Search for Violation of CPT and Lorentz invariance in $B_s$ meson oscillations.

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Why Search for CPT Violation?

• Test the CPT theorem:
  – … any Lorentz invariant local quantum field theory with a Hermitian Hamiltonian must have CPT symmetry…

• Standard Model Extension (SME) provides a framework for potential Lorentz and CPT invariance violation
  – Violations occur at Plank scale whilst still producing observable effects

• Searches already carried out in other neutral meson systems: 
  $K^0$ (Kloe), $D^0$ (Focus), $B_d^0$ (Belle and BaBar)

• Charge asymmetries in single and like-sign dimuon events could explained by CPT violation.
  V. Kostelecký and R Van Kooten Phys. Rev. D82: 101702, 2010
Neutral Meson Mixing

\[ H = \begin{pmatrix}
    \langle M^0 | H | M^0 \rangle & \langle M^0 | H | \bar{M}^0 \rangle \\
    \langle \bar{M}^0 | H | M^0 \rangle & \langle \bar{M}^0 | H | \bar{M}^0 \rangle 
\end{pmatrix} = \begin{pmatrix}
    M_{11} - \frac{i}{2} \Gamma_{11} & M_{12} - \frac{i}{2} \Gamma_{12} \\
    M_{12} - \frac{i}{2} \Gamma_{12} & M_{22} - \frac{i}{2} \Gamma_{22}
\end{pmatrix}
\]

Eigenvalue equation for \( H \) yields two eigenstates

- well defined masses and decay widths (lifetimes) correspond to physical states

If we have CPT violation the eigenstates can be written as

\[ |B_{sL}\rangle \propto p \sqrt{1 - \xi_s} |B_s^0\rangle + q \sqrt{1 + \xi_s} |\bar{B}_s^0\rangle, \]
\[ |B_{sH}\rangle \propto p \sqrt{1 + \xi_s} |B_s^0\rangle - q \sqrt{1 - \xi_s} |\bar{B}_s^0\rangle. \]

where \( \xi \) is zero if CPT is conserved and is given by

\[ \xi_s = \frac{(M_{11} - M_{22}) - \frac{i}{2} (\Gamma_{11} - \Gamma_{22})}{-\Delta m_s + \frac{i}{2} \Delta \Gamma_s / 2} \approx \frac{\beta^\mu \Delta a_\mu}{-\Delta m_s + i \Delta \Gamma_s / 2}, \]

tiny \( \rightarrow \) sensitivity

\[ \Delta m_s = 17.69 \pm 0.08 \text{ ps}^{-1} \quad 1 \text{ sec} = 1.52 \times 10^{24} \text{ GeV} \quad \Delta m_s = 1.16 \times 10^{-2} \text{ eV} \]
Sidereal Time Variation

- Size of effect: $\Delta a_\mu = r_s a^s_\mu - r_b a^b_\mu$

Orientation of DØ detector and Tevatron beam line changes w.r.t. vector field $a_\mu$ with the frequency of Earth's rotation

$\Omega = 2\pi / (23^h 56^m 04.0982^s)$ Earth's sidereal frequency

$T_\oplus$ local sidereal time of the collision event (time stamp)
Experimental Effect

• We choose (T,X,Y,Z) as coordinates in the Sun-centered frame with the rotation axis of the Earth, the Z-axis, and X(Y) is at right ascension 0° (90°).

• T = 0: vernal equinox of the year 2000.

