光光对撞中陶轻子的g-2和EDM

张成

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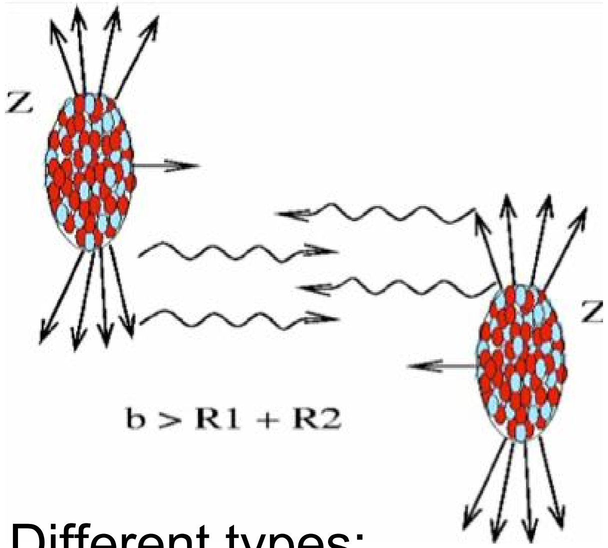
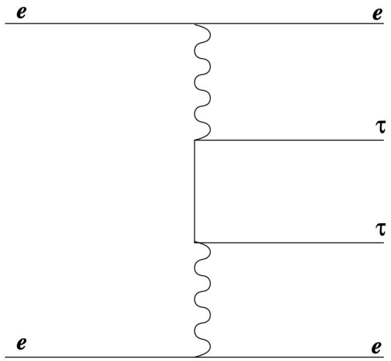
2310.14153, Ding-Yu Shao, Bin Yan, Shu-Run Yuan, **CZ**
accept by SCIENCE CHINA Physics

Ultraperipheral collisions (UPCs)

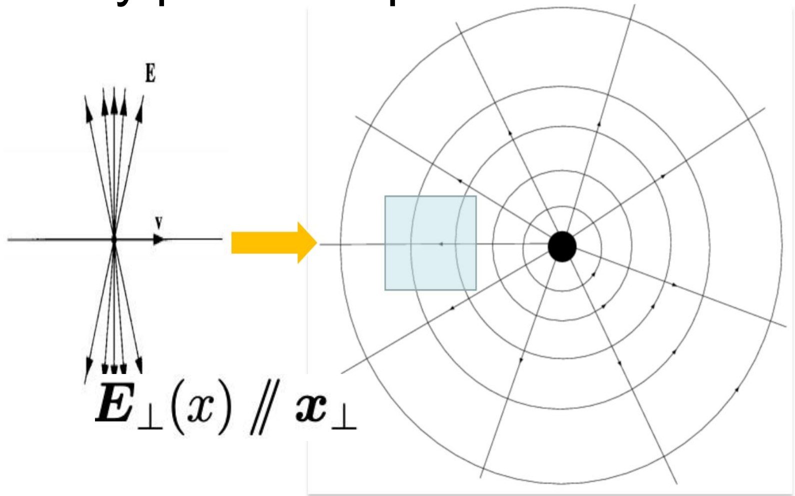
Two nuclei miss each other, interact electromagnetically

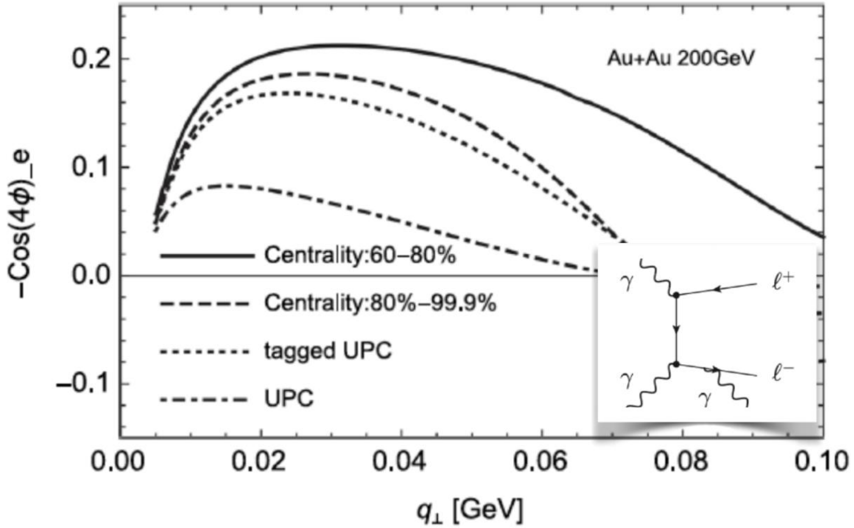


Different types:
1.光-核photo-nuclear
2.光-光photon-photon



linearly polarized photon



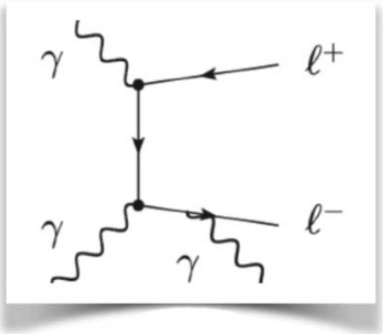


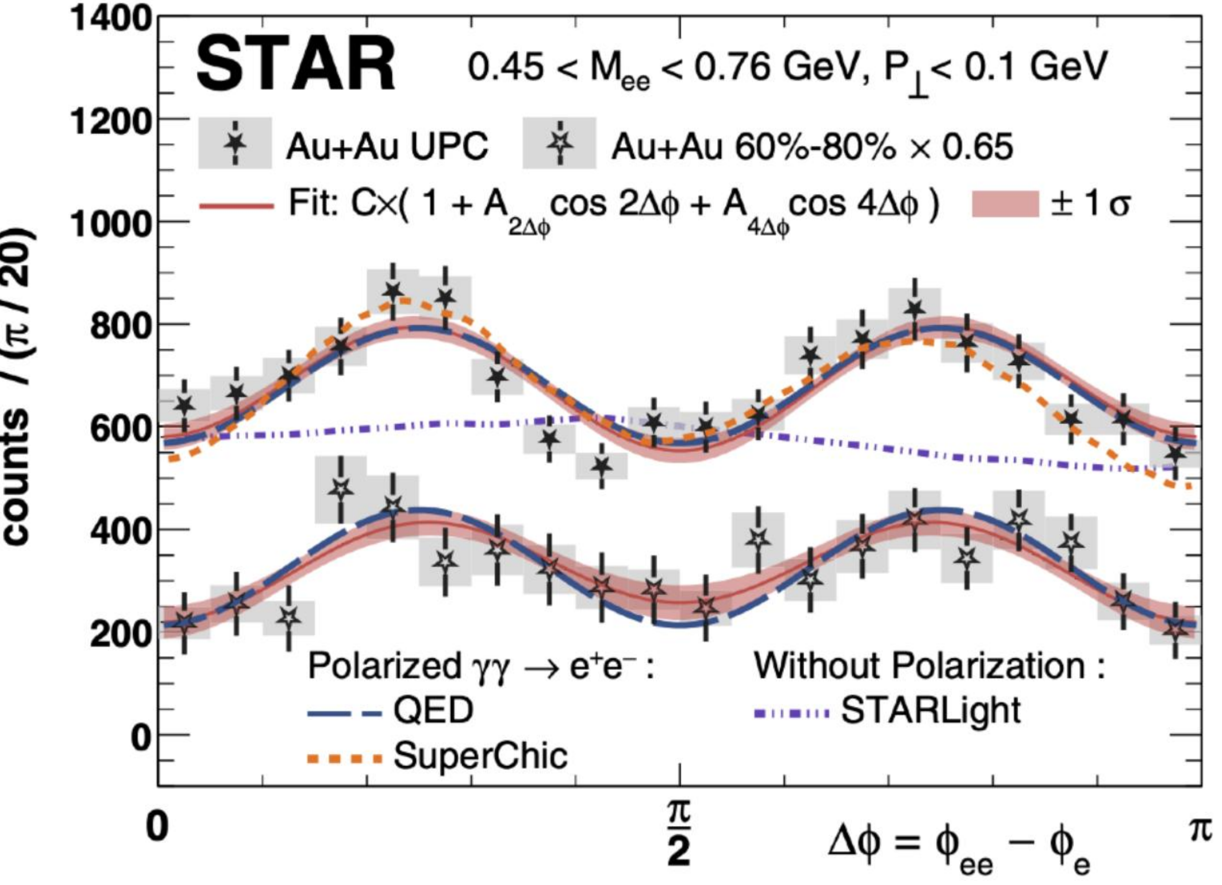
$$q_\perp \equiv p_{1\perp} + p_{2\perp}$$

