Search for CPT symmetry violation in neutral flavour meson oscillations

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On behalf of the LHCb collaboration

From Vacuum to the Universe
Humboldt Kolleg 28.06 2016

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Poland

CPT symmetry

CPT is the combination of discrete transformations:

- Charge conjugation (particle $\rightarrow$ antiparticle)
  $\hat{\mathrm{C}}|\vec{r}, t, q >= e^{i\alpha_1}|\vec{r}, t, -q >$
- Parity (spatial reflection)
  $\hat{\mathrm{P}}|\vec{r}, t, q >= e^{i\alpha_2}| - \vec{r}, t, q >$
- Time reversal
  $\hat{\mathrm{T}}|\vec{r}, t, q >= e^{i\alpha_3} < \vec{r}, -t, q|$

$\alpha_1, \alpha_2, \alpha_3$ are real phases.

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All laws of physics seem to be unchanged under CPT transformation.

Experimental searches of CPT violation

Phenomenological consequences of CPT symmetry: equality of particle/antiparticle masses, lifetimes, partial decay widths of mutually CPT-coupled channels etc.

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Precise tests of particle and antiparticle properties:

- positronium spectroscopy,
- experiments on beams of $\mu^+, \mu^-, \pi^+\pi^-$ in vacuum,
- antihydrogen spectroscopy (see Gerald Gabrielse's talk, Wed 29.06 at 10),
- ...
- mixing of neutral mesons.

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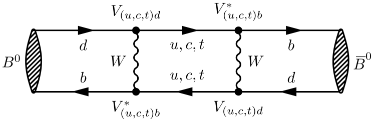
Interference effects in neutral flavour meson oscillation provide experimental precision reaching the Planck scale
e.g. -4.0×10^{-19} GeV $< m_{K^0} - m_{\bar{K}^0} < 4 \times 10^{-19}$ GeV at 95 % C.L.
Particle Data Group 2015 - http://pdg.lbl.gov/2015/reviews/rpp2015-rev-cpt-invariance-tests.pdf

Oscillation phenomena

Weak interactions do not conserve the flavour



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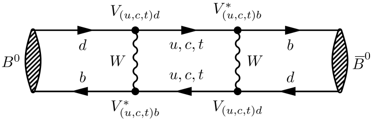

$|P^0\rangle, |\bar{P^0}\rangle$ are not eigenvectors of the full Hamiltonian

$$\frac{\partial}{\partial t}|\Phi >= H|\Phi >, \quad (1)$$

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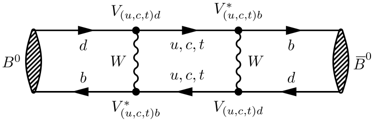

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Mass states with given lifetimes (e.g. K_L, K_S) and not flavour eigenstates (e.g.$K^0, \bar{K^0}$)

$$\omega_{H,L} = m_{H,S} - \frac{i}{2}\Gamma_{H,L} \quad (2)$$

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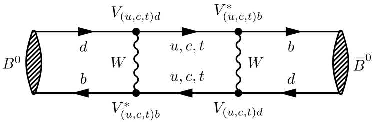

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The neutral mesons oscillate back and forth in time between its particle and antiparticle states.

Weisskopf-Wigner approach

$$|\Phi>= a(t)|P^0> +b(t)|\bar{P^0}> \tag{3}$$

$$\frac{\partial}{\partial t}|\Phi>= H|\Phi>, \tag{4}$$

- effective 2x2 Hamiltonian,
- time-independent,
- weak interactions treated as perturbation (non-diagonal elements),
- non-Hermitian since decays outside of the $|P^0>, |\bar{P^0}>$ subspace,

$$H = M - \frac{i}{2}\Gamma, \tag{5}$$

M and Γ are hermitian matrices (mass and decay matrix, respectively).

