A theoretical review of the implications of the OPERA results

or

Why do we study Lorentz violation ?

Sergey Sibiryakov
(INR RAS, Moscow)

XX International Workshop on Deep-Inelastic Scattering and Related Subjects

Motivation to consider theories with deviations from Lorentz invariance:

- Theoretical: A consequence of the (yet unknown) theory of quantum gravity (space-time foam, gravity with anisotropic scaling, ...) ?

  NB. String theory is consistent with LI, but allows Lorentz breaking backgrounds

- Phenomenological: A consistent framework to better pin down LI

Effective Field Theory description

$$\mathcal{L} = \bar{\psi}_a [i\gamma^0 D_0 + i c_a \gamma^i D_i - m_a] \psi_a + \ldots$$

species-dependent velocity

Impose a subgroup of the Lorentz group

E.g. spatial isotropy in a preferred frame

NB. Photon velocity is normalized to 1

Possibly, higher-order terms suppressed by M_{Pl}.
Subdominant at low energies

The best limits

Kostelecky, Russel (2011)

protons: $|\delta c_p| < 10^{-22}$

independence of nuclear levels of the spin orientation (the preferred frame identified with CMB ➡ anisotropy in the Earth-related system)

electrons: $|\delta c_e| < 10^{-15}$

synchrotron losses at LEP, spectrum of the Crab Nebula ($-\dot{E} \propto (1-v^2)^{-2}$, v - electron group velocity)

muons: $-\delta c_\mu < 10^{-11}$

TeV radiation from the Crab Nebula (absence of photon decay $\gamma \to \mu^+\mu^-$)

LV in neutrinos before OPERA: direct bounds

SN1987a: 24 $\bar{\nu}_e$ with $7.5\mathrm{MeV} \leq E \leq 39\mathrm{MeV}$ arrived within 12.4 seconds and 4 hours before the light

$$|\delta c_{\bar{\nu}_e}(15\mathrm{MeV})| < 10^{-9}$$

$$|\delta c_{\bar{\nu}_e}(30\mathrm{MeV}) - \delta c_{\bar{\nu}_e}(10\mathrm{MeV})| < 5 \times 10^{-13}$$

LV in neutrinos before OPERA: direct bounds

SN1987a: 24 $\bar{\nu}_e$ with $7.5\mathrm{MeV} \leq E \leq 39\mathrm{MeV}$ arrived within 12.4 seconds and 4 hours before the light

$$|\delta c_{\bar{\nu}_e}(15\mathrm{MeV})| < 10^{-9}$$

$$|\delta c_{\bar{\nu}_e}(30\mathrm{MeV}) - \delta c_{\bar{\nu}_e}(10\mathrm{MeV})| < 5 \times 10^{-13}$$

MINOS: baseline 735 km, $E \approx 3\mathrm{GeV}$

$$\delta c_{\nu_\mu}(3\mathrm{GeV}) = (5.1 \pm 2.9) \times 10^{-5}$$

LV in neutrinos before OPERA: direct bounds

SN1987a: 24 $\bar{\nu}_e$ with $7.5\mathrm{MeV} \leq E \leq 39\mathrm{MeV}$ arrived within 12.4 seconds and 4 hours before the light

