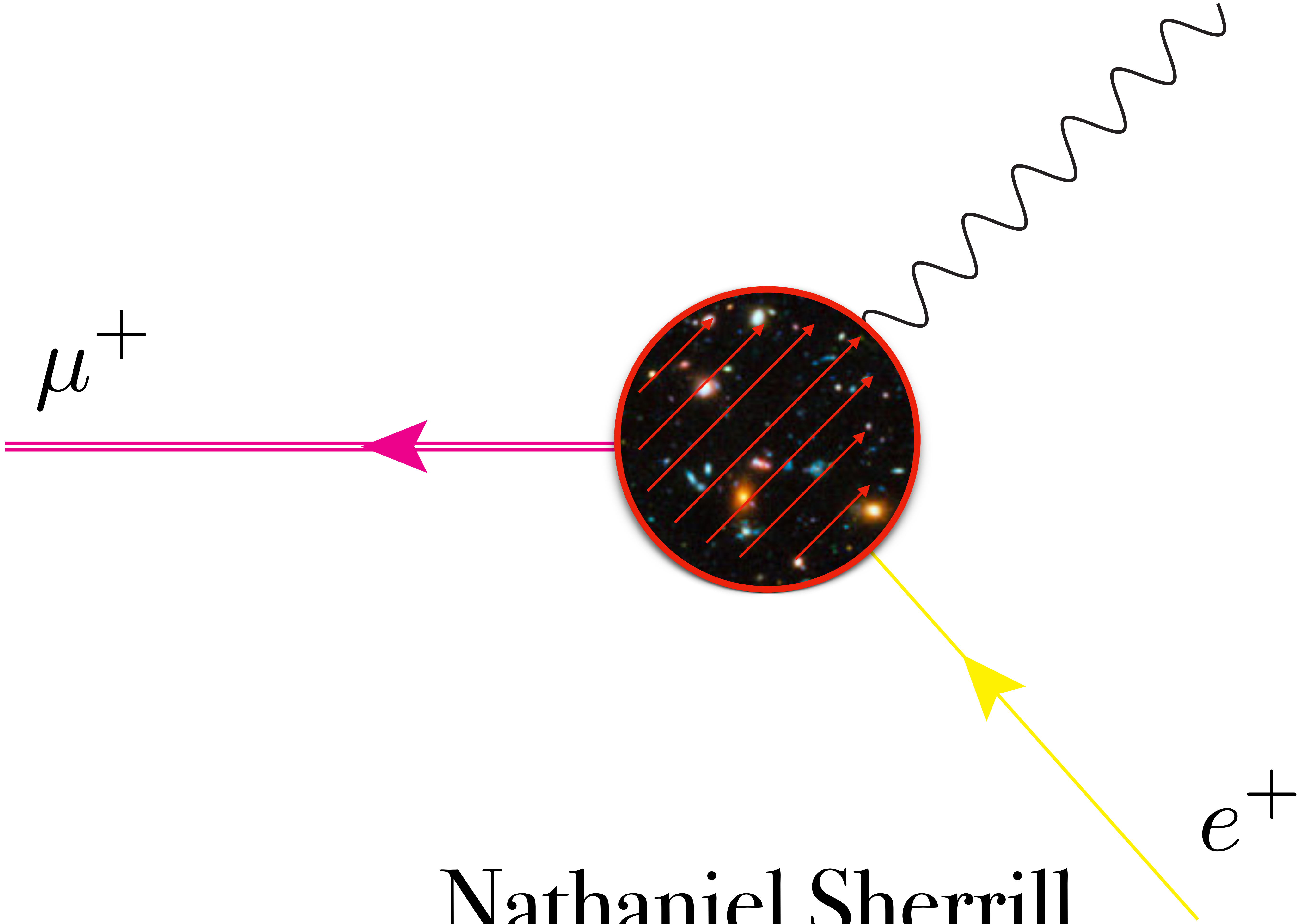
Charged-lepton-flavor violation from Lorentz violation



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Tau Lepton Physics (TAU2021)
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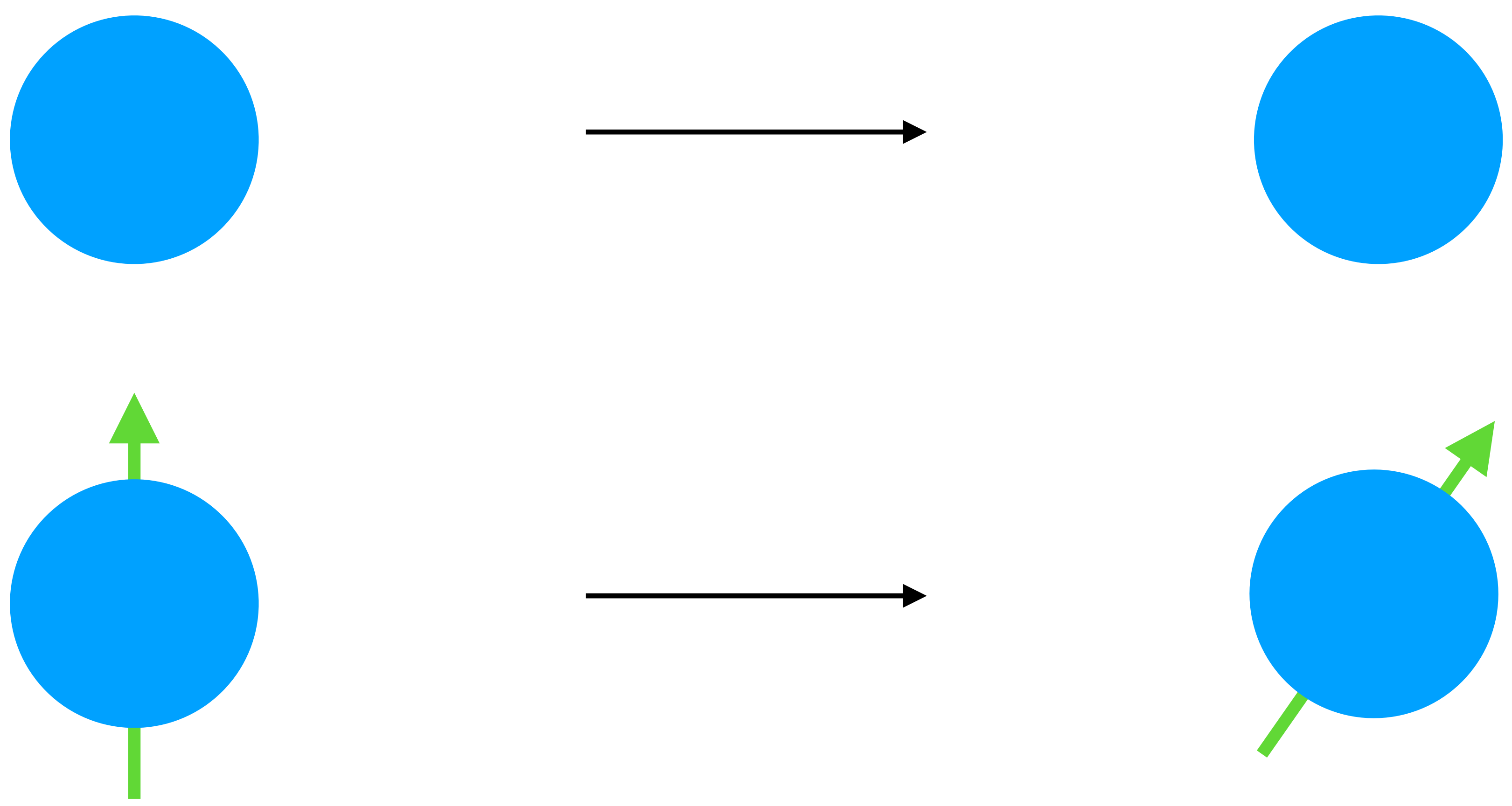
Symmetry and symmetry breaking

