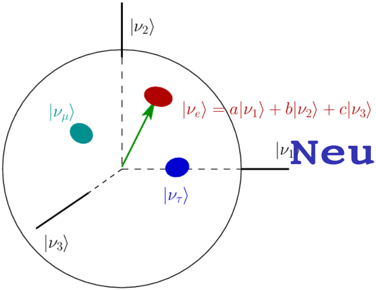
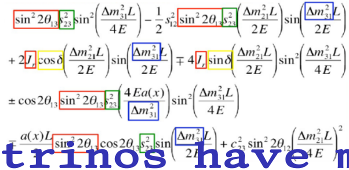
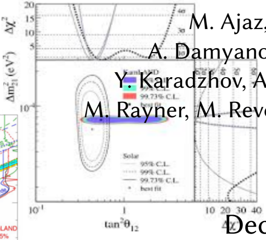


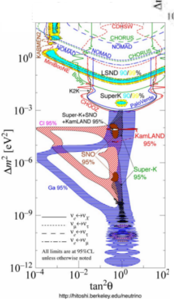




# Neutrinos have mass.

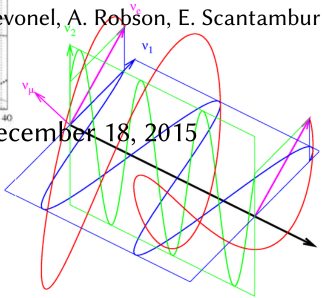
Is this a big deal?


M. Ajaz, A. Blondel, A. Bravar,
A. Damyanova, F. Drielsma, L. Haegel,
Y. Karadzhov, A. Korzenev, L. Maret, E. Noah,
M. Rayner, M. Revonel, A. Robson, E. Scantamburlo




December 18, 2015



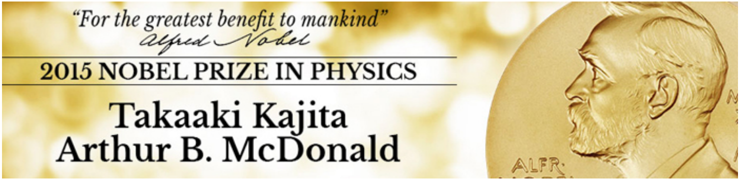



Photo © Takaaki Kajita

**Takaaki Kajita**

**Prize share:** 1/2

Photo: K. McFarlane. Queen's University /SNOLAB

**Arthur B. McDonald**

**Prize share:** 1/2

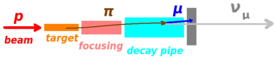
The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

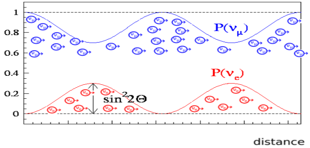
# Neutrino oscillations

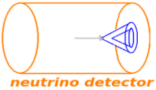
Weak interaction produces neutrino (muon neutrino $\nu_\mu$ in this example).

Mass (energy) states propagate with different velocities, causing oscillation.

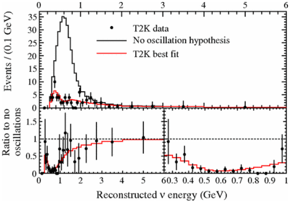
A neutrino interacts and is detected. It may have a new identity.

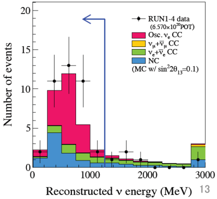



T2K experiment: $\nu_\mu$ disappearance & $\nu_e$ appearance




This quantum mechanical phenomenon is possible only if neutrinos are massive particles.

Okey ..., neutrinos have mass.
But what is mass?

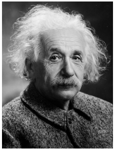
1687

Isaac Newton

In **Classical mechanics** (normal life) the mass determines:

- The gravitational force or weight.
- The force it takes to win over inertia and give/change movement.

1905

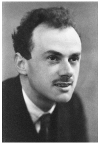


Albert Einstein

- In **Relativity** mass forbids a particle to go at the speed of light. $v = c\sqrt{1 - m^2c^4/E^2}$
- It also creates a **dilatation of time**!
  $t_{particle} = t_{humains}.mc^2/E \quad = 0\ ??$

Time for a massless particle is frozen and it cannot be seen to transform. If we see neutrinos transform (oscillate) they have mass.

