Adam Para

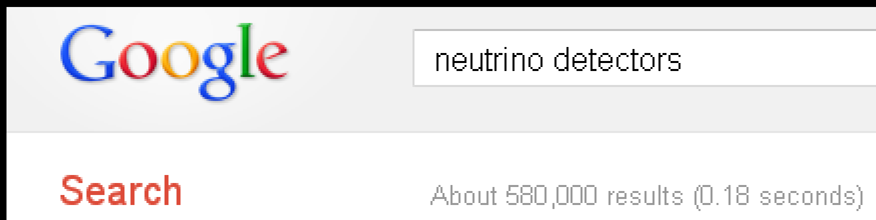
NEUTRINO DETECTORS

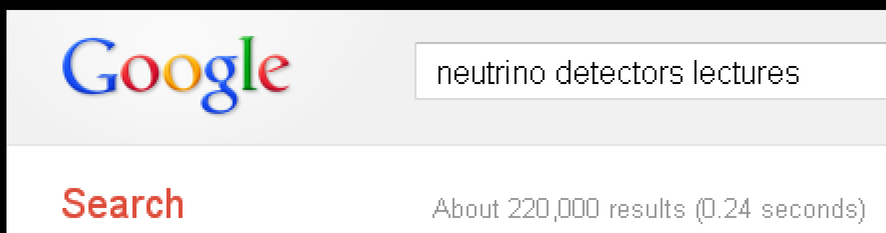
ART AND SCIENCE OF NEUTRINO DETECTORS

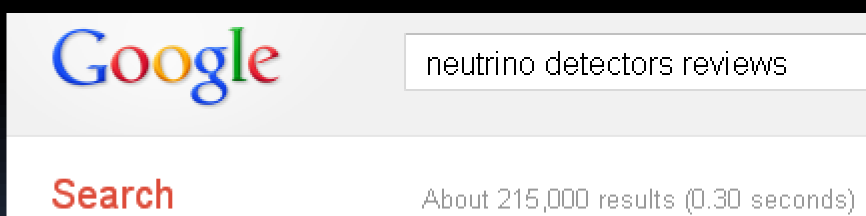
Or rather

Stories about neutrino detection

Lecturing in XXI Century



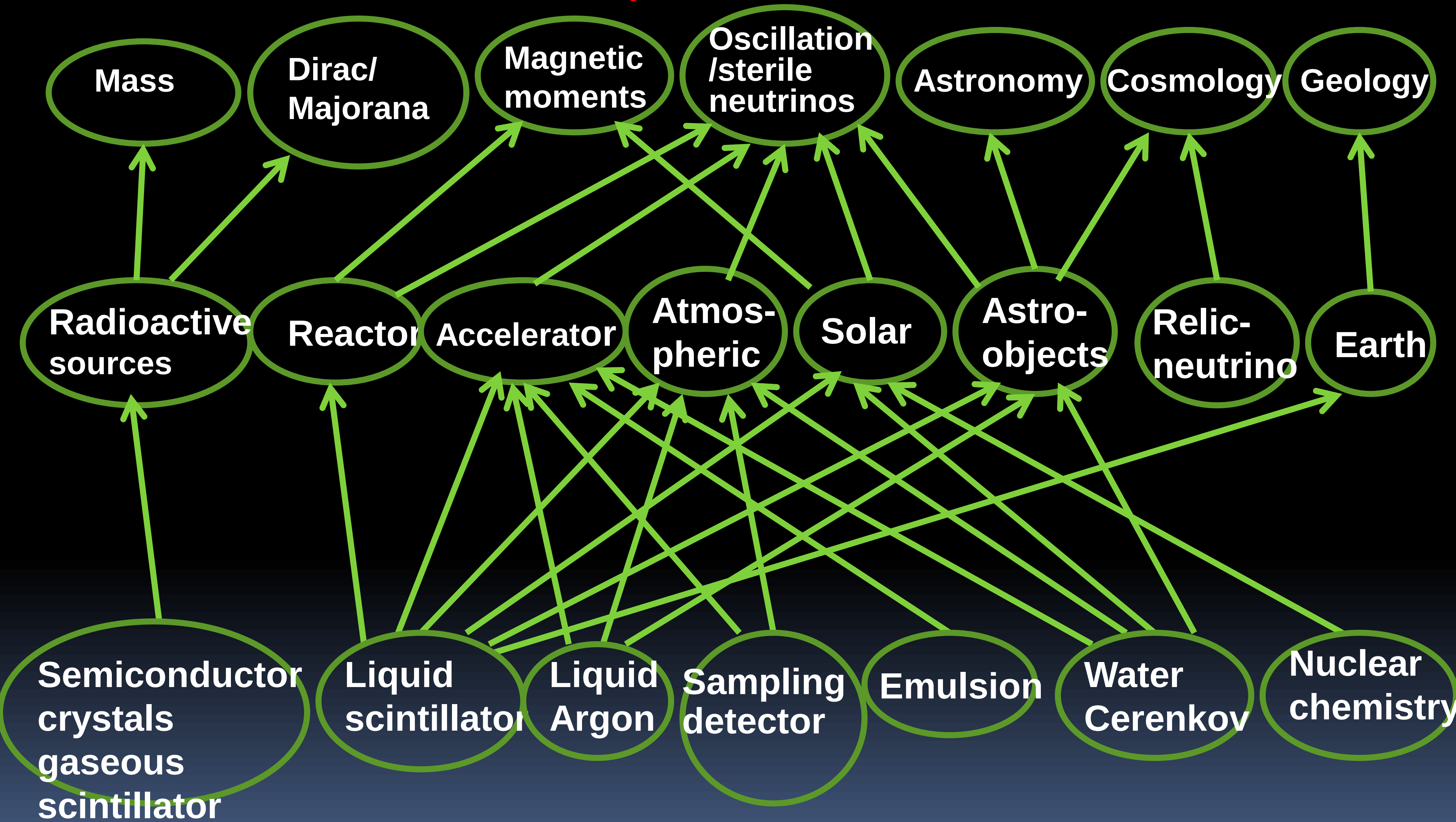




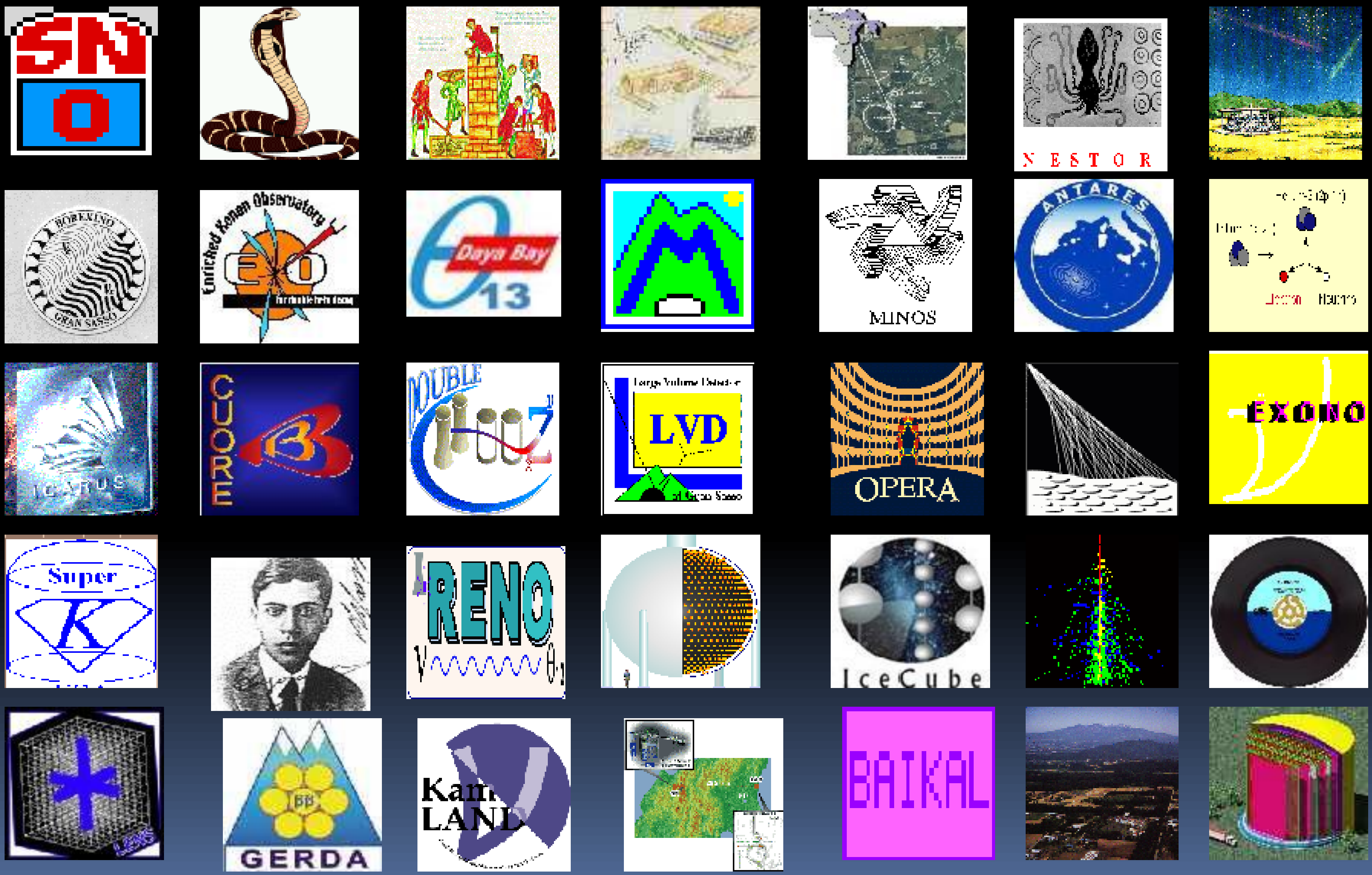
Many of these talks/lectures are very thoughtful
Many of them are quite complete
Many of them are unbiased
Many of them are very interesting and inspiring

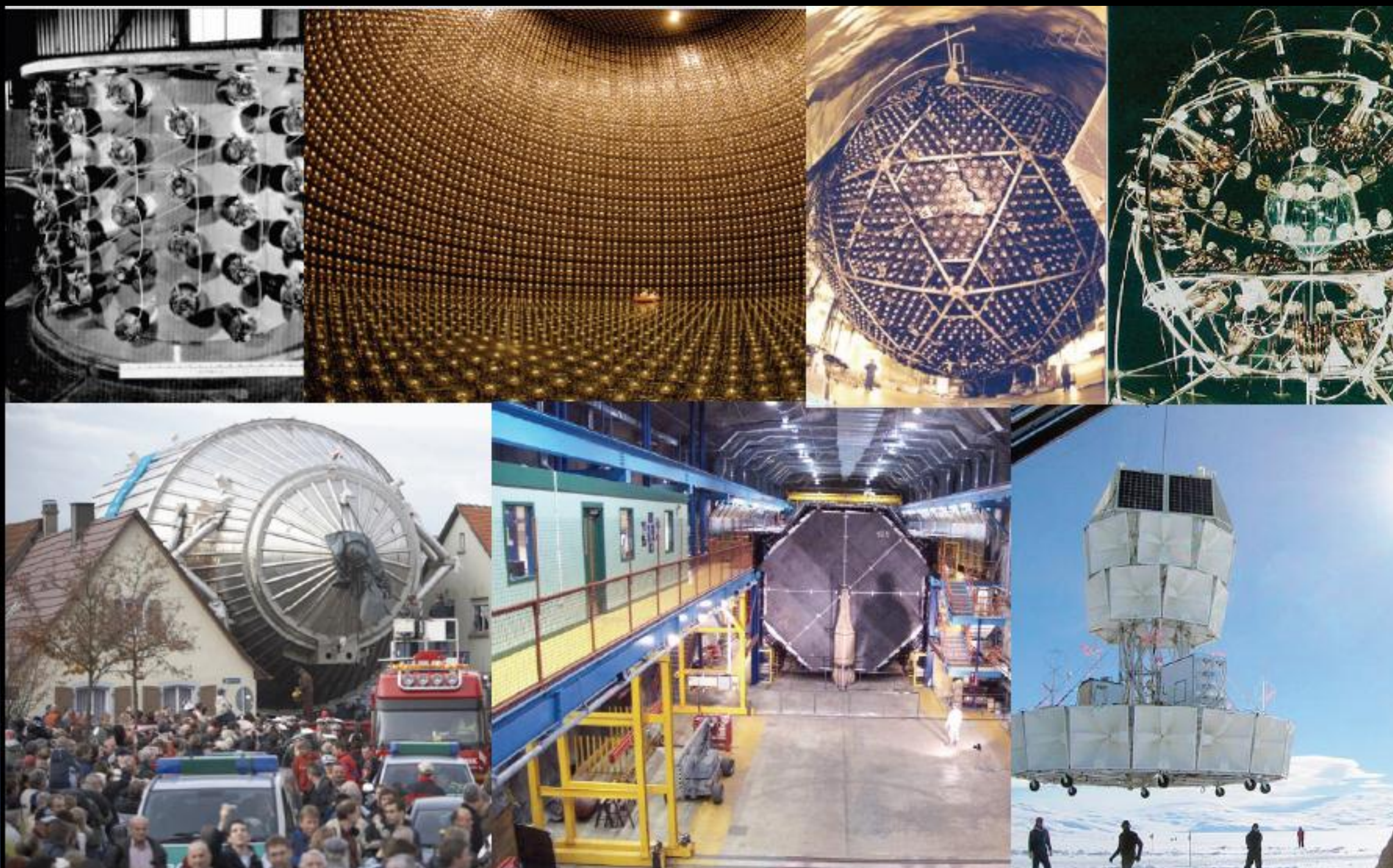
I have borrowed most of my materials from some of them

An intricate Web of Neutrino Physics and Experiments



Neutrino industry

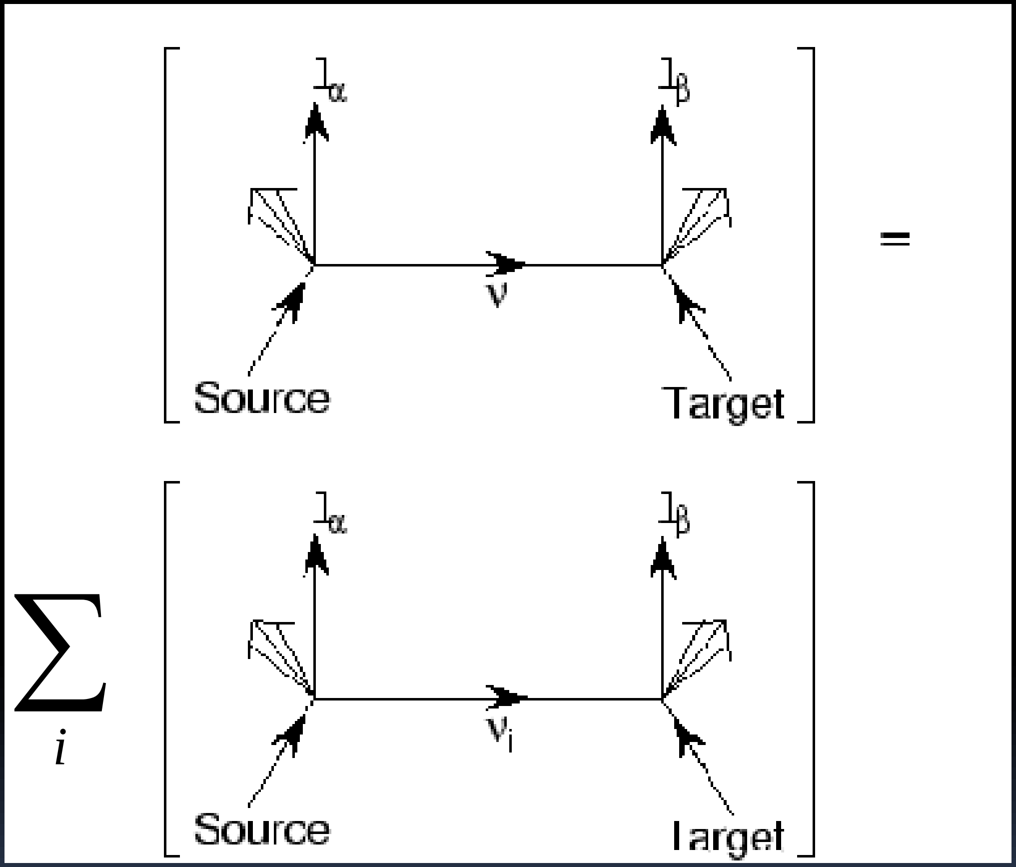




Neutrino Experiments: A Confluence of Multiple Disciplines

- High Energy Physics
- Nuclear Physics
- Radiochemistry
- Chemistry
- Computing
- Electrical Engineering
- Structural Engineering
- Civil Engineering
- Optics
- Photonics
- Geophysics
- Mining
- Nuclear Power Engineering
- Safety
- Cryogenics
- Material Science
- Quality Control
- Helioseismology

Theory of Neutrino Experiment According to Boris Kayser



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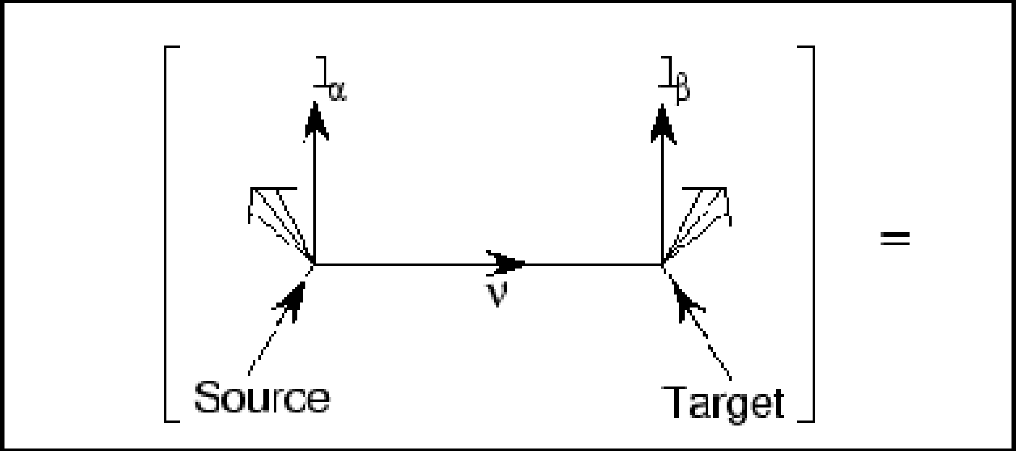
Theory of Neutrino Experiment According to Boris Kayser – An Example

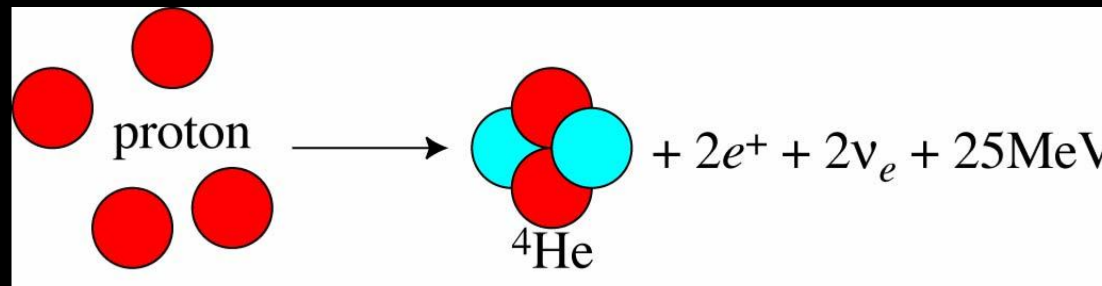


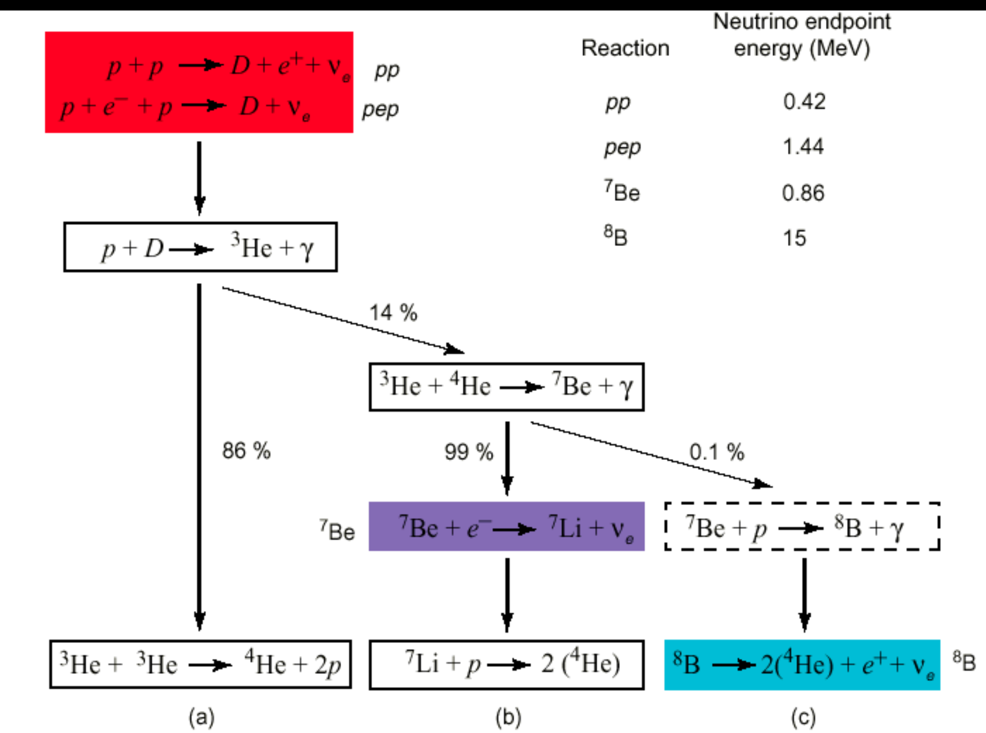
John Bahcall Ray Davies

▼

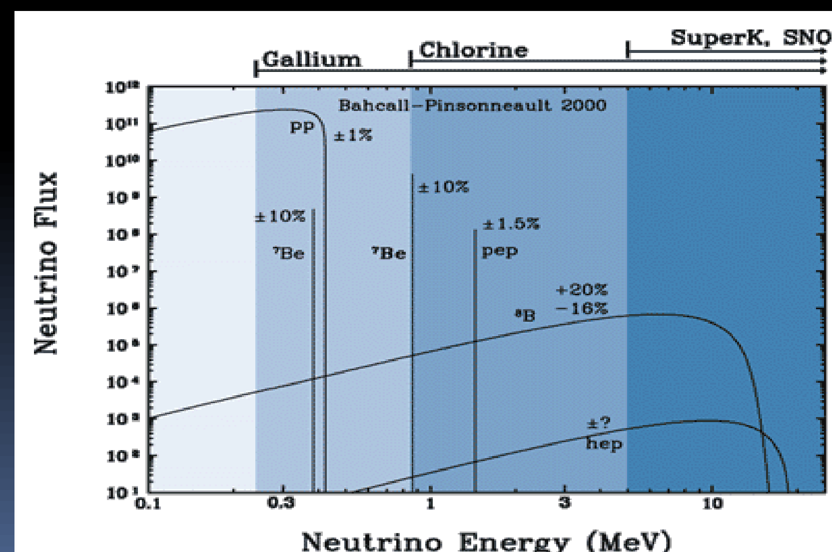
How the Sun Burns ?

