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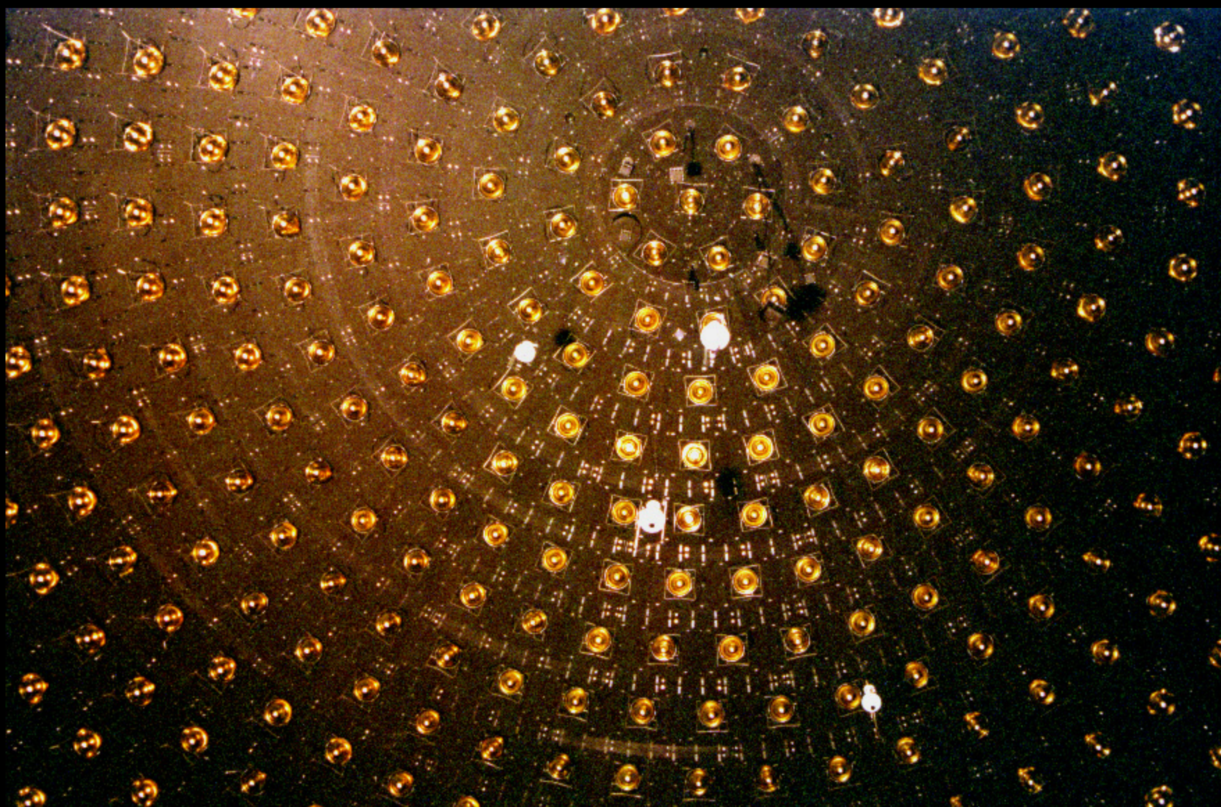
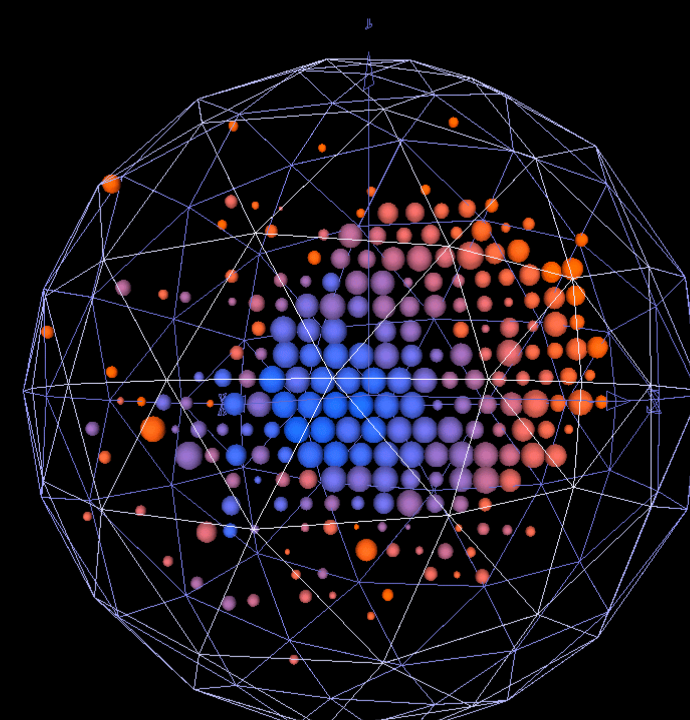
100

MiniBooNE’s First Neutrino Oscillation Result

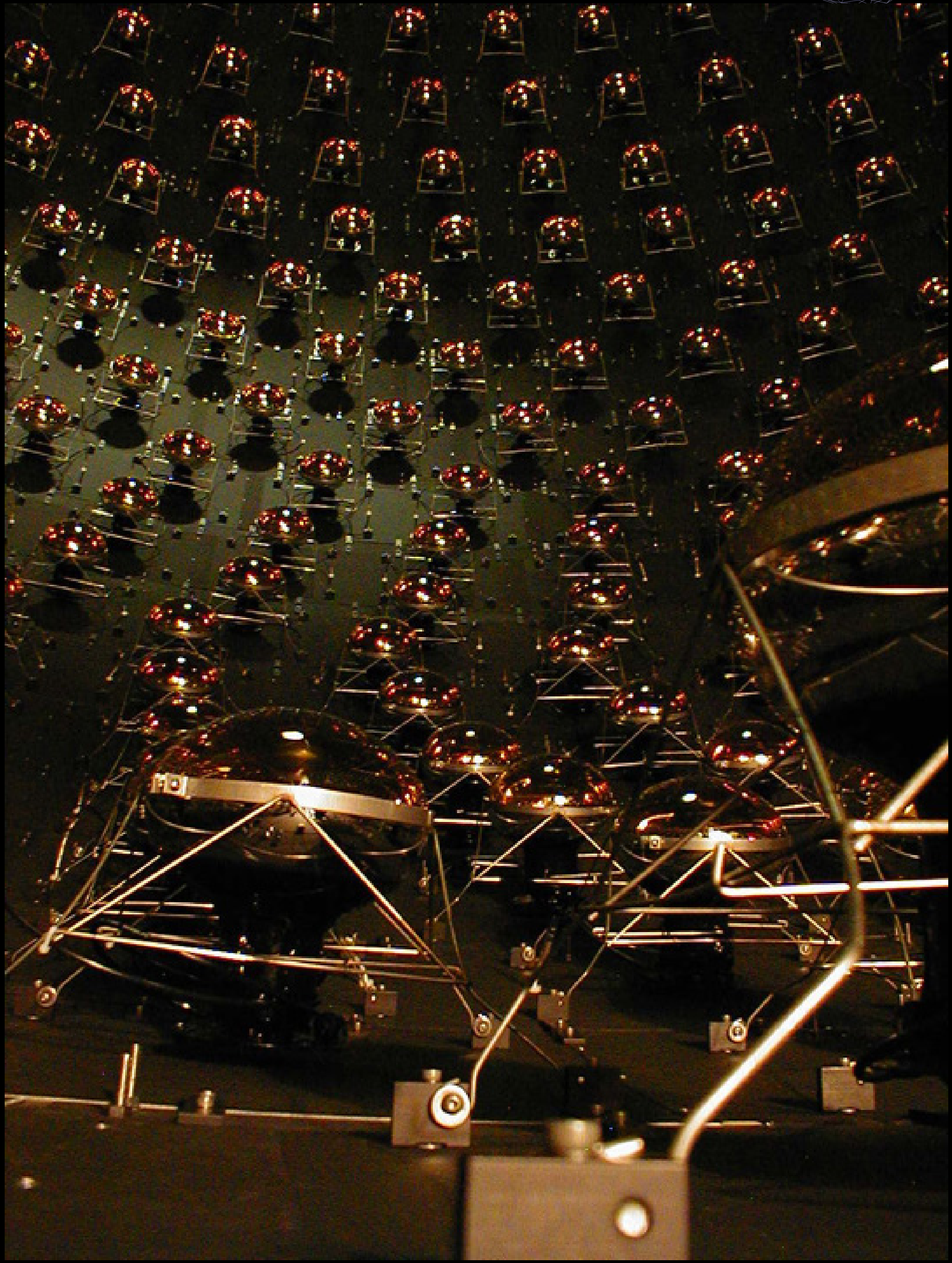




Morgan Wascko
Imperial College London

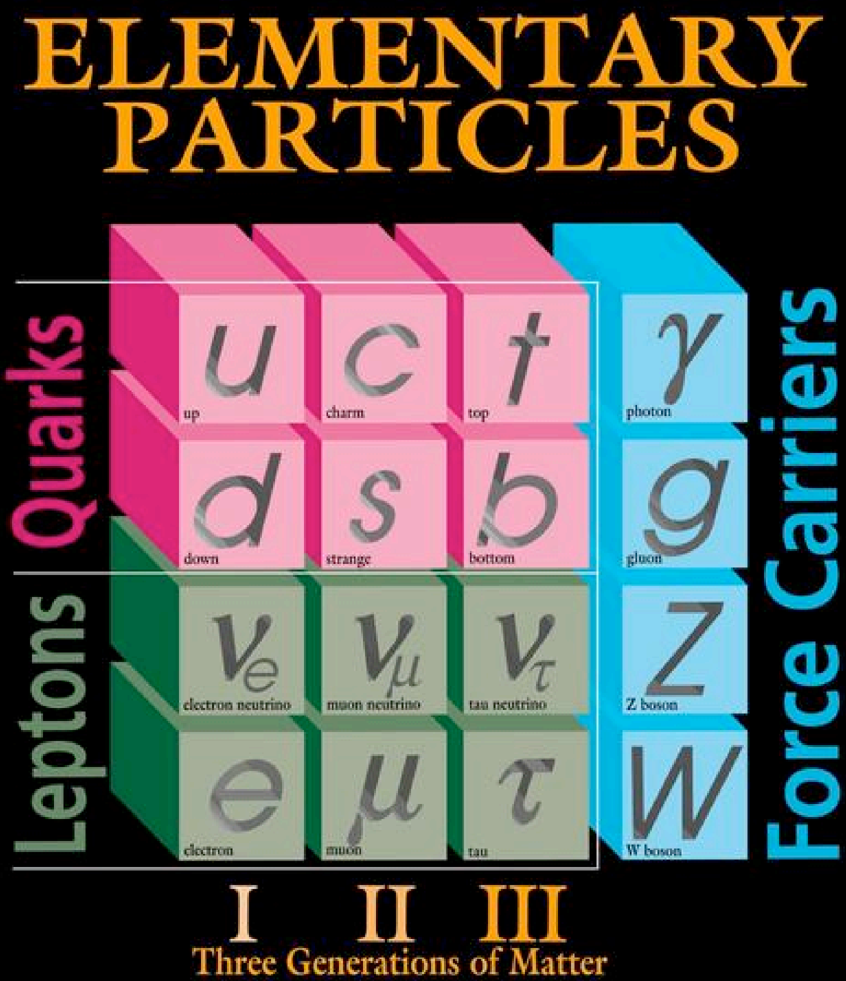
Outline

- A short course in the physics of ν oscillations
  - What are neutrinos? Oscillations?
  - ν oscillation landscape
- MiniBooNE
  - Experiment description
  - MiniBooNE's First Results
- Neutrino Physics Big Picture
  - Next Steps for the Field
  - What has MiniBooNE told us?



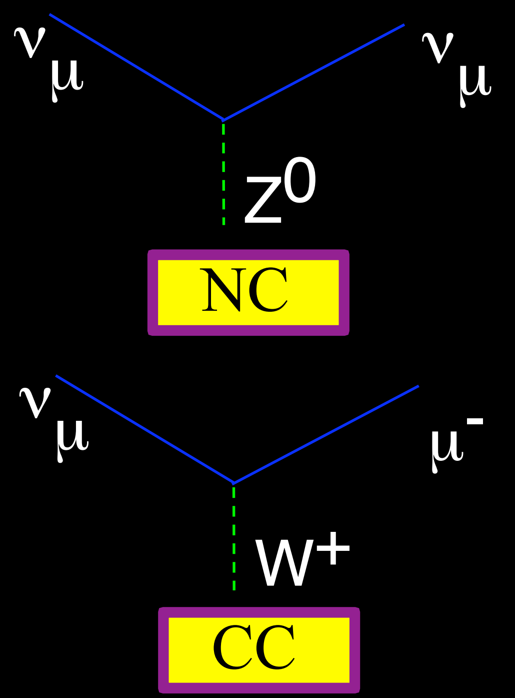
Neutrinos 101

- Particle physics is described by:
  - The Standard Model
- Matter: Fermions
  - Quarks and leptons
    - Doublets
    - Bound vs. free
  - Three generations of each
- Force Carriers: Bosons
  - EM: Photon
  - Strong force: Gluon
  - Weak force: W,Z
- Neutrinos are the lightest leptons
  - Massless in the standard model
  - Interact only via weak force



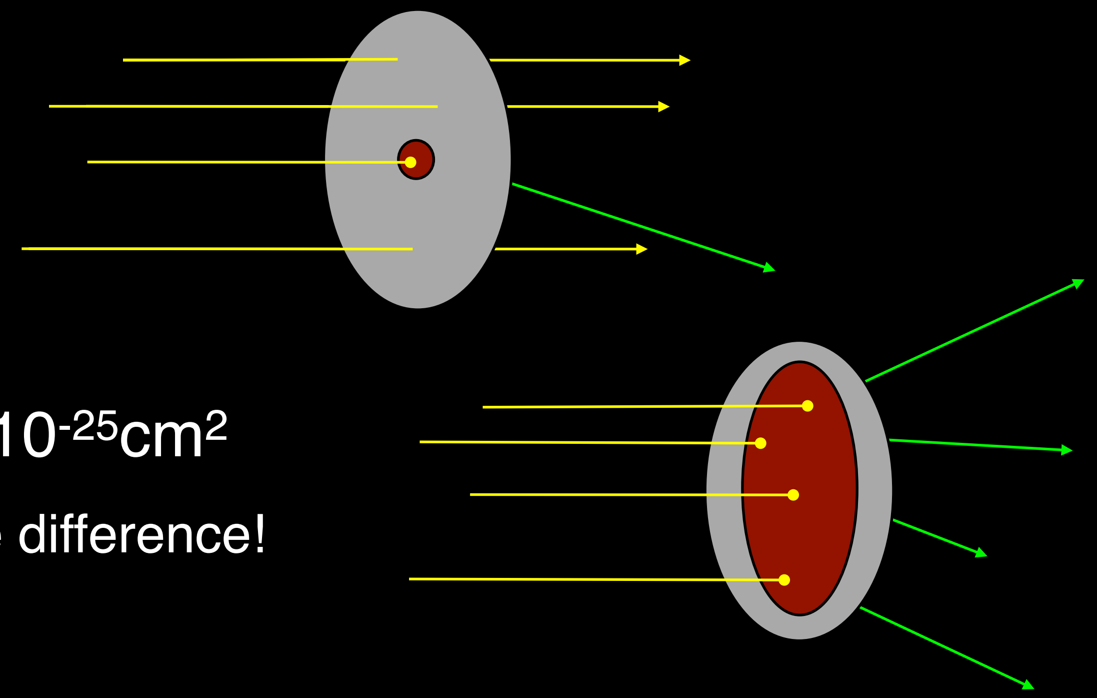
Neutrino Interactions

- Neutrinos are created as weak-flavor eigenstates
    - e, μ, τ
- Neutral Current Interactions
    - Z exchange
    - Neutrino in, neutrino out
- Charged Current Interactions
    - W exchange
    - Mix within the doublets
    - Neutrino in, negative lepton out
        - Antineutrino in, positive lepton out
- That's how we know a neutrino's flavor
    - Neutral current interactions don’t reveal the neutrino’s flavor

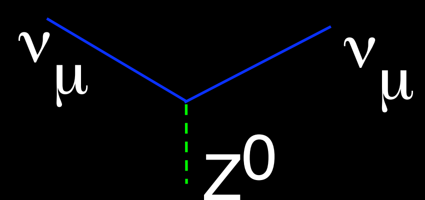


Feynman Diagrams

Neutrino Interactions 2



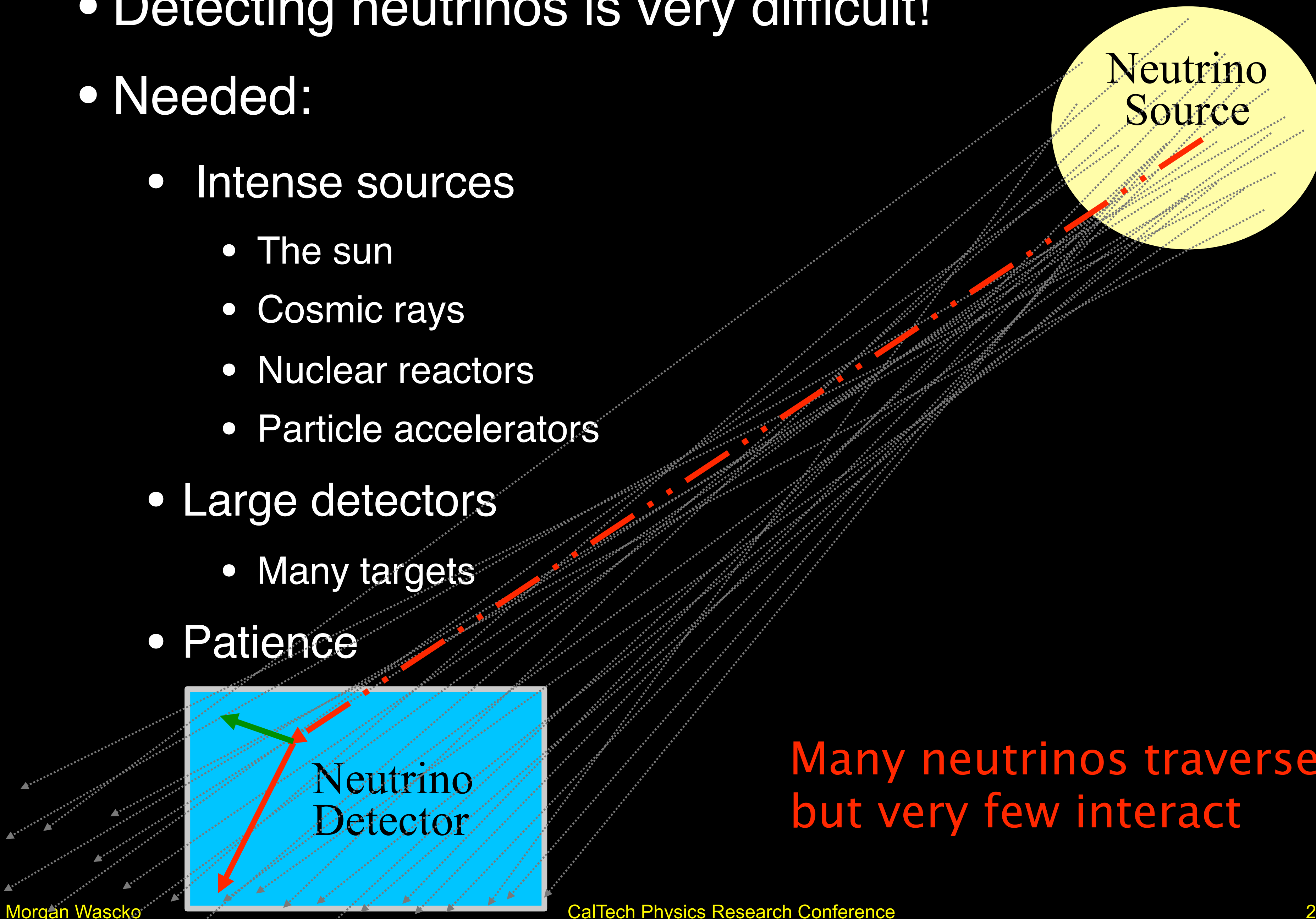
- The weak force is weak
  - $\sigma(\nu e) \sim 10^{-40}\mathrm{cm}^2$
  - $\sigma(\nu N) \sim 10^{-36}\mathrm{cm}^2$
  - For comparison: $\sigma(pp) \sim 10^{-25}\mathrm{cm}^2$
    - 11-15 orders of magnitude difference!
  - Reason: W,Z are heavy:
    - 80, 91 GeV/c2



- As an example:
  - A ~10 MeV neutrino from the sun has a mean free path of several light years in lead
  - Hundreds of billions of neutrinos from the sun pass through every square inch of you each second

Finding Neutrinos

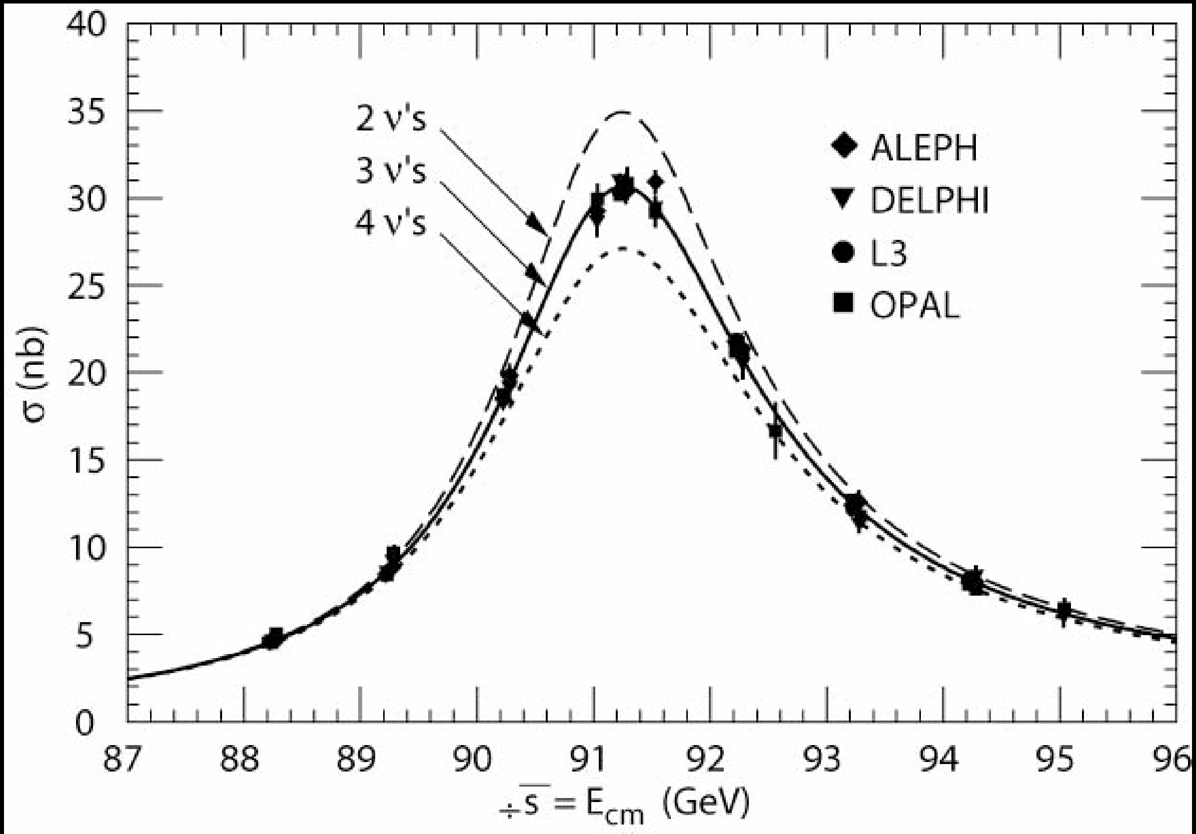
- Detecting neutrinos is very difficult!
- Needed:
  - Intense sources
    - The sun
    - Cosmic rays
    - Nuclear reactors
    - Particle accelerators
  - Large detectors
    - Many targets
  - Patience



Many neutrinos traverse,
but very few interact

Neutrino Flavours

- Neutrinos “seen” by colliders only as missing energy



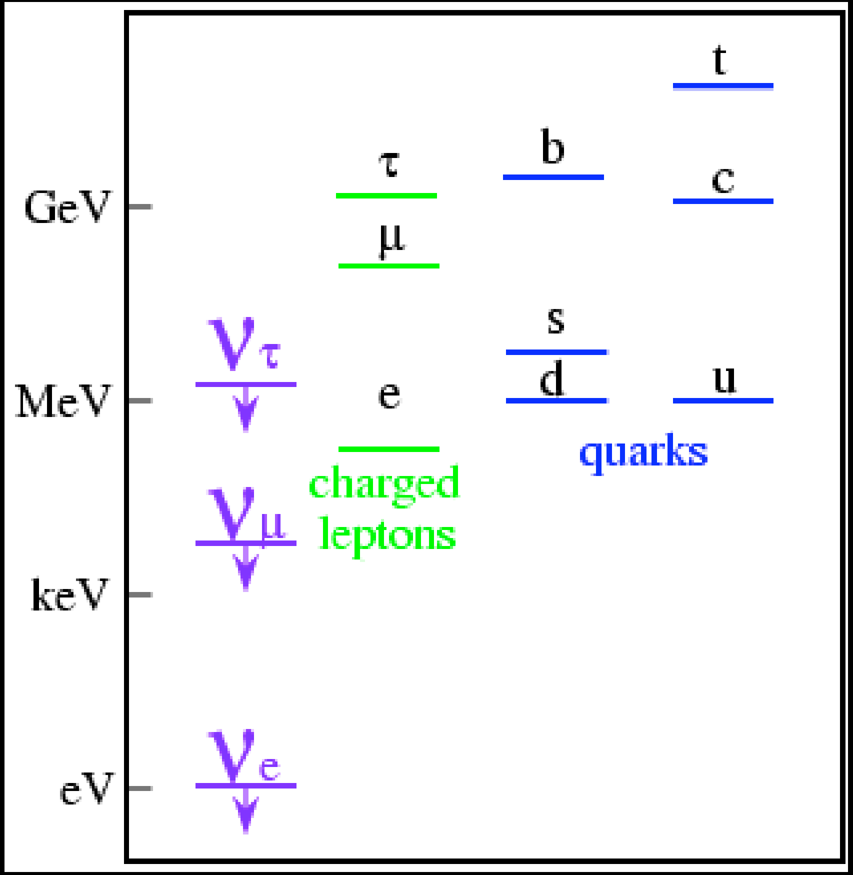
C. Caso et al., Euro.Phys.J C3, 1 (1998) and (URL: http://pdg.lbl.gov/)

Invisible width of the Z^0 measured by LEP expts

- Careful analysis of Z^0 decays reveals an interesting result:
  - Only three generations of light neutrinos!