$$|\delta c_{\bar{\nu}_e}(15\mathrm{MeV})| < 10^{-9}$$

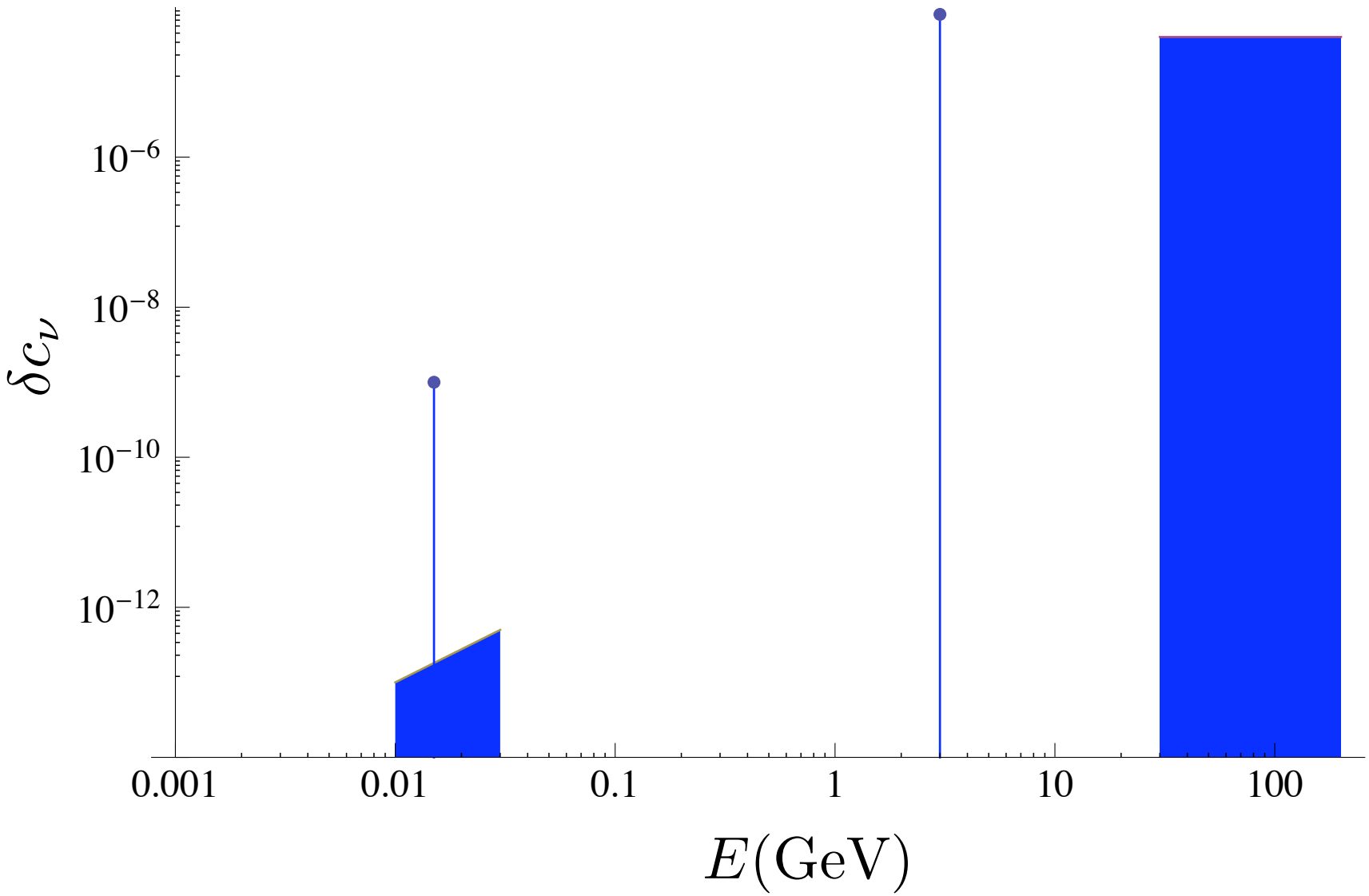
$$|\delta c_{\bar{\nu}_e}(30\mathrm{MeV}) - \delta c_{\bar{\nu}_e}(10\mathrm{MeV})| < 5 \times 10^{-13}$$

