Testing gravity on accelerators

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1506.08063 (PLB) Gravitational mass of relativistic matter and antimatter

1506.01963 (PLB) Testing general relativity on accelerators

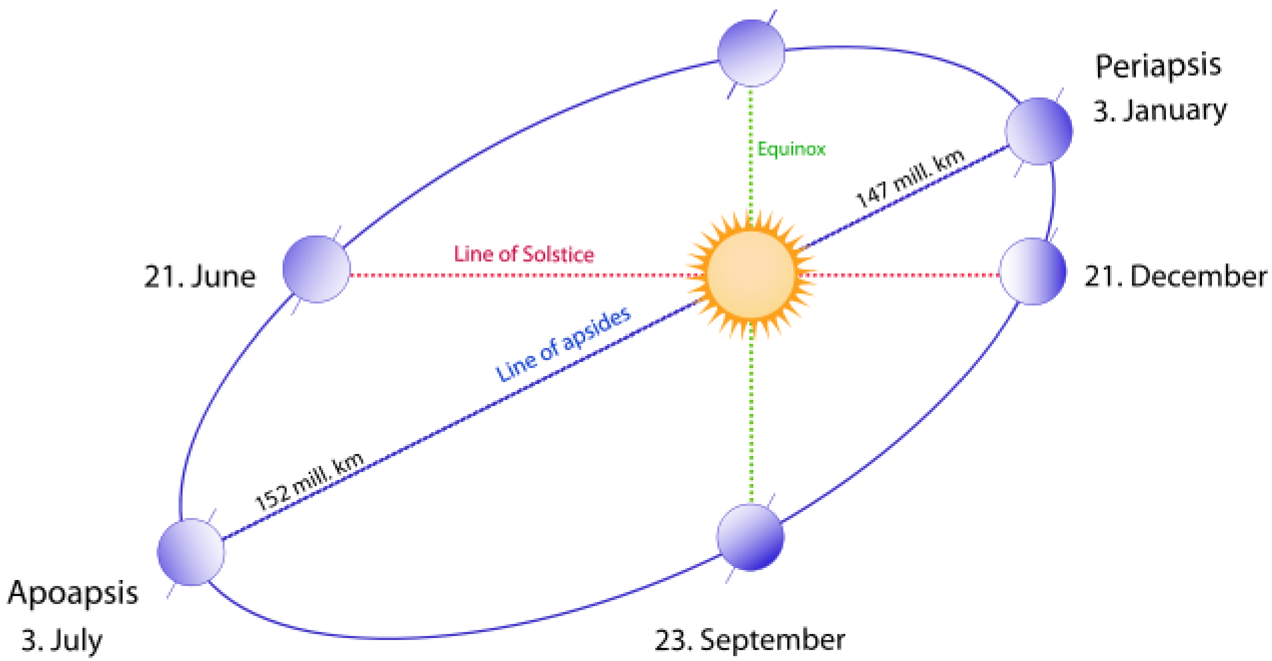
1604.04486 (PRL) Comment on “Testing Planck-Scale Gravity with Accelerators”

1508.04377 Gravitational mass of positron from LEP synchrotron losses

Motivation

- **Tests of gravity at high energies**
- **Antimatter gravity** $\left(-65 < m_g^{\bar{H}}/m^{\bar{H}} < 110\right)$

How?
Perform tests on the isotropic Lorentz violation on two different days of the year.



C. Amole et al. [ALPHA Collaboration], Nature Commun. 4, 1785 (2013).

Theory in brief

Gravitational field around the accelerator:

$$ds^2 = \mathcal{H}^2 dt^2 - \mathcal{H}^{-2}(dx^2 + dy^2 + dz^2)$$ **where** $$\mathcal{H}^2 = 1 + 2\Phi$$

For a massive particle (in our case ultrarelativistic electron or positron)

$$\Phi_m = \Phi \, \frac{m_{e,g}}{m_e} \, , \qquad \mathcal{H}_m^2 \equiv 1 + 2\Phi_m$$