$$P_\perp \equiv (p_{1\perp} - p_{2\perp})/2$$

Li, Zhou, Zhou, 2019

linearly polarized photon predicts cos4ϕ modulation





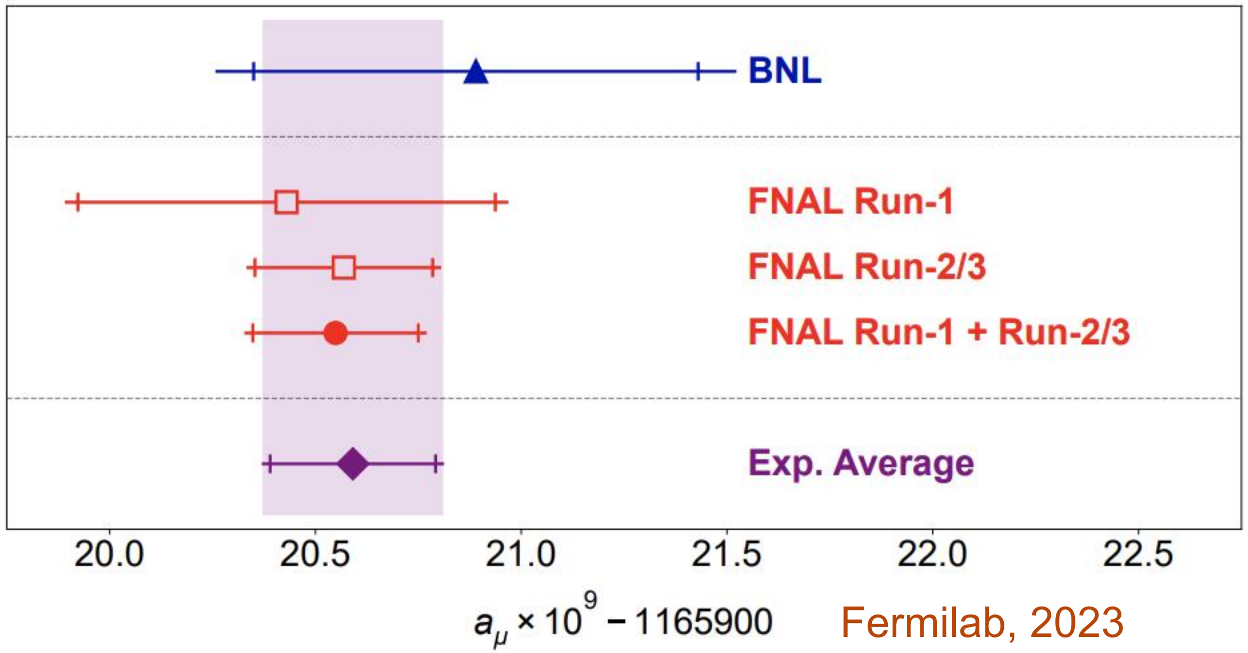
Phys. Rev. Lett. 127(2021)052302

				Data	QED
$A_{4\Delta\phi}$	Au+Au	UPC	ee	16.8 ± 2.5	16.5
	Au+Au	PC	ee	27 ± 6	34.5
	Ru/Zr	PC	ee	47 ± 14	40
	Au+Au	PC	μμ	35 ± 8± 7	22
$A_{2\Delta\phi}$	Au+Au	UPC	ee	2.0 ± 2.4	0
	Au+Au	PC	ee	6 ± 6	0
	Ru/Zr	PC	ee	6 ± 13	0
	Au+Au	**PC**	**μμ**	**20 ± 8± 3**	**13**

cos2φ modulation $\propto m_l^2/p_T^2$ *

$$a_\mu^{\rm SM} = a_\mu^{\rm QED} + a_\mu^{\rm EW} + a_\mu^{\rm hadron}$$
$$= 0.001\,165\,918\,04(51)$$

$$a_\mu = 0.001\,165\,920\,40(22)$$ Fermilab



Fermilab, 2023

$$a_\tau = 0.001\,177\,21(5)$$

$$a_\tau = -0.018 \pm 0.017$$ LEP, 2004

supersymmetry at energy scales MS: $\delta a_\ell \sim m_\ell^2/M_S^2$

$m_\tau^2/m_\mu^2 \sim 280$ times more sensitive to BSM physics than aμ

Poor constraints of tau: room for BSM physics, and motivate new experimental strategies.

Short lifetime: aτ and dτ can only be obtained from τ production and decays at colliders

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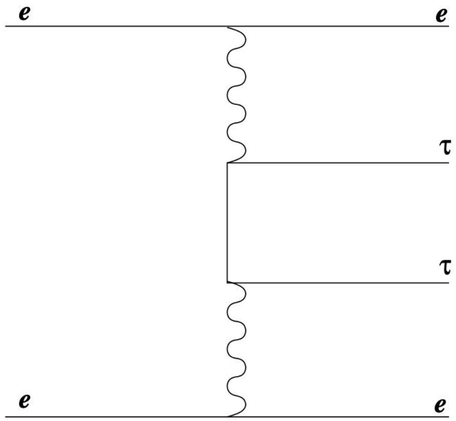
$$\Gamma^\mu(q^2) = -ie\left\{\gamma^\mu F_1(q^2) + \frac{\sigma^{\mu\nu}q_\nu}{2m_\tau}\left[iF_2(q^2) + F_3(q^2)\gamma^5\right]\right\} \quad F_1(0) = 1,\ F_2(0) = a_\tau \quad F_3(0) = 2m_\tau d_\tau / e$$