Neutrinos Mass

- In the standard model, neutrinos are massless
  - But it's difficult to confirm this
- Direct mass searches yield limits
  - ν_e: tritium decay: m < 2 eV
  - ν_μ: pion decay: m < 170 keV
  - ν_τ: tau decay: m < 18.2 MeV
  - Compare to hadron masses: larger than neutrino mass limits
    - pions ~ 140 Mev
    - kaons ~ 500 MeV
    - protons ~ 1 GeV
    - neutrons ~ 1 GeV

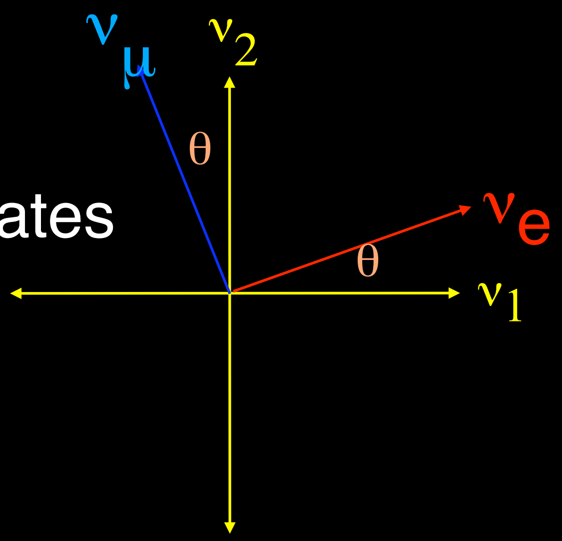


- Can learn about neutrino mass with indirect searches
  - use quantum mechanics

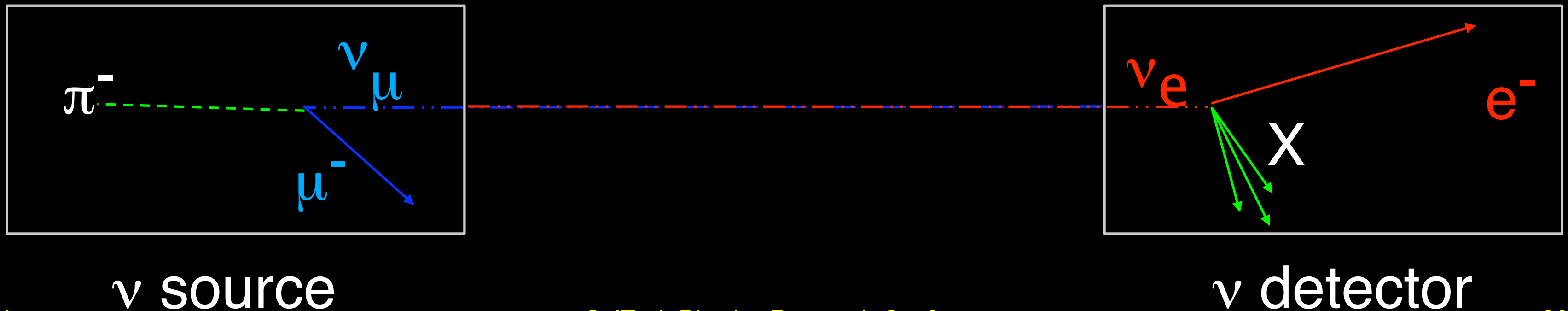
Neutrino Oscillations

- IF:
  - Neutrinos have (different) mass
    Weak states are a mixture of the mass states

$$\begin{bmatrix} \nu_e \\ \nu_\mu \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \end{bmatrix}$$



- THEN:
  - A neutrino created as one specific flavor might later be detected as a neutrino of a different flavor
  - Why? Neutrinos propagate as mass eigenstates



Oscillation Probability

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{12}\frac{L}{E})$$

Oscillation probability between two flavor states depends on:

Two fundamental parameters

$\Delta m_{12}^2 = m_1^2 - m_2^2$: "period"

mass difference between states

$\sin^2 2\theta_{12}$: "amplitude"

mixing between flavors

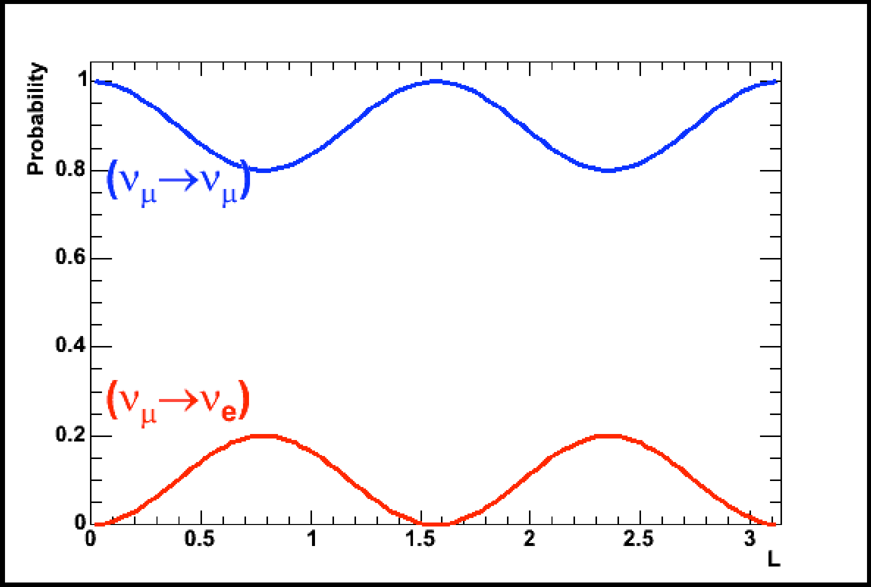
Two experimental parameters

L: distance from source to detector

E: neutrino energy

L,E determine Δm^2 region

Oscillations don't measure the absolute mass scale



Two possible experiments in this example:

ν_μ disappearance

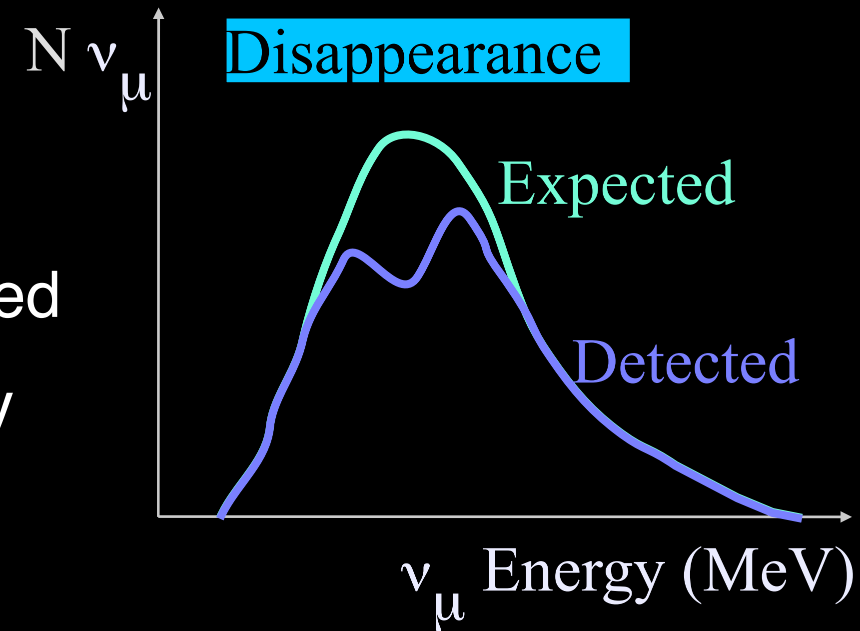
$P(\nu_\mu \rightarrow \nu_\mu)$

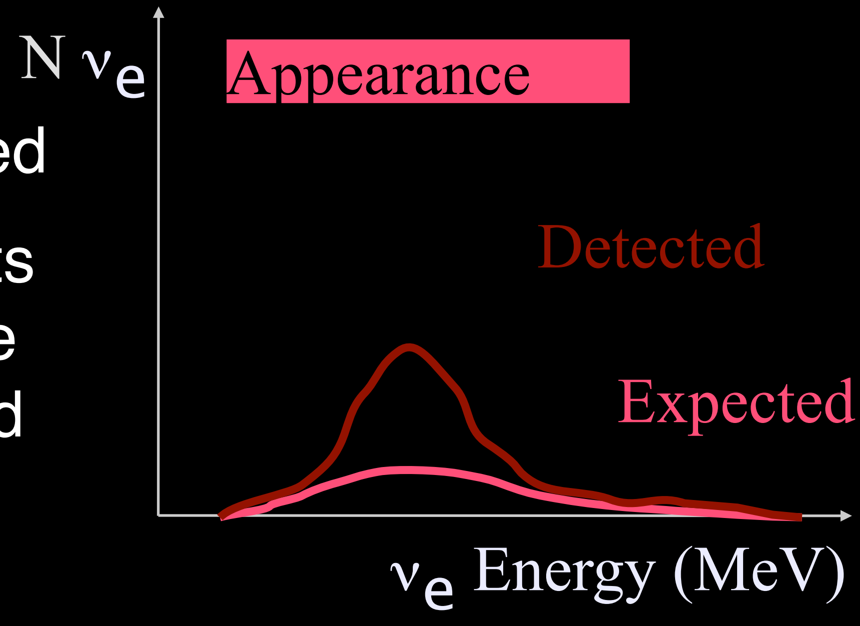
ν_e appearance

$P(\nu_\mu \rightarrow \nu_e)$

Detecting Oscillations

- Consider searching for $\nu_\mu \rightarrow \nu_e$
- Disappearance
  - Detect fewer ν_μ events than expected
  - Should have a characteristic energy signature – oscillation probability depends on E!
- Appearance
  - Detect more ν_e events than expected
  - Oscillation depends on E: the events that disappeared in the blue plot are related to those appearing in the red plot
- Goal: Determine Δm^2, $\sin^2 2\theta$

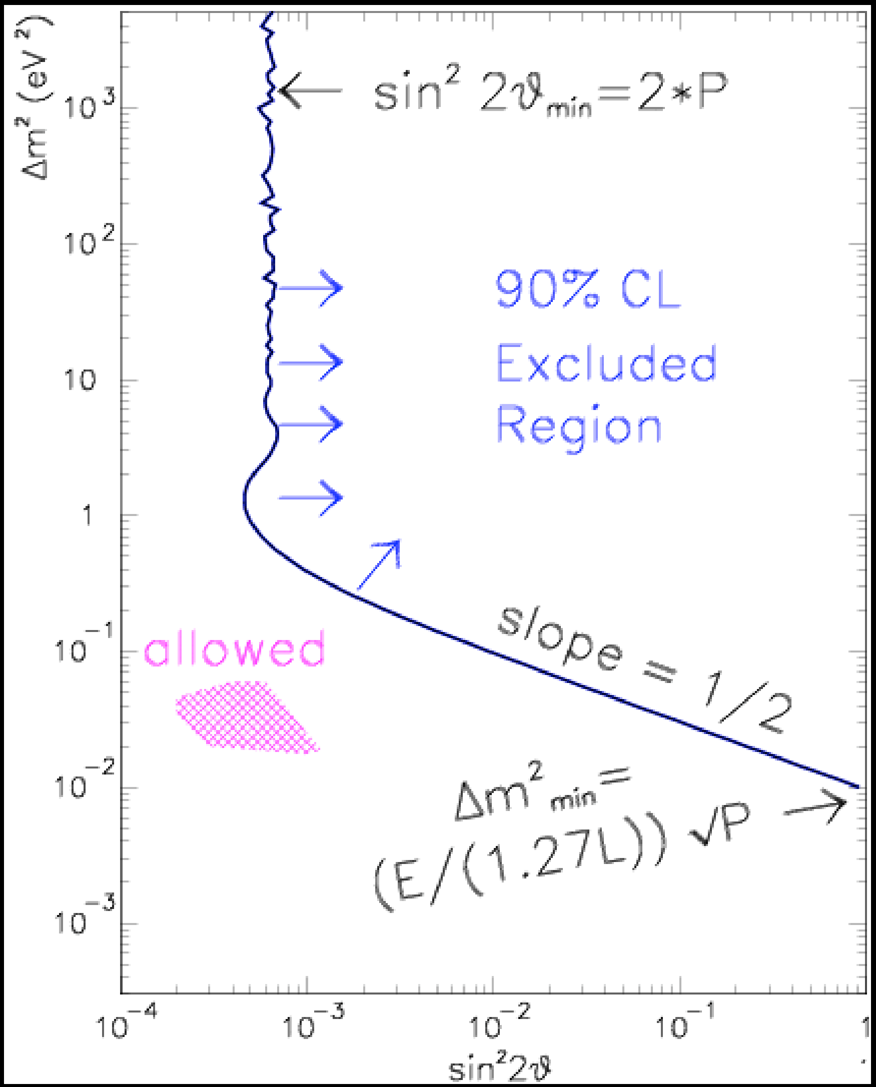




Presenting Oscillations

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{12}\frac{L}{E})$$

- Recall:
  - L and E determine the Δm² sensitivity region
  - sin²2θ gives amplitude of oscillations
- No signal: exclusion regions
  - Inside the region: excluded
  - Outside the region: cannot be ruled out
- Signal: allowed regions
  - Shown by shaded areas specifying Δm² and sin²2θ
  - Size of allowed region determined by experimental uncertainties



Three Flavour Mixing

There are actually three generations of neutrinos that can oscillate into each other

Flavour | Mass

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{+i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

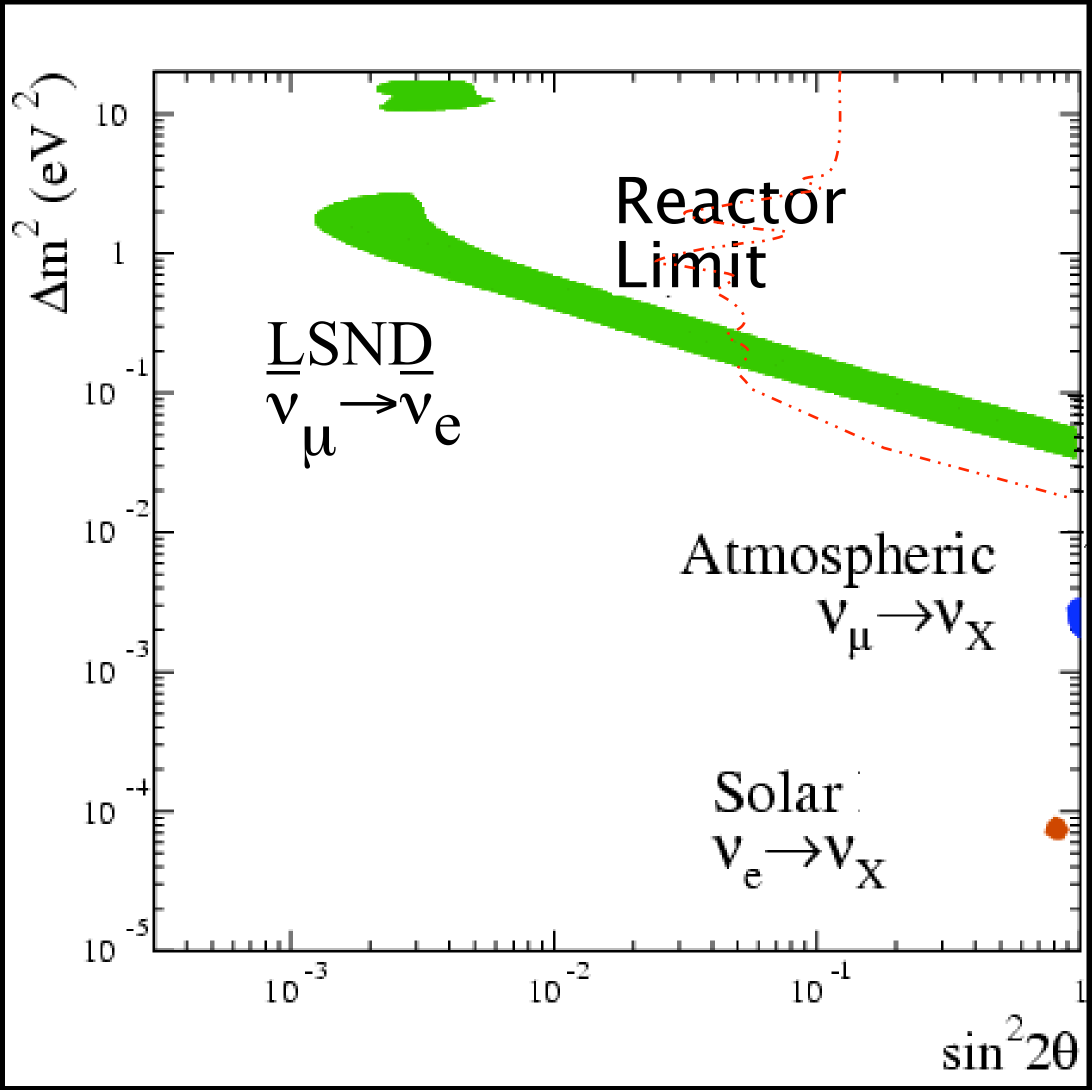
ATMOSPHERIC
SK, K2K, MINOS
θ_{23} =~45°
Δm^2_{23} = ~2.5E-3 eV^2

CROSS MIXING
CHOOZ, Bugey
θ_{13} <~12°
δ is unknown

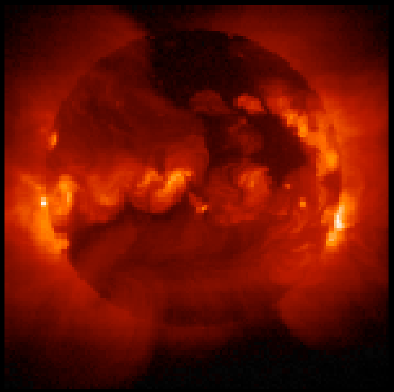
SOLAR
SNO, others, KamLAND
θ_{12} =~32°
Δm^2_{12}= ~8E-5 eV^2

Current Oscillation Picture

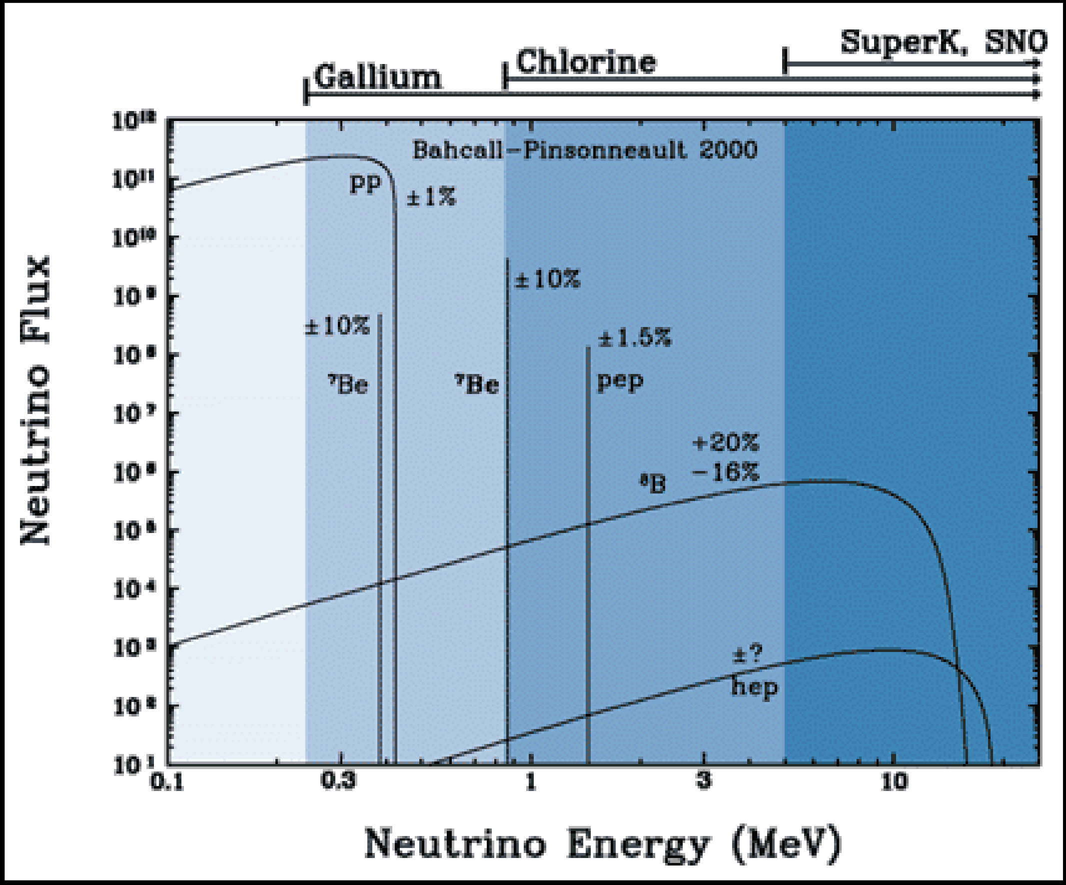
- Three different oscillation signals observed (so far...)
- Allowed regions indicated
  - Note: The true answers are actually single points!
- All indicate small mass^2 differences
  - Neutrinos are surprising!
- Solar neutrinos: $\Delta m^2 \sim 10^{-5} eV^2$
- Atmospheric: $\Delta m^2 \sim 10^{-3} eV^2$
- LSND: $\Delta m^2 \sim 1 eV^2$
  - Yet to be confirmed
- Only mass differences, not absolute scale



Neutrinos from the Sun



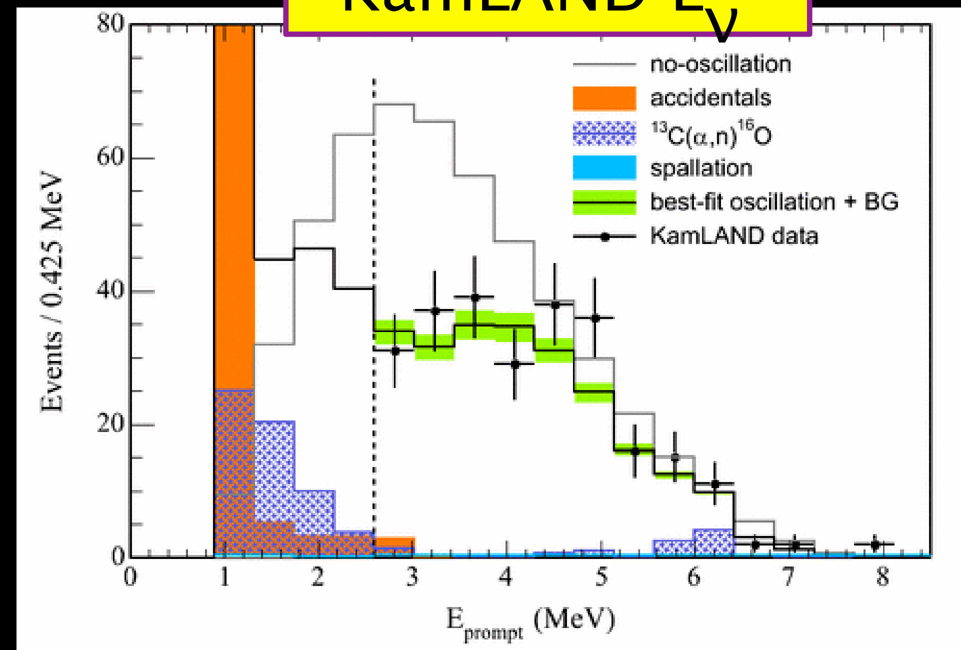
- The sun is fueled by fusion reactions
  - $4\ ^1H + 2e^- \rightarrow\ ^4He + 2\nu_e + 6\gamma$
  - More reaction chains follow...
- Neutrinos are produced copiously
  - Note all produce ν_e, below ~20MeV
- But when expts were built to search for them, they found too few!
  - Many techniques (Looking for CC reactions of ν_e - not enough energy to produce a μ or τ)
- Are the solar models wrong? Are the experiments wrong?



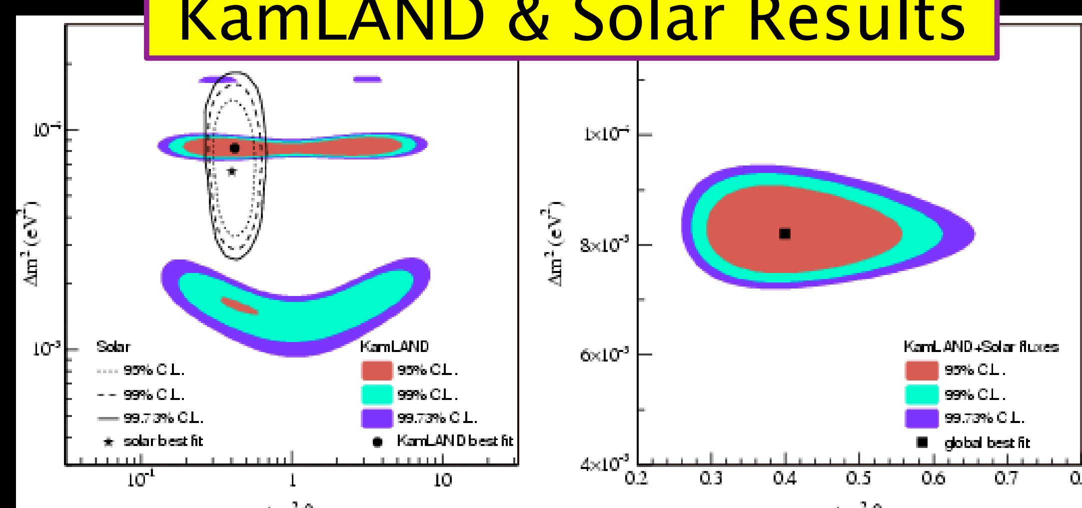
Solar ν Results

- SNO had the ability to see neutral current (ν→ν) as well as charged current ($\nu \to \ell^{\pm}$) reactions
  - Used heavy water
- They can see all flavors---
  - Oscillations! (PRL 87:071301, 2001)
  - Solution:
    - Mixing angle $\theta = 32^{\circ}$
    - $\Delta m^2 = 8.2 \times 10^{-5} eV^2$
- KamLAND: reactor antineutrinos
  - Confirm solar result (PRL 90:021802, 2003)
  - Spectral distortion! (PRL 94:081801, 2005)
  - $\bar{\nu}$ vs. ν
- The experiments were right!

