Review of Particle Measurements in Emulsion

Workshop on Hadron Production Measurements with Nuclear Emulsions

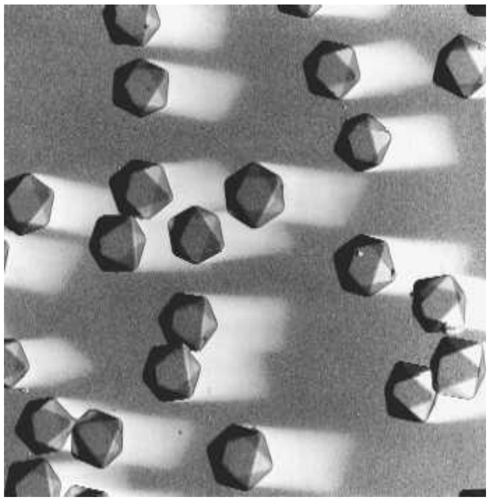
Masahiro Komatsu : Nagoya University

Nuclear Emulsion

Brief history of the Scanning System

EMULSION & SCANNING

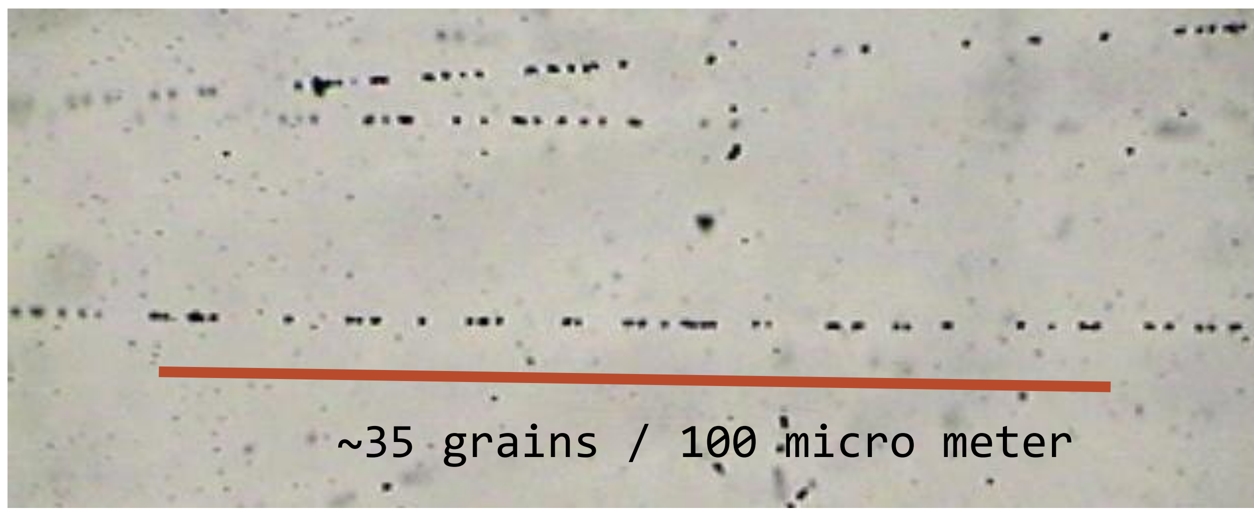
Nuclear emulsion



AgBr crystal : size 0.2 – 0.3 micro meter in diameter.

Charged particle produce latent image, developing process make Ag grain visible.

MIP



Grain Density (GD) : grains / 100 micro meter

Modern nuclear emulsion experiments

- Old type emulsion experiments
  - Fermilab E531 (neutrino induced charm) (1978)
  - CERN WA75 (B and charm) (1983-1984)
  - Fermilab E653 (B and charm) (1985-1987)
- Transition from Visual detector to Tracking detector
  - CERN WA95 CHORUS (1994-1997)
  - Fermilab E872 DONUT (1997)
  - OPERA (2008-2012)

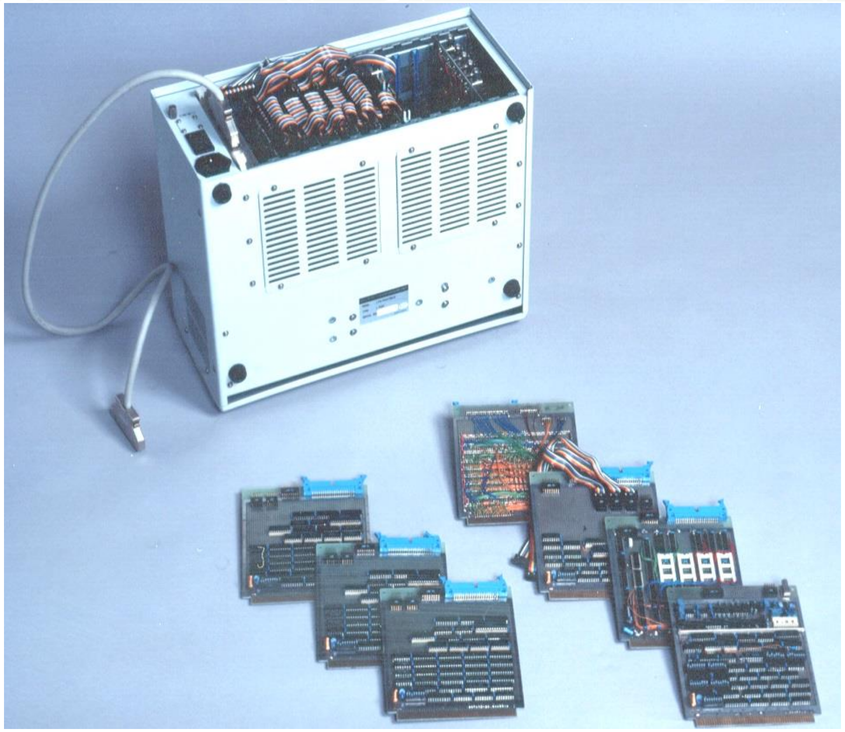
History of scanning system

semi-automatic scanning in late 1980's.

- Fermilab E653 and CERN WA75 analysis has been done with these systems with human aid.

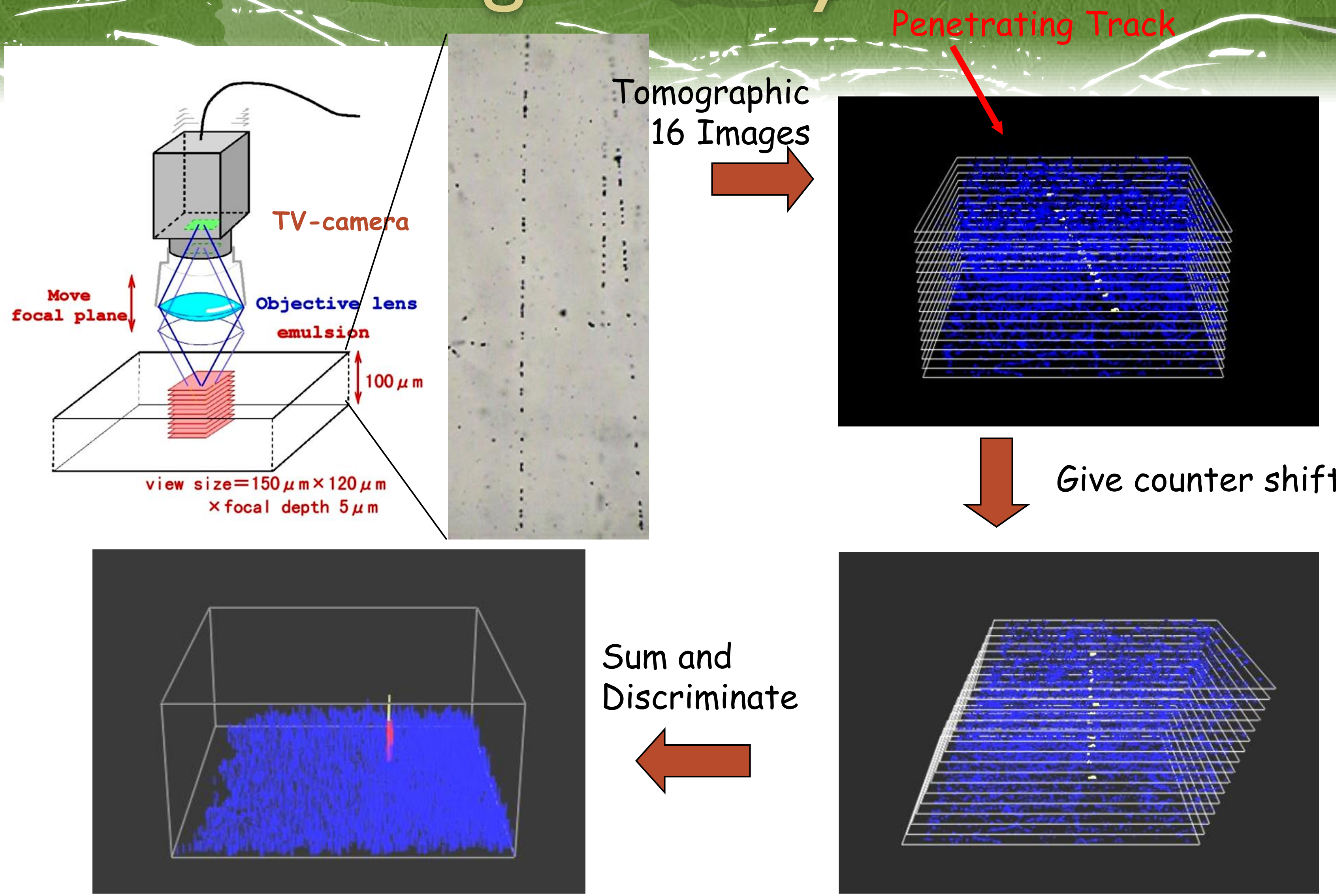
- Up to 1994, we used these systems for emulsion analysis.

Track Selector (TS) 1994



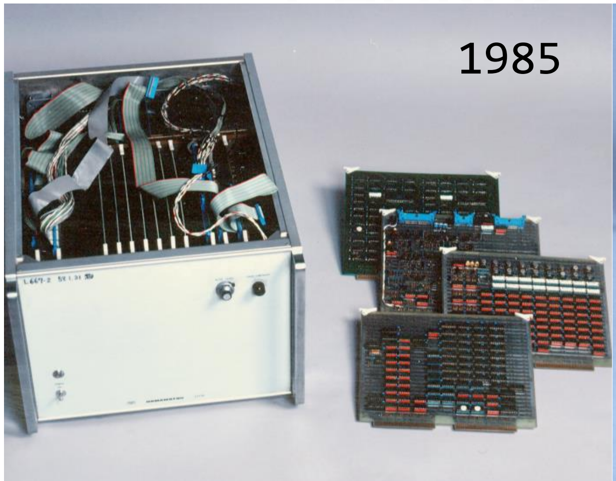
- 20 years ago, for CHORUS.
  - We made big decision to change future (current) emulsion scanning.

