Discovery of the tau neutrino

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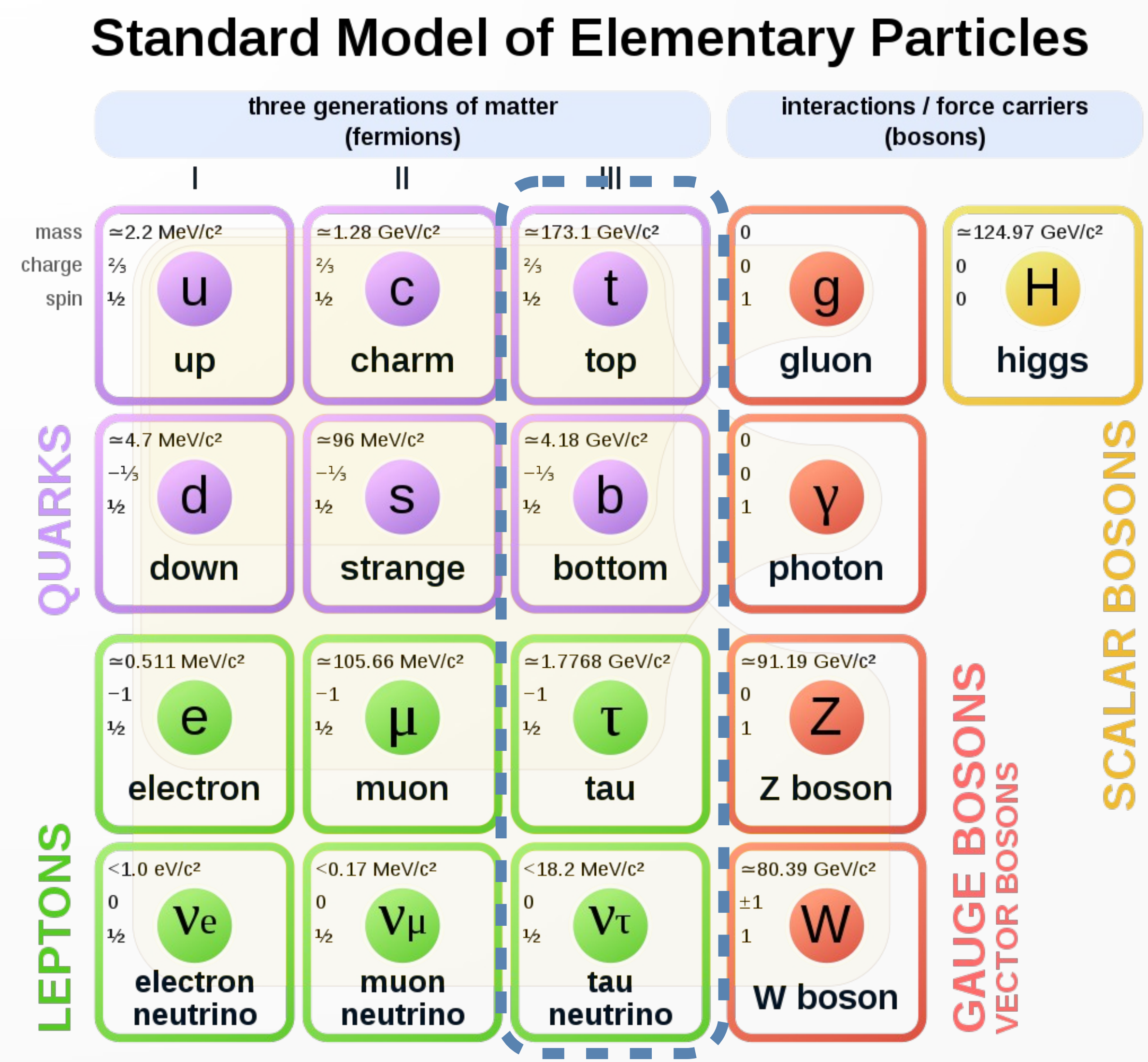
Build up to tau discovery

- Muon neutrino discovered in 1962 (See Peter's talk)
  - Evidence that the leptonic sector consists of multiple generations of doublets
- Late 1960s: the e-μ problem (discrepancies in hadronic interactions between electrons and muons) cited as possible evidence for more leptons or more complicated structure in the leptonic sector
- 1974: Mark I detector at SPEAR (SLAC) sees opposite sign eμ pairs with missing energy
- Identity of new particle uncertain at first
  - Why are tau and charm similar masses?
  - Observation of opposite sign lh events at rates corresponding to predictions from a heavy lepton cement the picture
- τ lepton named after τρίτος (tritos), the Greek word for third

Timeline of the 3rd Generation

- τ observed 1975 at SLAC/SPEAR by SLAC/LBL group lead by Martin Lewis Perl
  - Shared 1995 Nobel with Reines
  - His student, Sam Ting got the prize in ‘75 for the J/Ψ
- b quark discovered 1977 at FNAL, group lead by Leon Lederman (after a misfire)
  - See Greg’s talk 2 weeks ago
- Top quark discovered 1995 at Tevatron/FNAL
  - Referenced in 1999 Nobel to ‘t Hooft and Veltman



Expectations of a 3rd Neutrino

- The discovery of the τ immediately implied the existence of a third neutrino flavor
- Study of leptonic tau decay kinematics points to the tau being part of a weak isospin doublet with a light neutral particle
- Searches for the interaction $\nu_{e/\mu}+N \rightarrow \tau+X$ rule out that the tau neutrino is not unique and also place limits on oscillation

Indirect Evidence for ν_τ

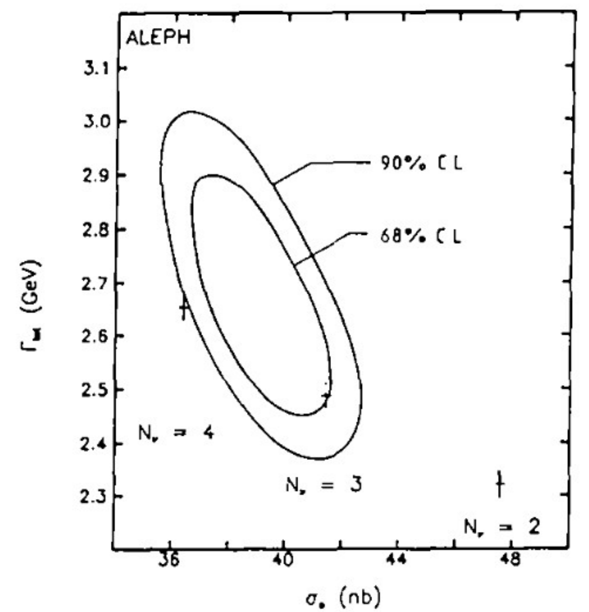
- LEP designed for precision studies of electroweak bosons, turned on at CERN in August 1989
- In November 1989 all 4 LEP experiments published measurements of Z properties which appeared sequentially in Phys. Lett. B
- Z width and cross-section related to number of light neutrinos

