Neutrino Detectors I

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The Neutrino Physics Summer School
Fermilab, July 2-13, 2007

Lecture I:
Broad Survey of Past Detectors

- Inverse Beta Decay
  - Discovery of the ν
  - KamLAND, LSND
- Tracking Detectors
  - Two ν Experiment
  - NuTeV, MINOS, CHARM II
- Bubble Chambers
  - Discovery of Neutral Currents
- Hybrid Detectors:
  - MINERνA, NOMAD
  - Discovery of Tau Neutrino

Lecture II:
The Challenges for ν_e Appearance

- Water Cherenkov
  - Super-Kamiokande
- Segmented Scintillator
  - NOνA
- Liquid Argon TPC
  - ICARUS & future experiments

Mixed throughout: fundamental physics of particle interactions, principles of operation of detector elements. Lots of diagrams, photos, and event displays.

- All particle detectors rely on the electromagnetic interaction of the particle with the detector material.
- Neutrinos do not have electromagnetic interactions.
- Ergo, there is no such thing as a neutrino detector.
- However, one can detect the products of neutrino interactions.
- The design choices for each detector are very much determined by the properties of the ν interactions under study, as well as other constraints such as the beam, backgrounds, etc. But in the end, it is the final state particles that are detected through their EM interactions.

Large Mass Required

$$Rate = \Phi \times \sigma \times N_{targets}$$

$\Phi(^{8}\mathrm{B\ solar}\ \nu) = 6\times10^{6}\,\mathrm{cm^{-1}s^{-1}}$

$\Phi(\mathrm{atm.}\ \nu) \approx 1\ \mathrm{cm^{-2}s^{-1}}$

$\sigma(\nu e) \sim 10^{-43}\ \mathrm{cm^2}\ \ (10\ \mathrm{MeV})$

$\sigma(\nu N) \sim 10^{-38}\ \mathrm{cm^2}\ \ (1\ \mathrm{GeV})$

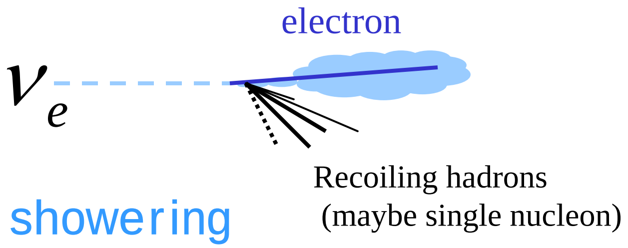
3×10^{32} electrons/kton

6×10^{32} nucleons/kton

$\Rightarrow$ 10’s events per day in 22.5 kton Super-K detector

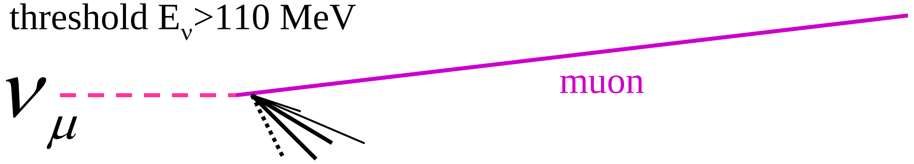
Equivalently, $\lambda = \dfrac{1}{n_{\mathrm{targets}}\sigma}$: famous light year of lead

Neutrino Flavor Identification



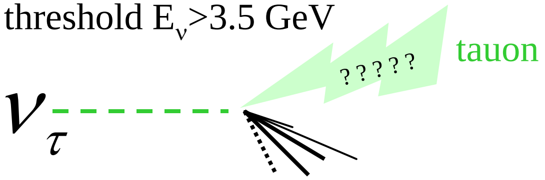
showering

threshold E_ν>110 MeV

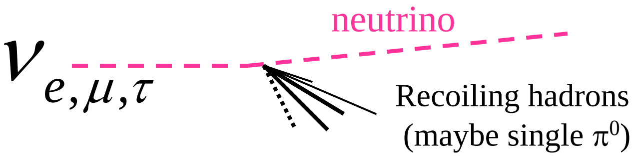


penetrating

threshold E_ν>3.5 GeV



challenging

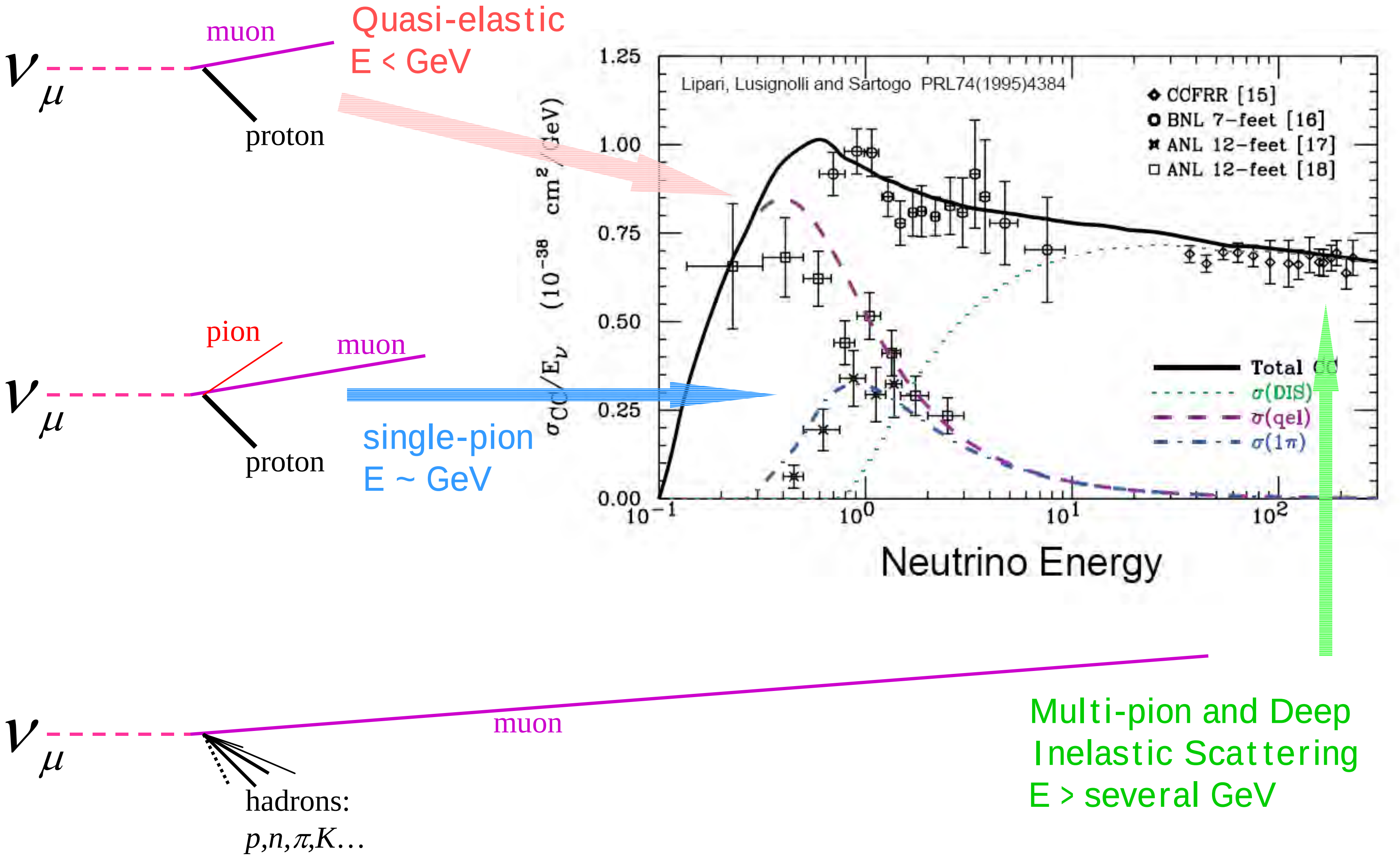


annoying (frequently background)

$\tau \rightarrow e\nu\nu$	18%
$\rightarrow \mu\nu\nu$	18%
$\rightarrow 3\pi\nu$	14%
$\rightarrow \pi\nu$	11%
…	

Energy Regimes

example: CC ν_μ



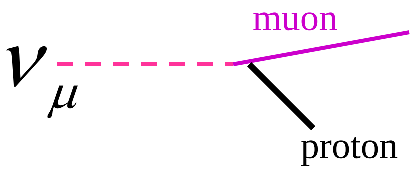
Quasi-elastic
E < GeV

single-pion
E ~ GeV

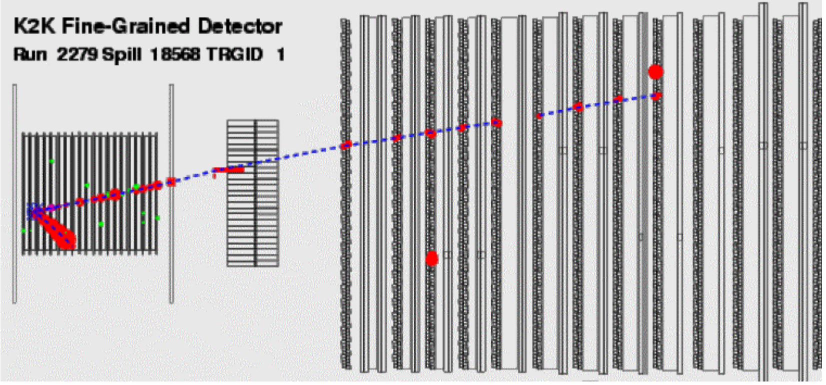
Multi-pion and Deep Inelastic Scattering
E > several GeV

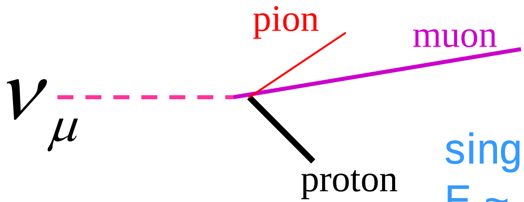
Energy Regimes

example events

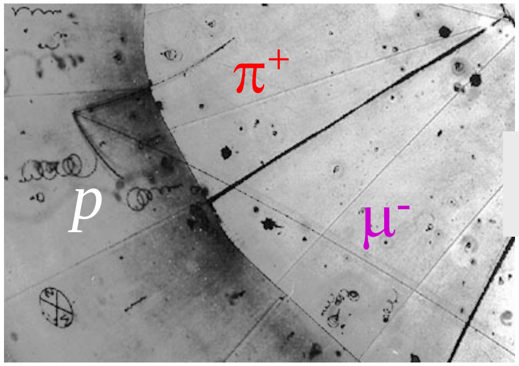


Quasi-elastic
E < GeV

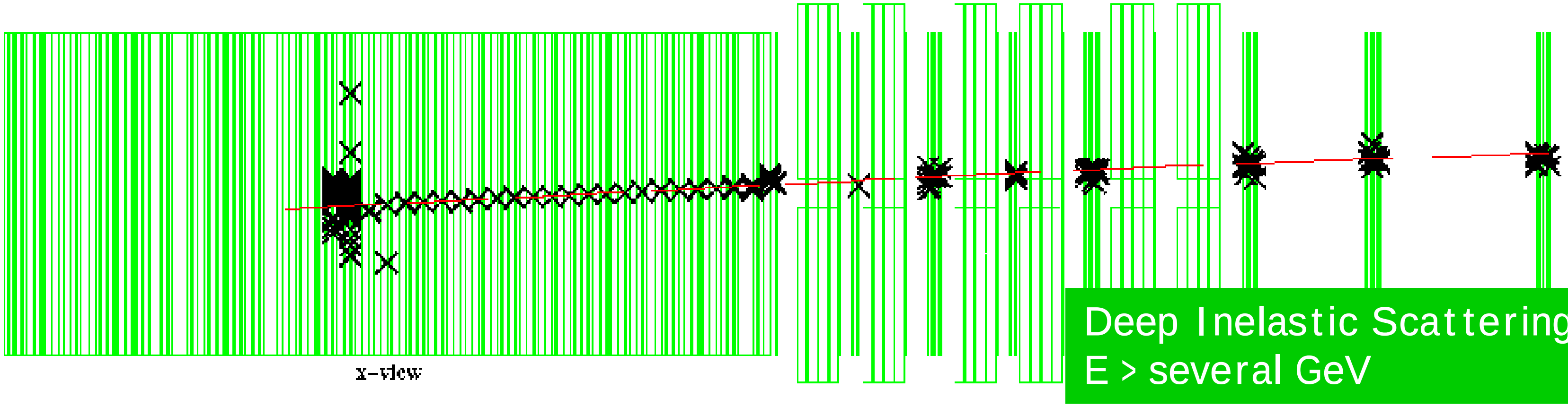




single-pion
E ~ GeV

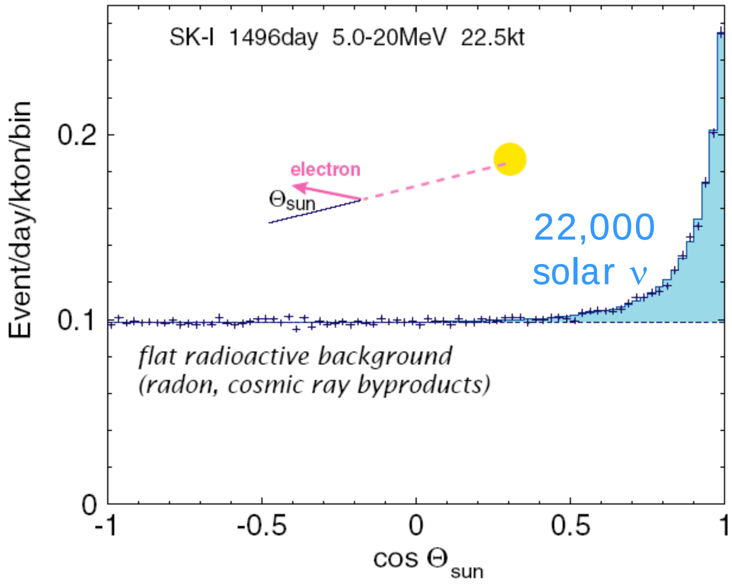


Note: “World’s First Neutrino Observation in a Bubble Chamber” Nov. 13, 1970, ANL



Deep Inelastic Scattering
E > several GeV

Interactions with Electrons



Elastic Scattering

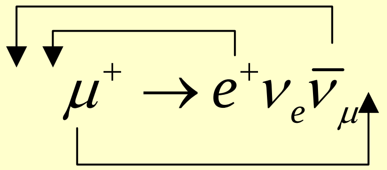
[both CC & NC diagrams contribute]

$$\nu_e + e^- \to \nu_e + e^-$$

Inverse Muon Decay

$$\nu_\mu + e^- \to \nu_e + \mu^-$$

Exercise in crossing symmetry:



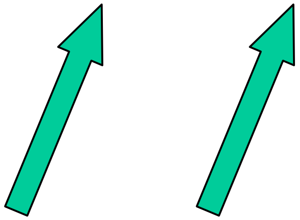
$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$

Move across reaction arrow and change particle to antiparticle

Both characterized by very forward scattering angle

Inverse Beta Decay Detectors

$$\bar{\nu}_e + p \rightarrow e^+ + n$$



Excellent detection opportunities

$$E_{thresh} = 1.8 \text{ MeV}$$

$$E_{prompt} = E_\nu - 0.8 \text{ MeV}$$

$$E_{capture} = 2.2 \text{ MeV (on proton, 10-several 100 } \mu\text{s later)}$$

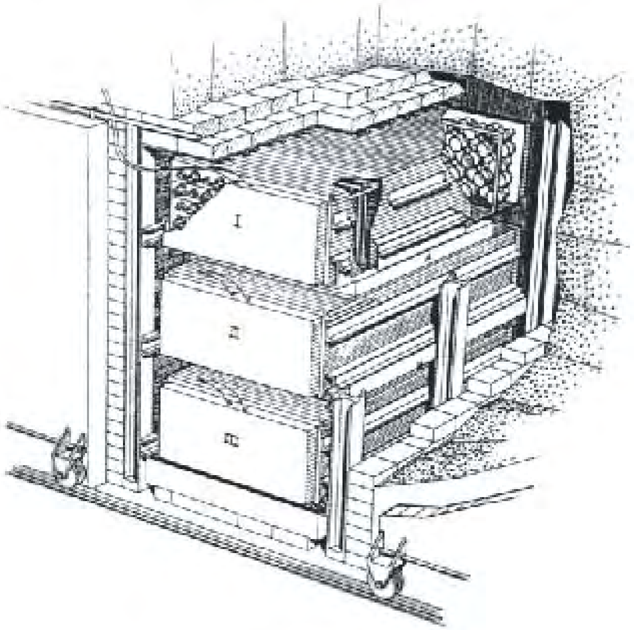
$$\sigma = 0.0952\left(\frac{E_e p_e}{1\text{MeV}^2}\right)\times 10^{-42}\,\text{cm}^2 \sim 5\times 10^{-43}\,\text{cm}^2$$

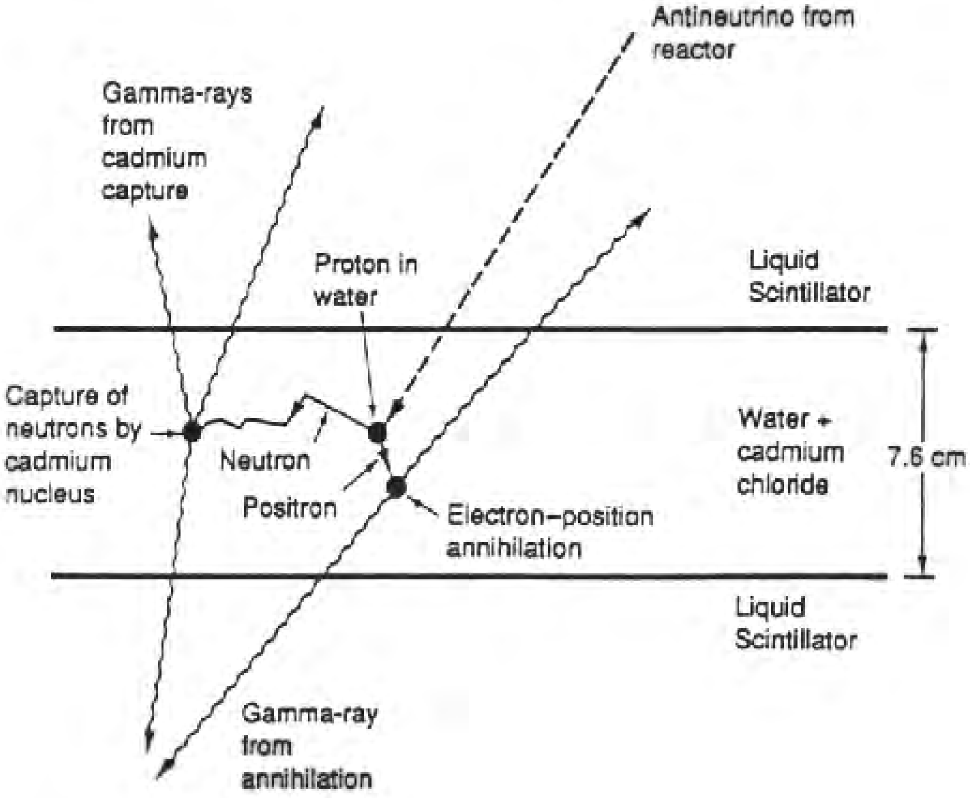
Phys.Rev.D66:033001,2002

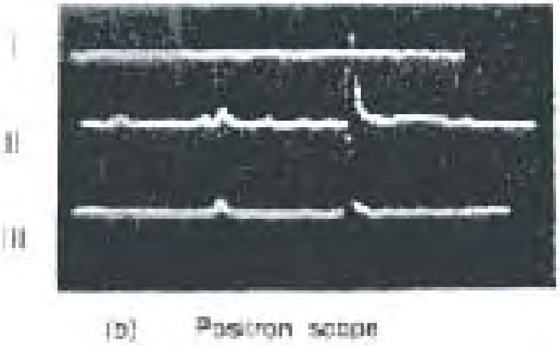
1956

Discovery of the Neutrino

1995 Nobel Prize: F. Reines







Data acquisition: oscilloscope traces!

