OPERA

RESULTS AND EMULSION DETECTOR APPLICATIONS

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Outline

- Why
- How
- Results
  - Cosmic events
  - Muon charge ration
  - Electron neutrinos
  - Tau neutrinos
  - Neutrino induced charm events

- Brief history of emulsion

History of neutrino physics

1930 Pauli: hypothesis of the neutrino to explain the b decay

1934 Fermi: theory of the b decay
Bethe & Peierls: cross section ~ 10^{-44} cm^2 at 1 MeV

1956 Cowan and Reines: discovery of n_e
Davis: $\nu \neq \bar{\nu}$

1958 Pontecorvo: hypothesis of $\nu \leftrightarrow \bar{\nu}$ oscillation

1962 Ledermann, Schwartz and Steinberger: discovery of n_m

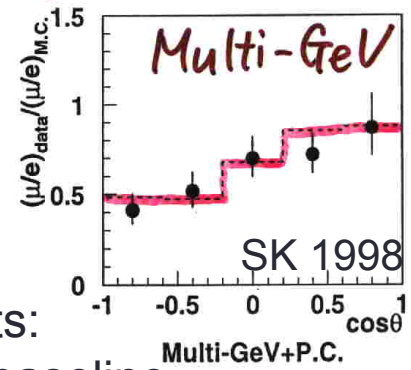
from 1962 Maki, Nakagawa, Sakata and Pontecorvo: n oscillations between flavors

1998 SuperKamiokande collaboration: measured atmospheric oscillation

2000 DONUT collaboration: **discovery of n_t with nuclear emulsions**

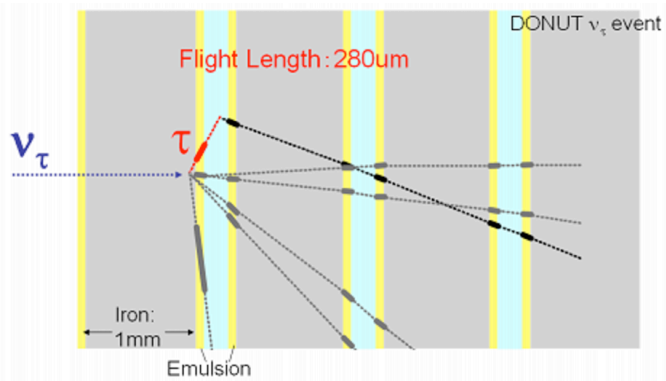
Motivation and Concept

SuperKamiokande 1998:
Disappearance of atmospheric neutrinos
Look for appearance mode using $\nu_\mu \rightarrow \nu_\tau$ by tau identification

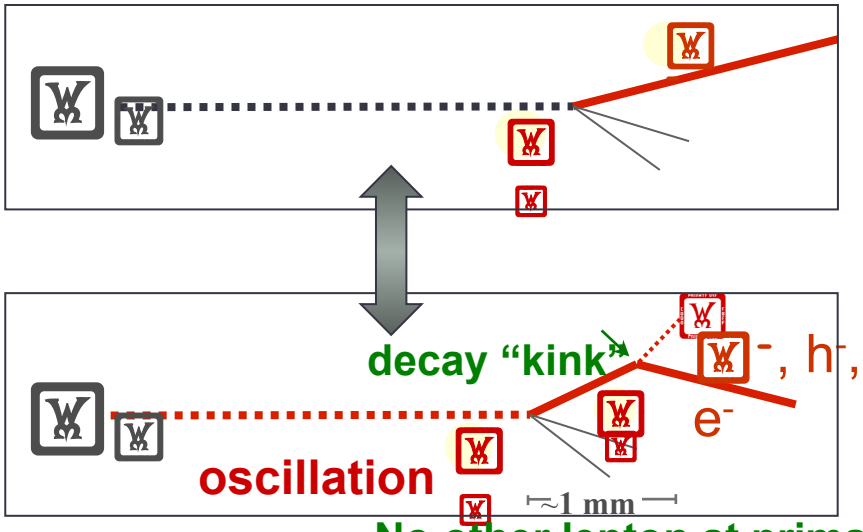


Requirements:

- long baseline
- high energy neutrinos
- large mass
- t identification capability



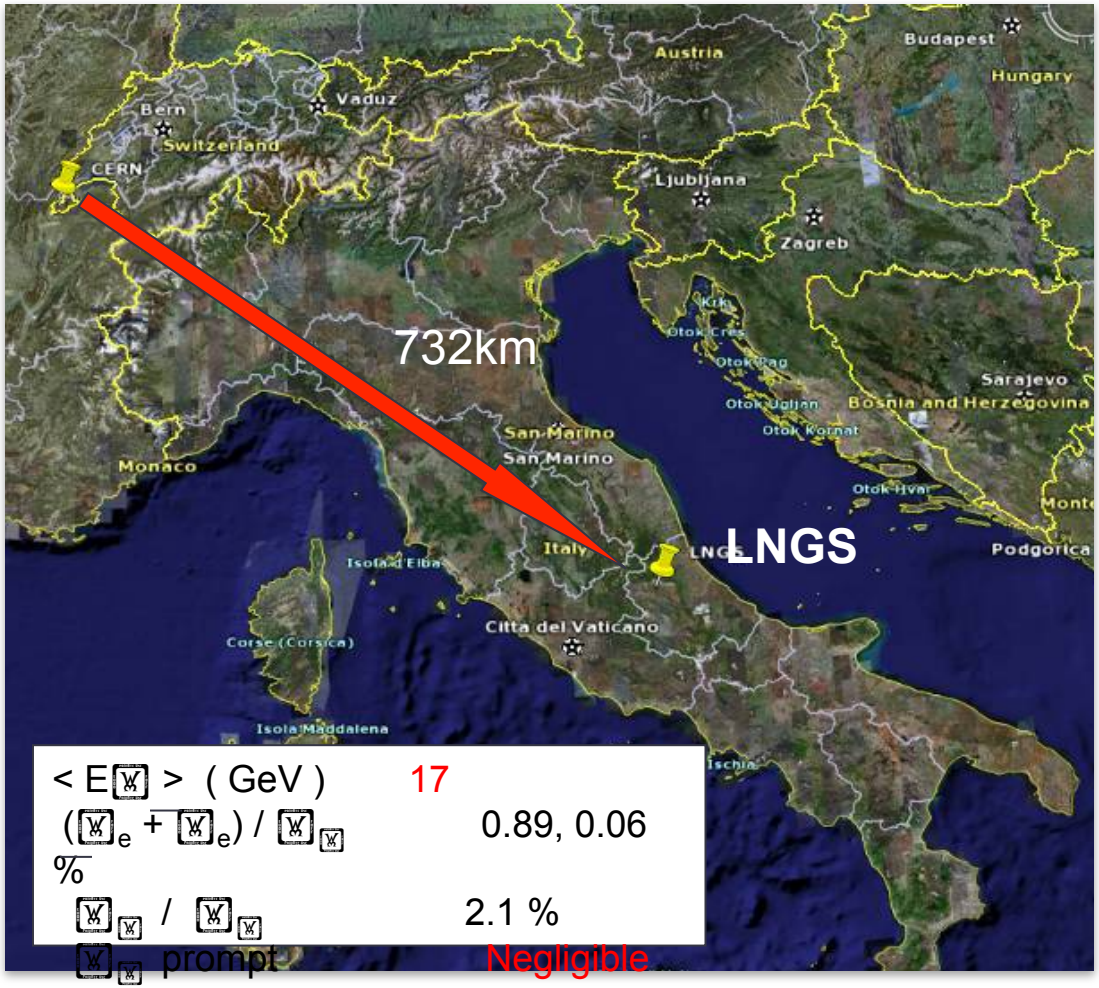
c_t = 87mm



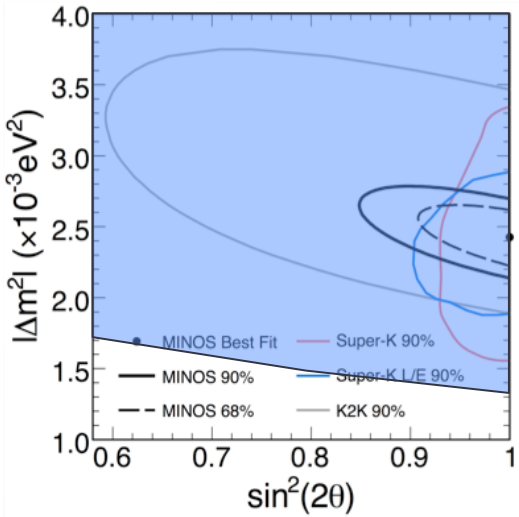
No other lepton at primary, plus 3-prong decay modes

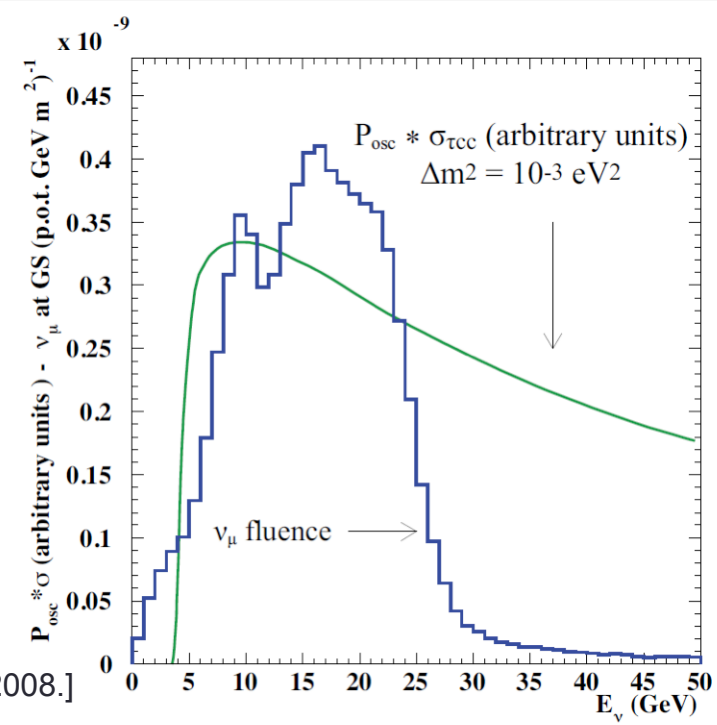
- Event-by-event identification of tau neutrino interaction
- Detection of t decay topology to identify ν_t
- High spatial resolution required

CNGS Beam



Covers the region indicated by Super-K, K2K & MINOS

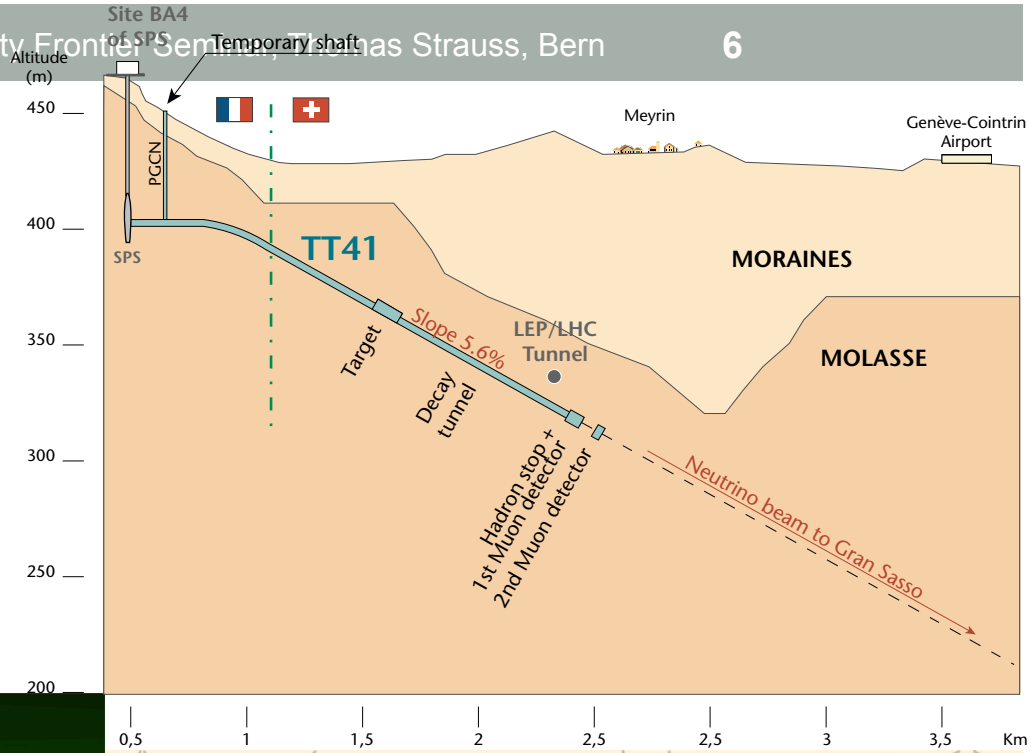




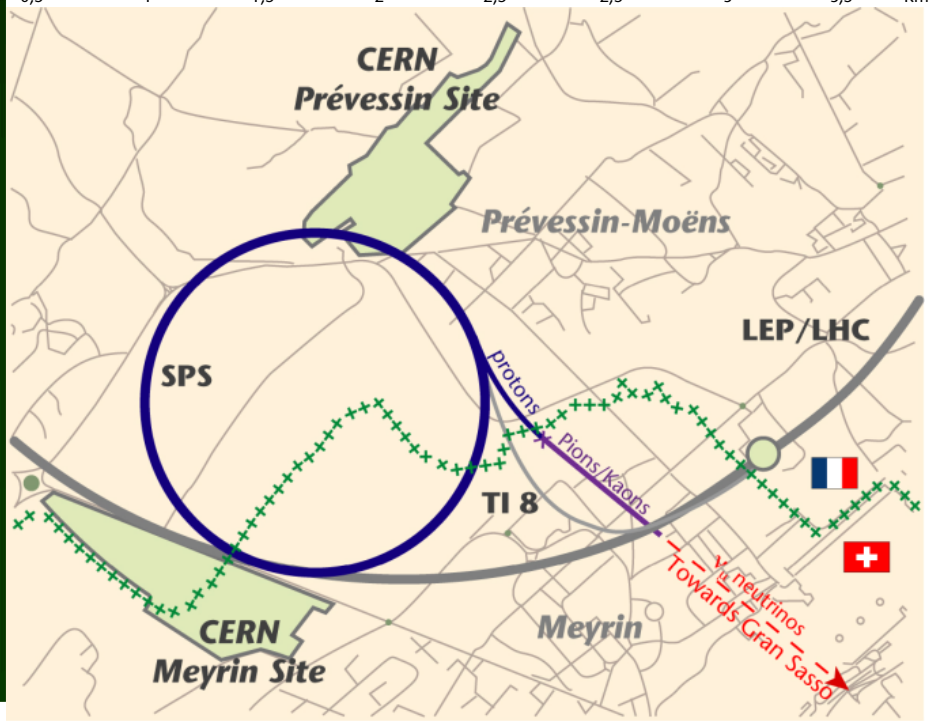
$$P(\nu_\mu \to \nu_\tau) \sim \sin^2(2\theta_{23}) \cdot \sin^2\left(1.27 \cdot \Delta m^2_{23} \cdot \frac{L}{E}\right) \sim 1.7\%$$

$\sin^2 2\theta_{23} = 1.0$, $\Delta m_{23}^2 = (2.43 \pm 0.13) \times 10^{-3}$ eV^2 [Phys.Rev.Lett.101:131802,2008.]

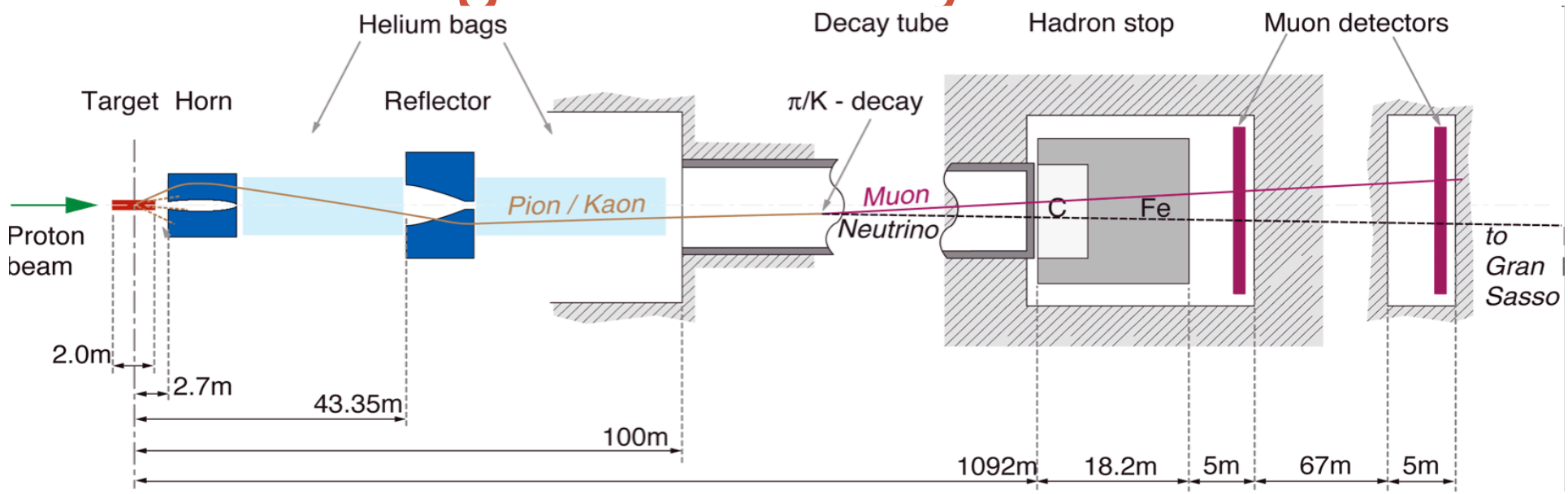
CNGS Beam


Site BA4 of SPS
Temporary shaft
Altitude (m)
450
400
350
300
250
200
PGCN
SPS
TT41
Meyrin
Genève-Cointrin Airport
MORAINES
MOLASSE
Slope 5.6%
LEP/LHC Tunnel
Target
Decay tunnel
Hadron stop + 1st Muon detector 2nd Muon detector
Neutrino beam to Gran Sasso
0,5
1
1,5
2
2,5
2,5
3
3,5
Km

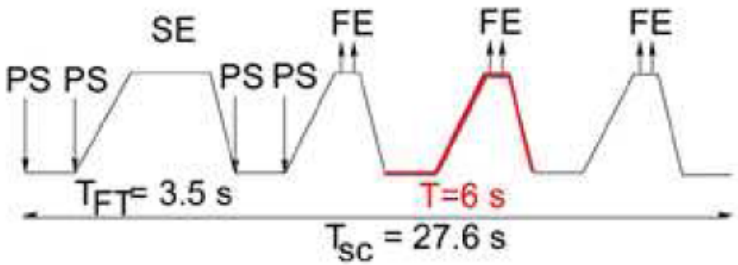
CERN NEUTRINOS TO GRAN SASSO
Underground structures at CERN
Excavated
Concreted
Decay tube (2nd contract)
Access shaft PGCN
SPS/ECA4
55m
TI8
SPS tunnel
protons
TT41
Access galleries
LHC/TI8 tunnel
Target chamber
Service gallery
LEP/LHC tunnel
140m
pions kaons
Decay tunnel
Hadron stop and first muon detector
Connection gallery to TI8/LHC
muons neutrinos
Second muon detector
neutrinos to Gran Sasso
06 / 2003
CERN-AC-DI-MM

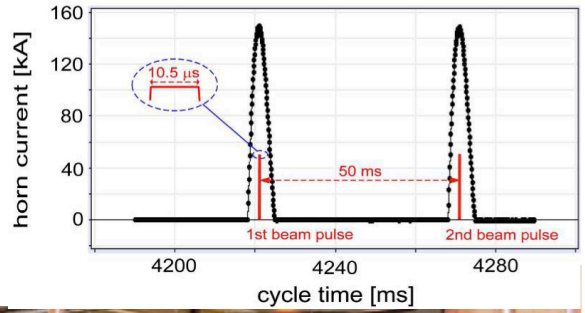

CERN Prévessin Site
Prévessin-Moëns
SPS
LEP/LHC
protons
Pions/Kaons
TI 8
CERN Meyrin Site
Meyrin
Towards Gran Sasso

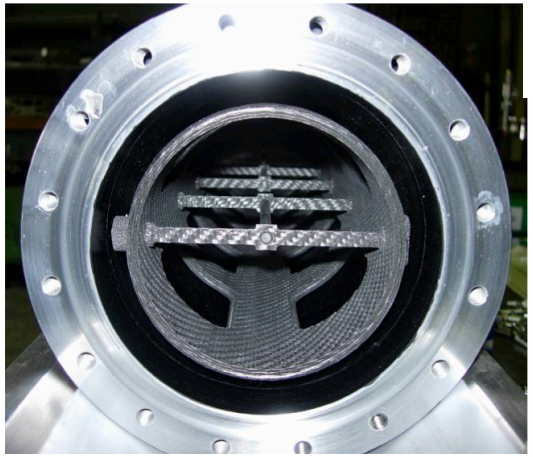
CNGS target and decay tunnel

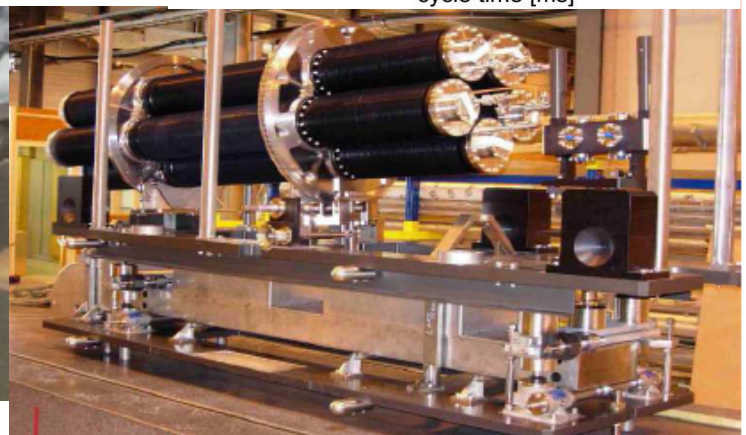


CERN SPS protons
455miles to Gran Sasso

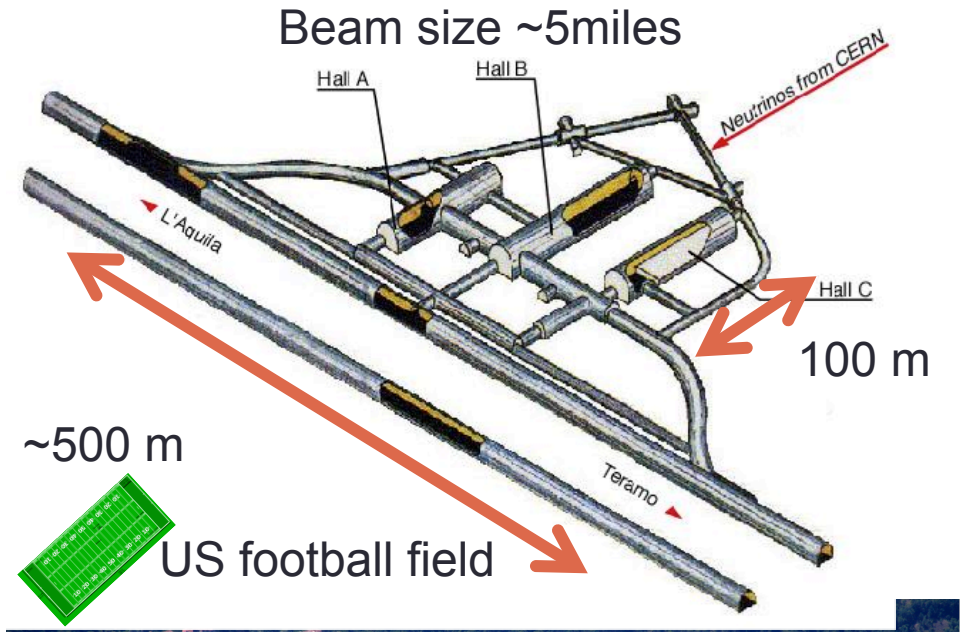


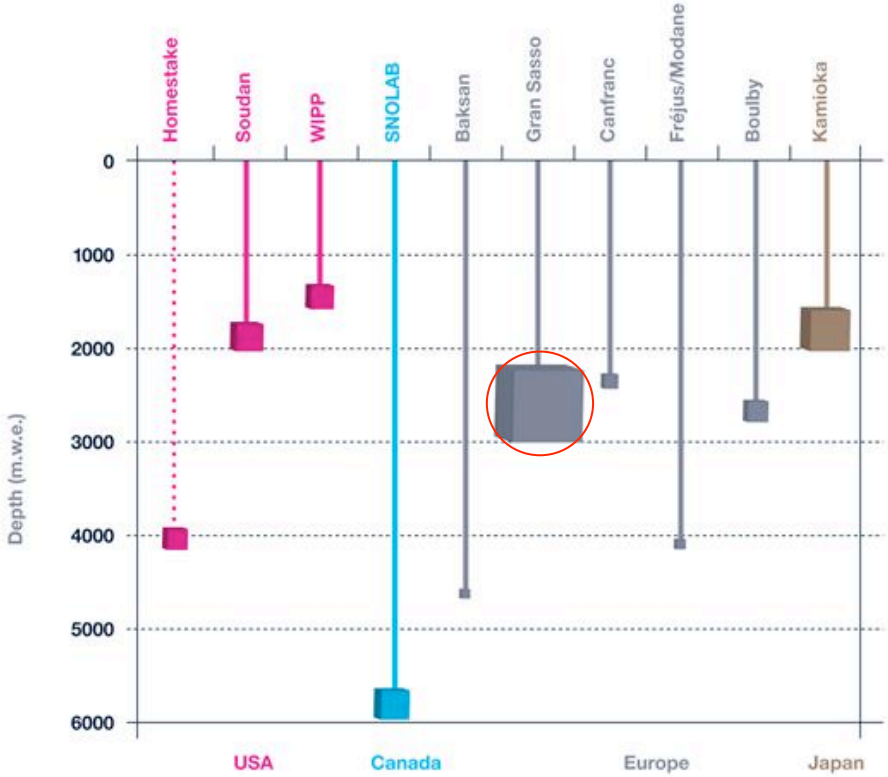


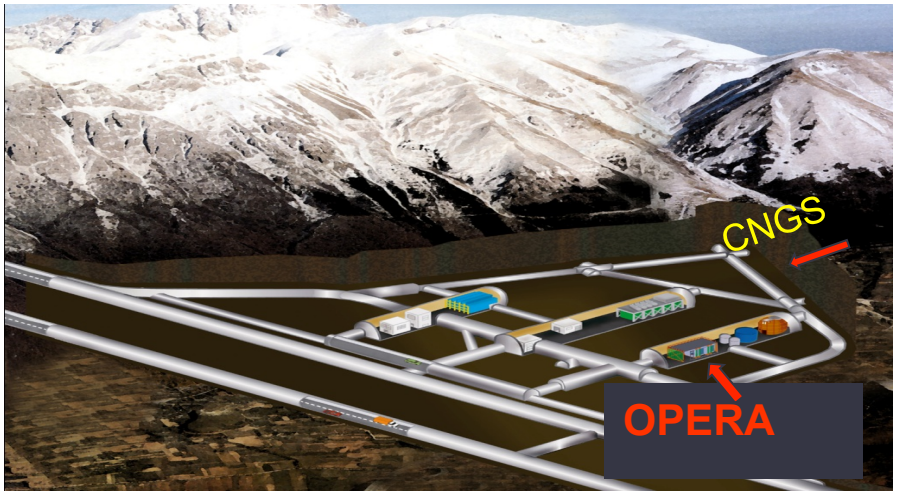




LNGS – National Laboratory Gran Sasso



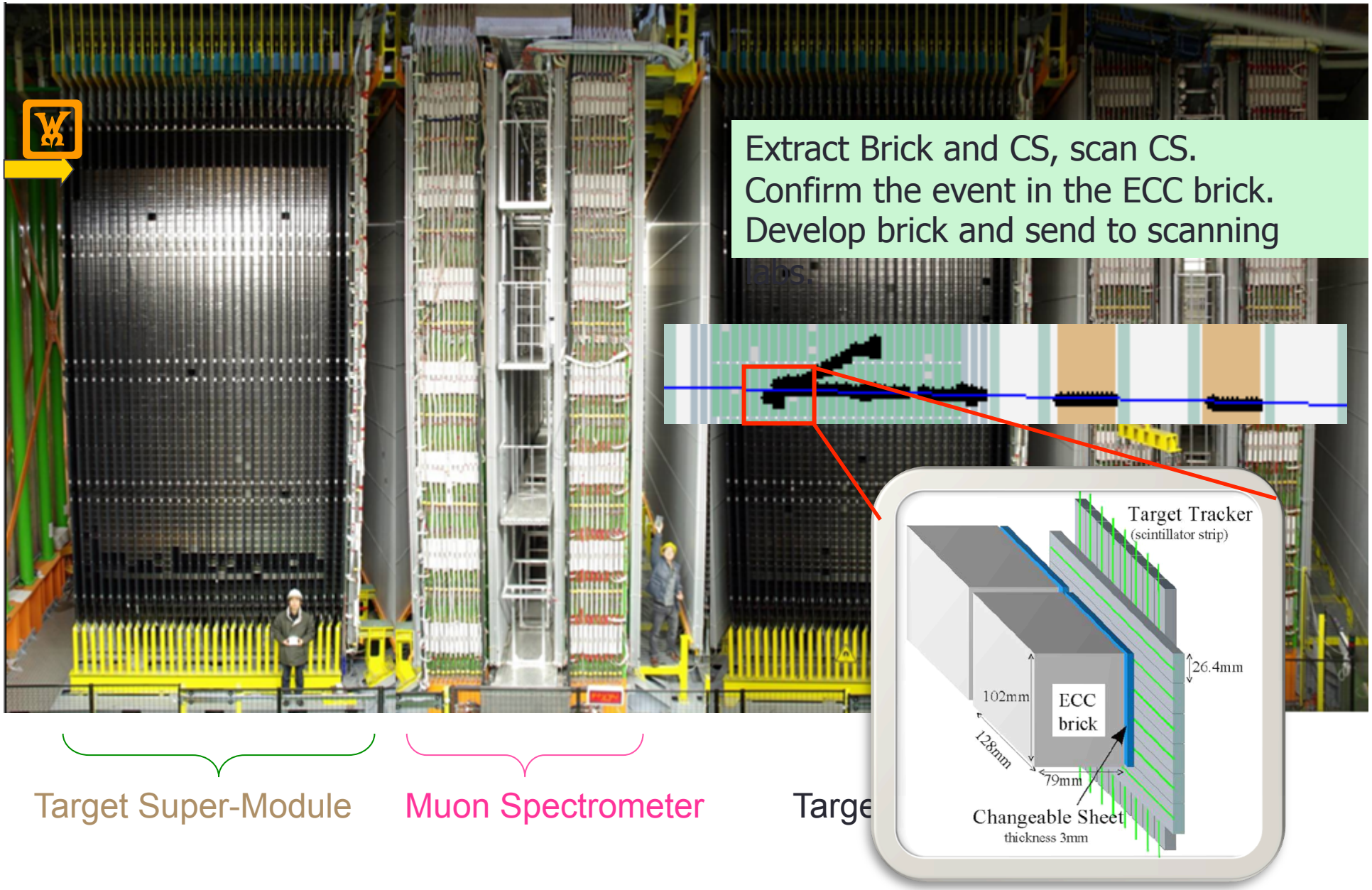




The OPERA detector – 9.2m x 9.6m

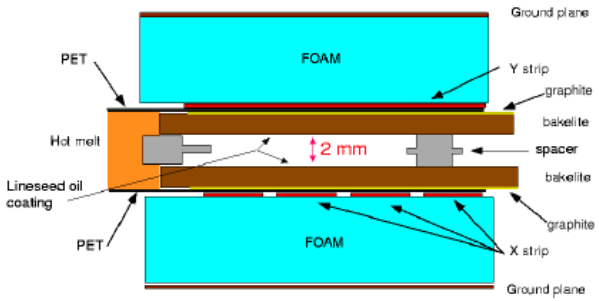
The OPERA detector

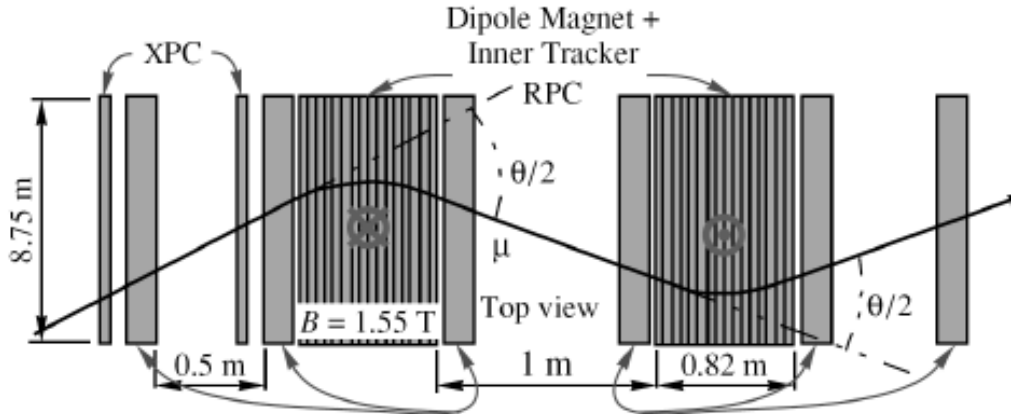
Underground@GranSasso, ~1400m



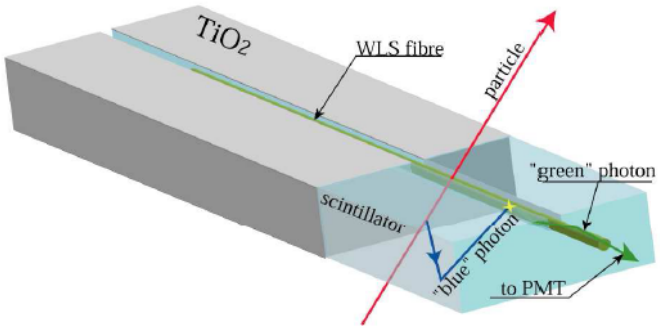
Electronic detector

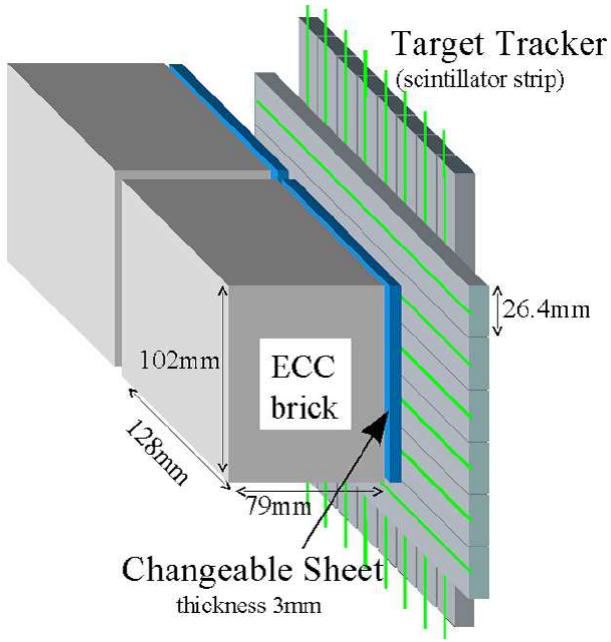
- Spectrometer (m moment
  - Resistive plate chambers
  - Drift tubes



