EDM and CPV in the τ system

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Outline

1. Electric Dipole Moment

   1.1 Definition d_f^B

   $B = \gamma, Z, g, \ldots$
   $f = e, \mu, \tau, \ldots, b, t$

   1.2 Experiments

2. Observables

   2.1 High energies
   2.2 Low energies

3. Conclusions

1. EDM 1.1Definition

P and T-odd interaction of a fermion with gauge fields:

Classical electromagnetism
Ordinary quantum mechanics

$$H_{EDM} = -\vec{\mathbf{d}} \cdot \vec{\mathbf{E}}\,, \qquad \vec{\mathbf{d}} = d\,\vec{s}$$

Relativistic quantum mechanics: Dirac equation

$$H = \bar{\Psi}\left(i(\partial\!\!\!/ + eA\!\!\!/) - m\right)\Psi + \frac{i}{2} d\,\bar{\Psi}\gamma^5\sigma^{\mu\nu}\Psi F_{\mu\nu}$$

Non-relativistic limit:

$$H \to H_{EDM} = -\vec{\mathbf{d}} \cdot \vec{\mathbf{E}}$$

1. EDM 1.1Definition

SYMMETRIES: Time reversal T, Parity P

Besides, chirality flip (some insight into the mass origin)

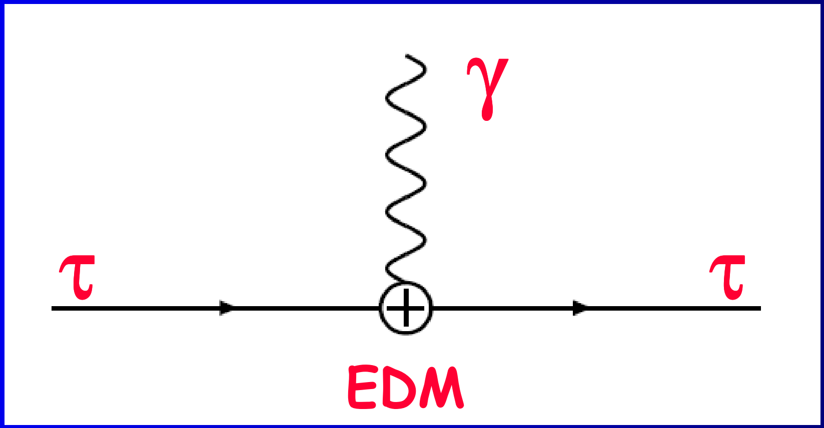
EDM ⟷ LANDAU 1957 ⟷ T , P odd interactions

$t \to -t$: $\vec{E} \to \vec{E}, \quad \vec{S} \to -\vec{S}$

$$H_{EDM} \to -H_{EDM}$$

In QFT: CPT Invariance $\not{C}\not{P} \approx \not{T}$

1. EDM 1.1 Definition

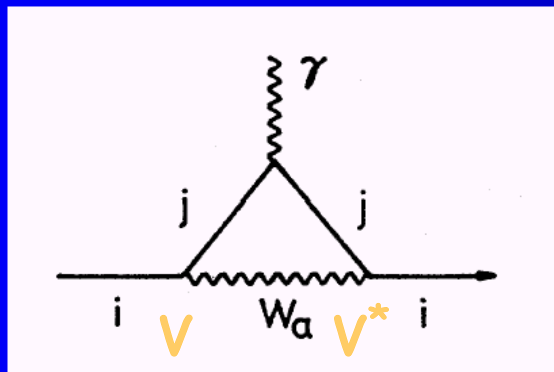


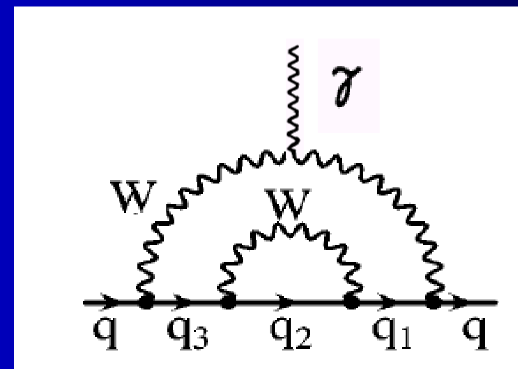
SM :
- vertex corrections
- at least 4-loops

