CPT-Symmetry Studies Involving Quarks

Rare Processes and Precision Frontier
Townhall Meeting

October 2, 2020

Mike Berger

1. **Neutral meson oscillations**
2. **Top quark production and decay**

Standard Model Extension

1. Add all possible Lorentz-violating terms to the Standard Model Lagrangian that are gauge-invariant, etc. For example,

$$\mathcal{L}'_a \equiv a_\mu \overline{\psi} \gamma^\mu \psi \quad , \qquad \mathcal{L}'_b \equiv b_\mu \overline{\psi} \gamma_5 \gamma^\mu \psi$$

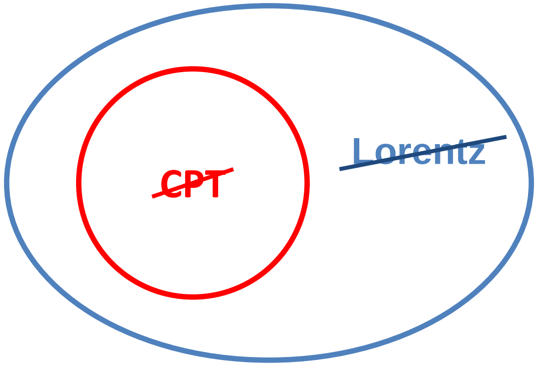
2. In general, there are flavor labels in the three-generation Standard model → many coefficients can be measured (dimension 3, 4 and higher dimensional operators)

3. The resulting theory is to be viewed as an *effective field theory* presumably up to the Planck scale where a more fundamental theory resides

4. Phenomenological formulation → consequences for experiment. Usually assume the Lorentz-violating coefficients are independent of spacetime position to maintain energy-momentum conservation → experiment (Earth) rotates in this fixed background

Colladay and Kostelecký, Phys. Rev. D **58**, 116002 (1998)

Lorentz violation in SM Quark Sector


~~CPT~~

~~Lorentz~~

Dimensionless, CPT-even

$$\begin{aligned}\mathcal{L}^{\rm CPT-even}_{\rm quark} &= \tfrac{1}{2} i (c_Q)_{\mu\nu AB} \overline{Q}_A \gamma^\mu \overleftrightarrow{D^\nu} Q_B \\ &+ \tfrac{1}{2} i (c_U)_{\mu\nu AB} \overline{U}_A \gamma^\mu \overleftrightarrow{D^\nu} U_B \\ &+ \tfrac{1}{2} i (c_D)_{\mu\nu AB} \overline{D}_A \gamma^\mu \overleftrightarrow{D^\nu} D_B \quad ,\end{aligned}$$

Dimensionful,

CPT-odd

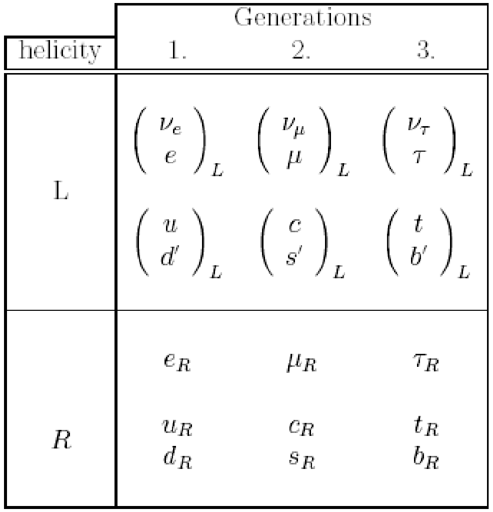
$$\begin{aligned}\mathcal{L}^{\rm CPT-odd}_{\rm quark} &= -(a_Q)_{\mu AB} \overline{Q}_A \gamma^\mu Q_B - (a_U)_{\mu AB} \overline{U}_A \gamma^\mu U_B \\ &-(a_D)_{\mu AB} \overline{D}_A \gamma^\mu D_B\end{aligned}$$

Dimensionless

CPT-even

$$\begin{aligned}\mathcal{L}^{\rm CPT-even}_{\rm Yukawa} &= -\tfrac{1}{2}\big[(H_U)_{\mu\nu AB} \overline{Q}_A \phi^c \sigma^{\mu\nu} U_B \\ &\quad (H_D)_{\mu\nu AB} \overline{Q}_A \phi \sigma^{\mu\nu} D_B\big] + \text{h.c.}\end{aligned}$$

