ICARUS T600 Trigger Study at the Short-Baseline Neutrino Experiment

Białasówka Seminar

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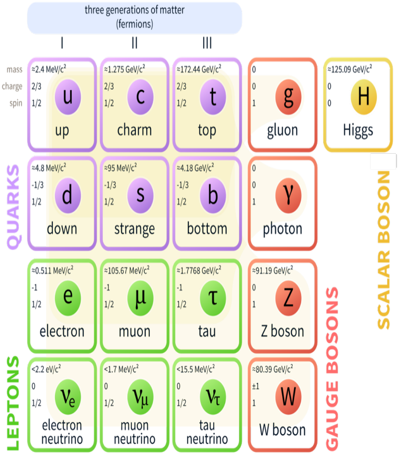
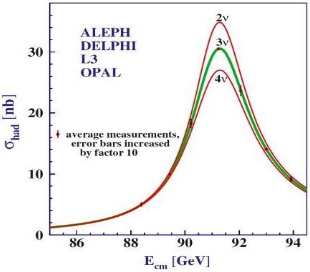
Outline

Neutrino physics

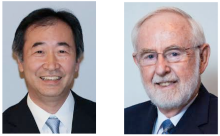


The SM assumption about zero mass neutrinos turned to be not in agreement with observed neutrino oscillations.



Number of neutrino flavours (light and coupling to the Z): 2.9840 ± 0.0082

Nobel Prize in Physics 2015 for the discovery of neutrino oscillations



Takaaki Kajita **Arthur B. McDonald**

Experimental results: Super-Kamiokande ($\nu_\mu \to \nu_\tau$) or SNO ($\nu_e \to \nu_{\mu,\tau}$).

Oscillations - description for 3 flavour states and 3 neutrino mass states

- Oscillations for the three neutrino flavours are a well-established experimental fact.
- But, some experiments indicate the possibility of a fourth type of neutrino from beyond the Standard Model.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix},$$

Parameter	best-fit	3σ
Δm^2_{21} $[10^{-5}$ eV $^2]$	7.37	$6.93 - 7.96$
$\Delta m^2_{31(23)}$ $[10^{-3}$ eV $^2]$	2.56 (2.54)	$2.45 - 2.69$ $(2.42 - 2.66)$
$\sin^2\theta_{12}$	0.297	$0.250 - 0.354$
$\sin^2\theta_{23}$, $\Delta m^2_{31(32)} > 0$	0.425	$0.381 - 0.615$
$\sin^2\theta_{23}$, $\Delta m^2_{32(31)} < 0$	0.589	$0.384 - 0.636$
$\sin^2\theta_{13}$, $\Delta m^2_{31(32)} > 0$	0.0215	$0.0190 - 0.0240$
$\sin^2\theta_{13}$, $\Delta m^2_{32(31)} < 0$	0.0216	$0.0190 - 0.0242$
δ/π*	1.38 (1.31)	2σ: (1.0 - 1.9) (2σ: (0.92-1.88))

M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018) and 2019 update.

*T2K Collaboration recently reported a new result at 3σ confidence level for δ_{CP}: $[-3.41, -0.03]\pi$ for the so-called normal mass ordering and $[-2.54, -0.32]\pi$ for the inverted mass ordering. *Nature volume 580, pages 339-344 (2020)*

Additional area of neutrino oscillations?

LSND: $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$

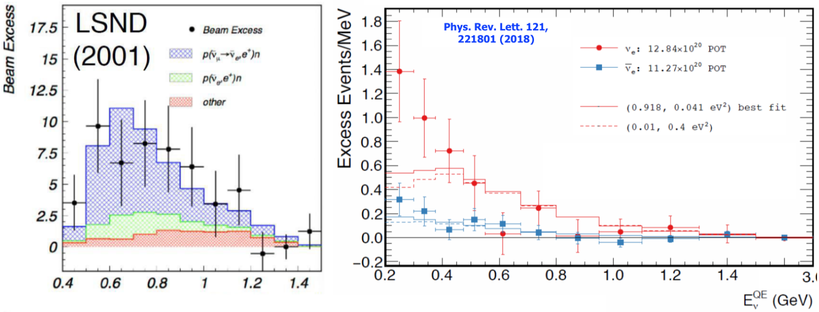
- Data taken in 1993-1998.
- Measurement $\overline{\nu}_\mu$ of the decay: $\mu^+ \rightarrow e^+ \nu_e \overline{\nu}_\mu$ from $\pi^+ \rightarrow \mu^+ \nu_\mu$.
- Observed excess $\overline{\nu}_e$ at $3.8\ \sigma$.
- This leads to Δm^2 within the range from $0.2eV^2$ to $2eV^2$ for transitions $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ due to oscillations between active neutrinos and another kind of neutrino(s) called sterile neutrino(s).

