Search for CPT symmetry violation in neutral flavour meson oscillations

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High Energy Physics Seminar
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Symmetries in physics

Role of symmetries:

- Simplify the description of phenomena,
- Relation between symmetries and conservation of laws (e.g. Noether theorem),
- Symmetry as a methodological indication,
- Symmetries constraining dynamical laws,
- Symmetry breaking e.g. chiral fields, origin of mass, flavour physics ...

It is only slightly overstating the case to say that physics is the study of symmetry

P.W. Anderson, Science, New Series, Vol.177,no.4047 (1972) 393-396

C, P and T operators

Discrete symmetries:

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

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

CPT theorem

Schwinger 1951 Lüders 1954 J S Bell 1954 Pauli 1955 Res Jost 1958

Taken for N. Mavromatos's talk: "Models and (some searches) for CPT violation"

CPT theorem (Schwinger, Bell, Jost, Pauli, Lunders)

A quantum field theory with the:

- hermitian,
- local Lagrangian,
- which conserves Lorentz symmetry
- and fulfils normal commutation(anti-commutation) rules

must have CPT symmetry (e.g. all particle theories in Standard Model (SM) but also many other proposed models).

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

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Remark (after J. Bernabeu): nothing in QM forbids CPT violation.

Experimental searches of CPT violation

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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,
- search for electric dipole moments of neutrons, atoms, molecules,
- mixing of neutral mesons.

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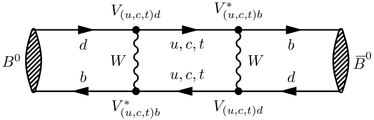
Interference effects in neutral flavour meson oscillation provide experimental precision reaching the Planck scale
e.g. -4.0×10^{-19} GeV $< m_{K^0} - m_{\bar{K}^0} < 4 \times 10^{-19}$ GeV at 95 % C.L.
Particle Data Group 2015 - http://pdg.lbl.gov/2015/reviews/rpp2015-rev-cpt-invariance-tests.pdf

Oscillation phenomena

Weak interactions do not conserve the flavour



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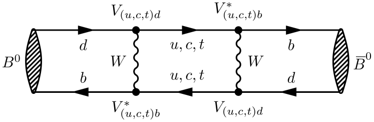

$|P^0\rangle, |\bar{P}^0\rangle$ are not eigenvectors of the full Hamiltonian

$$\frac{\partial}{\partial t}|\Phi >= H|\Phi >, \tag{1}$$

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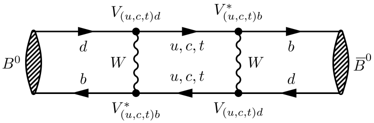

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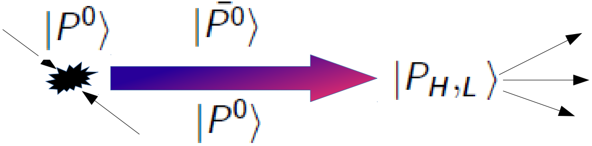
Mass eigenstates with given lifetimes (e.g. K_L, K_S) and not flavour eigenstates (e.g.$K^0, \bar{K^0}$)

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

Oscillation phenomena

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,
- non-diagonal elements change flavour,
- 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).

CP parameterization

$$
\begin{aligned}
|P_L\rangle &= p|\mathrm{P}^0\rangle + q|\bar{\mathrm{P}}^0\rangle \\
|P_H\rangle &= p|\mathrm{P}^0\rangle - q|\bar{\mathrm{P}}^0\rangle \ ,
\end{aligned} \tag{6}
$$

$$
\frac{q^2}{p^2} = \frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}} \tag{7}
$$

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

CPT parameterization

$$|P_L\rangle = p\sqrt{1-z}|\mathrm{P}^0\rangle + q\sqrt{1+z}|\bar{\mathrm{P}}^0\rangle$$
$$|P_H\rangle = p\sqrt{1+z}|\mathrm{P}^0\rangle - q\sqrt{1-z}|\bar{\mathrm{P}}^0\rangle \ , \quad (8)$$

$$z = \frac{\delta m - \frac{i}{2}(\delta\Gamma)}{\Delta m - \frac{i}{2}\Delta\Gamma}, \quad (9)$$

where:

- $\delta m = M_{11} - M_{22}$ and $\delta\Gamma = \Gamma_{11} - \Gamma_{22}$,
- $\Delta m = m_H - m_L$ and $\Delta\Gamma = \Gamma_H - \Gamma_L$ (Δm and $\Delta\Gamma$ are generally very small !!!)

