Neutrino Cross Section Experiments

45th Karpacz Winter School

Morgan Wascko
Imperial College London

Overview of Lectures

- Introduce neutrino cross section experiments
  - Only cover accelerator neutrino beams
  - Focus on recent measurements near 1 GeV
    - K2K, MiniBooNE, SciBooNE
- Experimental Methods
- Measurements, current and future
- Uncertainties

A note on style

- Informal lectures
- Please ask questions

A note on style

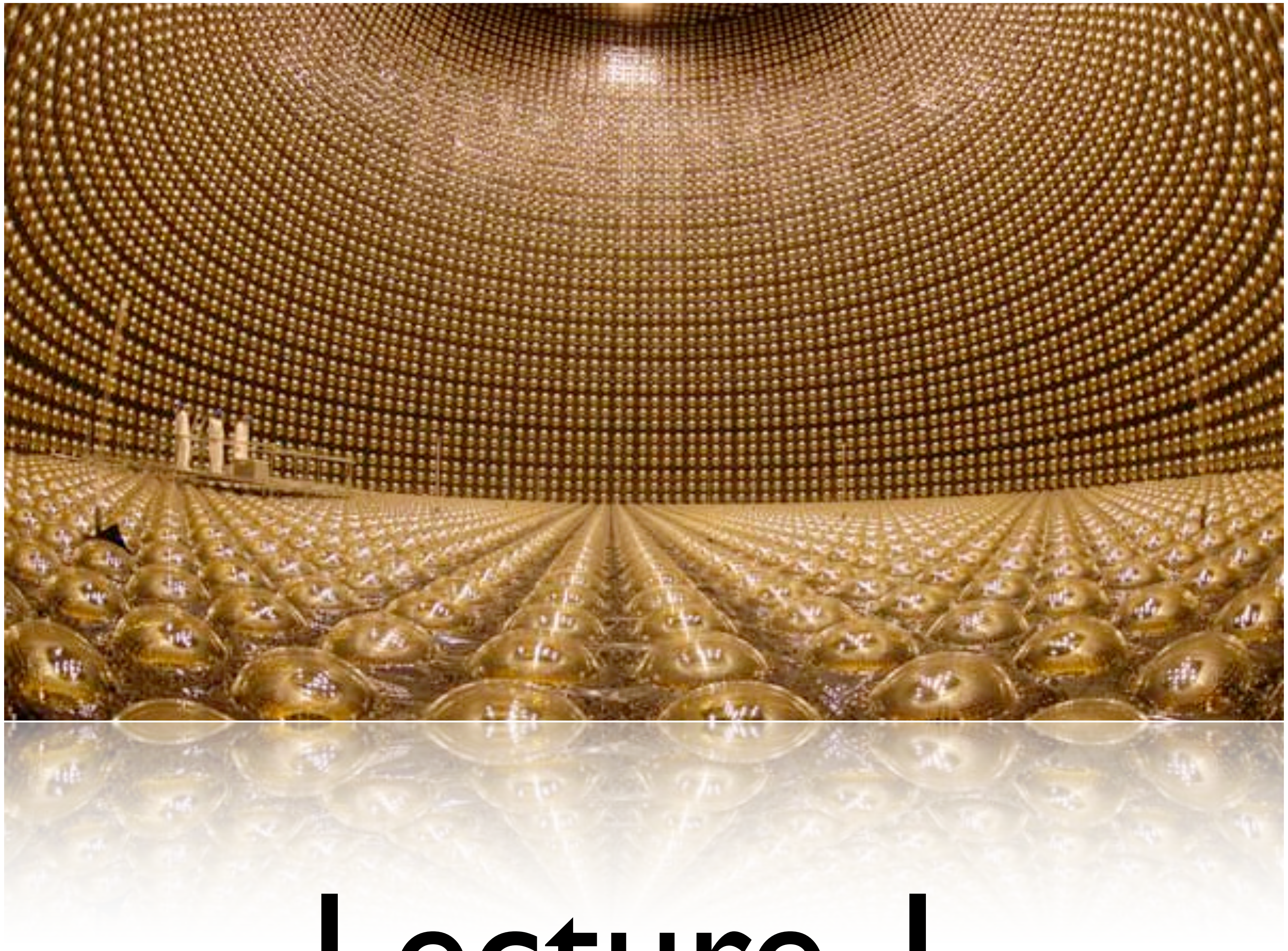
- Informal lectures
- Please ask questions

Especially basic questions!

Schedule of Talks

- 1 - Introduction & Experiments
- 2 - CCQE
- 3 - CC1π^+
- 4 - NC1π^0
- 5 - Other processes (NC Elastic, CC1π^0)
- 6 - Antineutrino measurements

Discuss
relation to oscillation
experiments here

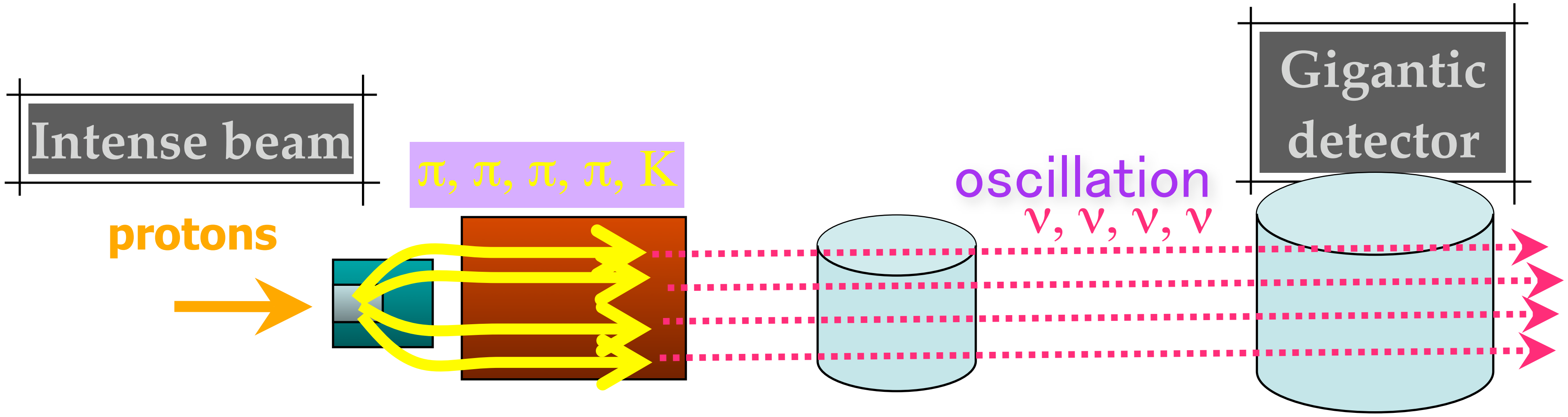


Lecture 1. Introduction

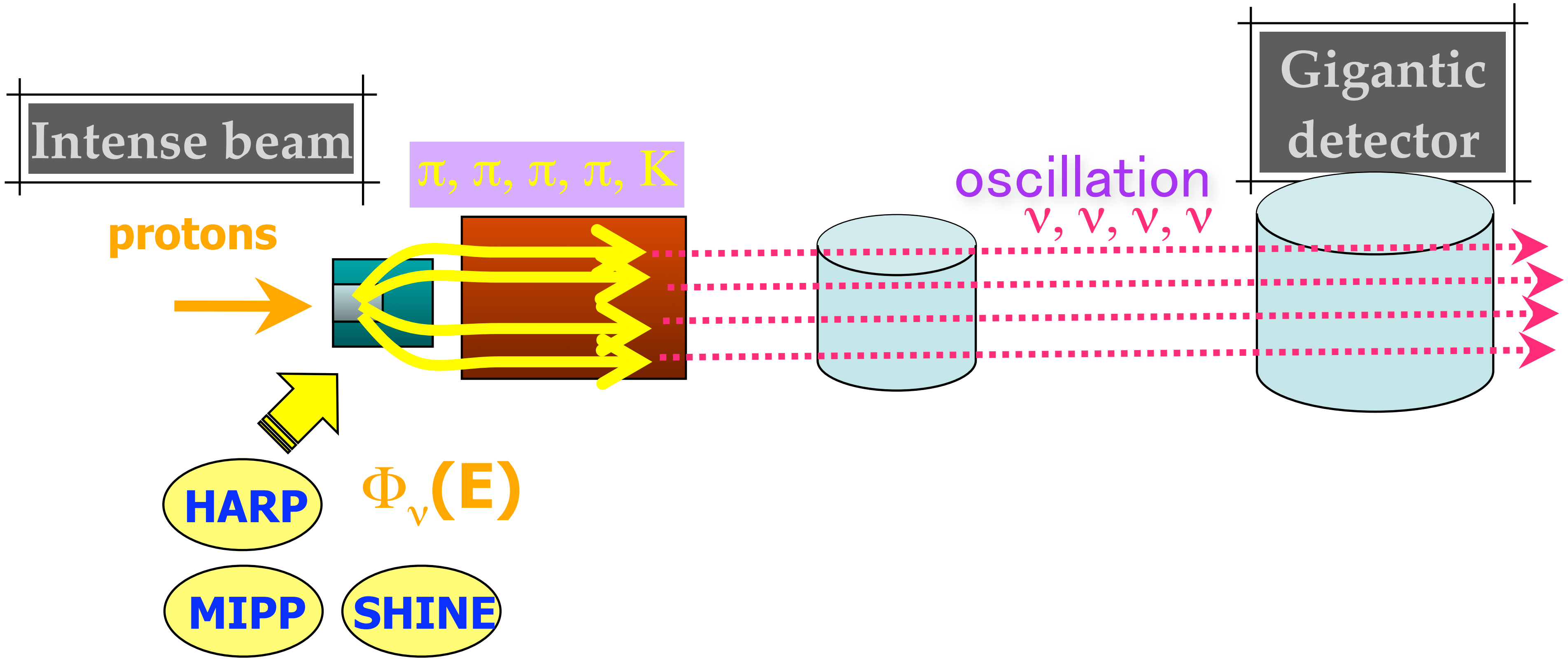
Lecture 1 Outline

- Overview of Accelerator ν Experiments
  - Motivation
- Past Experiments
- Hadron production experiments
- Current Experiments
  - K2K
  - MiniBooNE
  - SciBooNE
- Future Experiments

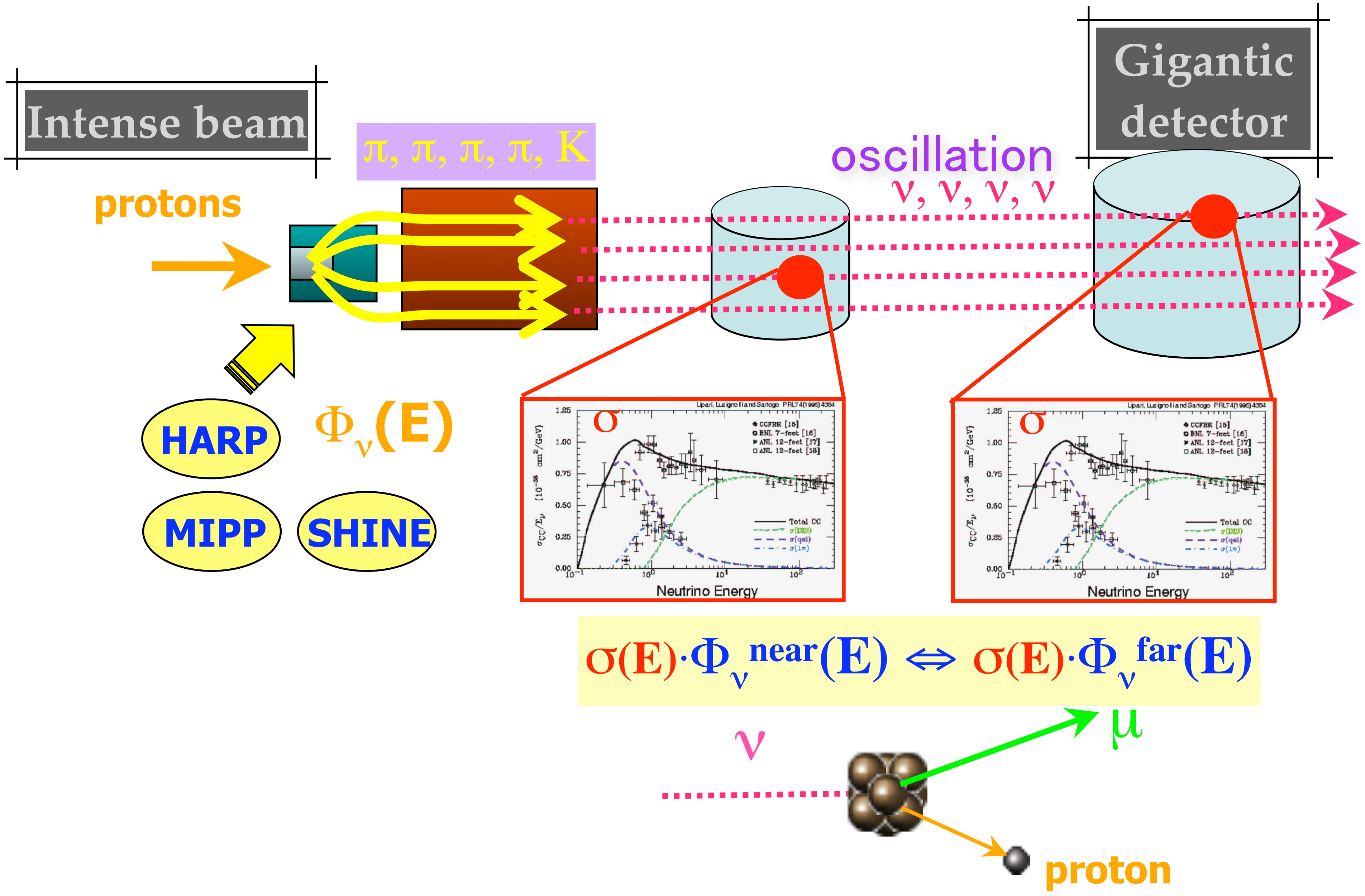
Accelerator Neutrino Experiments


Intense beam
protons
π, π, π, π, K
oscillation
ν, ν, ν, ν
Gigantic detector

Accelerator Neutrino Experiments


Intense beam
Gigantic detector
π, π, π, π, K
oscillation
ν, ν, ν, ν
protons
HARP
Φ_ν(E)
MIPP
SHINE

Accelerator Neutrino Experiments



Intense beam

π, π, π, π, K

protons

HARP

MIPP

SHINE

Φ_ν(E)

oscillation

ν, ν, ν, ν

Gigantic detector

σ

σ

Lipari, Lusignoli and Sartogo PRL74(1995)4384
CCFRR [15]
BNL 7-feet [16]
ANL 12-feet [17]
ANL 12-feet [18]
Total CC
σ(DIS)
σ(qel)
σ(1π)
Neutrino Energy
Lipari, Lusignoli and Sartogo PRL74(1995)4384
CCFRR [15]
BNL 7-feet [16]
ANL 12-feet [17]
ANL 12-feet [18]
Total CC
σ(DIS)
σ(qel)
σ(1π)
Neutrino Energy

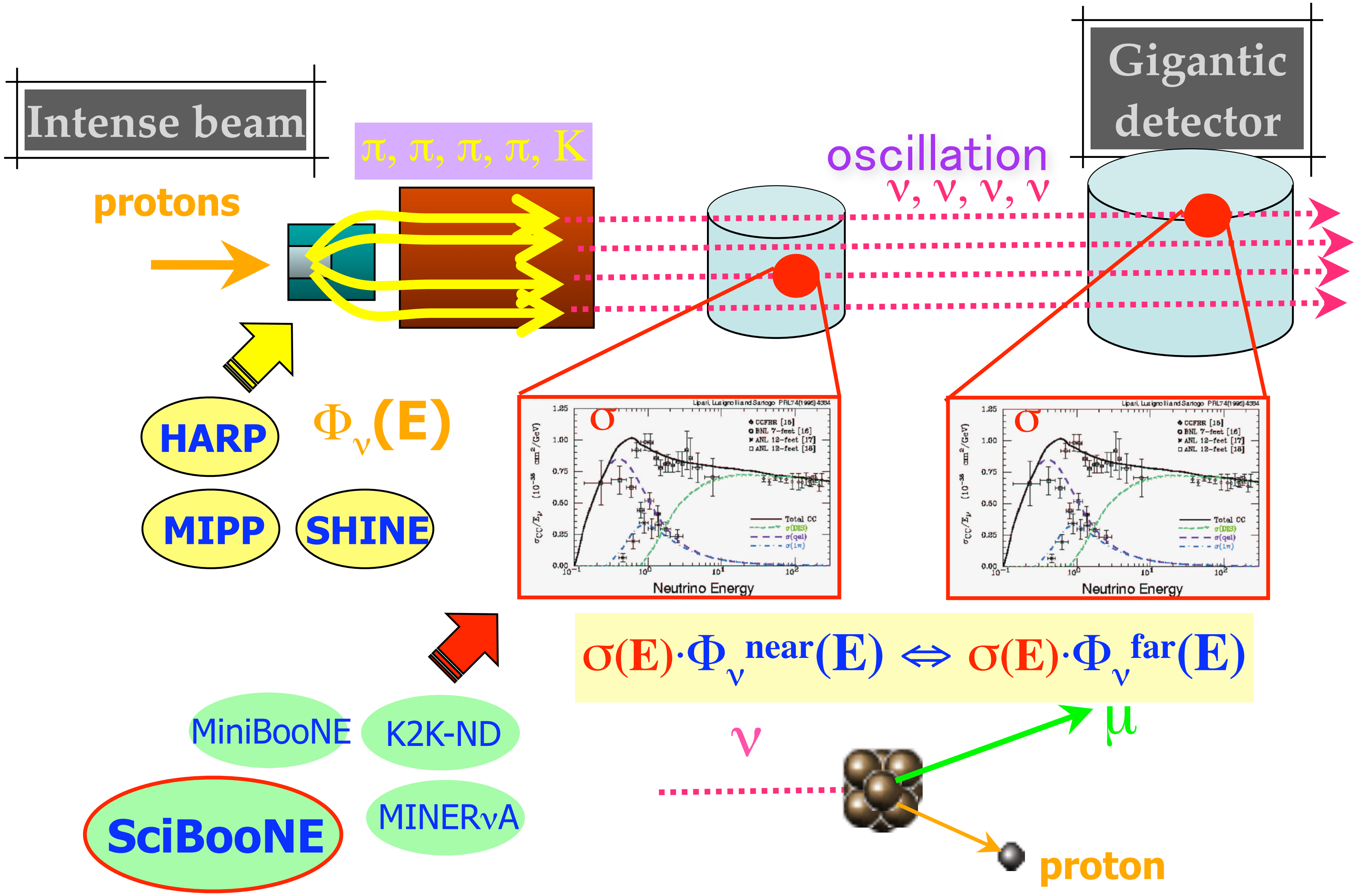
$$\sigma(E)\cdot\Phi_\nu^{near}(E) \Leftrightarrow \sigma(E)\cdot\Phi_\nu^{far}(E)$$

ν

μ

proton

Accelerator Neutrino Experiments


Lipari, Lusignoli and Sartogo PRL74(1995)4384
CCFRR [15]
BNL 7-feet [16]
ANL 12-feet [17]
ANL 12-feet [18]
Total CC
σ(DIS)
σ(qel)
σ(1π)
σ_{CC}/E_ν $[10^{-38}$ cm^2/GeV$]$
Neutrino Energy

Intense beam

protons

π, π, π, π, K

oscillation

ν, ν, ν, ν

Gigantic detector

HARP

MIPP

SHINE

$\Phi_\nu(E)$

σ

σ

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

MiniBooNE

K2K-ND

SciBooNE

MINERνA

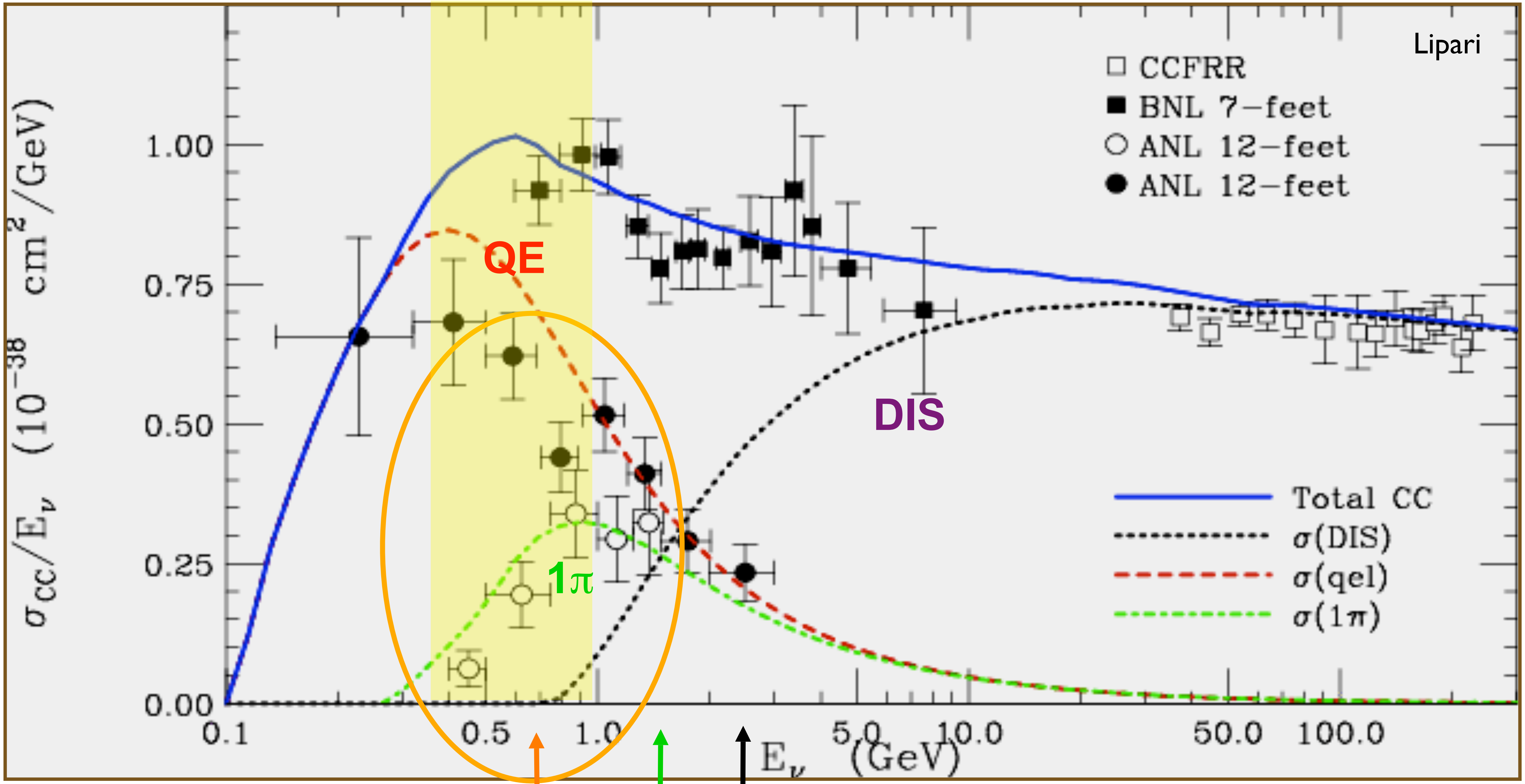
ν

μ

proton

Energy range

Neutrino oscillation searches drive need for better cross section knowledge



MINOS

K2K, NOvA

MiniBooNE, T2K, SciBooNE

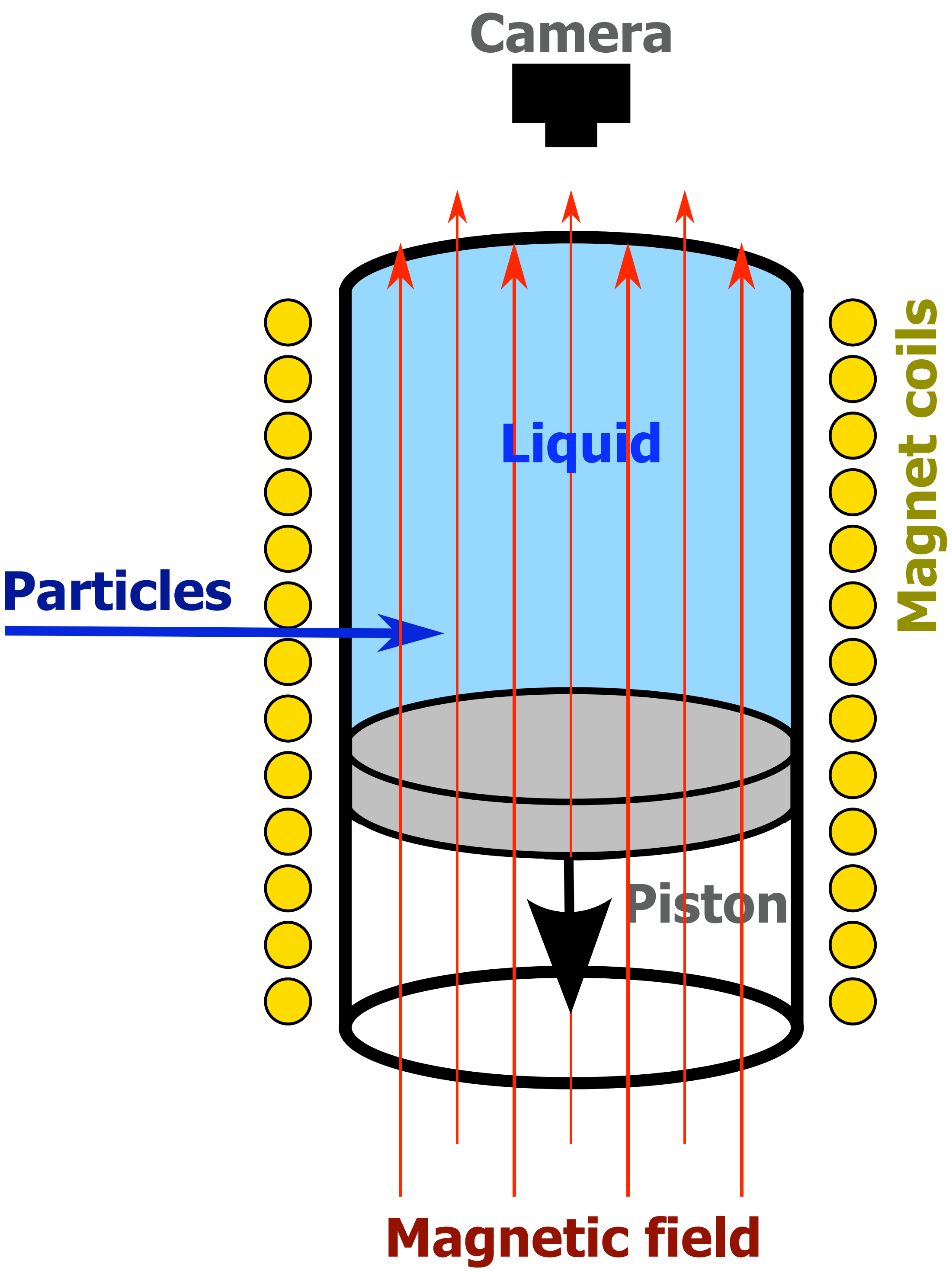
Super-K atmospheric ν

Past Experiments

- Bubble chambers
  - First measurements
- Conventional neutrino beams

Bubble Chambers

- Super heated liquid
  - Ionisation creates bubbles
- External trigger
  - Cameras
- Very good position resolutions
- Slow reconstruction - human hand scanning
  - Extremely limited statistics


Camera
Liquid
Particles
Magnet coils
Piston
Magnetic field

Bubble Chambers

- Super heated liquid
  - Ionisation creates bubbles
- External trigger
  - Cameras
- Very good position resolutions
- Slow reconstruction - human hand scanning
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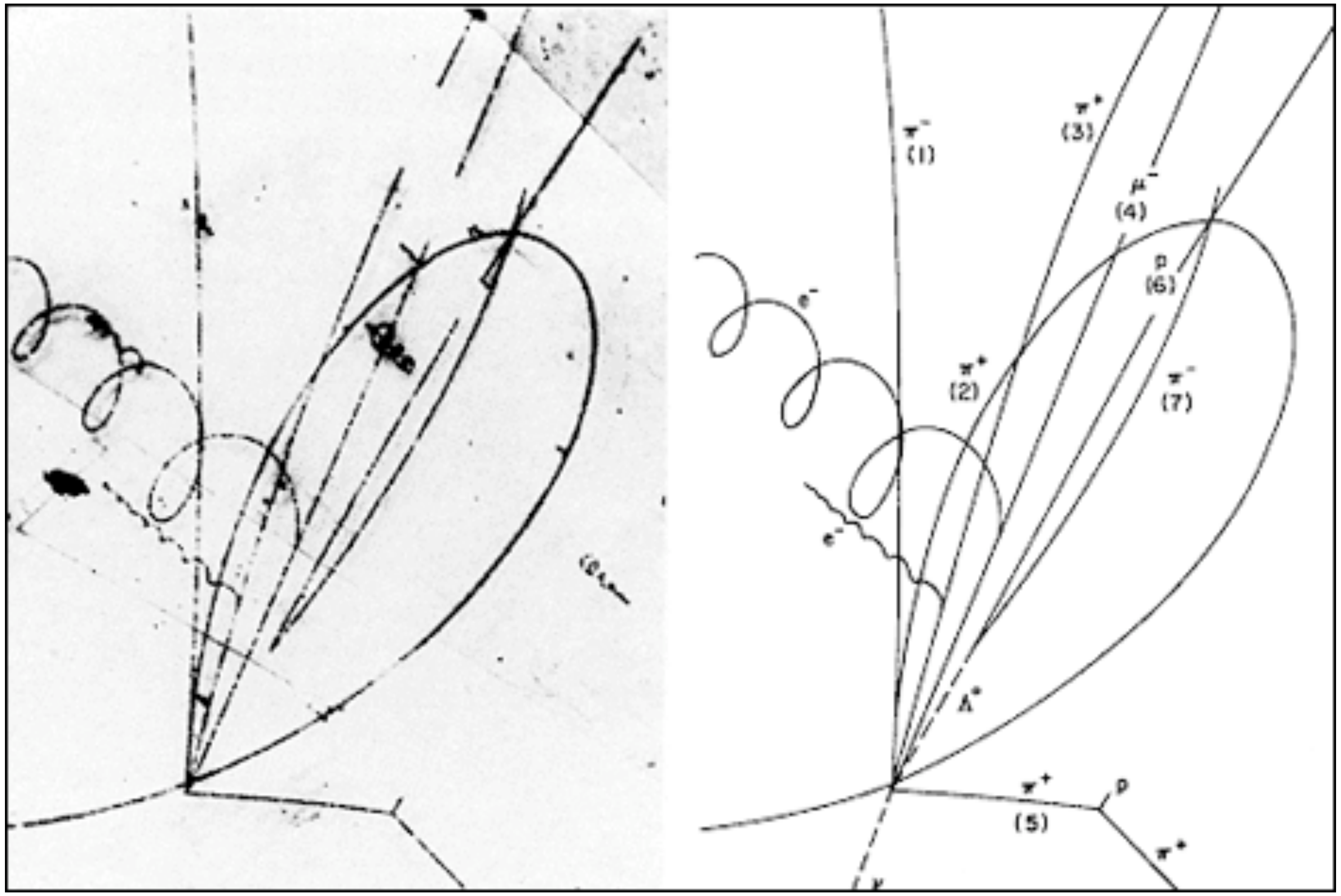
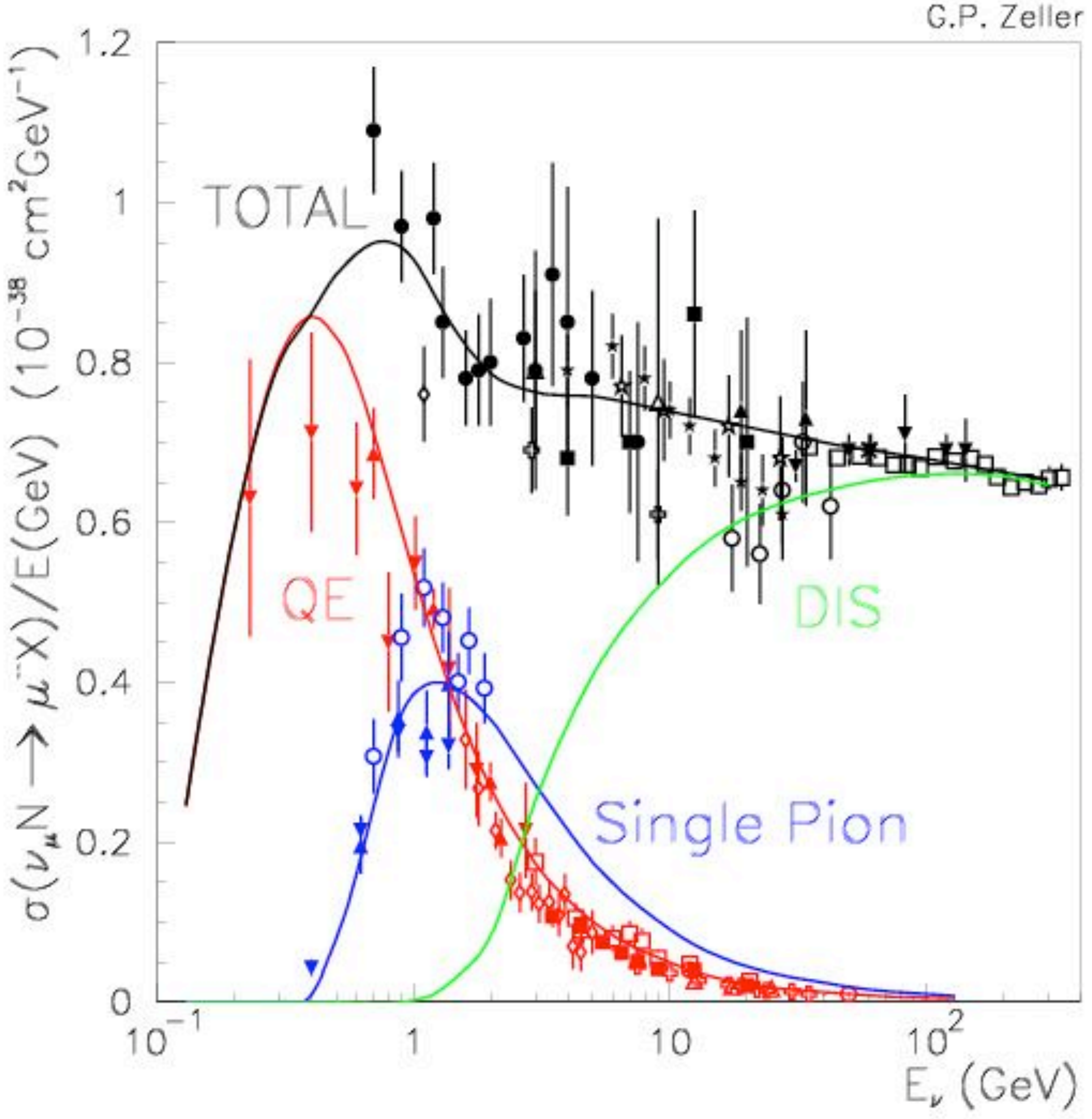

