Probing the intrinsic Lorentz Invariance Violation with DUNE

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(work done with G. Barenboim, C. A. Ternes, M. Tortola: PLB(2018))

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Present status of oscillation parameters

Table: de Salas, Forero, Ternes, Tortola, Valle: 1708.01186

Oscillation parameter	Best fit value	3σ range
$\theta_{12}/^\circ$	34.5	$31.5 \rightarrow 38.0$
$\theta_{23}/^\circ$	47.7	$41.8 \rightarrow 50.4$
$\theta_{13}/^\circ$	8.45	$8.0 \rightarrow 8.9$
$\delta_{\rm CP}/\pi$	-0.68	$[-\pi, \pi]$
$\Delta m^2_{21}/10^{-5} eV^2$	7.55	$7.05 \rightarrow 8.14$
$\Delta m^2_{31}/10^{-3} eV^2$	2.5	$2.41 \rightarrow 2.6$

Theory background (Kostelecky *et al.* (2012)

- $\mathcal{L} = \frac{1}{2}\bar{\Psi}(i\partial\!\!\!/ - M + \hat{\mathcal{Q}})\Psi + h.c.$
  with $\Psi = (\nu_e, \nu_\mu, \nu_\tau, \nu_e^C, \nu_\mu^C, \nu_\tau^C)^T$

- $\hat{\mathcal{Q}}$ is a general Lorentz violating operator:
  $\hat{\mathcal{Q}} = \hat{S} + i\mathcal{P}\gamma_5 + \hat{\nu}^\lambda\gamma_\lambda + \hat{\mathcal{A}}^\lambda\gamma_5\gamma_\lambda + \frac{1}{2}\hat{\mathcal{T}}^{\lambda\eta}\sigma_{\lambda\eta}$

- $\mathcal{L}_{\text{LIV}} = -\frac{1}{2}\left[a^\mu_{\alpha\beta}\bar{\psi}_\alpha\gamma_\mu\psi_\beta + b^\mu_{\alpha\beta}\bar{\psi}_\alpha\gamma_5\gamma_\mu\psi_\beta - ic^{\mu\nu}_{\alpha\beta}\bar{\psi}_\alpha\gamma_\mu\partial_\nu\psi_\beta - id^{\mu\nu}_{\alpha\beta}\bar{\psi}_\alpha\gamma_5\gamma_\mu\partial_\nu\psi_\beta\right]$

- CP-odd LIV: $(a_L)^\mu_{\alpha\beta} = (a+b)^\mu_{\alpha\beta}$ $\rightarrow$ probed in our analysis
  CP-even LIV: $(c_L)^{\mu\nu}_{\alpha\beta} = (c+d)^{\mu\nu}_{\alpha\beta}$ $\rightarrow$ already constrained tightly (Kostelecky *et al.*).

Theory background (Kostelecky *et al.* (2012))

- $H = H_{\text{vac}} + H_{\text{mat}} + H_{\text{LIV}}$,
- $H_{\text{vac}} = \frac{1}{2E} U \begin{pmatrix} 0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31} \end{pmatrix} U^\dagger, \quad H_{\text{mat}} = A \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$
- $H_{\text{LIV}} = \begin{pmatrix} a_{ee} & a_{e\mu} & a_{e\tau} \\ a^*_{e\mu} & a_{\mu\mu} & a_{\mu\tau} \\ a^*_{e\tau} & a^*_{\mu\tau} & a_{\tau\tau} \end{pmatrix} - \frac{4}{3} E \underbrace{\begin{pmatrix} c_{ee} & c_{e\mu} & c_{e\tau} \\ c^*_{e\mu} & c_{\mu\mu} & c_{\mu\tau} \\ c^*_{e\tau} & c^*_{\mu\tau} & c_{\tau\tau} \end{pmatrix}}_{\text{not considered}}$
- Similar to: $H = H_{\text{vac}} + H_{\text{mat}} + H_{\text{NSI}}$ where,

  $H_{\text{NSI}} = \sqrt{2} G_F N_e \begin{pmatrix} \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$
- $a_{\alpha\beta} \leftrightarrow \sqrt{2} G_F N_e \epsilon_{\alpha\beta}$

  But LIV is an intrinsic effect and nonzero even in vacuum

  NSI is an exotic matter effect, not present in vacuum

  (Diaz (2015))

What is DUNE (Deep Underground Neutrino Experiment)?