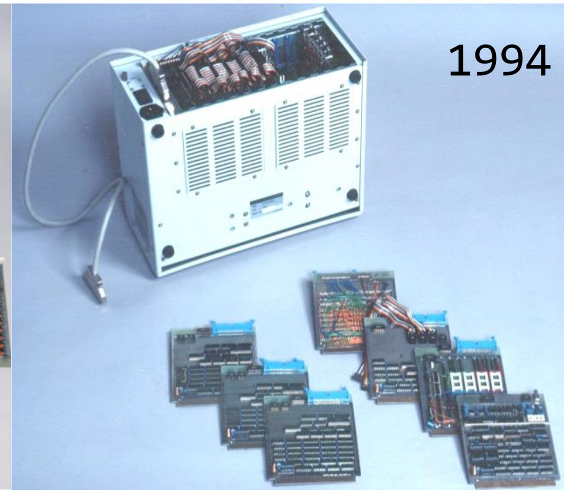
Track Recognition by TS

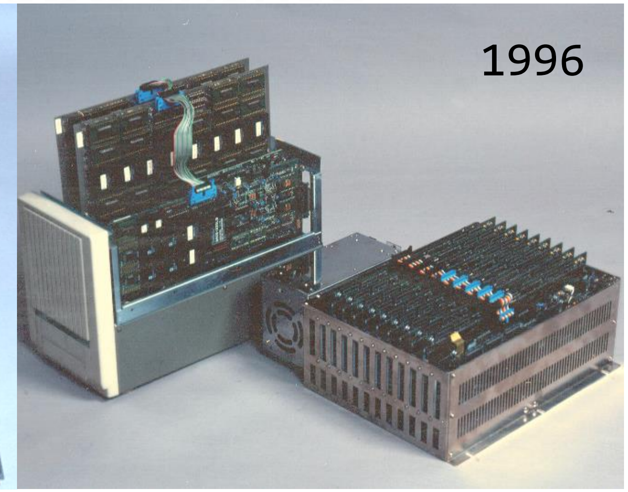


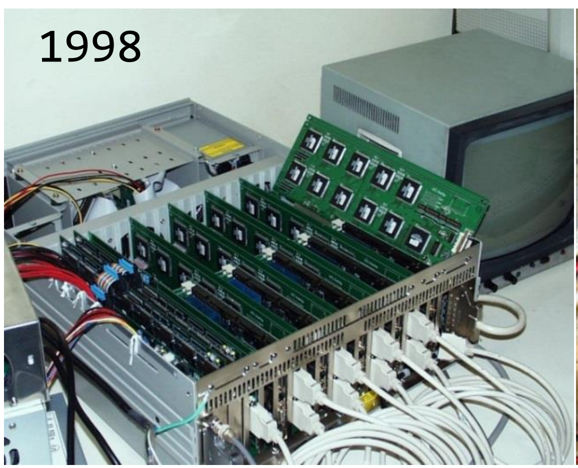
Evolution of the scanning system

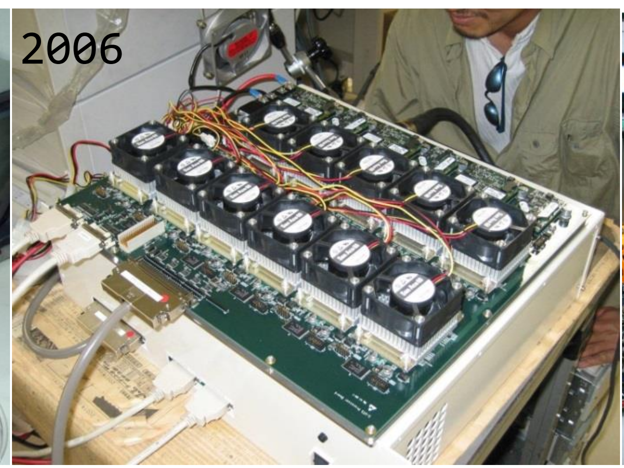
CHORUS, DONUT, OPERA and future…

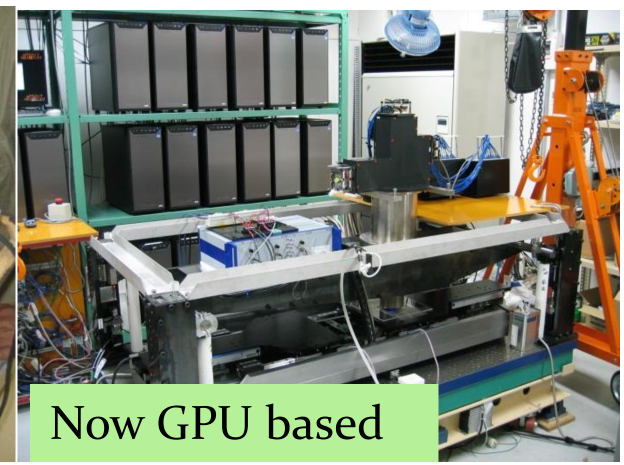






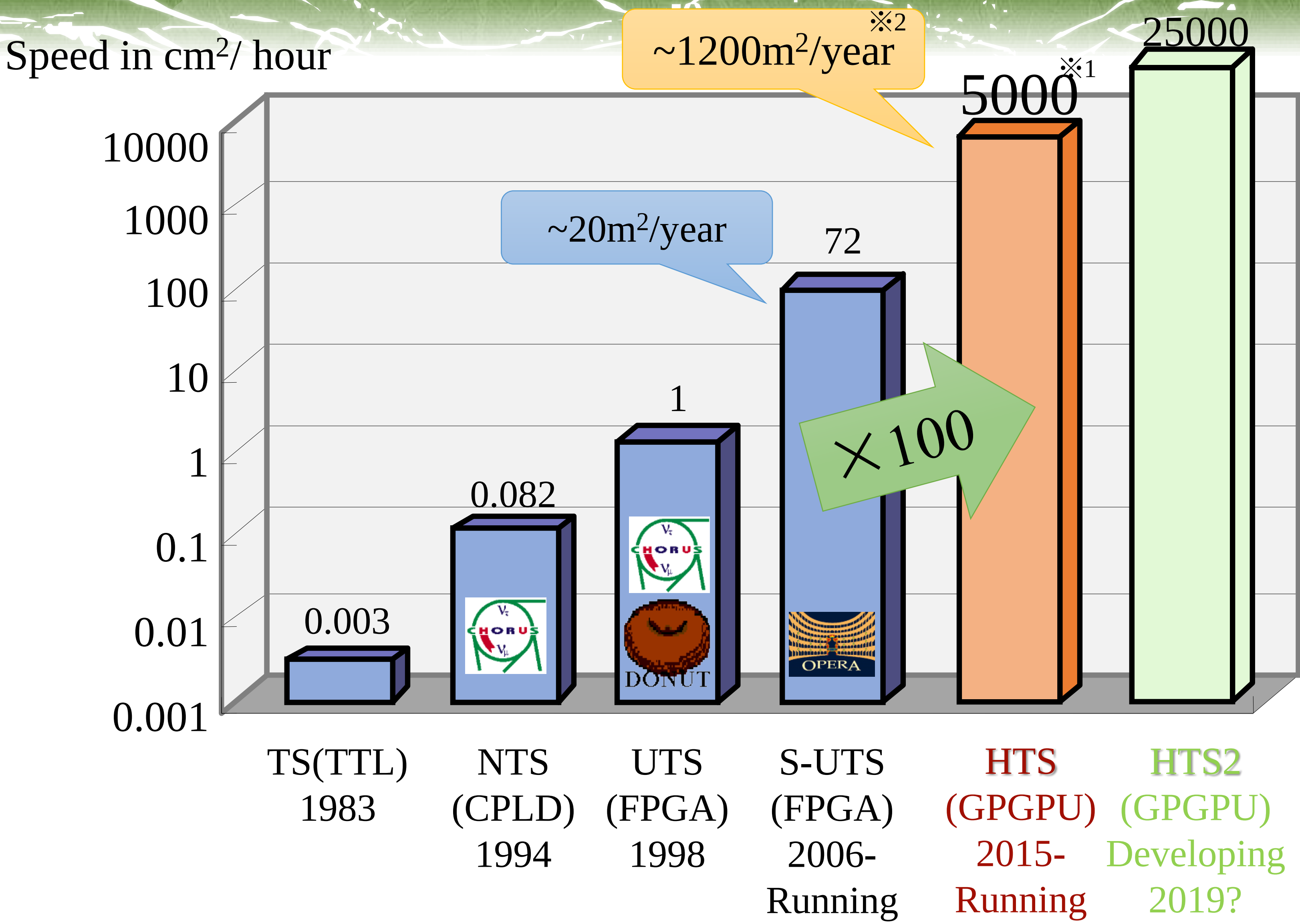






Scanning speed

※1 Area of each layer
※2 Area of the films



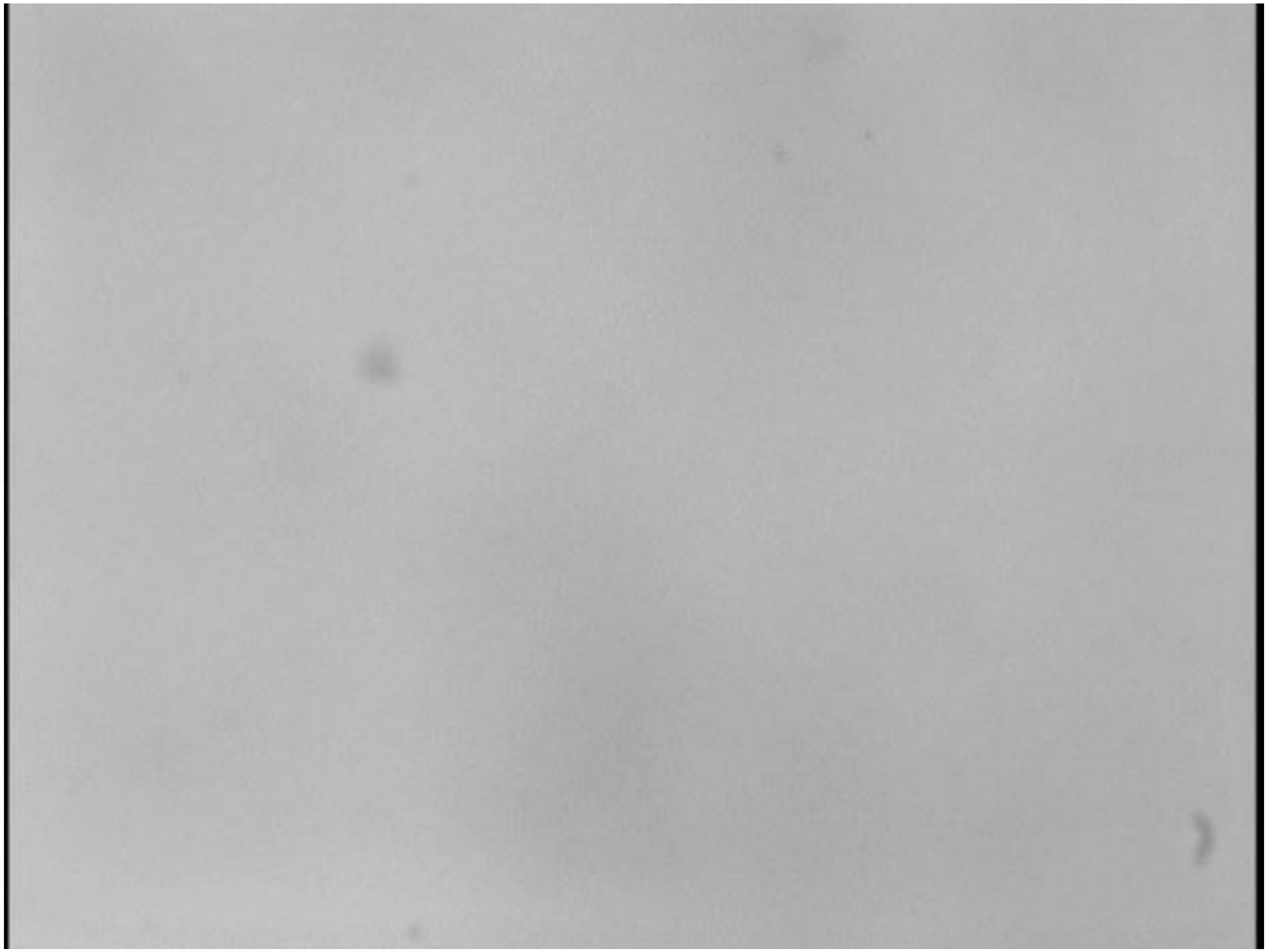
Type of emulsion

BULK & ECC

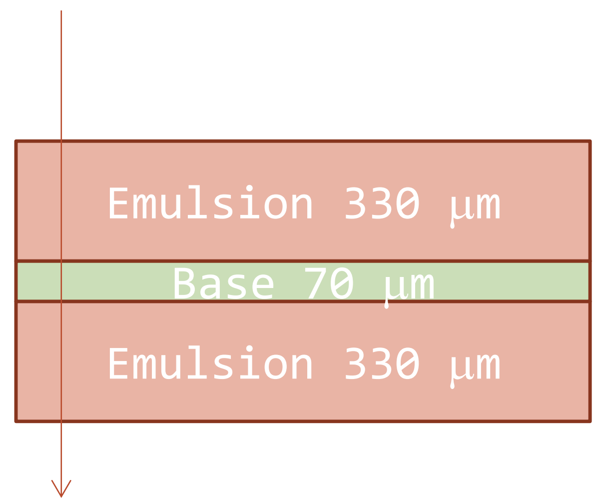
Type of Nuclear Emulsion detector

- Bulk emulsion
  - Emulsion is interaction target and tracking device.
  - All charged tracks are visible
    - Good for hyper nuclei : KEK-E176,E373, J-PARC:E07
  - Expensive, target nuclei is unknown
- ECC (Emulsion Cloud Chamber)
  - Emulsion is tracking detector
  - Interaction point is invisible
  - Good for kinematical measurements

Bulk emulsion



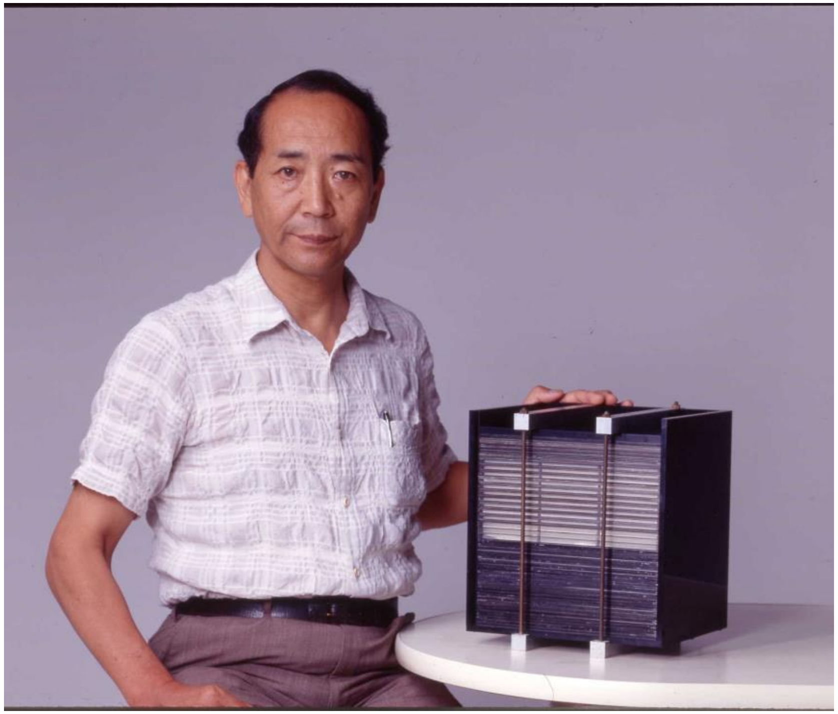
Fermilab E653 2nd run
600 GeV/c π^-

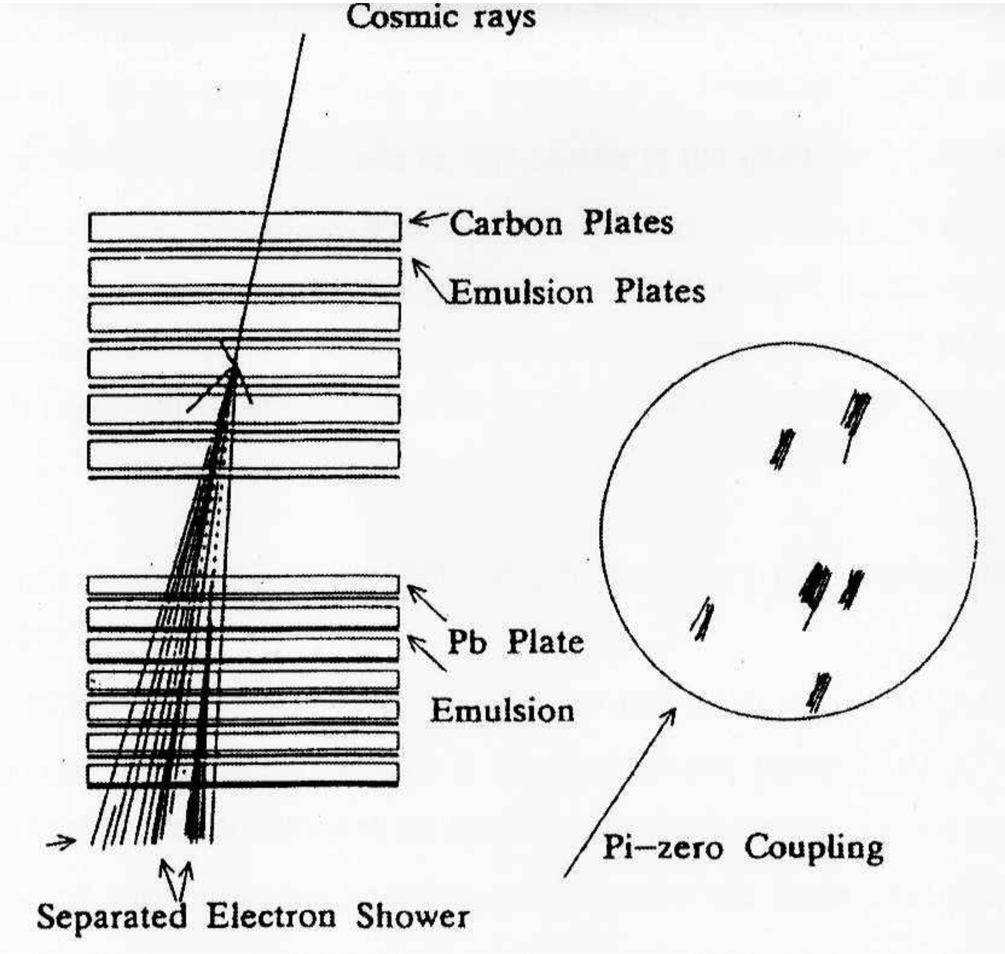


ECC (Emulsion Cloud Chamber)

ECC : Utilized in cosmic-ray exposure → Discovery of Charm in 1971 (K.Niu)

Prog. Theor. Phys. 46 (1971) 1644-1646

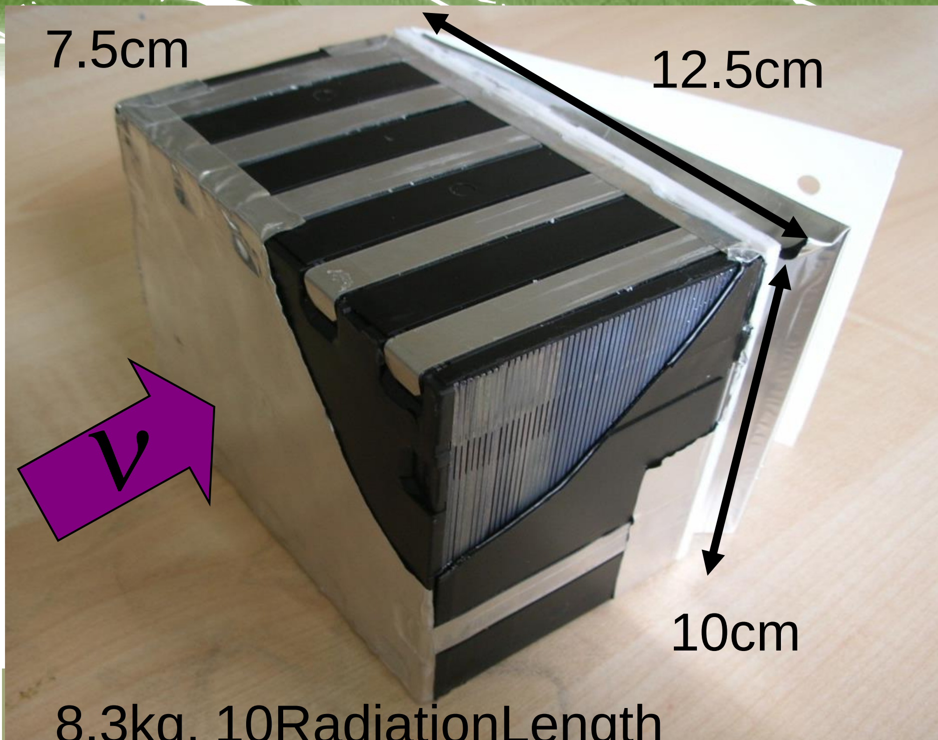


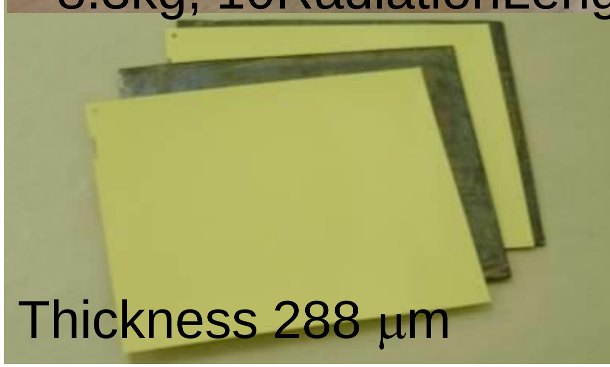


ECC (Emulsion Cloud Chamber)

- We can choose target (passive) material on purpose.
  - Ex. Carbon for interaction target and lead for calorimetry
  - DONUT : stainless steel
  - OPERA : lead
- Vertex detector and sampling colorimeter
  - Various detector design is possible

OPERA ECC brick





- ECC properties
  - 56 of 1mm thick lead plates interleaved with 57 emulsion films.
  - 8.3kg / brick
  - 10 radiation length
- 150,000 ECC bricks
  - 1.25 ktons
  - 9 million films
- Capability
  - Micrometric accuracy vertex analysis
  - Kinematical analysis
    - Momentum measurement by MCS.
    - EM energy measurement