KamLAND E_ν

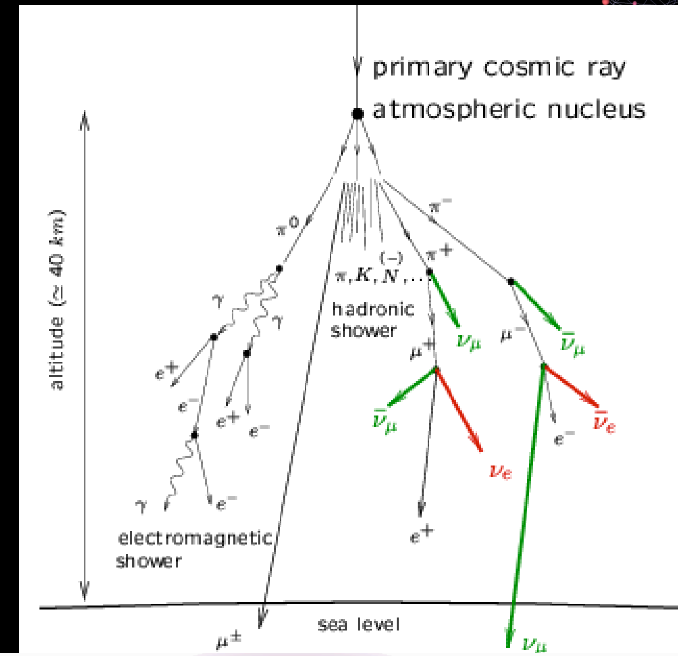


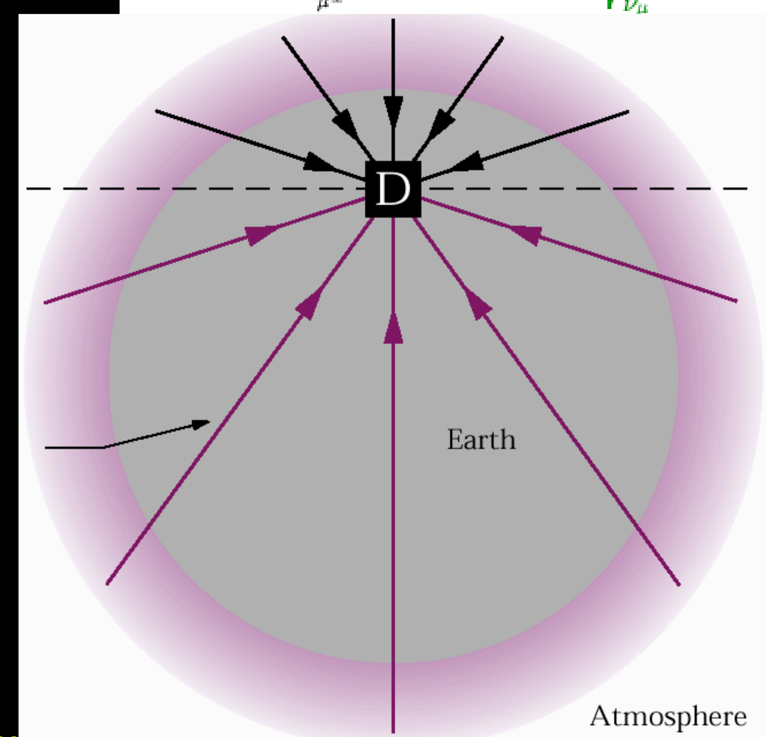
KamLAND & Solar Results



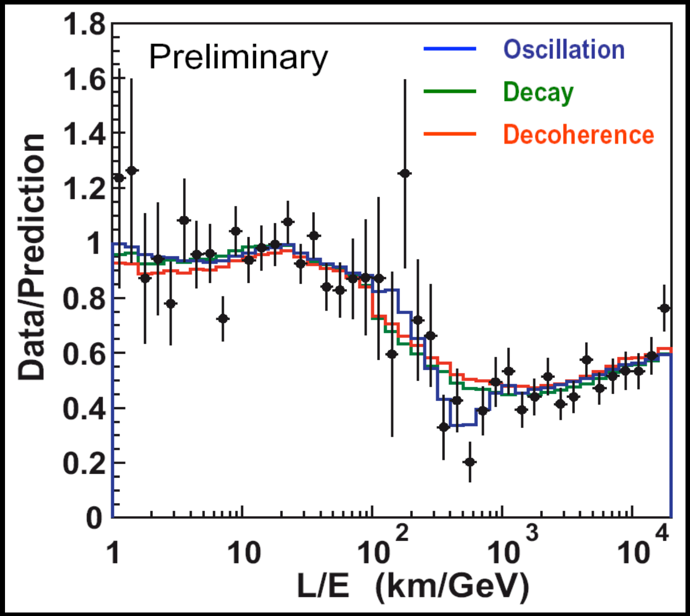
Atmospheric Neutrinos

- Neutrinos produced by cosmic ray induced air showers
  - $\bar{\nu}_\mu$ and ν_μ, $\bar{\nu}_e$ and ν_e
- High energy cosmic rays are isotropic
  - Same rates on this side of the Earth as the other
- Super-K measures a difference in flux as a function of zenith angle
  - Different L: wide range of (L/E)
  - $\bar{\nu}_\mu$,ν_μ disappearance (PRL 81 (1998) 1562-1567)





Atmospheric ν Oscillations



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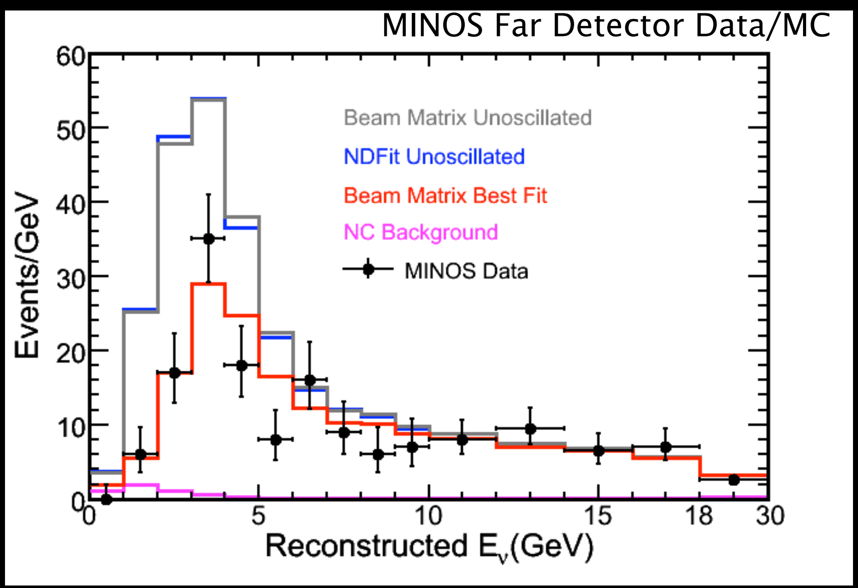
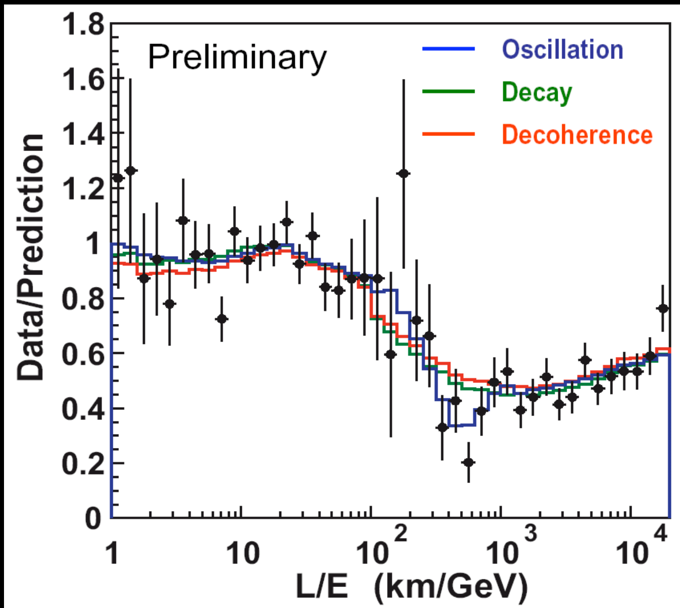


- L/E characteristic of oscillations
- Best fit to data:
  - Mixing angle ~45° (Maximal!)
    - Quite unexpected!
  - $\Delta m^2 = 2.4\times10^{-3} eV^2$
- Mix of $\bar{\nu}$ and ν
- This result is confirmed by other experiments: Soudan, MACRO
  - MINOS: separate $\bar{\nu}$ and ν
- Confirmed with accelerator by K2K & MINOS
  - Compare fluxes in near detectors to fluxes at far
  - See evidence for ν_μ disappearance
  - Similar oscillation parameters

Atmospheric ν Oscillations



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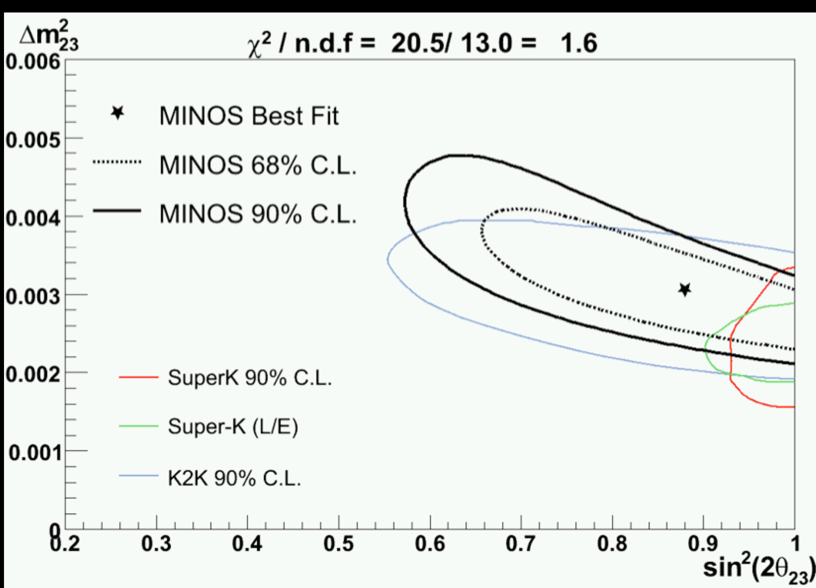

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Accelerator Neutrinos

Many null result SBL accelerator neutrino experiments

Positive result: LSND Experiment at LANL

Beam: μ^+ decay at rest

L/E ~ 1m/MeV

L ~ 30m

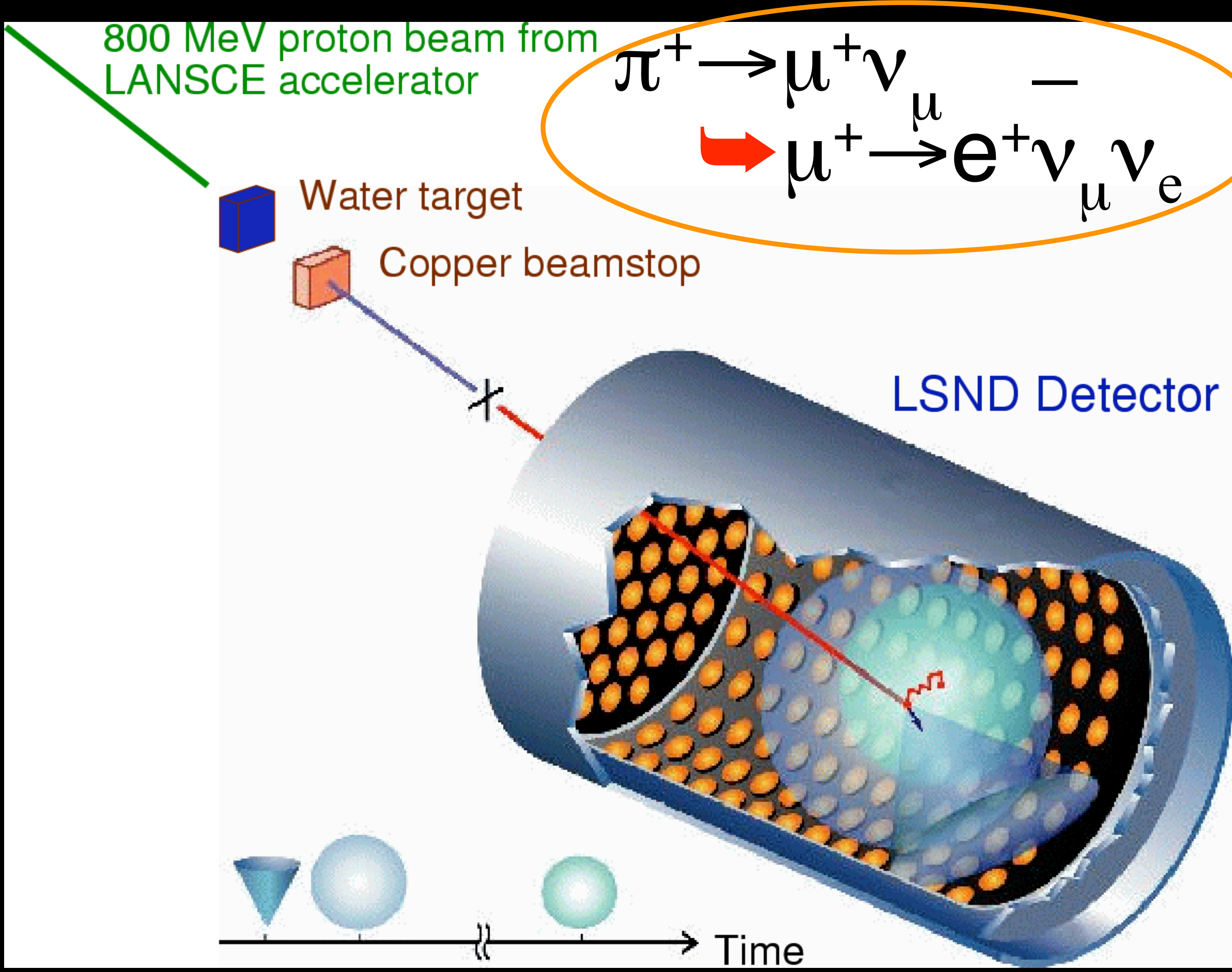
$20 < E_{\bar{\nu}} < 53$ MeV

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$?

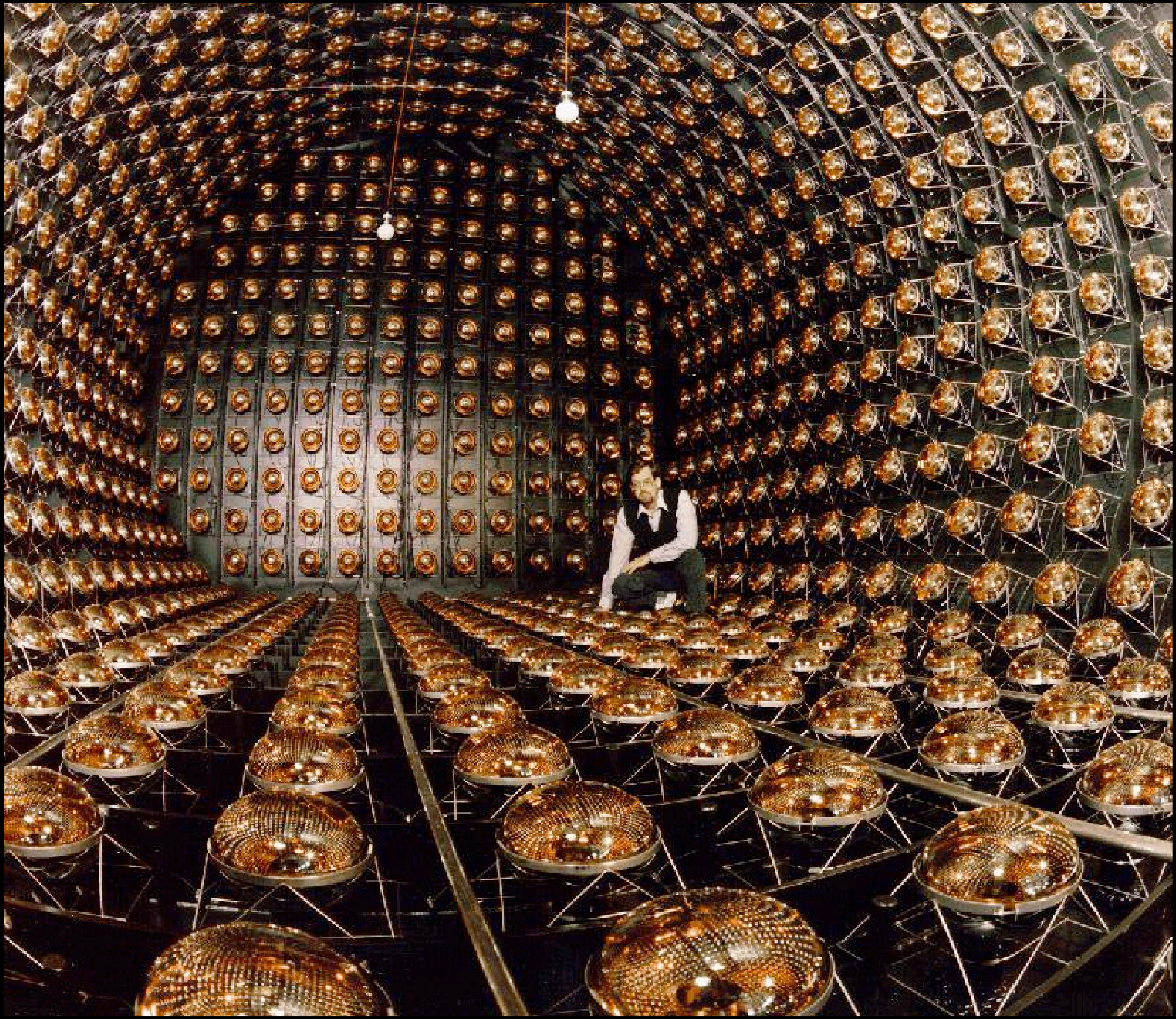
Appearance search

Clean detection signal

Inverse β decay



Inside LSND



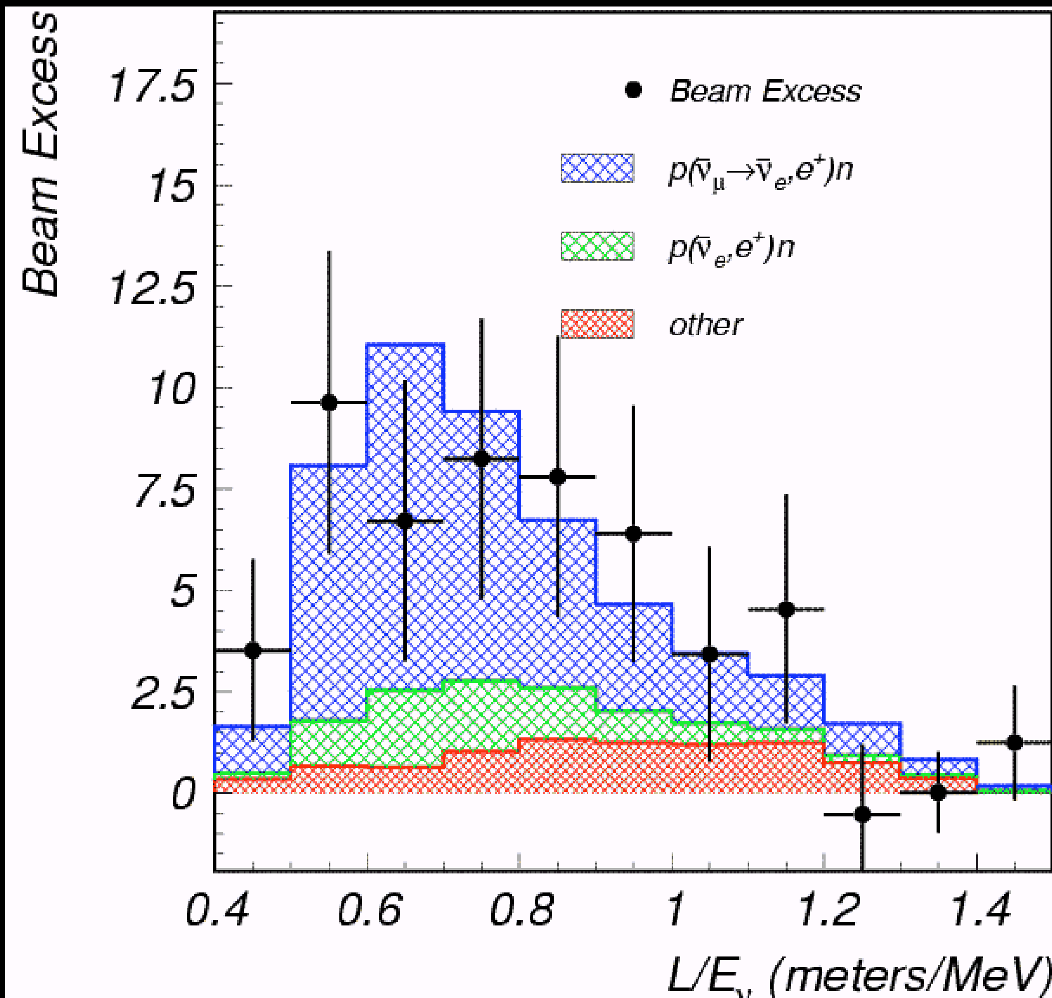
Remember these PMTs!
(photo-multiplier tubes)

The LSND signal

• $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation probability:

0.264±0.067±0.045%

3.8σ excess!



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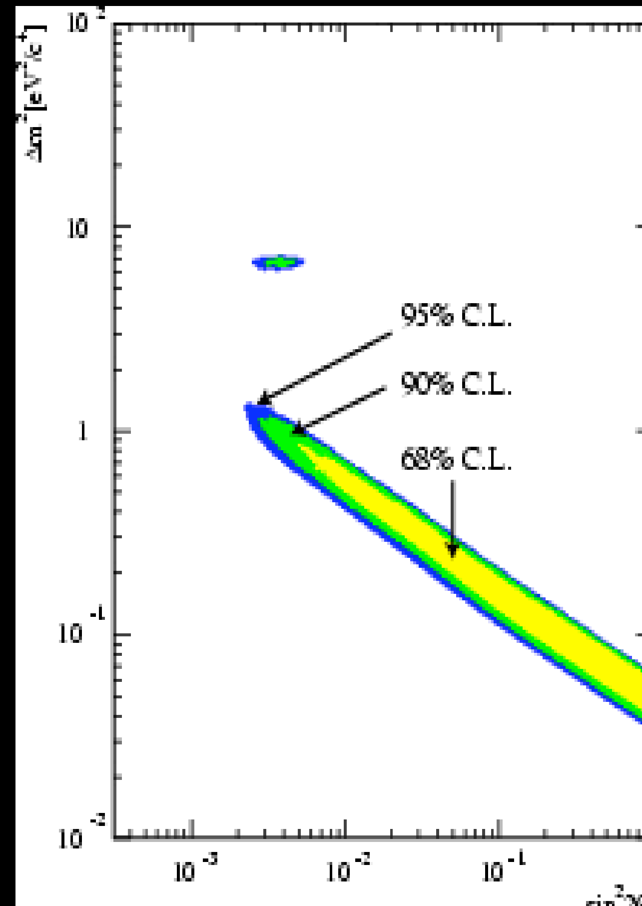
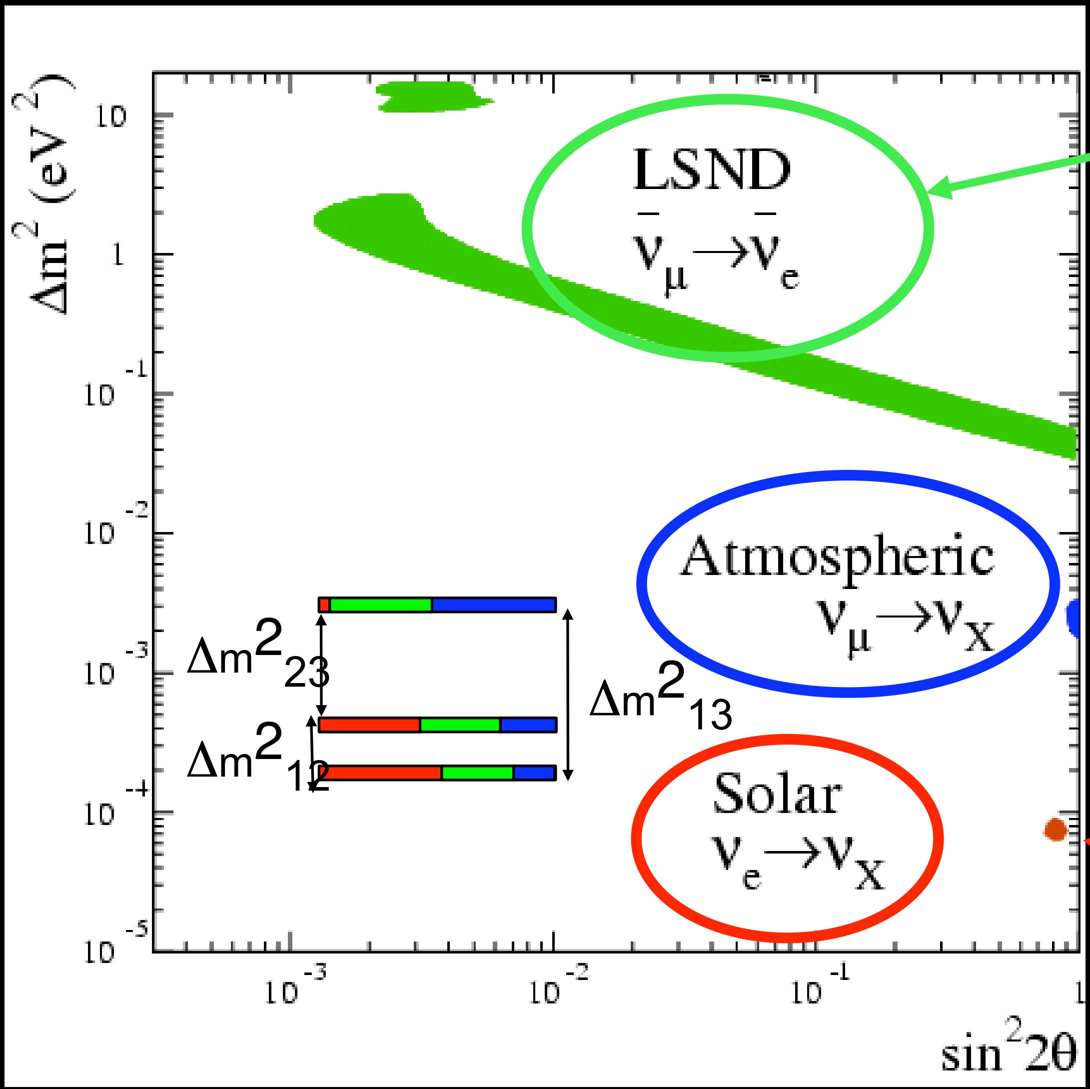


hep-ex/0203023

KARMEN2 and LSND collaborators performed joint analysis on both data sets - allowed regions remain!

$\Delta m^2 \sim 1 eV^2$, $\theta \sim 2°$

Current Oscillation Summary



LSND
$\Delta m^2 \sim 1 eV^2$
$\theta \sim 2°$

Atmospheric oscillations
$\Delta m^2 \sim 10^{-3} eV^2$
$\theta \sim 45°$

Solar oscillations
$\Delta m^2 \sim 10^{-5}\ eV^2$
$\theta \sim 32°$

- Problem: That's too many Δm2 regions!
  - Should find: $\Delta m^2_{12} + \Delta m^2_{23} = \Delta m^2_{13}$

$10^{-5} + 10^{-3} \neq 1$

The 3 Δm^2 Problem

- LSND signal not oscillations?
  - Anomalous muon decay: $\mu^+ \rightarrow e^+ \bar{\nu}_e \bar{\nu}_\mu$
    - New TWIST result rules this out
      - hep-ex/0409063, hep-ex/0410045
- If it is oscillations, it indicates that our model is incomplete

NEW physics beyond the standard model

- Sterile Neutrinos
  - One of the oscillation signals could include sterile states
  - LEP results require these extra νs have no weak coupling
- LSND needs to be confirmed experimentally!

Resolving LSND

- To test the oscillation hypothesis, want sensitivity to the same oscillation parameters as LSND
- Different systematics

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{12}\frac{L}{E})$$

- Choose similar L/E
  - Different E - different event signatures and backgrounds
  - Different L - chosen to achieve similar (L/E)
- MiniBooNE was designed to do exactly that!
  - Search for LSND-type oscillations
  - $\Delta m^2 \sim 1 eV^2$
- First look for $\nu_\mu \rightarrow \nu_e$ oscillations

Imperial College London
100 years of living science

MiniBooNE Collaboration

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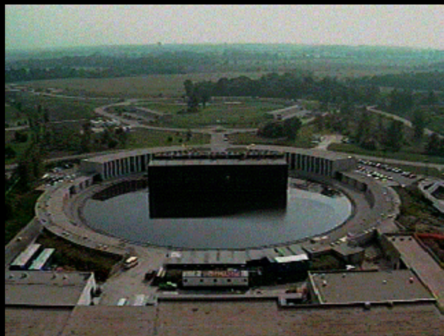
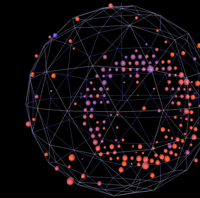
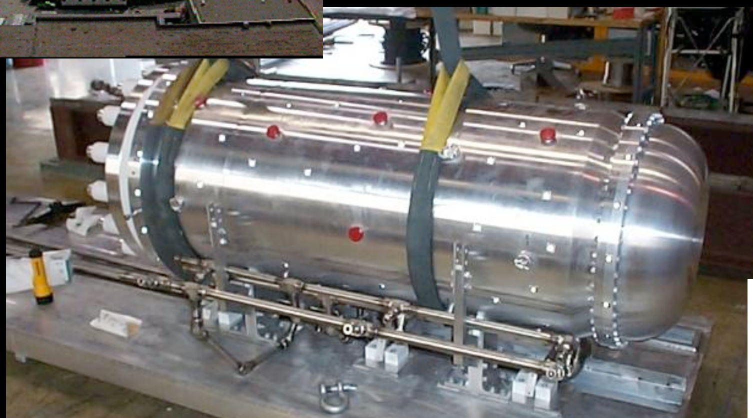
MiniBooNE Overview





8 GeV protons from Fermilab Booster

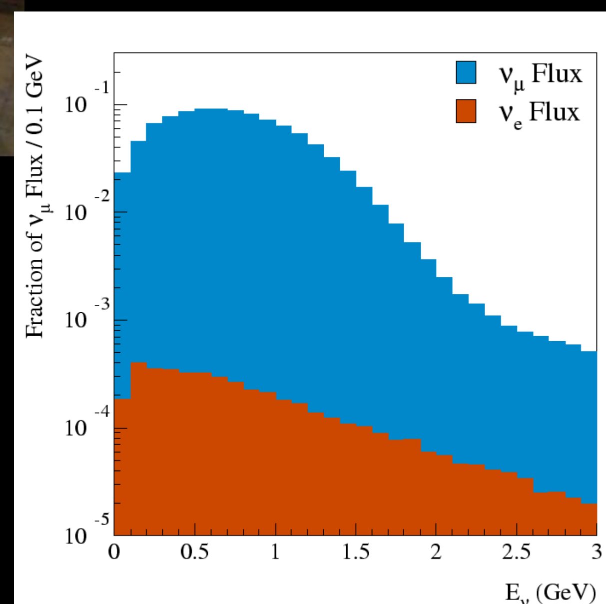
Beryllium target



Magnetic horn to focus mesons

meson decays produce neutrinos

Reversible polarity - $\bar{\nu}$ mode



50 m decay region

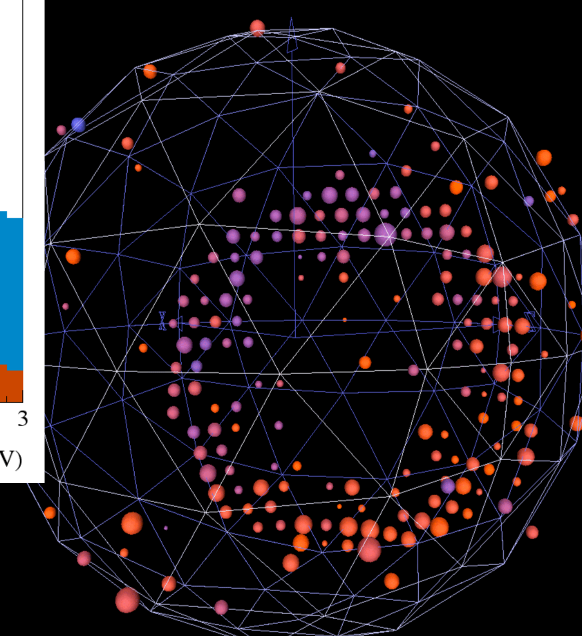
>99% pure $\nu_\mu, \bar{\nu}_\mu$ beam

~500 m dirt

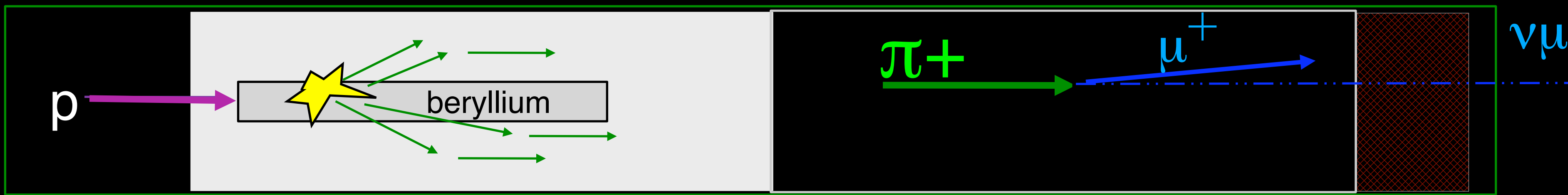
$\nu_\mu \rightarrow \nu_e$?

