Manifestation of the electric dipole moment in the decays of τ leptons produced in e^+e^- annihilation

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Introduction

One of the ways to search for New Physics is

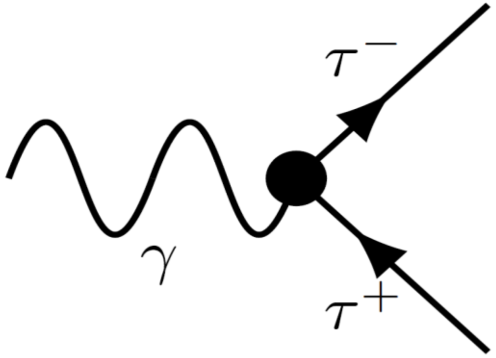
precision measurement of the τ lepton electric dipole moment

The manifestation of the τ lepton electric dipole moment can be sought

in the process of $\tau^+\tau^-$ pair production in e^+e^- annihilation

Electric dipole moment

$$\Gamma^{\mu} = -ie\left\{\gamma^{\mu} + \frac{\sigma^{\mu\nu}k_{\nu}}{2M}b\gamma_5\right\},$$



here b $= F_3^{\tau}(k^2)$ is the electric dipole formfactor, M is the τ lepton mass,

$F_3^{\tau}(0) = d_{\tau}\frac{2M}{e}$, d_{τ} is the τ lepton electric dipole moment

Estimation within the SM gives $|F_3^{\tau}(0)| \approx 10^{-23} \ll 1$

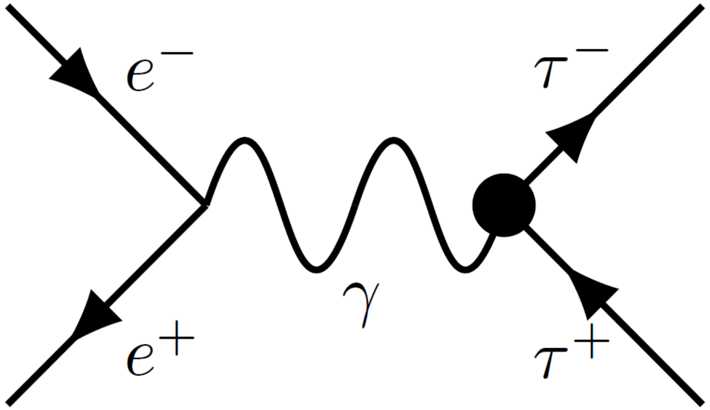
The sensitivity of modern experiments does not allow measuring $F_3^{\tau}(0)$ with an accuracy of 10^{-23}

Registration of a non-zero value of $F_3^{\tau}(0)$ in the experiment will confirm the existence of New Physics

$e^+e^- \to \tau^+\tau^-$ cross section

with a longitudinally polarized electron beam

$\sqrt{s} \ll m_Z$



after summation on τ^+ polarizations

$$\frac{d\sigma_0}{d\Omega_{\boldsymbol{q}}} \propto \left\{A + Im(b)\, B_1 \left[\frac{(\boldsymbol{\zeta}\cdot\boldsymbol{\Lambda})(\boldsymbol{q}\cdot\boldsymbol{\Lambda})}{E} - \frac{(\boldsymbol{\zeta}\cdot\boldsymbol{q})}{E^2}\left(M + \frac{(\boldsymbol{q}\cdot\boldsymbol{\Lambda})^2}{(E+M)}\right)\right] + Re(b)\, B_2 \frac{([\boldsymbol{q}\times\boldsymbol{\Lambda}]\cdot\boldsymbol{\zeta})}{M}\right\}$$

