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
  - Phys. Rev. D 39, 683 (1989), Nucl. Phys. B 359, 545 (1991)
  - 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

CPT & Lorentz violating: involves differences between *diagonal* terms

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

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 ξ is zero if CPT is conserved and is given by.

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

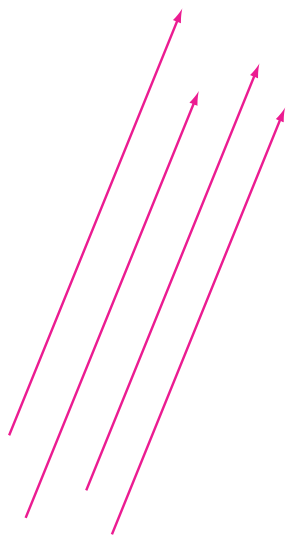
tiny → sensitivity

$$\Delta m_s = 17.69 \pm 0.08 \text{ ps}^{-1} \qquad 1 \text{ sec} = 1.52 \times 10^{24} \text{ GeV} \qquad \Delta m_s = 1.16 \times 10^{-2} \text{ eV}$$

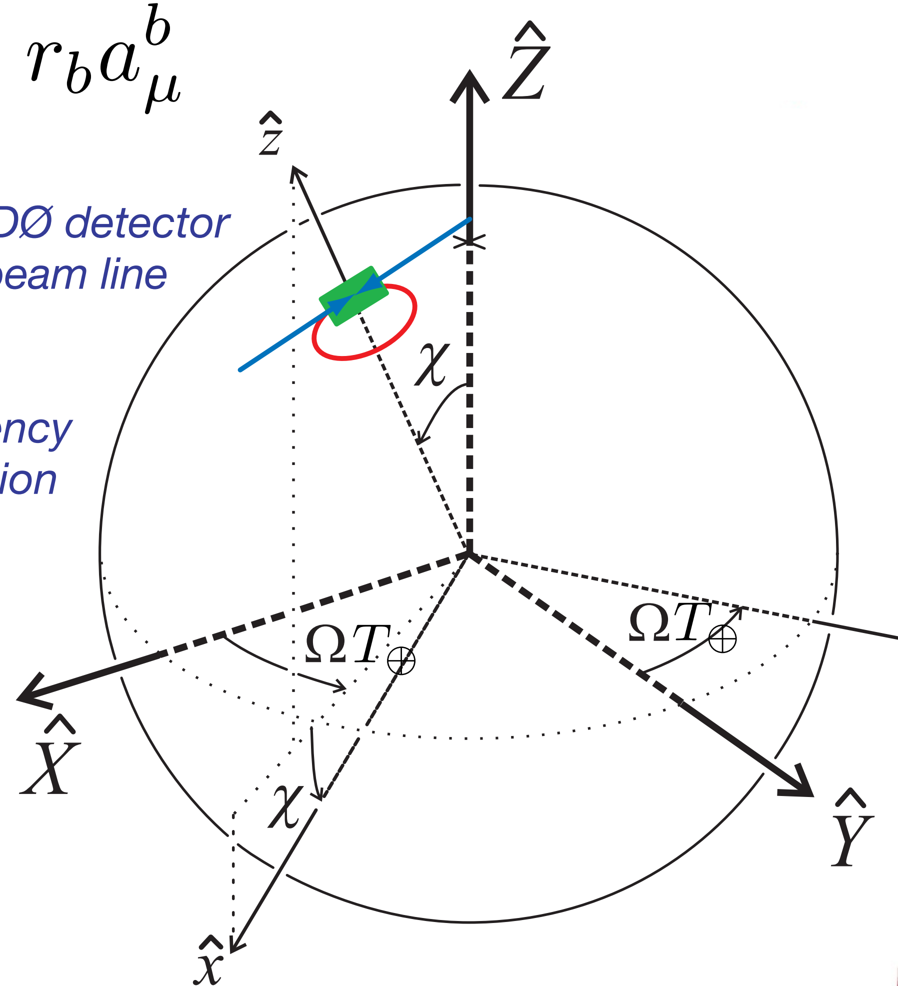
Sidereal Time Variation

- Size of effect: $\Delta a_\mu = r_s a_\mu^s - r_b a_\mu^b$

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



Constant vector field a_μ in universe

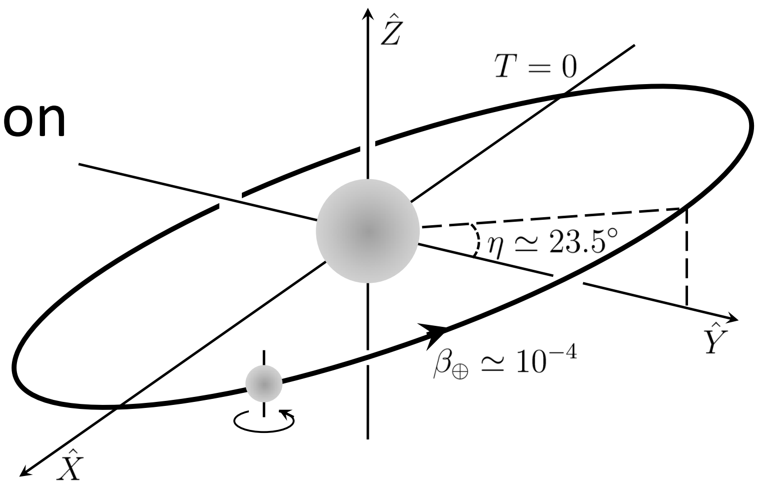


$\Omega = 2\pi/(23^h 56^m 04.0982^s)$ *Earth's sidereal frequency*

