Neutrino Physics with SciBooNE

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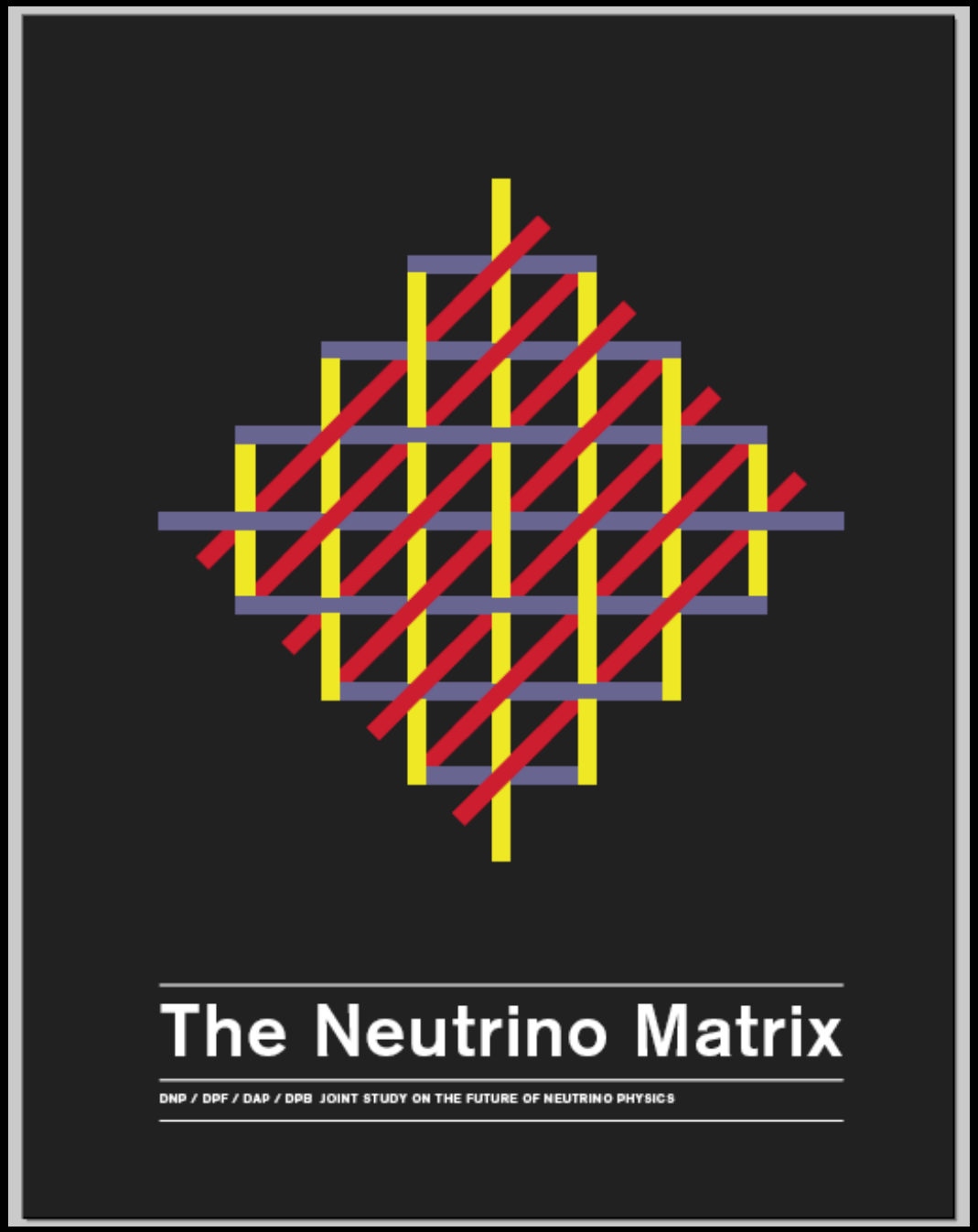
Imperial College London

MIT LNS Lunchtime Seminar
4 Dec 2007



http://www.aps.org/policy/reports/multidivisional/neutrino/index.cfm

- 1998-present: a decade of discovery
  - Neutrinos revealing their true nature
- We have new physics questions to answer
  - They require more precise measurements
  - The path forward for the field is clear

Outline

- SciBooNE overview
- Neutrino oscillation physics
  - Experimental HOWTO
  - Next steps forward
- Role of neutrino cross-sections
- SciBooNE's role
- SciBooNE details
- First SciBooNE data

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Lots of plots

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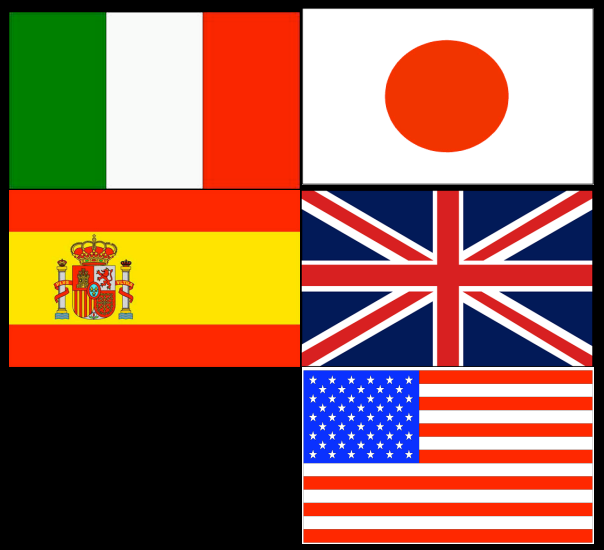
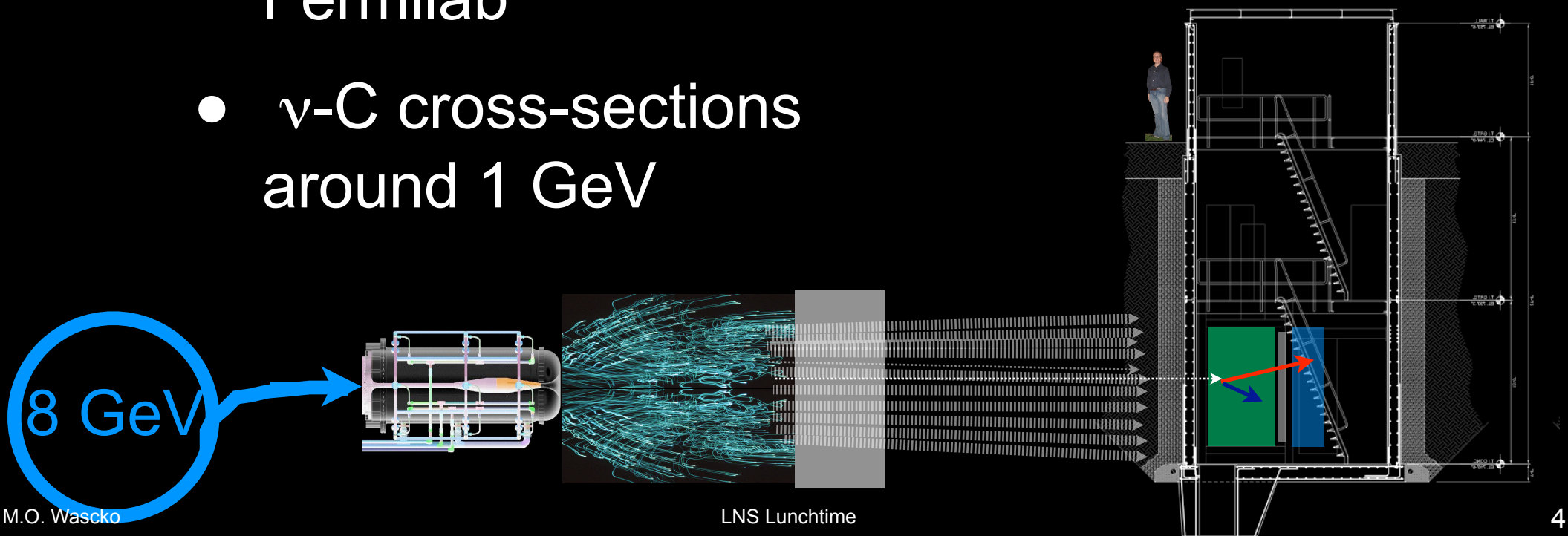
Lots of plots

Lots of pictures

SciBooNE Overview



- New neutrino experiment at Fermilab (E-954)
- SciBar detector from K2K
- Booster Neutrino Beam at Fermilab
- ν-C cross-sections around 1 GeV



- Particle physics is described by
  - ***The Standard Model***
- Matter: Fermions
- Force Carriers: Bosons

- Neutrinos are the lightest leptons
  - Massless in the standard model
  - Interact only via weak force

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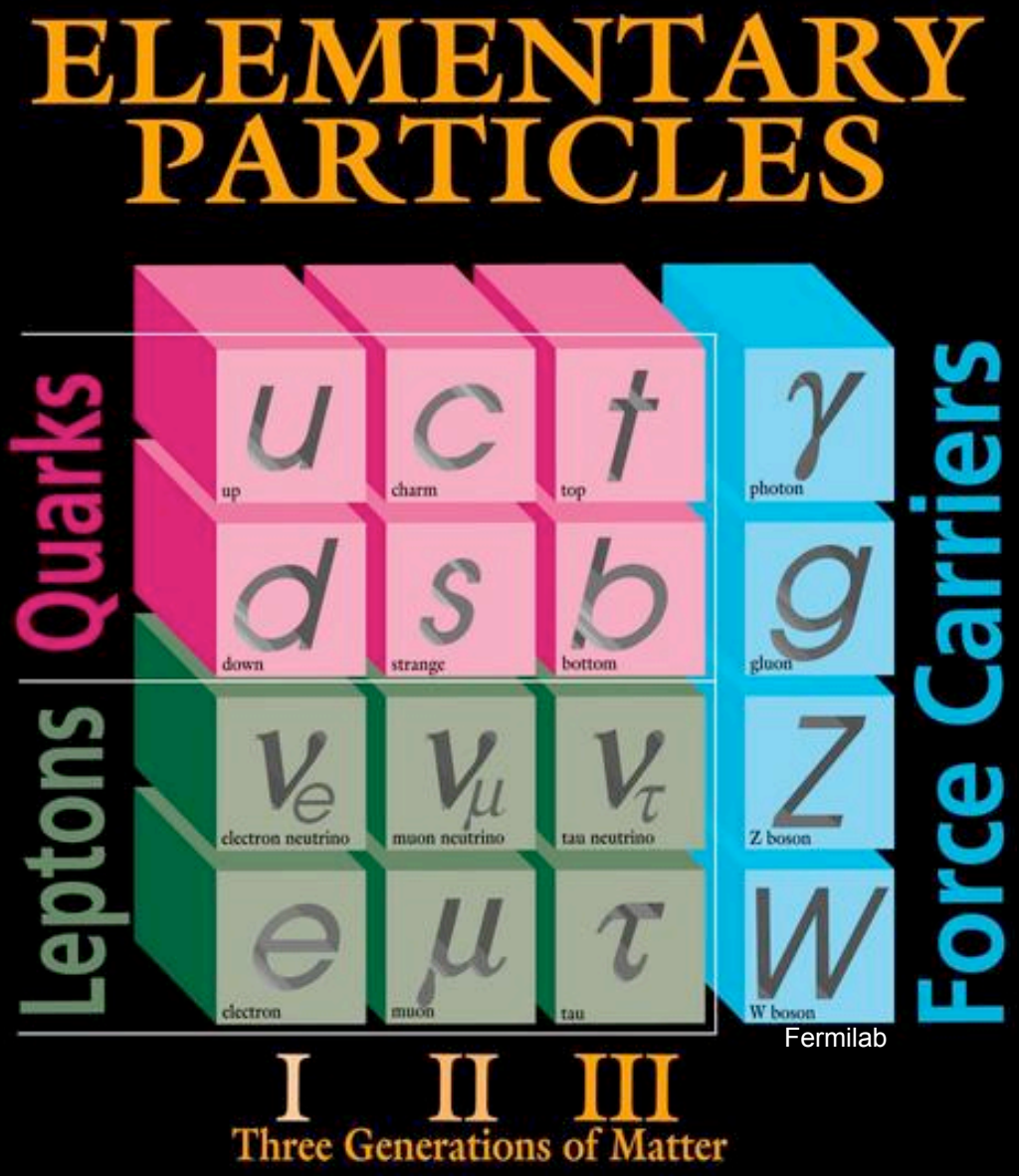
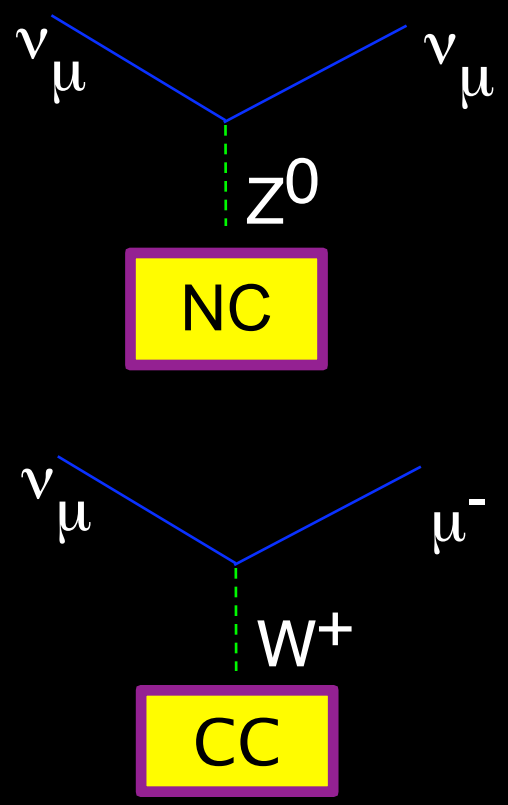
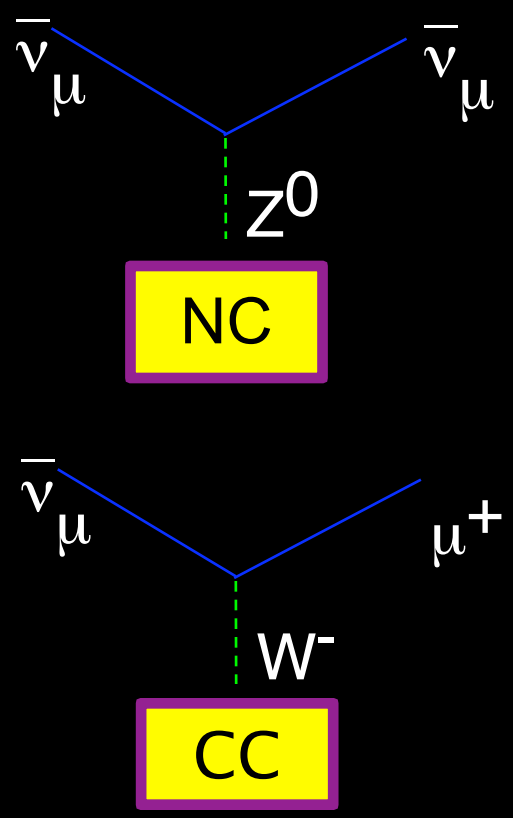


Fermilab



Feynman Diagrams

- Neutrinos are created as weak-flavor eigenstates
  - e, μ, τ
- Neutral Current
- Charged Current
  - Reveal neutrino flavour
  - Energy requirements



Feynman Diagrams

- Neutrinos are created as weak-flavor eigenstates
  - e, μ, τ
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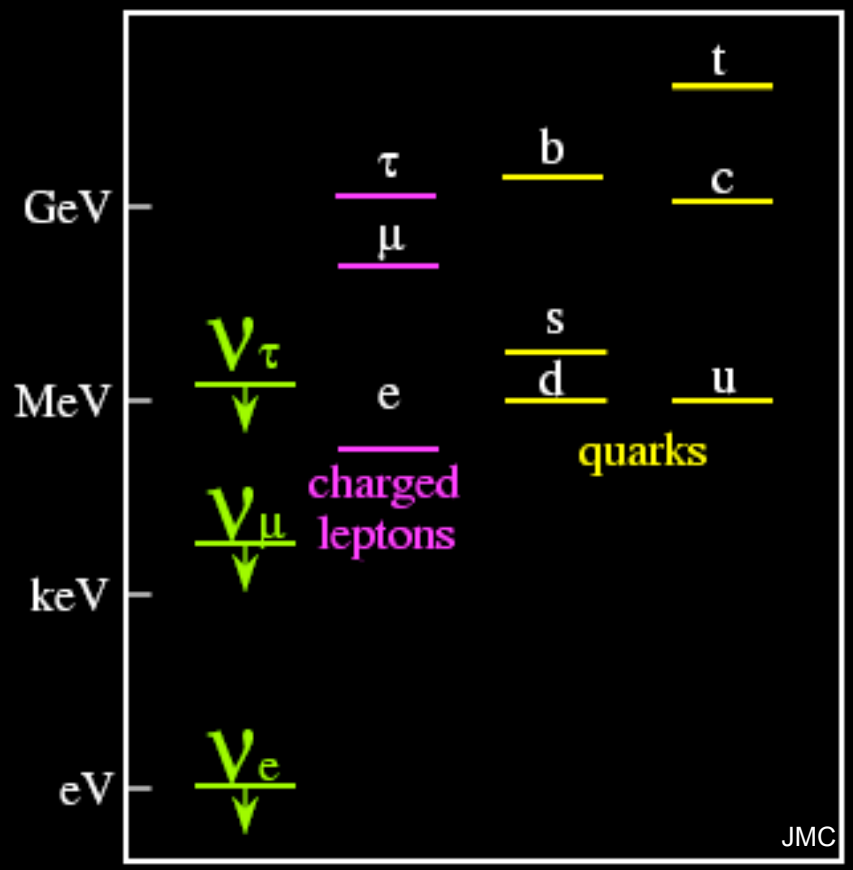
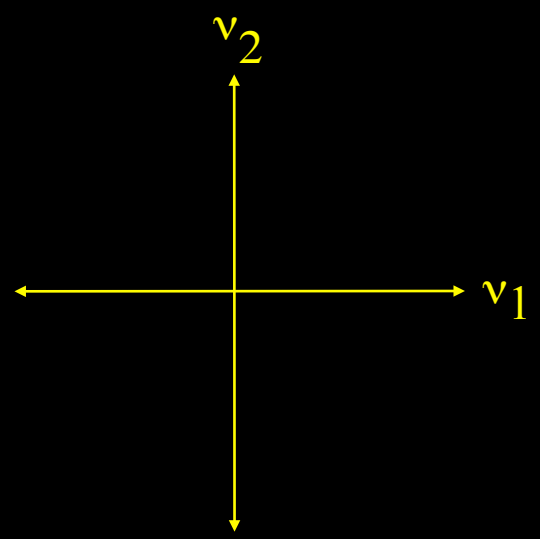
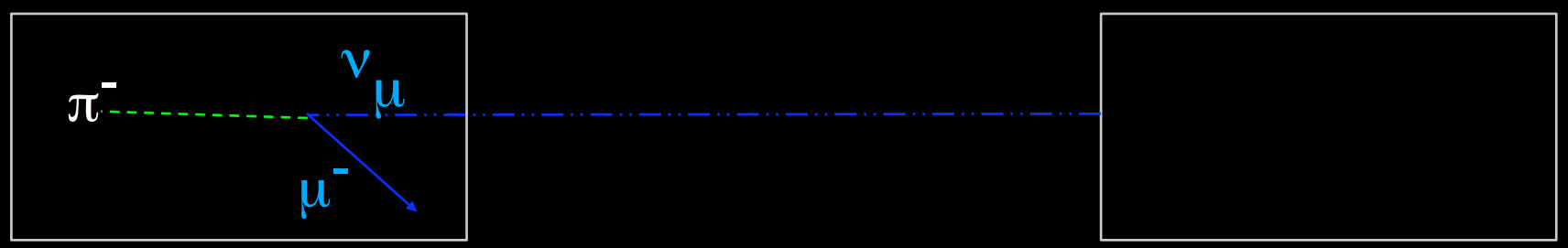
- In the standard model, neutrinos are massless
- Direct mass searches yield can only limits
  - ν_e: tritium decay: m < 2.2 eV (Mainz)
  - ν_μ: pion decay: m < 170 keV (Assamagan et al., PRD 1996)
  - ν_τ: tau decay: m < 18.2 MeV (Aleph, EPJ C2 395 1998)



SciBooNE

$$\begin{bmatrix} \nu_1 \\ \nu_2 \end{bmatrix}$$



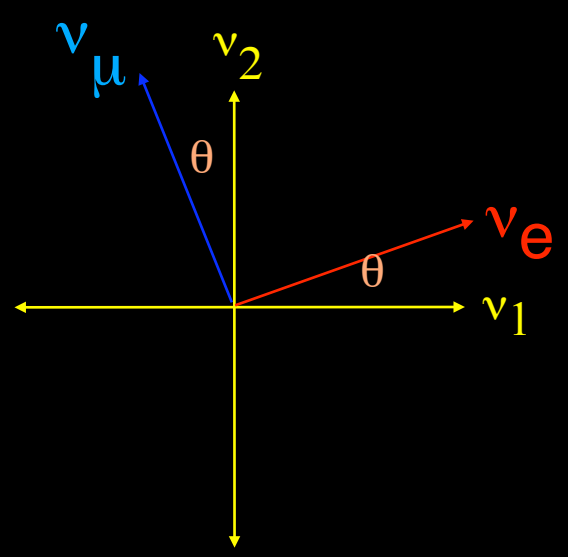


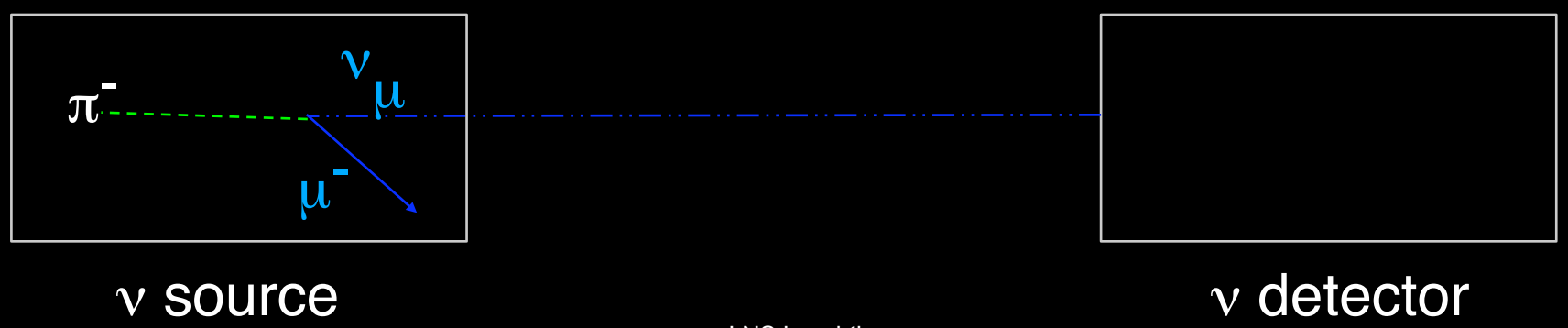
ν source

ν detector

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

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





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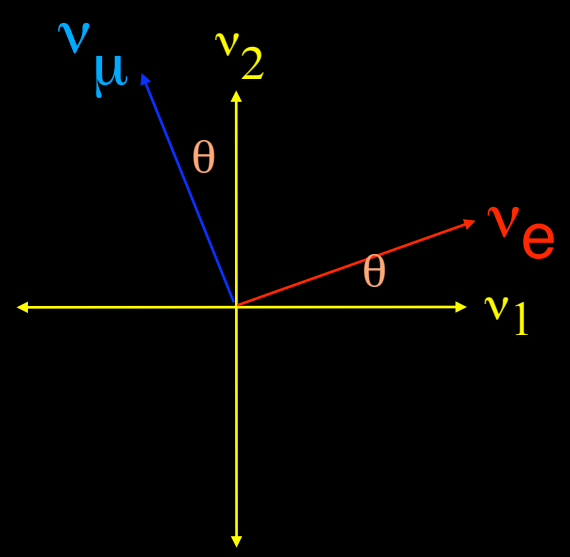
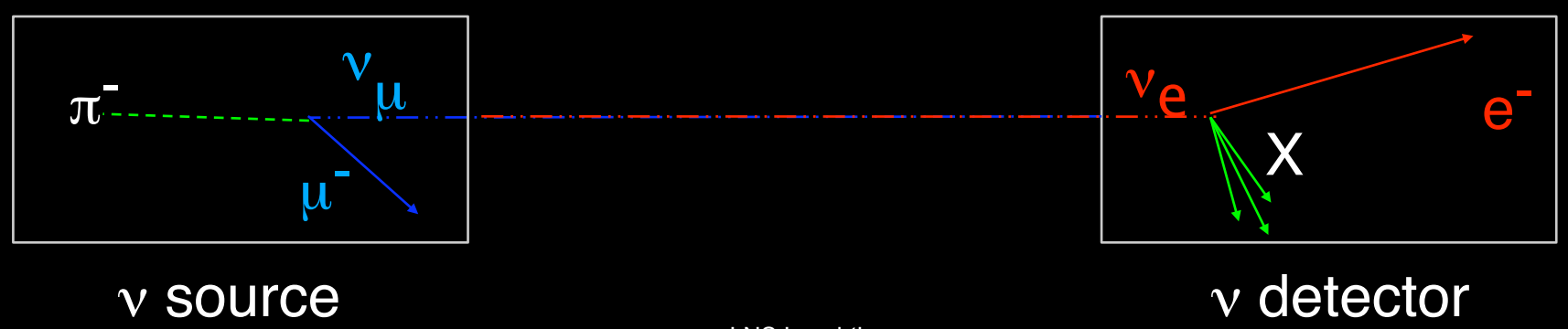
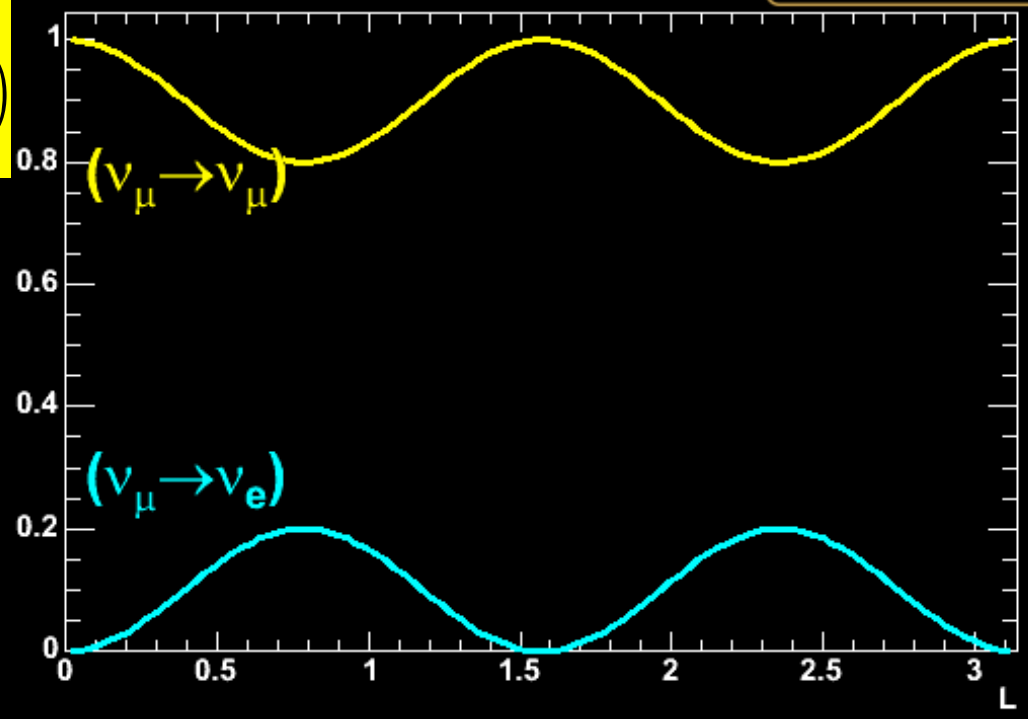


- THEN:
  - A muon neutrino might be detected as an electron neutrino
  - Why? Neutrinos propagate as mass eigenstates



SciBooNE

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



- 2 fundamental parameters
  - Δm^2 ↔ period
  - θ_{12} ↔ magnitude
- 2 experimental parameters
  - L = distance travelled
  - E = neutrino energy
- Choose L&E to target ranges of Δm^2 and θ
- Neutrinos disappear and appear

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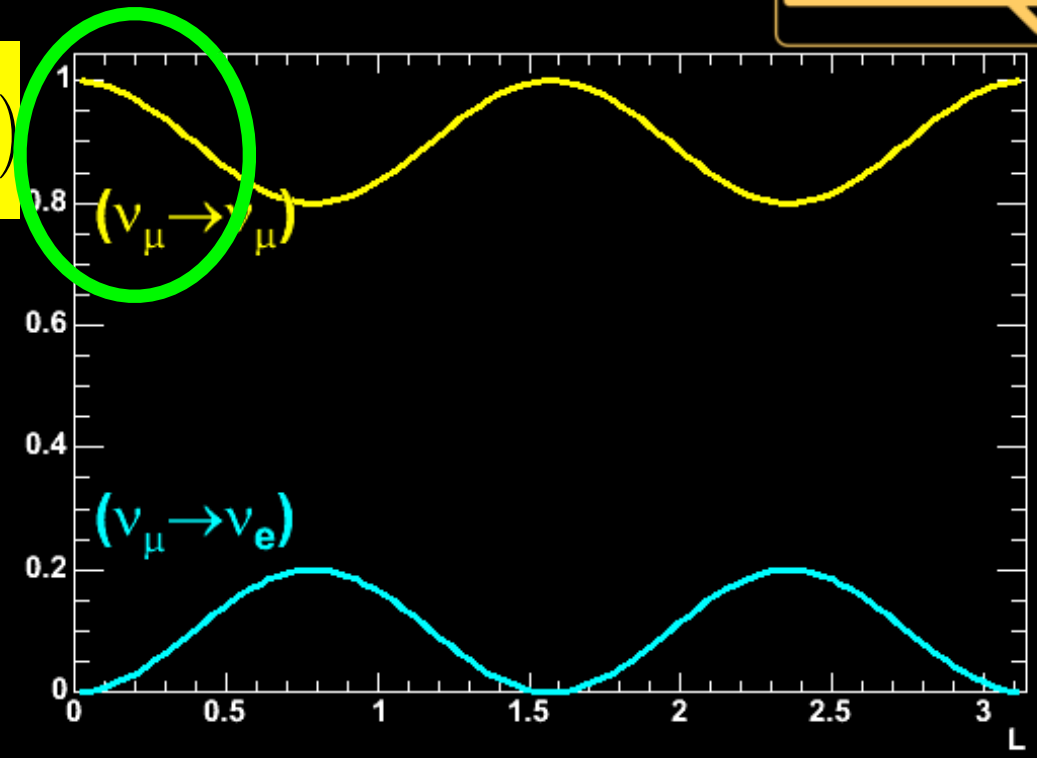

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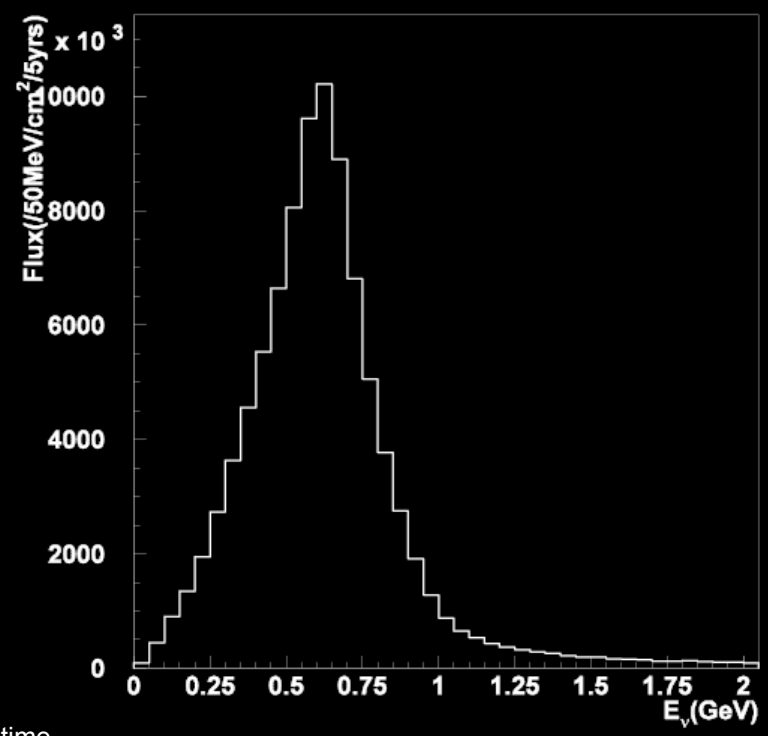

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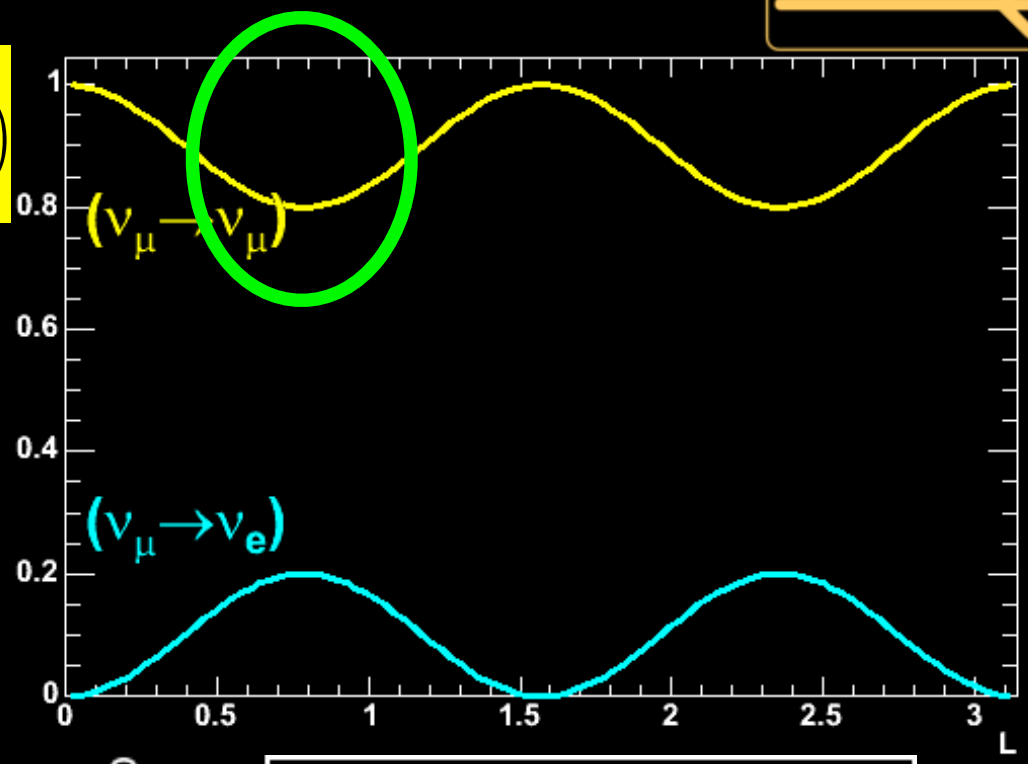