π^- (1)
π^+ (3)
μ^- (4)
p (6)
e^-
π^+ (2)
π^- (7)
e^-
Λ^0
π^+ (5)
p
π^+
ν

Bubble Chambers 2

- Bubble chambers used with neutrinos at CERN, ANL, BNL, FNAL
- Neutrino
- Antineutrino
- Slow data processing motivates use of electronic readout



Bubble Chambers 2

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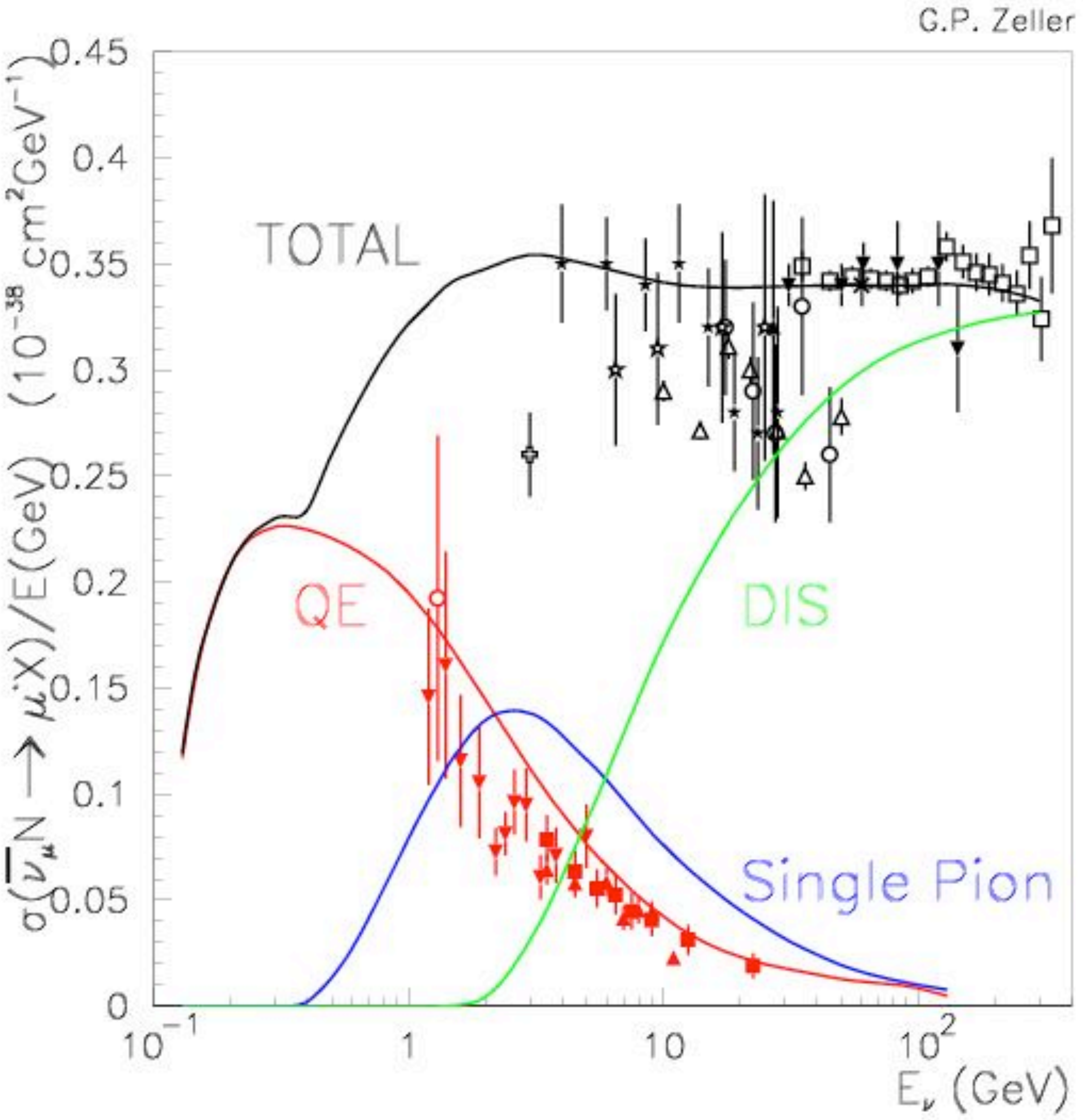
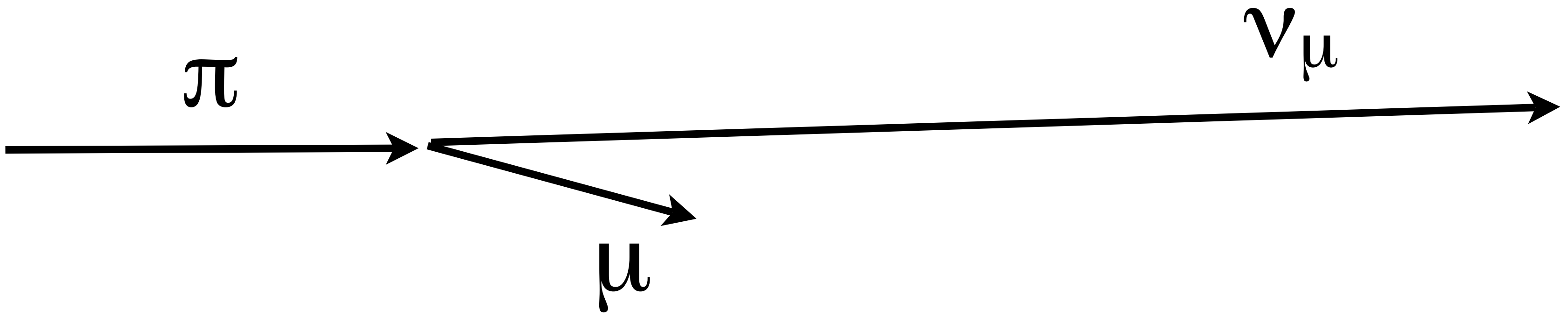




Conventional Neutrino Beams

First neutrino beam

- Lederman, Schwartz & Steinberger
  - Discovery of 2 types of neutrinos
- Used an undirected, unfocused beam of pions to create neutrinos

Phys. Rev. Lett. 9, 36 - 44 (1962)

$$\boxed{\pi \rightarrow \mu\nu}$$

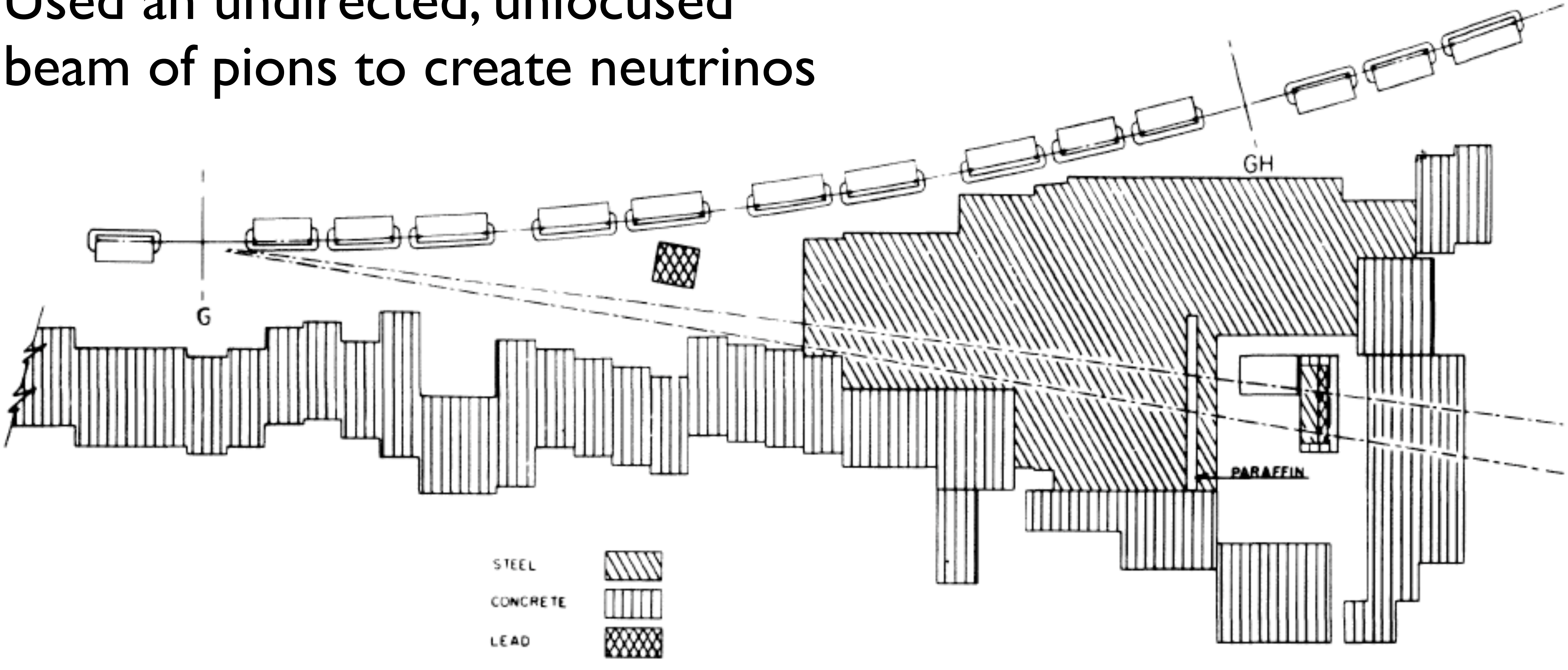
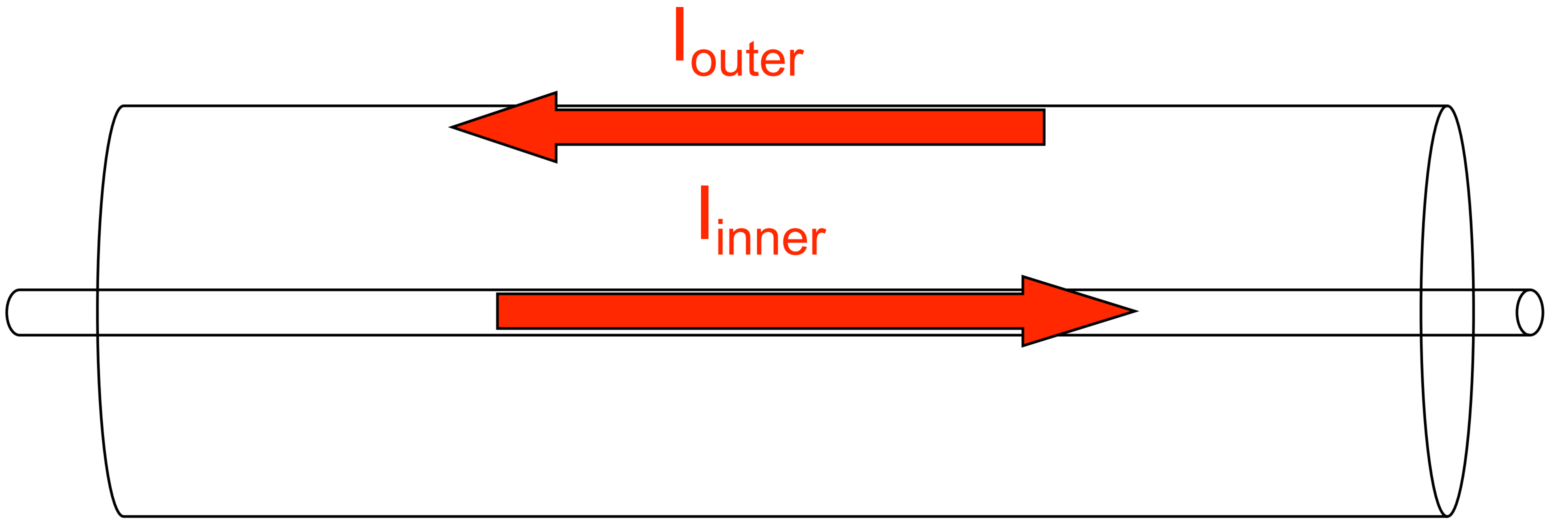

G
GH
PARAFFIN
STEEL
CONCRETE
LEAD

FIG. 1. Plan view of AGS neutrino experiment.

Increasing the flux of neutrino beams

- Simon van der Meer had an idea in the mid 60's:
    - Using two cylindrical current sheets
    - Create a toroidal magnetic field around the neutrino target to
    - Focus pions toward the neutrino detector
    - Increases flux, allows sign selection, some energy selection



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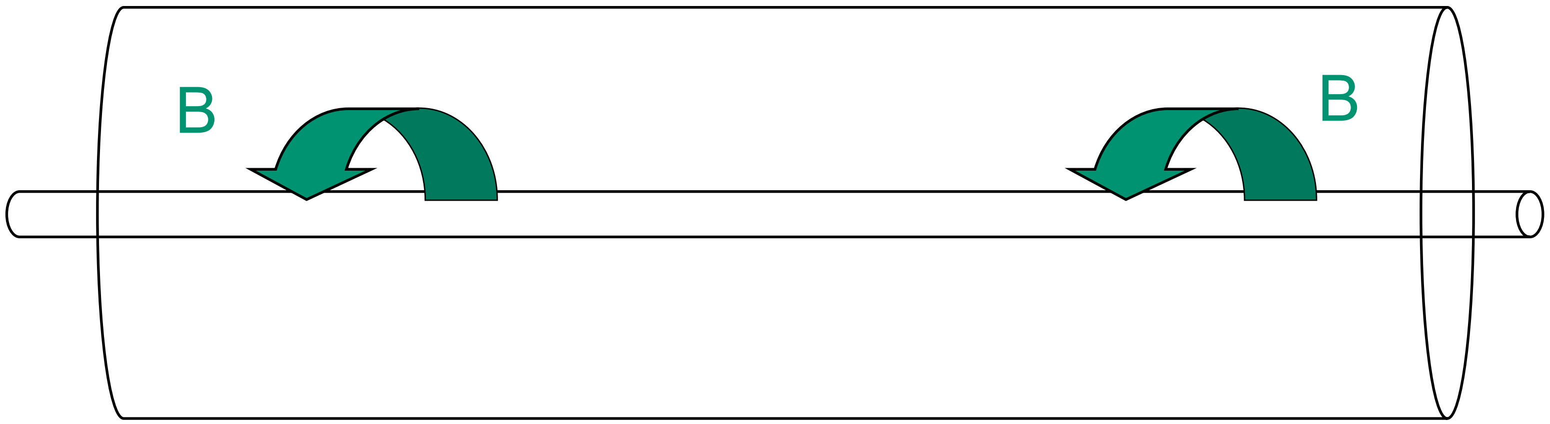

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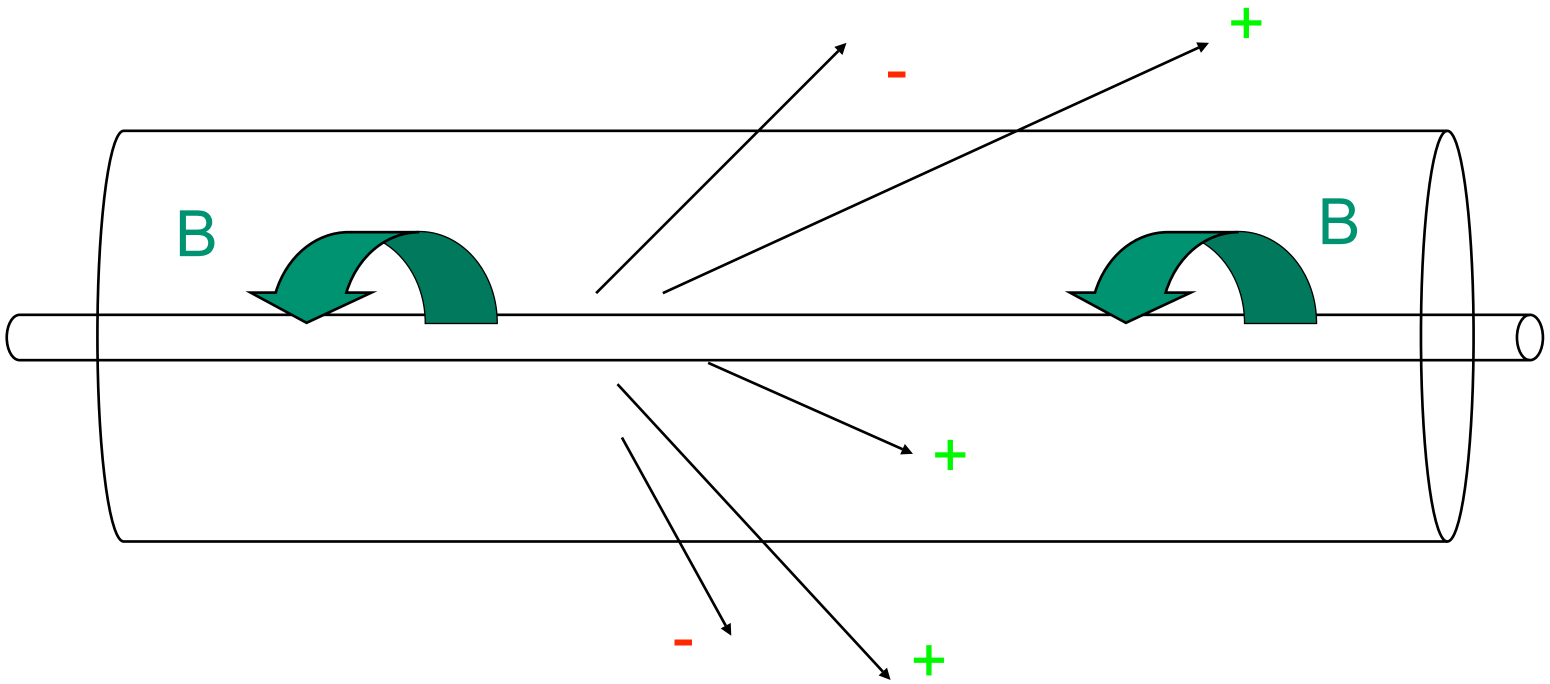

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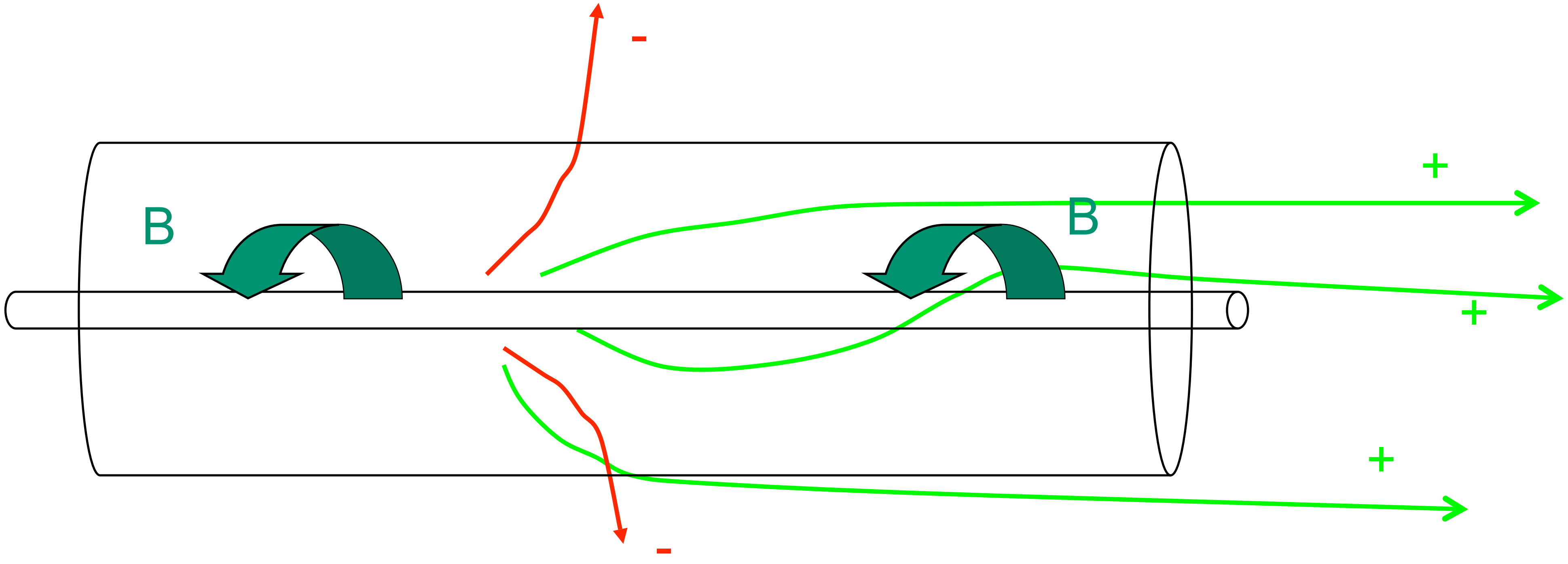
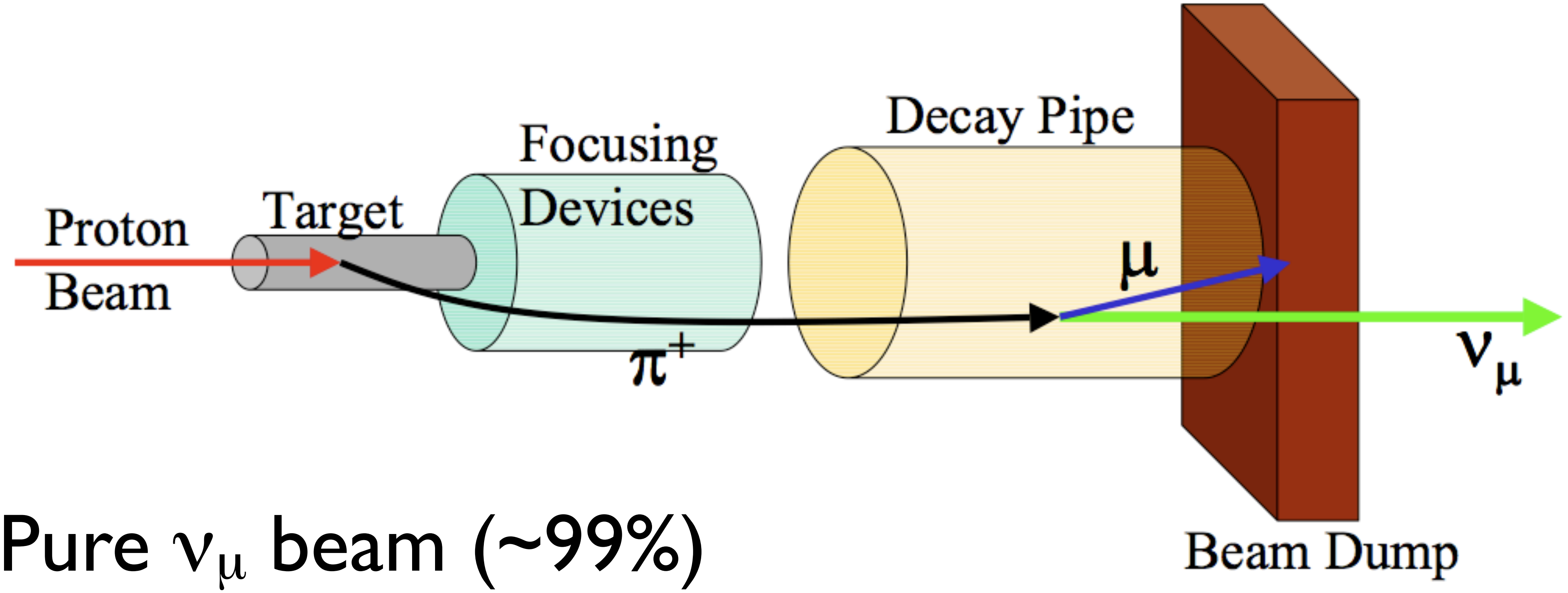


Horns

- These devices are called magnetic horns or just neutrino horns

Conventional characteristics


Proton
Beam
Target
Focusing
Devices
π^+
Decay Pipe
μ
ν_μ
Beam Dump

- Pure ν_μ beam (~99%)
- Slight ν_e contamination from muon and kaon (Ke3) decay
  - Muon decay mitigated with short decay region
  - Higher kaon content at higher proton energies
    - Tradeoff: beam power & purity

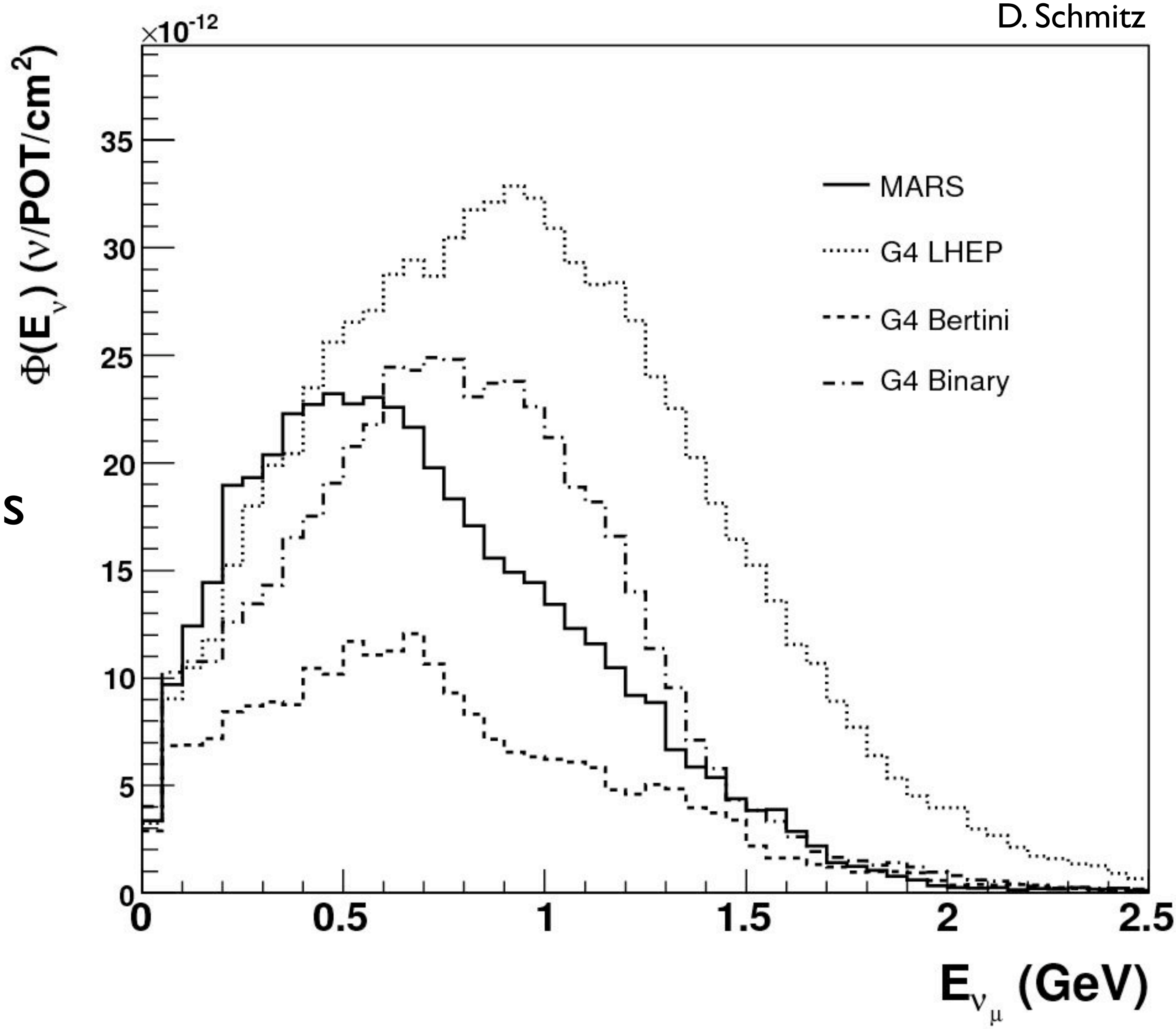
Beam References

- Phys.Rept.439:101-159,2007; arXiv:physics/0609129v1 [physics.acc-ph]

Hadron Production

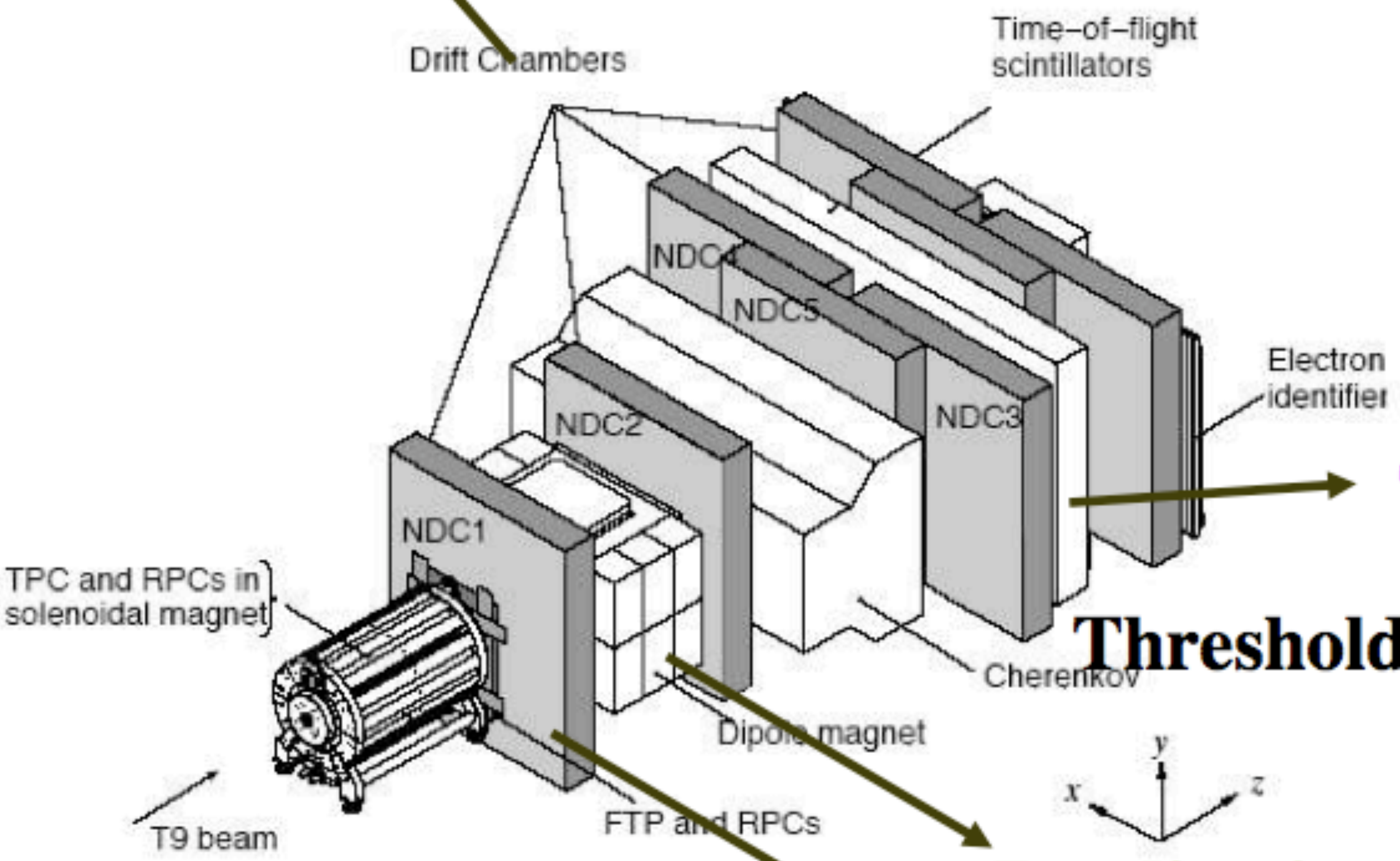
- Neutrino flux directly related to the meson flux in decay region
- Uncertainties in meson flux lead to uncertainties in neutrino flux
- Need good meson production measurements
  - HARP at CERN

D. Schmitz



Harp Detector

NDC modules = 4 chamber x 3 planes (u,v,x) = 12 planes/module


Drift Chambers
Time–of–flight scintillators
NDC4
NDC5
NDC2
NDC3
NDC1
Electron identifier
TPC and RPCs in solenoidal magnet
Cherenkov
Dipole magnet
T9 beam
FTP and RPCs
y
x
z

