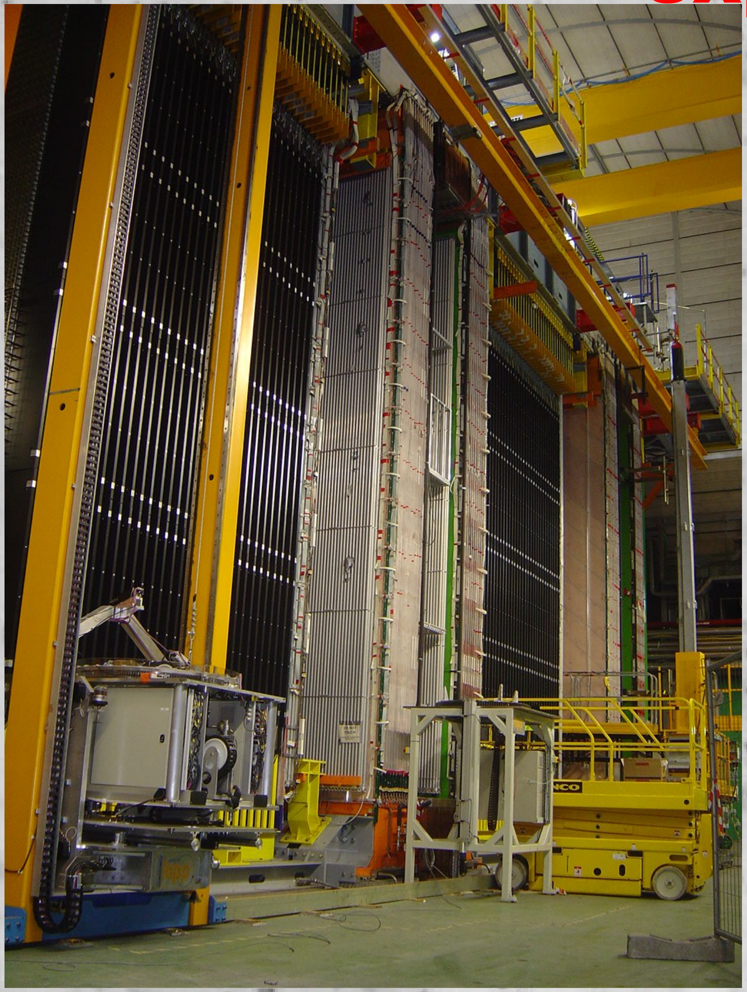
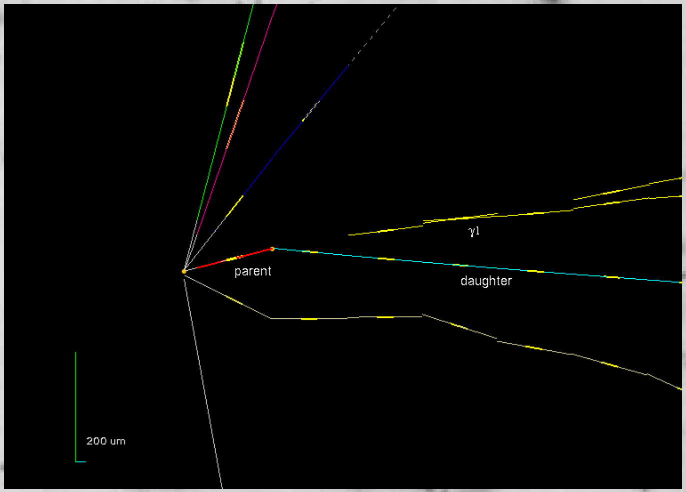
"Recent results from the OPERA experiment"





Yuri Gornushkin (JINR)

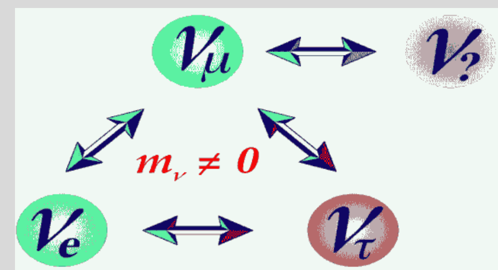
May,24,2013

Colloquium Prague v13

Bruno Pontecorvo (1913-1993)

PMNS

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



A father of the experimental neutrino physics

.

Created several brilliant ideas in neutrino physics
and a possibility of neutrino oscillations among them.

In 1998 the neutrino oscillations phenomena was confirmed by SK experiment.
But the mechanism of the oscillations was not obvious.

15 years ago our understanding of neutrino oscillations was rather different

Confusing experimental results
On atmospheric and solar neutrinos

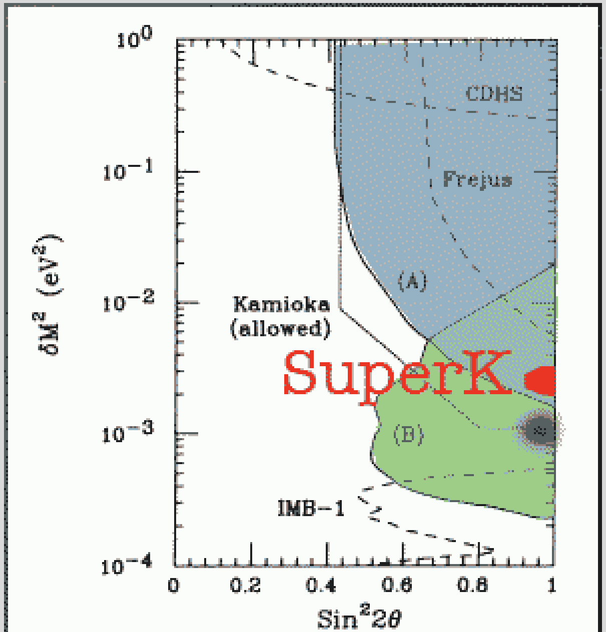
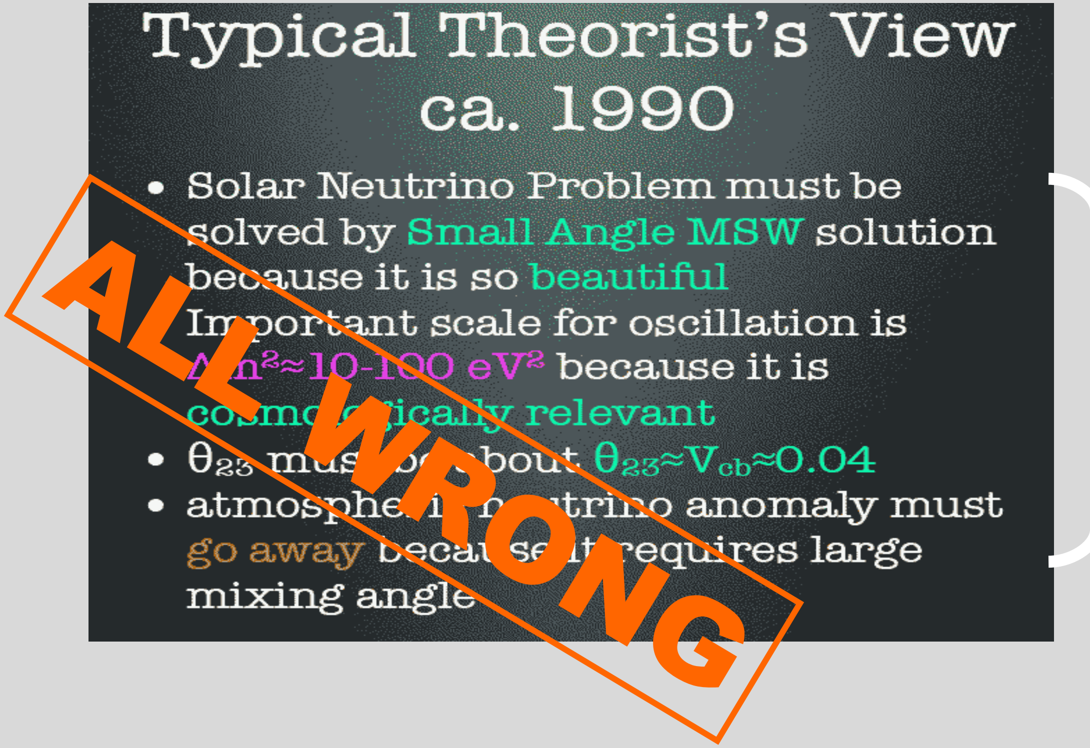


FIG. 2. 90% C.L. limits on ν_μ to ν_τ oscillations from rate (A) and stopping fraction (B). Dashed curves show limits from IMB-1 [14], Frejus [3], and CERN-Dortmund-Heidelberg-Saclay (CDHS) [15]. Dotted curve shows the allowed region from Kamiokande [16]. The Frejus limit is 95% C.L.; others are 90%.

+ LSND …

Strong theortical arguments:

- J. Ellis et al. (CERN-TH-6569-92)
- G. Altarelli et al. (Neutrino Telescope)



OPERA proposal in 1998 :

- **First direct detection of $\nu_\mu \rightarrow \nu_\tau$ neutrino oscillations in appearance mode** following the Super-Kamiokande discovery of oscillations with atmospheric neutrinos and the confirmation obtained with solar neutrinos and accelerator beams.

  Important, missing tile in the oscillation picture.

- Study of subdominant oscillation mode $\nu_\mu \rightarrow \nu_e$

OPERA collaboration

Belgium
ULB Brussels

Croatia
IRB Zagreb

France
LAPP Annecy
IPNL Lyon
IPHC Strasbourg

Germany
Hamburg

Israel
Technion Haifa

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

Japan
Aichi edu.
Kobe
Nagoya
Toho
Utsunomiya

Korea
Jinju

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

Switzerland
Bern
ETH Zurich

Turkey
METU Ankara

（11 countries、30 Institutes、~160 researchers）

CNGS beam launched in 2006

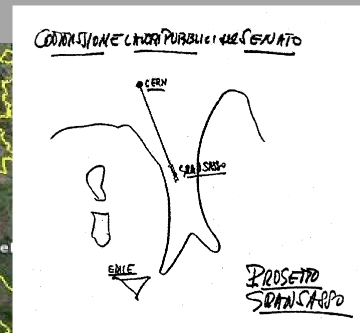


Figure 1.1.1: Sketch by A. Zichichi, 1979

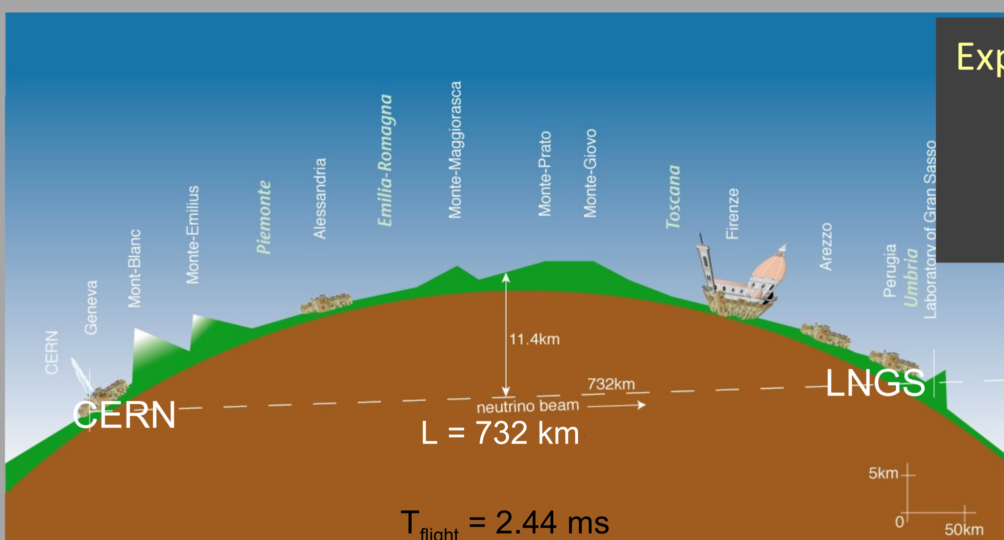
$< E_{\nu_\mu} >$	17 GeV
L	730 km
$(\bar{\nu}_e + \nu_e) / \nu_\mu$	0.87%
$\bar{\nu}_\mu / \nu_\mu$	4%
ν_τ prompt	

Expected produced interactions (22.5x10^{19}):

~25400 ν_μ CC + NC

~170 $\nu_e + \bar{\nu}_e$ CC

~125 ν_τ CC (Δm^2 = 2.5 x 10^{-3} eV^2)

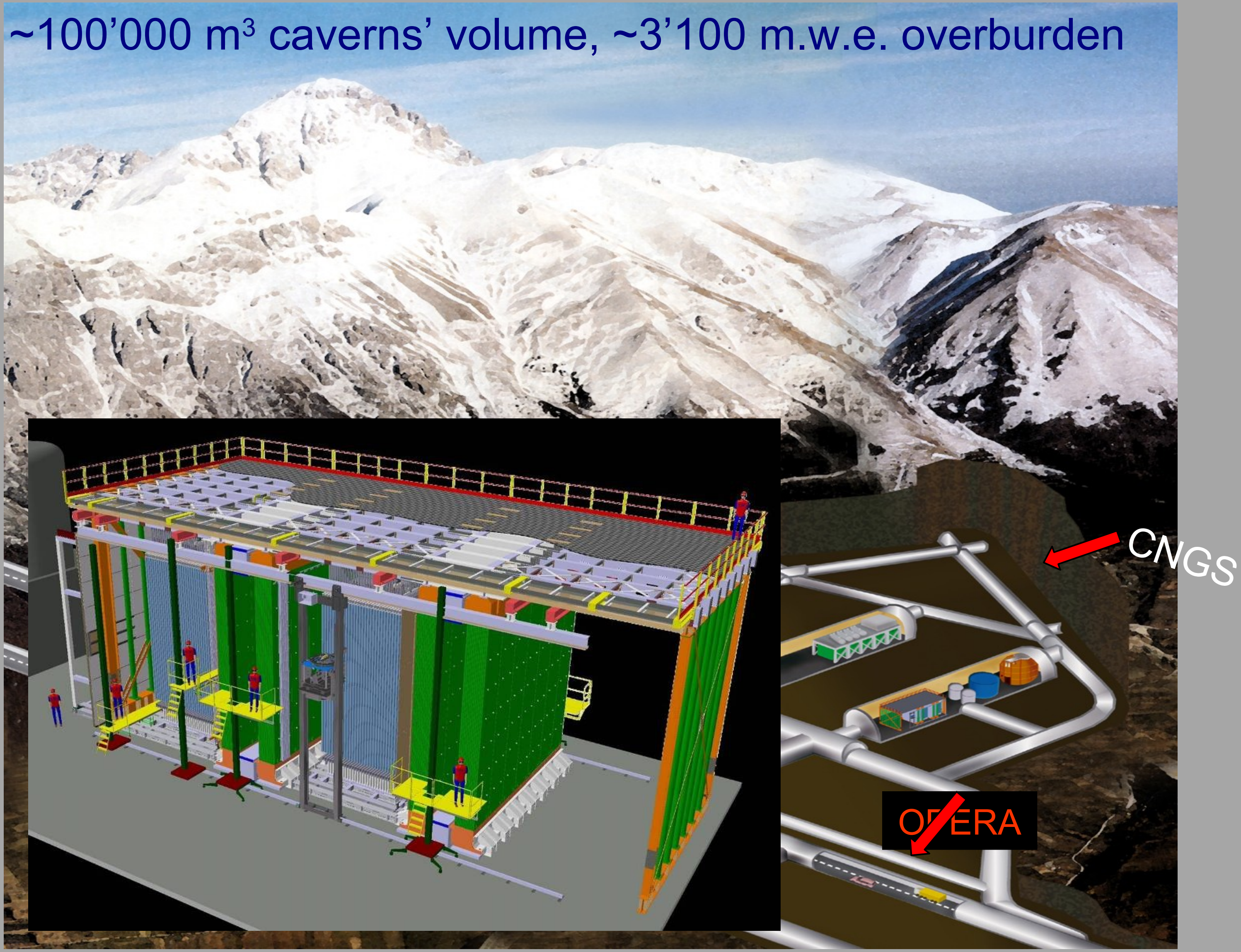


~10 tau decays are expected to be observed

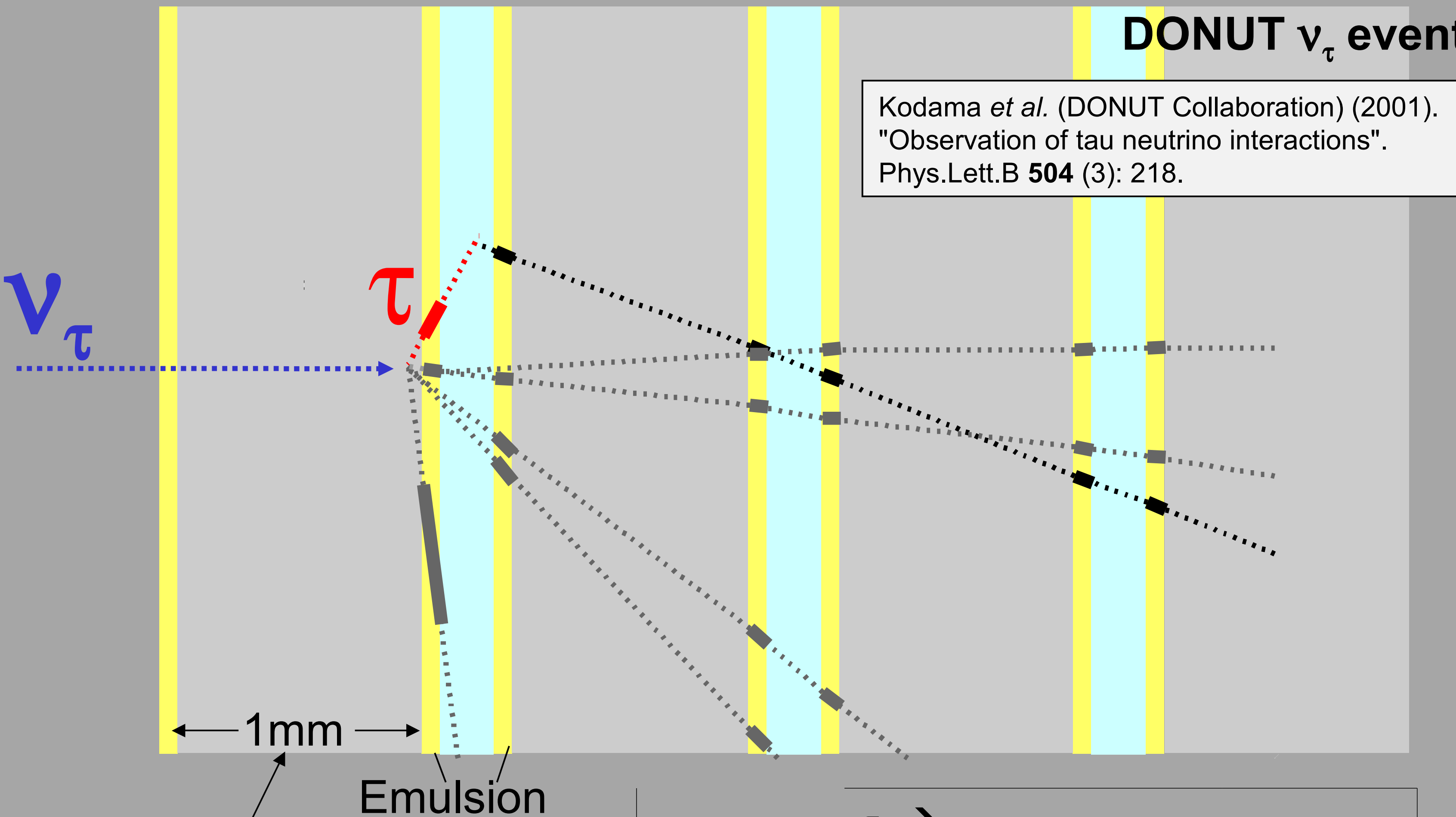
Less than 1 background after 5 years running

