Short-baseline oscillations of high-energy neutrinos

(on the “short term” quest of STERILE neutrinos at CERN)

Luca Stanco (INFN-PD)

September 12, 2012
“Tensions” in the Standard Model between Quark and Lepton sectors:

- No right handed neutrino (in classical SM)
- Majorana masses
- Very different from quarks: large mixings and tiny masses
- Non coherent picture: discrepancies at $\approx 3-4$ sigma level, in several measurements
- Neutrinos are neutral!

As Higgs is going to be where expected...
As many open questions stay (e.g. Dark Matter)...

Neutrinos are an excellent place for looking Beyond Standard Model
Beyond Three-Neutrino Mixing

$\nu_T$, $\nu_\mu$, $\nu_e$

$\nu_1$, $\nu_2$, $\nu_3$, $\nu_4$, $\nu_5$, $\ldots$

$m_1^2$, $m_2^2$, $m_3^2$, $m_4^2$, $m_5^2$, $\log m^2$

$\Delta m_{\text{SOL}}^2$, $\Delta m_{\text{ATM}}^2$, $\Delta m_{\text{SBL}}^2$

3$\nu$-mixing
The possible presence of oscillations into sterile neutrinos was proposed by B. Pontecorvo, (JETP, 53, 1717, 1967), but so far without conclusion.

“Sterile” means “No Standard Model Interactions” (i.e. think to anti-ν_R, light neutrinos which can oscillate with “active” neutrinos).

Smoking Gun: Neutral Current Deficit

Counterchecked Smoking Gun: NC/CC ratios

Two distinct classes of anomalies have been analyzed, namely

- the apparent **disappearance signal** in the anti-ν_e events detected from (1) near-by nuclear reactors and (2) the from Mega-Curie k-capture calibration sources in the Gallium experiments to detect solar ν_e
- observation for **excess signals** of anti-ν_e electrons from neutrinos from particle accelerators (LNSD/MiniBooNE)

At least a fourth non-standard neutrino state can oscillate at small distances, Δm^2_{new} ≈ 1 eV^2 (⇒ SHORT BASELINE projects)
1) Is it worthwhile to investigate further?

- $\theta_{13}$ measured in the "standard scenario"
  
  **Sure!**

- Missing MH, CP, Majorana/Fermi, masses

- What else? coherent picture

2) Are there Neutrino ANOMALIES or lack of Precise MEASURES/Computations?

**Almost sure**

- "anomalies" from SBL (LSND, MiniBooNE)

- "anomalies" from Reactor fluxes

- "anomalies" from Gallium

3) Do we need/want to optimize the World/European searches?

**Critical**

1) Standard Scenario

- $\theta_{13}$ is "very large" compared to previous studies

- Optimizations on the Facilities not done yet
  (even if Phenomenologists result much powerful than Experimentalists believe, Experimentalists are much clever than Phenomenologists believe)

- "Brute force" (i.e. Mass or Power) is challenging

MH from T2K+NO$\nu$A+PINGU+INO+Reactors+...+fit?

OLD study
What is going on?

It might be that we have only a 6 years window to wait!

100 % !!!

**shaded:** w/o INO
50 kt, 100 kt

**solid:** $\sigma_E = 10\%$, $\sigma_\theta = 10^\circ$
**dash:** $\sigma_E = 15\%$, $\sigma_\theta = 15^\circ$

**shaded:** w/o INO
50 kt, 100 kt

Blennow, TS, 1203.3388
# Long baseline projects

<table>
<thead>
<tr>
<th>Project</th>
<th>Beam power MW</th>
<th>Fiducial Mass kt</th>
<th>Baseline km</th>
<th>MH</th>
<th>CPV 90%CL, (3σ)</th>
<th>Physics starts</th>
<th>Astrophysical program</th>
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<tbody>
<tr>
<td>LBNO</td>
<td>0.8</td>
<td>20-100</td>
<td>2300</td>
<td>Excellent</td>
<td>71 (44)</td>
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<td>Yes</td>
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<tr>
<td>T2HK</td>
<td>0.75</td>
<td>500</td>
<td>295</td>
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<td>86 (74)*</td>
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<td>LBNE</td>
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<td>1300</td>
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<td>Lund</td>
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<td>365</td>
<td>Some</td>
<td>86 (70)</td>
<td>&gt;2019</td>
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<tr>
<td>CERN-Canfranc</td>
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<td>440</td>
<td>650</td>
<td>Some</td>
<td>80-88(80)</td>
<td>&gt;2020</td>
<td>Yes</td>
</tr>
</tbody>
</table>