$T_\oplus$ *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



$$\mathcal{A}_{\mathrm{CPT}} = \frac{-\Delta\Gamma_s \gamma^{\mathrm{D0}}}{\Gamma_s \Delta m_s} \Big[\Delta a_T - C_\alpha S_\chi \beta_z^{\mathrm{D0}} \Delta a_Z + \sqrt{C_\alpha^2 C_\chi^2 + S_\alpha^2}\,\sin(\Omega \hat{t} + \delta + \kappa)\beta_z^{\mathrm{D0}} \Delta a_\perp\Big],$$

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

Experimental Effect

$$\mathcal{A}_{\mathrm{CPT}} = \frac{-\Delta\Gamma_s \gamma^{\mathrm{D0}}}{\Gamma_s \Delta m_s} \Big[\Delta a_T - C_\alpha S_\chi \beta_z^{\mathrm{D0}} \Delta a_Z + \sqrt{C_\alpha^2 C_\chi^2 + S_\alpha^2} \sin(\Omega \hat{t} + \delta + \kappa) \beta_z^{\mathrm{D0}} \Delta a_\perp \Big],$$

Looking for A_{CPT} = Constant + Sin(t + c)

where: $\Delta a_\perp = \sqrt{\Delta a_X^2 + \Delta a_Y^2}$ $\delta = \mathrm{atan}(\Delta a_X / \Delta a_Y)$

$\kappa = \mathrm{atan2}(C_\alpha C_\chi, -S_\alpha)$ $C_x = \cos(x)$, $S_x = \sin(x)$

χ = colatitude of D0 detector (angle from north pole)