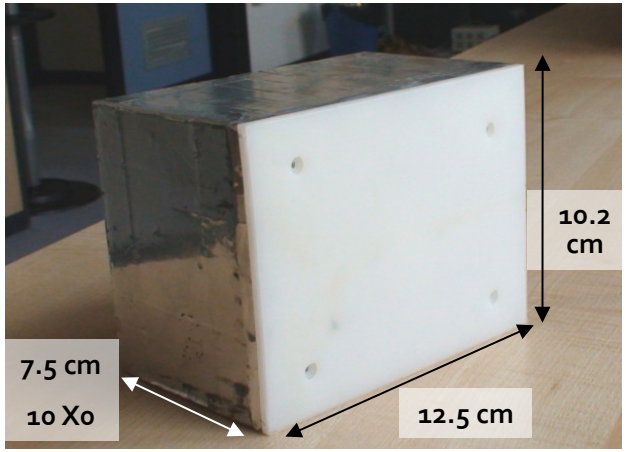


- Target tracker
  - Select the interaction brick

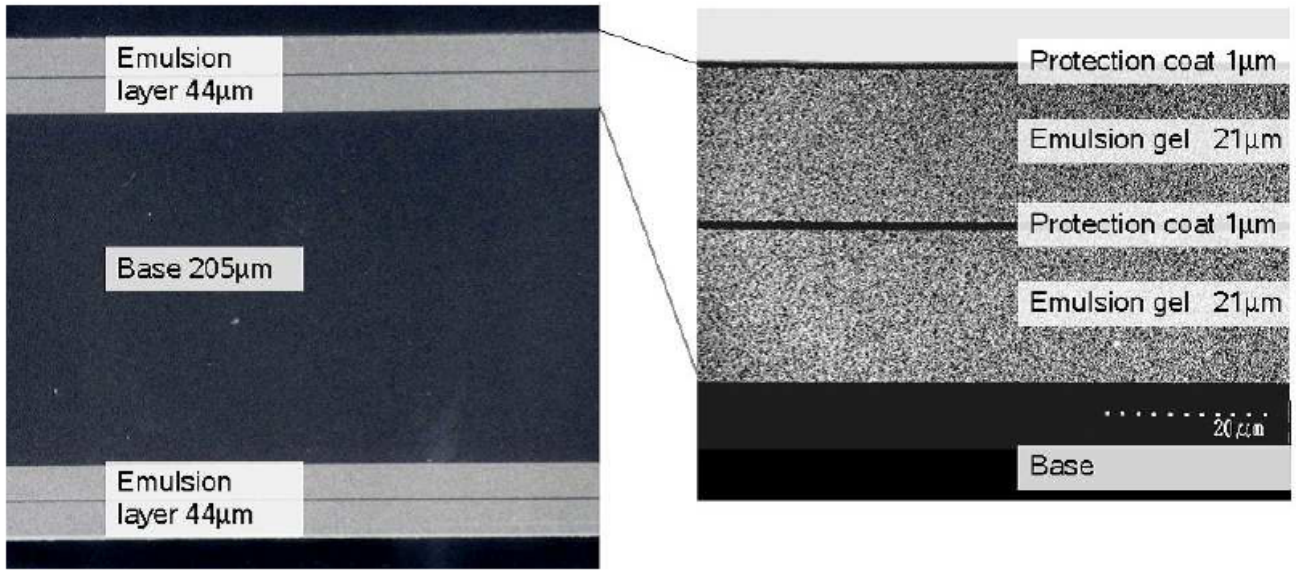


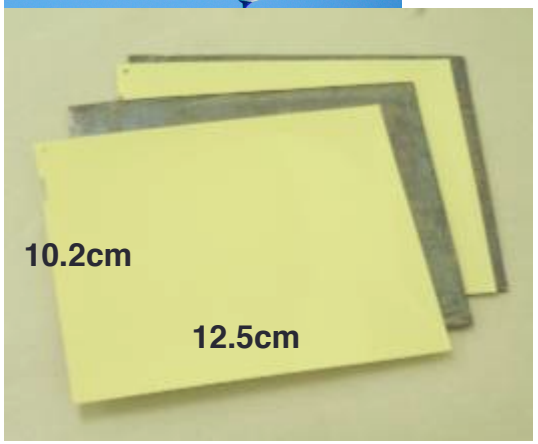


The OPERA brick

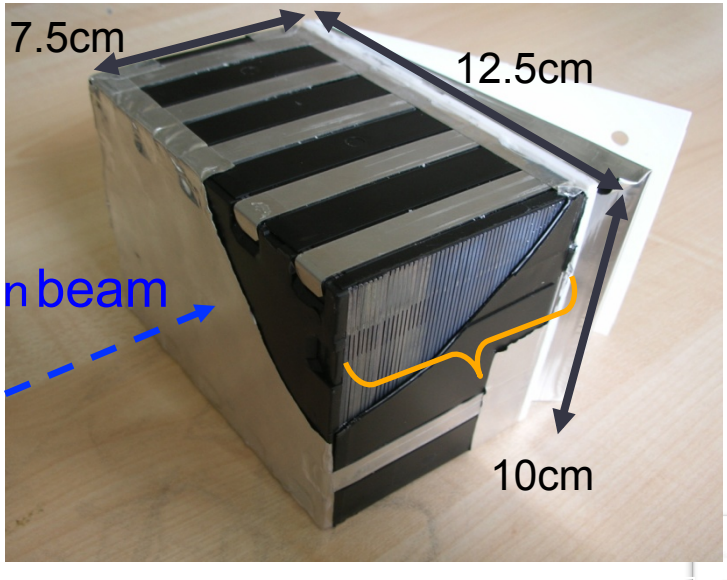


- Emulsion Cloud Chamber
  - Lead-emulsion sandwich (56/57), with an attached changeable sheet to confirm interaction before opening the brick
  - 8.3 kg, about 150.000 pieces build by an automatic assembly line at LNGS, total mass 1.25 kton (3 fully loaded Airbus A380)
  - Emulsion surface 112.500 m^2 (17.5 european soccer fields)
  - 10 radiation length for electrons

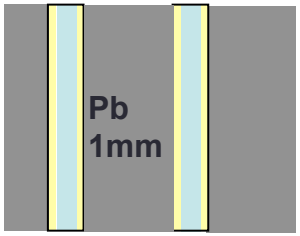




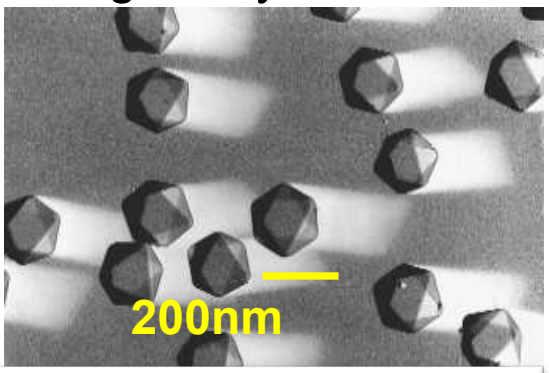
The OPERA brick

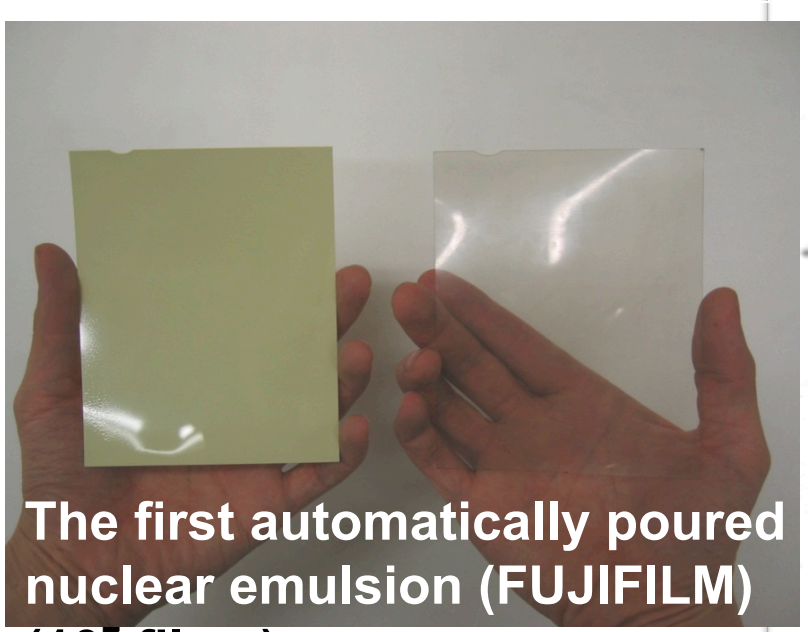


Emulsion Cloud Chamber (ECC)

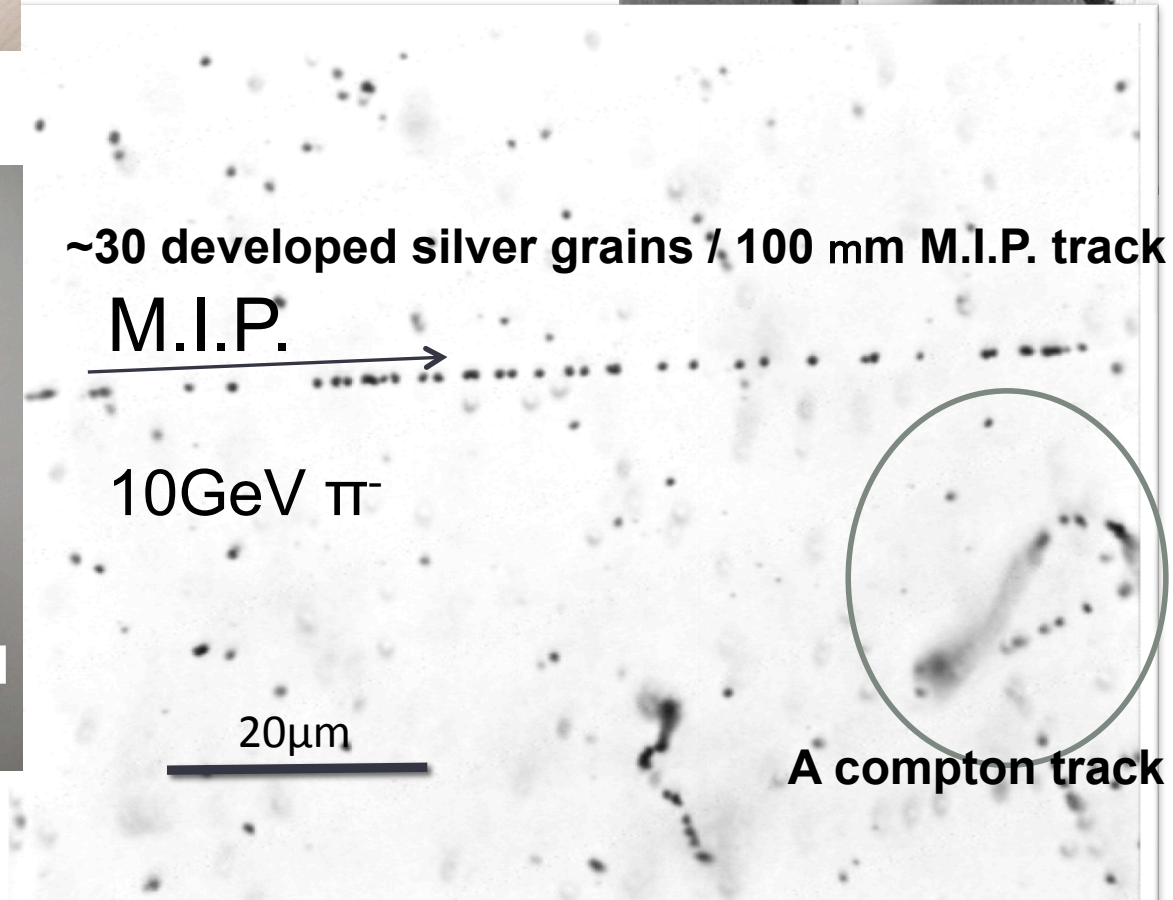


AgBr Crystals

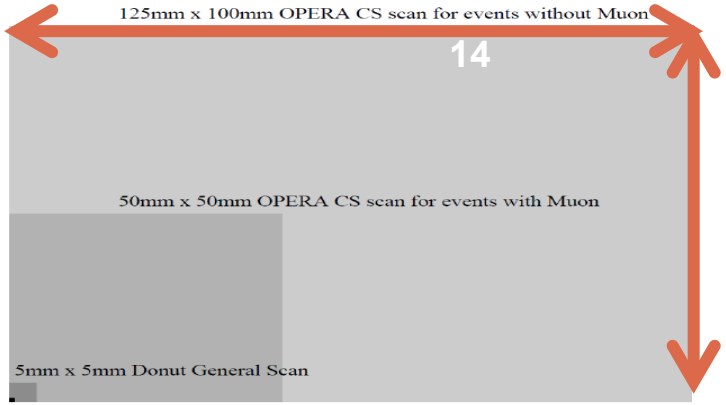




The first automatically poured nuclear emulsion (FUJIFILM) (10^7 films)

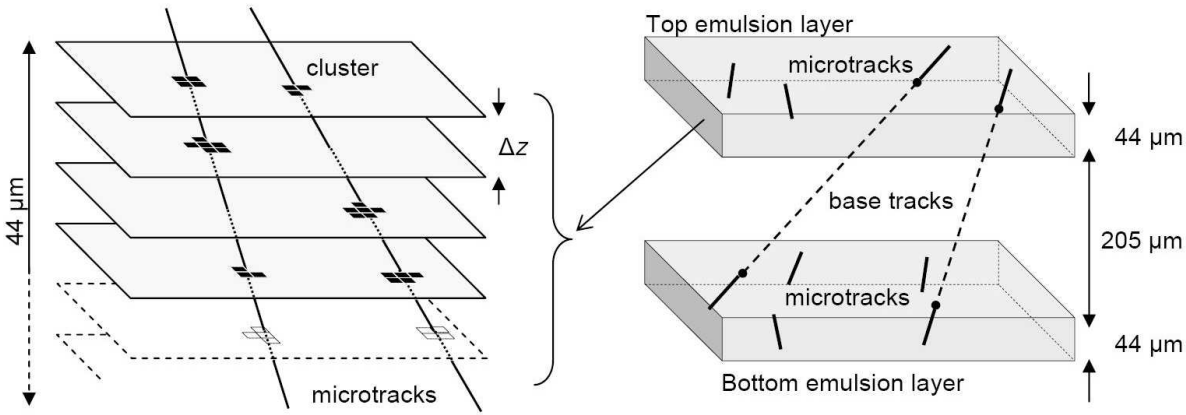


Emulsion scanning



16+2 tomographic pictures per layer (3 μm focal depth)

average residuals of grains from a straight line fit: 0.066 μm

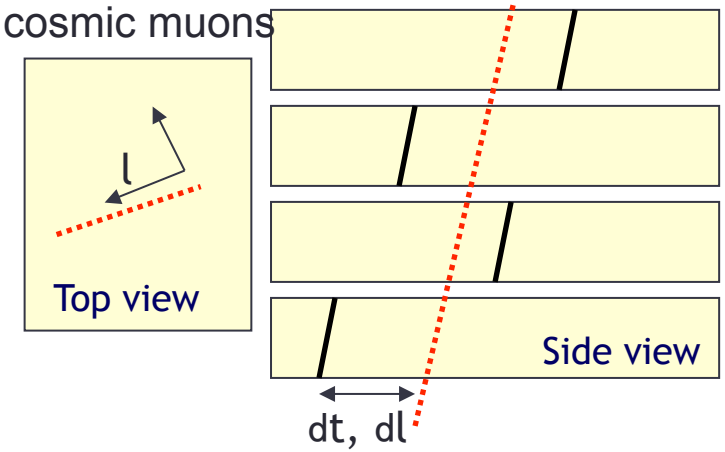


A basetrack is the result of the connection of two microtracks on opposite sides of the plastic base

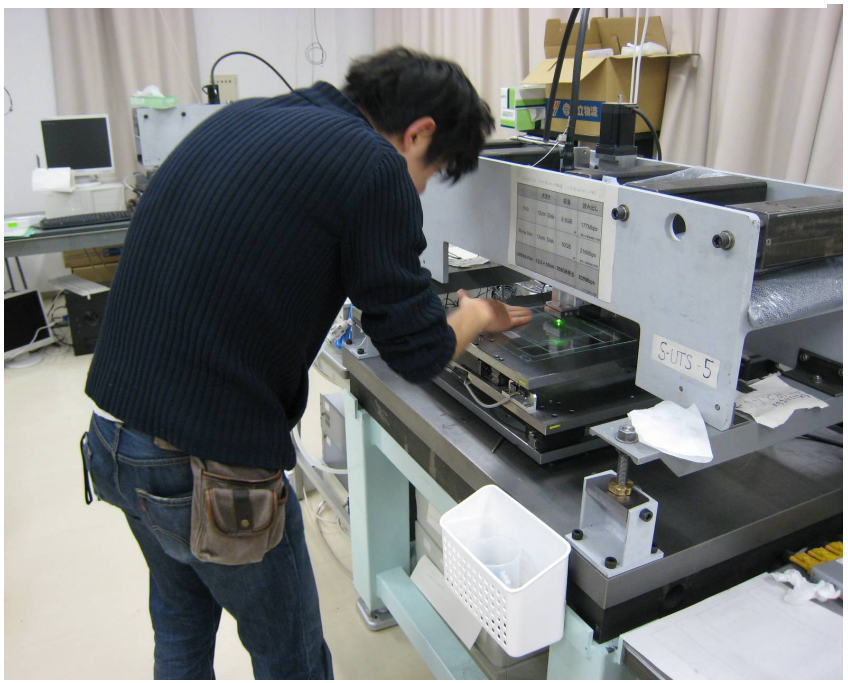
Precisision of 0.3±0.7 μm for reconstructed tracks

Topological analysis of interactions

Plate-to-plate alignment by high-energetic passing-through tracks from cosmic muons



Japanese Scanning System (SUTS)



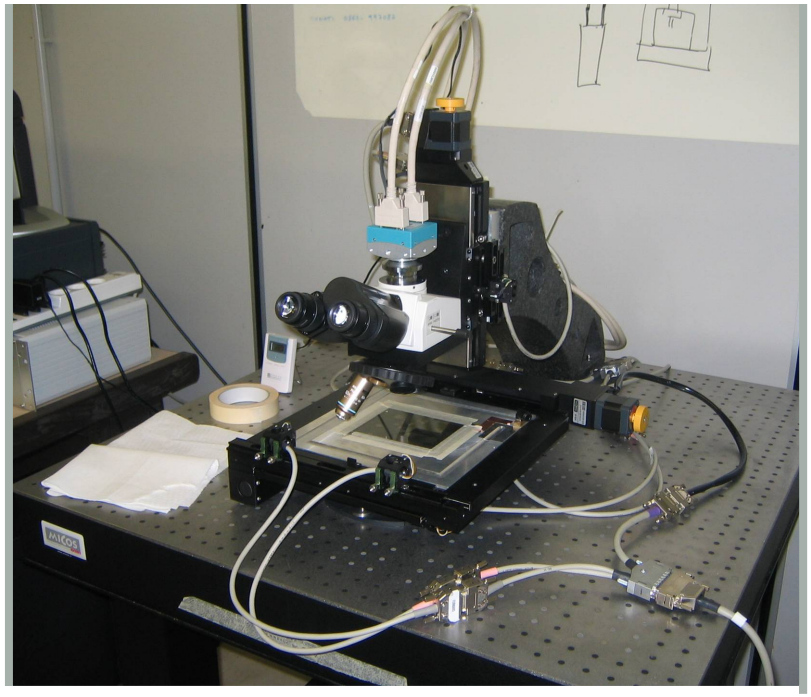
Scanning speed: 75cm^2/h

High speed CCD camera (3 kHz)

Piezo-controlled objective lens

FPGA Hard-coded algorithms

European Scanning System（ESS)



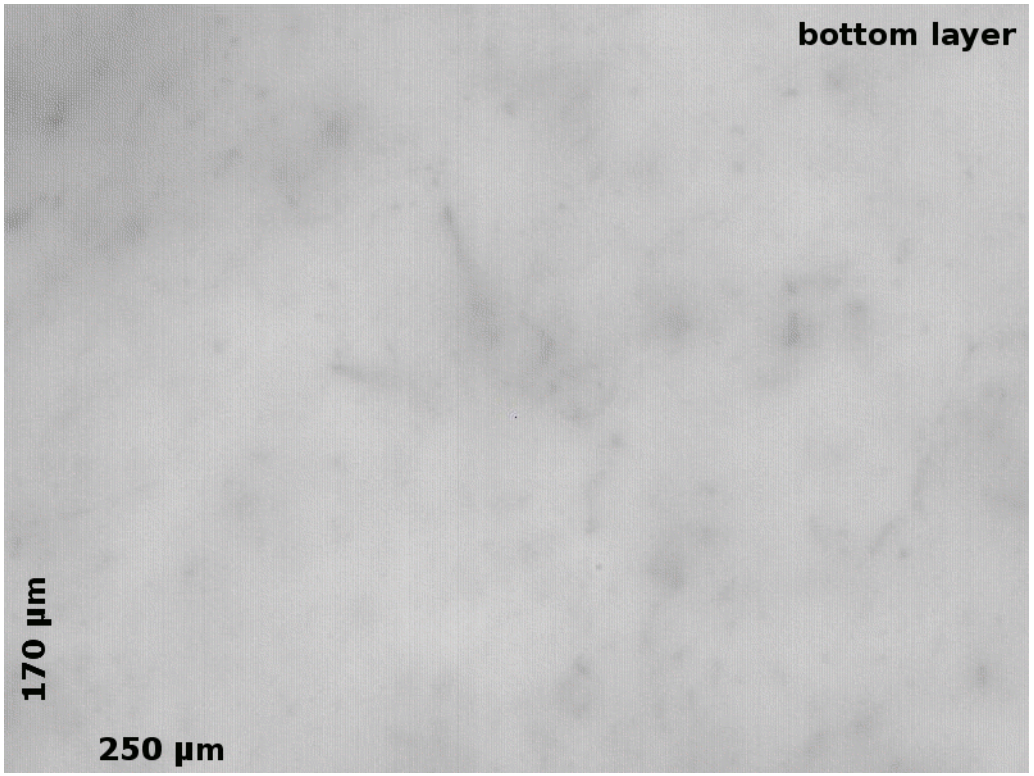
Scanning speed: 20cm2/h

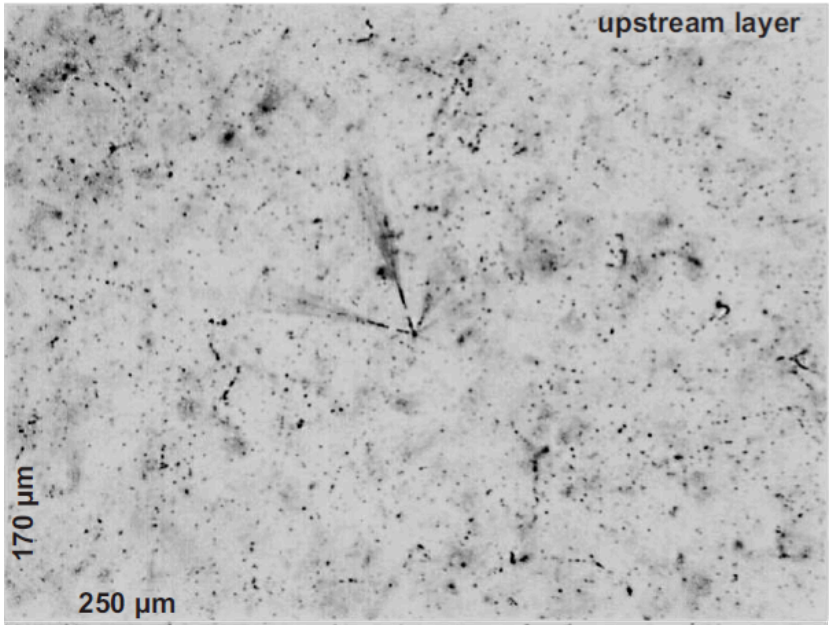
Customized commercial optics and mechanics

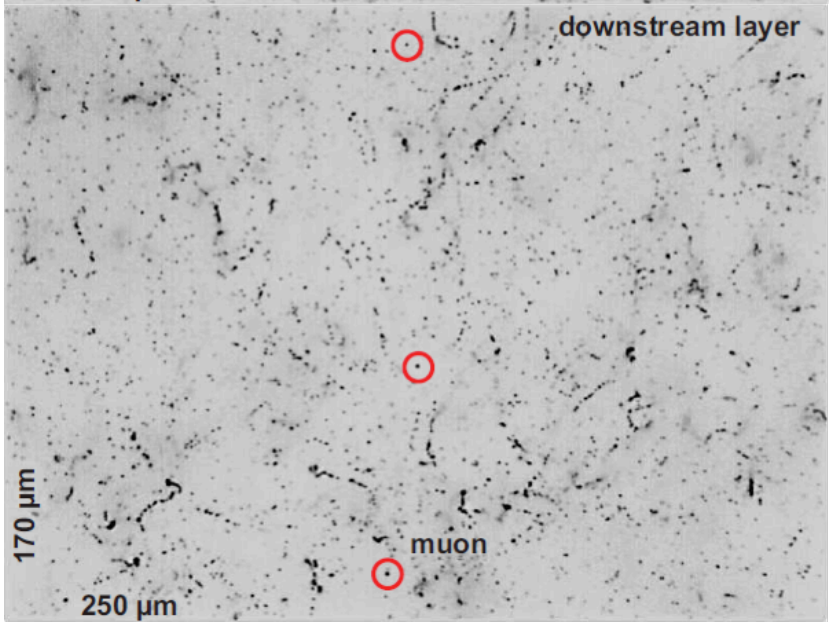
asynchronous DAQ software

Emulsion Scanning – how it looks like

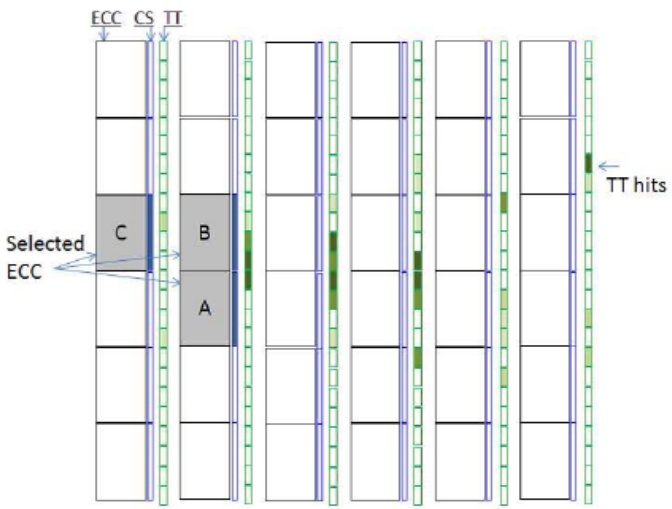
- This is a view along the top and bottom emulsion layer of a located neutrino interaction
- Still images on the right, red circles indicate the grain location in the tomographic views



