Recent results of the OPERA neutrino experiment

Natalia Di Marco

LNGS – INFN

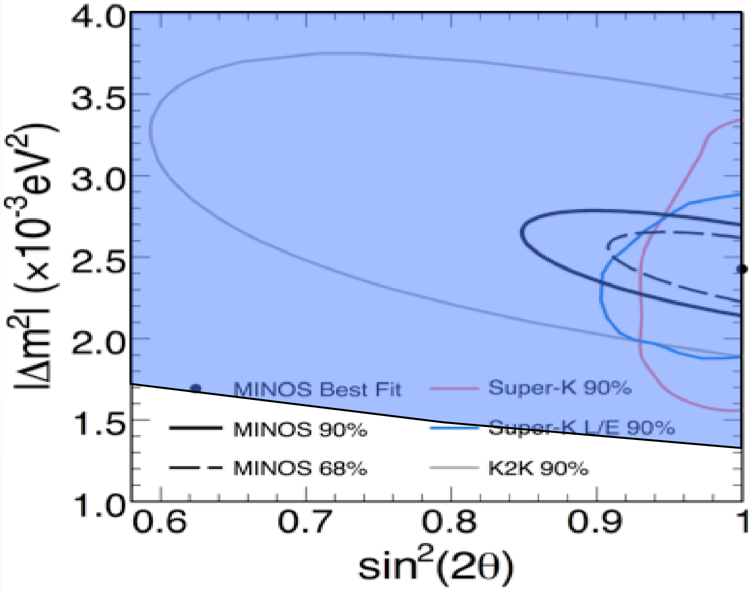
On behalf of the OPERA Collaboration

NOW 2012 – Conca Specchiulla - September 9-16, 2012

OutLine

- The OPERA experiment
  - Physics goal
  - Detection principle
  - Detector description
  - Data taking and analysis status
- $\nu_\mu \rightarrow \nu_\tau$ oscillation results
- $\nu_\mu \rightarrow \nu_e$ oscillation search: preliminary results

OPERA
Oscillation Project with Emulsion tRacking Apparatus

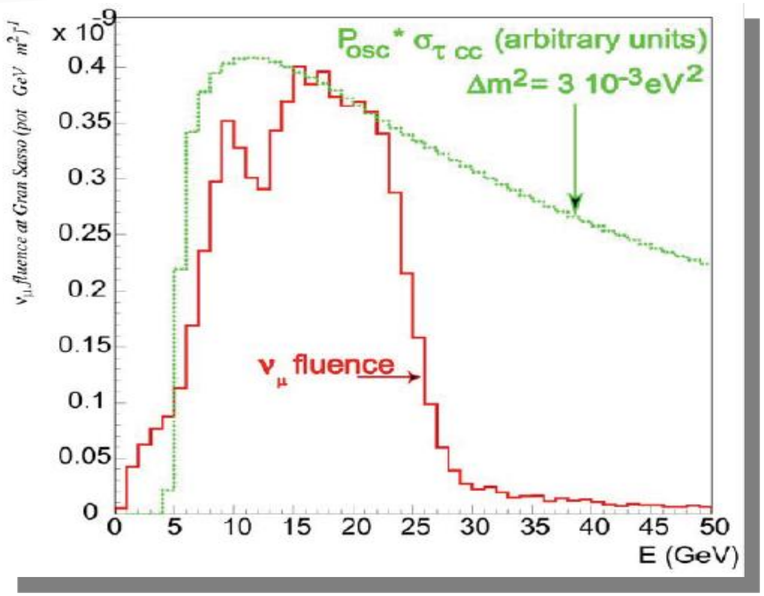


- Long baseline neutrino oscillation experiment in the CNGS (Cern Neutrino to Gran Sasso) ν_μ beam
- Direct detection of $\nu_\mu \rightarrow \nu_\tau$ oscillations in **appearance mode**
- Full coverage of the parameter space for the atmospheric neutrino sector
- Search for the subdominant $\nu_\mu \rightarrow \nu_e$ oscillations

CNGS
Cern Neutrinos to Gran Sasso

Conventional ν_μ **beam,** optimized for ν_τ appearance $\longrightarrow$ maximize the number of ν_τ CC interactions

• τ production threshold (3.5 GeV) and ν_τ CC cross section $\longrightarrow$ high energy beam
•"off peak" w.r.t. maximum oscillation probability (1.5 GeV)



Beam parameters

$< E_{\nu_\mu} >$	17 GeV
$(\nu_e + \bar{\nu}_e)/\nu_\mu$	0.89, 0.06 %
$\bar{\nu}_\mu/\nu_\mu$	2.1 %
ν_τ prompt	negligible
pot/year	4.5×10^{19}

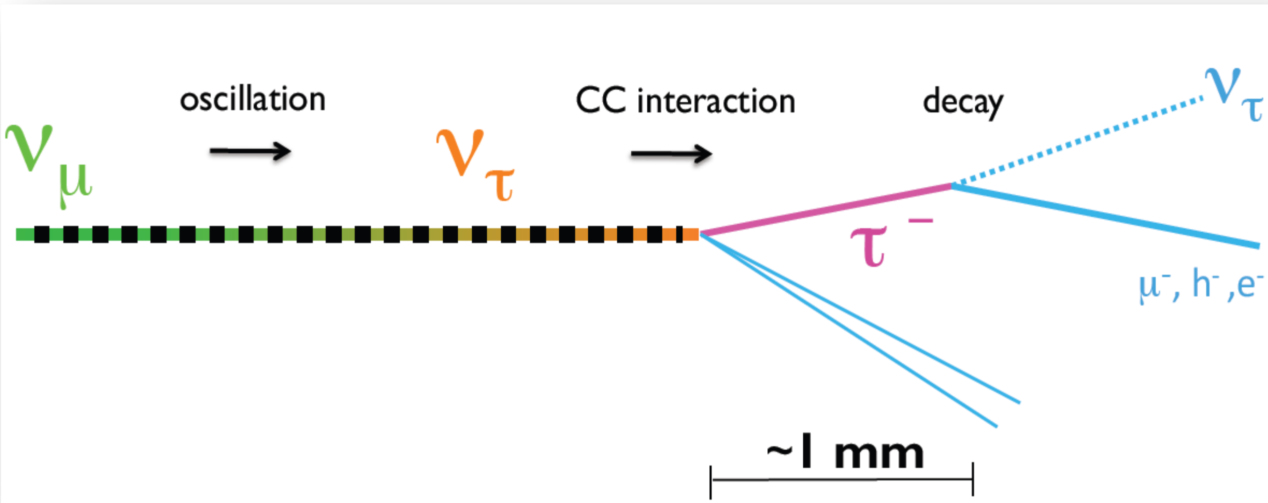
Contaminations given in terms of interaction rates in OPERA

For 22.5 x 10^{19} pot → Expected events 7.6 signal, 0.8 bg

New J. Phys. 14 (2012) 033017

ν_τ appearance: detection principle

Event-by-event separation of ν_τ CC interactions from dominant ν_μ interactions by direct observation of τ lepton decay

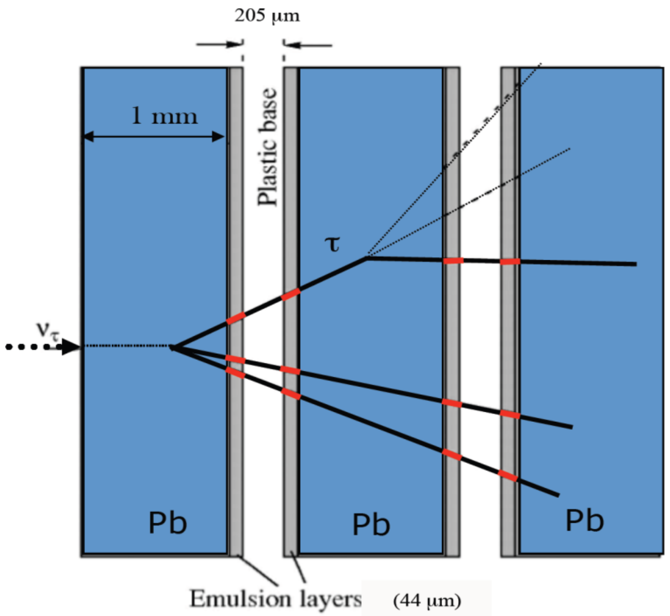


τ decay channel	B.R (%)
$\tau \to \mu$	17.7
$\tau \to e$	17.8
$\tau \to h$	49.5
$\tau \to 3h$	15.0

Target mass O(kton)
(low ν interaction cross-section)
High granularity detector
(τ decay detection, background rejection)

Neutrino interaction detector: ECC

- Target basic unit: **brick** of 57 nuclear emulsions interleaved by lead plates + 2 interface emulsions (CS)
- unambiguous measurement of the kink

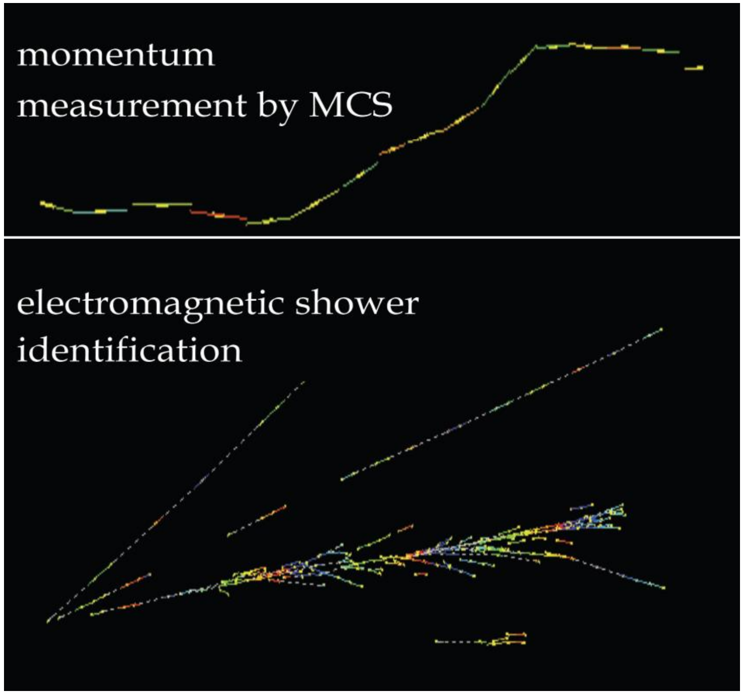


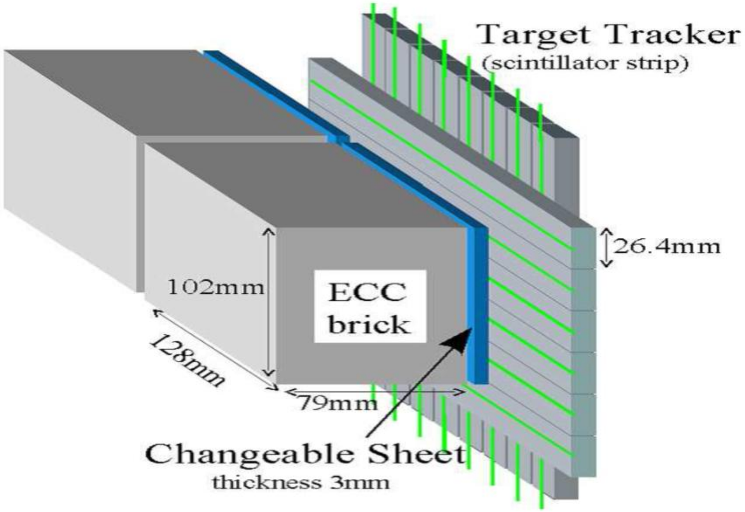
Total OPERA target : ~ 150000 bricks → 1.25 Kton

Neutrino interaction detector: ECC

"Stand- alone" detector:

- Momentum measurement by multiple Coulomb scattering
- E.m. shower detection and energy measurement
- Detection of highly-ionizing nuclear fragments produced in hadronic interactions (discrimination between interactions and decays)