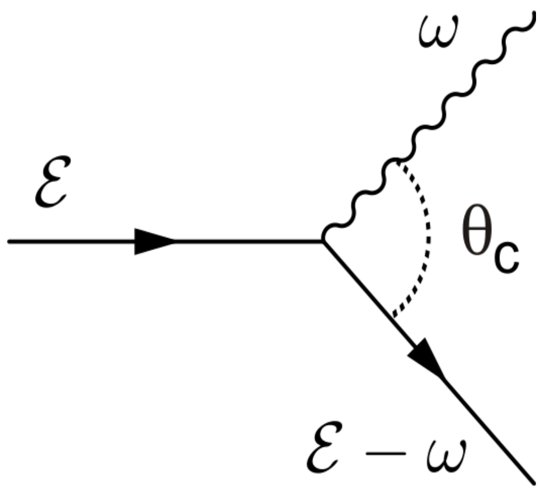
which will modify the dispersion relation of the particle and the relation between energy and mass (we assume the speed of light to be universal)

$$\mathbf{p}^2 = (1 - 2\kappa) \left(\mathcal{E}^2 - m_e^2\right) , \qquad \mathcal{E} = \frac{m_e \mathcal{H}^{-1} \mathcal{H}_m}{\sqrt{1 - \mathcal{H}^4 \mathcal{H}_m^{-4} \mathbf{v}^2}}$$

where $\kappa = 2\Phi \Delta m_e / m_e, \quad \Delta m_e = m_{e,g} - m_e.$

Imagine that $|\kappa| < \kappa_{1,2}$ **for two experiments, then** $$\left| \frac{\Delta m_e}{m_e} \right| < \frac{\kappa_1 + \kappa_2}{2\Delta\Phi}$$

1. Vacuum Cherenkov radiation



Threshold energy:

$$\mathcal{E}_{\rm th} = \frac{m_e}{\sqrt{-2\kappa}}$$

Emission rate:

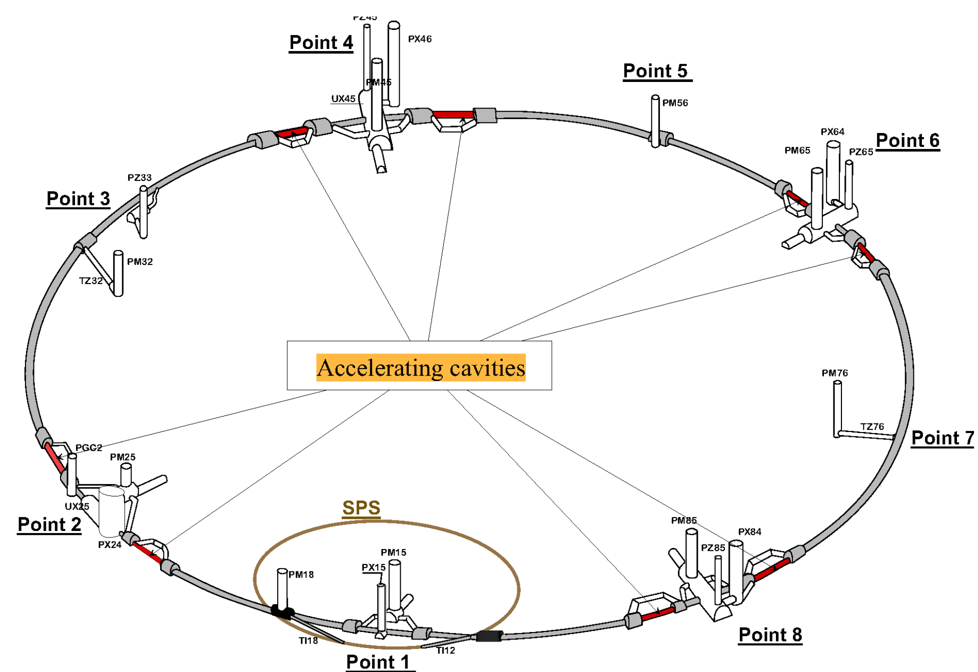
$$\Gamma_C = \alpha\, m_e^2\, \frac{(\mathcal{E} - \mathcal{E}_{\rm th})^2}{2\mathcal{E}^3}$$

Let us take E = 104.5 GeV electrons and positrons at LEP.

