Electromagnetic flavor-changing lepton decays from Lorentz and CPT violation

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Probing space-time properties (LIV/NC) at HEP experiments
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N. Sherrill (Sussex), Phys. Rev. D 106 (2022) 7, 076016

1. Introduction and Motivation

- Neutrino oscillations are the first evidence for lepton flavour violation

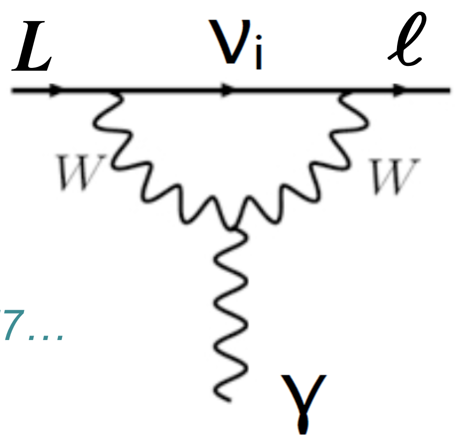
- How about in the charged lepton sector?

- In the *SM* with massive neutrinos effective CLFV vertices are tiny due to GIM suppression ⇒ *unobservably small rates!*

  E.g.: $\mu \to e\gamma$

$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^{*}_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M_W^2}\right|^2 < 10^{-54}$$

Petcov'77, Marciano & Sanda'77, Lee & Shrock'77…

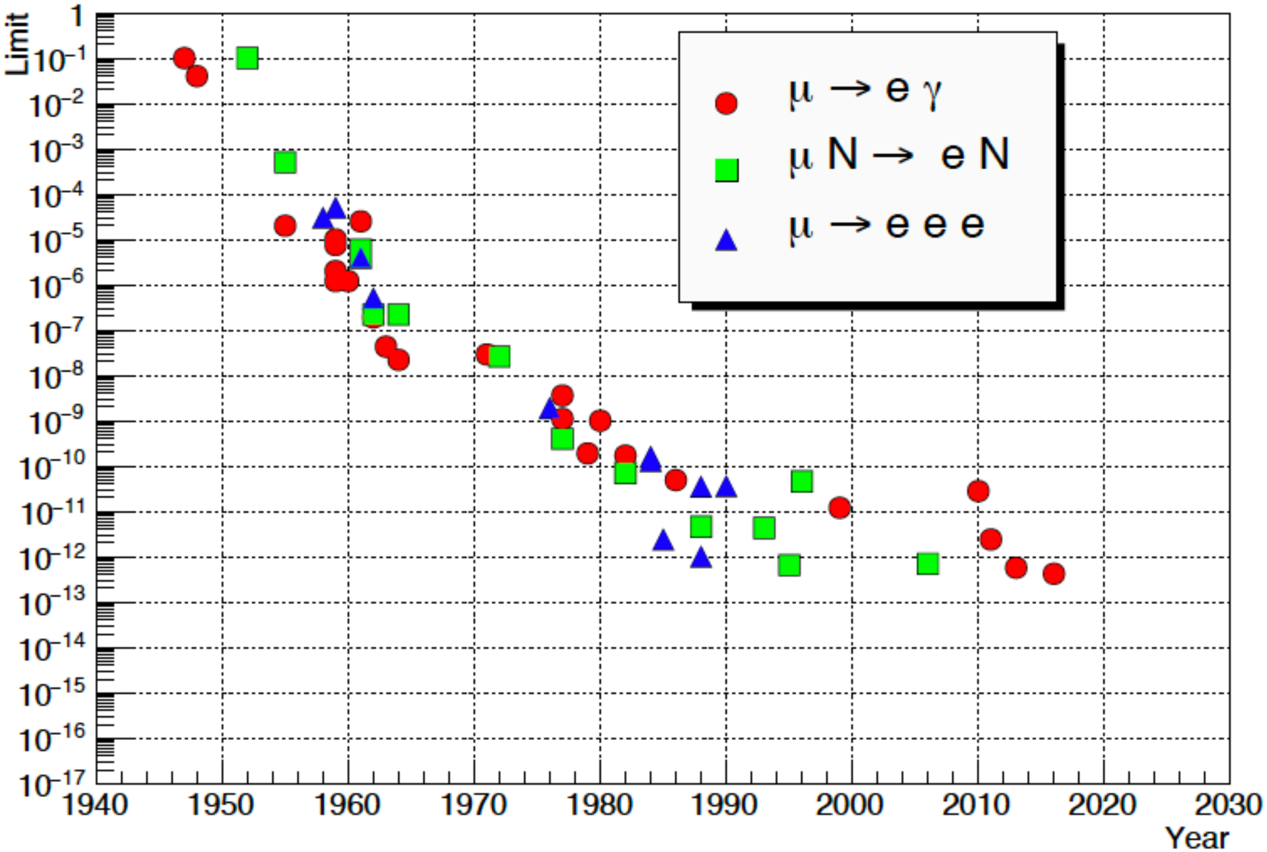


- Extremely *clean probe of beyond SM physics*

2. Experimental constraints: CLFV from muon decays

- Several processes: $\mu \to e\gamma$, $\mu \to e\bar{e}e$, $\mu(A,Z) \to e(A,Z)$