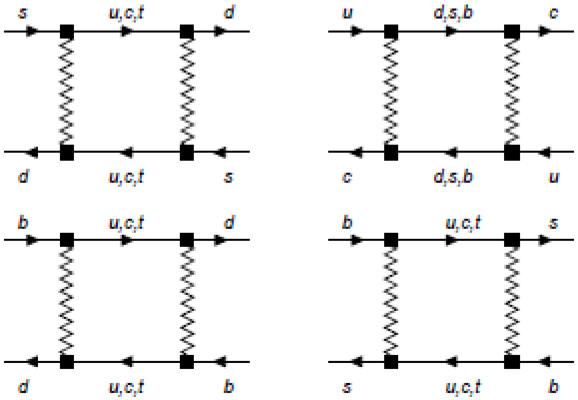
A,B are generational indices = 1,2,3



helicity	Generations 1.	2.	3.
L	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$ $\begin{pmatrix} u \\ d' \end{pmatrix}_L$	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$ $\begin{pmatrix} c \\ s' \end{pmatrix}_L$	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$ $\begin{pmatrix} t \\ b' \end{pmatrix}_L$
R	e_R u_R d_R	μ_R c_R s_R	τ_R t_R b_R

Neutral Meson Oscillations

- Oscillation phenomena – particles with the same quantum numbers can convert into each other (neutral mesons, neutrinos, etc.)
- Quantum mechanical mixing phenomena
- Flavor eigenstates (production and decay) are not the same as mass eigenstates (propagation)
- The neutral mesons (of a given flavor) can evolve into the antimeson via the weak interactions via loops (Flavor-changing neutral currents (FCNCs)) are absent in the Standard Model
- Highly sensitive measurements due to interferometric nature



- Candidate systems: $P = K, D, B_d, B_s$

$$\Lambda = \tfrac{1}{2}\Delta\lambda \begin{pmatrix} U+\xi & VW^{-1} \\ VW & U-\xi \end{pmatrix} \qquad i\frac{\partial\Psi}{\partial t} = \Lambda\Psi$$

CPT-violating parameter ξ (sometimes described by δ in other parameterizations) is calculable in the SME

Contrast with T violation: W = 1 (phase)

Calculation in the SME

- Corrections are proportional to a coefficients: $-a^q_\mu \overline{q}\gamma^\mu q$

$$\xi_P \propto (a^\mu_{q2} - a^\mu_{q1})\beta_\mu$$

- This effective parameter is a combination of the parameters for the valence quarks from the SME and which account for how the quarks are bound into mesons

- Many different parameters to measure depending on the meson flavors

The physical effects will depend on the meson momentum spectrum, angular distribution, and sidereal time.

Applies to all experiments: uncorrelelated and correlated, boosted and rest-frame

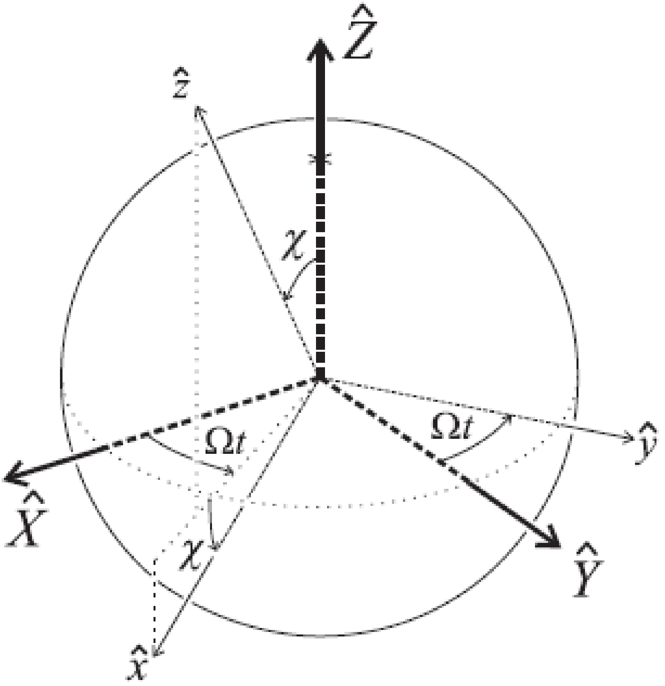
Sun-centered frame

- LV coefficients are defined in a sun-centered celestial equatorial frame

- Lab frame: x (south), y (east), z (vertically up)
- Sun centered frame: X,Y,Z

- Earth's sidereal angular frequency Ω = 2π/(23hr 56min 4.1s)
- Colatitude of the lab: χ

- Coefficients can produce sidereal signals, twice-sidereal signals, etc.



