Implications of a matter-antimatter mass asymmetry in Penning-trap experiments

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IMPRS
for Precision Tests of Fundamental Symmetries
INTERNATIONAL MAX PLANCK RESEARCH SCHOOL

CPT symmetry

- Local, Lorentz invariant, Hermitian, casual axiomatic field theory
  $\longrightarrow$ CPT conservation (CPT theorem)

- CPT conserved $\longrightarrow$ properties of particle = that of its antiparticle
  (e.g. mass and decay width)
- Motivation of CPT violation: matter v.s. antimatter abundance

  $\longrightarrow$ no need for the Sakharov conditions

Baryogenesis
- Baryon number violation
- C and CP violation
- Interactions out of thermal equilibrium

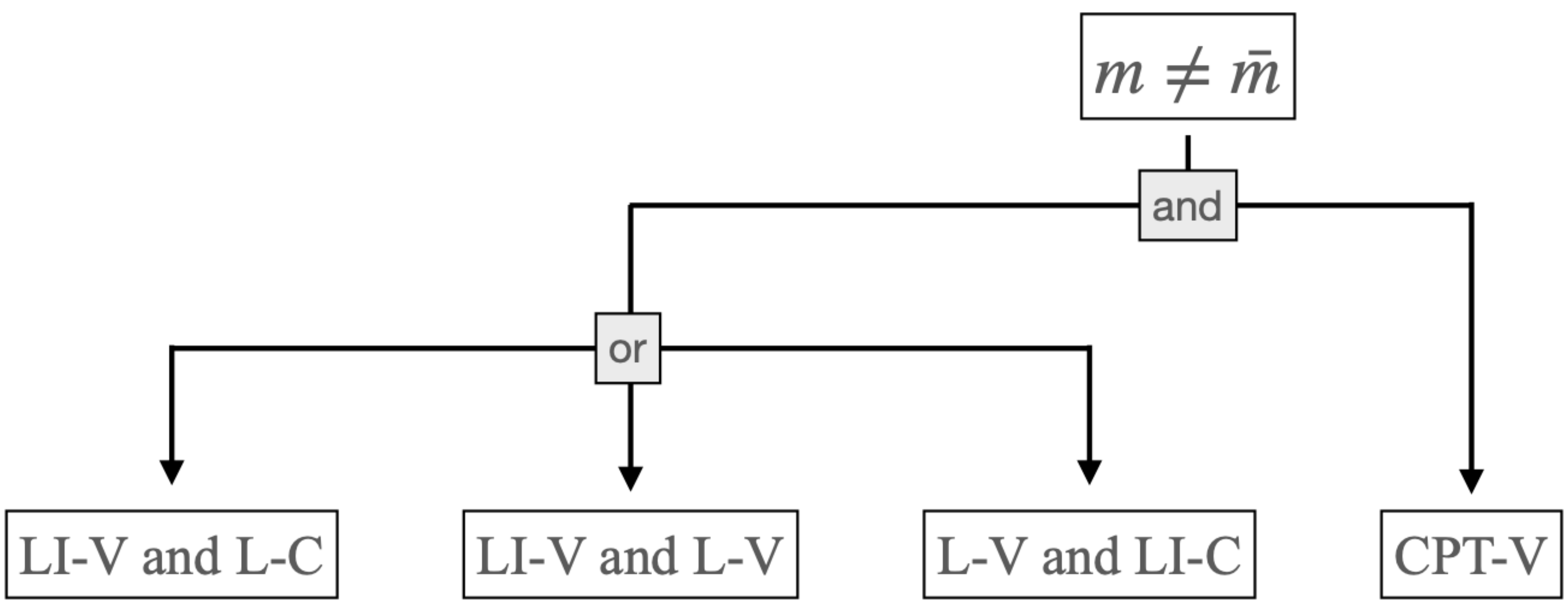
Matter - antimatter mass asymmetry (MAMA)

We believe in

- Local, ~~Lorentz~~ invariant, Hermitian, casual axiomatic field theory
  $\longrightarrow$ CPT conservation (CPT theorem)

~~Gravity~~

- CPT conserved $\longrightarrow$ properties of particle ~~=~~ that of its antiparticle
  (e.g. mass and decay width)