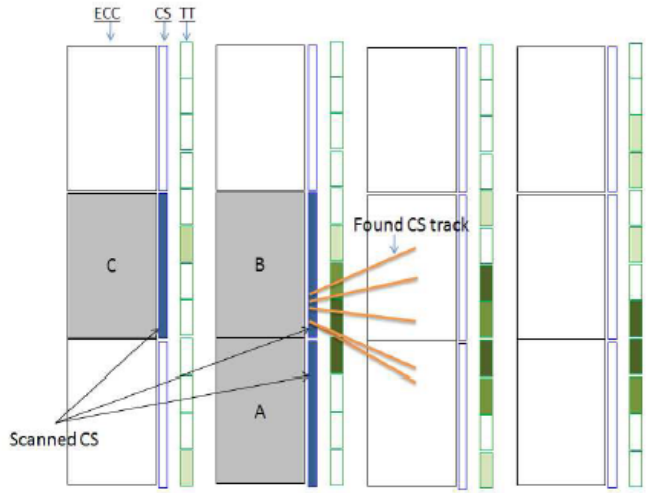




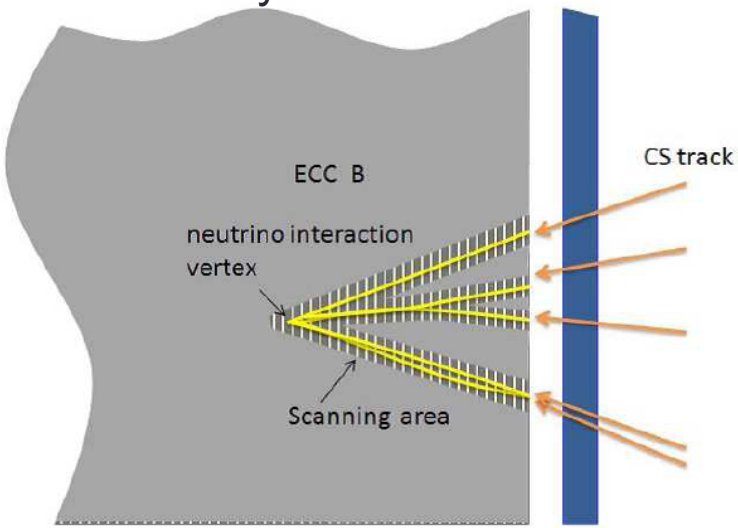
Scanning strategy



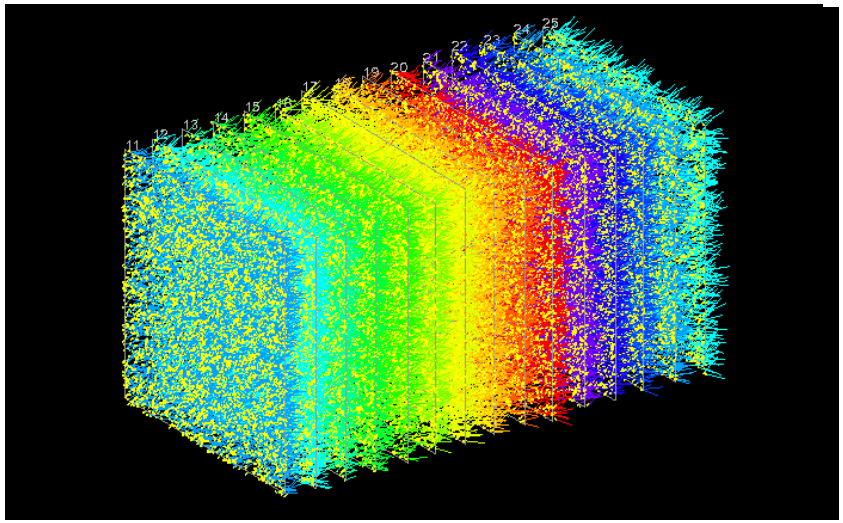
Prediction by electronic detector



CS scanning and results



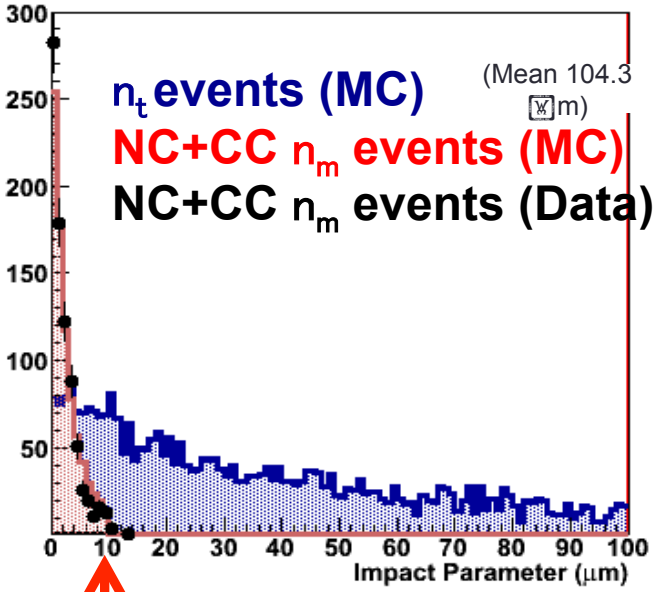
"Scanback" from emulsion to emulsion to locate interaction



Located Event

n_t CC detection

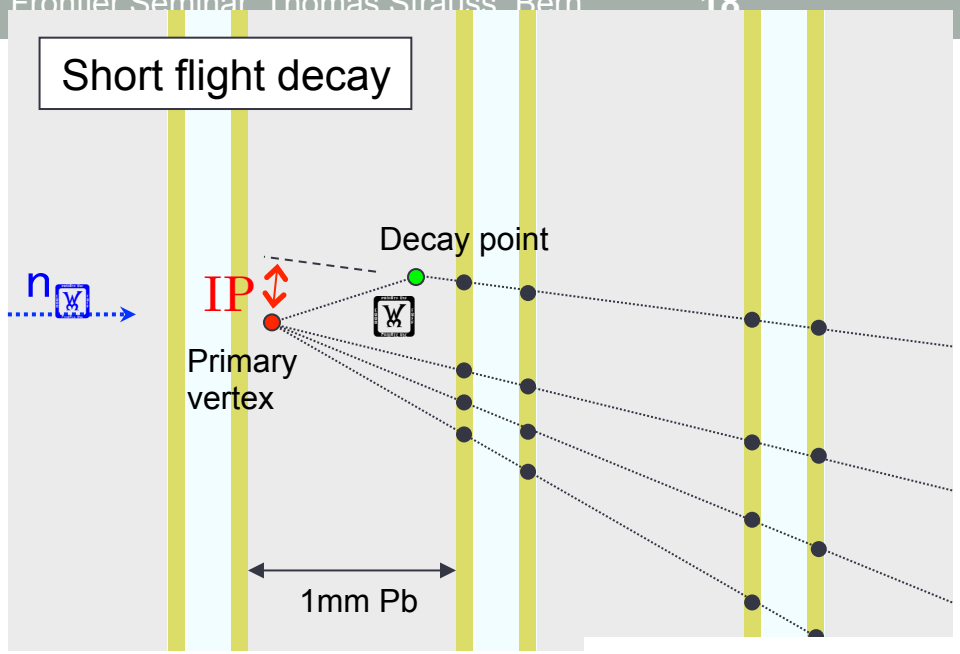
Impact Parameter distribution



10 μm ↔ (cτ = 87 μm)

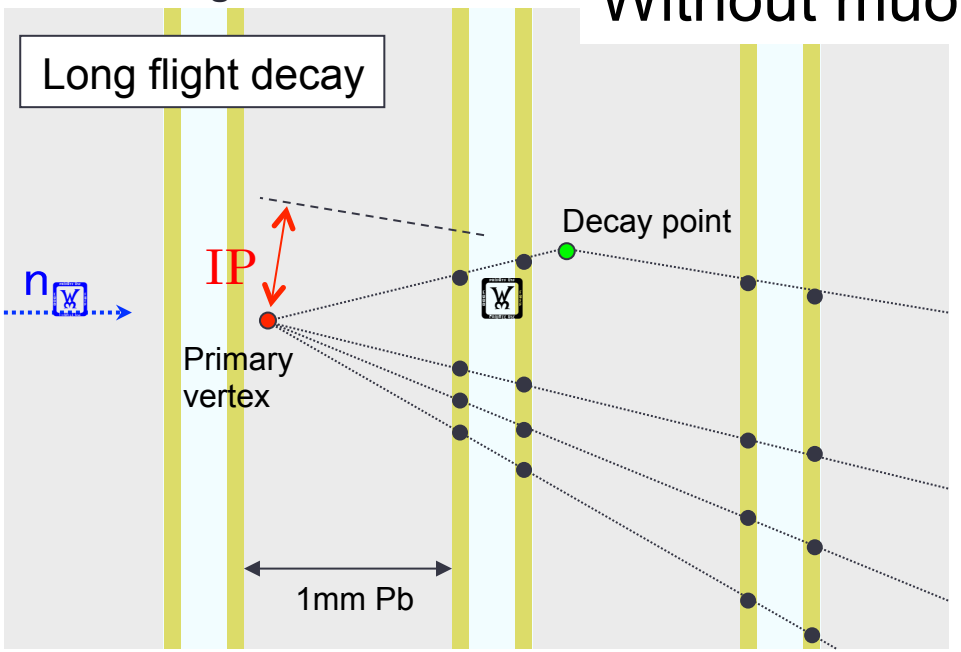
τ decay mode

Kink	$t^- \rightarrow e^-$	**17.8 %**
	$t^- \rightarrow \mu^-$	**17.4 %**
	$t^- \rightarrow h^-$	**49.5 %**
Trident	$t^- \rightarrow h^- h^- h^+$	**15.2 %**



Short : Long ~ 2:8

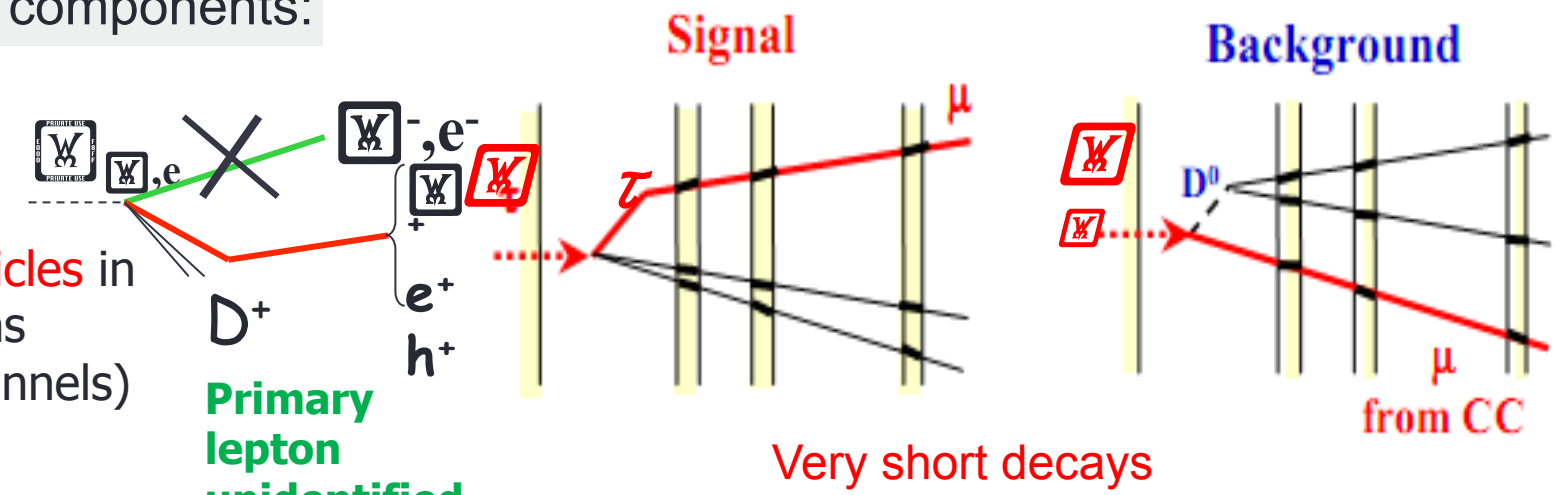
Without muon



Background sources of n_t events

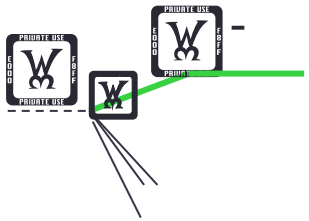
Background components:

Production of charmed particles in CC interactions (all decay channels)



Coulombian large angle scattering of muons in lead

Bck. to t m

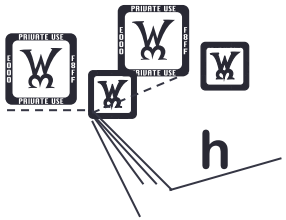


Hadronic interactions in lead:

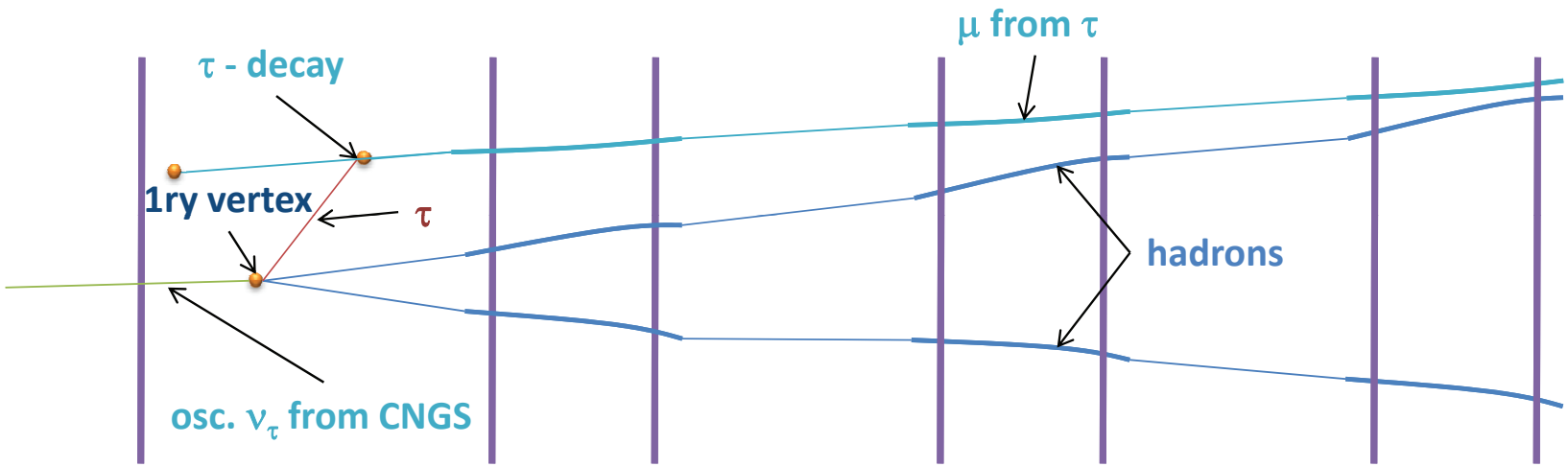
Bck. to t h

or to t m

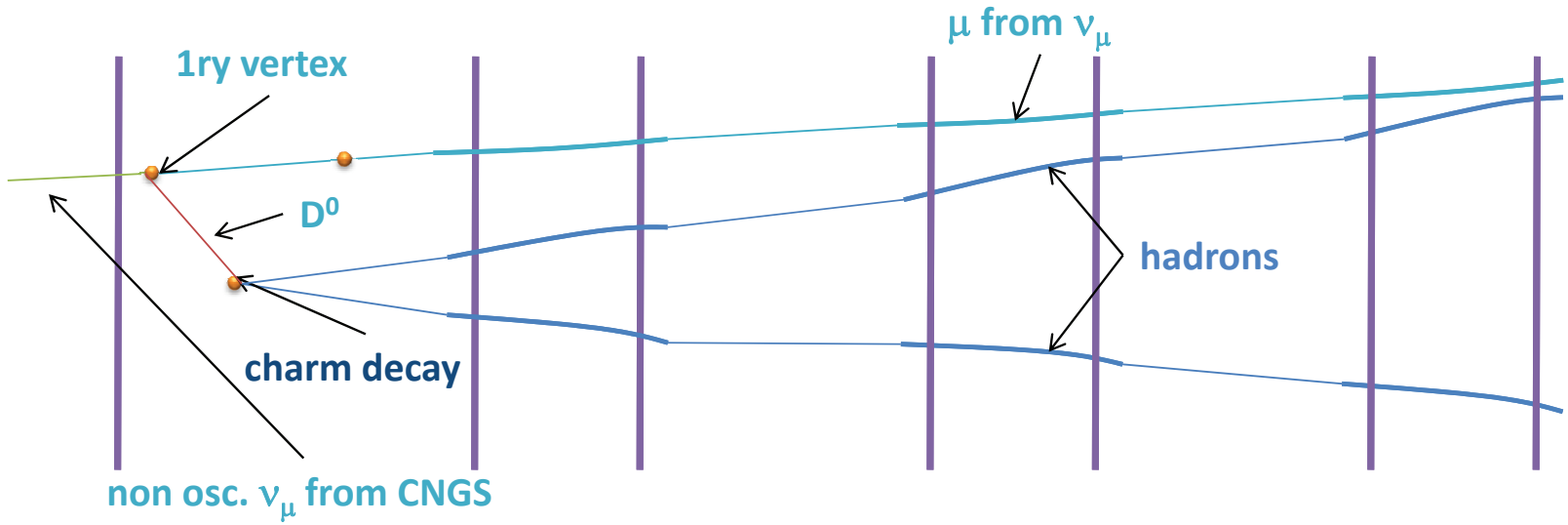
(if hadron misid. as muon)



τ-decay

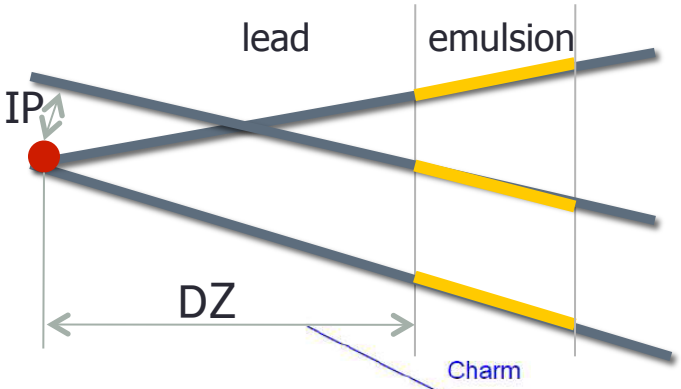


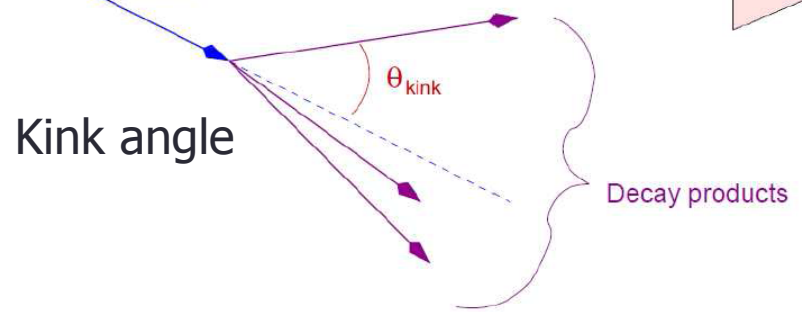
charm decay



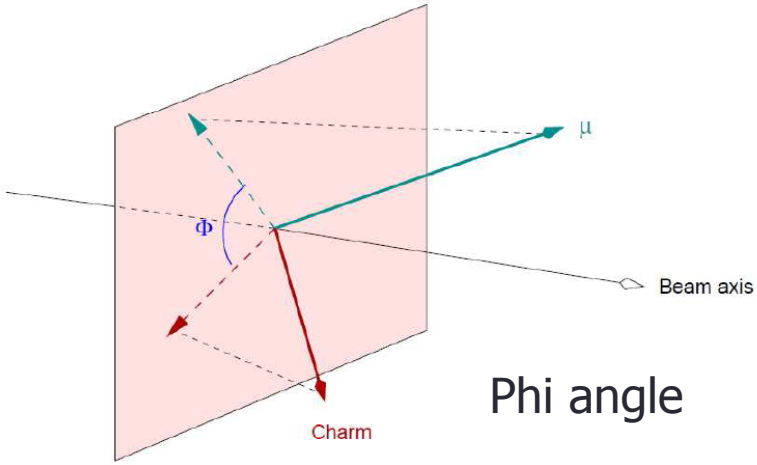
Decay Search

- Unification of the work in the 10 scanning laboratories
  - Implementation of a common Decay Search Procedure
  - Location of the primary interaction and search for daughter particle tracks depending on IP, kink-angle and Fangle

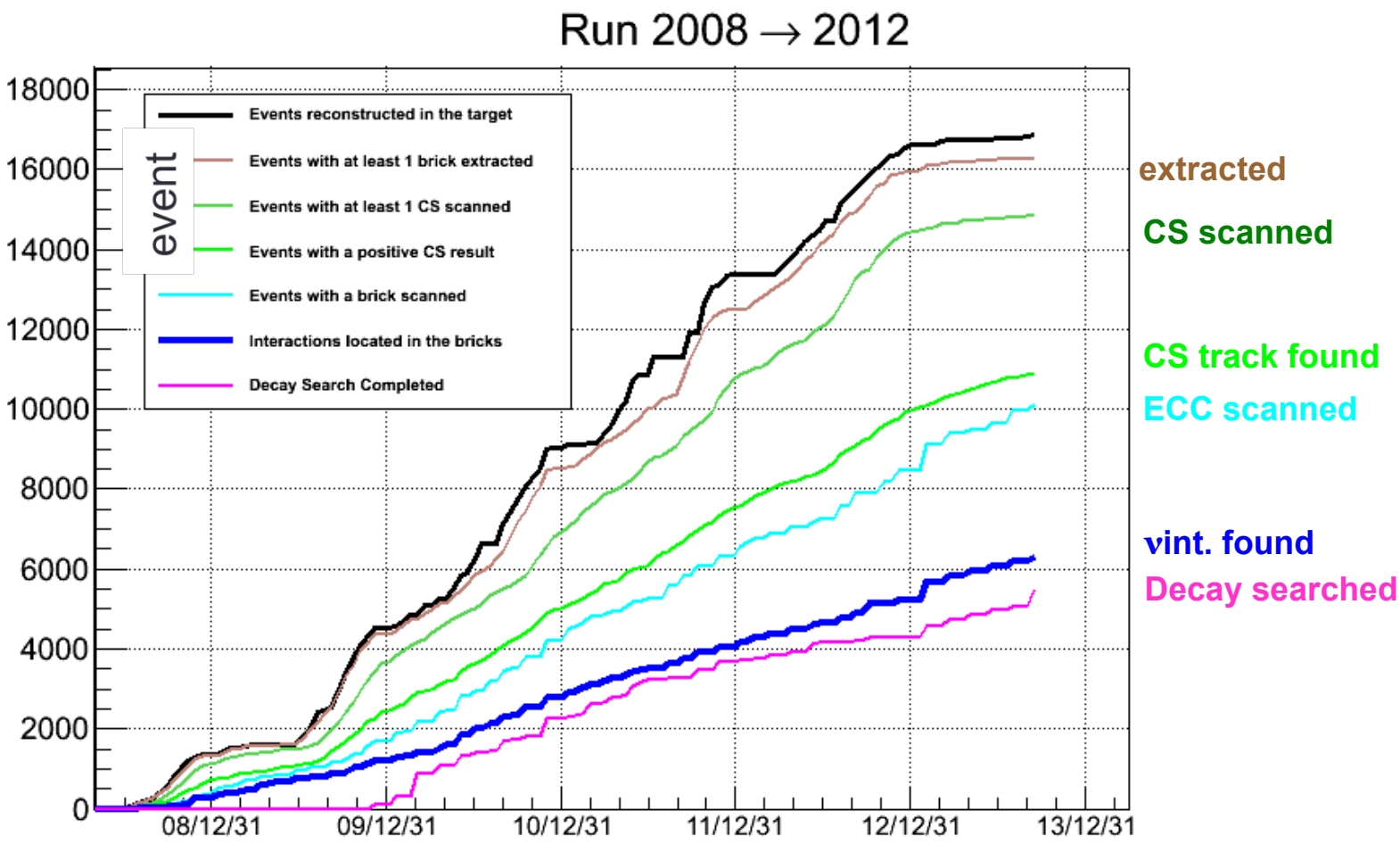




Kink angle



Phi angle

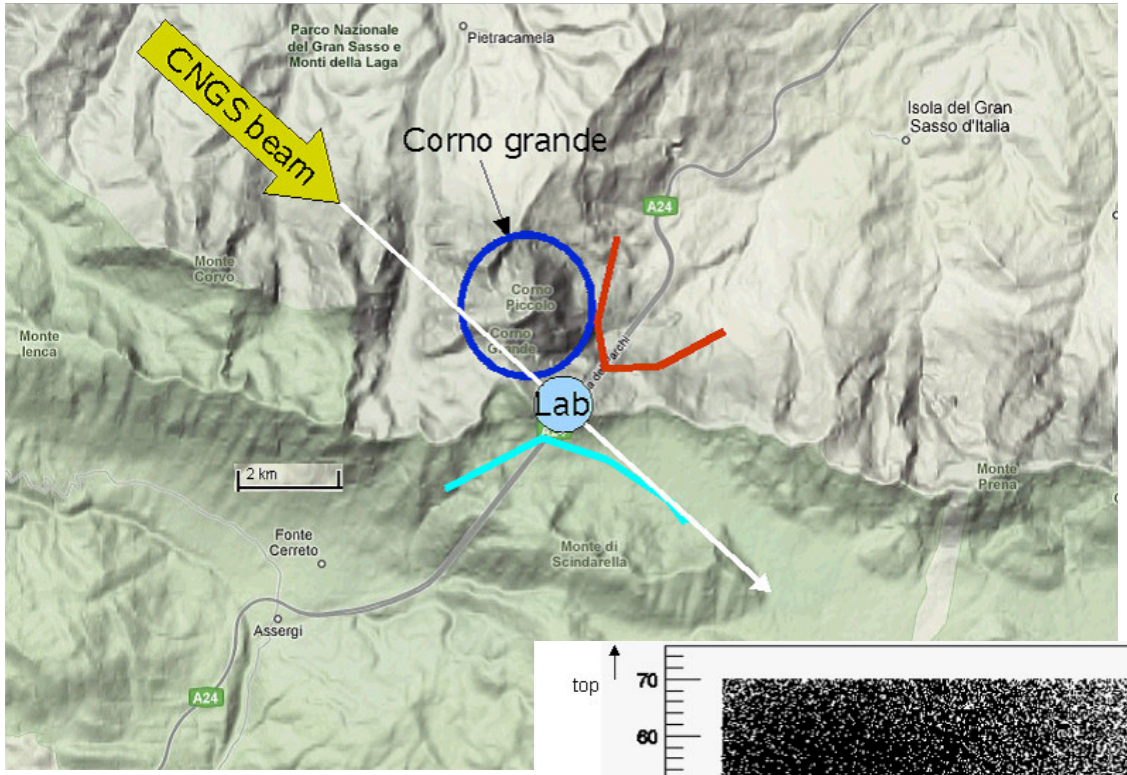


year	POT
2008	1.74 x 10^{19}
2009	3.53 x 10^{19}
2010	4.09 x 10^{19}
2011	4.75 x 10^{19}
2012	3.86 x 10^{19}
Total	17.97 x 10^{19}

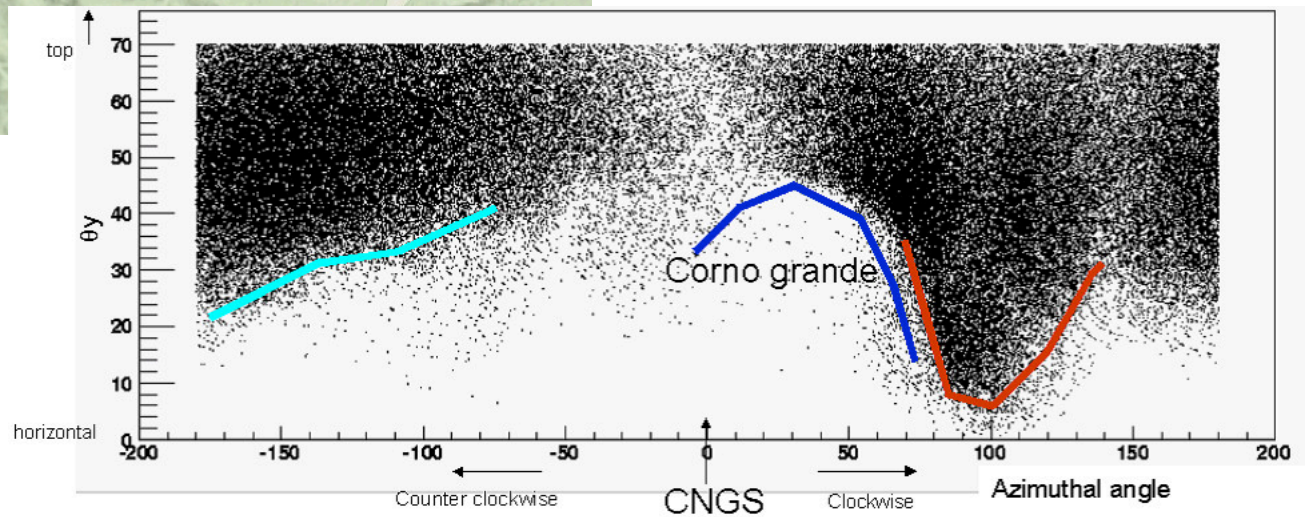
Completed: 2008, 2009
2010-12 on going with optimised strategy

Located: 6299, Decay search: 5497

Cosmic flux



Dark Blue – mountain peak
Light Blue – gentle sloped valley towards Assergi
Red – cliff type valley towards Teramo



Muon charge ratio

Old results: Eur.Phys.J. C67 (2010) 25-37

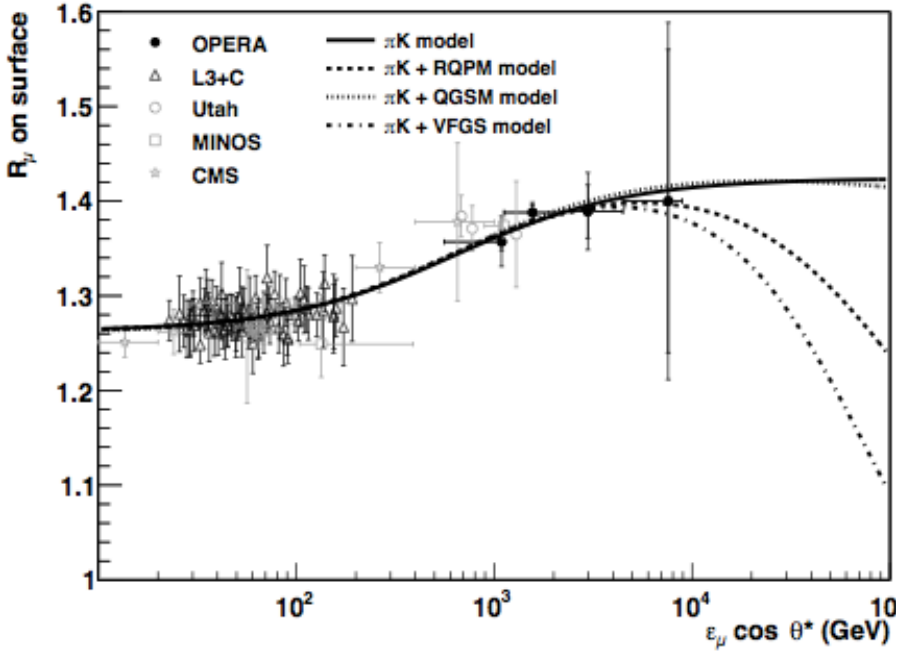
Physics Run	Events	Bundles	Exposure (days)
2008	403038	14576	113.3 (SP)
2009	434214	17138	121.1 (SP)
2010	616805	22427	172.6 (SP)
2011	766554	28545	218.0 (SP)
2012	823670	30976	234.8 (IP)

Table 1 Data sets with magnet configuration in standard polarity (SP) and inverted polarity (IP). For each Run the number of cosmic muon events, the number of muon bundles therein and the live time after the pre-selection of good quality running periods are reported.

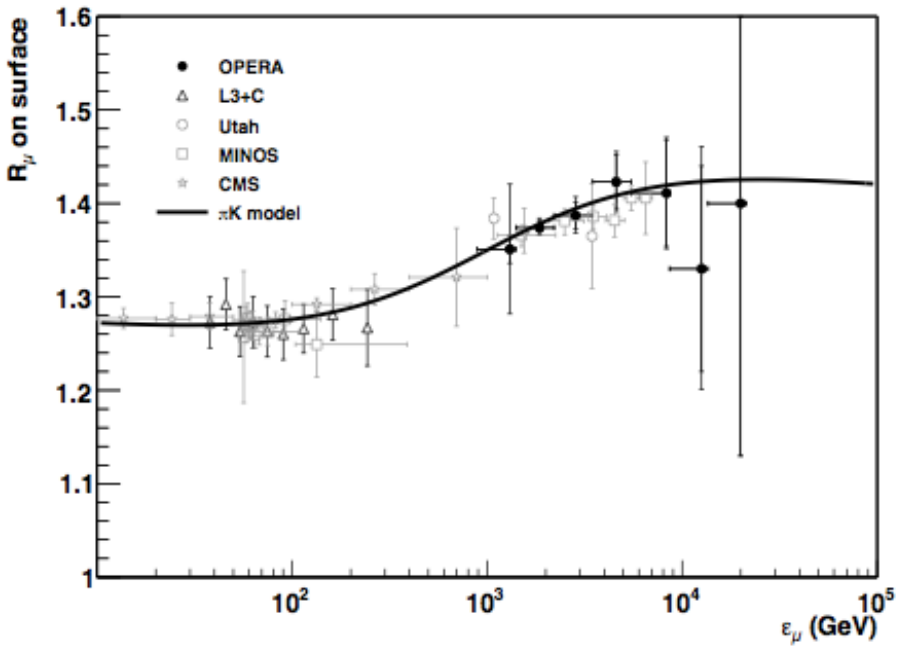
	Single μ		Bundle μ	
	N_{μ^+}	N_{μ^-}	N_{μ^+}	N_{μ^-}
SP	143628	105278	5252	4533
IP	53575	40086	1785	1740

Table 2 Final statistics for the muon charge ratio measurement; the number of muons surviving the cuts is quoted for both magnet polarity configurations. For muon bundles we provide the total number of muons and not the number of events.