* if mass hierarchy is known

- T2HK: 4MW, 500 kt
- LBNE: 0.8 MW, 33 kt
- C2P = LBNO : 0.8 MW, 100 kt

P. Coloma et al. hep-ph:1203.5651

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**Neutrino Oscillation Workshop, September 2012**
CPV and the baseline issues

- CPV sensitivity is mainly driven by the total exposure (MW Mt year) and by the control of systematic uncertainties
- The baseline has a relatively mild effect
- For ultimate exposure, the sensitivity to the second maximum is at premium
None of these experiments can be considered the definitive one:

- measure $\nu$ and $\text{anti-}\nu$, muons and electrons
- in different sites ($\geq 2$)
- provide a 5 sigma result

We need a Superior Class Experiment: 3 Kton Fe + 1 Kton LAr

The ultimate 3+1 experiment!
Effective SBL Oscillation Probabilities in 3+1 Schemes

\[ P_{\nu_\alpha \rightarrow \nu_\beta} = \sin^2 2\theta_{\alpha\beta} \sin^2 \left( \frac{\Delta m_{41}^2 L}{4E} \right) \]

\[ \sin^2 2\theta_{\alpha\beta} = 4 |U_{\alpha 4}|^2 |U_{\beta 4}|^2 \]

(no CP violation)

\[ P_{\nu_\alpha \rightarrow \nu_\alpha} = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2 \left( \frac{\Delta m_{41}^2 L}{4E} \right) \]

\[ \sin^2 2\theta_{\alpha\alpha} = 4 |U_{\alpha 4}|^2 \left( 1 - |U_{\alpha 4}|^2 \right) \]

Perturbation of 3ν Mixing

\[ |U_{e 4}|^2 \ll 1, \quad |U_{\mu 4}|^2 \ll 1, \quad |U_{\tau 4}|^2 \ll 1, \quad |U_{5 4}|^2 \approx 1 \]

\[ U = \begin{pmatrix}
U_{e 1} & U_{e 2} & U_{e 3} & U_{e 4} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\
U_{s 1} & U_{s 2} & U_{s 3} & U_{s 4}
\end{pmatrix} \]

\[ \sin^2 2\theta_{\alpha\alpha} \ll 1 \]

\[ |U_{\alpha 4}|^2 \approx \frac{\sin^2 2\theta_{\alpha\alpha}}{4} \]

M. Laveder©
Effective SBL Oscillation Probabilities in $3+2$ Schemes

\[ \phi_{kj} = \Delta m_{kj}^2 L/4E \]

\[ \eta = \arg[U_{e4}^* U_{\mu4} U_{e5} U_{\mu5}^*] \]

\[ P_{(-)}_{\nu_\mu \rightarrow \nu_e}^{(-)} = 4|U_{e4}|^2 |U_{\mu4}|^2 \sin^2 \phi_{41} + 4|U_{e5}|^2 |U_{\mu5}|^2 \sin^2 \phi_{51} + 8|U_{\mu4} U_{e4} U_{\mu5} U_{e5}| \sin \phi_{41} \sin \phi_{51} \cos(\phi_{54} - \eta) \]

\[ P_{(-)}_{\nu_\alpha \rightarrow \nu_\alpha}^{(-)} = 1 - 4(1 - |U_{\alpha4}|^2 - |U_{\alpha5}|^2)(|U_{\alpha4}|^2 \sin^2 \phi_{41} + |U_{\alpha5}|^2 \sin^2 \phi_{51}) - 4|U_{\alpha4}|^2 |U_{\alpha5}|^2 \sin^2 \phi_{54} \]

- More parameters: 7 many coupled measurements!!
- CP violation

Allowed regions in the plane for combined results:

the $\nu_e$ disappearance rate (right) (reactors and Gallium sources)

the LSND /MiniBooNE anti-$\nu_e$ accelerator driven anomaly (left).