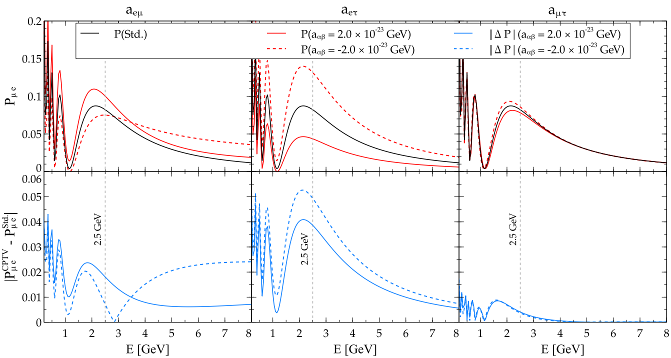
R. Acciarri *et. al.*(DUNE Collaboration): 1512.06148

- A proposed long baseline experiment (the erstwhile LBNE) with 1300 km baseline
- likely to have a 40 kt FD with 3.5 yrs. of ν and 3.5 yrs. of $\bar{\nu}$ run.
- The incident ν_μ beam is generated by 80 GeV proton beam delivered at 1.07 MW with a POT of 1.47×10^{21}
- Total exposure : 300 kt-MW-yr.

Simulation

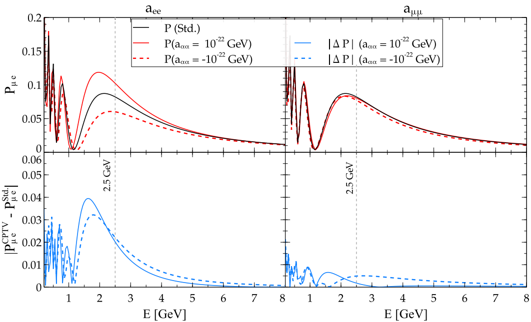
- We use GLoBES and the latest configuration files (Alion *et al.* (2016))
- Modify the GLoBES add-on *snu.c* to implement LIV scenario
- $$\Delta\chi^2 \simeq \sum_{i}^{channels} \sum_{j}^{bins} \frac{[N^{ij}_{true}(SI) - N^{ij}_{test}(a_{\alpha\beta})]^2}{N^{ij}_{true}(SI)}$$
- $$\Delta\chi^2_{\rm total} = \Delta\chi^2_{\nu_\mu\to\nu_e} + \Delta\chi^2_{\bar\nu_\mu\to\bar\nu_e} + \Delta\chi^2_{\nu_\mu\to\nu_\mu} + \Delta\chi^2_{\bar\nu_\mu\to\bar\nu_\mu}$$
- marginalisation over $\theta_{23}, \delta_{CP}, \Delta m^2_{31}$ and hierarchy and the phase $\phi_{\alpha\beta}$

Impact of LIV parameters (non-diagonal) at probability level



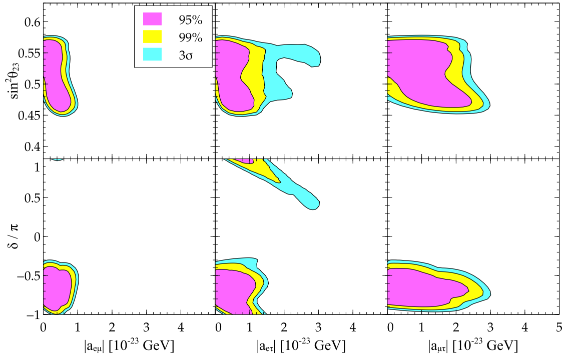
- Top row: $P^{\rm SI}_{\mu e}$ (black) and $P^{\rm LIV}_{\mu e}$ (red), Bottom row: $|P^{\rm LIV}_{\mu e} - P^{\rm SI}_{\mu e}|$
- $a_{e\mu}$ and $a_{e\tau}$ modify $P_{\mu e}$ in *opposite* direction.
- $a_{\mu\tau}$ has very small effect on ν_e appearance channel.