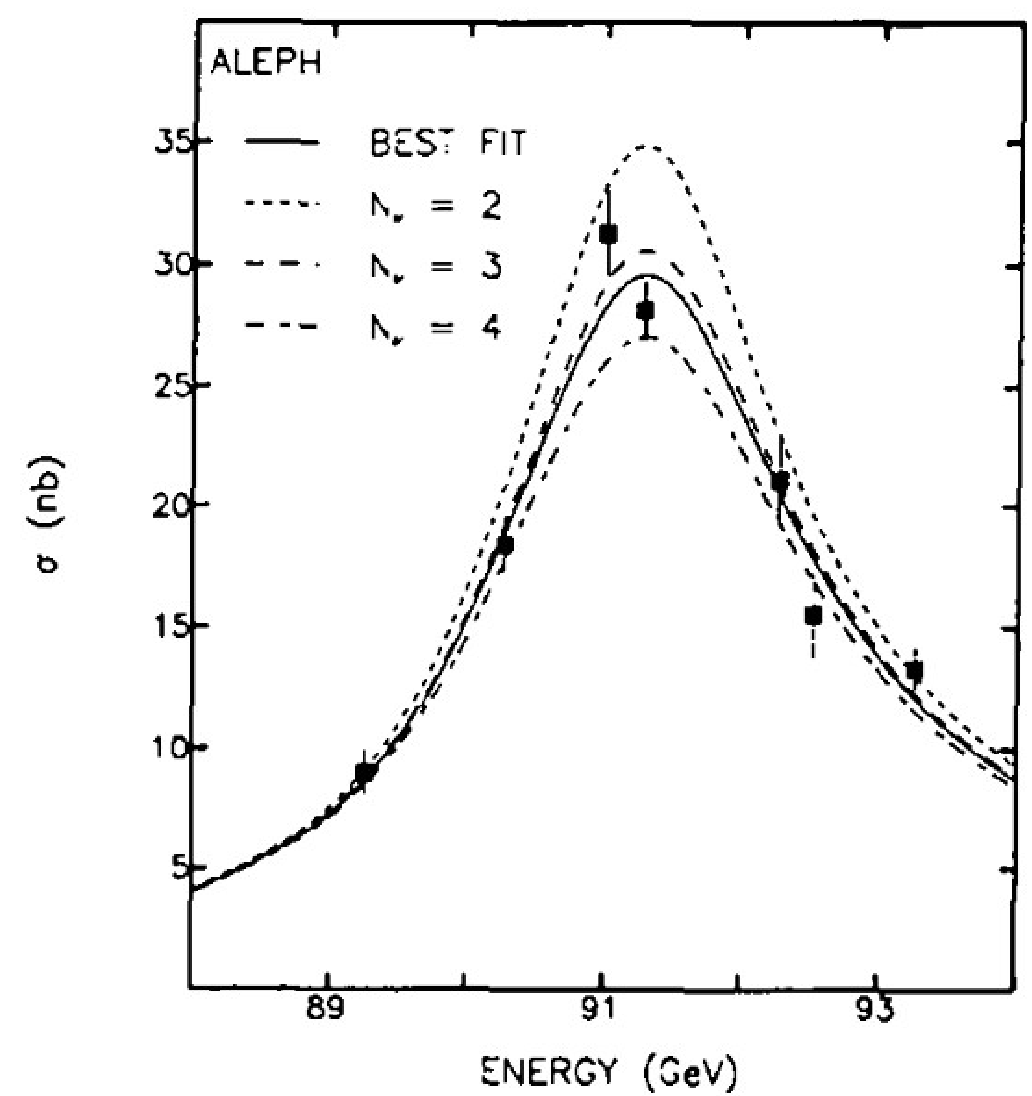
$$\sigma_f^{peak} = \frac{12\pi}{M_Z^2}\frac{\Gamma_{ee}\Gamma_f}{\Gamma_Z^2}(1-\delta_{rad}) \equiv \sigma_f^0(1-\delta_{rad})$$

$$\Gamma_Z = N_\nu \Gamma_\nu + 3\Gamma_{ee} + \Gamma_{had}$$

Indirect Evidence for ν_τ

- L3: $N_\nu = 3.42 \pm 0.48$
- ALEPH: $N_\nu = 3.27 \pm 0.30$
- OPAL: $N_\nu = 3.1 \pm 0.4$
- DELPHI: $N_\nu = 2.4 \pm 0.6$



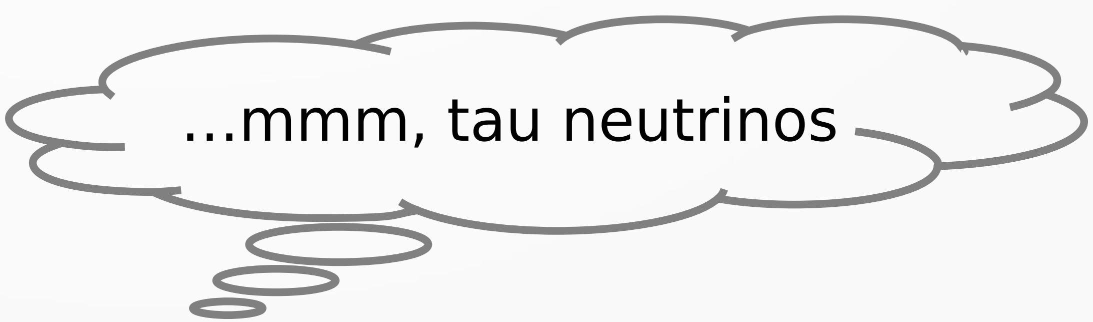


Challenges to Direct Observation

- Need a ν_τ source, but ν_τ is rarer than other neutrinos.
  - High tau mass means a source must rely on either high energy collisions or decays of heavy mesons.
- The unique signature of ν_τ is the creation of a tau in charged current (CC) interactions
  - Need to identify τ's in a neutrino target, but $c\tau_\tau = 8.7 \times 10^{-5}$ m
  - Decay products include lighter leptons, which are also one of the main backgrounds
  - Hadronic decays can be confused with NC interactions

Enter DONUT

- The experiment for the job was Fermilab's E872, a.k.a. Direct Observation of Nu Tau (DONuT)
- Data was taken from April to September 1997, with evidence for observation announced in 2000 and published in early 2001
- The experiment used a beam dump to create high energy neutrinos and a unique detector configuration to detect tau decays



