

質量のないダークフォトンの レプトンとの相互作用への制限

Constraints on leptonic interactions of
massless dark photon

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Dark photon

U(1) extensions of the SM

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{\varepsilon}{2}F_{\mu\nu}F'^{\mu\nu} + \dots$$

SM particles charged under the extra U(1) gauge

$$B - L, L_\mu - L_\tau, \dots$$

SM particles **not charged** under the extra U(1) gauge

dark photon

B. Holdom, PLB166, 196 (1986)

Dark sector, charged under U(1)', may exist.

Massless dark photon and its couplings

Discrimination between the ordinary and dark photons

Massive dark photon: mass eigenstates

Massless dark photon: interactions

$$\mathcal{L}_{\text{int}} = -j_{\text{em}}^{\mu} A_{\mu} + \dots$$

no massless DP couplings to the EM current

 higher dimensional operators

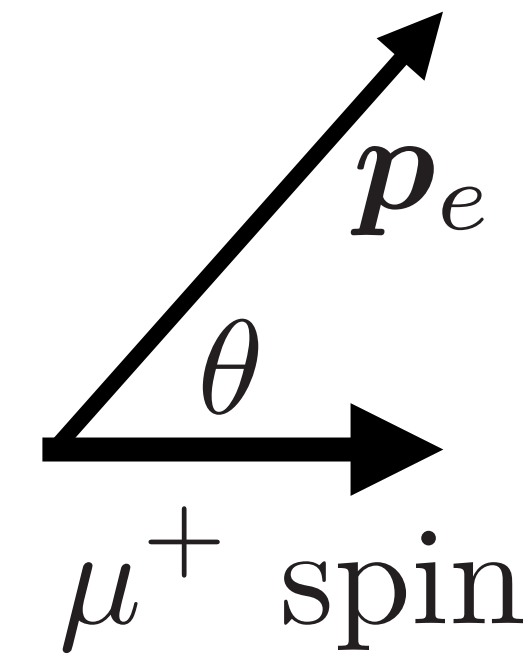
B.A. Dobrescu, PRL94, 151801 (2005)

$$\mathcal{L}_{\text{dipole}} = -\frac{1}{2} \sum_{f', f=e, \mu, \tau} \bar{f}' (D_R^{(f' f)} P_R + D_L^{(f' f)} P_L) \sigma^{\alpha\beta} f F'_{\alpha\beta}$$

Lepton Family Violation involved

Muon decays

- $\mu^+ \rightarrow e^+ \gamma'$



$$\frac{d\Gamma}{d\cos\theta} = \frac{m_\mu^3}{32\pi} (|D_R^{(\mu e)}|^2 + |D_L^{(\mu e)}|^2) (1 - AP_{\mu^+} \cos\theta)$$

$$A := -\frac{|D_R^{(\mu e)}|^2 - |D_L^{(\mu e)}|^2}{|D_R^{(\mu e)}|^2 + |D_L^{(\mu e)}|^2}$$