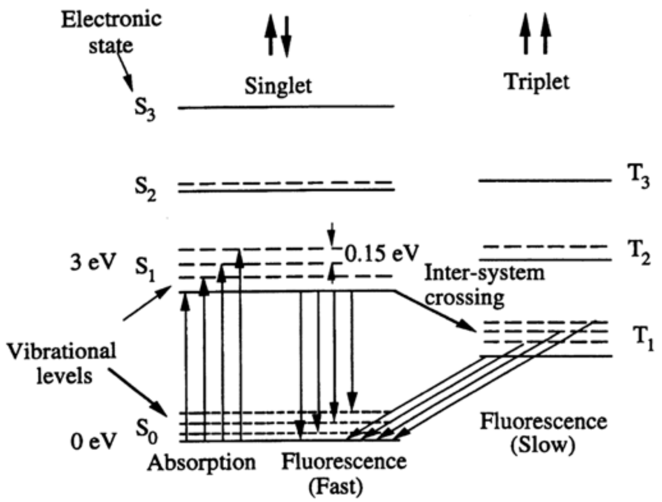
Principle of Detection: Scintillation

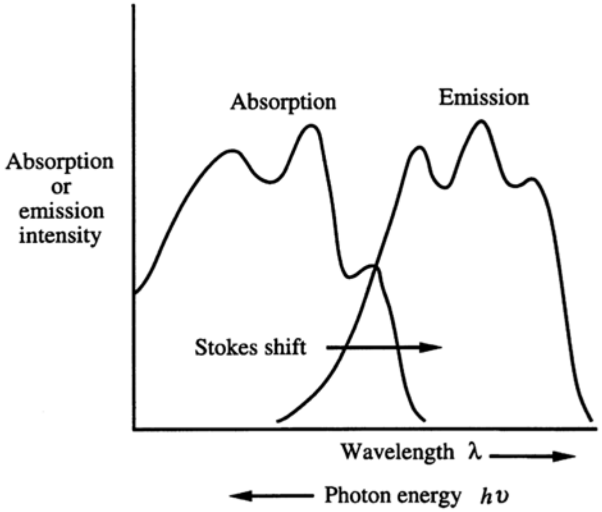
Emission of a pulse of light in response to ionization.
10,000-50,000 photons/MeV

Organic liquids & plastics

Inorganic crystals - NaI, CsI, BaF2, BGO

Nobel liquids - Ne, Ar, Xe



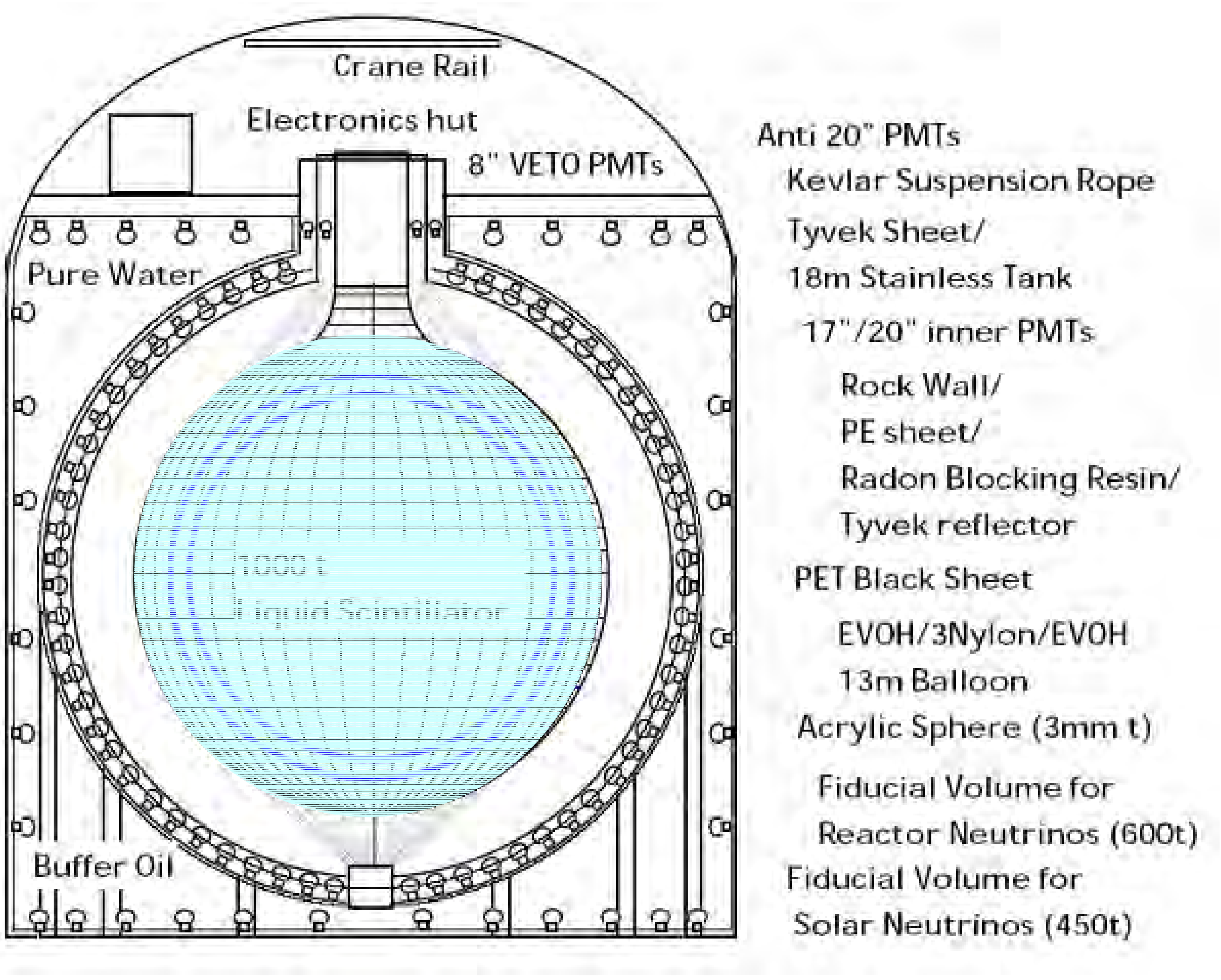


KamLAND

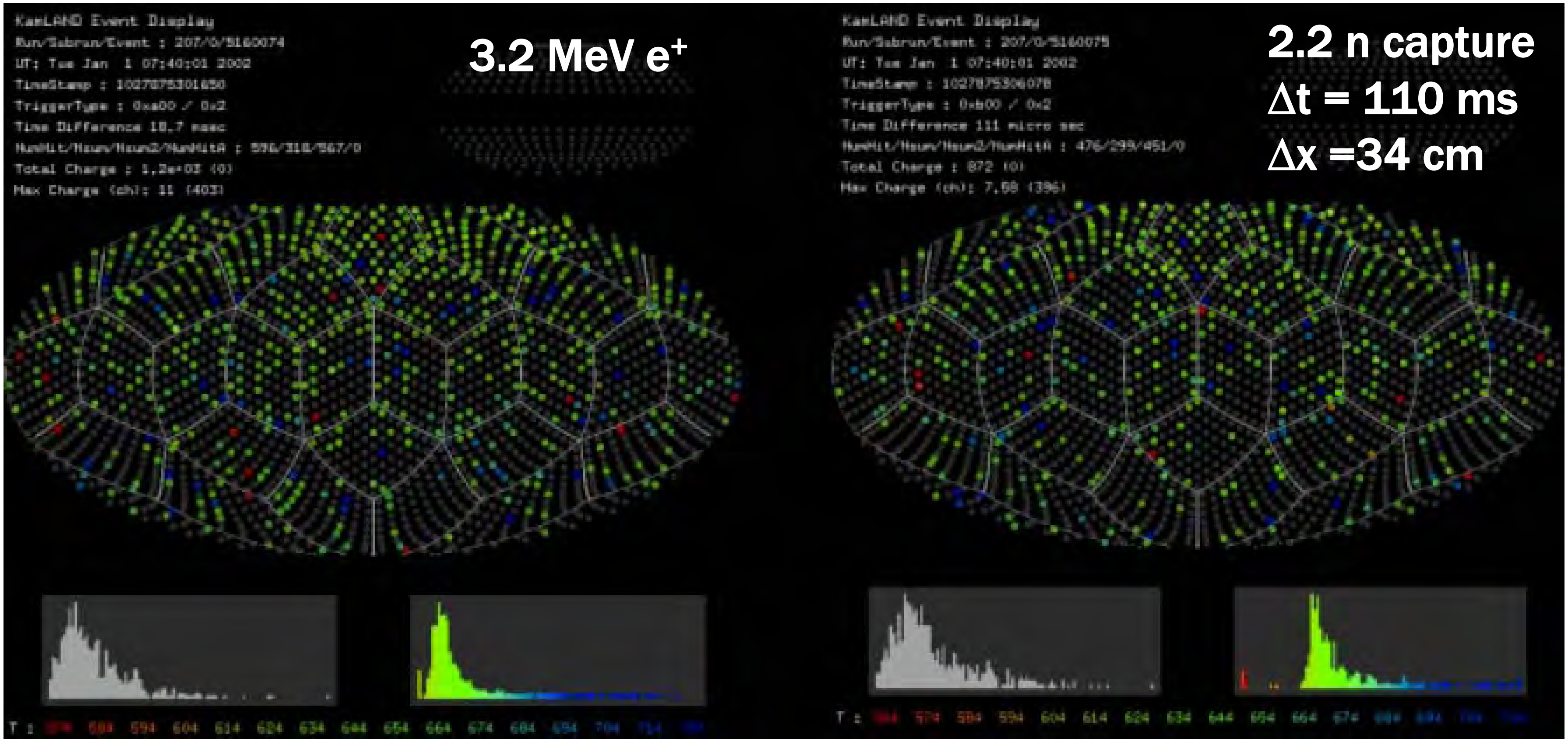
30% photo-coverage
1869 PMTs

Liquid scintillator:
80% dodecane
20% psuedocumene
1.5g/l PPO
~8000 photons/MeV
(500 pe/MeV detected)

U/Th purified to below
10^{-17} g/g



KamLAND Event



3.2 MeV e^+

```
KamLAND Event Display
Run/Subrun/Event : 207/0/5160074
UT: Tue Jan  1 07:40:01 2002
TimeStamp : 1027875301650
TriggerType : 0xa00 / 0x2
Time Difference 18.7 msec
NumHit/Nsum/Nsum2/NumHitA : 596/318/567/0
Total Charge : 1.2e+03 (0)
Max Charge (ch): 11 (403)
```

2.2 n capture

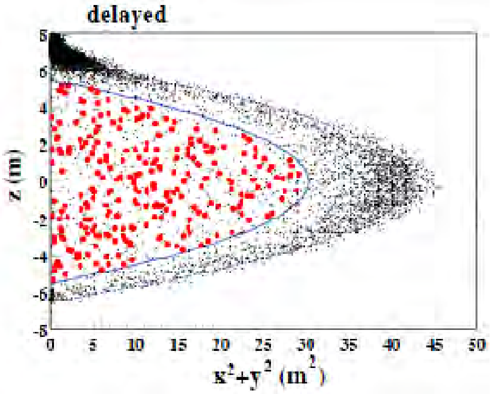
Δt = 110 ms

Δx =34 cm

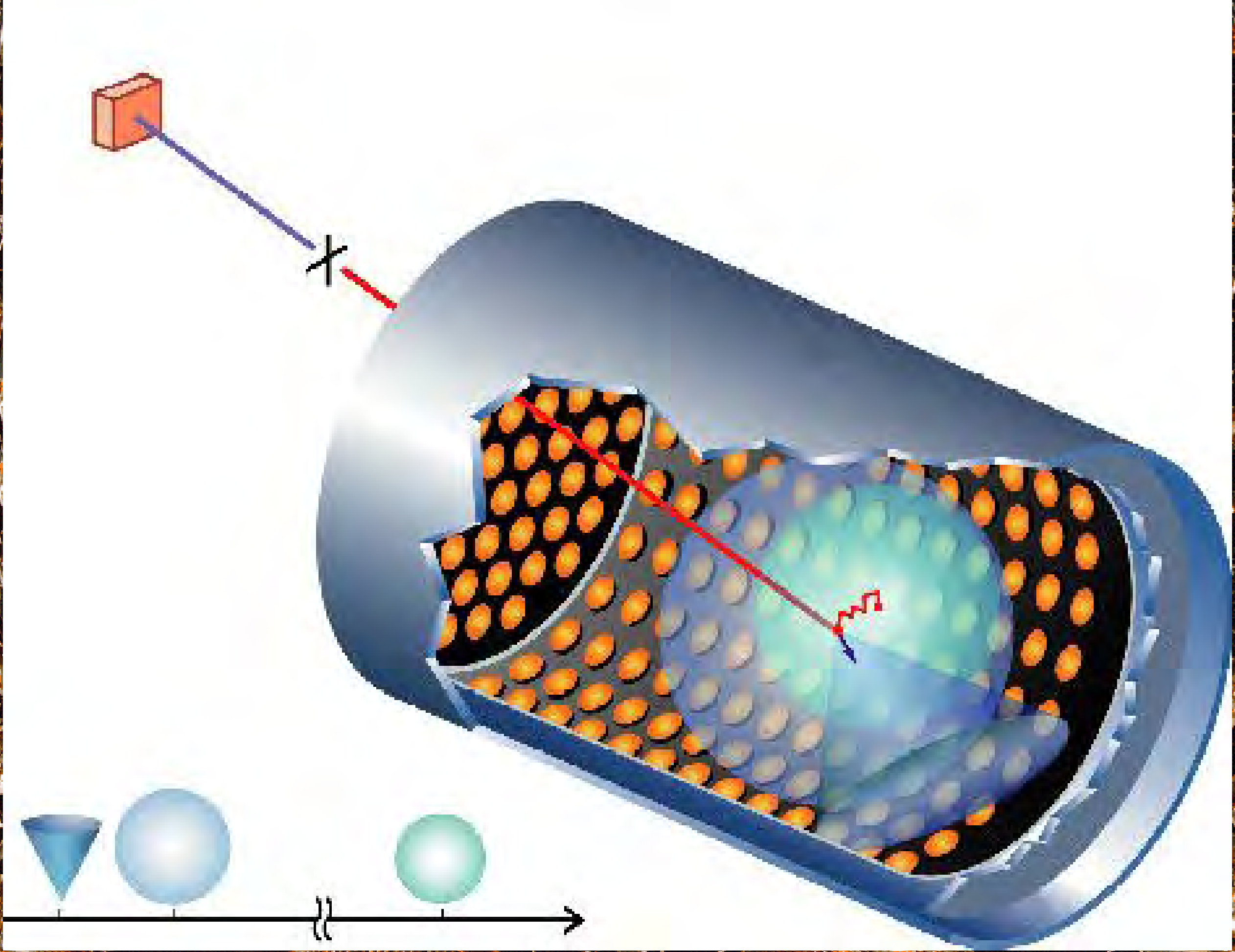
```
KamLAND Event Display
Run/Subrun/Event : 207/0/5160075
UT: Tue Jan  1 07:40:01 2002
TimeStamp : 1027875306078
TriggerType : 0xb00 / 0x2
Time Difference 111 micro sec
NumHit/Nsum/Nsum2/NumHitA : 476/299/451/0
Total Charge : 872 (0)
Max Charge (ch): 7.98 (396)
```

Important detector characteristic:
good fiducial volume determination

$$\sigma_{vtx} = 21\text{cm}/\sqrt{E(\text{MeV})}$$



LSND



Goal: $\bar{\nu}_e$ appearance in beam of $\bar{\nu}_\mu$.

Beam energy:
$E_\nu \sim 50$ MeV

Dilute mineral oil-based scintillator
0.031 g/l of b-BPD

Allows for Cherenkov light pattern for particle identification

~30 pe/MeV

$n = 1.47$

Scint./Cherenkov ~ 5:1

Remember the Time Domain

SNO pure D_20 phase
0.5 mb cross section
capture time few 100 μs
6.3 MeV gamma
capture on ^{1}H is 0.33b

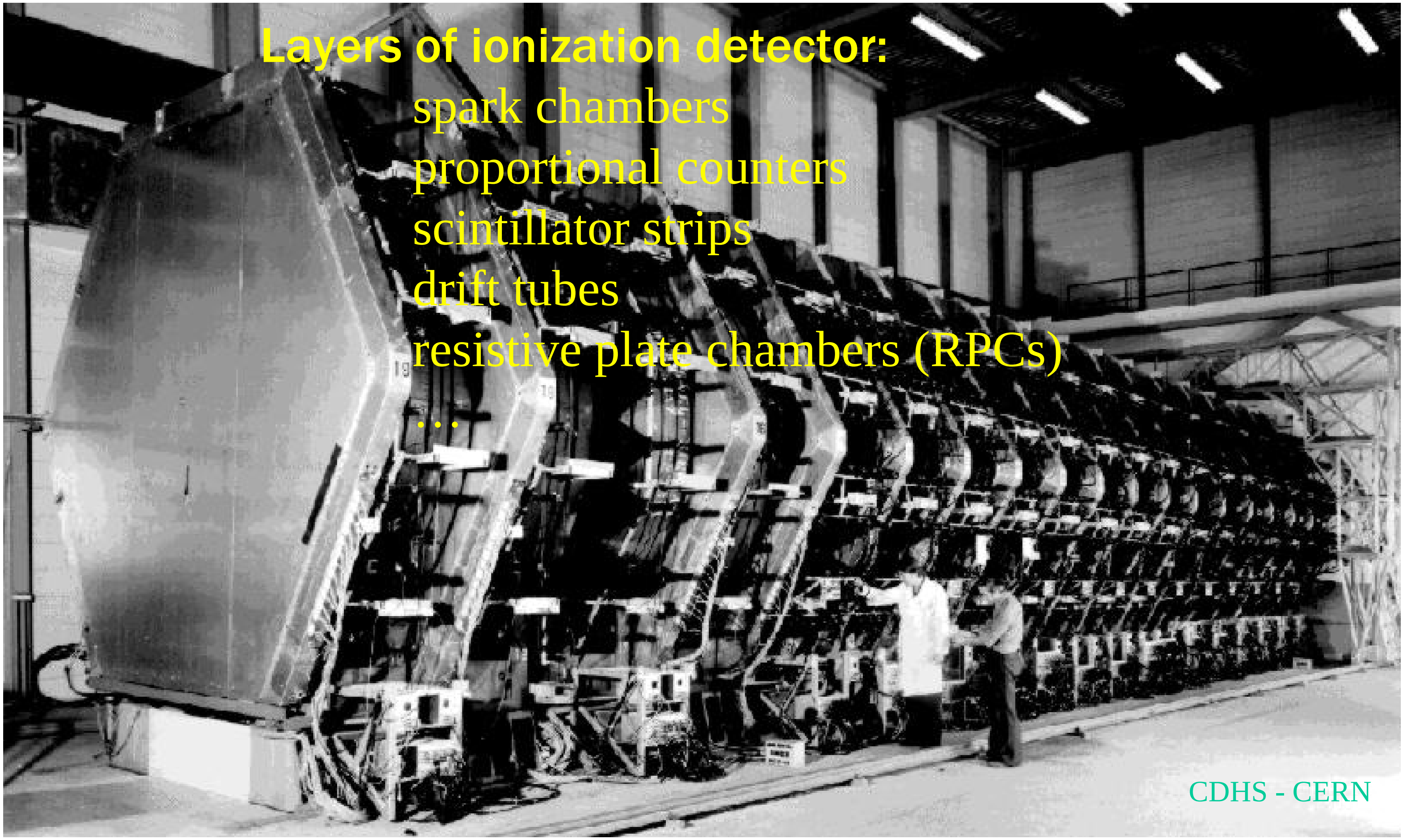
SNO salt-phase
44 b cross section
capture time 5.3 μs
8.6 MeV total gammas

We will also later see that the t=2.2 μs lifetime of muon decay is a valuable experimental handle for water Cherenkov detectors

Gadolinium
49,700 b cross section
Used for n-capture in Chooz reactor experiment
Proposal to put 0.5% Gd in Super-K

Tracking (Plane) Detectors

Layers of target: eg. steel, marble, glass



Layers of ionization detector:

spark chambers
proportional counters
scintillator strips
drift tubes
resistive plate chambers (RPCs)
…