Calibbi&Signorelli'17



MEG'16

$$BR(\mu \to e\gamma) < 4.2 \times 10^{-13}$$

$\Rightarrow$ 6×10^{-14}

Sindrum

$$BR(\mu \to eee) < 1.0 \times 10^{-12}$$

$\Rightarrow$ $10^{-15} - 10^{-16}$

Mu3e

Sindrum II

$$BR^{Ti}_{\mu-e} < 4.3 \times 10^{-12}$$

$\Rightarrow$ 10^{-14} DeeMee

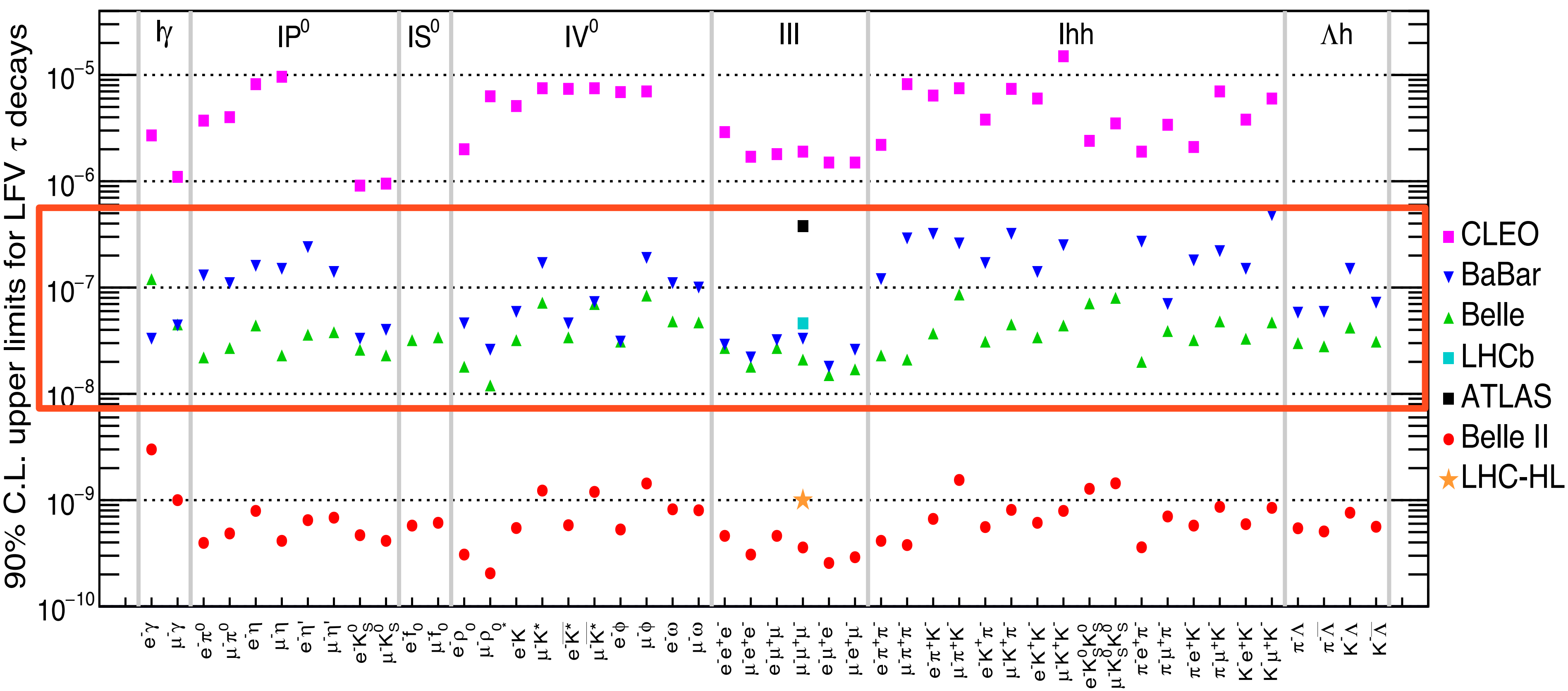
$10^{-16} - 10^{-17}$

Mu2e/COMET

2. Experimental constraints: CLFV from τ decays

Belle II Physics Book'18
HL-LHC&HE-LHC'18

- Several processes: $\tau \to \ell\gamma$, $\tau \to \ell_\alpha \bar{\ell}_\beta \ell_\beta$, $\tau \to \ell Y$ ← $P, S, V, P\bar{P}, \ldots$



