Time-varying resonant mass at collider and beam dump experiments

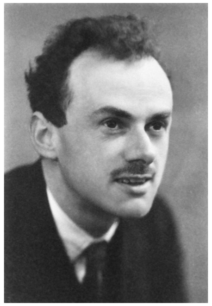
Ke-Pan Xie (谢柯盼)
University of Nebraska-Lincoln

2022.7.6 @SYSU-PKU forum (online)

arXiv:2206.14221, with Jinhui Guo, Yuxuan He, Jia Liu and Xiao-Ping Wang

Dirac's insight into physical constants

Relation between large numbers?[Dirac, Nature 139 (1937) 323]



$$\frac{e^2}{4\pi}/GM_eM_p \approx 10^{39}$$

$$\frac{M_{\rm matter}}{M_p} \approx 10^{80}$$

$$\frac{t_{\rm Universe}}{e^2/(m_pc^3)} \approx 10^{42}$$

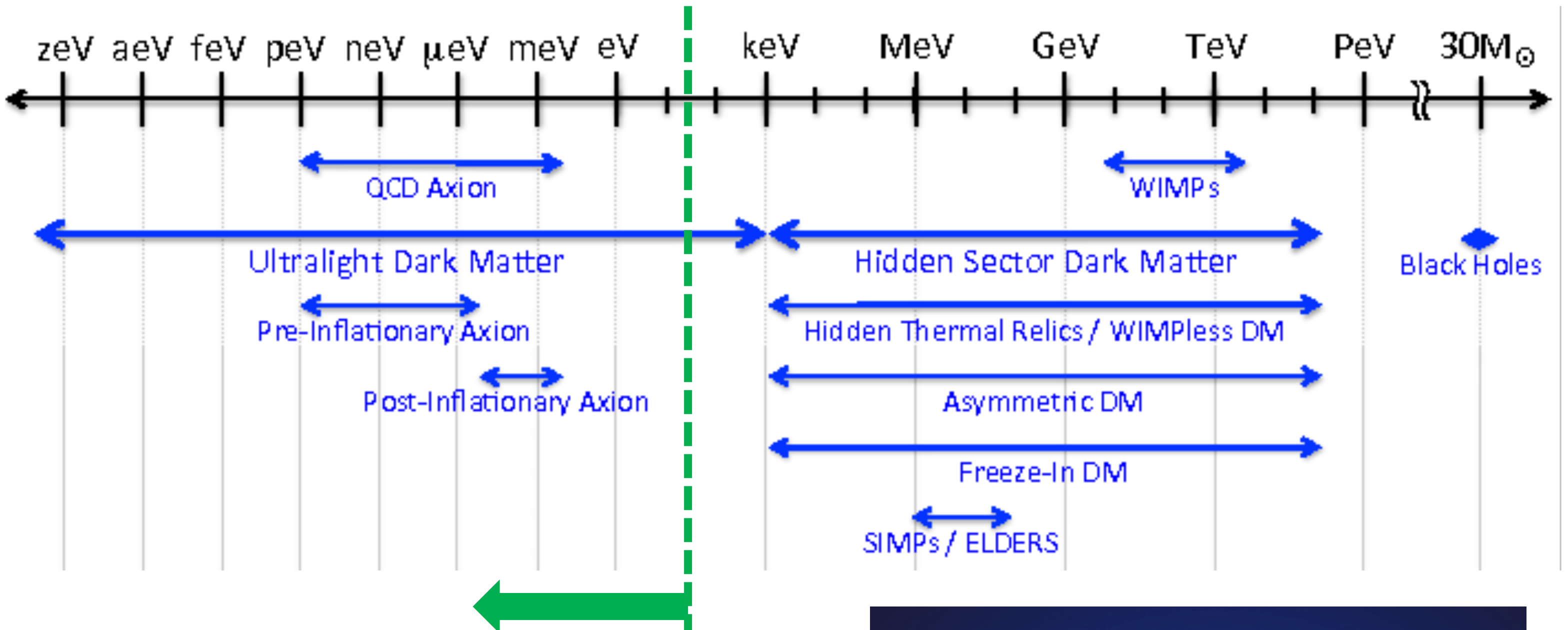
$$\frac{e^2}{4\pi}/(GM_eM_p) \approx \frac{t}{e^2/(m_pc^3)}?$$

$$\frac{M_{\rm matter}}{M_p} \approx \left(\frac{t}{e^2/(m_pc^3)}\right)^2?$$

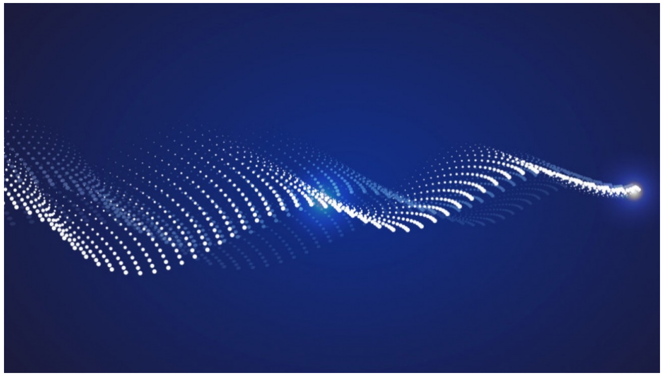
Hence $G \propto 1/t$

The idea of time-varying physical constants!

Varying physical constants from dark sector



m_ϕ < 30 eV: wave-like DM [Hui, 2101.11735]
Background fields!

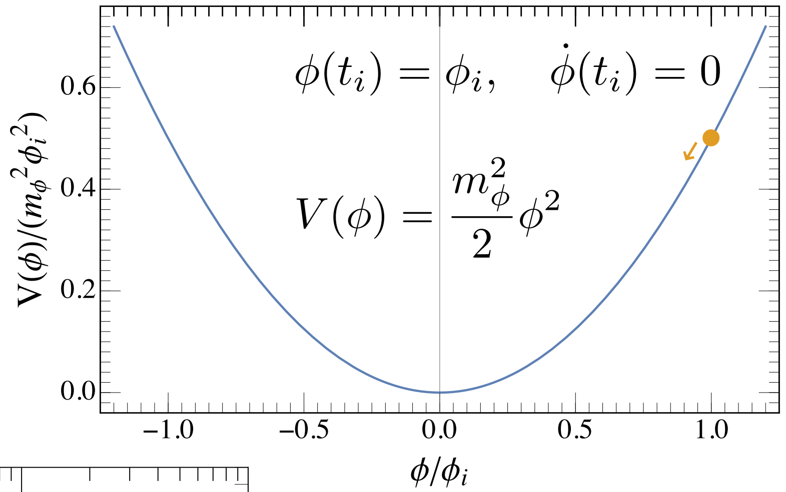


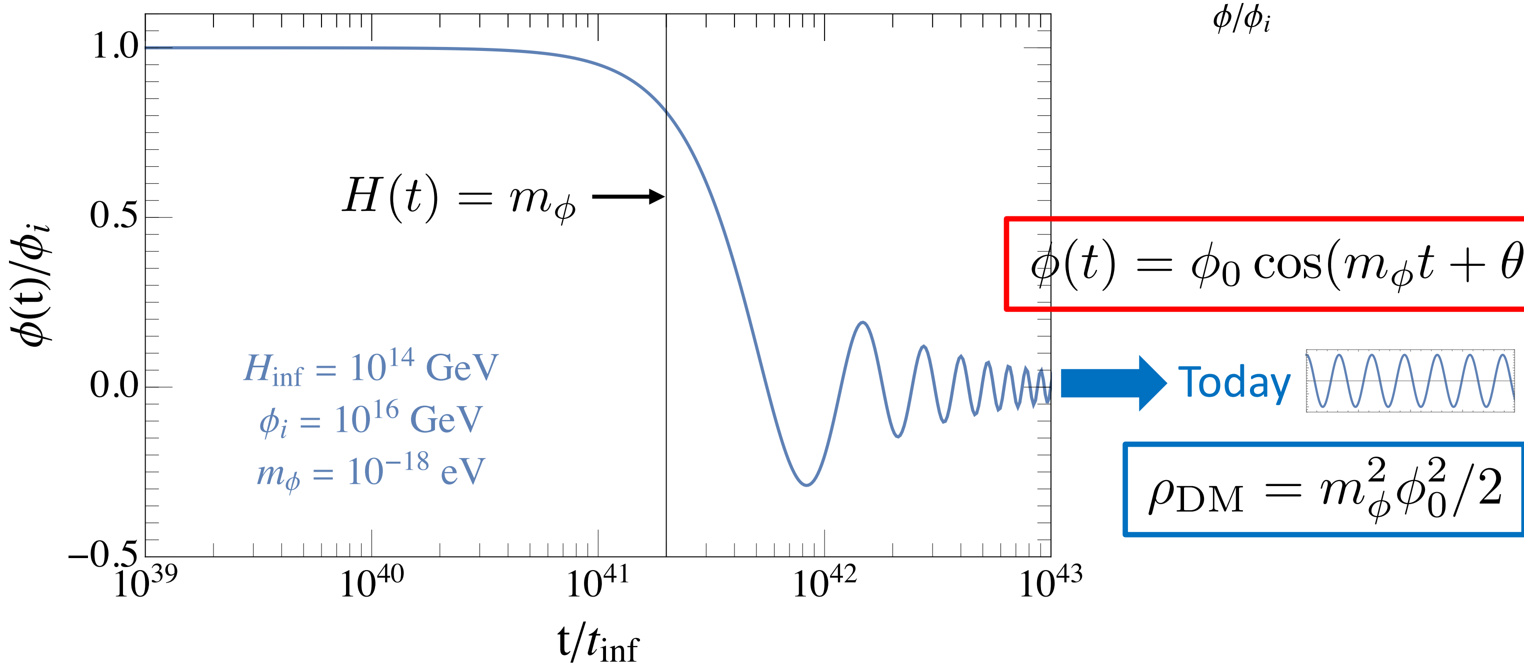
Ultralight dark matter

Misalignment mechanism

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

Hubble constant





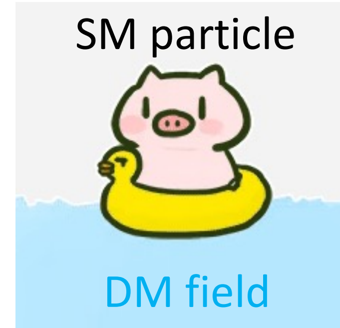
$$\phi(t) = \phi_0 \cos(m_\phi t + \theta_0)$$

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

Constraints: $m_\phi > 10^{-20}$ eV (Lyman-alpha forest)[Rogers *et al*, 2007.12705]