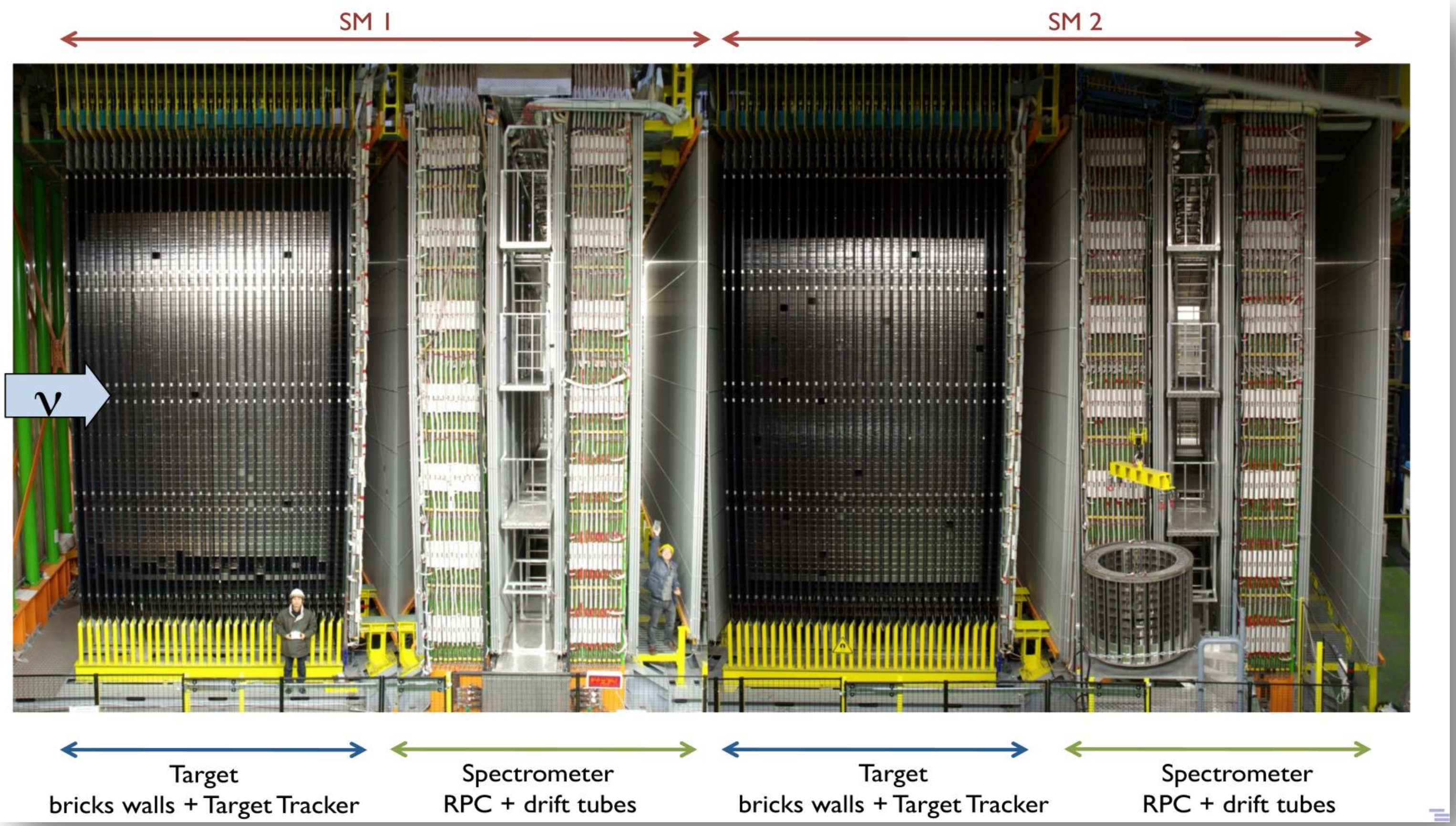
Each brick wall is followed by a plane of plastic scintillator strips oriented in X/Y direction and coupled by WLS optical fiber to PMTs.

Target Trackers (TT) are conceived to provide:
Neutrino Interaction Trigger
Brick Localization

The OPERA detector

Spectrometers:

- Muon ID, momentum and charge measurement
- Track measurements are performed by RPC planes inserted in the magnet yoke (1.5 T field) and by drift tubes planes to add more precision

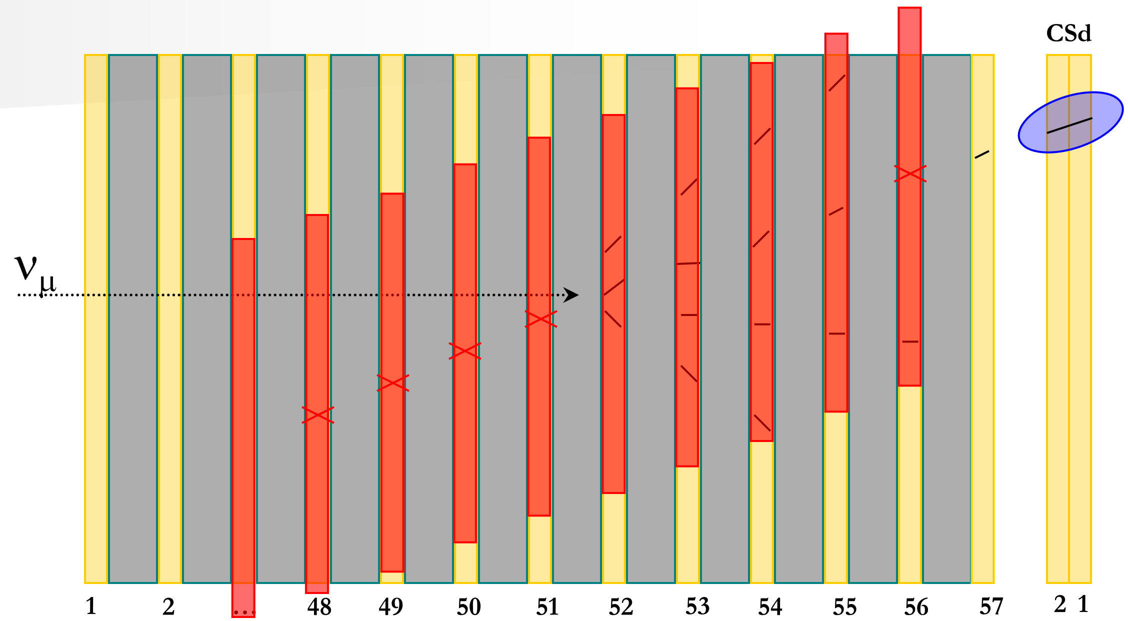


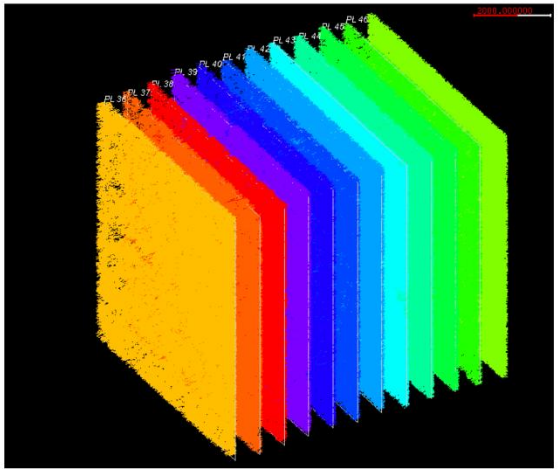
Vertex Location and Event Analysis

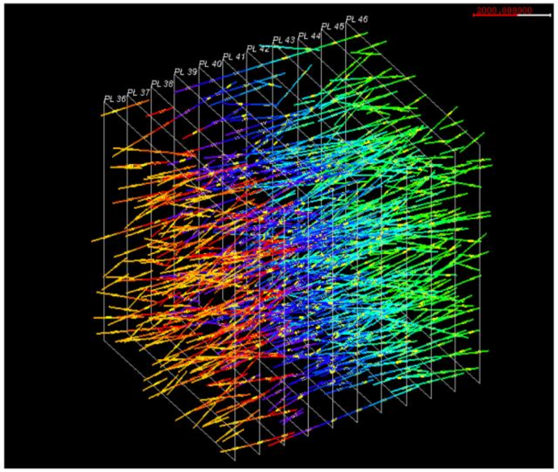
- CS analysis:
confirmation of electronic detector prediction

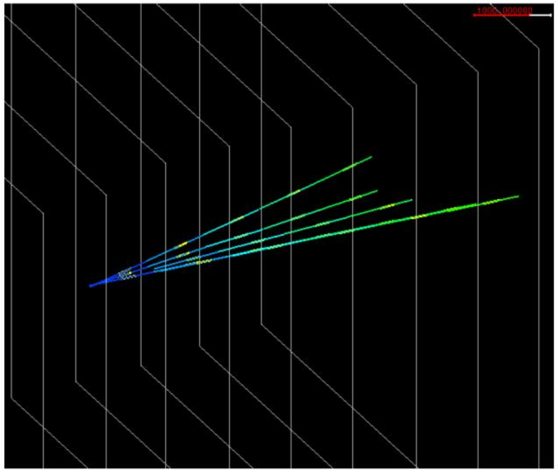
- Scan Back:
definition of the stopping point

- Volume Scan:
topological vertex reconstruction and decay search







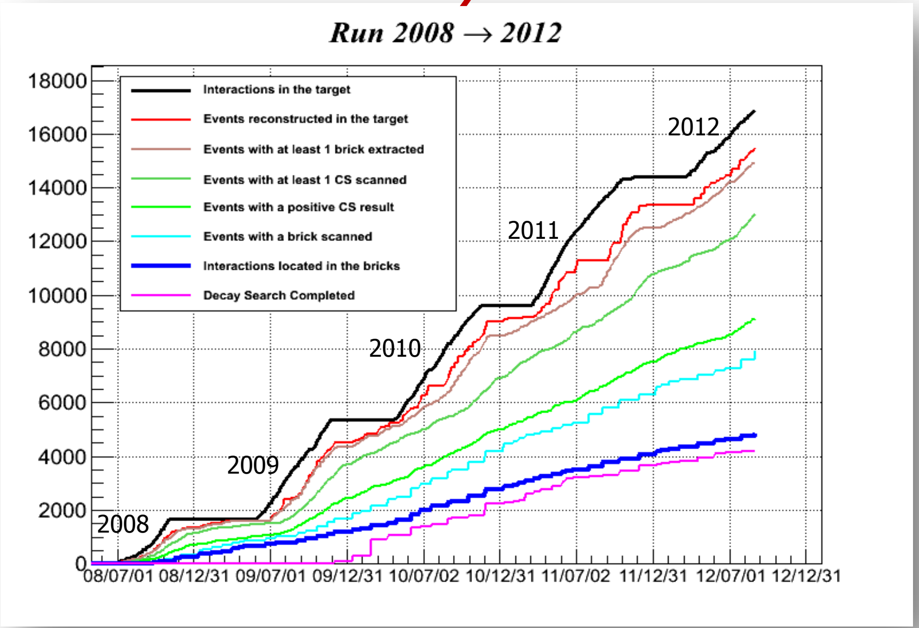


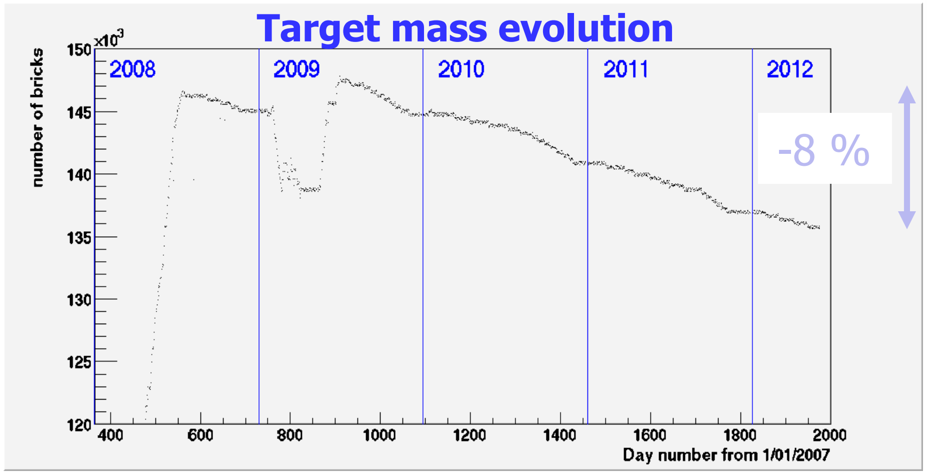
Data taking status

Run	Protons on target	In-targets events	Integrated POT / Proposed value
2008	1.78×10^{19}	1698	7.9 %
2009	3.52×10^{19}	3557	23.6 %
2010	4.04×10^{19}	3912	41.5 %
2011	4.84×10^{19}	4210	63.0 %
2012	($\sim 4.3 \times 10^{19}$)	(~ 3700)	(~ 82%)