DELPHI, 2004

$\sqrt{s_{ee}} = 183\ GeV\sim208GeV,\ 650\ pb^{-1}$

$a_\tau = -0.018 \pm 0.017,$

$d_\tau = (0.0 \pm 2.0)\cdot 10^{-16}\, e\cdot\text{cm}$

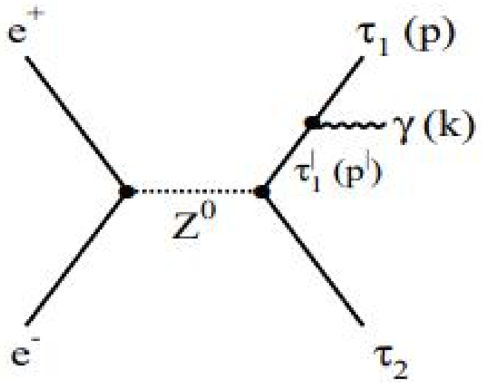


OPAL, 1998

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

$-0.068 < F_2 < 0.065$

$|eF_3| < 3.7\times10^{-16}\ e\,\text{cm}$



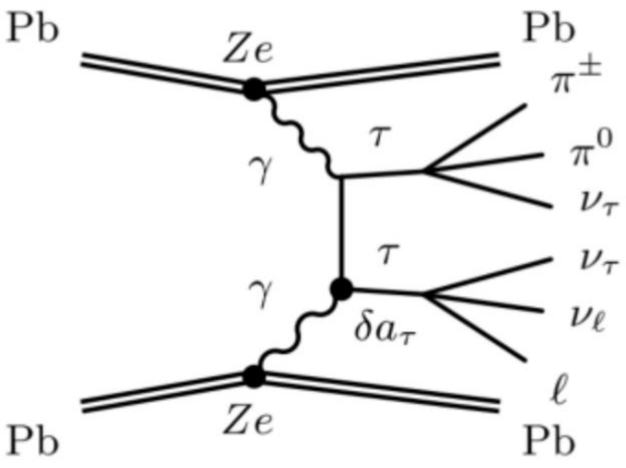
L3, 1998

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

$a_\tau = 0.004 \pm 0.027 \pm 0.023;$

$d_\tau = (0.0 \pm 1.5 \pm 1.3)\times 10^{-16} e\cdot\text{cm}$

In the SM, d_τ is very small, $d_\tau \sim \frac{m_\tau}{m_e} d_e \sim 10^{-33}\ e\ cm$



1908.05180

$$\sigma^{(\mathrm{PbPb})}_{\gamma\gamma\to XX} = \int \mathrm{d}x_1 \mathrm{d}x_2\, n(x_1) n(x_2)\, \sigma_{\gamma\gamma\to XX}$$

$$n(x) = \frac{2Z^2\alpha}{x\pi}\left\{\bar{x}K_0(\bar{x})K_1(\bar{x}) - \frac{\bar{x}^2}{2}\left[K_1^2(\bar{x}) - K_0^2(\bar{x})\right]\right\}$$

$\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

Constraints: $d_\tau < 3.4 \times 10^{-17}\ e\ cm$

$-0.008 < a_\tau < 0.0046$

2002.05503

$$\sigma\left(AA \to AA\ell^+\ell^-; \sqrt{s_{AA}}\right) = \int \sigma\left(\gamma\gamma \to \ell^+\ell^-; W_{\gamma\gamma}\right) N(\omega_1, \boldsymbol{b_1}) N(\omega_2, \boldsymbol{b_2}) S^2_{abs}(\boldsymbol{b}) \times \frac{W_{\gamma\gamma}}{2} dW_{\gamma\gamma}\, dY_{\ell\ell}\, d\bar{b}_x\, d\bar{b}_y\, d^2b\,.$$

