Test of Lorentz and CPT violation with Neutrinos

Teppei Katori
Massachusetts Institute of Technology

Pascos 2012, Mérida, México, June 5, 2012

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outline

1. Spontaneous Lorentz symmetry breaking
2. What is Lorentz and CPT violation?
3. Test for Lorentz violation with MiniBooNE data
4. Conclusion

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1. Spontaneous Lorentz symmetry breaking

2. What is Lorentz and CPT violation?

3. Test for Lorentz violation with MiniBooNE data

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1. Spontaneous symmetry breaking

Every fundamental symmetry needs to be tested, including Lorentz symmetry.

After the recognition of theoretical processes that create Lorentz violation, testing Lorentz invariance becomes very exciting

Lorentz and CPT violation has been shown to occur in Planck scale theories, including:
- string theory
- noncommutative field theory
- quantum loop gravity
- extra dimensions
- etc

However, it is very difficult to build a self-consistent theory with Lorentz violation...

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Spontaneous Symmetry Breaking (SSB)!

Y. Nambu
(Nobel prize winner 2008),
picture taken from CPT04 at
Bloomington, IN

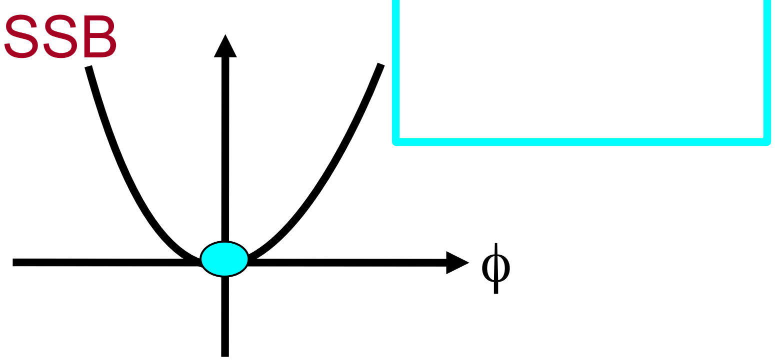
1. Spontaneous Lorentz symmetry breaking

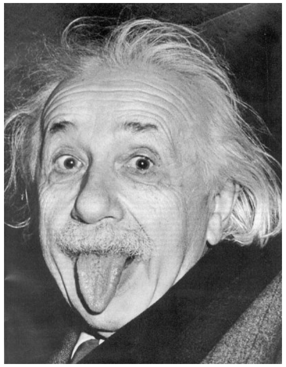
vacuum Lagrangian for fermion $L = i\bar{\Psi}\gamma_\mu \partial^\mu \Psi$

e.g.) SSB of scalar field in Standard Model (SM)

- If the scalar field has Mexican hat potential

$$L = \frac{1}{2}(\partial_\mu \varphi)^2 - \frac{1}{2}\mu^2(\varphi^*\varphi) - \frac{1}{4}\lambda(\varphi^*\varphi)^2$$





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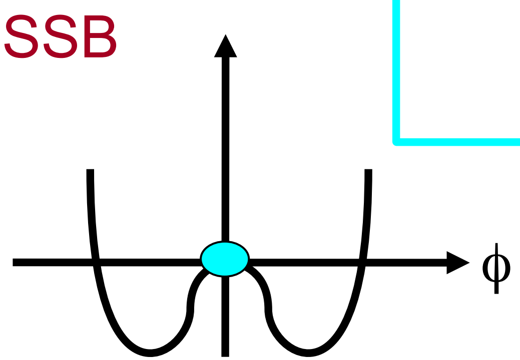

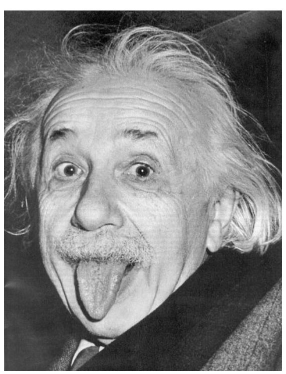

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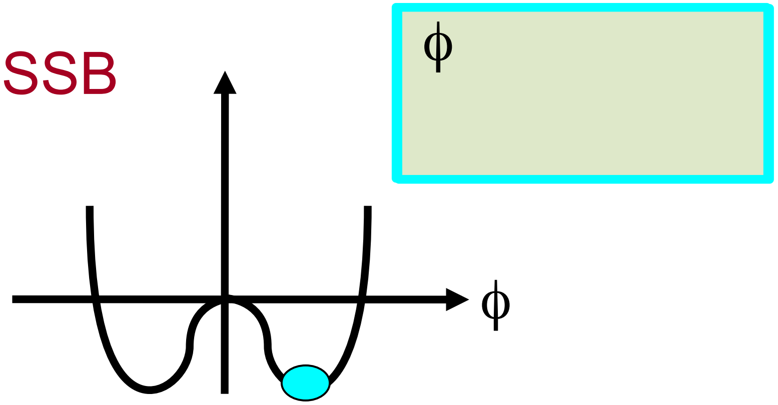
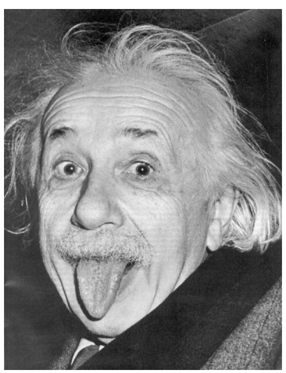
SSB





Particle acquires mass term!

Kostelecký and Samuel
PRD39(1989)683

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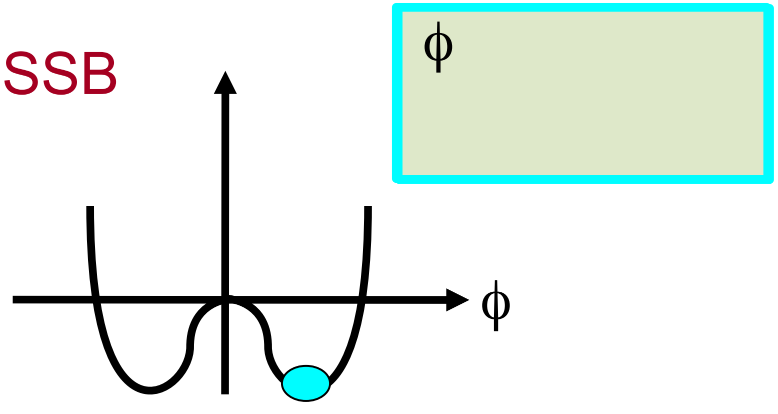
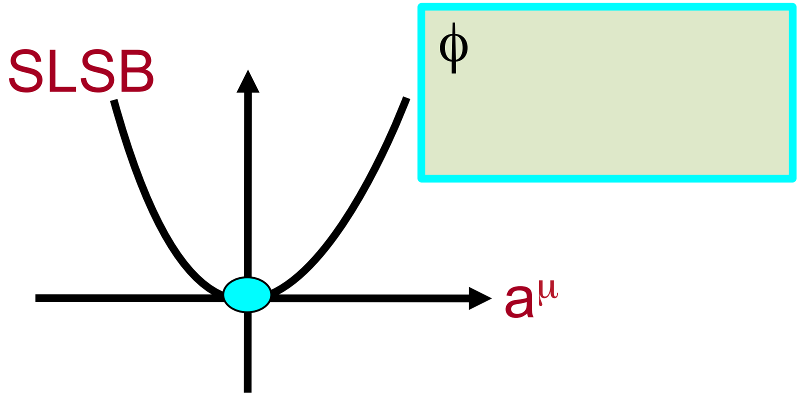
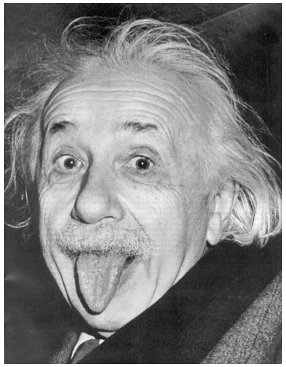


e.g.) SLSB in string field theory
- There are many Lorentz vector fields
- If any of vector field has Mexican hat potential





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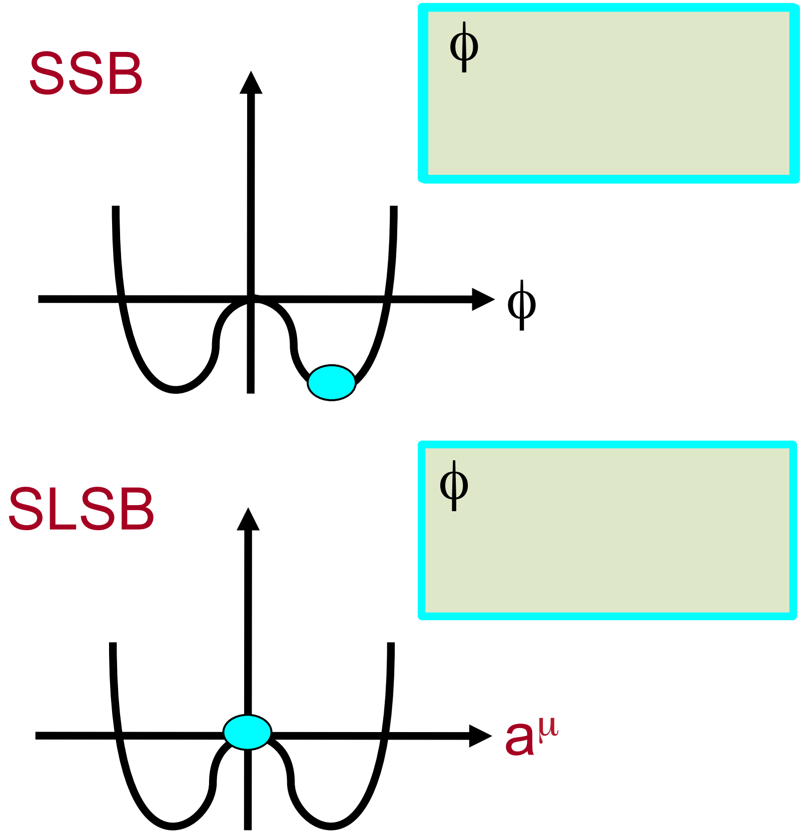

