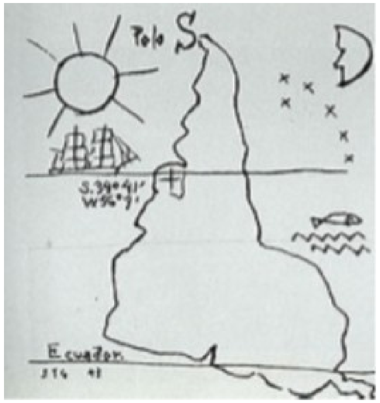
τ magnetic moment



Gabriel González-Sprinberg

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Cinvestav, May 2017

τ magnetic moment

Outline

- What: DEFINITION
- Why: SM - BSM
- How: Observables
- Where: B factories
- When: Summary/Future

τ magnetic moment

NR QM: $\mathcal{H} = -\vec{\mu} \cdot \vec{B}$

R QM: $\left(i \not\nabla - e \not A - m_\ell \right) \Psi(x) = 0$

τ magnetic moment

NR QM: $$\mathcal{H} = -\vec{\mu} \cdot \vec{B}$$

R QM: $$\left(i\not{\nabla} - e\not{A} - m_\ell \right) \Psi(x) = 0$$ Dirac equation

NR limit: $$\mathcal{H} = 2 \frac{e}{2 m_\ell c} \vec{s} \cdot \vec{B}$$

$$\mu_\ell = \frac{e \hbar}{2 m_\ell c}$$

τ magnetic moment

NR QM: $$\mathcal{H} = -\vec{\mu}\cdot\vec{B}$$

R QM: $$\left(i\not\nabla - e\not A - m_\ell + i\,a\frac{e}{4\,m_\ell}\sigma^{\mu\nu}F_{\mu\nu} \right)\Psi(x) = 0$$

NR limit: $$\mathcal{H} = 2(1+a)\frac{e}{2\,m_\ell\,c}\vec{s}\cdot\vec{B}$$

τ magnetic moment

NR QM:
$$\mathcal{H} = -\vec{\mu}\cdot\vec{B}$$

R QM:
$$\left(i\not{\nabla} - e\not{A} - m_f + i\,a\,\frac{e}{4 m_f}\sigma^{\mu\nu}F_{\mu\nu} \right)\Psi(x) = 0$$

NR limit:
$$\mathcal{H} = 2(1+a)\frac{e}{2 m_\ell c}\vec{s}\cdot\vec{B}$$

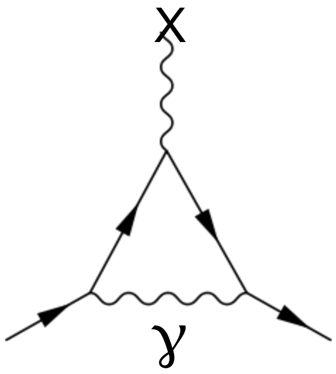
Quantum correction in QFT

Magnetic moment
$$\mu_\ell = (1+a)\frac{e\hbar}{2 m_\ell c}$$
$$g_\ell = 2(1+a)$$

τ magnetic moment

Anomalous magnetic moment: $$a_e^{QED_1} = \frac{\alpha}{2\pi}$$ Schwinger 1948

$$\frac{\alpha}{2\pi} \simeq 0.001\ 161\ldots$$



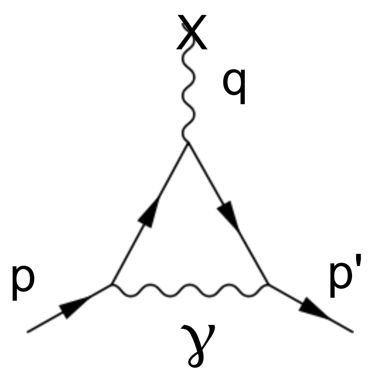
- One loop correction
- Flavor independent in QED
- External particles on-shell

τ magnetic moment

Anomalous magnetic moment: $a_\ell^{QED_1} = \frac{\alpha}{2\pi}$ Schwinger 1948

(one-loop)

$$A = -ie\,\bar{u}(p')\left(F_1(q^2)\gamma^\mu + i\,F_2(q^2)\sigma^{\mu\nu}\frac{q_\nu}{2m_\tau}\right)u(p)\epsilon_\mu(q)$$



- external particles on-shell, then

$$F_1(q^2=0)=1$$
$$F_2(q^2=0)=a_\tau$$

- gauge invariant quantity

τ magnetic moment

Anomalous magnetic moment:

$$a_\ell^{QED} = \frac{\alpha}{2\pi} + a_2\alpha^2 + a_3\alpha^3 \ldots$$

1, 7, 79, 891, ...

- except Schwinger, all terms are flavor dependent

KINOSHITA LAPORTA REMEDDI ......

τ magnetic moment

WHY

Anomalous magnetic moment: $$a_\tau^{SM} = 117\ 721(5) \times 10^{-8}$$

EIDELMAN PASSERA

QED: $$a_\tau^{QED}(3-loops) = 117\,324(2) \times 10^{-8}$$

1 %
Schwinger

1678 diags CZARNECKI KRAUSE MARCIANO

EW: $$a_\tau^{EW} = 47.4(5) \times 10^{-8}$$

(55.1 1-loop -7.74 2-loops)

HAD: $$a_\tau^{HAD} = 350.1(4.8) \times 10^{-8}$$

NARISON BARISH STRYNOVKI SAMUEL EIDELMAN JEGERLEHNER KRAUSE ....