CDHS - CERN

Two Neutrino Experiment

1962

5 GeV protons
Beryllium target

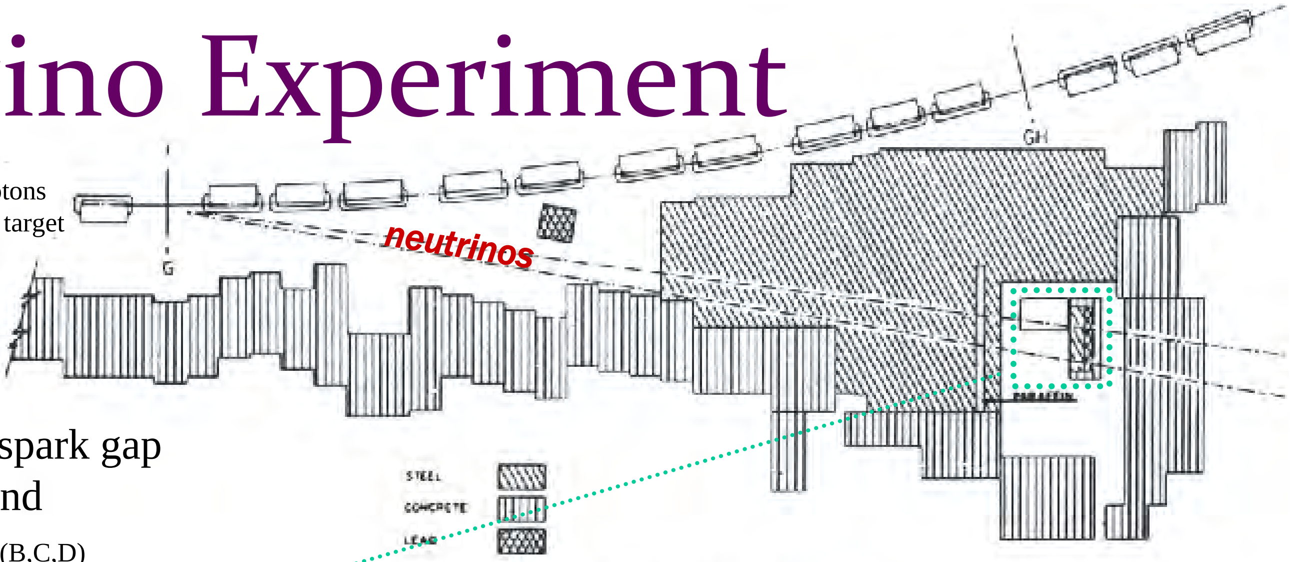
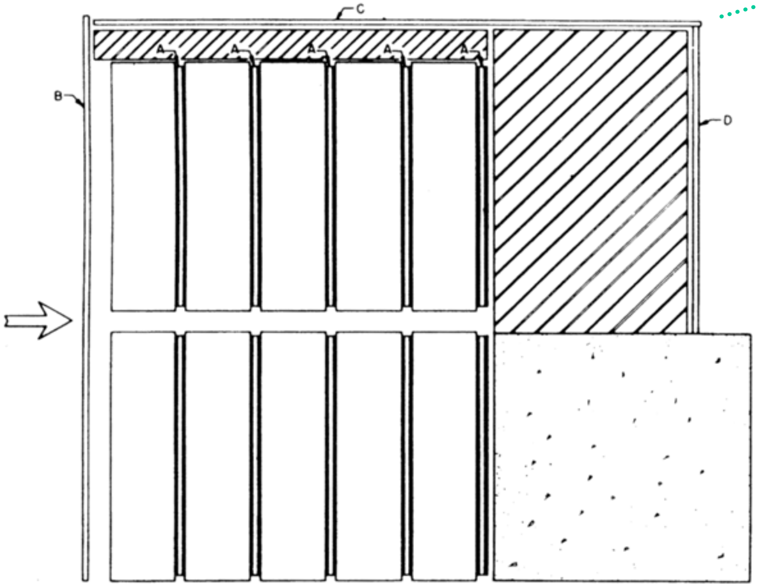
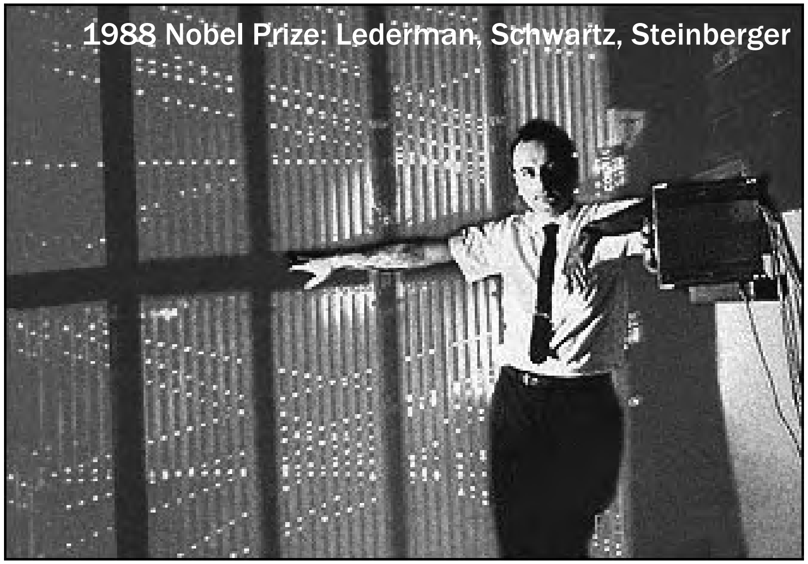


Fig. 1 Plan view of AGS neutrino experiment.

10× 1-ton modules
1” Aluminum plates with spark gap
Coincidence counters (A) and
Anticoincidence counters (B,C,D)

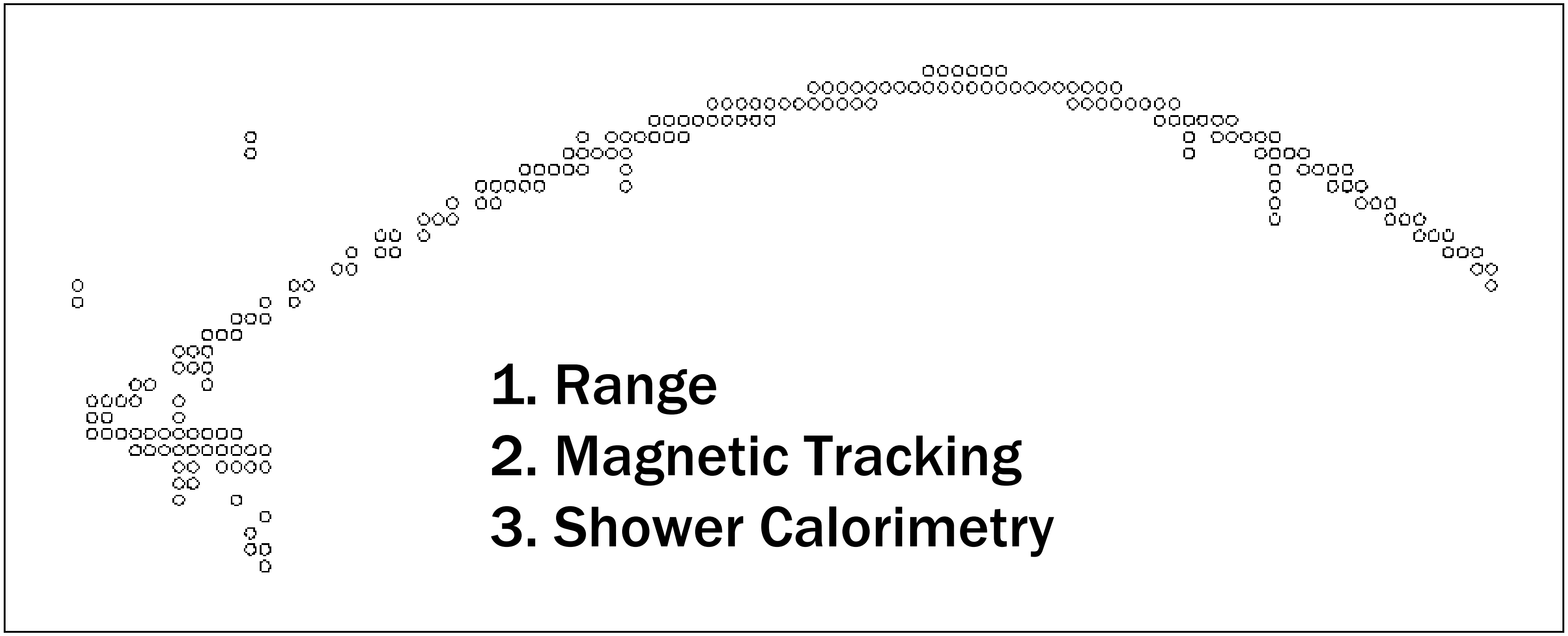




1988 Nobel Prize: Lederman, Schwartz, Steinberger

34 single muon events and only 6 showers ⇒ $\pi\to\mu\nu$ is ν_μ not ν_e

Energy Determination

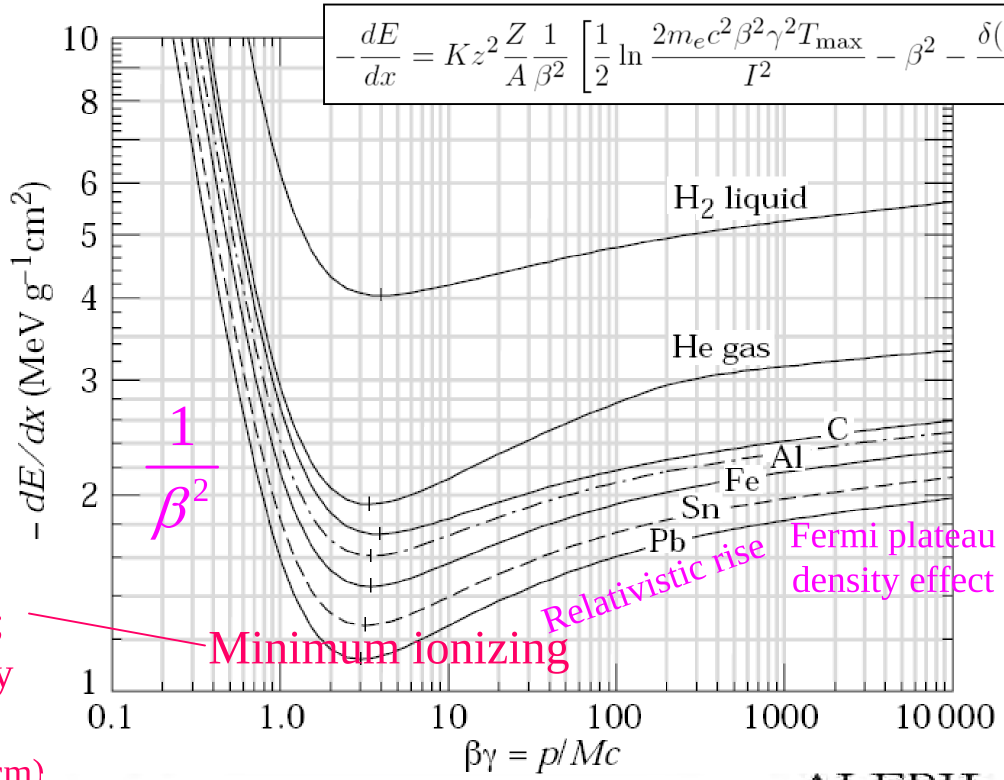


1. Range
2. Magnetic Tracking
3. Shower Calorimetry

dE/dx --- Range

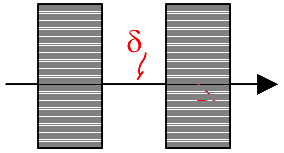
$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

Bethe-Bloch

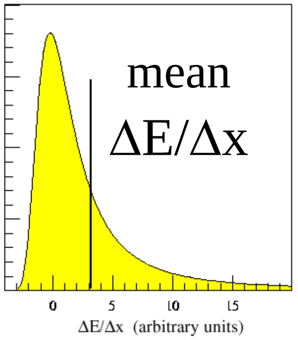


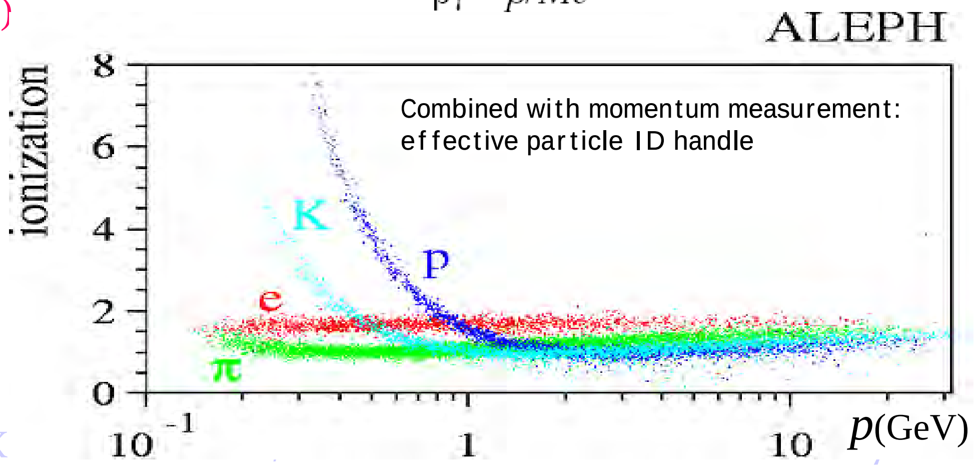
~1.5 MeV g^{-1} cm^2
for most materials;
multiply by density

(but water ~ 2 MeV/cm)



Fluctuations due to δ-rays cause high energy tail in sampling detector: "Landau tails"

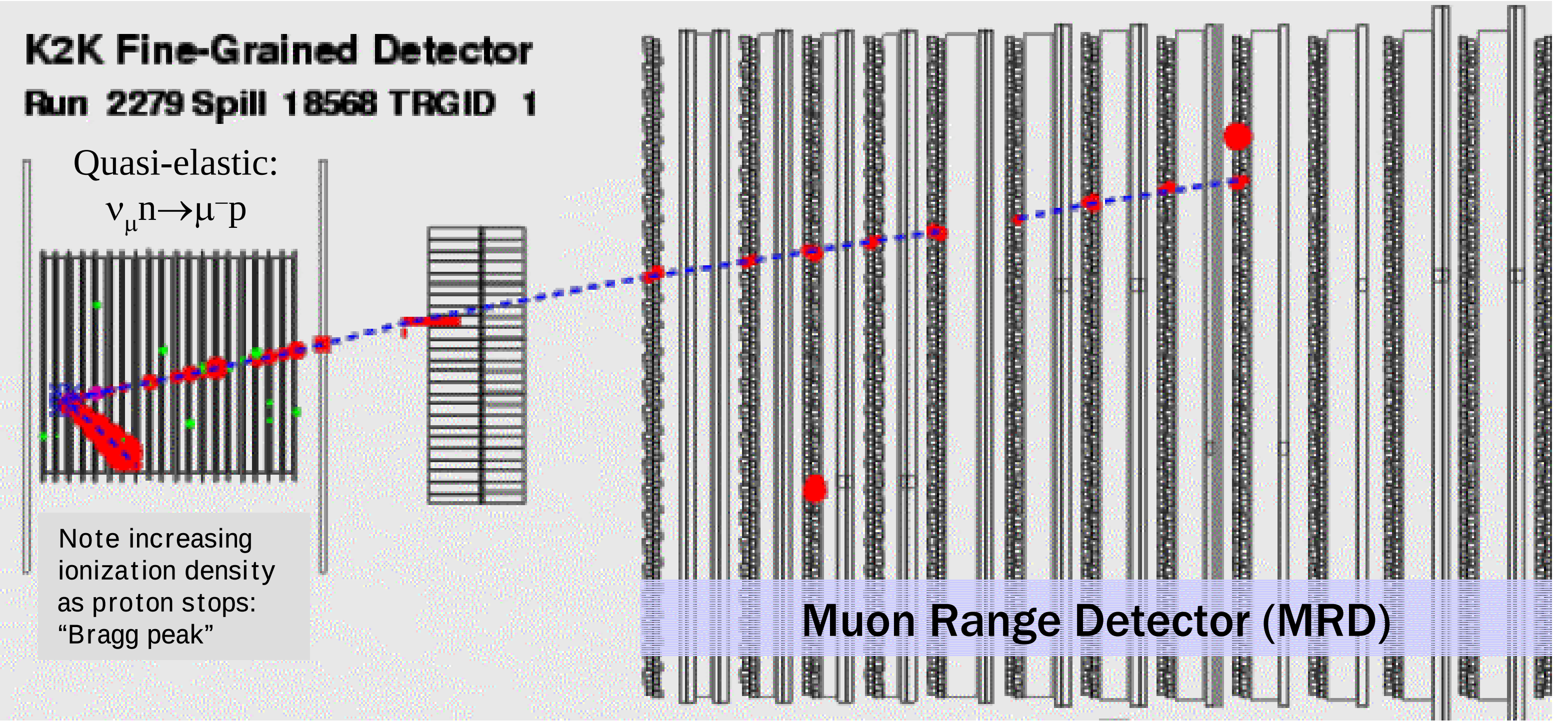




Combined with momentum measurement: effective particle ID handle

Muon Ranger

Simple, no magnetic field; limited by size.
Reconstructed energy: build range table, integrating Bethe-Bloch; incorporate each layer of differing material.(ask GEANT for help)



Quasi-elastic:
$\nu_\mu n \rightarrow \mu^- p$

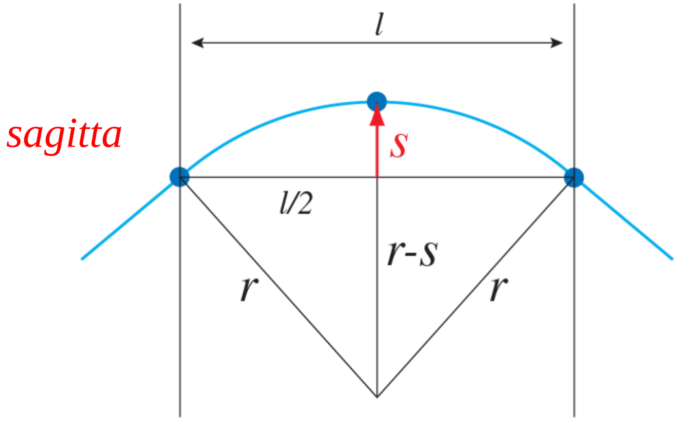
Note increasing ionization density as proton stops: “Bragg peak”

Muon Range Detector (MRD)

$(dE/dx)_{Fe}$= 1.45 MeV $g^{-1}cm^2 \times 7.9$ gm cm^{-3}=90 MeV/cm … 1 GeV muon travels ~ 1m

(careful use of range chart, eg. in PDG, gives 80 cm)

Magnetic Tracking



$$p_t[\text{GeV}] \;=\; 0.3\,B[\text{T}]\,r[\text{m}]$$

$$p_t \approx 0.3B\frac{l^2}{8s} \qquad \frac{\delta p_t}{p_t} = \frac{\delta s}{s}$$

$$\frac{\sigma_{p_t}}{p_t} = \frac{\sigma_x p_t}{0.3Bl^2}\sqrt{\frac{720}{N+4}}$$ for N $\geq$ 10 equidistant

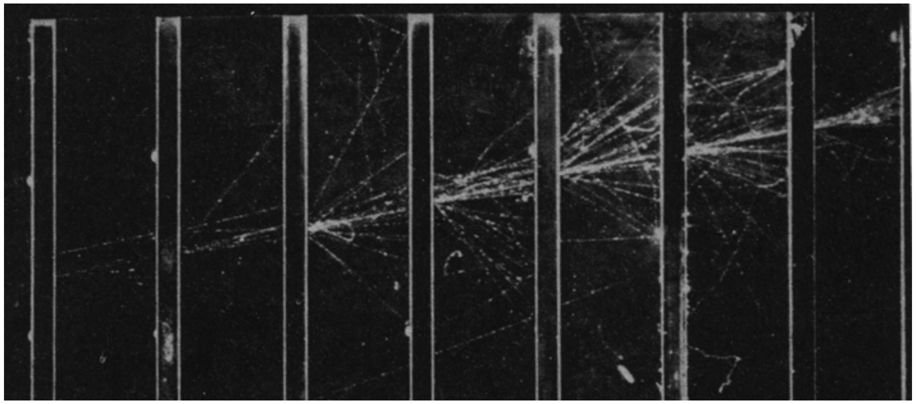
Gluckstern NIM24(1963) 381

Increase *l* (more leverage)

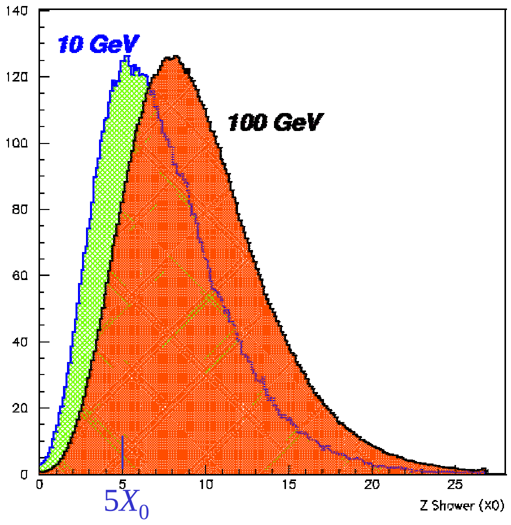
Increase *B* (more curvature)

Decrease σ_x (hit resolution) or increase *N* hits

Electromagnetic Showers



- Compton scattering
- Pair Production
- Bremsstrahlung



To see shower shape: ~ $1X_0$ per plane

- Characterized by radiation length: $X_0 \sim 180\ A/Z^2$
- Longitudinal profile ~ $x^{\alpha}e^{-\beta x}$
- Logarithmic growth of shower max. (i.e. calorimeter depth)
- Energy resolution: $\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b$
- Photon conversion probability: $\Phi(x) = \Phi_0 e^{-\frac{7}{9}\frac{x}{X_0}}$