- A system possesses a symmetry if it is unchanged under some action



- Fundamental physics is rooted in symmetry principles

SM symmetries: $G_{\text{gauge}} \times G_{\text{Poincaré}}$

- Nature follows patterns of both symmetry preservation and violation

Examples: C, P, T, G; gauge invariance…; CPT, Lorentz, flavor* (?)

Symmetry and symmetry breaking

- The past two decades have seen an immense amount of interest in Lorentz and CPT tests

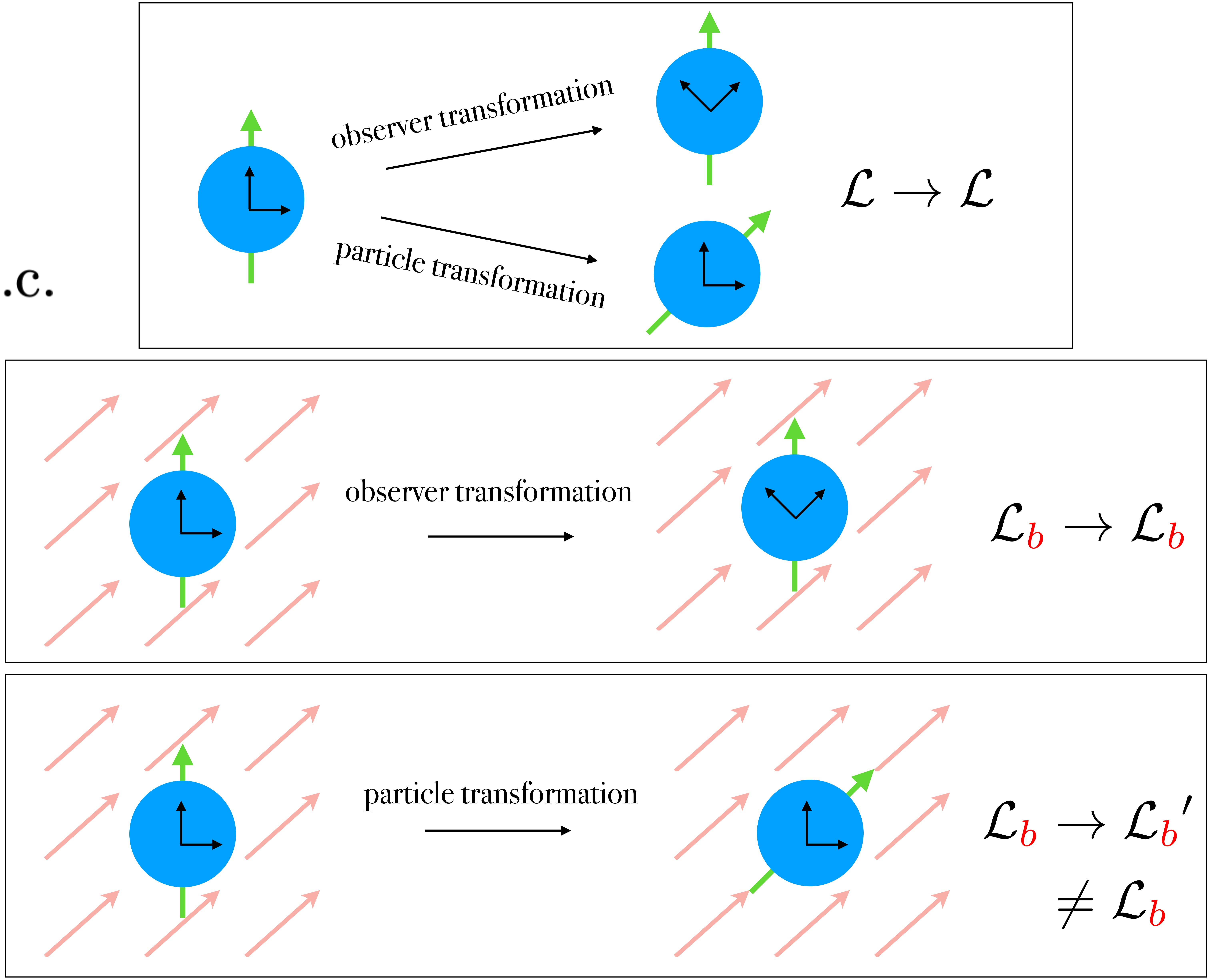
$$\mathcal{L}_{\text{LV}} \sim \frac{\lambda}{M^k} \langle T \rangle \cdot \bar{\psi} \Gamma (i\partial)^k \chi + \text{h.c.}$$

