Neutrino Detection 3

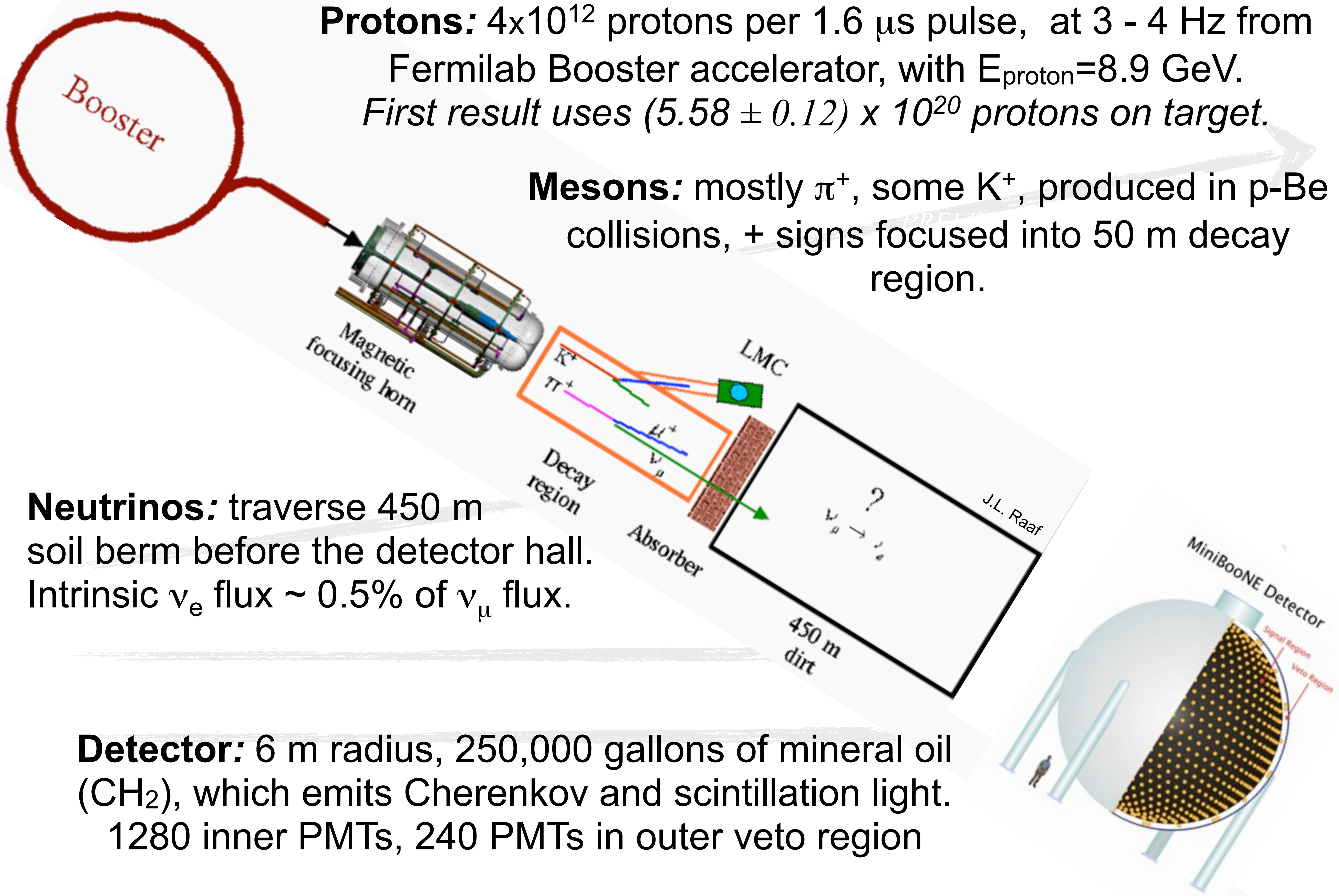
MO Wascko
Imperial College London

INSS 2014, St Andrews
2014 08 12

Specific Examples

- Day 1: Signals and backgrounds
- Day 2: Radiation in matter and detection techniques
- Today: Examples of real neutrino experiments building on techniques already discussed

MiniBooNE Overview: **Beam and Detector**

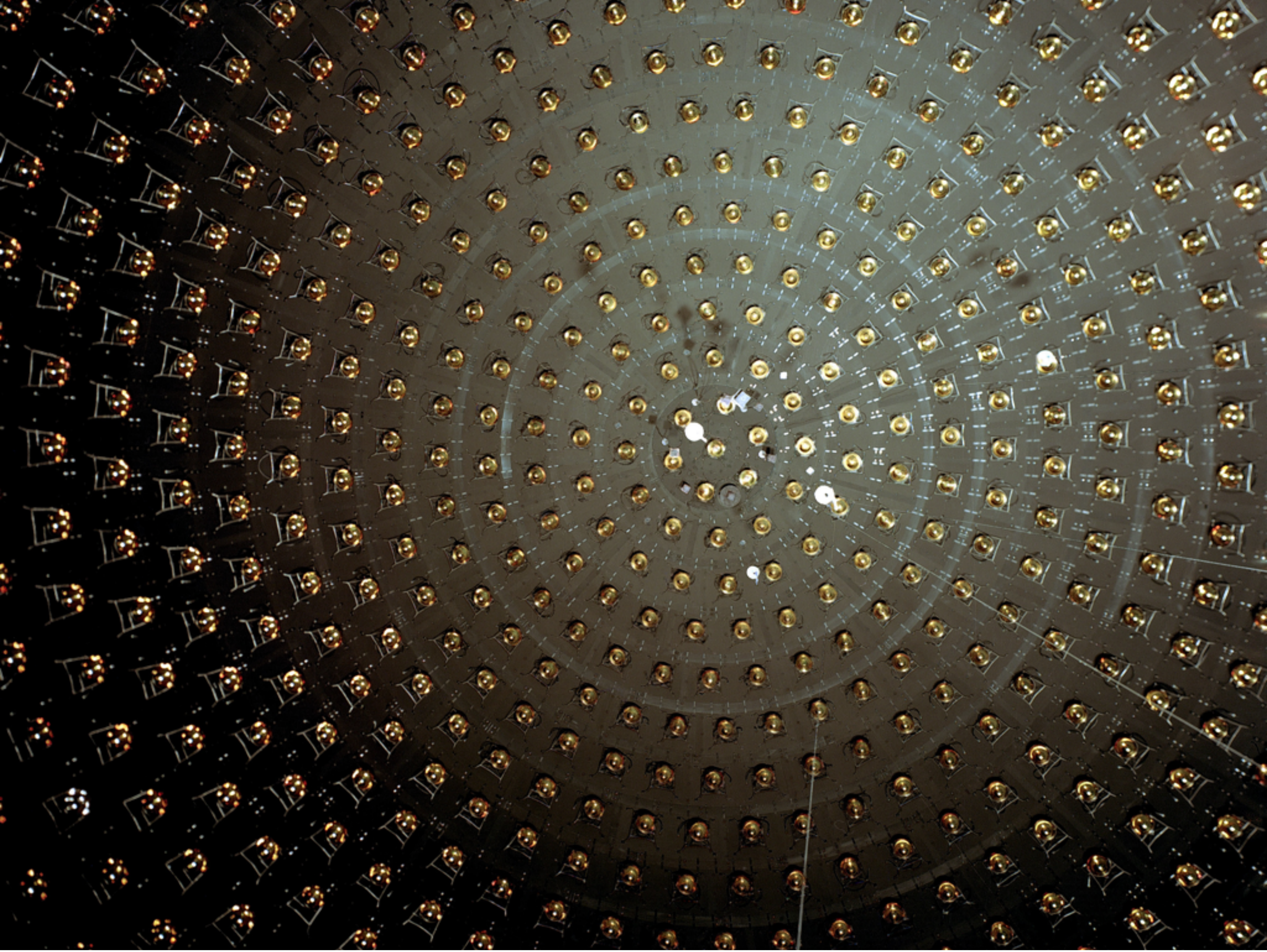


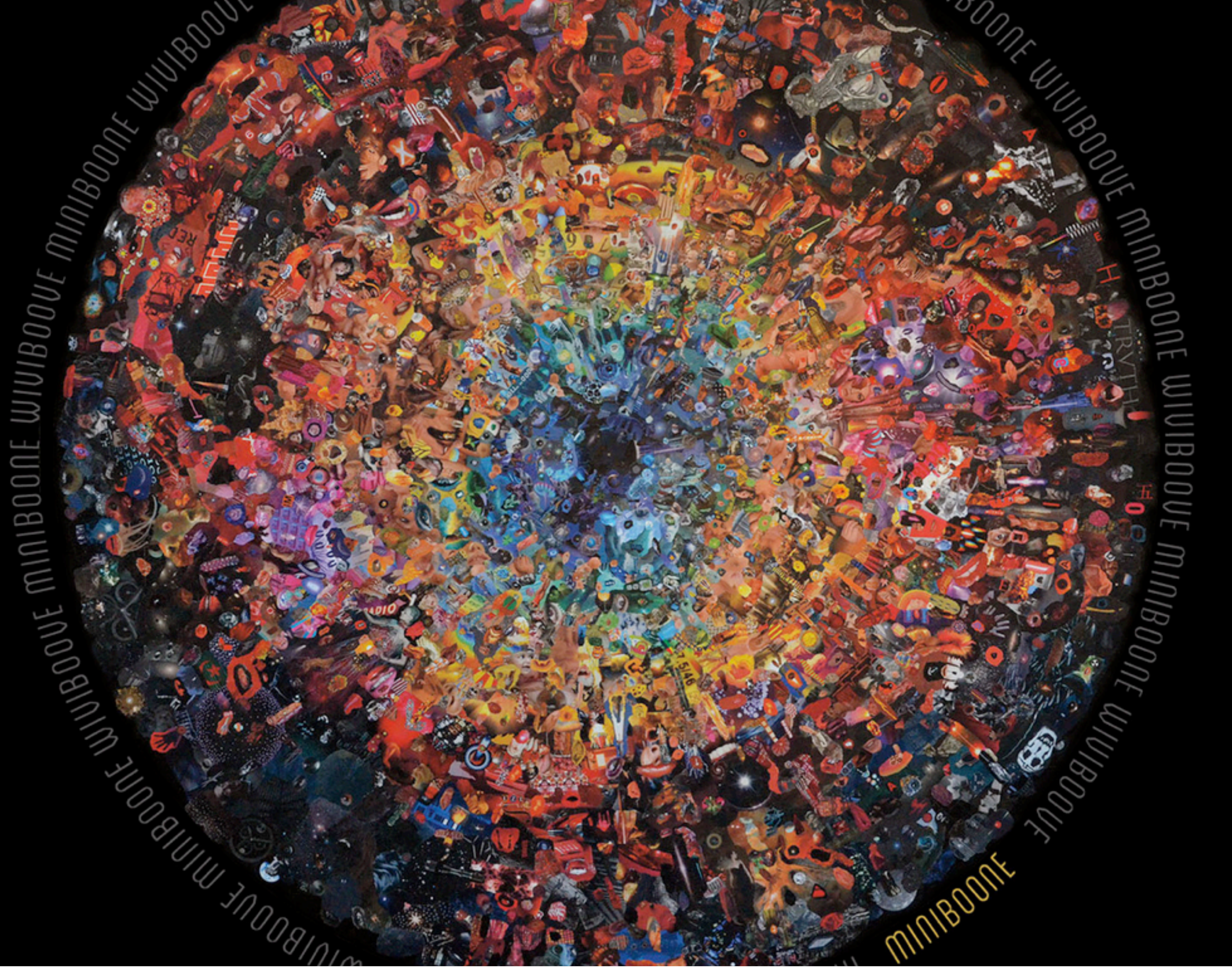
Protons*:* 4×10^{12} protons per 1.6 μs pulse, at 3 - 4 Hz from Fermilab Booster accelerator, with E_{proton}=8.9 GeV.
First result uses (5.58 ± 0.12) x 10^{20} protons on target.

Mesons*:* mostly π^+, some K^+, produced in p-Be collisions, + signs focused into 50 m decay region.

Neutrinos*:* traverse 450 m soil berm before the detector hall. Intrinsic ν_e flux ~ 0.5% of ν_μ flux.

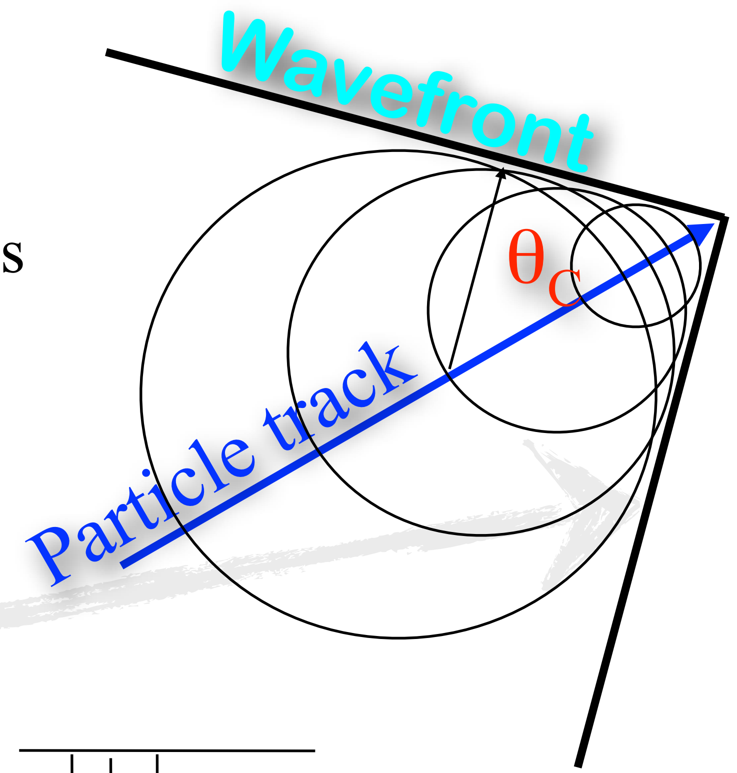
Detector*:* 6 m radius, 250,000 gallons of mineral oil (CH_2), which emits Cherenkov and scintillation light. 1280 inner PMTs, 240 PMTs in outer veto region




MINIBOONE

MiniBooNE Detector: **Optics**

charged final state particles produce γs

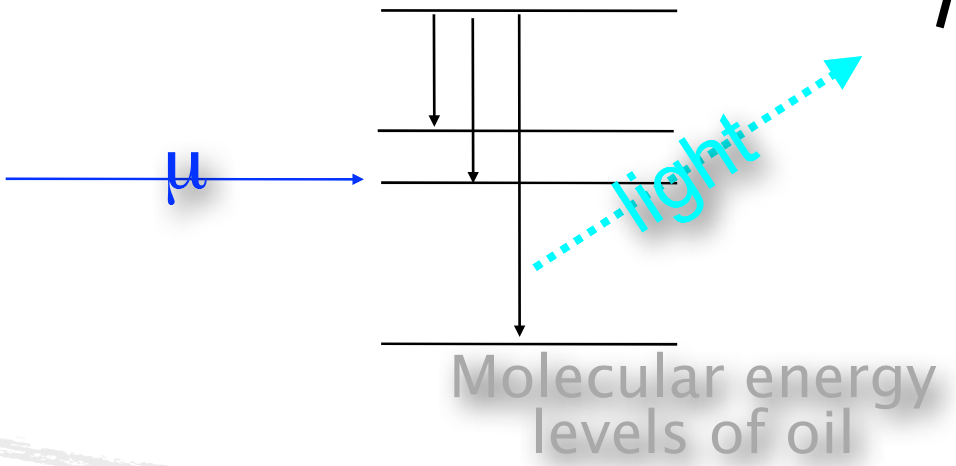


Cherenkov radiation

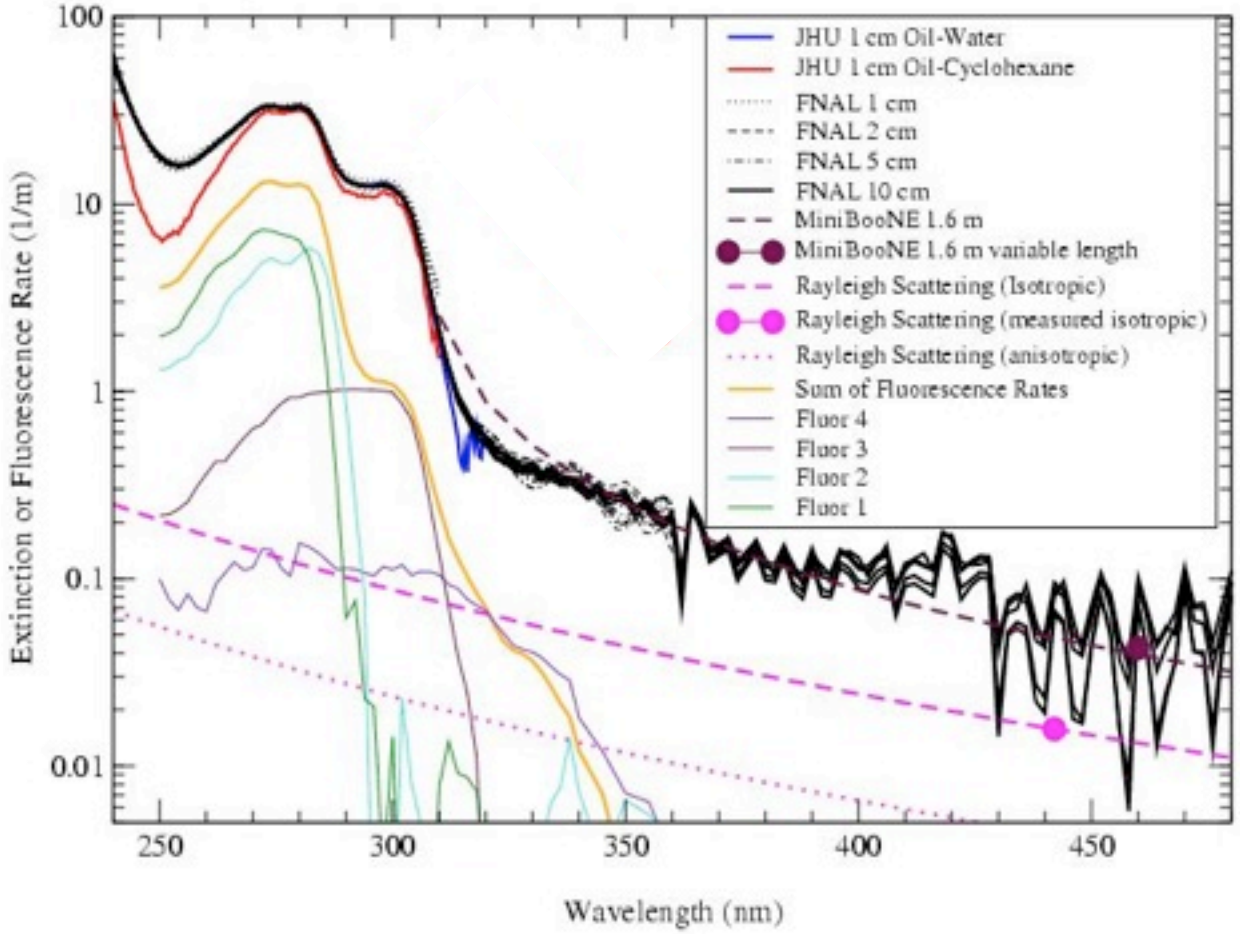
- Light emitted by oil if particle v > c/n
- forward and prompt in time

Scintillation

- Excited molecules emit de-excitation γs
- isotropic and late in time



Extinction Rate for MiniBooNE Marcol 7 Mineral Oil



B.C. Brown

γs are (possibly) detected by PMTs after undergoing absorption, reemission, scattering, fluorescence

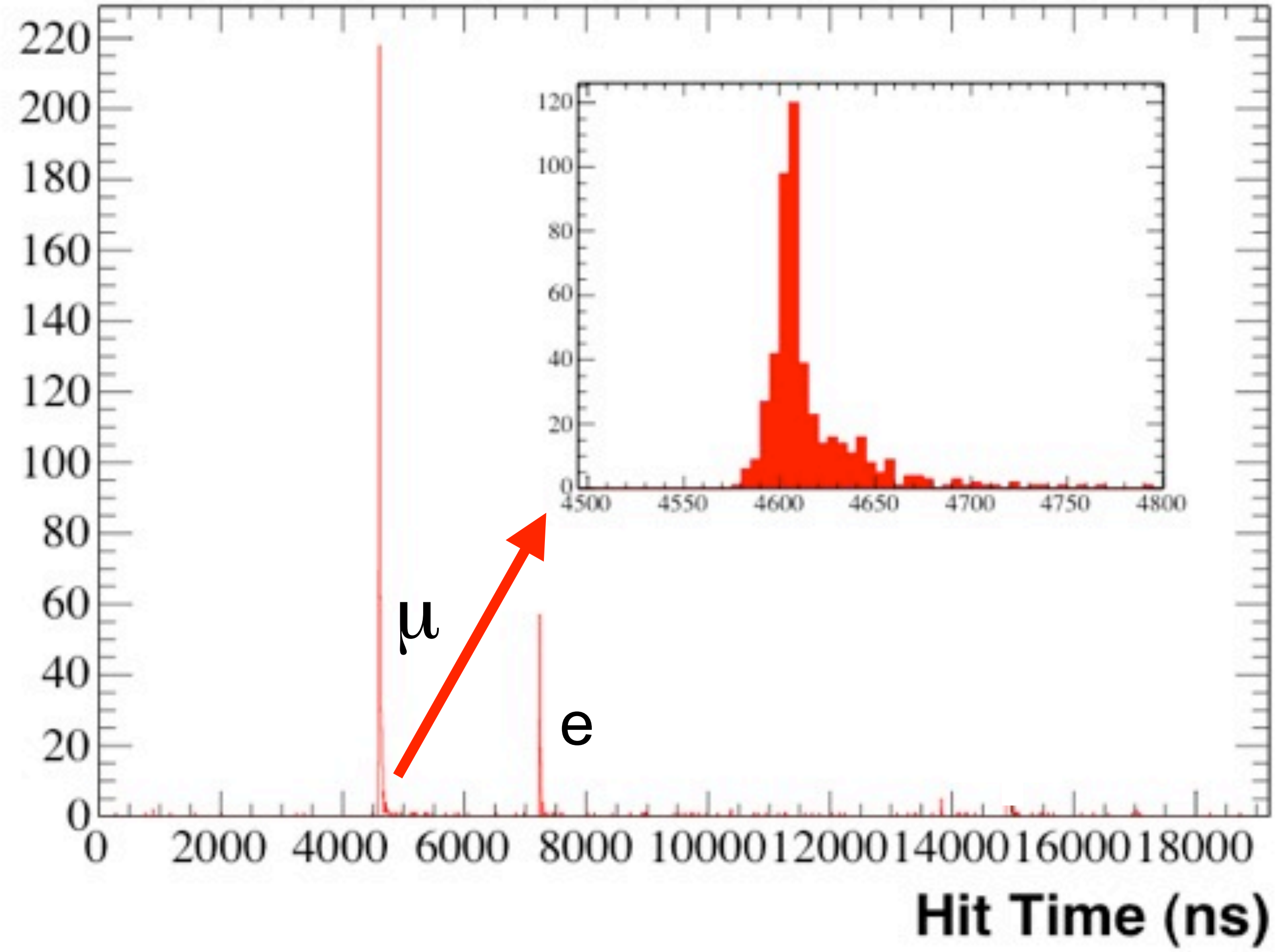
"the optical model"

MiniBooNE Detector: **Hits**

First set of cuts based on simple hit clusters in time: "sub-events."

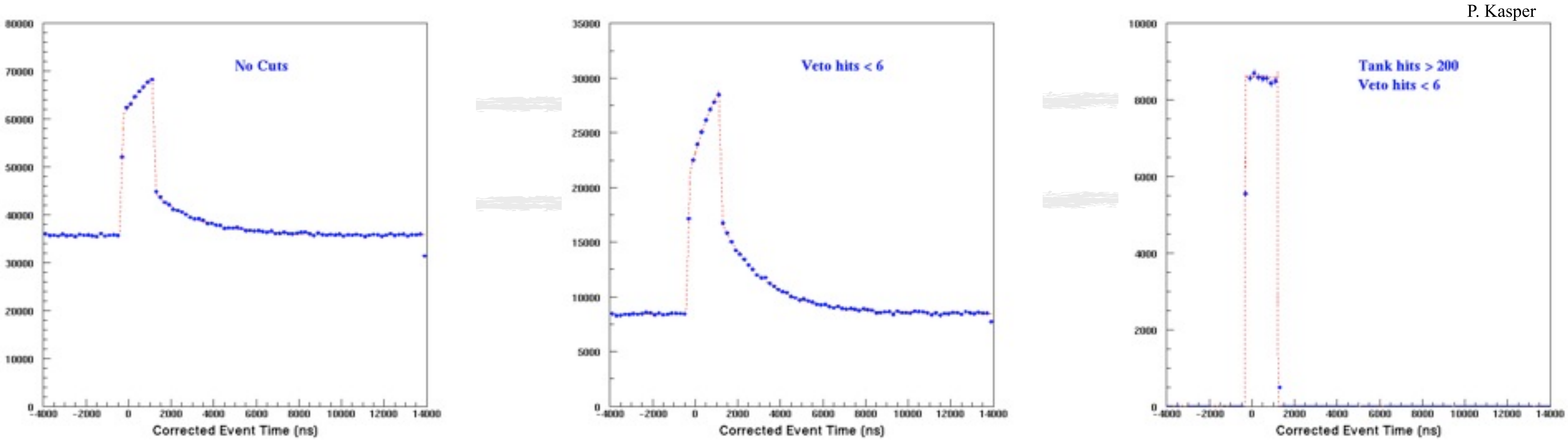
Most events are from ν_μ CC interactions, with characteristic two "sub-event" structure from stopped μ decay.

ν_e CC interactions have 1 "sub-event".



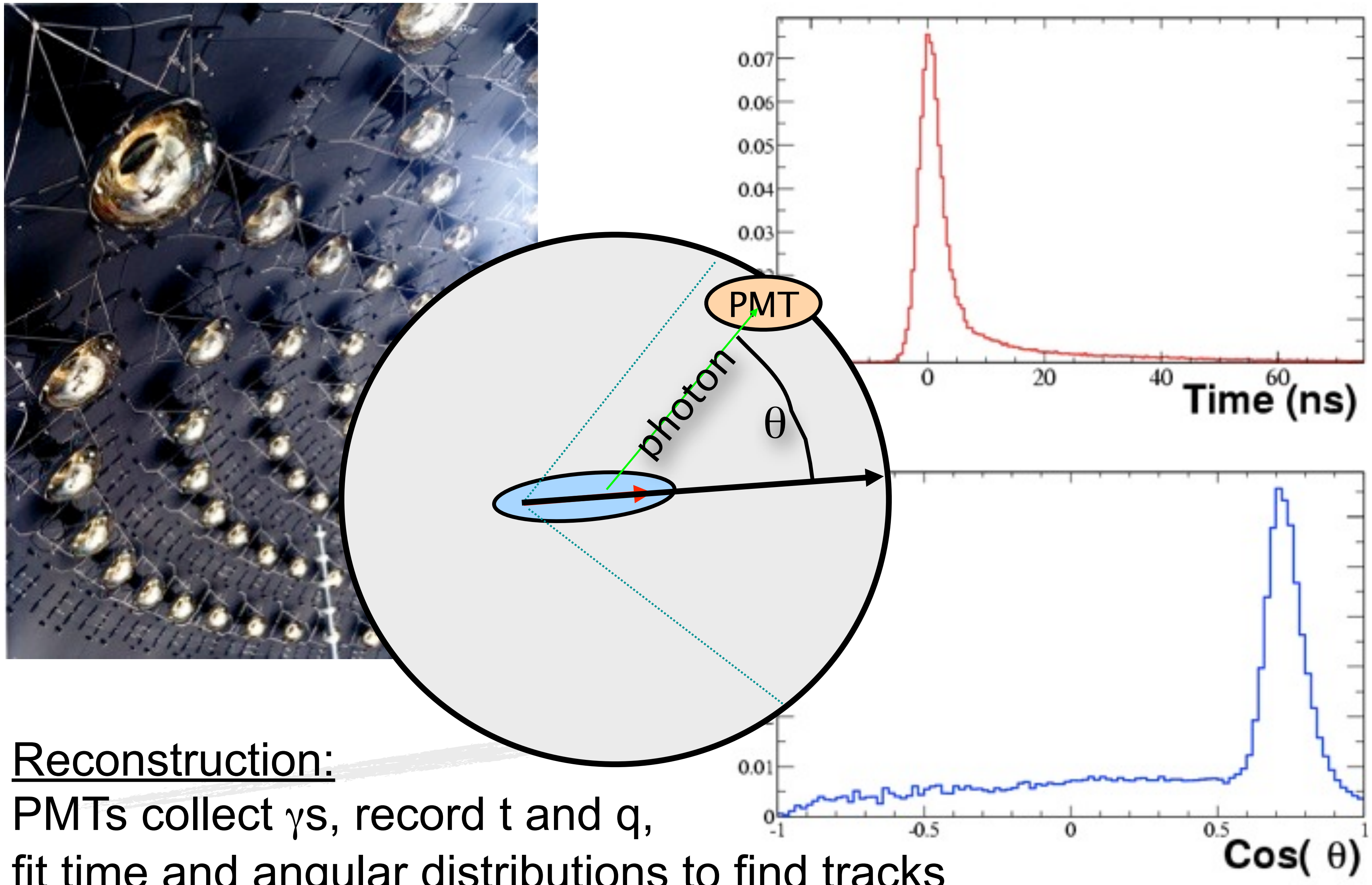
Simple cuts eliminate cosmic ray events:

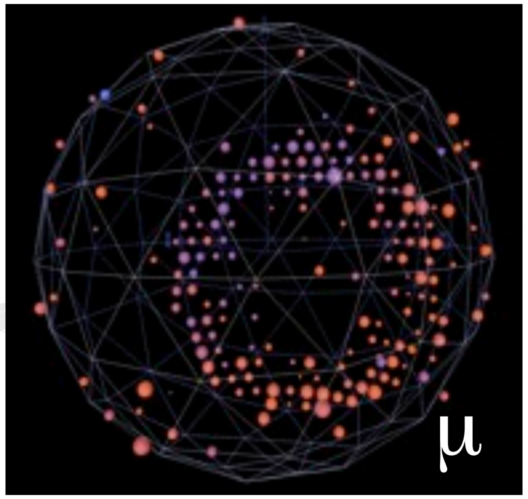
1. Require < 6 veto PMT hits,
2. Require > 200 tank PMT hits.

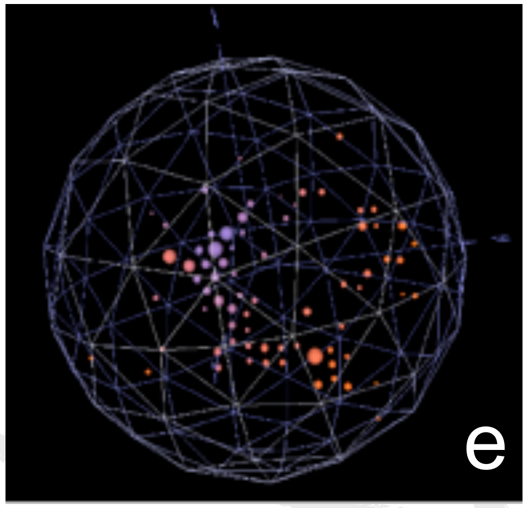


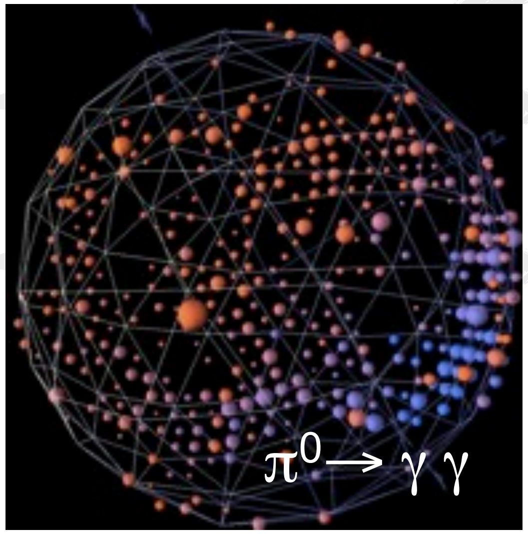
P. Kasper

MiniBooNE Detector: **Reconstruction and Particle ID**





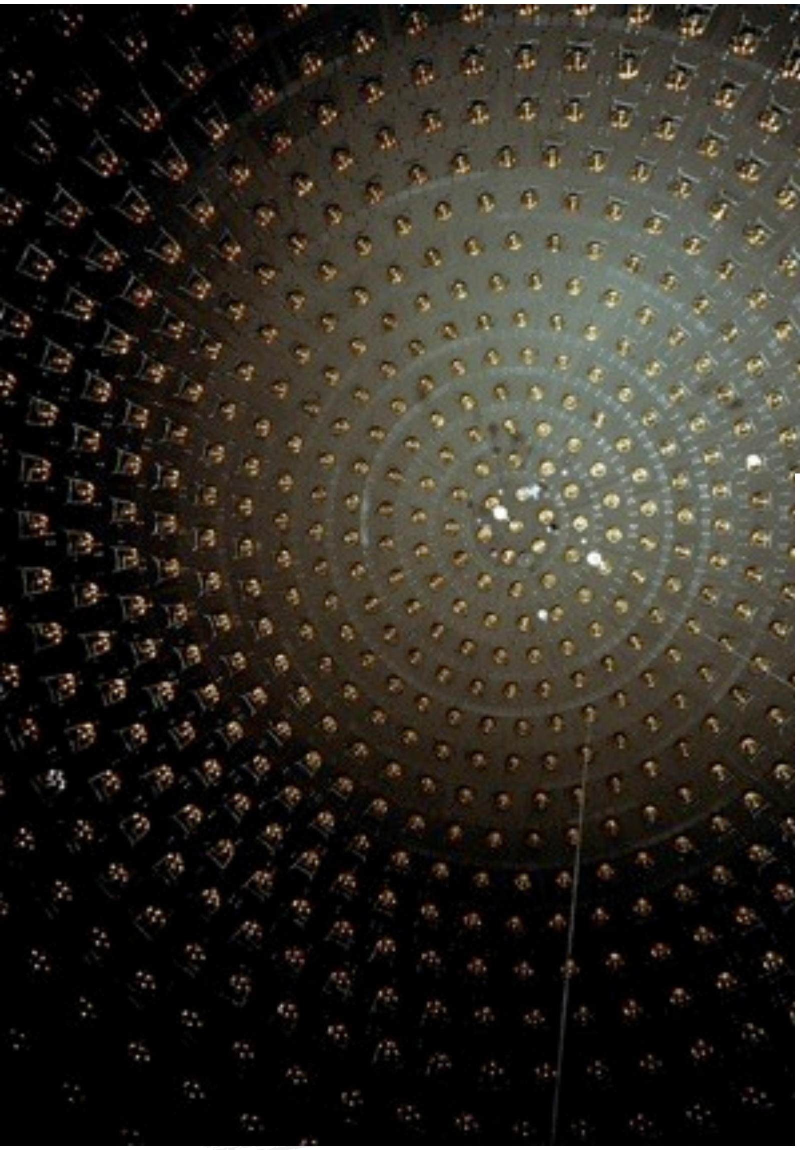




Reconstruction:
PMTs collect γs, record t and q,
fit time and angular distributions to find tracks

Final State Particle Identification:
muons have sharp Cherenkov rings and long tracks
electrons have fuzzy rings, from multiple scattering, and short tracks
neutral pions decay to 2 γs, which convert and produce 2 fuzzy rings,
easily misidentified as electrons if one ring gets lost!

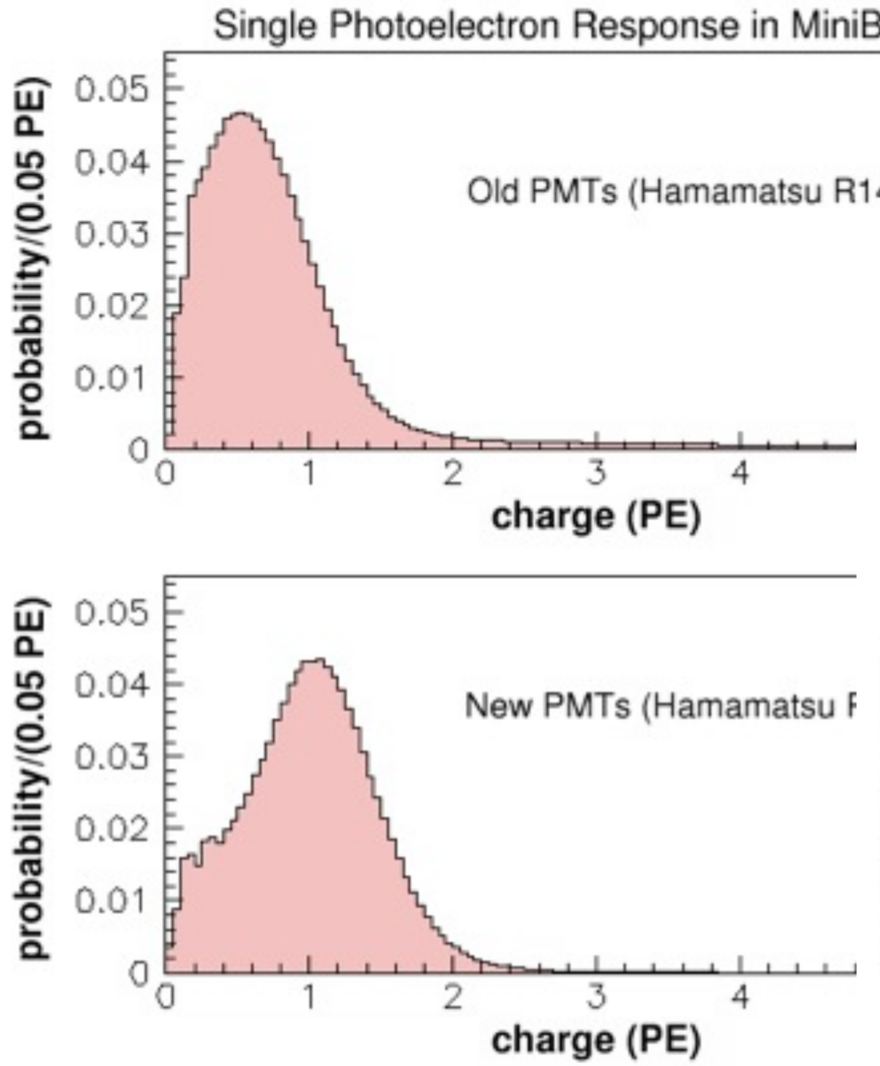
MiniBooNE Detector: **PMT Calibration**



10% photo-cathode coverage

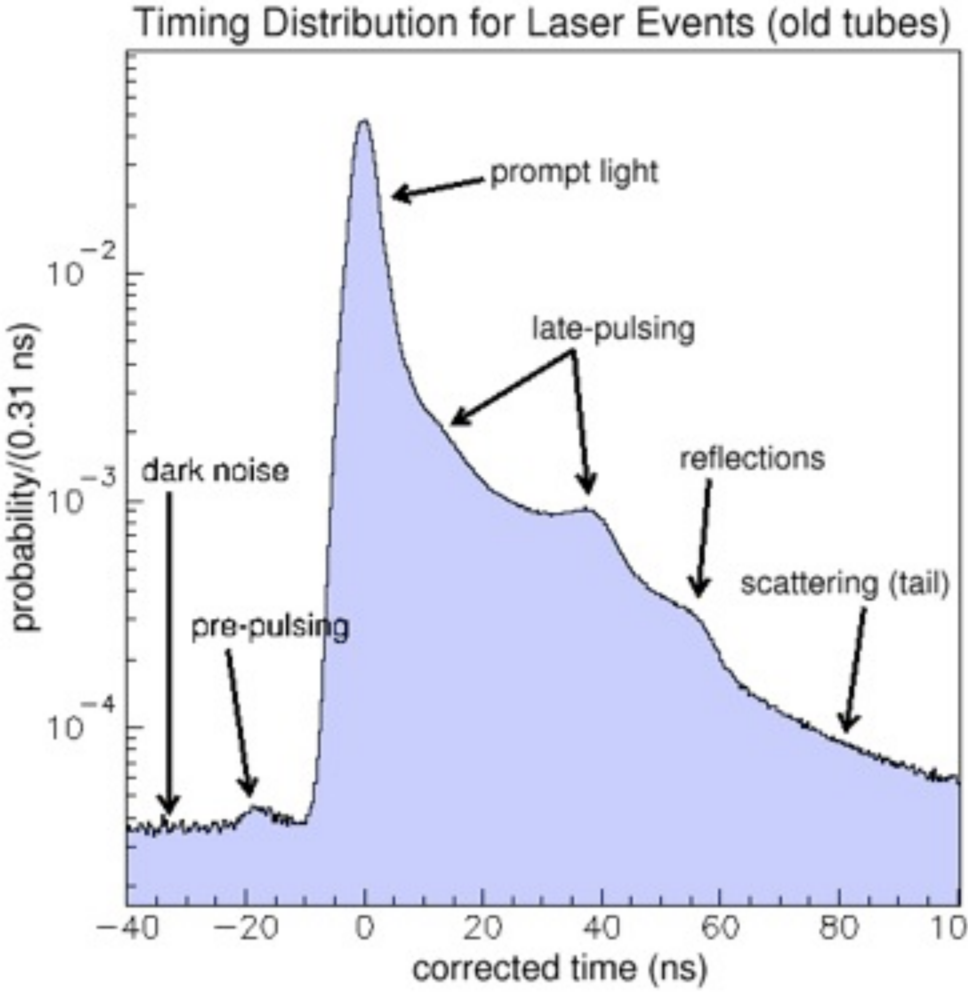
PMTs are calibrated with a laser + 4 flask system

PMT Charge Resolution: 1.4 PE, 0.5 PE
PMT Time Resolution: 1.7 ns, 1.1 ns



R.B. Patterson

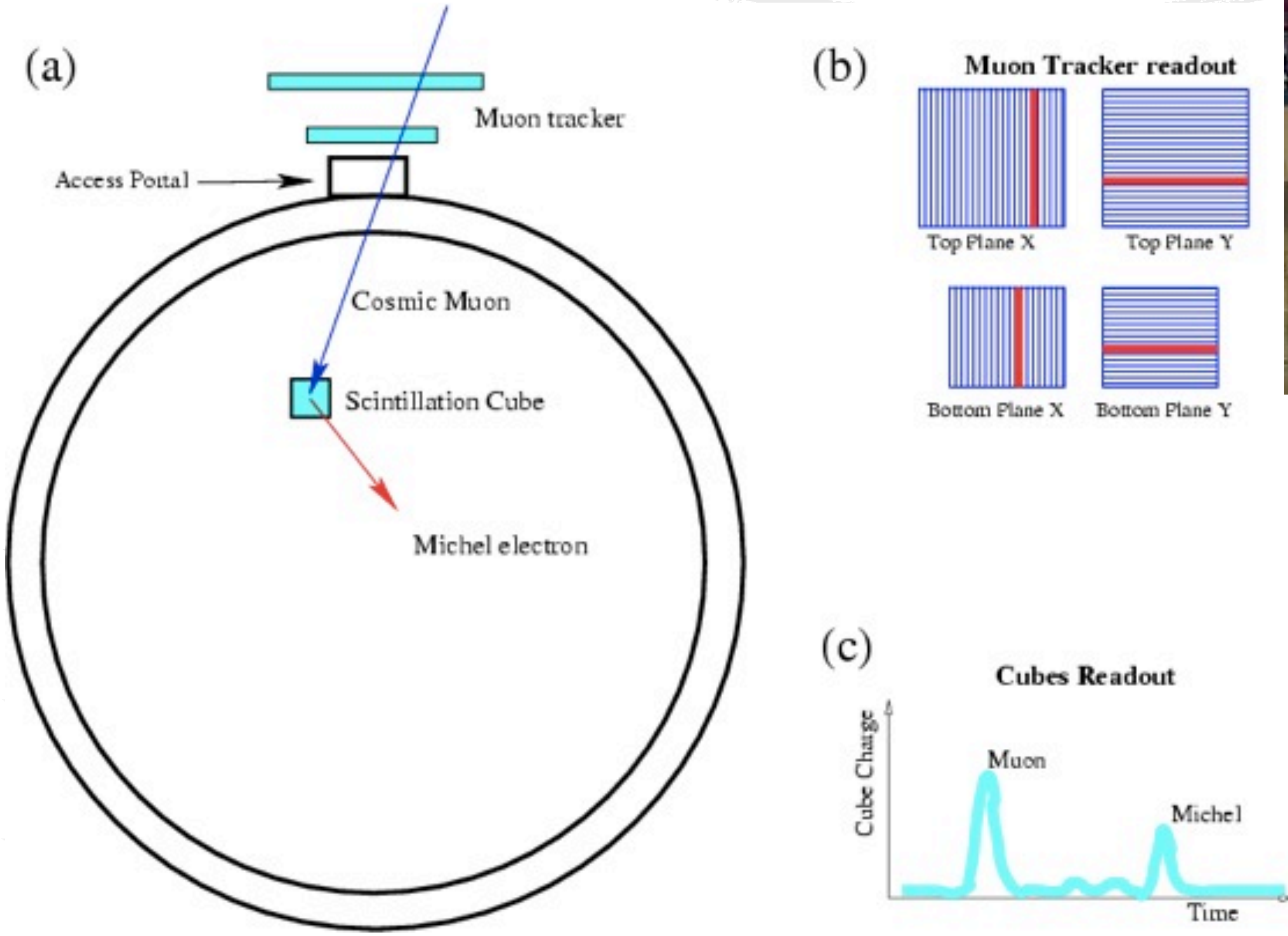
Two types of 8” Hamamatsu Tubes: R1408, R5912



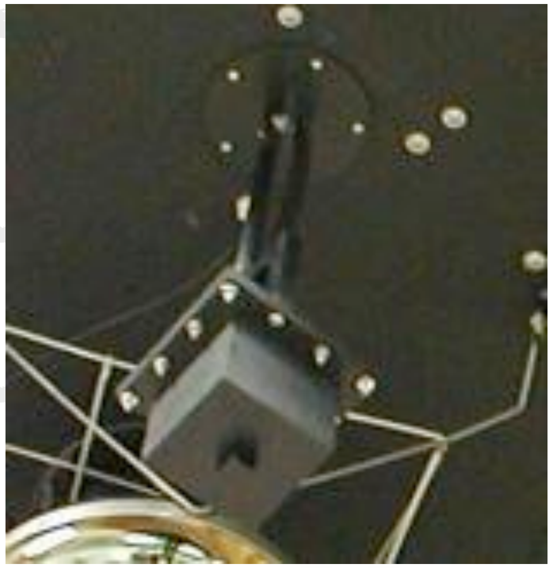
Laser data are acquired at 3.3 Hz to continuously calibrate PMT gain and timing constants

Calibrating Muons in MiniBooNE

- Hodoscope + 7 scintillator cubes track cosmic ray muons entering the tank



Muon Tracker

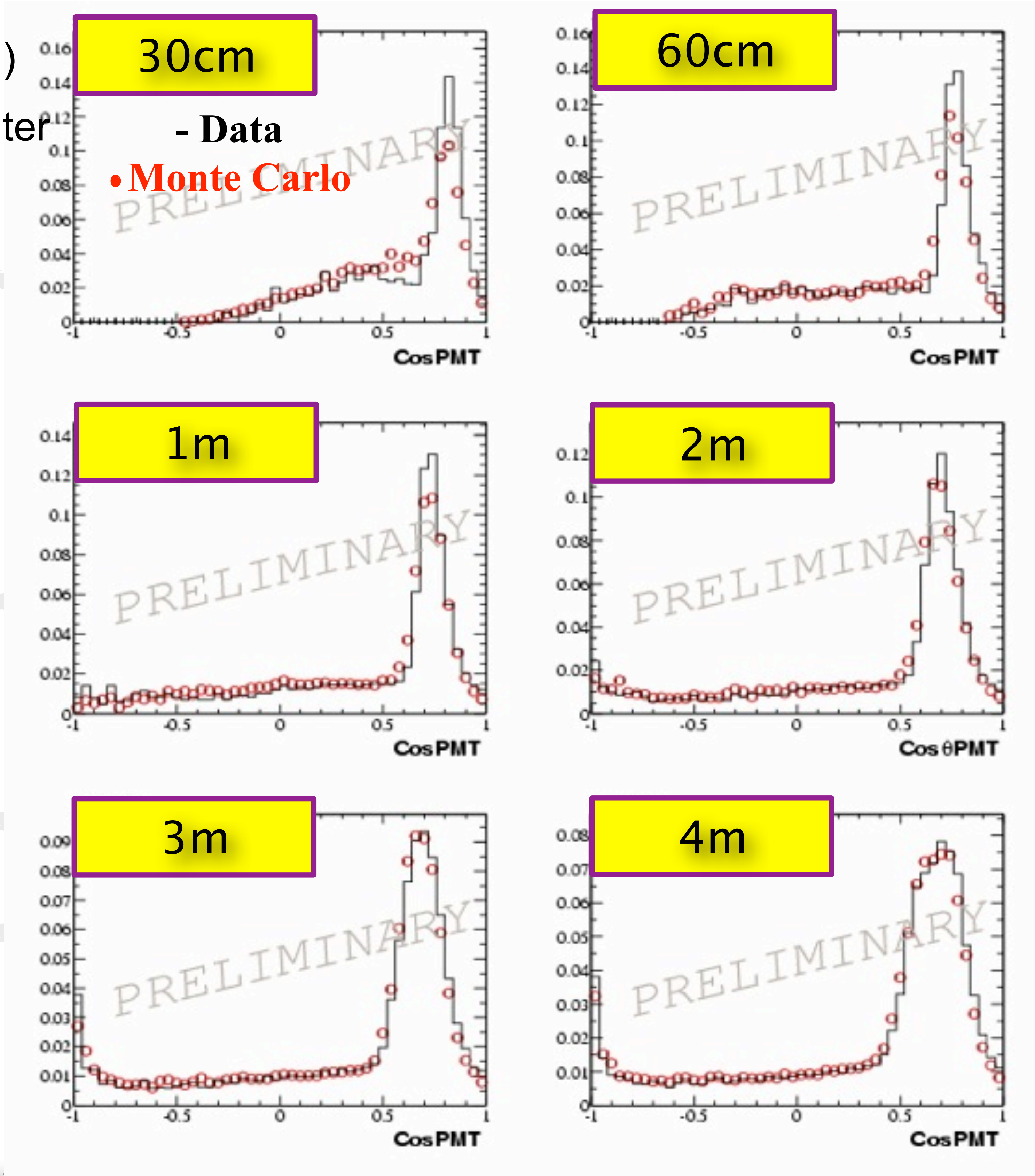


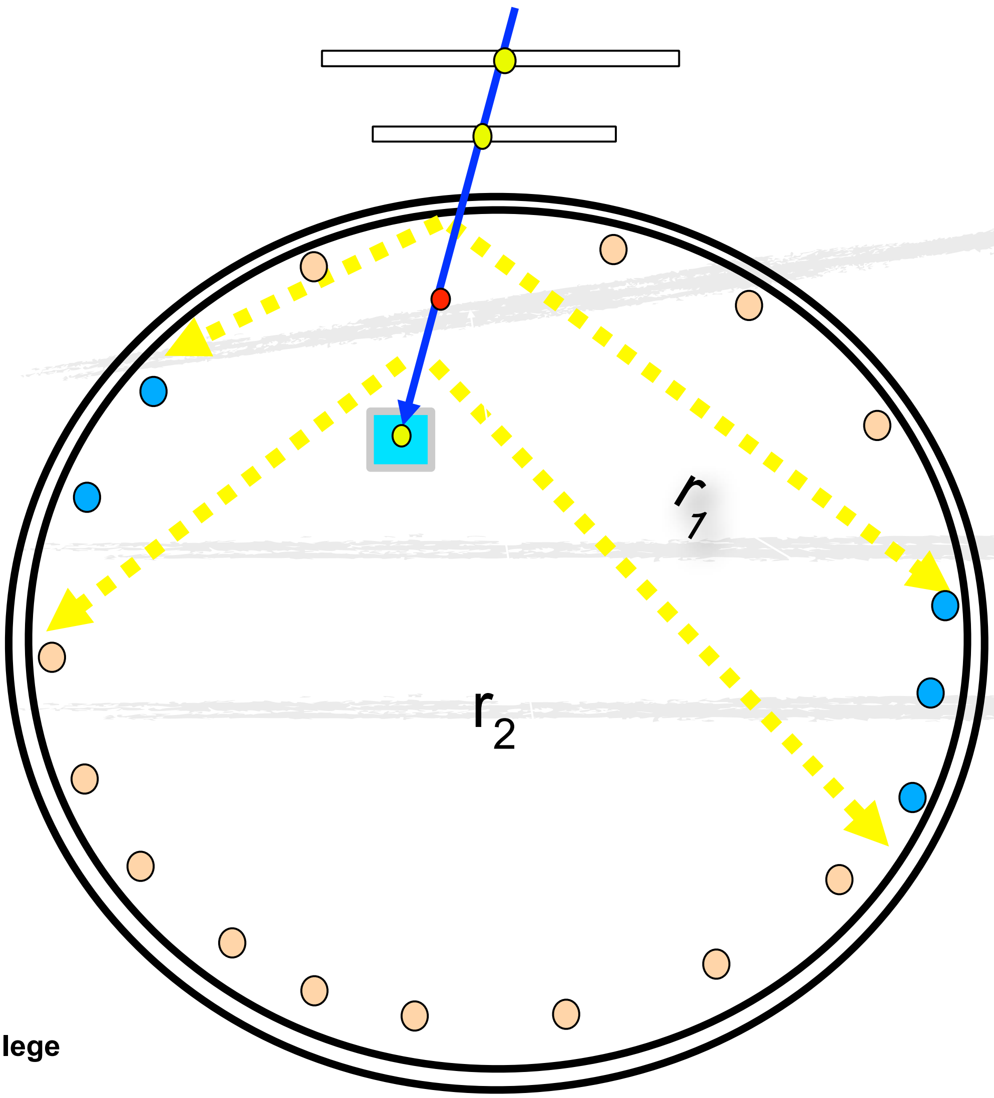
Scintillation cube

- Trigger: match tank subevents with cube hits

Calibrating Muons in MiniBooNE

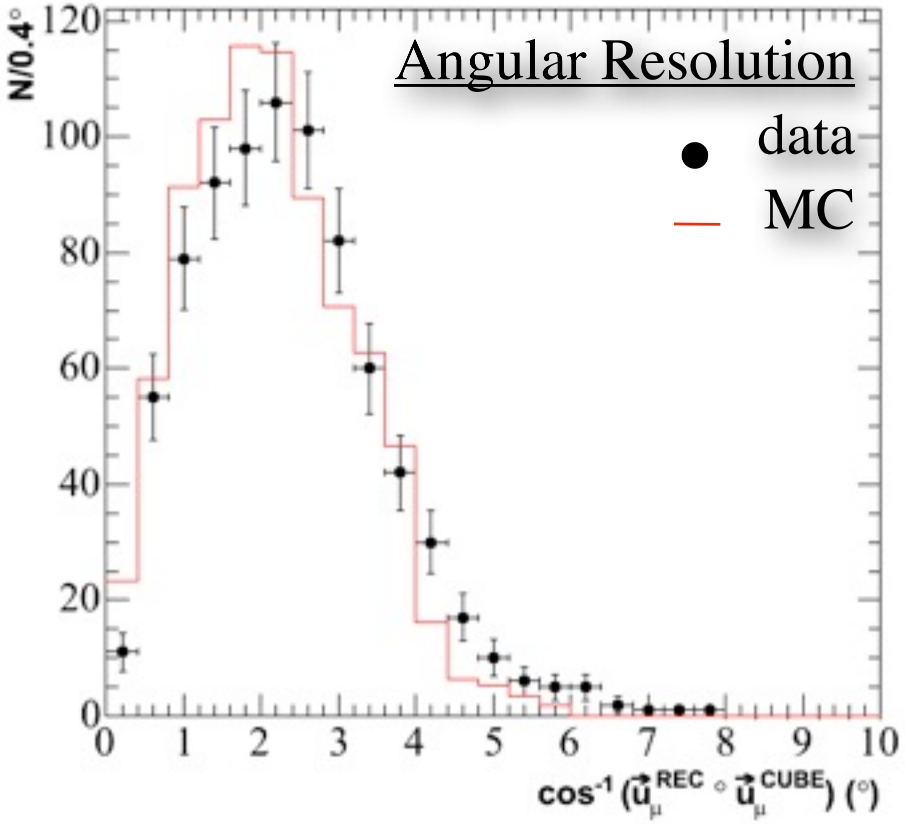
- Muon tracker determines event pars (x, t, u)
- Corrected times,angles w/ known track center
- Cherenkov rings and time peaks; isotropic and delayed emission
- Use cube data for optical model studies
  - separate scintillation and fluorescence