LNGS: the world largest underground physics laboratory:

~100’000 m^3 caverns’ volume, ~3’100 m.w.e. overburden



How to detect tau neutrino



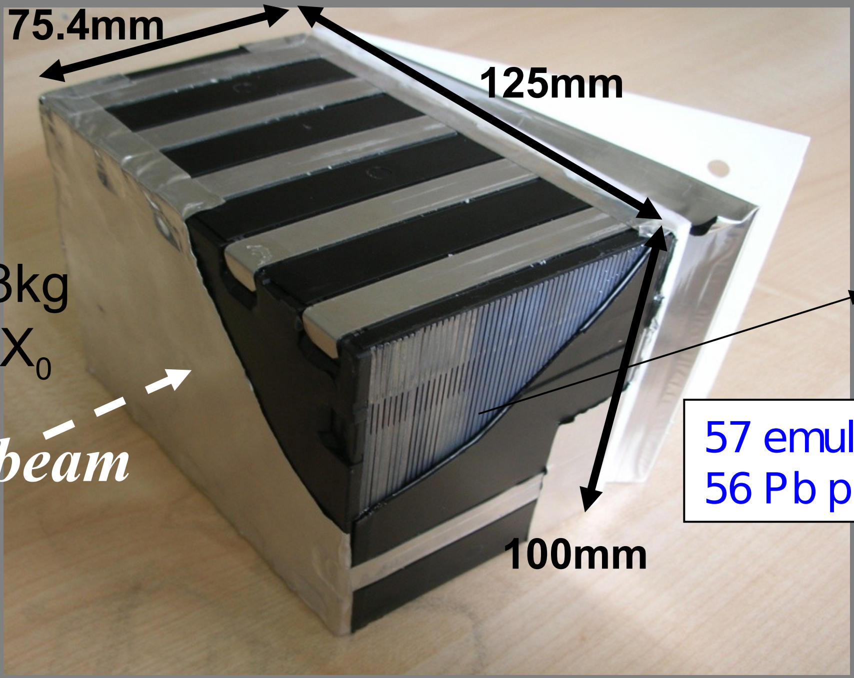
Kodama *et al.* (DONUT Collaboration) (2001). "Observation of tau neutrino interactions". Phys.Lett.B **504** (3): 218.

DONUT : Iron 1mm
OPERA : Lead 1mm

Kink	$\tau \rightarrow e$	18 %
	$\tau \rightarrow \mu$	17 %
	$\tau \rightarrow h$	49 %
Trident	$\tau \rightarrow 3h$ (h h h)	15 %

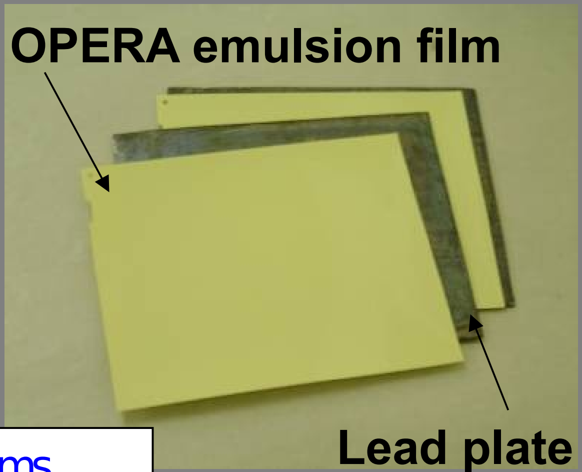
OPERA ECC brick – main detector

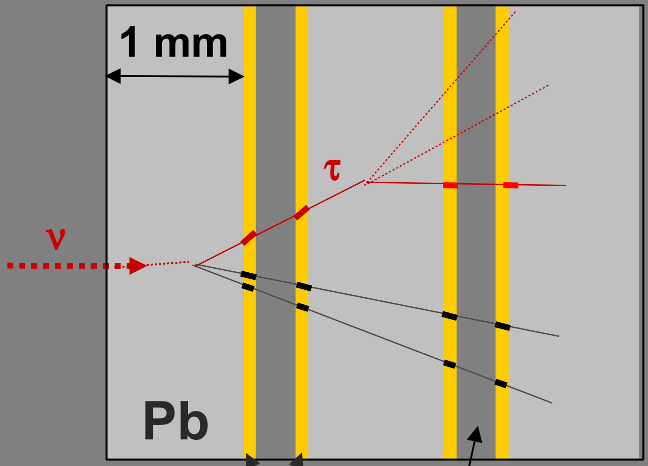
8.3kg
$10X_0$



57 emulsion films
56 Pb plates

“Emulsion Cloud Chamber”

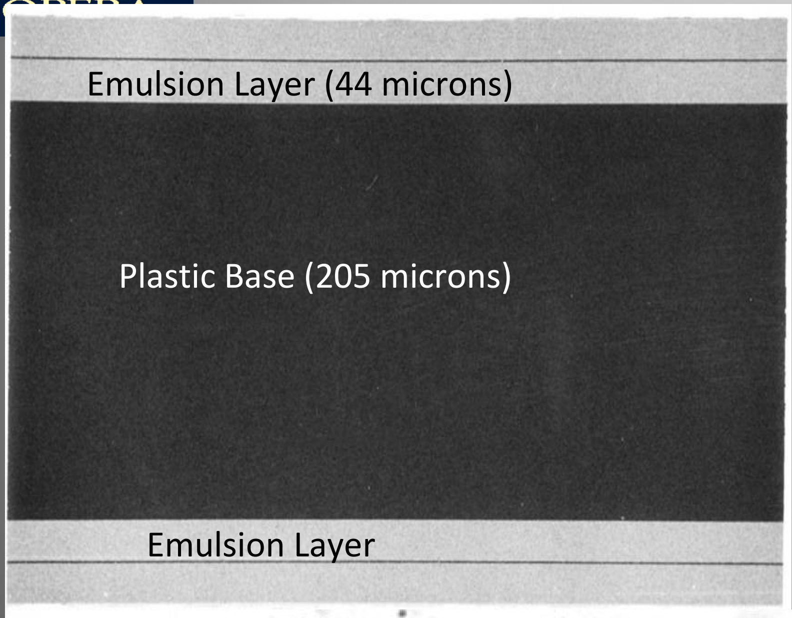


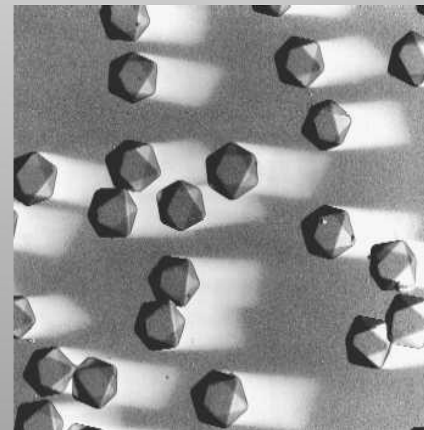


2 emulsion layers (44 μm thick) poured on a 200 μm plastic base

The OPERA target consists of 150’000 ECC bricks.
Total 105’000 m² of lead surface and 111’000 m² of film surface (~ 8.9 million films)
Total target mass: 1.25 kton

INDUSTRIAL EMULSION FILMS BY *FUJI FILM*





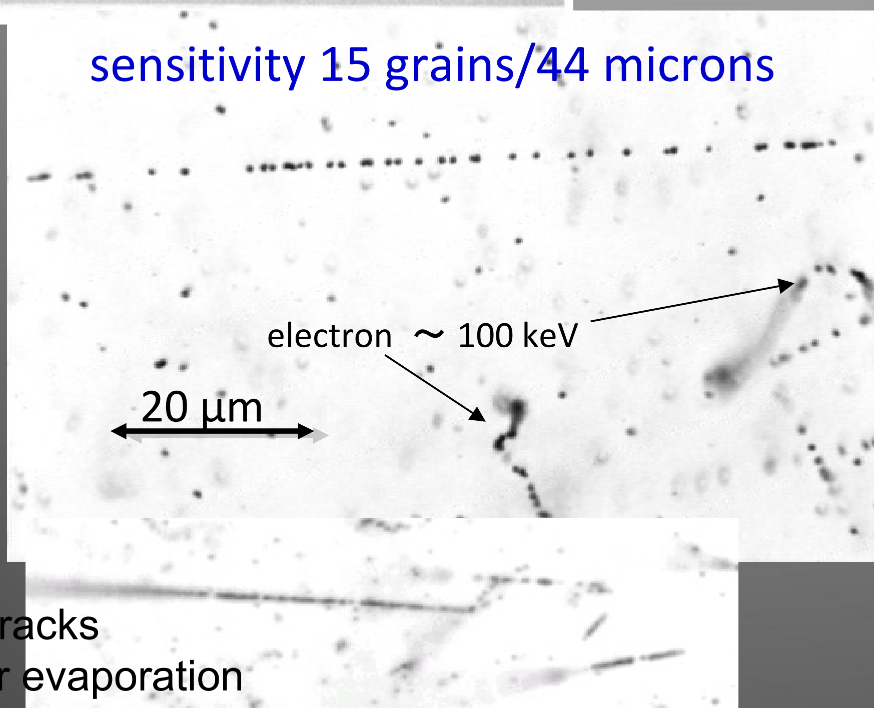
basic detector: AgBr crystal,

size = 0.2 micron

detection eff.= 0.16/crystal

10^{13} "detectors" per film

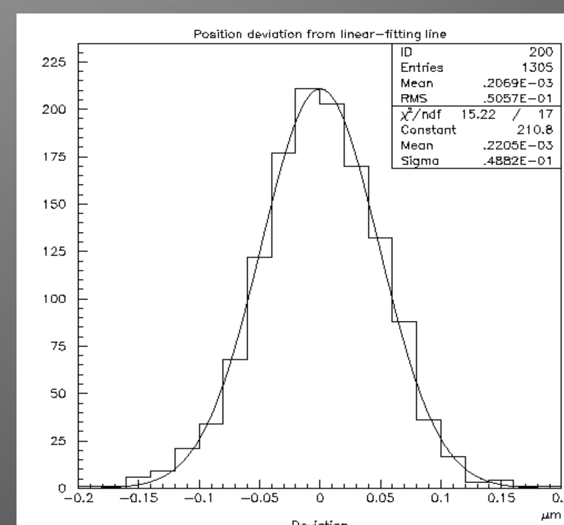
mip



high dE/dx tracks
from nuclear evaporation

intrinsic resolution: 50 nm

deviation from linear-fit line. (2D)



OPERA emulsion film as a data storage media

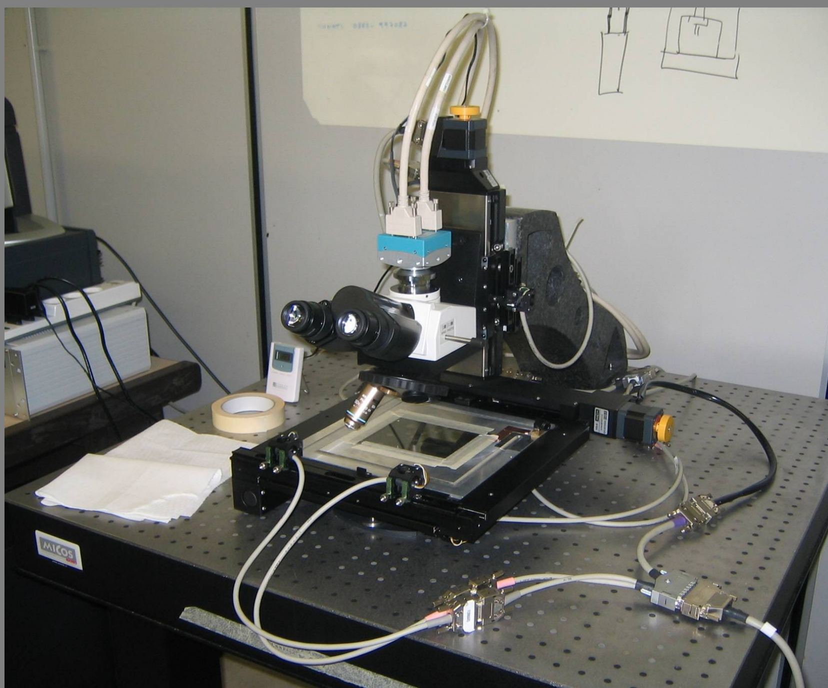
OPERA FILM, SUTS読み出しの情報量 (DVD Blu-ray Diskとの比較)

	大きさ	容量	読み出し
DVD	12cm Disk	8.5GB 2層	177Mbps 規格上の最高速度(11倍速)
Blu-ray Disc	12cm Disk	50GB 2層	216Mbps 規格上の最高速度(6倍速)
OPERA Film	12.5×10cm	556GB相当 (0.3um^2)/(100mm*125mm) *16layer * 両面	839Mbps SUTSで毎秒200視野

Emulsion scanning stations

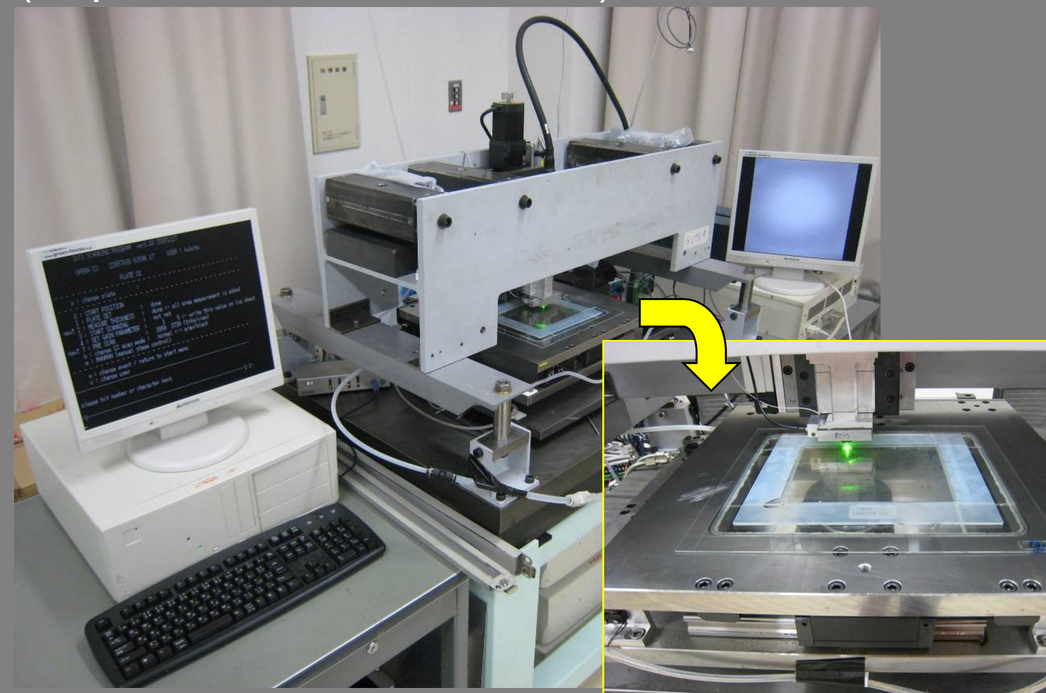
extract 3-D tracking information from emulsions

EU: ESS
(European Scanning System)



- **Scanning speed/system: 20cm²/h**
- **Customized commercial optics and mechanics**
- **Asynchronous DAQ**

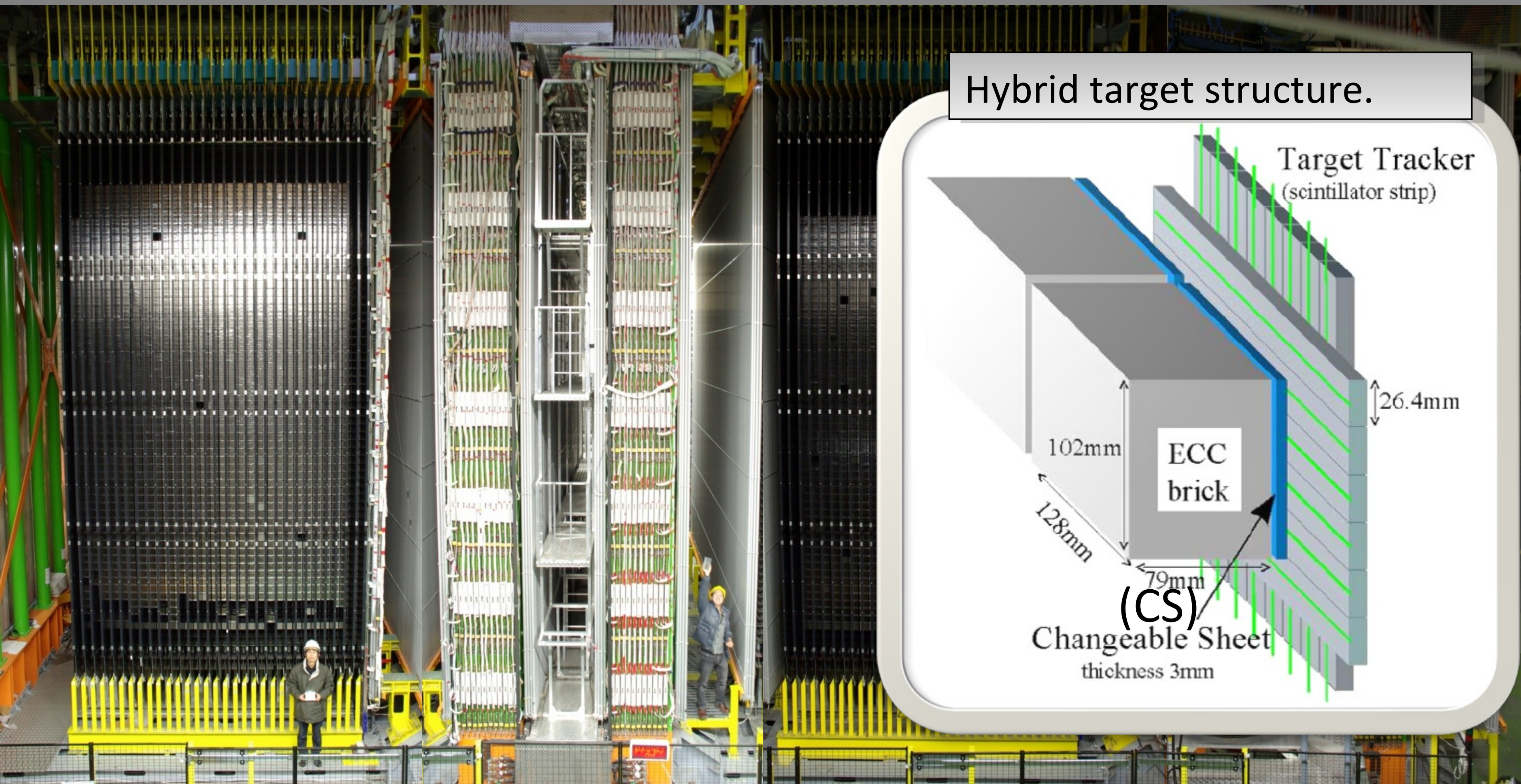
Japan: SUTS
(Super Ultra Track Selector)