V. A. Kostelecký, S. Samuel, PLB **207**, 169 (1989)
V. A. Kostelecký, R. Potting, NPB **359**, 545 (1991); PRD **51**, 3923 (1995)

- These terms have special properties

$$\mathcal{L}_b \supset -b_\mu \bar{\psi} \gamma_5 \gamma^\mu \psi$$

- Background breaks rotation invariance



The Standard-Model Extension (SME)

- A comprehensive Lorentz- and CPT-violating framework grounded in effective field theory (EFT)

D. Colladay, V. A. Kostelecký, PRD **55**, 6760 (1997); PRD **58**, 116002 (1998); V. A. Kostelecký, PRD **69**, 105009 (2004)

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

- Contains <u>all possible</u> terms that break Lorentz and CPT symmetry in EFT
- CPTV $\Rightarrow$ LV in realistic EFT

$$\mathcal{L}_{\text{LV}} \supset k^{\mu\cdots}{}_{\nu\cdots}{}^{a\cdots}(x)\mathcal{O}_{\mu\cdots}{}^{\nu\cdots}{}_{a\cdots}(x)$$

V. A. Kostelecký, Z. Li, PRD **103**, 024059 (2021)

- Numerous constraints have been placed on SME coefficients

Data Tables for Lorentz and CPT Violation,
V. A. Kostelecký, N. Russell, arXiv:0801.0287v14

- Operators that initiate charged-lepton-flavor violation (CLFV) largely unstudied

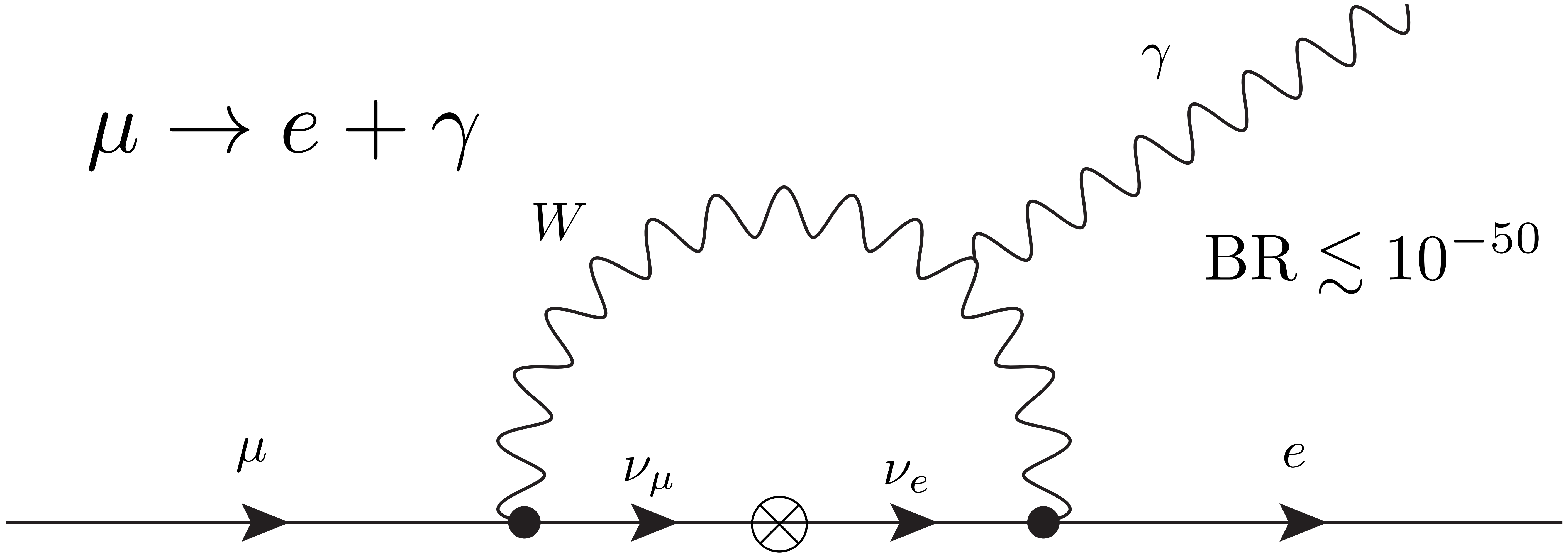
$$\sim -a_{AB\mu}\bar{\psi}_A\gamma^\mu\psi_B$$

A. Crivellin, F. Kirk, and M. Schreck, JHEP **04**, 082 (2021)

CLFV

- CLFV does not occur in the SM, but massive neutrinos provide a mechanism

$\mu \to e + \gamma$



$\mathrm{BR} \lesssim 10^{-50}$

Leptonic μ and τ constraints

Process	Bound	Exp.
$\mathrm{BR}(\mu^+ \to e^+ + \gamma)$	4.2×10^{-13}	MEG
$\mathrm{BR}(\tau^\pm \to e + \gamma)$	3.3×10^{-8}	BaBar
$\mathrm{BR}(\tau^\pm \to \mu + \gamma)$	4.4×10^{-8}	BaBar

B. Auber et al. [BaBar Collaboration], PRL **104**, 021802 (2012)
M. Baldini et al. [MEG Collaboration], EPJ C **76**, 43 (2016)

- Observation of CLFV would thus be highly suggestive of new physics beyond neutrino masses

- Use MEG and BaBar bounds and limit attention to Lorentz-violating effects in electromagnetic (EM) two-body decays