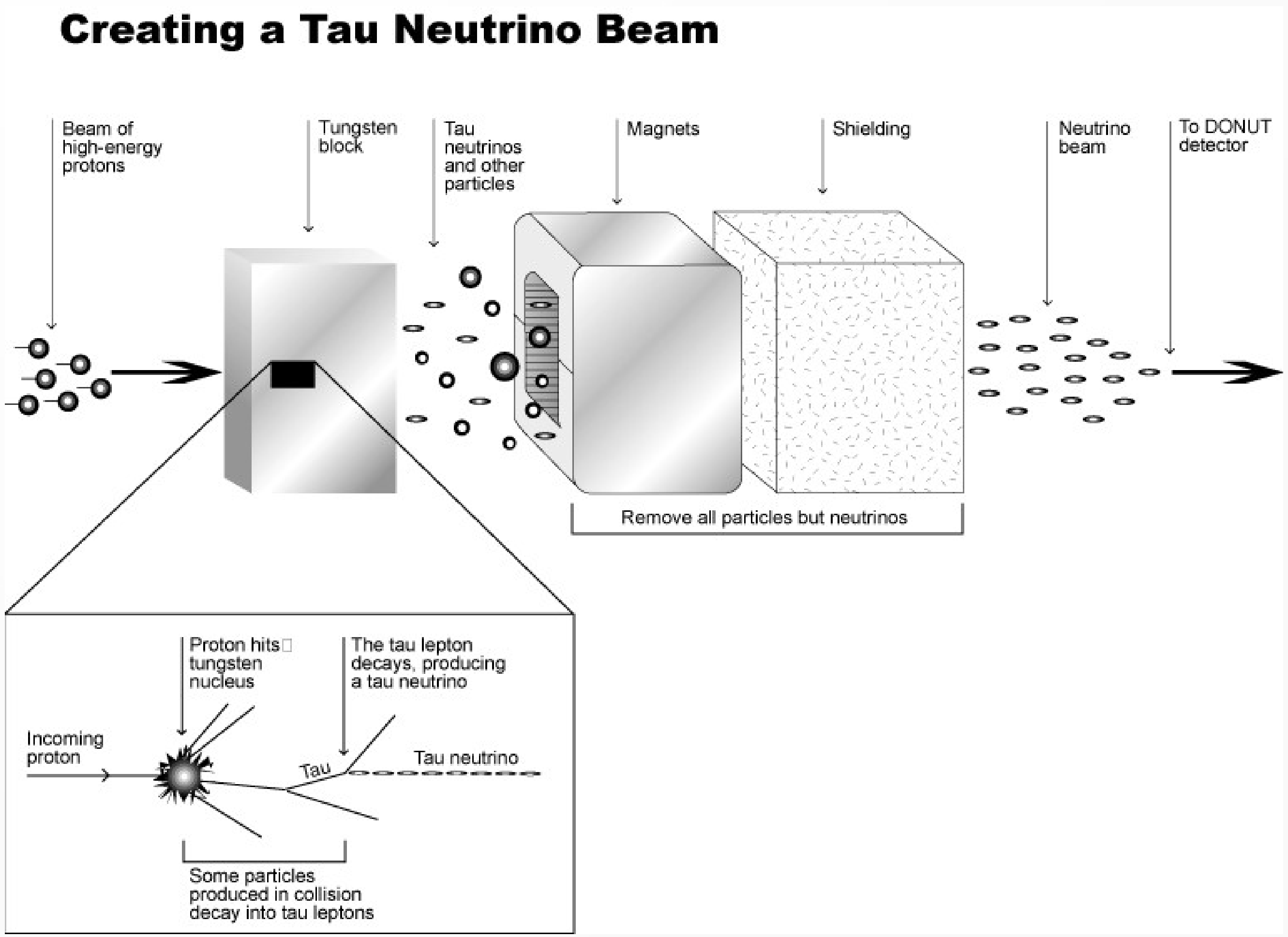
DONUT Source

Used 3.6×10^{17} 800 GeV protons from the Tevatron on a 1 m Tungsten target

Primary source (86%) of ν_τ is the decay of D_s mesons (quark content $c\bar{s}$)

Basically the lightest weakly decaying meson which can decay into τ

Branching ratio is 5.48%, with even more ν_e and ν_μ.

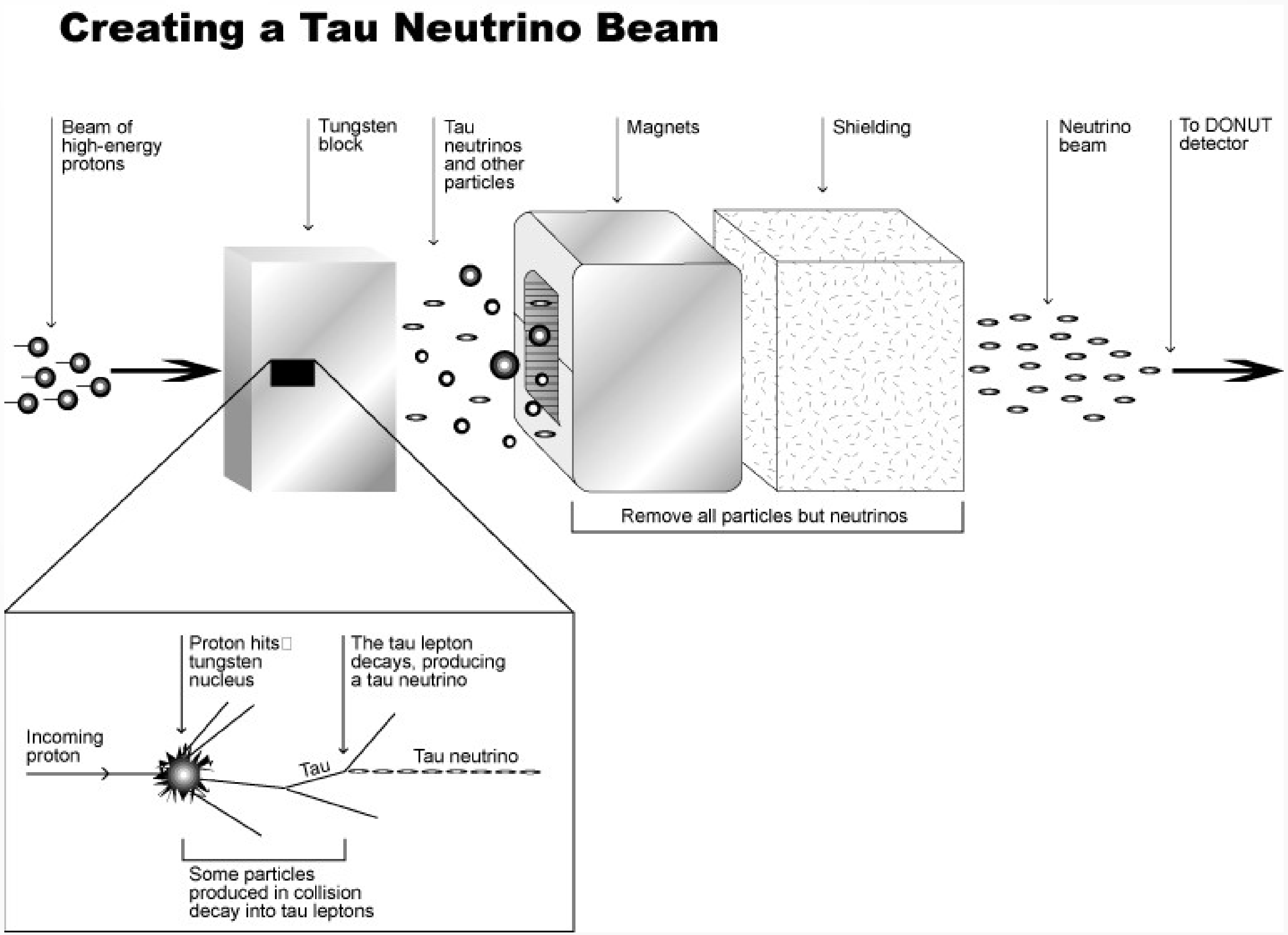


DONUT Neutrino Beam

The remaining 14% of ν_τ come from D_s interactions with the target and decays of other B and D mesons

Backgrounds of other neutrino flavors come from these processes and from downstream decays of pions muons, kaons, etc.

The resulting beam is 8.4% ν_τ



DONUT Shielding

Immediately after the target comes a large dipole magnet to deflect charged particles

Immediately afterward is another magnet, the toroidal MuSweep2 specifically targeting high energy muons

Finally, the beam passes through 17 m of passive steel shielding to stop any remaining hadrons

7.2×10^{8} muons expected to make it through to the target volume

DONUT spokesman Vittorio Paolone in the SELMA dipole magnet used to deflect charge particles after the beam dump. Grayscale in the '90s!