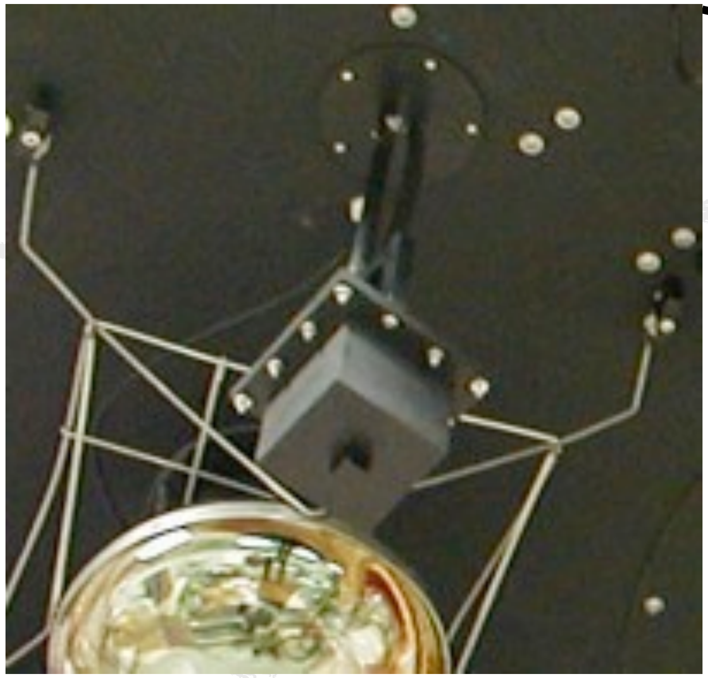


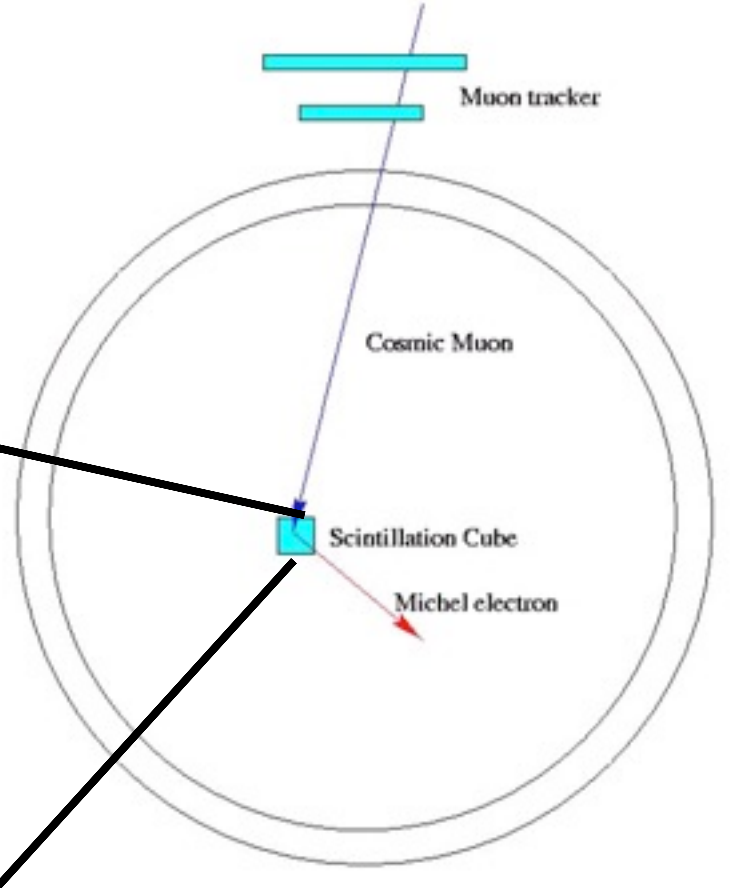


MiniBooNE Detector: **Cosmic Calibration**

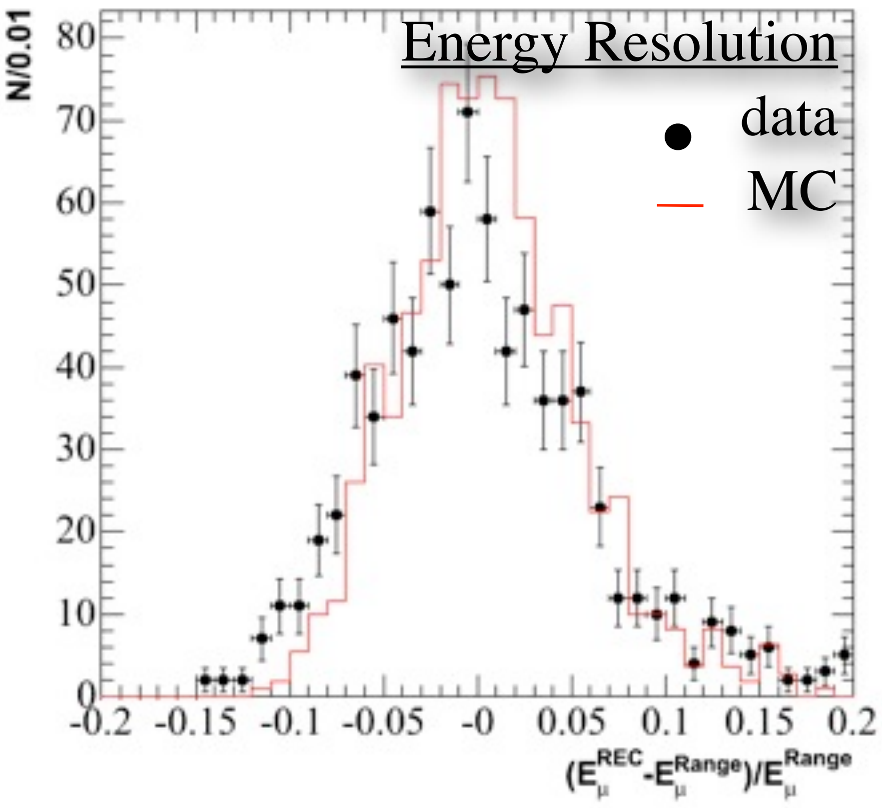
use cosmic muons and their decay electrons (Michels)







Muon tracker
7 scintillator cubes



Cosmic muons which stop in cubes:

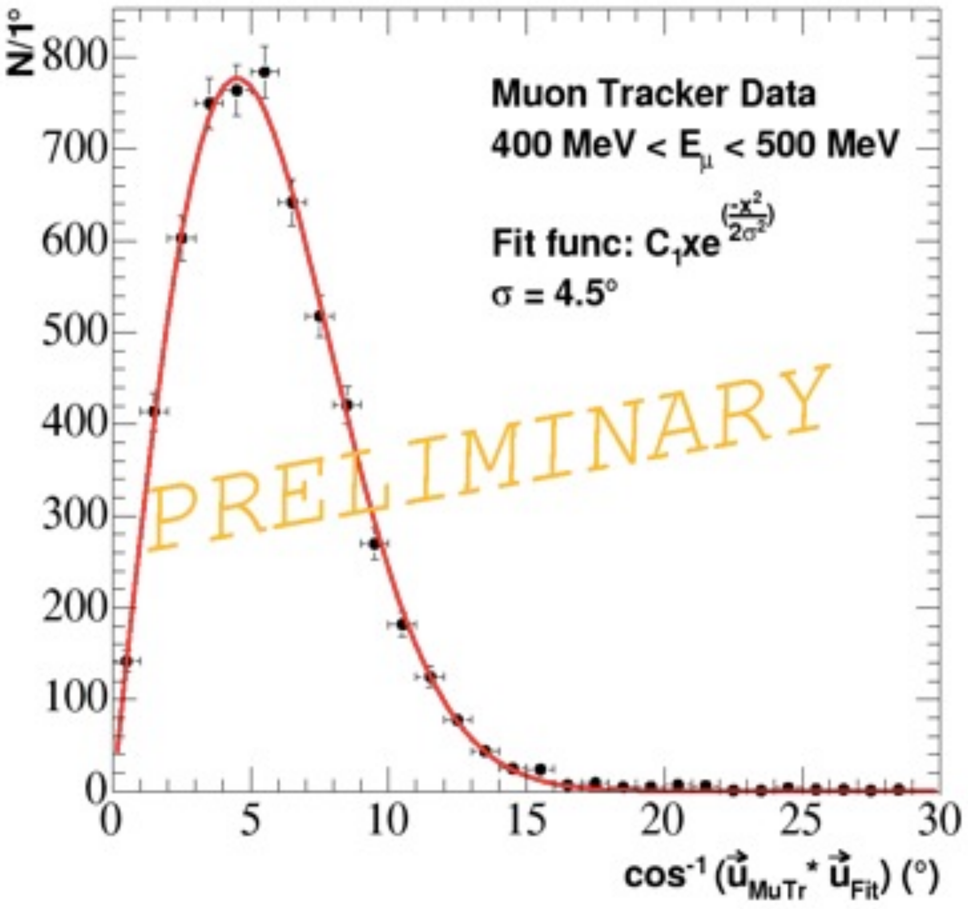
-test energy scale extrapolation up to 800 MeV

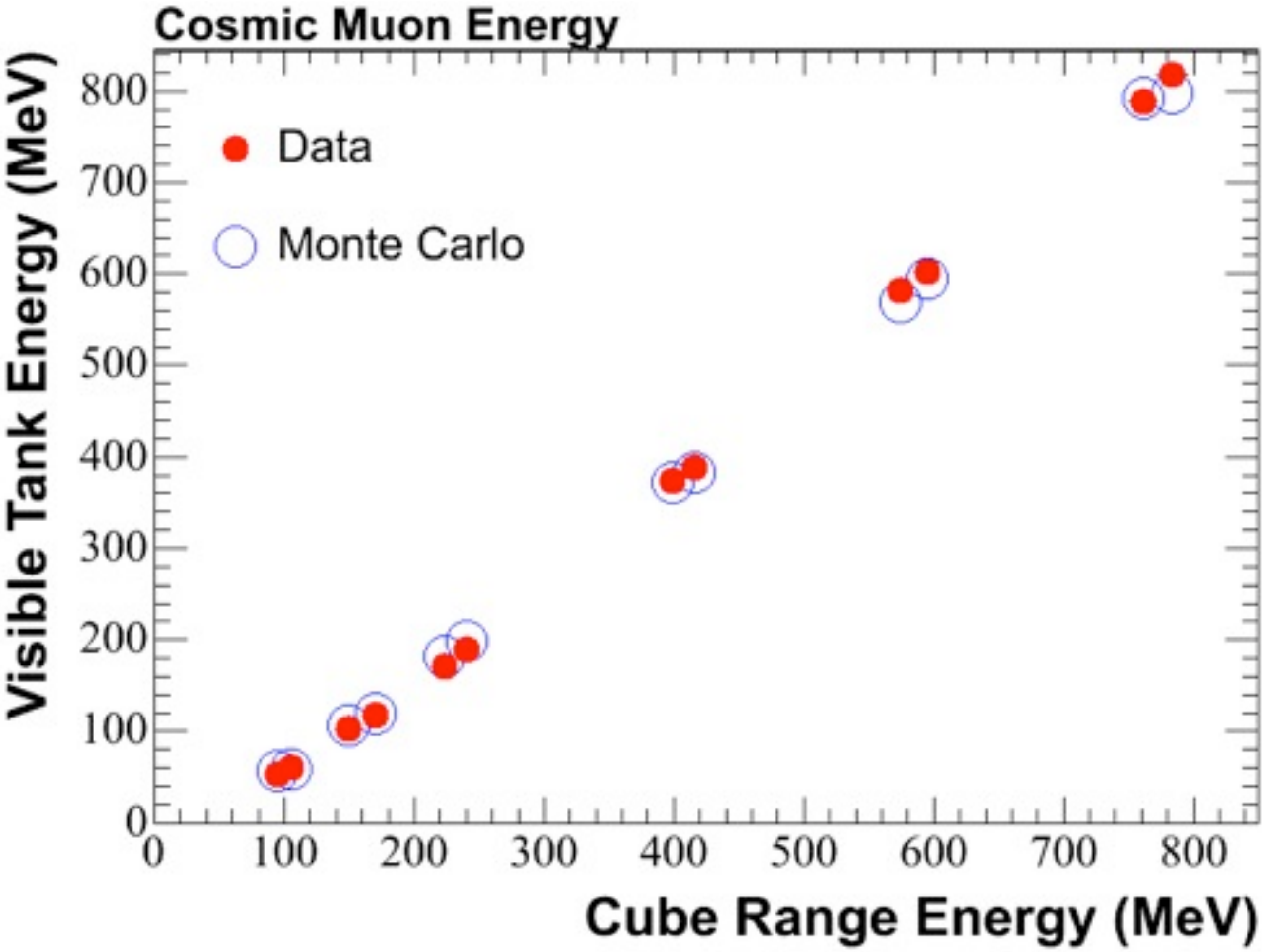
- measure energy, angle resolution
- compare data and MC

Muon tracker + cube calibration data continuously acquired at 1 Hz

Calibrating Muons in MiniBooNE

- Compare tracker & tank fitter directions
- Fit $\cos^{-1}(u_{MT} \cdot u_{Fit})$ to $x\exp(-x^2/2\sigma^2)$
- Extract angular resolution
  - ~4° at 400-500 MeV

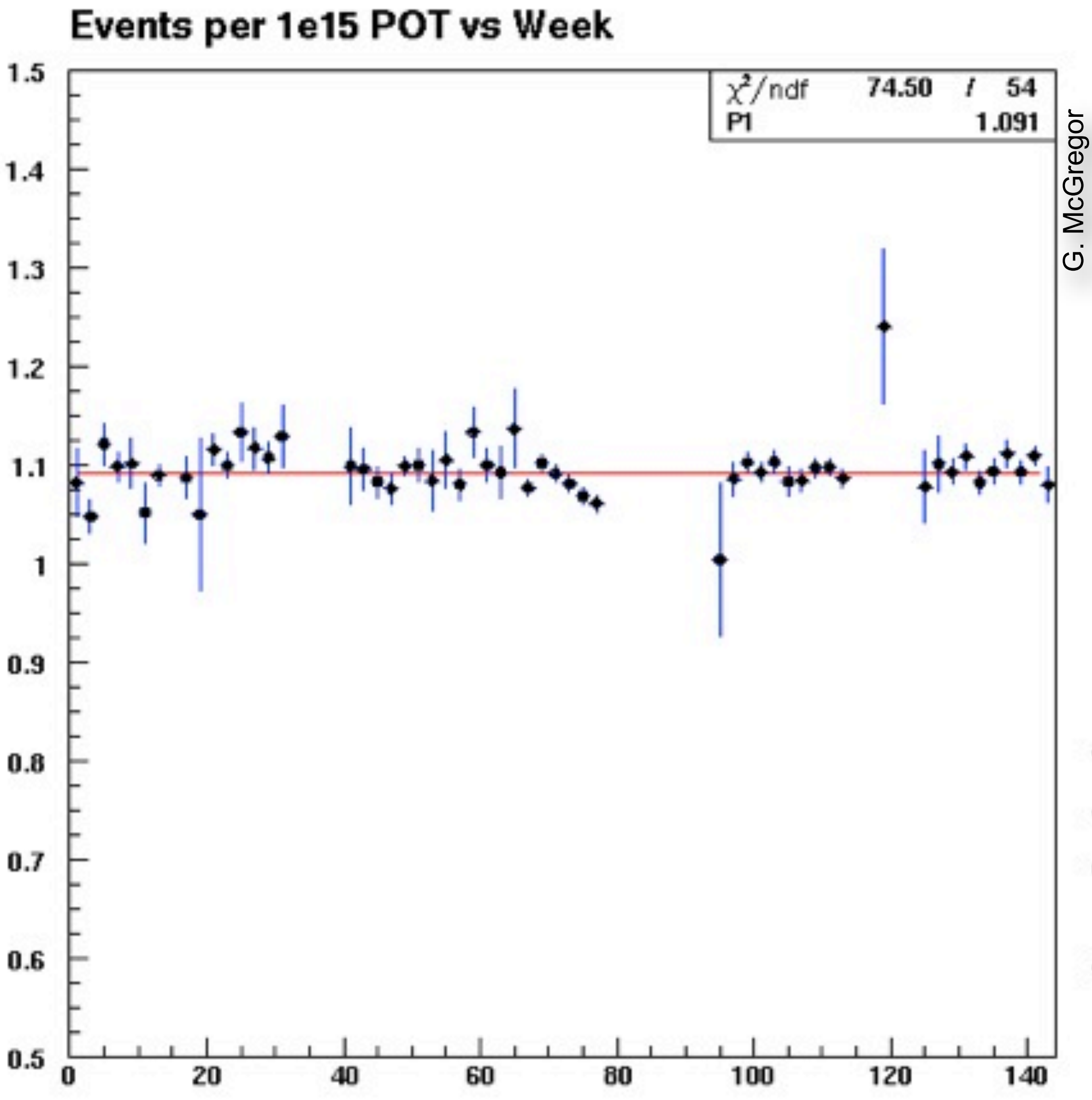




- Calibrate μ energy reconstruction using range measured with cubes + tracker
- Muon Tracker system energy resolution ~5%
- Will be used to set μ energy scale

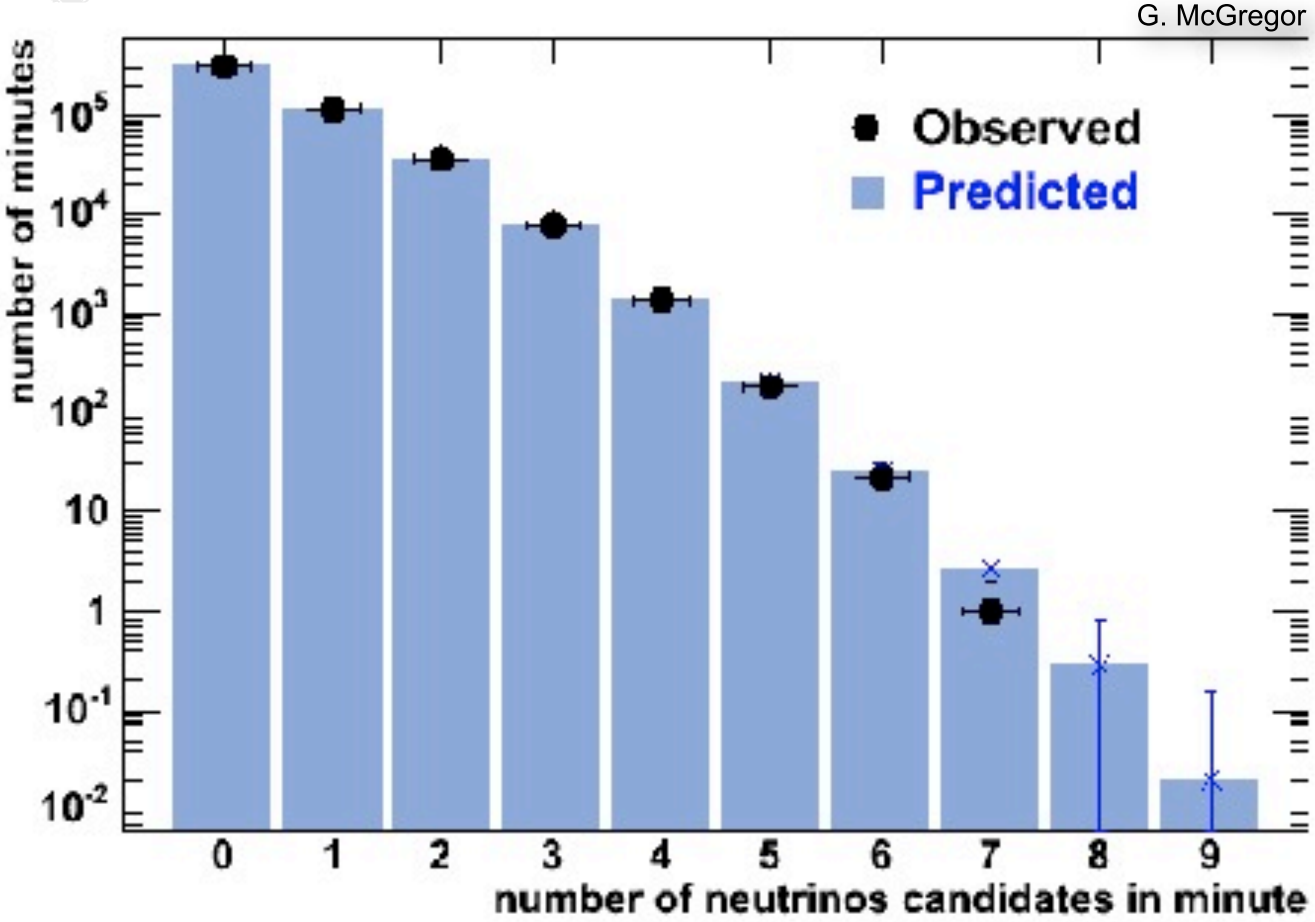
MiniBooNE Beam & Detector: **Stability**

Neutrinos per proton on target throughout the neutrino run:



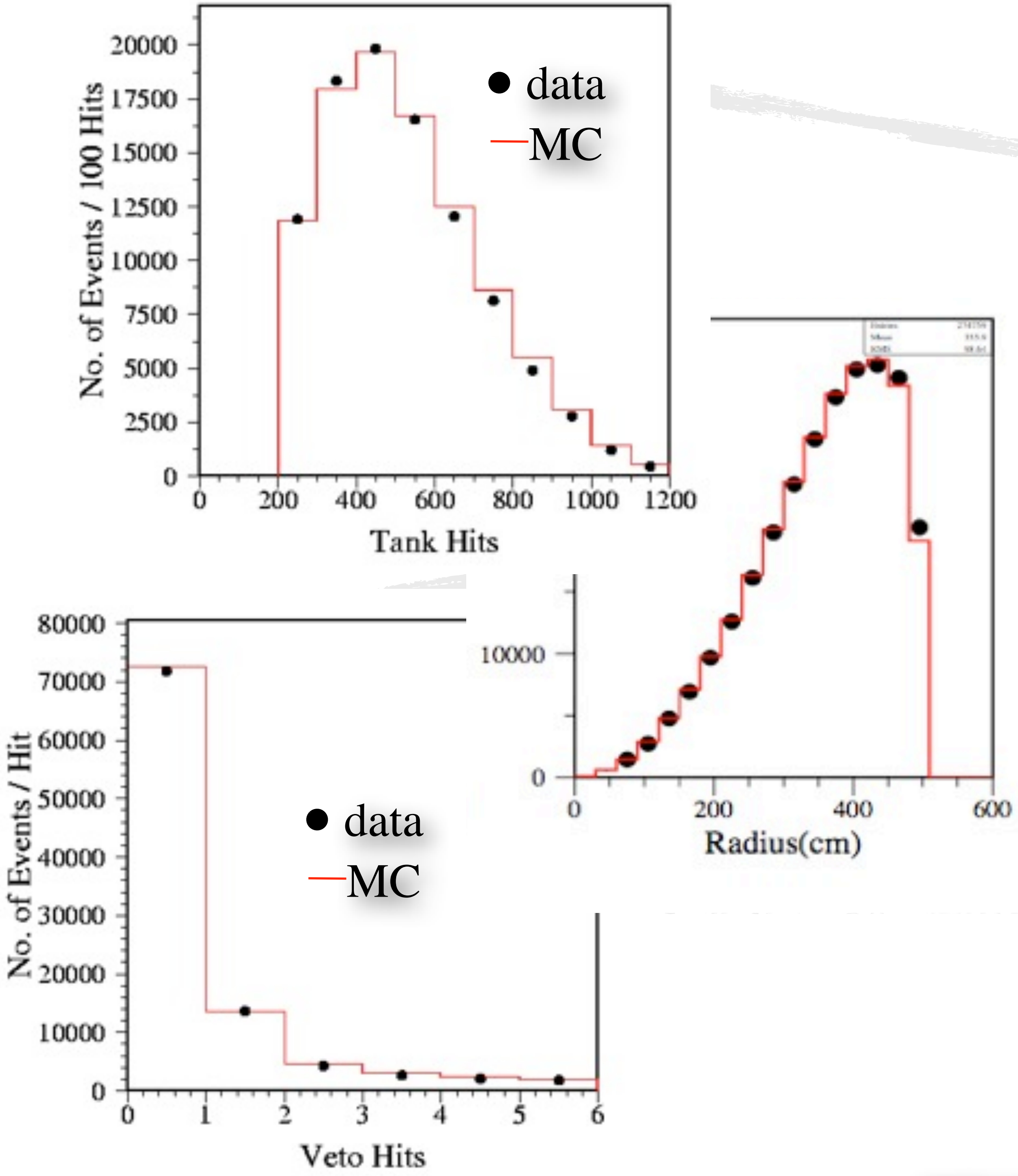
MiniBooNE observes
~1 neutrino interaction
per 1E15 protons.

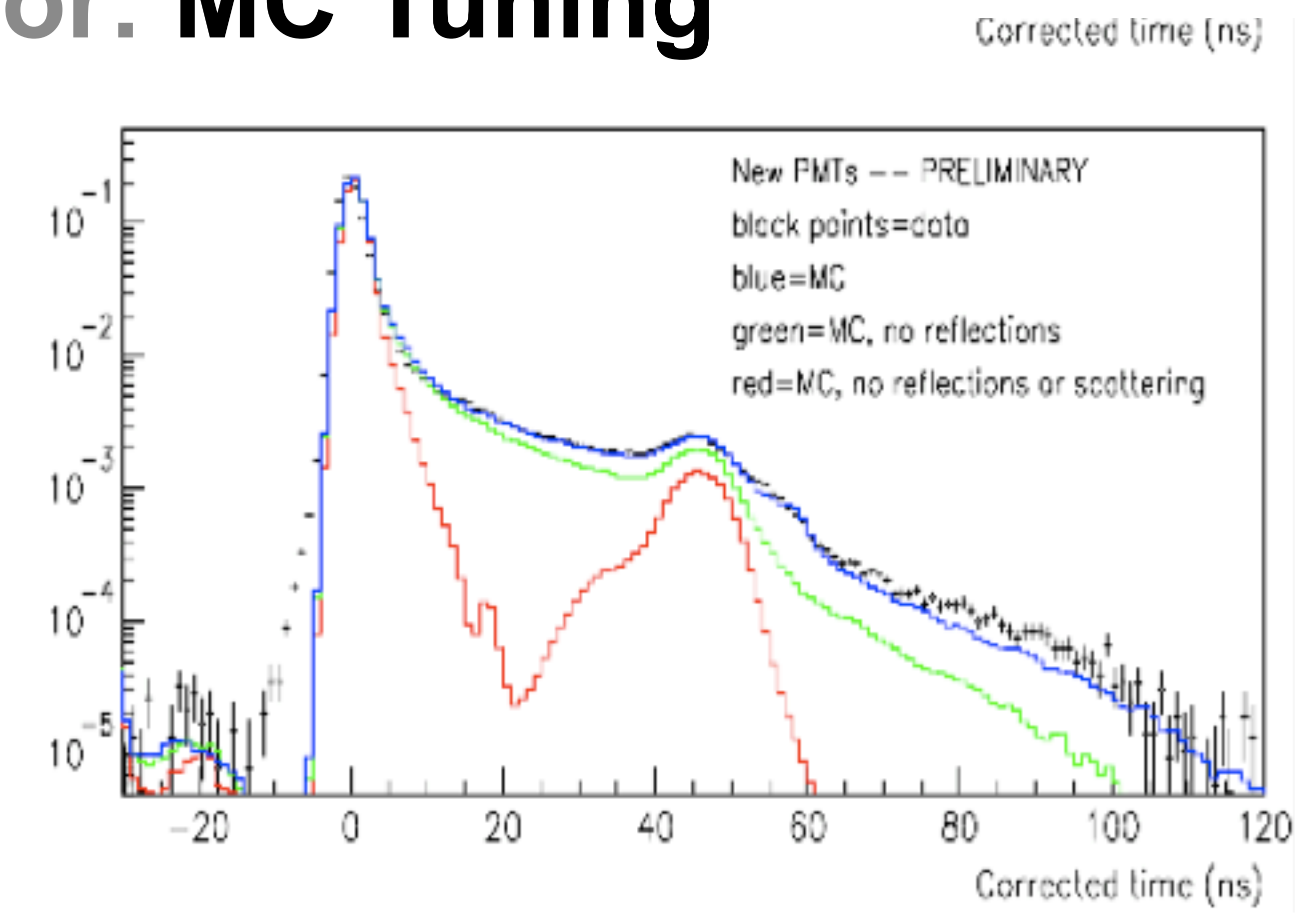
Observed and expected events per minute

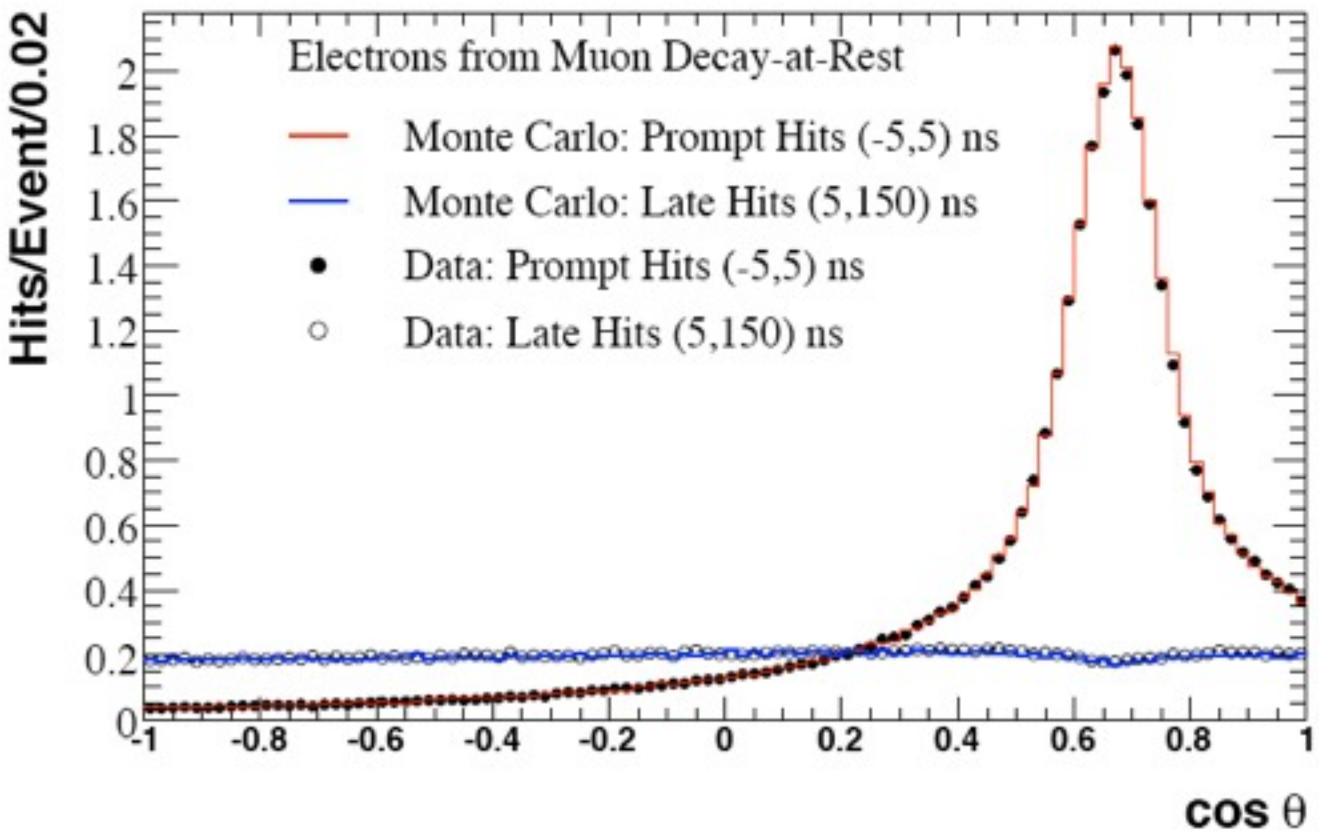


MiniBooNE Detector: **MC Tuning**

MC tuning with calibration data



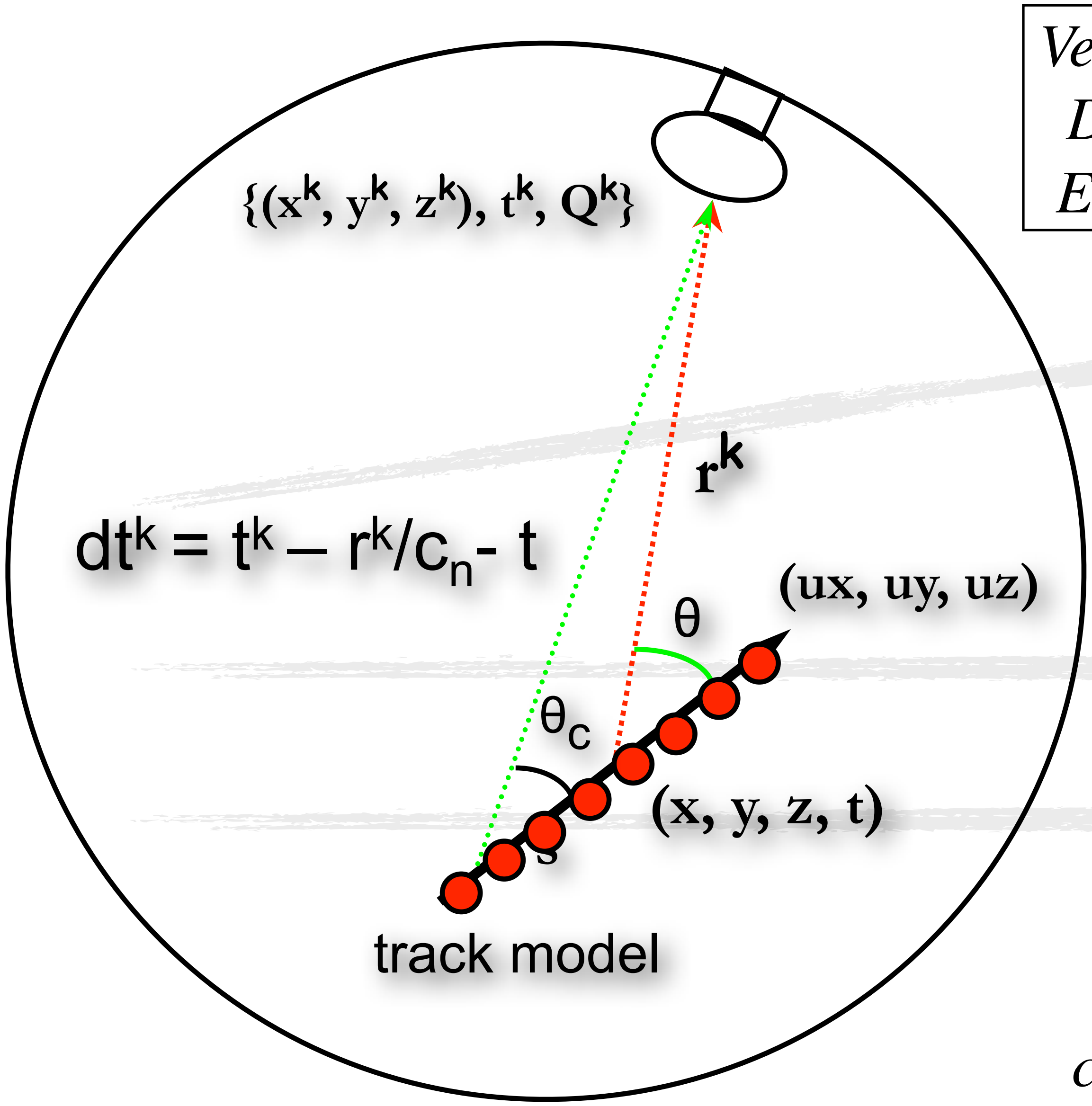




MiniBooNE Detector: **Analysis**

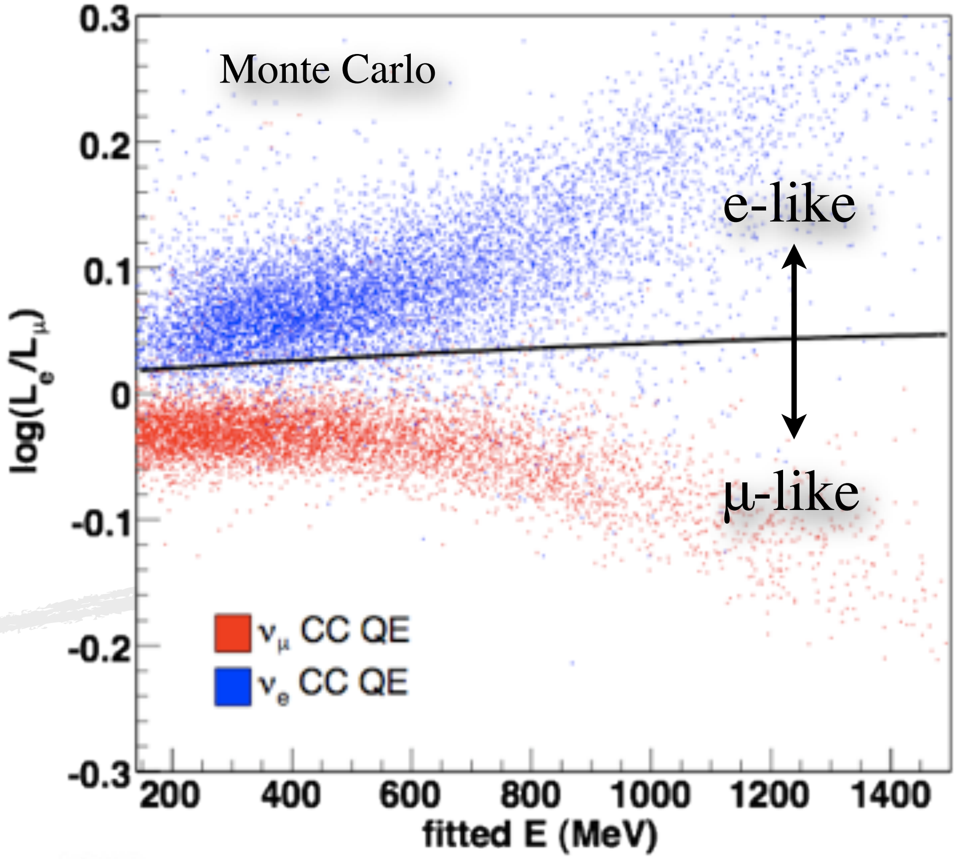
Reconstruction fits an extended light source with 7 parameters: vertex, direction (θ, ϕ), time, energy

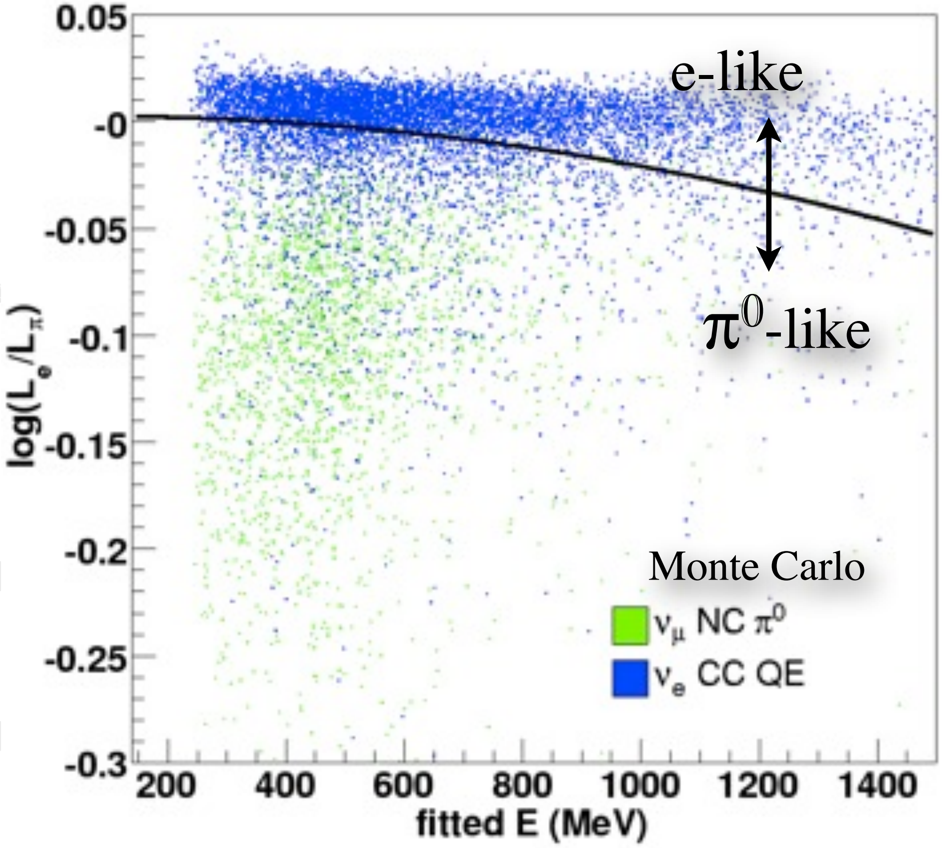
Fit events under 3 possible hypotheses:
μ-like, e-like, two track (π^0-like)



Fitter resolution

Vertex:	22 cm
Direction:	2.8°
Energy:	11%

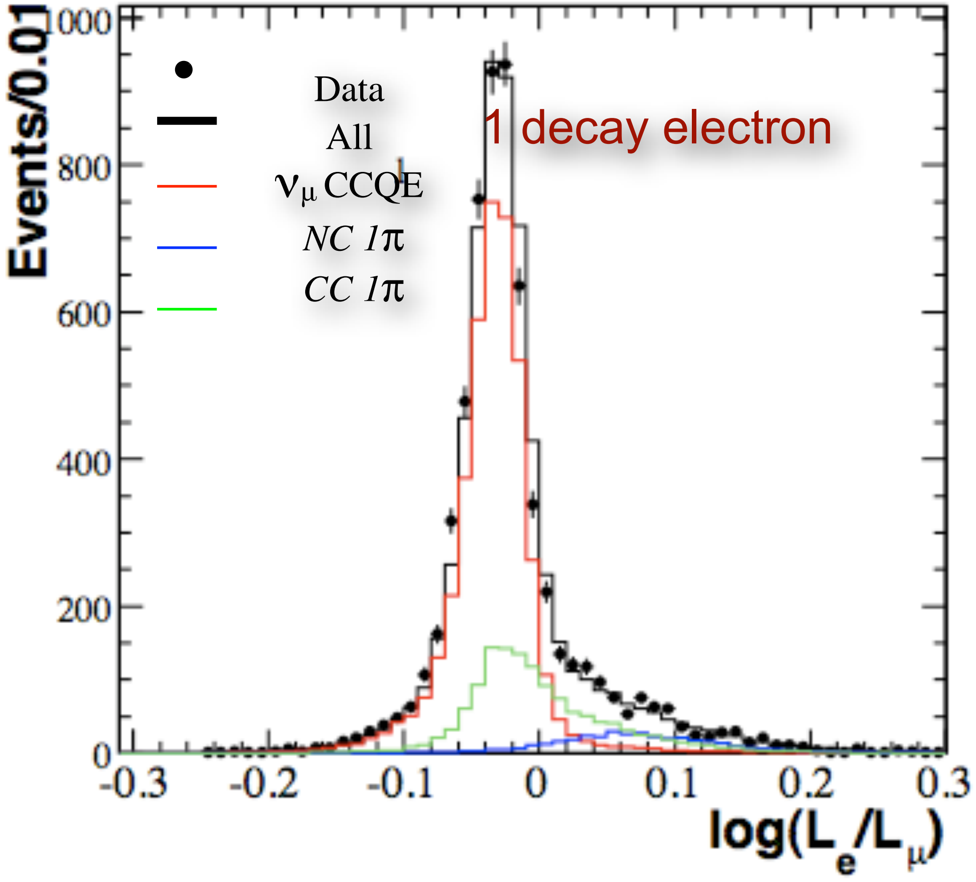




Particle ID relies on likelihood ratio cuts to select ν_e, cuts chosen to maximise sensitivity to $\nu_\mu \rightarrow \nu_e$ oscillation

MiniBooNE Detector: e/μ Likelihood

Test μ-e separation on data:

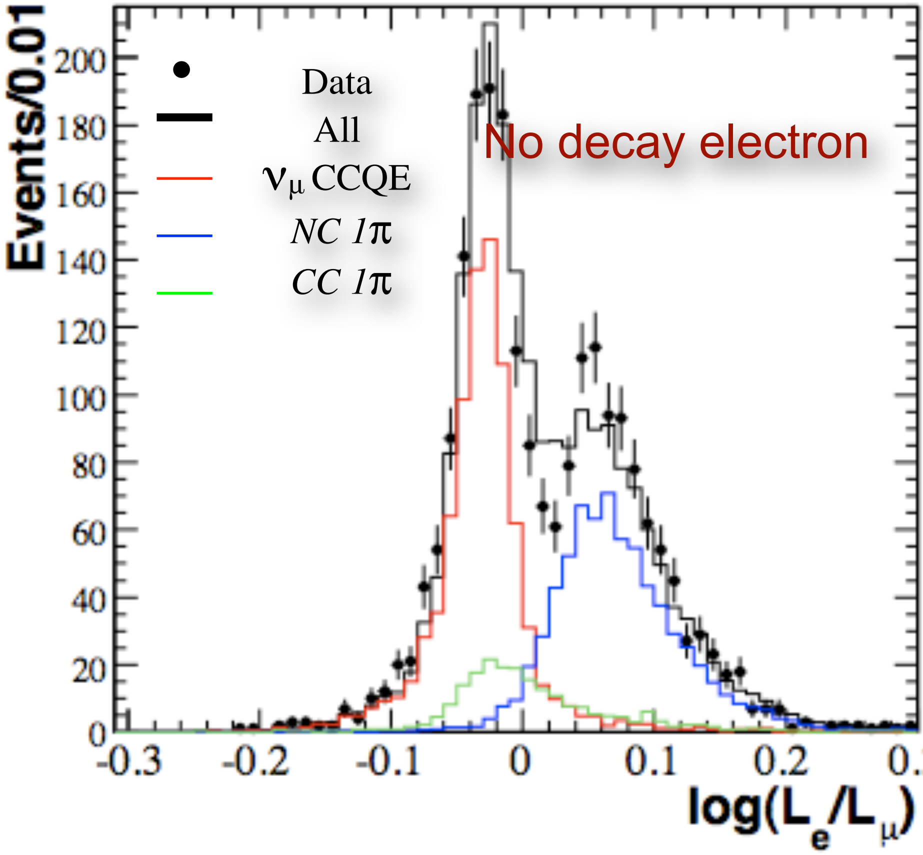


ν_μ CCQE data sample

Pre-selection cuts

Fiducial volume: (R < 500 cm)

2 subevents: muon + decay electron



"All-but-signal" data sample

Pre-selection cuts

Fiducial volume: (R < 500 cm)

1 subevent: 8% of muons capture on ^{12}C

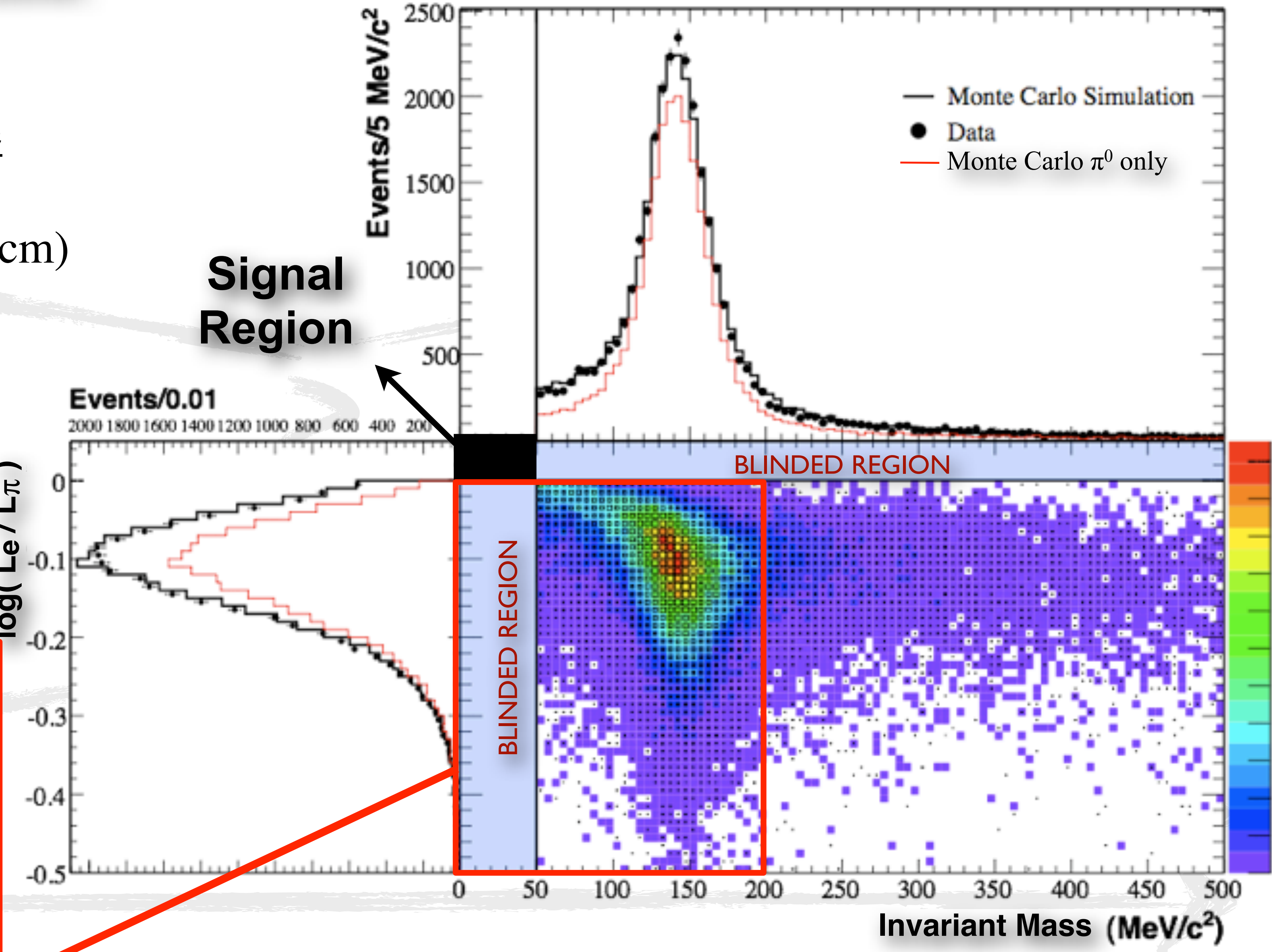
Events with $\log(L_e/L_\mu) > 0$ *(e-like) undergo additional fit with two-track hypothesis.*

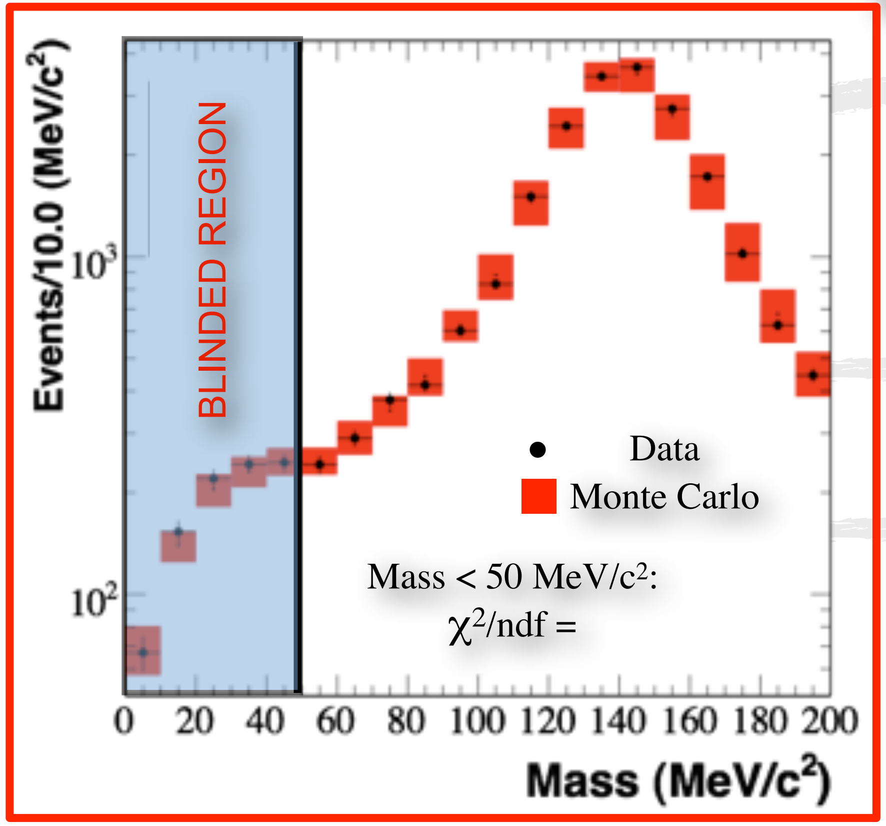
MiniBooNE Detector: e/π^0 Likelihood

Test e-π^0 separation on data:

“All-but-signal” data sample

- Pre-selection cuts
- Fiducial volume cut (R < 500 cm)
- 1 subevent
- Invariant mass > 50 MeV/c^2
- $\log(L_e / L_\pi) < 0$ (π-like)

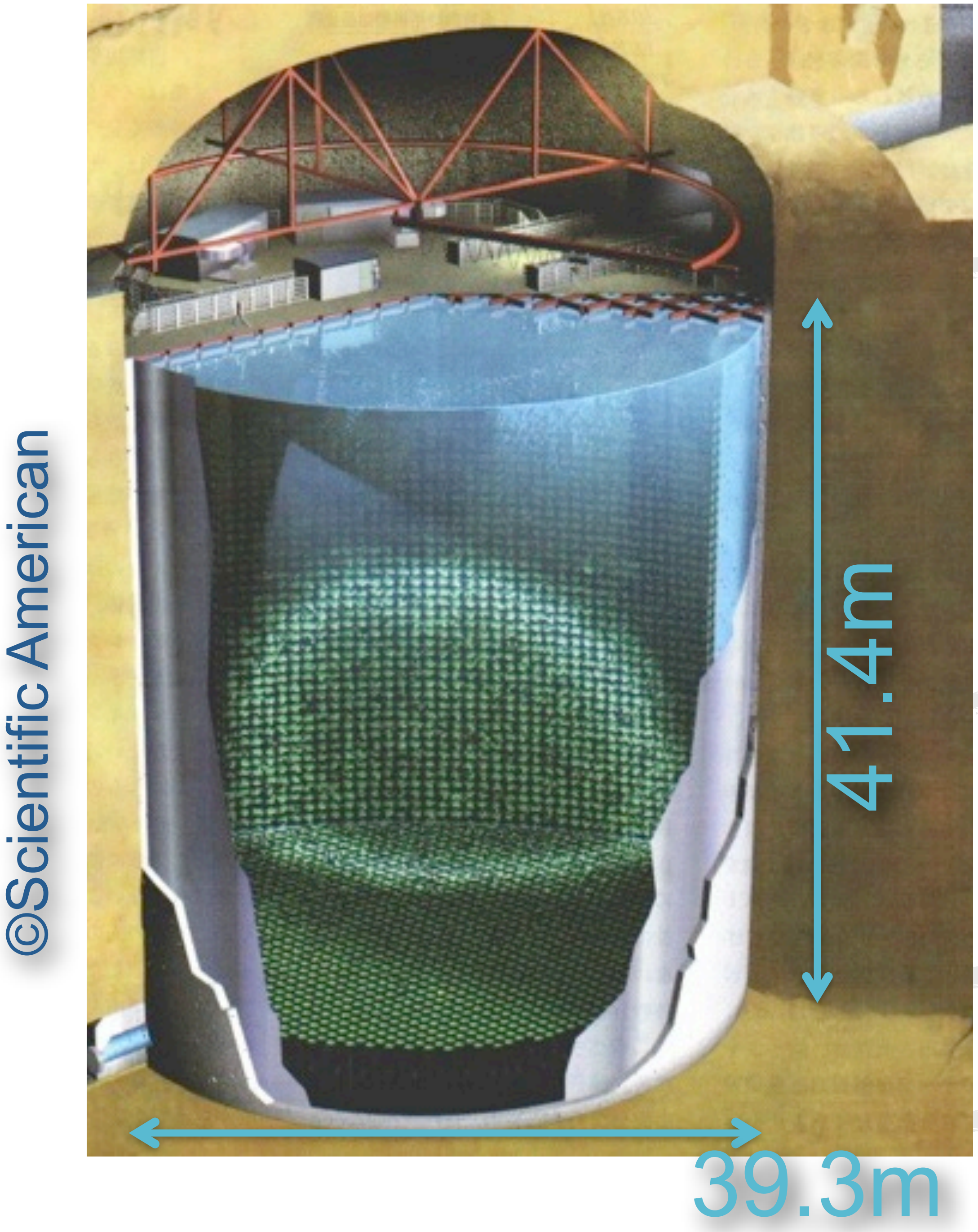




Tighter selection cuts:

- Invariant mass < 200 MeV/c^2
- $\log(L_e / L_\mu) > 0$ (e-like)
- $\log(L_e / L_\pi) < 0$ (π-like)

Super-Kamiokande



- 1km underground at Kamioka
  - Muon flux is 1E-5 from the surface.
- Total mass is 50kton and the fiducial mass is 22.5 kton.
  - Inner detector: 11,129 20inch PMT
  - Outer detector: 1,885 8inch PMT
- Dead-time-less DAQ
- GPPS record for the coincidence with the accelerator.