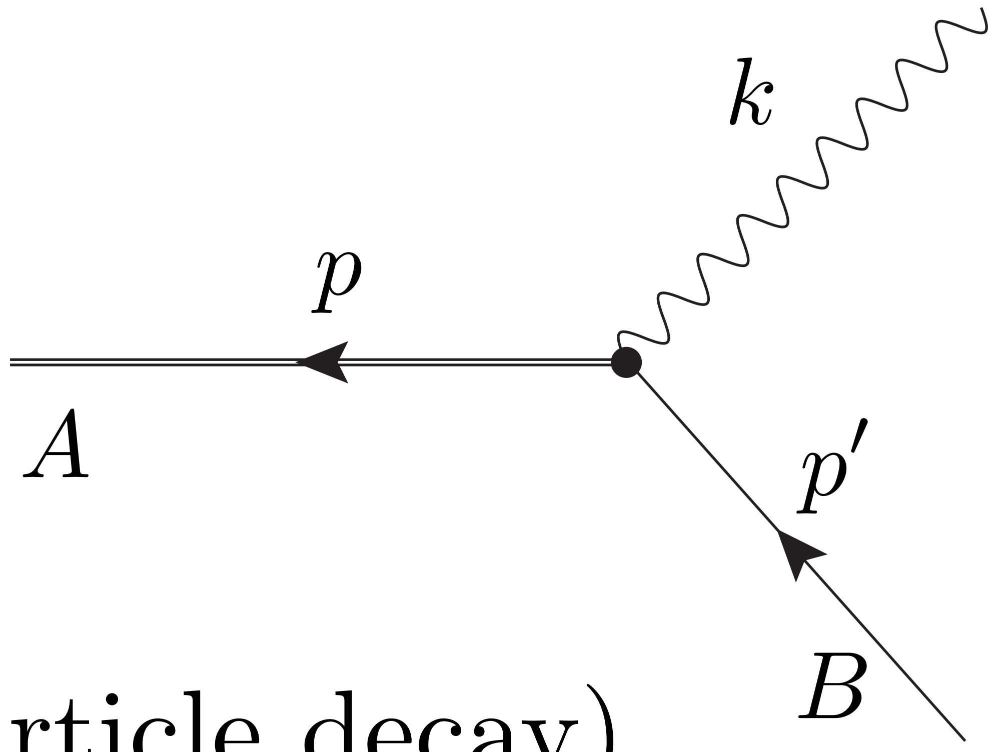
LV and CPTV effects

V. A. Kostelecký, E. Passemar, NS (in prep.)

- Set of $d = 5$ gauge-invariant effects contributing to EM 2-body decays

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

- Calculate modified decay amplitudes, decay rate, and theoretical branching ratio



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

$$d\Gamma \simeq \frac{1}{64\pi^2 m_A} d\Omega_{\text{exp.}} |\mathcal{M}|^2, \quad \text{BR}(A \to B + \gamma) = \tau_A \Gamma$$

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

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CPT even

CPT odd

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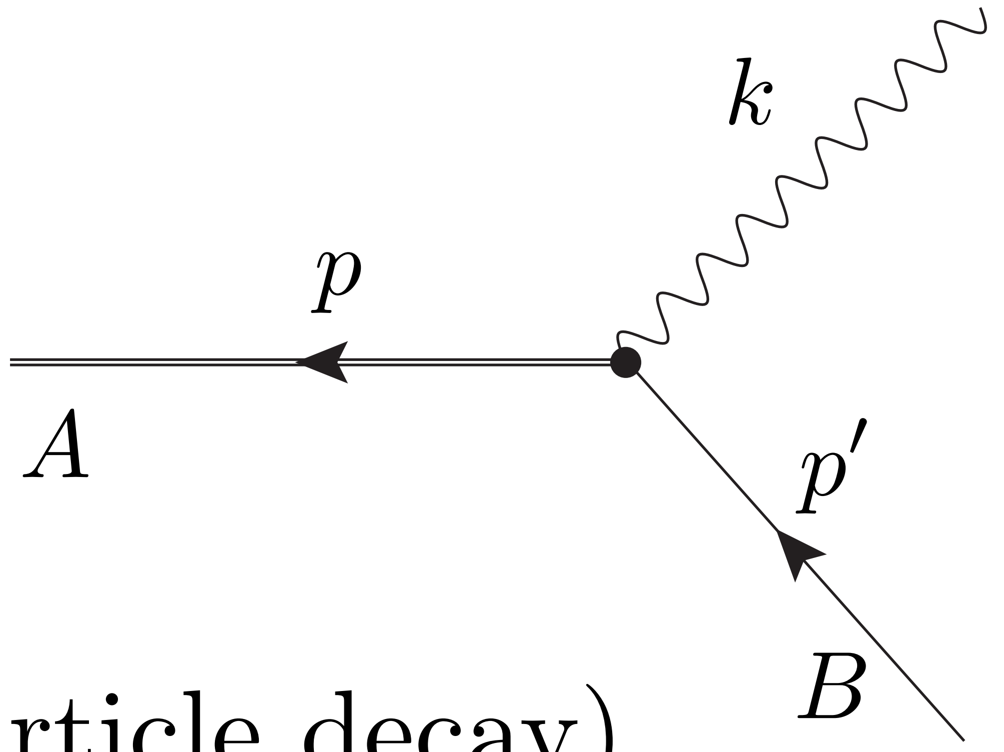