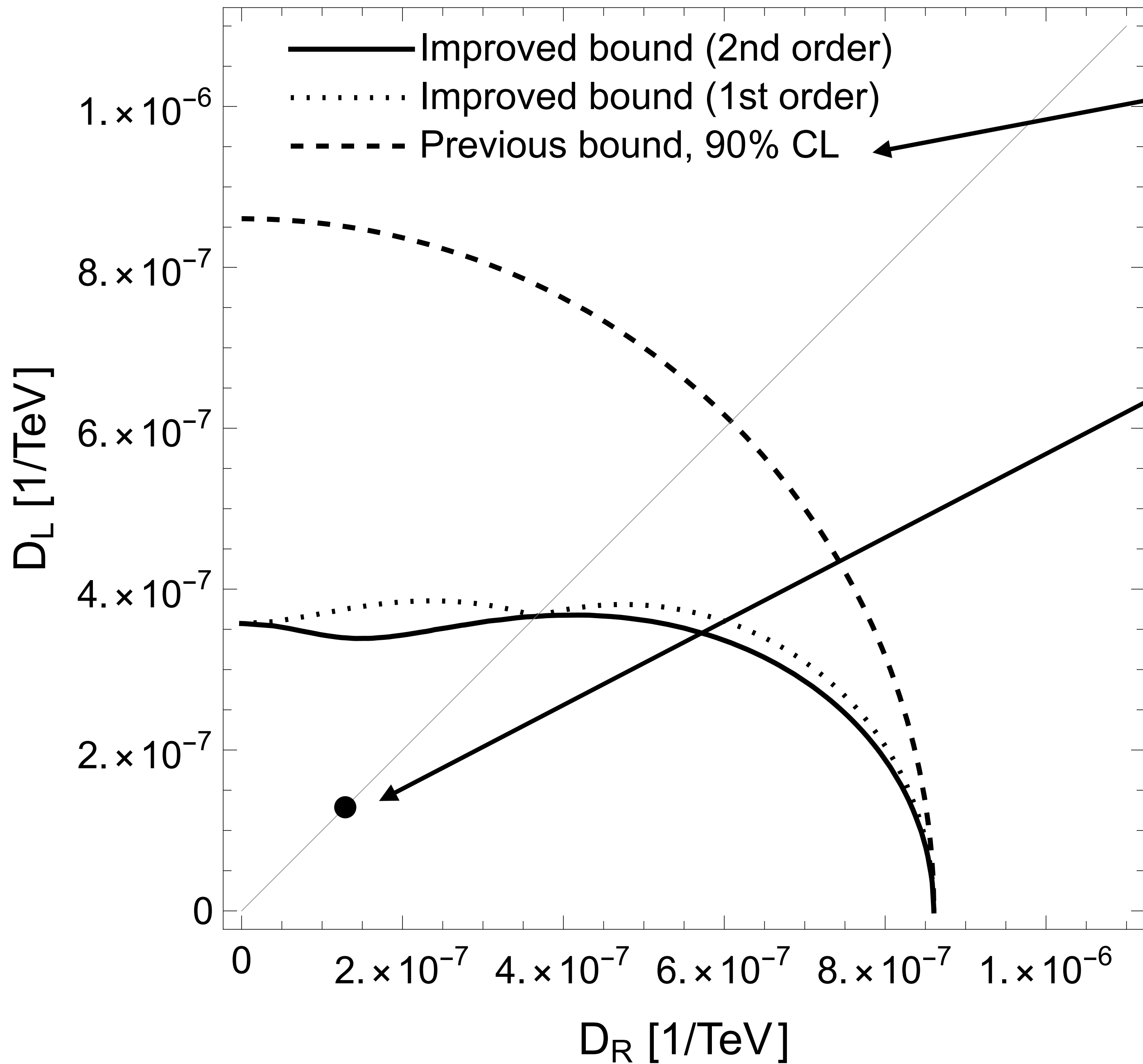
TWIST experiment @TRIUMF

R. Bays et al., PRD91, 052020 (2015)

$\mu^+ \rightarrow e^+ + \text{missing boson}$

muon polarization $P_{\mu^+} \simeq -1$  angular distribution

asymmetry	A	-1	0	+1
exp. upper bound	Br ($\times 10^{-5}$)	5.8	2.1	1.0
NP scale	$(D_R^{(\mu e)} ^2 + D_L^{(\mu e)} ^2)^{-1/2}$ [10^6 TeV]	1.2	1.9	2.8



Previous bound by
 M. Fabbrichesì, E. Gabrielli,
 G. Lanfranchi, arXiv:2005.01515

