Exploring the Potential of Short-Baseline Physics at Fermilab

Pedro S. Pasquini
O. G. Miranda, M. Tórtola and J. W. F. Valle

06/19/2018

New Perspectives

Phys.Rev. D97 (2018) no.9, 095026

Arxiv: hep-pheno/1802.02133

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics
Short-Baseline may hide lots of New Physics!

Near Detector Physics
Short-Baseline may hide lots of New Physics!

Near Detector Physics

Non-Unitary
Short-Baseline may hide lots of New Physics!

\[ \frac{|U_{e1}U_{e2}^*|}{|U_{\mu1}U_{\mu2}^*|} \]

\[ \frac{|U_{\tau1}U_{\tau2}^*|}{|U_{\mu1}U_{\mu2}^*|} \]
Short-Baseline may hide lots of New Physics!

Non-Unitary

\[ \begin{vmatrix} U_{e1}U_{e2}^* \\ U_{\mu1}U_{\mu2}^* \end{vmatrix} \begin{vmatrix} U_{\tau1}U_{\tau2}^* \\ U_{\mu1}U_{\mu2}^* \end{vmatrix} \]

Zero Distance Effect only
Short-Baseline may hide lots of New Physics!

Non-Unitary

Near Detector Physics

Light Sterile Neutrino

Zero Distance Effect only
Short-Baseline may hide lots of New Physics!

\[ \Delta m^2_{32} \]  
\[ \Delta m^2_{21} \]

Zero Distance Effect only
Short-Baseline may hide lots of New Physics!

Zero Distance Effect only

$$\Delta m_{43}^2$$

$$\Delta m_{32}^2$$

$$\Delta m_{21}^2$$

$$\nu_1$$

$$\nu_2$$

$$\nu_3$$

$$\nu_4$$
Short-Baseline may hide lots of New Physics!

\[ \Delta m_{43}^2 \]
\[ \Delta m_{32}^2 \]
\[ \Delta m_{21}^2 \]

\[ \Delta m_{4i}^2 \approx 1 \text{ eV}^2 \]
Short-Baseline may hide lots of New Physics!

Near Detector Physics

Non-Unitary

Non-Standard Interaction

Light Sterile Neutrino

Zero Distance Effect only

\[ \begin{vmatrix}
U_{e1}U_{\mu2}^* \\
U_{\mu1}U_{\mu2}^*
\end{vmatrix} \]

\[ \begin{vmatrix}
U_{\tau1}U_{\tau2}^* \\
U_{\mu1}U_{\mu2}^*
\end{vmatrix} \]

\[ \Delta m_{31}^2 \approx 1 \text{ eV}^2 \]

\( \Delta m_{4i}^2 \) with colors:
- \( \nu_1 \)
- \( \nu_2 \)
- \( \nu_3 \)
- \( \nu_4 \)
Short-Baseline may hide lots of New Physics!

Zero Distance Effect only

Non-Unitary Detector Physics

Non-Standard Interaction

Light Sterile Neutrino

$\Delta m_{43}^2$

$\Delta m_{32}^2$

$\Delta m_{21}^2$

$\Delta m_{4i}^2 \approx 1 \text{ eV}^2$

$U_{e1} U_{\tau 2}^* / U_{\mu 1} U_{\mu 2}^*$

$\left| U_{\tau 1} U_{\tau 2}^* / U_{\mu 1} U_{\mu 2}^* \right|$
Short-Baseline may hide lots of New Physics!

Zero Distance Effect only

Load Baseline may hide lots of New Physics!

Source/Detector NSI only

Light Sterile Neutrino

Non-Unitary Detector Physics

Near Detector Physics

Non-Standard Interaction

Light Sterile Neutrino

Non-Standard Interaction

Non-Standard Interaction
New physics change $\nu_e$ spectrum

Zero Distance Effect only

Source/Detector NSI only

$\Delta m_{4i}^2 \approx 1 \text{ eV}^2$
New physics change $\nu_e$ spectrum

Zero Distance Effect only

Source/Detector NSI only

$\Delta m^2_{4i} \approx 1 \text{ eV}^2$
New physics change $\nu_e$ spectrum

\[ L = 0 \rightarrow N_e \propto \phi_{\nu_e} + |\alpha_{21}|^2 \phi_{\nu_\mu} \]
New physics change $\nu_e$ spectrum

$\Delta m^2_{4i} \approx 1 \text{ eV}^2$

$P(\nu_\mu \rightarrow \nu_e) = 1 - \sin^2 2\theta_{\mu e} \sin \frac{\Delta m_{41} L}{4E}$
We can put better constrain to new physics!