- The Sun emits light because nuclear fusion produces a lot of energy

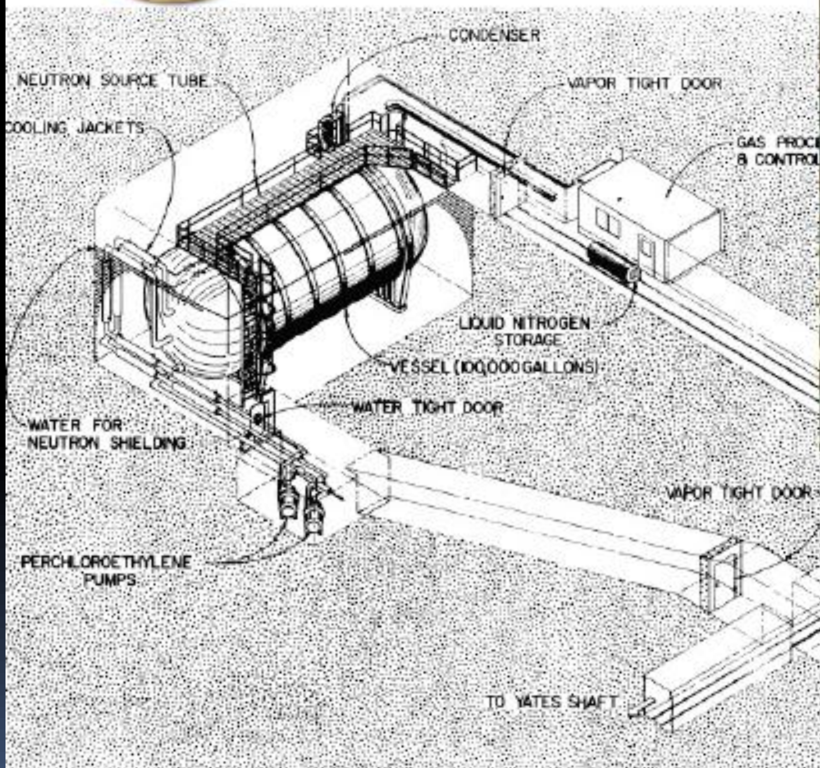


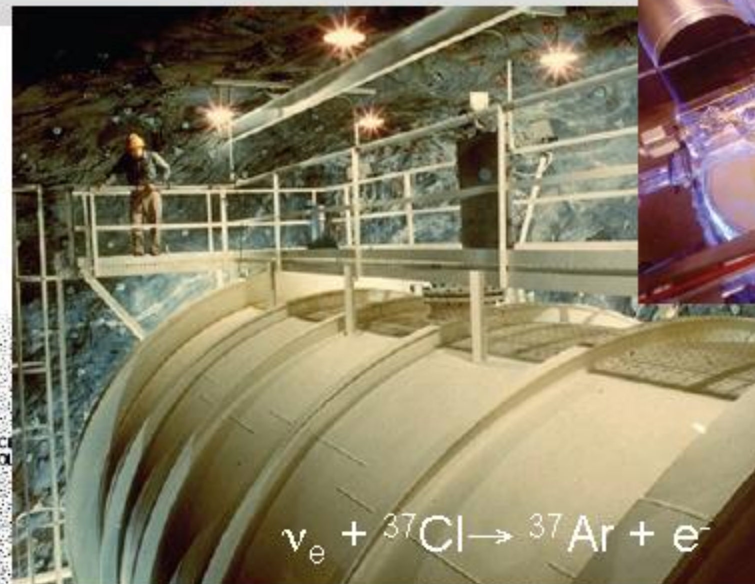


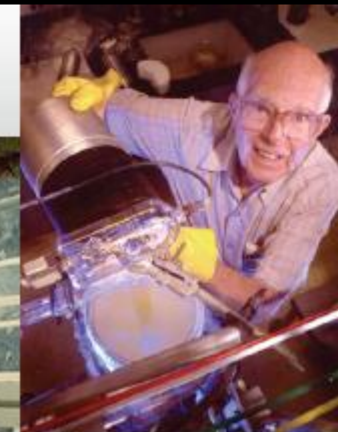
John Bahcall

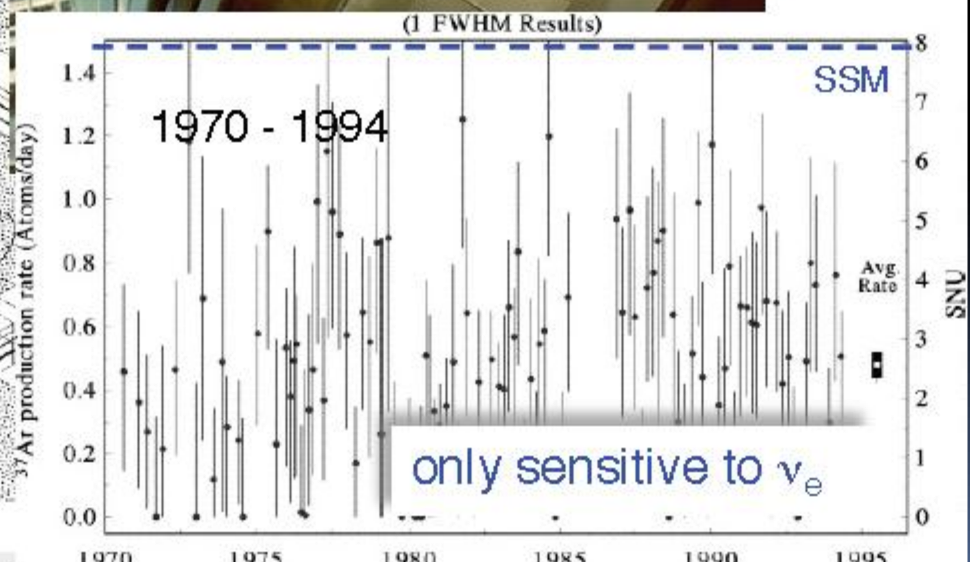


Cl-Ar Solar Neutrino Experiment at Homestake









25 years of 'Solar Neutrino Anomaly ' – an Amazing Story of Professional Persistence

- Calculated the expected rate of events related to a minute (~10^{-4}) fraction of the solar neutrino flux

- 600 tons of a washing powder solution
- 15 unstable atoms produced per month (τ=34 days)
- Atoms extracted and counted with known efficiency

• Experimental results and theoretical calculations agree within a factor of three: given the complexity of a problem a huge success for mere mortals

• Unbelievable confidence in the correctness of the prediction and the understanding of the experiment: trademark of highest level of science

Evolving Physics of/with Neutrinos

- Do neutrinos exist?
- How many different kinds?
- Theory of weak interactions? V-A? Neutral currents?
- Neutrinos as a probe of a nucleon structure and the theory of strong interactions
- Precision tests of the Standard Model
- How many families? Does the ν_τ really exist?
- Neutrino properties? Masses? Mixing? Magnetic moment?
- Nature of neutrinos? Dirac vs Majorana?
- Neutrinos as a probe of astrophysical objects: supernovae
- Neutrinos as a probe of the Earth interior
- Neutrinos as a probe of physics beyond the standard model

Neutrino Experiments

- Neutrino source (man-made or natural)
- Neutrino flux (measure, monitor, calculate)
- Neutrino detector

All these elements are quite specific to the physics problem in question. Examples of dual/triple purpose experiments are exceptions rather than a rule.

Neutrino Experiments: What do we Want to Measure?

- Counting neutrino interactions (== cross section)
- Identify the flavor (CC reactions)
- Identify the interaction (NC, CC)
- Measure the parent neutrino energy/spectrum
- Details of the final state (inclusive, exclusive)

Depending on the physics requirements AND the neutrino source AND the neutrino energy range the detectors are completely different.

Not to mention dedicated experiments for neutrino mass measurement and double beta decay experiments.

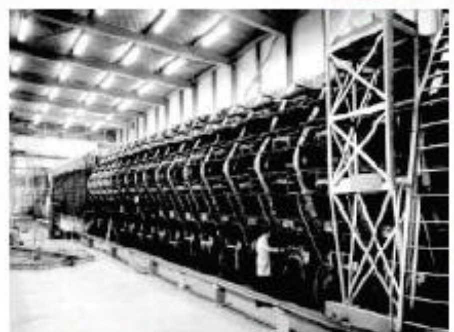
Neutrinos as a Probe

Understanding Matter and Interactions with Neutrinos

Reines-Cowan ν discovery
and the BNL 2ν experiment
fundamental ν properties

- hadronic weak currents
- observation of neutral currents
- cross sections

Bubble Chambers:
BNL, ANL, FNAL,
CERN, Serpukhov



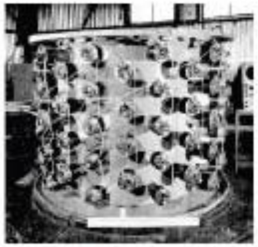
counter experiments:
CDHS, CHARM
CCFR, NuTEV

- structure functions (F_2, F_3)
- parton universality
- electroweak studies $\sin^2(\theta_w)$
- strange sea studies
- QCD measurements
- cross sections

Neutrinos as probes to understand matter and interactions

Probing Neutrinos

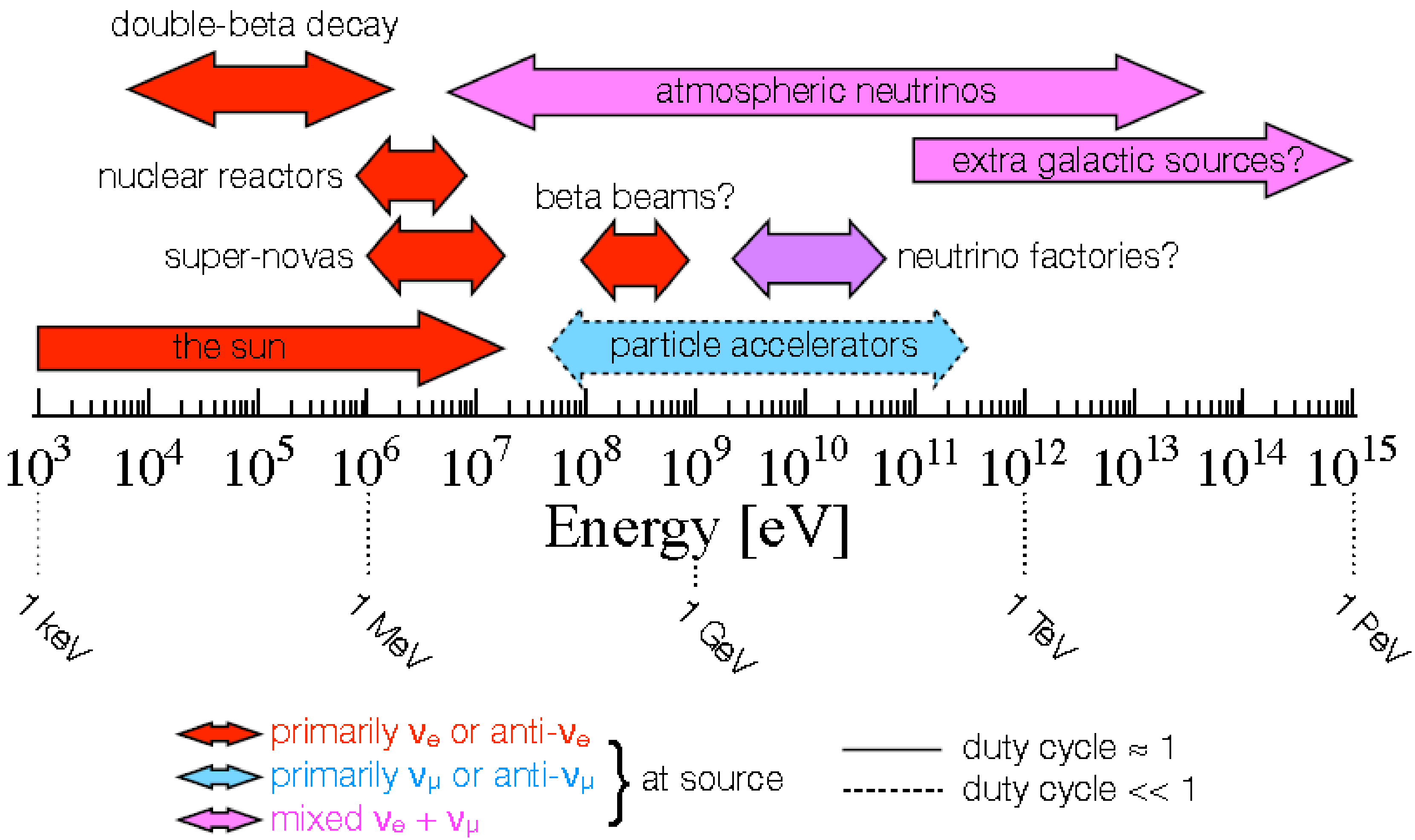
Neutrino Masses and Mixing, Non-Standard Effects



Reines-Cowan ν discovery
and the BNL 2ν experiment
fundamental ν properties

searches for neutrino oscillation with intense sources of ν_e, $\overline{\nu}_e$, ν_μ, …

Sources for neutrino detectors



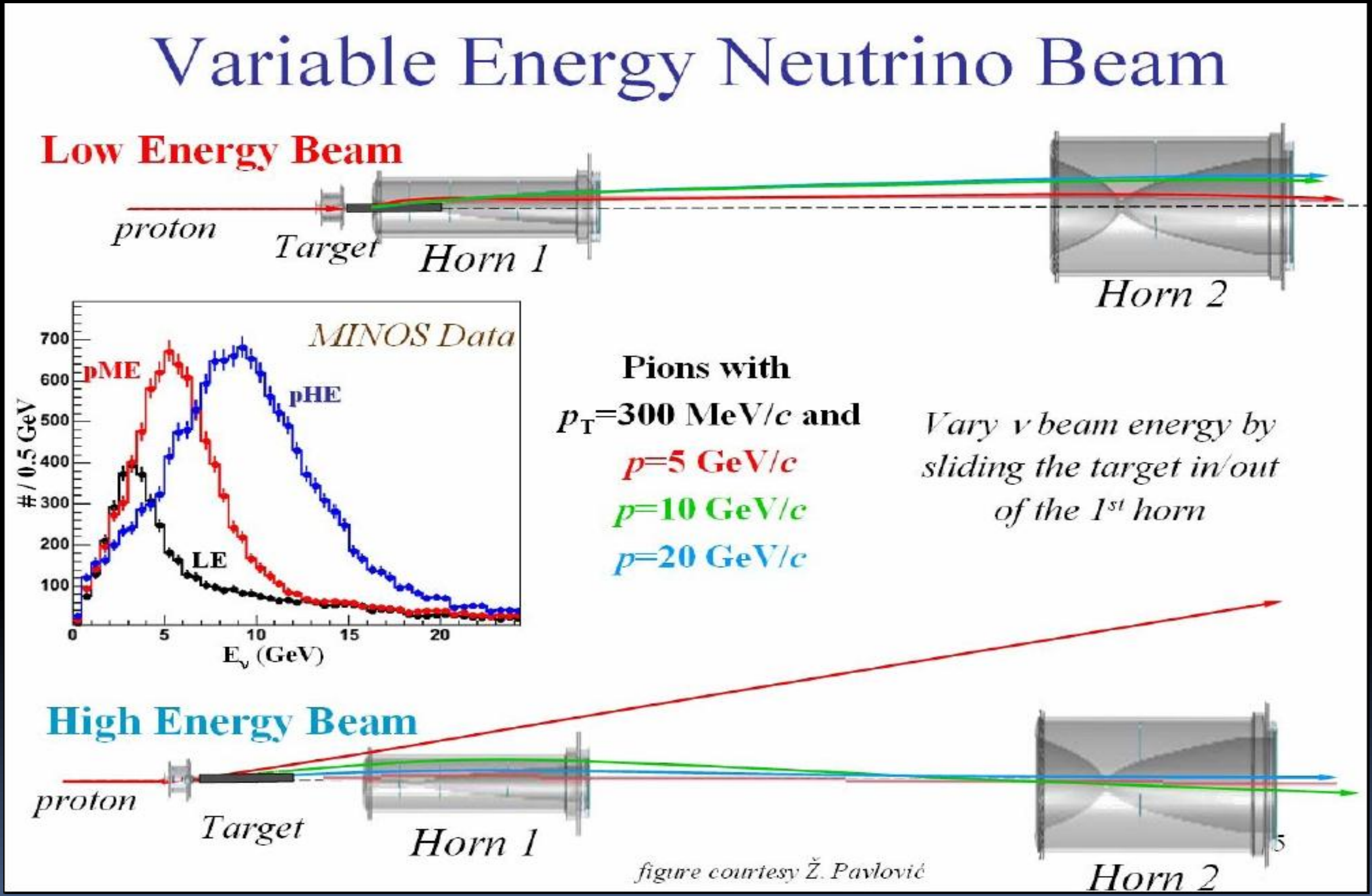
PRODUCING NEUTRINOS

Comments on Neutrino Beams/Sources

For a precision experiment one needs to know:

- Neutrino beam composition (neutrino/antineutrino contamination)
- Flavor composition (electron neutrino background, tau neutrino component of the beam)
- Total flux of neutrinos (measured or calculated, see the reactor neutrino 'anomaly')
- Energy distribution

Conventional Neutrino Beam



Near and Far Detector: Experimental Determination of the Beam Properties

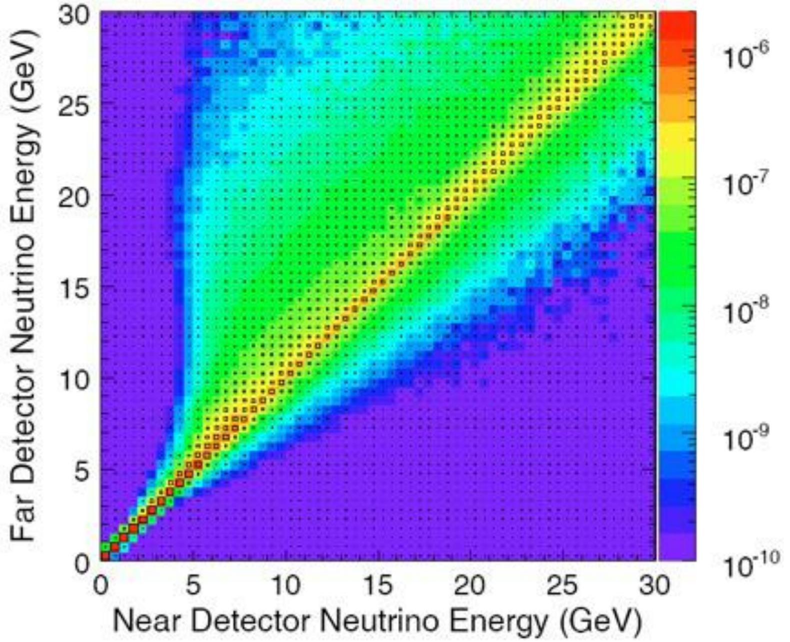


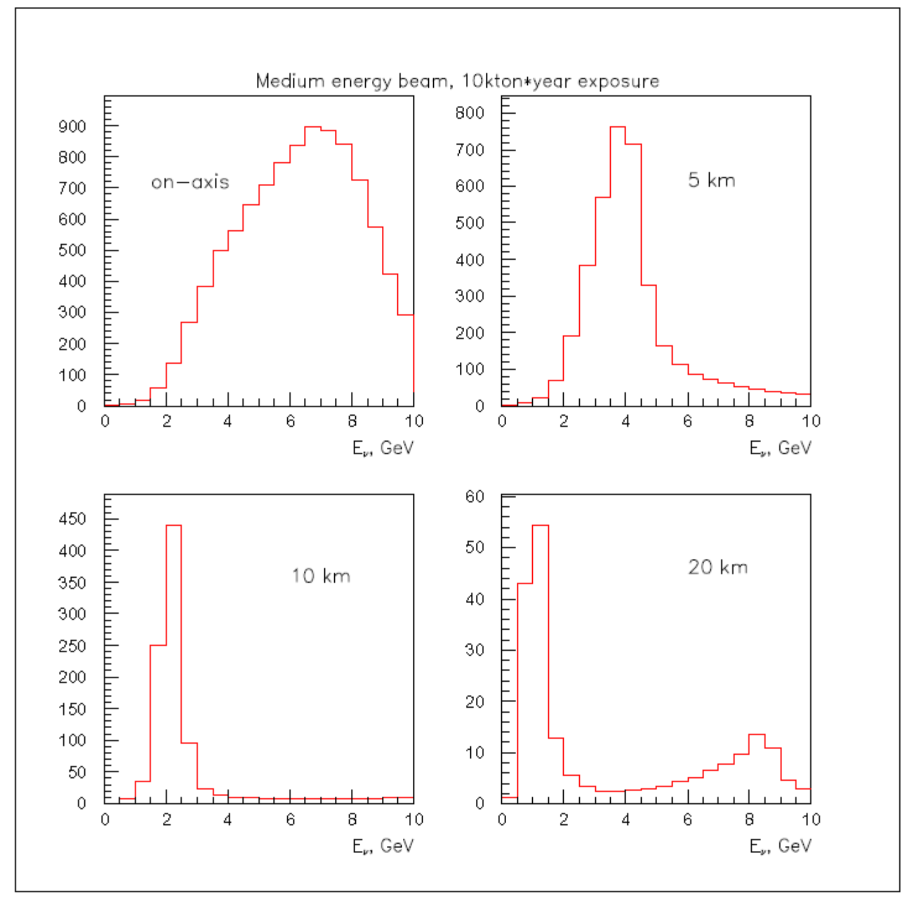
FIG. 31: The joint distribution of neutrino energies observed in the Near and Far Detectors. The contents of each cell represent the mean number of ν_μ events expected in the Far Detector for one event in the Near Detector. This distribution may be treated as a matrix, as in Eq. 9, to relate the energy spectra measured in the Near Detector to those in the Far Detector.

For a number of reasons the far and near detectors 'see' a different energy spectrum of the 'same' beam.

Both beam spectra are correlated: they come from the same parent hadron beam.

Far detector spectrum can be constructed from the event spectrum observed in the near detector.