MiniBooNE: $\nu_\mu \rightarrow \nu_e$ **and** $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$

- Data taken in 2002-2017, altogether 11.27×10^{20} POT $\overline{\nu}_\mu$ beam and 12.84×10^{20} ν_μ beam.
- Best fit with a 2-flavour model for $\Delta \mathrm{m}^2 = 0.041\ \mathrm{eV}^2$ and $\sin^2 2\theta = 0.918$.

Additional area of neutrino oscillations?

The LSND and MiniBooNE experiments indicate that.



MiniBooNE: 4.7σ
LSND: 3.8σ
Both: 6.0σ

Sterile neutrinos

Anomalies			
Experiment:	Confidence level (σ):	Channel:	E(MeV), L(m):
LSND	3.8	$\overline{\nu_\mu} \to \overline{\nu_e}$	40, 30
MiniBooNE	4.7	$\nu_\mu \to \nu_e, \overline{\nu_\mu} \to \overline{\nu_e}$	800, 600
Reactor	3.0	$\overline{\nu_e} \to \overline{\nu_x}$	3, 10-100
Gallium	2.9	$\nu_e \to \nu_x$	<3,10

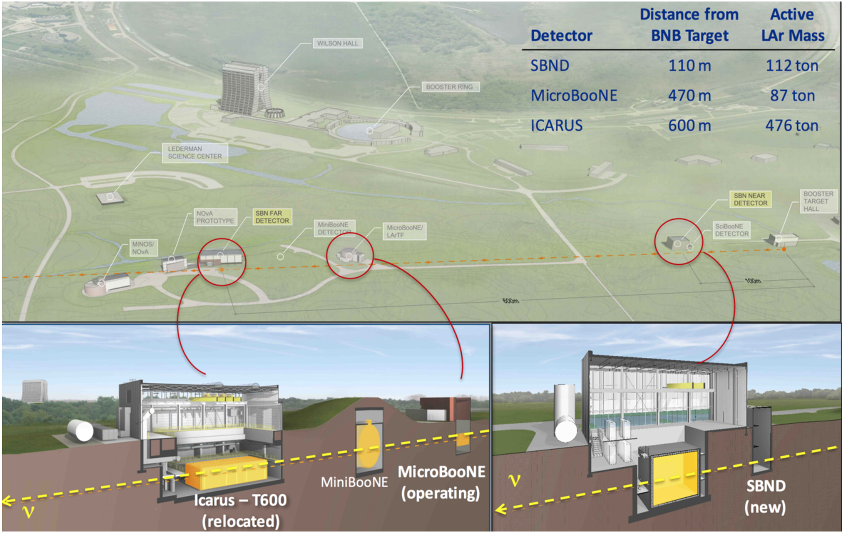
$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \\ |\nu_s\rangle \\ \vdots \end{pmatrix} = \begin{pmatrix} U^*_{e1} & U^*_{e2} & U^*_{e3} & U^*_{e4} & \cdots \\ U^*_{\mu 1} & U^*_{\mu 2} & U^*_{\mu 3} & U^*_{\mu 4} & \cdots \\ U^*_{\tau 1} & U^*_{\tau 2} & U^*_{\tau 3} & U^*_{\tau 4} & \cdots \\ U^*_{s1} & U^*_{s2} & U^*_{s3} & U^*_{s4} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \\ |\nu_4\rangle \\ \vdots \end{pmatrix}$$

The mixing matrix for neutrinos can be extended with sterile neutrinos.

→ ν_s can be detected by observing oscillations with active neutrinos.

Short Baseline Neutrino Experiment at Fermilab

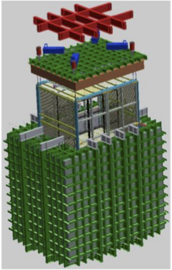
Purpose: final check of LSND and MiniBooNE observations.



Three liquid-argon time projection chambers located on the BNB beam.