- 48 LFV modes studied at Belle and BaBar ~10^{-7}-10^{-8}

2. Experimental constraints: CLFV from τ decays

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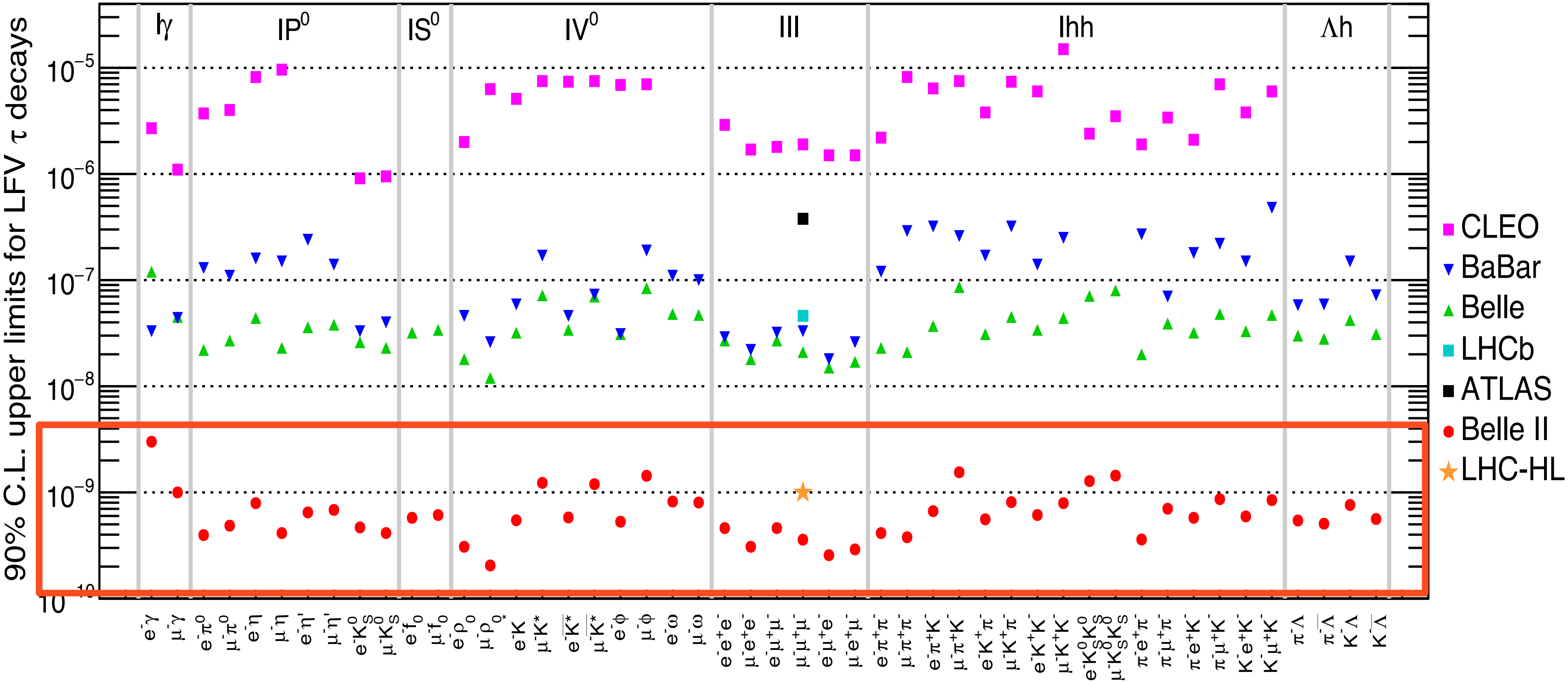
  ↖ $P, S, V, P\overline{P}, \ldots$



- Expected sensitivity 10^{-9} or better at *Belle II* improvement by 2 order of magnitude!

3. LFV and CPTV effects

- Use these bounds to constrain new physics scenarios where CLFV can reach observable levels in several channels

⇨ Model independent approach : build all Lorentz invariant operators of d > 5 which are invariant under the SM gauge group $SU(2)\ X\ U(1)$ and violate lepton flavour

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

See e.g.
Black, Han, He, Sher'02
Brignole & Rossi'04
Dassinger, Feldmann, Mannel, Turczyk'07
Matsuzaki & Sanda'08
Giffels et al.'08
Crivellin, Najjari, Rosiek'13
Petrov & Zhuridov'14
Cirigliano, Celis, E.P.'14

- For $\mu \to e\gamma$ and $\tau \to \mu(e)\gamma$ processes which give the most stringent bounds

⇨ Dipole term:

$$\mathcal{L}_{eff}^{D} \supset -\frac{C_D}{\Lambda^2} m_\tau \bar{e} \sigma^{\mu\nu} P_{L,R} \mu F_{\mu\nu}$$

Constrain C_D: Wilson Coefficient and Λ new physics scale

3. LFV and CPTV effects

- Now what happens if we relax the constraints on Lorentz invariant operators
  ⇨ More general we allow for Lorentz and CPT violation

