Long-Baseline Neutrino Oscillation Experiments 1

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Pontecorvo Neutrino School
Prague
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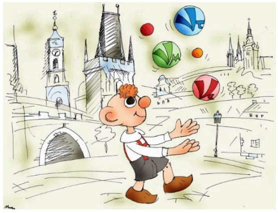
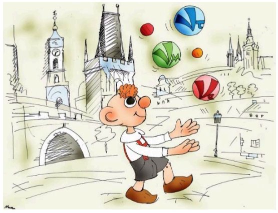
IMB Experiment



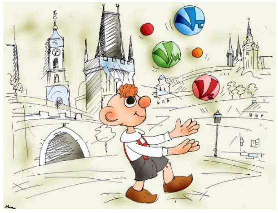
The Charge for these Lectures

- I have been asked to give two lectures on long-baseline neutrino oscillation experiments.
  - I will take long-baseline to mean 100's of km and oscillation to exclude other measurements that these experiments can do.
  - In addition, other lectures at this school further limit my charge with regard to the source of the neutrinos:
    - The Sun: Alexei Smirnov, following this lecture
    - Reactors: Yifang Wang, Wednesday and Friday
    - The cosmos: Christian Spiering, next week
    - Supernovae: Irene Tamborra, next week
  - And with regard to the type of neutrinos:
    - Sterile neutrinos: Jonathan Link, next week
  - Thus, for the most part, I will limit my lectures to Standard Model neutrinos from the atmosphere and from accelerators.



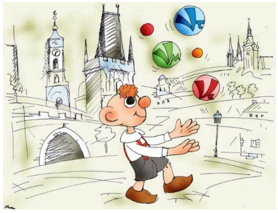
Outline

- Lecture 1
  - Atmospheric Oscillations
  - General Comments on Accelerator Oscillations
  - KEK Experiment
  - OPERA Experiment
  - ICARUS Experiment
- Lecture 2
  - MINOS Experiment
  - T2K Experiment
  - NOvA Experiment
  - Future Experiments

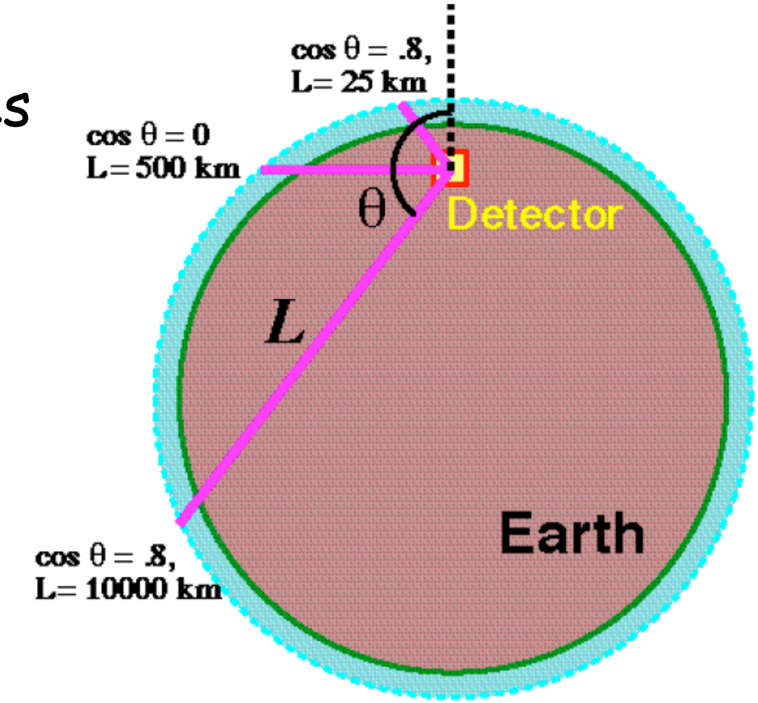


Serendipitous Discoveries

- The discovery of both types of neutrino oscillations was serendipitous – they were discovered by experiments built for other purposes:
  - The solar oscillations were first seen in an experiment designed to verify the model of solar energy production.
  - The atmospheric oscillations were discovered in experiments searching for proton decay, which is predicted by grand-unified theories. Ironically, no evidence for proton decay has been found to this day.



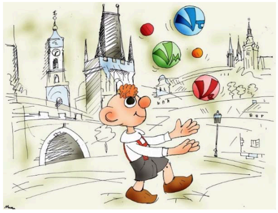
Atmospheric Neutrino Oscillations



- As a background to their searches for proton decay, underground detectors measured neutrinos produced when cosmic rays interact with the atmosphere.
- The primary process is

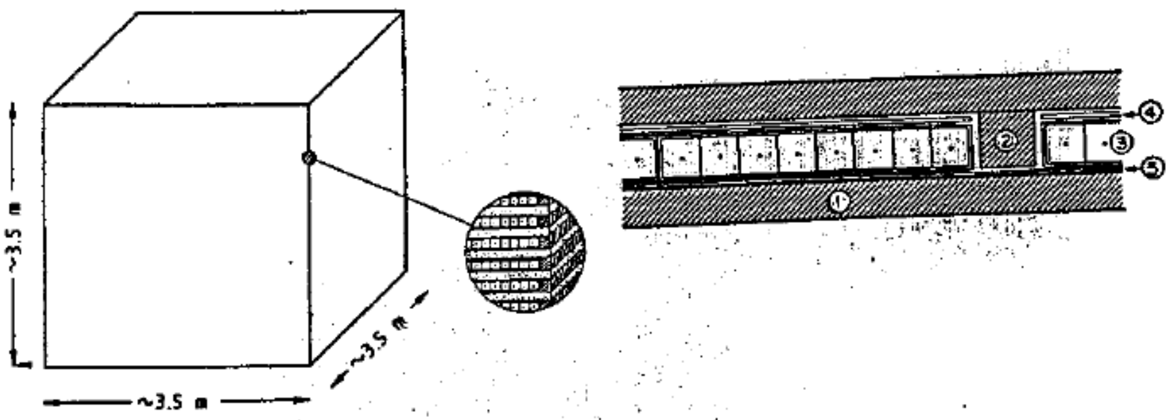
$$p + N \rightarrow X + \pi^{\pm}$$
$$\quad \hookrightarrow \mu + \nu_{\mu}$$
$$\quad\quad \hookrightarrow e + \nu_e + \nu_{\mu}$$

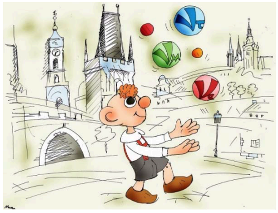
which yields roughly 2 ν_μ's for each ν_e.



"Iron" Detectors

- NUSEX (NUcleon Stability EXperiment) was an early search for proton decay. It ran from 1982 to 1988 in the Mont Blanc Tunnel.
- It was a 3.5 m cube consisting of iron plates and streamer tubes:



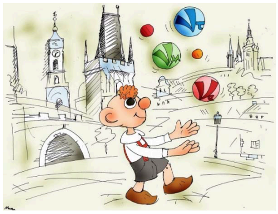


"Iron" Detectors

- In 1989, NUSEX reported

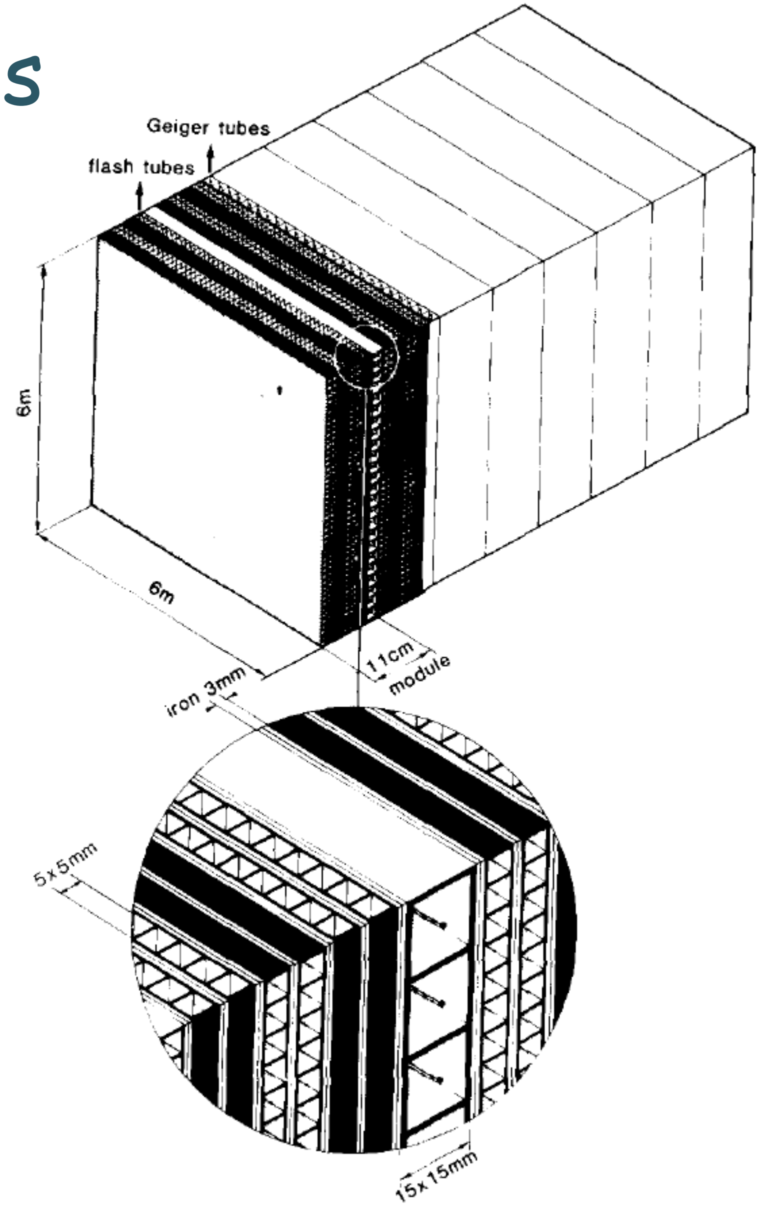
Abstract. – The fully contained events detected in the NUSEX nucleon stability experiment have been analysed to search for possible anomalies in the fluxes of atmospheric neutrinos. The measured flux of muon neutrinos is in very good agreement with predictions and no anomaly has been found in the ratio between the rate of electron and muon neutrino events.

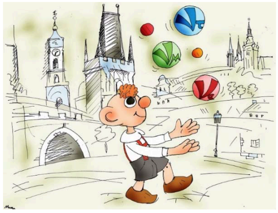
Europhys. Lett., 8 (7), pp. 611-614 (1989)



"Iron" Detectors

- A similar, but considerably larger detector was in the Fréjus Tunnel, 6 m x 6 m x 12.3 m.
- The Fréjus detector had vertical iron plates and a combination of flash and Geiger tubes.



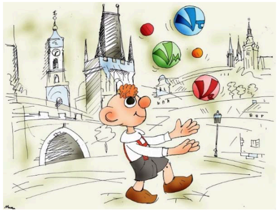


"Iron" Detectors

- In 1990, the Fréjus experiment also reported negative results:

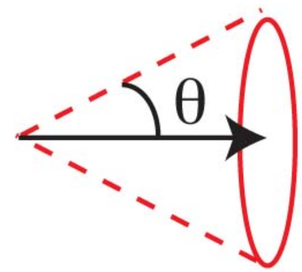
The Fréjus nucleon-decay detector has been operated between 19-02-1984 and 13-09-1988. The sample of atmospheric neutrino interactions recorded is compared with the predictions of a Monte Carlo simulation. A search for neutrino oscillations is performed. No evidence is found... Nuclear Physics B (Proc. Suppl.) 16 (1990) 490–492

- A slightly later, similar experiment in the Soudan mine in northern Minnesota did report positive results in 1993. (I will show all of the results in a few slides from now.)