τ magnetic moment

Anomalous magnetic moment:

$$a_\tau^{SM} = a_\tau^{QED} + a_\tau^{EW} + a_\tau^{HAD}$$

$$\frac{\alpha}{2\pi} \simeq 0.001\ 161\ldots$$

$$a_e^{SM} = 115\ 965\ .\ 218\ 091(26) \times 10^{-8}$$

$$a_\mu^{SM} = 116\ 591\ .\ 803(1)(42)(26) \times 10^{-8}$$

$$a_\tau^{SM} = 117\ 721(5) \times 10^{-8}$$

τ magnetic moment

Anomalous magnetic moment: $$a_\tau^{SM} = a_\tau^{QED} + a_\tau^{EW} + a_\tau^{HAD}$$

EW contributions: $\sim m_f^2 / m_W^2$

a_τ terms flip chirality!

NP contributions: $\sim m_f^2 / m_\Lambda^2$

relative sensitivity: $$\frac{m_\mu^2}{m_e^2} \sim 4\times 10^4 \qquad \frac{m_\tau^2}{m_e^2} \sim 1.2\times 10^7$$

τ magnetic moment

τ anomalous magnetic moment in BSM:

- Little Higgs, U. Puebla, Eur.Phys.J. C77 (2017) no.4, 227 ,
  M. A. Arroyo-Ureña, G. Hernández-Tomé, G. Tavares-Velasco
- Little Higgs, U.A. Zacatecas,Mod.Phys.Lett. A Vol.25, No.9 (2010) 703–713,
  A.Gutiérrez-Rodríguez
- E6, U.A.Zacatecas – IPN, Int.J.Mod.Phys. A22 (2007) 3493-3508
  A. Gutierrez-Rodriguez, M.A. Hernandez-Ruiz, M.A. Perez
- 331, U.A.Zacatecas, J.Phys. G40 (2013) 035001331
  A. Gutierrez-Rodriguez, M.A. Hernandez-Ruiz, C.P. Castaneda-Almanza

τ magnetic moment

Magnetic moments:

- Flip chirality, and in the SM fermion masses are the only source of chirality flips.

- Observables that are exactly zero when chirality is conserved are the best candidates in order to measure magnetic moments.

- These will only be sensitive to fermion masses and magnetic moments.

- Besides they will depend linearly on magnetic moments.

τ magnetic moment

PDG LIMIT IS:

$$-0.052 < a_\tau < 0.013$$

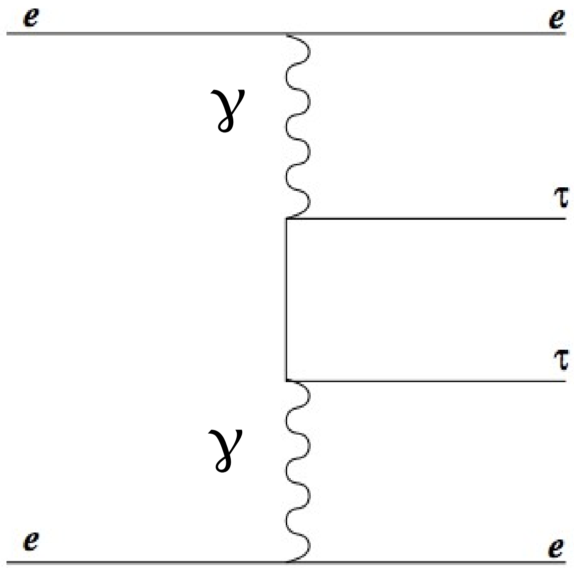
since 2004

95% CL, 650 pb-1, 1997 – 2000 data

2004 DELPHI / LEP2 183 < √s < 208 GeV total cross section

$$e^- \ e^+ \ \rightarrow \ e^- \ e^+ \ \tau^- \ \tau^+$$

2390 events



CORNET ILLANA

τ magnetic moment

HOW

PDG LIMIT IS:

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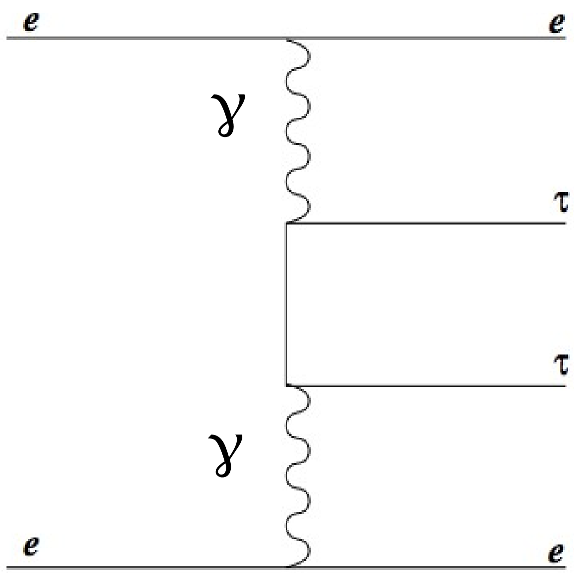
$$e^- \ e^+ \ \to \ e^- \ e^+ \ \tau^- \ \tau^+$$