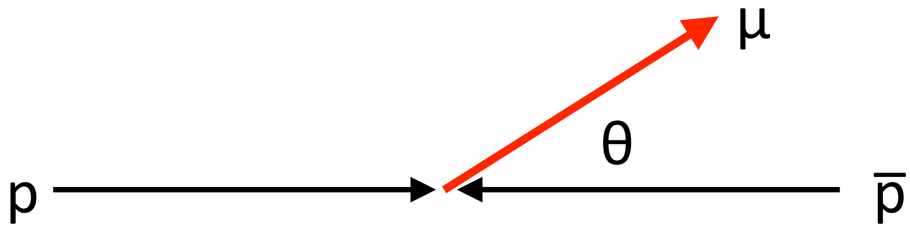
α = proton beam direction

B^0_s Oscillations

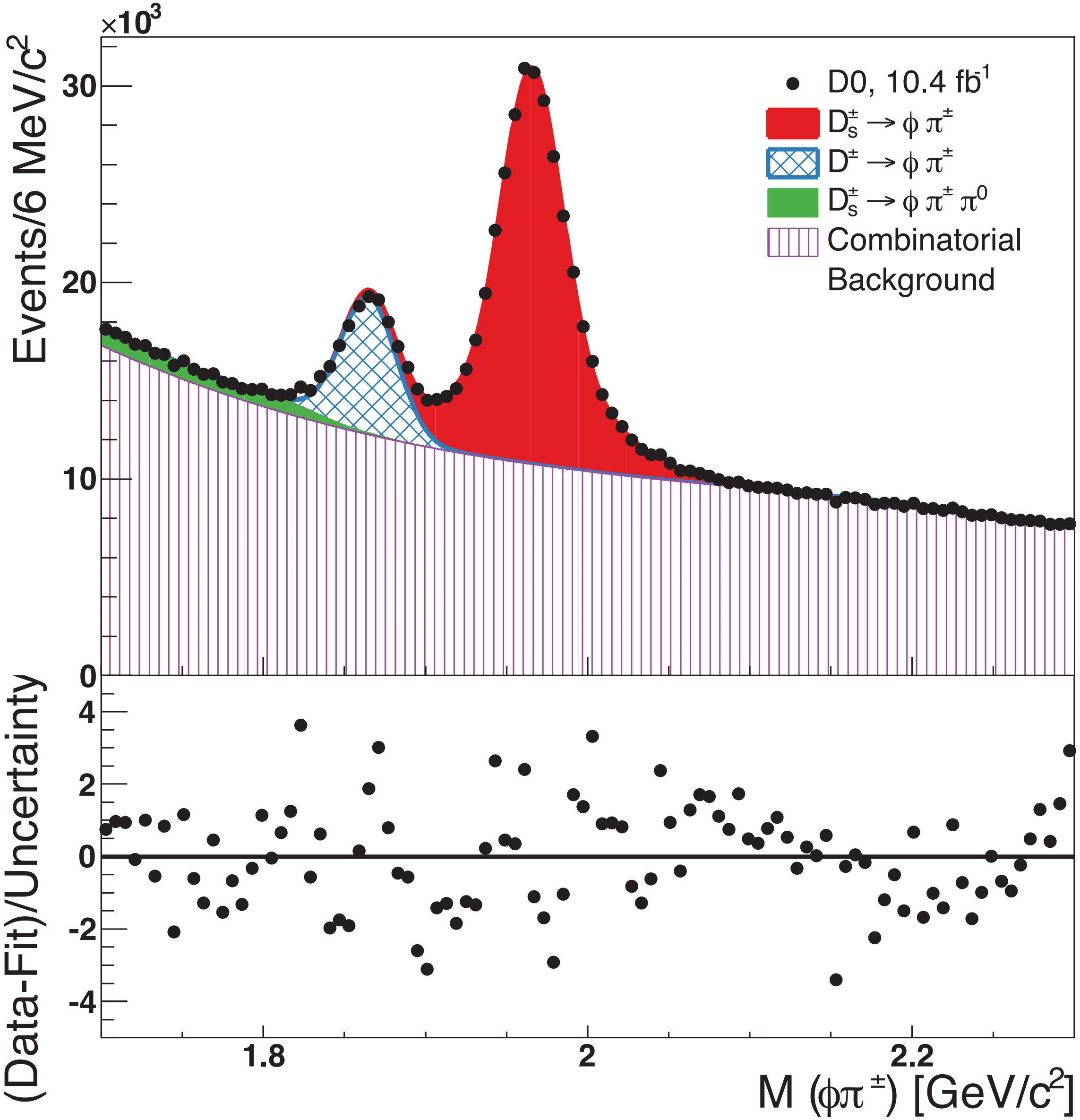
- Using the decay process $B_s \rightarrow D_s^- \mu^+ X$ in the analysis described in Phys. Rev. Lett., 110, 011801 (2013).
- Unlike other charge violation measurements looking at particle to particle oscillations: **$B_s \rightarrow B_s$**
- Measure a raw asymmetry in bins of sidereal phase