Ultralight dark matter and varying constants

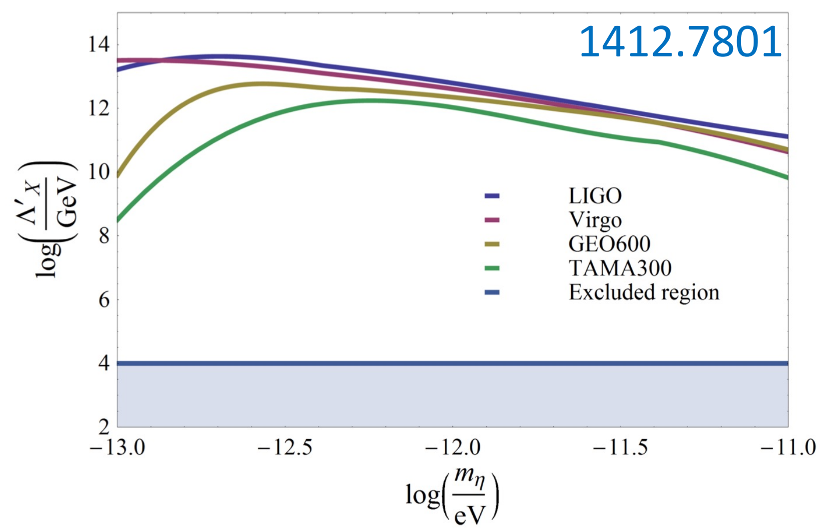
DM as an oscillating background



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

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

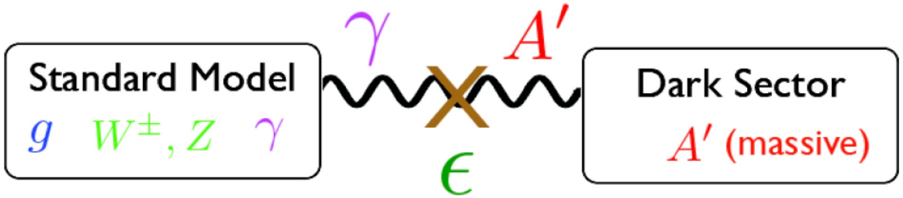
Time varying physical constants [Stadnik *et al*, 1412.7801, 1503.08540]



Constraints from laser/maser interferometry, BBN, etc

Varying dark particle mass [**this work**]

The classic dark $U(1)_D$ model



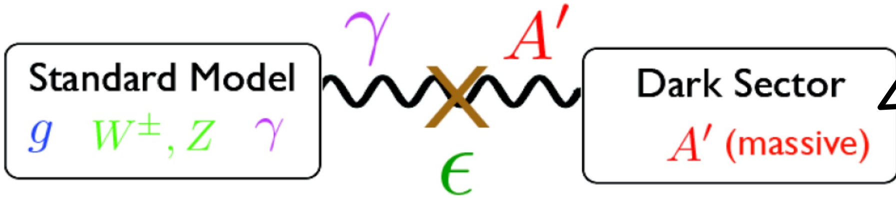
$$\Delta\mathcal{L} = \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$

"Kinetic Mixing" Holdom

Galison, Manohar

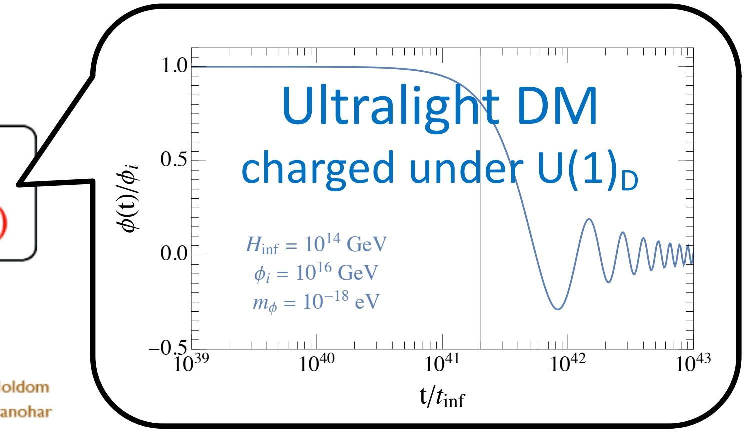
Varying dark particle mass [**this work**]

The classic dark $U(1)_D$ model



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

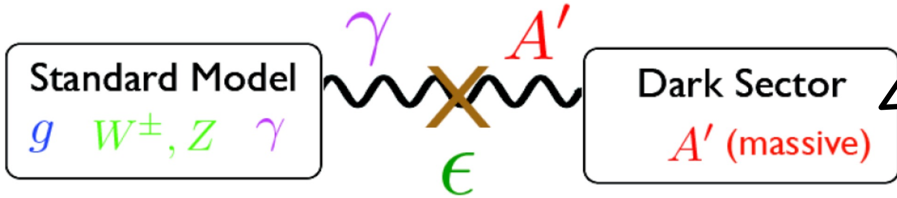
"Kinetic Mixing" Holdom Galison, Manohar



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

Varying dark particle mass [**this work**]

The classic dark $U(1)_D$ model

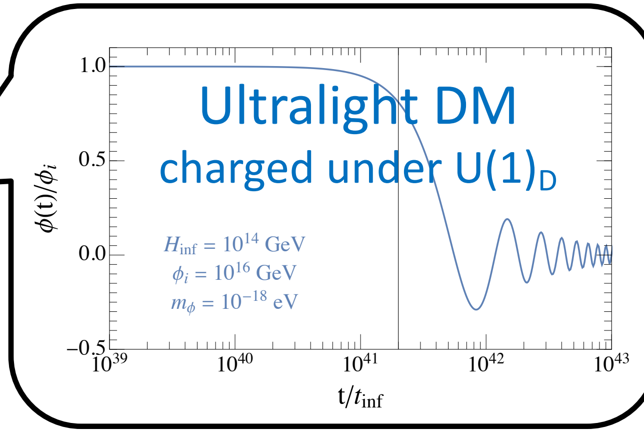


$$\Delta\mathcal{L} = \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$

"Kinetic Mixing"

Holdom

Galison, Manohar



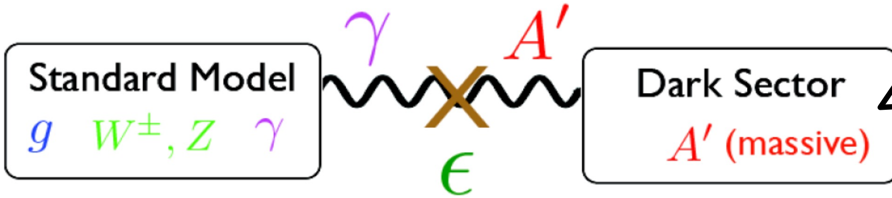
$$\phi(t) \approx \phi_0 \cos(m_\phi t)$$

DM couples to *A'*

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

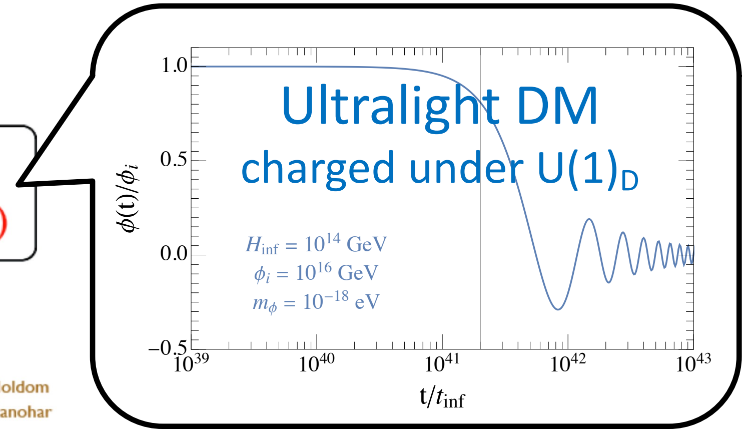
Varying dark particle mass [**this work**]

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



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

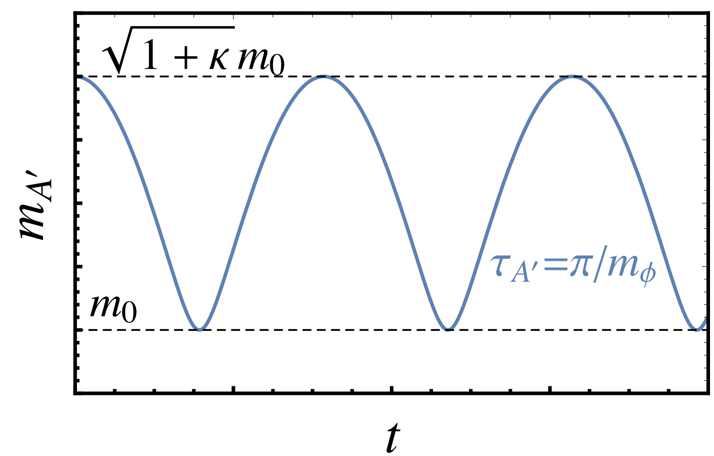
DM couples to *A'*

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

Dark photon mass oscillation!

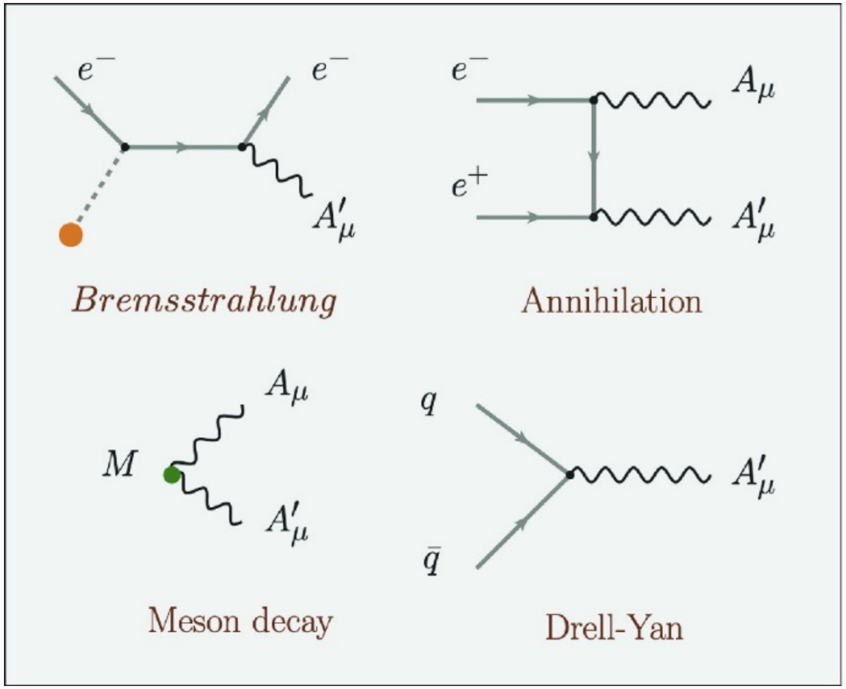
$$m_{A'}(t) = \sqrt{m_0^2 + 2(g'Q_\phi)^2 |\phi_0|^2 \cos^2(m_\phi t)}$$

