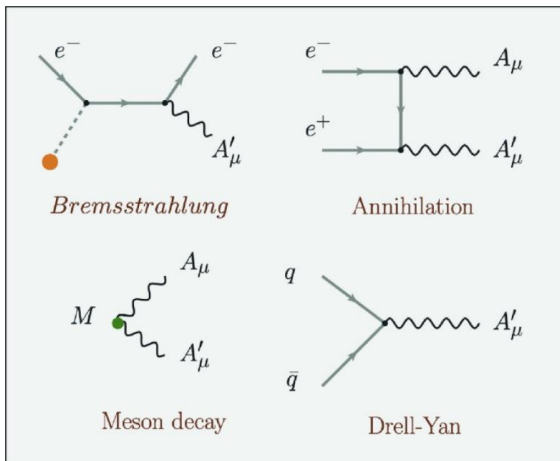


$$f(y) = \frac{2y}{\pi \sqrt{(y^2 - y_{\min}^2)(y_{\max}^2 - y^2)}}$$

double peak

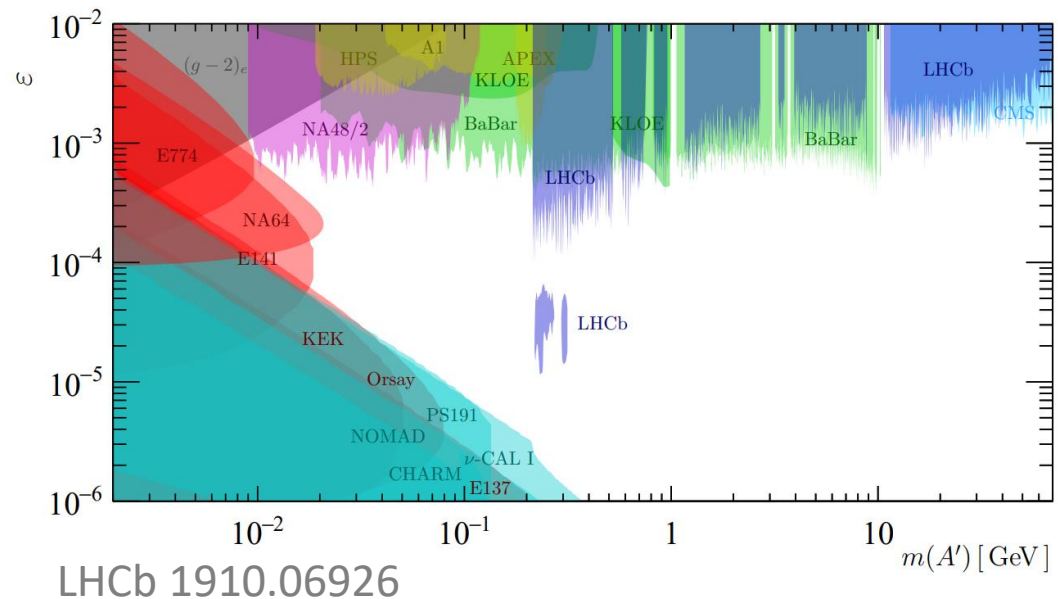
Time-varying mass of the particle

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



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

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