- Enlarge the EFT: SMEFT ⇨ SME

$$S_{\mathrm{SME}} = S_{\mathrm{SM}} + S_{\mathrm{GR}} + S_{\mathrm{LV}}$$

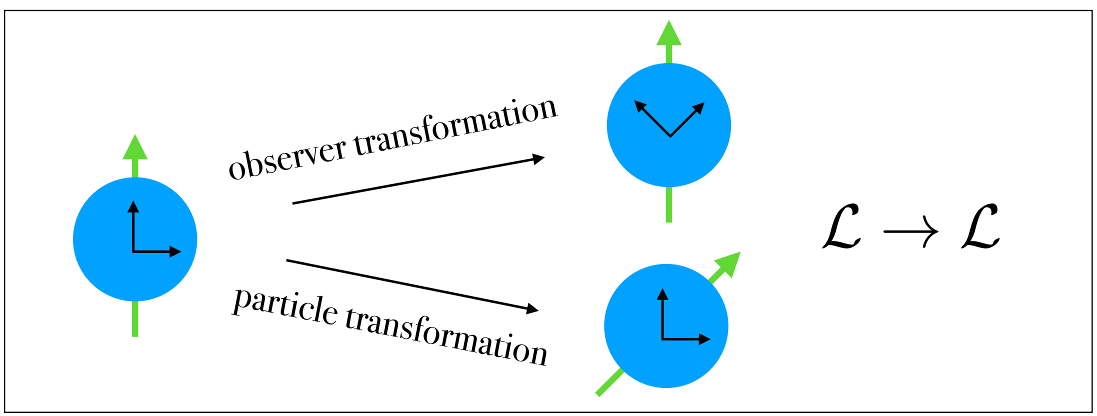
Colladay & Kostelecký'97, Kostelecký'04

- $$\mathcal{L}_{\mathrm{LV}} \sim \frac{\lambda}{M^k} \langle T \rangle \cdot \bar{\psi} \Gamma (i\partial)^k \chi + \mathrm{h.c.}$$

Kostelecký, Samuel'89, Kostelecký, R. Potting'91'95

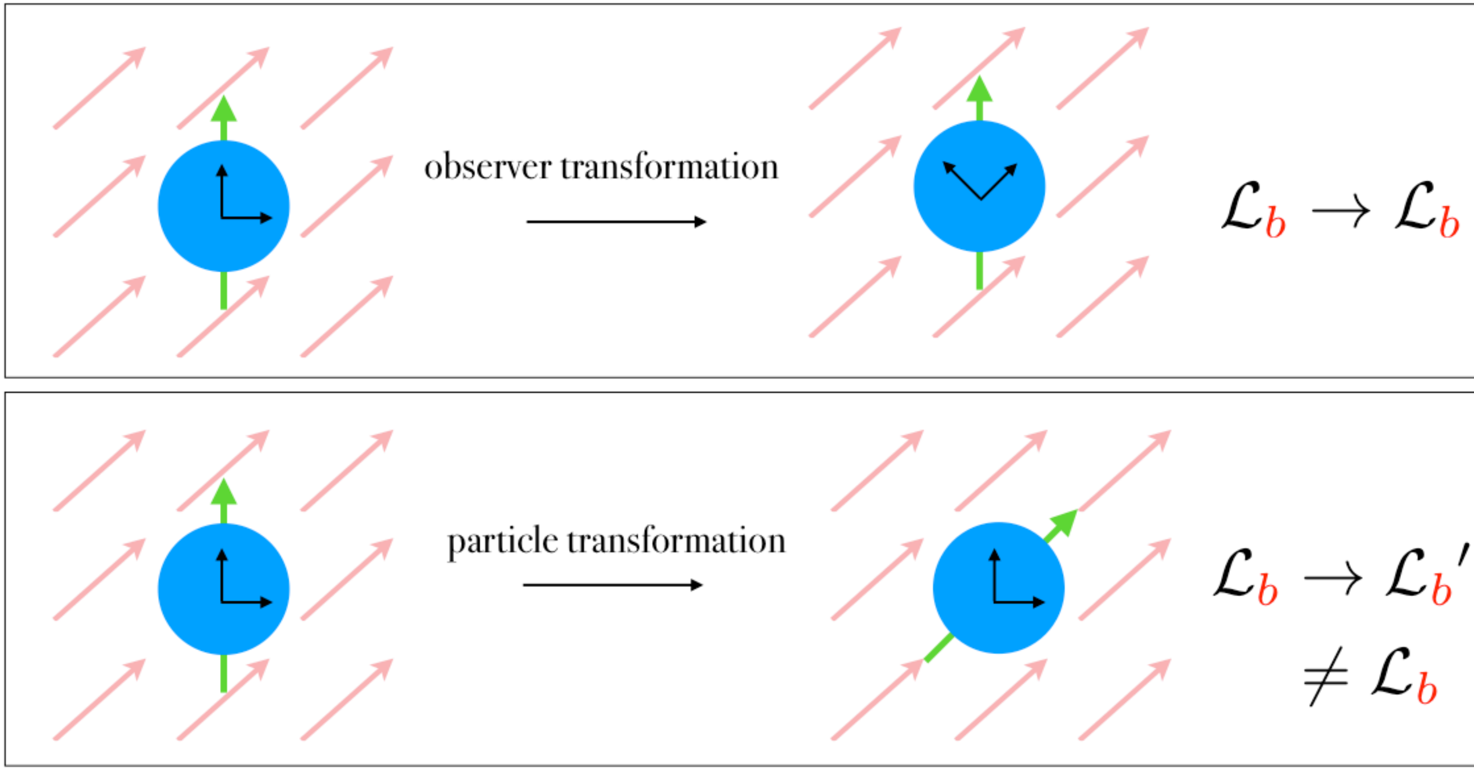
- These new terms have special properties:

Before:



3. LFV and CPTV effects

Now:



$$\mathcal{L}_b \supset -b_\mu \bar{\psi}\gamma_5\gamma^\mu\psi$$ ⇨ Background breaks rotation invariance

3. LFV and CPTV effects

- Operators that initiate charged-lepton-flavour largely unstudied except for

$$\sim -a_{AB\mu}\bar{\psi}_A\gamma^\mu\psi_B$$ Crivellin, Kirk, and Schreck'21

- Here study all the experimental constraints in the LFV sector to bound LV and CPTV effects

- Build all d = 5 LFV operators in the SME: these are the dominant ones as the d = 3 and d = 4 operators do not contribute to LFV

- In a first step, restrict ourselves to the d = 5 gauge-invariant operators contributing to EM 2-body decays: $\mu \to e\gamma$ and $\tau \to \mu(e)\gamma$ which give stringent constraints

$$\mathcal{L}^{(5)}_{\psi F} = -\frac{1}{2}(m^{(5)}_F)^{\alpha\beta}_{AB}F_{\alpha\beta}\bar{\psi}_A\psi_B - \frac{1}{2}i(m^{(5)}_{5F})^{\alpha\beta}_{AB}F_{\alpha\beta}\bar{\psi}_A\gamma_5\psi_B$$
$$-\frac{1}{2}(a^{(5)}_F)^{\mu\alpha\beta}_{AB}F_{\alpha\beta}\bar{\psi}_A\gamma_\mu\psi_B - \frac{1}{2}(b^{(5)}_F)^{\mu\alpha\beta}_{AB}F_{\alpha\beta}\bar{\psi}_A\gamma_\mu\gamma_5\psi_B - \frac{1}{4}(H^{(5)}_F)^{\mu\nu\alpha\beta}_{AB}F_{\alpha\beta}\bar{\psi}_A\sigma_{\mu\nu}\psi_B$$

3. LFV and CPTV effects

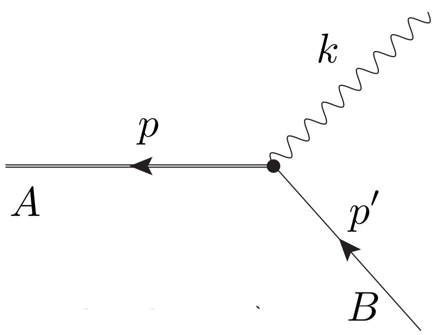
CPT even

$$\mathcal{L}^{(5)}_{\psi F} = -\frac{1}{2}(m_F^{(5)})^{\alpha\beta}_{AB} F_{\alpha\beta}\bar{\psi}_A\psi_B - \frac{1}{2}i(m_{5F}^{(5)})^{\alpha\beta}_{AB} F_{\alpha\beta}\bar{\psi}_A\gamma_5\psi_B$$
$$-\frac{1}{2}(a_F^{(5)})^{\mu\alpha\beta}_{AB} F_{\alpha\beta}\bar{\psi}_A\gamma_\mu\psi_B - \frac{1}{2}(b_F^{(5)})^{\mu\alpha\beta}_{AB} F_{\alpha\beta}\bar{\psi}_A\gamma_\mu\gamma_5\psi_B - \frac{1}{4}(H_F^{(5)})^{\mu\nu\alpha\beta}_{AB} F_{\alpha\beta}\bar{\psi}_A\sigma_{\mu\nu}\psi_B$$

CPT odd

- Compute the LFV amplitude generated by this Lagrangian:

$$\mathcal{M}^{(s,s',\lambda)}_{AB} = \bar{\nu}^{(s)}_A(p)V^\beta_{AB}(k)\nu^{(s')}_B(p')\epsilon^{*(\lambda)}_\beta(k)$$



with $$V^\beta_{AB}(k) = \begin{cases} V^\beta_{m_F} = (m_F^{(5)})^{\alpha\beta}_{AB}k_\alpha, \\ V^\beta_{m_{5F}} = i(m_{5F}^{(5)})^{\alpha\beta}_{AB}\gamma_5 k_\alpha, \\ V^\beta_{a_F} = (a_F^{(5)})^{\mu\alpha\beta}_{AB}\gamma_\mu k_\alpha, \\ V^\beta_{b_F} = (b_F^{(5)})^{\mu\alpha\beta}_{AB}\gamma_\mu\gamma_5 k_\alpha, \\ V^\beta_{H_F} = \frac{1}{2}(H_F^{(5)})^{\mu\nu\alpha\beta}_{AB}\sigma_{\mu\nu}k_\alpha. \end{cases}$$