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

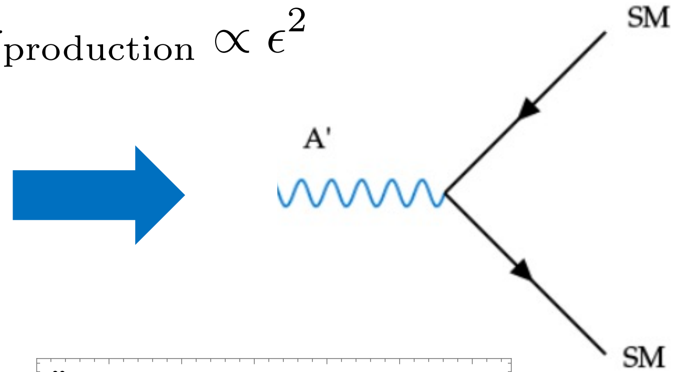


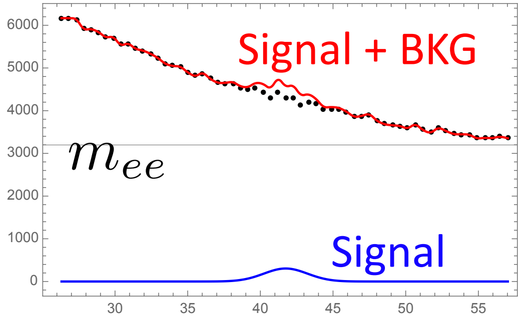
Focus: $m_0 \approx 100$ MeV, $\kappa \approx 10$

Searching for a dark photon – traditional approach



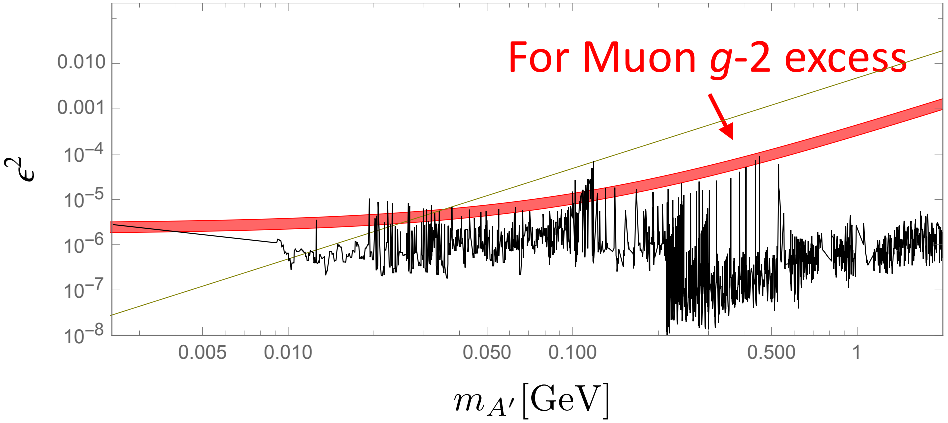
$\sigma_{\text{production}} \propto \epsilon^2$



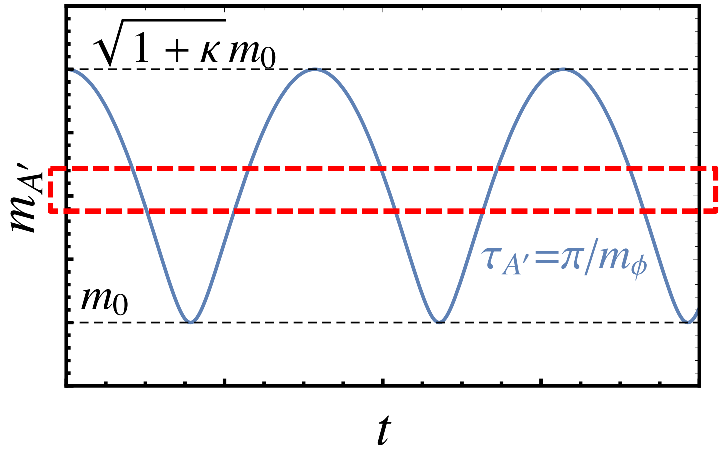


Constraints on mixing

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



Searching for a time-varying dark photon – [**this work**]

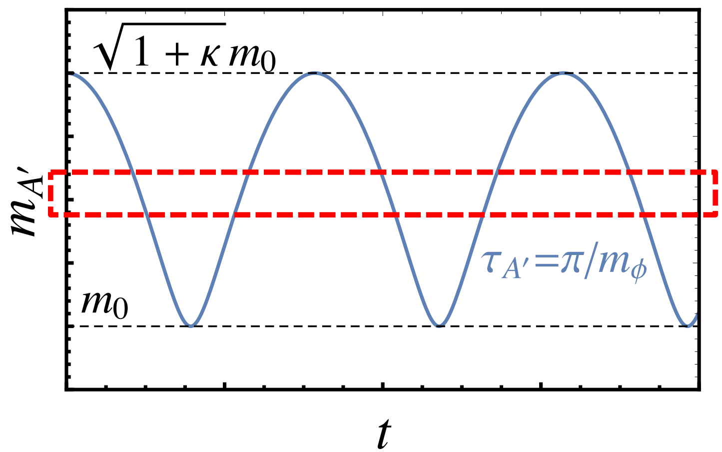


m_ϕ > 10^{-20} eV and hence $\tau_{A'}$ < 1 day

Oscillates many times during data taking

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

Searching for a time-varying dark photon – [**this work**]



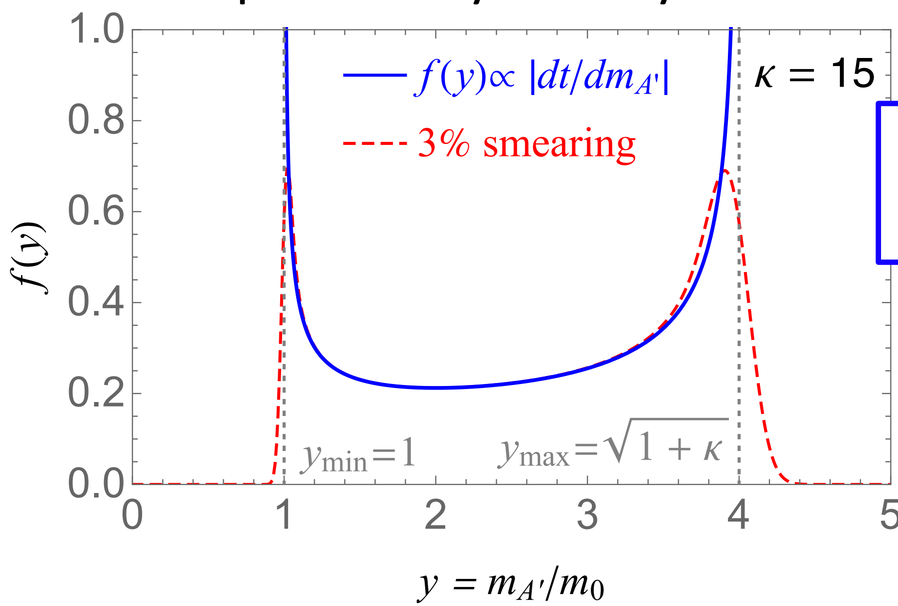
$m_\phi > 10^{-20}$ eV and hence $\tau_{A'} < 1$ day

Oscillates many times during data taking

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

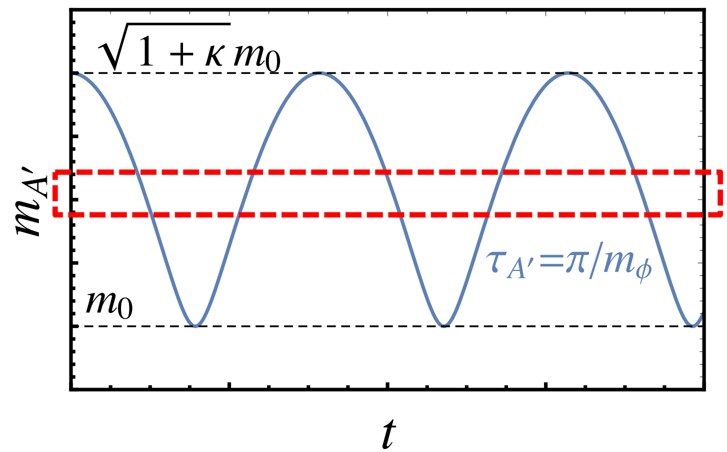
$$\left| \frac{dt}{dm_{A'}} \right| = \frac{\tau}{m_0} f\left(\frac{m_{A'}}{m_0} \right)$$

The mass probability density function



$$f(y) = \frac{2y}{\pi \sqrt{(y^2-1)(1+\kappa-y^2)}}$$

Searching for a time-varying dark photon – [**this work**]



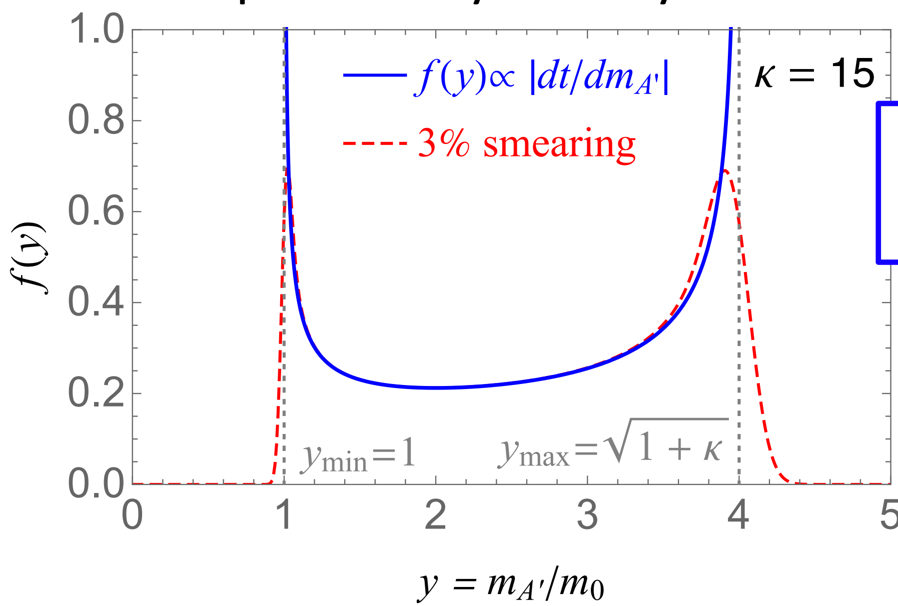
m_ϕ > 10^{-20} eV and hence $\tau_{A'}$ < 1 day

Oscillates many times during data taking

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

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

The mass probability density function

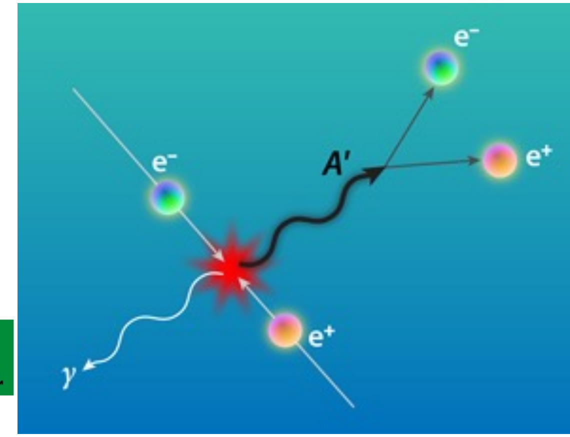


$$f(y) = \frac{2y}{\pi\sqrt{(y^2-1)(1+\kappa-y^2)}}$$

Reanalyzing existing exps

Fitting the dilepton mass spectrum

The BaBar experiment at SLAC[1406.2980]



$$e^+e^- \to \gamma A',\ A' \to e^+e^-/\mu^+\mu^-;$$

$$\sqrt{s} \approx 10\ \mathrm{GeV},\ \mathcal{L} \approx 514\ \mathrm{fb}^{-1}$$