2390 events

$$a_\tau^{SM} = 0.00\ 117\ 721(5)$$

$$a_\tau^{\exp} = -0.018 \pm 0.017$$



CORNET ILLANA

τ magnetic moment

HOW

PDG LIMIT IS:

$-0.0 \ldots 0.013$

since 2004

2000 data also

BOUNDS / SM PREDICTION ~ ONE ORDER OF MAGNITUDE

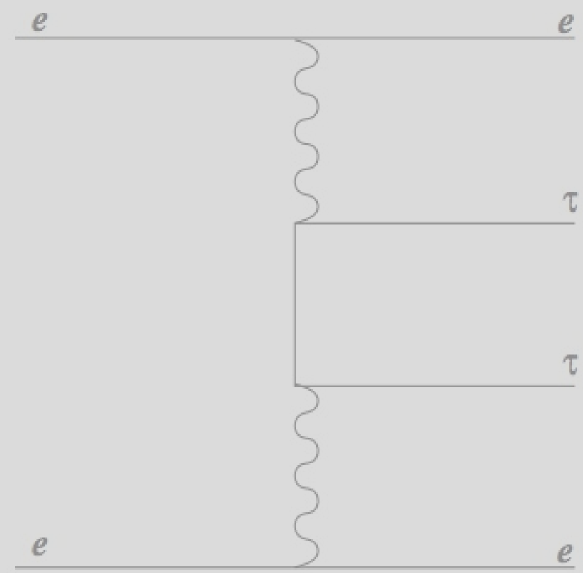
2004 DELPHI / LE… …8 GeV total cross section

$e^- \ e^+ \ \rightarrow \ \ldots \ \tau^- \ \tau^+$

2390 events

$$a_\tau^{SM} = 0.00\ 117\ 721(5)$$

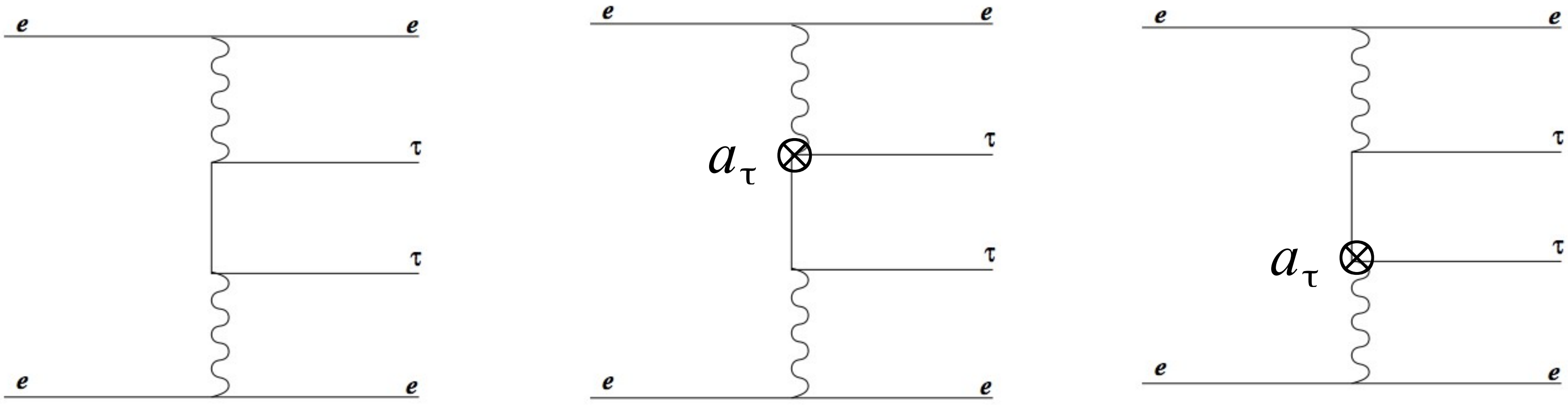
$$a_\tau^{exp} = -0.018 \pm 0.017$$



CORNET ILLANA

τ magnetic moment

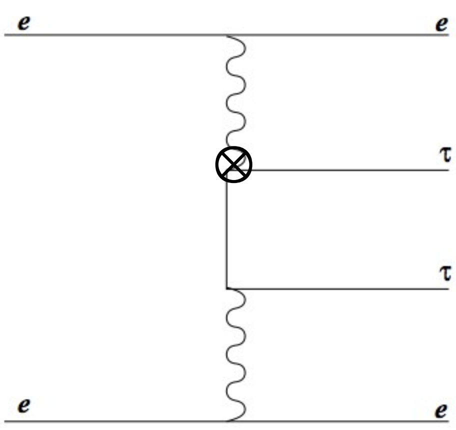
$$e^+ \; e^- \to e^+ \; e^- \; \tau^+ \; \tau^-$$