3. LFV and CPTV effects

- From the amplitude one can compute the decay rate

$$d\Gamma \simeq \frac{1}{64\pi^2 m_A} d\Omega_{\mathrm{exp.}} |\mathcal{M}|^2$$

and BR: $\mathrm{BR}(A \to B + \gamma) = \tau_A \Gamma$

3. LFV and CPTV effects

- From the amplitude one can compute the decay rate

$$d\Gamma \simeq \frac{1}{64\pi^2 m_A} d\Omega_{\rm exp} |\mathcal{M}|^2$$

and BR: $\mathrm{BR}(A \to B + \gamma) = \tau_A \Gamma$

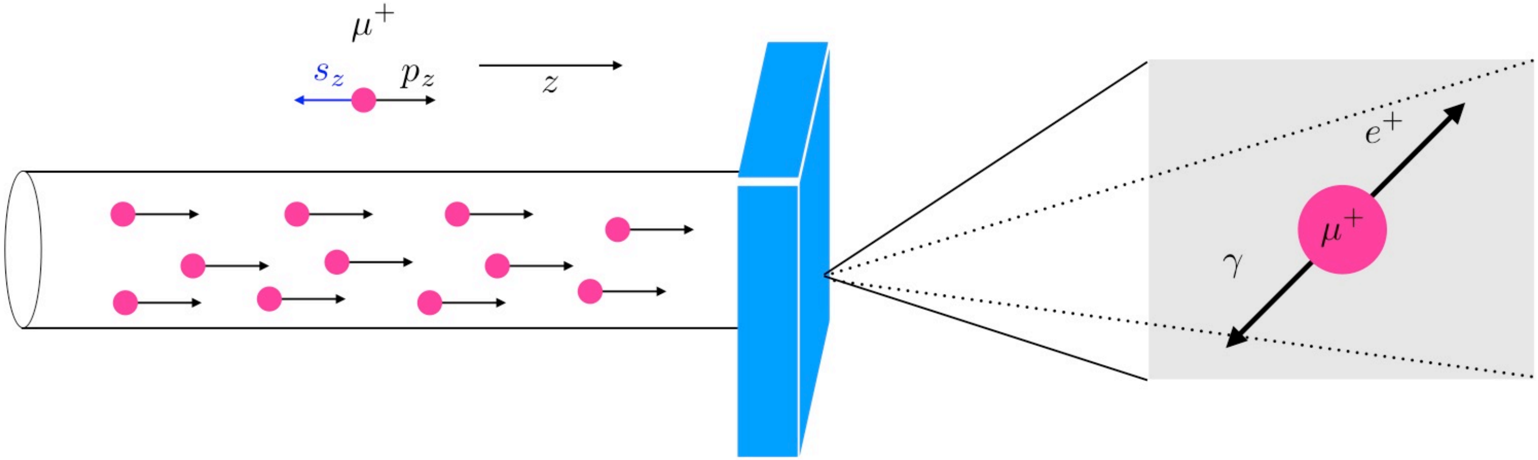
- To do that and compute $d\Omega_{exp}$ one needs to know the precise experimental conditions

- *MEG:* constraints from $\mu^+ \to e^+\gamma$

- *BABAR:* constraints from unpolarized Tau decays: $\tau^\pm \to e/\mu^\pm\gamma$

4. MEG experiment

- Polarized antimuons impinge on and decay in stopping target



MEG'13

$$E_\gamma = E_{e^+} = m_\mu/2$$

$$\vec{s}_\mu = \vec{s}_e + \vec{s}_\gamma \quad (?)$$

- Roughly 11% of full 4π steradian detector coverage is available:

$$\Gamma \simeq \frac{1}{64\pi^2 m_\mu} \int_{\theta_{\min}}^{\theta_{\max}} \int_{\phi_{\min}}^{\phi_{\max}} \sin\theta d\theta d\phi |\mathcal{M}(\theta,\phi)|^2$$

