Snapshots of the invisible: neutrinos

Highlights of DONUT and CHORUS, status of the OPERA

Masahiro Komatsu : Nagoya University, JAPAN

Tau neutrino and Emulsion

- Tau neutrino source
  - First measurement of $B(D_s \to \mu\nu)$ by emulsion experiment CERN WA75. (Prog. Theo. Phys. 89:131-138,1993)
- Tau neutrino detection
  - First observation of tau neutrino interactions by Fermilab E872 DONUT. (Phys. Lett. B504:218-224,2001)
  - First tau neutrino appearance in oscillation by OPERA. (Phys. Lett. B691:138-145, 2010)
  - And now?
- How this become possible?

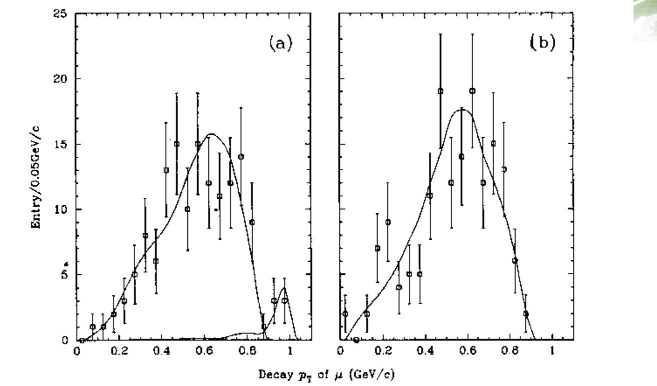
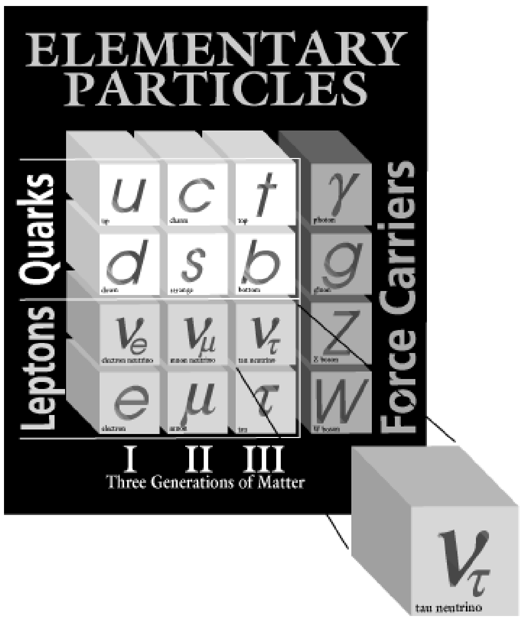
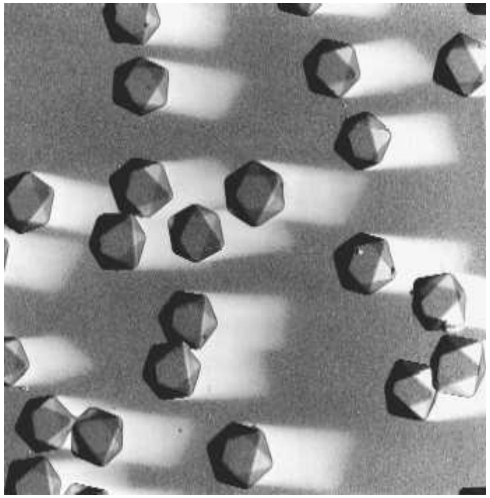


Fig. 1. Decay p_T distributions of muons from 144 C1 decays (a) and from 157 N2 decays (b). The solid lines represent Monte Carlo results; the contribution from $D_s^\pm \to \mu^\pm \nu_\mu$ in (a) is evaluated to be $9.1^{+3.8}_{-3.0}$ events in the absence of background.

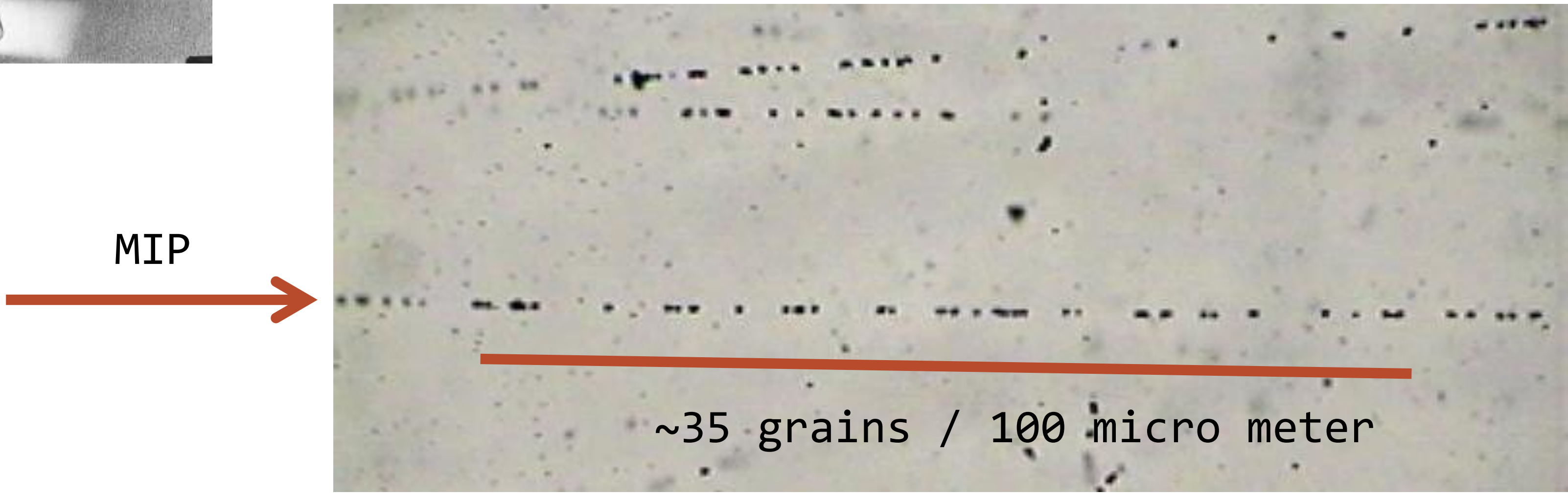


Nuclear emulsion



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

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



Modern nuclear emulsion experiments

- Old type emulsion experiments
  - CERN WA75 (B and charm)
  - Fermilab E653 (B and charm)
- Transition from Visual detector to Tracking detector
  - CERN WA95 CHORUS (1994-1997)
  - Fermilab E872 DONUT (1997)
  - OPERA (2008-2012)

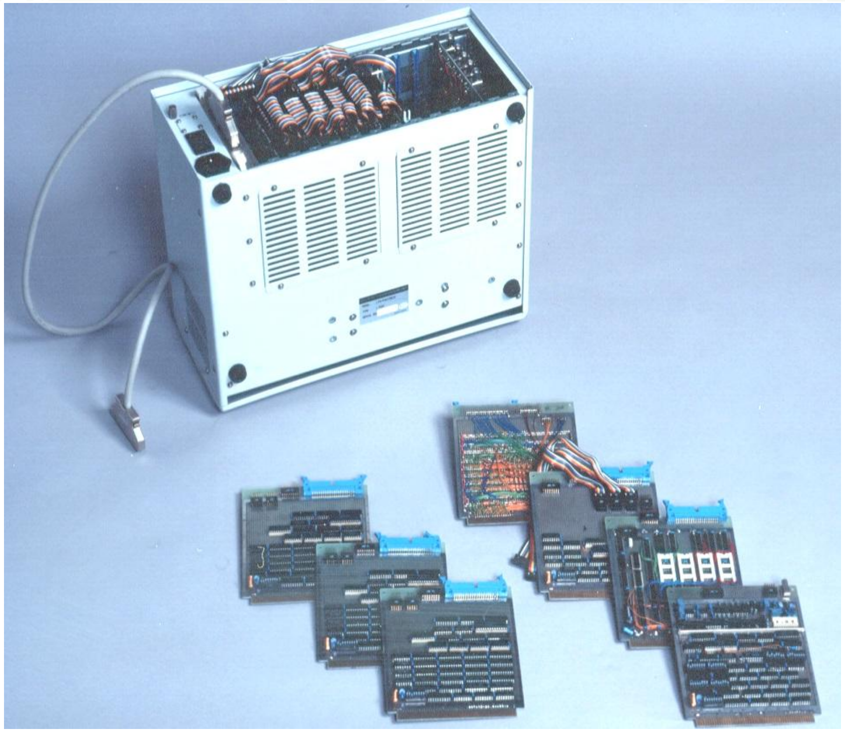
History of scanning system

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.

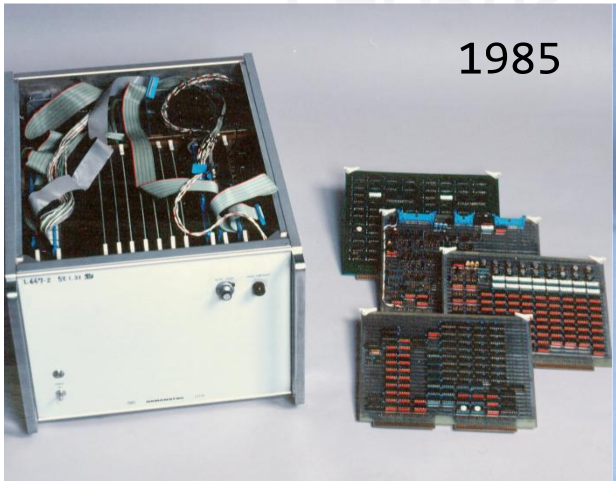
Track Selector (TS) 1994

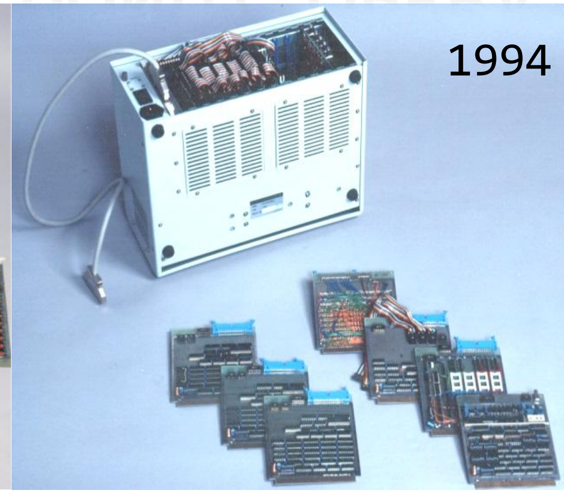


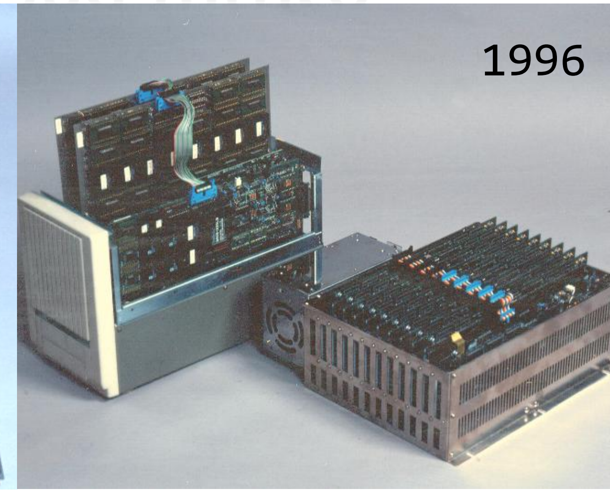
- 20 years ago, for CHORUS.
  - We made big decision to change future (current) emulsion scanning.

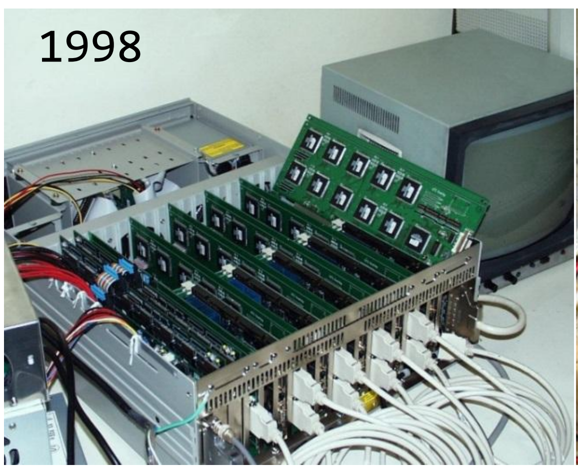
Evolution of the scanning system

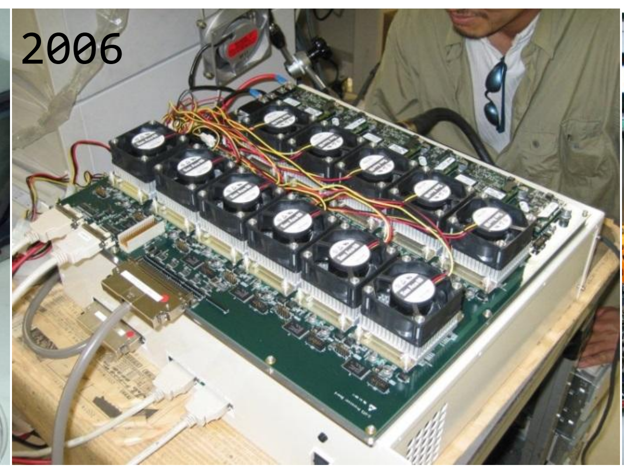
CHORUS, DONUT, OPERA and future…

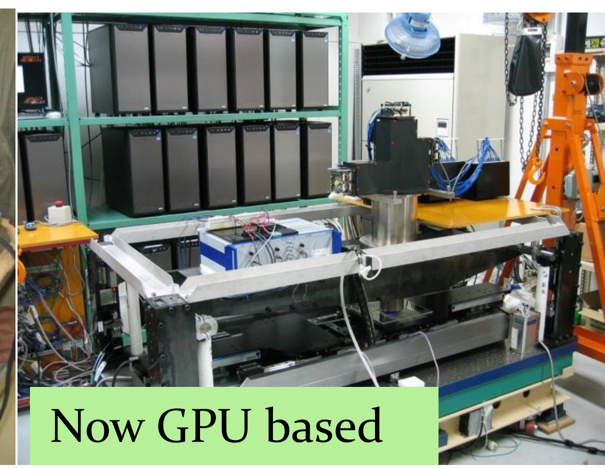




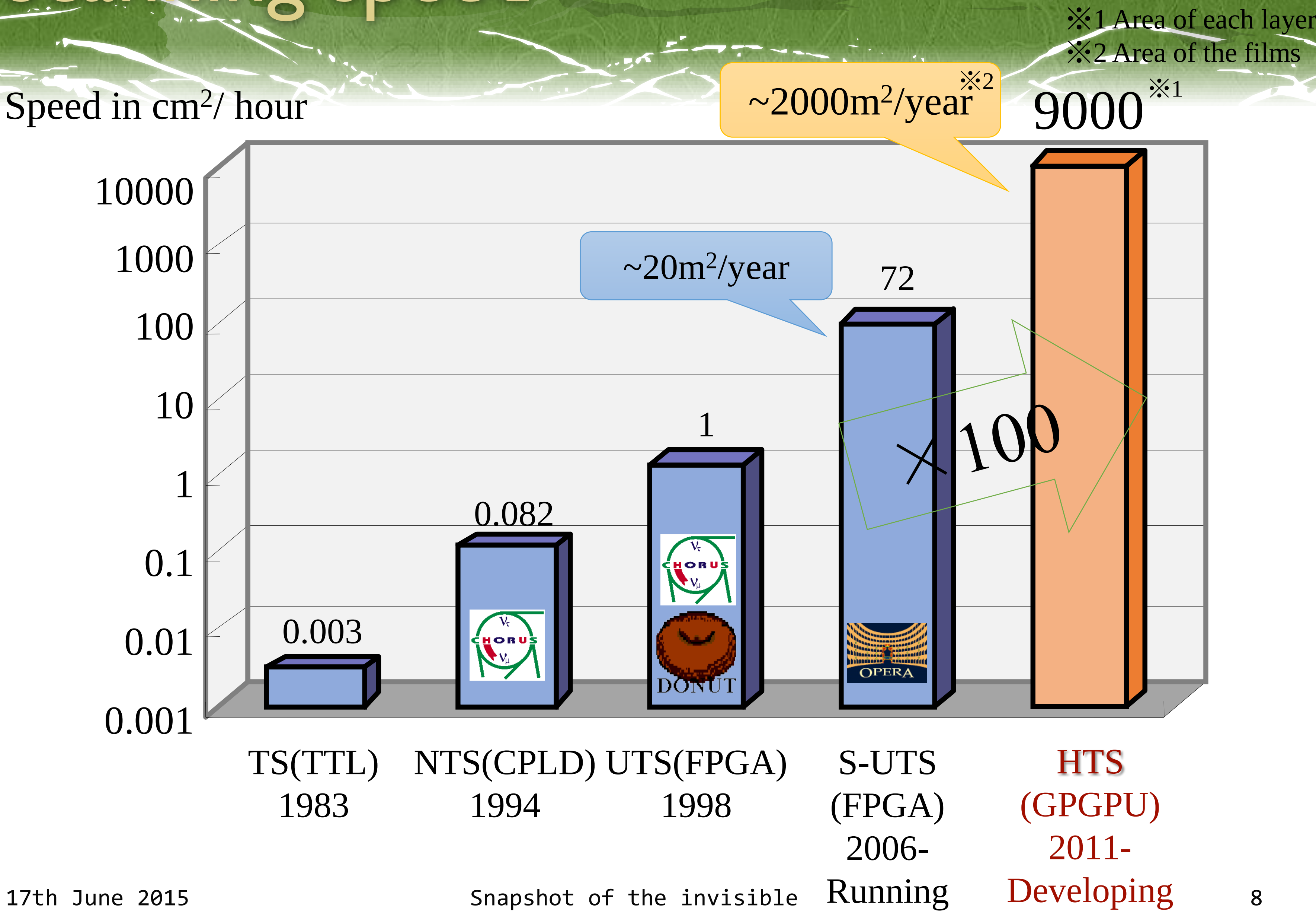








Scanning speed



Look for tau neutrino

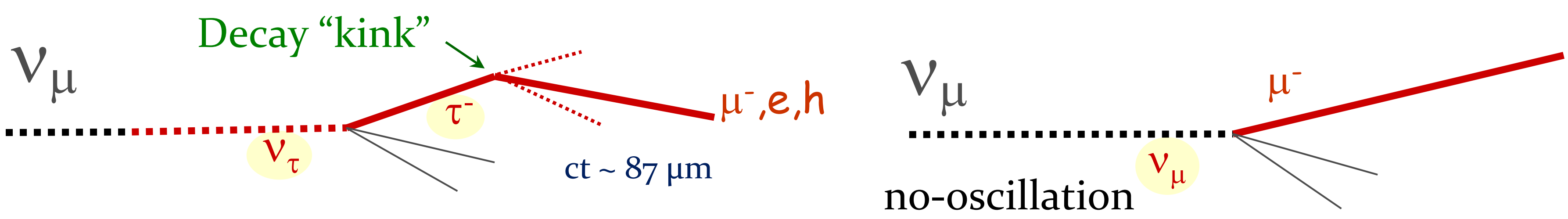
1994-1997
-2008

1997
-2008

2008-2012
-2018±1?