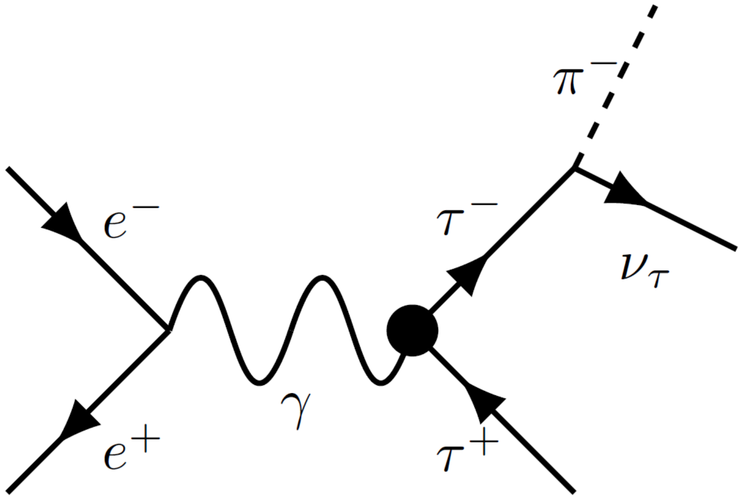
$\boldsymbol{\zeta}$ is the τ^- polarization vector, $\boldsymbol{q}$ is the τ^- momentum, $E = \sqrt{s}/2$, $\boldsymbol{\Lambda} = \lambda\, \boldsymbol{e}_z$,

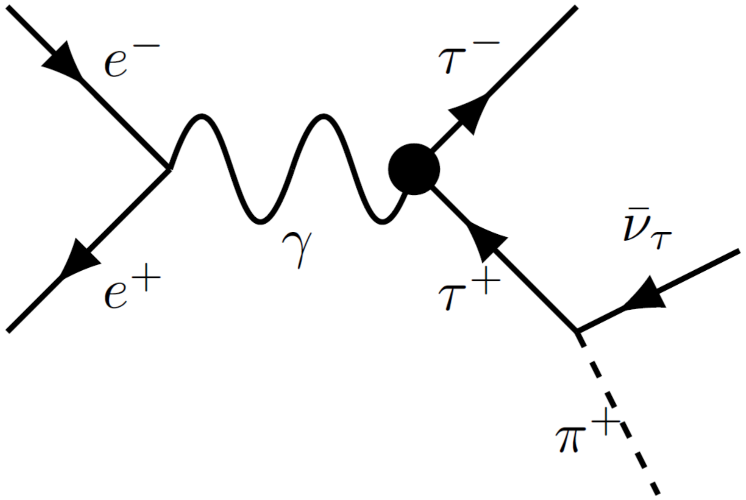
λ is the electron helicity, $\boldsymbol{e}_z$ vector is directed along the momentum of an electron

One needs to measure the polarization of τ^-

This can be done by studying the various τ decay channels

$e^+e^- \to \tau^+\pi^-\nu_\tau$ and $e^+e^- \to \tau^-\pi^+\bar{\nu}_\tau$



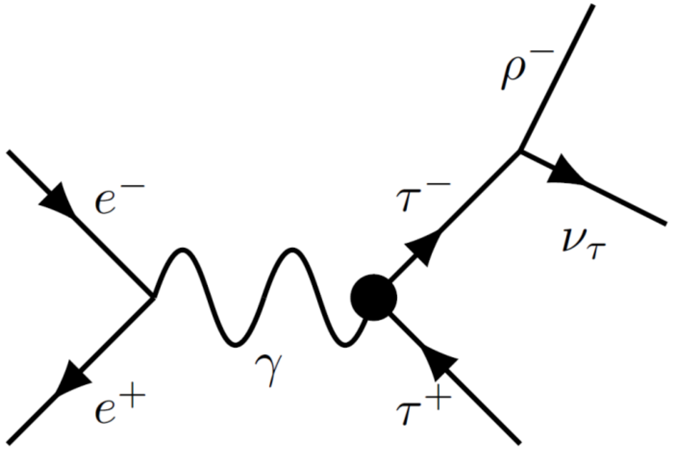


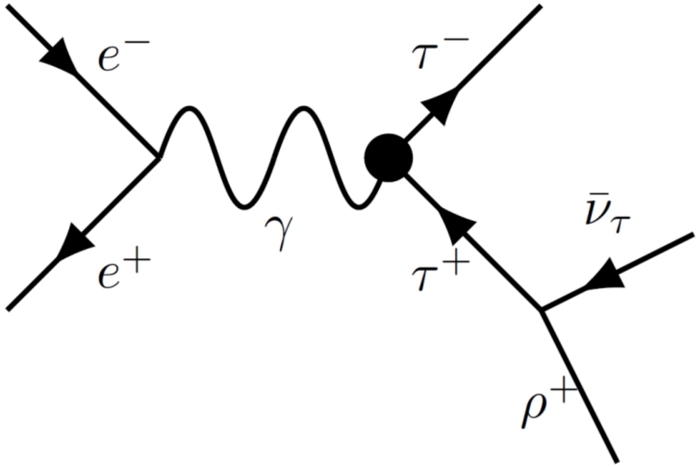
$$dA_\pi = \frac{d\sigma_\pi^{(-)}(\boldsymbol{k}) - d\sigma_\pi^{(+)}(-\boldsymbol{k})}{2\sigma_0} \propto Im(b)\, d\boldsymbol{k}$$