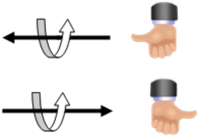
# 1928



Paul Dirac

In **Particle physics**:

- New quantum property of the particles, called helicity or handedness.



Right-handed

Left-handed

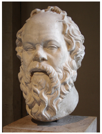
# 1964-2012

Englert & Higgs

- According to the **Higgs mechanism**, the particles acquire mass by interacting with the Higgs field. All particles change handedness when they collide with the Higgs boson.
- This mechanism gives mass to particles provided they have both right and left-handedness.

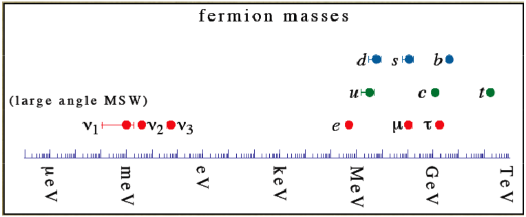
But experiments have shown that neutrinos are always Left-handed and anti-neutrinos are always Right-handed. Therefore the Standard Model predicts that neutrinos can never acquire mass.

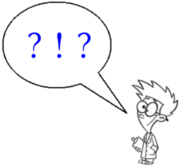
**There are several other questions that the SM does not answer ...**



In **Ancient Greek philosophy** (Socrates):
*Ipse se nihil scire id unum scia* - I know that I know nothing.
400 BC

1. Is mass turning neutrinos into antineutrinos? Or are there right-handed neutrinos (which we have never seen)? Or both?

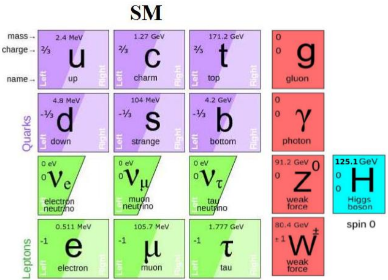


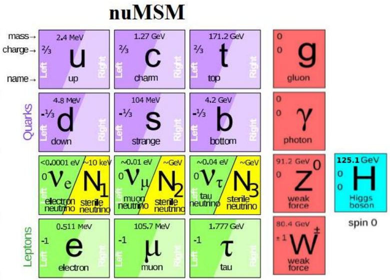




2. Why the neutrino masses are so small? But also ...
3. Why does the observable universe have more matter than antimatter? (Baryon Asymmetry of the Universe)
4. What is the Dark Matter made of?

# If **neutrinos have mass**

# the Standard Model cannot be a complete theory ...



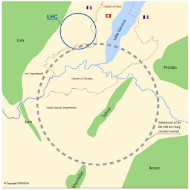

## ... and this very probably implies that new degrees of freedom are needed.

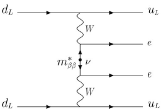
Right-Handed, Almost Sterile (very small couplings) Neutrinos completely unknown masses (meV to ZeV), nearly impossible to find.

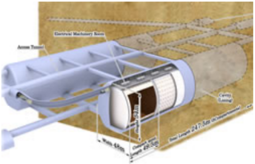
.... but could perhaps explain all: $\nu$-masses, DM, BAU.

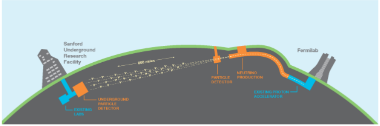
# An important and growing experimental program is happening and planned.

- T2K
- HYPERK
- DUNE
- $\nu$Storm
- Daya Bay
- SHIP
- FCC-ee
- ....

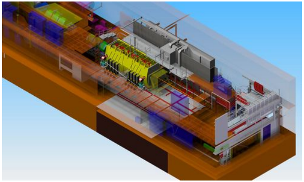






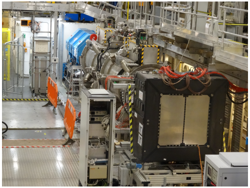

# MICE - R&D towards Neutrino Factory and Muon Collider



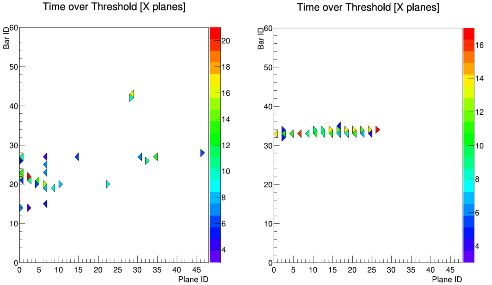
- Step IV construction is nearly completed and data-taking will start in 2016.
- On track to deliver demonstration of ionization cooling by 2018.

