Nuclear Emulsions – Kernspuremulsion – From Past Glory, Demise to Renaissance?

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OUTLINE

WHAT IS IT?

Half Silver Halide, Half Gelatin (by volume)

OUTSTANDING RESULTS:

π, Charged K's, Hypernuclei, $\tau - \theta$ Puzzle

WHY PEOPLE STOPPED USING IT?

Too finicky, Labor intensive, Trigger?

WHY USE IT AGAIN?

Emulsion Cloud Chamber, Automatization

WHAT IS IT?

Usually equal parts by volume of silver halide crystals which are about 0.3±0.05 microns in size (Ilford G5, C2 for ex.)

embedded in an organic matrix material, composed mostly of gelatin with water, glycerol etc. added to form a gel (density approx. 1.29 gm/ml at 58% R.H.)

Gelatin, hydrolyzed from calf or pig hides, not only determines the mechanical properties of the emulsions, plays a strong part in the in the photochemical process as it is amphoteric, permits penetration of solutions, is insoluble in alcohol etc.

HOW DOES IT WORK?

An ionizing particle crossing a crystal, leaves in a state whereby it develops faster than the innocent bystanders.

After development, followed by fixing and washing away of the undeveloped crystals, we are left with a trail of silver grains in a transparent medium.

Use a 1000x microscope to measure the grain density distributions, scatters both large and small, emissions and total length of the track, noting especially the topology of the ending.

PRACTICAL CONSIDERATIONS

Nuclear emulsions are usually made in thin films, from about 20 to 1000 microns, of sizes up to 50cmx50cm.

They are usually mounted individually on glass plates, and placed on microscope stages for examination. At the most convenient magnification for an examiner of the pellicle, the thickness of the pellicle should not exceed 600 microns (even then one often has to change objectives two to three times).

Of course, the track does not necessarily confine itself to stay within a 2-D layer only 600μ thick, hence the necessity to make stacks from 40 to 250 pellicles high.

HOW DOES ONE TRACK A PARTICLE ACROSS?

Remember that after exposure to the particles, the emulsion stack has to be taken apart, the pellicle processed individually:

(1) mount each pellicle on glass, Ilford glass coated with gelatin-like material, adhere emulsion to glass in cold water containing also wetting agent, handle on edges, put both through a wringer to get rid of bubbles without distorting emulsion, allow time to form bond,

(2) develop in amidol, or D-19 if thin pellicles, grain density dependent on temperature (25°C),

(3) stop by lowering temperature and lowering the PH of the solution (5° C, 3.2), about 2 hrs,

(4) fix, *i.e.* dissolve the silver halide in “hypo”, sodium thiosulfate solution with emulsions facing downward, at medium temp.(19° C),

(5) dilute and wash, after the fixing which took hours, the emulsion is quite swollen, the procedure of dilution and washing is very delicate (punch blisters) and lengthy, days...

(6) drying, soak in successive baths of increasing concentrations of alcohol to water, say 50%, 75%, to 90% alcohol with 5% of glycerine added of 2.5 hrs each. Then remove plates from tanks until thickness is re-established. INTOXICATING!!!

A database of shrinkage is maintained for all pellicles.

ANSWER: FIRST MARK THE SURFACES

Now we have to reassemble the stack so to speak, so that the microscope examiner, usually called "scanner" can still follow a track across a now processed (shrunken?) pellicle, like a diver trailing a particular shark or seal as it plunges down or swerves up during its passage in a stack.

The earliest method was to place X-ray marks at the edges of the stack, before the stack's exposure to the particles. This neglects all the surface distortions during processing. My first "mark" in HEP was literally from my head, i.e. testing making pressure reference marks crossing two single strand of human hair between pellicles as the stack is assembled.

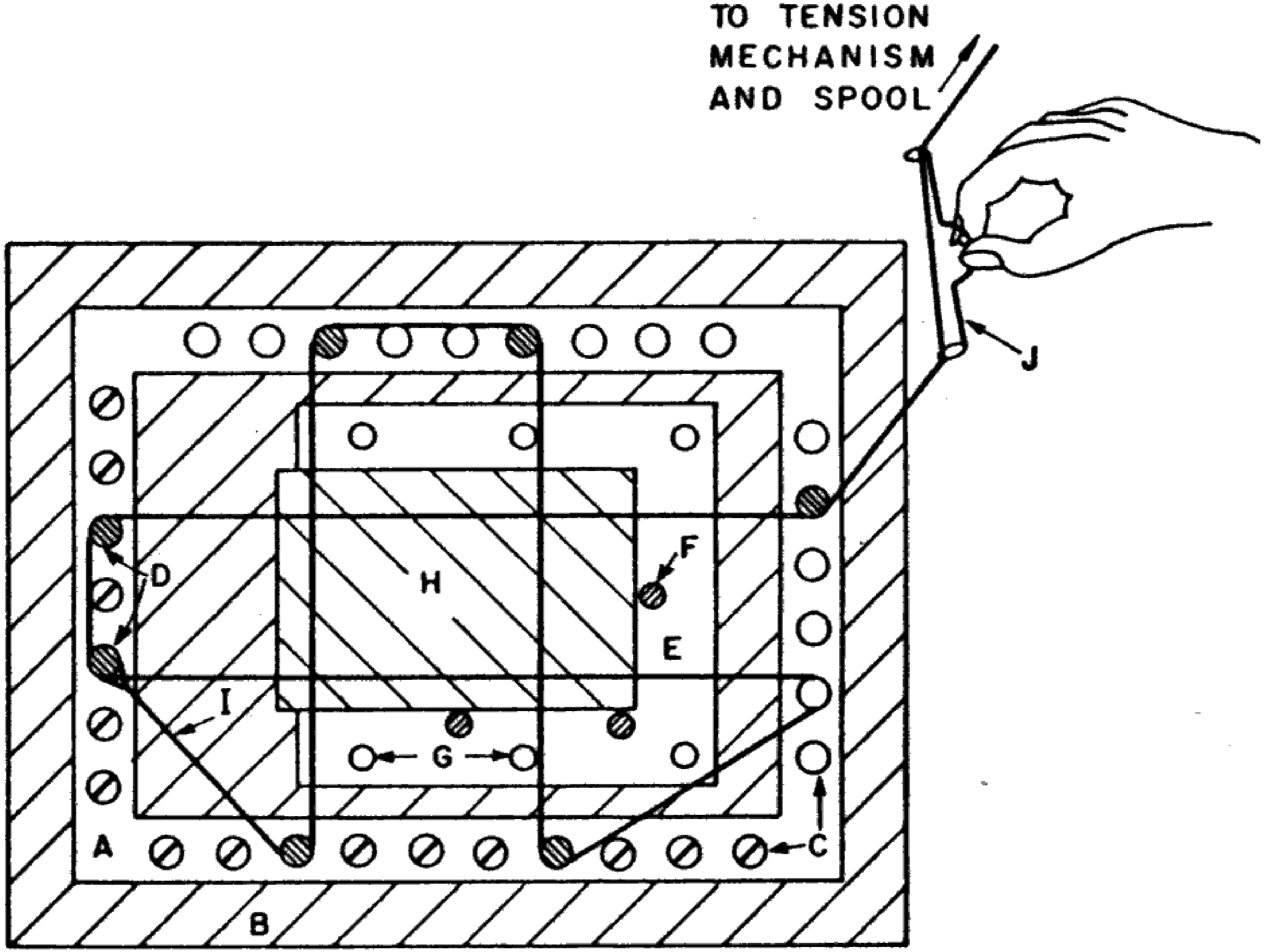


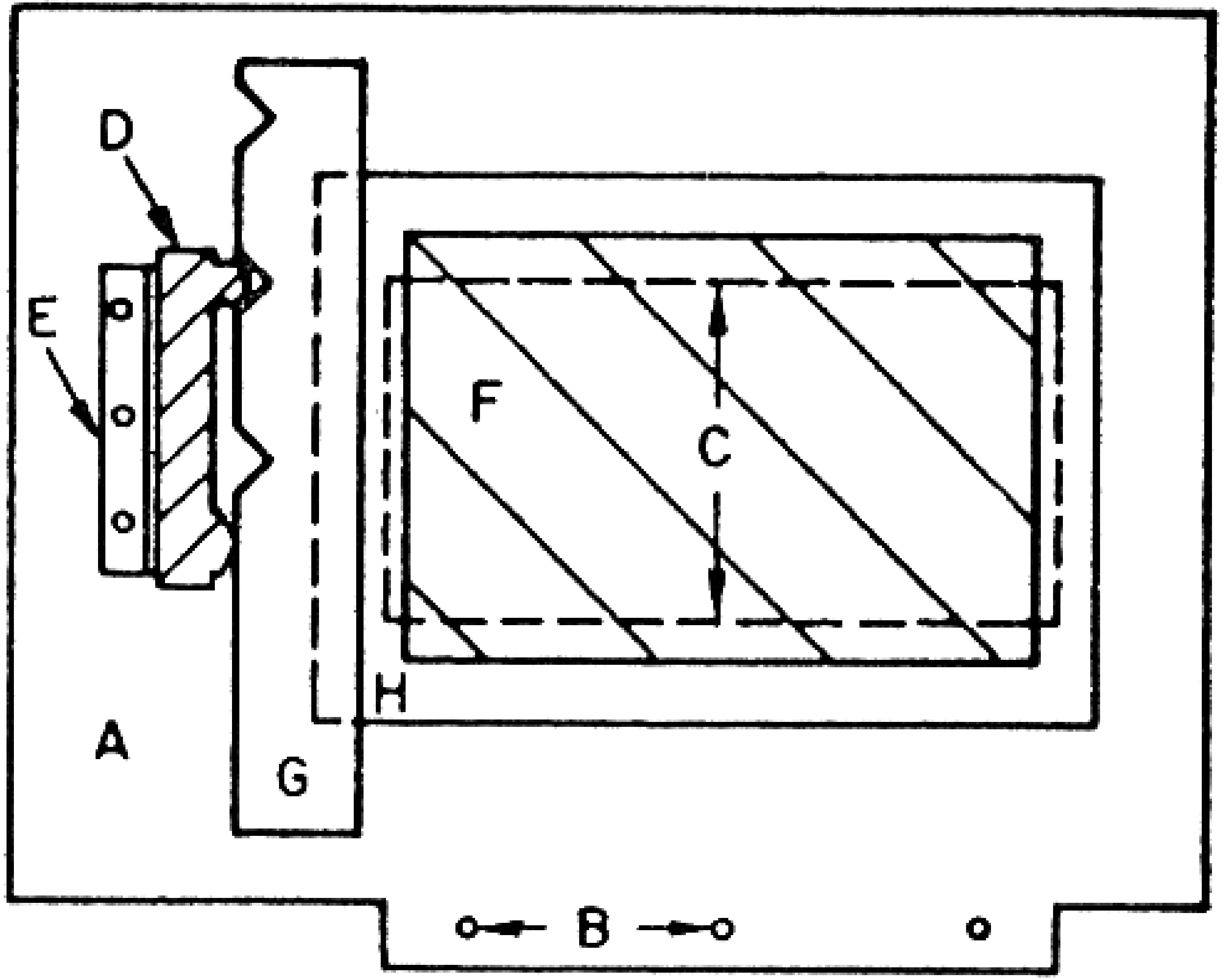
FIG. 1. Method of inserting nylon threads between the pellicles of a nuclear emulsion stack.

After processing only the cross marks show up at the two interfaces as 30 μ diameter dots.

THEN LINE UP THE PLATES

The scanners have to be able to quickly mount and unmount pellicles in such a way they can follow their "prey" automatically.