$$A = \frac{N_+ - N_-}{N_+ + N_-}$$

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



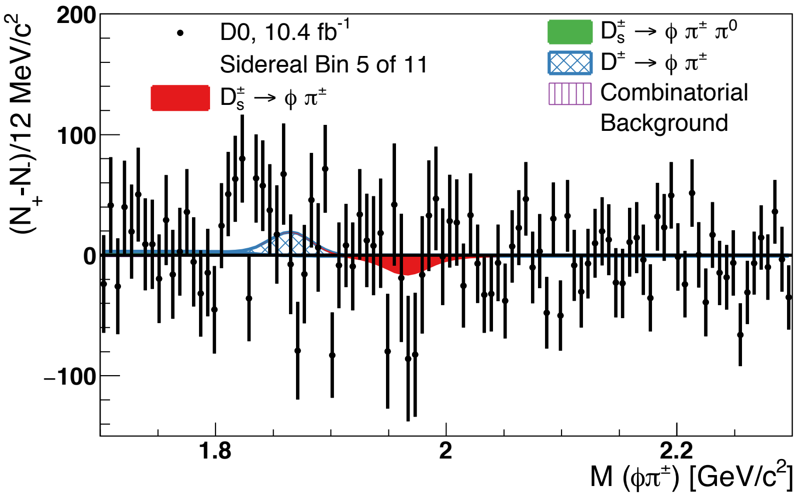
Dataset

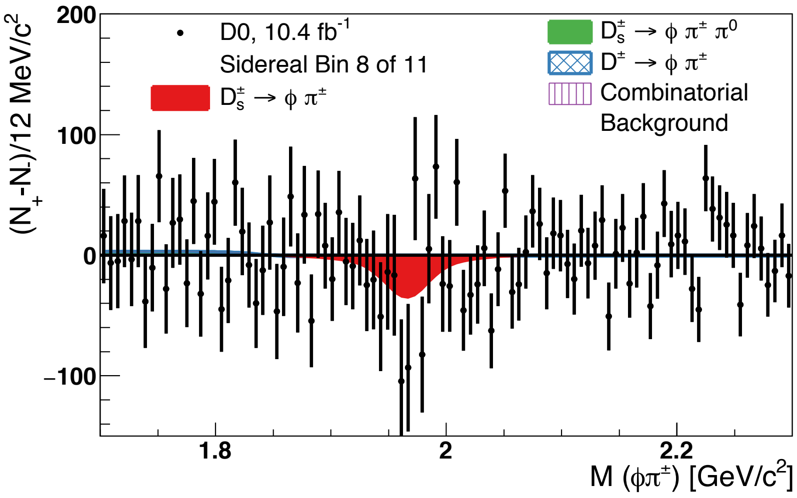


×10^3
Events/6 MeV/c^2
30
20
10
0
D0, 10.4 fb^-1
D_s^± → φ π^±
D^± → φ π^±
D_s^± → φ π^± π^0
Combinatorial Background
(Data-Fit)/Uncertainty
4
2
0
-2
-4
1.8
2
2.2
M (φπ^±) [GeV/c^2]

Sensitivity

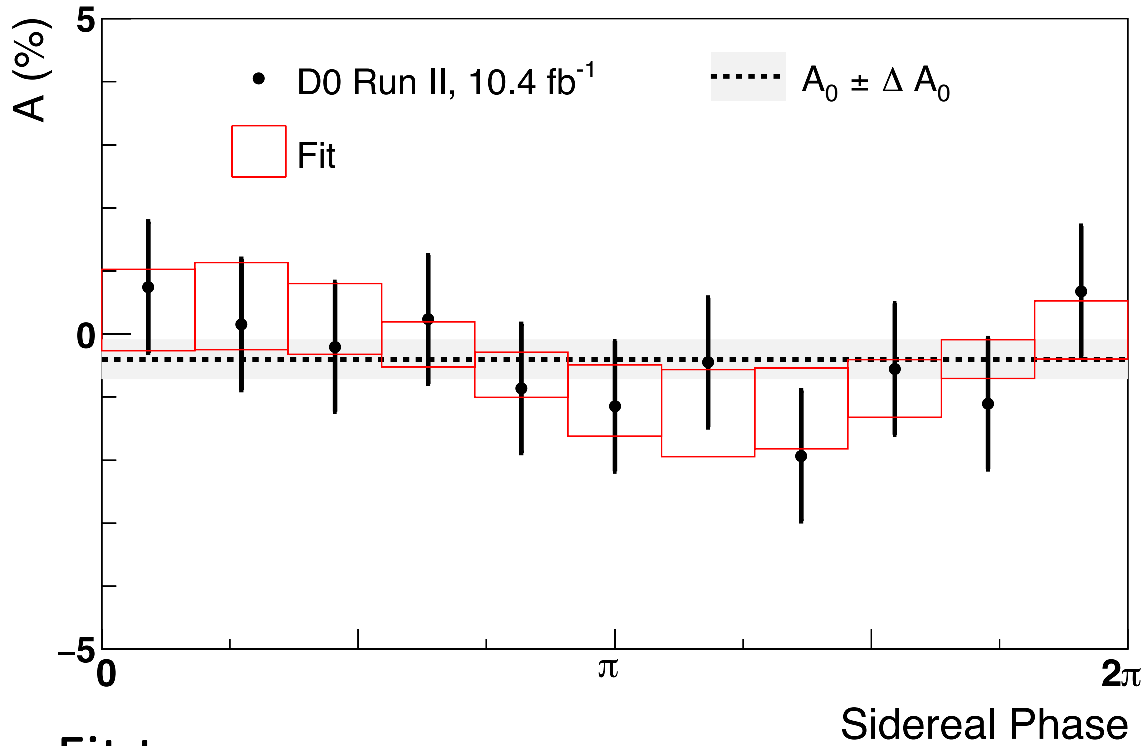
- Use charge injection to optimise number of bins in sidereal phase (using asymmetries of 0, 1, 2 and 5%) - Use 11 bins
- Fit all sidereal bins simultaneously
  - Common Signal peaks and background
  - Only Asymmetry of Ds peak and D peak varies as function of sidereal phase.