## Electron-Muon Ranger (EMR) - to separate electrons from muons

EMR at RAL



electron muon

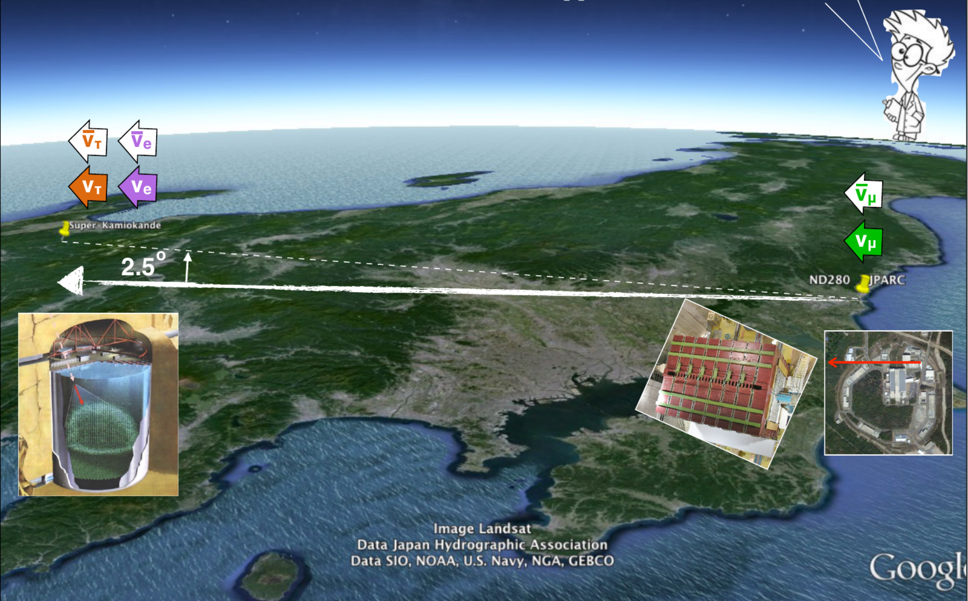



Electrons can be identified with 98.6% efficiency using the EMR alone. Published in 2015.

# The T2K Experiment

World leading constraints on mixing angles

The first demonstration of the appearance of a flavour



# The T2K Experiment

World leading constraints on mixing angles

The first demonstration of the appearance of a flavour

Our group leads efforts to…

Perform global appearance/ disappearance fits to the oscillation parameters

Propagate detector systematics

$\bar{\nu}_\tau$ $\bar{\nu}_e$ $\nu_\tau$ $\nu_e$

Super-Kamiokande

2.5°

$\bar{\nu}_\mu$ $\nu_\mu$

ND280 JPARC

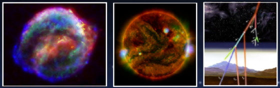
Measure the water/ carbon cross-section, a large and irreducible systematic for CPV

Baby-MIND / Wagasci for cross-section constraints

Upgrade the near detector

NA61 and flux constraints

Image Landsat
Data Japan Hydrographic Association
Data SIO, NOAA, U.S. Navy, NGA, GEBCO



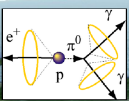
# Super → Hyper-Kamiokande

Detector mass ×25, flux ×2

Definitive measurement of CP violation

Also proton decay, sterile ν, SN ν, atmospheric ν, solar ν…

Our group is at the forefront of optimising the design of the near and far detectors



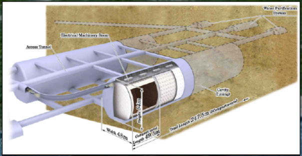

Super-Kamiokande

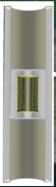
$2.5^\circ$

$\bar{\nu}_\mu$

$\nu_\mu$

ND280 JPARC





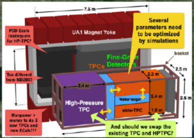
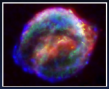
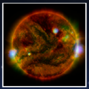
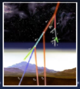