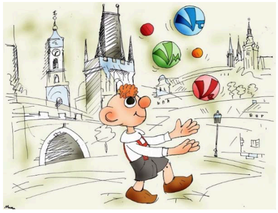
Water Cherenkov Detectors

- Review of Cherenkov Radiation:
  - When a particle's speed exceeds the speed of light in the medium it is going through, an optical shock wave is created in a similar way to the acoustic shock wave caused by a plane going faster than the speed of sound. This is called Cherenkov radiation.
  - Light is emitted along a cone of angle θ

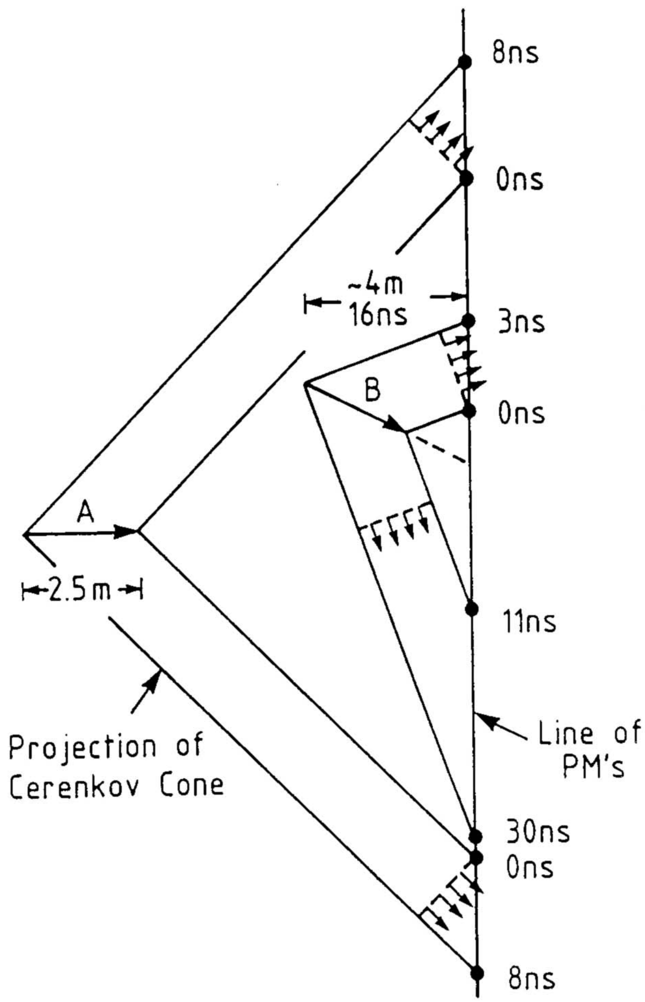


$$\cos\theta = 1/\beta n, \quad \beta > 1/n$$

  - For water (n = 1.33) and β = 1, this gives about 200 photons of visible light per cm at an angle of 41°.



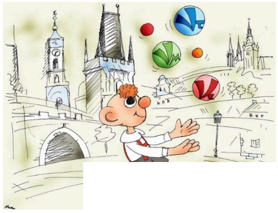
The Principle of a Water Cerenkov Detector



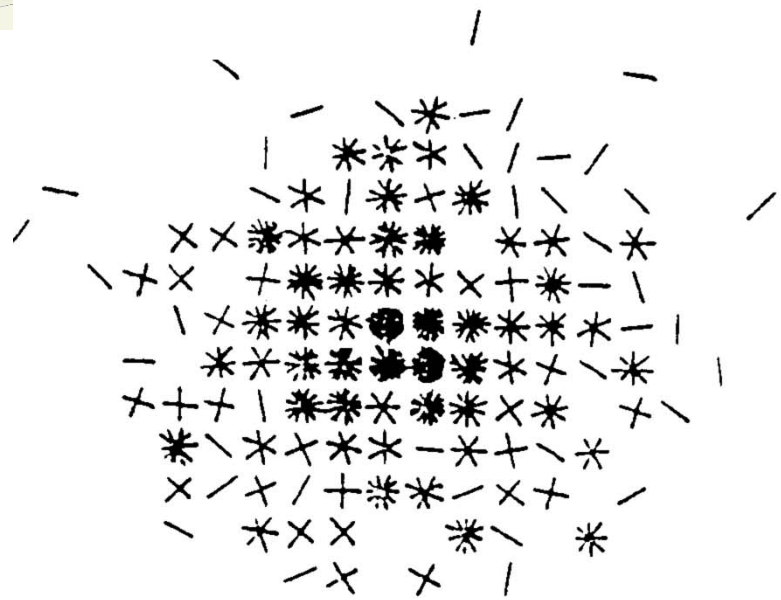
The radiation length of water is 36 cm, so most of an e-m shower will be contained in 2.5 m or 7 X_0, or less.

dE/dx = 2 MeV/cm, so a 500 MeV particle can only go 2.5 m.

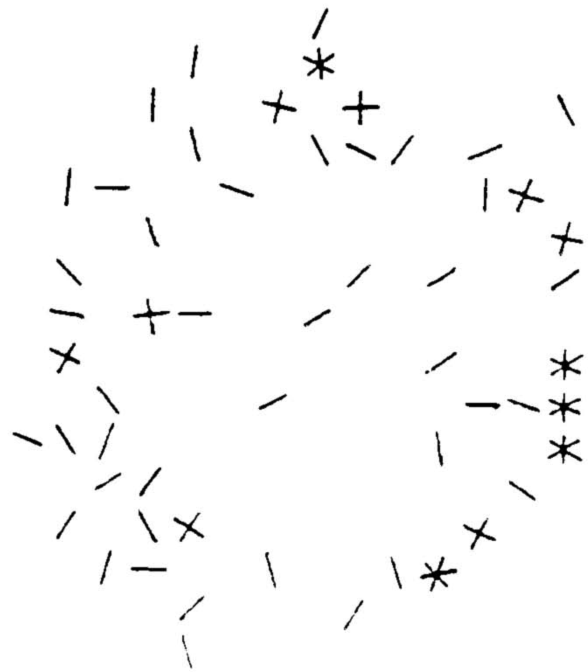
The diagram shows how the location and arrival times of the Cerenkov light at the photomultiplier plane allows a track to be reconstructed.



Examples of Muon Tracks

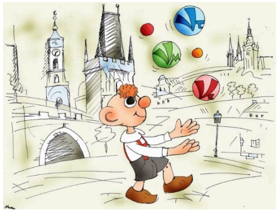


Through-going muon



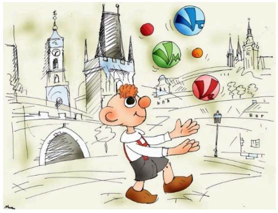
Stopping muon

Each point represents a photomultipler tube and the number of crossing lines indicates the relative photomultiplier pulse height.



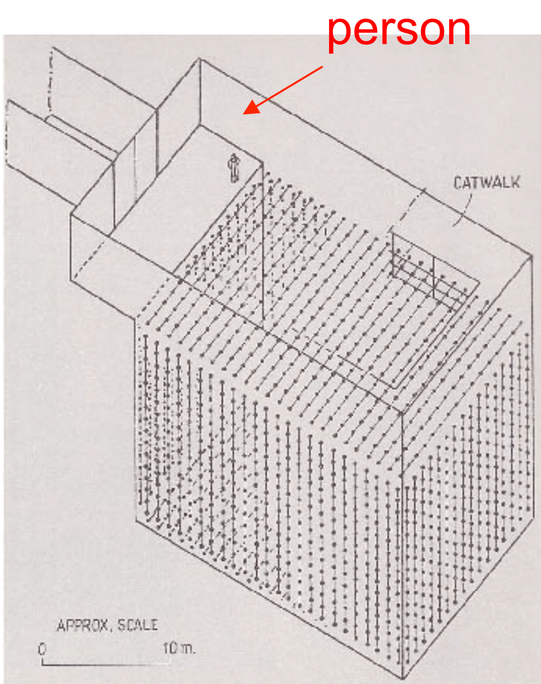
KamiokaNDE Experiment

- KamiokaNDE (Kamioka Nuclear Decay Experiment) was an experiment in the Kamioka mine in Japan designed to search for proton decay. It was a water Cherenkov detector with 3 kt of water and about 1000 50-cm photomultipliers.
- It started running in 1983.

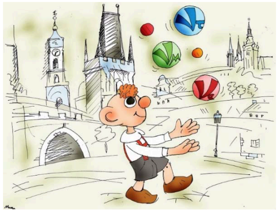


IMB Experiment

- The IMB (Irvine-Michigan-Brookhaven) experiment was a large tank of water with photomultipliers on all six surfaces, spaced 1 meter apart. It was located in the Morton Salt Mine near Cleveland, Ohio and began running in 1982,

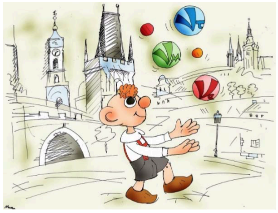


Dimensions: 22.5 m x 17 m x 18 m
2048 photomultipliers
Total volume: 8000 tons of water
Fiducial volume: 3300 tons of water
(2 m in from each side)



Advantages/Disadvantages of Water Cherenkov Detectors

- Advantages:
  - Water is cheap -> can build massive detectors
- Disadvantages:
  - Low energy charged particles are invisible ($p < 0.66$ m)
  - Multiple rings from a vertex are difficult to reconstruct.
- Conclusion: Water Cherenkov detectors are most suitable for low energy neutrinos.



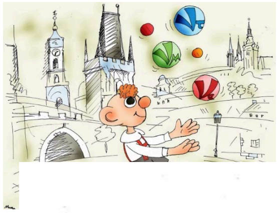
ν_μ Disappearance

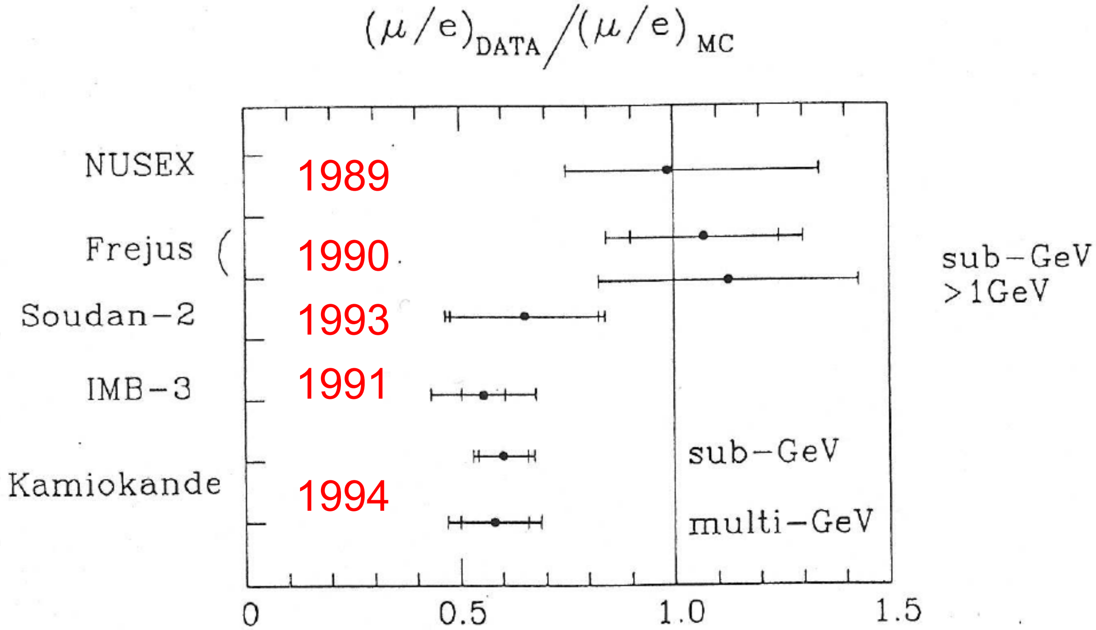
- For the purpose of this lecture,

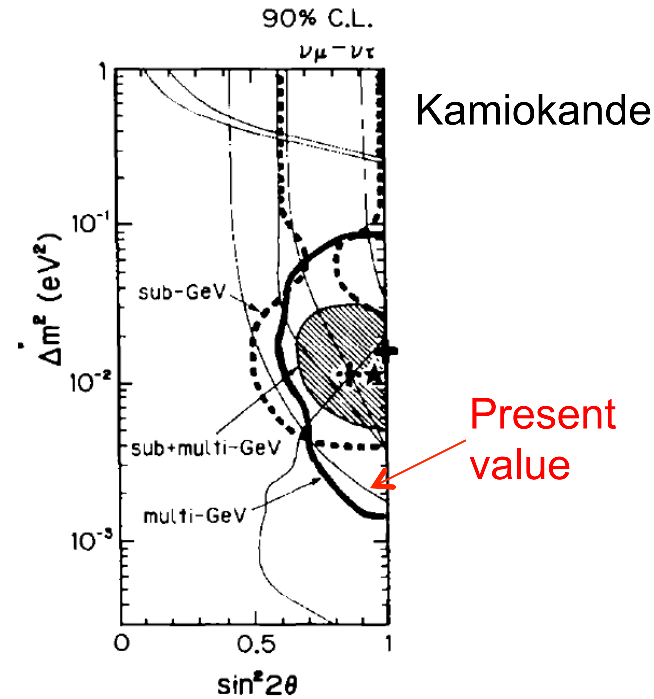
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2}{4E}\right),$$

where the meaning of θ and Δm^2 will become clearer in the next lecture.