- **Scanning speed/system: 75cm²/h**
- **High speed CCD camera (3 kHz), Piezo-controlled objective lens**

OPERA hybrid detector:

SM1 SM2



Target and Target Tracker (6.7*m*)²

- Target : 77500 bricks, 29 walls
- Target tracker : 31 XY doublets of 256 scintillator strips

+ WLS fibres + multi-anodes PMT for
  - Vertex brick identification
  - Calorimetry

JINST 4 (2009) P04018

Muon spectrometer (8×10 *m*2)

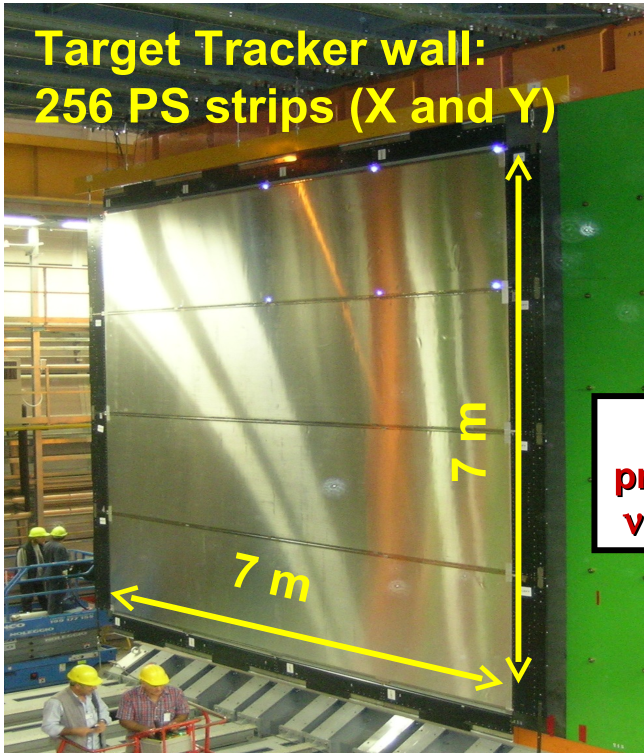
Instrumented dipole magnet

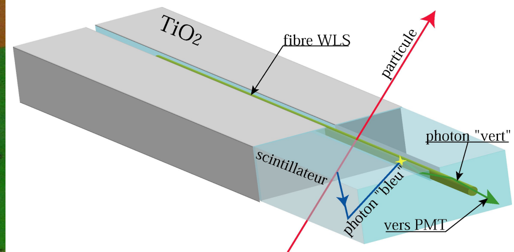
- 1.53 *T*
- 22 XY planes in both arms

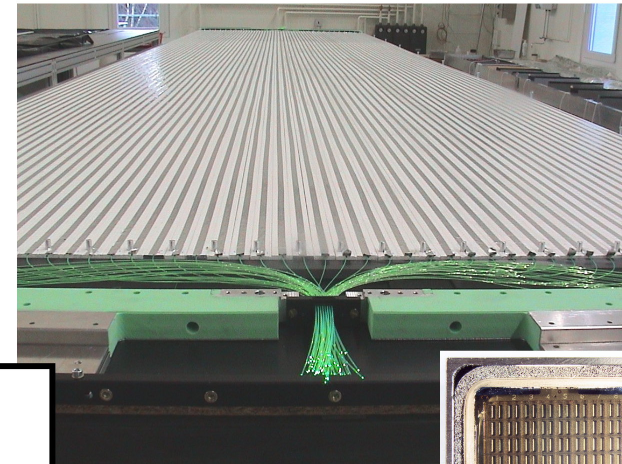
High precision tracker

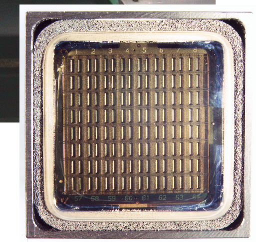
6 4-fold layers of drift tubes

Target Tracker

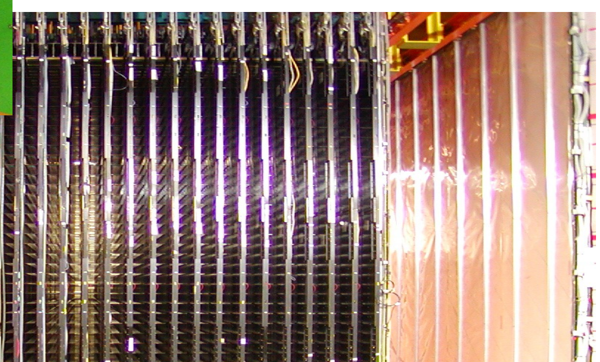


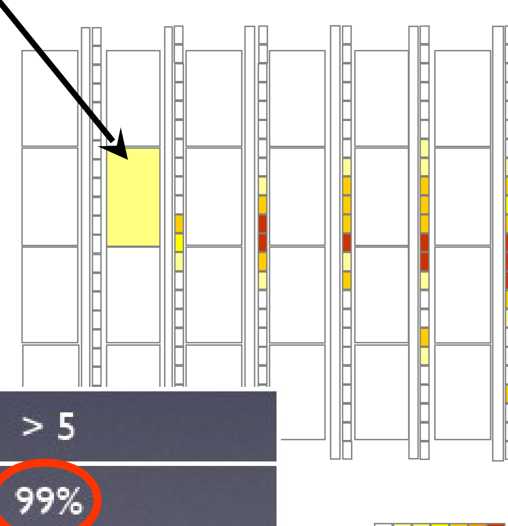






provides information for ν interaction brick identification



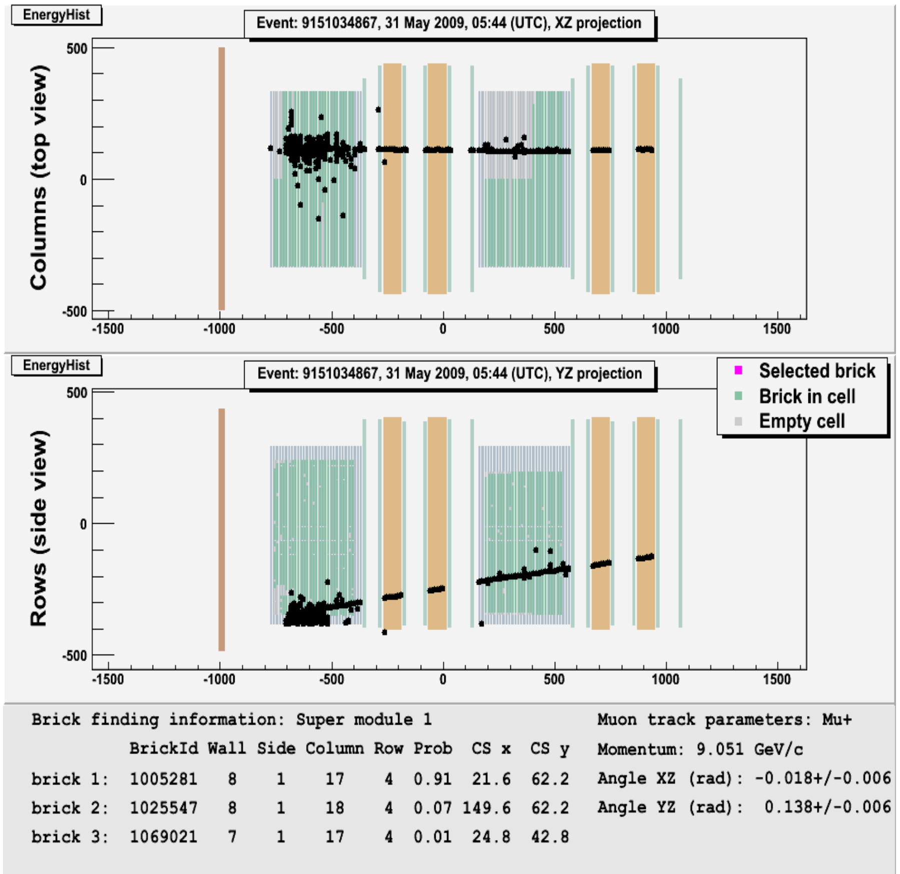


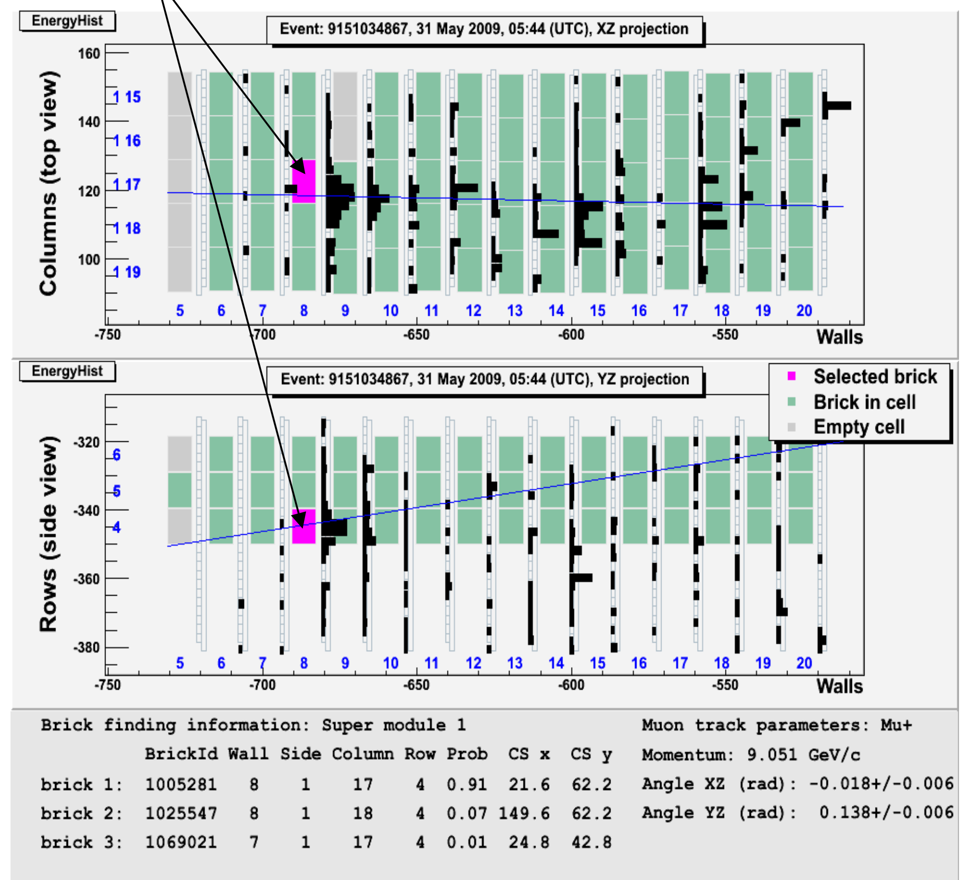
# p.e. per mip (2.15 MeV)	> 5
Detection efficiency	99%
Brick finding efficiency	80%

Brick Finding

Event trigger and reconstruction

Brick identification

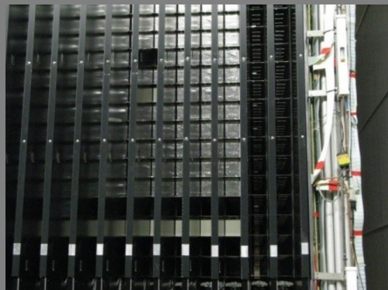




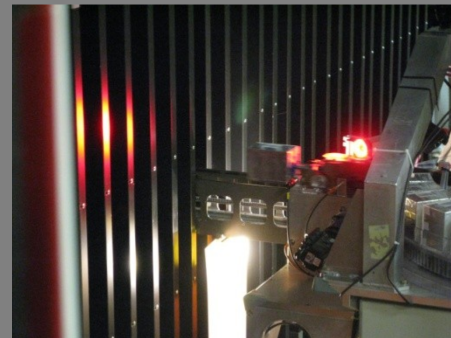
Selection of a brick most probably containing the neutrino interaction

- Reduce scanning load
- Minimize the target mass loss

OPERATIONS ON BRICKS



Waiting for neutrinos in the target…



Extracted by the Brick Manipulator System

X-ray exposure for alignment

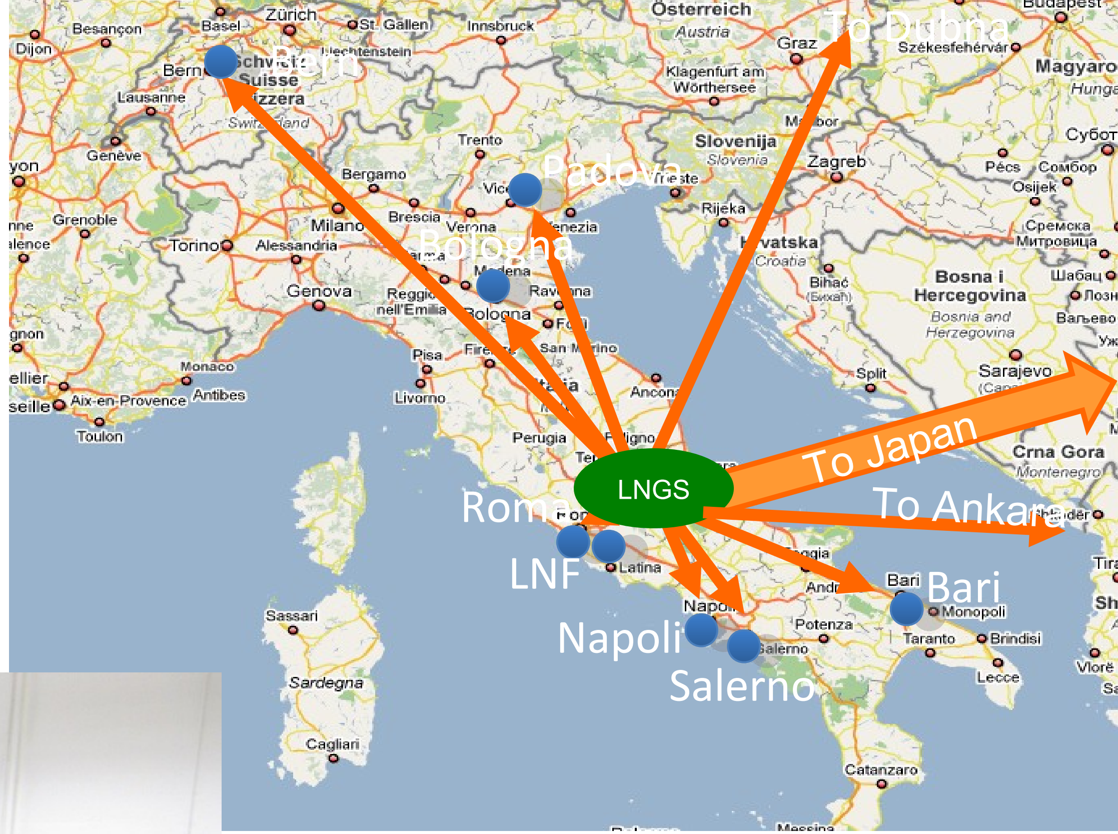
Stored underground (waiting for the CS response)

Exposed to cosmic-rays for precision film alignment

Films developed at surface

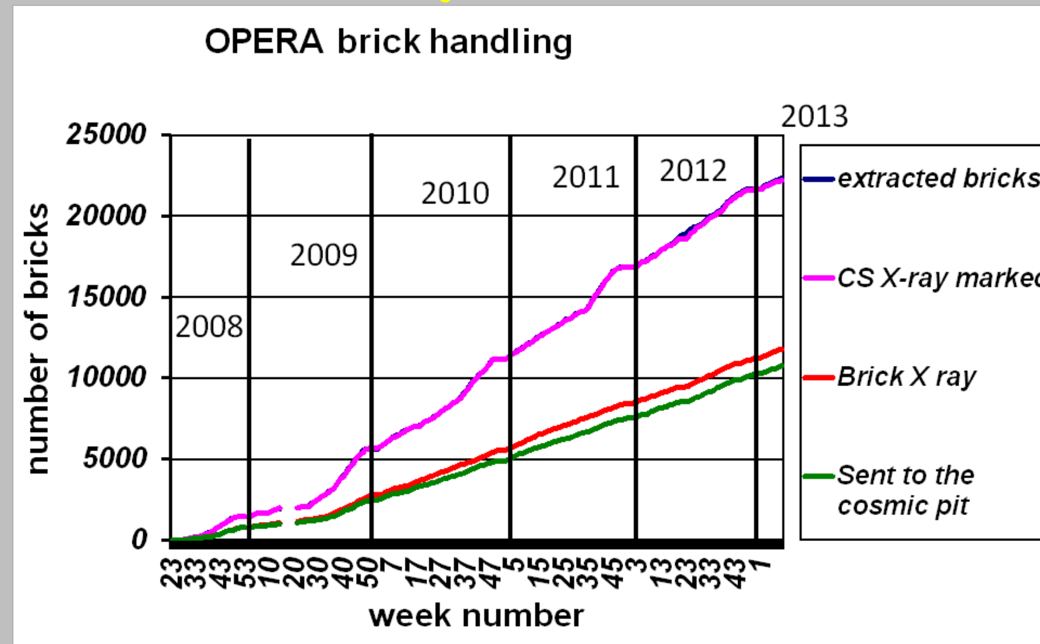
PARALLEL ANALYSIS OF BRICKS

selected bricks sent to scanning labs (**presently 12**)