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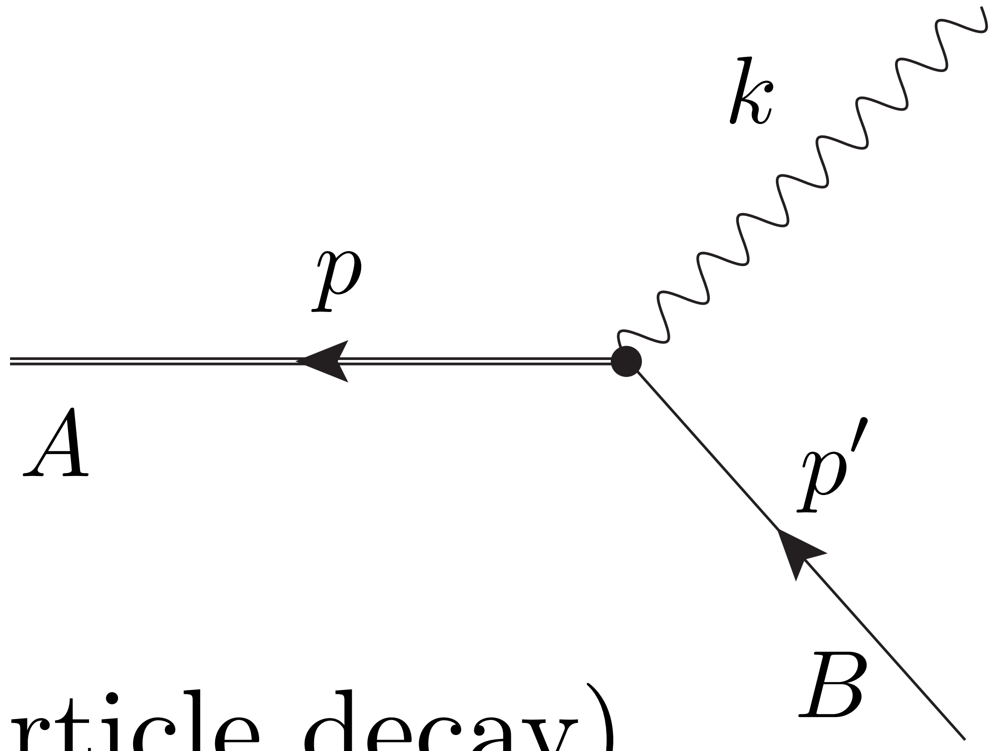

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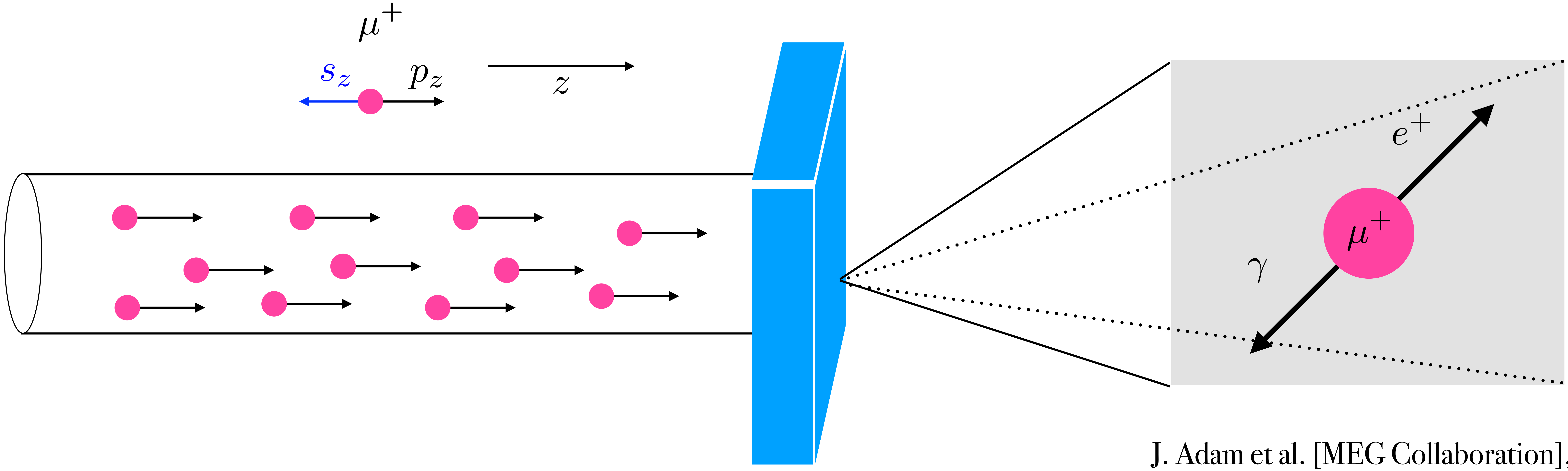
Muon decays and the MEG experiment

- MEG experiment: polarized antimuons impinge on and decay in stopping target



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

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

J. Adam et al. [MEG Collaboration], Eur. Phys. J. **C** 73, 2365 (2013)

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

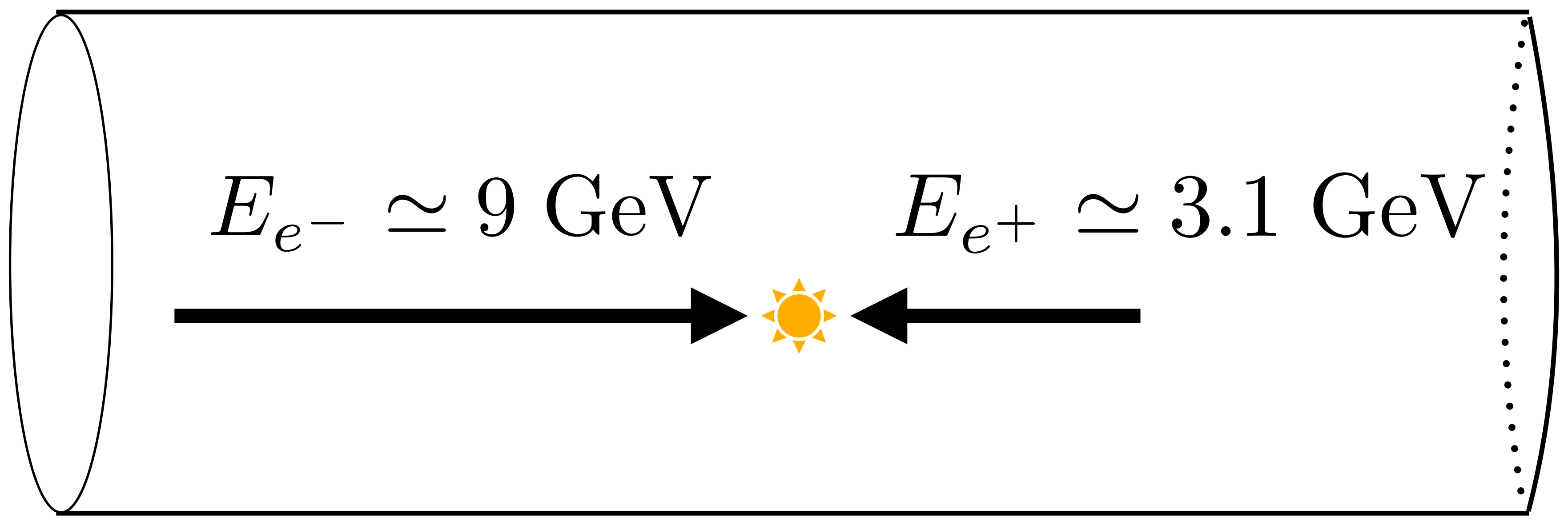
$$\Rightarrow \quad \Gamma \simeq \frac{1}{64\pi^2 m_\mu} \int_{\theta_{\rm min}}^{\theta_{\rm max}} \int_{\phi_{\rm min}}^{\phi_{\rm max}} \sin\theta d\theta d\phi |\mathcal{M}(\theta,\phi)|^2$$