🔴

Booster Proton accelerator

- 8 GeV protons sent to target

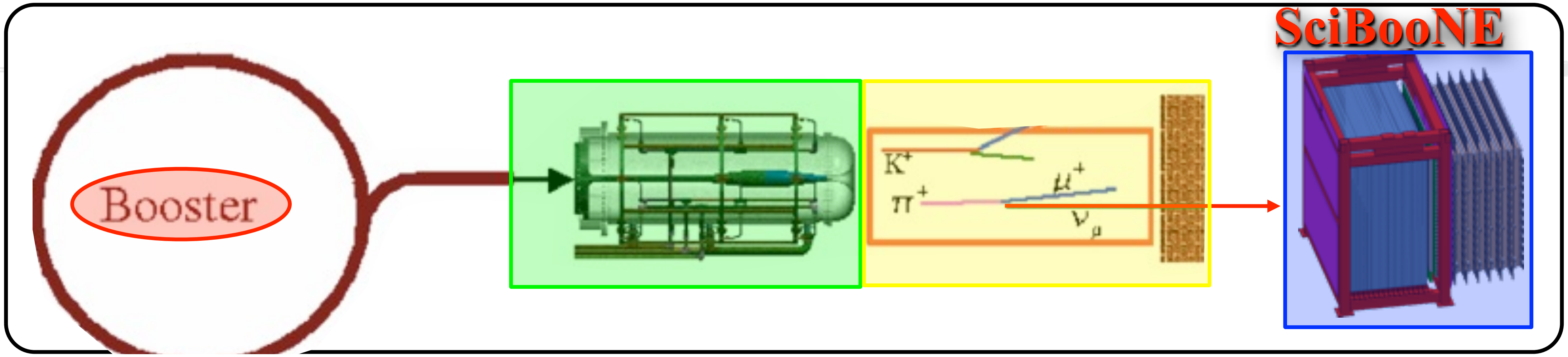
🟩 Target Hall

- Beryllium target:
  71cm long 1cm diameter
- Resultant mesons focused with magnetic horn
- Reversible horn polarity

🟨 50m decay volume

- Mesons decay to μ & ν_μ
- Short decay pipe minimizes $\mu \rightarrow \nu_e$decay

🟦 SciBooNE located 100m from the beryllium target

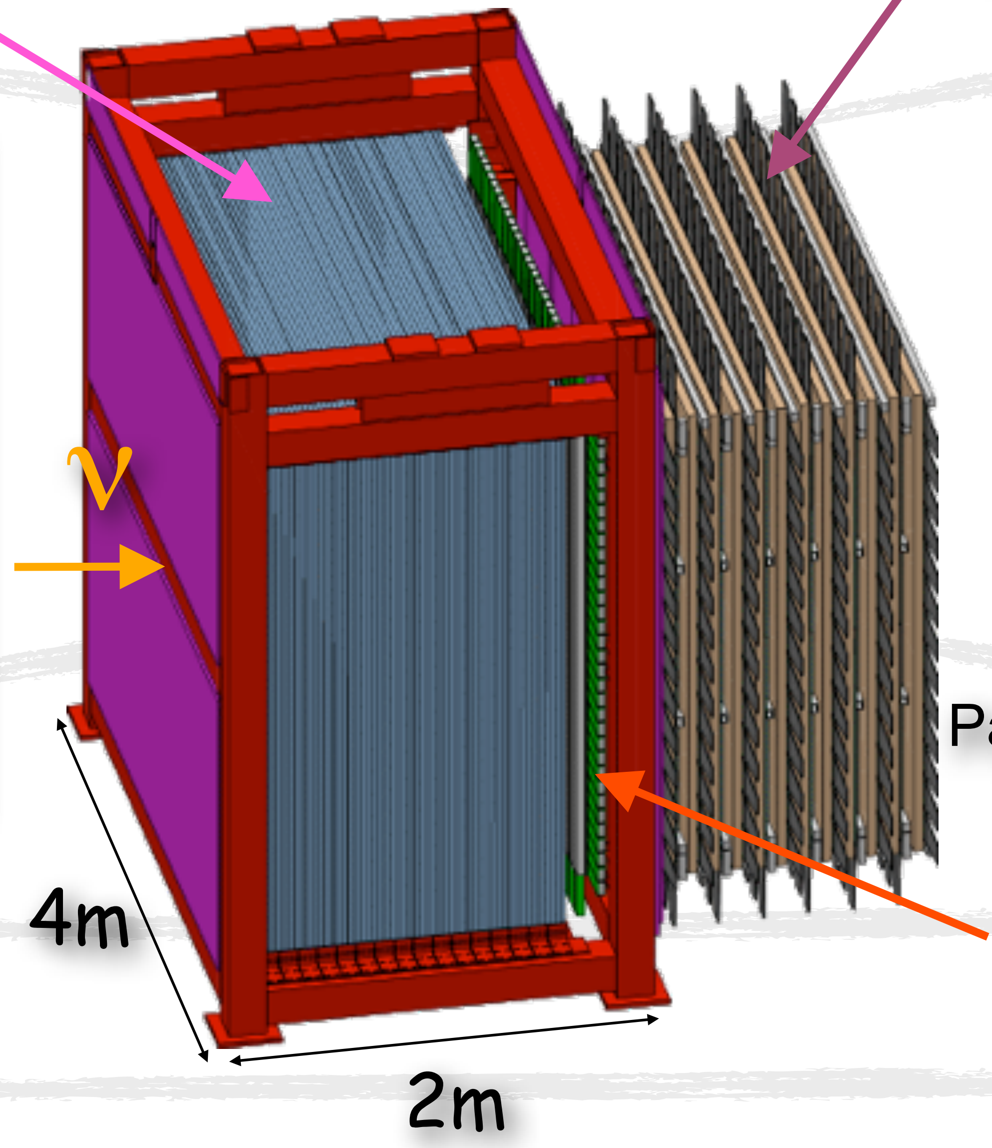


SciBooNE detector

SciBar

- scintillator tracking detector
- 14,336 scintillator bars (15 tons)
- Neutrino target
- detect all charged particles
- p/π separation using dE/dx

Used in K2K experiment



Muon Range Detector (MRD)

- 12 2”-thick steel + scintillator planes
- measure muon momentum with range up to 1.2 GeV/c

Parts recycled from past experiments

Electron Catcher (EC)

- spaghetti calorimeter
- 2 planes (11 X_0)
- identify π^0 and ν_e

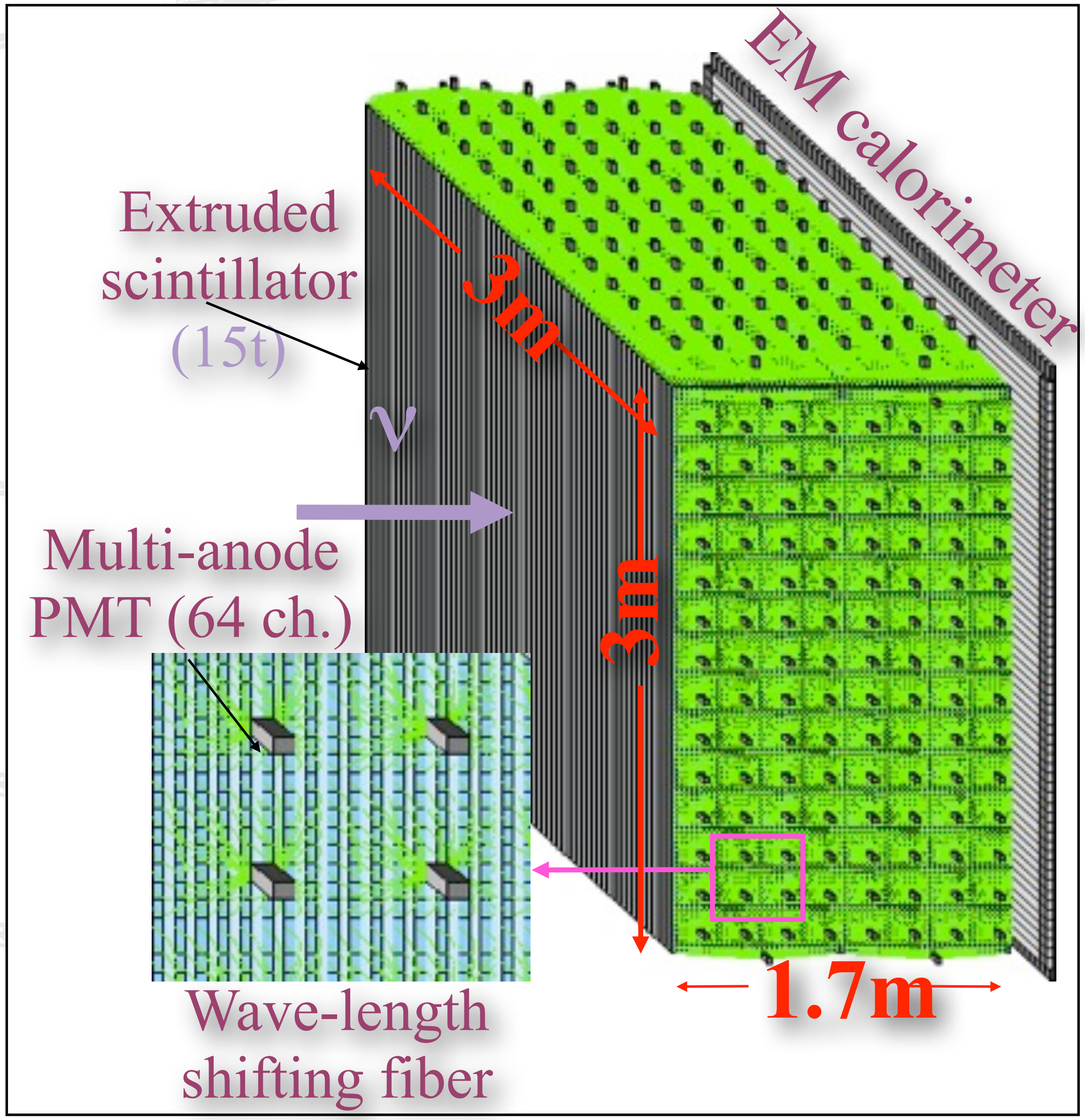
Used in CHORUS, HARP and K2K

DOE-wide Pollution Prevention Star (P2 Star) Award

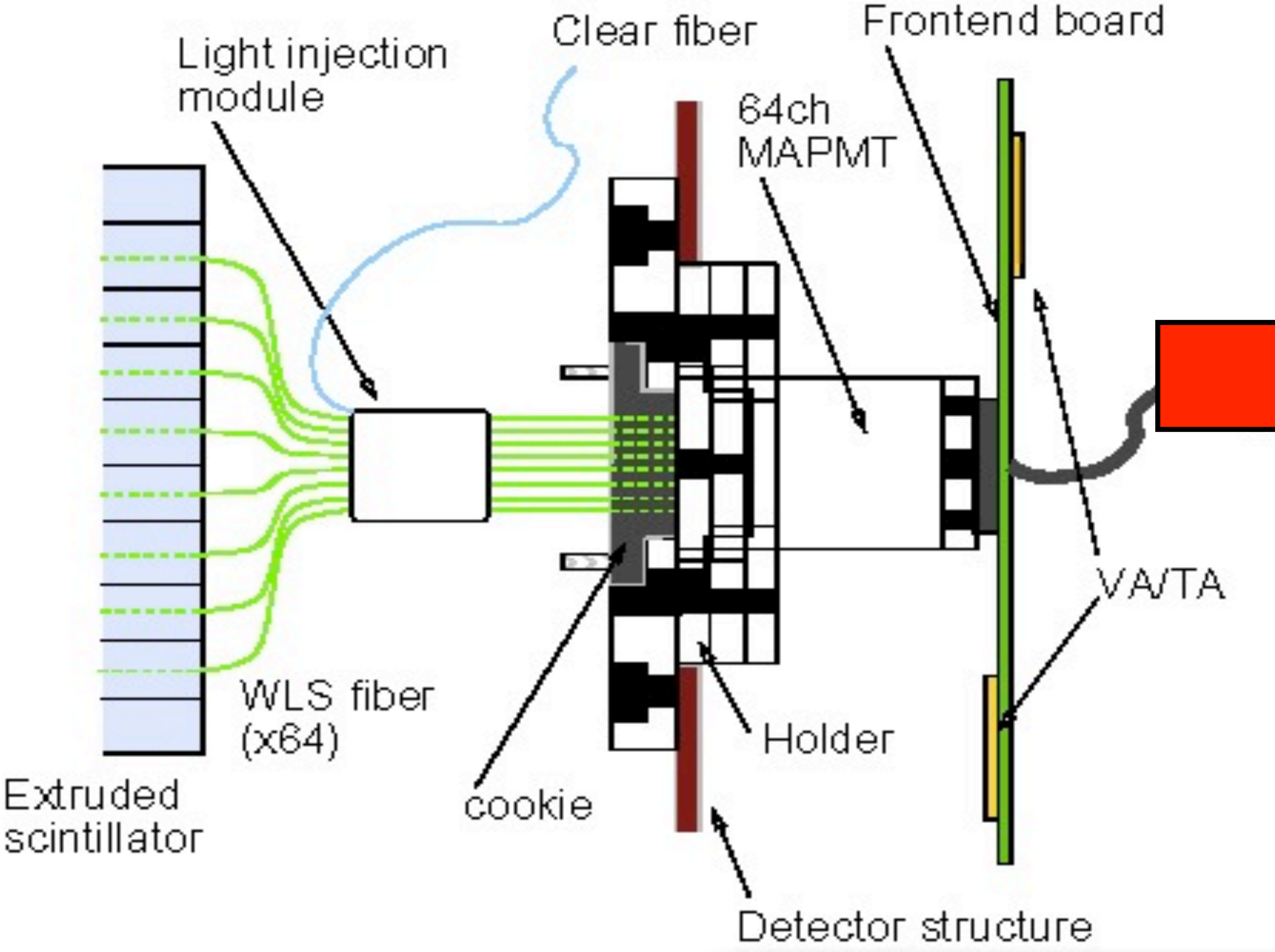
SciBar detector

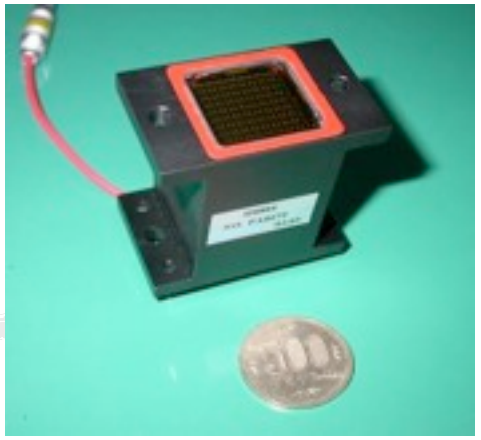
- **Extruded scintillators with WLS fiber readout**
- **Scintillators are the neutrino target**
- **3m x 3m x 1.7m (Total: 15 tons)**
- **14,336 channels**
- **Detect short tracks (>8cm)**
- **Distinguish a proton from a pion by dE/dx**

→Clear identification of ν interaction process

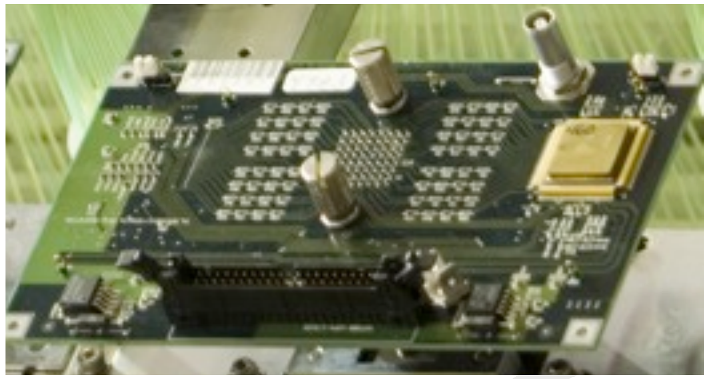


SciBar readout





64 charge info.
2 timing info.



Extruded Scintillator (1.3×2.5×300cm³)
- **made by FNAL (similar to MINOS)**

Wave length shifting fiber (1.5mmΦ)
- **Long attenuation length (~350cm)**
  → Light Yield : ~20p.e./1.3cm/MIP

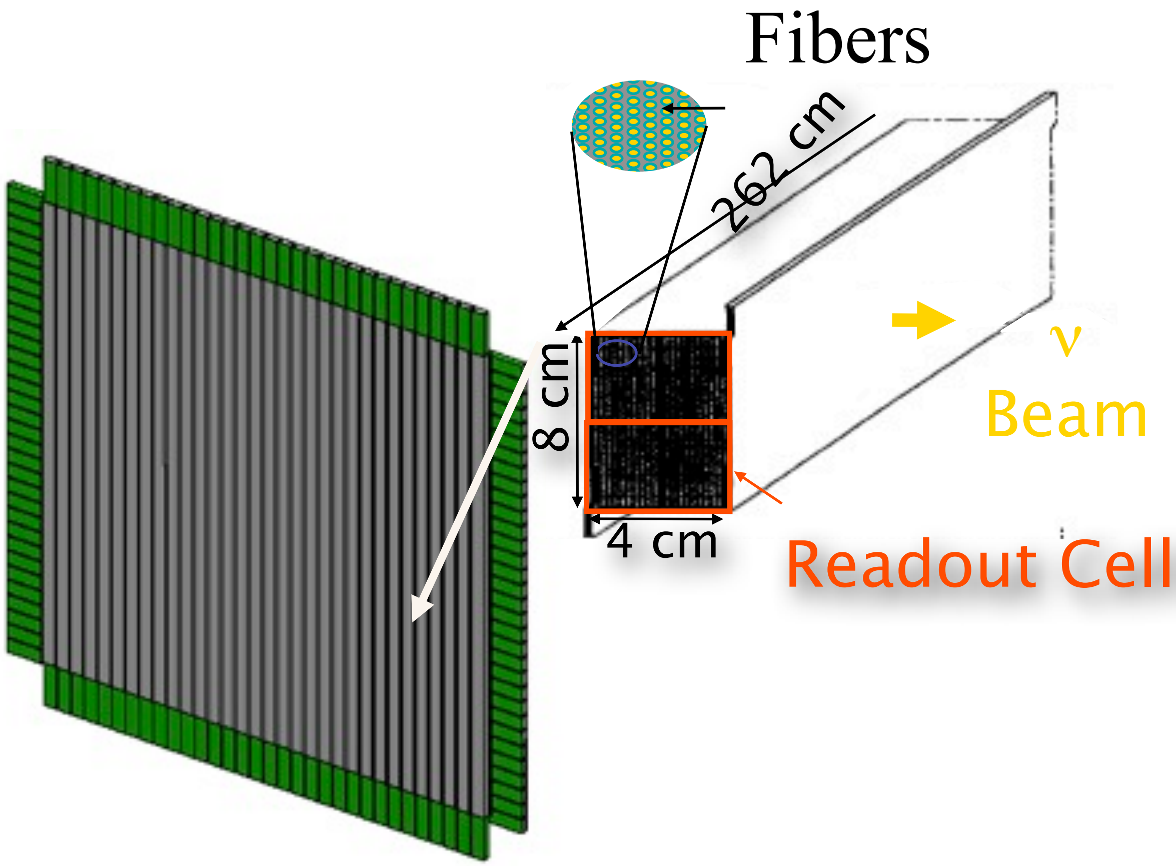
64-channel Multi-Anode PMT
- **2x2mm² pixel (3% cross talk@1.5mmΦ)**
- **Gain Uniformity (20% RMS)**
- **Good linearity (~200p.e. @6×10⁵)**

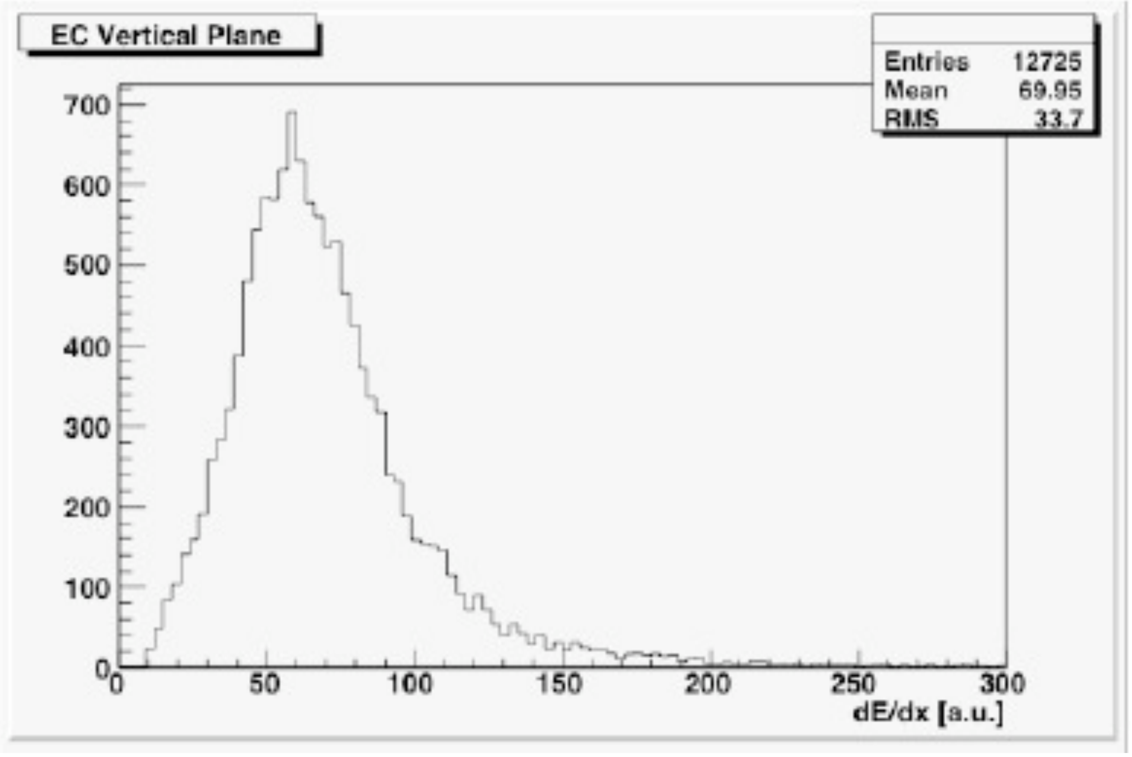
Readout electronics with VA/TA
- **ADC for all 14,336 channels**
- **TDC for 448 sets (32 channels-OR)**

Electron Catcher (EC)

- "spaghetti" calorimeter
- 1mm diameter fibers in the grooves of lead foils
- 4x4cm² cell read out from both ends
- 2 planes (11X$_0$)

  Horizontal: 32 modules
  Vertical : 32 modules
- Total 256 readout channels
- Expected resolution 14%/√E (GeV)
- Linearity: better than 10%

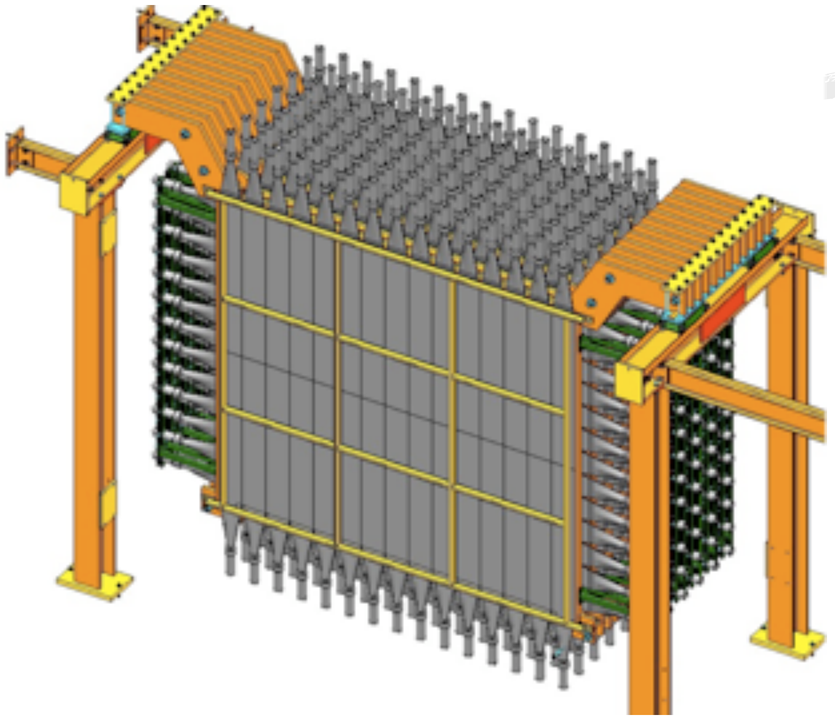




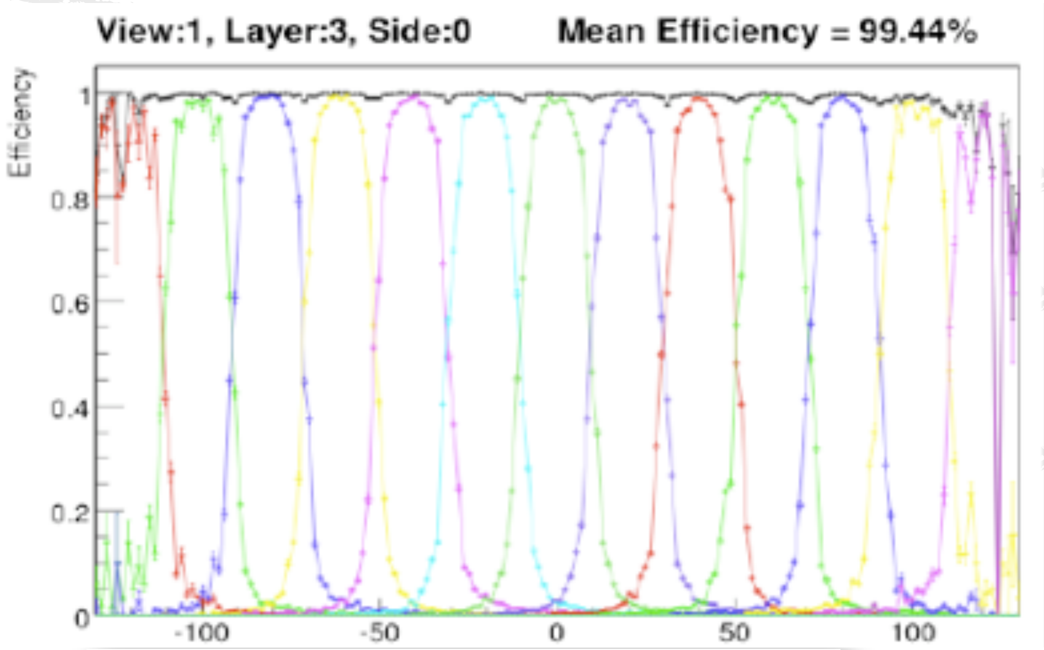
dE/dx distribution of vertical plane for cosmic ray muons

Muon Range Detector (MRD)

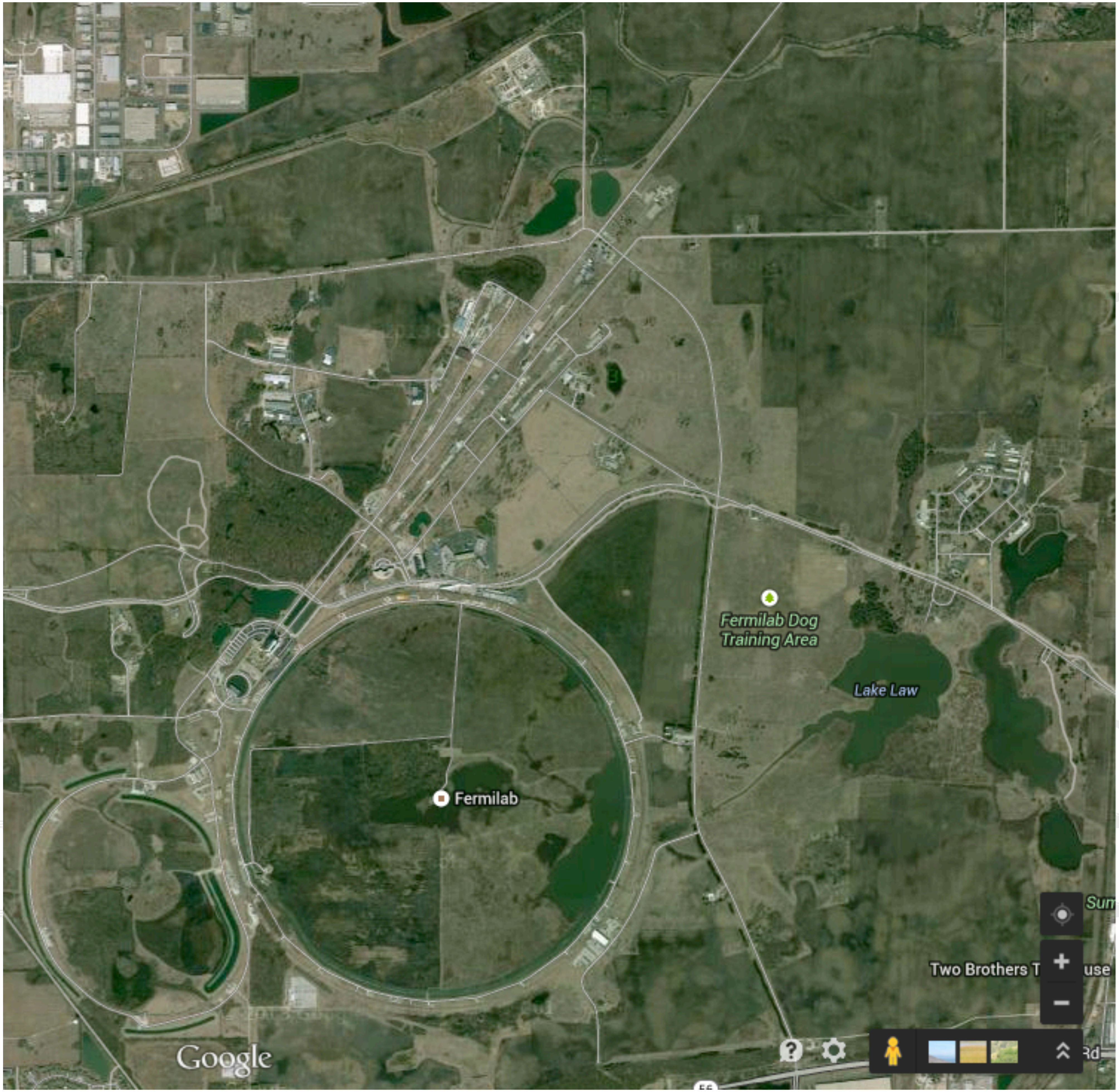
A new detector built with the used scintillators, iron plates and PMTs to measure the muon momentum up to 1.2 GeV/c.



- Iron Plates
  - 305x274x5cm^3
  - Total 12 layers
- Scintillator Planes
  - Alternating horizontal and vertical planes
  - Total 362 channels



Hit efficiency of a typical horizontal plane

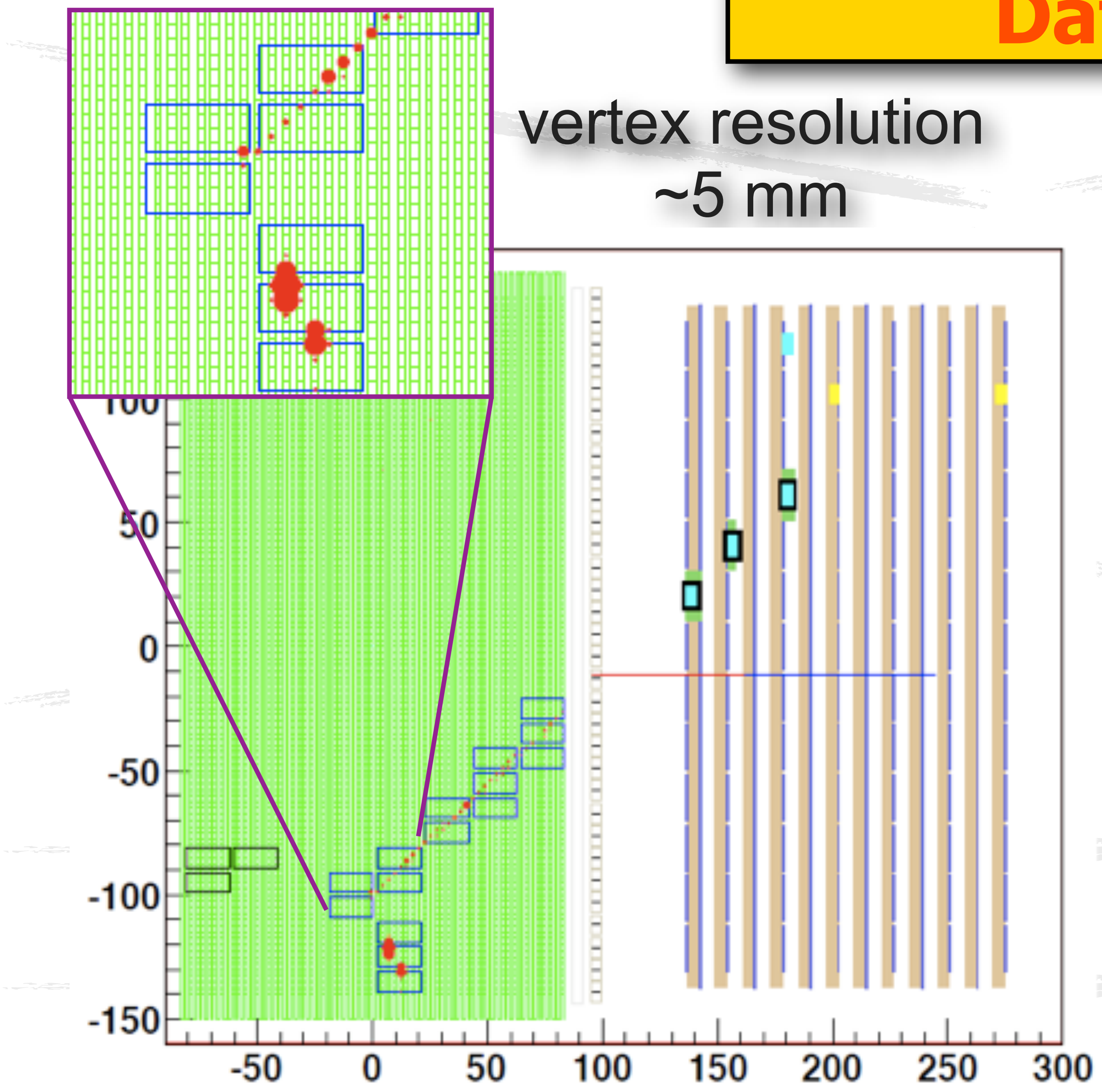

Fermilab Dog Training Area
Lake Law
Fermilab
Two Brothers T use
Sum
Rd
Google

Neutrino event displays

Real SciBooNE Data

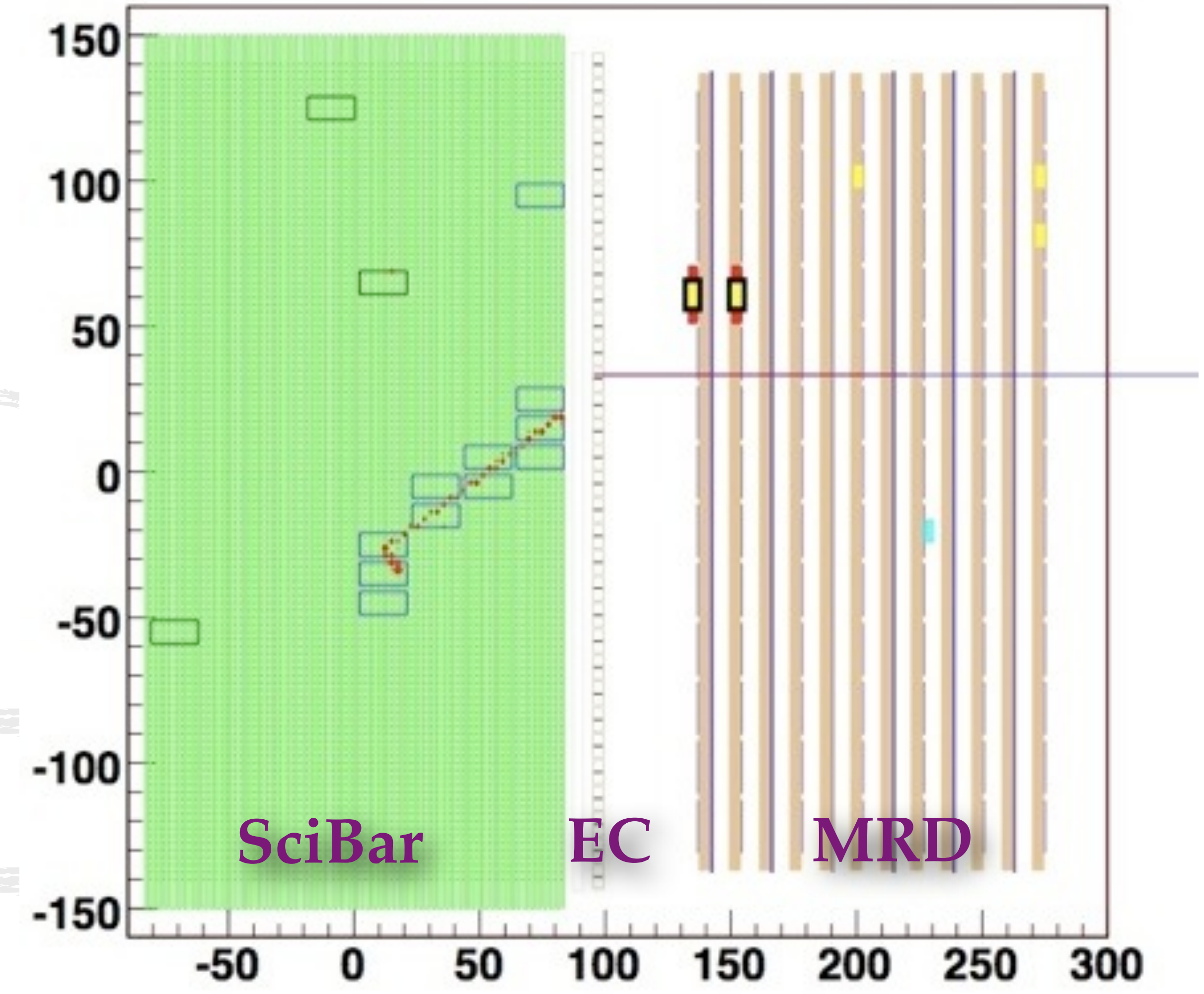
● ADC hits (area ∝ charge)

☐ TDC hits (32ch "OR")



anti-ν_μ CC-QE candidate

($\bar{\nu}_\mu + p \rightarrow \mu + n$)

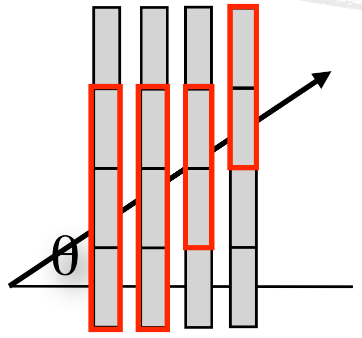


ν_μ CC-QE candidate

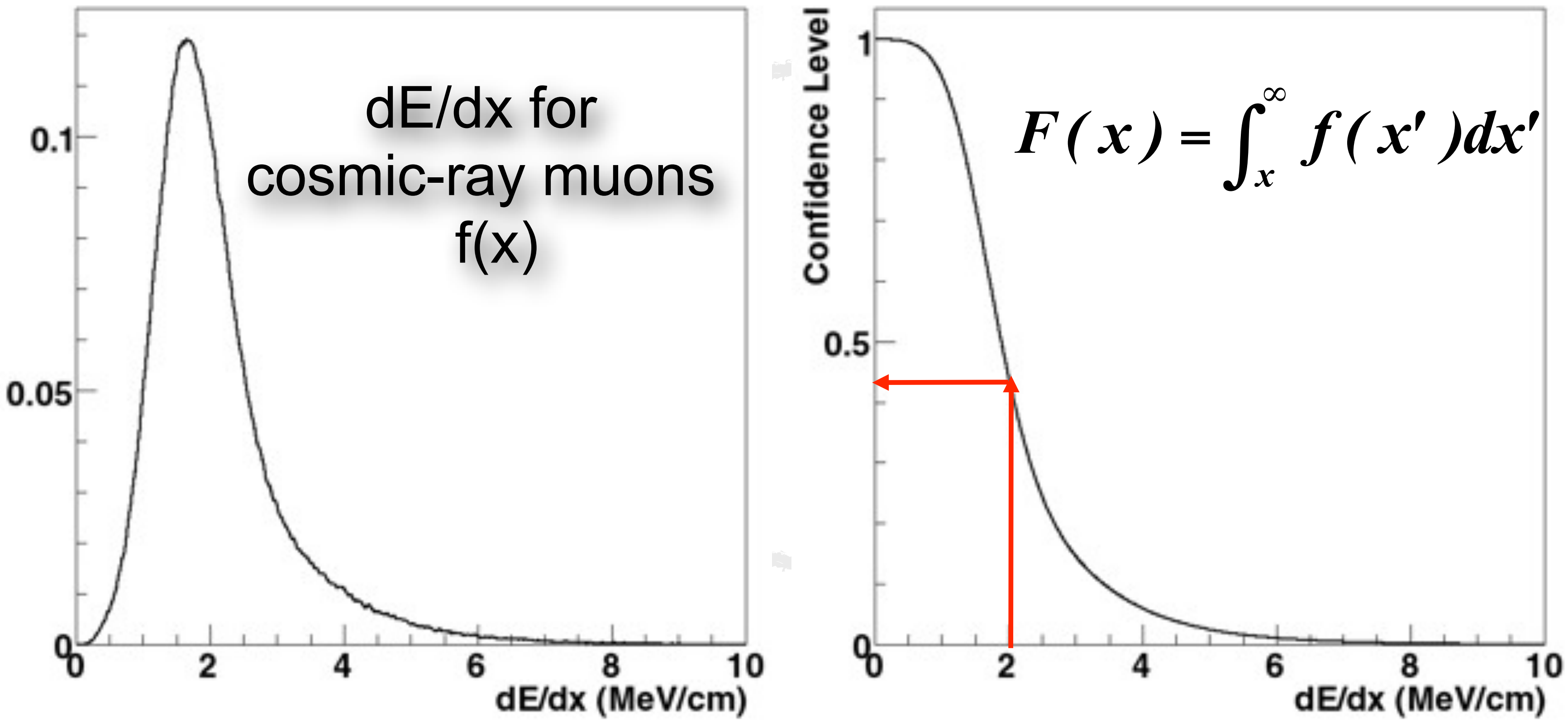
($\nu_\mu + n \rightarrow \mu + p$)

MuCL calculation

plane-by-plane dE/dx measurement



$$dE/dx = \frac{\Delta E}{1.3cm/cos\theta}$$



$$F(x) = \int_x^\infty f(x')dx'$$

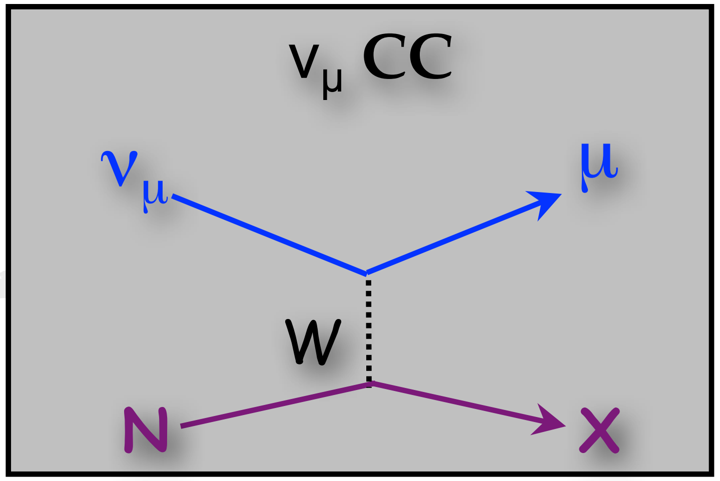
confidence level at each plane is calculated from the plot

MuCL: combined confidence level

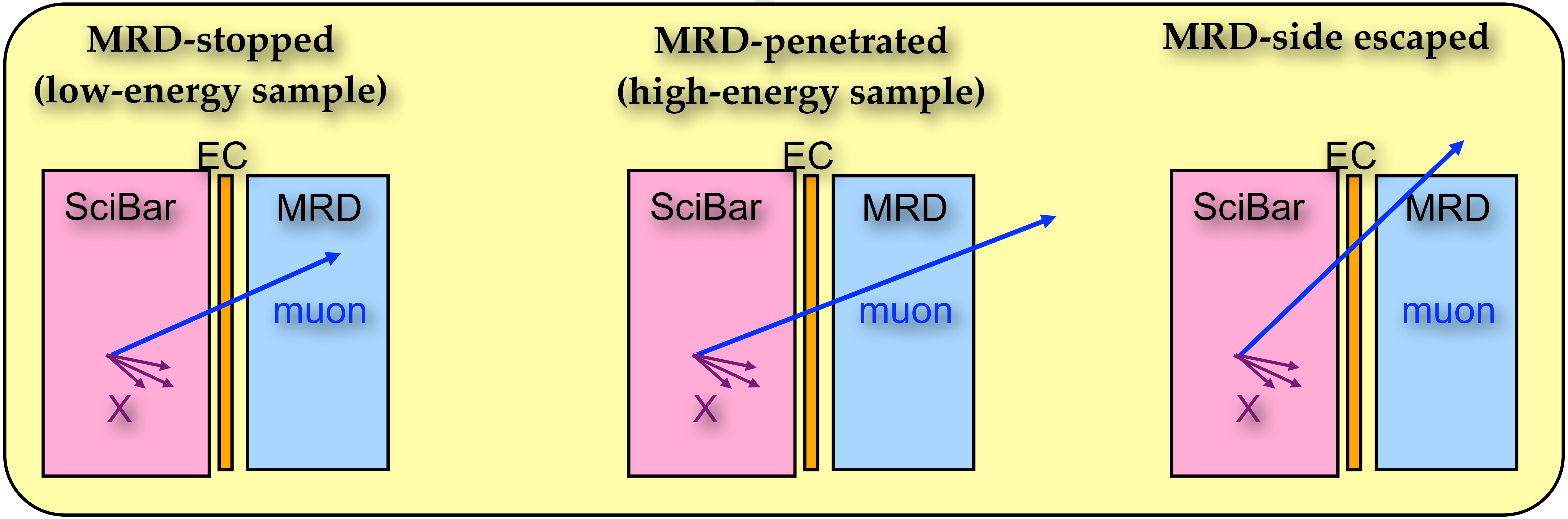
$$MuCL = P \times \sum_{i=0}^{n-1} \frac{(-\ln P)^i}{i!} \qquad P = \prod_{i=1}^{n} CL_i$$

Charged Current (CC) event selection

- Muons identified using MRD
- Tracks should start from SciBar fiducial volume



SciBar-MRD matched event (~30k events)



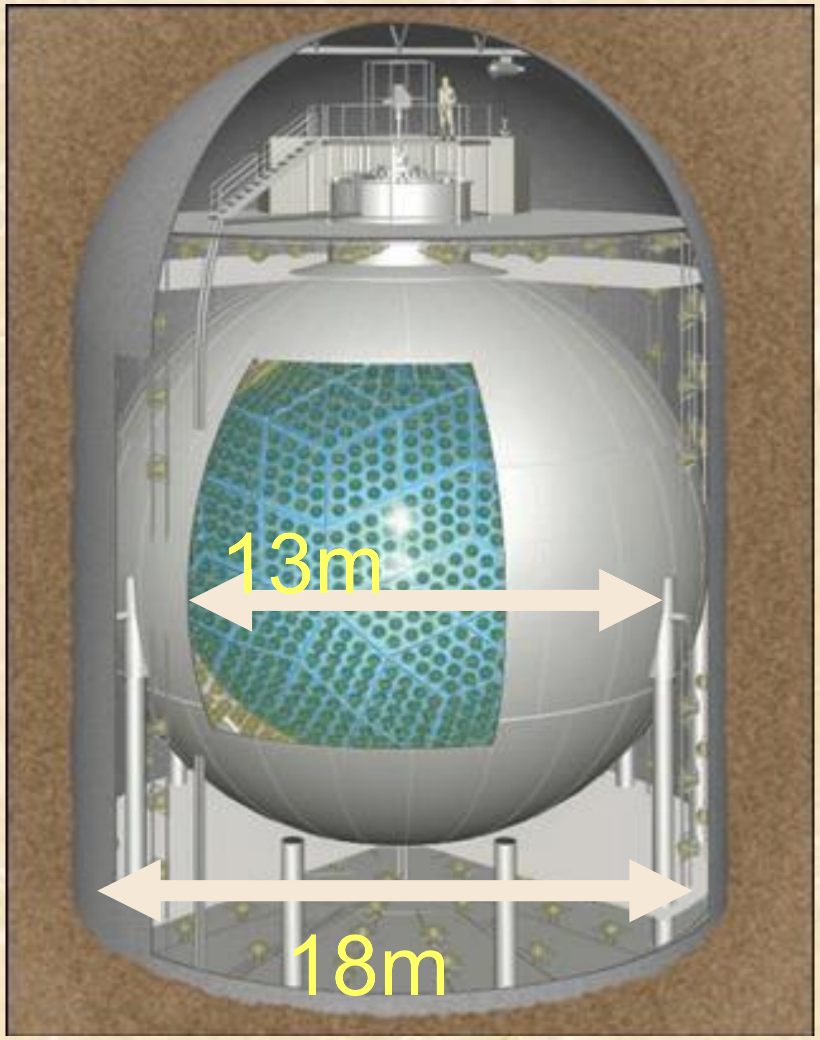
MRD-stopped (low-energy sample)

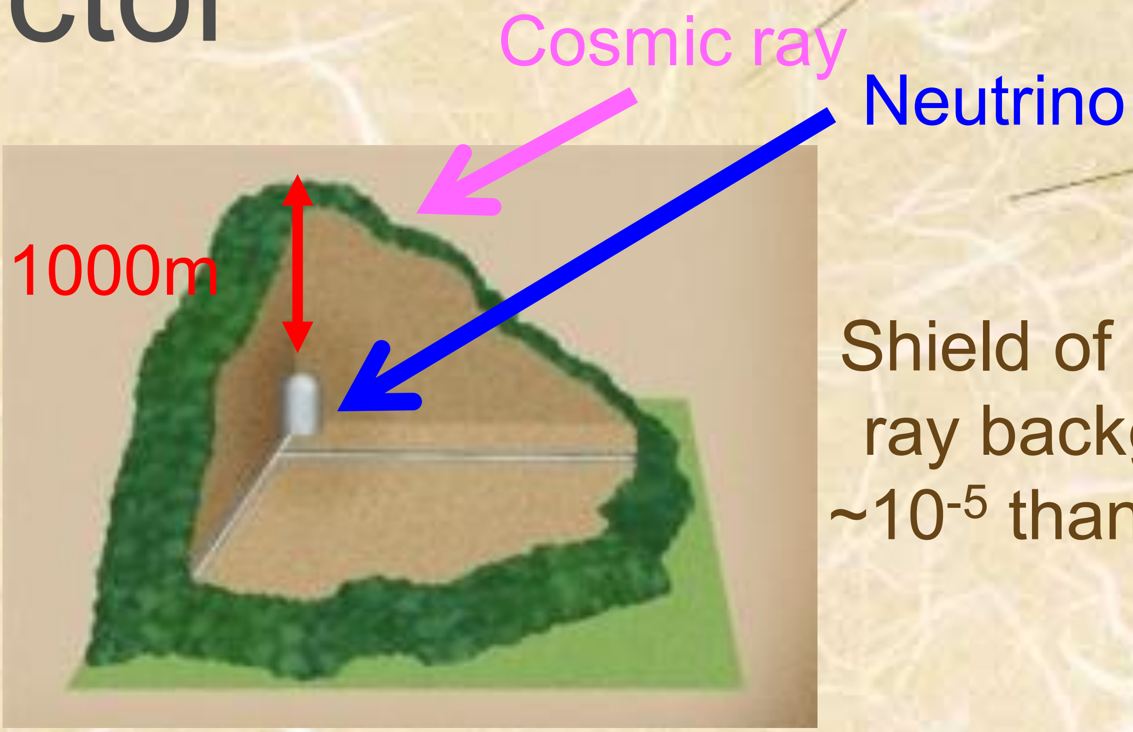
MRD-penetrated (high-energy sample)

MRD-side escaped

93% pure CC-inclusive ($\nu+N\rightarrow\mu+X$) sample

KamLAND detector





Shield of cosmic ray background ~10^{-5} than ground

1,000 tons pure liquid scintillator (LS)

Buffer oil : Shield for environmental radiation

PMT : 17inch :1325 + 20inch : 554

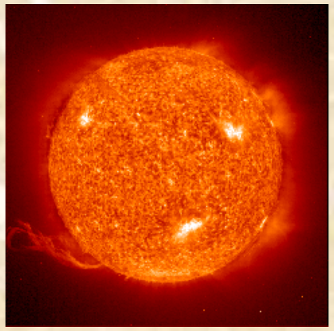
Water cherencov anti counter
225 20inch PMT with water

Energy range :
few hundred keV ~ few ten MeV

^{238}U : 3.5×10^{-18}g/g
^{232}Th : 5.2×10^{-17}g/g in LS

Resolution : ~12cm / $\sqrt{E(MeV)}$
~6.4% / $\sqrt{E(MeV)}$

Physics targets of KamLAND



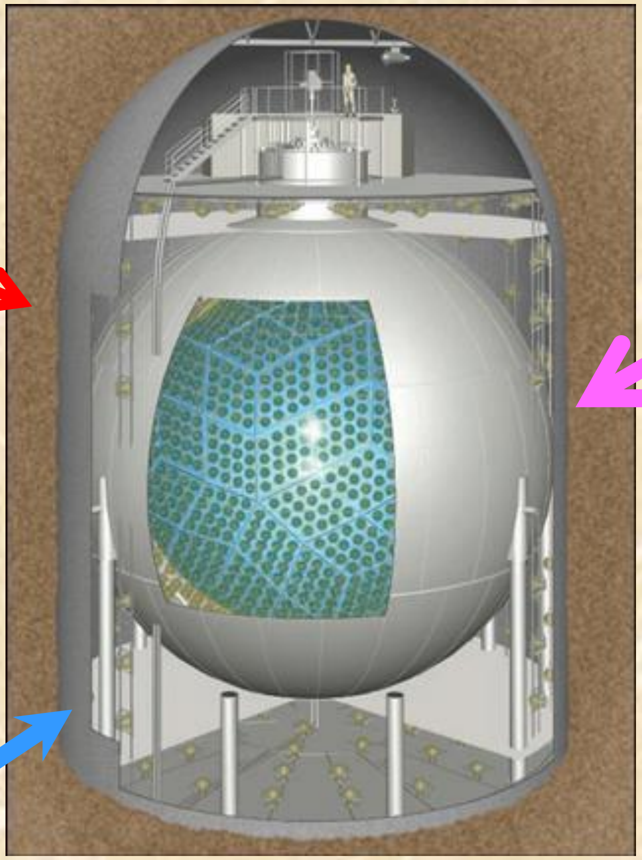
The Sun

ν_e

~500 events / day (^{7}Be)

~1 events/day (^{8}B)

Verification of solar model



Reactor core

$\bar{\nu}_e$

~1event / day

Precision measurements of neutrino oscillation

$\bar{\nu}_e$

~1event / 20days

Interior of the Earth

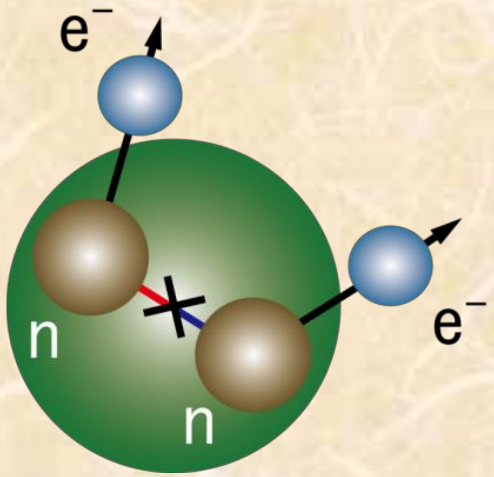
Verification of earth evolution model

Double beta decay

Majorana neutrino

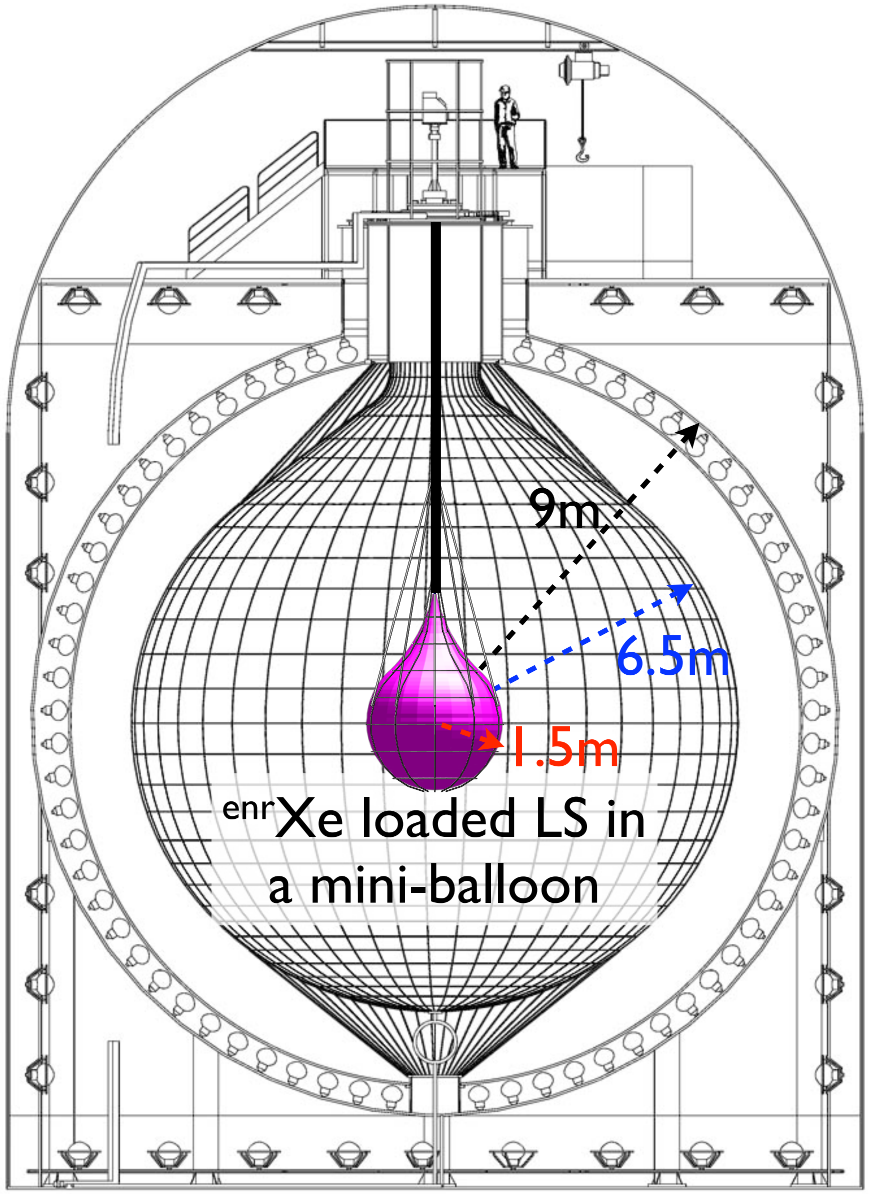
Neutrino mass hierarchy

few events/year ?