$d\sigma_\pi^{(\mp)}$ are $e^+e^- \to \tau^\pm\pi^\mp\nu_\tau$ cross sections, $\pm\boldsymbol{k}$ are $\pi^\mp$ momenta

To observe $\mathrm{R}e(b)$ one has an additional vector

$e^+e^- \to \tau^+\rho^-\nu_\tau$ and $e^+e^- \to \tau^-\rho^+\bar{\nu}_\tau$





$$dA_\rho = \frac{d\sigma_\rho^{(-)}(\boldsymbol{p},\boldsymbol{f}) - d\sigma_\rho^{(+)}(-\boldsymbol{p},-\boldsymbol{f})}{2\sigma_0} \propto \left[C_1^\rho Re(b) + C_2^\rho Im(b)\right] d\boldsymbol{p}$$

$d\sigma_\rho^{(\mp)}$ are $e^+e^- \to \tau^\pm\rho^\mp\nu_\tau$ cross sections, $\pm\boldsymbol{p}$ and $\pm\boldsymbol{f}$ are $\rho^\mp$ momenta and polarization vectors

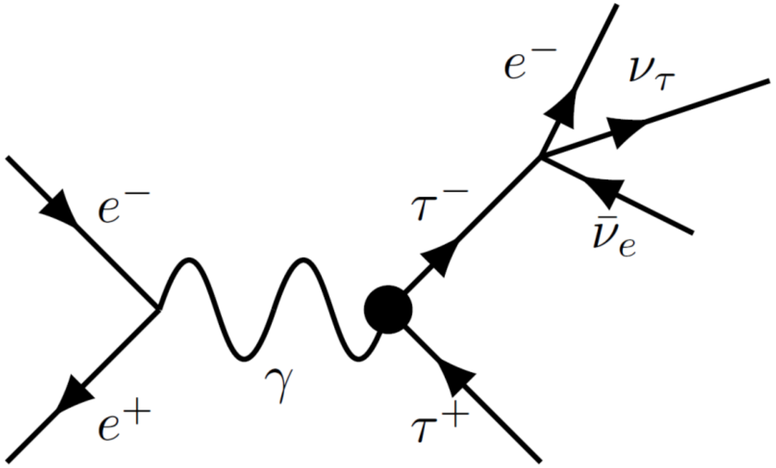
$$C_1^\rho \propto ([\boldsymbol{\Lambda} \times \boldsymbol{f}] \cdot \boldsymbol{p}), \ \boldsymbol{\Lambda} = \lambda\, \boldsymbol{e}_z,$$

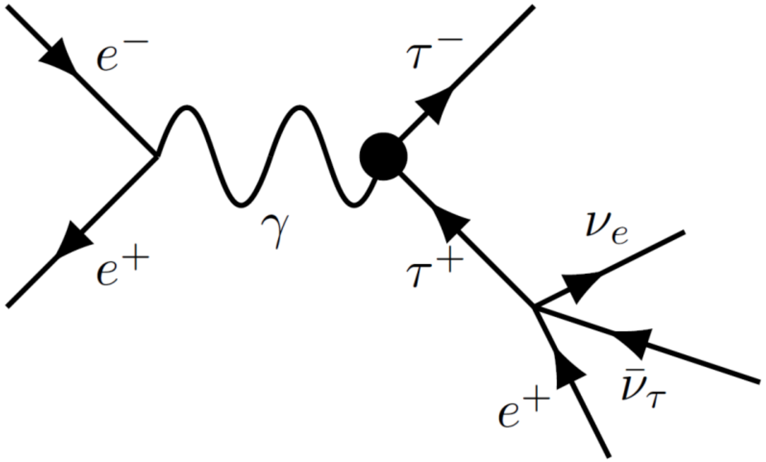
λ is the e^- helicity, $\boldsymbol{e}_z$ vector is directed along the e^- momentum