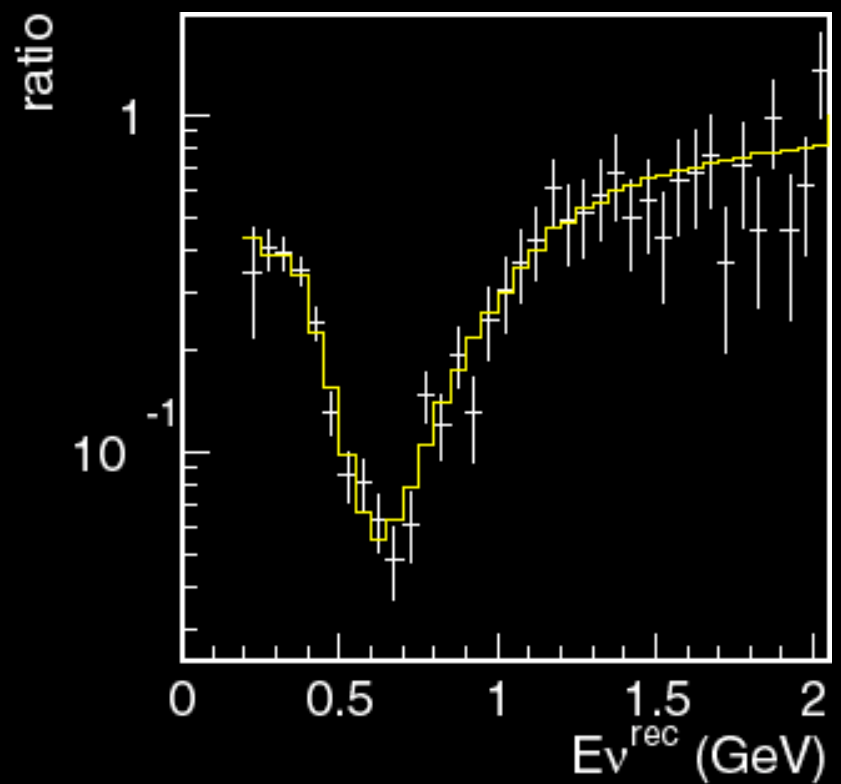

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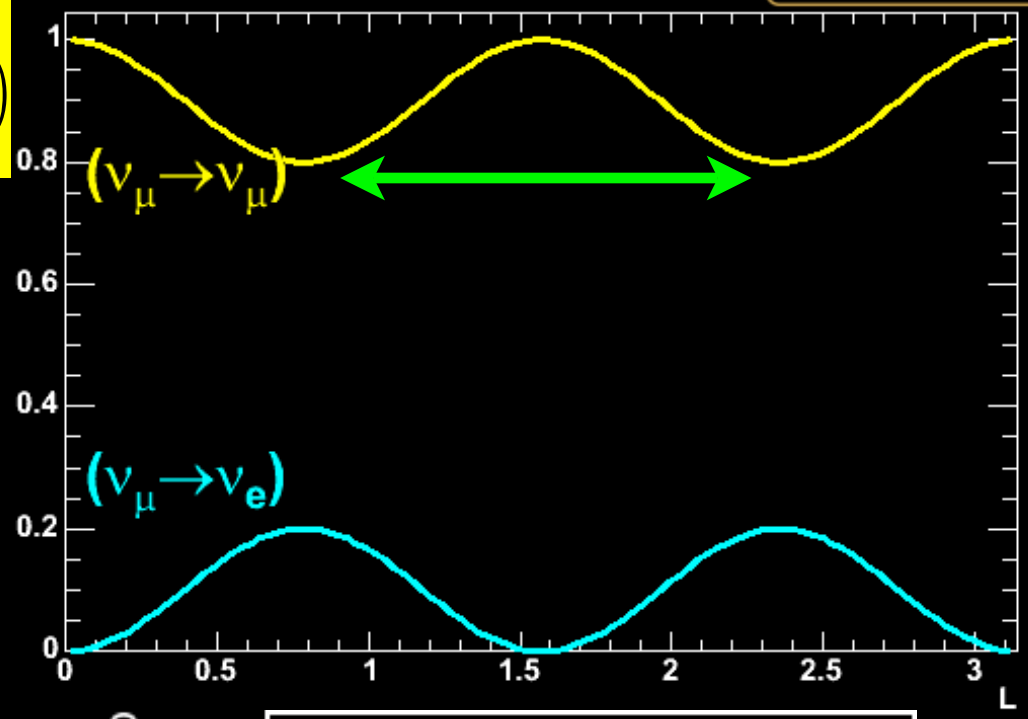

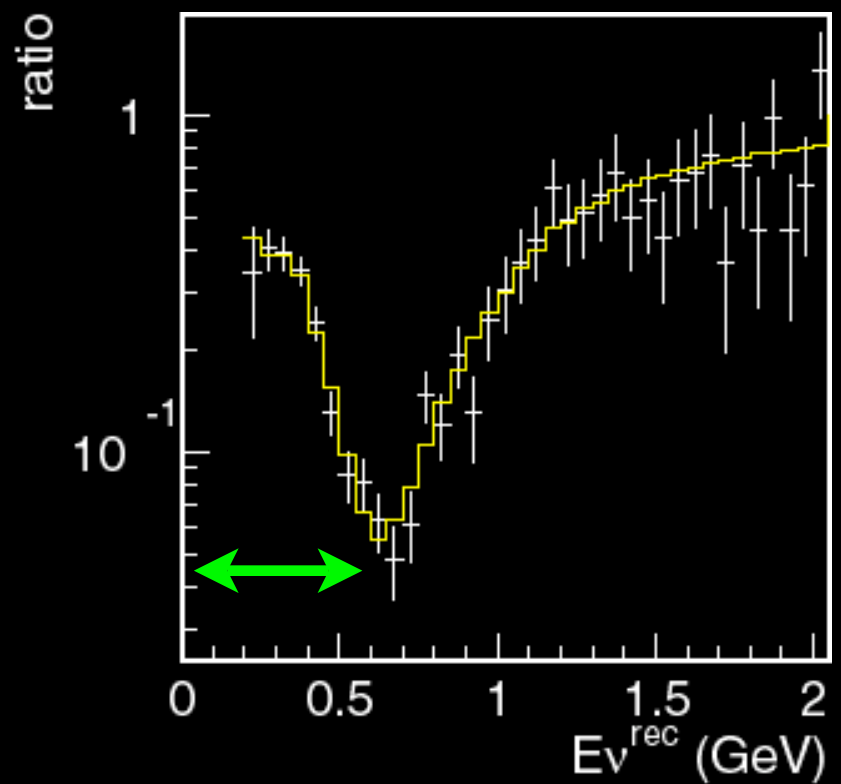

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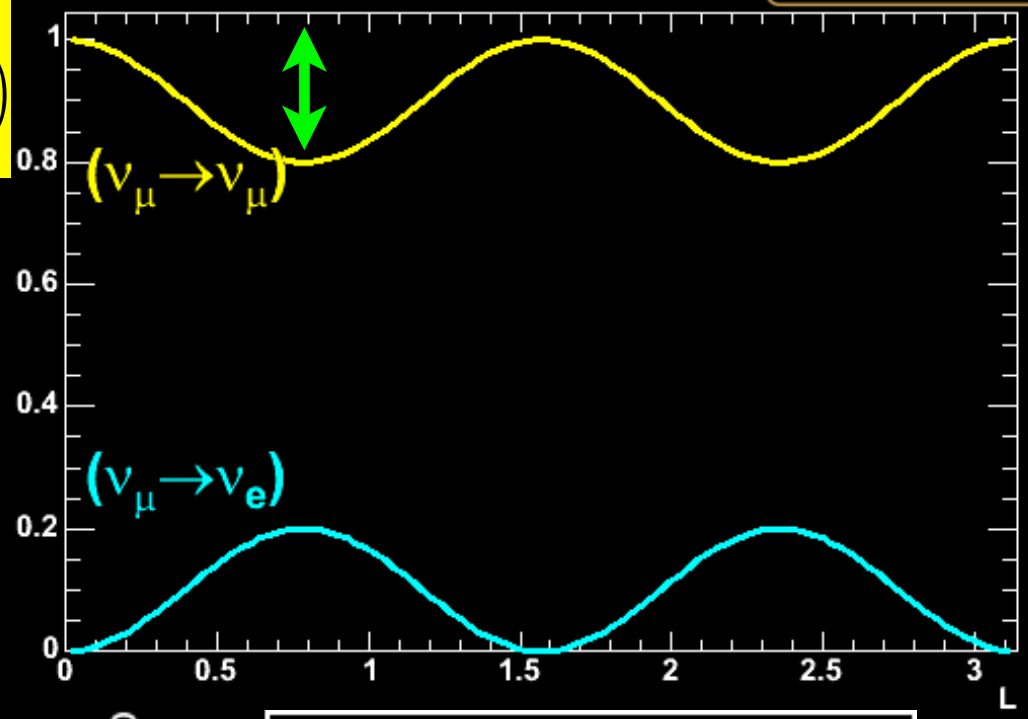

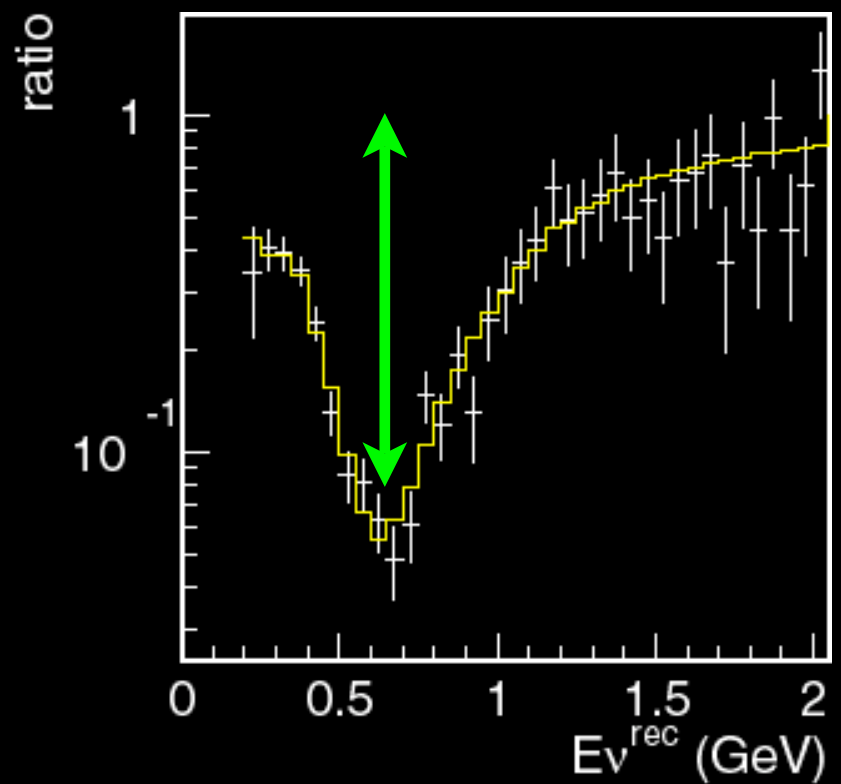

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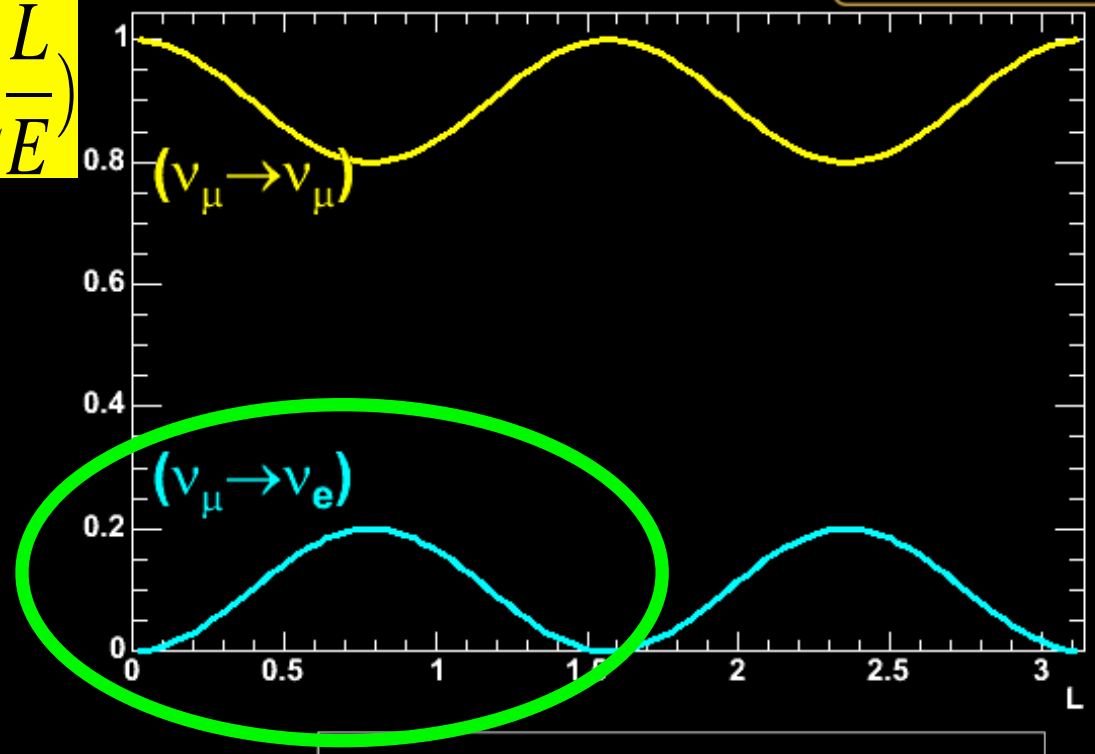

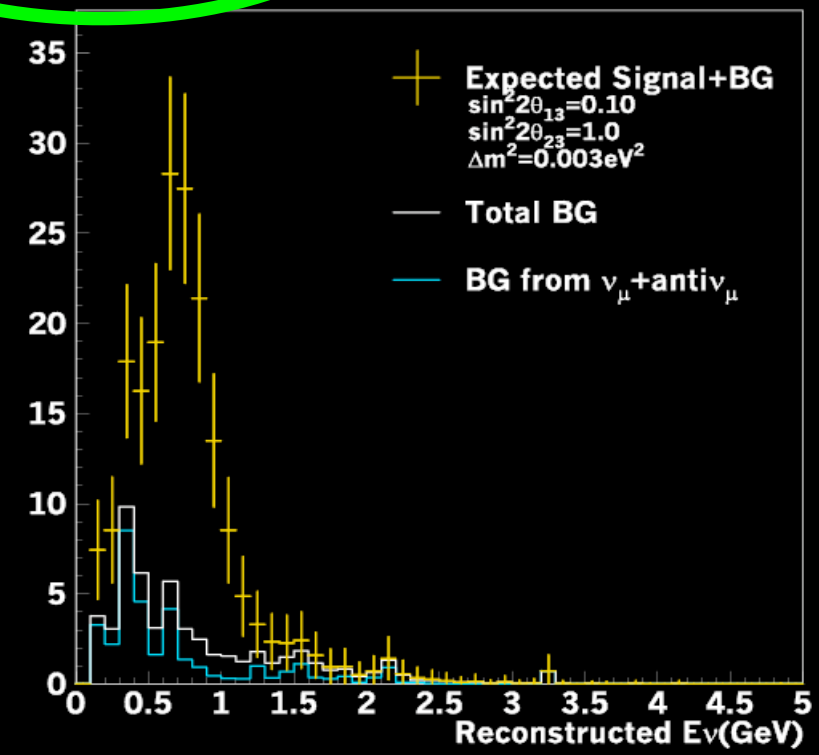

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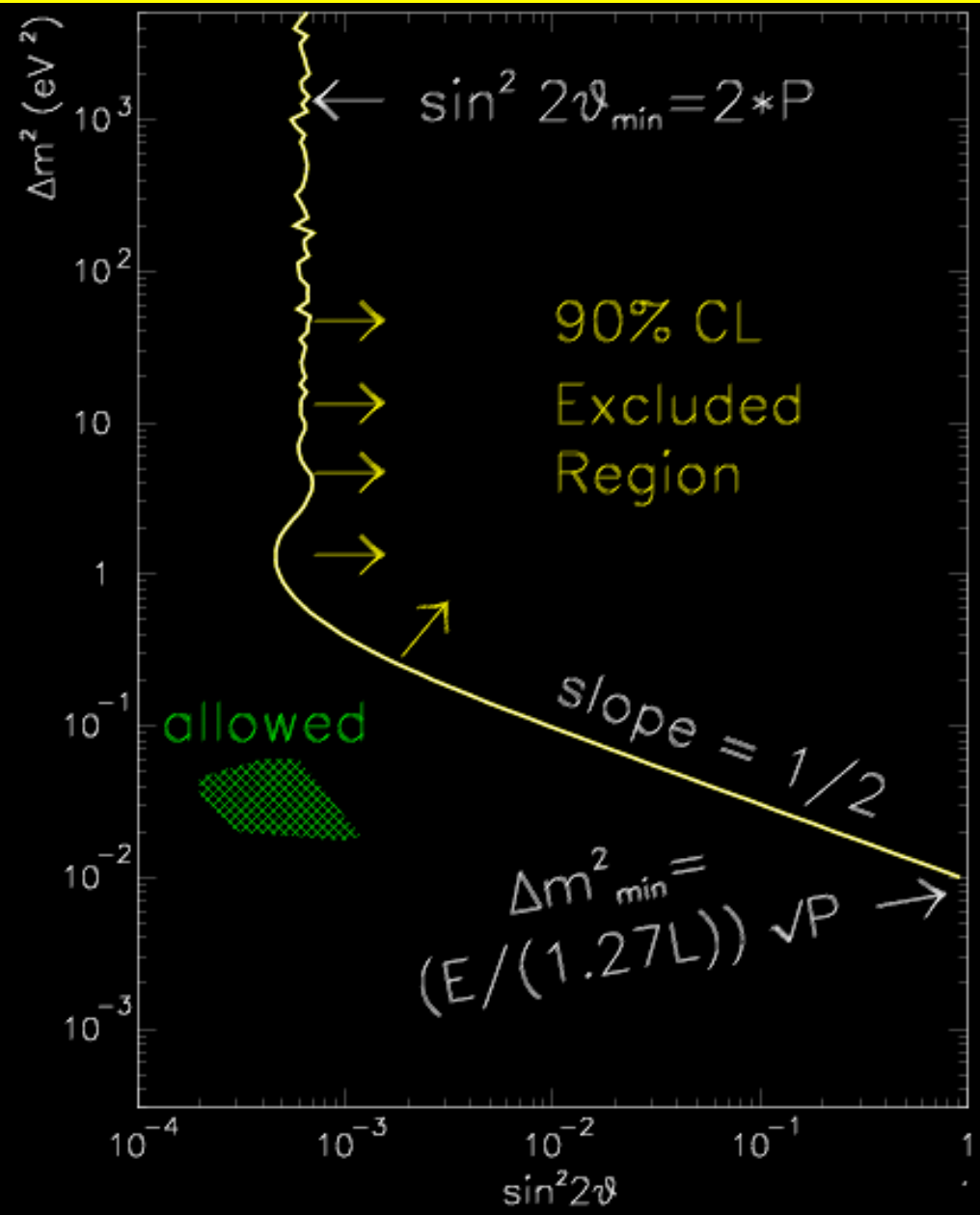

- Recall:
  - L and E determine Δm^2 sensitivity
  - θ_{12} sensitivity determined by statistics, backgrounds, and uncertainties
- No signal: exclusion curve
- Signal: allowed region

3 ν Oscillation

$$|\nu_l\rangle = \sum U_{li}|\nu_i\rangle$$

flavour mass

3 ν Oscillation

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{i1} & U_{i2} & U_{i3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$where\ c_{ij} = \cos\theta_{ij},\ and\ s_{ij} = \sin\theta_{ij}$$

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flavour mass

Atmospheric Oscillation

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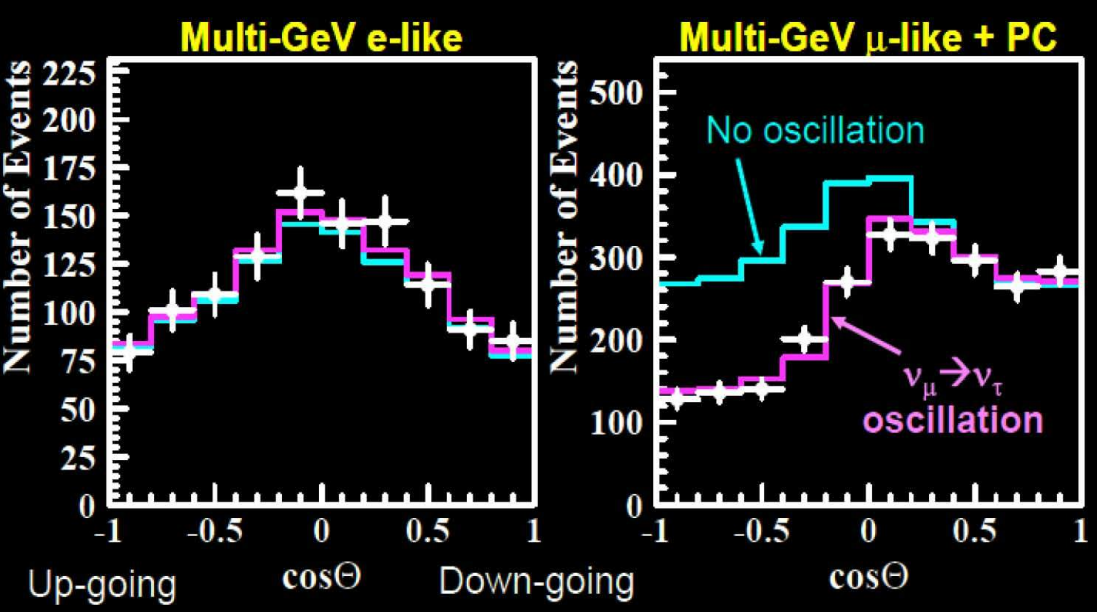
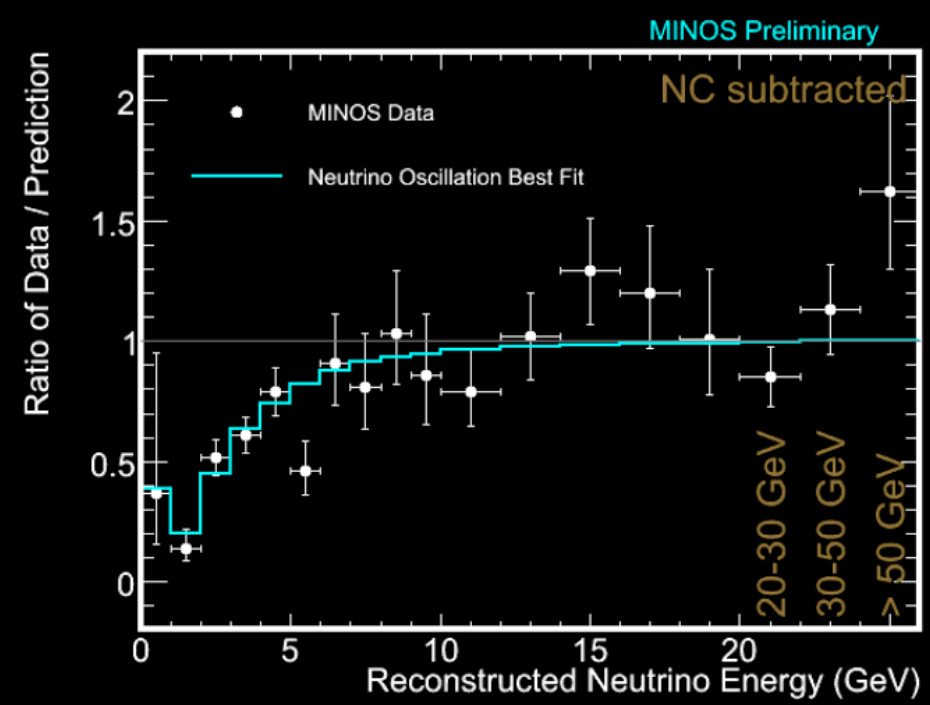


Super-K



MINOS

Solar Oscillation

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{i1} & U_{i2} & U_{i3} \\ U_{\hat{o}1} & U_{\hat{o}2} & U_{\hat{o}3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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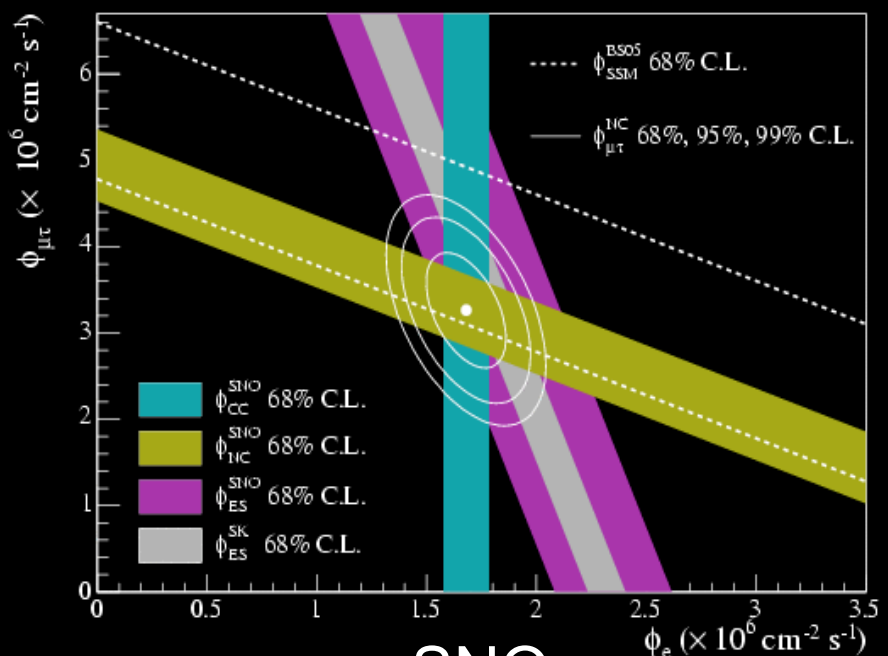
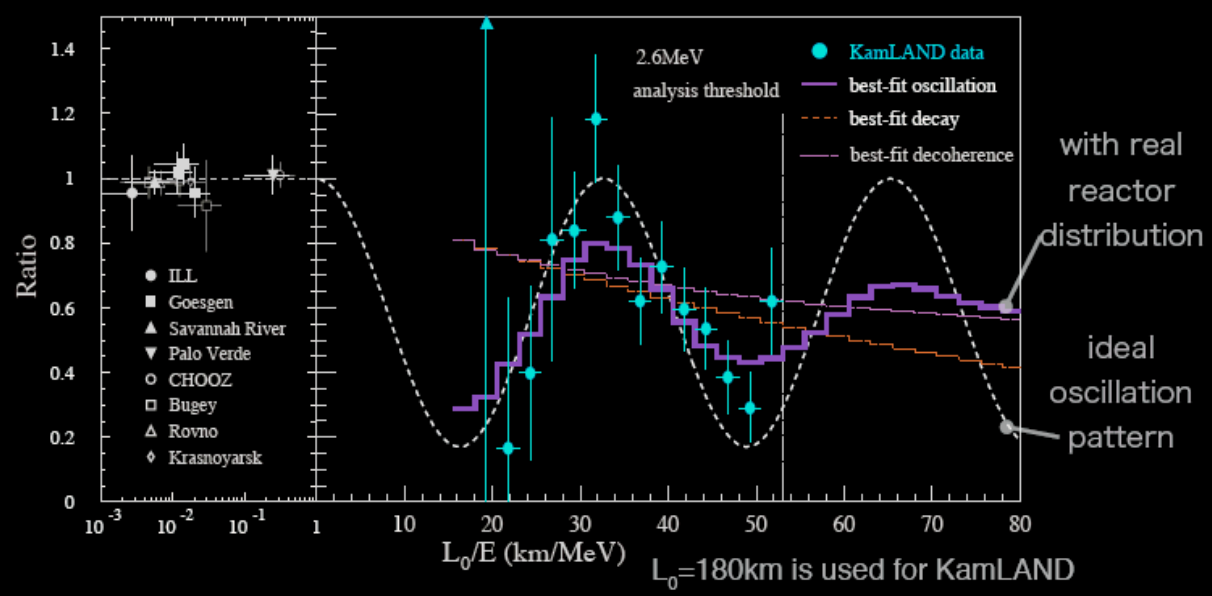


SNO



KamLAND

Sub-dominant Oscillation

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{i1} & U_{i2} & U_{i3} \\ U_{\hat{o}1} & U_{\hat{o}2} & U_{\hat{o}3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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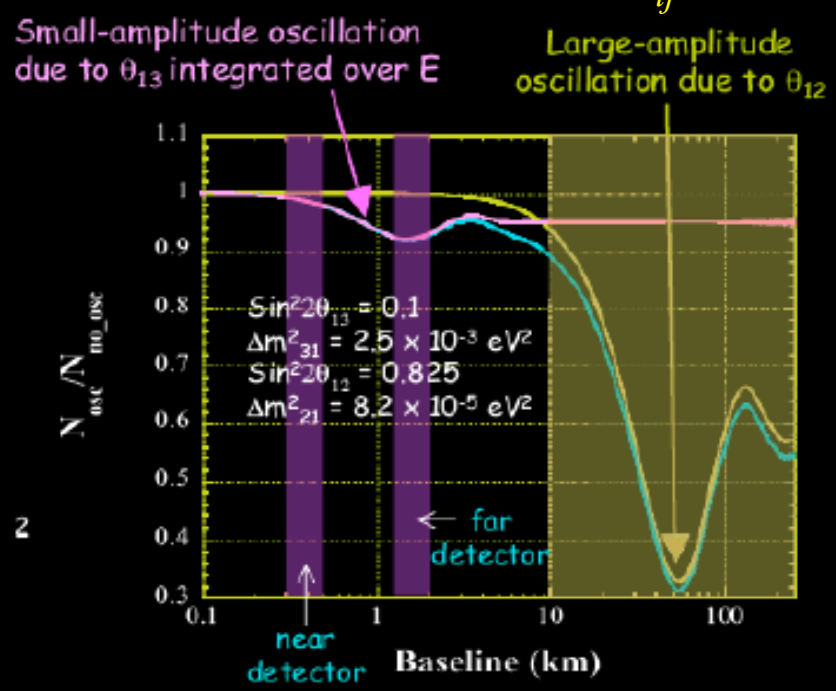

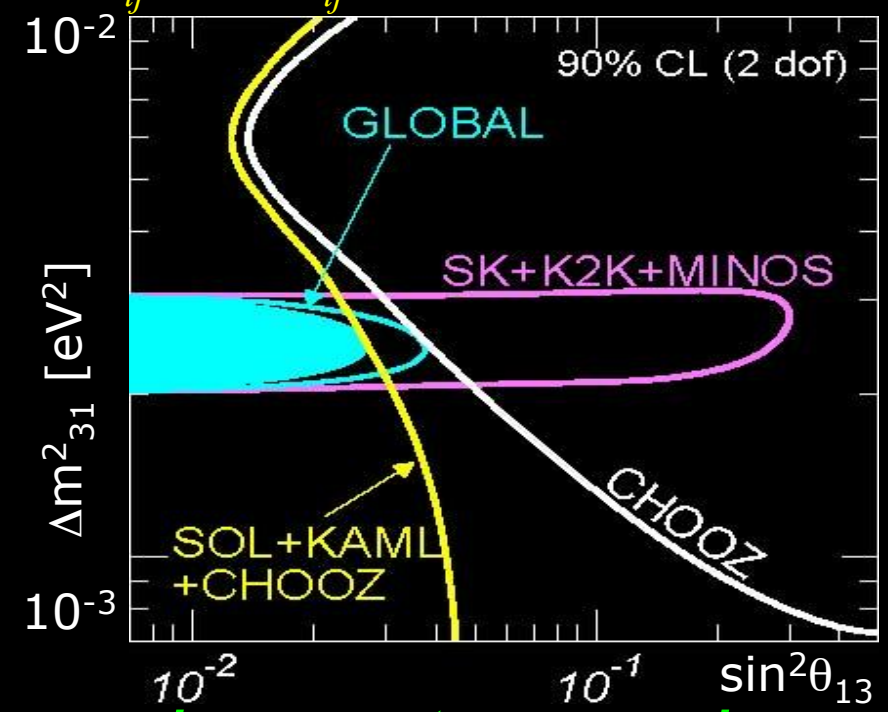

Causes $\bar{\nu}e$ disappearance in reactors and νe appearance in accelerator experiments

Sub-dominant Oscillation

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CP violating phase δ might cause

$P(\nu\mu \rightarrow \nu e) \neq P(\bar{\nu}\mu \rightarrow \bar{\nu} e)$

This is really hard to measure

Might explain matter/antimatter asymmetry

Sub-dominant Oscillation

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CP v use

Th e

Mig er

3 ν Oscillation

In vacuum:

$$P(\nu_\mu(\overline{\nu}_\mu) \to \nu_e(\overline{\nu}_e)) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta_{31}$$ Atmospheric

$$+ \sin 2\theta_{13} \cos \theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \times \sin \Delta_{31} \sin \Delta_{21} \cos(\Delta_{32} \pm \delta)$$ } Interference – CP effects

$$+ \sin^2 2\theta_{12} \cos^2 \theta_{23} \cos^2 \theta_{13} \sin^2 \Delta_{21}$$ Solar

where $\Delta_{ij} = 1.27 \Delta m^2_{ij}(eV^2) L(km)/E(GeV)$

and the CP violating term $\pm\delta$ has opposite signs for $\nu, \overline{\nu}$

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and the CP violating term $\pm\delta$ has opposite signs for $\nu, \overline{\nu}$

Bottom Line: Need high precision measurements of *everything* to extract the value of δ.

Joint Study Recommendation

WE RECOMMEND, AS A HIGH PRIORITY, A COMPREHENSIVE U.S. PROGRAM TO COMPLETE OUR UNDERSTANDING OF NEUTRINO MIXING, TO DETERMINE THE CHARACTER OF THE NEUTRINO MASS SPECTRUM AND TO SEARCH FOR CP VIOLATION AMONG NEUTRINOS.

http://www.aps.org/policy/reports/multidivisional/neutrino/index.cfm

page ii

Exploring the New Paradigm

Mass (eV)

$m_{\nu\tau} = 0$ ν_3

$m_{\nu\mu} = 0$ ν_2

$m_{\nu e} = 0$ ν_1

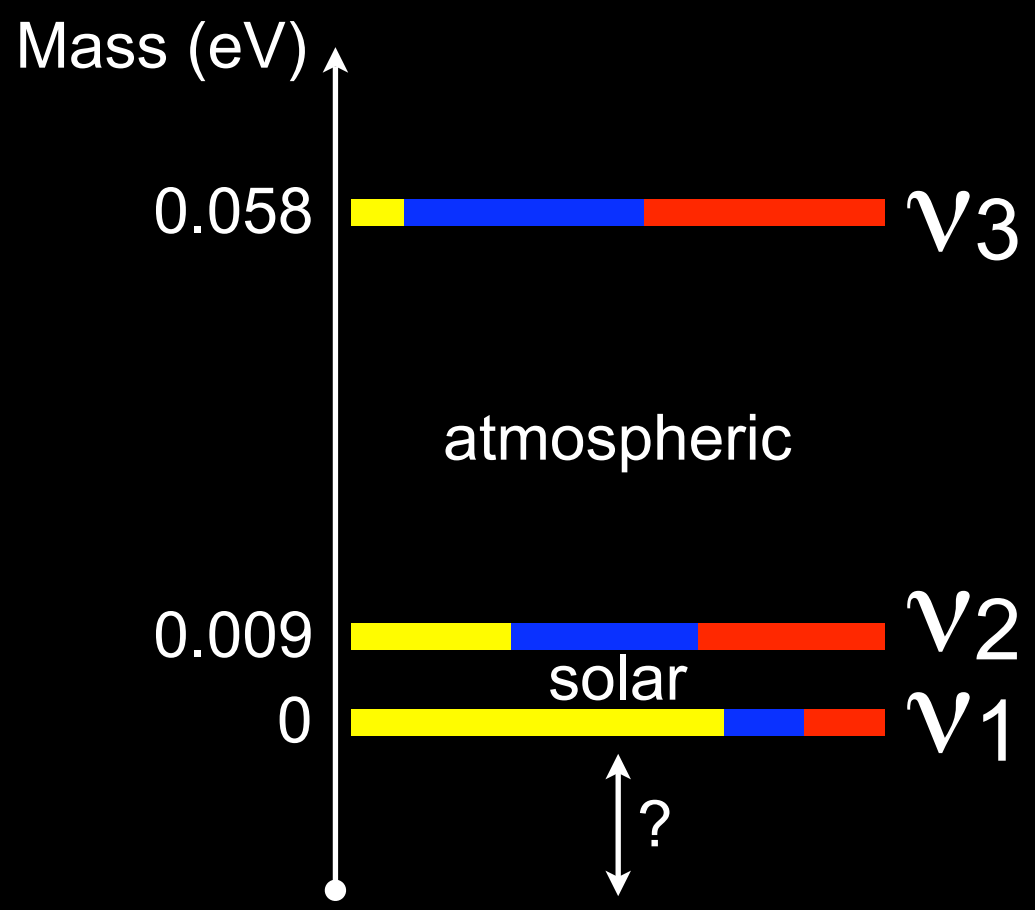
In the Standard Model...

flavour key:

ν_e ν_μ ν_τ

Exploring the New Paradigm

Today...