CHORUS, DONUT AND OPERA

Concept of tau neutrino detection



- Decay topology detection
  - Tau, charm, hadronic interaction
- No primary lepton other than tau
  - Muon and electron ID
- Kinematical requirements
  - Decay P_T, flight length, azimuthal angle

CERN WA95 CHORUS

CERN Hybrid Oscillation Research apparatUS

- Look for neutrino oscillation @10eV^2 range as a DM candidate.
  - Unfortunately, answer was not there!
  - How many of us predicted large mixing and small δm^2?
- Largest emulsion experiments ever built (770kg)
  - We had to invent new analysis method.
  - Automatic scanning system
- Capable to observe tau neutrino CC interaction, but no one has seen before.
- Good for neutrino induced charm production study

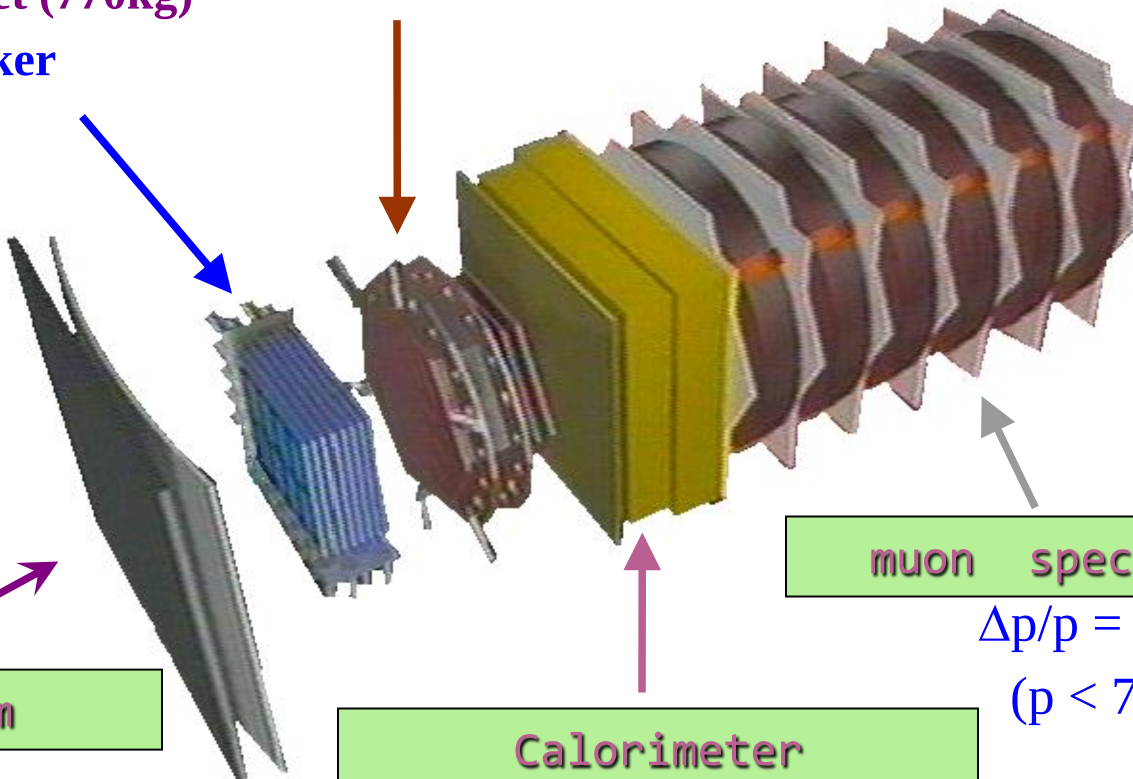
CHORUS detector

Active target

-nuclear emulsion target (770kg)

-scintillating fiber tracker

$\Delta p/p = 0.035\, p\ (\mathrm{GeV}/c) \oplus 0.22$



ν

$E\nu \sim 27$ GeV

Neutrino beam

ν_μ	:	$\bar{\nu}_\mu$	:	ν_e	:	$\bar{\nu}_e$
1.00	:	0.05	:	0.017	:	0.007

muon spectrometer

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

$(p < 70\ \mathrm{GeV}/c)$

Calorimeter

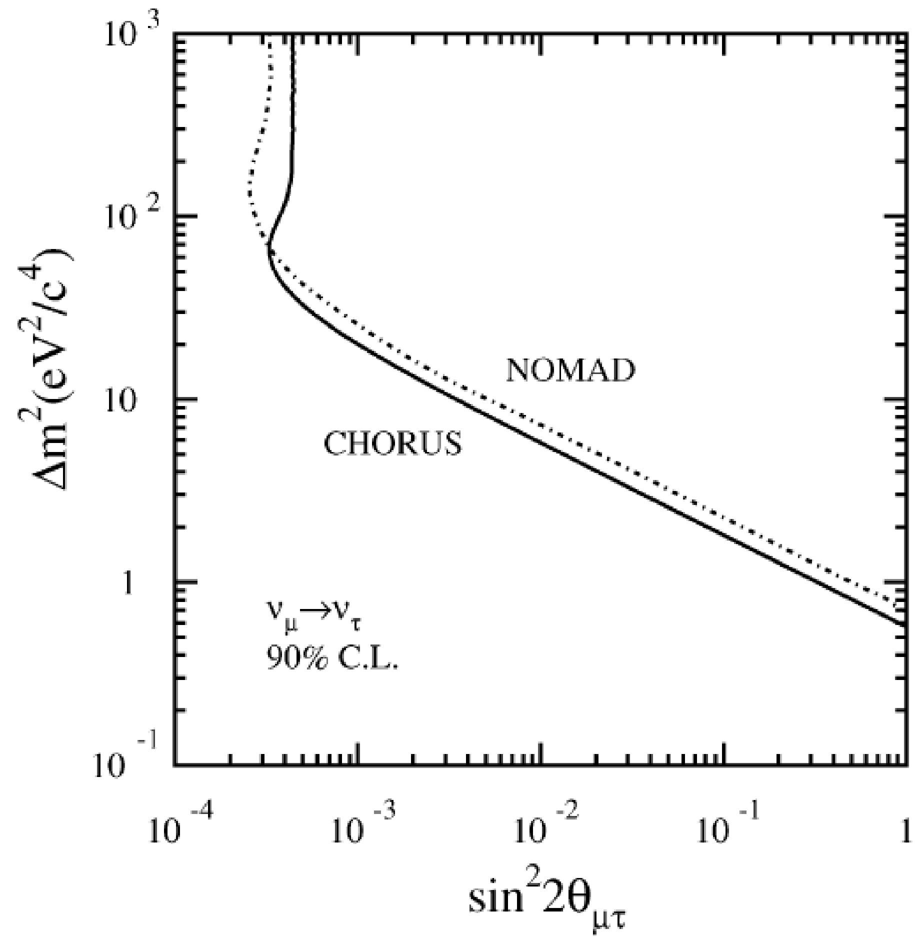
$\Delta E/E = 32\ \%/\sqrt{E}$ (hadrons)

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

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

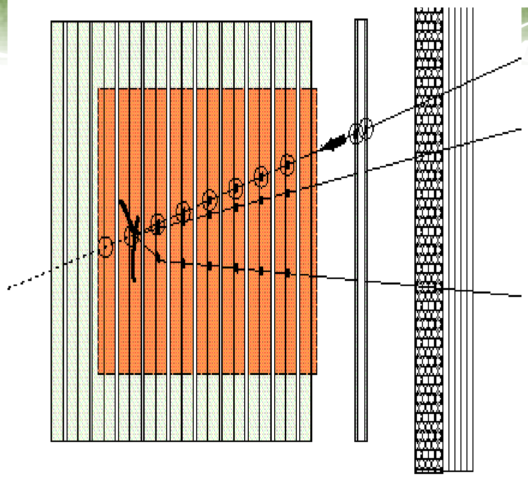
CHORUS Oscillation result

- Oscillation analysis with phase I and II
  - No tau neutrino event
  - $\sin^2(2\theta_{\mu\tau}) < 4.4\text{x}10^{-4}$
- New analysis technique developed in the DONUT experiment
  - Reconstruct event topology around interaction point to detect short lived particle like tau and charms.



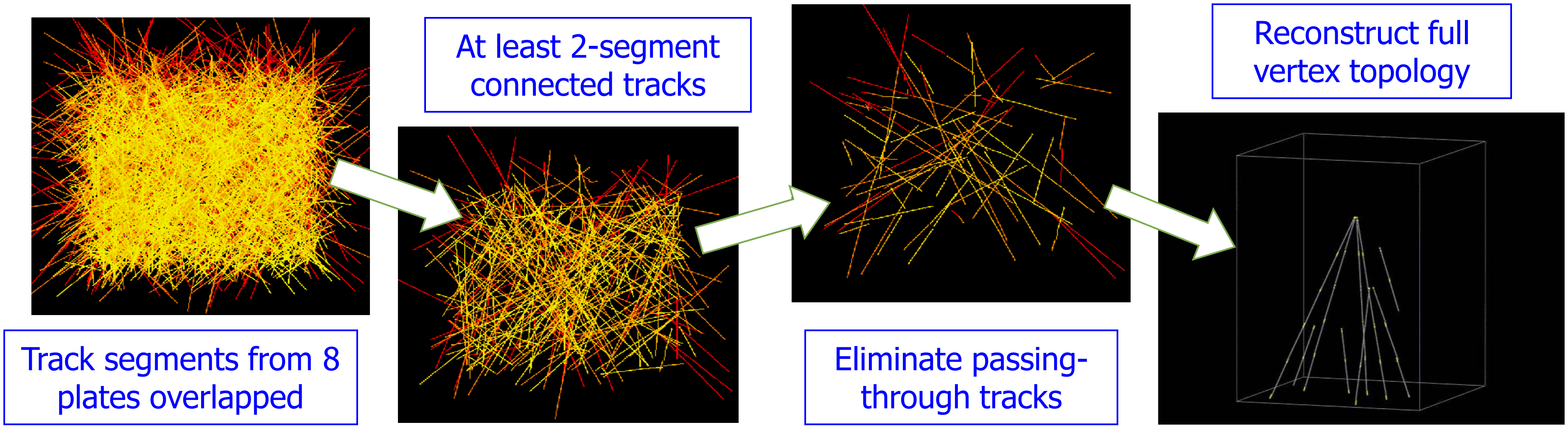
Nucl.Phys. B793 (2008) 326-343

CHORUS phase II



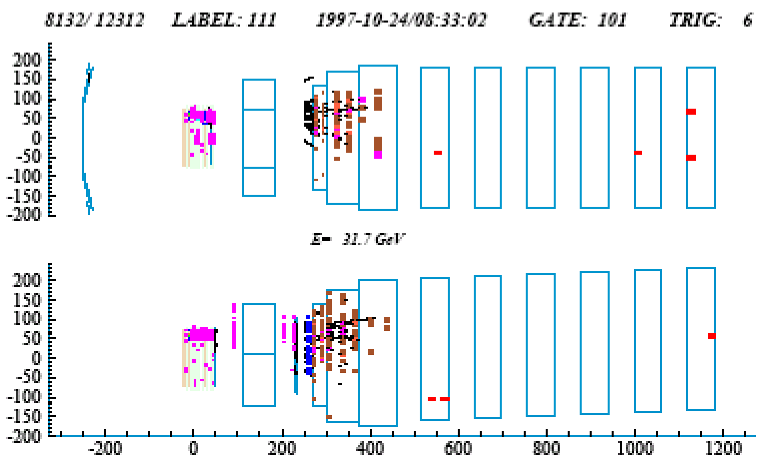
- Analysis method developed in the DONUT.

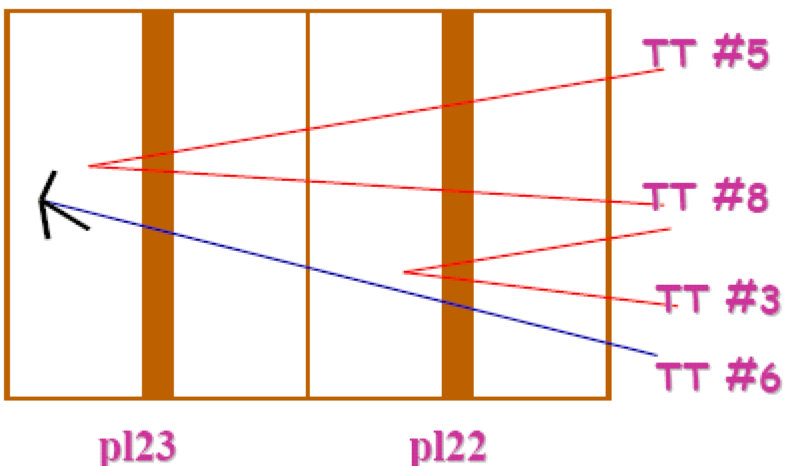
- All track segments ($\theta < 0.4$ rad)
- Fiducial volume: 1.5 x 1.5 mm^2 x 8 plates
- Offline analysis of emulsion data
- For 200K located events



Associated charm production in NC

Event 81332312





V2&V2 in 0mu

1ry@pl23

Ns=1, Nh=3

V2(1) @pl 23

$\Delta\theta$ =96.3 mrad

fl= 62.8μm

V2(2) @pl 22

fl= 976.6μm

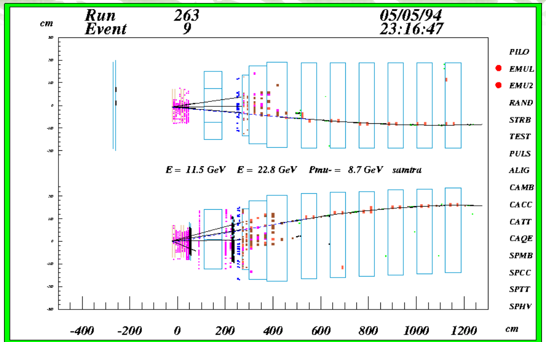
$\Delta\theta$ =203.4 mrad

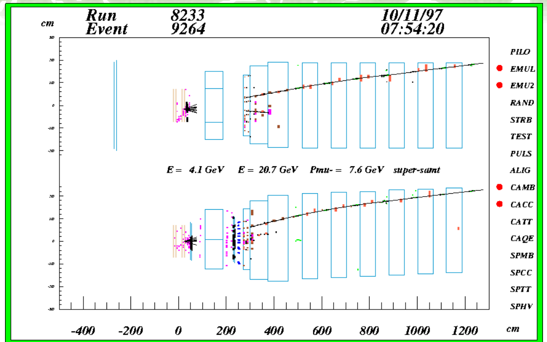
Charm physics in CHORUS

Charm production	*New J. Phys. 13 (2011) 093002*
Associated charm production	*Eur. Phys. J. C52 (2007) 543*
Topological muonic branch	*Phys. Lett. B626 (2005) 24*
Super fragment search	*Nucl. Phys. B718 (2005) 35*
D^{*+} production	*Phys. Lett. B614 (2005) 155*
D^0 production and branch	*Phys. Lett. B613 (2005) 105*
Anti neutrino charm production	*Phys. Lett. B604 (2004) 11*
Charm fragmentation	*Phys. Lett. B604 (2004) 145*
Λ_c production	*Phys. Lett. B555 (2003) 156*
QE charm production	*Phys. Lett. B575 (2003) 198*
D^0 production	*Phys. Lett. B527 (2002) 173*
CC associate charm production	*Phys. Lett. B539 (2002) 188*
BR $\rightarrow \mu$	*Phys. Lett. B549 (2002) 48*
Diffractive D_s^* production	*Phys. Lett. B435 (1998) 458*

About 2000 charms

CHORUS Era


Run 263
Event 9
05/05/94
23:16:47
E = 11.5 GeV E = 22.8 GeV Pmu- = 8.7 GeV samtra
PILO
EMUL
EMU2
RAND
STRB
TEST
PULS
ALIG
CAMB
CACC
CATT
CAQE
SPMB
SPCC
SPTT
SPHV
-400 -200 0 200 400 600 800 1000 1200
cm


Run 8233
Event 9264
10/11/97
07:54:20
E = 4.1 GeV E = 20.7 GeV Pmu- = 7.6 GeV super-samt
PILO
EMUL
EMU2
RAND
STRB
TEST
PULS
ALIG
CAMB
CACC
CATT
CAQE
SPMB
SPCC
SPTT
SPHV
-400 -200 0 200 400 600 800 1000 1200
cm


Chorus at Eihei-ji Temple – Oct 97

DONUT (Direct Observation of NU Tau)

- 1975 Tau lepton discovered
  - Tau neutrino assumed to exist
- Tau neutrino interaction has never observed at the time of the CHORUS.
  - CHORUS aimed to detect tau neutrino interaction through neutrino oscillation. But, both of them were not confirmed.
- DONUT(Direct Observation of NU Tau)
  - Tau neutrino beam from decays of D_s in beam dump.
  - Hard experiment to cope with high BG condition.

