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

Ting Cheng

IMPRS - PTFS Seminar

21.09.2023

In collaboration with Manfred Lindner and Manibrata Sen

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

nature

Explore content ⌄ About the journal ⌄ Publish with us ⌄ Subscribe

nature > articles > article

Article | Published: 05 January 2022

A 16-parts-per-trillion measurement of the antiproton-to-proton charge–mass ratio

M. J. Borchert, J. A. Devlin, S. R. Erlewein, M. Fleck, J. A. Harrington, T. Higuchi, B. M. Latacz, F. Voelksen, E. J. Wursten, F. Abbass, M. A. Bohman, A. H. Mooser, D. Popper, M. Wiesinger, C. Will, K. Blaum, Y. Matsuda, C. Ospelkaus, W. Quint, J. Walz, Y. Yamazaki, C. Smorra & S. Ulmer

Nature **601**, 53–57 (2022) |

ELSEVIER

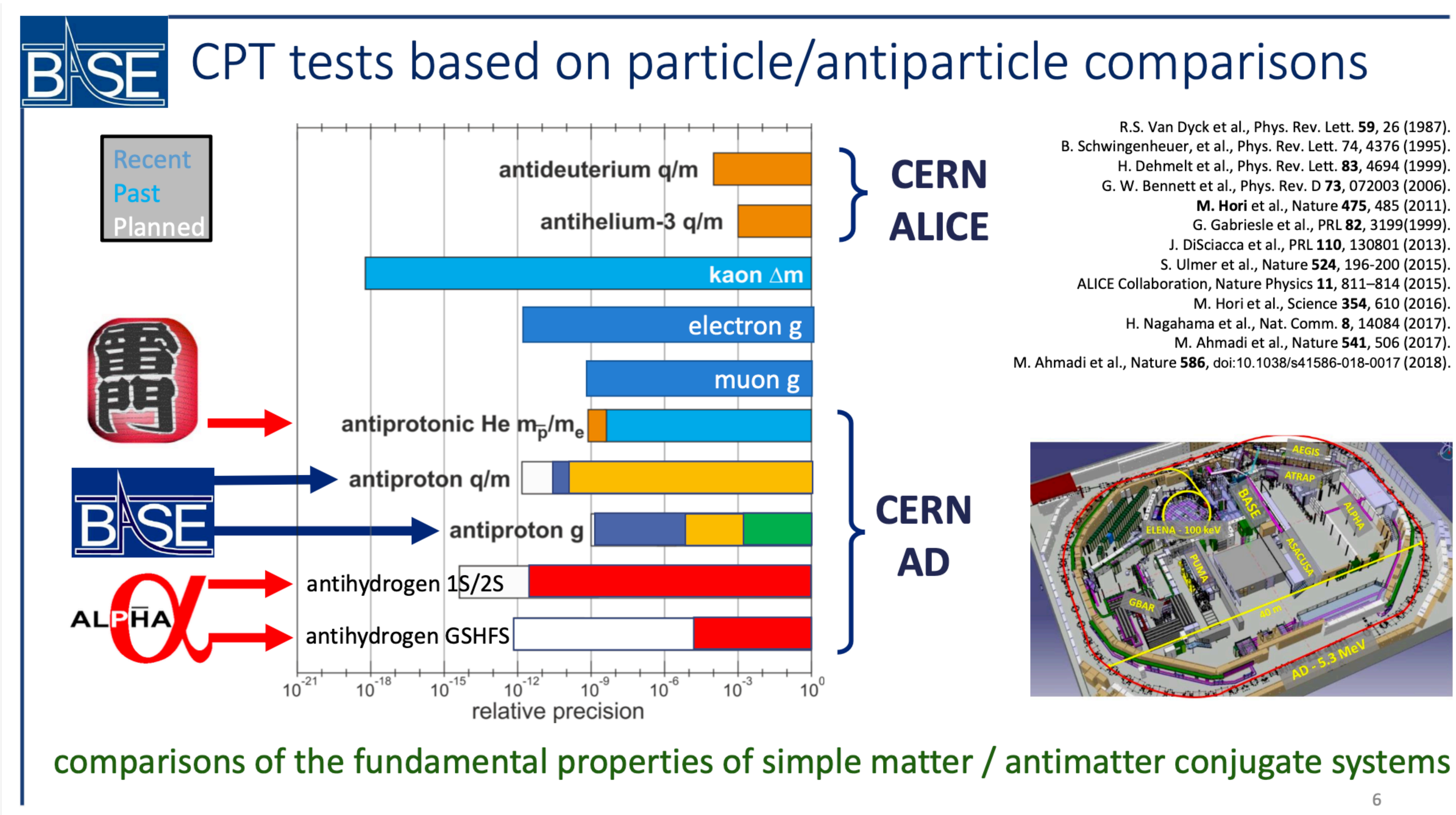
Physics Letters B

Volume 844, 10 September 2023, 138068

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