Expected POT after 2012 Run: 18.45×10^{19} (Proposal: 22.5×10^{19})

Data analysis status



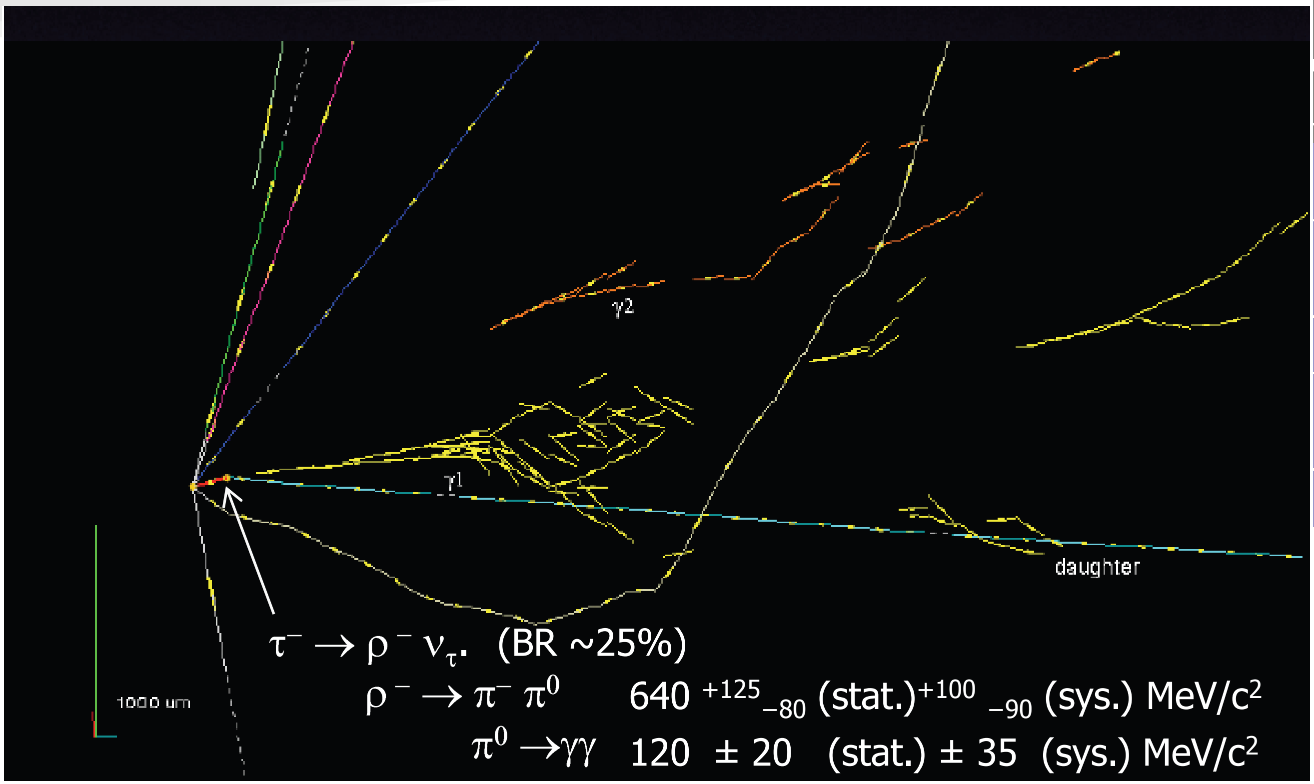


Located neutrino interactions	4611
Fully analysed events	4126
$\nu\tau$ candidate events	2

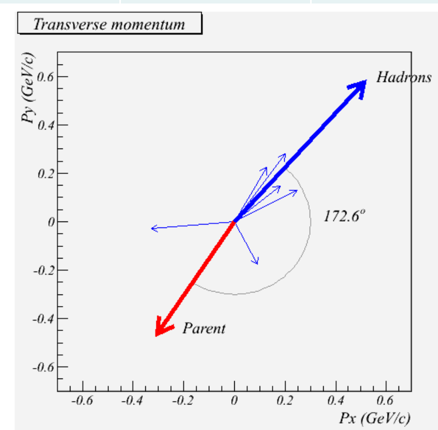
First ν_τ candidate event

Found in the decay search of 2008 and 2009 Physics Runs released in June 2010

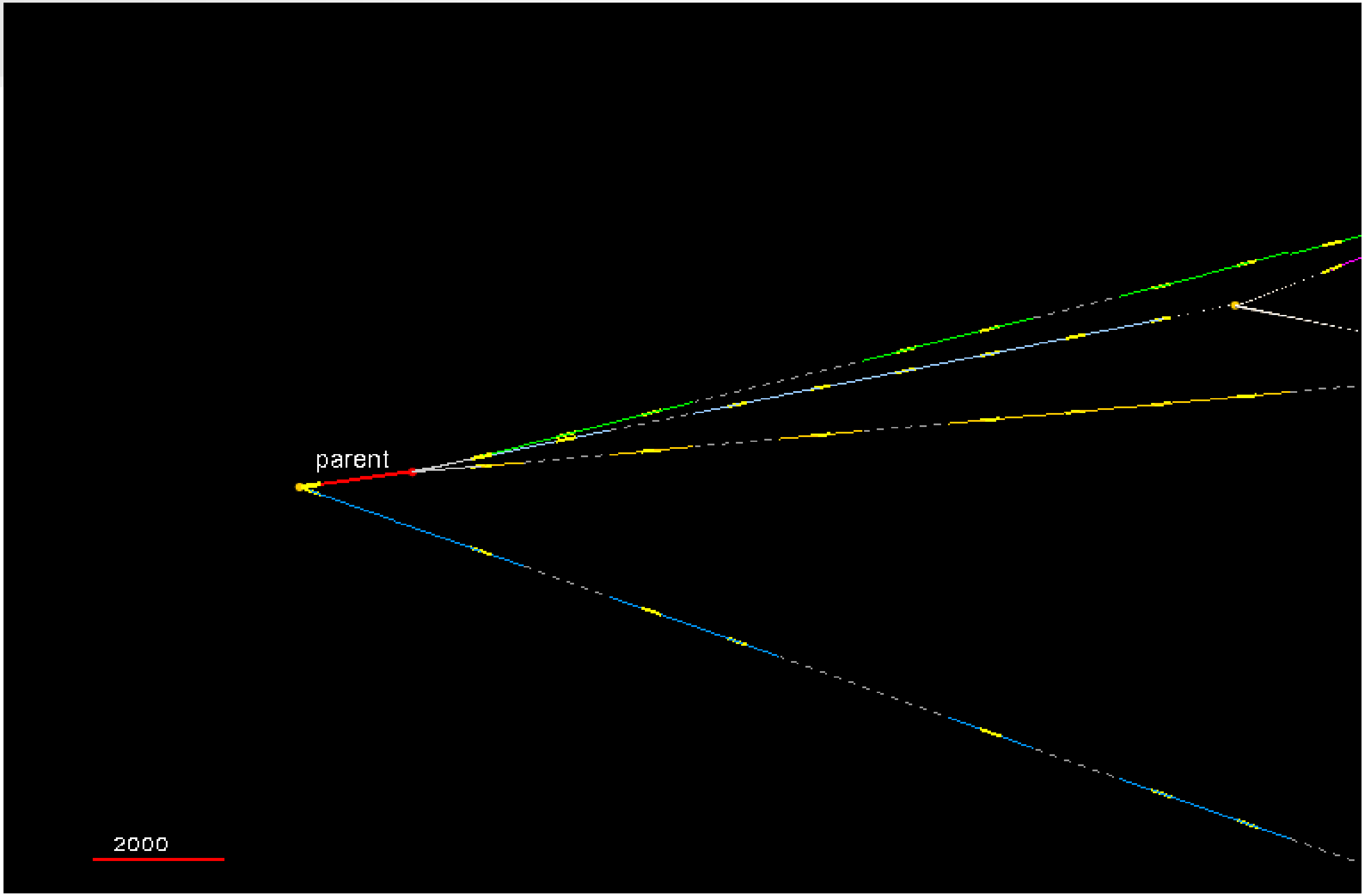
(Phys. Lett. B 691 (2010) 138)



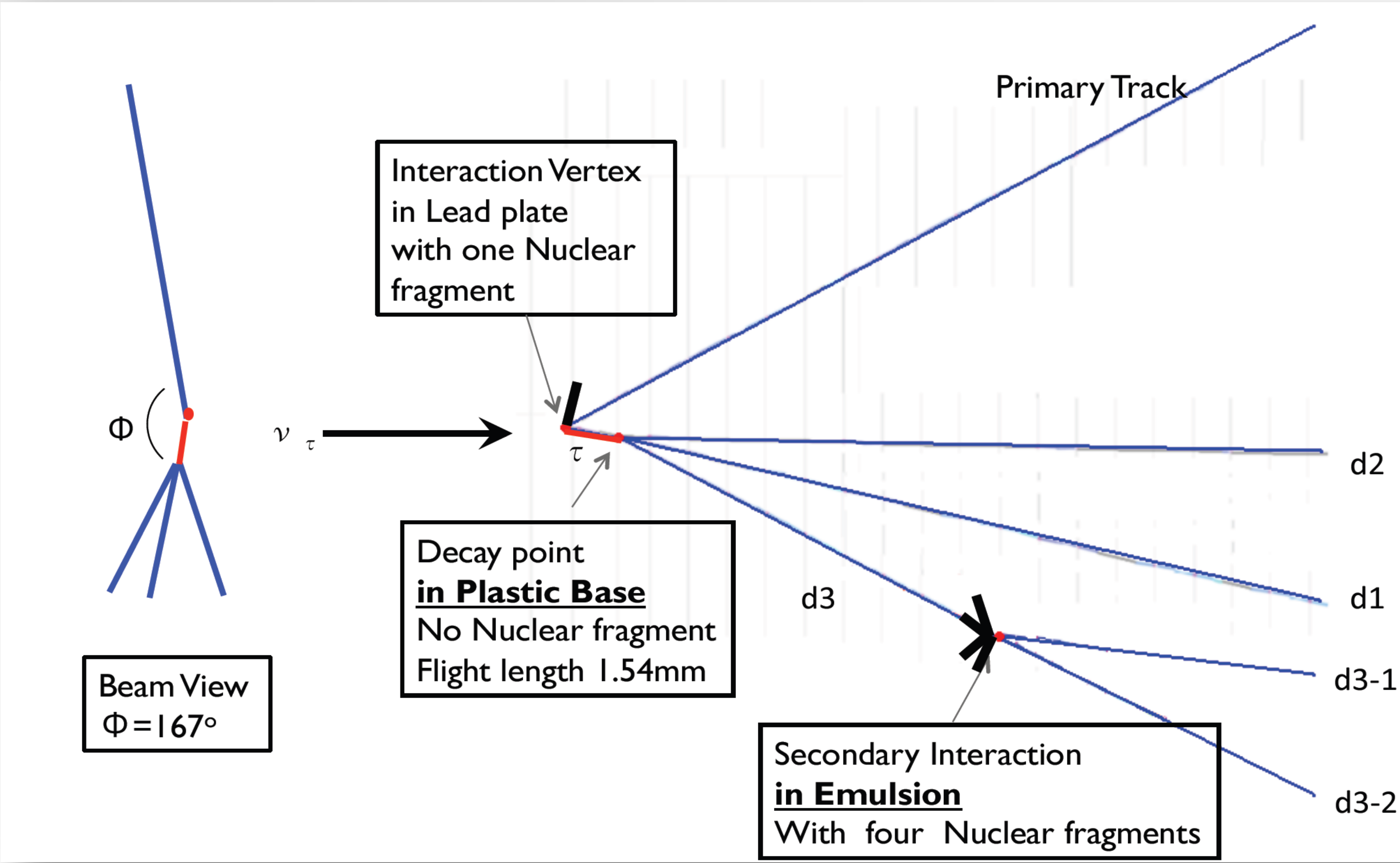
VARIABLE	AVERAGE	Selection criteria
kink (mrad)	41 ± 2	>20
decay length (μm)	1335 ± 35	within 2 lead plates
P daughter (GeV/c)	$12\ ^{+6}_{-3}$	>2
Pt (MeV/c)	$470\ ^{+230}_{-120}$	>300 (γ attached)
missing Pt (MeV/c)	$570\ ^{+320}_{-170}$	<1000
ϕ (deg)	173 ± 2	>90