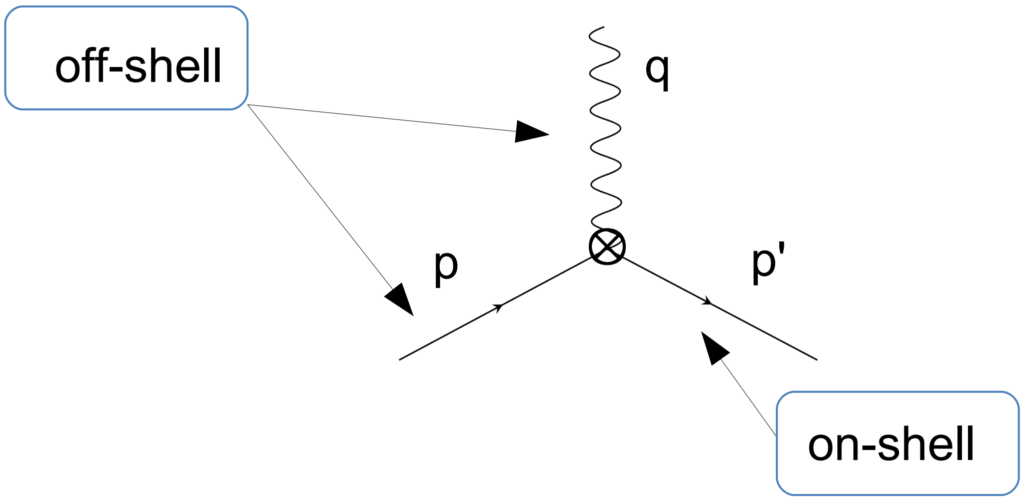


Amplitude: first order interference with leading diagram

τ magnetic moment

$$e^+ \; e^- \rightarrow e^+ \; e^- \; \tau^+ \; \tau^-$$





Amplitude Lorentz structure: far more general, and depending on two scalar functions (q^2, p^2)

τ magnetic moment

Recent study: $\tau^- \to \ell^- \ \nu_\tau \ \bar{\nu}_\ell \ \gamma$

magnetic moment from radiative decay

S.Eidelman, D.Epifanov, M.Fael, L.Mercolli, M.Passera, JHEP 1603 (2016) 140

The DELPHI bound 0.017 can be improved to 0.012 at BELLE II.

Bounds on the EDM are not competitive with BELLE.

Other ideas:

$e^- \ e^+ \to \tau^- \ \tau^+ \ \gamma$

$\gamma \ \gamma \to \tau^- \ \tau^+$

$H \to \tau^- \ \tau^+ \ \gamma$

τ magnetic moment

EFFECTIVE LAGRANGIAN APPROACH

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{eff} \qquad \mathcal{L}_{eff} = \frac{\mathcal{O}_6}{\Lambda^2} + \ldots$$

Magnetic moment:

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

$$\mathcal{O}_B = \frac{g'}{2\Lambda^2} \overline{L_L} \varphi \sigma_{\mu\nu} \tau_R B^{\mu\nu} \qquad \mathcal{O}_W = \frac{g}{2\Lambda^2} \overline{L_L} \vec{\tau} \varphi \sigma_{\mu\nu} \tau_R \vec{W}^{\mu\nu}$$

Model independent bounds on the tau lepton electromagnetic and weak magnetic moments

G.G.S., Arcadi Santamaria, Jordi Vidal, Nuclear Physics B 582 (2000) 3–18

τ magnetic moment

EFFECTIVE LAGRANGIAN APPROACH

$$\mathcal{L}_{\text{eff}} = \epsilon_\gamma \frac{e}{2m_Z} \overline{\tau} \sigma_{\mu\nu} \tau F^{\mu\nu} + \epsilon_Z \frac{e}{2m_Z s_W c_W} \overline{\tau} \sigma_{\mu\nu} \tau Z^{\mu\nu} + \left(\epsilon_W \frac{e}{2m_Z s_W} \overline{\nu_{\tau L}} \sigma_{\mu\nu} \tau_R W_+^{\mu\nu} + \text{h.c.} \right)$$

$$\epsilon_\gamma = (\alpha_B - \alpha_W) \frac{u m_Z}{\sqrt{2}\Lambda^2},$$

$$\epsilon_Z = -(\alpha_W c_W^2 + \alpha_B s_W^2) \frac{u m_Z}{\sqrt{2}\Lambda^2},$$

$$\epsilon_W = \alpha_W \frac{u m_Z}{\Lambda^2} = -\sqrt{2}(\epsilon_Z + s_W^2 \epsilon_\gamma)$$