So we modified the stage to add an alnico magnet with notches, which will hold steel strips with V-shaped which are glued individually on the glass plates with emulsions mounted on them. The gluing of the steel strips are done under low magnification. Its eventual write up is also my first RSI paper: Rev. Sci. Inst., **30**, 244 (1959).


D
E
F
C
H
A
G
B

WHY PEOPLE USED IT?

As seen from the previous discussion, we are dealing with COMPACT objects, as we'll see a small volume can contain a great deal of information about the radiation crossing it.

It allows for a three(four) dimensional study of the event, no triangulation, shape tells you the time evolution as well.

It is a hundred percent live or a long memory, essentially records all the tracks during its exposure time, good for collecting rare events.

CHEAP!!!, about 1$ per cm^3.

No need for high tech, nor super trained staff.

CONCLUSION: GOOD FOR DISCOVERIES.

Powell and Occhialini had been working with Ilford to improve photographic emulsions. The first new batch they left at various high altitude cosmic rays stations.

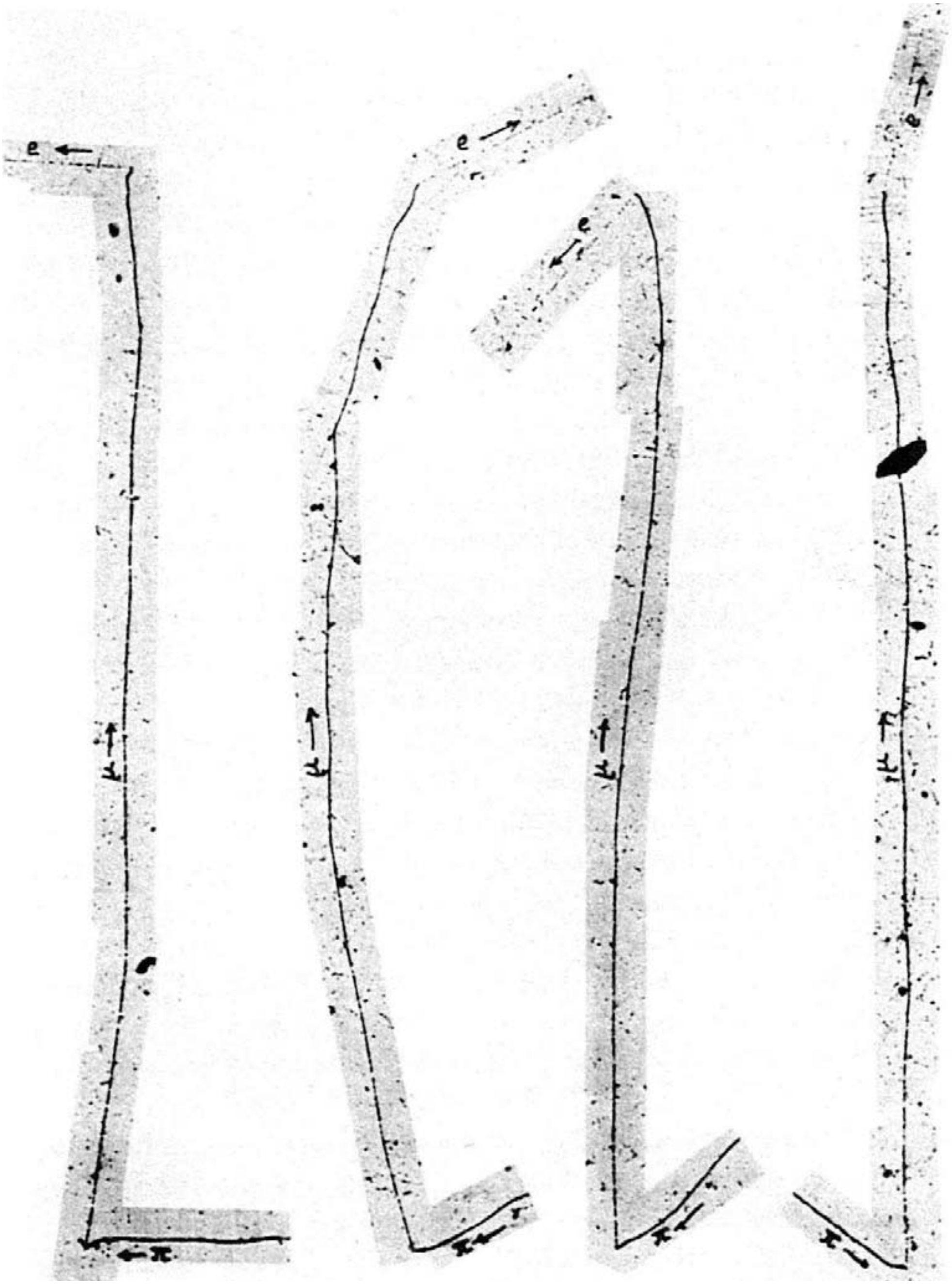
After exposures of weeks, they found a group of tracks which showed an increase of grains and scatters, signalling a stopping particle, followed by another track which slowed and stopped. The primary particle was dubbed a pion, had a mass of about 350 electron masses, m_e.

The daughter, dubbed the muon, had a mass of about 200-300 m_e. All the secondaries had identical path length, circa 600 microns, hence had the same kinetic energy, signifying a two body decay, the other secondary particle was invisible (neutral).

Meanwhile, little “stars” were also observed in nuclear emulsions at other labs, signifying nuclear interacting “mesotron”’s existed as well.

Thus two kinds of negative “mesotrons” coexist: the negative pion interacts strongly with matter, the negative muon decays.

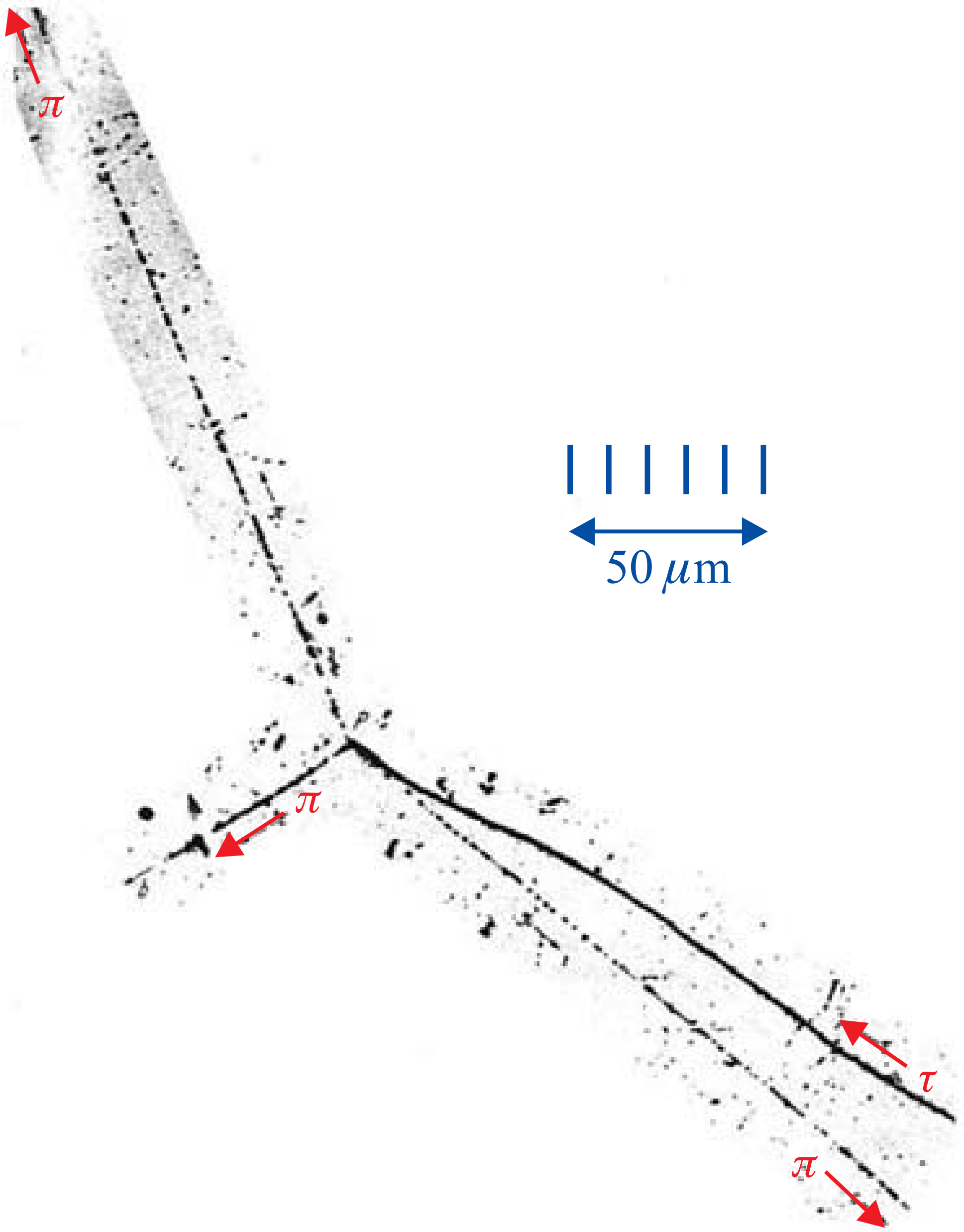
In short, the Yukawa particle was found.


e
e
e
e
μ
μ
μ
μ
π
π
π
π

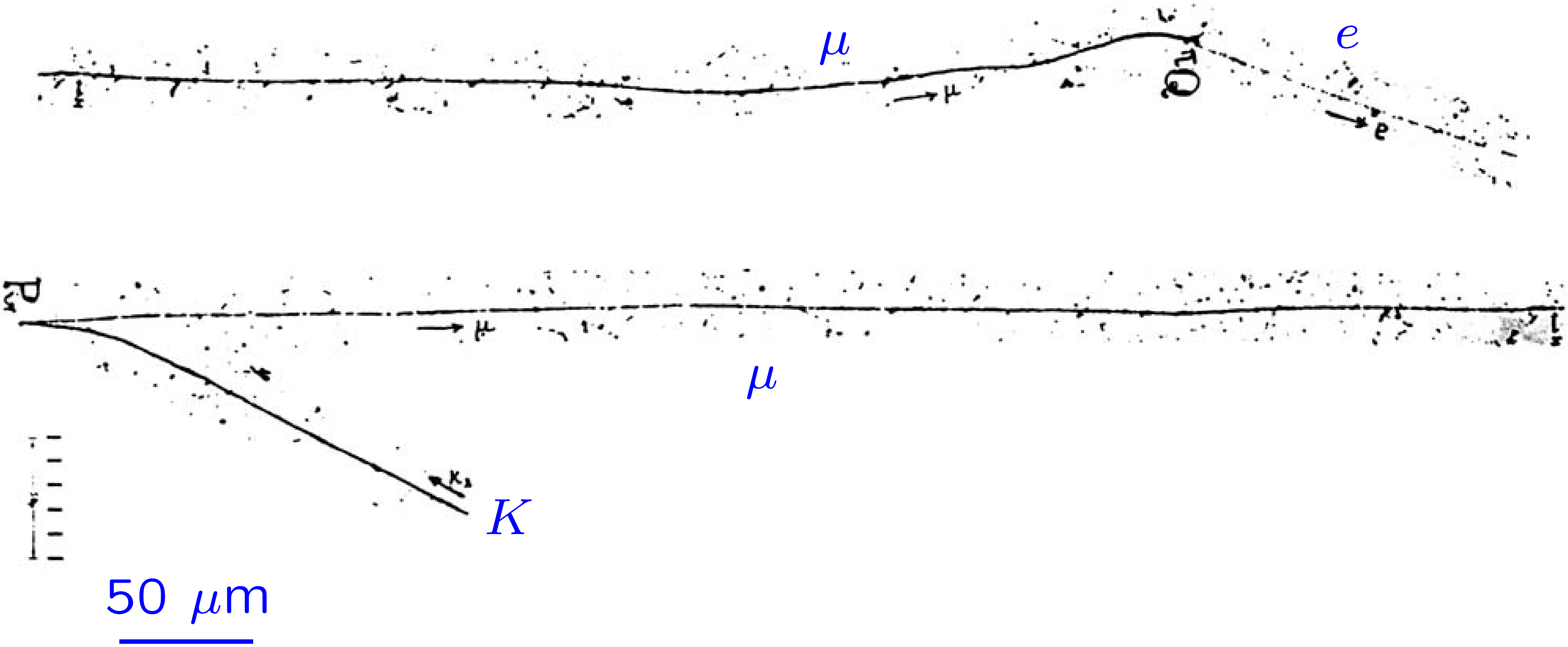
During the late 1940's and early 1950's, research groups multiplied as fast as did new event types. There was keen competition between cloud chamber and nuclear emulsion groups, for ex. a 960 m_e particle was seen to decay clearly into three pions in nuclear emulsions in 1951

To clarify the nature of these new objects, it became imperative to have man-made sources for them, which meant high energy machines,

In fact the first production of π^0's was observed at LBL in 1950, strange particles were copiously produced at the Cosmotron in 1953.