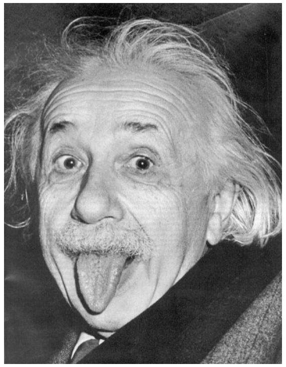

Kostelecký and Samuel
PRD39(1989)683

1. Spontaneous Lorentz symmetry breaking

vacuum Lagrangian for fermion $L = i\overline{\Psi}\gamma_\mu \partial^\mu \Psi - m\overline{\Psi}\Psi + \overline{\Psi}\gamma_\mu a^\mu \Psi$

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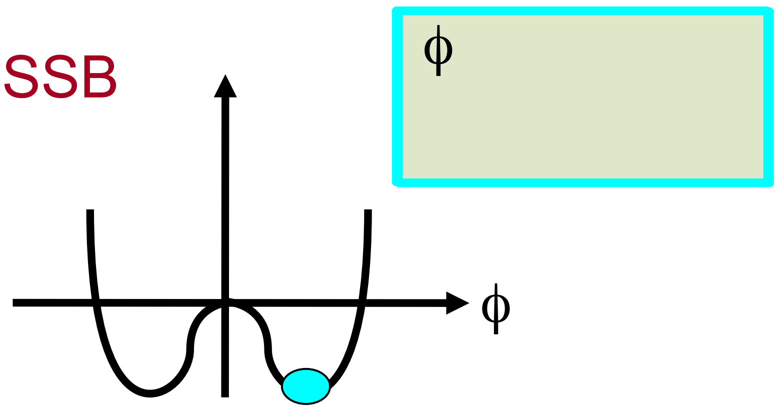

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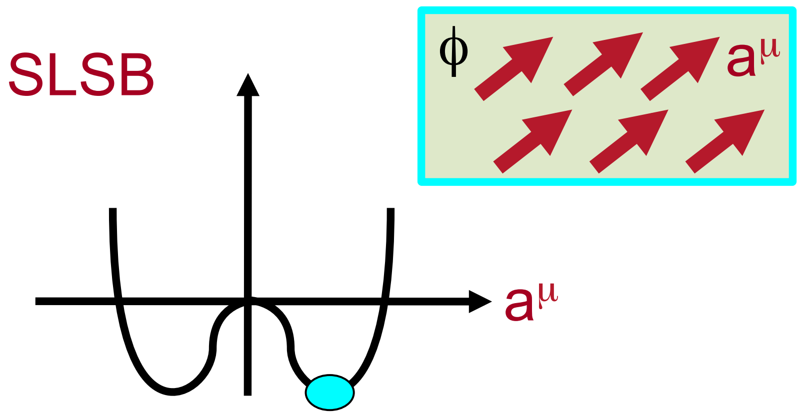


Lorentz symmetry is spontaneously broken!

1. Spontaneous Lorentz symmetry breaking

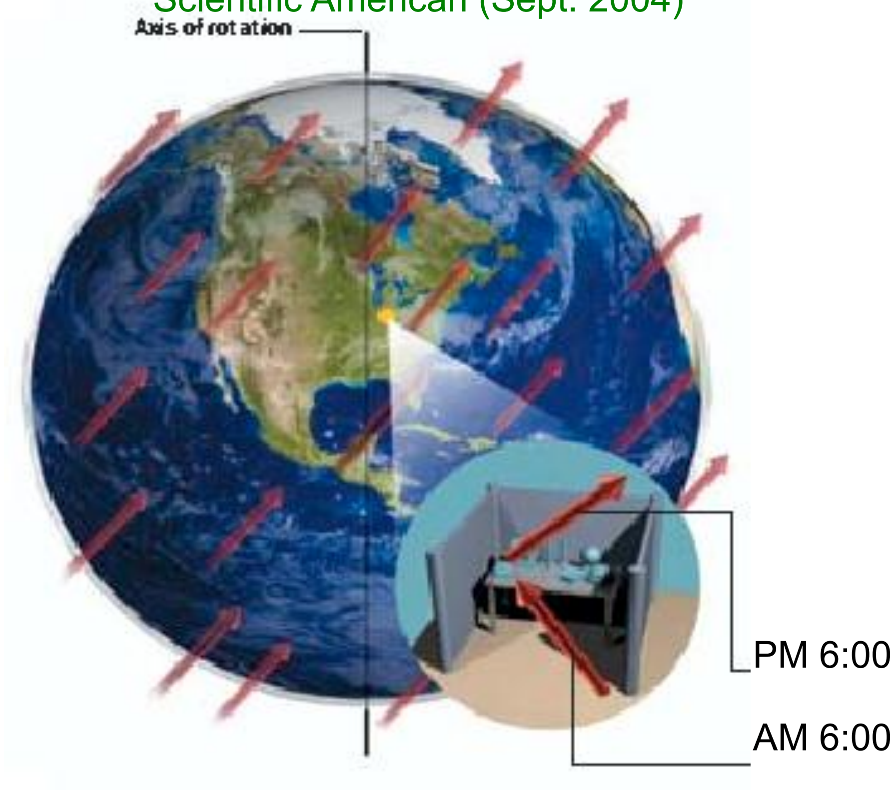
Test of Lorentz violation is to find the coupling of these background fields and ordinary fields (electrons, muons, neutrinos etc), then physical quantities may depend on the rotation of the earth.

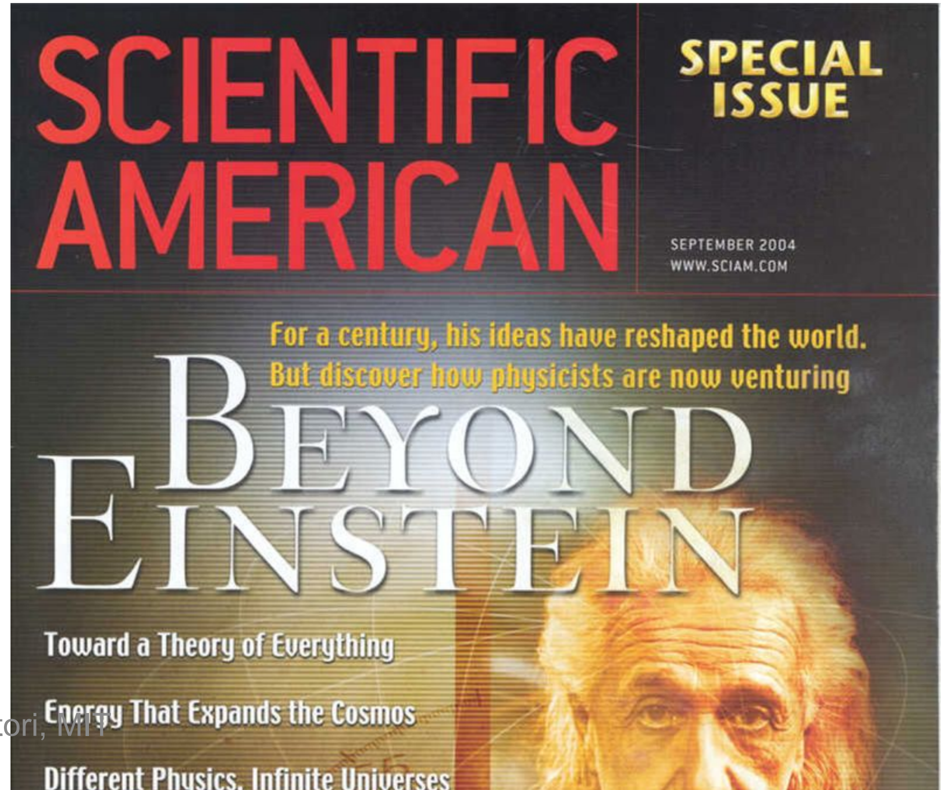
background field of the universe

vacuum Lagrangian for fermion

$$L = i\bar{\Psi}\gamma_\mu\partial^\mu\Psi - m\bar{\Psi}\Psi + \bar{\Psi}\gamma_\mu \boxed{a^\mu}\Psi + \bar{\Psi}\gamma_\mu \boxed{c^{\mu\nu}}\partial_\nu\Psi \ldots$$

Scientific American (Sept. 2004)





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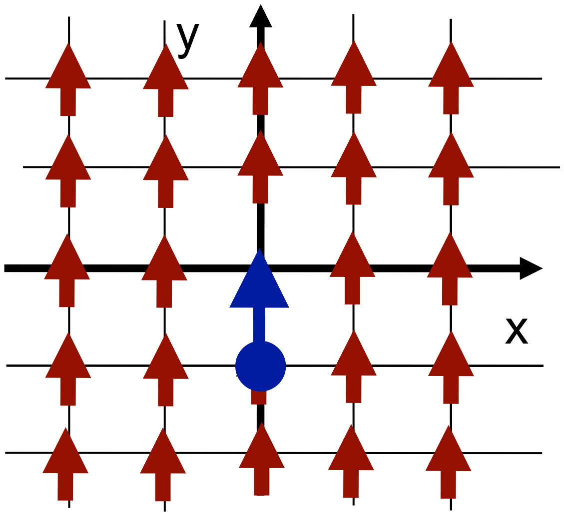
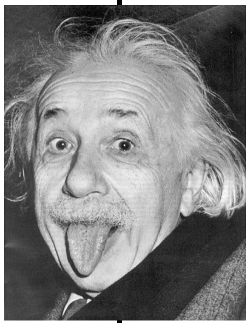
2. What is Lorentz violation?