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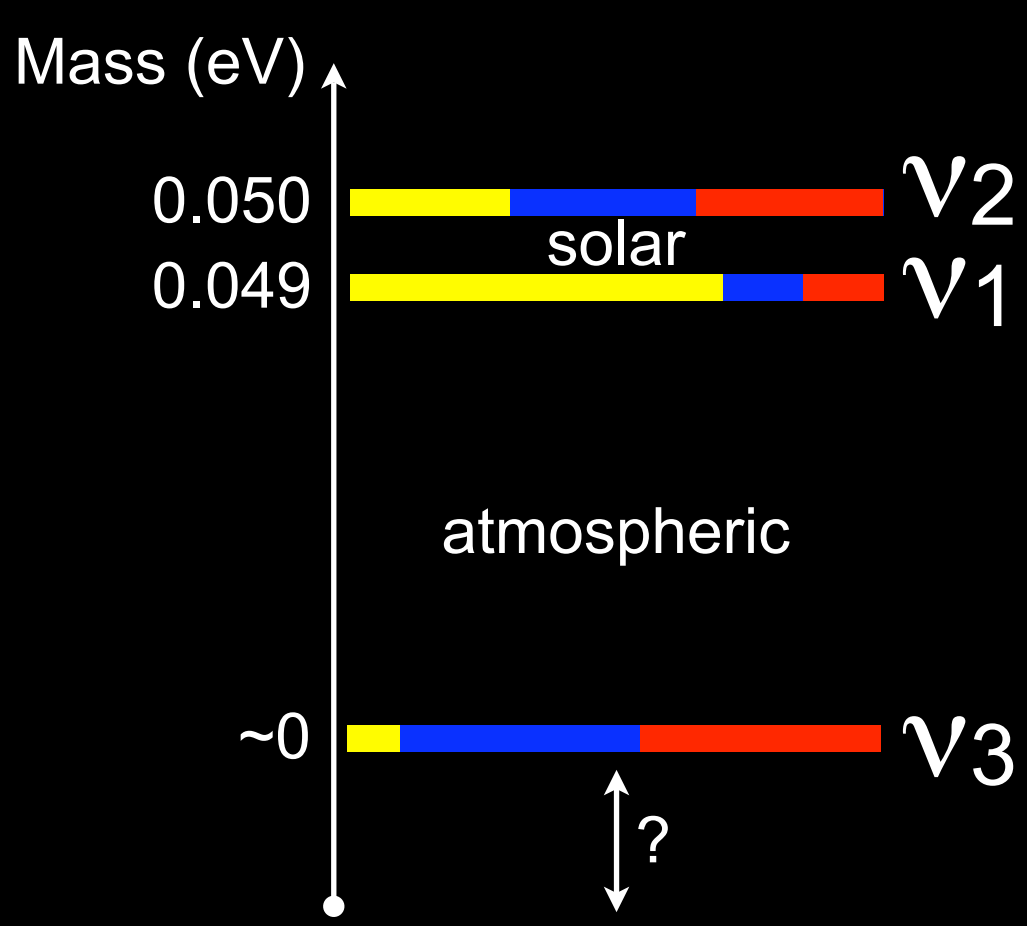
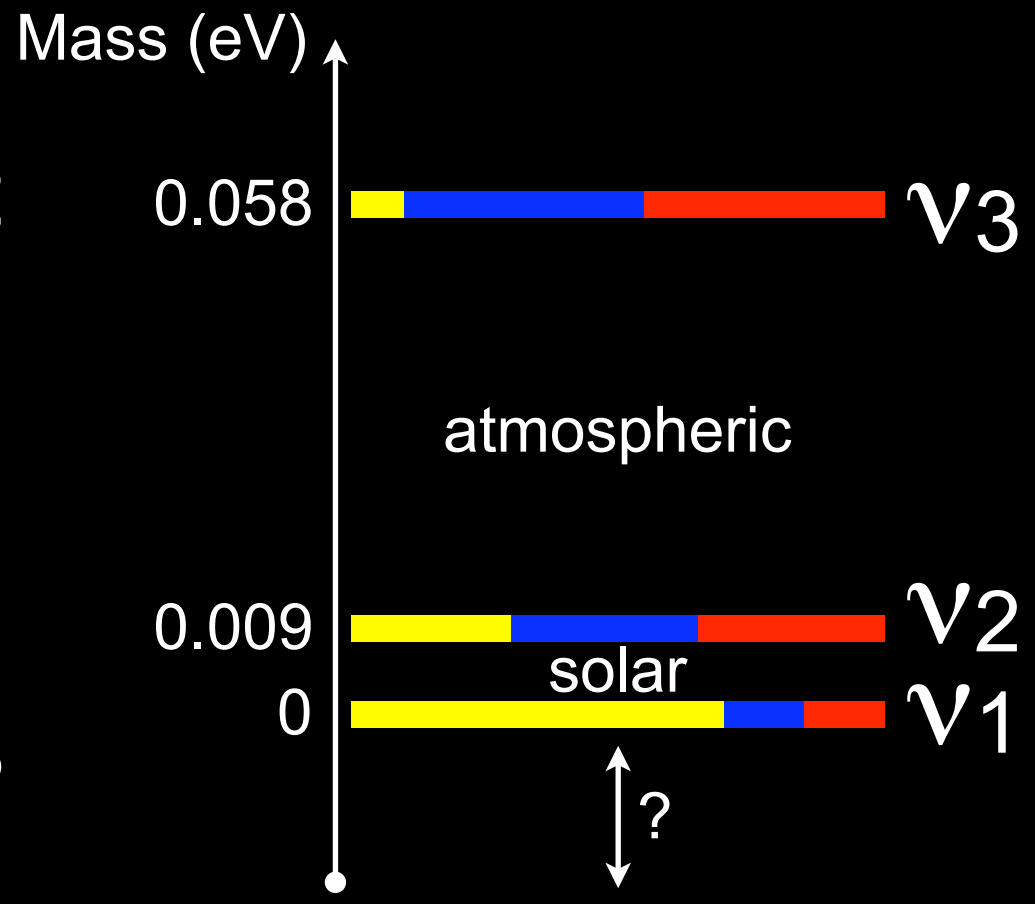
Exploring the New Paradigm

Which way does it go?





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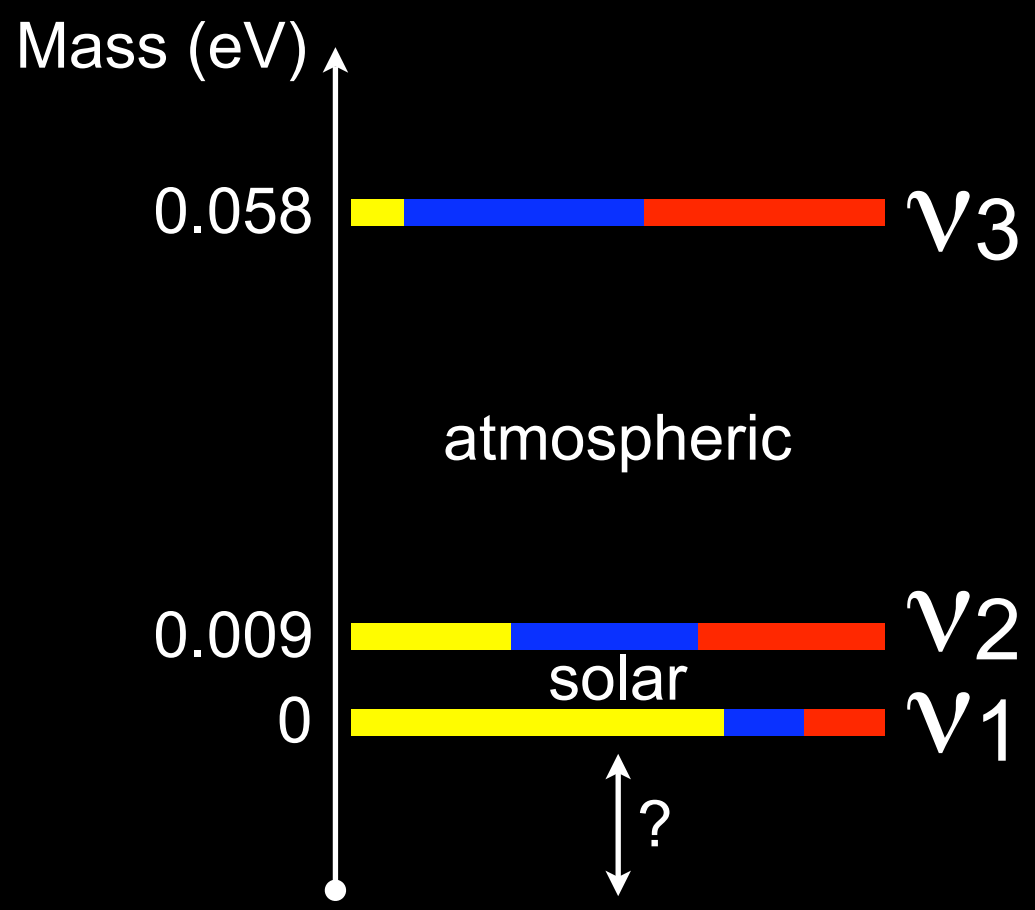
Exploring the New Paradigm

- Strategy:
  - Is $\theta_{13} = 0$?
  - Is $\theta_{23} = 45°$?
  - Mass hierarchy?
  - CP violation???
    - Requires precise answers to the above



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Exploring the New Paradigm

- Strategy:
  - Is $\theta_{13} = 0$?
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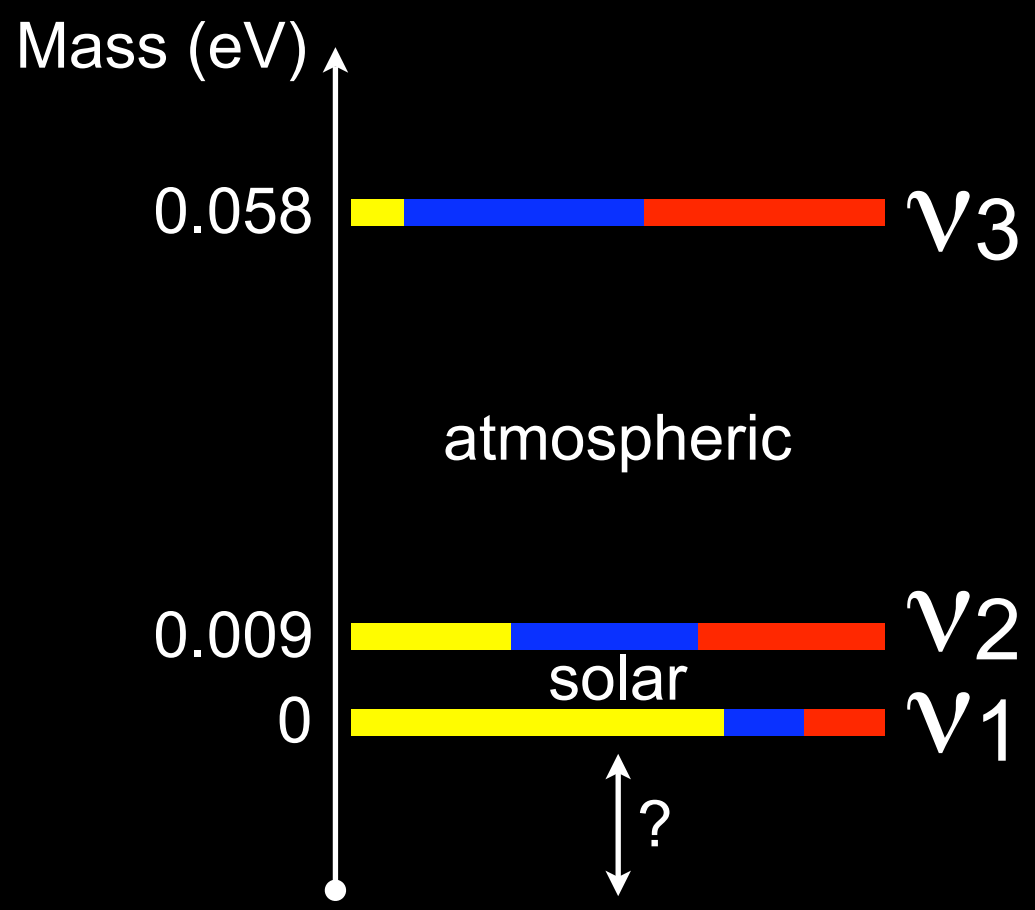
- Need reactor and accelerator experiments

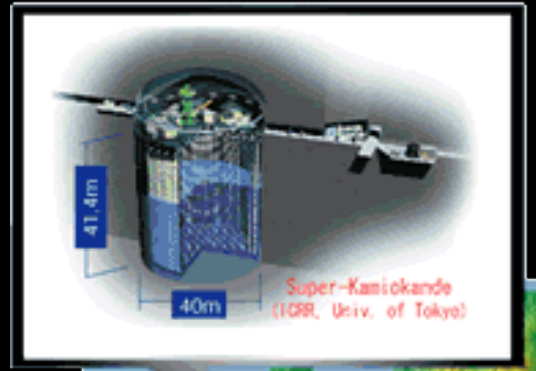


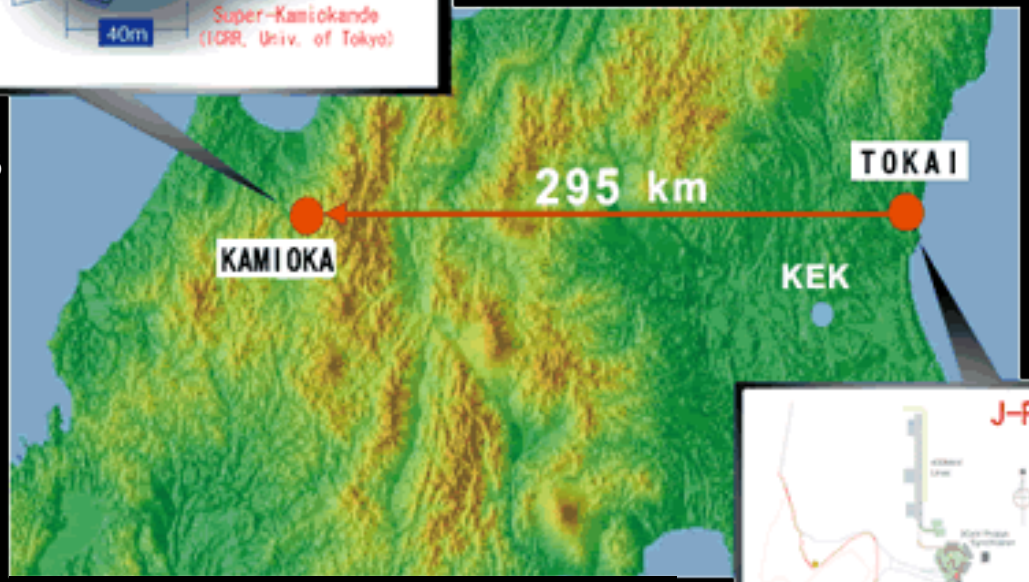
flavour key:

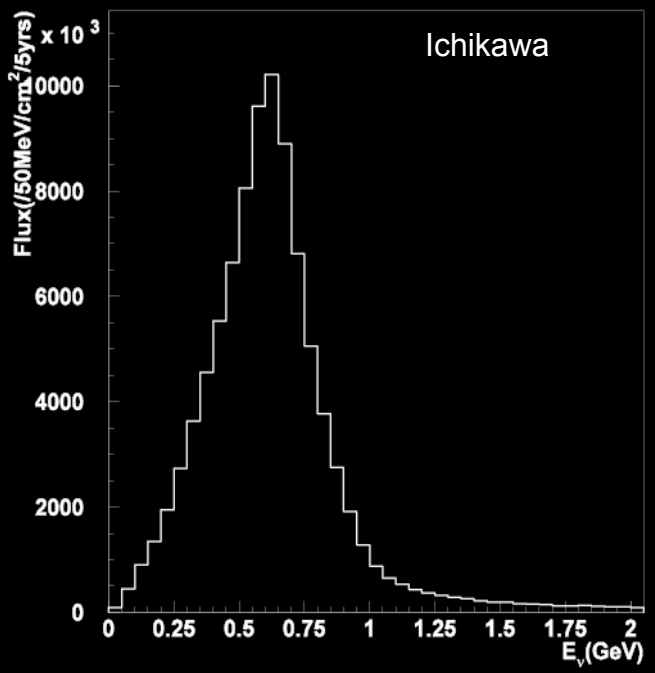
ν_e ν_μ ν_τ

T2K

- Goals: precise θ_{23} measurement & search for θ_{13}
- Start with world's largest detector: Super-Kamiokande
- Build new neutrino beam
- Off-axis beam to Super-K
  - L = 295 km
  - E = 0.7 GeV
- Near detector at 280m to constrain beam flux
- Beam will start running in April 2009
- Expect 5E21 POT in 5 years







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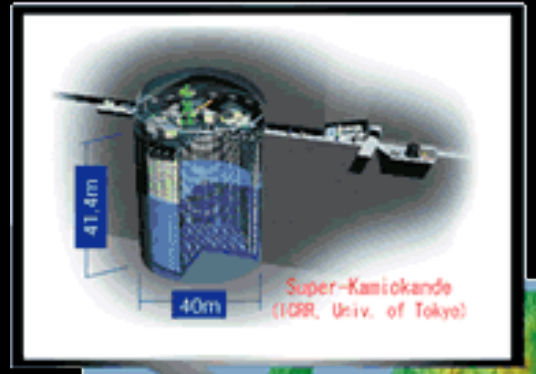

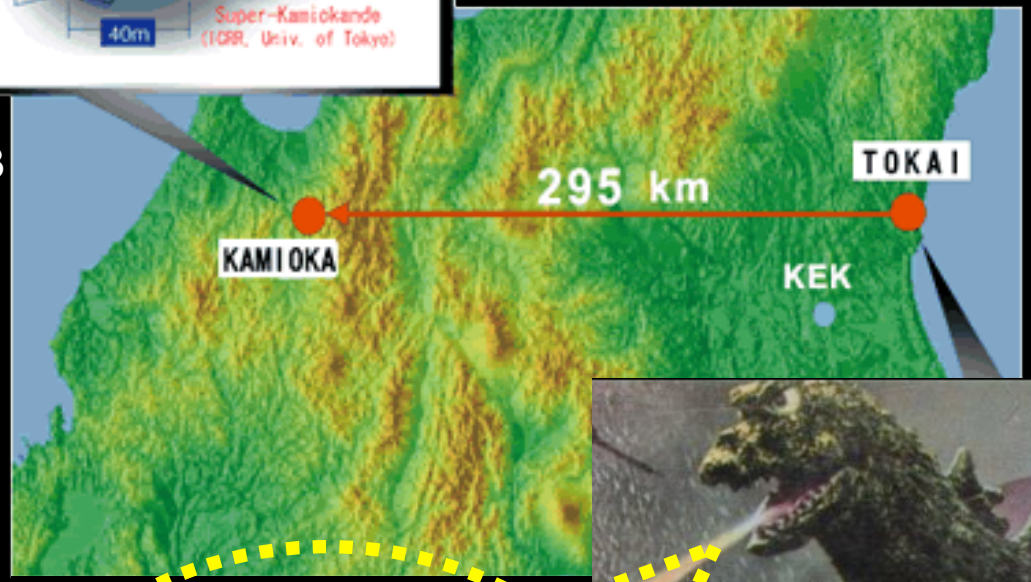

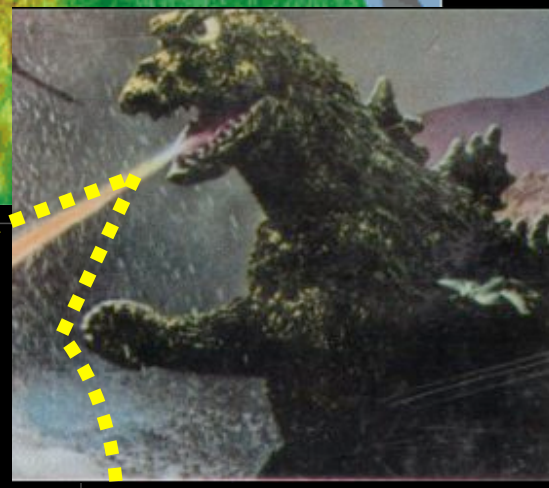

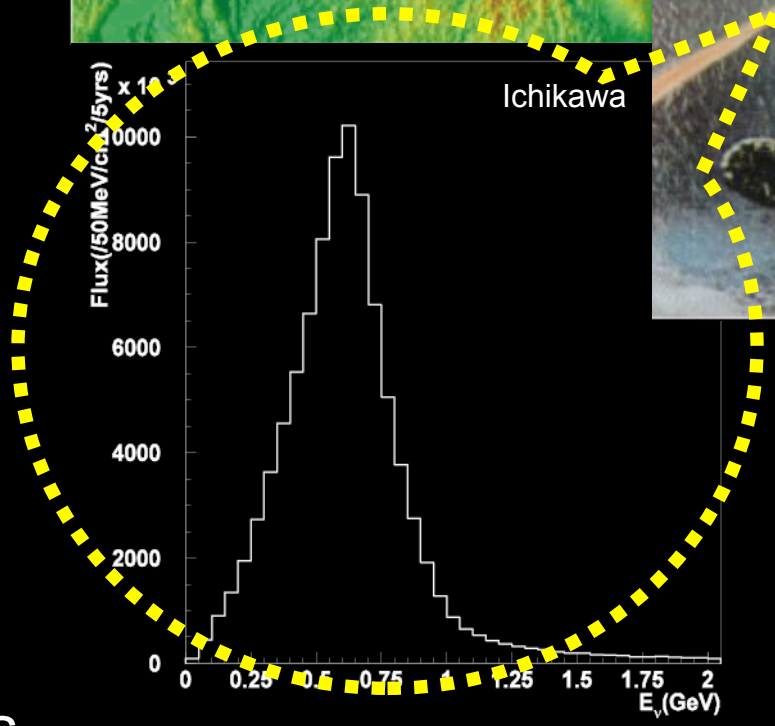

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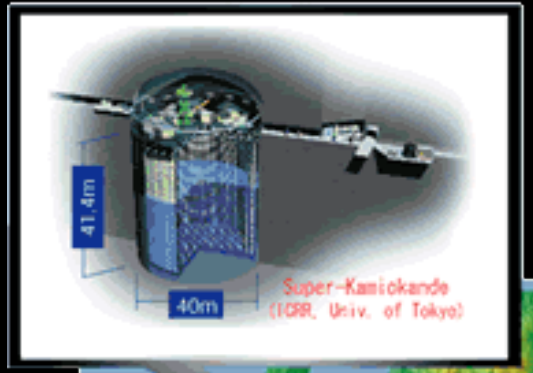
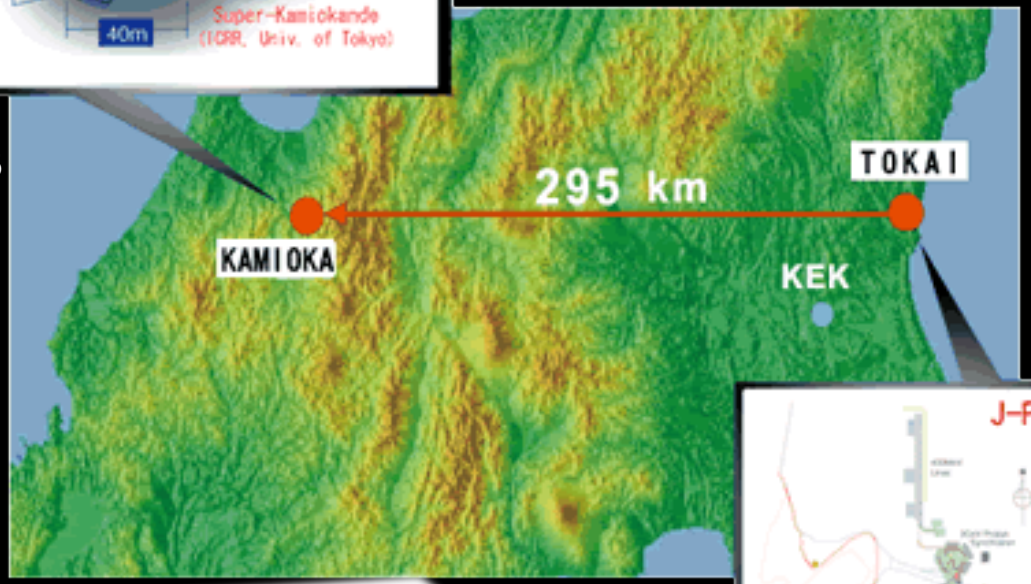
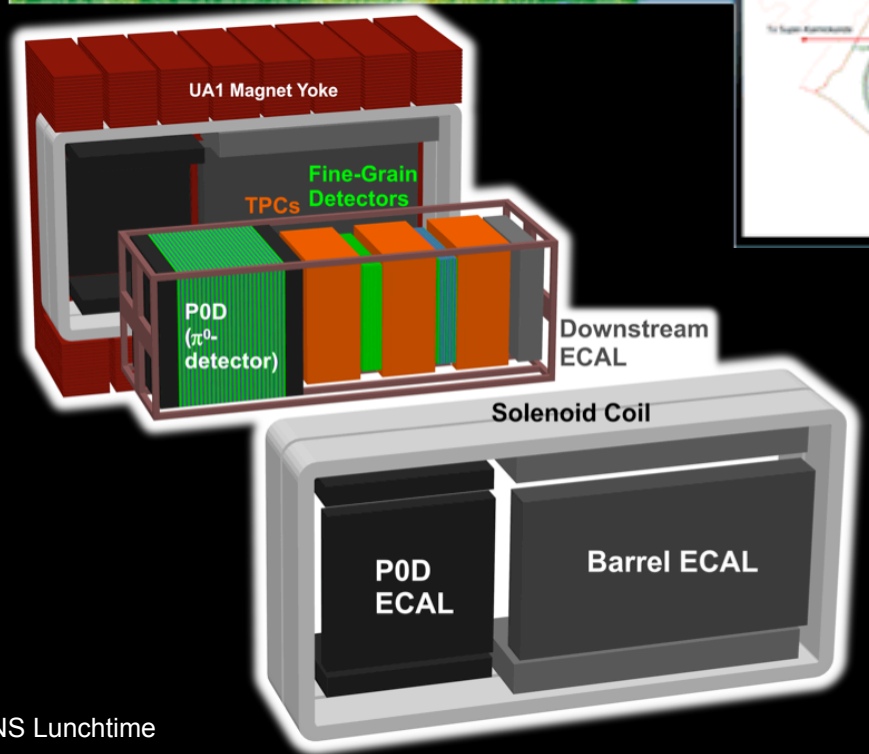
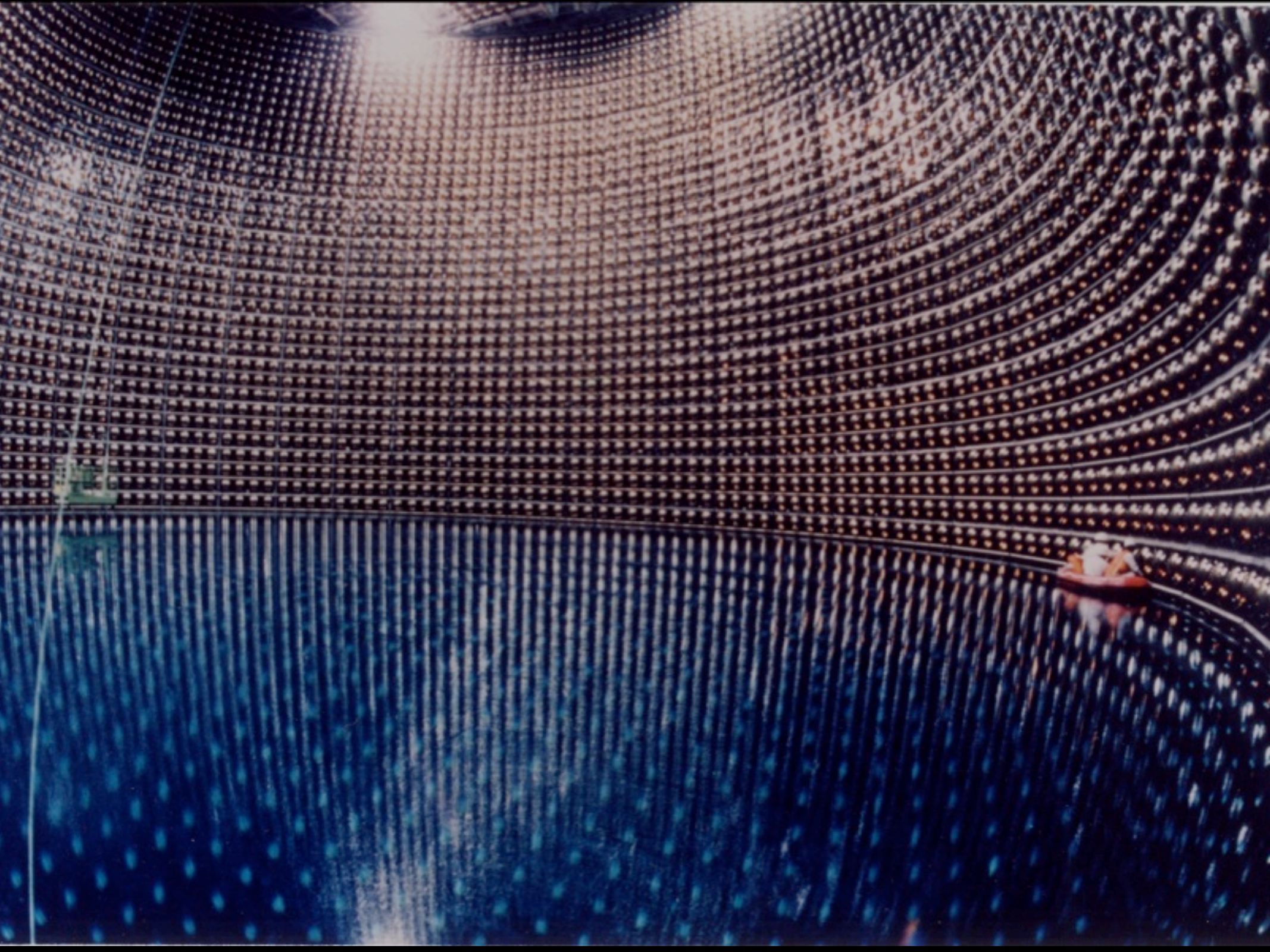




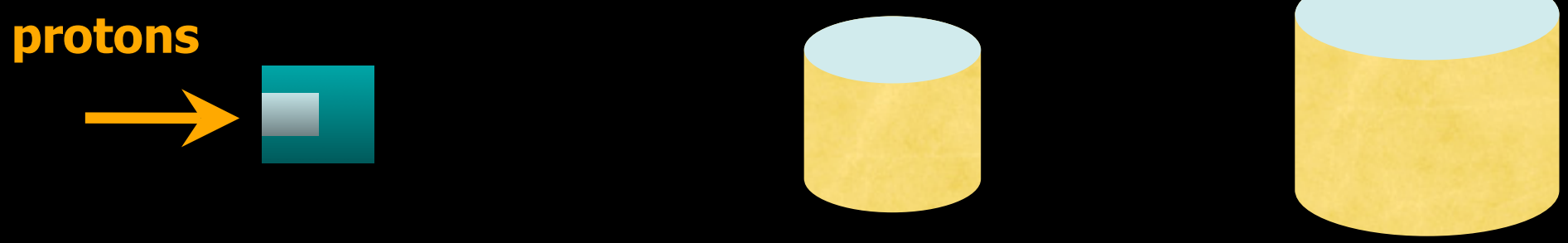




Strategy of accelerator ν experiments

Intense beam

Gigantic detector



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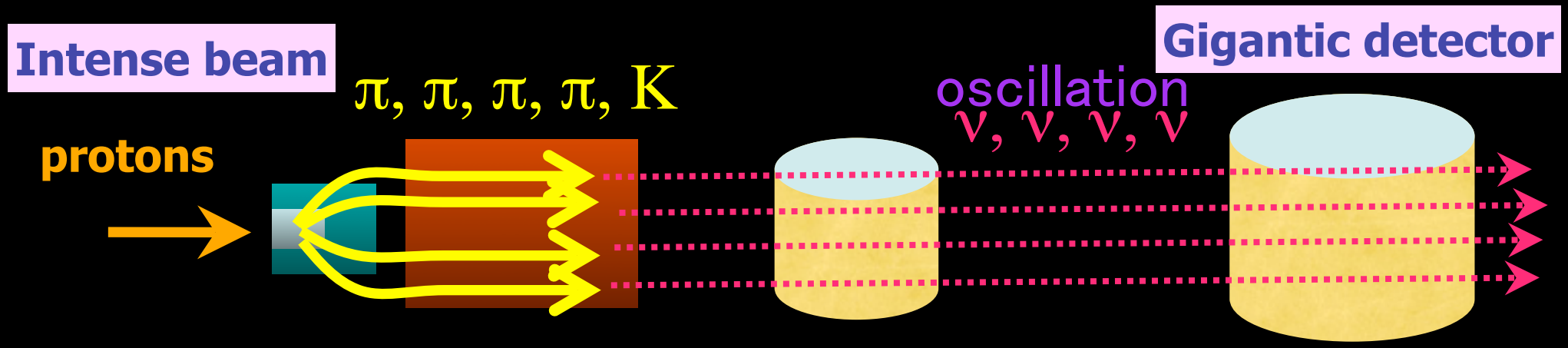

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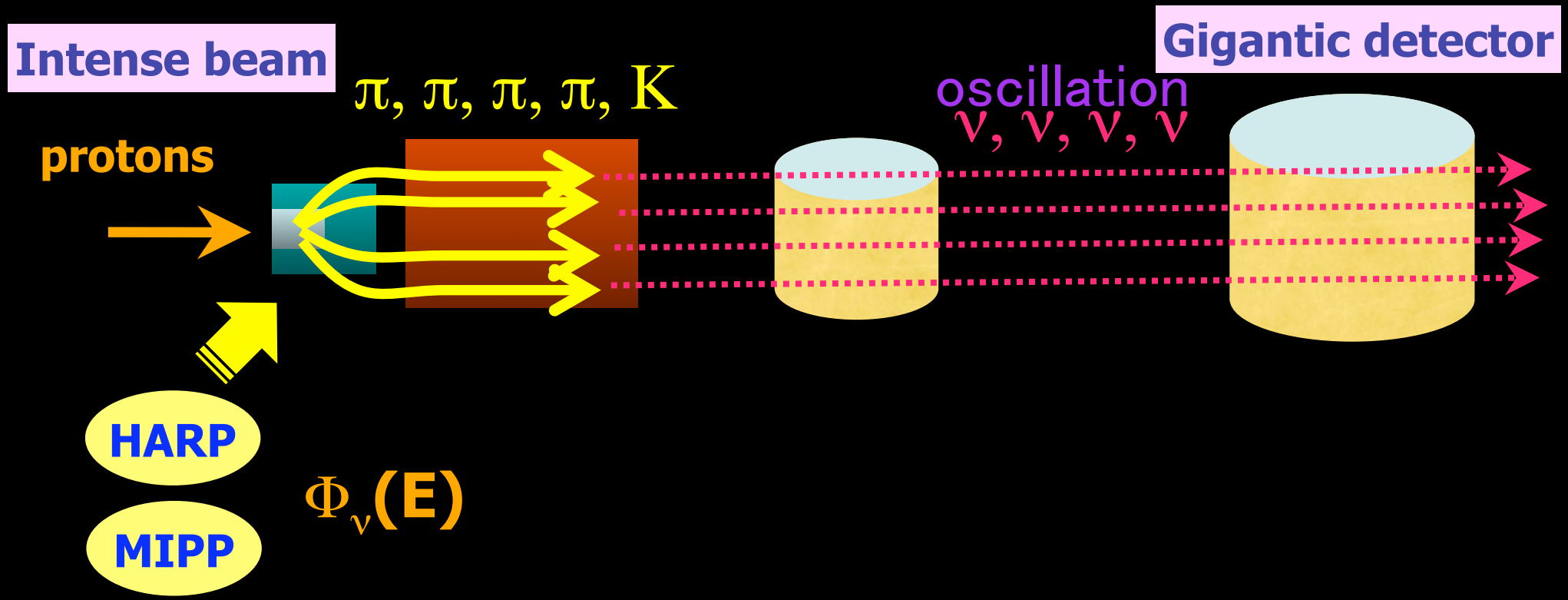