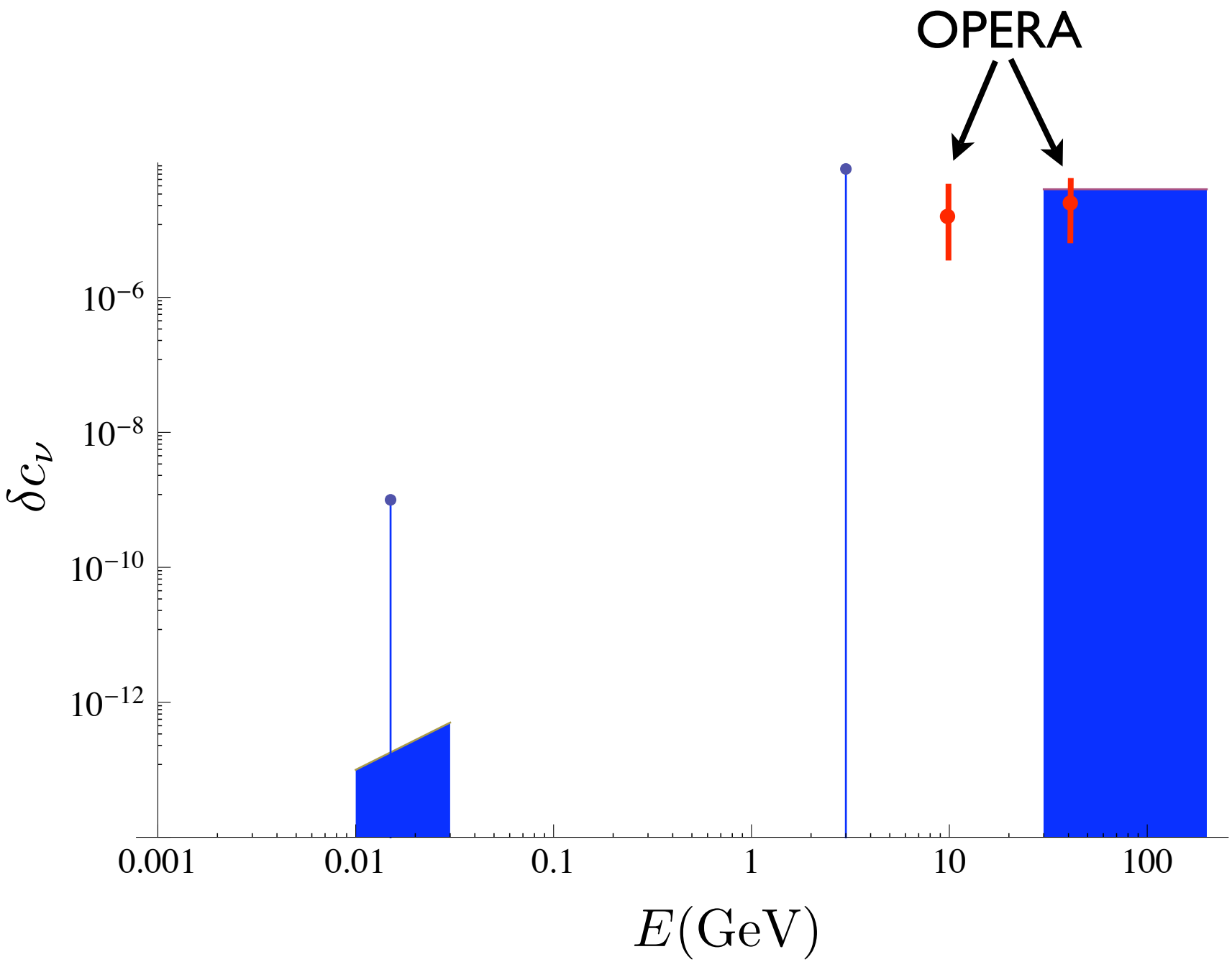
MINOS: baseline 735 km, $E \approx 3\mathrm{GeV}$

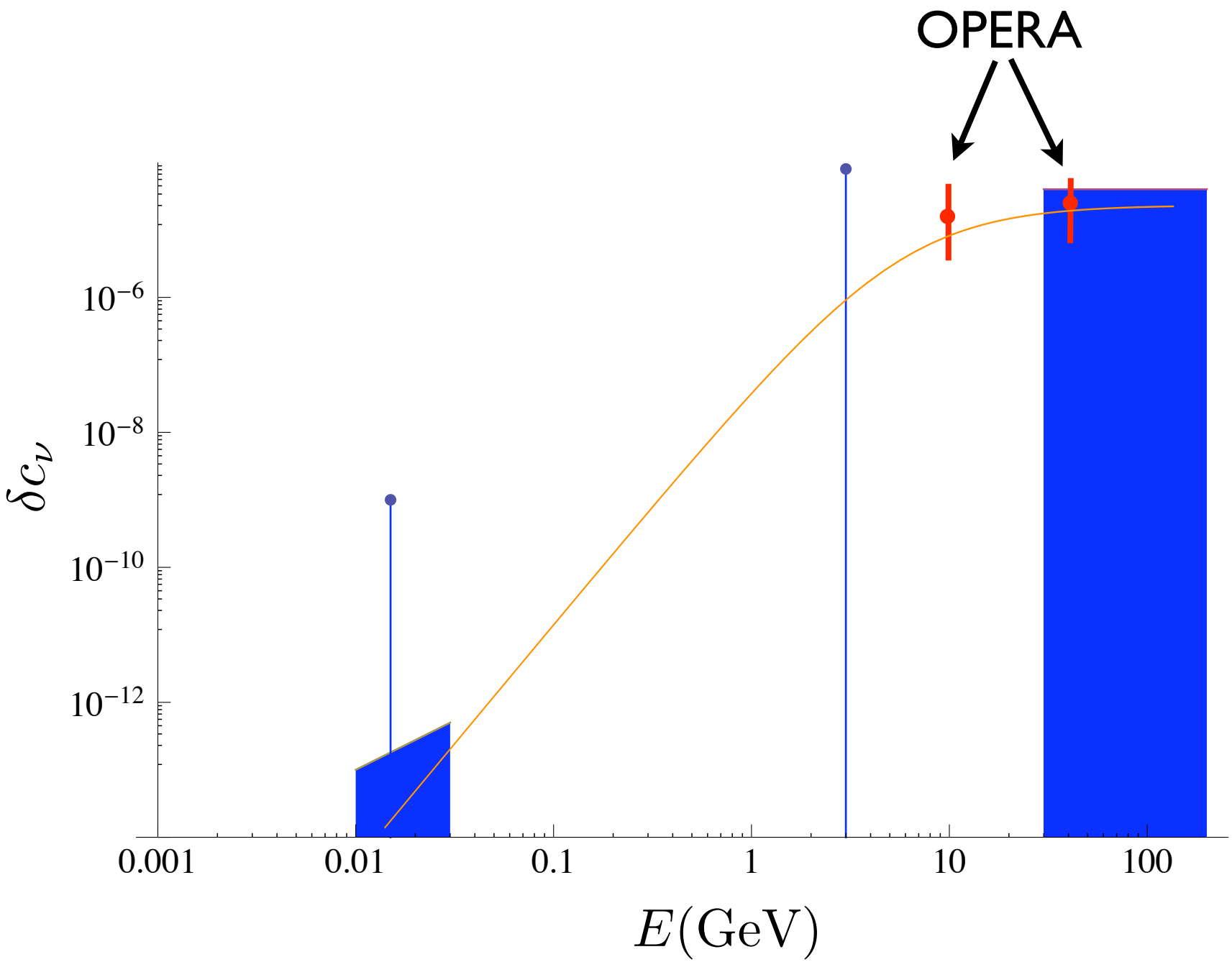
$$\delta c_{\nu_\mu}(3\mathrm{GeV}) = (5.1 \pm 2.9) \times 10^{-5}$$