• Transform to local (D0) coordinates.

\[
\mathcal{A}_{\text{CPT}} = \frac{-\Delta \Gamma_s \gamma^{D0}}{\Gamma_s \Delta m_s} \left[ \Delta a_T - C_\alpha S_\chi \beta^{D0}_z \Delta a_Z \right. \\
\left. + \sqrt{C^2_\alpha C^2_\chi + S^2_\alpha \sin(\Omega \hat{t} + \delta + \kappa) \beta^{D0}_z \Delta a_\perp} \right],
\]

it’s more like a big ball of wibbly wobbly... time-y wimey... stuff - Dr John Smith
Experimental Effect

\[
A_{\text{CPT}} = \frac{-\Delta \Gamma_s \gamma^{D_0}}{\Gamma_s \Delta m_s} \left[ \Delta a_T - C_\alpha S_\chi \beta_{z}^{D_0} \Delta a_Z \\
+ \sqrt{C_{\alpha}^2 C_\chi^2 + S_{\alpha}^2 \sin(\Omega t + \delta + \kappa)} \beta_{z}^{D_0} \Delta a_\perp \right],
\]

Looking for

\[A_{\text{CPT}} = \text{Constant} + \sin(t + c)\]

where:

\[\Delta a_\perp = \sqrt{\Delta a_X^2 + \Delta a_Y^2}\]
\[\delta = \arctan(\Delta a_X / \Delta a_Y)\]
\[\kappa = \arctan2(C_\alpha C_\chi, -S_\alpha)\]
\[C_x = \cos(x), \quad S_x = \sin(x)\]

\[\chi = \text{colatitude of D0 detector (angle from north pole)}\]
\[\alpha = \text{proton beam direction}\]
**B^0_s Oscillations**

- Using the decay process $B_s \rightarrow D_s^-\mu^+X$ in the analysis described in *Phys. Rev. Lett.*, 110, 011801 (2013).

- Unlike other charge violation measurements looking at particle to particle oscillations: $B_s \rightarrow B_s$

- Measure a raw asymmetry in bins of sidereal phase

\[
A = \frac{N_+ - N_-}{N_+ + N_-}
\]

where $N_{+(-)}$ is the number of events where $Q^\mu \text{sgn}(\cos \theta) > 0$
Dataset

\[ M (\phi \pi^\pm) \text{ [GeV/c}^2] \]

Events/6 MeV/c^2

(Data-Fit)/Uncertainty

D0, 10.4 fb

D^+_s \rightarrow \phi \pi^\pm

D^- \rightarrow \phi \pi^\pm

D^+_s \rightarrow \phi \pi^- \pi^0

Combinatorial Background
Sensitivity

- Use charge injection to optimise number of bins in sidereal phase (using asymmetries of 0, 1, 2 and 5%) - Use 11 bins
- Fit all sidereal bins simultaneously
  - Common Signal peaks and background
  - Only Asymmetry of Ds peak and D peak varies as function of sidereal phase.
Sidereal Bins

<table>
<thead>
<tr>
<th>$A_{Ds}$</th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>0.74%</td>
<td>±</td>
<td>1.03%</td>
</tr>
<tr>
<td>0.15%</td>
<td>±</td>
<td>1.03%</td>
</tr>
<tr>
<td>-0.20%</td>
<td>±</td>
<td>1.02%</td>
</tr>
<tr>
<td>0.23%</td>
<td>±</td>
<td>1.01%</td>
</tr>
<tr>
<td>-0.86%</td>
<td>±</td>
<td>1.02%</td>
</tr>
<tr>
<td>-1.14%</td>
<td>±</td>
<td>1.02%</td>
</tr>
<tr>
<td>-0.45%</td>
<td>±</td>
<td>1.02%</td>
</tr>
<tr>
<td>-1.93%</td>
<td>±</td>
<td>1.03%</td>
</tr>
<tr>
<td>-0.55%</td>
<td>±</td>
<td>1.03%</td>
</tr>
<tr>
<td>-1.11%</td>
<td>±</td>
<td>1.03%</td>
</tr>
<tr>
<td>0.68%</td>
<td>±</td>
<td>1.03%</td>
</tr>
</tbody>
</table>

Fit to:

$$A(\hat{t}) = A_0 - A_1 \sin(\Omega \hat{t} + \phi),$$

Significance (Wilk’s Theorem):
0.58σ deviation from zero (constant).
Limit Setting