KamLAND-Zen

Zero Neutrino
double beta decay search

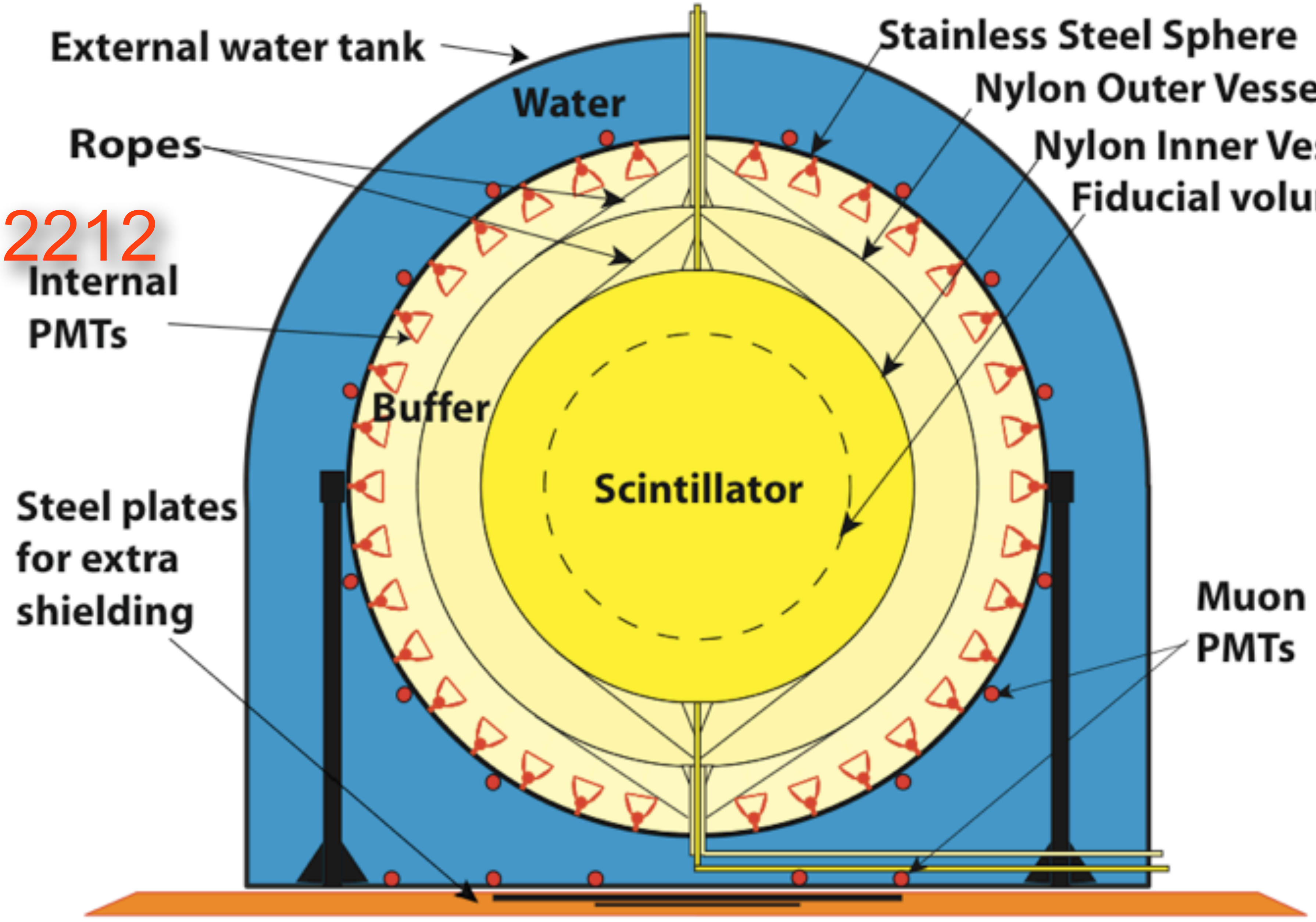


^{enr}Xe loaded LS in a mini-balloon

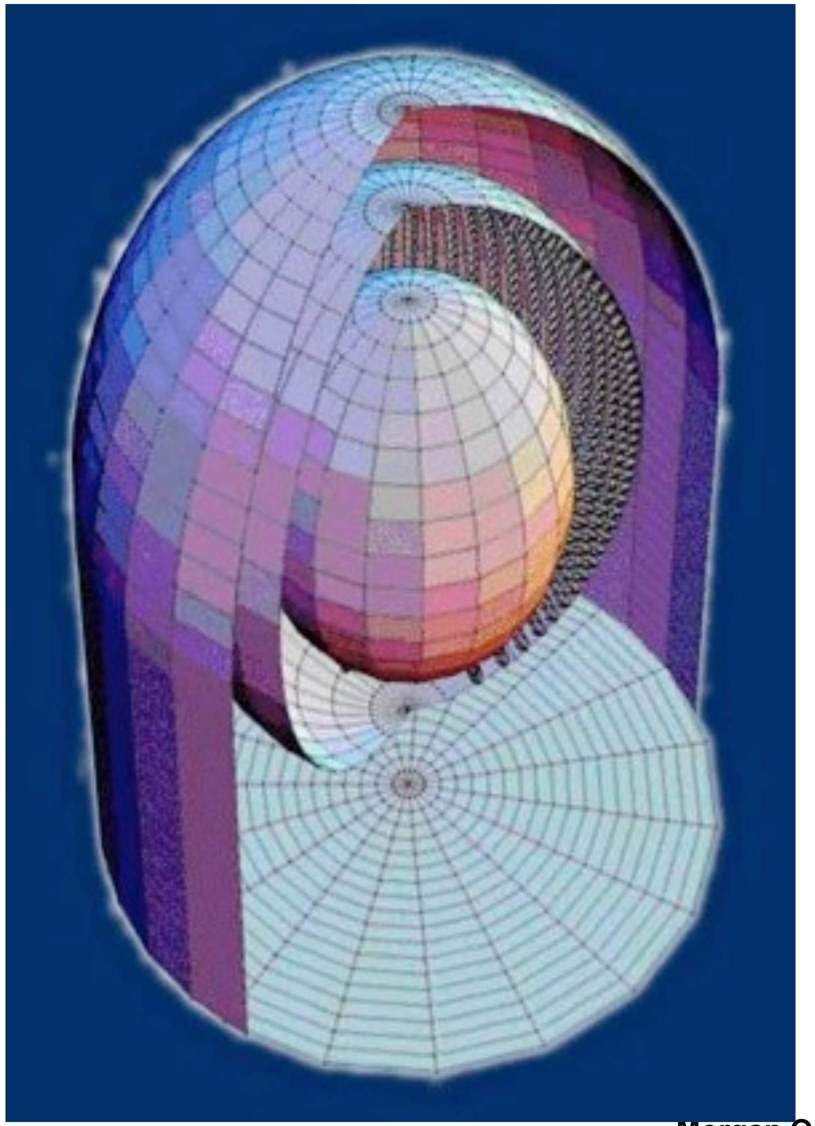
idea to load Xe into LS is from Raju PRL72,1411(1994)

~320kg 90% enriched ^{136}Xe installed so far
total 600+ kg in the mine
production reaches 700kg in this year

Borexino Detector



2212



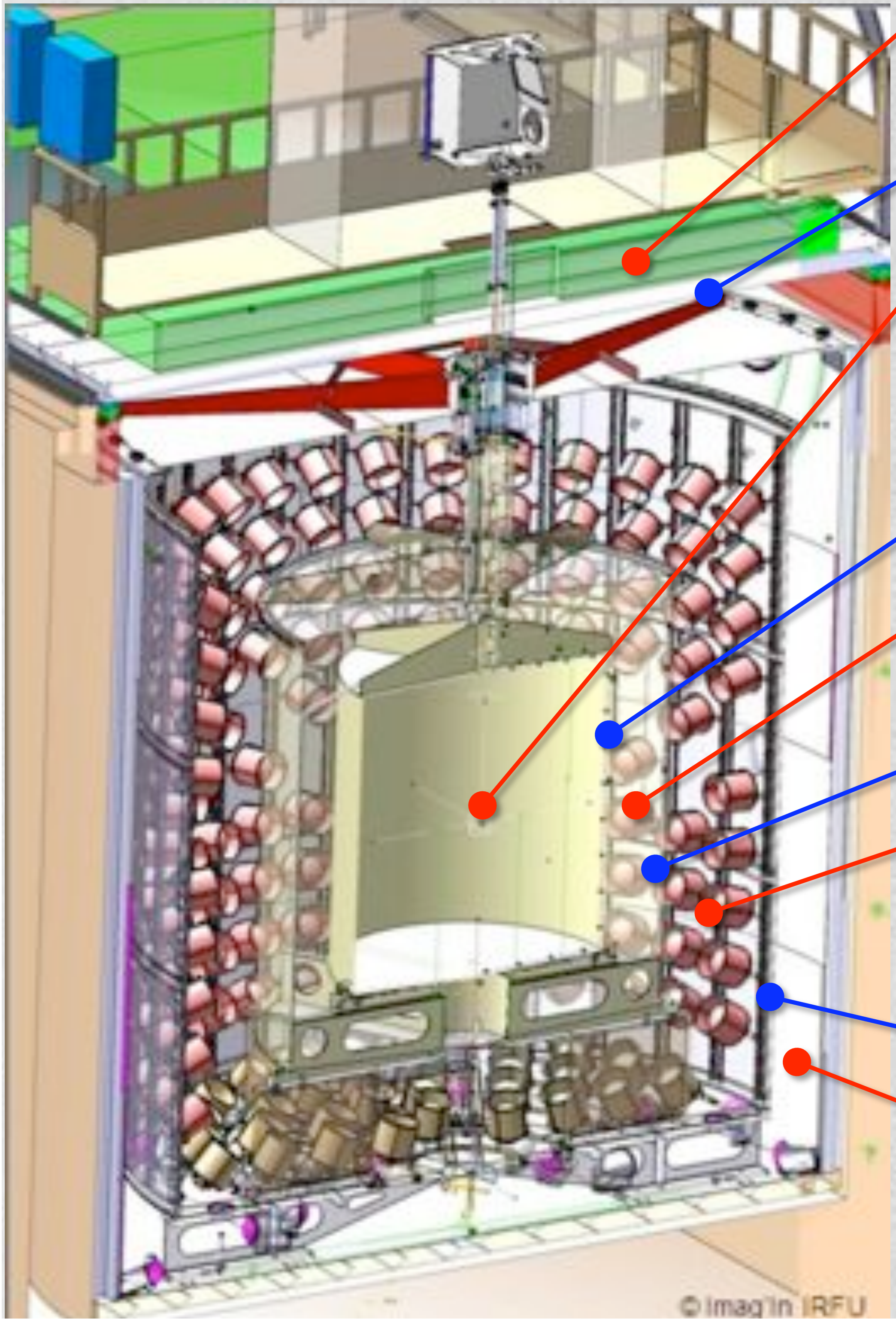
SBL Reactor $\overline{\nu}_e$ detectors

Exp’t	Power (GWth)	Distance N/F (m)	Target N/F (t)
Double Chooz	8.6	400/1050	8.6/8.6
RENO	17.3	290/1380	16/16
Daya Bay	11.6 (17.4)	360(500)/ 1990(1620)	6×20

S. Kopp, Lepton-Photon

figures courtesy M. Dierckxsens, Chicago

Double Chooz detector



Outer Veto: Plastic scintillator strips

Identify cosmic μ

Steel shield (15cm thick)

ν-target:

Gd loaded (1g/l) liquid scint. (10m^3)

Target of neutrino interaction

Neutrons captured on Gd

Acrylic vessel

γ-catcher: Liquid scintillator (22m^3)

Measure γ's escaped from ν-target

Acrylic vessel

Buffer:

Mineral oil (110m^3) & 390 10-inch PMT

Reduction of environmental γ's

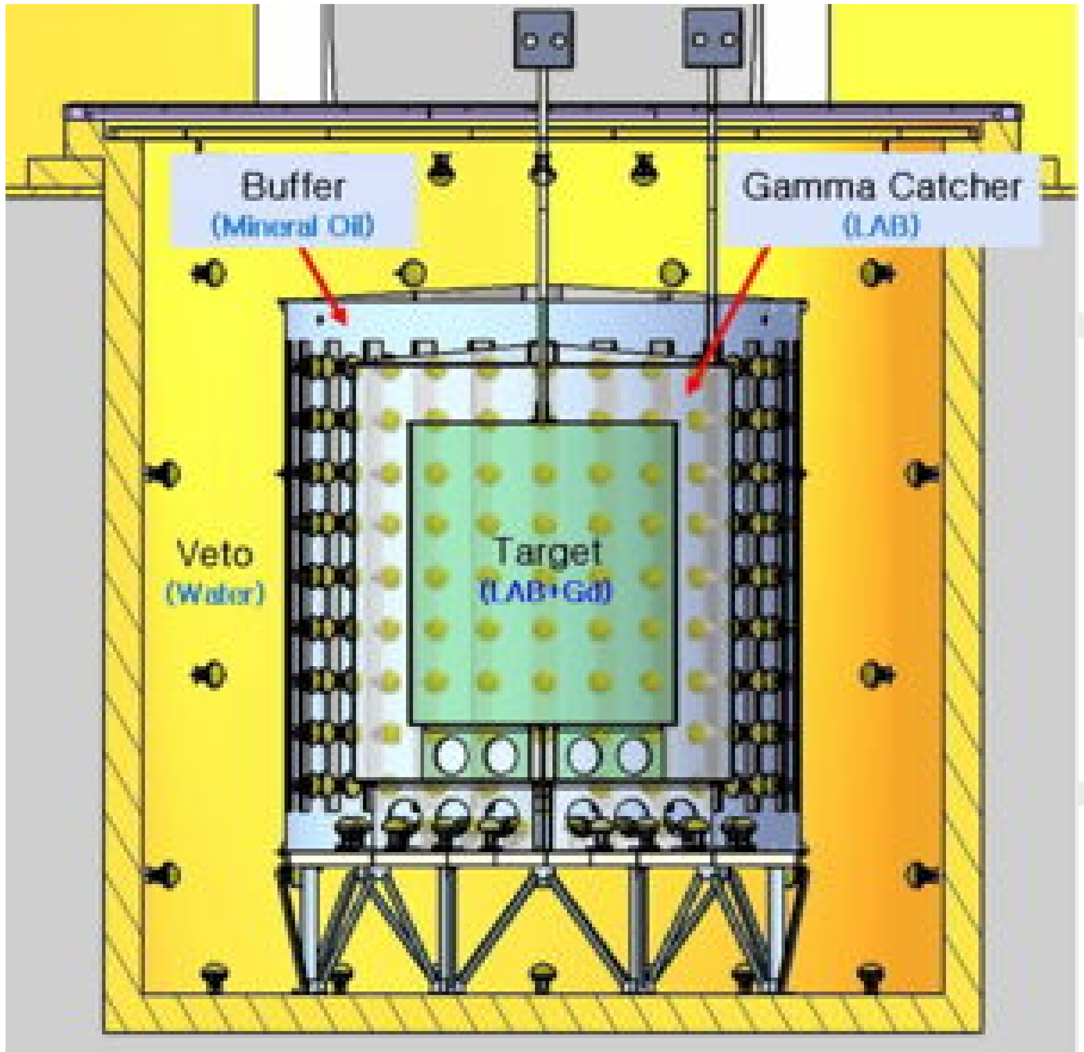
Steel tank

Inner Veto:

Liquid scintillator (90m^3) & 78 8-inch PMT

Identify cosmic μ &reduction neutrons

RENO Detector

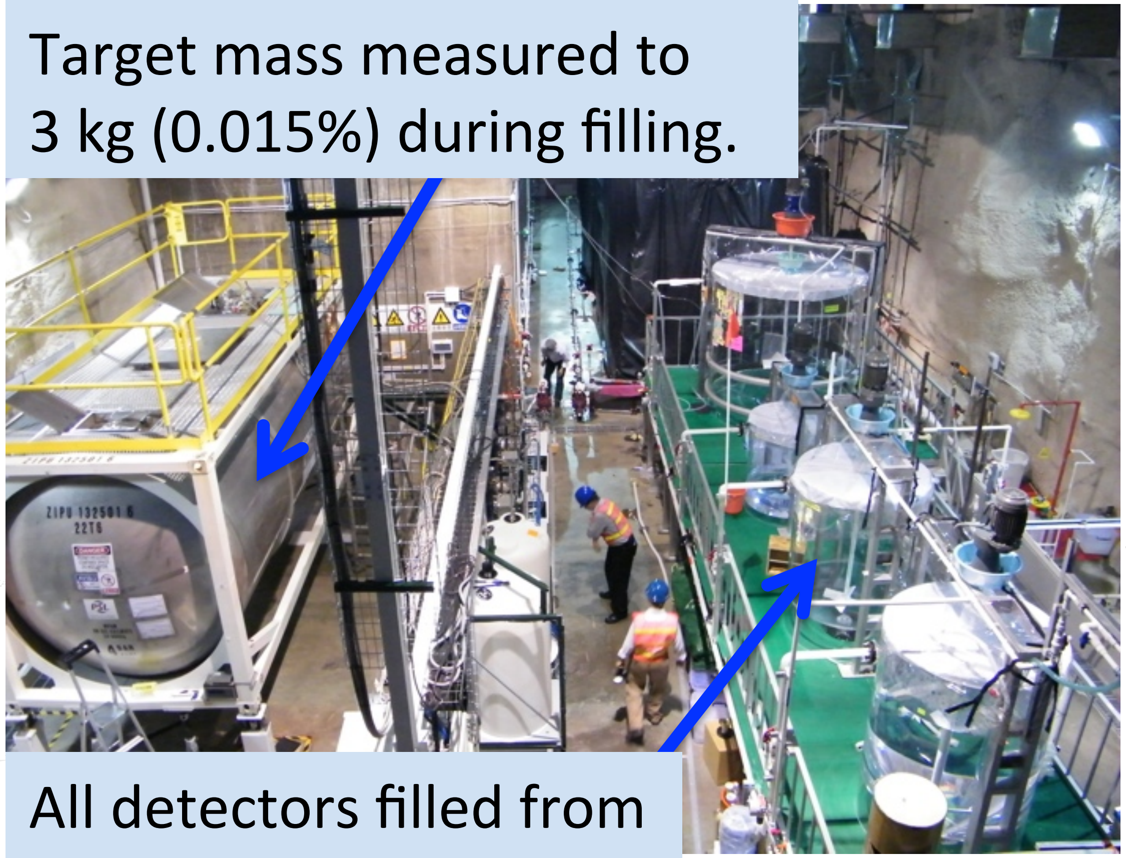


- 354 ID +67 OD 10” PMTs
- Target : 16.5 ton Gd-LS,   R=1.4m, H=3.2m
- Gamma Catcher : 30 ton LS,   R=2.0m, H=4.4m
- Buffer : 65 ton mineral oil,   R=2.7m, H=5.8m
- Veto : 350 ton water,   R=4.2m, H=8.8m

Antineutrino Detectors

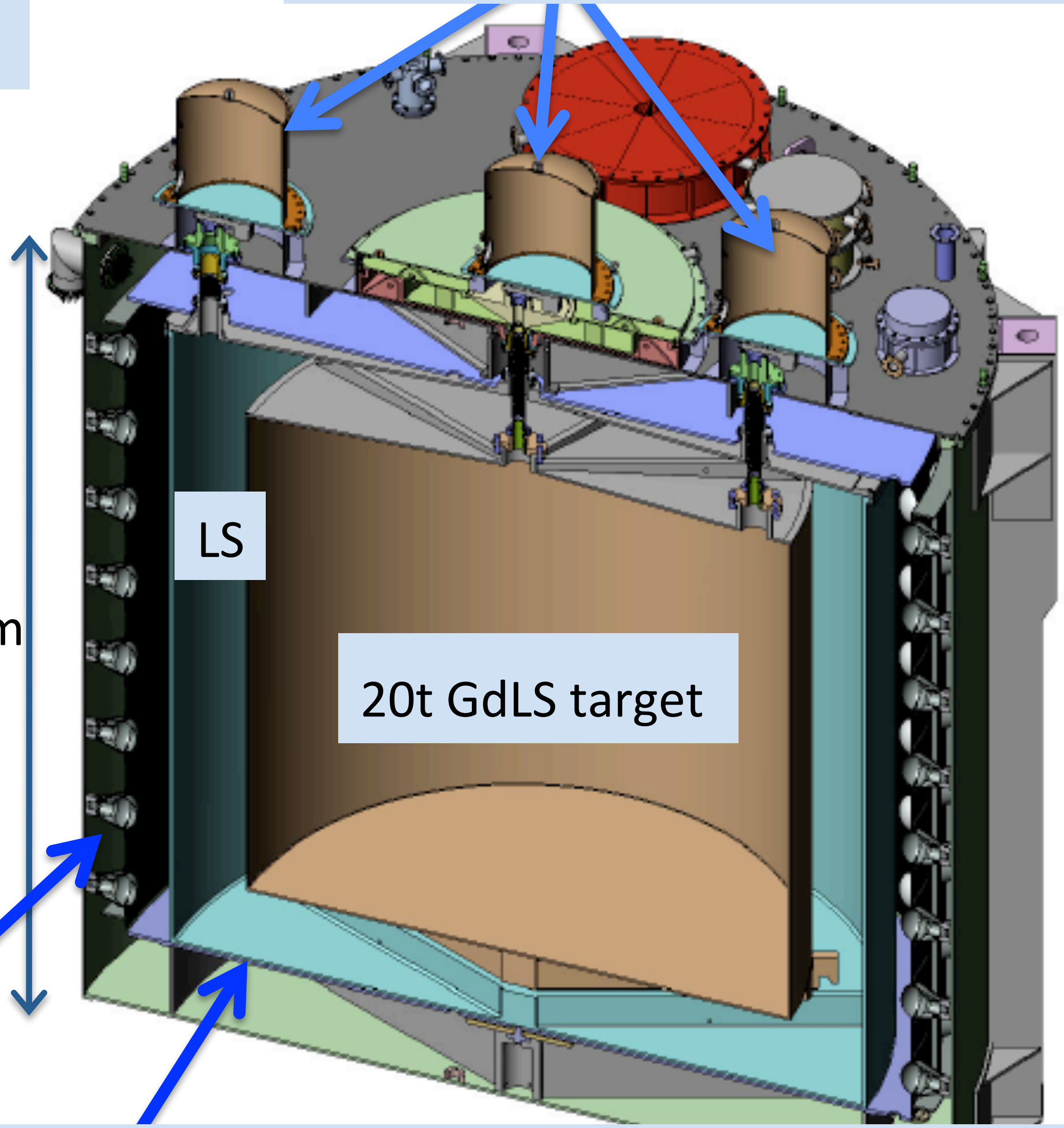
6 ‘functionally identical’ detectors:
Reduce systematic uncertainties

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



All detectors filled from common GdLS tanks.

Calibration robots insert radioactive sources and LEDs.



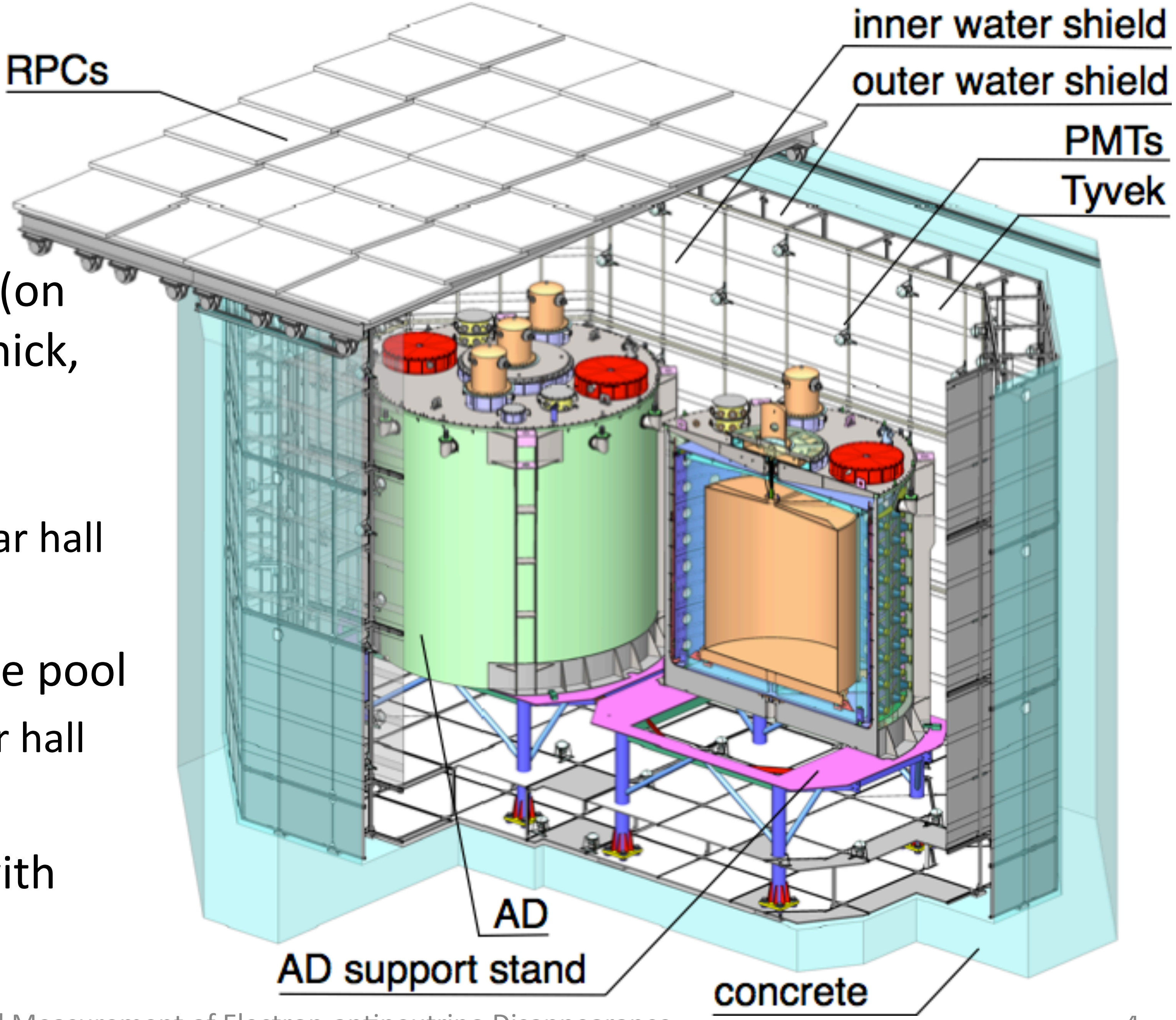
192 8” PMTs detect light in target, ~163 p.e./MeV.

Reflectors improve light collection uniformity.

Muon Tagging System

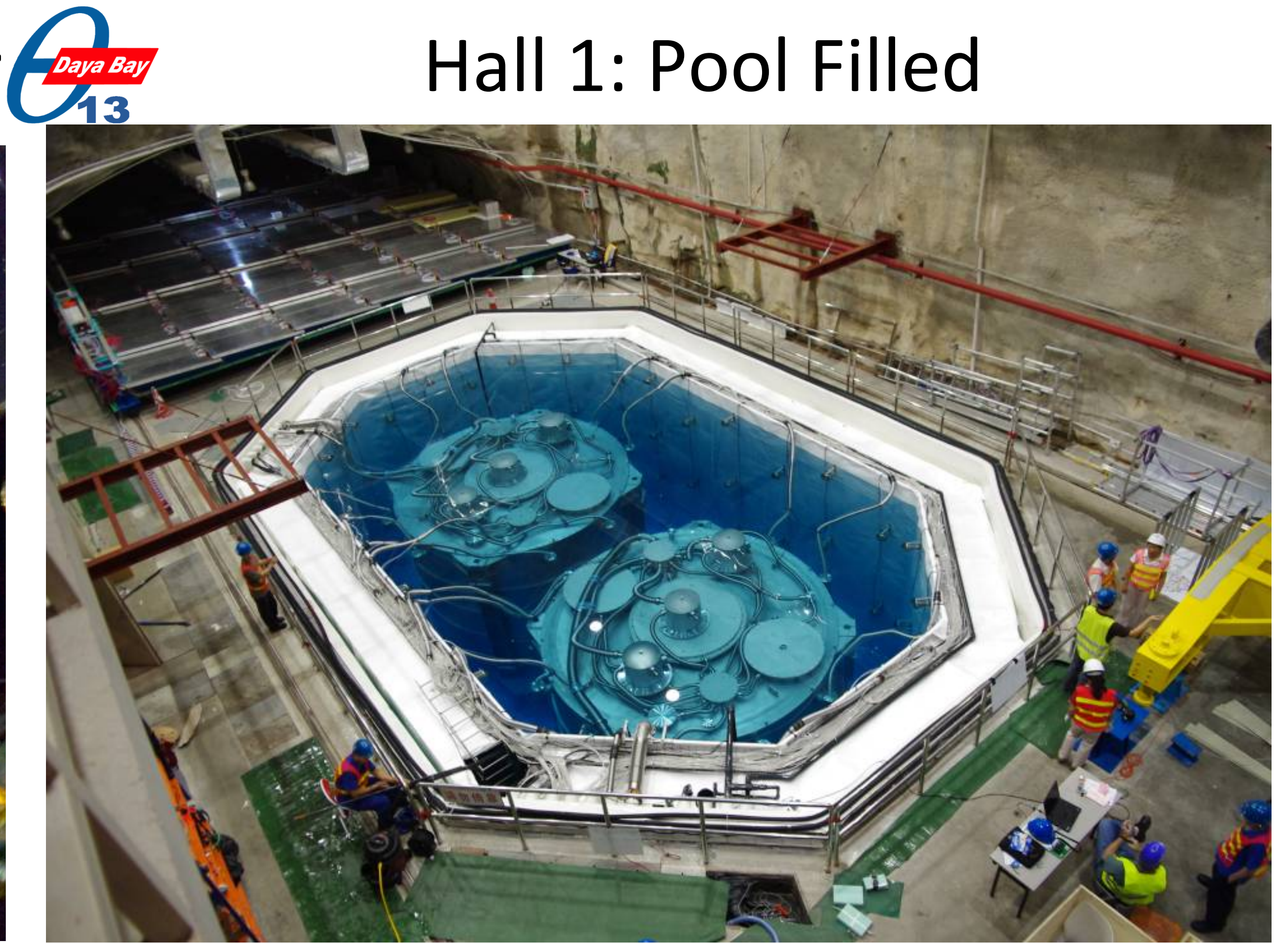
Dual tagging systems: 2.5 meter thick two-section water shield and RPCs

- Outer layer of water veto (on sides and bottom) is 1m thick, inner layer >1.5m. Water extends 2.5m above ADs
    - 288 8” PMTs in each near hall
    - 384 8” PMTs in Far Hall
- 4-layer RPC modules above pool
    - 54 modules in each near hall
    - 81 modules in Far Hall
- Goal efficiency: > 99.5% with uncertainty <0.25%



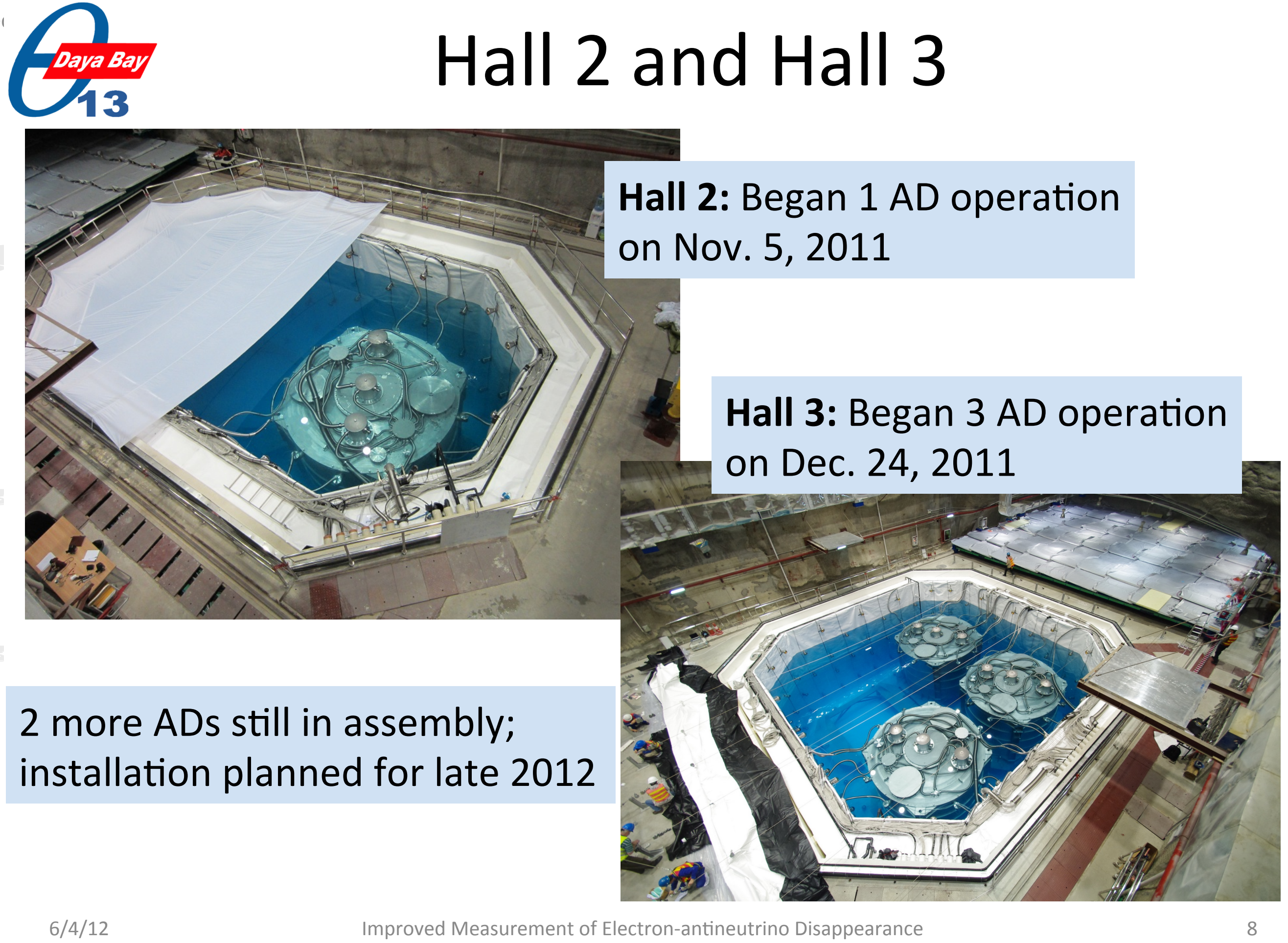
Interior of Antineutrino Detector

6/4/12 Improved Measurement of Ele



Hall 1: Pool Filled

on-antineutrino Disappearance 6



Hall 2 and Hall 3

Hall 2: Began 1 AD operation on Nov. 5, 2011

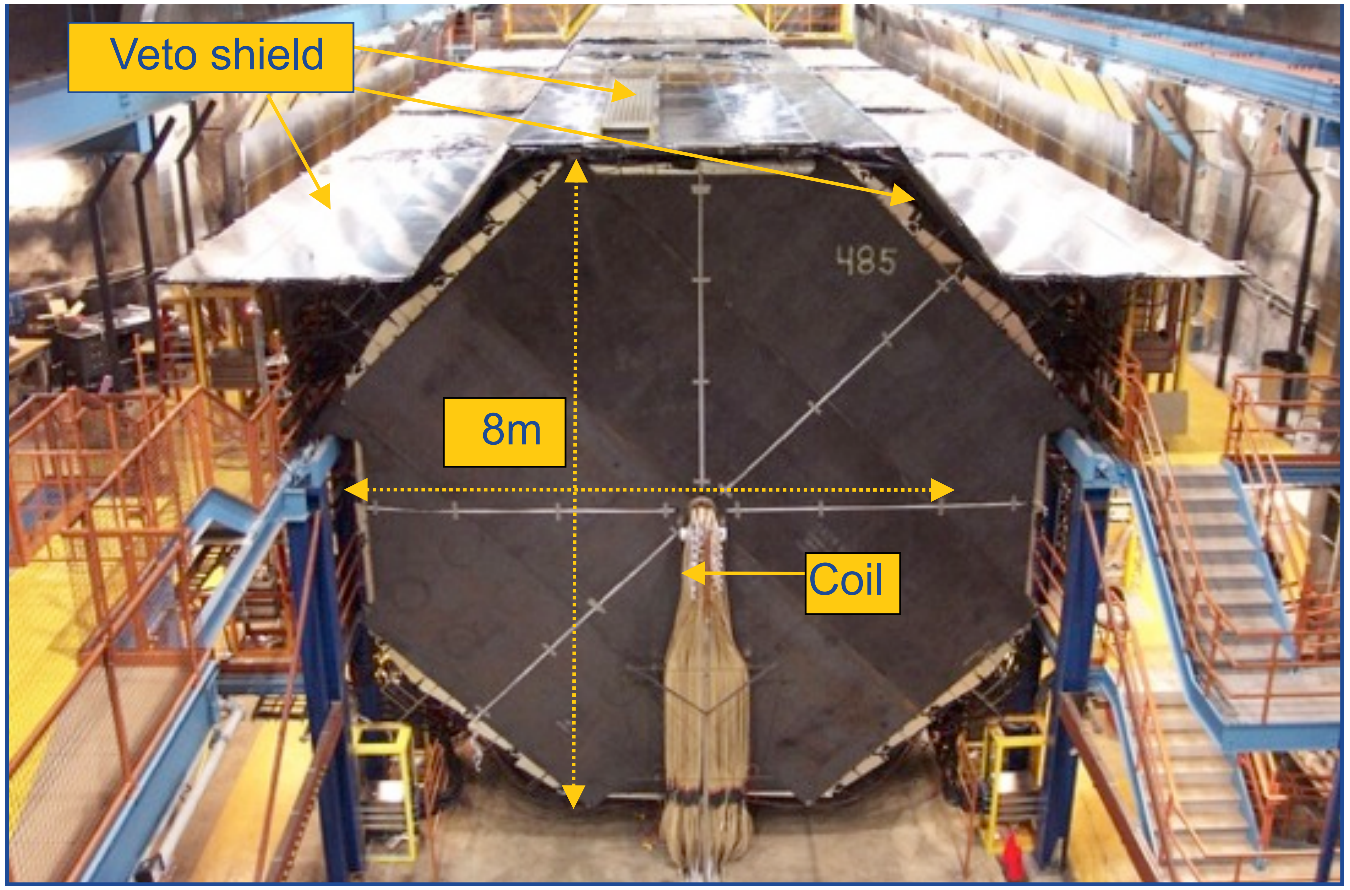
Hall 3: Began 3 AD operation on Dec. 24, 2011

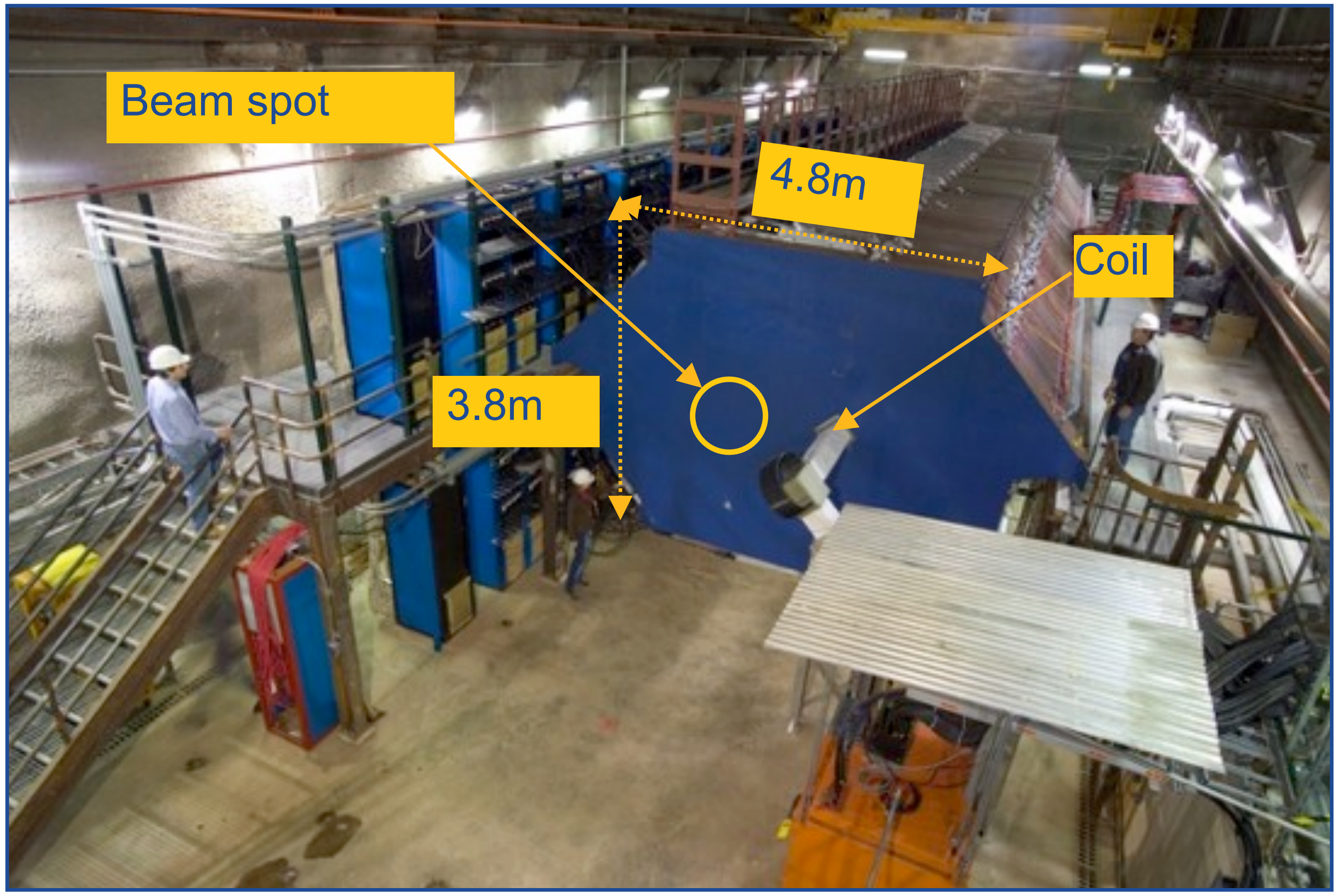
2 more ADs still in assembly; installation planned for late 2012

6/4/12 Improved Measurement of Electron-antineutrino Disappearance 8

MINOS Detectors

- 980 ton Near Detector
- 5.4 kiloton Far Detector
    - Magnetised to 1.3T
    - Similar design mitigates many systematic uncertainties
    - Event-by-event charge discrimination of muons

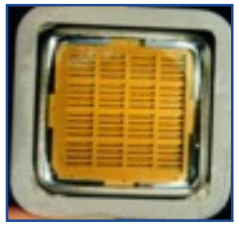




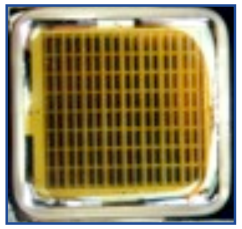
9 MINOS @ Neutrino 2012 by Ryan Nichol

MINOS Detector Technology

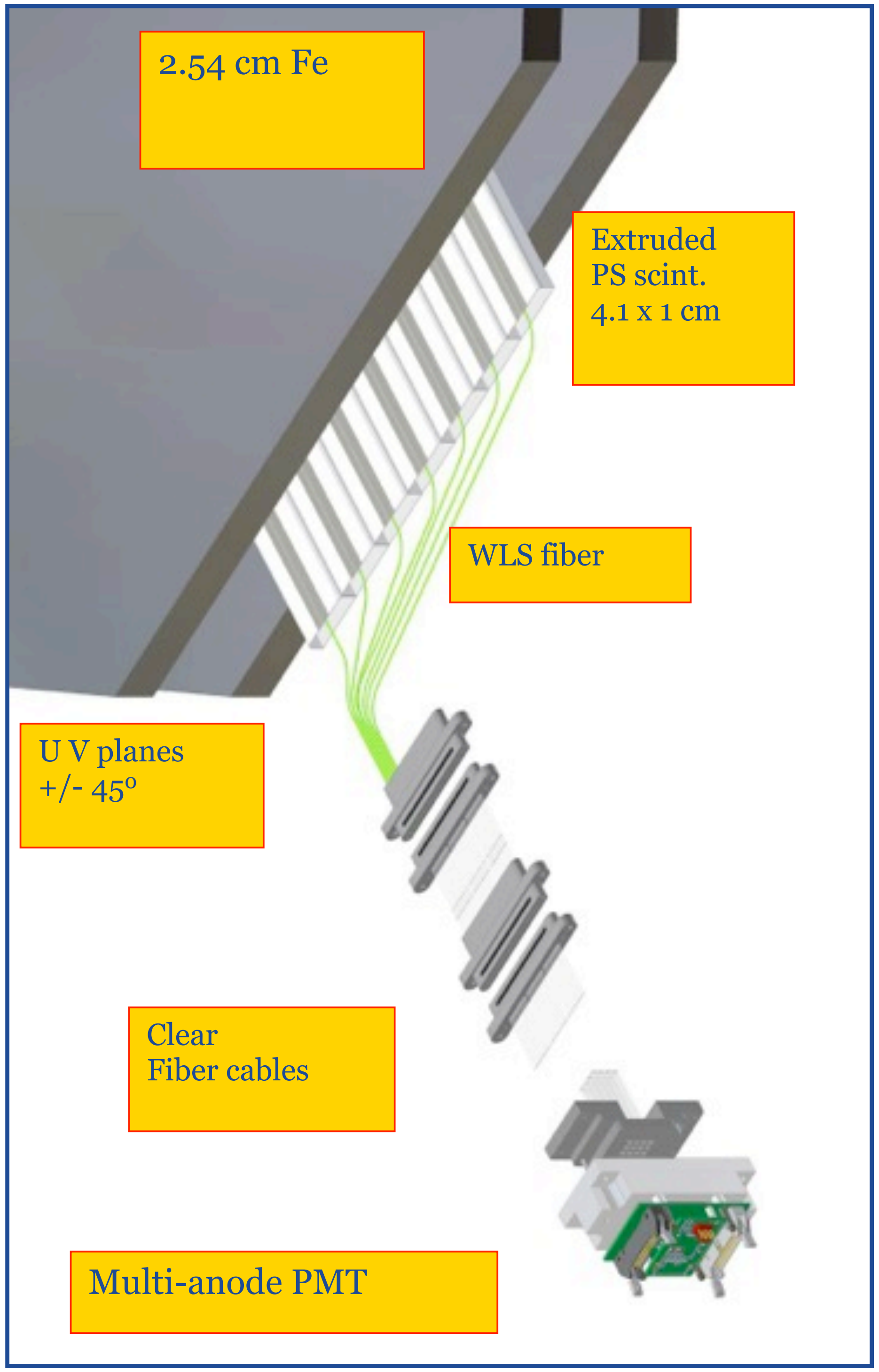
- Magnetised steel-scintillator tracking calorimeters
    - 2.54cm steel planes
    - 1cm x 4.1cm scintillator strips
    - Hamamatsu multi-anode PMTs



M16



M64



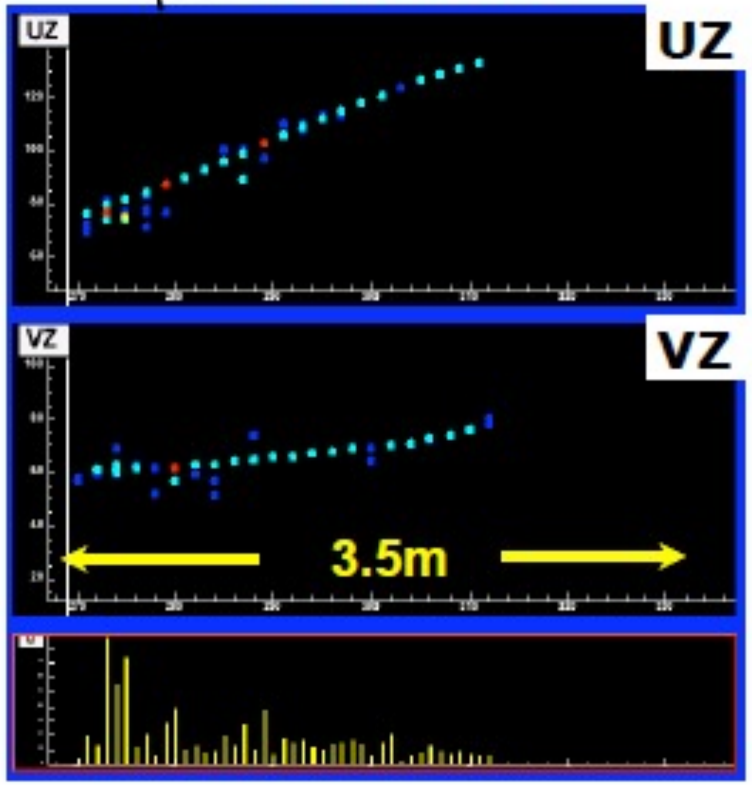
8 MINOS @ Neutrino 2012 by Ryan Nichol

Event Topologies

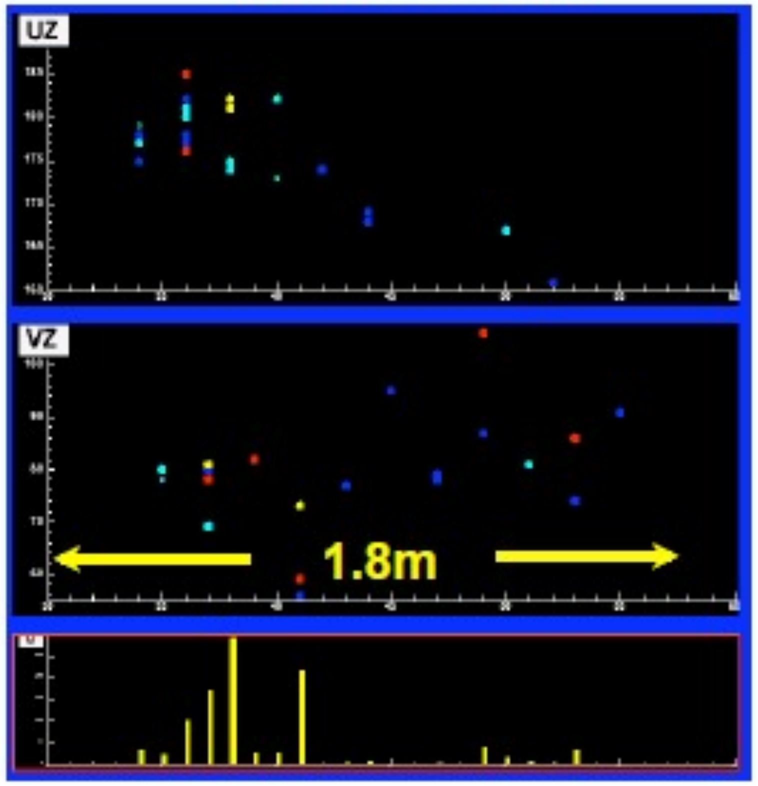
H. Gallagher
Tufts University
Neutrino 2008
May 27, 2008