Off-axis Neutrino Beams

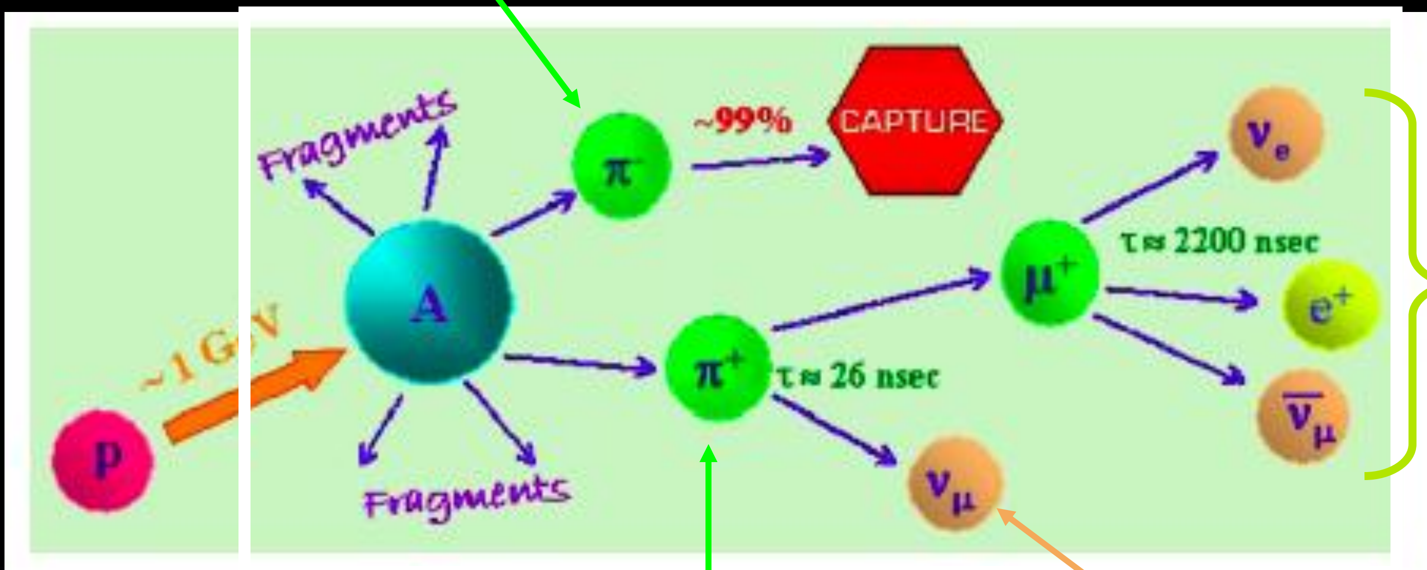


- An un-avoidable consequence of the beam production procedure.
- With some luck could provide a highly optimized (intensity and energy spectrum) beam

Spallation Neutron Source

Accelerator based Decay at Rest

π^- absorbed by target



E range up to 52.8 MeV

Target Area

π^+ DAR

Mono-Energetic!
ν_μ = 29.8 MeV

ν-source Proposal Overview

Type	channel	Background	Source	Production	Activity (Mci)		Proposal
ν_e	$\nu_e\, e \rightarrow \nu_e\, e$ Compton edge 5% E_{res} 15cm R_{res}	radioactivity (managable) Solar ν (irreducible) ν-Source (out ok but in ?)	^{51}Cr 0.75 MeV $t_{1/2}$=26d	n_{th} irradiation in Reactor	in	>3	Sage LENS
					out	5-10	SOX SNO+
			^{37}Ar 0.8 MeV $t_{1/2}$=35d	n_{fast} irradiation in Reactor (breeder)	in	>1	-
					out	5	Ricochet (NC)
$\bar{\nu}_e$	$\bar{\nu}_e\, p \rightarrow e^+\, n$ E_{th}=1.8 MeV (e^+,n) Coincidence 5% E_{res} 15cm R_{res}	reactor ν & ν-Source → Background free!	^{144}Ce E<3MeV $t_{1/2}$=285d	spent nuclear fuel reprocessing	in	0.005-0.05	CeLAND SOX
					out	0.5	Daya-Bay
			^{90}Sr ^{106}Rh		-	-	-
			^{42}Ar	?	-	-	-

ν-source Proposal Overview

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			^{37}Ar 0.8 MeV $t_{1/2}$=35d	n_{fast} irradiation in Reactor (breeder)	in	>1	-
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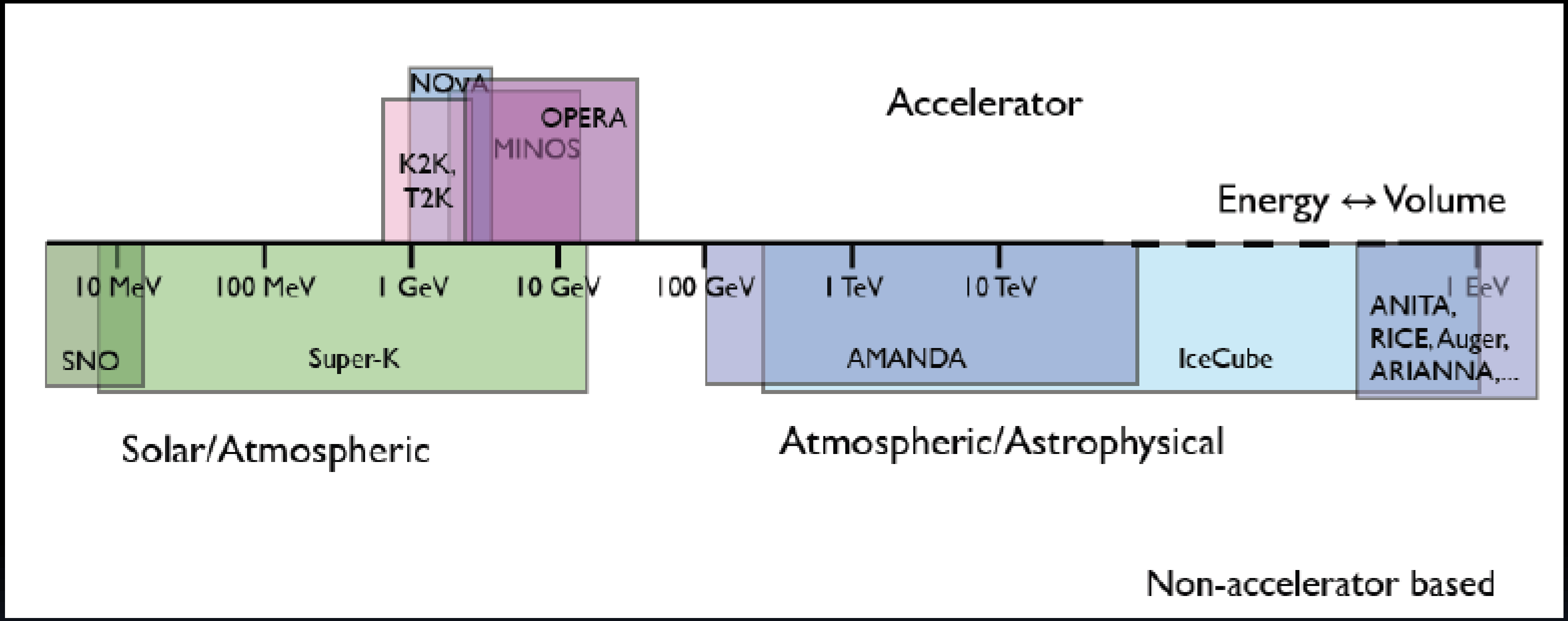
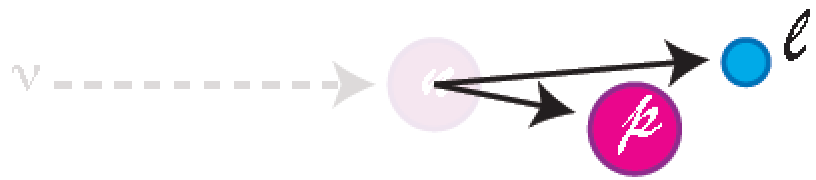
			^{90}Sr ^{106}Rh		-	-	-
			^{42}Ar	?	-	-	-

DETECTING NEUTRINOS



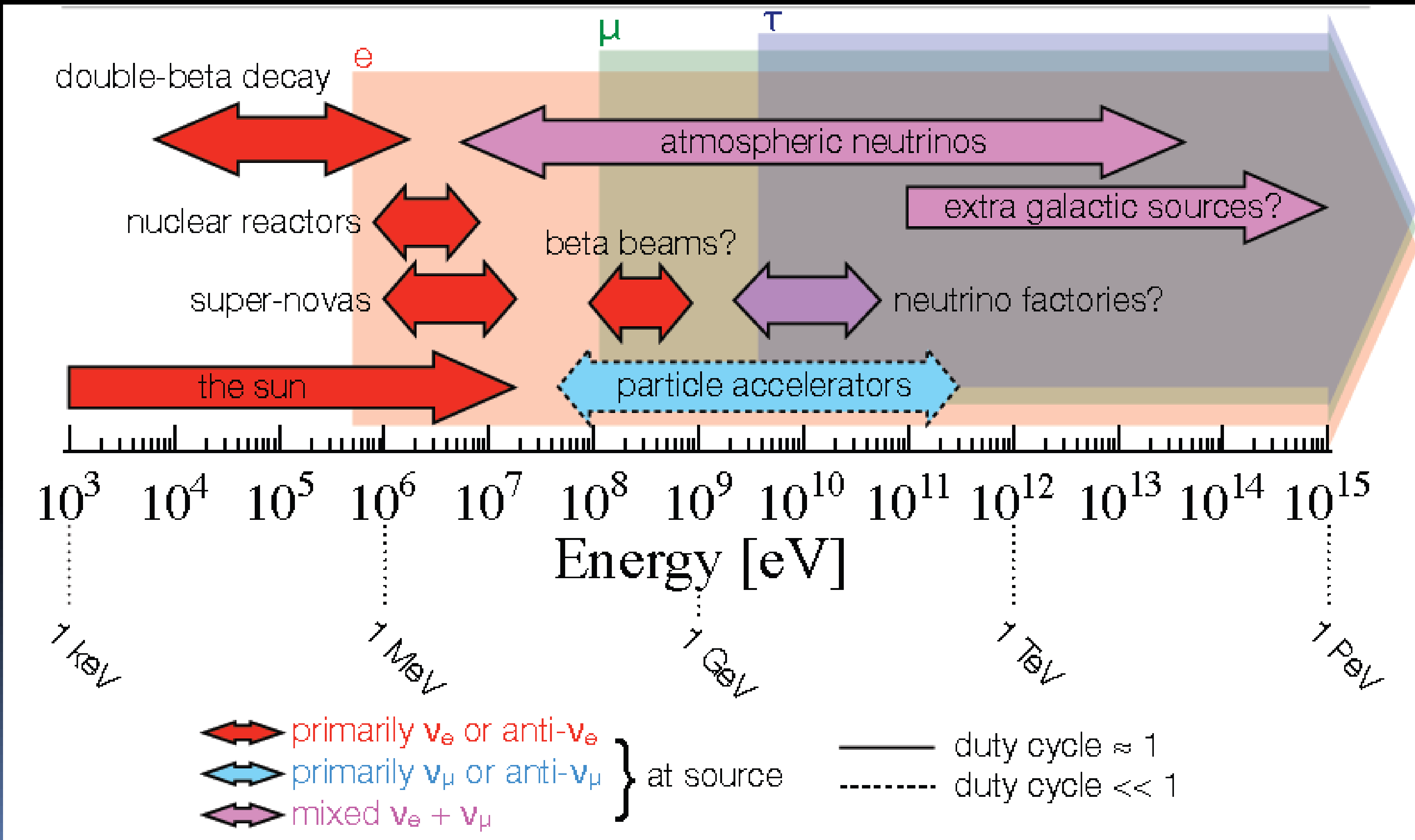
Experimenting with Neutrinos (especially lately)

- Interacting neutrino flavor of primary importance, charged current reactions a principal detection channel



$$l = e \quad m_e = 0.511\ \mathrm{MeV} \quad P_{\mathrm{thresh}} = 0.511\ \mathrm{MeV}$$
$$l = \mu \quad m_\mu = 106\ \mathrm{MeV} \quad P_{\mathrm{thresh}} = 112\ \mathrm{MeV}$$
$$l = \tau \quad m_\tau = 1.78\ \mathrm{GeV} \quad P_{\mathrm{thresh}} = 3.47\ \mathrm{GeV}$$

Energy Regimes Available for Studies



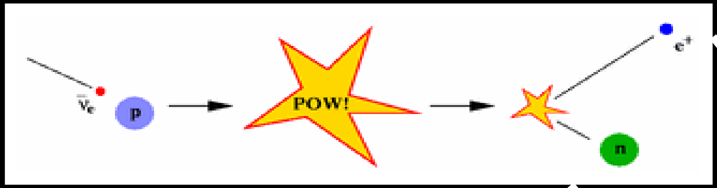
Detection and Measurement of Neutrino Interactions

- E < 100 MeV
  - Electron neutrinos and antineutrinos CC only
  - Neutral currents
  - Rate
  - Energy spectra
  - Electron direction
- 100 MeV < E < 1 GeV (enter muon neutrinos CC)
  - Mostly quasi-elastic interactions, low multiplicity
  - Neutrino energy from kinematics
- E>1 GeV (enter, slowly, tau neutrinos CC)
  - Increasingly complex final states
  - Calorimetric measurement of neutrino energy
- E > 1 TeV: surpisingly clean separation of neutrino flavors

CC Low Energy Physics

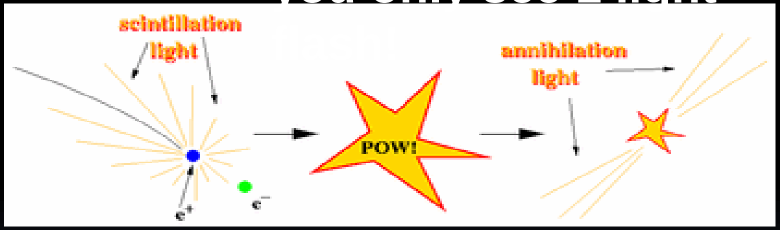
- CC: $\nu_{e,\mu} + {}^{12}C_{gs} \rightarrow \quad + {}^{12}N_{gs}$
- CC: $\nu_{e,\mu} + {}^{12}C_{gs} \rightarrow \quad + {}^{12}N^*$
- CC: anti-$\nu_e + p \rightarrow \quad + n$
  - $n + p \rightarrow d +$ 2.2 MeV photon

- $\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N_{gs}$
- ${}^{12}N_{gs} \rightarrow {}^{12}C + e^+ + \nu_e$
- 11 ms half life

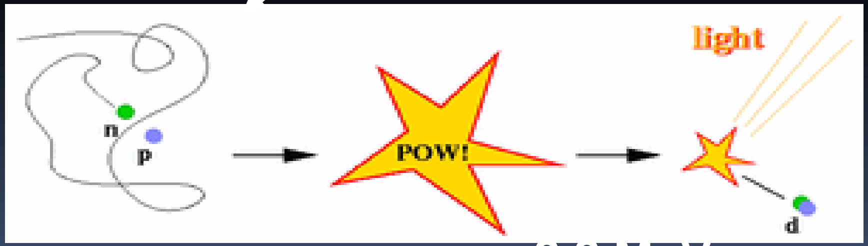


happens so quickly you only see 1 light

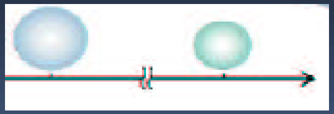
neutron thermalization mean time = 200 μs



two 0.511 MeV photons



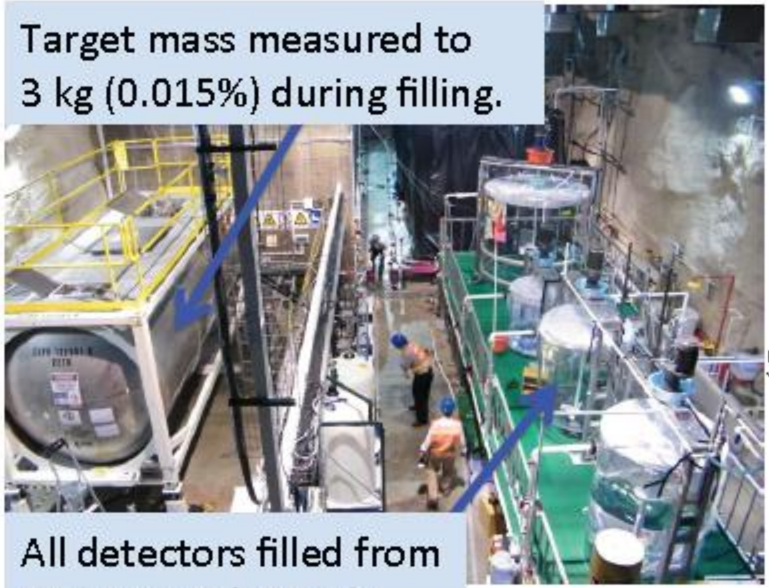
one 2.2 MeV photon



Antineutrino Detectors

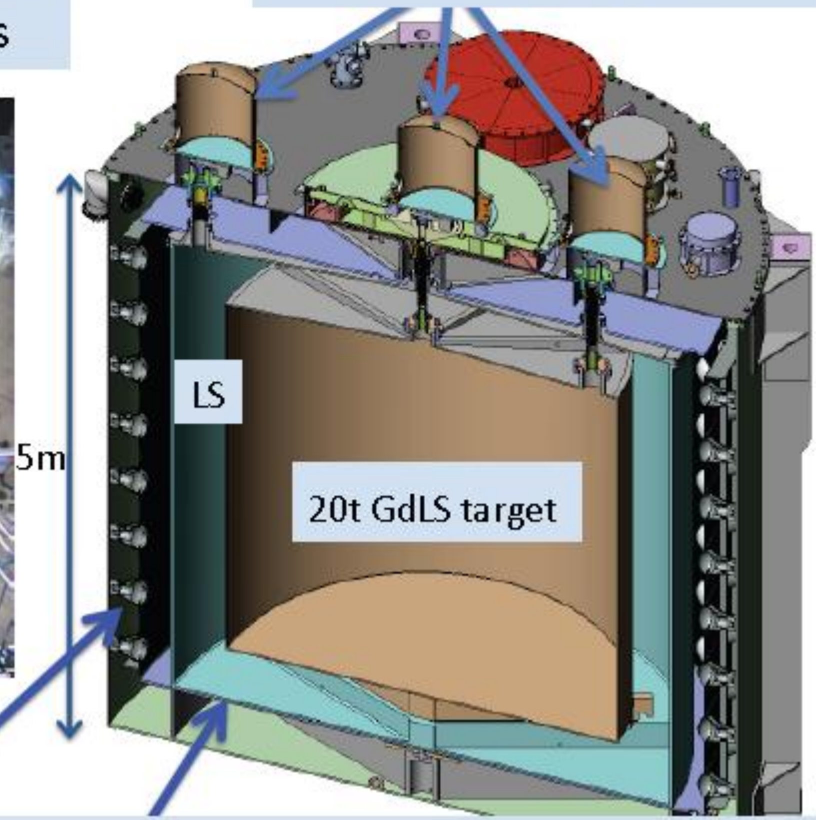
6 'functionally identical' detectors:
Reduce systematic uncertainties

Target mass measured to 3 kg (0.015%) during filling.



All detectors filled from common GdLS tanks.

Calibration robots insert radioactive sources and LEDs.



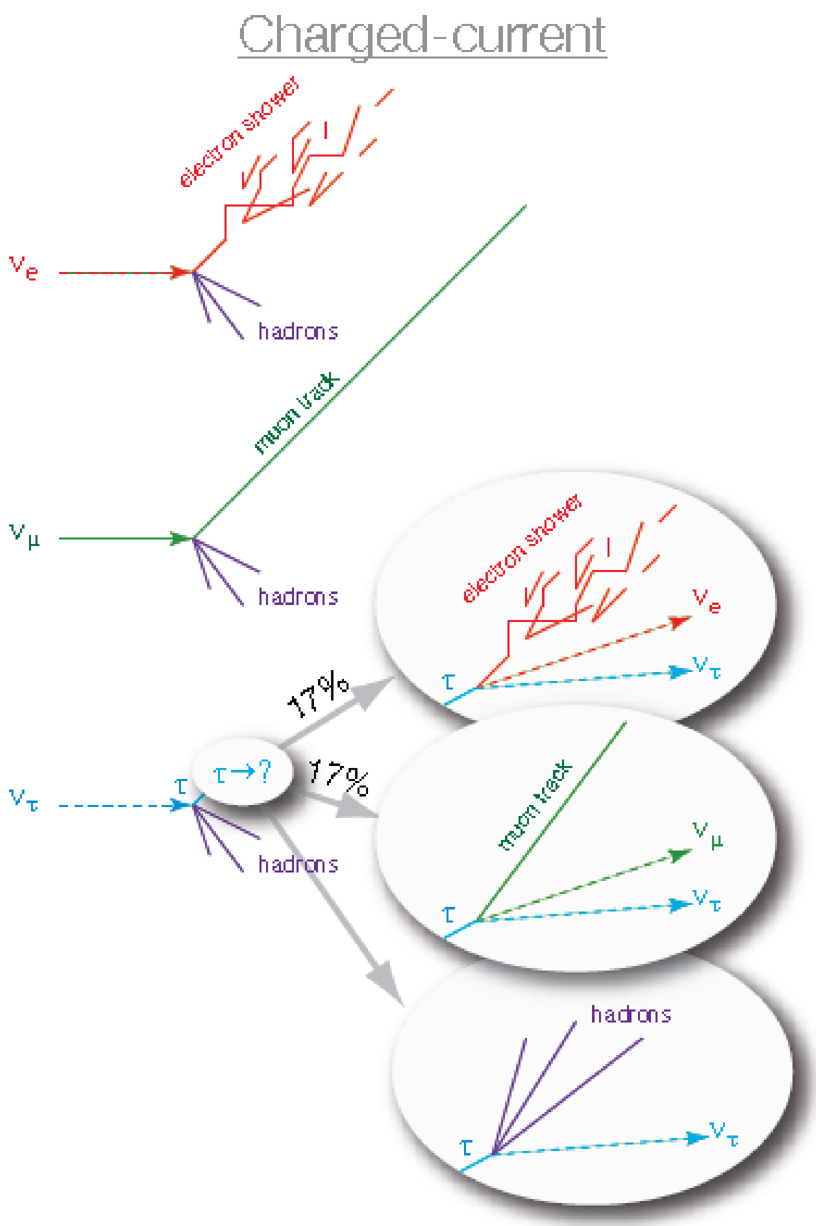
192 8" PMTs detect light in target, ~163 p.e./MeV.

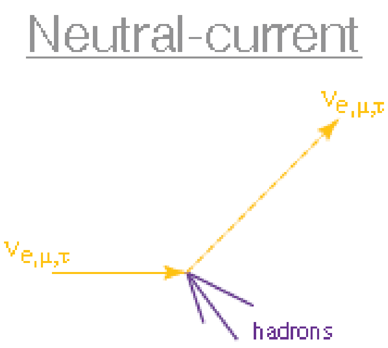
Reflectors improve light collection uniformity.

