EFT at FASERν: An experiment to probe them all

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Virginia Tech

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“EFT at FASERν”,
A. Falkowski, M. Gonzalez-Alonso, J. Kopp, Y. Soreq, Z. Tabrizi
[arXiv: 2105.12136 [hep-ph]]
Neutrinos are massless in the SM!

However in nature.....

Neutrino oscillation needs masses and mixing!
Oscillation experiments are sensitive not only to neutrino masses and mixing, but also to how neutrinos interact with matter.

- Coherent CC and NC forward scattering of neutrinos

New effective 4-fermion interactions between leptons and quarks may give observable effects in neutrino production, propagation, and detection.

How to use EFT language to “systematically” explore new physics beyond the neutrino masses and mixing in neutrino experiments?
Why EFT?

- Wealth of low-energy observables probing different aspects of particle interactions are described within one consistent framework.
- Constraints from different observables can be meaningfully compared.
- Results obtained in the language of EFT can be translated into constraints on particular new physics models.

The point is that one can probe very heavy particles, often beyond the reach of present colliders, by precisely measuring low-energy observables.
Constraints on BSM #1

Constraints on BSM #2

Constraints on the EFT coefficients

By measurements of WEFT parameters at $E << m_Z$ we can drive constraints on higher dimensional SMEFT interactions.
Approach:

- If BSM particles are much heavier than the Z boson mass and the EWSB is linearly realized, then the relevant effective theory above the weak scale is the so-called SMEFT.

- It has the same particle content and local symmetry as the SM, but differs by the presence of higher-dimensional (non-renormalizable) interactions in the Lagrangian.

\[ \mathcal{L}_{\text{SM EFT}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda_L} \mathcal{L}^{D=5} + \frac{1}{\Lambda^2} \mathcal{L}^{D=6} \]

- The SMEFT framework allows one to describe effects of new physics beyond the SM in a model independent way.
Approach:

- In particular, considering the CC interactions of neutrinos.

- At this scale heavy particles such as W and Z bosons, Higgs and top can be integrated out from the SMEFT, leading to Weak EFT (WEFT).

\[
L_{\text{WEFT}} \supset - \frac{2V_{ud}}{\nu^2} \{ [1 + \epsilon_L] \bar{\alpha}_\beta (\bar{u} \gamma^\mu P_L d)(\bar{\ell}_\alpha \gamma_\mu P_L \nu_\beta) \\
+ \epsilon_R \bar{\alpha}_\beta (\bar{u} \gamma^\mu P_R d)(\bar{\ell}_\alpha \gamma_\mu P_L \nu_\beta) \\
+ \frac{1}{2} \epsilon_S \bar{\alpha}_\beta (\bar{u} d)(\bar{\ell}_\alpha P_L \nu_\beta) - \frac{1}{2} \epsilon_P \bar{\alpha}_\beta (\bar{u} \gamma_5 d)(\bar{\ell}_\alpha P_L \nu_\beta) \\
+ \frac{1}{4} \epsilon_T \bar{\alpha}_\beta (\bar{u} \sigma^{\mu\nu} P_L d)(\bar{\ell}_\alpha \sigma_{\mu\nu} P_L \nu_\beta) + \text{h.c.} \}
\]

- Apart from the SM-like V-A interactions \((1 + \epsilon_L)\), right-handed \((\epsilon_R)\), scalar \((\epsilon_S)\), pseudoscalar \((\epsilon_P)\), and tensor \((\epsilon_T)\) interactions are allowed.
QFT Description

A. Falkowski, M. González-Alonso, ZT
arXiv: 1910.02971

depends on the kinematic and spin variables
**QFT Description**

**Observable:** rate of detected events

\[ \sim (\text{flux}) \times (\text{det. cross section}) \times (\text{oscillation}) \]
EFT at Oscillation Experiments:

\[ R^{\text{SM}}_{\alpha \beta} = \Phi^{\text{SM}}_{\alpha} \sigma^{\text{SM}}_{\beta} \sum_{k,l} e^{-i \frac{L \Delta m_{kl}^2}{2E_{\nu}}} U_{\alpha k}^* U_{\alpha l} U_{\beta k} U_{\beta l}^* \]