Short Baseline Neutrino Detectors

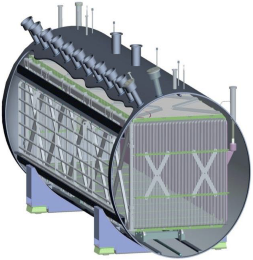
SBND



- 110 m from ν production
- 112 ton active volume
- 2 × 2.0 m drift length
- 100 kV high voltage
- 1.28 ms drift time at 500V/cm
- 3 wire planes: 0, ∓60°, 3mm wire pitch, 11264 wires
- Cold analog and digital electronics
- 120 8” PMTs and scint. bars

UNDER CONSTRUCTION

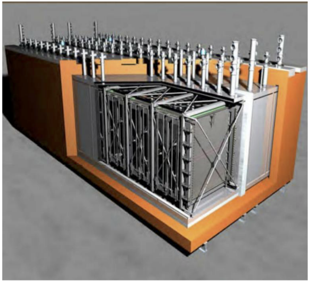
MicroBooNE



- 470 m from ν production
- 85 ton active volume
- 2.56 m drift length
- 128 kV high voltage
- 1.6 ms drift time at 500V/cm
- 3 wire planes: 0, ∓60°, 3mm wire pitch, 8256 wires
- Cold analog/warm digital electronics
- 32 8” PMTs

RUNNING SINCE 2015

ICARUS T600

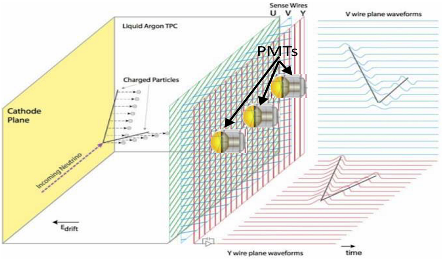


- 600 m from ν production
- 476 ton active volume
- 4 × 1.5 m drift length
- 75 kV high voltage
- 0.95 ms drift time at 500V/cm
- 3 wire planes: horizontal, ∓30°, 3mm wire pitch, 53246 wires
- Warm analog and digital electronics
- 360 8” PMTs

START RUNNING: SUMMER 2020

Liquid Argon Time Projection Chambers

- **Possibility of charge (slow signal) and light (fast signal) detection** to obtain information on neutrino interaction time and 3D reconstruction of charged particles tracks.

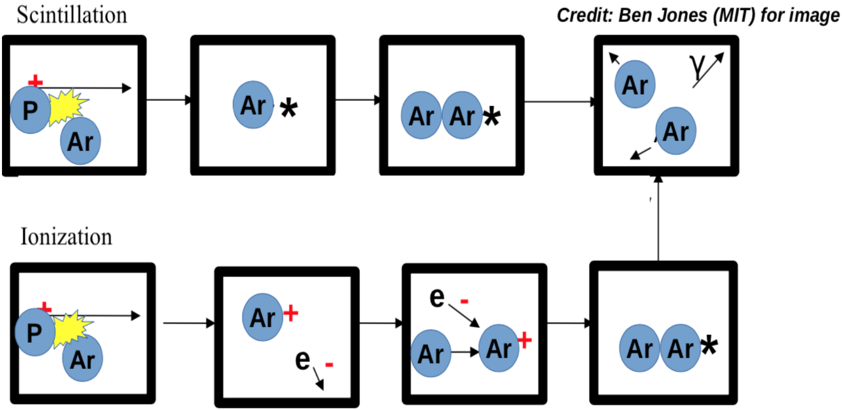


- **High spatial and energetic resolution**, which is required for studying details of the final states in neutrino interactions.

- **Possibility of building huge detectors** to compensate for very small cross-sections of neutrino interactions with matter.

Detectors using the liquid-argon time projection technique: ***ICARUS***, *ArgoNeut, MicroBooNE, SBND, ProtoDUNE, DUNE*.

Liquid Argon - two types of signals

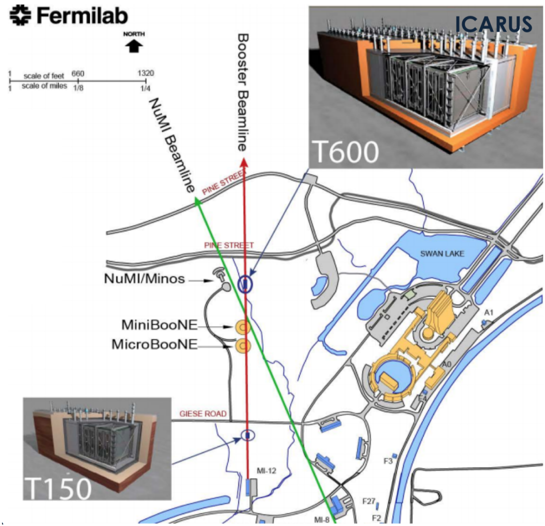


Fast (~ 6 ns) LAr scintillation light signal peaked at 128 nm can be used for timing/triggering by PMTs.