The DONUT Collaboration (2000)

DONUT

Aichi Univ. of Education
K. Kodama, N. Ushida

Kobe University
S. Aoki, T. Hara

Nagoya University
N. Hashizume, K. Hoshino, H. Iinuma, K. Ito,
M. Kobayashi, M. Miyanishi, M. Komatsu,
M. Nakamura, K. Nakajima, T. Nakano, K. Niwa,
N. Nonaka, K. Okada, T. Yamamori

Univ. of California/Davis
P. Yager

Fermilab
B.Baller, D.Boehnlein, W.Freeman,
B.Lundberg, J.Morfin, R. Rameika

Kansas State Univ.
P. Berghaus, M. Kubanstev, N.W. Reay,
R. Sidwell, N. Stanton, S. Yoshida

Univ. of Minnesota
D. Ciampa, C. Erickson, K. Heller, R. Rusack,
R. Schwienhorst, J. Sielaff, J. Trammell, J. Wilcox

Univ. of Pittsburgh
T. Akdogan, V. Paolone

Univ. of South Carolina
A. Kulik, C. Rosenfeld

Tufts University
T. Kafka, W. Oliver, J. Schneps, T. Patzak

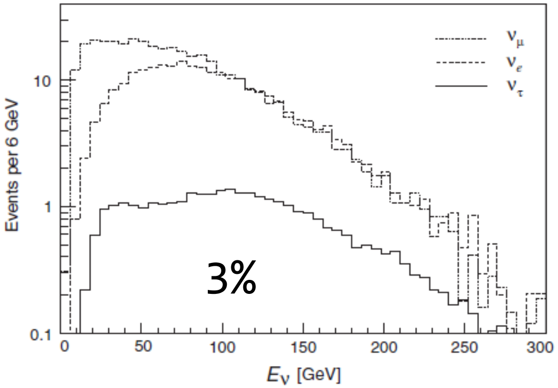
Univ. of Athens
C. Andreopoulos, G. Tzanakos, N. Saoulidou

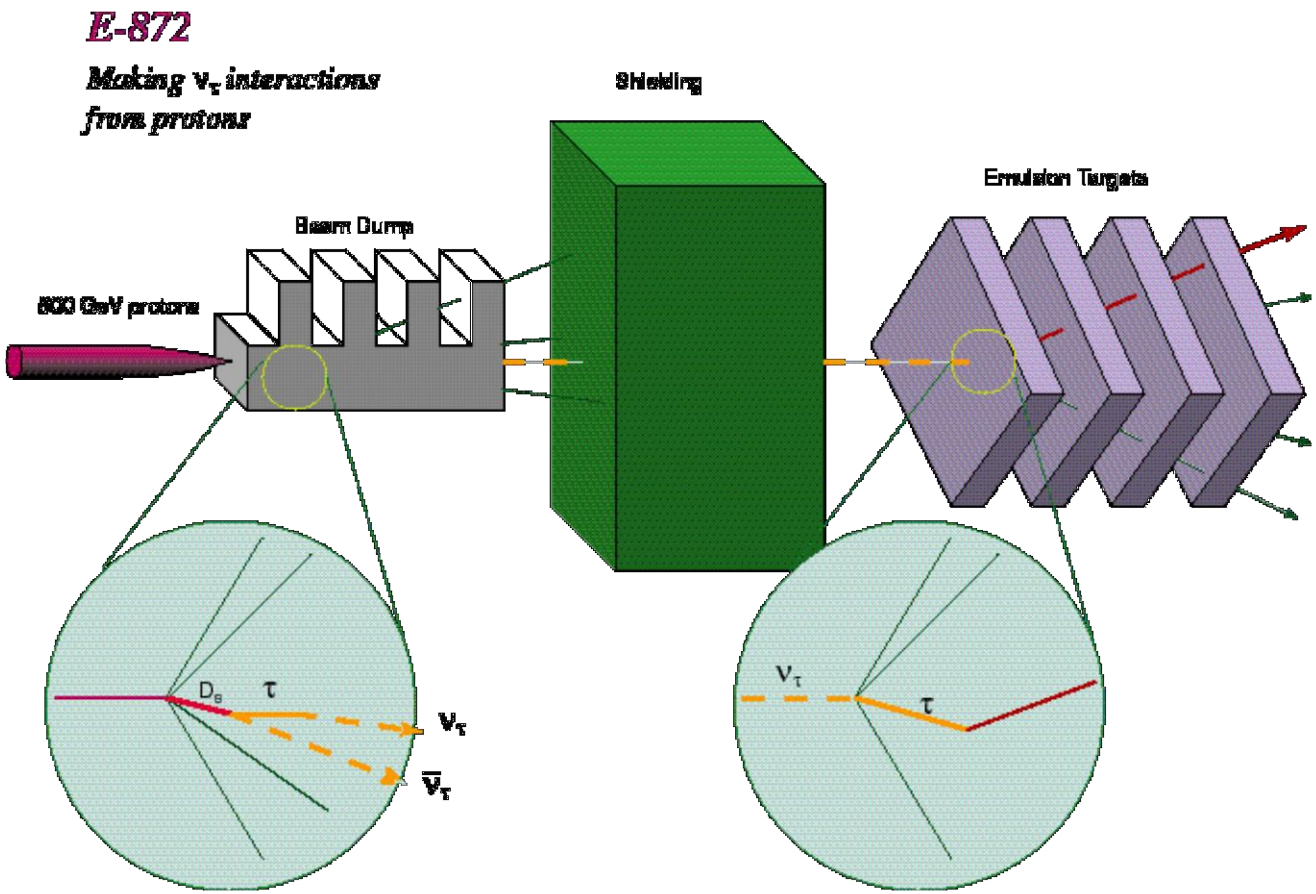
Gyeongsang University
J.S. Song, I.G. Park, S.H. Chung

Kon-kuk University
J.T. Rhee

Prompt Neutrino Beam

DONUT



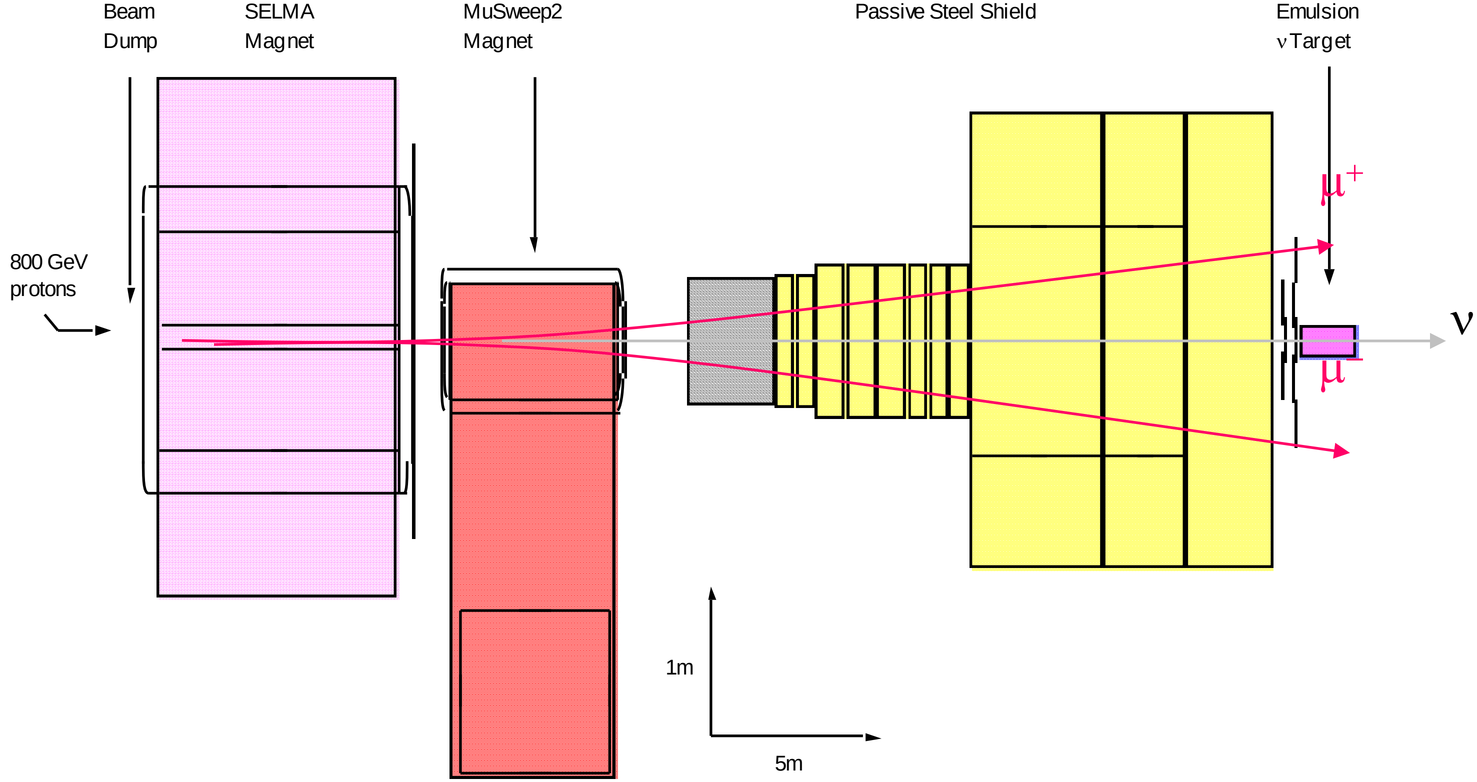


3.54x10^{17} PoT

8×10^{12} protons/ spill

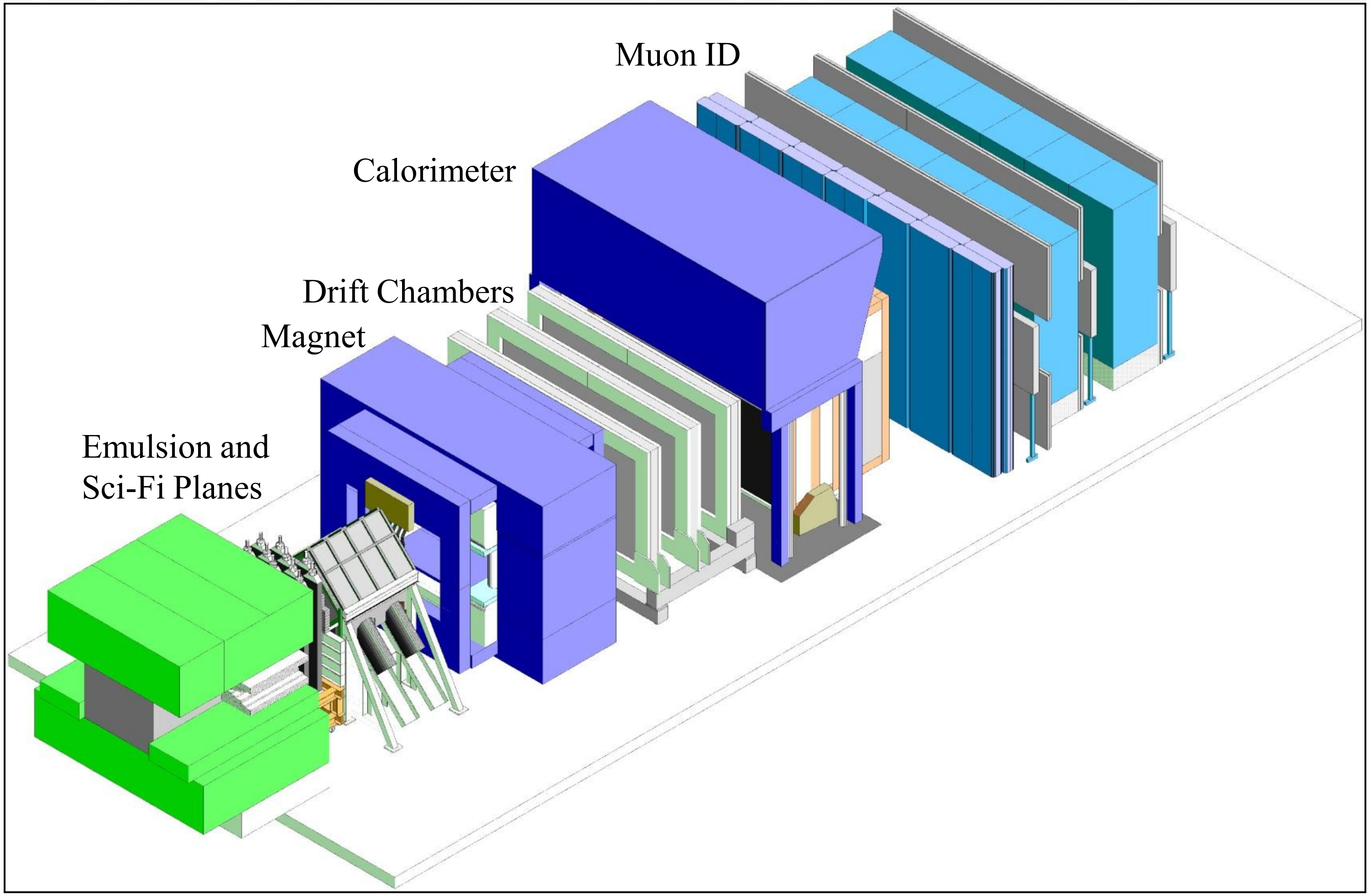
20 sec spill/ minute

Prompt Neutrino Beam & Shield

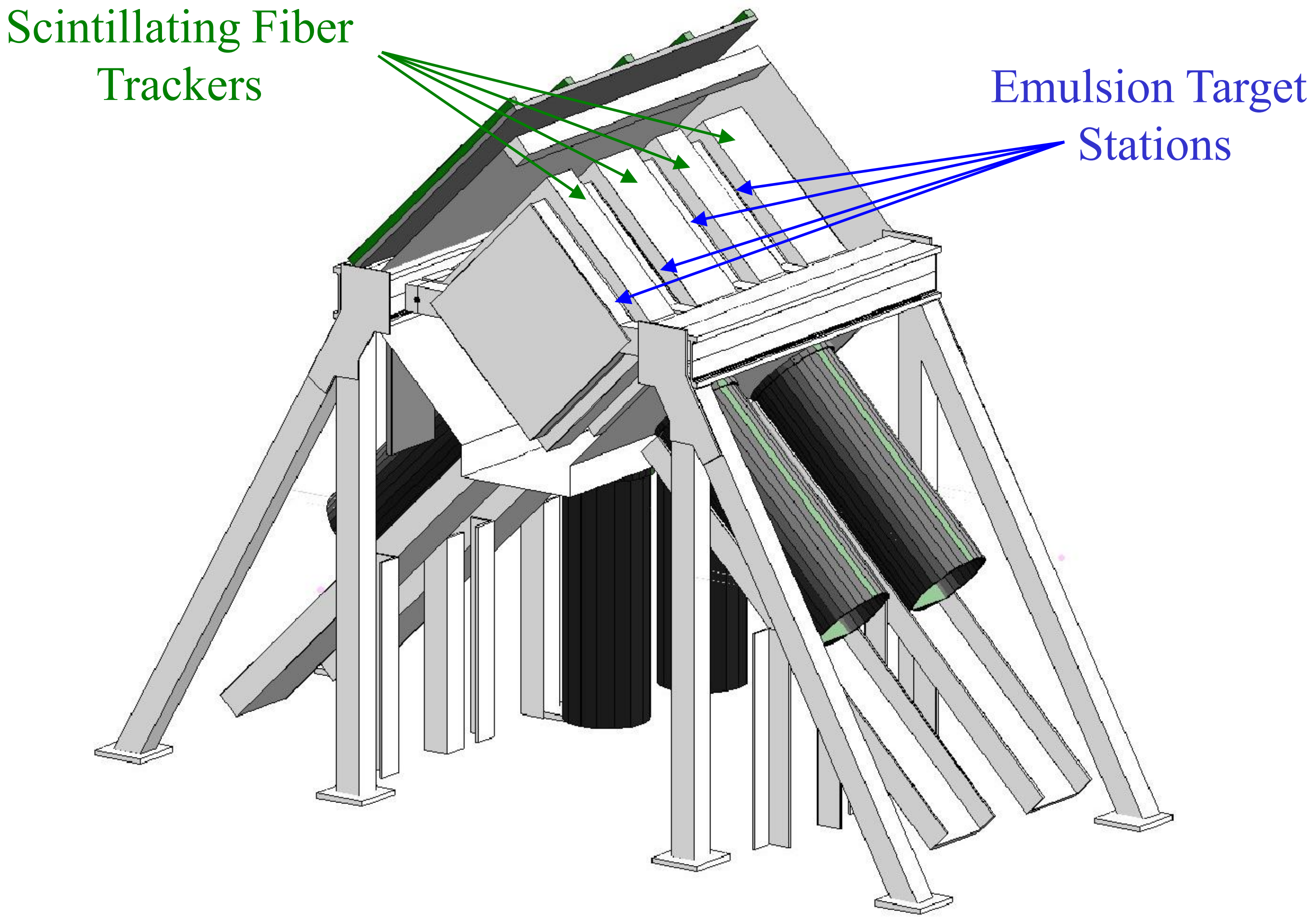


- Emulsion Target 36m from beam dump
- Muon rate ~ 2×10^4 per 10^{13} *pot* in target area