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

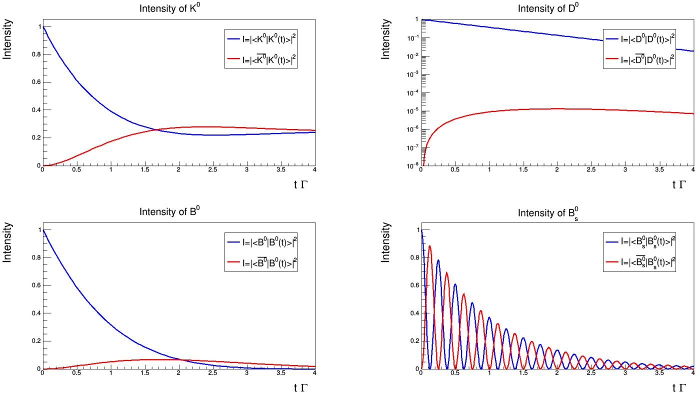
Oscillation phenomenology

Mixing parameters

$\Delta m = m_H - m_L$ and $\Delta\Gamma = \Gamma_H - \Gamma_L$, $\quad x = \frac{\Delta m}{\Gamma}$, $y = \frac{\Delta\Gamma}{2\Gamma}$

$K^0 : x \approx 1, y \approx -1,$ $\quad D^0 : x \approx 0.001, y \approx 0.001,$

$B^0 : x \approx 0.77, y \approx 0,$ $\quad B_s^0 : x \approx 26, y \approx 0.15,$



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

Greenberg theorem [PRL 89 (2002) 231602]

CPT violation implies Lorentz symmetry violation

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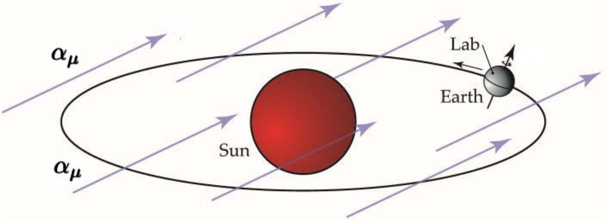


The vacuum state is anisotropic in space which violates rotational invariance (Lorentz symmetry)

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.);

$$z \simeq \frac{\beta^{\mu} \Delta a_{\mu}}{\Delta m - i\Delta\Gamma/2} \,, \tag{10}$$

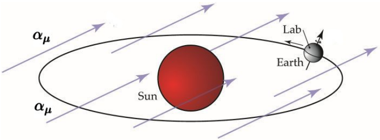
$\beta^{\mu} = \gamma(1, \vec{\beta})$ meson four-velocity in the observer frame

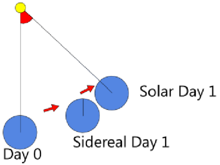
$$\Delta a_{\mu} \simeq a_{\mu}^{q_1} - a_{\mu}^{q_2}$$

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

Sidereal modulations

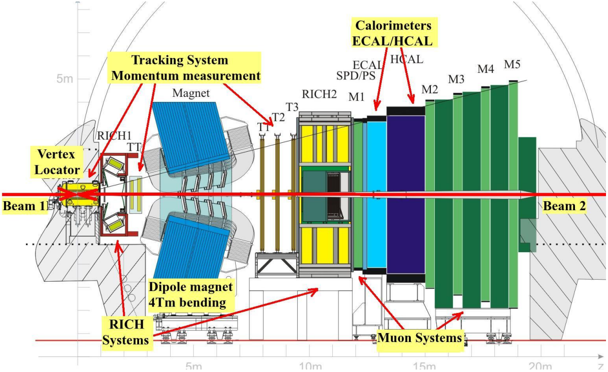
CPT-violating observable z undergoes sidereal modulations, and depends on the geographical location of the detector.