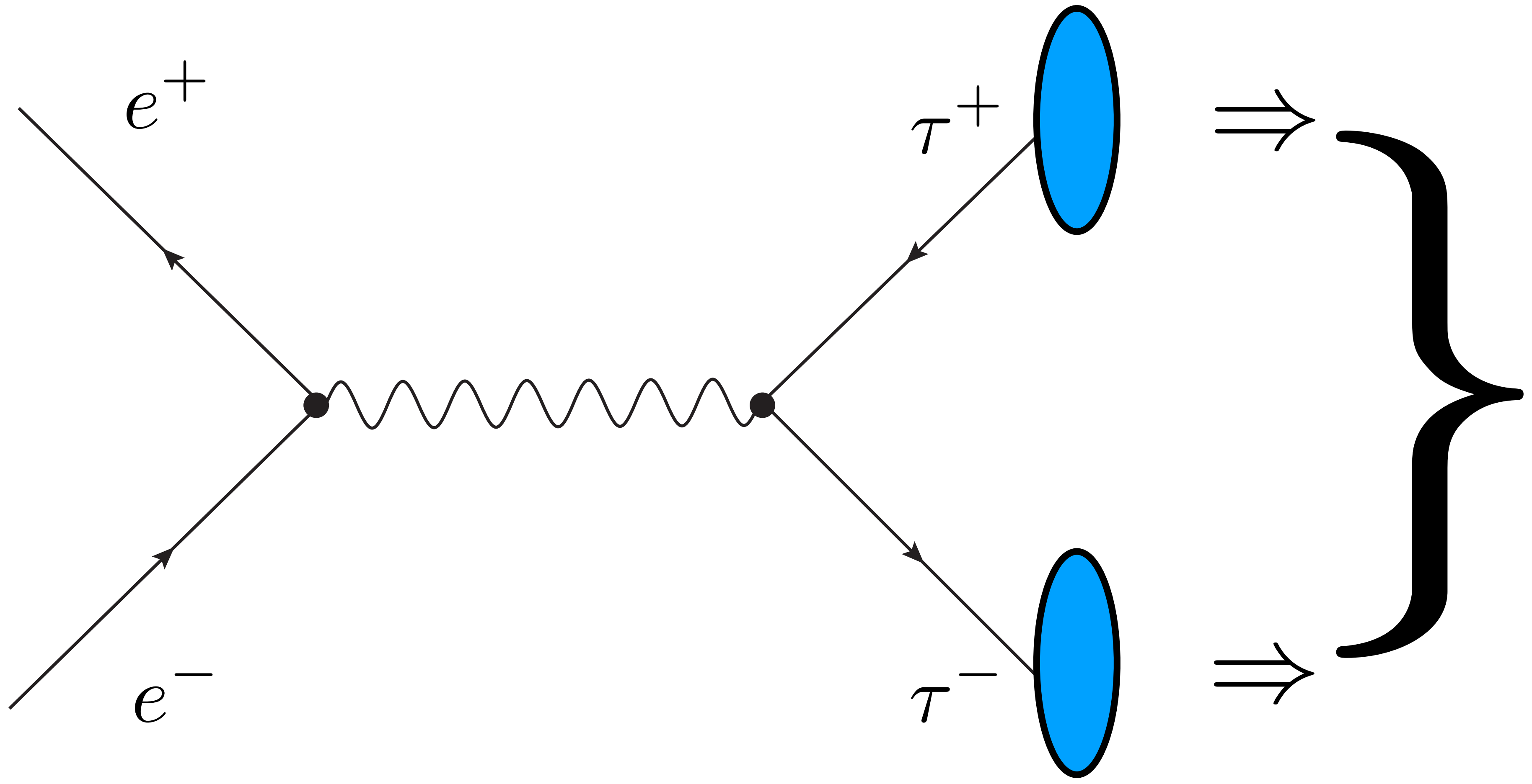
$$\theta \in (1.21, 1.93)$$

$$\phi \in \left(\frac{2\pi}{3}, \frac{4\pi}{3}\right)$$

Tau decays and the BaBar experiment

- BaBar experiment: tau pairs are produced by antisymmetric electron-positron annihilation