Strong bounds on CPT-Violation

e.g. in the K system

Δa_0^K	$(-6.0 \pm 7.7_{\mathrm{stat}} \pm 3.1_{\mathrm{syst}}) \times 10^{-18}$ GeV	K oscillations
Δa_X^K	$(0.9 \pm 1.5_{\mathrm{stat}} \pm 0.6_{\mathrm{syst}}) \times 10^{-18}$ GeV	”
Δa_Y^K	$(-2.0 \pm 1.5_{\mathrm{stat}} \pm 0.5_{\mathrm{syst}}) \times 10^{-18}$ GeV	”
Δa_Z^K	$(3.1 \pm 1.7_{\mathrm{stat}} \pm 0.5_{\mathrm{syst}}) \times 10^{-18}$ GeV	”
Δa_0^K	$(0.4 \pm 1.8) \times 10^{-17}$ GeV	”
Δa_X^K	$(-6.3 \pm 6.0) \times 10^{-18}$ GeV	”
Δa_Y^K	$(2.8 \pm 5.9) \times 10^{-18}$ GeV	”
Δa_Z^K	$(2.4 \pm 9.7) \times 10^{-18}$ GeV	”
Δa_Z^K	$(-1 \pm 4) \times 10^{-17}$ GeV	”

KLOE Collaboration

Higher dimensional operators

- Effective scalar field theory of mesons
- A dimension-5 coefficient has 16 components for each P

$$\mathcal{L}_{\text{CPT}} \supset -\tfrac{1}{2} i k_P^{\mu\rho\sigma} \phi_P^\dagger \partial_\mu \partial_\rho \partial_\sigma \phi_P + \text{h.c.}$$

- Giving rise to many signals with sidereal, twice-sidereal, etc. time dependent signals

$$\xi_P \propto \beta_\mu \beta_\rho \beta_\sigma \, k_P^{\mu\rho\sigma} .$$

- Previously published bounds on CPT-violation can be translated into bounds for components which vary according to sidereal frequency. For example, the LHCb experiment:

	GeV^{-1}	
$(k^{(5)}_{a,B_d})_{TTX}$	$(1.0 \pm 0.8) \times 10^{-19}$	sidereal
$(k^{(5)}_{a,B_d})_{TTY}$	$(2.3 \pm 8.1) \times 10^{-20}$	sidereal
$(k^{(5)}_{a,B_d})_{TTT} - 0.7(k^{(5)}_{a,B_d})_{TTZ}$	$(-8.0 \pm 5.1) \times 10^{-16}$	time-independent

- Many more coefficients to bound.

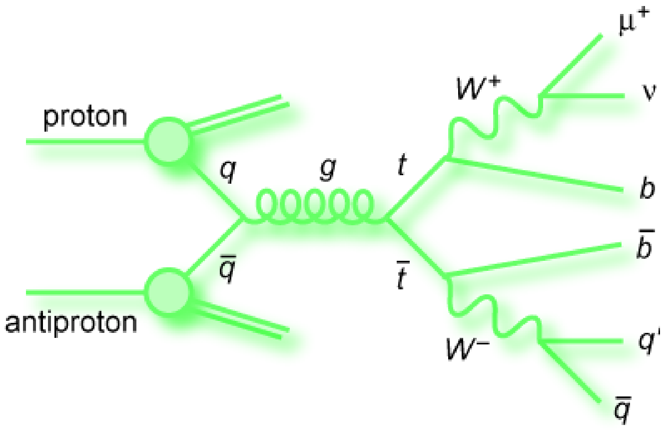
Edwards and Kostelecky, PLB795, 620 (2019)

CPT-Violation and the Top-Quark

- The only quark which decays before it hadronizes – allows certain tests largely independent of long distance physics (no meson oscillations)
- Can presently be studied directly at hadron colliders – LHC, Fermilab Tevatron
- New physics may appear in the top quark interactions – production and decay
- Effective field theory requires top and antitop to have the same mass

Top-Quark Lorentz violation

SME contains various Lorentz violating coefficients. These can be inserted, according to Feynman rules, into the relevant diagrams.

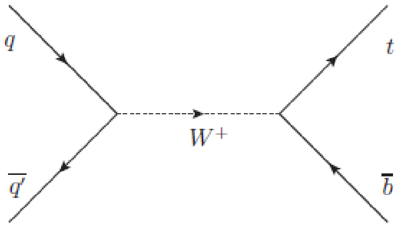


Many possible ways LV could contribute (light quarks and leptons, gluon, electroweak interactions).