Fundamental Principles

- Lorentz invariant: physical laws are the same for different observers

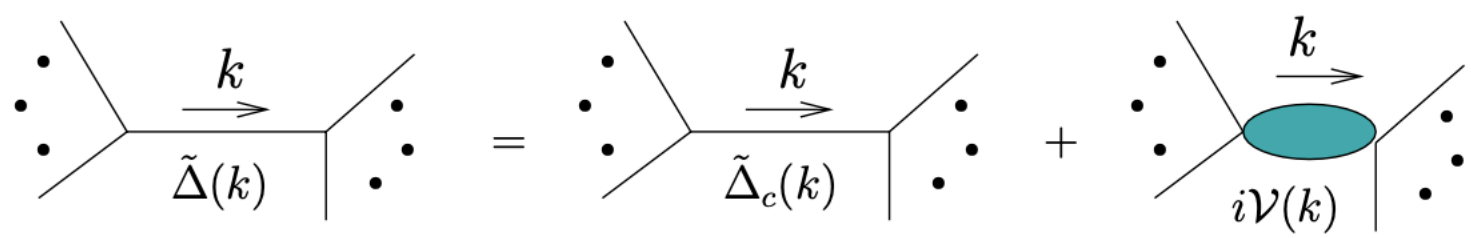
$$\mathscr{L} \to \mathscr{L}' : \; E^2 = m^2 + p^2 + f(p), \qquad \text{SME: } \mathscr{L} \supset \sum_{n=4} \mathcal{O}^{(n)}$$

Can be CPT even or odd

(Updated bounds by V. Alan Kostelecky and Neil Russell in 0801.0287)

- Locality: an object is influenced directly only by its immediate surroundings → Already not exact : EPR & Bell inequality

  Non-local interactions:



(E. T. Tomboulis, 1507.00981)

- Weak equivalence principle: WEP - free fall, WEP - clock

  Inertia mass ≠ gravitation mass

e.g. Free fall of H^- at alpha
(See talk by Andrea Capra yesterday)

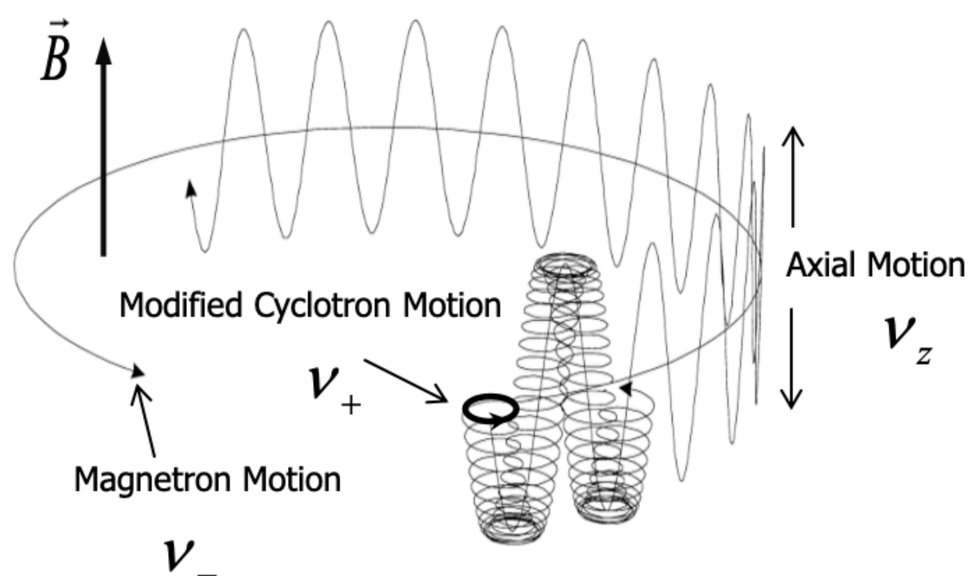
e.g. annual cyclotron-clock-frequencies at BASE