$\Leftrightarrow$

$$a_\gamma = \frac{2m_\tau}{m_Z} \epsilon_\gamma,$$

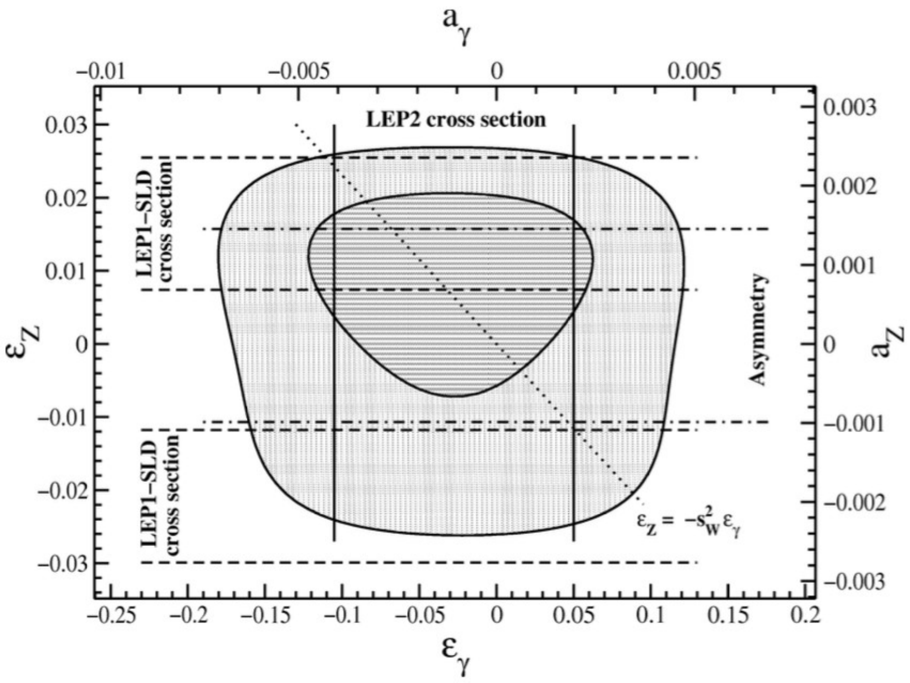
$$a_Z = \frac{2m_\tau}{m_Z} \frac{1}{s_W c_W} \epsilon_Z,$$

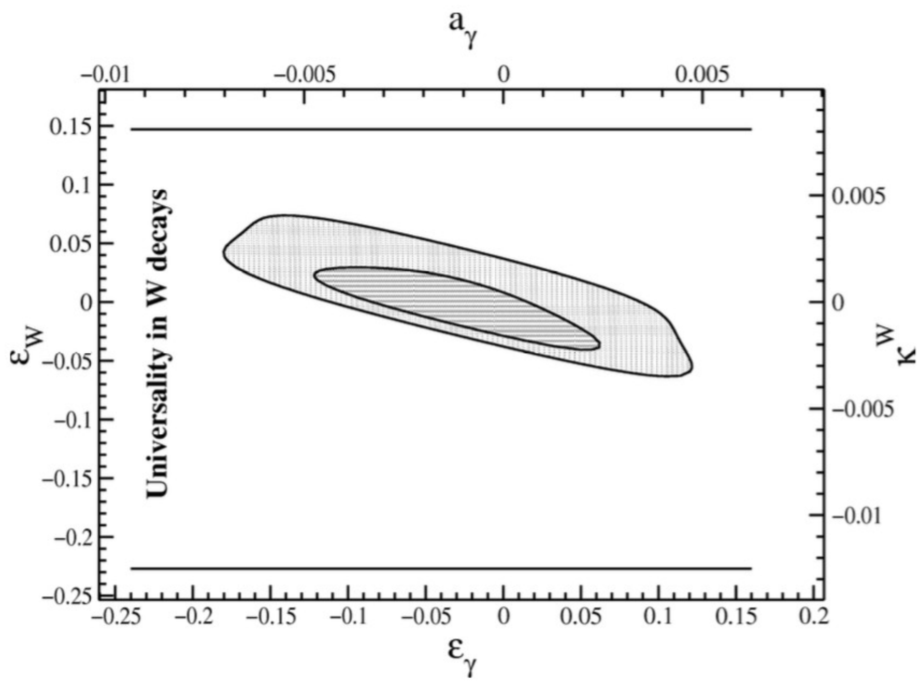
$$\kappa^W = \sqrt{2} \frac{2m_\tau}{m_Z} \epsilon_W.$$

τ magnetic moment

EFFECTIVE LAGRANGIAN APPROACH

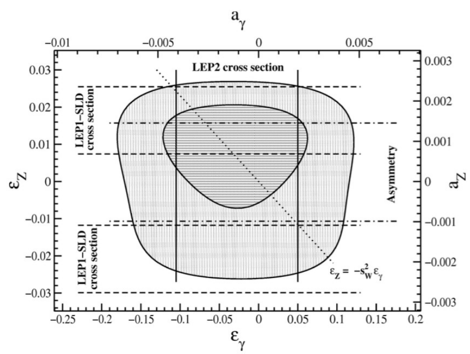
High energy data: LEP1/SLD (Z decay rates, pol asymm.),
LEP2 (W decay rates, xsections),
CDF-D0 (W decay rates).

