

Testing general relativity on accelerators

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1508.04377: Gravitational mass of positron from LEP synchrotron losses

1506.08063: Gravitational mass of relativistic matter
and antimatter

1506.01963: Testing general relativity on accelerators

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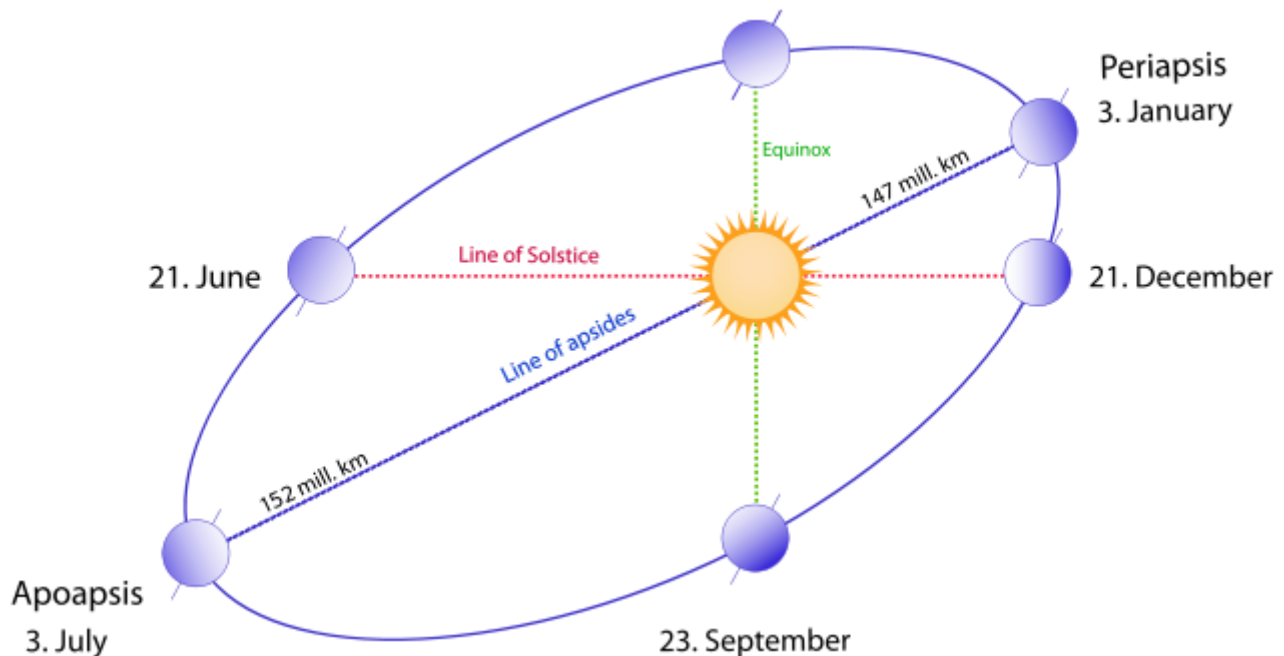
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AT CHICAGO

Motivation

- Tests of gravity at high energies
- Antimatter gravity

How?

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



Theory in brief

Gravitational field around the accelerator:

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

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

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

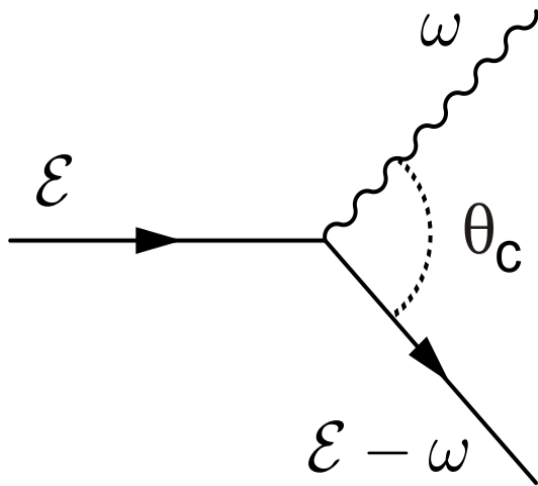
which will modify the dispersion relation of the particle and the relation between energy and mass (we assume the speed of light to be universal)

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

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

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:

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

Emission rate:

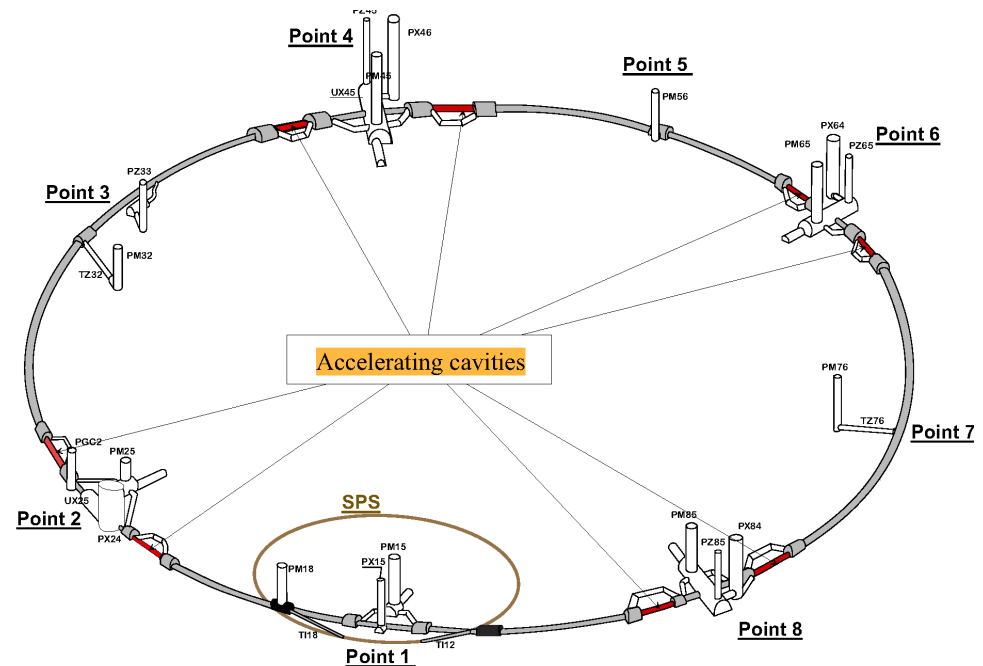
$$\Gamma_C = \alpha m_e^2 \frac{(\mathcal{E} - \mathcal{E}_{\text{th}})^2}{2\mathcal{E}^3}$$

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

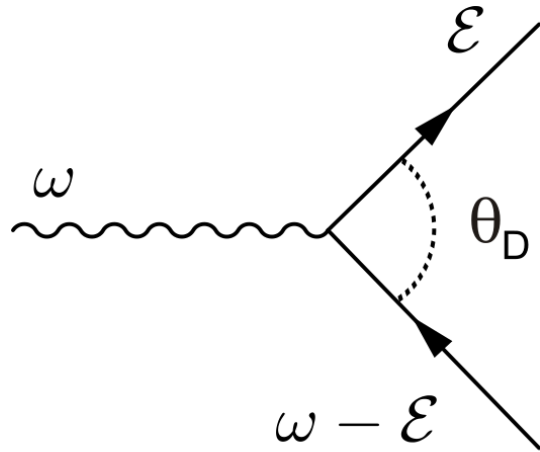
$$\mathcal{E}_{\text{th}} = 100 \text{ GeV}$$

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:

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

Decay rate:

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

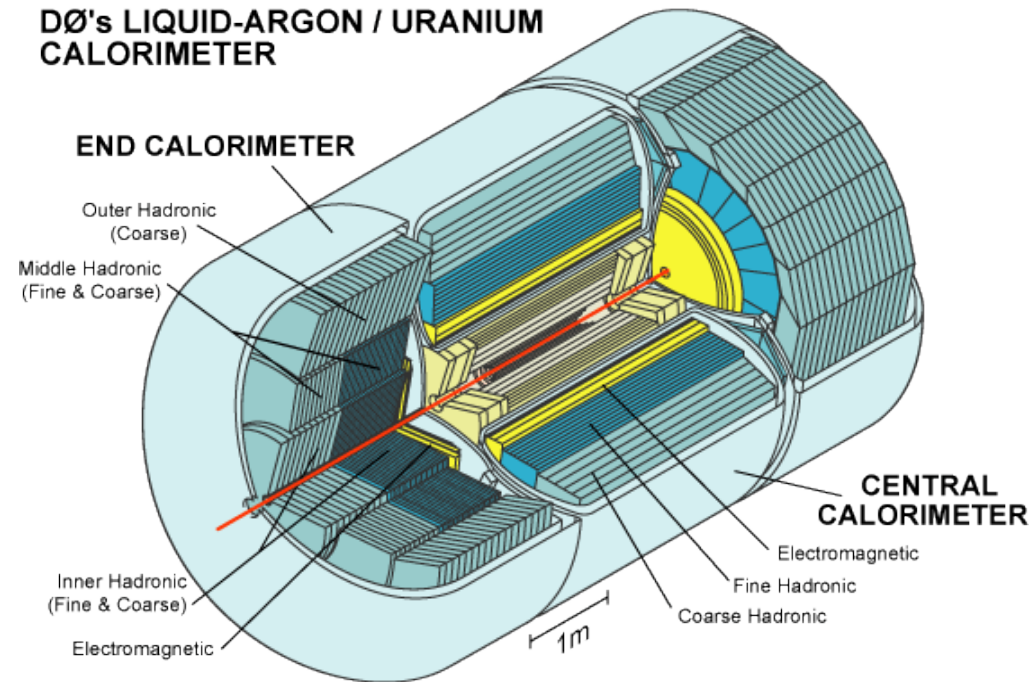
Let us take $E = 340.5 \text{ GeV}$ photons at Fermilab's Tevatron.

$$\omega_{\text{th}} = 300 \text{ GeV}$$

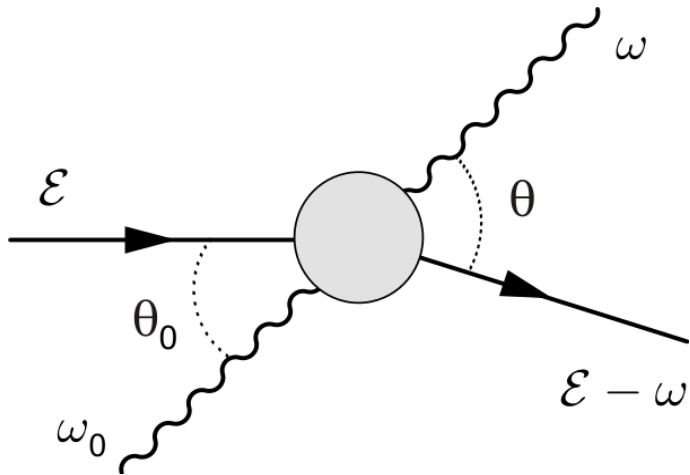
Compare: 0.1 mm (decay distance) vs 78 cm (minimal path from interaction point to the central calorimeter of D0 detector).