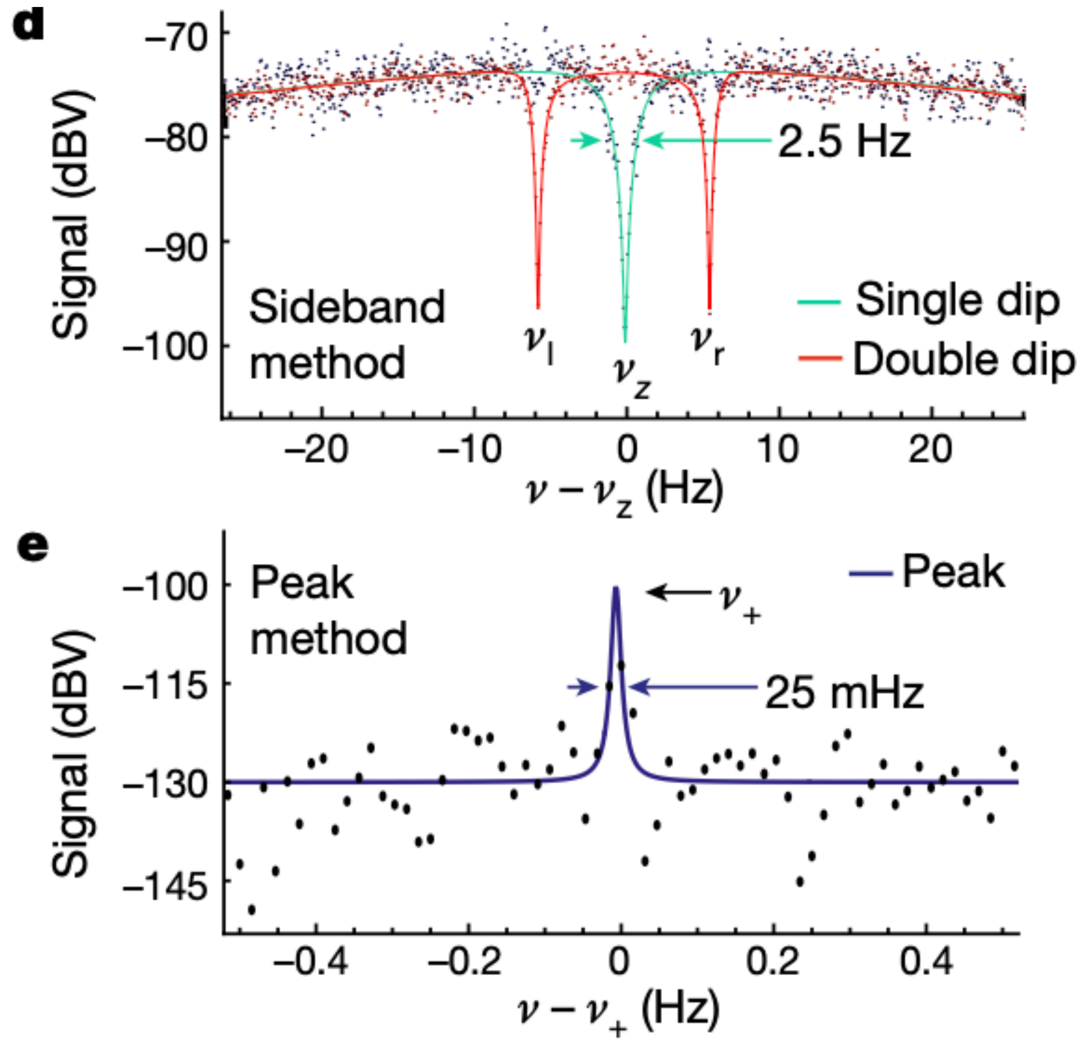
(BASE collaboration, Nature 2022)

Experiments testing MAMA

The Penning Trap Experiment @ BASE

Trap H^- and antiproton in a Penning trap
(From CREN)





(BASE collaboration, Nature 2022)