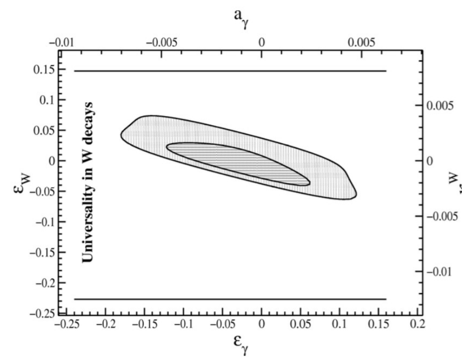




τ magnetic moment

EFFECTIVE LAGRANGIAN APPROACH





Bounds on **new physics** contributions to the magnetic moment

$$(1\sigma) \rightarrow \begin{cases} -0.005 < a_\gamma < 0.002, \\ -0.0007 < a_Z < 0.0019, \end{cases}$$

$$(2\sigma) \rightarrow \begin{cases} -0.007 < a_\gamma < 0.005, \\ -0.0024 < a_Z < 0.0025. \end{cases}$$

One order of magnitude above $\alpha/2\pi \sim 0.00116$

τ magnetic moment

B factories: Belle II

L $\approx 10^{35}$ cm^{-2} s^{-1}

$$e^{+}\ e^{-} \rightarrow \tau^{+}\ \tau^{-}$$

$$q^2 \approx (10\,GeV)^2$$

τ magnetic moment

WHERE

B factories: Belle II

L $\approx 10^{35}$ cm^{-2} s^{-1}

$$e^+ \ e^- \rightarrow \tau^+ \ \tau^-$$

$$q^2 \approx (10\,GeV)^2$$

Nucl. Phys. B790 (2008) 160-174
GGS, A.Santamaría, J.Vidal

one-loop QED
(EW suppressed q^2/M_Z^2)

Gauge independent in QED !!

$$F_2(q^2) = \left(\frac{\alpha}{2\pi}\right) \frac{2 m_\tau^2}{q^2} \frac{1}{\beta} \left(\log\frac{1+\beta}{1-\beta} - i\pi\right)$$

$$q^2 > 4 m_\tau^2$$

$$\beta = \sqrt{1 - \frac{4 m_\tau^2}{q^2}}$$

$$F_2(M_\Upsilon^2) = (2.65 - 2.45\, i) \times 10^{-4}$$

τ magnetic moment

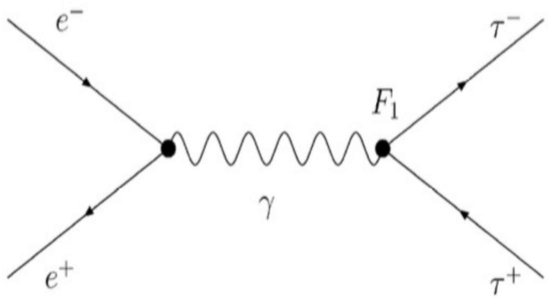
B factories: Belle II

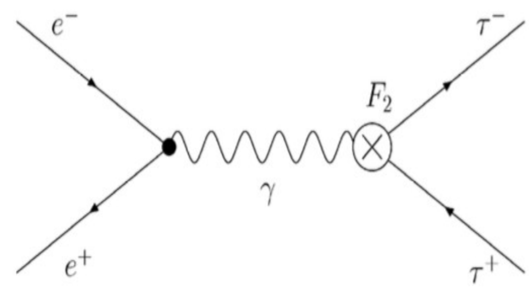
$L \approx 10^{35}\, cm^{-2}\; s^{-1}$

$$e^{+}\; e^{-} \rightarrow \tau^{+}\; \tau^{-}$$

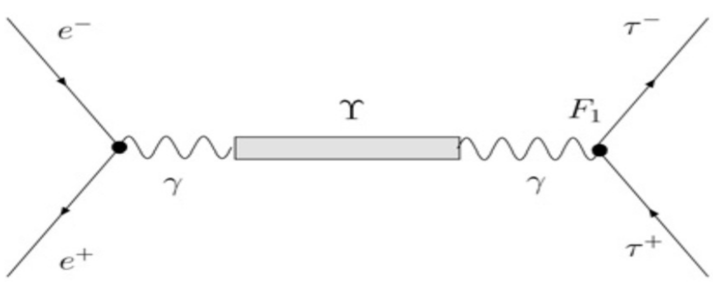
$$q^{2} \approx (10\, GeV)^{2}$$

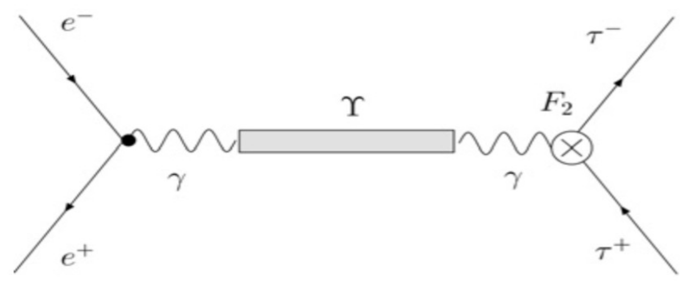
Direct





Resonant





τ magnetic moment

B factories: Belle II

$$q^2 \approx (10\,GeV)^2$$

$$e^+e^- \to \gamma \to \tau^+(\vec{s}_+)\tau^-(\vec{s}_-) \to h^+\bar{\nu}_\tau h^-\nu_\tau$$

$$\frac{d\sigma}{d\cos\theta_{\tau^-}} = \frac{\pi\alpha^2}{2s}\beta\left[\left(2-\beta^2\sin^2\theta_{\tau^-}\right)\left|F_1(s)\right|^2 + 4\,\mathrm{Re}\{F_2(s)\}\right]$$
$$\times\,\mathrm{Br}\left(\tau^- \to h^-\nu_\tau\right)\mathrm{Br}\left(\tau^+ \to h^+\bar{\nu}_\tau\right)$$