Atmospheric Neutrino Oscillations in 1995

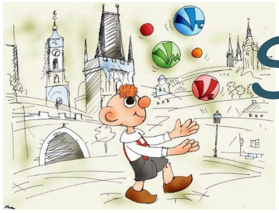




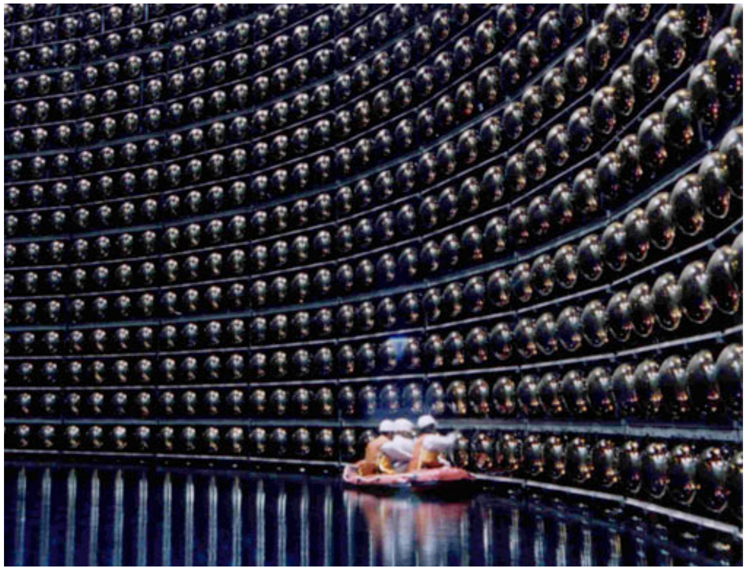


At present we have no compelling evidence neither in support of an anomaly from neutrino oscillation nor for a more conventional explanation of the anomaly. Confirmation by better statistics is required and will start with the operation of the Superkamiokande experiment in 1996.

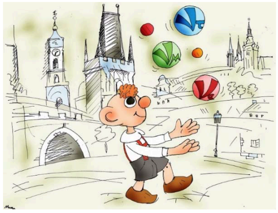
-Klaus Winter,
Lepton-Photon Conference, 1995



Super-Kamiokande

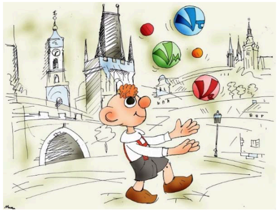


- Super-Kamiokande was the follow-up to Kamiokande. It is also a cylindrical water Cerenkov detector, but with an order of magnitude more mass. 50,000 t of water and over 11,000 50-cm photomultipliers. Depth of 1000m water equivalent.
- SK played an important role in every aspect of neutrino oscillations from its start in 1996 to the present and it will continue to do so for at least another decade.
- Masatoshi Koshiba in 2002 and Takaaki Kajita in 2015 won Nobel Prizes for Kamiokande and Super-Kamiokande.

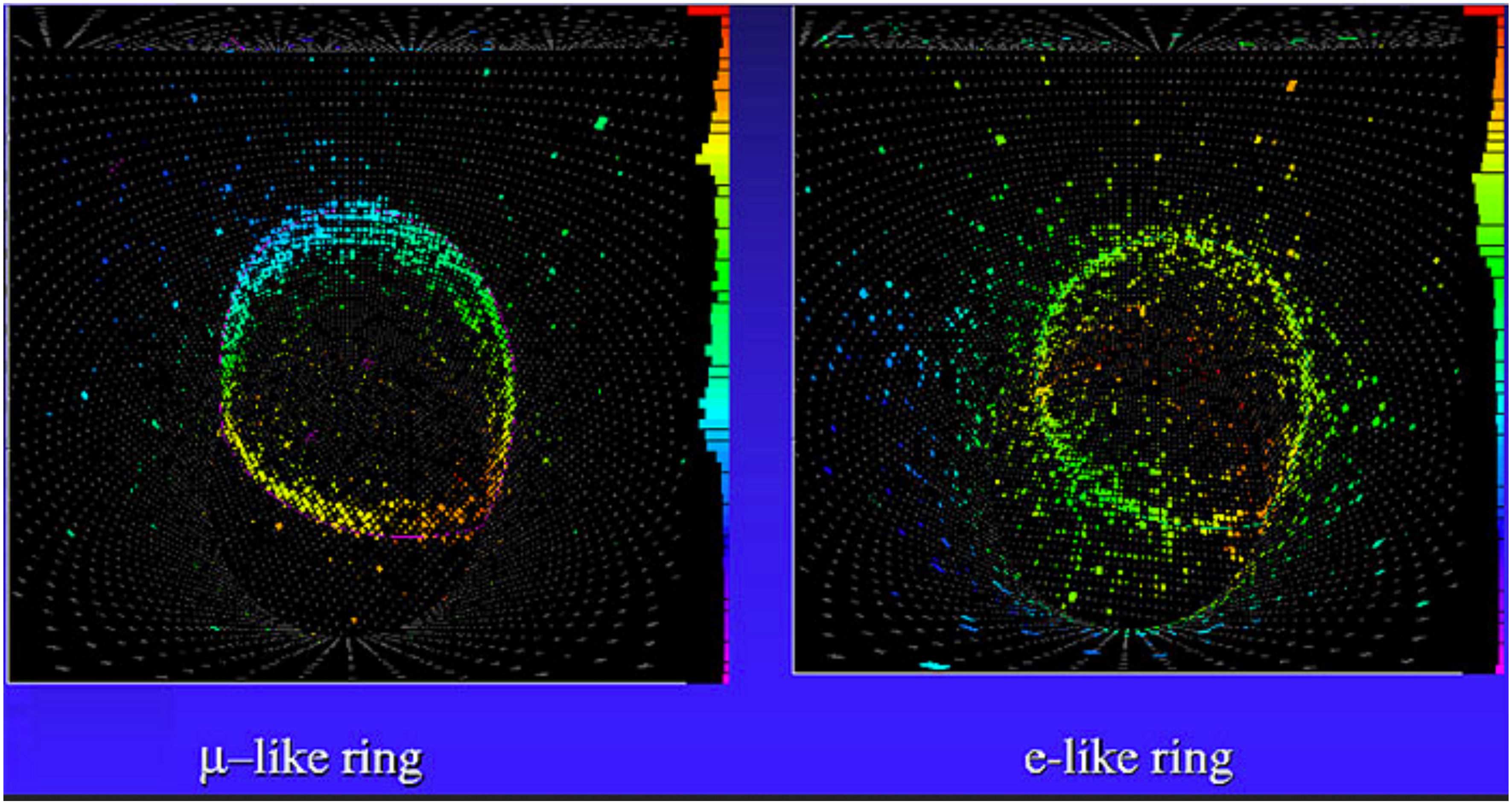


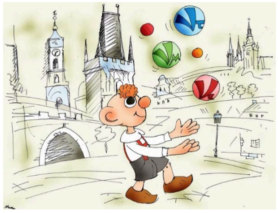
Super-Kamiokande

- Super-Kamiokande started taking data in April 1996 and reported first results in 1998 on 1.5 years of data. (Phys. Rev. Lett. 81, 1562) These data were conclusive.
- On a personal note, I was dubious up to this point, but on seeing the data, I was convinced and decided to join the MINOS experiment.
- We will first see how Super-K tells electrons from muons and then look at the data.