$\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

Constraints: $|d_\tau| < 6.3 \times 10^{-17}\ e\ cm$

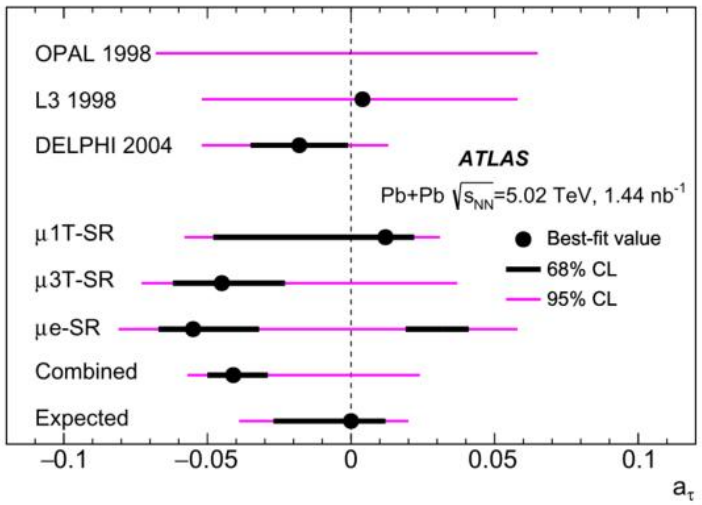
$-0.021 < a_\tau < 0.017$

ATLAS, Phys.Rev.Lett. 131 (2023) 15, 151802

$\sqrt{s_{NN}} = 5.02\ TeV,\ 1.44\ nb^{-1}$

One muon from one tau, an electron or charged-particle tracks from the other tau

95% CL : $-0.057 < a_\tau < 0.024$



CMS, Phys.Rev.Lett. 131 (2023) 151803

$\sqrt{s_{NN}} = 5.02\ TeV,\ 404\mu b^{-1}$

One muon from one tau, three charged hadron

68% CL :$a_\tau = 0.001^{+0.055}_{-0.089}$

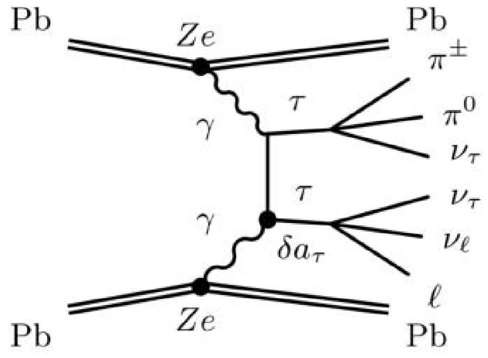


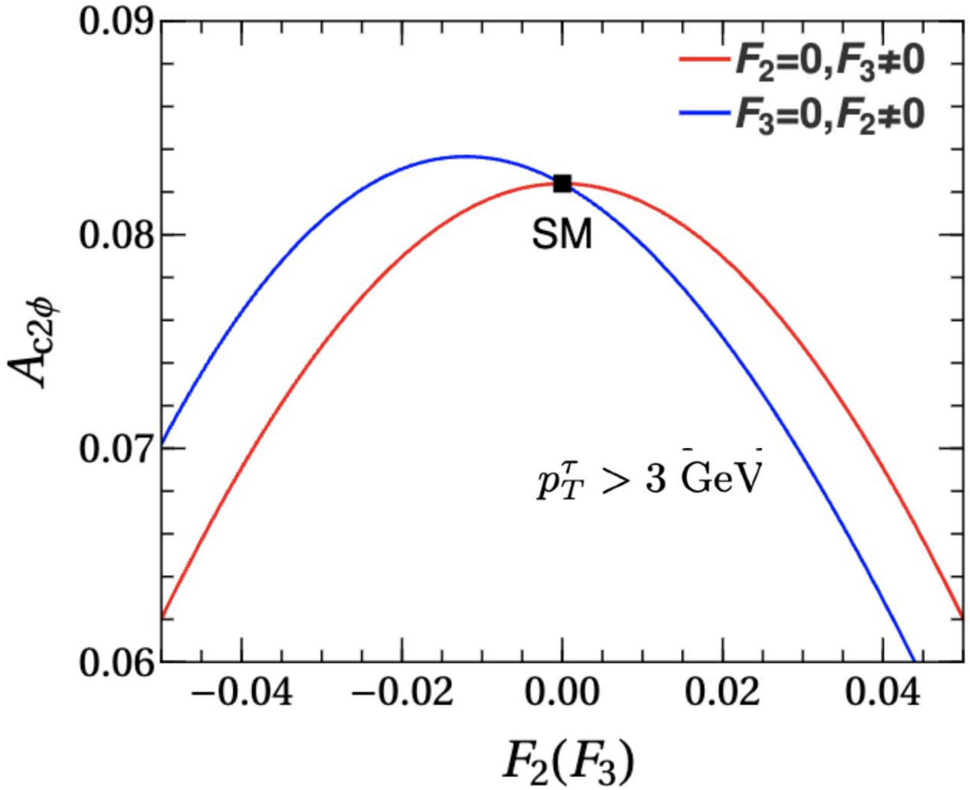
FIG. 1. Pair production of tau leptons τ from ultraperipheral lead ion (Pb) collisions in two of the most common decay modes: $\pi^\pm\pi^0\nu_\tau$ and $\ell\nu_\ell\nu_\tau$. New physics can modify tau–photon couplings affecting the magnetic moment by δa_τ.

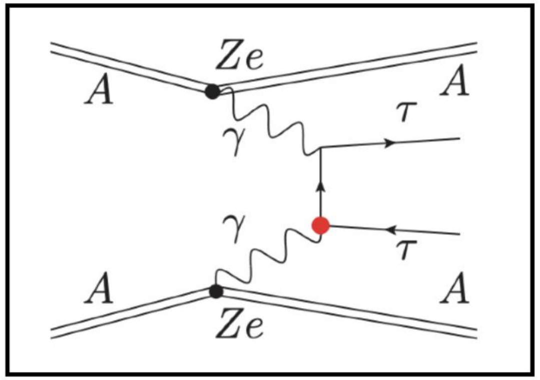
$$\mathcal{B}(\tau^\pm \to \ell^\pm\nu_\ell\nu_\tau) = 35\%,$$
$$\mathcal{B}(\tau^\pm \to \pi^\pm\nu_\tau + \text{neutral pions}) = 45.6\%,$$
$$\mathcal{B}(\tau^\pm \to \pi^\pm\pi^\mp\pi^\pm\nu_\tau + \text{neutral pions}) = 19.4\%.$$

Shao, Yan, Yuan, CZ, 2023

The joint impact parameter $b_\perp$ and $q_\perp$ dependent cross section from the QED and dipole interactions

$$d\sigma \sim \left[A_0 + B_0^{(1)} F_2 + B_0^{(2)} F_2^2 + C_0^{(2)} F_3^2 + \left(A_2 + B_2^{(2)} F_2^2 + C_2^{(2)} F_3^2\right) \cos 2\phi + A_4 \cos 4\phi\right]$$





$$\Gamma^\mu(q^2) = -ie\left\{\gamma^\mu F_1(q^2) + \frac{\sigma^{\mu\nu} q_\nu}{2m_\tau}\left[iF_2(q^2) + F_3(q^2)\gamma^5\right]\right\}$$

$$F_1(0) = 1,\ F_2(0) = a_\tau$$

$$F_3(0) = 2m_\tau d_\tau / e$$

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Shao, Yan, Yuan, CZ, 2023

joint b⊥ and q⊥ dependent cross section:

$$\frac{d\sigma}{d^2\boldsymbol{q}_\perp d^2\boldsymbol{P}_\perp dy_1 dy_2 d^2\boldsymbol{b}_\perp} = \frac{\alpha_e^2}{2M^4\pi^2}\left[A_0 + B_0^{(1)}F_2 + B_0^{(2)}F_2^2 + C_0^{(2)}F_3^2 + \left(A_2 + B_2^{(2)}F_2^2 + C_2^{(2)}F_3^2\right)\cos 2\phi + A_4\cos 4\phi\right]$$

polarized differential cross section and the azmimuthal asymmetries arising from linearly polarized coherent photons:

$$A_0 = \frac{M^2 - 2P_\perp^2}{P_\perp^2}\int [d\mathcal{K}_\perp]\cos(\phi_{k_{1\perp}} - \phi_{\bar{k}_{1\perp}} + \phi_{k_{2\perp}} - \phi_{\bar{k}_{2\perp}}),$$

$$A_2 = \frac{8m_\tau^2}{P_\perp^2}\int [d\mathcal{K}_\perp]\cos(\phi_{k_{1\perp}} - \phi_{k_{2\perp}}) \times \cos(\phi_{\bar{k}_{1\perp}} + \phi_{\bar{k}_{2\perp}} - 2\phi_{q_\perp}),$$

$$A_4 = -2\int [d\mathcal{K}_\perp]\cos(\phi_{k_{1\perp}} + \phi_{\bar{k}_{1\perp}} + \phi_{k_{2\perp}} + \phi_{\bar{k}_{2\perp}} - 4\phi_{q_\perp}),$$

$$B_0^{(1)} = \frac{4M^2}{P_\perp^2}\int [d\mathcal{K}_\perp]\sin(\phi_{k_{1\perp}} - \phi_{\bar{k}_{2\perp}})\sin(\phi_{\bar{k}_{1\perp}} - \phi_{k_{2\perp}})$$

$$B_0^{(2)} = C_0^{(2)} = \frac{2M^2}{m_\tau^2}\int [d\mathcal{K}_\perp]\cos(\phi_{k_{1\perp}} - \phi_{\bar{k}_{1\perp}}) \times \cos(\phi_{k_{2\perp}} - \phi_{\bar{k}_{2\perp}}),$$

$$B_2^{(2)} = C_2^{(2)} = -\frac{2M^2}{m_\tau^2}\int [d\mathcal{K}_\perp]\cos(\phi_{k_{1\perp}} - \phi_{k_{2\perp}}) \times \cos(\phi_{\bar{k}_{1\perp}} + \phi_{\bar{k}_{2\perp}} - 2\phi_{q_\perp}).$$