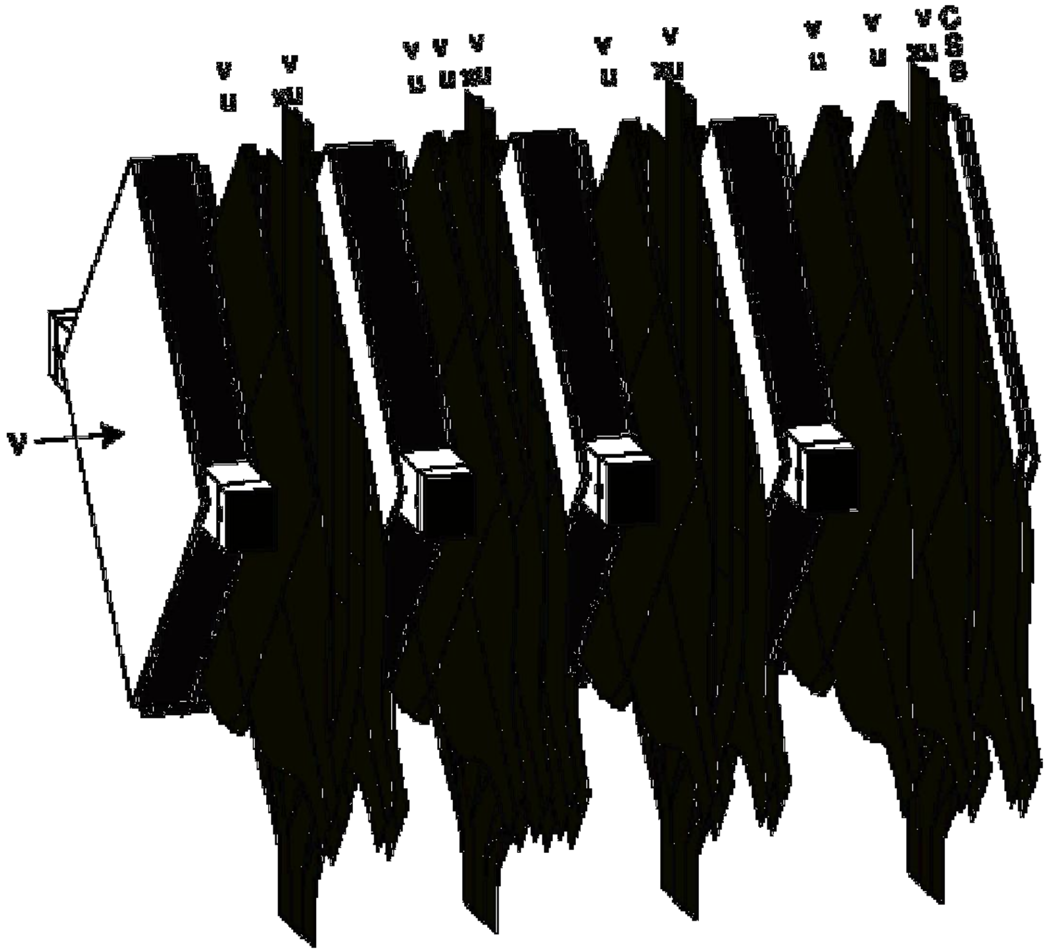
Detector complex



Emulsion Target Stations

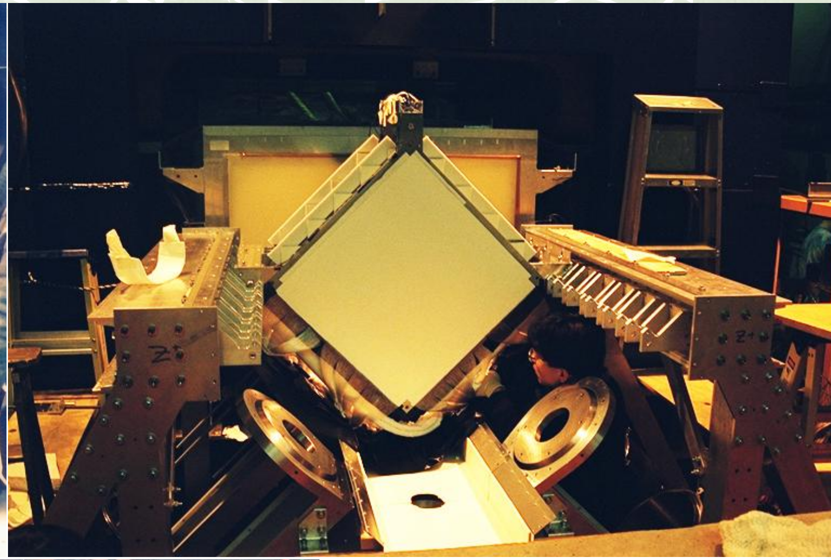


Emulsion Target / Vertex Detector



- 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

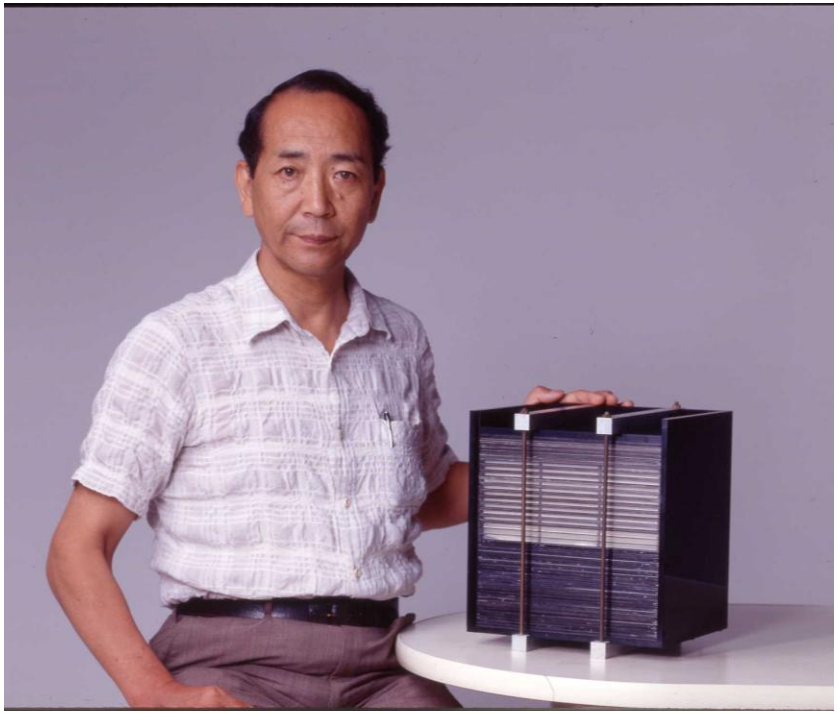
DONUT in construction

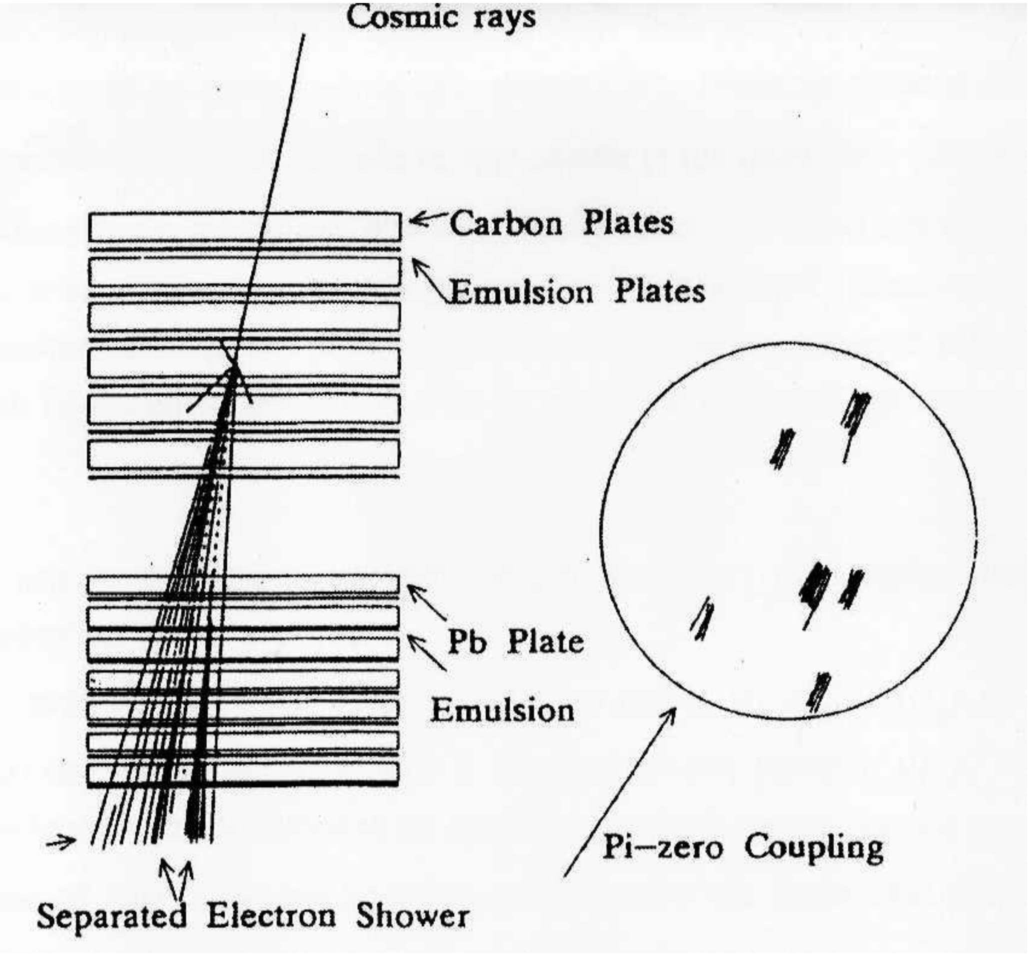


ECC (Emulsion Cloud Chamber)

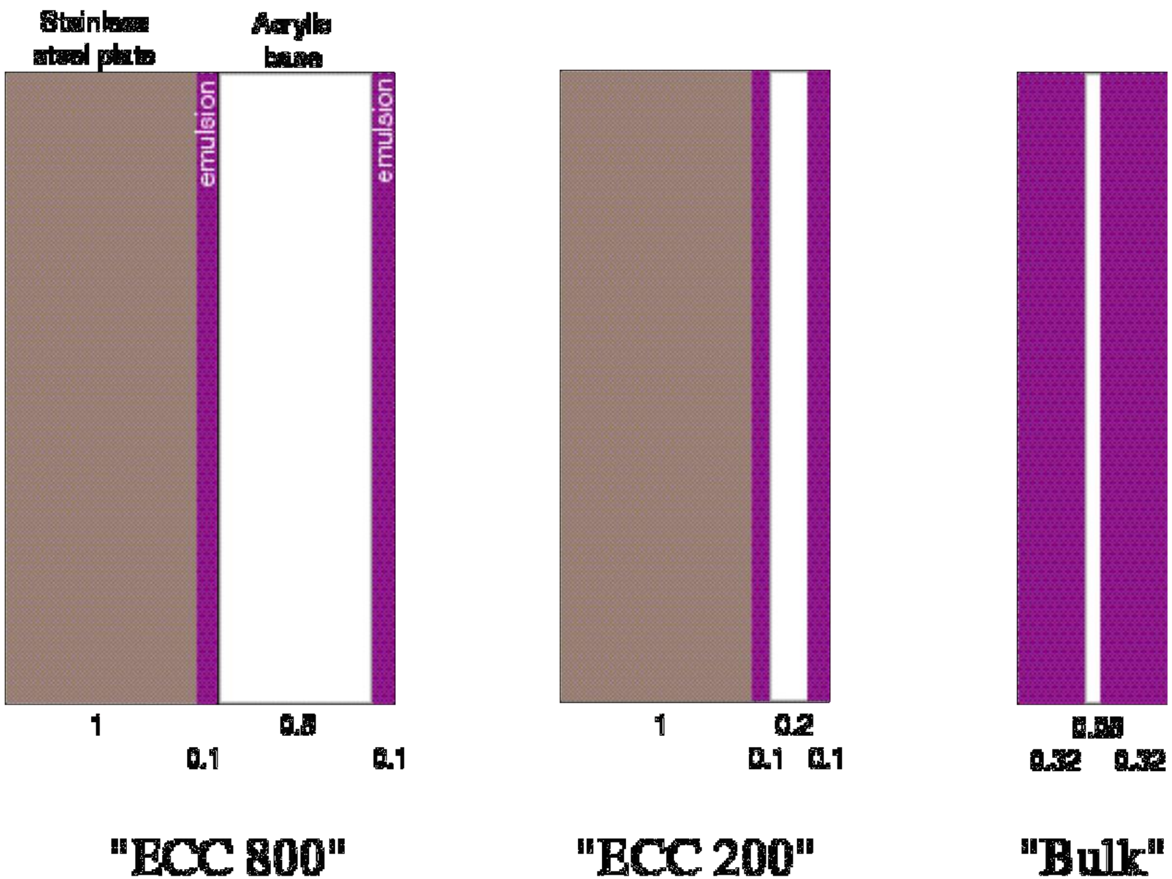
ECC : Utilized in cosmic-ray exposure → Discovery of Charm in 1971 (K.Niu)

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





Target Design



(mm)

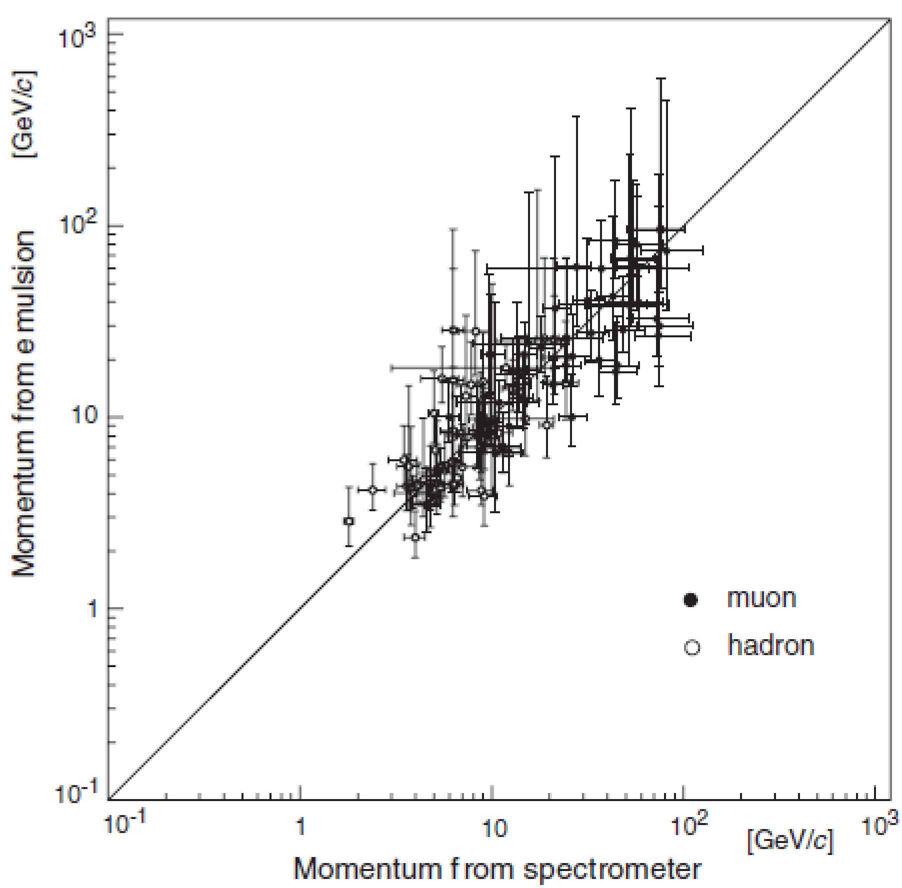
- 3 target types
- Bulk 95% emulsion
- ECC 5% emulsion

DONUT 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

Momentum Measurement in ECC

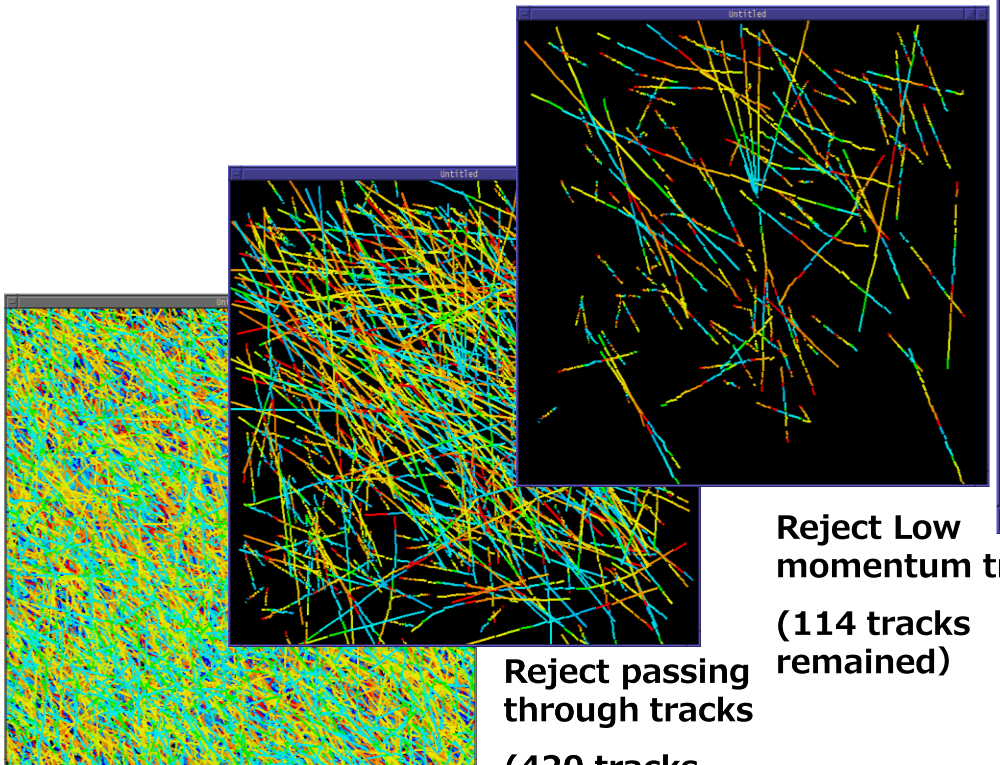
DONUT



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

Data taking and offline reconstruction

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



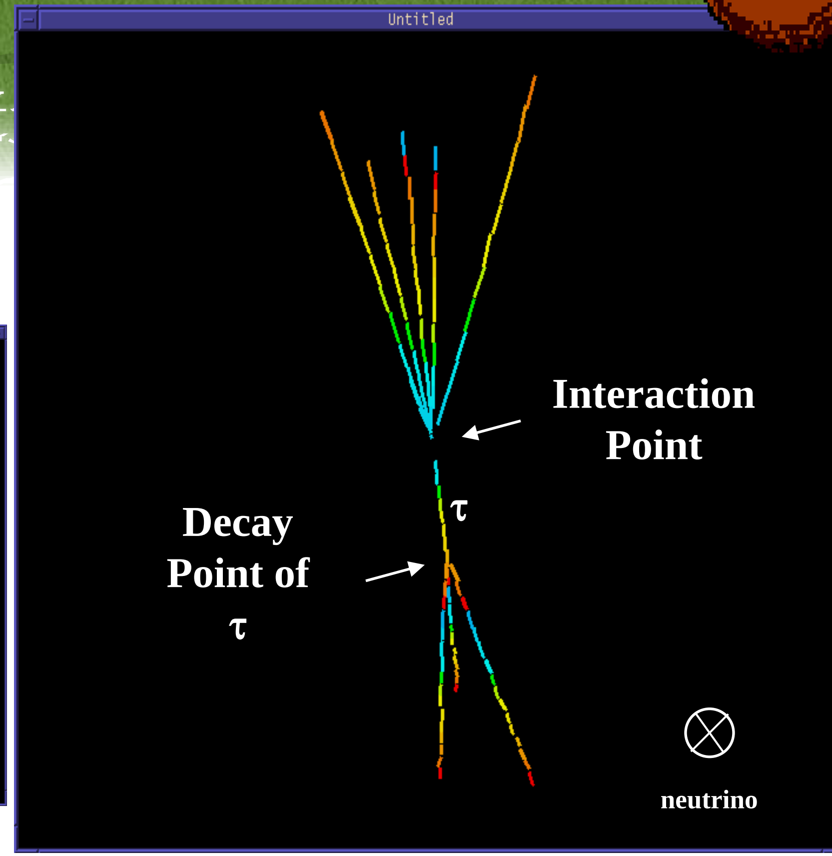
All tracks in the Scanning region (4179 tracks)

Reject passing through tracks

(420 tracks remained)