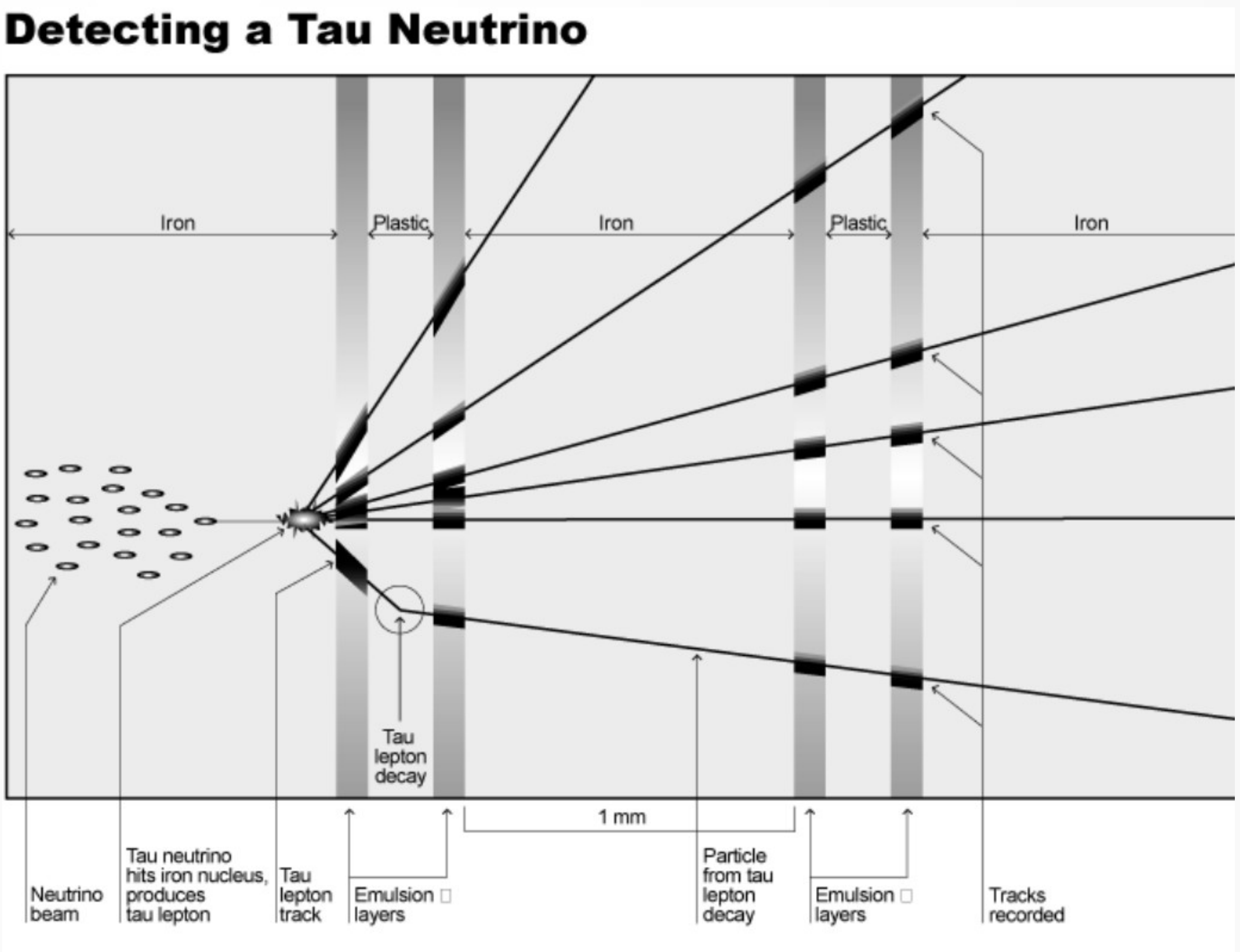
DONUT Signal Topology

Smoking gun has to come from CC interaction of ν_τ, i.e. production of τ in the detector volume.

At these energies, the average τ travels 2 mm before decay

Focus on decays to 1 charged particle: branching fraction 85% (34% leptonic + 51% hadronic)

Characteristic topology is a track with a kink



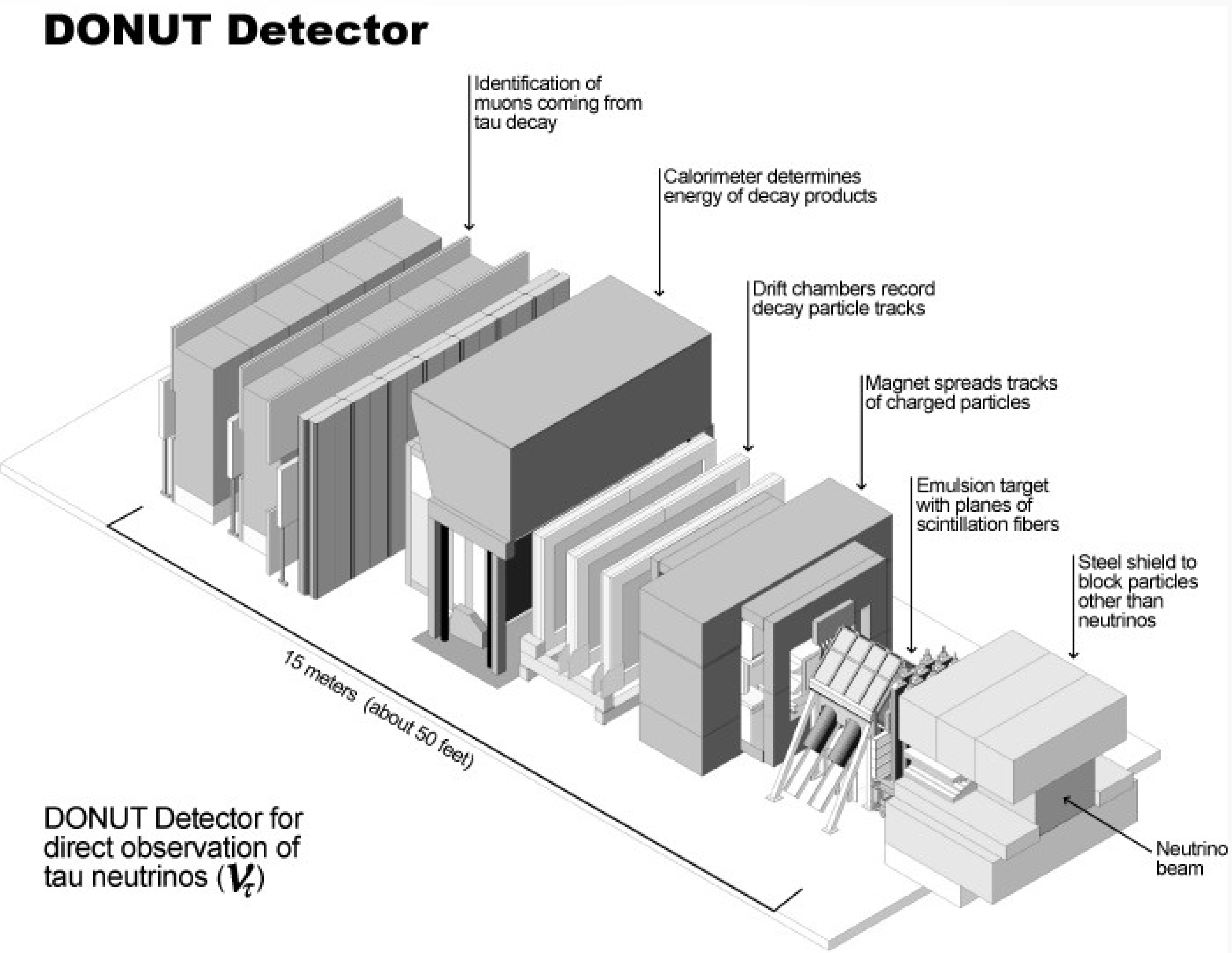
DONUT Detector from 1000 yards

Topology referred to as hybrid emulsion spectrometer

Principle is to combine emulsion plates with a one armed spectrometer and some form of digital tracking