π
π
τ
π
50 μm

$K \to \mu + \nu$



NOW ONE CAN MAKE DETAILED STUDIES!

With man made beams one is no longer at the mercy at the Cosmic Ray prescribed cocktail of particle mixtures, one can now DESIGN experiments to measure the properties of these STRANGE particles.

I'm going to describe one such experiment because it demonstrates the analysis techniques, is my first Physics Publication, Phys. Rev. 108, pp.1561, 1957 (one serves a long apprenticeship then, that was after I had worked three years in the group), and played a significant role in the discovery of Parity Violation in Weak Interactions: namely, the $\tau - \theta$ puzzle.

MAKE TWO STACKS OF EMULSIONS...

one from 49 pellicles of dimensions 4”x4”x600μ, Stack A, another with 149 pellicles, stack B. Note stack B (8.9cm emulsions) is three times thicker than stack A (2.94cm).

Fly stacks from New York to Berkeley,

learn about the K^+ beam made from 6.2 BeV protons on Ta target.

Place stack A 161” downstream (about $1.5\times\tau_{K^+}$), and stack B 233” (about $2.1\times\tau_{K^+}$) downstream from target.

Expose stacks to about 5000 K’s, (there are protons contamination too).

Fly back to N.Y., undo stacks, process, mount on glass etc. etc.

DETERMINE KAON FLUX

Kaons (and pions and protons) have an average momentum of 365±10 MeV/c^2. Pions are exactly minimum ionizing at the entrance of the stack, establishing the $\mathrm{d}E/\mathrm{d}x]_{\mathrm{min}}$ ≡min standard. They become grey about at about 2cm residual range, and visually are distinguished from the protons which are discarded.

Grain count kaon tracks, follow each to their end, look for secondaries must account for every single ending!

stack A has 240 K/m^2, stack B has 130 K/cm^2.

Each scanner can study 13 kaon endings per day.

The fluxes determine the lifetime, τ, of these kaons.

CLASSIFY THE SECONDARIES...,

Grain count periodically.

For ex. a 109 MeV pion ionizes 1.18×min, 92 MeV pion 1.25×min, 53 MeV pion has 1.57×min.

Grain count is also used to determine mass, for ex. at 1.25×min, a muon would have 70 MeV.

Measure the range (including DIP angle corrections).

A charge kaon which decays into two pions, called θ^+, will yield a pion of range 11.7cm (107.7 MeV)

A charged kaon which decays into three pions, called τ, will yield a charged pion whose maximum range is 3.95cm (53.3 MeV)

When faced with an anomaly, do detailed scatter measurement between successive 20 μ chords.

ANOMALOUS K^+ DECAY

Out of 5000 kaon endings examined, their single charged secondaries all have ranges consistent with the known two body θ^+, K_{μ_2}, three body τ' and K_{μ_3} decays, except for one:

IT HAD A RANGE OF 4.8 cm!!! and then decayed into a muon.

What could it be??

(1) $K^+ \to \pi^+ + \pi^0 + \gamma$? Dipole transition

(2) or $K^+ \to \pi^+ + 2\gamma$? 1×10^{-6}

(3) or $K^+ \to \pi^+ + \nu + \bar{\nu}$? no charged lepton

Much agitation, discussions with “young” theory colleague R. Dalitz, calculations on Monroe...

this is tex

Assuming mode (1), one pion with energy of about 60 MeV (γ energy between 55-158 MeV) out of 5000 is consistent with expected rate. (PDG $(1.8 \pm 0.4) \times 10^{-5}$).

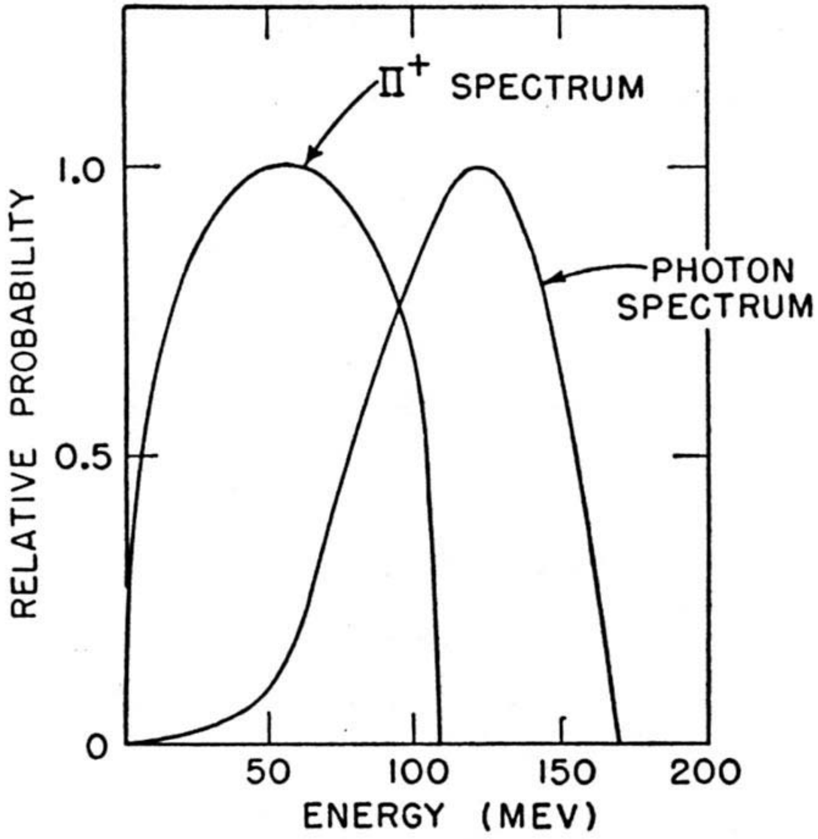


FIG. 1. Photon and π^+ energy spectra for the decay mode $K^+ \rightarrow \pi^+ + \pi^0 + \gamma$ using the dipole matrix element in the paper of Dalitz.[4]

Proof of $\pi\mu$ decay "junction" by gap count:

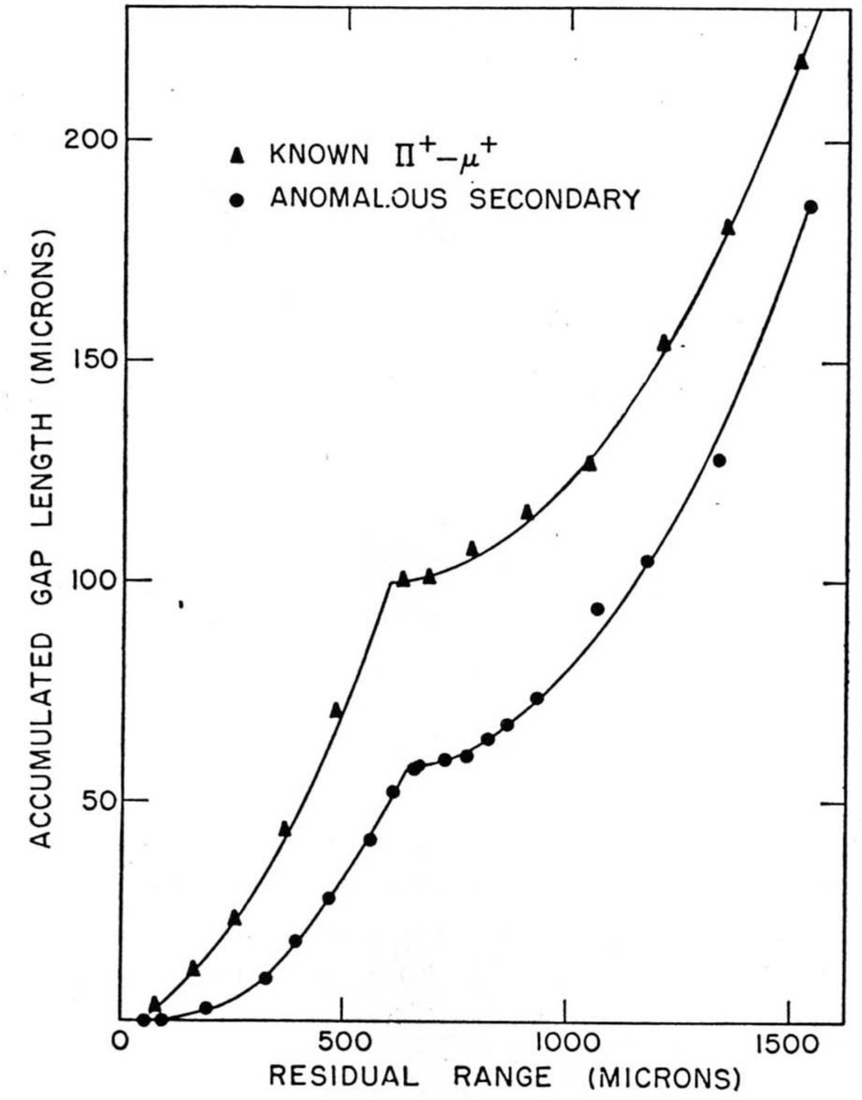
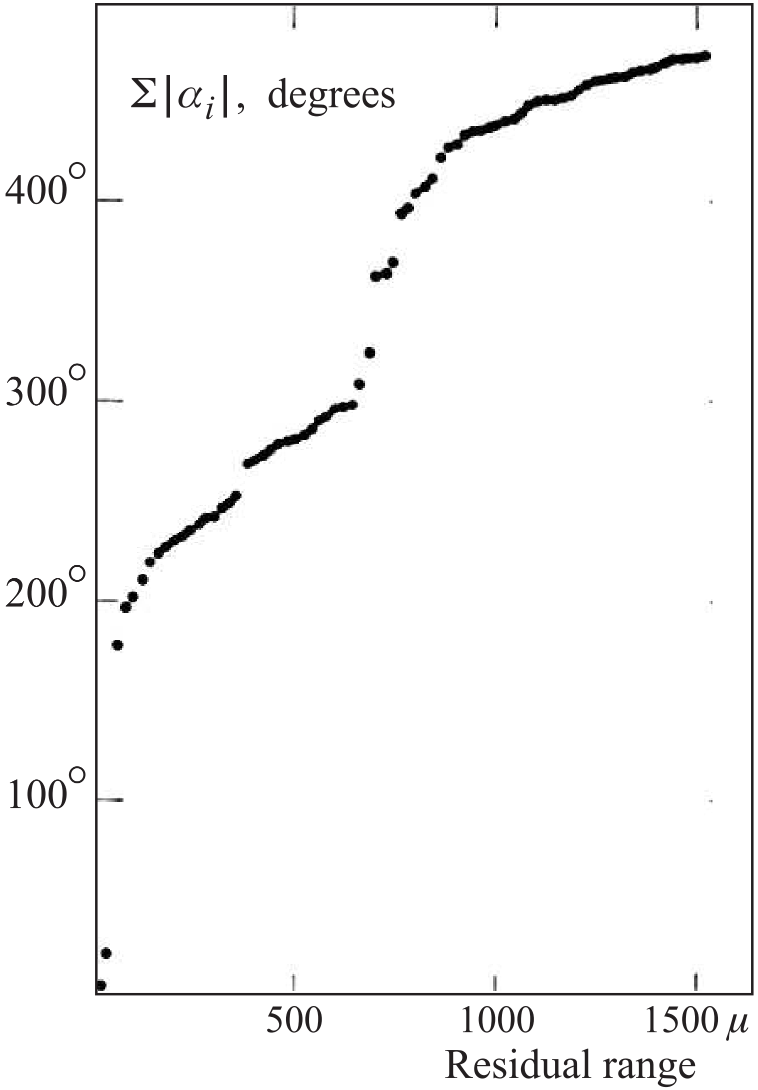


FIG. 2. Accumulated gap length *vs* residual range for a known π-μ decay and for the anomalous secondary.