Beyond SM:
- one loop effect (SUSY, 2HDM, ...)
- dimension six effective operator

1. EDM 1.1Definition

SM :

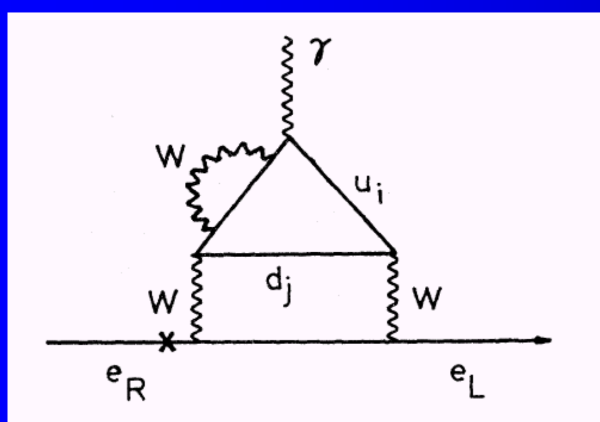




= 0 !!!

E.P.Shabalin '78

We need 3-loops for a quark-EDM, and 4 loops for a lepton...



$$d_e \simeq e G_F m_e \alpha^2 \alpha_s J / (4\pi)^5$$

J.F.Donoghue '78
I.B.Khriplovich,M.E.Pospelov '90
A.Czarnecki,B.Krause '97

1. EDM 1.1Definition

Fermion of mass m_f generated by physics at $\Lambda-$ scale has

$$EDM \approx m_f/\Lambda^2$$

T-odd $\tau-$EDM has particular interest and depends on the underlying physics of CP violation

1. EDM 1.1Definition

Effective Lagrangian:

$$\mathcal{L}_{eff} = \mathcal{L}_0 + \frac{1}{\Lambda^2} \sum_i C_i O_i + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

CPV:

$$\mathcal{L}_{\text{eff}} = i\alpha_B \mathcal{O}_B + i\alpha_W \mathcal{O}_W + \text{h.c.}$$

Operators:

$$\mathcal{O}_W = \frac{g}{2\Lambda^2} \bar{L}_L \vec{\tau} \varphi \sigma_{\mu\nu} \tau_R \vec{W}^{\mu\nu}$$

$$\mathcal{O}_B = \frac{g'}{2\Lambda^2} \bar{L}_L \varphi \sigma_{\mu\nu} \tau_R B^{\mu\nu}$$

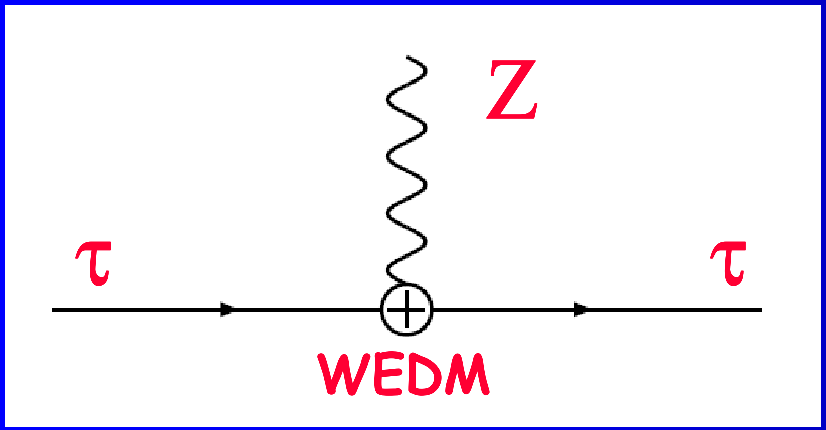
Other operators:

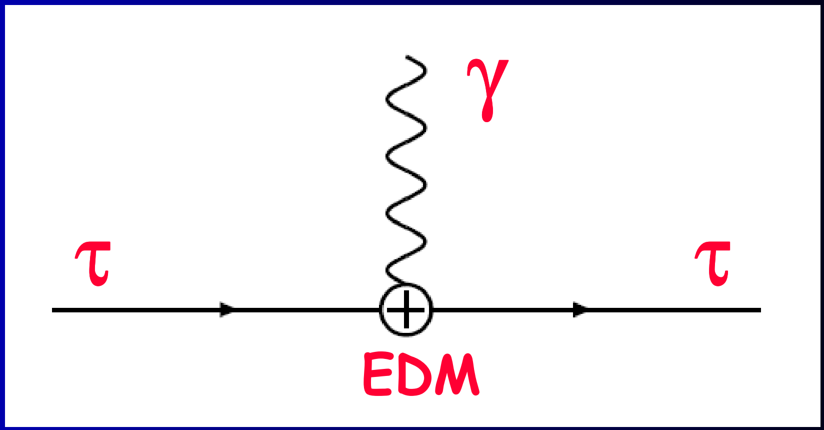
$$O_{LW} = i[\overline{L} \gamma^\mu \tau^I D^\nu L - \overline{D^\nu L} \gamma^\mu \tau^I L] W^I_{\mu\nu},$$

$$O_{LB} = i[\overline{L} \gamma^\mu D^\nu L - \overline{D^\nu L} \gamma^\mu L] B_{\mu\nu},$$

$$O_{\tau B} = i[\overline{\tau_R} \gamma^\mu D^\nu \tau_R - \overline{D^\nu \tau_R} \gamma^\mu \tau_R] B_{\mu\nu},$$

1. EDM 1.1Definition





More sensitivity

HIGH ENERGY (Z-peak)

LOW ENERGY

1. EDM 1.1Definition

$$\Gamma_5^{\mu}(p_-, p_+) = ie \left[\gamma^{\mu}\gamma^5 a_V(q^2) + \sigma^{\mu\nu}\gamma^5 q_\nu d_V(q^2) \right]$$

V = γ, Z

For $q^2=0$ EDM d_γ^τ

$q^2=M_Z^2$ WEDM d_Z^τ

GAUGE INVARIANT OBSERVABLE QUANTITIES

Beyond SM EDM: Loop calculations

1. EDM 1.2 Experiments

PDG '06 95% CL

EDM BELLE '02

$$\mathrm{Re}(d_\gamma^\tau): \ (-2.2 \text{ to } 0.45) \times 10^{-16} \text{ e cm}$$

$$\mathrm{Im}(d_\gamma^\tau): (-0.25 \text{ to } 0.008) \times 10^{-16} \text{ e cm}$$

WEDM ALEPH 1990-95 LEP runs

$$\left|\mathrm{Re}(d_Z^\tau)\right| \leq 0.50 \times 10^{-17} \text{ e cm}$$

$$\left|\mathrm{Im}(d_Z^\tau)\right| \leq 1.1 \times 10^{-17} \text{ e cm}$$

1. EDM   1.2 Experiments

For other fermions....

$$d_\gamma^e = (0.069 \pm 0.074) \times 10^{-26} \text{ e cm}$$

$$d_\gamma^\mu = (3.7 \pm 3.4) \times 10^{-19} \text{ e cm}$$

$$d_\gamma^n < 0.63 \times 10^{-25} \text{ e cm, } 90\% \text{ CL}$$

2. Observables

SM for EDM is well below within present experimental limits:

$$d_\gamma^q \approx 10^{-32} - 10^{-34}\,ecm$$

CKM 3-loops

$$d_\gamma^e \approx 10^{-38}\,ecm$$

CKM 4-loops

SM prediction

Hopefully

$$d_\gamma^\tau \approx \frac{m_\tau}{m_e} d_\gamma^e \approx 10^{-33} - 10^{-34}\,ecm$$

in the SM

…15 orders of magnitude below experiments...

2. Observables

Currents limits on electron EDM gives: $d_\gamma^\tau < 2.4 \times 10^{-24}$ ecm

However, in many models the EDM do not necessarily scale as the first power of the masses.