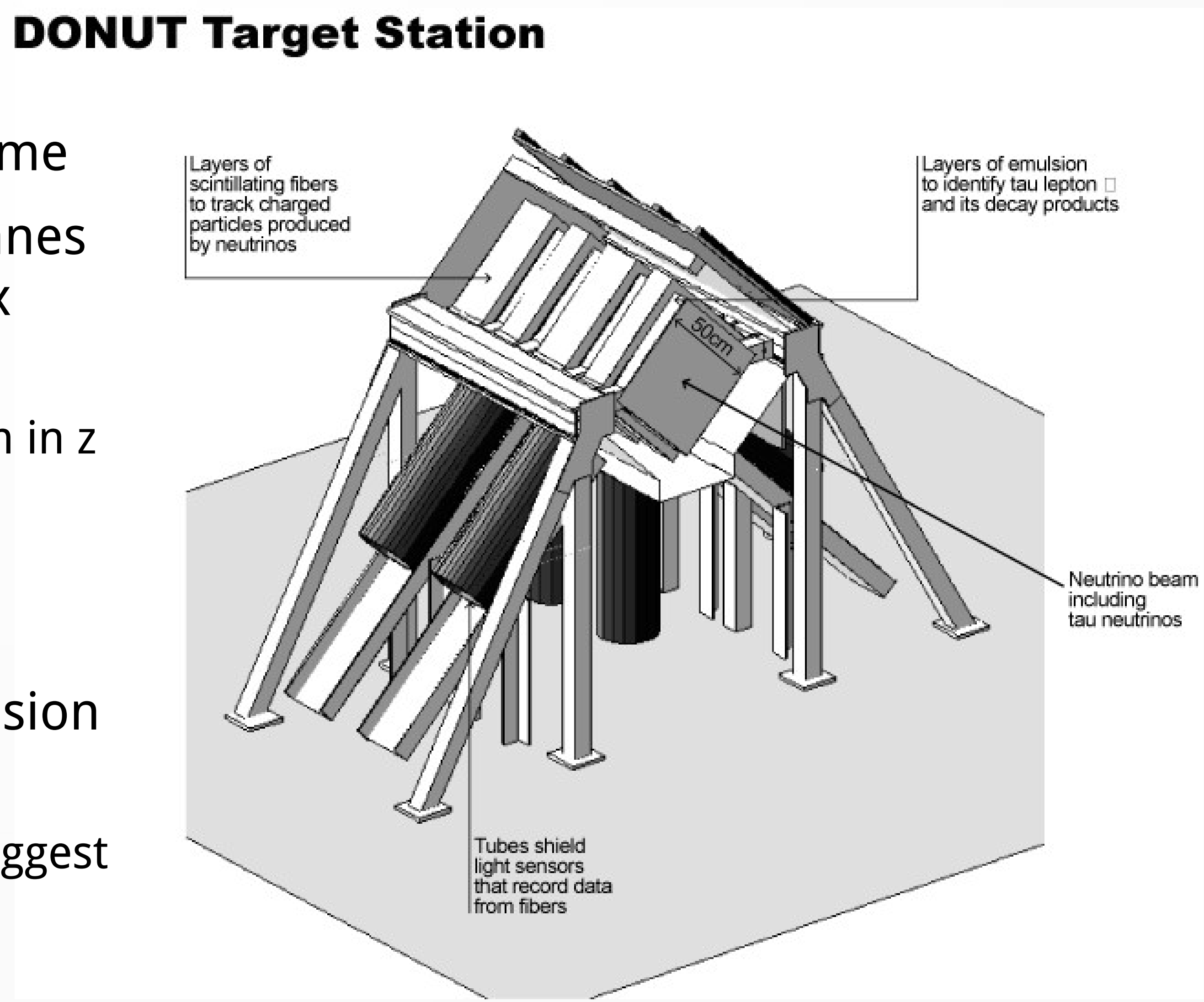
Use the spectrometer for lepton ID and vertex finding, in collaboration with SFT at the target station, then look at vertices in the emulsion offline

First used at FNAL to study charm production from neutrino interactions in 1980



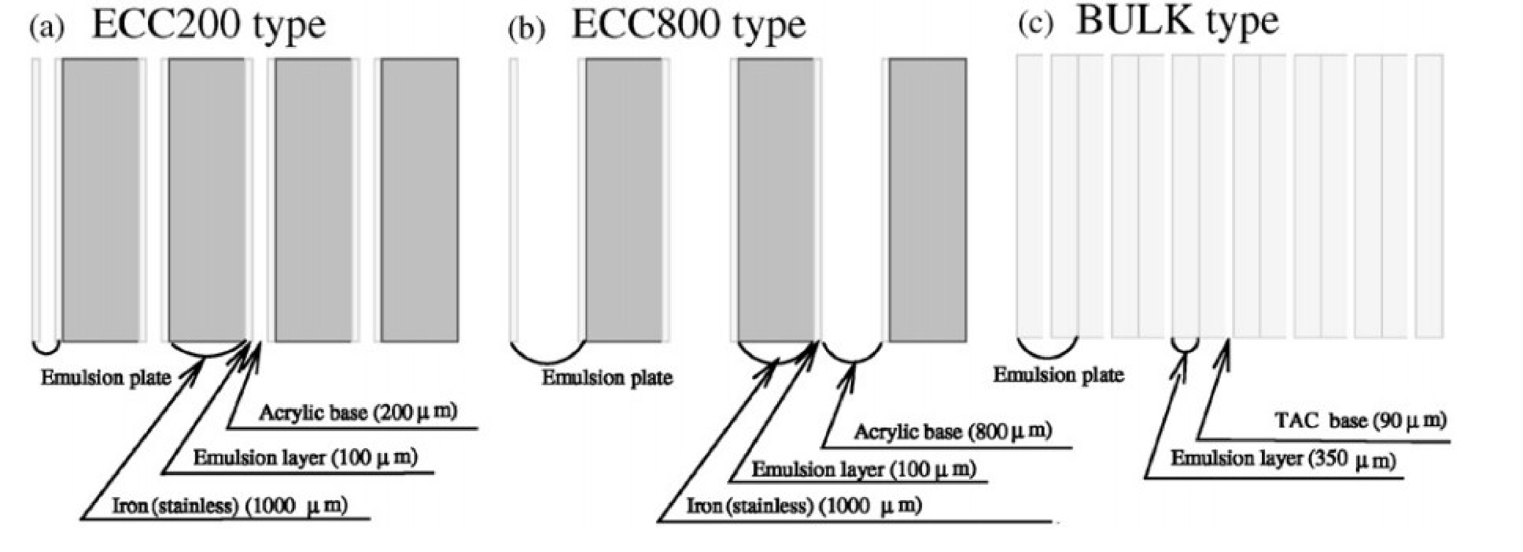
Target Station

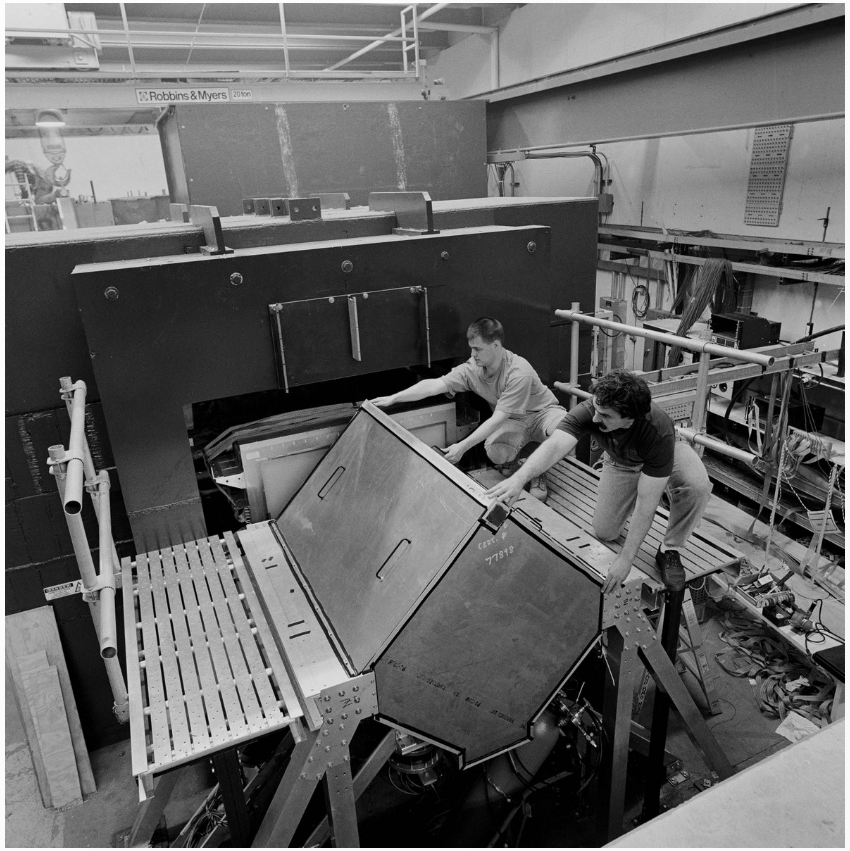
- Neutrino interactions and tau decays happen within the target station volume
- The target station contained of 44 planes of 0.5 mm scintillating fiber for vertex finding
  - Typical precision 1 mm transverse/7 mm in z
  - Timing resolution very good!
- The crown jewel were the emulsion modules: 50 cm×50 cm laminates of stainless steel, plastic base, and emulsion plates (~photographic film)
  - Provides position resolution ~0.1 μm! Biggest effect is slippage between plates.
  - Timing resolution is ~months



Emulsion Detector

- Several types of emulsion modules were produced
- The modules were exposed up to 4 at a time for about a month each
  - Exposure time determined by the limitation of μ track density < 10^5 cm^{-2}





John Trammell and Dave Ciampa, University of Minnesota, working on the target station of the DONUT experiment.