Monte Carlo

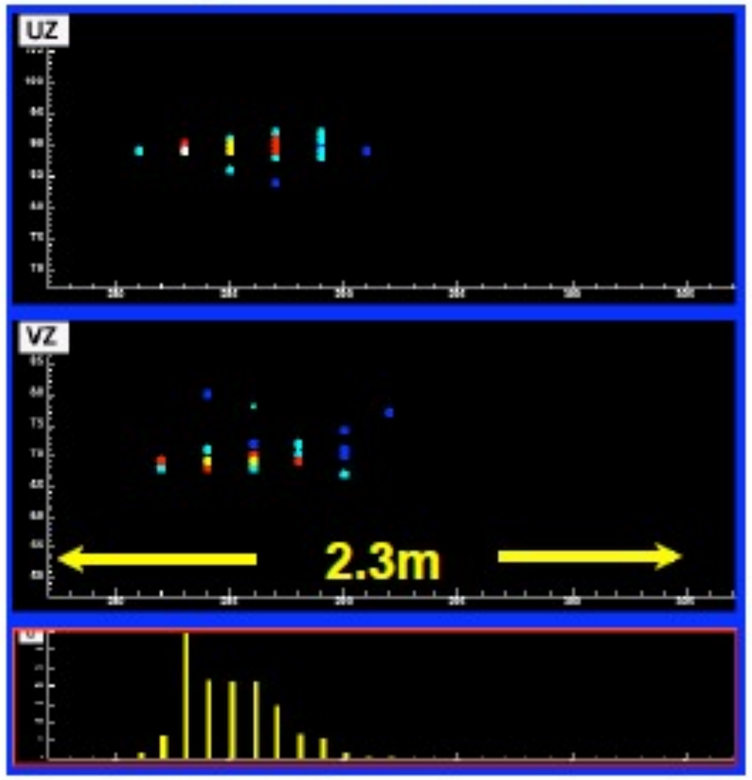
ν_μ CC Event



NC Event



ν_e CC Event



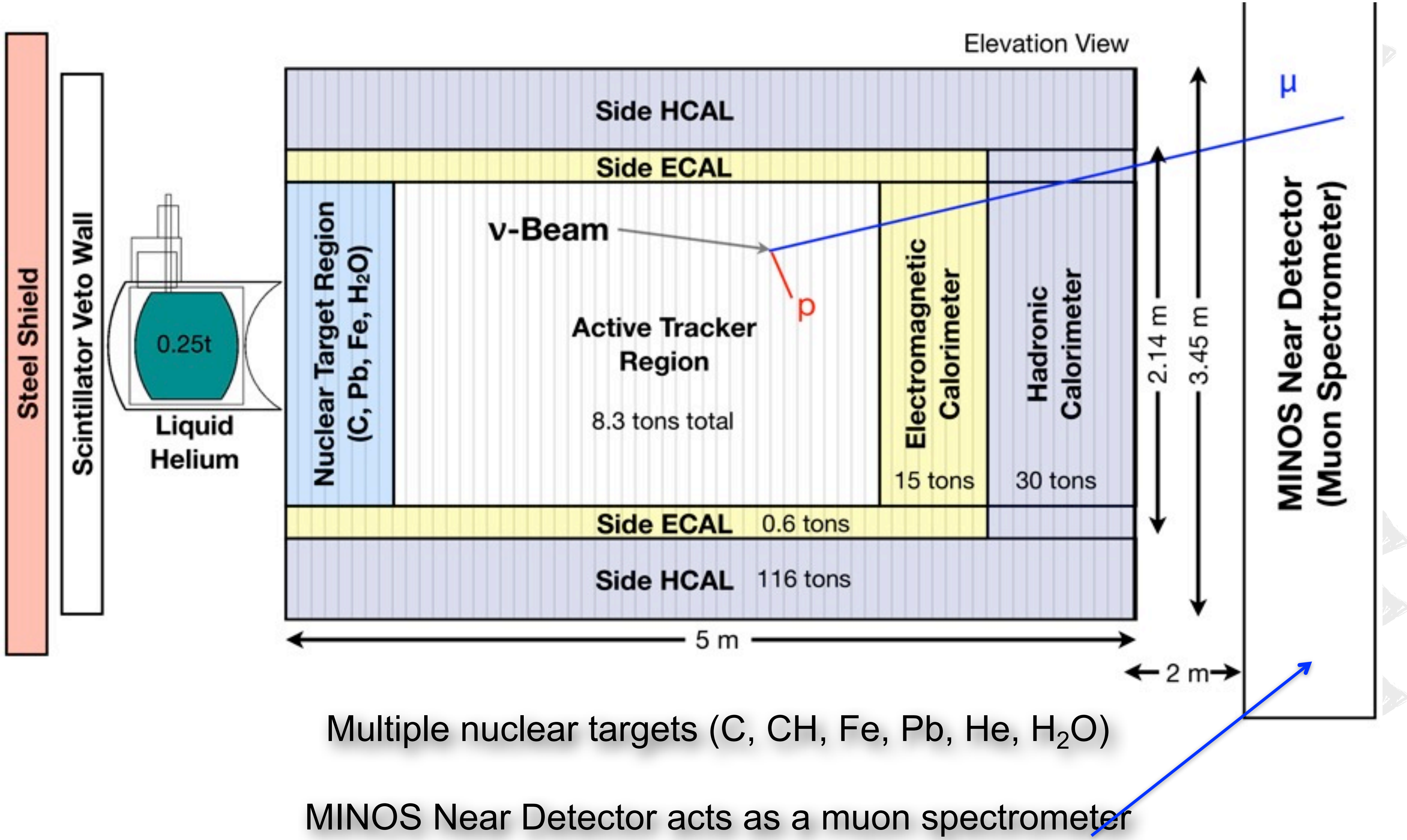
- long μ track+ hadronic activity at vertex
- short event, often diffuse
- short, with typical EM shower profile

$$E_\nu = E_{shower} + P_\mu$$

55%/√E

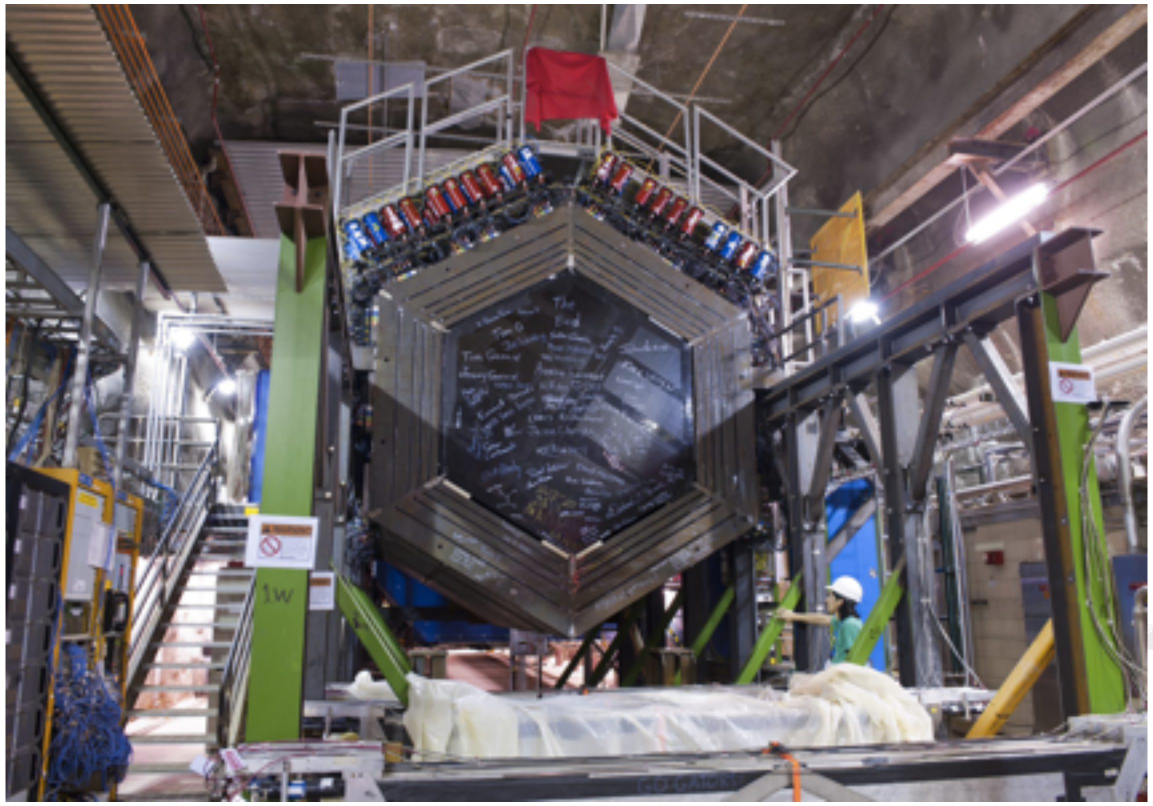
6% range, 10% curvature

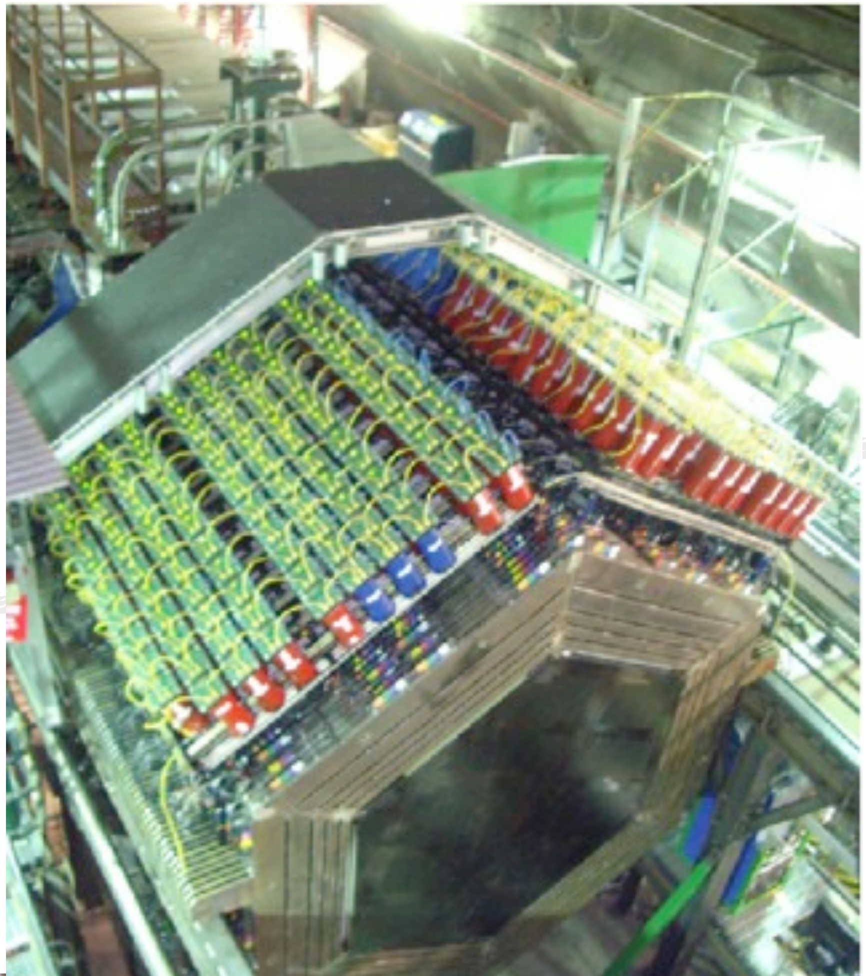
The MINERvA Detector

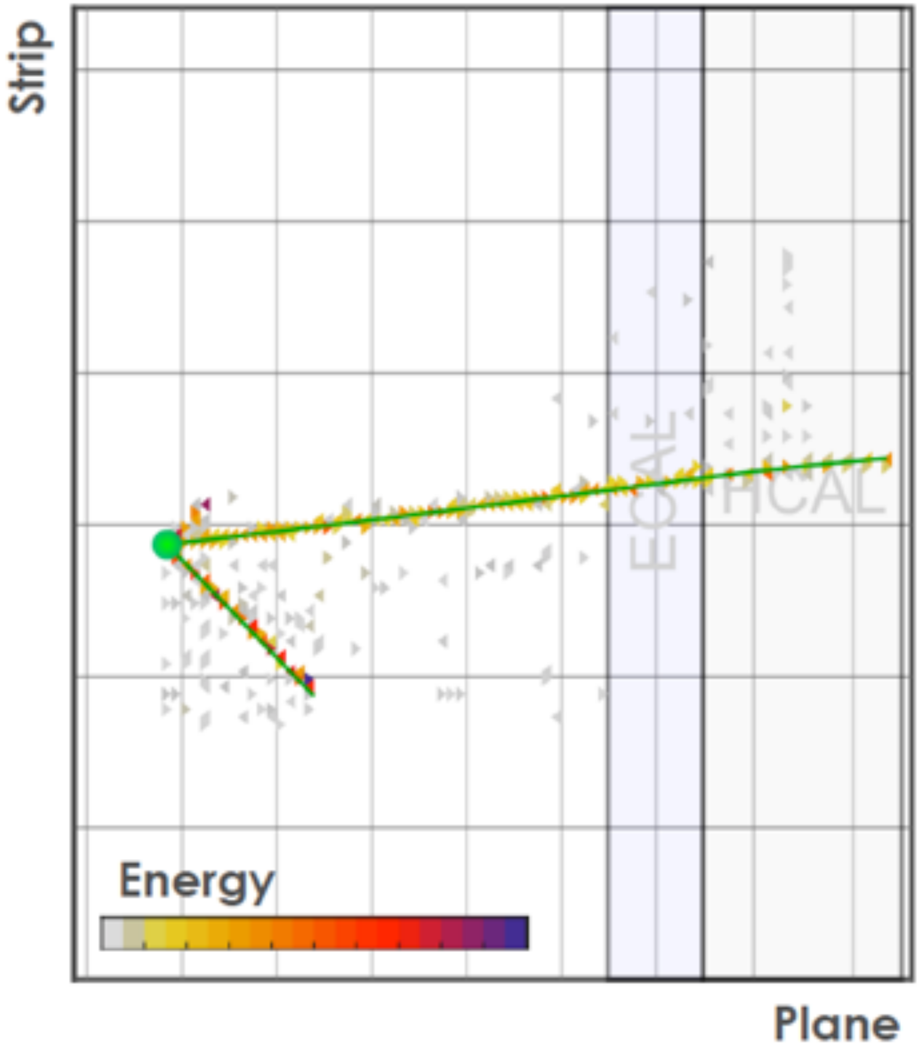


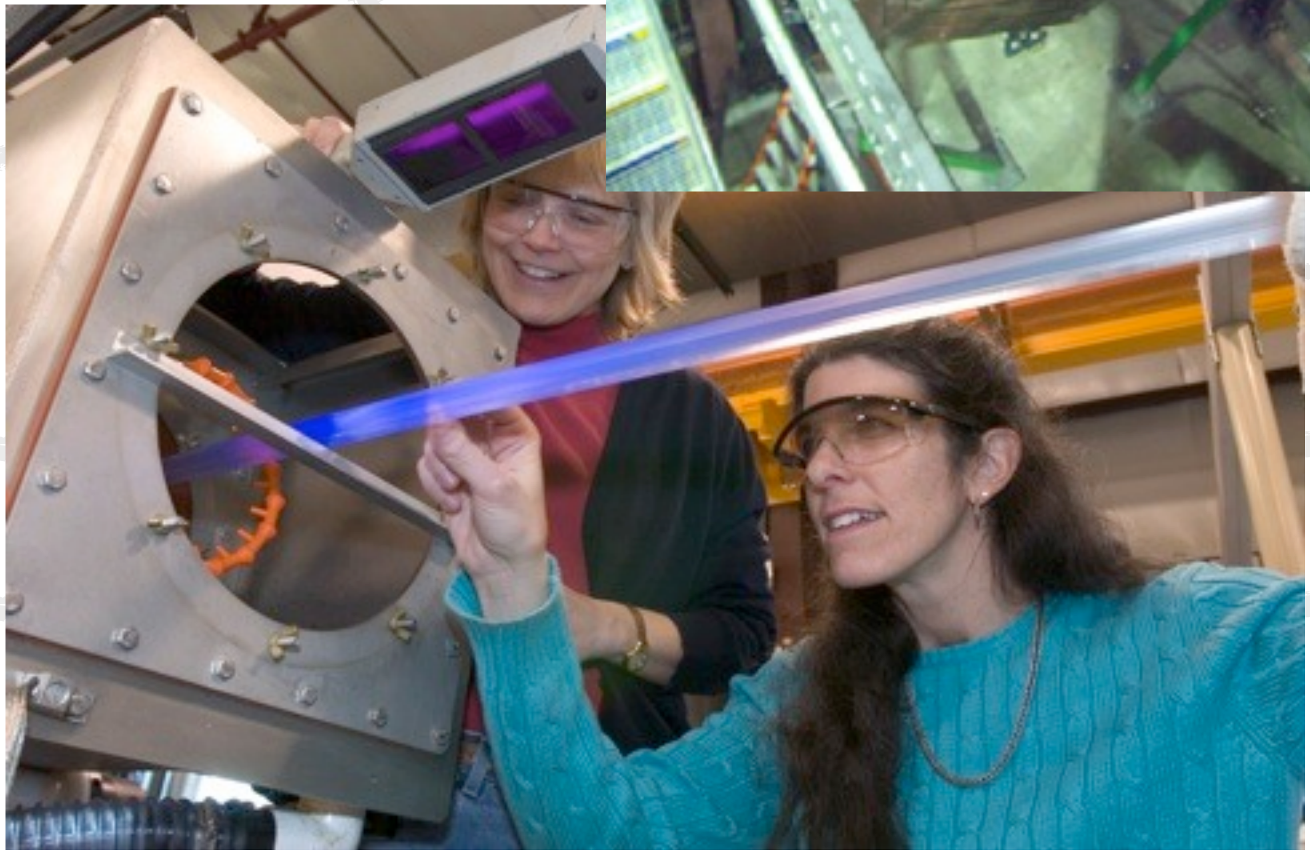
Multiple nuclear targets (C, CH, Fe, Pb, He, H_2O)

MINOS Near Detector acts as a muon spectrometer



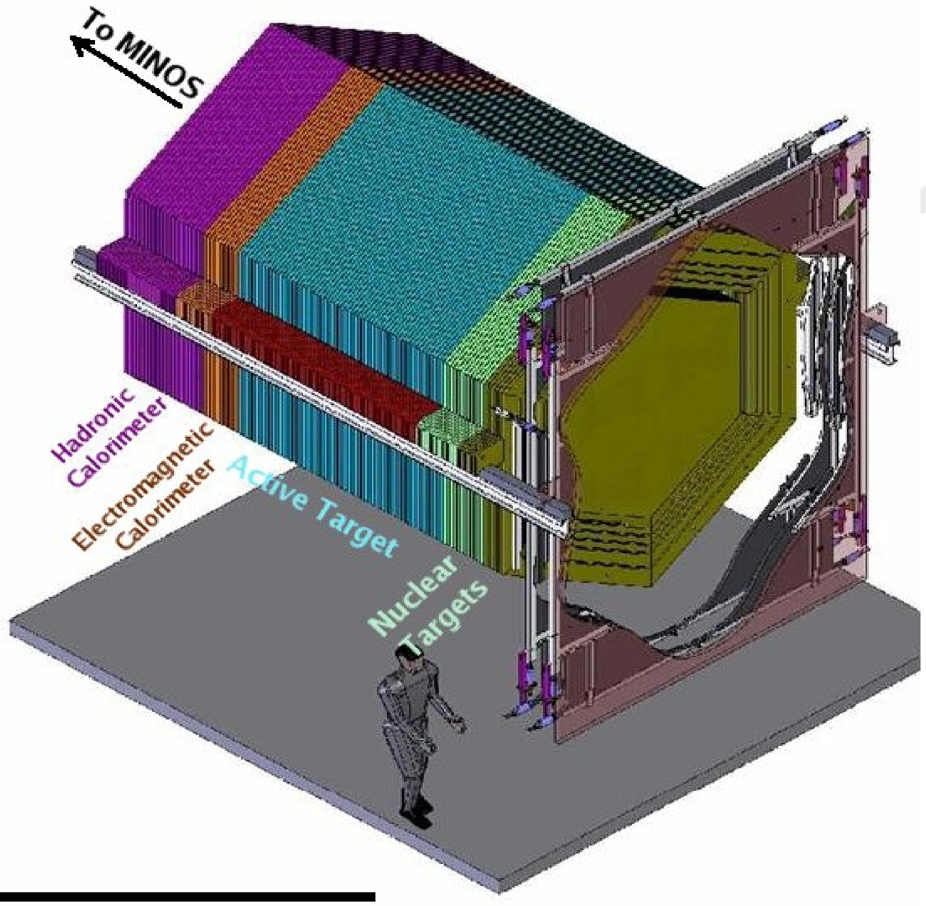



Strip
ECAL
HCAL
Energy
Plane



Detector description

- **30K scintillator channels grouped into inner and outer detectors**
- **Electromagnetic (lead) and hadronic (iron) calorimetry regions**
- **Nuclear targets (^{4}He, C, Fe, Pb, H_2O)**
- **Veto wall in front of the detector**
- **MINOS near detector as muon catcher**



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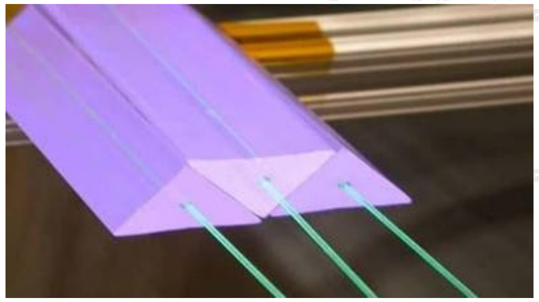
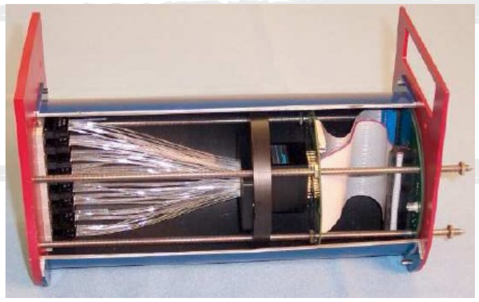
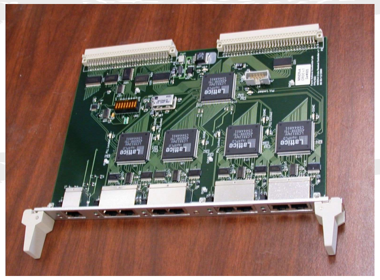
scintillator light
WLS fiber
clear fiber → **PMT** → **front-end board** → **crate** → **storage**



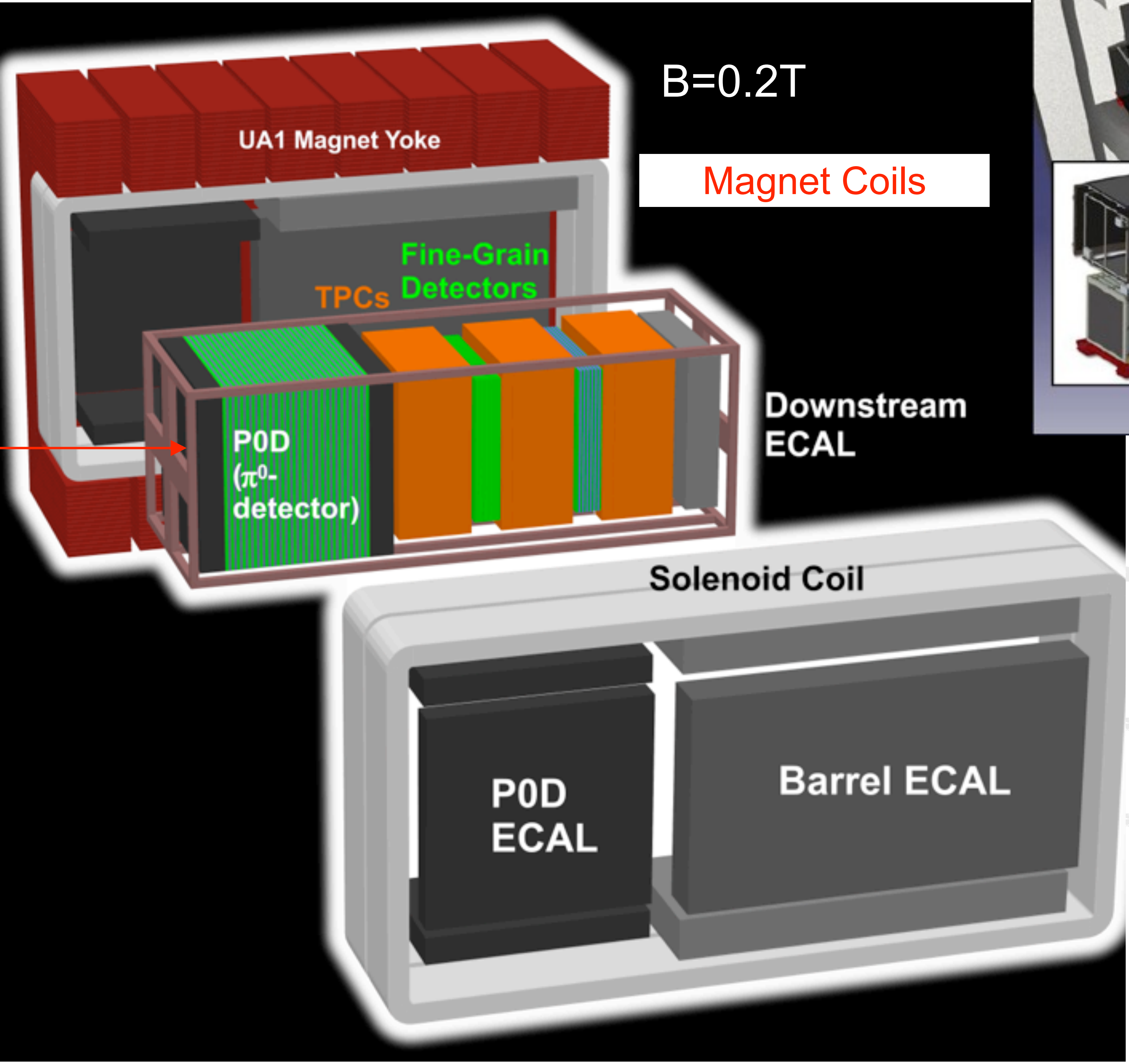


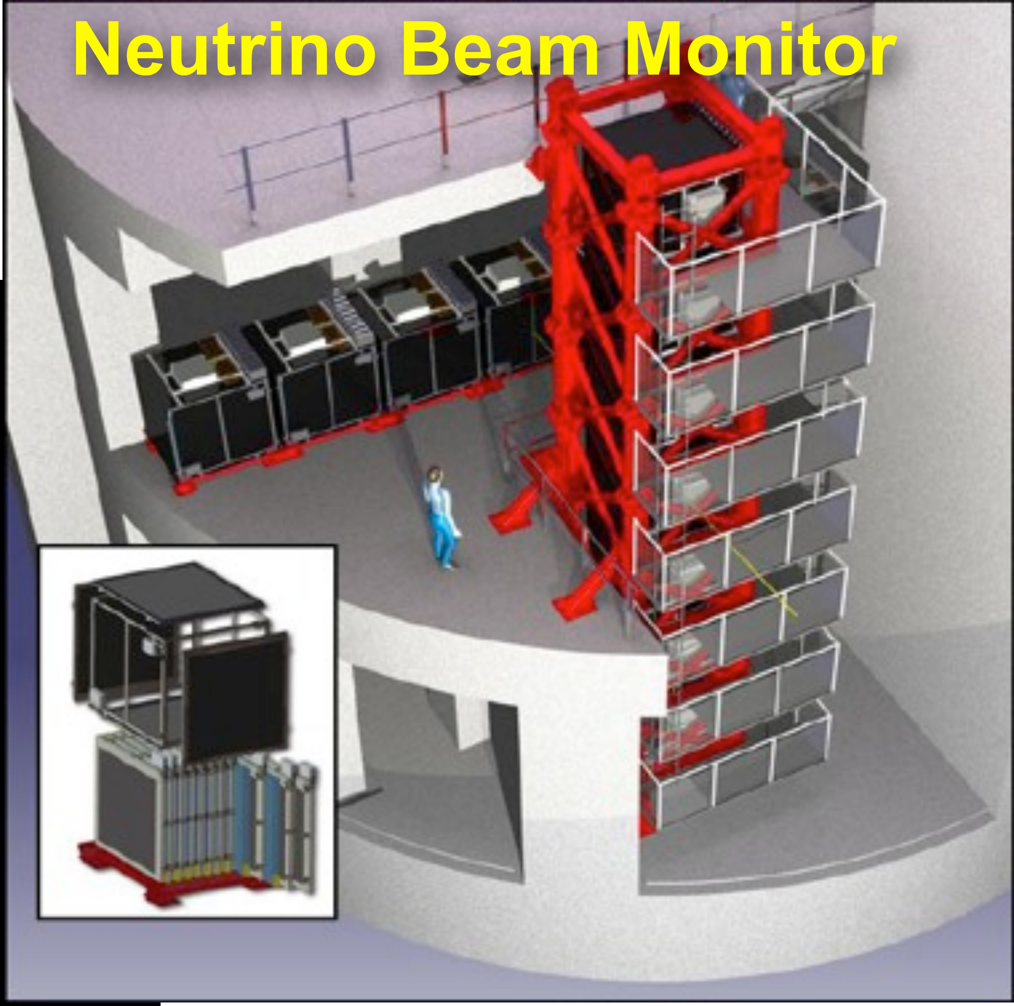


DPF-2011, Brown University, RI, USA, August 9-13, 2011

Bari Osmanov@DPS2011

T2K-ND280

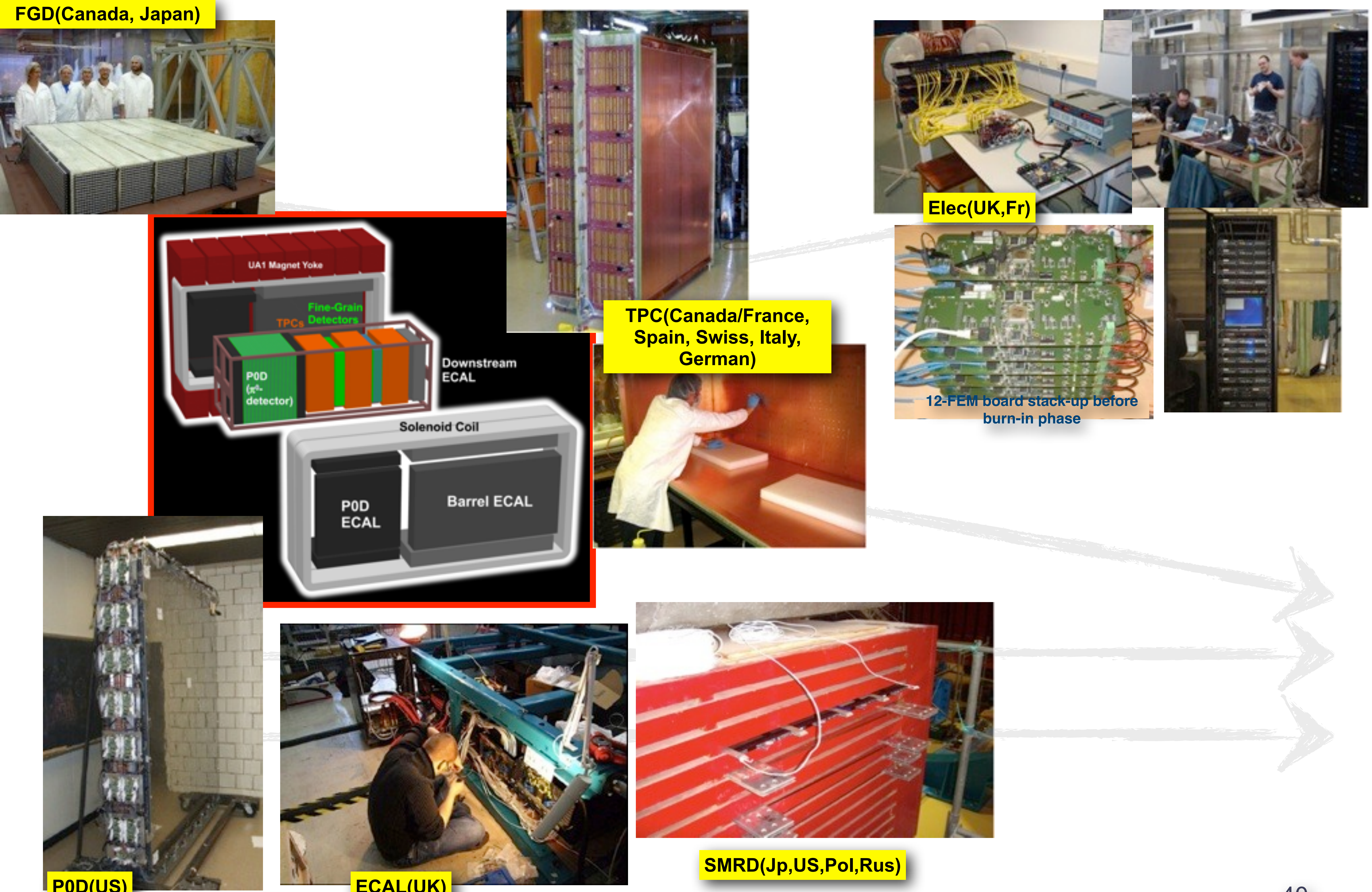




- Volume:
  - $3.5 \times 3.5 \times 7.0 \mathrm{m}^3$
- **P0D:** π^0 Detector
- **FGD+TPC:** Charged Particle tracking
- **EM calorimeter**
- **Side-Muon-Range Detector**

Morgan O. Wascko

T2K-ND280 Detector components



FGD(Canada, Japan)

TPC(Canada/France, Spain, Swiss, Italy, German)

Elec(UK,Fr)

12-FEM board stack-up before burn-in phase

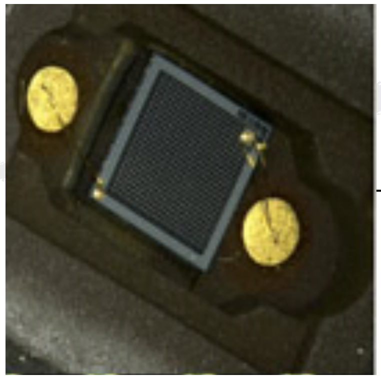
P0D(US)

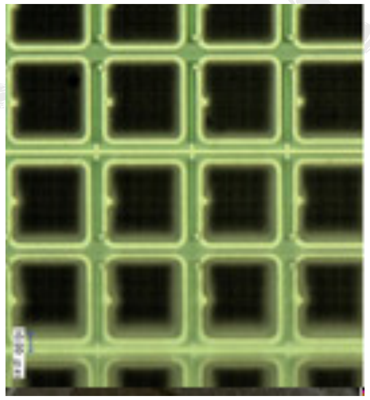
ECAL(UK)

SMRD(Jp,US,Pol,Rus)

ND280: Photosensers MPPCs

Scintillator detectors read out via WLS fiber coupled to Si MPPC (667 pixel avalanche photodiode, area of 1.3x 1.3mm^2).





- **First large-scale use in HEP experiment: ~50,000 MPPCs for ND280**

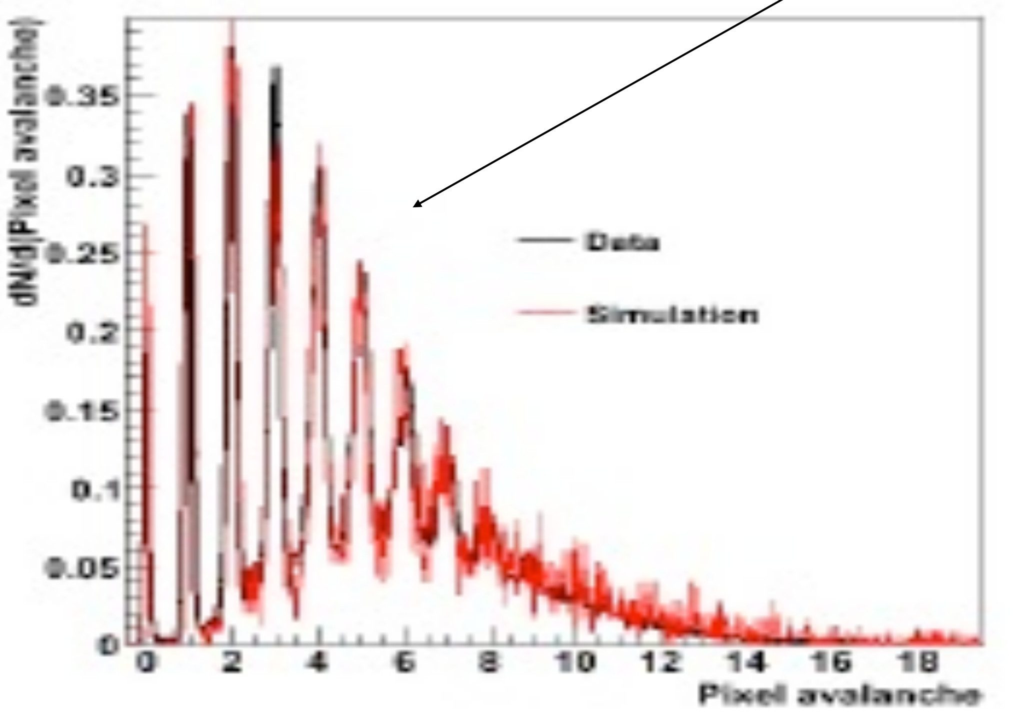
- **After First year of operation with MPPCs few-to-none have failed.**

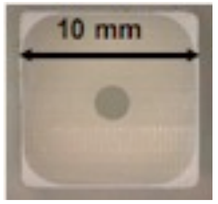
Properties:

- Can isolate single PE's!
- High γ eff, ~20-30% (green)
- gain similar to PMT's
- Operating voltage ~70V.
- Hard to damage
- Insensitive to magnetic fields

But..

- High dark noise rates: ~0.5MHz.
- Cross-talk/afterpulsing.
- Properties (e.g. gain) depend strongly on temp and voltage.

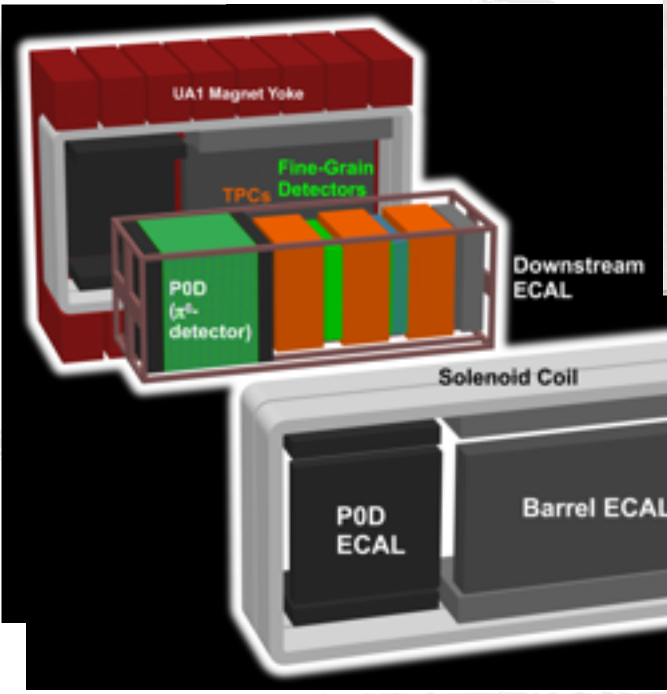


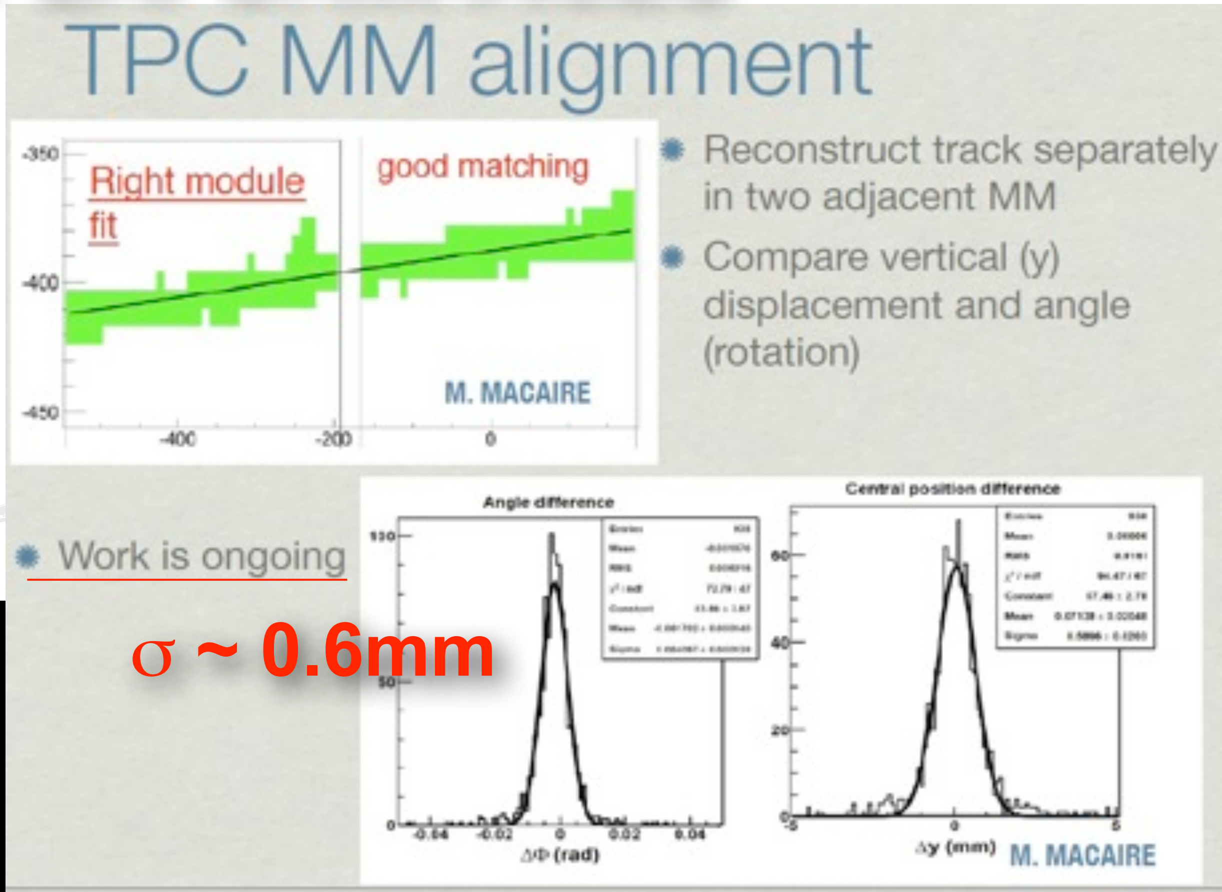


OFF-AXIS DETECTOR PERFORMANCES

System	Channels	Bad chan.	Fraction
DSECAL	3400	11	0.3%
SMRD	4016	3	0.07%
P0D	10400	7	0.07%
INGRID	8360	8	0.1%
TPC	124416	12	0.01%
FGD	8448	55	0.7%

Very small number of bad channels



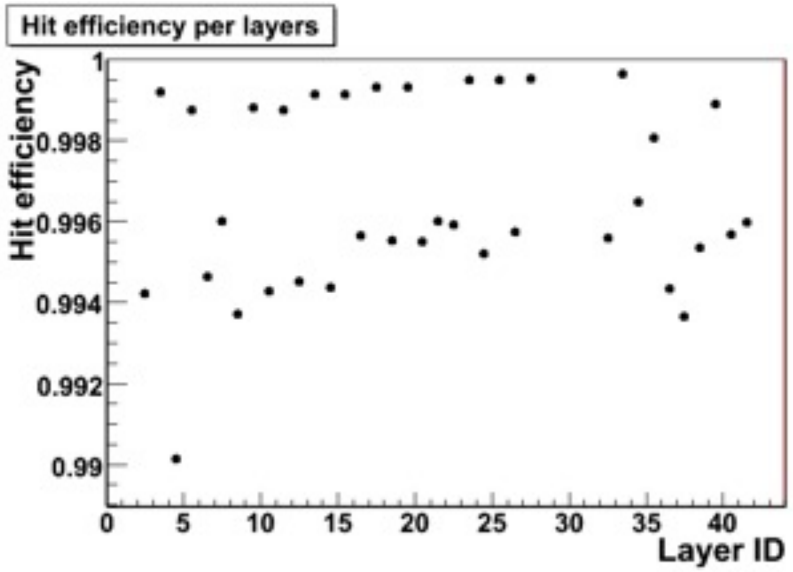


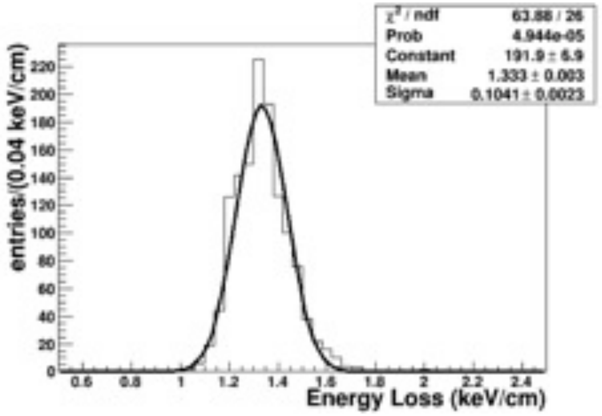
TPC MM alignment

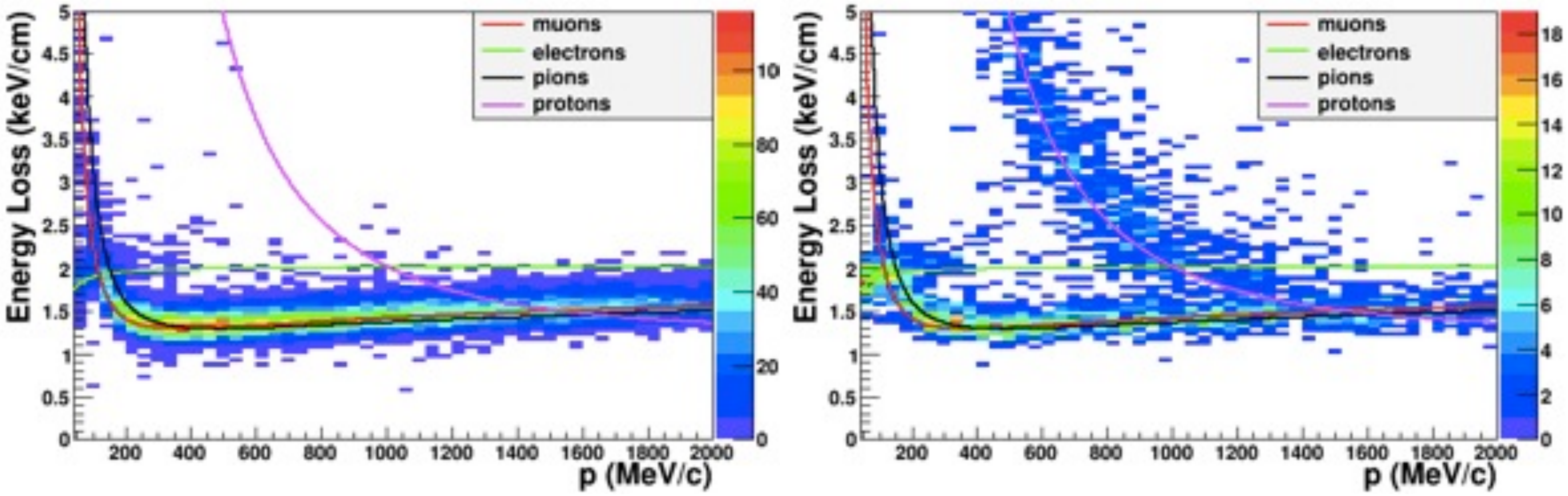
- Reconstruct track separately in two adjacent MM
- Compare vertical (y) displacement and angle (rotation)
- Work is ongoing

σ ~ 0.6mm

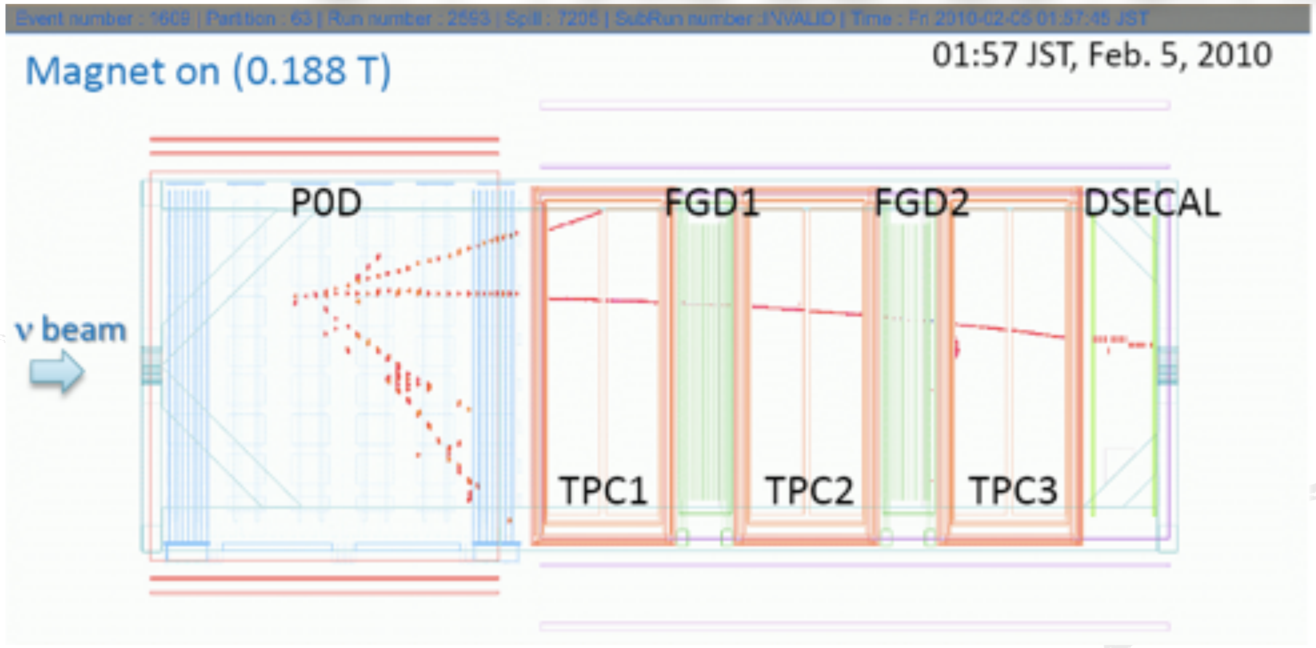
Hit Efficiencies >99%
For all layers (FGD)