Fermilab1979: baseline 800 m, $30\mathrm{GeV} < E < 200\mathrm{GeV}$ comparison between ν_μ $(\bar{\nu}_\mu)$ and muon velocities

$$|\delta c_{\nu,\bar{\nu}} - \delta c_\mu| < 4 \times 10^{-5}$$


10^{-6}
10^{-8}
10^{-10}
10^{-12}
δc_ν
0.001
0.01
0.1
1
10
100
$E(\mathrm{GeV})$


OPERA
10^{-6}
10^{-8}
10^{-10}
10^{-12}
δc_ν
0.001
0.01
0.1
1
10
100
$E(\mathrm{GeV})$


OPERA
10^{-6}
10^{-8}
10^{-10}
10^{-12}
δc_ν
0.001
0.01
0.1
1
10
100
$E(\mathrm{GeV})$

Indirect bounds: neutrino oscillations

$$H_{eff} = (1 + \delta c_\nu)E + \frac{m^2}{2E}$$

No distortion of the oscillation spectrum

Coleman, Glashow (1998)

$$|\delta c_{ij}| < 2 \times 10^{-19} \left(\frac{\mathrm{GeV}}{E}\right)\left(\frac{\mathrm{km}}{L}\right)$$

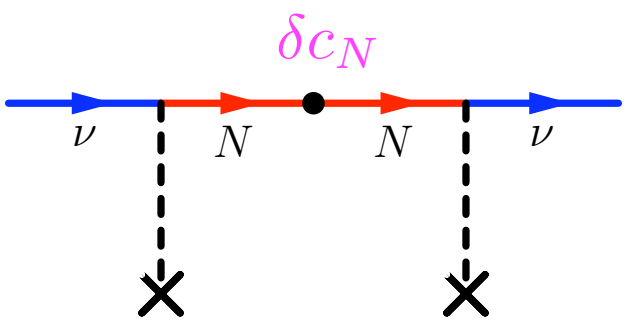
$$|\delta c_{ii} - \delta c_{jj}| < 2 \times 10^{-20}$$

Indirect bounds: charged leptons I

Neutrinos and charged leptons belong to the same gauge multiplets

they must have the same velocity ?

No. Below the EW scale neutrinos can mix with gauge singlets. Putting LV in the latter is fine