800 ton mineral oil detector

Photomultipliers (PMTs) to detect light



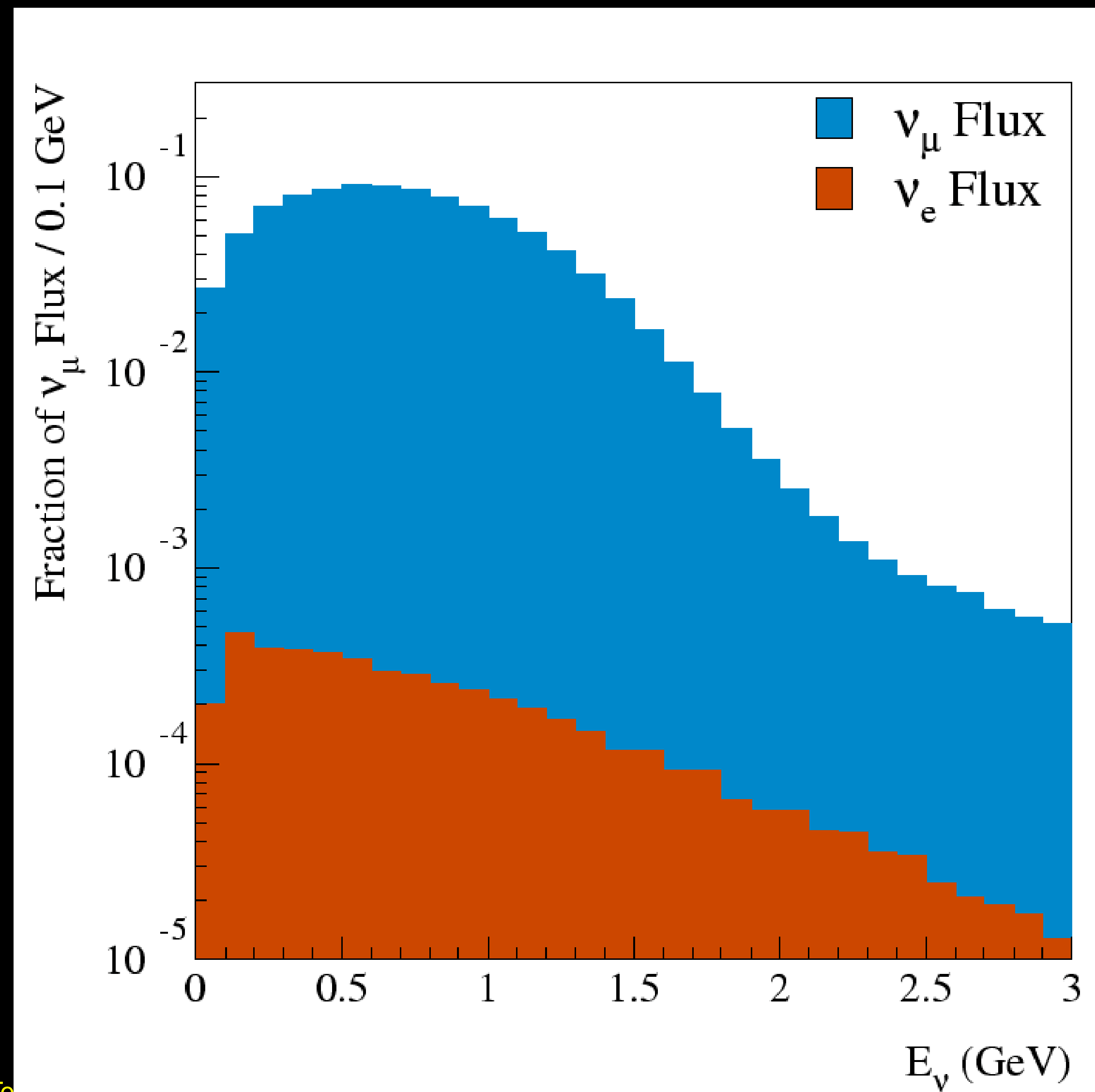
Neutrino Flux



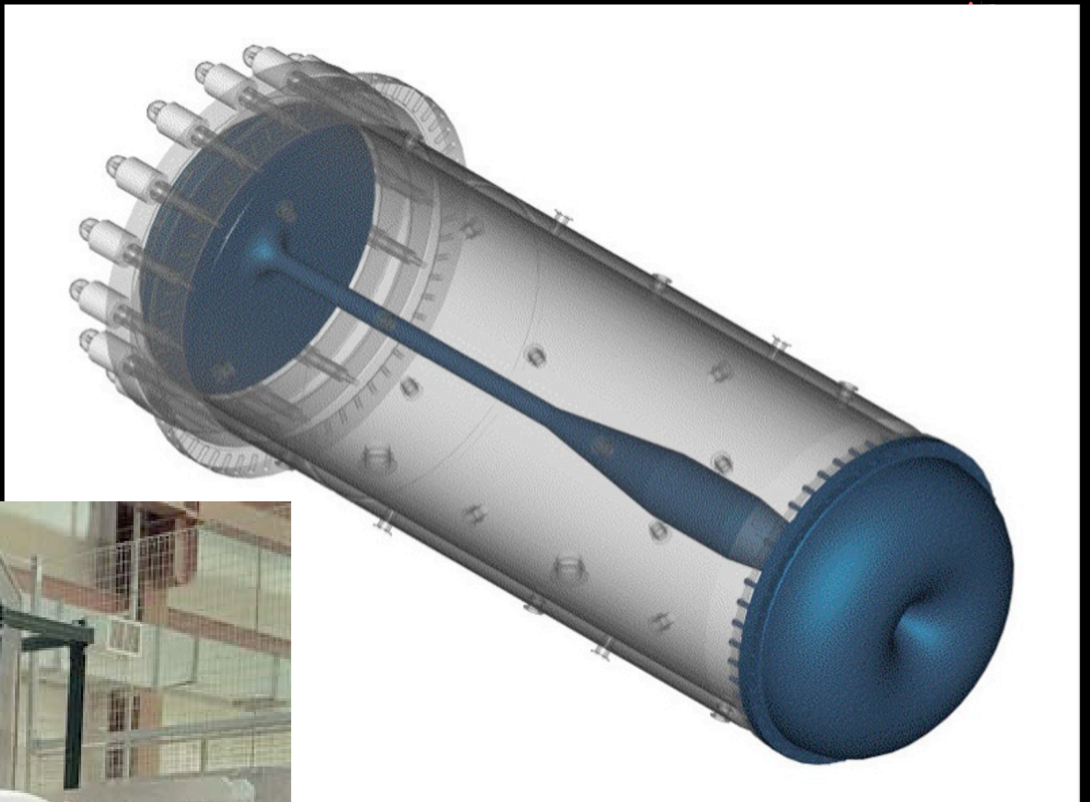
- Use external meson production data to predict rates
- Monte Carlo simulation predicts neutrino flux at detector
  - 99.5% are muon neutrinos
  - 0.5% intrinsic ν_e

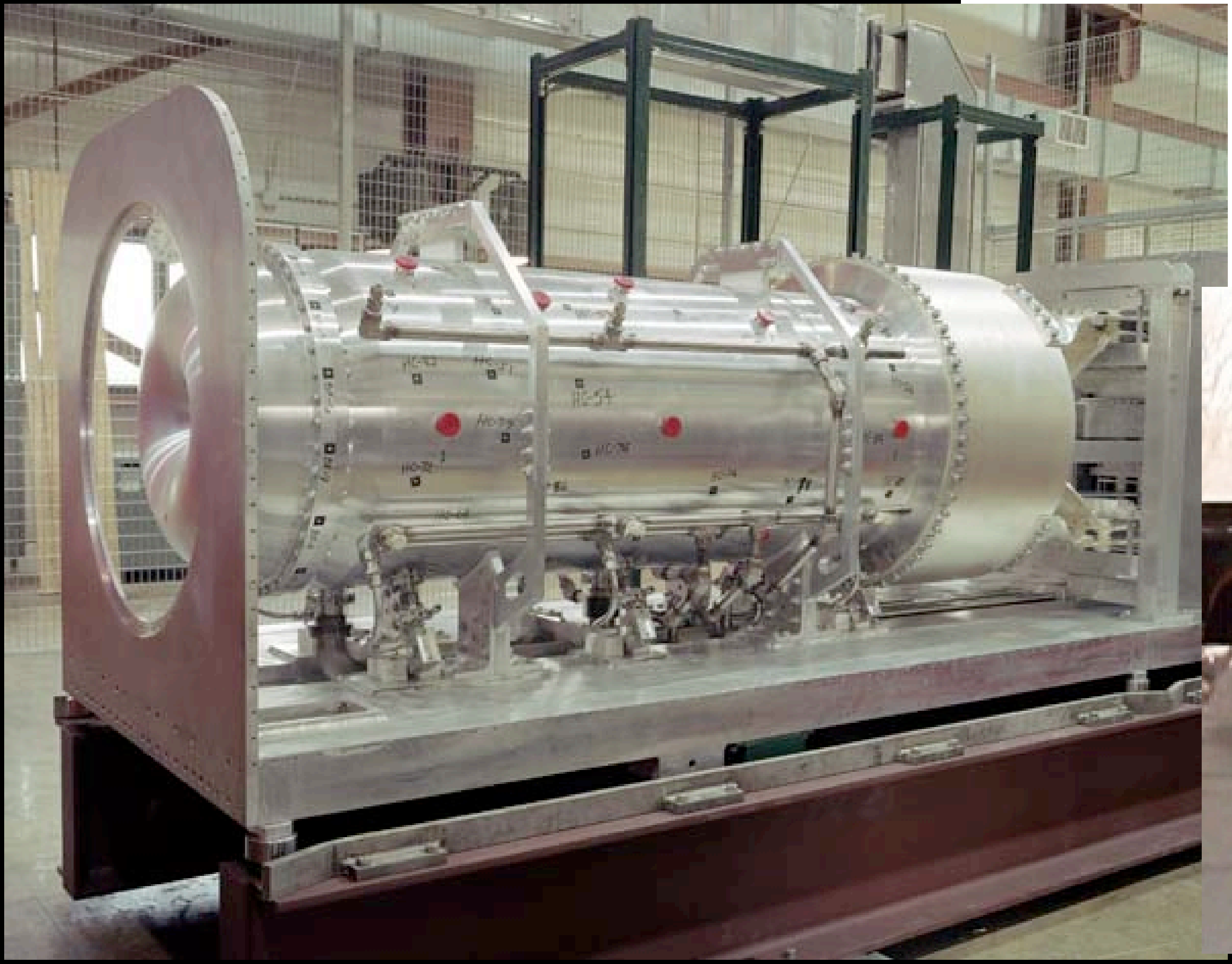
$$\pi^+/K^+ \rightarrow \mu^+\nu_\mu$$
$$\pi^-/K^- \rightarrow \mu^-\bar{\nu}_\mu$$

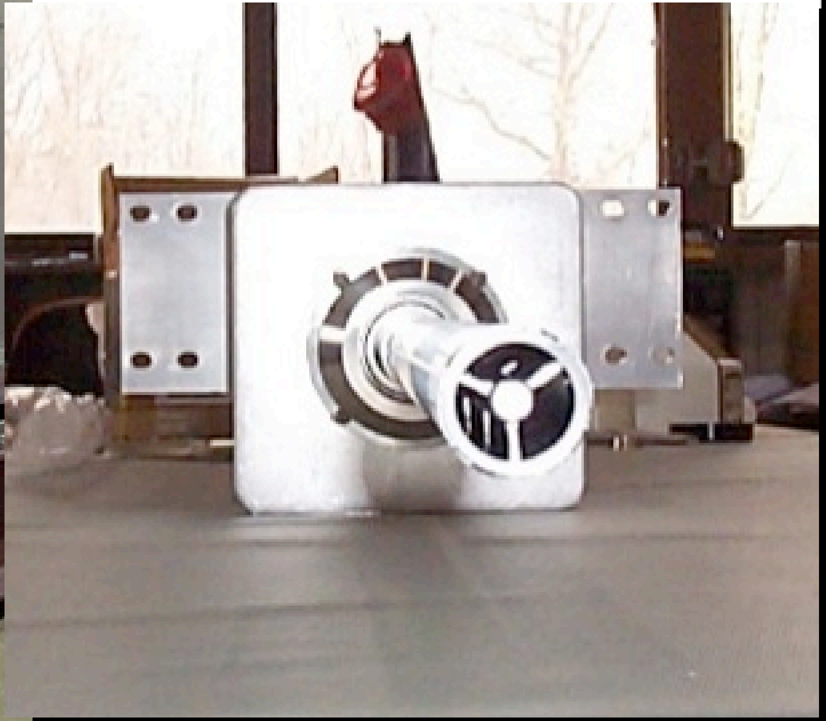
$$K^+/K^0_L \rightarrow \pi e \nu_e$$
$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$



MiniBooNE Horn and Target

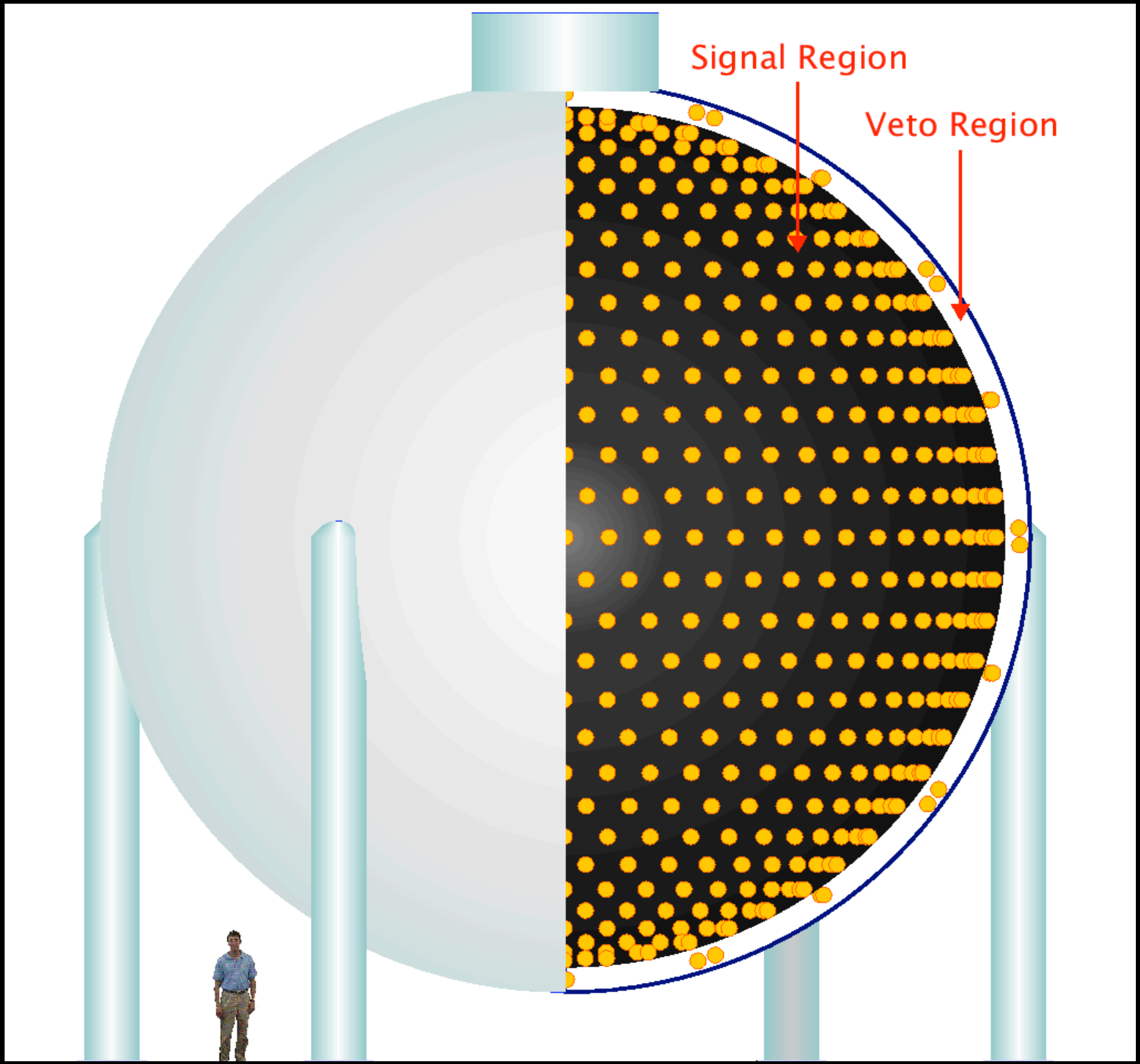


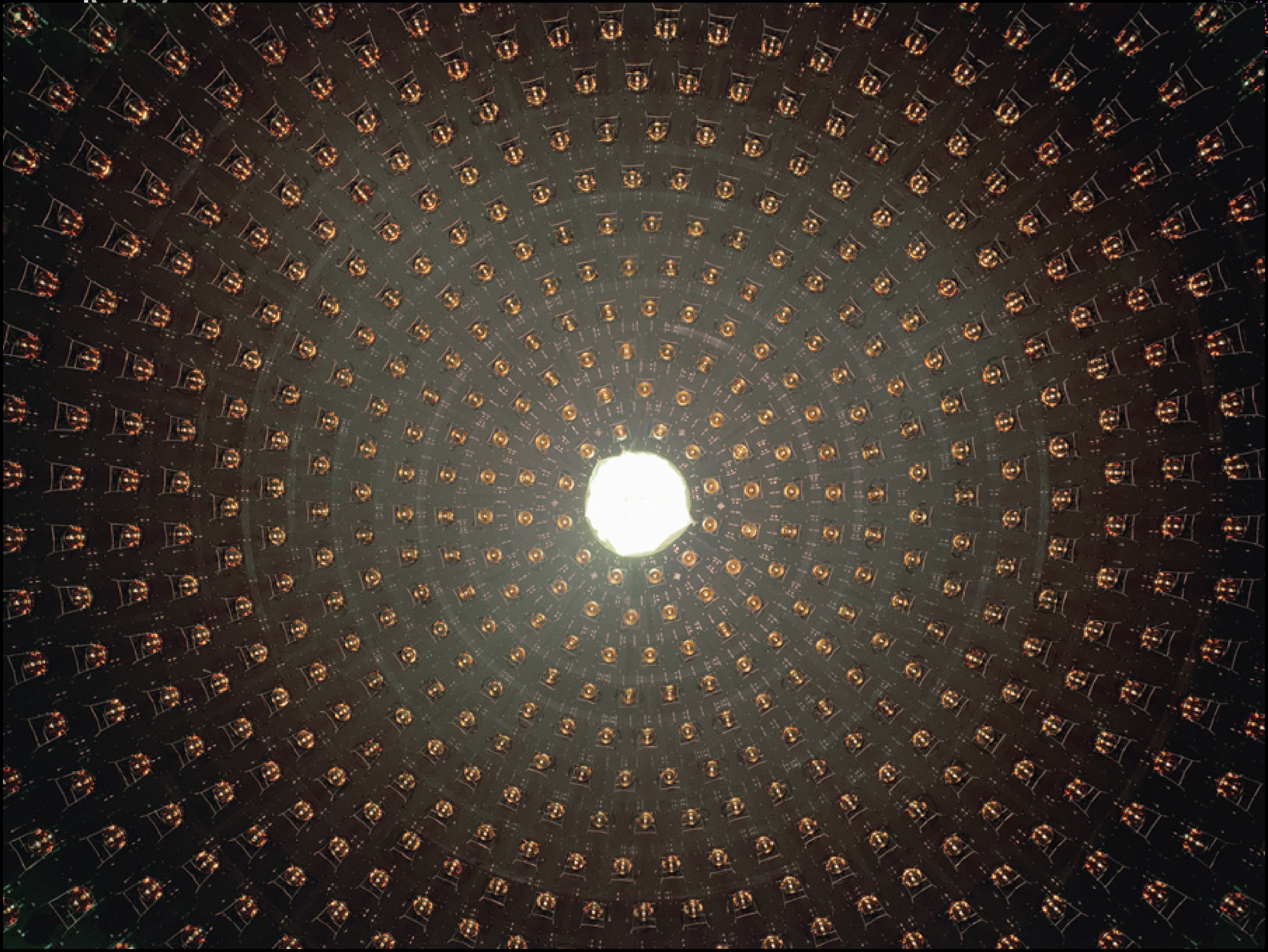




MiniBooNE Detector

- 800 tons of pure mineral oil
- 6m radius steel sphere
- ~2m earth overburden
- 1520 8" PMTs
  - 1280 in main tank (sphere)
  - 240 in veto region (shell)
  - LSND PMTs/New PMTs
- DAQ records t,Q
  - "Hits"





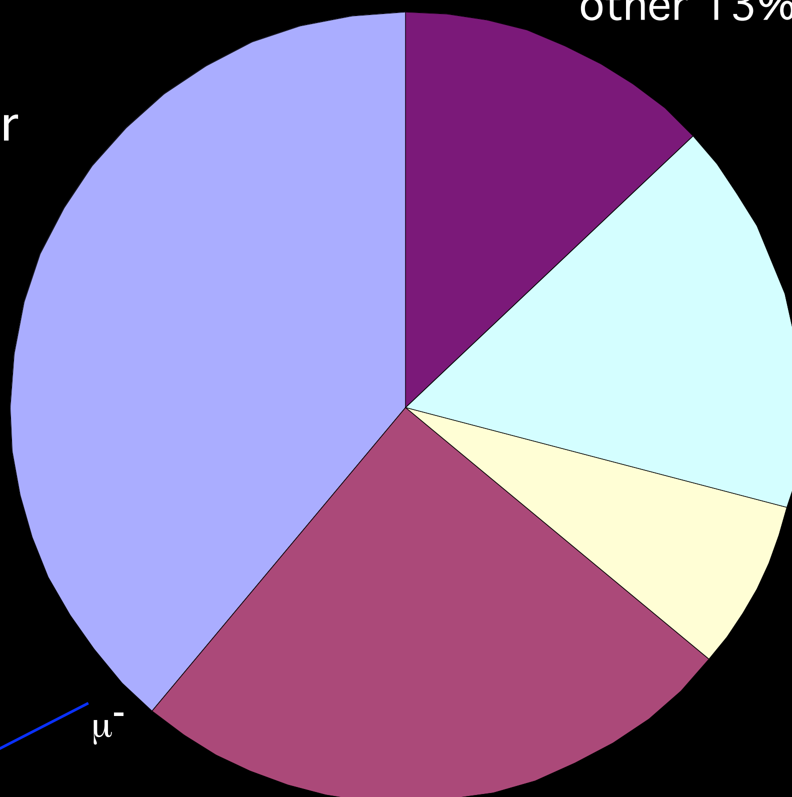
Neutrinos in oil

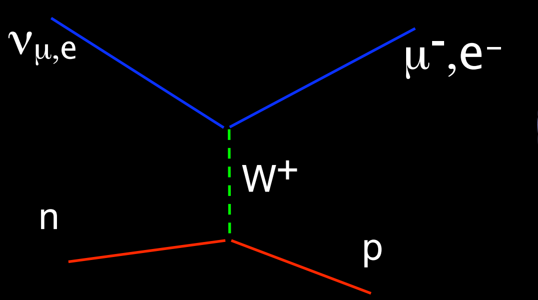
A neutrino can do many things in mineral oil...