Brown-Gabrielse invariance theorem:

$$\nu_c^2 = \nu_+^2 + \nu_z^2 + \nu_-^2$$

$$\nu_c = \frac{1}{2\pi}\boxed{\frac{q}{m}}B$$

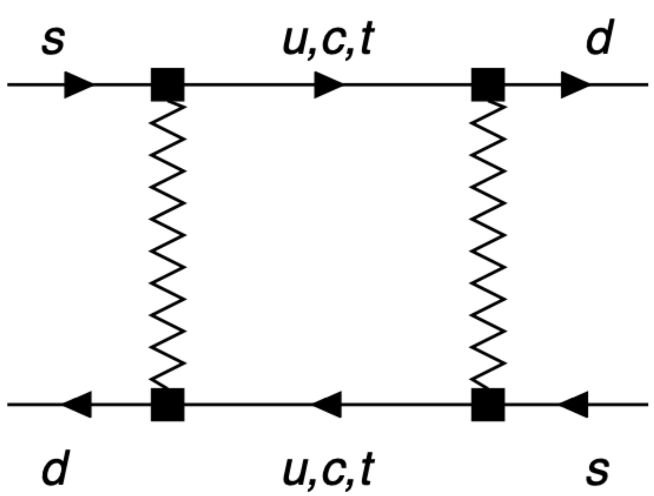
For proton (H^-) and antiproton

Kaon Oscillation

Mixing of neutral kaon - antikaon

$$i\frac{d}{dt}\begin{bmatrix}K^0\\ \overline{K}^0\end{bmatrix} = [M - i\Gamma/2]\begin{bmatrix}K^0\\ \overline{K}^0\end{bmatrix} \quad ,$$

CPT requires
$M_{11} = M_{22}$ and $\Gamma_{11} = \Gamma_{22}$



In propagation basis: K-long and K-short

$$K_{S,L} = \frac{1}{\sqrt{2\left(1+|\epsilon_{S,L}|^2\right)}}\left[(1+\epsilon_{S,L})\,K^0 \pm (1-\epsilon_{S,L})\,\overline{K}^0\right]$$

$$\epsilon_{S,L} = \frac{-i\Im\left(M_{12}\right) - \frac{1}{2}\Im\left(\Gamma_{12}\right) \mp \frac{1}{2}\left[M_{11} - M_{22} - \frac{i}{2}\left(\Gamma_{11} - \Gamma_{22}\right)\right]}{m_L - m_S + i(\Gamma_S - \Gamma_L)/2} \equiv \epsilon \pm \delta.$$

CPT violation term

Bell - Steinberger relation (assuming unitarity):

$$\left[\frac{\Gamma_S+\Gamma_L}{\Gamma_S-\Gamma_L} + i\tan\phi_{SW}\right]\left[\frac{\Re(\epsilon)}{1+|\epsilon|^2} - i\Im(\delta)\right] = \frac{1}{\Gamma_S-\Gamma_L}\sum_f A_L(f)A_S^*(f),$$

$A_{L,S}(f) \equiv A(K_{L,S} \to f).$

Tells us about the decay branching ration
(The observable)

$$\varphi_{SW} \equiv \arctan\frac{2(m_L-m_S)}{\Gamma_S-\Gamma_L}$$

Neutrino Oscillation

1. Have a set of oscillation parameters (mixing angles, mass splittings) for neutrinos and another set for antineutrinos

$$P_{\nu_\alpha \to \nu_\beta}(\Delta m^2_{12}, \Delta m^2_{13}, \theta_{12}, \theta_{13}) \qquad \& \qquad P_{\bar{\nu}_\alpha \to \bar{\nu}_\beta}(\Delta \bar{m}^2_{12}, \Delta \bar{m}^2_{13}, \bar{\theta}_{12}, \bar{\theta}_{13})$$

2. Instead of fitting one set of parameters to the oscillation data, fit two

$$\chi^2(\Delta x) = \chi^2(|x - \overline{x}|) = \chi^2(x) + \chi^2(\overline{x}),$$

x: the oscillation parameters

$\Delta x \neq 0$: CPT violation

Note that there as other ways to test CPT by neutrinos (e.g. by neutrino flight time), but we focus here on only the mass difference between particle and antiparticle