$$\theta \in (1.21, 1.93)$$

$$\phi \in (\tfrac{2\pi}{3}, \tfrac{4\pi}{3})$$

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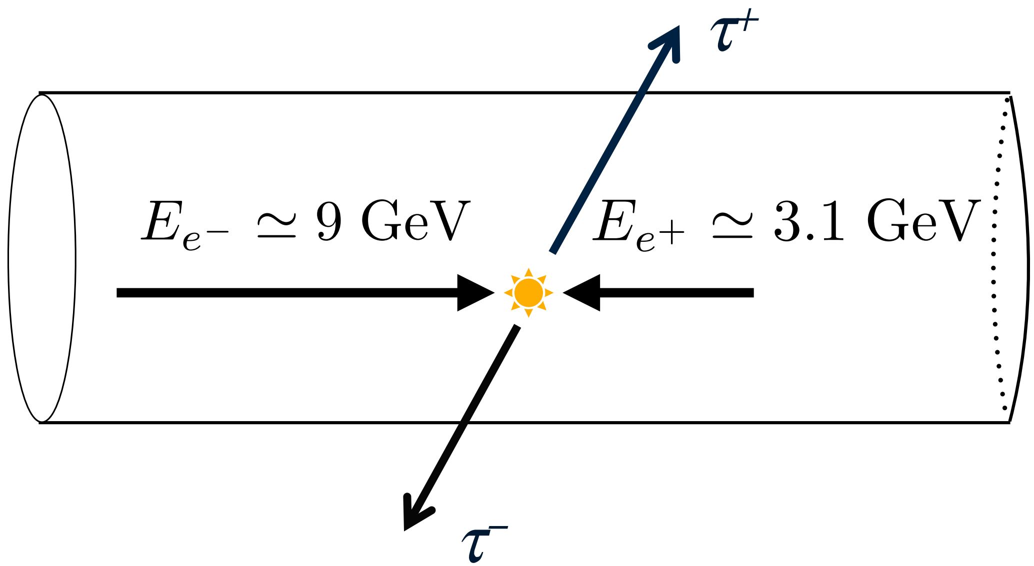
5. BABAR experiment

- Tau pairs are produced by antisymmetric electron-positron annihilation



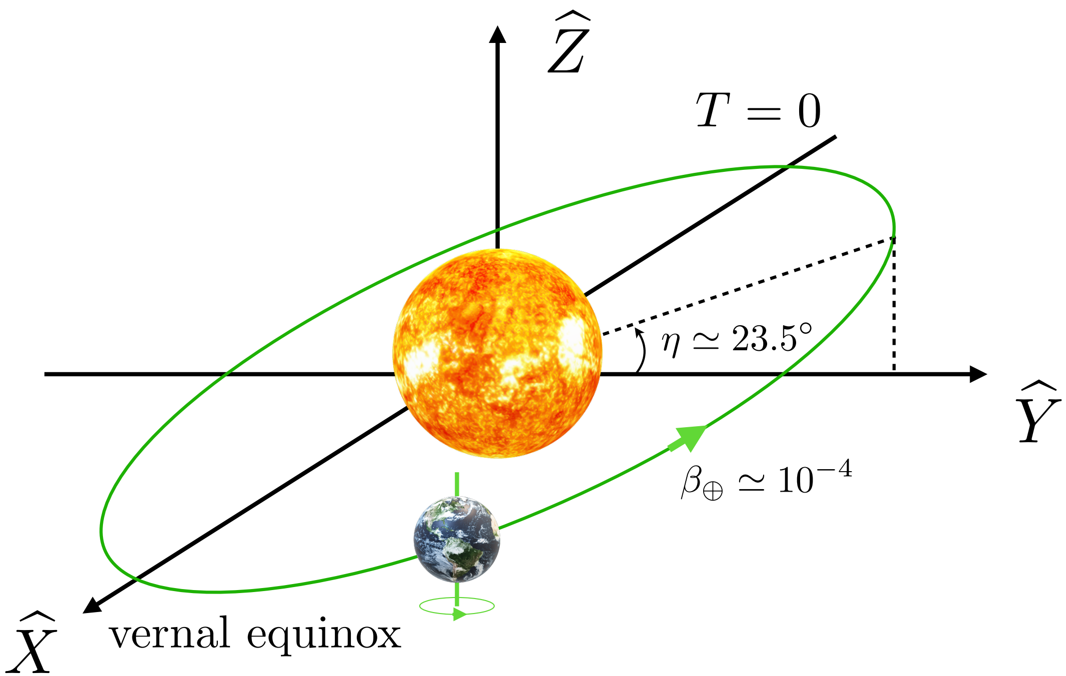
- Acceptance window: 90% of full phase-space volume

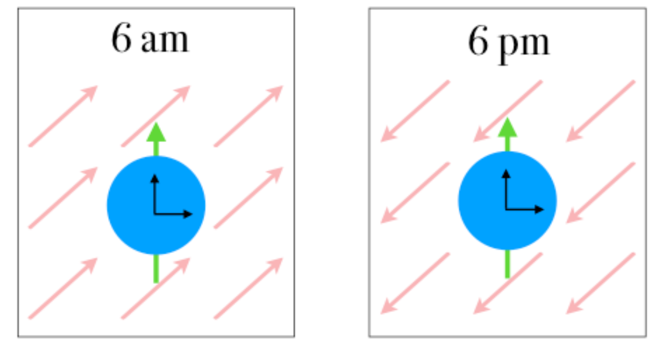
$$\Gamma \simeq \frac{1}{64\pi^2 m_\tau} \int_{4\pi} d\Omega \sum_{\text{spins}} \overline{|\mathcal{M}|^2}$$ with

$$\sum_{\text{spins}} \overline{|\mathcal{M}_{m_F^{(5)}}|^2} = 2(m_A m_B + p \cdot p')(m_F^{(5)})^{k\mu}_{AB}(m_F^{*(5)})_{AB\mu}{}^{k}$$