f^μ can be find from the main decay mode $\rho^\mp \to \pi^\mp\pi^0$

$$f^\mu = k_1^\mu - k_2^\mu, \qquad p^\mu = k_1^\mu + k_2^\mu$$

$e^+e^- \to \tau^+e^-\nu_\tau\bar{\nu}_e$ and $e^+e^- \to \tau^-e^+\bar{\nu}_\tau\nu_e$





$$dA_e = \frac{d\sigma_e^{(-)}(\boldsymbol{k}) - d\sigma_e^{(+)}(-\boldsymbol{k})}{2\sigma_0} \propto [C_1^e Re(b) + C_2^e Im(b)]d\Omega_{\boldsymbol{q}} d\boldsymbol{k}$$

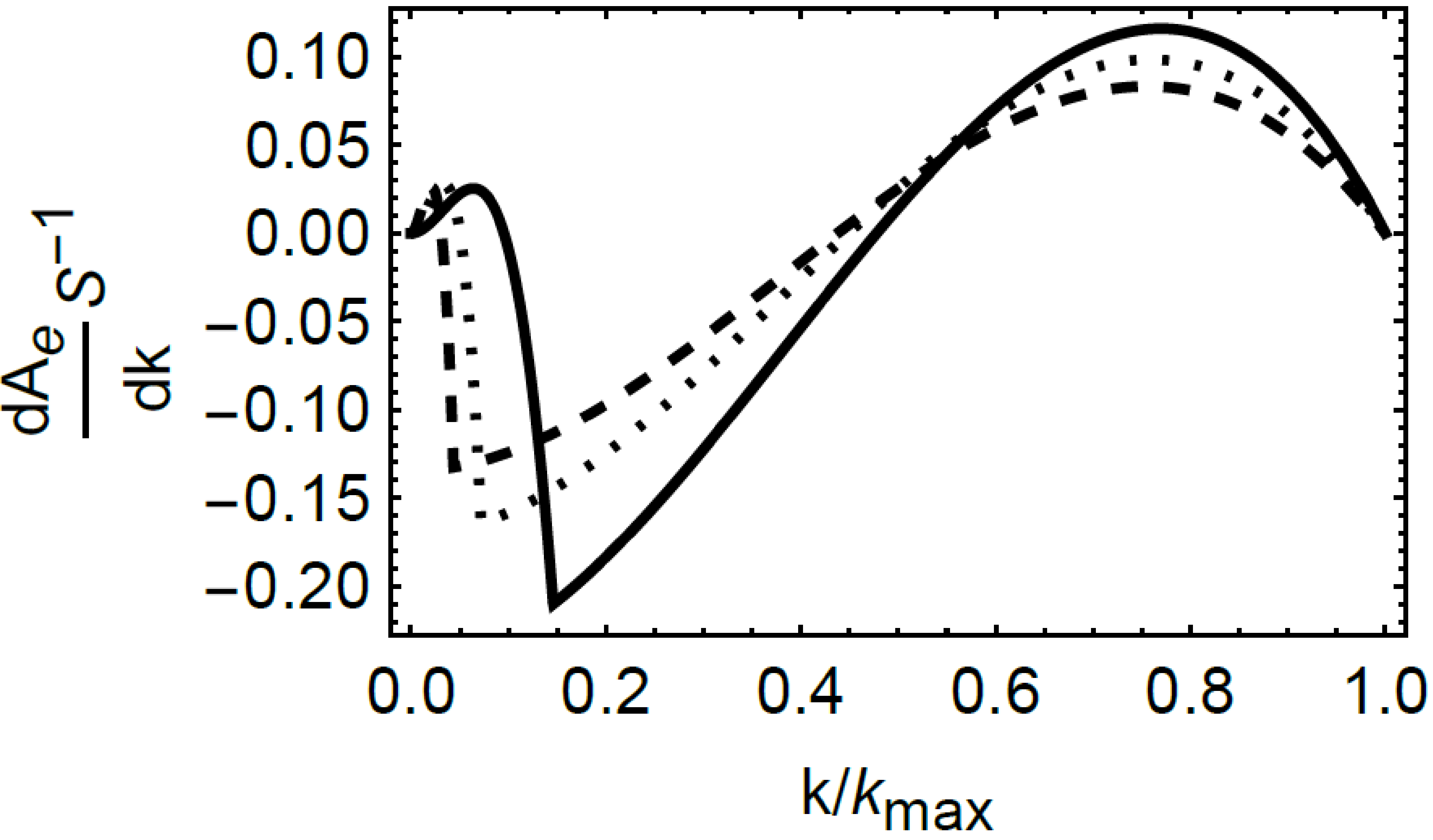
$d\sigma_e^{(\mp)}$ are $e^+e^- \to \tau^\pm e^\mp \nu_\tau \nu_e$ cross sections, $\pm\boldsymbol{k}$ are $e^\mp$ momenta