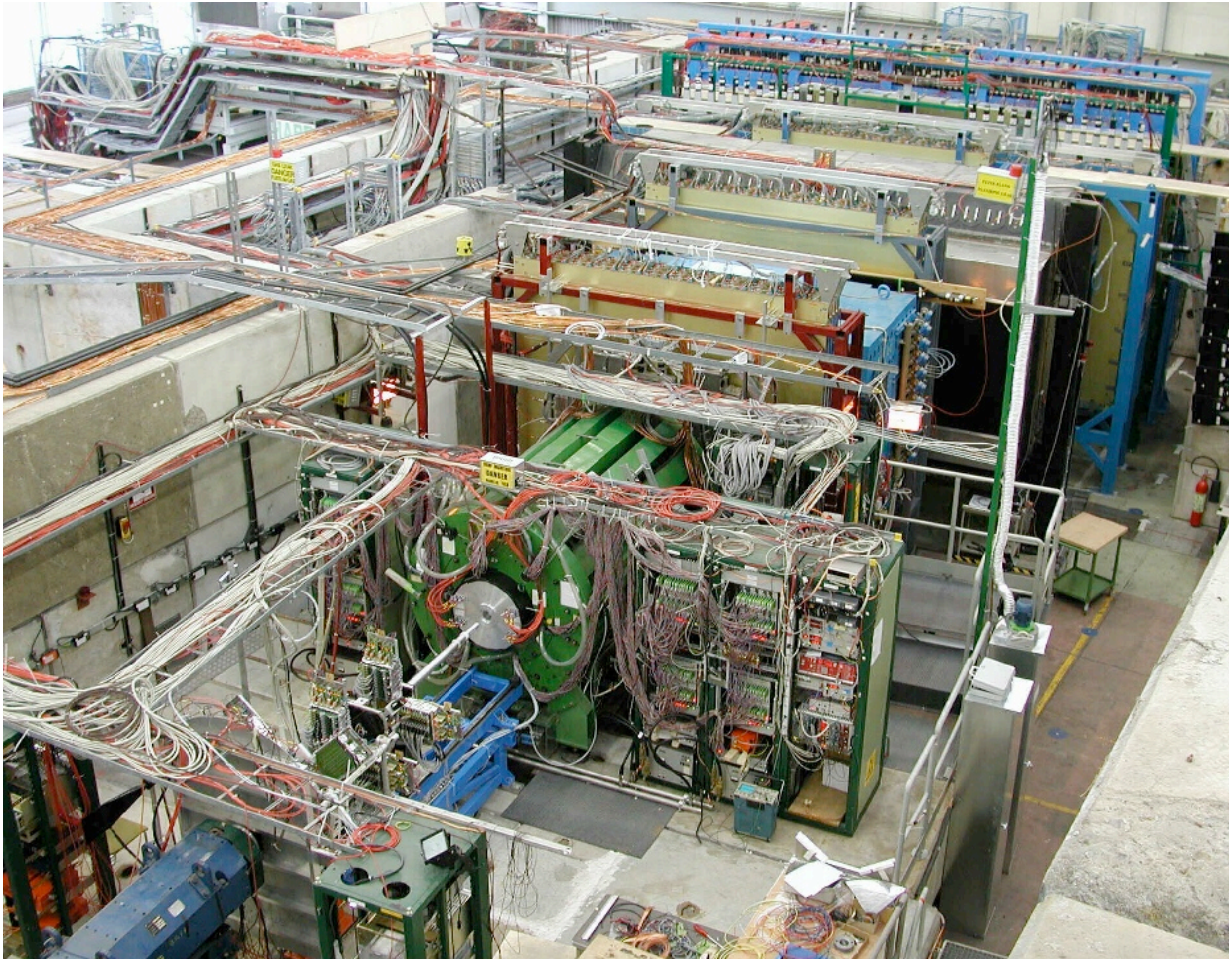
TOFW + t0 Δt ~180 ps

Threshold mode: $E_{th}^{\pi} = 2.6$ GeV

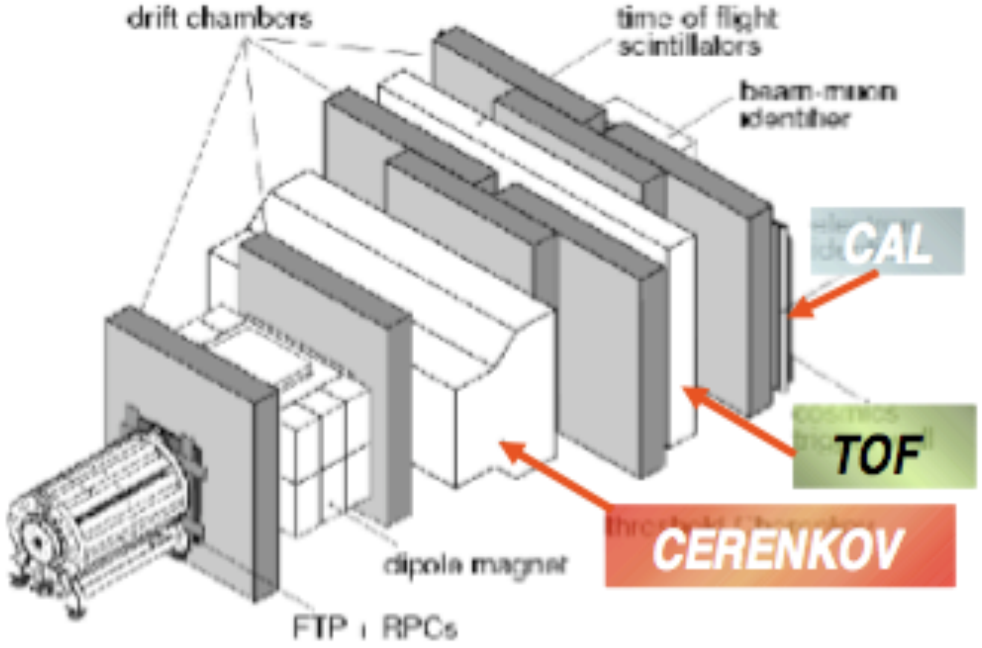
Bending in xz plane: 0.5 T

Beam instrumentation

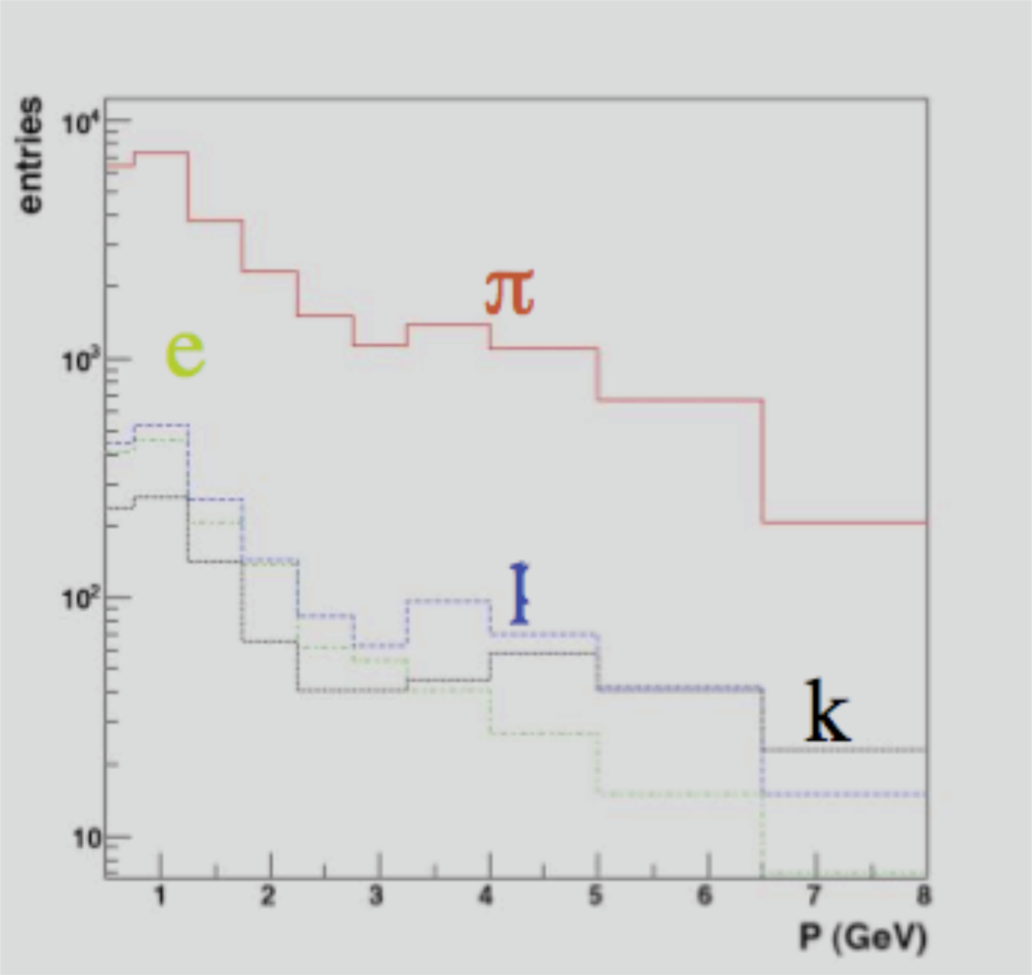
FTP gives interaction trigger

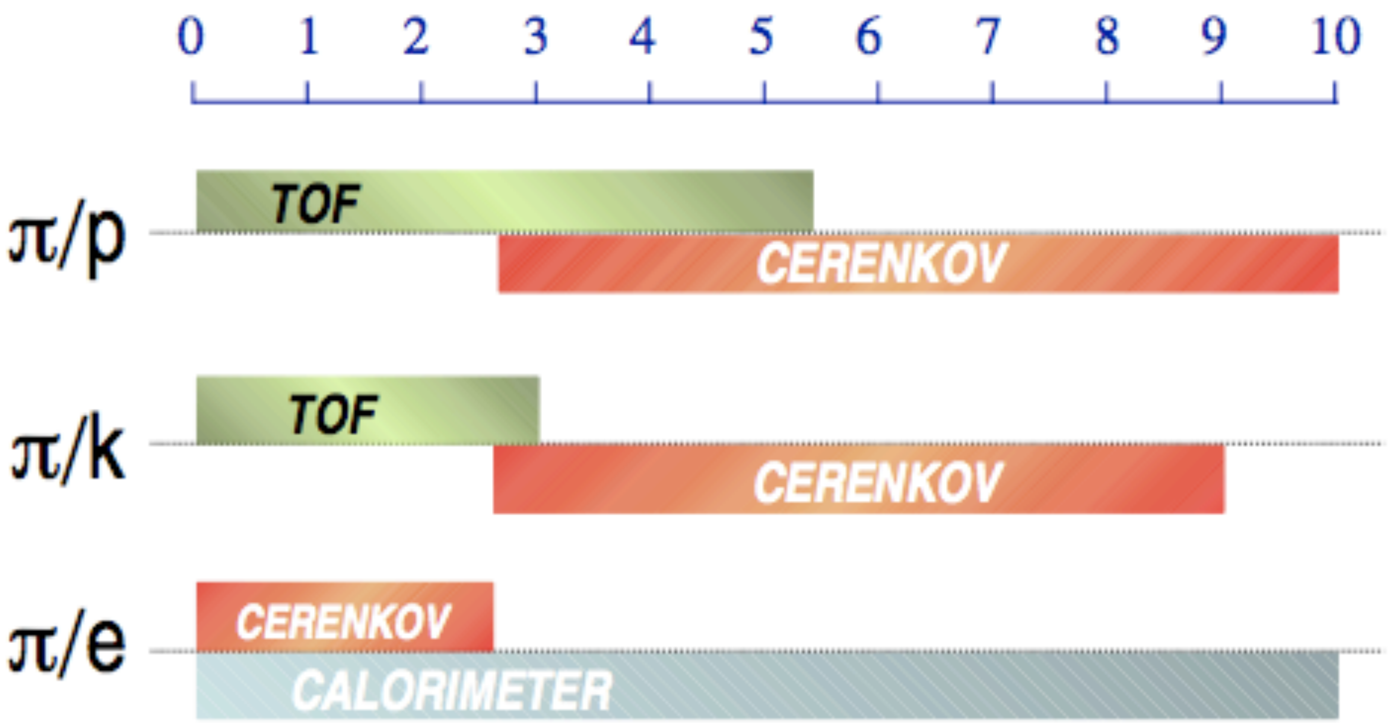

DANGER
DANGER

PID in Harp


drift chambers
time of flight scintillators
beam-muon identifier
CAL
TOF
CERENKOV
dipole magnet
FTP + RPCs

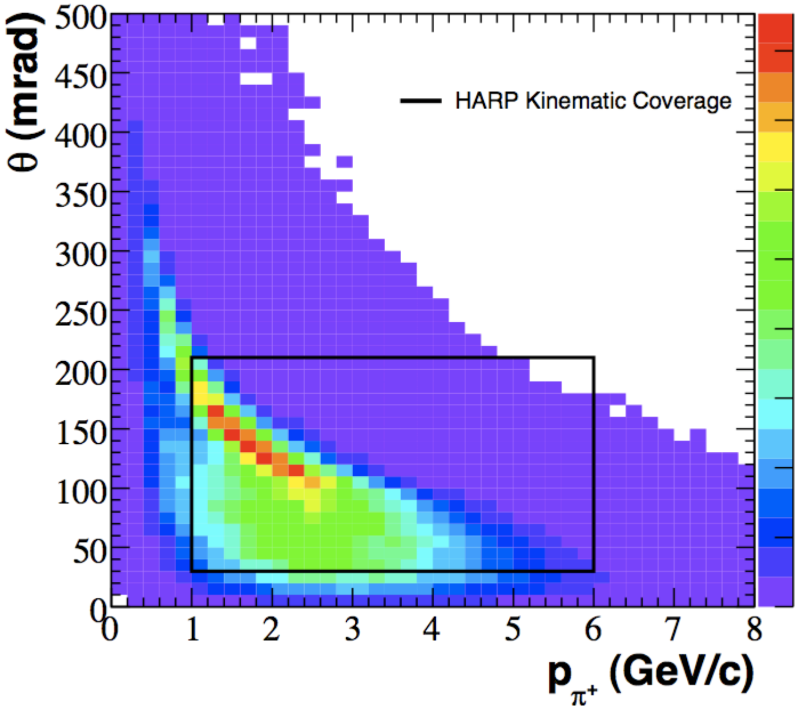
MC simulation of particle yields

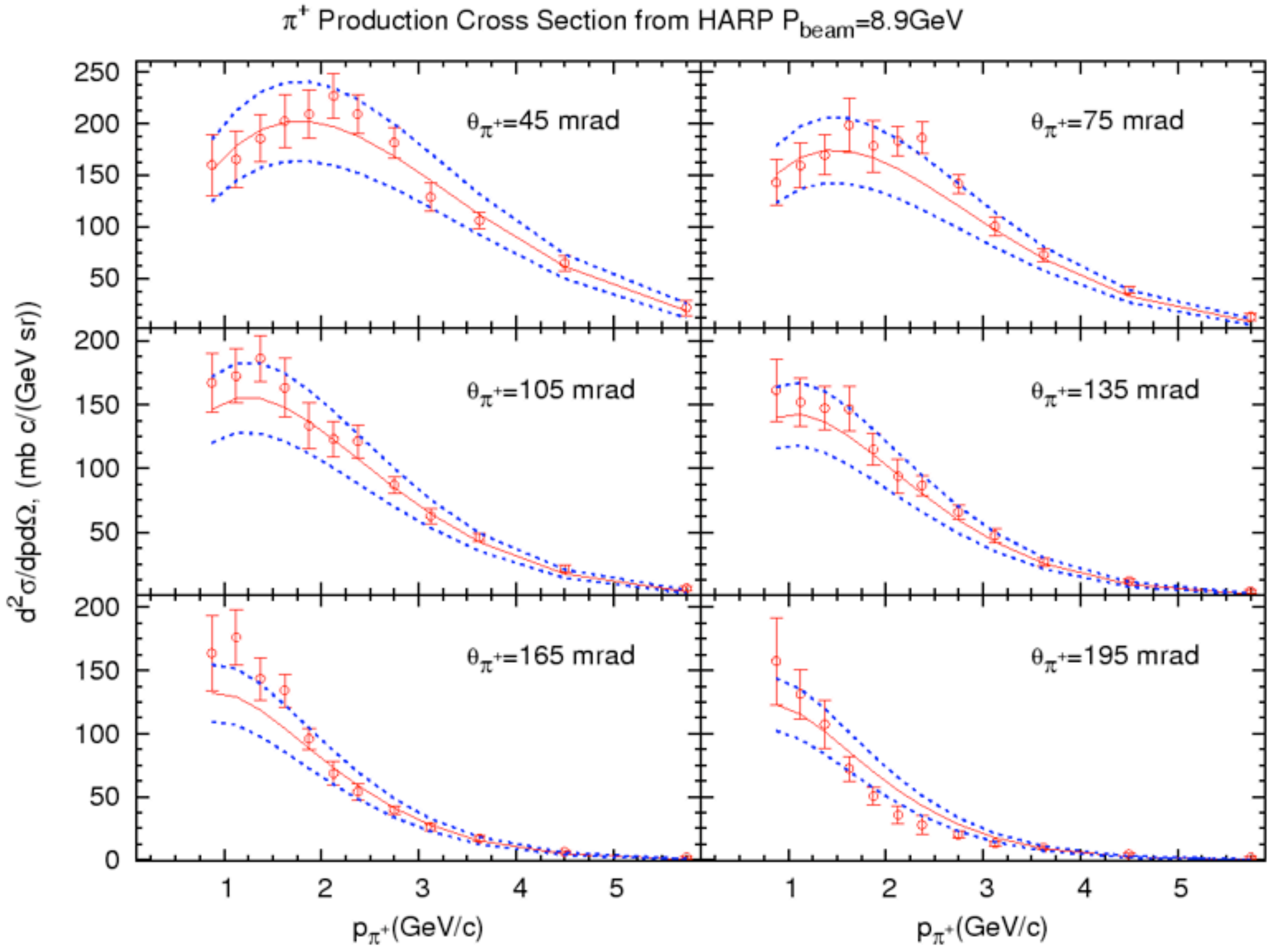




HARP Results (Be)

- 8 GeV KE protons
- Beryllium target
  - thin target
  - MiniBooNE replica target
- Wide coverage of meson phase space

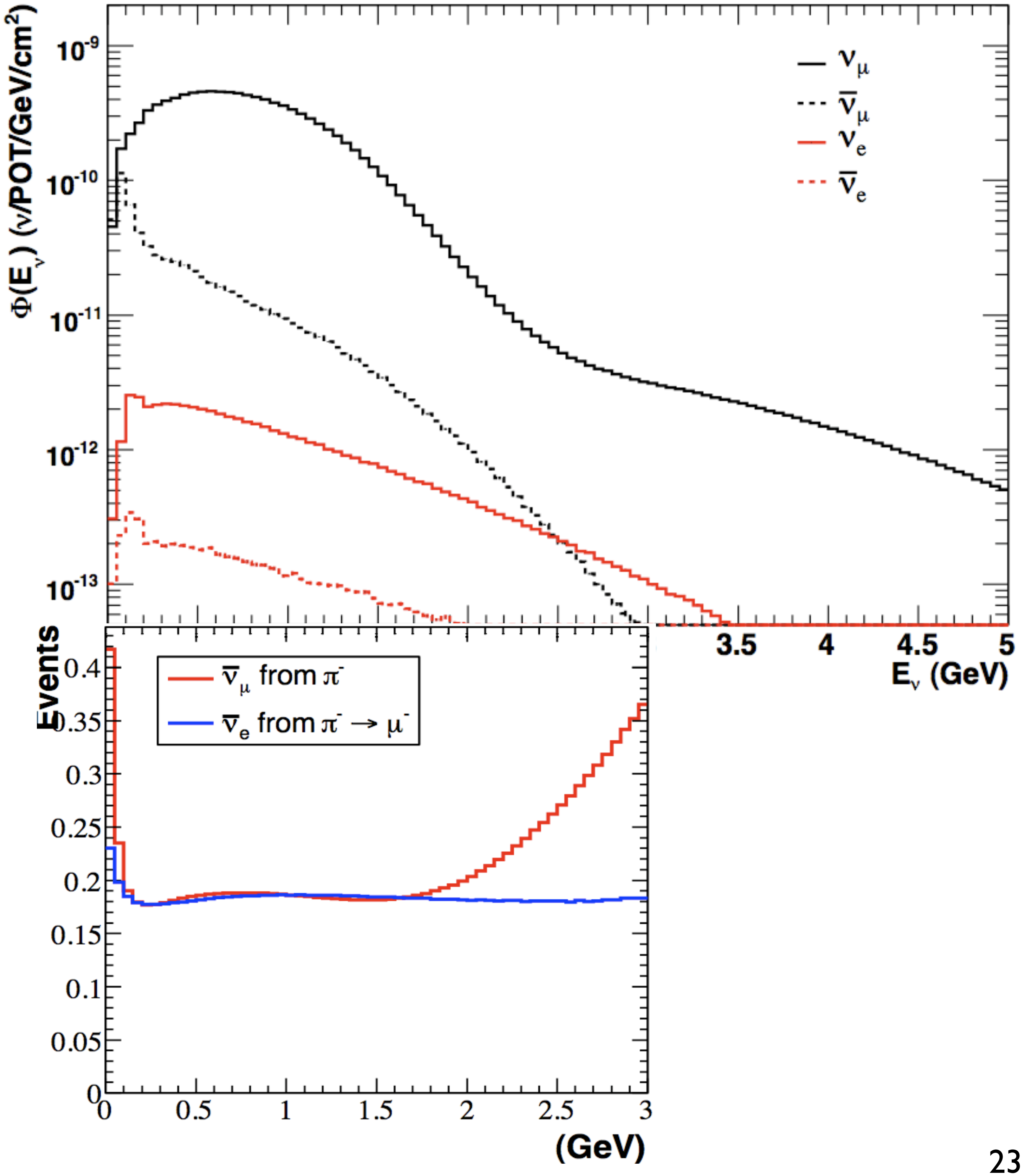




BooNE Flux w/HARP

- Use HARP data with Sanford-Wang parameterization directl in BooNE flux MC
- ~17% uncertainty
    - Direct interpolation of data (no S-W) yields ~8% uncertainty

arXiv:0806.1449 [hep-ex].

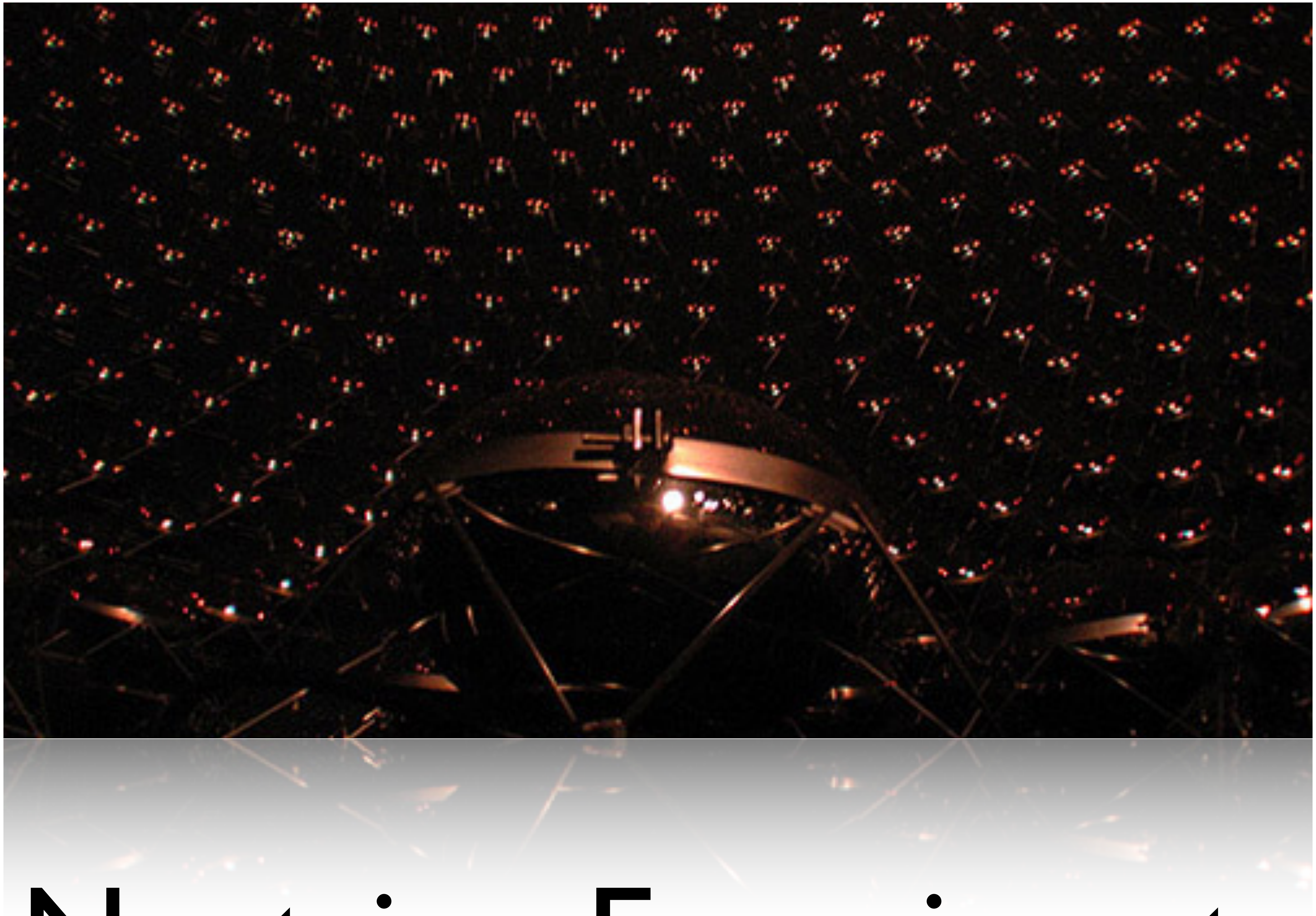


HARP References

- http://harp.web.cern.ch/harp
- Al: Nucl. Phys. **B732** (2006) 1, arXiv:hep-ex/0510039.
- Be: Eur. Phys. J. **C52** (2007) 29-53, arXiv:hep-ex/0702024.

Other Hadron production experiments

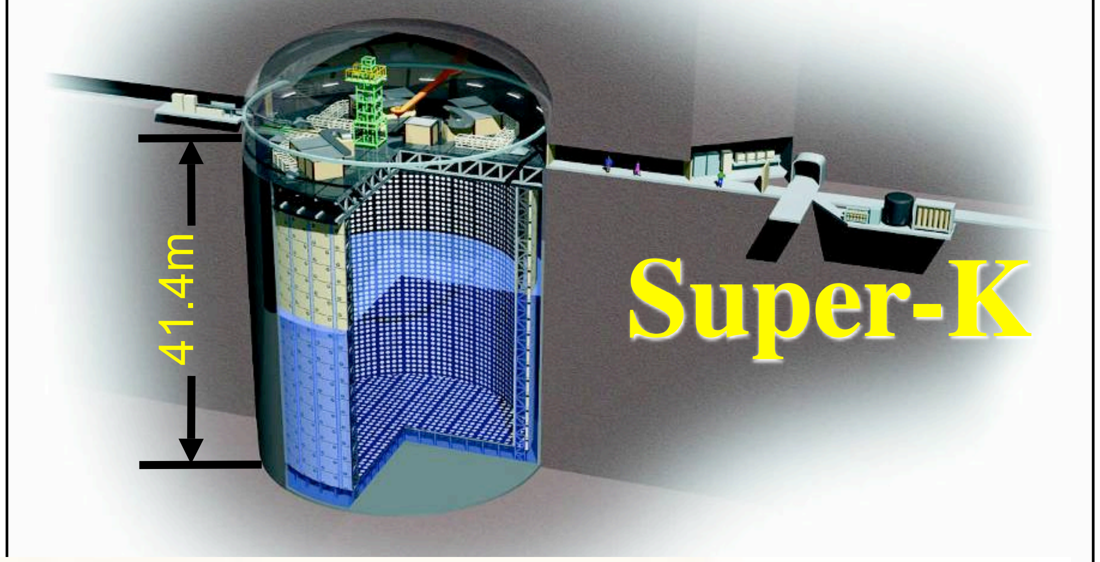
- MIPP (Main Injector Particle Production)
  - Fermilab
  - Ran in 2004-5
  - Analyzing data now
- SHINE (NA-61)
  - CERN
  - for T2K
  - Took data in 2007
  - Running more this spring (2009)

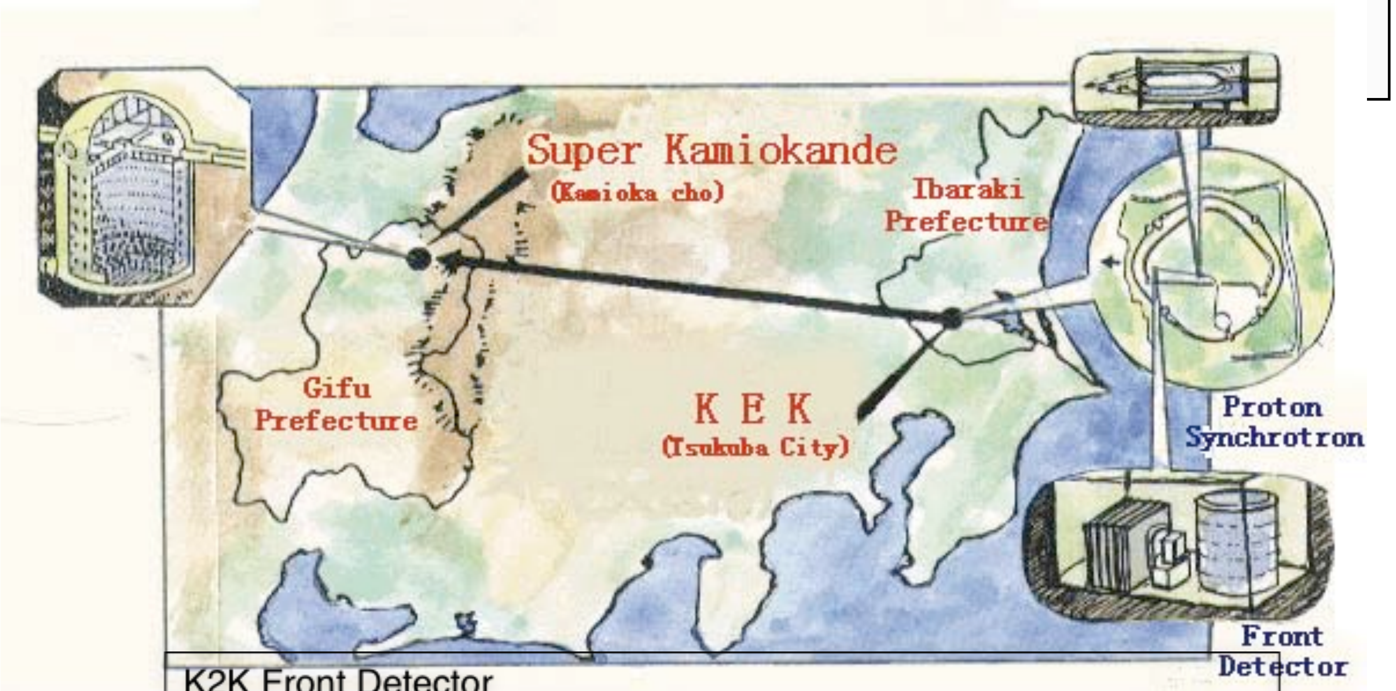


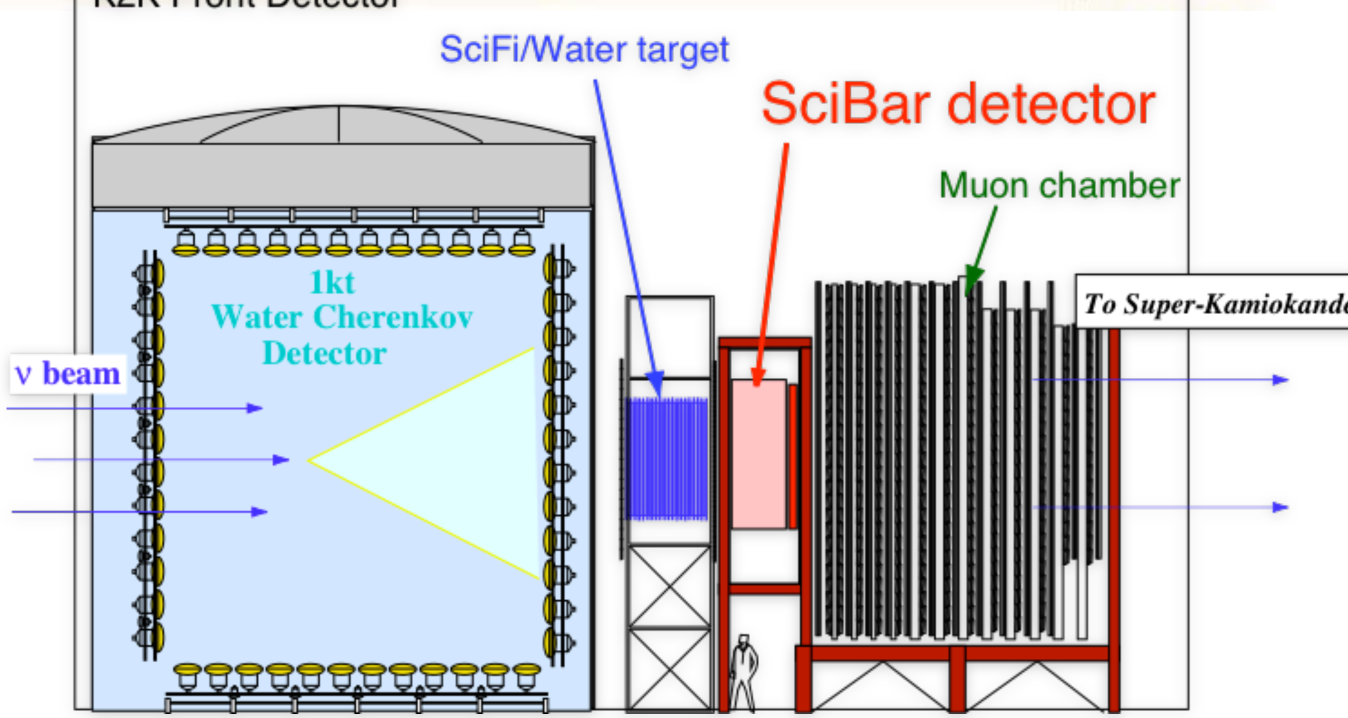
Neutrino Experiments

K2K Intro

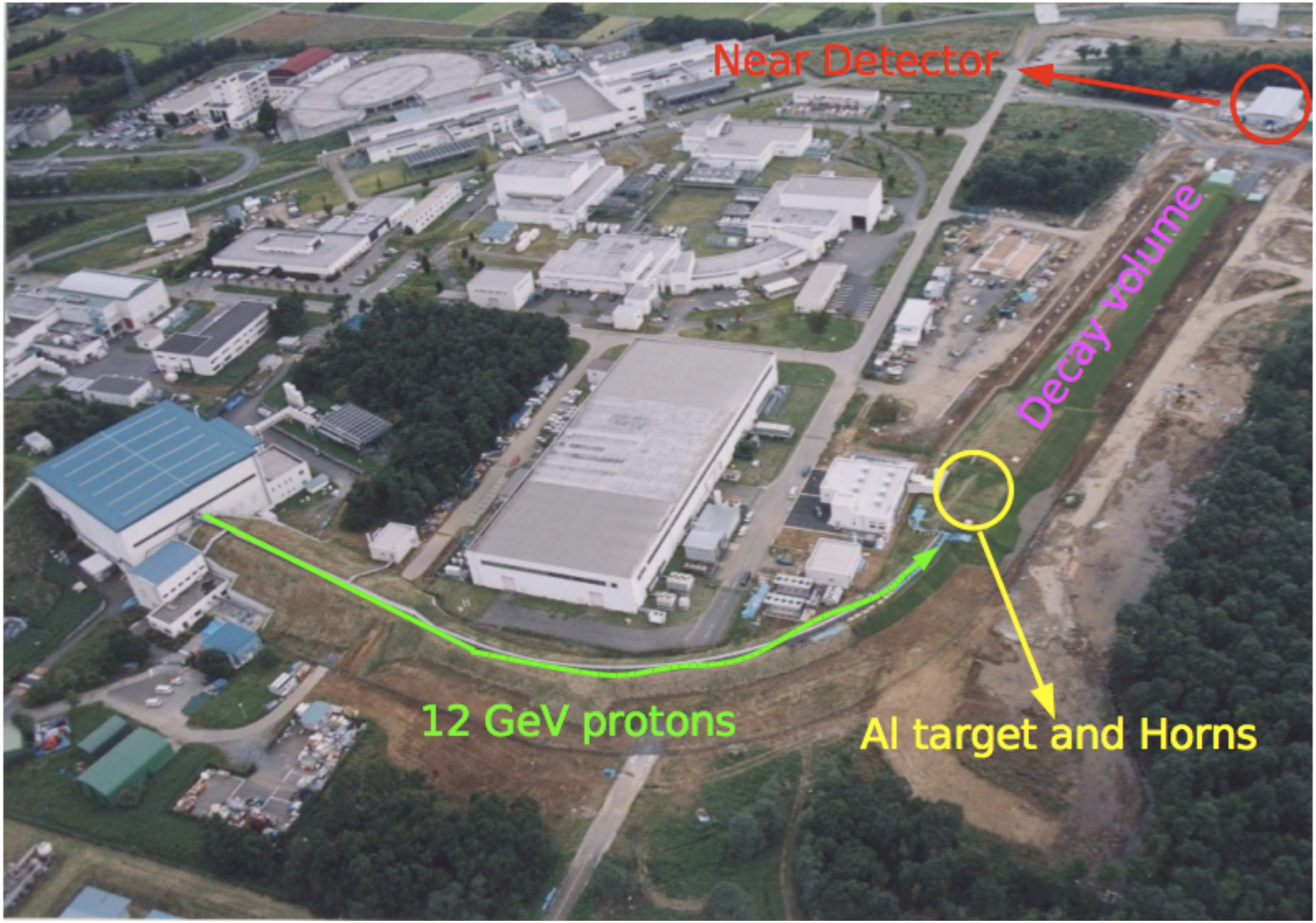
- Designed to confirm atmospheric neutrino oscillations using Super-K as the far detector
- Suite of near detectors to observe un-oscillated neutrinos and measure neutrino cross sections
- Peak ν energy 1.3 GeV
  - Renewed interest in neutrino cross sections at these energies