A. Falkowski, M. González-Alonso, ZT

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau \\
\end{pmatrix} =
\begin{pmatrix}
\nu_1 & \nu_2 & \nu_3 \\

\end{pmatrix}
\]
EFT at Oscillation Experiments:

\[ R_{\alpha \beta} = \Phi^\text{SM}_{\alpha} \sigma^\text{SM}_\beta \sum_{k,l} e^{i \frac{L \Delta m^2_{kl}}{2 E_N}} \]

\[ \times \left[ U^*_{\alpha k} U_{\alpha l} + p_{XL} (\epsilon_X U)^*_{\alpha k} U_{\alpha l} + p_{XY}^* (\epsilon_X U)_{\alpha k} (\epsilon_Y U)_{\alpha l} \right] \]

\[ \times \left[ U^*_{\beta k} U_{\beta l} + d_{XL} (\epsilon_X U)_{\beta k} U_{\beta l} + d_{XY}^* (\epsilon_X U)_{\beta k} (\epsilon_Y U)_{\beta l} \right] \]

Production and detection coefficients, depend on amplitudes

One needs to calculate these coefficients for different production and detection processes.

\[ p_{XY} = \frac{\int d\Pi_P A_X^P \bar{A}_Y^P}{\int d\Pi_P |A_L^P|^2}, \quad d_{XY} = \frac{\int d\Pi_D A_X^D \bar{A}_Y^D}{\int d\Pi_D |A_L^D|^2}. \]
DIS: FASERν
 Kaon/Muon decay: ISODAR, KDAR
 Solar neutrinos: Borexino
 QE, Resonances: MINOS, NOvA, DUNE
 Atmospheric Neutrinos: IceCube
 Beta decay and IBD: Reactor Experiments

\[ \nu \rightarrow l, \nu \]

\[ K^- \rightarrow \{\bar{u} \bar{d}\} \pi^0 \]

\[ \mu^- \rightarrow W^- \bar{\nu}_e \]

\[ \tau^+ \rightarrow e^+ \nu_e \]

\[ 3^3 He + p \rightarrow 4^4 He + e^+ + \nu_e \]

\[ p + e^- + p \rightarrow 2^2 H + \nu_e \]

\[ \nu \rightarrow l, \nu \]

\[ W, Z \]

\[ N, N' \]

\[ R \]

Cosmic ray

Experimental setups and theoretical frameworks are illustrated, along with particle decays and interactions.
DIS: FASERν

Kaon/Muon decay:

ISODAR, KDAR, QE, Resonances,

DIS: MINOS, NOvA, DUNE

Solar neutrinos:

Borexino

Atmospheric Neutrinos:

IceCube

Beta decay and IBD: Reactor Experiments

Well...
EFT at FASERν

- will be located downstream of the ATLAS interaction point at a distance of 480 m.
- Ideal for detecting high-energy neutrinos produced at LHC.
- 1.2-t of tungsten material.
Why FASERV?

DIS detection, easy to include NP
(compared with QE and Resonances)
EFT at FASERν

- No new physics at the linear order!
- Good sensitivity to the right handed and tensor interactions.

A. Falkowski, M. González-Alonso, J. Kopp, Y. Soreq, ZT
arXiv: 2105.12136
Why FASERν?

- Several production modes
- Pion and Kaon decays are the dominant ones
- All (anti)neutrino flavors are available

### Generators and FASERν

<table>
<thead>
<tr>
<th>Generators</th>
<th>FASERν</th>
<th>light hadrons</th>
<th>heavy hadrons</th>
<th>( \nu_e + \bar{\nu}_e )</th>
<th>( \nu_\mu + \bar{\nu}_\mu )</th>
<th>( \nu_\tau + \bar{\nu}_\tau )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIBYLL</td>
<td>SIBYLL</td>
<td>1343</td>
<td>6072</td>
<td>21.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DPMJET</td>
<td>DPMJET</td>
<td>4614</td>
<td>9198</td>
<td>131</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EPOS LHC</td>
<td>Pythia8 (Hard)</td>
<td>2109</td>
<td>7763</td>
<td>48.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>QGSJET</td>
<td>Pythia8 (Soft)</td>
<td>1437</td>
<td>7162</td>
<td>24.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Leptonic Pion Decay:

Due to the pseudoscalar nature of the pion, it is sensitive only to axial ($\varepsilon_L - \varepsilon_R$) and pseudo-scalar ($\varepsilon_P$) interactions.

\[
p_{LL} = -p_{RL} = 1, \quad p_{PL} = -p_{PR} = -\frac{m^2_\pi}{m_\mu(m_u + m_d)}, \quad p_{RR} = 1, \quad p_{PP} = \frac{m^4_\pi}{m^2_\mu(m_u + m_d)^2}.
\]

\[
\sim -27
\]

• Larger $P_{XY} \implies$ smaller $\varepsilon$!
Leptonic Pion Decay:

Due to the pseudoscalar nature of the pion, it is sensitive only to axial \((\varepsilon_L - \varepsilon_R)\) and pseudo-scalar \((\varepsilon_P)\) interactions.

\[
\begin{align*}
p_{LL} &= -p_{RL} = 1, \\
p_{PL} &= -p_{PR} = -\frac{m_{\pi}^2}{m_\mu (m_u + m_d)}, \\
p_{RR} &= 1, \\
p_{PP} &= \frac{m_{\pi}^4}{m_\mu^2 (m_u + m_d)^2}.
\end{align*}
\]

\(~700!\)

We will have a great chiral enhancement for the pseudoscalar NP!

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Kaon Decay:

Both 2-body and 3-body kaon decays contribute:

$$\mathcal{P}_{XY,\alpha}^{S,jk} = \frac{\int dE_S \frac{\phi_S(E_S)}{E_S} \sum_i \beta_i^S(E_S) \int d\Pi_{i} A_{X,\alpha}^{S_i,jk} A_{Y,\alpha}^{S_i,jk*} \frac{dE_S}{E_S} \sum_i' \beta_i'(E_S) \int d\Pi_{i}' A_{L,\alpha}^{S_i,j'k'} |2}{\int dE_S \frac{\phi_S(E_S)}{E_S} \sum_i' \beta_i'(E_S) \int d\Pi_{i}' A_{L,\alpha}^{S_i,j'k'} |2}$$

Energy distribution of $K^\pm$, $K_L$ or $K_S$

Thanks to Felix Kling

Kaon Decay:

Both 2-body and 3-body kaon decays contribute:

We see "more" chiral-enhancement for the decay into electrons!!!

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EFT at FASERν

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Turning on one interaction at a time: Pseudo-Scalar

Optimistic (5%, 10%, 15%) and Pessimistic (30%, 40%, 50%), uncertainties on electron muon and tau neutrinos

- The rates scale linearly wrt volume:
  - Diagonal $\varepsilon \sim (V^2 / V_1)^{1/2}$
  - Off-diagonal $\varepsilon \sim (V^2 / V_1)^{1/4}$
- 20 times larger lum. gives ~ 4 (2) times better sensitivity for (off-)diagonal elements
Conclusion:

• We have proposed a systematic approach to neutrino experiments in the SMEFT framework.

• We applied the formalism to FASERv experiment, however the formalism can be readily extended to other types of neutrino experiments.

• Constraints of the order of $10^{-3} \ (10 \text{ TeV})$ can be derived for pseudo-scalar interaction at FASERv. In total 81 different operators can be probed at FASERv.
Thanks for your attention
QM-NSI Description

Neutrinos are not pure flavor states:

Standard NSI approach

Normalization

Rotation of flavor states at the source

Rotation of flavor states at the detector

NSI parameters

\[ |\nu^s_{\alpha}\rangle = \frac{1}{N^s_{\alpha}} \left[ |\nu_{\alpha}\rangle + \sum_{\gamma=e,\mu,\tau} \epsilon^s_{\alpha\gamma} |\nu_{\gamma}\rangle \right] \]

\[ \langle \nu^d_{\beta} | = \frac{1}{N^d_{\beta}} \left[ \langle \nu_{\beta} | + \sum_{\gamma=e,\mu,\tau} \langle \nu_{\gamma} | \epsilon^d_{\gamma\beta} \right] \]
QM-NSI Description