Proof of $\pi\mu$ decay "junction" by absolute value of scattering angles versus residual range:



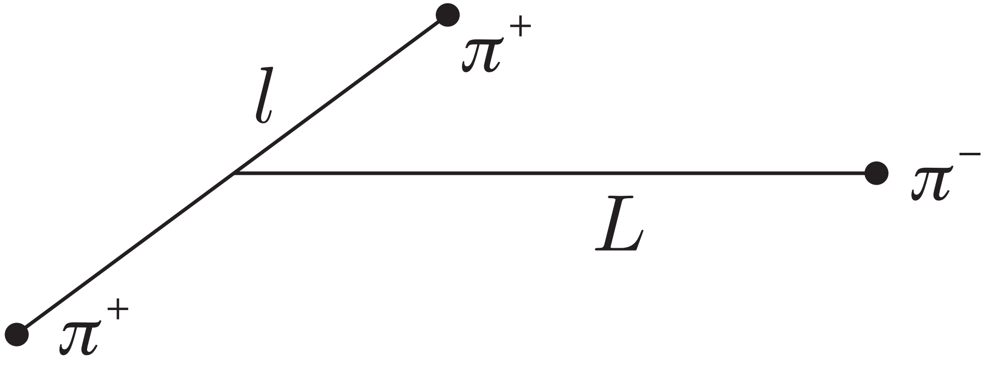
THE $\tau\theta$ PUZZLE

From these detailed measurements of lifetimes, mass and decay spectra, one would conclude that the τ and θ are the different decay modes of the "SAME" particle, so ought to have the same Spin and Parity, J^P.

(1) First consider the θ, its neutral member decays into a pair of charged pions, not to $\pi^0\gamma$, hence must have 0 spin, 0 - 0 transitions not allowed.

For the charged θ, whatever its spin, its parity would be $(-1)^J, 0^+, 1^+, 2^+$.

(2) Now consider the τ^+, lets define the relative angular momentum of the two π^+ to be l, which must be even, and the orbital angular momentum of the π^-, with respect to the π^+'s c.o.m. L, then the spin of the τ^+ is the vector sum of l and L, could be 0, 1, 2. . .



DALITZ PLOTS

the energy measured for the three pions from a τ decay is usually plotted on a two dimensional plot, the ordinate is the energy of the third, i.e. unlike pion, and the abscissa is the difference of the energy of the two like pions.

The decay rate for the three body decay is proportional to $|M|^2 d(E_1 - E_2) dE_3$, where M is the transition amplitude.

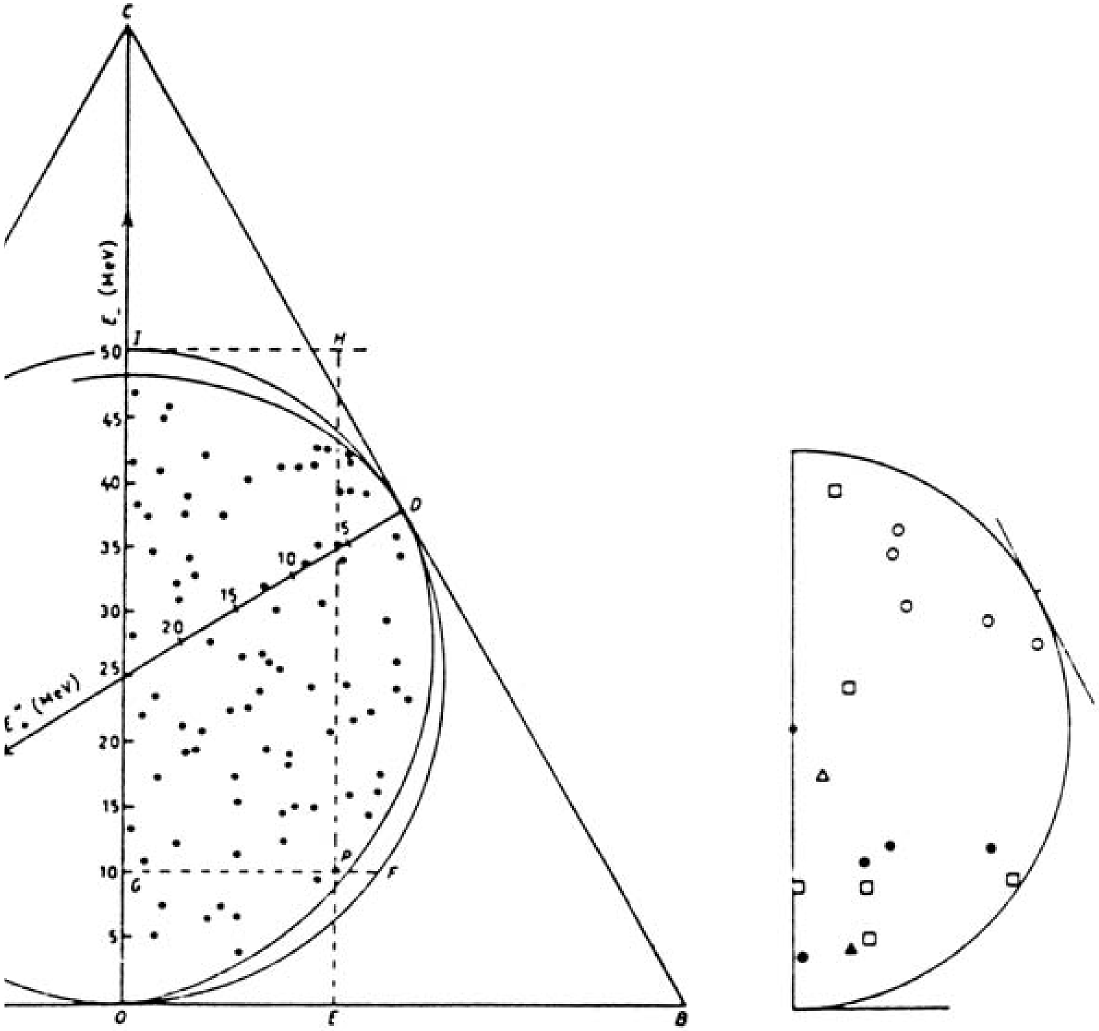
(a) If the τ has spin 0, M is a constant, and events fall evenly on the Dalitz plot.

(b) If the τ has spin 1, the amplitude must be linear in its polarization vector $\vec{\epsilon}$, and must be the dot product of $\vec{\epsilon}$ with a vector made from the various pion momenta:

(i) $\vec{\epsilon} \cdot \vec{p}_3$, $P = (-1)^3 \times (-1)$, $J^P = 1^+$.

(ii) $\vec{\epsilon} \cdot (\vec{p}_1 - \vec{p}_2)\ \times \vec{p}_3[(\vec{p}_1 - \vec{p}_2) \cdot \vec{p}_3]$,
$P = (-1)^4 \times (-1)^3$, $J^P = 1^-$.

In both cases, the amplitude should decrease as p_3 goes to zero, which is CONTRARY to what was seen:



the τ's $J^P = 0^-$!!! (not 0^+ as for the θ^+).

LED TO LEE and YANG's PARITY VIOLATION PAPER.

WHY PEOPLE STOPPED USING IT?

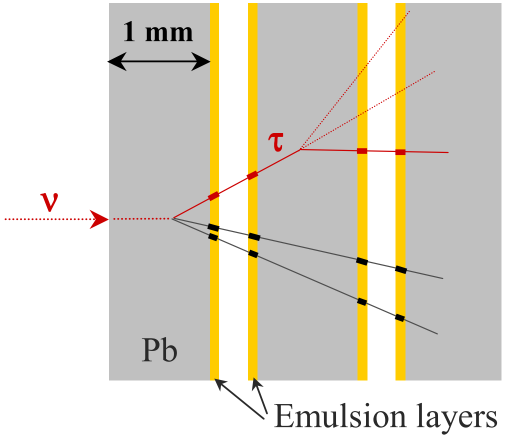
Too finicky, Labor intensive, Trigger?

WHY USE IT AGAIN?

Nevertheless it has the best resolution per $ per cm^3.

So called “Emulsion Cloud Chamber” sandwiches Pb between thin emulsion pellicles, uses scintillators and chambers to locate blocks which contain vertex, uses robots to pick them out for fully automatic processing and scanning.