Impact of LIV parameters (diagonal) at probability



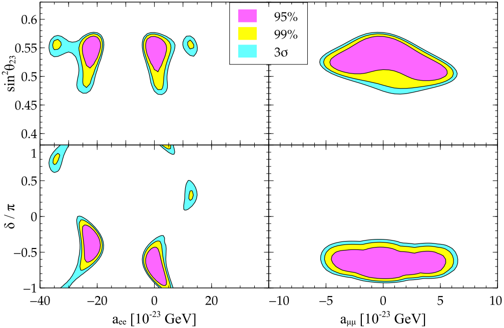
- Top row: $P^{\text{SI}}_{\mu e}$ (black) and $P^{\text{LIV}}_{\mu e}$ (red), Bottom row: $|P^{\text{LIV}}_{\mu e} - P^{\text{SI}}_{\mu e}|$
- a_{ee} and $a_{\mu\mu}$ increase or decrease the probability depending on the sign.

Constraining LIV-SI parameter space



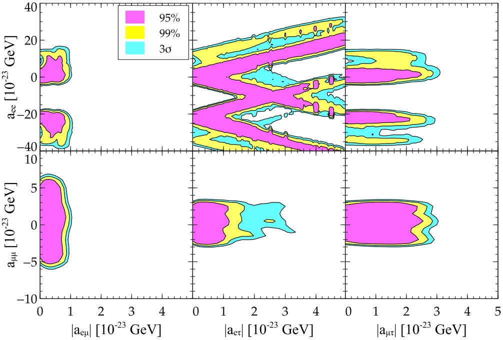
- Shows the correlations between $a_{\alpha\beta}$ and standard oscillation parameters (δ, θ_{23})
- The sensitivity to δ gets modified in presence of $a_{e\tau}$

Constraining LIV-SI parameter space



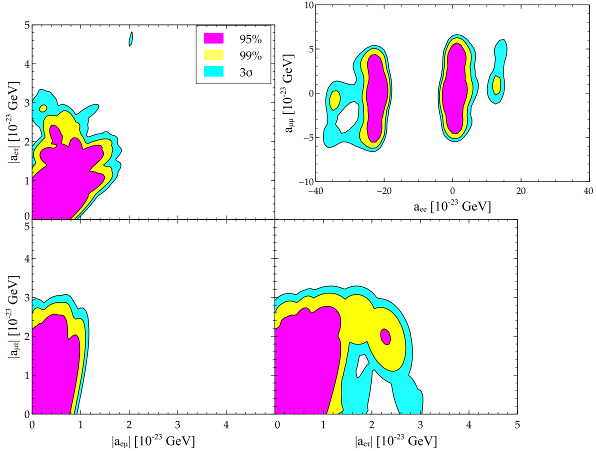
- Shows the correlations between $a_{\alpha\alpha}$ and standard oscillation parameters
- New degeneracy around $a_{ee} \approx -22 \times 10^{-23}$ GeV : - an effect of marginalisation over both mass orderings.