Experiments recast

- **Reanalyzing of existing experiments**

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

Log likelihood ratio

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

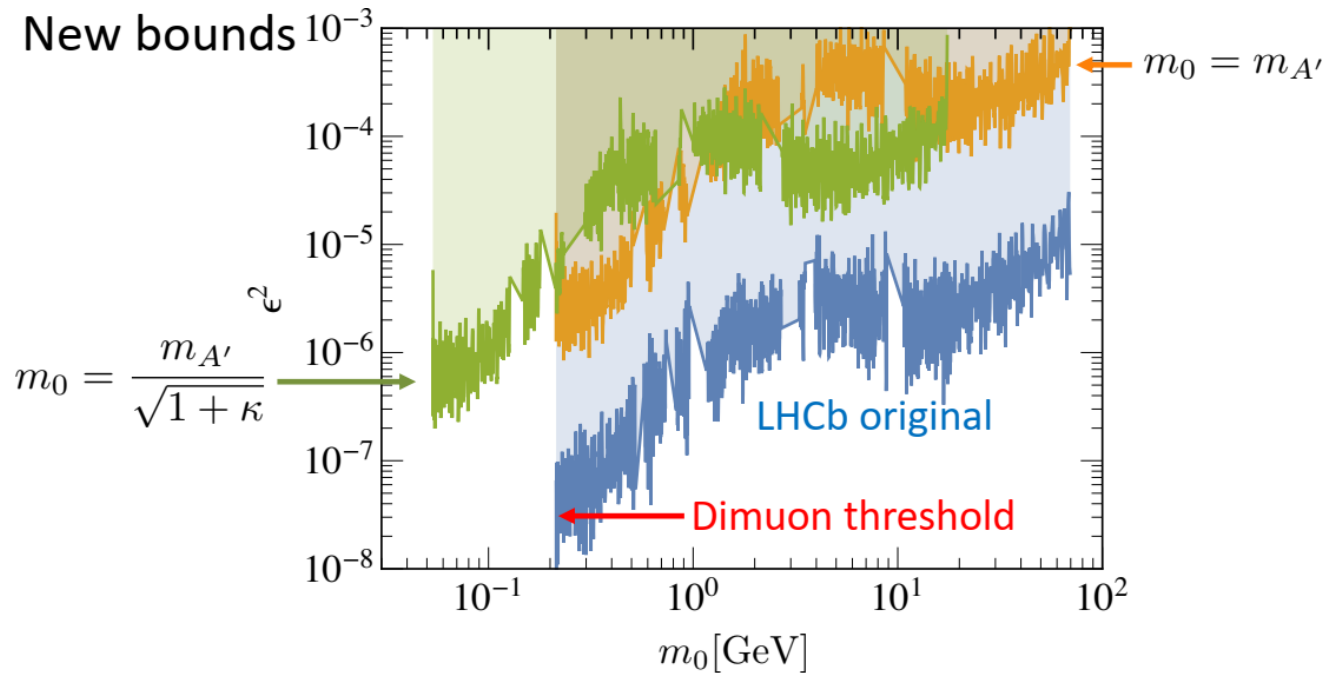
Background fit by $B(m_i, \vec{a}) = a_0 + a_1 m_i + a_2 m_i^2$

Constraints obtained by $\mathcal{S} \equiv -2 \ln(\mathcal{L}/\mathcal{L}_0) = 3.84$