To fit the spectrum at

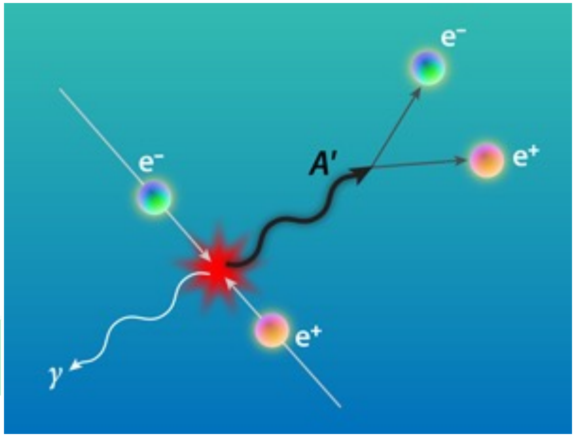
$$m_{A'} \in [0.02,\ 10.2]\ \mathrm{GeV}; \quad m_{A'} \pm 10\,\sigma_{\rm re}; \quad \sigma_{\rm re} \in [1.5,\ 8]\ \mathrm{MeV}$$

Fitting the dilepton mass spectrum

The BaBar experiment at SLAC[1406.2980]

$$e^+e^- \to \gamma A',\ A' \to e^+e^-/\mu^+\mu^-;$$

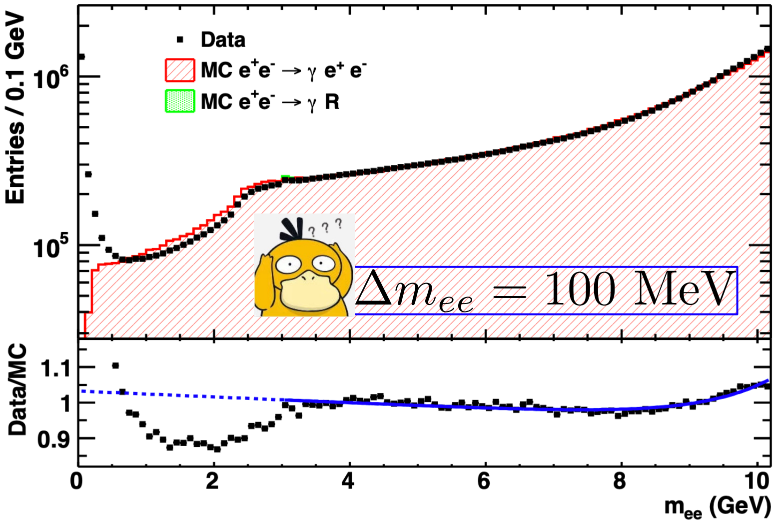
$$\sqrt{s} \approx 10\ \text{GeV},\ \mathcal{L} \approx 514\ \text{fb}^{-1}$$

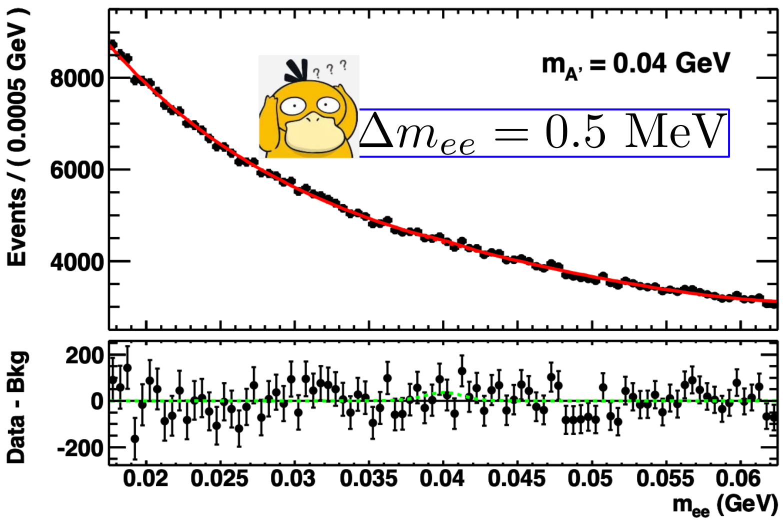


To fit the spectrum at

$$m_{A'} \in [0.02,\ 10.2]\ \text{GeV};\quad m_{A'} \pm 10\,\sigma_{\text{re}};\quad \sigma_{\text{re}} \in [1.5,\ 8]\ \text{MeV}$$

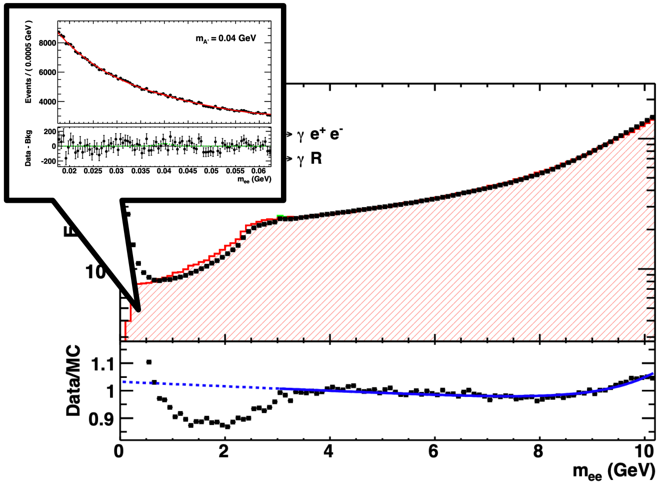
However, BaBar only provides…

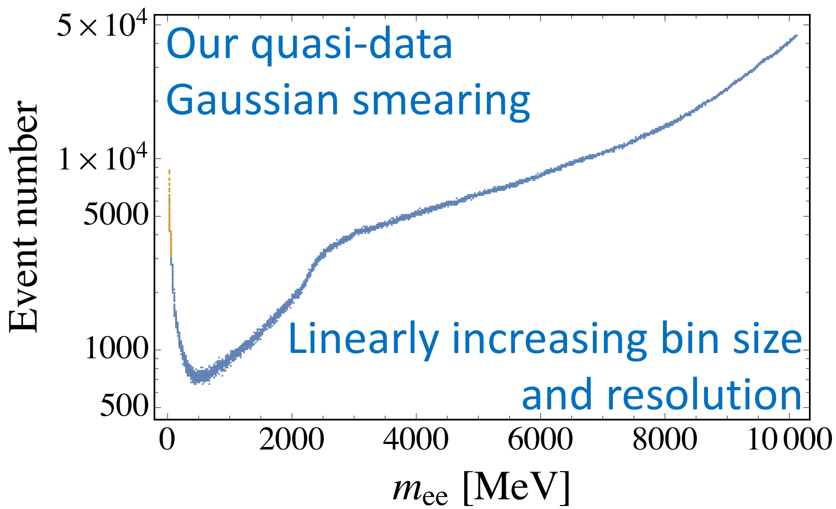




Fitting the dilepton mass spectrum

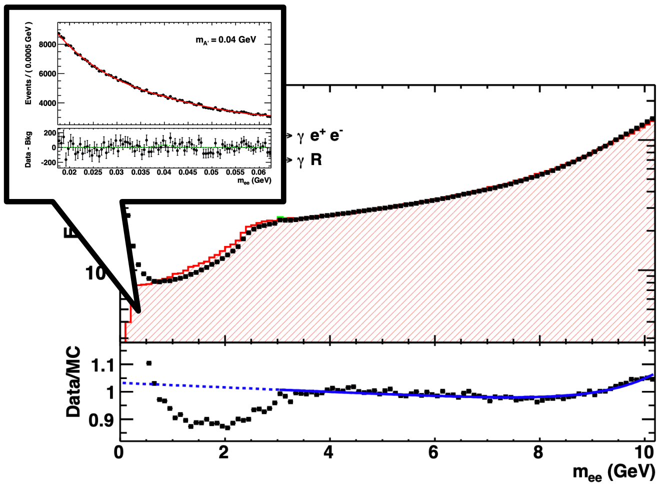
Repeating BaBar analysis[1406.2980] with quasi-data