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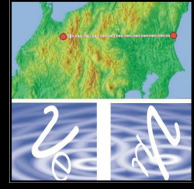


Intense beam

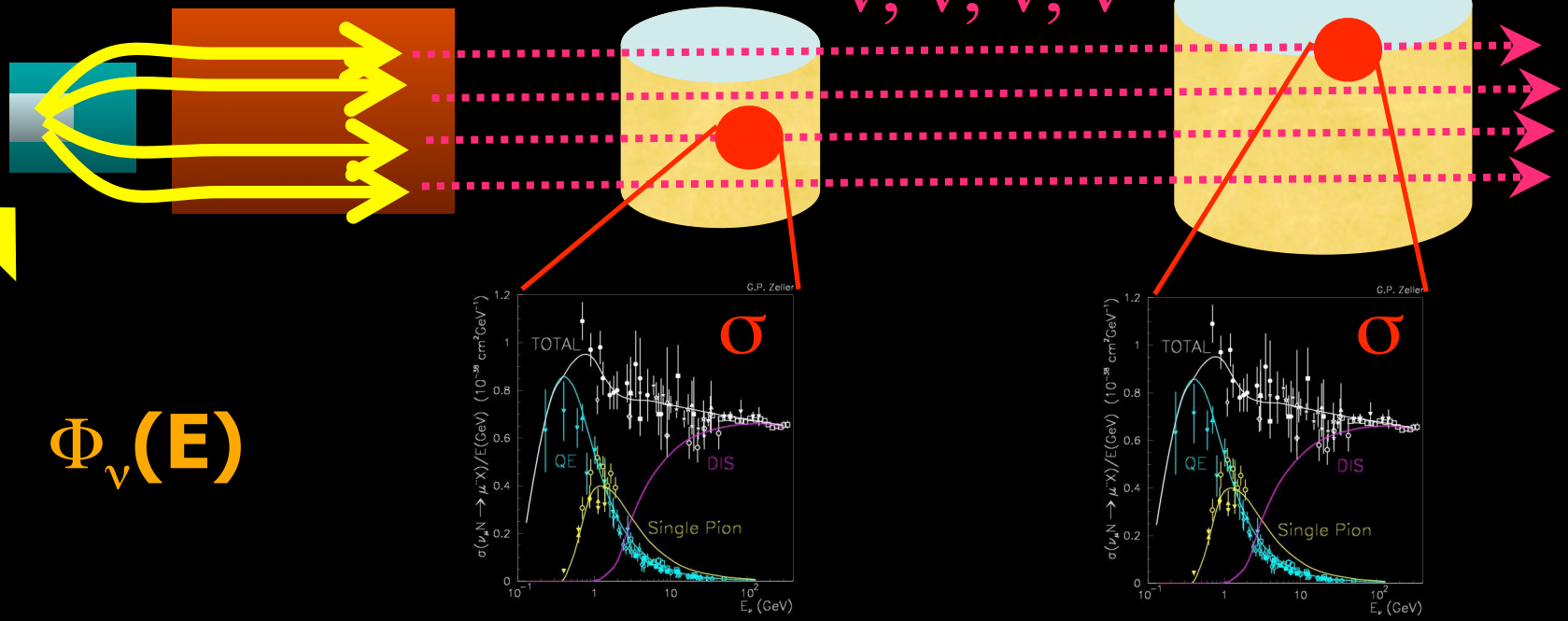
Gigantic detector

π, π, π, π, K

oscillation

ν, ν, ν, ν

protons

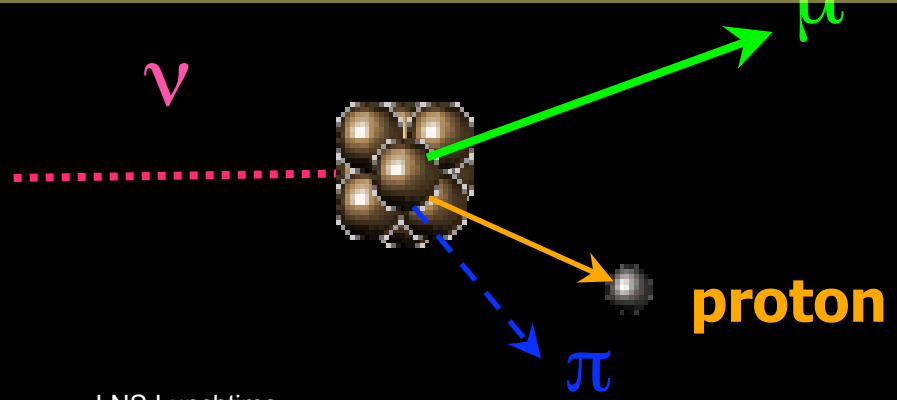


HARP

MIPP

$\Phi_\nu(E)$

$$\sigma(E)\cdot\Phi_\nu^{near}(E) \Leftrightarrow \sigma(E)\cdot\Phi_\nu^{far}(E)$$



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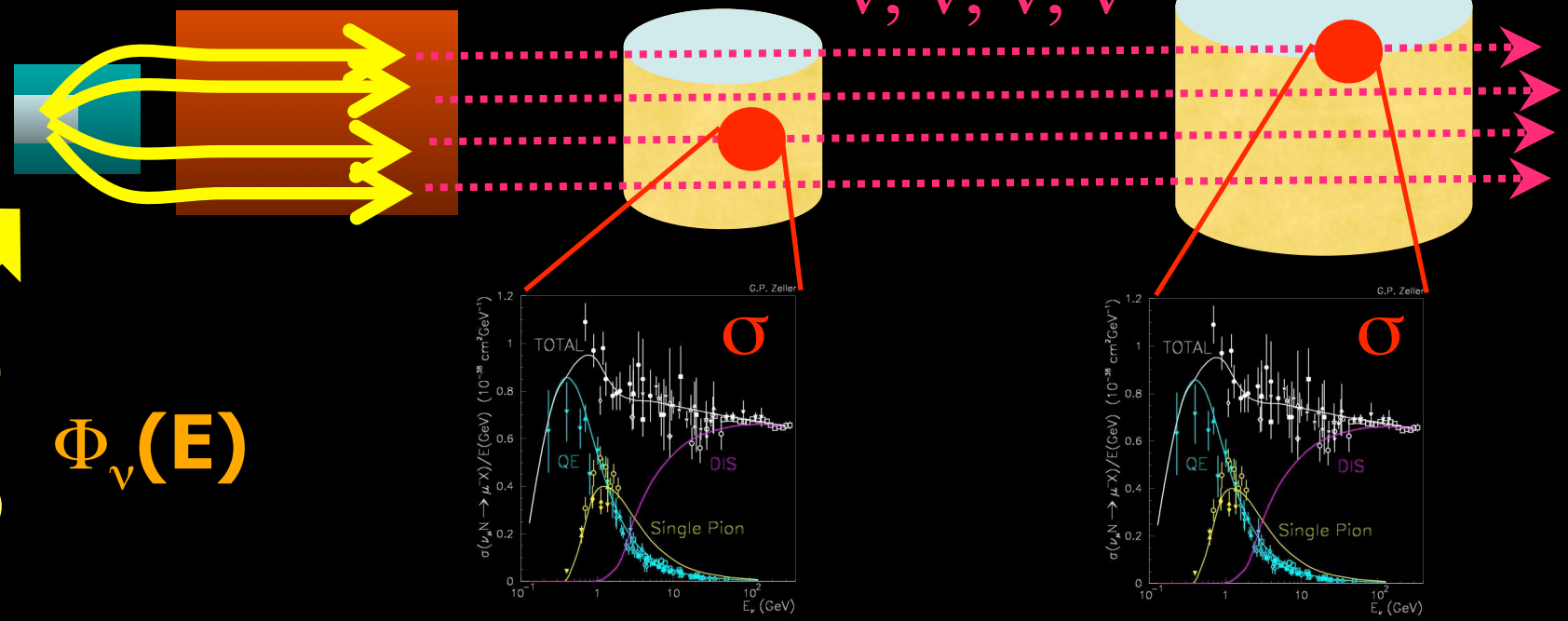

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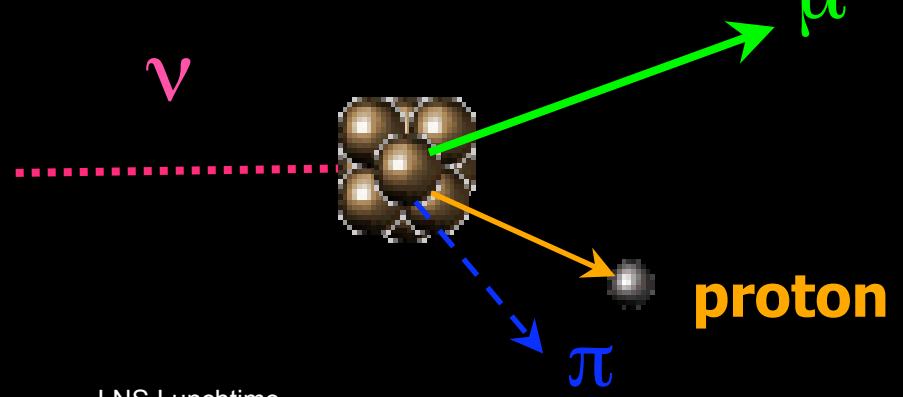
MiniBooNE

K2K-ND

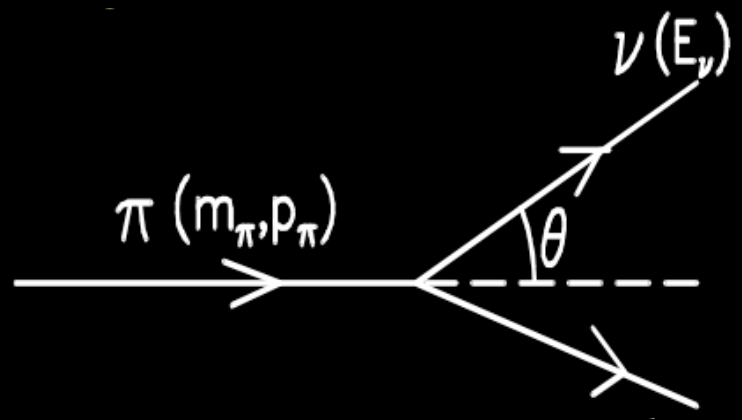
SciBooNE

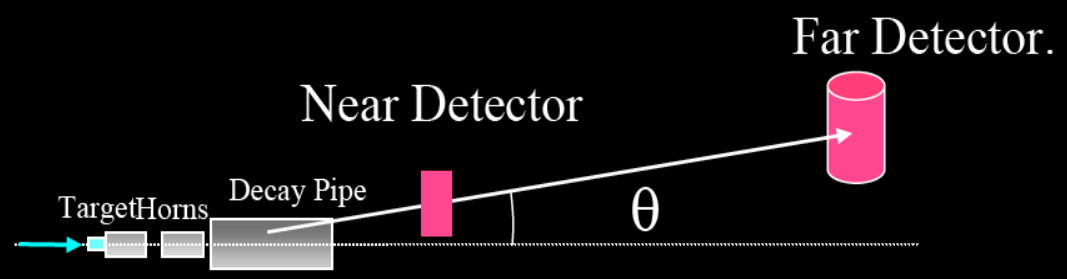
MINERνA



Off-Axis Beam

- Use kinematics of pion decay to tune the neutrino energy
- Flux peak at target energy for desired value of L/E
  - L is often constrained by geographic considerations…





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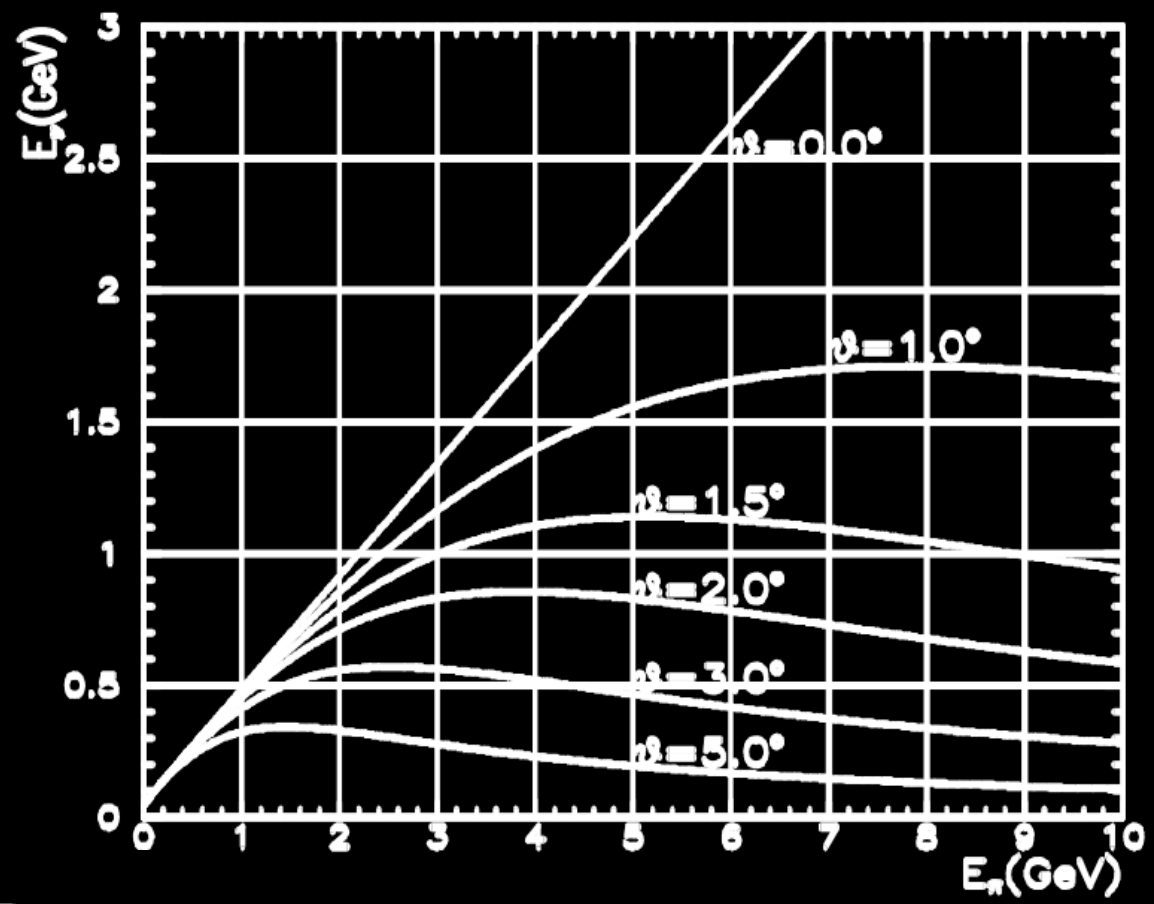

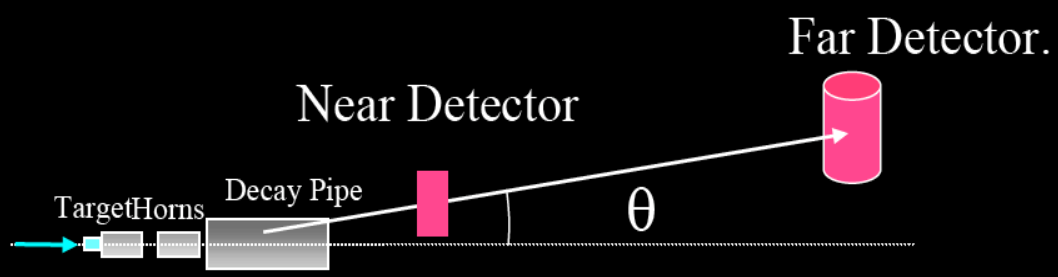

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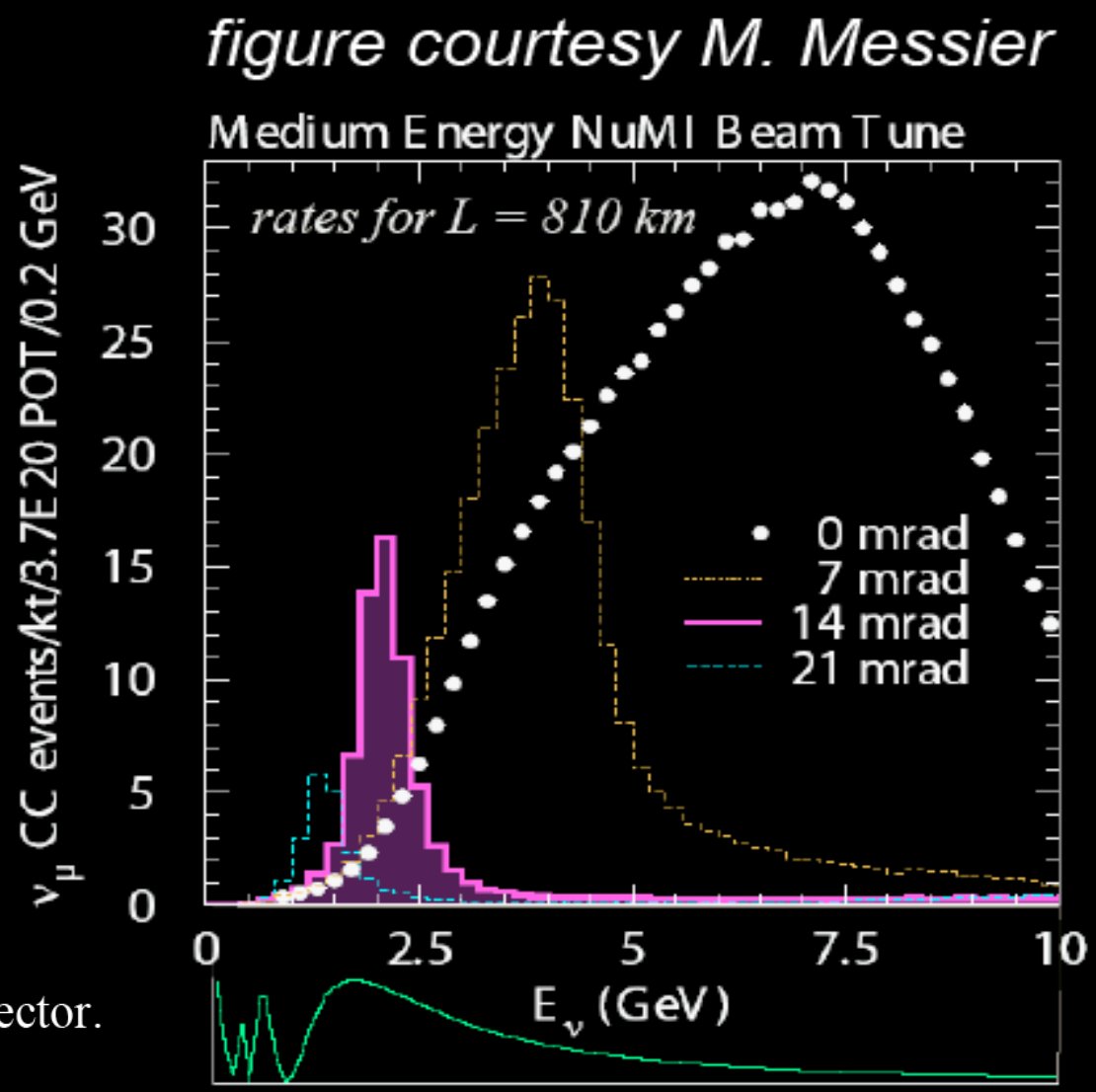
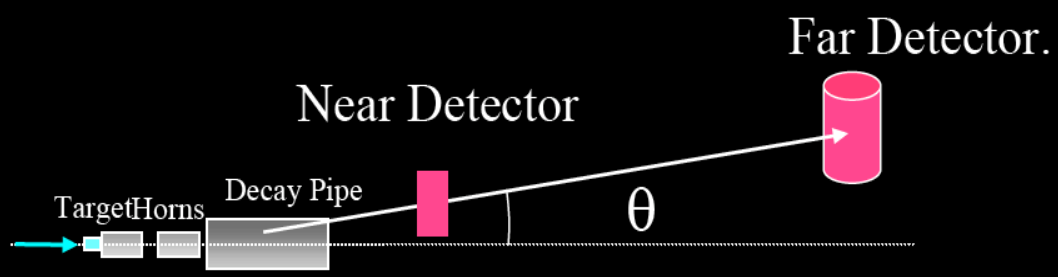
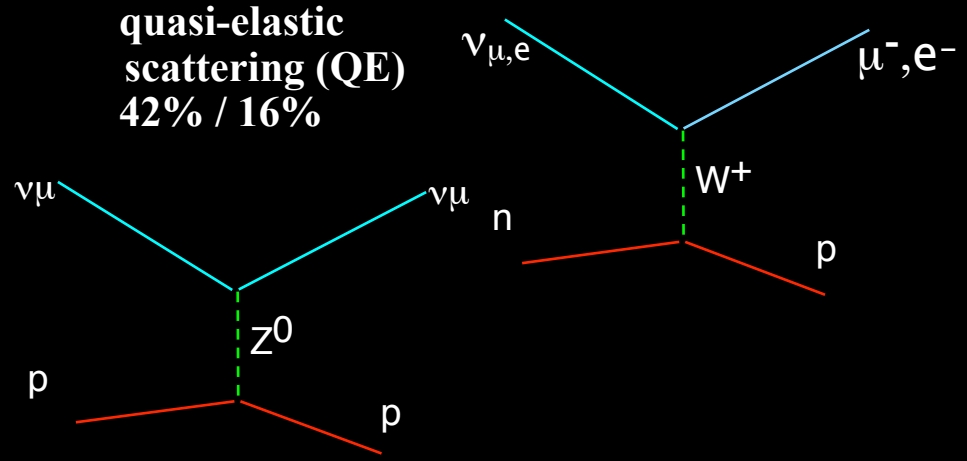




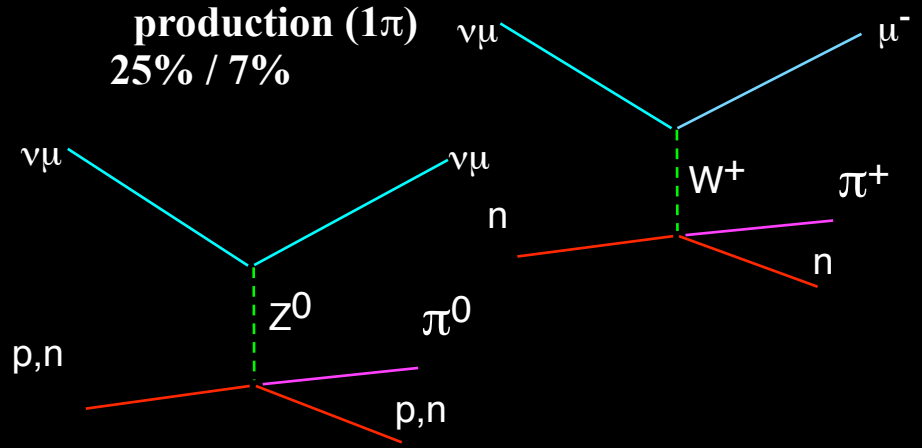
uming $\Delta m^2 = 2.5 \times 10^{-3} eV^2$

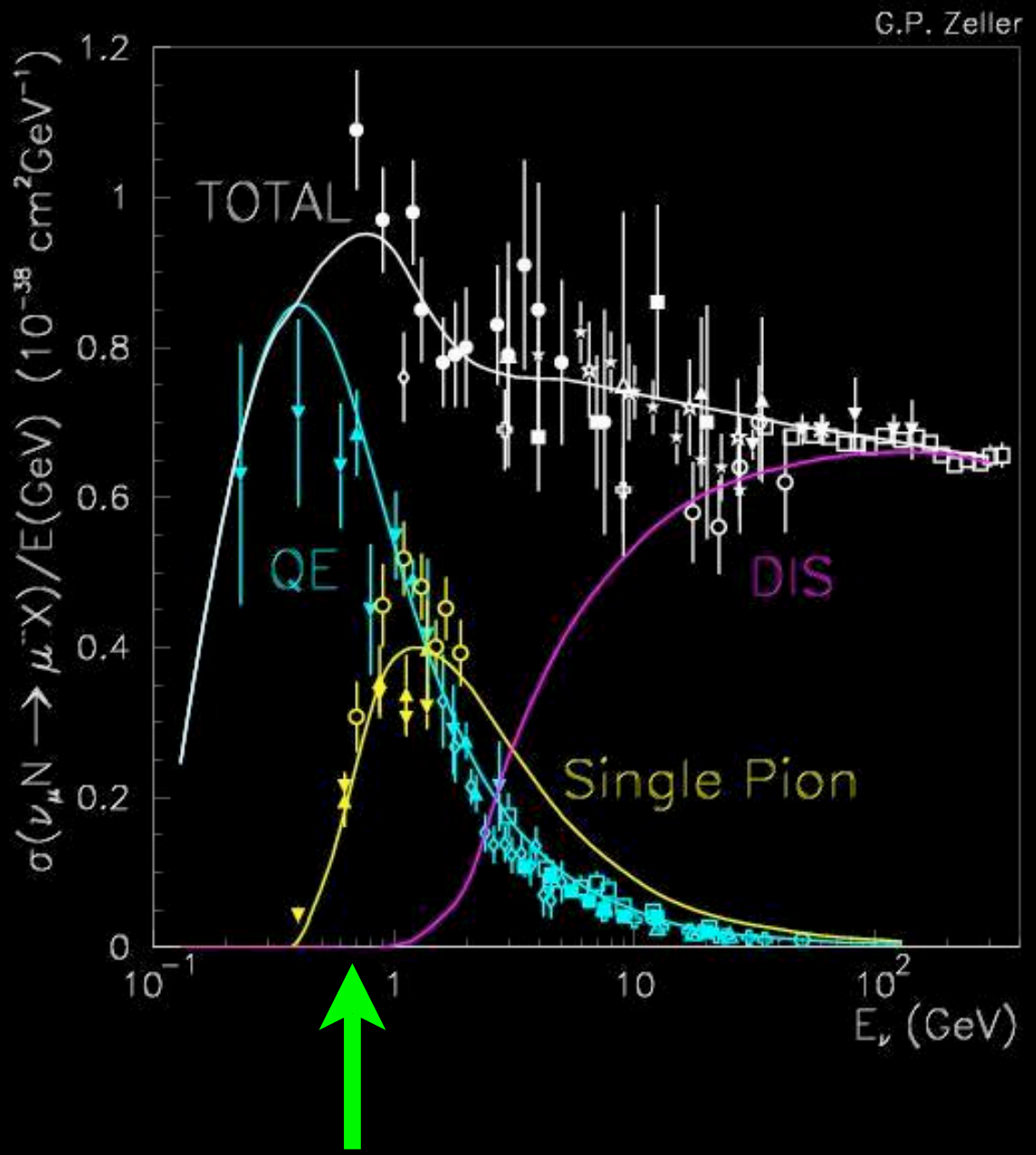
ν Cross-sections

CC / NC quasi-elastic scattering (QE) 42% / 16%



CC / NC resonance production (1π) 25% / 7%





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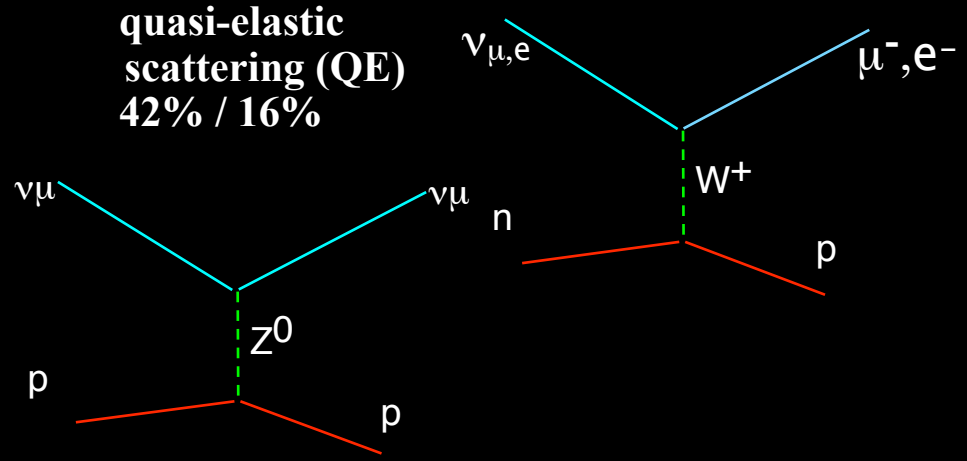

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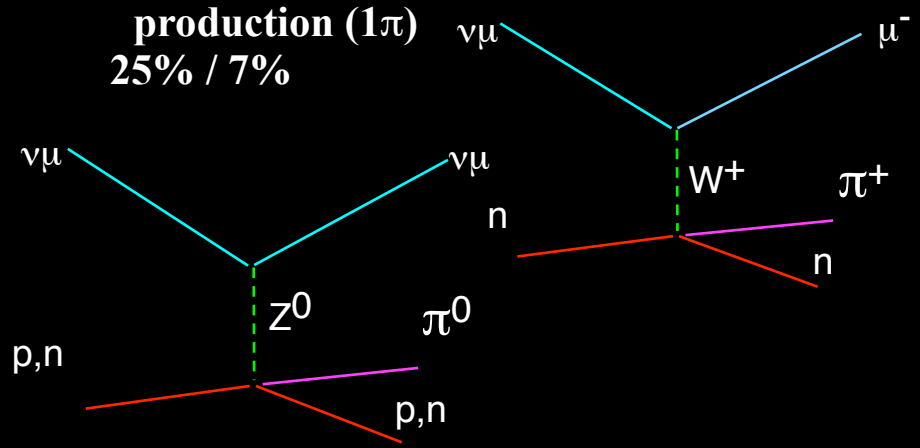

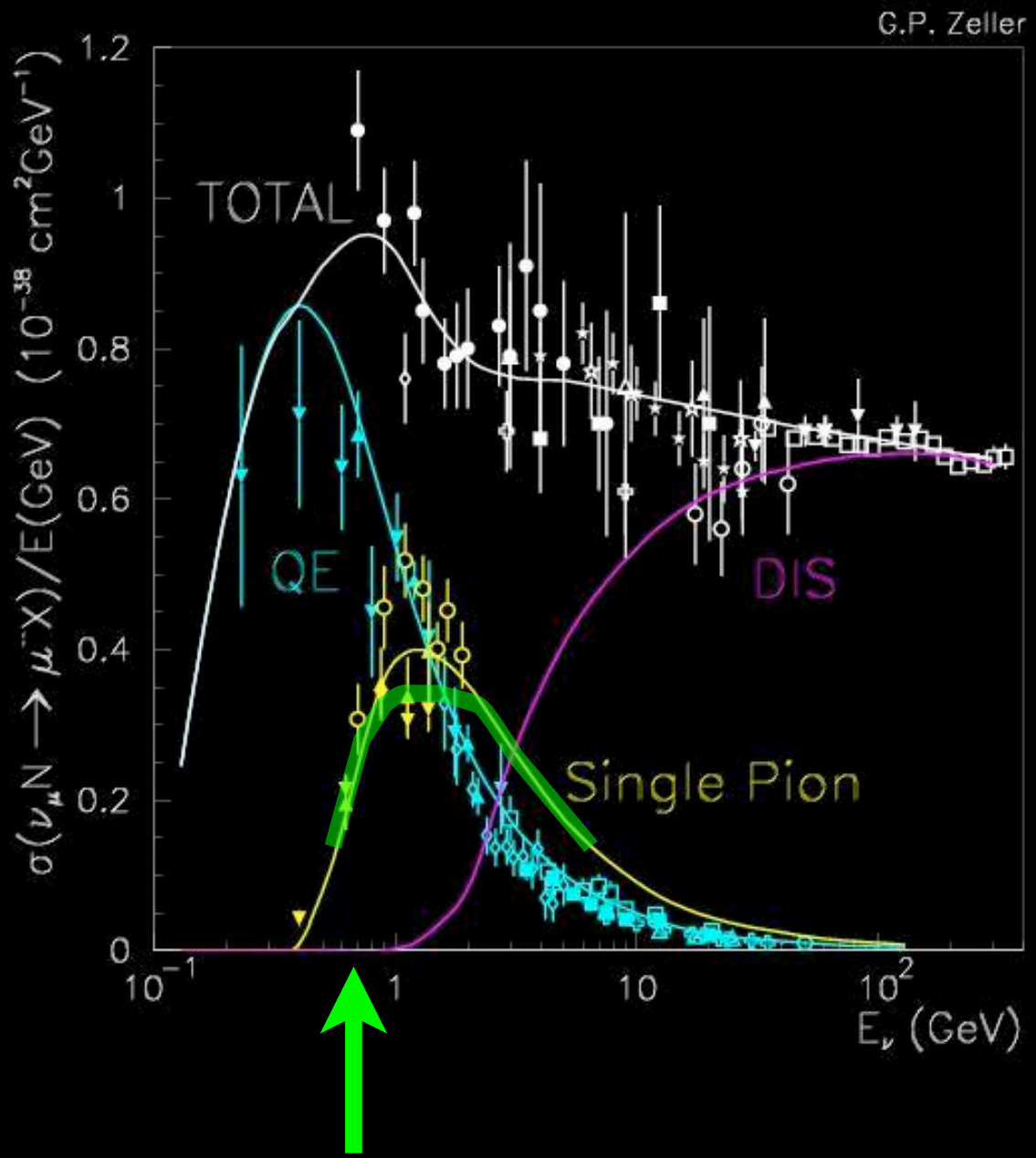

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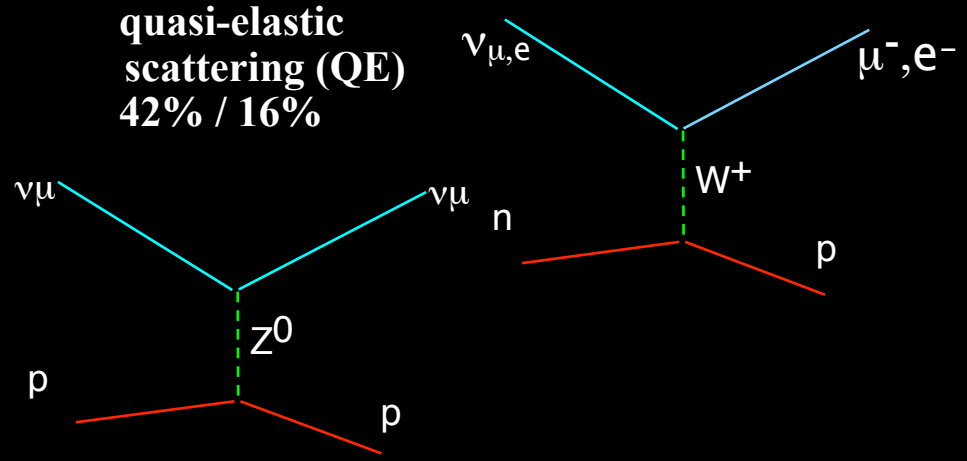