Shao, C.Z., Zhou, Zhou, 2023

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$A_1 A_2 \to A_1 A_2 \tau^+ \tau^-$ cross section:

$$\sigma = \int \frac{\mathrm{d}^2 \boldsymbol{b}_\perp \mathrm{d}^3 \boldsymbol{p}_1 \mathrm{d}^3 \boldsymbol{p}_2}{(2\pi)^3 2E_1 (2\pi)^3 2E_2} \left| \int \frac{d^4 k_1 d^4 k_2}{(2\pi)^4 (2\pi)^4} (2\pi)^4 \delta^{(4)}(k_1 + k_2 - p_1 - p_2) \mathcal{M}_{\mu\nu}(k_1, k_2, p_1, p_2) A_1^\mu(k_1, b_\perp) A_2^\nu(k_2, 0) \right|^2$$

electromagnetic potentials:

$$A_1^\mu(k_1, b_\perp) = 2\pi Z e \frac{F(-k_1^2)}{-k_1^2} \delta(k_1 \cdot u_1) u_1^\mu e^{i \boldsymbol{k}_{1\perp} \cdot \boldsymbol{b}_\perp}$$

$$A_2^\mu(k_2, 0) = 2\pi Z e \frac{F(-k_2^2)}{-k_2^2} \delta(k_2 \cdot u_2) u_2^\mu .$$

Greiner, 1993

$\gamma(k_1)\gamma(k_2) \to \tau^+(p_1)\tau^-(p_2)$ amplitude:

$$\mathcal{M}_{\mu\nu} = e^2 \bar{u}(p_1) \left[\Gamma_\mu \frac{\not{p}_1 - \not{k}_1 + m_\tau}{(p_1 - k_1)^2 - m_\tau^2} \Gamma_\nu + \Gamma_\nu \frac{\not{p}_1 - \not{k}_2 + m_\tau}{(p_1 - k_2)^2 - m_\tau^2} \Gamma_\mu \right] v(p_2)$$

$\tau^+ \tau^- \gamma$ effective vertex:

$$\Gamma^\mu(q^2) = -ie \left\{ \gamma^\mu F_1(q^2) + \frac{\sigma^{\mu\nu} q_\nu}{2 m_\tau} \left[i F_2(q^2) + F_3(q^2) \gamma^5 \right] \right\}$$

*

$$d\sigma \sim \left[A_0 + B_0^{(1)} F_2 + B_0^{(2)} F_2^2 + C_0^{(2)} F_3^2 + \left(A_2 + B_2^{(2)} F_2^2 + C_2^{(2)} F_3^2\right) \cos 2\phi + A_4 \cos 4\phi\right]$$

Shao, Yan, Yuan, CZ, 2023

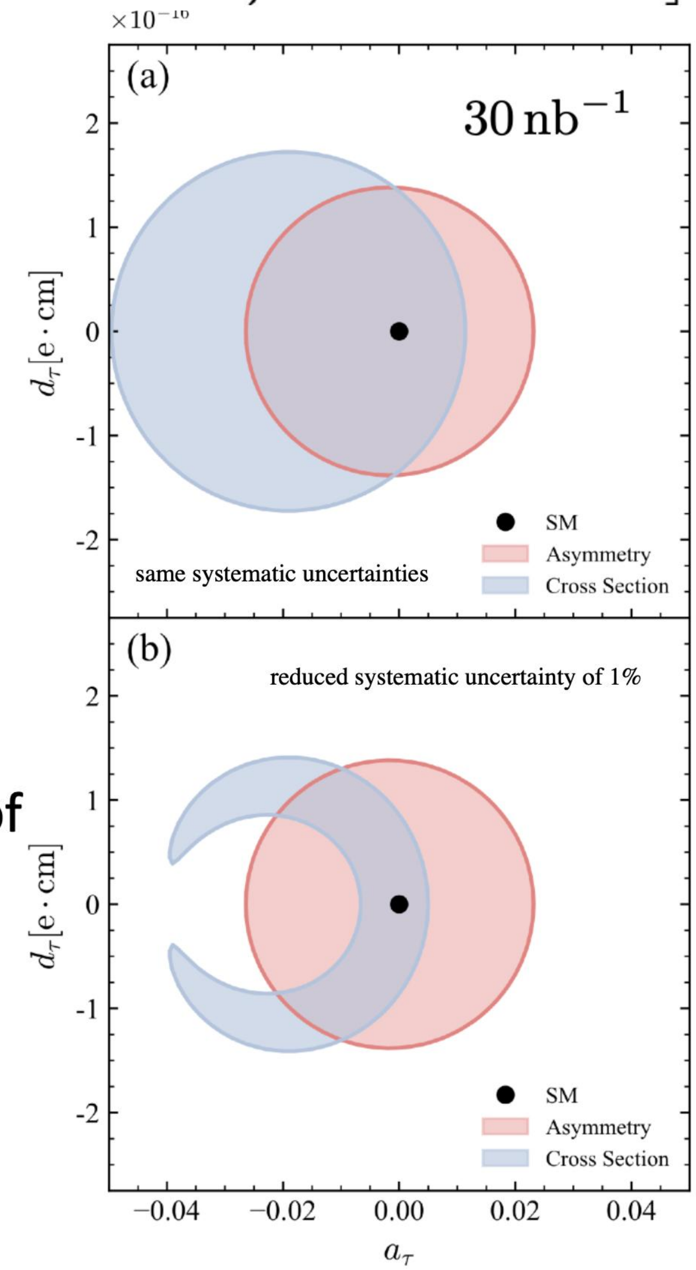
$$-0.02 < a_\tau < 0.005 \text{ and } |d_\tau| < 1.2 \times 10^{-16}\, \mathrm{e \cdot cm}$$

$$\chi^2 = \sum_i \left[\frac{V^i - V^i_{SM}}{\delta V^i}\right]^2$$

- Assume that the cut efficiencies for future Pb+Pb collision would be same as the current values of the ATLAS and CMS experiments, and the statistical uncertainty $\delta A_{c2\phi}$ can be obtained by properly rescaling.

- Incorporating the azimuthal asymmetry into the analysis can significantly reduce the parameter space of a_τ and d_τ

- With the inclusion of more decay modes of τ leptons and further optimization, we expect that future experimental analyses could significantly improve the limit for d_τ



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Outlook: STCF $e^+e^- \to e^+e^-\tau^+\tau^-$

$A_1A_2 \to A_1A_2\tau^+\tau^-$ cross section:

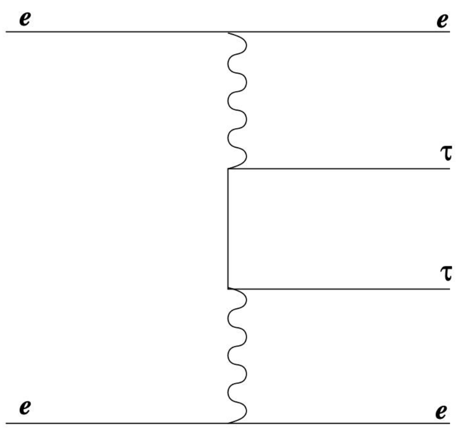
$$\sigma = \int \frac{\mathrm{d}^2\boldsymbol{b}_\perp \mathrm{d}^3\boldsymbol{p}_1 \mathrm{d}^3\boldsymbol{p}_2}{(2\pi)^3 2E_1 (2\pi)^3 2E_2} \left| \int \frac{d^4k_1 d^4k_2}{(2\pi)^4(2\pi)^4} (2\pi)^4 \delta^{(4)}(k_1+k_2-p_1-p_2) \mathcal{M}_{\mu\nu}(k_1,k_2,p_1,p_2) A_1^\mu(k_1,b_\perp) A_2^\nu(k_2,0) \right|^2$$