CPT parameterization

$$|P_L\rangle = p\sqrt{1-z}|\mathrm{P}^0\rangle + q\sqrt{1+z}|\bar{\mathrm{P}}^0\rangle$$
$$|P_H\rangle = p\sqrt{1+z}|\mathrm{P}^0\rangle - q\sqrt{1-z}|\bar{\mathrm{P}}^0\rangle \ , \qquad (6)$$

$$z = \frac{\delta m - \frac{i}{2}(\delta\Gamma)}{\Delta m - \frac{i}{2}\Delta\Gamma}, \qquad (7)$$

where:

- $\delta m = M_{11} - M_{22}$ and $\delta\Gamma = \Gamma_{11} - \Gamma_{22}$,
- $\Delta m = m_H - m_L$ and $\Delta\Gamma = \Gamma_H - \Gamma_L$ (small in neutral flavour mesons !!!)

- Conservation of CP or CPT: $z = 0$
- Conservation of CP or T: $|\frac{q}{p}| = 1$

Back to the 'ether' concept ? - Lorentz symmetry breaking

Greenberg theorem [PRL 89 (2002) 231602]

CPT violation implies Lorentz symmetry violation

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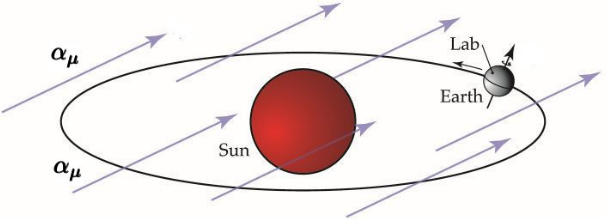


The vacuum state is anisotropic in space which violates rotational invariance (Lorentz symmetry)

R. Lehnert Frascati Phys.Ser. 43 (2007) 131-154, MIT-CTP-3786 http://arxiv.org/abs/hep-ph/0611177

Lorentz symmetry violation introduces dependence of the particle boost and momentum direction.

Standard Model Extension(SME)

- Theoretical framework to test CPT violation in broad classes of experiments (Kostelecky, PRD55 (1997) 6760),
- Effective QFT with components breaking Lorentz and CPT symmetries,
- All properties of "good" QFT remain (renormalization, locality, spin-statistics relation, etc.);

$$z \simeq \frac{\beta^{\mu} \Delta a_{\mu}}{\Delta m - i \Delta \Gamma / 2}, \tag{8}$$

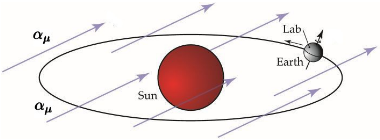
$\beta^{\mu} = \gamma(1, \vec{\beta})$ meson four-velocity in the observer frame

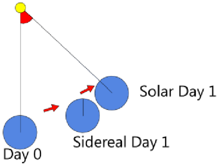
$$\Delta a_{\mu} \simeq a_{\mu}^{q_1} - a_{\mu}^{q_2}$$

a_{μ} valence quark coupling to Lorentz-violating field
(maybe expressed in some more fundamental physics beyond SME)

Sidereal modulations

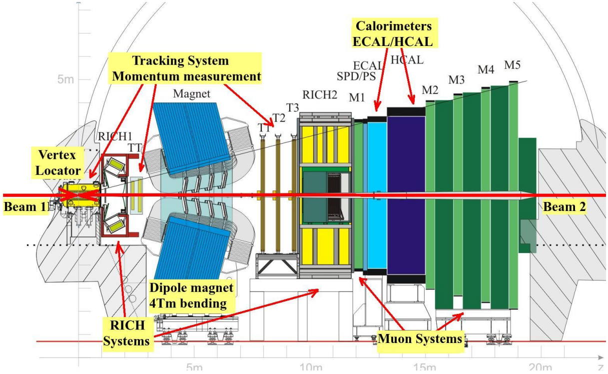
CPT-violating observable z undergoes sidereal modulations, and depends on the geographical location of the detector.