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

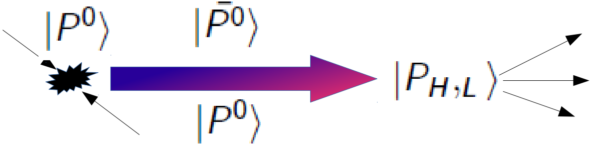
Large Hadron Collider beauty Detector



- 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

Experimental methodology in (heavy) neutral meson -recap

1. Determine (tag) initial flavour (P^0 or $\bar{P}^0$)
2. Determine (tag) final flavour (P^0 or $\bar{P}^0$)
3. From vertex displacement determine time
4. Construct time-dependent asymmetry ($A_{CPT}(t)$)
5. Fit the theoretical formula and extract CPT violating parameters (Re(z), Im(z))
6. in SME: search for the sidereal modulations, and direction dependence in Re(z), and extract coupling parameters Δa_μ



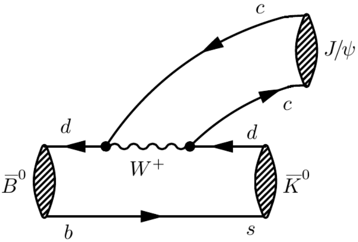
Flavour-specific vs CP eigenstate

- decay to distinct flavour-specific state $A_{\bar{f}} = \bar{A}_f = 0$ e.g. in semi-leptonic decays (sensitive to Im(z)).
- decay to same CP final state $\bar{f} = f$ e.g. $\mathrm{B}^0 \to \mathrm{J}/\psi\,\mathrm{K}^0_\mathrm{S}$ (sensitive to Re(z)).

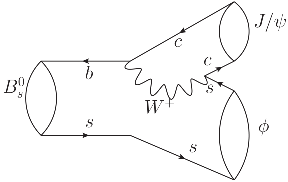
Time-dependent analyses in beauty sector

- 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

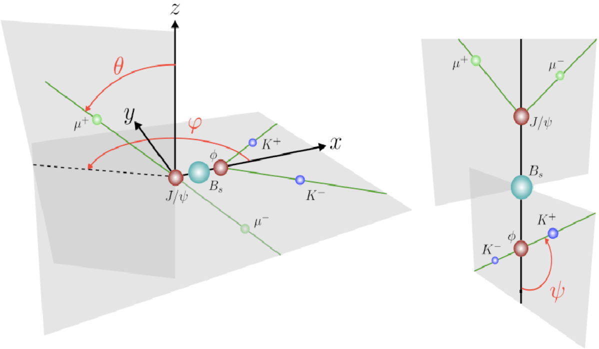


- $B^0_s \to J/\Psi\Phi$
- $P \to VV$
- $L = 0 \to L = 1$ and $L = 1$
- Mixture of CP odd and CP even final states
- time and angular dependent fit



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

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



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

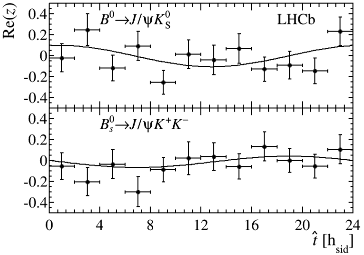
Results for $B^0 \to J/\Psi K^0_S$ and $B^0_s \to J/\Psi\Phi$

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

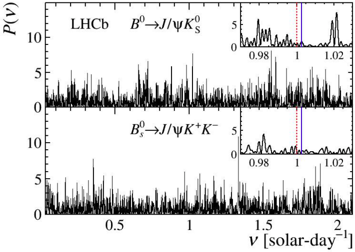
- Ω and $\hat{t}$ - sidereal frequency and time respectively,
- Due to the LHCb geographical location: $\cos\chi = -0.38$ (const term), $\sin\chi = 0.92$ (sidereal modulated term)

PRL 116 (2016) 241601:

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



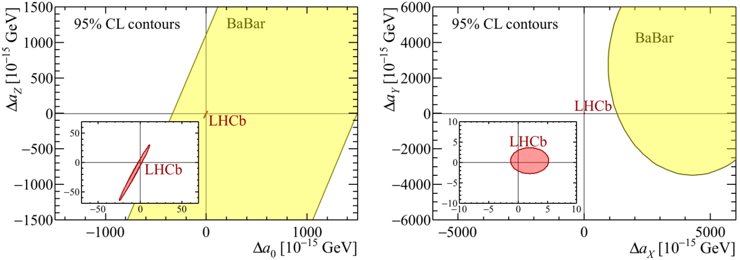
Periodogram analysis



Comparison with BaBar

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

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

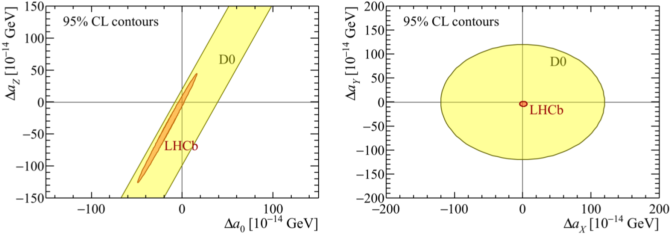


- BaBar used inclusive dilepton B decays (PRL 100 (2008) 131801),
- Much smaller boost comparing to LHCb (0.5 vs 20),
- New LHCb result 1000 more precise than BaBar result.

Comparison with D0

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

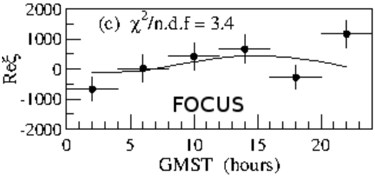
$\Delta a_0 - 0.38\Delta a_z = -0.89 \pm 1.41 \pm 0.36 \times 10^{-14}$ GeV,
$0.38\Delta a_0 + \Delta a_z = -0.47 \pm 0.22 \pm 0.08 \times 10^{-12}$ GeV,
$\Delta a_x = 1.01 \pm 2.08 \pm 0.71 \times 10^{-14}$ GeV,
$\Delta a_y = 3.83 \pm 2.09 \pm 0.71 \times 10^{-14}$ GeV,
$\mathrm{Re}z = -0.022 \pm 0.033 \pm 0.003$ (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),
- Experiment @FERMILAB (γ beam with energy of $\approx$ 180 GeV on fixed BeO target),
- $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$, both in classical and SME approach,
- $\mathrm{Re}(\,z\,) - \mathrm{Im}(\,z\,) \approx O(1)$,
- $\Delta a_\mu \approx 3 \times 10^{-13}$ GeV,

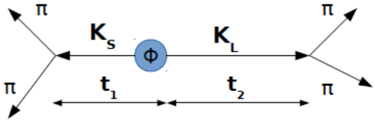


LHCb perspectives based on 2011 and 2012 data (3 fb^{-1}):

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

$M(\Phi) = 1020$ MeV

Quantum entanglement (EPR)



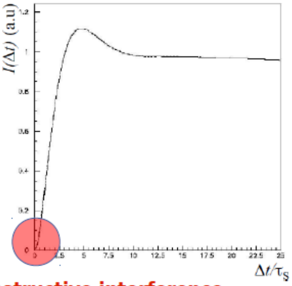
Quantum decoherence via gravity effects:

S. Hawking, Comm.Math.Phys.87 (1982) 395

$\Phi \rightarrow K_S K_L$

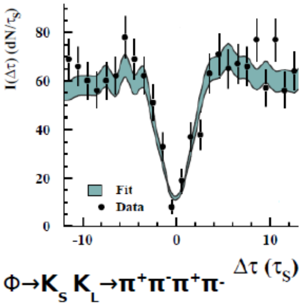
Antisymmetric quantum state

$J^{PC} = 1^{--}$



Destructive interference for identical final states

Neutral strange sector - KLOE results



$$\begin{aligned}
\Delta a_0 &= (-6.0 \pm 7.7_{stat} \pm 3.1_{syst}) \times 10^{-18}\ \mathrm{GeV} \\
\Delta a_X &= (\ \ 0.9 \pm 1.5_{stat} \pm 0.6_{syst}) \times 10^{-18}\ \mathrm{GeV} \\
\Delta a_Y &= (-2.0 \pm 1.5_{stat} \pm 0.5_{syst}) \times 10^{-18}\ \mathrm{GeV} \\
\Delta a_Z &= (\ \ 3.1 \pm 1.7_{stat} \pm 0.5_{syst}) \times 10^{-18}\ \mathrm{GeV}
\end{aligned}$$