While the values of $\Delta m^2_{\text{new}}$ may indeed have a common origin, the different values of $\sin^2(2\theta_{\text{new}})$ may reflect within the four neutrino hypothesis the structure of $U_{(4,k)}$ mass matrix, with $k = \mu$ and $e$. 

C. Rubbia©
3+1 SBL oscillations

appearance

\[ P_{\mu e} = \sin^2 2\theta_{\mu e} \sin^2 \frac{\Delta m^2_{41} L}{4E} \quad \sin^2 2\theta_{\mu e} = 4|U_{e4}|^2 |U_{\mu 4}|^2 \]

disappearance (\(\alpha = e, \mu\))

\[ P_{\alpha\alpha} = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2 \frac{\Delta m^2_{41} L}{4E} \quad \sin^2 2\theta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 (1 - |U_{\alpha 4}|^2) \]

\[ \sin^2 2\theta_{\mu e} \approx \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu} \]

\(\nu_\mu \rightarrow \nu_e\) app. signal requires also signal in both, \(\nu_e\) and \(\nu_\mu\) disappearance (appearance mixing angle quadratically suppressed)
Fitting all together?

there are three classes of data:

- $\nu_e \rightarrow \nu_e$ disappearance \hspace{1cm} $\sin^2 2\theta_{ee}$
- $\nu_\mu \rightarrow \nu_\mu$ disappearance \hspace{1cm} $\sin^2 2\theta_{\mu\mu}$
- $\nu_\mu \rightarrow \nu_e$ appearance \hspace{1cm} $\sin^2 2\theta_{\mu e}$

$\sin^2 2\theta_{\mu e} \approx \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}$
TENSIONS also for the 3+2 scheme, due to disappearance bounds, particularly for $\nu_\mu$. On top of that, coupling to standard 3-flavour scenario is weak:

*is it a convenient game to play?*
Just after Kyoto 2012, a new $3.8 \sigma$ measure. MiniBooNE just released full data analysis, arXiv:1207.4809

is there something going on here?
a complicate picture, if any...

it is worth for physics

\textit{periculum in mora}
**NuMI** (Neutrinos at the Main Injector)
- 120 GeV protons from MI
- 90 cm graphite target
- 675 m decay region

**BNB** (Booster Neutrino Beam)
- 8 GeV protons from Booster
- 71 cm beryllium target
- 50 m decay region
RECENT FNAL SBL EXPERIMENTS

Booster Beam Experiments (+ NuMI Off-Axis)

SciBooNE (2007-2008)

MiniBooNE (2002-2011)

NuMI Beam Experiments

Argoneut (2009-2010)

MINERνA (ongoing)
MicroBooNE

- Short baseline experiment to explore the origin of the low energy excess reported by MiniBooNE, measure neutrino cross-sections, & develop liquid argon time projection (LArTPC) technology for future facilities.
- Will use a 170 ton LArTPC in the Booster Neutrino Beam (E=0.7 GeV) at a distance of L=0.5 km. It also sees the NuMI beam at a wide off-axis angle.