The experimental technique

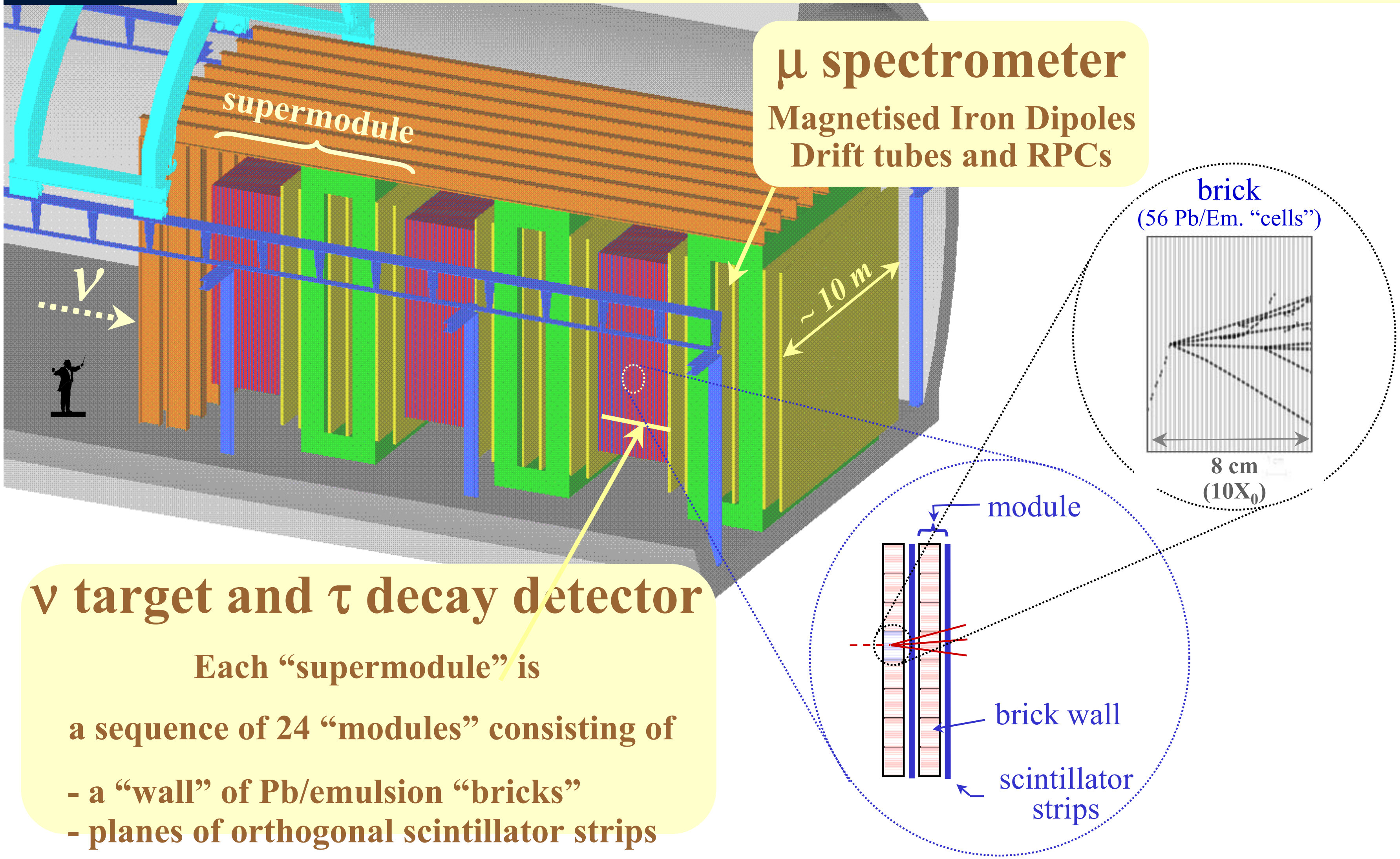


- **Emulsion Cloud Chamber (ECC)**
  - Emulsions for tracking, passive material as target
  - Basic technique works
    - charmed “X-particle” first observed in cosmic rays (1971)
    - DONUT/FNAL beam-dump experiment: ν_τ events observed
- **$\Delta m^2 = (1.5 - 5) \times 10^{-3}$ eV^2** (SuperK) → **$M_{target} \sim$ 2 kton** of “compact” ECC (baseline)
  - large detector → sensitivity, complexity
  - modular structure (“bricks”): basic performance is preserved
- **Ongoing developments** in the emulsion technique, required by the large vertex detector mass:
  - industrially produced emulsion films
  - automatic scanning microscopes with ultra high-speed

Experience with emulsions and/or ν_τ searches : E531, CHORUS, NOMAD and DONUT

The detector at Gran Sasso

(modular structure, configuration with three "supermodules")



μ spectrometer

Magnetised Iron Dipoles
Drift tubes and RPCs

ν target and τ decay detector

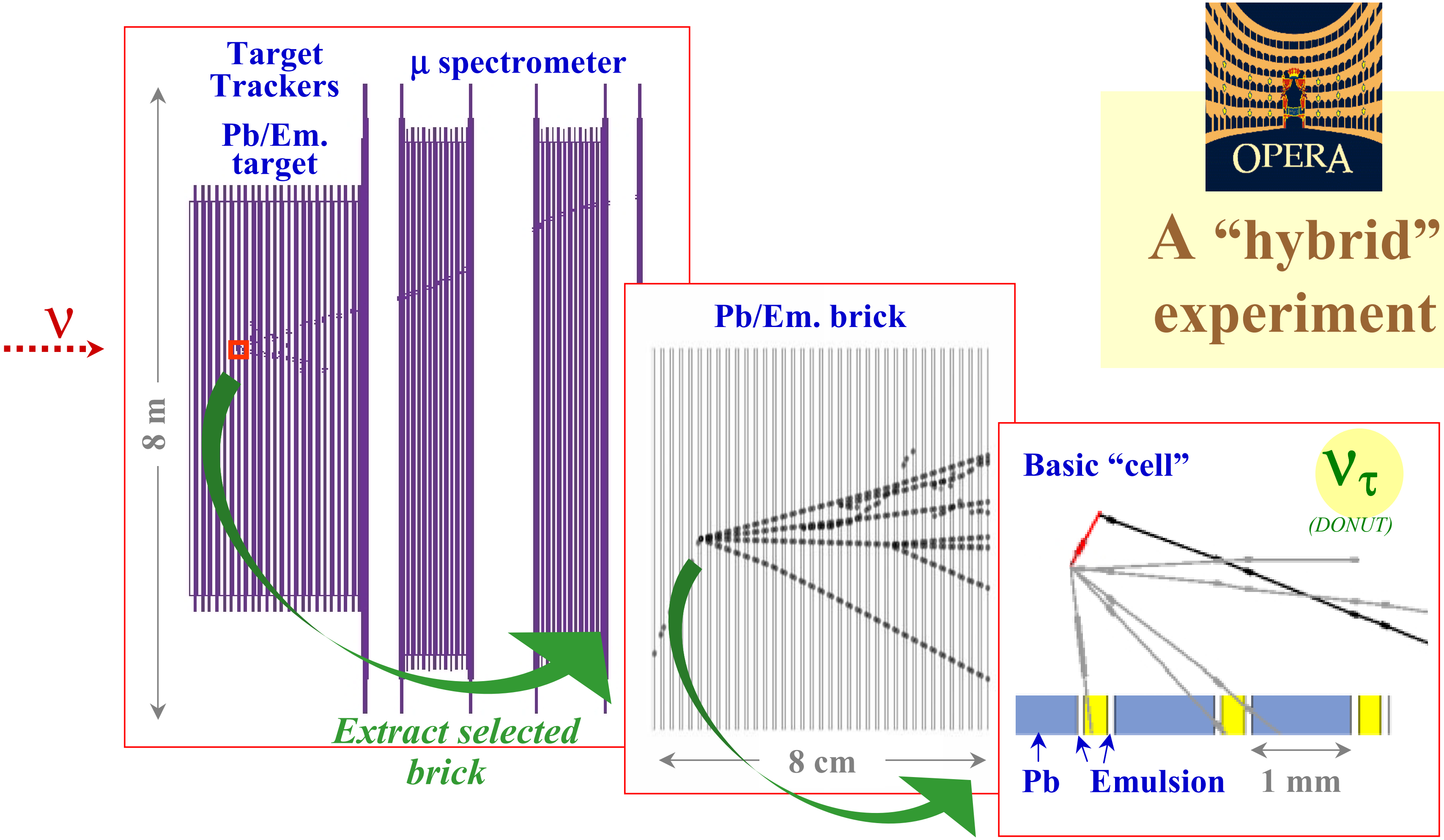
Each "supermodule" is

a sequence of 24 "modules" consisting of

- **a "wall" of Pb/emulsion "bricks"**
- **planes of orthogonal scintillator strips**

OPERA

A “hybrid” experiment



Electronic detectors

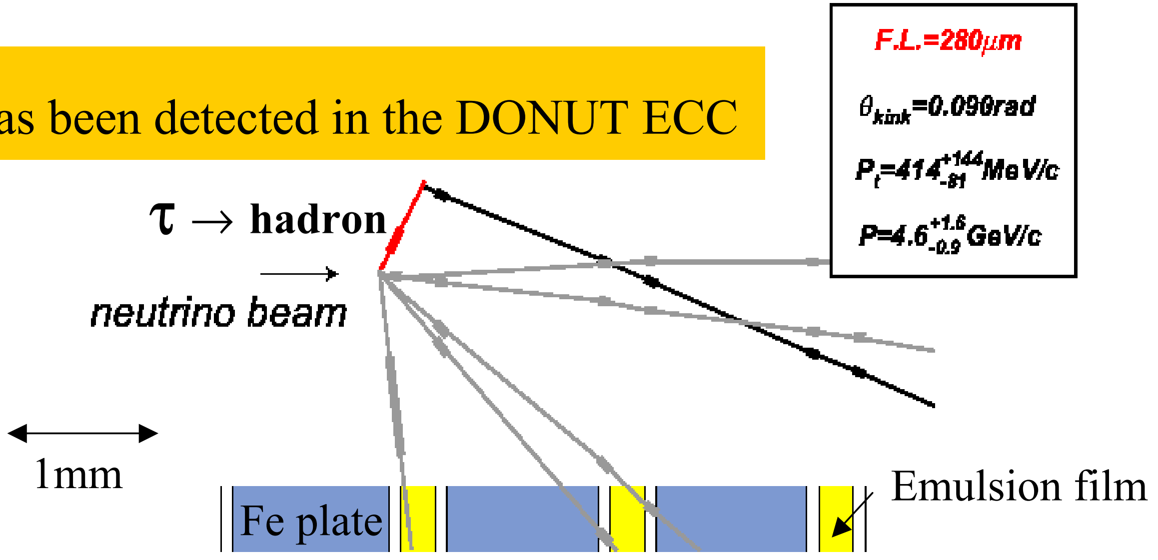
- → select ν-interaction brick
- → μ ID, charge and p

Emulsion scanning

- → vertex search
- → decay search
- → e/γ ID, kinematics

Emulsion Cloud Chamber for ν_τ detection

ν_τ has been detected in the DONUT ECC



closeup view near the neutrino interaction

Structure: OPERA ECC = DONUT ECC

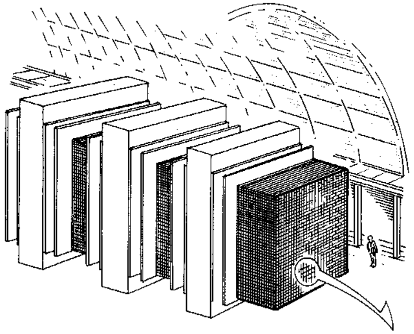
Material : Lead ≠ Iron

Better performance for physics analysis

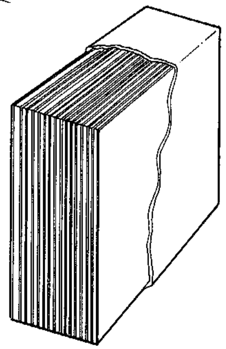
"Compact" brick as a baseline option for OPERA