Bridging Different Systems

Mass Decomposition of Hadrons

Using energy momentum tension in QCD: $T_{\mu\nu} = \frac{1}{4}\bar{\psi}\gamma_{(\mu}\overleftrightarrow{D}_{\nu)}\psi + F_{\mu\alpha}F_{\nu\alpha} - \frac{1}{4}\delta_{\mu\nu}F^2,$

the QCD Hamiltonian operator, $H_{\rm QCD} = -\int d^3x\, T_{44}(x)$, can be decomposed as:

$$H_{\rm QCD} = H_E + H_g + H_m + H_a \ ,$$

where

$$H_E = \sum_q \int d^3x\, \bar{\psi}_q(\vec{D}.\vec{\gamma})\psi_q \ ,$$ (Kinematic term)

$$H_g = \int d^3x\, \frac{1}{2}(B^2 - E^2) \ ,$$ (Gluon term) Cancel out between hadron and antihadron

✔ $$H_m = \sum_q \int d^3x\, m_q\bar{\psi}_q\psi_q \ ,$$ (Bare quark mass term)

Absorbed by rescaling (difference still comes from quark mass)

$$H_a = \int d^3x \left[\frac{\gamma_m}{4}\sum_q m_q\bar{\psi}_q\psi_q - \frac{\beta(g)}{4g}(B^2 + E^2)\right]$$ (Anomaly term)

These contributions are calculated through *lattice QCD*

(Yi-Bo Yang et al, 1405.4440)

Sensitivity Comparison

- From the Penning trap exp.
  (BASE collaboration, Nature 2022)
  $$\left|\frac{m_{\bar{p}}}{m_p} - 1\right| < 3. \times 10^{-12}$$

- From Kaon oscillation
  (PDG)
  $$|m_{K^0} - m_{\bar{K}^0}| < 4 \times 10^{-16}\,\mathrm{MeV}$$

- From neutrino oscillation
  (Gabriela Barenboim et al, 1712.01714)
  $$\Delta m_{21}^2 - \Delta \bar{m}_{21}^2 < 4.7 \times 10^{-5}\,\mathrm{eV}^2$$
  $$\Delta m_{31}^2 - \Delta \bar{m}_{31}^2 < 3.7 \times 10^{-4}\,\mathrm{eV}^2$$

- Difference parametriztion:
  $\delta_q \equiv m_{\bar{q}} - m_q$ $\quad q = s, d, u$ denote valence quarks
  $\delta_i = \bar{m}_i - m_i$ $\quad i = 2{,}3$ are two heavier neutrino masses, (assuming the lightest one is massless)

- Ratio parametriztion:
  $$r_x \equiv m_{\bar{x}}/m_x$$

- Expansion parametriztion:
  $$m_x = m_0(1+\alpha) \qquad m_{\bar{x}} = m_0(1-\alpha) \longrightarrow \alpha \equiv \left|\frac{m_{\bar{x}} - m_x}{m_{\bar{x}} + m_x}\right| \simeq \left|\frac{\sum_j \delta_j}{2m_x}\right|$$

Assume all δ_j are identical $\longrightarrow$

MAMA	Proton	Kaon	Neutrino
$\lvert\sum_j \delta_j\rvert$ (MeV)	2.8×10^{-9}	4.0×10^{-16}	$(2.7, 3.7) \times 10^{-9}$
δ (MeV)	9.3×10^{-10}	trivial	2.7×10^{-9}
$r - 1$	3.1×10^{-10}	4.5×10^{-18}	$(0.8, 0.4)$
α	1.5×10^{-12}	4.0×10^{-19}	$(0.16, 0.04)$

Implications

What if there is a positive signal from the Penning trap/neutrino experiment within the bounds set by kaon oscillation?