Sidereal Bins

A_{Ds}		
0.74%	±	1.03%
0.15%	±	1.03%
-0.20%	±	1.02%
0.23%	±	1.01%
-0.86%	±	1.02%
-1.14%	±	1.02%
-0.45%	±	1.02%
-1.93%	±	1.03%
-0.55%	±	1.03%
-1.11%	±	1.03%
0.68%	±	1.03%



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 $a_\perp$

$$A_1 \sin(\Omega\hat{t} + \phi) = \frac{F^{\text{non-osc}}_{B_s^0} \Delta\Gamma_s \langle \gamma^{\text{D0}} \beta_z^{\text{D0}} \rangle}{\Gamma_s \Delta m_s} \times \sqrt{C_\alpha^2 C_\chi^2 + S_\alpha^2} \sin(\Omega\hat{t} + \delta + \kappa) \Delta a_\perp,$$

where $F^{\text{non-osc}}$ is the fraction of $D_s^\pm \to \phi\pi^\pm$ 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. Kostelecky´ 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:

$$(\Delta a_T - 0.396\Delta a_Z) \simeq \times(3.7 \pm 3.8)10^{-12}\ \text{GeV}$$

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

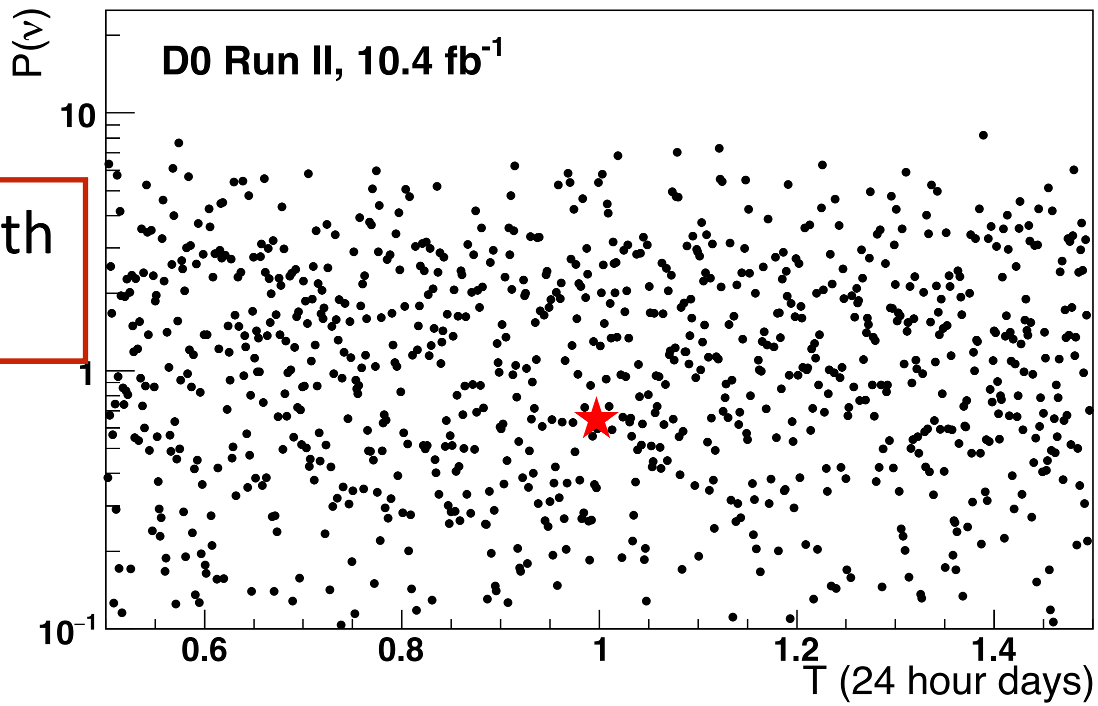
These limits imply that CPT violation is unlikely to contribute a significant fraction of the observed dimuon charge asymmetry, and that other explanations need to be sought.