Multihiggs models 1-loop contributions
Vectorlike leptons

EDM scale as the cube of the mass!

BSM τ-EDM can go up to 10^{-19} e cm

2. Observables

Non-vanishing signal in a τ—EDM observable

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NEW PHYSICS

One expects: $$d_\gamma^\tau \approx e\frac{m_\tau}{\Lambda^2}$$

special interest in heavy flavours

τ—EDM: In order to be able to measure a genuine non-vanishing signal one has to deal with a $\not{CP}$ **-observable**

2. Observables 2.1 High energies

Indirect arguments:

$$\left.\begin{array}{c}\Delta\sigma(e^+e^- \to \tau^+\tau^-)\\ \Delta\Gamma(Z \to \tau^+\tau^-)\end{array}\right. \approx \left|d_Z^\tau\right|^2$$

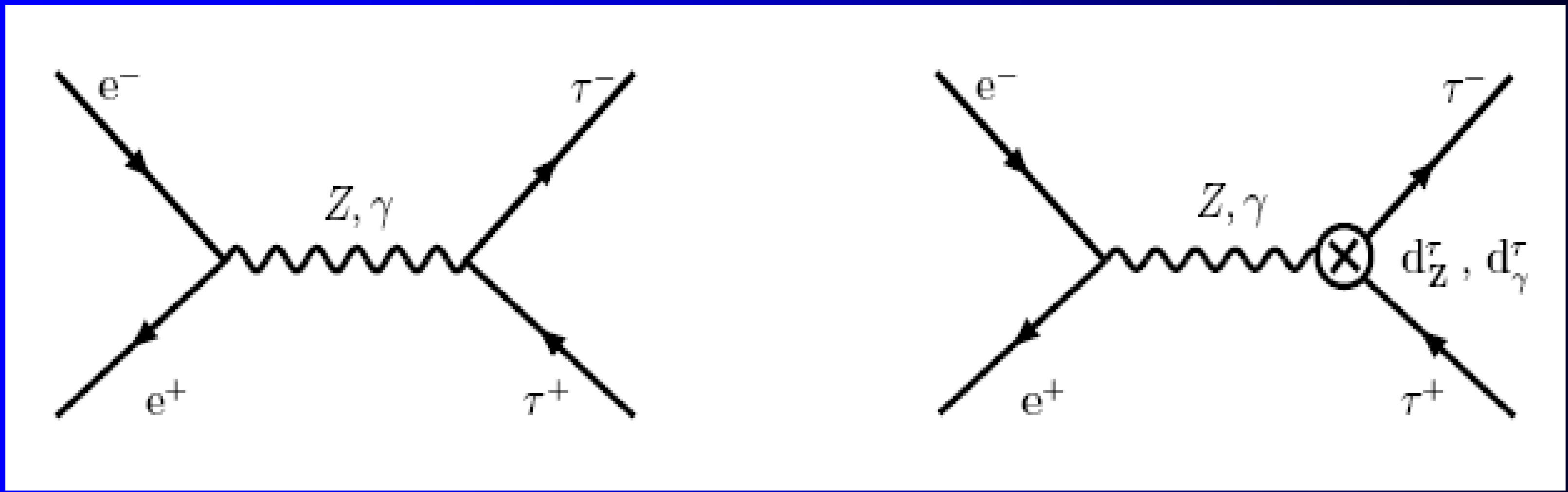
any other physics may also contribute...