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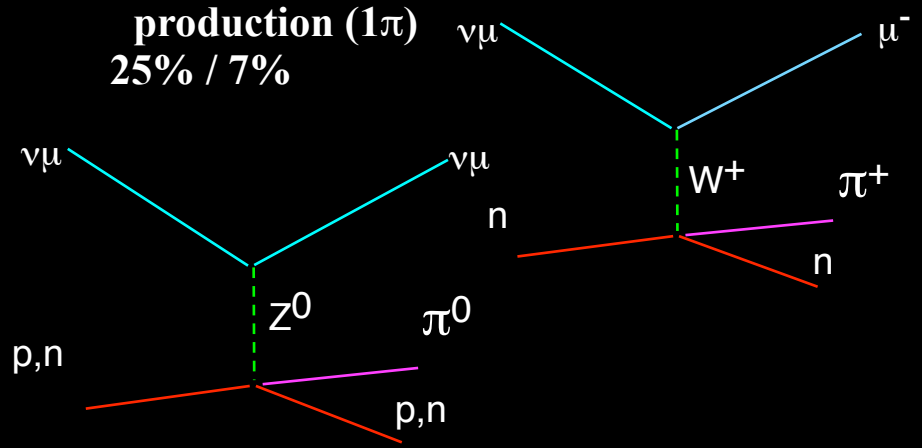

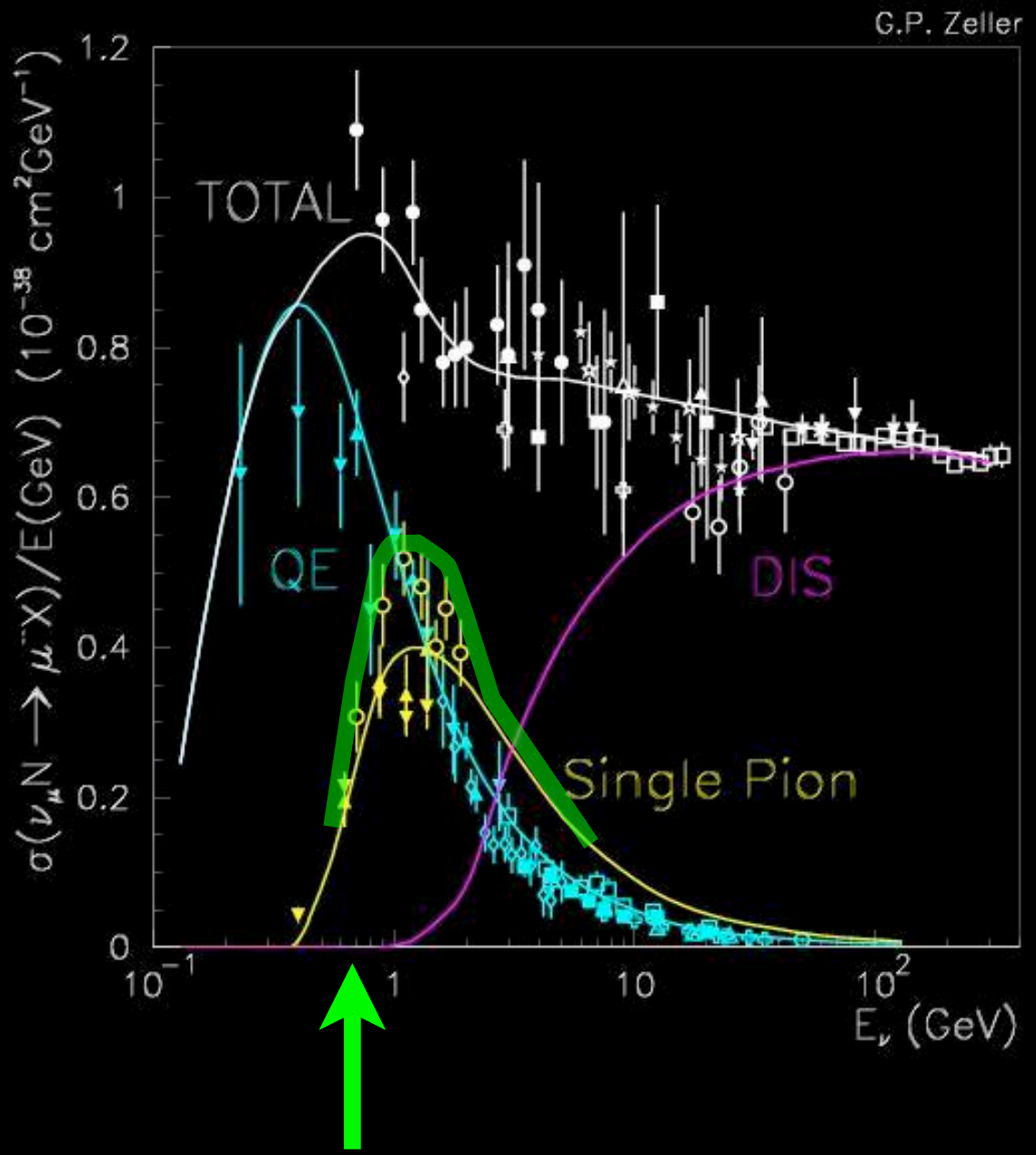

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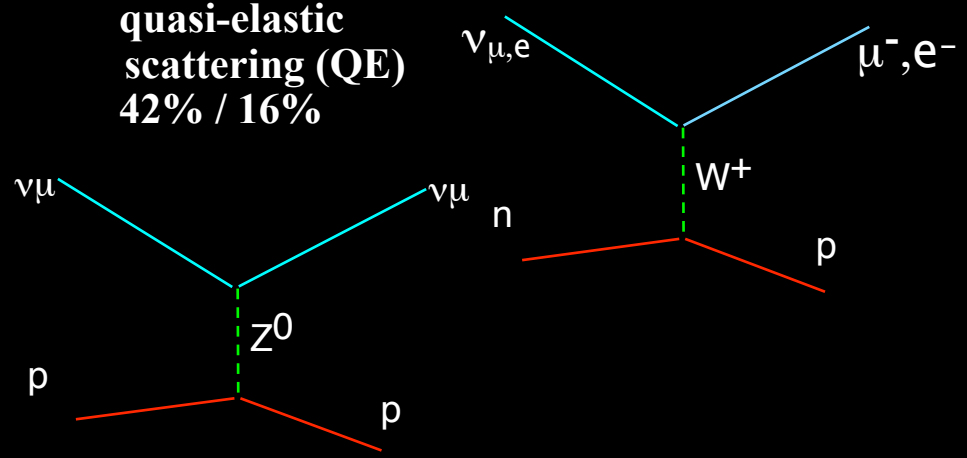

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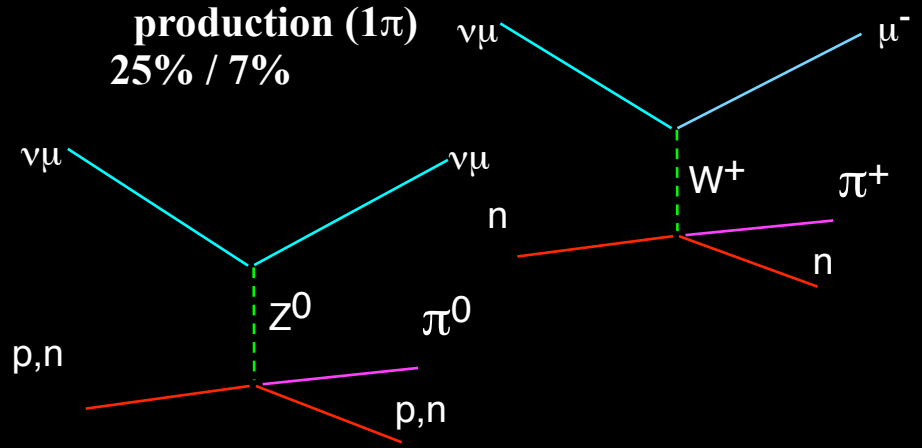
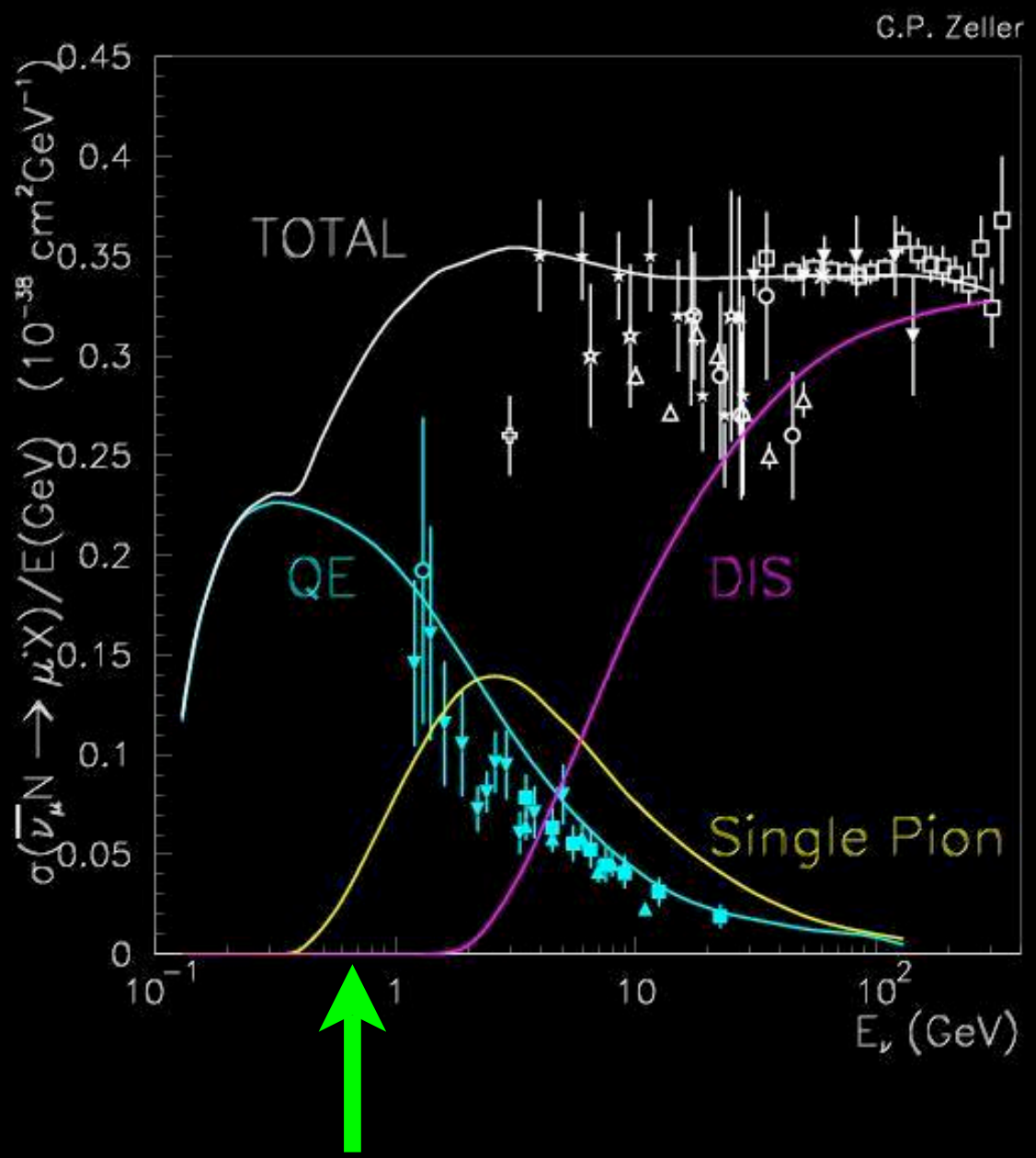
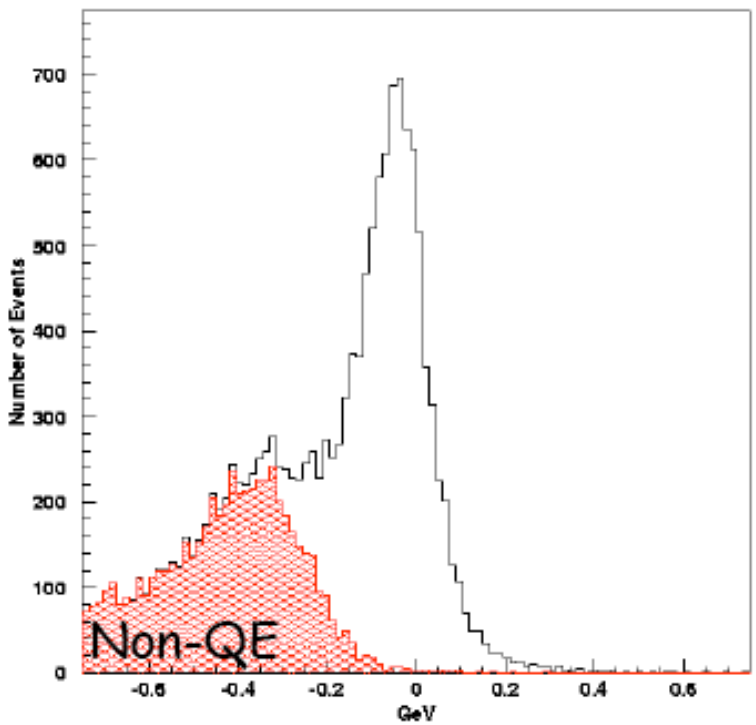




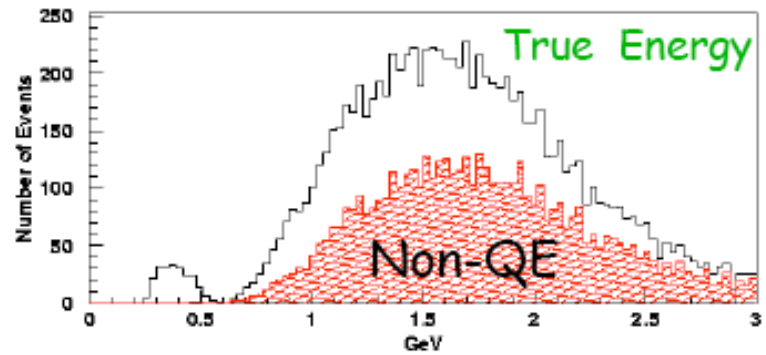
Effect of non-QE BGs

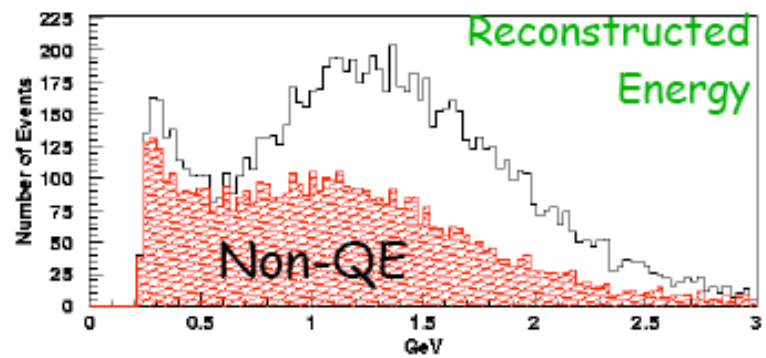
Non-QE interactions and E_ν Reconstruction

Example: K2K Flux MC



True - Reconstructed Energy

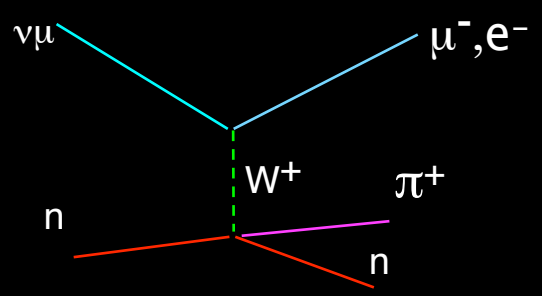




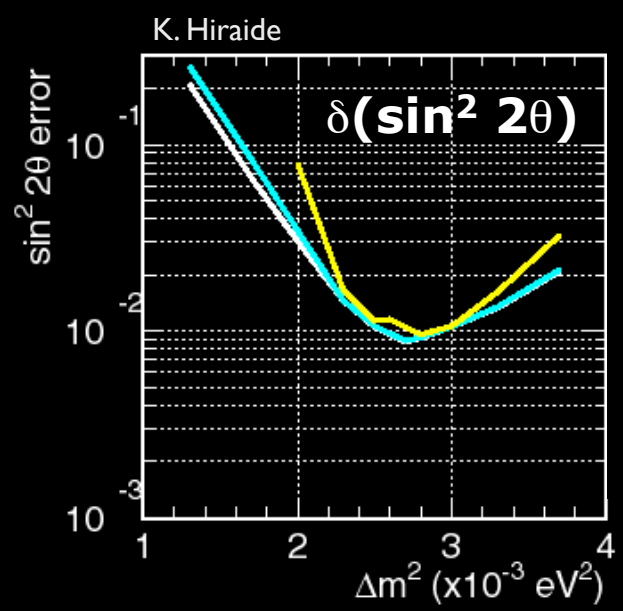
Non-QE reconstructs at low-energy in the oscillation dip!

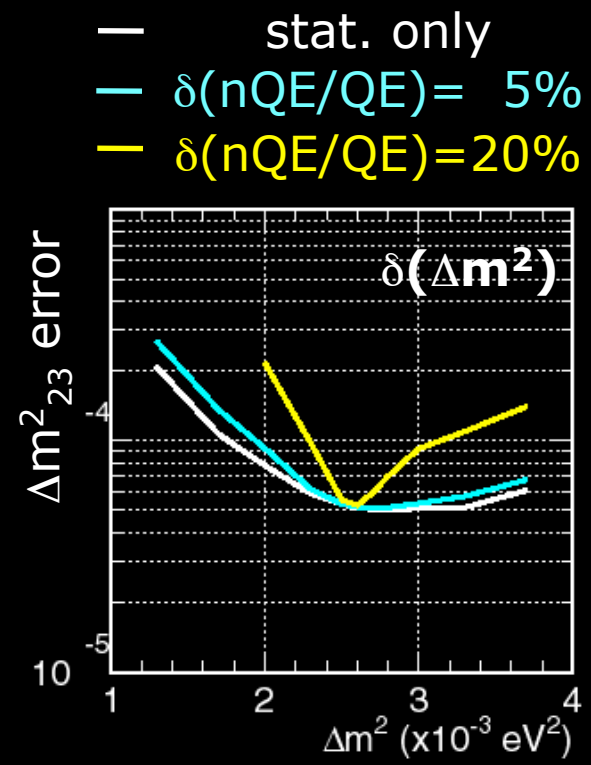
C. Walter, NuInt07

Need for σ_ν Measurements

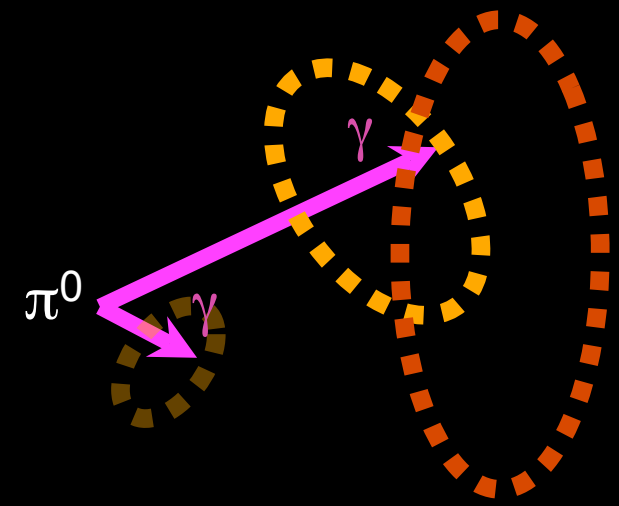


- CC1π^+ events can create *bias* in oscillation parameter extraction
- Must reduce uncertainty in $\sigma(CC1\pi^+)$ from 20% to 5%





Search for θ_{13}: ν_e appearance

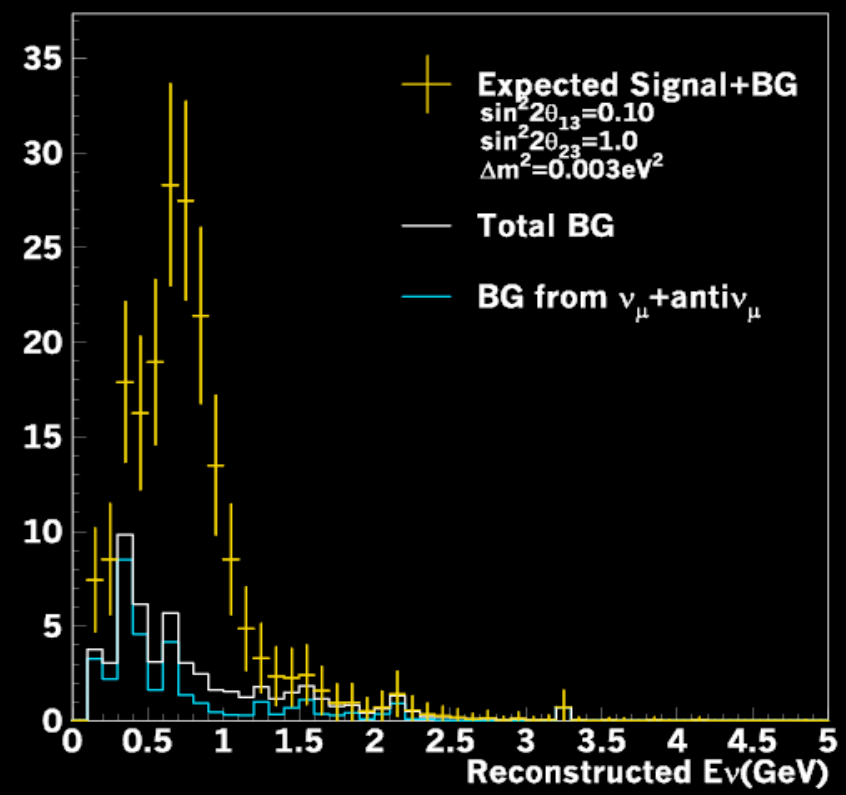


- Subdominant oscillation

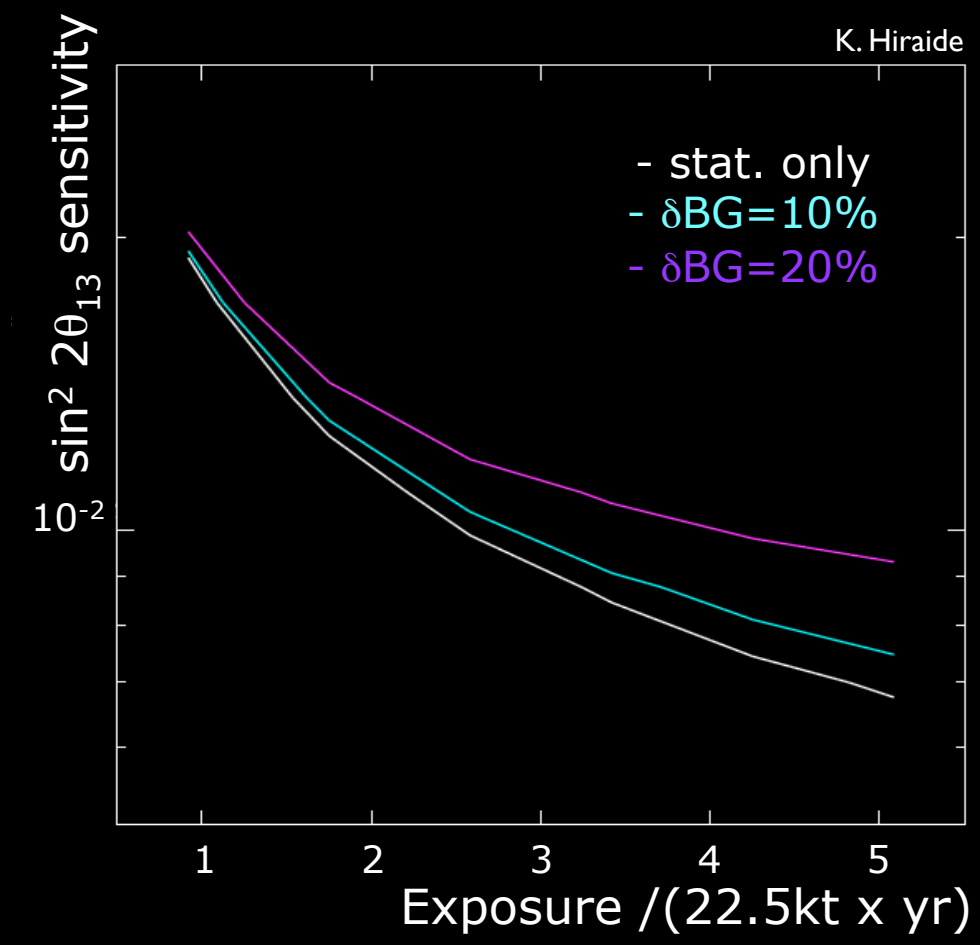
  $\sin^2 2\theta_{\mu e} \sim \sin^2\theta_{23} \cdot \sin^2 2\theta_{13}$

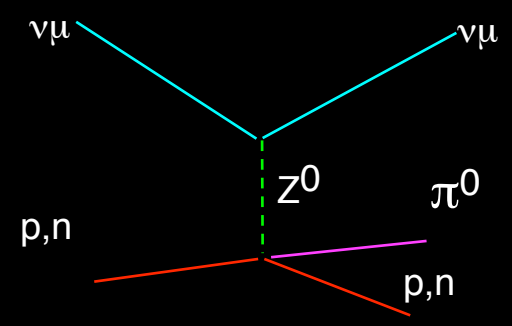
  Need good measurement of θ_{23}

- Major background from NCπ^0 events
  - γ rings mimic e rings in Super-K
- Must reduce uncertainty on NCπ^0 cross section



Need for σ_ν Measurements





- Want to reduce uncertainty in $\sigma(NC\pi^0)$ from 20% to 10%
  - improvement of factor of 2 in ultimate T2K sensitivity to θ_{13}
  - or 2.5 years vs. 4 years to 10^{-2}

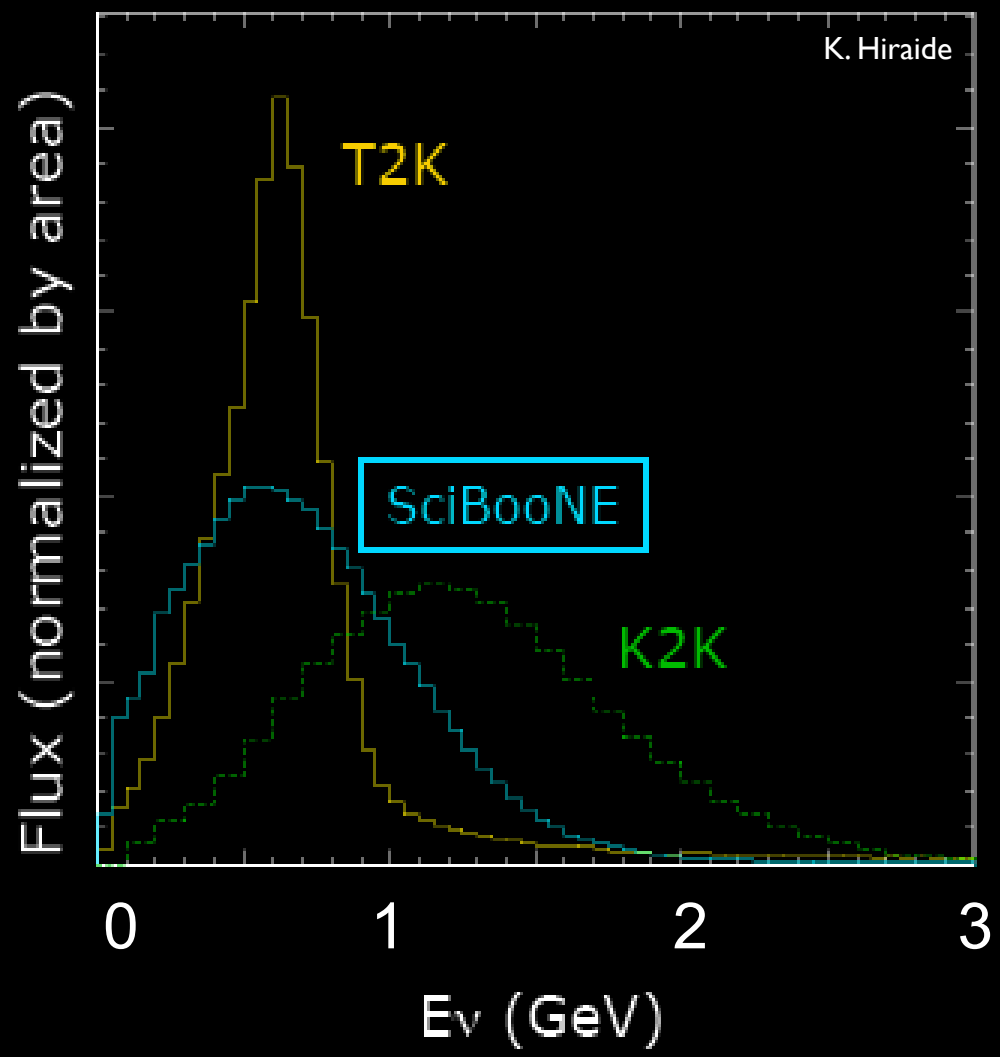
Joint Study Recommendations

Long Term Strategy

- NEW HIGH-PRECISION CROSS-SECTION EXPERIMENTS SHOULD BE UNDERTAKEN.

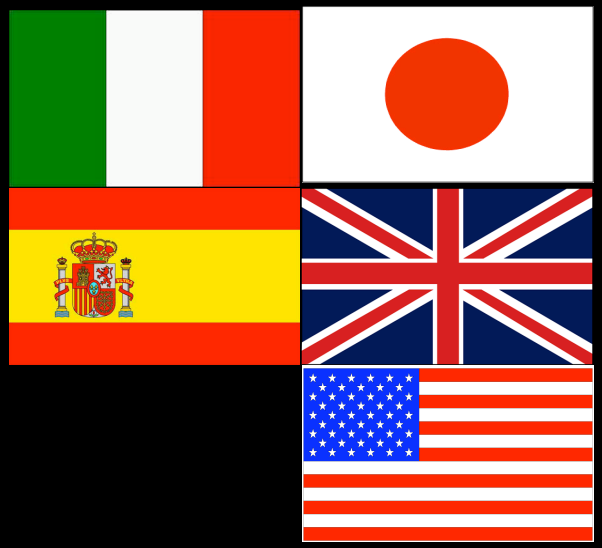
ancel some of the uncertainty in cross sections, the better a
more precise solution is to actually measure the cross sections better than currently known once and for all! We encourage that the experiments necessary for this be carried out.

Enter SciBooNE

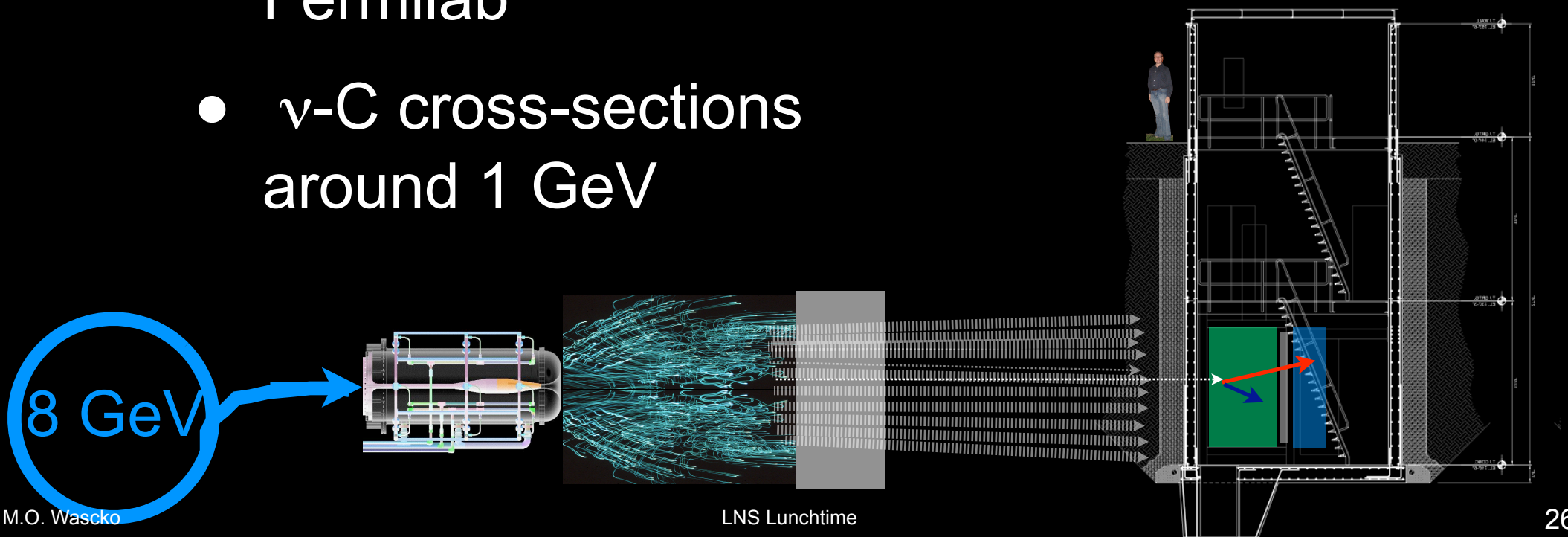


- Good match to T2K flux
- Booster Neutrino Beam already well understood
  - (HARP data)
- Similar flux shape to MiniBooNE
  - Antineutrino mode too

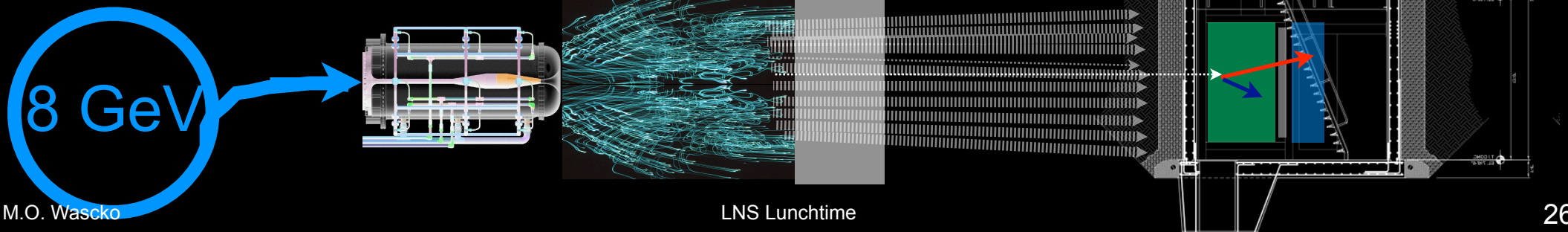
SciBooNE Overview



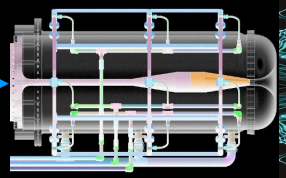
- New neutrino experiment at Fermilab (E-954)
- SciBar detector from K2K
- Booster Neutrino Beam at Fermilab
- ν-C cross-sections around 1 GeV