photon TMD PDF of electron:

$$\int \frac{dy^- d^2y_\perp}{P^+(2\pi)^3} e^{ik\cdot y} \langle e| F^\mu_{+\perp}(0) F^\nu_{+\perp}(y) |e\rangle \Big|_{y^+=0}$$
$$= \frac{\delta_\perp^{\mu\nu}}{2} x f(x,k_\perp^2) + \left(\frac{k_\perp^\mu k_\perp^\nu}{k_\perp^2} - \frac{\delta_\perp^{\mu\nu}}{2} \right) x h_1^\perp(x,k_\perp^2)$$

unpolarized and linearly-polarized photon TMD PDF of electron:

$$f(x,k_\perp^2) = \frac{\alpha_e}{2\pi^2} \frac{1+(1-x)^2}{x} \frac{k_\perp^2}{(k_\perp^2 + x^2 m_e^2)^2},$$
$$h_1^\perp(x,k_\perp^2) = \frac{\alpha_e}{\pi^2} \frac{1-x}{x} \frac{k_\perp^2}{(k_\perp^2 + x^2 m_e^2)^2},$$



DELPHI, 2004

$\sqrt{s_{ee}} = 183\ GeV \sim 208 GeV,\ 650\ pb^{-1}$

$a_\tau = -0.018 \pm 0.017,$

$d_\tau = (0.0 \pm 2.0) \cdot 10^{-16}\, e \cdot \mathrm{cm}$

Thanks!

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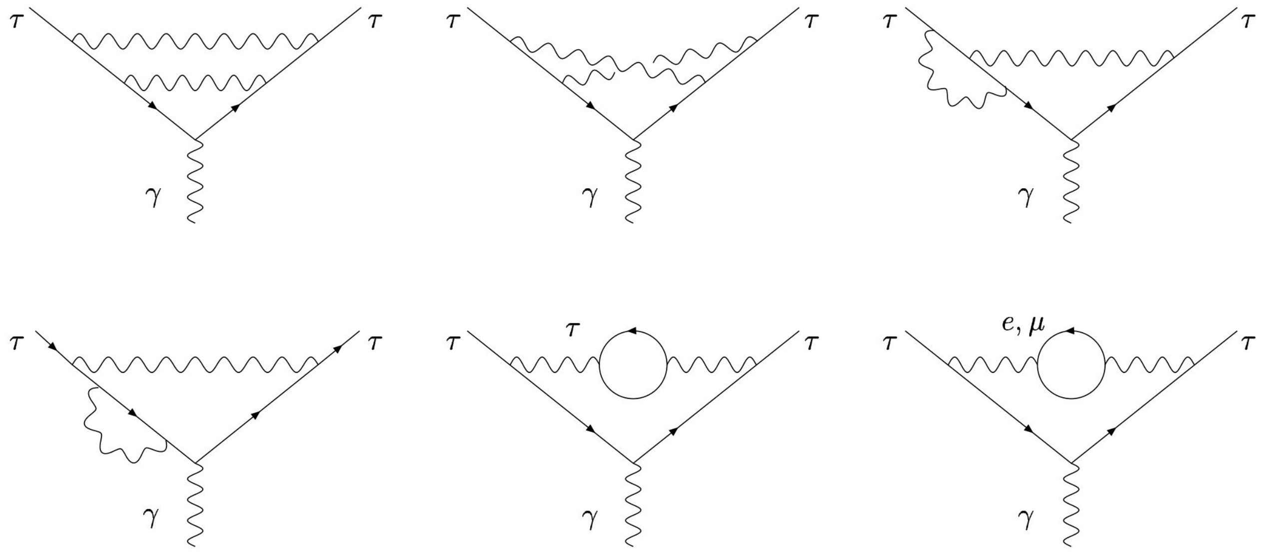

Fig. 1. The QED diagrams contributing to the τ lepton $g-2$ at order α^2. The mirror reflections (not shown) of the third and fourth diagrams must be included as well.

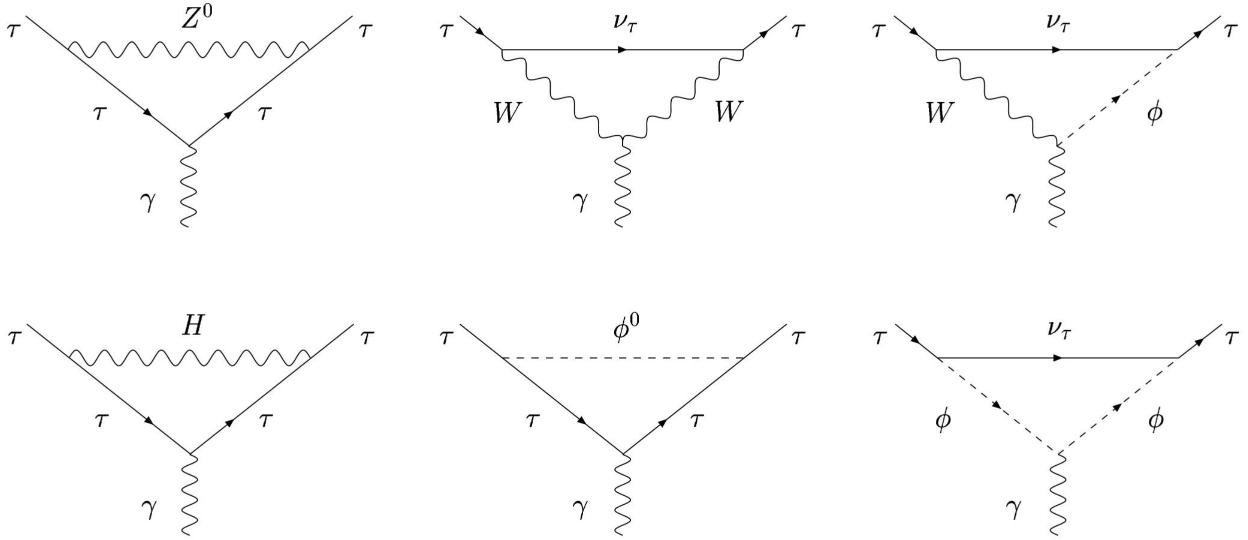

Fig. 2. One-loop electroweak contributions to a_τ. The diagram with a W and a Goldstone boson (ϕ) must be counted twice.