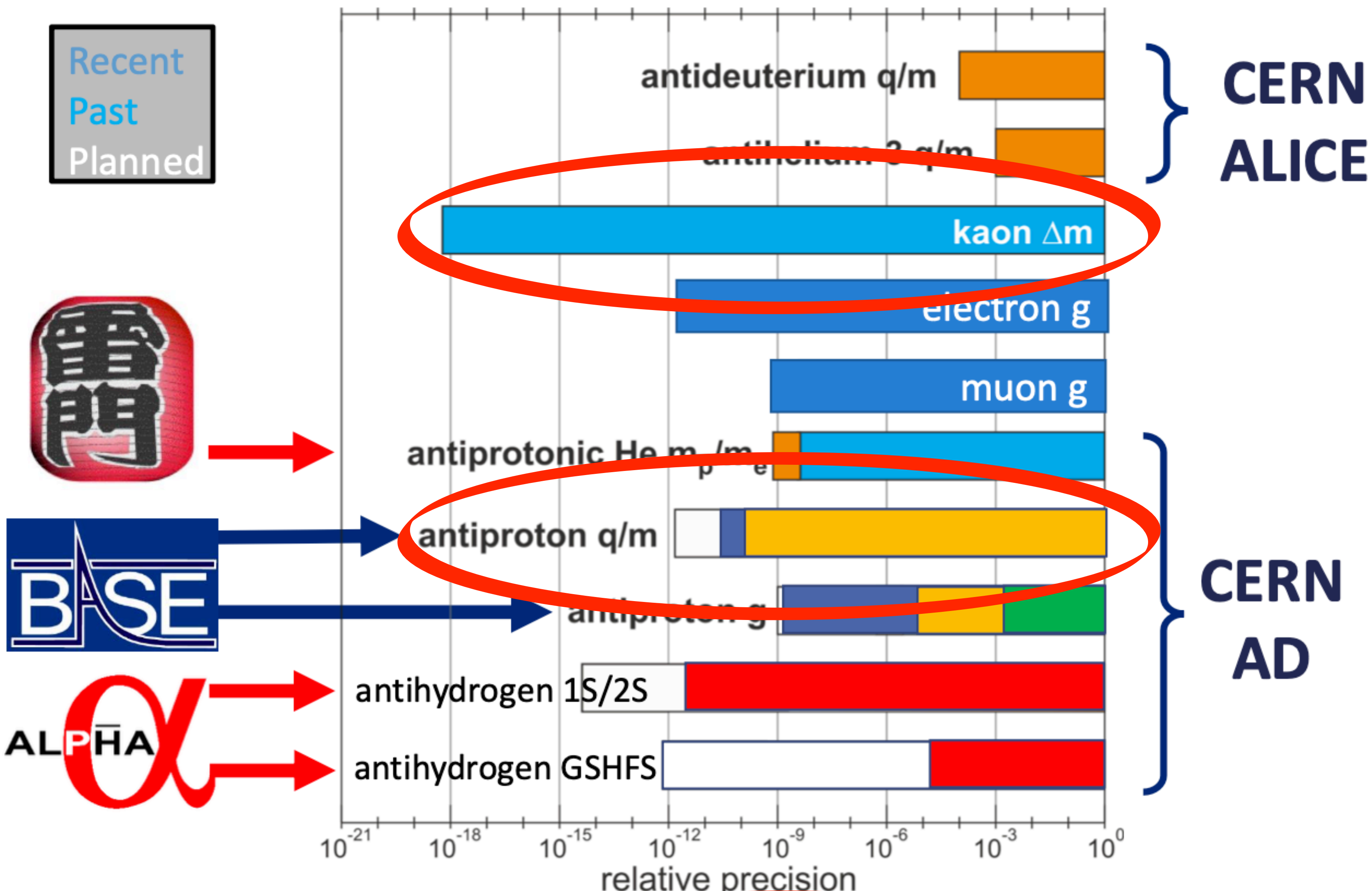
Ting Cheng, Manfred Lindner, Manibrata Sen

Julia Jäger′s slide at the IMPRS retreat on 07.04.2022 :

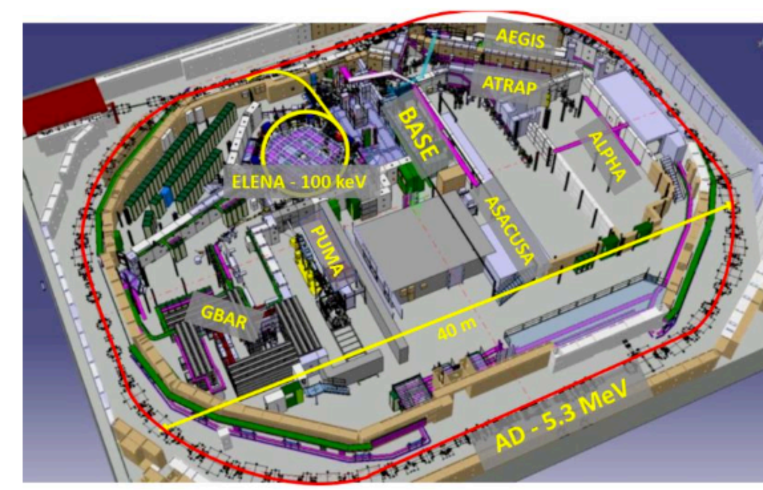


We focus on …

CPT tests based on particle/antiparticle comparisons



R.S. Van Dyck et al., Phys. Rev. Lett. **59**, 26 (1987).
B. Schwingenheuer, et al., Phys. Rev. Lett. 74, 4376 (1995).
H. Dehmelt et al., Phys. Rev. Lett. **83**, 4694 (1999).
G. W. Bennett et al., Phys. Rev. D **73**, 072003 (2006).
M. Hori et al., Nature **475**, 485 (2011).
G. Gabrielse et al., PRL **82**, 3199(1999).
J. DiSciacca et al., PRL **110**, 130801 (2013).
S. Ulmer et al., Nature **524**, 196-200 (2015).
ALICE Collaboration, Nature Physics **11**, 811–814 (2015).
M. Hori et al., Science **354**, 610 (2016).
H. Nagahama et al., Nat. Comm. **8**, 14084 (2017).
M. Ahmadi et al., Nature **541**, 506 (2017).
M. Ahmadi et al., Nature **586**, doi:10.1038/s41586-018-0017 (2018).