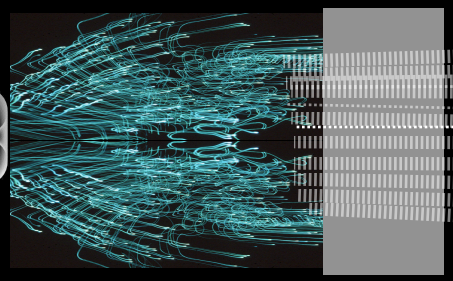


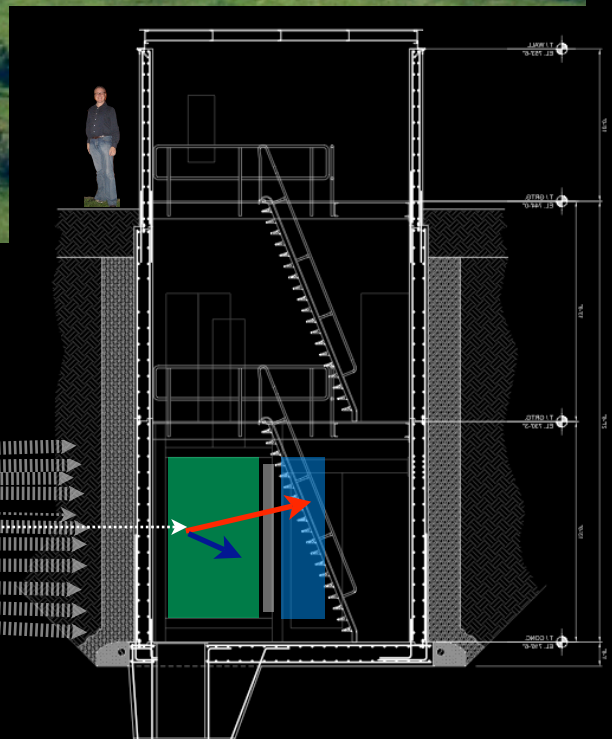
SciBooNE Overview



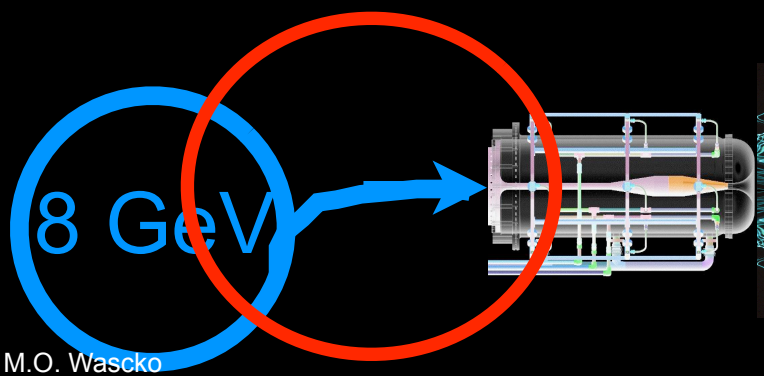
SciBooNE Overview

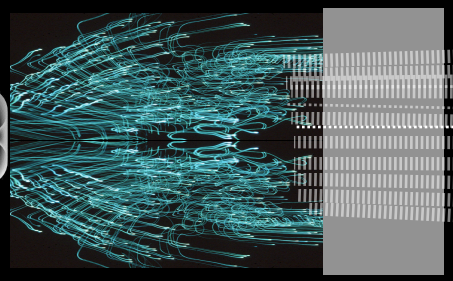


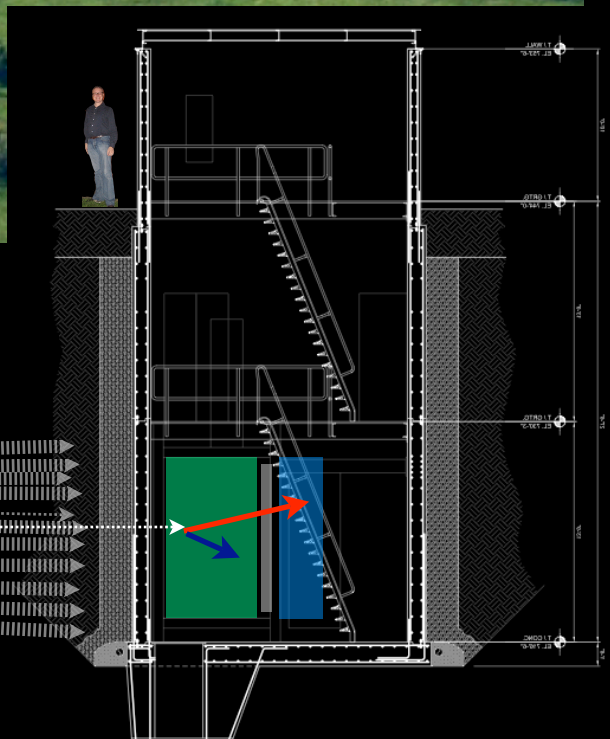




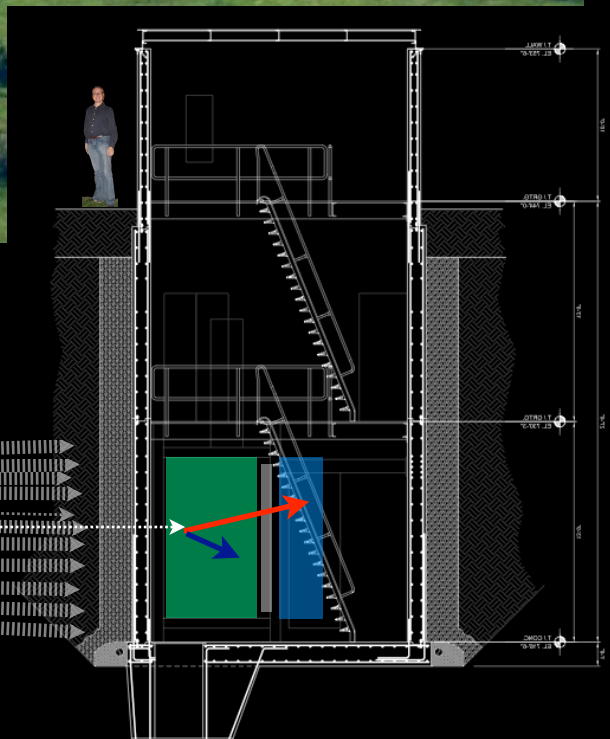
SciBooNE Overview

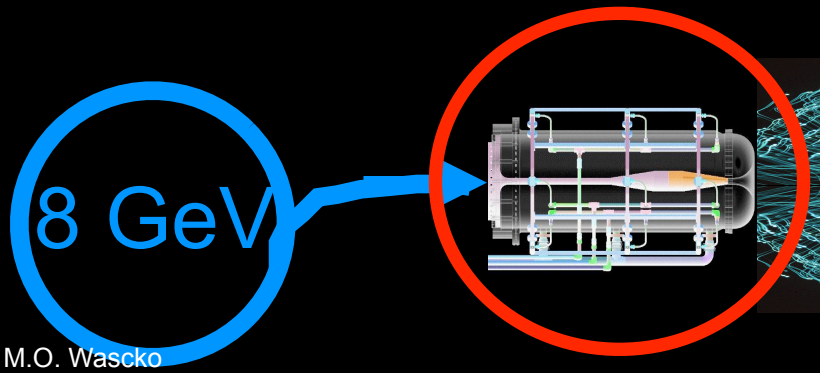




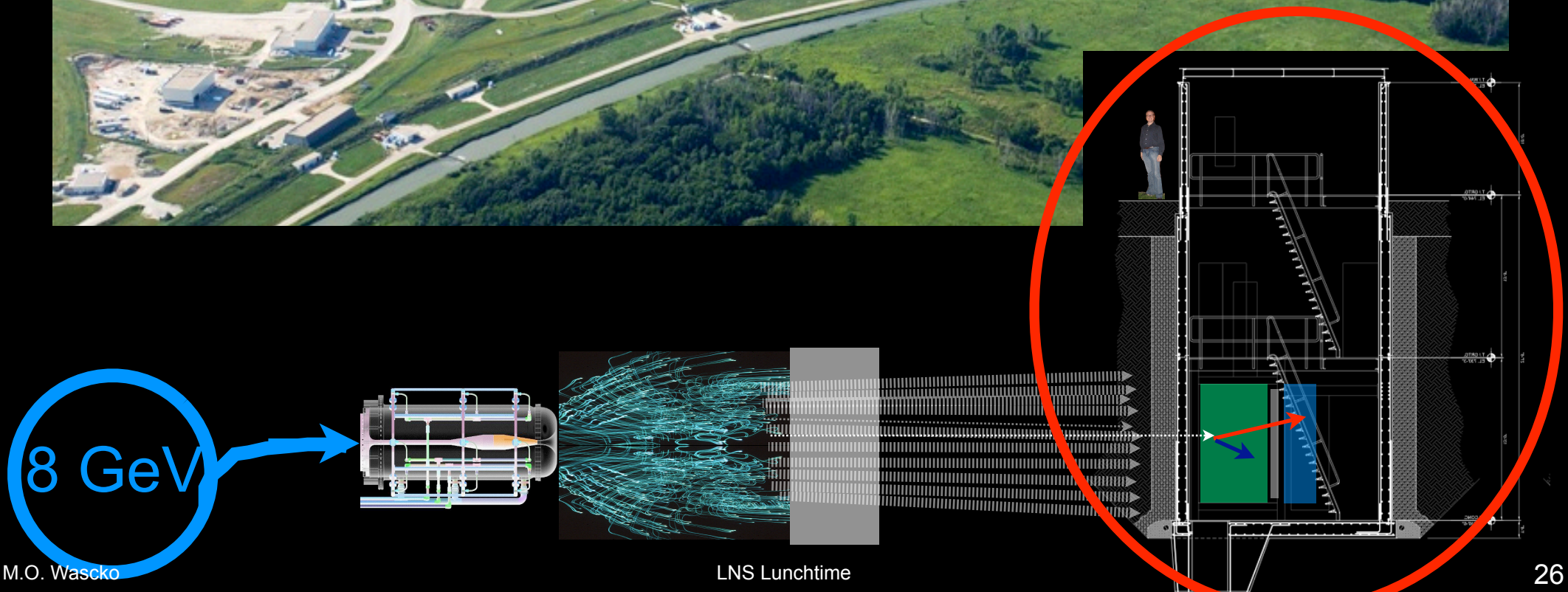


SciBooNE Overview

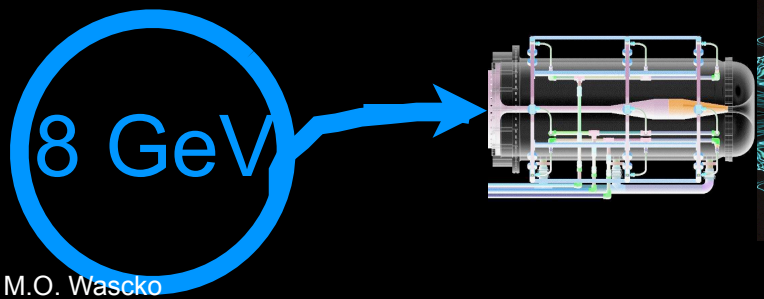


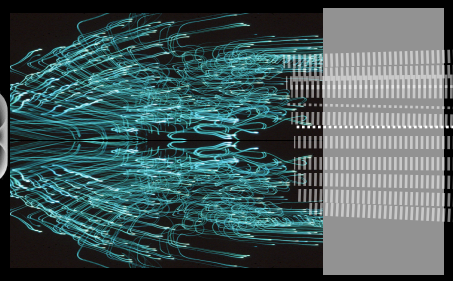


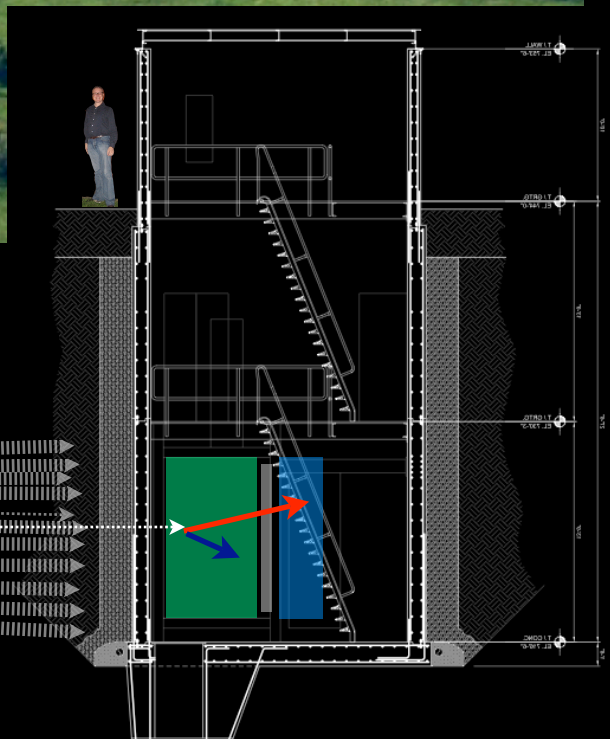
SciBooNE Overview



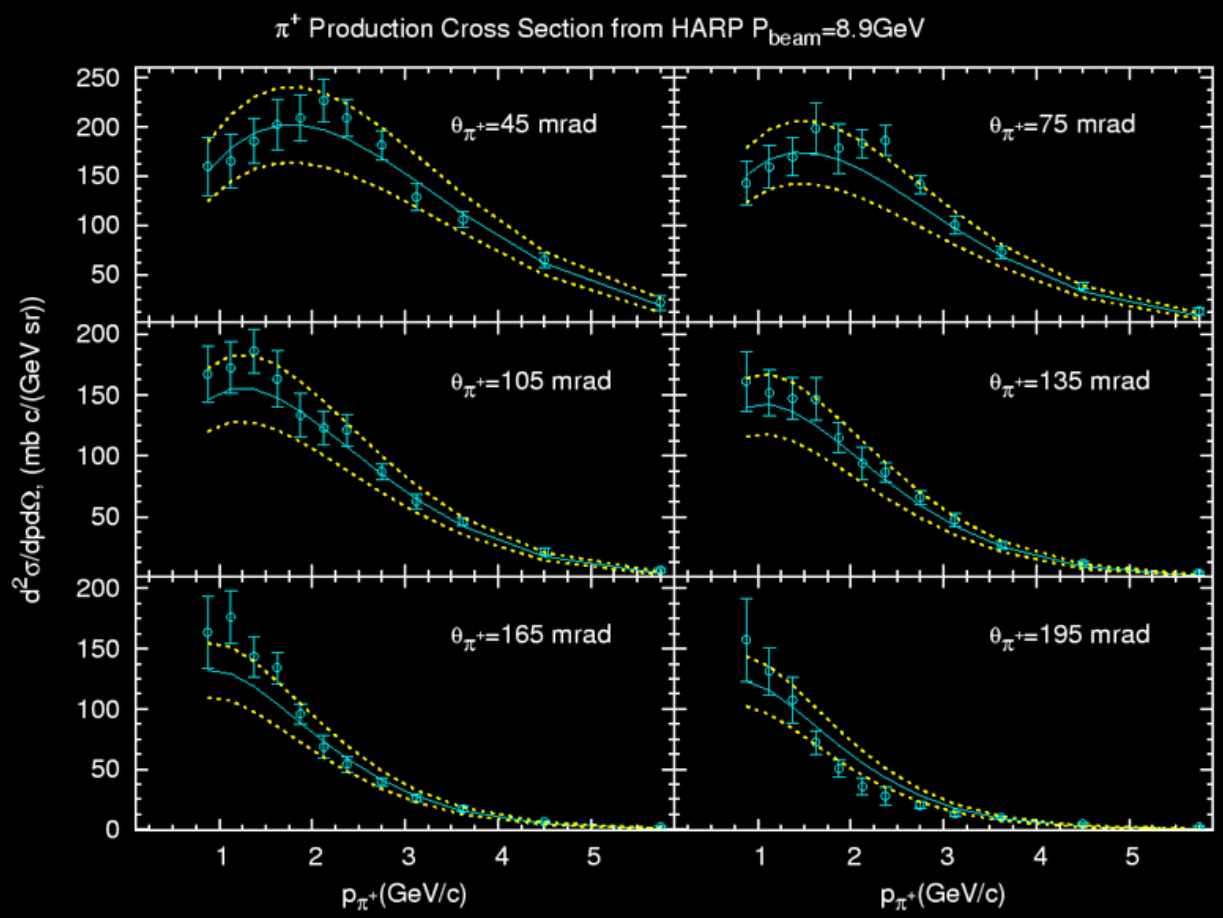
SciBooNE Overview





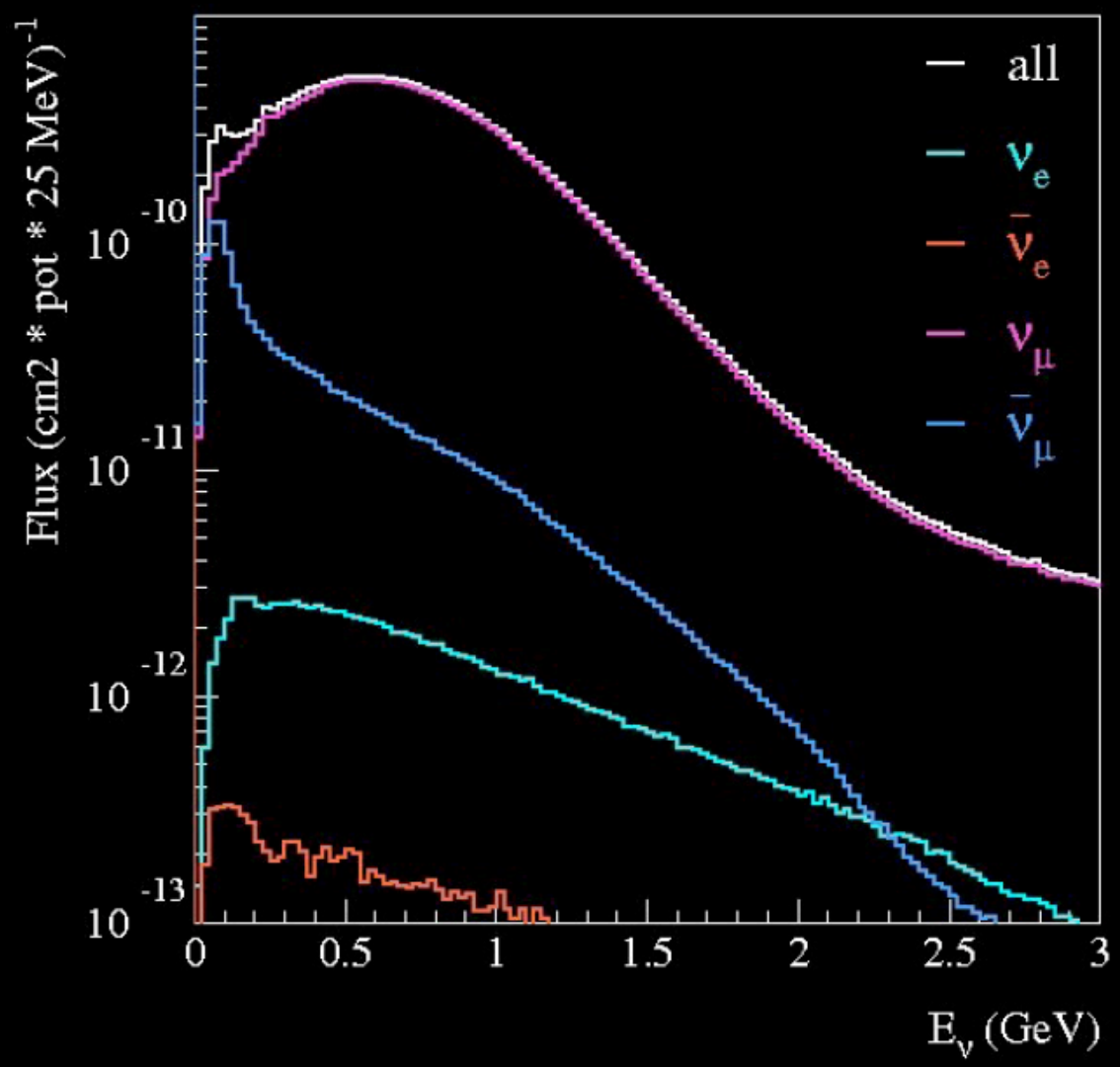


Neutrino Flux



- Use external data for meson flux predictions
  - HARP data for pions
  - Feynman scaling model for kaons
- GEANT4 simulation of neutrino decay volume
  - ν and $\bar{\nu}$ fluxes
- Same as MiniBooNE beam simulation

Neutrino Flux



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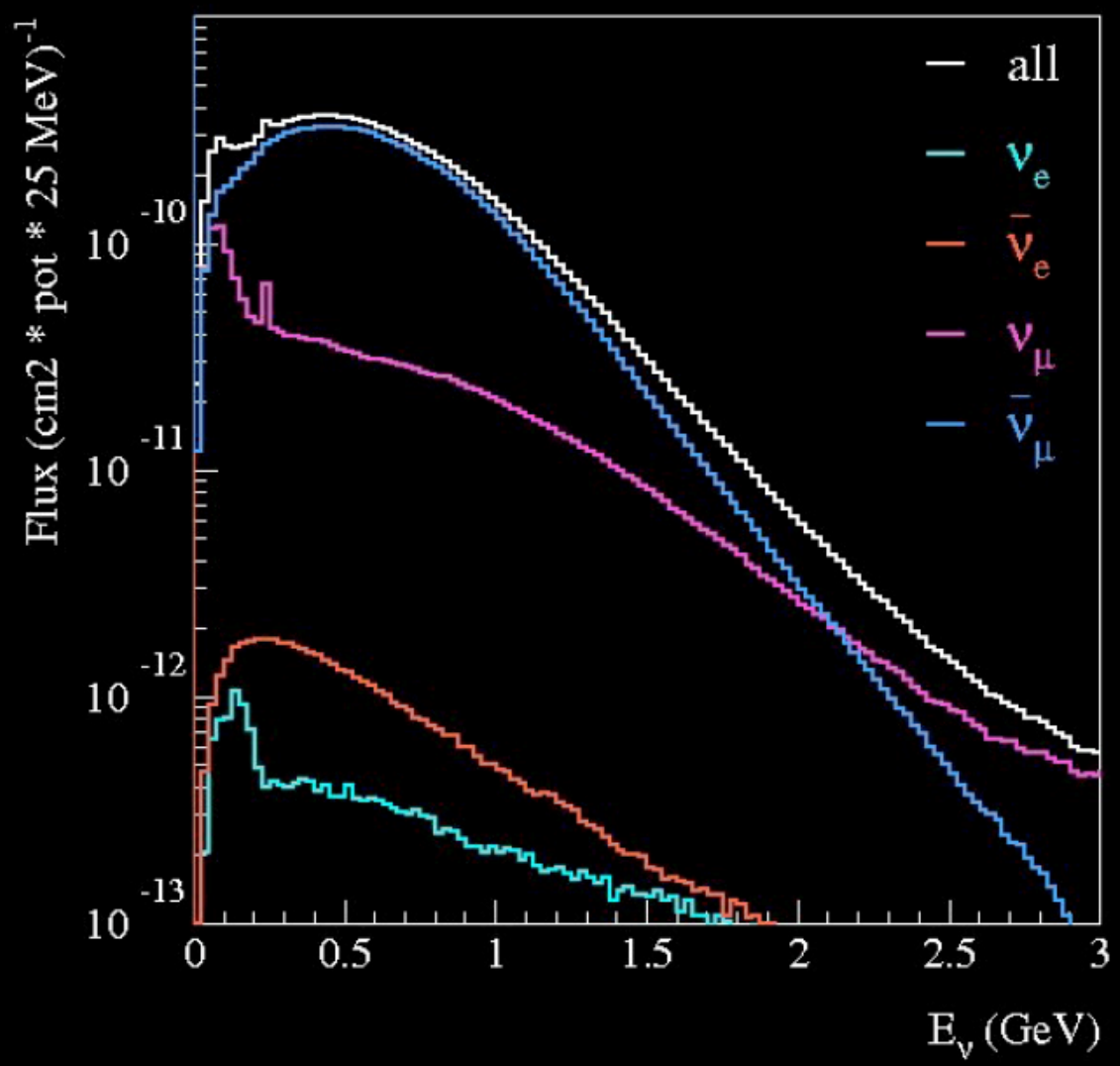

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Event rates

Channel	Number ν_μ
CCQE	39k
NCE	17k
CC1π^+	24k
CCnπ	5k
NC1π^0	9k
Misc	2.1k
NCcohπ	0.8k
CCcohπ	1.2k?
TOTAL	98k

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CCcohπ	1.2k?
TOTAL	98k

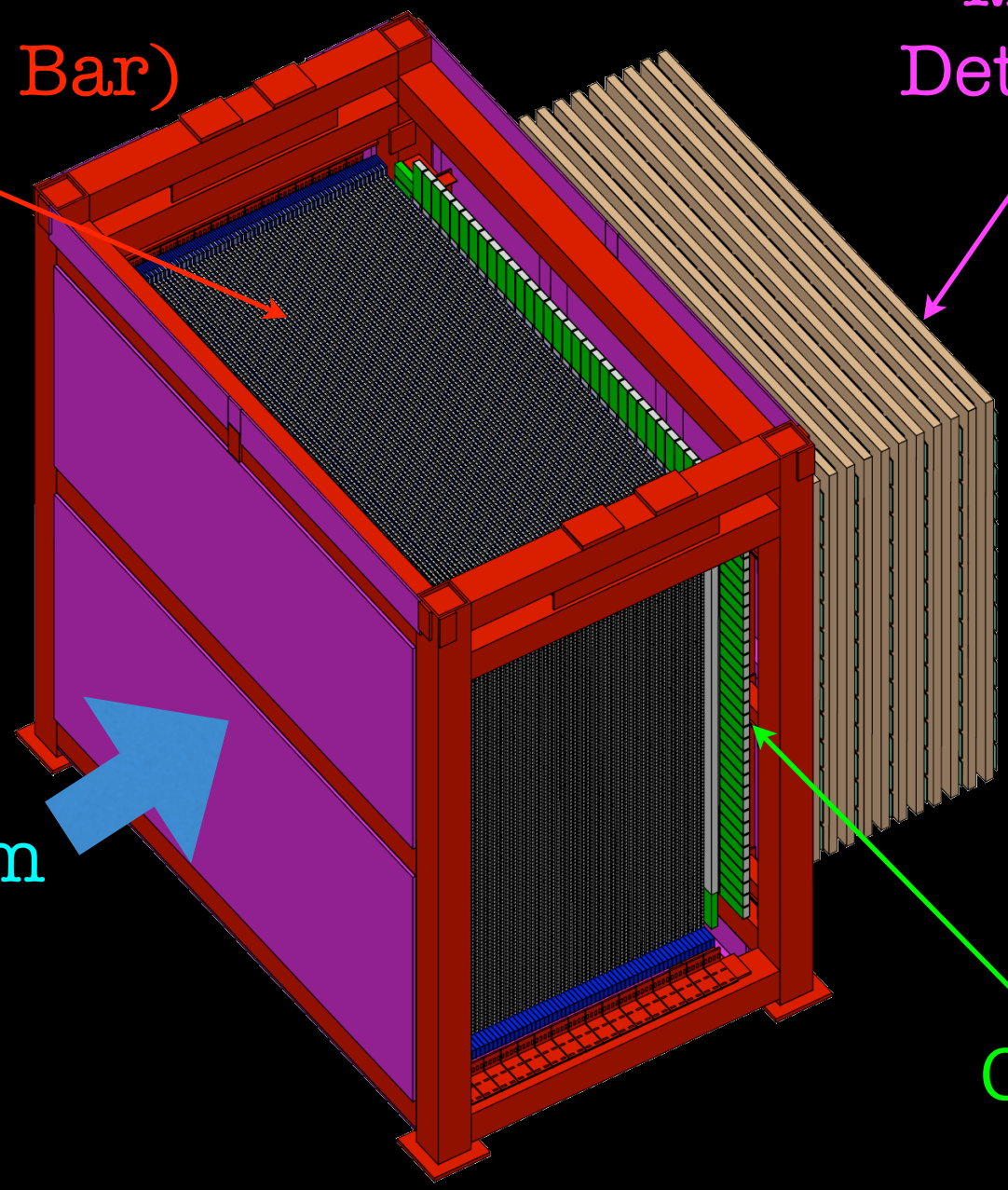
- Neutrino mode
  - 1e20 POT
  - Also expect ~800 ν_e events

Event rates

Channel	Number $\bar{\nu}_\mu$
CCQE	7.5k
NCE	3k
CC1π^-	2k
CCnπ	0.5k
NC1π^0	1.3k
Misc	1k
NCcohπ	0.3k
CCcohπ	0.5k?
TOTAL	16k

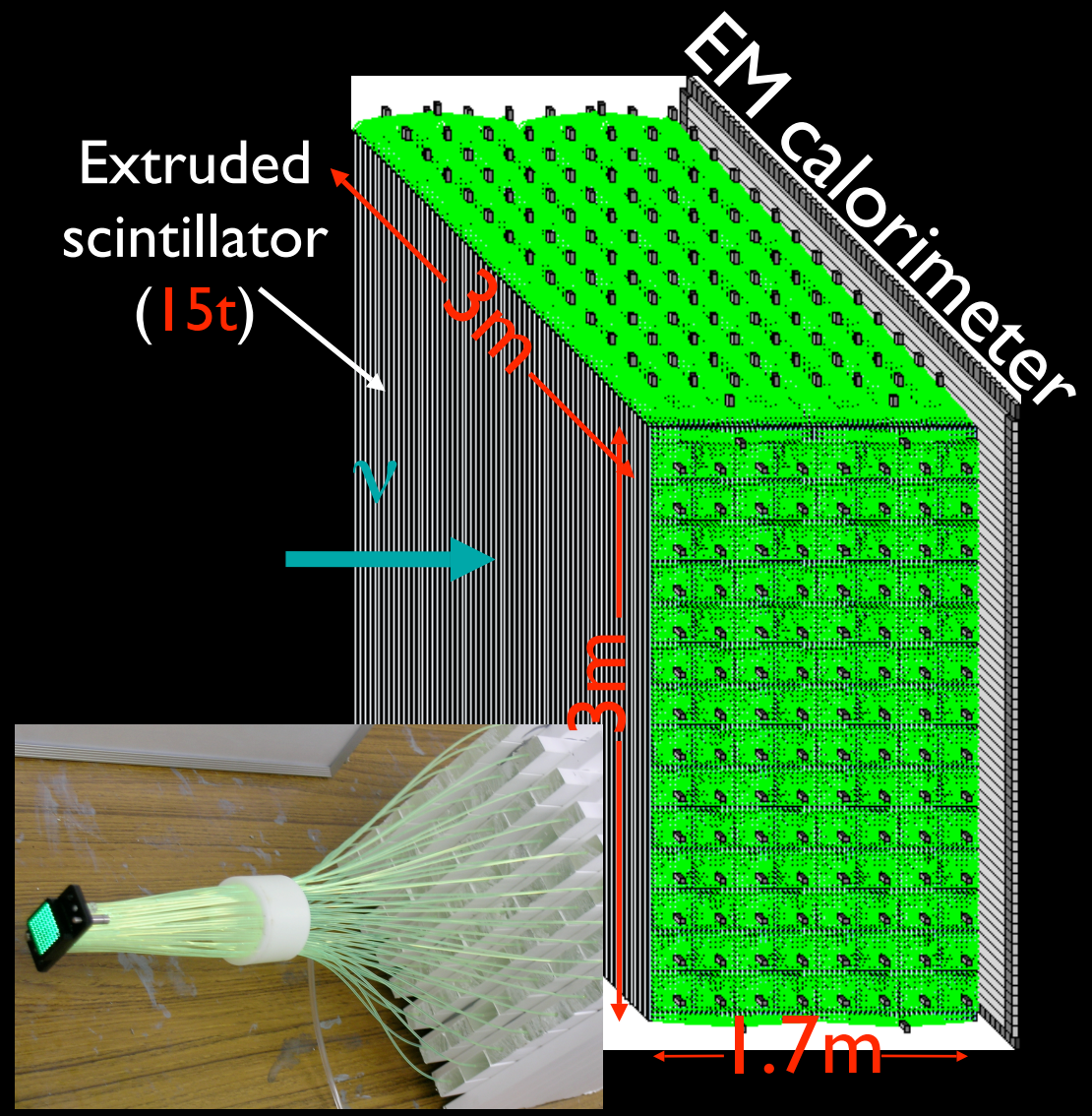
- Neutrino mode
  - 1e20 POT
  - Also expect ~800 ν_e events
- Antineutrino mode
  - 1e20 POT
  - Also expect 8k ν_μ events

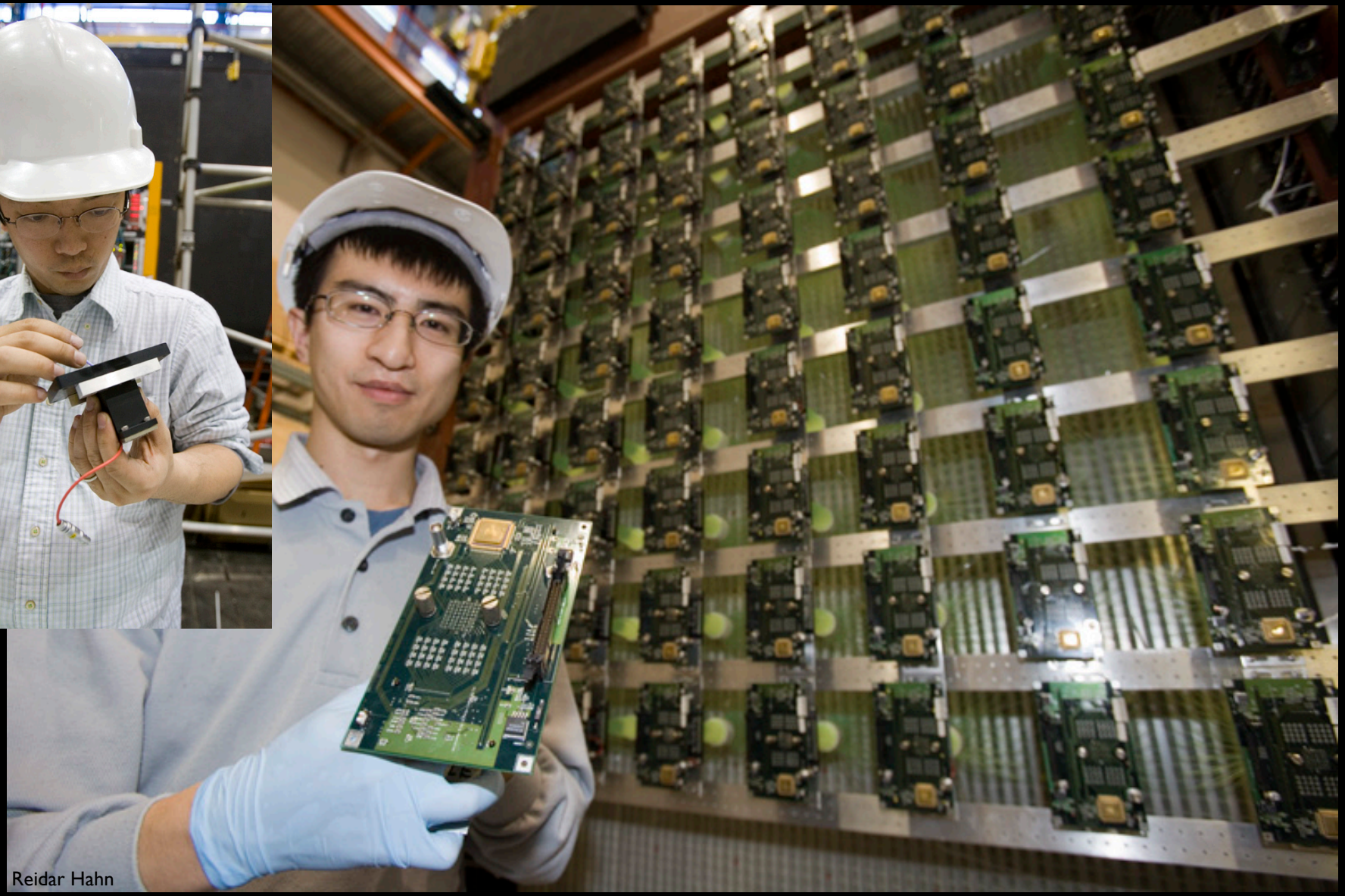
SciBooNE Detectors



SciBar Detector

- Fine-grained neutrino vertex detector
- Extruded plastic scintillator with WLS fibres
  - 64 channel MAPMTs
  - ~15k channels
- 15 t total mass
- Originally used in K2K experiment in Japan