• Convert $A_1$ into limit on $a_\perp$

$$A_1 \sin(\Omega \hat{t} + \phi) = \frac{F_{B^0_s}^{\text{non-osc}} \Delta \Gamma_s \langle \gamma_{D^0} \beta_{Z_{D^0}} \rangle}{\Gamma_s \Delta m_s} \times \sqrt{C^2_\alpha C^2_\chi + S^2_\alpha} \sin(\Omega \hat{t} + \delta + \kappa) \Delta a_\perp,$$

where $F_{\text{non-osc}}$ is the fraction of $D_s^\pm \rightarrow \phi \pi^\pm$ decays for which an observed $B_s^0$ has the same flavour as at birth

• giving

$$\Delta a_\perp < 1.2 \times 10^{-12} \text{ GeV}$$

• Convert $A_0$ into a limit on $a_T$ and $a_Z$

$$(-0.8 < \Delta a_T - 0.396 \Delta a_Z < 3.9) \times 10^{-13} \text{ GeV}$$
Comparison with Dimuon

\[ -0.8 < \Delta a_T - 0.396 \Delta a_Z < 3.9 \times 10^{-13} \text{ GeV} \]

- V.A. Kostelecký and R.J. Van Kooten, Phys. Rev. D. 82, 101702(R) (2010), arXiv:1007.5312 makes a prediction of this value to explain the dimuon asymmetry:
  \[ (\Delta a_T - 0.396 \Delta a_Z) \simeq \times (3.7 \pm 3.8) \times 10^{-12} \text{ GeV} \]

so need effect of order \(10^{-12}\) GeV to make significant contribution.

These limits imply that CPT violation is unlikely to contribute a significant fraction of the observed dimuon charge asymmetry, and that other explanations need to be sought.
• Carry out cross check using periodogram
  - only good for varying part:

\[
P(\nu) \equiv \left( \frac{\sum_{j=1}^{N} w_j \exp(-2\pi i \nu \hat{t}_j)}{N \sigma_w^2} \right)^2
\]

\[
\Delta a_\perp < 6.9 \times 10^{-13} \text{ GeV}
\]

Consistent with no signal
Summary

• first limit placed on CPT violation exclusively in the $B_s$ mixing system

$$\Delta a_\perp < 1.2 \times 10^{-12} \text{ GeV}$$

$$(-0.8 < \Delta a_T - 0.396 \Delta a_Z < 3.9) \times 10^{-13} \text{ GeV}$$

• No evidence of CPT violation

• Submitted to PRL: arXiv:1506.04123 [hep-ex]
  http://www-d0.fnal.gov/Run2Physics/WWW/results/final/B/B15C/
\( B^0 \bar{B}^0 \) Mixing and Oscillations

For \( B_d^0 \):

\[ \text{Prob}[B_d^0](t) \]

\[ \text{Prob}[\bar{B}_d^0](t) \]

Proper Lifetimes

\[ 0.5 \quad 1 \quad 1.5 \quad 2 \quad 2.5 \quad 3 \]

With \( T \) (and therefore \( CP \)) violation:

\[ \left| \frac{p}{q} \right|^2 \neq 1, \]

\[ |\langle M^0 | \bar{M}^0(t) \rangle|^2 \neq |\langle \bar{M}^0 | M^0(t) \rangle|^2 \]

\[ P(M^0 \rightarrow \bar{M}^0; t) \neq P(\bar{M}^0 \rightarrow M^0; t) \]