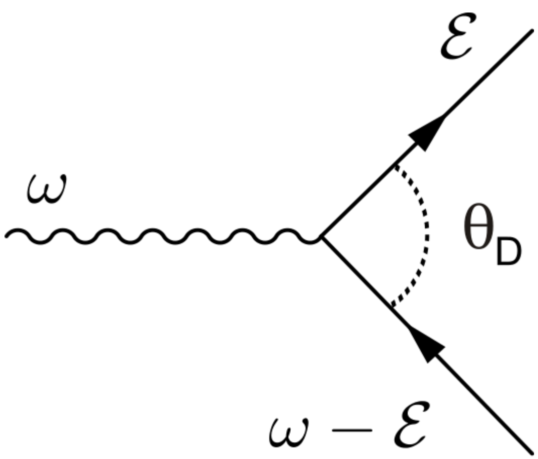
$$\mathcal{E}_{\rm th} = 100\,\mathrm{GeV}$$

Compare: 1.2cm (decceleration distance) vs 6 km (approximate distance between accelerating RF systems).

$$\kappa > -1.3 \times 10^{-11}$$



2. Photon decay



Threshold energy:

$$\omega_{\rm th} = \sqrt{\frac{2}{\kappa}} m_e$$

Decay rate:

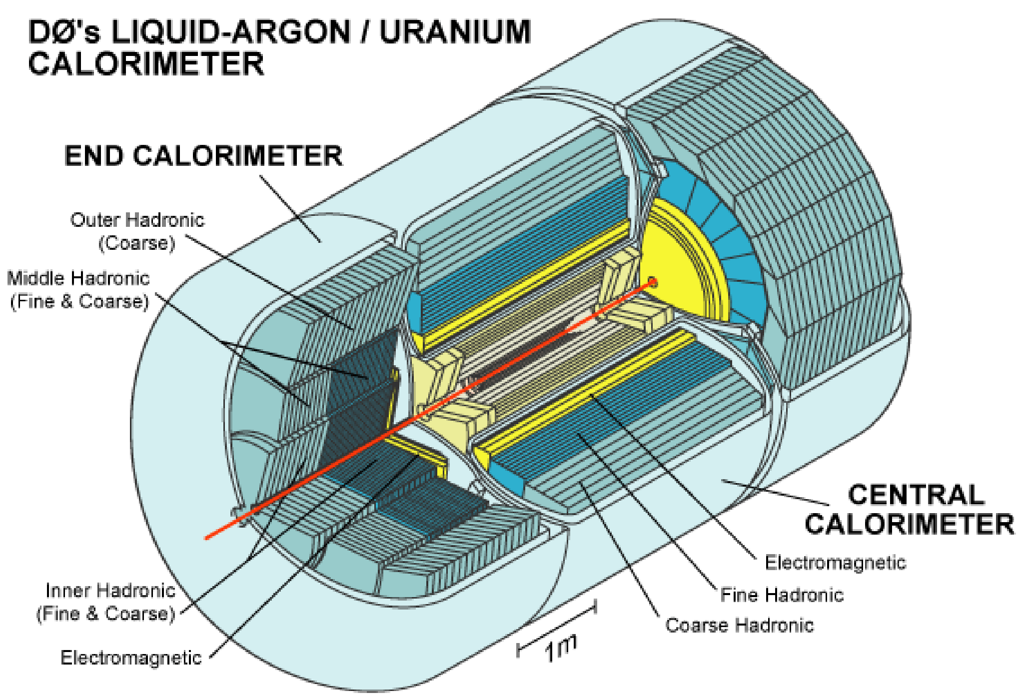
$$\Gamma_D = \frac{2}{3}\alpha\,\omega\,\frac{m_e^2}{\omega_{\rm th}^2}\left(2+\frac{\omega_{\rm th}^2}{\omega^2}\right)\sqrt{1-\frac{\omega_{\rm th}^2}{\omega^2}}$$

Let us take E = 340.5 GeV photons at Fermilab's Tevatron.

$$\omega_{\rm th} = 300\,\mathrm{GeV}$$

Compare: 0.1 mm (decay distance) vs 78 cm (minimal path from interaction point to the central calorimeter of D0 detector).