New ν_τ candidate event



New ν_τ candidate event

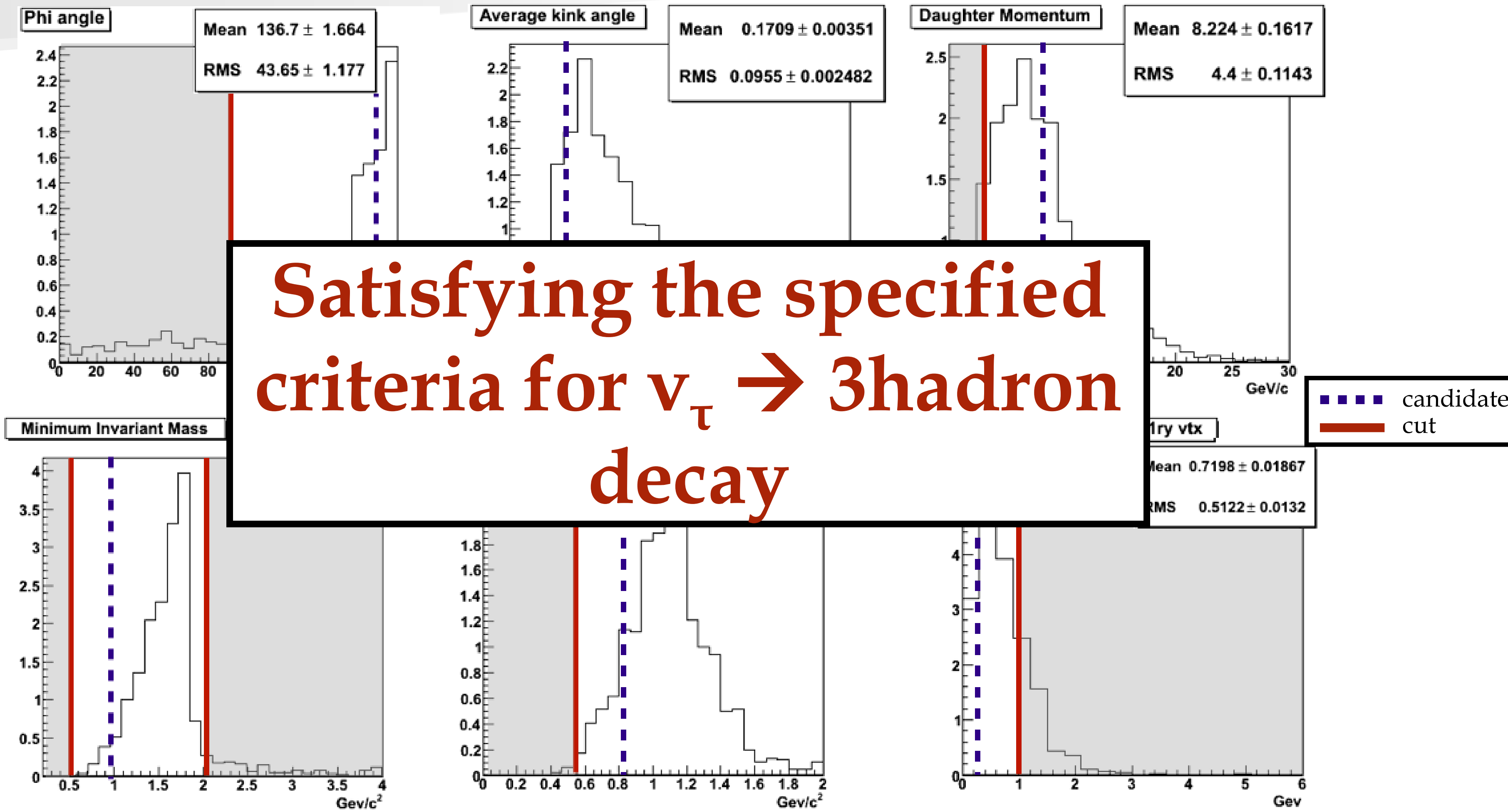


New ν_τ candidate event

- No muons at the 1ry vertex: primary track incompatible with muon hypothesis (p/range)
- Independent momentum measurements were carried out in two different labs.

Track#	Momentum (1σ interval) [GeV/c]	Particle ID	Method / Comments
Primary	2.8 (2.1-3.5)	Hadron	• Momentum-Range Consistency Check Stops after 2 brick walls. Incompatible with muon (26~44 brick walls)
d1	6.6 (5.2 - 8.6)	Hadron	• Momentum-Range Consistency Check
d2	1.3 (1.1 -1.5)	Hadron	• Momentum-Range Consistency Check
d3	2.0 (1.4 - 2.9)	Hadron	• Interaction in the Brick @ 1.3cm downstream

New ν_τ candidate event



Satisfying the specified criteria for $\nu_\tau \rightarrow$ 3hadron decay

ν_τ search status

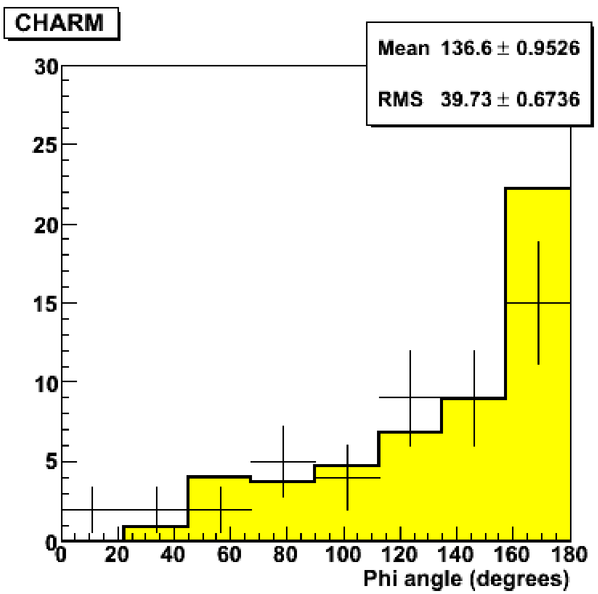
Years	Status	Number of analysed events	Expected ν_τ events (Preliminary)	Observed ν_τ Candidate Events	Expected BG (Preliminary)
2008-2009	Finished	2783		1	
2010-2011	In analysis	1343		1	
2012	Started				
Total		4126	2.1	2	0.2

Preliminary

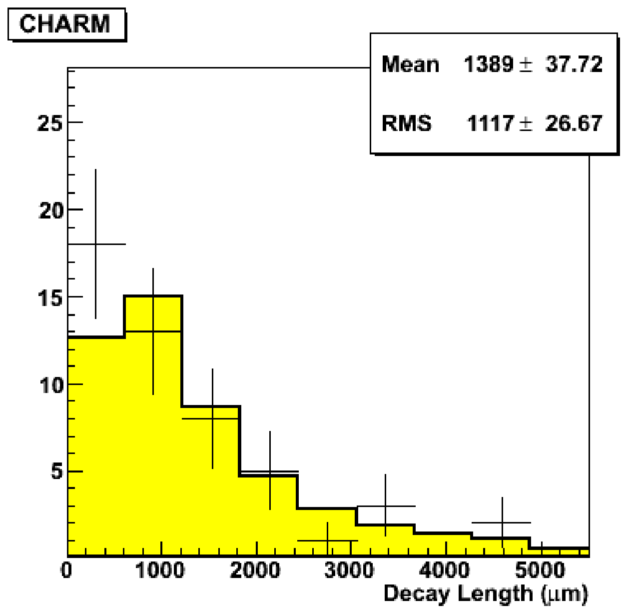
$\nu_\mu \rightarrow \nu_\tau$ control sample

Charm Data – MC comparison: proof of the τ efficiency

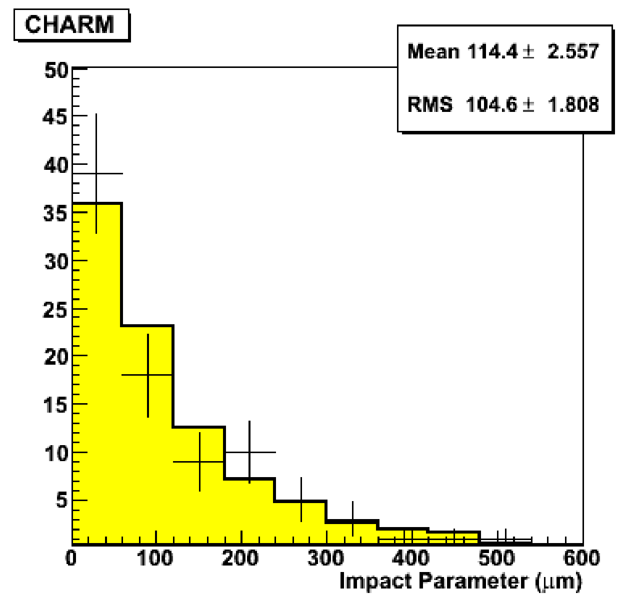
Detected : 49 events ⇔ Expected 51±7.5 events



<u>**Phi angle**</u>



<u>**Decay length**</u>

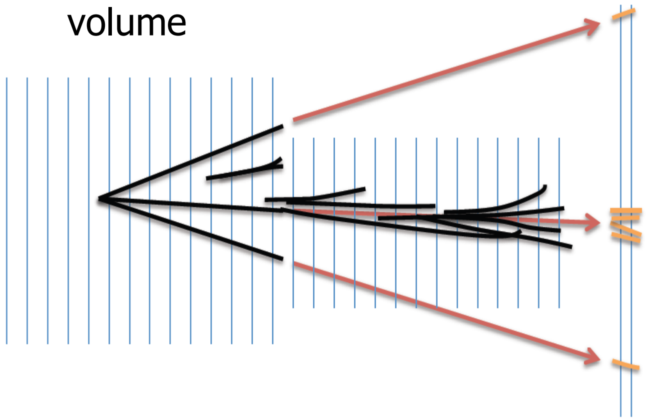


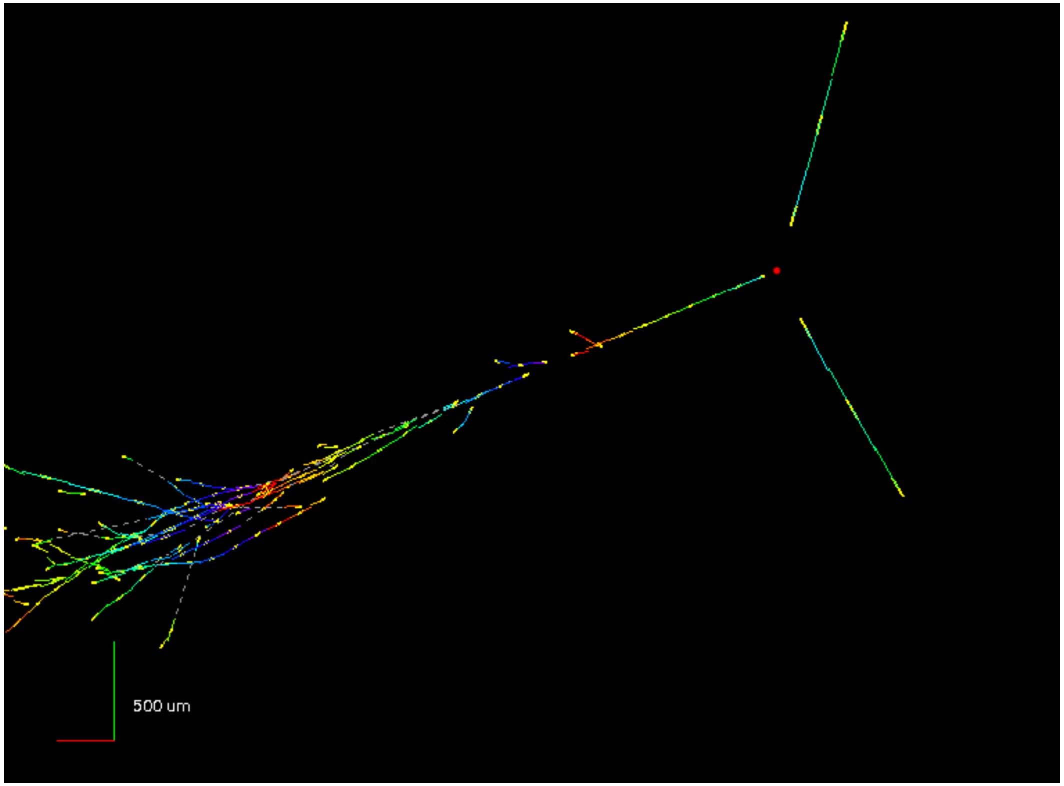
<u>**Impact Parameter**</u>

$\nu_\mu \rightarrow \nu_e$ oscillation search

Systematic ν_e search applied to the 2008 and 2009 located event data sample without μ in the final state (NC-like)