Reject Low momentum tracks

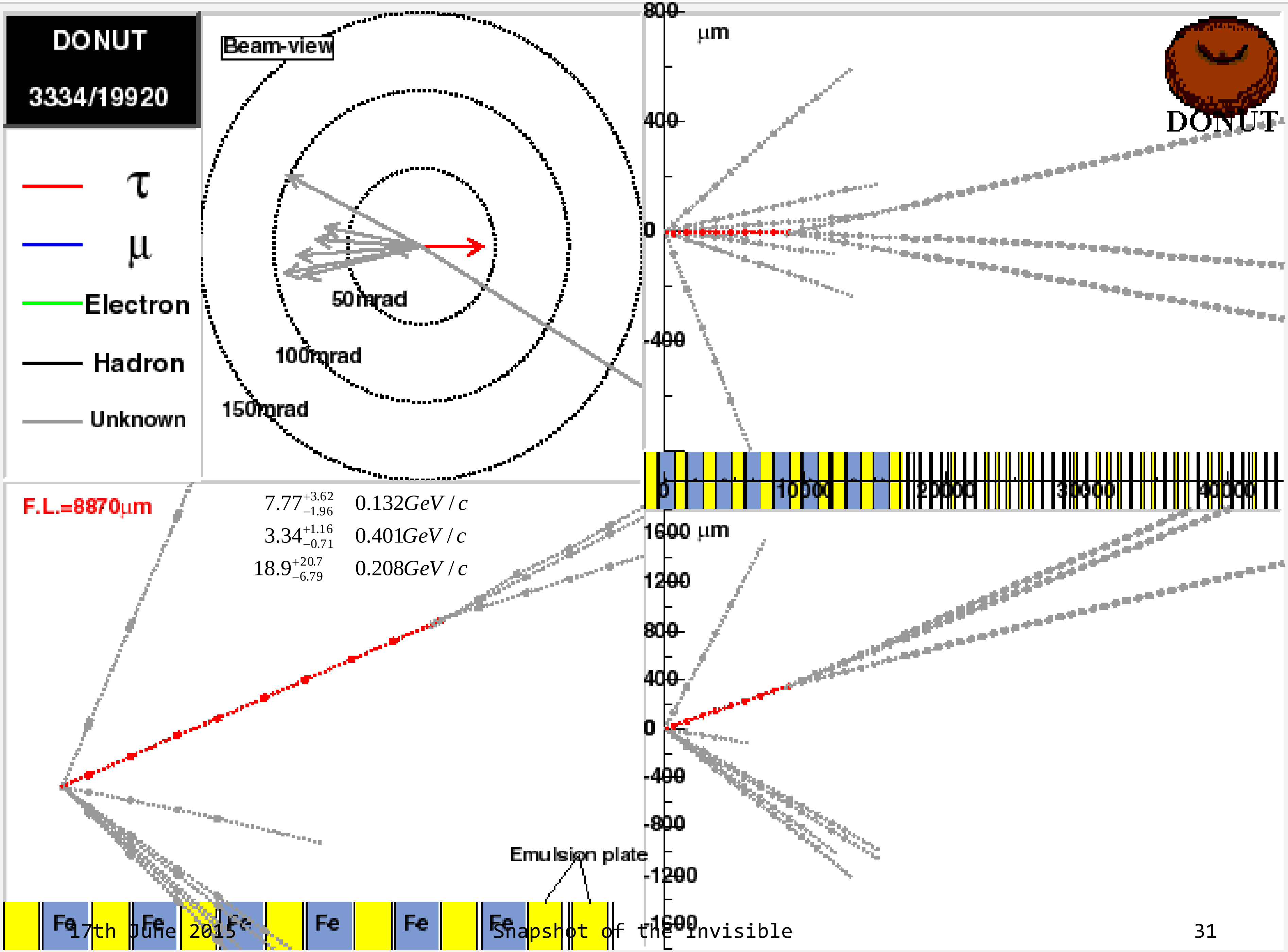
(114 tracks remained)

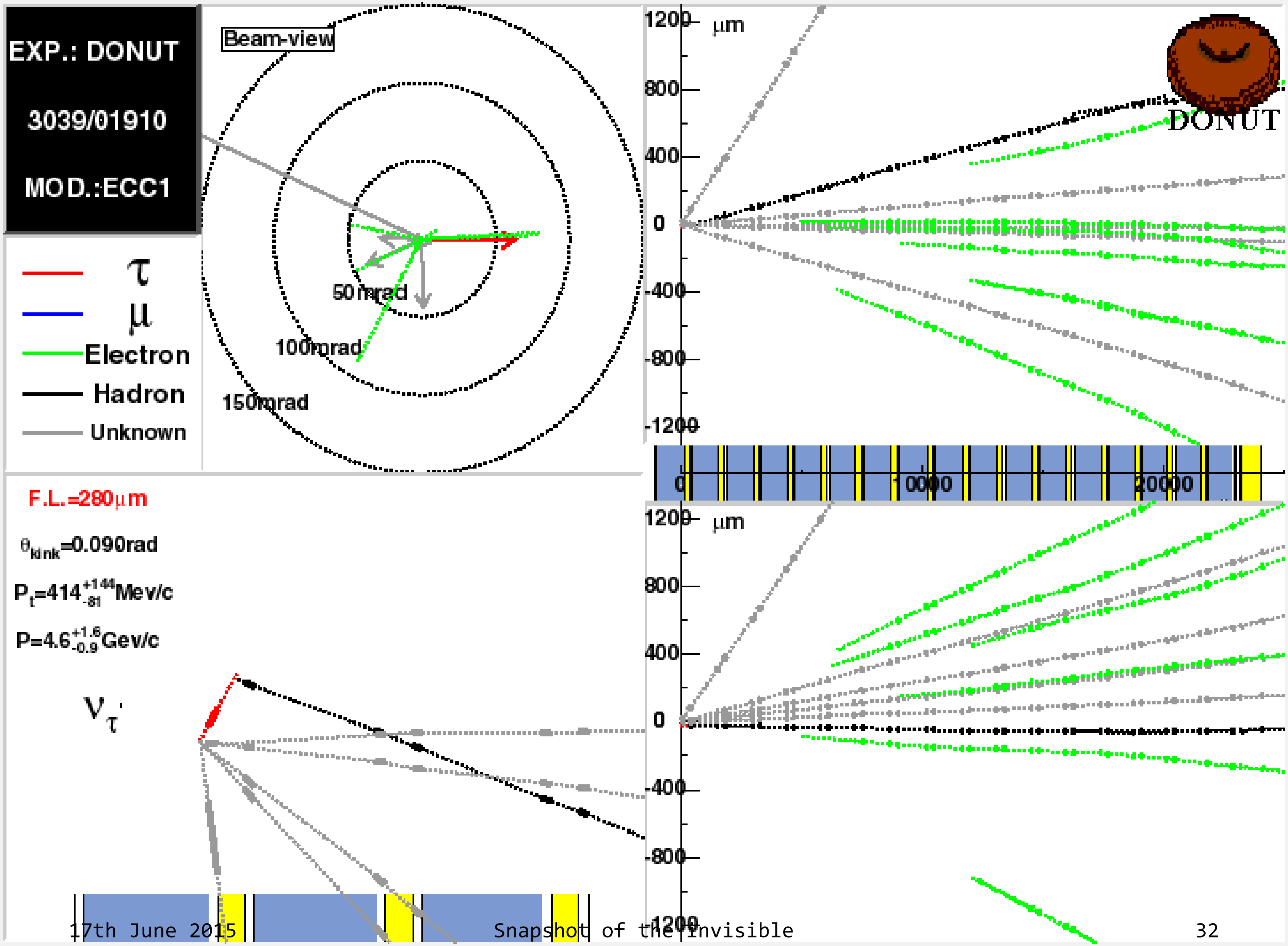


Vertex detection :

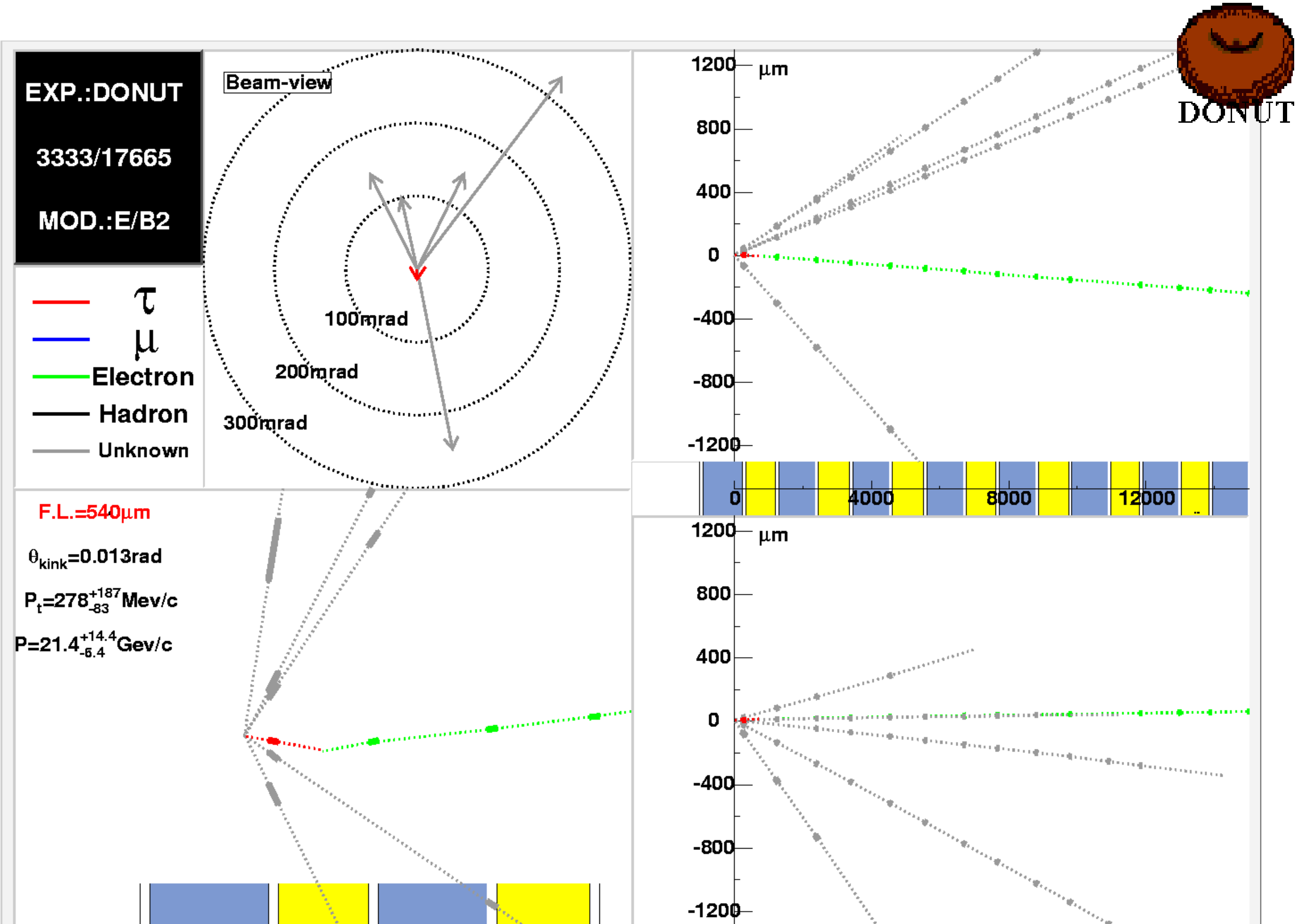
Neutrino interaction and decay of short lived particles

Detection of ν_τ^{CC} in DONUT

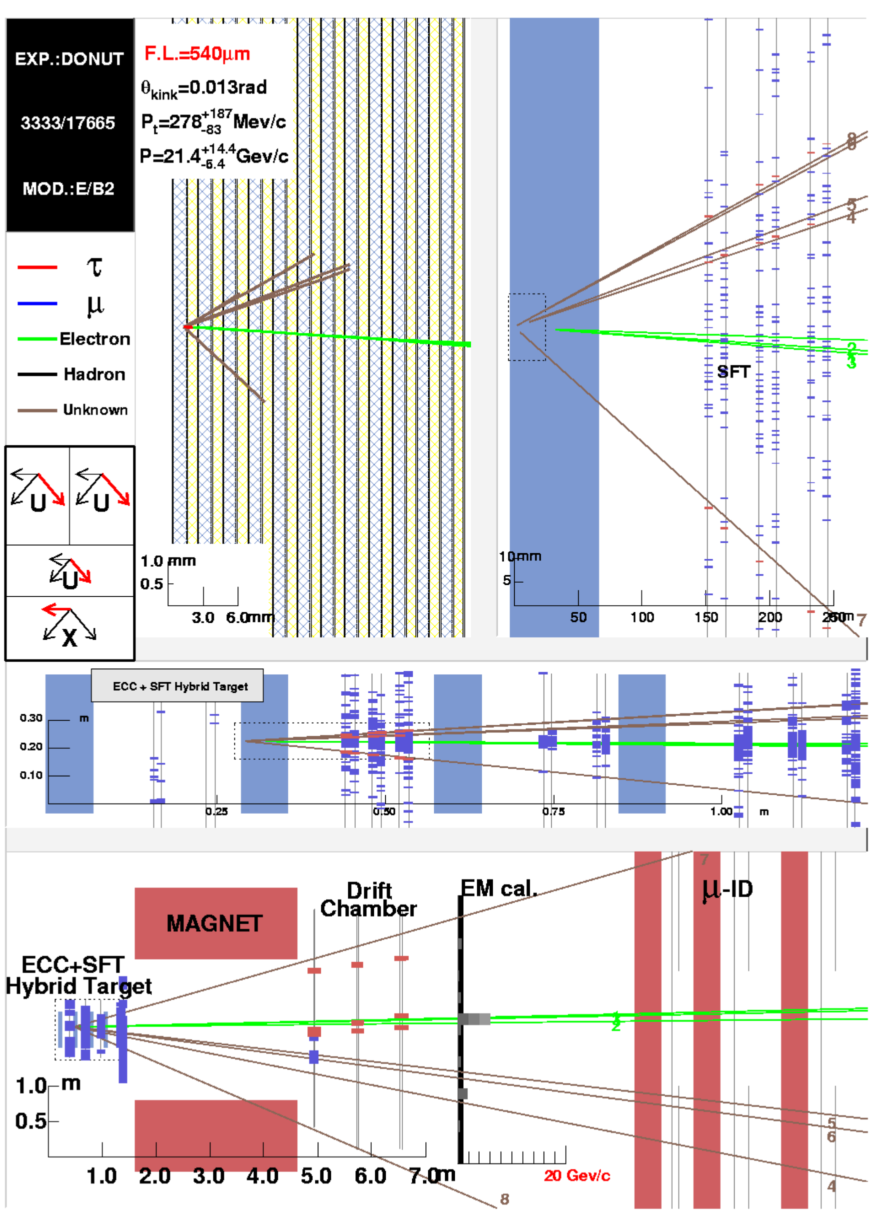

DONUT
3334/19920
τ
μ
Electron
Hadron
Unknown
Beam-view
50mrad
100mrad
150mrad
F.L.=8870μm
$7.77^{+3.62}_{-1.96}$ $0.132 GeV/c$
$3.34^{+1.16}_{-0.71}$ $0.401 GeV/c$
$18.9^{+20.7}_{-6.79}$ $0.208 GeV/c$
800
μm
400
0
-400
0
10000
20000
30000
40000
1600 μm
1200
800
400
0
-400
-800
-1200
-1600
DONUT
Emulsion plate
Fe
Fe
Fe
Fe
Fe
Fe

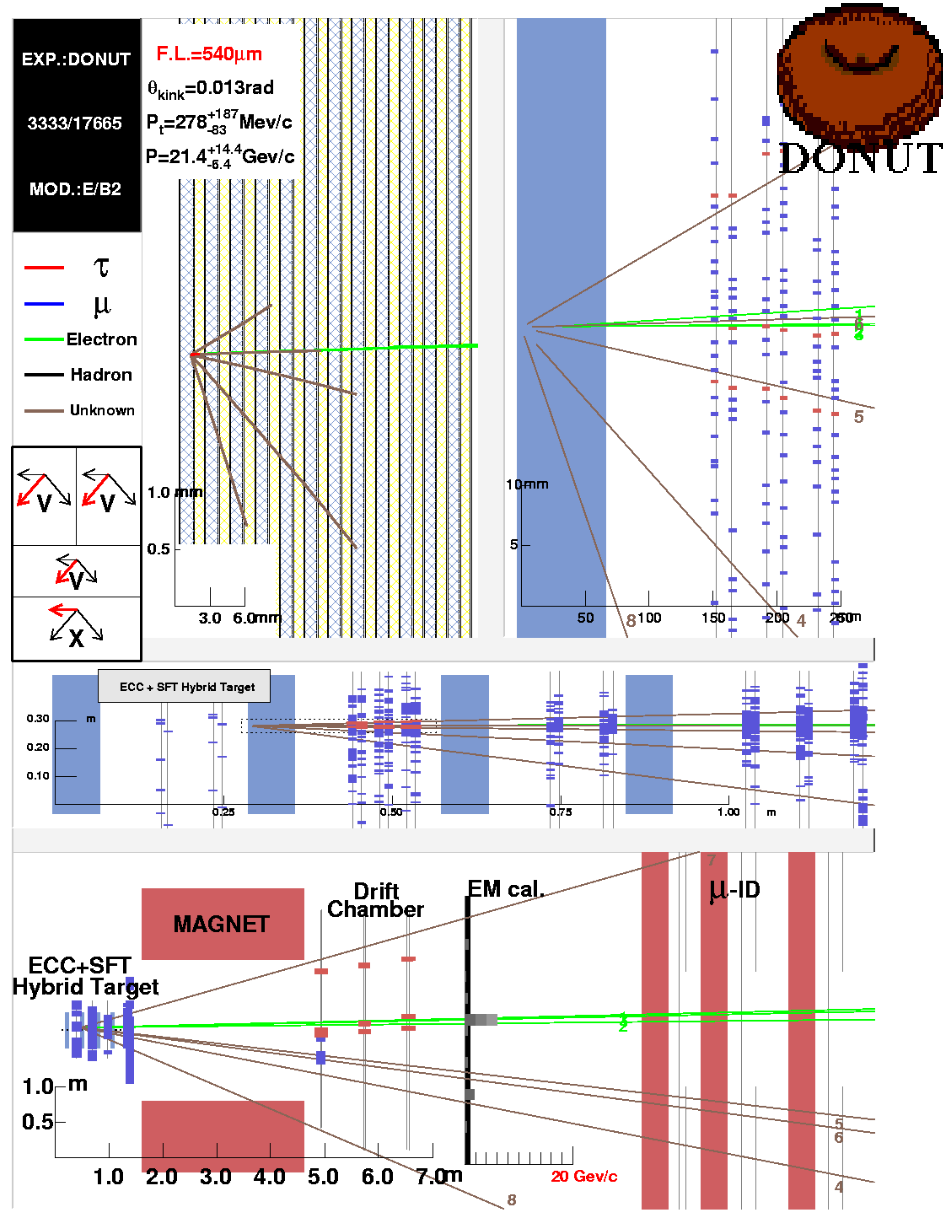


EXP.: DONUT
3039/01910
MOD.:ECC1
τ
μ
Electron
Hadron
Unknown
Beam-view
50mrad
100mrad
150mrad
F.L.=280μm
θ_{kink}=0.090rad
$P_t=414^{+144}_{-81}$Mev/c
$P=4.6^{+1.6}_{-0.9}$Gev/c
ν_τ
1200 μm
800
400
0
-400
-800
-1200
0
10000
20000
DONUT