New results: arXiv:1403.0244v1 [hep-ex] 2 Mar 2014



The muon charge ratio measured by OPERA as a function of the vertical surface energy Em cos q (black points)



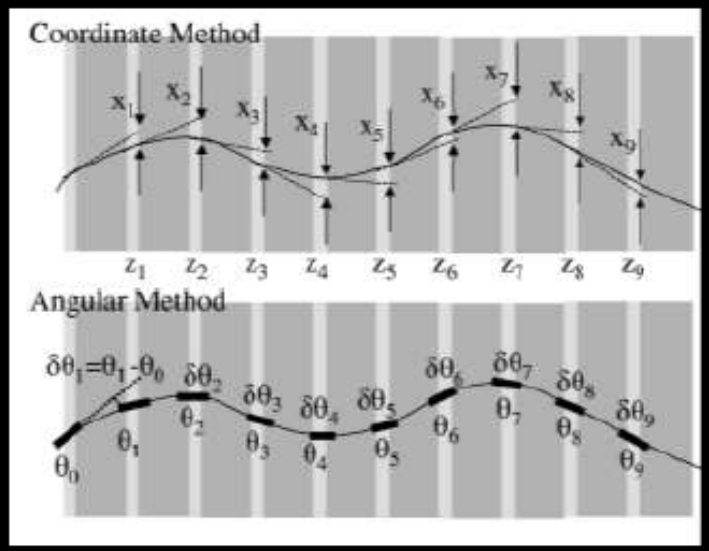
Measurement of the muon charge ratio as a function of the surface energy Em (black points)

ECC features

Momentum measurement

Measurement of the position or angular displacement given by Multiple Coulomb Scattering (MCS)

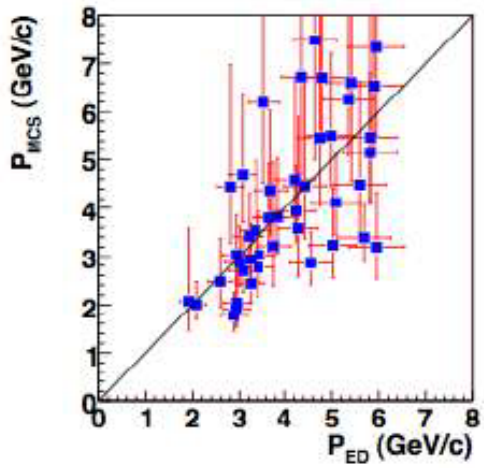
Ref: New Journal of Physics 14(2012)013026



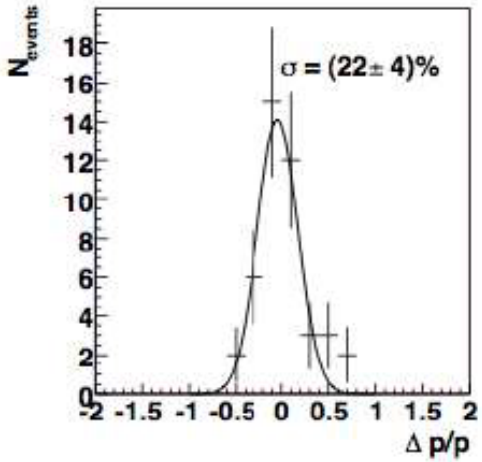
$$d\theta^{RMS} = \frac{13.6}{pc\beta} z \sqrt{\frac{x}{X_0}} \left(1 + 0.038 \ln\left(\frac{x}{X_0}\right)\right)$$

Soft muon data sample

Muon momenta measured by MCS as a function of the momenta obtained from the electronic detectors.



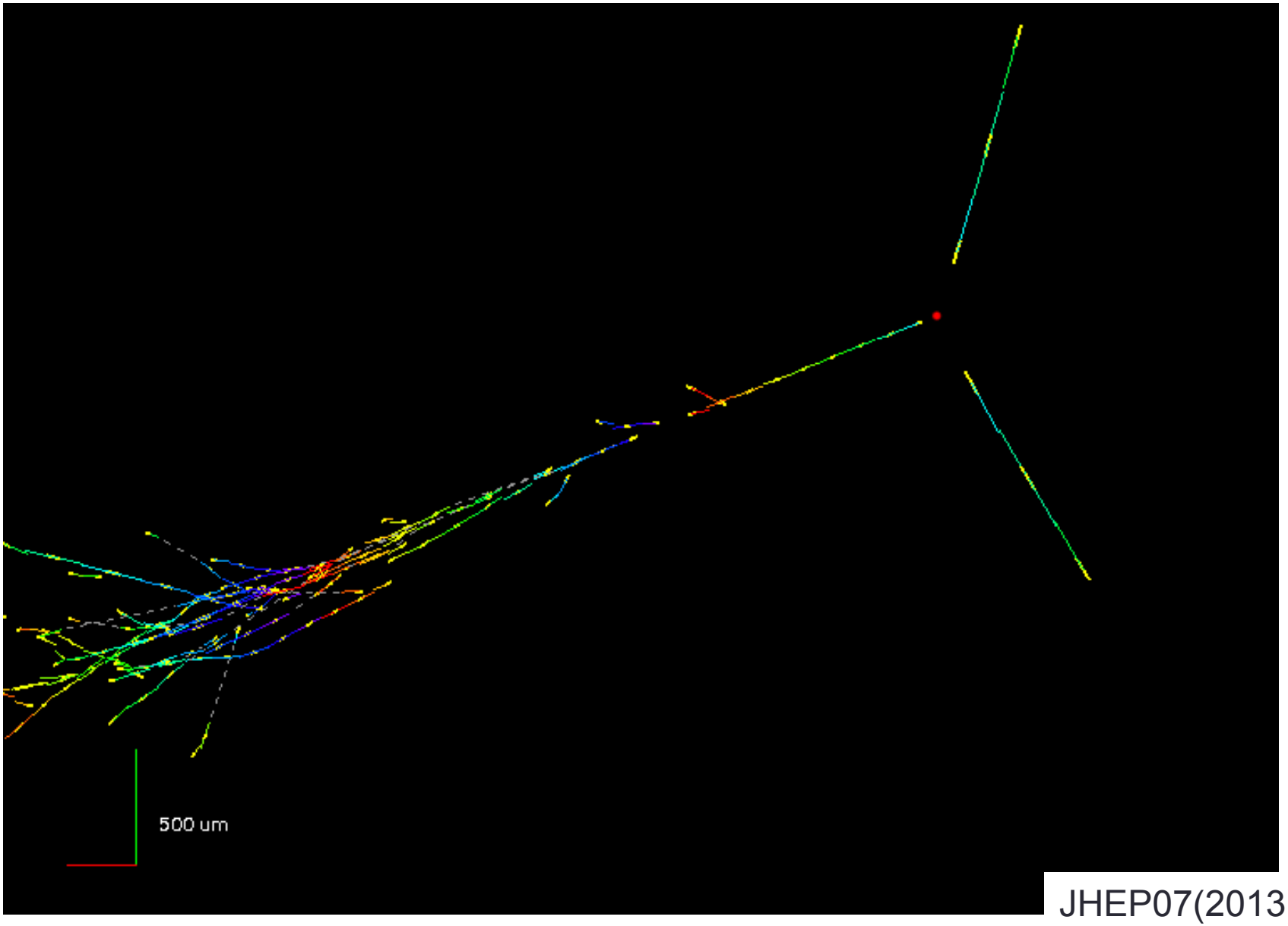
The relative difference between the two measurements with respect to the electronic detector measurement.



Particle ID

Particle ID is possible in ECC by detecting secondary interactions (Hadron), cascade showers (Electron) and dE/dX measurement.

$n_m \rightarrow n_e$ oscillation analysis in OPERA

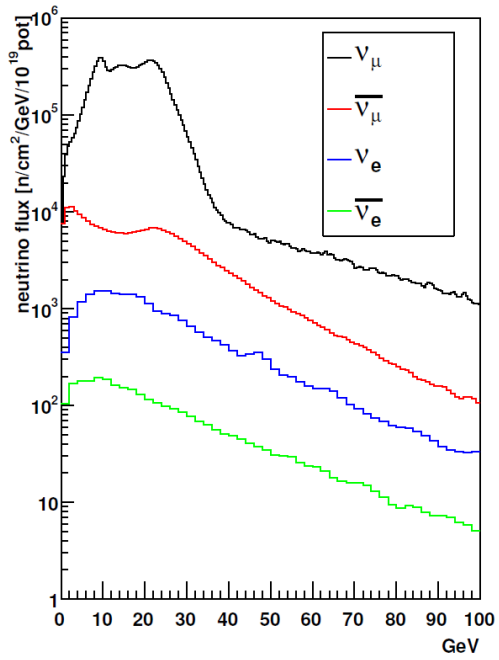


JHEP07(2013)004

n_m–>n_e oscillation analysis in OPERA

- prompt n_e contamination of CNGS neutrino beam is ~1%
  –> prompt n_e is the main background for oscillation analysis
  –>optimize energy region

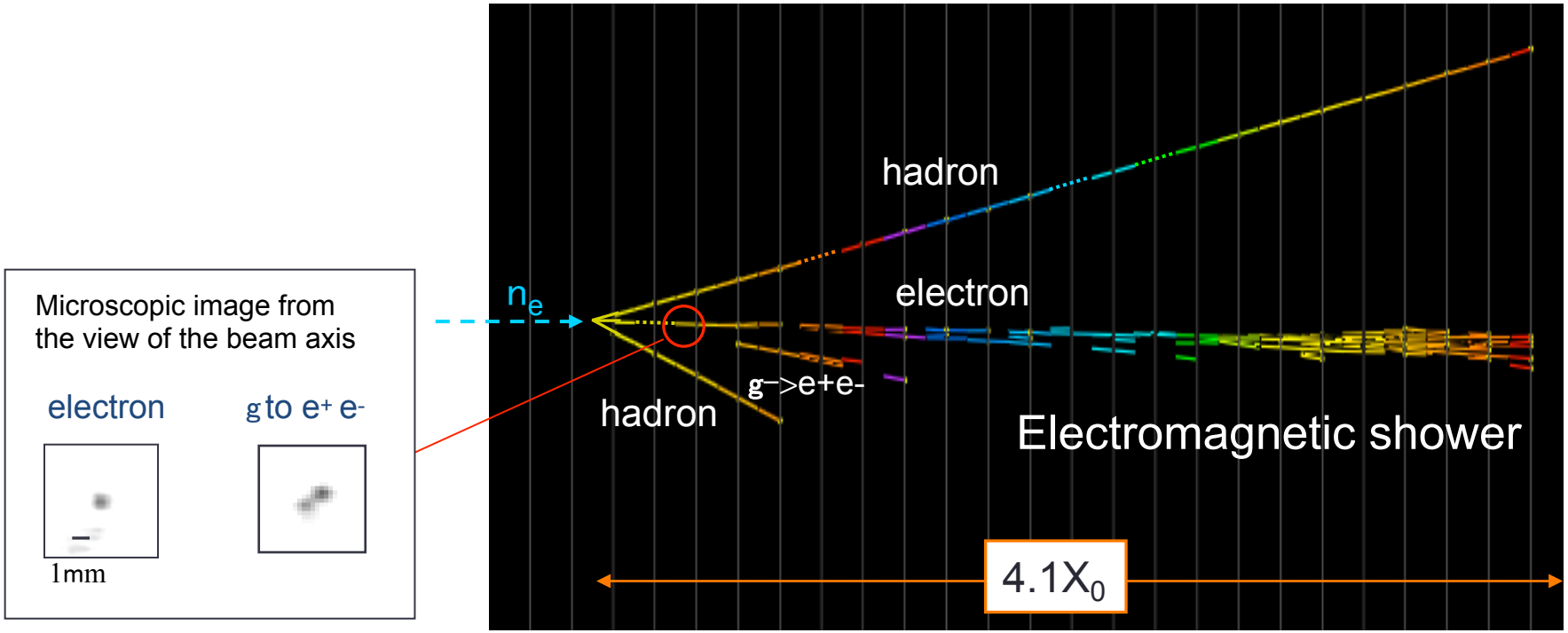
- CNGS neutrino beam is wide-band spectrum
  –>sensitive to high Dm^2 region



Search for n_e events in the 505 located events without muon identified by the electronic detector (0m events) of 2008-2009 data set

JHEP07(2013)004

Electron Identification in ECC



- Primary electron track observed as an isolated track, not pair tracks

fine position resolution of nuclear emulsion and fine segmentation (track reconstruction each 1mm lead plate ($0.18X_0$)) in ECC
-> separate electron from g->e+e-

- Electromagnetic shower developed in ECC

-> separate electron from pion

JHEP07(2013)004

Background estimation
(misidentified as n_e)

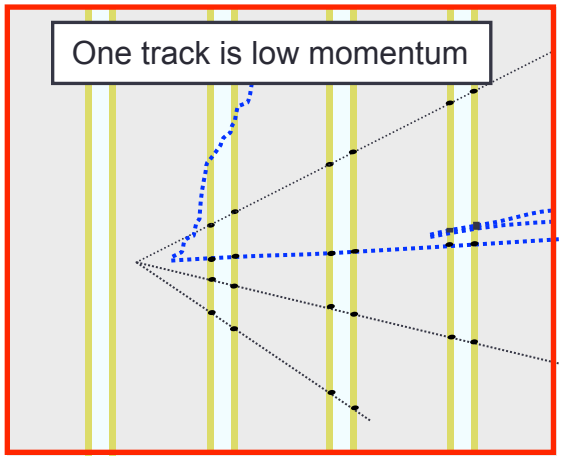
- p^0 decay

g conversion nearby the vertex and e+e- are not observed pair track

→Estimate from the data sample

g converting in the second and third lead plates after the interaction vertex were searched in the 1106 n interactions

0.2±0.2 (inclusive)

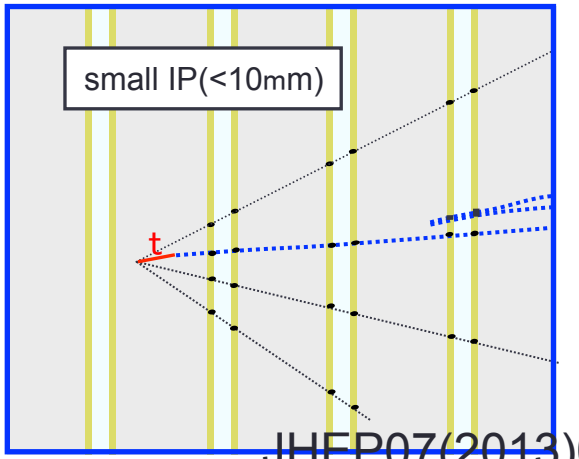


- t−>e decay

the electron track has small impact parameter (IP<10mm) to the primary vertex

→Estimate from MC simulation

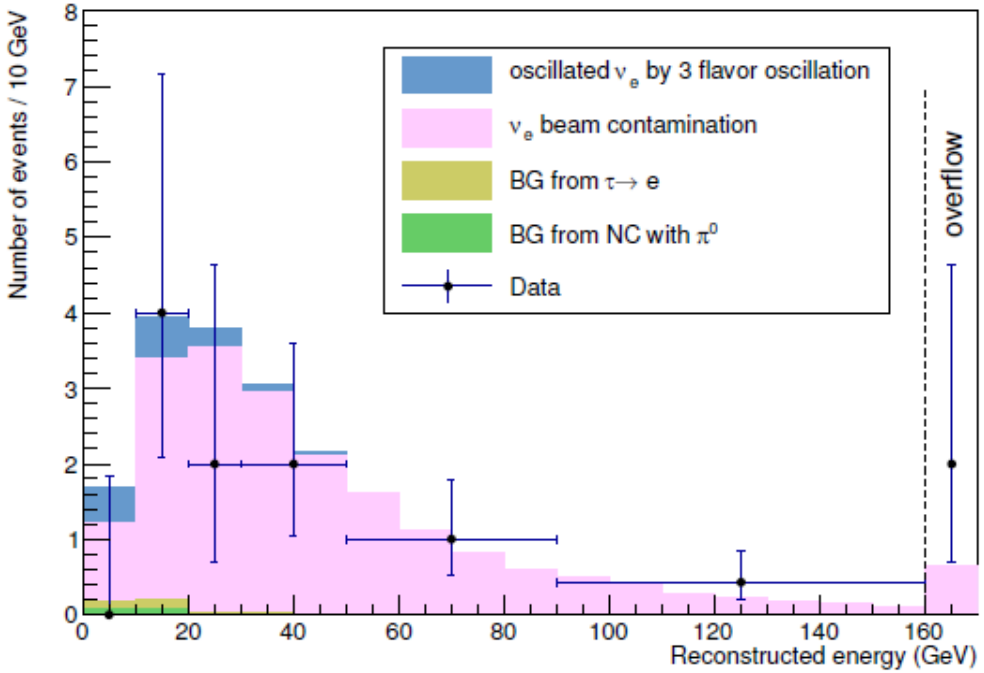
0.3±0.1 (inclusive)



JHEP07(2013)004

Analysis of 2008-2009 data sample (5.27x10^{19} POT)

19 n_e events observed out of 505 0m events



Systematic Uncertainty

1 : Beam flux 10%
2 : Detection efficiency
10%(En>=10GeV)
20%(En<10GeV)

Expected number of background n_e events :19.8±2.8(sys)
(prompt n_e, NC with p^0, t->e)

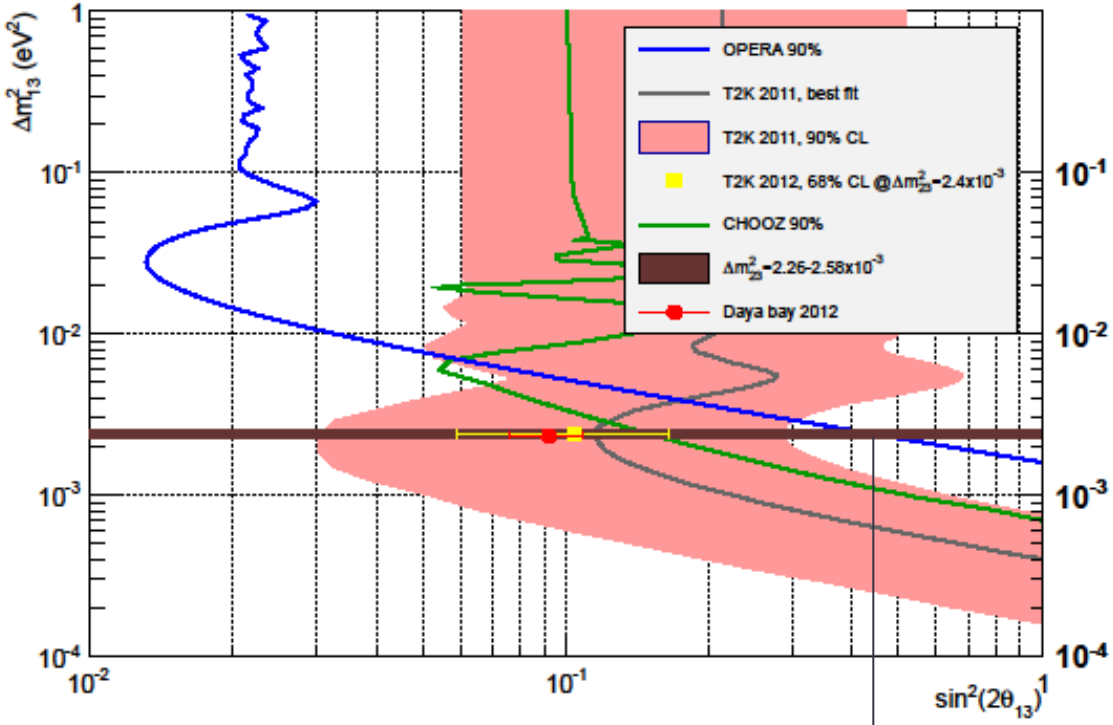
-> Observation agrees with background expectation

JHEP07(2013)004

OPERA n_m->n_e oscillation results

(in 2008+2009 data set)

3 flavor mixing model for standard oscillation



Upper limit (90%C.L.) @Dm^2_{13}=2.32 x 10^{-3} (eV^2)

$\sin^2(2q_{13}) = 0.44$

N_{expBG} = 4.6±0.7(sys), N_{obs} = 4 (E_{n_rec}<20GeV)

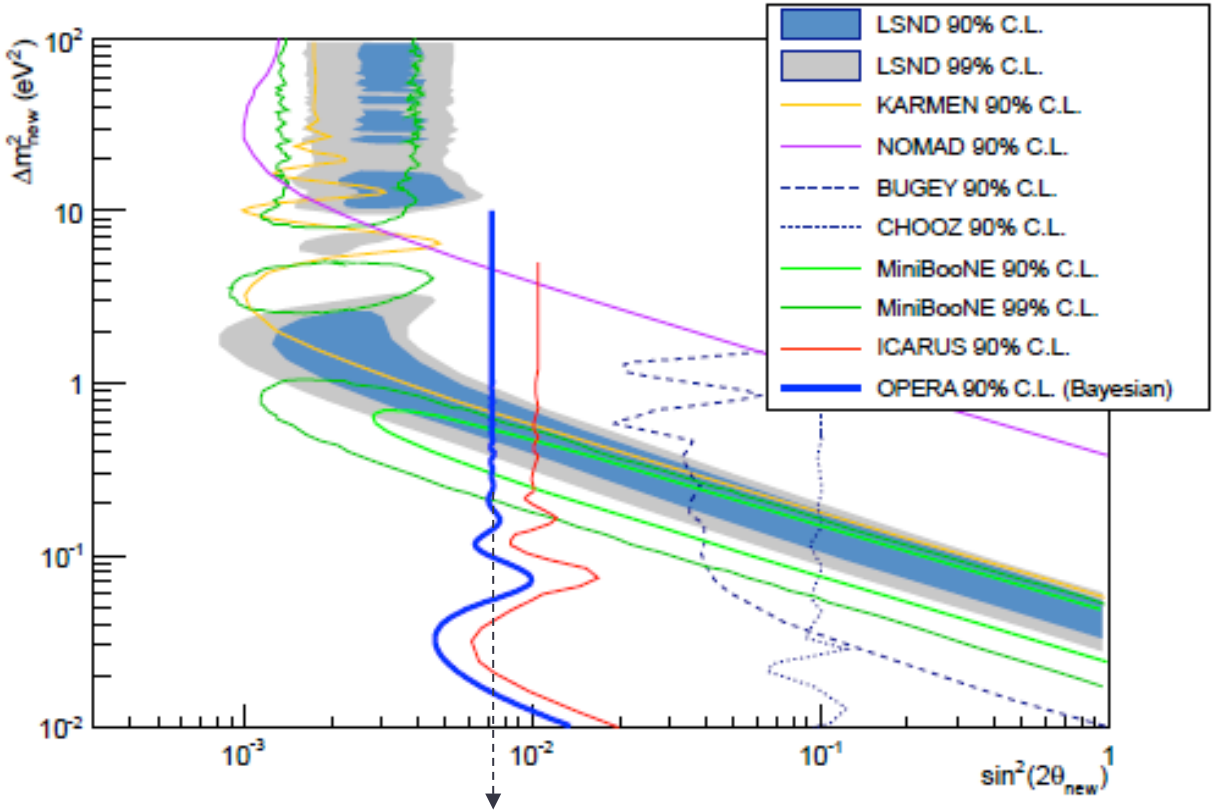
Observation is compatible with non-oscillation hypothesis

JHEP07(2013)004

OPERA n_m->n_e oscillation results

(in 2008+2009 data set)

2 flavor mixing model for non-standard oscillation with a dominant mass scale



N_{expBG} = 9.4±1.3(sys)
N_{obs} = 6
(E_{n_rec}<30GeV)

Upper limit (90%C.L.) @largeDm^2
$\sin^2(2q) = 7.2 \times 10^{-3}$

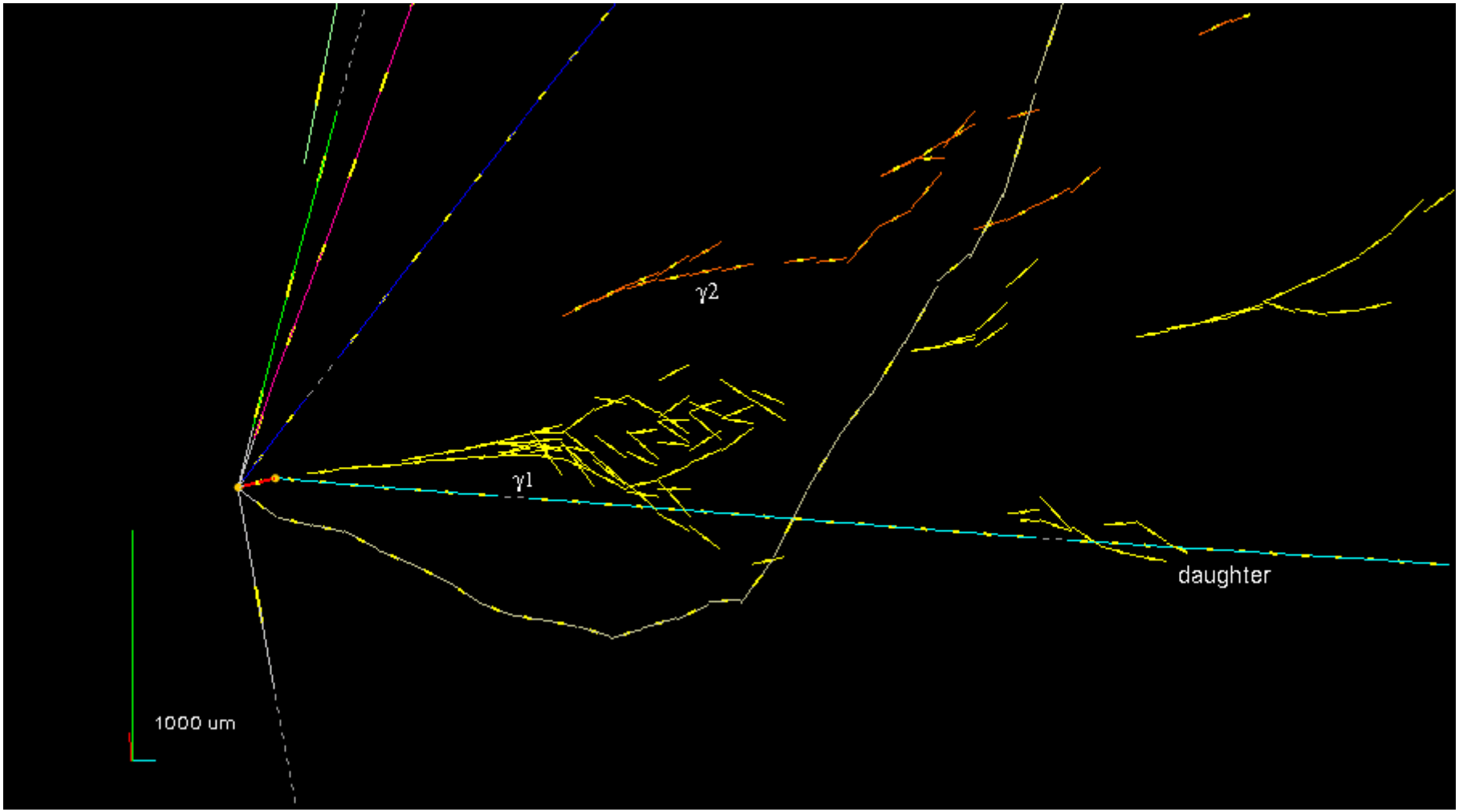
JHEP07(2013)004

n_t event - one

Reported in May 2010

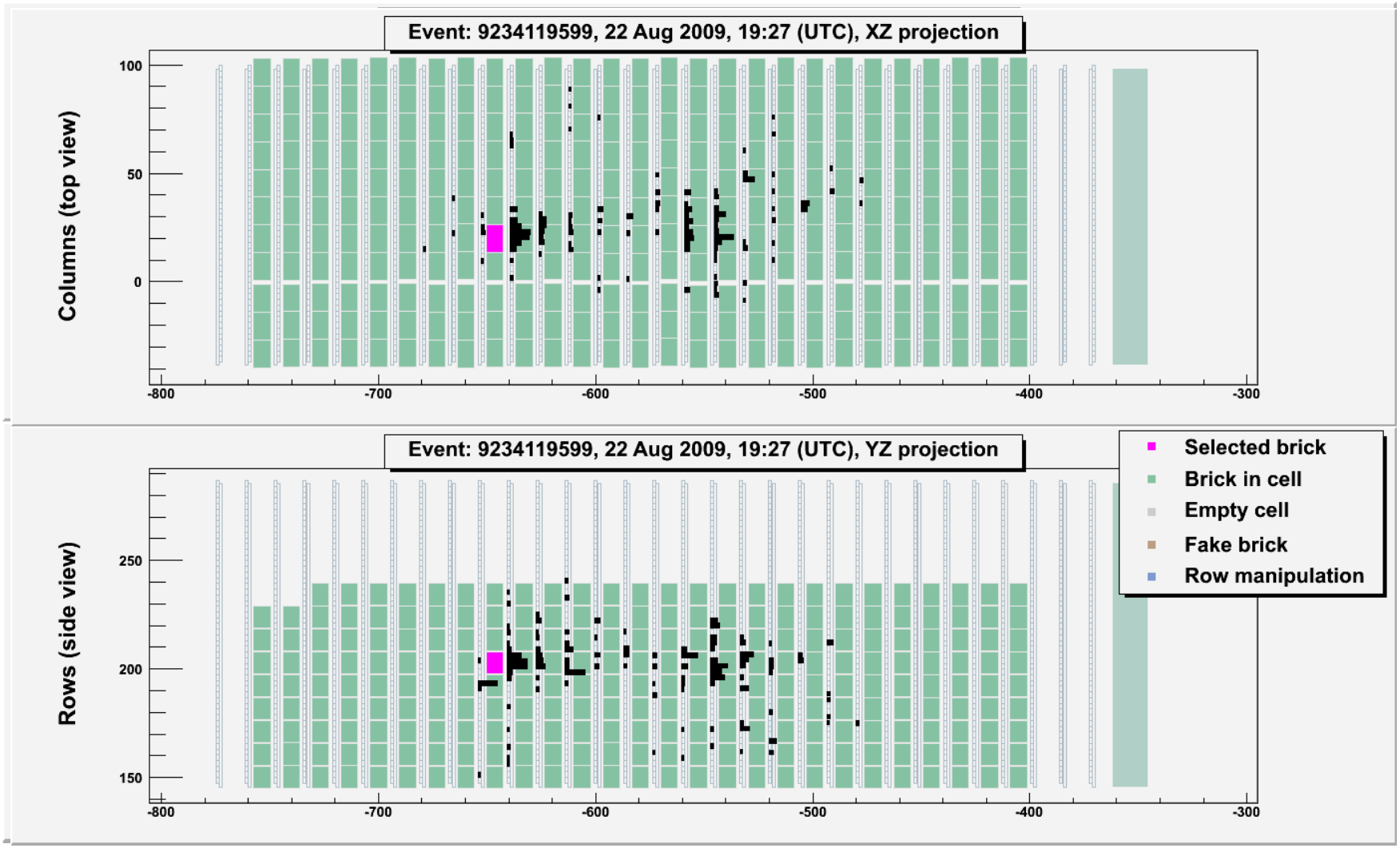
Decay channel: $\tau \rightarrow 1h$

($\tau \rightarrow \rho\, \nu_\tau$, $\rho \rightarrow \pi^0\, \pi$, $\pi^0 \rightarrow 2\gamma$)