"\( T \) (\( CP \)) Violation in Mixing"
$B^0\bar{B}^0$ Mixing and Oscillations

• For $B_d^0$

$B_d^0$ mixing diagram with $V_{td}$

$B_d^0$ proper lifetimes

• For $B_s^0$

$B_s^0$ mixing diagram with $V_{ts}$

$B_s^0$ proper lifetimes

With $T$ (and therefore $CP$) violation:

$$\left| \frac{p}{q} \right|^2 \neq 1,$$

$$\left| \langle M^0 | M^0(t) \rangle \right|^2 \neq \left| \langle \bar{M}^0 | \bar{M}^0(t) \rangle \right|^2.$$

$$P(M^0 \to M^0; t) \neq P(\bar{M}^0 \to \bar{M}^0; t)$$

"$CPT$ Violation in Mixing"
Introduction

- Interpretation of Charge asymmetries in single and like-sign dimuon events suggest that asymmetry due to $B_s$ mesons.
- Currently no explanation!
- This could be explained by CPT violation.

V. Kostelecký and R Van Kooten

$$a_{s,l}^s(WA) = (-0.83 \pm 0.43)\%,$$
$$a_{s,l}^d(WA) = (-0.09 \pm 0.21)\%,$$
$$\Delta \Gamma_d / \Gamma_d(WA) = (1.51 \pm 0.91)\%,$$

$$\rho_{s,d} = -0.25,$$
$$\rho_{d,\Delta \Gamma} = +0.23$$
$$\rho_{s,\Delta \Gamma} = +0.47$$
TABLE I. Parameters and uncertainties in the extraction of the CPT-violating parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_0$</td>
<td>$(−0.40 \pm 0.31)%$</td>
<td>Eq. 6</td>
</tr>
<tr>
<td>$A_1$</td>
<td>$(0.87 \pm 0.45)%$</td>
<td>Eq. 6</td>
</tr>
<tr>
<td>$\phi$</td>
<td>$−2.28 \pm 0.51$</td>
<td>Eq. 6</td>
</tr>
<tr>
<td>$m_{B^0_s}$</td>
<td>$(5.36677 \pm 0.00024) \text{GeV}$</td>
<td>[17]</td>
</tr>
<tr>
<td>$\Delta m_s$</td>
<td>$(17.761 \pm 0.022) \times 10^{12} \hbar \text{s}^{-1}$</td>
<td>[17]</td>
</tr>
<tr>
<td>$\Delta \Gamma_s / \Gamma_s$</td>
<td>$(0.138 \pm 0.012)$</td>
<td>[17]</td>
</tr>
<tr>
<td>$\bar{h}$</td>
<td>$6.58211928 \times 10^{-25} \text{GeV} \cdot \text{s}$</td>
<td>[17]</td>
</tr>
<tr>
<td>$F_{B^0_s}^{\text{non-osc}} = F_{B^0_s}^{\text{osc}}$</td>
<td>$(0.465 \pm 0.017)$</td>
<td>[12]</td>
</tr>
<tr>
<td>$\langle p_z \rangle$</td>
<td>$(17.8 \pm 1.6) \text{GeV}$</td>
<td></td>
</tr>
<tr>
<td>$\langle p \rangle$</td>
<td>$(25.3 \pm 2.3) \text{GeV}$</td>
<td></td>
</tr>
<tr>
<td>Proton beam dir$^n \alpha$</td>
<td>219.53°</td>
<td></td>
</tr>
<tr>
<td>Colatitude $\chi$</td>
<td>48.17°</td>
<td></td>
</tr>
</tbody>
</table>
Systematic Uncertainties

- Fitting Uncertainties
- Mass Binning, Mass Range, Background polynomial, Fit Variations.

<p>| | |</p>
<table>
<thead>
<tr>
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<th></th>
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</thead>
<tbody>
<tr>
<td>Mass Range</td>
<td>0.035%</td>
</tr>
<tr>
<td>Mass Binning</td>
<td>0.071%</td>
</tr>
<tr>
<td>Fit Function</td>
<td>0.085%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.12%</strong></td>
</tr>
</tbody>
</table>

- Number of sidereal bins: relative uncertainty of central value of 8%
- Reconstruction asymmetries: relative uncertainty of 1%
- Added in quadrature