Image Landsat
Data Japan Hydrographic Association
Data SIO, NOAA, U.S. Navy, NGA, GEBCO

# Super -> Hyper-Kamiokande

Detector mass ×25, flux ×2

Definitive measurement of CP violation

Also proton decay, sterile ν, SN ν, atmospheric ν, solar ν…

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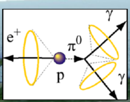
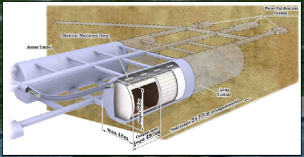


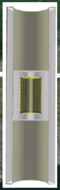

Super-Kamiokande

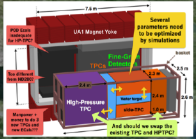
2.5°

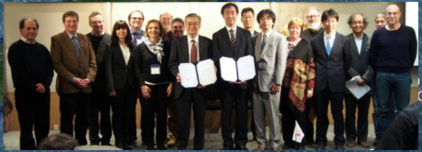
ND280

JPARC







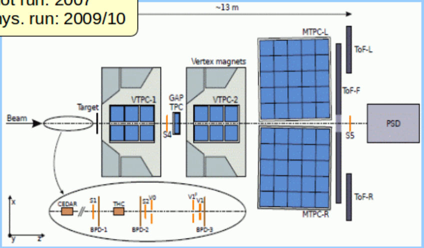
**The Science Council of Japan has selected Hyper-K as a top priority project in the "Japanese Master Plan of Large Research Projects"**

**The Inaugural Symposium of the Hyper-Kamiokande Proto-Collaboration took place on 31 January**

# Hadron production measurements for the ν flux in T2K

## NA61/SHINE at CERN SPS

Pilot run: 2007
Phys. run: 2009/10

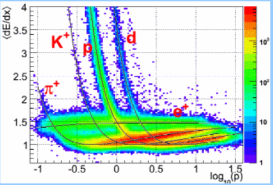



## Data with the ***graphite target***

| Beam (GeV/c) | | target | year | N($\times10^6$) |
|---|---|---|---|---|
| p | 31 | thin | 2007 | 0.7 |
| | | | 2009 | 5.4 |
| p | 31 | T2K replica | 2007 | 0.2 |
| | | | 2009 | 4 |
| | | | 2010 | 10 |

- Cross sections measurements for $\pi^\pm$, $K^\pm$, $K^0_S$, $\Lambda$ and protons have been published!
- Cover ~90% of the phase space of T2K
- Thin target analysis – A.Korzenev
- T2K replica target analysis – A.Haesler

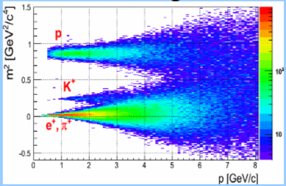
### Energy loss in TPC (*dE/dx*)




**PID in NA61**

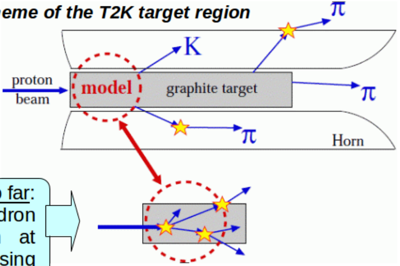
- ToF detector by UniGe (A.Bravar)
- Energy loss in TPC

### Time-of-Flight (ToF)



# Approaches for the ν flux constraint (constraint on parent hadrons)

*Scheme of the T2K target region*

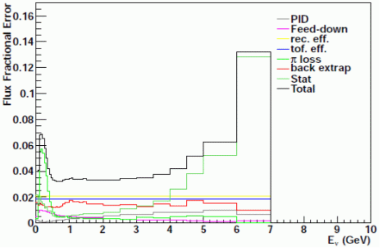



**Alternative approach:**
re-weighting of the hadron production yields at the target surface using the T2K replica target results of NA61.
Model independent!

**Approach used by T2K so far:**
re-weighting of the hadron production cross-section at the interaction vertex using results of NA61.
Model dependent!