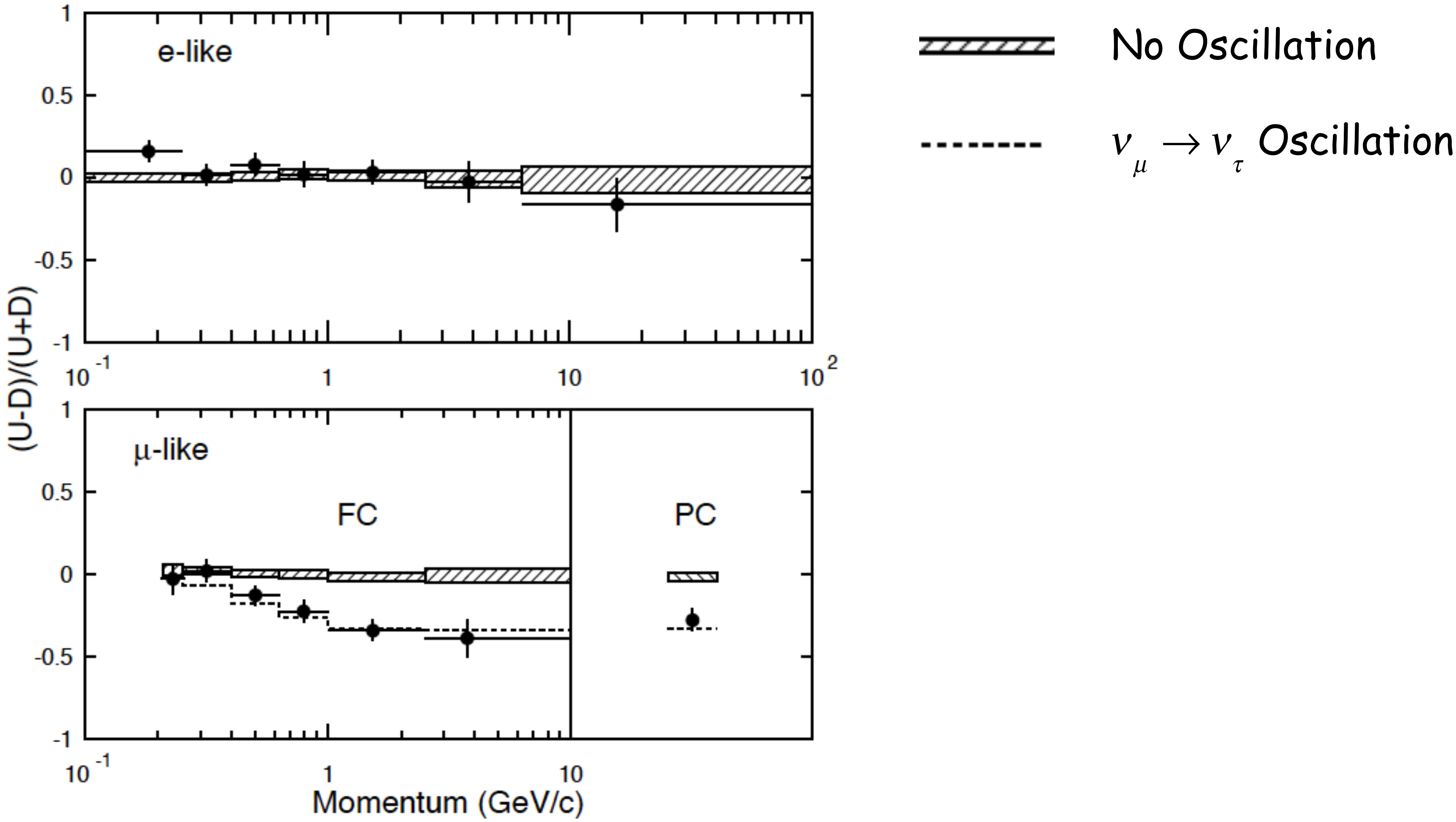


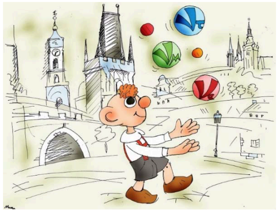
Muon and Electron Rings



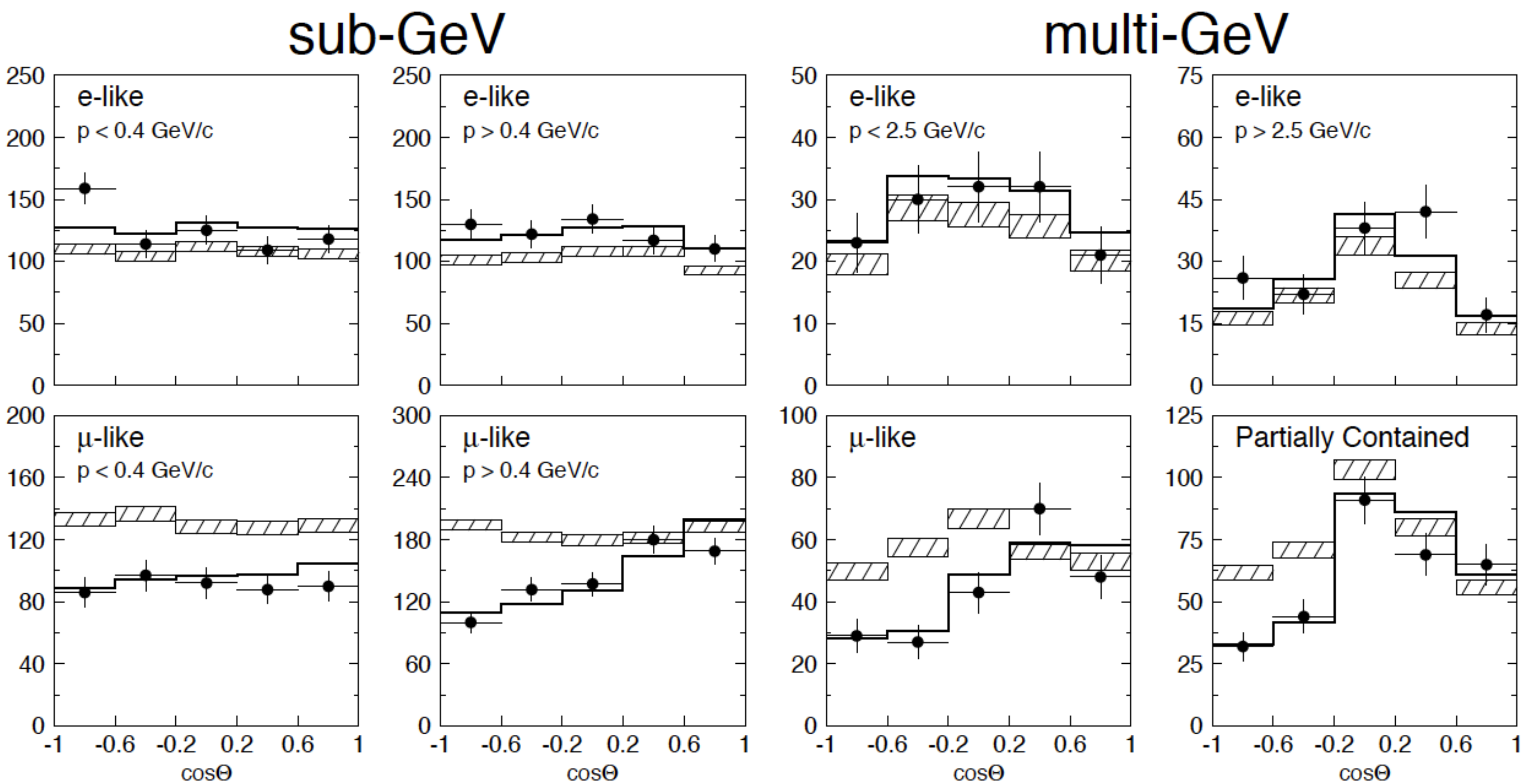


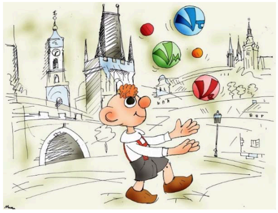
Super-Kamiokande 1998 Up-Down Asymmetry



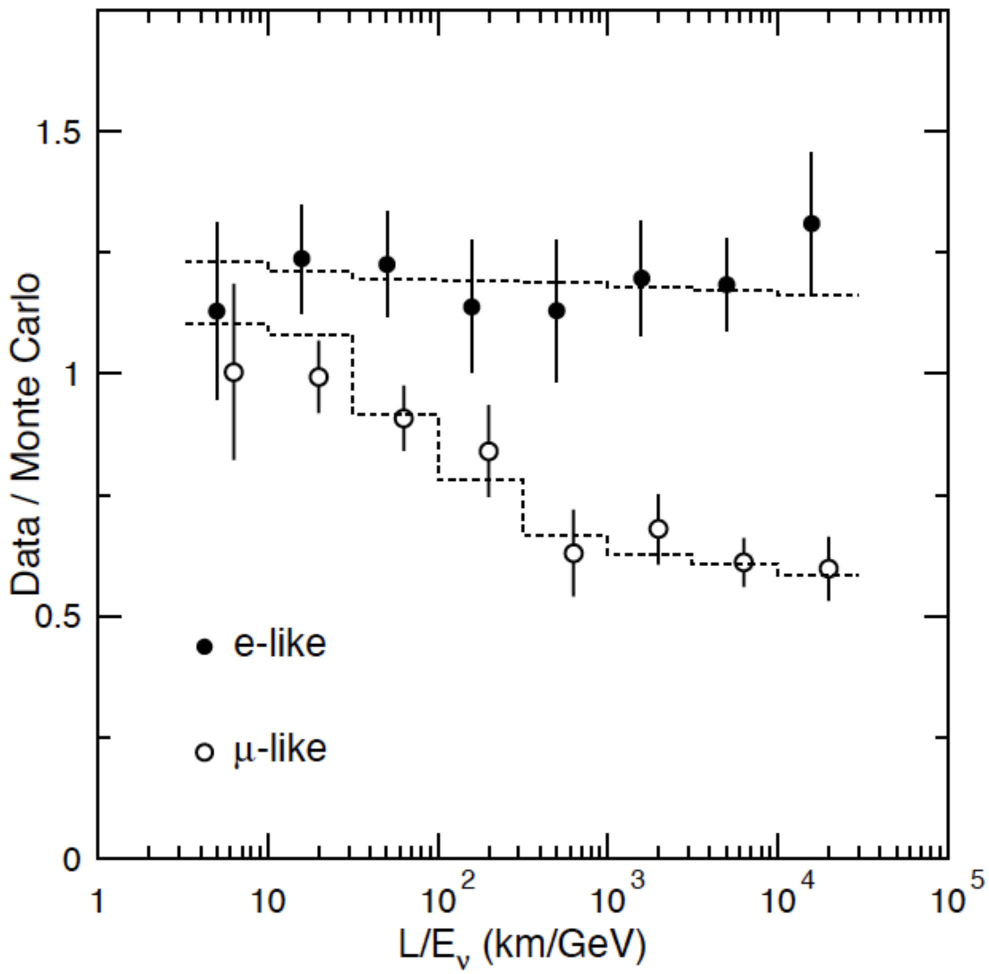


Super-Kamiokande 1998 Zenith Angle Dependence

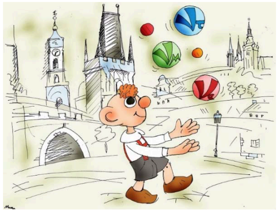




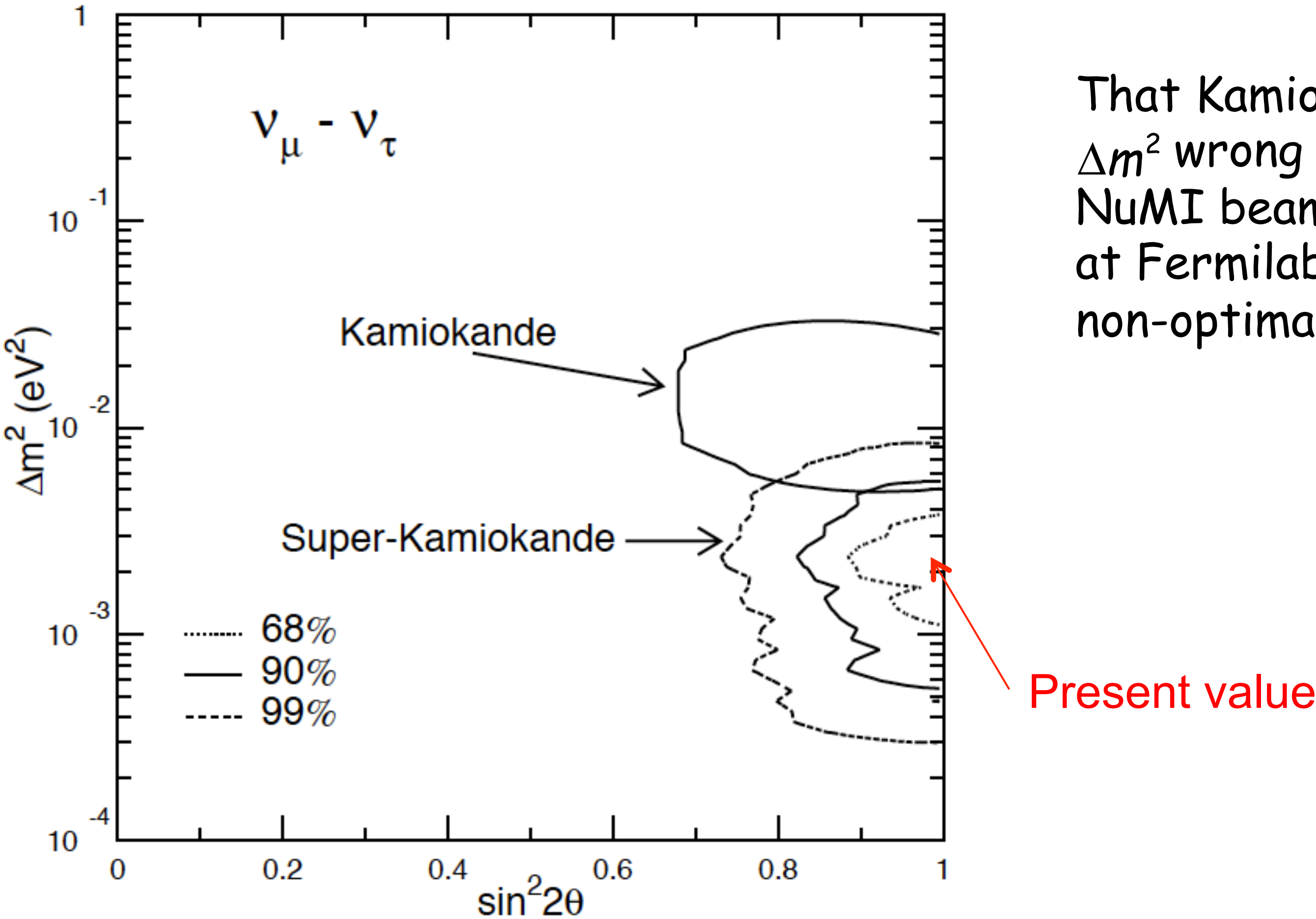
Super-Kamiokande 1998 L/E Dependence



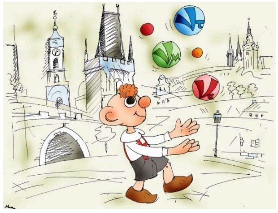
Super-K's limited resolution wipes out what should be a sharp dip at 500 km/GeV.



Super-Kamiokande 1998 Δm^2 versus $\sin^2(2\theta)$

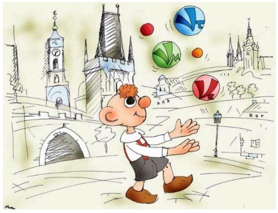


That Kamiokande got Δm^2 wrong caused the NuMI beam being built at Fermilab to be non-optimal.



Moving On

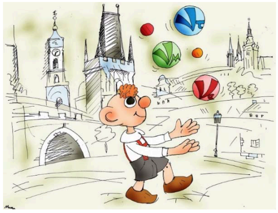
- I want to move on now to the subject of accelerator long-baseline experiments, although we will return to atmospheric results from time to time.
- However, before getting into the details a few more general topics:
  - Blind analysis
  - Near detectors
  - Neutrino accelerator beams.



The story of Clever Hans

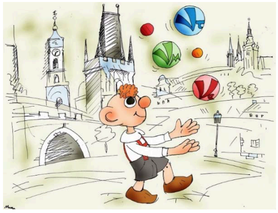
- In the early 1900's, Clever Hans had the ability to solve all sorts of mathematical problems such as adding together two single-digit numbers that were written on a blackboard.
- What made this noteworthy was that Clever Hans was a horse.

Clever Hans performing in Germany in 1904.



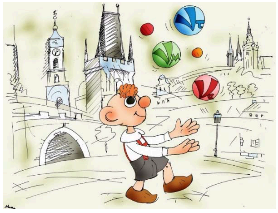
The story of Clever Hans

- People suspected that Hans's trainer was giving him clues, so they had the trainer go away and have members of the audience ask him questions.
- Hans still got the right answer about 90% of the time.
- A commission was appointed to study this and its head, a psychiatrist named Carl Stumpf, discovered what was happening.
- When Stumpf arranged the situation such that the audience did not know the answer, Hans answered randomly.
- Hans was picking up body language clues from the audience.



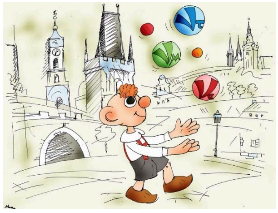
Story from the NOMAD Experiment

- The NOMAD experiment was a 1995-1998 short-baseline neutrino oscillation experiment to search for 20 eV tau neutrinos, which were widely predicted at that time to be the dark matter in the universe.
- Each analysis team analyzed one decay mode in either the quasi-elastic or non-quasi-elastic mode. So there were about 10 analyses that were combined for the final result.
- Seeing no signal, each team optimized their result for the optimum sensitivity, which was to have no events and an expected background of 0.5 events, a 61% probability.



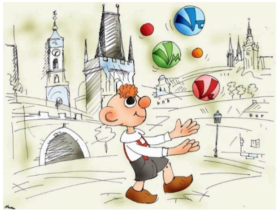
Story from the NOMAD Experiment

- The problem was that on combining the 10 results from the first year of running, NOMAD had no events for 5 background events expected, a 0.7% probability.
- Realizing that this was highly biased, NOMAD went to blind analyses, and all subsequent results were statistically reasonable.