41.4m
Super-K


Super Kamiokande
(Kamioka cho)
Ibaraki
Prefecture
Gifu
Prefecture
K E K
(Tsukuba City)
Proton
Synchrotron
Front
Detector

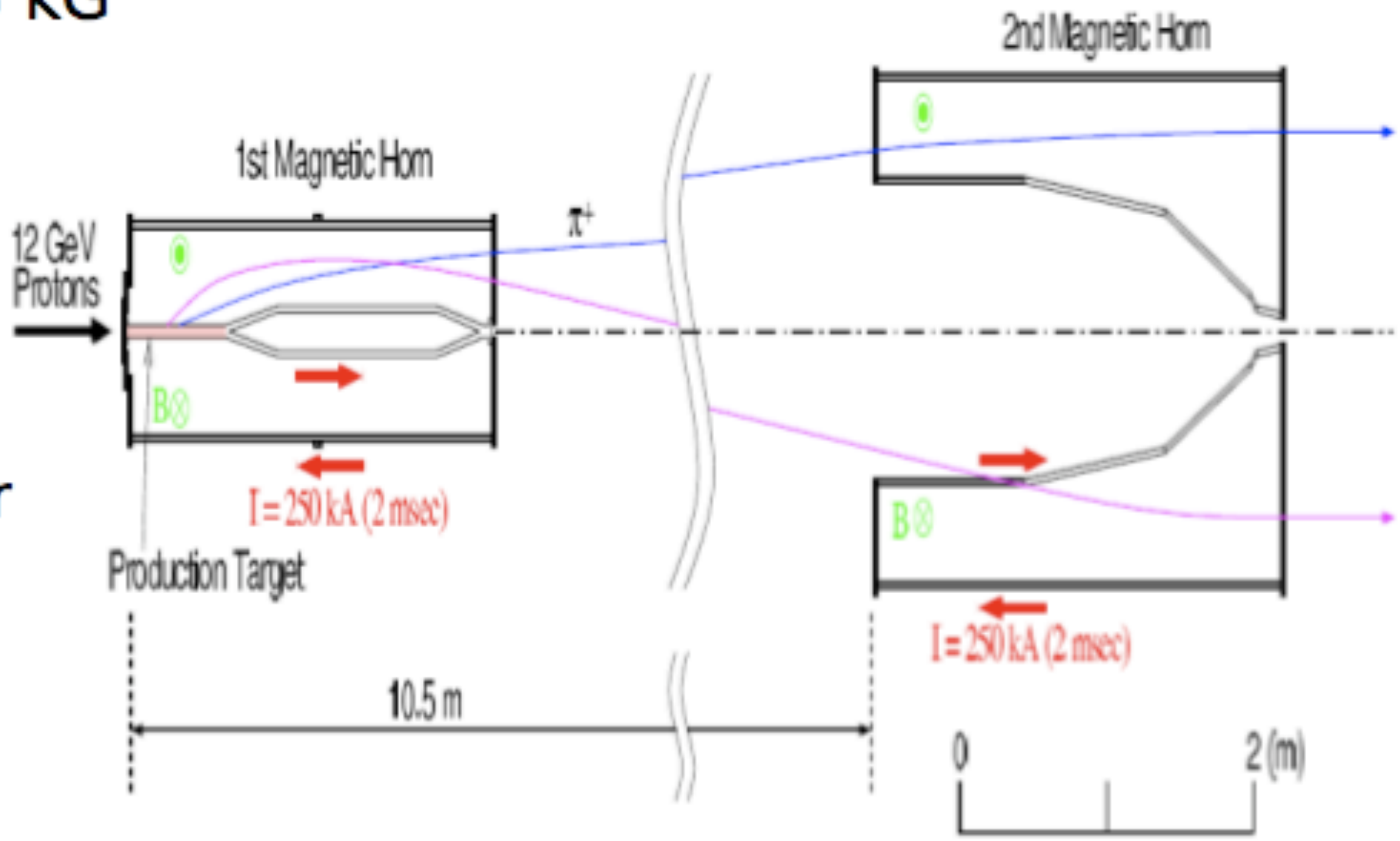

K2K Front Detector
SciFi/Water target
SciBar detector
Muon chamber
1kt
Water Cherenkov
Detector
ν beam
To Super-Kamiokand

K2K Overview


Near Detector
Decay volume
12 GeV protons
Al target and Horns

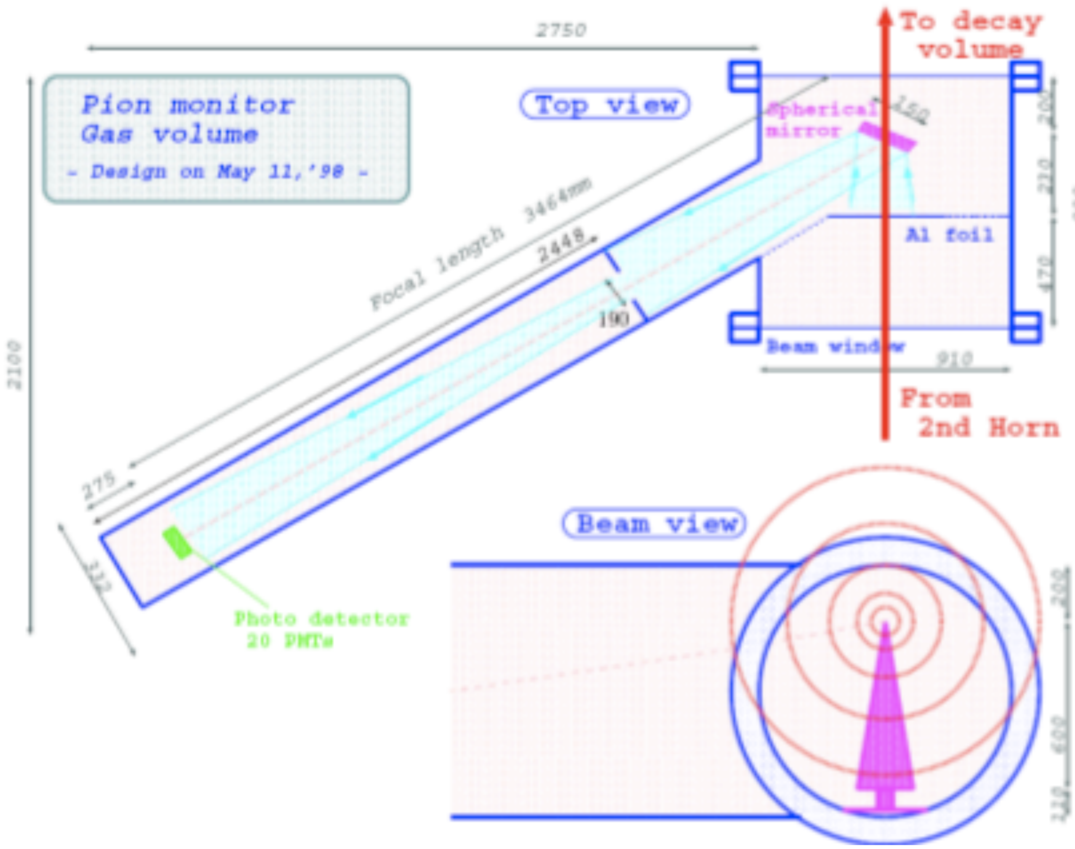
K2K target/horns

- The production target is an Al rod
- Two magnetic horns focus mainly π^+
  - π^+ momentum ~ 2-3 GeV/c → E_ν ~ 1-1.5 GeV
- Neutrino flux with horns magnets is 22 times greater than without
- Maximum magnetic field 33 kG


2nd Magnetic Horn
1st Magnetic Horn
12 GeV
Protons
π^+
B⊗
I=250 kA (2 msec)
Production Target
B⊗
I=250 kA (2 msec)
10.5 m
0
2 (m)

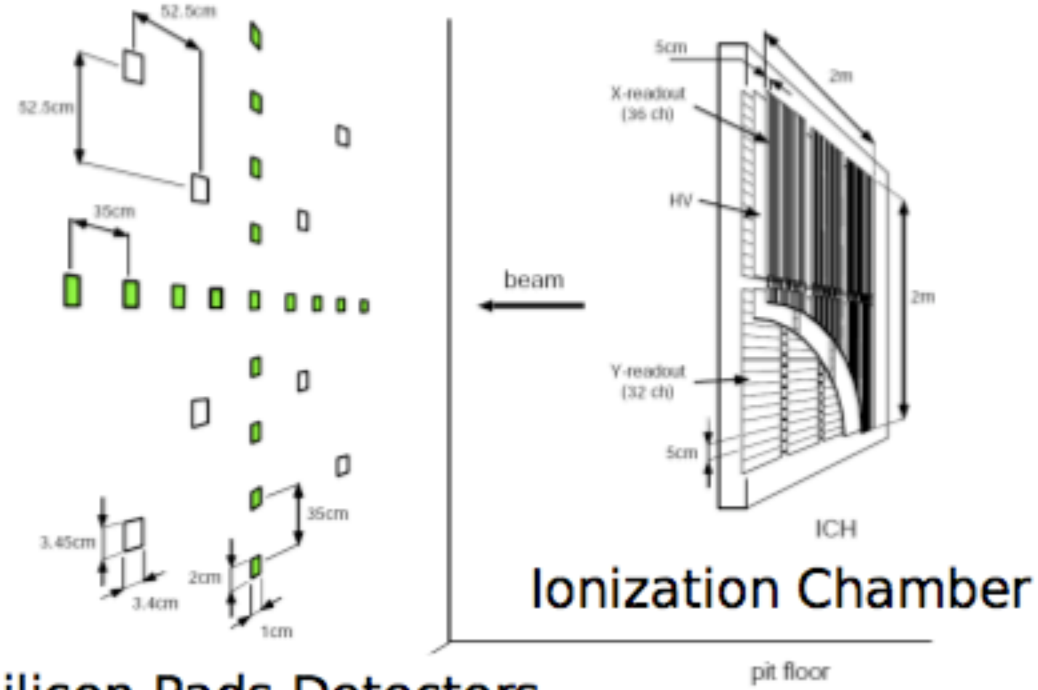
- Target:
  66 cm length, 3 cm diameter
- First horn:
  2.37 m length, 0.70 m diameter
- Second horn:
  2.76 m length, 1.65 m diameter
- Pulsed current:
  2 msec duration and 250 kA amplitude

K2K Beam Monitoring


2750
Pion monitor
Gas volume
- Design on May 11,'98 -
Top view
To decay
volume
Spherical
mirror
150
Focal length 3464mm
2448
190
Al foil
200
220
470
900
Beam window
910
From
2nd Horn
2100
275
232
Photo detector
20 PMTs
Beam view
200
600
110
910

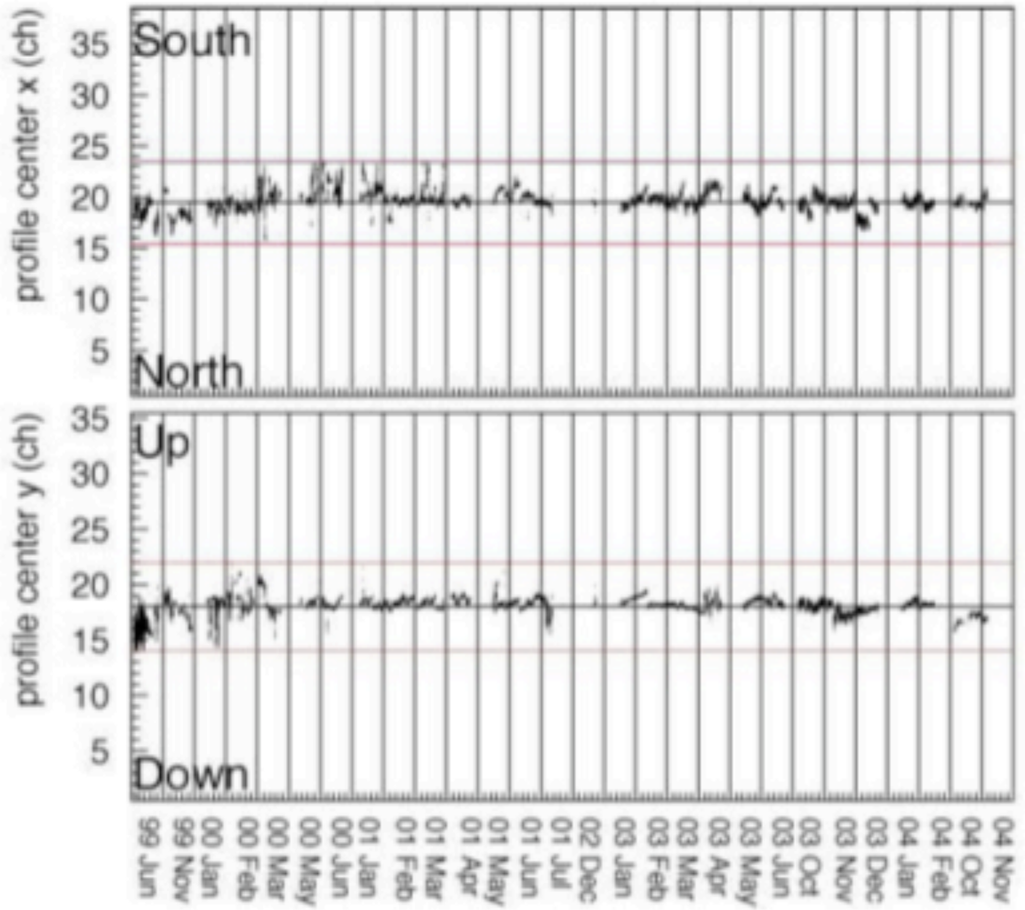
PIMON measured pion momentum spectrum

MUMON measured beam center position (pointing to SK)

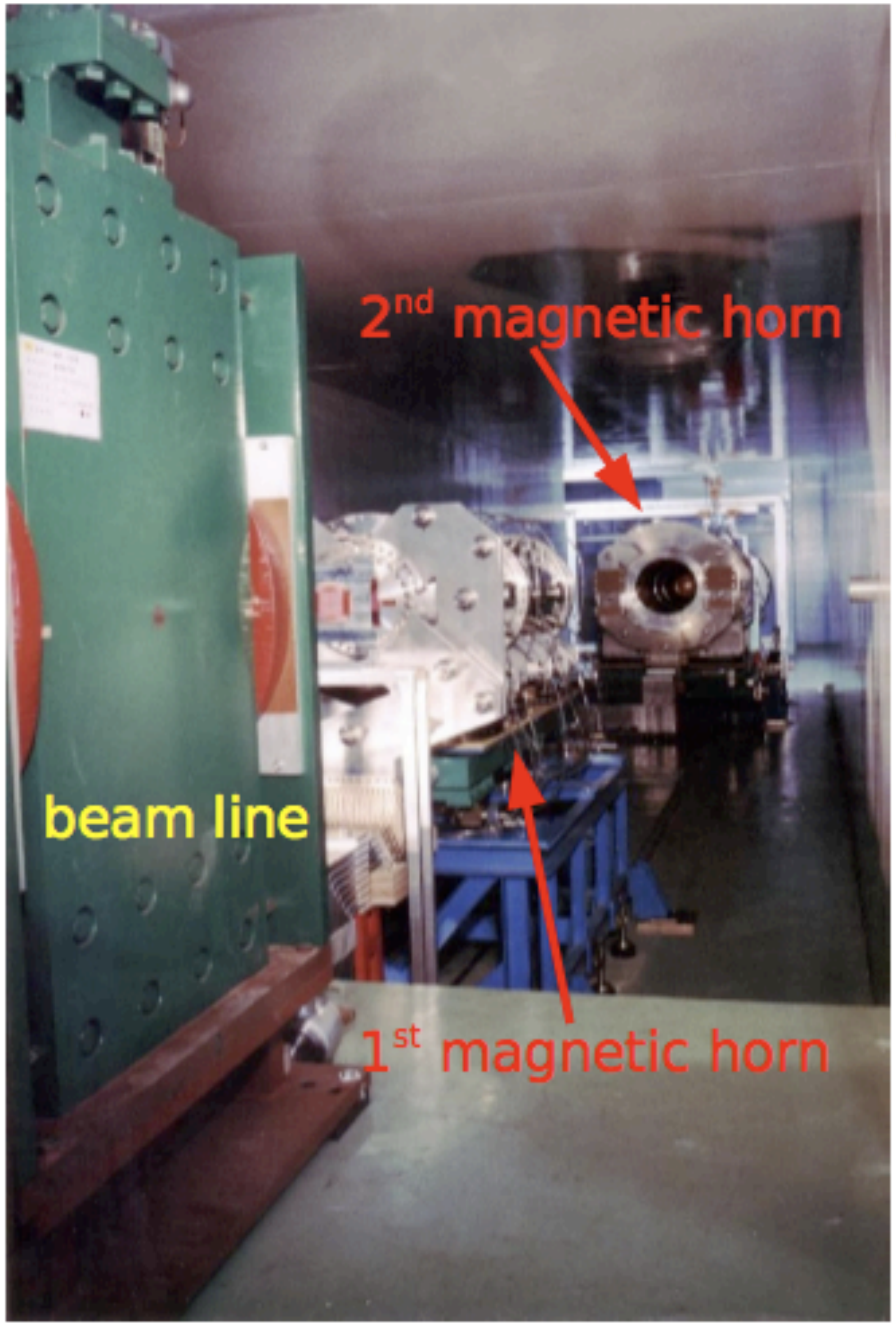

52.5cm
52.5cm
35cm
3.45cm
3.4cm
2cm
1cm
35cm
beam
5cm
X-readout
(36 ch)
HV
Y-readout
(32 ch)
5cm
2m
2m
ICH
pit floor

Ionization Chamber

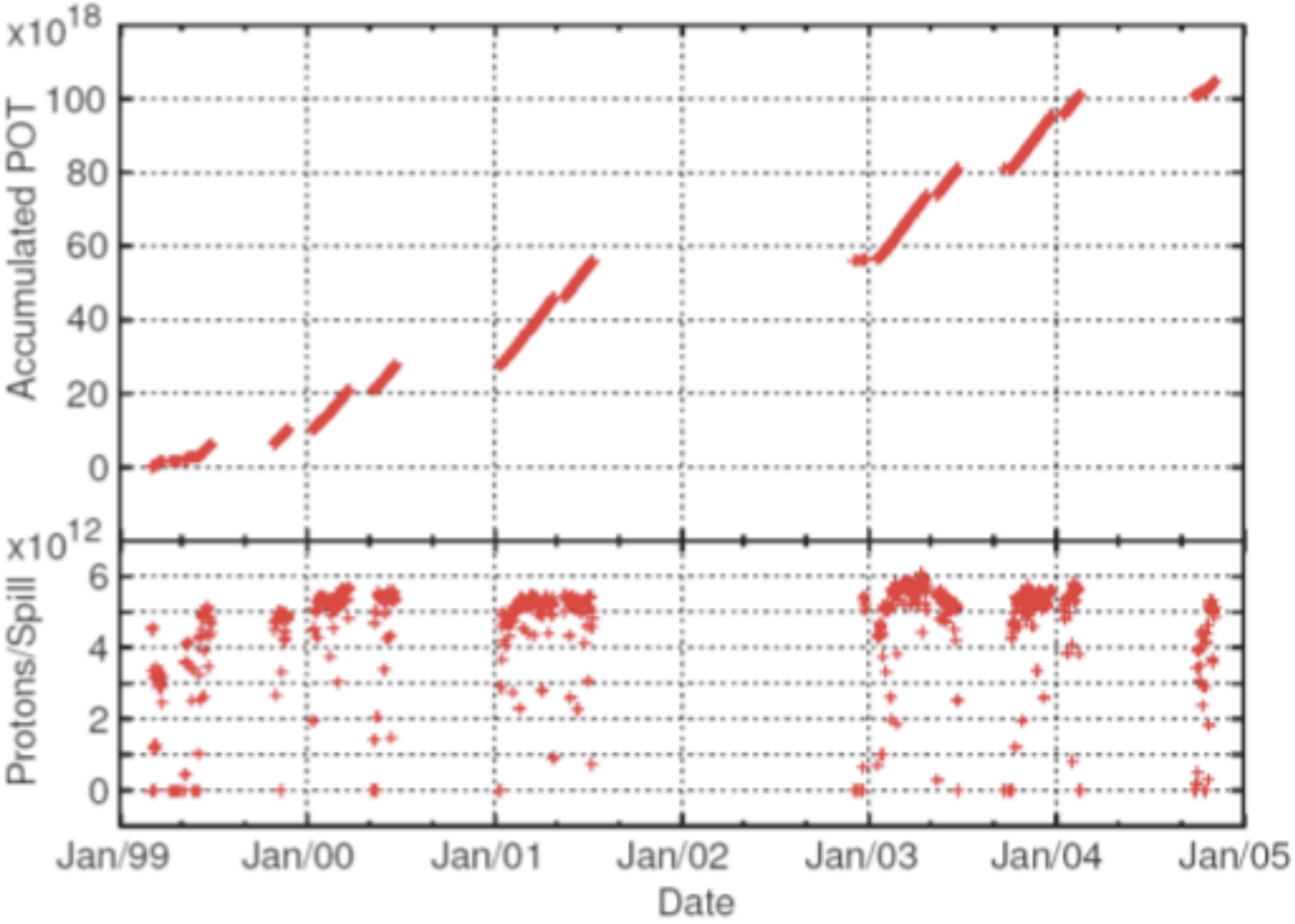
Silicon Pads Detectors

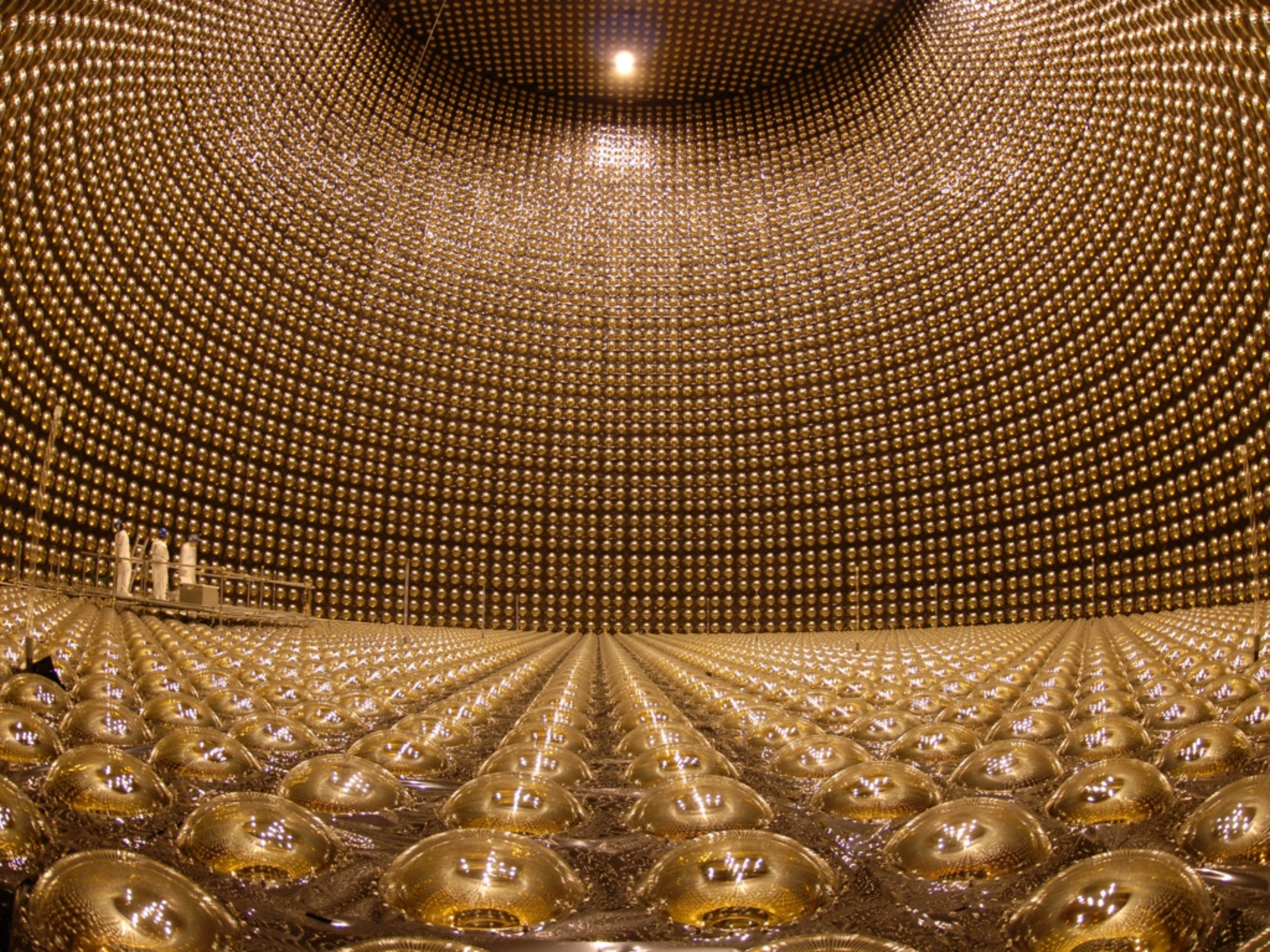


K2K Performance

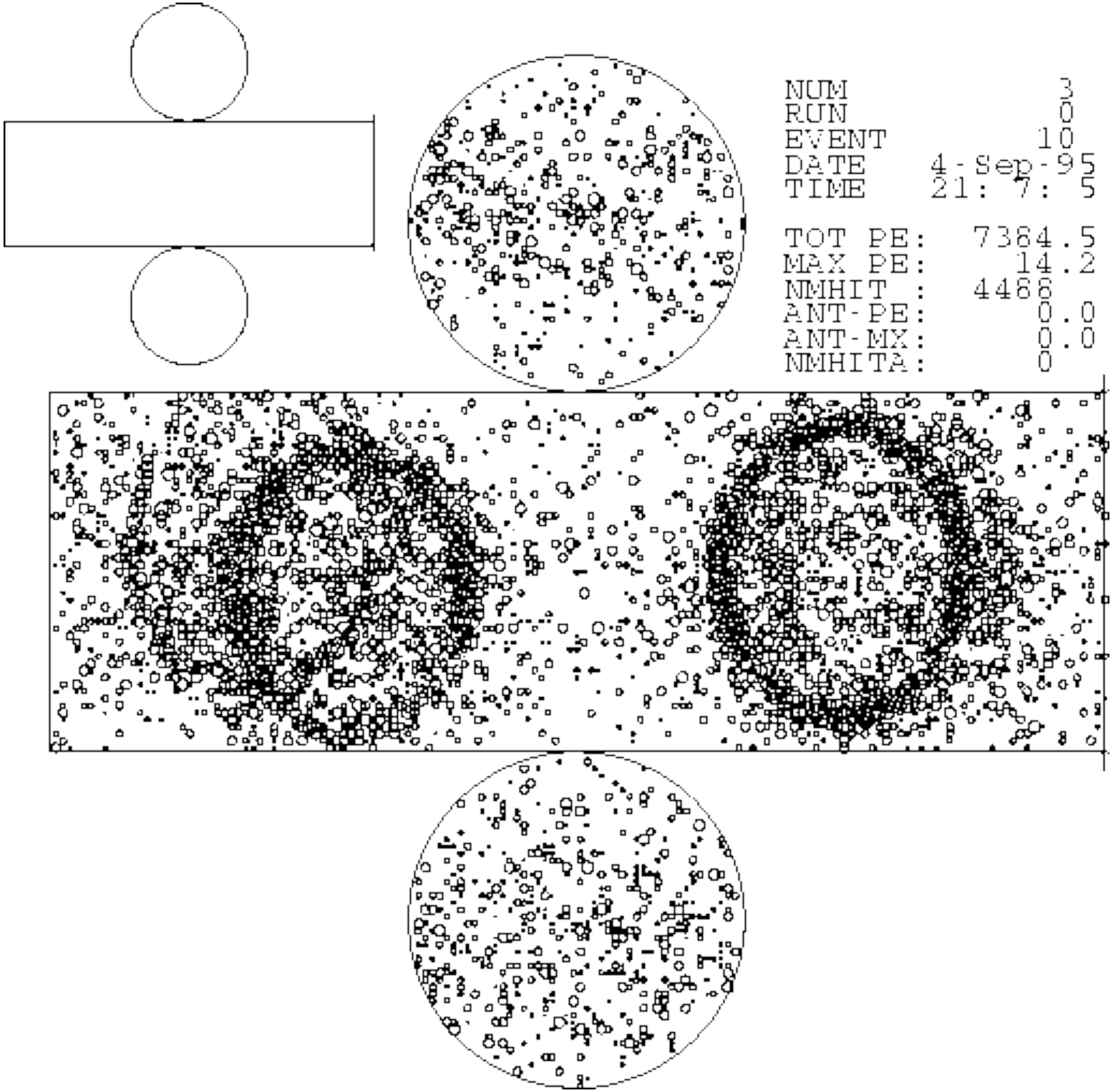

2nd magnetic horn
beam line
1st magnetic horn

10^{20} POT were delivered to the production target





Super-K Event

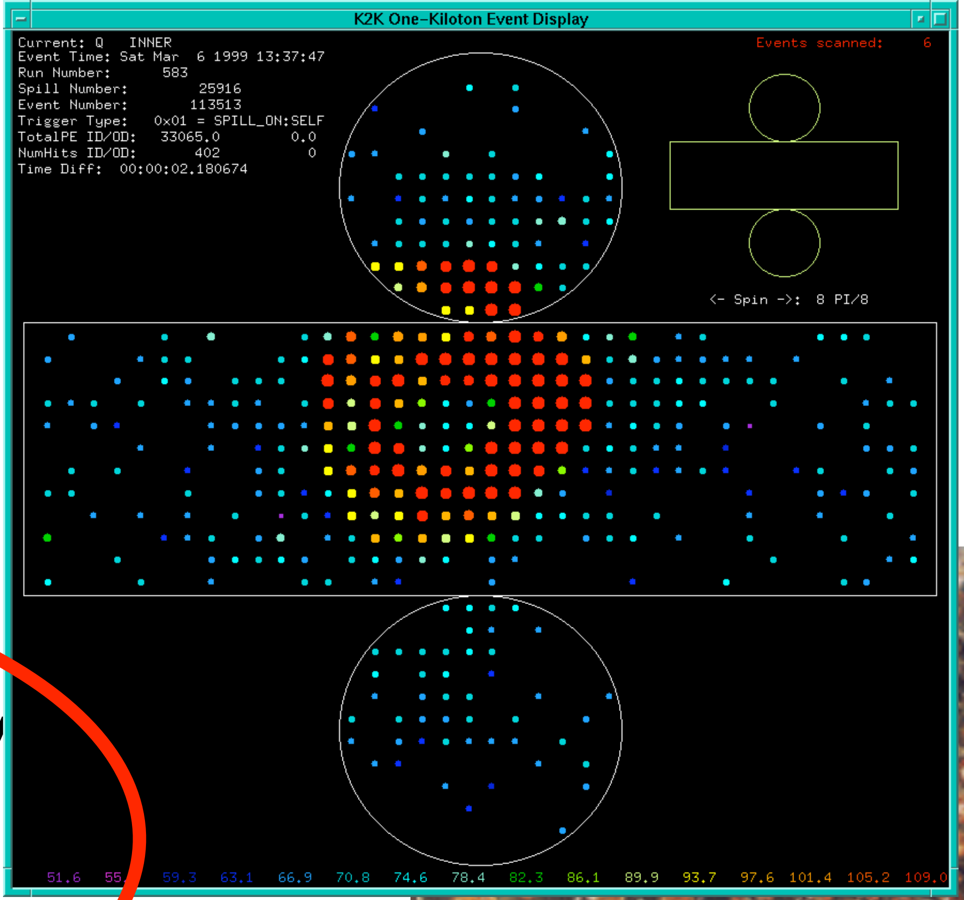


```
NUM            3
RUN            0
EVENT         10
DATE    4-Sep-95
TIME    21: 7: 5

TOT PE:   7384.5
MAX PE:     14.2
NMHIT :   4488
ANT-PE:      0.0
ANT-MX:      0.0
NMHITA:      0
```

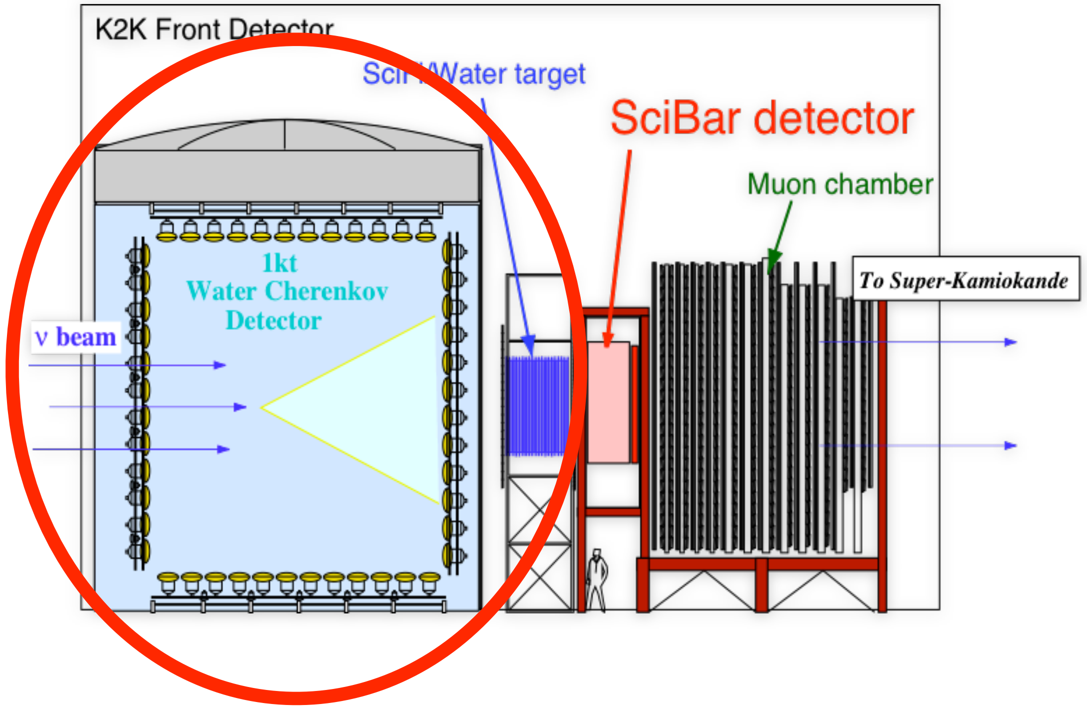
K2K: 1kT

- 1 kt Water Cherenkov
  - Oxygen target
  - 0.64e20 POT
- SciFi
  - Oxygen target
  - 0.64e20 POT
- SciBar
  - Carbon target
  - Only 0.2e20 POT total!

