Prospects for BSM physics searches at HK and T2HKK

-Phill Litchfield
Outline:

(Very) brief introduction to Hyper-K & JPARC beam

Lorentz violation with neutrinos

Sterile Neutrinos

Non-standard interactions
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Sterile Neutrinos

Non-standard interactions

Apologies:

[What is not covered]

Dark matter in beam

Nucleon Decay

Any astrophysical searches
- Dark matter, Monopoles, ...

BSM physics affecting solar neutrinos
Muon neutrino beam produced at J-PARC on Japan’s east coast
- Directed ‘towards’ Super-Kamiokande, 295km away.
- Near Detector complex at 280m (ND280) to study beam and interactions
Intermediate Water Cherenkov Detector
- 2km from target
- Adjust OA angle between 1~4°
Lorentz violation
Effect of the Lorentz violating term can be expressed with perturbation theory. Using $S_{ab} = e^{-iH_{ab}t}$:

$$P(\nu_a \rightarrow \nu_b) \sim |S_{ab}^{(0)} + S_{ab}^{(1)} + S_{ab}^{(2)} + \cdots|^2$$

$$\sim |S_{ab}^{(0)}|^2 + 2\Re \left[ (S_{ab}^{(0)})^* S_{ab}^{(1)} \right] + 2\Re \left[ (S_{ab}^{(0)})^* S_{ab}^{(2)} \right] + |S_{ab}^{(1)}|^2 + \cdots$$

- 0\textsuperscript{th} order $\rightarrow$ regular PMNS oscillations
- 1\textsuperscript{st} order $\rightarrow$ LV-enhanced PMNS oscillations
  - Precision measurement at long baselines
- 2\textsuperscript{nd} order $\rightarrow$ LV-PMNS + pure LV mixing
  - Smaller effect in p.t. but does not require PMNS oscillation to develop
  - Can test with near detectors: INGRID, ND280+, Intermediate detector
Encapsulated using the **Standard Model Extension (SME)**

- LV manifests as fixed absolute 4-vectors &/or tensors
  - New flavour-changing operators can depend on these

- *Sidereal rotation* of earth will produce oscillations in time with base period $T_\oplus = 23^h 56^m 4.1^s$

- Components parallel to $z$ and $t$ not probed by sidereal variation, but all are proportional to $L$ and $L \times E$
  - Enhancement at Korea site relative to Kamioka
T2K analysis uses INGRID near detector ⇒ 2\textsuperscript{nd} order LV-only term

\[ P^{SBL}(\nu_a \rightarrow \nu_b) = L^2 \begin{vmatrix} C_{ab} + A_{ab} \sin \omega \Theta t + A'_{ab} \cos \omega \Theta t \\ + B_{ab} \sin 2\omega \Theta t + B'_{ab} \cos 2\omega \Theta t \end{vmatrix}^2 \]

- \{C, A, B\} specific to neutrino direction & energy: \( p_\varepsilon = E_\nu (1, -\hat{n}) \)
- SME coefficients are the vectors & tensors: \( \{a_\varepsilon^L, c_\varepsilon^{\varepsilon\delta}\} \)
- Period depends on number of \( x \) & \( y \) components

**Vector - \( a_\varepsilon^L p_\varepsilon \):**
- \( a_\varepsilon^t, a_\varepsilon^z \rightarrow C \)
- \( a_\varepsilon^x, a_\varepsilon^y \rightarrow A, A' \)

**Tensor - \( c_\varepsilon^{\varepsilon\delta} p_\varepsilon p_\delta \):**
- \( E[c_L^{tt}, c_L^{tz}, c_L^{zz}] \rightarrow C \)
- \( E[c_L^{tx}, c_L^{ty}, c_L^{zx}, c_L^{zy}] \rightarrow A, A' \)
- \( E[c_L^{xx}, c_L^{xy}, c_L^{yy}] \rightarrow B, B' \)
Time dependent coefficients \{A, B\} can be extracted using a FFT with frequencies up to \(4\omega \oplus\)

- \(C\) is a normalisation, so poor sensitivity with only 1 detector.
- Don’t attempt to fix \(t=0\) \(\Rightarrow\) combine sine and cosine terms
- Null MC used to check significance of Fourier coefficients
  \(\rightarrow\) All consistent with no effect