$$C_1^e \propto ([\boldsymbol{\Lambda} \times \boldsymbol{q}] \cdot \boldsymbol{k}),\ \boldsymbol{\Lambda} = \lambda\, \boldsymbol{e}_z,$$

λ is the e^- helicity, $\boldsymbol{e}_z$ vector is directed along the e^- momentum

After integration dA_e by the angles of $\boldsymbol{q}$ vector $dA_e \propto Im(b)\, d\boldsymbol{k}$

$e^+e^- \to \tau^+e^-\nu_\tau\bar{\nu}_e$ and $e^+e^- \to \tau^-e^+\bar{\nu}_\tau\nu_e$



$$S = \frac{B_e Im(b)}{M}$$

$$k_{max} = \frac{E+q}{2}$$

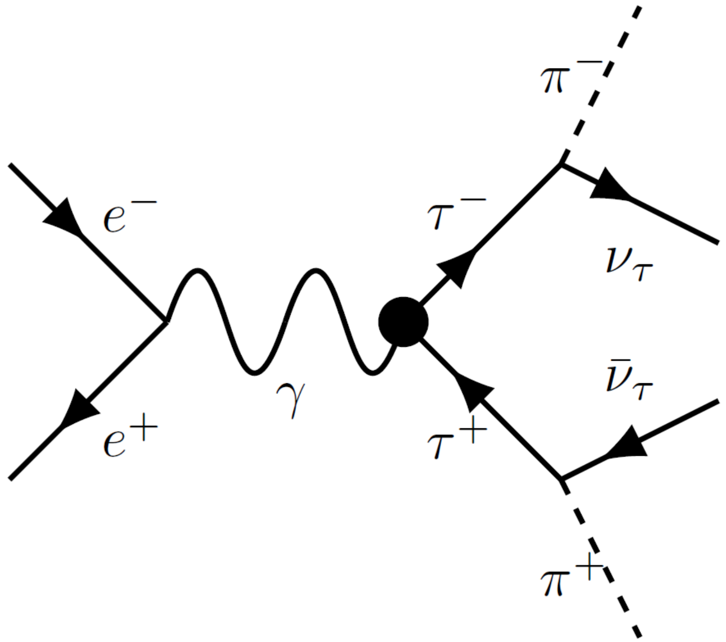
Asymmetry dA_e/dk in units of S

$e^+e^- \to \pi^+\pi^-\nu_\tau\bar{\nu}_\tau$

$$dA_{\pi\pi} = \frac{d\sigma_{\pi\pi}(\boldsymbol{k_1}, \boldsymbol{k_2}) - d\sigma_{\pi\pi}(-\boldsymbol{k_2}, -\boldsymbol{k_1})}{2\sigma_0} \propto [D_1^{\pi} Re(b) + D_2^{\pi} Im(b)] d\boldsymbol{k_1} d\boldsymbol{k_2}$$

$d\sigma_{\pi\pi}$ is the $e^+e^- \to \pi^+\pi^-\nu_\tau\bar{\nu}_\tau$ cross section,