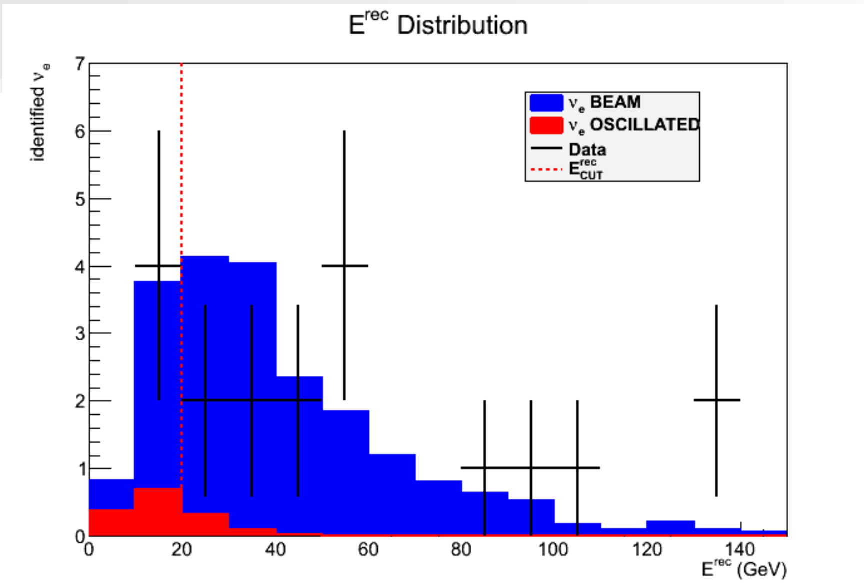
- Extrapolate primary tracks to CS
- Search for shower hints on CS
- If shower hints, open additional volume





Expected events:
1.5 oscillated + 19.2 beam
Confirmed: 19

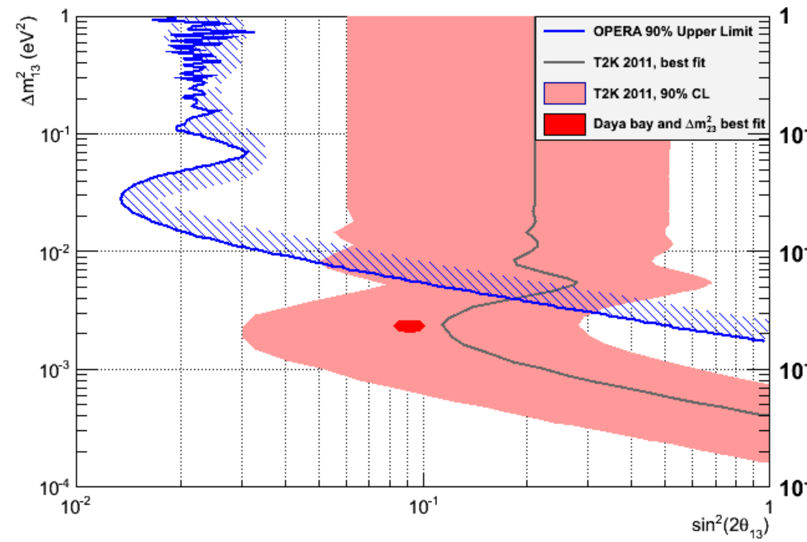
$\nu_\mu \rightarrow \nu_e$ oscillation search



Low-energy selection to improve S/N:
E_ν<20GeV

Expected events:
1.1 oscillated + 3.7 beam
Observed ν_e: 4 events

Δm_{23}=2.45E-3
$\text{Sin}^2\theta_{23}$=0.51



Conclusions

✓ OPERA is successfully collecting data since 2008.

✓ We expect to reach 18.45 x 10^{19} integrated p.o.t. by the end of 2012 run, corresponding to ~ 82% of the nominal intensity.

✓ $\nu_\mu \rightarrow \nu_\tau$ oscillation search:
2 ν_τ candidate events observed so far
(expected: 2 signal, 0.2 BG – preliminary -)
A few more events are under study.

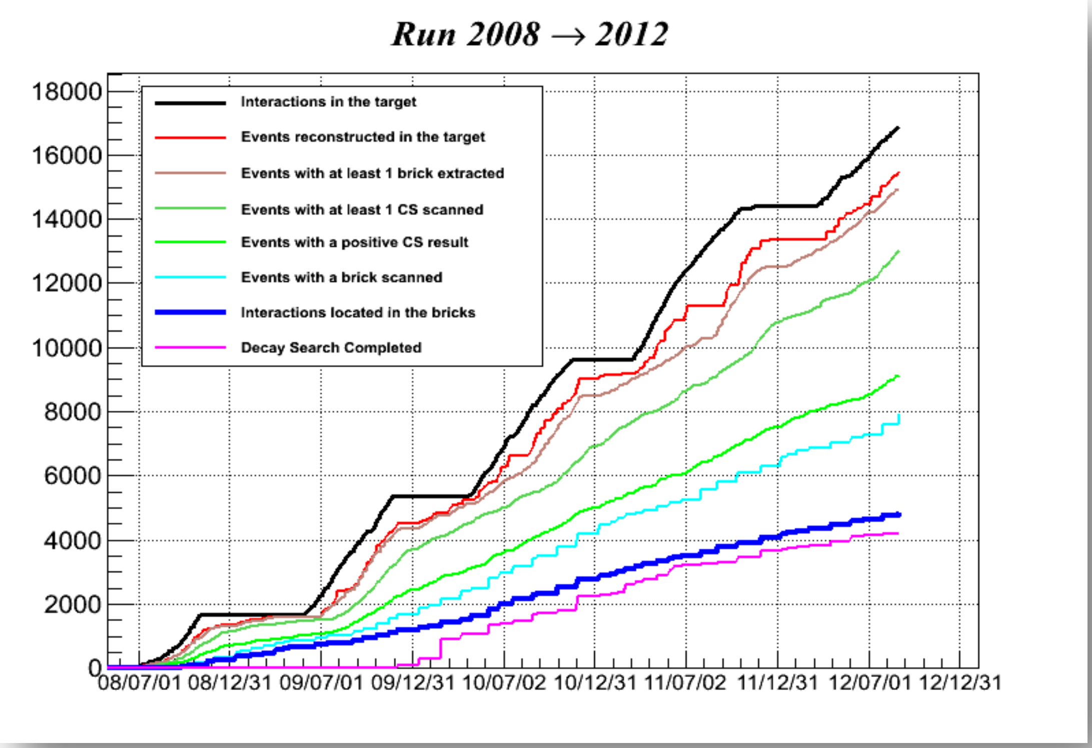
✓ $\nu_\mu \rightarrow \nu_e$ oscillation search:
19 ν_e events observed in 2008 – 2009 statistics
4 with E_ν < 20 GeV (expected: 1.1 oscillated, 3.7 BG).

Statistics will be improved by a factor of ~3

…and perspectives

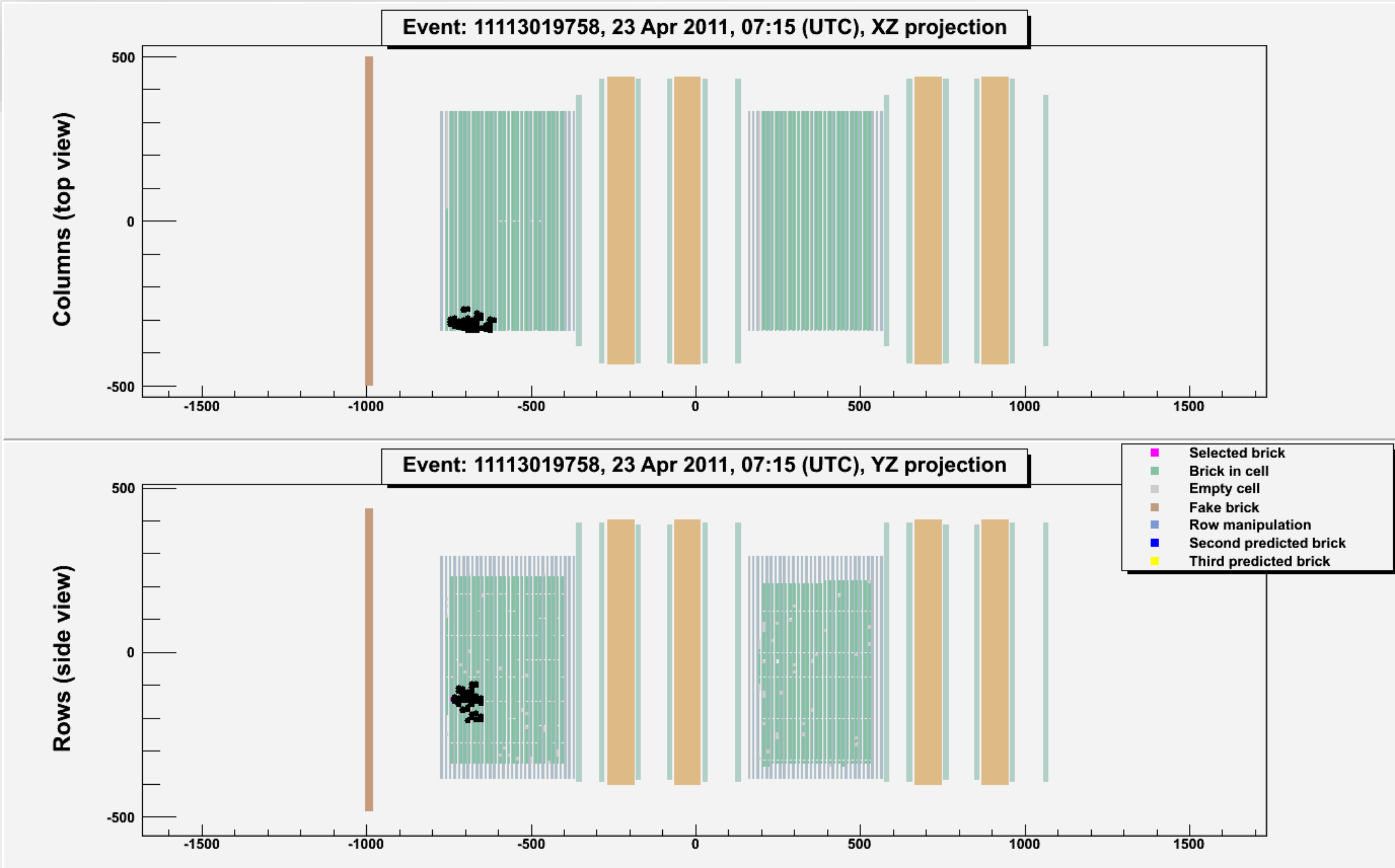
Plan for the next coming months →

Big boosts are foreseen both for scanning (new event location) and analysis (backgroud reduction)