D. Babusci et al. Phys. Lett. B 730C (2014), pp. 89-94

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 $t = 0$:

$$|\mathrm{P}^0\rangle = \frac{1}{2p}(\sqrt{1-z}|P_L\rangle + \sqrt{1+z}|P_H\rangle) \tag{12}$$

The time evolution will be given by:

$$|\mathrm{P}^0(t)\rangle = \frac{1}{2p}(\sqrt{1-z}e^{-iM_L t}e^{-\Gamma_L t}|P_L\rangle + \sqrt{1+z}e^{-iM_H t}e^{-\Gamma_H t}|P_H\rangle) \tag{13}$$

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

$$|\mathrm{P}^0(t)\rangle = g_+(t) + zg_-(t)|\mathrm{P}^0\rangle - \frac{q}{p}\sqrt{1-z^2}g_-(t)|\bar{\mathrm{P}}^0\rangle, \tag{14}$$

where: $g_\pm(t) = \frac{1}{2}(e^{-iM_H t}e^{-\Gamma_H t} \pm e^{-iM_L t}e^{-\Gamma_L t})$.

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 ($z = 0$, $|\frac{q}{p}| \neq 1$)

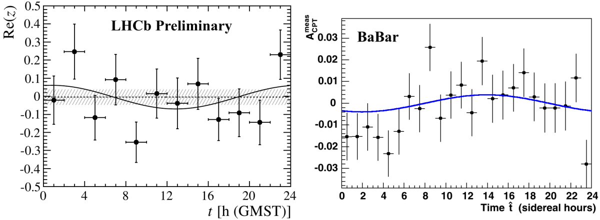
CPT is not conserved when:

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

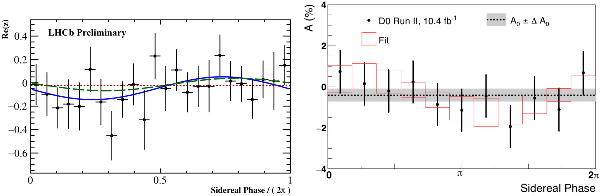
LHCb (PRL 116 (2016) 241601)



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,

CP, T and CPT symmetry

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

$$[H, U] = 0 \leftrightarrow U^{-1}HU = H \tag{15}$$

- 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: $|H_{12}| = |H_{21}|$.

LHCb parameters

- LHC beam energy in pp collisions ($\sqrt{s}$): 7 and 8 TeV (2010-2012), 13 to 14 TeV (ongoing Run II)
- Collected integrated luminosity: 1 fb $^{-1}$ (2011), 2 fb $^{-1}$ (2012)
- Acceptance: 2 ¡ η ¡ 5
- data taking efficency ¿ 90 %
- trigger efficiency: 90 % for dimuon channels, 30% for multi-body hadronic final states
- track reco. efficiency: ¿96 % for long tracks
- Momentum resolution: $\frac{\Delta p}{p}$ =0.5 % for low momentum till 1% at 200 GeV/c
- ECAL resolution: 1% + 10% $\overline{E[GeV]}$
- impact parameter resolution: 20 μm for high-pT tracks
- invariant mass resolution: 8 MeV/c^2 for B to J/Psi decays, 22 Mev/C for two-body B decays, 100 MeV/c^2 for Bsto phi photon
- decay time resolution: 45 fs for Bs tp J/Psi and Bs to Ds pi
- electron ID efficiecny: 90 % (5 % miss probabilty)
- kaon ID efficiecny: 95 % (5 % miss probabilty)
- muon ID efficiecny: 97 % (1-3 % miss probabilty)