Experiments recast

- Reanalyzing of existing experiments

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Experiments recast

- **Beam Dump Experiments**

E774

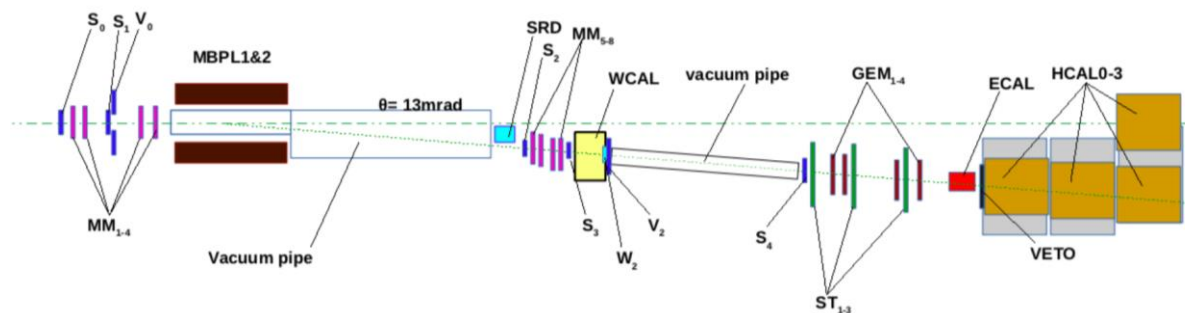
PRL67(1991)2942

E141

PRL59(1987)755

NA64

1912.11389

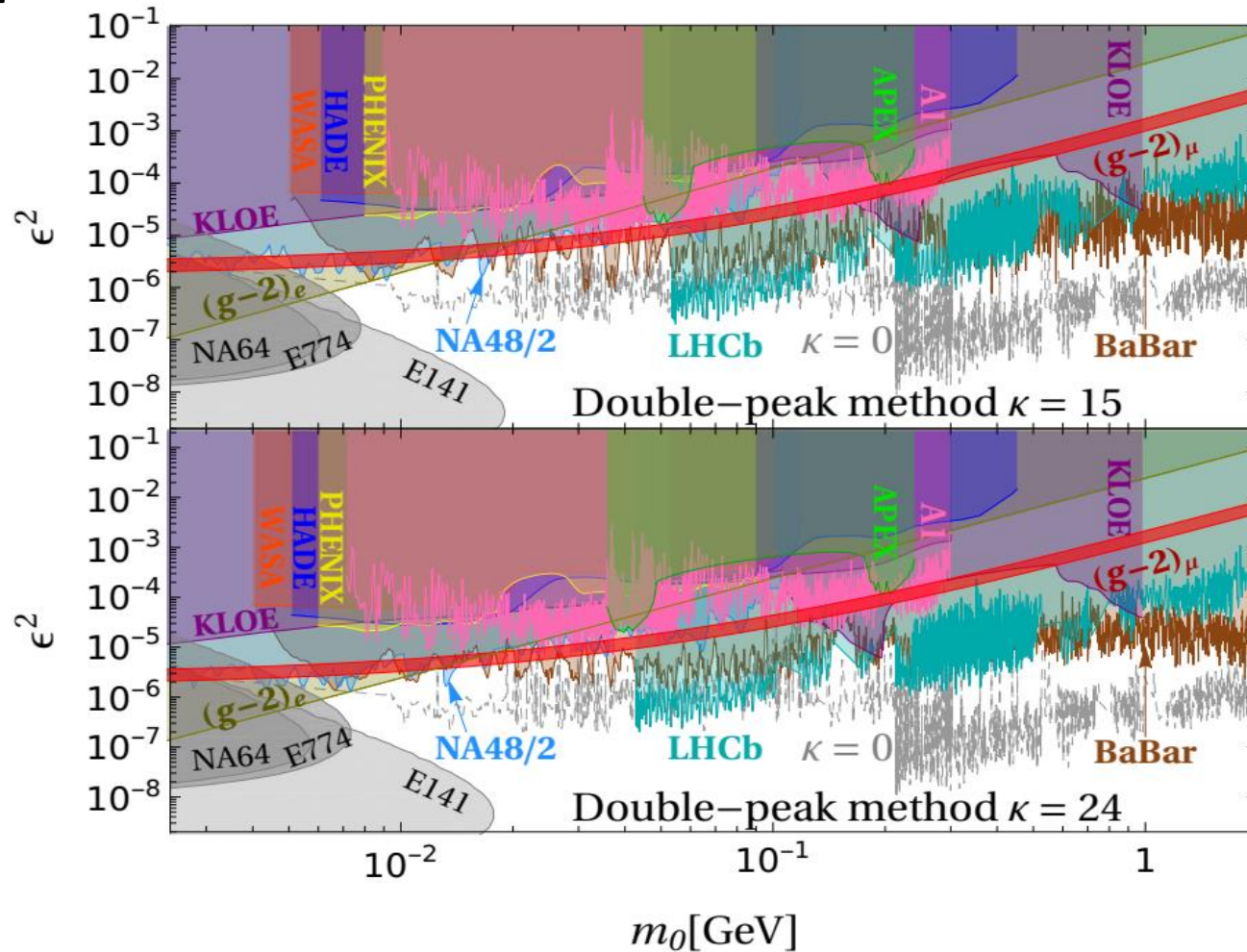


Production process in NA64 $e^- Z \rightarrow e^- Z A'$

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

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

Experiments recast

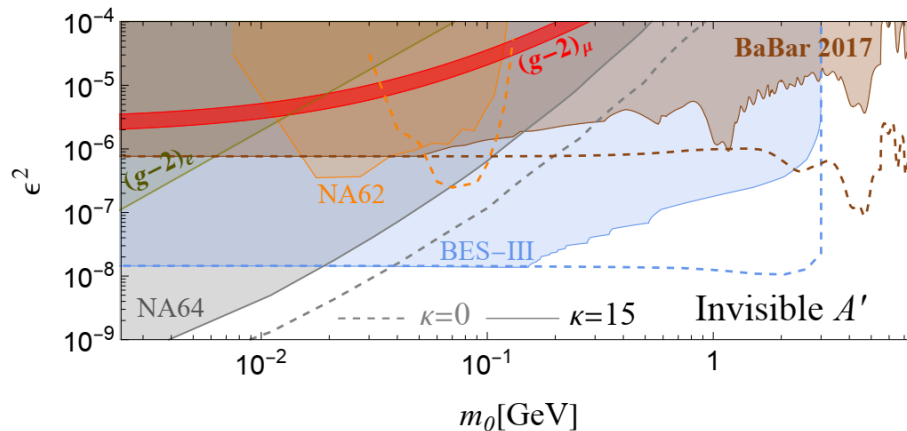