Cross section

(Im(F_2) is T- odd)

τ magnetic moment

WHERE

B factories: Belle II

$$\frac{d\sigma_{\rm FB}}{d\phi_+} = \mp\frac{\pi\alpha^2}{12s}\,{\rm Br}(\tau^+\to h^+\bar\nu_\tau)\,{\rm Br}(\tau^-\to h^-\nu_\tau)(\alpha_\pm)\beta^3\gamma\,{\rm Im}\{F_2(s)\}\sin\phi_\pm.$$

$$\sigma_{\rm FB}(\vec s_+,\vec s_-) \equiv 2\pi\left\{\int_0^1 d(\cos\theta_{\tau^-})\left[\frac{d\sigma}{d\Omega_{\tau^-}}\right] - \int_{-1}^0 d(\cos\theta_{\tau^-})\left[\frac{d\sigma}{d\Omega_{\tau^-}}\right]\right\}$$

$$= \frac{\pi\alpha^2}{6\,s}\beta^3\gamma(s_- + s_+)_y\,{\rm Im}\{F_2(s)\}$$

$$\sigma_L^\pm \equiv \int_\pi^{2\pi} d\phi_\pm\left[\frac{d\sigma_{\rm FB}}{d\phi_\pm}\right], \qquad \sigma_R^\pm \equiv \int_0^\pi d\phi_\pm\left[\frac{d\sigma_{\rm FB}}{d\phi_\pm}\right] = -\sigma_L^\pm$$

Normal polarization

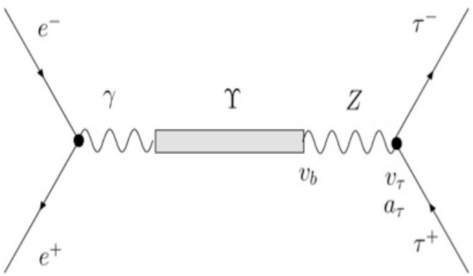
$$A_N^\pm = \frac{\sigma_L^\pm - \sigma_R^\pm}{\sigma} = \pm\alpha_\pm\frac{1}{2(3-\beta^2)}\beta^2\gamma\,{\rm Im}\{F_2(s)\}$$

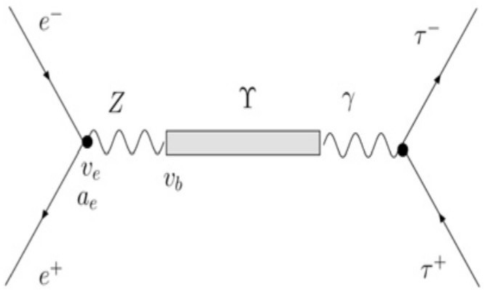
τ magnetic moment

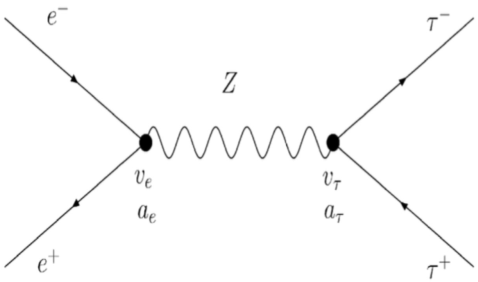
B factories: Belle II

$$e^+ \; e^- \rightarrow \Upsilon / \gamma \rightarrow \tau^+ \; \tau^-$$

- Z “contamination" (resonant and non-resonant) under control







τ magnetic moment

B factories: Belle II

$$e^+ e^- \rightarrow \Upsilon / \gamma \rightarrow \tau^+ \tau^-$$

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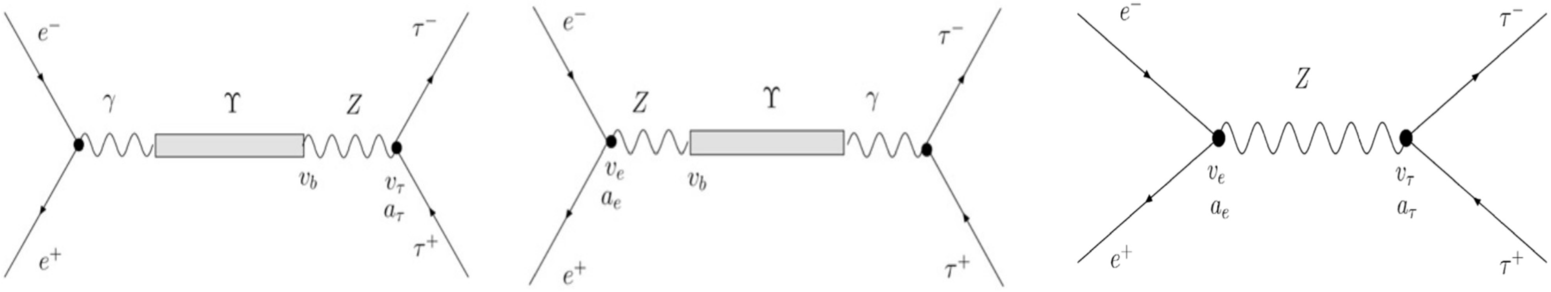
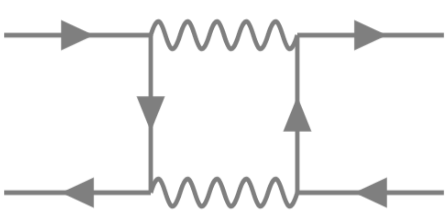