$$\overline{\Psi}(x)\gamma_\mu a^\mu \Psi(x)$$





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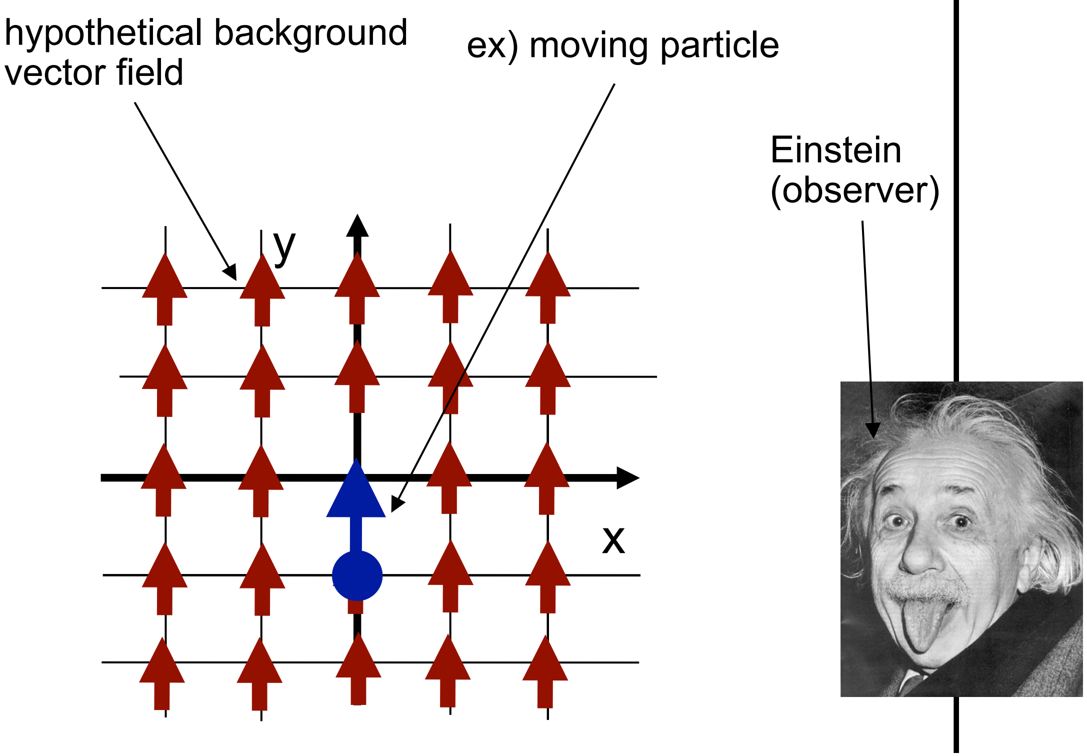

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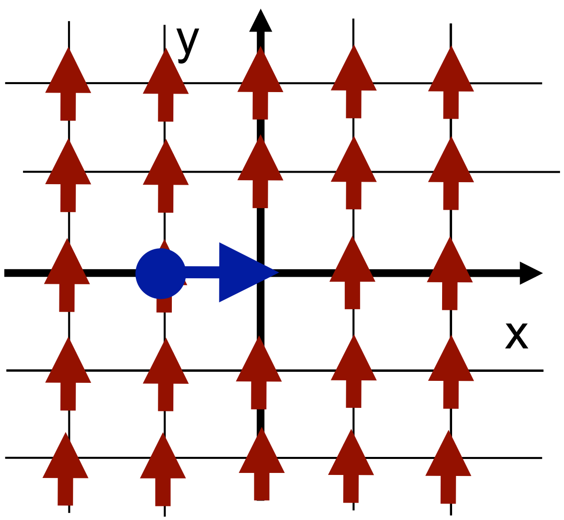
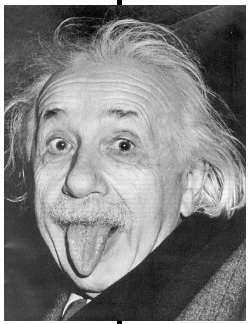
Under the particle Lorentz Transformation;

$$U\,\overline{\Psi}(x)\gamma_\mu a^\mu \Psi(x)\,U^{-1}$$





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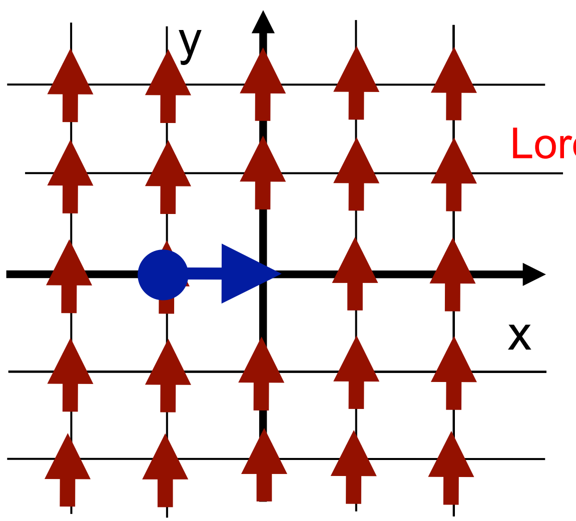
$$\overline{\Psi}(x)\gamma_\mu a^\mu \Psi(x) \rightarrow U[\overline{\Psi}(x)\gamma_\mu a^\mu \Psi(x)]U^{-1}$$

$$\neq \overline{\Psi}(\Lambda x)\gamma_\mu a^\mu \Psi(\Lambda x)$$

Lorentz violation is observable when particle is moving in the fixed coordinate space



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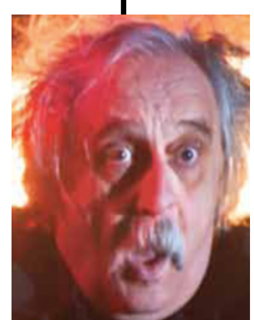

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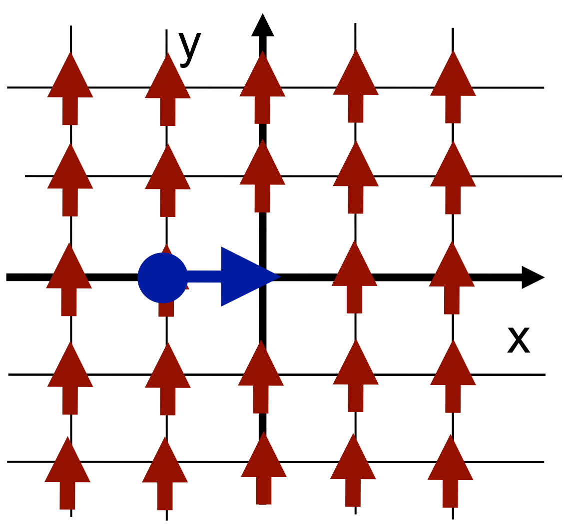

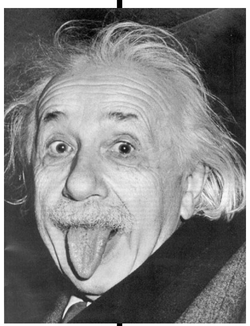

Under the observer Lorentz Transformation;

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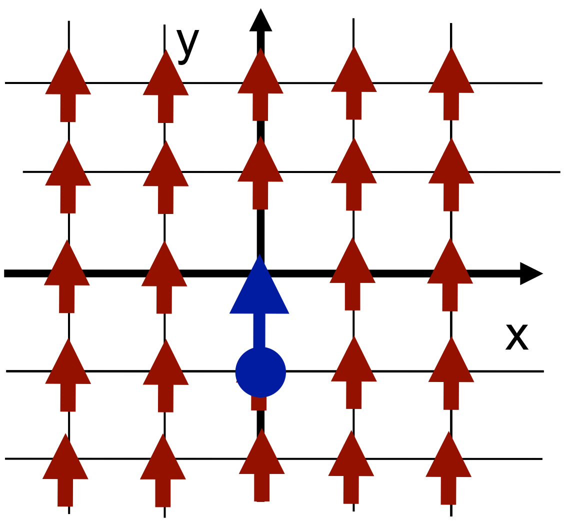

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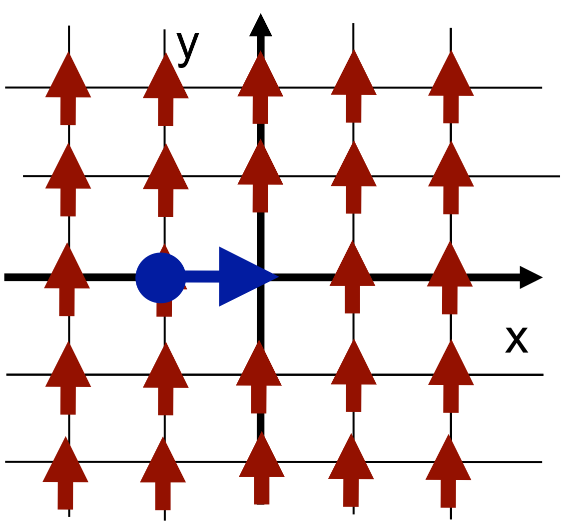