Principal Challenges

- Light yield (→ energy resolution)
- Radiopurity (→ low detection thresholds)
- Gd loading
- Transparency (light attenuation)
- Photodetector coverage (→ affordable photodetectors)

Neutrino detection channels



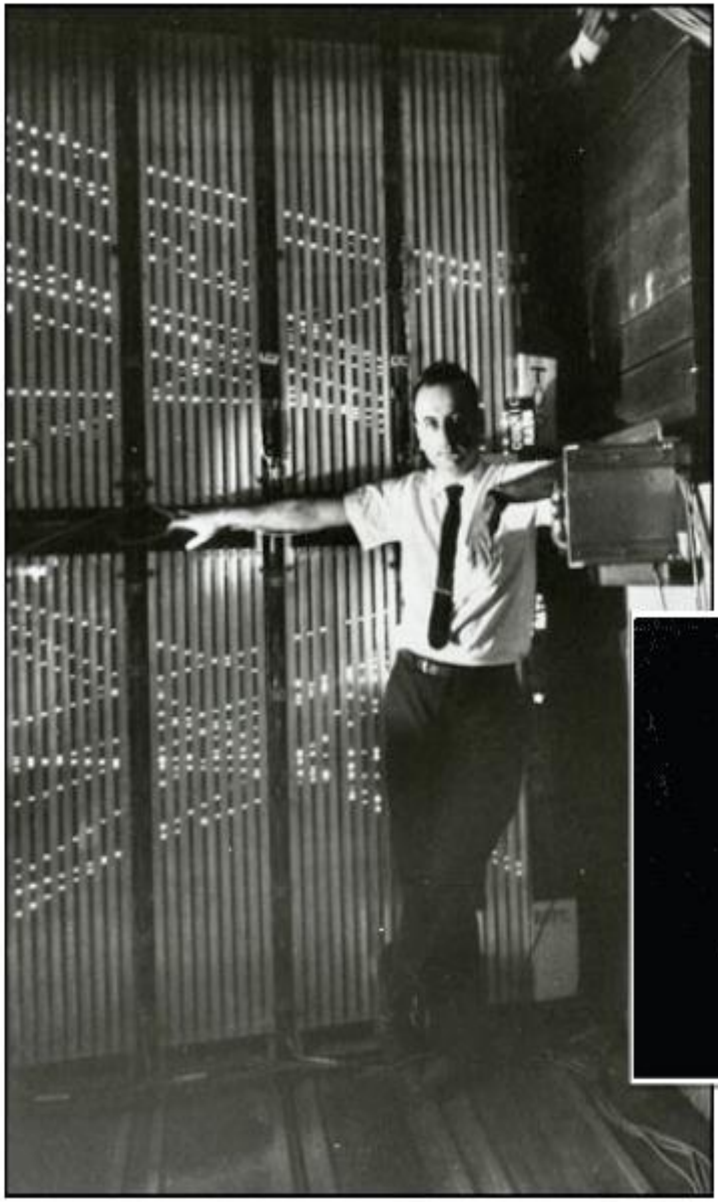


- In charged-current (CC) events outgoing lepton tags incoming neutrino flavor.
  - *In the case of ν_τ, the presence of a τ must be deduced from the τ decay products*
- In CC events nearly all the neutrino energy is deposited in the detector
- In neutral-current events, only hadrons are present and no information about the incident neutrino flavor is available
- CC rates are affected by oscillations
- NC rates are not affected by oscillations
  - *In only a few analyses are NC events considered to be signal. In most cases NC events are backgrounds to the CC processes*

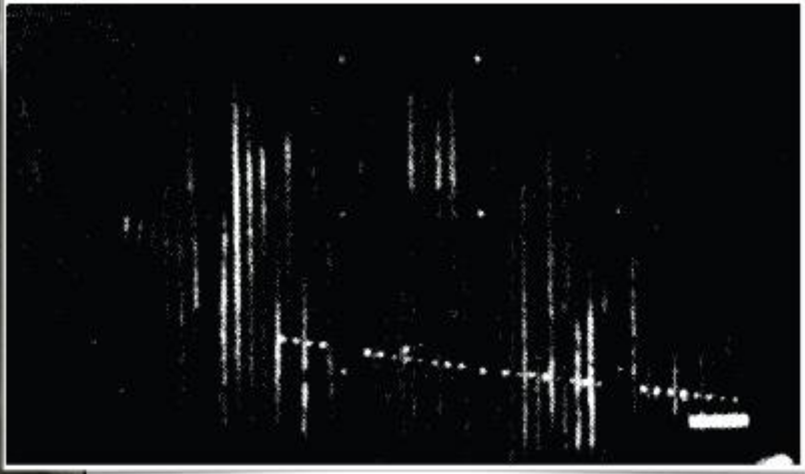
Discovery of the muon neutrino (1962)

Leon M. Lederman
Melvin Schwartz
Jack Steinberger

[Nobel prize 1988]

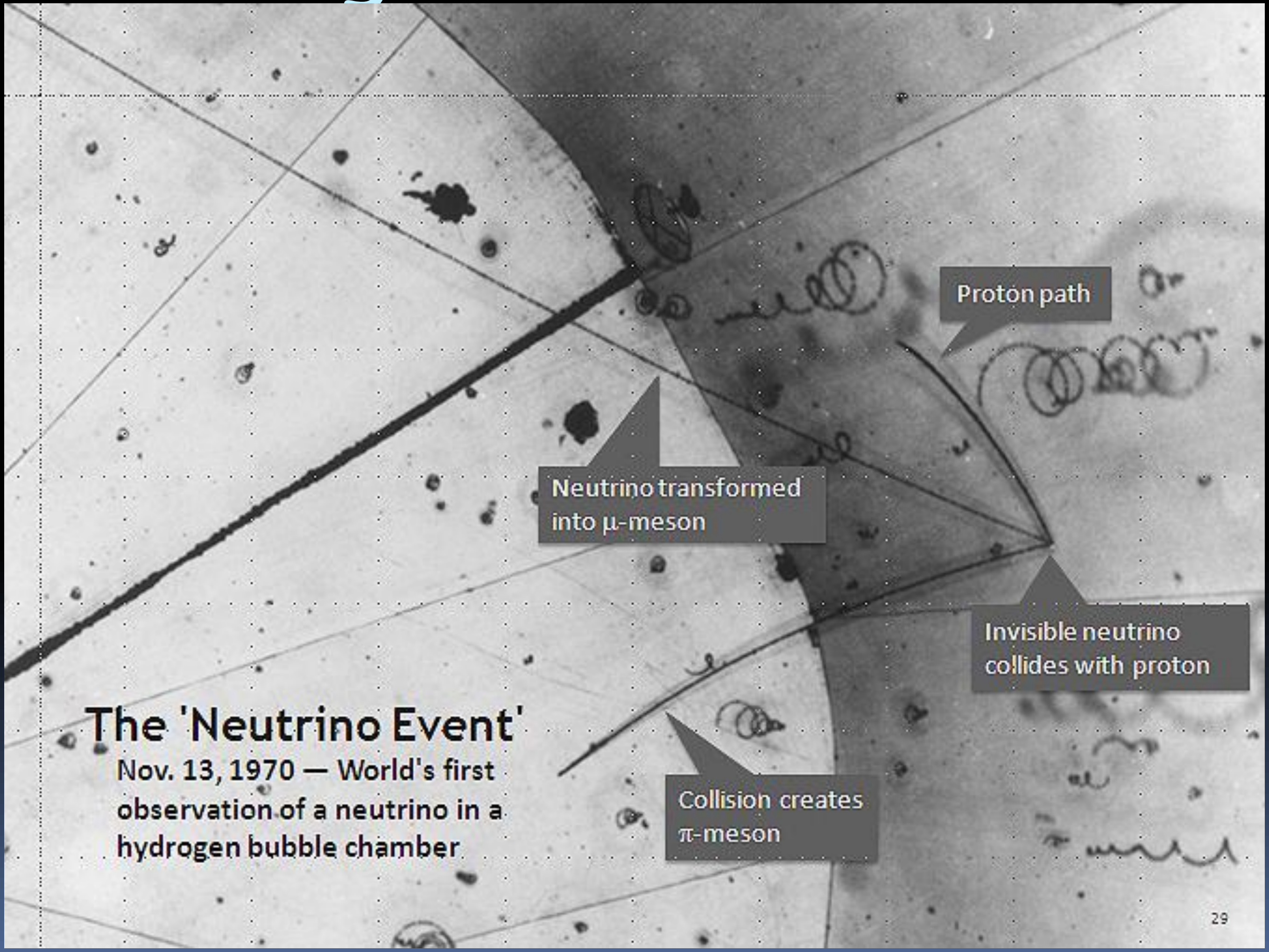


Melvin Schwartz in front of the spark chamber used to discover the muon neutrino

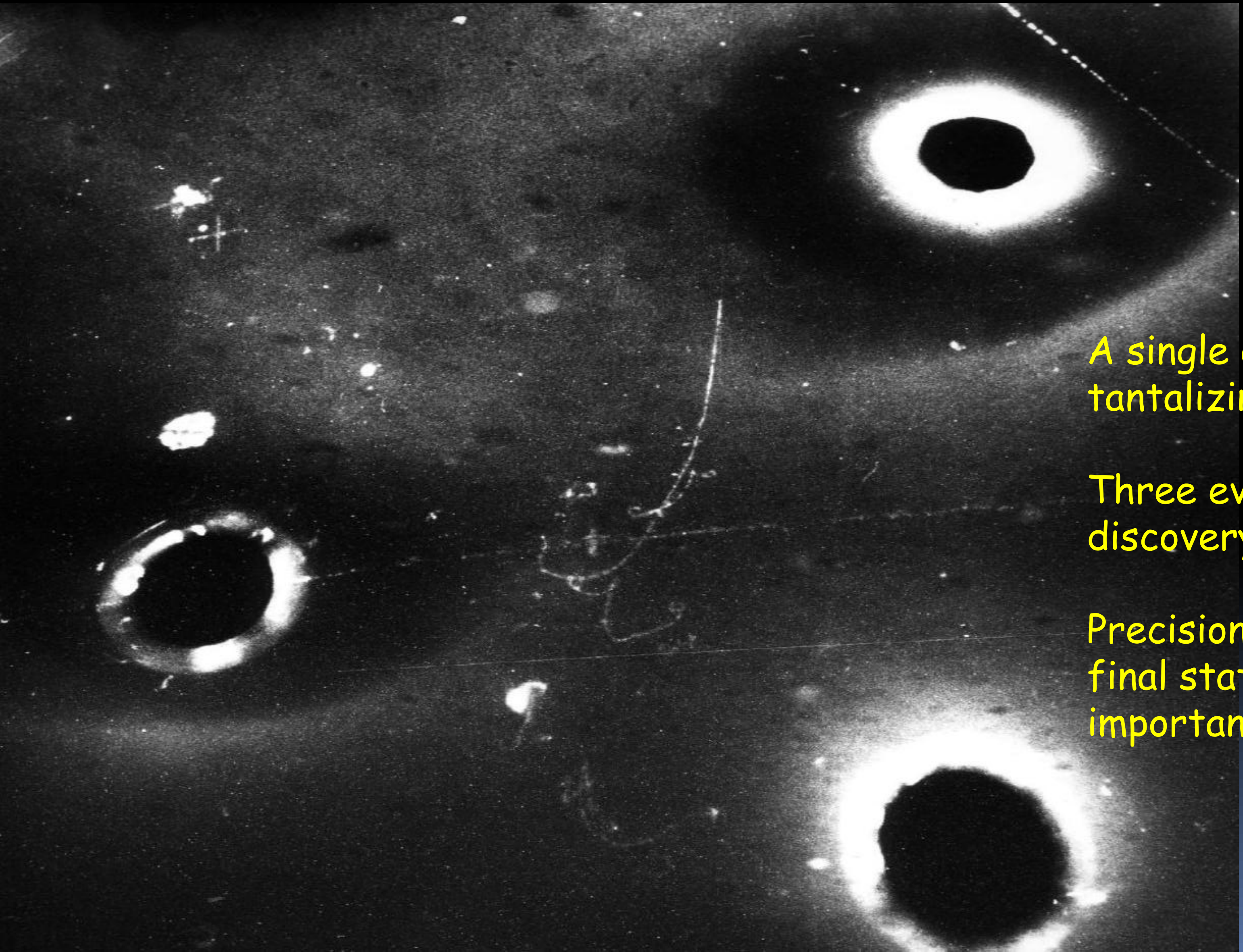


Single muon event from original publication

A Buble Chamber: Ultimate Tracking Detector



A Perfect Experiment: GGM at PS

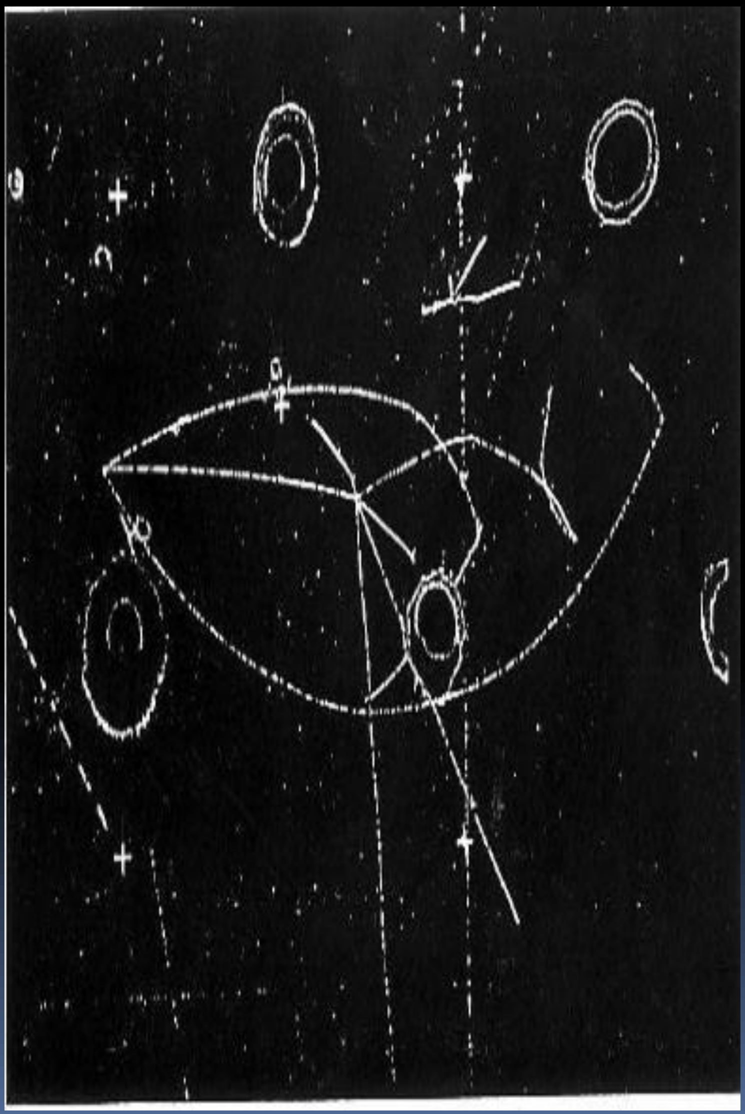


A single event a tantalizing hint.

Three events a major discovery

Precision view of the final state of critical importance.

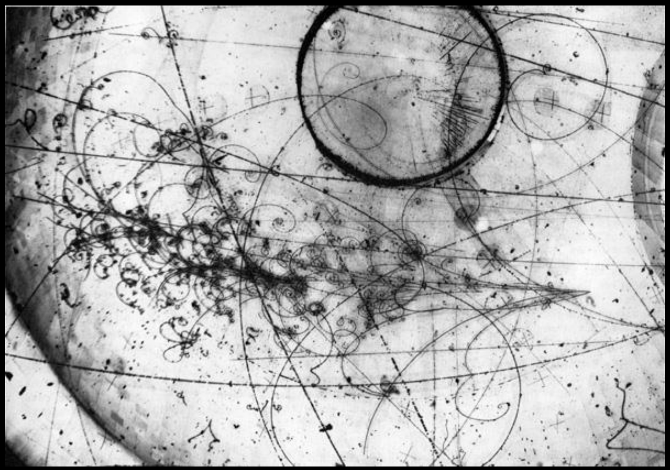
Difficult Experiment: Search for NC with GGM at PS



- Exquisite view of the final state.
- Clear interaction of a neutral particle with no muon or electron in the final state
- Neutrino or neutron?

- It is not detector alone which decides about the quality of the expriement. Beam and environment is an important factor too.

High Energy Neutrinos Era: Decline of the Bubble Chambers



Leakage of hadronic shower
Muon identification
Confusion caused by electromagnetic showers form pi-zeros

(typical) Detector Requirements

- Large volume (inexpensive, please)
- Identify the flavor of the neutrino (i.e. identify the charged lepton)
- Measure the total energy of the event (~ estimator of the neutrino energy)
- Provide some kinematical information about the event (direction of a hadronic jet)
- Determine the direction of the incoming neutrino

Quasi-elastic reconstruction $\nu_\mu + n \rightarrow \mu^- + p$

$$E_\nu = \frac{m_N E_l - m_l^2/2}{m_N - E_l + p_l cos\theta_l}$$

From 2 body kinematics

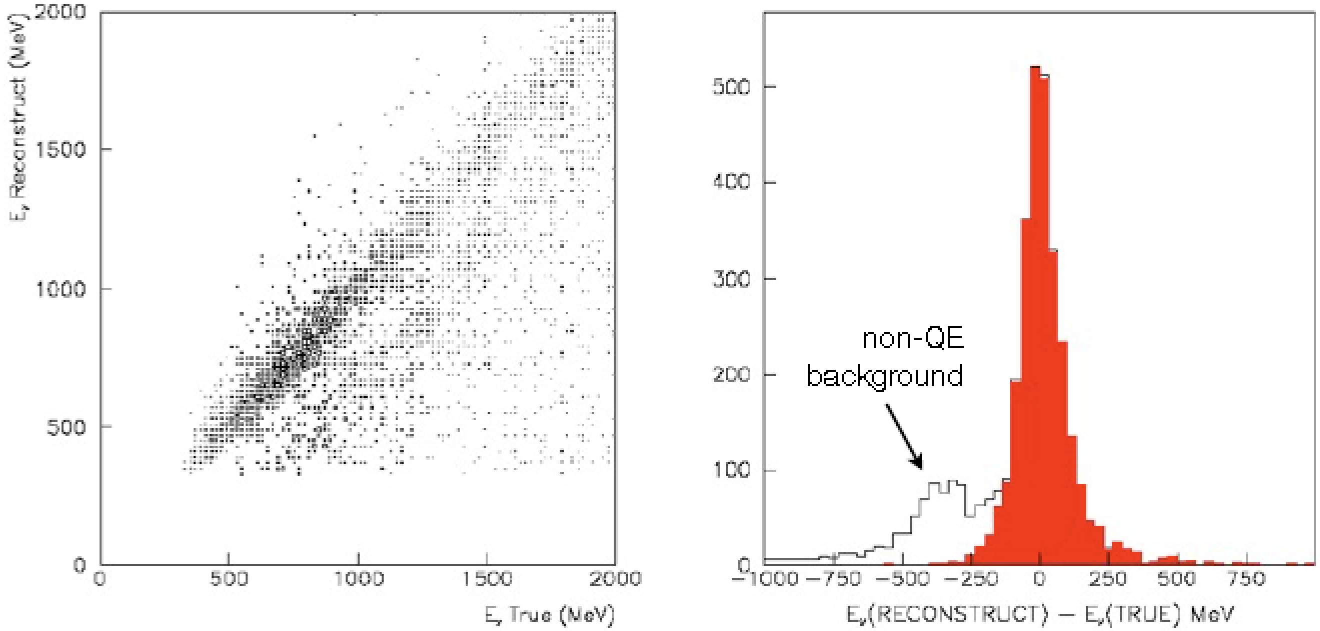
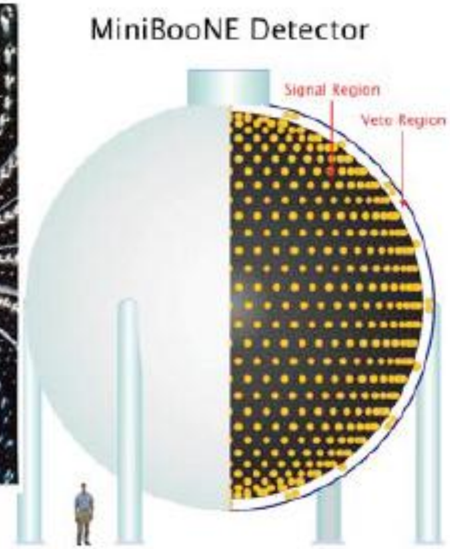
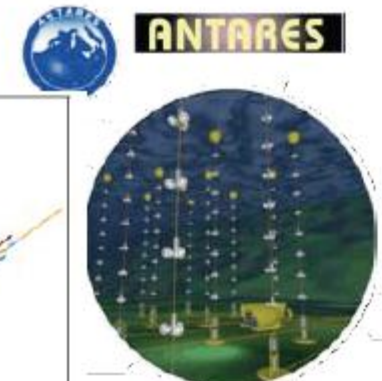
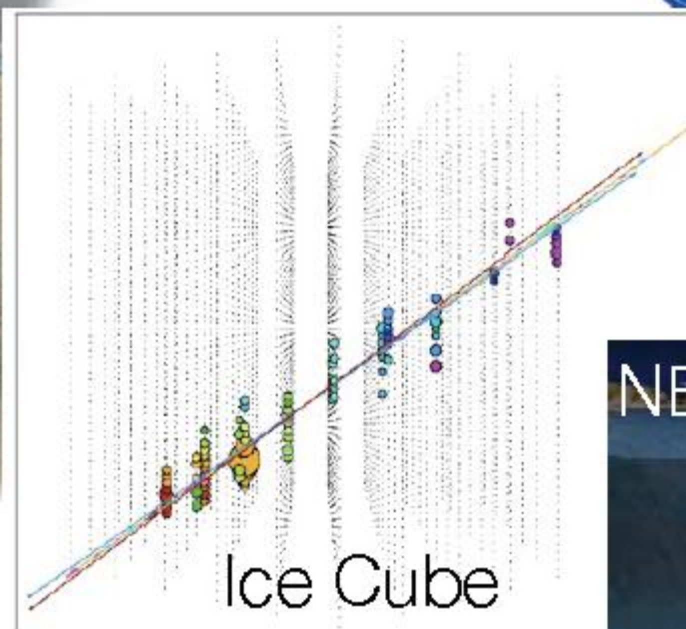


Figure 2: (left) The scatter plots of the reconstructed neutrino energy versus the true one for ν_μ events. The method of the energy reconstruction is expressed in Equation 14. (right) The energy resolution of ν_μ events for 2 degree off-axis beam. The shaded (red) histogram is for the true QE events.