Photon has significant chance of traveling one to several radiation lengths before converting to e^+e^-

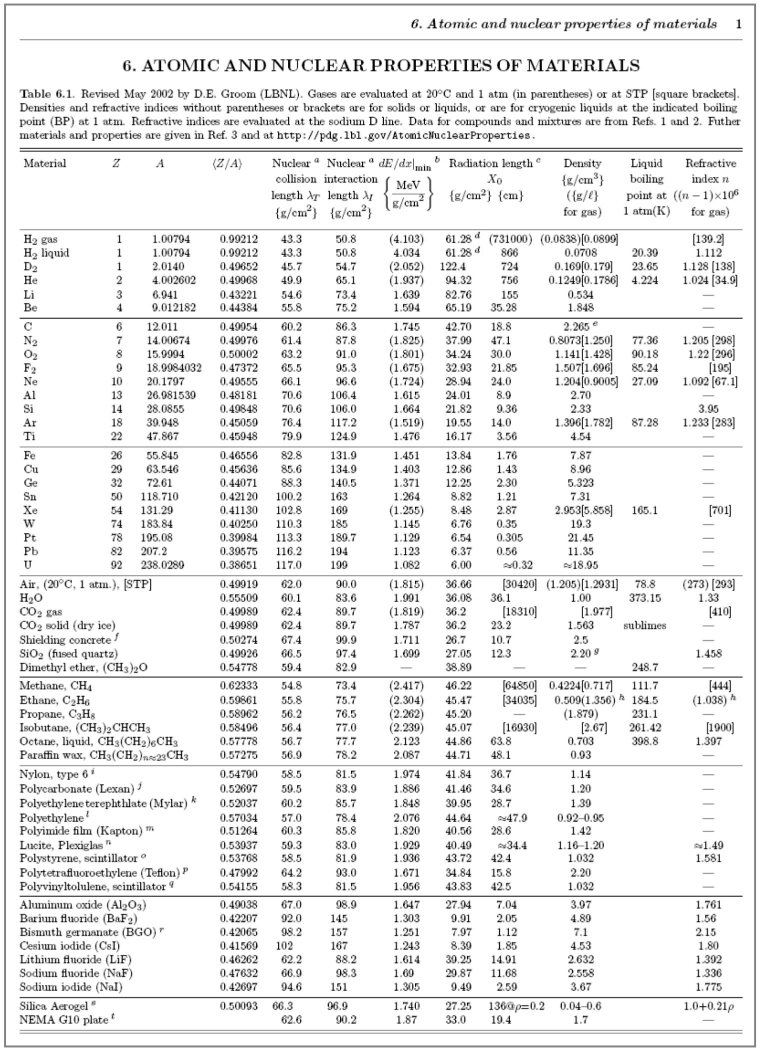
Will be important in next lecture

Material Properties

	ρ [g cm-3]	X0 [cm]	λint [cm]	dE/dx [MeV/cm]
H_2O	1.00	36	83.6	1.99
LAr	1.40	14	83.7	2.12
Al	2.70	8.9	39.4	4.36
Fe	7.87	1.8	16.8	11.4
Pb	11.35	0.56	17.1	12.7

Relevant for hadronic showers

PDG: Review of Particle Properties



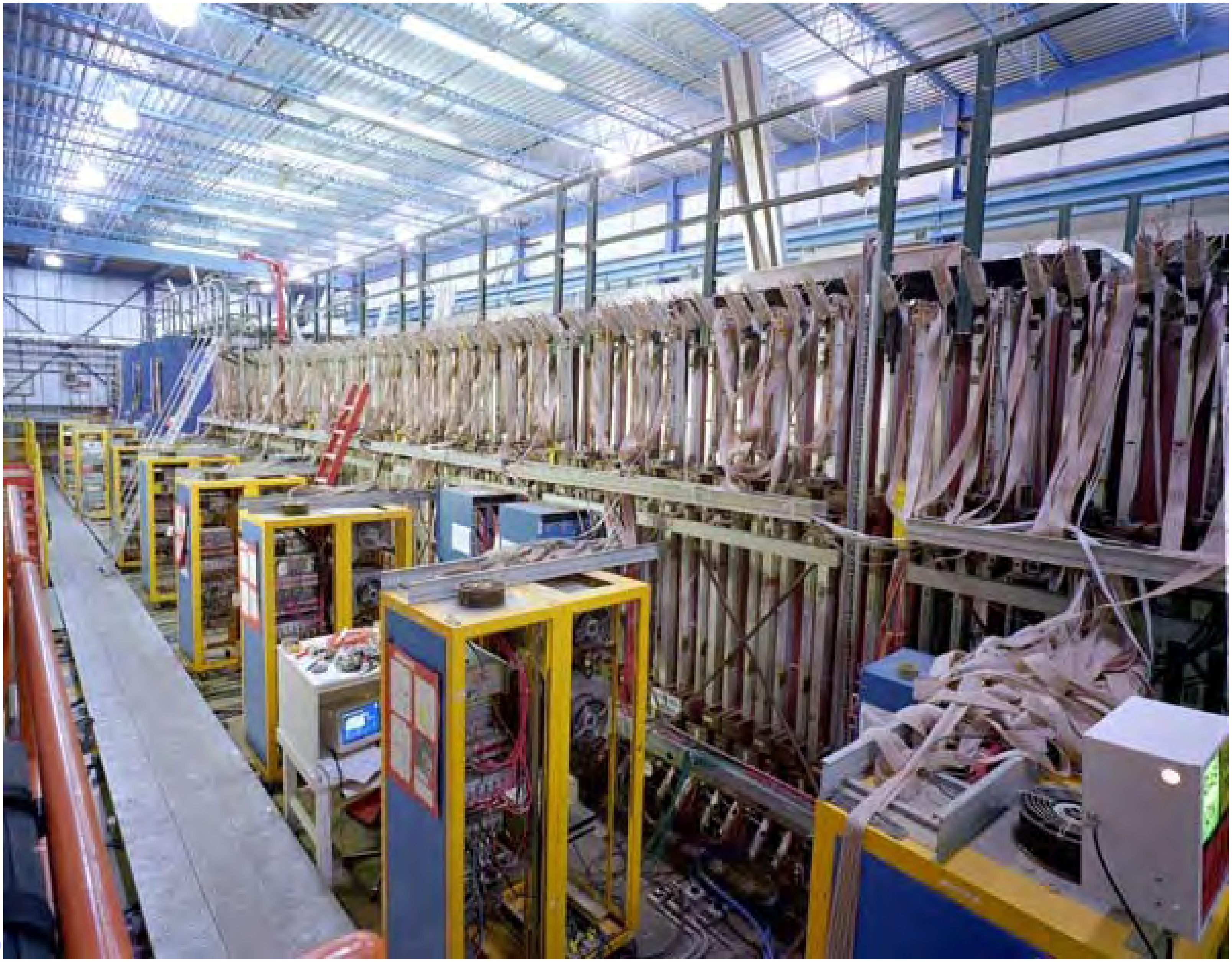
6. Atomic and nuclear properties of materials 1

6. ATOMIC AND NUCLEAR PROPERTIES OF MATERIALS

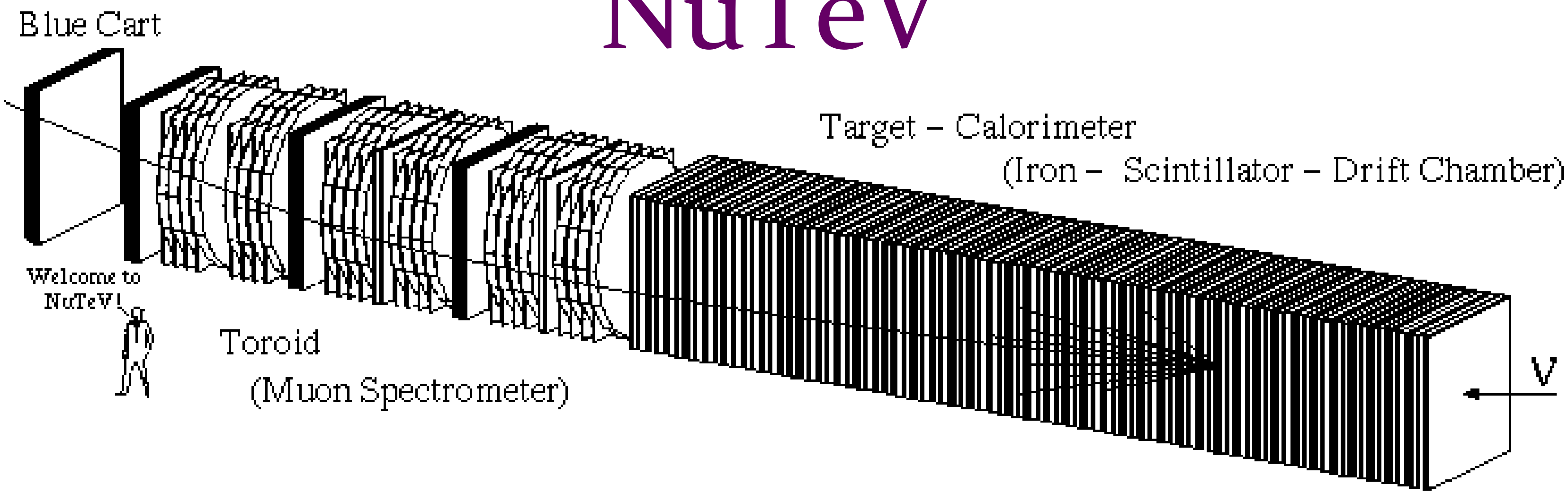
Table 6.1. Revised May 2002 by D.E. Groom (LBNL). Gases are evaluated at 20°C and 1 atm (in parentheses) or at STP [square brackets]. Densities and refractive indices without parentheses or brackets are for solids or liquids, or are for cryogenic liquids at the indicated boiling point (BP) at 1 atm. Refractive indices are evaluated at the sodium D line. Data for compounds and mixtures are from Refs. 1 and 2. Futher materials and properties are given in Ref. 3 and at `http://pdg.lbl.gov/AtomicNuclearProperties`.

Material	Z	A	$\langle Z/A \rangle$	Nuclear [a] collision length λ_T {g/cm²}	Nuclear [a] interaction length λ_I {g/cm²}	$dE/dx\|_{\rm min}$ [b] $\left\{\frac{\rm MeV}{\rm g/cm^2}\right\}$	Radiation length [c] X_0 {g/cm²}	{cm}	Density {g/cm³} ({g/ℓ} for gas)	Liquid boiling point at 1 atm(K)	Refractive index n (($n-1$)×10⁶ for gas)
H_2 gas	1	1.00794	0.99212	43.3	50.8	(4.103)	61.28 [d]	(731000)	(0.0838)[0.0899]		[139.2]
H_2 liquid	1	1.00794	0.99212	43.3	50.8	4.034	61.28 [d]	866	0.0708	20.39	1.112
D_2	1	2.0140	0.49652	45.7	54.7	(2.052)	122.4	724	0.169[0.179]	23.65	1.128 [138]
He	2	4.002602	0.49968	49.9	65.1	(1.937)	94.32	756	0.1249[0.1786]	4.224	1.024 [34.9]
Li	3	6.941	0.43221	54.6	73.4	1.639	82.76	155	0.534		—
Be	4	9.012182	0.44384	55.8	75.2	1.594	65.19	35.28	1.848		—
C	6	12.011	0.49954	60.2	86.3	1.745	42.70	18.8	2.265 [e]		—
N_2	7	14.00674	0.49976	61.4	87.8	(1.825)	37.99	47.1	0.8073[1.250]	77.36	1.205 [298]
O_2	8	15.9994	0.50002	63.2	91.0	(1.801)	34.24	30.0	1.141[1.428]	90.18	1.22 [296]
F_2	9	18.9984032	0.47372	65.5	95.3	(1.675)	32.93	21.85	1.507[1.696]	85.24	[195]
Ne	10	20.1797	0.49555	66.1	96.6	(1.724)	28.94	24.0	1.204[0.9005]	27.09	1.092 [67.1]
Al	13	26.981539	0.48181	70.6	106.4	1.615	24.01	8.9	2.70		—
Si	14	28.0855	0.49848	70.6	106.0	1.664	21.82	9.36	2.33		3.95
Ar	18	39.948	0.45059	76.4	117.2	(1.519)	19.55	14.0	1.396[1.782]	87.28	1.233 [283]
Ti	22	47.867	0.45948	79.9	124.9	1.476	16.17	3.56	4.54		—
Fe	26	55.845	0.46556	82.8	131.9	1.451	13.84	1.76	7.87		—
Cu	29	63.546	0.45636	85.6	134.9	1.403	12.86	1.43	8.96		—
Ge	32	72.61	0.44071	88.3	140.5	1.371	12.25	2.30	5.323		—
Sn	50	118.710	0.42120	100.2	163	1.264	8.82	1.21	7.31		—
Xe	54	131.29	0.41130	102.8	169	(1.255)	8.48	2.87	2.953[5.858]	165.1	[701]
W	74	183.84	0.40250	110.3	185	1.145	6.76	0.35	19.3		—
Pt	78	195.08	0.39984	113.3	189.7	1.129	6.54	0.305	21.45		—
Pb	82	207.2	0.39575	116.2	194	1.123	6.37	0.56	11.35		—
U	92	238.0289	0.38651	117.0	199	1.082	6.00	≈0.32	≈18.95		—
Air, (20°C, 1 atm.), [STP]			0.49919	62.0	90.0	(1.815)	36.66	[30420]	(1.205)[1.2931]	78.8	(273) [293]
H_2O			0.55509	60.1	83.6	1.991	36.08	36.1	1.00	373.15	1.33
CO_2 gas			0.49989	62.4	89.7	(1.819)	36.2	[18310]	[1.977]		[410]
CO_2 solid (dry ice)			0.49989	62.4	89.7	1.787	36.2	23.2	1.563	sublimes	—
Shielding concrete [f]			0.50274	67.4	99.9	1.711	26.7	10.7	2.5		—
SiO_2 (fused quartz)			0.49926	66.5	97.4	1.699	27.05	12.3	2.20 [g]		1.458
Dimethyl ether, $(CH_3)_2O$			0.54778	59.4	82.9	—	38.89	—	—	248.7	—
Methane, CH_4			0.62333	54.8	73.4	(2.417)	46.22	[64850]	0.4224[0.717]	111.7	[444]
Ethane, C_2H_6			0.59861	55.8	75.7	(2.304)	45.47	[34035]	0.509(1.356) [h]	184.5	(1.038) [h]
Propane, C_3H_8			0.58962	56.2	76.5	(2.262)	45.20	—	(1.879)	231.1	—
Isobutane, $(CH_3)_2CHCH_3$			0.58496	56.4	77.0	(2.239)	45.07	[16930]	[2.67]	261.42	[1900]
Octane, liquid, $CH_3(CH_2)_6CH_3$			0.57778	56.7	77.7	2.123	44.86	63.8	0.703	398.8	1.397
Paraffin wax, $CH_3(CH_2)_{n\approx 23}CH_3$			0.57275	56.9	78.2	2.087	44.71	48.1	0.93		—
Nylon, type 6 [i]			0.54790	58.5	81.5	1.974	41.84	36.7	1.14		—
Polycarbonate (Lexan) [j]			0.52697	59.5	83.9	1.886	41.46	34.6	1.20		—
Polyethylene terephthlate (Mylar) [k]			0.52037	60.2	85.7	1.848	39.95	28.7	1.39		—
Polyethylene [l]			0.57034	57.0	78.4	2.076	44.64	≈47.9	0.92–0.95		—
Polyimide film (Kapton) [m]			0.51264	60.3	85.8	1.820	40.56	28.6	1.42		—
Lucite, Plexiglas [n]			0.53937	59.3	83.0	1.929	40.49	≈34.4	1.16–1.20		≈1.49
Polystyrene, scintillator [o]			0.53768	58.5	81.9	1.936	43.72	42.4	1.032		1.581
Polytetrafluoroethylene (Teflon) [p]			0.47992	64.2	93.0	1.671	34.84	15.8	2.20		—
Polyvinyltolulene, scintillator [q]			0.54155	58.3	81.5	1.956	43.83	42.5	1.032		—
Aluminum oxide (Al_2O_3)			0.49038	67.0	98.9	1.647	27.94	7.04	3.97		1.761
Barium fluoride (BaF_2)			0.42207	92.0	145	1.303	9.91	2.05	4.89		1.56
Bismuth germanate (BGO) [r]			0.42065	98.2	157	1.251	7.97	1.12	7.1		2.15
Cesium iodide (CsI)			0.41569	102	167	1.243	8.39	1.85	4.53		1.80
Lithium fluoride (LiF)			0.46262	62.2	88.2	1.614	39.25	14.91	2.632		1.392
Sodium fluoride (NaF)			0.47632	66.9	98.3	1.69	29.87	11.68	2.558		1.336
Sodium iodide (NaI)			0.42697	94.6	151	1.305	9.49	2.59	3.67		1.775
Silica Aerogel [s]			0.50093	66.3	96.9	1.740	27.25	136@ρ=0.2	0.04–0.6		1.0+0.21ρ
NEMA G10 plate [t]				62.6	90.2	1.87	33.0	19.4	1.7		—