Neutrinos are not pure flavor states:

$$|\nu^s_\alpha\rangle = \frac{(1 + \epsilon^s)_{\alpha\gamma}}{N^s_\alpha} |\nu_\gamma\rangle, \quad \langle \nu^d_\beta| = \langle \nu_\gamma| \frac{(1 + \epsilon^d)_{\gamma\beta}}{N^d_\beta}$$

**Observable:** rate of detected events

$$\sim (\text{flux}) \times (\text{det. cross section}) \times (\text{oscillation})$$

$$R^{QM}_{\alpha\beta} = \Phi^{SM}_\alpha \sigma^{SM}_\beta \sum_{k,l} e^{-i \frac{L \Delta m^2_{kl}}{2E_N}} [x^s]_{\alpha k} [x^s]^{*}_{\alpha l} [x^d]_{\beta k} [x^d]^{*}_{\beta l}$$

$$x^s_s \equiv (1 + \epsilon^s)U^* \ & \ x^d_d \equiv (1 + \epsilon^d)^TU$$
QFT vs QM-NSI

- Can one “validate” QM-NSI approach from the QFT results?
- If yes, relation between NSI parameters and Lagrangian (EFT) parameters?
- Does the matching hold at all orders in perturbation?
Can one “validate” QM-NSI approach from the QFT results? Yes...

If yes, relation between NSI parameters and Lagrangian (EFT) parameters?

Does the matching hold at all orders in perturbation? No...

Observable is the same, we can match the two
(only at the linear level)

\[ \epsilon^s_{\alpha\beta} = \sum_X p_{XL}[\epsilon^*_X]_{\alpha\beta}, \quad \epsilon^d_{\beta\alpha} = \sum_X d_{XL}[\epsilon^*_X]_{\alpha\beta} \]

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Comparing QM and QFT

At the linear order we have:

- Different NP interactions appear at the source or detection simultaneously.
- Some of the p/d coefficients depend on the neutrino energy.
- There are chiral enhancements in some cases.

<table>
<thead>
<tr>
<th>Neutrino Process</th>
<th>NSI Matching with EFT</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$ produced in beta decay</td>
<td>$\epsilon_{e\beta} = [\epsilon_L]<em>{e\beta} - [\epsilon_R]</em>{e\beta} - \frac{g_T}{g_A f_T(E_\nu)} \frac{m_e}{m} [\epsilon_T]_{e\beta}$</td>
</tr>
<tr>
<td>$\nu_e$ detected in inverse beta decay</td>
<td>$\epsilon_{\beta e} = [\epsilon_L]<em>{e\beta} + \frac{1 - 3g_A^2}{1 + 3g_A^2} [\epsilon_R]</em>{e\beta} - \frac{m_e}{E_\nu - \Delta} \left( \frac{g_S}{1 + 3g_A^2} [\epsilon_S]<em>{e\beta} - \frac{3g_A g_T}{1 + 3g_A^2} [\epsilon_T]</em>{e\beta} \right)$</td>
</tr>
<tr>
<td>$\nu_\mu$ produced in pion decay</td>
<td>$\epsilon_{\mu\beta} = [\epsilon_L]<em>{\mu\beta} - [\epsilon_R]</em>{\mu\beta} - \frac{m_P^2}{m_\mu (m_u + m_d)} [\epsilon_P]_{\mu\beta}$</td>
</tr>
</tbody>
</table>

These correlations, energy dependence etc. cannot be seen in the traditional QM approach.
Comparing QM and QFT

Beyond the linear order in new physics parameters, the NSI formula matches the (correct) one derived in the EFT only if the consistency condition is satisfied

\[ p_{XL} p_{YL}^* = p_{XY}, \quad d_{XL} d_{YL}^* = d_{XY} \]