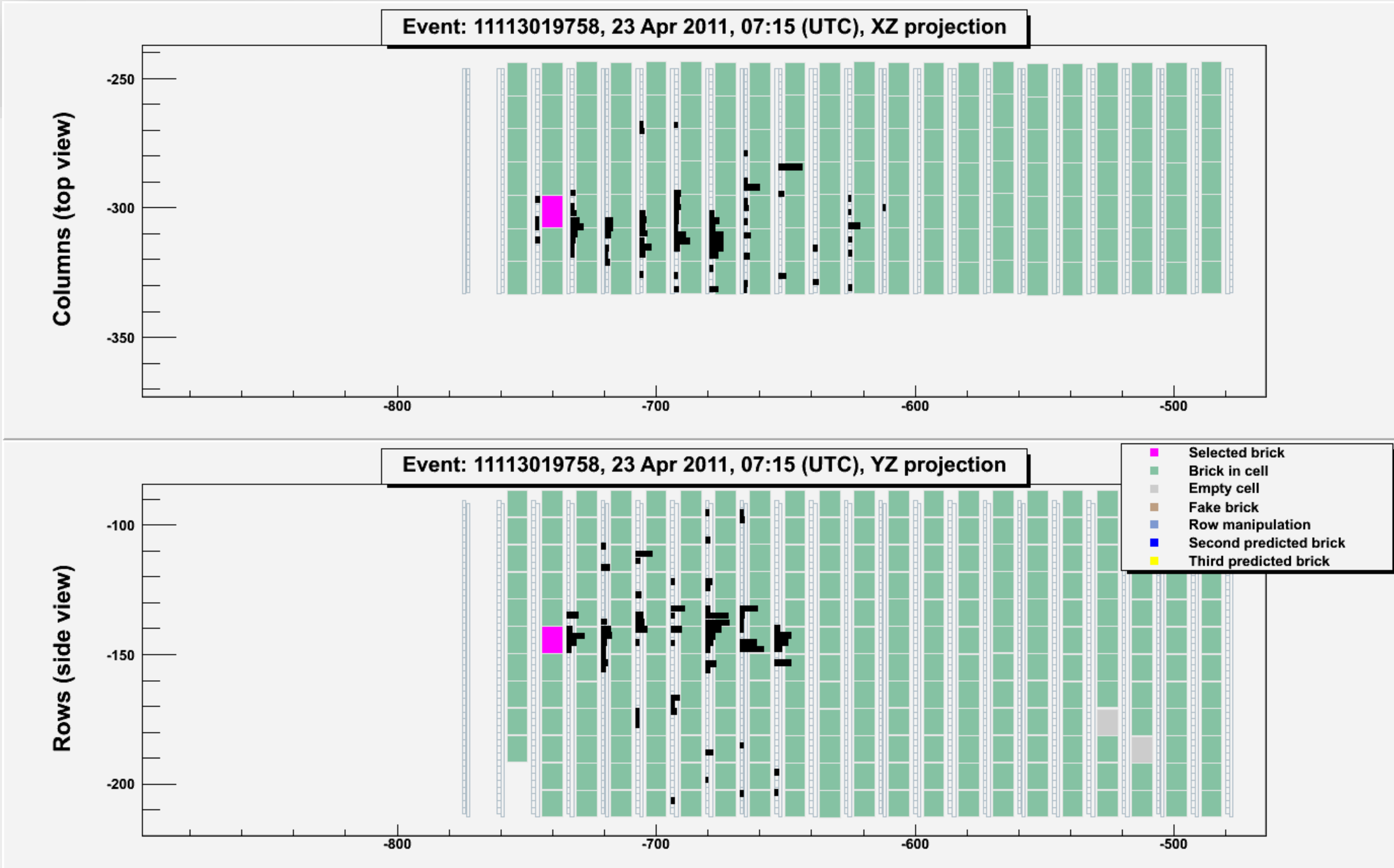


- backup

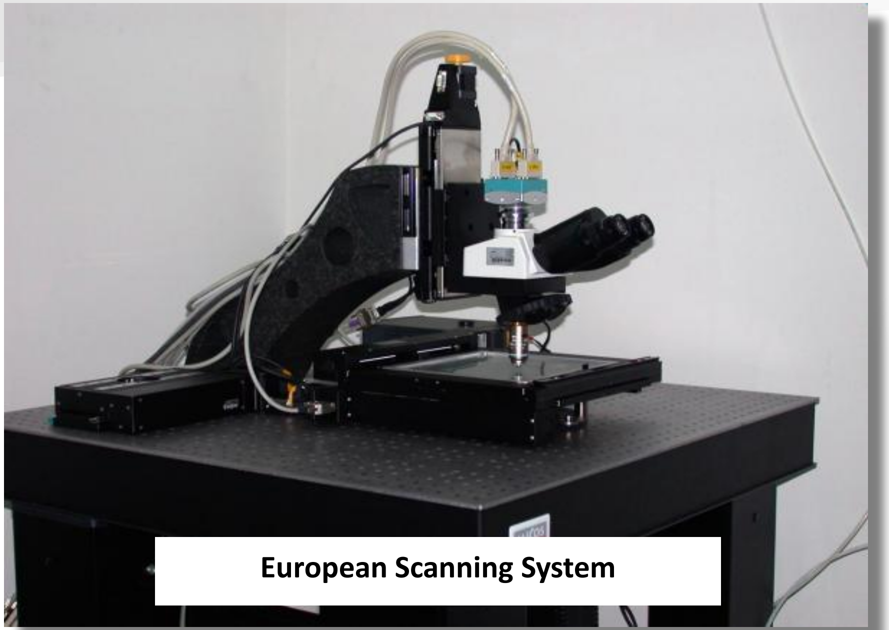
New ν_τ candidate event



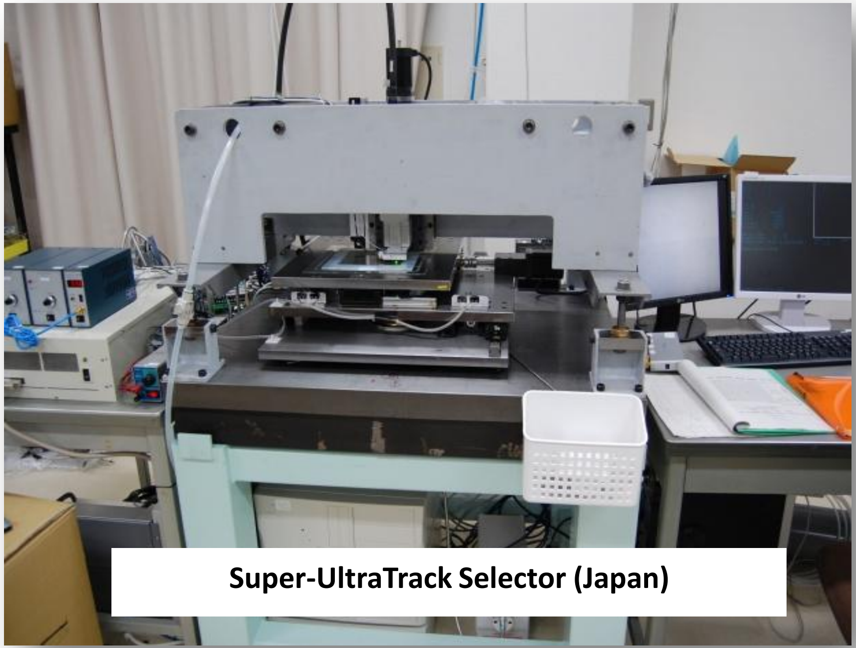
New ν_τ candidate event



Emulsion Scanning System



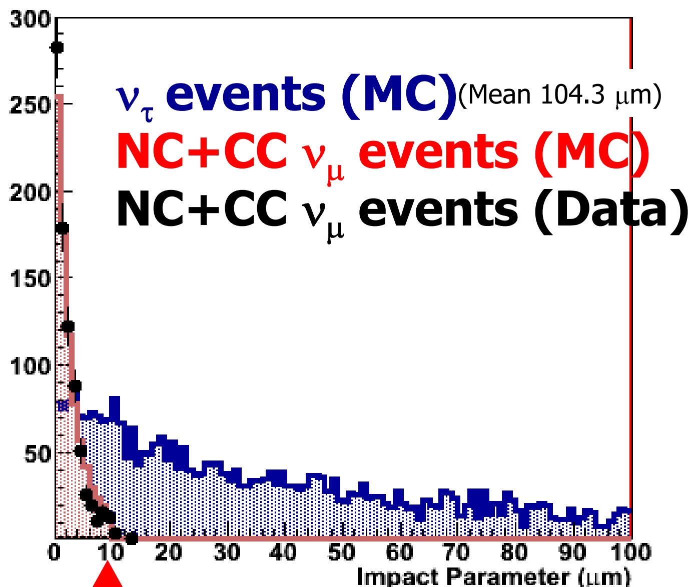
European Scanning System



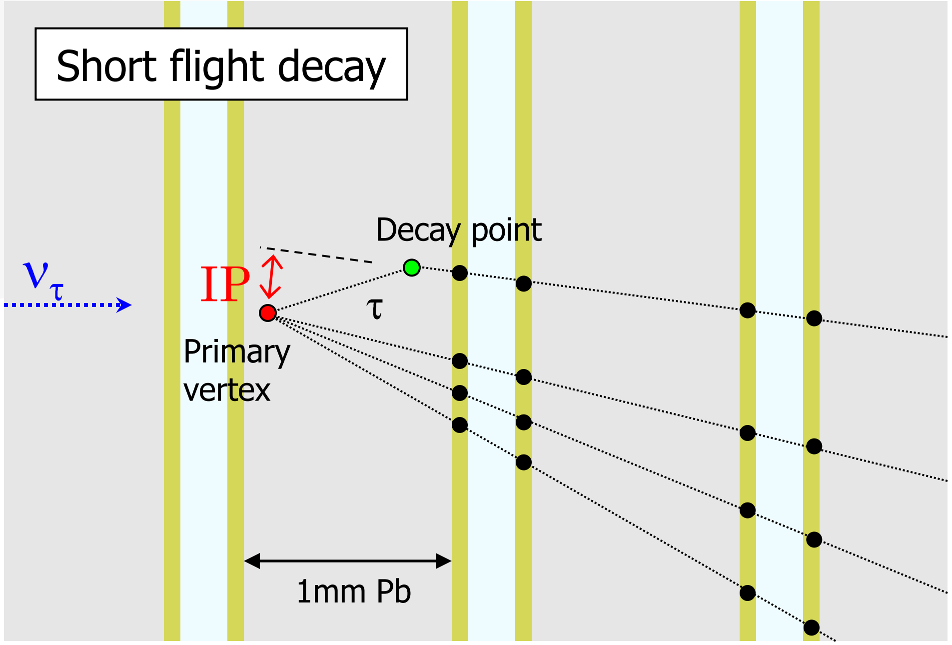
Super-UltraTrack Selector (Japan)

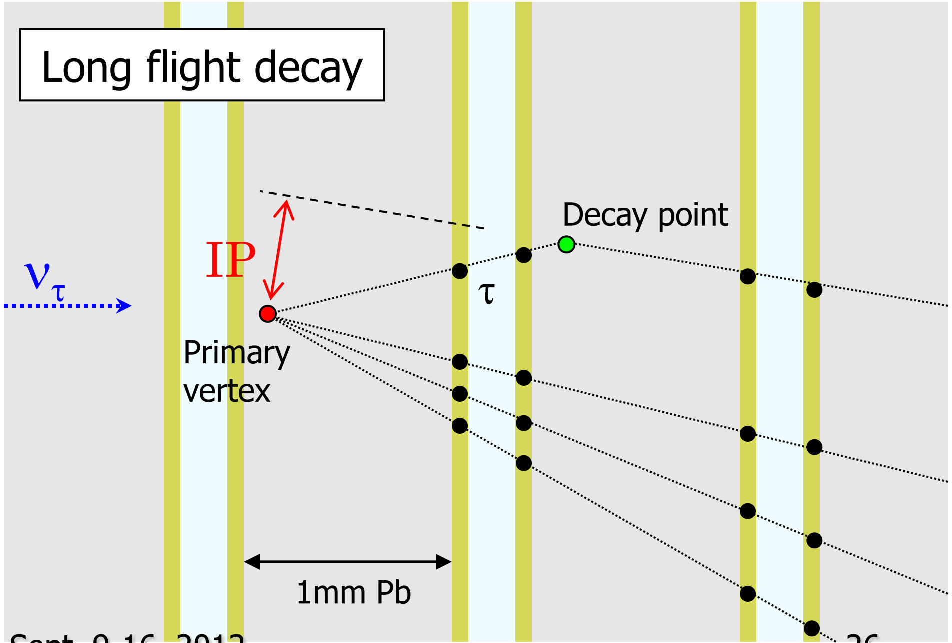
ν_τ CC Detection

Impact Parameter distribution



10 μm ↔ (cτ = 87μm)