EXP.:DONUT
3333/17665
MOD.:E/B2
τ
μ
Electron
Hadron
Unknown
Beam-view
100mrad
200mrad
300mrad
F.L.=540μm
θkink=0.013rad
Pt=278+187-83Mev/c
P=21.4+14.4-6.4Gev/c
1200
800
400
0
-400
-800
-1200
μm
0
4000
8000
12000
DONUT


EXP.:DONUT
3333/17665
MOD.:E/B2
F.L.=540μm
θkink=0.013rad
Pt=278+187-83Mev/c
P=21.4+14.4-6.4Gev/c
τ
μ
Electron
Hadron
Unknown
U
X
SFT
ECC + SFT Hybrid Target
MAGNET
Drift Chamber
EM cal.
μ-ID
ECC+SFT Hybrid Target
20 Gev/c


EXP.:DONUT
3333/17665
MOD.:E/B2
F.L.=540μm
θkink=0.013rad
Pt=278+187-83Mev/c
P=21.4+14.4-6.4Gev/c
DONUT
τ
μ
Electron
Hadron
Unknown
V
X
ECC + SFT Hybrid Target
MAGNET
Drift Chamber
EM cal.
μ-ID
ECC+SFT Hybrid Target
20 Gev/c

Physics and technical output

- Observation of tau neutrino
  - Phys. Lett. B504 (2001) 218-224
  - 500+ citation in INSPIRE
- Upper limit of magnetic moment
  - Phys. Lett. B513 (2001) 23-29
- Tau neutrino cross section
  - Phys. Rev. D78 (2008) 052002
  - 9 (7.5) tau neutrino candidate events
  - $\sigma^{const}(\nu_\tau)=(0.39\pm0.13\pm0.13)\times10^{-38}$ cm^2 GeV^{-1}
- Detection and analysis of tau neutrino
  - Nucl. Instrum. Meth. A493 (2002) 45-66
- Momentum measurement by MCS
  - Nucl. Instrum. Meth. A574 (2007) 192-198

OPERA experiment

Oscillation Project with Emulsion-tRacking Apparatus

- τ appearance @ a few $x10^{-3}$ eV^2
  - Must be high energy to create tau
  - Long baseline experiment : ~1000km
- Contradicting request
  - Must be massive (kilo tons)
  - Must be high resolution (micro meteric)
- Significant jump from past largest experiment CHORUS.
  - 800kg → 1000 tons (x1000)

The OPERA Collaboration

OPERA

140 physicists, 28 institutions in 11 countries

Belgium
IIHE-ULB Brussels

Croatia
IRB Zagreb

France
LAPP Annecy
IPHC Strasbourg

Germany
Hamburg

Israel
Technion Haifa

Italy
Bari
Bologna
Frascati
L'Aquila,
LNGS
Naples
Padova
Rome
Salerno

Japan
Aichi
Toho
Kobe
Nagoya
Nihon

Korea
Jinju

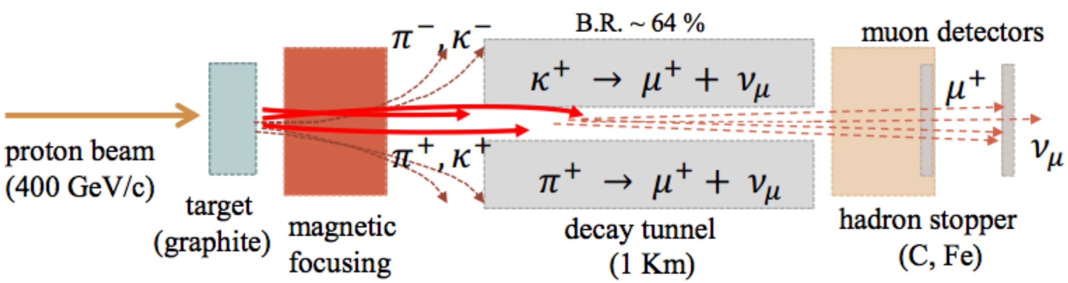
Russia
INR RAS Moscow
LPI RAS Moscow
ITEP Moscow
SINP MSU Moscow
JINR Dubna

Switzerland
Bern

Turkey
METU, Ankara

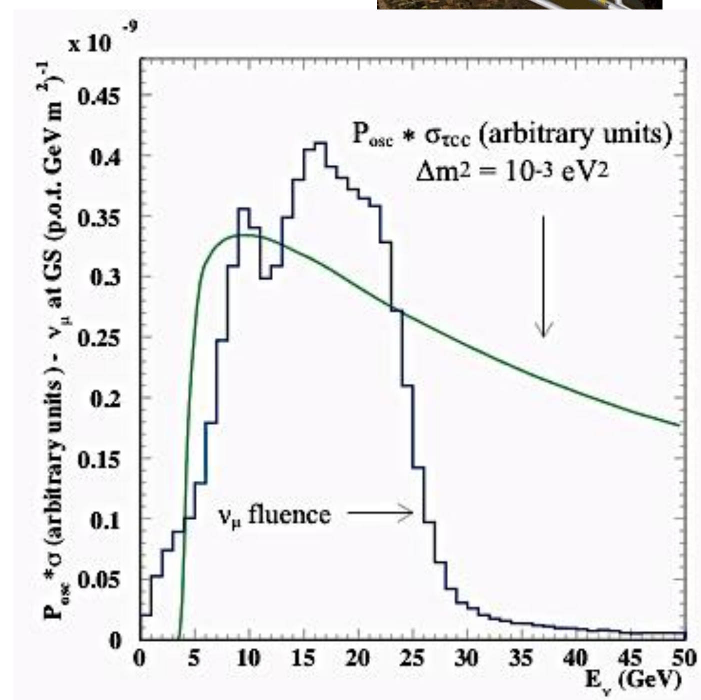
http://operaweb.lngs.infn.it/

CNGS (CERN Neutrino to Gran Sasso)

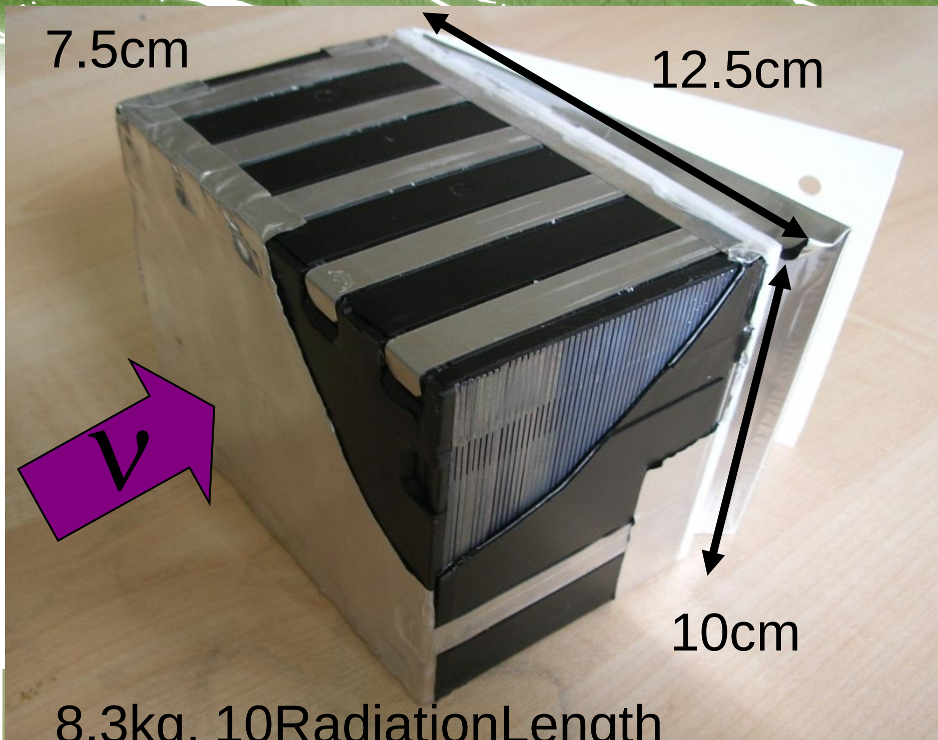


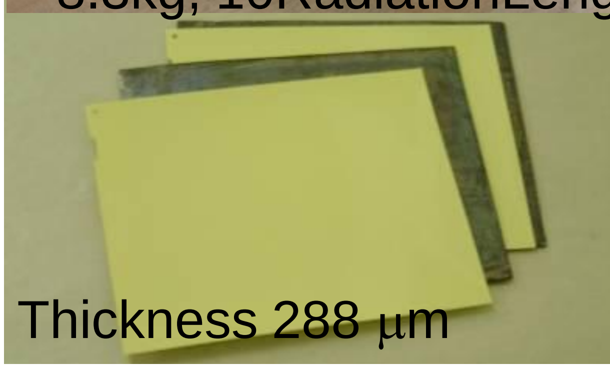
732km

- High energy neutrino
  - $\langle E_\nu \rangle$ ~17GeV (tau neutrino CC cross section above 3.5GeV)
- Long baseline
  - L=732km
- High energy beam optimized to maximize tau neutrino interactions
  - $P(\nu_\mu \rightarrow \nu_\tau) \sim 1\%$



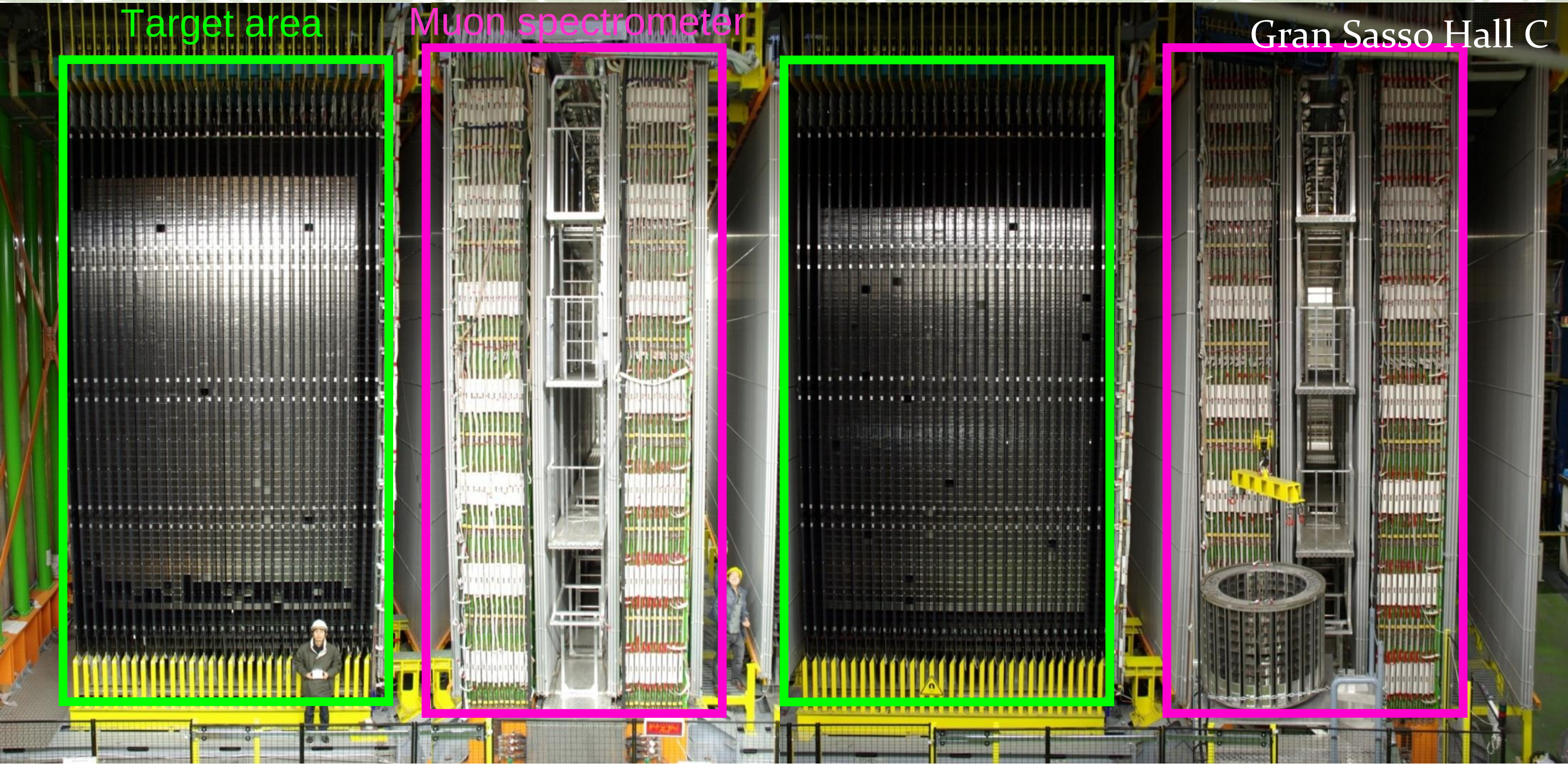
OPERA ECC brick





- 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

OPERA detector

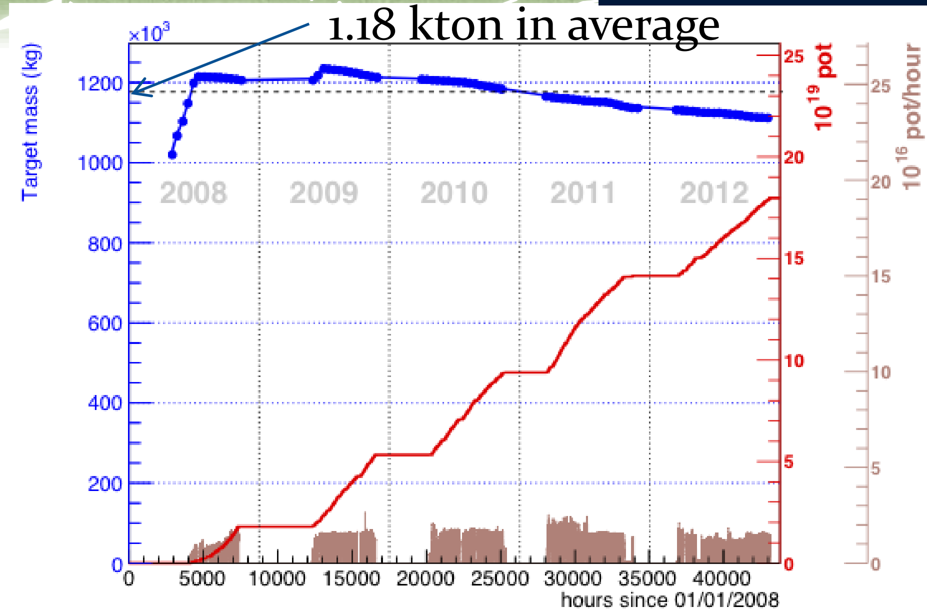


- 150,000 ECC bricks = 1.25 ktons of active target

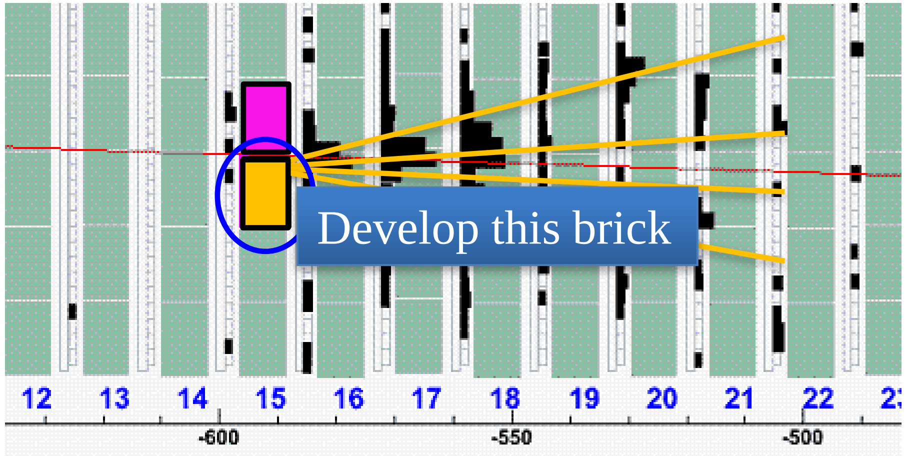
Collected data

Year	P.O.T. (10^{19})	SPS Eff.	Beam days	ν interactions
2008	1.74	61%	123	1931
2009	3.53	73%	155	4005
2010	4.09	80%	187	4515
2011	4.75	79%	243	5131
2012	3.86	82%	257	3923
Total	17.97	77%	965	19505