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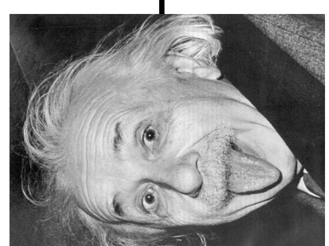

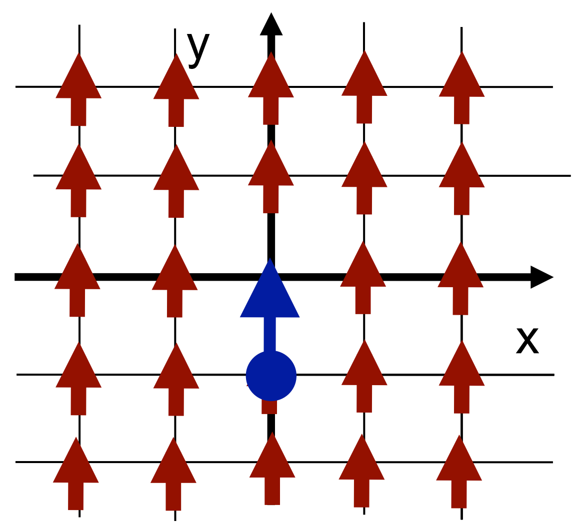

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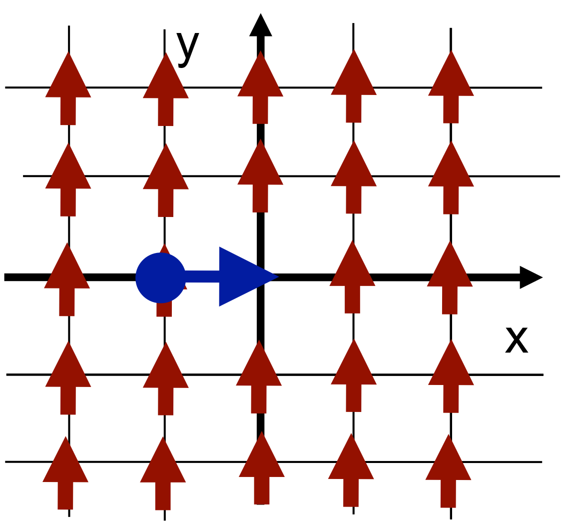

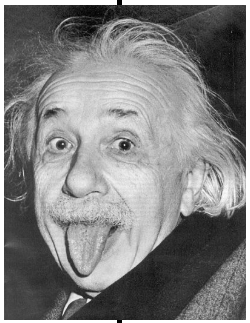

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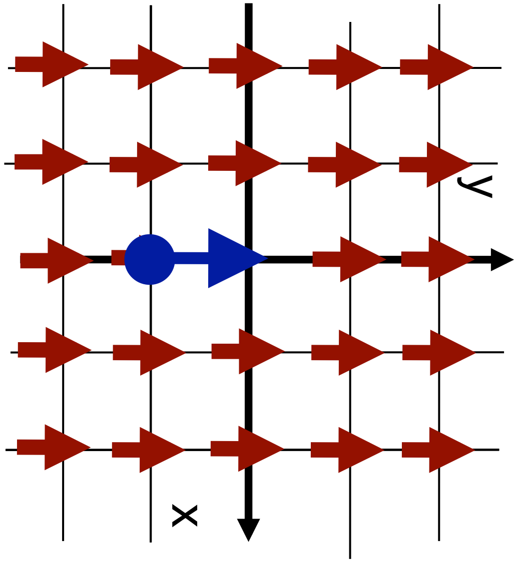

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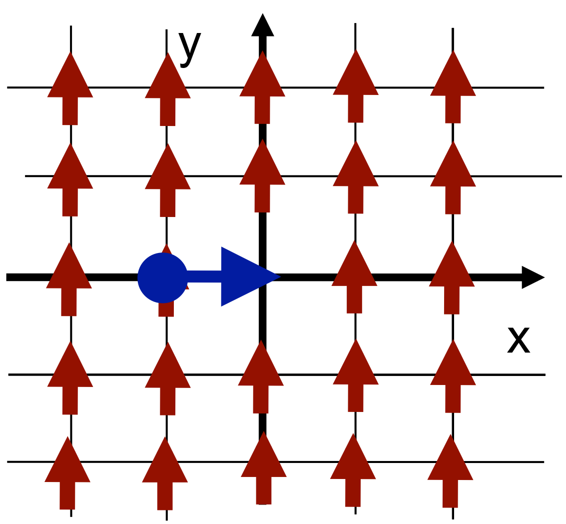
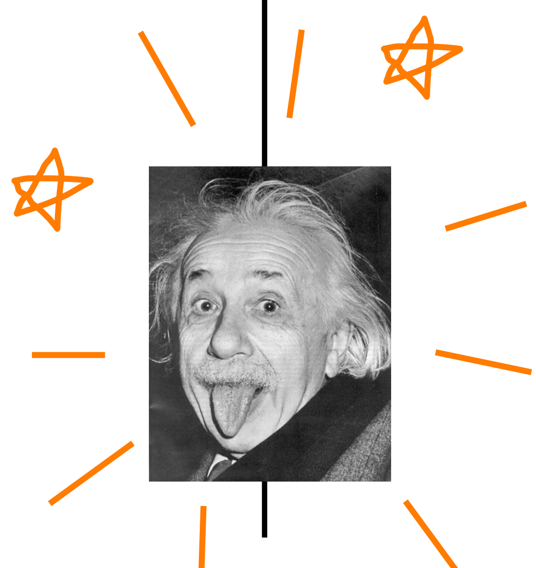


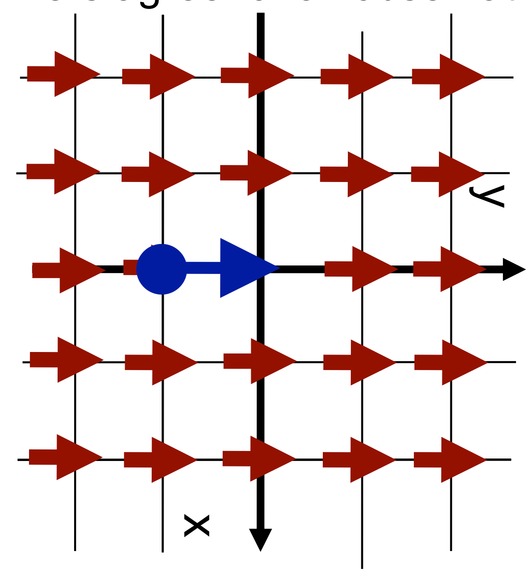
Under the observer Lorentz Transformation;

$$\overline{\Psi}(x)\gamma_\mu a^\mu \Psi(x) \xrightarrow{\Lambda^{-1}} \overline{\Psi}(\Lambda^{-1}x)\gamma_\mu a^\mu \Psi(\Lambda^{-1}x)$$

Lorentz violation cannot be seen by observers motion (coordinate transformation is unbroken)

any observers agree for all observations





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3. MiniBooNE experiment

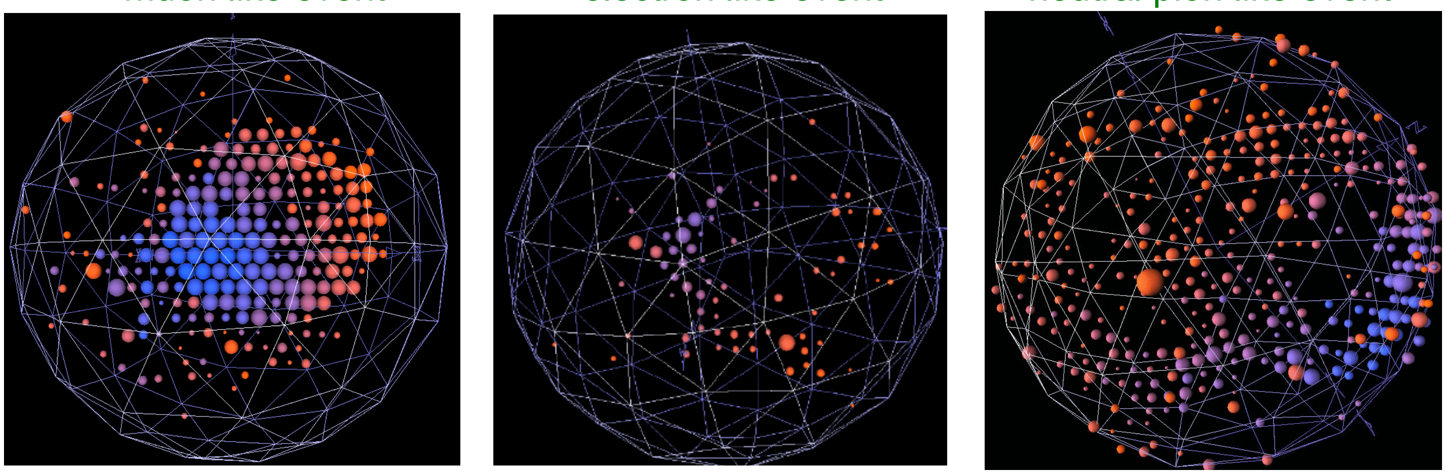
MiniBooNE collaboration,
PRD79(2009)072002
NIM.A599(2009)28

MiniBooNE neutrino oscillation experiment at Fermilab is looking for ν_μ to ν_e oscillation