Data taking expected to start in 2014.
2-3 years run will yield $6 \times 10^{20}$ POT and $10^5$ neutrino events

<table>
<thead>
<tr>
<th>TABLE 2. Summary of event rates in MicroBooNE’s 60 ton volume by the neutrino mode BNB (6E20 POT), 468 m from the target.</th>
</tr>
</thead>
<tbody>
<tr>
<td>production mode</td>
</tr>
<tr>
<td>----------------------</td>
</tr>
<tr>
<td>CC quasi-elastic</td>
</tr>
<tr>
<td>NC elastic</td>
</tr>
<tr>
<td>CC resonance $\pi^+$</td>
</tr>
<tr>
<td>CC resonance $\pi^0$</td>
</tr>
<tr>
<td>NC resonance $\pi^0$</td>
</tr>
<tr>
<td>NC resonance $\pi^\pm$</td>
</tr>
<tr>
<td>CC DIS</td>
</tr>
<tr>
<td>NC DIS</td>
</tr>
<tr>
<td>CC coherent $\pi^0$</td>
</tr>
<tr>
<td>NC coherent $\pi^\pm$</td>
</tr>
<tr>
<td>CC Kaon production</td>
</tr>
<tr>
<td>NC Kaon production</td>
</tr>
<tr>
<td>others</td>
</tr>
<tr>
<td>total</td>
</tr>
</tbody>
</table>
But...

- Is the LAr mass sufficient?
- Is the CC measurement (in)essential?
3) Let’s do something!

- CERN, towards? For the time being decide the place: North Area! create an infrastructure for beams/R&D/multi-experiments

- Now!

- Multistep project
  Begin with SBL

- What? (decide on technology)
  we are proposing LAr+Fe
100 GeV primary beam fast extracted from SPS; target station next to TCC2; decay pipe $l = 100 \text{m}$, $\varnothing = 3 \text{m}$; beam dump: 15m of Fe with graphite core, followed by $\mu$ stations. Neutrino beam angle: pointing upwards; at -3m in the far detector ~5mrad slope.

CERN (see the talk by Daniele Gibin this afternoon)
Passed proposals...

- **Option A:** LSS6 extraction, target near BA2
  - LSS6 fast extraction and TT60 beam line exists
  - New switch to direct the proton beam towards North
  - Long (~1.6km) proton tunnel to bring the beam towards BA2

- **Option B:** LSS2 extraction, target near TCC2
  - New fast extraction system in LSS2
  - TT20 beam line exists
  - Target area near existing TCC2

**Solution:** take the best from each option and be ready in 2015!

By Ilias Efthymiopoulos, June 14 2012
Beam Studies at SPS

- 100 GeV proton, Fast Extraction (10.5 µs), Luminosity as at CNGS (conservative)

On-Axis !!

CC muons

Scenario defined for DATA Taking: 2 years of anti-$\nu$ followed by 1 year $\nu$

CC electrons
T600 layout in the CERN-SPS

Existing T600 detector inside new insulation
The present design of the T600 is extended to the basic structure of the T150 module. The module contains a high precision, high stability stainless steel structure independent of the container that supports two wire chambers, with three read-out planes each, the field shaping electrodes and one cathode, separating the two 1.5 m drift regions.

Most of the solutions already successfully adopted for the T600 at LNGS will be used. Existing equipment will be conveniently re-used (wiring tables, cleaning tools, etc.).
NESSiE (Neutrino Experiment with Spectrometers in Europe)

- **Goal:**
  - Allow charge separation and momentum measurement of as many muons as possible escaping from LAr
    (large statistics ↔ low $\sin^2 2\theta$)
  - Go as low as possible in muon momentum
    (low momenta ↔ low $\Delta m^2$)
  - Possibility to also study (NESSiE) internal events
    (coarser resolution w.r.t. LAr)

- **Solution:**
  - Air-core magnets for low momentum muons escaping from LAr
    ($E_\mu < 0.5$ GeV/c in NESSiE ↔ $\langle E_\nu \rangle < 1$ GeV in LAr)
  - Downstream massive iron dipolar magnets for higher momenta extension
NESSiE Detector configuration (far position)

Charge mis-reconstruction at few percent level in all dynamical range of interest (full simulation including selection, efficiency and reconstruction)

Picture credits: G. Sirri
A direct, new approach to sterile oscillations at CERN/SPS

● The direct, unambiguous measurement of an oscillation pattern requires necessarily the (simultaneous) observation at several different distances. It is only in this way that the values of $\Delta m^2$ and of $\sin^2(2\theta)$ can be separately identified.