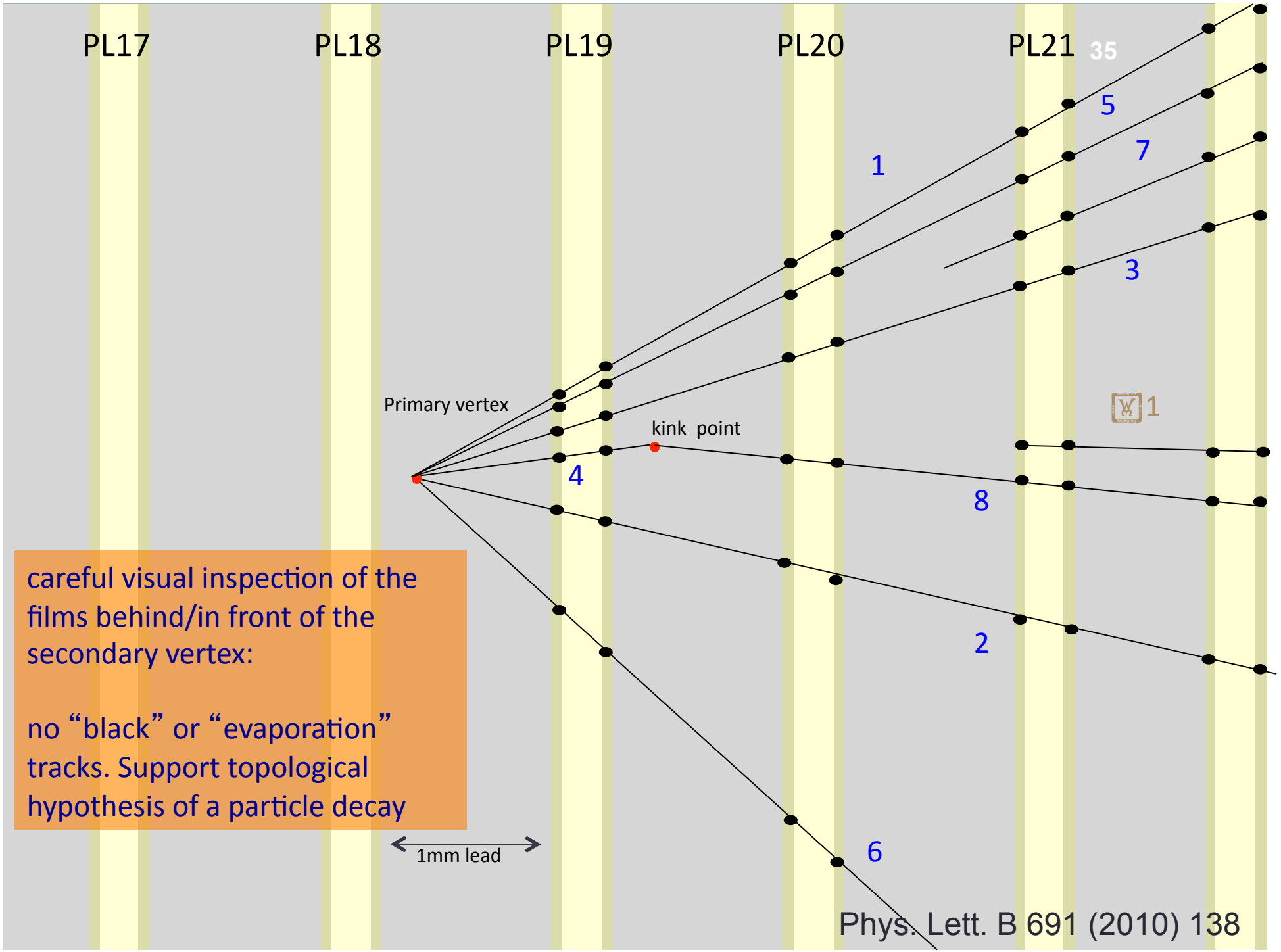


Phys. Lett. B 691 (2010) 138

Muonless event 9234119599, taken on 22nd August 2009 (as seen by the electronic detectors)



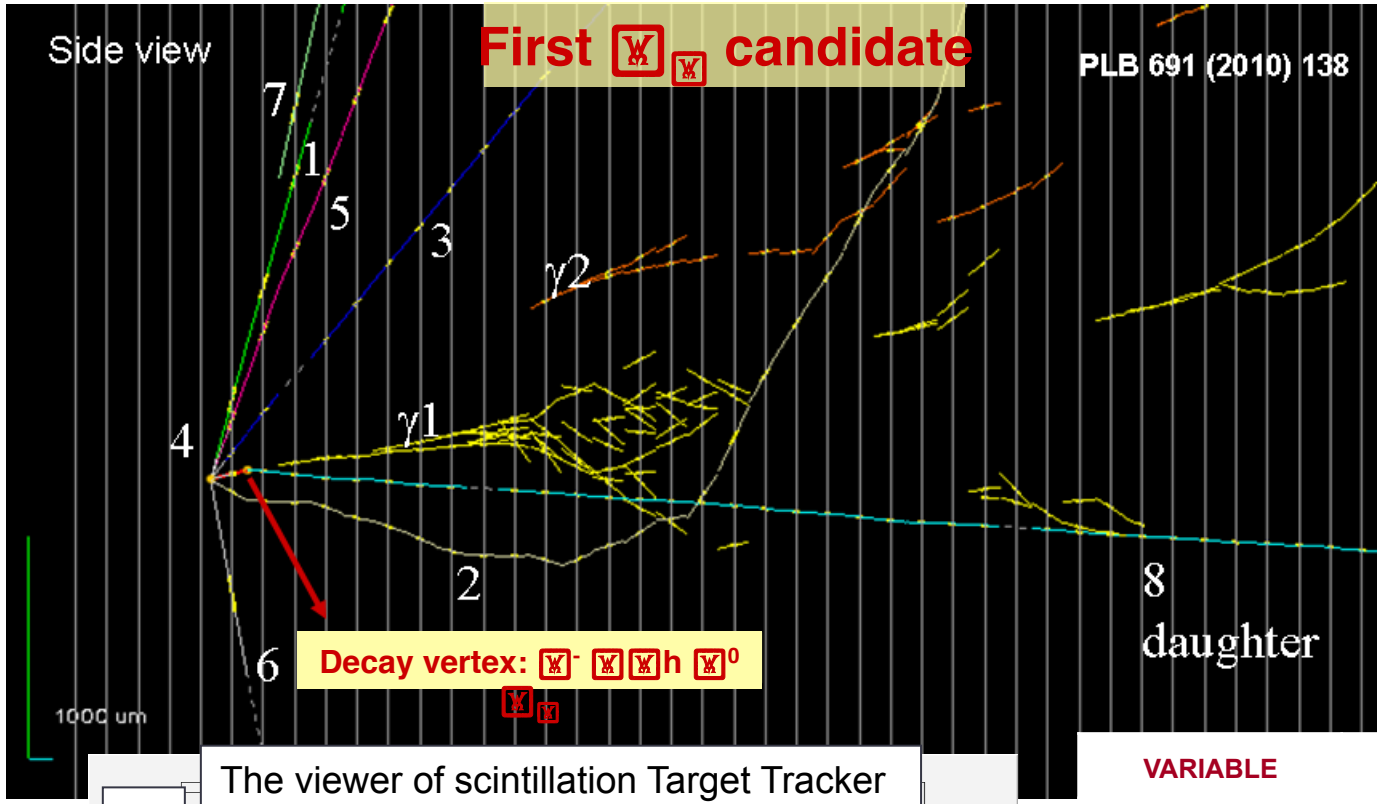
Phys. Lett. B 691 (2010) 138

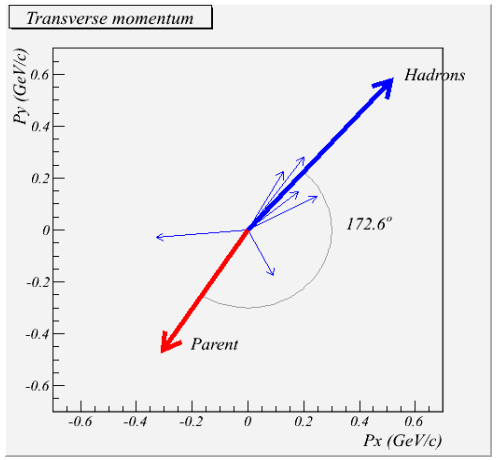


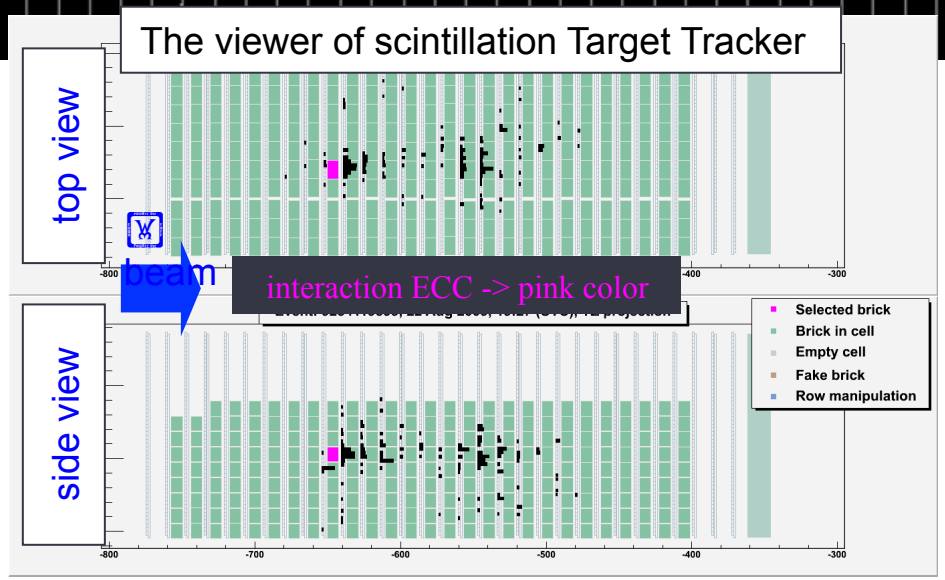
careful visual inspection of the films behind/in front of the secondary vertex:

no “black” or “evaporation” tracks. Support topological hypothesis of a particle decay

Phys. Lett. B 691 (2010) 138





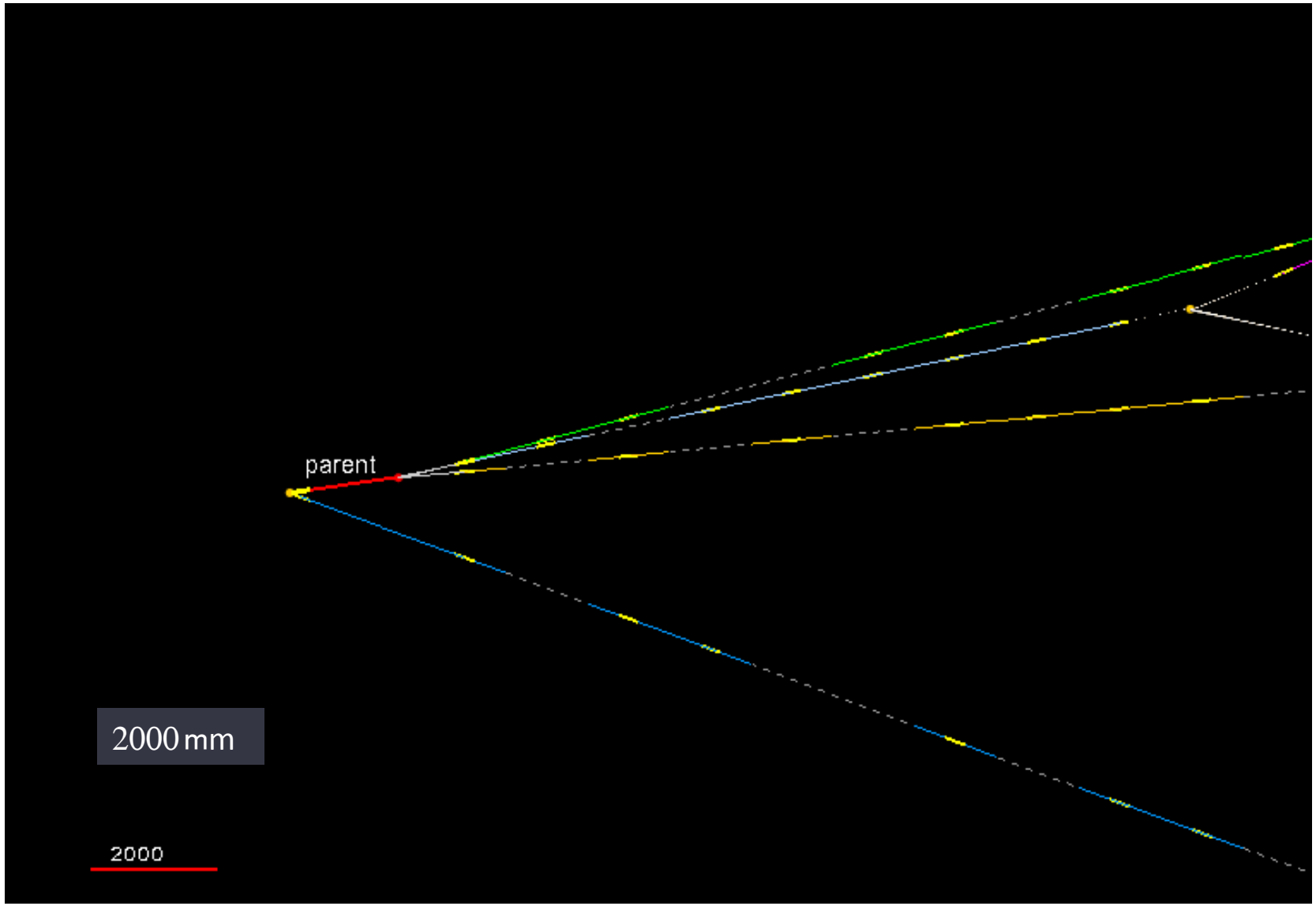


VARIABLE	AVERAGE	Selection criteria
kink (mrad)	41 ± 2	>20
decay length (mm)	1335 ± 35	within 2 lead plates
P daughter (GeV/c)	12^{+6}_{-3}	>2
Pt (MeV/c)	470^{+230}_{-120}	>300 (γ attached)
missing Pt (MeV/c)	570^{+320}_{-170}	<1000
τ (deg)	173 ± 2	>90

Phys. Lett. B 691 (2010) 138

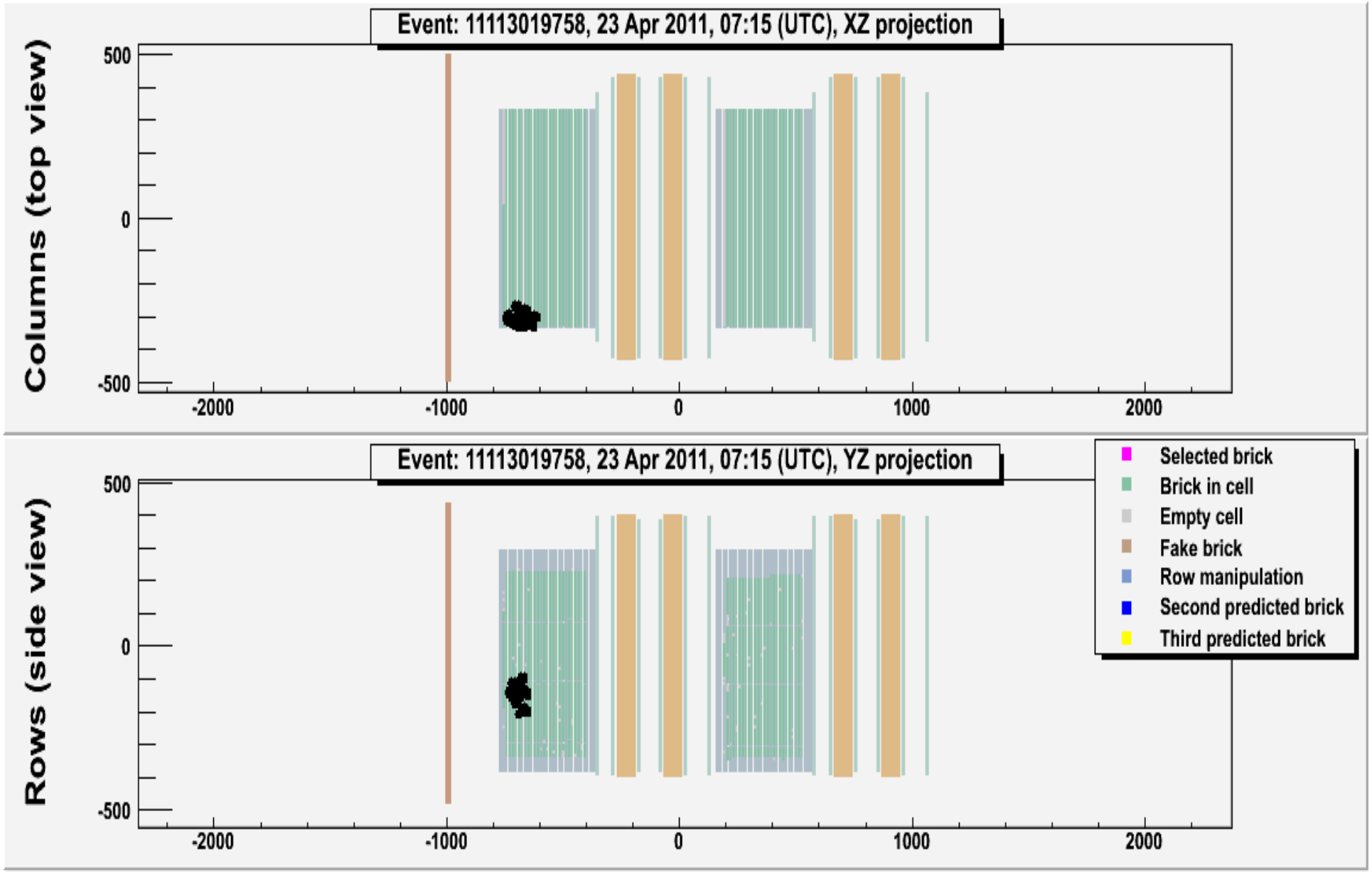
n_t event - two

Reported in June 2012
Decay channel: τ → 3h



JHEP 1311 (2013) 036

Second neutrino tau candidate event taken on 23rd April 2011

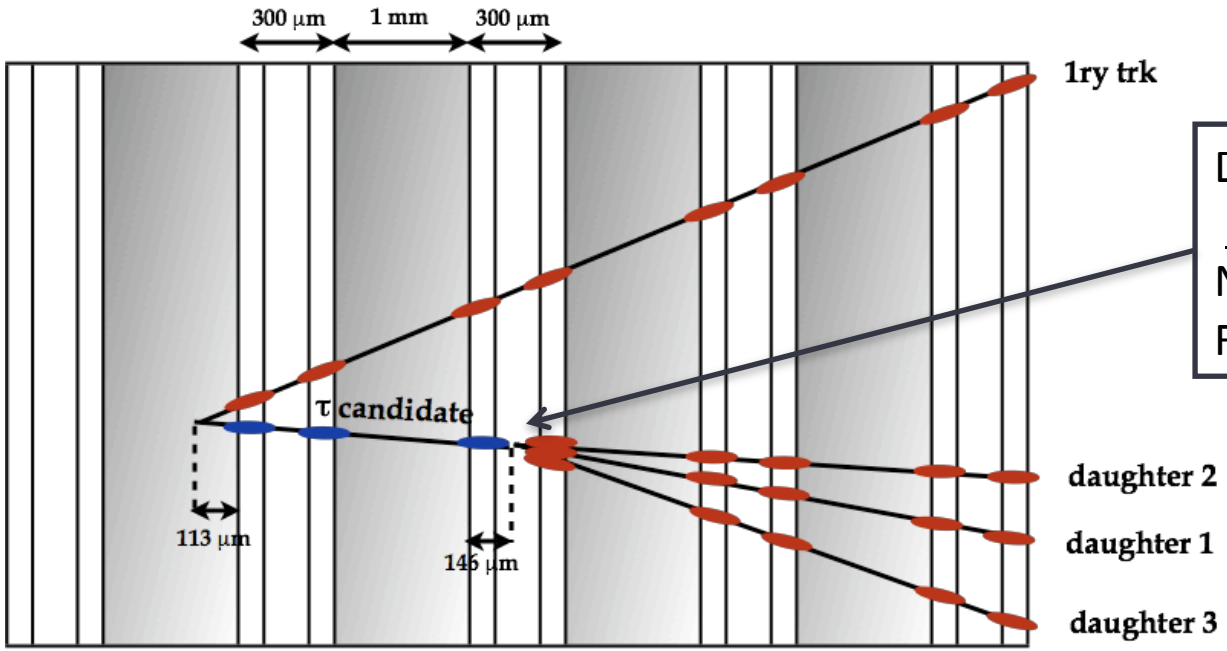


JHEP 1311 (2013) 036

Topology of the event

	Cut	Value
φ (Tau - Hadron) [degree]	>90	167.8±1.1
average kink angle [mrad]	< 500	87.4±1.5
Total momentum at 2ry vtx [GeV/c]	> 3.0	8.4±1.7
Min Invariant mass [GeV/c²]	> 0.5 & < 2.0	0.96±0.13
Invariant mass [GeV/c²]	> 0.5 & < 2.0	0.80±0.12
Transverse Momentum at 1ry vtx [GeV/c]	< 1.0	0.31±0.11

Beam View
Φ=167°



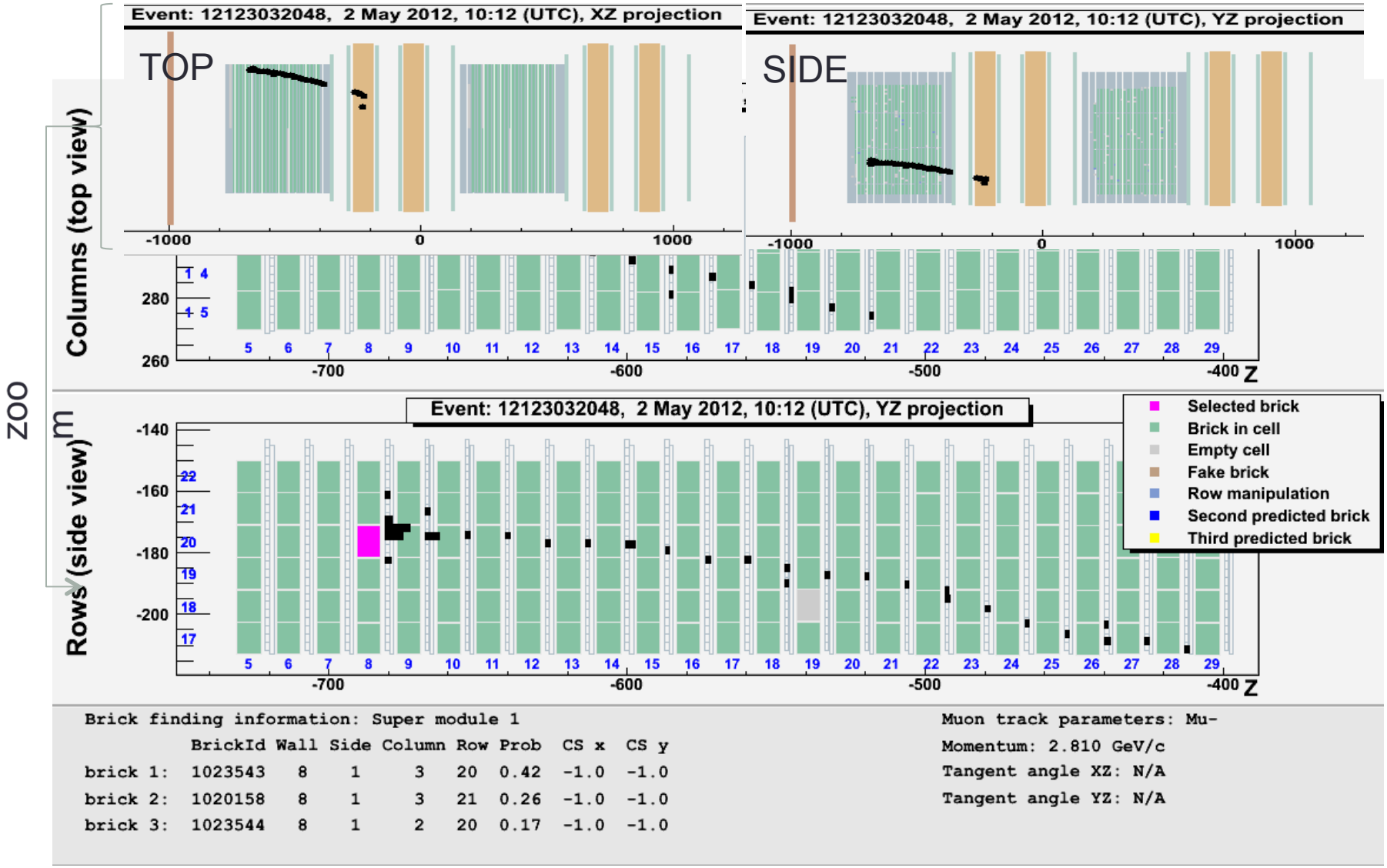
Decay point
In Plastic Base
No Nuclear fragment
Flight length 1.54mm

n_t event - three

Reported in March 2013

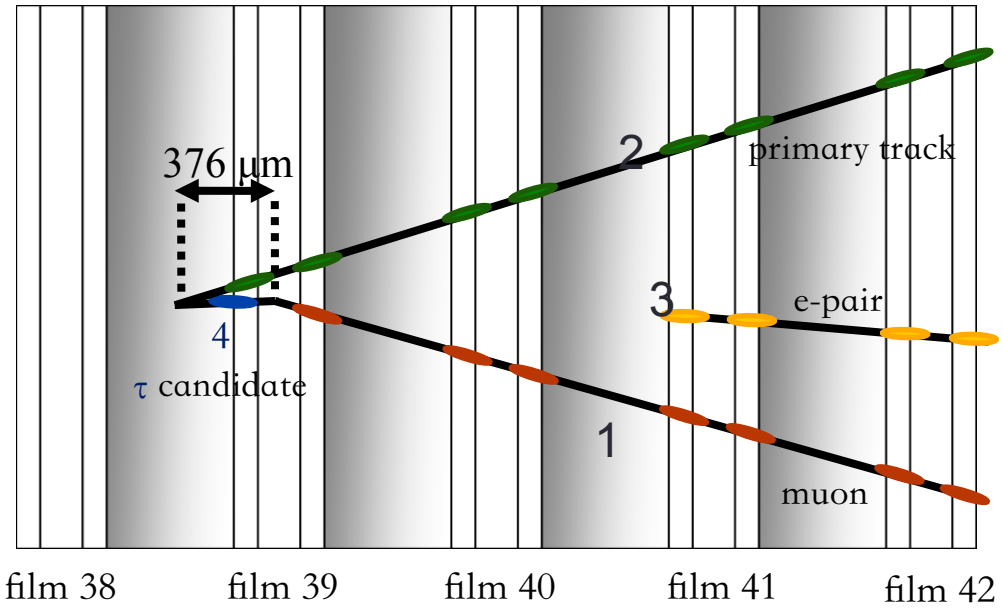
Decay channel: τ → m

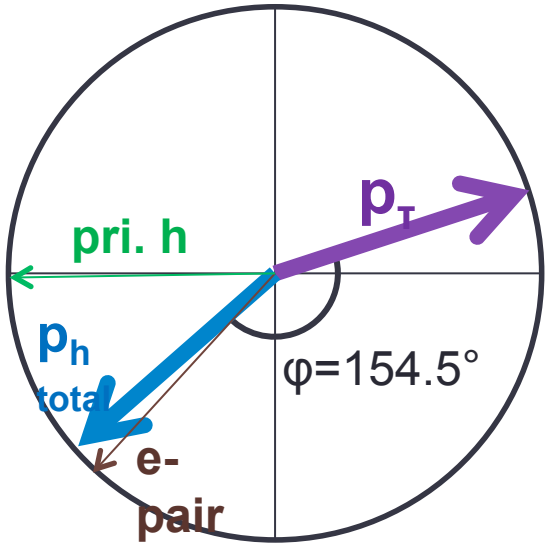
Electronic detector



ZOOM

Topology of the τ→μ decay event

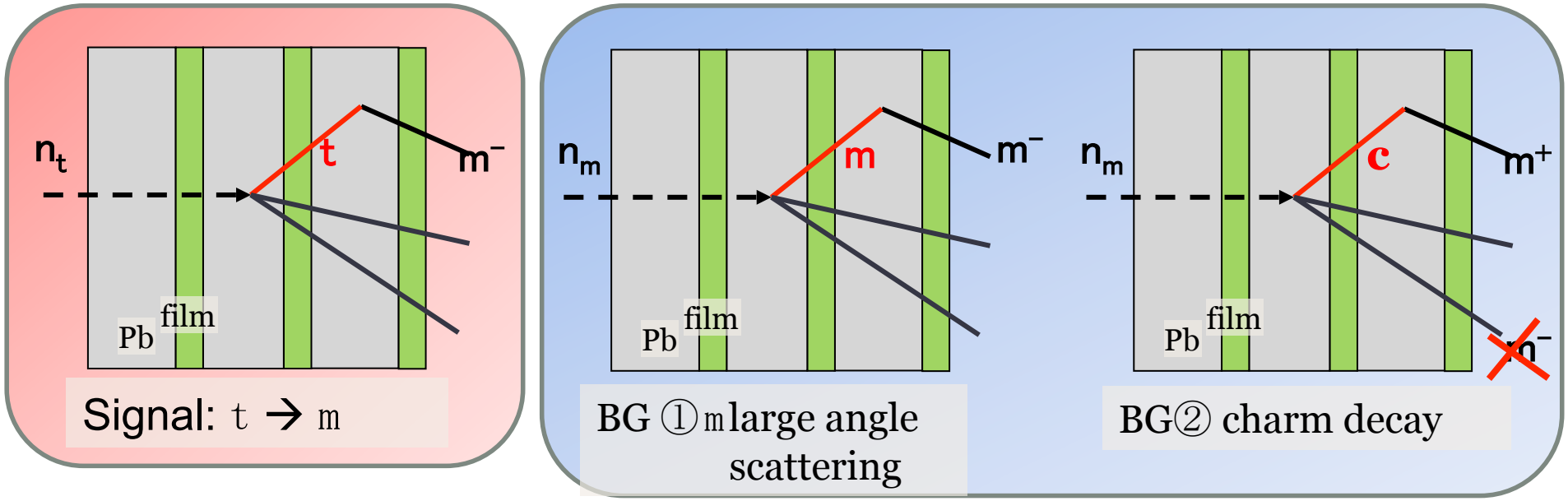




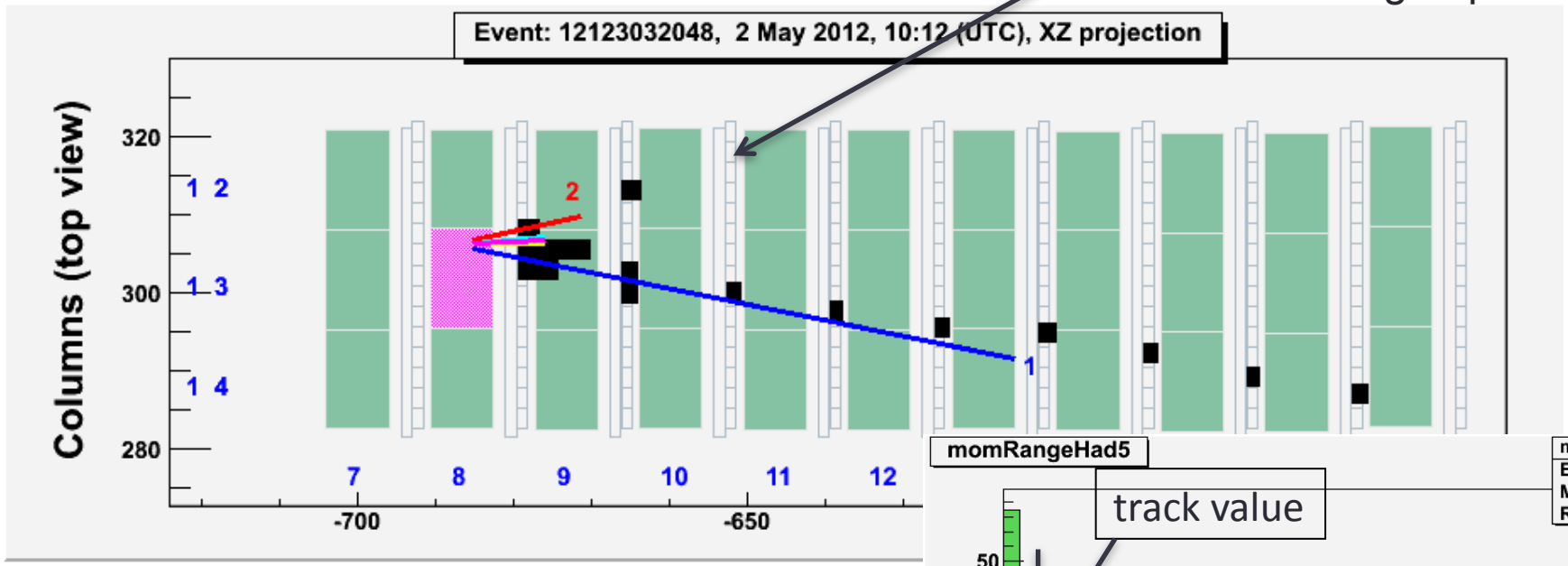
VARIABLE	AVERAGE
Kink angle (mrad)	**245 ± 5**
decay length (μm)	**376 ± 10**
Pμ (GeV/c)	**2.8±0.2**
Pt (MeV/c)	**690±50**
ϕ (degrees)	**154.5 ± 1.5**