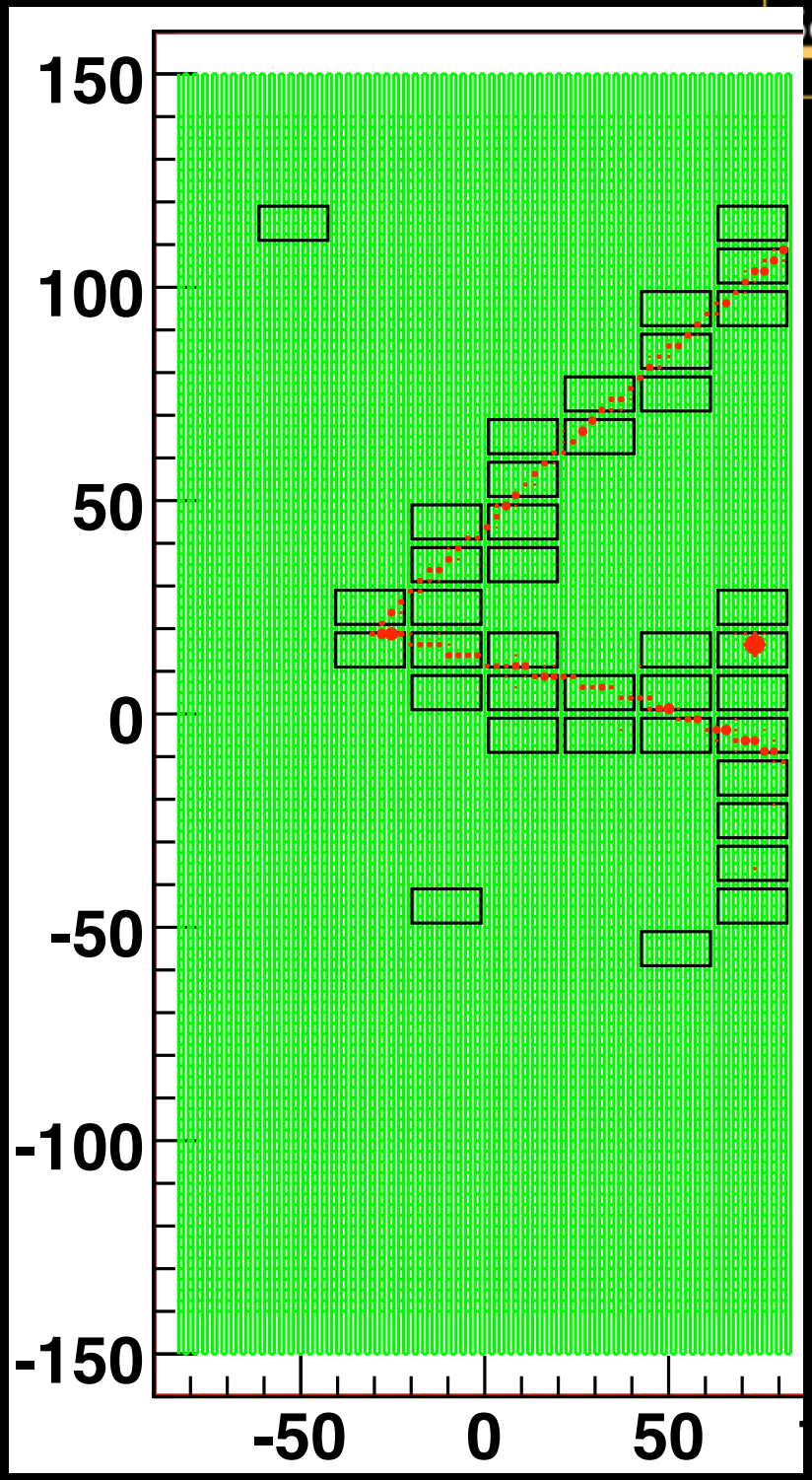




Reidar Hahn

Tracks in SciBar

- Energy deposit from charged particles confined to individual cells
- Clear identification of interaction process
  - Use dE/dx for particle ID
  - Red circles = single anode ADC
  - Boxes = 32 anodes into one TDC



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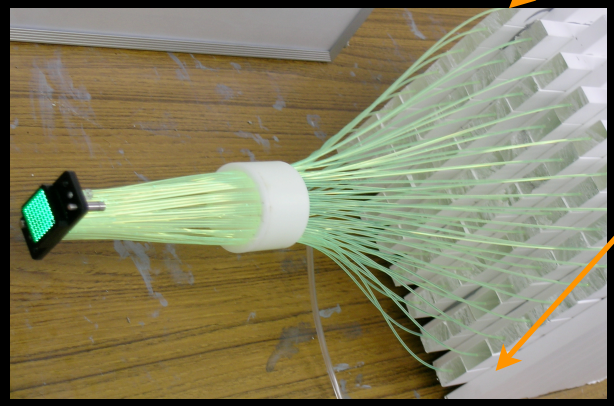
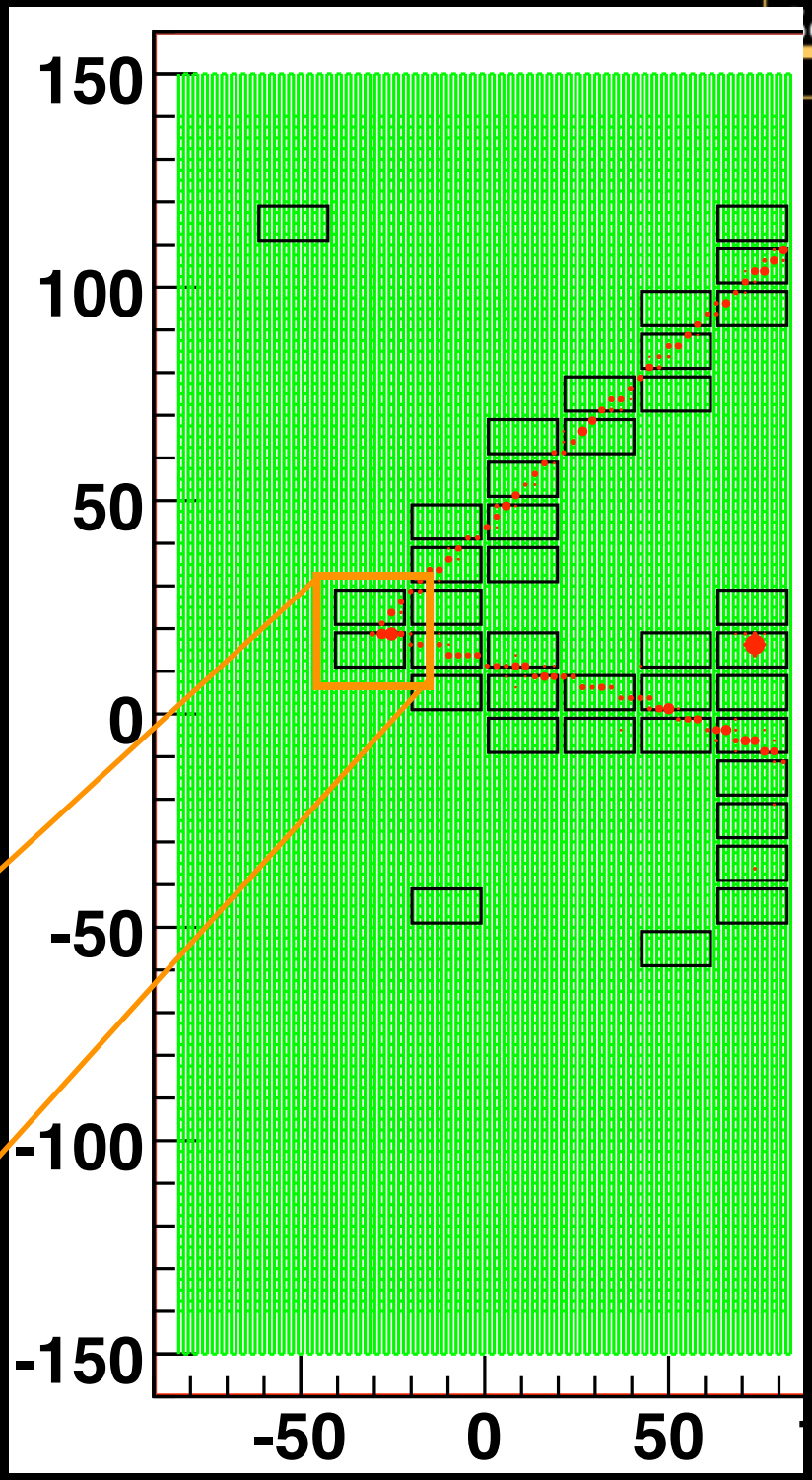
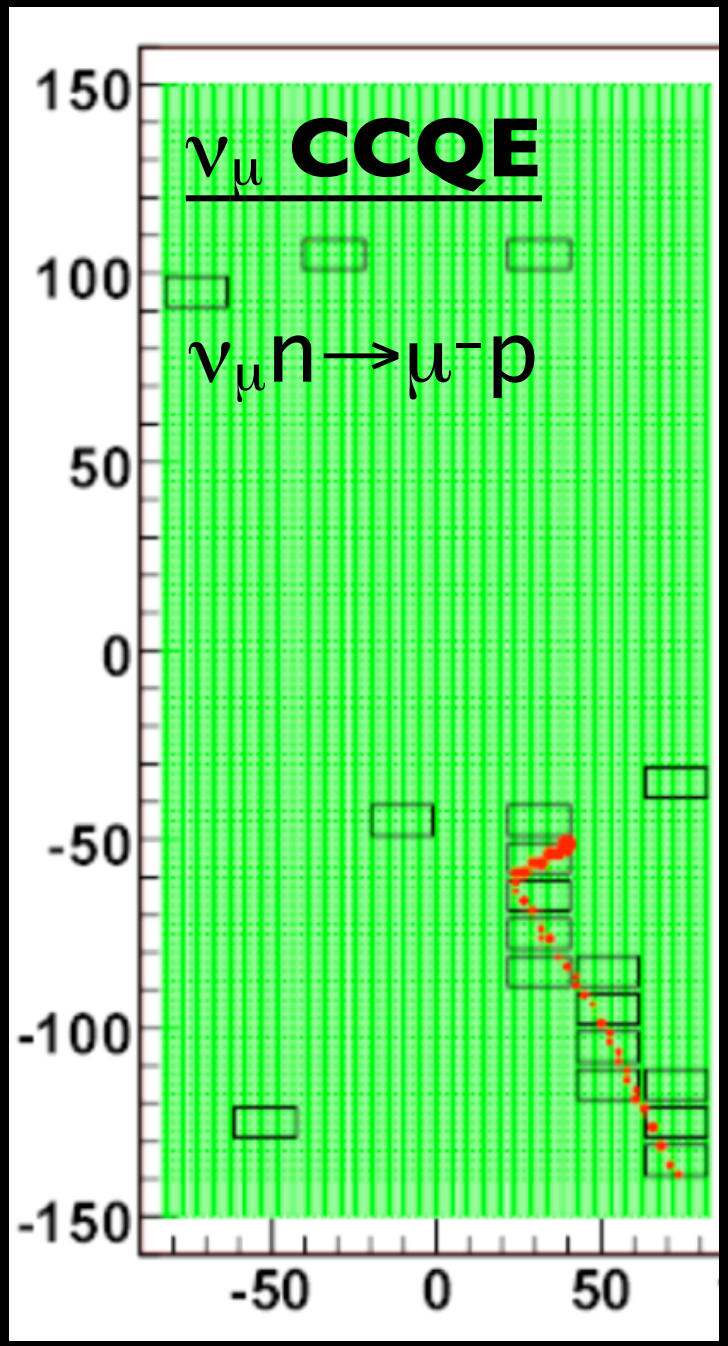
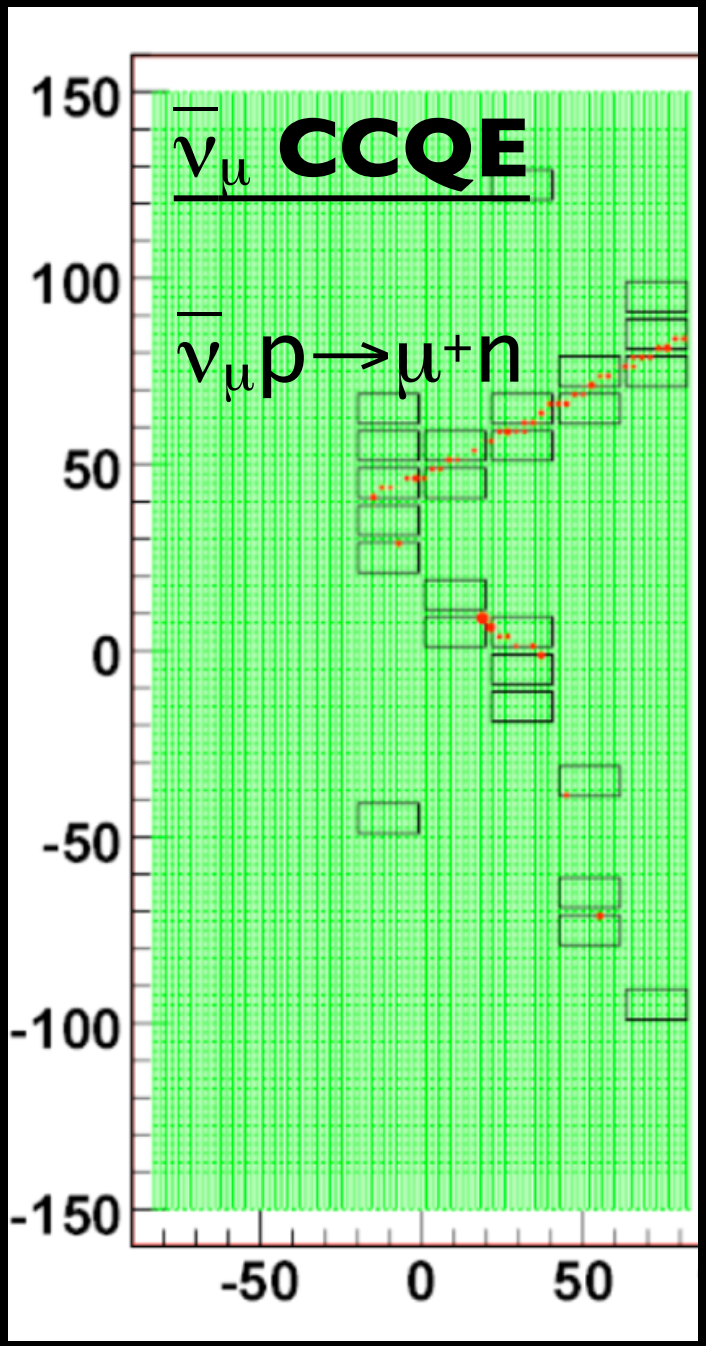




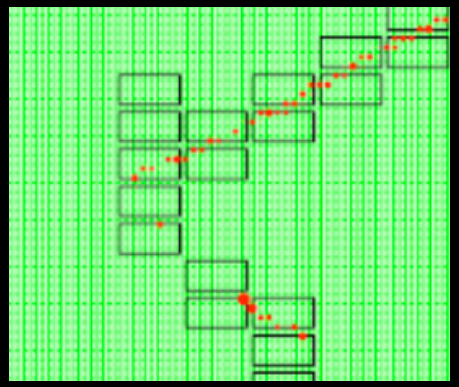
ν vs. $\bar{\nu}$

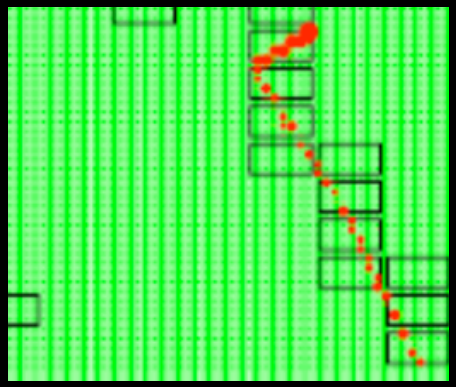

ν_μ CCQE
$\nu_\mu n \rightarrow \mu^- p$
150
100
50
0
-50
-100
-150
-50
0
50


$\bar{\nu}_\mu$ CCQE
$\bar{\nu}_\mu p \rightarrow \mu^+ n$
150
100
50
0
-50
-100
-150
-50
0
50

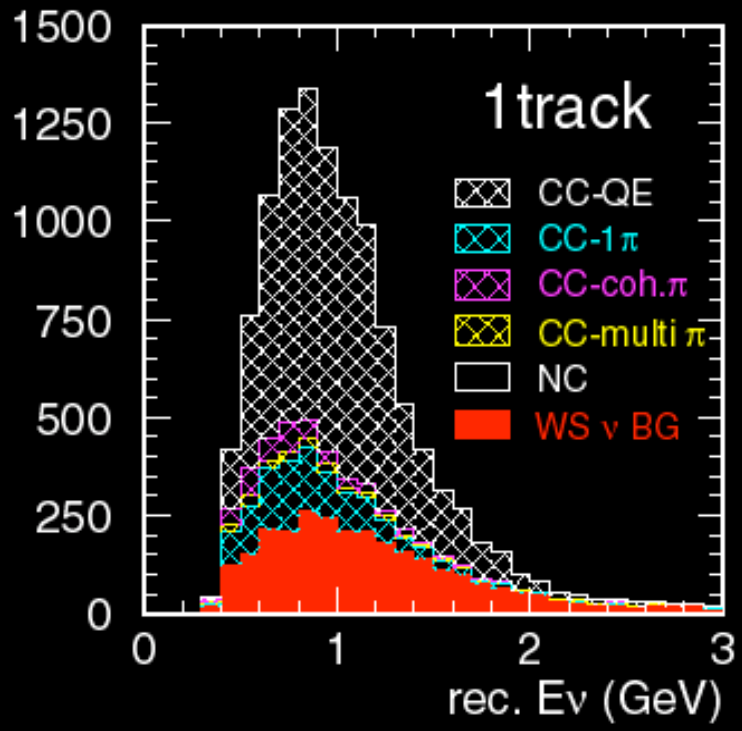
Wrong-Sign BGs

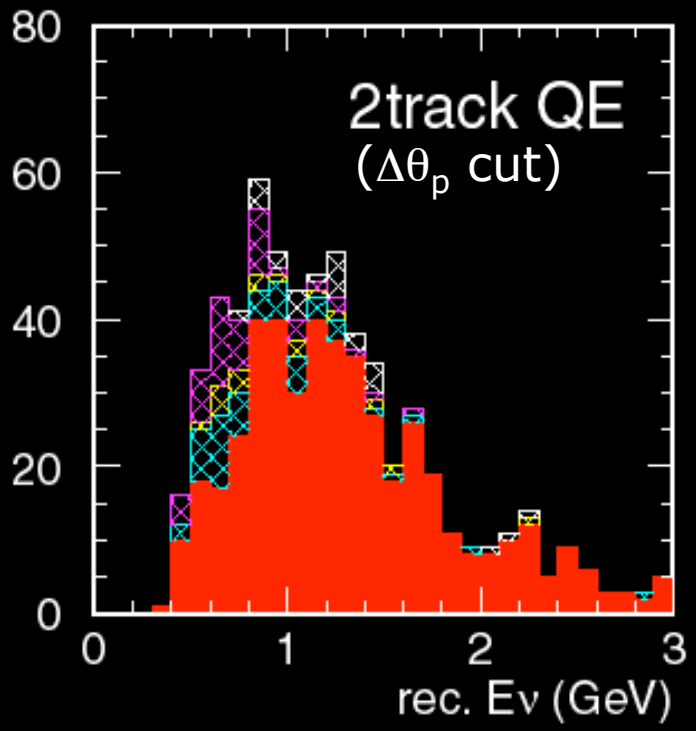
Right Sign





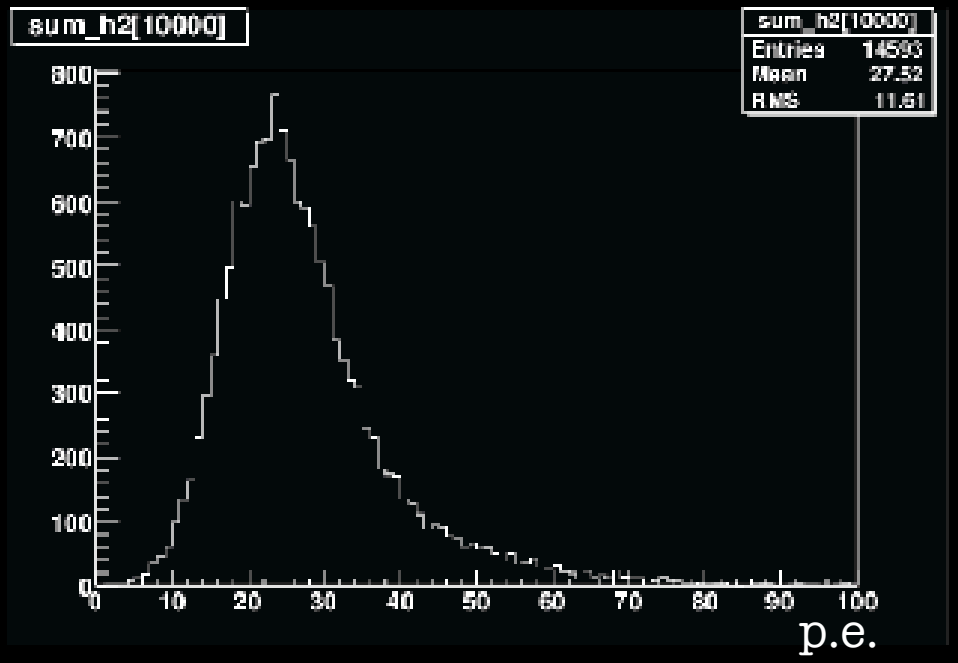
Wrong Sign

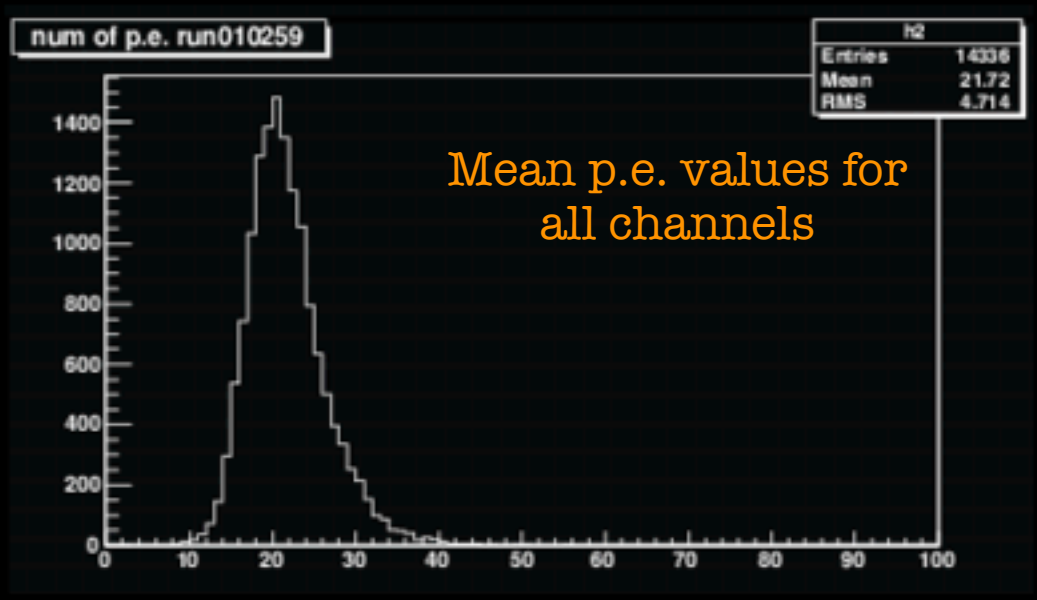




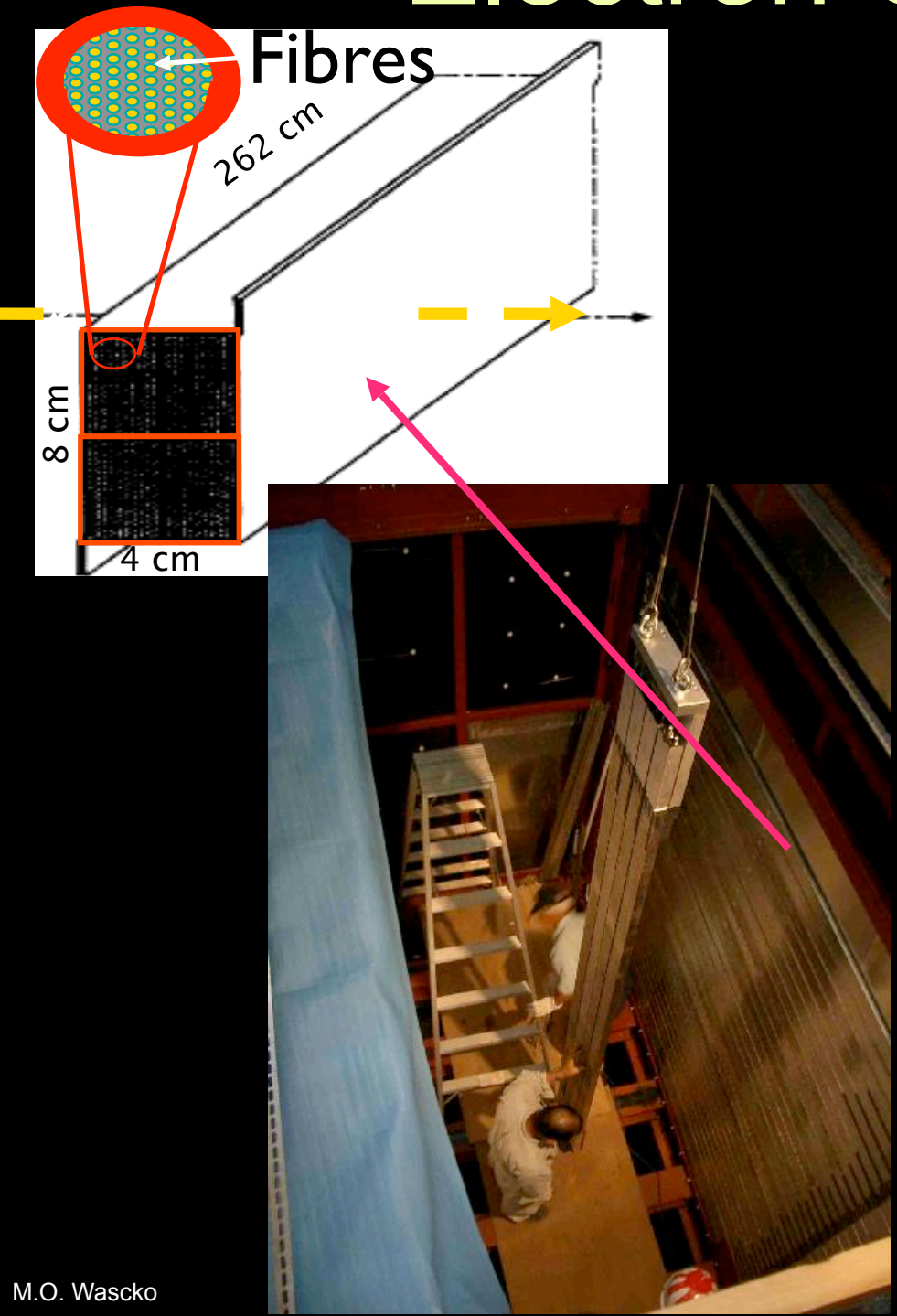
Basic SciBar Performance

- Light yield for minimum ionizing particle:
  - ~20 p.e./1.3 cm @ 30cm from PMT
- Hit finding efficiency:
  - Horizontal plane: 99.9%
  - Vertical plane: 99.8%
- dead channels:
  - 4/14336 in nubar run
  - 1/14336 now

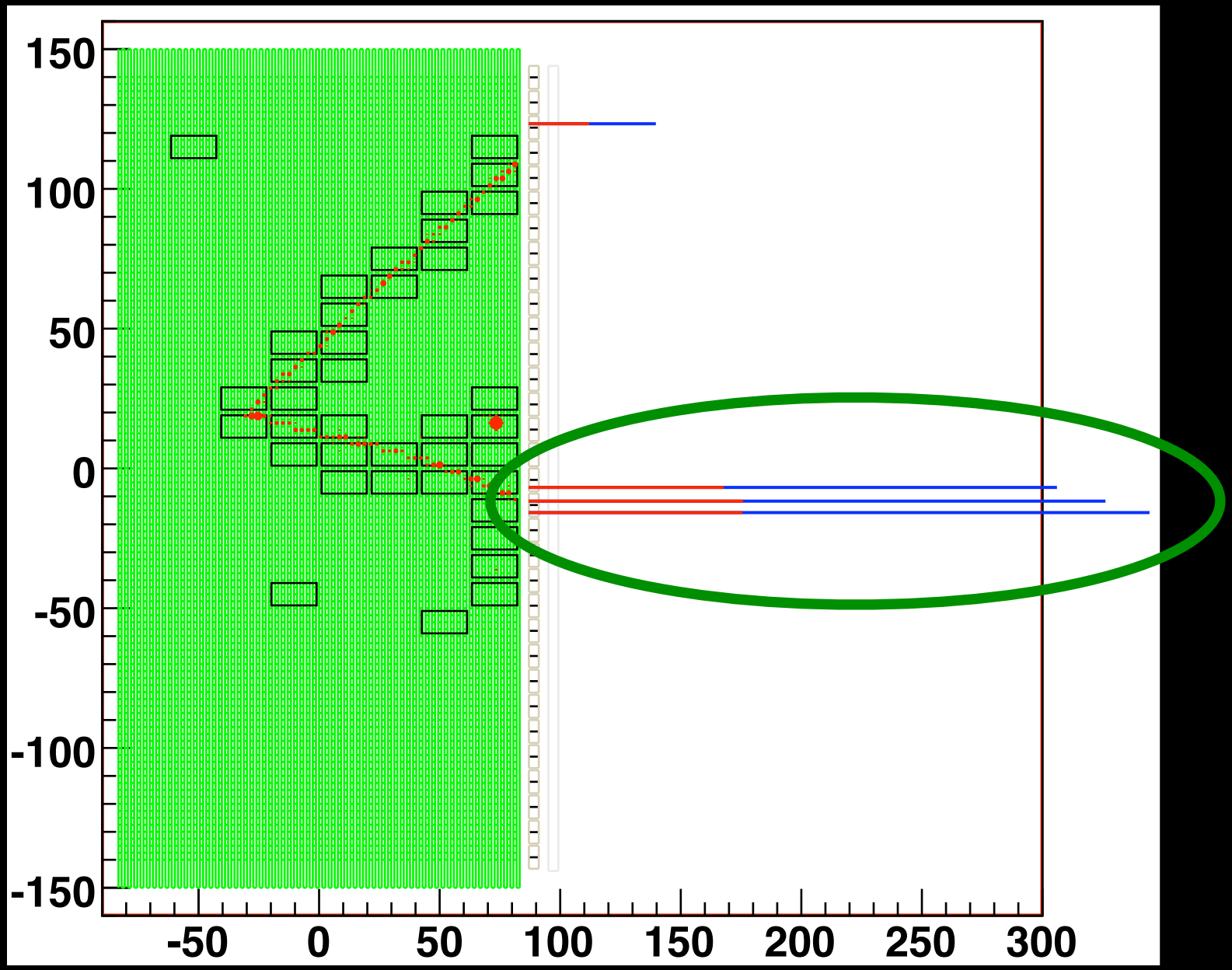




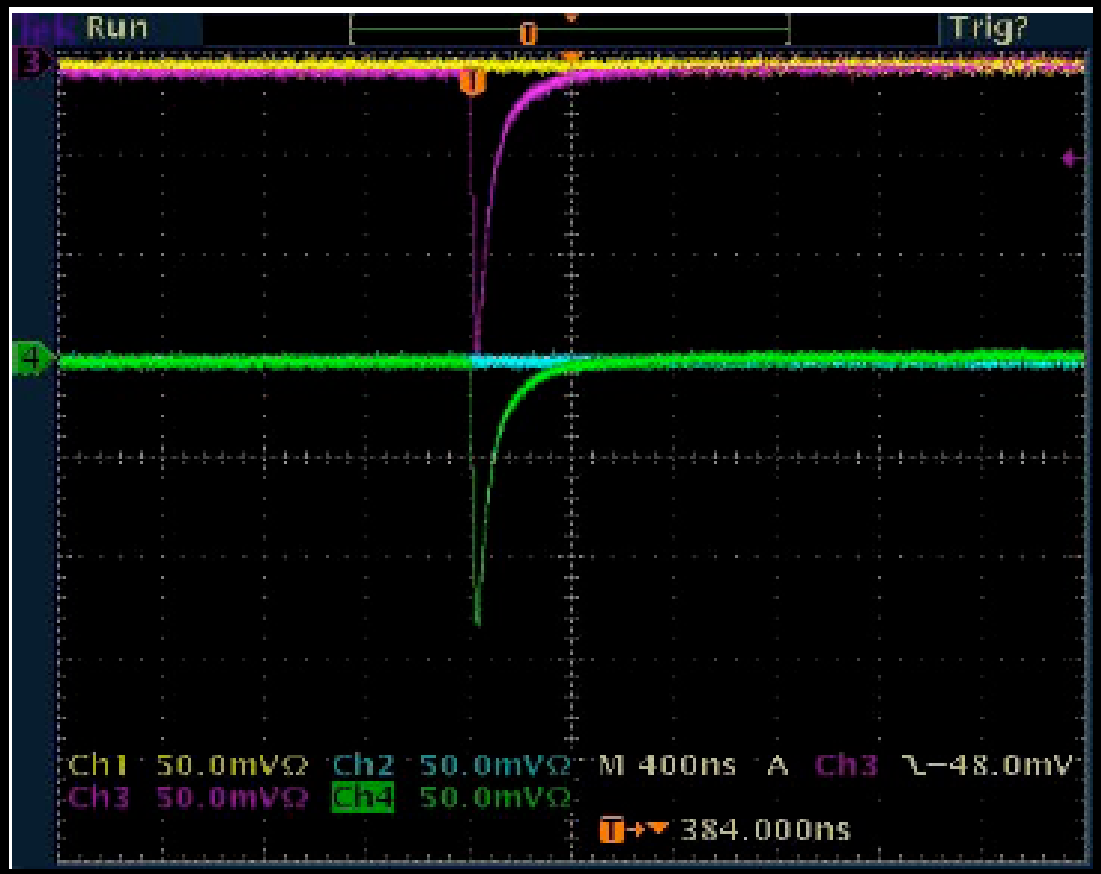
Electron Catcher (EC)



- "Spaghetti" calorimeter
  - Scintillating fibres sandwiched in lead foils
  - PMT readout at both ends
- good energy resolution and linearity
- 11 X_0 thick
- Originally built for CHORUS; used in K2K