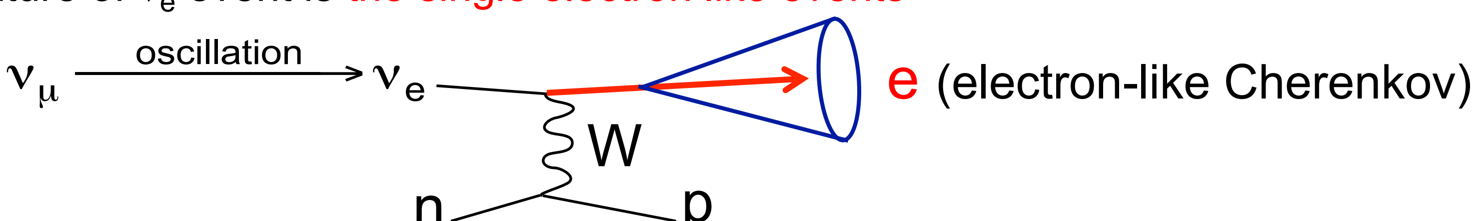
- Booster Neutrino Beamline (BNB) creates:
  ~800 MeV muon neutrino beam by π^+ decay-in-flight
  ~600 MeV muon anti-neutrino beam by π^- decay-in-flight

- MiniBooNE detector identifies particles from Cherenkov ring profiles

muon like event | electron like event | neutral pion like event



Signature of ν_e event is the single electron like events

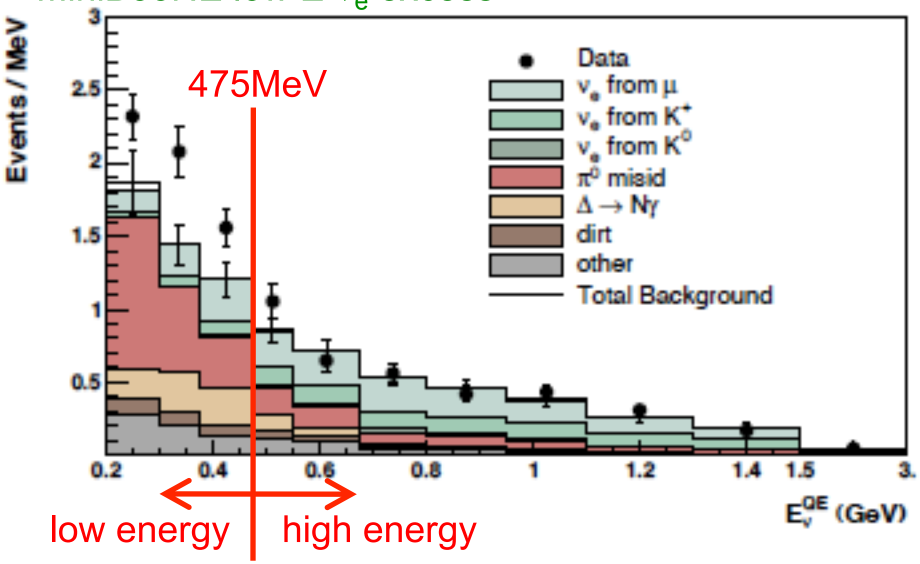


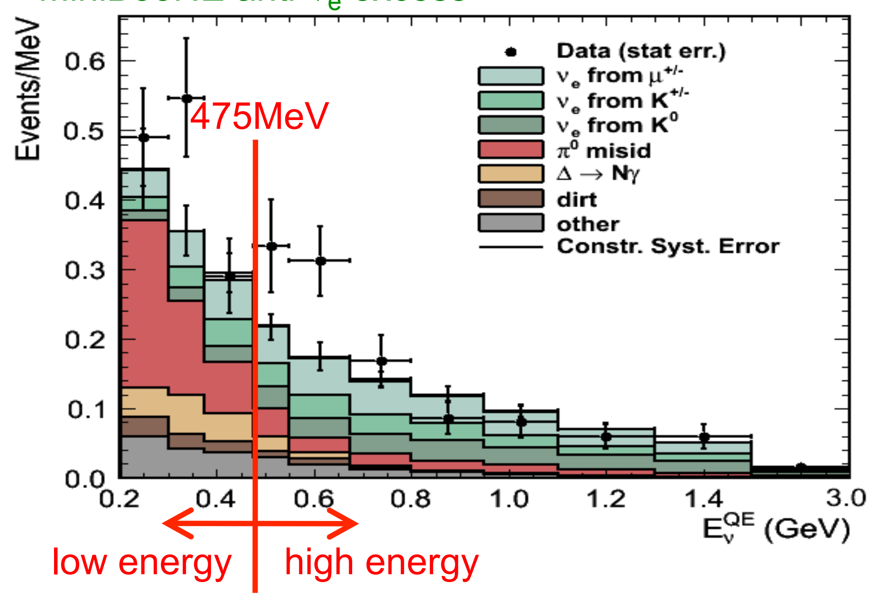
MiniBooNE collaboration,
PRL102(2009)101802,
PRL105(2010)181801

3. MiniBooNE oscillation analysis results

Neutrino mode low energy excess
MiniBooNE see the excess at low energy region.

Antineutrino mode excess
MiniBooNE see the excess at combined region.





These excesses are not predicted by neutrino Standard Model (νSM).
Oscillation candidate events may have sidereal time dependence.

3. Test of Lorentz violation with neutrino oscillation experiments

Lorentz violation is realized as a coupling of particle fields and the background fields, so the basic strategy is to find the Lorentz violation is:

(1) fix the coordinate system
(2) write down Lagrangian including Lorentz violating terms under the formalism
(3) write down the observables using this Lagrangian

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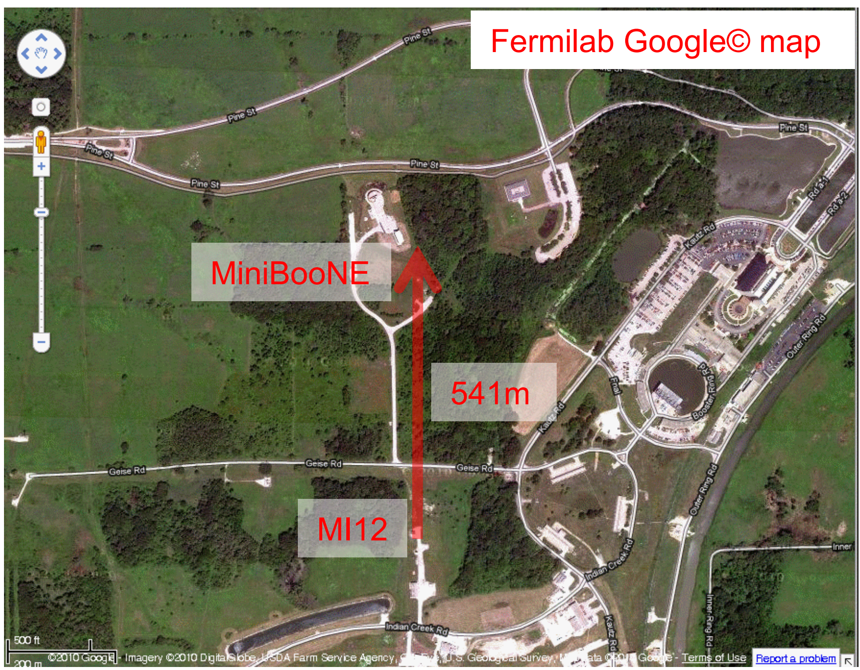
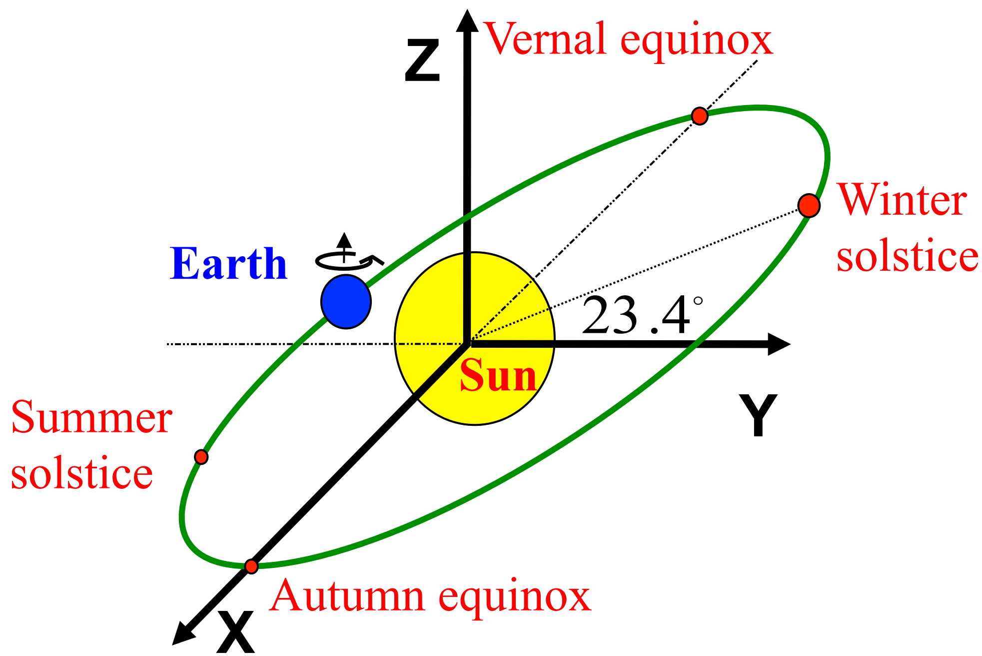
- Booster neutrino beamline is described in Sun-centred coordinates





Kostelecký and Mewes
PRD69(2004)016005

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Standard Model Extension (SME) is a standard formalism for the general search of Lorentz violation. SME is a minimum extension of QFT with Particle Lorentz violation

Modified Dirac Equation (MDE) of neutrinos

$$i(\Gamma^{\nu}_{AB}\partial_{\nu} - M_{AB})\nu_B = 0$$

SME coefficients

$$\Gamma^{\nu}_{AB} = \gamma^{\nu}\delta_{AB} + c^{\mu\nu}_{AB}\gamma_{\mu} + d^{\mu\nu}_{AB}\gamma_{\mu}\gamma_5 + e^{\nu}_{AB} + if^{\nu}_{AB}\gamma_5 + \frac{1}{2}g^{\lambda\mu\nu}_{AB}\sigma_{\lambda\mu}$$

$$M_{AB} = m_{AB} + im_{5AB}\gamma_5 + a^{\mu}_{AB}\gamma_{\mu} + b^{\mu}_{AB}\gamma_5\gamma_{\mu} + \frac{1}{2}H^{\mu\nu}_{AB}\sigma_{\mu\nu}$$

Kostelecký and Mewes
PRD70(2004)076002

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Various physics is predicted under SME, but among them, the smoking gun of Lorentz violation is the sidereal time dependence of the observables.