HYBRID DETECTOR

Hybrid detectors

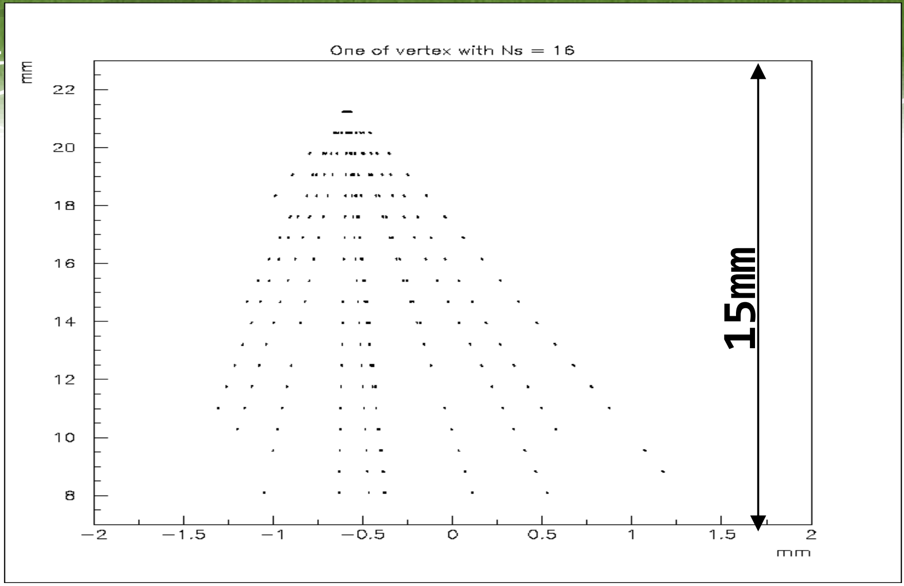
E653, CHORUS, DONUT, OPERA and SHiP

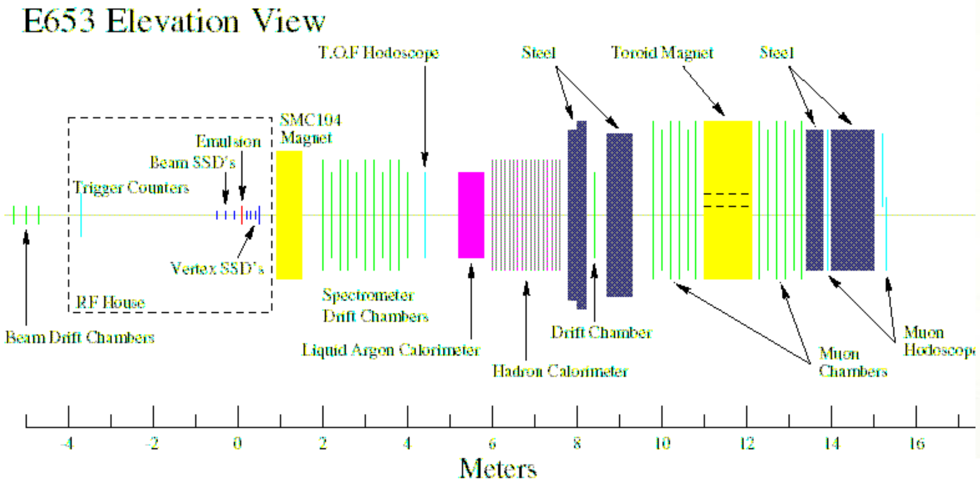
Hybrid detector

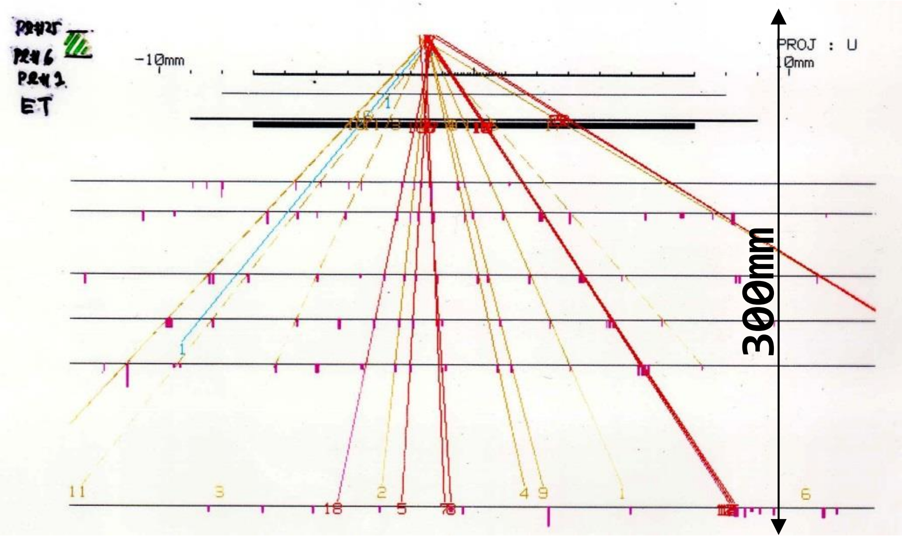
- Hybrid detector has been used in the past experiments
  - Vertex prediction, calorimetry, charge and momentum, time stamp and muon ID
  - High energy beauty and charm hadro-production experiments (WA75,E653)
  - Neutrino experiments (E531,CHORUS,DONUT,OPERA)
- Some part of functions can be replaced by emulsion detector
  - Calorimetry, Momentum : ECC
  - Charge, Momentum : Emulsion spectrometer
  - Time stamp : Emulsion Shifter

Fermilab E653

- Beam exposure in 1985(May to August). 10^8 interactions are recorded in emulsion modules.
- Analysis of E653 finished in 1996.
- Event location is guided by 18 layers of SSD. Accuracy was 100μm in transverse and 1mm in longitudinal.

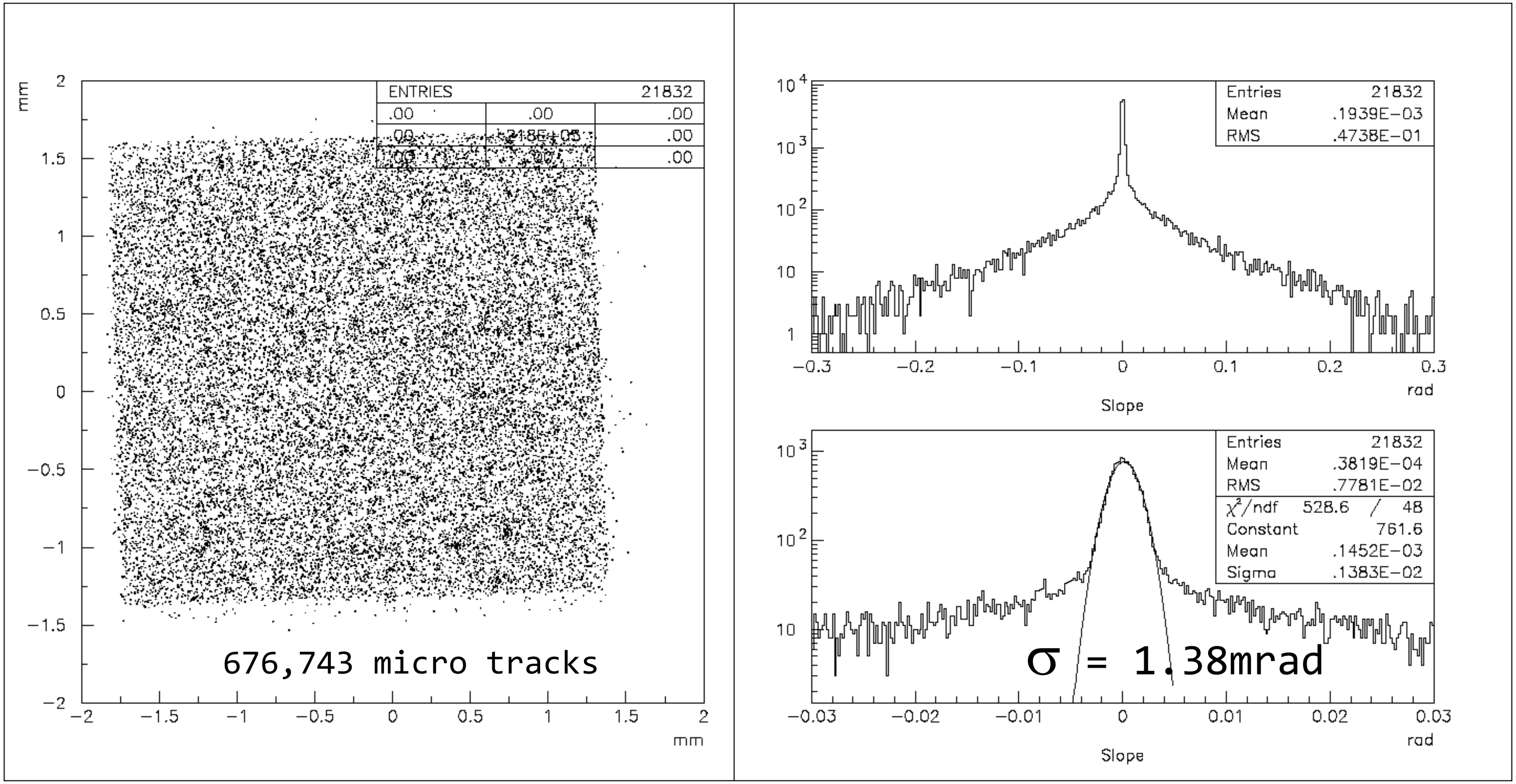




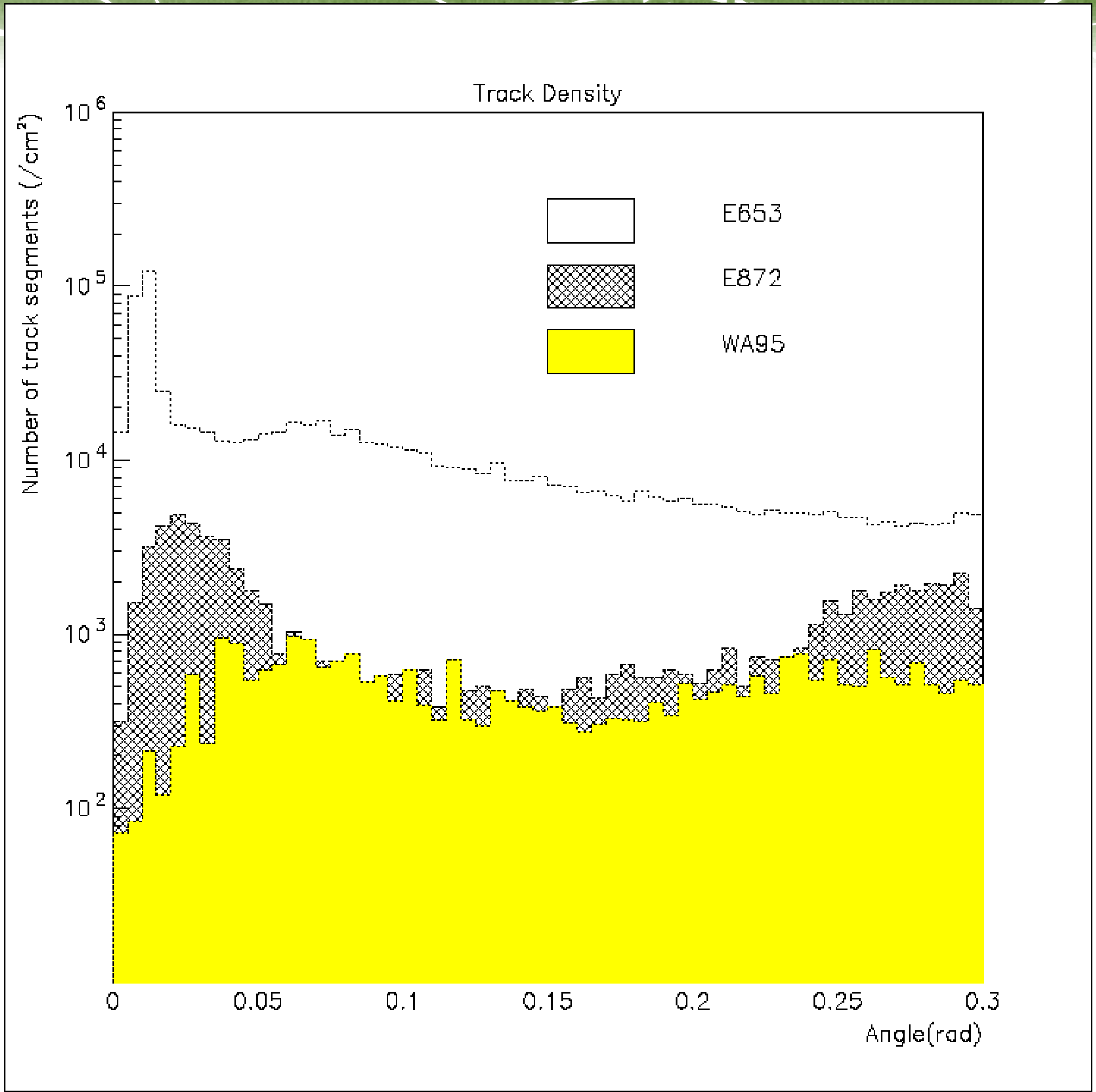


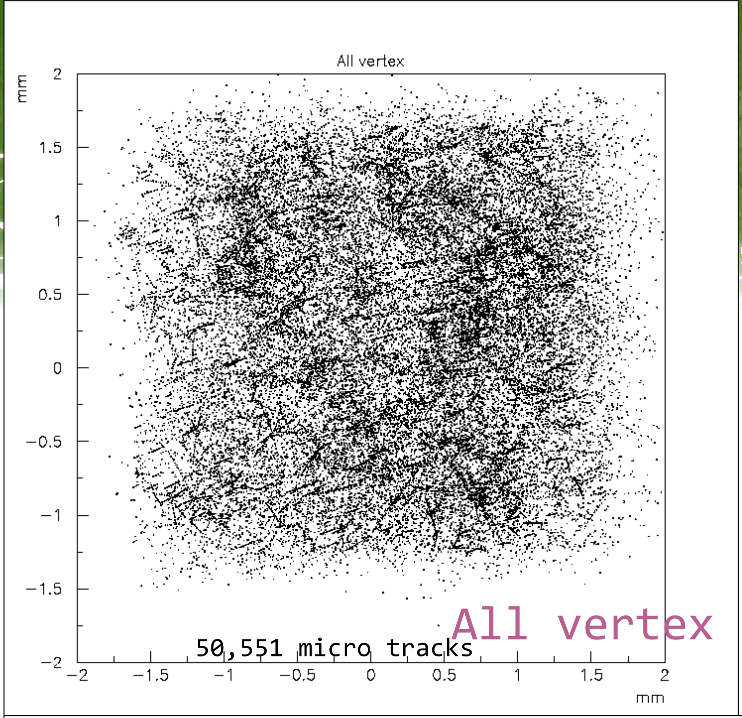
NetScan data of Fermilab E653 with Software developed in DONUT

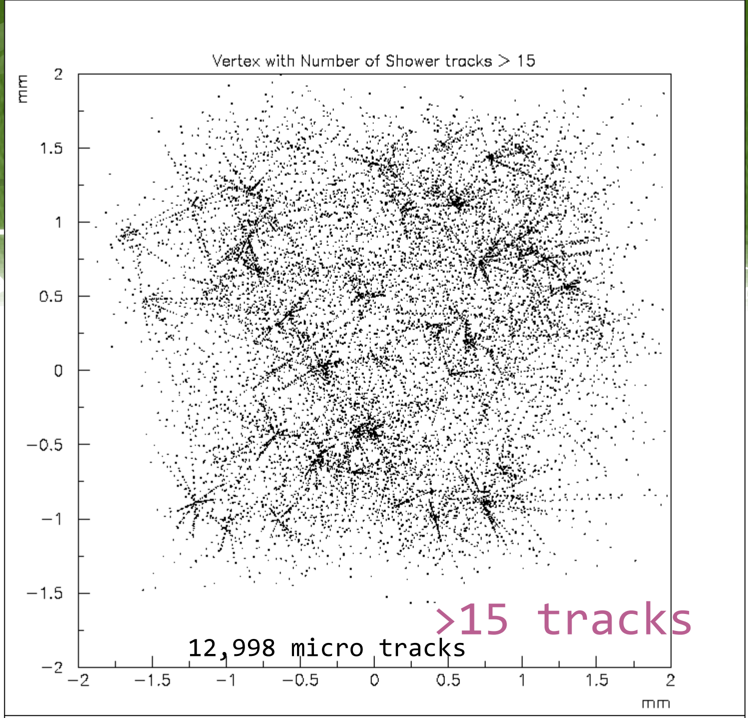
NetScan application in very high track density emulsion (2002) : 10^5 tracks /cm^2
800 GeV proton beam exposure. 3mm x 3mm within 300mrad tracks for 20 plates.