We simulated:
We can put better constrain to new physics!

We simulated:

$$SBNE = SBND + \mu\text{BooNE} + ICARUS$$
We can put better constrain to new physics!

We simulated:

\[ SBNE = SBND + \mu\text{BooNE} + ICARUS \]

LBNF beam with: protoDUNE and ICARUS as ND
We can put better constrain to new physics!

![Graph showing $\Delta \chi^2$ vs. $|\alpha_{21}|^2$]
We can put better constrain to new physics!

\[ \Delta \chi^2 \]

- **SBNE**
- **ICARUS at LBNF**
- **ICARUS+ at LBNF**
- **protoDUNE-SP**

**SBNE:**

\[ |\alpha_{21}|^2 < 2 \times 10^{-4} \]
We can put better constrain to new physics!

\[
|\alpha_{21}|^2 < 2 \times 10^{-5}
\]

LBNF:

\[
|\alpha_{21}|^2 < 2 \times 10^{-4}
\]

SBNE:
We can put better constrain to new physics!

\[ |\alpha_{21}|^2 < 7 \times 10^{-4} \]

\[ |\alpha_{21}|^2 < 2 \times 10^{-5} \]

\[ |\alpha_{21}|^2 < 2 \times 10^{-4} \]
We can put better constrain to new physics!

Can we really reach this level?
We need to know the expected flux precisely!

We saw that New Physics changes $\nu$ spectrum,
We need to know the expected flux precisely!

We saw that New Physics changes $\nu$ spectrum,

\[ N_{\nu_e} \propto \phi_{\nu_e} + |\alpha_{21}|^2 \phi_{\nu_\mu} \text{ and } P(\nu_\mu \rightarrow \nu_e) = 1 - \sin^2 2\theta_{\mu e} \sin \frac{\Delta m_{41} L}{4E} \]
We need to know the expected flux precisely!

We saw that New Physics changes $\nu$ spectrum,

$$N_{\nu_e} \propto \phi_{\nu_e} + |\alpha_{21}|^2 \phi_{\nu_\mu} \quad \text{and} \quad P(\nu_\mu \to \nu_e) = 1 - \sin^2 2\theta_{\mu e} \sin \frac{\Delta m_{41} L}{4E}$$

Thus, we need to know the expected flux:
We need to know the expected flux precisely!

We saw that New Physics changes $\nu$ spectrum,

$$N_{\nu_e} \propto \phi_{\nu_e} + |\alpha_{21}|^2 \phi_{\nu_\mu} \quad \text{and} \quad P(\nu_\mu \to \nu_e) = 1 - \sin^2 2\theta_{\mu e} \sin \frac{\Delta m_{41} L}{4E}$$

Thus, we need to know the expected flux:

We need good production simulation and measurement ($\mu$, hadron)
We parametrized our lack of knowledge

Let’s parametrize our lack of knowledge to see its impact:
Let’s parametrize our lack of knowledge to see its impact:
Normalization: $N^0(1 + a)$
We parametrized our lack of knowledge

Let’s parametrize our lack of knowledge to see its impact:

Normalization: $N^0(1 + a)$

$a = 0$
We parametrized our lack of knowledge

Let’s parametrize our lack of knowledge to see its impact:

Normalization: $N^0(1 + a)$

$a = 0$

$a = -5\%$
Let’s parametrize our lack of knowledge to see its impact:

Normalization: $N^0(1 + a)$

![Graph with different values of $a$]
Shape uncertainty can spoil the sensitivity!

Let’s parametrize our lack of knowledge to see its impact:
Shape uncertainty can spoil the sensitivity!

Let’s parametrize our lack of knowledge to see its impact:

Shape: $N_i^0(1 + a_i)$, bin $i = 1, 2, ...$
Shape uncertainty can spoil the sensitivity!

Let’s parametrize our lack of knowledge to see its impact:

Shape: $N_i^0 (1 + a_i)$, bin $i = 1, 2, ...$

\[ a_i = 0 \]
Shape uncertainty can spoil the sensitivity!