Slower (~ ms) signal from ionization electrons is read by the anode wires.

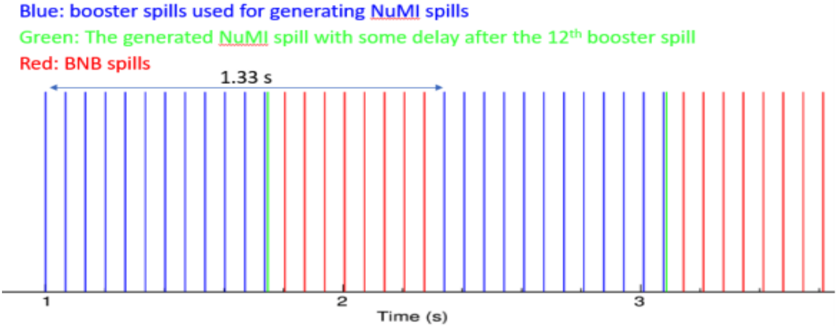
BNB and NuMI beams

- Short Baseline Neutrino experiment at Fermilab makes use of the well established Fermilab Booster Neutrino Beamline (BNB).
- 8 GeV proton beam, ν flux peaks at 700 MeV.
- ICARUS also sees the NuMI beam (used for NOvA) at $\sim 6^\circ$ off-axis.



BNB and NuMI beams time structures

- The Booster spill duration is 1.6 μs with nominally 5×10^{12} protons per spill.
- The NuMI spill duration is 9.5 μs with nominally 4×10^{13} protons per spill.



Event rates

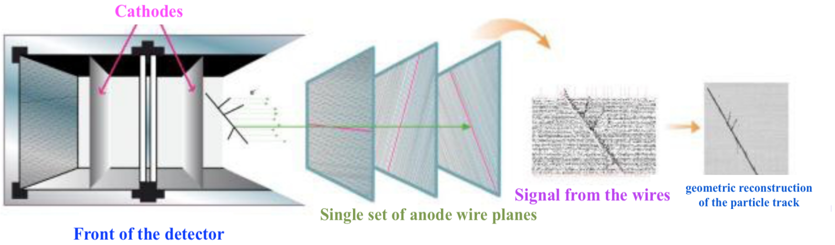
1. **BNB:**
   - $\sim 1\ \nu$ interaction every 180 spills.
   - A similar rate is expected from beam-associated events: mainly interactions of muons from beam halo and some neutrinos interacting in the material surrounding the T600 detector.
   - The dominant event rate, 1 over 55 spills, is due to cosmic rays inside the beam spill time window.
   - In summary, ~1 event over 35 spills, i.e. ~1 event every ~7 s, is expected in T600 due to above three sources.
2. **NuMI:**
   - $\sim 1\ \nu$ interaction every 53 spills.
   - 1 background event, mainly due to cosmic rays, is expected every 7 spills.
   - In summary, ~1 event over ~6 spills, i.e ~ 1 event every ~9 s is expected in the T600.
3. **Background due to Ar^{39} decays and due to random noise**
   - ~ 1.2 decay in the BNB beam window, and 7 decays in NuMI beam window.

ICARUS T600 detector

- Two identical modules adjacent to each other.
- Dimensions of one module: 3.6 m × 3.9 m × 19.9 m .
- Each module contains two time projection chambers which have a common cathode.
- HV: 75 kV.
- Maximum electron drift length: 1.5 m.
- Maximum electron drift time: ~1 ms (500 V/cm).

ICARUS T600 detector

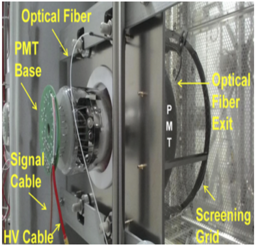
- Three are four sets of three planes of anode wires (in total 53248 wires) and two cathode planes in the ICARUS T600 detector.
- In each set of three planes of anode wires, difference in inclination angles of wires of subsequent planes is 60°.
- Distance between wires: 3 mm, distance between planes: 3 mm.
- 360 8" PMTs placed behind the anode planes (90 PMTs per TPC).