Neutrino Oscillation

In general: CPT breaking from matter-antimatter mass asymmetry

CPT-V & MAMA

CPT symmetry

[G. Lüders]

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

[W. Pauli]

Wightman function: $W^{(n)}(x_1, x_2, ..., x_n) = \langle 0|\phi(x_1)\phi(x_2)\cdots\phi(x_n)|0\rangle$

Weak local commutativity: $W^{(n)}(x_1, x_2, ..., x_n) = W^{(n)}(x_n, x_{n-1}, ..., x_1)$

Causality: $\left\langle 0 \middle| [\phi(x), \phi^\dagger(y)] \middle| 0 \right\rangle \to 0$ when x, y are spacelike separated $(x-y)^2 < 0$

[R. Jost]

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

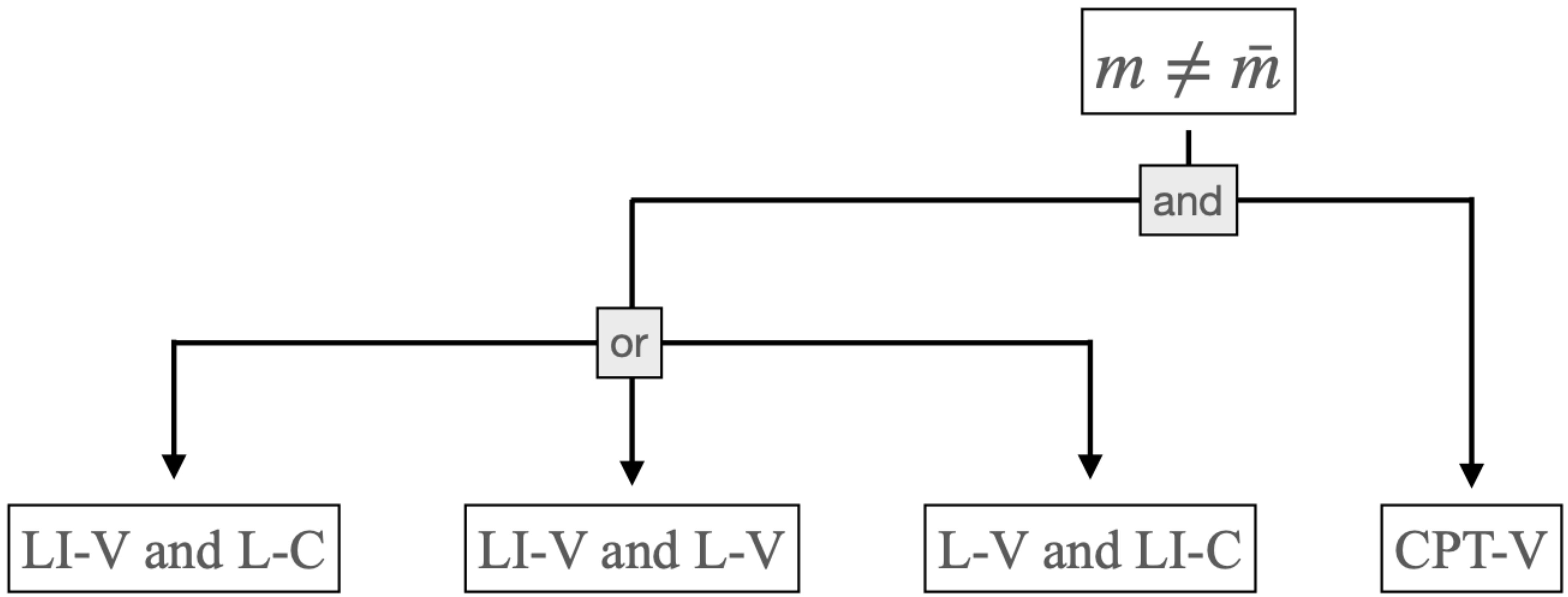
Matter - antimatter mass asymmetry (MAMA)

We believe in

- Local, Lorentz invariant, Hermitian, casual axiomatic field theory
  → CPT conservation (CPT theorem)

Gravity

- CPT conserved → properties of particle = that of its antiparticle (e.g. mass and decay width)



Motivation of CPT symmetry breaking

- Matter v.s. antimatter abundance

  → Sakharov conditions: Baryogenesis
  - Baryon number violation
  - ~~C and CP violation~~
  - ~~Interactions out of thermal equi.~~

- Test fundamental principles

  2022 Nobel Prize: "For experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science"

  Non-locality

  [S. Liberati, 1304.5795]

  In QG: "an underlying Lorentz invariance of the system is not sufficient (and could be not even necessary) in order to provide an almost exact Lorentz invariant physics in the emergent spacetime. "

  Lorentz-invariance violation

- A window to the phenomenology of Planck scale physics through precision tests

Fundamental Principles

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

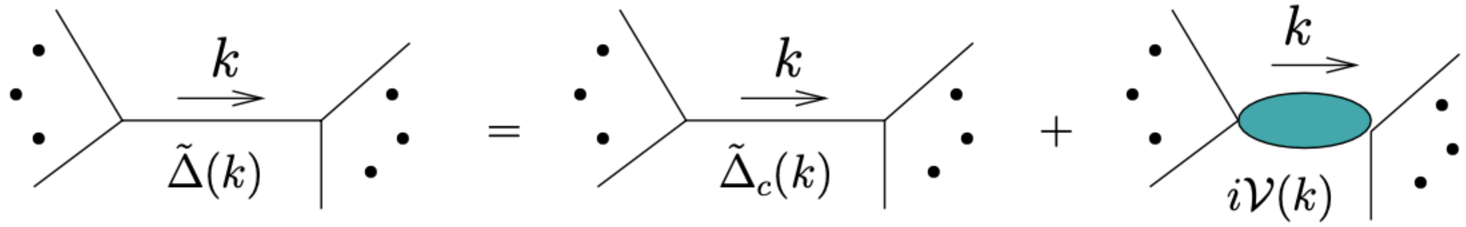
$$\mathscr{L} \to \mathscr{L}' : \; E^2 = m^2 + p^2 + f(p), \qquad \text{SME: } \mathscr{L} \supset \sum_{n=4} \mathscr{O}^{(n)}$$

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

  Non-local interactions:



[E. T. Tomboulis, 1507.00981]