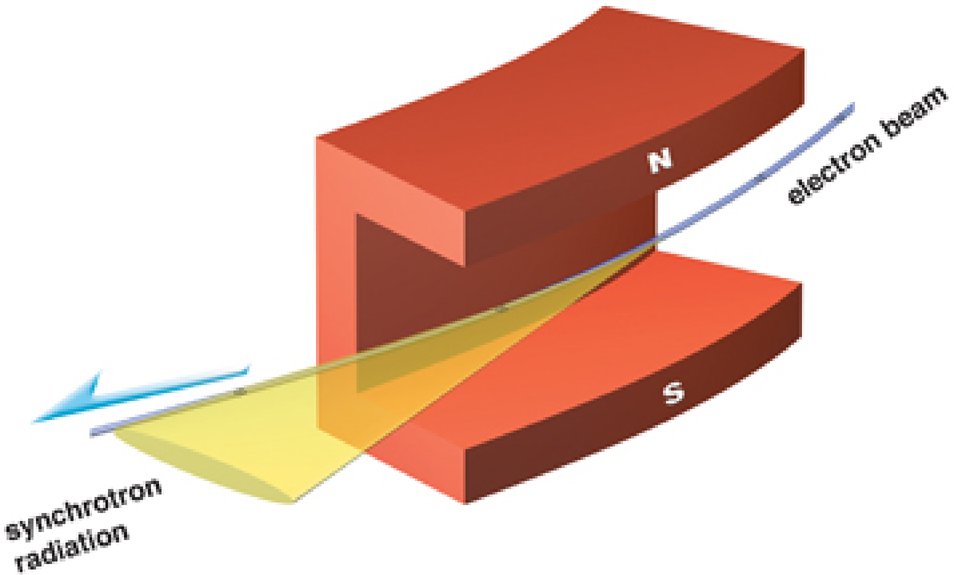
$$\kappa < 5.8\times 10^{-12}$$



3. Synchrotron radiation

Radiation power without gravity

$$P = \frac{2}{3}\frac{e^2\dot{\mathbf{v}}^2}{c^3}\left(\frac{\mathcal{E}}{m_e}\right)^4$$



Modification of the gamma-factor leads to

$$\Delta P/P = 4\kappa\gamma^2$$

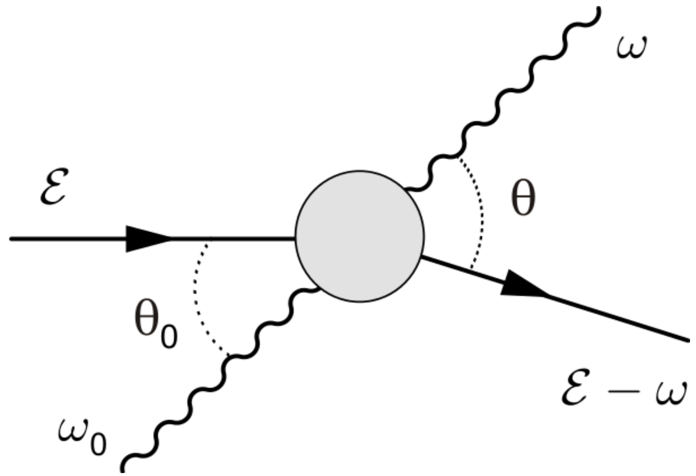
LEP E = 80 GeV electrons and positrons.
Energy was estimated by 3 methods: NMR and flux-loop magnetic field measurement; spectrometry; synchrotron tune vs RF voltage fit.

$$Q_s^4 = \left(\frac{\alpha_c h}{2\pi}\right)^2 \left\{\frac{g^2e^2V_{RF}^2}{E^2} + Mg^4V_{RF}^4 - \frac{U^2}{E^2}\right\}$$

One can reinterpret it as a fit to *U* and possible uncertainty in the synchrotron losses