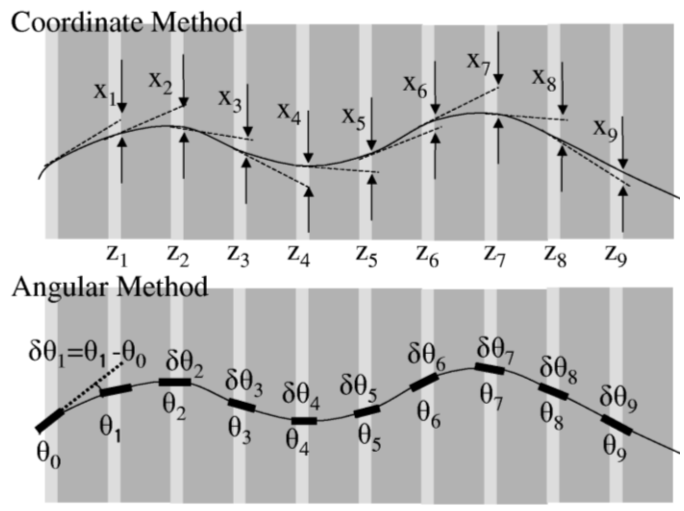




ECC features

Momentum measurement

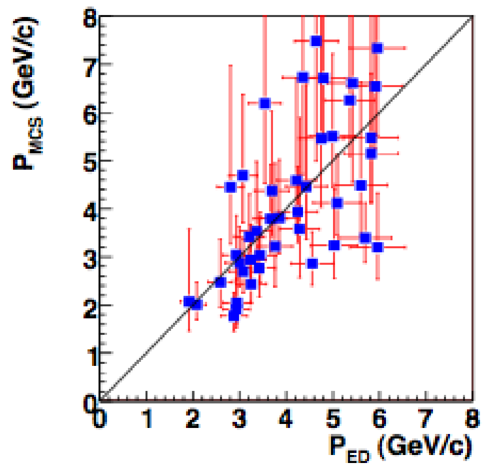
Measurement of the position or angular displacement given by Multiple Coulomb Scattering (MCS) Ref: New Journal of Physics 14(2012)013026



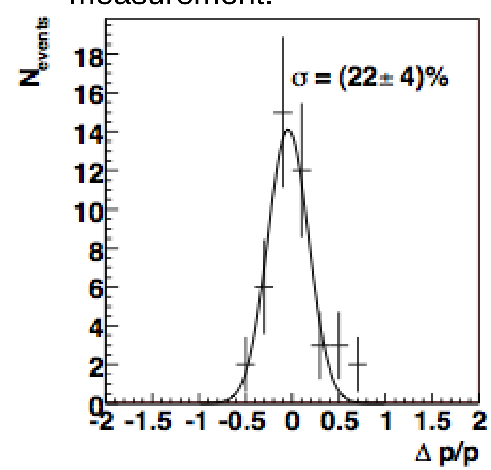
$$d\theta^{RMS} = \frac{13.6}{pc\beta} z \sqrt{\frac{x}{X_0}}\left(1+0.038\ln\left(\frac{x}{X_0}\right)\right)$$

Soft muon data sample

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



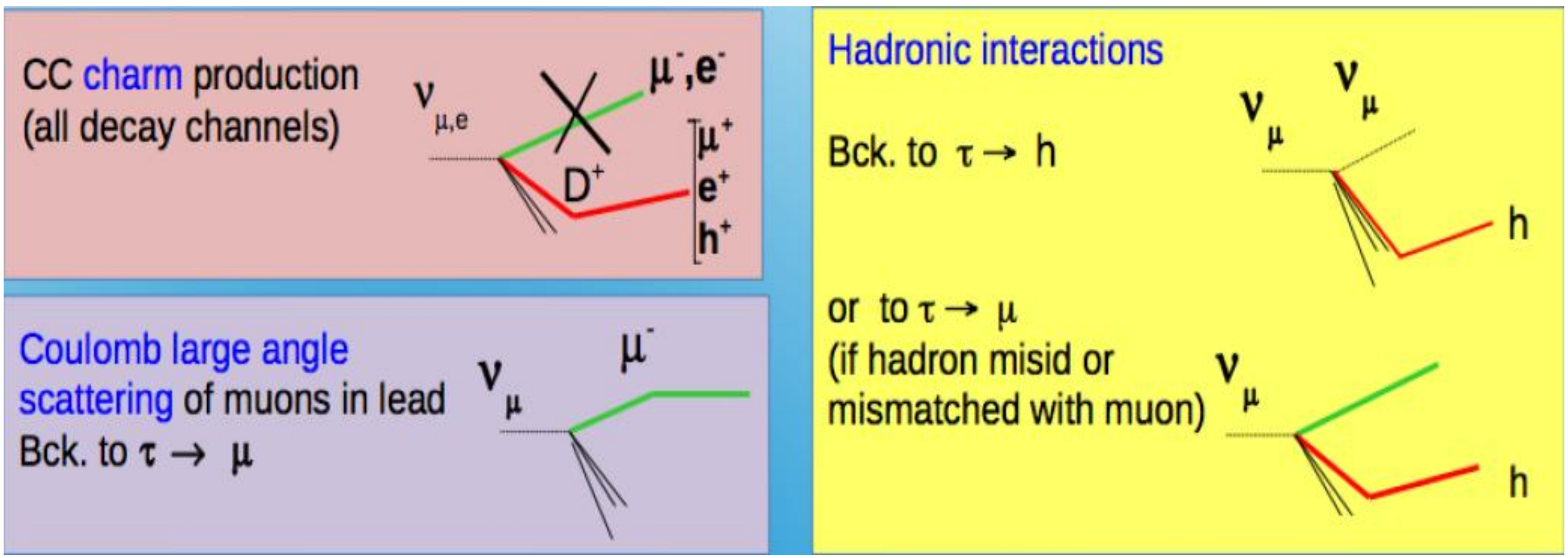
The relative difference between the two measurements with respect to the electronic detector measurement.



Particle ID

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

Background


CC charm production
(all decay channels)
ν μ,e
μ⁻,e⁻
D⁺
μ⁺
e⁺
h⁺
Coulomb large angle
scattering of muons in lead
Bck. to τ → μ
ν μ
μ⁻
Hadronic interactions
Bck. to τ → h
ν μ
ν μ
h
or to τ → μ
(if hadron misid or
mismatched with muon)
ν μ
h

$\nu_\mu \rightarrow \nu_\tau$ oscillation analysis

2008-2009 data analysis completed (New Journal of Physics 14 (2012) 033017)

- 4.8×10^{19} pot, 34% of available sample, 2.6 × more statistics w.r.t. 1^{st} τ candidate publication
- 2738 fully analysed events (decay search). **No new τ**

Analysis improvements

1. Search of highly ionizing tracks in hadronic interactions ($\downarrow$ bckg for $\tau \rightarrow h$)
2. Follow down of vertex tracks in the emulsion $\rightarrow$ p-range correlations $\rightarrow$ increased μ-ID efficiency

   $\downarrow$ charm background

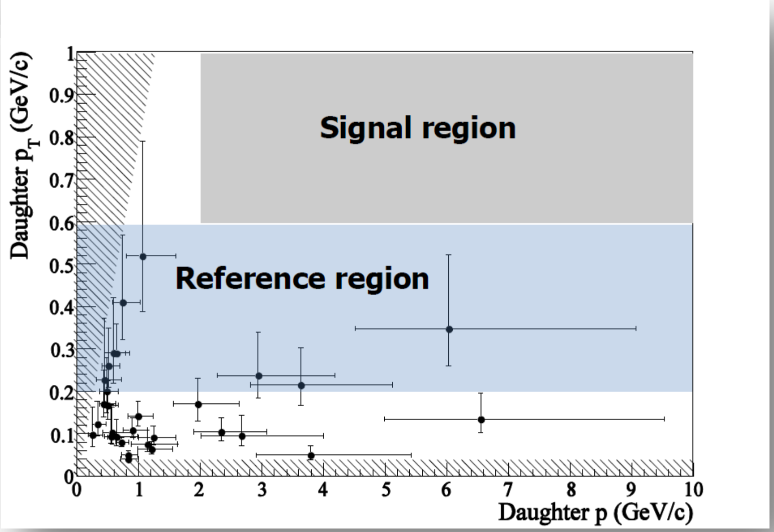
   $\downarrow$ hadronic bckg from ν_μ CC with μ misID

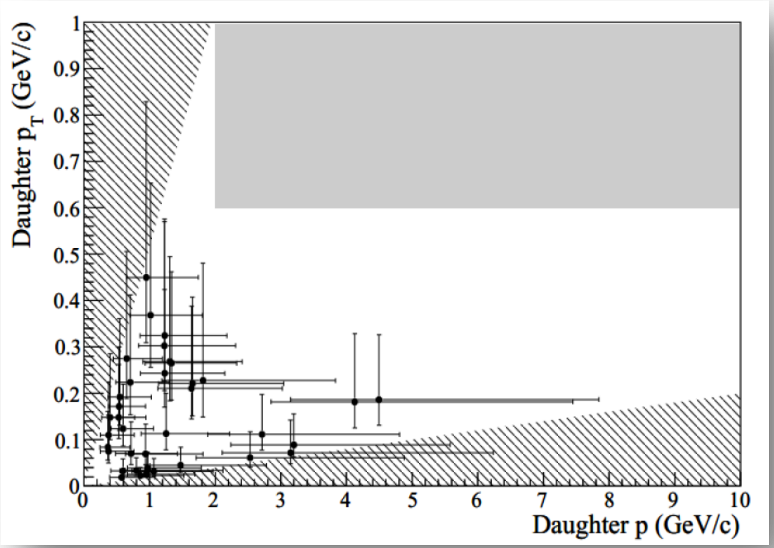
1. Implementation of state-of-the art charm cross section from CHORUS ($\uparrow\sigma$)

   Increase of charm background from x1.6 to x 2.4 depending on the channel (h-μ)

$\nu_\mu \rightarrow \nu_\tau$ oscillation analysis

Hadronic interaction background



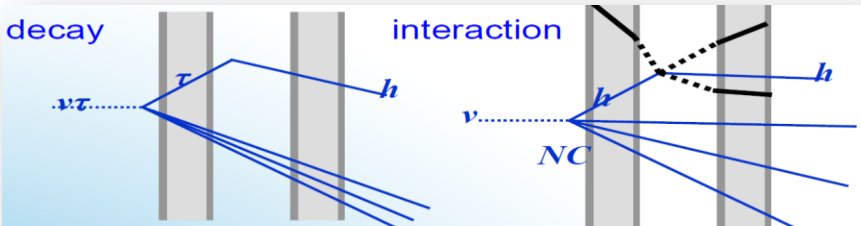


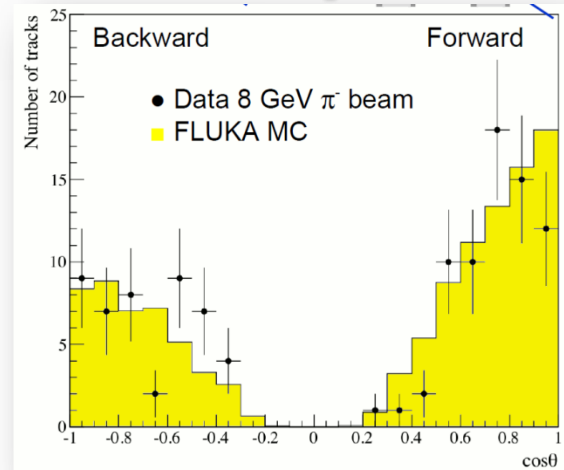
Hadronic tracks produced in ν interactions showing kink topology:
- 14 m of tracks scanned (equivalent to 2300 NC events)
- No events in the signal region
- 10 events in reference region (P_t 200 ÷ 600 MeV/c), 10.8 expected

