A FIRST CONSTRAINT ON CPT VIOLATION IN TOP QUARKS

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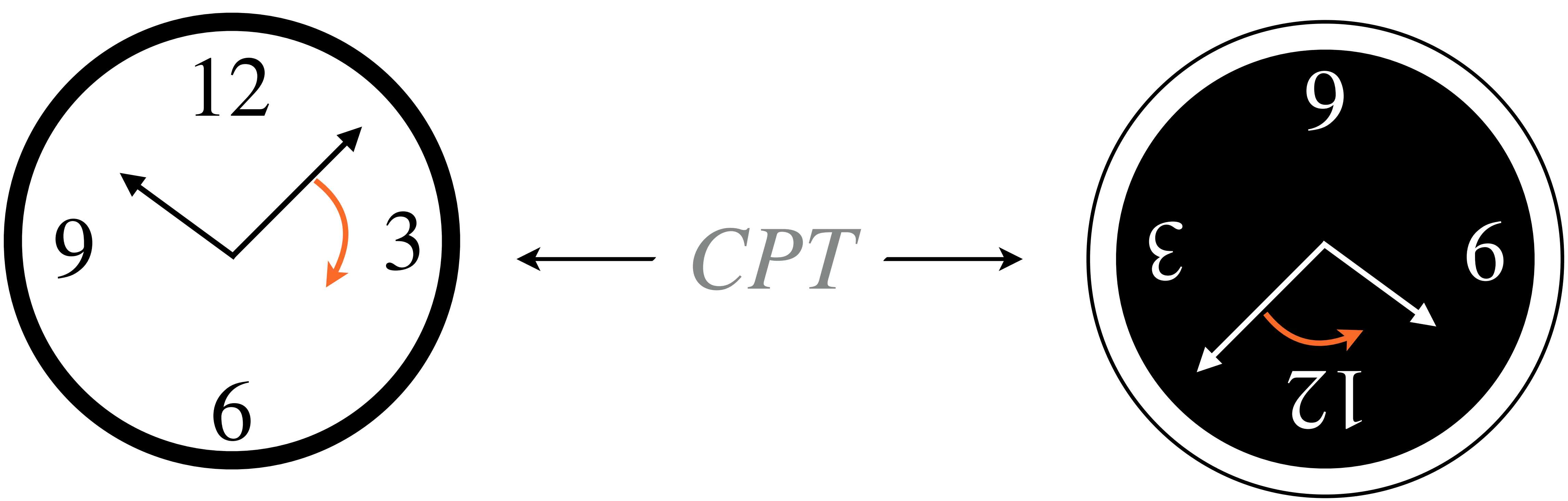
A. Belyaev, L. Cerrito, E. Lunghi, S. Moretti, **NS**
Phys. Rev. Lett **133**, 221601 (2024)
arXiv:2405.12162

DISCRETE 2024
LJUBLJANA

2024/12/03

CPT = product of C, P, T

C transforms particle to antiparticle
P inverts spatial coordinates
T reverses time



CPT *invariance*: physical laws are invariant under the CPT transformation

THEOREM: local, Hermitian, Lorentz invariant QFTs in Minkowski spacetime are CPT invariant

$$(\Theta_{\mathrm{CPT}})\mathcal{L}(\Theta_{\mathrm{CPT}})^{-1} = \mathcal{L}$$

- Cornerstone of physics ⇒ **must be tested!**
- Several existing constraints, some stringent
- Exception: top/antitop *completely unexplored*

Data Tables for Lorentz and CPT Violation,
V. A. Kostelecký, N. Russell, arXiv:0801.0287v16

TOP QUARK

Citation: S. Navas *et al.* (Particle Data Group), Phys. Rev. D **110**, 030001 (2024)

t

$$I(J^P) = 0(\tfrac{1}{2}^+)$$

Charge = $\frac{2}{3}\,e$ Top = $+1$

Mass (direct measurements) $m = 172.57 \pm 0.29$ GeV [a,b] (S = 1.5)
Mass (from cross-section measurements) $m = 162.5^{+2.1}_{-1.5}$ GeV [a]
Mass (Pole from cross-section measurements) $m = 172.4 \pm 0.7$ GeV
$m_t - m_{\bar{t}} = -0.15 \pm 0.20$ GeV (S = 1.1)
Full width $\Gamma = 1.42^{+0.19}_{-0.15}$ GeV (S = 1.4)
$\Gamma(W b)/\Gamma(W q(q = b, s, d)) = 0.957 \pm 0.034$ (S = 1.5)

CPT-violating EFTs: $m_t = m_{\bar{t}}$

D. Colladay, V. A. Kostelecký, PRD **55**, 6760 (1997); PRD **58**, 116002 (1998)
O. W. Greenberg, PRL **89**, 231602 (2002)

How to interpret measurement?