Let’s parametrize our lack of knowledge to see its impact:

Shape: $N_i^0(1 + a_i)$, bin $i = 1, 2, ...$

$a_i = 0$

$a_i \neq 0$
Let’s parametrize our lack of knowledge to see its impact:

Shape: $N_i^0(1 + a_i)$, bin $i = 1, 2, ...$

We may lose any oscillation pattern!!
\( \sigma_s \) the real parameter here

A bit of math....
A bit of math....

\[ \chi^2 = \sum_{i=1}^{N_{\text{bin}}} \left( \frac{N_i^{\text{exp}} - (1 - a - a_i)N_i^{\text{th}} - (1 - b - b_i)N_i^{\text{bg}}}{\sqrt{N_i^{\text{exp}}}} \right)^2 + \chi^2_{\text{SYS}}, \]
A bit of math....

\[ \chi^2 = \sum_{i=1}^{N_{\text{bin}}} \left( \frac{N_{i}^{\text{exp}} - (1 - a - a_i) N_{i}^{\text{th}} - (1 - b - b_i) N_{i}^{\text{bg}}}{\sqrt{N_{i}^{\text{exp}}}} \right)^2 + \chi_{\text{SYS}}^2, \]
A bit of math....

$$\chi^2 = \sum_{i=1}^{N_{\text{bin}}} \left( \frac{N_i^{\text{exp}} - (1 - a - a_i) N_i^{\text{th}} - (1 - b - b_i) N_i^{\text{bg}}}{\sqrt{N_i^{\text{exp}}}} \right)^2 + \chi^2_{\text{SYS}},$$
\[ \chi^2 = \sum_{i=1}^{N_{\text{bin}}} \left( \frac{N_{\text{exp}}^i - (1 - a - a_i) N_{\text{th}}^i - (1 - b - b_i) N_{\text{bg}}^i}{\sqrt{N_{\text{exp}}^i}} \right)^2 + \chi_{\text{SYS}}^2, \]

\[ \chi_{\text{SYS}}^2 = \left( \frac{a}{\sigma_a} \right)^2 + \left( \frac{b}{\sigma_b} \right)^2 + \sum_{i=1}^{N_{\text{bin}}} \left( \frac{a_i}{\sigma_{sa}} \right)^2 + \left( \frac{b_i}{\sigma_{sb}} \right)^2, \]
A bit of math....

\[
\chi^2 = \sum_{i=1}^{N_{\text{bin}}} \left( \frac{N_i^{\text{exp}} - (1 - a - a_i) N_i^{\text{th}} - (1 - b - b_i) N_i^{\text{bg}}}{\sqrt{N_i^{\text{exp}}}} \right)^2 + \chi^2_{\text{SYS}},
\]

\[
\chi^2_{\text{SYS}} = \left( \frac{a}{\sigma_a} \right)^2 + \left( \frac{b}{\sigma_b} \right)^2 + \sum_{i=1}^{N_{\text{bin}}} \left( \frac{a_i}{\sigma_{sa}} \right)^2 + \left( \frac{b_i}{\sigma_{sb}} \right)^2,
\]

We minimize over \( a, b, a_i, b_i \)
A bit of math....

\[
\chi^2 = \sum_{i=1}^{N_{\text{bin}}} \left( \frac{N_i^{\text{exp}} - (1 - a - a_i) N_i^{\text{th}} - (1 - b - b_i) N_i^{\text{bg}}}{\sqrt{N_i^{\text{exp}}}} \right)^2 + \chi^2_{\text{SYS}},
\]

\[
\chi^2_{\text{SYS}} = \left( \frac{a}{\sigma_a} \right)^2 + \left( \frac{b}{\sigma_b} \right)^2 + \sum_{i=1}^{N_{\text{bin}}} \left( \frac{a_i}{\sigma_{sa}} \right)^2 + \left( \frac{b_i}{\sigma_{sb}} \right)^2
\]

We minimize over \( a, b, a_i, b_i \)

\( \sigma_{sa} = \sigma_{sb} = \sigma_s \) Spectrum error
We need $\sigma_s \sim O(1)$%

What we got (for $|\alpha_{21}^2|$:
We need $\sigma_s \sim O(1)\%$

What we got (for $|\alpha_{21}^2|$:

![Graph showing spectrum error for ICARUS and ICARUS+ at LBNF and protoDUNE-SP at LBNF.](image-url)
We need $\sigma_s \sim O(1)\%$