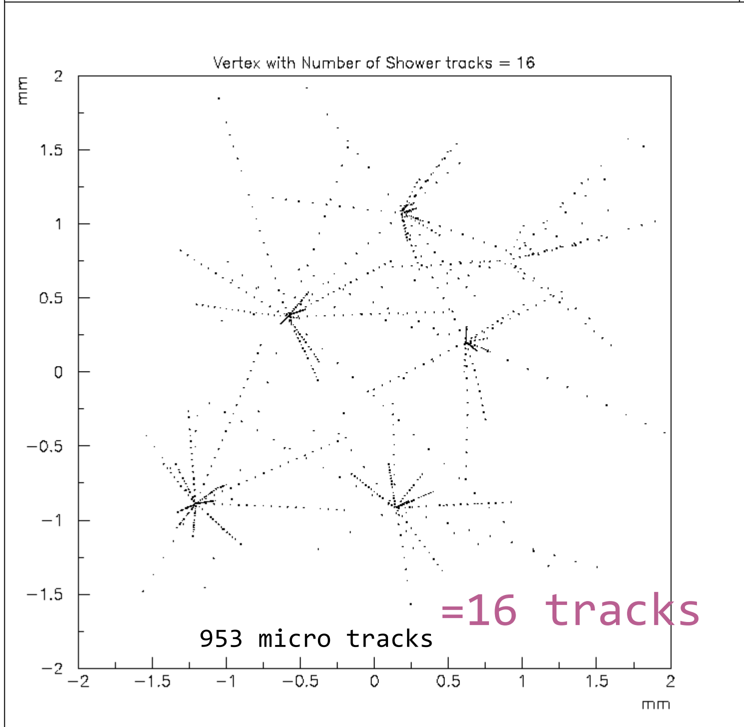


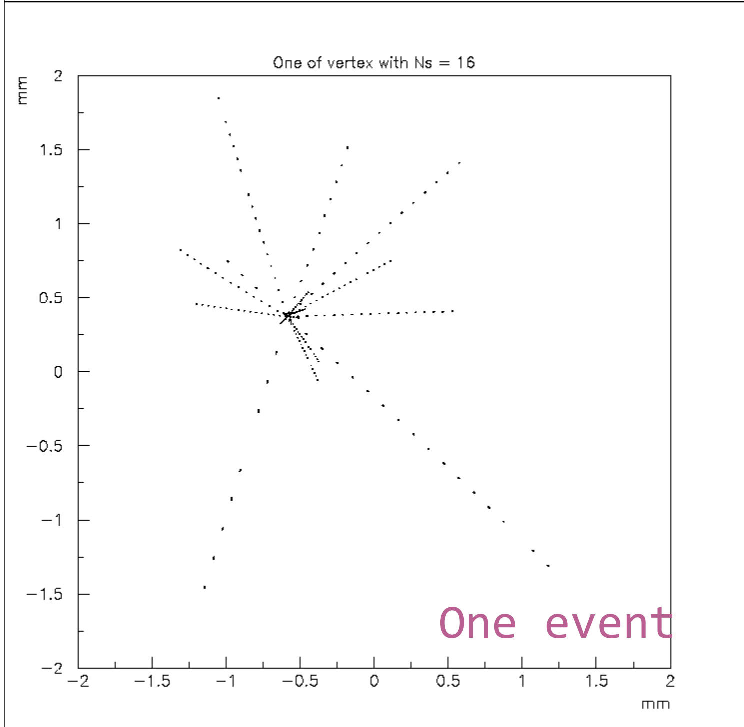
Track density in NetScan




All vertex
mm
2
1.5
1
0.5
0
−0.5
−1
−1.5
−2
−2 −1.5 −1 −0.5 0 0.5 1 1.5 2
mm
All vertex
50,551 micro tracks

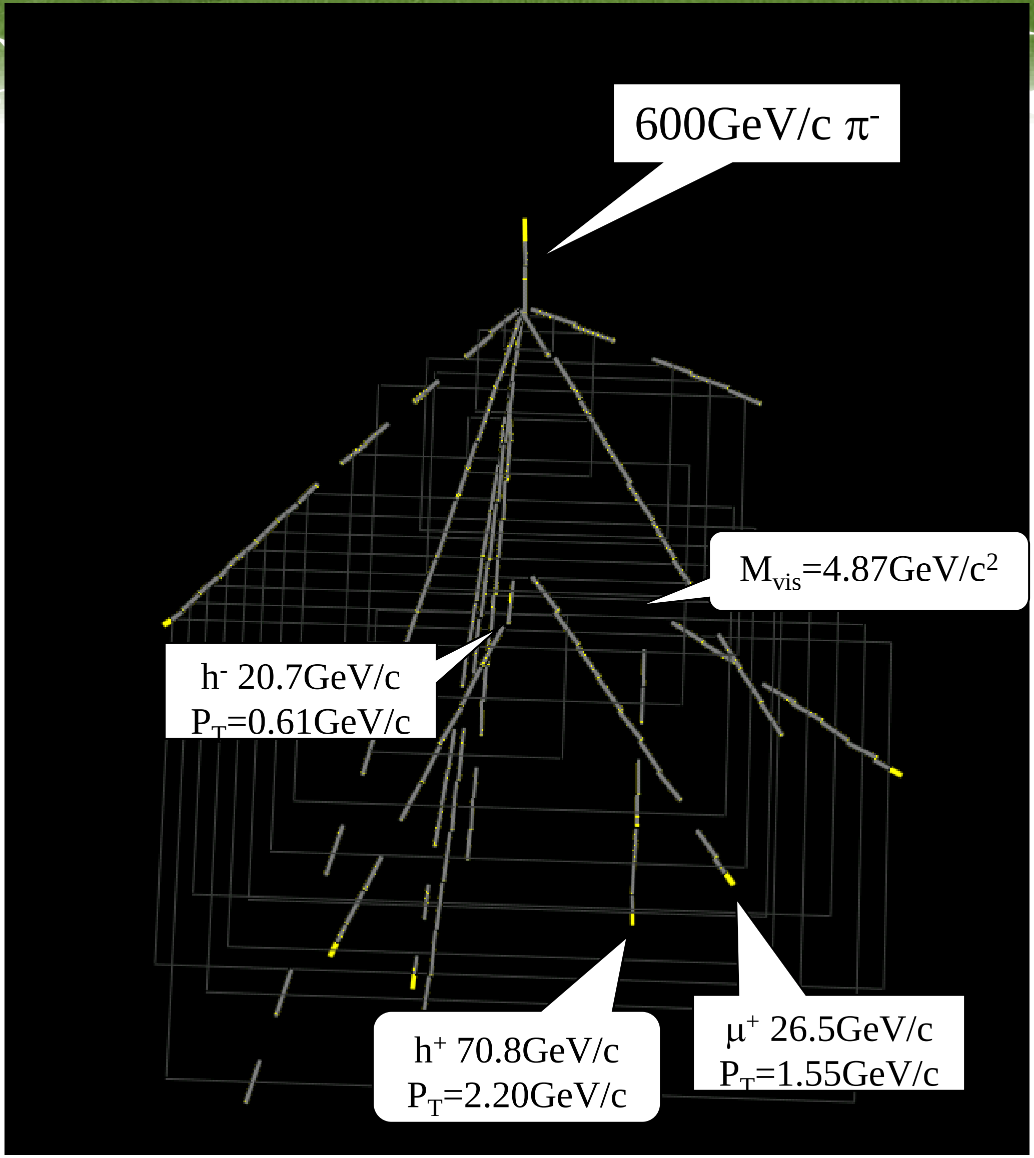

Vertex with Number of Shower tracks > 15
mm
2
1.5
1
0.5
0
−0.5
−1
−1.5
−2
−2 −1.5 −1 −0.5 0 0.5 1 1.5 2
mm
>15 tracks
12,998 micro tracks


Vertex with Number of Shower tracks = 16
mm
2
1.5
1
0.5
0
−0.5
−1
−1.5
−2
−2 −1.5 −1 −0.5 0 0.5 1 1.5 2
mm
=16 tracks
953 micro tracks


One of vertex with Ns = 16
mm
2
1.5
1
0.5
0
−0.5
−1
−1.5
−2
−2 −1.5 −1 −0.5 0 0.5 1 1.5 2
mm
One event

B event in Fermilab E653 2nd run

- Beam exposure in August to November 1987.
  - 5×10^5 beam/cm2 ,5 times higher track density than 1st RUN.
- The first B events was found in June 18, 1990.
  - Prog. Theor. Phys.89:679-696,1993
- Full event structure is also reconstructed with NetScan method in March 2002.



CHORUS detector

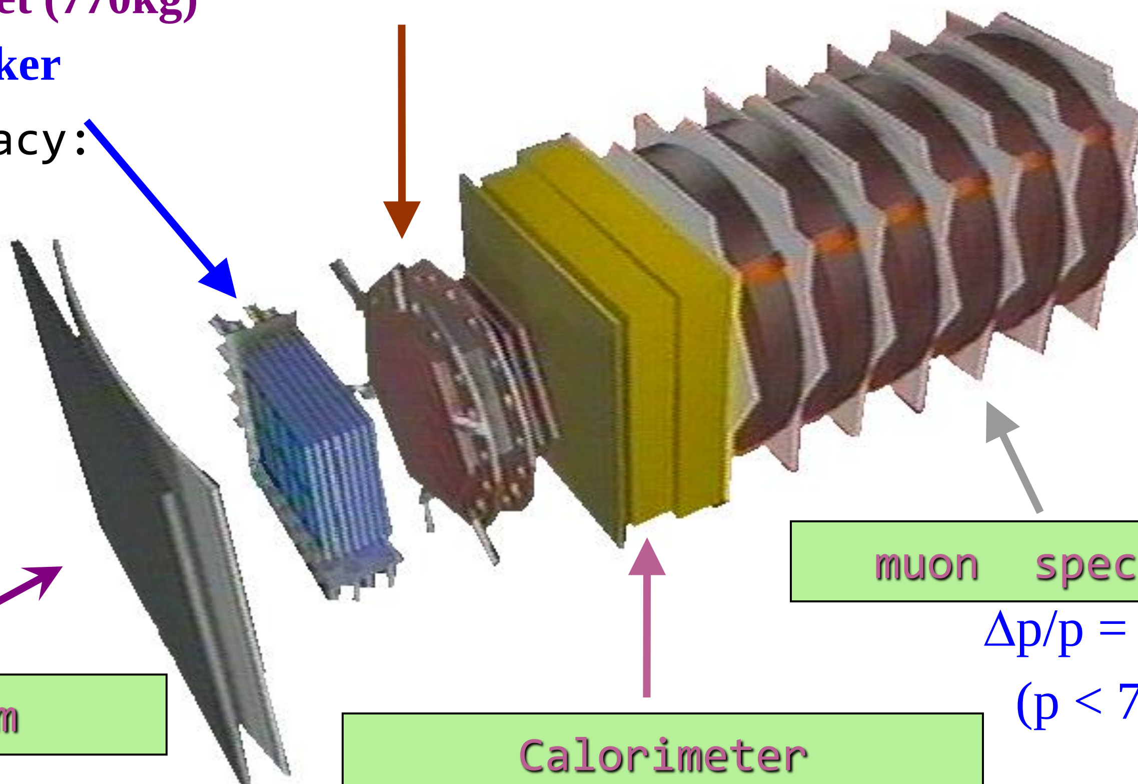
Active target

-nuclear emulsion target (770kg)

-scintillating fiber tracker

Prediction accuracy:
150-200μm in XY

$\Delta p/p = 0.035\ p\ (GeV/c) \oplus\ 0.22$



ν

Eν ~ 27 GeV

Neutrino beam

ν_μ :	ν_μ :	ν_e :	ν_e
1.00 :	0.05 :	0.017 :	0.007

muon spectrometer

$\Delta p/p = 10 \div 15\%$

$(p < 70\ GeV/c)$

Calorimeter

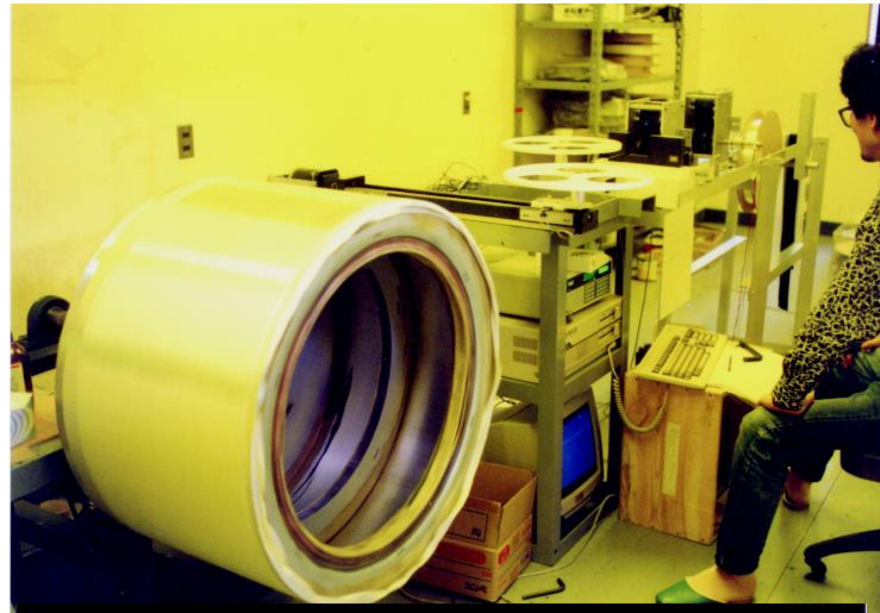
$\Delta E/E = 32\ \%/\sqrt{E}$ (hadrons)

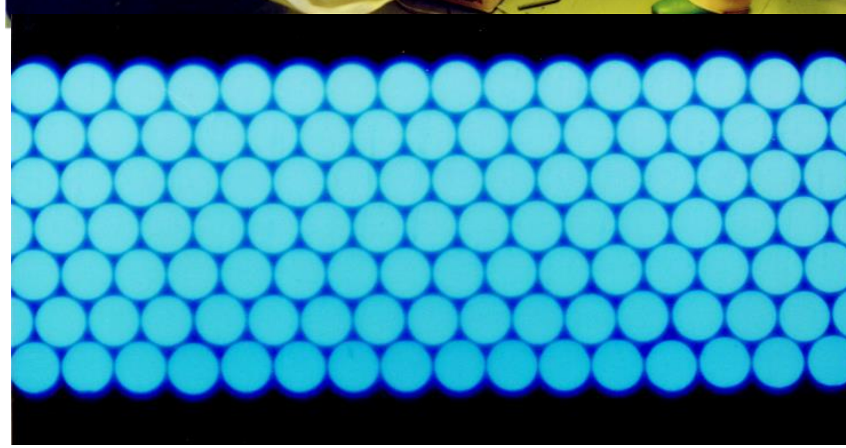
$= 14\ \%/\sqrt{E}$ (electrons)