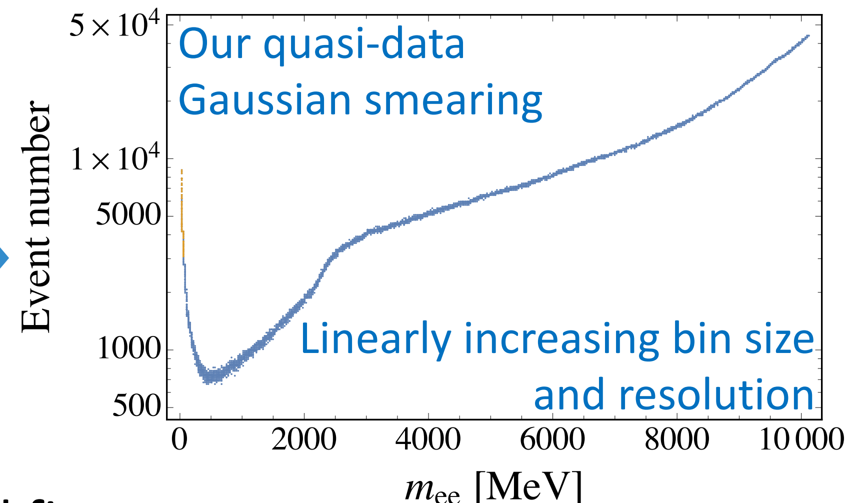




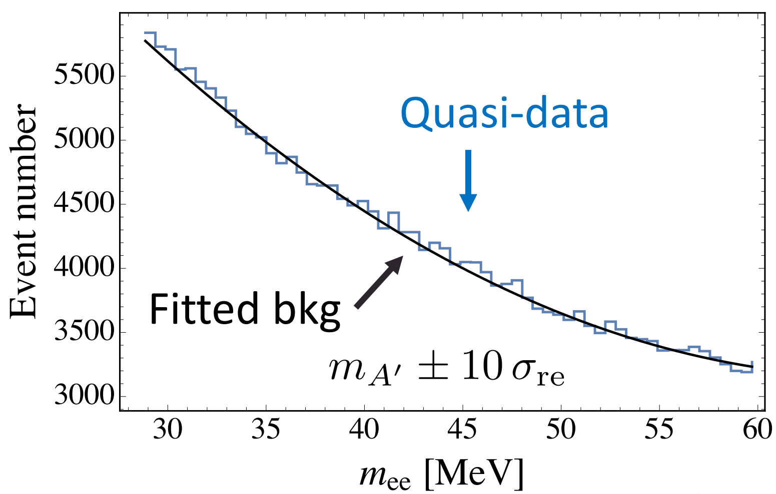
Fitting the dilepton mass spectrum

Repeating BaBar analysis[1406.2980] with traditional signal



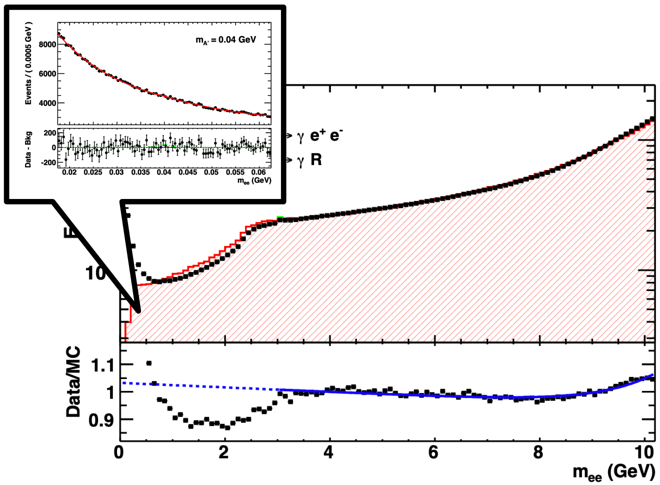


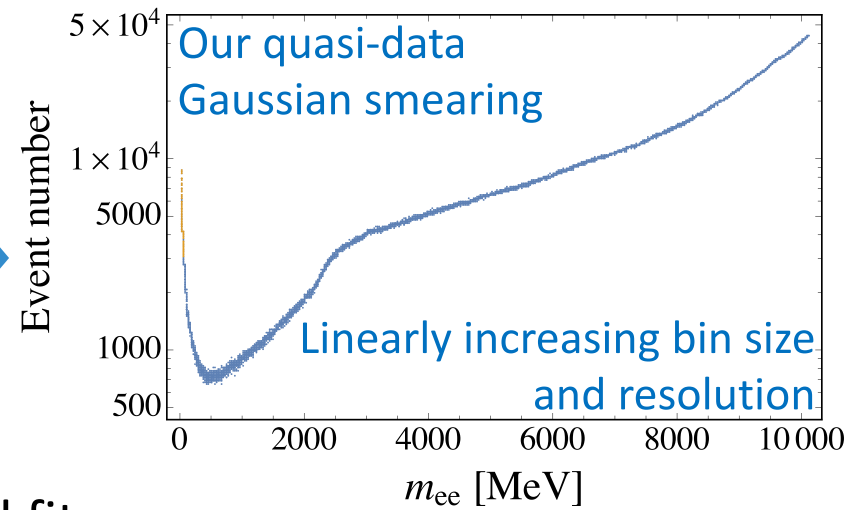
Cutting out a mass window and fit



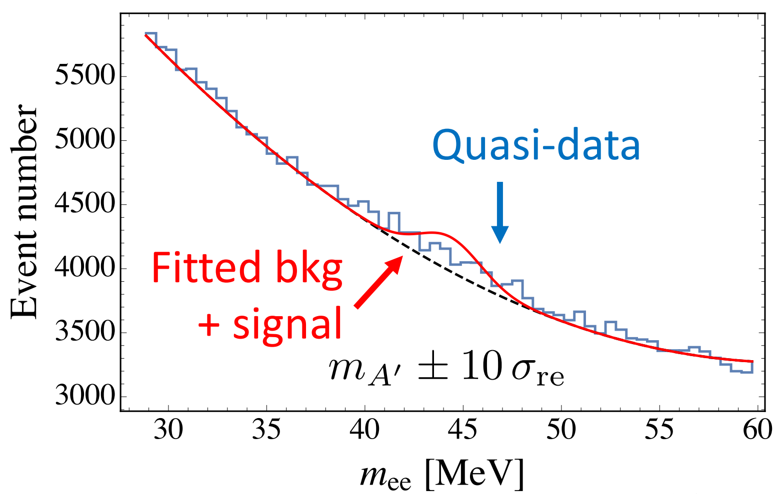
Fitting the dilepton mass spectrum

Repeating BaBar analysis[1406.2980] with traditional signal



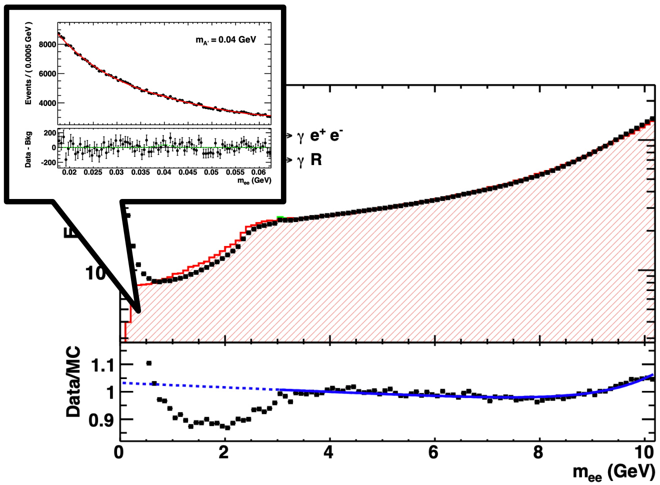


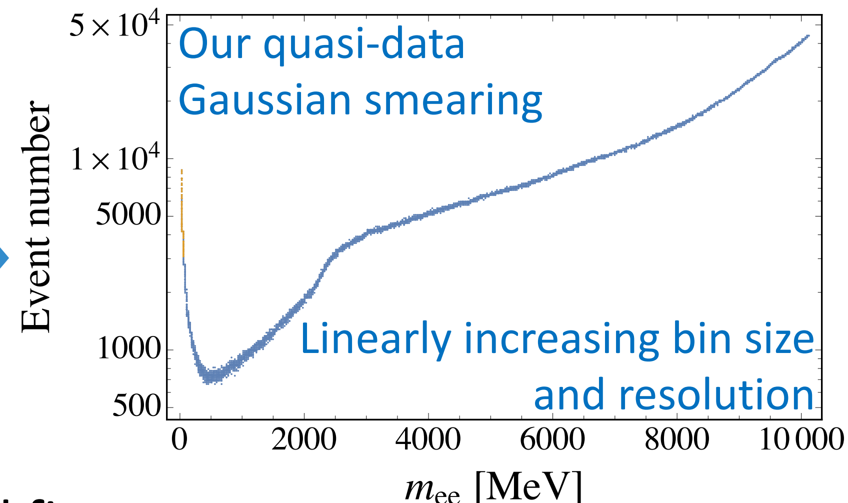
Cutting out a mass window and fit



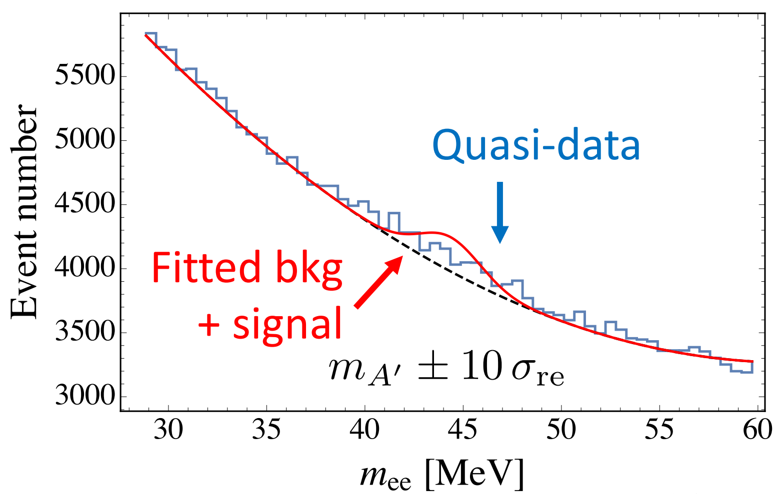
Fitting the dilepton mass spectrum

Repeating BaBar analysis[1406.2980] with traditional signal





Cutting out a mass window and fit



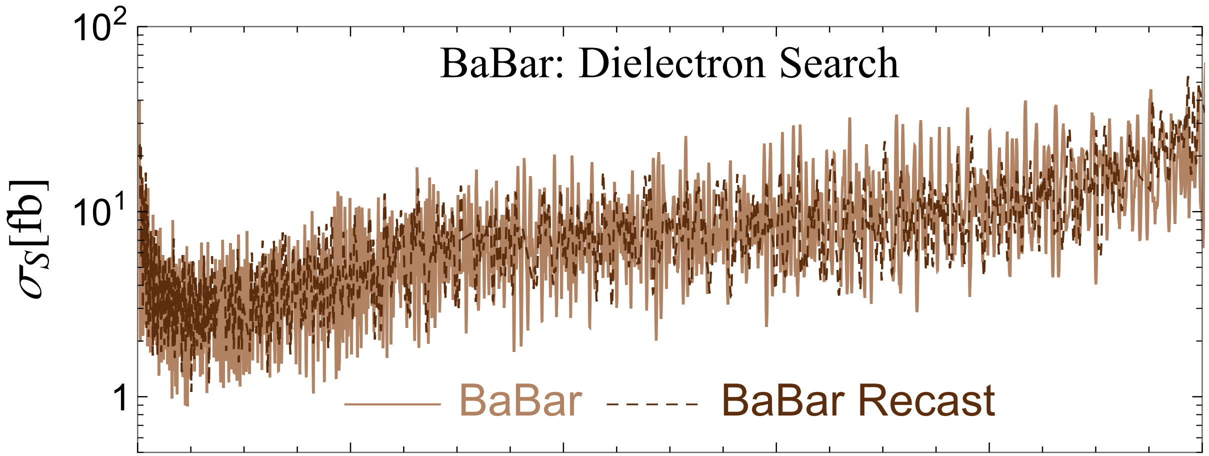
Log likelihood ratio (LLR)

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

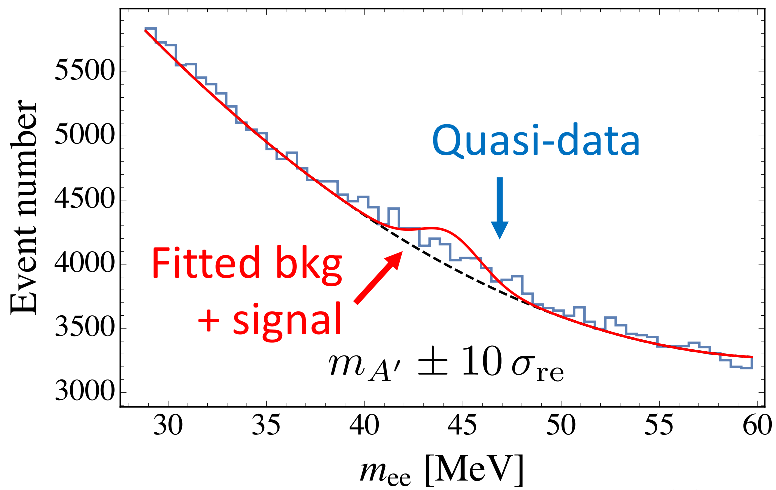
LLR = 3.84 exclusion criterion

Fitting the dilepton mass spectrum

Repeating BaBar analysis[1406.2980] with traditional signal



Cutting out a mass window and fit



Match!!