→ Look for $\not{P}$, $\not{CP}$ linear effects

Genuine CPV observables in τ-pair production:

SPIN TERMS and/or **SPIN CORRELATIONS**

2. Observables 2.1 High energies



Spin terms → **angular distribution of decay products**

~~CP~~ :
- **Asymmetries in the decay products**
- **Expectation values of tensor observables**

2. Observables 2.1 High energies

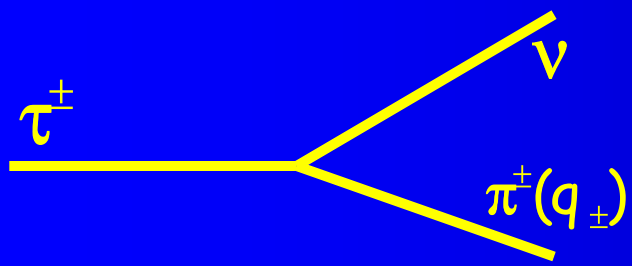
Polarizations	P	CP	T
$(\mathbf{s}_1 + \mathbf{s}_2)_{x,z}$	$-$	$+$	$+$
$(\mathbf{s}_1 + \mathbf{s}_2)_y$	$+$	$+$	$-$
$(\mathbf{s}_1 - \mathbf{s}_2)_y$	$+$	$-$	$-$
$(\mathbf{s}_1 - \mathbf{s}_2)_{x,z}$	$-$	$-$	$+$

Correlations	P	CP	T
$s_{xx},\ s_{yy},\ s_{zz},$ $(s_{xz} + s_{zx})$	$+$	$+$	$+$
$(s_{xy} + s_{yx}),$ $(s_{yz} + s_{zy})$	$-$	$+$	$-$
$(\mathbf{s}_1 \times \mathbf{s}_2)_{x,z}$	$-$	$-$	$-$
$(\mathbf{s}_1 \times \mathbf{s}_2)_y$	$+$	$-$	$+$

x: Transverse y: Normal z: Longitudinal

2. Observables 2.1 High energies

Tensor observables: $T_{ij} = (q_+ - q_-)_i \, (q_+ \times q_-)_j + (i \leftrightarrow j)$



Z-peak: $\left\langle T_{ij} \right\rangle_{\pi\pi} \approx \frac{m_Z}{e} c_{\pi\pi} s_{ij} d_Z^{\tau}$

W.Bernreuther,O.Nachtmann '89

Normal polarization: $P_N^{\tau} \leftrightarrow T-\text{odd},\ P-\text{even}$

(and needs helicity-flip)

Genuine CPV if $P_N^{\tau^+} \leftrightarrow P_N^{\tau^-}$

J.Bernabeu,GGS,J.Vidal '93

2. Observables 2.1 High energies

$$P_N^\tau \propto a\gamma\beta\sin\theta_\tau\left[2v^2+(v^2+a^2)\beta\cos\theta_\tau\right]m_\tau\frac{d_Z^\tau}{e}$$

EDM (and P_N^τ) is proportional to angular asymmetries, to extract $\sin\theta_\tau$ $\cos\theta_\tau\sin\phi_h$

$$A=\frac{\sigma^+-\sigma^-}{\sigma^++\sigma^-}$$

(more details latter..)