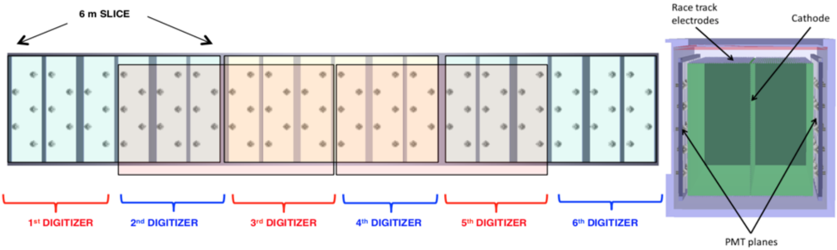


The PMT light detection system

The ICARUS PMT system is dedicated to perform three tasks:

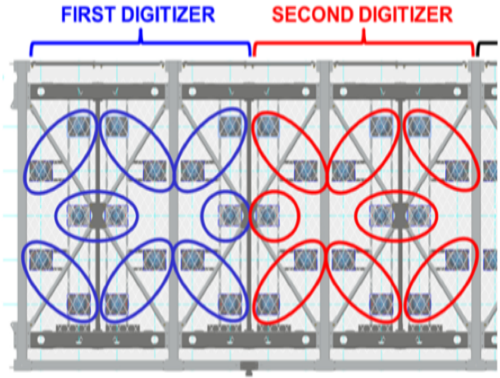
- the identification of the time of occurrence (t_0) of each interaction,
- the generation of a light-based trigger signal,
- the initial recognition of event topologies for the fast event selection.





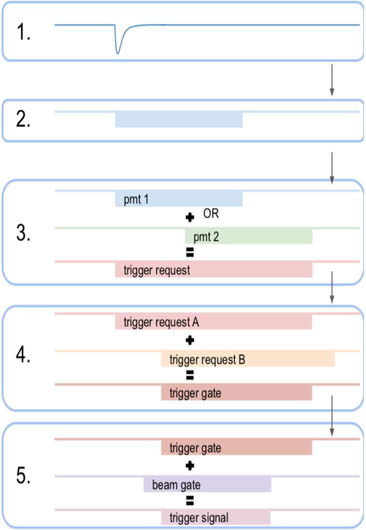
Trigger system of the ICARUS T600 detector

- The trigger hardware takes the combined discriminated signals of paired PMTs.
- The combination is done using either AND or OR logic.
  - AND - both PMTs have signals above threshold at overlapping times.
  - OR - at least one PMT has signal above threshold.



Trigger implementation in the simulation

1. Implementation of the PMT digitised signals (waveforms).
2. The waveforms are converted into discriminated waveforms with a length defined by a PMT gate.
3. Discriminated waveforms from paired PMTs are combined with either AND or OR logic to form a single trigger request.
4. Trigger requests are then combined with all other requests to form a combined trigger gate.
5. The combined trigger gate that occurs in coincidence with the neutrino beam gate is labeled as taken.



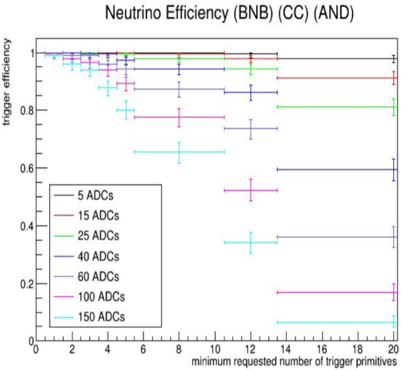
Trigger Monte Carlo Study

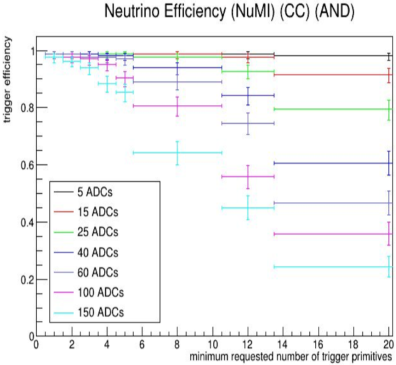
- The evaluation of the trigger system in terms of the efficiency of detecting neutrino interactions.
- The following trigger parameters are used to evaluate the signal and background trigger rates:
  - AND/OR logic,
  - trigger gate length,
  - PMT multiplicity requirement,
  - waveform discrimination threshold.
- The study has been performed in parralel for the two beams due to different physical features and beam gate windows of the NuMI and BNB beams.
- The study has been focused on the charged current (CC) interactions, because they result in at least one charged particle (charged lepton) in the final states and measureable amount of scintillation light is provided for the trigger evaluation.