$\boldsymbol{k}_{1,2}$ are $\pi^{-,+}$ momenta

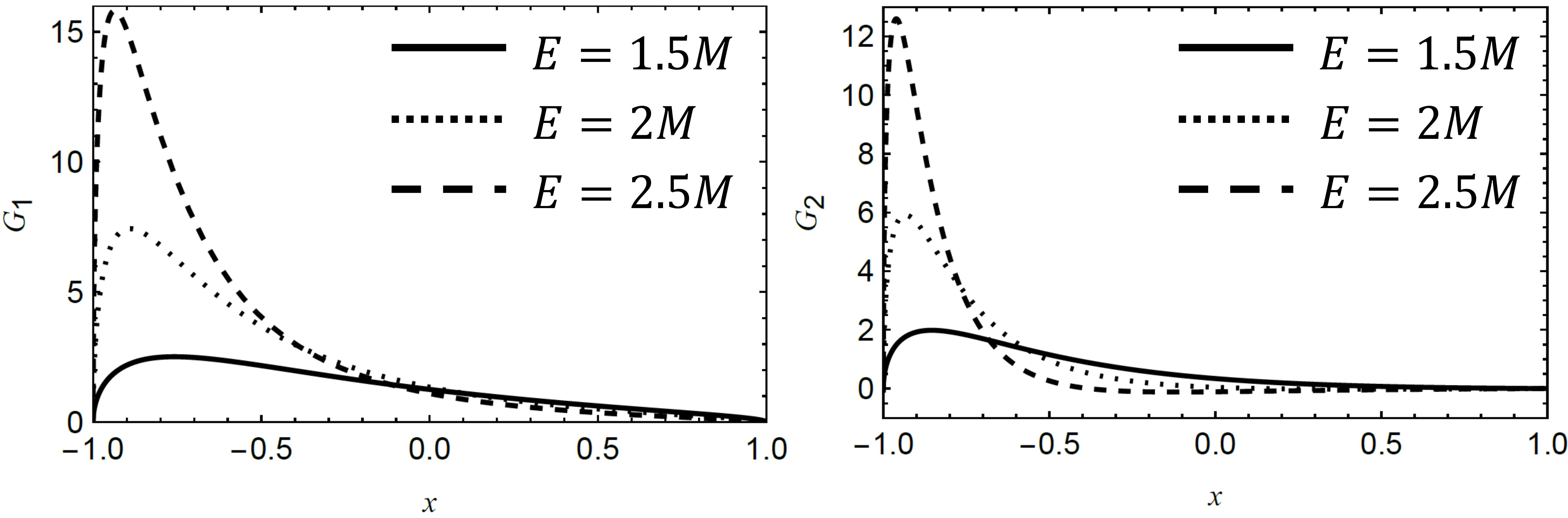


After integration $dA_{\pi\pi}$ by modules of $\boldsymbol{k}_{1,2}$ vectors

$$\frac{dA_{\pi\pi}}{d\Omega_1 d\Omega_2} \propto \left\{ G_1(x) \frac{[(\boldsymbol{\Lambda}\cdot\boldsymbol{n_1})^2 - (\boldsymbol{\Lambda}\cdot\boldsymbol{n_2})^2]}{\sqrt{1-x^2}} Im(b) + G_2(x) \frac{[(\boldsymbol{\Lambda}\cdot\boldsymbol{n_1}) - (\boldsymbol{\Lambda}\cdot\boldsymbol{n_2})]([\boldsymbol{n_1}\times\boldsymbol{n_2}]\cdot\boldsymbol{\Lambda})}{\sqrt{2(1-x)(1-x^2)}} Re(b) \right\}$$

$$x = (\boldsymbol{n_1}\cdot\boldsymbol{n_2}), \boldsymbol{n}_{1,2} = \boldsymbol{k}_{1,2}/k_{1,2}$$

$e^+e^- \to \pi^+\pi^-\nu_\tau\bar{\nu}_\tau$



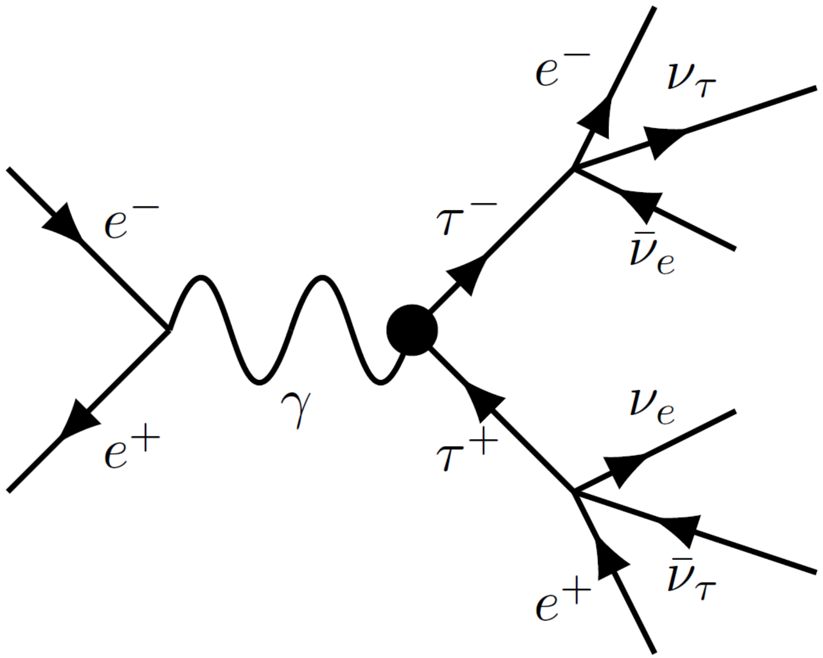
Functions $G_1(x)$ and $G_2(x)$, $x = (\boldsymbol{n}_1 \cdot \boldsymbol{n}_2)$