Triggering/Vertex Finding

- The electronic detector readouts were triggered with 4 scintillator planes upstream, downstream, and inside the target station
  - Veto on incoming charged particles, trigger on outgoing
- Next experimenters combined tracks from the downstream drift chambers and target station SFT
  - Keep events with all hits within 10 ns and for which a vertex is located in the fiducial region of the emulsion detector
- Finally, they performed a “physicist scan” to veto events from high energy muon showers or “other pathologies”, reducing data by a final factor of 20
  - Cross check estimate shows physicists are 86% efficient
- Total 72% efficiency for signal events through the electronic processing

Vertex Finding in Emulsion

- When vertex finding works well, it returns an emulsion volume of 5×5×13 mm^3 and a vertex location with transverse resolution 1 mm and beam-direction resolution 5 mm
- The emulsion is scanned by an automated system which processes the emulsion plate into segments called microtracks, which are connected together to form tracks
- After requiring tracks to point at the vertex, connect to SFT tracks, and pass certain quality cuts, the picture becomes much cleaner
- Another round of physicist checks by eye confirms that the topology of the events is consistent with a neutrino interaction

Automated Scanning

- All scanning for DONUT (and many other important experiments) performed at Nagoya University in Japan
- Automated setup initially scanned 0.2 cm^2/hr
  - New setup (1998) with FPGA's gave a factor of 5
  - Recall track density is 10^5 cm^{-2}
- Significant improvement over manual scanning!

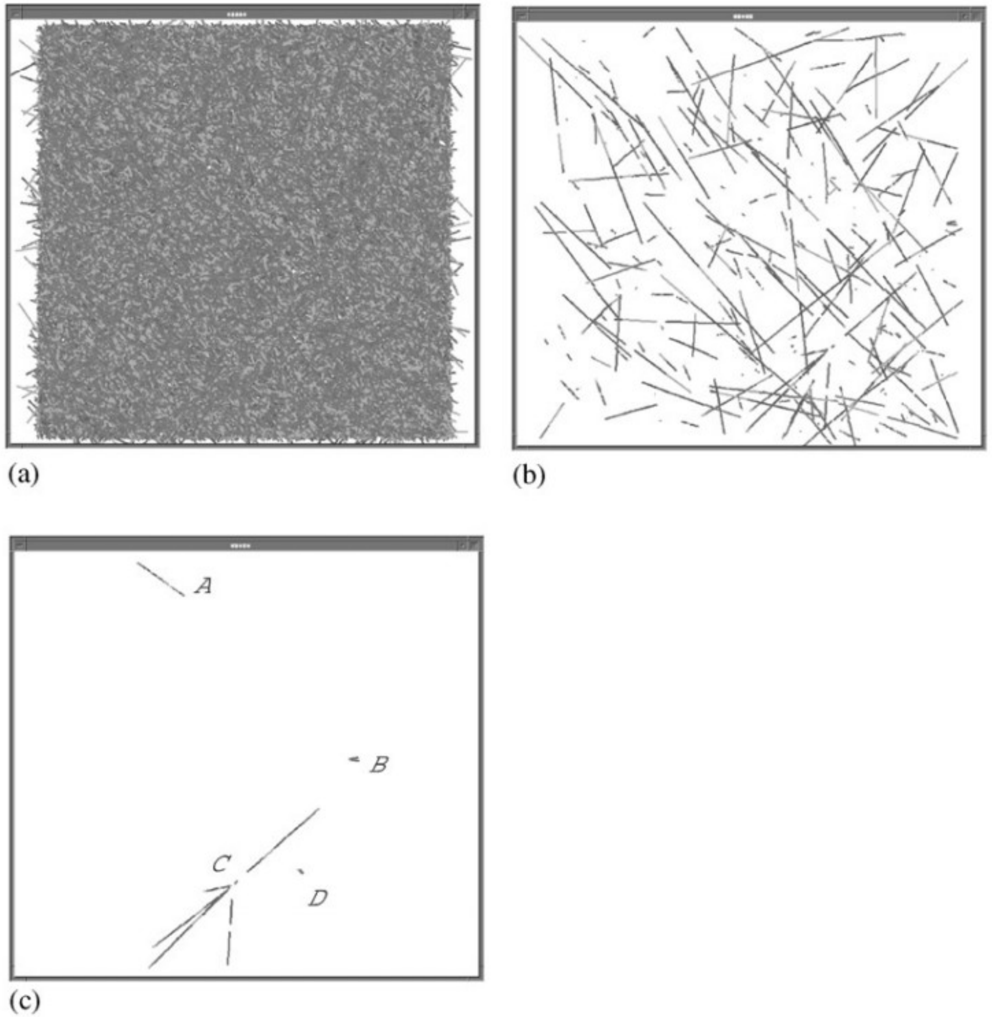
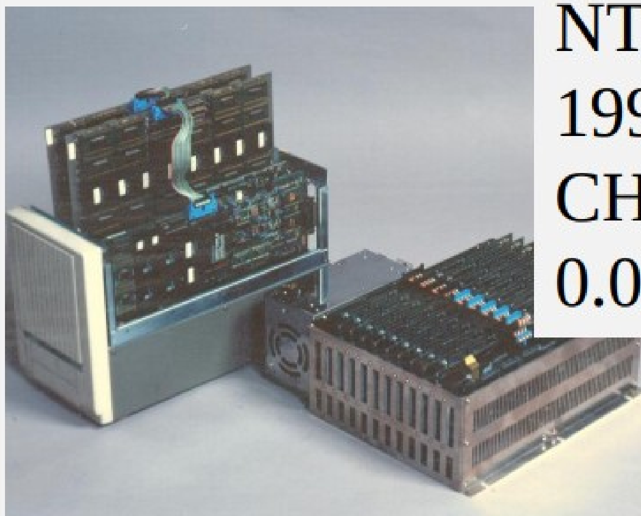


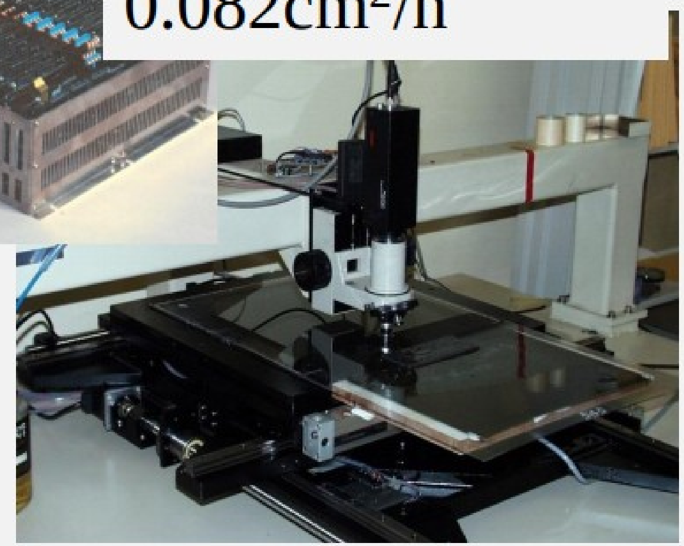
Fig. 18. Vertex location sequence by the NETSCAN in the case of a event (Run 3118 Event 11989): (a) after alignment, (b) after the rejection of penetrating tracks, and (c) after the vertex requirement.