Marginal Likelihood fit (with flat priors) used to report limits on the SME coefficients \(\{a_L^\xi, c_L^\xi\delta\}\)

Parameter limits from T2K are in the range:

\[\mathcal{O}(10^{-20})\] for the \(c_L^\xi\delta\) and \[\mathcal{O}(10^{-20})\ \text{GeV}\] for the \(a_L^\xi\)

and currently statistics-limited.
Extensions with Hyper-K

Update the SBL analysis using the IWCD:

- Effect size increases by ~100 due to longer baseline ($\propto L^2$ dependence)

$$P_{SBL}(\nu_a \rightarrow \nu_b) = L^2 \left| C_{ab} + A_{ab} \sin \omega_\oplus t + A'_{ab} \cos \omega_\oplus t + B_{ab} \sin 2\omega_\oplus t + B'_{ab} \cos 2\omega_\oplus t \right|^2$$

Do a LBL (PMNS-LV interference term) search: (T2K could also do this)

- At Hyper-K (295km)
- At Korean detector (>1000km)
  - Perturbation size grows with $L$ (same benefits as CP term)

$$\Delta P_{LBL}(\nu_a \rightarrow \nu_b) = 2L \left( (P_C)_{ab} + (P_A)_{ab} \sin \omega_\oplus t + (P_A')_{ab} \cos \omega_\oplus t + (P_B)_{ab} \sin 2\omega_\oplus t + (P_B')_{ab} \cos 2\omega_\oplus t \right)$$

[Note: Because PMNS term is large, MINOS found LBL search was more sensitive]
Sterile neutrinos
Oscillations are an inevitable consequence of a non-diagonal propagation Hamiltonian [in the flavour basis]:

\[
i \frac{\partial}{\partial t} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \frac{1}{2E_\nu} U_{PMNS} \begin{pmatrix} 0 & \Delta m_{21}^2 \\ \Delta m_{21}^2 & \Delta m_{31}^2 \end{pmatrix} U_{PMNS}^\dagger + \begin{pmatrix} V_e + V_A \\ V_A \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}
\]

**Vacuum term:**

- Parameterise \( U_{PMNS} = R(\theta_{23})U(\theta_{13}, \delta_{CP})R(\theta_{12}) \)

**Matter term:**

- Coherent forward scattering \((W, Z)\)
- \(V_e, V_A \propto \rho\), the (number) density
- No \(1/E_\nu\) factor \(\Rightarrow\) dominates at high \(E_\nu\)
Can break unitarity of $3 \times 3$ PMNS matrix...

...but must preserve unitarity overall

\[ \frac{di}{dt} \left( \begin{array}{c} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \vdots \end{array} \right) = \frac{1}{2E_v} U_{3+n} \left( \begin{array}{ccc} 0 & \Delta m^2_{21} & \Delta m^2_{31} \\ \Delta m^2_{21} & \ddots & \Delta m^2_{31} \\ \Delta m^2_{31} & \ddots & \ddots \end{array} \right) U_{3+n}^\dagger + \left( \begin{array}{ccc} V_e + V_A \\ V_A \\ V_A \\ 0 \end{array} \right) \left( \begin{array}{c} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \vdots \end{array} \right) \]

Add extra neutrinos

- LEP $Z^0$-pole data rules out low-mass neutrinos with weak charges
- If new mass(es) $m_4 \geq m_e$ can use decays to normal neutrinos to measure mixing $\Rightarrow$ Heavy Neutral Leptons
- If new masses $m_4 < m_e$ no decay signature, but can take part in oscillations $\Rightarrow$ Sterile Neutrinos
Degrees of freedom of $3 + n$ mixing matrix grows as $n^2$, so most experiments stick to $n = 1$

There are two approaches to sterile neutrino searches
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There are two approaches to sterile neutrino searches:

**Look for evidence of the fourth mass state: $\Delta m^2_{41}$**

- Large $\Delta m^2_{41}$ can generate rapid oscillations among active flavours
- Search for short-baseline $\nu_\mu \rightarrow \nu_e$, $\nu_\mu \rightarrow \nu_\mu$, $\nu_e \rightarrow \nu_e$ signals
Sterile neutrino signatures

Degrees of freedom of $3 + n$ mixing matrix grows as $n^2$, so most experiments stick to $n = 1$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