Initial results of the trigger simulations for ICARUS T600

- Monte Carlo simulation has delivered the following initial values of the trigger parameters:
  - trigger gate length: 200 ns - reduces trigger rates due to long lasting cosmic background;
  - ADC threshold: 40 ADC - reduces trigger rates of cosmic rays, Argon-39 decays, and random noise;
  - PMT multiplicity requirement: 2 (BNB) or 3 (NuMI) - reduces trigger rates of Argon-39 decays and random noise;
  - trigger logic: AND - reduces trigger rates of Argon-39 decays and random noise;
- The optimization of above parameters serves for minimizing the background trigger rates and maximizing the trigger efficiency of neutrino interactions.
- Charged current neutrino interactions from the BNB beam will be triggered more efficiently than those from NuMI.

Trigger Efficiencies in a function of the waveform discrimination threshold





Conclusions and Outlook

- The SBN experiment should finally clarify the anomalies observed by LSND and MiniBooNE.
- The ICARUS trigger system is extremely important for the detector operation on a surface with a large cosmic muon background.
- The trigger system simulation is well advanced and more quantitative studies are on going.
- The trigger system based on the LAr scintillation light is under development and both its simulation and its performance will be subjects of my PhD thesis.

Neutrino physics

The SM has been built assuming neutrinos are massless...

Limits on the neutrino masses (95% CL):

$m_{\nu_e} < 2.2$ eV $\sim 4.3 \times 10^{-6}$ m_e
$m_{\nu_\mu} < 170$ keV ~ 0.0018 m_μ
$m_{\nu_\tau} < 15.5$ MeV ~ 0.01 m_τ

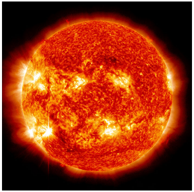
Neutrinos have very small interaction cross sections.

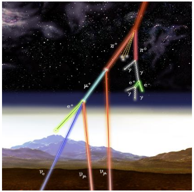
For neutrinos with energies of a few MeV:

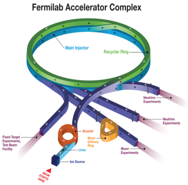
$$\sigma_{\nu N} \sim 10^{-43}\ \text{cm}^2$$

The average free path of a neutrino with the energy of 1 GeV (10^9 eV) in the Earth's matter is 10^6 diameters of the Earth, i.e. 10^6 neutrinos are needed for one of them to interact in the Earth.

Studying neutrino interactions is only possible by using very intensive neutrino sources and huge detectors







Additional area of neutrino oscillations?

SAGE i GALLEX: ***gallium anomaly***

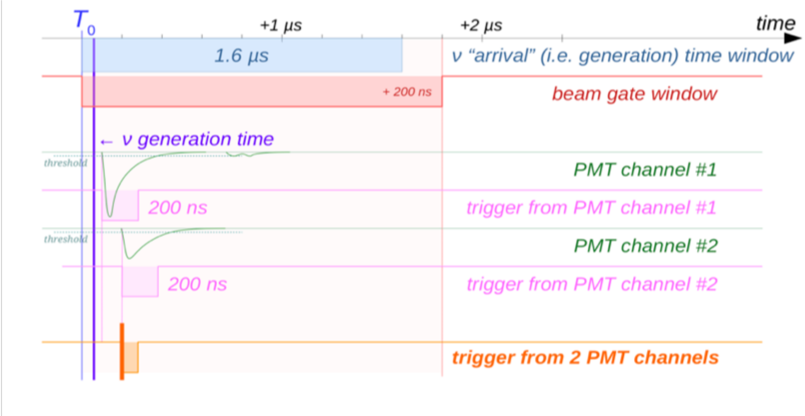
- Study of the ν_e coming from ^{51}Cr and ^{37}Ar, used for calibration, resulted in $\sim$ 15 % lower number of interactions that expected.

Reactor anti-neutrino: ***stream anomaly***

- A data deficit of ~6% is called a reactor antineutrino anomaly
- Study of the $\overline{\nu}_e$ produced in the reactor as a result of β decay of the four fissionable nuclides ^{235}U, ^{238}U,^{239}Pu i ^{241}Pu.

arXiv:1904.07812

Trigger timing



- The number of the PMT pairs whose trigger gates overlap with the beam gate are called *LVDS on*.
- If the channels trigger gate overlaps with the beam gate, the channel contributes to the trigger.