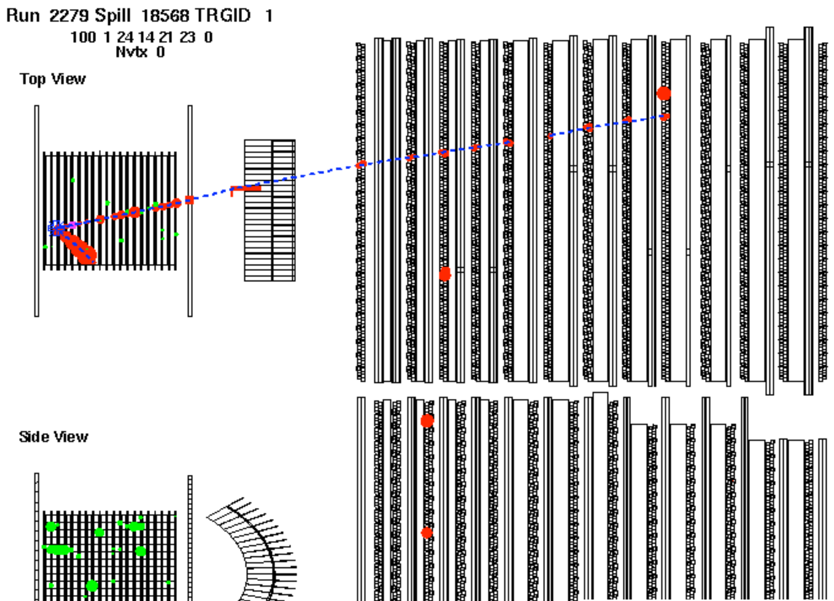

K2K One-Kiloton Event Display

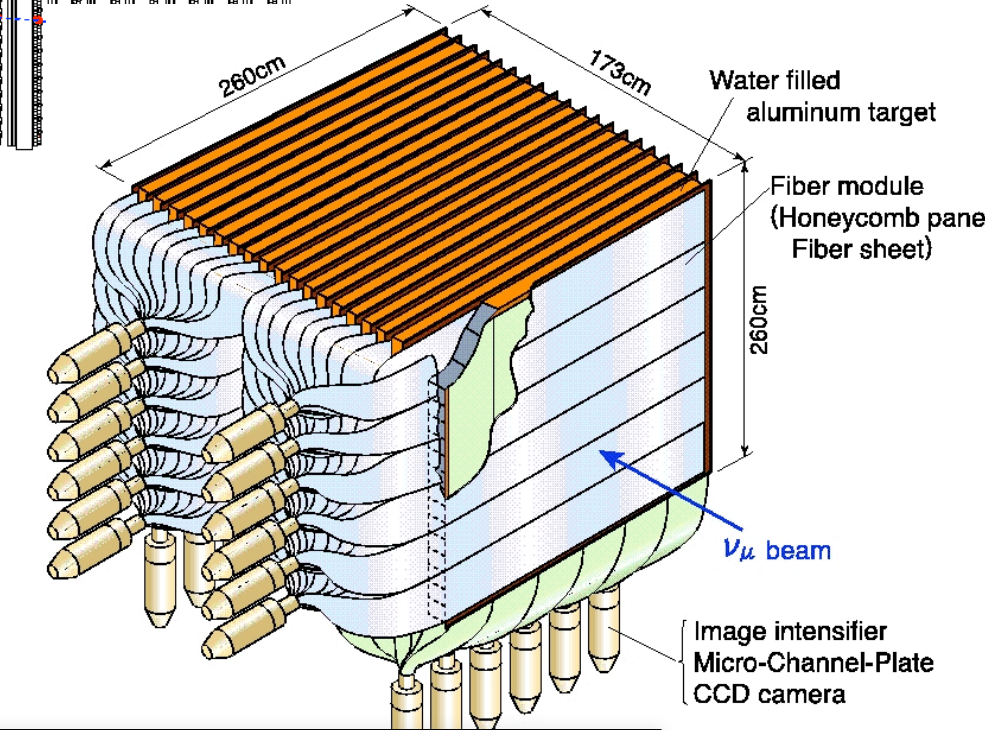
```
Current: Q   INNER
Event Time: Sat Mar  6 1999 13:37:47
Run Number:       583
Spill Number:          25916
Event Number:         113513
Trigger Type:   0x01 = SPILL_ON:SELF
TotalPE ID/OD:   33065.0         0.0
NumHits ID/OD:       402           0
Time Diff:  00:00:02.180674
```

Events scanned: 6
<- Spin ->: 8 PI/8
51.6
55.
59.3
63.1
66.9
70.8
74.6
78.4
82.3
86.1
89.9
93.7
97.6
101.4
105.2
109.0

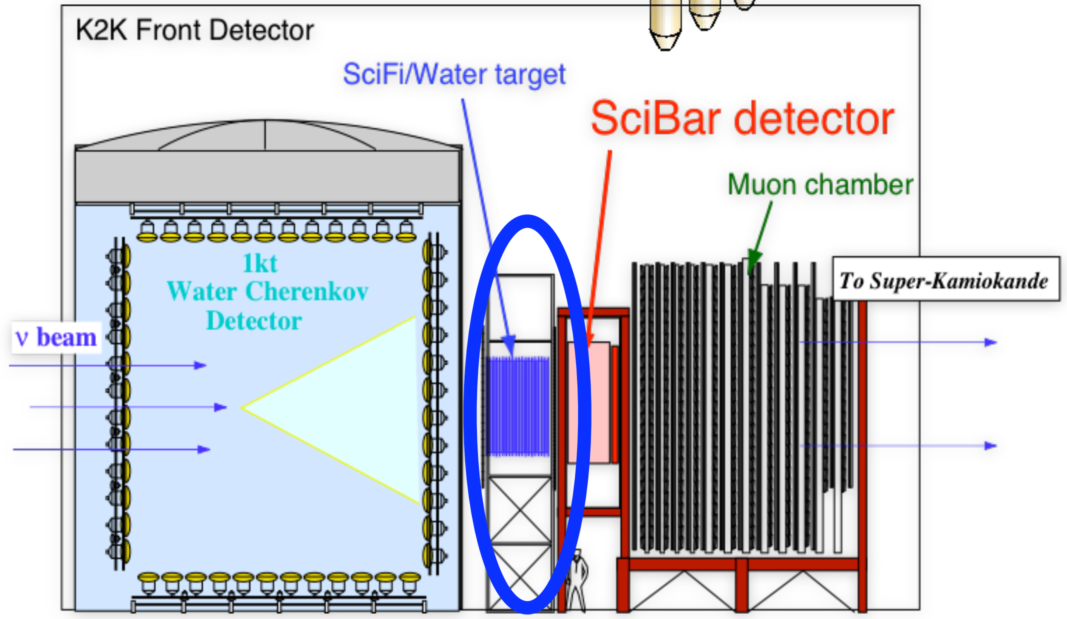

K2K Front Detector
SciFi/Water target
SciBar detector
Muon chamber
To Super-Kamiokande
1kt
Water Cherenkov
Detector
ν beam

K2K: SciFi

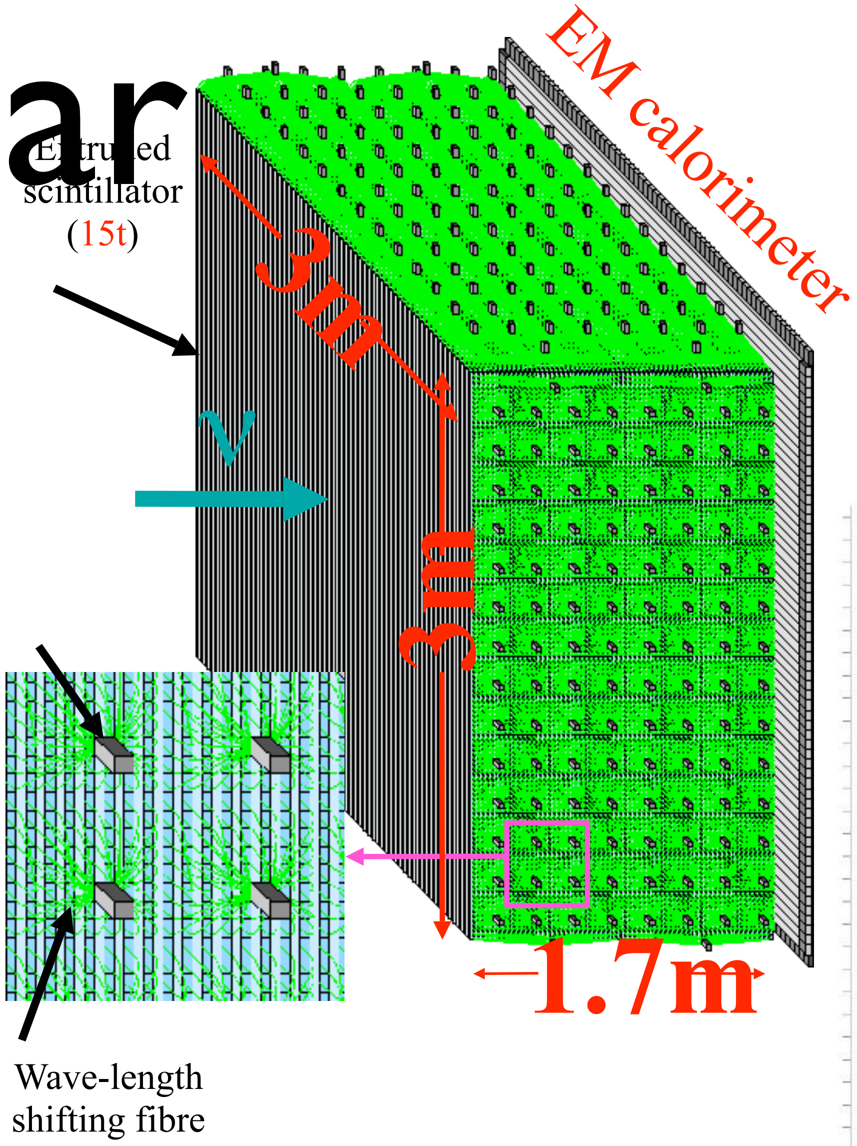

Run 2279 Spill 18568 TRGID 1
100 1 24 14 21 23 0
Nvtx 0
Top View
Side View


260cm
173cm
Water filled aluminum target
Fiber module (Honeycomb pane
Fiber sheet)
260cm
ν_μ beam
Image intensifier
Micro-Channel-Plate
CCD camera

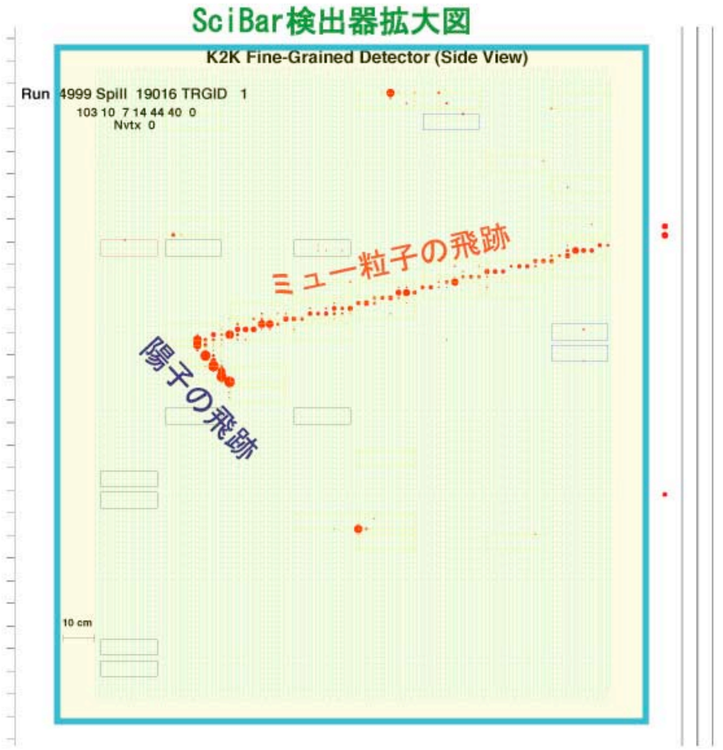
- 1 kt Water Cherenkov
  - Oxygen target
  - 0.64e20 POT
- SciFi
  - Oxygen target
  - 0.64e20 POT
- SciBar
  - Carbon target
  - Only 0.2e20 POT total!

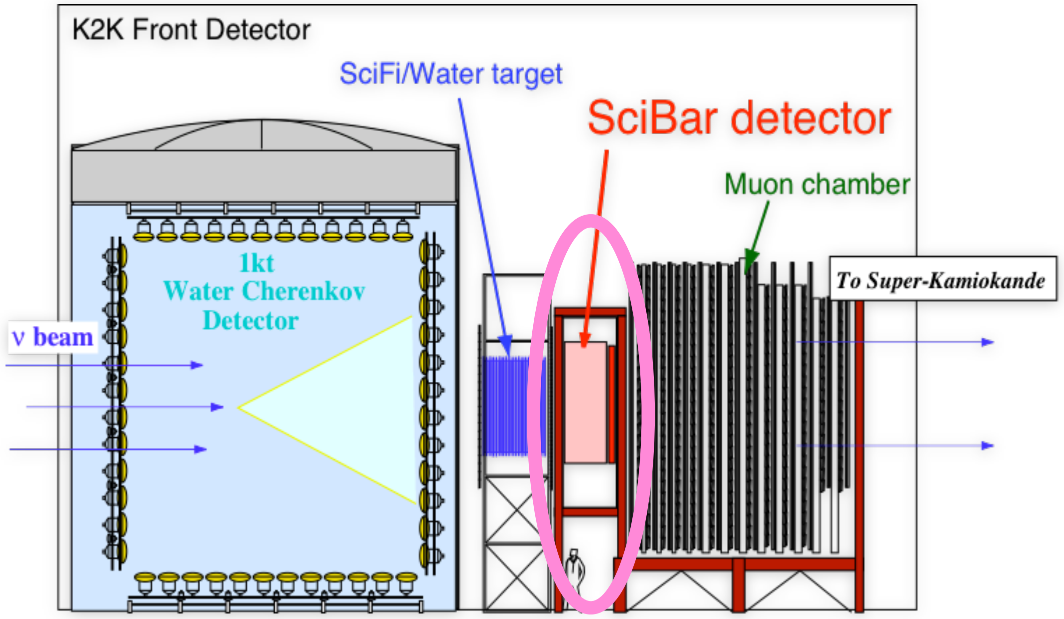

K2K Front Detector
SciFi/Water target
SciBar detector
Muon chamber
To Super-Kamiokande
1kt Water Cherenkov Detector
ν beam

K2K: SciBar


Extruded
scintillator
(15t)
EM calorimeter
3m
ν
3m
1.7m
Wave-length
shifting fibre

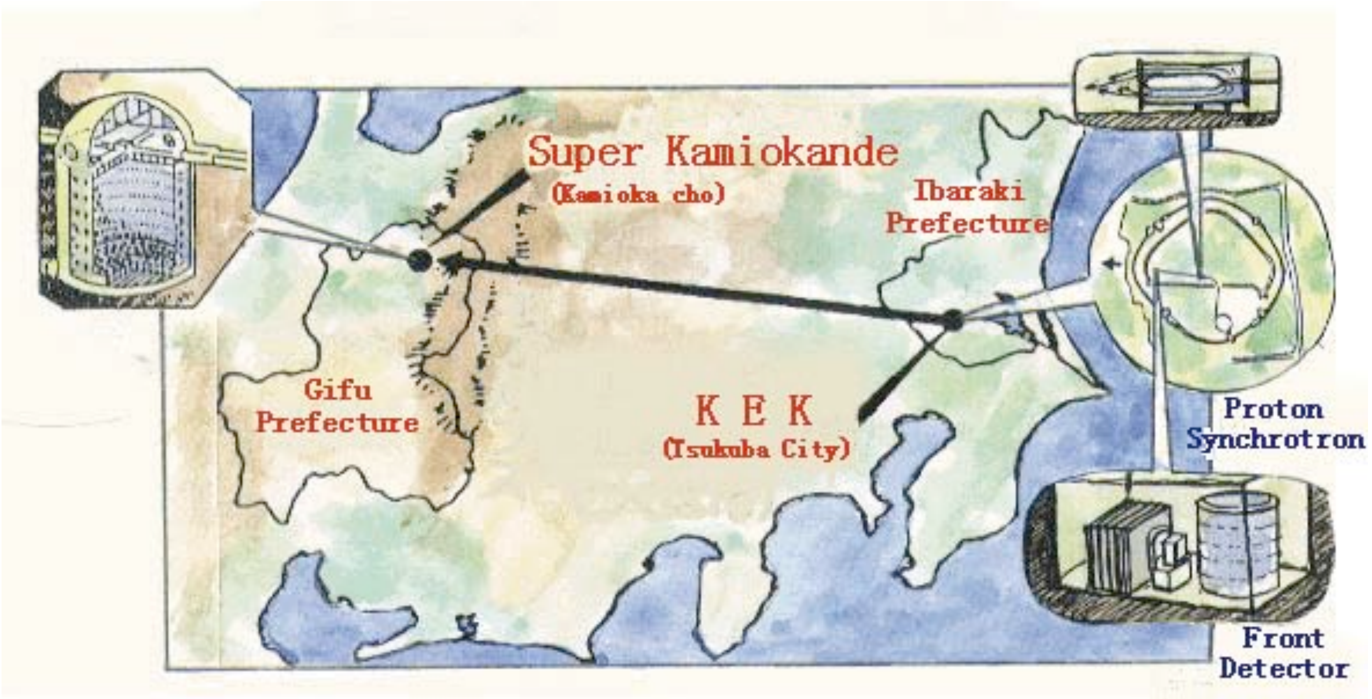
- 1 kt Water Cherenkov
  - Oxygen target
  - 0.64e20 POT
- SciFi
  - Oxygen target
  - 0.64e20 POT
- SciBar
  - Carbon target
  - Only 0.2e20 POT total!




K2K Front Detector
SciFi/Water target
SciBar detector
Muon chamber
To Super-Kamiokande
ν beam
1kt
Water Cherenkov
Detector

K2K Measurements

- CCQE
  - SciFi
  - SciBar
- CC1pi+
  - SciBar
- NCpi0
  - 1 kton


Super Kamiokande
(Kamioka cho)
Ibaraki
Prefecture
Gifu
Prefecture
K E K
(Tsukuba City)
Proton
Synchrotron
Front
Detector

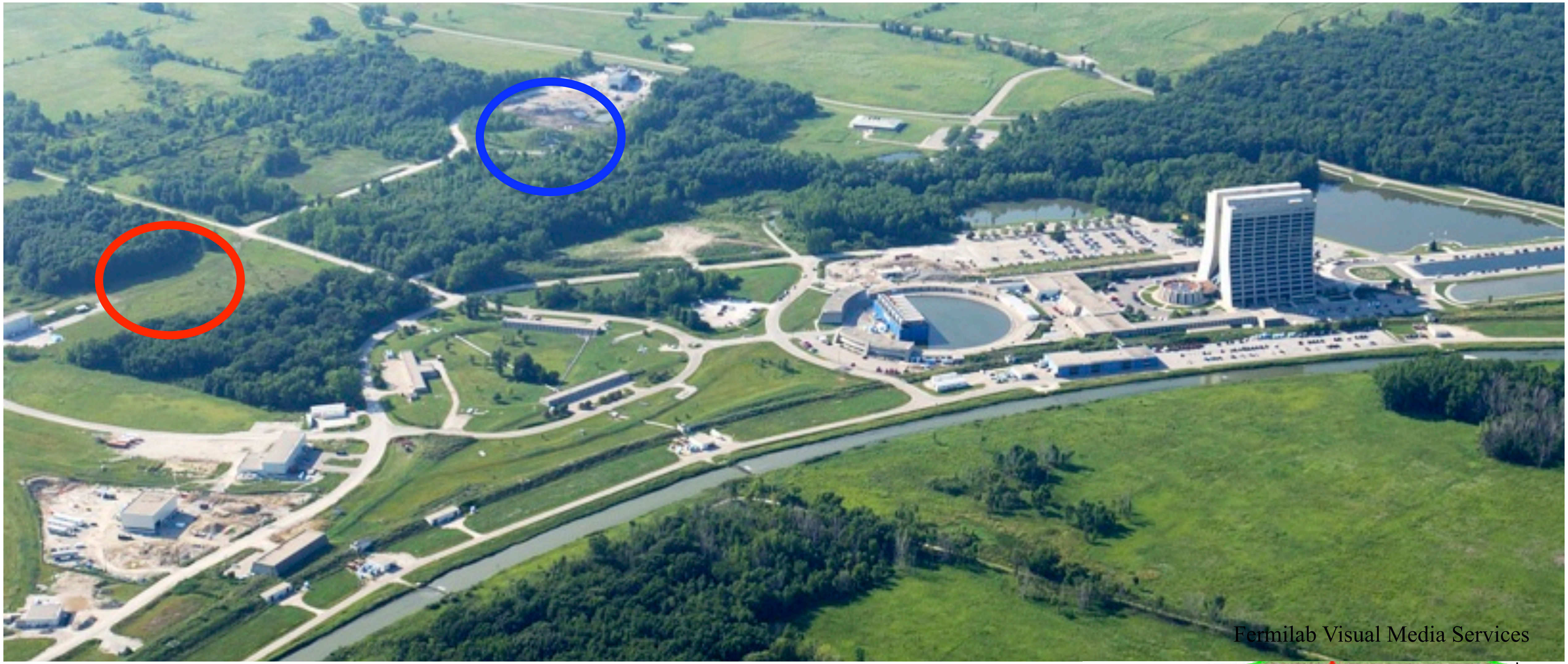
Booster Neutrino Experiments

- Booster Neutrino Beam at Fermilab
- MiniBooNE
  - proposed 1998
  - started 2002
  - still running
- SciBooNE
  - proposed 2005
  - started 2007
  - finished 2008

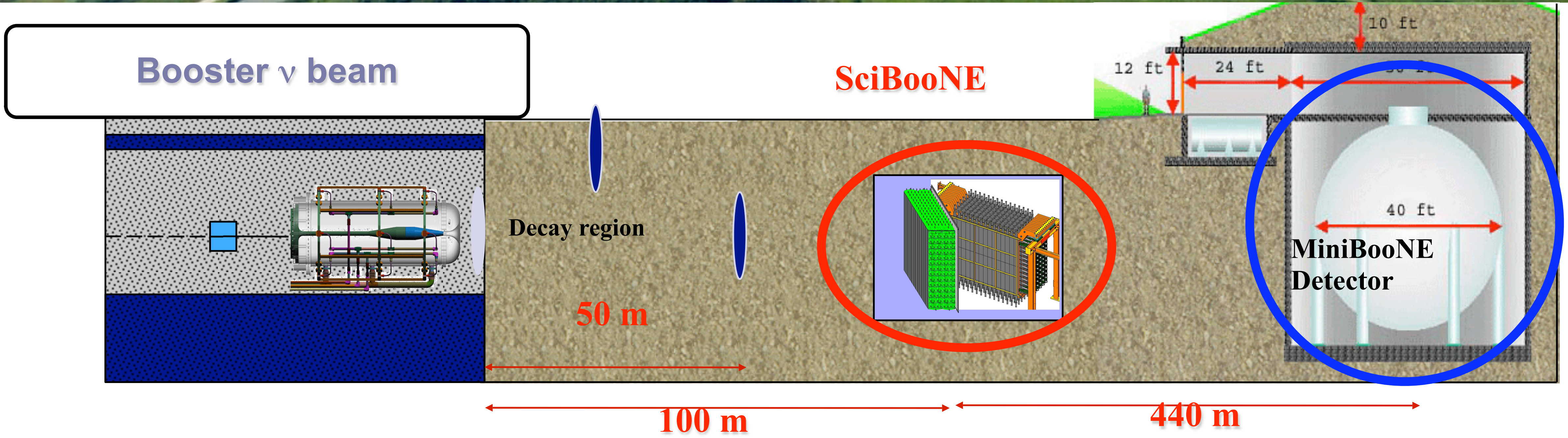
MiniBooNE, 2002

SciBooNE, 2008

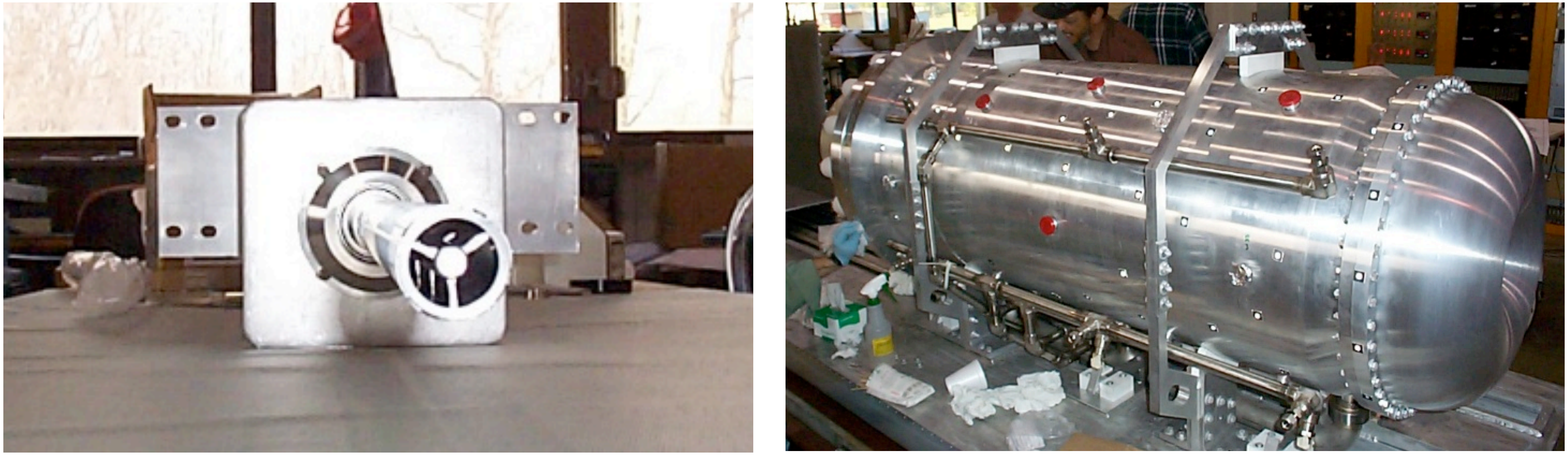
BooNEs Overview



Fermilab Visual Media Services

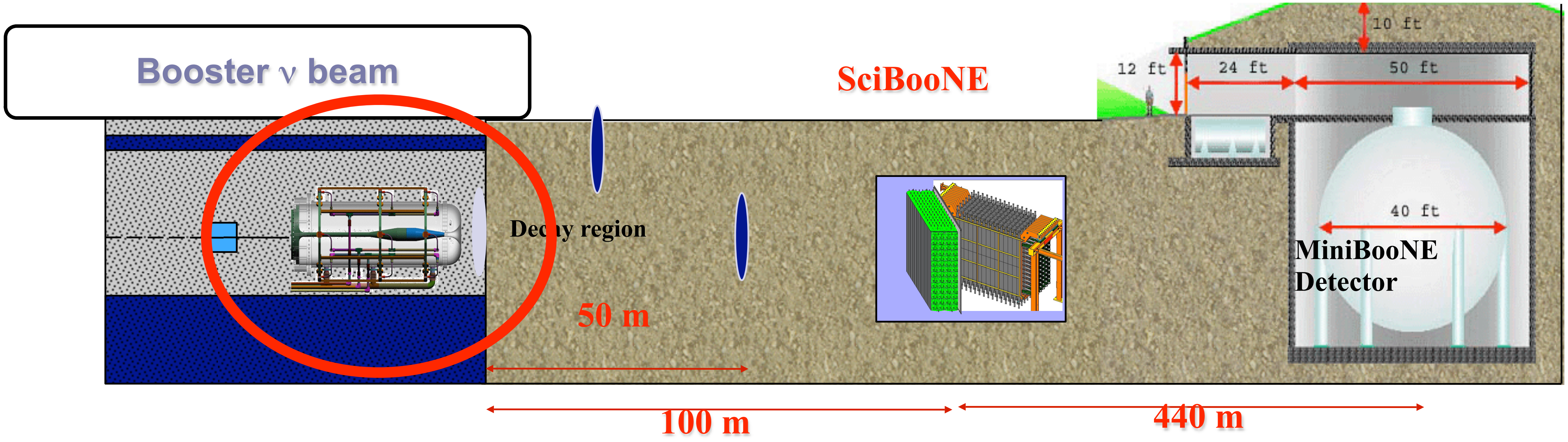

Booster ν beam
SciBooNE
10 ft
12 ft
24 ft
40 ft
Decay region
50 m
MiniBooNE
Detector
100 m
440 m

Target & Horn

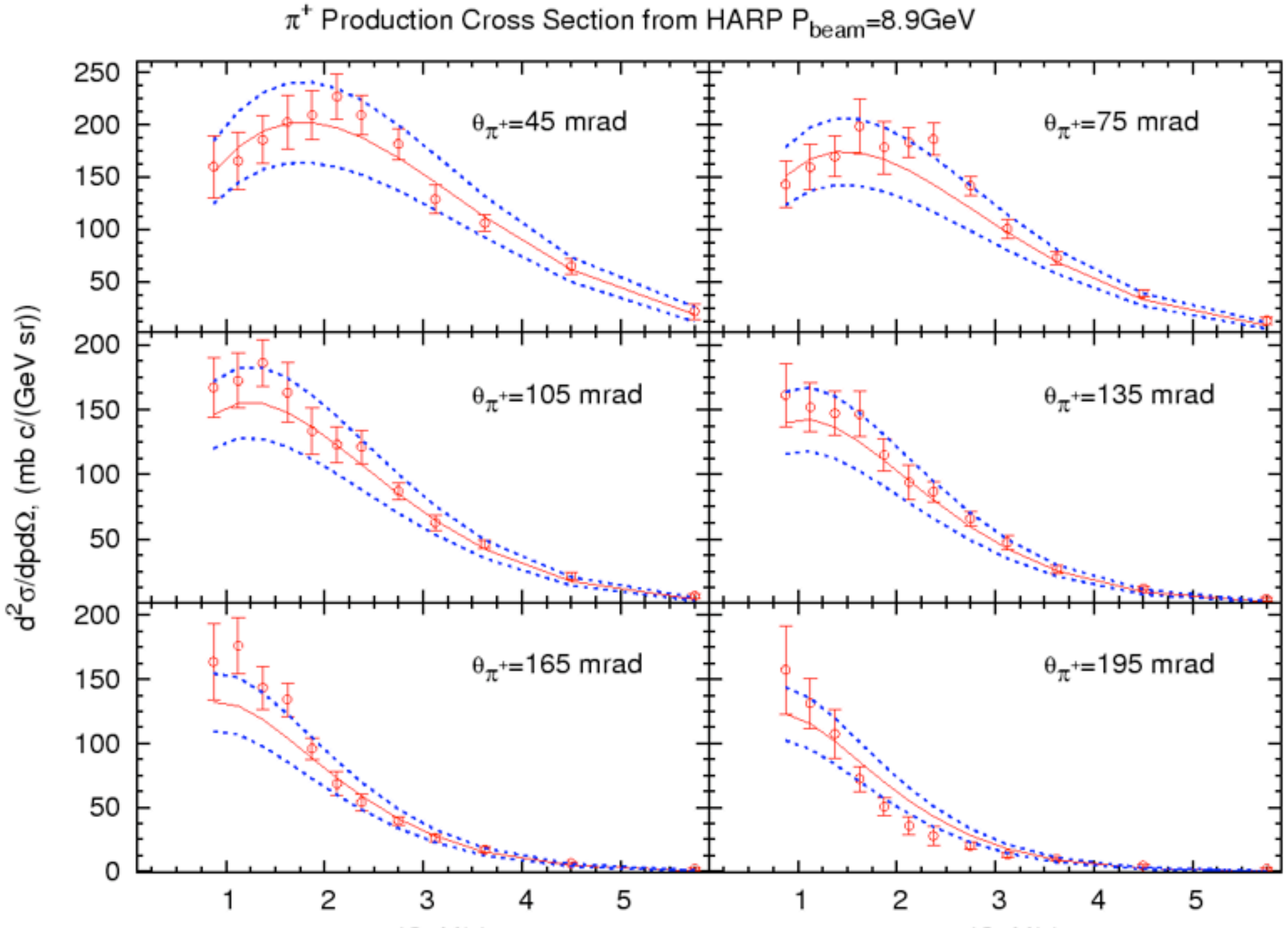


Main components of Booster Neutrino Beam (BNB)