- Different origins of CPT breaking

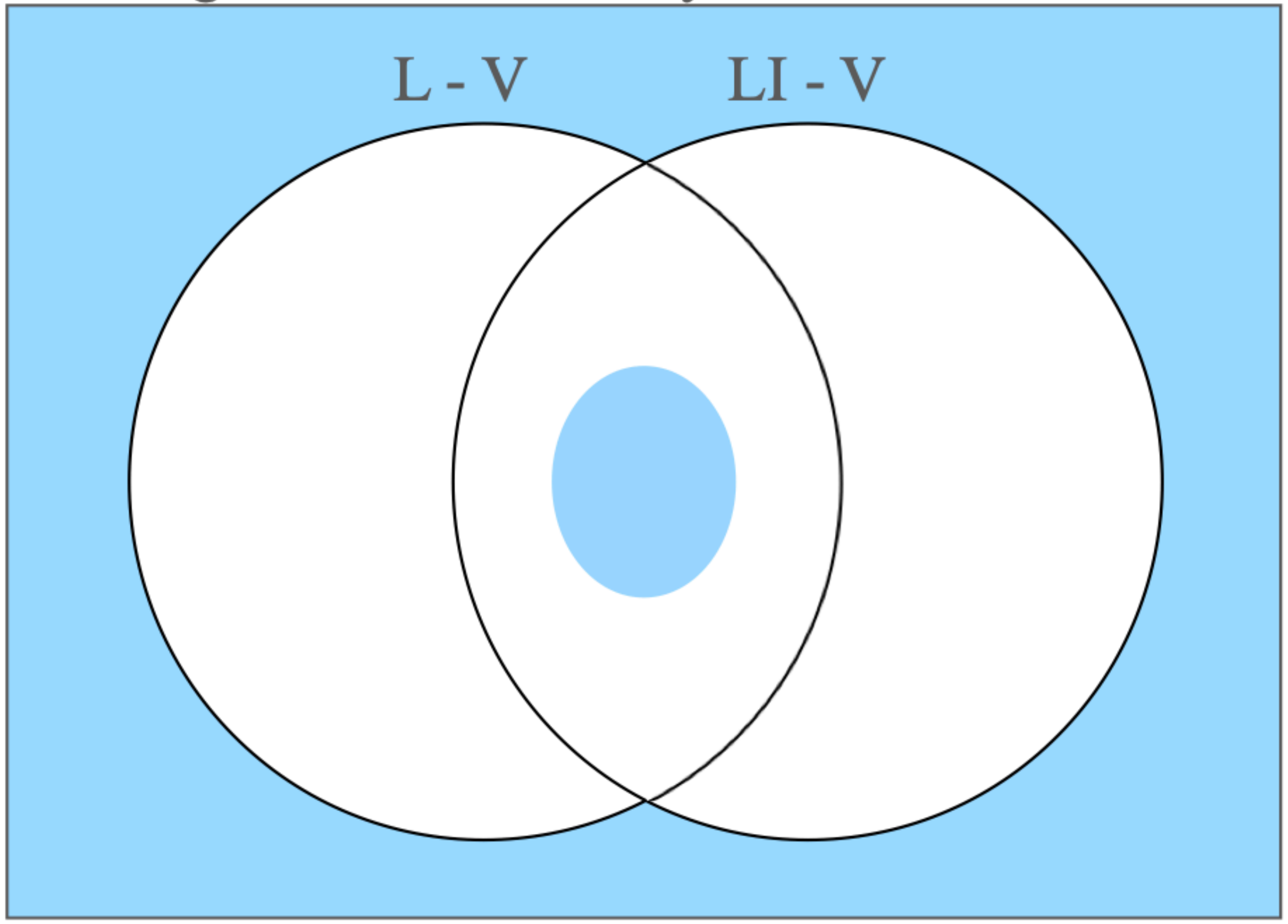
— locality violation, Lorentz Invariance violation, which can be relation in terms of causality:

$$\langle 0|\{\psi_\alpha(x),\, \bar{\psi}_\beta(y)\}|0\rangle\ = 0$$

$$\text{for}\ (x-y)^2 < 0\ .$$

Need investigation in concrete theories (QG, string, composite quark, …) that has L - V and/or LI - V

Blue region: micro-causality *can* be conserved



- Something wrong with our understanding of QCD
- An additional symmetry which sets δ_s (nearly) identical to δ_d

Summary

- The conservation of CPT symmetry is a sacrosanct feature of any local, Lorentz invariant field theory
- By the mass decomposition of hadrons supported by lattice calculations, bounds from kaon oscillation are orders of magnitude above the sensitivity of the BASE collaboration measuring charge-to-mass ratio of protons and antiprotons
- Lay out a road map to possibly disentangle CPT violation in different systems and experiments that measure mass differences between matter and antimatter