● The CERN experiment introduces important new features, which should allow a definitive clarification of all the present "anomalies":
  - L/E oscillation paths lengths to ensure appropriate matching to the $\Delta m^2$ window for the expected anomalies.
  - "Imaging" detector capable to identify unambiguously all reaction channels with a "Gargamelle class" LAr-TPC
  - Magnetic spectrometers to determine muon charge and p
  - Interchangeable $\nu$ and anti-$\nu$ focussed beams
  - Very high rates due to large masses, in order to record relevant effects at the % level ($>10^6 \nu\mu, \approx 10^4 \nu e$)
  - Both initial $\nu e$ and $\nu\mu$ components cleanly identified.
Basic features of the proposed experiment

- Our proposed experiment, collecting a large amount of data both with neutrino and antineutrino focussing and muon momentum determination may be able to give a likely definitive answer to the 4 following queries:
  - the LSND/+MiniBooNe both antineutrino and neutrino $\nu_\mu \rightarrow \nu_e$ oscillation anomalies;
  - The Gallex + Reactor oscillatory disappearance of the initial $\nu$–$e$ signal, both for neutrino and antineutrinos
  - an oscillatory disappearance maybe present in the $\nu$–$\mu$ signal, so far unknown.
  - Accurate comparison between neutrino and antineutrino related oscillatory anomalies, maybe due to CPT violation.

- In absence of these “anomalies”, the signals of the detectors should be a precise copy of each other for all experimental signatures and without any need of Monte Carlo comparisons.
Comparing LSND sensitivities

Expected sensitivity for the proposed experiment: $\nu_{\mu}$ beam (left) and anti-$\nu_{\mu}$ (right) for $4.5 \times 10^{19}$ pot (1 year) and $9.0 \times 10^{19}$ pot (2 years) respectively. LSND allowed region is fully explored in both cases.
Sensitivity to $\nu_\mu$ disappearance

90% C.L. sensitivity for 2 years anti-$\nu$ + 1 year $\nu$

Exclusion limits:
- CCFR
- CDHS
- SciBooNE
- MiniBooNE

Present proposal (2+1 years)
Sensitivity to $\nu_e$ disappearance anomalies

- Oscillation sensitivity in $\sin^2(2\theta_{\text{new}})$ vs. $\Delta m^2_{\text{new}}$ distribution for CERN-SPS neutrino beam (1 year). A 3% systematic uncertainty on energy spectrum is included. See also combined “anomalies” from reactor neutrino, Gallex and Sage experiments.
Expected signal for LSND/MiniBooNE anomalies

- Event rates for the near and far detectors given for $4.5 \times 10^{19}$ pot. The oscillated signals are clustered below 3 GeV of visible energy.
- Values for $\Delta m^2$ around 2 eV$^2$ are reported as example

<table>
<thead>
<tr>
<th>Produced</th>
<th>NEAR ($\nu$–bar)</th>
<th>NEAR($\nu$)</th>
<th>FAR($\nu$–bar)</th>
<th>FAR($\nu$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e + \bar{\nu}_e$ (LAr)</td>
<td>35 K</td>
<td>54 K</td>
<td>4.2 K</td>
<td>6.4 K</td>
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<tr>
<td>$\nu_\mu + \bar{\nu}_\mu$ (LAr)</td>
<td>2000 K</td>
<td>5250 K</td>
<td>270 K</td>
<td>670 K</td>
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<tr>
<td>Appear. test point</td>
<td>590</td>
<td>1900</td>
<td>360</td>
<td>910</td>
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</table>