TOP CPT-VIOLATING EFFECTS

Gauge-invariant EFT operators

M. S. Berger, V. A. Kostelecký, Z. Liu
PRD **93**, 036005 (2016)

$$\mathcal{L}_{\mathrm{CPT}} = -(a_Q)^\mu_A \bar{Q}_A \gamma_\mu Q_A - (a_U)^\mu_A \bar{U}_A \gamma_\mu U_B - (a_D)^\mu_A \bar{D}_A \gamma_\mu D_B$$

Third generation

$$Q_3 = \begin{pmatrix} t \\ b \end{pmatrix}_L, \quad U_3 = t_R, \quad D_3 = b_R$$

Field redefinitions in $m_b = 0$ limit permit simplification

$$\mathcal{L}^{\mathrm{top}}_{\mathrm{CPT}} = b^\mu \bar{t}_R \gamma_\mu t_R$$

$$b^\mu = (a_U)^\mu_3 - (a_Q)^\mu_3$$

$$(\Theta_{\mathrm{CPT}})\mathcal{L}(\Theta_{\mathrm{CPT}})^{-1} = b_\mu(-\bar{t}_R \gamma^\mu t_R)$$

Modified Dirac equation

$$\left[i\partial\!\!\!/ + \frac{1}{2}(1-\gamma_5)b\!\!\!/ - m_t\right] t = 0$$

$$p^2 = \begin{cases} m_t^2 - p\cdot b \pm \left[(p\cdot b)^2 - m_t^2 b^2\right]^{1/2} & \text{(top)} \\ m_t^2 + p\cdot b \pm \left[(p\cdot b)^2 - m_t^2 b^2\right]^{1/2} & \text{(antitop)} \end{cases}$$

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Experiments really reconstruct "kinematical mass"

$$m^{\text{kin}} \equiv \sqrt{p^2} \neq m_t$$ **if CPT violated!**

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$$m^{\text{kin}} \equiv \sqrt{p^2} \neq m_t \qquad \textbf{if CPT violated!}$$

$$\boxed{\Delta m^{\text{kin}}_{t\bar{t}}(p, \lambda_p, \bar{p}, \lambda_{\bar{p}}, m_t, b) \equiv m_t^{\text{kin}} - m_{\bar{t}}^{\text{kin}}}$$

https://atlas.cern/about

EXPERIMENTS

Both ATLAS and CMS have measured $\langle \Delta m_{t\bar{t}}^{\text{kin}} \rangle$

$$\langle \Delta m_{t\bar{t}}^{\text{kin}} \rangle = \begin{cases} (+0.67 \pm 0.61 \pm 0.41)\ \text{GeV} & \textbf{ATLAS} \\ (-0.15 \pm 0.19 \pm 0.09)\ \text{GeV} & \textbf{CMS} \end{cases}$$

$\langle\rangle$ **indicates average over all events**

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ATLAS

1. $\sqrt{s} = 7$ TeV, $\mathscr{L} = 4.7$ fb^{-1}
2. $t\bar{t}$ from lepton + jets channel
3. Data regularly collected over several months in 2011

G. Aad et al. (ATLAS), PLB **728**, 363 (2014)

CMS

1. $\sqrt{s} = 8$ TeV, $\mathscr{L} = 19.6$ fb^{-1}
2. $t\bar{t}$ from separate ℓ^+, ℓ^- samples in lepton + jets
3. Collected over 2012

S. Chatrchyan et al. (CMS), JHEP **06**, 109 (2012); PLB **770**, 50 (2017)

Both

1. No sensitivity to top polarizations
2. Time-averaged results only sensitive to b_0

EXPERIMENTS

Events/dataset average $\langle \vec{p}_t + \vec{p}_{\bar{t}} \rangle = 0$

$$\Rightarrow \langle \Delta m_{t\bar{t}}^{\text{kin}} \rangle = -\frac{\langle E_t + E_{\bar{t}} \rangle}{2m_t} b_T \qquad (b_T = b_0)$$

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Calculate $\langle E_t + E_{\bar{t}} \rangle$ in experimental (fiducial) phase space

	[GeV] $t\bar{t}$	$t\bar{t} \to \ell\nu jjb\bar{b}$ total	$t\bar{t} \to \ell\nu jjb\bar{b}$ fiducial
$\langle E_t + E_{\bar{t}} \rangle_{\text{at 7 TeV}}$	706.3	708.9	658.4
$\langle E_t + E_{\bar{t}} \rangle_{\text{at 8 TeV}}$	738.9	742.2	674.4
$\langle E_t + E_{\bar{t}} \rangle_{\text{at 13 TeV}}$	878.8	883.7	725.2
$\langle E_t + E_{\bar{t}} \rangle_{\text{at 13.6 TeV}}$	892.5	898.7	729.1

CONSTRAINTS

Constraints on b_T at 95% CL

$$b_T \in \begin{cases} [-1.10, 0.41]\ \mathrm{GeV} & \textbf{ATLAS} \\ [-0.13, 0.29]\ \mathrm{GeV} & \textbf{CMS} \end{cases}$$

A model-independent assessment of CPT violation for the top sector

CONCLUSIONS

CPT is a fundamental symmetry of QFTs

Constraint on CPT-violating parameter b_T from ATLAS and CMS kinematical mass differences

[Also provide paths for (b_X, b_Y) and b_Z searches!]

- **"Anti" CPT Theorem: CPT violation => Lorentz violation**
- **Time-dependent observables due to Earth's rotation**
- **ATLAS and CMS can simultaneously search for CPT and Lorentz violation (see paper for details)**