One can measure A for τ^+ and/or τ^-

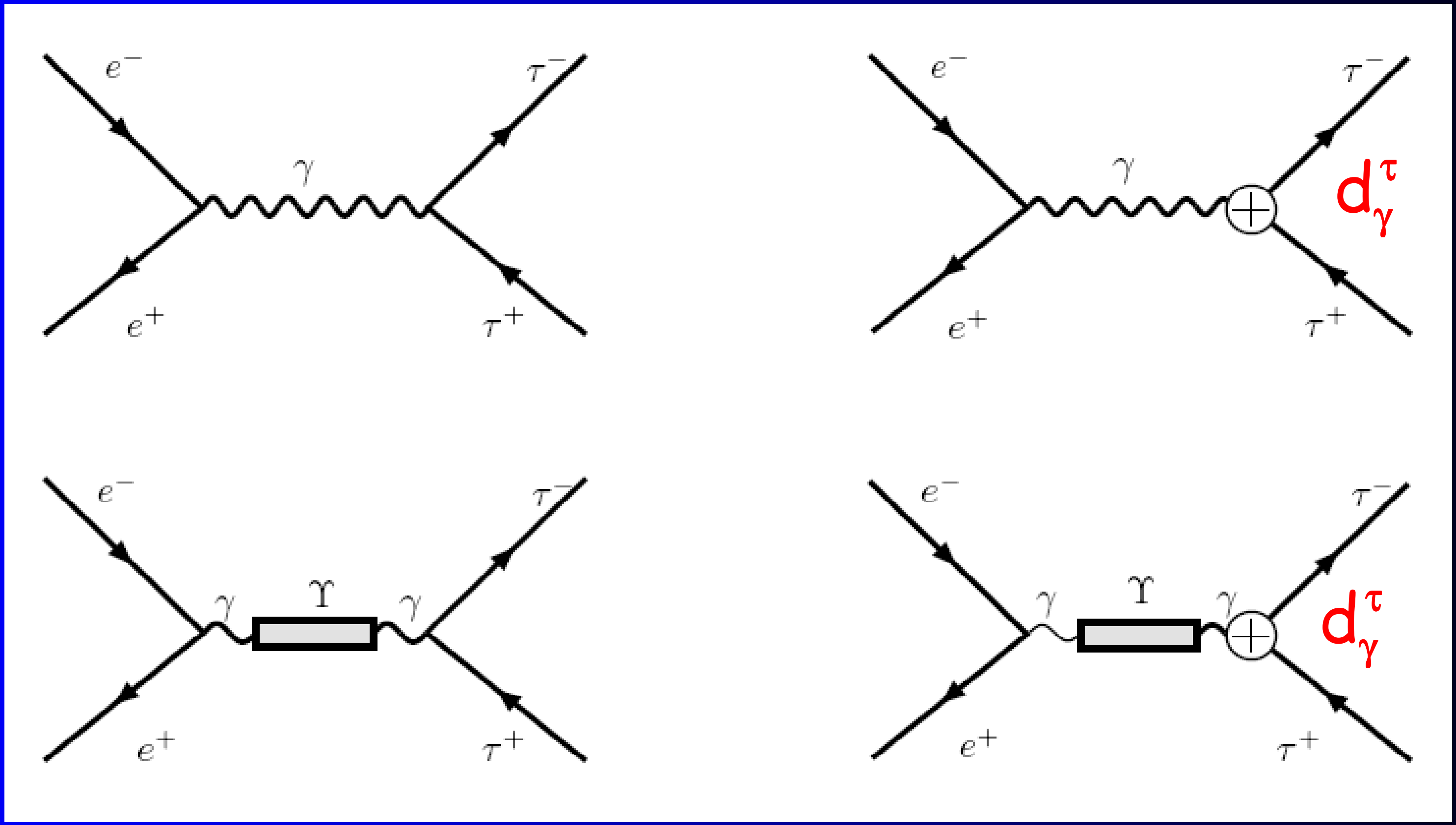
$\not{CP}$:

$$\boxed{A^{CPV}\equiv\frac{1}{2}(A^++A^-)}$$

2. Observables 2.2 Low energies

$$e^+e^- \to \gamma, \Upsilon \to \tau^+(s_+)\,\tau^-(s_-)$$

Diagrams:



2. Observables 2.2 Low energies

EDM $\longleftrightarrow$ Spin correlation terms only

NORMAL-TRANSVERSE T-odd $(s_+ \times s_-)_{N,T}$

NORMAL-LONGITUDINAL $(s_+ \times s_-)_{N,L}$

Discrete symmetries: P, CP, T and helicity flip.

J.Bernabeu,GGS,J.Vidal '04

What about the linear terms?

Normal polarization: P-even, T-odd $(s_+ - s_-)$

vs.

EDM lagrangian P and T-odd.

Interference with the axial part of Z-exchange, suppressed by q^2/M_Z^2

2. Observables 2.2 Low energies

SPIN CORRELATIONS

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ANGULAR DISTRIBUTION OF TAU DECAYS

$\tau \to h\,\nu$ kinematic variables :

- $e^-\tau^-$ CM angle θ
- Azimuthal ϕ_{h^+}, $\phi_{h'^-}$
- Polar θ_{h^+}, $\theta_{h'^-}$ angles of the produced hadrons h^+ and h'^-