Periodogram

- Carry out cross check using periodogram
  - only good for varying part:

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

Consistent with no signal



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

Summary

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

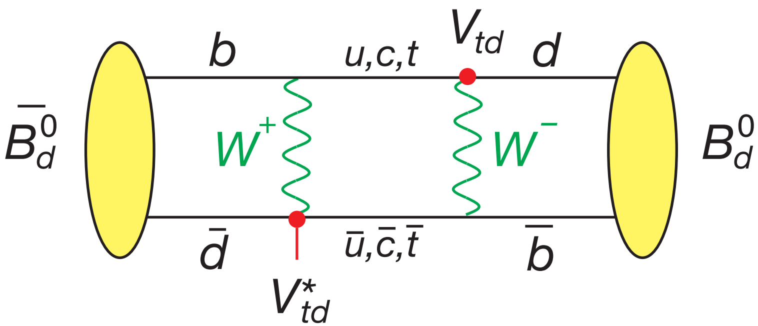
$$\Delta a_{\perp} < 1.2 \times 10^{-12}\ \text{GeV}$$

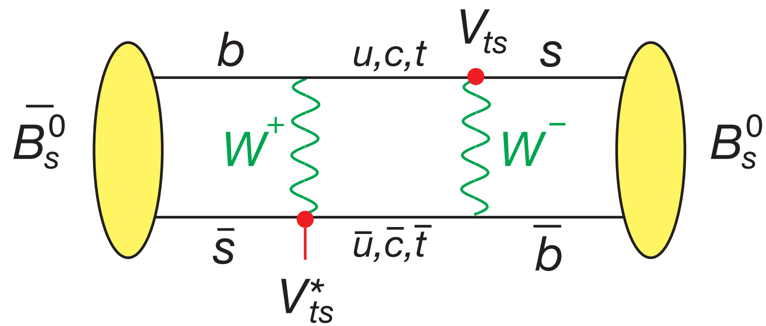
$$(-0.8 < \Delta a_T - 0.396 \Delta a_Z < 3.9) \times 10^{-13}\ \text{GeV}$$

- No evidence of CPT violation
- Submitted to PRL: arXiv:1506.04123 [hep-ex]
  http://www-d0.fnal.gov/Run2Physics/WWW/results/final/B/B15C/

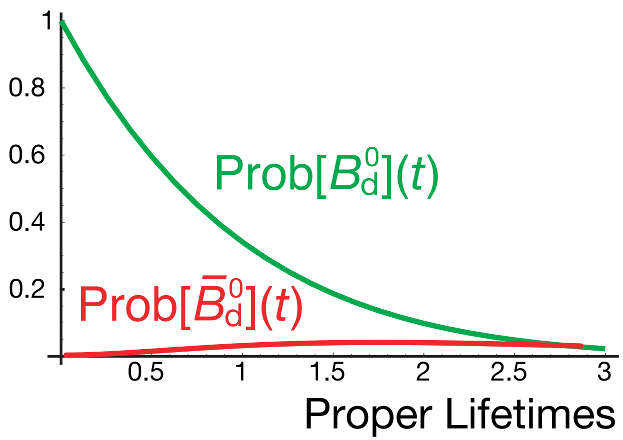
Backup

B^0-$\bar{B}^0$ Mixing and Oscillations





- For B_d^0



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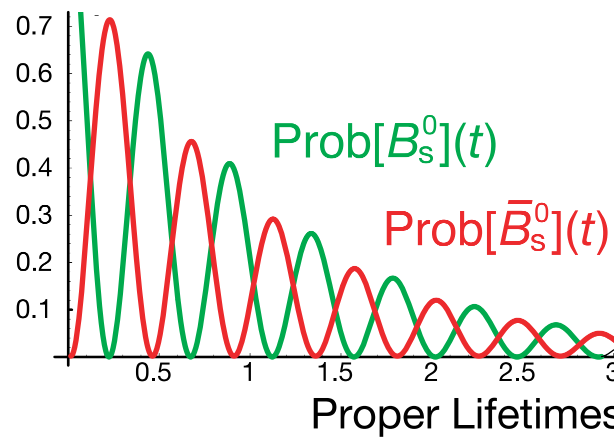
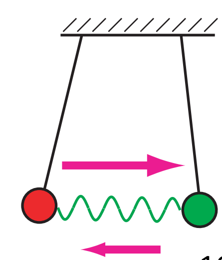