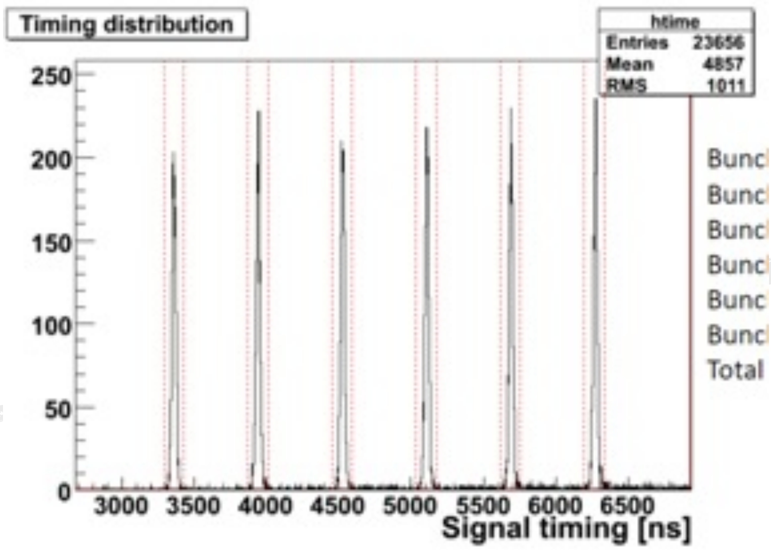


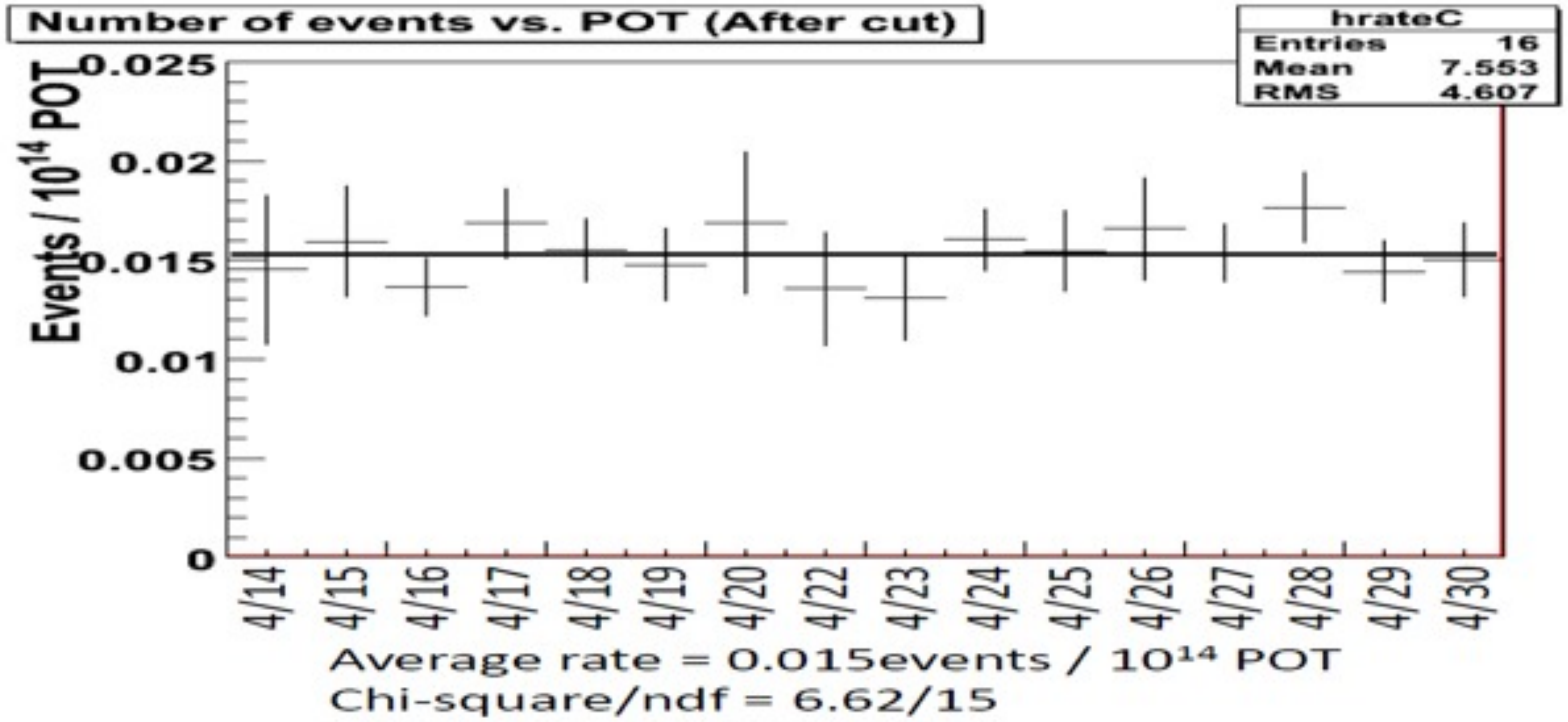


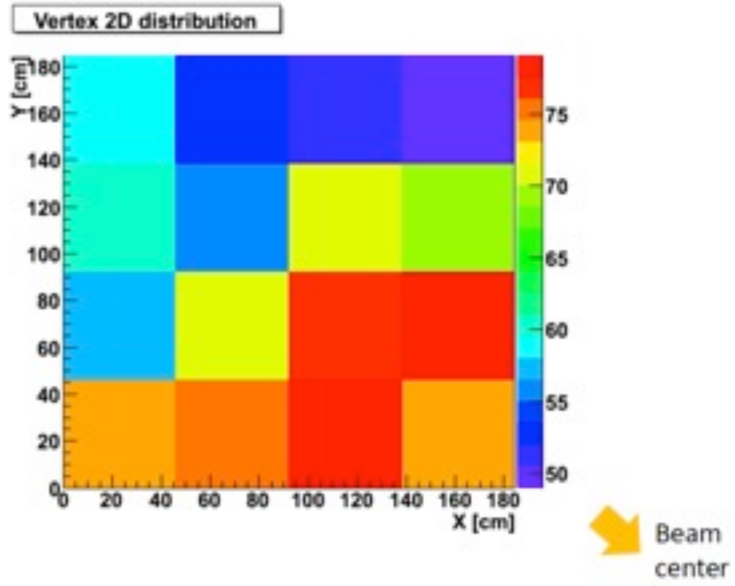


OFF-AXIS DETECTOR MEASUREMENTS



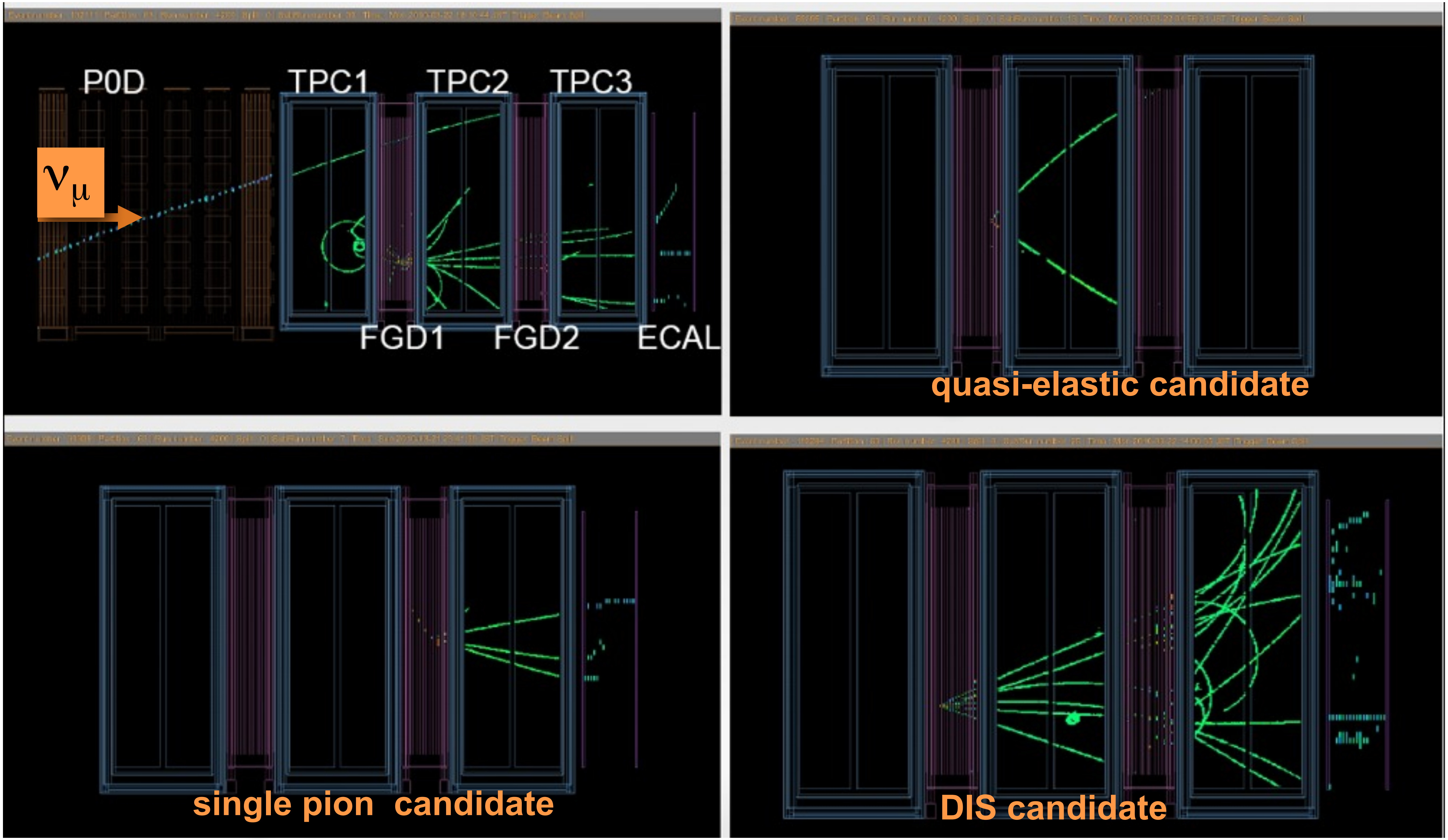






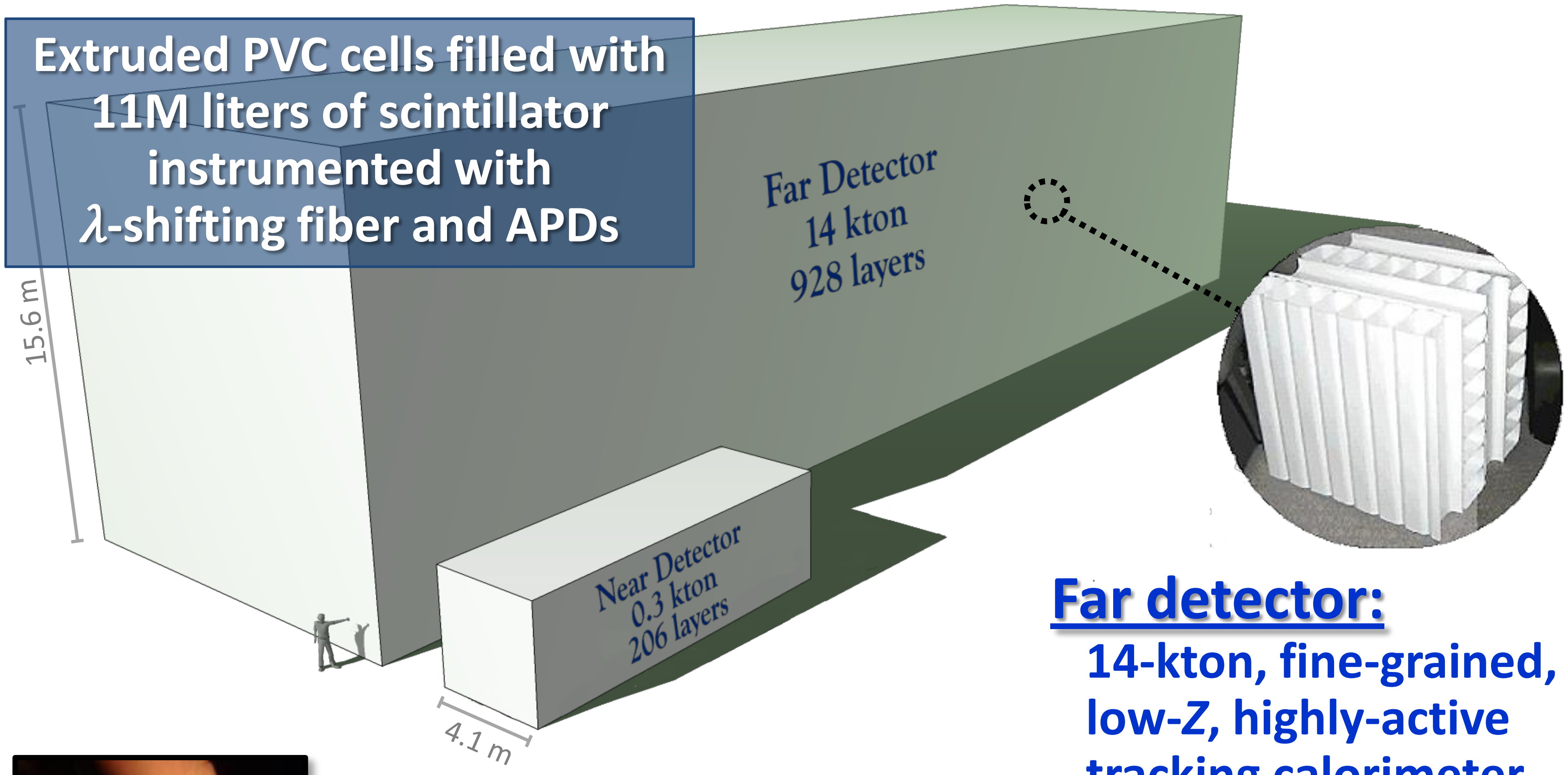
View from Downstream to Upstream

A few ND280 neutrino interaction candidates



NOνA Detectors

Extruded PVC cells filled with 11M liters of scintillator instrumented with λ-shifting fiber and APDs



Far detector:

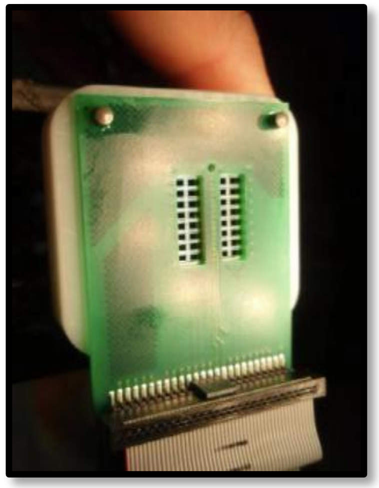
14-kton, fine-grained, low-*Z*, highly-active tracking calorimeter

- → *360,000 channels*
- → *77% active by mass*

Near detector:

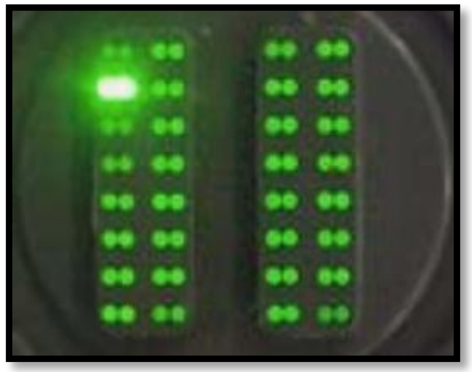
0.3-kton version of the same

- → *18,000 channels*

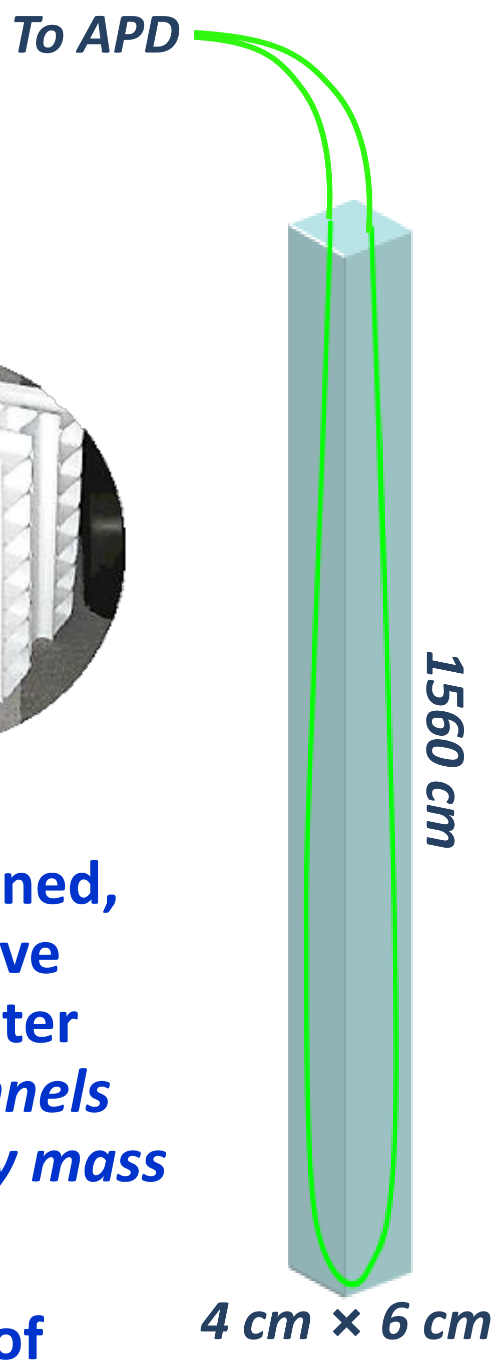


32-pixel APD

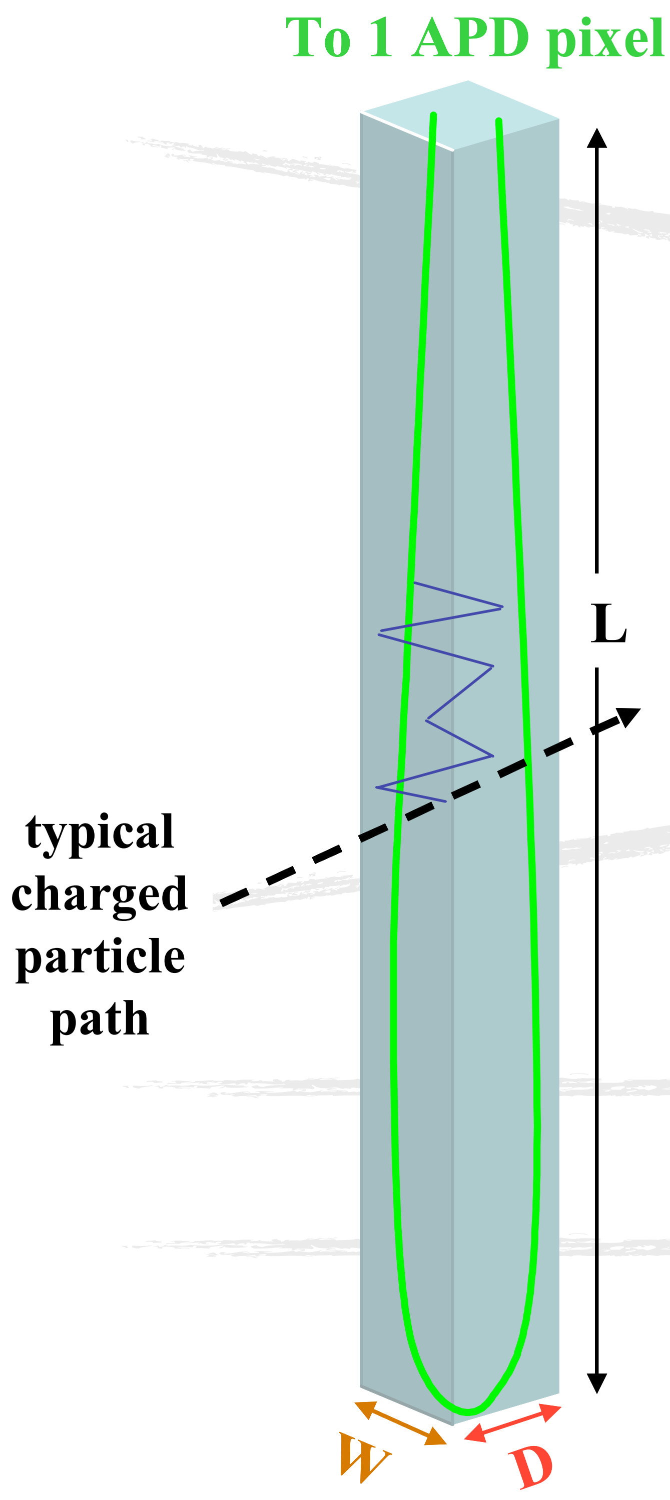
Fiber pairs from 32 cells



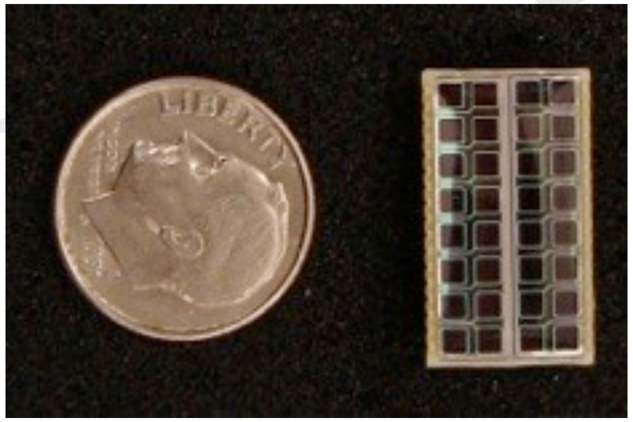
A NOνA cell



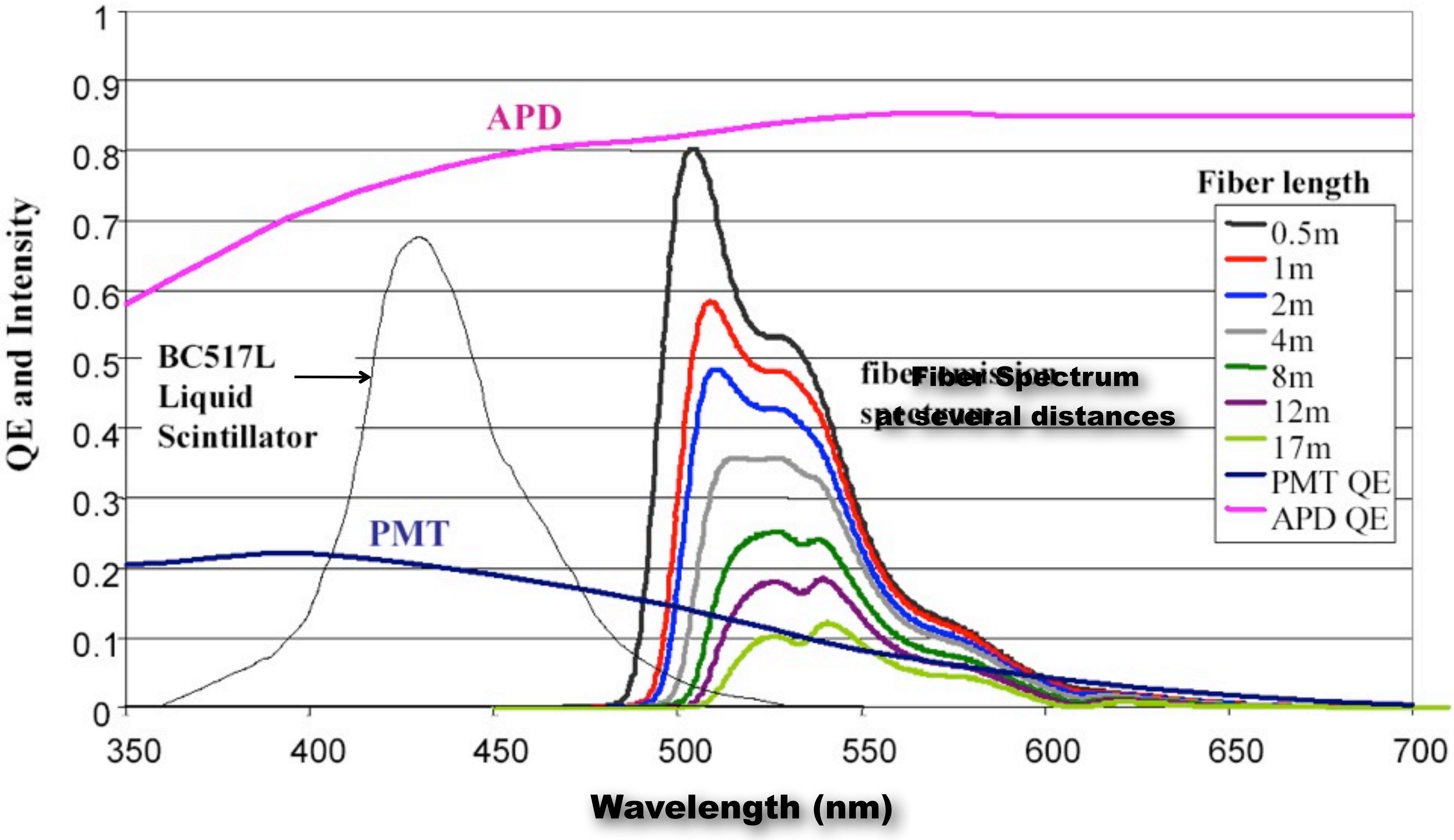
The Basic Detector element



- Liquid Scintillator
  - 4.1% pseudocumene as scintillant
  - Mineral oil and waveshifters (PPO, bis-MSB)
- PVC cell for primary containment
  - Horizontals:3.87 cm x 6.0 cm x 15.4 m long
  - Verticals: 3.76 cm x 5.7 cm x 15.4 m long
  - Highly reflective, 15% titanium dioxide
- Looped wavelength shifting fiber to collect light
  - 0.7 mm diameter, double clad, K27 waveshifter
  - Almost perfect mirror, 3.6*light in 1 fiber
- Avalanche Photodiode
  - 85% quantum efficiency
  - Gain of 100, operate at -15°C
- Low noise amplifier



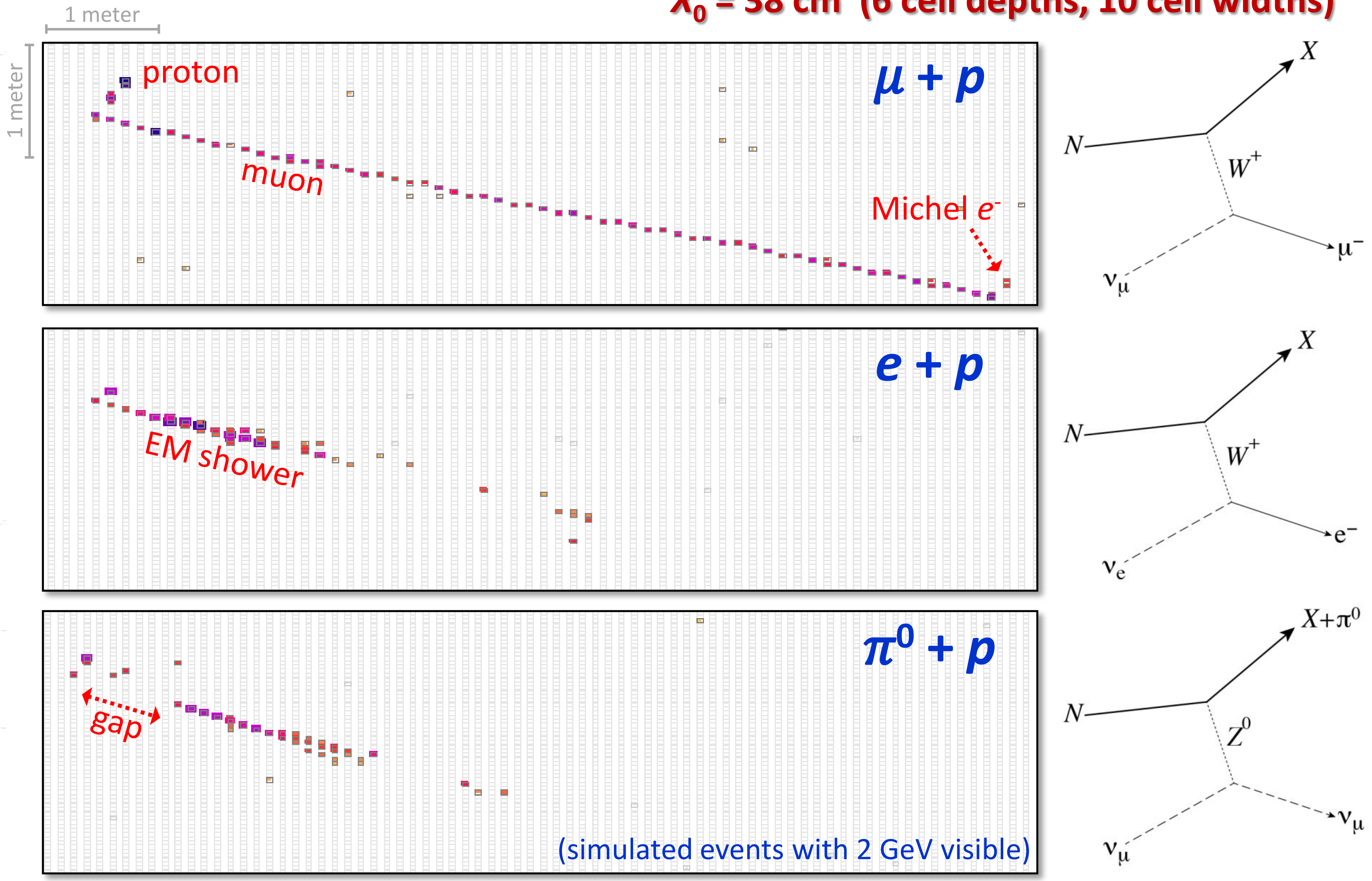
APD Advantage



Events in NOνA

Superb spatial granularity for a detector of this scale

X_0 = 38 cm (6 cell depths, 10 cell widths)



(simulated events with 2 GeV visible)

Ryan Patterson, Caltech 5 Neutrino 2012

Assembly status

- **Pivoter essentially complete**
  (a few reinforcement plates to be added; final flatn[illegible]imming)
- **Bookend, lifters [illegible]s ready**
- **1st block ass[illegible]egin this month!**

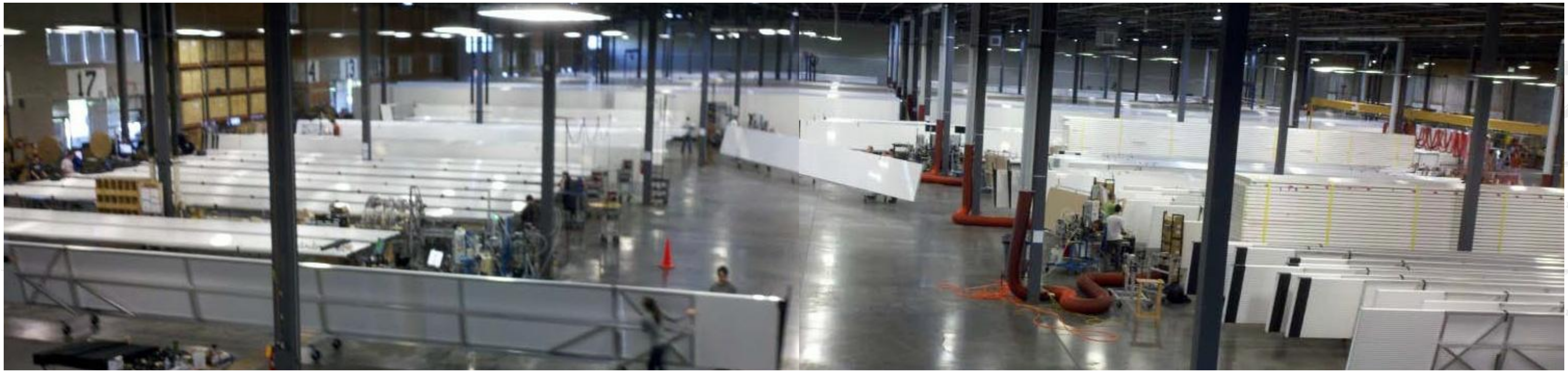
DONE!

Near D[illegible]r

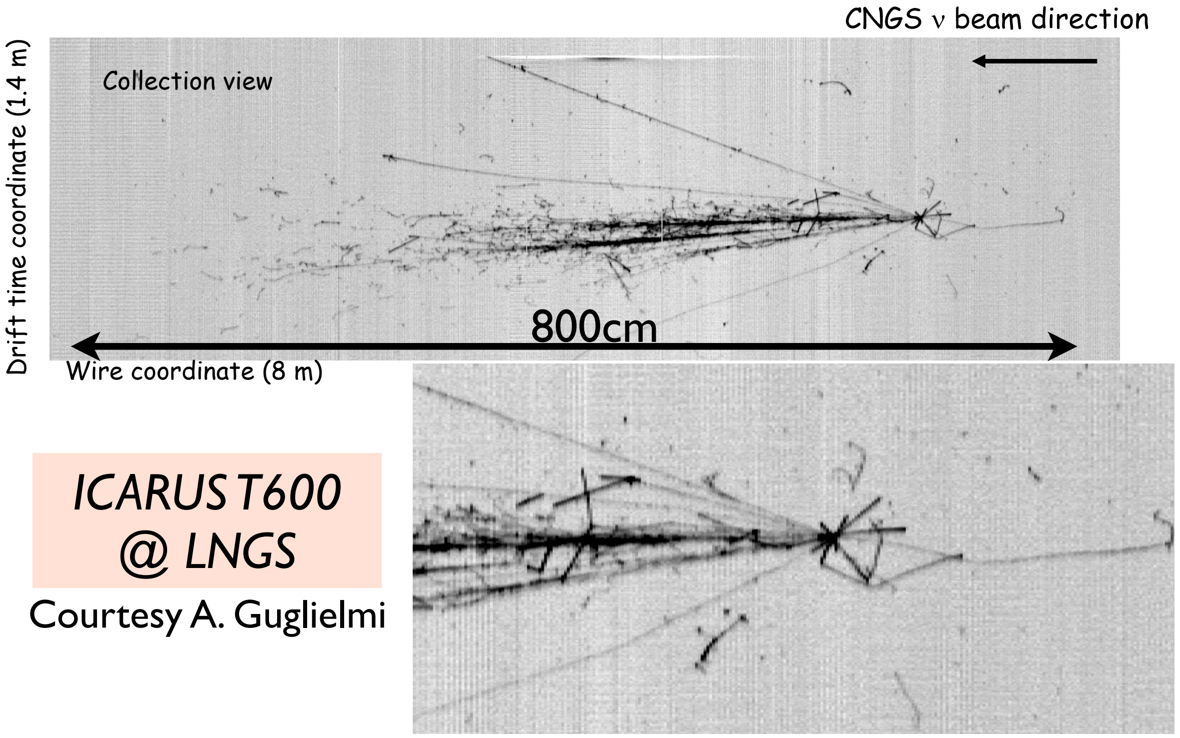
- **ND[illegible]avation and assembly to p[illegible]n parallel at Fermilab**
- **Chang[illegible]g to (96 cell) × (96 cell) design**
  - *NDOS is 64×96*
  - *Improved ND event containment*

Lifting fixture and adhesive dispenser

NOνA module factory

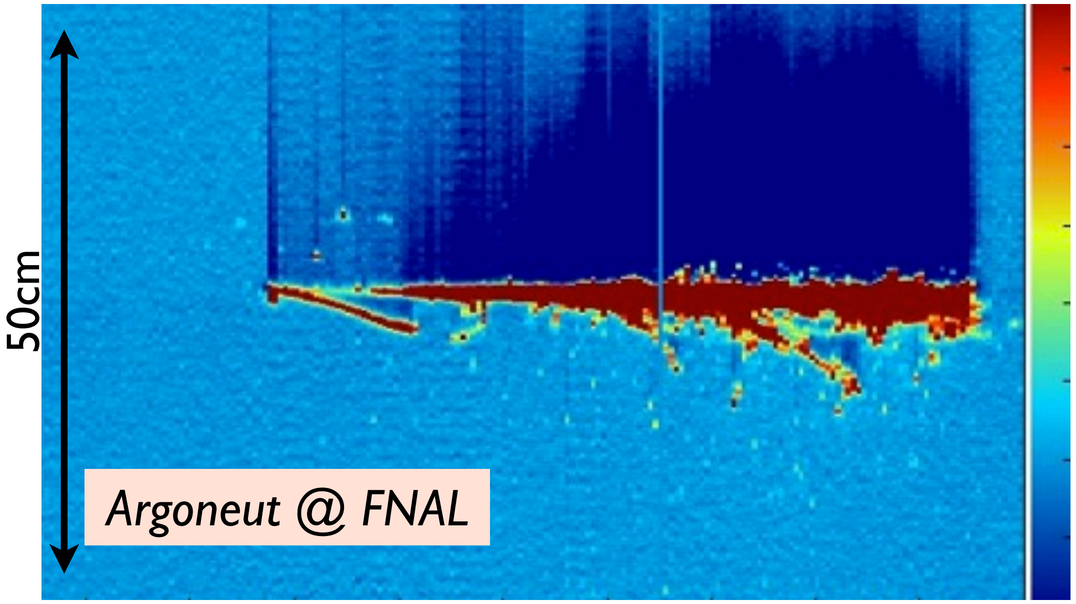


The “electronic bubble chamber”



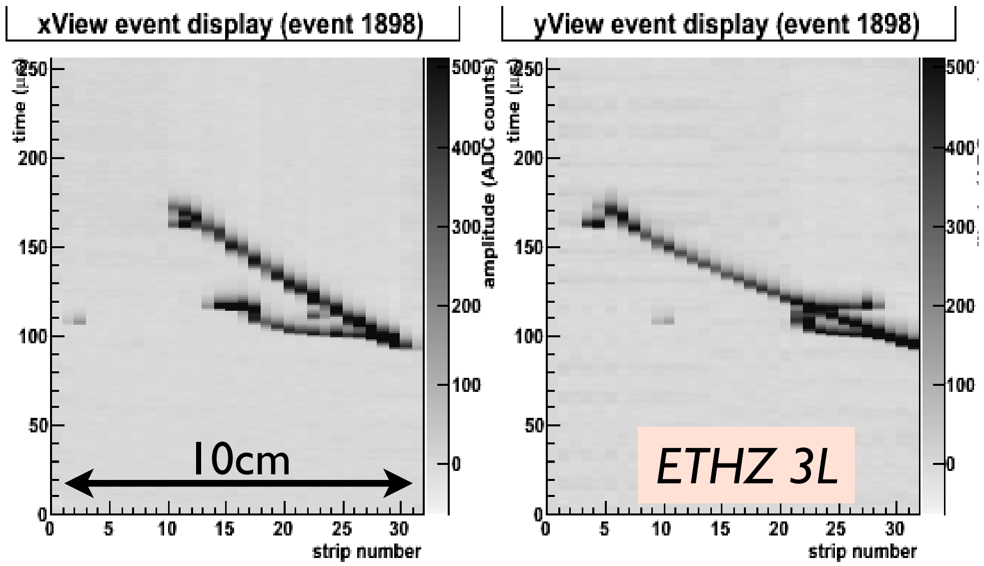
ICARUS T600 @ LNGS

Courtesy A. Guglielmi



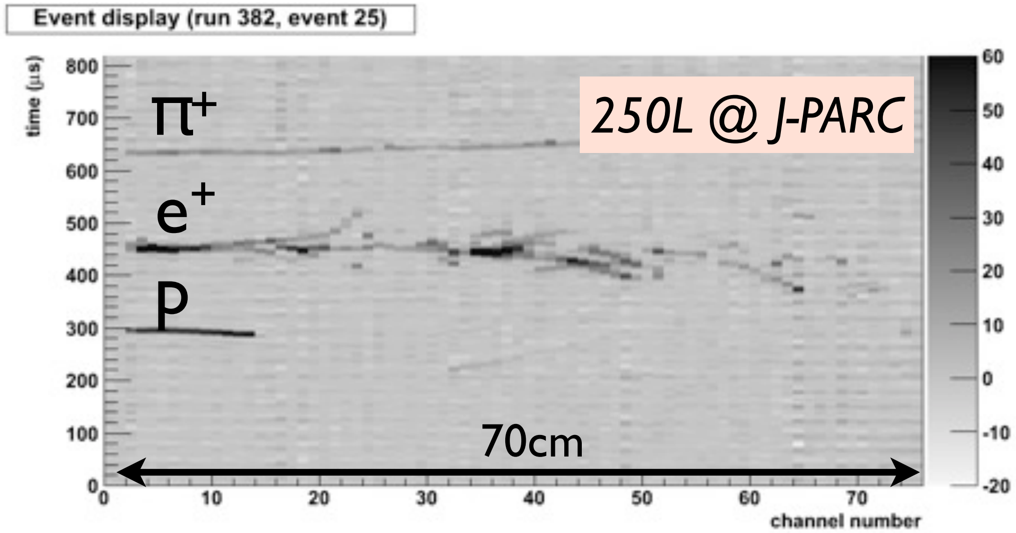
Courtesy B. Fleming

Cosmic track in double phase 3L LAr-LEM TPC with adjustable gain @ CERN-ETHZ



Much improved S/N (>100) compared to single-phase LAr operation (≈15)

Charged particle beam ≈800 MeV/c exposure

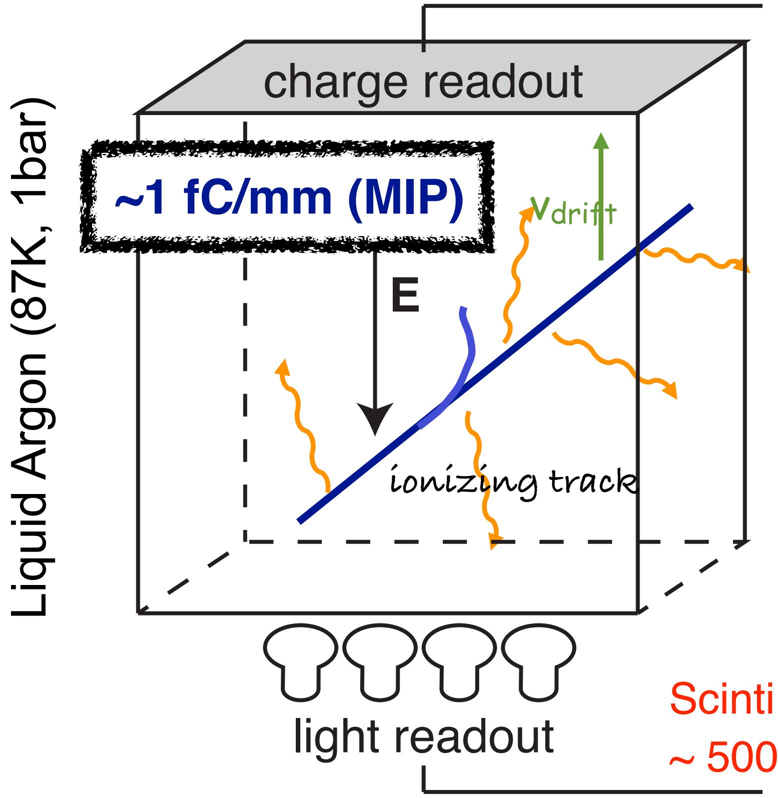


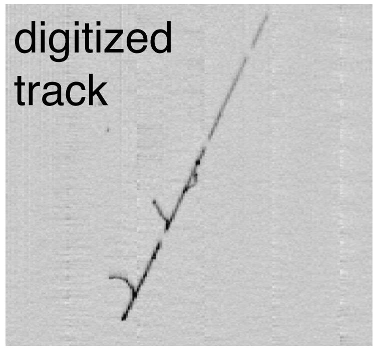
Physical parameters and challenges

Liquid Argon:
+ High density, cheap medium
+ Quasi free electrons from ionizing tracks are drifted in LAr (87K, 1bar) by E_{drift}.
+ Electron drift velocity ≈ 2mm/μs @ 1 kV/cm
+ Electron cloud diffusion is small
($\sigma \approx \sqrt{2Dx/v_{drift}} \approx$ mm after several meters of drift)
+ High scintillation yield (@ 128 nm) can be used for T_0, trigger, ...

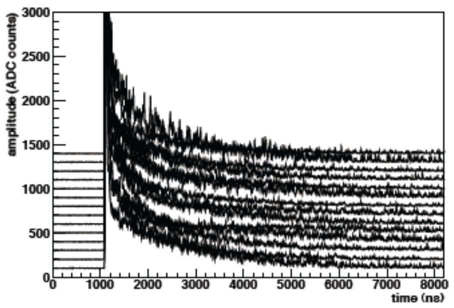
Technical challenges:
– Long drift requires ultra high purity
  * free of electro-negative molecules (O_2, H_2O, ...)
    Goal << 100 ppt O_2 equivalent !!
  * Drift field implies high voltage on the cathode
– Large wire chambers at cryogenic T
– No charge amplification in liquid: fC-level charge sensitive preamplifiers (can be partially solved by LAr LEM TPC – see later)
– Large #readout channels
– Large cryogenic systems

Charge yield after e-ion recombination (mip) ~ 1 fC/mm (~ 6000 electrons/mm) before finite e-lifetime correction

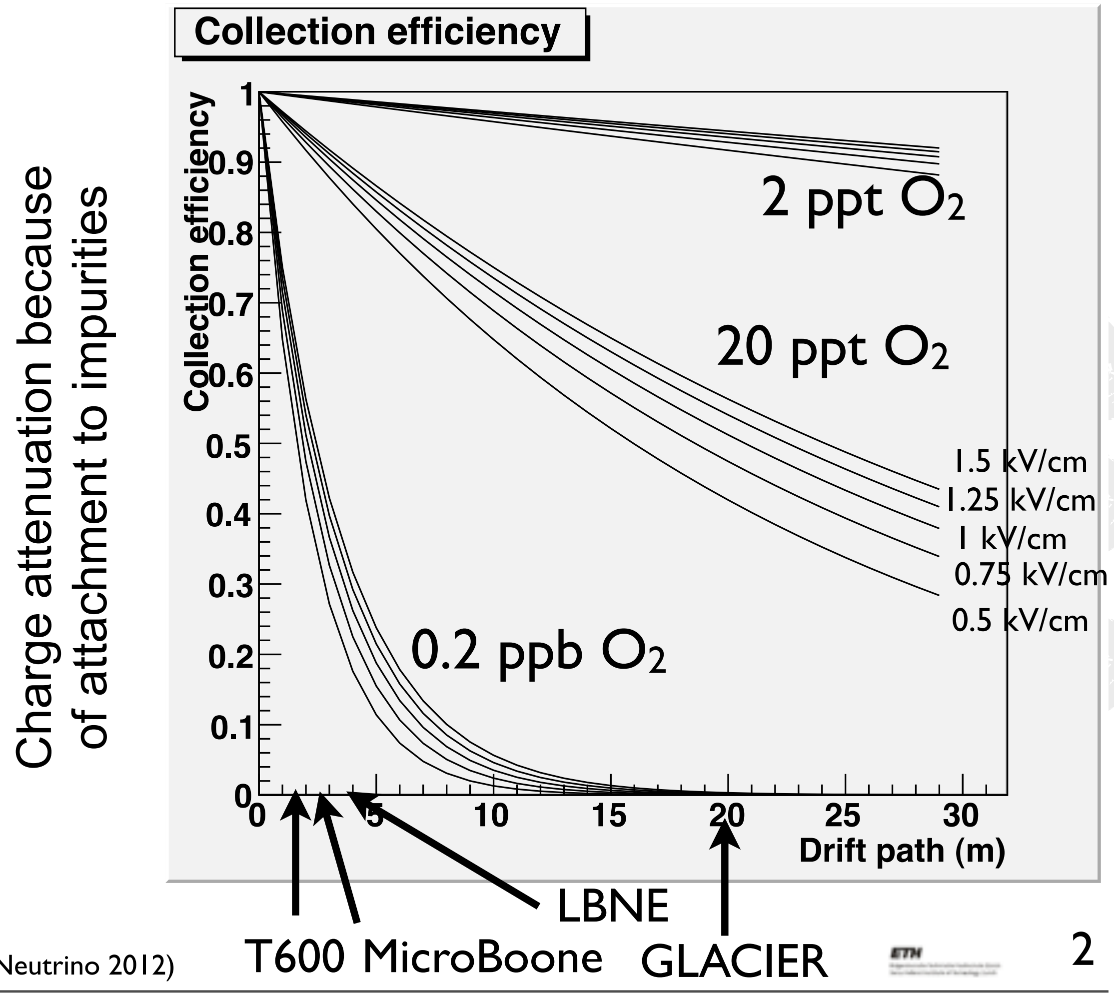




scintillation light



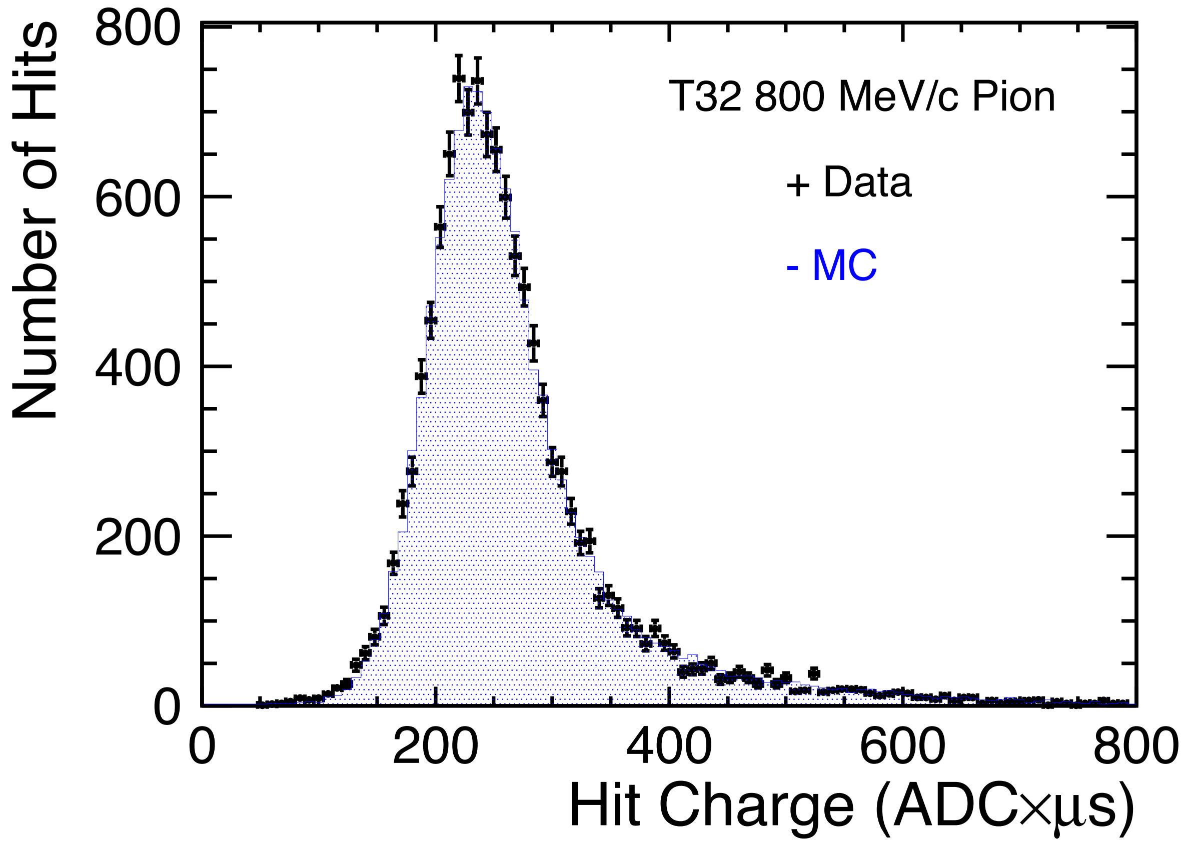
Scintillation yield (mip) ~ 5000/mm @ 128nm



Tracking performance

JPARC T32 exposed to K1.1BR tagged beam

J.Phys.Conf.Ser. 308 (2011) 012008



Data well described by:

Birks Law

Raw charge

Observable charge

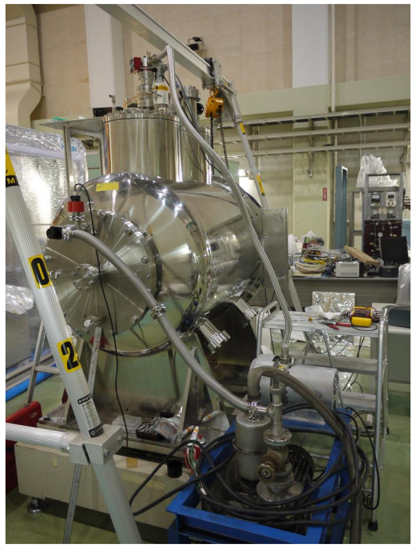
$$Q = A \frac{Q_0}{1+(k/\varepsilon)\times(dE/dx)\times(1/\rho)}$$

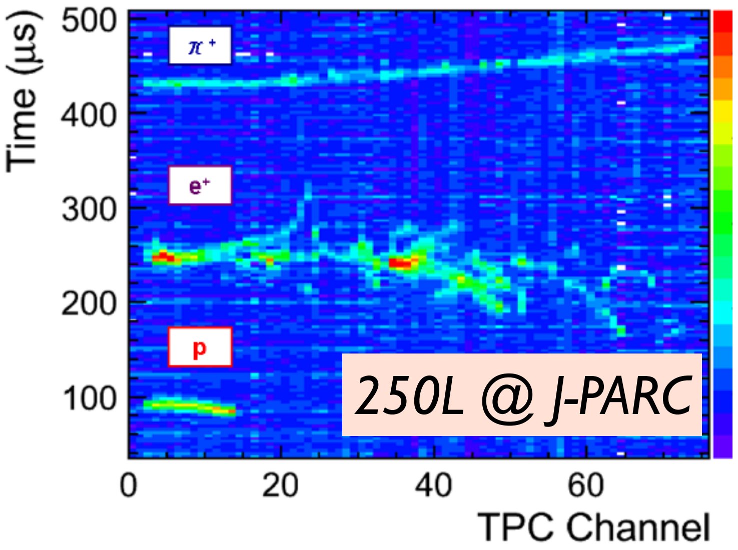
$$A = 0.8$$

$$k = 0.0486\ \mathrm{kV/cm}\frac{\mathrm{g/cm^2}}{\mathrm{MeV}}$$

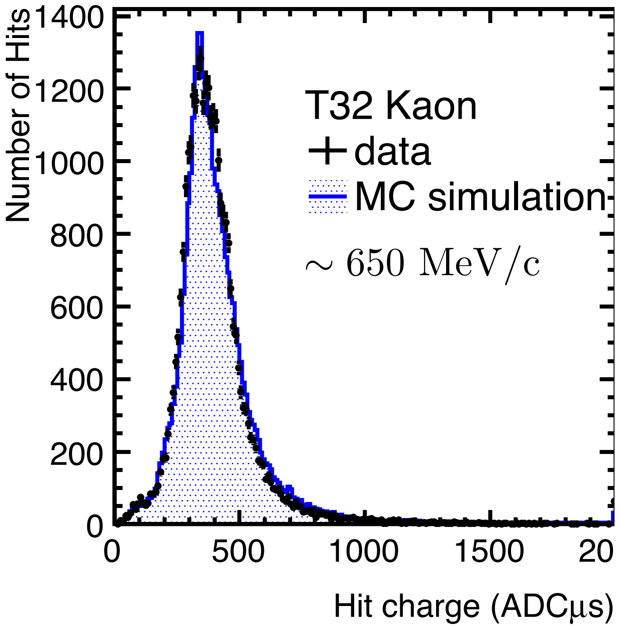
NIM A 523, 275 (2004)

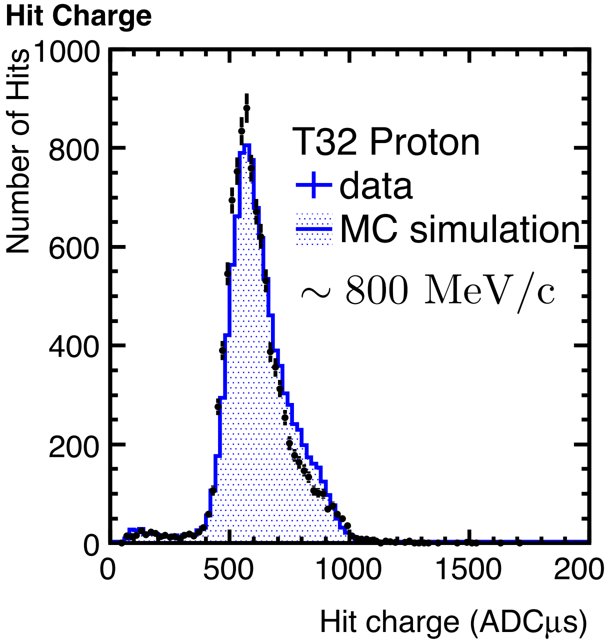
J-PARC T32 chamber (ETHZ-KEK-Iwate-Waseda)