$|\kappa| < 9\times 10^{-15}$ **for two experiments (13 Aug & 15 Sep 1999)**

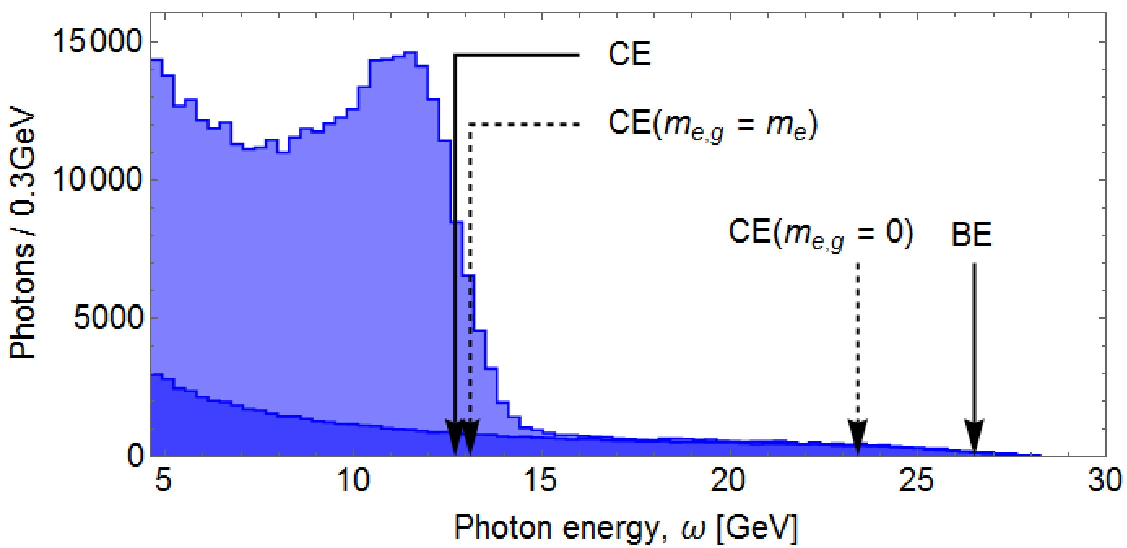
4. Compton scattering

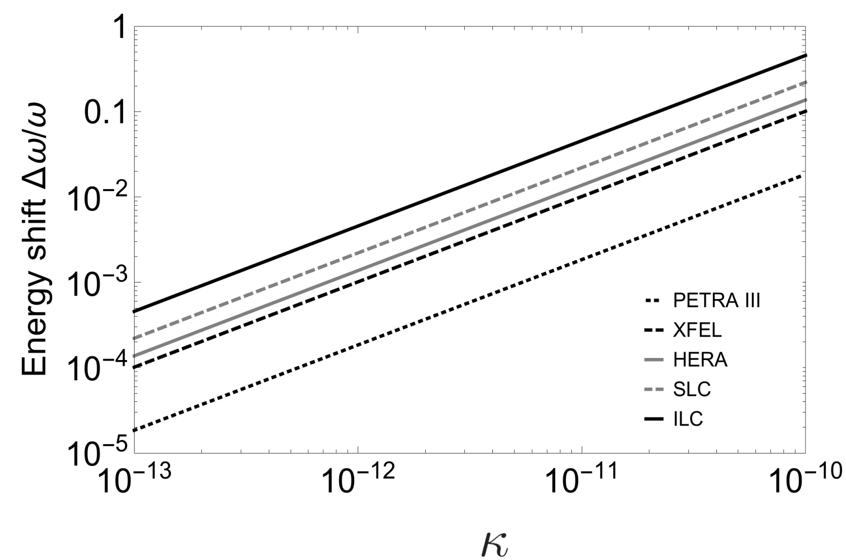


Shifts in the Compton edge give

$$\left|\frac{\Delta m_e}{m_e}\right| < \frac{\Delta\omega_1 + \Delta\omega_2}{\omega_{max}} \cdot \frac{m^2(1+x)^2}{4\mathcal{E}^2|\Delta\Phi|}$$

where $x \equiv 4\mathcal{E}\omega_0 \sin^2(\theta_0/2)/m_e^2$





Results

- **Absence of vacuum Cherenkov radiation at LEP and photon stability at Tevatron give 4% limit on the difference between the gravitational and inertial masses of the electron/positron at GeV energies.**
- **Synchrotron losses at LEP reduce this figure to 0.13%**
- **Compton scattering can provide a similar or better precision if performed at ILC/CLIC twice: when Earth is at the aphelion and perihelion of its orbit. One can also study day to day variations.**

With development of accelerator technologies, we are finally able to rule out antigravity and confirm weak equivalence principle for the high-energy matter and antimatter.