$e^+e^- \to e^+e^-\nu_\tau\bar{\nu}_\tau\nu_e\bar{\nu}_e$

$$dA_{ee} = \frac{d\sigma_{ee}(\boldsymbol{k_1}, \boldsymbol{k_2}) - d\sigma_{ee}(-\boldsymbol{k_2}, -\boldsymbol{k_1})}{2\sigma_0} \propto [D_1^e Re(b) + D_2^e Im(b)] d\boldsymbol{k_1} d\boldsymbol{k_2}$$

$d\sigma_{ee}$ is the $e^+e^- \to e^+e^-\nu_\tau\bar{\nu}_\tau\nu_e\bar{\nu}_e$ cross section,

$\boldsymbol{k}_{1,2}$ are $e^{-,+}$ momenta



After integration dA_{ee} by modules of $\boldsymbol{k}_{1,2}$ vectors

$$\frac{dA_{ee}}{d\Omega_1 d\Omega_2} \propto \left\{ -\frac{G_1(x)}{3} \frac{[(\boldsymbol{\Lambda}\cdot\boldsymbol{n_1})^2 - (\boldsymbol{\Lambda}\cdot\boldsymbol{n_2})^2]}{\sqrt{1-x^2}} Im(b) + \frac{G_2(x)}{9} \frac{[(\boldsymbol{\Lambda}\cdot\boldsymbol{n_1}) - (\boldsymbol{\Lambda}\cdot\boldsymbol{n_2})]([\boldsymbol{n_1}\times\boldsymbol{n_2}]\cdot\boldsymbol{\Lambda})}{\sqrt{2(1-x)(1-x^2)}} Re(b) \right\}$$

$$x = (\boldsymbol{n_1}\cdot\boldsymbol{n_2}), \boldsymbol{n}_{1,2} = \boldsymbol{k}_{1,2}/k_{1,2}$$

Conclusion

- We obtain analytic formulas for CP-odd parts of cross sections at $\sqrt{s} \ll m_Z$ for the following processes $e^+e^- \to \tau^+\pi^-\nu_\tau$, $e^+e^- \to \tau^-\pi^+\bar{\nu}_\tau$, $e^+e^- \to \tau^+\rho^-\nu_\tau$, $e^+e^- \to \tau^-\rho^+\bar{\nu}_\tau$, $e^+e^- \to \tau^+e^-\nu_\tau\bar{\nu}_e$ and $e^+e^- \to \tau^-e^+\bar{\nu}_\tau\nu_e$ with longitudinally polarized electron and unpolarized positron beams
- We obtain analytic formulas for CP-odd parts of cross sections at $\sqrt{s} \ll m_Z$ for the following processes $e^+e^- \to \pi^+\pi^-\nu_\tau\bar{\nu}_\tau$, $e^+e^- \to e^+e^-\nu_\tau\bar{\nu}_\tau\nu_e\bar{\nu}_e$, $e^+e^- \to \mu^+\mu^-\nu_\tau\bar{\nu}_\tau\nu_\mu\bar{\nu}_\mu$, $e^+e^- \to \mu^+e^-\nu_\tau\bar{\nu}_\tau\nu_\mu\bar{\nu}_e$ and $e^+e^- \to e^+\mu^-\nu_\tau\bar{\nu}_\tau\nu_e\bar{\nu}_\mu$ with unpolarized electron and positron beams
- It is shown that measuring of $Im(b)$ can be done without polarization and for measuring of $Re(b)$ polarization is not necessary, but simplifies the experiment

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