Operation of the Experiment

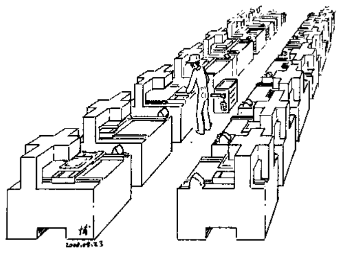
To be sensitive in Super-K region



~2kton
235k ECC bricks
Hybrid Emulsion Detector



ECC brick

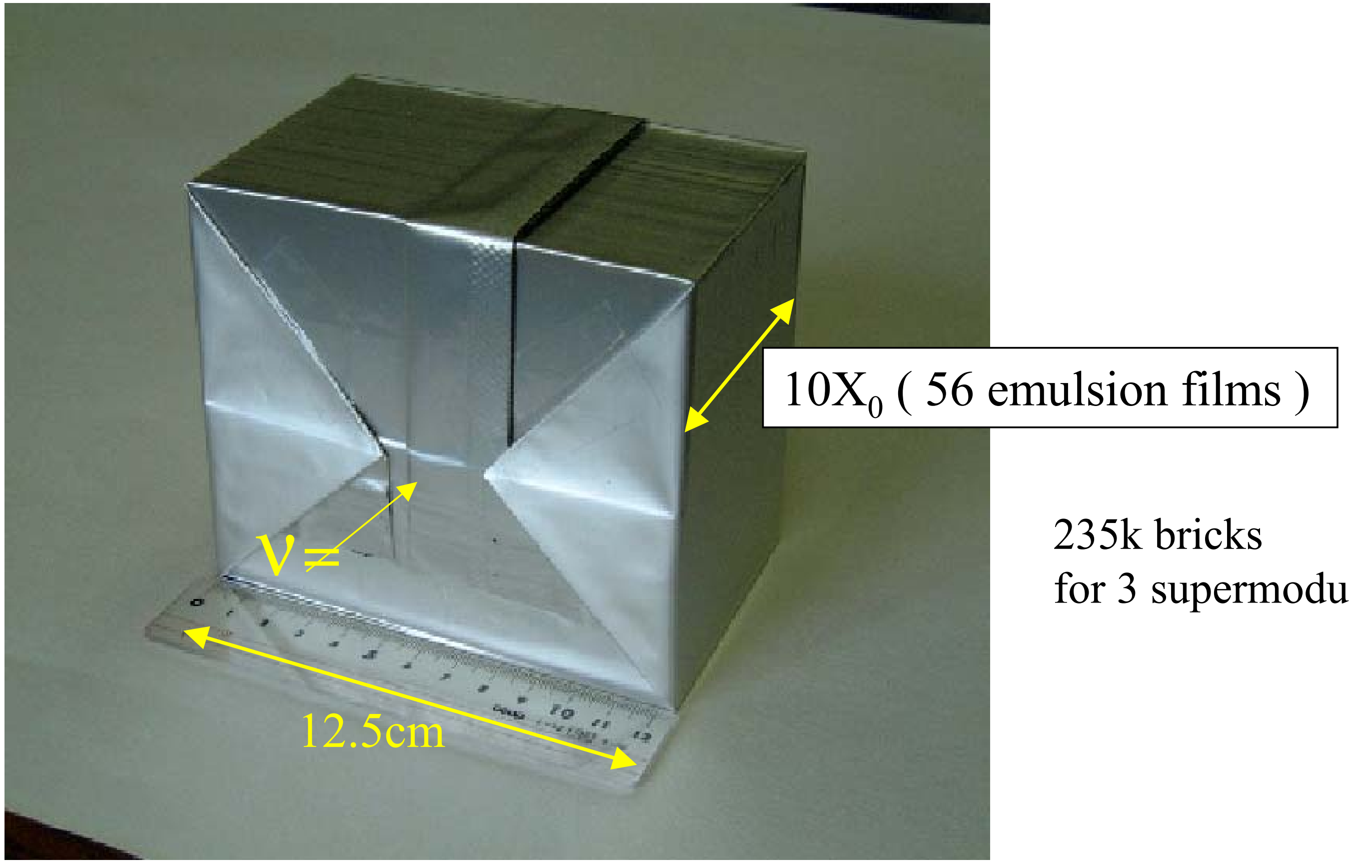


Detector in Gran Sasso
DAQ for brick tagging
- Tag ν interactions
- select fired brick

Daily extraction (~ 30 bricks/day) by a robot
cosmic ray exposure
emulsion film processing

Scanning stations in Japan and Europe
DAQ for τ detection
- Locate neutrino interaction
- τ decay detection
- τ event FULL DAQ

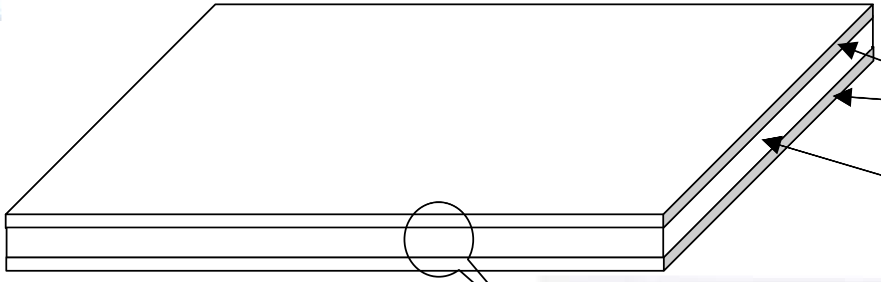
Origami packed ECC brick for OPERA

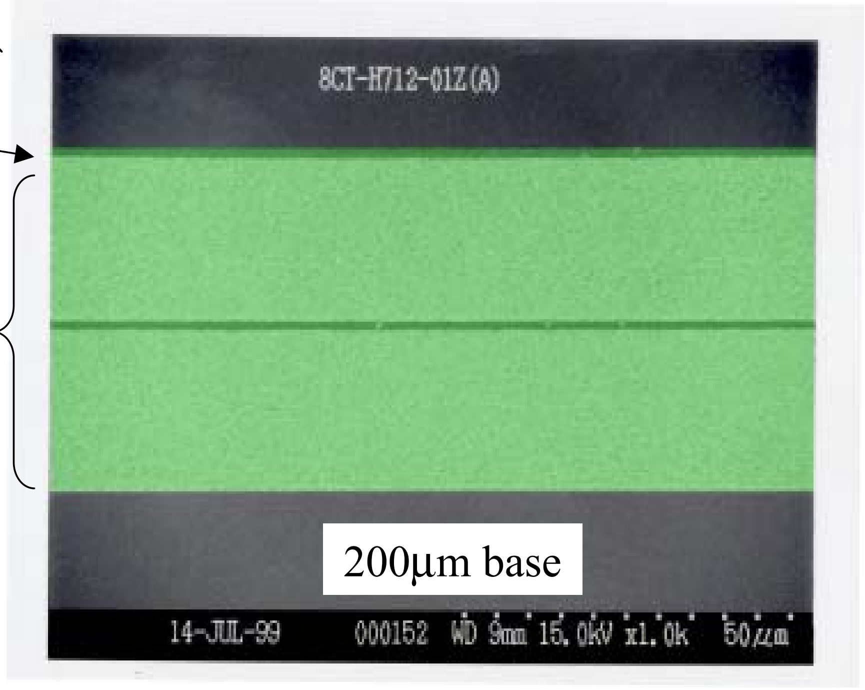


235k bricks
for 3 supermodules

Origami packing = vacuum packing
- (1) Protection against light and humidity variations.
- (2) Keep the position between films and Pb plates.
- (3) Vacuum preserved over 10 years

Industrially mass-produced emulsion film





Surface protection by gelatin layer
for Pb plate contact

50µm emulsion layer

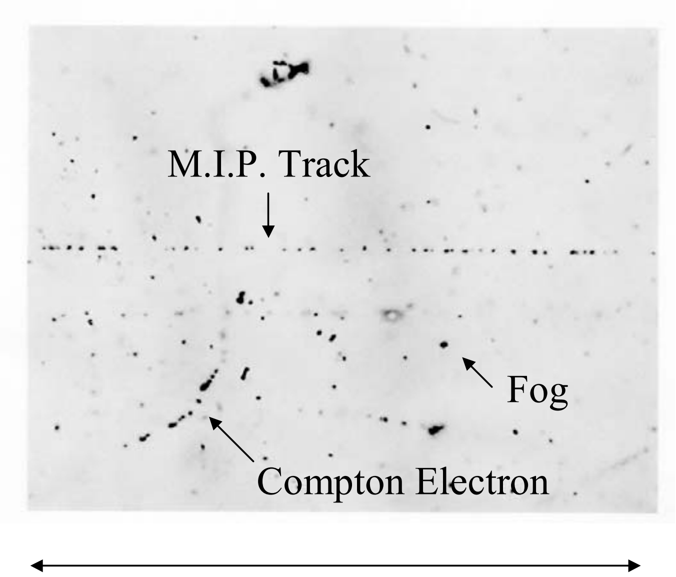
Products by Fuji Film Co.

Suitable for mass production: < 2 years for production for OPERA (13.6M films)

Precise mechanical size : emulsion layer thickness (~ 1 µm accuracy)

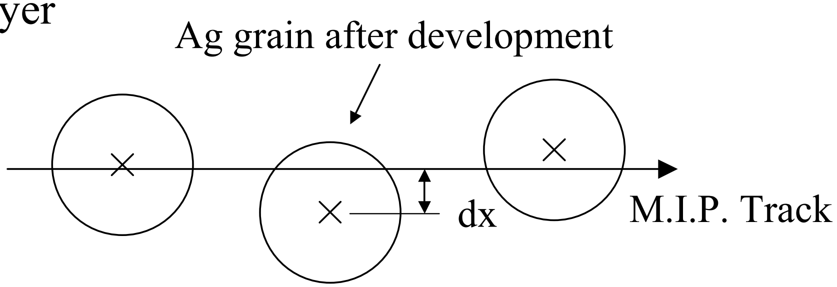
Intrinsic tracking resolution of the emulsion

Cross sectional view of an emulsion layer



100µm

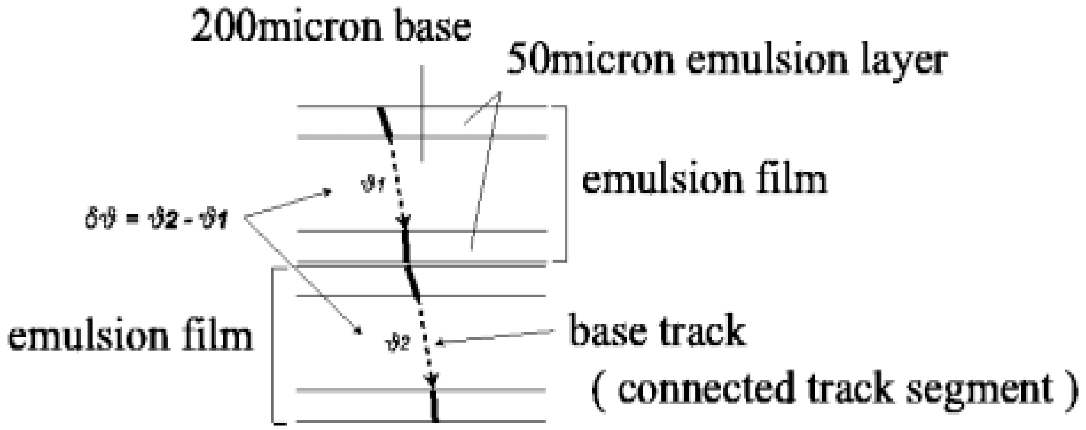
30grains/100µm
grain diameter ~ 0.6µm



intrinsic tracking accuracy

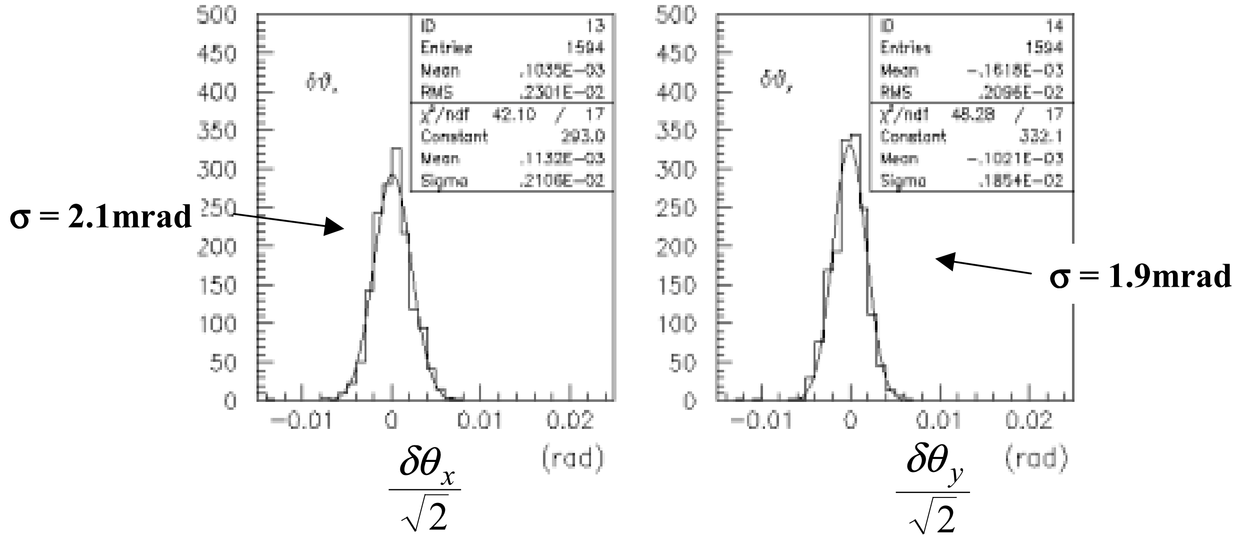
$\sigma = 0.06\mu m$

Actual resolution with Track Selector readout



Resolution is limited
due to digitization error
in image processing
by Track Selector