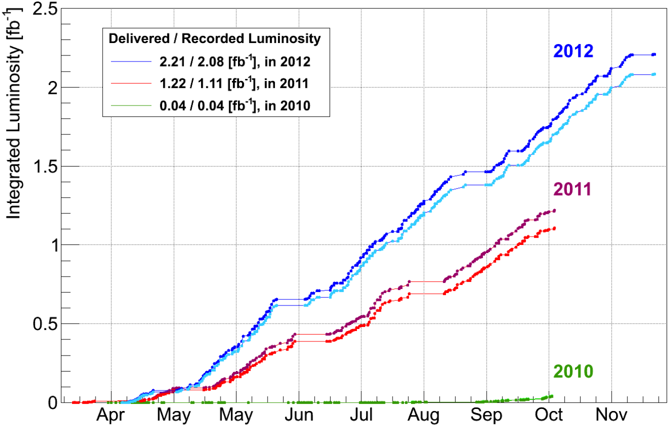
- $\Phi_{sid} = \Omega\hat{t} = \Omega t_{GPS} + \Phi^0_{sid}$
- Sidereal angular frequency: $\Omega = \frac{2\pi}{T_{sid}} = 7.292 \times 10^{-11}$ rad μs^{-1}
- $T_{sol} = 86400s$
- $T_{sid} \approx \frac{365.25}{366.25} T_{sol} = 86164.1s$

Large Hadron Collider beauty Detector



- Single-arm forward spectrometer covering range: $2 < \eta < 5$ ($10 < \theta < 300$ (250) mrad)
- Momentum resolution: $\frac{\Delta p}{p} = 0.5\%$ at 5GeV/c to 1 % at 200 GeV/c
- Impact parameter resolution: 20 μm for high p_T tracks

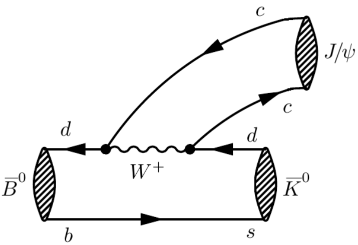
Run I luminosity



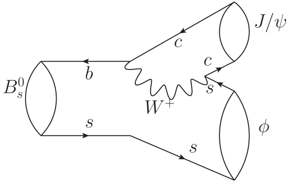
Time-dependent analyses in beauty sector

- Time-dependent analyses based on data gathered in 2011 and 2012 ($3\,\text{fb}^{-1}$, pp @7 TeV and @8 TeV respectively).
- Both decays to CP final state (sensitivity to Re(z), In SME: $|\frac{Re(z)}{Im(z)}| >> 1$)
  J. van Tilburg and M. van Veghel PLB 742 (2015) 236

- $B^0 \to J/\Psi K^0_S$
- CP odd final state
- time-dependent fit



- $B^0_s \to J/\Psi\Phi$
- $P \to VV$
- $S = 0 \to S = 1, S = 1$
- Mixture of CP odd and CP even final states
- time and angular dependent fit



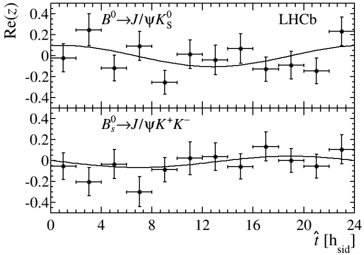
Results for $B^0 \to J/\Psi K_S^0$ and $B_s^0 \to J/\Psi \Phi$

$$Re(z) = \frac{\gamma}{\Delta m}[\Delta a_0 + \beta \Delta a_Z \cos\chi + \beta \sin\chi(\Delta a_Y \sin\Omega\hat{t} + \Delta a_X \cos\Omega\hat{t})].$$

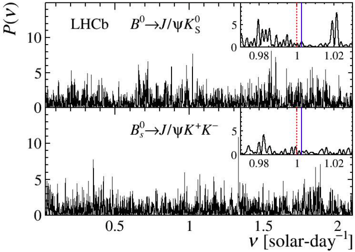
- Ω and $\hat{t}$ - sidereal frequency and time respectively,
- Due to the LHCb geographical location: $\cos\chi = -0.38$ (const term), $\sin\chi = 0.92$ (sidereal modulated term)

PRL 116 (2016) 241601:

$\mathrm{Re}(z)$ as a function of sidereal phase



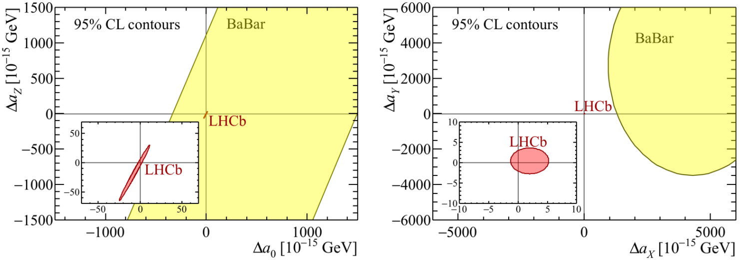
Periodogram analysis



Comparison with BaBar

LHCb - PRL 116 (2016) 241601: $B^0 \to J/\Psi K^0_S$

$\Delta a_0 - 0.38\Delta a_z = -0.10 \pm 0.82 \pm 0.54 \times 10^{-15}$ GeV,
$0.38\Delta a_0 + \Delta a_z = -0.20 \pm 0.22 \pm 0.004 \times 10^{-13}$ GeV,
$\Delta a_x = 1.97 \pm 1.30 \pm 0.29 \times 10^{-15}$ GeV,
$\Delta a_y = 0.44 \pm 1.26 \pm 0.29 \times 10^{-15}$ GeV,

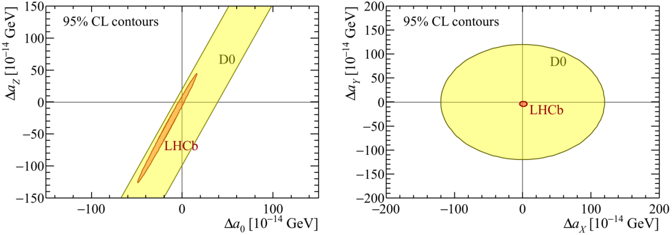


- BaBar used inclusive dilepton B decays (PRL 100 (2008) 131801),
- Much smaller boost comparing to LHCb (0.5 vs 20),
- New LHCb result 1000 more precise than BaBar result.

Comparison with D0

LHCb - PRL 116 (2016) 241601:$B_s^0 \to J/\Psi\Phi$

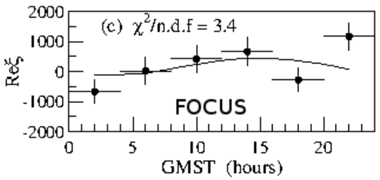
$\Delta a_0 - 0.38\Delta a_z = -0.89 \pm 1.41 \pm 0.36 \times 10^{-14}$ GeV,
$0.38\Delta a_0 + \Delta a_z = -0.47 \pm 0.22 \pm 0.08 \times 10^{-12}$ GeV,
$\Delta a_x = 1.01 \pm 2.08 \pm 0.71 \times 10^{-14}$ GeV,
$\Delta a_y = 3.83 \pm 2.09 \pm 0.71 \times 10^{-14}$ GeV,
$\mathrm{Re}z = -0.022 \pm 0.033 \pm 0.003$ (Without assumption on Lorentz breaking),
$\mathrm{Im}z = -0.004 \pm 0.011 \pm 0.002$ (Without assumption on Lorentz breaking)



- D0 used semileptonic B decays (PRL 115 (2015) 161601),
- Much smaller boost comparing to LHCb (4.7 vs 20),
- New LHCb result 10 more precise than D0 result.

Neutral charm sector

- Upper limit in the charm sector from FOCUS (PLB 556 (2003)7),
- $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$, both in classical and SME approach,
- $\mathrm{Re}(\, z \,) - \mathrm{Im}(\, z \,) \approx O(1)$,
- $\Delta a_\mu \approx 3 \times 10^{-13}$ GeV,



LHCb perspectives based on 2011 and 2012 data (3 fb^{-1}):

- Much higher statistics: $N_{LHCb} = 65 \times 10^6$ vs $N_{FOCUS} = 35 \times 10^3$,
- Similar boost
- Improvement by factor ≈44 (statistics).