$\Delta\theta_h = 60$ mrad @ 10 GeV

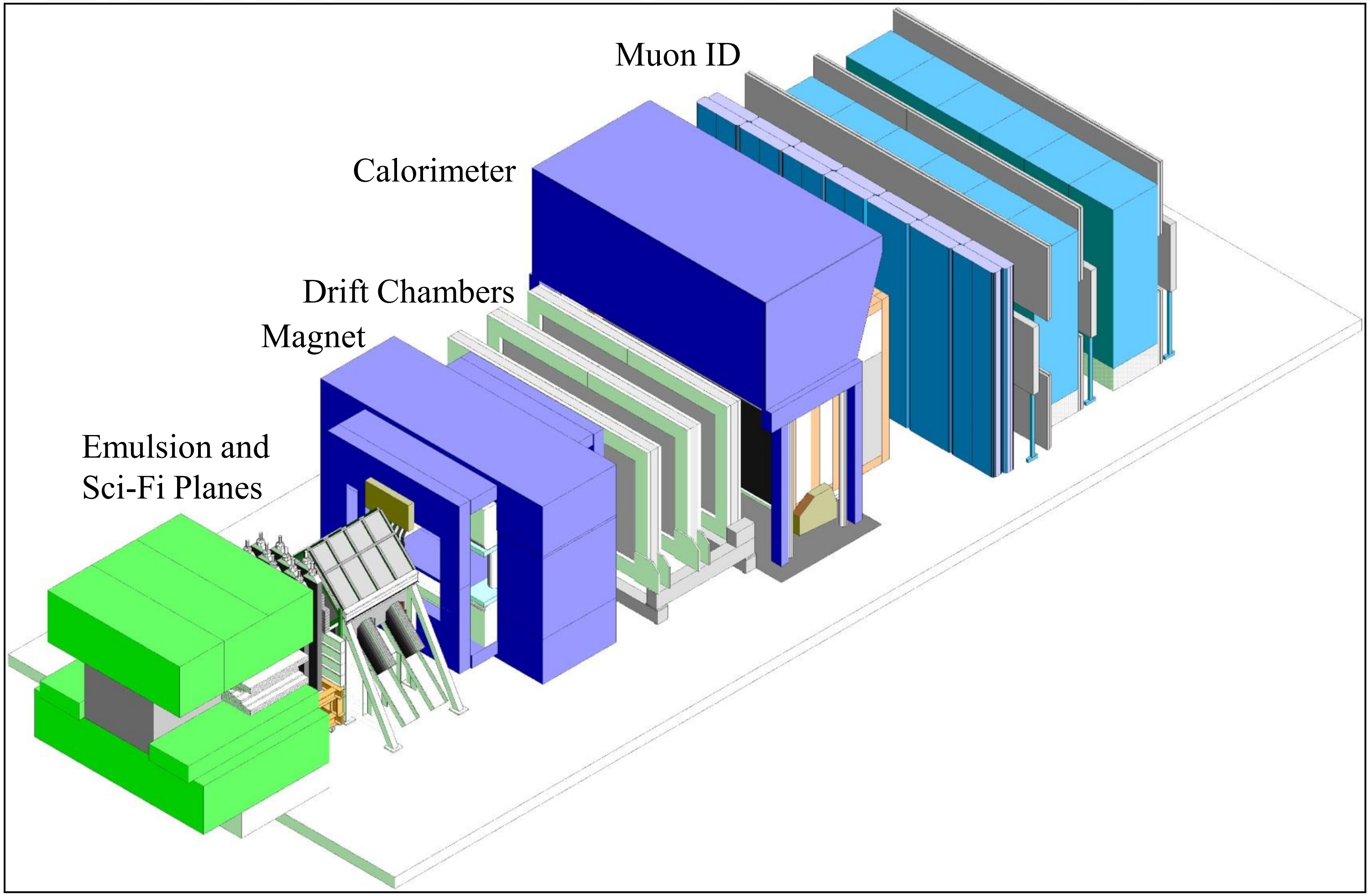
CHORUS SFT in production

In 1992, CHORUS SFT
Nakano, Sato, Kozaki and Nakamura

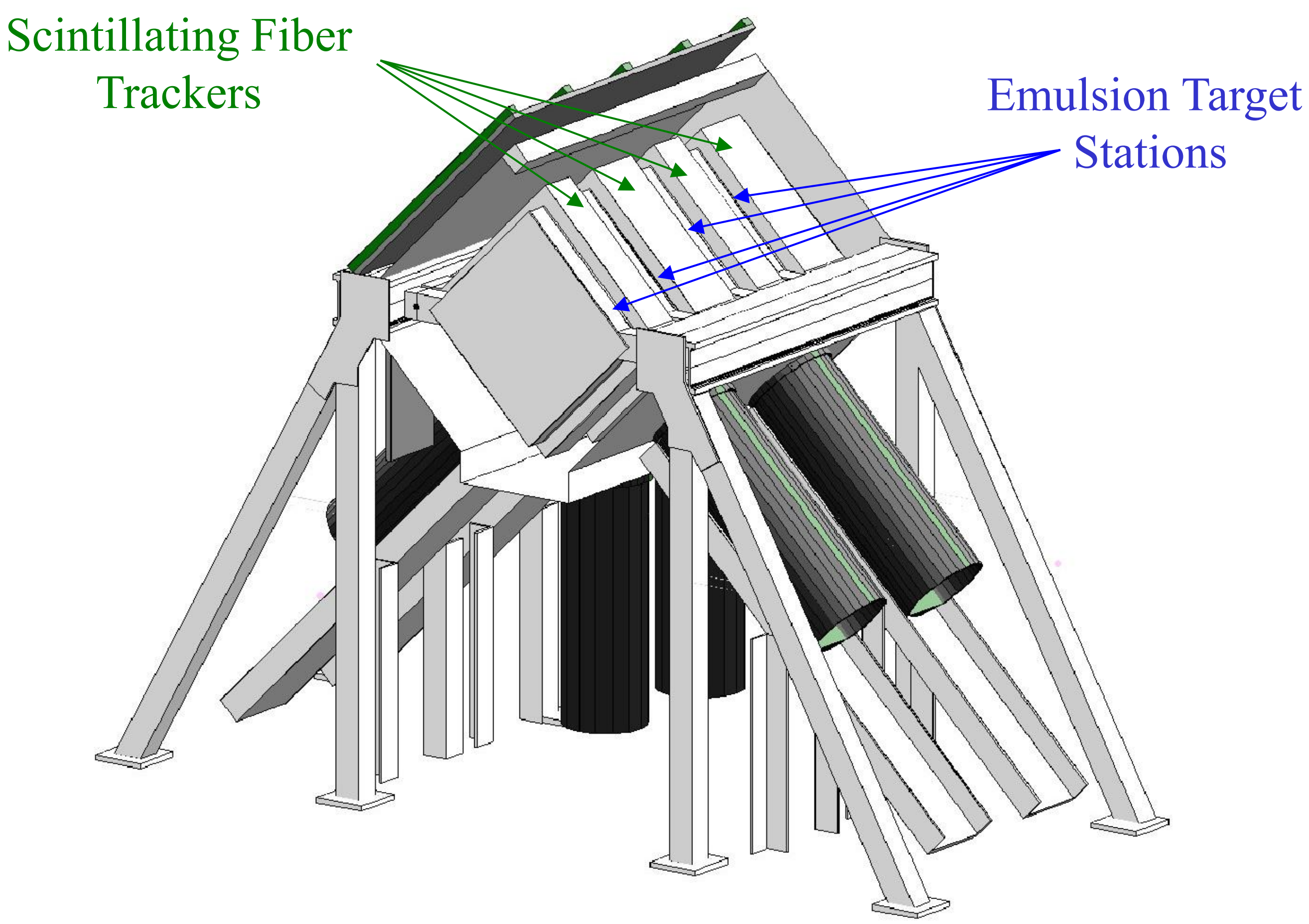




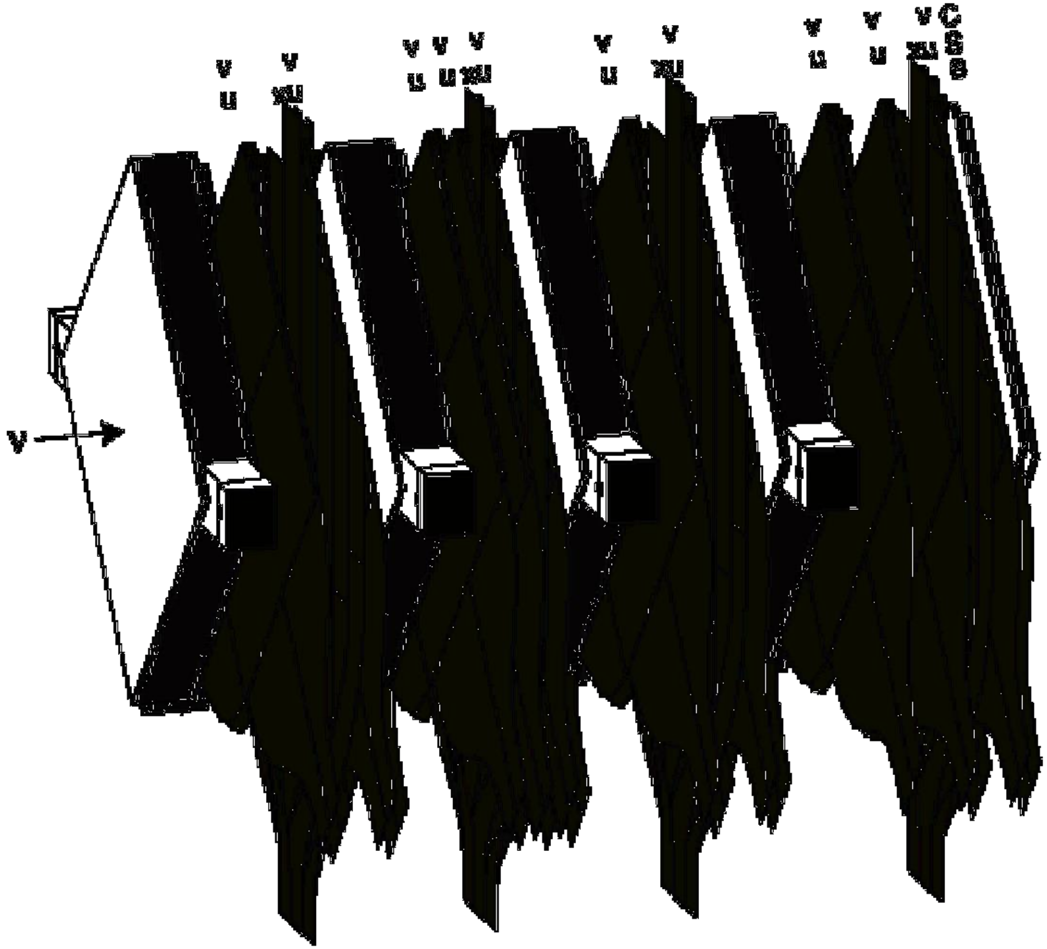
DONUT Detector complex



Emulsion Target Stations

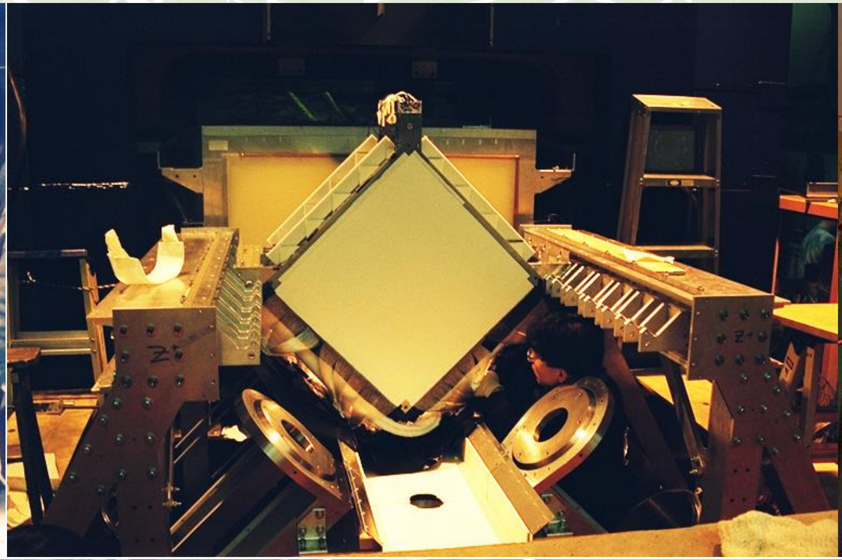


Emulsion Target / Vertex Detector

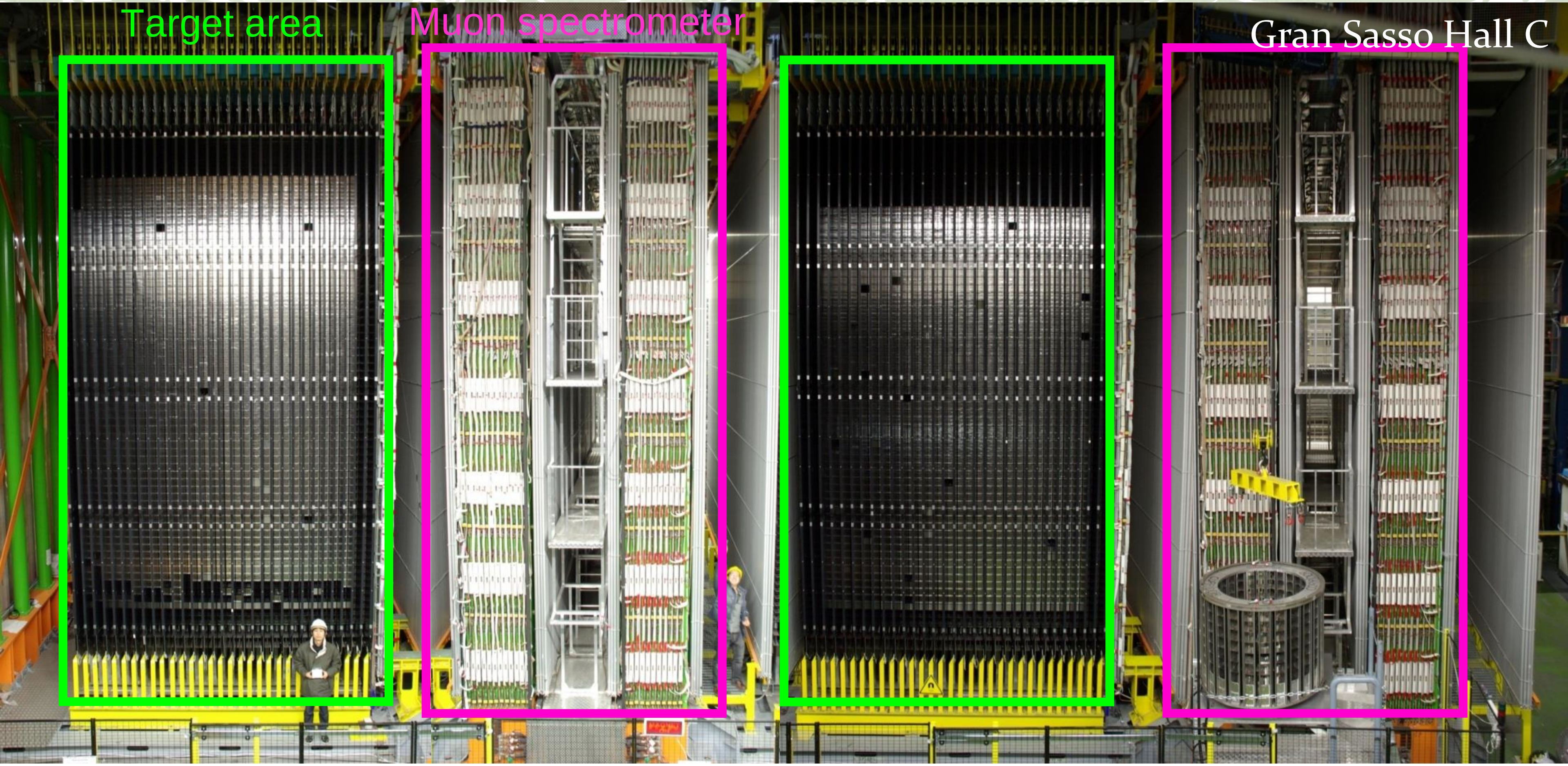


- Four target stations
- 260 kg total mass
- Interleaved with sci-fi
- Fibers → vtx prediction
- Total 7 modules exposed
- Modules ~2-3 X_0 each
- $\sim 0.2 - 0.3\ \lambda_{int}$ each

DONUT in construction



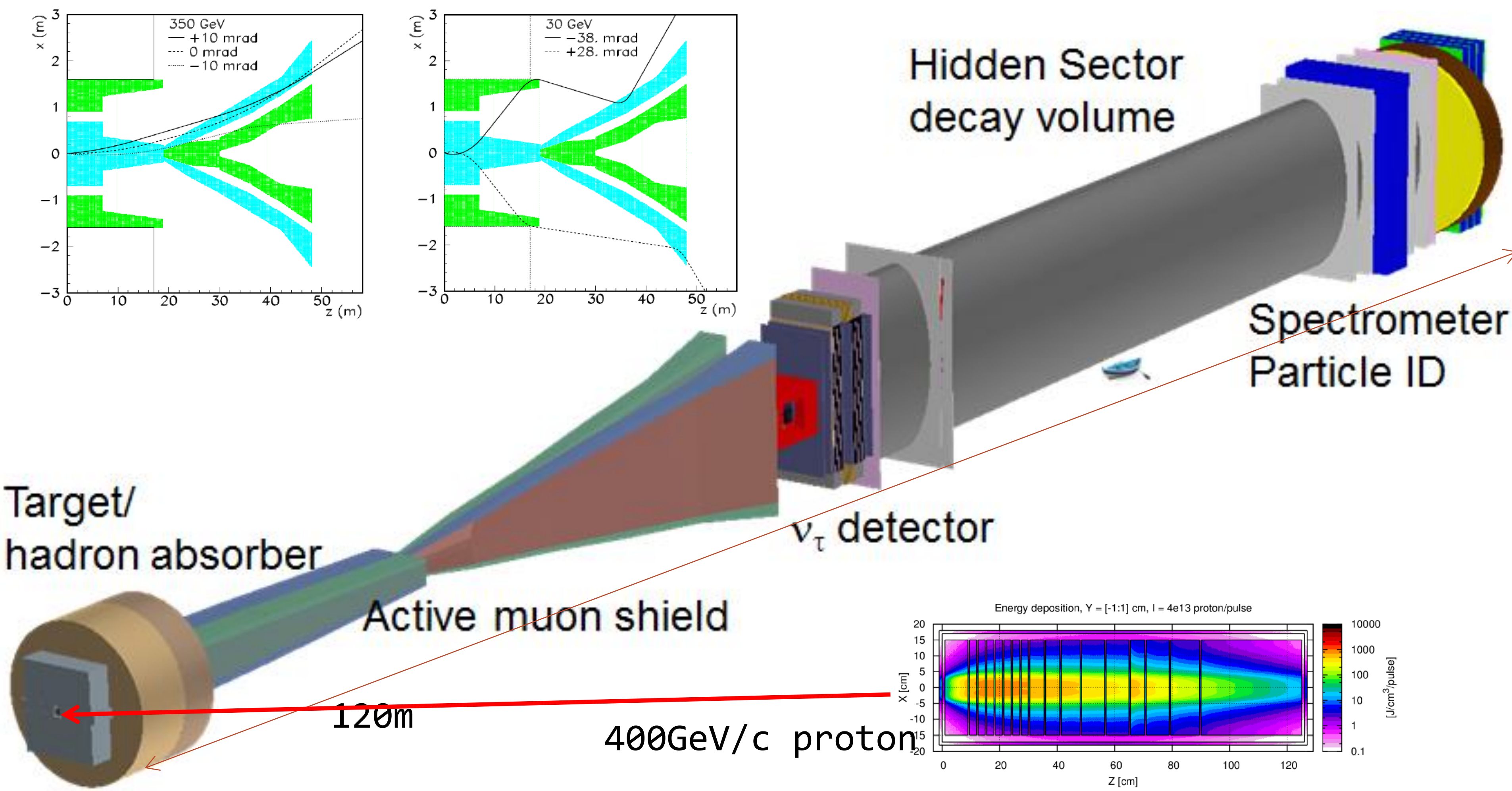
OPERA detector



- 150,000 ECC bricks = 1.25 ktons of active target

Next beam dump exp. : SHiP
DONUT x 400

Proposal submitted : Apr. 2015



Position resolution (Short lived particle)