σ(angle) = 2.1mrad
σ(position) = 0.21µm
for base track

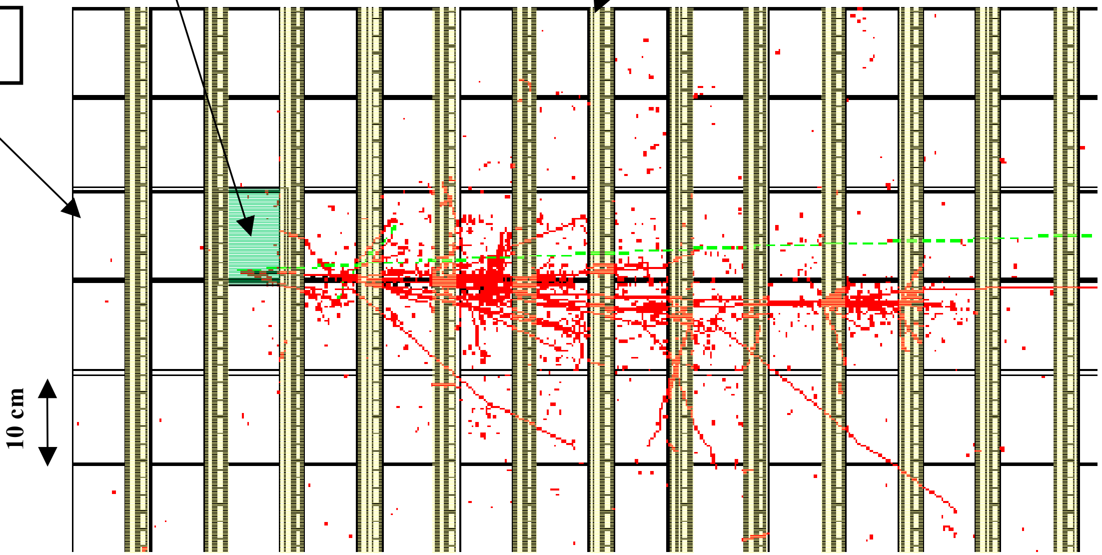


σ = 2.1mrad

σ = 1.9mrad

Precise measurement for small sample → better resolution close to the intrinsic resolution

How to select the ν interaction brick ?

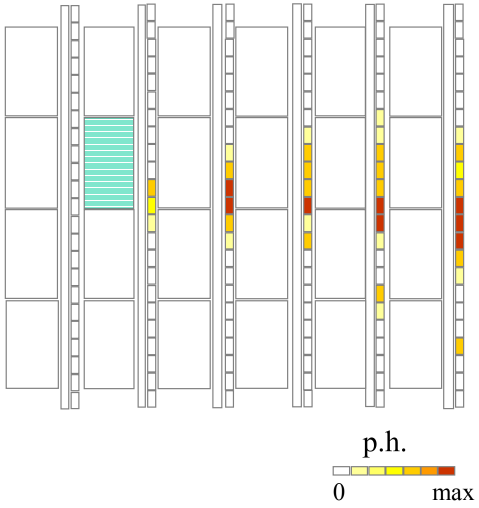


Selected brick

Sampling by Target Tracker planes (X,Y)

Brick wall

Event as seen
by the target tracker

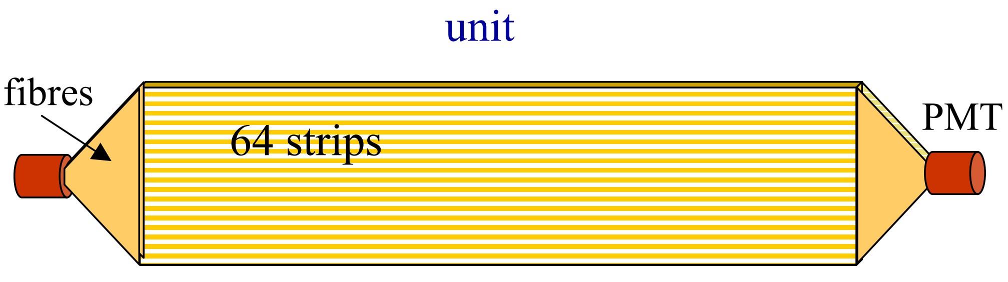


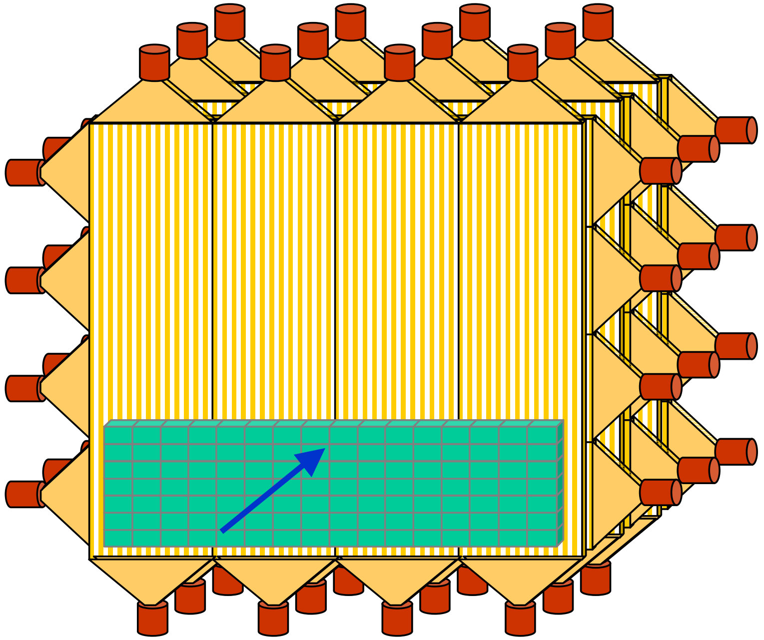
Selected bricks extracted daily
using dedicated robot

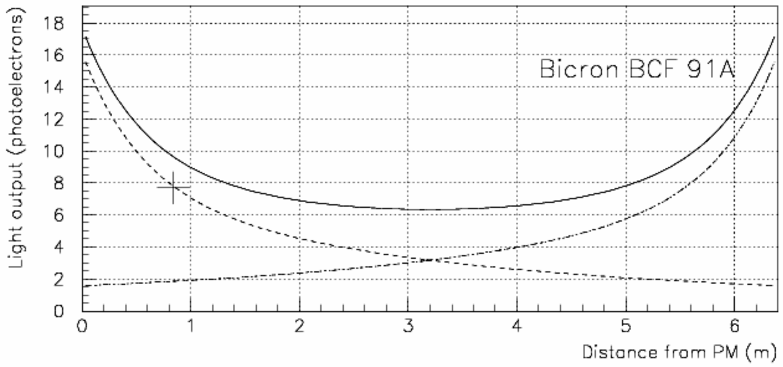
Emulsion-Scintillator strip Hybrid Target

- Tracker task
  select bricks efficiently
- High scanning power + low background
  allow coarse tracking

Scintillator strip Target Trackers

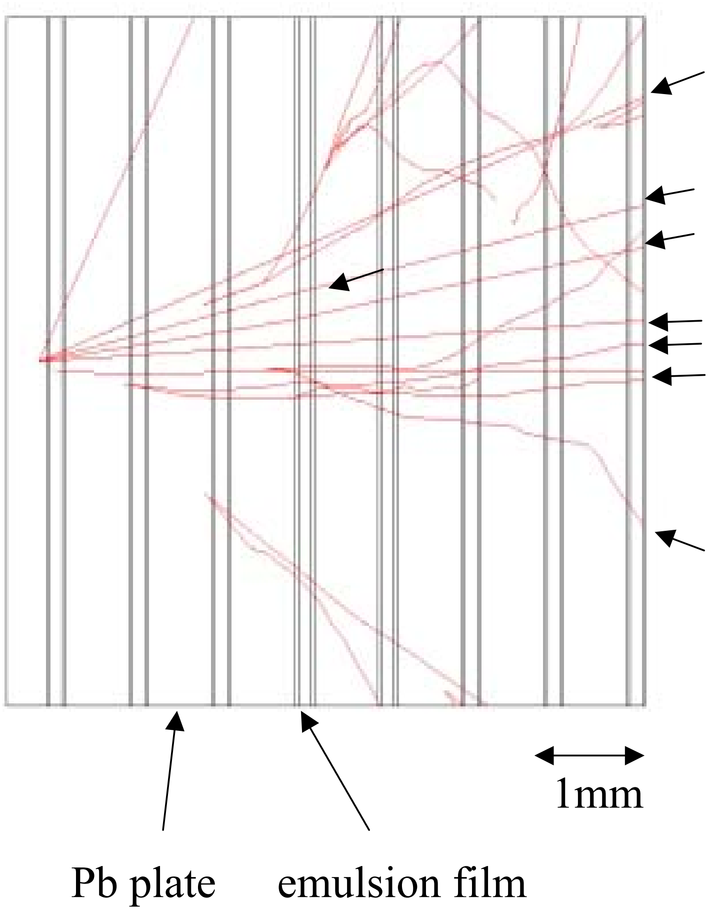






- Scintillator strips (**2.6 cm wide**, 1 cm thick)
- Light read out at both WLS fibre ends
- Multi anode 64 ch. PMT (baseline)
- Minimum: 6 p.e.
- Probability for 0 p.e. = 0.2%

How to locate the ν-interaction in a brick ?