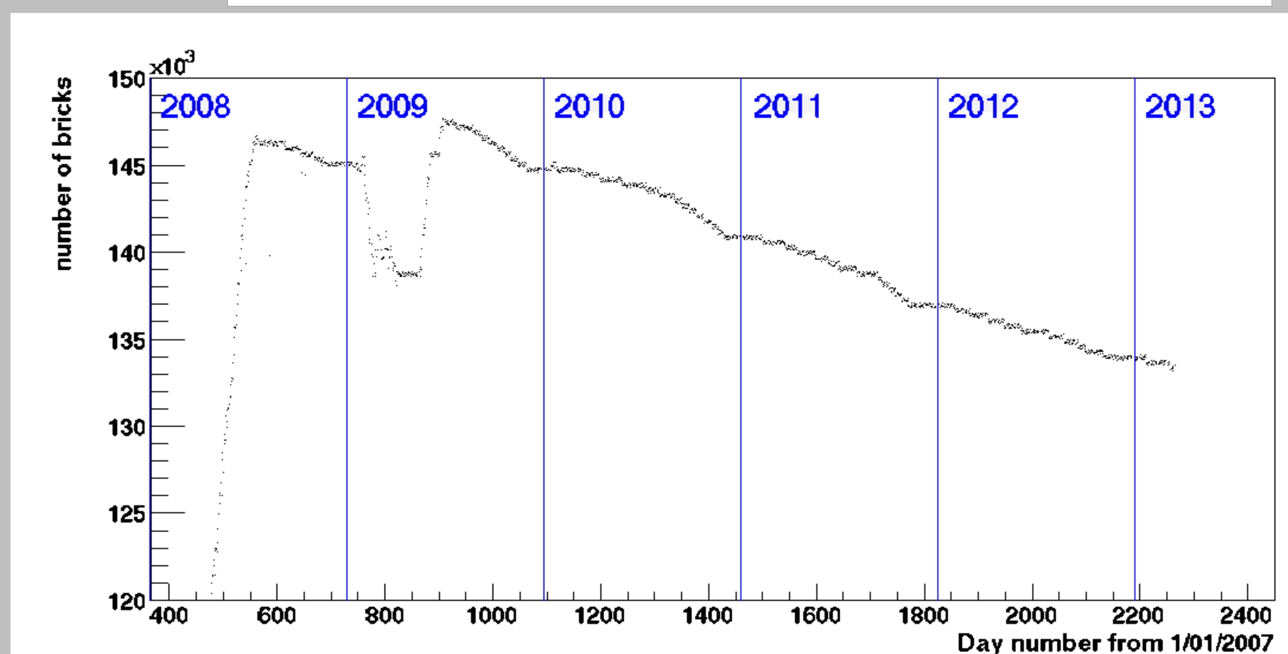
one of the brick scanning labs

Bricks operation by BMS



date	bricks
16/07/08	146398
24/06/09	147292
31/05/12	135606
13/03/13	133425

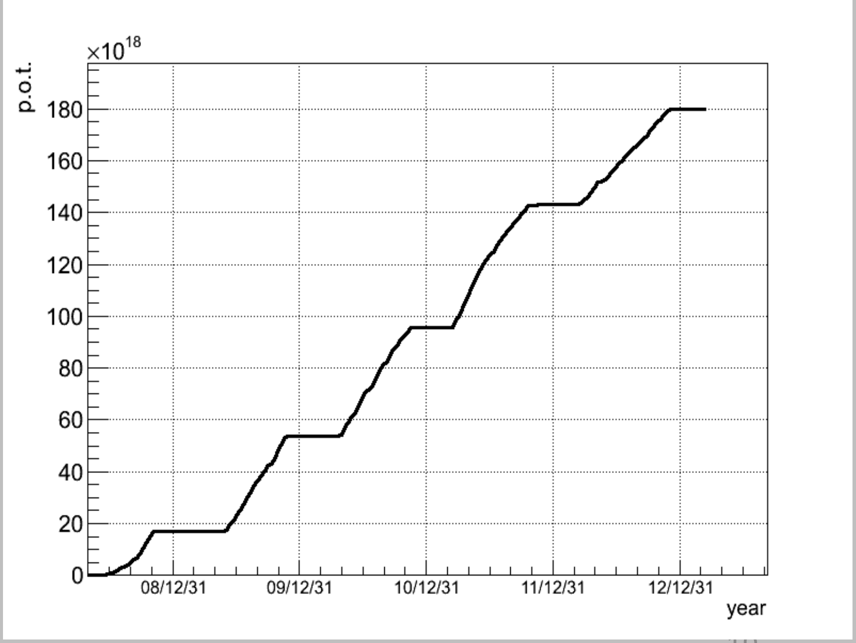
Target loss ~ 112 tons



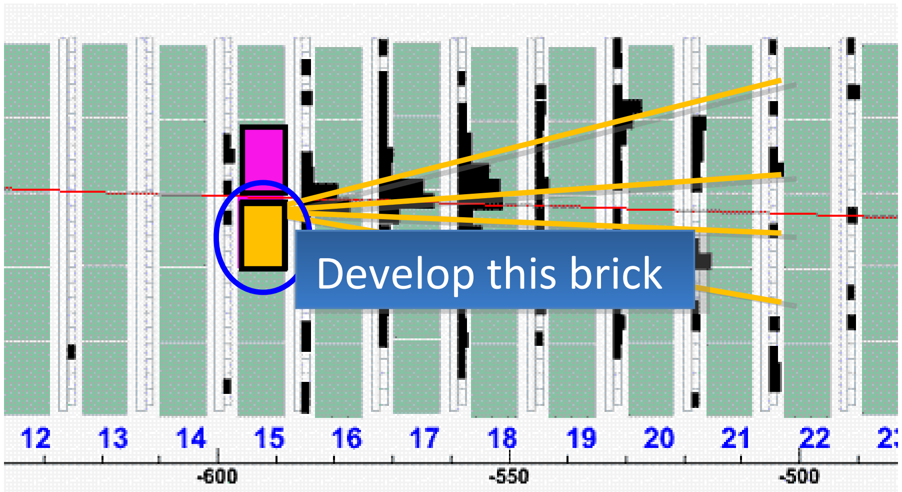
CNGS physics runs

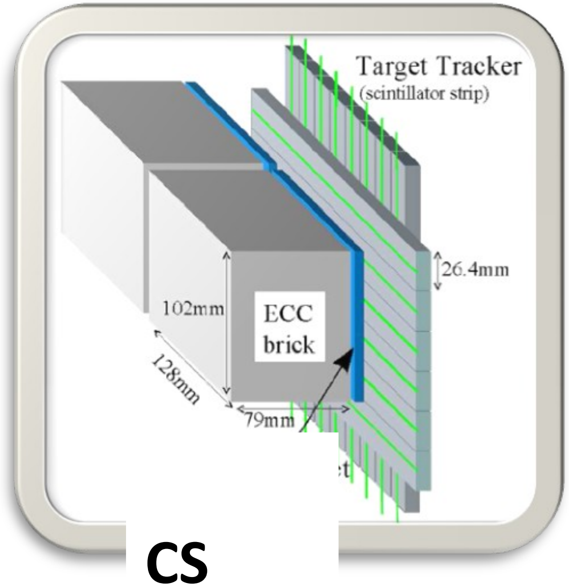
Year	Proton on Target (POT 10^{19})	Number of neutrino interactions	Integrated POT/proposal value
2008	1.74	1698	7.7%
2009	3.53	3557	23.4%
2010	4.09	3912	41.6%
2011	4.75	4210	62.7%
2012	3.86	3680	79.9%
Total	$17.97\ 10^{19}$ pot → 80% of the nominal value ($22.5\ 10^{19}$)		

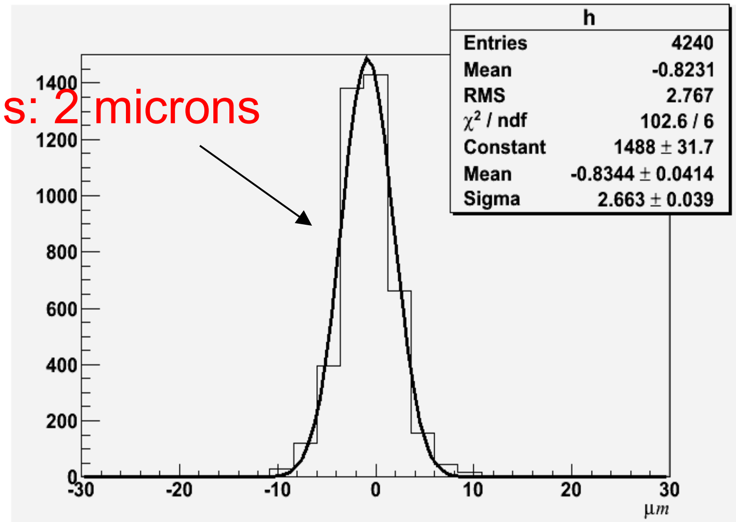
Year	Analysis status	# of decay searched events
2008-2009	Completed	2783
2010-2011-2012	On going	1722
Total		4505



BRICK VALIDATION BY THE CS







CS doublet alignment by Compton electrons: 2 microns

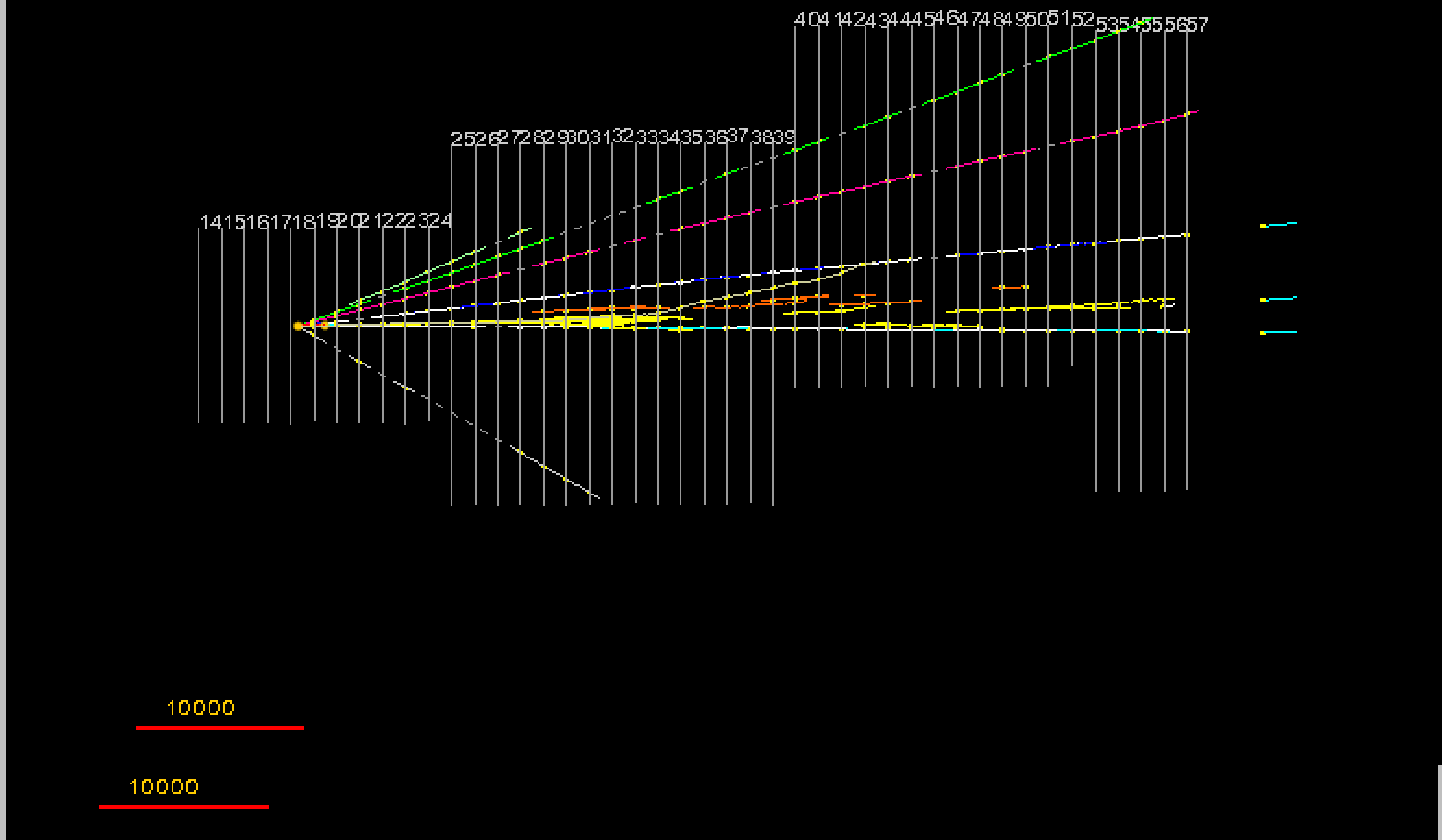
Scan only bricks containing neutrino interactions
(save analysis time, minimize the loss of target mass)

Scanning effort/event: CHORUS 1x1 mm^2
DONUT 5x5 mm^2
OPERA 100x100 mm^2

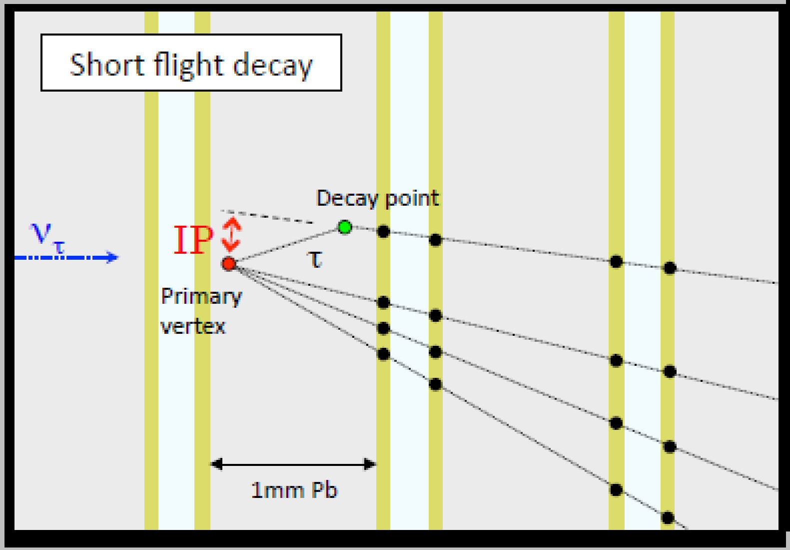
So far, 640'000 cm^2 of CS surface have been scanned in OPERA

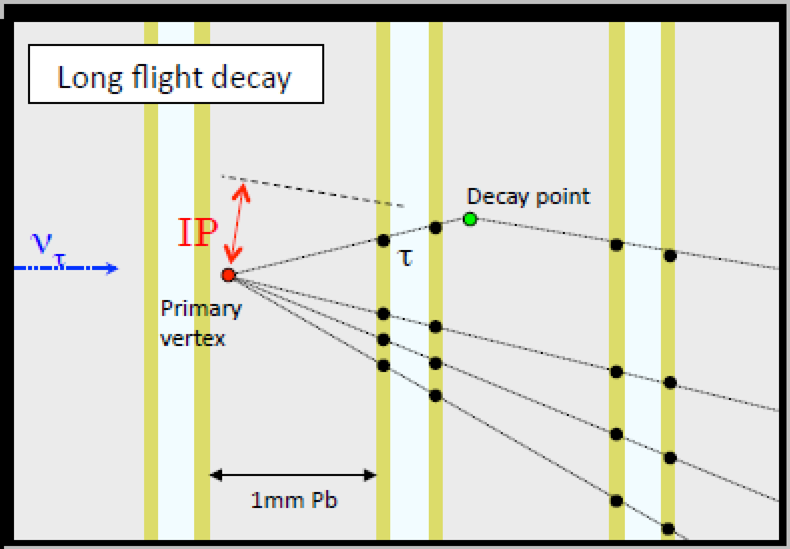
FROM CS TO VERTEX LOCATION

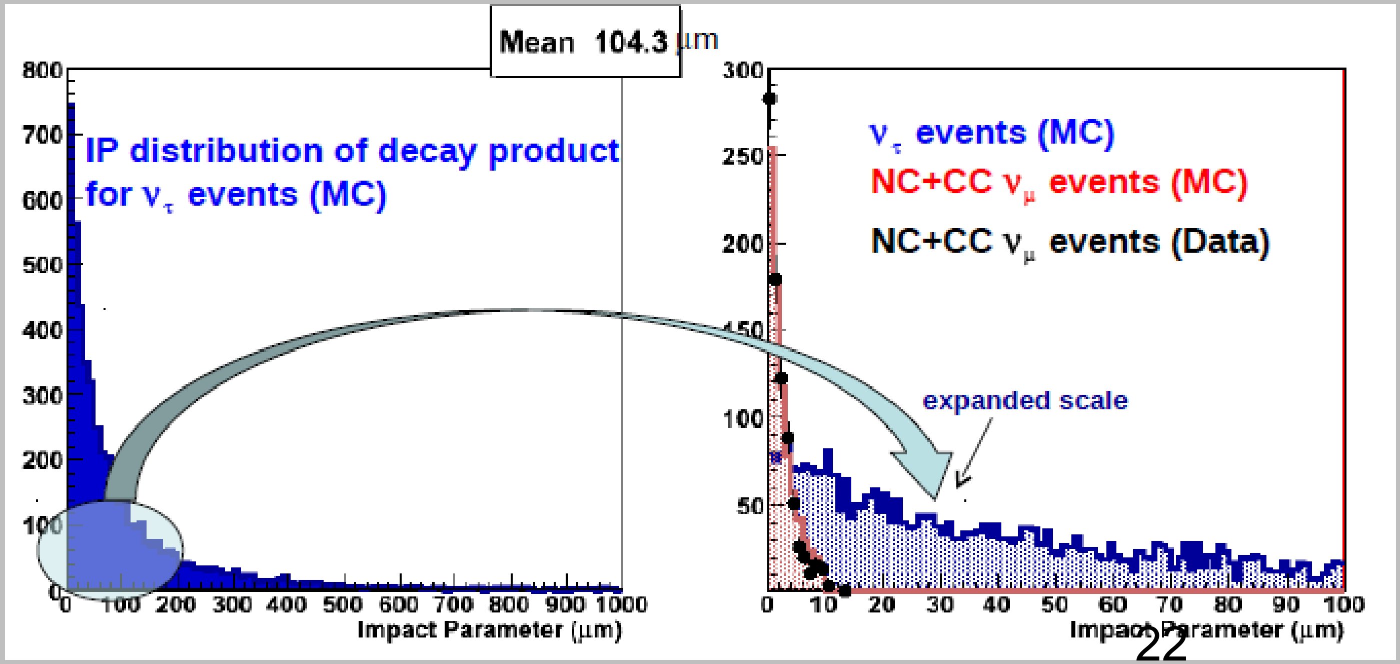
Large area scanning
Full reconstruction of vertices and gammas