Particle ID

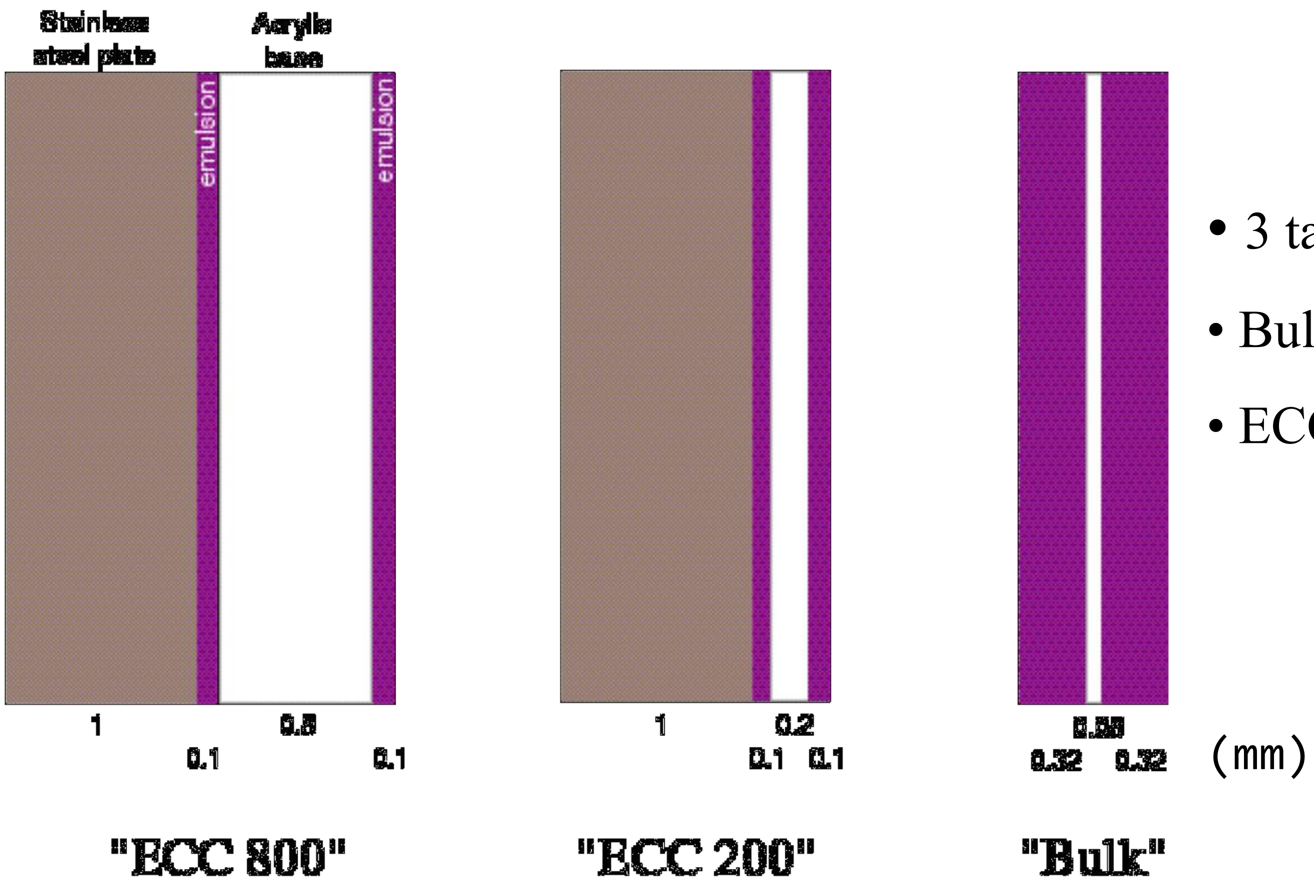
Kinematics

PERFORMANCE

ECC performance

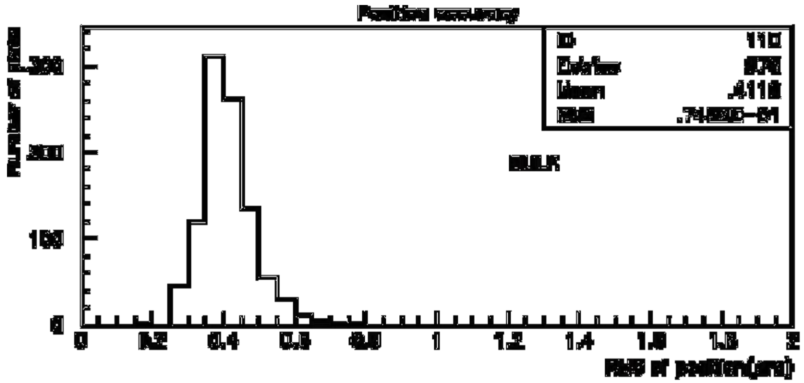
- Topological analysis
  - Tau & charm : lifetime @ $10^{-12} \sim 10^{-13}$s
- Particle ID
  - Electron ID by EM shower
  - Partial Hadron ID by re-interaction
- Kinematics
  - Momentum measurement by MCS(Multiple Coulomb Scattering)
  - Electron, gamma energy by shower and MCS

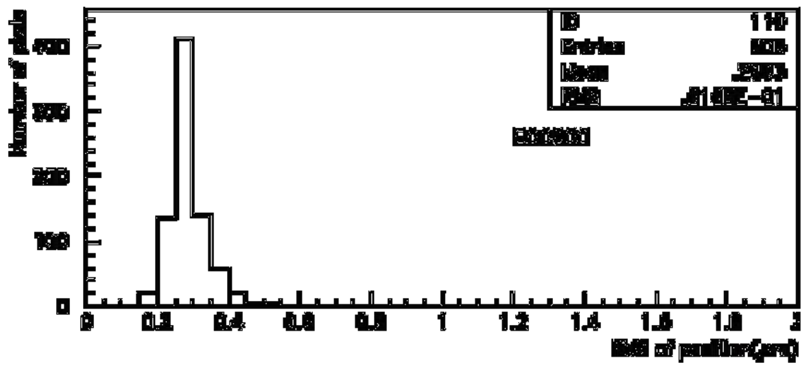
Target Design in DONUT

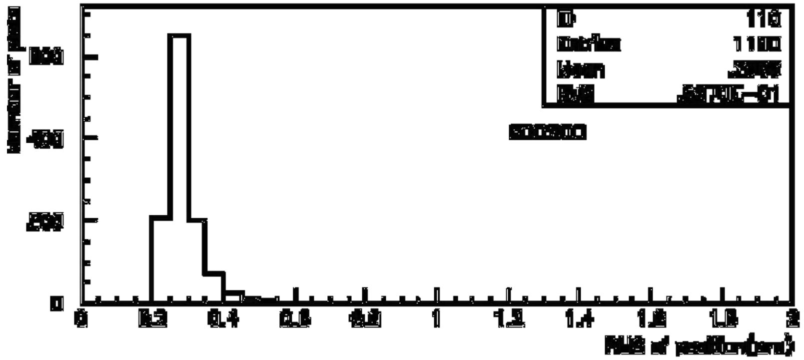


- 3 target types
- Bulk 95% emulsion
- ECC 5% emulsion

Spatial resolution in DONUT





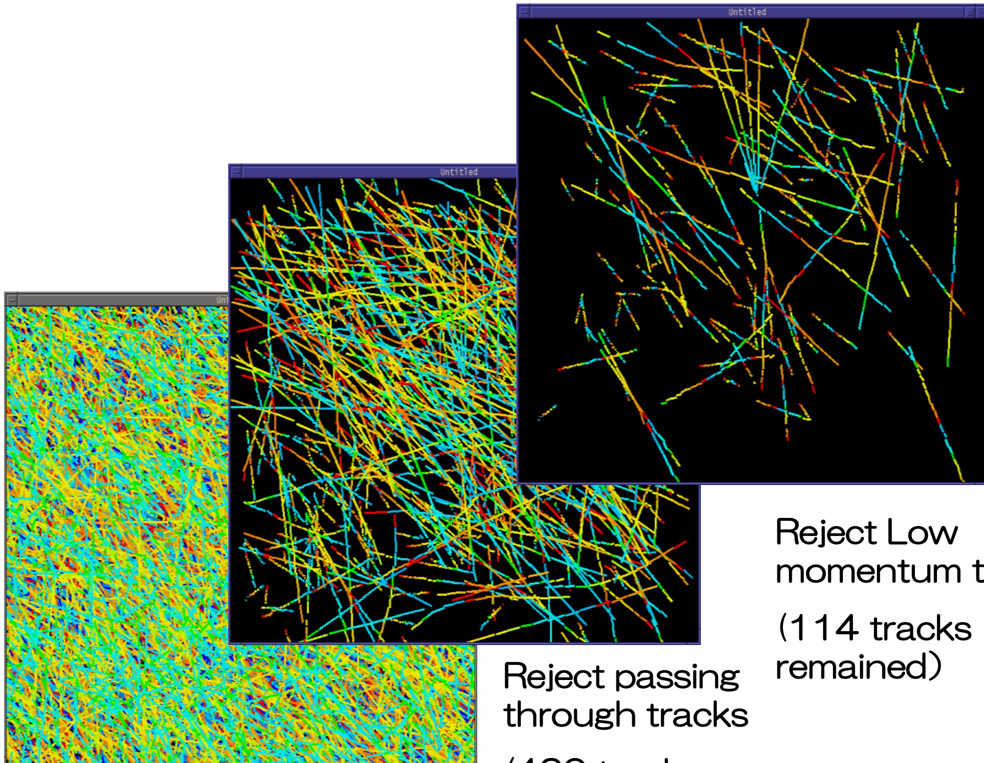


Emulsion data calibrated to 0.3 μm in transverse coordinates (0.4 μm for bulk emulsion)

Typical vertex precision (C5) 0.5 μm transverse, and 15 μm along beam

Data taking and offline reconstruction

Nucl. Instrum. Meth. A493 (2002) 45-66



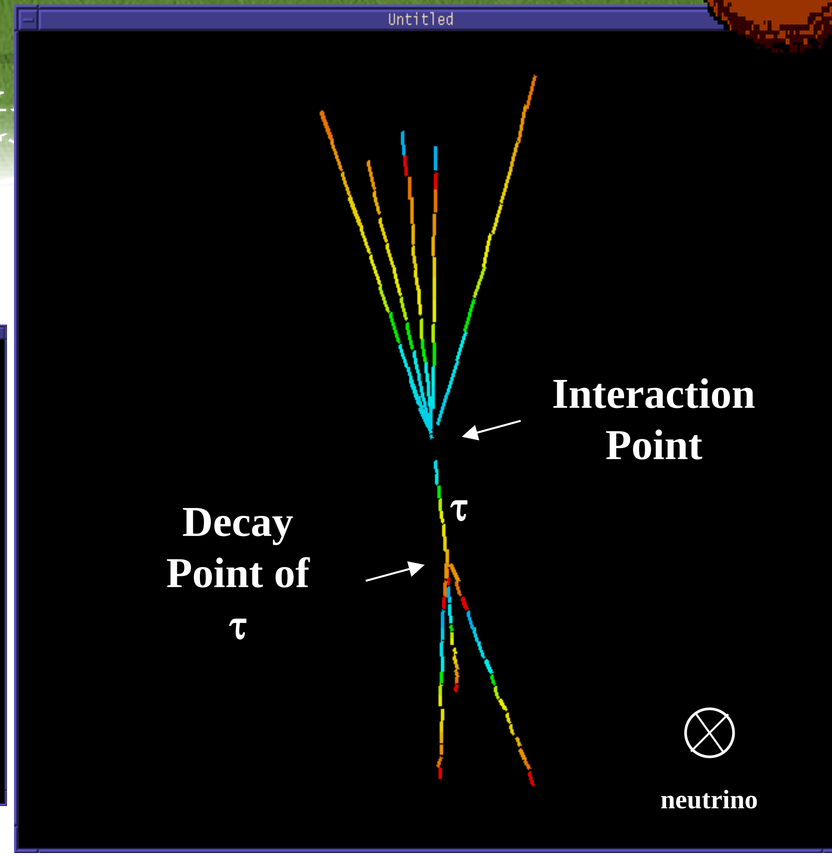
All tracks in the Scanning region (4179 tracks)

Reject passing through tracks

(420 tracks remained)

Reject Low momentum tracks

(114 tracks remained)

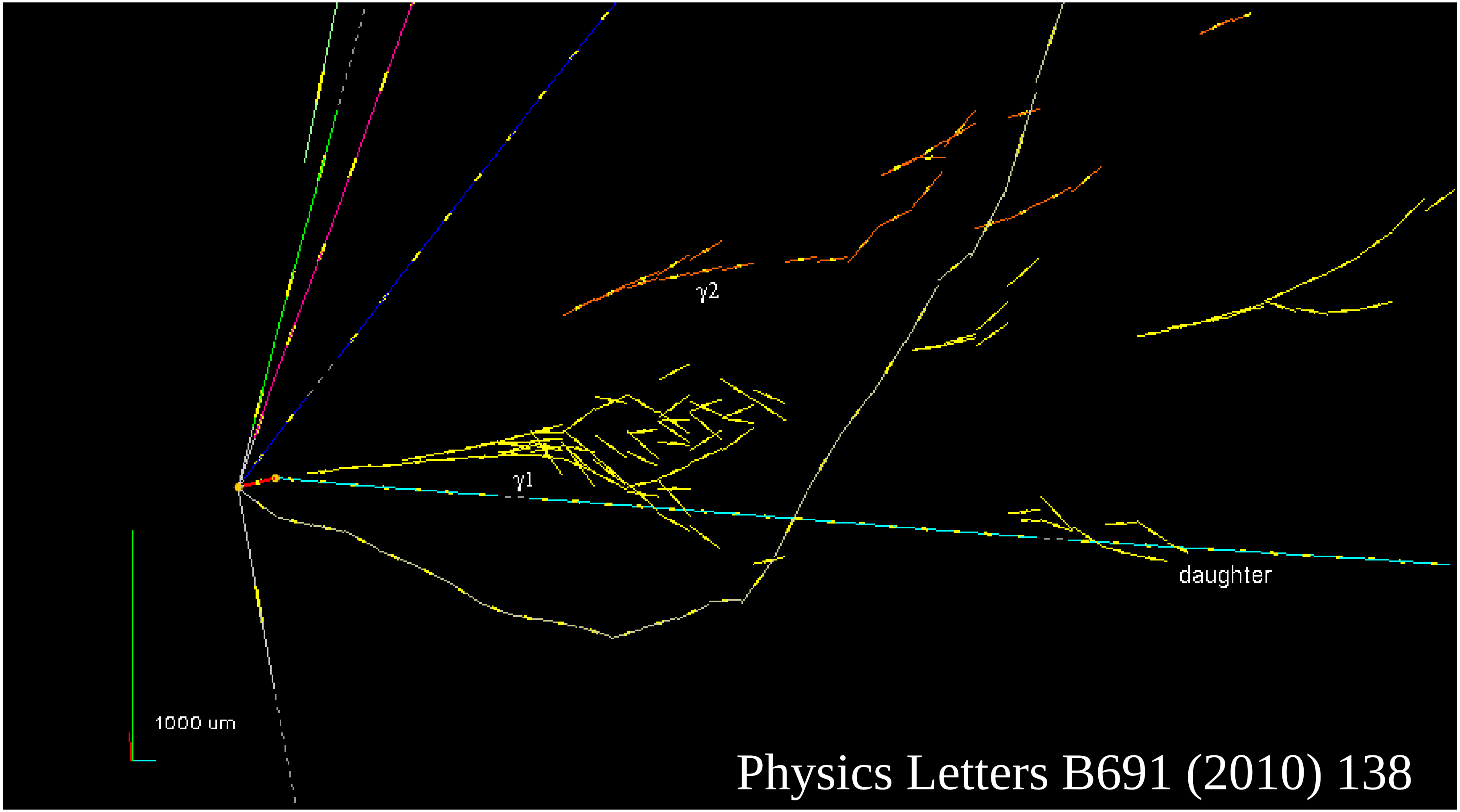


Vertex detection :

Neutrino interaction and decay of short lived particles

Detection of ν_τ^{CC} in DONUT

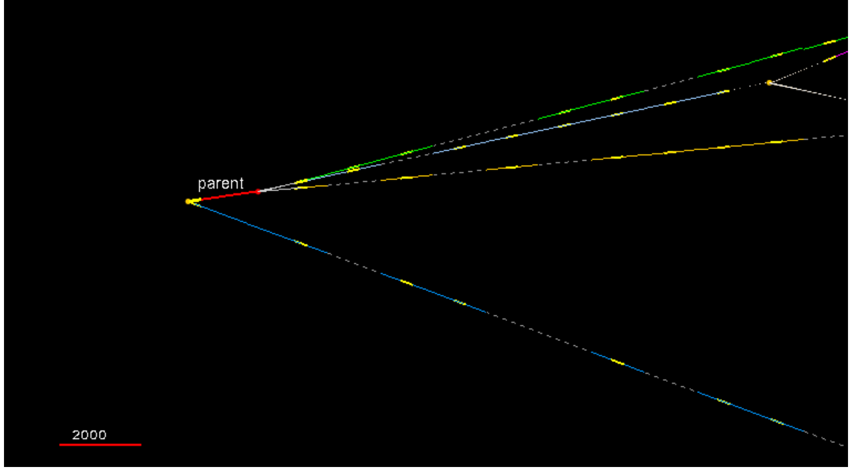
First ν_τ candidate ($\tau \rightarrow h$) (2010)



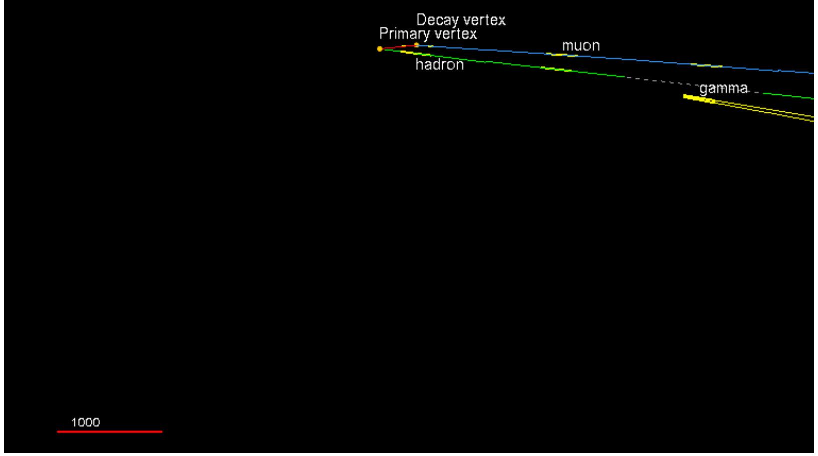
Physics Letters B691 (2010) 138

2^{nd} to 5^{th} tau candidates

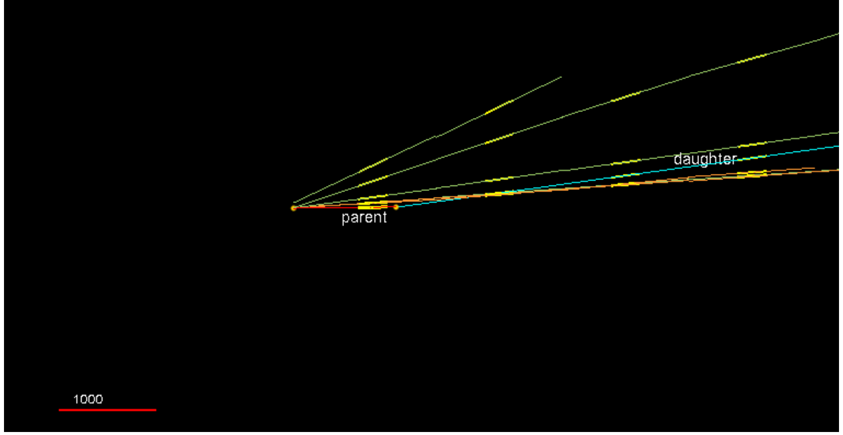
Journal of High Energy Physics 11 (2013) 036
2^{nd} ($\tau \rightarrow 3h$)