Summary

The LHCb provides new CPT limits in the beauty sector:

- The most precise limits for B^0 and B_s^0 provided,
- Classical limit for $\mathrm{Re}(z)$ and $\mathrm{Im}(z)$ in B_s^0 established for the first time.

- KLOE: $K^0 : \Delta a_0, \Delta a_{X,Y,Z} \approx 10^{-18}$ GeV
- FOCUS:$D^0 : \Delta a_0, \Delta a_{X,Y,Z} \approx 10^{-13}$ GeV
- LHCb: $B^0 : \Delta a_0, \Delta a_Z \approx 10^{-15}$ GeV, $\Delta a_X, \Delta a_Y \approx 10^{-15}$ GeV
- LHCb: $B_s^0 : \Delta a_0, \Delta a_Z \approx 10^{-12}$ GeV, $\Delta a_X, \Delta a_Y \approx 10^{-14}$ GeV

Outlook

- In the charm sector current limits can be improved with already collected LHCb data,
- In the beauty sector, by exploiting the decays to flavour-specific states, the improvement in $\mathrm{Im}(z)$ is possible,
- New data from Run II:
  - expected data sample of about $5\,\mathrm{fb}^{-1}$,
  - energies from @7, @8 TeV to @13 TeV,
  - larger boost by a factor of 30 %.

THANK YOU FOR YOUR ATTENTION

BACKUP SLIDES

BACKUP SLIDES

Time evolution starting from a given flavour state

At $t = 0$:

$$|\mathrm{P}^0\rangle = \frac{1}{2p}(\sqrt{1-z}|P_L\rangle + \sqrt{1+z}|P_H\rangle) \quad (9)$$

The time evolution will be given by:

$$|\mathrm{P}^0(t)\rangle = \frac{1}{2p}(\sqrt{1-z}e^{-iM_Lt}e^{-\Gamma_Lt}|P_L\rangle + \sqrt{1+z}e^{-iM_Ht}e^{-\Gamma_Ht}|P_H\rangle) \quad (10)$$

which can be expressed again in $|\mathrm{P}^0\rangle, |\bar{\mathrm{P}}^0\rangle$ base:

$$|\mathrm{P}^0(t)\rangle = g_+(t) + zg_-(t)|\mathrm{P}^0\rangle - \frac{q}{p}\sqrt{1-z^2}g_-(t)|\bar{\mathrm{P}}^0\rangle, \quad (11)$$

where: $g_\pm(t) = \frac{1}{2}(e^{-iM_Ht}e^{-\Gamma_Ht} \pm e^{-iM_Lt}e^{-\Gamma_Lt})$.

CP,T, CPT in z, p, q language

- Conservation of CP or CPT: $z = 0$
- Conservation of CP or T: $|\frac{q}{p}| = 1$

CPT is conserved when:

1. CP, and T is conserved ($z = 0$, $|\frac{q}{p}| = 1$)
2. no CP nor T are conserved ($z = 0$, $|\frac{q}{p}| \neq 1$)

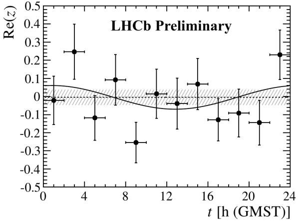
CPT is not conserved when:

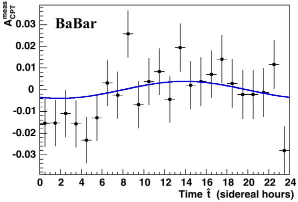
1. CP is not conserved and T is conserved ($z \neq 0$, $|\frac{q}{p}| = 1$)
2. CP is conserved and T is not conserved ($z = 0$, $|\frac{q}{p}| = 1$)
3. no CP nor T are conserved ($z \neq 0$, $|\frac{q}{p}| \neq 1$)

One cannot experimentally distinguish between CPT conserved or violated if $z = 0$, $|\frac{q}{p}| = 1$.