Fundamental Principles

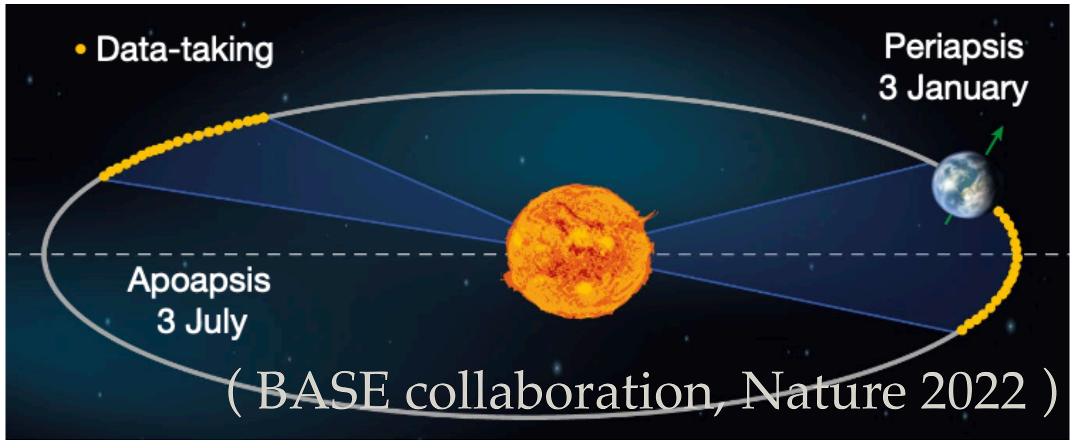
- **Weak equivalence principle**: WEP - free fall, WEP - clock

  Inertia mass ≠ gravitation mass

e.g. Free fall of H^- at alpha

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

"If there was a scalar- or tensor-like gravitational coupling to the energy of antimatter that violates the WEP-clock, there will be, at the same height in a gravitational field, a cyclotron frequency difference"



(BASE collaboration, Nature 2022)

- Causality & Micro-causality

Micro-causality: any two local observables with spacelike separation commute

Causality: arrow of causality, wavefront velocity do not exceed c, breaking of micro-causality arises entirely from inside the bounded kernel support region

[J. Donoghue, G. Menezes, 1908.04170] [T. Hollowood, G. Shore, 0707.2302] [E. T. Tomboulis, 1507.00981]

Experiments testing MAMA

The Penning Trap Experiment @ BASE

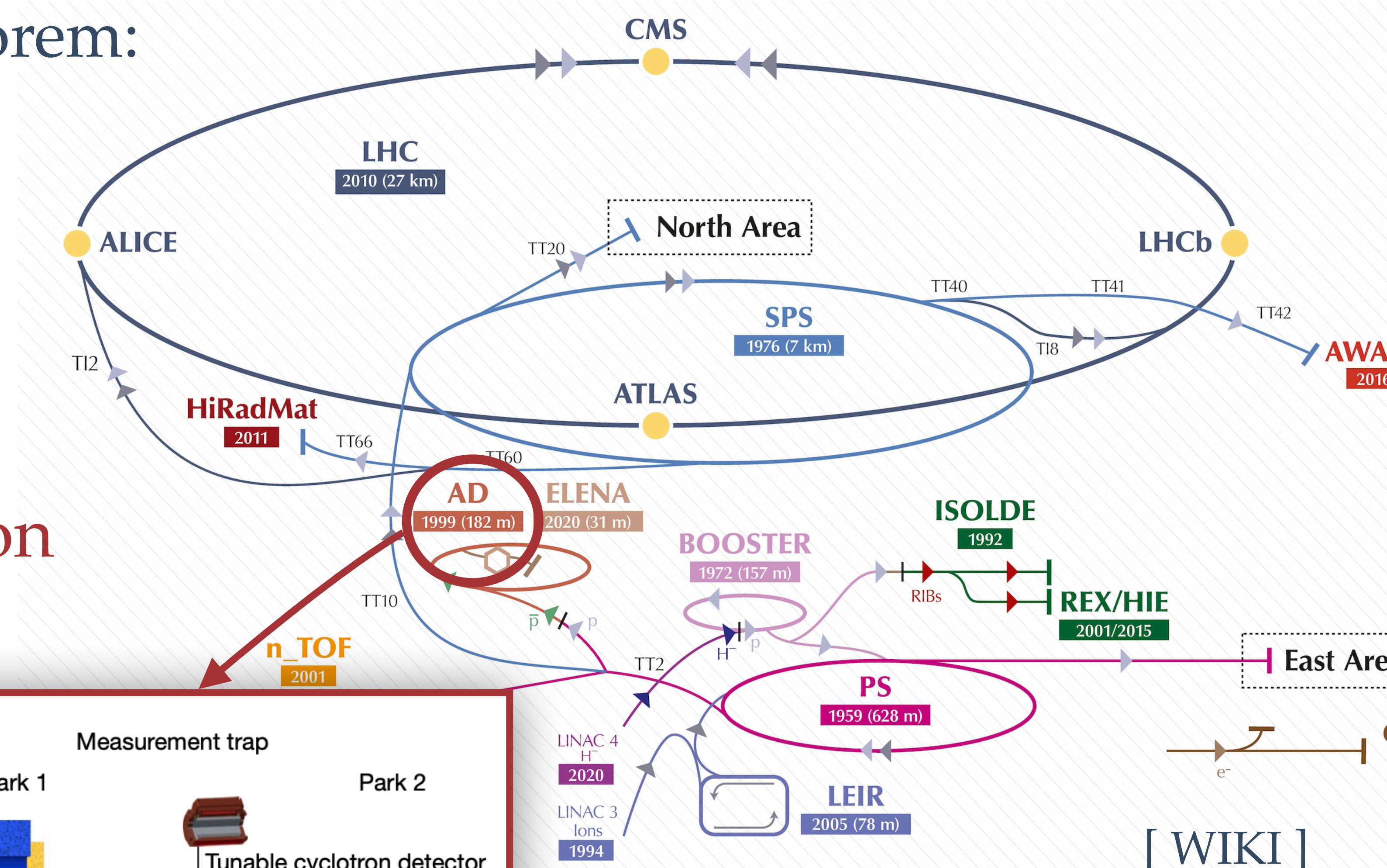
— measure charge-to-mass ratio by the cyclotron frequency

Brown-Gabrielse invariance theorem:

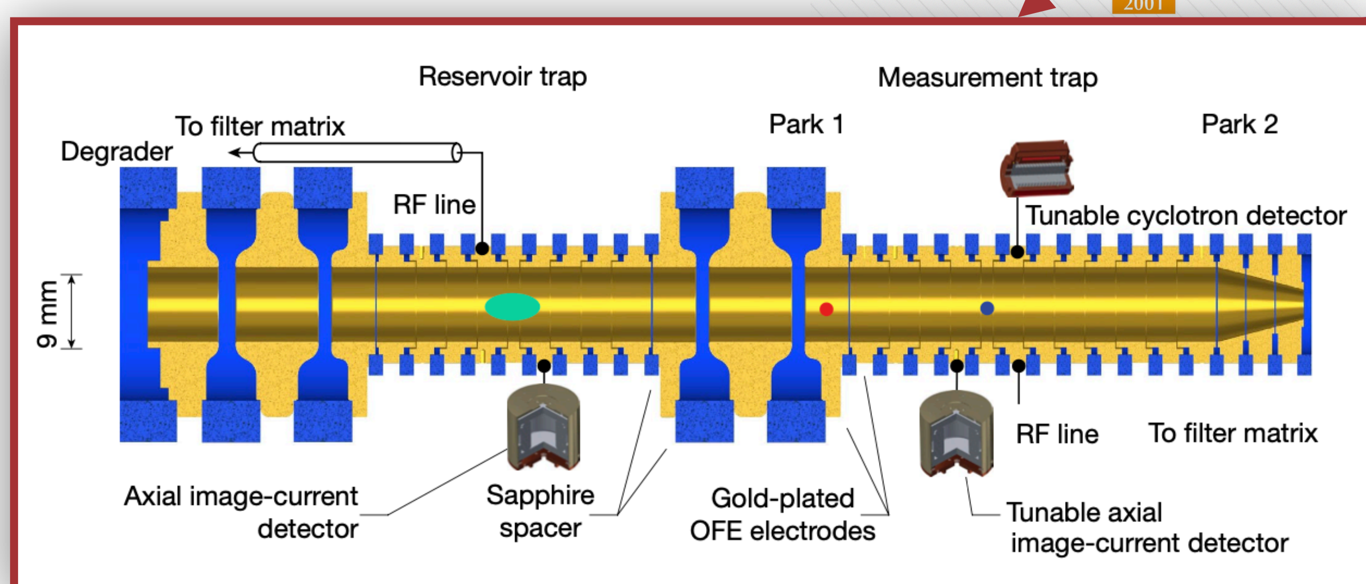
$$\nu_c^2 = \nu_+^2 + \nu_z^2 + \nu_-^2$$

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

For proton (H^-) & antiproton



[WIKI]



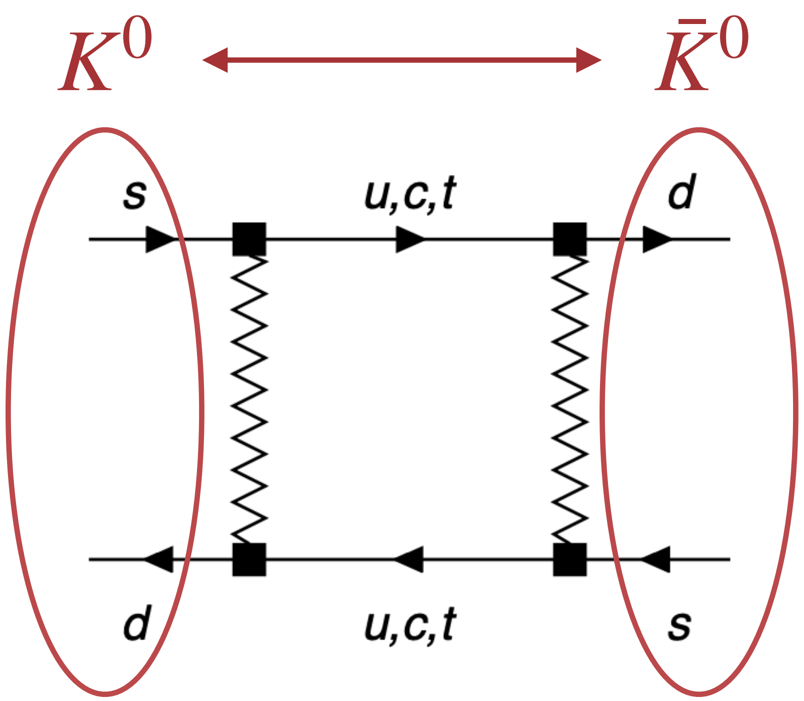
[BASE collaboration, Nature 2022]

Kaon Oscillation

Mixing of neutral kaon - antikaon

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

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



In propagation basis: K-long and K-short

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

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

CPT violation term

Mean lifetime:

K_S: $(8.954 \pm 0.004) \times 10^{-11}$ s

K_L: $(5.116 \pm 0.021) \times 10^{-8}$ s

Kaon Oscillation

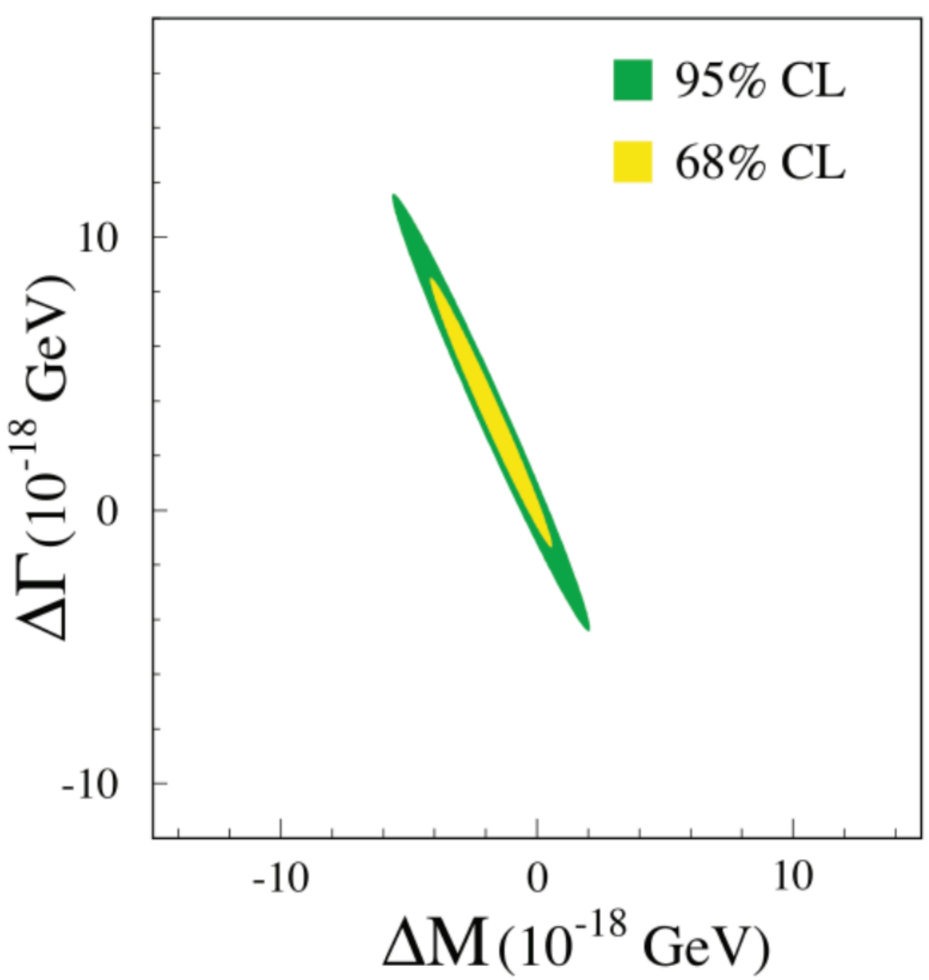
Bell - Steinberger relation (assuming unitarity):

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

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

Tells us about the decay branching ration (The observable)

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



$$\alpha_i \equiv \frac{1}{\Gamma_S}\langle \mathcal{A}_L(i)\mathcal{A}_S^*(i)\rangle = \eta_i\, \mathcal{B}(K_S \to i),$$

$$i = \pi^0\pi^0, \pi^+\pi^-(\gamma), 3\pi^0, \pi^0\pi^+\pi^-(\gamma),$$

Neutrino Oscillation

Parameters: 3 mixing angles + 1 CP phase + 3 mass splittings

Neutrino:

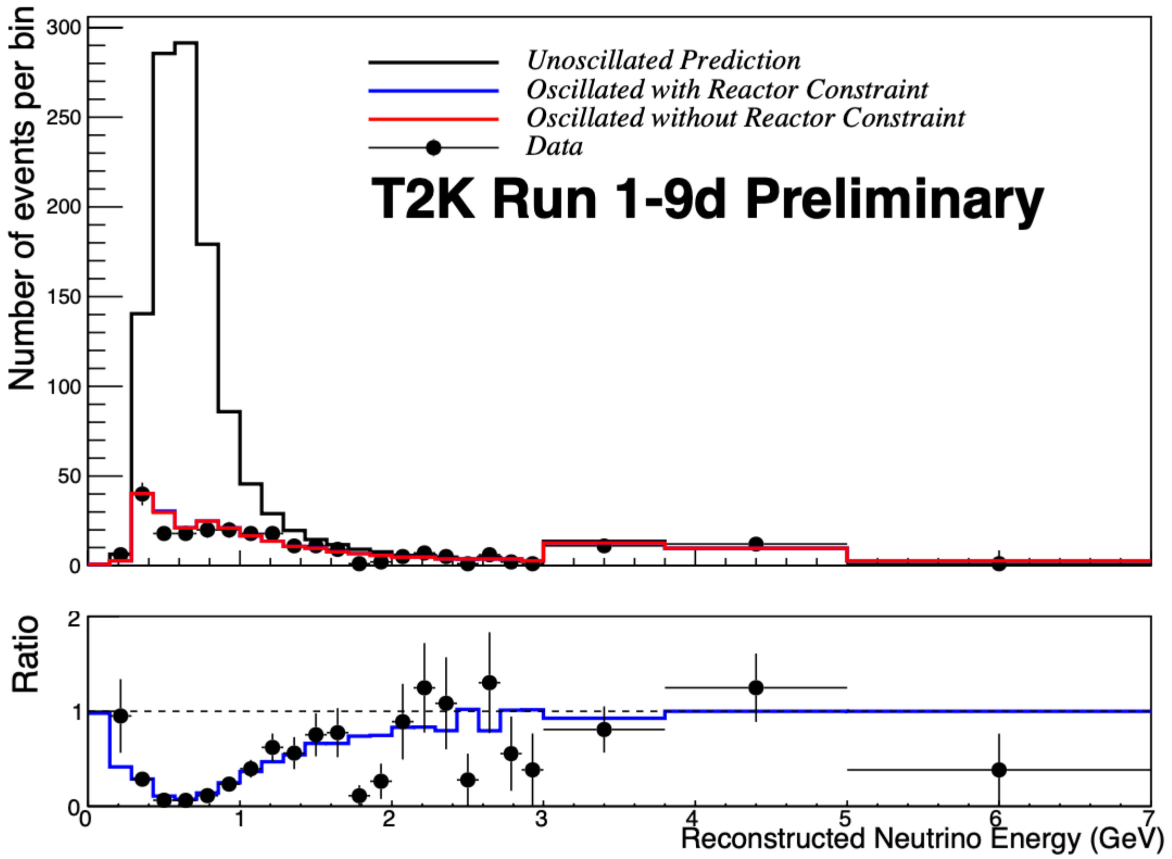
$$P(\nu_\alpha \to \nu_\beta) = \sum_{i,j} U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j} \exp\left[-i \frac{\Delta m^2_{ji}}{2} \frac{L}{E}\right]$$