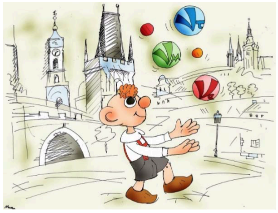
MINOS and NOνA Analyses

- Most large modern experiments use blind analyses these days.
- The experiments I know best, MINOS and NOvA, both use blind analyses for all oscillation results.
  - This was a difficult sell in the early days of MINOS. The young members of the collaboration embraced it enthusiastically, but some senior members were dubious, arguing "I'm not biased, why should I not be able to look at all of the data?"
  - The answer is that everyone has some biases, which my be hidden. For example, if the result is what you expect, say in agreement with a previous result, you tend to stop looking for problems. On the other hand, if it is unexpected, you look at it more closely.



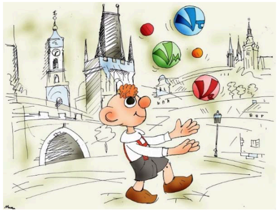
MINOS and NOνA Analyses

- Once you are used to doing blind analyses, it becomes automatic and you cannot imagine doing it any other way.
  - Since most of the NOvA collaboration worked on MINOS, there was never any controversy over using blind analyses.
- There are many ways of blinding data.
  - In both MINOS and NOvA, the near detector was open and the far detector was closed. You could only look at far detector data to do data quality checks or to examine sidebands to the signal region.
  - Analyses are optimized for sensitivity based on Monte Carlo simulations. The one exception is cosmic background. Beam off-time data are used, but two different data sets are used, one for setting the analysis and the other (blind) one for estimating the background in the measurement.



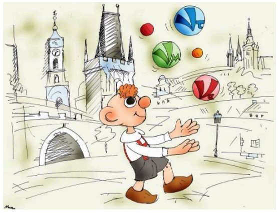
MINOS and NOνA Analyses

- "Opening the box" is a formal procedure accompanied by extensive documentation and a clear protocol. Permission to open the box requires the consent of the whole collaboration.



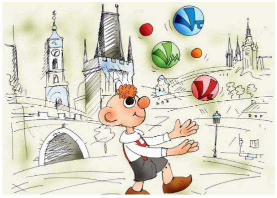
Near Detector Discussion

- Any experiment that aims at high precision must have (at least) two detectors: a near detector that measures neutrinos before they have time to oscillate and a far detector to measure them after they have oscillated.
- The near detector does two things:
  - It measures the expected background in the far detector, and
  - It normalizes the signal in the far detector.
- Neutrino fluxes are not well known, particularly at the low energies that oscillation experiments typically need. With a near detector, the flux uncertainty largely cancels.

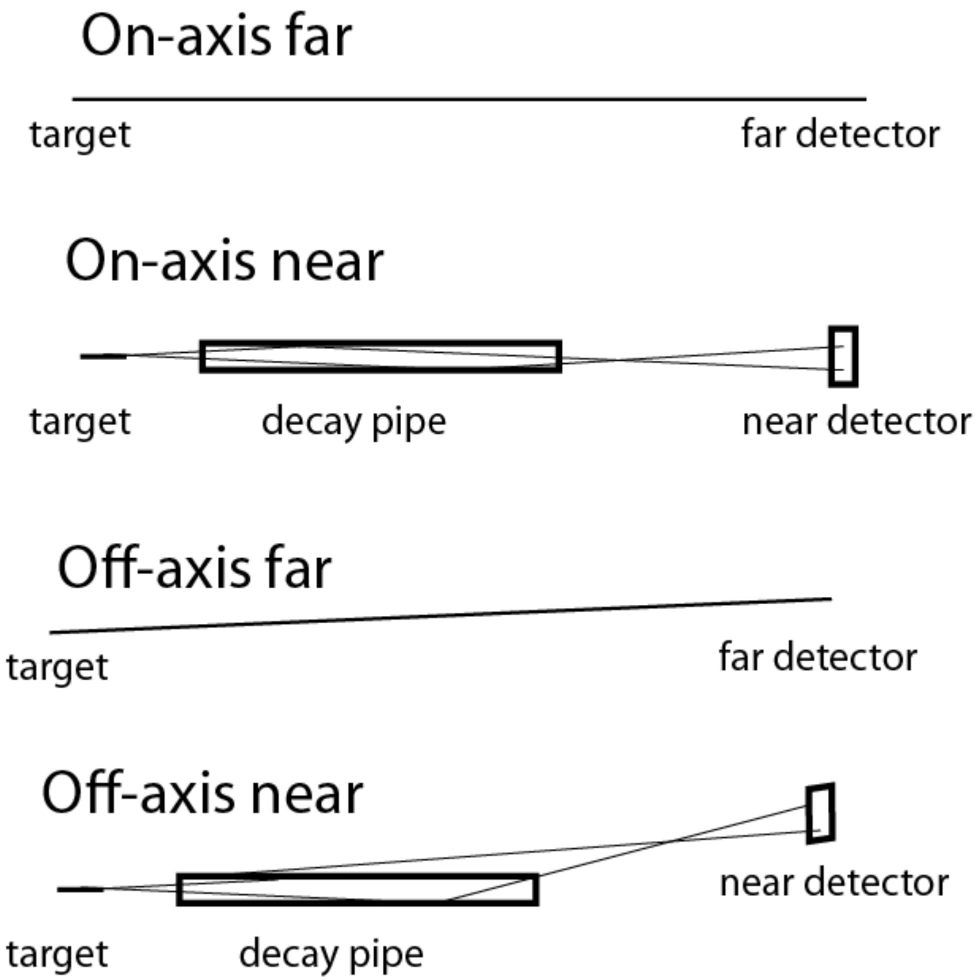


Near Detector Discussion

- At least part of the near detector should be functionally equivalent to the far detector; otherwise additional uncertainties are introduced.
- It is also useful to have some more finely gained detectors in the near detector. MINOS and NOvA have functionally equivalent near detectors, but no fine-grained detectors. T2K has only fine-grained near detectors, but does have water as part of the near detector target.
- Near detectors can never be perfect predictors because the inherent geometry is different. The far detector sees the source as a very small point. The near detector sees it as a line.

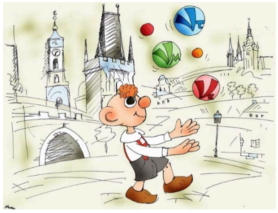


Near Detector Discussion



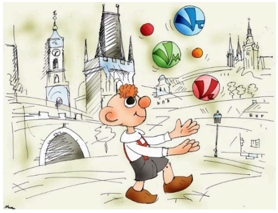
For on-axis detectors, the energy spectrum will be harder in the far detector than in the near.

For off-axis detectors, the energy spectrum will be narrower in the far detector than in the near.



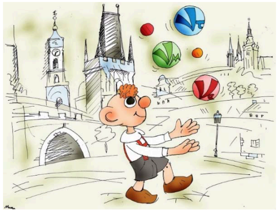
Near Detector Discussion

- For the reasons we just discussed, it is better to place the near detector "far" from the target to make it have more of a point-like source.
  - For example, the NOvA near detector was placed 1 km from the target. We would have preferred 2 km.
  - This would have placed it underneath the laboratory director's house.
  - However, that is not the primary reason it did not happen. The primary reason is that since we go through the Earth at about 3 degrees, it would have to be 100 m underground, and this would have been too expensive.
  - In addition to their near detector at 280 m, T2K wanted an additional near detector at 2 km, which would include a functionally equivalent detector, but it was never funded.



Near Detector Discussion

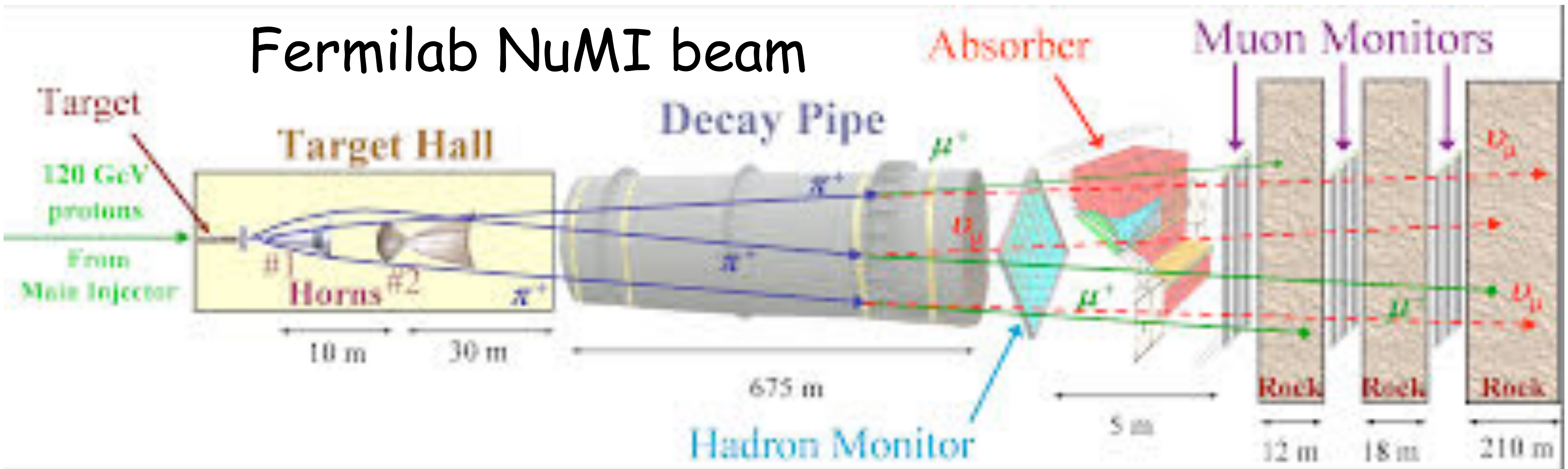
- Another reason that near detectors cannot perfectly predict the far detector backgrounds and signal normalization is that there are three classes of neutrino interactions that need to be extrapolated, and each of them extrapolates differently.
  - The neutral currents extrapolate "normally."
  - The ν_μ charged currents mostly oscillate away.
  - The ν_e charged currents come mostly from muon decay, which occurs farther down the decay pipe since it is a secondary decay.
- This decomposition uses simulations and/or data-driven techniques. This is also where a fine-grained section of near detector would be useful.



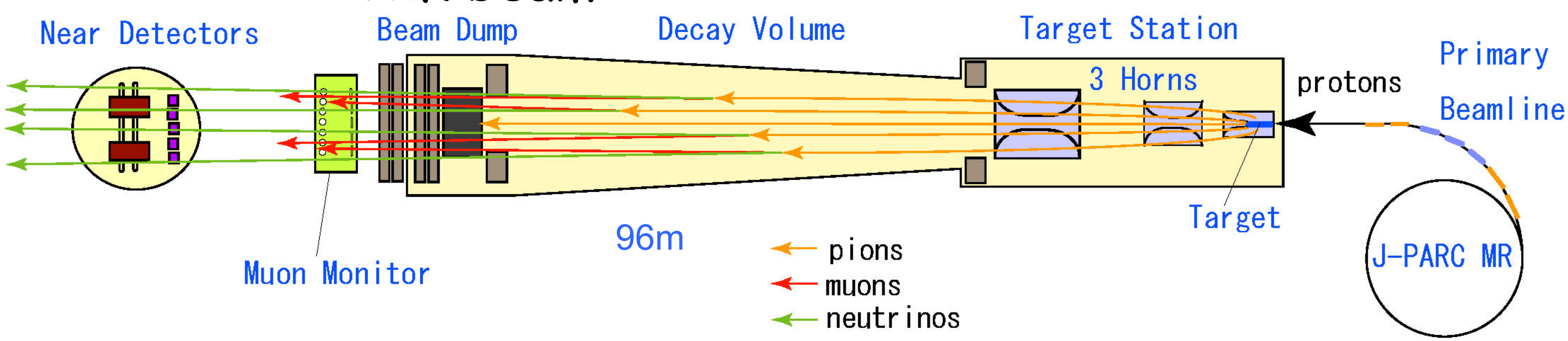
Near Detector Discussion

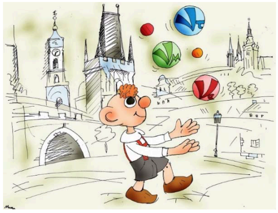
- Of course, for atmospheric detectors, the far and near detectors are the same detector, which is ideal.