Cherenkov detectors



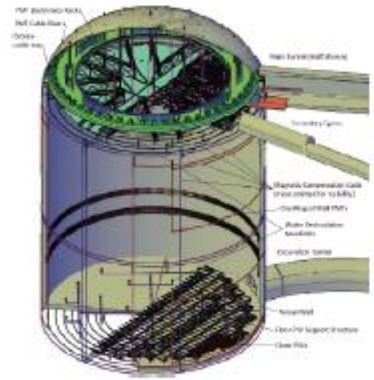


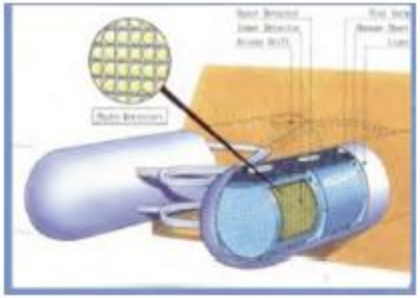


Why Take This Approach?

- **Large Size:** for rare events, low fluxes
- **Low Threshold:** 3 MeV with high efficiency
- **Excellent e/μ** >99% ν_μ rejection in T2K ν_e data
- **Low cost/kton**
- **Free protons**
- **Mature technology:** short development time
- **Safety, Maintenance, Accessibility**

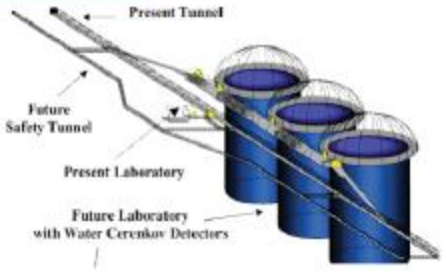
LBNE



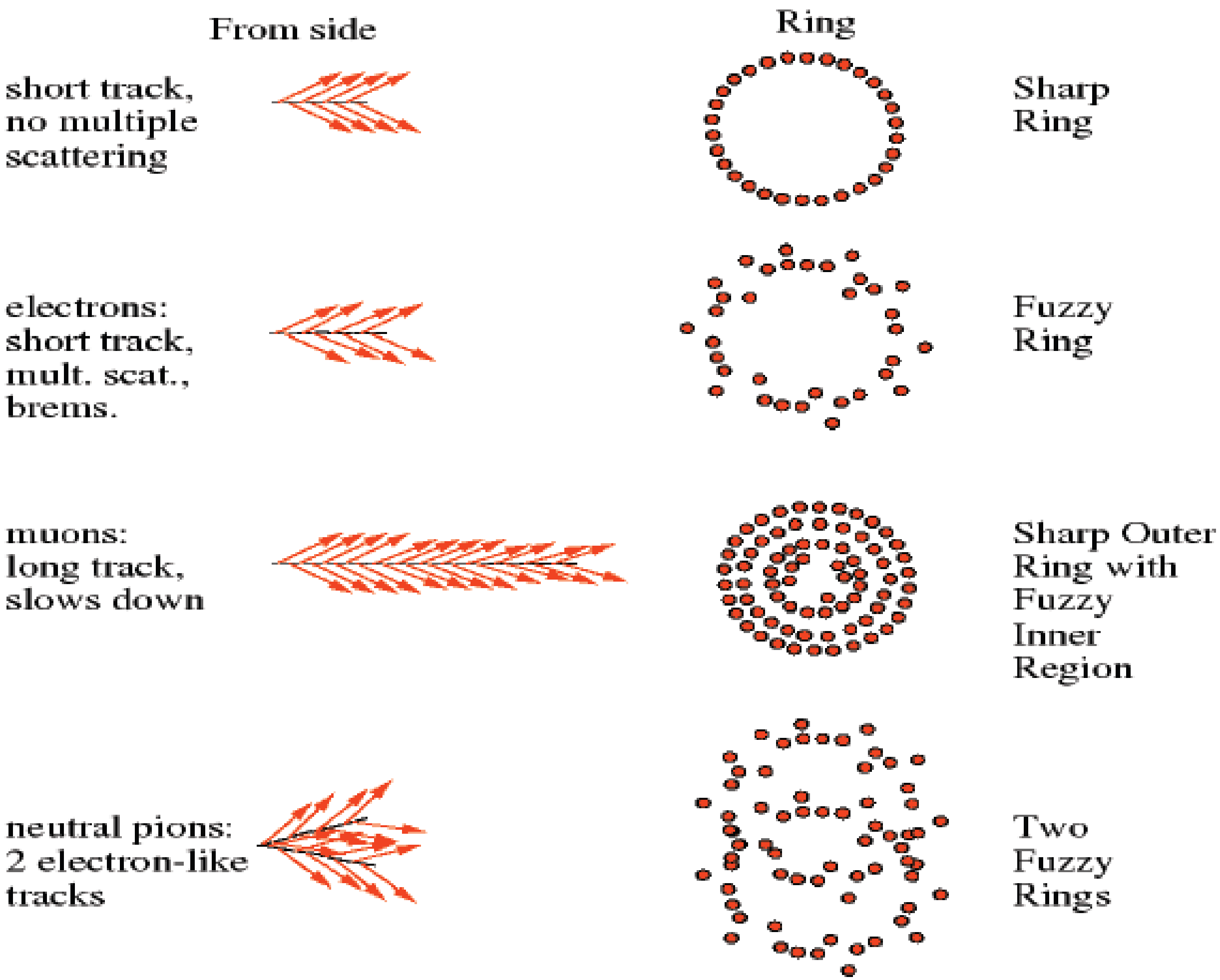


HYPER-K

MEMPHYS

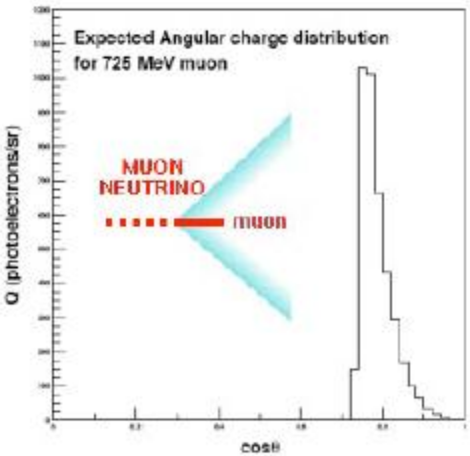


Particle ID Using Cerenkov Light

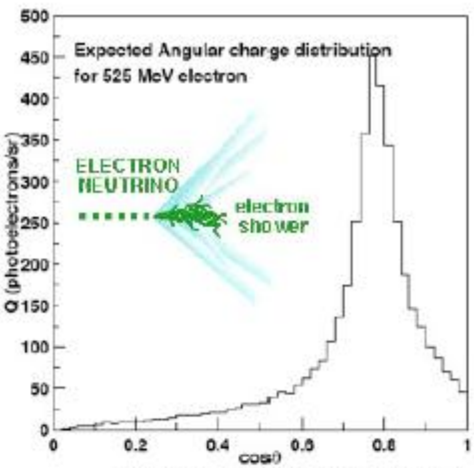


Water Cherenkov: e/μ identification

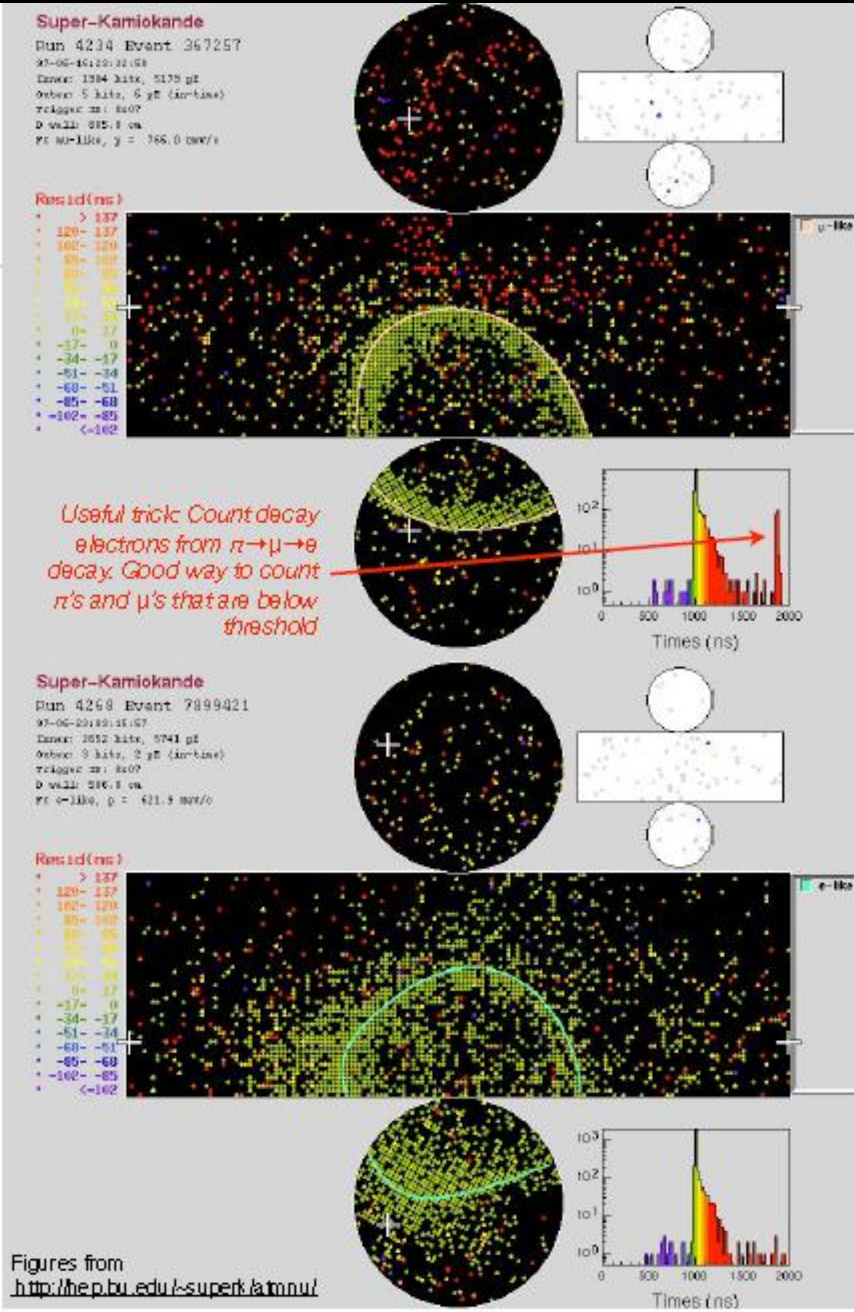
- At low momenta one can correlate the particle visible energy with the Cherenkov angle. Muons will have "collapsed" rings while electrons are ~always at 42°.



- At higher momenta, look at the distribution of light around Cherenkov angle. Muons are "crisp", electron showers are "fuzzy". See plots and figures at the right.

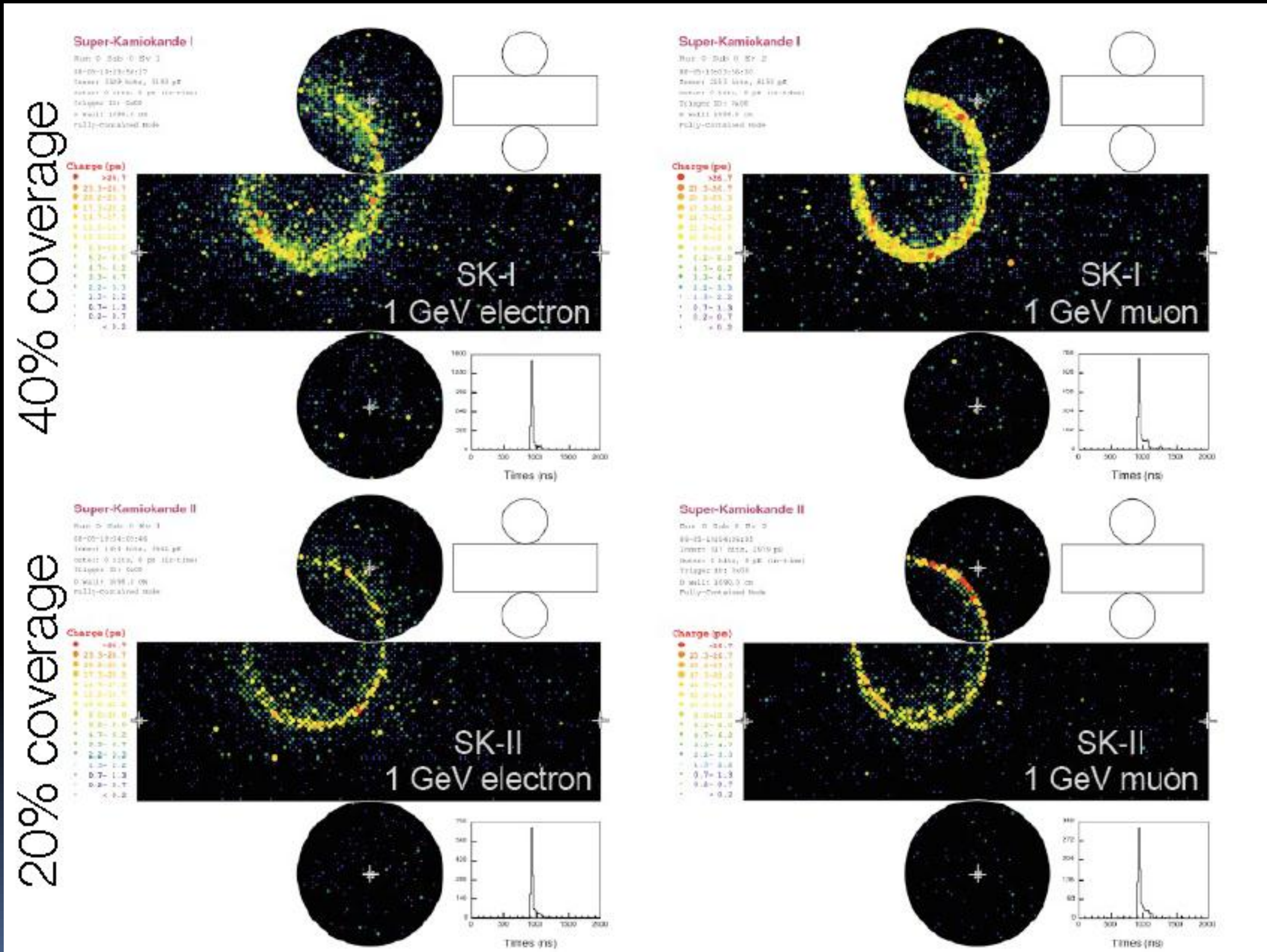


Figures from M. Earl's PhD Thesis



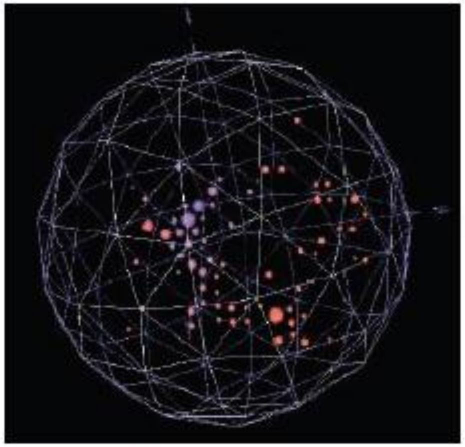
Figures from http://hep.bu.edu/~superk/atmnu/

Tuesday, July 7, 2009

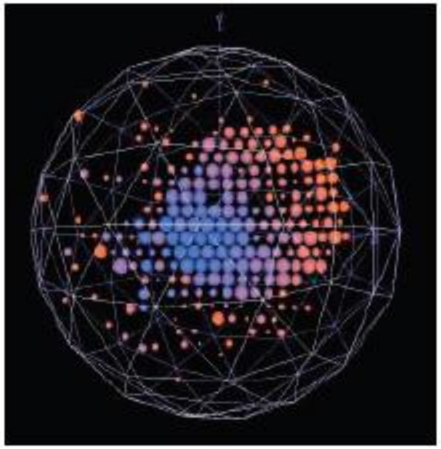

40% coverage
20% coverage
Super-Kamiokande I
SK-I
1 GeV electron
Super-Kamiokande I
SK-I
1 GeV muon
Super-Kamiokande II
SK-II
1 GeV electron
Super-Kamiokande II
SK-II
1 GeV muon
Charge (pe)
Times (ns)

MiniBoone

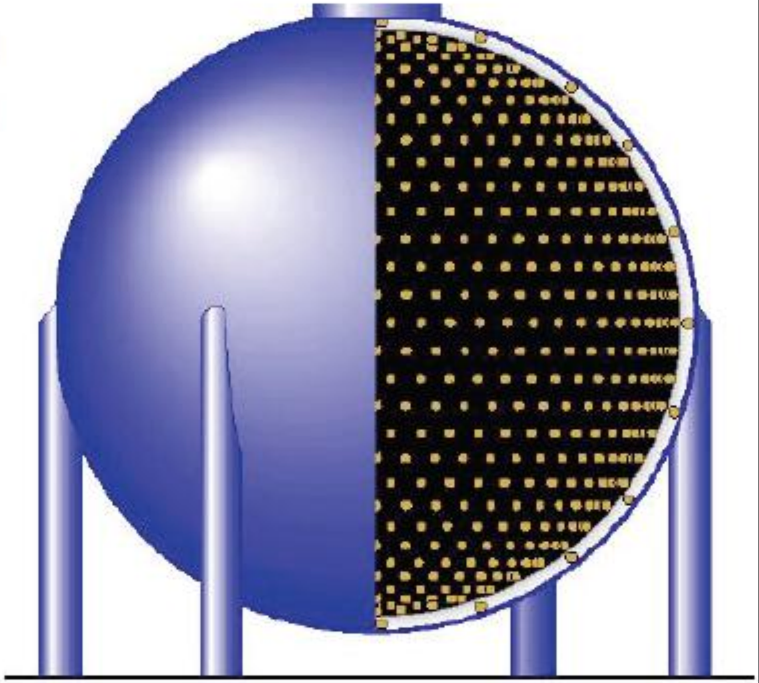
total volume: 800 tons (6 m radius)
fiducial volume: 445 tons (5m radius)
1280 PMTs in detector at 5.5 m radius
10% photocathode coverage
240 PMTs in veto