- With T (and therefore CP) violation:

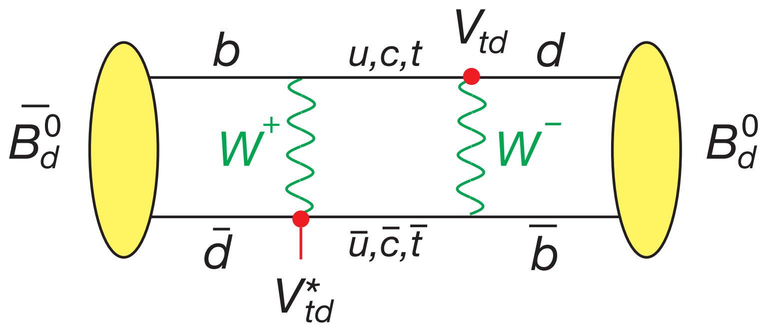
$$\left|\frac{p}{q}\right|^2 \neq 1, \qquad |\langle M^0|\bar{M}^0(t)\rangle|^2 \neq |\langle \bar{M}^0|M^0(t)\rangle|^2$$

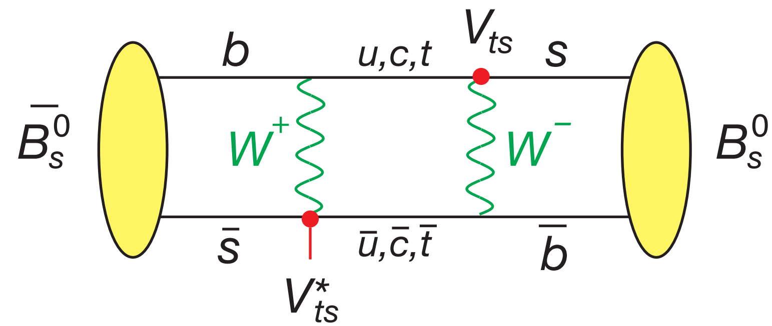
$$P(M^0 \to \bar{M}^0; t) \neq P(\bar{M}^0 \to M^0; t)$$



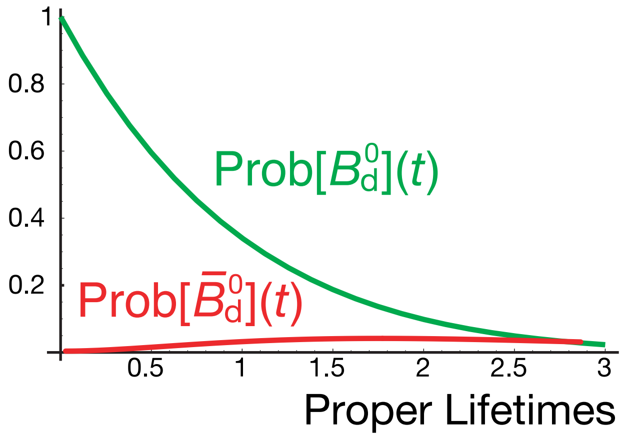
"T (CP) Violation in Mixing"