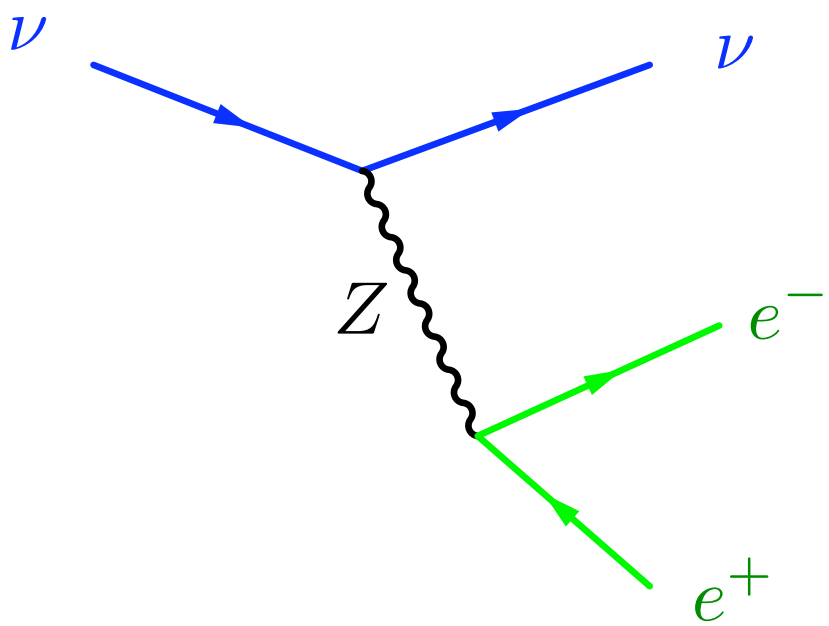
$\delta c_\nu \sim \theta^2 \delta c_N$

With several LV sterile neutrinos with masses of order a few GeV possible to obtain non-trivial dependence of δc_ν on energy

Indirect bounds: charged leptons II

Bremsstrahlung radiation

Cohen, Glashow (2011)



$$\Gamma \sim G_F^2 (m_\nu(E))^5 \cdot \frac{m_\nu(E)}{E}$$

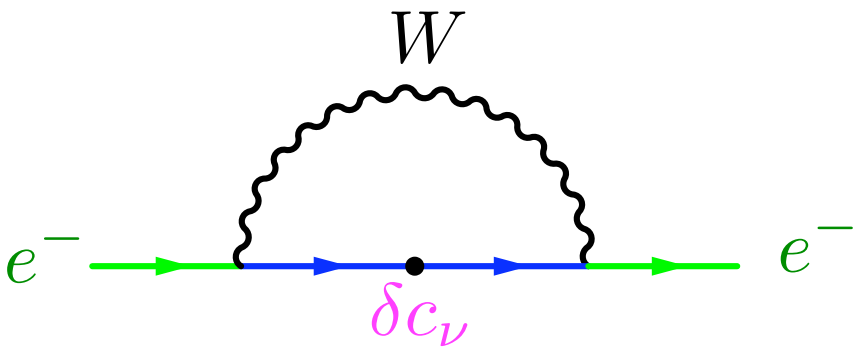
$$\sqrt{E^2 - p^2} \sim \sqrt{2\delta c_\nu}\, E$$

No e^+e^- pairs ⇒ $\delta c_\nu \lesssim 10^{-8}$ *ICARUS (2011)*

Indirect bounds: charged leptons III

Radiative corrections

Giudice, S.S., Strumia (2011)



$$\delta c_l \sim \left(\frac{\Lambda}{4\pi V}\right)^2 \delta c_\nu$$

If $\Lambda \sim 20\mathrm{GeV}$ ⇒ $|\delta c_\nu| < 10^{-11}$

Conclusions

Conclusions

- Existing constraints on LV in charged lepton are tight

$$|\delta c_e| < 10^{-15}$$

Conclusions

- Existing constraints on LV in charged lepton are tight

$$|\delta c_e| < 10^{-15}$$

- A stronger LV in neutrinos is allowed

Conclusions

- Existing constraints on LV in charged lepton are tight

$$|\delta c_e| < 10^{-15}$$

- A stronger LV in neutrinos is allowed

- But would be unnatural if exceeds LV in charged leptons by more than four orders of magnitude

$$|\delta c_\nu| < 10^{-11}$$

Conclusions

- Existing constraints on LV in charged lepton are tight

$$|\delta c_e| < 10^{-15}$$

- A stronger LV in neutrinos is allowed

- But would be unnatural if exceeds LV in charged leptons by more than four orders of magnitude

$$|\delta c_\nu| < 10^{-11}$$

- Direct upper limit from bremsstrahlung

$$\delta c_\nu \lesssim 10^{-8}$$

Conclusions

- Existing constraints on LV in charged lepton are tight

$$|\delta c_e| < 10^{-15}$$

- A stronger LV in neutrinos is allowed

- But would be unnatural if exceeds LV in charged leptons by more than four orders of magnitude

$$|\delta c_\nu| < 10^{-11}$$

- Direct upper limit from bremsstrahlung

$$\delta c_\nu \lesssim 10^{-8}$$

- Tests of Lorentz invariance can still produce surprises !