Solar time: 24h 00m 00.0s
sidereal time: 23h 56m 04.1s

sidereal frequency $w_{\oplus} = \frac{2\pi}{23h56m4.1s}$

sidereal time $T_{\oplus}$

Lorentz violating neutrino oscillation probability for short baseline experiments

$$P_{\nu_e \to \nu_\mu} = \left(\frac{L}{\hbar c}\right)^2 \left|(C)_{e\mu} + (A_s)_{e\mu} \sin w_{\oplus} T_{\oplus} + (A_c)_{e\mu} \cos w_{\oplus} T_{\oplus} + (B_s)_{e\mu} \sin 2w_{\oplus} T_{\oplus} + (B_c)_{e\mu} \cos 2w_{\oplus} T_{\oplus}\right|^2$$

Sidereal variation analysis for MiniBooNE is 5 parameter fitting problem

Kostelecký and Mewes PRD70(2004)076002

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Sidereal variation analysis for MiniBooNE is 5 parameter fitting problem

In the fit, high correlation of parameters expand contours too much, so we focus on 3 parameter fit for error evaluation (contours are evaluated from fake data)

MiniBooNE collaboration,
ArXiv:1109.3480

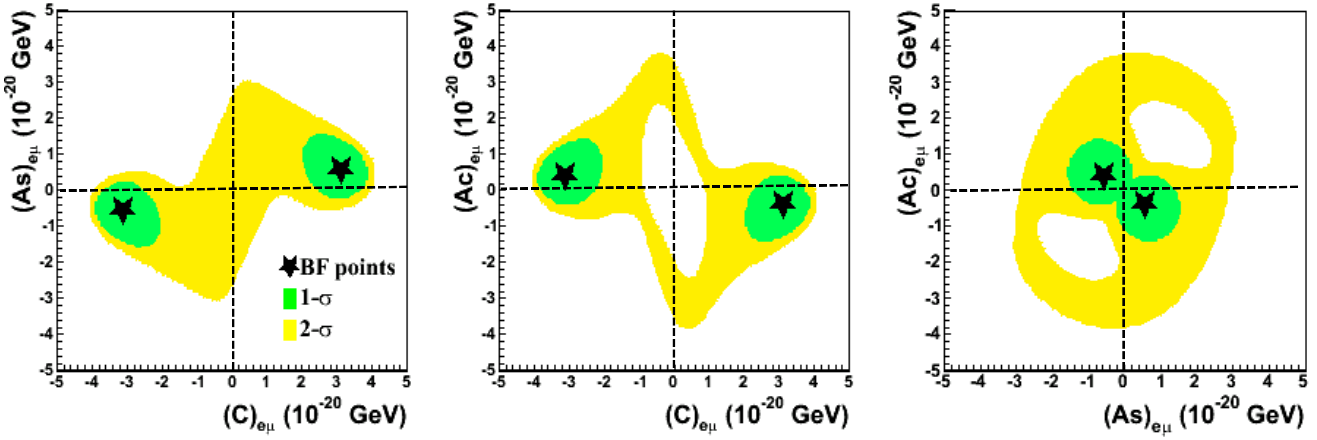
3. Lorentz violation with MiniBooNE neutrino data

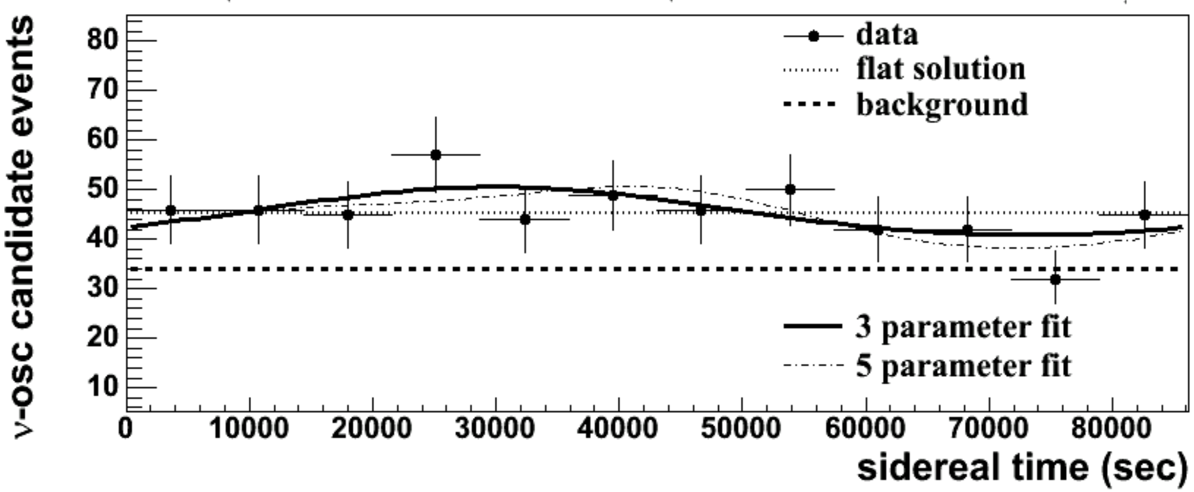
Neutrino mode result, low energy region

Only C-parameter is nonzero, but this is sidereal independent parameter.

26.9% C.L. with flat hypothesis by fake data $\Delta\chi^2$ study

The neutrino mode low energy excess is consistent with no sidereal variation.





MiniBooNE collaboration,
ArXiv:1109.3480

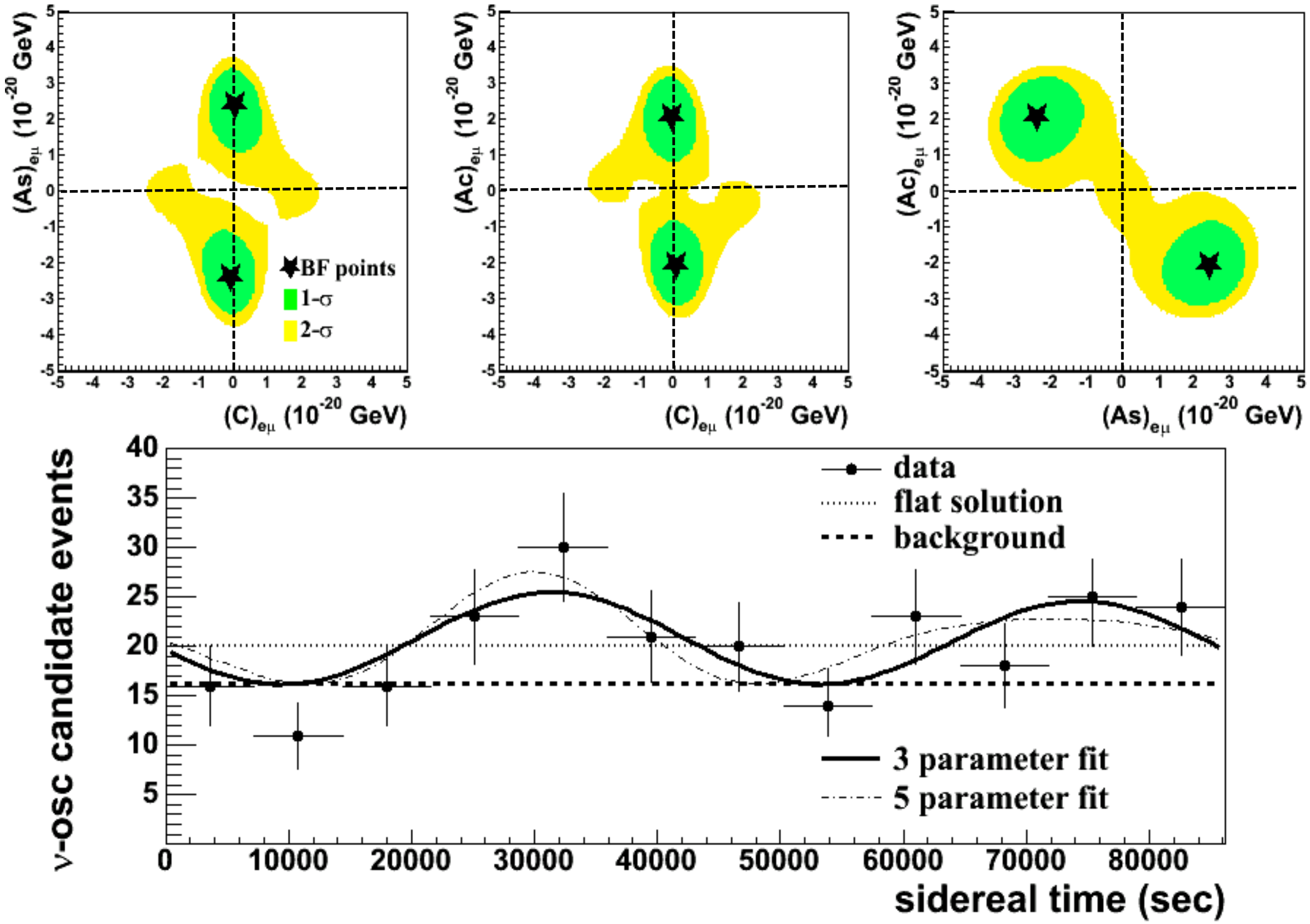
3. Lorentz violation with MiniBooNE anti-neutrino data

Anti-neutrino mode result, combined energy region

As and Ac-parameters are nonzero, which are sidereal dependent parameters.