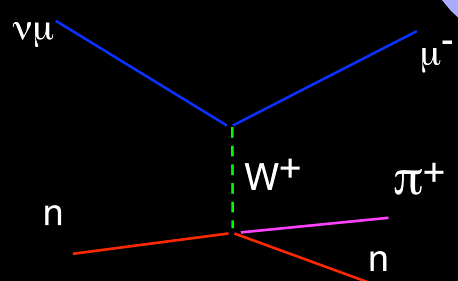
About 75% CC, 25 % NC

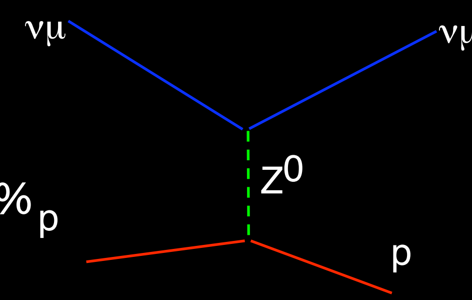
NC events lose energy when neutrino escapes detector

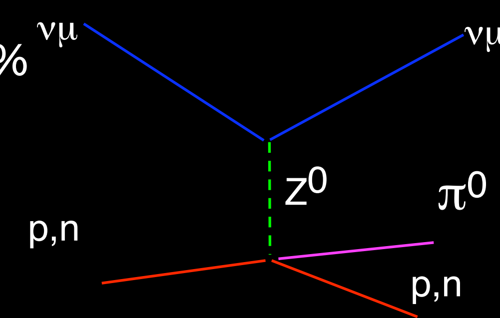
CC events deposit all energy in detector





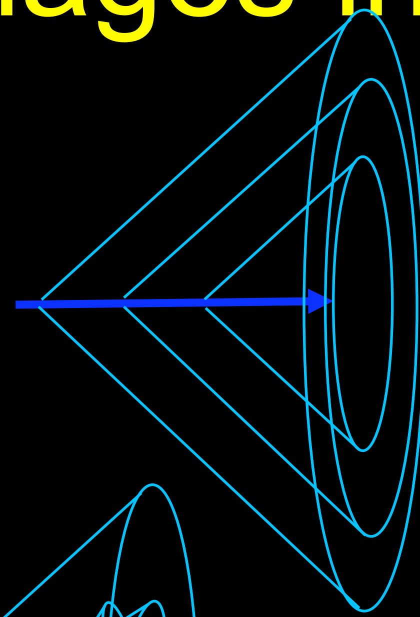


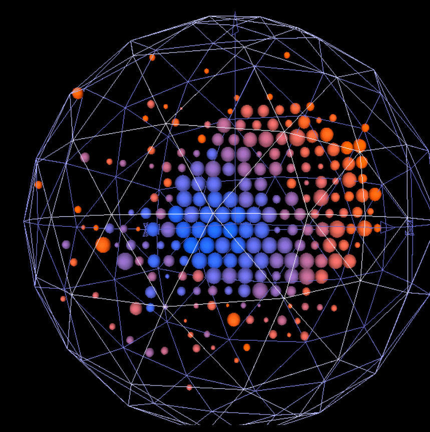




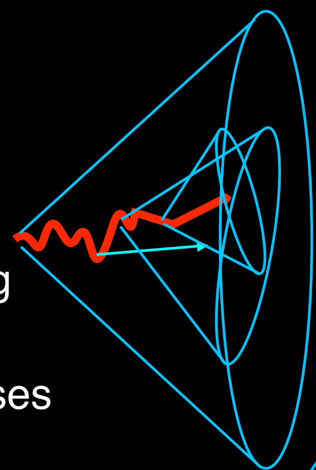
Particle Images in MiniBooNE

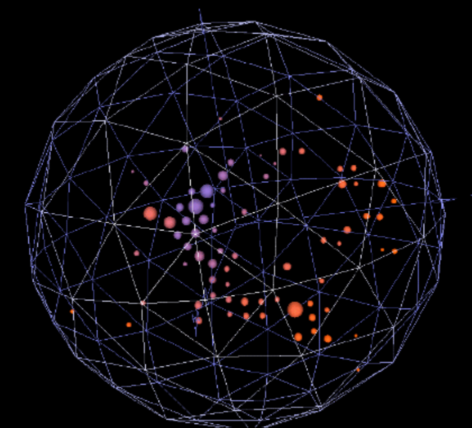
- Muons
  - Sharp, clear rings
    - Long, straight tracks



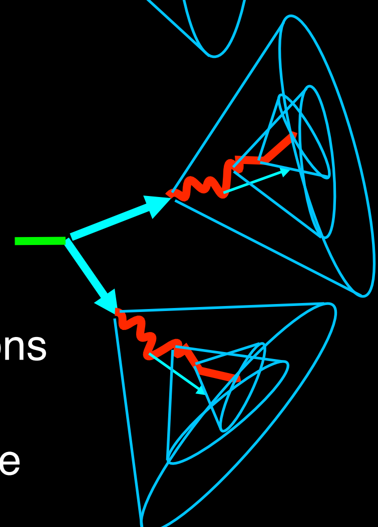
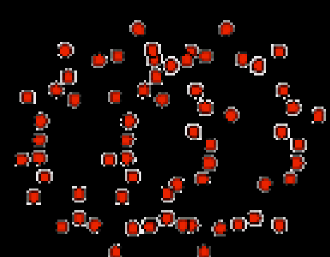
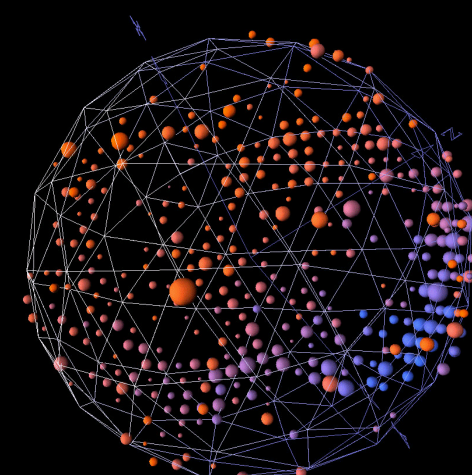


- Electrons
  - Scattered rings
    - Multiple scattering
    - Radiative processes



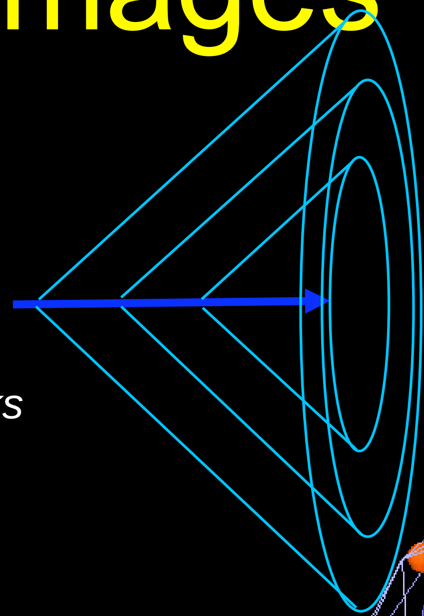


- Neutral Pions
  - Double rings
    - Decays to two photons
    - Photons pair produce

Particle Images in MiniBooNE

- *Muons*
  - *Sharp, clear rings*
    - *Long, straight tracks*



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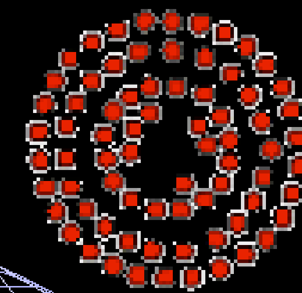

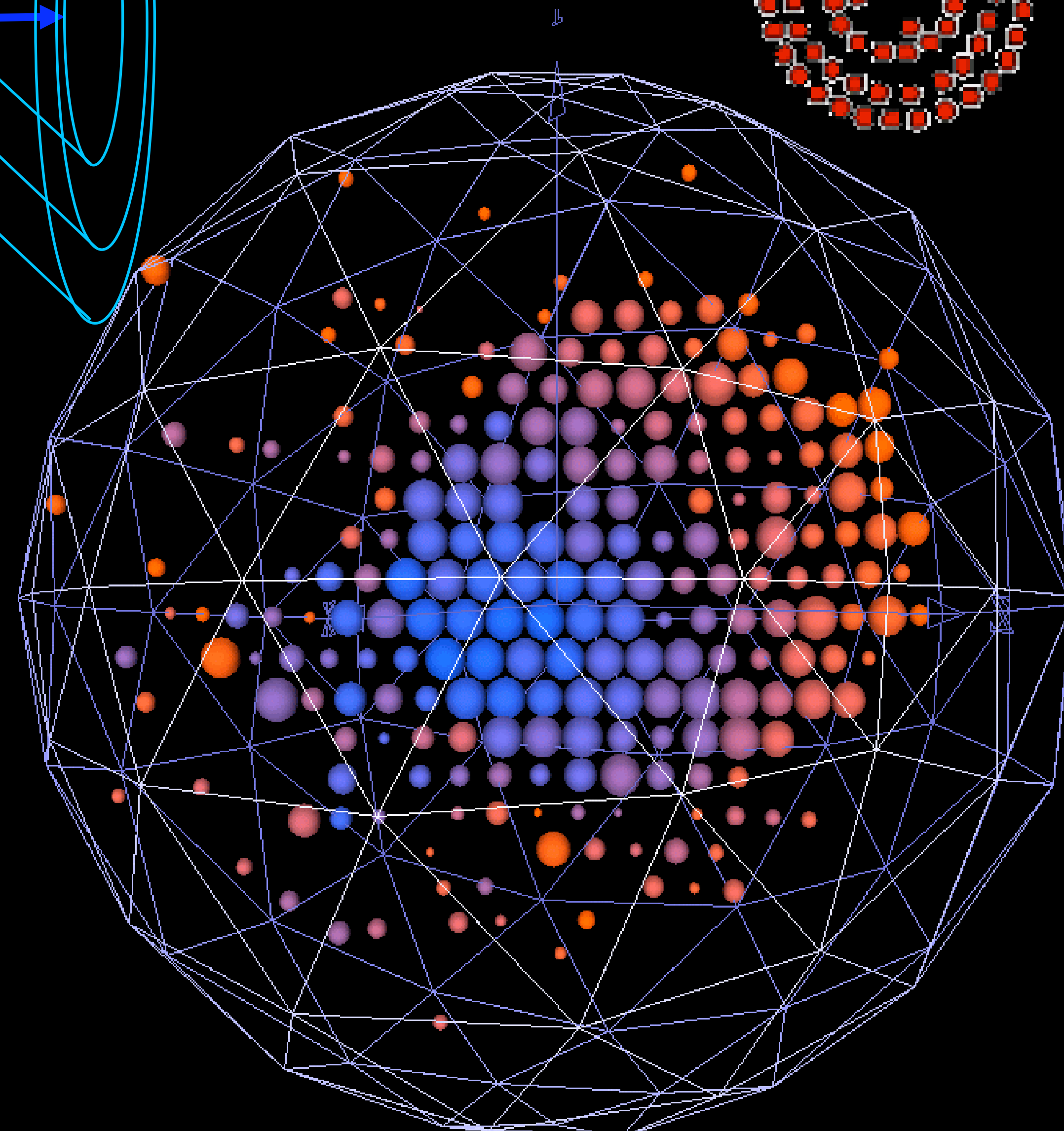

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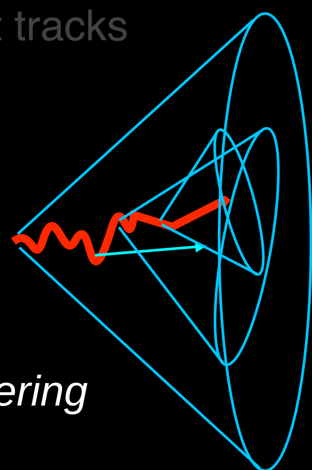

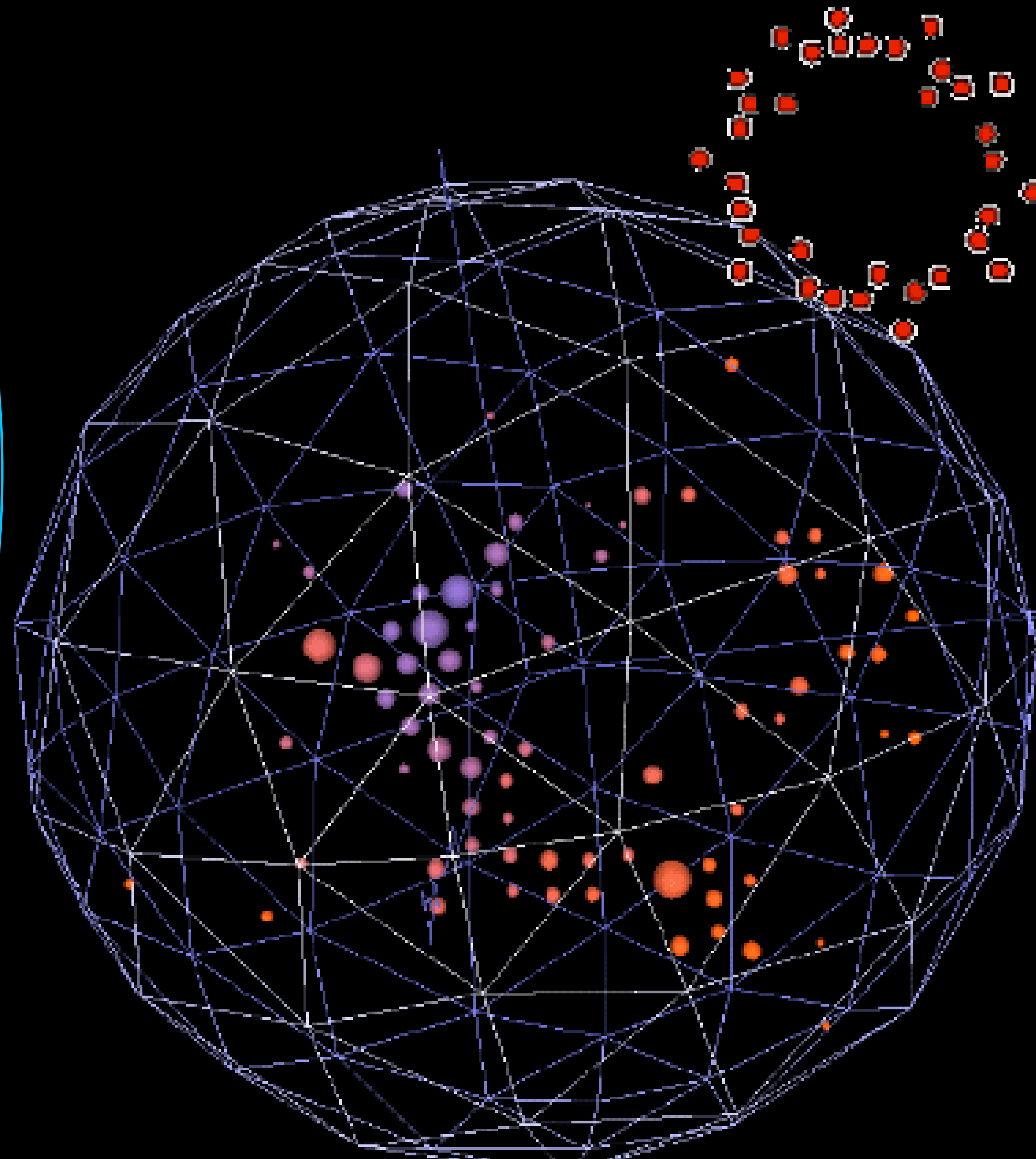

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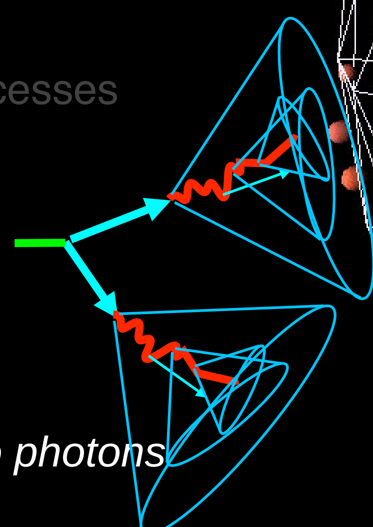
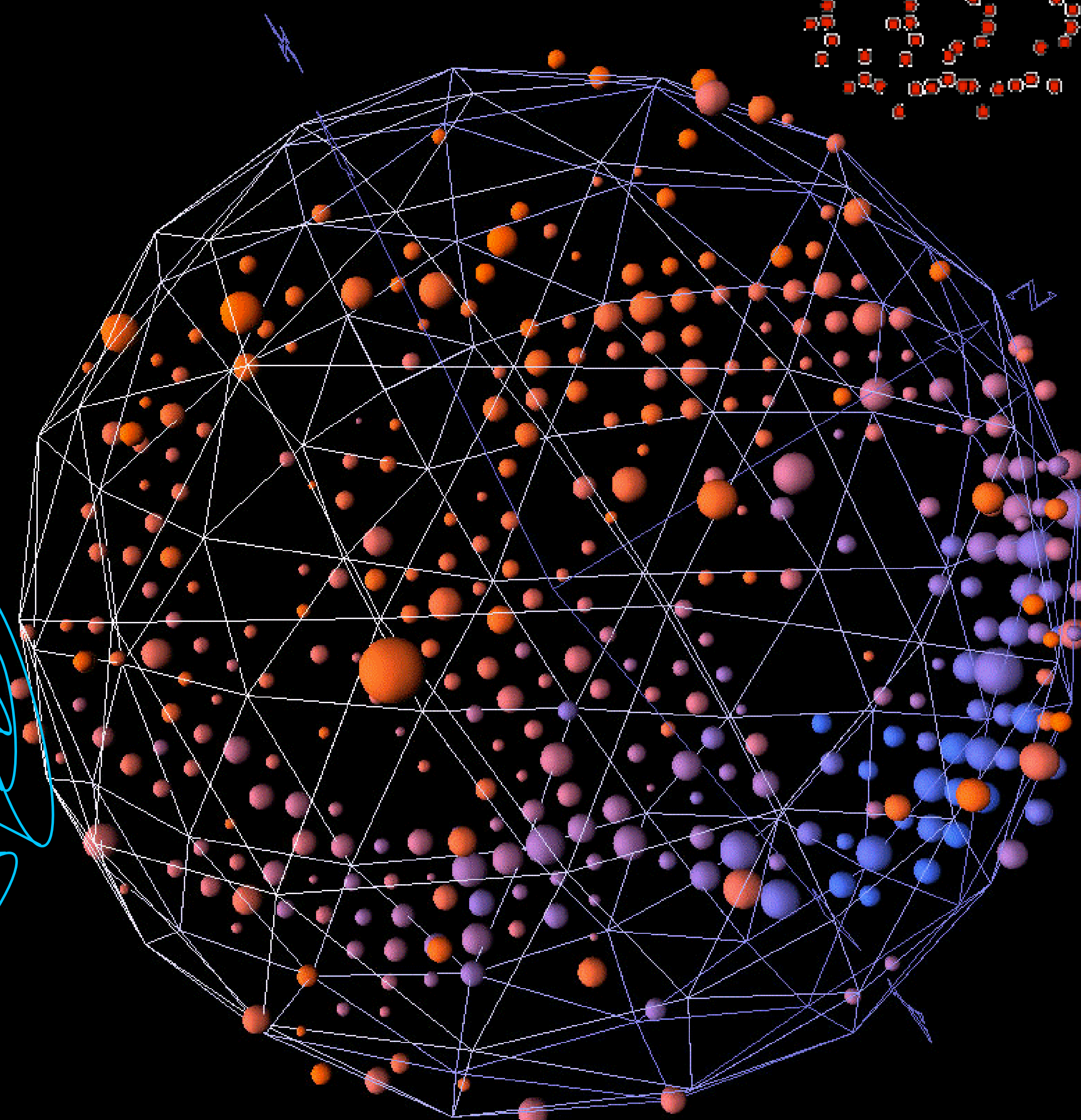
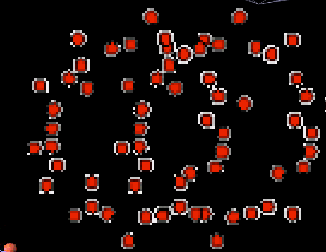
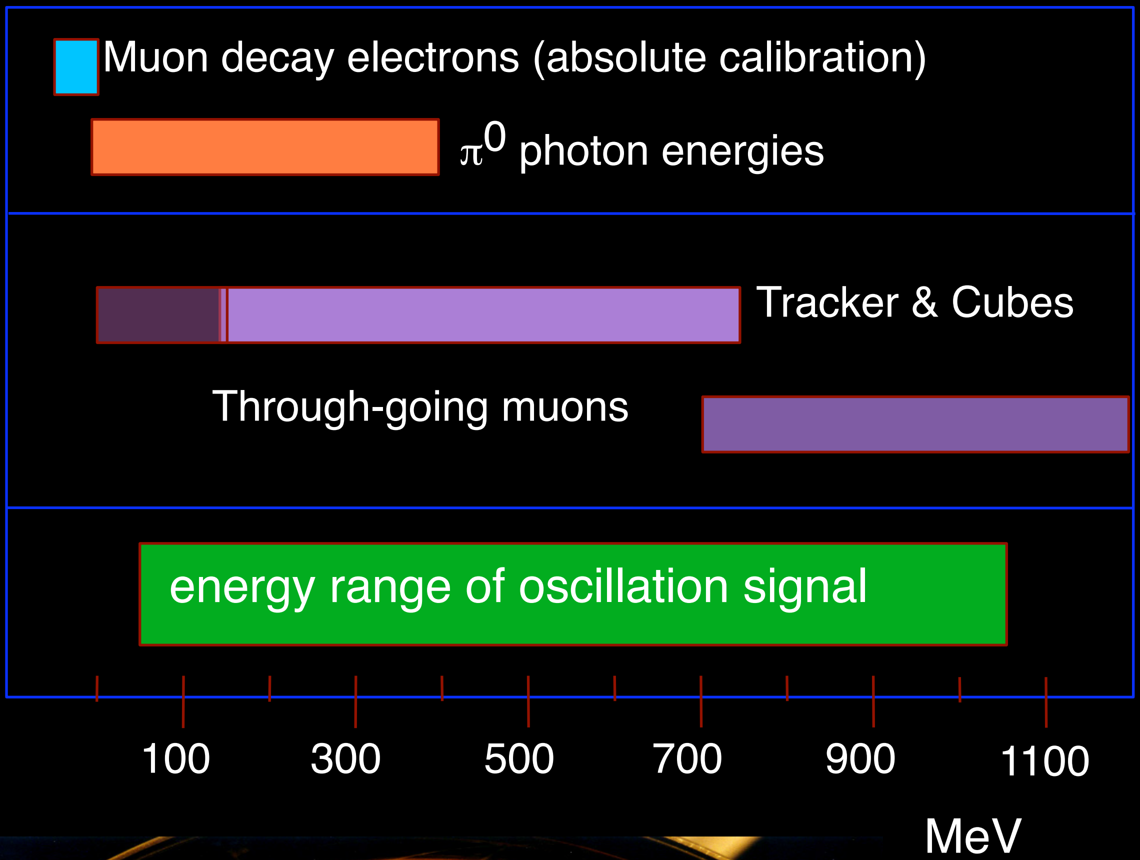






Imperial College London
100 years of living science
100

Detector Calibration



Why we think we understand the detector ...

PMTs calibrated with laser system

Calibration data samples span oscillation signal energy range

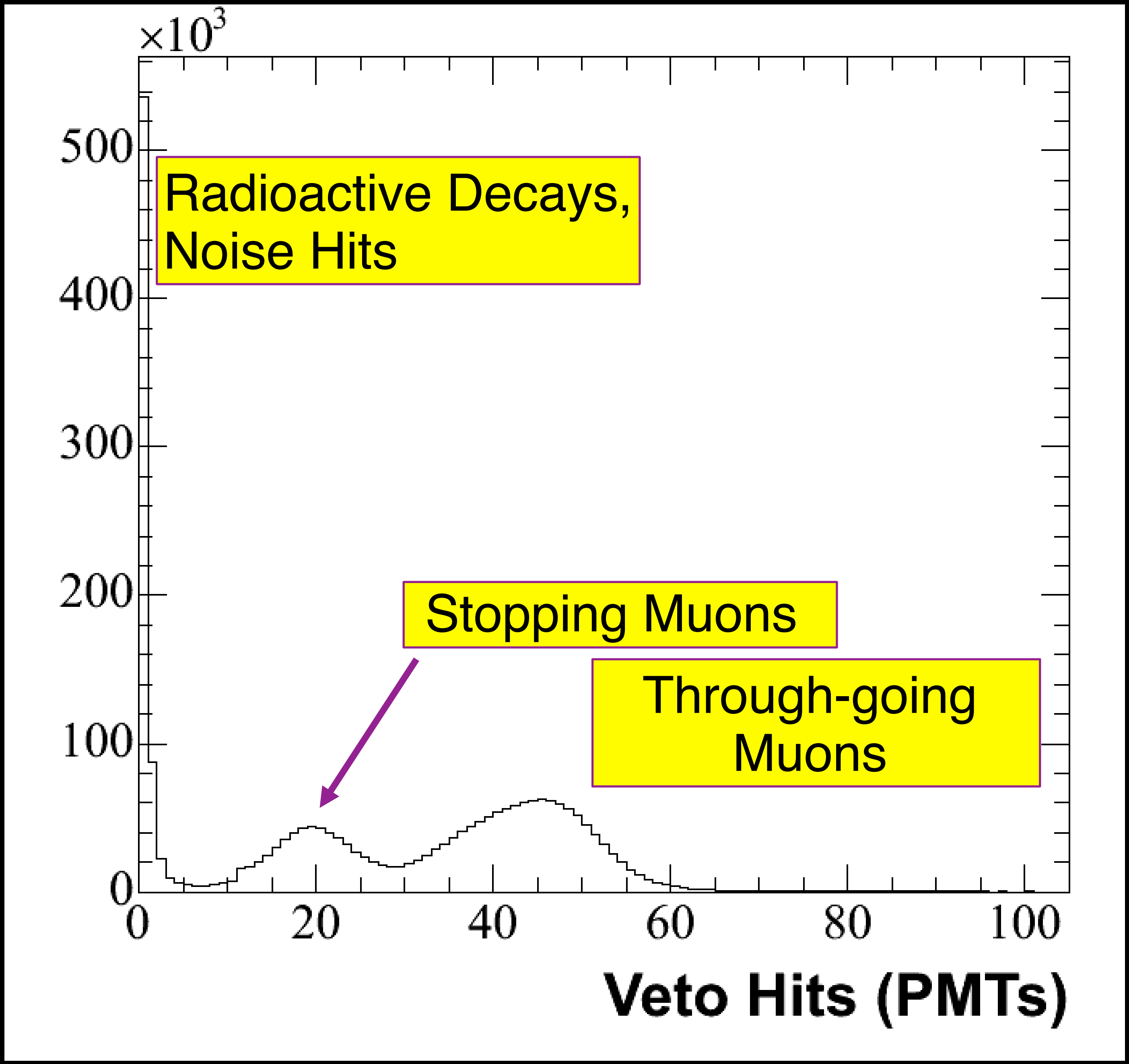
Electron data samples

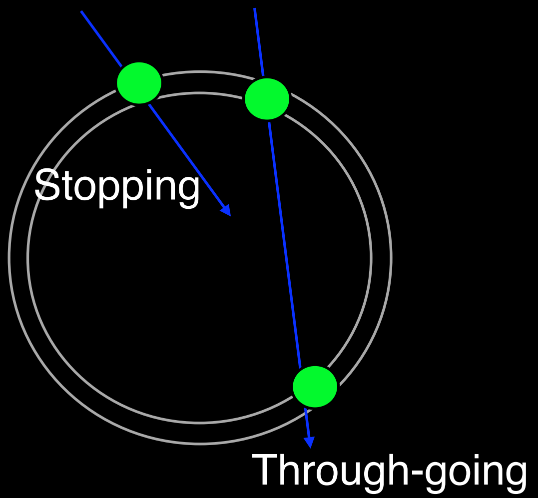
- Muon decay at rest electrons
- π^0 photons

Cosmic Muons

- Stopping, through-going
- *Very important: most neutrino events have muons*

Looking at Tank Data





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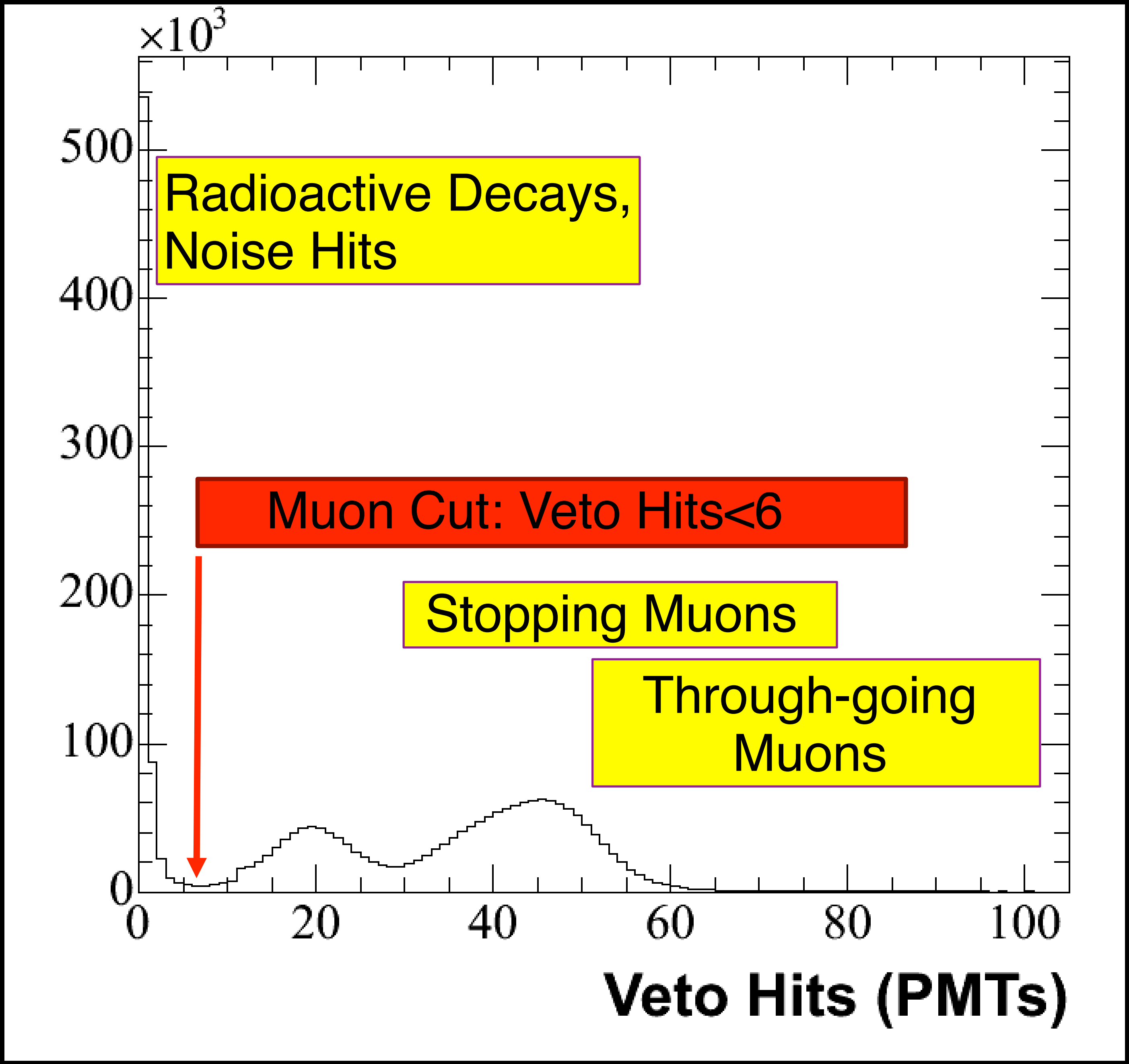