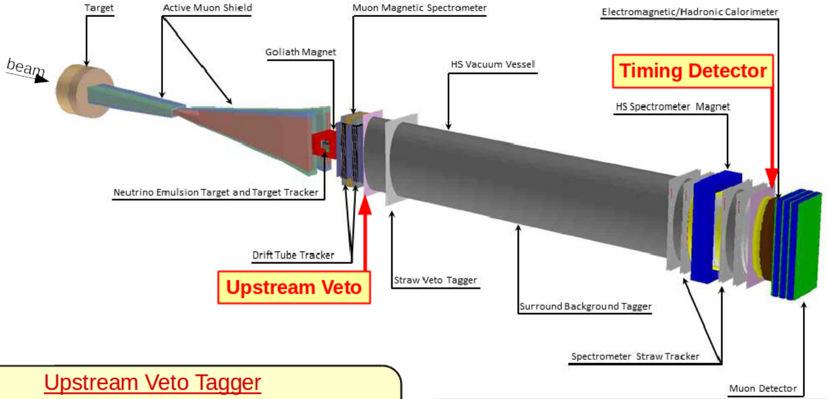
- Thesis defended by Alexis Haesler this summer: "T2K replica target hadron production measurements in NA61/SHINE and T2K neutrino flux predictions"
- The article will be submitted to EPJ early next year
- Systematic uncertainty to neutrino flux due to pions reduced to ~4%

*Systematic uncertainty of ν flux due to π*



# SHiP (Search for Hidden Particles) project

*in collaboration with Philippe Mermod and Uni Zurich*




## Upstream Veto Tagger

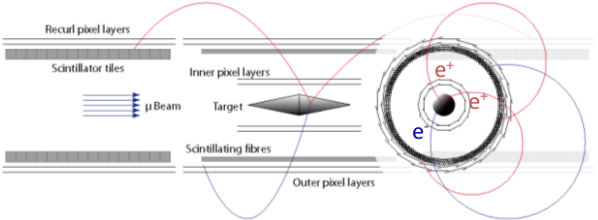
- Aim is to suppress the background source from neutral K/Λ produced by neutrino and muon interactions upstream the vacuum vessel. Also to tag muons
- Resolution should be $\lesssim$1 ns
- Extruded scintillator slabs with light collection by WLS fibers coupled to photodiods from both ends

## Timing Detector

- Aim is to reduce a combinatorial background by tagging tracks belonging to a single event. Also to tag muons.
- Can be used for PID of few GeV's particles
- Resolution should be $\lesssim$100 ps
- Cast plastic slabs with light collection by PMTs or array of SiPMs from both ends

# Search for lepton flavour violation through $\mu^+ \to e^+e^-e^+$

The Mu3e group at DPNC works on the development of the scintillating fiber timing sub-detector



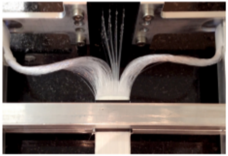

## Fiber ribbons specifications:

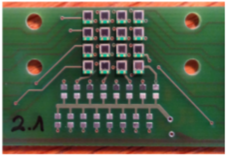
- 250 μm diameter fibers
- ribbons of 2-5 layers
- 64÷128 fibers per layer
- 15 cm and 40 cm long ribbons

## Ribbons performance in test beams:

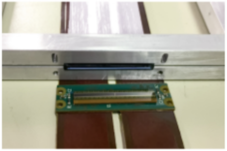
| | Argon 40 GeV/c | Protons 150 GeV/c |
|---|---|---|
| Position: | $\sigma_{pos}$ = 55 μm | $\sigma_{pos}$ = 140 μm |
| Time: | $\sigma_{time}$ = 120 ps | $\sigma_{pos}$ = 1 ns |

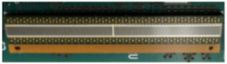
## Two possible fiber-SiPM readout schemes






Single fiber readout scheme





Array readout scheme

# Conclusion: Neutrinos have mass ...

... and so far this is the only evidence for a new physics beyond the Standard Model.

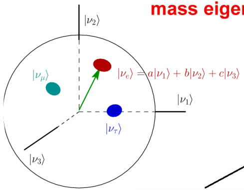
2015

Neutrinos will keep us busy making discoveries during the next 100 years.