NuTeV

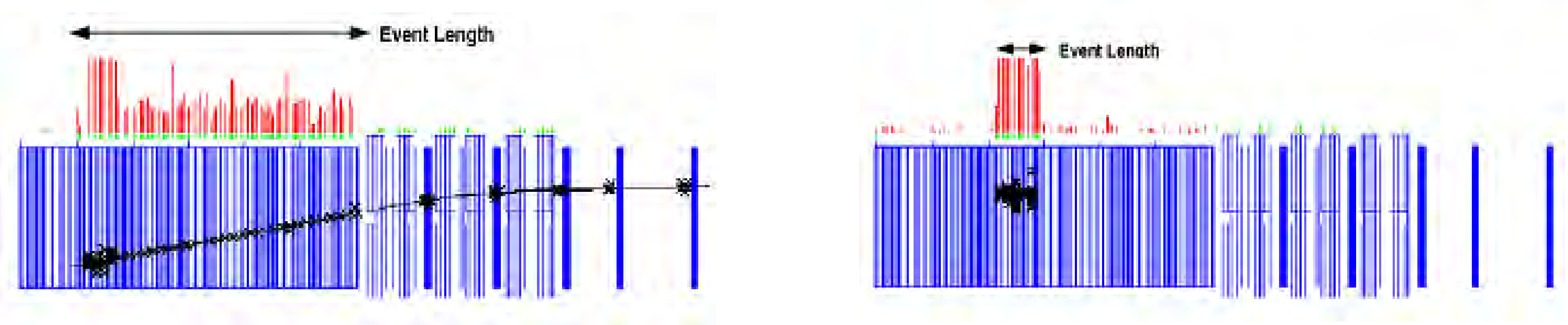


NuTeV



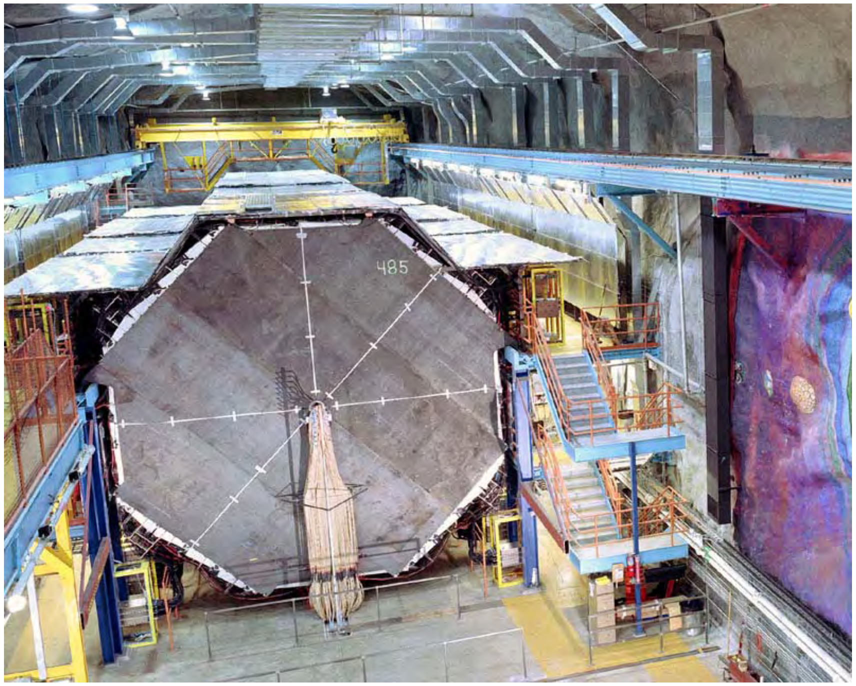
Paschos-Wolfenstein

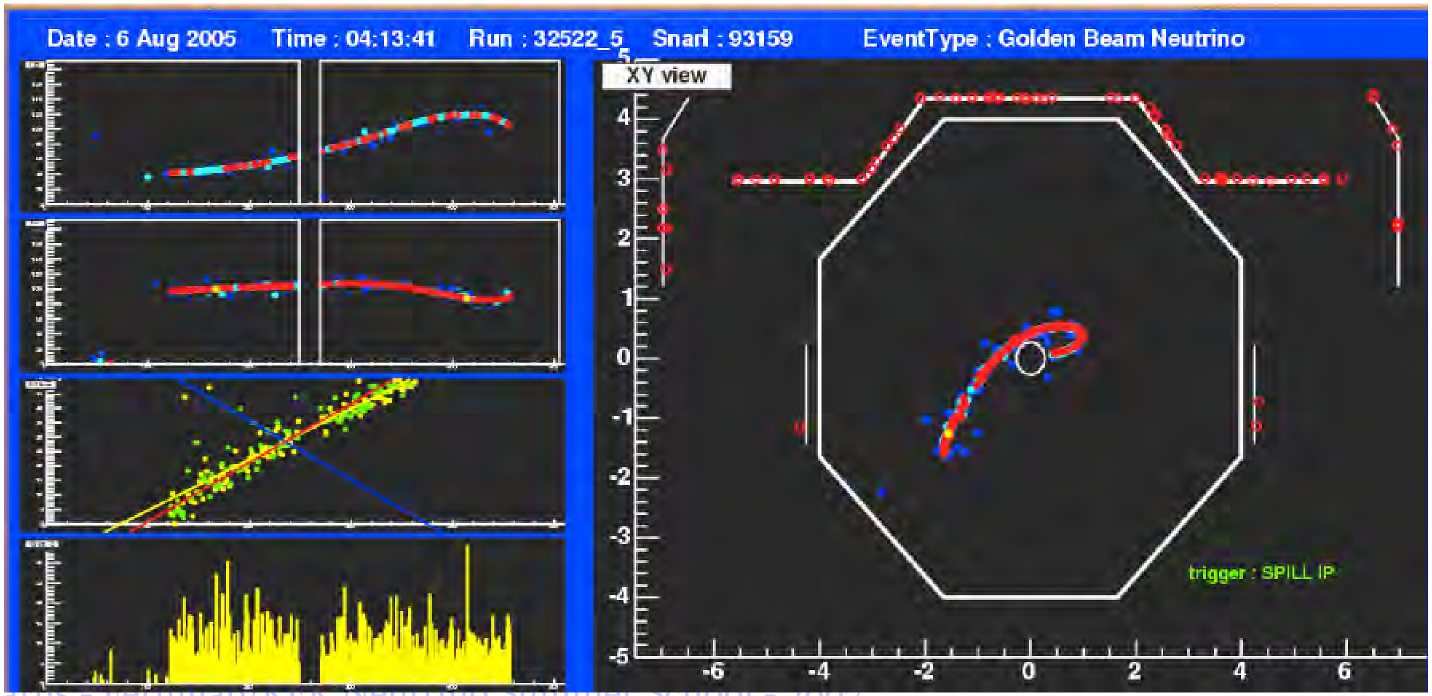
$$\frac{\sigma(NC,\nu)-\sigma(NC,\bar{\nu})}{\sigma(CC,\nu)-\sigma(CC,\bar{\nu})}=\frac{1}{2}-\sin^2\theta_W$$



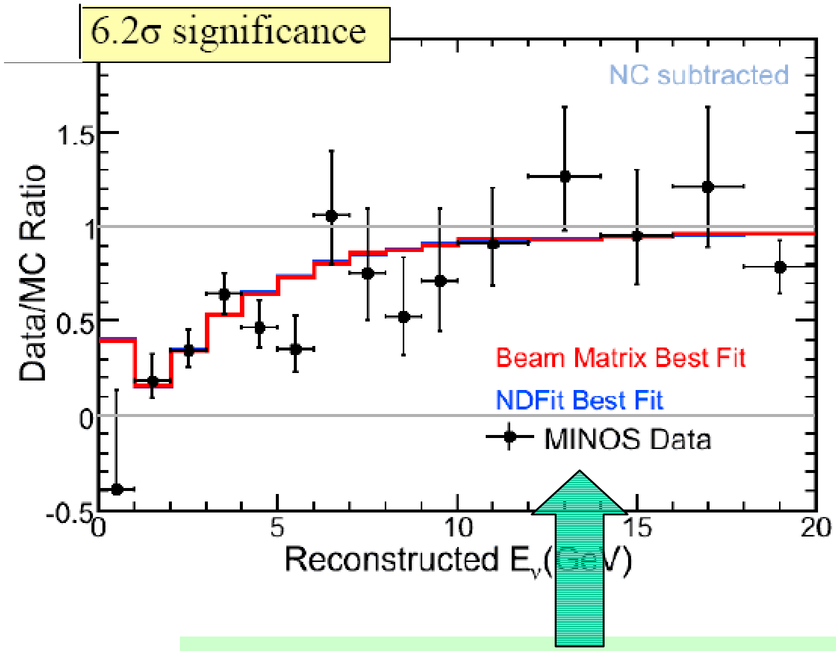
MINOS

- 5.4 kton far detector, 1 kton near
- 484 steel/scintillator planes
- 2.54 cm thick steel plates (1.4X_0)
- 1.2 T solenoidal magnetic field
- peak neutrino energy ~ 3 GeV
- 92% ν_μ, 1.5% ν_e/ν_e-bar

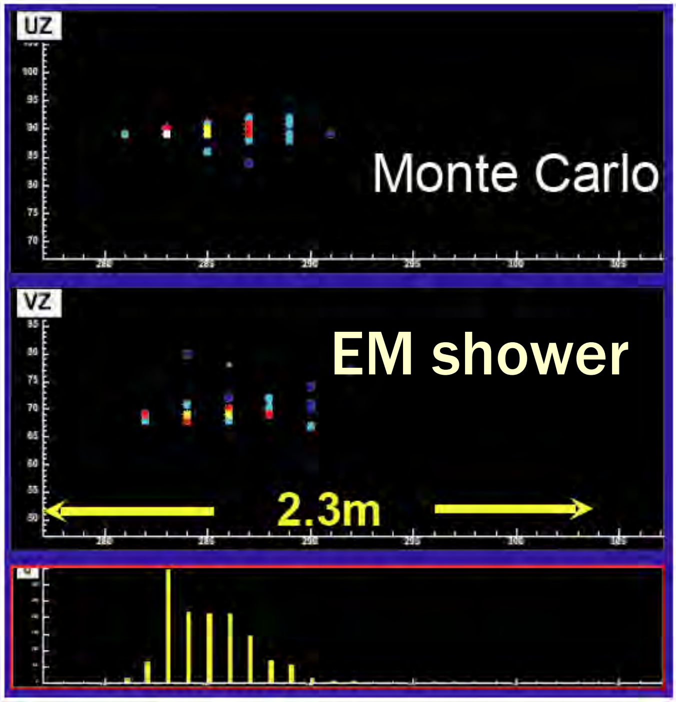



Date : 6 Aug 2005 Time : 04:13:41 Run : 32522_5 Snarl : 93159 EventType : Golden Beam Neutrino

MINOS - neutrino appearance



If early atmospheric results had held up, $\Delta m^2 > 10^{-2}$ eV^2. MINOS originally envisioned for statistical study of τ-appearance.

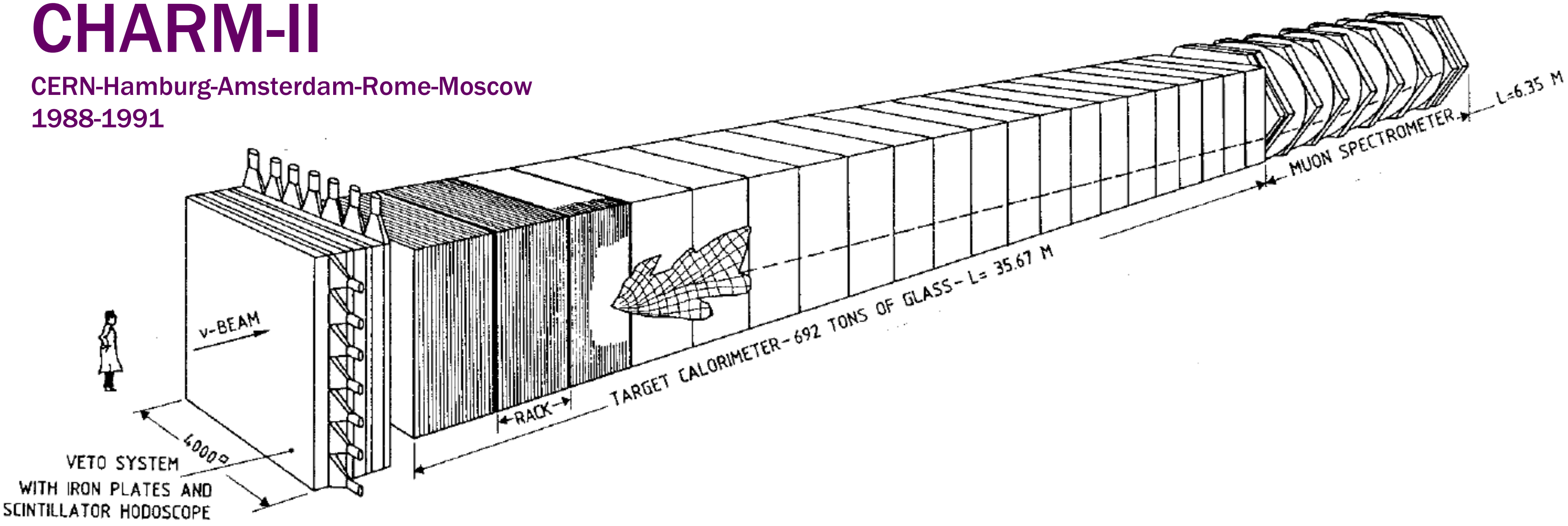


MINOS has some sensitivity for ν_e appearance but detector is not optimum.

But for now-- it is the only running experiment that can extend beyond Chooz limit.

CHARM-II

CERN-Hamburg-Amsterdam-Rome-Moscow
1988-1991



Target material: 692 tons of glass

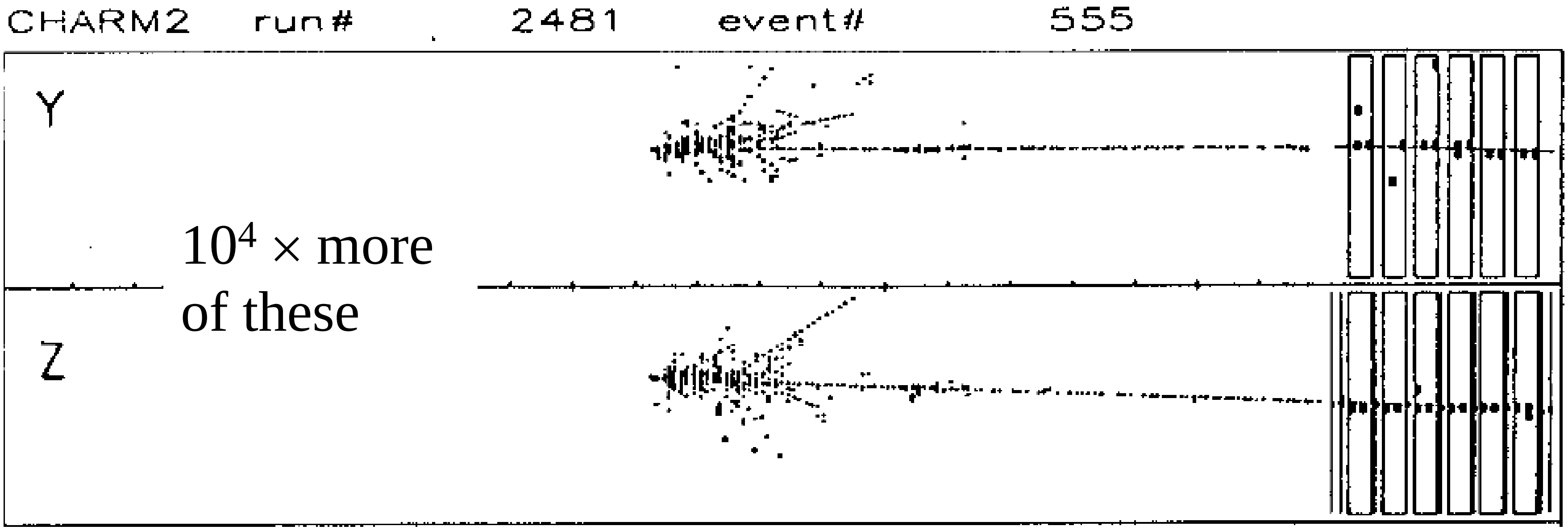
Z~11 ρ=2.2 g/cm^3 X_0=12 cm λ=44 cm inexpensive

One plane: 4.8 cm thick plate + 1 cm streamer tube

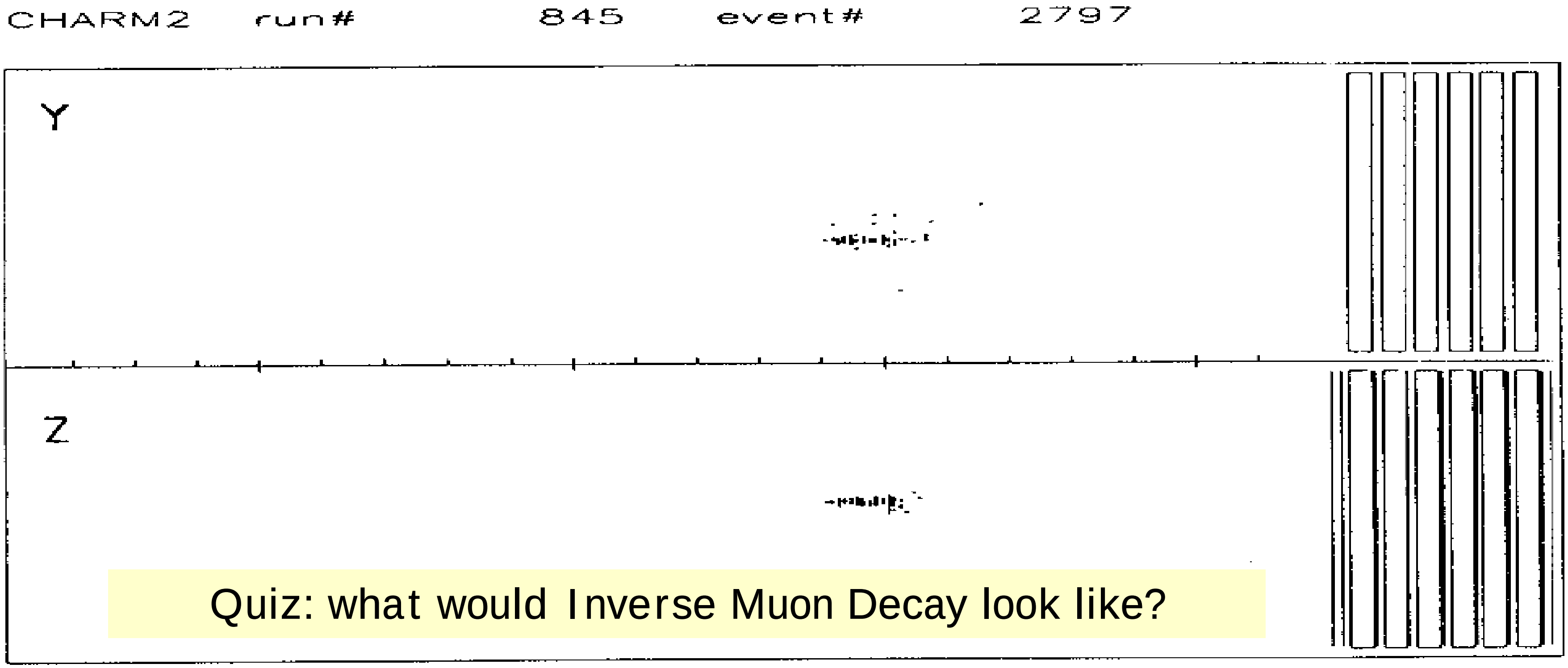
Detector for Neutrino-Electron Scattering (and Inverse Muon Decay)

- Isolated electromagnetic shower: low Z
- Strongly peaked in neutrino direction - want good angular resolution (low density)
- Backgrounds: ν-nucleon scattering
  neutral current π production

Ideas bouncing around to revisit this at Fermilab

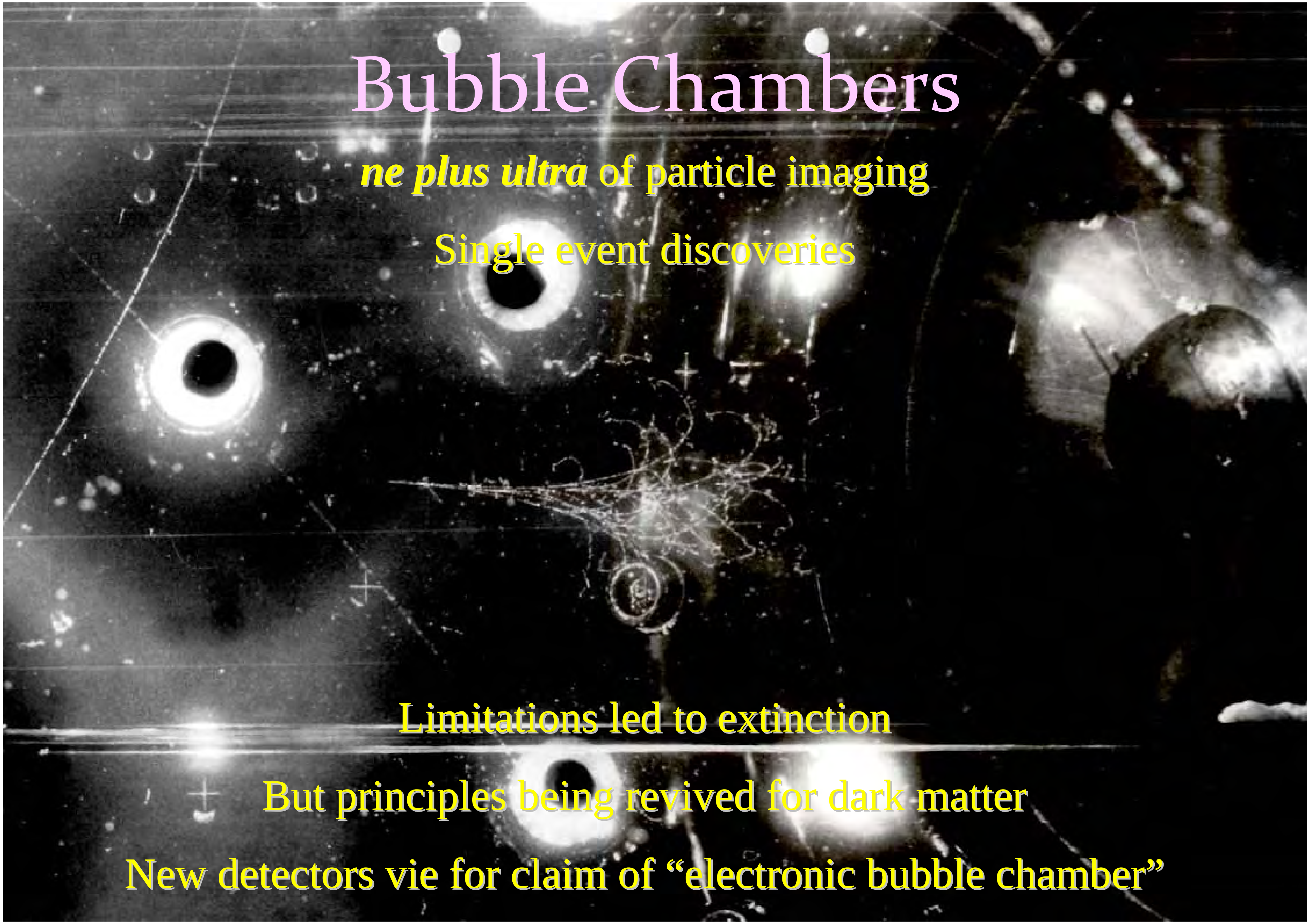


10^4 × more of these



Quiz: what would Inverse Muon Decay look like?