$g-2$ in time varying case: $\frac{1}{\tau} \int_0^\tau dt \Delta a_\mu(m_{A'}(t))$

Experiments recast

- **Invisible Dark Photon**

For dark photon decay to dark matter dominantly
monophoton search



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

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

Time varying photon energy spectrum

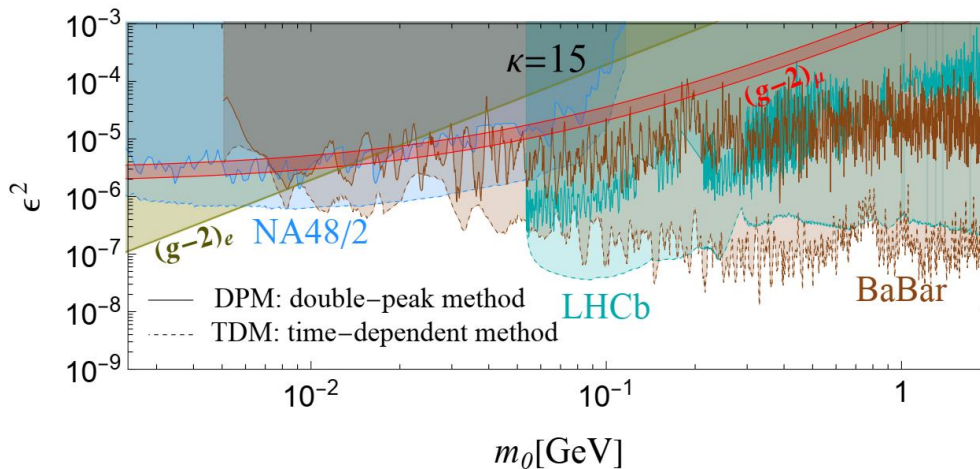
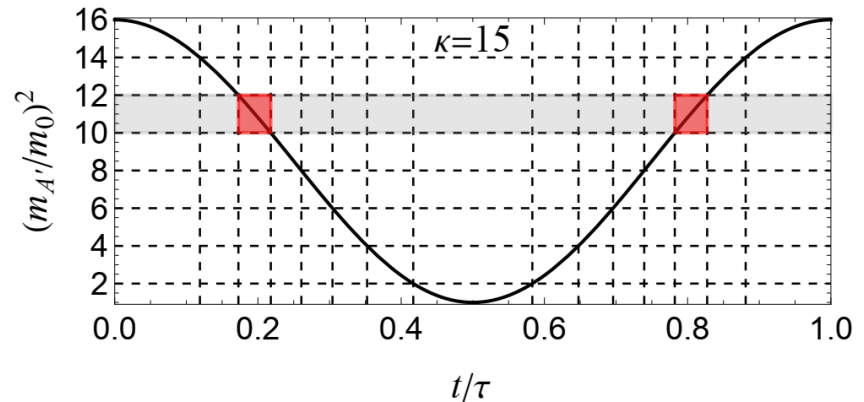
$$\left| \frac{dt}{dE_\gamma} \right| = \frac{\tau}{\pi \sqrt{(E_\gamma - E_{\min})(E_{\max} - E_\gamma)}}$$