family search @TRIUMF

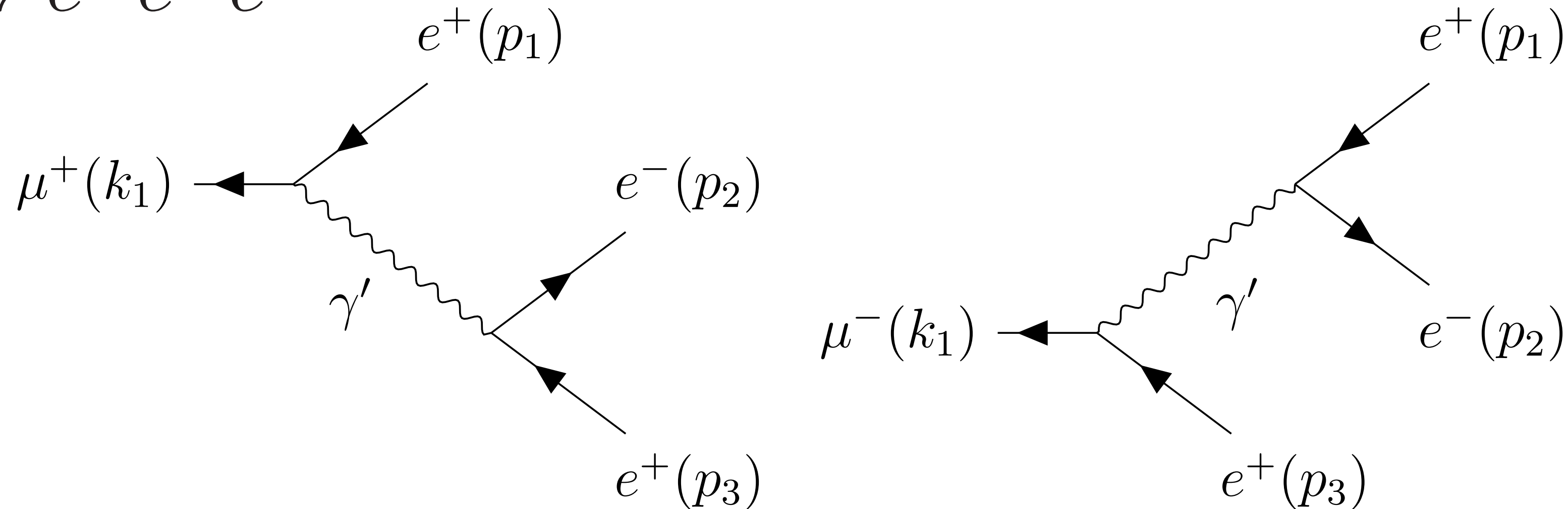
A. Jodidio et al., PRD34, 1967 (1986)

$$A = 0$$

$$\left(|D_R^{(\mu e)}|^2 + |D_L^{(\mu e)}|^2 \right)^{-1/2}$$

$$> 5.5 \times 10^6 \text{ TeV}$$

- $\mu^+ \rightarrow e^+ e^- e^+$




$$\Gamma = \frac{5m_\mu^5}{2048\pi^3} (|D_R^{(\mu e)}|^2 + |D_L^{(\mu e)}|^2) |D_R^{(ee)}|^2$$

Experimental bound by SINDRUM

U. Bellgardt et al., NPB299, 1 (1988)

$$\text{Br}(\mu^+ \rightarrow e^+ e^- e^+) < 1.0 \times 10^{-12}$$

 $\frac{1}{[(|D_R^{(\mu e)}|^2 + |D_L^{(\mu e)}|^2) |D_R^{(ee)}|^2]^{1/4}} > 243 \text{ TeV}$

Tau decays

$$D_{R,L}^{(\mu e)} = 0 \text{ assumed}$$

- $\tau \rightarrow l\gamma'$ ($l = \mu, e$)

Experimental bounds by ARGUS

H. Albrecht et al., ZPC68, 25 (1995)

$$\text{Br}(\tau \rightarrow \mu(e) + X) < 4.5(2.7) \times 10^{-3}$$



$$\frac{1}{\sqrt{|D_R^{(\tau\mu)}|^2 + |D_L^{(\tau\mu)}|^2}} \geq 3.3 \times 10^3 \text{ TeV}$$

$$\frac{1}{\sqrt{|D_R^{(\tau e)}|^2 + |D_L^{(\tau e)}|^2}} \geq 4.3 \times 10^3 \text{ TeV}$$

- $\tau^+ \rightarrow \ell^+ \ell^- \ell^+$ ($\ell = \mu, e$)


similar to $\mu^+ \rightarrow e^+ e^- e^+$

$$\Gamma(\tau^+ \rightarrow \ell^+ \ell^- \ell^+) = \frac{5m_\tau^5}{2048\pi^3} (|D_R^{(\tau\ell)}|^2 + |D_L^{(\tau\ell)}|^2) |D_R^{(\ell\ell)}|^2.$$

Experimental bounds by Belle

K. Hayasaka et al., PLB687, 139 (2010)

$$\text{Br}(\tau^+ \rightarrow \ell^+ \ell^- \ell^+) < 2.1(2.7) \times 10^{-8} \quad (\ell = \mu(e))$$



$$\frac{1}{[(|D_R^{(\tau\mu)}|^2 + |D_L^{(\tau\mu)}|^2) |D_R^{(\mu\mu)}|^2]^{1/4}} > 13.1 \text{ TeV}$$

$$\frac{1}{[(|D_R^{(\tau e)}|^2 + |D_L^{(\tau e)}|^2) |D_R^{(ee)}|^2]^{1/4}} > 12.3 \text{ TeV}$$