This is always satisfied for new physics correcting V-A interactions only as \( p_{LL} = d_{LL} = 1 \) by definition

However for non-V-A new physics the consistency condition is not satisfied in general

We can compare the QFT and QM rates at all orders.

e.g. at KamLAND experiment

\[ p_{XY} \equiv \frac{\int d\Pi_P A^P_X A^P_Y}{\int d\Pi_P |A^P_L|^2}, \quad d_{XY} \equiv \frac{\int d\Pi_D A^D_X A^D_Y}{\int d\Pi_D |A^D_L|^2} \]
Matching WEFT and SMEFT parameters:

\[
[\epsilon_L]_{\alpha\beta} \approx \frac{v^2}{\Lambda^2 V_{ud}} \left( V_{ud}[c^{(3)}_{Hl}]_{\alpha\beta} + V_{jd}[c^{(3)}_{Hq}]_{1j} \delta_{\alpha\beta} - V_{jd}[c^{(3)}_{lq}]_{\alpha\beta1j} \right),
\]

\[
[\epsilon_R]_{\alpha\beta} \approx \frac{v^2}{2\Lambda^2 V_{ud}} [c_{Hud}]_{11} \delta_{\alpha\beta},
\]

\[
[\epsilon_S]_{\alpha\beta} \approx -\frac{v^2}{2\Lambda^2 V_{ud}} \left( V_{jd}[c^{(1)}_{lequ}]_{\beta\alpha1j} + [c_{ledq}]^{*}_{\beta\alpha11} \right),
\]

\[
[\epsilon_P]_{\alpha\beta} \approx -\frac{v^2}{2\Lambda^2 V_{ud}} \left( V_{jd}[c^{(1)}_{lequ}]^{*}_{\beta\alpha1j} - [c_{ledq}]^{*}_{\beta\alpha11} \right),
\]

\[
[\hat{\epsilon}_T]_{\alpha\beta} \approx -\frac{2v^2}{\Lambda^2 V_{ud}} V_{jd}[c^{(3)}_{lequ}]^{*}_{\beta\alpha1j},
\]

- All $\epsilon_{\alpha}$ arise at $O(\Lambda^{-2})$ in the SMEFT, thus they are equally important.

- No off-diagonal right handed interactions in SMEFT.
Kaon Decay:

Both 2-body and 3-body kaon decays contribute:

We see chiral-enhancement for the decay into muons!
EFT at FASERν

\[ \tilde{P}_{\alpha\beta}|_{L=0} \simeq \left( 1 + 2 \sum_{X,j,k} p_{XL,\alpha}^{jk} |\epsilon_{X,\alpha\beta}^{jk}| \cos \phi_{X,\alpha\beta}^{jk} \right) \delta_{\alpha\beta} + \sum_{X,Y,j,k} |\epsilon_{X,\alpha\beta}^{jk}|^2 P_{XY,\alpha}^{jk} + \sum_{X,Y,r,s} |\epsilon_{X,\beta\alpha}^{rs}|^2 d_{XY,\beta}^{rs} , \]

- Only the diagonal elements at the linear order
- Off diagonal elements at the quadratic order

No oscillation, only zero-distance effect!
RESULTS

Turning on one interaction at a time: Scalar

Optimistic (5%, 10%, 15%) and Pessimistic (30%, 40%, 50%), uncertainties on electron muon and tau neutrinos

From kaon decay
Turning on one interaction at a time: Right handed

Optimistic (5%, 10%, 15%) and Pessimistic (30%, 40%, 50%), uncertainties on electron, muon and tau neutrinos from charm decay and DIS.


From pion decay and DIS

From kaon decay and DIS

From charm decay and DIS

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Turning on one interaction at a time: Pseudo-Scalar

Optimistic (5%, 10%, 15%) and Pessimistic (30%, 40%, 50%), uncertainties on electron muon and tau neutrinos

- From pion decay
- From kaon decay
- From charm decay

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Turning on one interaction at a time: Tensor

Optimistic (5%, 10%, 15%) and Pessimistic (30%, 40%, 50%), uncertainties on electron muon and tau neutrinos

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