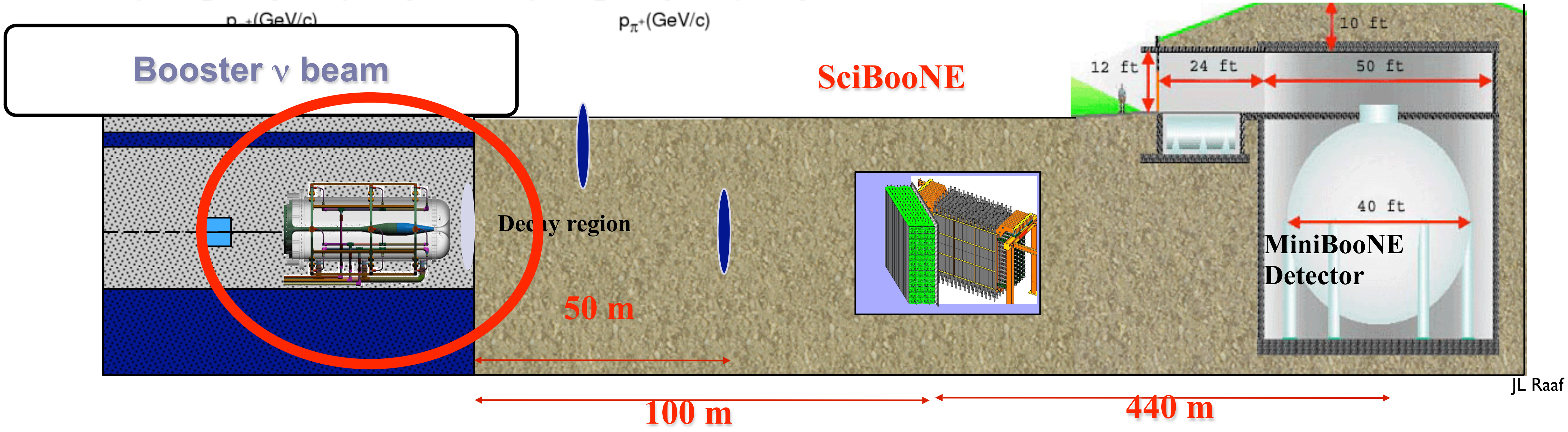
(96M and 200M+ pulses)


Booster ν beam
SciBooNE
Decay region
50 m
100 m
440 m
10 ft
12 ft
24 ft
50 ft
40 ft
MiniBooNE
Detector

Meson Production



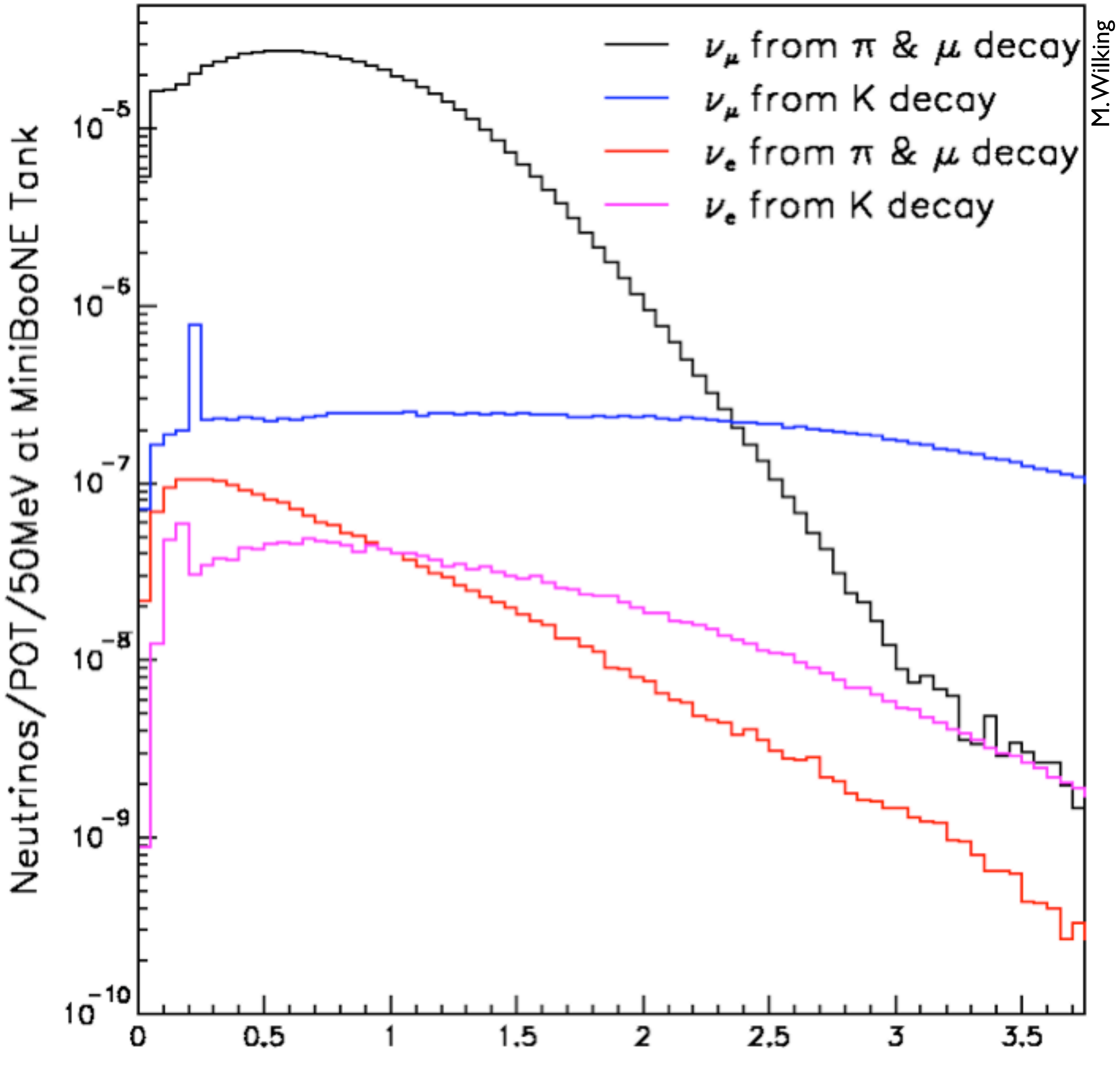
- External meson production data
  - HARP data (CERN)
- Parametrisation of cross-sections
  - Sanford-Wang for pions
  - Feynman scaling for kaons


Booster ν beam
Decay region
50 m
SciBooNE
100 m
440 m
10 ft
12 ft
24 ft
50 ft
40 ft
MiniBooNE Detector

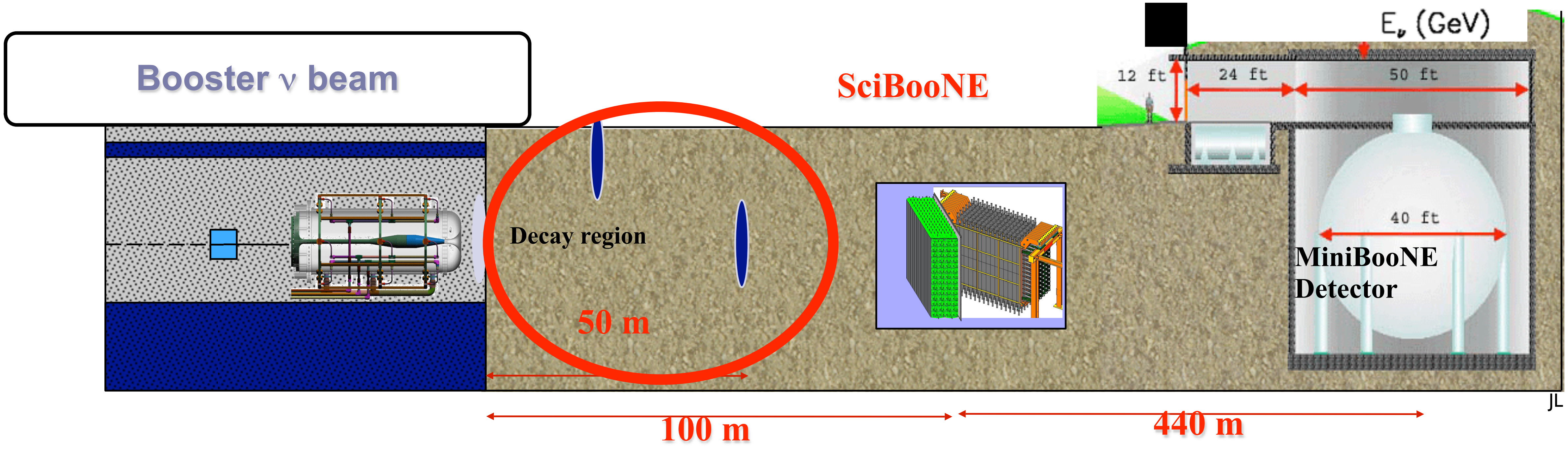
JL Raaf

ν Flux

- 99.5% pure muon flavour
- 0.5% intrinsic ν_e
- Constrain ν_e content with ν_μ measurements

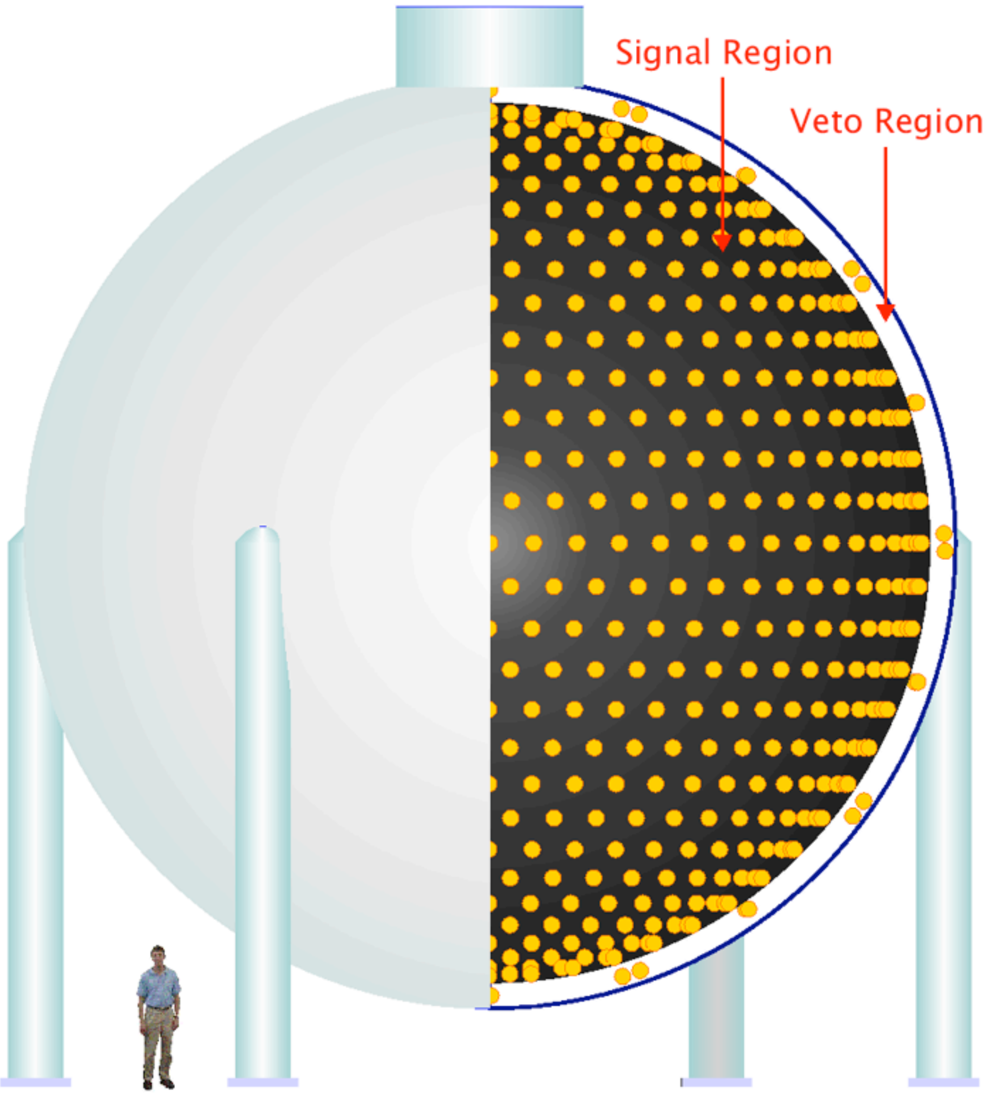


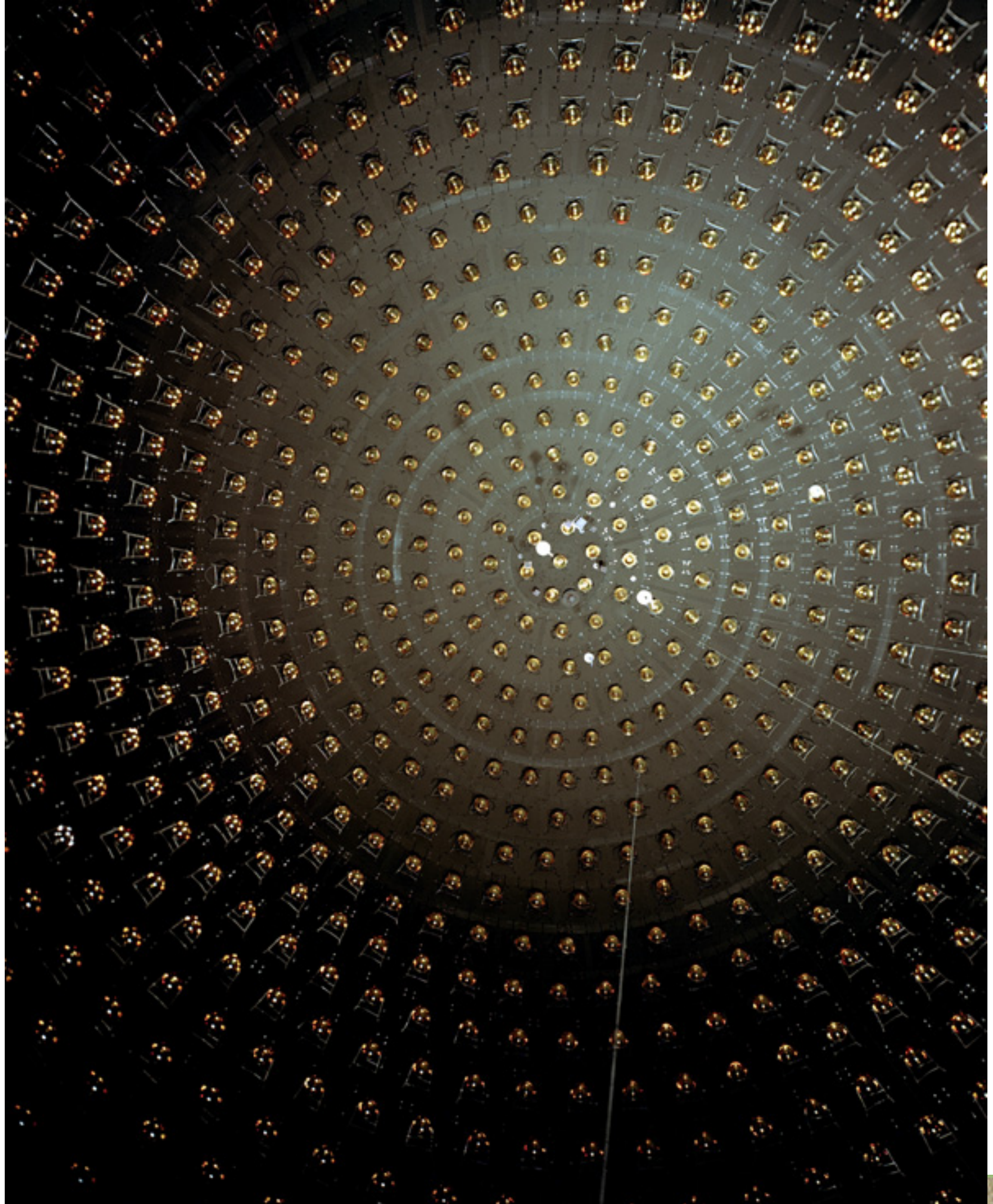
M.Wilking

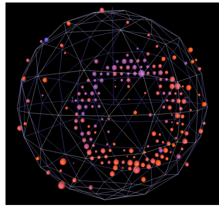

Booster ν beam
SciBooNE
12 ft
24 ft
50 ft
Decay region
50 m
40 ft
MiniBooNE Detector
100 m
440 m

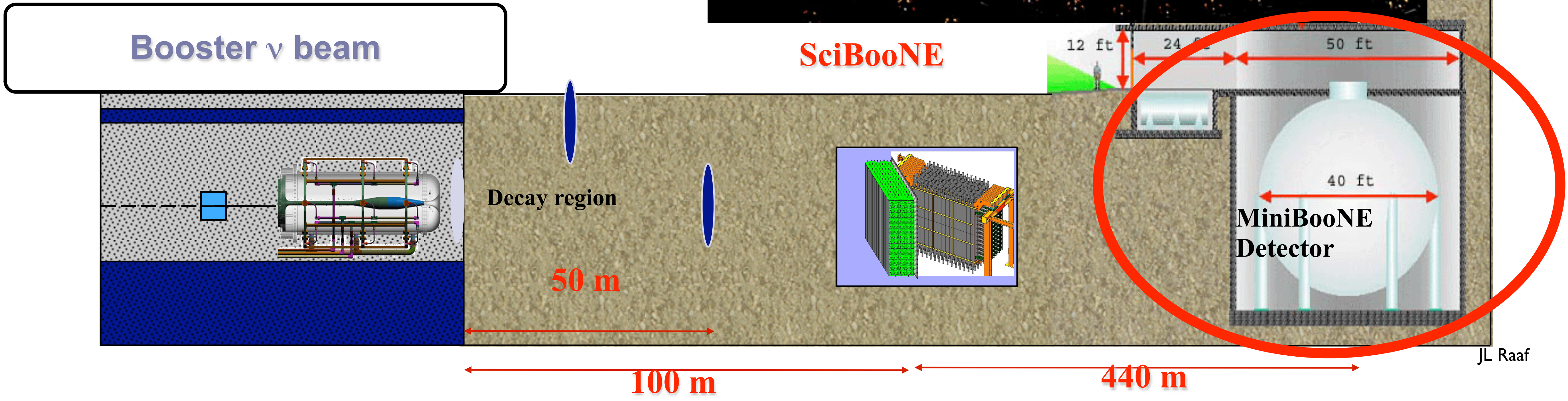
JL Raaf

MiniBooNE


Signal Region
Veto Region

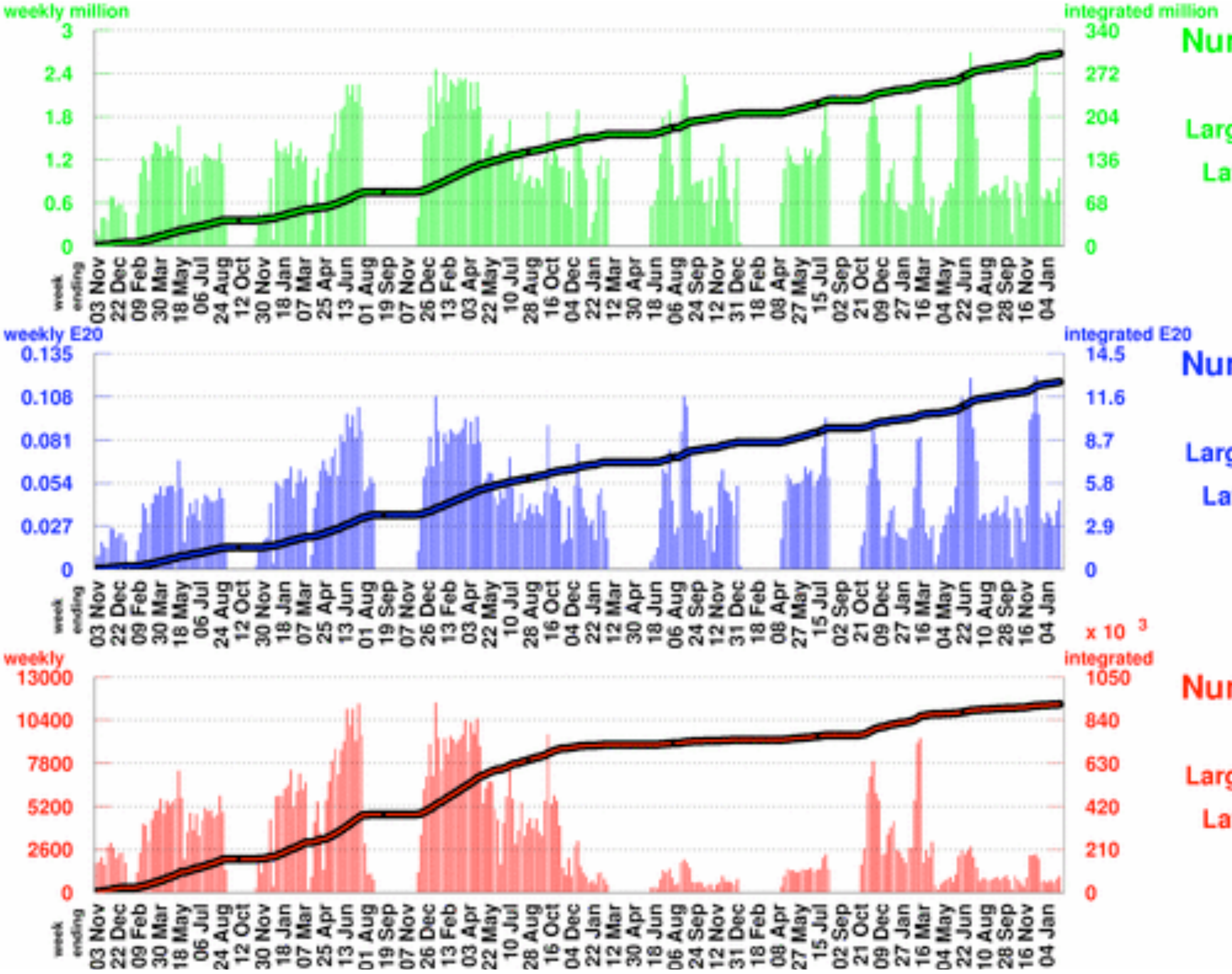





Booster ν beam
SciBooNE
12 ft
24 ft
50 ft
40 ft
MiniBooNE Detector
Decay region
50 m
100 m
440 m

JL Raaf

MiniBooNE Progress



Number of Horn Pulses

To date: 303.18 million

Largest week: 2.69 million

Latest week: 0.95 million

Number of Protons on Target

To date:12.6114 E20

Largest week: 0.1208 E20

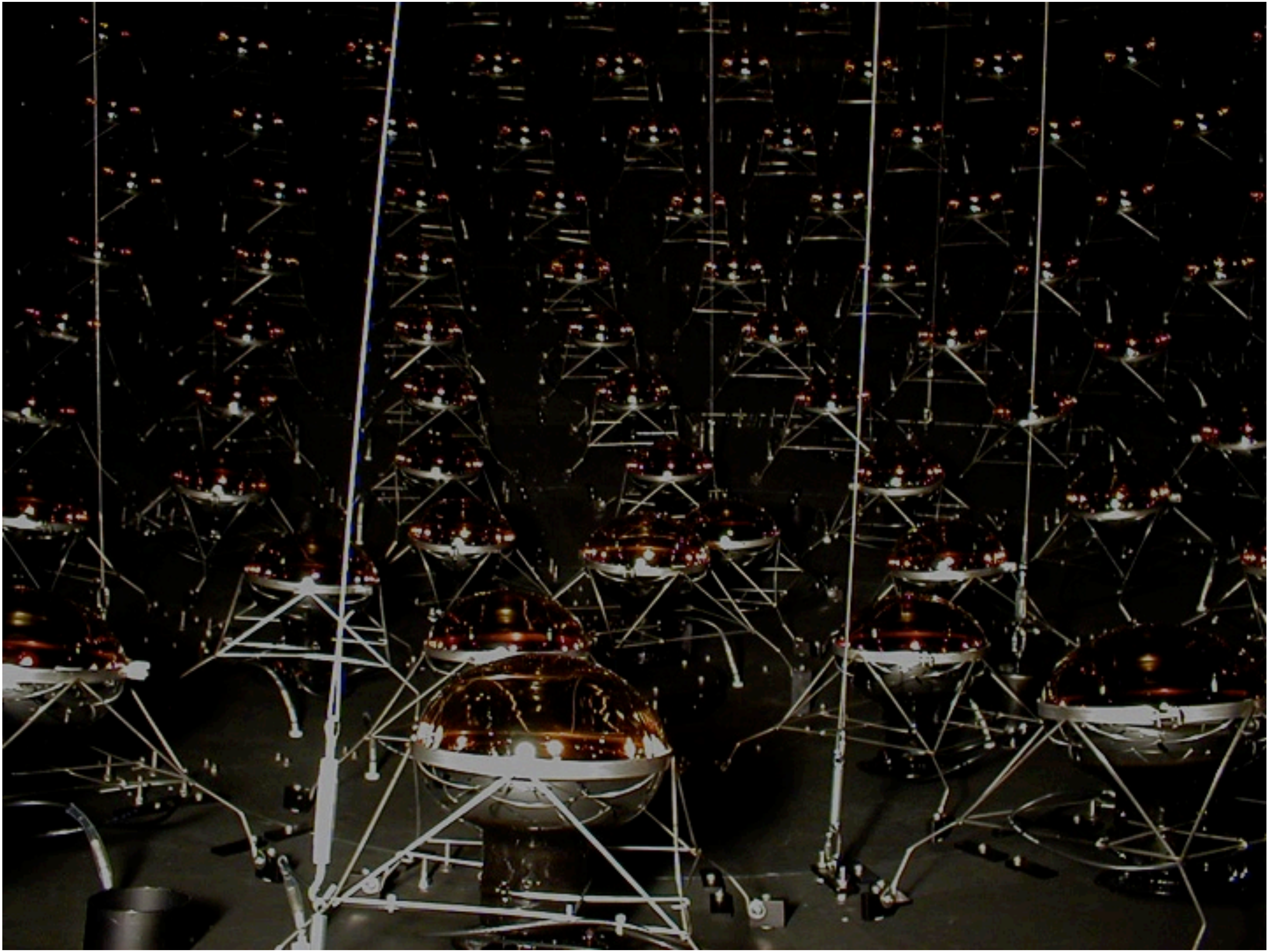
Latest week: 0.0435 E20

Number of Neutrino Events

To date:916559

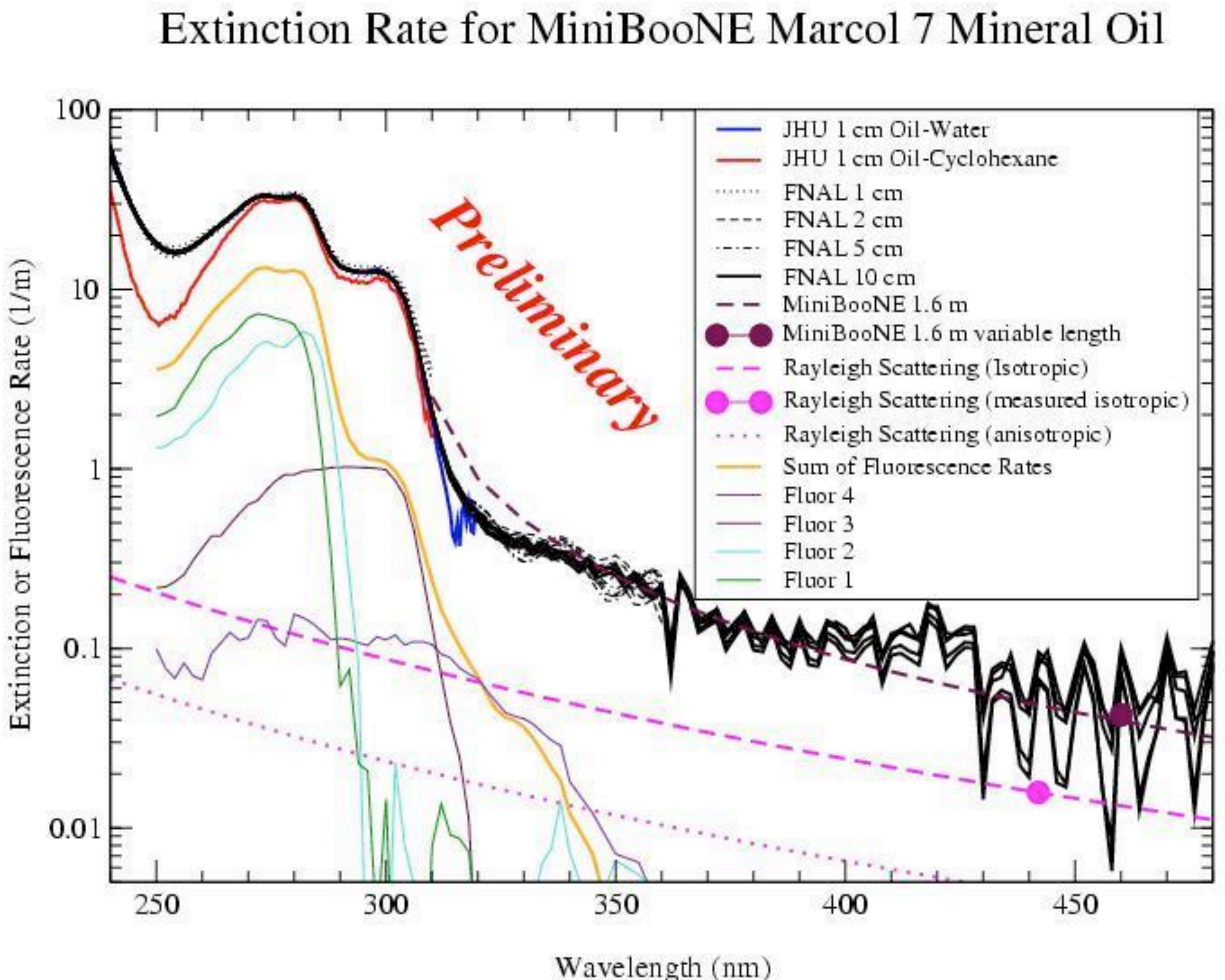
Largest week: 11447

Latest week: 976

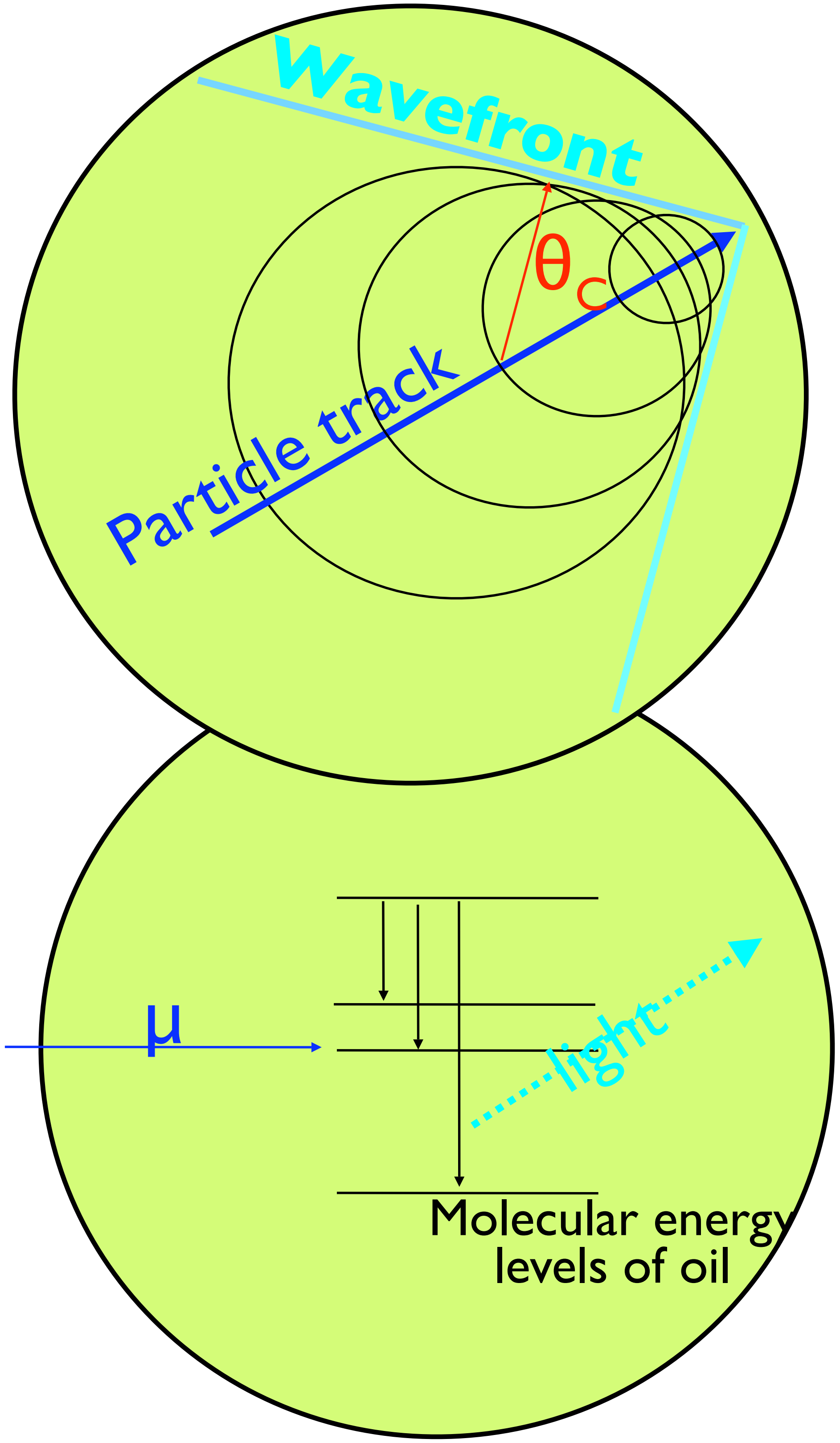


Mineral Oil Optics

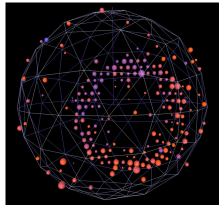
- Production:
  - Cherenkov and scintillation
- Secondary:
  - Fluorescence and scattering (Raman, Rayleigh)