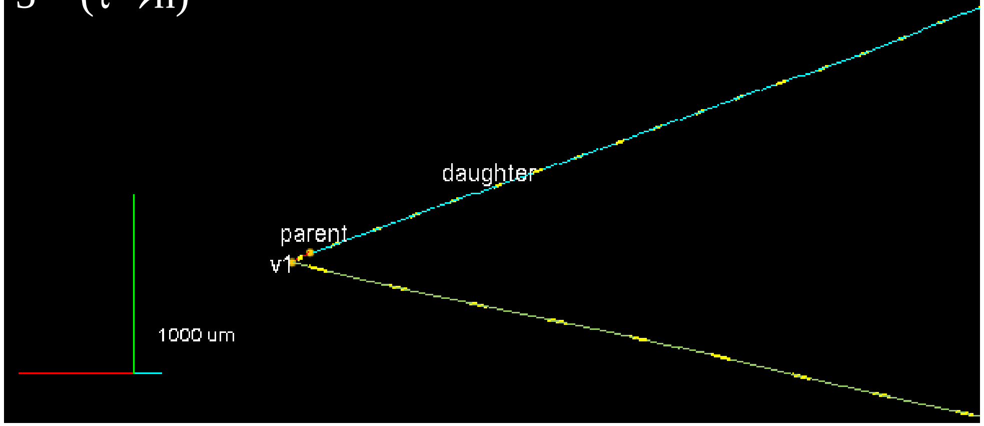
PHYSICAL REVIEW D 89 (2014) 051102(R)
3^{rd} ($\tau \rightarrow \mu$)



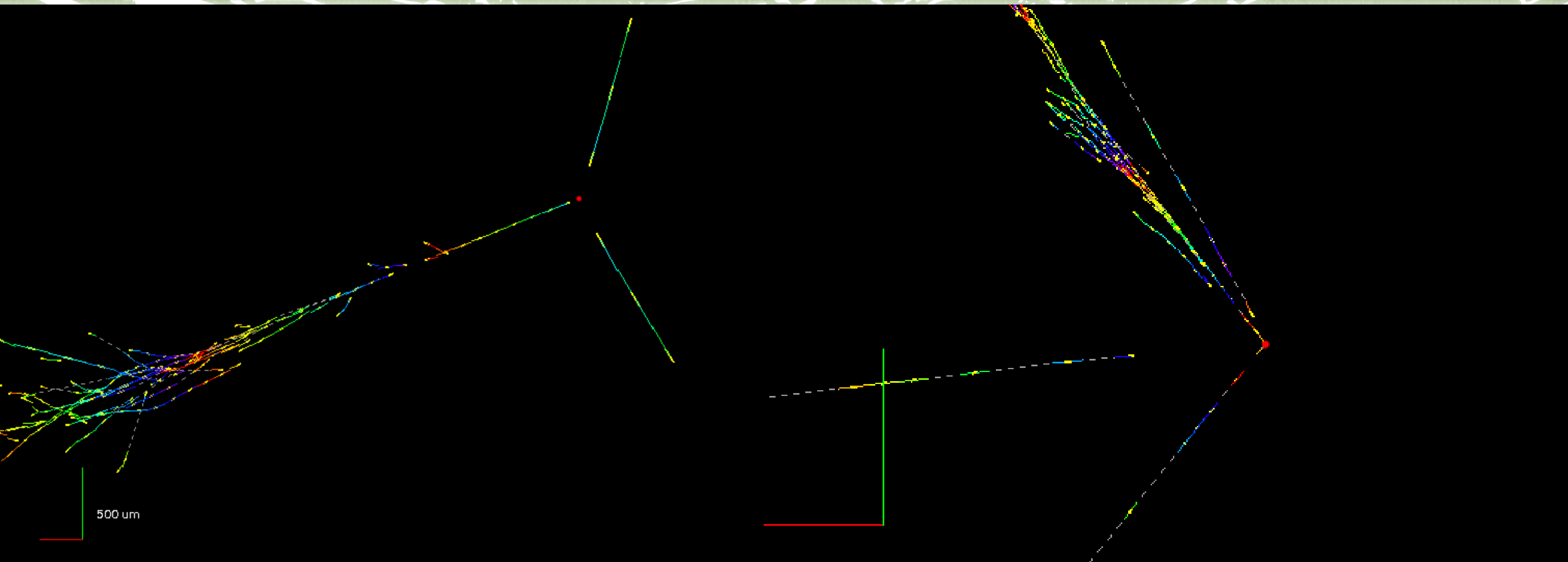
Progress of Theoretical and Experimental Physics 9 (2014) 093C01
4^{th} ($\tau \rightarrow h$)

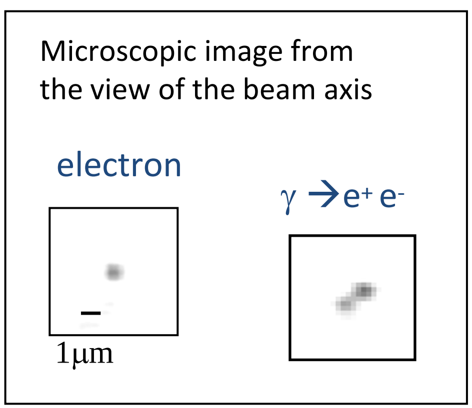


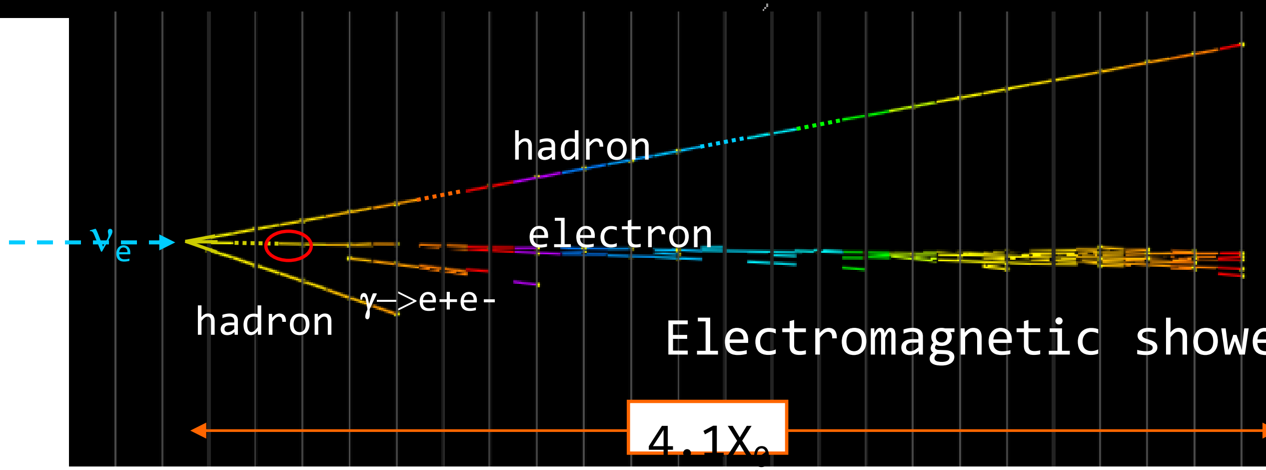
Phys.Rev.Lett. 115 (2015) no.12, 121802
5^{th} ($\tau \rightarrow h$)



ν_e event in OPERA ECC



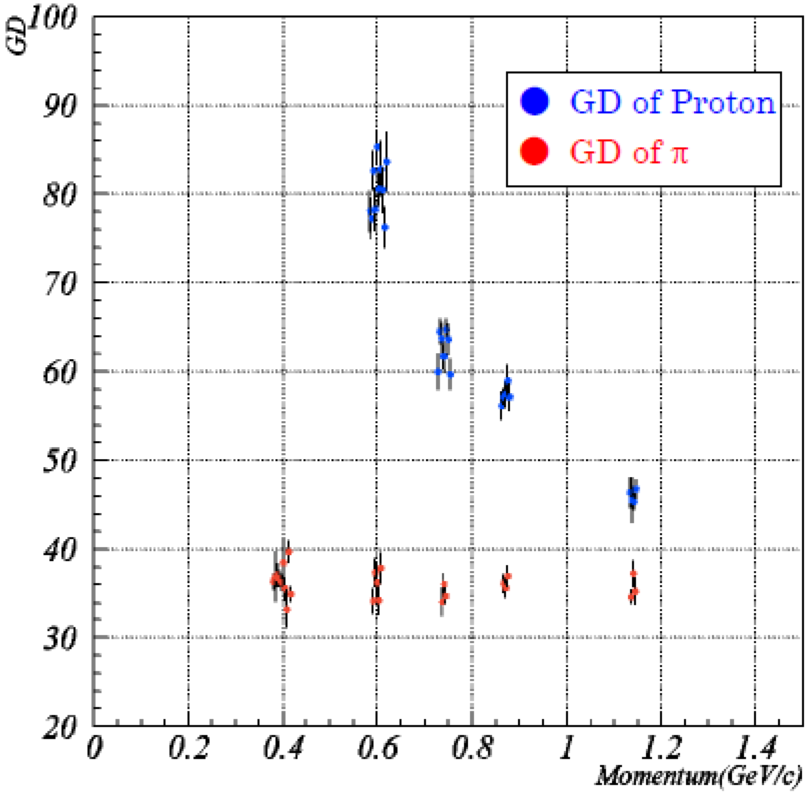


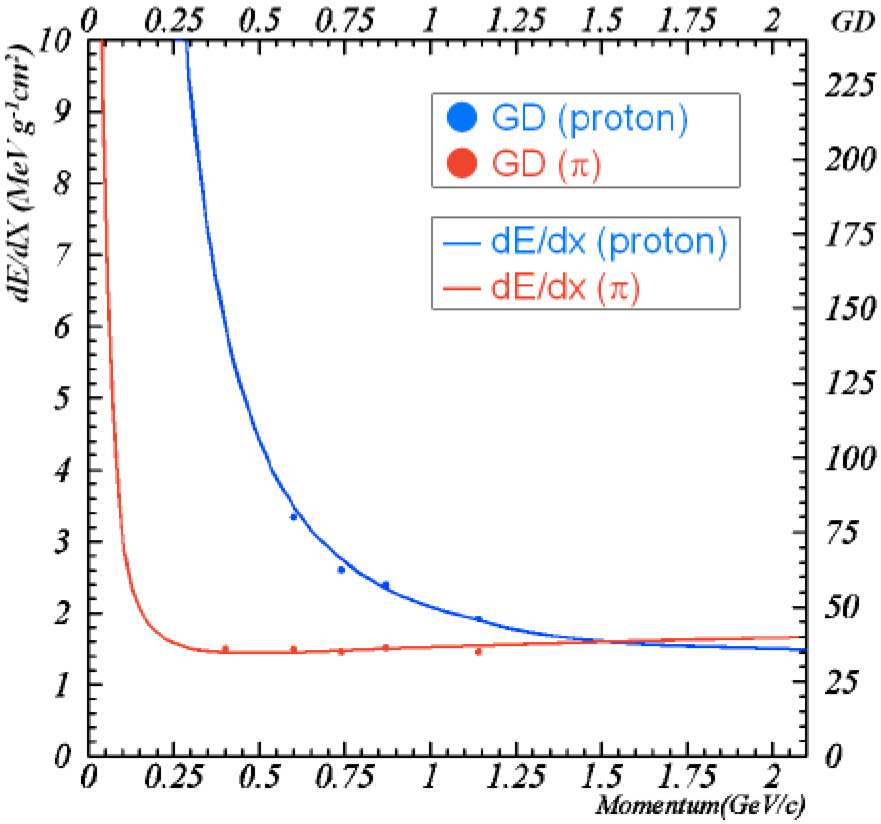


Particle ID & kinematics in ECC

- Hadron ID
  - Track Follow down : To find hadronic re-interaction in downstream
  - Pion / Proton separation by dE/dX
    - Nucl.Instrum.Meth. A516 (2004) 436-439
- Momentum
  - Momentum by MCS
    - Nucl.Instrum.Meth. A574 (2007) 192-198
    - New J.Phys. 14 (2012) 013026
  - Momentum by Emulsion Spectrometer (by H. Shibuya)
    - Nucl.Instrum.Meth. A592 (2008) 56-62
- Electron ID
  - Shower detection for high energy
  - Low energy region ID & energy measurement
    - Rev.Sci.Instrum. 74 (2003) 53-56
    - Phys.Procedia 80 (2015) 87-89

dE/dX measurement by G.D.

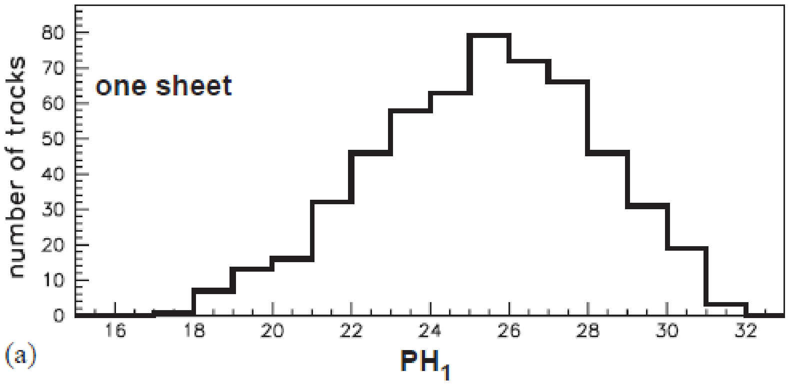


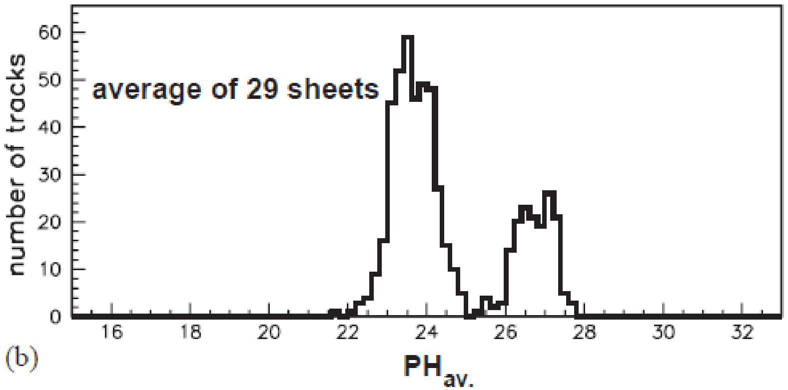


T. Fukuda
http://operaweb.lngs.infn.it/Opera/publicnotes/OPERA_note_179.pdf

Pion / Proton separation by dE/dX

- pi / p separation at 1.2-GeV/c by an emulsion cloud chamber
  - Beta=0.99(pi), =0.79(proton)
  - dE/dX =1.08(pi), =1.23(proton) of MIP
  - Nucl.Instrum.Meth. A516 (2004) 436-439



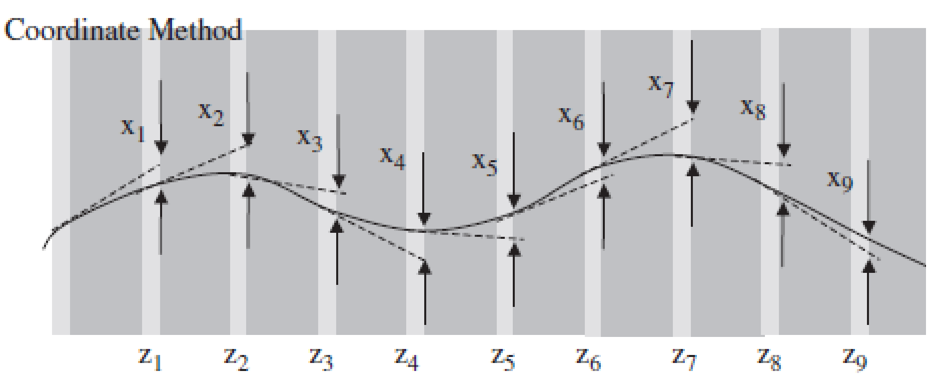


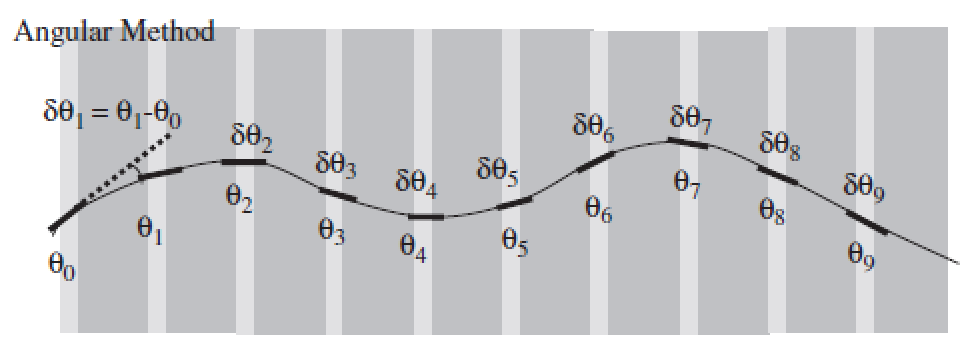
Momentum by MCS(Multiple Coulomb Scattering)