electron ring

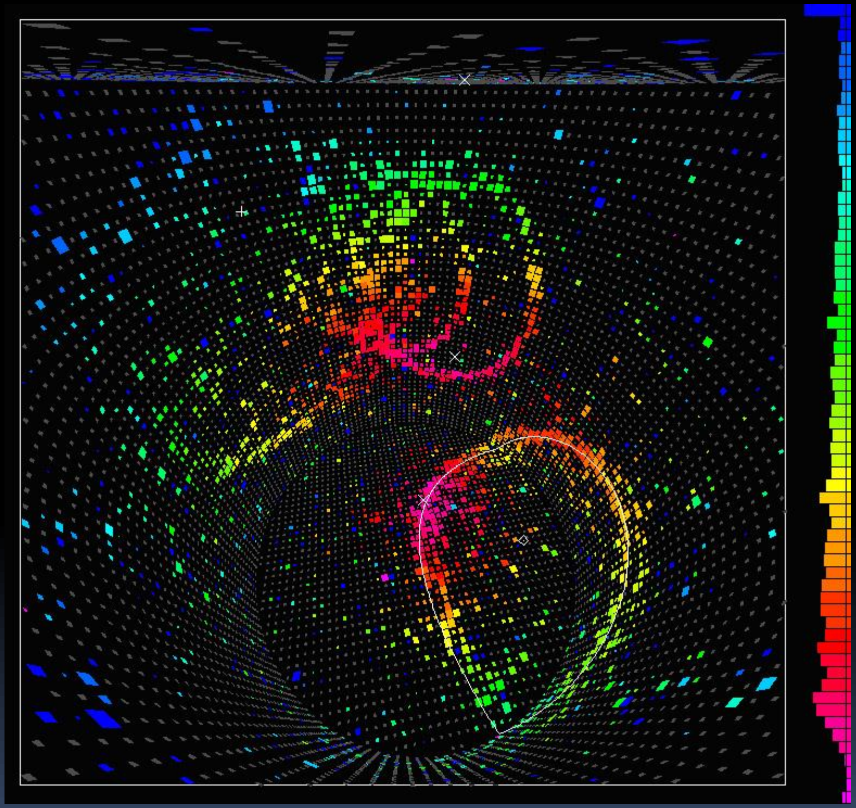


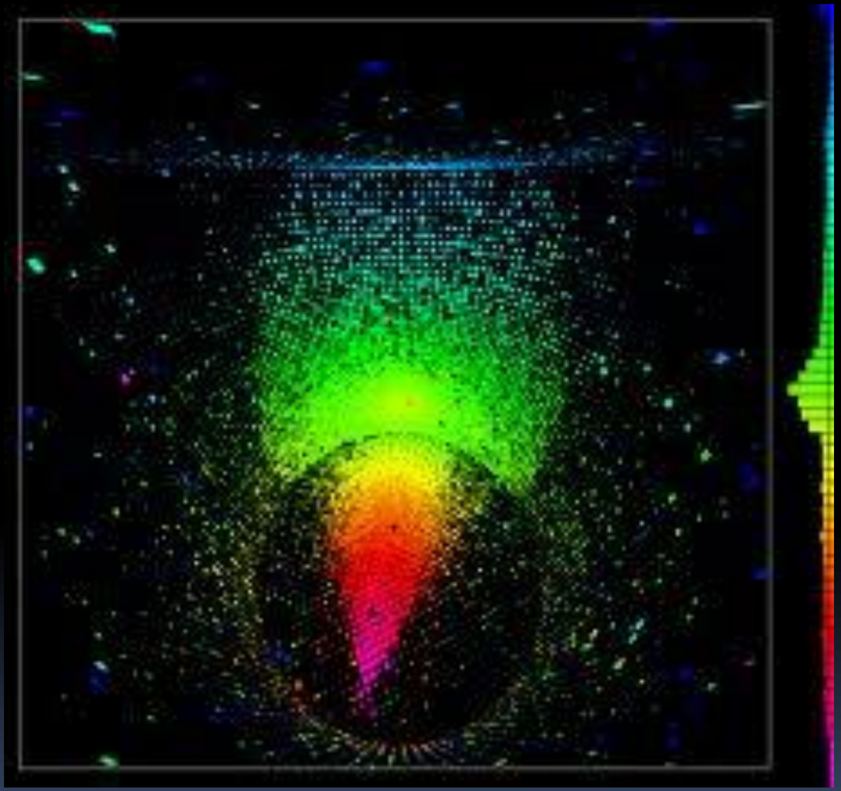
μ ring



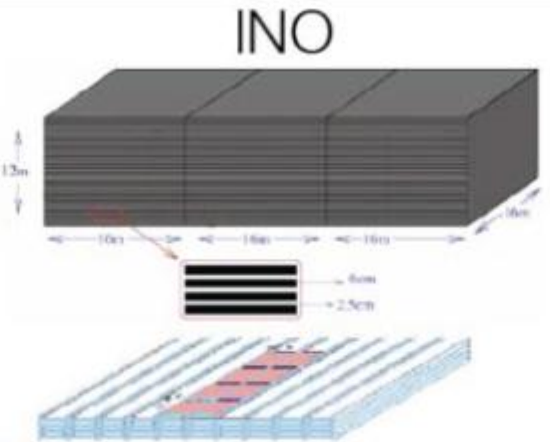
Events courtesy G. Zeller

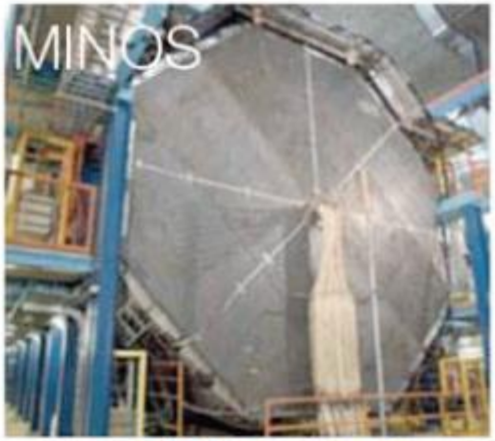
Challenges of High Energies

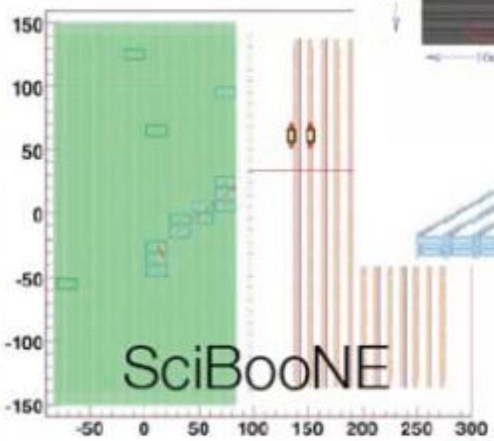


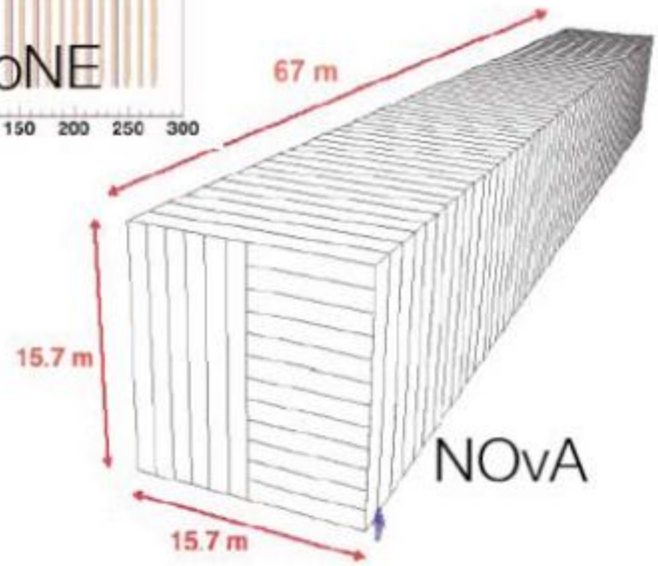


Tracking Calorimeters









CHARM: marble – drift tubes

CDHS(W): magnetized iron-scintillator calorimeter

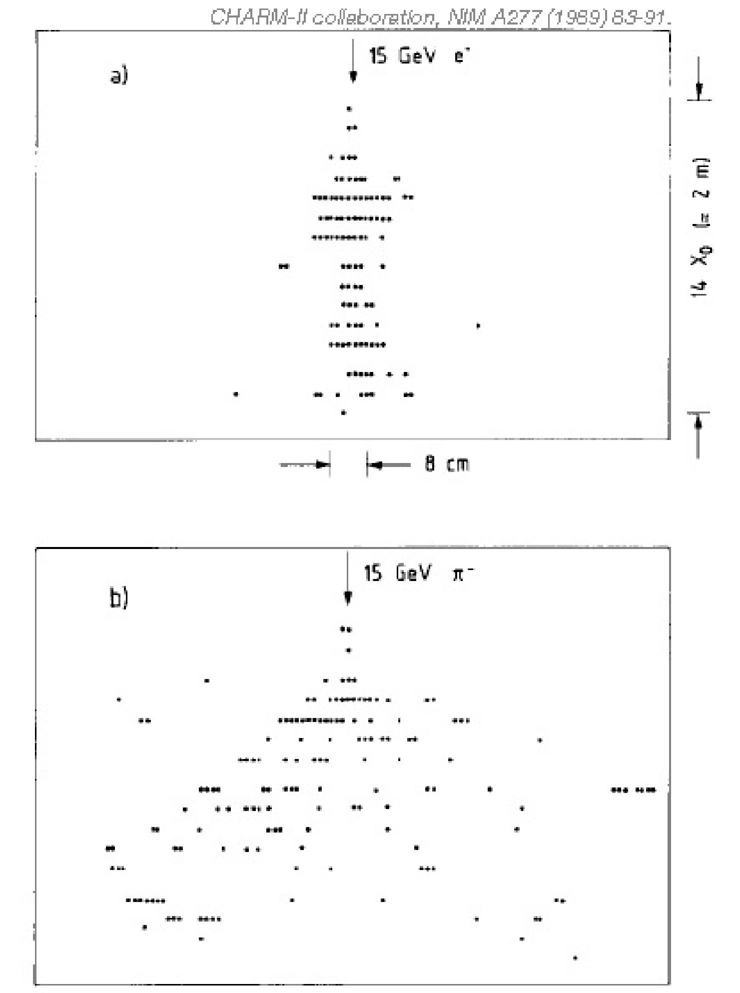
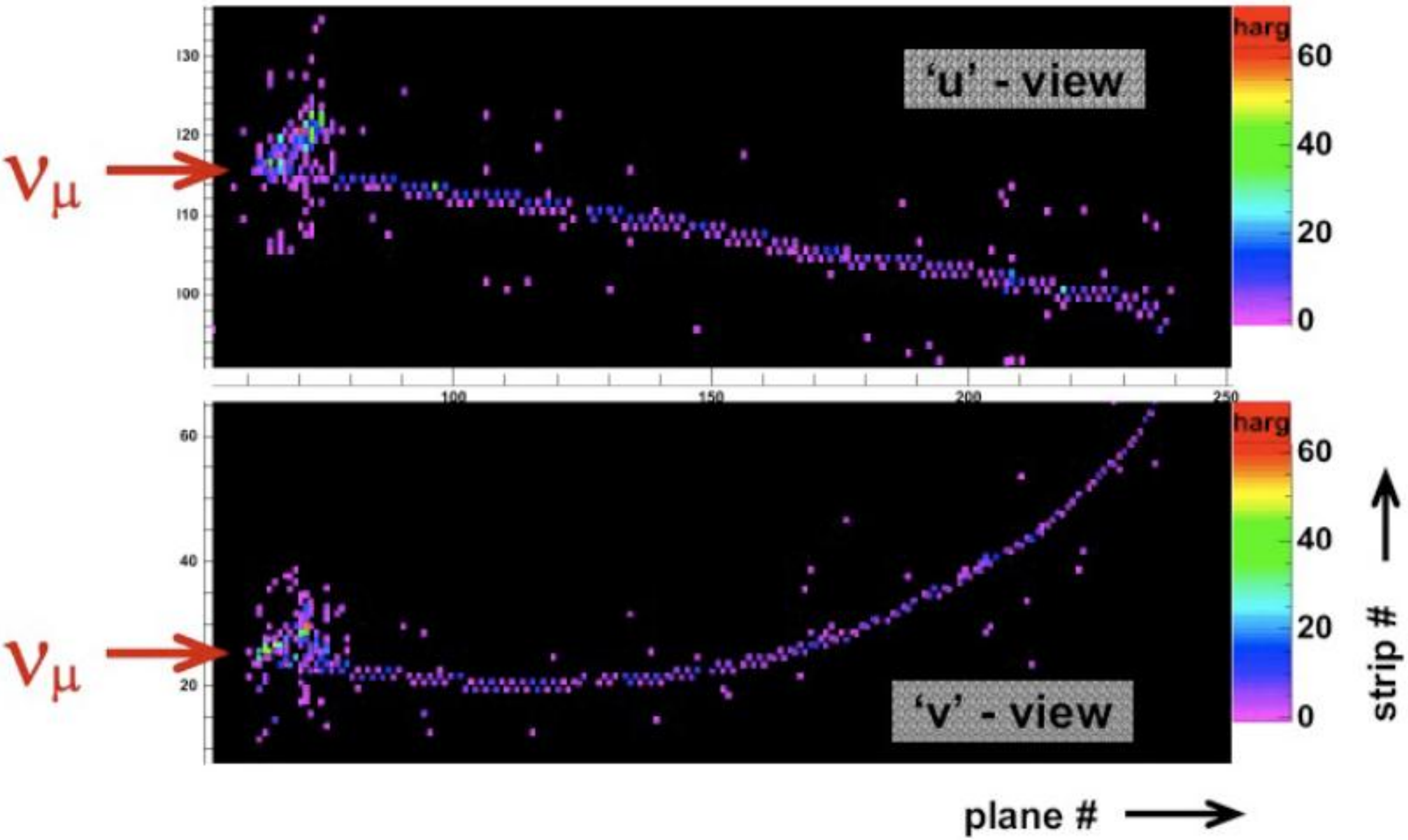
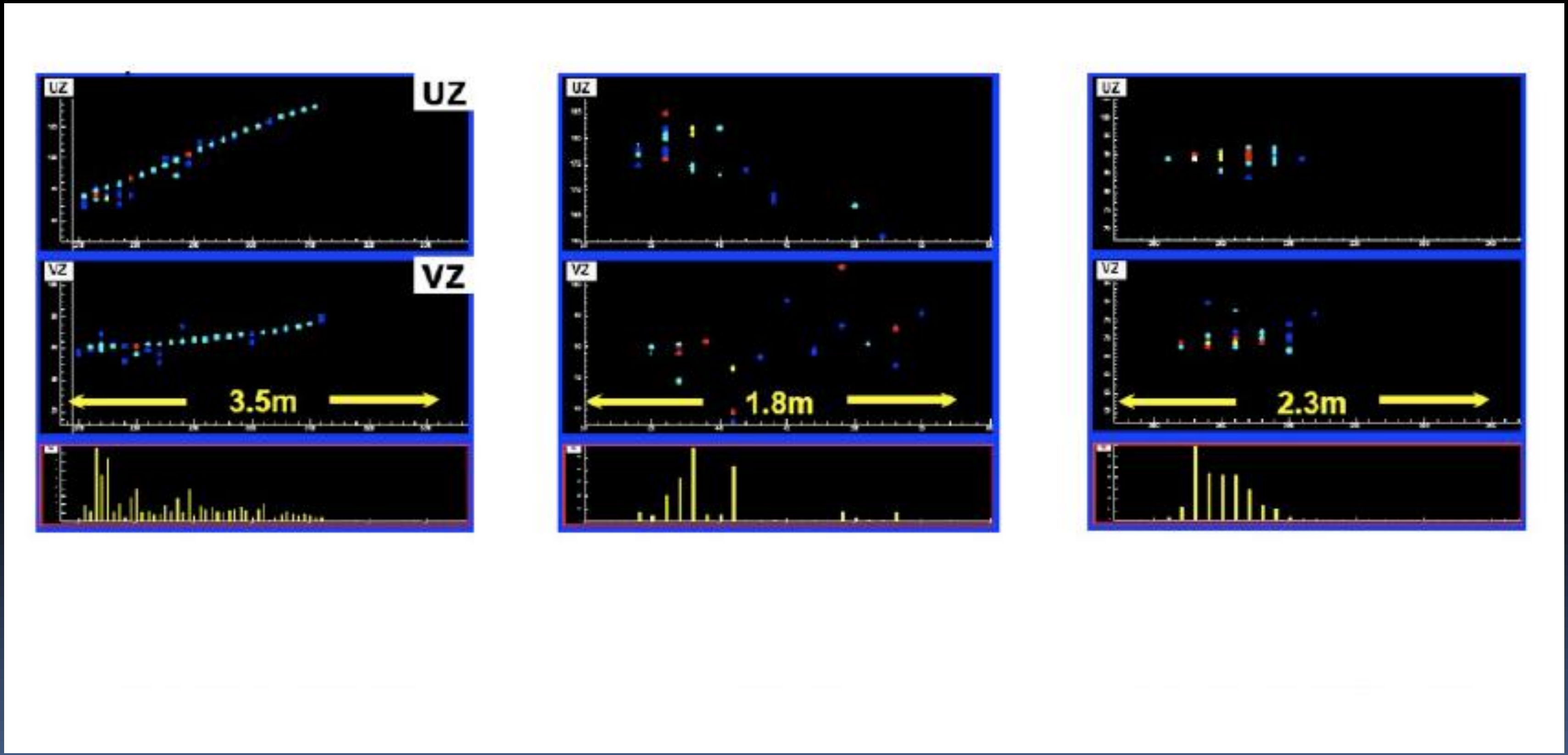


Fig. 13. Pattern of tube hits for two typical events: (a) electron-induced, (b) pion-induced.

MINOS Event



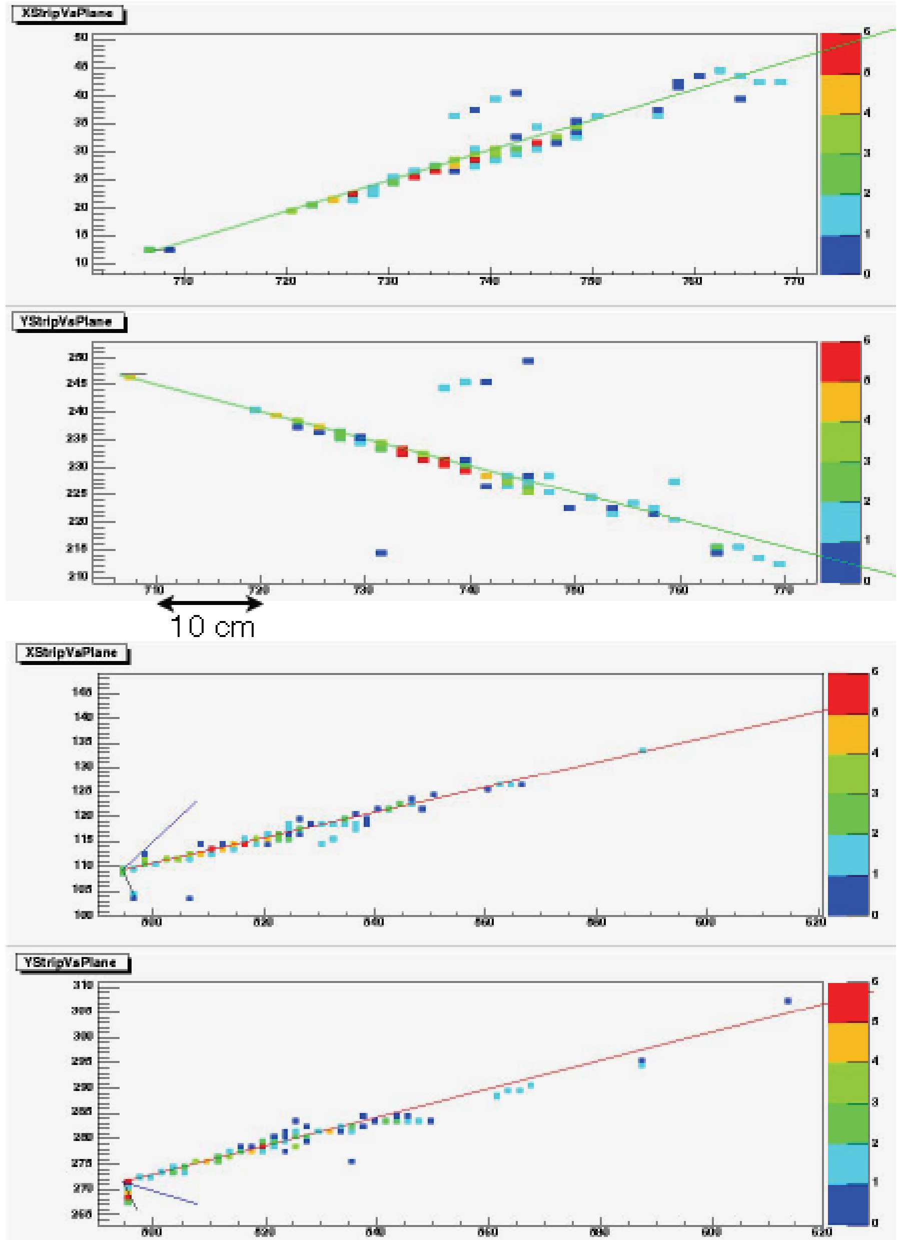
Interactions Classification with Iron-Scintillator Tracking Calorimeter (MINOS)



The Ultimate Tracking Calorimeter

- Fully active
- Good energy resolution
- Excellent electron identification
- Good electron-pizero rejection