3.0% C.L. with flat hypothesis by fake data $\Delta\chi^2$ study

The anti-neutrino mode combined energy region excess prefer sidereal time dependent solution, but not statistically significant level.



3. Summary of results

SME coefficients combination

- The combinations of SME coefficients are extracted
- First time constrained time independent SME coefficients for e-μ sector

	ν−mode BF	2σ limit	$\bar{\nu}$−mode BF	2σ limit	SME coefficients combination (unit 10^{-20} GeV)
$\|(\mathcal{C})_{e\mu}\|$	$3.1 \pm 0.6 \pm 0.9$	< 4.2	$0.1 \pm 0.8 \pm 0.1$	< 2.6	$\pm[(a_L)^T_{e\mu} + 0.75(a_L)^Z_{e\mu}] - <E> [1.22(c_L)^{TT}_{e\mu} + 1.50(c_L)^{TZ}_{e\mu} + 0.34(c_L)^{ZZ}_{e\mu}]$
$\|(\mathcal{A}_s)_{e\mu}\|$	$0.6 \pm 0.9 \pm 0.3$	< 3.3	$2.4 \pm 1.3 \pm 0.5$	< 3.9	$\pm[0.66(a_L)^Y_{e\mu}] - <E> [1.33(c_L)^{TY}_{e\mu} + 0.99(c_L)^{YZ}_{e\mu}]$
$\|(\mathcal{A}_c)_{e\mu}\|$	$0.4 \pm 0.9 \pm 0.4$	< 4.0	$2.1 \pm 1.2 \pm 0.4$	< 3.7	$\pm[0.66(a_L)^X_{e\mu}] - <E> [1.33(c_L)^{TX}_{e\mu} + 0.99(c_L)^{XZ}_{e\mu}]$

SME coefficient limit

2σ limit of each SME coefficient

Are they consistent with other experiments? such as LSND.

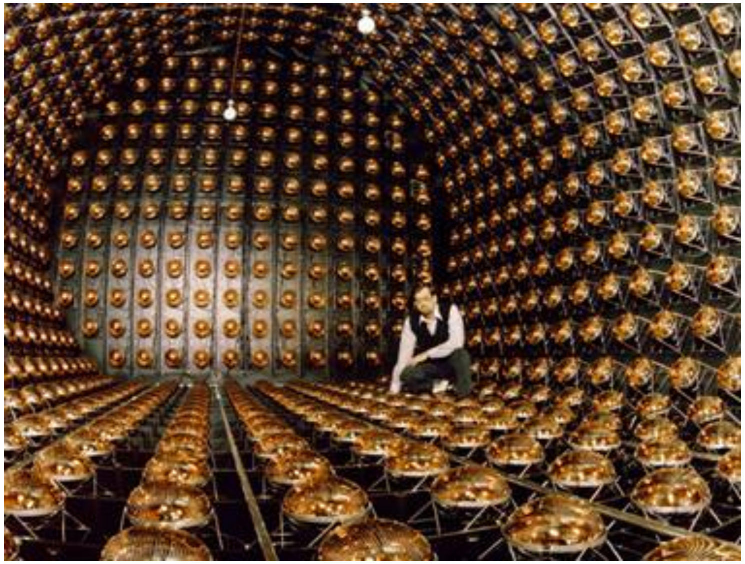
Coefficient	$e\mu$ (ν mode low energy region)	$e\mu$ ($\bar{\nu}$ mode combined region)
$\mathrm{Re}(a_L)^T$ or $\mathrm{Im}(a_L)^T$	4.2×10^{-20} GeV	2.6×10^{-20} GeV
$\mathrm{Re}(a_L)^X$ or $\mathrm{Im}(a_L)^X$	6.0×10^{-20} GeV	5.6×10^{-20} GeV
$\mathrm{Re}(a_L)^Y$ or $\mathrm{Im}(a_L)^Y$	5.0×10^{-20} GeV	5.9×10^{-20} GeV
$\mathrm{Re}(a_L)^Z$ or $\mathrm{Im}(a_L)^Z$	5.6×10^{-20} GeV	3.5×10^{-20} GeV
$\mathrm{Re}(c_L)^{XY}$ or $\mathrm{Im}(c_L)^{XY}$	—	—
$\mathrm{Re}(c_L)^{XZ}$ or $\mathrm{Im}(c_L)^{XZ}$	1.1×10^{-19}	6.2×10^{-20}
$\mathrm{Re}(c_L)^{YZ}$ or $\mathrm{Im}(c_L)^{YZ}$	9.2×10^{-20}	6.5×10^{-20}
$\mathrm{Re}(c_L)^{XX}$ or $\mathrm{Im}(c_L)^{XX}$	—	—
$\mathrm{Re}(c_L)^{YY}$ or $\mathrm{Im}(c_L)^{YY}$	—	—
$\mathrm{Re}(c_L)^{ZZ}$ or $\mathrm{Im}(c_L)^{ZZ}$	3.4×10^{-19}	1.3×10^{-19}
$\mathrm{Re}(c_L)^{TT}$ or $\mathrm{Im}(c_L)^{TT}$	9.6×10^{-20}	3.6×10^{-20}
$\mathrm{Re}(c_L)^{TX}$ or $\mathrm{Im}(c_L)^{TX}$	8.4×10^{-20}	4.6×10^{-20}
$\mathrm{Re}(c_L)^{TY}$ or $\mathrm{Im}(c_L)^{TY}$	6.9×10^{-20}	4.9×10^{-20}
$\mathrm{Re}(c_L)^{TZ}$ or $\mathrm{Im}(c_L)^{TZ}$	7.8×10^{-20}	2.9×10^{-20}

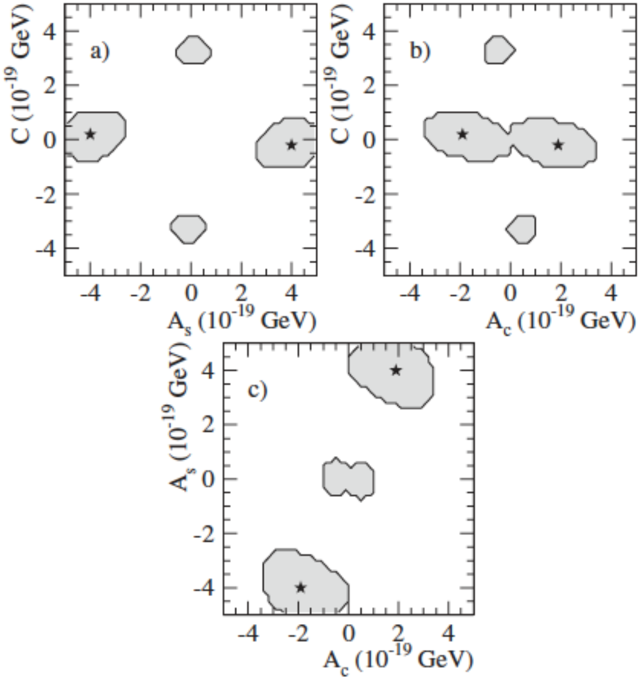
LSND collaboration,
PRD72(2005)076004

3. LSND experiment

Consistency with LSND
 - Similar analysis was done with LSND data, prior of MiniBooNE analysis

LSND detector





LSND data is explained by nonzero SME coefficients
 - SME limit from MiniBooNE data exclude SME coefficient extracted from LSND
 - Simple scenario cannot accommodate LSND and MiniBooNE result under minimal SME

Conclusion

Lorentz and CPT violation has been shown to occur in Planck scale physics.

There are world wide effort for the test of Lorentz violation using various type of state-of-art technologies.

LSND and MiniBooNE data suggest Lorentz violation is an interesting solution of neutrino oscillation.

MiniBooNE neutrino mode data prefer sidereal time independent solution. On the other hand, anti-neutrino mode data prefer sidereal time dependent solution, although statistical significance is not high enough.

Thank you for your attention!