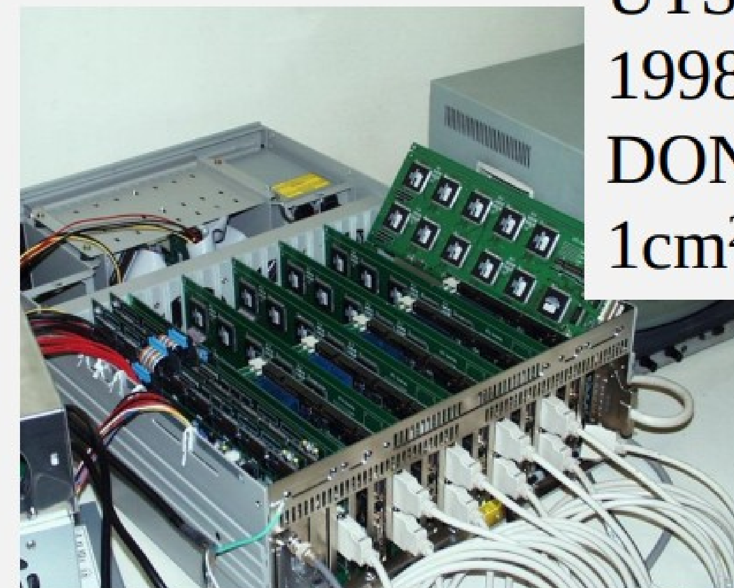
- Slide from T. Nakano, whose oft-cited thesis is on the development of emulsion readout