Courtesy T. Maruyama





Good understand of tracking

Calorimetric performance

Michel electrons form stopping muon decay sample

$$\frac{\sigma_e}{E} \simeq \frac{11\%}{\sqrt{E(\mathrm{MeV})}} \oplus 4\%$$

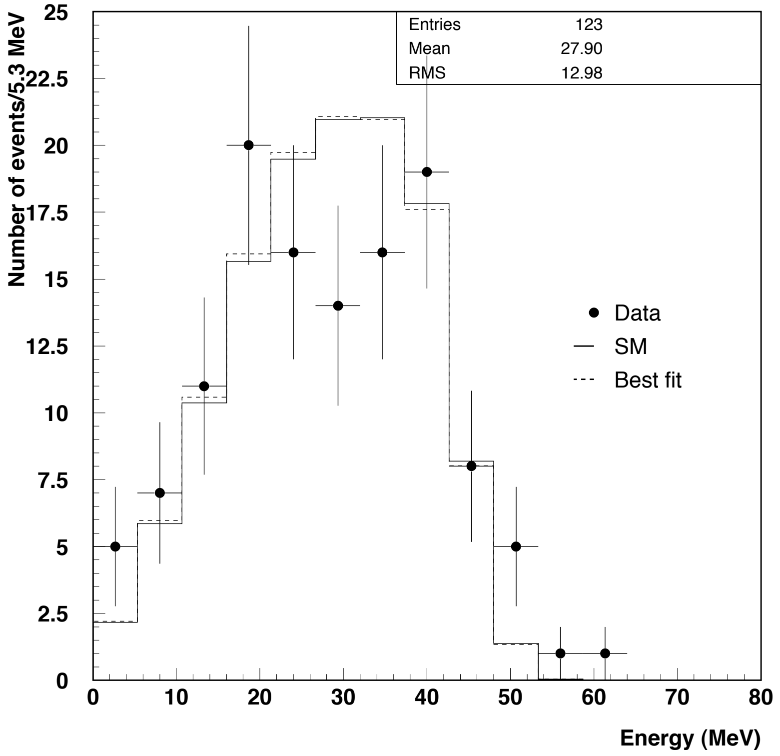
MC simulations at higher energies:

$$\frac{\sigma_{em}^{MC}}{E} \simeq \frac{3\%}{\sqrt{E}} \oplus 1\%$$

$$\frac{\sigma_{had}^{MC}}{E} \simeq \frac{15\%}{\sqrt{E}} \oplus 10\%$$

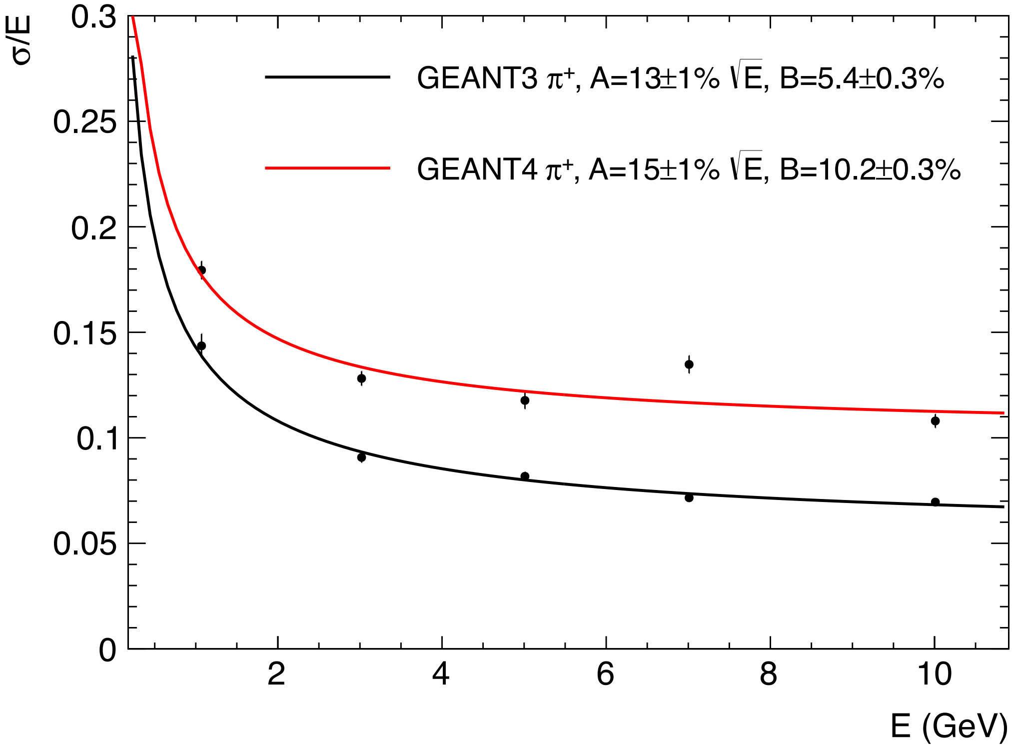
↑

needs to be confirmed by experimental data

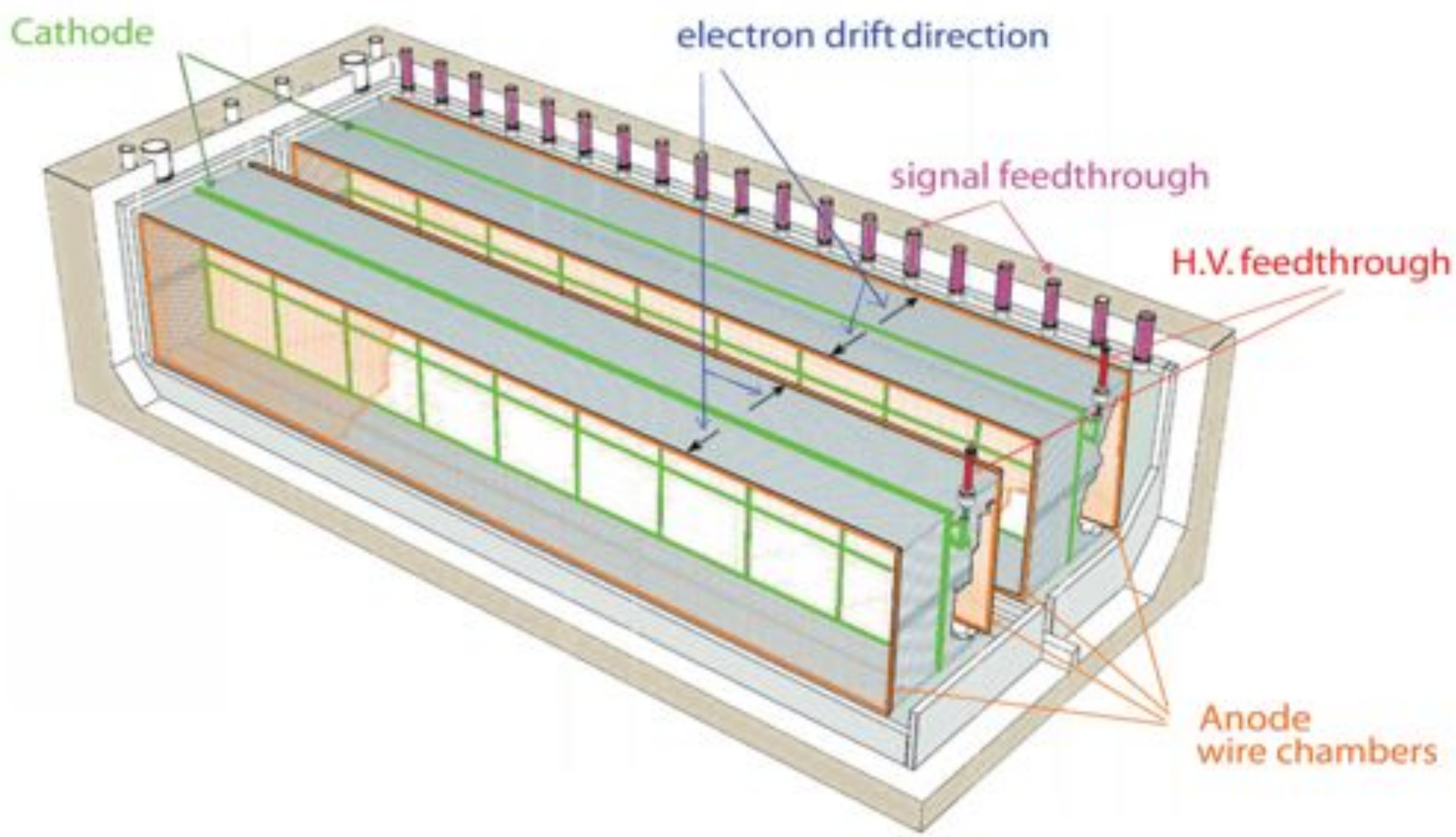


Eur. Phys. J. C33, 233 (2004)

G3 and G4 comparison



The ICARUS T600 detector



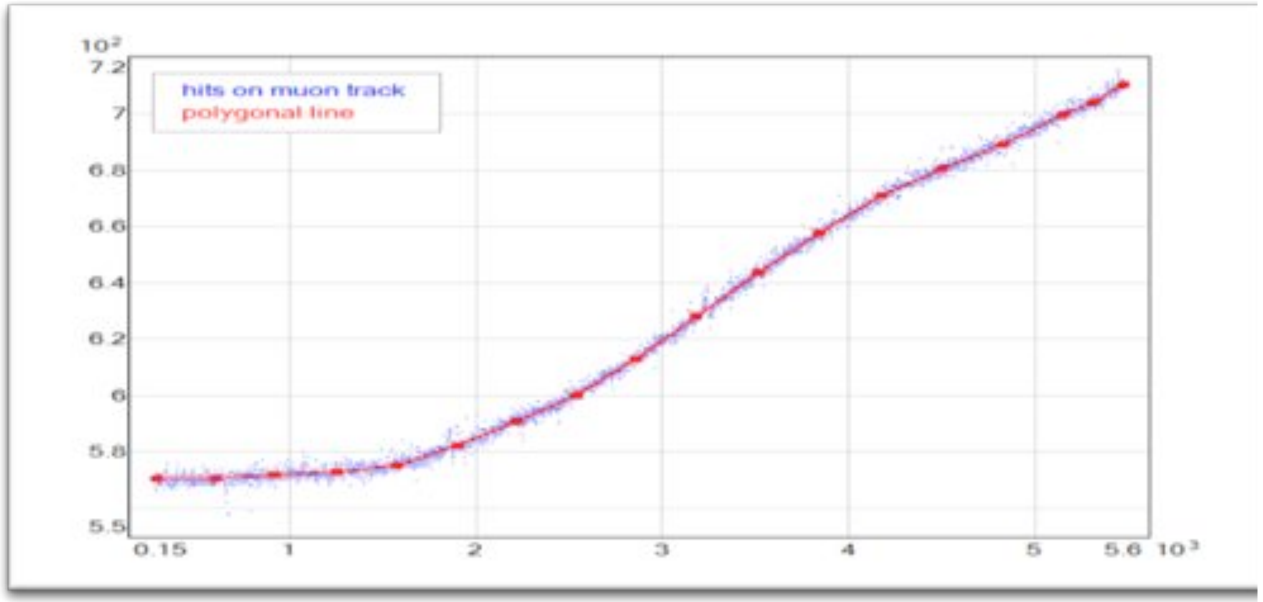
- Two identical modules
  - 3.6 x 3.9 x 19.6 ≈ 275 m^3 each
  - Liquid Ar active mass: ≈ 476 t
  - Drift length = 1.5 m (1 ms)
  - HV = -75 kV E = 0.5 kV/cm
  - v-drift = 1.55 mm/μs
- 4 wire chambers:
  - 2 chambers per module
  - 3 readout wire planes per chamber, wires at 0,±60°
  - ≈ 54000 wires, 3 mm pitch, 3 mm plane spacing
- 20+54 PMTs , 8” Ø, for scintillation light detection:
  - VUV sensitive (128nm) with wave shifter (TPB)

Taking data in LNGS hall B

F. Pietropaolo@NEUTRINO2012

3D reconstruction and particle identification

- 3D reconstruction from 2D based on Polygonal Line Algorithm (PLA), linking hits in different views according to:
  - drift sampling;
  - sequence of hits.

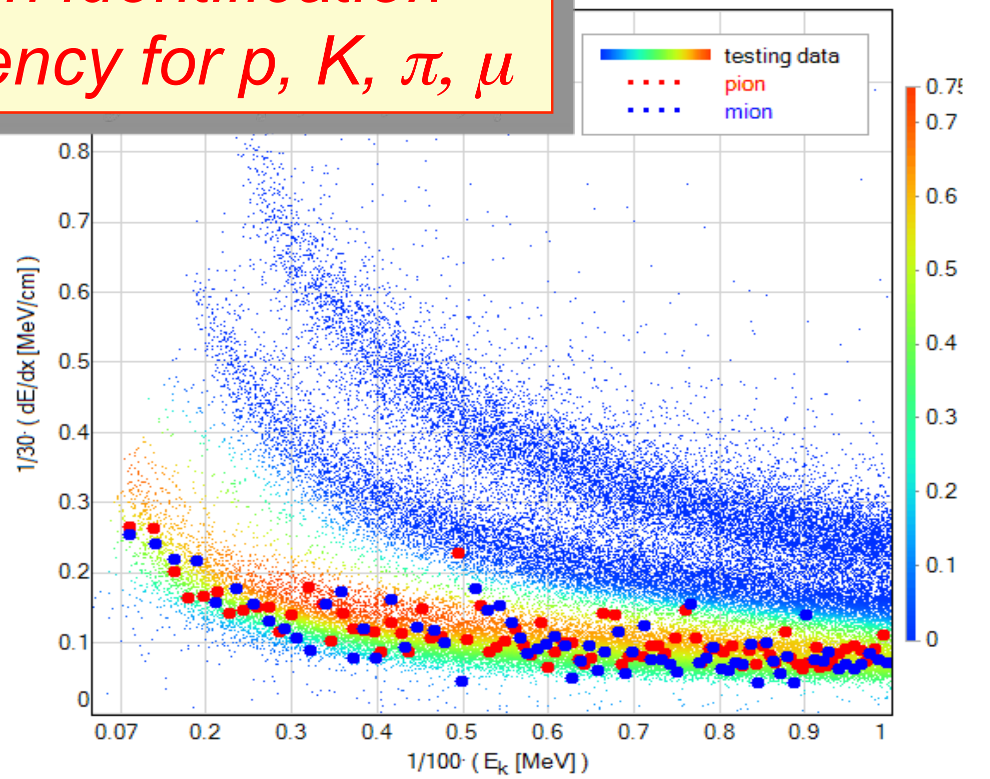


- Particle identification based on:
  - distance between nearby 3D hits: dx
  - 3D hits and charge deposition : dE/dx

- Energy reconstructed, quenching included

High identification efficiency for p, K, π, μ

pid MC	p	K	π	μ	efficiency [%]	purity [%]
p	**481**	4	0	0	99.2	98.0
K	10	**380**	0	0	97.4	99.0
π	0	0	**196**	40	83.1	98.5
μ	0	0	3	**216**	98.6	84.4



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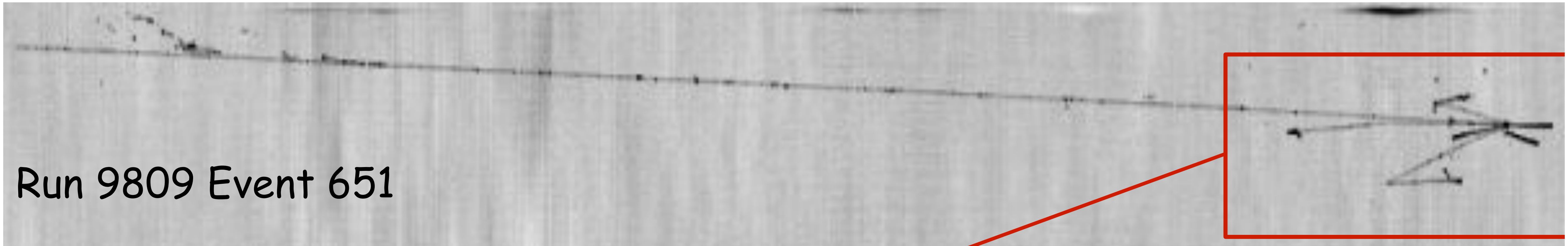
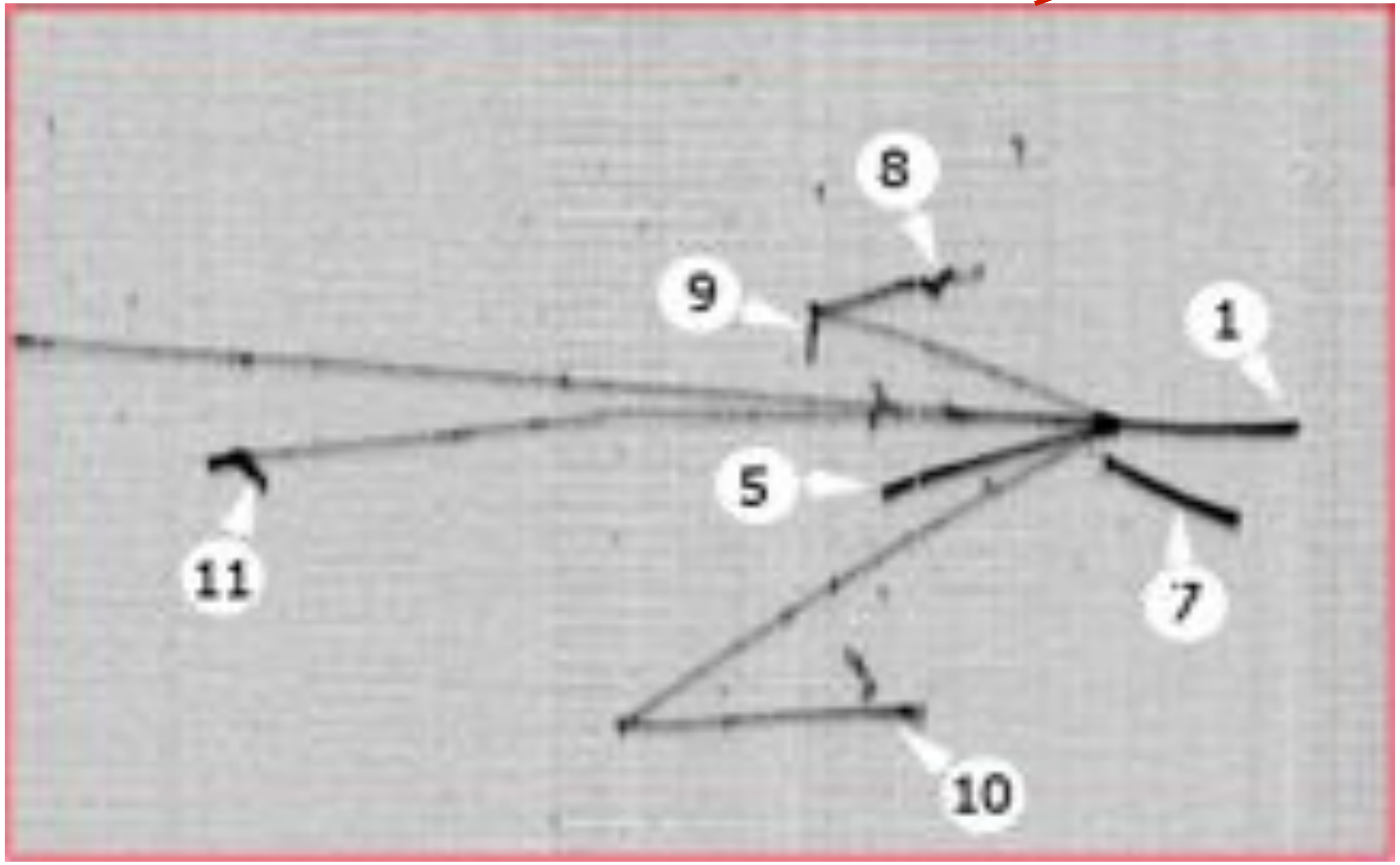
ν_μ CC CNGS event: reconstruction of stopping tracks



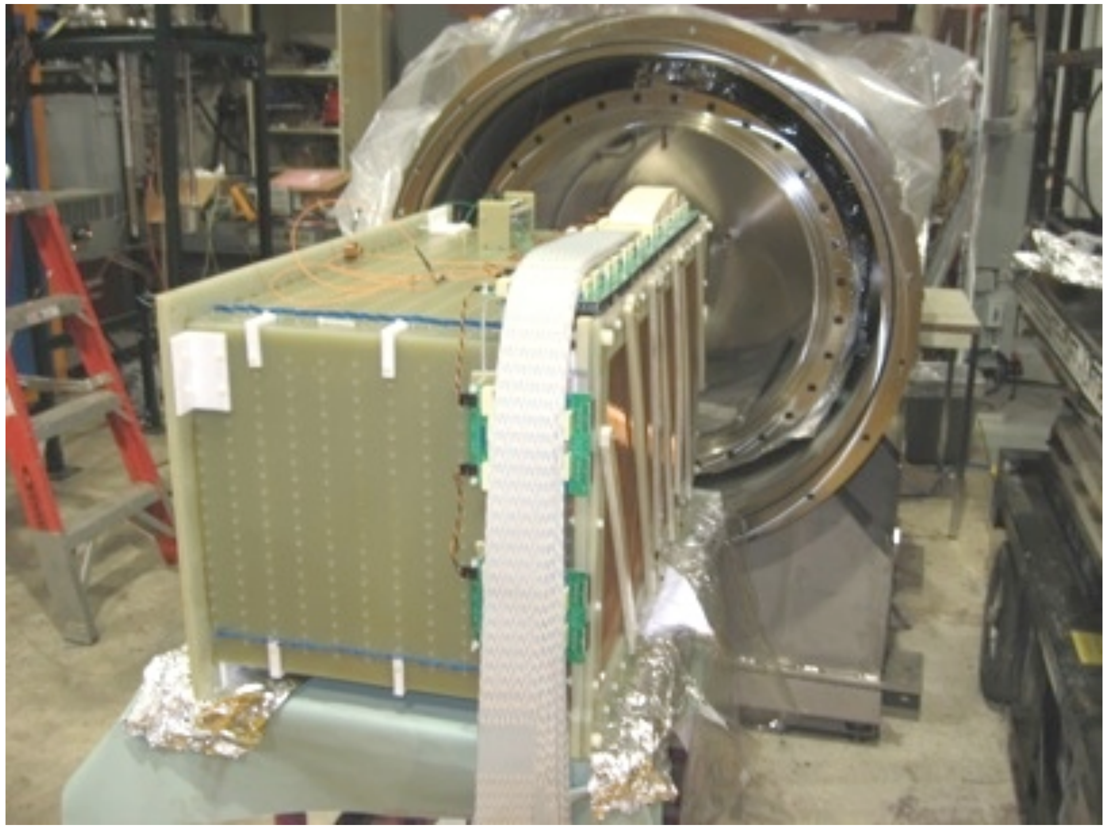


Track	E_{dep} [MeV]	range [cm]
1(p)	185±16	15
5(p)	192±16	20
7(p)	142±12	17
8(π)	94±8	12
9(p)	26±2	4
10(p)	141±12	23
11(p)	123±10	6

6 protons, 1 pion decays at rest

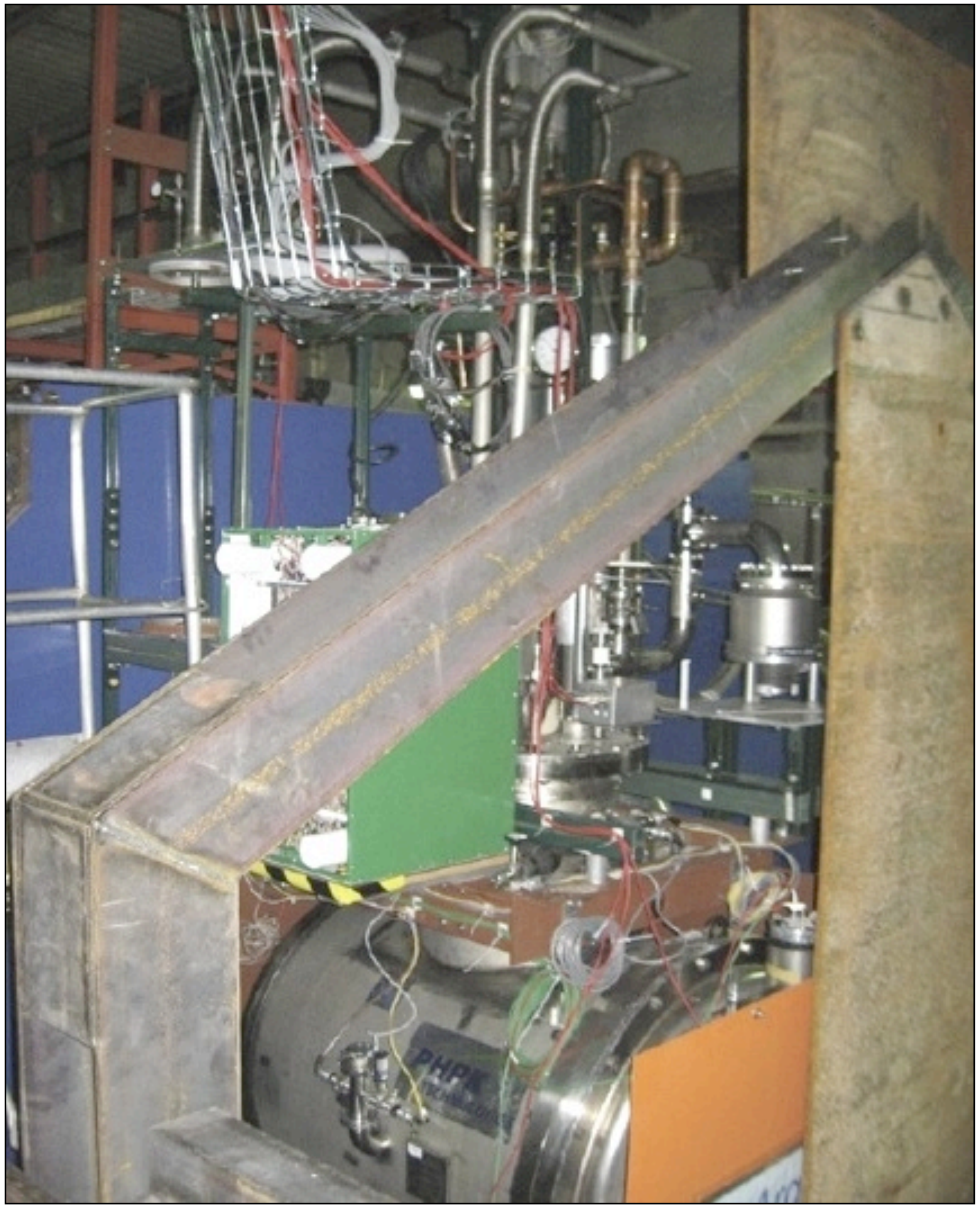
F. Pietropaolo@NEUTRINO2012

ArgoNeuT TPC and cryostat



The TPC, about to enter the inner cryostat

Cryostat Volume	500 Liters
TPC Volume	170 Liters
# Electronic Channels	480
Wire Pitch	4 mm
Electronics Style (Temperature)	JFET (293 K)
Max. Drift Length	47 cm
Light Collection	None

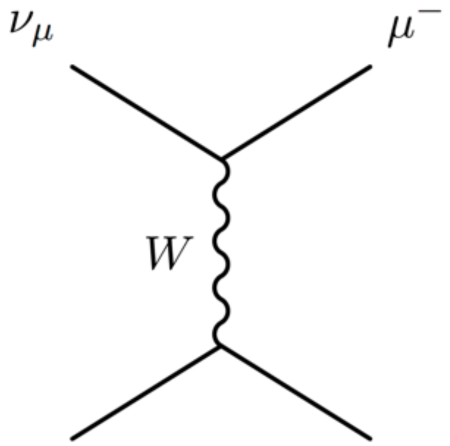


The fully-instrumented detector in the beamline

J. Spitz@NNN11

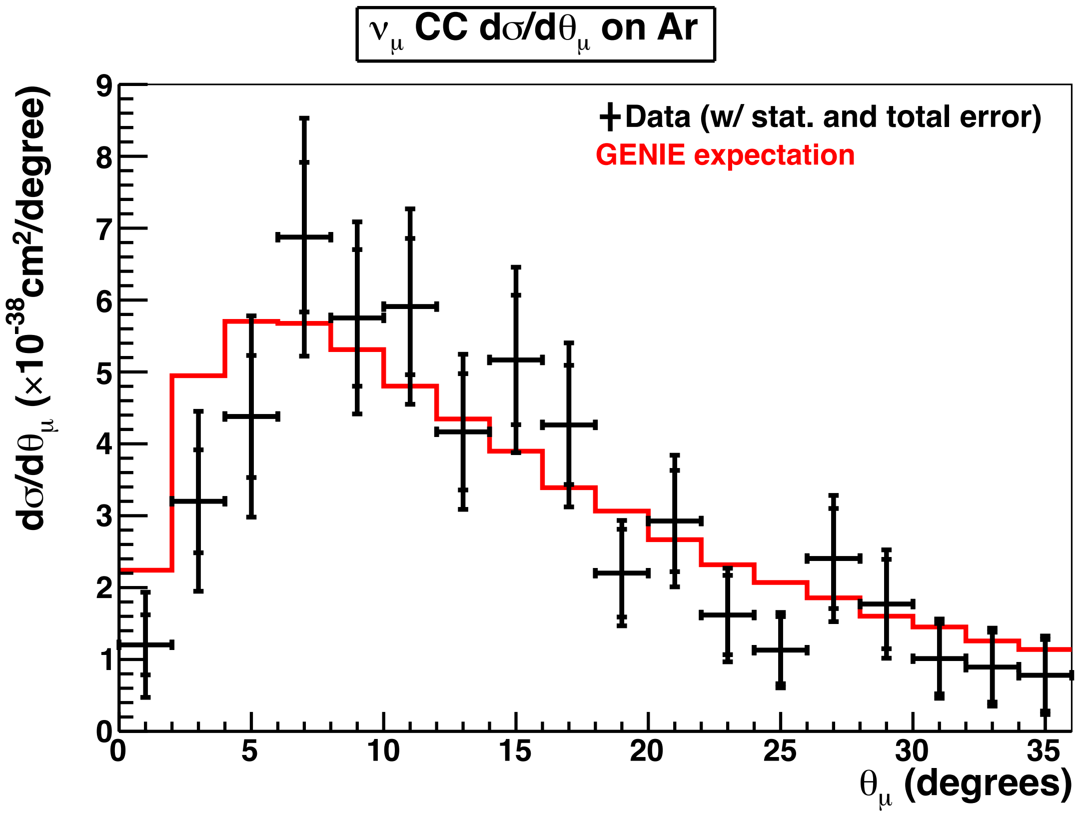
Differential cross sections on argon

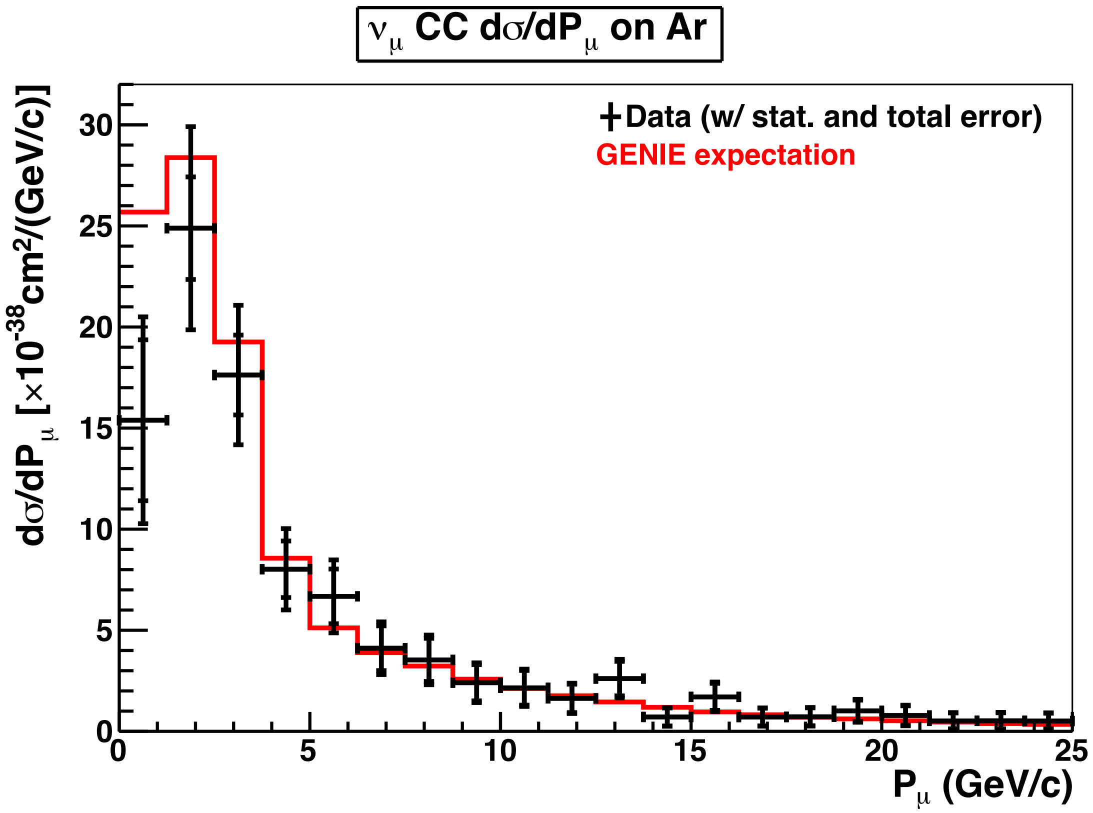
arXiv:1111.0103, Submitted to PRL



$$\frac{\partial\sigma(u_i)}{\partial u} = \frac{N_{\mathrm{measured},i} - N_{\mathrm{background},i}}{\Delta u_i \epsilon_i N_{\mathrm{targ}} \Phi}$$

$(u = \theta_\mu$ and $P_\mu)$



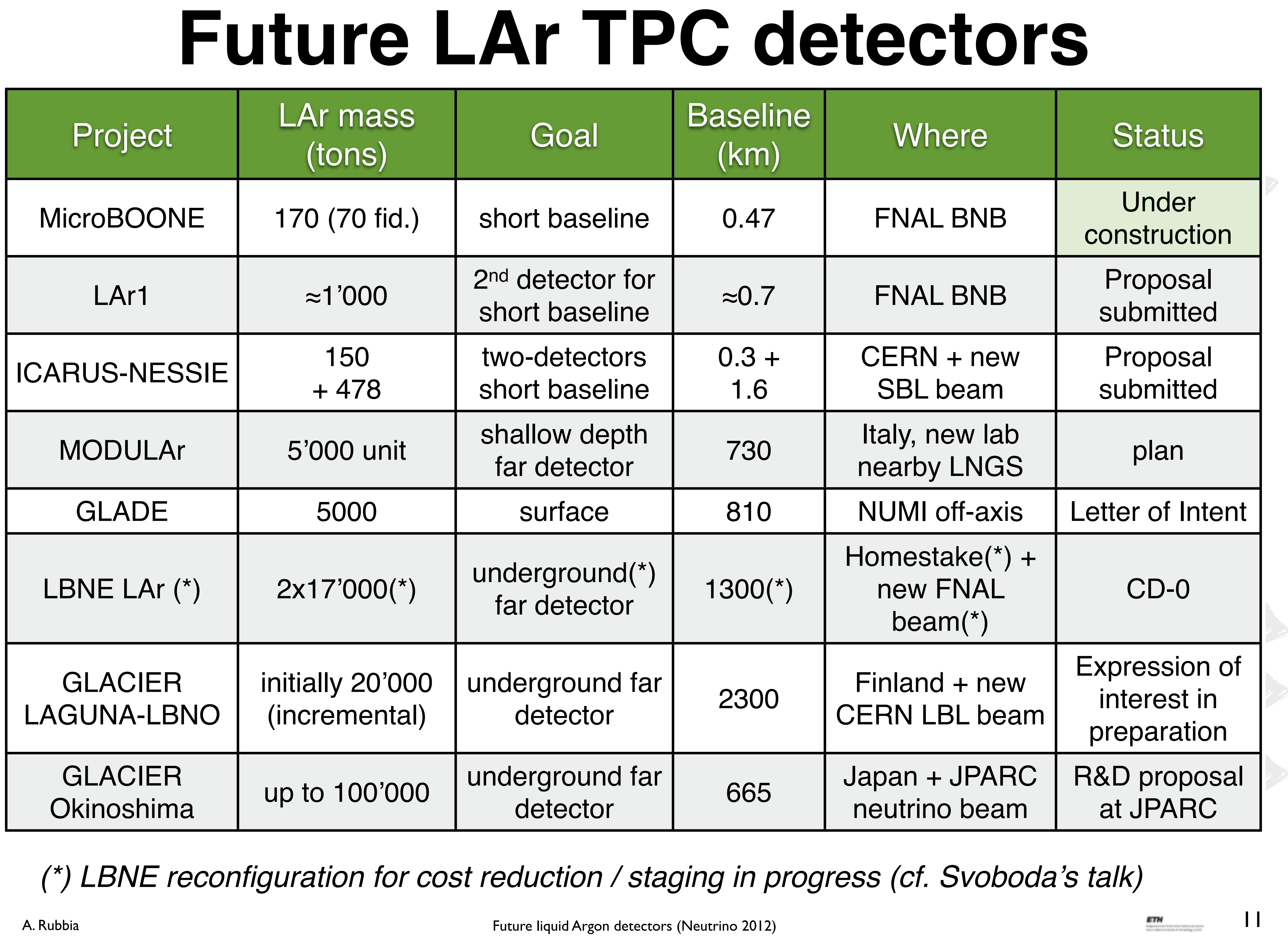


$$\sigma_{\mathrm{tot}}/E_\nu = (7.3 \pm 1.2) \times 10^{-39} \frac{\mathrm{cm}^2}{\mathrm{GeV}} \text{ per isoscalar nucleon at } \langle E_\nu \rangle = 4.3 \text{ GeV}$$

J. Spitz@NNN11

21

Future LAr TPC detectors

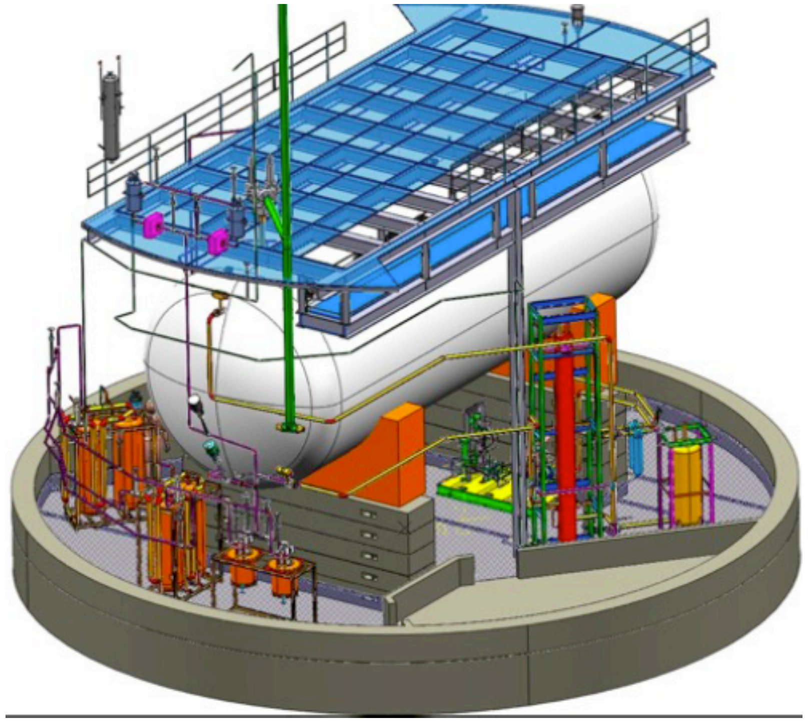


Project	LAr mass (tons)	Goal	Baseline (km)	Where	Status
MicroBOONE	170 (70 fid.)	short baseline	0.47	FNAL BNB	Under construction
LAr1	≈1'000	2nd detector for short baseline	≈0.7	FNAL BNB	Proposal submitted
ICARUS-NESSIE	150 + 478	two-detectors short baseline	0.3 + 1.6	CERN + new SBL beam	Proposal submitted
MODULAr	5'000 unit	shallow depth far detector	730	Italy, new lab nearby LNGS	plan
GLADE	5000	surface	810	NUMI off-axis	Letter of Intent
LBNE LAr (*)	2x17'000(*)	underground(*) far detector	1300(*)	Homestake(*) + new FNAL beam(*)	CD-0
GLACIER LAGUNA-LBNO	initially 20'000 (incremental)	underground far detector	2300	Finland + new CERN LBL beam	Expression of interest in preparation
GLACIER Okinoshima	up to 100'000	underground far detector	665	Japan + JPARC neutrino beam	R&D proposal at JPARC

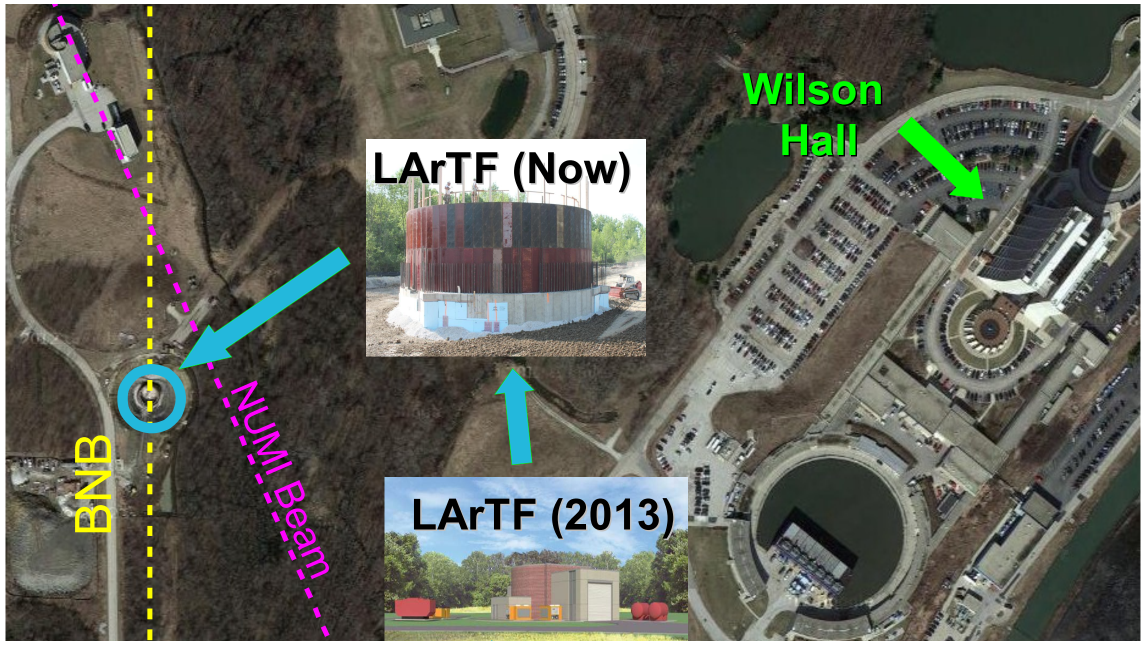
(*) LBNE reconfiguration for cost reduction / staging in progress (cf. Svoboda's talk)

MicroBOONE @ FNAL

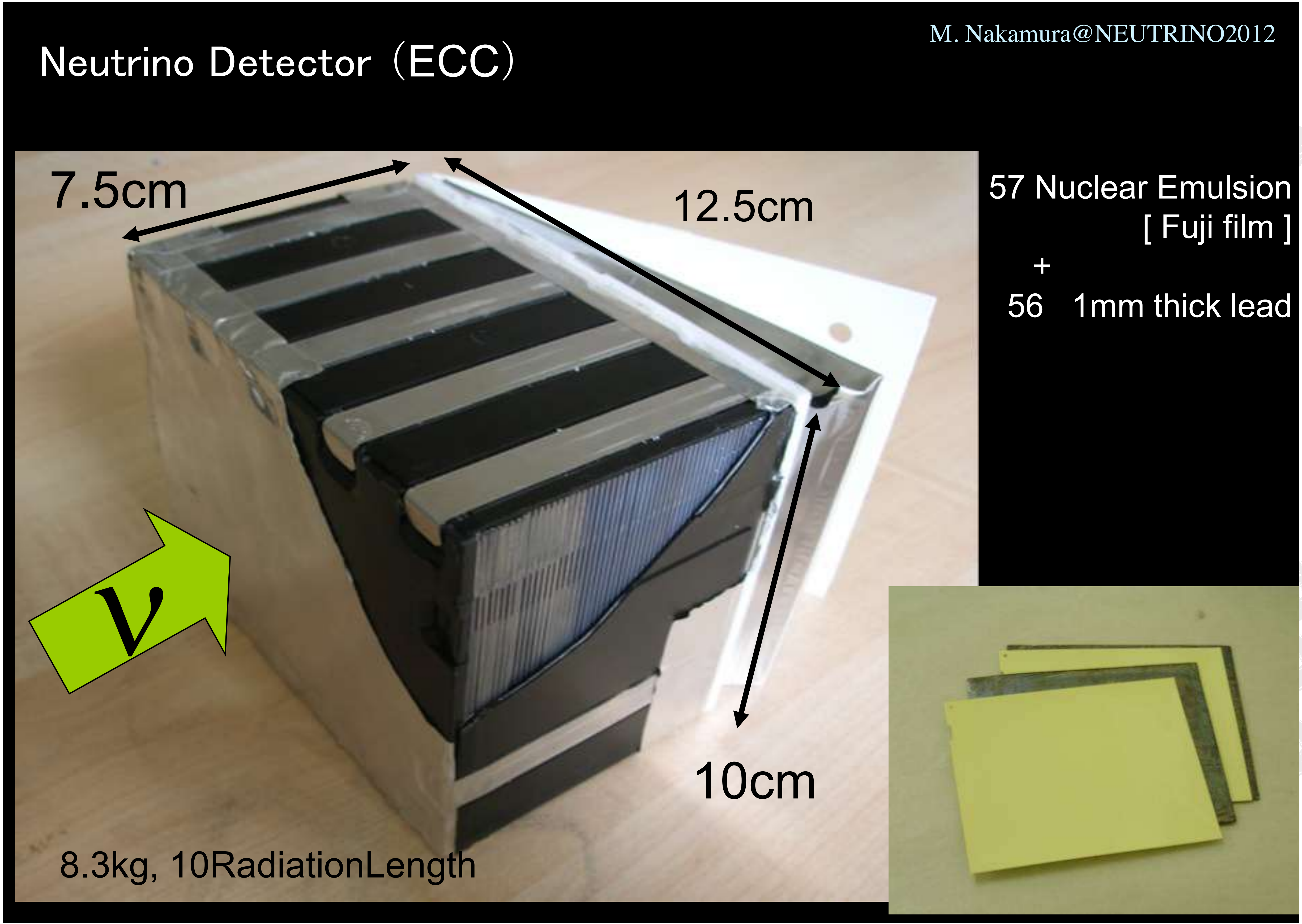
- Single phase LAr TPC located in new Liquid Argon Test Facility (LArTF) at Fermilab in the Booster Neutrino Beam (BNB) but also NUMI off-axis
- Parameters:
  - ~70 t active mass (170 t total mass)
  - 2.5m drift length, 3 mm wire pitch, 8256 wires
- Physics goals:
  - Study electrons or photons in neutrino interactions to test help resolve MiniBoone “low energy excess” puzzle with >3sigma stat. C.L.
    - Electron efficiency ~2x better than MiniBooNE
    - e/γ differentiation removes νμ induced single photon backgrounds
    - good efficiency for low energy (down to MeV)
  - First <u>large statistics</u> neutrino exclusive final states in GeV range and cross-section measurements
- Technology achievements:
  - Purity without evacuation
  - Foam insulation
  - Cold (in liquid) electronics



LArTF under construction; ready in 2013



6.1 Emulsion

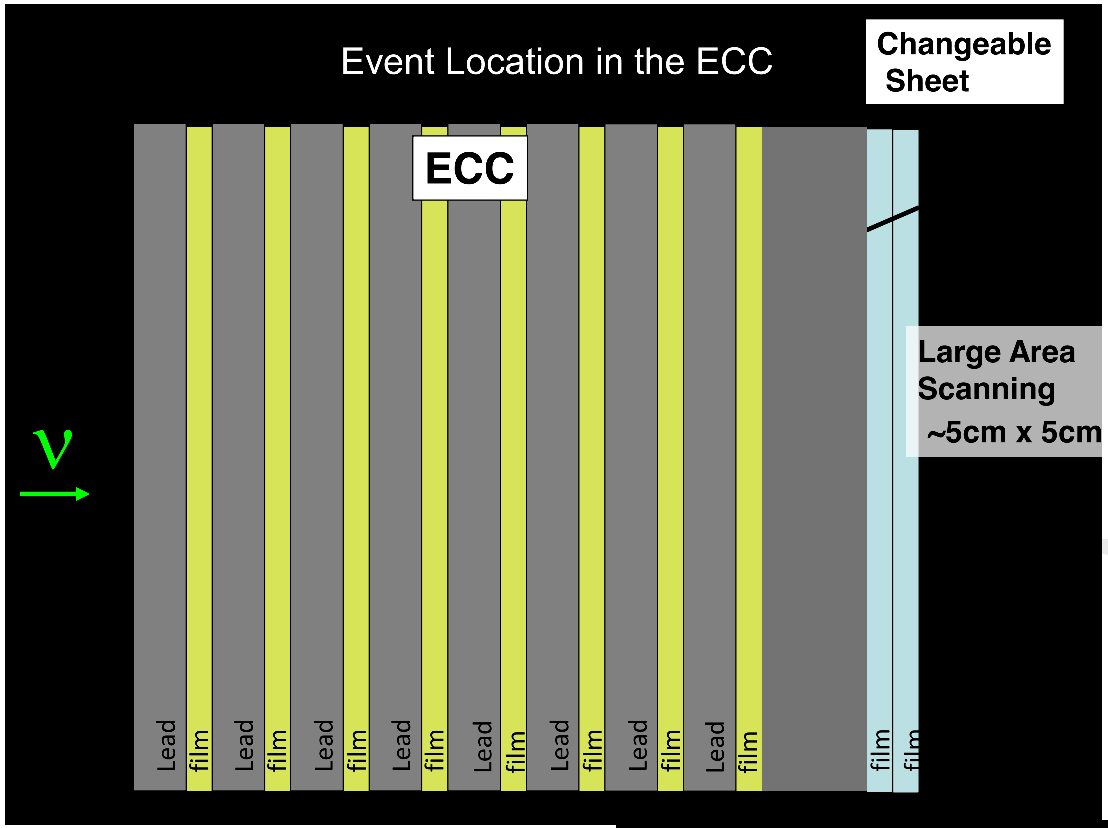


Neutrino Detector（ECC）

M. Nakamura@NEUTRINO2012

57 Nuclear Emulsion
[Fuji film]
+
56 1mm thick lead

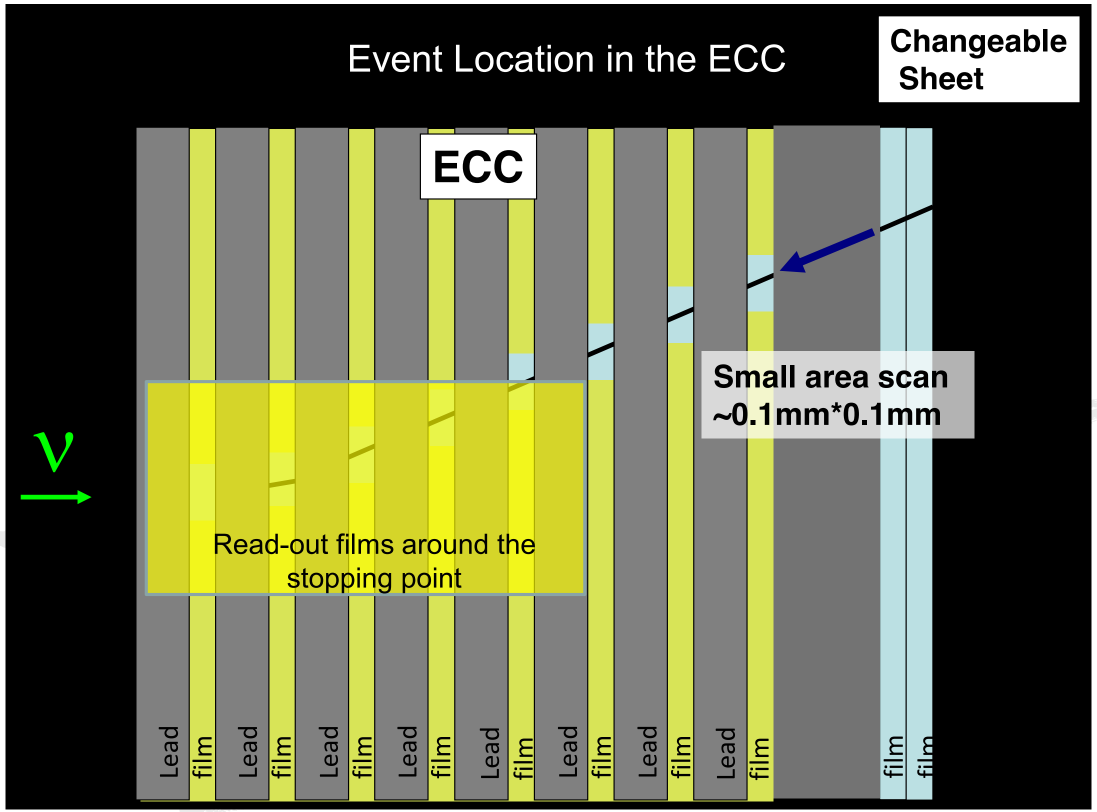
8.3kg, 10RadiationLength



Event Location in the ECC

Changeable Sheet

Large Area Scanning
~5cm x 5cm

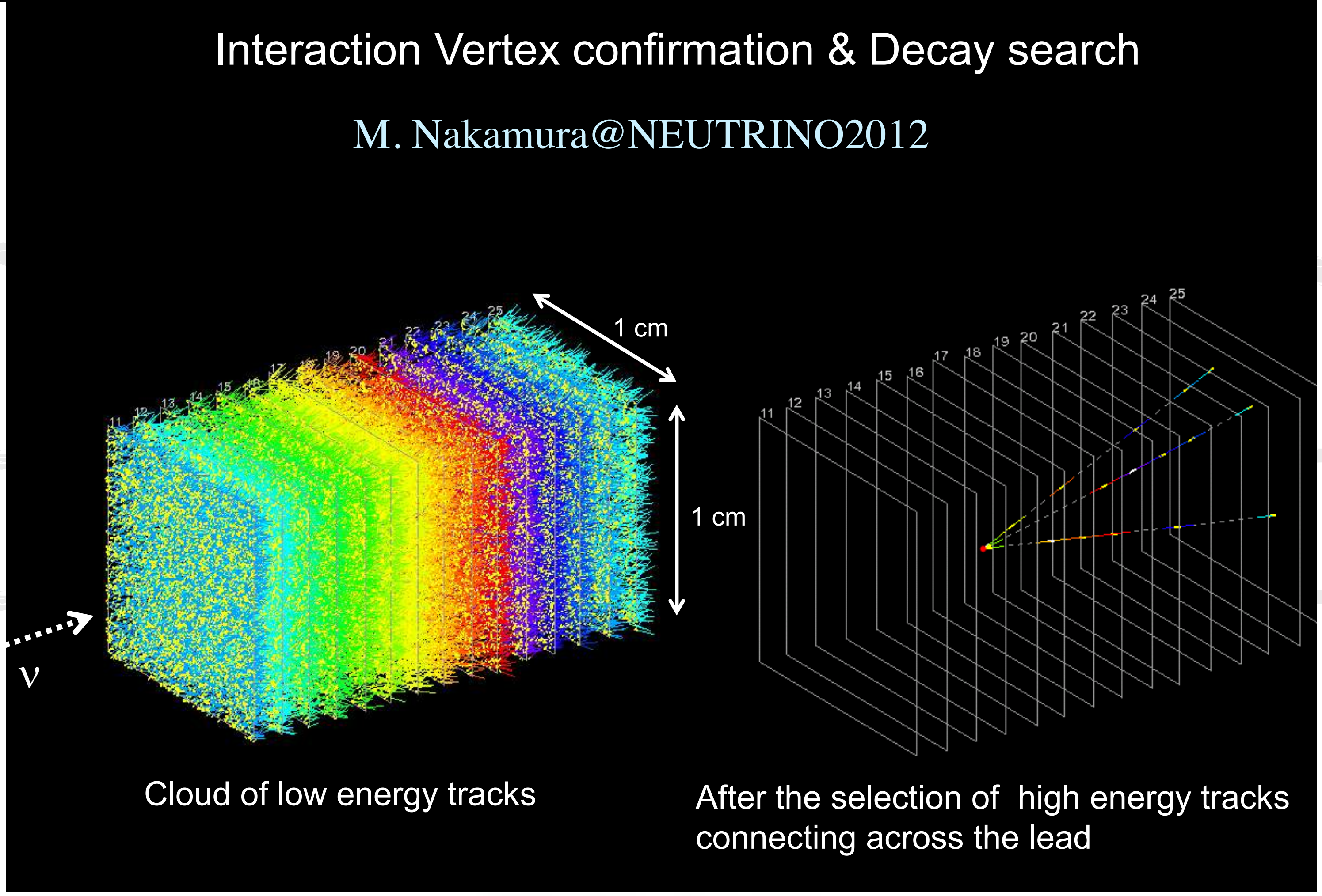


Event Location in the ECC

Changeable Sheet

Small area scan
~0.1mm*0.1mm

Read-out films around the stopping point



Interaction Vertex confirmation & Decay search

M. Nakamura@NEUTRINO2012

Cloud of low energy tracks

After the selection of high energy tracks connecting across the lead

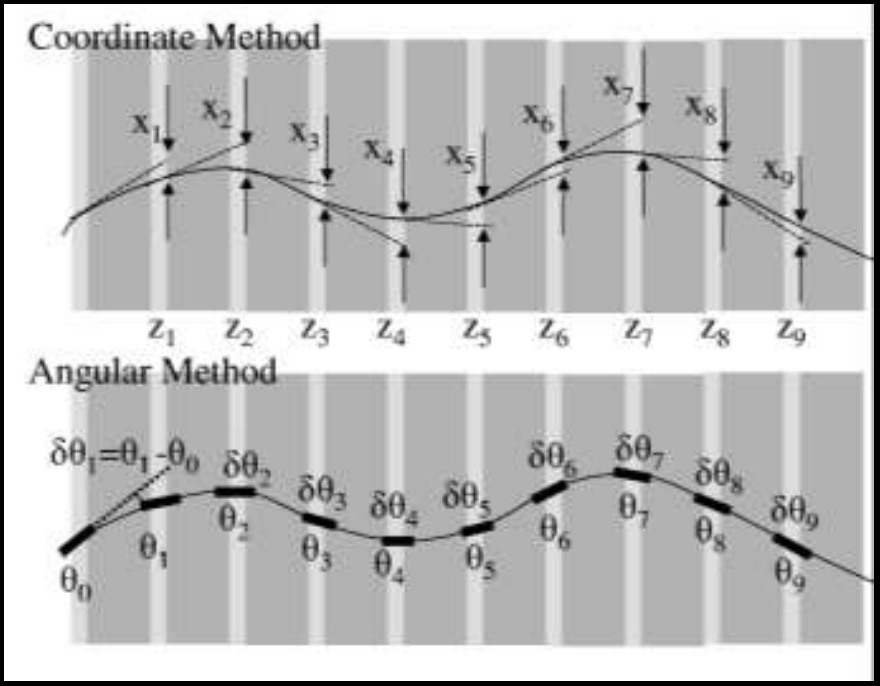
ECC features

M. Nakamura@NEUTRINO2012

Momentum measurement

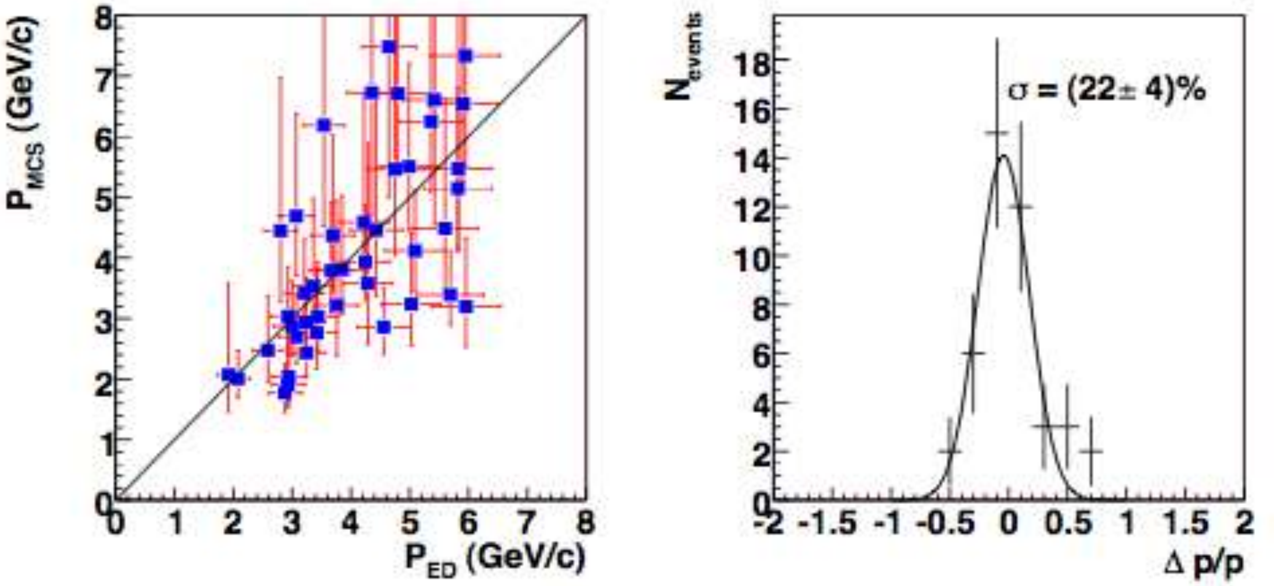
Measurement of the position or angular displacement given by Multiple Coulomb Scattering (MCS)