Bubble Chambers



ne plus ultra of particle imaging

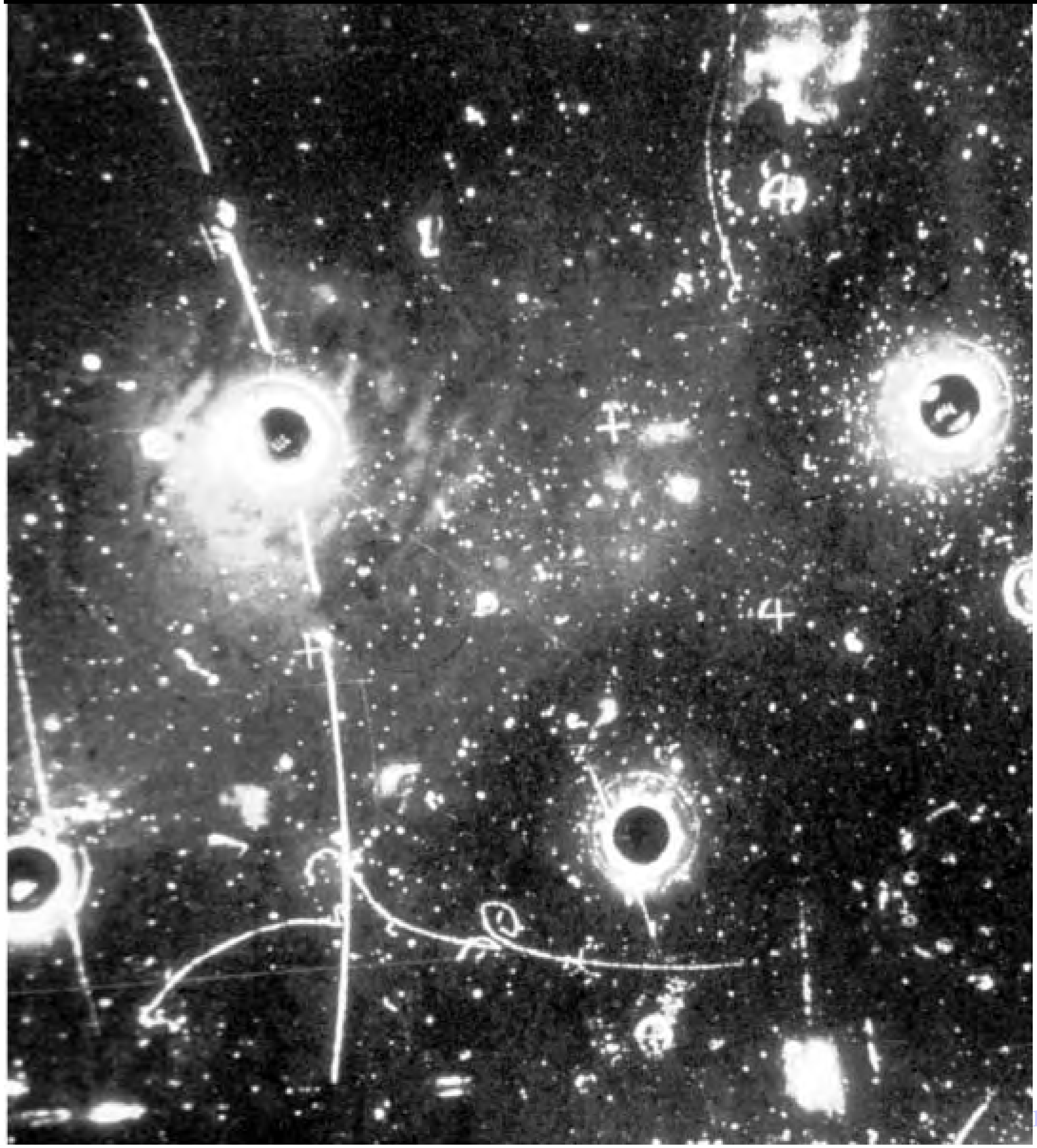
Single event discoveries

Limitations led to extinction

But principles being revived for dark matter

New detectors vie for claim of “electronic bubble chamber”

Discovery of Neutral Currents



Gargamelle bubble chamber
- CERN, 1973
- $E_\nu \sim$ 1-2 GeV
- 15 tons freon

$\nu_\mu + N \rightarrow \nu_\mu + hadrons$ (NC)

$\nu_\mu + N \rightarrow \mu^- + hadrons$ (CC)

$\nu_e + N \rightarrow e^- + hadrons$ (CC)

$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$ (NC)

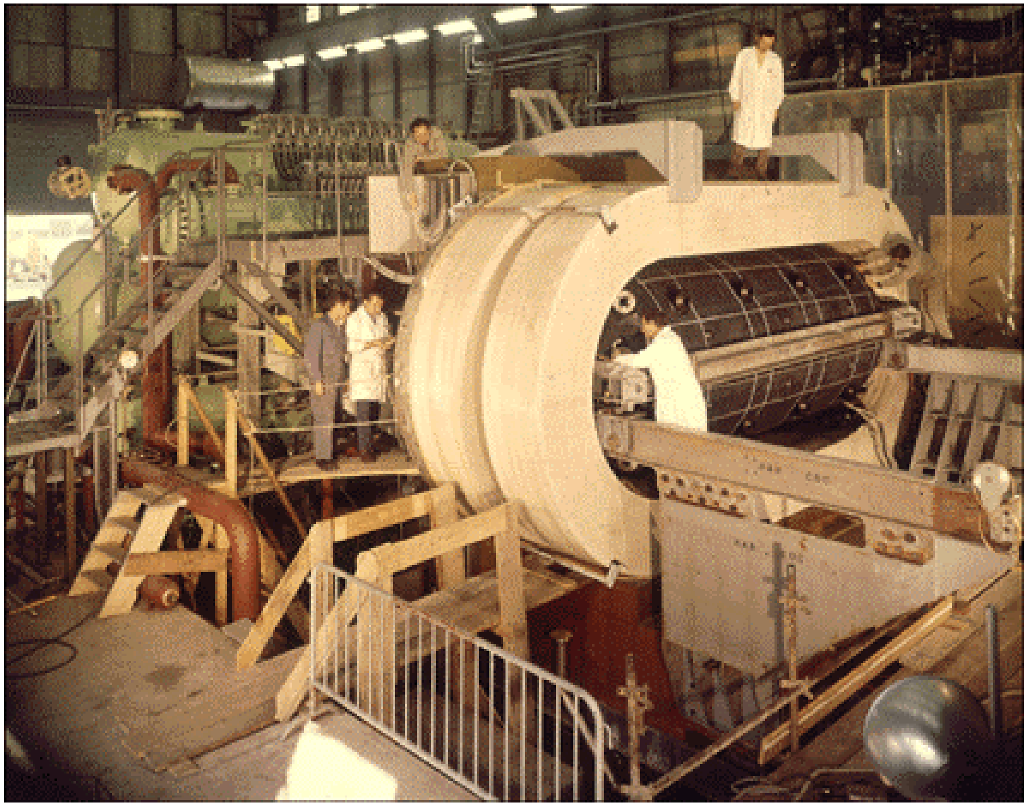
$n + N \rightarrow hadrons$ (contamination)

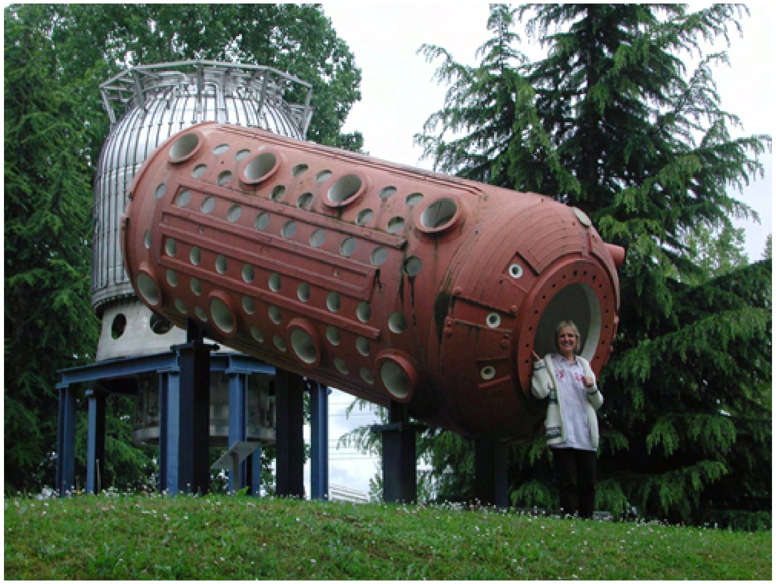
also antineutrino beam ($\bar{\nu}_\mu$)

Single event discovery
BG estimate 0.03±0.02

E_e=385 ± 100 MeV
angle w. beam 1.4°±1.5°

Gargamelle





$\nu N \to \nu N \pi^0$

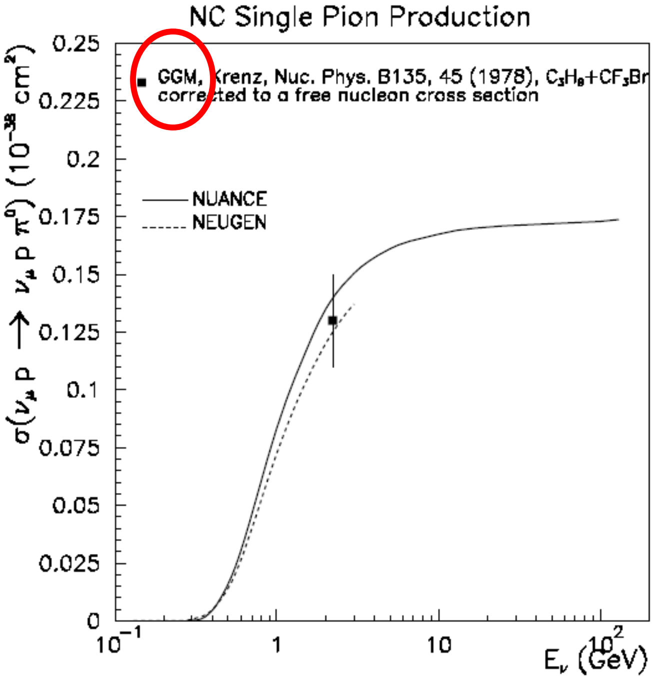


Figure 7. NC 1π cross section $\sigma(\nu_\mu\, p \to \nu_\mu\, p\, \pi^0)$ Shown are the free nucleon cross section predictions from NUANCE and NEUGEN with $m_A = 1.032$ GeV, $m_V = 0.84$ GeV, and $\sin^2\theta_W = 0.233$.

G.P. Zeller, hep-ex/0312061

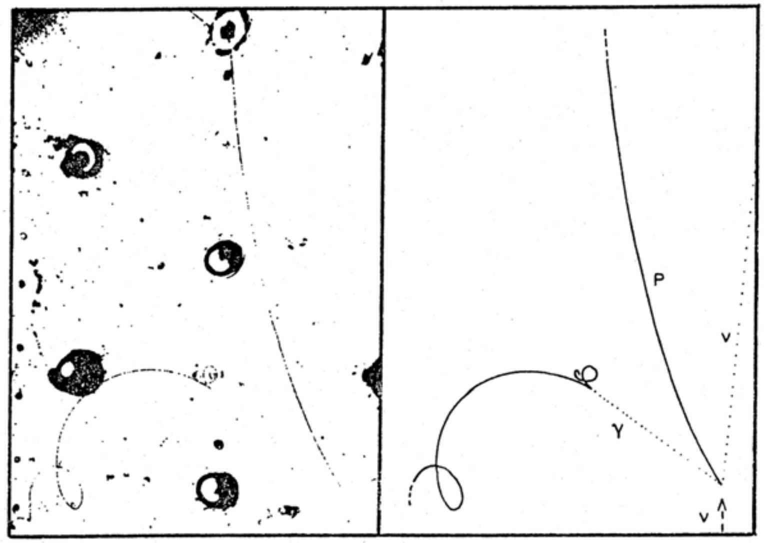


Abb. 13: Ein Kandidat für die Reaktion ($\nu p \to \nu p \pi^0$). Das π^0 wird durch Konversion eines seiner Zerfalls-Photonen nachgewiesen.

M. Pohl, Ph.D. thesis

Not much data! Actually, there are many more measurements of NC/CC ratios. These reactions are the dominant background to T2K, NOνA and other ν_e appearance experiments.

Principle of Operation: Bubble Chamber

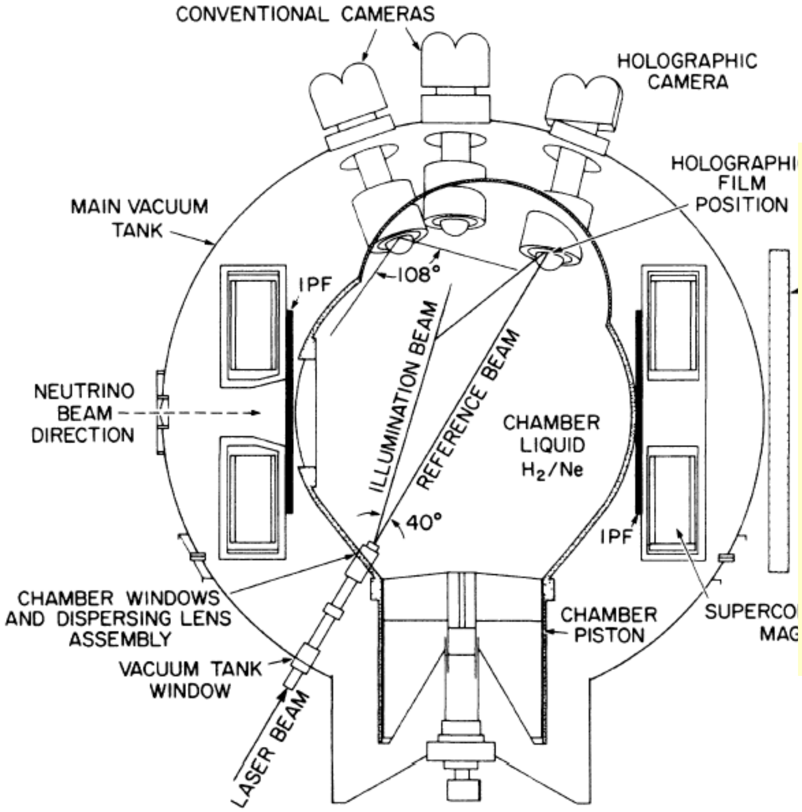


FIG. 2. Side view of the 15-ft bubble chamber.

- Liquified gas, H_2, D_2, Ne, Ar, Freon, Xe kept close to boiling.
- After trigger, piston expands volume, gas bubbles form along track.
- Bubble growth stops when piston pushed back.
- Illuminate with flash and photograph.
- Last experiments used holographic illumination, achieved ~100μm bubbles.

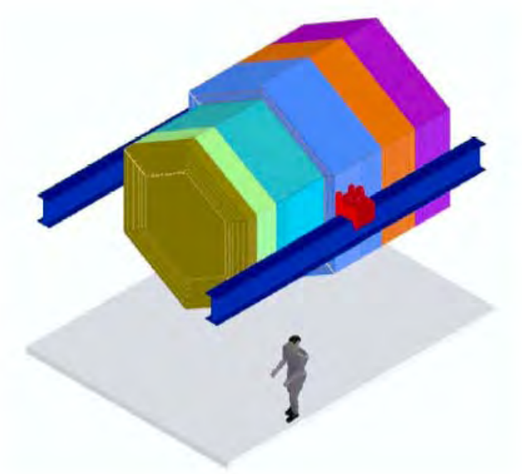
But…

- Fixed target only.
- High energy particles not contained; ∫B•dl only 10 T m.
- Photograph scanning difficult (some automation developed).

Hybrid Detectors

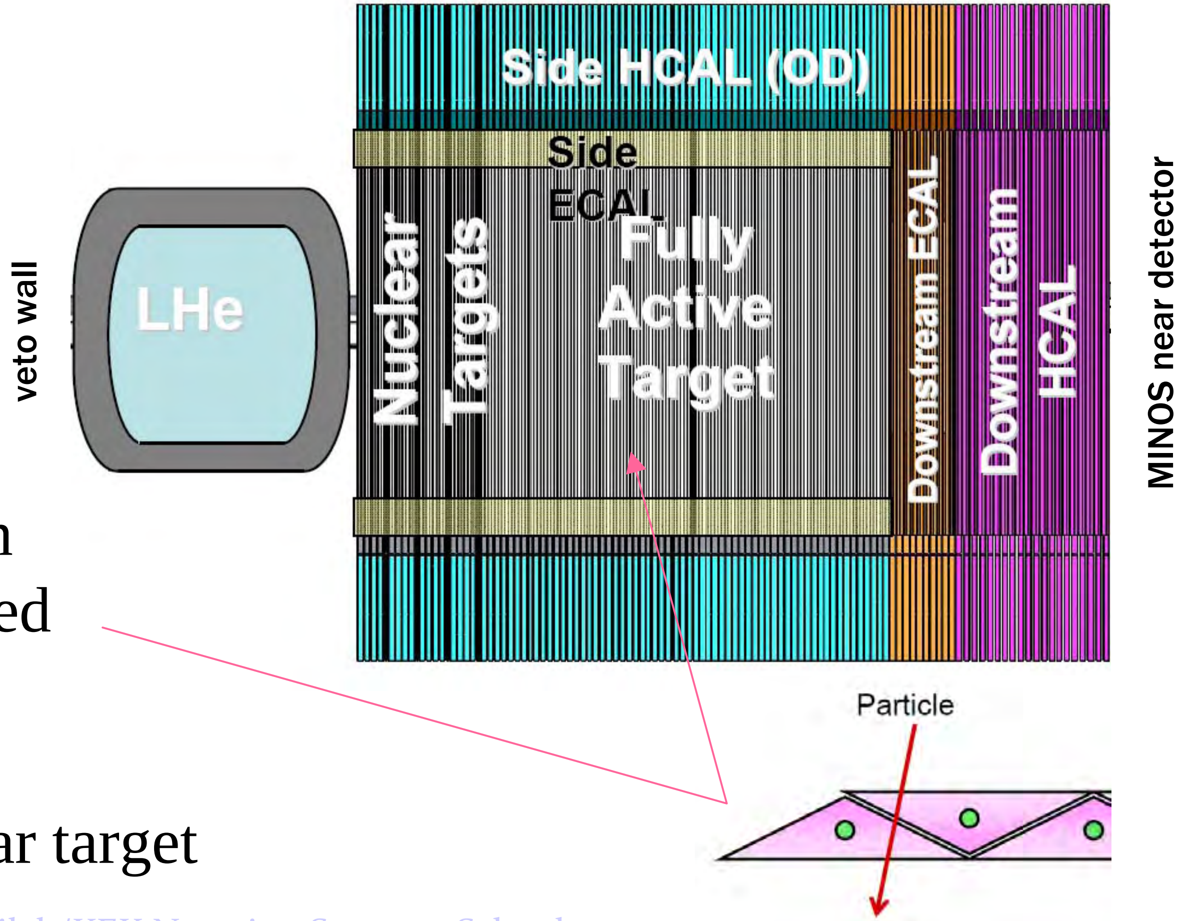
More like a collider detector than a detector of nearly monolithic design:

- Vertex detector
- Tracking region
- Particle identification
- EM calorimeter
- Hadron calorimeter
- Muon spectrometer



MINERνA

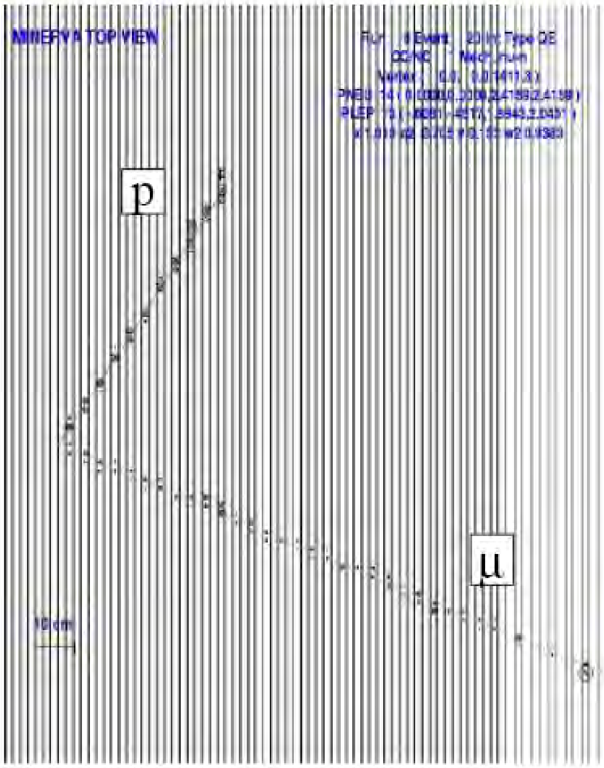
- νN scattering • nuclear effects • single-π production
- coherent-π production • parton distributions
- strange particle production