CPT conserved anti-neutrino:

$$P(\overline{\nu_\alpha} \to \overline{\nu_\beta}) = \sum_{i,j} \left(U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}\right)^* \exp\left[-i \frac{\Delta m^2_{ji}}{2} \frac{L}{E}\right]$$

anti-neutrino:

$$P(\overline{\nu_\alpha} \to \overline{\nu_\beta}) = \sum_{i,j} \left(\overline{U_{\alpha i}} \overline{U^*_{\beta i}} \overline{U^*_{\alpha j}} \overline{U_{\beta j}}\right)^* \exp\left[-i \frac{\Delta \overline{m}^2_{ji}}{2} \frac{L}{E}\right]$$



Neutrino Oscillation

CPT test: Instead of fitting one set of parameters to the oscillation data, fit two

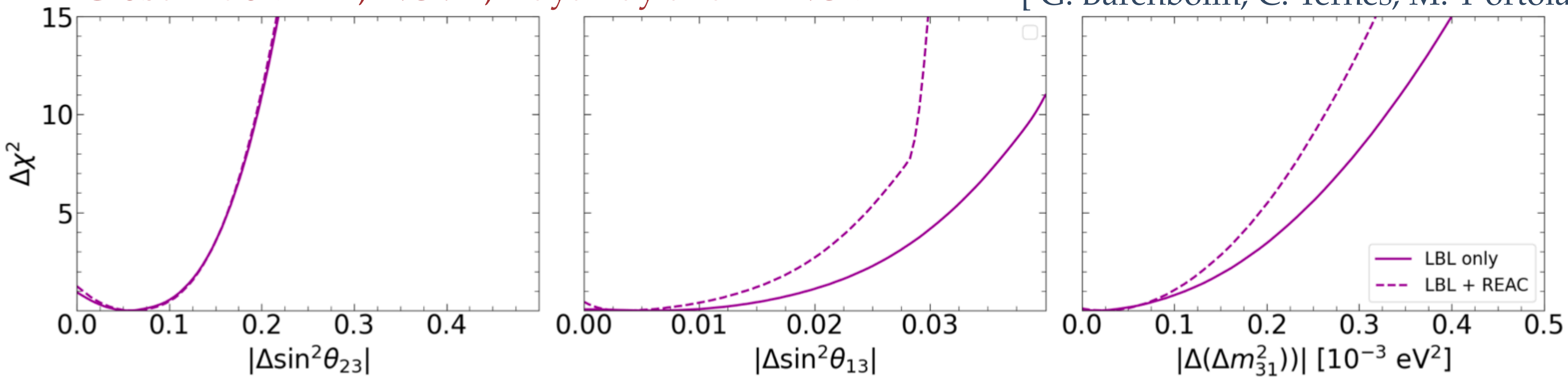
$$\chi^2(\Delta x) = \chi^2(|x - \overline{x}|) = \chi^2(x) + \chi^2(\overline{x}),$$

x: the oscillation parameters

$\Delta x \neq 0$: CPT violation

Global fit of: T2K, NOvA, Daya Bay and RENO :

[G. Barenboim, C. Ternes, M. T′ortola]



* 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

Proton mass $\simeq$ 938 MeV, $2m_d + m_u \simeq 9$ MeV

How much can a CPT violation contribute?
If MAMA $\neq 0$ where can it come from?
How much can be "canceled out"?

Rest Mass of Hadrons

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

rest mass of a single hadron state $|x\rangle$: $m_x = \frac{\langle x|H_{\rm QCD}|x\rangle}{\langle x|x\rangle}$ $\quad H_{\rm QCD} = -\int d^3x\, T_{44}(x)$

CPT transformation $|x\rangle \rightarrow |\bar{x}\rangle$

Determined by quarks

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

[X. Ji, hep-ph/9410274]

Mass Decomposition of Hadrons

Which terms are the same for m_x and $m_{\bar{x}}$ even when CPT is not exact?

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

$$H_g = \int d^3x\, \frac{1}{2}(B^2 - E^2) \;, \quad \text{(Gluon term)}$$

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

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

Calculation through *lattice QCD:*

Proton: 68 % from $H_E + H_g$ [Yi-Bo Yang et al, 1808.08677]

Kaon: 50 - 60 % from $H_E + H_g$ [Yi-Bo Yang et al, 1405.4440]

Parametrization

- Fermion mass difference:

$$\delta_q \equiv m_{\bar{q}} - m_q$$ $q = s, d, u$ denote the quark mass

$$\delta_i = \bar{m}_i - m_i$$ $i = 2{,}3$ are two heavier neutrino masses, (assuming the lightest one is massless)

- Fermion mass ratio:

$$r_x \equiv m_{\bar{q}}/m_q \qquad r_i \equiv \bar{m}_i/m_i$$

- Observable mass expansion:

$$m_x = m_0(1+\alpha)$$
$$m_{\bar{x}} = m_0(1-\alpha)$$

$$\longrightarrow \alpha \equiv \left|\frac{m_{\bar{x}} - m_x}{m_{\bar{x}} + m_x}\right| \simeq \left|\frac{\sum_j \delta_j}{2m_x}\right|$$

Extract CPT-V Contributions

Measurement

Parametrization

$$\left|\frac{m_{\bar{p}}}{m_p} - 1\right| \simeq \begin{cases} \Sigma_q \dfrac{C_q \delta_q}{m_p} & \text{Fermion mass difference parametrization} \\ (r-1)\,\Sigma_q \dfrac{C_q m_q}{m_p} & \text{Fermion ratio difference parametrization} \end{cases}$$

Mass decomposition

$$C_q = \langle P|\bar{\psi}_q \psi_q|P\rangle$$

- Directly by the *lattice* calculation of the isovector scalar charge
- Pion-nucleon scattering experiments

$$\sigma_{\pi N} = (m_d + m_u)/2\langle N|\bar{\psi}_u \psi_u + \bar{\psi}_d \psi_d|N\rangle.$$

Feynman-Hellmann relation: $\dfrac{\partial m_N}{\partial m_q} = \langle N(k,s)\,|\,\bar{\psi}_q \psi_q\,|\,N(k,s)\rangle$

Comparison of Experiments

- 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)

$$\Delta m^2_{21} - \Delta \bar{m}^2_{21} < 4.7 \times 10^{-5}\,\mathrm{eV}^2 \qquad \Delta m^2_{31} - \Delta \bar{m}^2_{31} < 3.7 \times 10^{-4}\,\mathrm{eV}^2$$