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

DØ's LIQUID-ARGON / URANIUM CALORIMETER



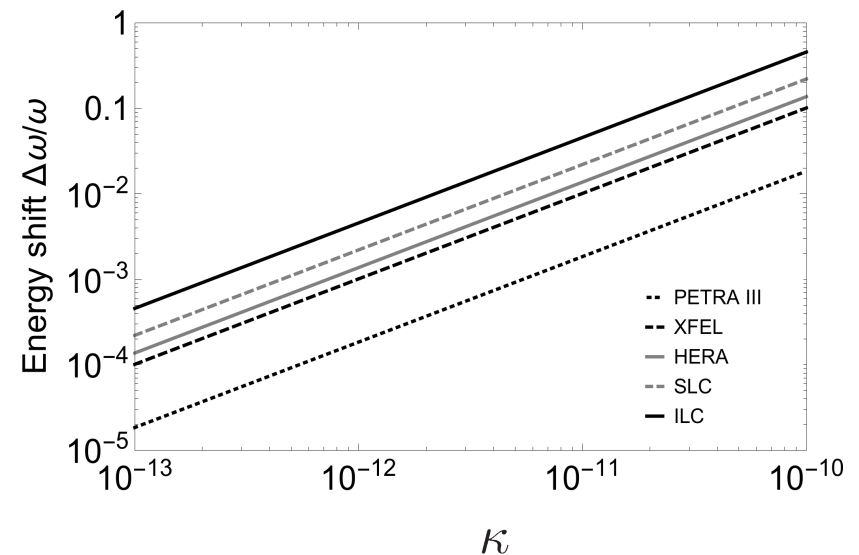
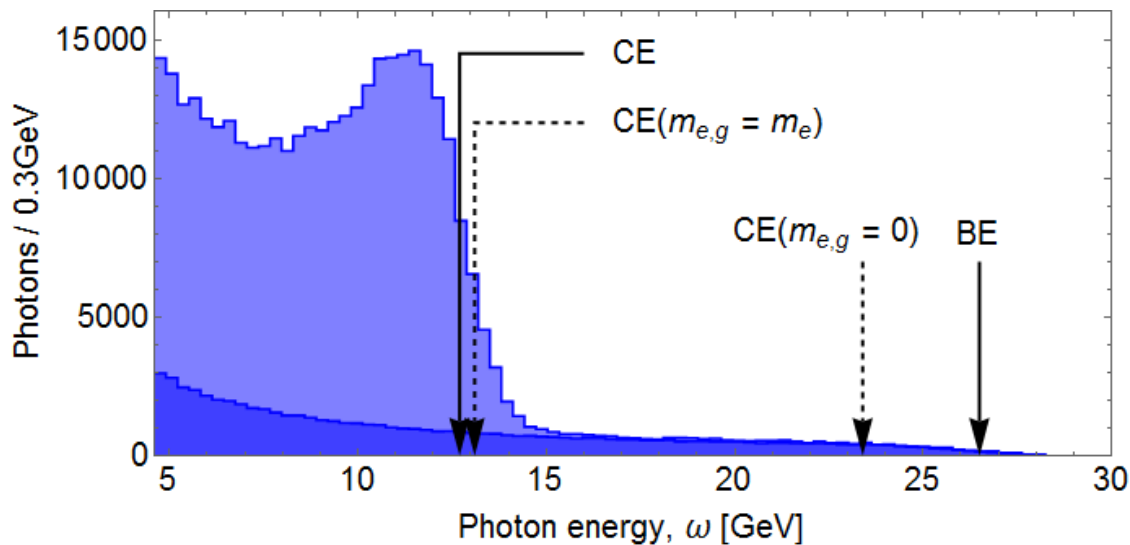
3. Compton scattering



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



4. 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

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

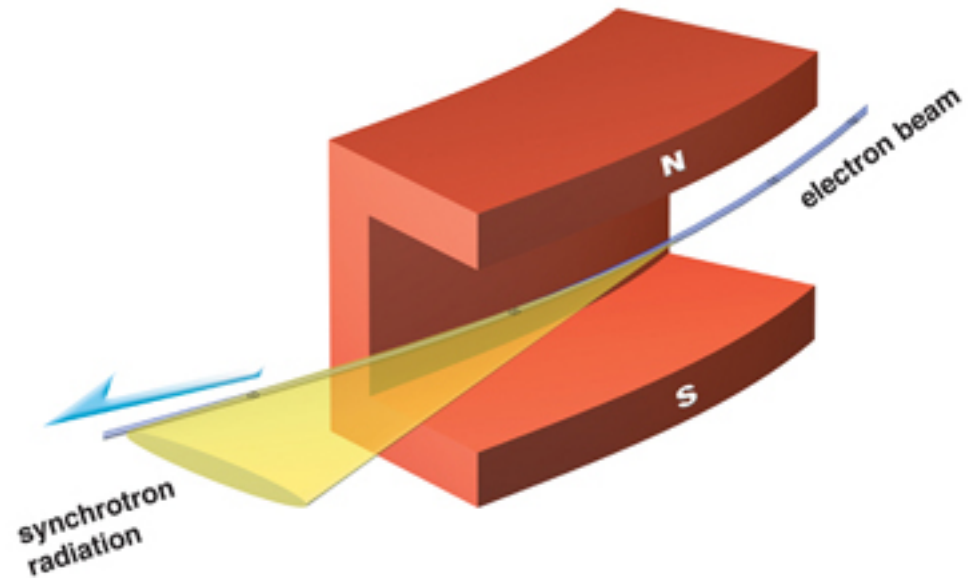
LEP E = 80 GeV electrons and positrons.

Energy was estimated by 3 methods: NMR and flux-loop magnetic field measurement; spectrometry; synchrotron tune vs RF voltage fit.

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

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)



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 radiation at LEP reduces it 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.**

At the beginning of the 21st century, we are finally able to rule out antigravity and confirm weak equivalence principle for the high-energy matter and antimatter.