Extinction Rate for MiniBooNE Marcol 7 Mineral Oil

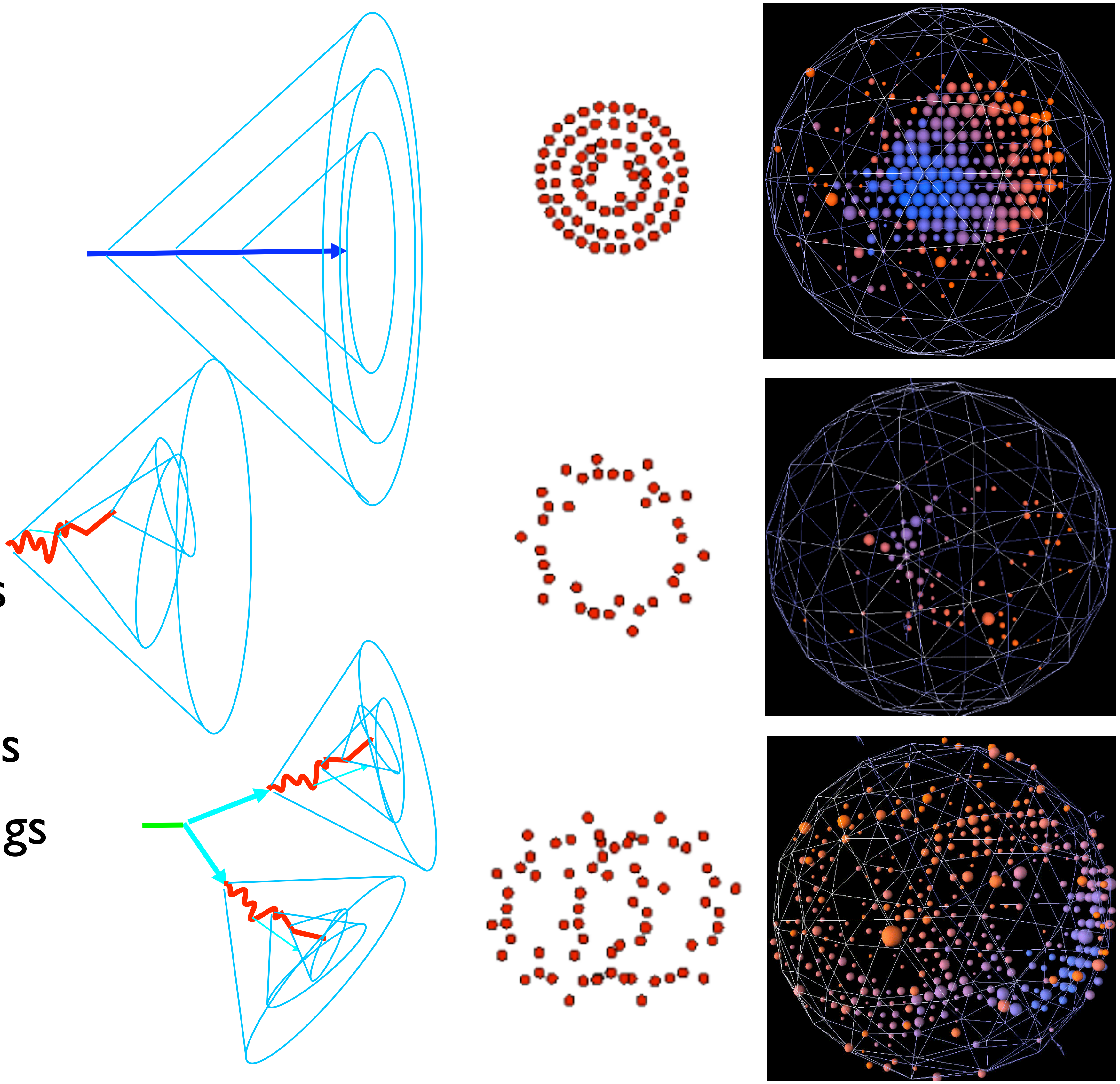


Wavefront
θ_C
Particle track
μ
light
Molecular energy levels of oil

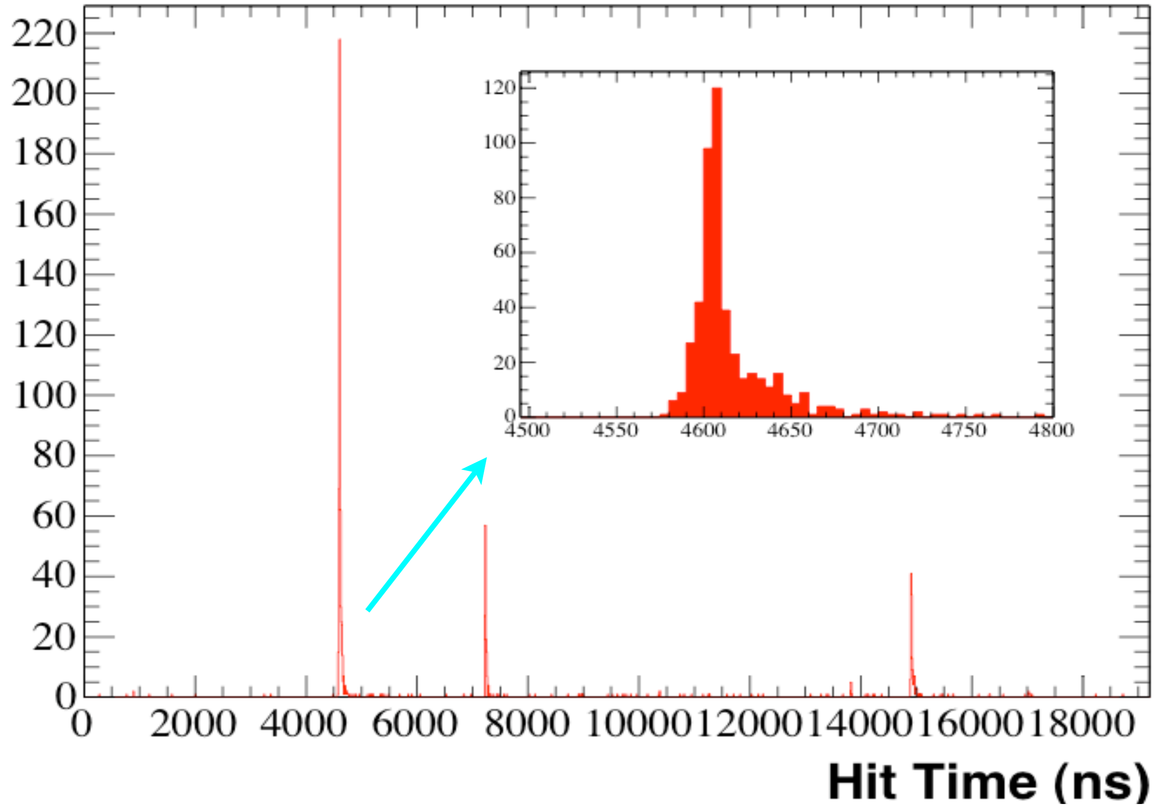


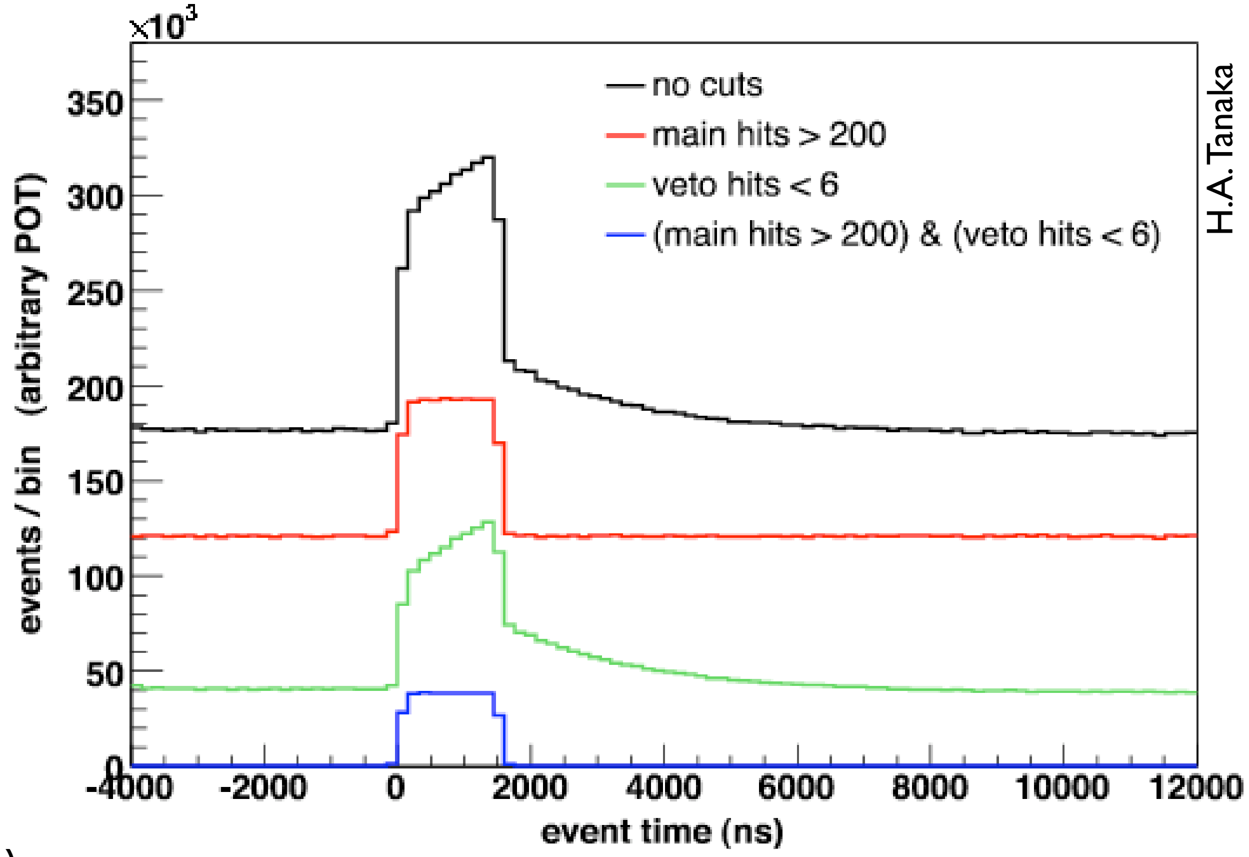
Track Images

- Muons
  - full rings
- Electrons
  - fuzzy rings
- Neutral pions
  - double rings



PMT Hit Clusters

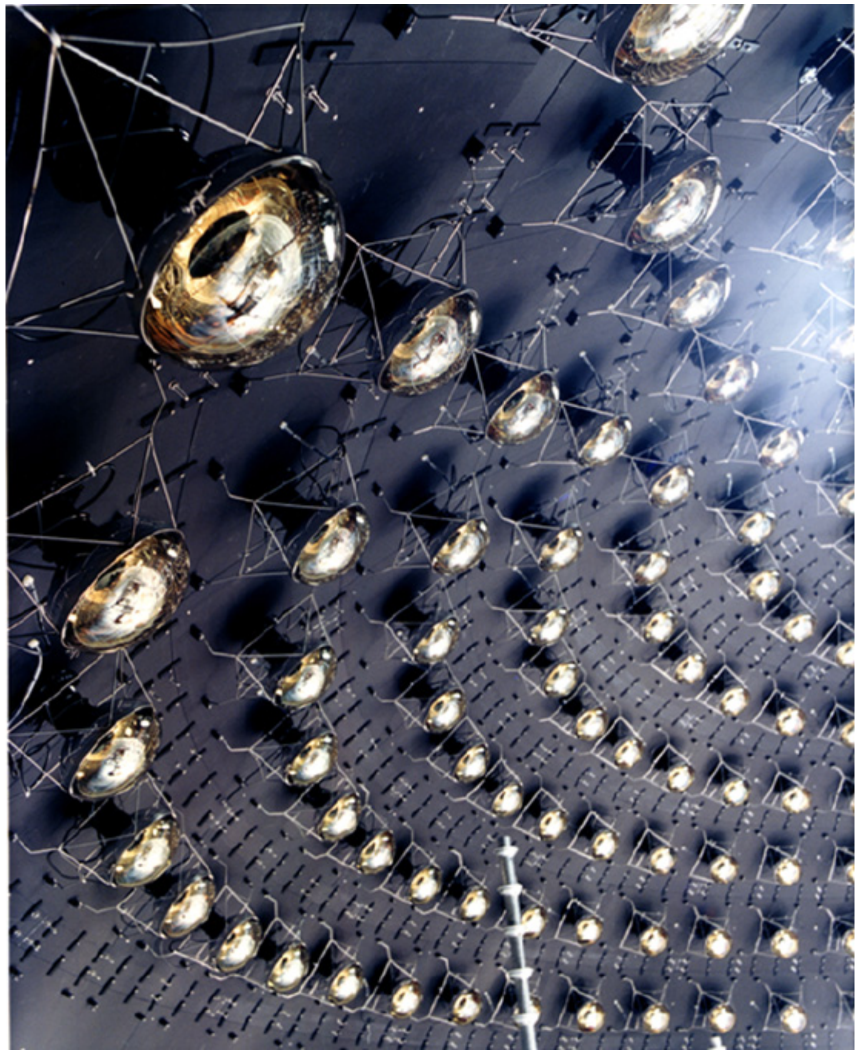


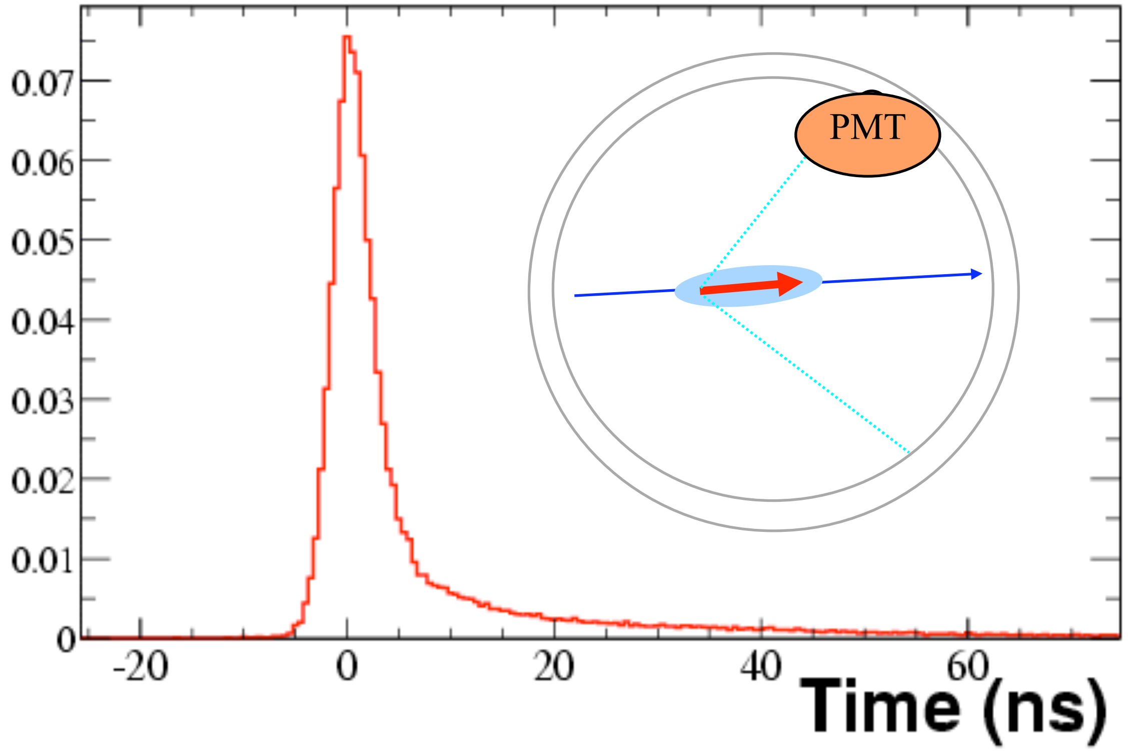


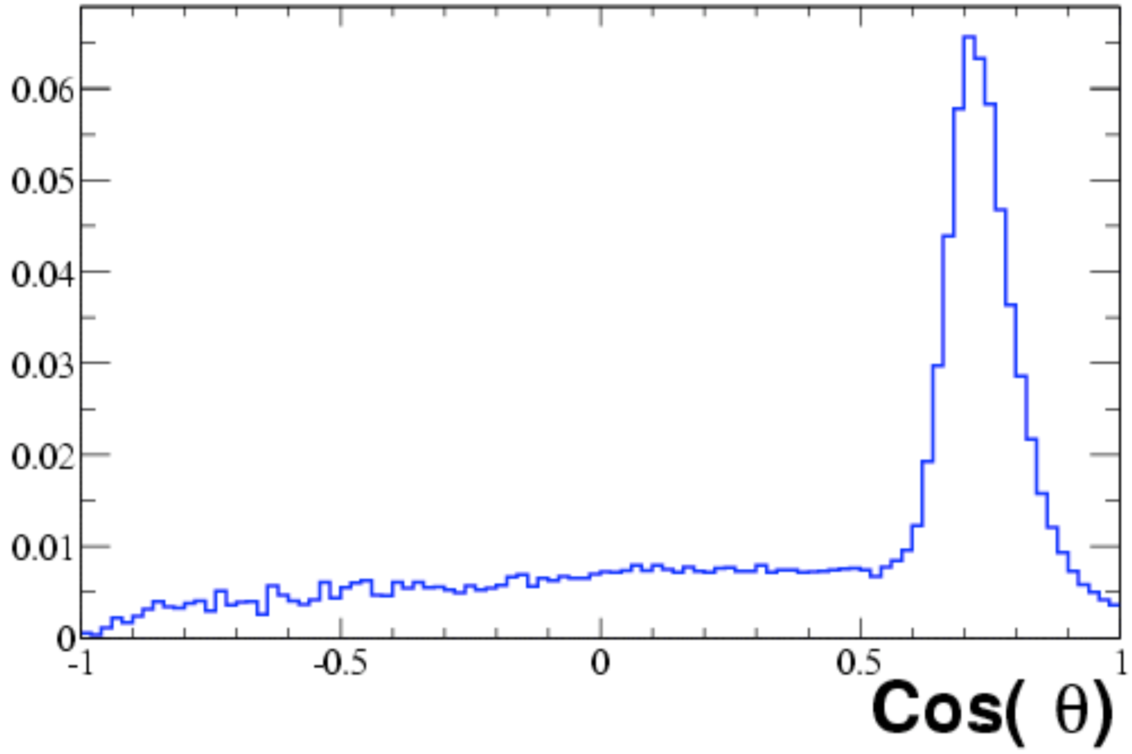
- PMT hits clusters in time form "subevents"
- ν_μ events have 2 subevents
    - μ, followed by e
- ν_e events have 1 subevent
- Simple cuts on subevents remove cosmic backgrounds
    - "pre-cuts"

Track Reconstruction

Charged particles produce Cherenkov and scintillation light in oil







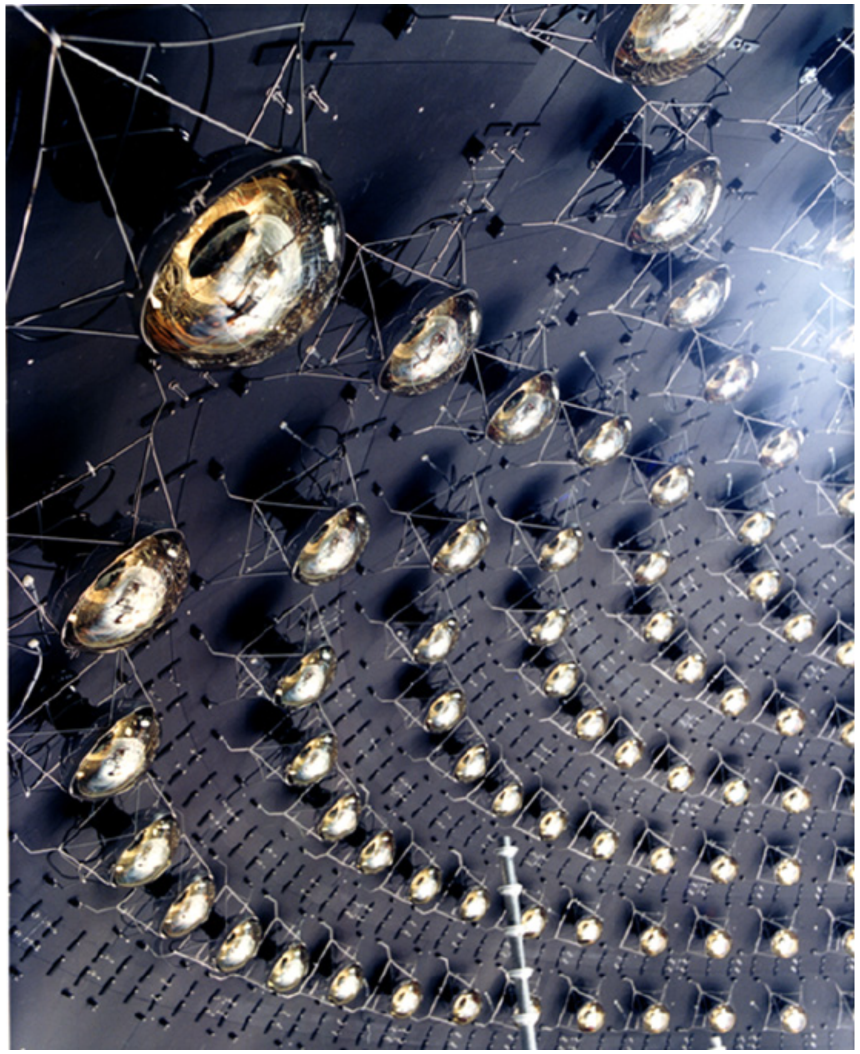
PMTs collect photons, record t,Q

Reconstruct tracks by fitting time and angular distributions

Find position, direction, energy

MiniBooNE Measurements

- Default MC=NUANCE
- CCQE
- CC1pi+
- CC1pi0
- NCpi0
- NCE
- Antineutrinos



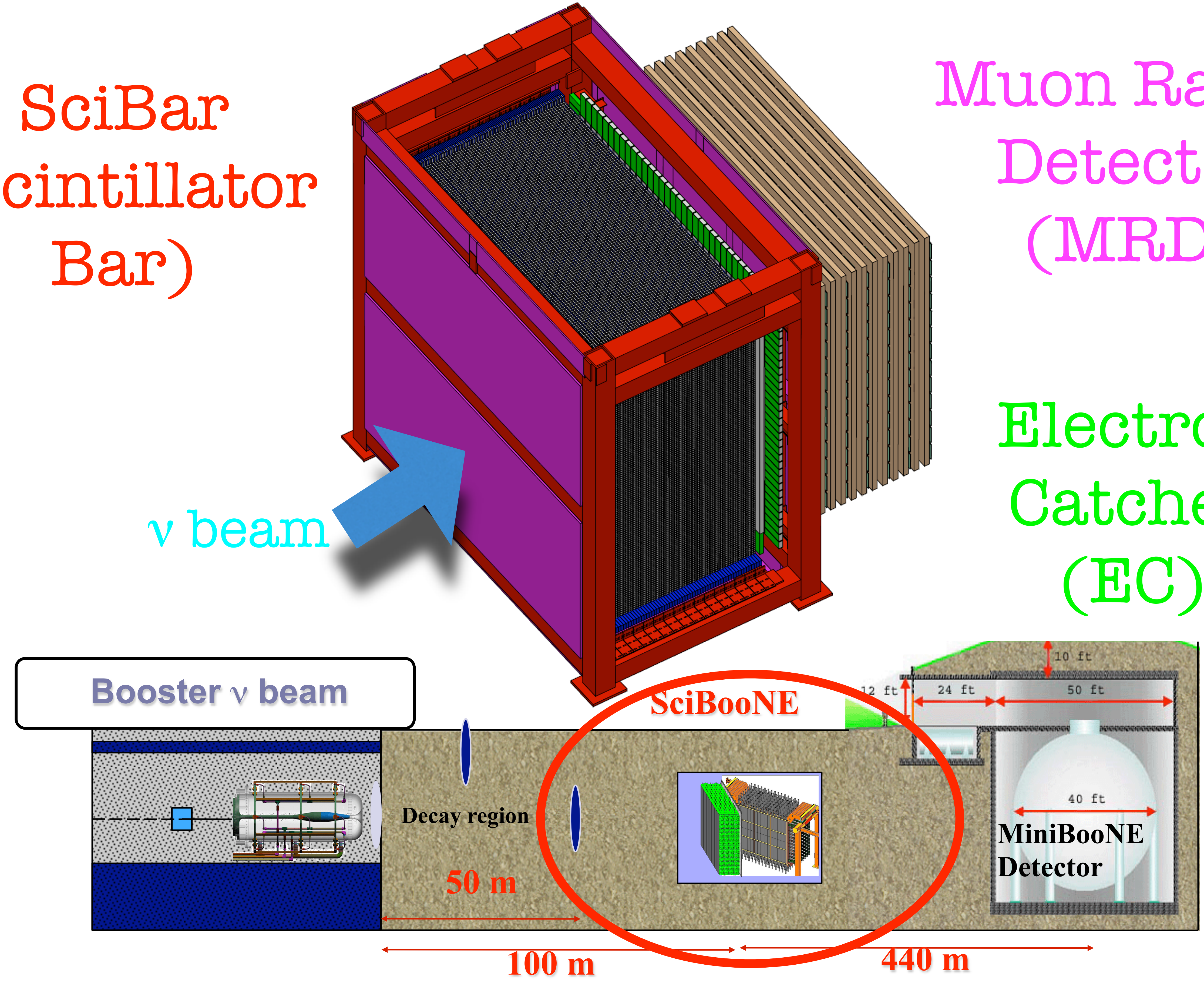
SciBooNE

SciBar
(Scintillator
Bar)

Muon Range
Detector
(MRD)

Electron
Catcher
(EC)

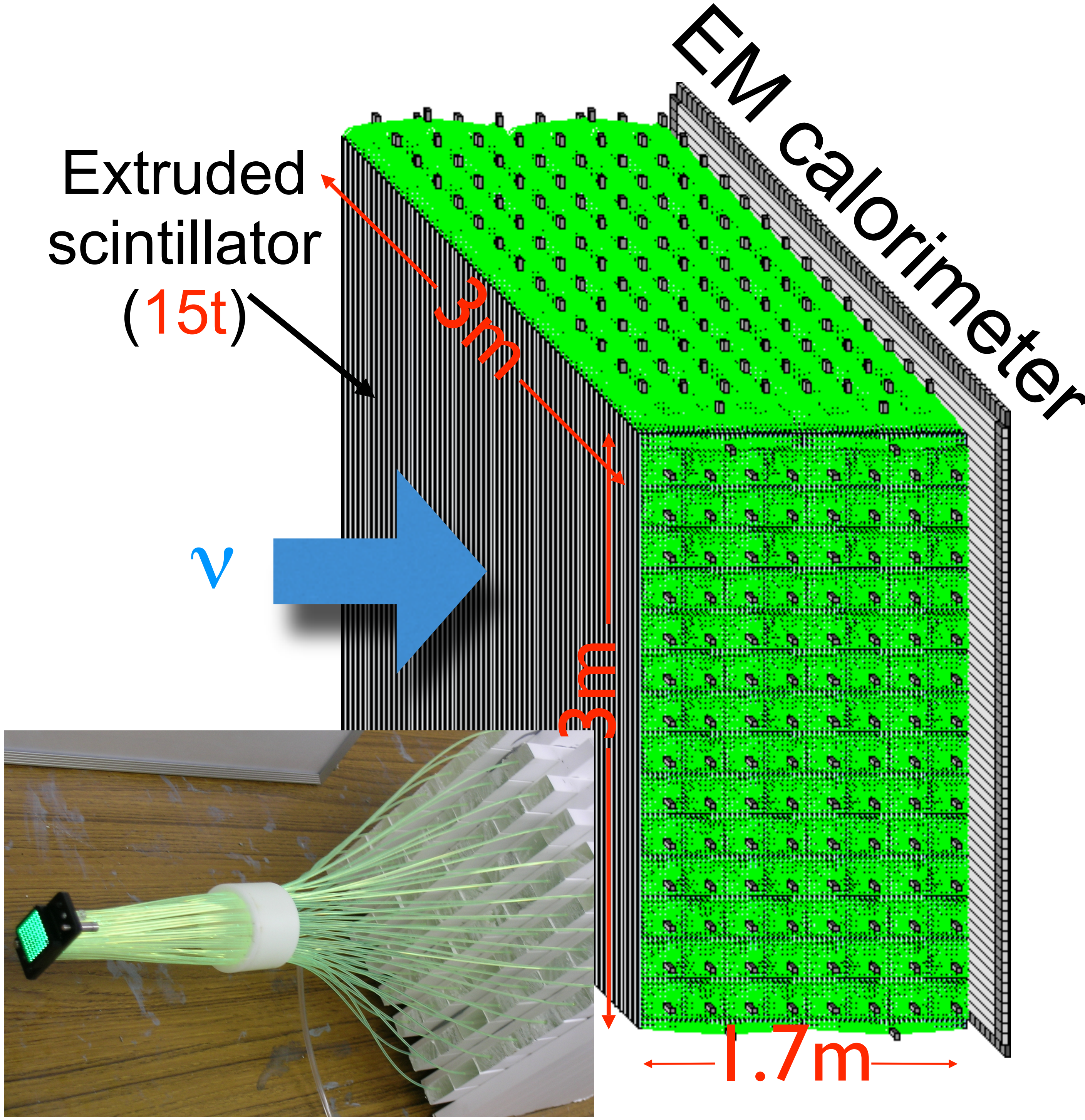
ν beam

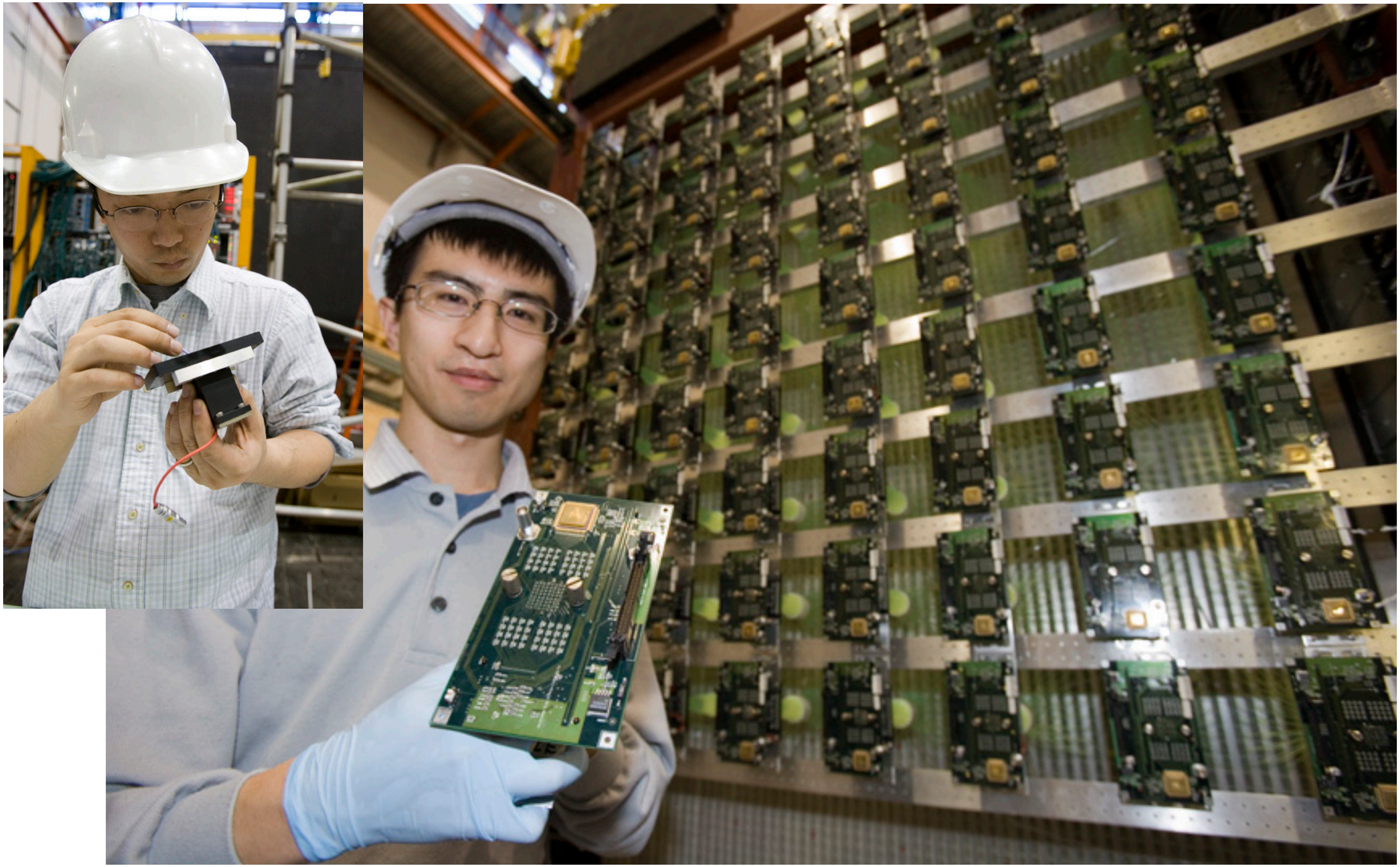

Booster ν beam
SciBooNE
Decay region
50 m
100 m
440 m
10 ft
12 ft
24 ft
50 ft
40 ft
MiniBooNE
Detector