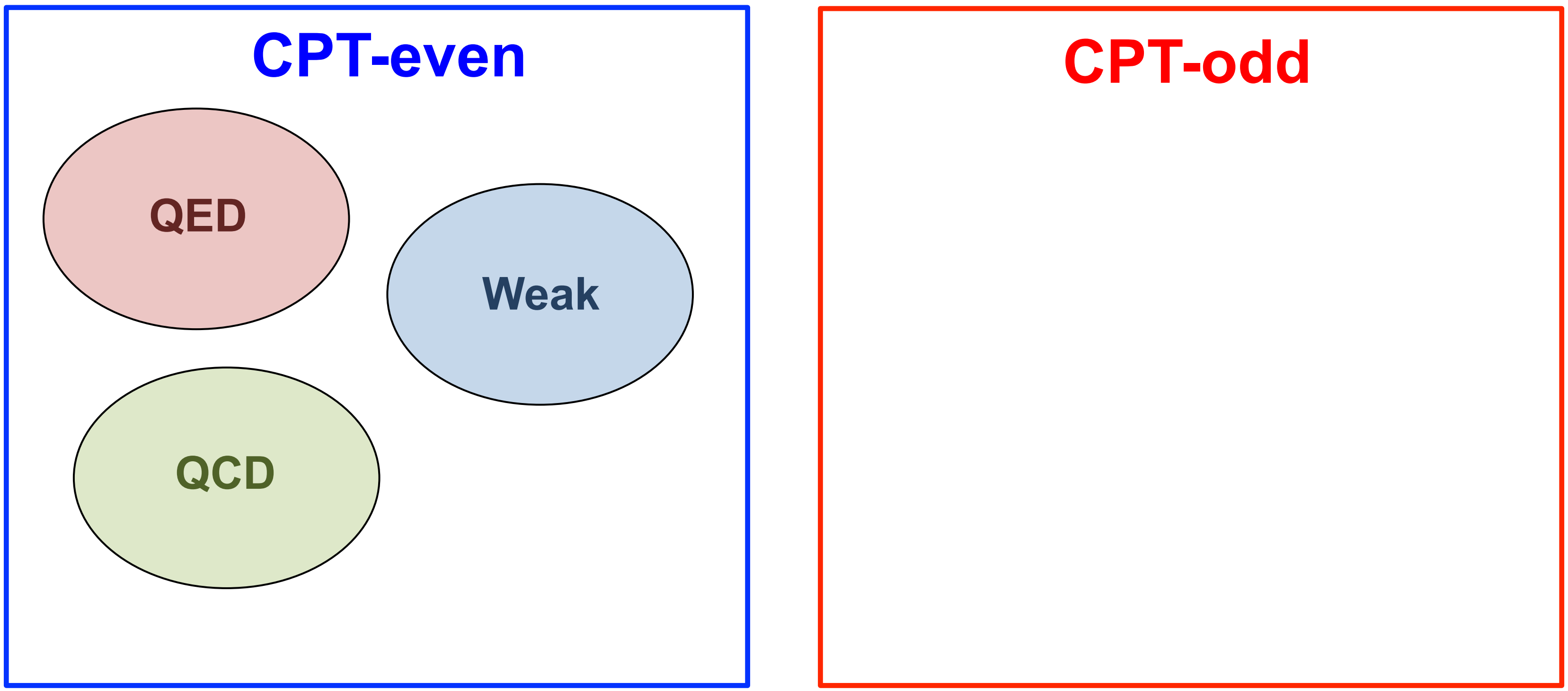
Backup

2. What is CPT violation?

CPT symmetry is the invariance under the CPT transformation

$$L \xrightarrow{CPT} \Theta L \Theta^{-1} = L' = L, \qquad \Theta = CPT$$

CPT is the perfect symmetry of the Standard Model, due to CPT theorem



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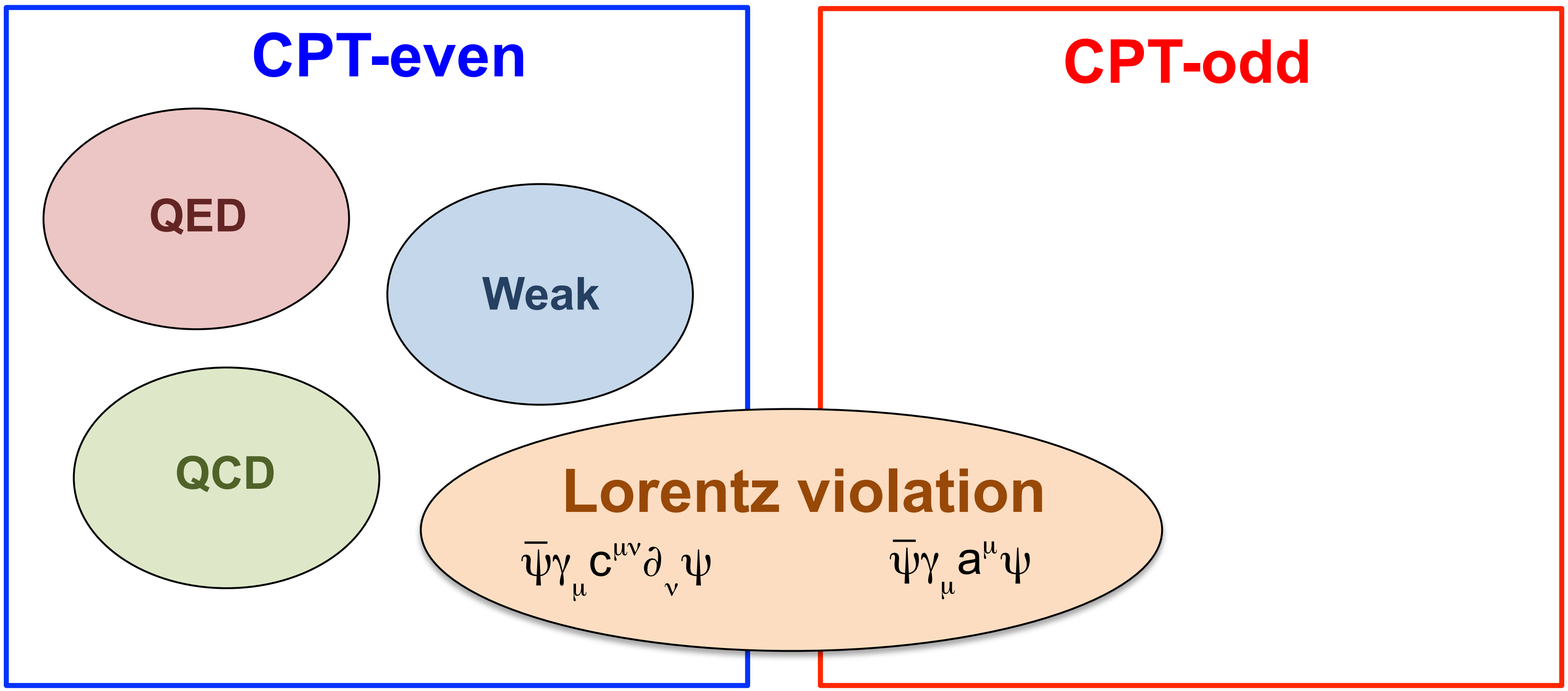


CPT-odd Lorentz violating coefficients (odd number Lorentz indices, ex., a^μ , $g^{\lambda\mu\nu}$)
CPT-even Lorentz violating coefficients (even number Lorentz indices, ex., $c^{\mu\nu}$, $\kappa^{\alpha\beta\mu\nu}$)

5. Oscillation analysis background summary

475 MeV – 1250 MeV

ν_e^K	94
ν_e^μ	132
π^0	62
dirt	17
$\Delta \rightarrow N\gamma$	20
other	33
total	358

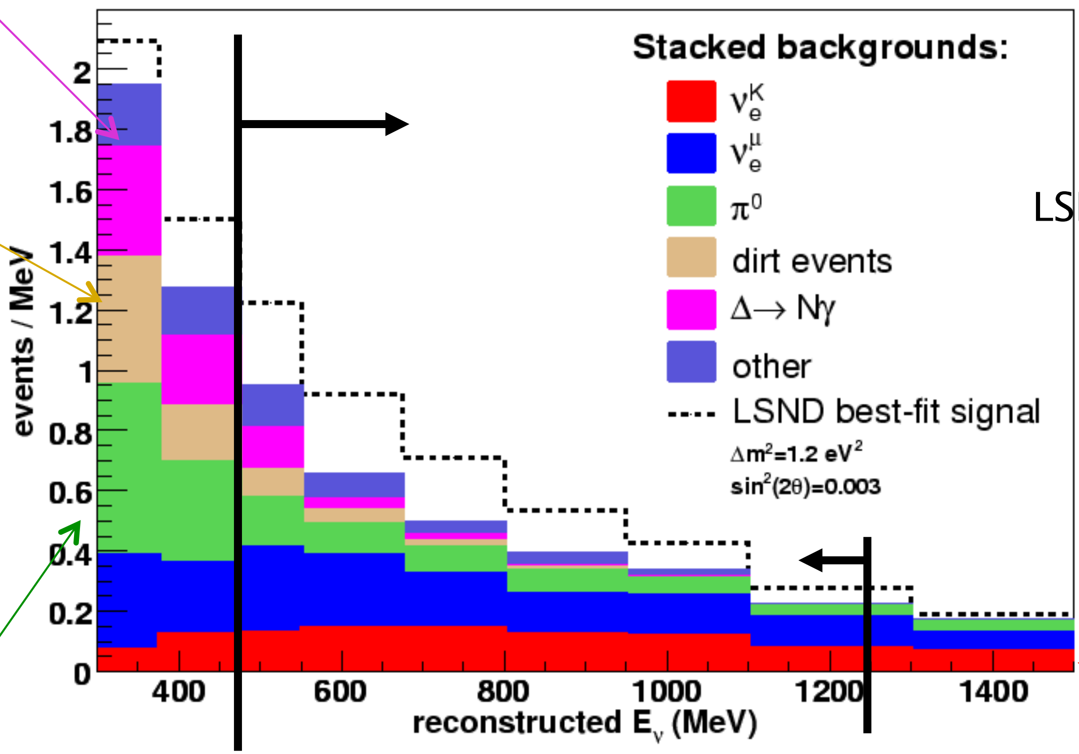
LSND best-fit $\nu_\mu \rightarrow \nu_e$ 126

Oscillation analysis summary

- Oscillation analysis uses 475MeV<E<1250MeV

Δ resonance rate is constrained from measured CCπ^o rate

dirt rate is measured from dirt data sample



ν_e from μ decay is constrained from ν_μCCQE measurement

ν_e from K decay is constrained from high energy ν_e event measurement

Asymmetric π^o decay is constrained from measured CCπ^o rate ($\pi^o \rightarrow \gamma$)

All backgrounds are measured in other data sample and their errors are constrained!