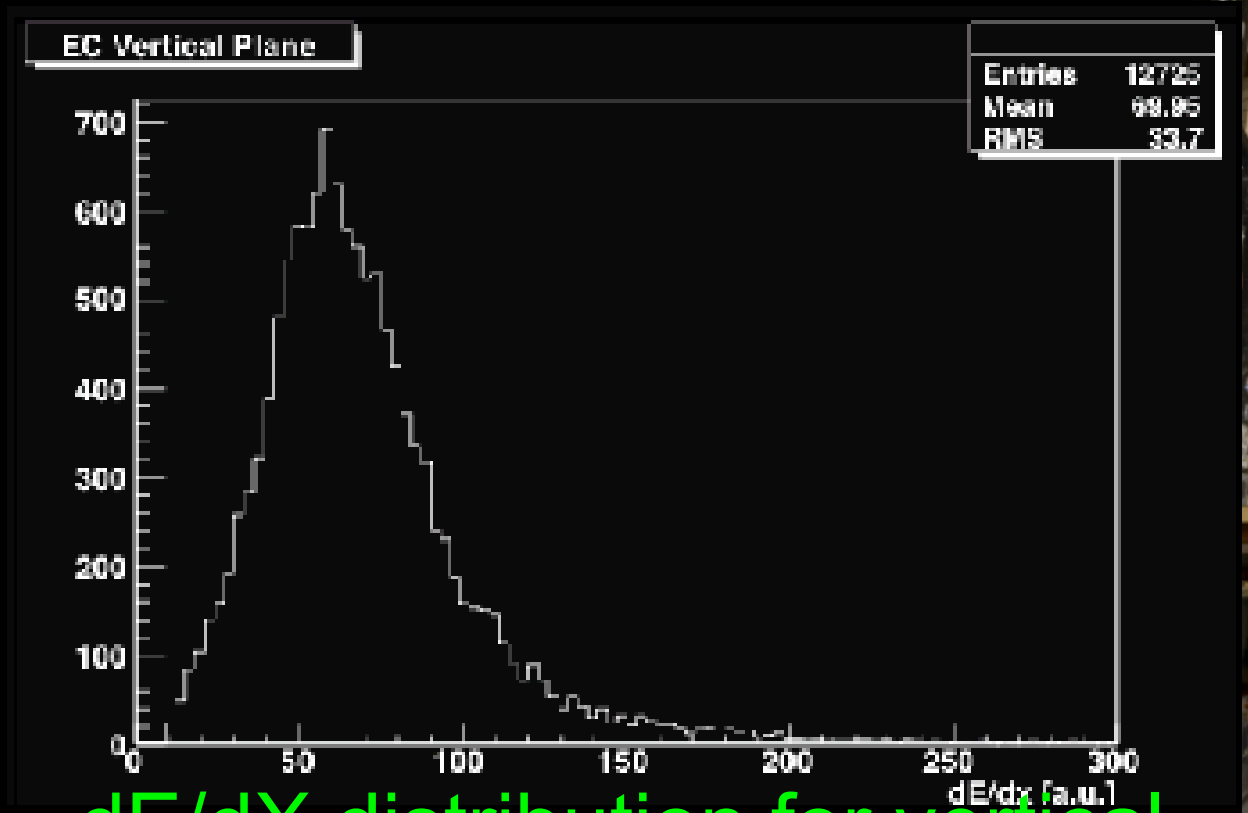

150
100
50
0
-50
-100
-150
-50
0
50
100
150
200
250
300

EC commissioning data



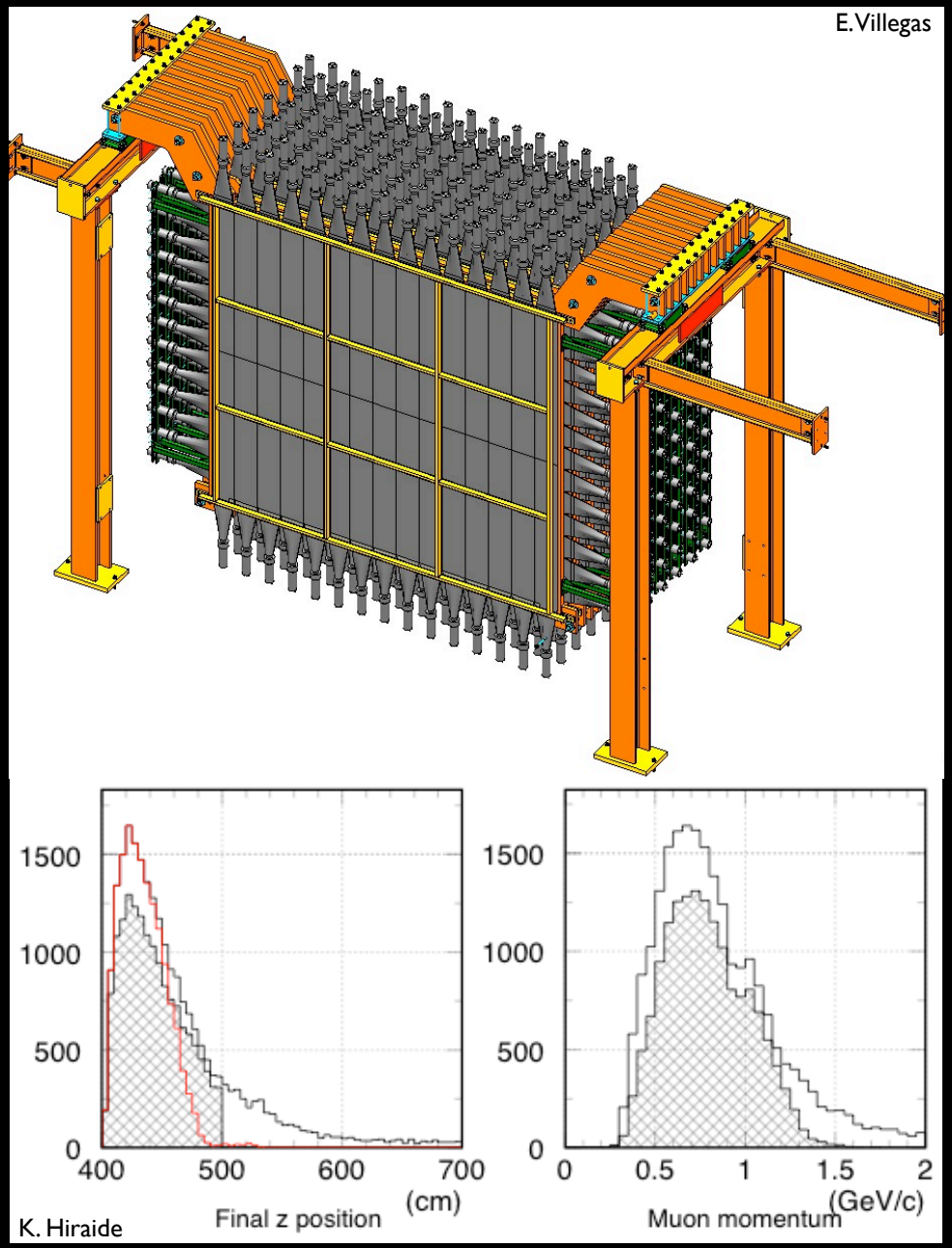
SciBooNE's first cosmic data

EC commissioning data



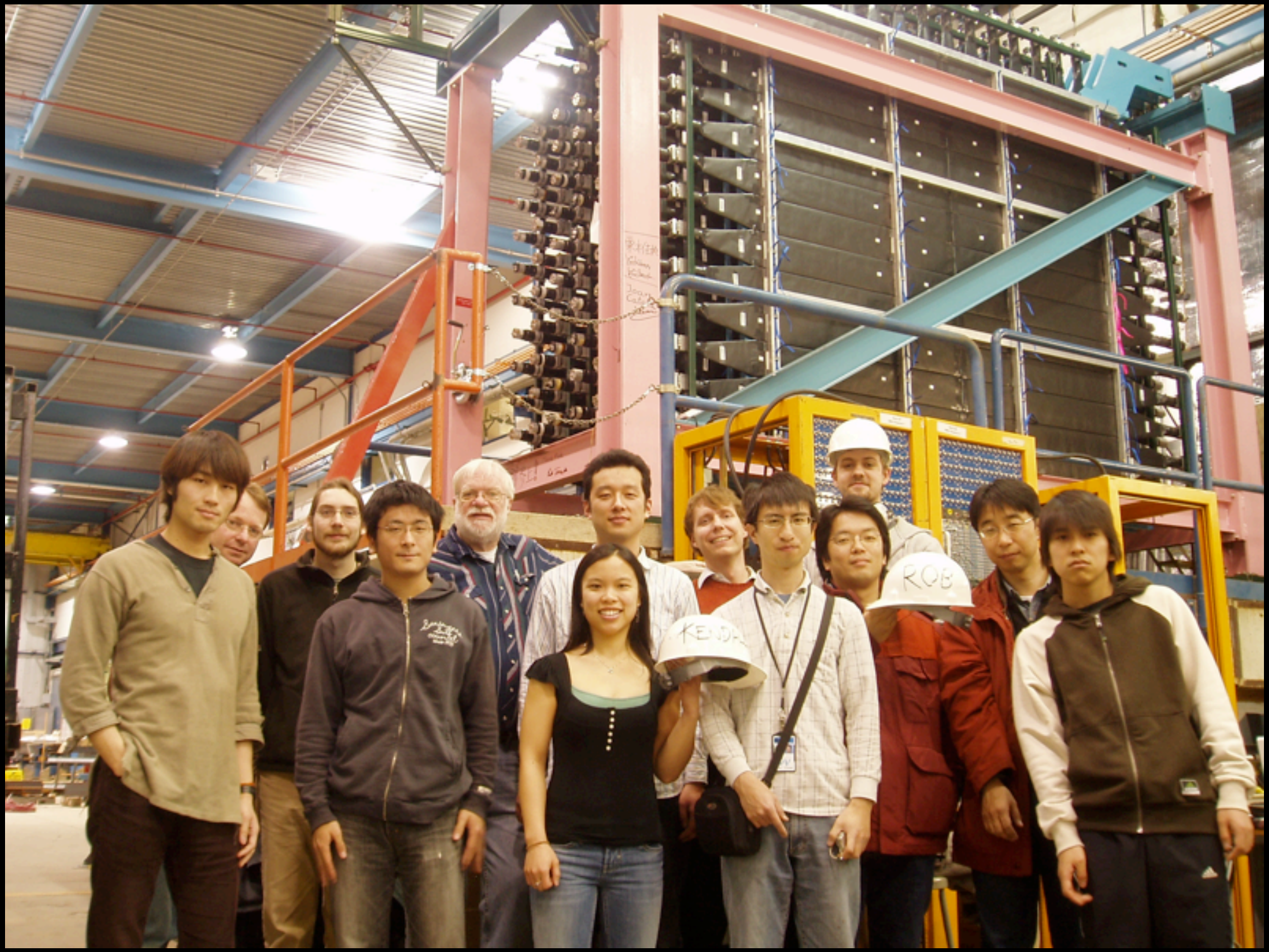
dE/dX distribution for vertical plane from cosmic ray muons

Muon Range Detector(MRD)

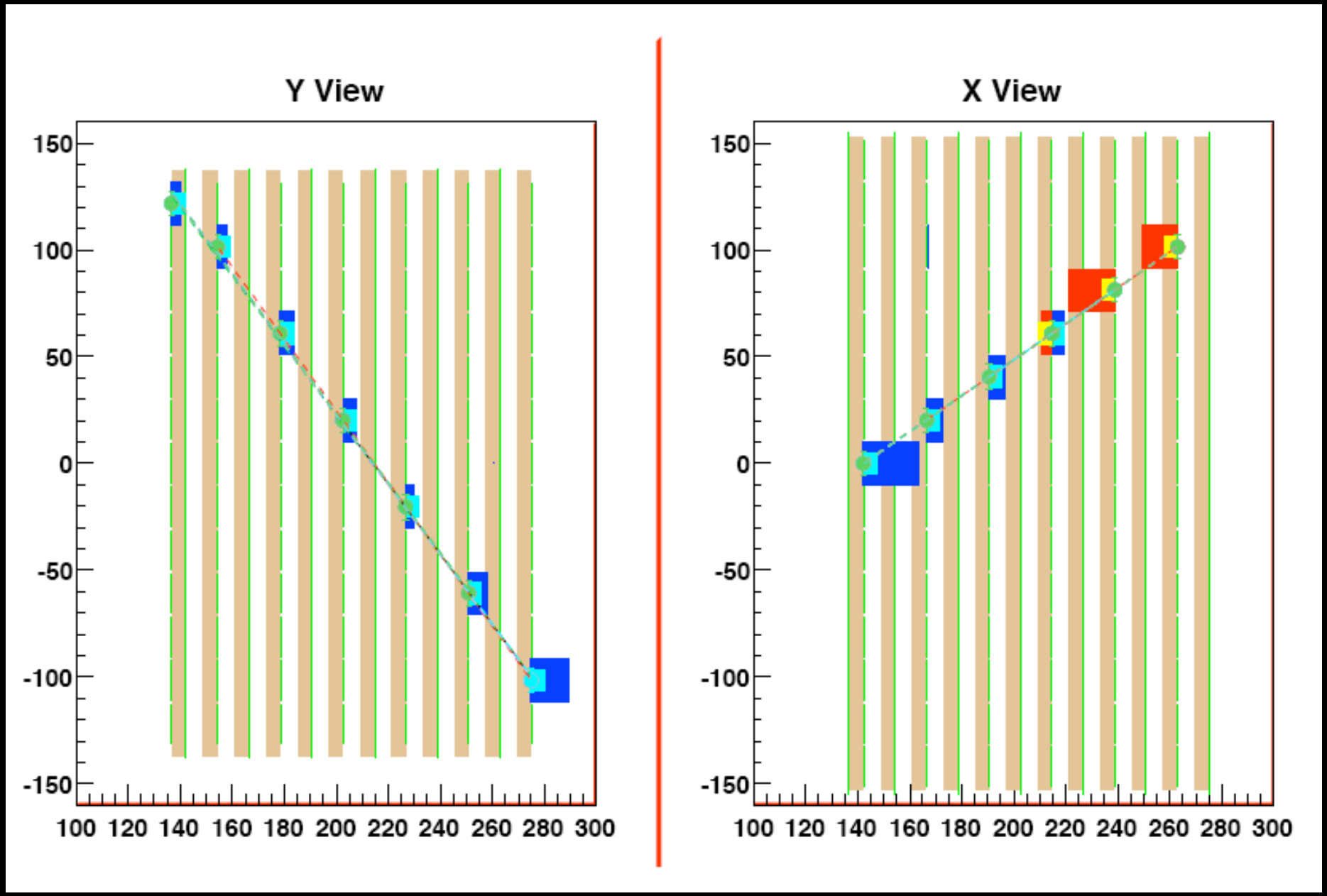


- Iron plates (5cm) with scintillation counters
  - Measure up to 1.2 GeV muons
  - ~10% momentum resolution
- Recycled from past FNAL experiments

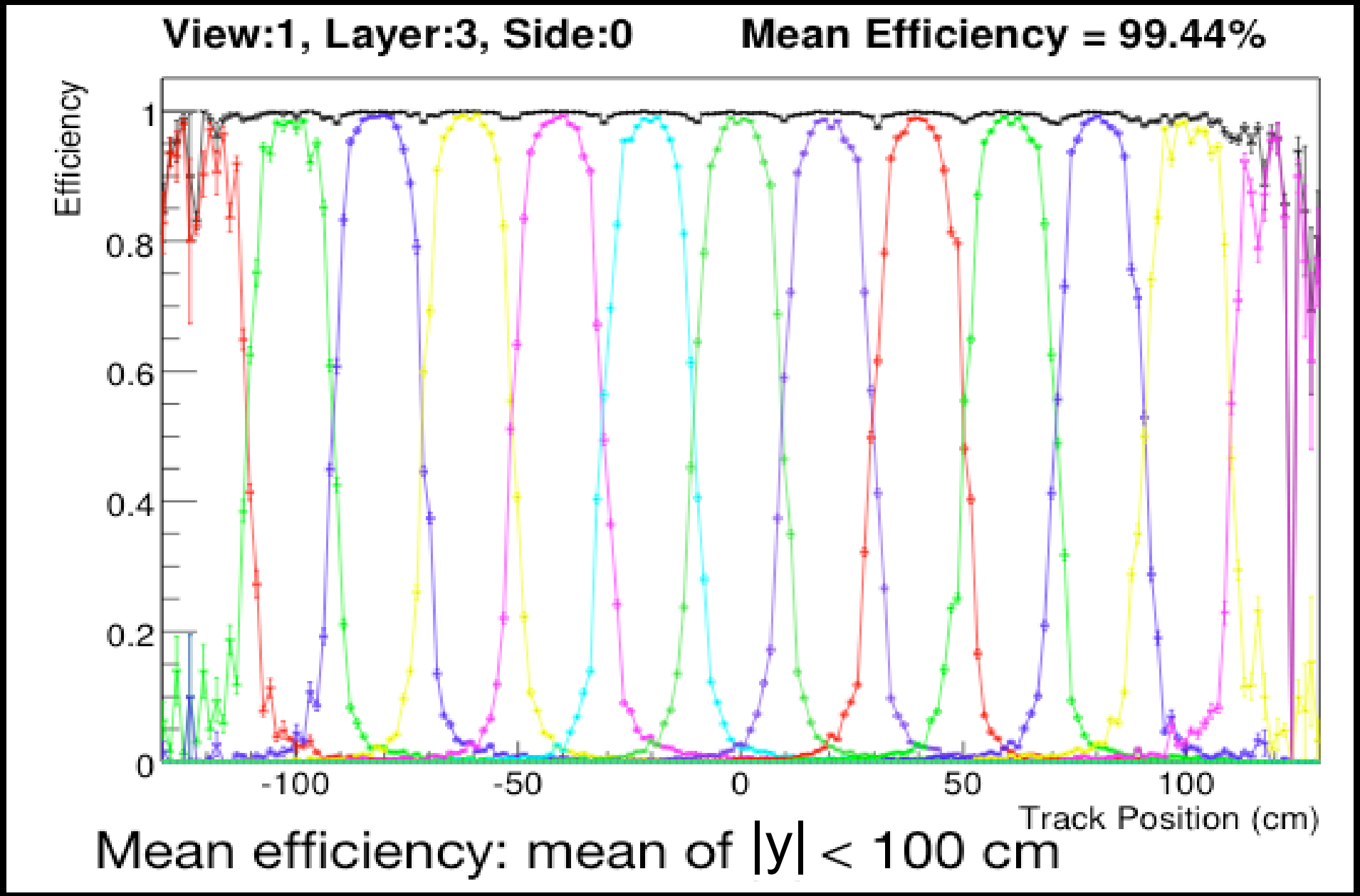
Reidar Hahn


KENDA
ROB

MRD Cosmic Data



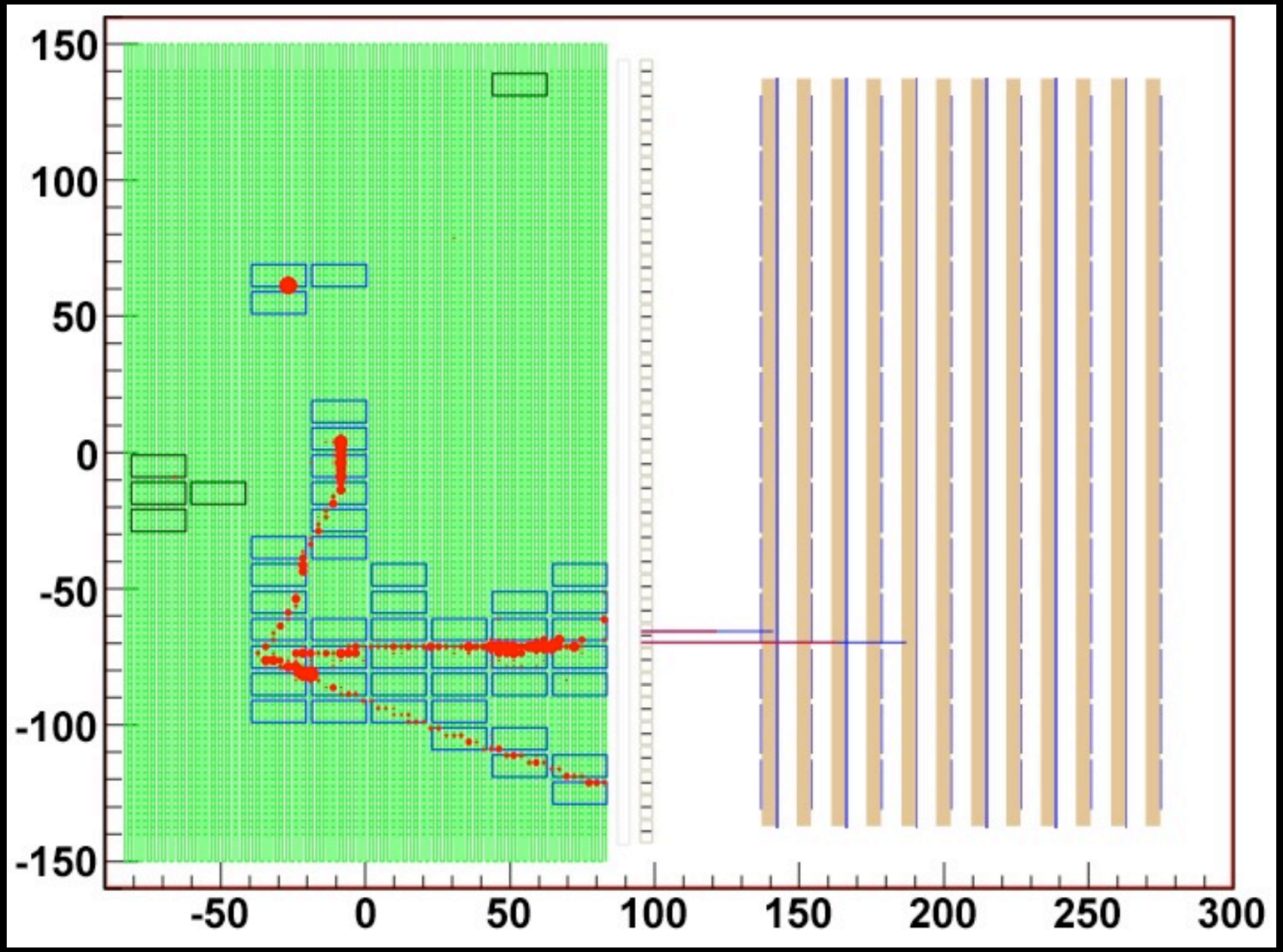
MRD Cosmic Data



SciBooNE Timeline

- 2005, Summer - Collaboration formed
- 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 - Antineutrino Data Run
- 2007, Oct - Neutrino Data Run

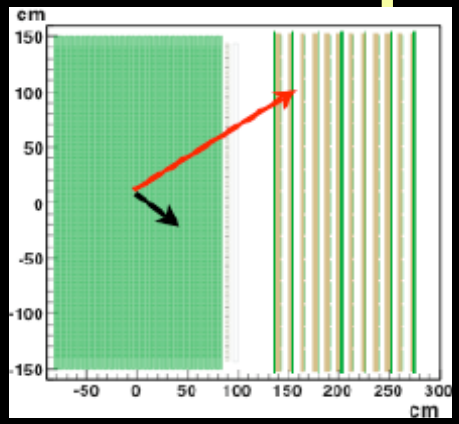
Two years from formation to first data!

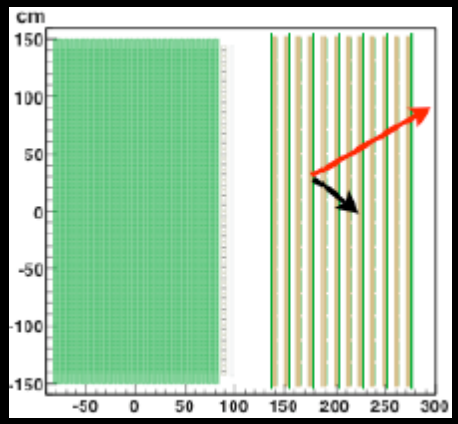


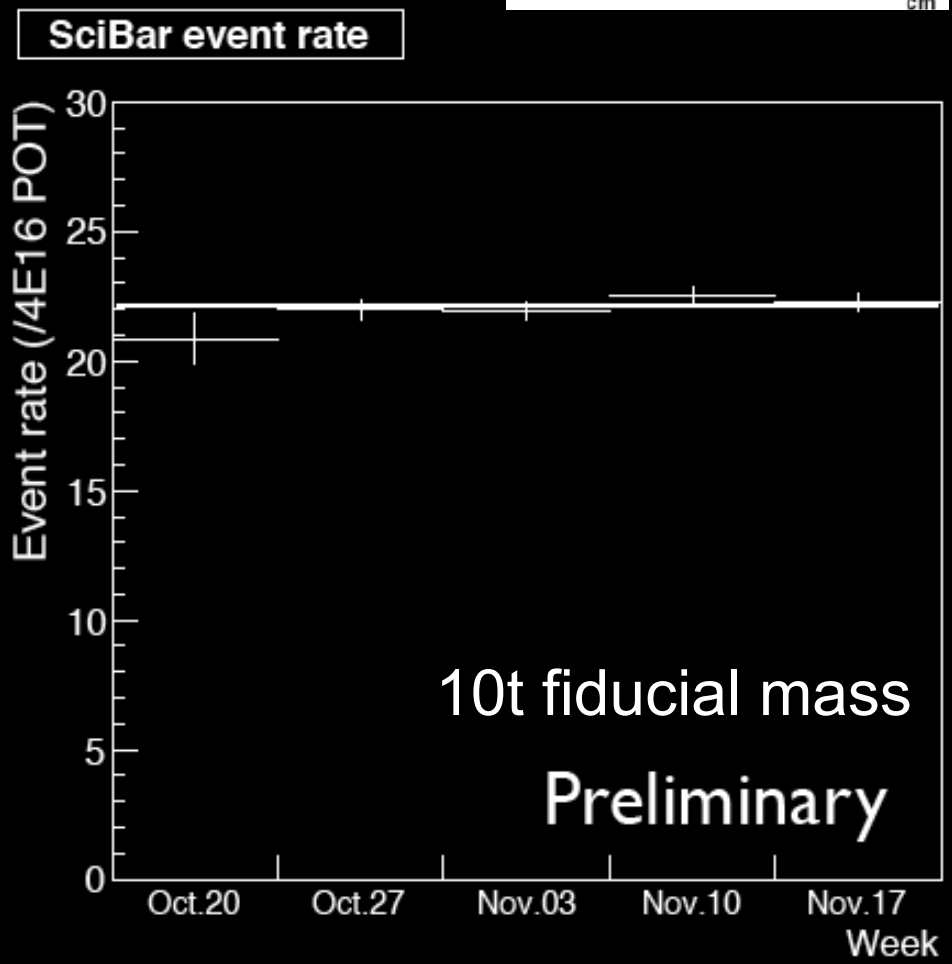
SciBar/EC Detectors

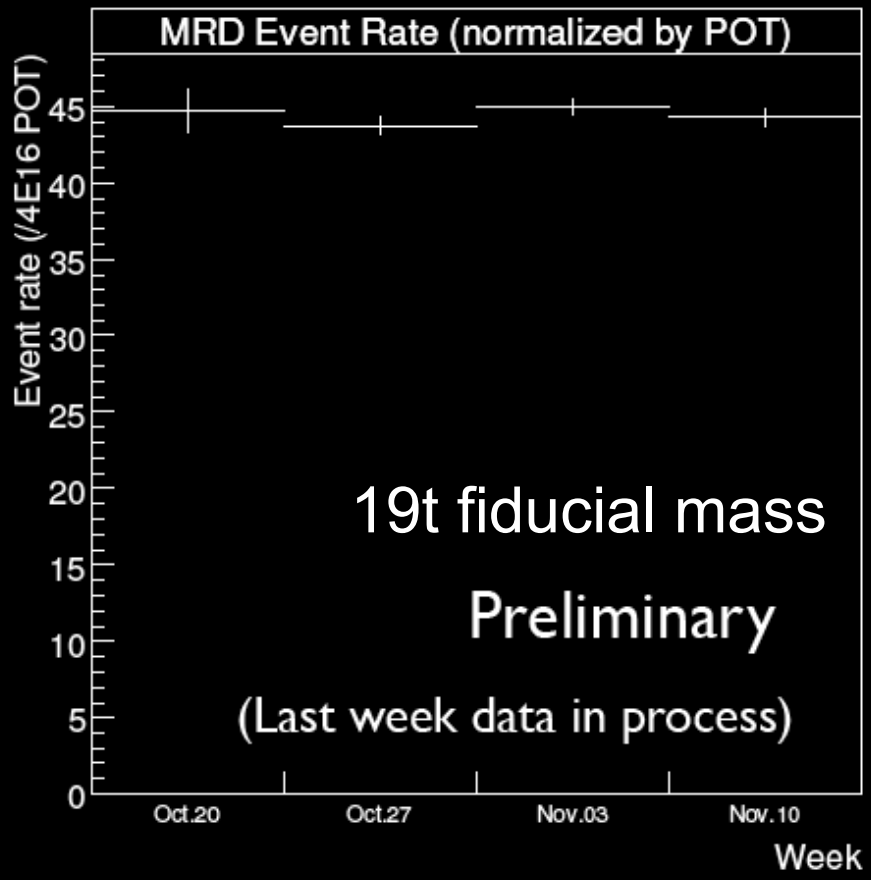
Muon Range Detector

νs per POT


cm
150
100
50
0
-50
-100
-150
-50 0 50 100 150 200 250 300
cm

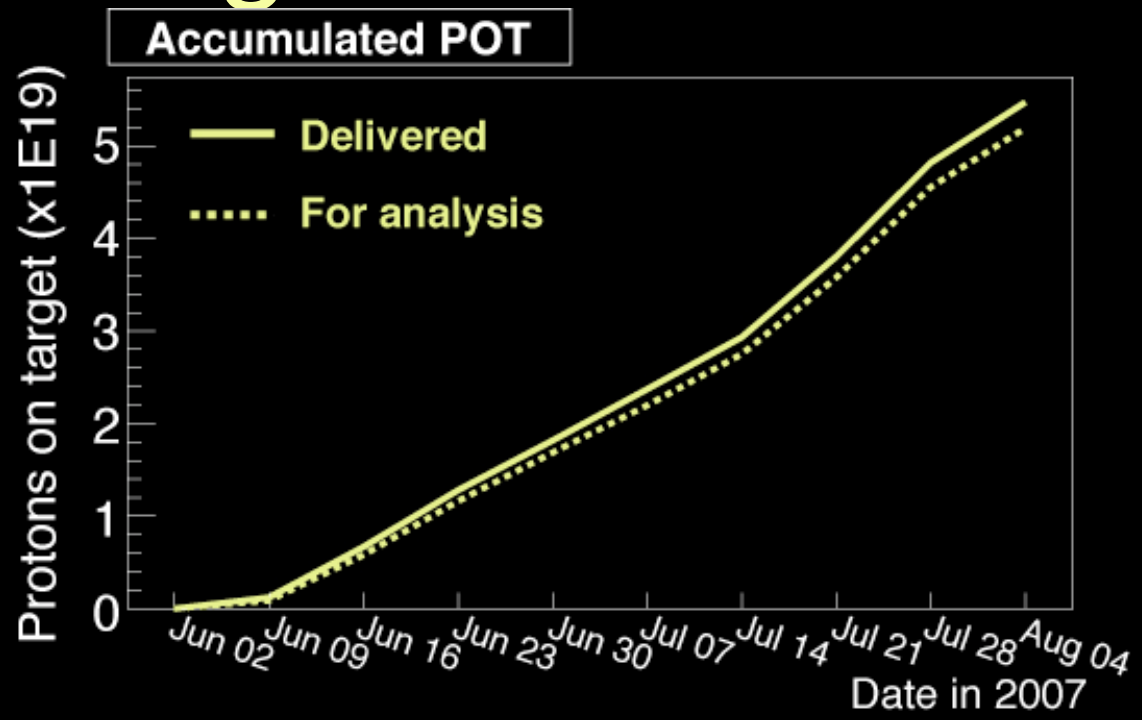

cm
150
100
50
0
-50
-100
-150
-50 0 50 100 150 200 250 300

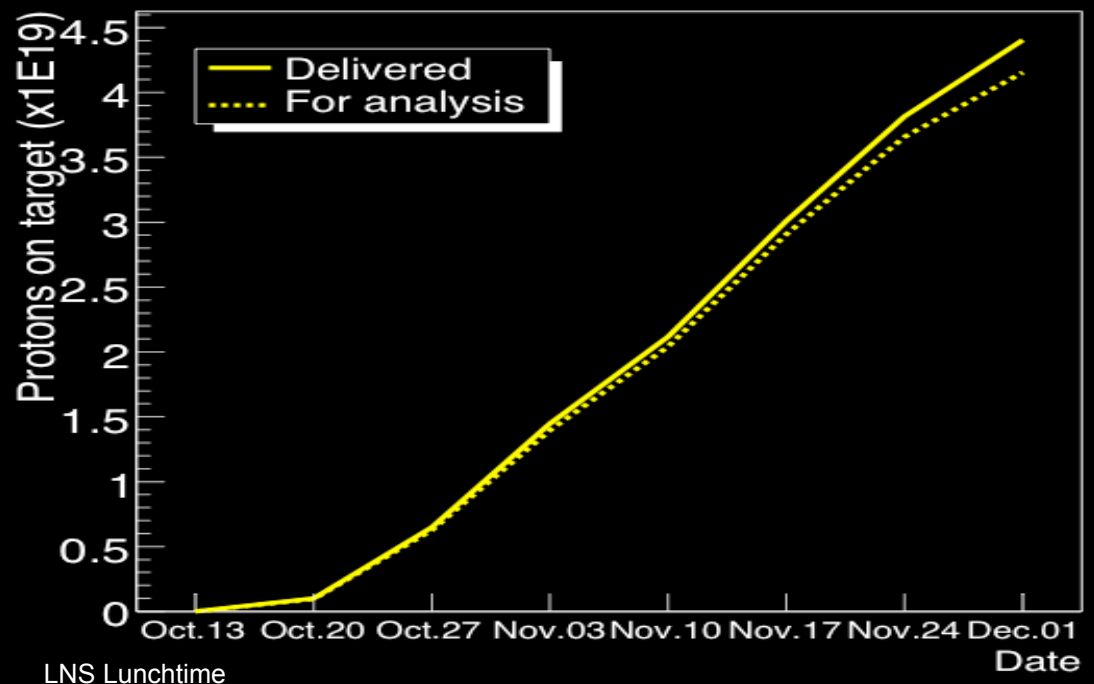

SciBar event rate
Event rate (/4E16 POT)
30
25
20
15
10
5
0
Oct.20
Oct.27
Nov.03
Nov.10
Nov.17
Week
10t fiducial mass
Preliminary


MRD Event Rate (normalized by POT)
Event rate (/4E16 POT)
45
40
35
30
25
20
15
10
5
0
Oct.20
Oct.27
Nov.03
Nov.10
Week
19t fiducial mass
Preliminary
(Last week data in process)

Data Progress

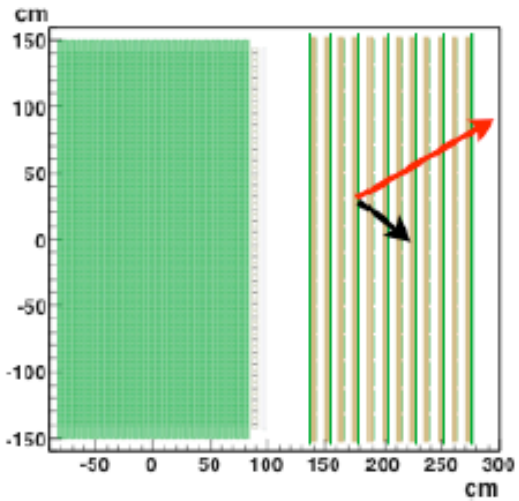
- Started beam run in antineutrino mode
  - Collected 0.54e20 POT
  - ~25% of total request
- Switched to neutrino mode during accelerator shutdown
  - Collected 0.42e20 POT so far
  - Expect to switch back to neutrino mode in ~March





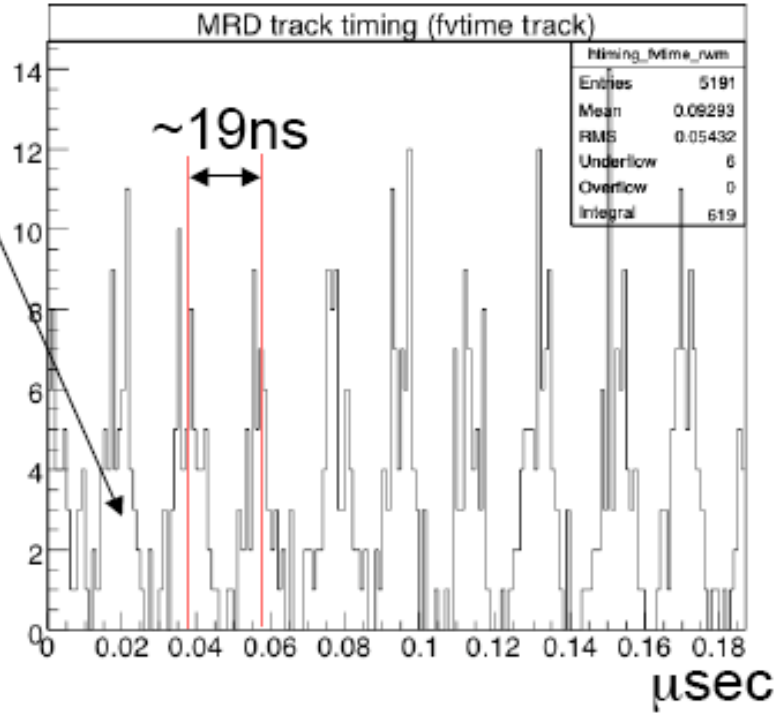
ν Event Timing w.r.t Beam

Charged current event candidates in MRD



Clear bunch structure

cf. - Bunches are 19 ns apart.
- 84 bunches in a spill (1.6us)



NOTE: Timing corrections (TOF, light propagation) are not applied yet.

H.-K Tanaka (Columbia) FNAL AEM 2007/11/26 5

~~Conclusion~~ Introduction

- Useful and important measurements of ν_μ & $\bar{\nu}_\mu$ cross-sections on carbon near 1 GeV
- In the midst of our 2e20 POT data run
- First physics results next summer
- More information: http://www-sciboone.fnal.gov