8.3 ton high resolution (1.7cm×3.3cm) segmented scintillator target

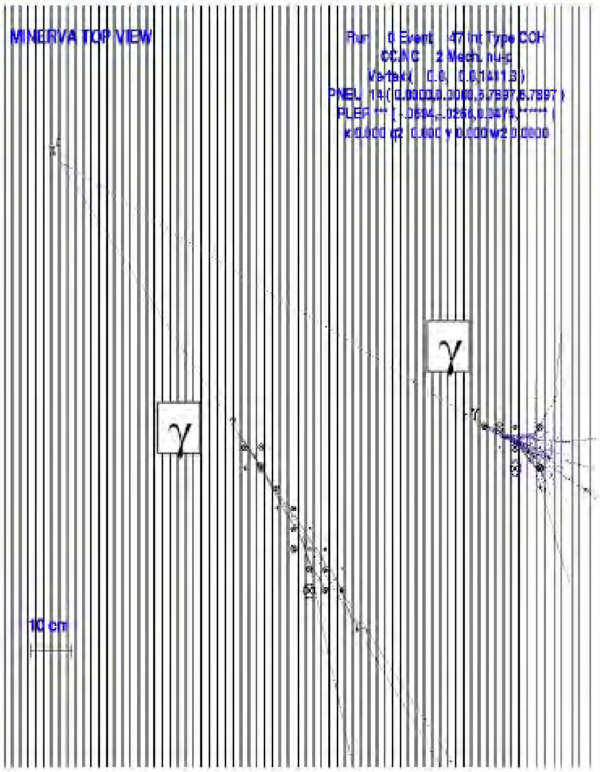
+ 40% ×6.2 ton nuclear target

Simulated MINERνA Events



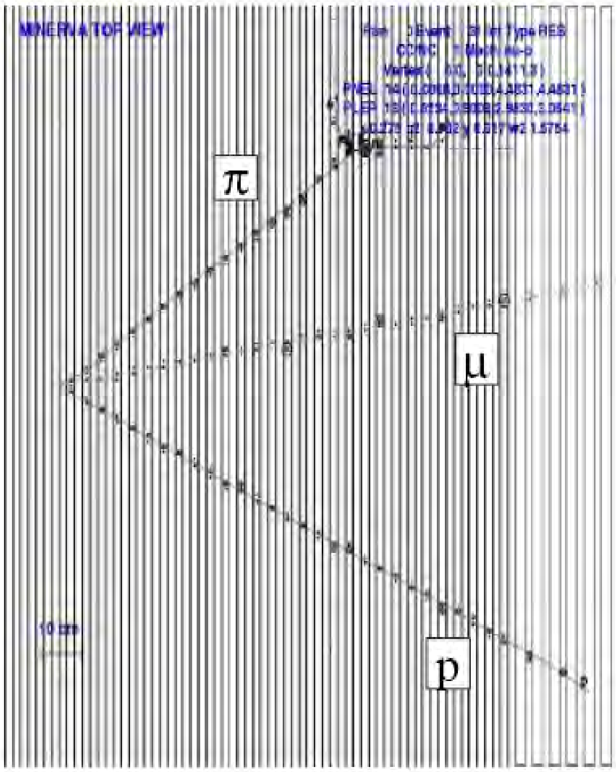
Quasielastic event

$\nu_\mu\, n \to \mu^-\, p$



Neutral Current π^0

$\nu_\mu\, A \to \nu_\mu A\, \pi^0$



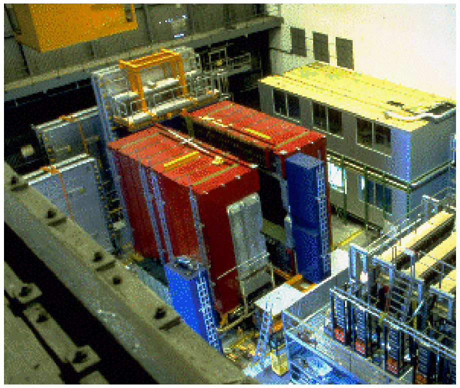
Resonance production

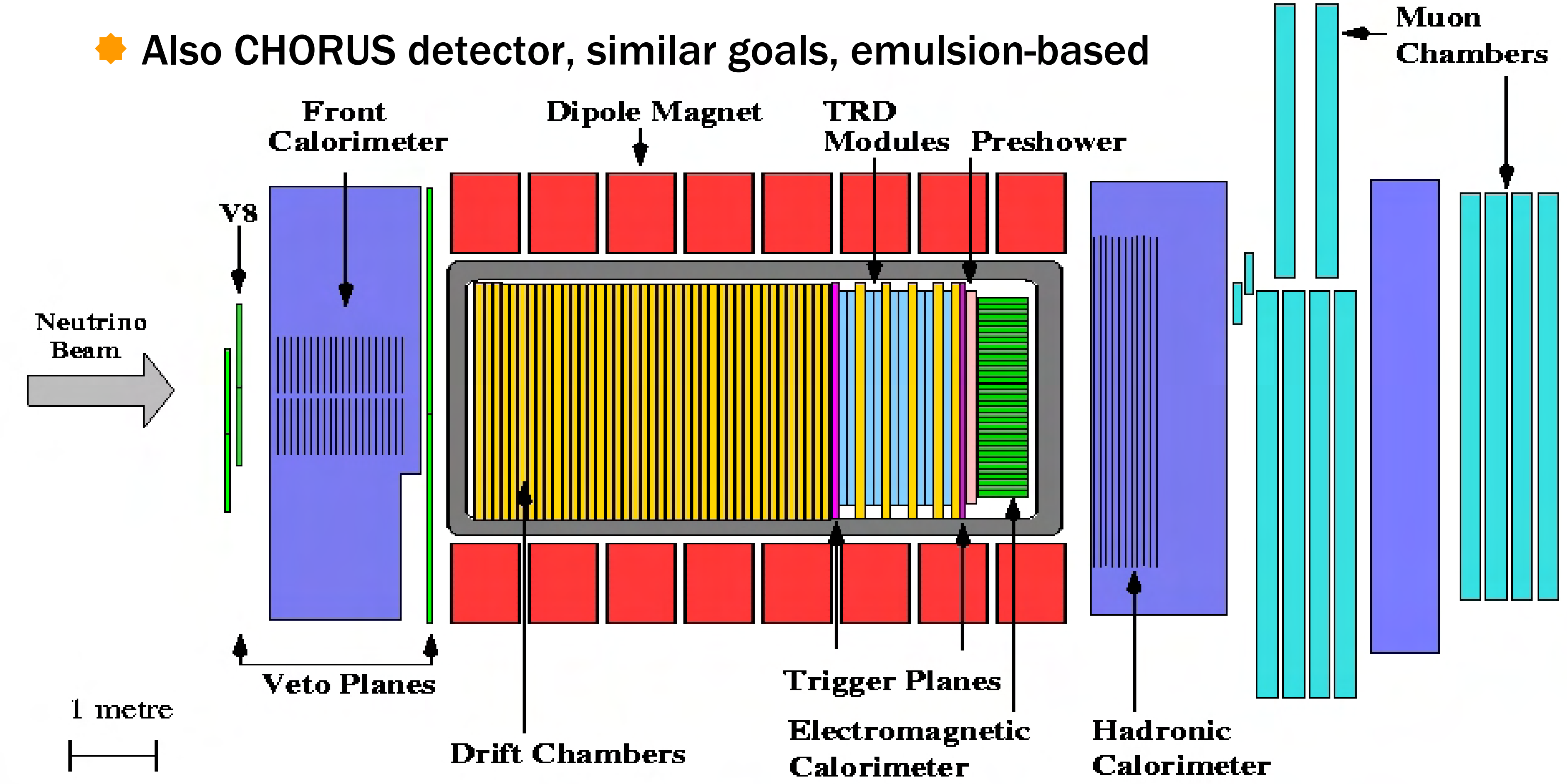
$\nu_\mu\, p \to \mu^-\, \Delta^{++} \to \mu^-\, p\, \pi^+$

J. Nelson, NuINT07

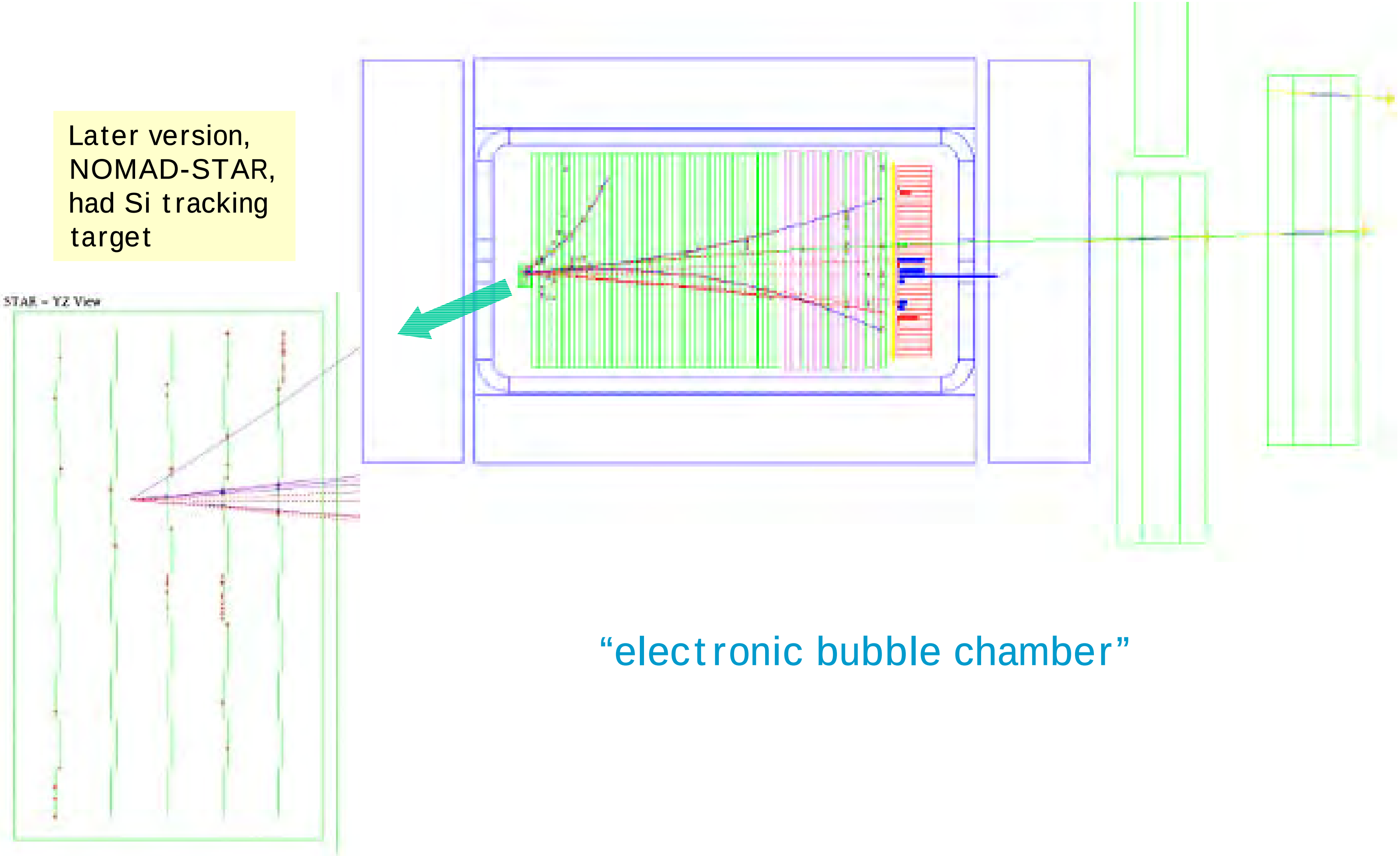
NOMAD

- ν_τ appearance at small $\sin^2 2\theta$ - comparable to quarks
- Δm^2 range 1-1000 eV^2 motivated by Hot Dark Matter
- E_ν ~ 20-40 GeV, L = 600 m at CERN SPS
- Also CHORUS detector, similar goals, emulsion-based





NOMAD Event Display



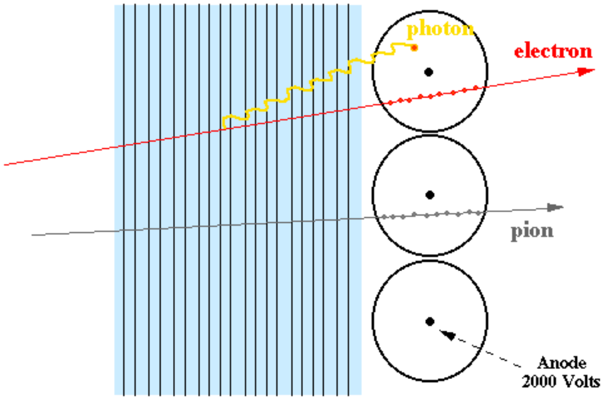
Later version,
NOMAD-STAR,
had Si tracking
target

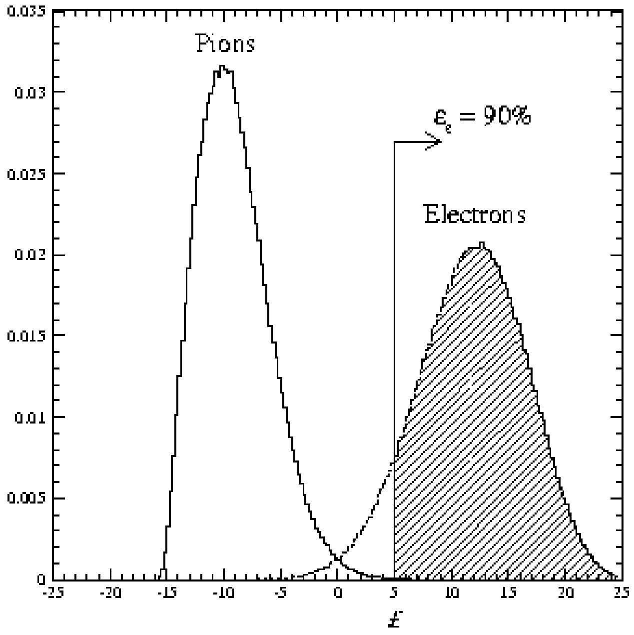
“electronic bubble chamber”

Transition Radiation

EM radiation (X-rays) emitted when a relativistic charged particle crosses boundaries of differing indices of refraction.

- N_γ~1/137 per boundary $\Rightarrow$ stacks of foils
- X-rays counted by gaseous detector e.g. Xe





- Radiated energy $\propto$ $\gamma = \frac{E}{m}$

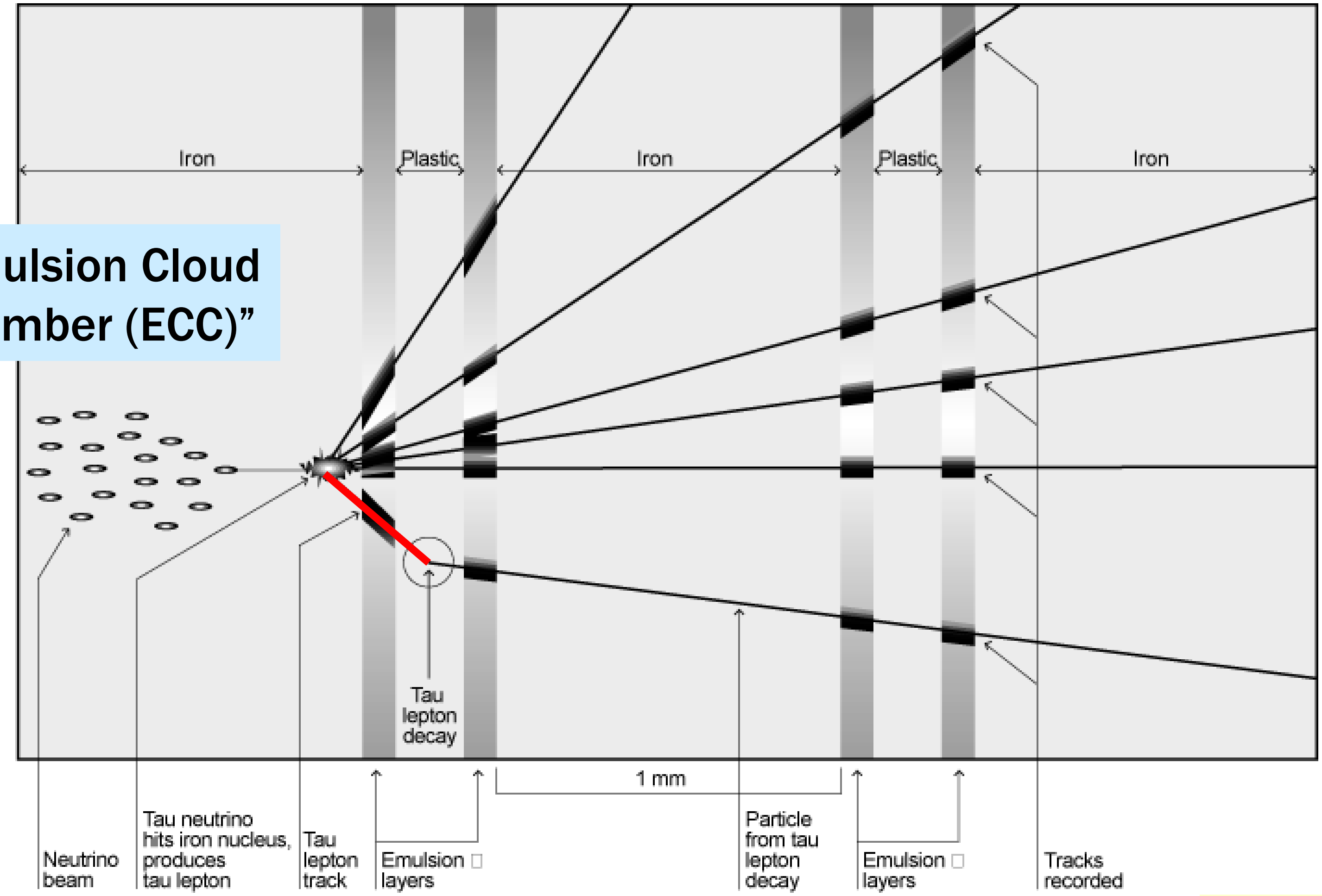
$\Rightarrow$ **Identify high energy (GeV) electrons (γ > few 1000)**

rejecting charged pions (which can shower early in EM calorimeter

Also can be used to estimate energy of high energy muons, eg. 0.1-1 TeV cosmic ray muons in MACRO experiment.

ν_τ was detected … but not by oscillation*

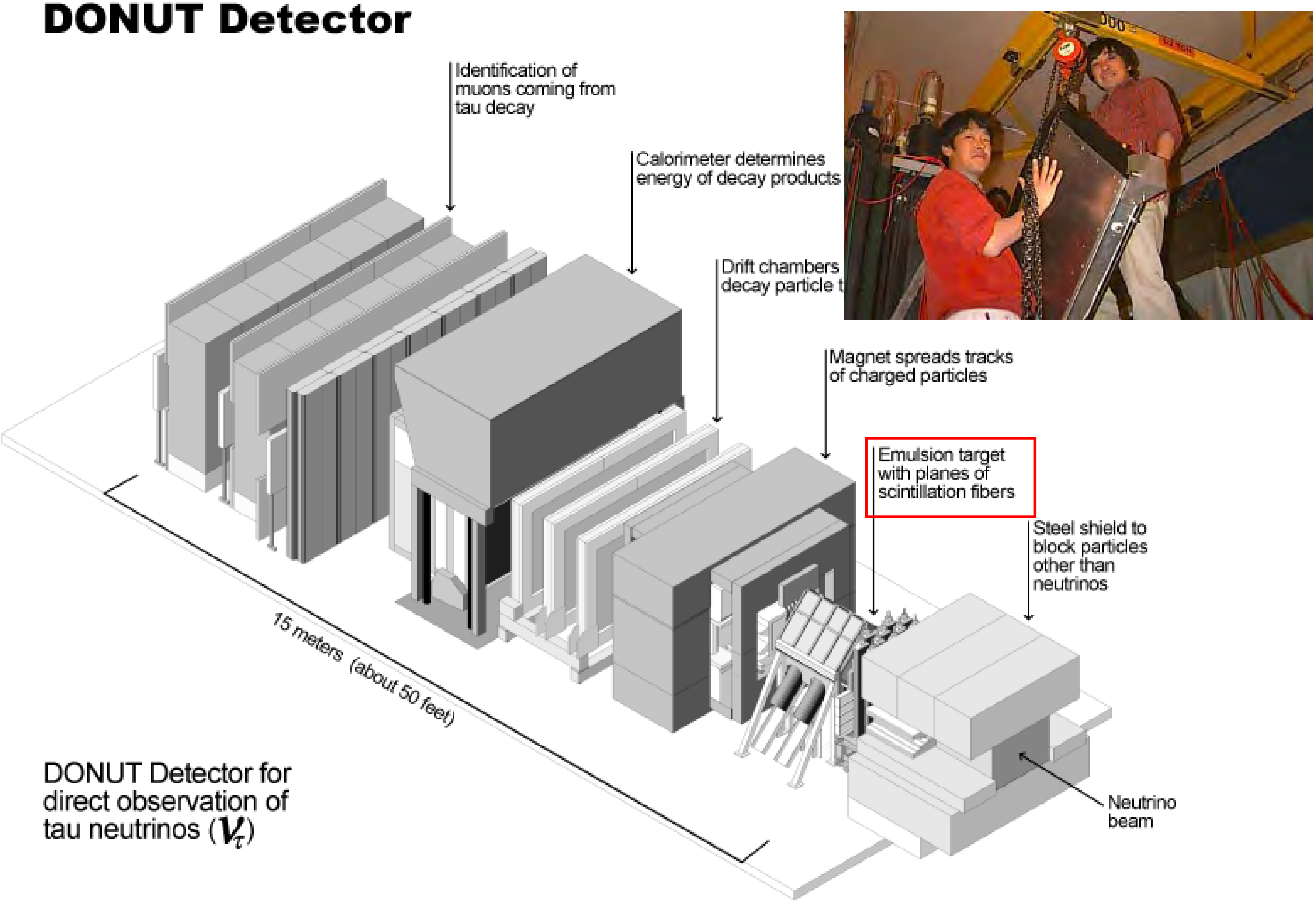
“Emulsion Cloud Chamber (ECC)”



Of one million million tau neutrinos crossing the DONUT detector, scientists expect about one to interact with an iron nucleus.