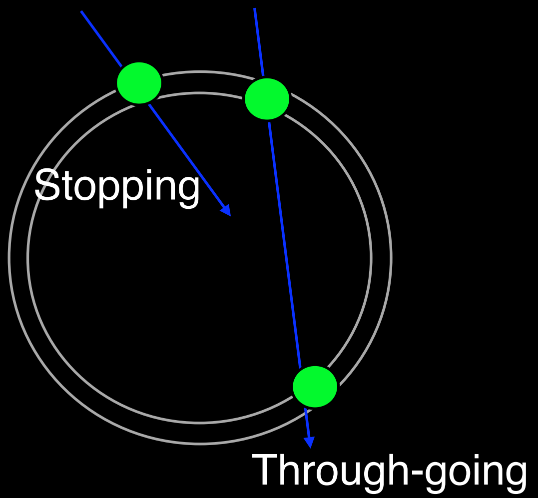

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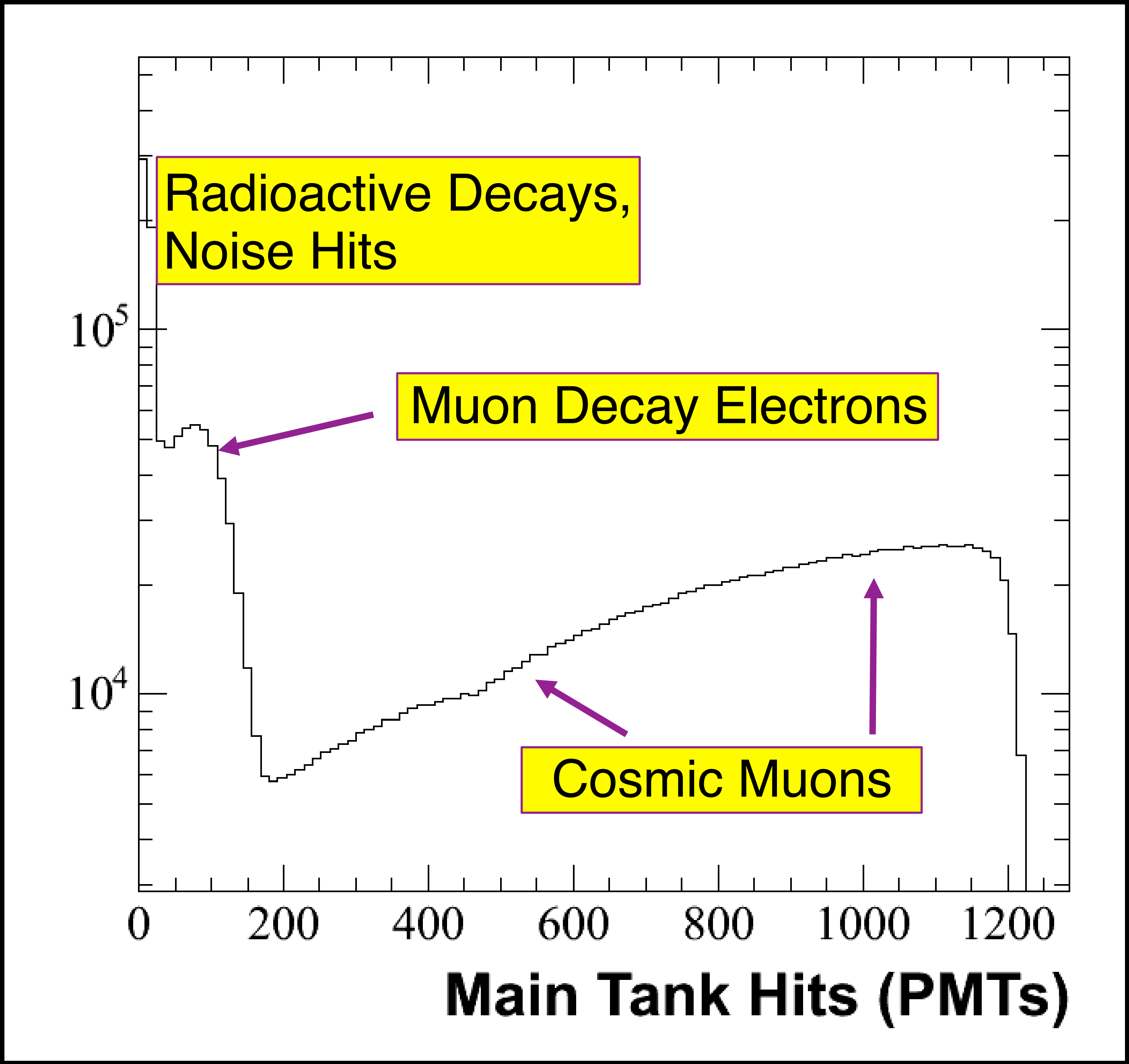
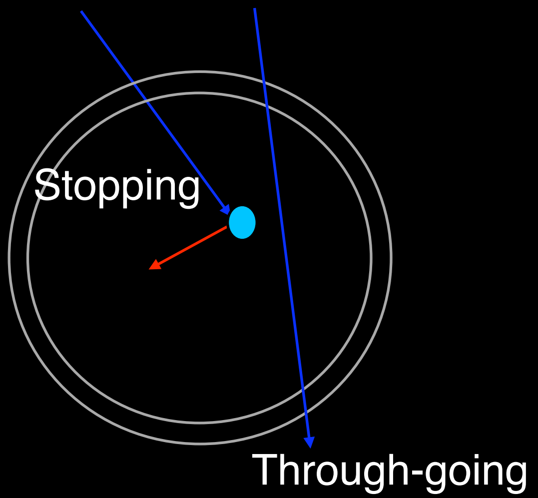


Putting it all together...



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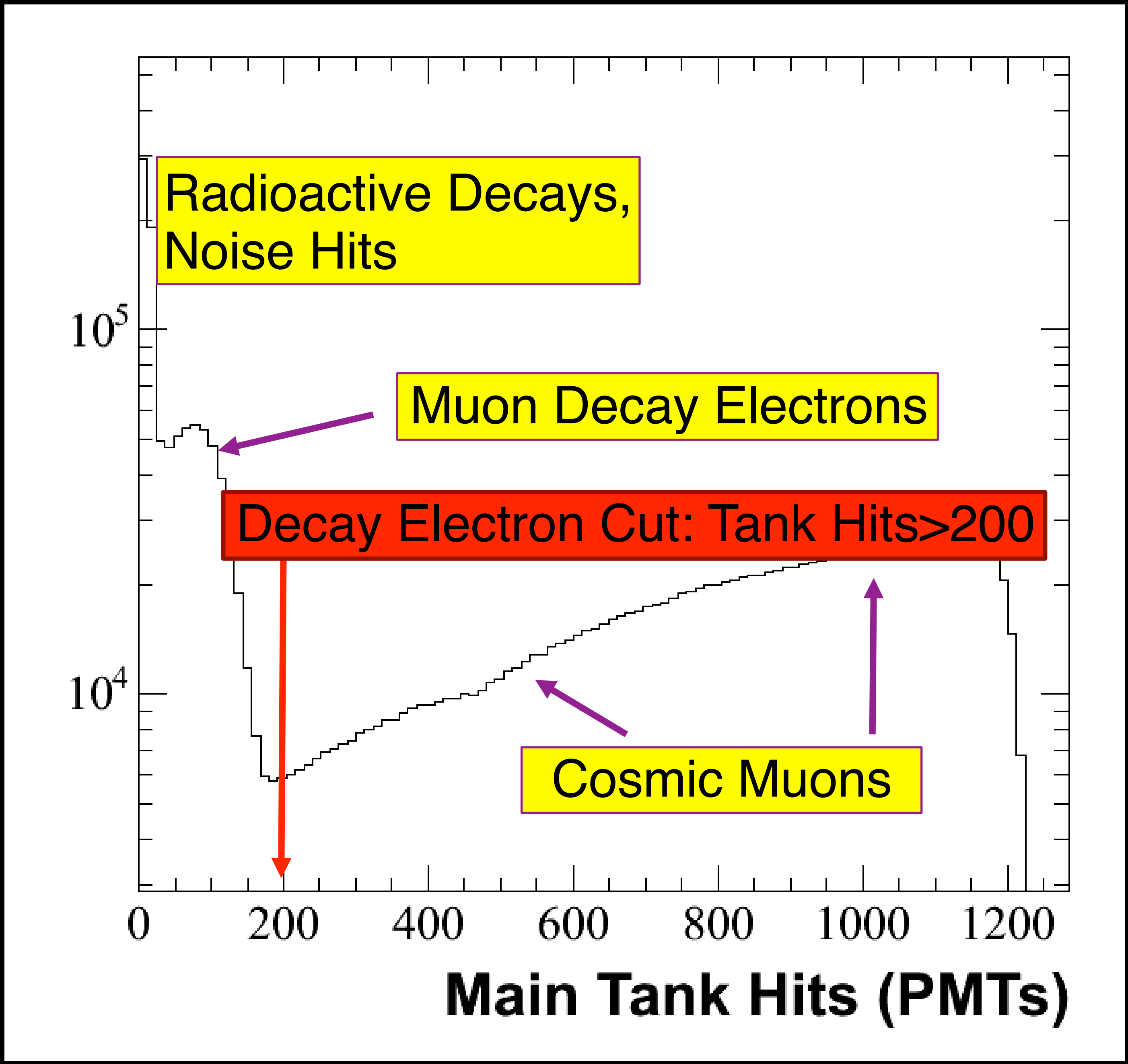

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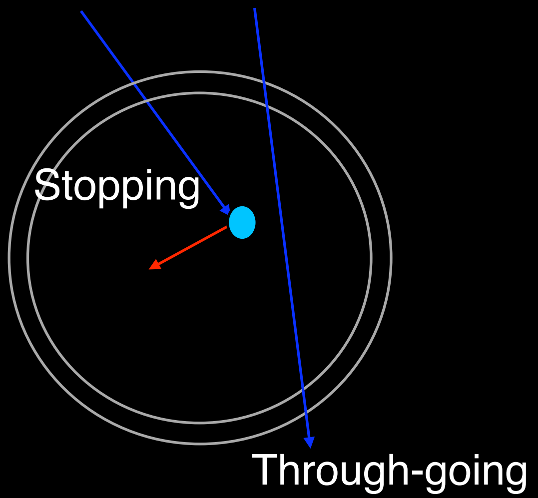

Triggering on Neutrinos

- MiniBooNE's neutrino trigger is unbiased
- The Booster dumps protons onto our target in 1.6μs intervals, several times per second
    - “Beam spill”
- We know exactly when neutrinos from the beam are passing through the detector
- When this happens, we record all detector activity in a 20μs interval around the beam spill

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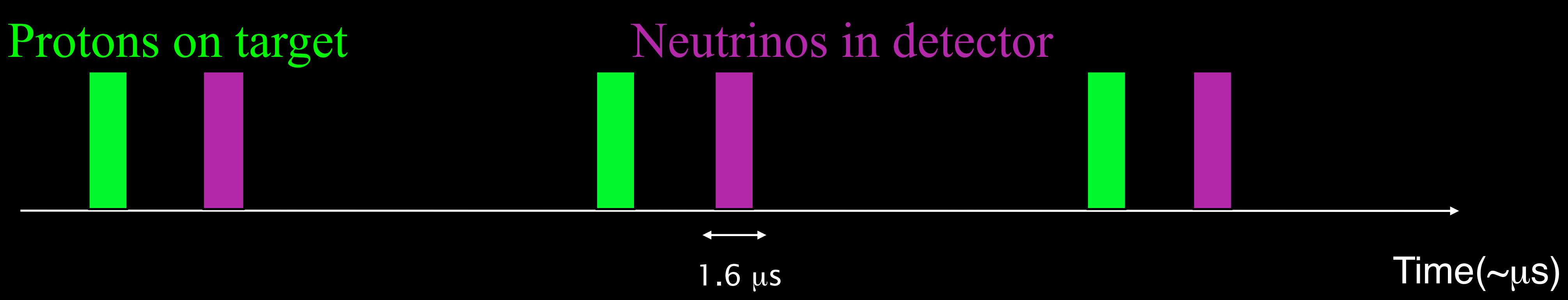

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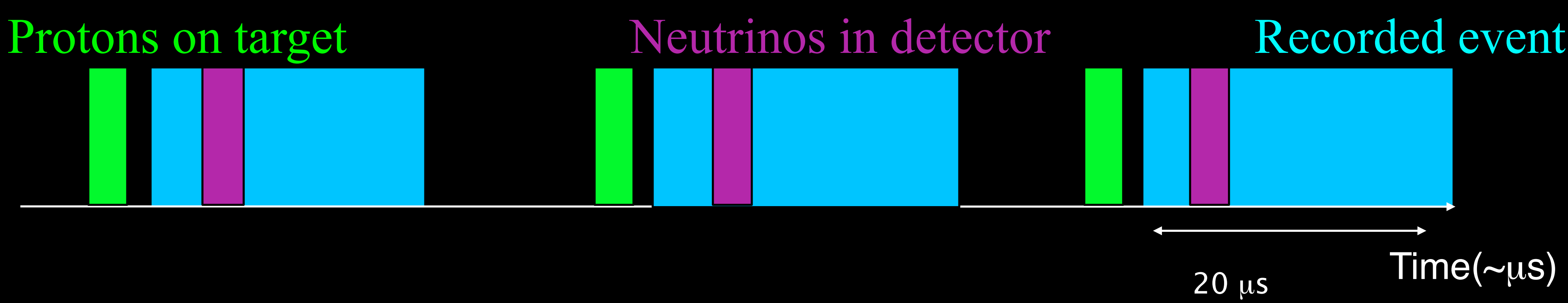
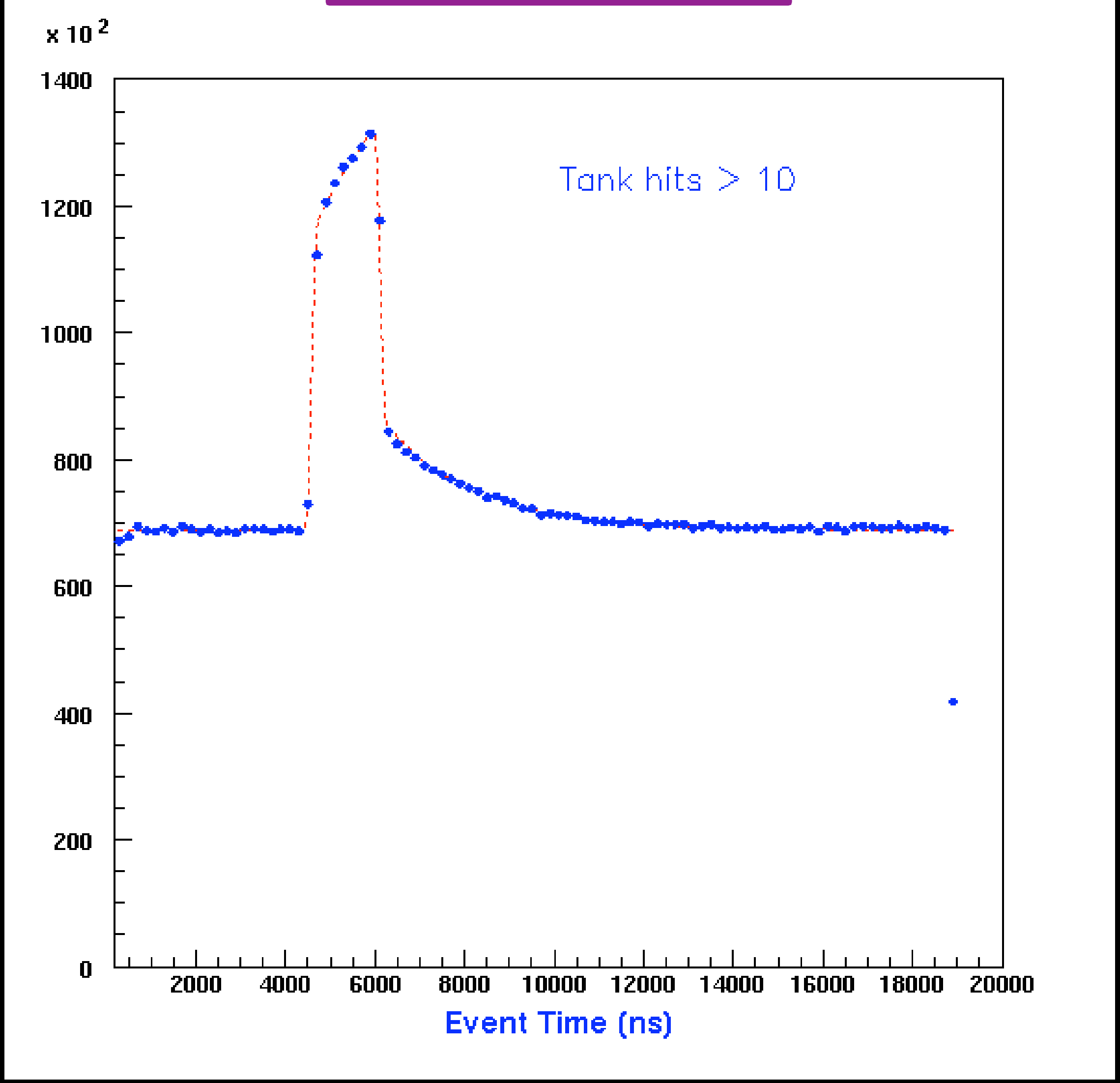


Picking out Neutrinos

- Times of hit-clusters (sub-events)
- Beam spill (1.6μs) is clearly evident
  - simple cuts eliminate cosmic backgrounds
- Neutrino Candidate Cuts
  - <6 veto PMT hits
    - Gets rid of muons
  - >200 tank PMT hits
    - Gets rid of Decay e

Beam and Cosmic BG



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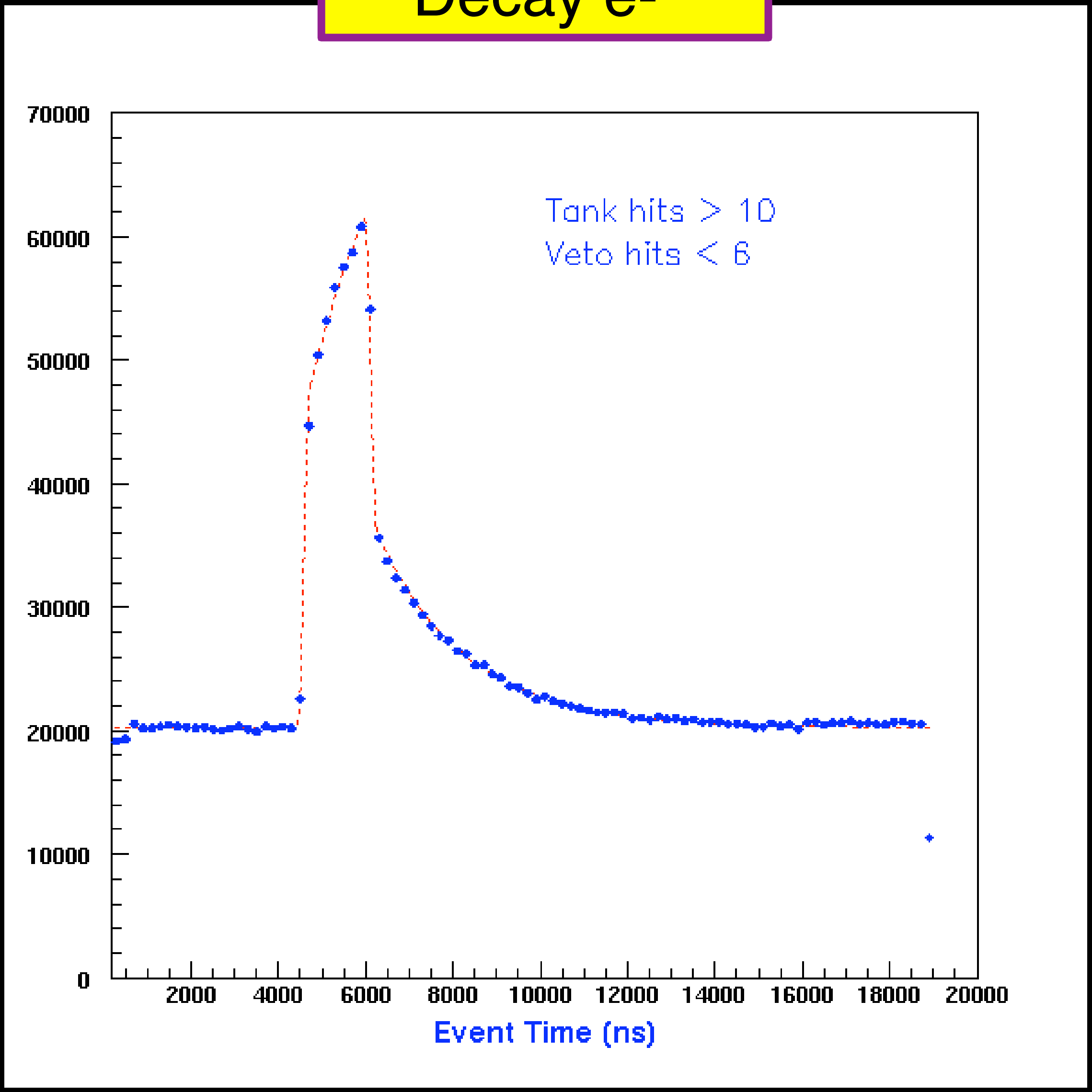
Beam and Decay e-



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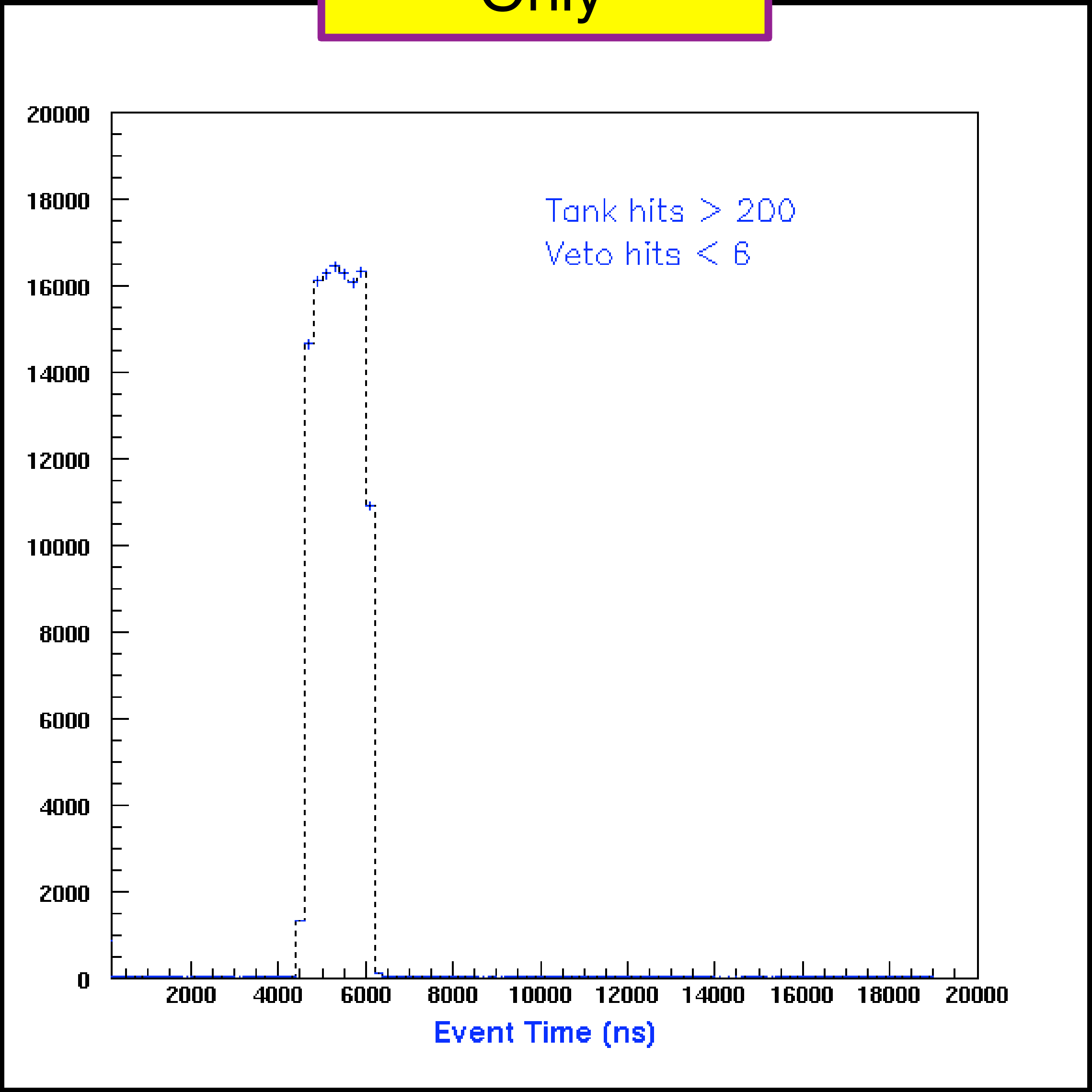
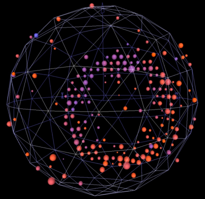
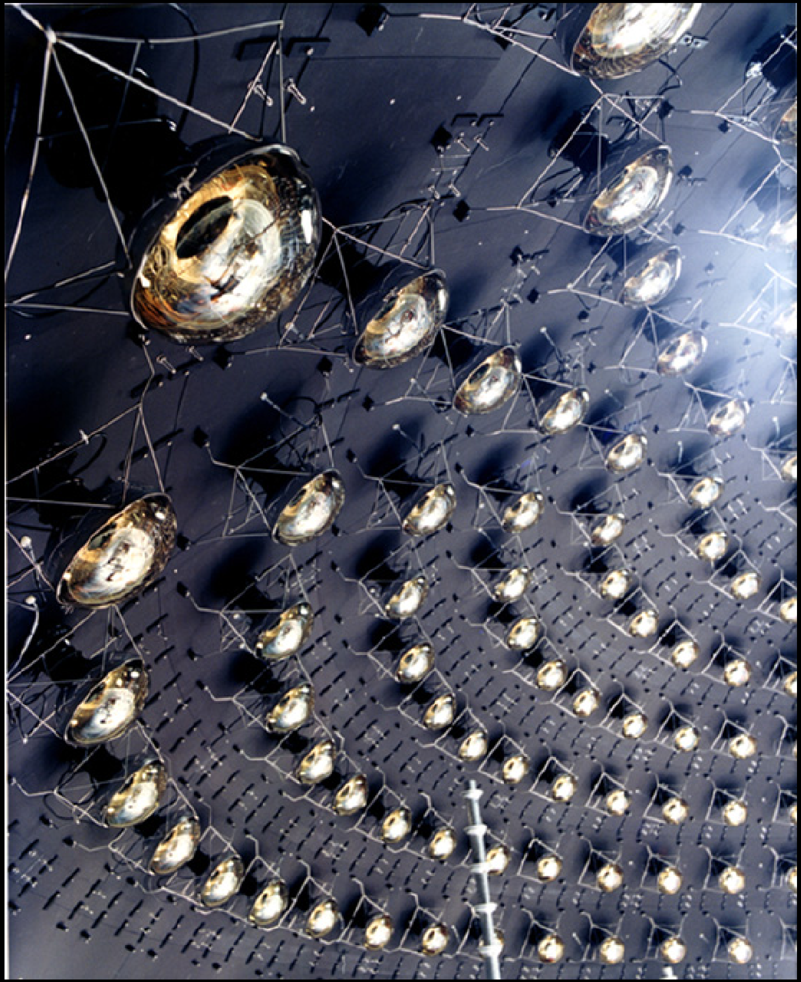
  - simple cuts eliminate cosmic backgrounds
- Neutrino Candidate Cuts
  - <6 veto PMT hits
    - Gets rid of muons
  - >200 tank PMT hits
    - Gets rid of Decay e
  - Only neutrinos are left!