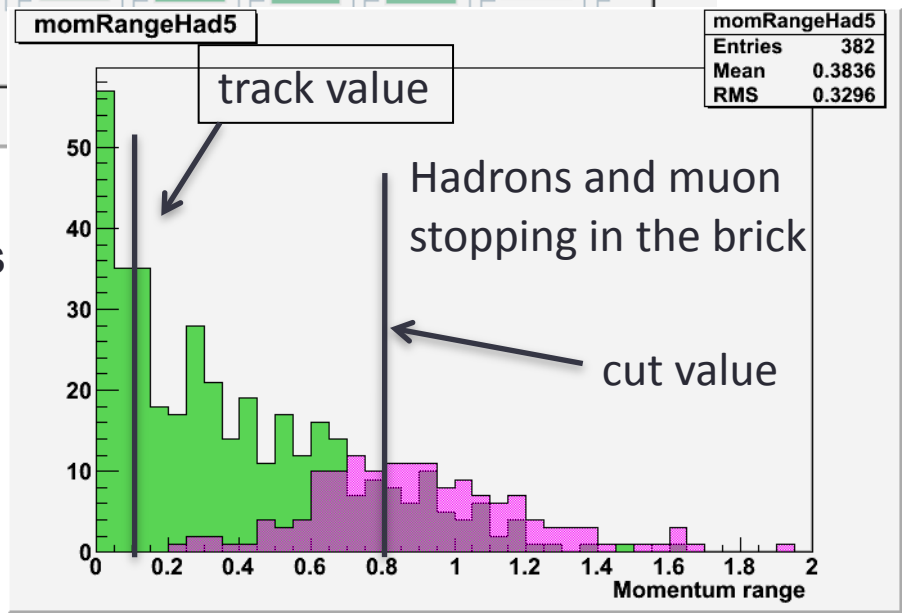
- All variables passed the kinematical cuts of OPERA
- γ is attached to the primary vertex

Main background source



Track 2 interacting in the downstream brick without visible charged particles





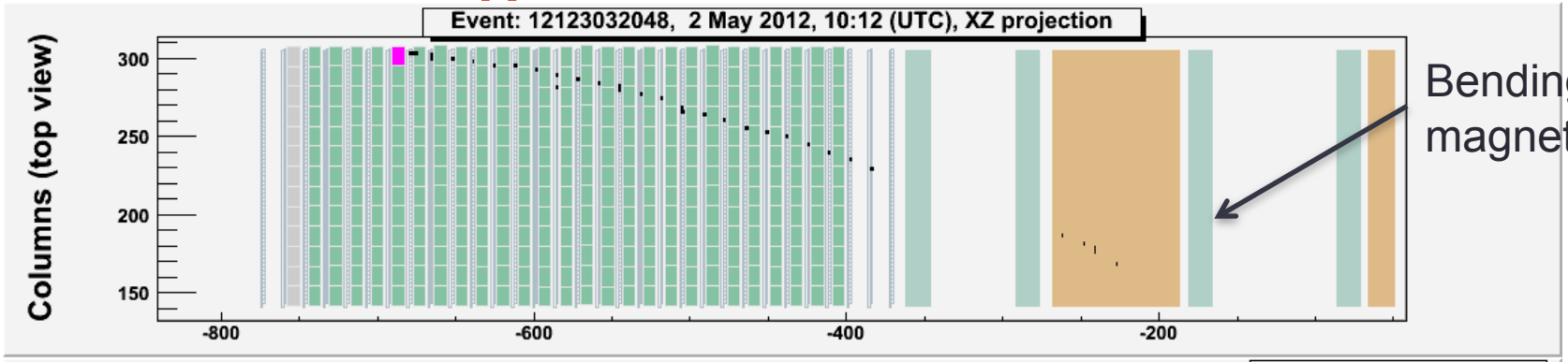
Momentum/range inconsistent with μ hypothes
0.9 GeV/4 cm Lead

$$D = \frac{L}{R_{lead}(p)} \frac{\rho_{lead}}{\rho_{average}}$$

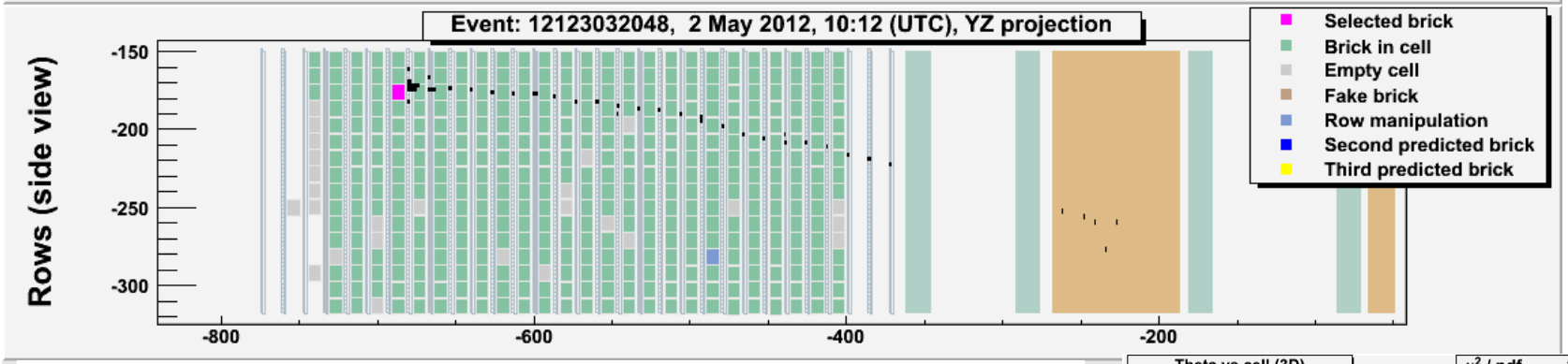
L = track length
R_{lead} = μ range
$\rho_{average}$ = average density
ρ_{lead} = lead density
p = momentum in emulsion

D variable

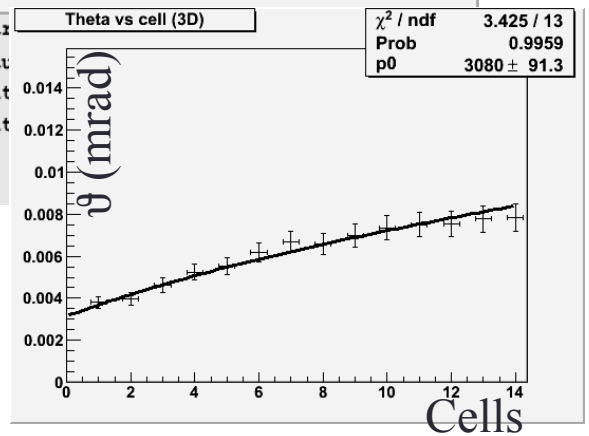
Muon charge and momentum reconstruction



Bending by the magnetic field



Muon momentum
by range in the electronic detector: 2.8±0.2 GeV/c
MCS in the brick consistent 3.1 [2.6,4.0] GeV/caru



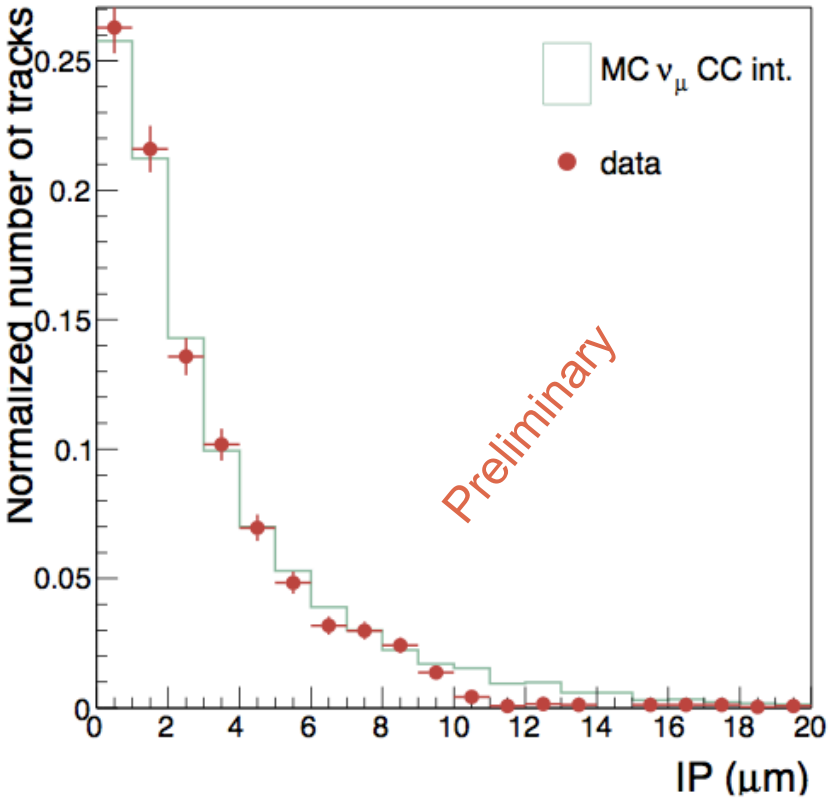
Summary of $n_m \to n_t$ search status

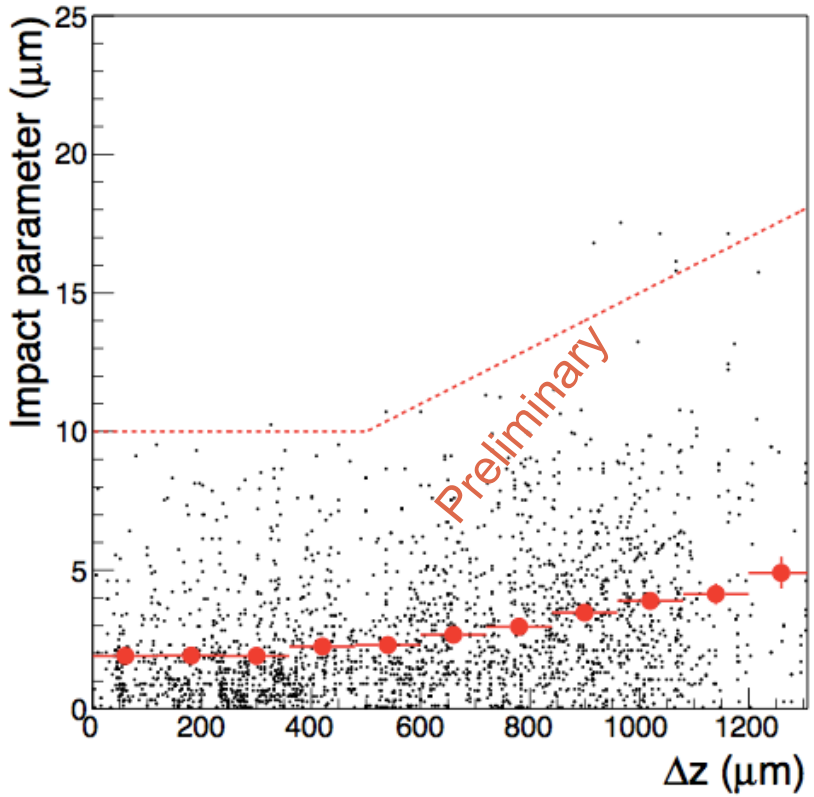
- Three n_t candidates have been found, 1st : t−> h, 2nd : t−> 3h, 3rd : t −> m.
- The 3rd n_t event is pure t−>m channel with low background and tagged as n_t by its muon sign.
- Probability explained by only background ~ 7.29 x 10^{-4}
- The singnificance value : counting method : 3.2 s of non-null observation, likelihood approach : 3.5 s

	Signal	Background	Charm	m scattering	had int
t→ h	0.66	0.045	0.029		0.016
t → 3h	0.51	0.090	0.087		0.003
t→ m	0.56	0.026	0.0084	0.018	
t → e	0.49	0.065	0.065		
total	2.22	**0.226**	0.19	0.018	0.019

Decay Search

- Check the distribution of IP, #tracks at primary vertex





Charm production in the OPERA experiment

Charmed particles have similar decay topologies as the ν_τ decay

Particle	mass (MeV)	c_t(mm)
D^0	1864.6 ±0.5	122.9
D^+	1869.3 ±0.5	311.8
D_s^+	1968.5 ±0.6	149.9
L_c^+	2284.9 ±0.6	59.9
t	1776.8 ±0.2	87.11

Charm branching ratio and fraction extrapolated from CHORUS

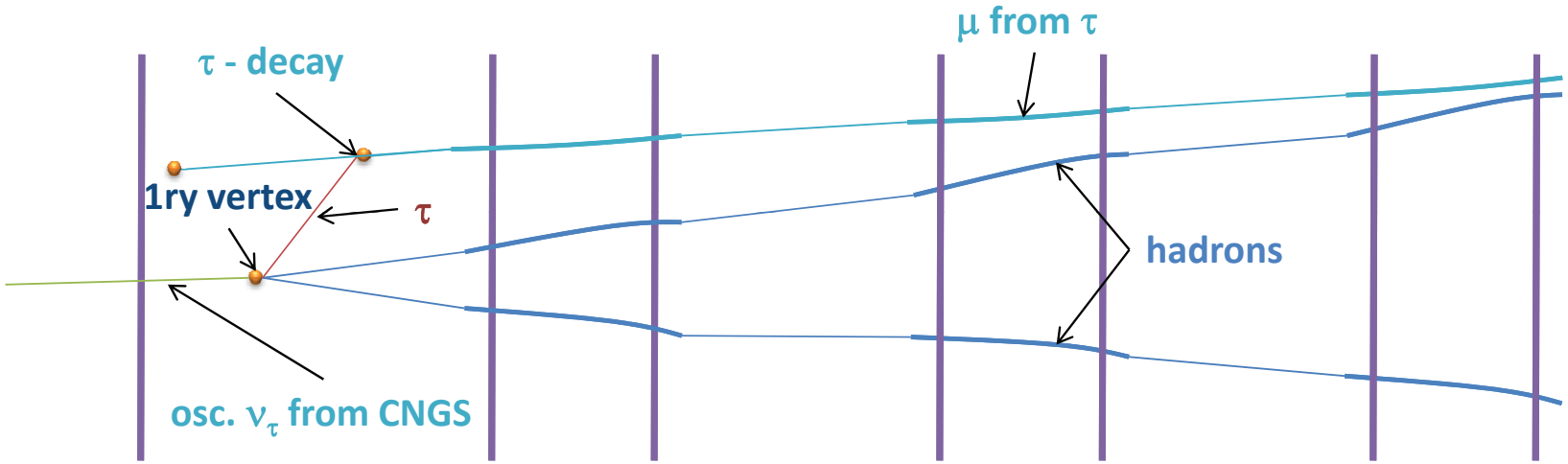
$$\frac{d^2\sigma^{\nu_\mu T\to\mu^- cX}}{d^2\sigma^{\nu_\mu T\to\mu^- X}} = (4.38 \pm 0.26)\%$$

- Understanding charm production & detection:
  - Detection of short lived particle decays ν_τ charm efficiency
  - Background to charm decays itself

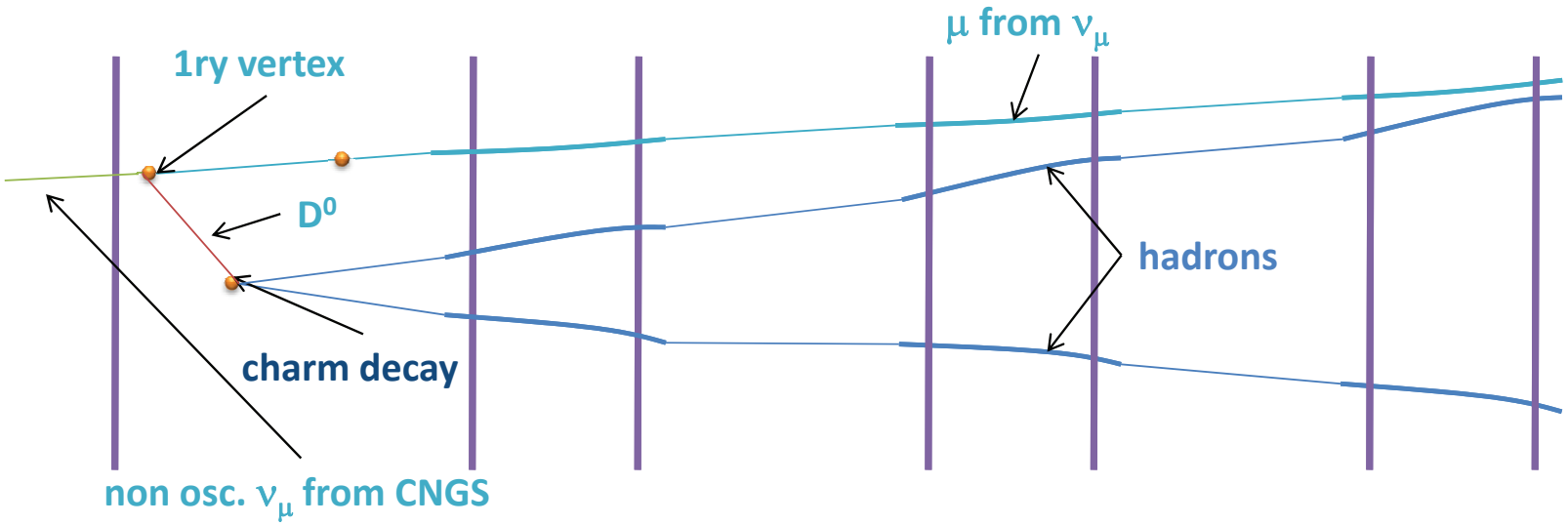
- Charm control sample to show that eff & bg for t search are understood

→ Good understanding of charm production is mandatory for n_t measurements

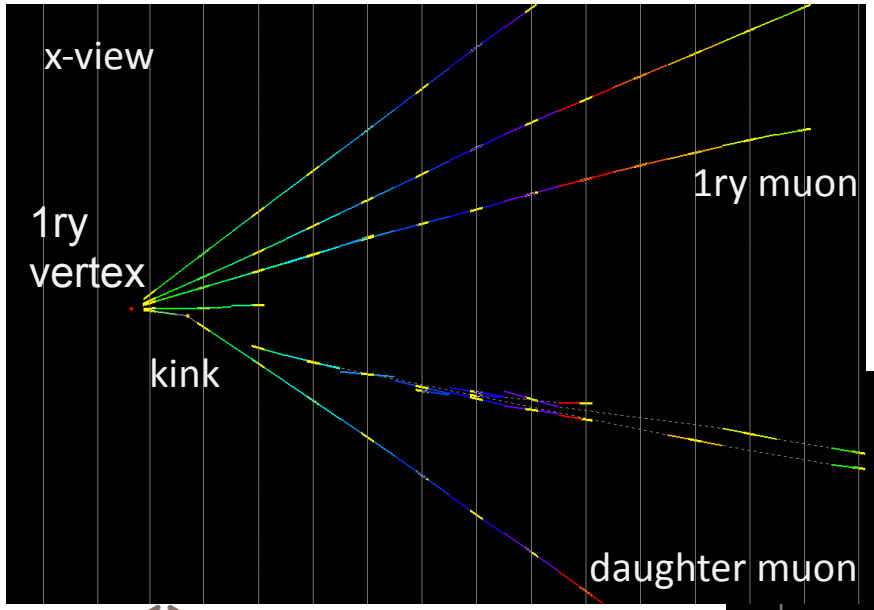
τ-decay



charm decay



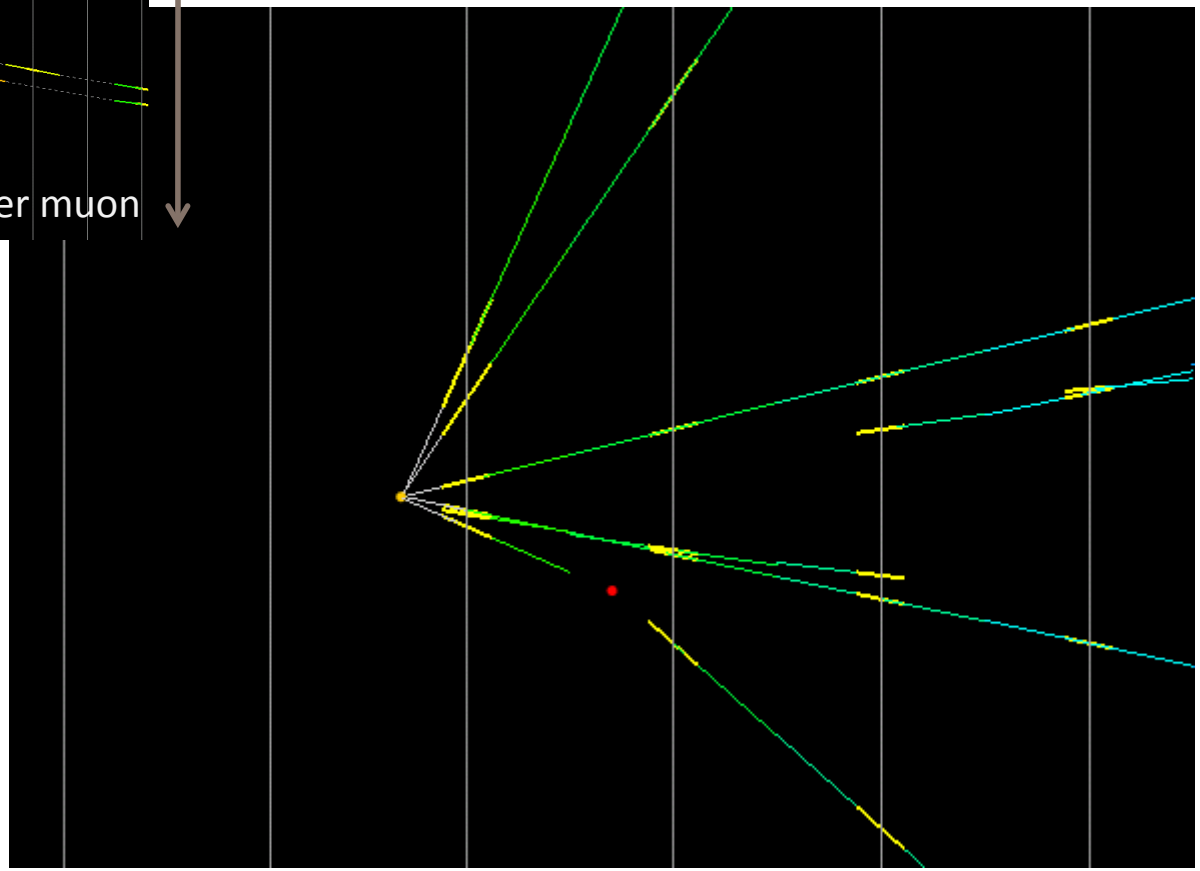
Di-muon event



4 mm

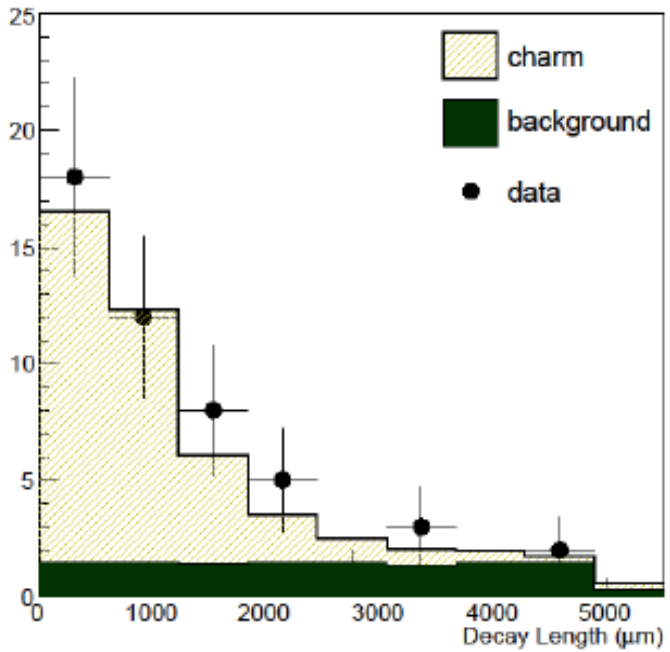
1.3 mm

flight length: 1330 microns
kink angle: 209 mrad
IP of daughter: 262 microns
daughter muon: 2.2 GeV/c
decay P_t: 0.46 GeV/c



Di muon candidate
m^+ and m^- in spectrometer

Charm Decay Event Candidates



Charm yield from the analysis of 2008÷2010 data

	charm	background	expected	data
1 prong	20.5 ± 4.8	9 ± 3	29.5 ± 5.8	19
2 prong	14.9 ± 3.9	3.8 ± 1.1	18.7 ± 4.3	22
3 prong	4.6 ± 2.1	1.0 ± 0.3	5.6 ± 2.1	5
4 prong	0.8 ± 0.9	-	0.8 ± 0.9	4
All	**40.8±6.6**	**13.8±3.2**	**54.6±7.3**	**50**

Charm events from n_m CC interaction

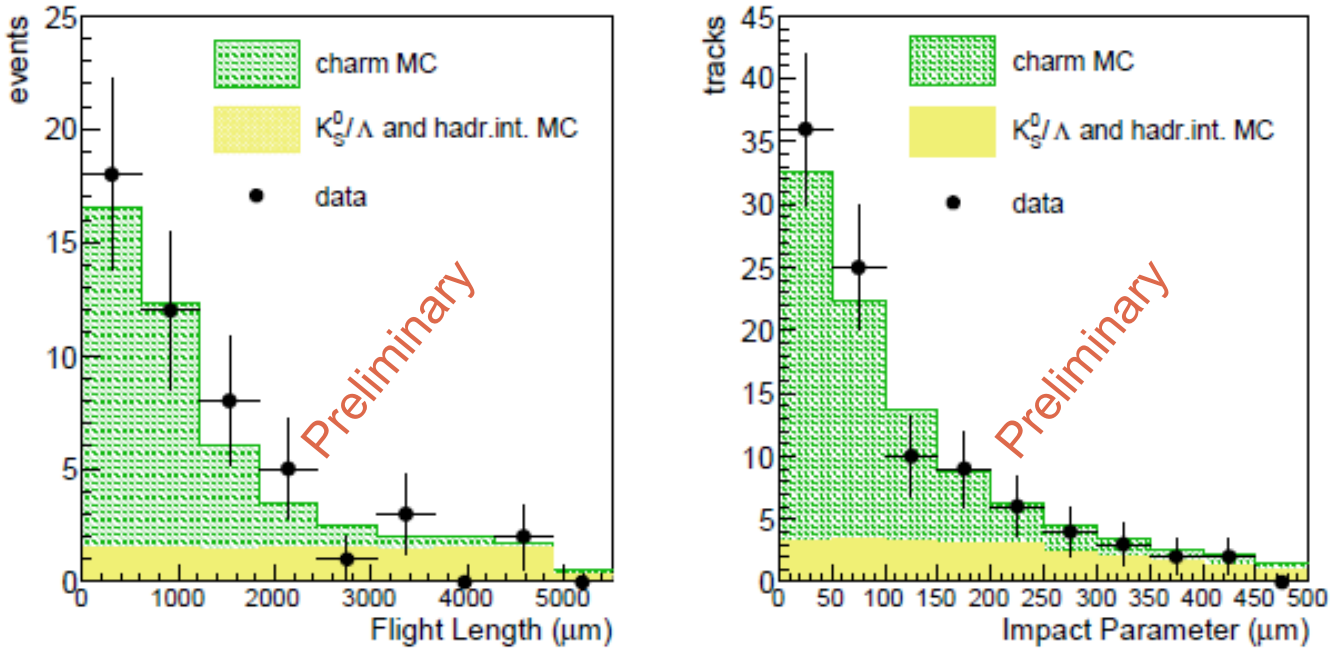


Figure 5. Shape comparison of the distributions of the flight length (left) and the tracks' impact parameters with respect to the primary vertex (right) for the charm data sample of 50 events, described in Sect. 3.4.1, (bullets) and the MC simulation of 40 ± 3 expected charm events (green hatched histogram) and 14 ± 3 expected hadronic interactions and strange meson decays (yellow hatched histograms).