Spectrum error ($\sigma_s$)

What we got (for $|\alpha_{21}^2|$:

![Graph showing spectrum error for ICARUS and ICARUS+ at LBNF vs. protoDUNE-SP at LBNF.](#)
We need $\sigma_s \sim O(1)\%$

Spectrum error ($\sigma_s$)

What we got (for $|\alpha_{21}^2|$):
We need $\sigma_s \sim O(1)\%$

Spectrum error ($\sigma_s$)

What we got (for $|\alpha_{21}^2|$:}

![Graph showing spectrum error for different distances and experiments.](image)
We need $\sigma_s \sim O(1)\%$

Spectrum error ($\sigma_s$)
We need $\sigma_s \sim O(1)\%$

Spectrum error ($\sigma_s$)

What we got (for $|\alpha_{21}^2|$:

- ICARUS and ICARUS+ at LBNF
- protoDUNE-SP at LBNF

Baseline not too far

Spectrum Error [%]

Distance (km)

Distance (km)
We need $\sigma_s \sim O(1)\%$

Spectrum error ($\sigma_s$)

What we got (for $|\alpha_{21}^2|$):

ICARUS and ICARUS+ at LBNF

protoDUNE–SP at LBNF

$\sigma_s \sim O(1)\%$

not too far
σ_s defines maximum resolution

Spectrum error (σ_s)

What we got (for |α_{21}^2|

ICARUS and ICARUS+ at LBNF

protoDUNE–SP at LBNF

Baseline
$\sigma_s$ defines maximum resolution

Spectrum error ($\sigma_s$)

What we got (for $|\alpha_{21}^2|$):

- ICARUS and ICARUS+ at LBNF
- protoDUNE-SP at LBNF

Spectrum Error [%]

Baseline
$\sigma_s$ defines maximum resolution

What we got (for $|\alpha_{21}|^2$):

Spectrum error ($\sigma_s$) vs Distance (km) for ICARUS and ICARUS+ at LBNF and protoDUNE-SP at LBNF.
$\sigma_s$ defines maximum resolution

Spectrum error ($\sigma_s$)

What we got (for $|\alpha_{21}^2|$:

<table>
<thead>
<tr>
<th>Distance (km)</th>
<th>Spectrum Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>5.0 $\times 10^{-5}$</td>
</tr>
<tr>
<td>0.5</td>
<td>4.0 $\times 10^{-5}$</td>
</tr>
<tr>
<td>1.0</td>
<td>5.0 $\times 10^{-5}$</td>
</tr>
<tr>
<td>1.5</td>
<td>2.0 $\times 10^{-5}$</td>
</tr>
<tr>
<td>2.0</td>
<td>1.0 $\times 10^{-5}$</td>
</tr>
<tr>
<td>2.5</td>
<td>0.5 $\times 10^{-5}$</td>
</tr>
</tbody>
</table>

Baseline

ICARUS and ICARUS+ at LBNF

protoDUNE–SP at LBNF
What we got (for $|\alpha_{21}^2|$):

Spectrum error ($\sigma_s$)
Setting a $\sigma_s$ goal, we can get minimum requirements.
We can probe sterile neutrinos too!

similar for sterile neutrino!
We can probe sterile neutrinos too!

similar for sterile neutrino!
New physics can be probed if $\sigma_s \sim O(1)\%$

Conclusion:
New physics can be probed if $\sigma_s \sim O(1)\%$

Conclusion:

SBN can slightly improve NSI/Non-unitary
New physics can be probed if $\sigma_s \sim O(1)\%$

Conclusion:

SBN can slightly improve NSI/Non-unitary

LBNF We can probe NSI/Non-unitary if $\sigma \sim O(1)\%$
New physics can be probed if $\sigma_s \sim O(1)\%$

Conclusion:

SBN can slightly improve NSI/Non-unitary

LBNF We can probe NSI/Non-unitary if $\sigma \sim O(1)\%$
(depending on detector size/location)
New physics can be probed if $\sigma_s \sim O(1)\%$

Conclusion:

SBN can slightly improve NSI/Non-unitary

LBNF We can probe NSI/Non-unitary if $\sigma \sim O(1)\%$
(depending on detector size/location)

Similar for sterile neutrino
Thanks for the supporters

Thanks

G. V. Stenico for SBN codes

Generalitat Valenciana

Ramón y Cajal

CONACyT and SNI (Mexico).