Sample signal and background events in NOvA



$\nu_\mu N \rightarrow \nu_\mu p \pi^0$

E_ν=10.6 GeV

E_p=1.04GeV

$E_{\pi 0}$ =1.97GeV

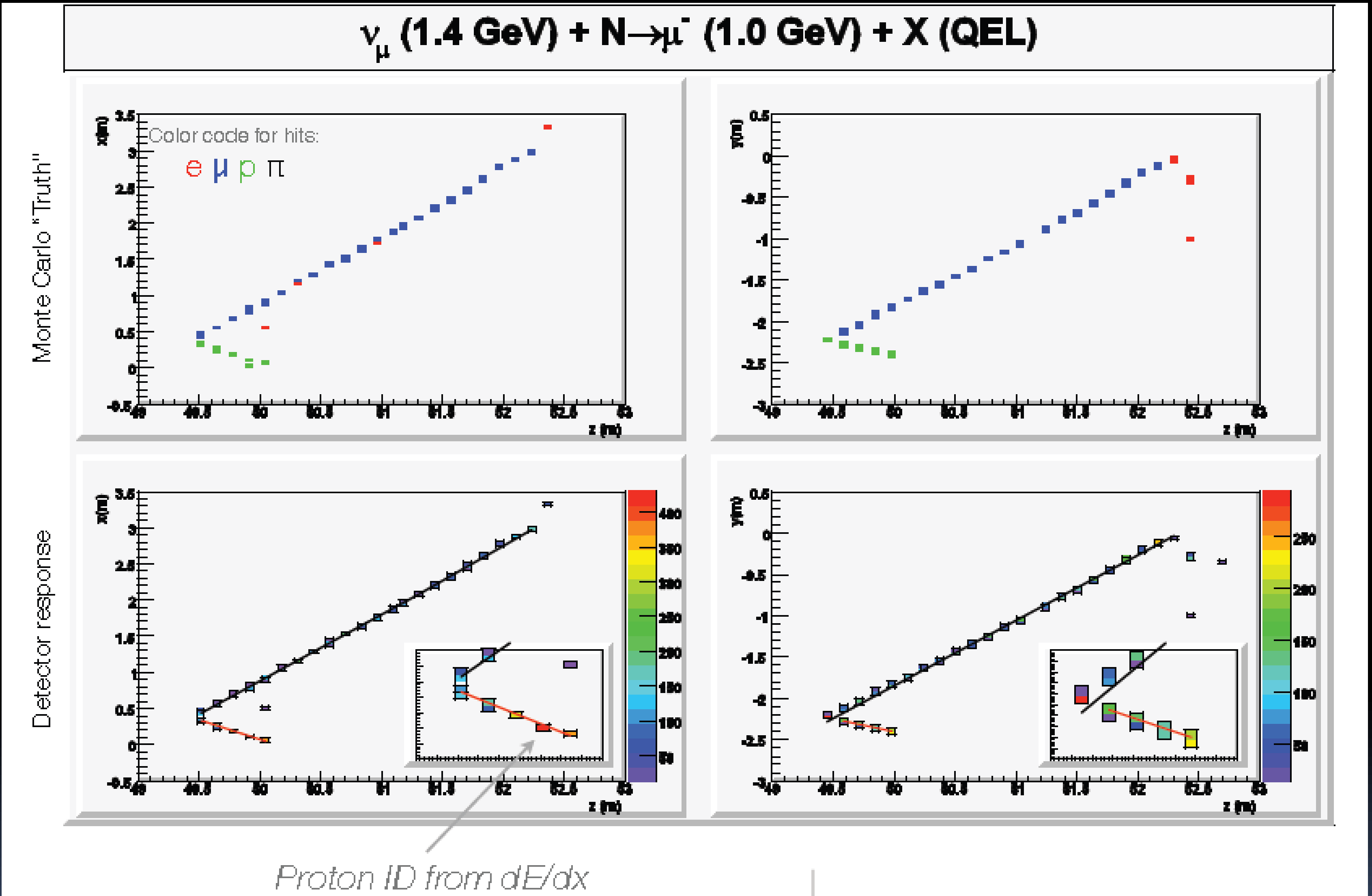
$\nu_e p \rightarrow e^- p \pi^+$

E_ν=2.5GeV

E_e=1.9GeV

E_p=1.1GeV

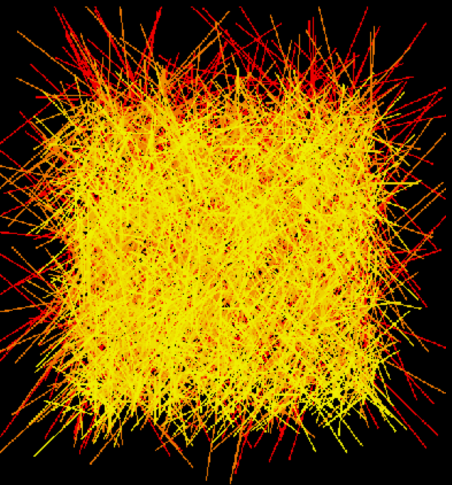
E_π=0.2GeV

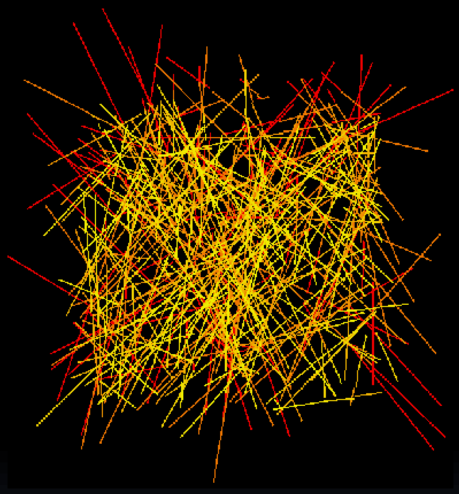


ν_μ Quasi-Elastic Event

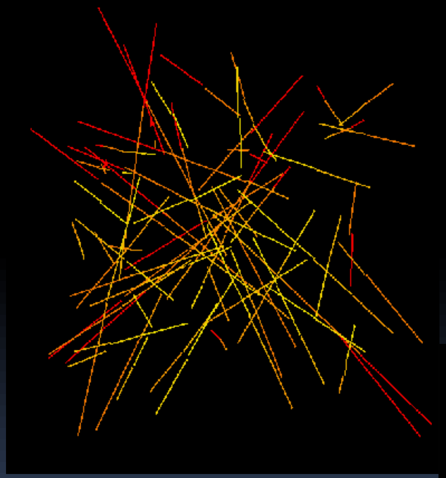
Searching for tau neutrinos

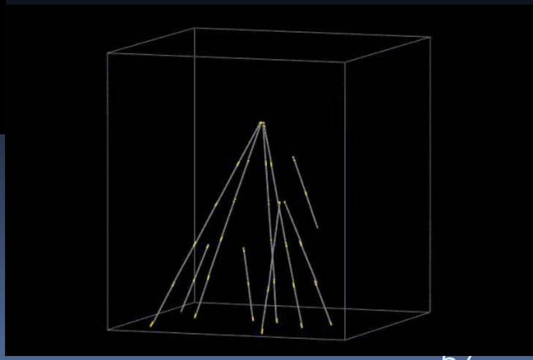
With Nuclear Emulsions



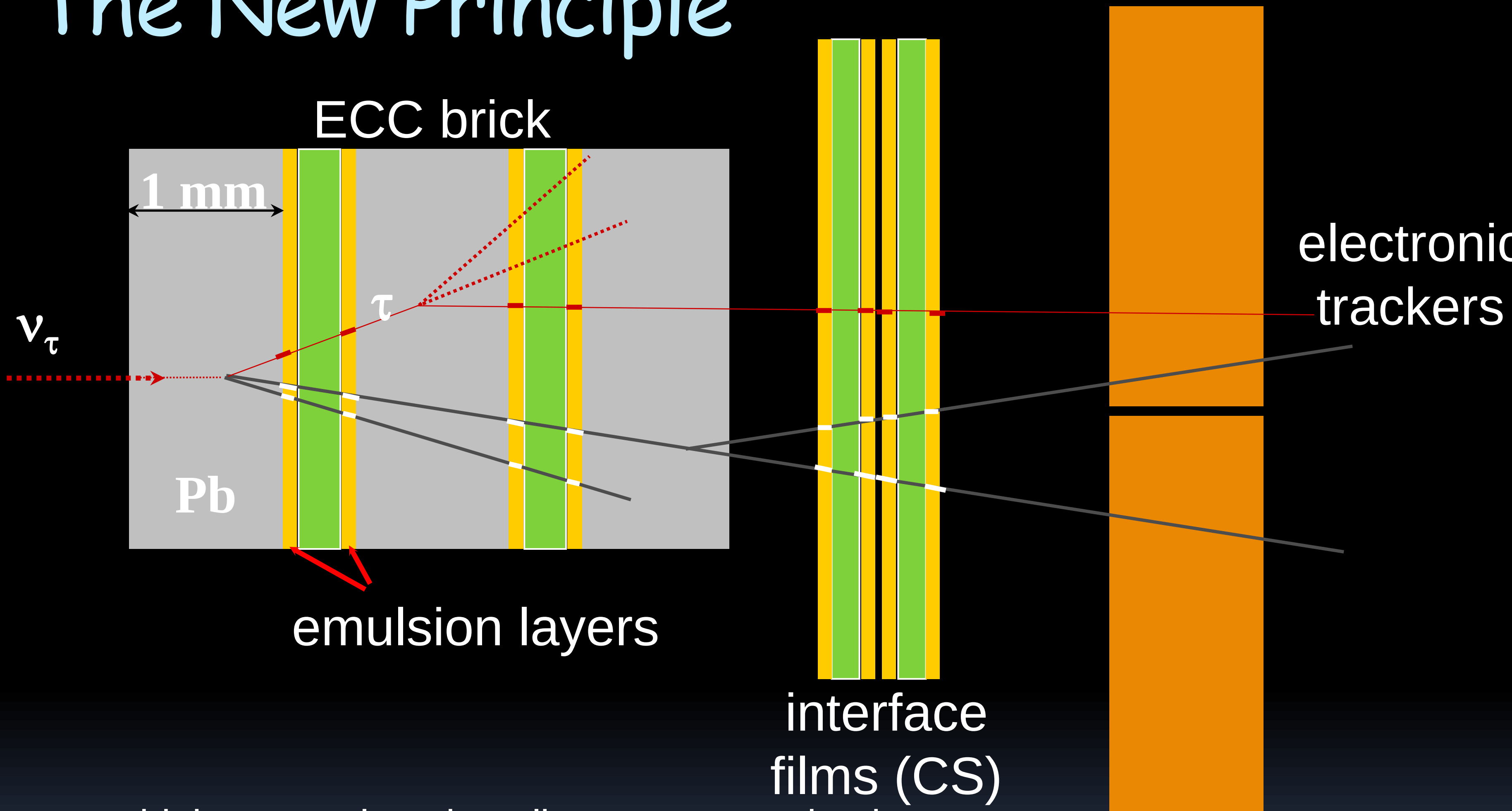


Exquisite spatial resolution and granularity



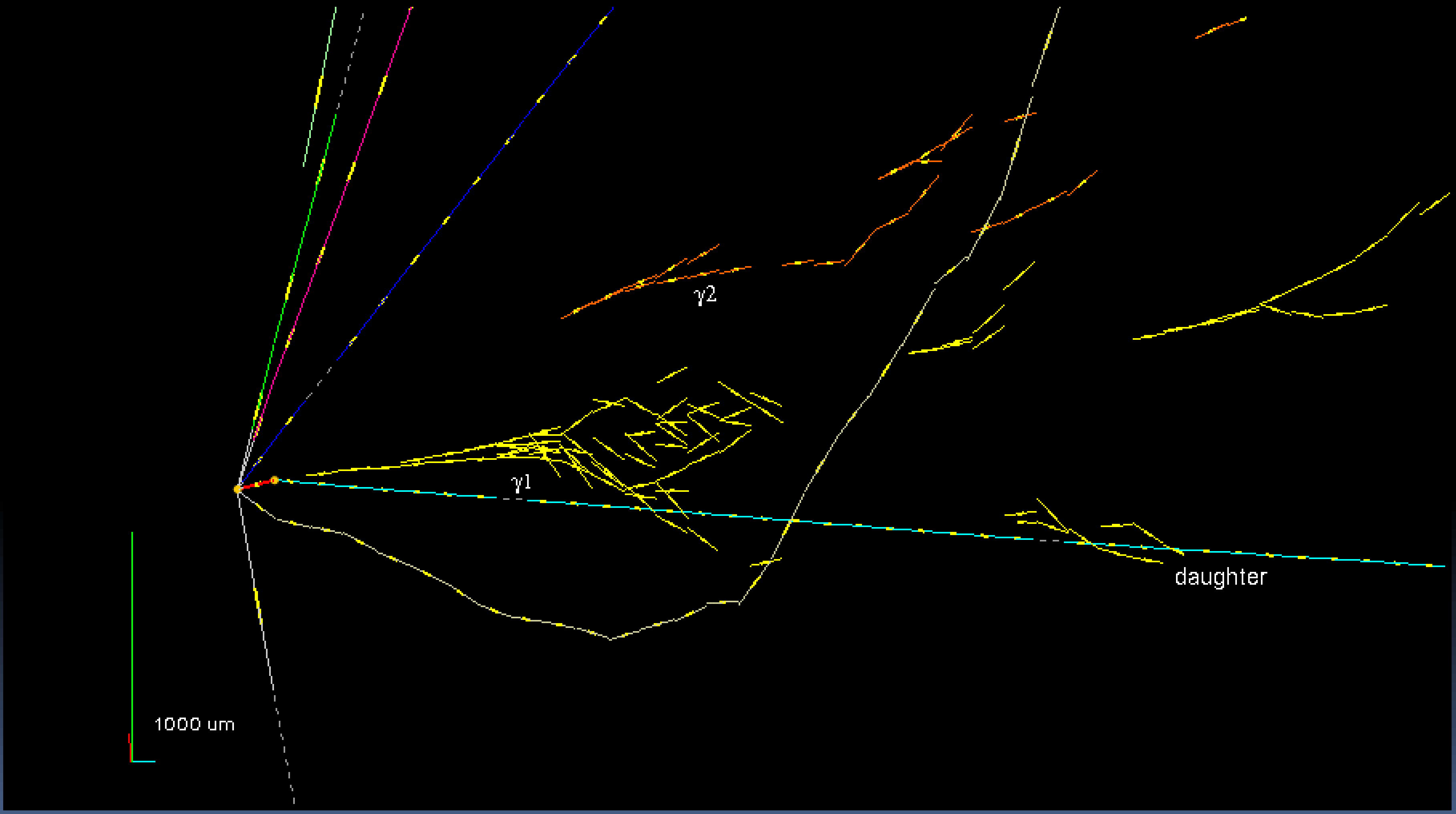


The New Principle

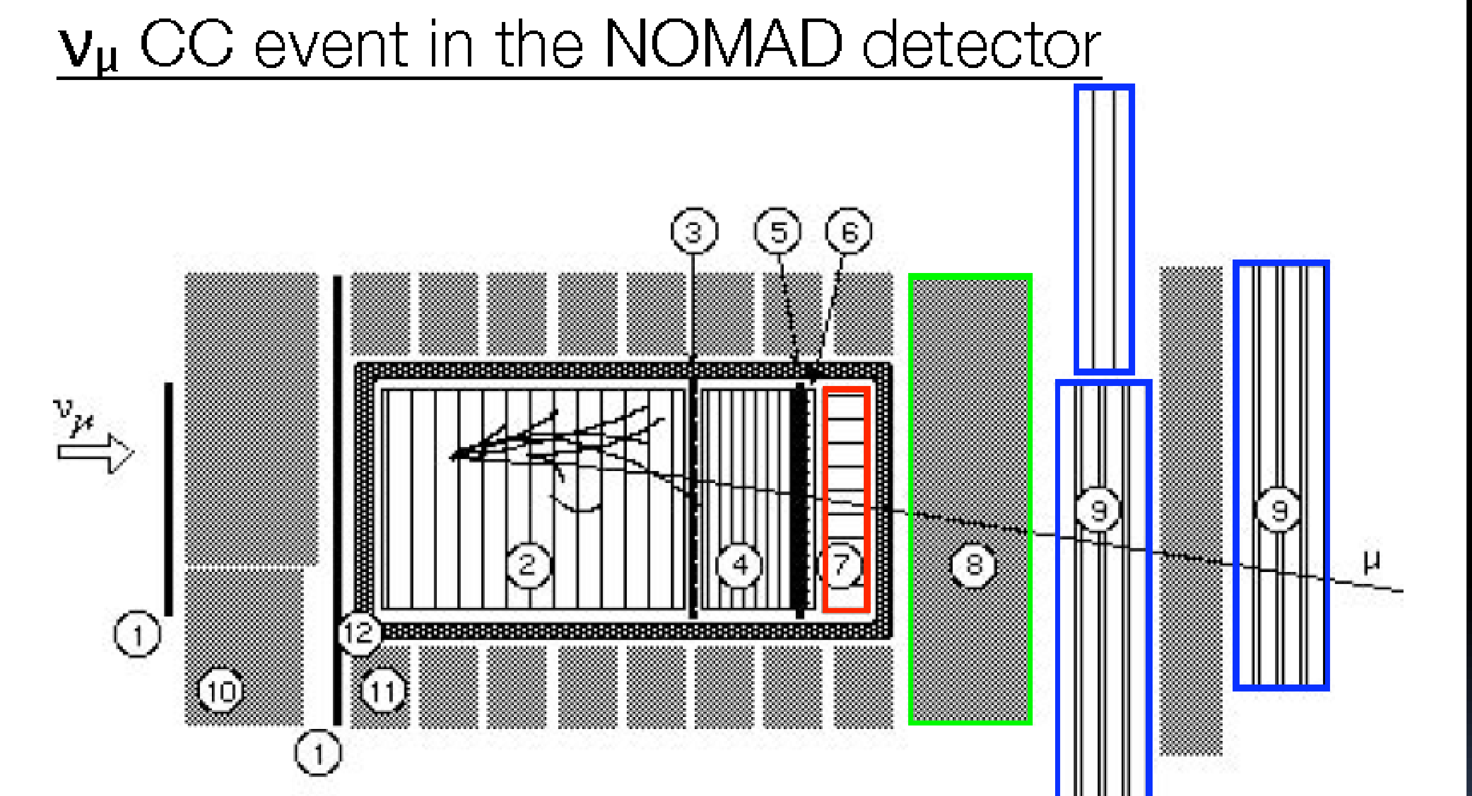


- Intense, high-energy long baseline muon-neutrino beam
- Massive active target with micrometric space resolution
- Detect tau-lepton production and decay
- Underground location
- Use electronic detectors to provide “time resolution” to the emulsions and preselect the interaction region

Proof of the Pudding

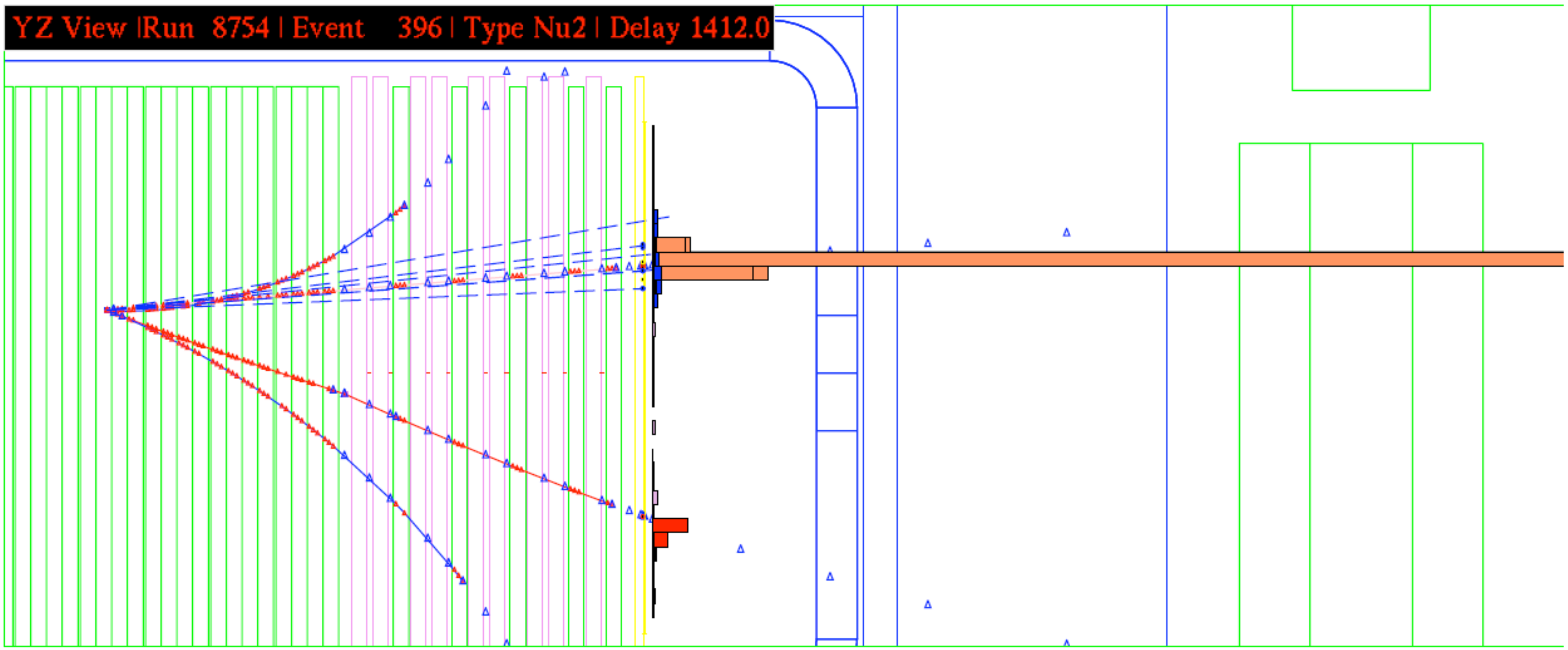


An Alternative Approach: Kinematical Reconstruction



(1) Veto wall
(2) Drift chambers
(3) Trigger plane
(4) Transition radiation tracker
(5) Trigger plane
(6) Preshower region
(7) Electromagnetic calorimeter
(8) Hadron calorimeter
(9) Muon tracking
(10) Forward calorimeter
(11) Magnet return yoke
(12) Magnet

A $\bar{\nu}_e$ CC candidate in NOMAD



NOMAD's Search of $\nu_\mu \twoheadrightarrow \nu_\tau$

* *Understanding the Control-samples*
  * Data-simulator technique: Control-Data/MC provide the calibration
  * x2 more hits along Z-axis (No τ +)

* *Completely blind analysis*
  * Divide search into Low- and High-background regions

* *Multivariate analysis: Pt-balance, track-reconstruction, missing-particles*

* *Improved 4π μ-ID*
  * 4π-Coverage: min-$P_\mu \twoheadrightarrow$ 0.3 GeV

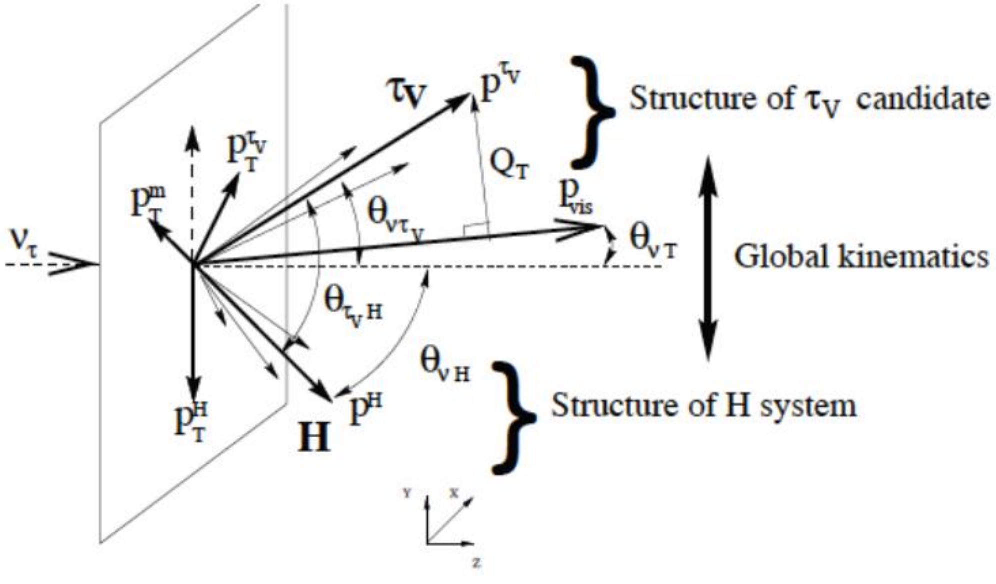
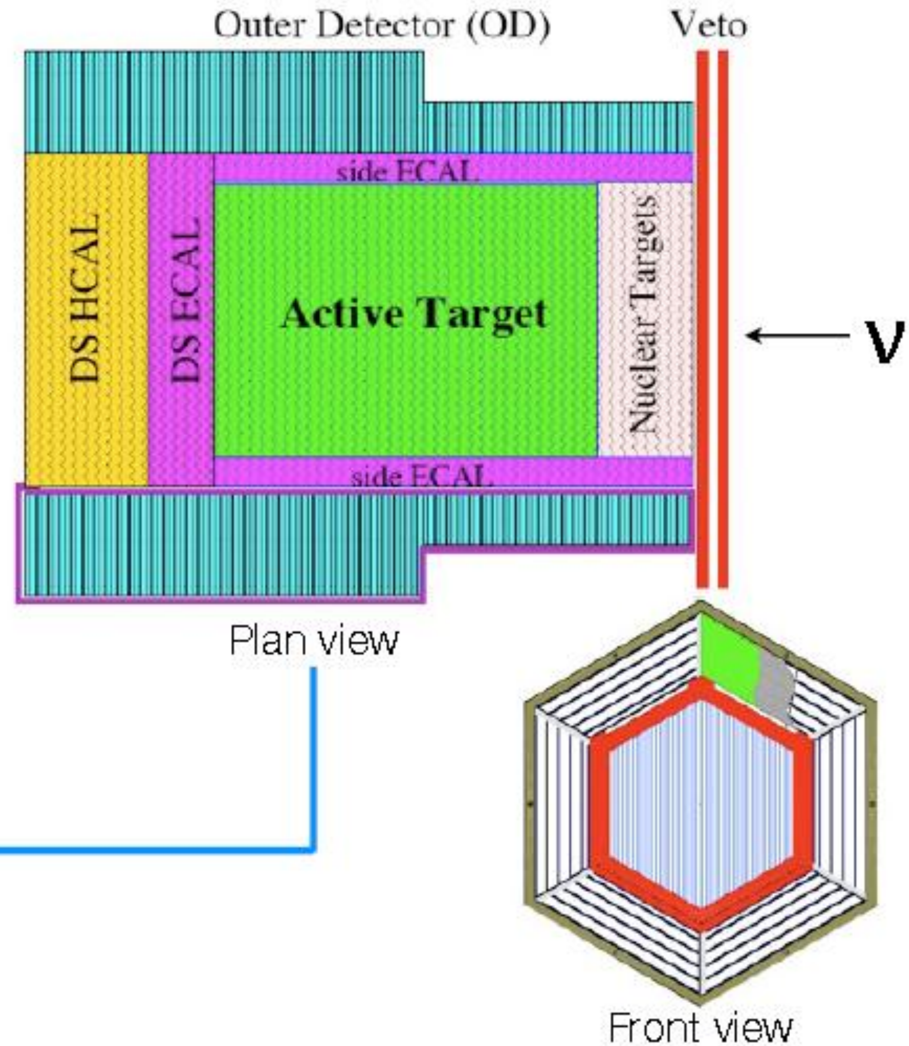


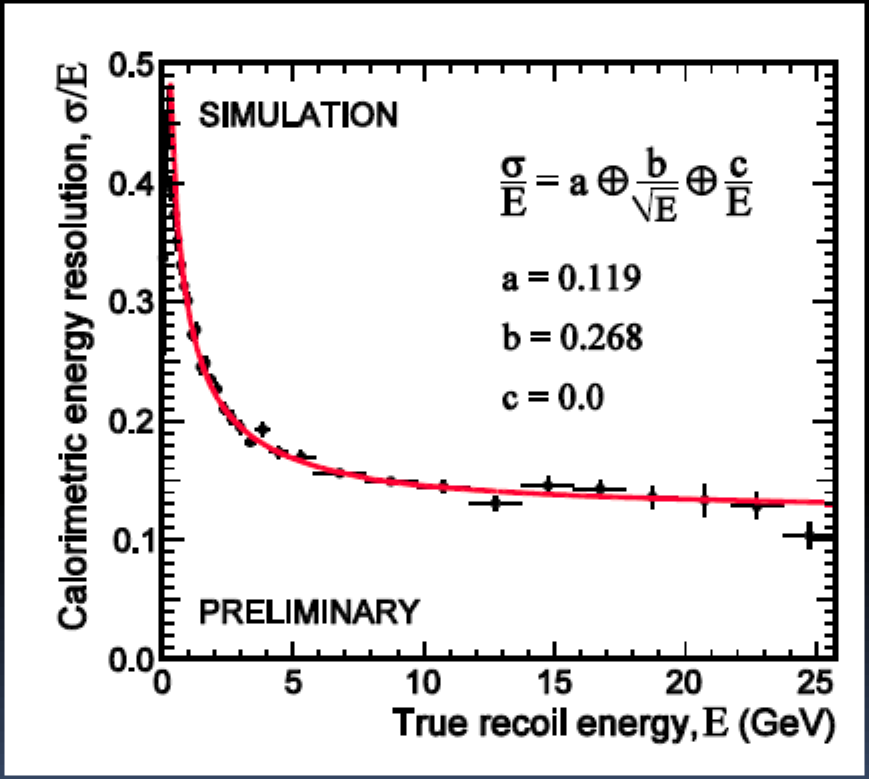
Fig. A.1. Definition of the NOMAD kinematics for a ν_τ CC event.