Summary of all interesting events

- 19 electron neutrinos – compatible with no oscillation
- 3 tau neutrino candidates 3.4 sigma significance
- 50 charm decay candidates
- Thousands of muon neutrino interactions

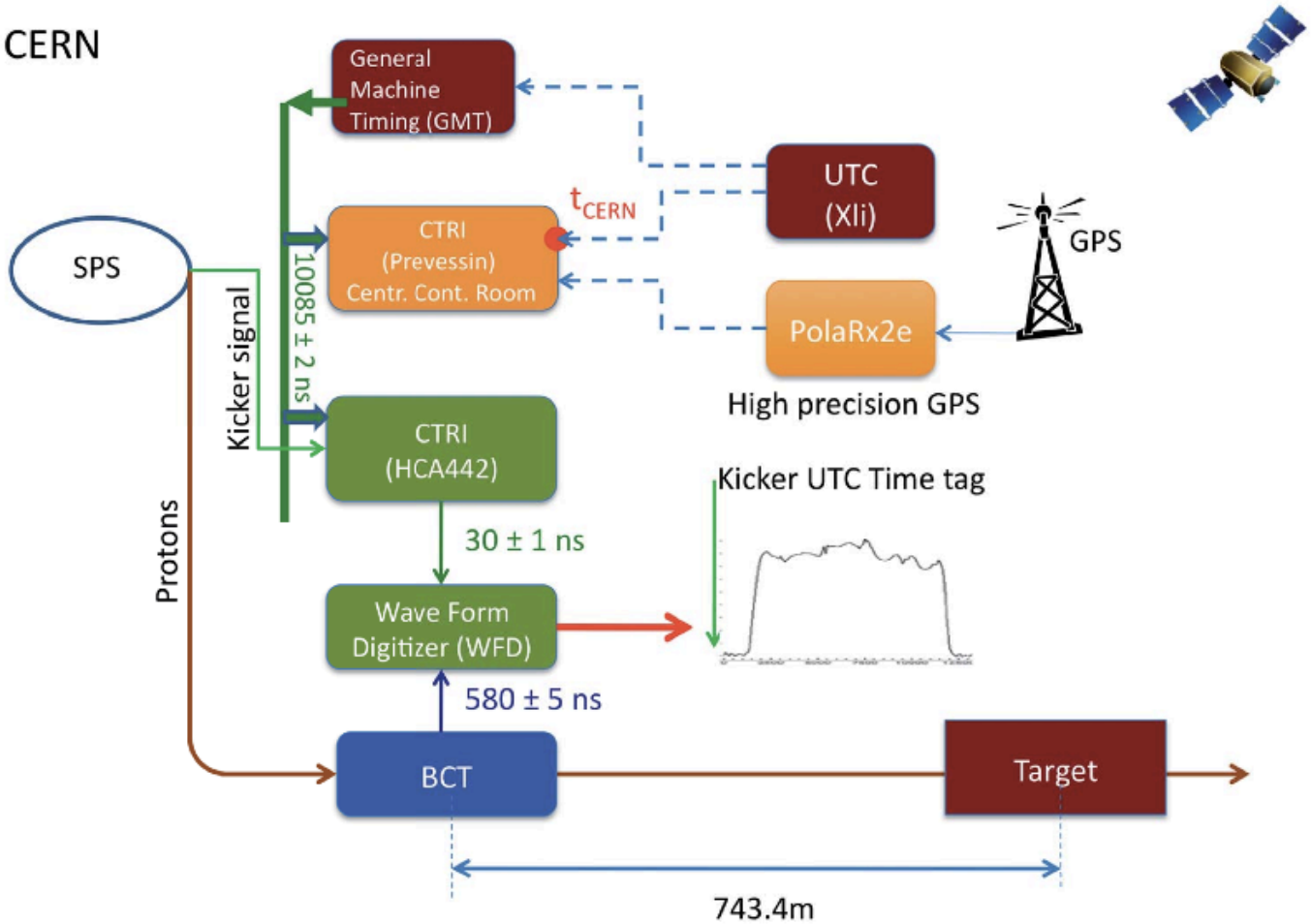
Neutrino velocity measurement

- Just a brief description of technics and conceptTOF: Time of flight $TOF_n = t_B - t_A - t_{delay}$
  - t_A – prodcution time
  - t_B - detection time
- Distance: between source (CNGS) and detector (Opera)
- Velocity: distance / TOF_n
- Statistical analysis on neutrino events collected 2009-2012
- Special bunched beam mode end of 2011 and in may 2012 for direct comparison event by event

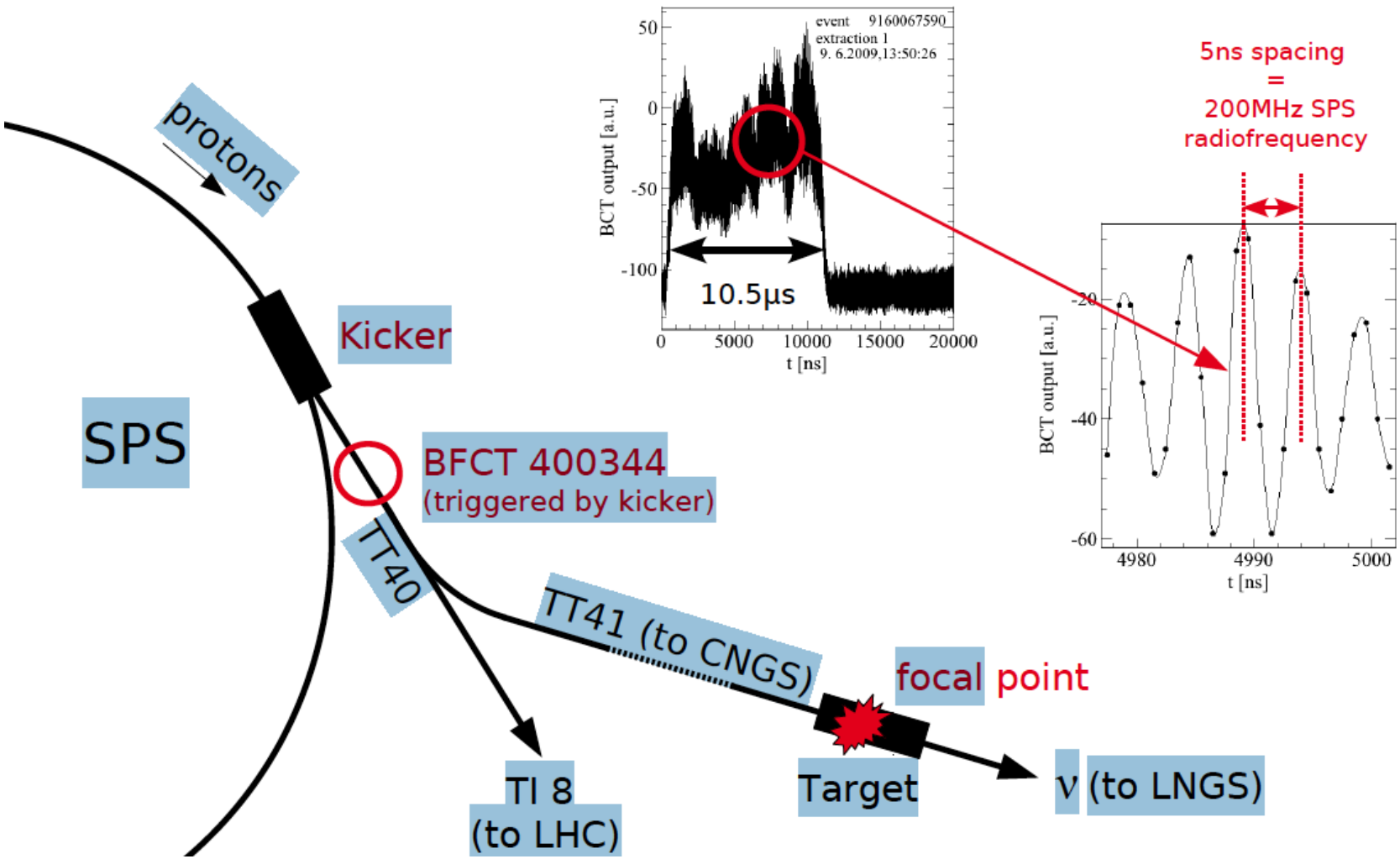
Previous measurements

- 1979: FNAL **(Phys. Rev. Lett. 43 (1979) 1361)**
- short distance, 30 GeV ν_μ, comparison of ν_μ and μ TOF
- $|v-c|/c \leq 4\times10^{-5}$
- 1988: SN1987A **(Phys. Lett. B 201 (1988) 353)**
- very long distance (168.000 light years), 10 MeV anti-ve,
- comparison of ν and photon arrival time (not SN mod.-dep.)
- $|v-c|/c \leq 2\times10^{-9}$
- 2007: MINOS **(Phys. Rev. D 76 (2007) 072005)**
- 730km distance, ~3 GeV ν_μ, near detector comparison
- $(v-c)/c = (5.1 \pm 2.9)\times10^{-5}$
- 2011: OPERA
- 730km distance, ~17 GeV ν_μ, proton – BCT comparison

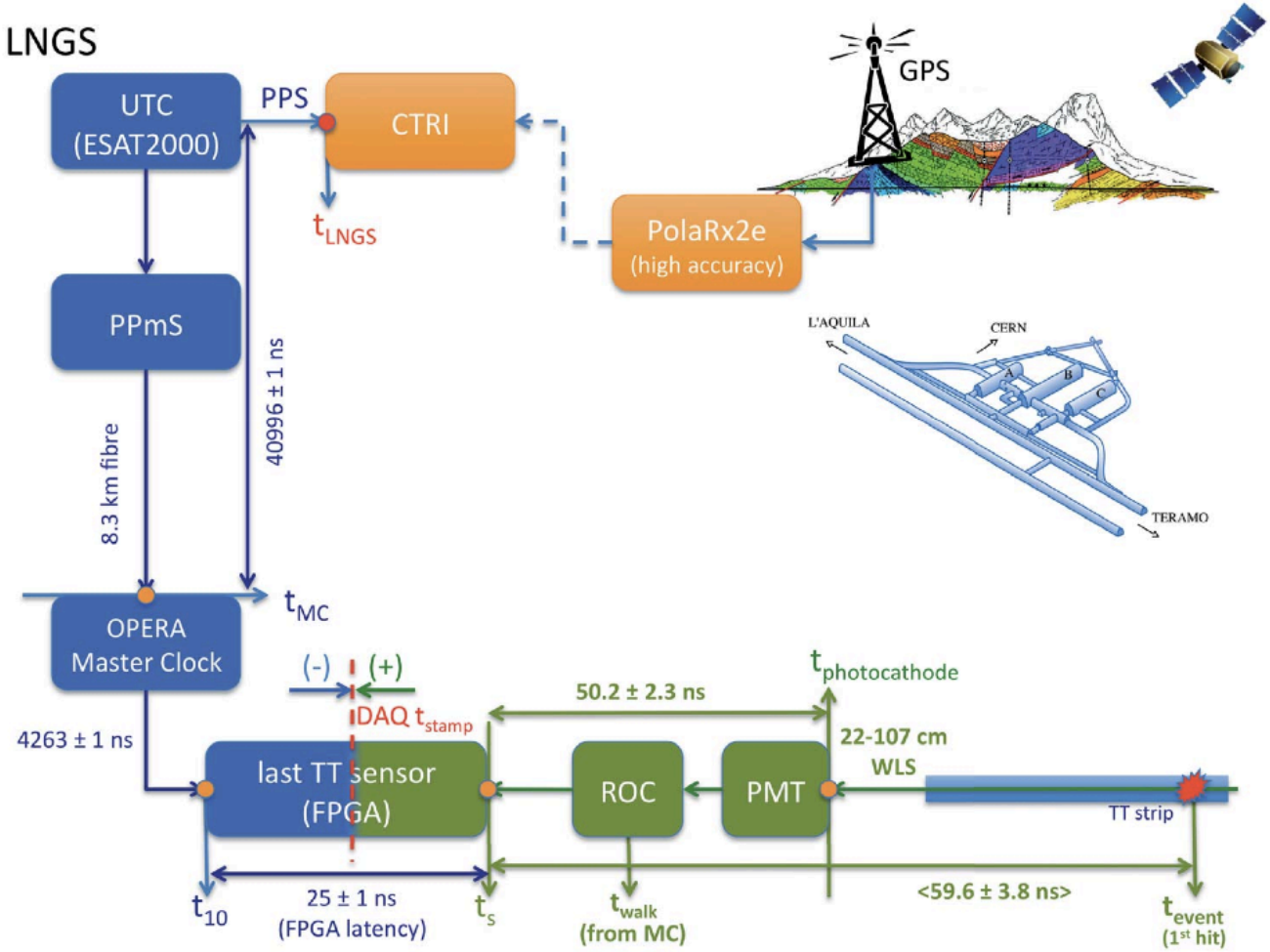
Time link at CERN



CERN production timestamp creation t_A

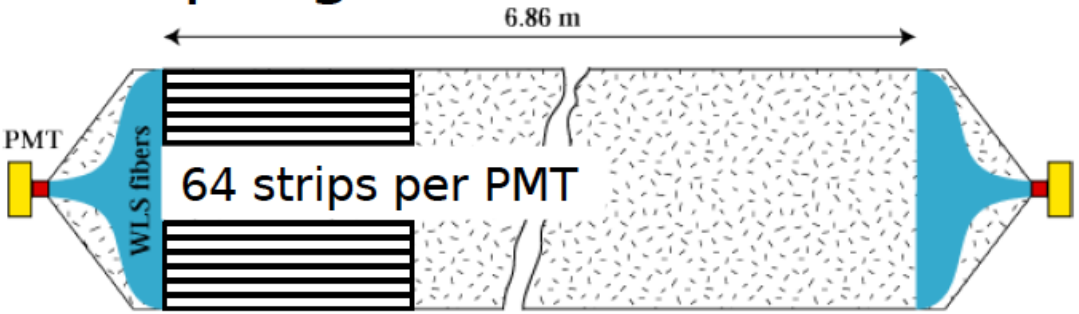


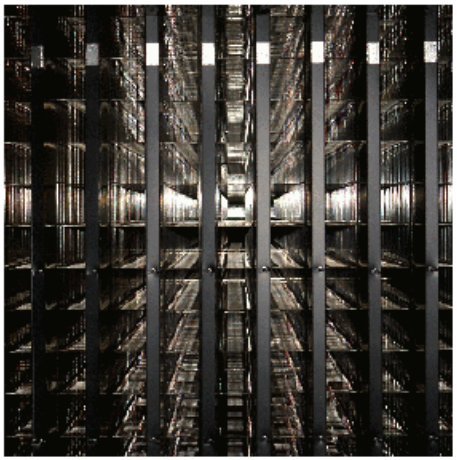
Time link at LNGS

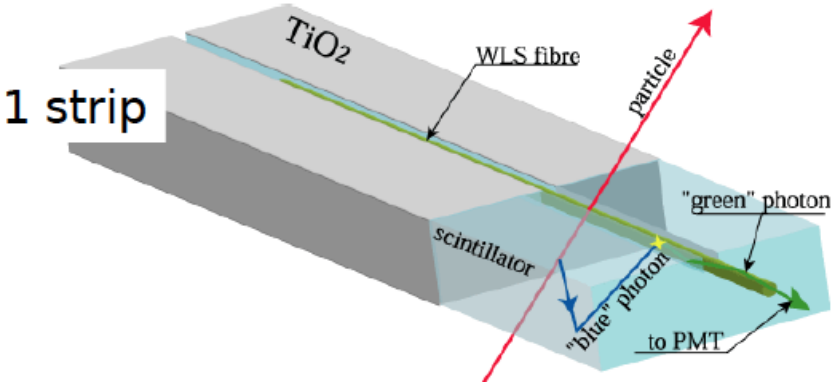


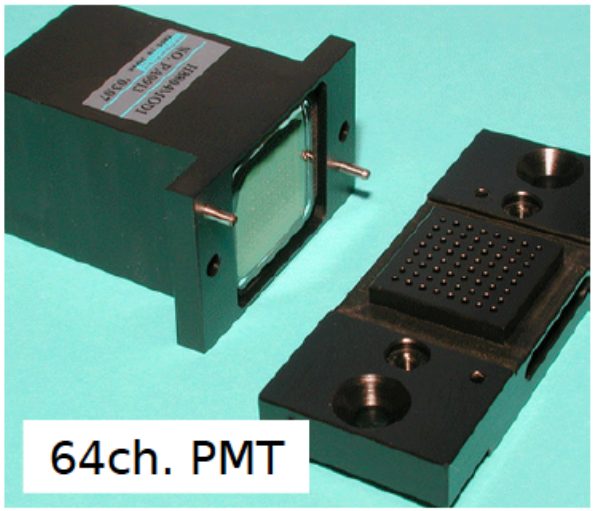
OPERA detection time t_B (LNGS)

- use plastic scintillators only
- first hit in target trackers is the stop signal

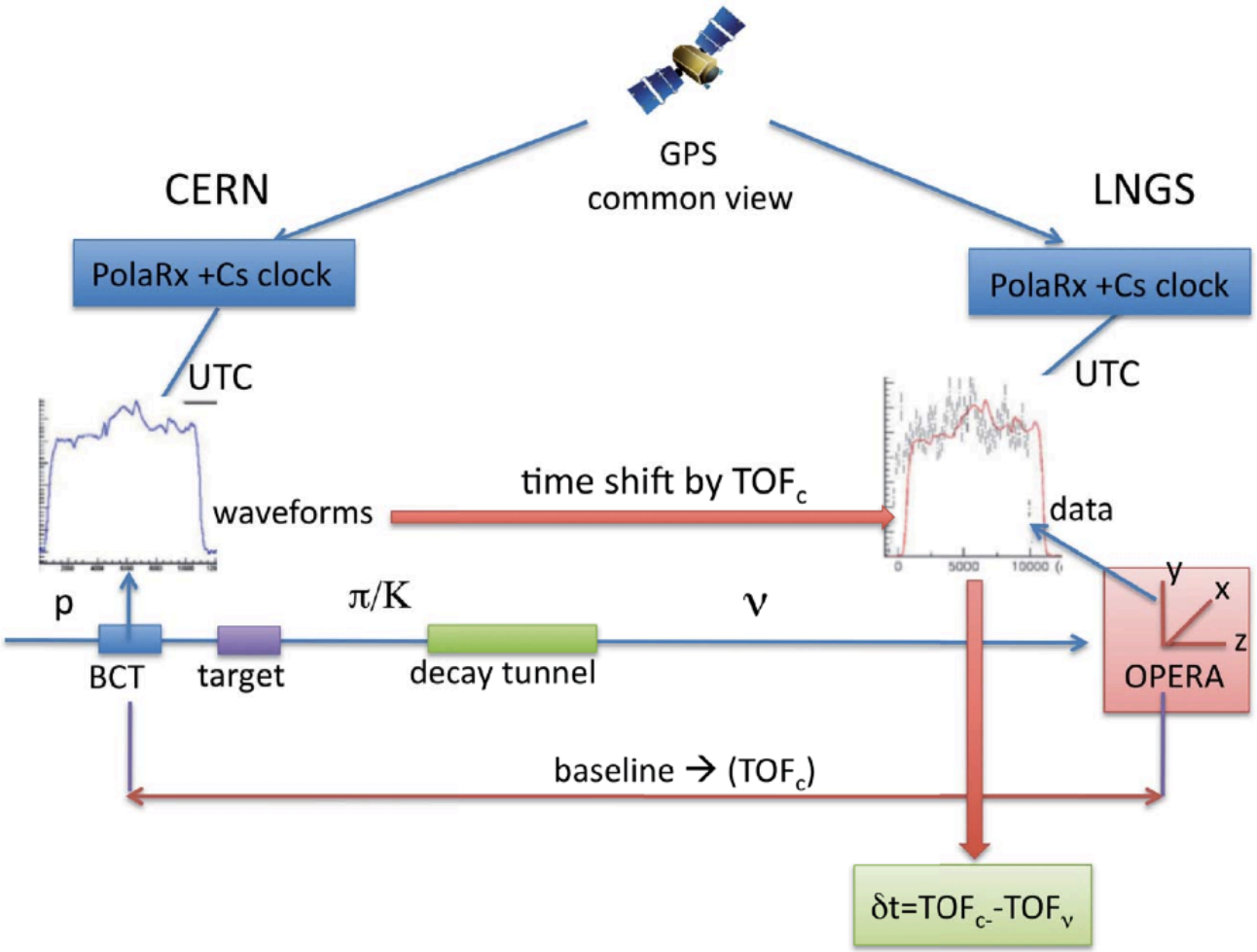








What do we measure

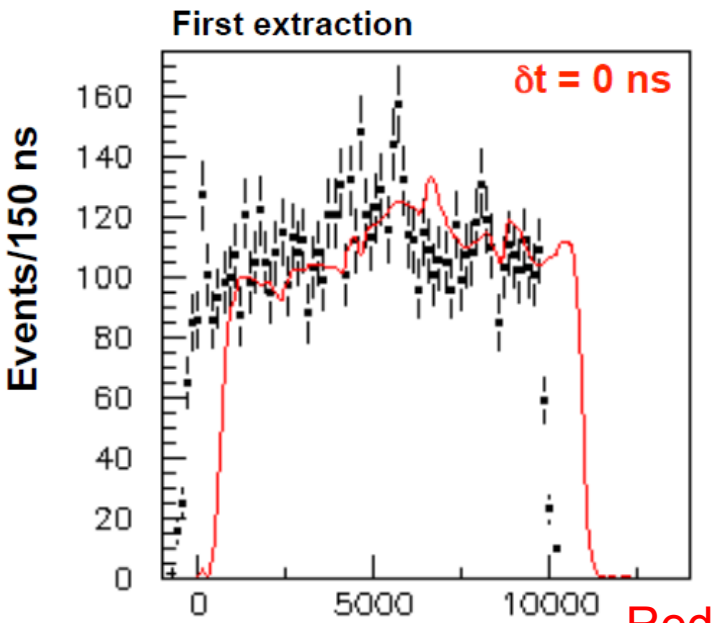


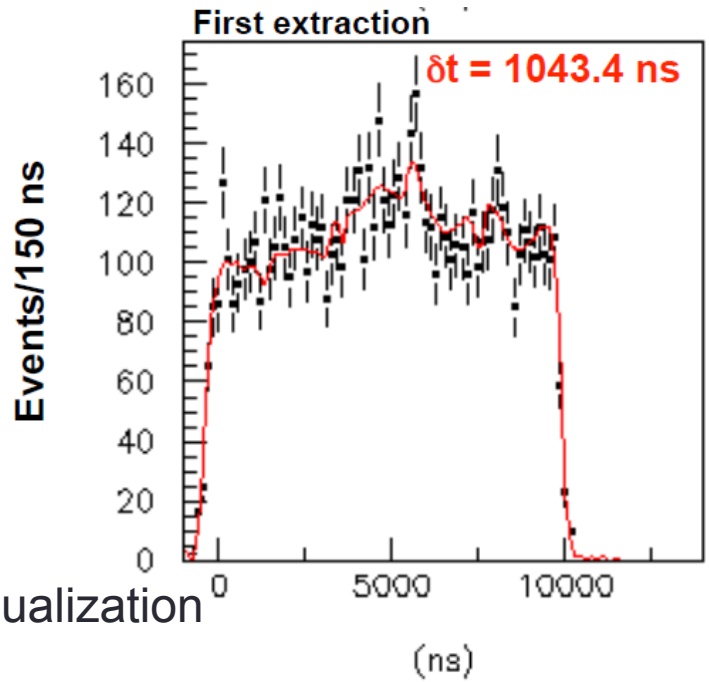
Statistical anlysis

- Build a likelihood from the sum of the waveforms
  - All waveforms/ only waveform of events which were selected

$$L_k(\delta t_k) = \prod_j w_k(t_j + \delta t_k) \quad k = 1,2 \text{ extractions}$$

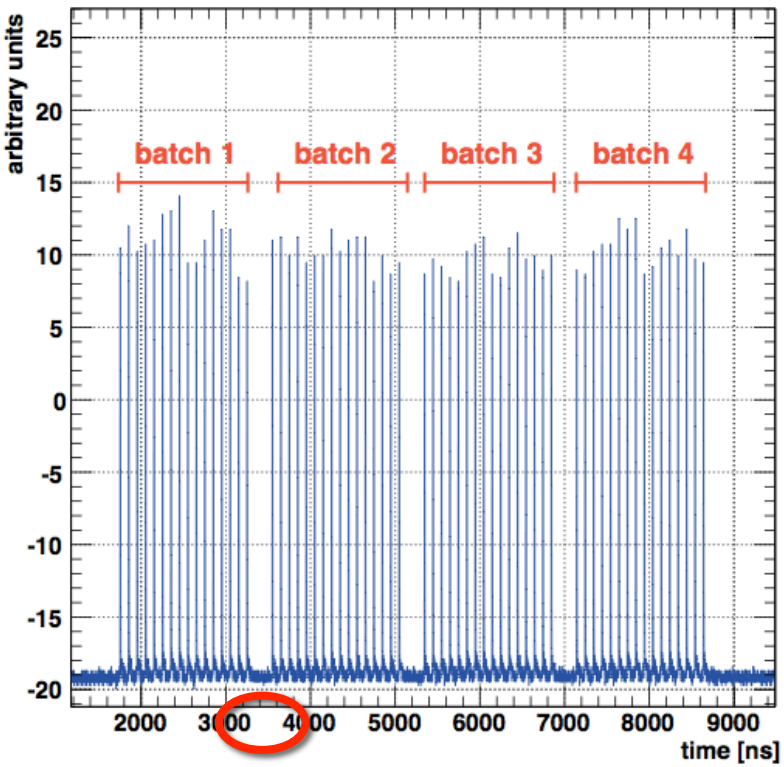
- measurement of delay dt for Opera

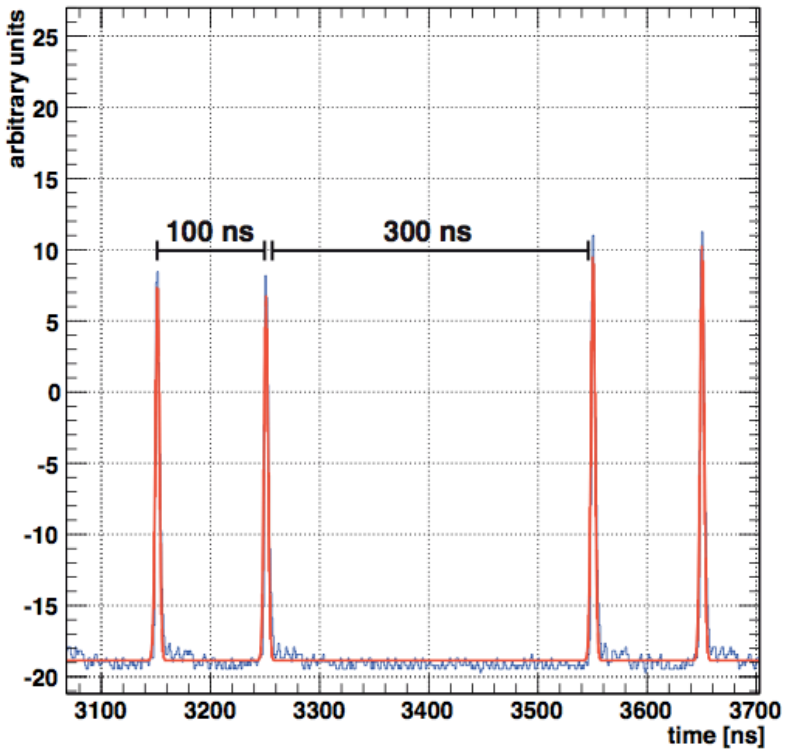




Red curve only visualization

Bunched beam delivery





So the result is…

The final result of the measurement is then:

$$\delta t = TOF_c - TOF_\nu = (6.5 \pm 7.4 \ (stat.) \ ^{+8.3}_{-8.0} \ (sys.)) \ ns$$

The relative difference of the muon neutrino velocity with respect to the speed of light is:

$$(v - c)/c = \delta t/(TOF'_c - \delta t) = (2.7 \pm 3.1 \ (stat.) \ ^{+3.4}_{-3.3} \ (sys.)) \times 10^{-6}$$

Summary

- Opera is a 1.2kton emulsion hybrid target (with a 1kt magnet)
- Data collection from 2008-2012, analysis still ongoing
  - Charm results coming soon
- Emulsion scanning is though business
  - A lot of information in the emulsion, and a lot of area to scan
- We learned a lot about neutrinos
  - Electron, tau apperance and neutrino induced charm events
- We learned a lot about GPS – and theoretical ideas

- Do we still have time?!
  - Future ideas from WNTE workshop summary

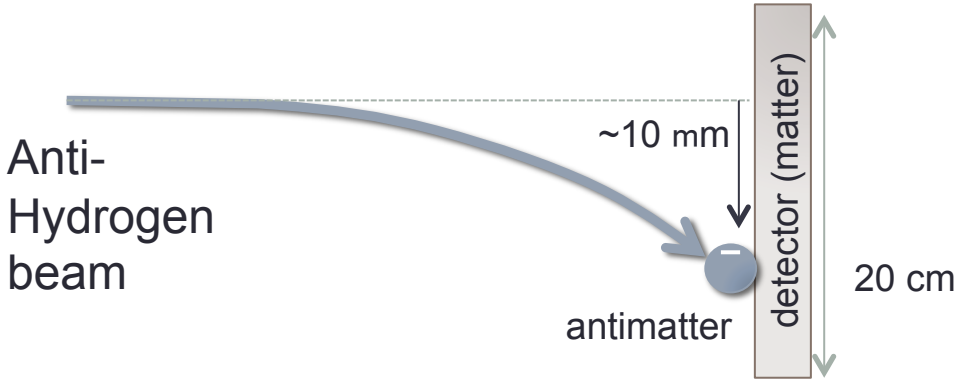
Thanks ☺

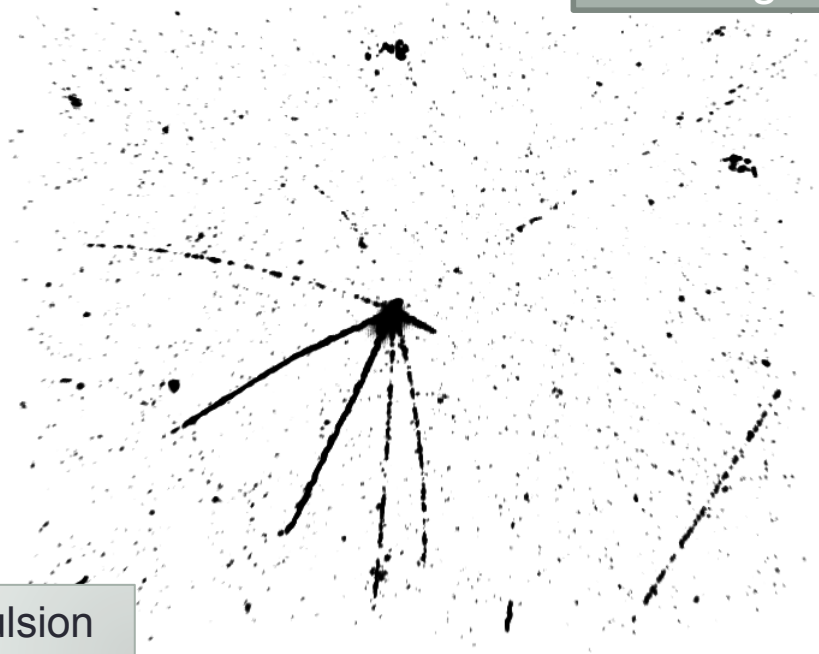
- Q/A

A. Ariga

AEgIS experiment

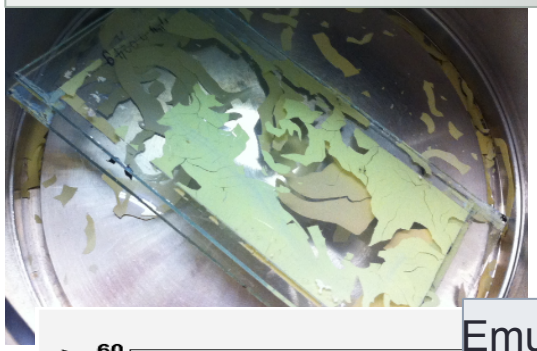
Meas. of gravity on antimatter



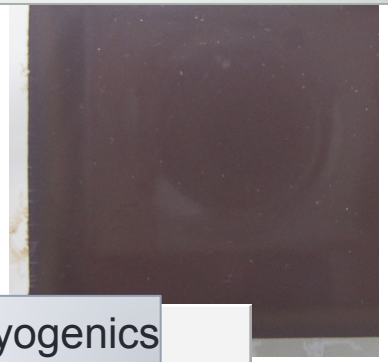


Antiproton beam at CERN
2012 run

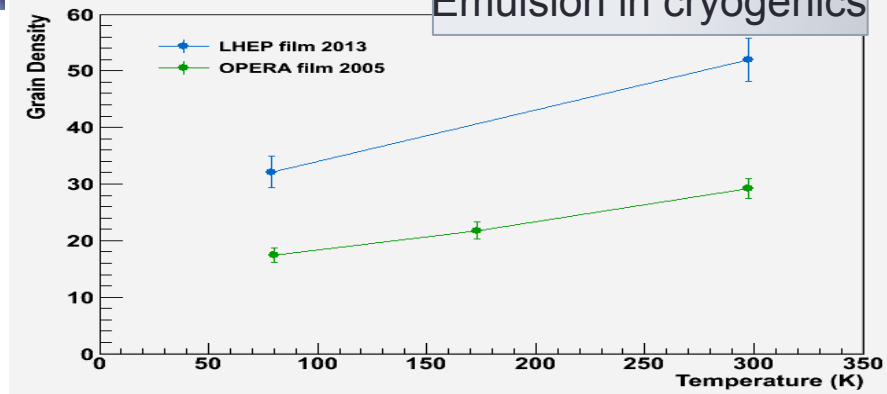
Normal emulsion in vacuum

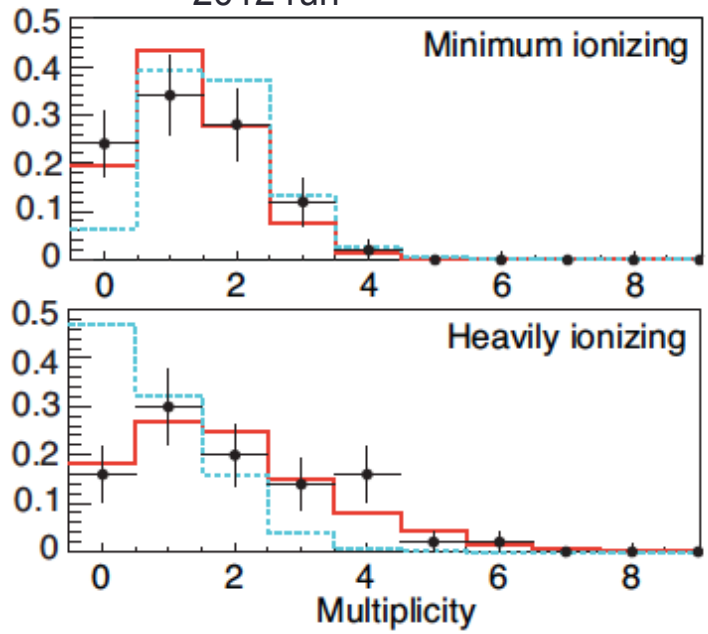


Glycerin added emulsion



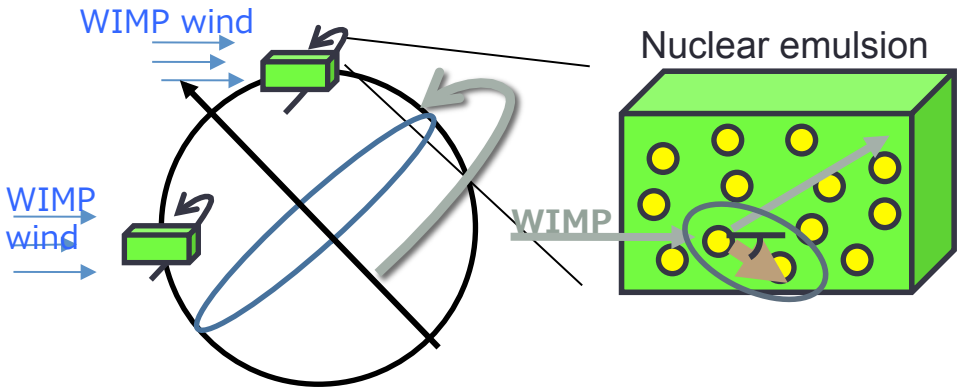
Emulsion in cryogenics



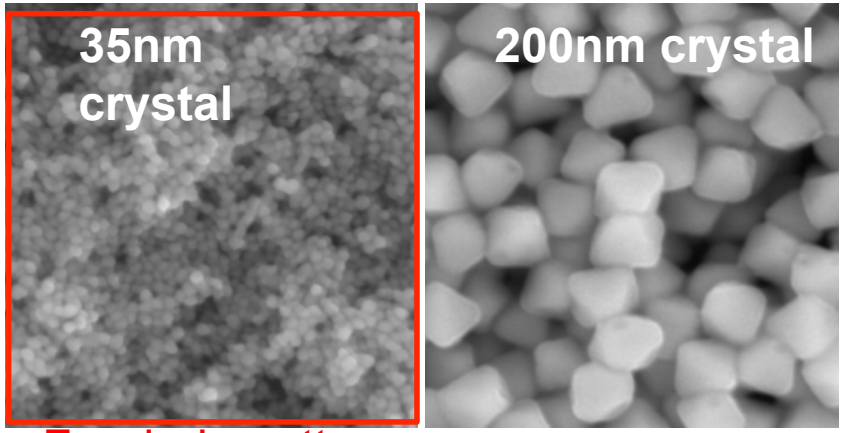


T. Asada

Directional Dark Matter Search With Ultra Fine Grain Nuclear Emulsion

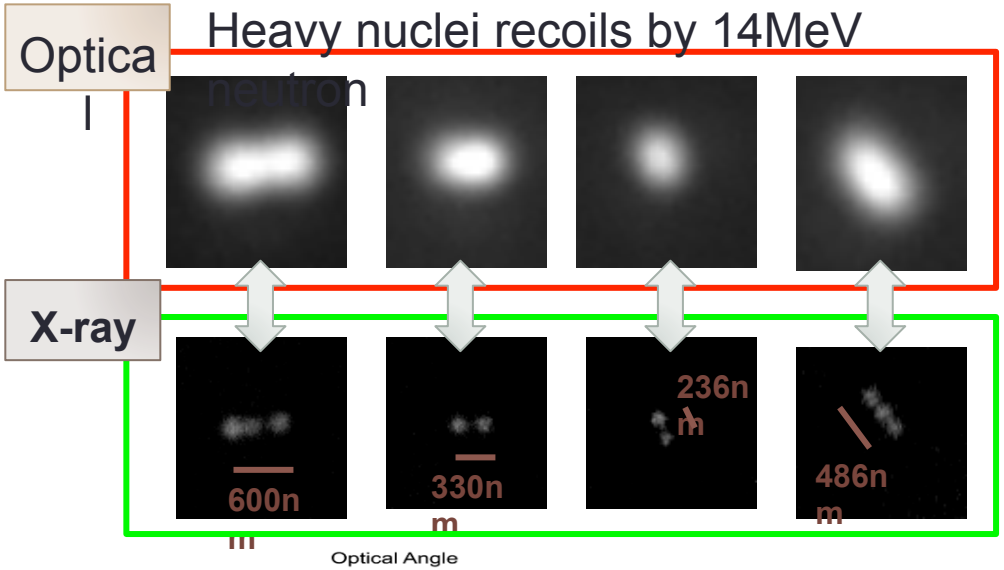


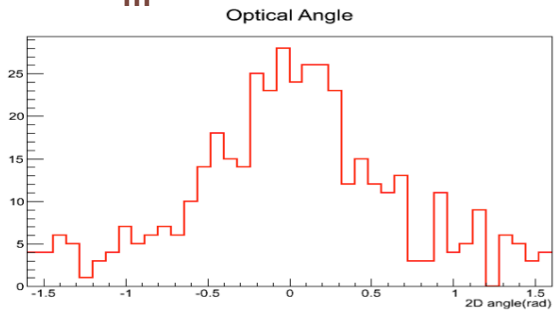
Fine grain crystals produced in Nagoya University