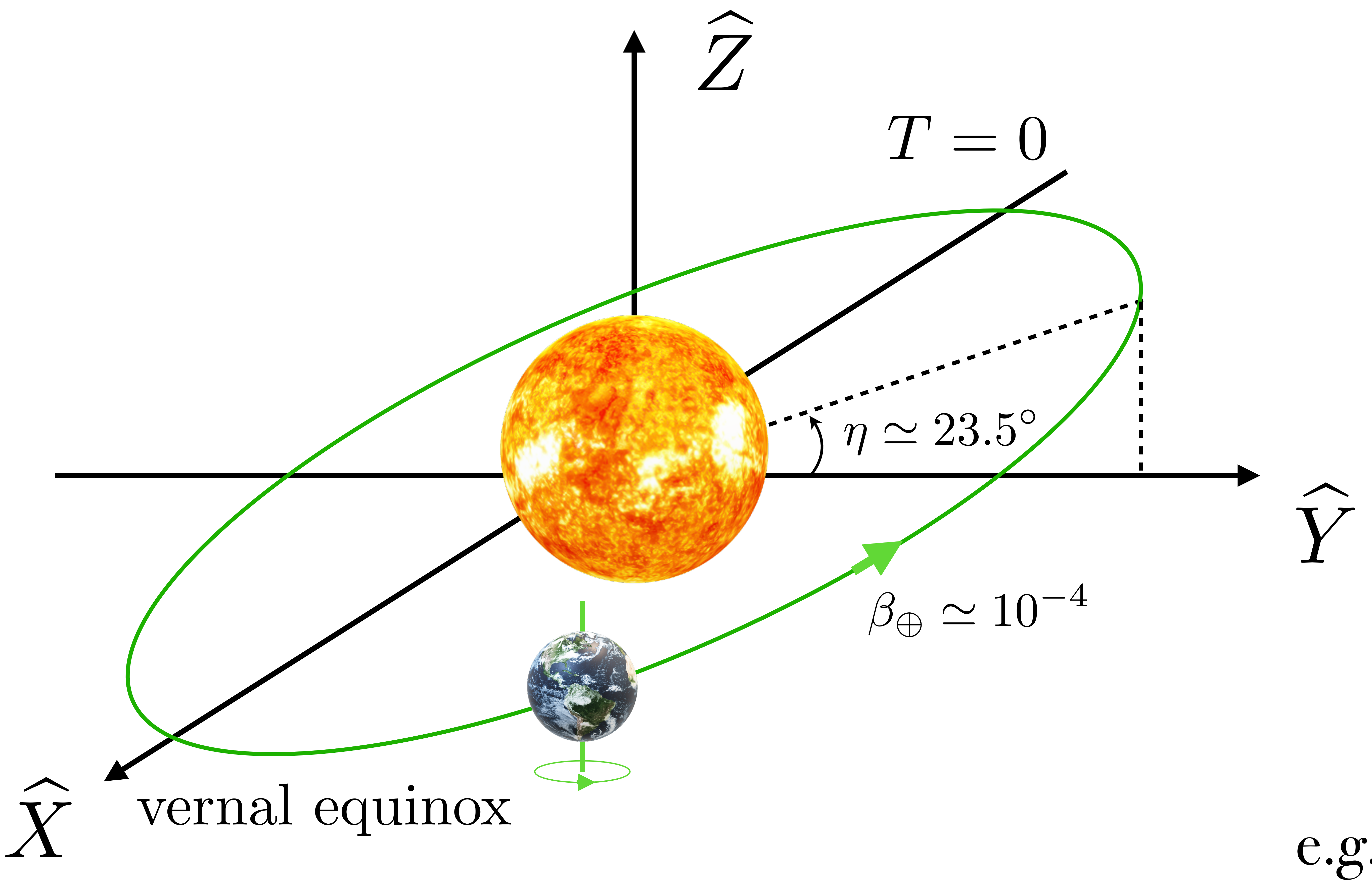
many further decay modes from unpolarized taus

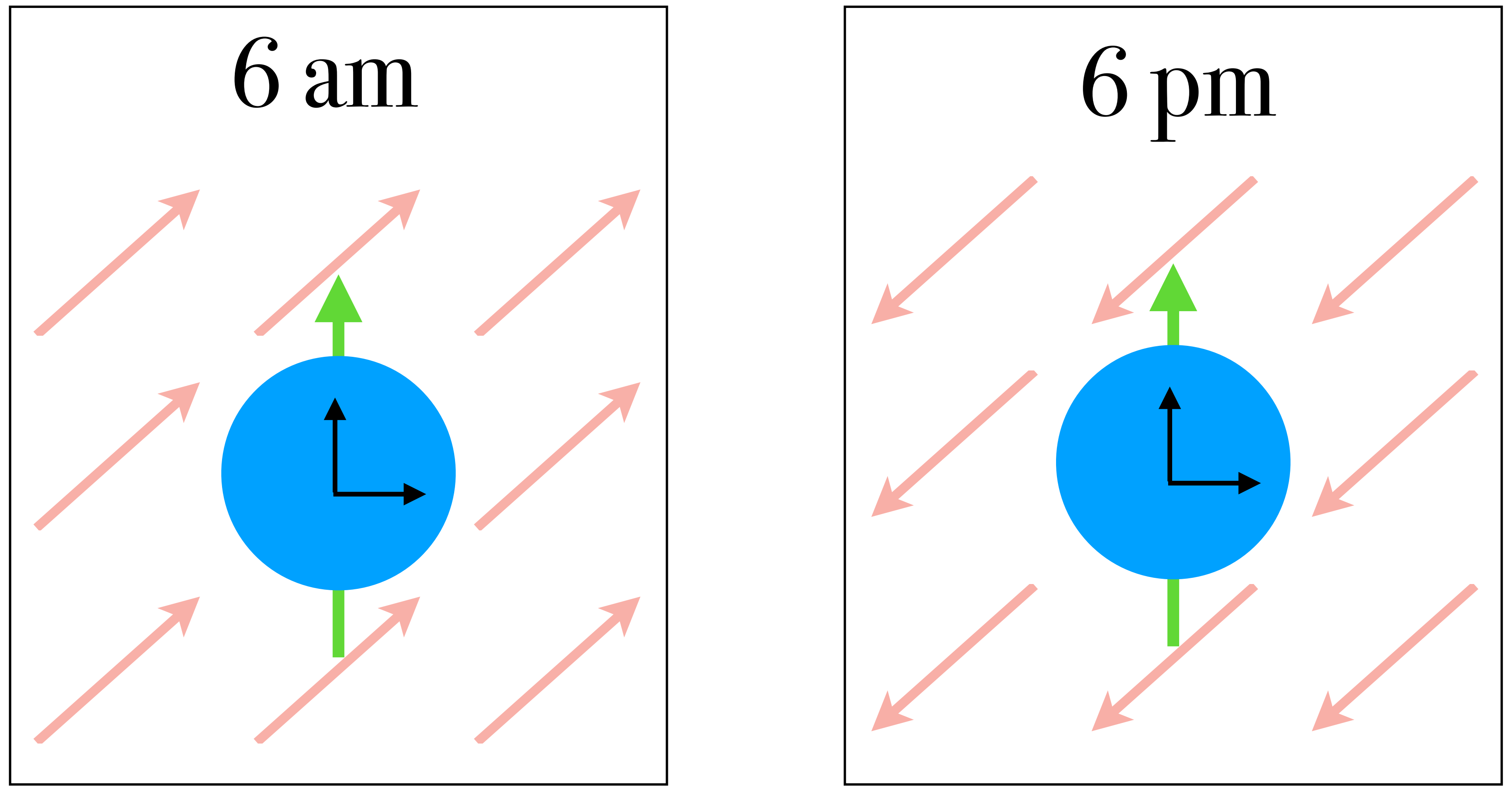
- Acceptance window $\simeq 90\%$ full phase-space volume; tau pair fairly low longitudinal momentum