Beam Only

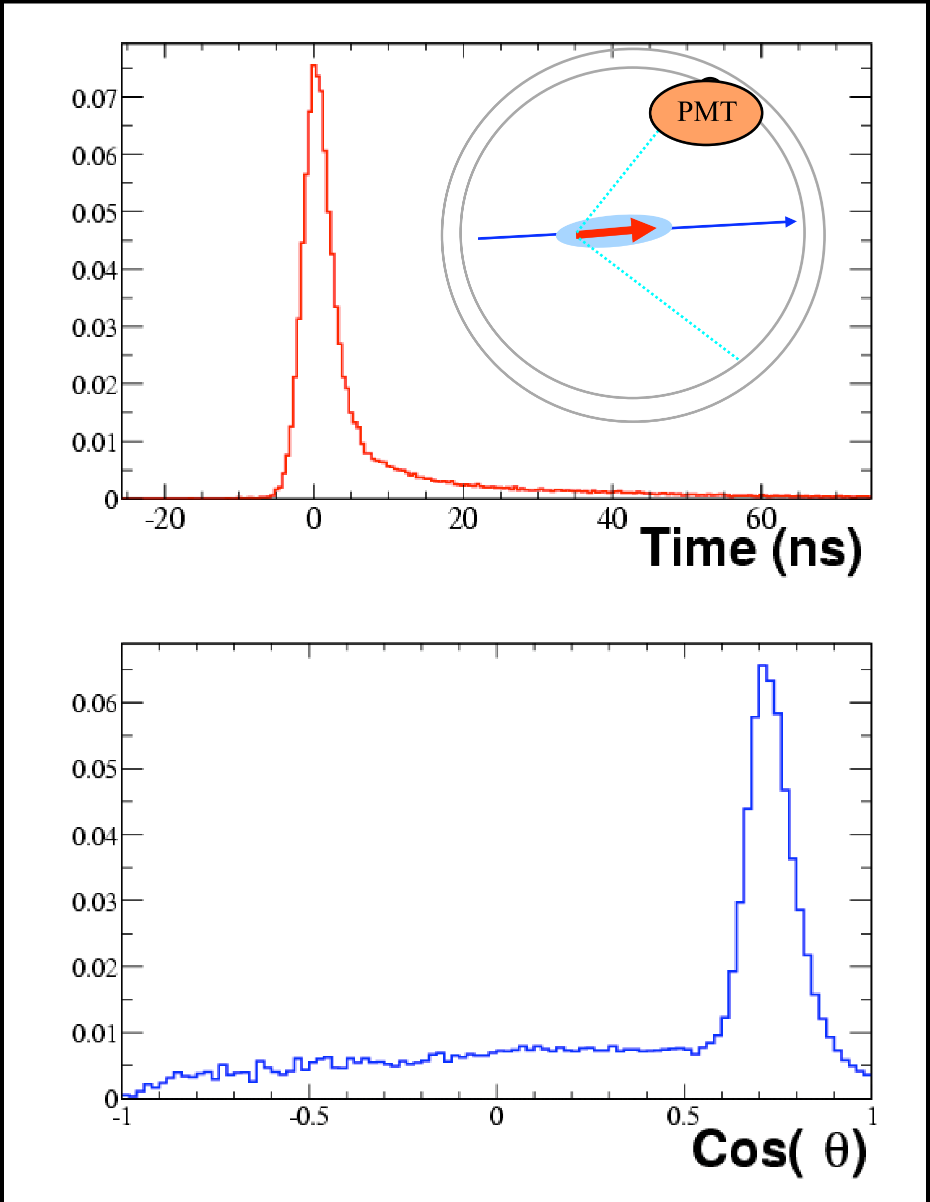


Track Reconstruction





Neutrino interactions create energetic charged particle emission and hence light production



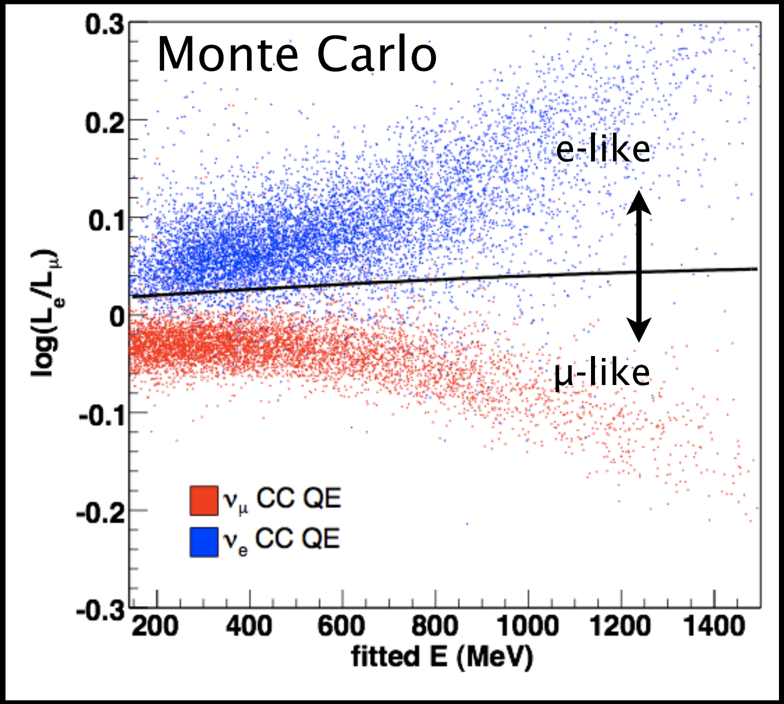
PMTs collect photons, record t,Q

Reconstruct tracks by fitting time and angular distributions

Find position, direction, energy

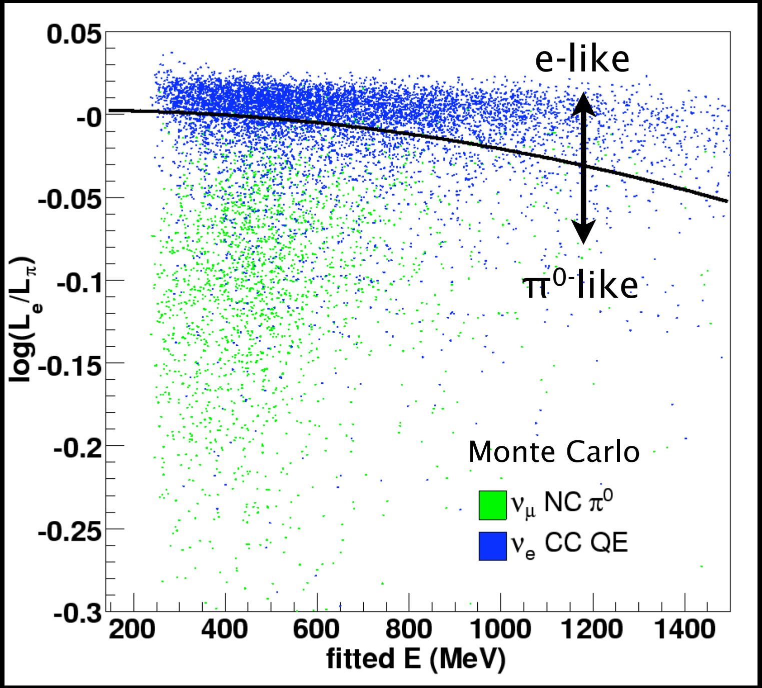
Particle Identification

Reconstruct under 3 possible hypotheses: μ-like, e-like, π^0-like



Reconstruction produces likelihoods for the three hypotheses

- Likelihood = product of probabilities for observed pattern, t, Q of PMT hits



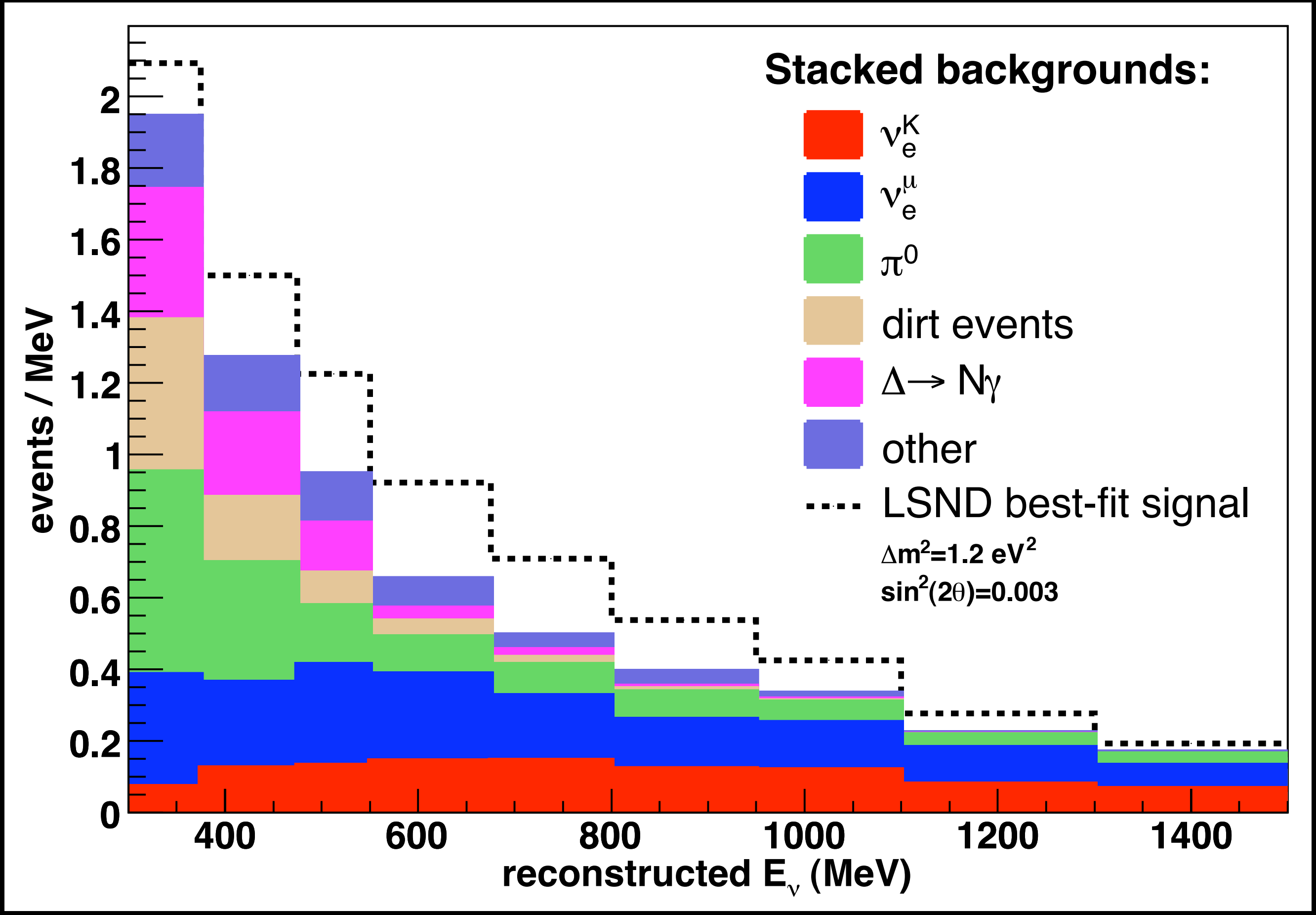
ν_e particle ID cuts on likelihood ratios

- cuts chosen to maximise sensitivity to $\nu_\mu \rightarrow \nu_e$ oscillation

Oscillation Search

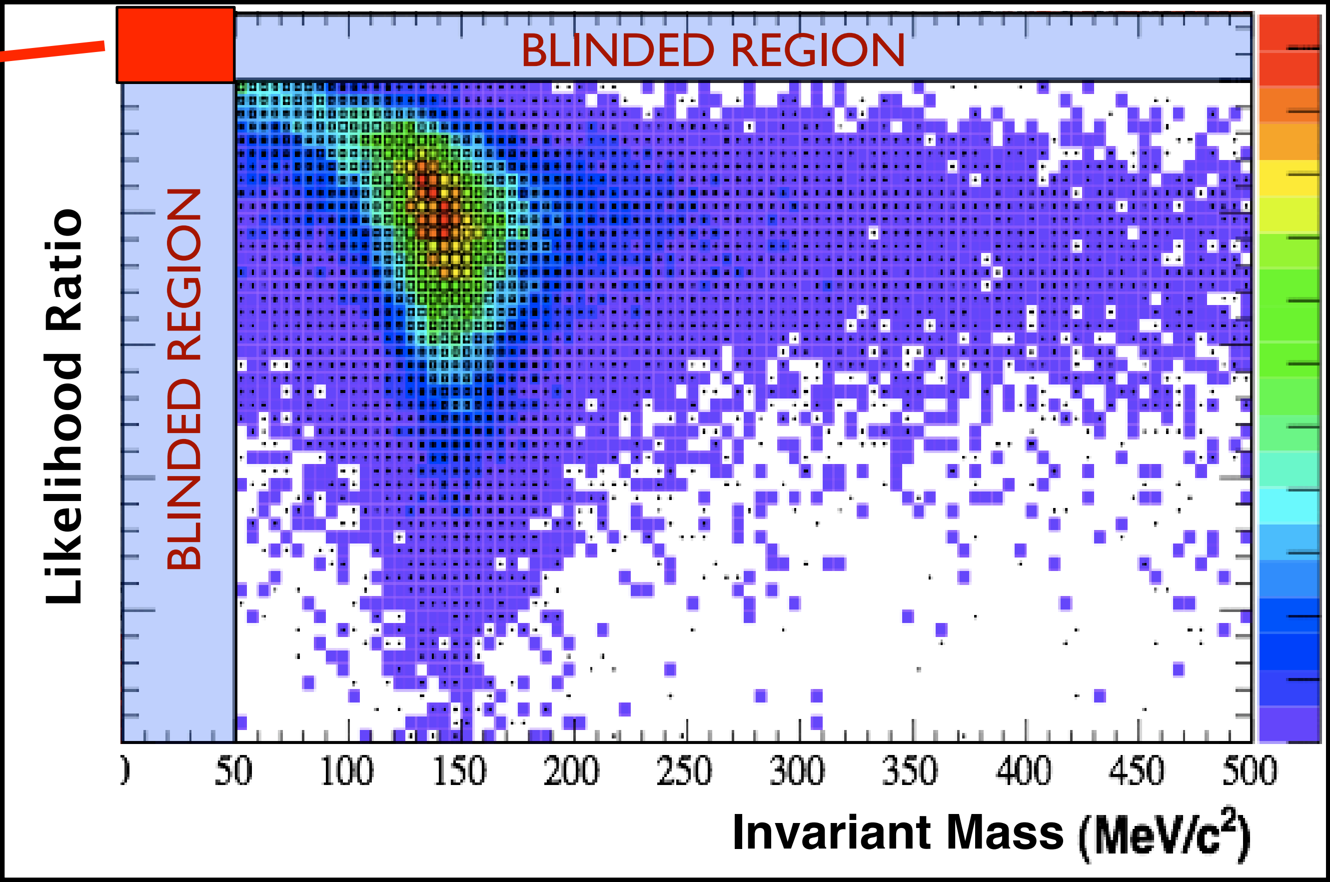
- To search for oscillations, look for excess of ν_e events above expected backgrounds
- Develop neutrino analysis with ν_μ data
  - Energy reconstruction
  - Backgrounds
  - Check with calibration data
- Apply to $\nu_\mu \rightarrow \nu_e$ appearance search
  - Use rates of ν_μ to predict ν_e rates

Predicted ν_e energy distribution



Blind Analysis

- For the ν_e appearance search, MiniBooNE performed a blind analysis
- "Closed box"
- Sequestered ν_e candidates and did not use them for analysis until all algorithms were finalised



R.B. Patterson

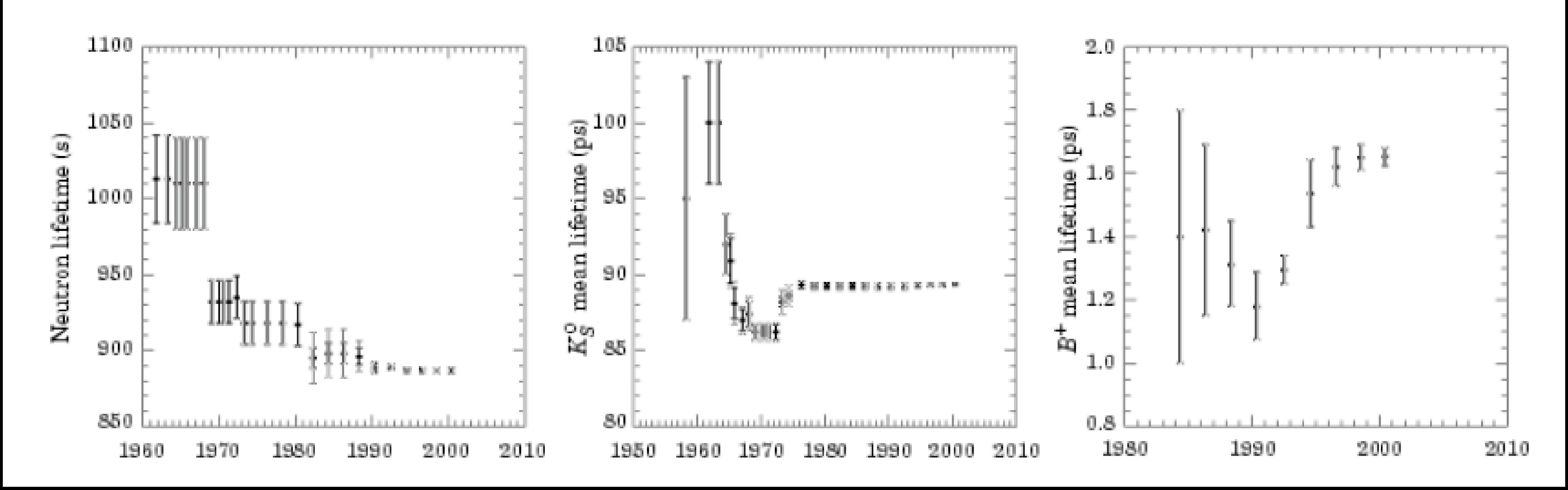
- Tested final two algorithms on sideband data

Why Blindness?

- Blind Analyses are employed to prevent introduction of unconscious bias
  - Cases where source of bias is unknown
- Philosophy: the “correctness” of our result is unrelated to the number of ν_e events - so don’t look!
- Common techniques in biological sciences and medicine
  - Double blind vs. single blind
- Even conference organisers now use blind analyses:
  - “All Submitted papers will be reviewed by a double-blind (at least three reviewers), non-blind, and participative peer review. These three kinds of review will support the selection process” Journal of Systemics, Cybernetics and Informatics

Need for Blindness

- Blind analysis is particularly useful if a previous measurement has been made



Examples from PDG (2000)

- Many examples of measurements that have come out artificially close to previous measurements

MOW
(blinded)
c.2002

We opened the box March 26, 2007

Search for ν_e Excess

Primary Analysis

Counting Experiment:
$475<E_\nu<1250$ MeV

expectation:
358 ±19 (stat) ± 35 (sys)

data: **380**

significance: **0.55 σ**

Cross-check Analysis

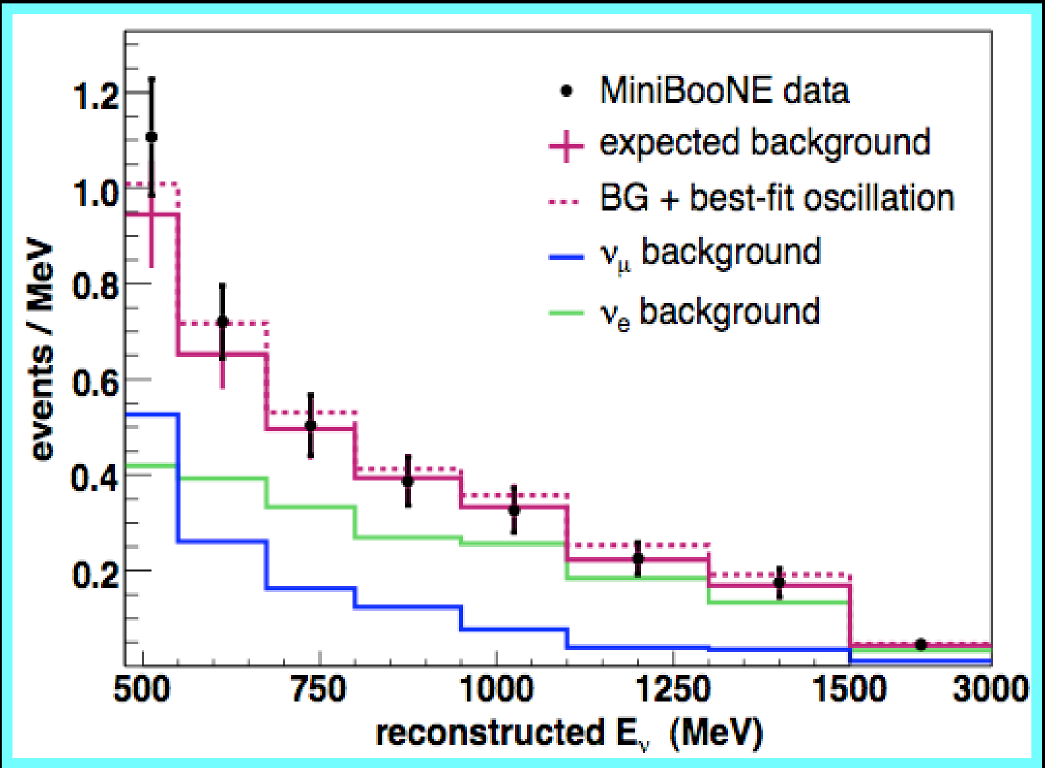
Counting Experiment:
$300<E_\nu<1500$ MeV

expectation:
1070 ±33 (stat) ± 225(sys)

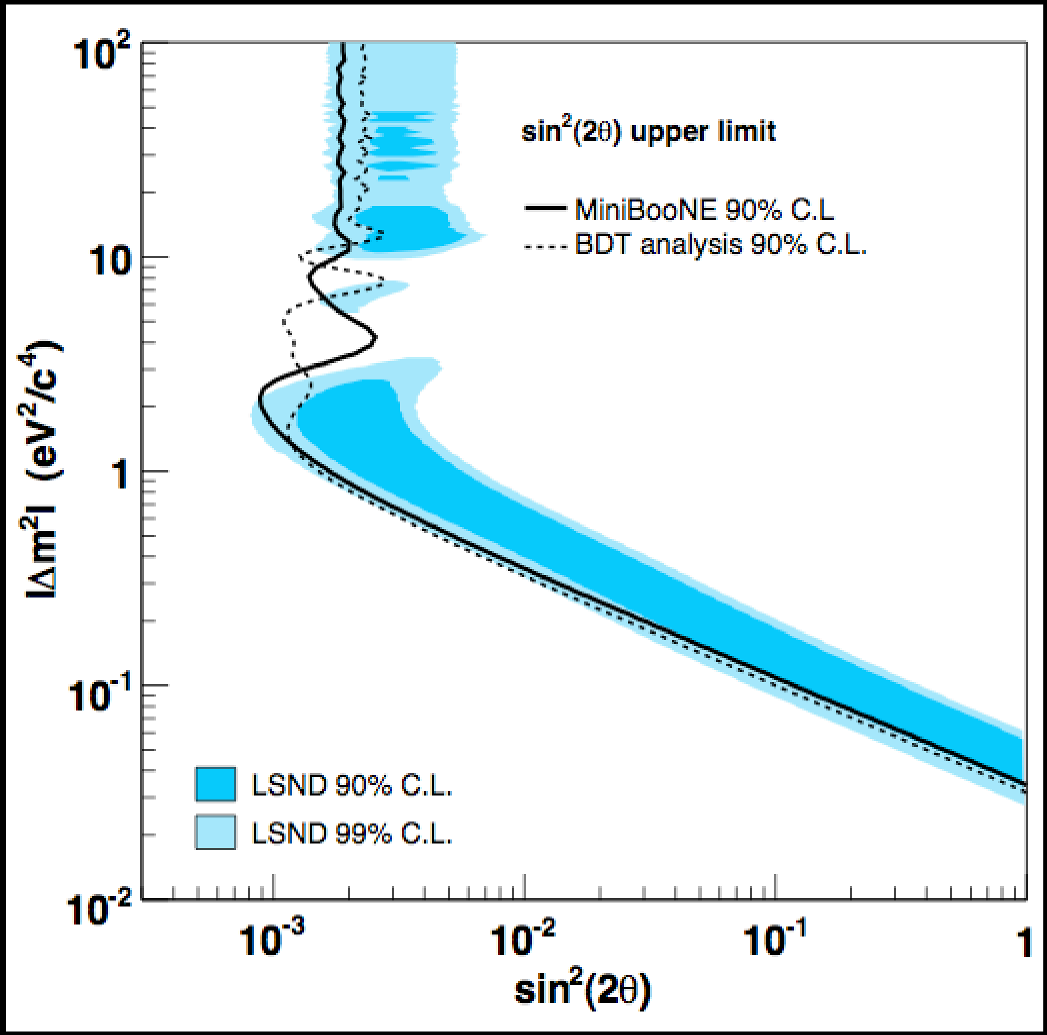
data: **971**

significance: **-0.38 σ**

Oscillation Hypothesis Test



MiniBooNE First Result



The two independent oscillation analyses are in agreement!

What Does It Mean?

- With the blind analysis, we have asked the question:

Do ν_μs oscillate directly to ν_es with $\Delta m^2 \sim$ 1eV^2, ala LSND?

- We have a clear answer:

NO

More work yet to do...