(1) Pick up all tracks from the ν interaction on a down most film

5x5cm^2 for CC
full surface of a film for NC → 250cm^2/brick

Require scanning power

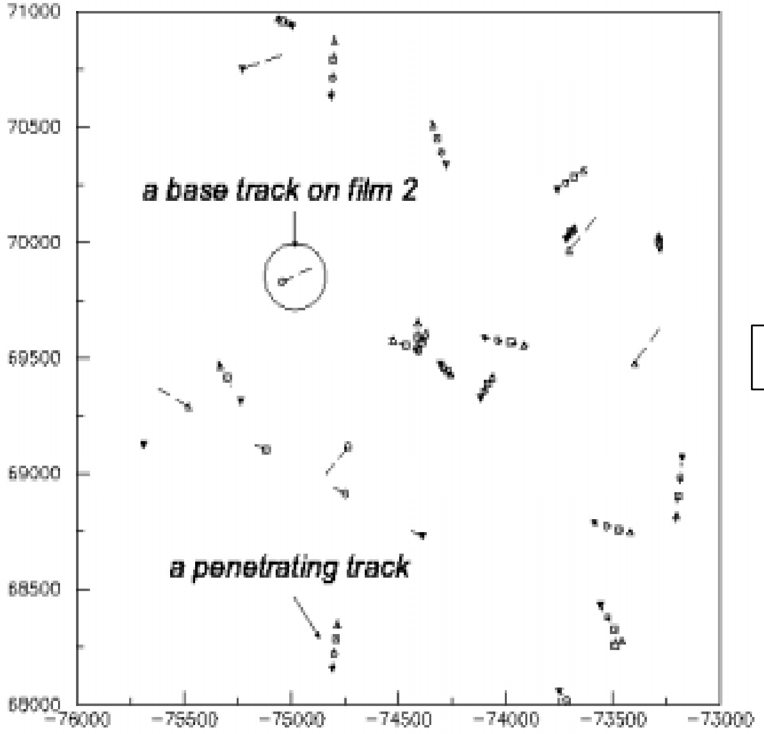
(2) Scan back picked up tracks

(3) confirm ν interaction vertex;

when stopped in 2 consecutive films
check the existence of a vertex by NET scan

Established techniques in CHORUS and DONUT

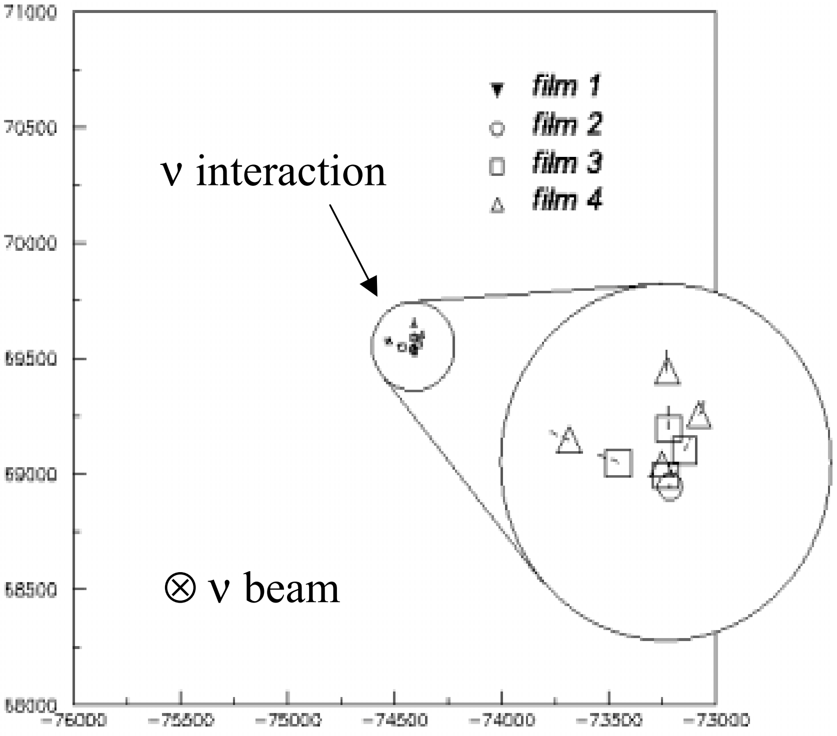
Vertex Reconstruction by Net Scan



a base track on film 2

a penetrating track

All tracks around the ν interaction
(3 x 3 mm^2 and 4 films)
simulated for OPERA using DONUT data

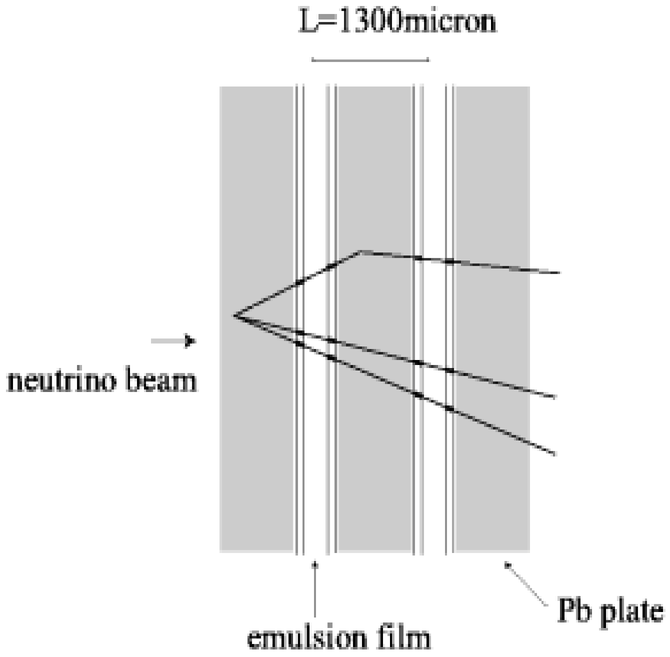


ν interaction

⊗ ν beam

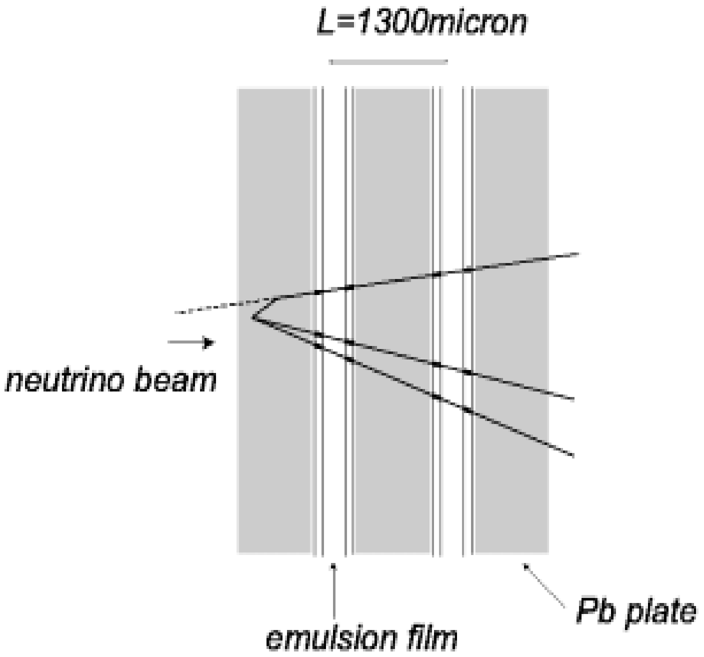
Excluding tracks which are
penetrating + recorded in only 1 film

Select ν_τ candidates to be passed to the FULL data taking



“ Long decays”

reconstruct kink topology



“ Short decays ”

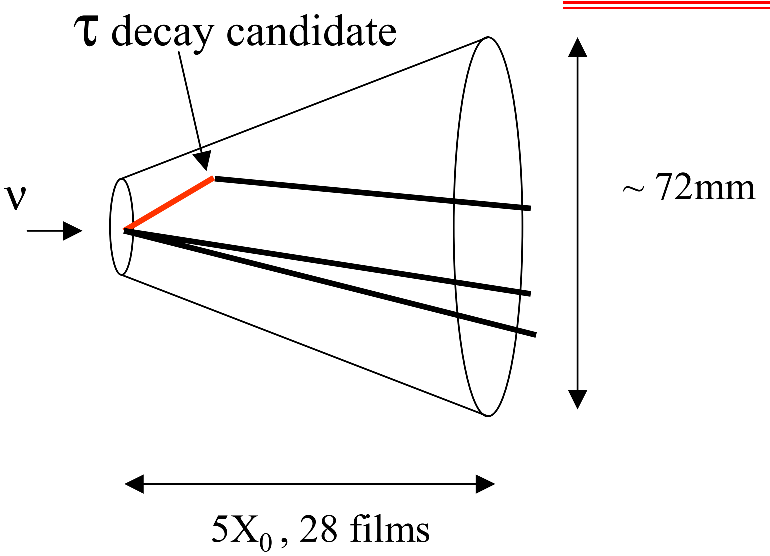
detect large impact parameter track

Loose cut to reject low momentum tracks

Small fraction of the located events are passed to the FULL DAQ

FULL data taking for selected ν_τ candidates

to reconstruct most of the event related activities in a brick



- **P measurement**
- **μ and e identification**
- **Detection of γ rays from both primary and decay vertex**

Physics analysis to be performed

- **Decay Pt**
- **ID of daughter particle**
- **Primary leptons**
- **Missing Pt of the event**

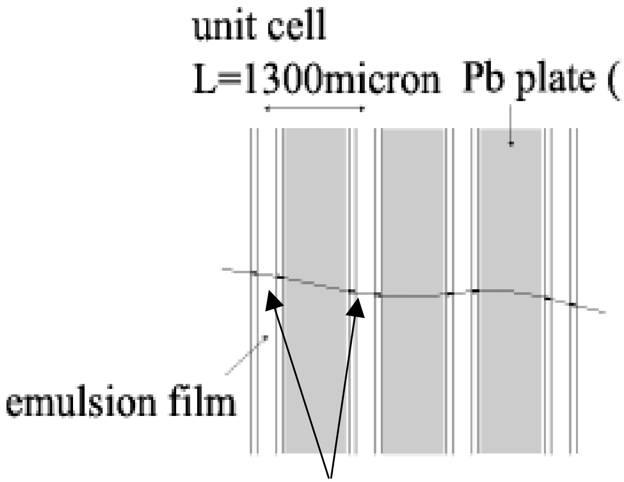
Required scanning area = $1000 cm^2$
$\tan\theta < 1$ and $5X_0$
for all charged particles

Brick-to-brick connection for the downstream events in the brick.

Precise re-measurement for small kink angle or small impact

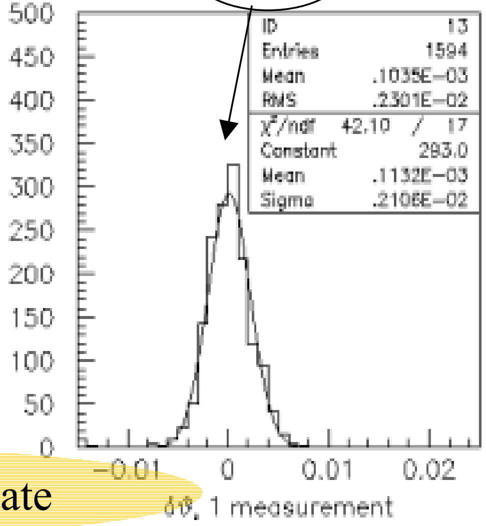
Momentum measurement in ECC brick (angular method)

maximum detectable momentum
by tracking $5X_0$ and
allowing $\Delta p/p < 0.2$

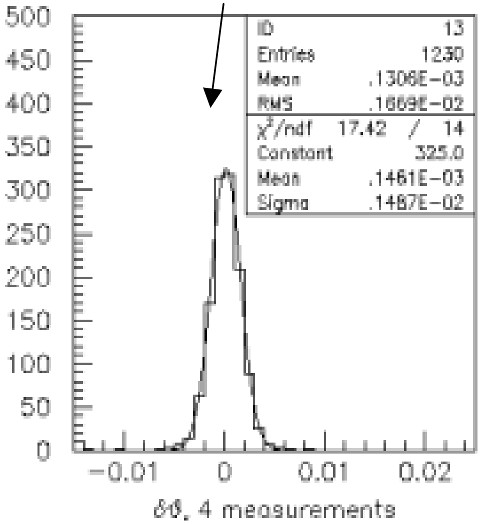


Compare angle difference

Normal meas^t
Pmax = 2.0 GeV/c



Improved by multiple meas^t
Pmax = 2.8 GeV/c



Multiple Scattering in Pb plate

Base thickness = lever arm for deflection measurement

Pmax = 10.0 GeV/c ← intrinsic resolution

Not relying on alignment of emulsion films
relying on parallelism of Pb plates and emulsion films

CONCLUSION: THE PHOENIX RISES AGAIN?

So fifty some years later, an 80 MChF experiment is approved to run for ν_τ appearance discovery using Nuclear Emulsions, capitalizing on its special properties, and hopefully, mitigating its shortcomings by modernization and automation.

WHEN WILL IT RUN?

WILL IT SUCCEED?

I hope we'll know within this decade.