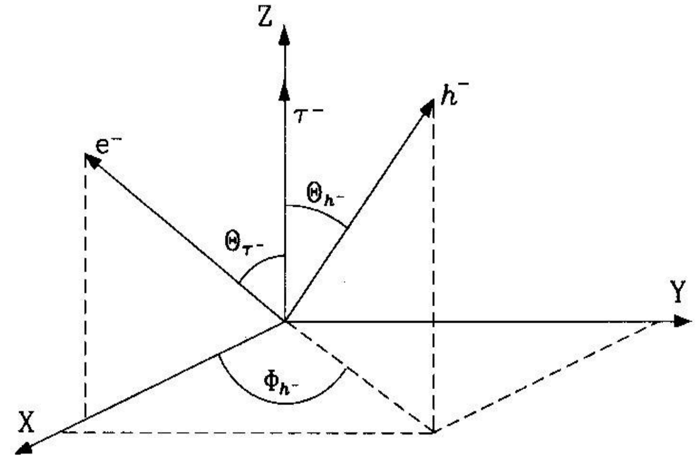

Fig. 2. Reference system for the process $e^+e^- \to \tau^+\tau^- \to h_1^+ + h_2^- + X$

2. Observables 2.2 Low energies

τ^- momenta $\leftrightarrow$ LONGITUDINAL $\leftrightarrow$ z axe

$\boldsymbol{p}_{\tau^-} \times \boldsymbol{p}_{e^-}$ $\leftrightarrow$ NORMAL $\leftrightarrow$ y axe

CORRELATIONS:

$$\begin{aligned}\frac{d\sigma^{corr}}{d\Omega_{\tau^-}} = \; & \frac{\alpha^2}{16s}\beta\Big(s_+^x s_-^x C_{xx} + s_+^y s_-^y C_{yy} + s_+^z s_-^z C_{zz} + \\ & (s_+^x s_-^y + s_+^y s_-^x) C_{xy}^+ + (s_+^x s_-^z + s_+^z s_-^x) C_{xz}^+ + \\ & (s_+^y s_-^z + s_+^z s_-^y) C_{yz}^+ + (\boldsymbol{s}_+ \times \boldsymbol{s}_-)_x C_{yz}^- + \\ & (\boldsymbol{s}_+ \times \boldsymbol{s}_-)_y C_{xz}^- + (\boldsymbol{s}_+ \times \boldsymbol{s}_-)_z C_{xy}^-\Big)\end{aligned}$$

$$C_{xx} = (2-\beta^2)\sin^2\theta \qquad C_{xz}^+ = \frac{1}{\gamma} sin 2\theta$$

$$C_{yy} = -\sin^2\theta \qquad C_{xy}^- = 2\beta\sin^2\theta\, d_\tau^\gamma$$

$$C_{zz} = \beta^2 + (2-\beta^2)\cos^2\theta \qquad C_{yz}^- = \gamma\beta sin^2\theta\, d_\tau^\gamma$$

2. Observables 2.2 Low energies

$\not{T}$, $\not{P}$

CPV

NORMAL-TRANSVERSE CORRELATION

C^{-}_{xy} term in $d\sigma(e^+e^- \to \gamma \to \tau^+\tau^- \to h^+\bar{\nu}h'^-\nu)$

$$\frac{d\sigma^8}{d\Omega_\tau d^3q^*_- d^3q^*_+}\Big|_{C^-_{xy}} = \frac{\alpha^2\beta^2}{128\pi^3 s^2} Br_+ Br_- \, d^\gamma_\tau \, \sin^2\theta \, (n^*_{+x}n^*_{-y} - n^*_{+y}n^*_{-x}) \, \delta(q^*_- - P_-)\delta(q^*_+ - P_+)$$