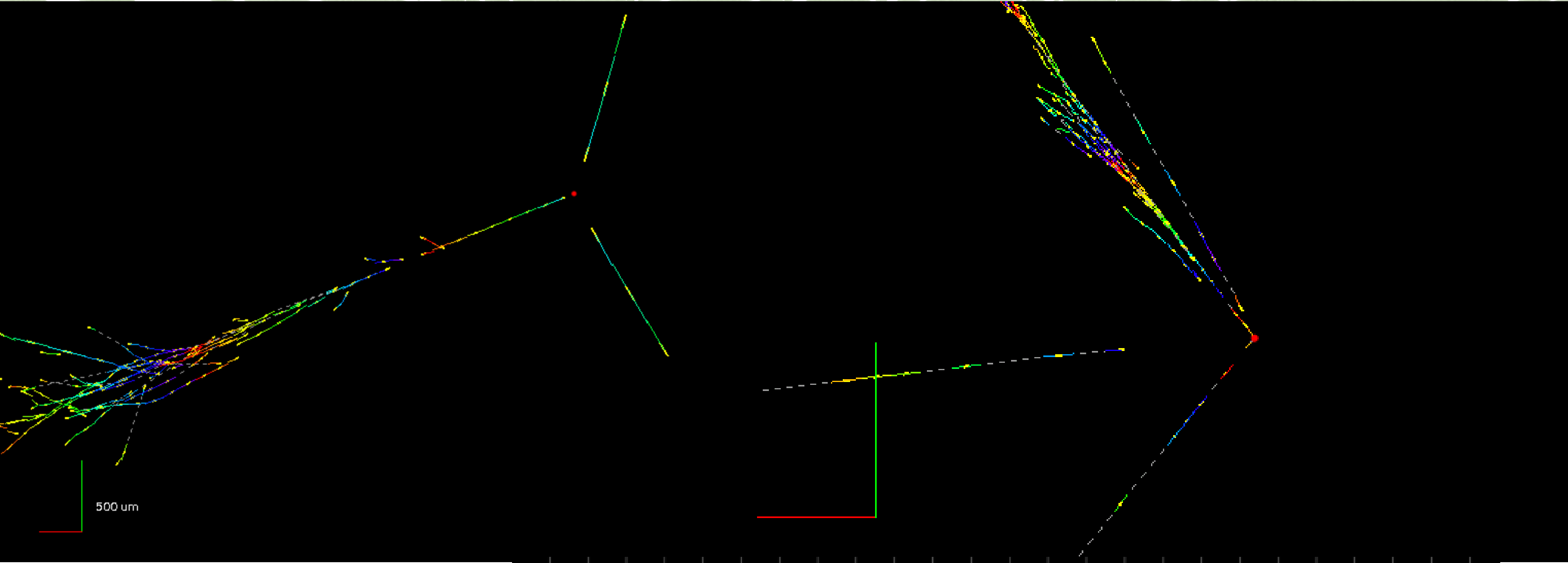
80% of the design

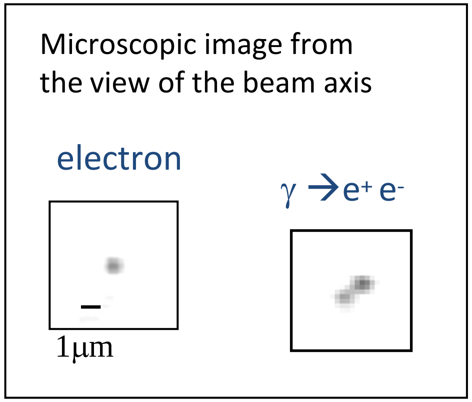


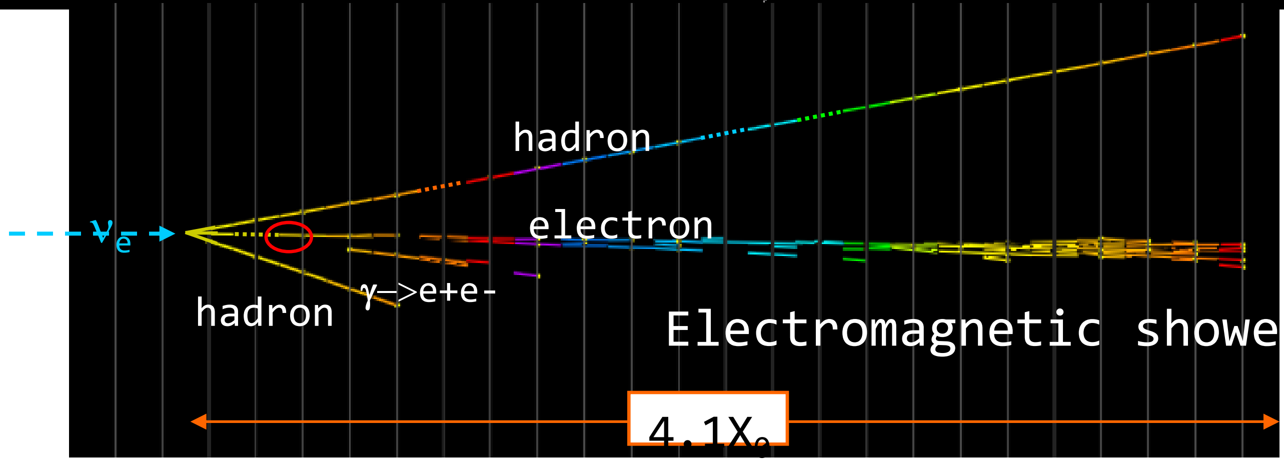
- Analysis strategy
  - 1st and 2nd probable brick
  - Muon momentum < 15GeV/c



ν_e event in OPERA ECC







1^{st} ν_τ candidate $(5I \rightarrow h)$ (2010)

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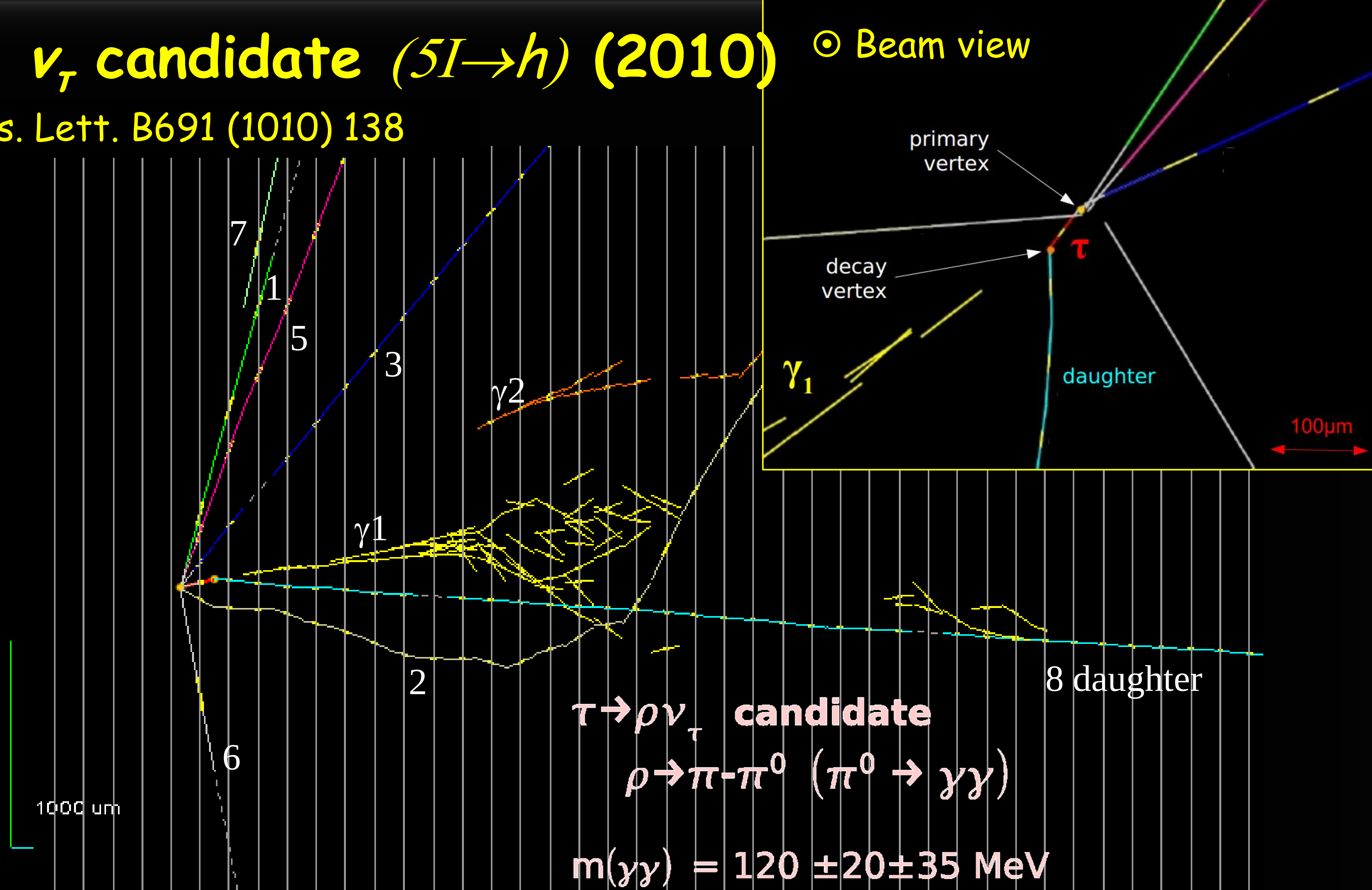


$\tau \rightarrow \rho \nu_\tau$ **candidate**

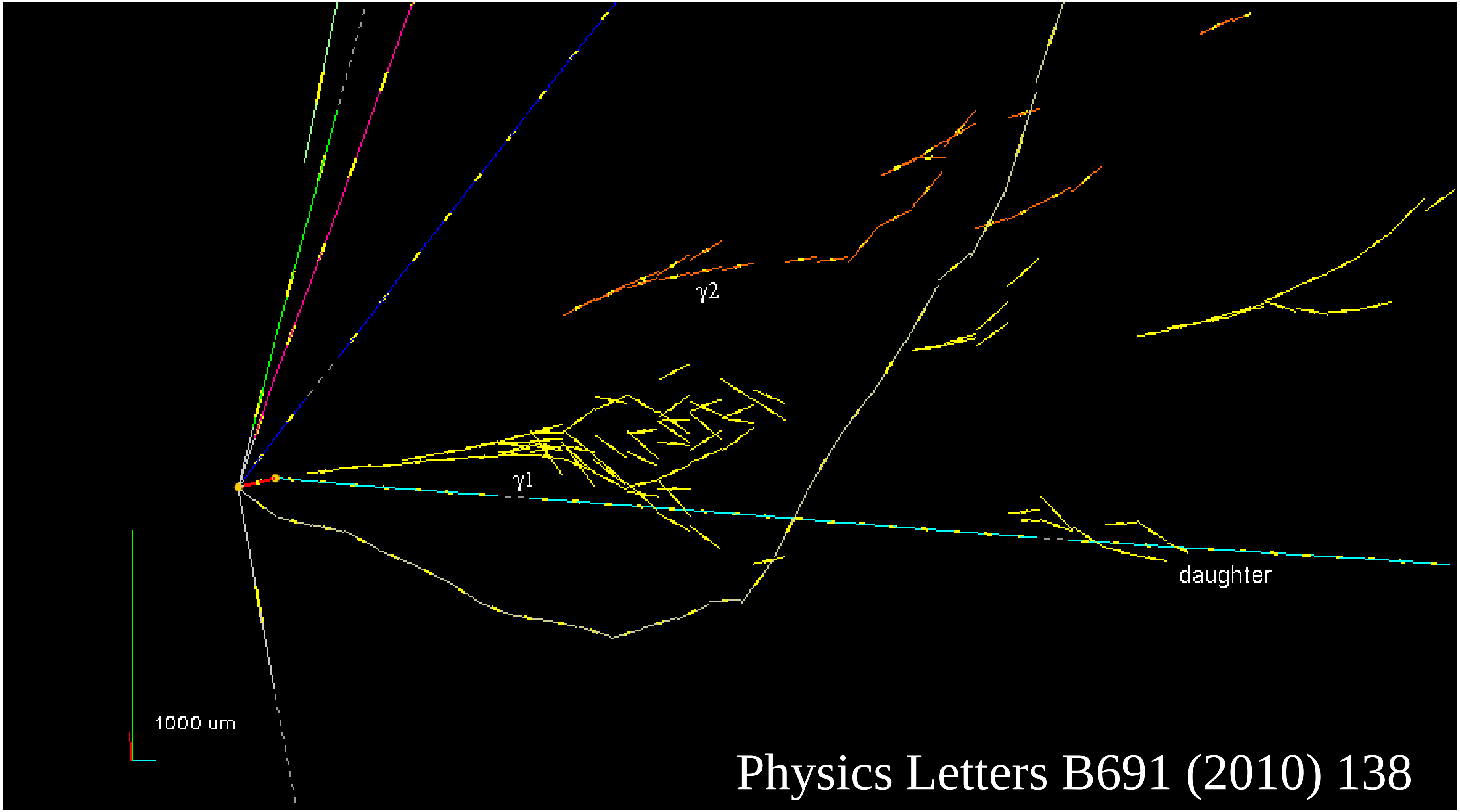
$\rho \rightarrow \pi^- \pi^0 \ (\pi^0 \rightarrow \gamma\gamma)$

$m(\gamma\gamma) = 120 \pm 20 \pm 35$ MeV

$m(\pi^- \gamma\gamma) = 640^{+125}_{-80}{}^{+100}_{-90}$ MeV

$Br(\tau \rightarrow \rho \nu_\tau) \sim 25\%$

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



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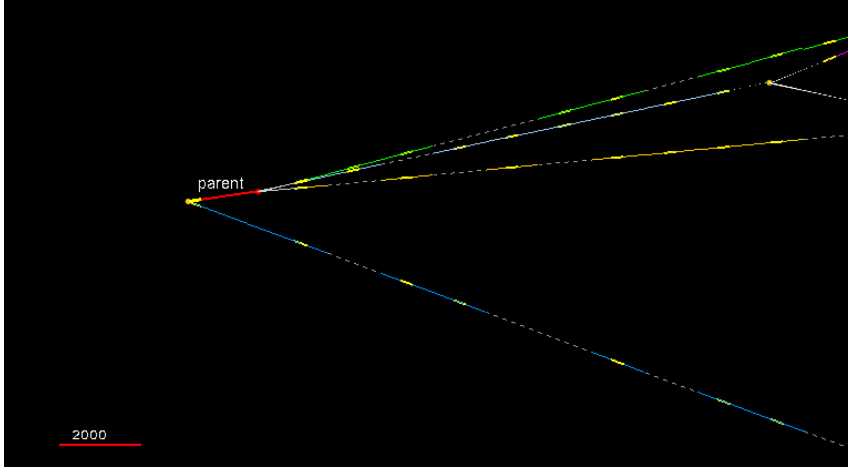
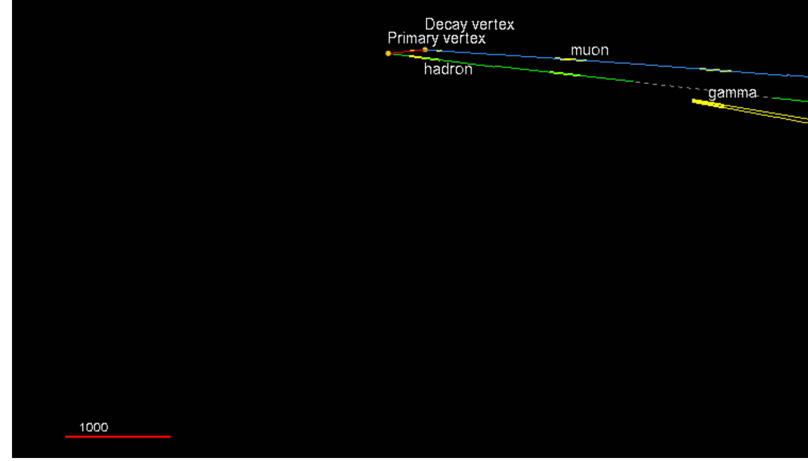
2nd to 5th tau candidates

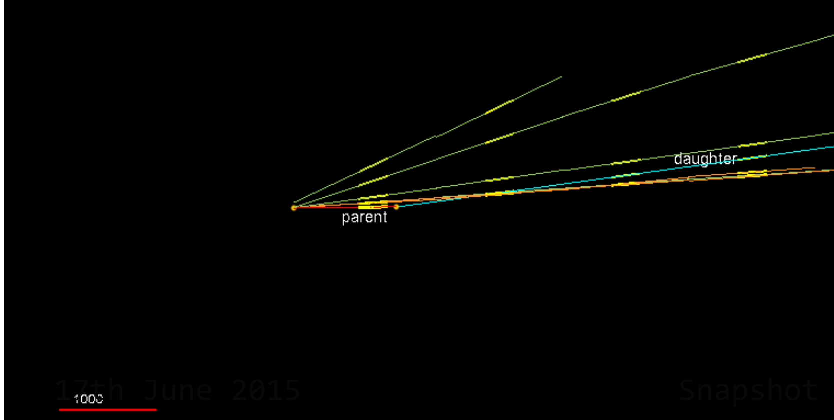
Journal of High Energy Physics 11 (2013) 036
2nd ($\tau \rightarrow 3h$)



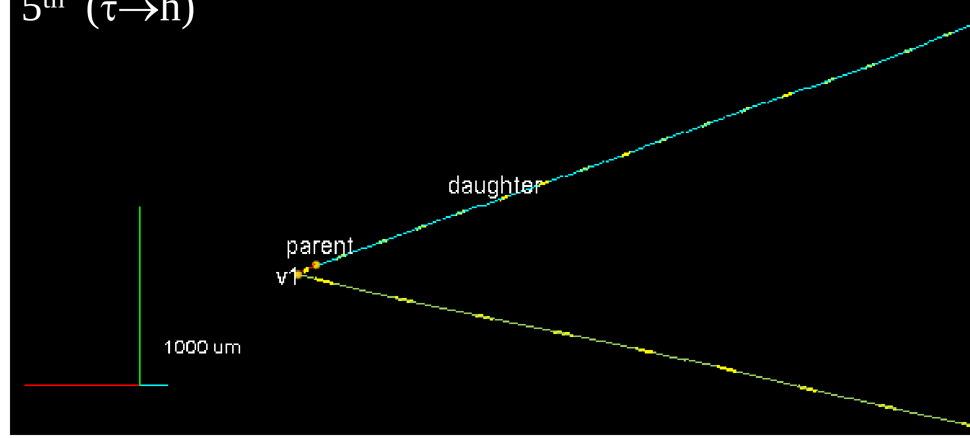
PHYSICAL REVIEW D 89 (2014) 051102(R)
3rd ($\tau \rightarrow \mu$)



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



To be submitted …
5th ($\tau \rightarrow h$)



Significance

2008-2012 : 1144 (0μ events) + 4264 (1μ events with $P_\mu < 15$ GeV/c)

The expected signal and background is normalized to the number of analyzed events

$$n^{0\mu}(\nu_\tau^{CC}) = \frac{N(\nu_\tau^{CC})}{N(\nu_\mu^{CC})} \frac{n^{0\mu} < \epsilon^{0\mu}(\nu_\tau^{CC}) >}{< \epsilon^{0\mu}(\nu_\mu^{CC}) > + \alpha < \epsilon^{0\mu}(\nu_\mu^{NC}) >} \qquad \alpha = \frac{NC}{CC}$$

Decay channel	Expected signal $\Delta m_{23}^2 = 2.44$ meV^2	Total background	Observed
$\tau \rightarrow h$	0.52 ± 0.10	0.038 ± 0.007	3
$\tau \rightarrow 3h$	0.73 ± 0.15	0.174 ± 0.034	1
$\tau \rightarrow \mu$	0.61 ± 0.12	0.004 ± 0.001	1
$\tau \rightarrow e$	0.78 ± 0.16	0.031 ± 0.006	0
Total	2.64 ± 0.53	0.247 ± 0.045	5

- Two statistical methods
  - p-value = 1.10×10^{-7} : Fisher combination
  - p-value = 1.07×10^{-7} : Likelihood ratio

no oscillations excluded at $5.1\,\sigma$ CL

OPERA conclusion

- OPERA has recorded neutrino interactions equivalent to ~1.8 x 10^{20} pot delivered by CNGS beam from 2008 to 2012 (80% of design)
- 5 ν_τ events observed with 0.25 background.
- No oscillation hypothesis excluded at 5.1 σ
- First measurement of Δm^2_{32} = [2.0 – 5.0] x 10^{-3} eV^2 (90% CL) for $\sin^2(2\theta_{23}) = 1$ in appearance mode.
  - PDG value 2.44×10^{-3} eV^2 is in our interval

20 years of tau neutrino search (I)

- In 1994, we made big decision to change future emulsion experiments.
  - Semi-automatic to automatic
  - Visual detector to tracking detector

- CHORUS could not find ν_τ, just because the answer was not there.
  - Technical advancement on new analysis method based on automatic scanning system.
  - Rich neutrino induced charm physics.