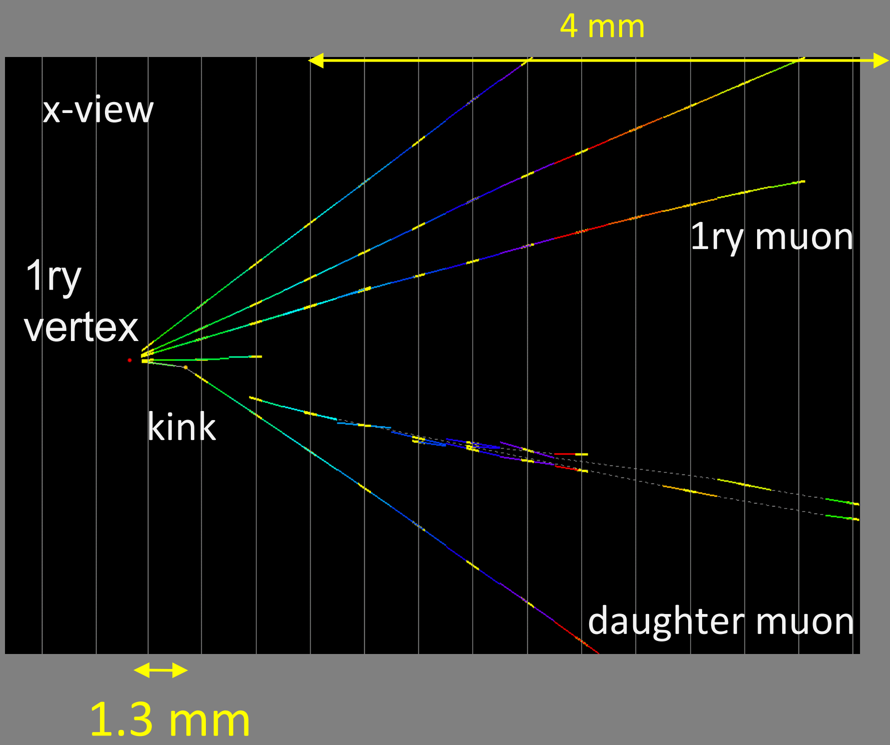
Impact Parameter (IP) measurement:





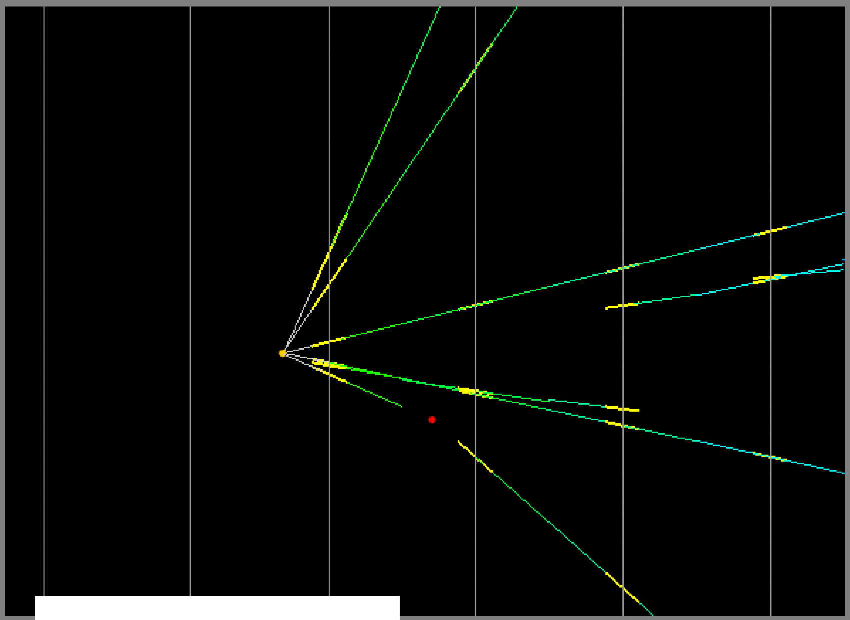


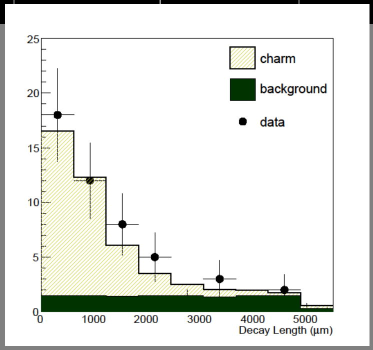
Charm events as a control sample



Dimuon charm decay event:

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

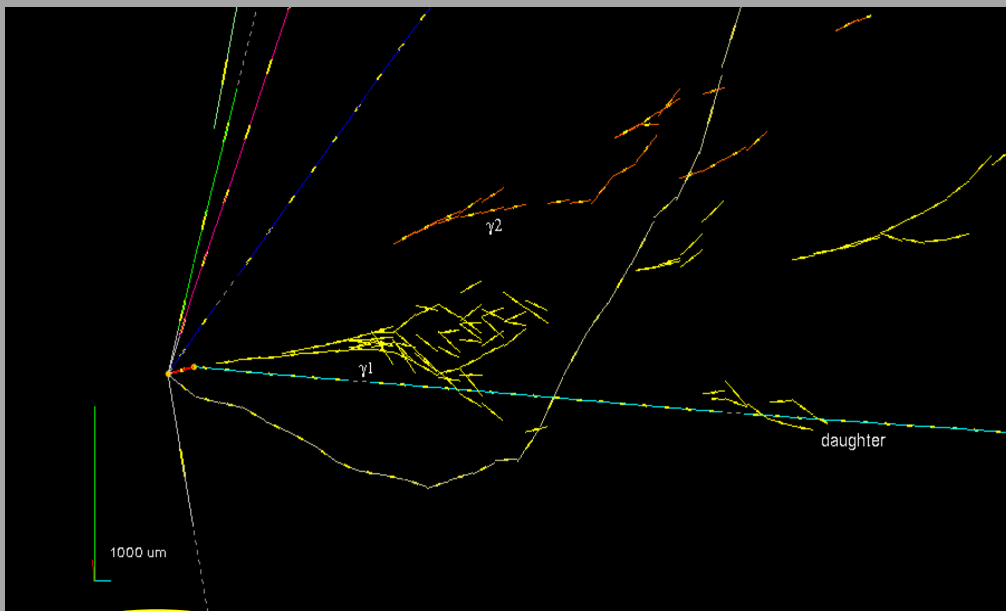




	charm	background	expected	data
1 prong	20.5 ± 9.1	9 ± 3	29.5 ± 9.6	19
2 prong	14.9 ± 3.6	3.8 ± 1.1	18.7 ± 3.8	22
3 prong	4.6 ± 2.0	1.0 ± 0.3	5.6 ± 2.0	5
4 prong	0.8 ± 0.1	-	0.8 ± 0.1	4
All	40.8±9.8	13.8±3.2	55±10	50

First ν_τ candidate

2008-2009 decay search, released in 2010
(Phys. Lett. B (2010) 138)



$\tau^- \rightarrow \rho^- \nu_\tau$

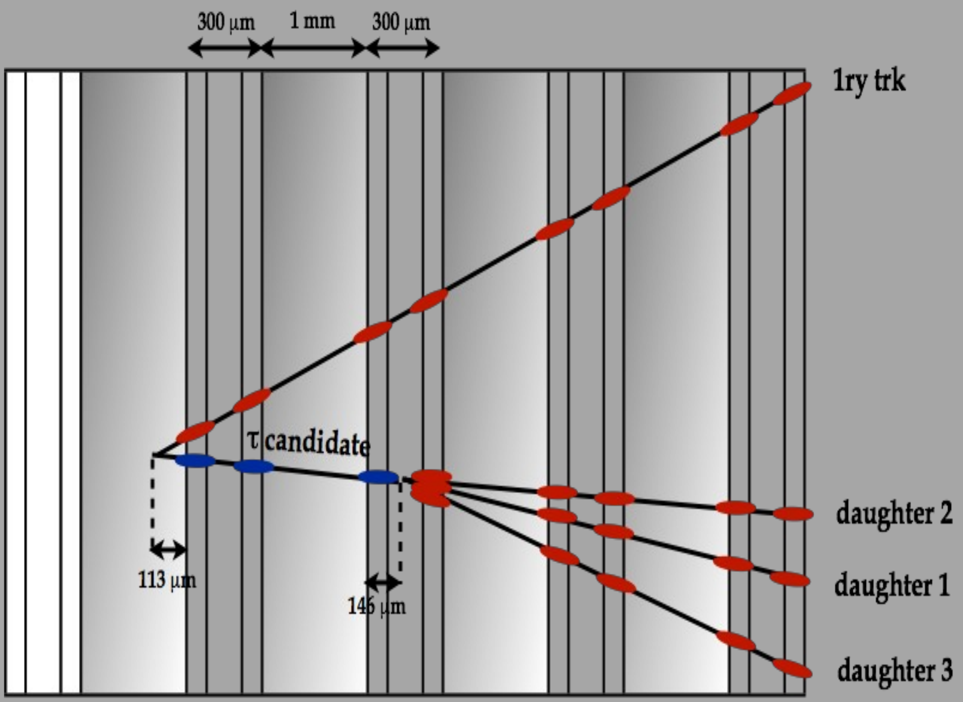
VARIABLE	Measured	Selection criteria
Kink (mrad)	**41 ± 2**	**>20**
Decay length (μm)	**1335 ± 35**	**Within 2 plates**
P daughter (GeV/c)	**12^{+6}_{-3}**	**>2**
Pt daughter (MeV/c)	**470^{+230}_{-120}**	**>300 (γ attached)**
Missing Pt (MeV/c)	**570^{+320}_{-170}**	**<1000**
ϕ (deg)	**173 ± 2**	**>90**

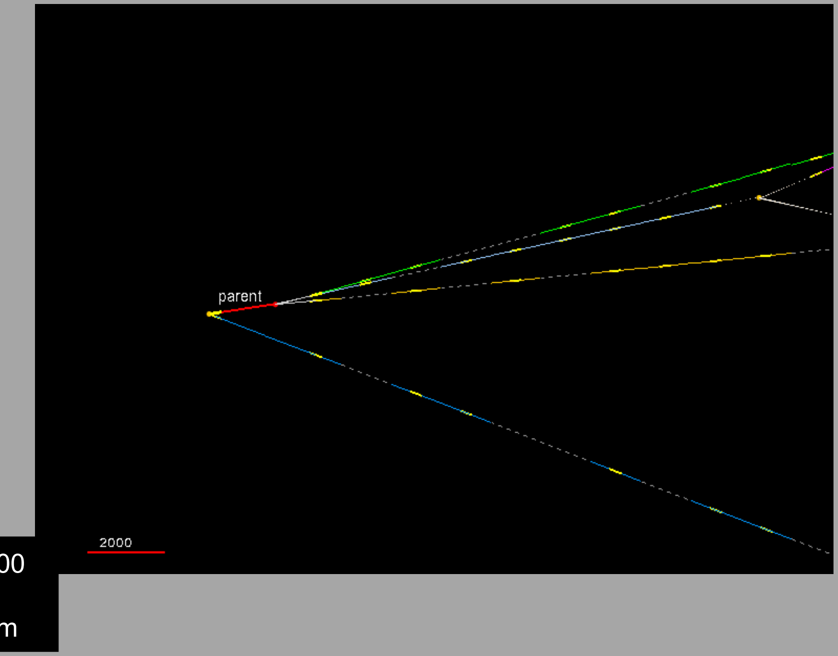
$\gamma 1 + \gamma 2$ — *120 ± 20 ± 35 MeV*

$\pi^- + \gamma 1 + \gamma 2$ — *$640^{+125}_{-80}{}^{+100}_{-90}$ MeV*

Prompt ν_τ ~ 10^{-7}/CC
Decay of charmed particles produced in ν_e interactions ~ 10^{-6}/CC
Double charm production ~ 10^{-6}/CC
Decay of charmed particles produced in ν_μ interactions ~ 10^{-5}/CC
Hadronic interactions ~ 10^{-5}/CC

Second ν_τ candidate





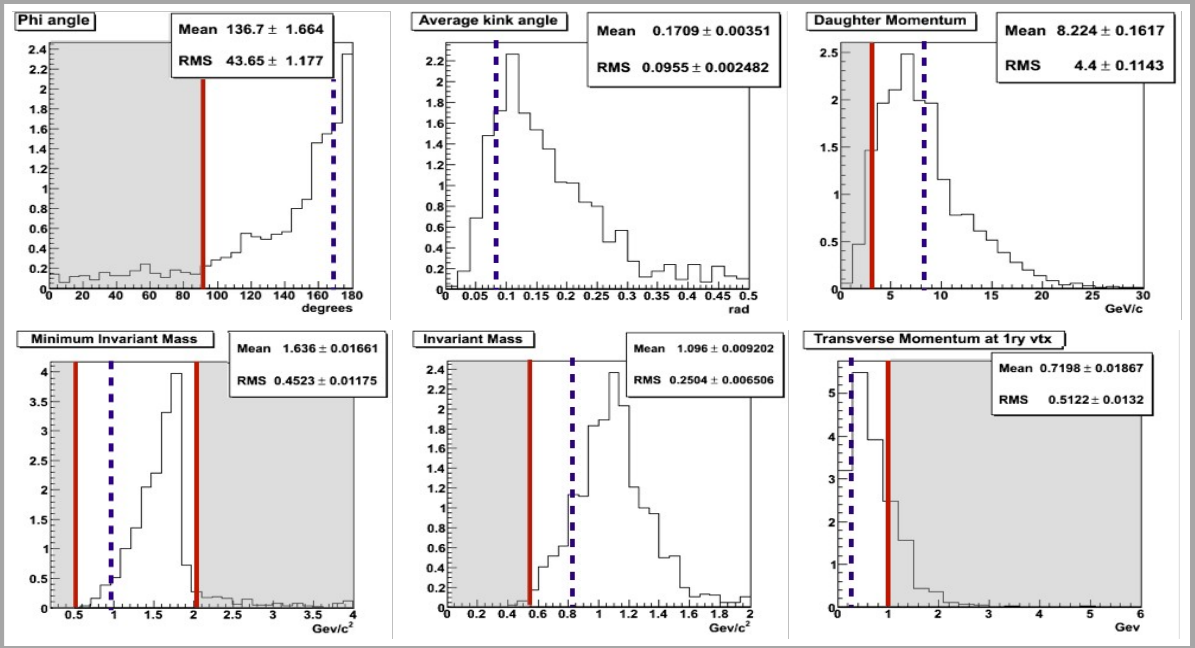
Second ν_τ candidate kinematic analysis

Reported at Neutrino-2012 conference

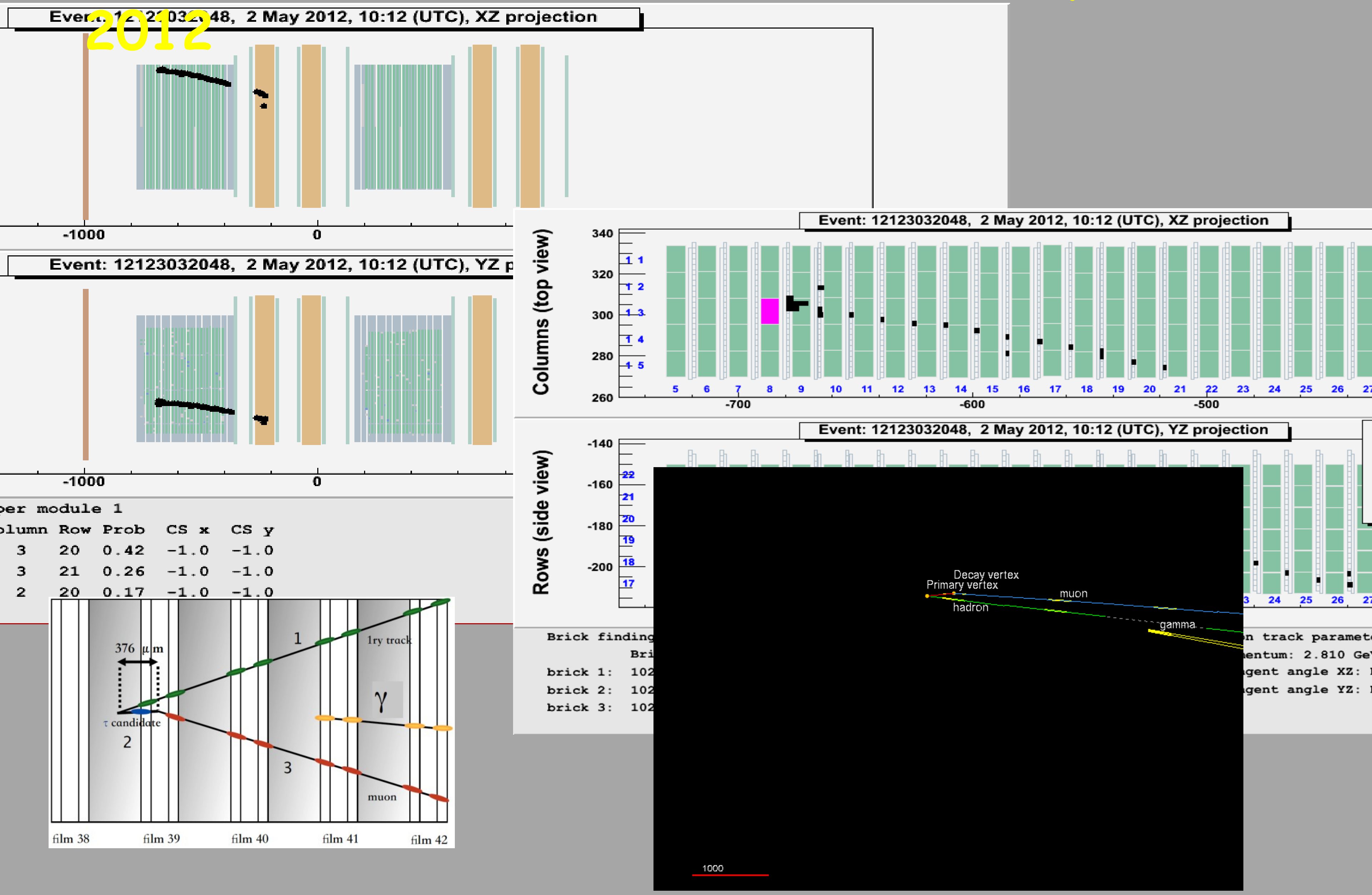
	Cut	Value	Error
Phi (Tau - Hadron) [degree]	>90	167.8	± 1.1
average kink angle [mrad]	< 500	87.4	± 1.5
Total momentum at 2ry vtx [GeV/c]	> 3.0	8.4	± 1.7
Min Invariant mass [GeV/c^2]	0.5 < < 2.0	0.96	± 0.13
Invariant mass [GeV/c^2]	0.5 < < 2.0	0.80	± 0.12
Transverse Momentum at 1ry vtx [GeV/c]	< 1.0	0.31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

All track were identified as hadron.