- Magnet or MCS
  - Magnet : P_T kick is constant → single measurement
  - MCS : P_T kick is Gaussian → multiple measurement
- Two different method
  - Coordinate method
    - Works even for high energy : x^(3/2)
    - Require good position alignment
  - Angular method
    - Works for lower energy : x^(1/2)

$$y_{\text{plane}}^{\text{rms}} = \frac{1}{\sqrt{3}}\, x\, \theta_{\text{plane}}^{\text{rms}} = \frac{1}{\sqrt{3}}\, x\, \theta_0$$

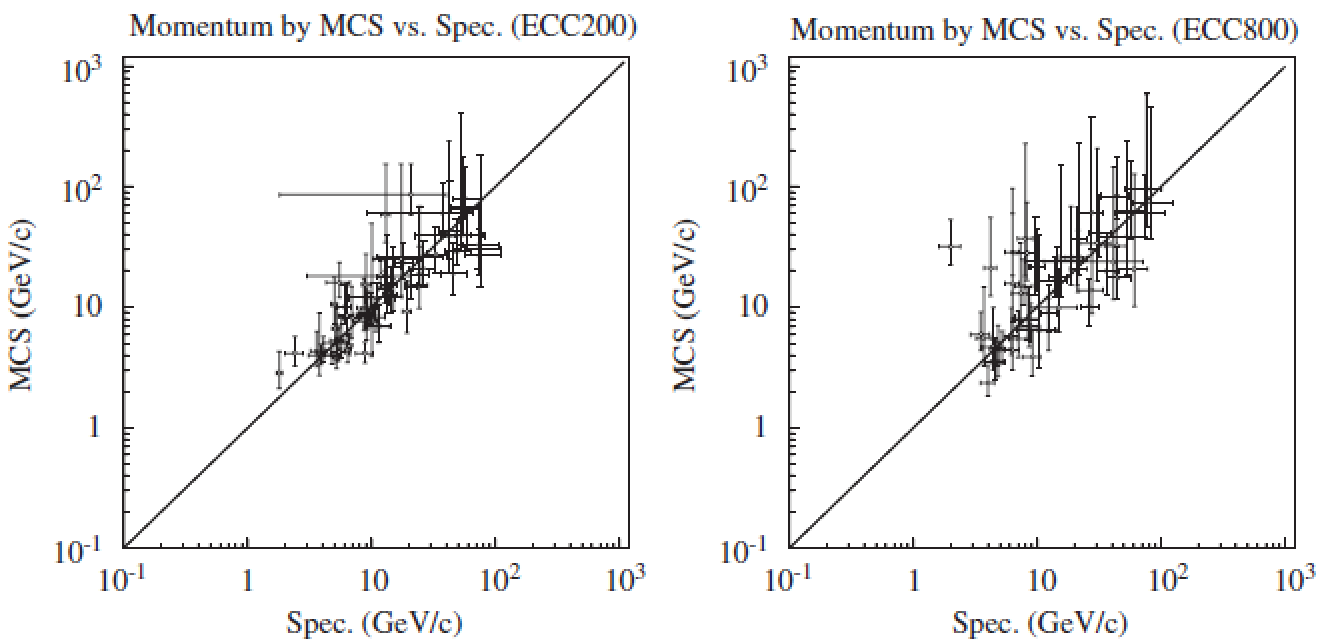
$$\theta_0 = \frac{13.6\ \text{MeV}}{\beta c p}\, z\, \sqrt{x/X_0}\Big[1 + 0.038 \ln(x/X_0)\Big]$$





Momentum measurement in DONUT ECC

DONUT



Nucl.Instrum.Meth. A574 (2007) 192-198

Momentum measurement by multiple scattering.

Consistent result with momentum measured by spectrometer.

Momentum measurement by Angular method

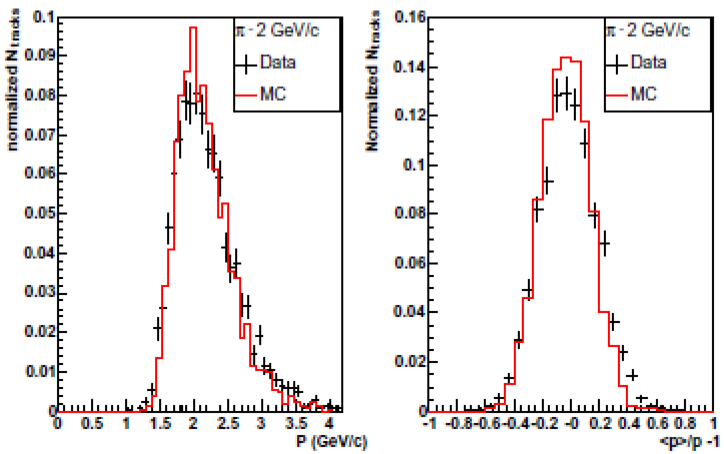


Figure 10. Data/MC comparison for $2\,\mathrm{GeV\,c^{-1}}$ pions. Left: momentum distribution. Right: inverted momentum distribution ($\langle p \rangle / p - 1$).

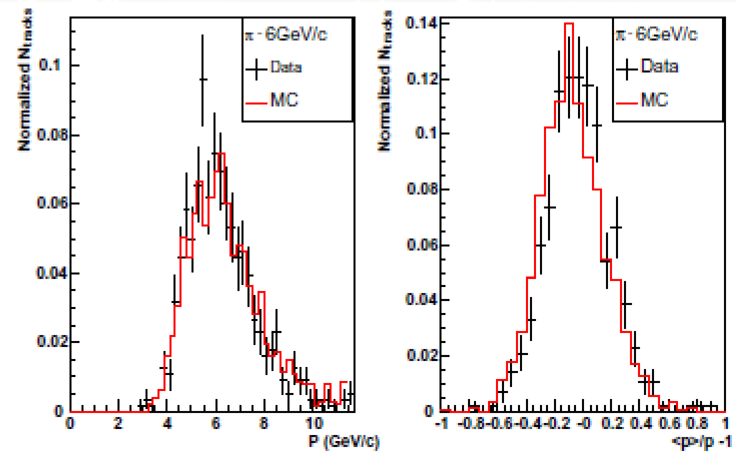
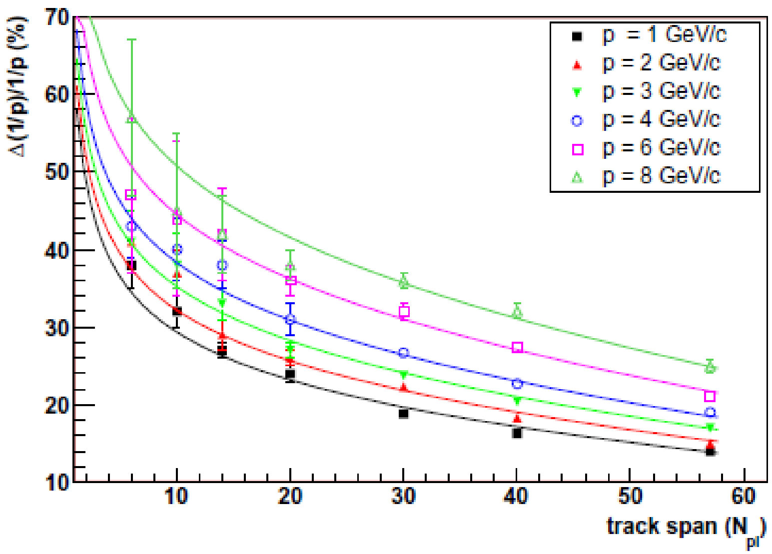


Figure 11. Data/MC comparison for $6\,\mathrm{GeV\,c^{-1}}$ pions. Left: momentum distribution. Right: inverted momentum distribution ($\langle p \rangle / p - 1$).

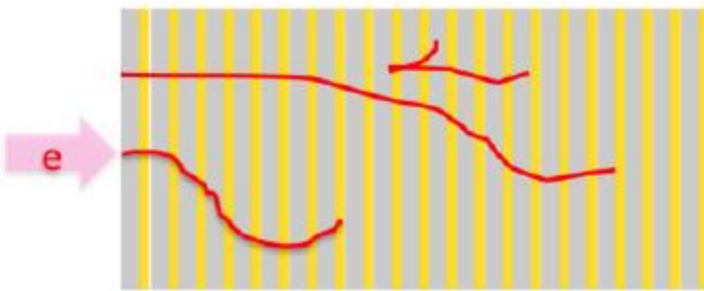


New J.Phys. 14 (2012) 013026

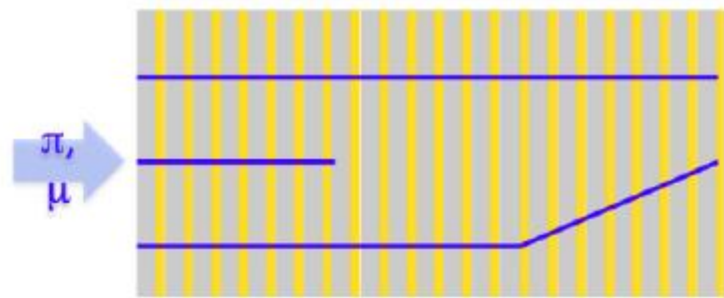
Error is a function of number of measured visible scattering. It is a error on RMS measured. 1/sqrt(2N)

Low energy electron ID & energy

- For electron does not make large EM shower
  - Pi to electron mis-ID ~ 1% level

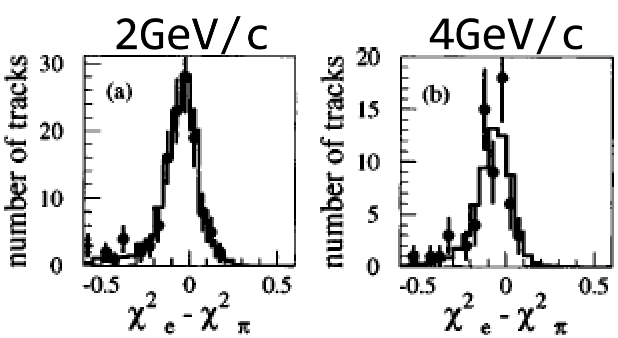


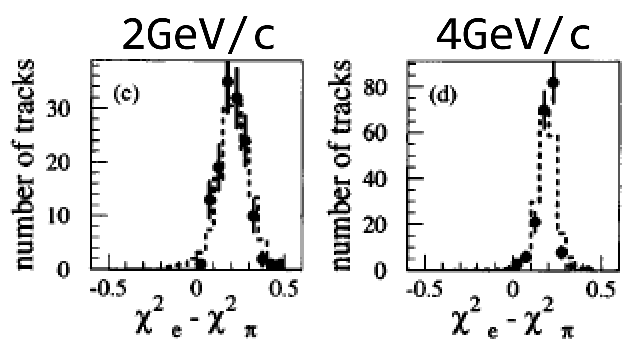
$$E(x) = E_0 \exp\left({}^{x}\!/\!{}_{X_0} \right)$$



$$E(x) = E_0$$

$$\chi^2_{e,\pi} \equiv \sum_{i=1}^{N-1} \frac{\{[\Delta\theta_x(i) - \Delta\Theta_{e,\pi}(i)]/\Delta\Theta_{e,\pi}(i)\}^2 + \{[\Delta\theta_y(i) - \Delta\Theta_{e,\pi}(i)]/\Delta\Theta_{e,\pi}(i)\}^2}{2(N-1)}$$

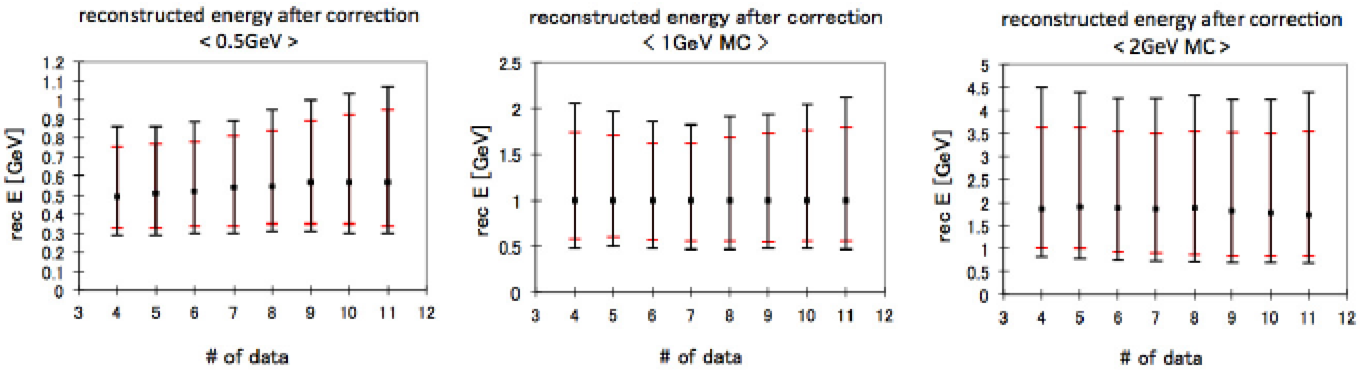




Rev.Sci.Instrum. 74 (2003) 53-56

Low energy electron ID & energy

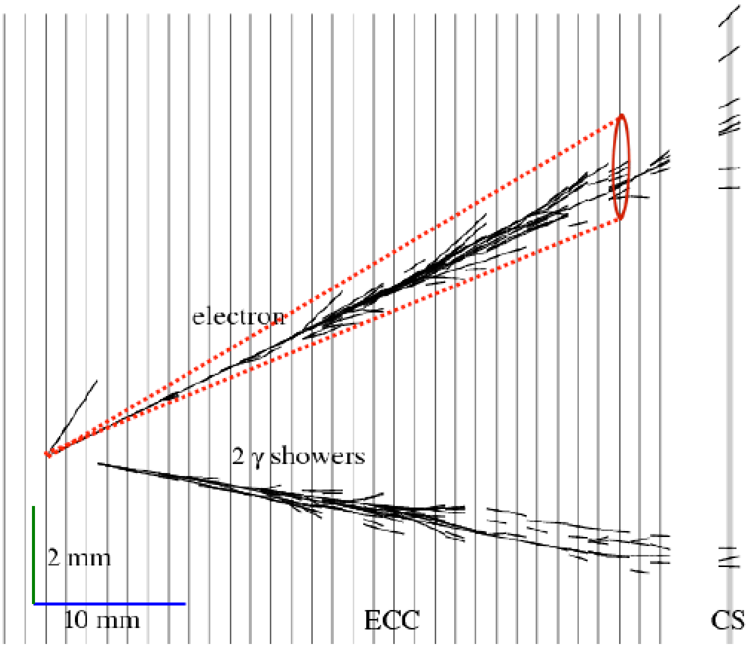
- For electron does not make large EM shower
  - Electron energy can be estimated by MCS angular method under a consideration of exponential energy loss.
  - Energy resolution is about 50% within 2 X0.

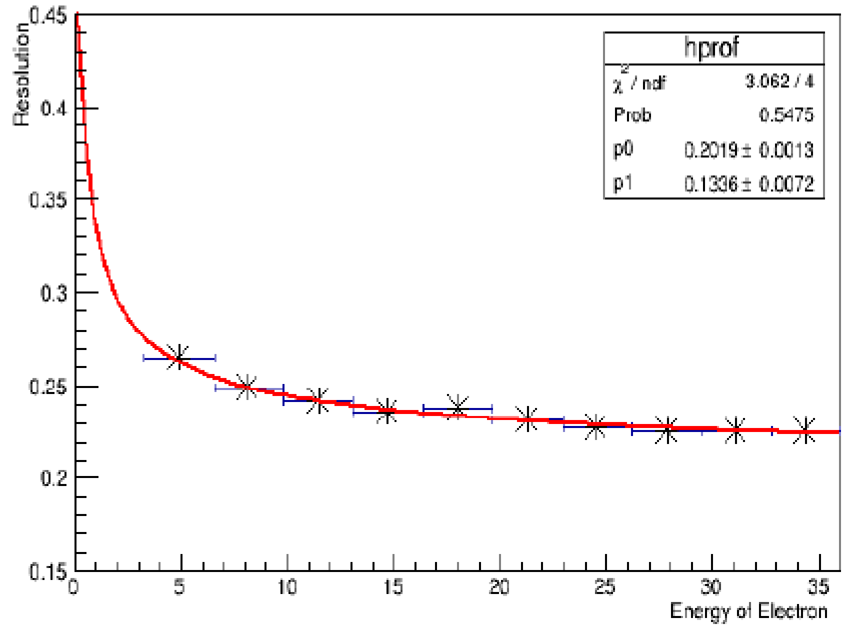


Phys.Procedia 80 (2015) 87-89

High energy electron

- Calorimetric shower counting





Ph.D Thesis of Behzad Hosseini, Napoli Univ.

Summary

- Emulsion is the most thin, light and high resolution 3D tracking detector
  - High granularity make possible to see beauty, charm and tau track.
  - Combination with target or passive materials (ECC) provides many functions such as kinematical analysis capability.
- More than 20 years of experience of emulsion hybrid detector.
  - Hybrid detector was used for event location in emulsion and kinematical analysis.
  - Best combination has to be chosen for each experiments.
- See more details in the given references.