Log likelihood ratio (LLR)

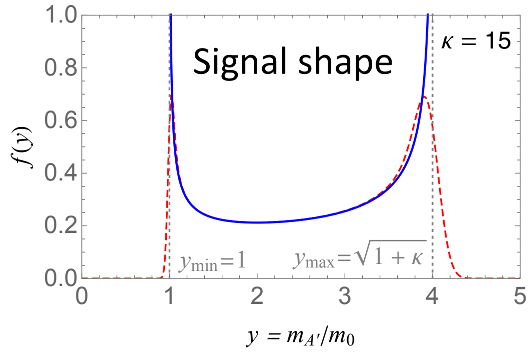
$$-2\log\left[\frac{\mathrm{Max}_{\vec{a}'}\prod_i \mathcal{N}(B_i - B(m_i,\vec{a}') - Sf_G(m_i)|B_i)}{\mathrm{Max}_{\vec{a}}\prod_i \mathcal{N}(B_i - B(m_i,\vec{a})|B_i)}\right]$$

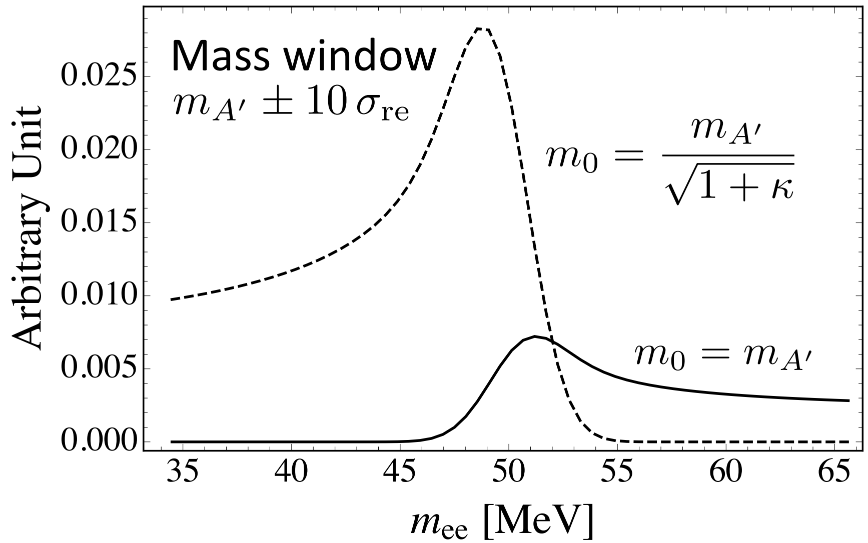
LLR = 3.84 exclusion criterion

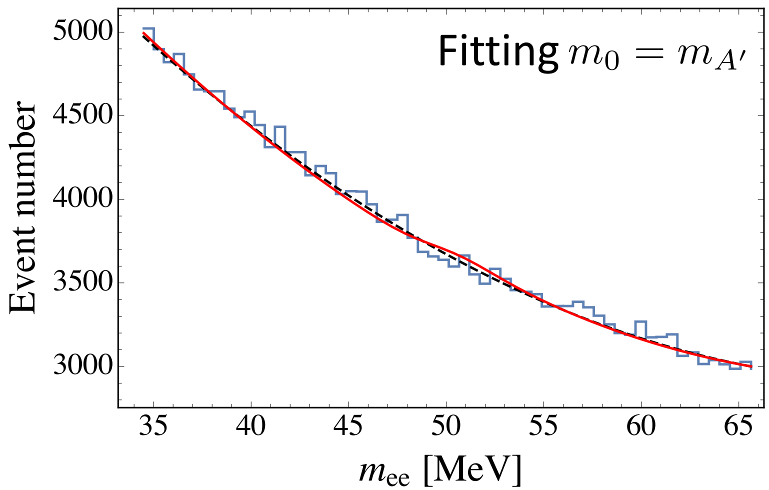
Fitting the dilepton mass spectrum

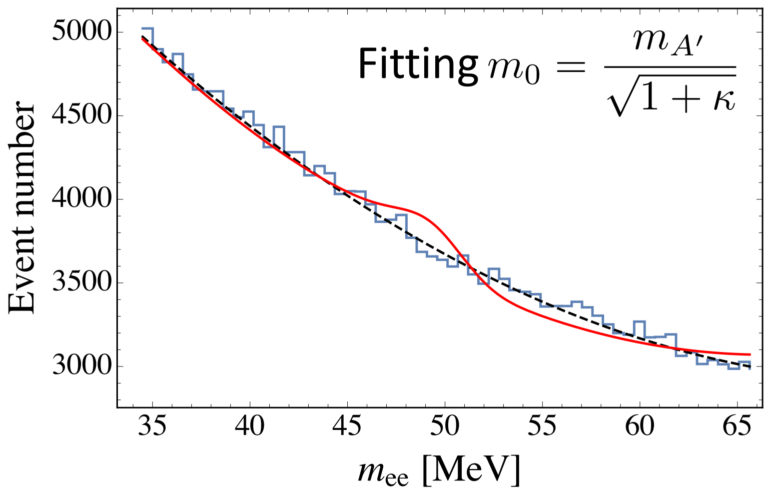
Repeating BaBar analysis[1406.2980] with **novel signal**