Event satisfies the specified criteria for $\tau^- \rightarrow h^+ h^- h^- \nu_\tau$



Third tau neutrino event taken on May 2nd 2012



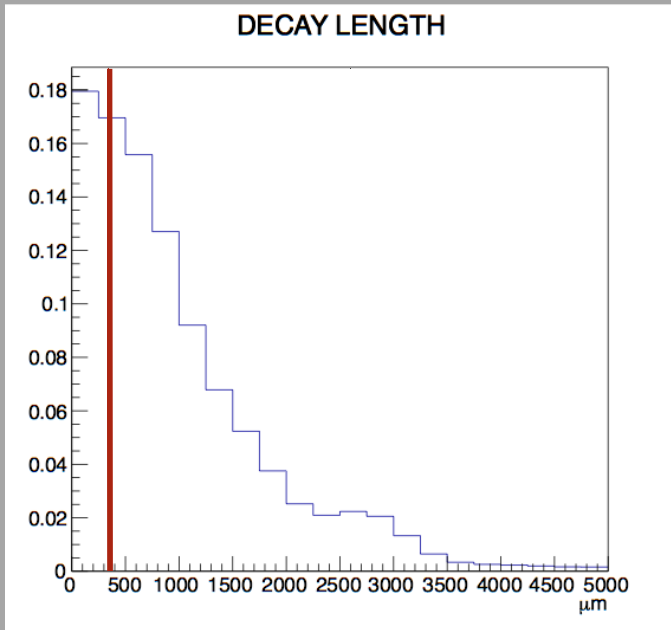
Event tracks' features

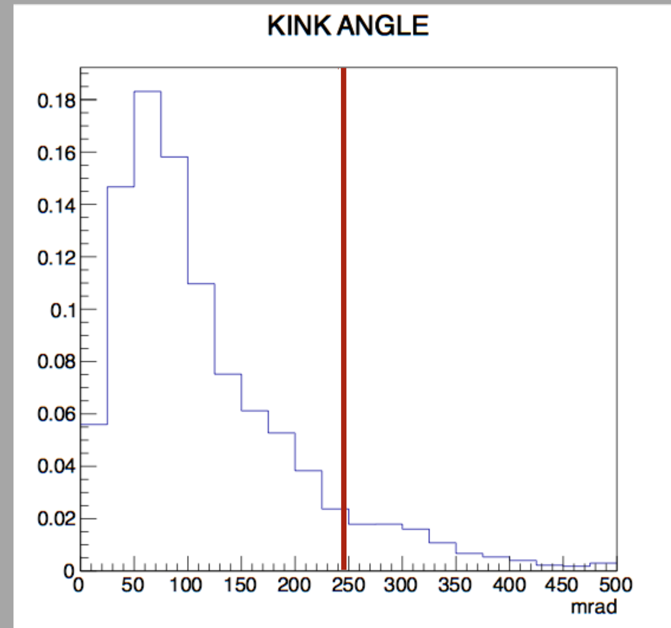
TRACK NUMBER	PID	MEASUREMENT 1	MEASUREMENT 2				
		ΘX	ΘY	P (GeV/c)	ΘX	ΘY	P (GeV/c)
1 DAUGHTER	MUON	-0.217	-0.069	3.1 [2.6,4.0]MCS	-0.223	-0.069	2.8±0.2 Range (TT+RPC)
2	HADRON Range	0.203	-0.125	0.85 [0.70,1.10]	0.205	-0.115	0.96 [0.76,1.22]
3	PHOTON	0.024	-0.155	2.64 [1.9,4.3]	0.029	-0.160	3.24 [2.52,4.55]
4 PARENT	TAU	-0.040	0.098		-0.035	0.096	

γ attachment

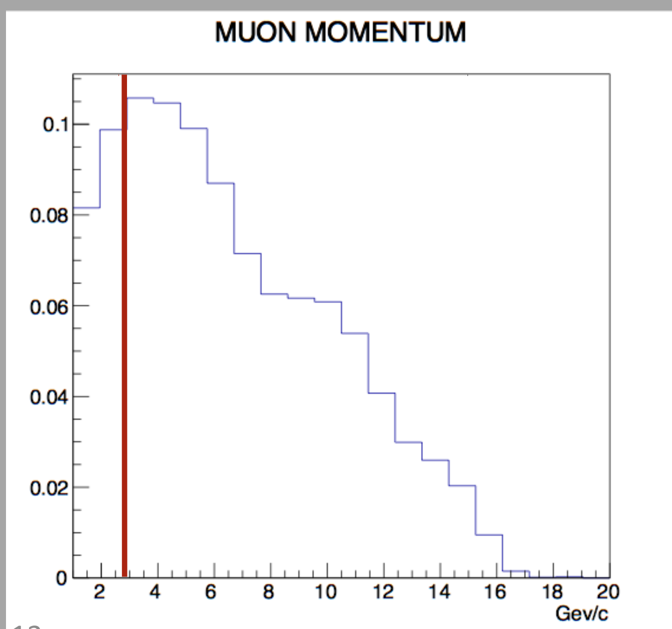
$\delta\theta_{RMS}$ (mrad)

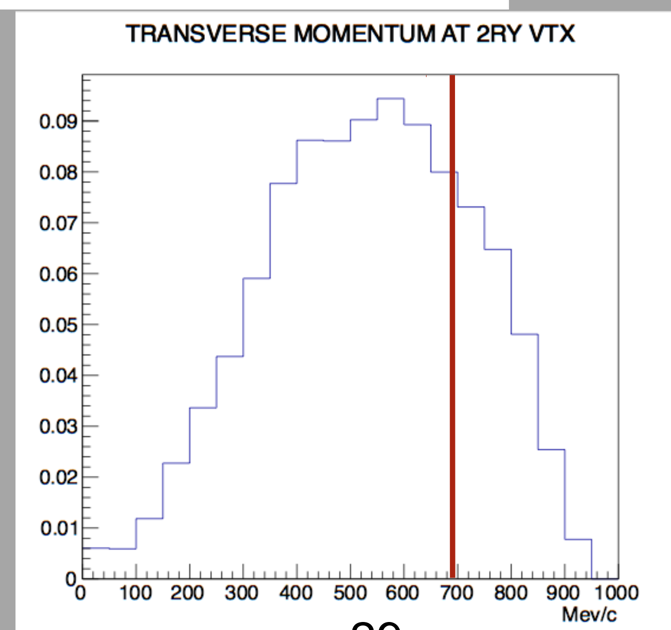
Kinematical variables. All cuts passed: $\tau \rightarrow \mu$ candidate





τ→µ MC
τ→µ candidate
excluded region





Statistical considerations

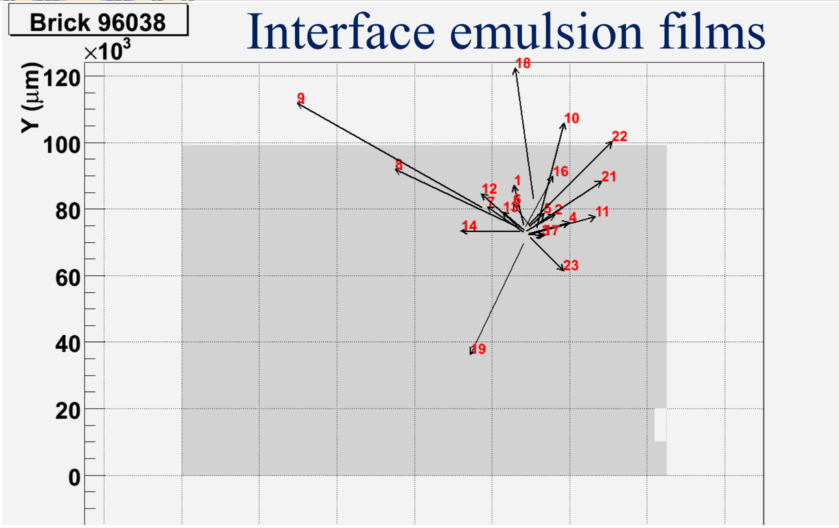
	Signal	Background	Charm	μ scattering	had int
τ→ h	0.66	0.045	0.029		0.016
τ → 3h	0.61	0.090	0.087		0.003
τ → μ	0.56	0.026	0.0084	0.018	
τ → e	0.49	0.065	0.065		
total	2.32	**0.226**	0.19	0.018	0.019

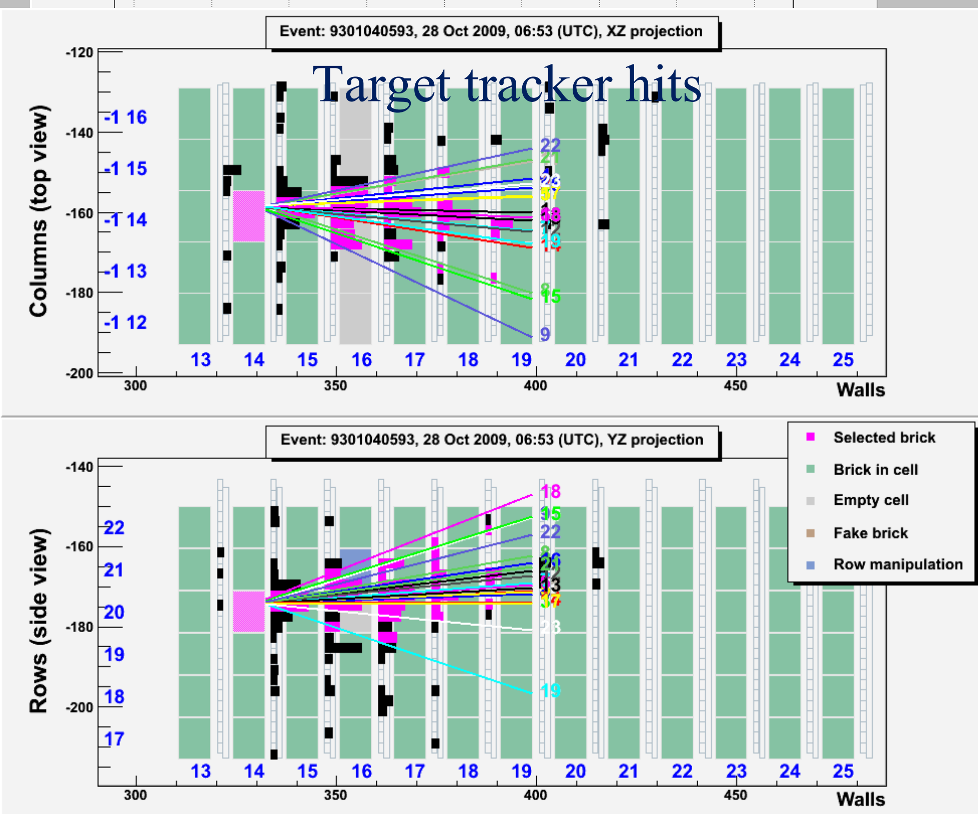
3 observed events in the τ→ h and τ→ 3h and τ→μ channels
Pvalue = P0 = 1.125 x 10-4
Probability to be explained by background = 7.29 10-4
This corresponds to **3.2 σ** significance of non-null observation

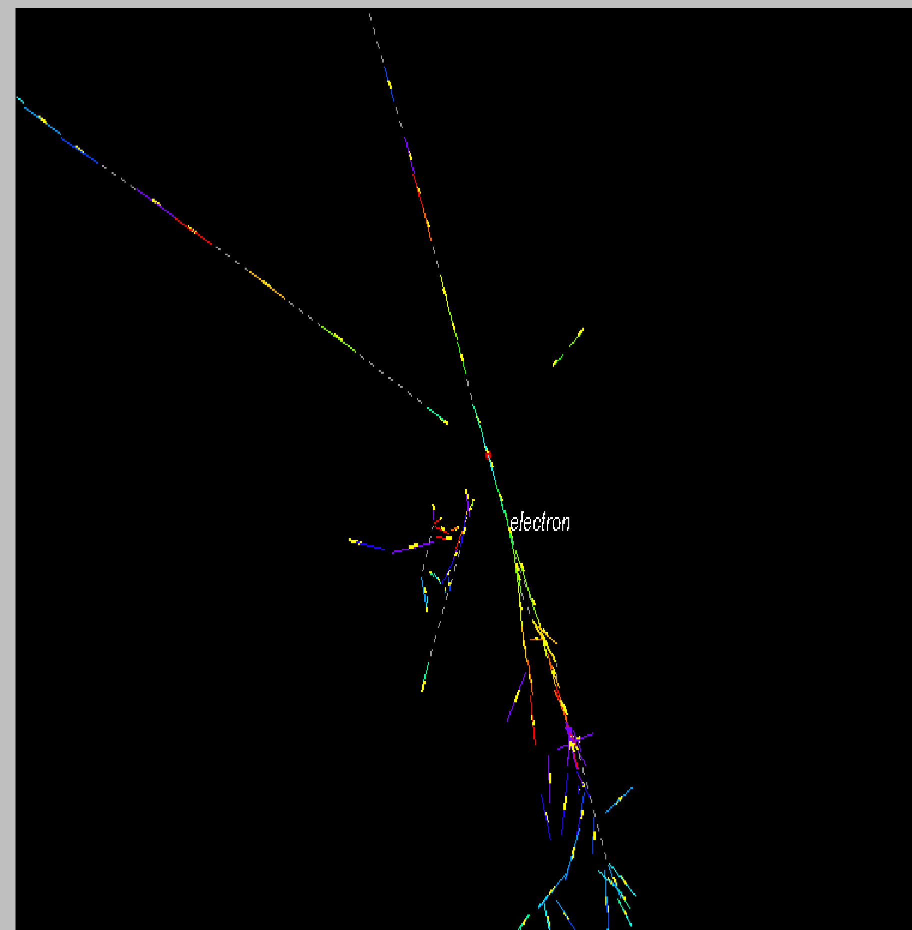
Preliminary

Combining different channels: Likelihood based method,
see e.g. G. Cowan et al., Eur. Phys. J. C71 (2011) 1554 3.6 sigma significance

Electron shower pre-selection





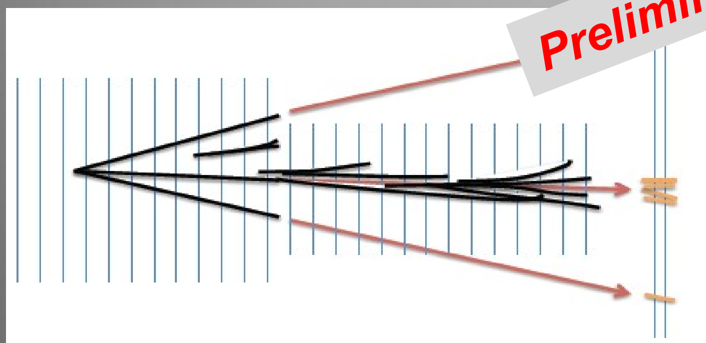


One of the electron neutrinos located as seen after the brick analysis

$\nu_\mu \rightarrow \nu_e$ oscillations search I

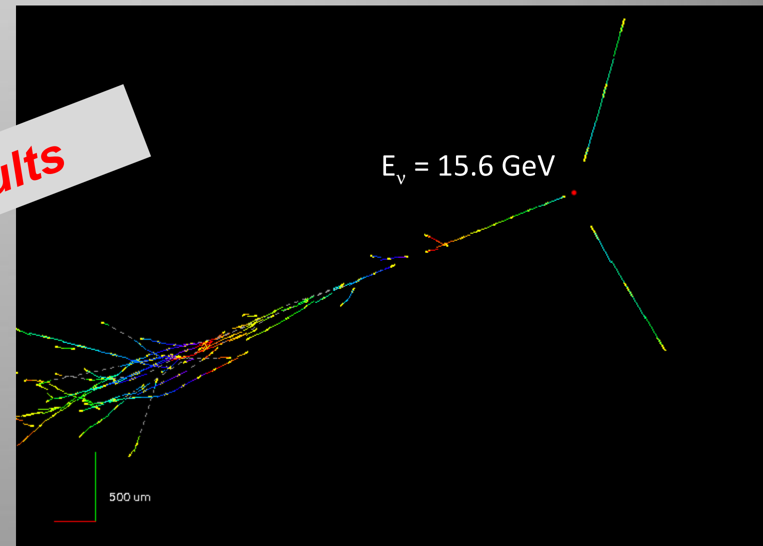
Systematic search for electron neutrinos applied to 505 located events without muon in the final state (runs 2008 – 2009)

Preliminary results

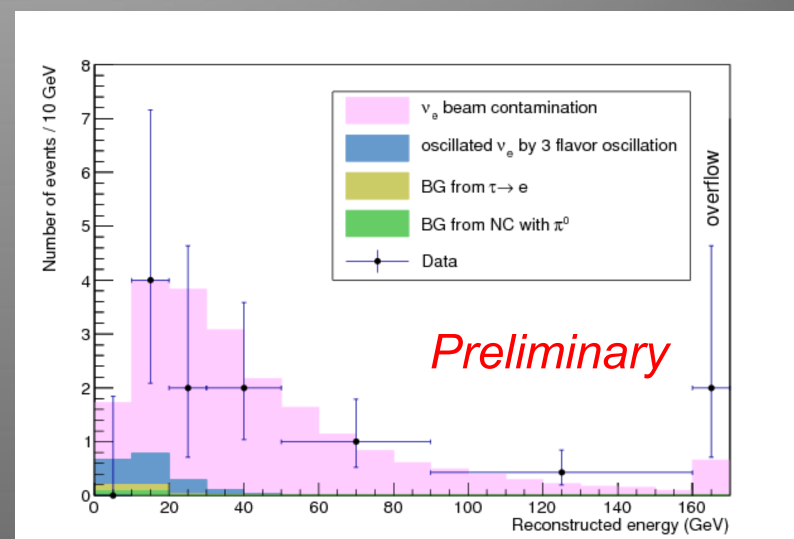


For each located event:

- **Extrapolate primary tracks to CS**
- **Search for cluster of shower on CS**
- **if shower hints found on CS, open an additional volume.**



As a result 19 ν_e event observed, compatible with background-only hypothesis expectation of 19.8±2.8(syst).