There are two approaches to sterile neutrino searches:

Look for evidence of the fourth mass state: $\Delta m_{41}^2$

Look for evidence a flavour state with no NC interactions

- Depletion of NC events at long baselines
- Distortions of $\nu_\mu \to \nu_\mu$ due to matter effects
Degrees of freedom of $3 + n$ mixing matrix grows as $n^2$, so most experiments stick to $n = 1$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_3 \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

There are two approaches to sterile neutrino searches:

Look for evidence of the fourth mass state: $\Delta m_{41}^2$

Look for evidence a flavour state with no NC interactions

Hyper-Kamiokande can pursue both approaches
Constrain flux with $\nu_\mu$; look for $\nu_e$ disappearance.

- Mostly sensitive to $(\Delta m^2_{41}, U_{e4})$

Combination of CC and NC channels, sensitive to $(\Delta m^2_{41}, U_{\mu4})$
Can simply extend/improve on T2K analyses, with more statistics and improved systematic controls.

• Possibly do $P(\nu_\mu \rightarrow \nu_\mu)$ as well

• Also update SK search for $\nu_s$ with atmospheric neutrinos
  • Uses active-sterile matter effect in the core.

More interesting is prospects from IWCD at 2km

• Via $\nu_\mu \rightarrow \nu_e$ channel

• Still have ND280 constraint

• Use OA variation to constrain BGs

$L/E$ perfect for testing LSND/MB regime
Non-standard interactions
Oscillations are an inevitable consequence of a non-diagonal propagation Hamiltonian [in the flavour basis]:

\[
i \frac{\partial}{\partial t} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \frac{1}{2E_\nu} U_{PMNS} \begin{pmatrix} 0 & \Delta m_{21}^2 \\ \Delta m_{21}^2 & 0 \end{pmatrix} U_{PMNS}^\dagger + V_e \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}
\]

Non-standard Interaction matter term:

- New contributions in many models of neutrino mass generation
- Can have non-trivial flavour structure
- Parametrise as fractions of standard matter potential \( V_e = \sqrt{2} G_F \rho \)
Limits set by global analyses are both non-Gaussian and quite variable, but are typically $\mathcal{O}(0.1) \sim \mathcal{O}(1)$.

$V_{\text{NSI}} \simeq V_e \begin{pmatrix} 1 + \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau} \end{pmatrix}$

90% limits from NPB 936, (2018) 91: [As quoted in SK Kang plenary talk]

\[
\begin{align*}
|\varepsilon_{ee}^\oplus| & \lesssim 4.2 \\
|\varepsilon_{e\mu}^\oplus| & \lesssim 0.33 \\
\varepsilon_{\mu\mu}^\oplus & \lesssim 0.07 \\
|\varepsilon_{\mu\tau}^\oplus| & \lesssim 0.33 \\
|\varepsilon_{\tau\tau}^\oplus| & \lesssim 21
\end{align*}
\]

[I didn’t work out how all $\varepsilon_{\alpha\alpha} \neq 0...$]
Limits set by global analyses are both non-Gaussian and quite variable, but are typically $\mathcal{O}(0.1) \sim \mathcal{O}(1)$

$$V_{\text{NSI}} \simeq V_e \begin{pmatrix} 1 + \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau} \end{pmatrix}$$

Approx-2\(\sigma\) limits from JHEP 06 (2019) 055:
[Global fit; the strongest limits I found]

$$|\varepsilon_{ee}| \lesssim 0.55 \quad |\varepsilon_{e\mu}| \lesssim 0.17 \quad |\varepsilon_{e\tau}| \lesssim 0.4$$

$$|\varepsilon_{\mu\mu}| \equiv 0 \quad |\varepsilon_{\mu\tau}| \lesssim 0.03 \quad |\varepsilon_{\tau\tau}| \lesssim 0.5$$

[As with normal matter effect, trace of matrix is not measurable, so set $\varepsilon_{\mu\mu} \equiv 0$]
• $\nu_\mu$ disappearance improves $\varepsilon_{\tau\tau}$:
  $\sim 21 \rightarrow 0.3 \sim 0.4$

• Limits $\varepsilon_{ex}$ row from $\nu_e$ appearance (below):

$$V_{NSI} \approx V_e \begin{pmatrix}
1 + \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\
\varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\
\varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau}
\end{pmatrix}$$
Another effect:
NSI can resemble the CP-violation signal that we are looking for!