Neutrino Beamlines



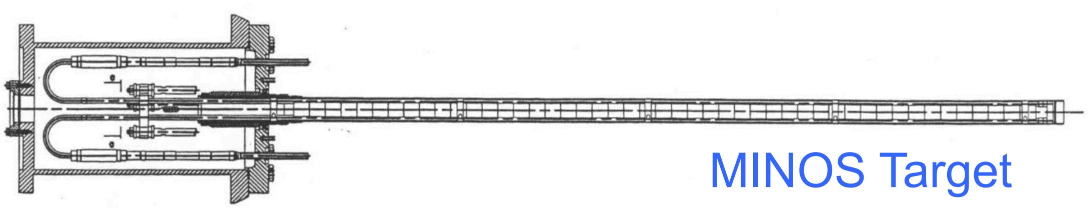
T2K beam



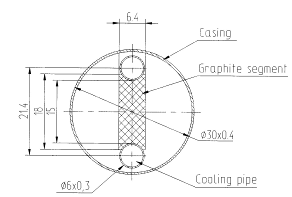


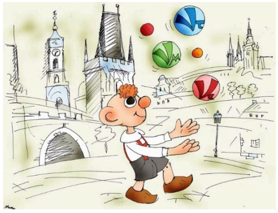
Targets

- The target should be long enough to have at least 90% of the protons interact. The MINOS, NOvA, and T2K target are all about 1 m long, around 2 interaction lengths.
- The target should be made from low-Z materials to avoid large multiple scattering. The MINOS, NOvA, and T2K targets are made of graphite.
- The targets should be thin to allow the pions to escape.
  - The T2K target is a rod with a 2.6 cm diameter cooled by helium gas.
  - The MINOS and NOvA targets are rectangular shaped (to facilitate water cooling), 0.64 x 1.5 cm and 0.74 x 2.45 cm.



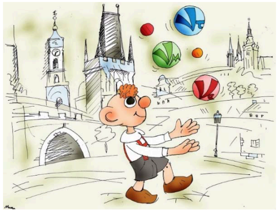
MINOS Target





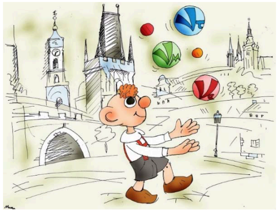
Target Tradeoffs

- From a physics point of view, you want the beam spot and the target transverse dimensions to be as small as possible, but the trade off is the target lifetime due to material fatigue from the beam shock and heating.
- You might think that it would be better to have longer, less dense targets. The tradeoff is that they would be more of a mismatch to the field depth of the horns.



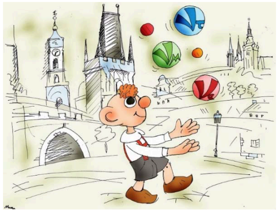
Magnetic Horns

- Ideally, you would want to focus all of the pions coming from the target to be parallel to the beam line (perfect focusing). This is not possible, but the magnetic horns get more than half of the perfect focusing flux in an energy range of interest and increase the flux going to the far detector by about a factor of 20 over no focusing.



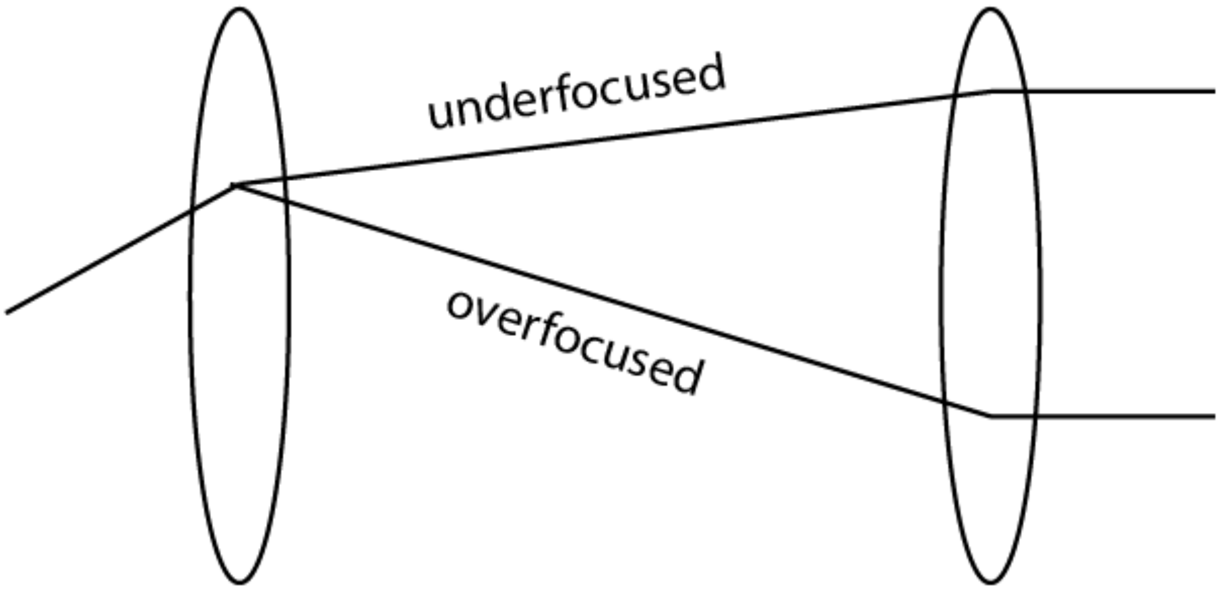
Magnetic Horns

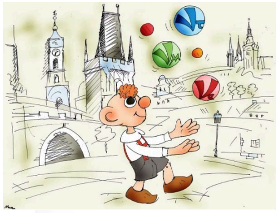
- The horns have a toroidal field, which is particularly advantageous because
  - It focuses one sign of pions and defocuses the other, producing a neutrino-enhanced or a antineutrino-enhanced beam.
  - The field falls of a 1/r, which is useful since the higher energy pions will be at lower radii and need more focusing while the lower energy pions will be at higher radii and need less focusing.



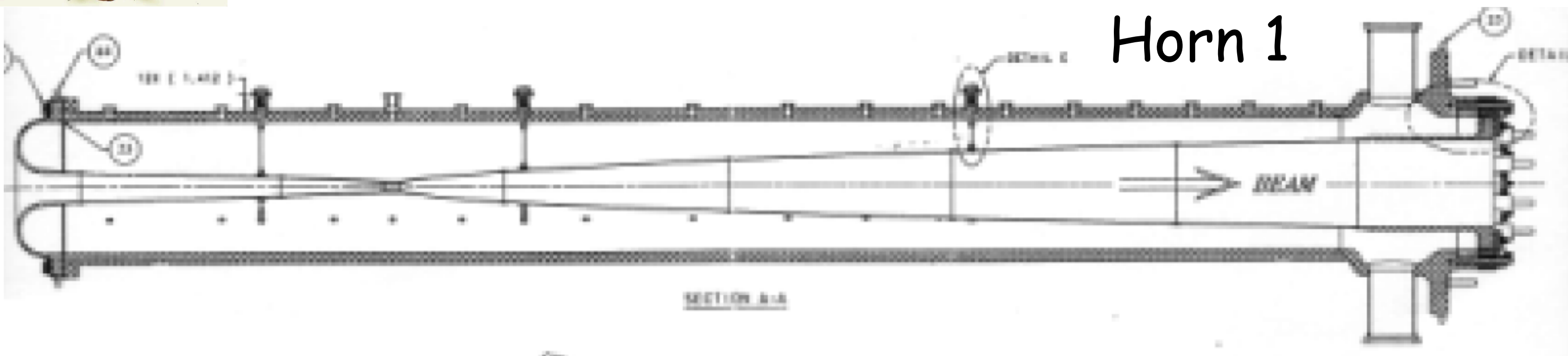
Magnetic Horns

- A two-horn system tries to correct over- and under-focused particles.

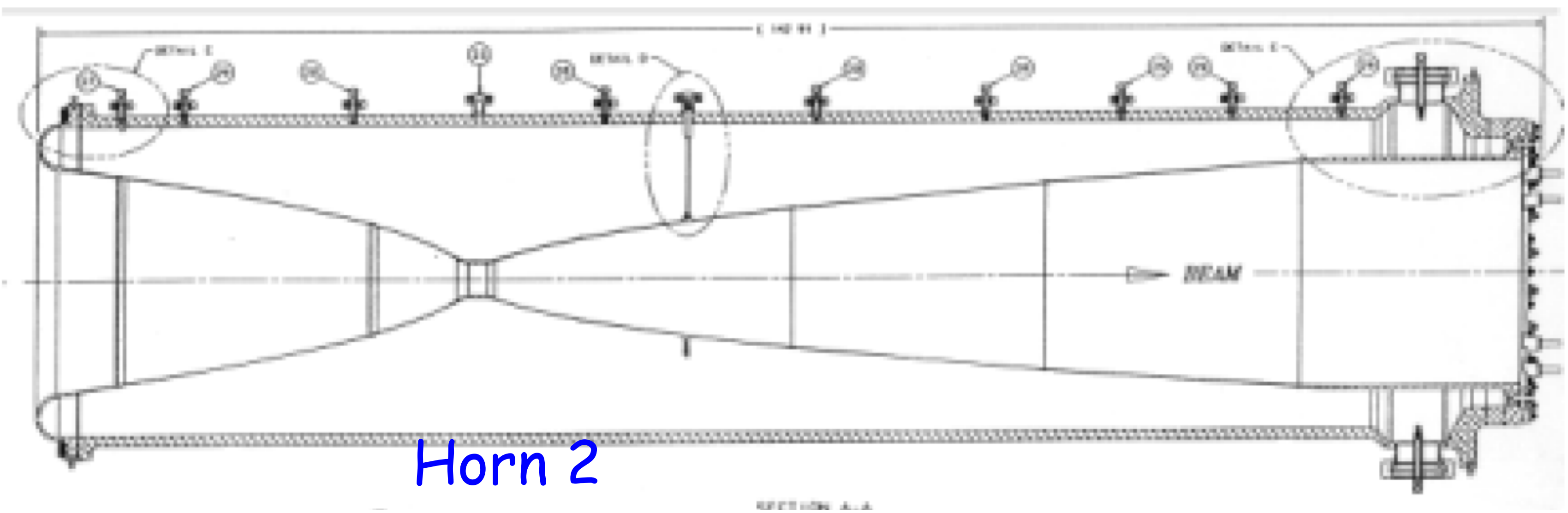


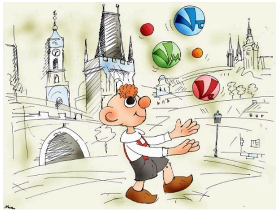


NuMI horns



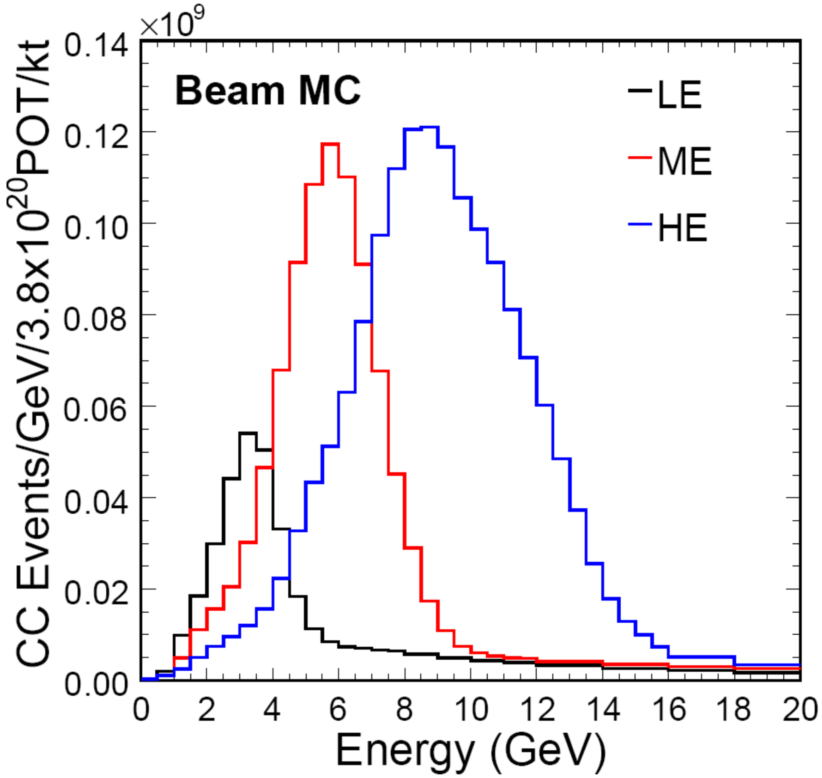
Horn 1: at the neck, B= 3T, I = 200kA for 5.2 ms

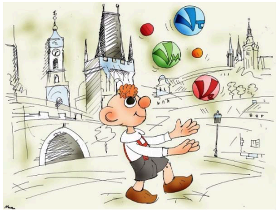




Changing the Horn's Focus

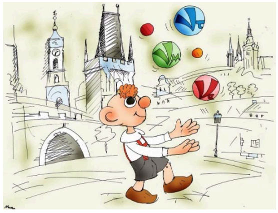
- An effective way of changing the horns' focus is to move the target. This was used in the NuMI beam to focus three different energy regions.
- The low energy setting required inserting the target into the opening of horn 1.