$$\Gamma \simeq \frac{1}{64\pi^2 m_\tau} \int_{4\pi} d\Omega \sum_{\text{spins}} \overline{|\mathcal{M}|^2} \qquad \text{e.g.} \quad \sum_{\text{spins}} \overline{|\mathcal{M}_{m_F^{(5)}}|^2} = 2(m_A m_B + p \cdot p')(m_F^{(5)})^{k\mu}_{AB}(m_F^{*(5)})_{AB\mu}{}^{k}$$

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

$$a^\mu_{\text{lab}} = \Lambda^\mu{}_\nu a^\nu_{\text{SCF}}$$

e.g. $$\Lambda^\mu{}_\nu \simeq R^\mu{}_\nu(\omega_\oplus T_\oplus, \chi_{\text{lab}}, \cdots)$$

Constraints (*preliminary*)

- Summary of first constraints extracted from MEG and BaBar measurements

Coefficient	# Components	Bounds
$(m_F^{(5)})_{AB}^{\alpha\beta}$	6	$\lvert\mathrm{Re}(m_F^{(5)})_{AB}^{\alpha\beta}\rvert, \lvert\mathrm{Im}(m_F^{(5)})_{AB}^{\alpha\beta}\rvert \lesssim \begin{cases} 10^{-13}\ \mathrm{GeV}^{-1}, (A,B)=(\mu,e) \\ 10^{-9}\ \mathrm{GeV}^{-1}, (A,B)=(\tau,(\mu,e)) \end{cases}$
$(m_{5F}^{(5)})_{AB}^{\alpha\beta}$	6	$\lvert\mathrm{Re}(m_{5F}^{(5)})_{AB}^{\alpha\beta}\rvert, \lvert\mathrm{Im}(m_{5F}^{(5)})_{AB}^{\alpha\beta}\rvert \lesssim \begin{cases} 10^{-13}\ \mathrm{GeV}^{-1}, (A,B)=(\mu,e) \\ 10^{-9}\ \mathrm{GeV}^{-1}, (A,B)=(\tau,(\mu,e)) \end{cases}$
$(a_F^{(5)})_{AB}^{\mu\alpha\beta}$	24	$\lvert\mathrm{Re}(a_F^{(5)})_{AB}^{\mu\alpha\beta}\rvert, \lvert\mathrm{Im}(a_F^{(5)})_{AB}^{\mu\alpha\beta}\rvert \lesssim \begin{cases} 10^{-13}\ \mathrm{GeV}^{-1}, (A,B)=(\mu,e) \\ 10^{-9}\ \mathrm{GeV}^{-1}, (A,B)=(\tau,(\mu,e)) \end{cases}$
$(b_F^{(5)})_{AB}^{\mu\alpha\beta}$	24	$\lvert\mathrm{Re}(b_F^{(5)})_{AB}^{\mu\alpha\beta}\rvert, \lvert\mathrm{Im}(b_F^{(5)})_{AB}^{\mu\alpha\beta}\rvert \lesssim \begin{cases} 10^{-13}\ \mathrm{GeV}^{-1}, (A,B)=(\mu,e) \\ 10^{-9}\ \mathrm{GeV}^{-1}, (A,B)=(\tau,(\mu,e)) \end{cases}$
$(H_F^{(5)})_{AB}^{\mu\nu\alpha\beta}$	36	$\lvert\mathrm{Re}(H_F^{(5)})_{AB}^{\mu\nu\alpha\beta}\rvert, \lvert\mathrm{Im}(H_F^{(5)})_{AB}^{\mu\nu\alpha\beta}\rvert \lesssim \begin{cases} 10^{-13}\ \mathrm{GeV}^{-1}, (A,B)=(\mu,e) \\ 10^{-9}\ \mathrm{GeV}^{-1}, (A,B)=(\tau,(\mu,e)) \end{cases}$
	Total = 96	

- Including complexity of coefficients & three channels = 576 coefficients

Conclusions and outlook

- CLFV has been studied in the context of dimension-five Lorentz- and CPT-violating effects

- Existing MEG and BaBar data enables first constraints to be placed on many unexamined effects

- Sidereal signals could also be analyzed by binning data in time

- Future experiments, e.g. MEG-II and Belle II, expected to increase limits on muon and tau decays by 1-2 orders of magnitude

M. Baldini et al. [MEG-II Collaboration], EPJC **78**, 380 (2018)
E. Kou et al., *The Belle II Physics Book*, Prog. There. Exp. Phys. **2019**, 123C01

- Great outlook for future CLFV & LV studies!