6. Time-dependent signals

- Earth-based lab is a noninertial frame ⇨ work in Sun-centered frame (SCF)





- Express lab-frame coefficients in terms of SCF coefficients

$$a^\mu_{\rm lab} = \Lambda^\mu{}_\nu a^\nu_{\rm SCF} \quad \text{with} \quad \Lambda^\mu{}_\nu \simeq R^\mu{}_\nu(\omega_\oplus T_\oplus, \chi_{\rm lab}, \cdots)$$

7. Results

- Summary of first constraints extracted from *MEG* and *BaBar* measurements

Coefficient	# Components	Bounds
$(m_F^{(5)})^{\alpha\beta}_{AB}$	6	$\lvert\mathrm{Re}(m_F^{(5)})^{\alpha\beta}_{AB}\rvert, \lvert\mathrm{Im}(m_F^{(5)})^{\alpha\beta}_{AB}\rvert \lesssim \begin{cases} < 6.0\times10^{-13}\ \mathrm{GeV}^{-1}; (A,B)=(\mu,e) \\ < 1.6\times10^{-9}\ \mathrm{GeV}^{-1}, (A,B)=(\tau,(\mu,e)) \end{cases}$
$(m_{5F}^{(5)})^{\alpha\beta}_{AB}$	6	$\lvert\mathrm{Re}(m_{5F}^{(5)})^{\alpha\beta}_{AB}\rvert, \lvert\mathrm{Im}(m_{5F}^{(5)})^{\alpha\beta}_{AB}\rvert \lesssim \begin{cases} < 6.4\times10^{-13}\ \mathrm{GeV}^{-1}; (A,B)=(\mu,e) \\ < 1.6\times10^{-9}\ \mathrm{GeV}^{-1}, (A,B)=(\tau,(\mu,e)) \end{cases}$
$(a_F^{(5)})^{\mu\alpha\beta}_{AB}$	24	$\lvert\mathrm{Re}(a_F^{(5)})^{\mu\alpha\beta}_{AB}\rvert, \lvert\mathrm{Im}(a_F^{(5)})^{\mu\alpha\beta}_{AB}\rvert \lesssim \begin{cases} < 6.0\times10^{-13}\ \mathrm{GeV}^{-1}; (A,B)=(\mu,e) \\ < 1.9\times10^{-9}\ \mathrm{GeV}^{-1}, (A,B)=(\tau,(\mu,e)) \end{cases}$
$(b_F^{(5)})^{\mu\alpha\beta}_{AB}$	24	$\lvert\mathrm{Re}(b_F^{(5)})^{\mu\alpha\beta}_{AB}\rvert, \lvert\mathrm{Im}(b_F^{(5)})^{\mu\alpha\beta}_{AB}\rvert \lesssim \begin{cases} < 6.4\times10^{-13}\ \mathrm{GeV}^{-1}; (A,B)=(\mu,e) \\ < 2.0\times10^{-9}\ \mathrm{GeV}^{-1}, (A,B)=(\tau,(\mu,e)) \end{cases}$
$(H_F^{(5)})^{\mu\nu\alpha\beta}_{AB}$	36	$\lvert\mathrm{Re}(H_F^{(5)})^{\mu\nu\alpha\beta}_{AB}\rvert, \lvert\mathrm{Im}(H_F^{(5)})^{\mu\nu\alpha\beta}_{AB}\rvert \lesssim \begin{cases} < 6.0\times10^{-13}\ \mathrm{GeV}^{-1}; (A,B)=(\mu,e) \\ < 2.0\times10^{-9}\ \mathrm{GeV}^{-1}, (A,B)=(\tau,(\mu,e)) \end{cases}$
	Total = 96	

- Constraints at the level of
  - $6\mathrm{x}10^{-13}$ coming from $\mu^+ \to e^+\gamma$
  - $2\mathrm{x}10^{-9}$ coming from $\tau^\pm \to e/\mu^\pm\gamma$ ⇨ expected 10^{-11} with 50 ab^{-1} at *Belle II*
- Including complexity of coefficients & three channels = *576 coefficients*

8. Conclusion and Outlook

- CLFV has been studied in the context of dimension-five Lorentz- and CPT-violating effects for the first time
- Many experimental constraints on CLFV ⇨ open a new range of opportunities to constrain Lorentz- and CPT-violating effects
- Here we have explored the bounds given by $\mu^+ \to e^+\gamma$ from *MEG* and on $\tau^\pm \to e/\mu^\pm\gamma$ from *BABAR*

  ⇨ Future experiments, e.g. *MEG-II* and *Belle II*, expected to increase limits on muon and tau decays by 1-2 orders of magnitude
- Sidereal signals could also be analyzed by binning data in time
- Many other channels we can explore !