More specifically:
Some NSI parameter combinations are near-degenerate with normal mixing.

→ We couldn’t discover NSI, but we would still get $\delta_{\text{CP}}$ wrong.

Also analysed in JHEP 01 (2017) 071:
• T2HKK only exp’t with any good control of degeneracy: $\delta_{\text{NSI}} \sim \delta$
Shown 3 BSM models that can be investigated Hyper-K $\otimes$ J-PARC beam

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<td>Studied by T2K?</td>
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<td>✓</td>
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<tr>
<td>Systematic limit</td>
<td>Not yet</td>
<td>Same as $3\nu$</td>
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<td>Hyper-K design study?</td>
<td>✓ (SBL)</td>
<td>✓</td>
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<td>Not yet studied for T2HKK</td>
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</tbody>
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Plenty more! Non-beam, non-$\nu$ models not covered:

Nucleon decay, DM, Heavy neutral leptons, ...
Beyond Standard... Maps?

Report on Russia Today, 2019/08/19

\[ T_{2HKK} \]

\[ L \approx 5000\text{km} \]

\[ \theta_{OA} \approx 70^\circ \]
Extras
Neutrino beams are produced in high-intensity proton collisions.

- Includes DM candidates, provided they can be produce in a 30 GeV $p$ beam.
- Can search for low mass ($m \lesssim 500$ MeV) DM candidates
- Detect \textit{delayed} de-excitation photon
  From oxygen $p_{3/2}$ is dominant (6 MeV)
- Analysis being developed for T2K
FIG. 161. Reconstructed invariant mass and total momentum distributions for the $p \rightarrow e^+\pi^0$ MC (left) and atmospheric neutrino MC (right) after all event selections except the cuts on these variables. The final signal regions are shown by two black boxes in the plane. In the signal plot decays from bound and free protons have been separated by color, dark blue and cyan respectively. Background events have been generated for a 45 Mton-year exposure and those falling in the signal regions have been enlarged for visibility.

FIG. 162. Total momentum distribution of events passing all steps of the $p \rightarrow e^+\pi^0$ event selection except the momentum cut after a 10 year exposure of a single Hyper-K tank (left). Reconstructed invariant mass distribution of events passing all steps of the $p \rightarrow e^+\pi^0$ event selection except the invariant mass cut after a 10 year exposure of a single Hyper-K tank (right). The hatched histograms show the atmospheric neutrino background and the solid crosses denote the sum of the background and proton decay signal. Here the proton lifetime is assumed to be, $1.7 \times 10^{34}$ years, just beyond current Super-K limits. The free and bound proton-enhanced bins are shown by the lines in the left plot, and are the upper and lower panels of the right plot.
FIG. 163. Comparison of the $3\sigma$ $p \rightarrow e^+\pi^0$ discovery potential as a function of year Hyper-K (red solid) assuming a single tank as well as that of the 40 kton liquid argon detector DUNE (cyan solid) following [176]. In the orange dashed line an additional Hyper-K tank is assumed to come online six years after the start of the experiment. Super-K’s discovery potential in 2026 assuming 23 years of data is also shown.
Proton decay ($\bar{\nu} K^+$)

Dune CDR [1512.06148]
Assumes ~97% efficiency
Reconstruction performance not yet demonstrated (~25%)

FIG. 167. Comparison of the $3\sigma p \to \bar{\nu} K^+$ discovery potential as a function of year for the Hyper-K as well as that of the 40 kton DUNE detector (cyan solid) based on [176] and the 20 kton JUNO detector based on [39]. The red line denotes a single Hyper-K tank, while the orange line shows the expectation when a second tank comes online after six years. The expected discovery potential for Super-K by 2026 assuming 23 years of data is also shown.
• Disappearance improves $\varepsilon_{\tau\tau}$: 
  \[ \sim 0.5 \rightarrow 0.3 \sim 0.4 \]
• Limits $\varepsilon_{ex}$ row from $\nu_e$ appearance (below):

\[
V_{NSI} \approx V_e \begin{pmatrix}
1 + \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\
\varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\
\varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau}
\end{pmatrix}
\]