Correlations among LIV parameters ($a_{\alpha\alpha}$ vs. $a_{\alpha\beta}$)



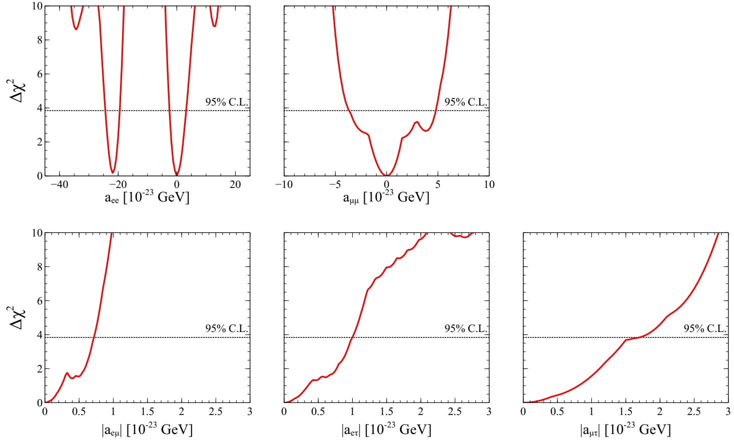
- New degeneracy around $a_{ee} \approx -22 \times 10^{-23}$ GeV
- $a_{ee} - a_{e\tau}$ correlation: A pair of *linear* branches around $a_{ee} \approx 0$ and $\approx -22 \times 10^{-23}$ GeV $\Longrightarrow$ a consequence of $(a_{ee} - |a_{e\tau}|)$-like term.

Correlations among LIV parameters



- Indication of $|a_{e\mu}|$ and $|a_{e\tau}|$ acting in *opposite* directions is apparent

one dimensional projection for the LIV parameters



Constraints on LIV parameters

Parameter	Existing bounds (Abe *et al.* 2015 (SK collab.))	Our work
$\lvert a_{e\mu}\rvert$ [GeV]	2.5×10^{-23}	7×10^{-24}
$\lvert a_{e\tau}\rvert$ [GeV]	5×10^{-23}	1×10^{-23}
$\lvert a_{\mu\tau}\rvert$ [GeV]	8.3×10^{-24}	1.7×10^{-23}
a_{ee} [GeV]	–	$-2.5 \times 10^{-22} < a_{ee} < -2 \times 10^{-22}$ and $-2.5 \times 10^{-23} < a_{ee} < 3.2 \times 10^{-23}$
$a_{\mu\mu}$ [GeV]	–	$-3.7 \times 10^{-23} < a_{\mu\mu} < 4.8 \times 10^{-23}$

- 3 times Improvement of bound for $\lvert a_{e\mu}\rvert$ and 5 times for $\lvert a_{e\tau}\rvert$

Conclusion

- Realization of a Plank suppressed effect such as LIV in a much anticipated neutrino experiment
- Correlations in the new LIV parameter space
- Improvement of the bounds on $e\mu$ and $e\tau$ sector LIV parameters
- New bounds on diagonal LIV parameters a_{ee} and $a_{\mu\mu}$

Thank You!

Backup

$$\Delta P_{\mu e}(\varepsilon_{e\mu}) = P^{NSI}_{\mu e}(\varepsilon_{e\mu}) - P^{SI}_{\mu e}$$
$$\approx -4A\Delta \sin\Delta |\varepsilon_{e\mu}| s_{13} s_{2(23)} c_{23} D_1^{e\mu} \sin(\delta + \varphi_{e\mu} - \gamma_1^{e\mu})$$

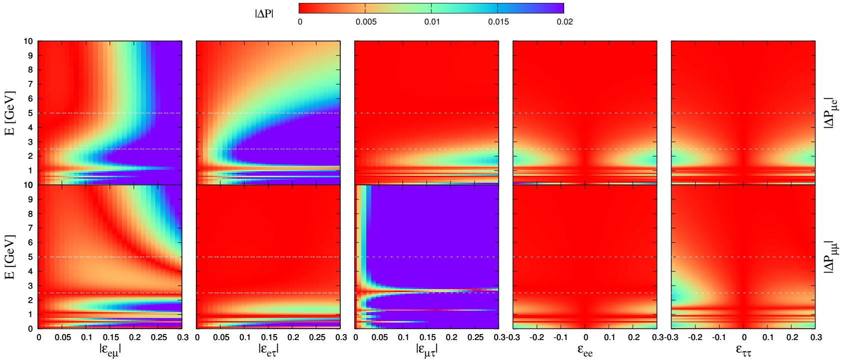
&

$$\Delta P_{\mu e}(\varepsilon_{e\tau}) \approx 4A\Delta \sin\Delta |\varepsilon_{e\tau}| s_{13} s_{2(23)} s_{23} D_1^{e\tau} \sin(\delta + \varphi_{e\tau} + \gamma_1^{e\tau})$$