<table>
<thead>
<tr>
<th>Detected</th>
<th>NEAR (LAr+NESSiE)</th>
<th>NEAR(NESSiE)</th>
<th>FAR(LAr+NESSiE)</th>
<th>FAR(NESSiE)</th>
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<tbody>
<tr>
<td>$\nu_\mu$ (LAr+NESSiE)</td>
<td>230 K</td>
<td>1200 K</td>
<td>21 K</td>
<td>110 K</td>
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<td>$\nu_\mu$ (NESSiE)</td>
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<td>280 K</td>
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<td>$\nu_\mu$–bar (LAr+NESSiE)</td>
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<td>56 K</td>
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<td>6.9 K</td>
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<td>$\nu_\mu$–bar (NESSiE)</td>
<td>1100 K</td>
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<td>89 K</td>
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<td>Disappear. test point</td>
<td>1800</td>
<td>4700</td>
<td>1700</td>
<td>5000</td>
</tr>
</tbody>
</table>

*NOTE: $\nu$ “contamination” in anti-$\nu$ negative polarity beam*
Muon disappearance signal

Measured muon momenta in Far detector for anti-$\nu_\mu$ CC and $\nu_\mu$ CC with oscillation (red) compared to the non-oscillated distribution. Event rates are for $4.5 \times 10^{19}$ pot at 100 GeV, negative polarity reconstructed in the fiducial volumes of the Spectrometer alone.

1 year of anti-neutrinos!
Comparison with MINOS+ limits

$\nu_\mu$ disappearance

$\nu_e$ dis/appearance

Luca Stanco - INFN
### Time Schedule

<table>
<thead>
<tr>
<th>Name</th>
<th>Days</th>
<th>Months</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buildings in NA: preparation-erection</td>
<td>356</td>
<td></td>
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<tr>
<td>T600</td>
<td>833</td>
<td></td>
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<tr>
<td>Vessels, thermal isolation: design, orders...</td>
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<tr>
<td>Transport frame: design, order, construction...</td>
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<tr>
<td>Working area equipment...</td>
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<tr>
<td>T600 decommissioning &amp; disassembly...</td>
<td>106</td>
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<td>T600 first vessels delivery...</td>
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<td>T600 first TPC transport to CERN</td>
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<td>T600 First module assembly</td>
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<tr>
<td>T600 First module transport in NA</td>
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<td>T600 thermal isolation erection...</td>
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<td>T600 second vessels delivery</td>
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<tr>
<td>T600 second module assembly</td>
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<tr>
<td>T600 second module transport in NA</td>
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<td>T600 plant assembly...</td>
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<td>T600 final tests, commissioning, filling...</td>
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<tr>
<td>T150</td>
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<td>T150 TPC order, construction, delivery</td>
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<td>T150 vessel delivery</td>
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<td>T150 cryostat assembly</td>
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<td>T150 thermal isolation erection</td>
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<td>T150 transport in NA</td>
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<td>T150 plant assembly</td>
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<tr>
<td>T150 final tests, commissioning, filling...</td>
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<td>NESSIE</td>
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<td>prototype construction</td>
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<td>iron production-Lamination</td>
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<tr>
<td>Construction Assembling Tools</td>
<td>194</td>
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<tr>
<td>Coils and cooling</td>
<td>196</td>
<td></td>
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<tr>
<td>FAR Iron Magnet – Assembling</td>
<td>261</td>
<td></td>
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<tr>
<td>FAR Commissioning</td>
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<tr>
<td>NEAR Iron Magnet – Assembling</td>
<td>218</td>
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<tr>
<td>NEAR Commissioning</td>
<td>43</td>
<td></td>
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<tr>
<td>Air Magnet construction</td>
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<td></td>
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<tr>
<td>Air Magnet insertion on site</td>
<td>15</td>
<td></td>
</tr>
</tbody>
</table>