20 years of tau neutrino search (II)

- DONUT successfully observed 9 ν_τ (2008)
  - High speed automatic scanning system completely changed analysis strategy.
    - In the CHORUS phase I analysis, automatic scanning system was replacement of human.
    - 1998, automatic scanning system completely exceed human ability.
- ECC become baseline
  - Massive and high resolution.
  - Highly modular structure.
  - Kinematical measurement and particle ID

20 years of tau neutrino search (III)

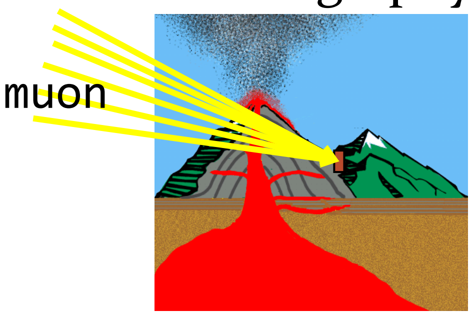
- OPERA achieved five ν_τ observation
  - First ν_τ event found in 2010.
  - Three orders of scale up was achieved by ECC and 100 times faster scanning systems than DONUT.
- $\nu_\mu \rightarrow \nu_\tau$ oscillation is established by ν_τ appearance in the OPERA experiment.
  - 5.1 sigma significance (2015)
- 20 years of efforts are now rewarded.

However!

- We only observed 14(9+5) ν_τ
  - All these ν_τ observation is done in emulsion.
- Our knowledge of ν_τ is still poor
  - We need new experiment to study ν_τ
- Evolution of scanning system open new possibilities.
  - CHORUS, DONUT and OPERA is the history of scanning system evolution.

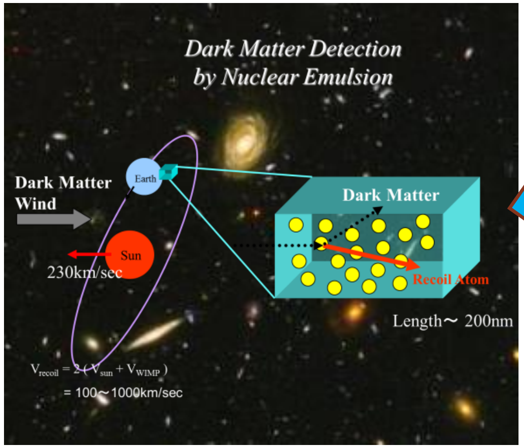
As a result of 20 years of evolution

Muon Radiography



Emulsion Production

Gamma Ray Telescope



Directional Dark Matter

Scanning System (HTS)

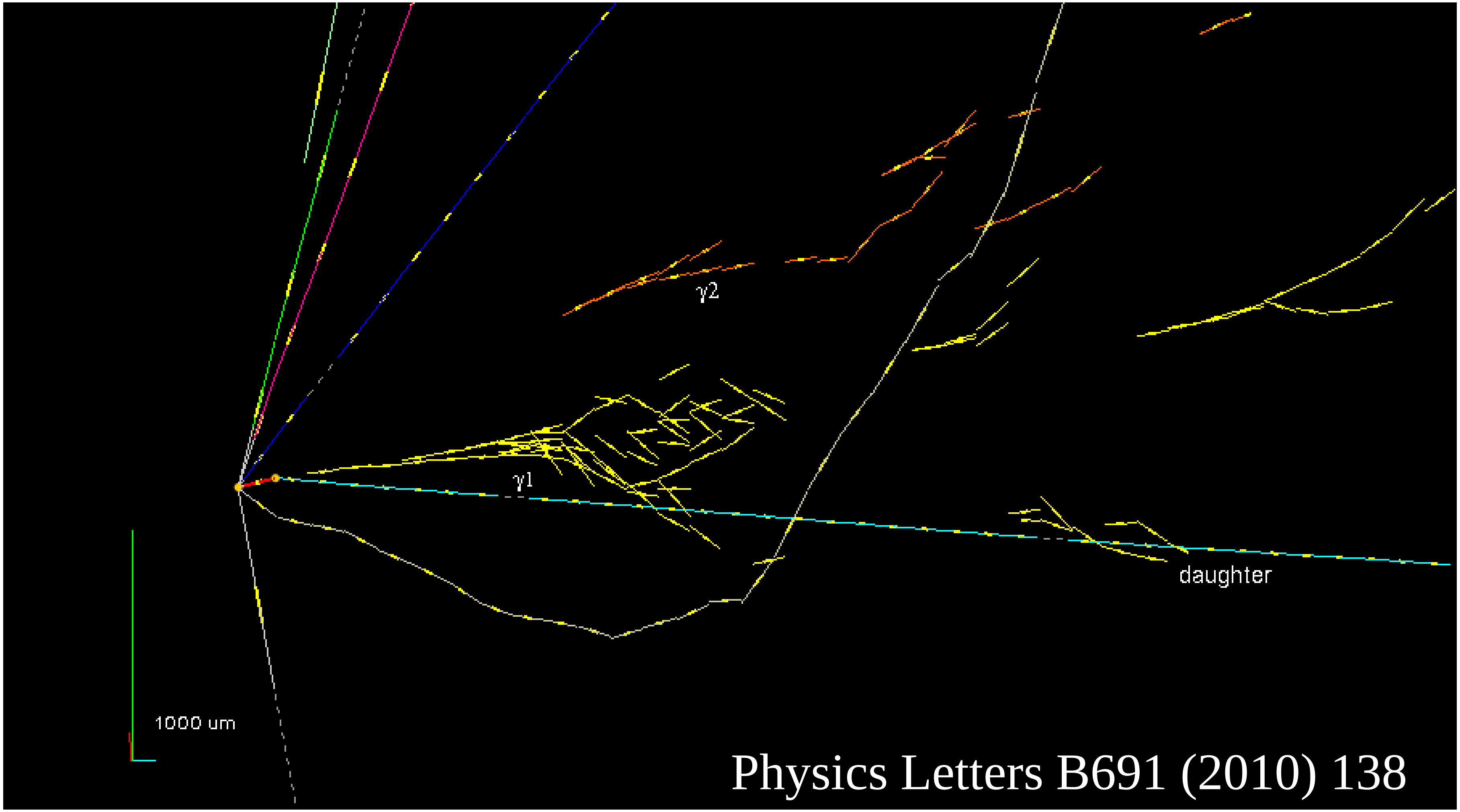
SHiP
Search for Hidden Particles

Tau Neutrino Physics

A new journey start with …

Thank you

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



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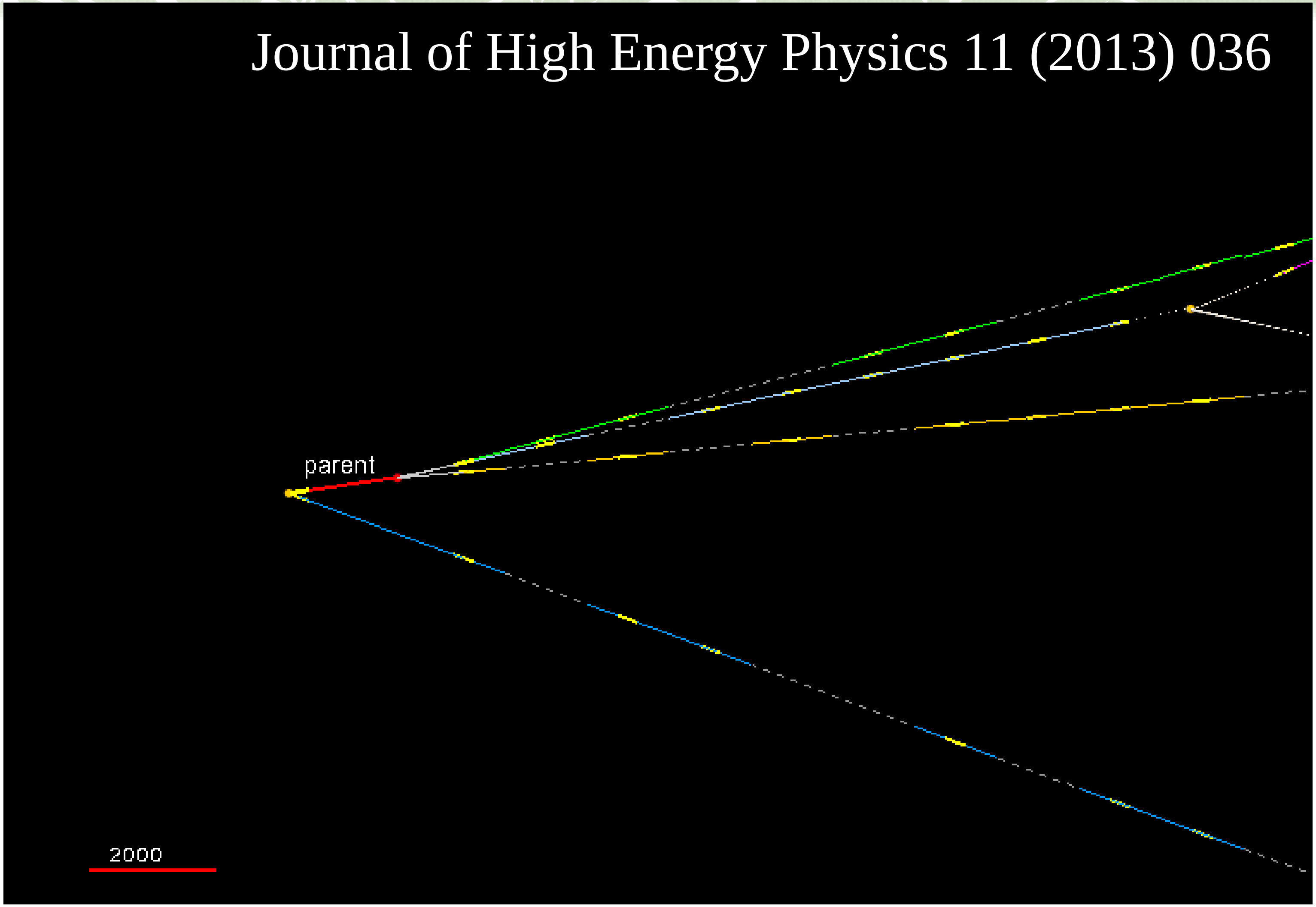
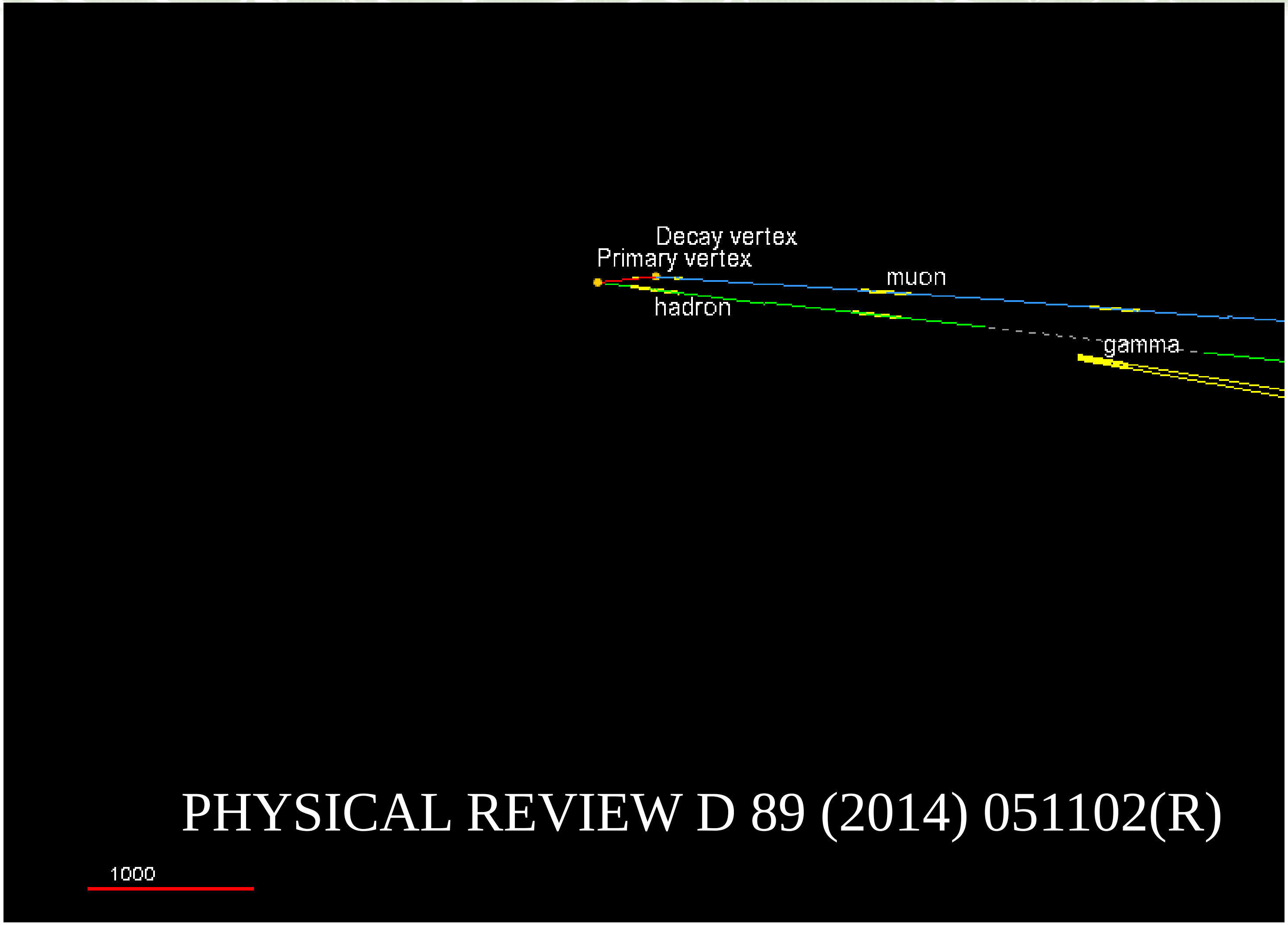
Second ν_τ candidate ($\tau \to 3h$)



Third ν_τ candidate ($\tau^- \rightarrow \mu^-$)



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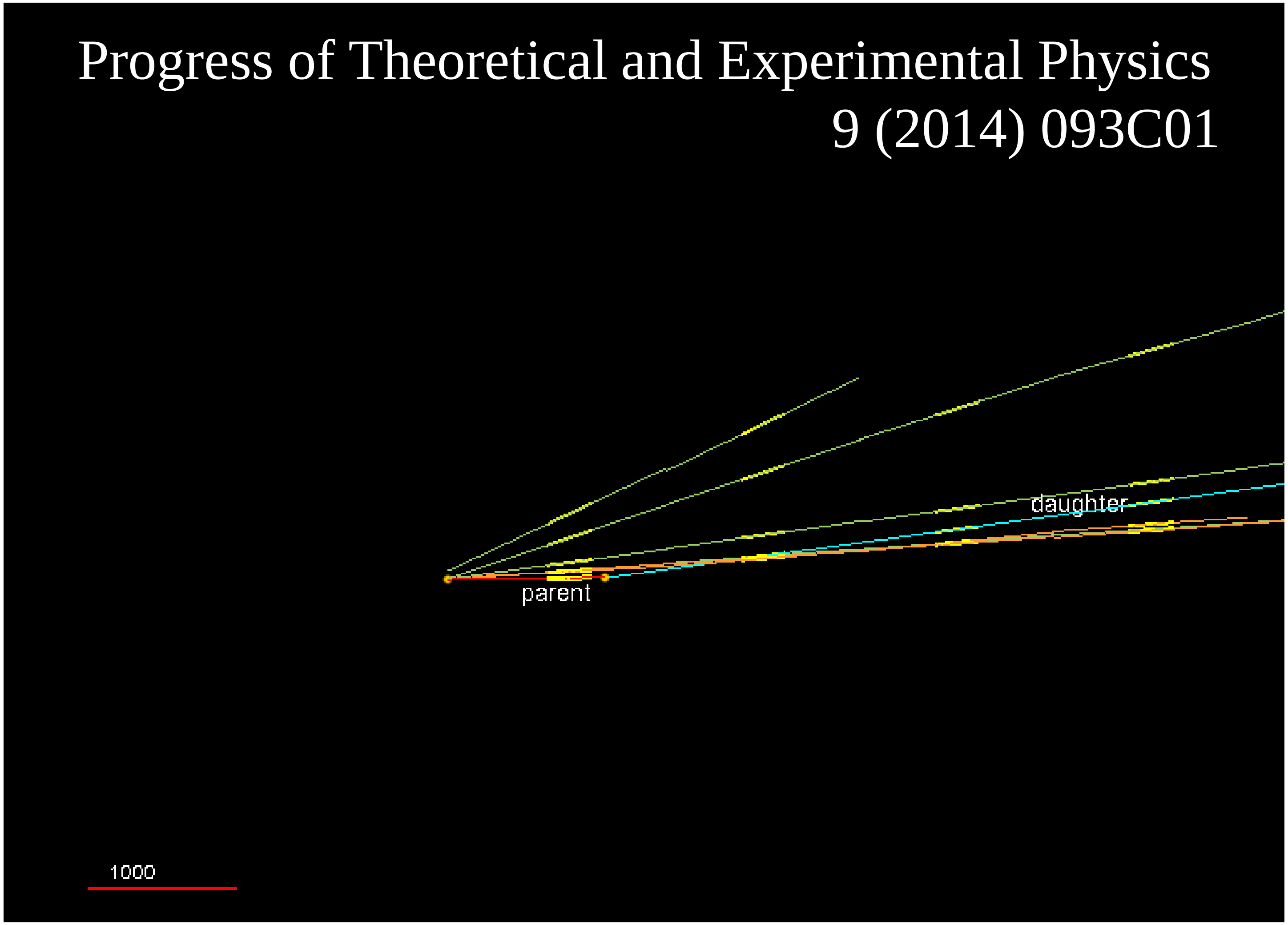
4th ν_τ candidate ($\tau \rightarrow h$)



5th ν_τ candidate ($\tau \rightarrow h$)