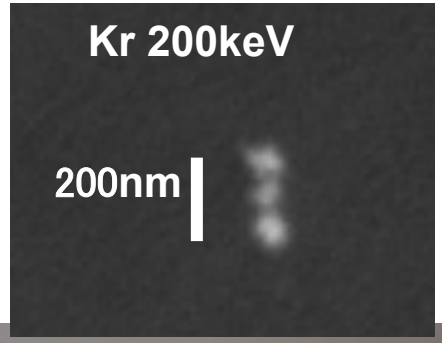


For dark matter

500nm

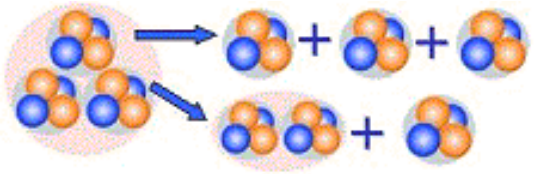


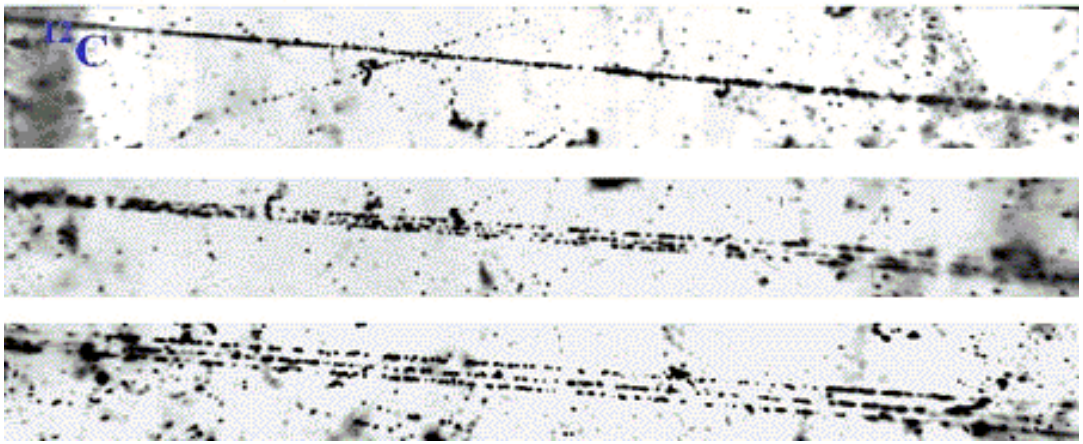




Study of light nuclei cluster structure with nuclear track emulsion (Becquerel)

^{12}C 3 , 3.65 A GeV



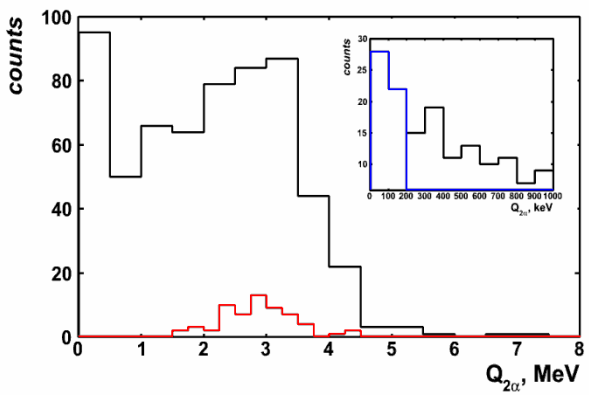


^{9}Be→2α
(1.2 A GeV)

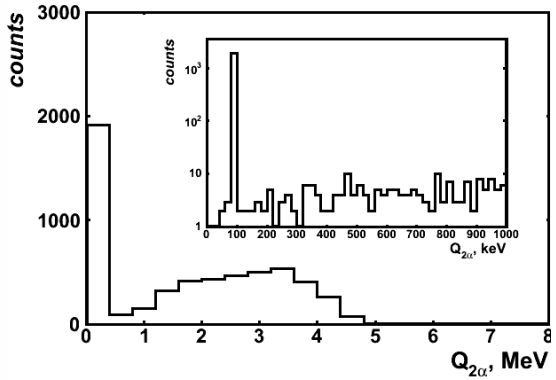
^{10}C→2α+2p
(1.2 A GeV)

^{7}Be→α+^{3}He (2^{3}He)
^{7}Be→^{6}Be→α+2p
(1.2 A GeV)

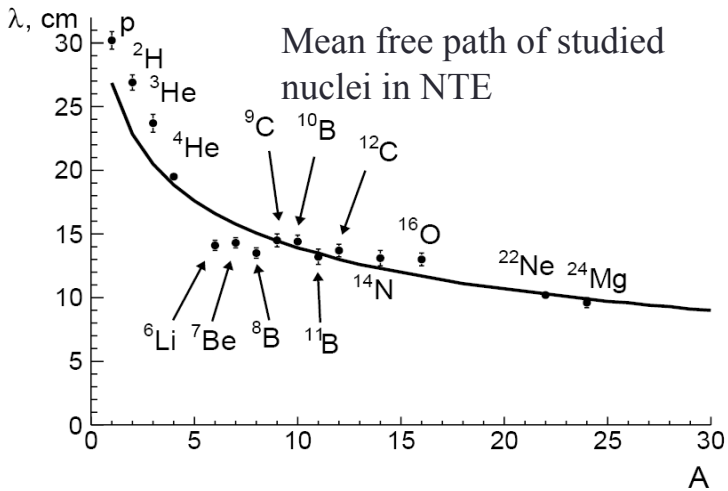
Some data/model (CHIPS) observed.



experiment



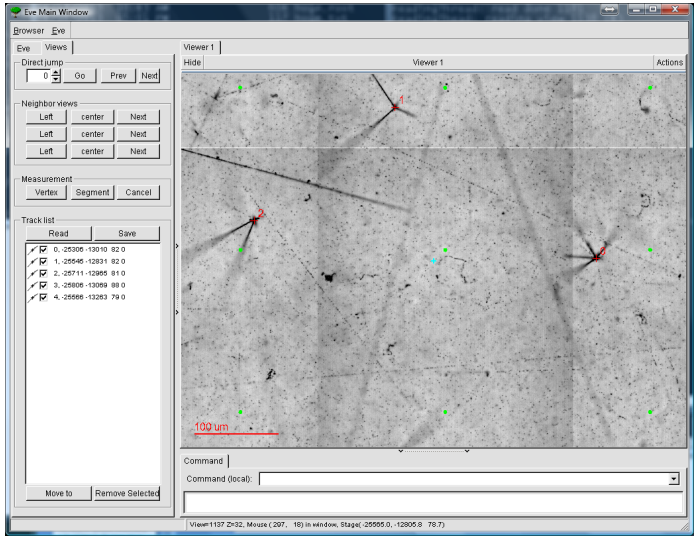
model

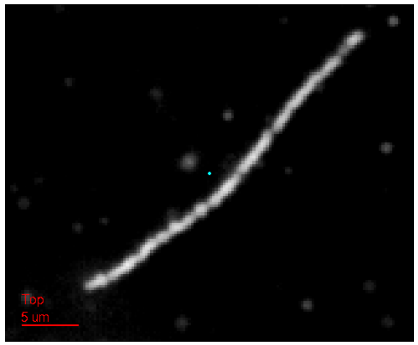


ATMic: Fast 4p tracking based on GPUs and its framework

New framework for general purpose emulsion scanning.
- from data taking to analysis
High performance and flexibility.

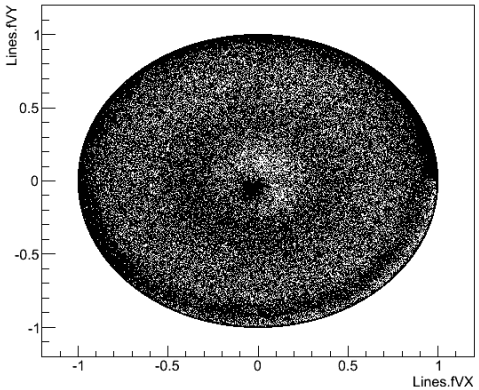
Image display





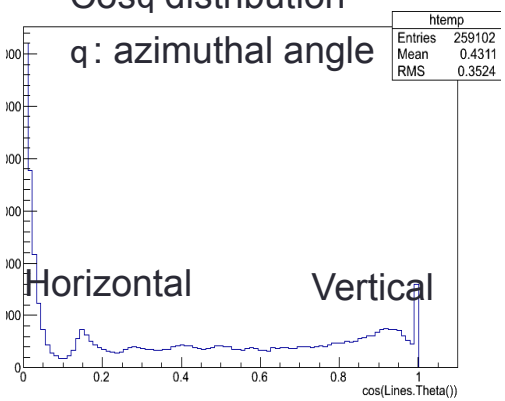
Tracking using GPU

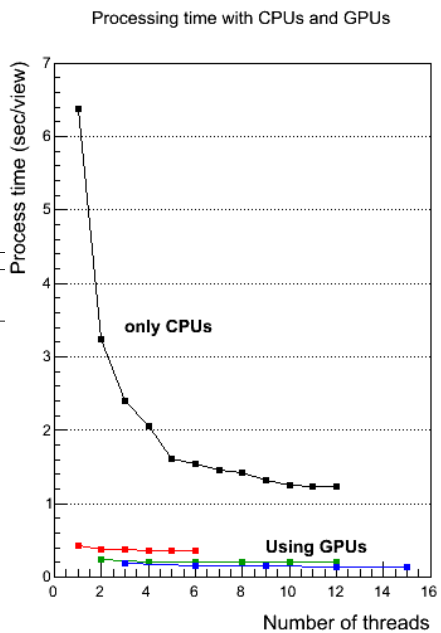
Angle as 3D unit vector, VX-VY

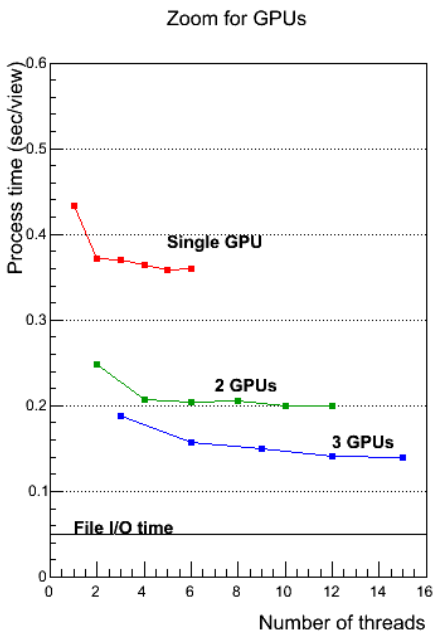


Cosq distribution

q : azimuthal angle





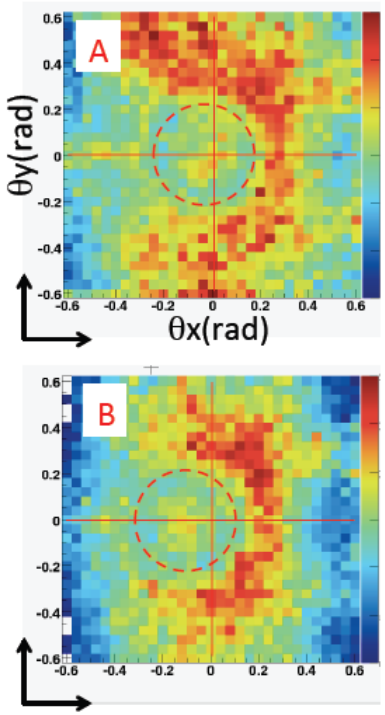


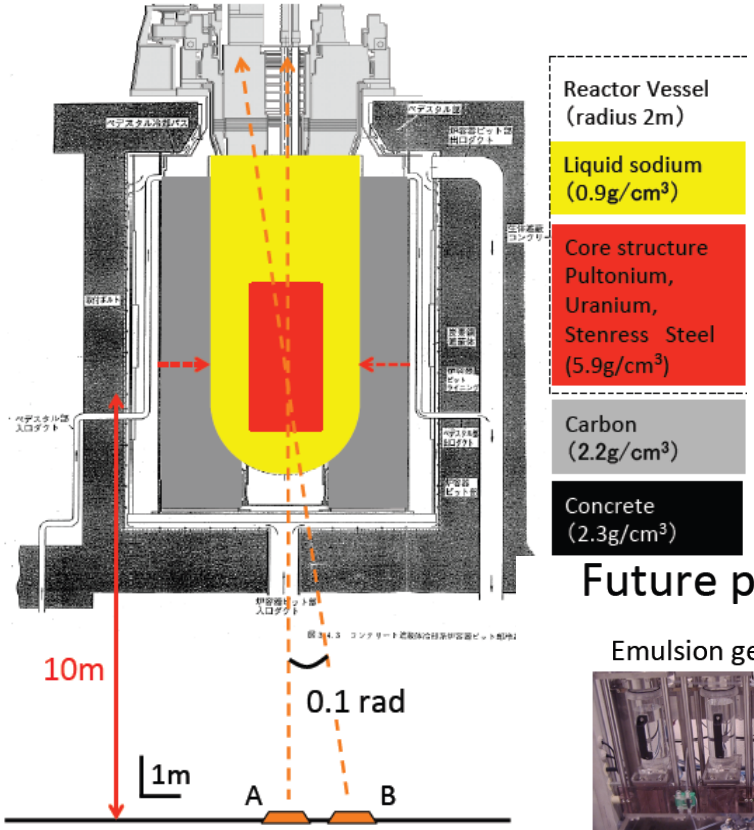
Development of muon radiography system

Application for nuclear power plant

Test experiment : Using experimental fast reactor Joyo

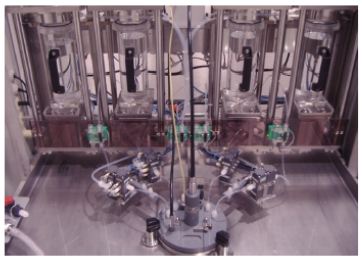
Results





Future prospects of production speed

Emulsion gel production

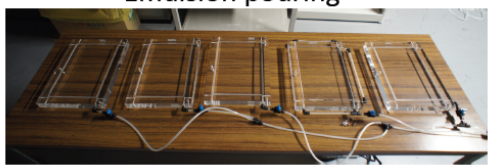


Threefold scale emulsion gel production machine

- design was fixed
- operation test will be started December, 2013

Speed ~ 1m²/batch

Emulsion pouring



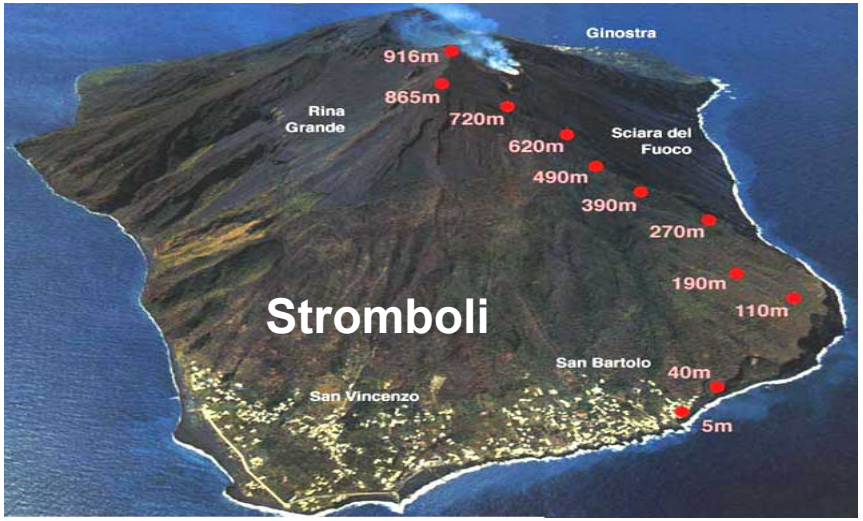
Automated emulsion pouring machine

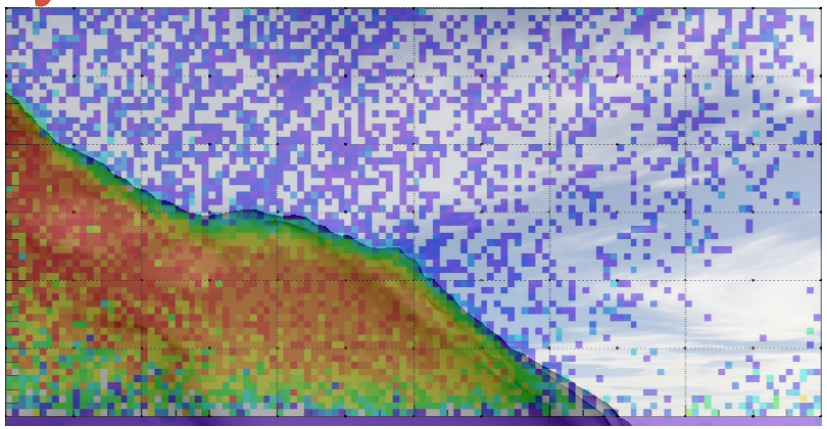
- under designing

Speed ~ 10m²/day

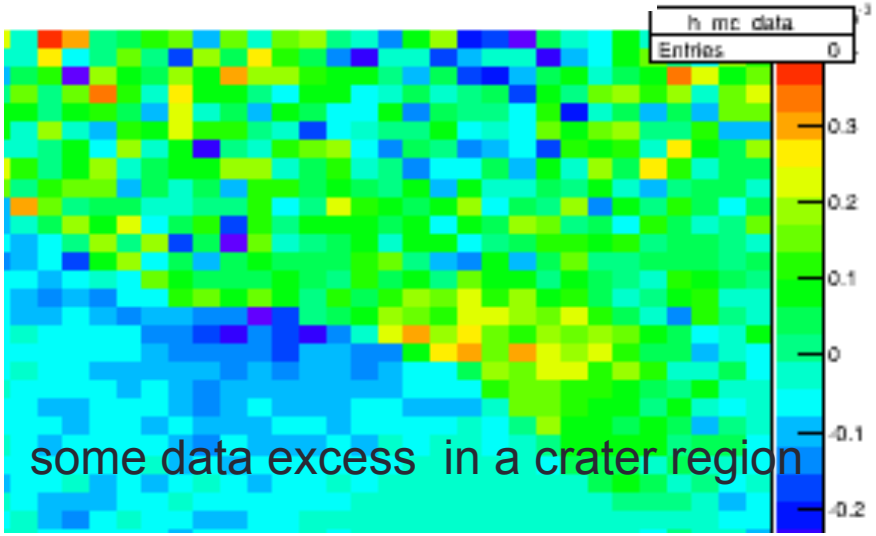
V. Tioukov

Muon radiography of volcanoes with nuclear emulsions in Italy





Data subtracted from MC

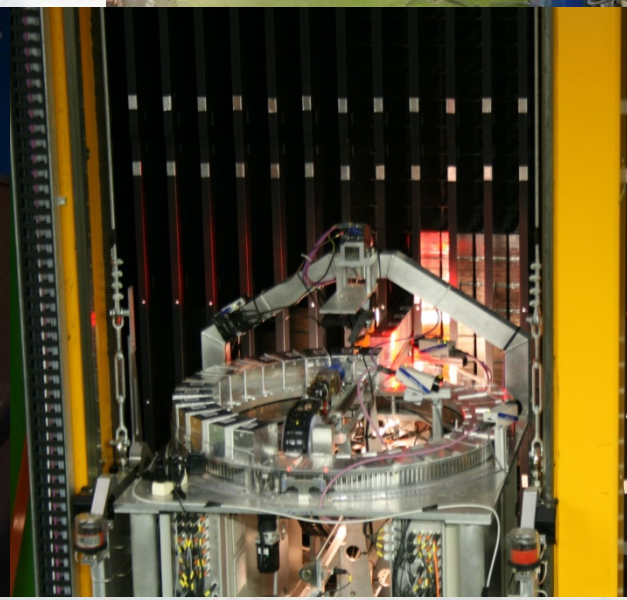


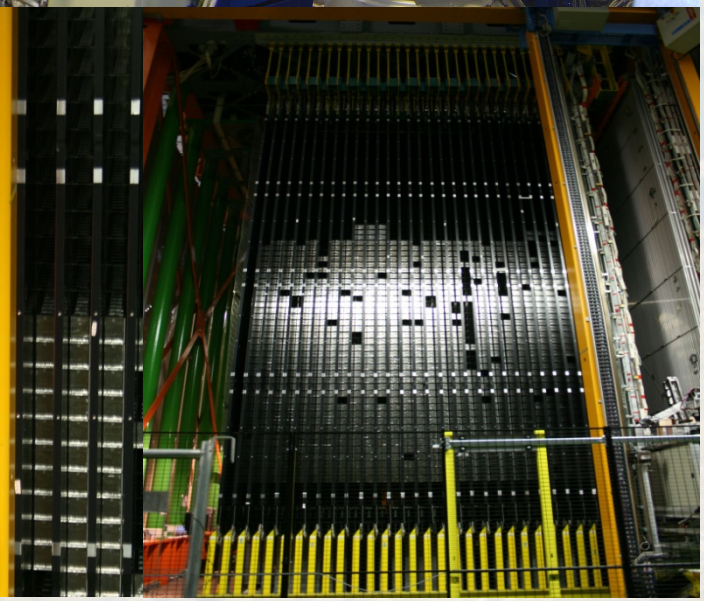
Backup slides

Brick production and handling

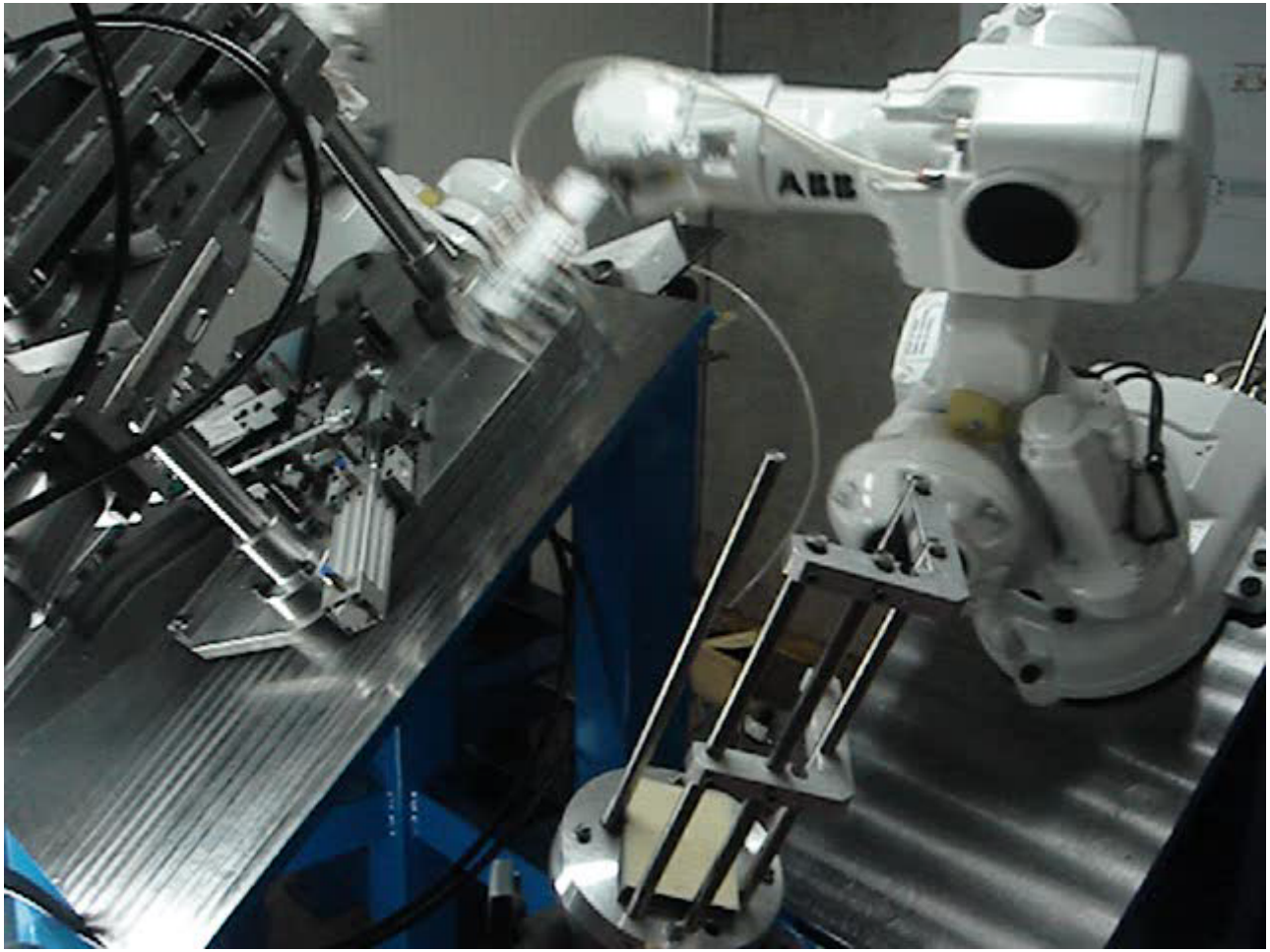
- Bricks are produced by Brick Assembling Mashine (BAM) and handled with the Brick Manipulating System (BMS)

- Nearly all bricks are inserted, some missing due to burned down production hall of JLGoslar

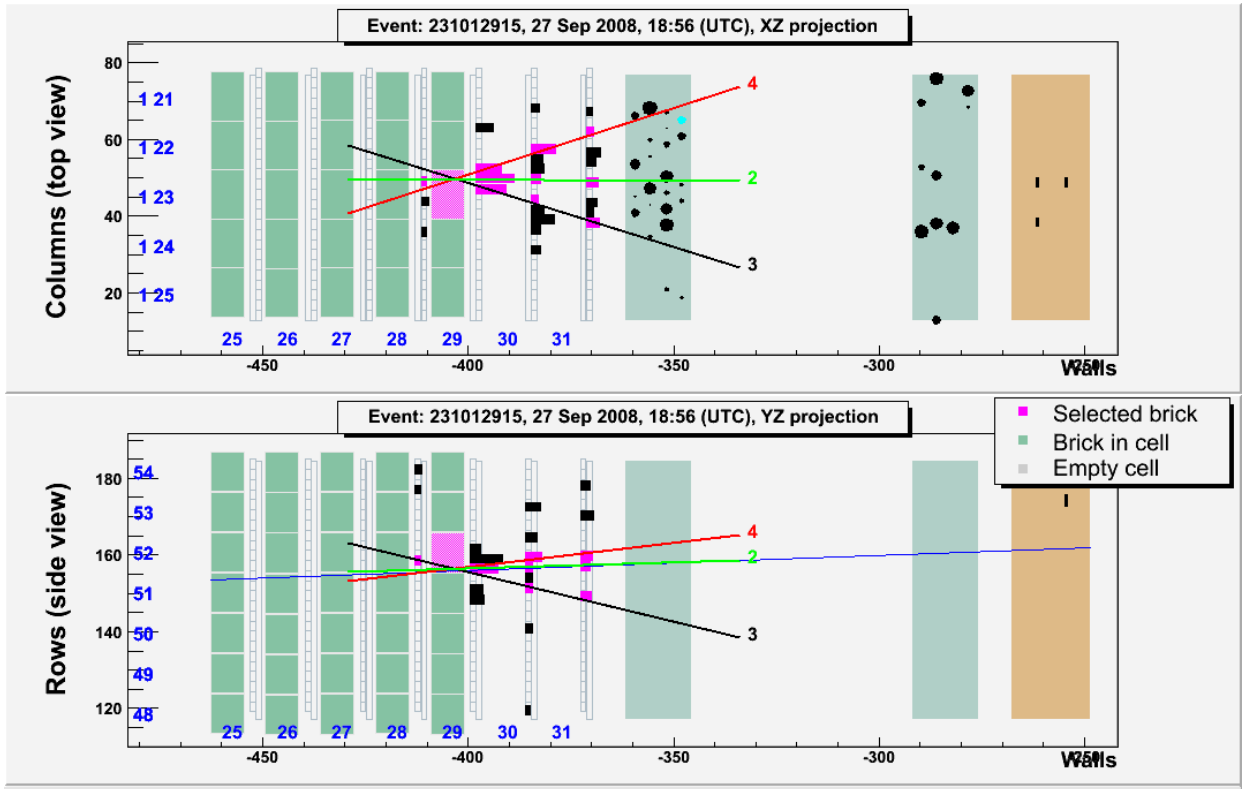




Brick building



Brick 72853 – Charm el det display



Brick finding information: Super module 1

	BrickId	Wall	Side	Column	Row	Prob	CS x	CS y
brick 1:	1072853	29	1	23	52	0.43	-1.0	-1.0
brick 2:	1071956	29	1	23	51	0.32	-1.0	-1.0
brick 3:	1019729	28	1	23	51	0.13	-1.0	-1.0

Muon track parameters: Mu-
Momentum: 17.181 GeV/c
Angle XZ (rad): N/A
Angle YZ (rad): 0.040+/-0.009