MAMA	Proton	Kaon	Neutrino
$\lvert\sum_j \delta_j\rvert$ (MeV)	$\mathcal{O}(10^{-10} - 10^{-9})$	$\mathcal{O}(10^{-16})$	$\mathcal{O}(10^{-9})$
δ (MeV)	$\mathcal{O}(10^{-10} - 10^{-9})$	trivial	$\mathcal{O}(10^{-9})$
$r - 1$	$\mathcal{O}(10^{-11} - 10^{-10})$	$\mathcal{O}(10^{-18})$	$\mathcal{O}(10^{-1})$
α	$\mathcal{O}(10^{-12})$	$\mathcal{O}(10^{-19})$	$\mathcal{O}(10^{-2})$

Assume all δ_j are identical

Implications

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

- Locality vs Lorentz invariance → Disentangled if micro-causality is not exact

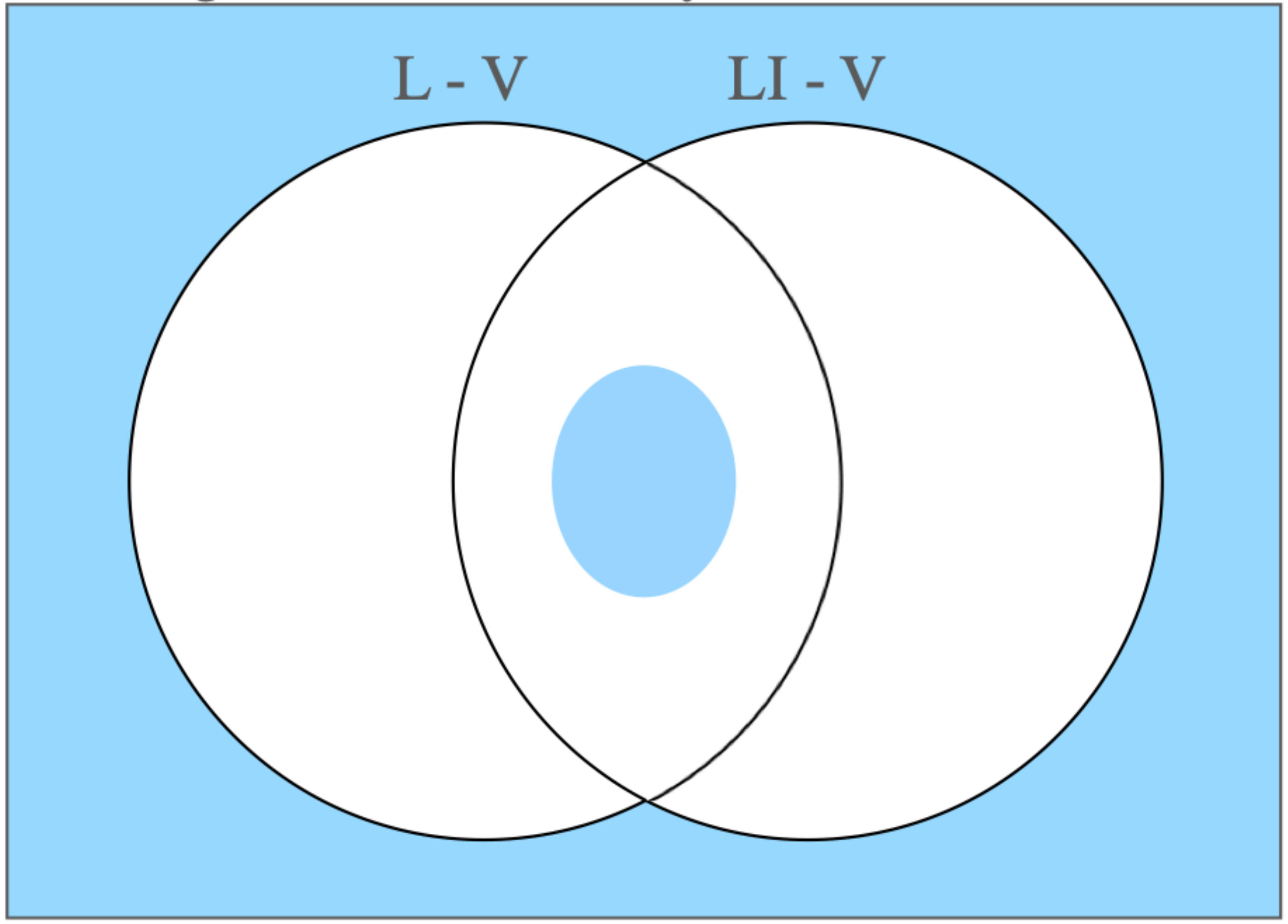
- An additional symmetry which sets δ_s (nearly) identical to δ_d

- Something wrong with our understanding of QCD

- Spin dependence on rest mass

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

Blue region: micro-causality *can* be conserved



Summary

- CPT symmetry breaking indicates a violation of locality and Lorentz invariant in any Hermitian and causal field theory

- Under premises: "CPT symmetry features hadron's rest mass holds", "the mass decomposition of hadrons applies" bounds from kaon oscillation are orders of magnitude above other MAMA-testing experiments

- Lay out a road map to possibly disentangle CPT violation in different systems and experiments that measure mass differences between matter and antimatter

Outlook

- Different systems may be sensitive to different principles
  e.g. traveling distance — Lorentz invariance violation
  number of vertices — non-locality

- Correlation of different principle-violations through (micro-)causality

- Correlate more experiments, such as
  1. CPT testing experiments beyond mass and/or rest frame
     e.g. magnetic moment, transition frequency, life-time measurements

  2. Principle testing experiments
     e.g. Non-locality by quantum decoherence, [D. Karamitros et al, 2208.10425]
     WEP breaking by GW observation, [H.J. Kuan et al, 2203.03672]
     Lorentz invariance violation by neutrino flight time. [S. Liberati, 1304.5795]

- Model/theory testing