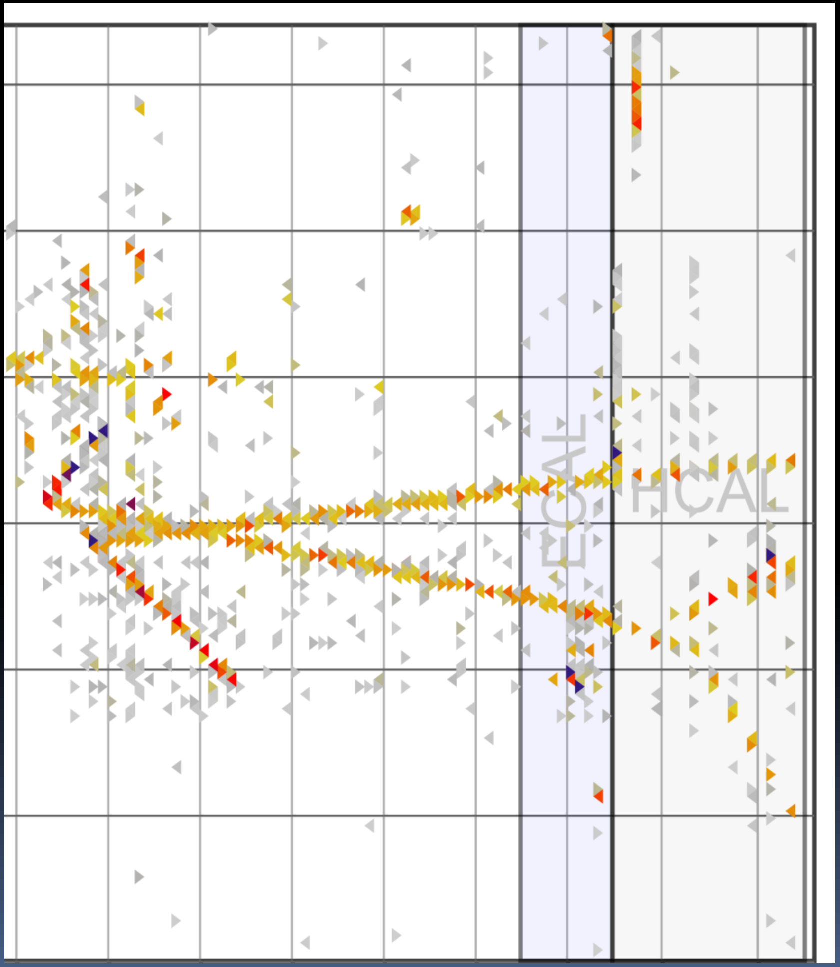
The MINERvA Detector

MINOS steel/
scintillator detector
used as muon
ranger



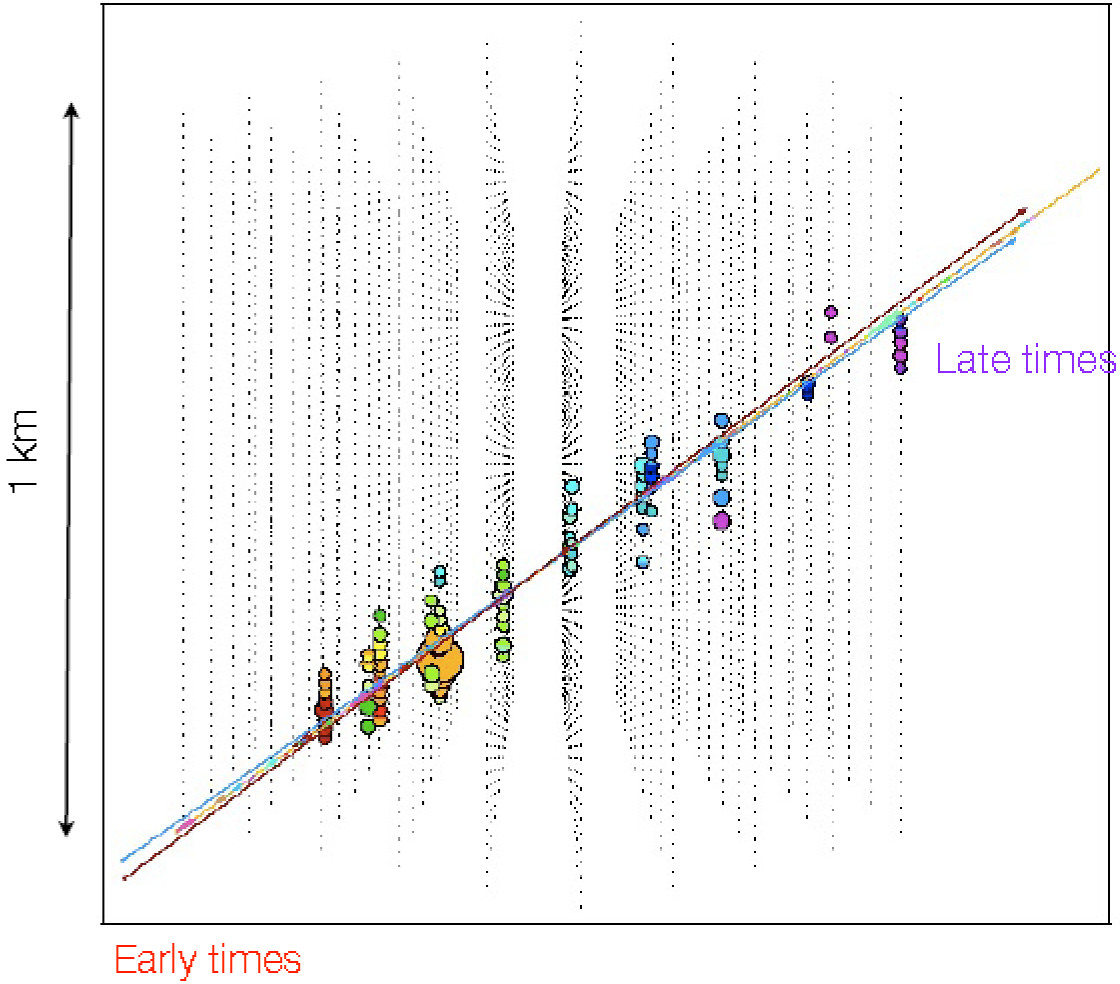
Very High Granularity Tracking Detector





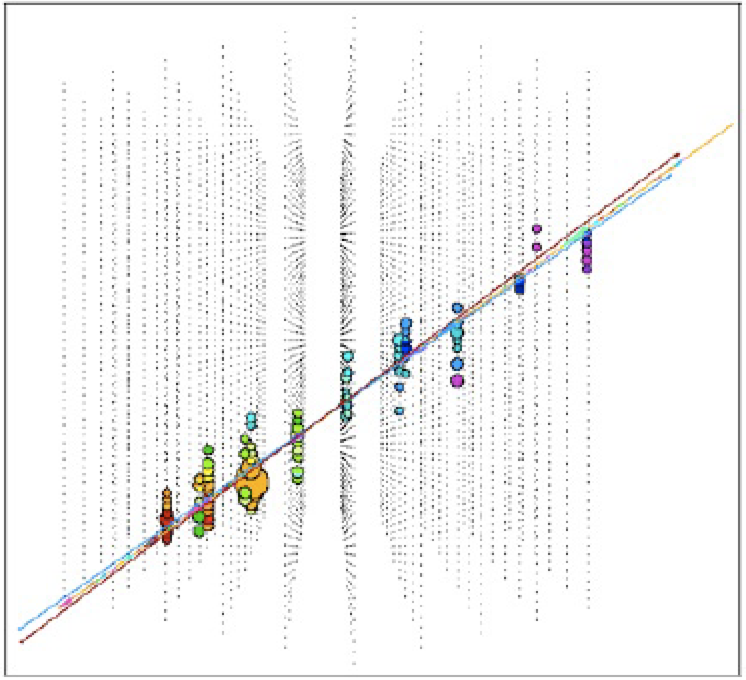
ULTRA HIGH ENERGY NEUTRINOS

10 TeV neutrino induced muon neutrino in Ice Cube

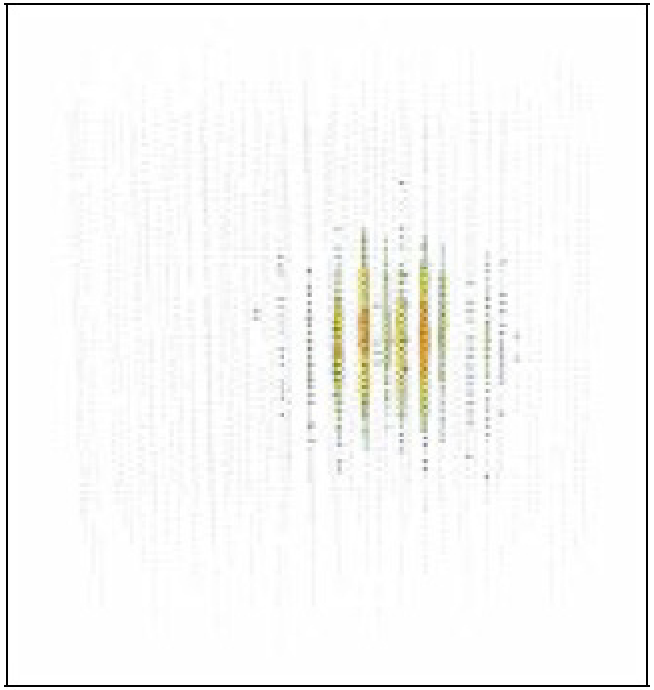


Times differ by roughly 2.5 usec. For PMT with ~10 ns time resolution this gives an up vs. down discrimination of > 250 sigma !

Particle ID in Ice Cube



10 TeV muon neutrino induced upward muon

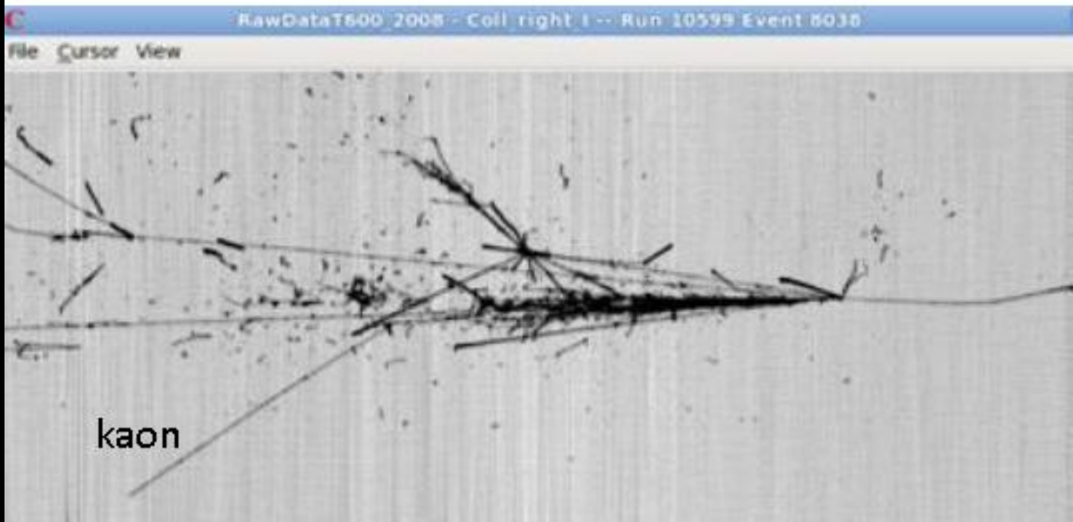


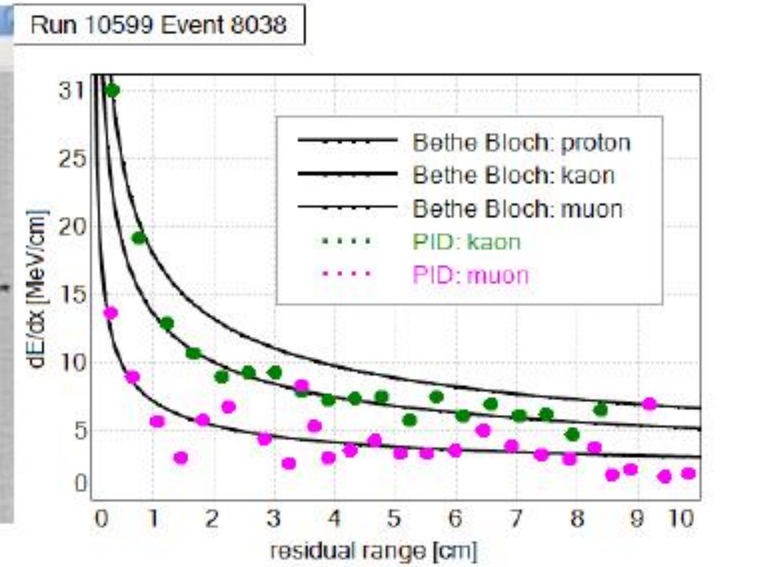
375 TeV electron neutrino

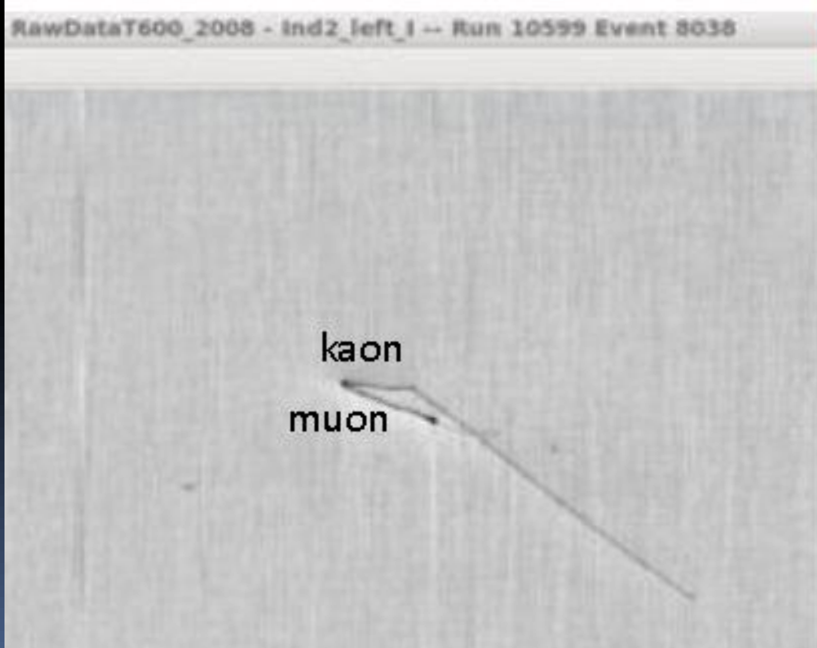
Ultimate Heavy Liquid Bubble Chamber: Liquid Argon Detectors

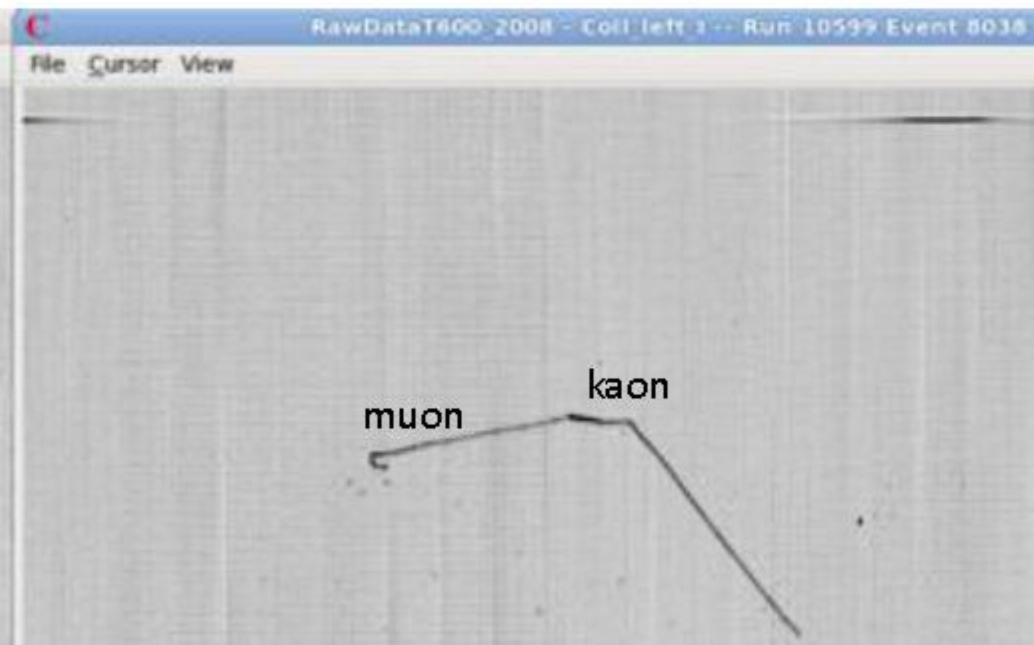
- ICARUS T600@LNGS
- ArgoNEUT@FNAL
- MicroBOONE@FNAL
- 250L@JPARC
- LBNE (USA)
- GLACIER (dual phase) (Europe)

- Exquisite granularity/tracking resulotion
- Good hadron energy resolution $\Delta E/E \sim 10\%$

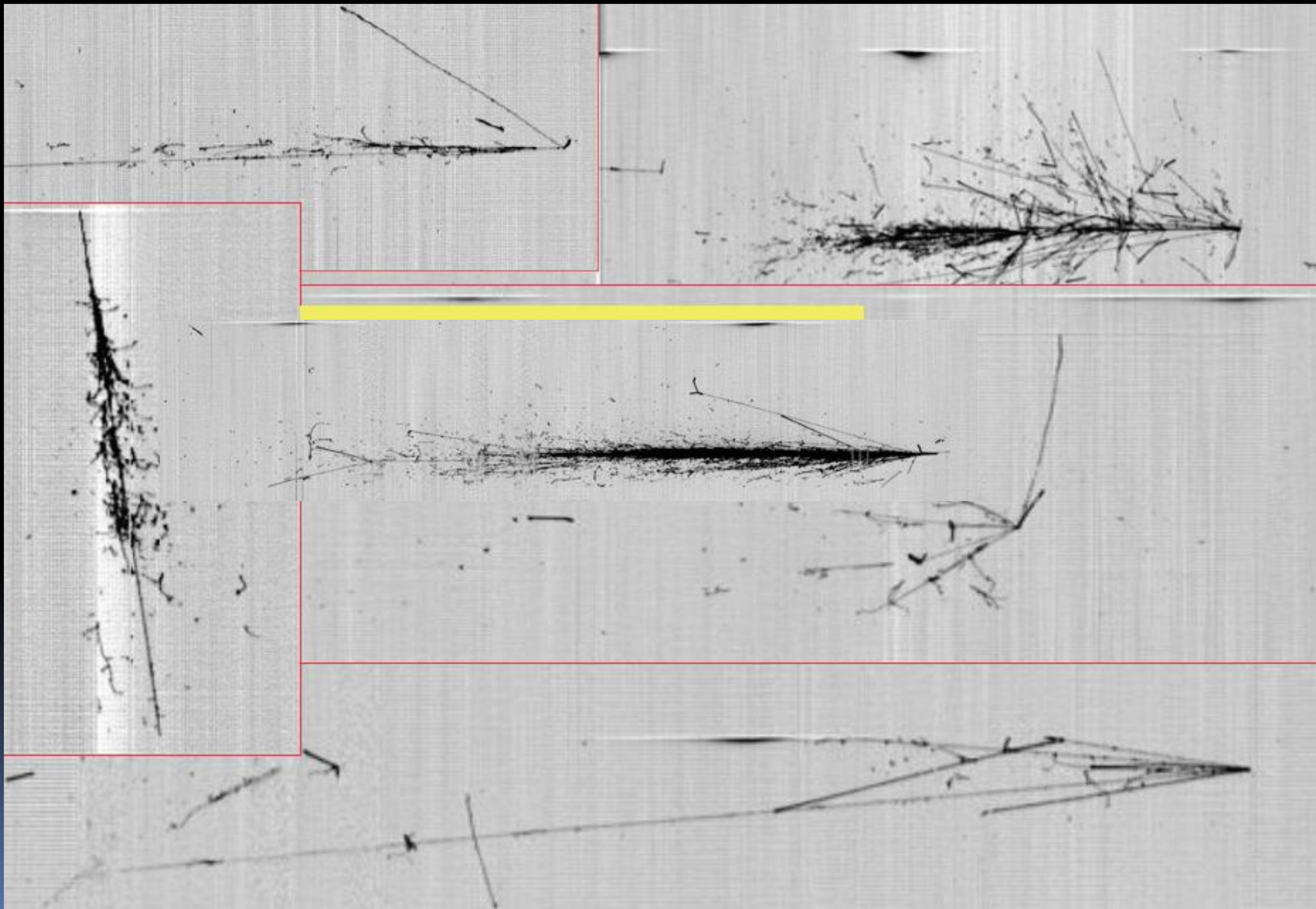

RawDataT600_2008 - Coll_right_I -- Run 10599 Event 8038
File Cursor View
kaon


Run 10599 Event 8038
Bethe Bloch: proton
Bethe Bloch: kaon
Bethe Bloch: muon
PID: kaon
PID: muon
dE/dx [MeV/cm]
residual range [cm]
31
25
20
15
10
5
0
0
1
2
3
4
5
6
7
8
9
10


RawDataT600_2008 - Ind2_left_I -- Run 10599 Event 8038
kaon
muon


RawDataT600_2008 - Coll_left_I -- Run 10599 Event 8038
File Cursor View
muon
kaon

ICARUS, LNGS beam



Instead of Summary

- After all these years of experimentation and R&D we have developed experimental techniques which allow us most of the conceivable questions regarding neutrinos.
- However not all the solutions may be affordable.
- Even affordable solutions may not be available all/many at the same time. Global collaboration/coordination may be called for.
- For man-made neutrino beams: physics potential = beam intensity x detector mass. Careful optimization is necessary.
- Optimization is considerably more difficult if multi-purpose facilities are considered.
- For subtle effects a careful inclusion of systematics: background and efficiencies, calibrations, etc.. is critical..
- We live in a golden age of neutrino physics. Let's convince others (i.e. funding agencies) about it.