Results for $B^0 \to J/\Psi K_S^0$

LHCb (PRL 116 (2016) 241601)

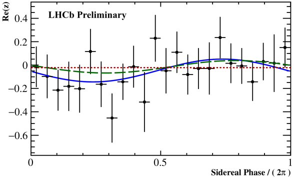


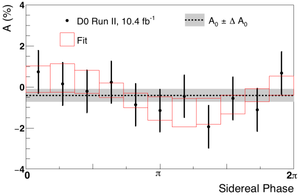


BaBar PRL 100, 131802 (2008)

$\Delta a_0 - 0.30\Delta a_z = 0.6 \pm 0.5 \times 10^{-14}$ GeV,
$\Delta a_x = 4.2 \pm 1.3 \times 10^{-14}$ GeV,
$\Delta a_y = 2.6 \pm 2.5 \times 10^{-14}$ GeV,

Results for $B_s^0 \to J/\Psi\Phi$



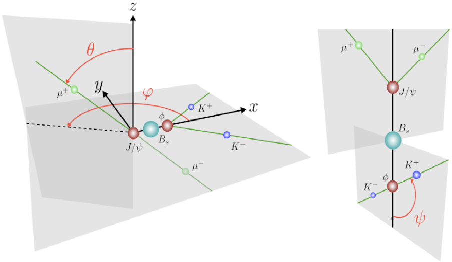


D0: $B_s^0 \to \mu^{\pm} D_s^{\mp}$ PRL 115, 161601 (2015)

$a_{perpend} < 1.2 \times 10^{-12}$ GeV,
$-0.8 < \Delta a_0 - 0.396\Delta a_z < 3.9 \times 10^{-13}$ GeV,

Angular analysis of $B_s^0 \to J/\Psi\Phi$

The four polarization states can be separated statistically by measurement of three angles



$$\frac{d\Gamma}{d^3\vec{\Omega}dt} = \sum_{k=1}^{10} h_k(t) \times f_k(\vec{\Omega})$$

CP, T and CPT symmetry

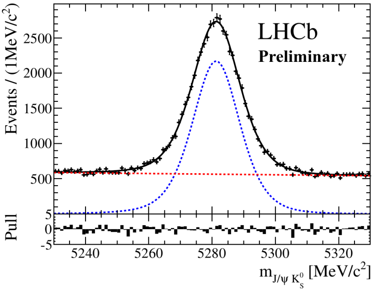
Conditions for H elements assuming CP/T/CPT symmetry:

$$[H, U] = 0 \leftrightarrow U^{-1}HU = H \tag{12}$$

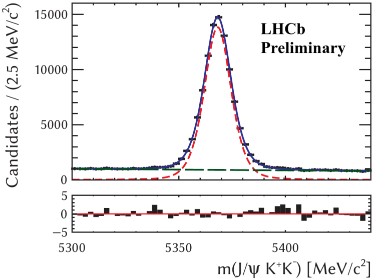
- Conservation of CP or CPT:
  $H_{11} = H_{22} \rightarrow M_{11} = M_{22}$, $\Gamma_{11} = \Gamma_{22}$.
  (Equality of masses and decay rates)
- Conservation of CP or T: $|H_{12}| = |H_{21}|$.

Two analyses in beauty sector II

- $B^0 \to J/\Psi K^0_S$
- $N_{events} = 41500$
- Likelihood fit : 9 observables



- $B^0_s \to J/\Psi \Phi$
- $N_{events} = 96000$
- Likelihood fit : 9 observables +2 angles



Oscillation phenomenology

Mixing parameters

$\Delta m = m_H - m_L$ and $\Delta\Gamma = \Gamma_H - \Gamma_L$, $x = \frac{\Delta m}{\Gamma}$, $y = \frac{\Delta\Gamma}{2\Gamma}$
$K^0 : x \approx 1, y \approx -1$, $D^0 : x \approx 0.005, y \approx 0.008$,
$B^0 : x \approx 0.77, y \approx 0$, $B_s^0 : x \approx 25, y \approx 0.05$,