Double-peak



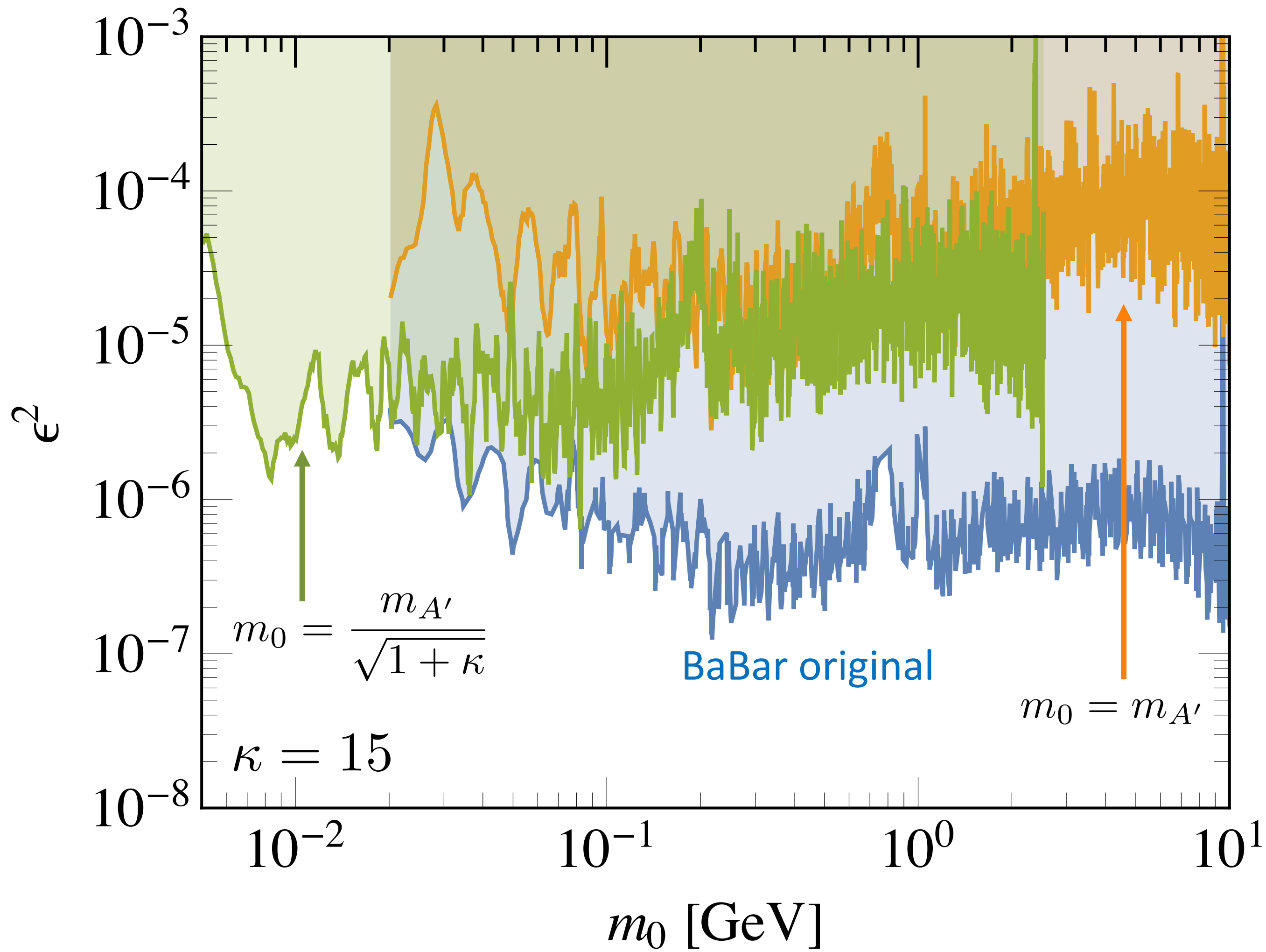






Fitting the dilepton mass spectrum

Repeating BaBar analysis[1406.2980] with **novel signal**

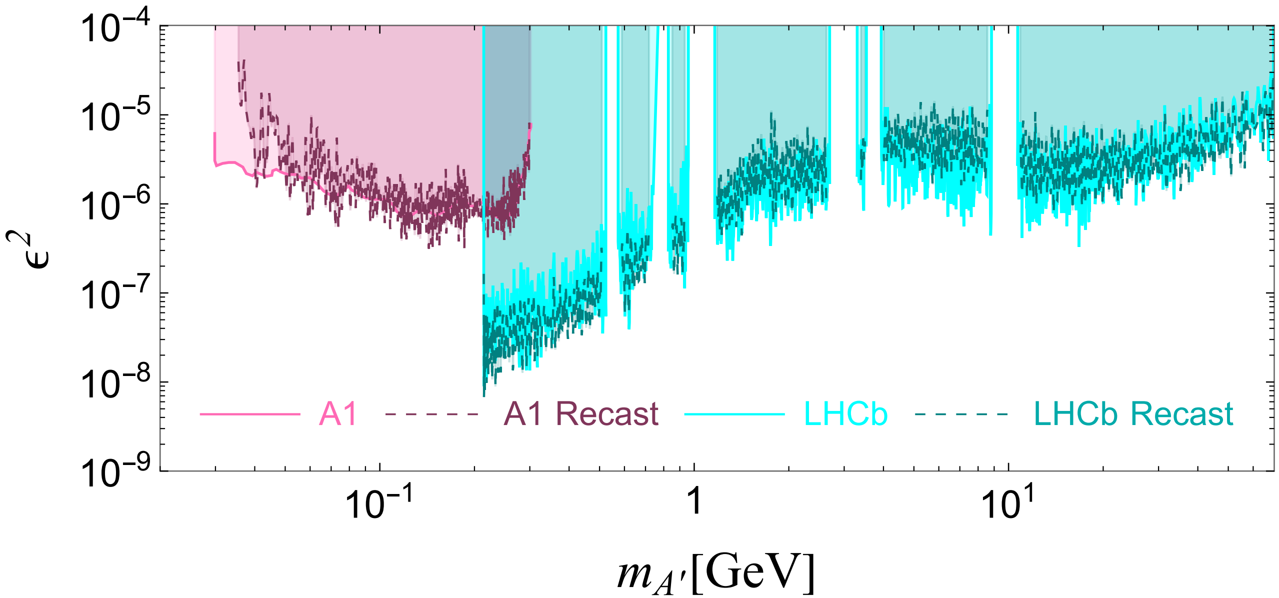


Fitting the dilepton mass spectrum: a summary

Experiments we have recast

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

First, repeat the existing bounds with the traditional signals

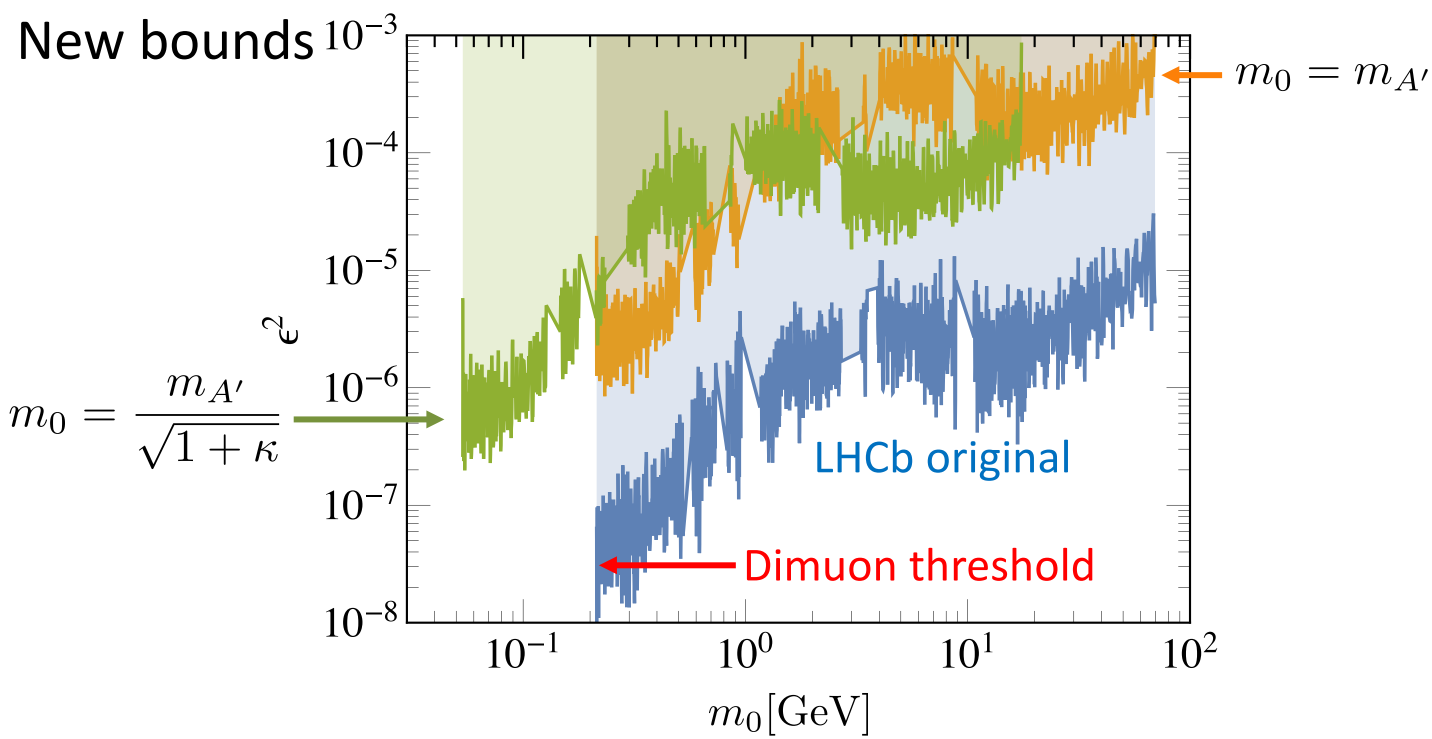


Fitting the dilepton mass spectrum: a summary

Experiments we have recast

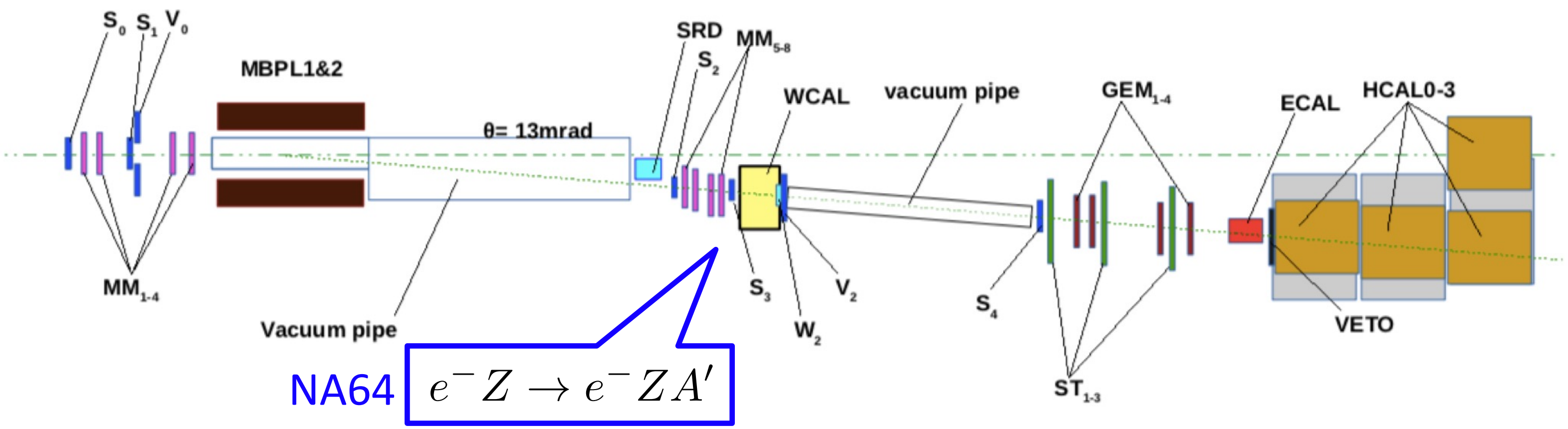
Collaboration	Production mode	Experimental environment	Spectrum	Resolution $\sigma_{\rm re}$	Fit window
BaBar [1406.2980]	$e^+e^- \to \gamma A'$	$\sqrt{s} \approx 10$ GeV, 514 fb^{-1}	m_{ee}, $m_{\mu\mu}$	[1.5, 8] MeV	$m_{A'} \pm 10\,\sigma_{\rm re}$
LHCb [1910.06926]	$pp \to A'$	$\sqrt{s} = 13$ TeV, ~ 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

New bounds



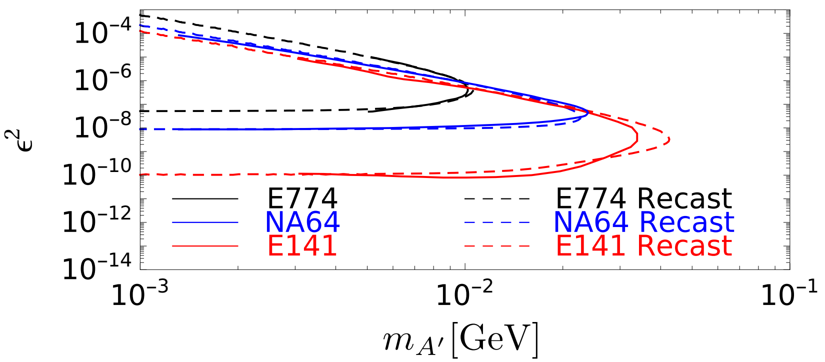
Beam dump experiments

Including E774[PRL67(1991)2942] E141[PRL59(1987)755] and NA64[1912.11389]



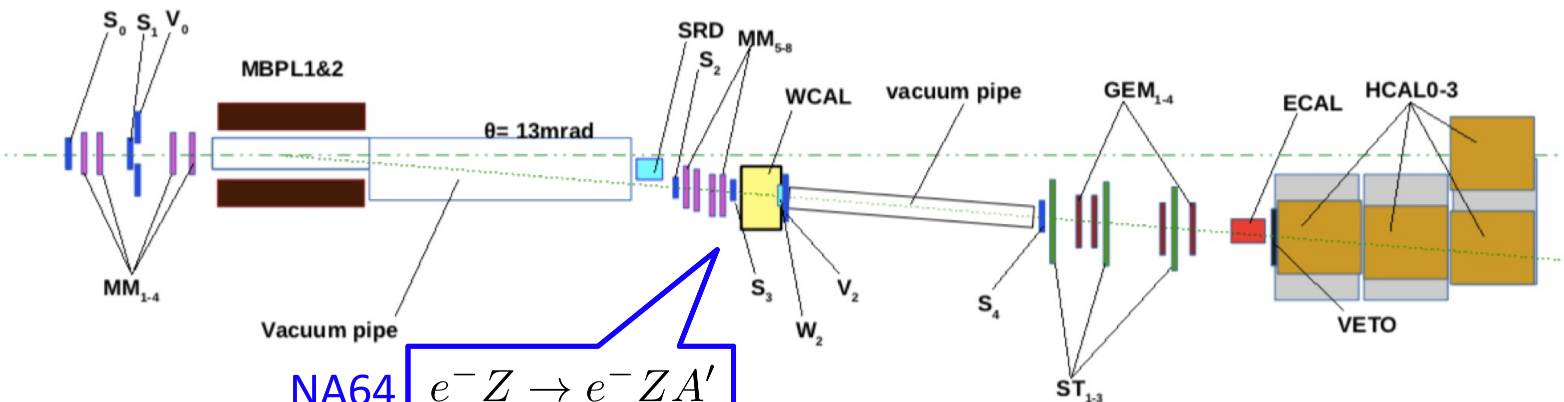
Event number

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



Beam dump experiments

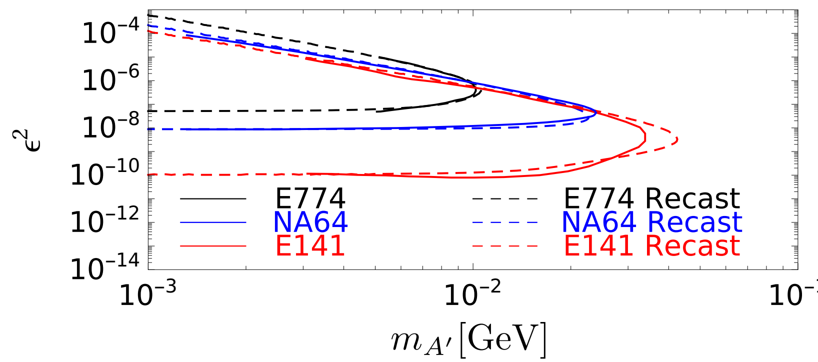
Including E774[PRL67(1991)2942] E141[PRL59(1987)755] and NA64[1912.11389]