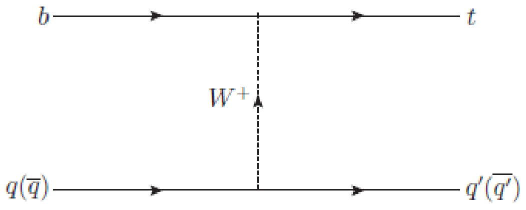
Focus analysis on only those which involve the top quark.

MB, Kostelecky and Liu – Phys. Rev. D93, 036005 (2016)
Whittington – D0 Collaboration – PRL108 (2012) 261603
Carle, Chanon, Perries – LHC – Eur. Phys. J. C 80 (2020) 128

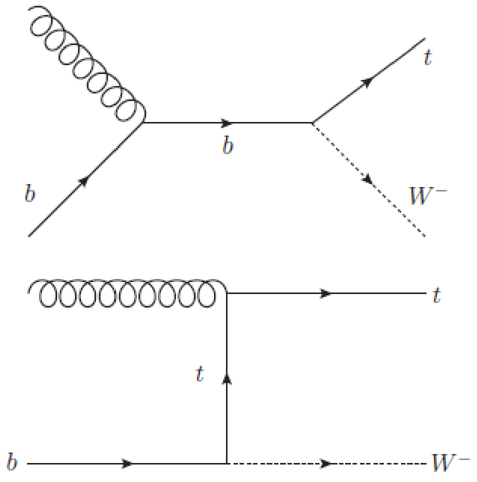
Single Top Quark Production



s-channel



t-channel



tW-mode

$$s = (p_1 + p_2)^2 = (p_3 + p_4)^2$$
$$t = (p_1 - p_3)^2 = (p_2 - p_4)^2$$
$$u = (p_1 - p_4)^2 = (p_2 - p_3)^2$$

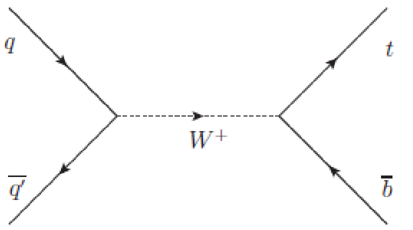
-electroweak process suppressed relative to pair production via QCD

-single top quark production (s & t-channels) seen at Tevatron, also tW-mode at LHC

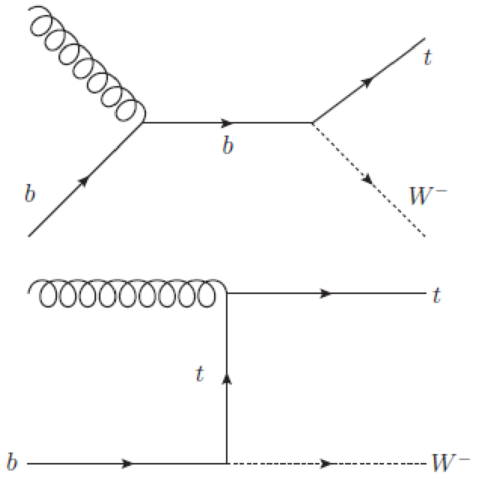
-sensitive to CPT violation

-various production modes have different dependences on the SME parameters

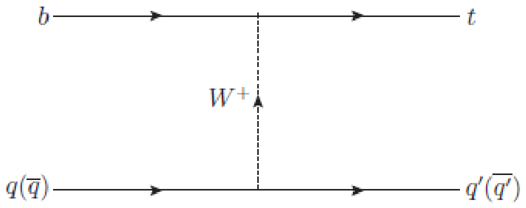
Single Top Quark Production



s-channel



tW-mode



t-channel

Cross section	t channel	s channel	tW mode
$\sigma^{t}_{\text{Tevatron}}$	1.15 ± 0.07 pb	0.54 ± 0.04 pb	0.14 ± 0.03 pb
σ^{t}_{LHC}	150 ± 6 pb	7.8 ± 0.7 pb	44 ± 5 pb
$\sigma^{\bar{t}}_{\text{LHC}}$	92 ± 4 pb	4.3 ± 0.3 pb	44 ± 5 pb

same

Summary

- Many Lorentz frames available simultaneously as the produced particles have different rest frames from event to event, e.g. In a high energy hadron collider (like the LHC) there tend to be large boosts which can enhance sensitivity
- Distinctive time-dependent experimental signatures
- Very sensitive tests are possible in meson oscillations because of their interferometric nature
- Potential to access many CPT-violating coefficients simultaneously
- CPT violation can appear as a sidereal signal in single-top production, but also as a different rate in the tW mode for quark versus antiquark