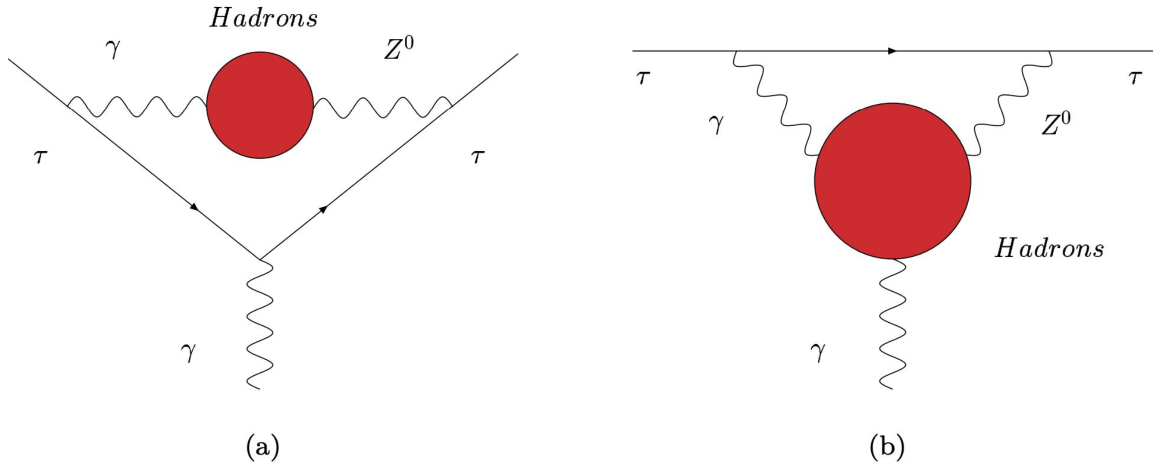

Fig. 3. Some of the fermion-loop diagrams contributing to the τ anomalous magnetic moment.

through τ-pair production in UPCs. The primary decay channels of the τ lepton include leptonic decay with one charged lepton, and hadronic decay with one or three charged hadrons (pions or kaons). The experimental measurements have considered the following typical event topologies for the signals: (a) one muon and one electron; (b) one muon and one charged hadron; and (c) one muon and three charged hadrons. Using a data sample of one muon and three charged hadrons collected from 5.02 TeV Pb+Pb collisions, with an integrated luminosity of 404 μb^{-1}, the CMS collaboration obtained the fiducial cross section of τ-pair production $\sigma = 4.8 \pm 0.6(\text{stat}) \pm 0.5(\text{syst})\,\mu\text{b}$ [34]. On

efficiency, $\mathcal{L}_{\text{int}} = 404 \pm 20\ \mu\text{b}^{-1}$ is the total integrated luminosity, and $\mathcal{B}_{\tau_\mu} = (17.39 \pm 0.04)\%$ and $\mathcal{B}_{\tau_{\text{3prong}}} = (14.55 \pm 0.06)\%$ [13] are the branching fractions for the two τ lepton decay modes. The factor of 2 accounts for the two potential τ lepton decay combinations yielding the same final state, whereas three-prong decays could include additional neutral pions. The efficiency is the product of the pion and muon reconstruction, the trigger, and the analysis selection efficiencies, and is evaluated using simulated signal events. The efficiency is calculated as the number of reconstructed events passing the analysis selection criteria divided by the number of generated events inside the fiducial phase space region, and is found to be $\epsilon = (78.5 \pm 0.8)\%$.

Combining all of the above, the fiducial cross section is found to be $\sigma(\gamma\gamma \to \tau^+\tau^-) = 4.8 \pm 0.6(\text{stat}) \pm 0.5(\text{syst})\,\mu\text{b}$.

$$d\sigma \sim \left[A_0 + B_0^{(1)} F_2 + B_0^{(2)} F_2^2 + C_0^{(2)} F_3^2 + \left(A_2 + B_2^{(2)} F_2^2 + C_2^{(2)} F_3^2\right)\cos 2\phi + A_4 \cos 4\phi\right]$$

CS Unit:mb	1	Cos2ϕ	Cos4ϕ	F2	F2^2	Cos2ϕ F2^2	F3^2	Cos2ϕ F3^2
P_T>0GeV	1.12128	0.173431	-0.013339	3.01183	8.55912	-2.12471	6.93618	-2.12471
P_T>1GeV	0.772365	0.139503	-0.0129661	2.00072	7.21247	-2.07976	6.10566	-2.07976
P_T>3GeV	0.135994	0.0168713	-0.00545854	0.387829	3.50723	-1.32171	3.27991	-1.32171

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polarized differential cross section and the azmimuthal asymmetries arising from linearly polarized coherent photons:

$$A_0 = \frac{M^2 - 2P_\perp^2}{P_\perp^2} \int [\mathrm{d}\mathcal{K}_\perp] \cos(\phi_{k_{1\perp}} - \phi_{\bar{k}_{1\perp}} + \phi_{k_{2\perp}} - \phi_{\bar{k}_{2\perp}}),$$

$$A_2 = \frac{8m_\tau^2}{P_\perp^2} \int [d\mathcal{K}_\perp] \cos(\phi_{k_{1\perp}} - \phi_{k_{2\perp}}) \times \cos(\phi_{\bar{k}_{1\perp}} + \phi_{\bar{k}_{2\perp}} - 2\phi_{q_\perp}),$$

$$A_4 = -2 \int [d\mathcal{K}_\perp] \cos(\phi_{k_{1\perp}} + \phi_{\bar{k}_{1\perp}} + \phi_{k_{2\perp}} + \phi_{\bar{k}_{2\perp}} - 4\phi_{q_\perp}),$$

$$B_0^{(1)} = \frac{4M^2}{P_\perp^2} \int [\mathrm{d}\mathcal{K}_\perp] \sin(\phi_{k_{1\perp}} - \phi_{\bar{k}_{2\perp}}) \sin(\phi_{\bar{k}_{1\perp}} - \phi_{k_{2\perp}})$$

$$B_0^{(2)} = C_0^{(2)} = \frac{2M^2}{m_\tau^2} \int [\mathrm{d}\mathcal{K}_\perp] \cos(\phi_{k_{1\perp}} - \phi_{\bar{k}_{1\perp}}) \times \cos(\phi_{k_{2\perp}} - \phi_{\bar{k}_{2\perp}}),$$

$$B_2^{(2)} = C_2^{(2)} = -\frac{2M^2}{m_\tau^2} \int [\mathrm{d}\mathcal{K}_\perp] \cos(\phi_{k_{1\perp}} - \phi_{k_{2\perp}}) \times \cos(\phi_{\bar{k}_{1\perp}} + \phi_{\bar{k}_{2\perp}} - 2\phi_{q_\perp}).$$

$$\int [\mathrm{d}\mathcal{K}_\perp] \equiv \int \mathrm{d}^2\boldsymbol{k}_{1\perp} \mathrm{d}^2\boldsymbol{k}_{2\perp} \mathrm{d}^2\bar{\boldsymbol{k}}_{1\perp} \mathrm{d}^2\bar{\boldsymbol{k}}_{2\perp} e^{i(\boldsymbol{k}_{1\perp} - \bar{\boldsymbol{k}}_{1\perp}) \cdot \boldsymbol{b}_\perp} \times \delta^{(2)}(\boldsymbol{k}_{1\perp} + \boldsymbol{k}_{2\perp} - \boldsymbol{q}_\perp) \delta^{(2)}(\bar{\boldsymbol{k}}_{1\perp} + \bar{\boldsymbol{k}}_{2\perp} - \boldsymbol{q}_\perp) \times \mathcal{F}(x_1, \boldsymbol{k}_{1\perp}^2) \mathcal{F}(x_2, \boldsymbol{k}_{2\perp}^2) \mathcal{F}(x_1, \bar{\boldsymbol{k}}_{1\perp}^2) \mathcal{F}(x_2, \bar{\boldsymbol{k}}_{2\perp}^2), \quad ($$