Ref: New Journal of Physics 14(2012)013026



$$d\theta^{RMS}=\frac{13.6}{pc\beta}z\sqrt{\frac{x}{X_0}}\left(1+0.038\ln\left(\frac{x}{X_0}\right)\right)$$

Soft muon data sample



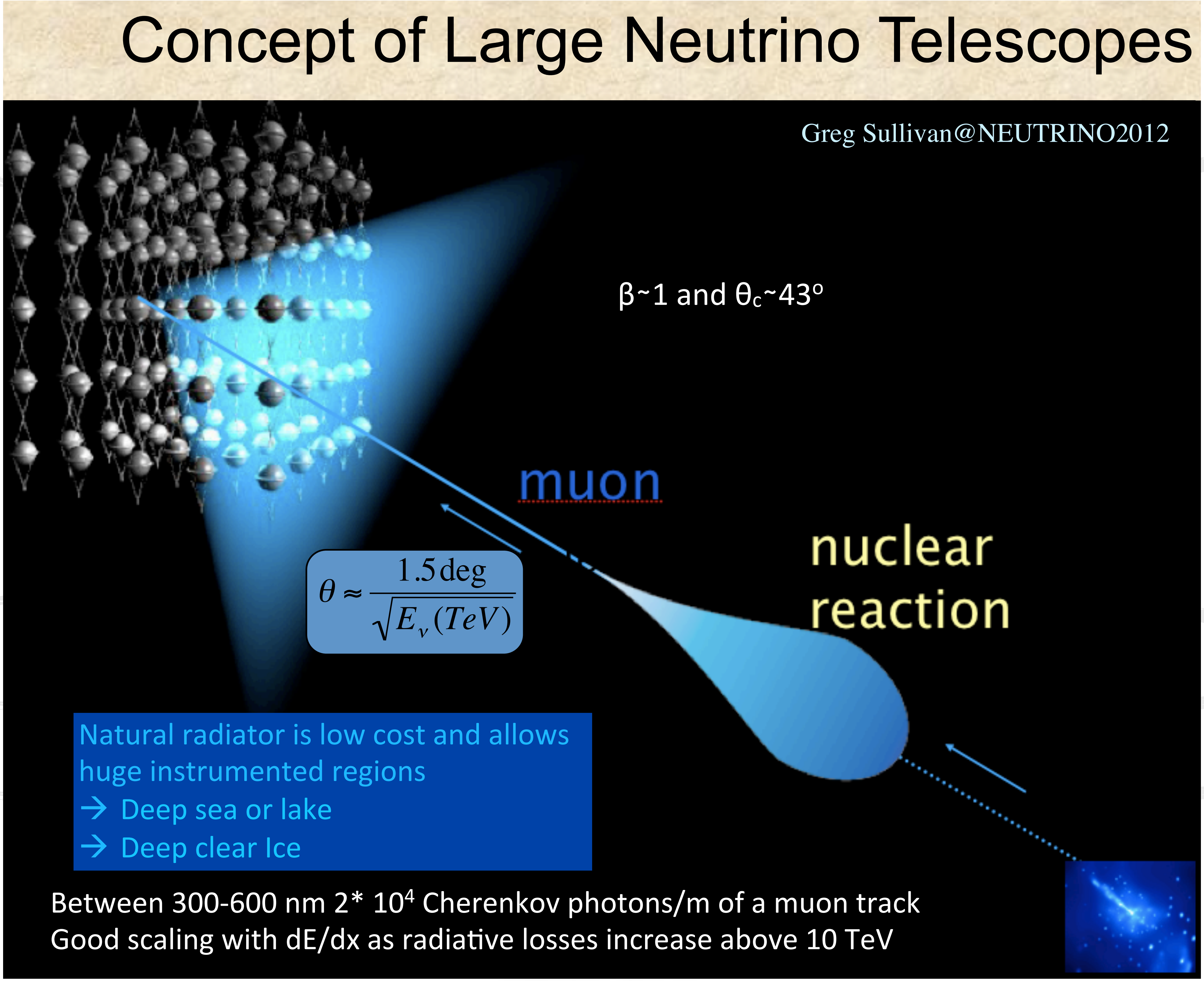
Muon momenta measured by MCS as a function of the momenta obtained from the electronic detectors.

The relative difference between the two measurements with respect to the electronic detector measurement.

Particle ID

Particle ID is possible in ECC by detecting secondary interactions (Hadron), cascade showers (Electron) and dE/dX measurement.

6.2 Ice/Ocean Cherenkov detector



Concept of Large Neutrino Telescopes

Greg Sullivan@NEUTRINO2012

β~1 and θ_c~43°

$$\theta \approx \frac{1.5\,\mathrm{deg}}{\sqrt{E_\nu(TeV)}}$$

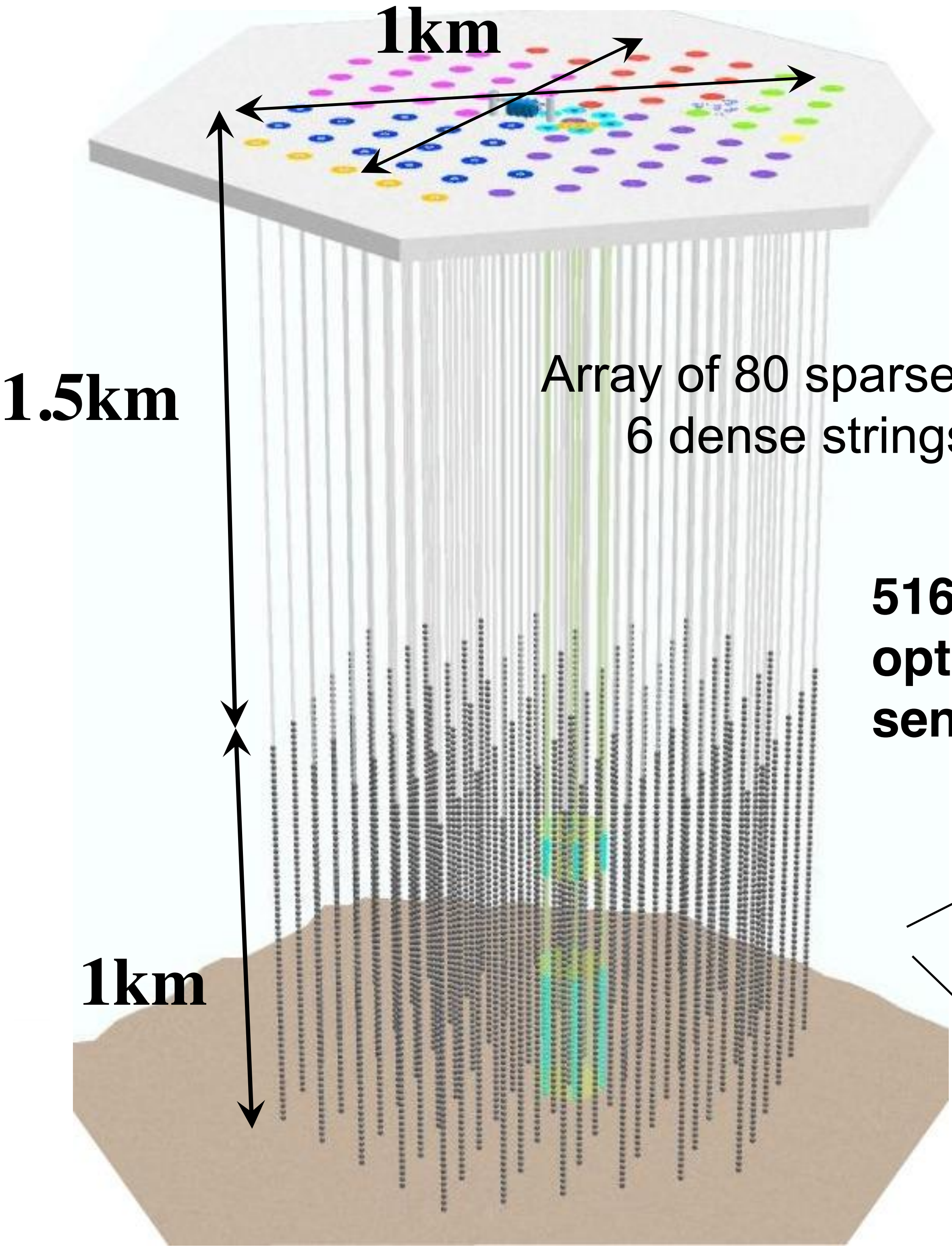
Natural radiator is low cost and allows huge instrumented regions

- → Deep sea or lake
- → Deep clear Ice

Between 300-600 nm 2* 10^4 Cherenkov photons/m of a muon track

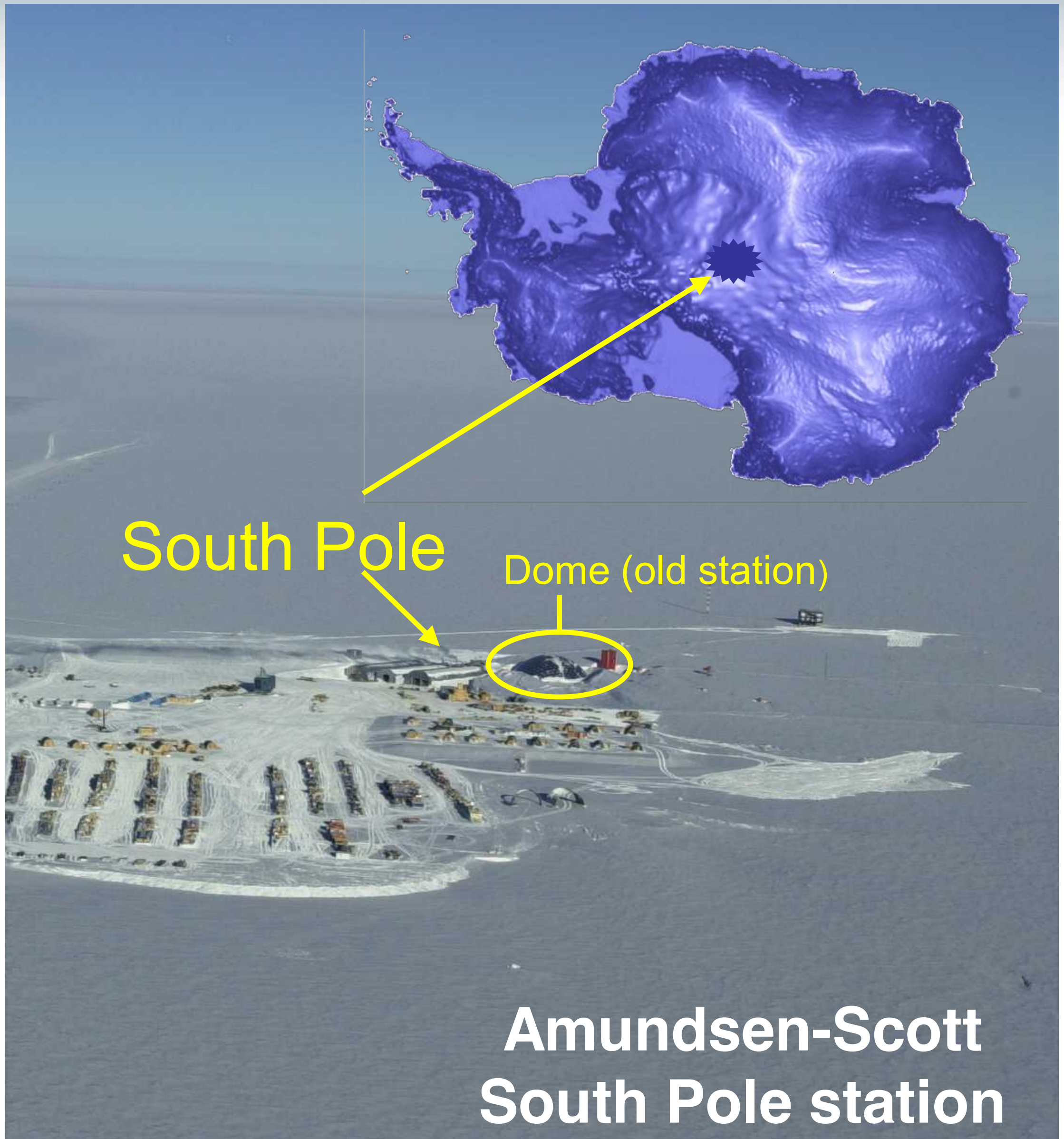
Good scaling with dE/dx as radiative losses increase above 10 TeV

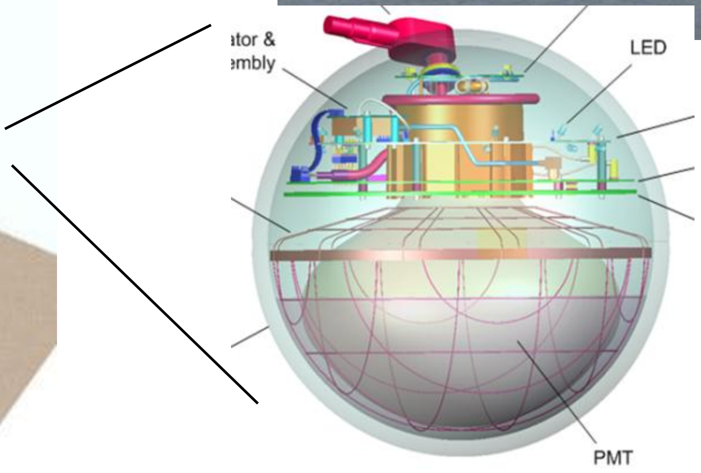
The IceCube Detector



Array of 80 sparse and
6 dense strings

5160 optical sensors





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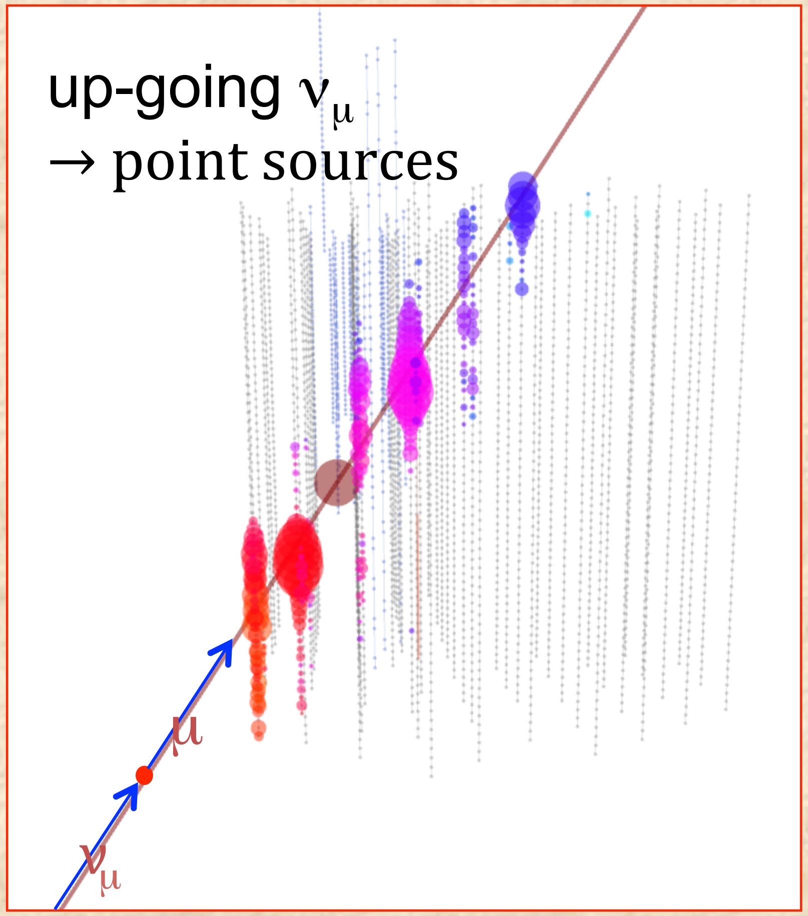
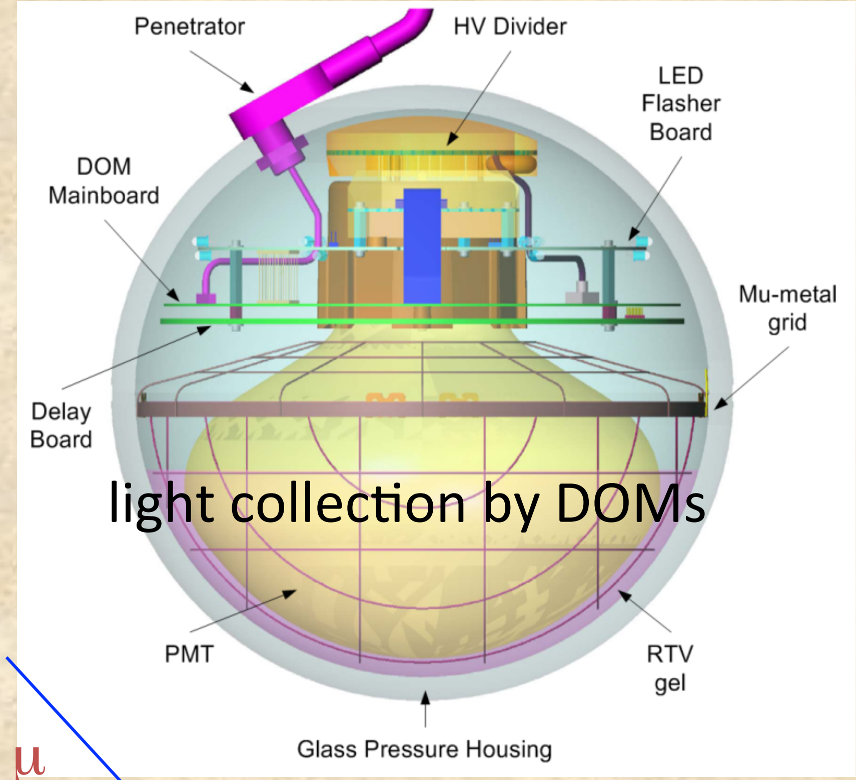
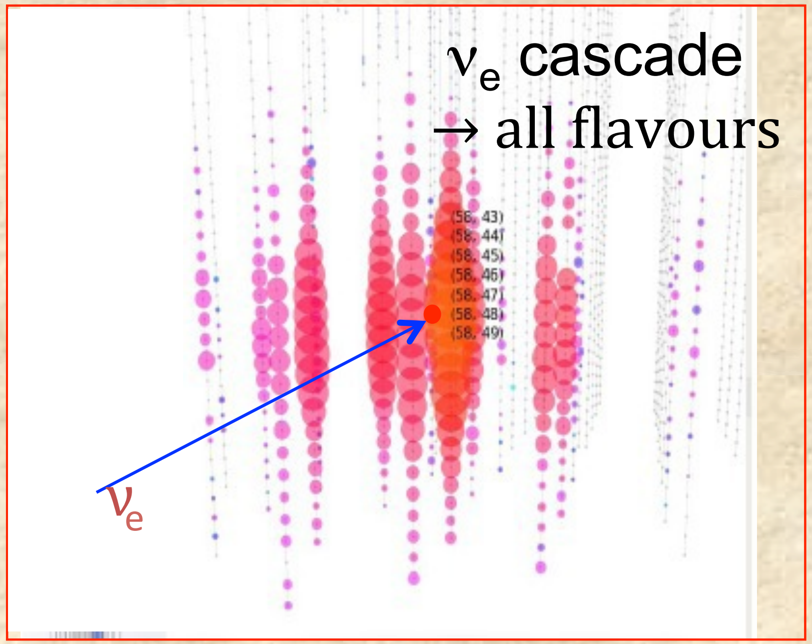
Detection Methods

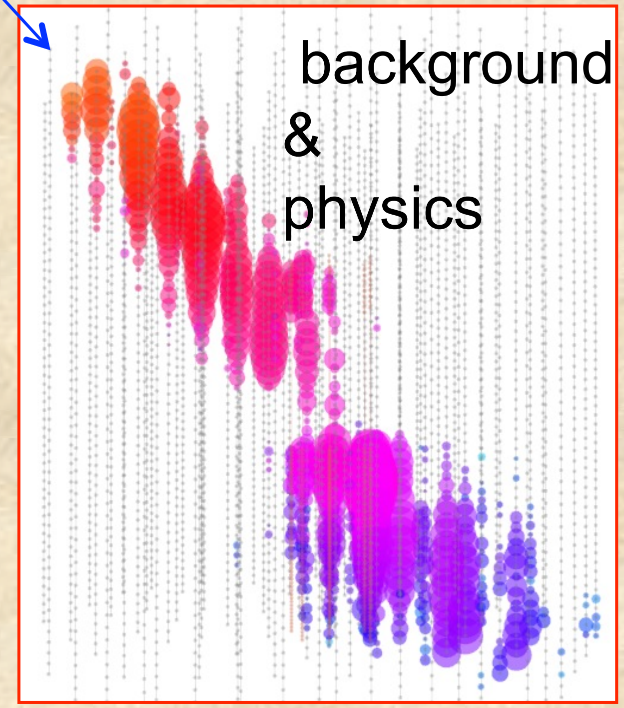

up-going ν_μ
→ point sources

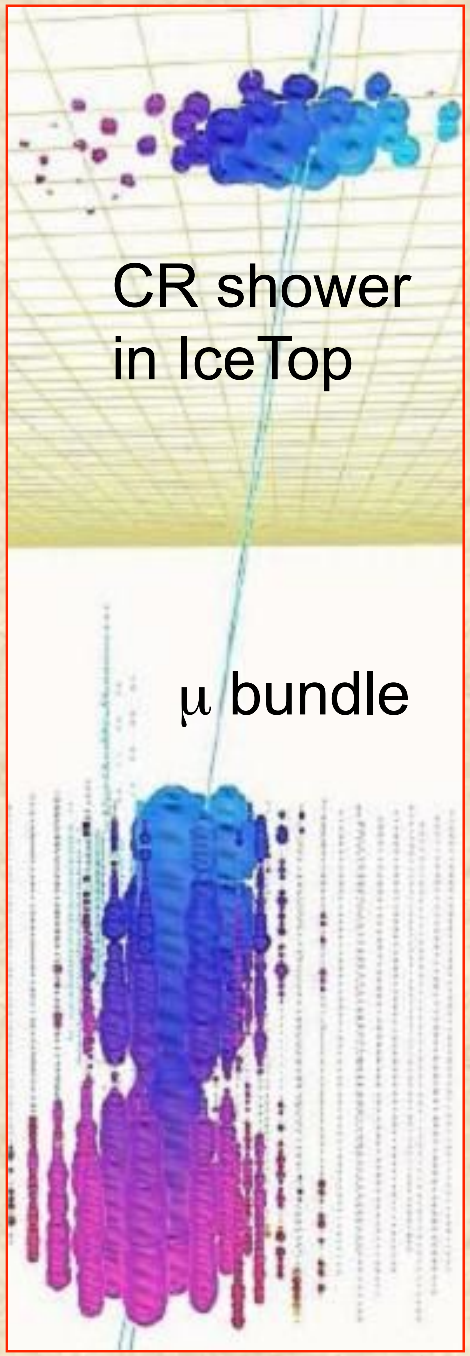


light collection by DOMs

μ


ν_e cascade
→ all flavours


background
&
physics


CR shower
in IceTop

μ bundle

Greg Sullivan@NEUTRINO2012

6.3 Radio Cherenkov detection

10^7 to 10^{11} GeV: Radio ice Cherenkov detection

Detection principle: Coherent radio emission from e.m. cascade

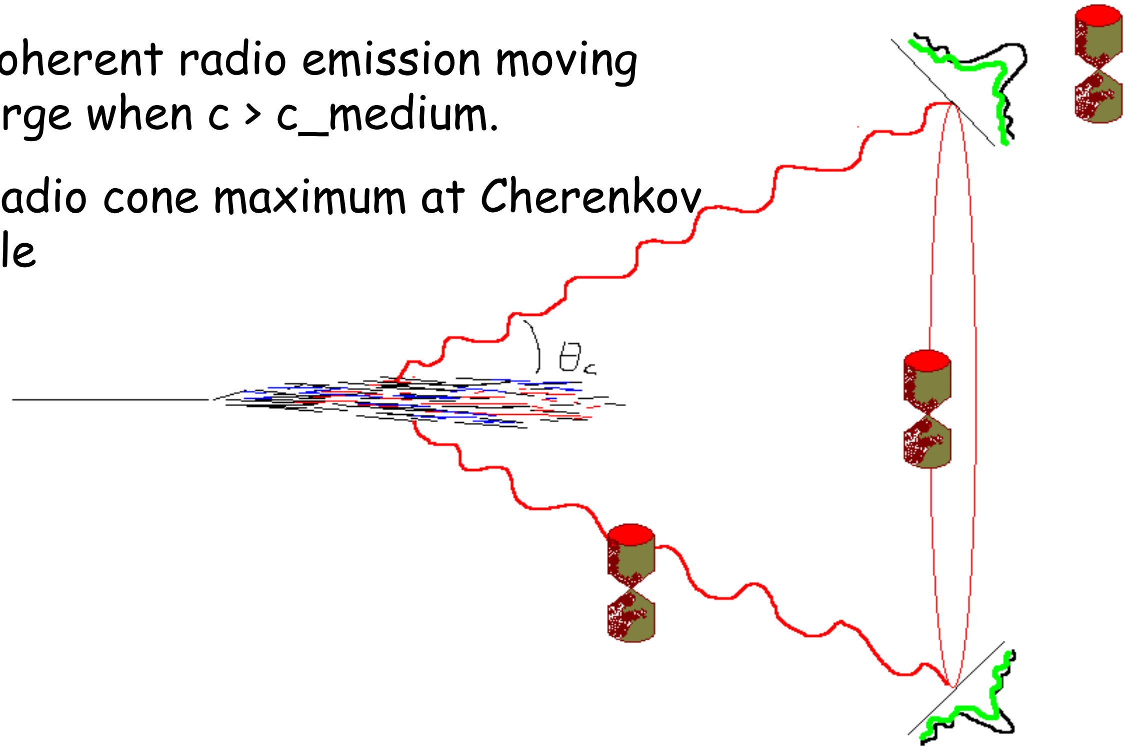
Gurgen Askaryan, 1962
proposes radio detection of showers

Principle:

Charge asymmetry in particle shower development produces a net charge of cm extension.

→coherent radio emission moving charge when c > c_medium.

→Radio cone maximum at Cherenkov angle

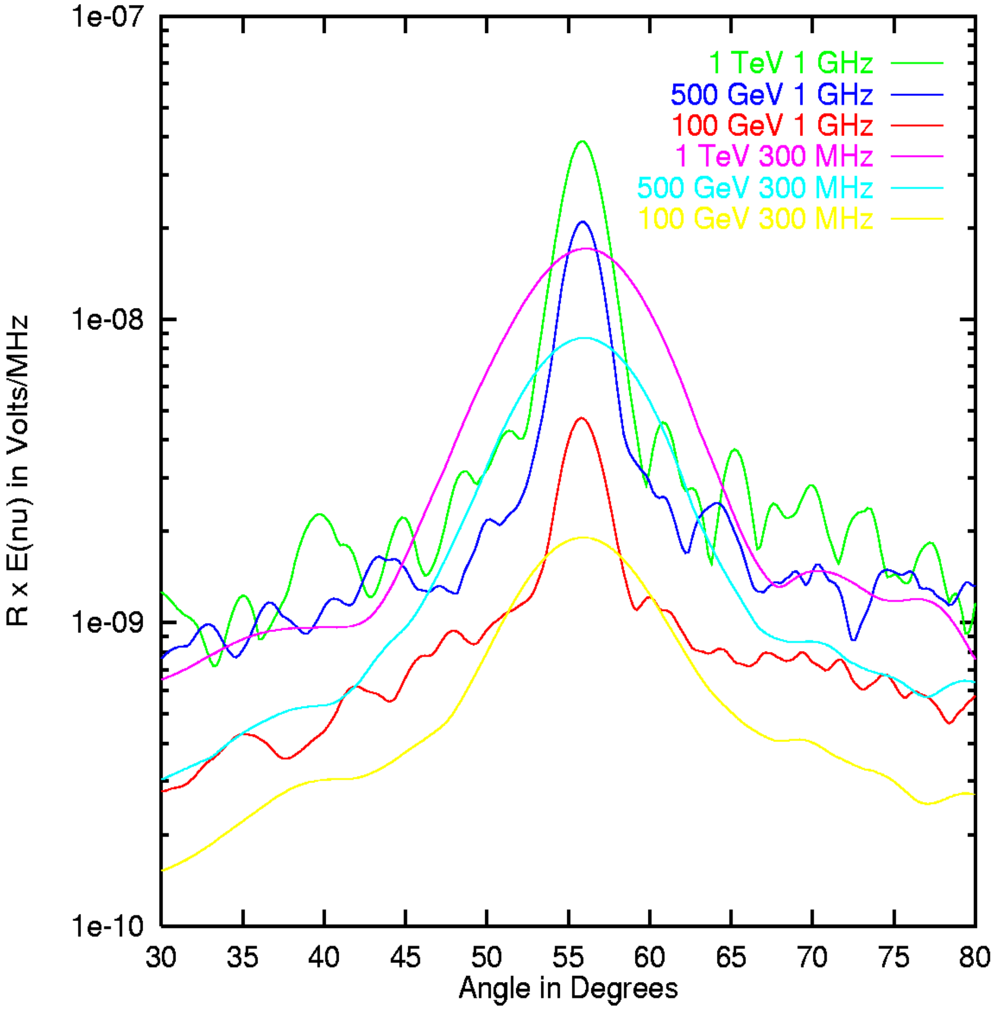


$\lambda >> \ell$

Add coherently!

SLAC 25 GeV electrons on a block of ice make radio pulses in good agreement of theory with data:
D. Saltzberg *et al.*, PRL **86**, 2802 (2001)

cone narrows for higher frequencies
- analogous to single slit diffraction



see eg.: J. Alvarez-Muniz et al., Astrop. Phys. 35 (2012) 287-299 and references therein

A. Karle@NEUTRINO2012

10^7 to 10^{11} GeV: Radio ice Cherenkov detection

Askaryan Radio Array (ARA)

- a very large radio neutrino detector at the South Pole

Ref: Allison et al., Astropart.Phys. 35 (2012) 457-477, arXiv:1105.2854 (Design and performance paper)

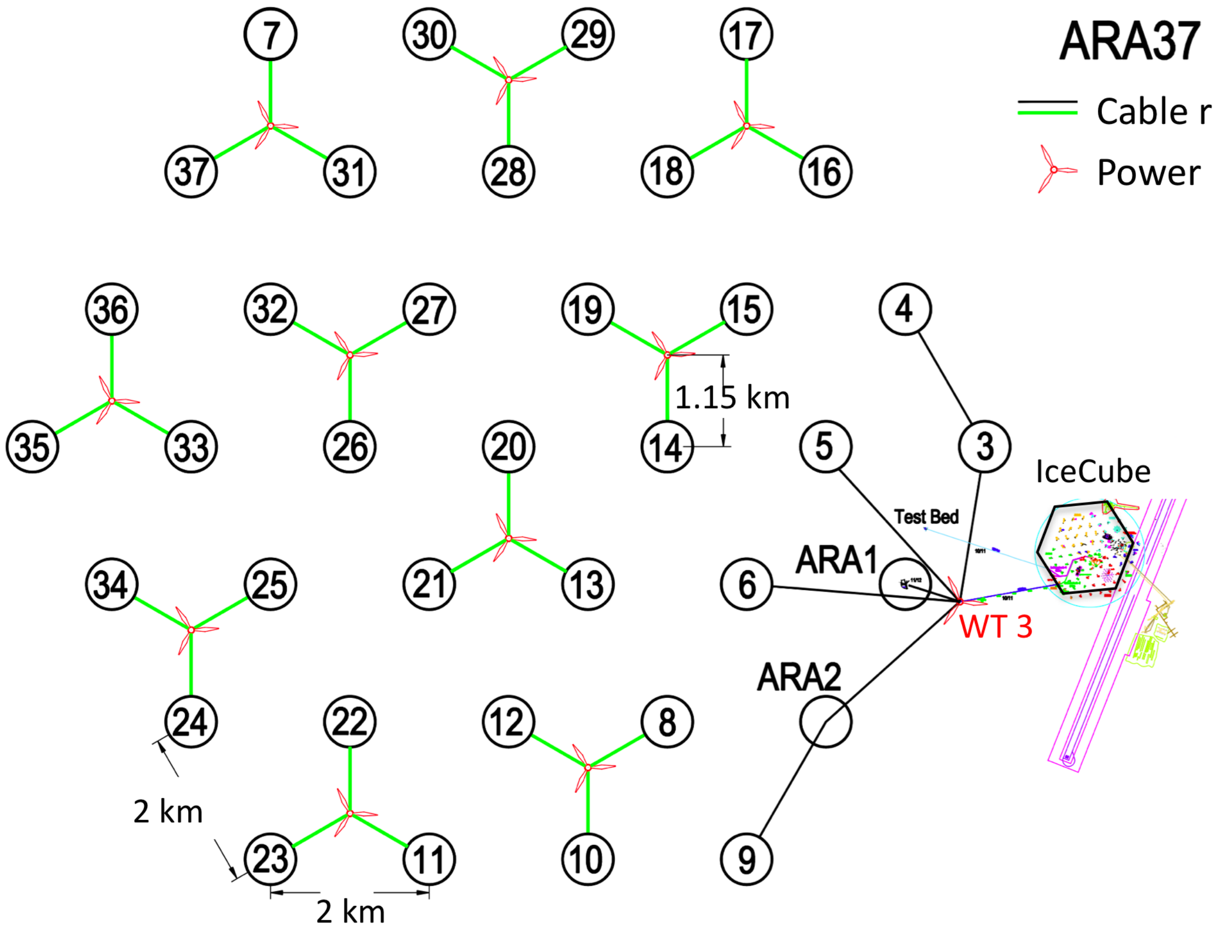
Poster session at this conference:
→ H. Landsman, ARA Design and Status
→ J. Davies, ARA prototype and first station

Scientific Goal:

- Discover and determine the flux of highest energy cosmic neutrinos.
- Understanding of highest energy cosmic rays, other phenomena at highest energies.

Method:

Monitor the ice for radio pulses generated by interactions of cosmic neutrinos with nuclei of the 2.8km thick ice sheet at the South Pole



Areal coverage: ~150km^2

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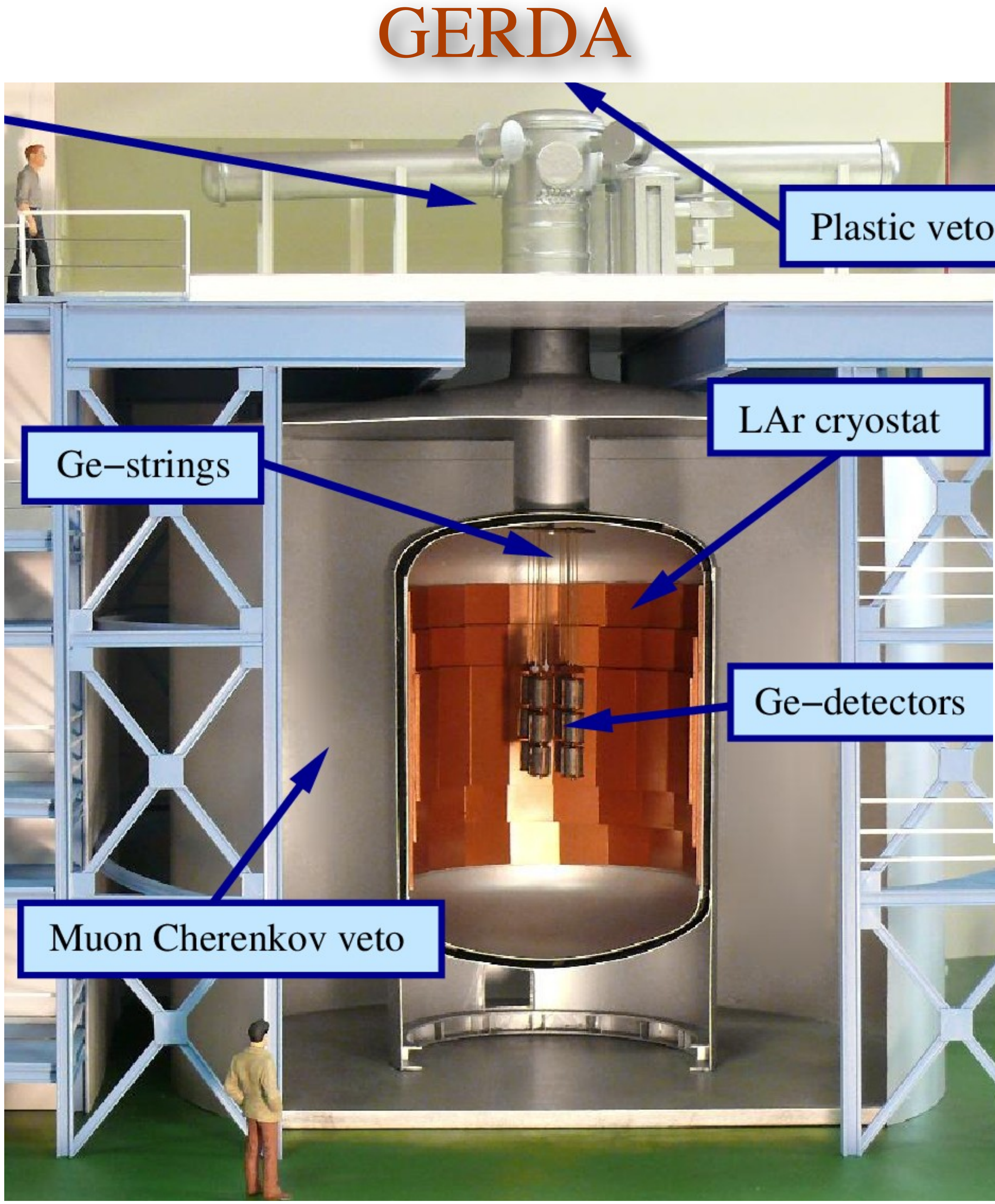
6.4 Double beta decay detector



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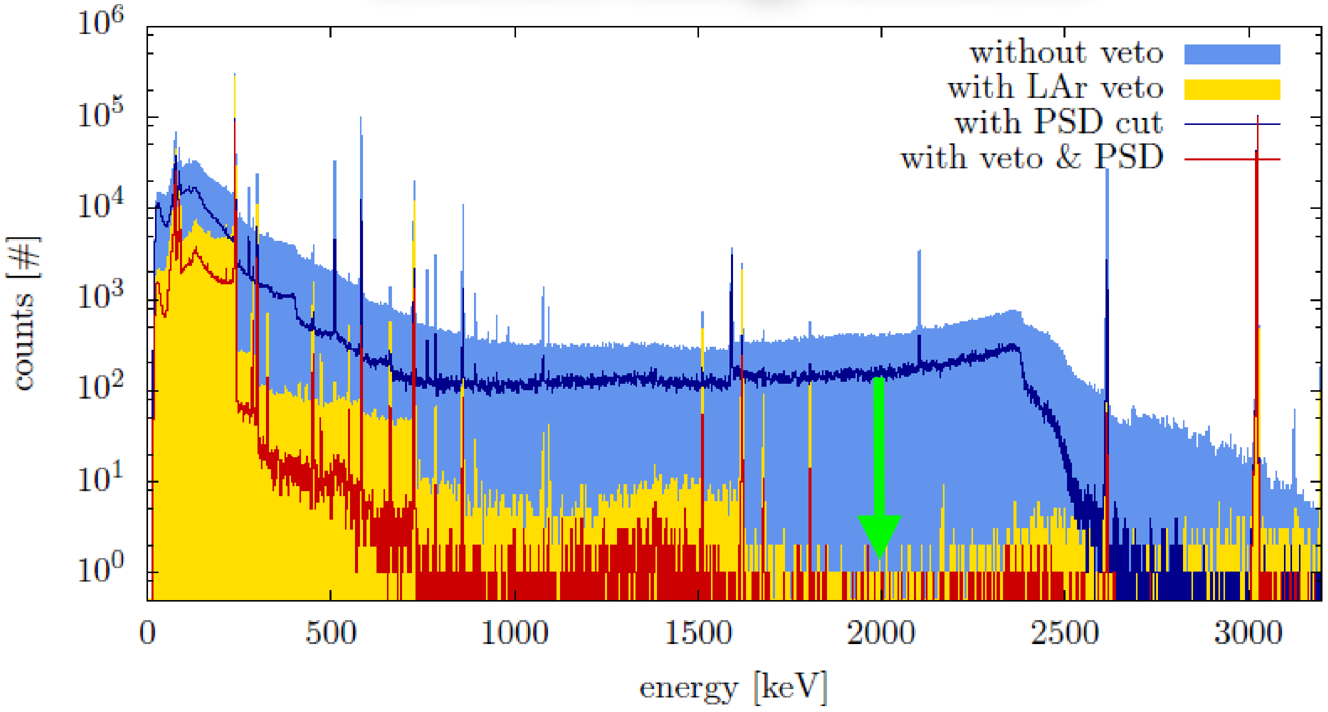
Excellent Energy resolution

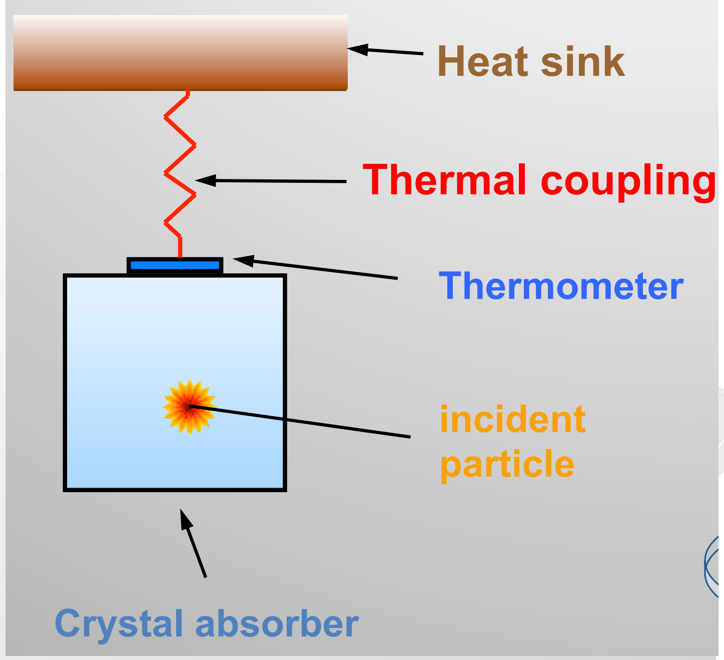


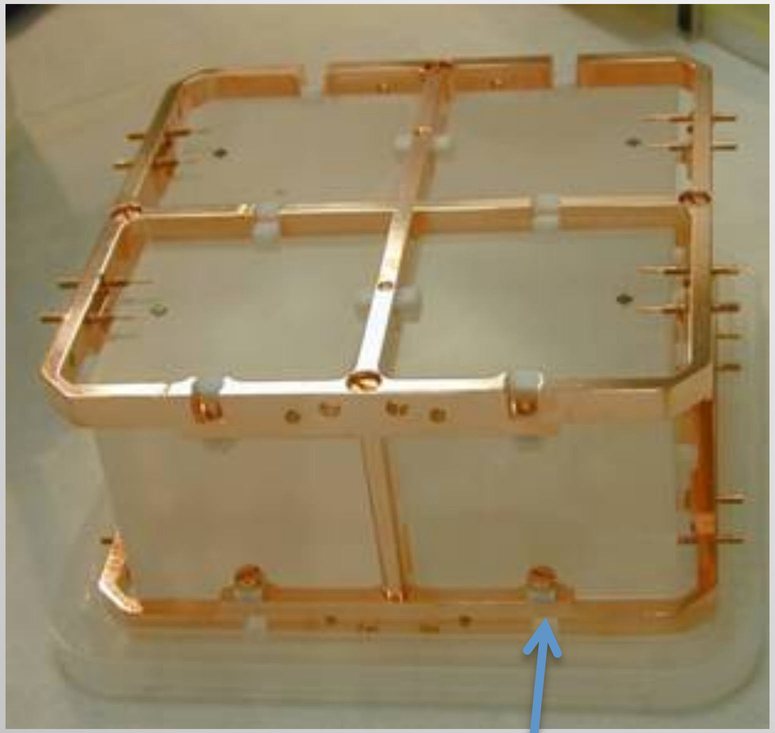
$Q_{\beta\beta}$ = 2039 keV

M. Pedretti@NEUTRINO2012

CUORE

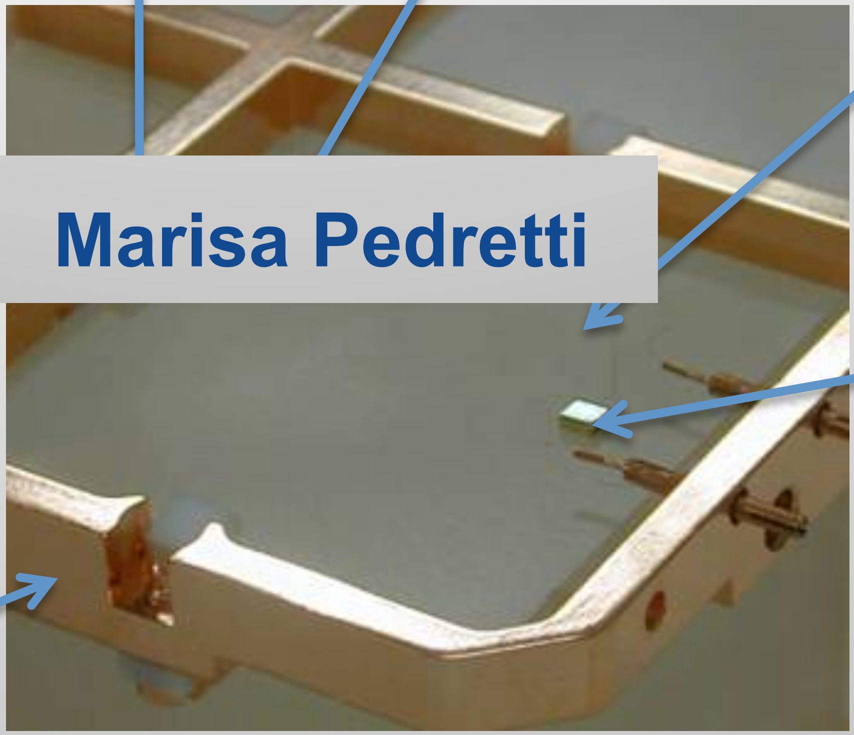
TeO_2 Bolometers





PTFE pieces

TeO_2 crystal



Marisa Pedretti

25 μm gold wire connection

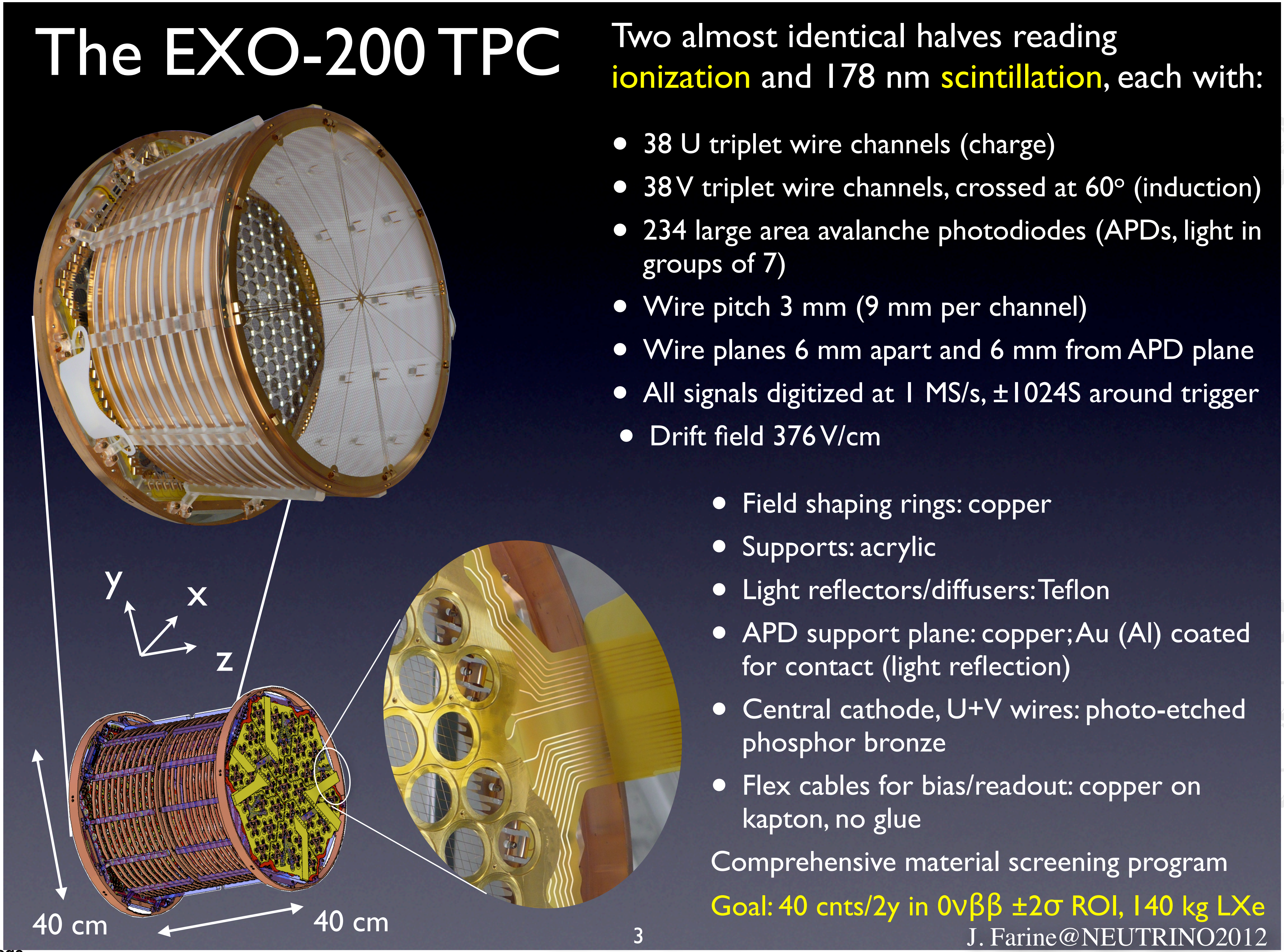
Neutron Transmutation Doped Ge sensor

Copper holder

Pros: - good energy resolution
- different sources could be investigated
- high efficiency (internal sources)

Cons: - no dead layer
- low temperature tech required
- slow pulses

These advantages could be crucial in view of future experiments that aim to investigate all the inverted hierarchy region



The EXO-200 TPC

Two almost identical halves reading ionization and 178 nm scintillation, each with:

- 38 U triplet wire channels (charge)
- 38 V triplet wire channels, crossed at 60° (induction)
- 234 large area avalanche photodiodes (APDs, light in groups of 7)
- Wire pitch 3 mm (9 mm per channel)
- Wire planes 6 mm apart and 6 mm from APD plane
- All signals digitized at 1 MS/s, ±1024S around trigger
- Drift field 376 V/cm

- Field shaping rings: copper
- Supports: acrylic
- Light reflectors/diffusers: Teflon
- APD support plane: copper; Au (Al) coated for contact (light reflection)
- Central cathode, U+V wires: photo-etched phosphor bronze
- Flex cables for bias/readout: copper on kapton, no glue

Comprehensive material screening program

Goal: 40 cnts/2y in 0νββ ±2σ ROI, 140 kg LXe

J. Farine@NEUTRINO2012

Thank you for your attention!

ご清聴ありがとうございました

水戸の梅の花

Many thanks to:
J Monroe, T Nakaya, F Sanchez