*Super-K has 2-3σ indications of a statistical appearance of τ-like events

DONUT Detector



Identification of muons coming from tau decay

Calorimeter determines energy of decay products

Drift chambers
decay particle t

Magnet spreads tracks of charged particles

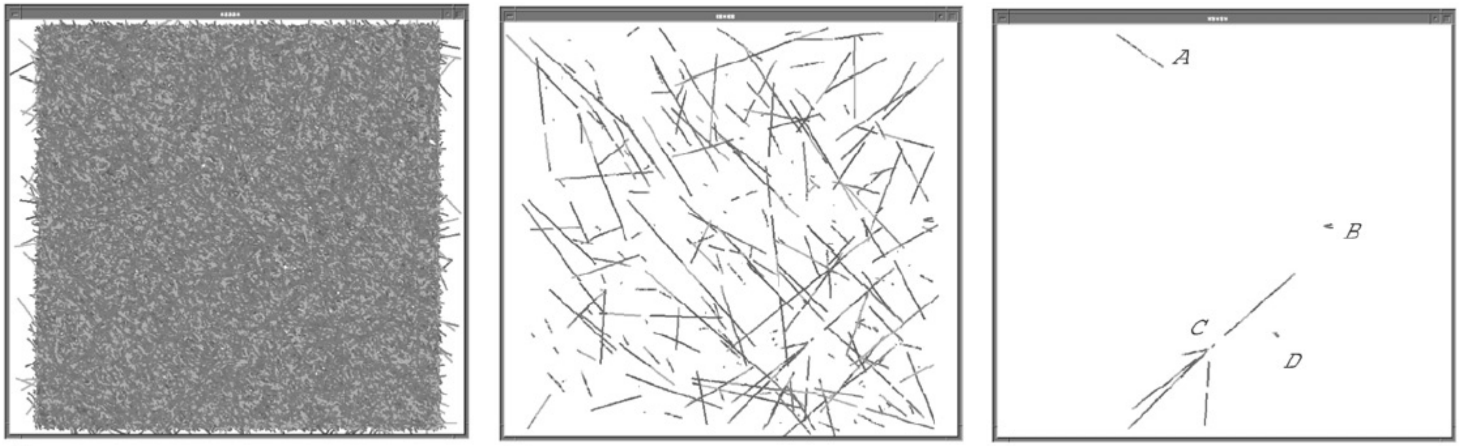
Emulsion target with planes of scintillation fibers

Steel shield to block particles other than neutrinos

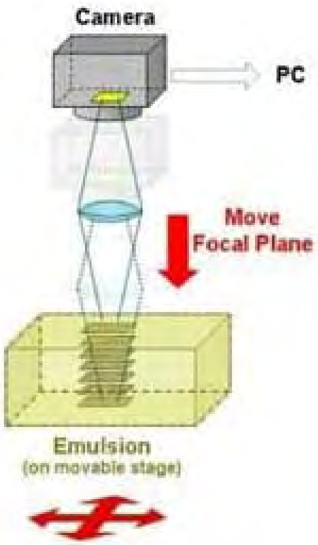
Neutrino beam

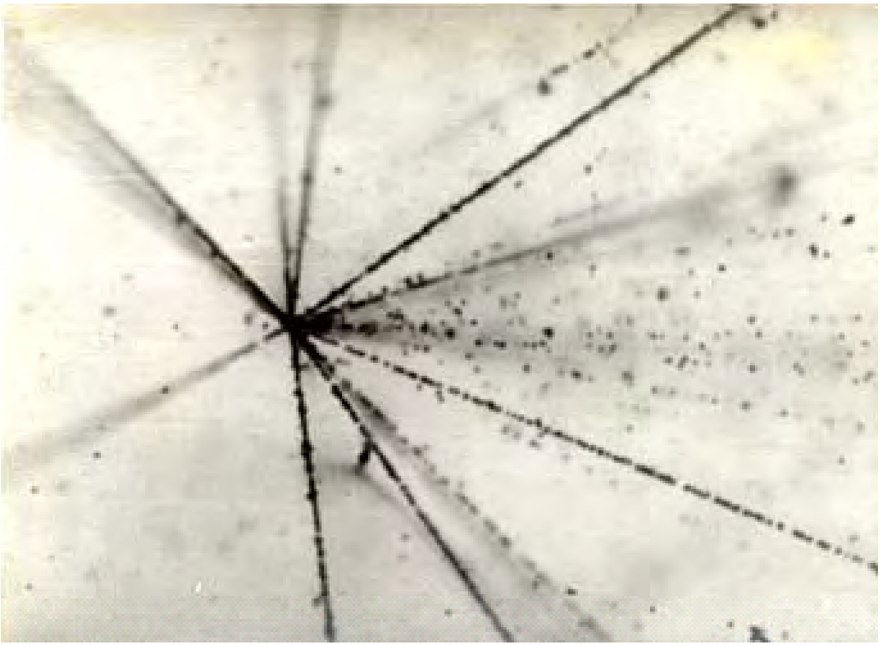
DONUT Detector for direct observation of tau neutrinos (ν_τ)

Nuclear Emulsions



(a) (b) (c)

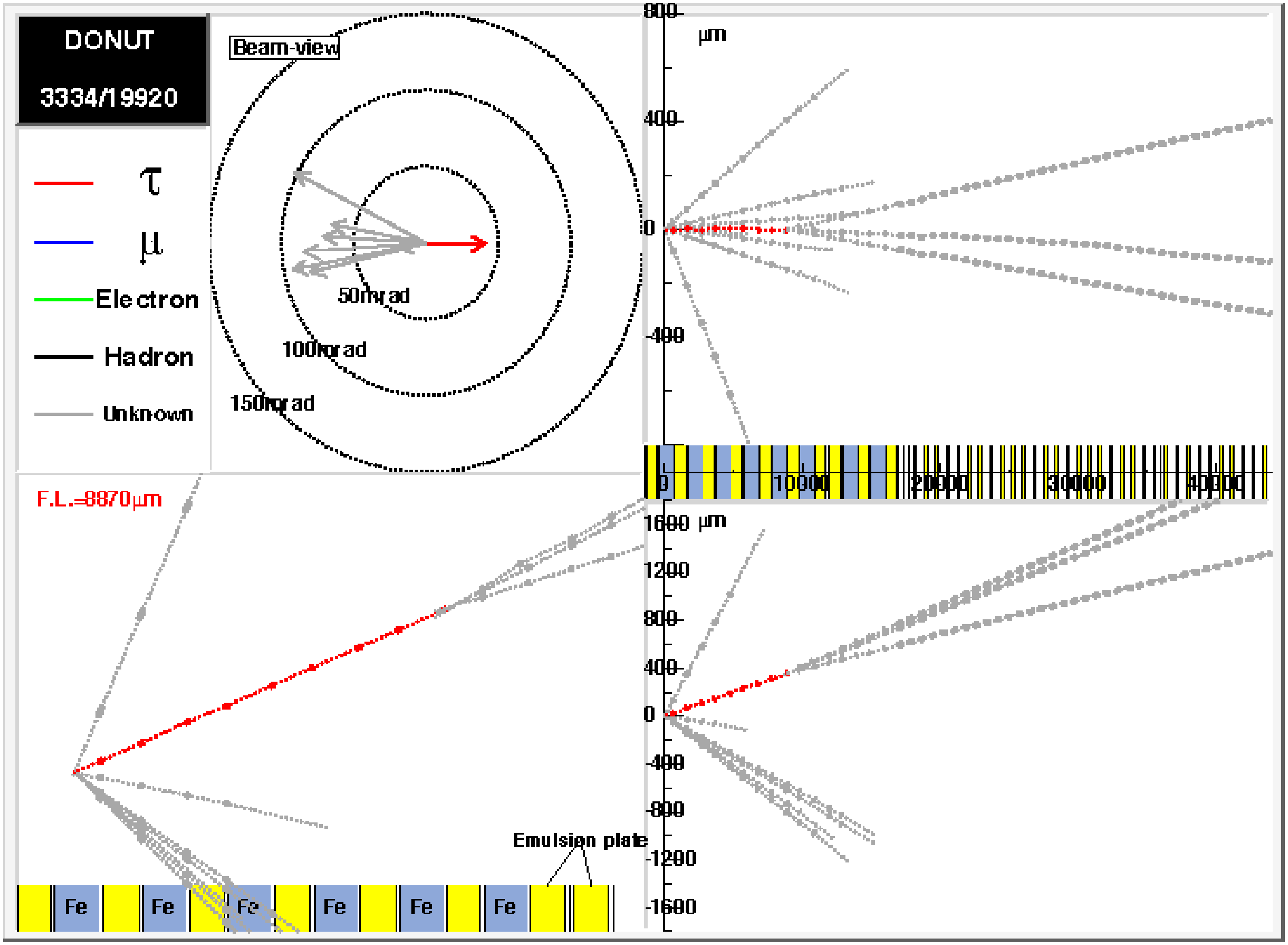




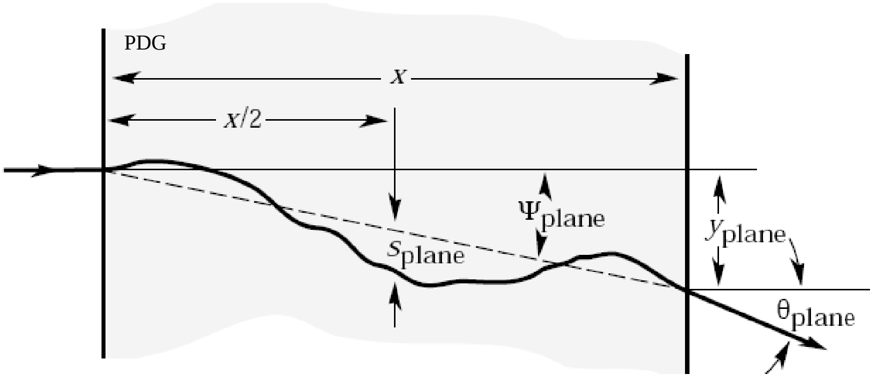
Photograph of emulsion tracks (from CHORUS)

ν_τ Event

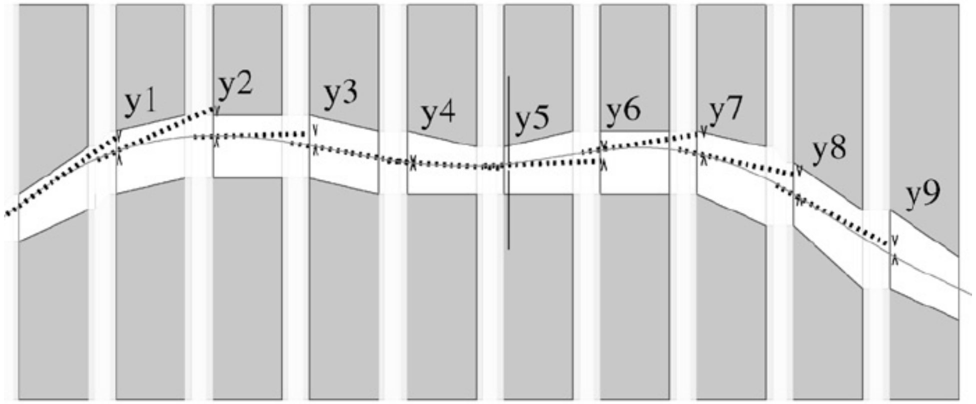
$$\nu_\tau N \rightarrow \tau \; X$$
$$\hookrightarrow 3h \, \nu_\tau \; (X)$$



Multiple Coulomb Scattering



$$\theta_{RMS}^{plane} = \frac{13.6}{\beta c p} z \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \ln \frac{x}{X_0} \right]$$



Important experimental constraint:

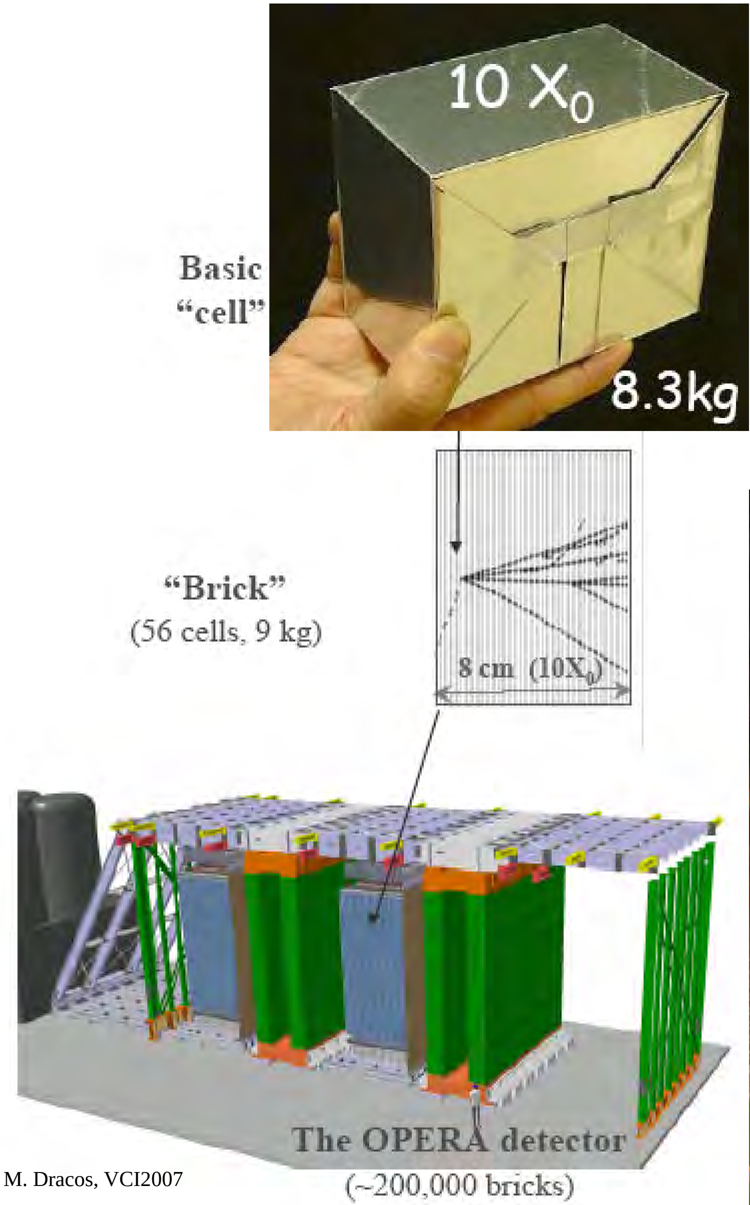
- **He in ν decay volume**
- **Low *Z* (Be) collider beam pipe**
- **Kalman filter for improved track reconstruction**
- **Momentum estimate (DONUT, MACRO)**

Tested with π tracks in test beam -

Resolution ~ 30%

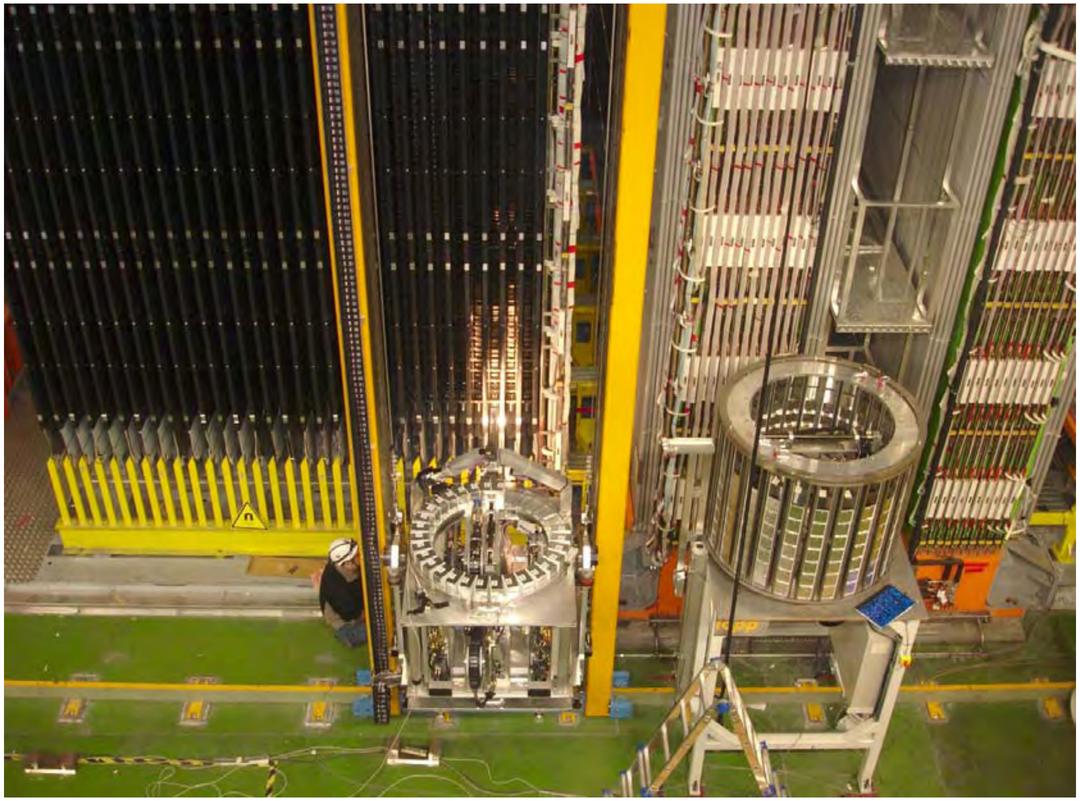
OPERA

ν_τ appearance in ν_μ beam
(atmospheric Δm^2)



M. Dracos, VCI2007

1.8 kton



What have I skipped?

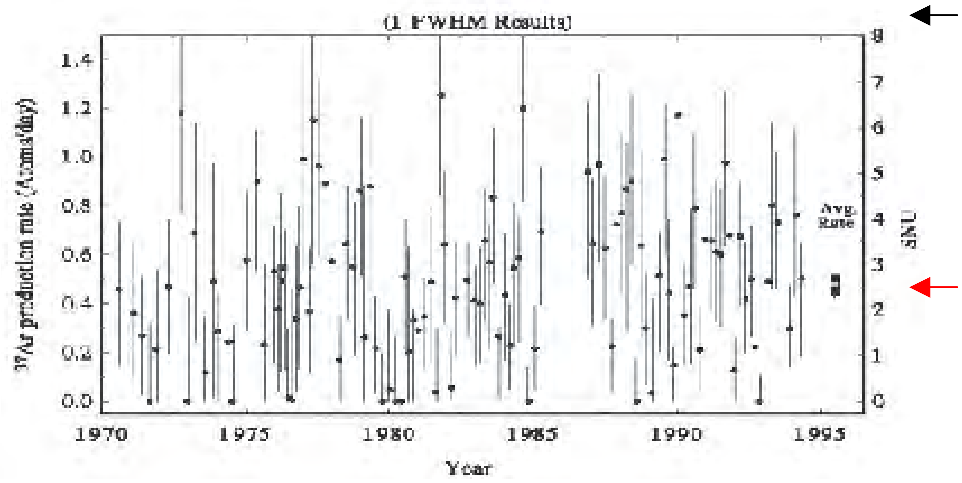
- Highest energy detected - neutrino telescope AMANDA, IceCube (see F. Halzen lecture)
- Lowest energy detected - *pp* solar (GALLEX/GNO, SAGE) also ^{7}Be: Ray Davis Homestake Mine experiment

1995 Nobel Prize: R. Davis
& M. Koshiba (Kamiokande)

615 tons of C_2Cl_4
(dry cleaning fluid)

1500 meters depth

Individual Ar atoms extracted and counted by radioactive decay ($\tau \sim 35$ days)



$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$

Back to inverse beta decay again!