where,

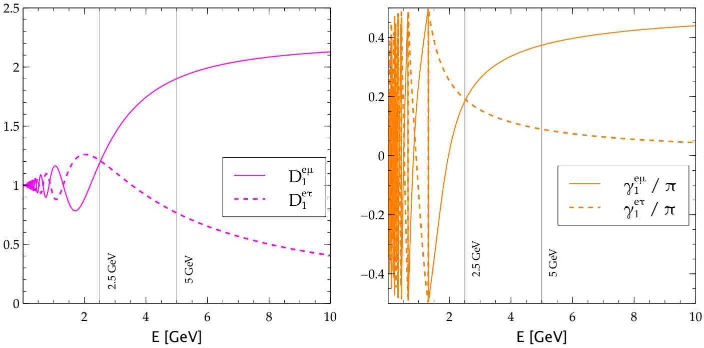
$$D_1^{e\mu} = [\sin^2\Delta + (\tan^2\theta_{23}\frac{\sin\Delta}{\Delta} + \cos\Delta)^2]^{1/2} \qquad \gamma_1^{e\mu} = \tan^{-1}(\frac{\tan^2\theta_{23}}{\Delta} + \cot\Delta)$$
$$D_1^{e\tau} = [\sin^2\Delta + (\frac{\sin\Delta}{\Delta} - \cos\Delta)^2]^{1/2}; \qquad \gamma_1^{e\tau} = \tan^{-1}(\frac{1}{\Delta} - \cot\Delta)$$

Backup



|ΔP|
0
0.005
0.01
0.015
0.02
E [GeV]
$|\varepsilon_{e\mu}|$
$|\varepsilon_{e\tau}|$
$|\varepsilon_{\mu\tau}|$
ε_{ee}
$\varepsilon_{\tau\tau}$
$|\Delta P_{\mu e}|$
$|\Delta P_{\mu\mu}|$

Backup



2.5
2
1.5
1
0.5
0
2
4
6
8
10
E [GeV]
2.5 GeV
5 GeV
$D_1^{e\mu}$
$D_1^{e\tau}$
0.4
0.2
0
−0.2
−0.4
2
4
6
8
10
E [GeV]
2.5 GeV
5 GeV
$\gamma_1^{e\mu} / \pi$
$\gamma_1^{e\tau} / \pi$

Backup

$$\hat{\mathcal{Q}} = \hat{S} + i\mathcal{P}\gamma_5 + \hat{\nu}^{\lambda}\gamma_{\lambda} + \hat{\mathcal{A}}^{\lambda}\gamma_5\gamma_{\lambda} + \frac{1}{2}\hat{\mathcal{T}}^{\lambda\eta}\sigma_{\lambda\eta}$$

Backup

$$h_{ab} = E\delta_{ab} + \frac{(m_{ab})^2}{2E} + (a_L)^{\alpha}_{ab} p_{\alpha} - (c_L)^{\alpha}_{ab} p_{\alpha} p_{\beta} E$$

$$h_{\bar{a}\bar{b}} = E\delta_{\bar{a}\bar{b}} + \frac{(m_{\bar{a}\bar{b}})^2}{2E} + (a_L)^{\alpha}_{\bar{a}\bar{b}} p_{\alpha} - (c_R)^{\alpha}_{\bar{a}\bar{b}} p_{\alpha} p_{\beta} E$$

$$h_{a\bar{b}} \sim i\sqrt{2}(H^{\alpha}_{a\bar{b}} - g^{\alpha\beta}_{a\bar{b}} p_{\beta} E) \quad (1)$$