Decay Pipe

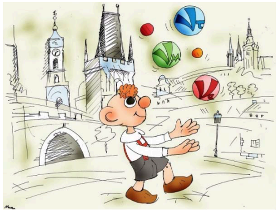
- The longer the decay pipe, the more pions that will decay. However, muons will decay at a higher rate, giving a larger beam ν_e background to $\nu_\mu \rightarrow \nu_e$ oscillations.
- For low-energy neutrinos, the beam pipe must be fairly broad.
- As I indicated earlier in this lecture, the NuMI beam was designed relying on the Kamiokande atmospheric results, which had the value of Δm^2 about a factor 5 too high. Expecting the oscillation of higher energy neutrinos, the decay pipe was 675 m long with a 1 m radius. In retrospect, a MINOS would have done better with a decay pipe half that length with twice the diameter.



Long-Baseline Experiments

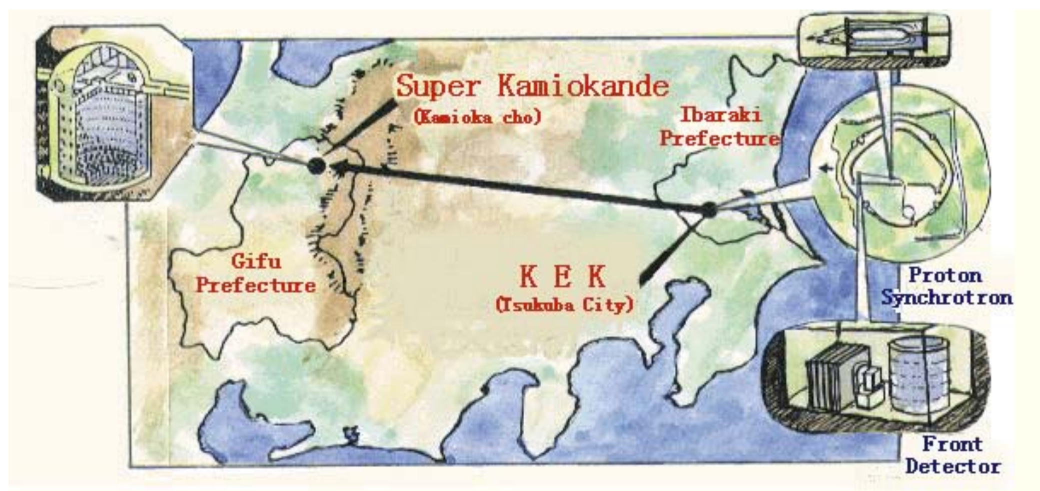
Name	Beamline	Baseline (km)	Near Detector*	Start Date	Finish Date
K2K	K2K	250	Yes – FE+FG	1999	2004
MINOS	NuMI	735	Yes – FE	2005	2012**
OPERA	CNGS	732	No	2008	2012
T2K	T2K	295	Yes – FG	2010	ongoing
ICARUS	CNGS	732	No	2010	2012
NOvA	NuMI	810	Yes – FE	2014	ongoing

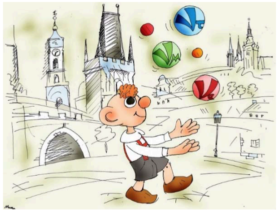
* FE = Functionally Equivalent; FG = Fine Grained
** Continued until 2016 as MINOS+ in a medium energy beam



K2K (KEK to Kamioka)

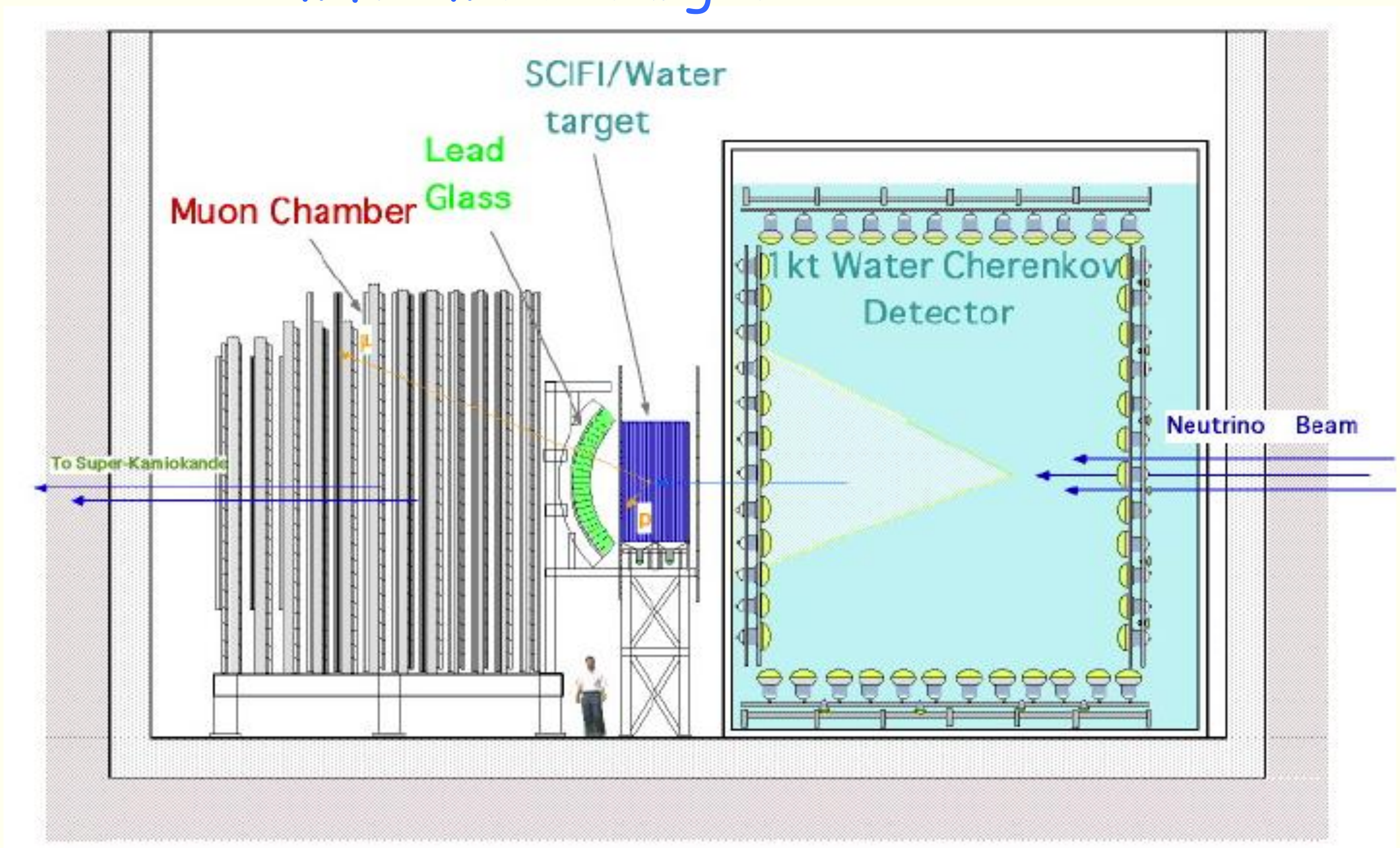
- K2K was the first long-baseline accelerator experiment. It was recognized that it would not be very precise, but it was felt that it was important to verify the Super-Kamiokande atmospheric results with a different technology.
- The neutrino beam was produced from the 12-GeV proton synchrotron at the KEK laboratory in Tsukuba, Japan and sent to the Super-K detector, a distance of 250 km.

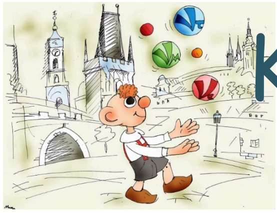




K2K Near Detector

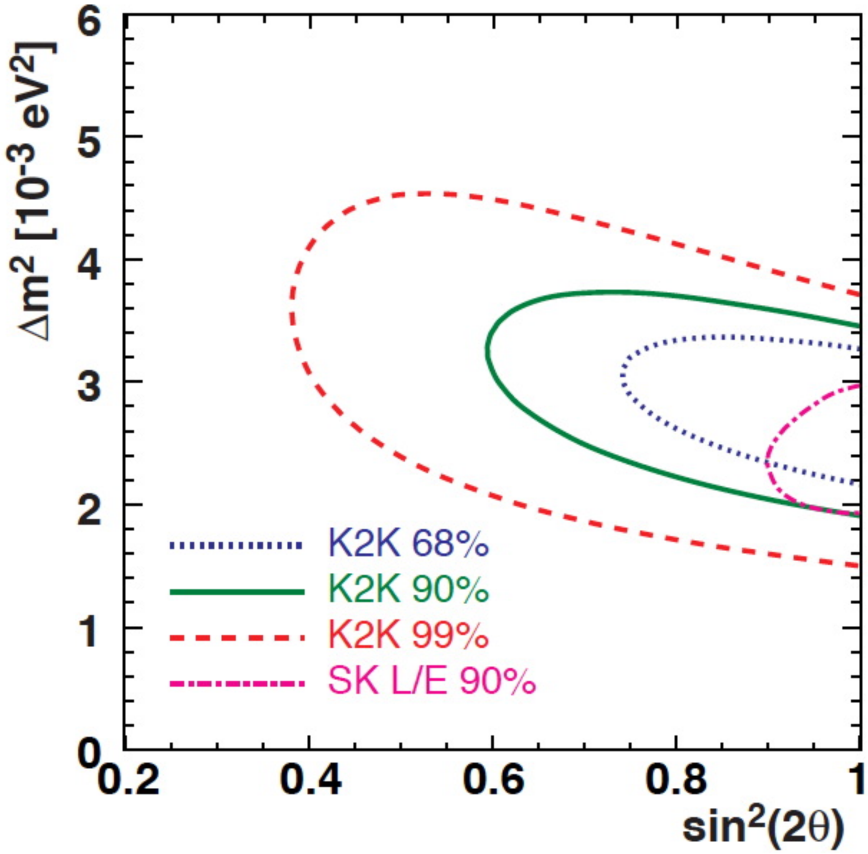
300 m from the target



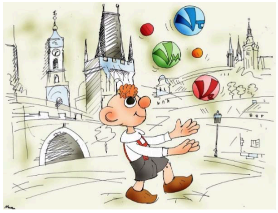


K2K Experiment Results

- The total recorded data for the experiment was 0.9×10^{20} protons on target (PoT).
- The K2K central values were
  $\Delta m^2 = 2.8 \times 10^{-3}$ eV^2
  $\sin^2(2\theta_{23}) = 1.0$
- SK central values were
  $\Delta m^2 = (2.0$ to $2.5) \times 10^{-3}$ eV^2
  $\sin^2(2\theta_{23}) = 1.0$

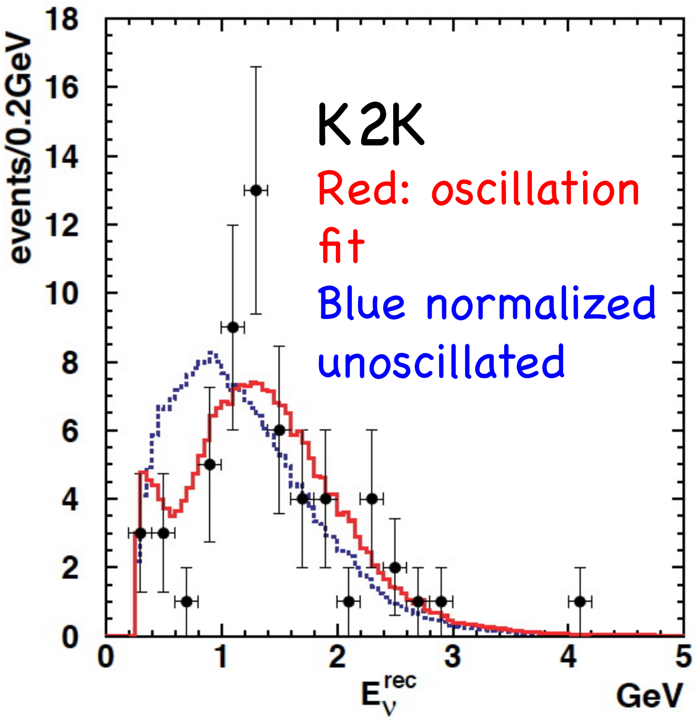


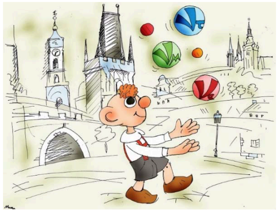
M. H. Ahn et al., Phys. Rev. D 74, 072003 (2006)