- $\tau^+ \rightarrow \ell^+ \ell'^- \ell'^+$

one diagram in the case of $D_{R,L}^{(\mu e)} = 0$


$$\Gamma(\tau^+ \rightarrow \ell^+ \ell'^- \ell'^+) = \frac{m_\tau^5}{1024\pi^3} (|D_R^{(\tau\ell)}|^2 + |D_L^{(\tau\ell)}|^2) |D_R^{(\ell'\ell')}|^2$$

Experimental bounds by Belle

K. Hayasaka et al., PLB687, 139 (2010)

$$\text{Br}(\tau^+ \rightarrow \mu^+ e^- e^+) < 1.8 \times 10^{-8}$$

$$\text{Br}(\tau^+ \rightarrow e^+ \mu^- \mu^+) < 2.7 \times 10^{-8}$$



$$\frac{1}{[(|D_R^{(\tau\mu)}|^2 + |D_L^{(\tau\mu)}|^2) |D_R^{(ee)}|^2]^{1/4}} > 10.8 \text{ TeV}$$

$$\frac{1}{[(|D_R^{(\tau e)}|^2 + |D_L^{(\tau e)}|^2) |D_R^{(\mu\mu)}|^2]^{1/4}} > 9.77 \text{ TeV}$$

Future colliders


μ TRISTAN: $\mu^+ e^-$ collider $\sqrt{s} = 346 \text{ GeV}$, $\mathcal{L} = 4.6 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$

Y. Hamada et al., PTEP053B02 (2022)

- $\mu^+ e^- \rightarrow \mu^- e^+$


$$\sigma = \frac{s}{128\pi} \left[5(|D_R^{(\mu e)}|^2 + |D_L^{(\mu e)}|^2)^2 - \frac{1}{3}(|D_R^{(\mu e)}|^2 - |D_L^{(\mu e)}|^2)^2 \right]$$

$$= 541 \text{ fb} \left(\frac{|D_R^{(\mu e)}|}{\text{TeV}^{-1}} \right)^4 \left(\frac{\sqrt{s}}{346 \text{ GeV}} \right)^2 \quad (\text{for } D_L^{(\mu e)} = 0)$$

 $|D_R^{(\mu e)}|^{-1} \gtrsim 7 \text{ TeV}$ (requiring 10 events/y, no BG)

- $\mu^+ e^- \rightarrow \gamma\gamma'$

$$\sigma = \frac{\alpha}{2} (|D_R^{(\mu e)}|^2 + |D_L^{(\mu e)}|^2) = 1521 \text{ fb} \left(\frac{\sqrt{|D_R^{(\mu e)}|^2 + |D_L^{(\mu e)}|^2}}{1 \text{ TeV}^{-1}} \right)^2$$

 $(|D_R^{(\mu e)}|^2 + |D_L^{(\mu e)}|^2)^{-1/2} \gtrsim 33 \text{ TeV}$ SM BG $\mu^+ e^- \rightarrow \bar{\nu}_\mu \nu_e \gamma$
 $\delta E_\gamma = 1 \text{ GeV} @ \sqrt{s}/2$

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

$\sigma \propto |D_{R/L}^{(\mu\tau)} D_{R/L}^{(\tau e)}|^2$ strongly constrained by $\tau \rightarrow \ell \gamma'$

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

$\sigma \propto |D_{R/L}^{(\mu\tau)} D_{R/L}^{(ee)}|^2, |D_{R/L}^{(e\tau)} D_{R/L}^{(\mu\mu)}|^2$ constrained by $\tau^+ \rightarrow \ell^+ \ell'^- \ell'^+$

ILC

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

$\sigma \propto |D_{R/L}^{(\mu\tau)} D_{R/L}^{(ee)}|^2, |D_{R/L}^{(e\tau)} D_{R/L}^{(ee)}|^2$ constrained by $\tau^+ \rightarrow \ell^+ \ell'^- \ell'^+$

Family conserving interactions

Big-bang nucleosynthesis

B.A. Dobrescu, PRL94, 151801 (2005)