Time dependent analysis

- Using time information

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

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



Signal not changed, while
background suppressed

Conclusion

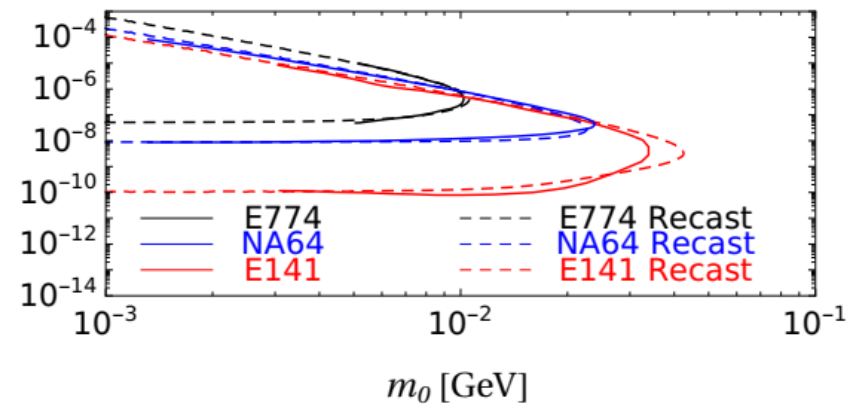
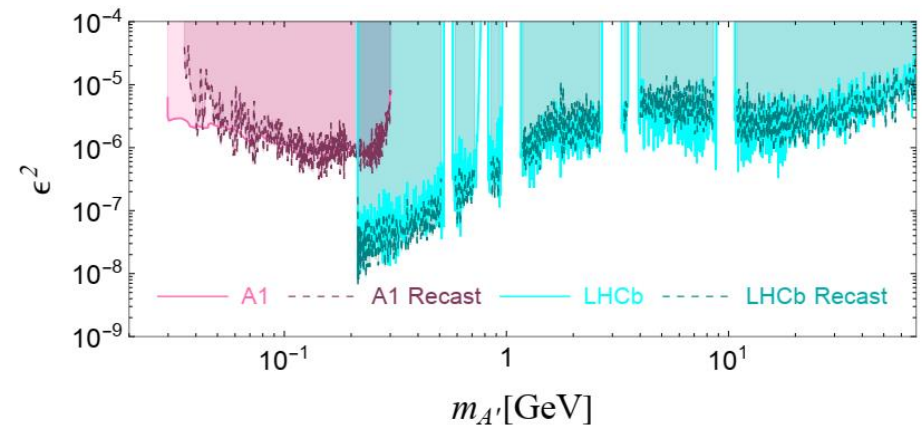
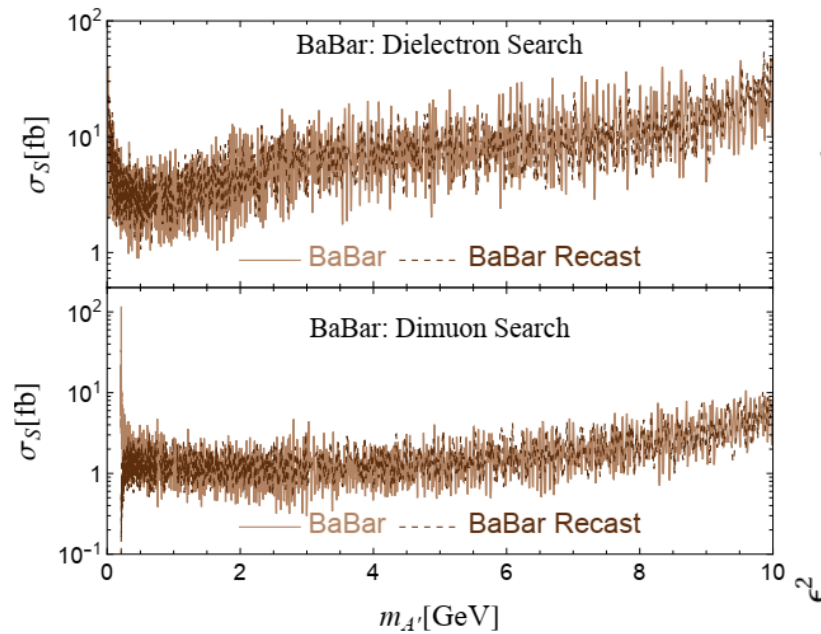
dark photon can have a time varying mass by coupling with ultralight scalar DM:

- The existing bounds are significantly weakened
- The muon $g-2$ solution becomes viable again
- Including time information of experiments can improve sensitivity

Thank You

backup

- Repeating of existing constraints



backup

- Other constraints

Varying SM fermion mass

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

Early universe constraints