B^0-$\bar{B}^0$ Mixing and Oscillations

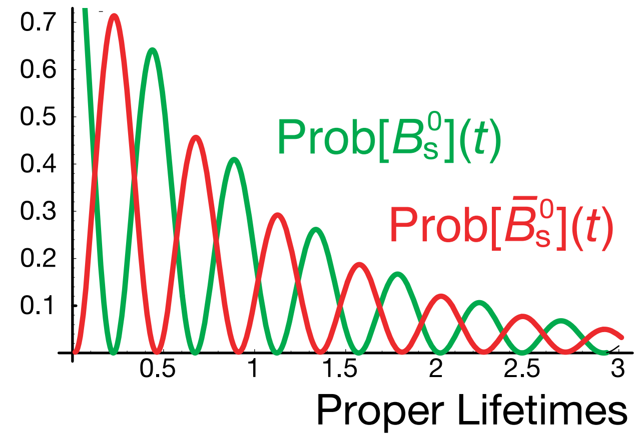




- For B_d^0



- For B_s^0



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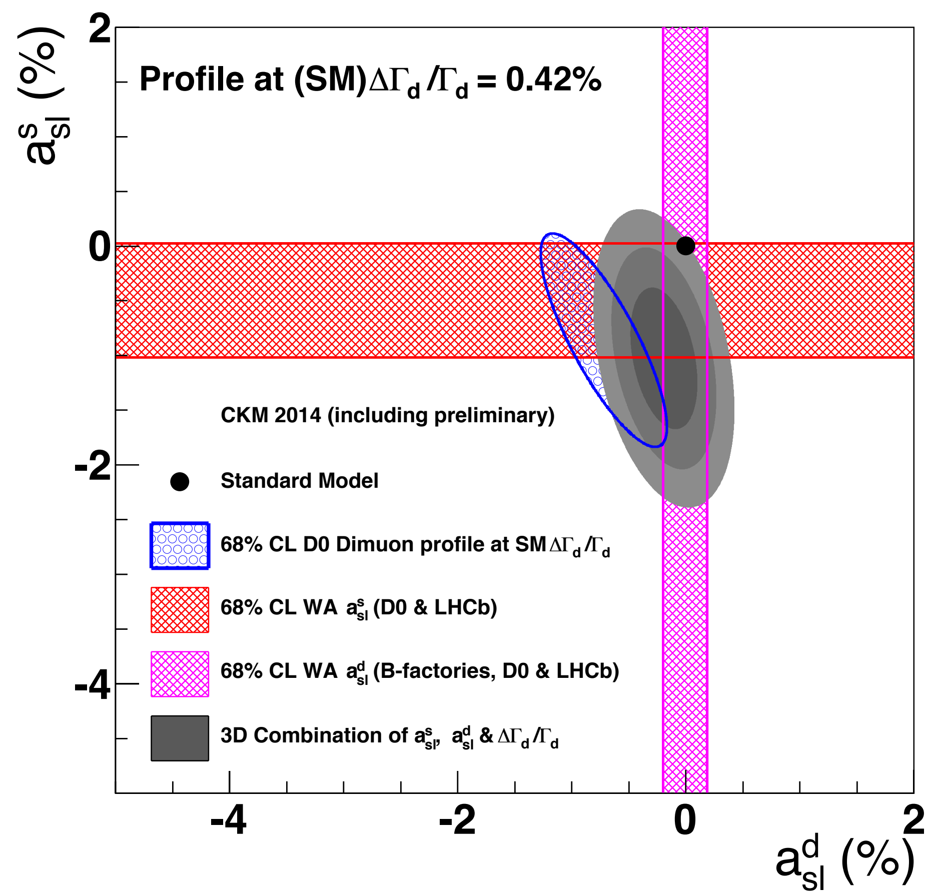
$$P(M^0 \to M^0; t) \neq P(\bar{M}^0 \to \bar{M}^0; t)$$

"*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
  Phys. Rev. D82: 101702, 2010



$$a^s_{\rm sl}(\mathrm{WA}) = (-0.83 \pm 0.43)\,\%, \qquad \rho_{s,d} = -\,0.25,$$
$$a^d_{\rm sl}(\mathrm{WA}) = (-0.09 \pm 0.21)\,\%, \qquad \rho_{d,\Delta\Gamma} = +\,0.23$$
$$\Delta\Gamma_d/\Gamma_d(\mathrm{WA}) = (1.51 \pm 0.91)\,\%, \qquad \rho_{s,\Delta\Gamma} = +\,0.47$$

.

Paramaters

TABLE I. Parameters and uncertainties in the extraction of the CPT-violating parameters.

Parameter	Value	Ref.
A_0	$(-0.40 \pm 0.31)\%$	Eq. 6
A_1	$(0.87 \pm 0.45)\%$	Eq. 6
ϕ	-2.28 ± 0.51	Eq. 6
$m_{B_s^0}$	(5.36677 ± 0.00024) GeV	[17]
Δm_s	$(17.761 \pm 0.022) \times 10^{12}\ \hbar\mathrm{s}^{-1}$	[17]
$\Delta\Gamma_s/\Gamma_s$	(0.138 ± 0.012)	[17]
$\hbar$	$6.58211928 \times 10^{-25}$ GeV·s	[17]
$F_{B_s^0}^{\text{non-osc}} = F_{B_s^0}^{\text{osc}}$	(0.465 ± 0.017)	[12]
$\langle p_z \rangle$	(17.8 ± 1.6) GeV	
$\langle p \rangle$	(25.3 ± 2.3) GeV	
Proton beam dir$^{\text{n}}$ α	219.53°	
Colatitude χ	48.17°	

Systematic Uncertainties

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

Mass Range	0.035%
Mass Binning	0.071%
Fit Function	0.085%
Total	0.12%

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