M. Fabbrichesi, E. Gabrielli, G. Lanfranchi, arXiv:2005.01515

$$N_{\text{eff}} = 2.878 \pm 0.278$$

earlier dark photon decoupling $T_d \sim 150 \text{ MeV}$

→ $|D_{R,L}^{(\ell\ell)}|^{-1} \gtrsim 1 \times 10^4 \text{ TeV}, \ell = \mu, e$

Stellar cooling

M. Giannotti et al., JCAP05(2016)057

M. Fabbrichesi, E. Gabrielli, G. Lanfranchi, arXiv:2005.01515

white dwarves, red giants → $|D_{R,L}^{(ee)}|^{-1} \gtrsim 7 \times 10^6 \text{ TeV}$

LEP

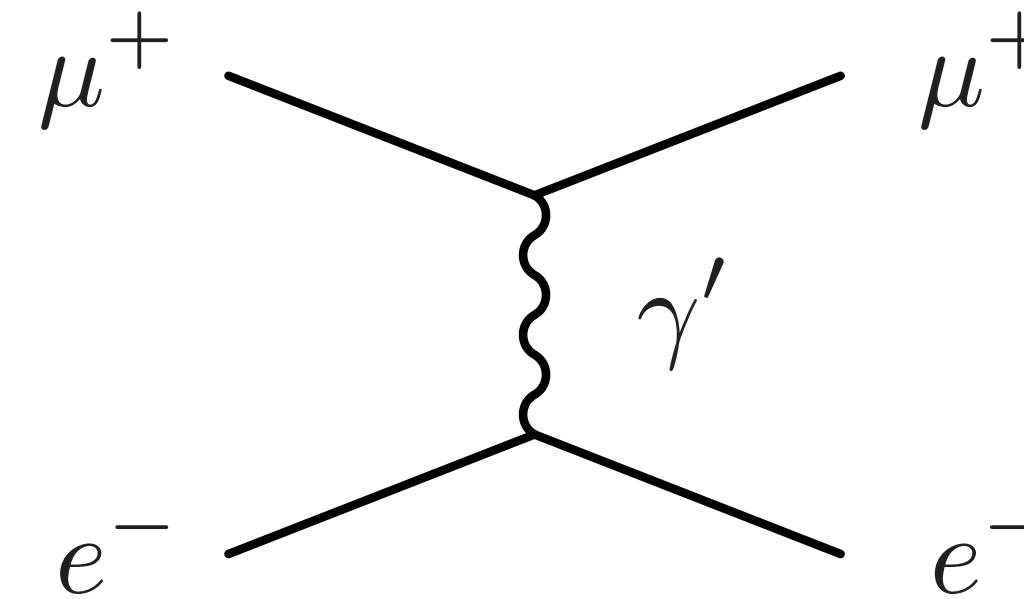
M. Fabbrichesi, E. Gabrielli, G. Lanfranchi, arXiv:2005.01515

$e^+e^- \rightarrow \gamma\gamma'$ search by OPAL, L3, ALEPH

→ $|D_{R,L}^{(ee)}|^{-1} \gtrsim 2 \text{ TeV}$

Muonium hyperfine splitting

$\mu^+ e^-$ bound state



$$\Delta E_{HF}(nS) := E_{HF}(nS)|_{F=1} - E_{HF}(nS)|_{F=0}$$

$$= \left(\frac{2}{3} D_M^{(ee)} D_M^{(\mu\mu)} - \frac{1}{3} D_E^{(ee)} D_E^{(\mu\mu)} \right) \frac{1}{\pi} \left(\frac{Z\alpha m_r}{n} \right)^3$$

$$D_{R/L}^{(\ell\ell)} = D_M^{(\ell\ell)} \pm i D_E^{(\ell\ell)}$$

$|\Delta E_{HF}(1S)/h| < 500$ Hz (uncertainty in the SM prediction)

→ $\left| \frac{2}{3} D_M^{(ee)} D_M^{(\mu\mu)} - \frac{1}{3} D_E^{(ee)} D_E^{(\mu\mu)} \right|^{-1/2} > 222$ GeV

Summary

- Massless dark photon interaction with the SM sector
no coupling to the EM current, higher dim. operators
LFV dipole interactions are allowed.

- Constraints by various LFV processes

Probed NP scales: $\mu \rightarrow e\gamma'$: $O(10^6)$ TeV (improved)

$\tau \rightarrow l\gamma'$: $O(10^3)$ TeV (new)

- Prospect

High energy colliders: less sensitive

Belle, Belle II may probe higher scales in tau decays.