NA64 $e^- Z \to e^- Z A'$

Event number

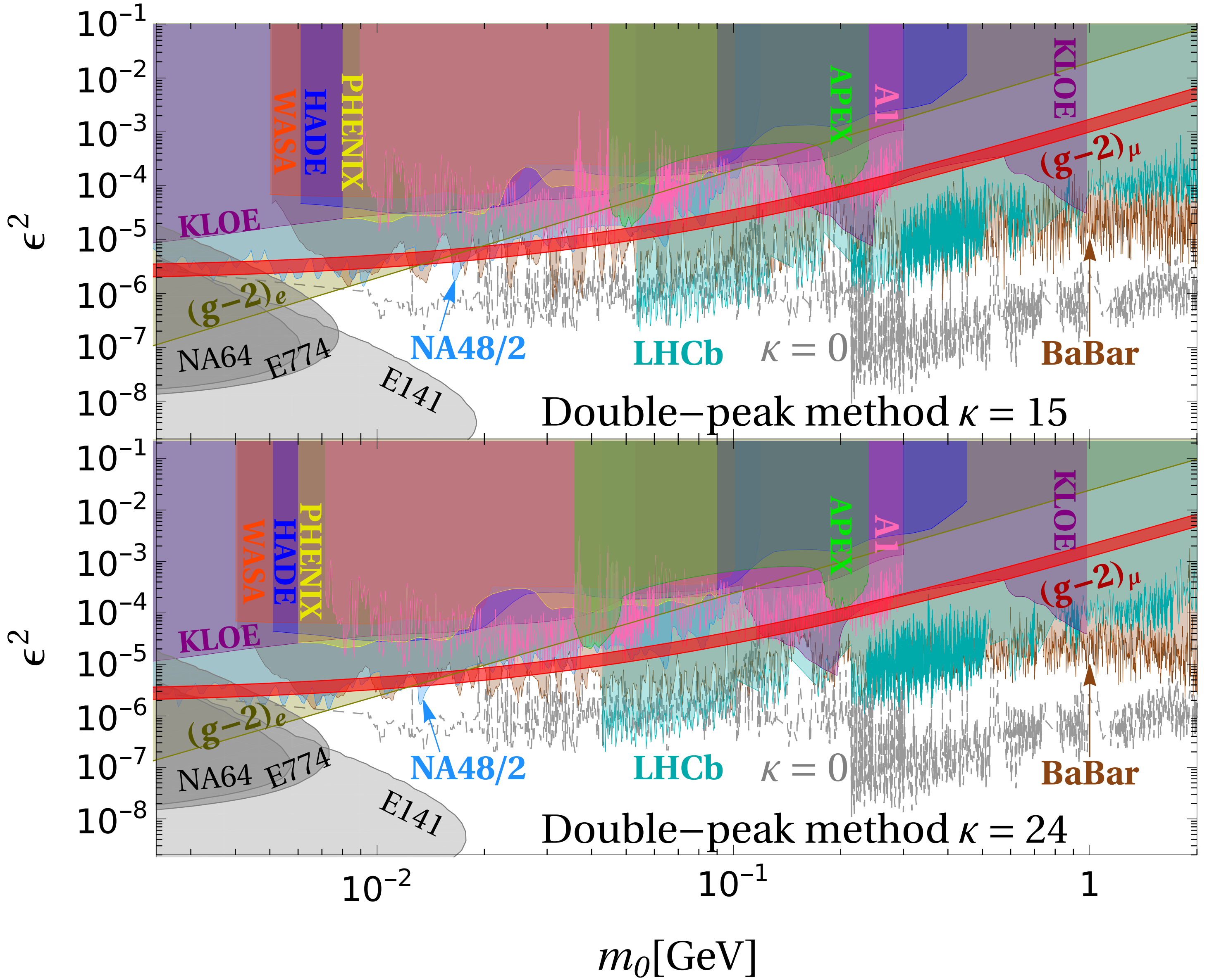
$$N(\epsilon, m_{A'}) = N_e \mathcal{C}' \epsilon^2 \frac{m_e^2}{m_{A'}^2} e^{-a_1 L_{\rm sh} \Gamma_{A'}} \times \left(1 - e^{-a_2 L_{\rm dec} \Gamma_{A'}}\right),$$



For our signal model

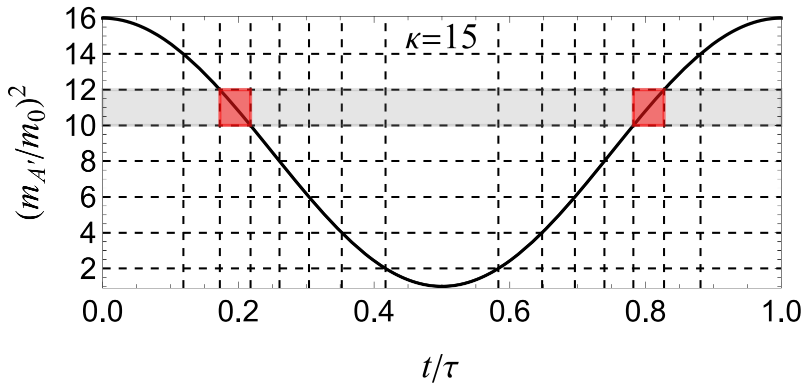
$$N(\epsilon, m_0, \kappa) = \frac{1}{\tau_{A'}} \int_{m_0}^{\sqrt{1+\kappa} m_0} N(\epsilon, m_{A'}) \left| \frac{dt}{dm_{A'}} \right| dm_{A'}.$$

Our main result

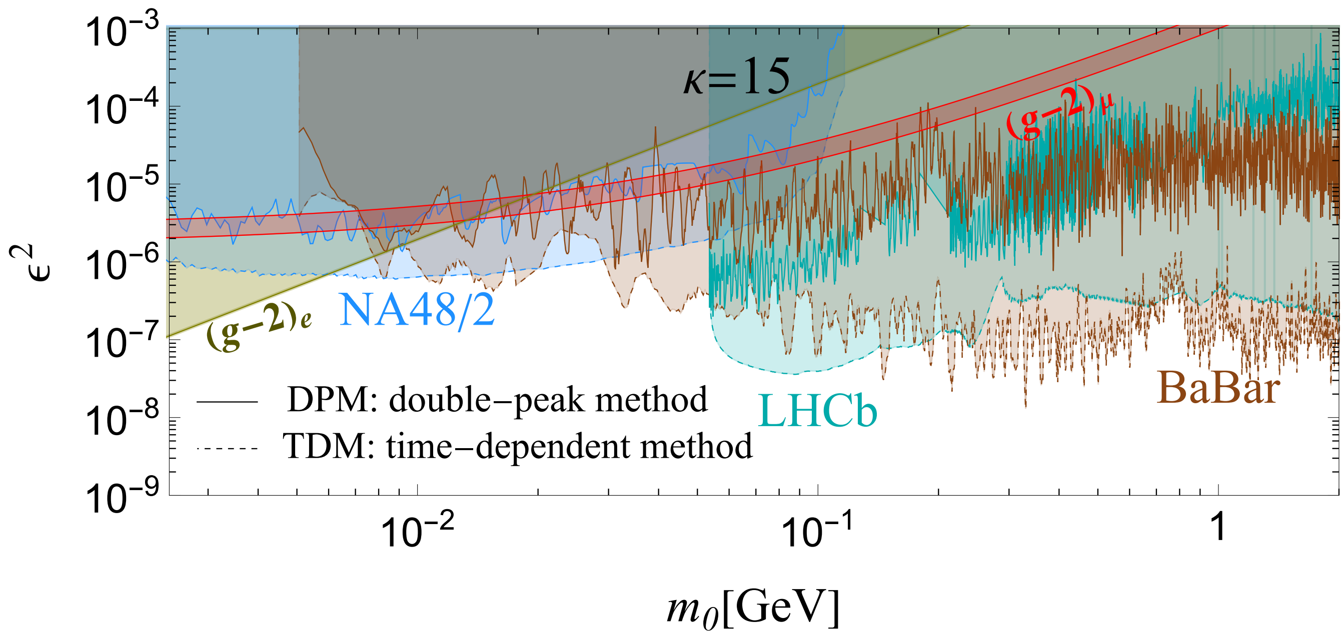


Improving the bounds: time information

If the time information is available



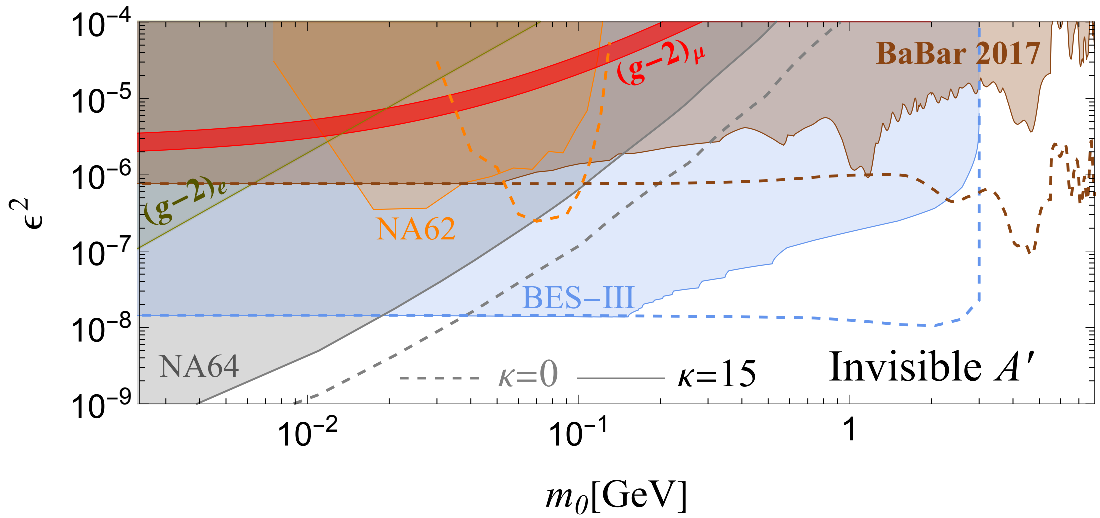
Signal not changed, while background suppressed!



A brief comment on invisible decay

Previously we have assumed *A'* decays dominantly to SM pair

A' may decay to dark particles!



Monophoton

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

Traditional: single-peak $E_\gamma = \dfrac{s - m_{A'}^2}{2\sqrt{s}}$

For time-varying dark photon:

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

Conclusion

Ultralight scalar DM can result in time-varying mass of dark photon:

1. The existing bounds are significantly weakened;
2. The muon *g*-2 solution becomes viable again;
3. Including time information of experiments can improve sensitivity.

Thank you!

Backup: other constraints

Varying SM fermion mass

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