Note on Maximal Disappearance

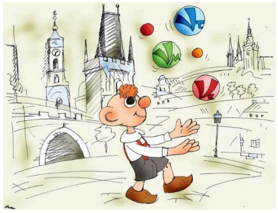
- In a 2-flavor analysis, the disappearance is proportional to $\sin^2(2\theta_{23})$, which is obviously bounded by one. However, even for maximal disappearance, $\sin^2(2\theta_{23}) = 1$, the data will not normally go to zero at the oscillation maximum due to backgrounds and energy smearing. Thus it is possible for the oscillation fit to get $\sin^2(2\theta_{23}) > 1$, in which case the experiment will report $\sin^2(2\theta_{23}) = 1$.
- K2K actually got $\sin^2(2\theta_{23}) = 1.19$.
- To what extent the mixing is maximal is an important issue, particularly for $\nu_\mu \rightarrow \nu_e$ oscillations





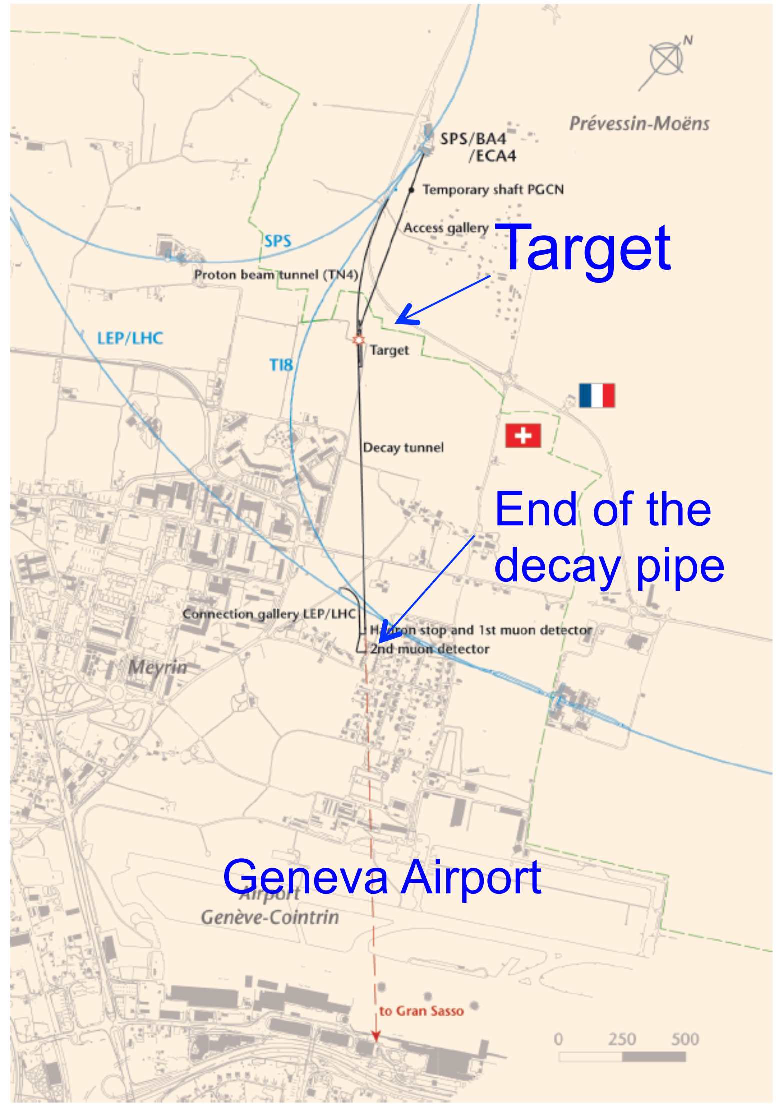
CNGS (CERN Neutrinos to the Gran Sasso)

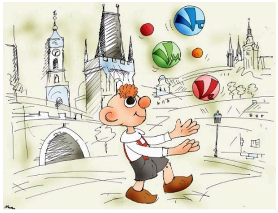
- In 1999, at the strong urging of the Italian Physics Community, CERN approved the construction of a neutrino beam to the Gran Sasso Laboratory in Italy.
- A special fund was raised for this project, with Italy contributing more than half the cost.
- The plan was not to compete with the MINOS experiment in the United States, but to do complementary physics.
- From the inception of this program, it was clear to me and to many others that this program was not going to produce much useful physics.



CNGS

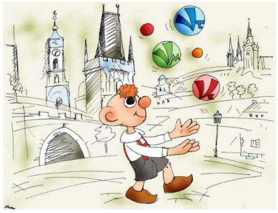
- The fatal flaw was that there was no room for a near detector.
- The argument that was made was that there was no need for a near detector because the experiments were going to do appearance measurements.
- The correct argument should have been that there was no need for a near detector because the experiments were not going to do precise measurements





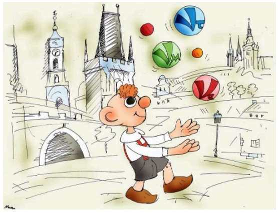
CNGS: OPERA

- The CNGS program had two experiments, both with powerful technology.
- The lead experiment was OPERA (Oscillation Project with Emulsion-tRacking Apparatus) with the goal of showing that the disappearing ν_μ's were oscillating to ν_τ's by observing ν_τ CC events. There are two problems with this approach.
  - (1) To avoid large threshold effects, high energy neutrinos are needed to produce τ's, ideally around 15 GeV. However, the atmospheric oscillation at 732 km occurs at 1.5 GeV. Thus the oscillation probability is suppressed by about a factor of 100.



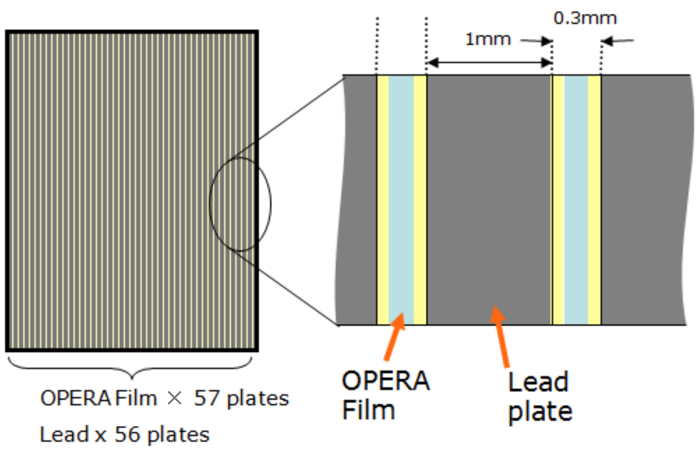
CNGS: OPERA

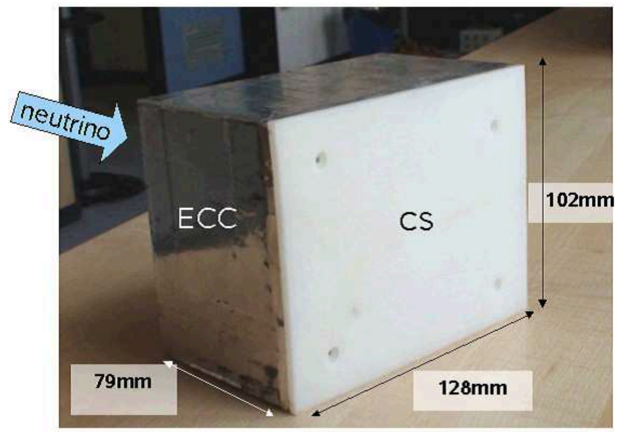
- (2) There is an easier and more precise way to do it. From Z decays, we know that there are only 3 active neutrinos. Thus, the disappearing ν_μ's must either oscillate into ν_τ's or some sort of sterile neutrinos. However, the latter case can be studied by looking for the disappearance of neutral current interactions. This has been done by Super-K, MINOS, and others with no evidence of this effect.



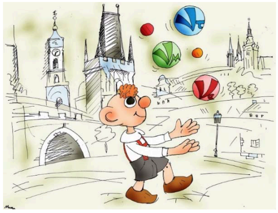
OPERA Detector

- The basic unit of the OPERA detector is a “brick” of 57 layers of 1 mm lead plates and 0.3 mm photographic emulsions.



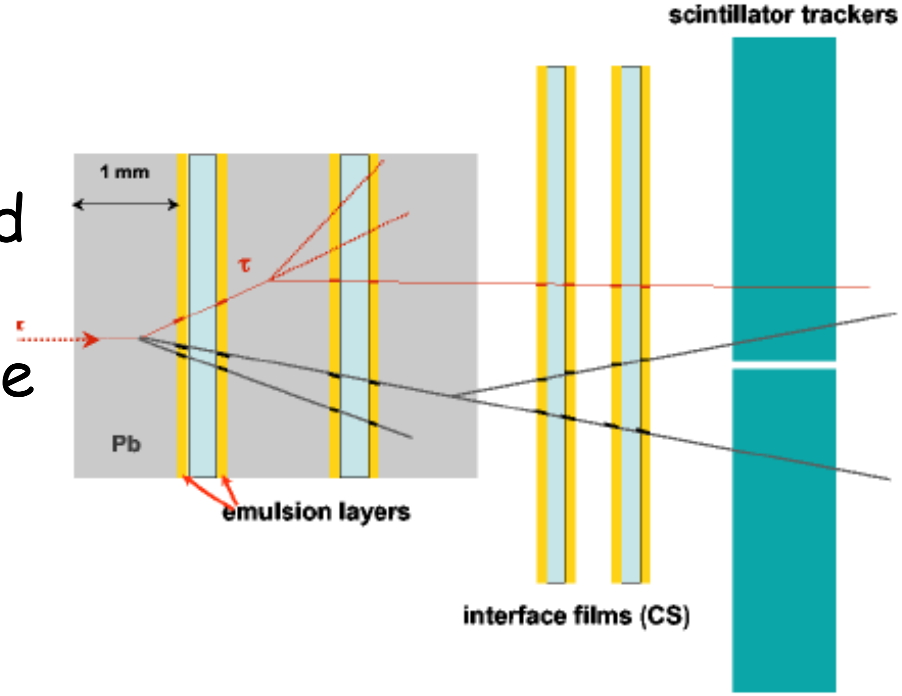


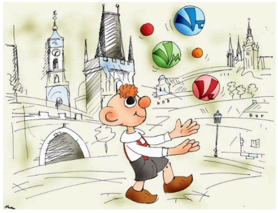
- The detector has 150,000 bricks for a total mass of 1.25 kt.



OPERA Detector

- OPERA searches for kinks from τ decays. When a brick is triggered by a scintillation tracker, it is removed for measurement.
- There are two modules of bricks and trackers, each of which is followed by a magnetic spectrometer to measure muons.

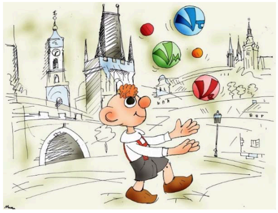




OPERA Results

- Using oscillation parameters from other experiments, OPERA expected 2.6 ± 0.5 events, including 0.25 background events, mostly from charm, and observed 5 events. Phys. Rev. Lett **115**, 121802 (2015)

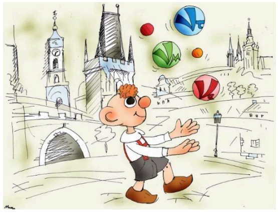
- Another item of note is that the OPERA experiment is most famous, or notorious, for reporting that neutrinos travel faster than light. This effect was found to be due to a loose cable. It did inspire both the MINOS and ICARUS experiments to do precise measurements of the speed of neutrinos, which found no anomalies.



ICARUS

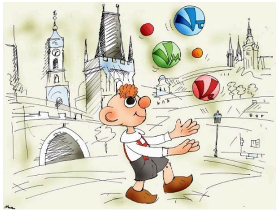
(**I**maging **C**osmic **A**nd **R**are **U**nderground **S**ignals)

- The ICARUS experiment pioneered the first to use the very powerful liquid argon TPC chamber technology, which is being used in the Fermilab short baseline program and which will be used in the future DUNE detector.
- However, it produced no results of interest to the topics of this lecture series for two reasons.
  - It was in a high-energy beam when the physics was all at low energy.
  - It was supposed to be a 2.4 kt detector, but it was only funded for 0.6 kt.



ICARUS

- I will not describe the detector, because it is being refurbished to be the "far" detector in the Fermilab short baseline project, and thus will be discussed in the sterile neutrino lectures.
- The only oscillation result from ICARUS was a search for $\nu_\mu \rightarrow \nu_e$ oscillations that would correspond to the LSND anomaly. They saw 4 events and expected 6.4 ± 0.9 from known sources. Eur. Phys. J. C **73**, 2345 (2013).



Questions?