Applying cut on reconstructed energy in order to increase signal to background ratio, we observe 4 events with an expectation of 4.6 events. Gives an upper limit $\sin^2(2\theta_{13})$ < 0.44 at 90% C.L.

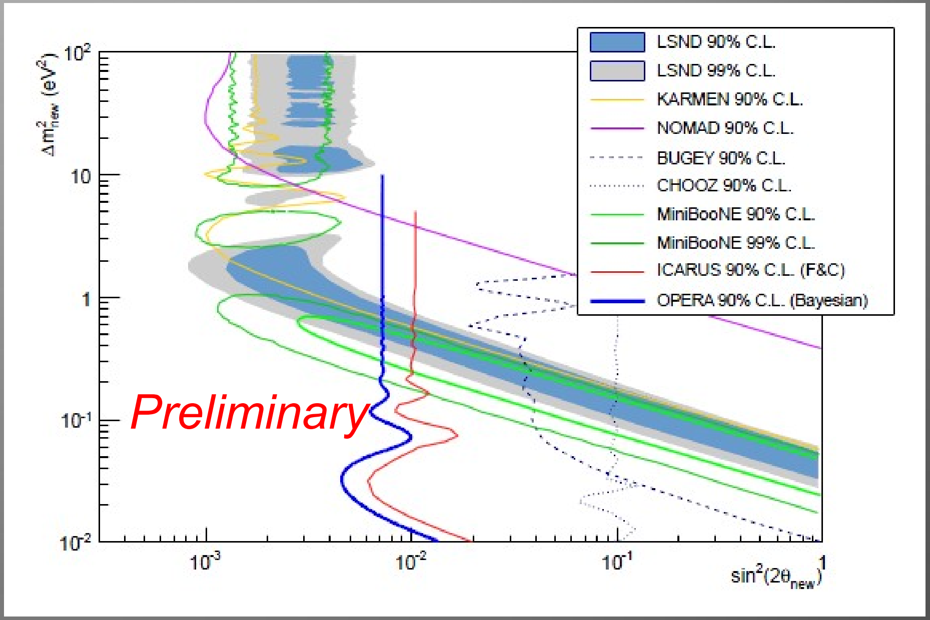
$\nu_\mu \to \nu_e$ oscillations search II

Search at large Δm^2

We have used the conventional approach of translating the $\nu_\mu \to \nu_e$ oscillation probability as

$$P = \sin^2(2\theta_{new}) \cdot \sin^2(1.27 \Delta m^2_{new} L(\mathrm{km})/E(\mathrm{GeV}))$$

We observe 6 events below 30GeV cut on reconstructed energy with an expectation of 9.4±1.3 events. This result yields an upper limit of 7.2 10^{-3} on $\sin^2(2\theta_{new})$ at 90% C.L.

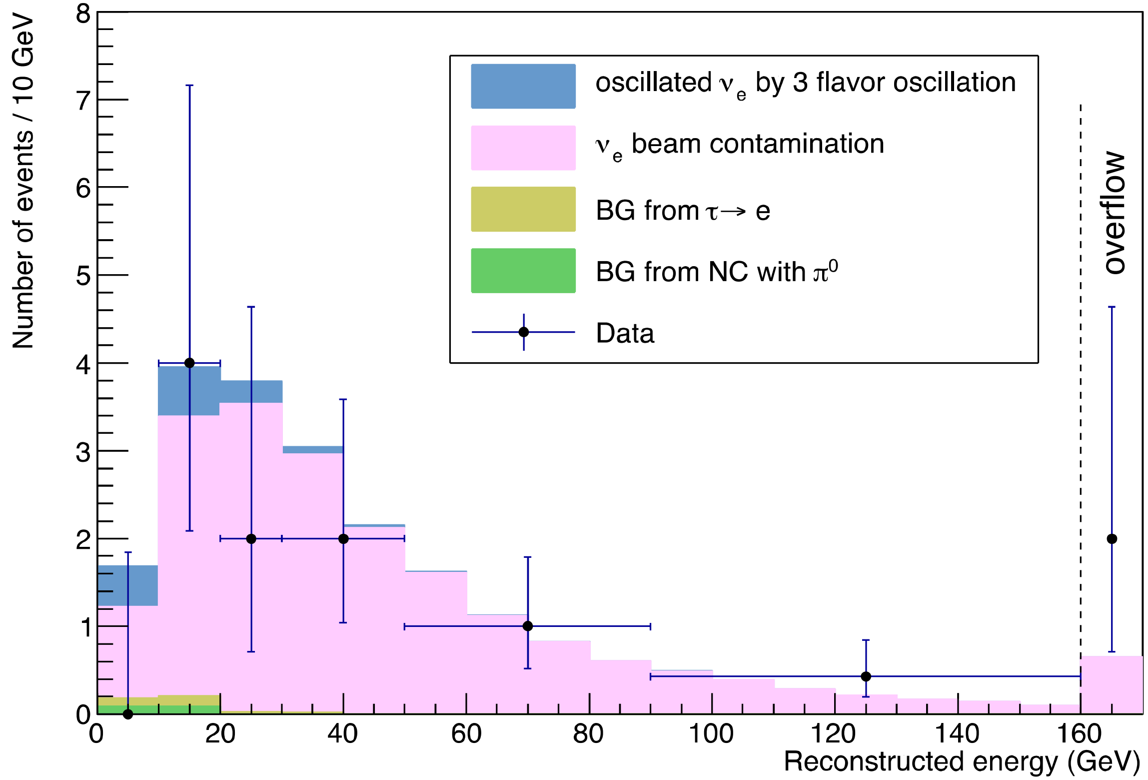


Summary:

As a result of continuos analysis of the data, OPERA achieved an «evidence» for $\nu_\mu \rightarrow \nu_\tau$ in appearance mode

- Three events reported in an extended sample
- Conservative background evaluation
- Significance of 3.2σ with simple counting method
- With a first likelihood approach, 3.5σ level
- 4σ observation within reach in 2013
- Non-standard oscillations restriction obtained via $\nu_\mu \rightarrow \nu_e$ analysis

Energy distribution of the 19 νe candidates



Energy cut		20 GeV	30 GeV	No cut
BG common to both analyses	BG (a) from π^0	0.2	0.2	0.2
	BG (b) from $\tau \rightarrow e$	0.2	0.3	0.3
	ν_e beam contamination	4.2	7.7	19.4
Total expected BG in 3-flavour oscillation analysis		4.6	8.2	19.8
BG to non-standard oscillation analysis only	ν_e via 3-flavour oscillation	1.0	1.3	1.4
Total expected BG in non-standard oscillation analysis		5.6	9.4	21.3
Data		4	6	19

Observation compatible with background-only hypothesis: 19.8±2.8 (syst) events

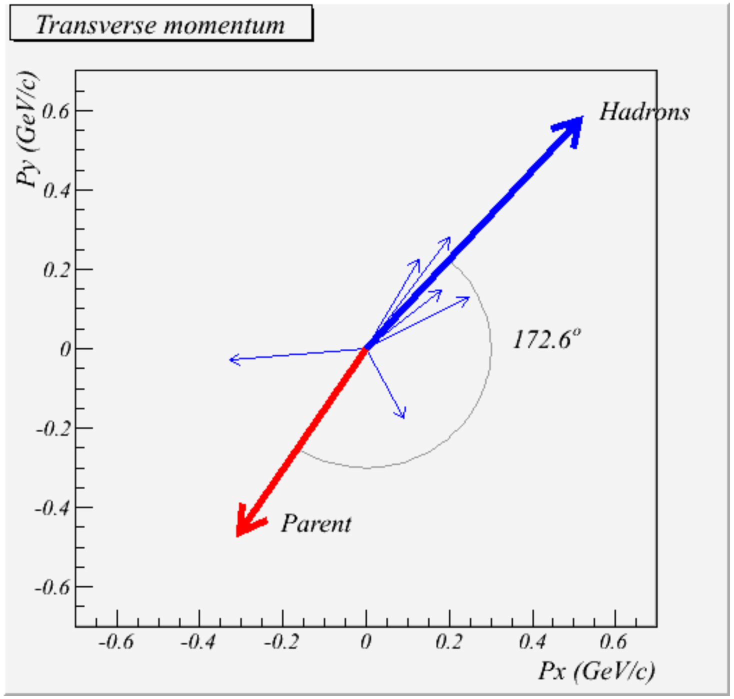
3 flavour analysis

Energy cut to increase the S/N

4 observed events
4.6 expected
⇒ $\sin^2(2\theta_{13})<0.44$ at 90% C.L.

Kinematical variables

- Kinematical variables are computed by averaging the two independent sets of measurements
- γ1 and γ2 both attached to 2ry vertex



VARIABLE	AVERAGE
kink (mrad)	41 ± 2
decay length (μm)	1335 ± 35
P daughter (GeV/c)	12 +6-3
Pt (MeV/c)	470 +240-120
missing Pt (MeV/c)	570 +320-170
ϕ (deg)	173 ± 2

Strategy for the 2010÷2012 runs

- Apply kinematical selection
- 15 GeV μ momentum cut (upper bound)
- Anticipate the analysis of the most probable brick for all the events before moving to the second (and further ones): optimal ratio between efficiency and analysis time
- Anticipate the analysis of 0μ events (events without any μ in the final state)
- In view of 2012 Summer conferences: 1μ sample for 2010 run, for 2011 run stick to 0μ sample only, 2012 not yet analysed

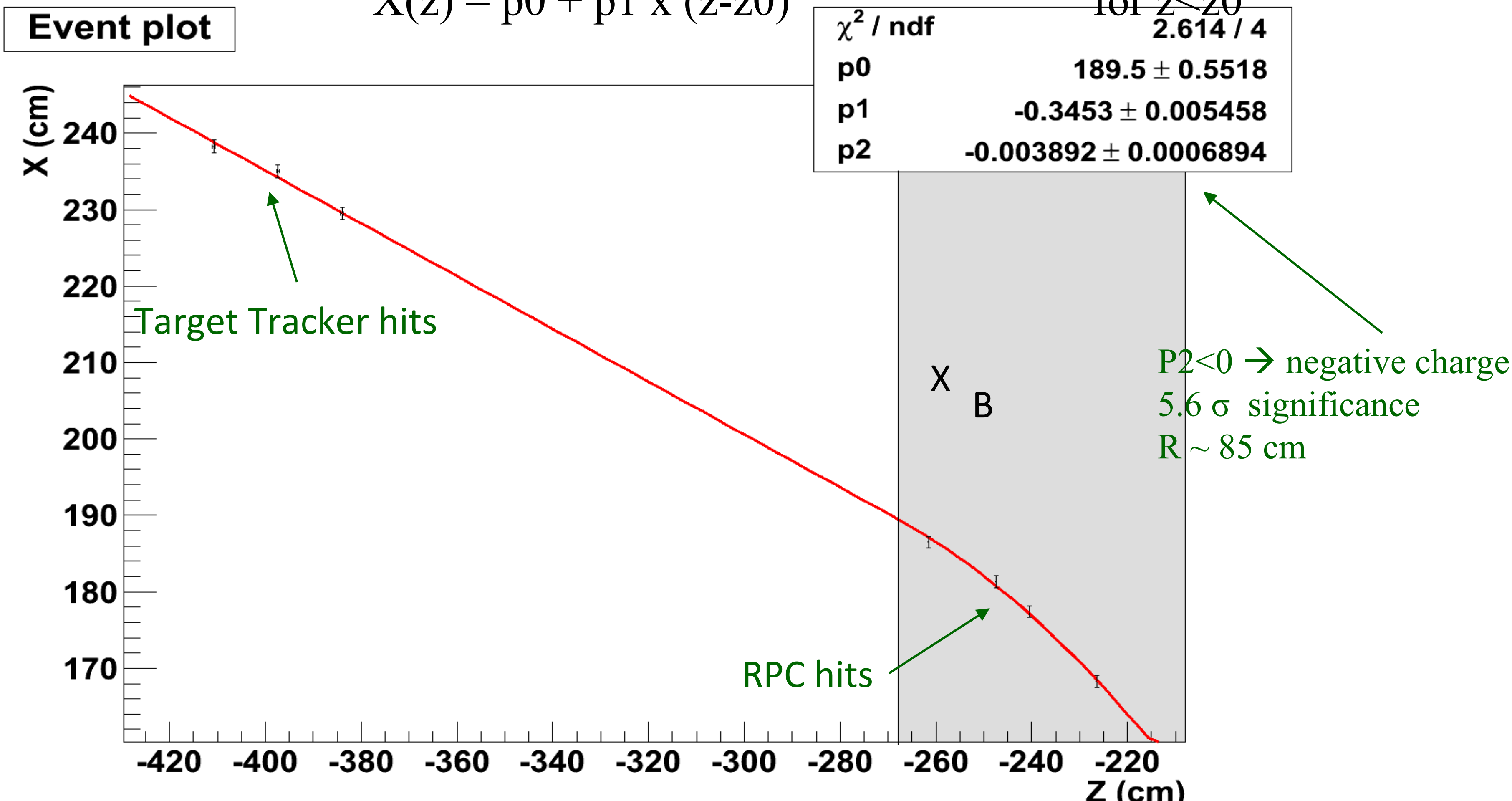
Charge determination of the muon

Charge measurement based on TT and RPC hits when no hits in drift tubes

Fit function:

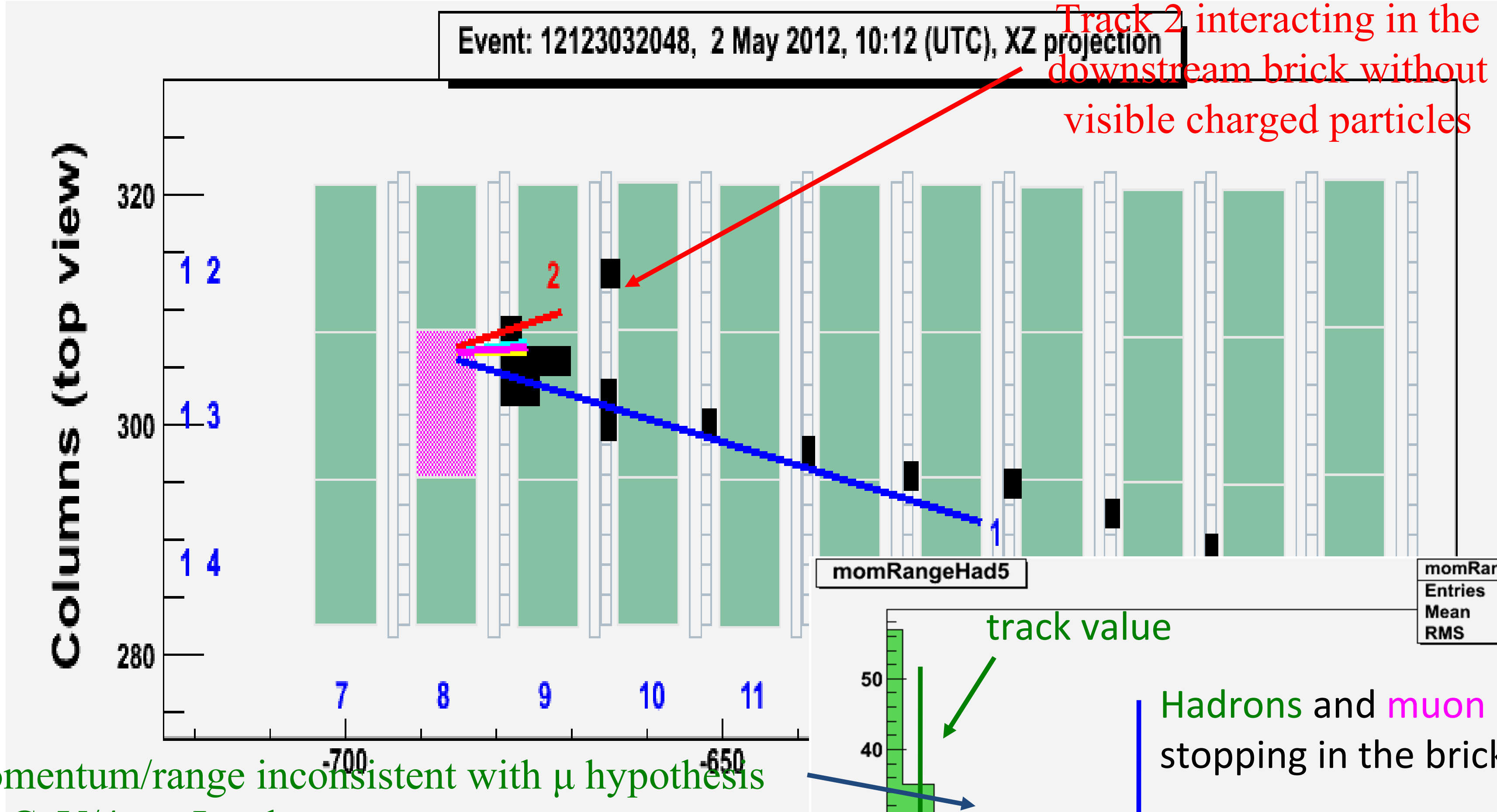
X(z) = p0 + p1 x (z-z0) + p2 x (z-z0)2 for z>z0, start of magnetized region

X(z) = p0 + p1 x (z-z0) for z<z0

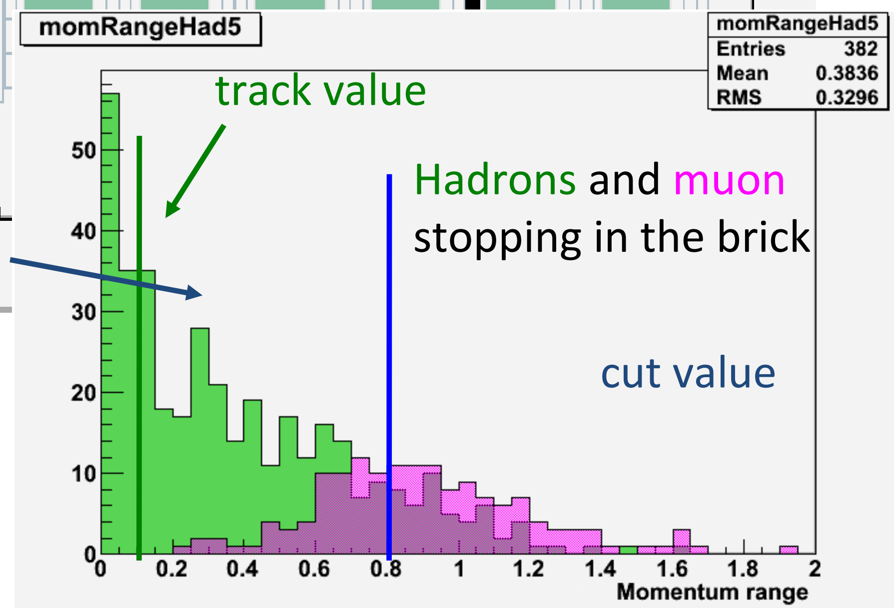


P-value = 0.063% (probability to reconstruct a μ+ stopping in the 7th iron layer with p2 < -0.00389 cm-1)