Vertex Detector: SciBar

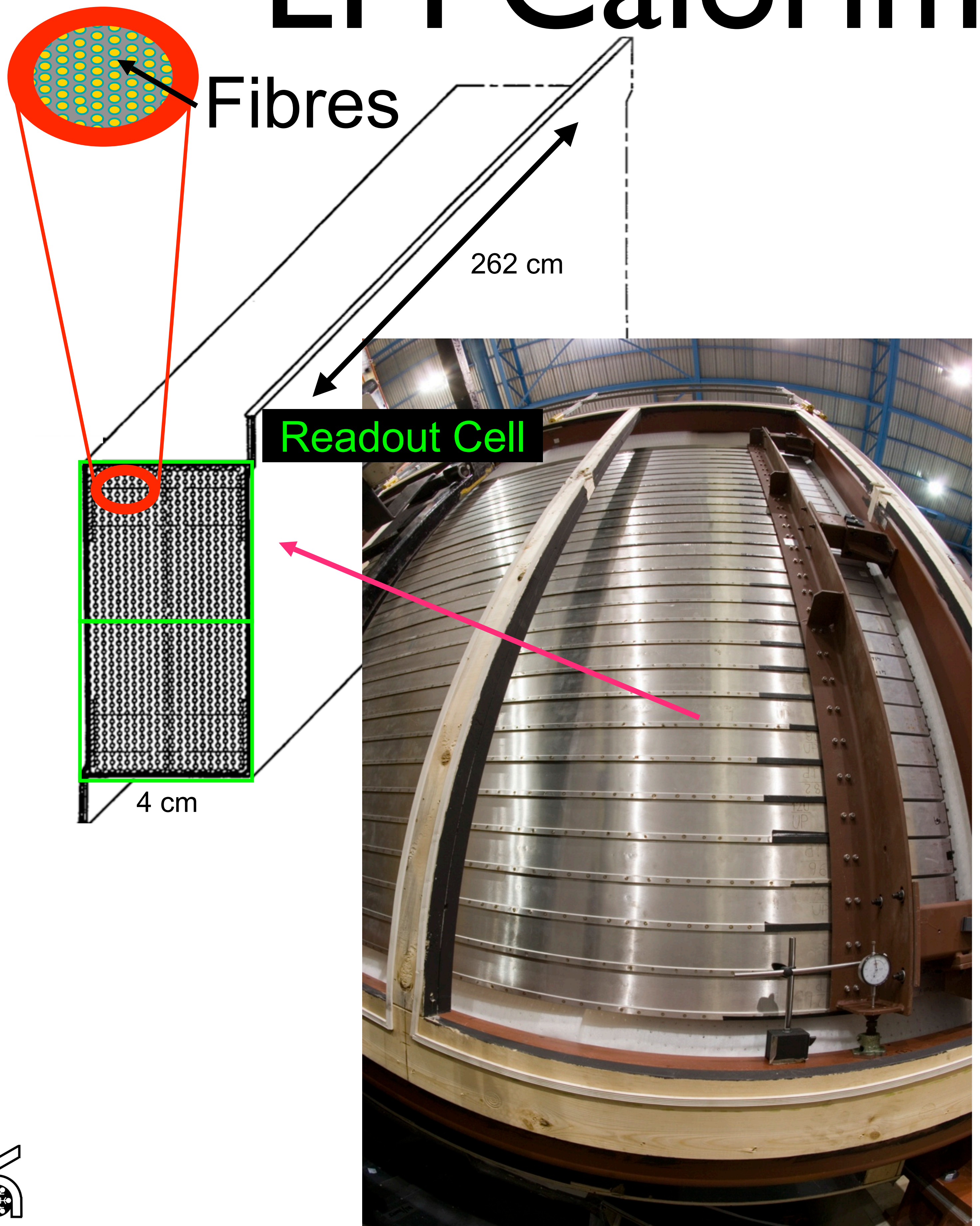
- Fine-grained neutrino vertex detector
- Extruded plastic scintillator with WLS fibres
  - 64 channel MAPMTs
  - ~15k channels
    - All channels operational
- 15 tonne total mass

Originally used in K2K experiment in Japan


Extruded
scintillator
(15t)
EM calorimeter
3m
ν
3m
1.7m



EM Calorimeter: EC



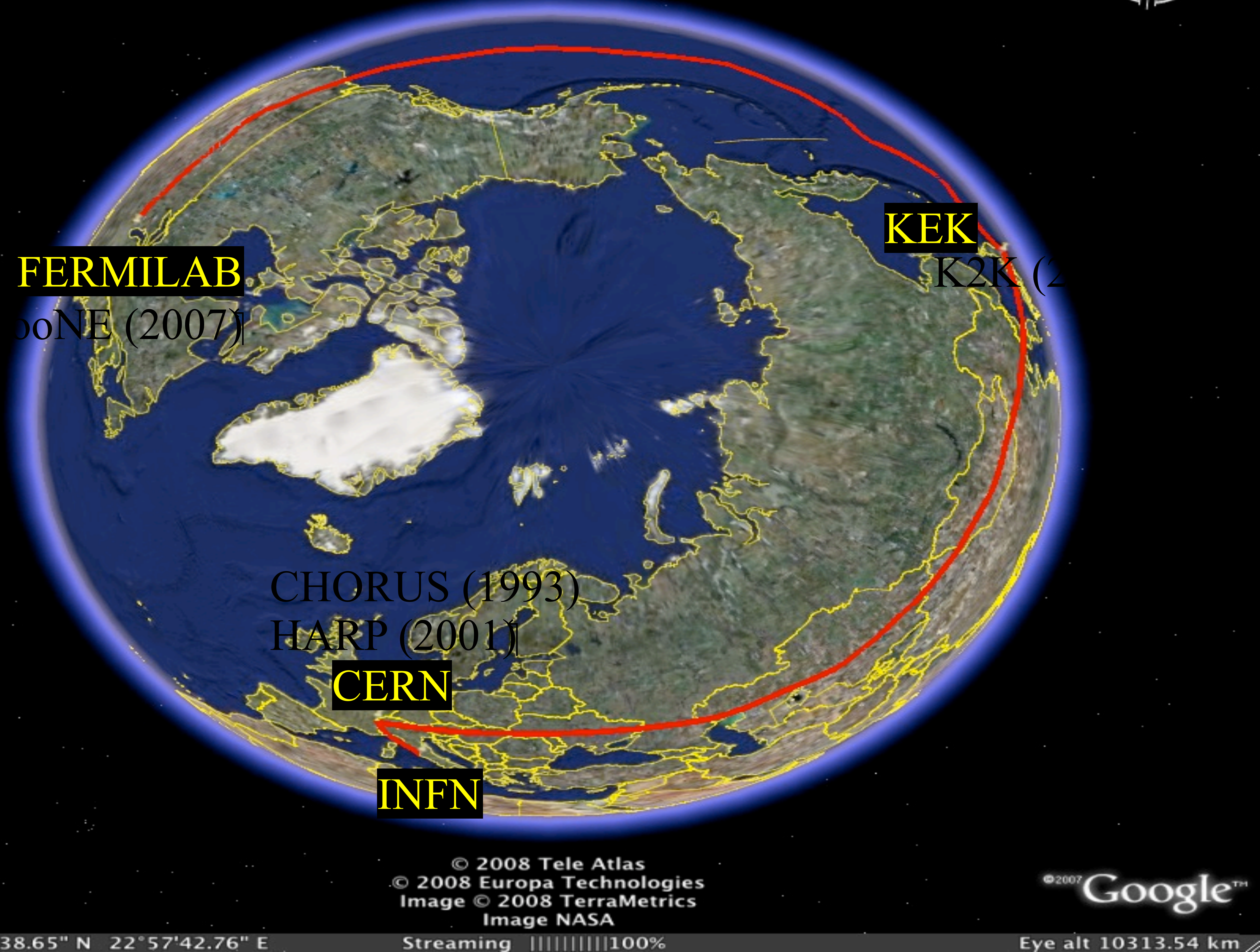
- “Spaghetti” calorimeter
  - Scintillating fibres sandwiched in lead foils
  - PMT readout at both ends

- good energy resolution and linearity
  - 14%/√E resolution
  - MC tuned with cosmic data

- 11 X_0 thick

Originally built for CHORUS; used in K2K

EC modules's travels

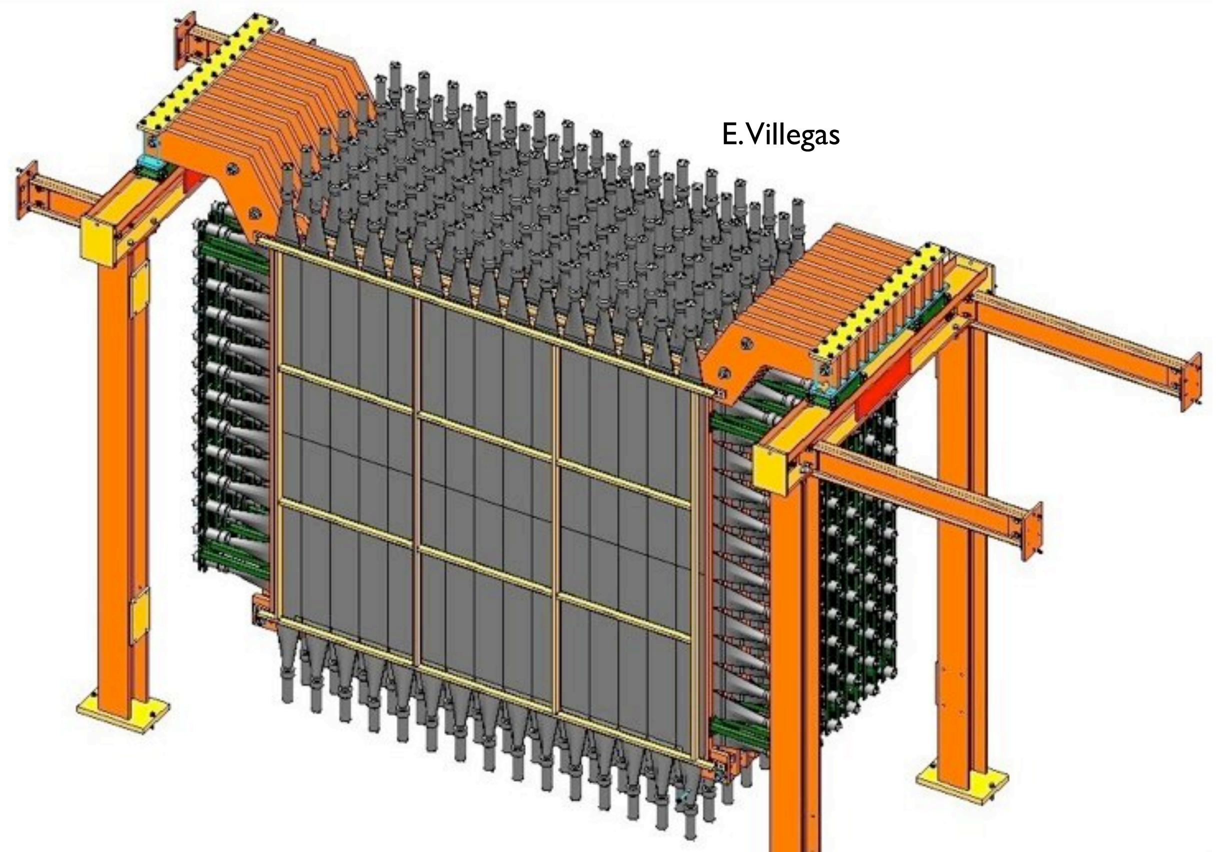

FERMILAB
boNE (2007)
KEK
K2K (2
CHORUS (1993)
HARP (2001)
CERN
INFN
© 2008 Tele Atlas
© 2008 Europa Technologies
Image © 2008 TerraMetrics
Image NASA
©2007 Google™
Pointer 85°11'38.65" N 22°57'42.76" E
Streaming ||||||||||100%
Eye alt 10313.54 km

Muon Range Detector

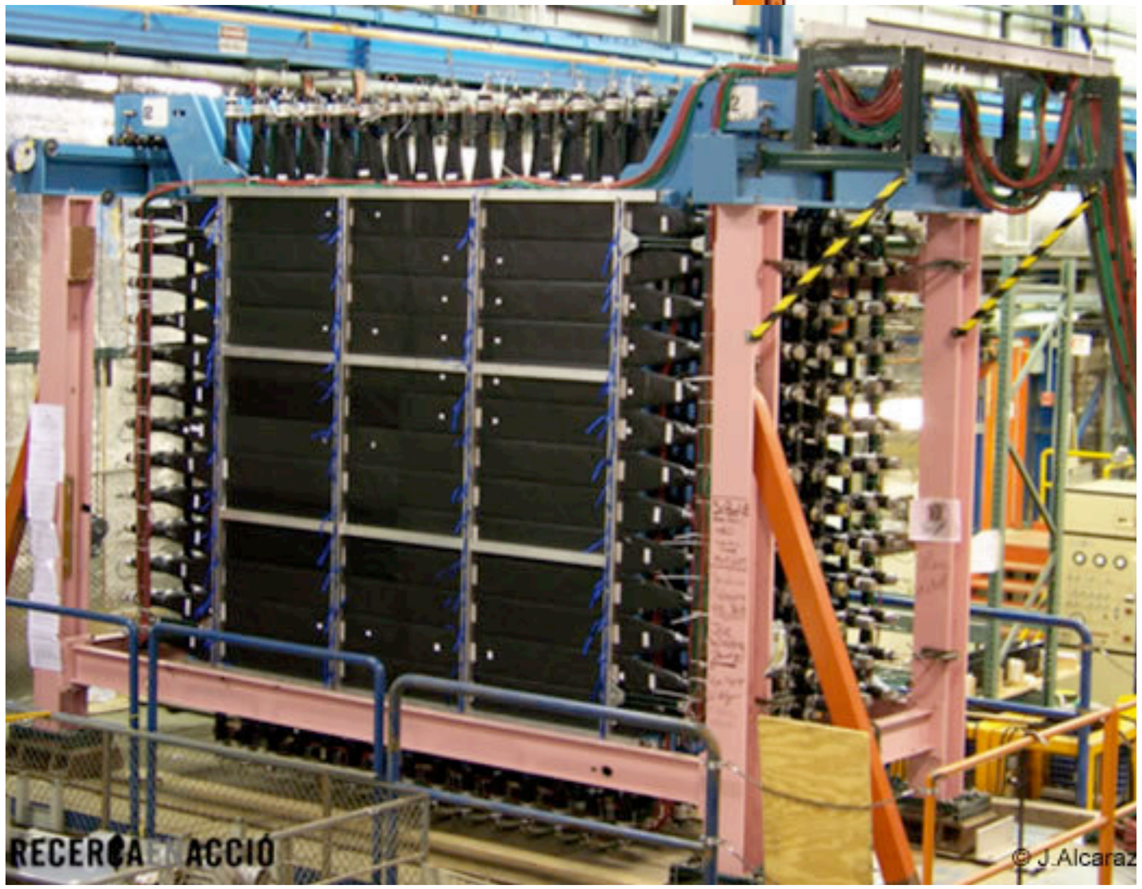
- Iron plates (5cm) with scintillation counters
  - Measure up to ~1.2 GeV muons
  - ~5% momentum resolution

Recycled from past FNAL experiments

Won DOE "Closing the Circle" and P2 awards

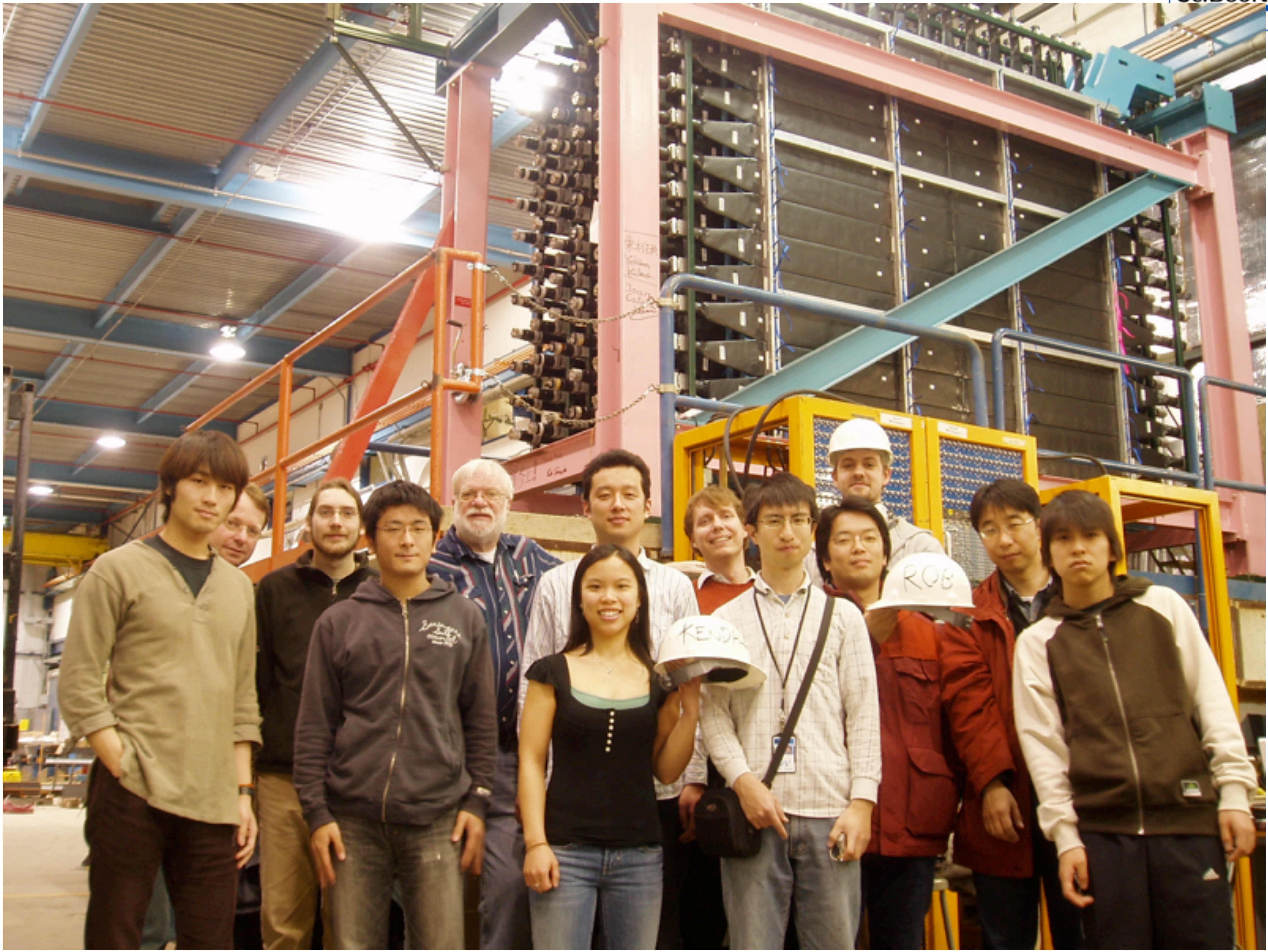


E.Villegas



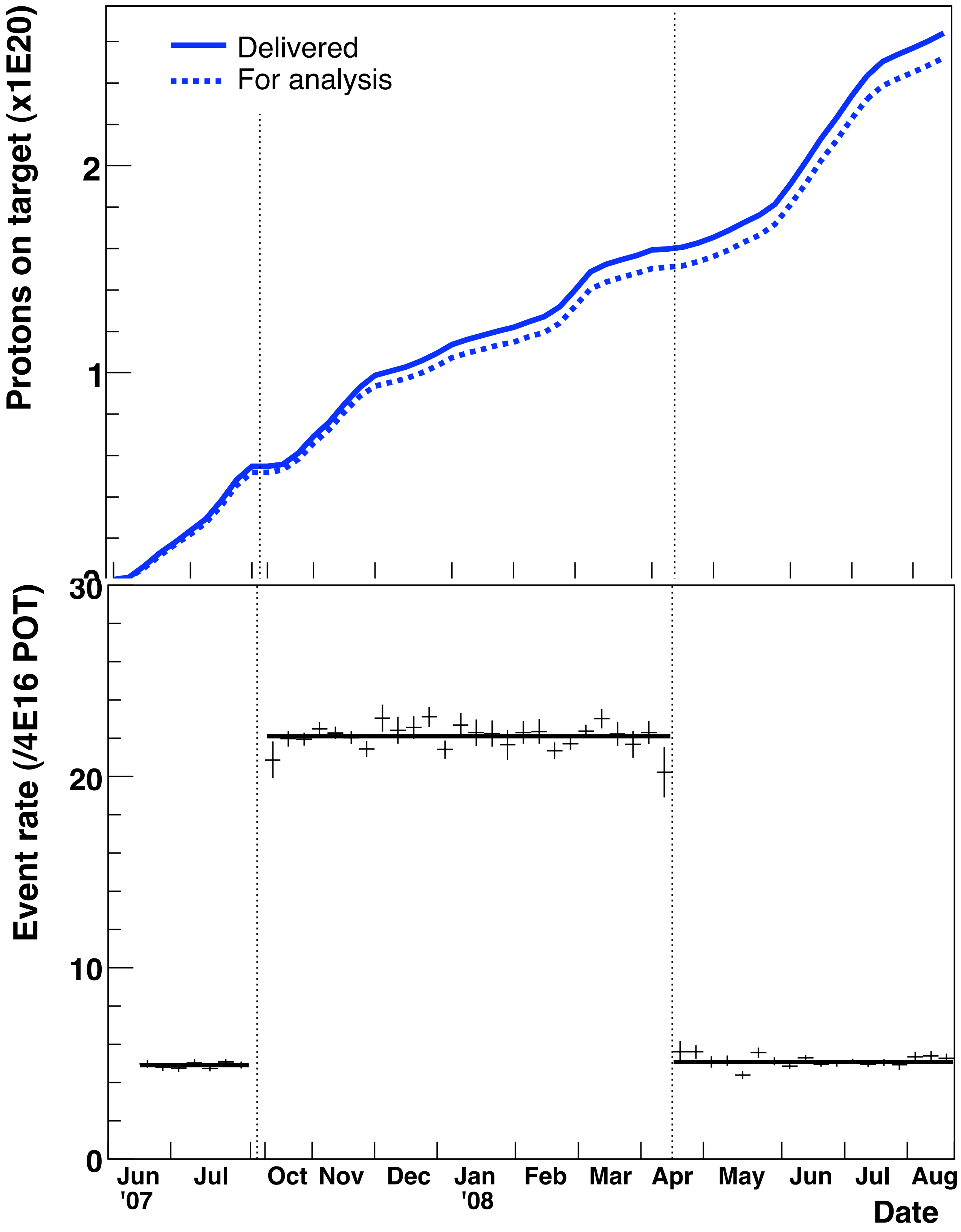
© J.Alcaraz

MRD 396


KENDA
ROB

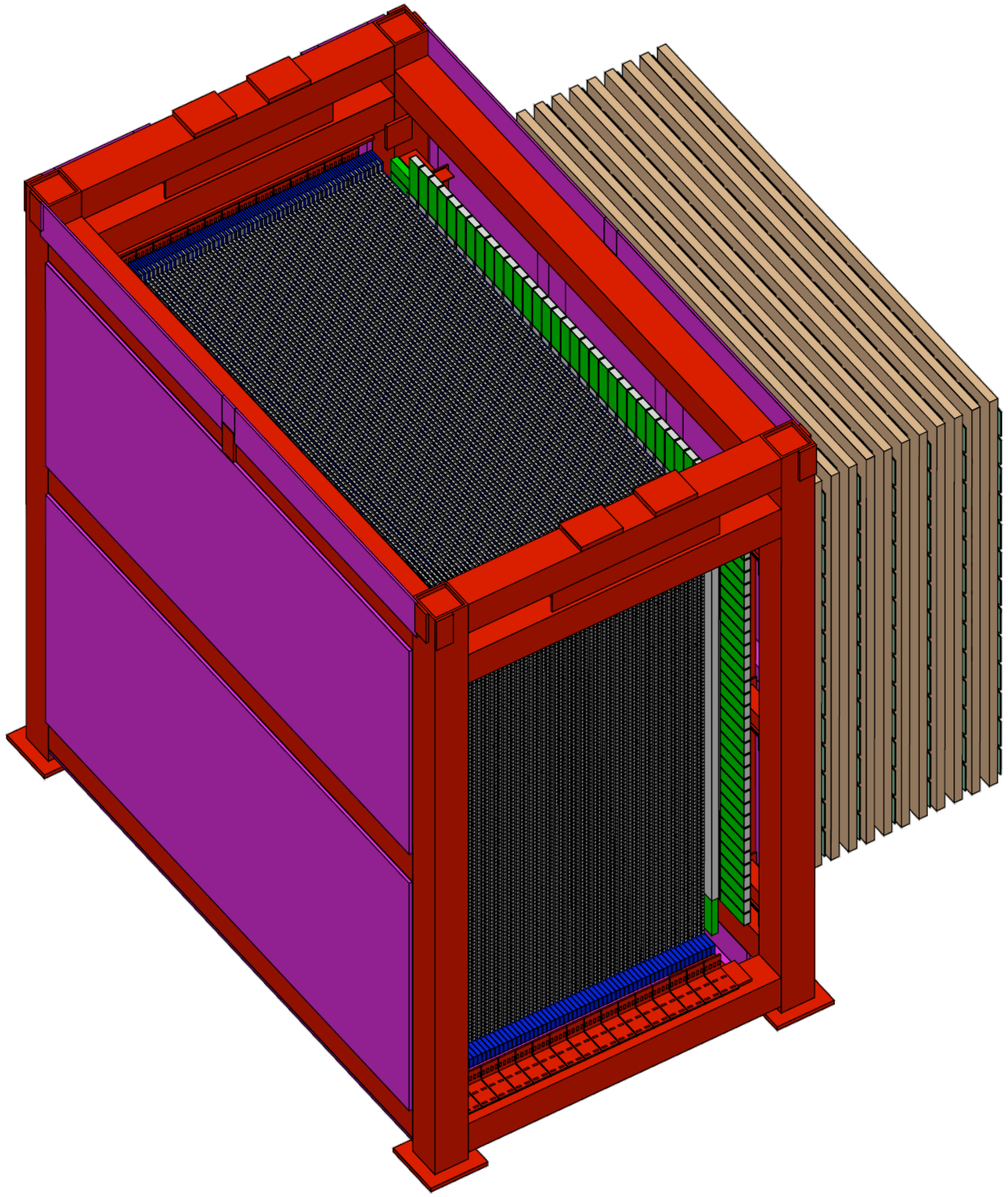
SciBooNE Performance

SciBooNE installed and commissioned in spring 2007



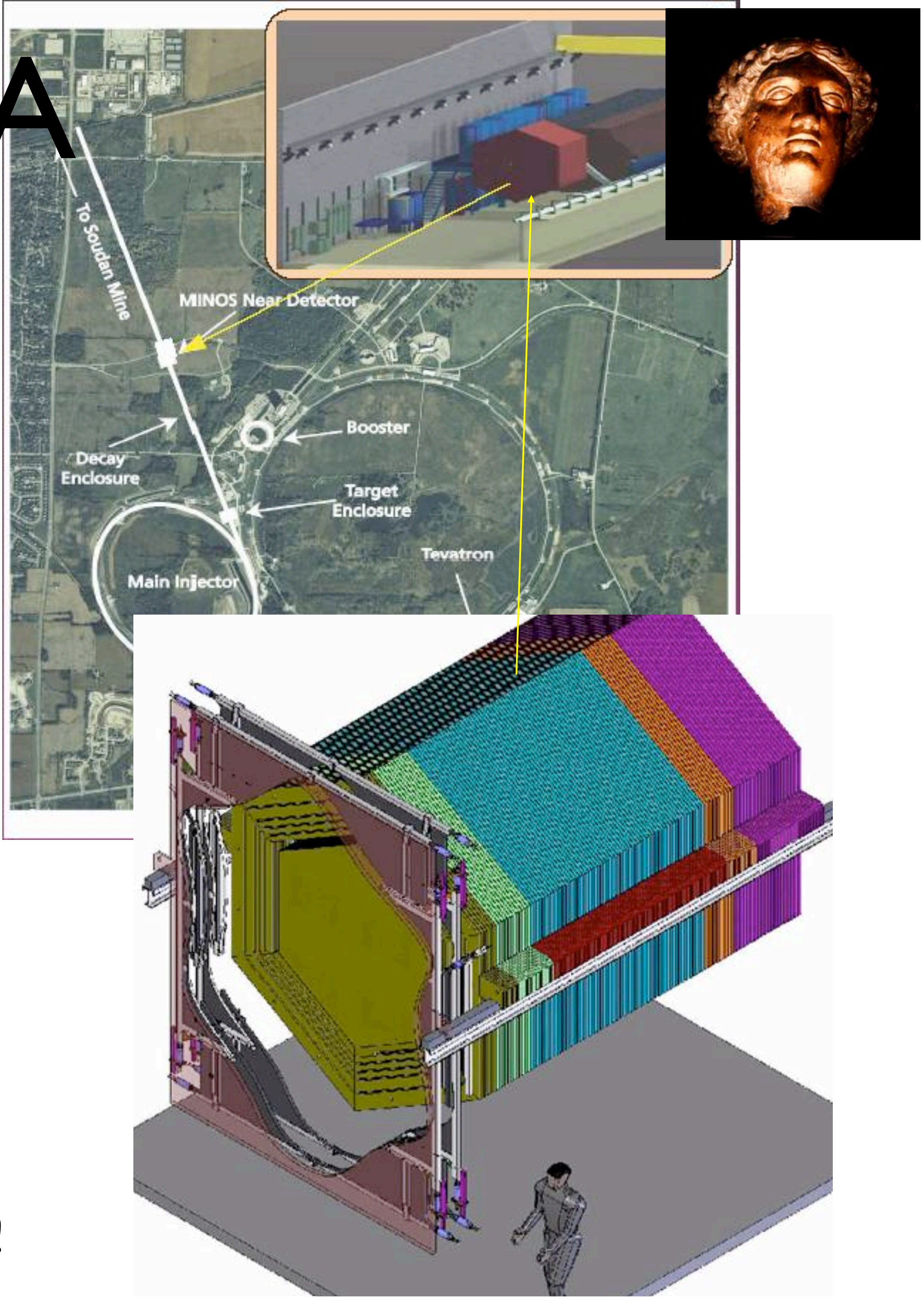
SciBooNE Measurements

- CCQE
- CC1π+
- CCπ0
- NCπ0
- NCE
- Antineutrinos

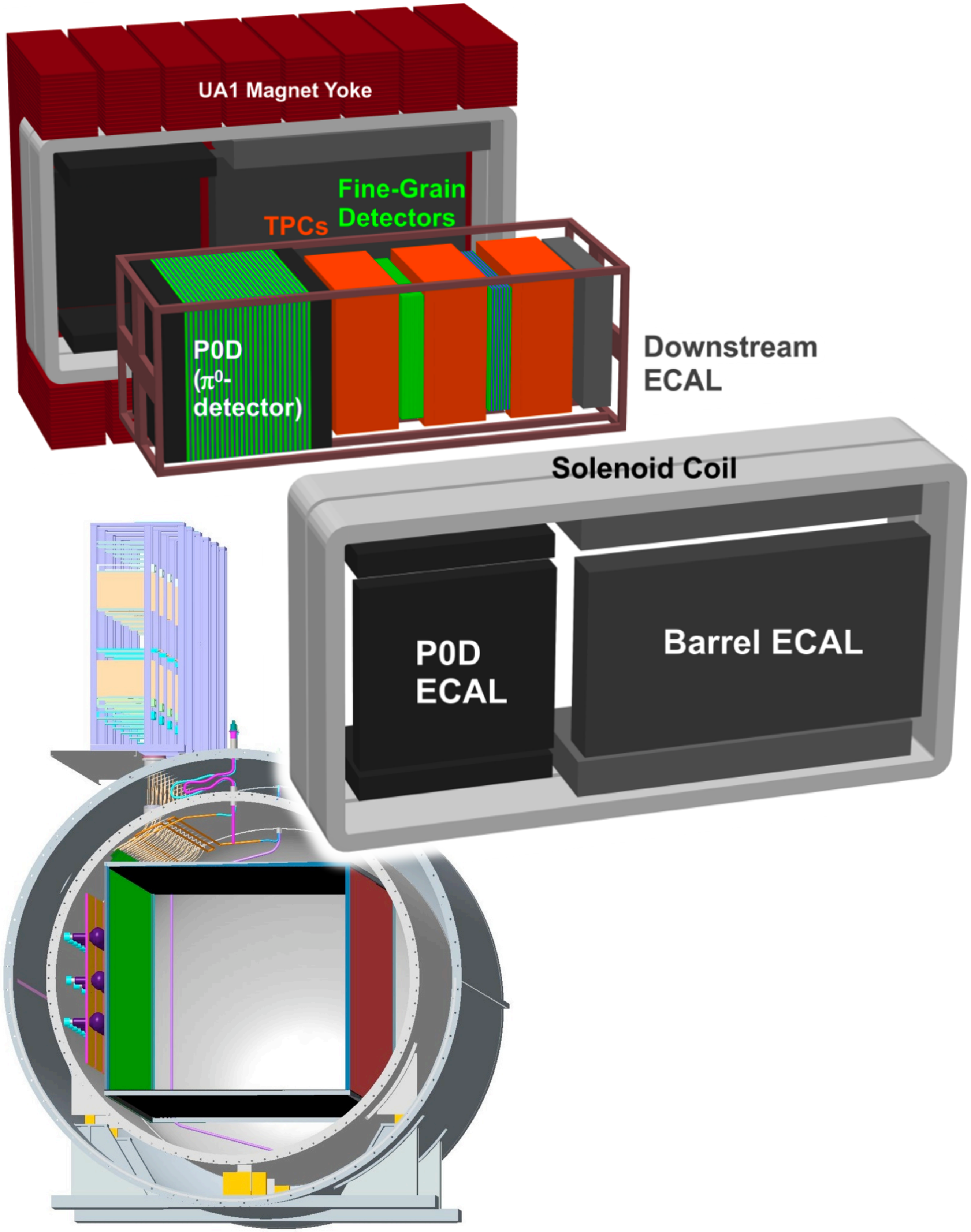


Future: MINERνA

- MINERνA is designed to study ν-nucleus interactions with unprecedented detail
- The detector will be placed upstream of the MINOS Near Detector in the NuMI beam line
- The NuMI beam provides a wide range of neutrino energies
- Detector with several different nuclear targets allows study of neutrino nuclear effects
    - Unique to this experiment!


To Soudan Mine
MINOS Near Detector
Booster
Decay Enclosure
Target Enclosure
Tevatron
Main Injector

Other Experiments


UA1 Magnet Yoke
Fine-Grain Detectors
TPCs
P0D (π^0-detector)
Downstream ECAL
Solenoid Coil
P0D ECAL
Barrel ECAL

- Oscillation experiments developing increasingly complex near detectors
- MINOS, NOvA
- T2K ND280
  - High resolution detector
  - Most powerful nu beam
- MicroBooNE
  - Liquid Argon