Next Steps for MiniBooNE

- MiniBooNE will publish several more papers soon:
  - Neutrino cross section measurements
  - Joint analysis of MiniBooNE, LSND and KARMEN data
  - More exotic oscillation analyses
    - Combining the two independent analyses into one, etc.
- MiniBooNE is running in antineutrino mode now

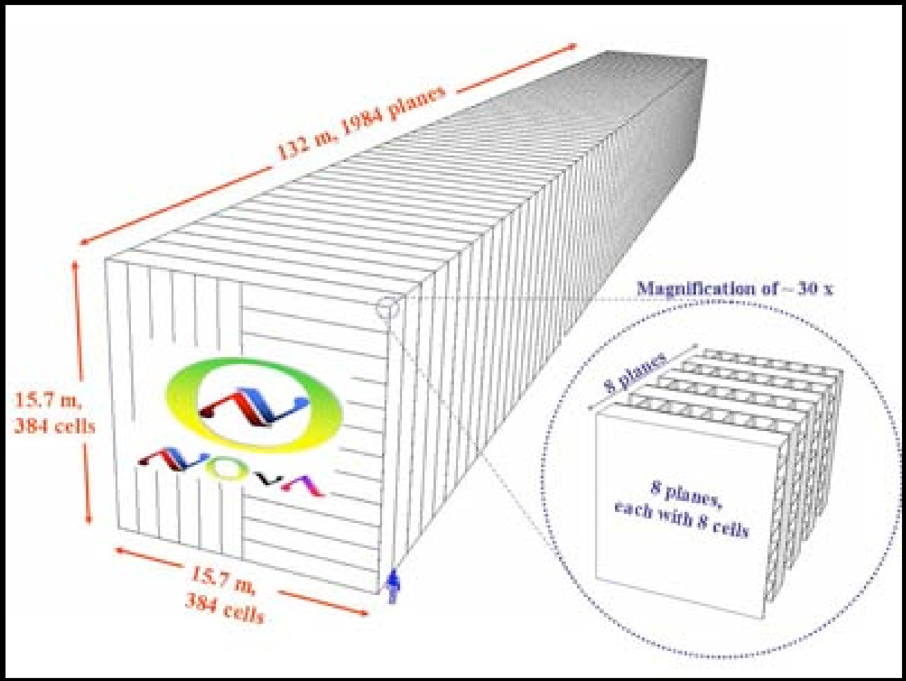
Next Steps for the Field

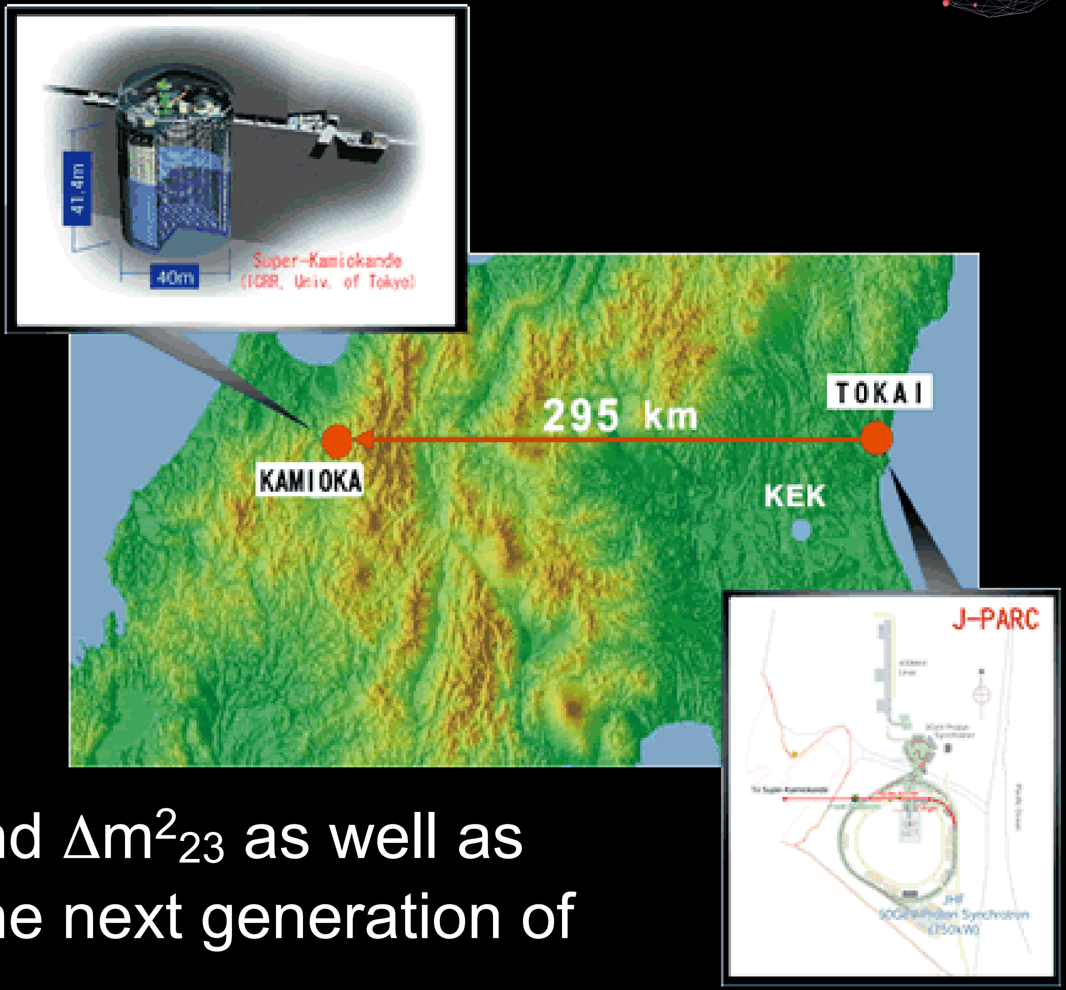
The Open Questions of Neutrino Physics

- How does the mixing really work?
    - Parameters of 3-neutrino oscillations
    - Do leptons violate CP?
- What is the nature of neutrino mass?
    - Direct mass measurements
    - Dirac vs Majorana particles
- What do neutrinos tell us about cosmology?
- What else can neutrinos reveal beyond the Standard Model?
    - ~~Extra Generations?~~

These require precision measurements!

3-ν Oscillations





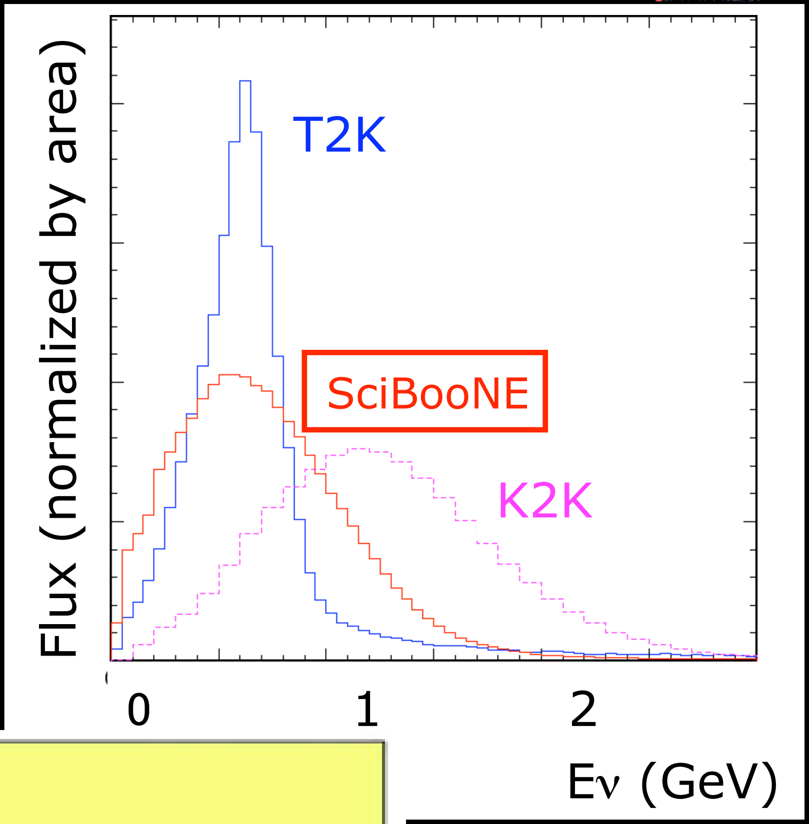
Precise measurements of θ_{23} and Δm^2_{23} as well as search for θ_{13} will be made by the next generation of accelerator experiments:

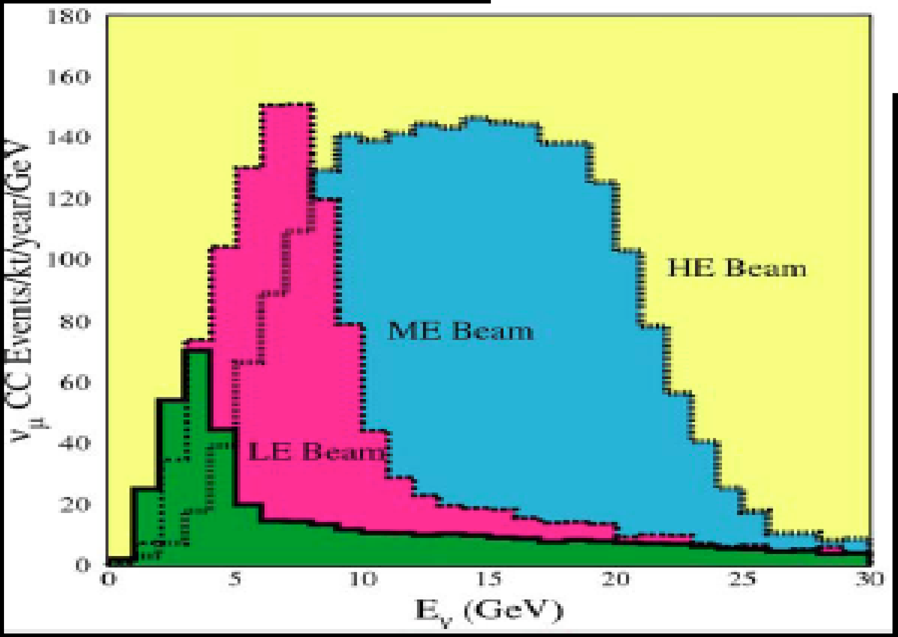
T2K in Japan - starting in 2009

NOvA in the US - starting as early as 2011

Technical Details

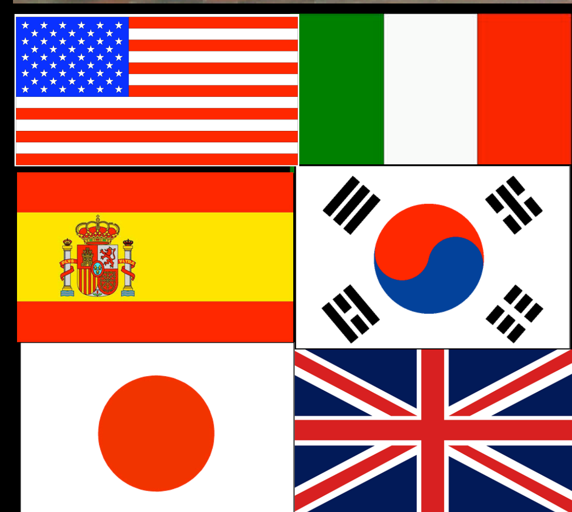
- As for MiniBooNE, neutrino cross sections are the largest uncertainty for T2K and NOvA
- To solve this, Fermilab is launching a program of precision cross section measurements
- SciBooNE in the Booster Neutrino Beam
- MINERvA in NuMI Beam



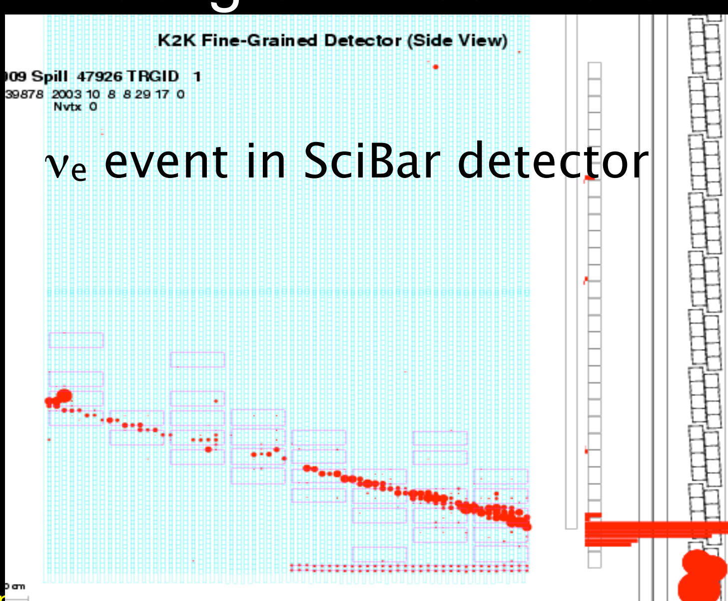


SciBooNE

- SciBooNE uses SciBar vertex detector & EM calorimeter from K2K in Japan
- Muon momentum detector built at Fermilab
- We can precisely measure the intrinsic ν_e content of BNB
  - Check MiniBooNE's background estimate

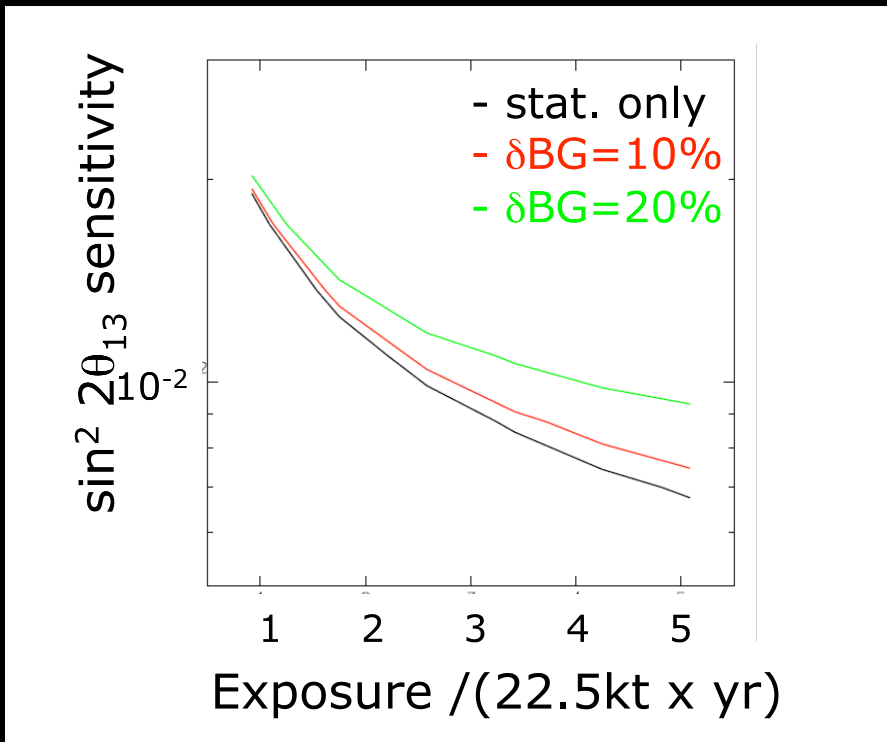


<u>Spokespeople</u>:
T. Nakaya, Kyoto University
M.O. Wascko, Imperial College

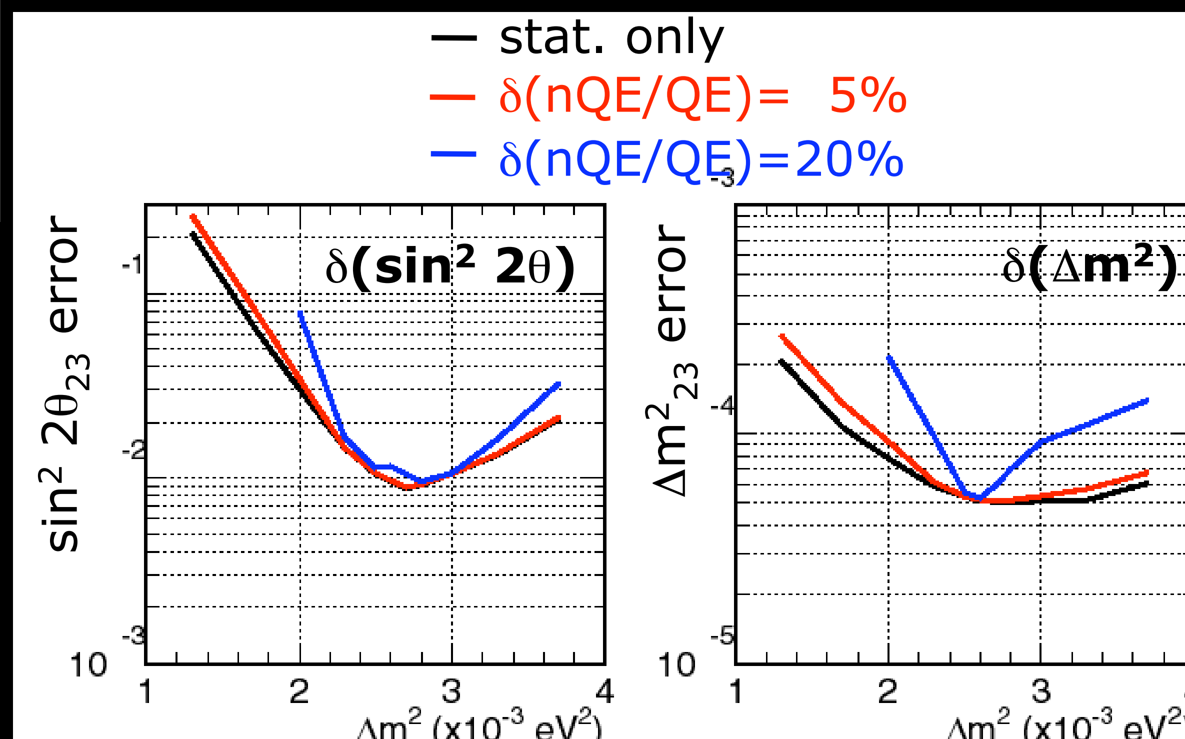


Impact of SciBooNE

SciBooNE



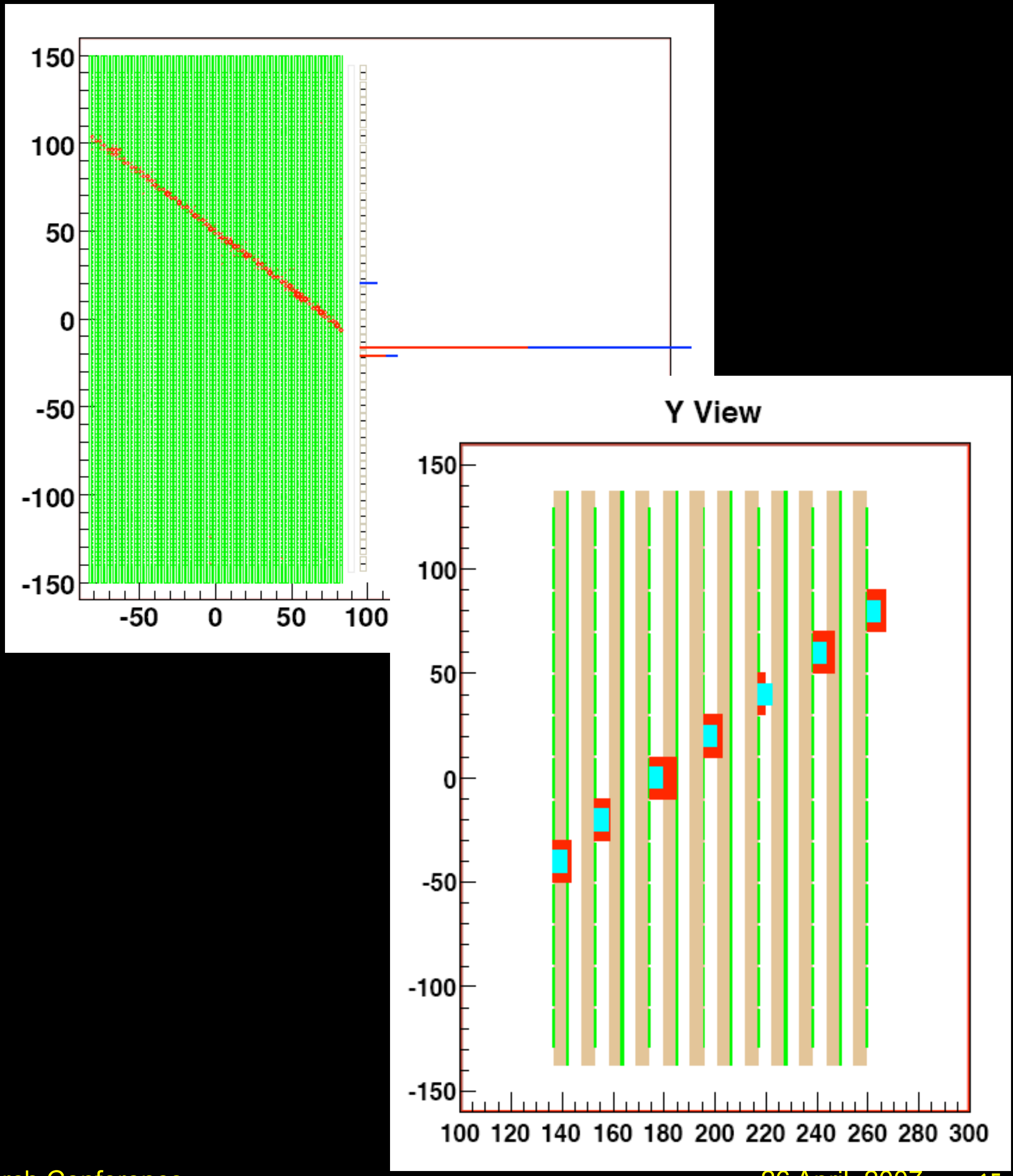
- SciBooNE will reduce uncertainty in $\sigma(NC\pi^0)$ from 20% to 10%
    - improvement of factor of 2 in ultimate T2K sensitivity to θ_{13}
    - or 3 years vs. 5 years to 10^{-2}

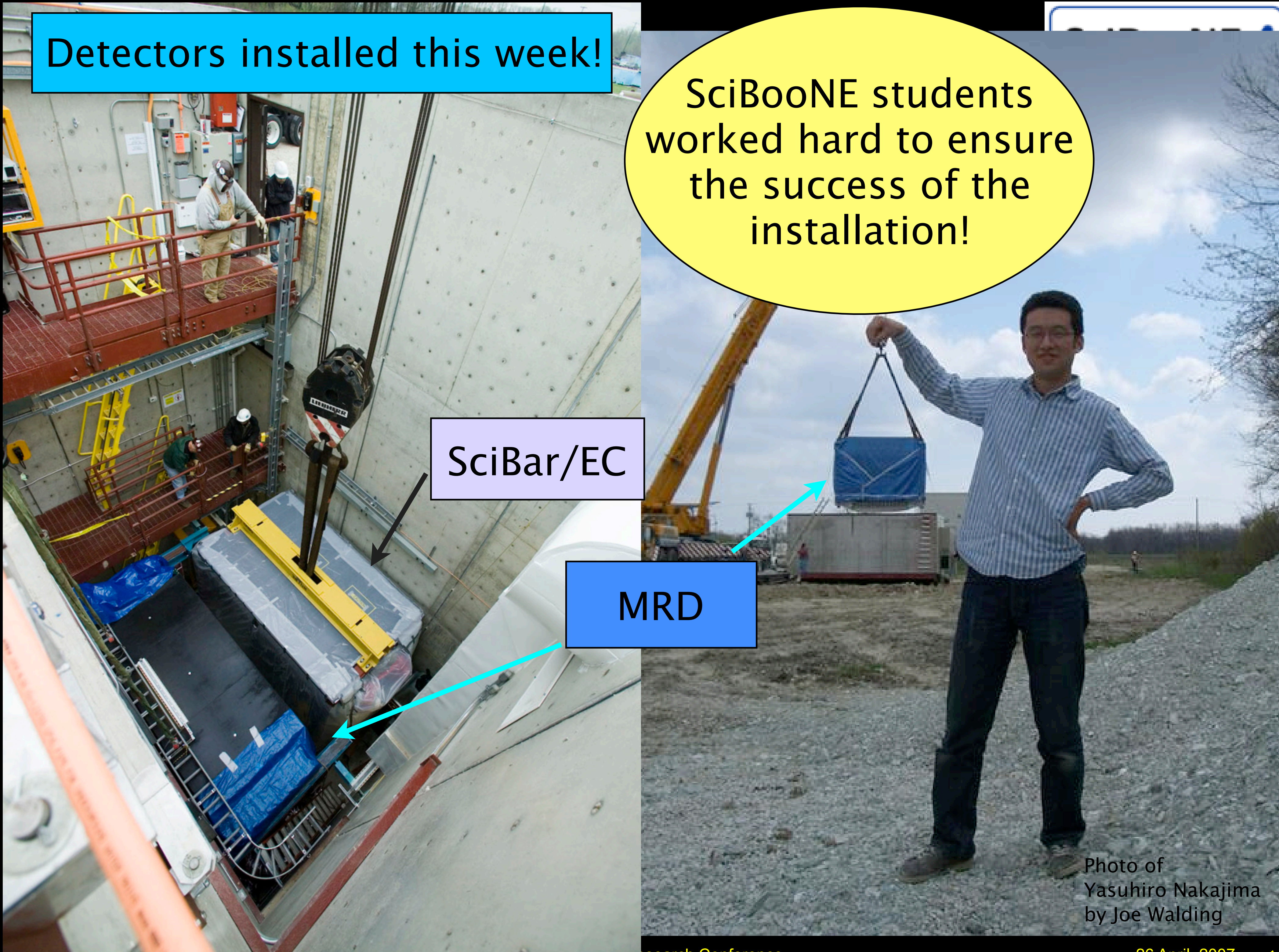


- SciBooNE will reduce uncertainty in $\sigma(CC1\pi^+)$ from 20% to 5%
    - reduces bias in oscillation parameter extraction

Status of SciBooNE

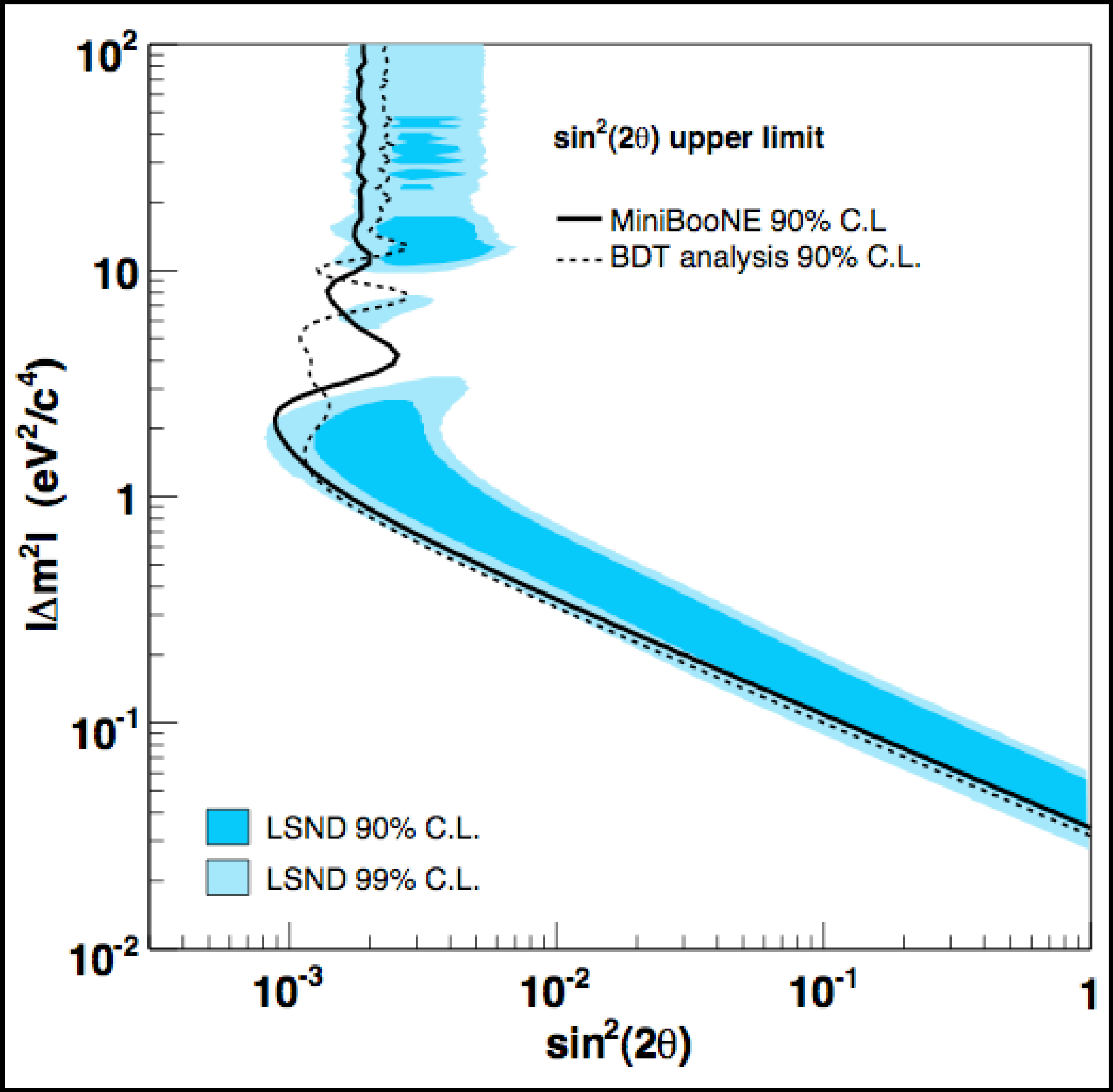
- 2005, Dec - Proposal
- 2006, Jul - Detectors move to FNAL
- 2006, Sep - Groundbreaking
- 2006, Nov - EC Assembly
- 2007, Feb - SciBar Assembly
- 2007, Mar - MRD Assembly
- 2007, Mar - Cosmic Ray Data
- 2007, Apr - Detector Installation
- 2007, May - Commissioning
- 2007, Jun - Neutrino Data Run




Detectors installed this week!
SciBooNE students worked hard to ensure the success of the installation!
SciBar/EC
MRD
Photo of Yasuhiro Nakajima by Joe Walding

Conclusions

MiniBooNE First Result



- MiniBooNE has searched for $\nu_\mu \rightarrow \nu_e$ oscillations with $\Delta m^2 \sim 1 eV^2$
- We find no evidence for ν_e appearance in our data
- We set a limit on $\nu_\mu \rightarrow \nu_e$ oscillations excluding the LSND allowed region
- With this result, the way forward in the field is now clear

- *For more technical details of the analyses, please see the KRL Seminar tomorrow by J. Monroe (MIT)*