History of emulsion readout system in Nagoya



NTS (CPLD)
1994~
CHORUS
0.082cm^2/h





UTS (FPGA)
1998~
DONUT
1cm^2/h

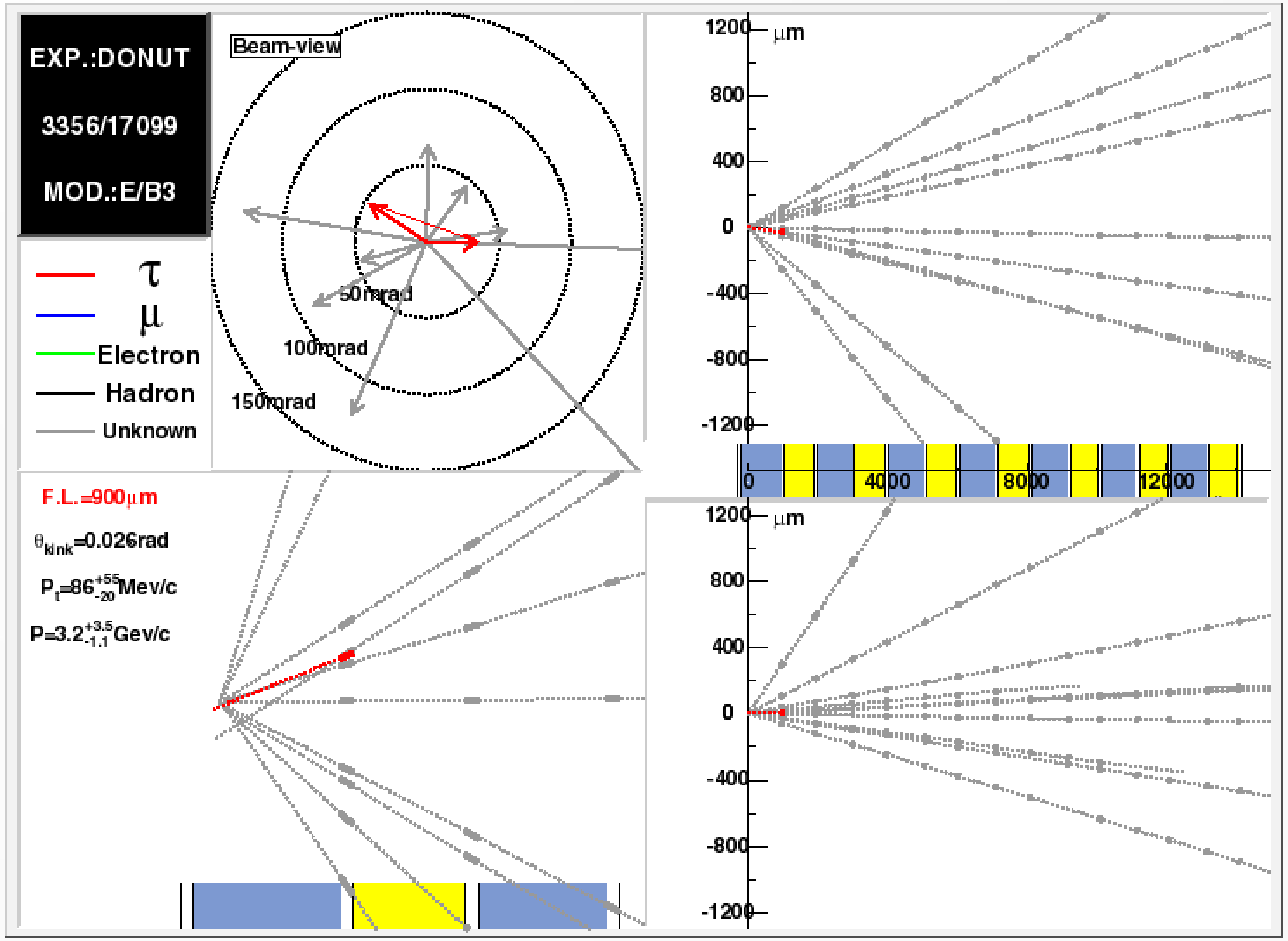
No picture

TS (TTL)
1983~
E653
0.003cm^2/h

Each new system has enabled new experiment

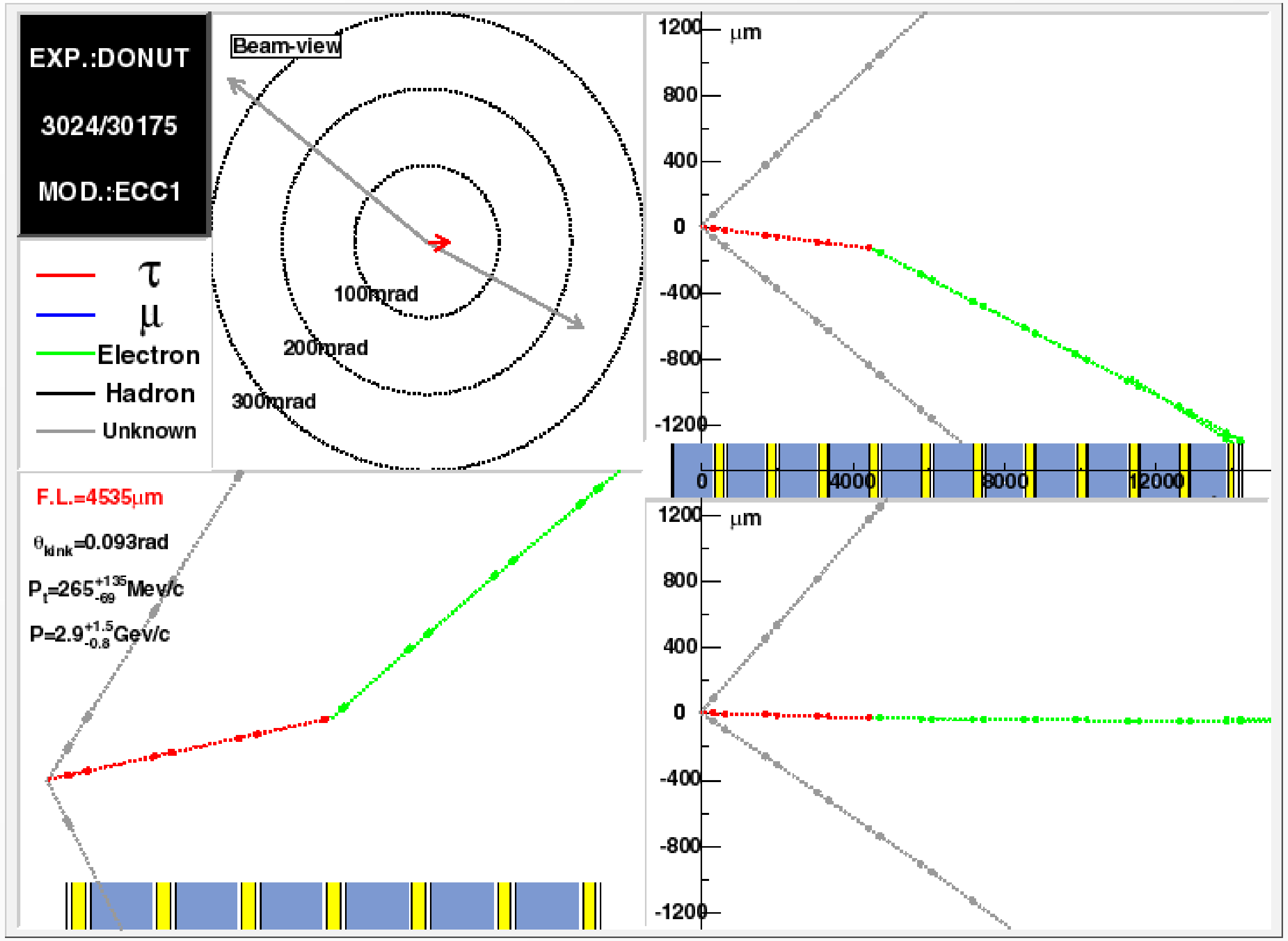
Refined Vertex Analysis

- Having identified candidate vertices of neutrino interactions, the analysis then tries to sort out ν_τ CC interactions
- Redo the scan and track construction in the region around and up to 2 plates downstream of the identified vertex, require track resolution better than 0.6 μm
- Label tracks pointing to vertex which stop in the scan volume as decay candidates
  - Tracks starting withing 2 plates downstream and approaching within 10 μm of a decay candidate are considered daughter candidates



Final Selections

- At least one segment of parent track in emulsion data
- Only 1 daughter per parent
- Parent track < 5 mm
- Angle of daughter w.r.t. parent is 10 mrad < θ < 400 mrad
- Impact parameter of parent to vertex < 10 μm
- Impact parameter of daughter to vertex < 500 μm
- Daughter momentum > 1 GeV
- P_T of decay > 250 MeV
- No ID'd μ or e at primary vertex



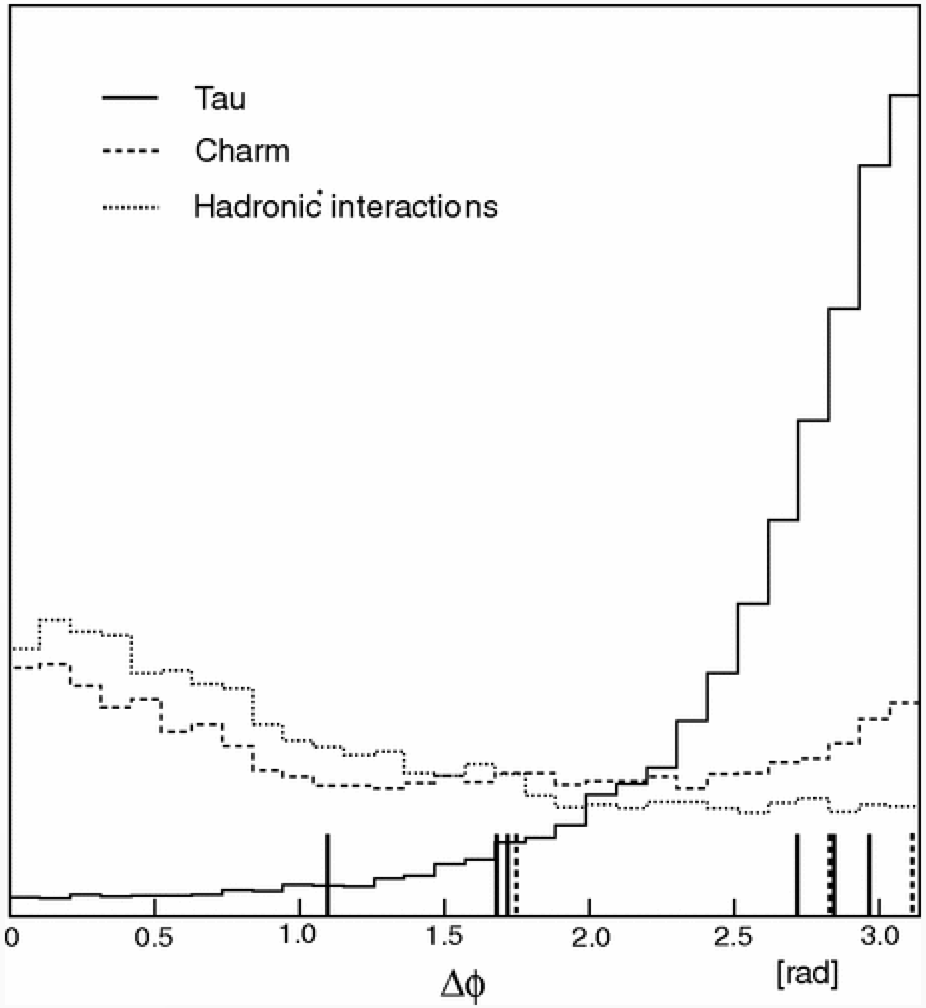
First Results (Discovery, 2000)

- After all selections, experimenters observed 4 ν_τ interactions with an expected background of 0.34 events
- Dominant backgrounds include
  - Charmed meson decays from other neutrino interactions (0.18 ± 0.03)
  - Hadronic interactions of particles from primary vertex (0.16 ± 0.04)
- 4 signal events classified as 2 electronic and 2 hadronic decays

DONUT Nutritional Facts (not USDA certified):	
Serving size:	4.6×10^{17} protons on target
Triggers:	6.6×10^{6}
triggers from neutrino interactions	~1100 +/- 300
predicted vertices	901
vertices located in emulsion	699
digitized vertices	511
vertex locations attempted	451
vertices located	264
vertices scanned	203
tau neutrinos observed	5
Notes:	
If the track that caused the trigger was found to originate in the emulsion target it became a candidate for examination. For a vertex to be considered for examination it had to be projected into the emulsion, contain no showering from nearby muon interactions and have a visible energy above 2 GeV. Of the vertices scanned, 71 were identified to be muon interactions. The calorimeter was used to separate the electron neutrino, muon neutrino and neutral current interactions resulting in electron production from the tau events.	

Final Results (Refined Analysis, 2008)

- The final result from the collaboration came 11 years after data taking
- Analysis refinements included
  - Addition of 3-prong τ decays to the analysis
  - Separate cutflows for hadronic and leptonic decay candidates
  - Multivariate analysis to assign probabilties that final candidates belong to each of 3 categories (ν_τ CC/D decays/ν_l w/2nd interaction)
- Final event tallies:
  - NC: 224 (244±15 exp.)
  - ν_e: 120 (110±10 exp.)
  - ν_μ: 214 (225±15 exp.)
  - ν_τ candidates: 9 (10±3 exp.)
    - 7.52 ν_τ
    - 1.26 charm
    - 0.22 secondary interaction
- Measured ν_τ cross-section with 30% uncertainty



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Thanks for listening!