≥ 20 M€, All Inclusive!
## Oscillation Studies

<table>
<thead>
<tr>
<th>Oscillation type</th>
<th>Neutrinos</th>
<th>Experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_{12}$</td>
<td>$\nu_e$ (solar, reactors)</td>
<td>SNO, SK, Borexino, Kamland</td>
</tr>
<tr>
<td>$\theta_{23}$</td>
<td>$\nu_\nu$ (atmospheric, accelerators)</td>
<td>SK, Minos, T2K</td>
</tr>
<tr>
<td>$\theta_{13}$</td>
<td>$\nu_e$ (reactors)</td>
<td>Daya Bay, RENO, Double Chooz</td>
</tr>
<tr>
<td>$\theta_{14}$</td>
<td>$\nu_e$ (reactors, radioactive sources)</td>
<td>SBL Reactors, Gallex, Sage. <strong>This Proposal</strong></td>
</tr>
<tr>
<td>$\theta_{24}$</td>
<td>$\nu_\nu$ (accelerators)</td>
<td>CDHS, Miniboone. MINOS+ <strong>This Proposal</strong></td>
</tr>
</tbody>
</table>

*Measure at L/E corresponding to $\Delta m^2 \sim 1$ eV$^2*$

$\nu_\mu$ AND $\overline{\nu}_\mu$

**AND with $\geq 2$ sites**

- in Appearance ($\nu_e$)
- AND
- in Disappearance ($\nu_\mu$)

$2^3$ combs

L.Stanco©
Thank you!
BACKUP slides
Are neutrino a simple “carbon copy” repetition of quarks?

- Over the last several years, neutrinos have been the origin of an impressive number of “Surprises”:
  - Mass differences, once zero “by ignorance”, are important
  - Large mixing oscillations
  - Oscillations due to matter exist, due to neutral currents

- But this isn’t all! Important discoveries may be ahead:
  - CP violation in the lepton sector, following the $\theta_{13} \gg 0$ result
  - Majorana or Dirac $\nu$’s?; $\nu$-less $\beta$-decay
  - Actual values of $\nu$-masses
  - Right handed neutrinos and see-saw mechanisms
  - Sterile neutrino and other “surprises”

- Of course the astronomical importance of neutrinos in space is immense, so is their role in the cosmic evolution.

- Just a few eV neutrino may be the source of the dark mass.

C. Rubbia©
Future sterile neutrino searches elsewhere

● **Radioactive sources** (EC, fission fragments) plus low energy detectors to search for $\nu_e$, anti-$\nu_e$ disappearance. Elastic Scattering: Daya Bay, Borexino, SNO+Cr; Charged Current: LENS, Baksan, Ce-LAND, Borexino; Neutral Current: RICOCHET. Most use existing detectors.

● **Reactors**. Several ideas for new reactor experiments. Some, piggy-backing on safe guards measurements are under construction: Nucifer, SCRAAM, Stereo. Need to be very close to reactor core. Small cores advantageous.

● **Stopped $\pi$ Beams**: (Direct test of LSND anomaly): OscSNS: Improved LSND (Off beam axis, lower duty factor, gadolinium?); LSND-Reloaded: Gd-loaded Super-K plus cyclotron. What if LSND is new physics but not oscillations?

● **Decay in Flight Beams**: MicroBooNE, BooNE, LArLAr, VLENF: the CERN idea of a two-detector experiments is now also considered in order to clarify the MiniBooNE/LSND anomaly.

(visit http://cnp.phys.vt.edu/white_paper/ )

C. Rubbia®
**Unique features of the CERN beam**

- The present proposal is a search for spectral differences of electron like specific signatures in two identical detectors but at two different neutrino decay distances.
- **In absence of oscillations**, apart some beam related small spatial corrections, the two spectra are a precise copy of each other, independently of the specific experimental event signatures and without any Monte Carlo comparisons.
- Therefore an exact, observed proportionality between the two $\nu_e$ spectra implies directly the absence of neutrino oscillations over the measured interval of L/E.

[Graph showing $\nu_e + \bar{\nu}_e$ event rates for near and far positions with an expected anomaly marked.]
The present method, unlike LNSD and MiniBooNE, determines both the mass difference and the value of the mixing angle.

Very different and clearly distinguishable patterns (1-4) are possible, depending on the values in the \((\Delta m^2 - \sin^2 2\theta)\) plane.

The intrinsic \(\nu\)-e background (5) is also shown.