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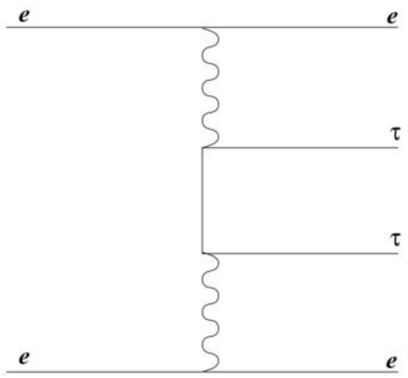
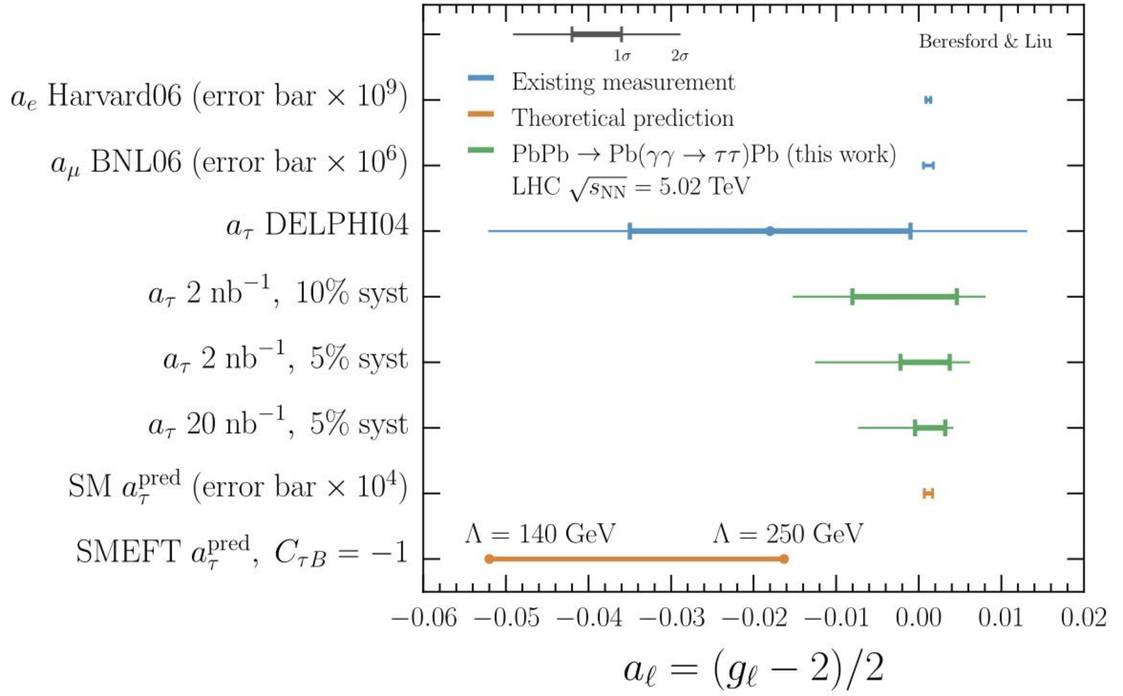
Hep-ex/0406010 DELPHI

$$\sqrt{s_{ee}} = 183\ GeV \sim 208 GeV,\ 650\ pb^{-1}$$

$$-0.052 < a_\tau < 0.013, \quad 95\%\ \text{CL}$$
$$|d_\tau| < 3.7 \cdot 10^{-16}\ e \cdot \text{cm}, \quad 95\%\ \text{CL.}$$



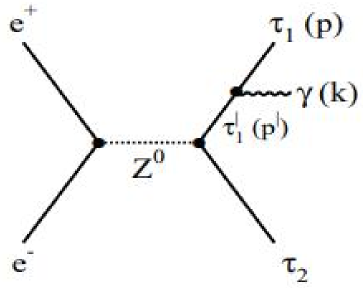


Hep-ex/9803020 OPAL

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

$$-0.068 < F_2 < 0.065$$

$$-3.8 \times 10^{-16}\, e\,\text{cm} < eF_3 < 3.6 \times 10^{-16}\, e\,\text{cm}$$



L3

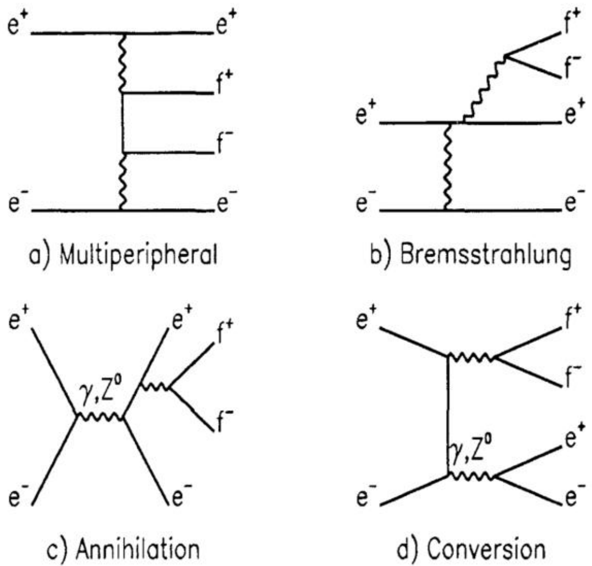
$$e^- e^+ \to Z \to \tau^- \tau^+ \gamma$$

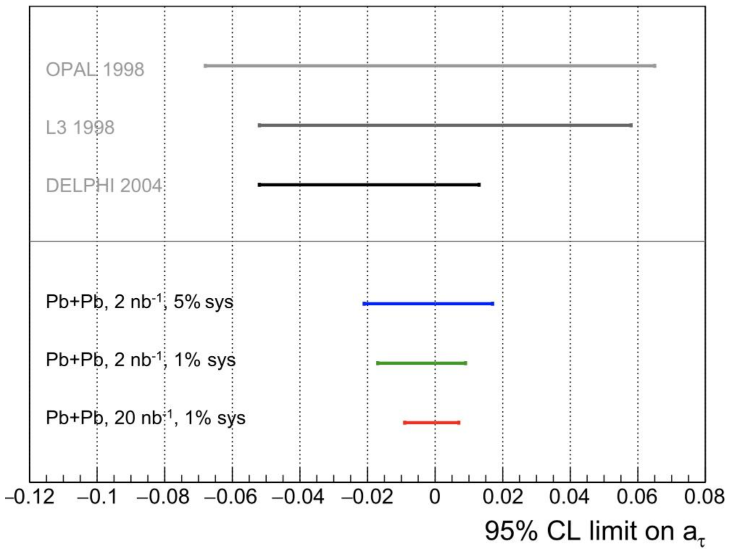
$$a_\tau = 0.004 \pm 0.027 \pm 0.023$$

$$d_\tau = (0.0 \pm 1.5 \pm 1.3) \times 10^{-16} e \cdot \text{cm}$$

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

$$|F_2(0)| \leq 0.107, \quad |d_\tau| \leq 1.14 \cdot 10^{-15}\ e\,\text{cm}$$





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