- boxes contributions are negligible/taken into account



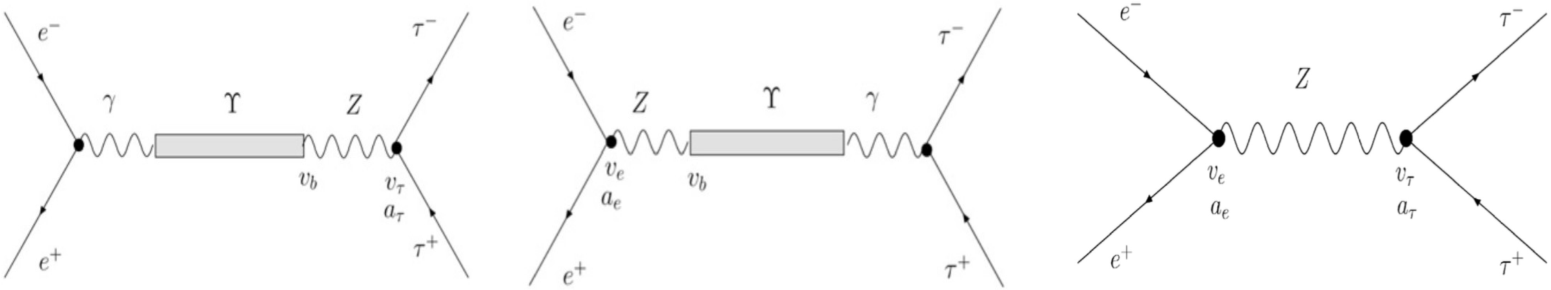
τ magnetic moment

WHERE

B factories: Belle II

$$e^{+}\ e^{-} \rightarrow \Upsilon / \gamma \rightarrow \tau^{+}\ \tau^{-}$$

- Z “contamination" (resonant and non-resonant) under control



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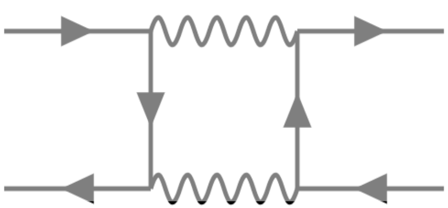

- same results as in the direct production holds

τ magnetic moment

B factories: Belle II

$$e^+ \; e^- \rightarrow \Upsilon / \gamma \rightarrow \tau^+ \; \tau^-$$

Sensitivity on F_2 at Υ-energy $F_2(M_\Upsilon^2) = (2.65 - 2.45\,i) \times 10^{-4}$			
Int. Lum.	Cross-section	Normal asymmetry	T/L asymm. *
(ab^{-1})	Re{F_2 }	Im{F_2 }	Re{F_2 }
2	4.6×10^{-6}	2.1×10^{-5}	1.0×10^{-5}
15	1.7×10^{-6}	7.8×10^{-6}	3.7×10^{-6}
75	7.5×10^{-7}	3.5×10^{-6}	3.7×10^{-6}

* Polarized electrons required.

τ magnetic moment

Summary

- SM predictions are well known for the tau AMM
- Exp. bounds are very poor when compared to other leptons
- Not even the sign of the SM-AMM for the tau is known
- AMM-BSM bounds are more stringent but far from SM prediction
- Several observables have been investigated in the literature
- Great opportunity for a high luminosity and statistics like Belle II

τ magnetic moment

CODA

Many thanks to the organizers for the invitation,

and I would like to acknowledge very useful discussions with

Jordi Vidal
José Bernabéu
Arcadi Santamaría

- Ratio of cross sections $R_{\tau\mu} = \frac{\sigma(e^+e^- \to \tau^+\tau^-)}{\sigma(e^+e^- \to \mu^+\mu^-)}$ (Eq. (3.16), Lepton Universality), at LEP1 and SLD (Eq. (3.18));
- Ratio of cross sections $R_{\tau\bar{\tau}} \equiv \frac{\sigma(e^+e^- \to \tau^+\tau^-)}{\sigma(e^+e^- \to \tau^+\tau^-)_{\mathrm{SM}}}$ (Eq. (3.21)), for the two highest energies measured at LEP2 (Table 1);
- Transverse tau polarization and the tau polarization asymmetry

$$A_{cc}^{\mp} = \frac{\sigma_{cc}^{\mp}(+) - \sigma_{cc}^{\mp}(-)}{\sigma_{cc}^{\mp}(+) + \sigma_{cc}^{\mp}(-)}$$

  (Eq. (3.25)) measured at SLD and LEP1 (Eq. (3.30));
- Ratios of decay widths of W-gauge bosons

$$R_{\tau\mathrm{e}}^{W} \equiv \frac{\Gamma(W \to \tau\nu)}{\Gamma(W \to e\nu)}$$

  (Eq. (4.1)) measured at LEP2 and $p\bar{p}$ colliders (Eq. (4.4)).

Escribano : Z width, $a_z = 0$