Track follow down to assess the nature of track 2



Track 2 interacting in the downstream brick without visible charged particles



D variable

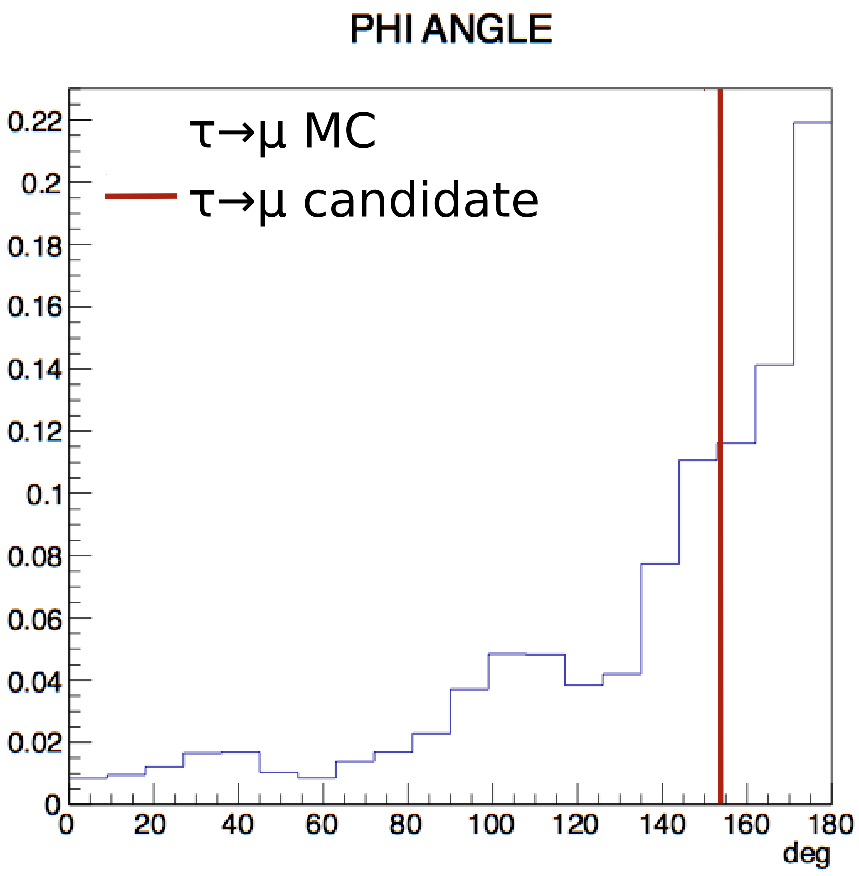
Momentum/range inconsistent with μ hypothesis
0.9 GeV/4 cm Lead

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

L = track length
Rlead = μ range
ρaverage = average density
ρlead = lead density
p = momentum in emulsion

Kinematical variables

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**



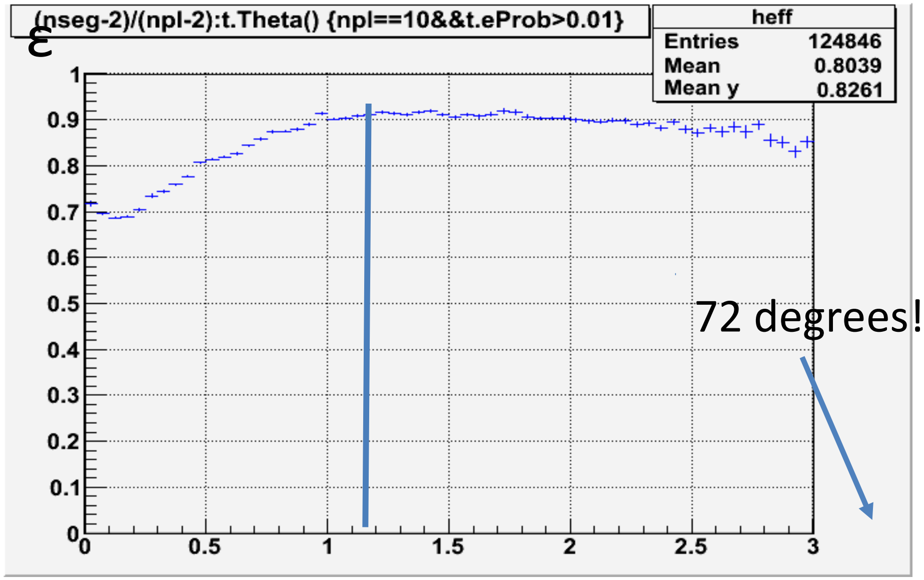
Background studies

Improvements on the background rejection: large angle track detection

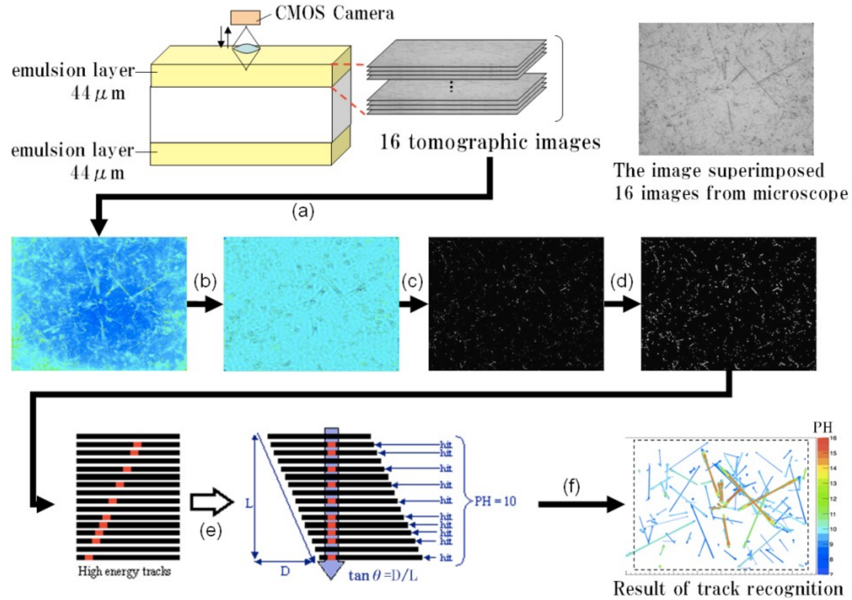
Undetected soft and large angle muons are the source of charm background

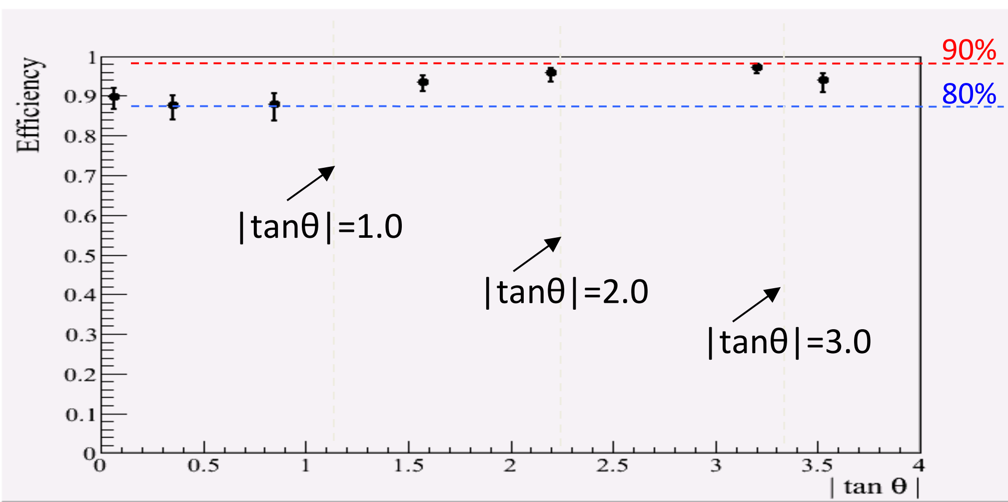
Detection of particles and nuclear fragments in hadronic interactions

Tracking efficiency



tg(theta)





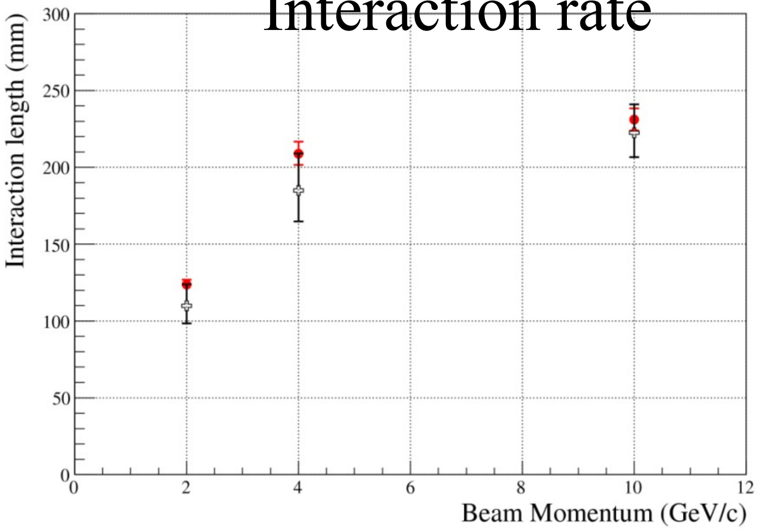
Two different approaches get comparable results

Background studies: hadronic interactions

Comparison of large data sample (π- beam test at CERN) with Fluka simulation: check the agreement and estimate the systematic error of simulation

Track length analysed in the brick: 2 GeV/c : 8.5 m, 4 GeV/c : 12.6 m, 10 GeV/c : 38.5 m

Interaction rate



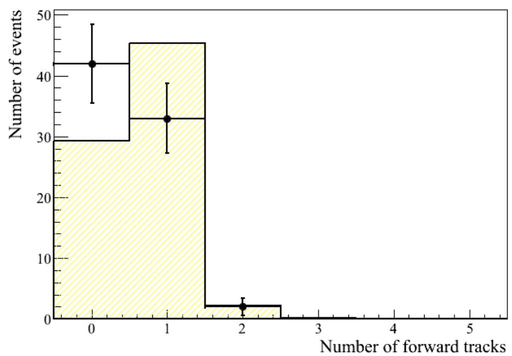
Black : π- beam data
Red : MC (FLUKA) simulation

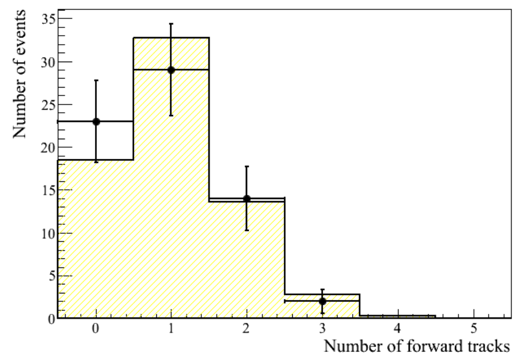
Secondary track emission

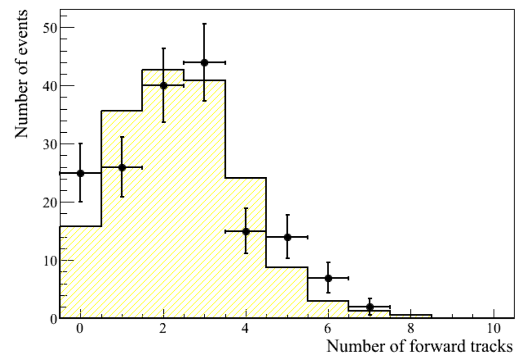
2GeV/c | 4GeV/c | 10GeV/c

Multiplicity

10 GeV/c

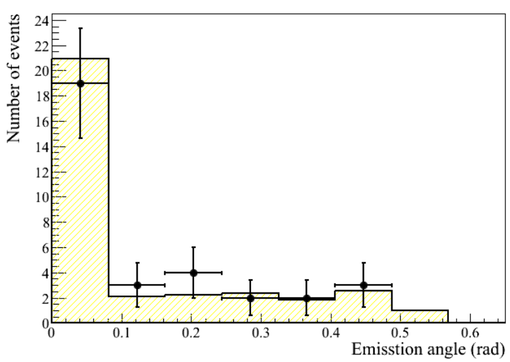


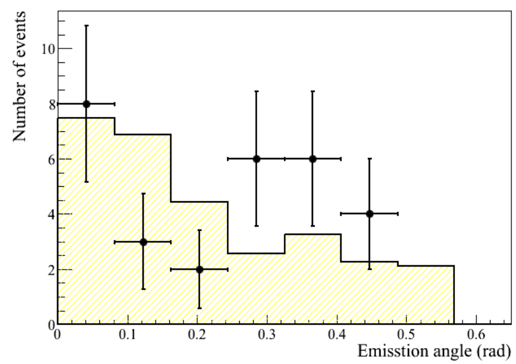


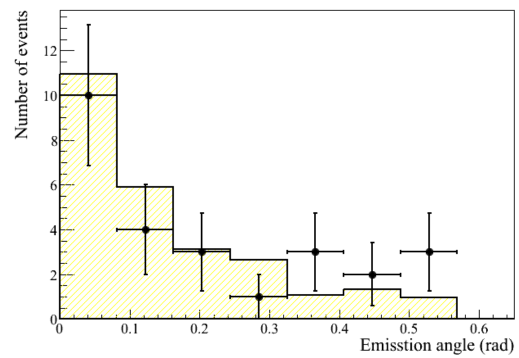


Error bars : Experimental data
Histogram : Simulated data

Kink angle (1-prong)

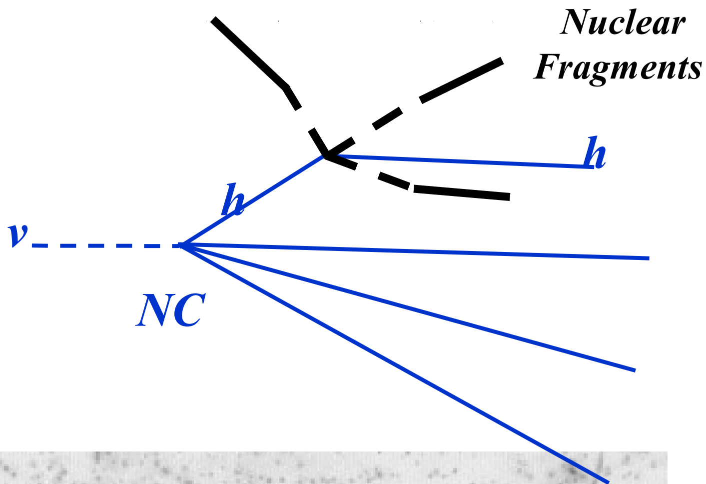


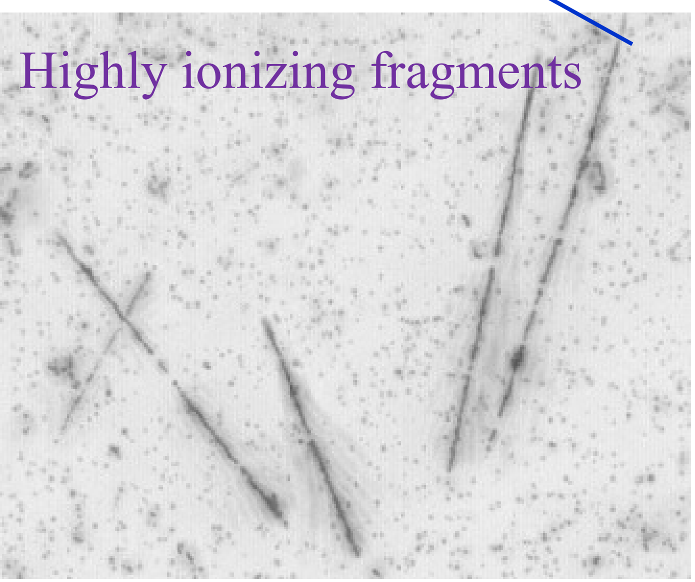


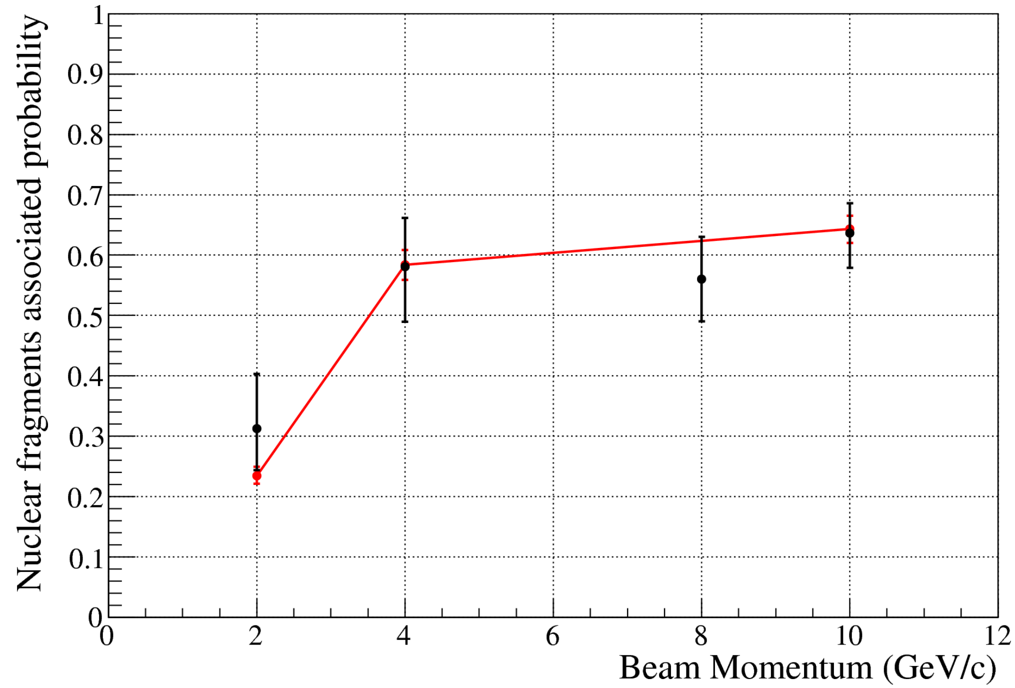


Good agreement within the statistical error: systematic error reduced to 30%

Nuclear fragments emission probability







Black : experimental data

Red : simulated data ($\beta = p/E = 0.7$)

It provides additional background reduction.