$n^*_\pm = \pm\alpha_\pm \hat{q}^*_\pm$

$q_\pm$ are the momentum of the hadrons

$P_\pm = \frac{m_\tau^2 - m_\pm}{2m_\tau}$

2. Observables 2.2 Low energies

$$\frac{d^2\sigma}{d\phi^*_- d\phi^*_+} = \frac{\alpha^2\beta^2}{192 s^2} Br_- Br_+ \alpha_- \alpha_+ \sin(\phi^*_- - \phi^*_+)\, d^\gamma_\tau$$

$$A_{NT} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

$$\sigma^\pm = \int_{w \gtrless 0} \frac{d^2\sigma}{d\phi^*_- d\phi^*_+}\, d\phi^*_-\, d\phi^*_+$$

$$w = \sin(\phi^*_- - \phi^*_+)$$

$$A_{NT} = \frac{4\beta}{\pi} \frac{\alpha_-\alpha_+}{3-\beta^2} d^\gamma_\tau$$

2. Observables — 2.2 Low energies

NORMAL-LONGITUDINAL CORRELATION

$$\left.\frac{d\sigma^8}{d\Omega_\tau d^3q^*_- d^3q^*_+}\right|_{C^-_{yz}} = \frac{\alpha^2\beta^2}{128\pi^3 s^2} Br_+ Br_- \gamma\, d^\gamma_\tau \sin 2\theta (n^*_{+z} n^*_{-y} - n^*_{+y} n^*_{-z}) \delta(q^*_- - P_-)\delta(q^*_+ - P_+)$$

$$A^-_{NL} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

$$\sigma^\pm = \int_{w \gtrless 0} \frac{d^3\sigma}{d\phi^*_- d\theta^*_- d\theta^*_+} d\phi^*_- d\theta^*_- d\theta^*_+$$

$$A_{NL} = \frac{1}{2}\left(A^+_{NL} - A^-_{NL}\right) = \frac{\beta\gamma}{4(3-\beta^2)} \alpha_h^2 \frac{2m_\tau}{e} d^\gamma_\tau$$

2. Observables 2.2 Low energies

e^+e^- at Υ energies

τ pair production: $e^+e^- \to \Upsilon \to \tau^+\tau^-$

- Multiplicative factor appears in the cross section
- Interference of diagrams (a) and (d) plus the interference of diagrams (b) and (c) is exactly zero.
- Only the interference of diagrams (b) and (d) contributes

$$\left(\frac{e^2 Q_b^2 |F_\Upsilon|^2}{s\Gamma_\Upsilon M_\Upsilon}\right)^2 = \left(\frac{3}{\alpha} Br(\Upsilon \to e^+e^-)\right)^2$$

The asymmetries do not change at the Υ peak

2. Observables — 2.2 Low energies

EDM imaginary part:

LONGITUDINAL AND TRANSVERSE POLARIZATION TERMS

$$A_T^{\pm} = \frac{\sigma_+^{\pm} - \sigma_-^{\pm}}{\sigma_+^{\pm} + \sigma_-^{\pm}}$$

$$\sigma_{\pm}^{\pm} = \int_{w \gtrless 0} \frac{d^2\sigma}{d\cos\theta_{\tau^-} d\phi_{\pm}} d\cos\theta_{\tau^-} d\phi_{\pm}$$

$$w = \sin 2\theta_{\tau^-} \cos\phi_{\pm}$$

$$A_T^{\pm} = -\frac{\beta\gamma}{2(3-\beta^2)} \alpha_{\pm} \frac{2m_\tau}{e} \mathrm{Im}\left[d_\tau^\gamma\right]$$

$$A^{CPV} = \frac{1}{2}\left(A_T^+ + A_T^-\right)$$

2. Observables

2.2 Low energies

Bounds:

For $10^{6/7}$ τ and at low/Υ energies

upper bound

$$\left|Re(d_{\gamma}^{\tau})\right| < 10^{-16/-17}\, e\, cm$$

3. Conclusions

- τ EDM can be well bounded at low energy experiments
- Different CP-odd asymmetries allow to study the correlation and linear spin terms
- Bounds from these observables are competitive with present limits

➔ **Polarized beams open the possibility for new observables**

➔ **Improving the number of τ–pairs (...10^{11}?) allows to lower the EDM bound by many (...2?) orders of magnitude**

➔ **These new bounds may be important for beyond the SM τ–physics**

3. Summary

Discussions with J.Bernabeu, J.Vidal and A.Santamaría are gratefully acknowledged

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