Perhaps you should translate this in Latin.

# Backup

★ If neutrinos are massive particles, then it is possible that the **mass eigenstates** and the **weak eigenstates** are not the same:

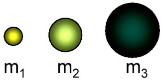


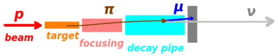

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

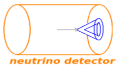
Weak eigenstates „flavor eigenstates“

***3 independent parameters + 1 complex phase***

Mass eigenstates


Weak interaction produces flavour eigenstates ($\nu_\mu$ for example).

$$|\nu_\mu\rangle = \begin{array}{l} U_{1\mu}|\nu_1\rangle + \\ U_{2\mu}|\nu_2\rangle + \\ U_{3\mu}|\nu_3\rangle \end{array}$$

Mass (energy) eigenstates propagate with different velocities.

$$|\nu(t)\rangle = \begin{array}{l} U_{1\mu}|\nu_1\rangle e^{iE_1 t} + \\ U_{2\mu}|\nu_2\rangle e^{iE_2 t} + \\ U_{3\mu}|\nu_3\rangle e^{iE_3 t} \end{array}$$

$$t \propto L/E$$

The weak interaction (CC) has to choose one of the flavour eigenstates

$$\begin{array}{l} |\nu_e\rangle + N \to e + X \\ |\nu_\mu\rangle + N \to \mu + X \\ |\nu_\tau\rangle + N \to \tau + X \end{array}$$

$$P(\mu \to e) = |\langle \nu_e | \nu(t) \rangle|^2$$

# Super-Kamiokande - Japan

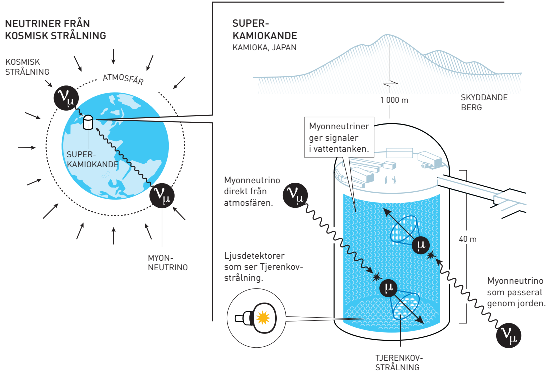



Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

SK detects atmospheric neutrinos. The muon-neutrinos that arrived at the detector from above were more numerous than those that travelled through the entire globe. This indicated that the muon neutrinos that travelled longer had time to change into another identity on their way.

# Sudbury Neutrino Observatory (SNO) - Canada

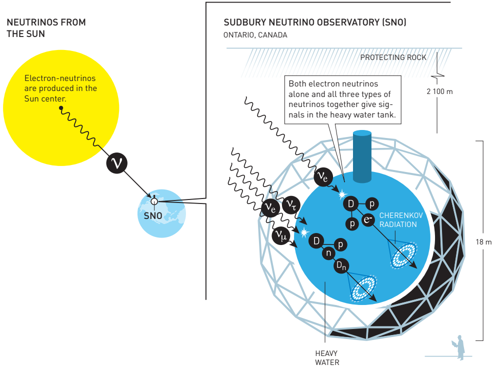
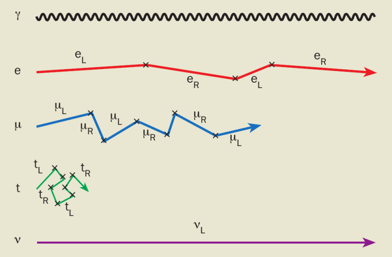



Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

SNO detects neutrinos from the Sun, where only electron-neutrinos are produced. It was discovered that the electron-neutrinos were fewer than expected, while the total number of all three types of neutrinos combined still corresponded to expectations. The conclusion was that some of the electron-neutrinos had changed into another identity

# Neutrinos meet the Higgs boson




- According to the Higgs mechanism, the particles acquire mass by interacting with the Higgs field.
- All particles including electrons (e), muons ($\mu$) and top quarks (t), change handedness when they collide with the Higgs boson.

- But experiments have shown that neutrinos ($\nu$) are always Left-handed, therefore the Standard Model predicts that neutrinos can never acquire mass.