4 GeV/c pion interactions in test beam bricks:
- 190 m of tracks scanned
- 534 interactions found
- 214 kinks detected
- No events in the signal region

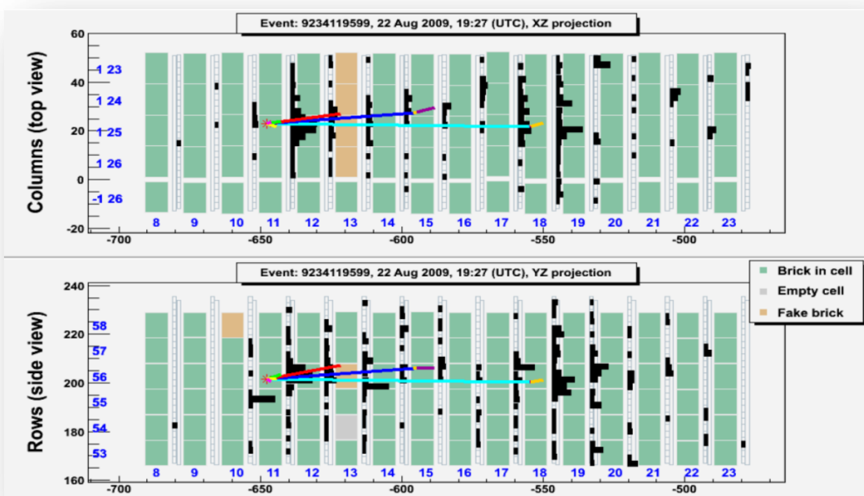
$\nu_\mu \rightarrow \nu_\tau$ oscillation analysis

Bkg reduction: search for "black" tracks in a large field of view 2.5 x 2.1 mm^2





Bkg reduction: track follow-down



Tracks produced in potentially interesting ν interactions are followed in downstream bricks to detect secondary interactions and/or apply momentum-range consistency checks:

Misidentified muons from charm events: 5% -> 3.3%

Factor 100 BG reduction in $\tau \rightarrow \mu$ channel due to muon mismatch in CC and NC interactions

BEAM

CNGS “standard” beam

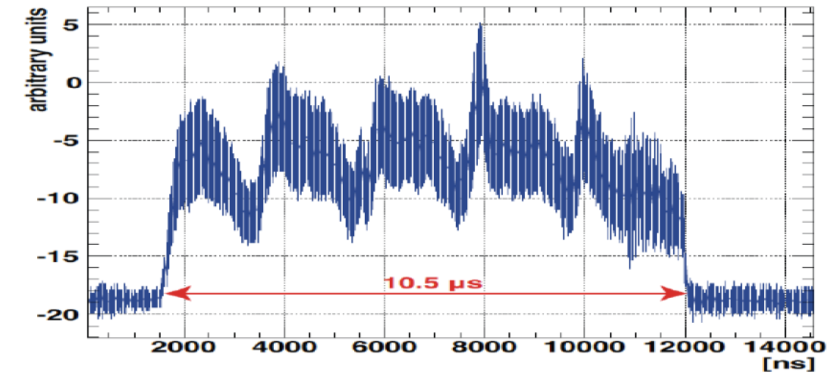
- Used for oscillation studies and “statistical” ν velocity measurement
- 2 fast extractions (10.5 μs long) per SPS cycle (6 s) separated by 50 ms
- $\sim 2.1\times10^{13}$ pot/extraction, $\sim 4.5\times10^{19}$ pot/year

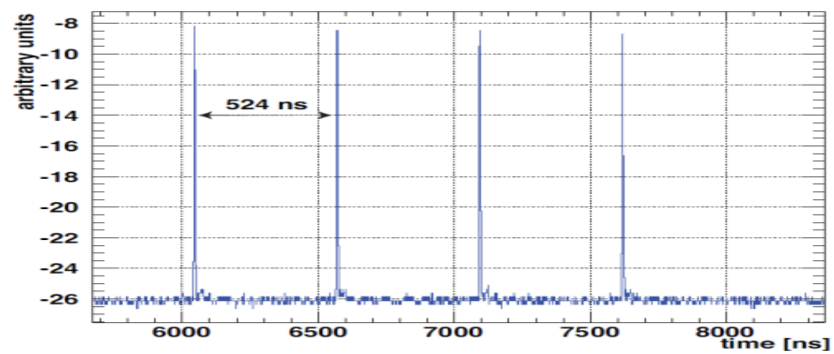
CNGS short bunched beam in Nov 2011

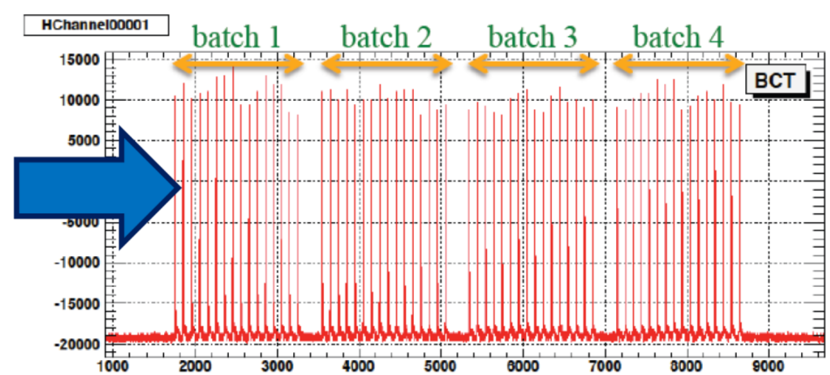
- Designed for ν velocity measurement (validation of statistical procedure)
- Oct 22-Nov 6, 2011 ($\sim 4\times10^{16}$ pot in total)
- 1 extraction/cycle (13.2 s long)
- 4 bunches/extraction (524 ns separation)
- Bunch width s ~ 3 ns

CNGS short bunched beams in May 2012

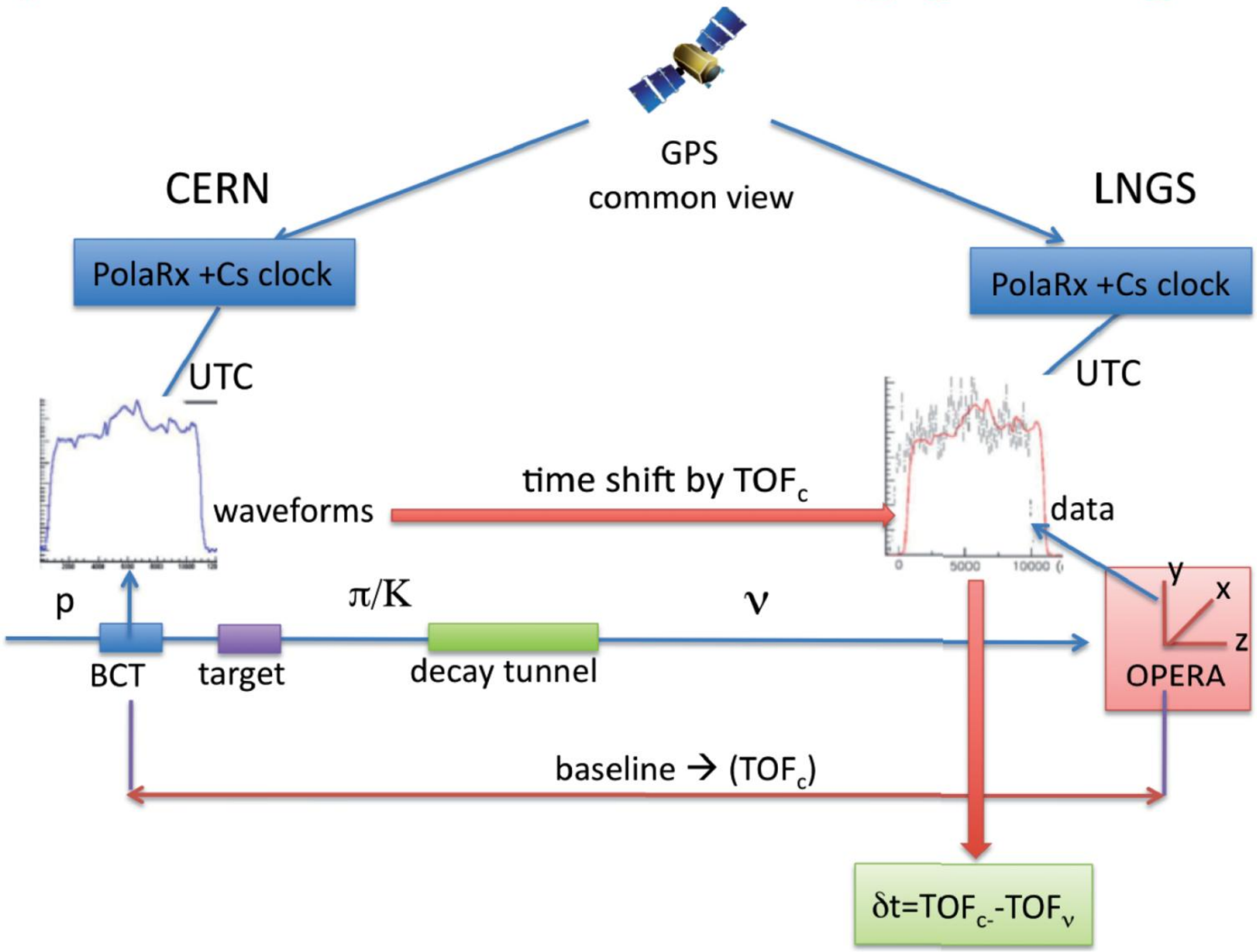
- Designed for ν velocity measurement (final assessment)
- May 10-24, 2012 ($\sim 2\times10^{17}$ pot in total)
- 1 extraction/cycle (13.2 s long)
- 4 batches/extraction (300 ns separation)
- 16 bunches/batch (100 ns separation)
- Bunch width s = 1.8 ns







Syncronization



The two systematic errors

Time delay of the 8.3 km optical fiber from external to internal Labs

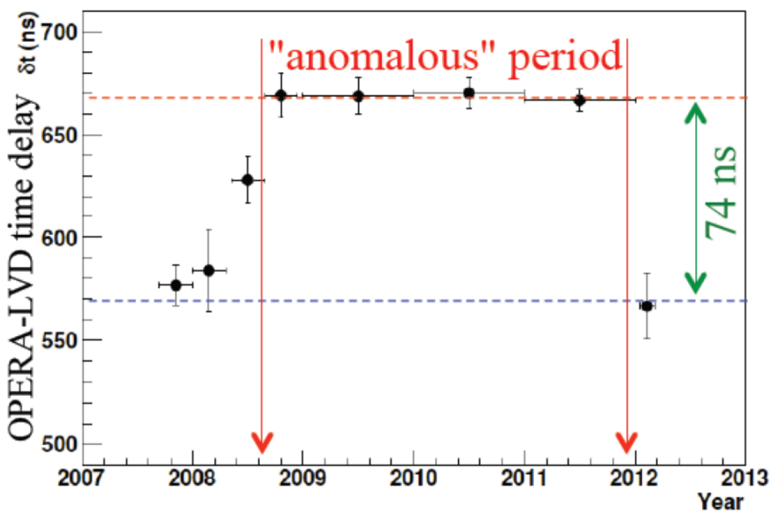
- Measurements during winter shutdown different from the previous ones: 74 ns to increase the neutrino anticipation (dominant effect)
- Explanation of the mismatch: fiber not properly connected to the OPERA Master Clock

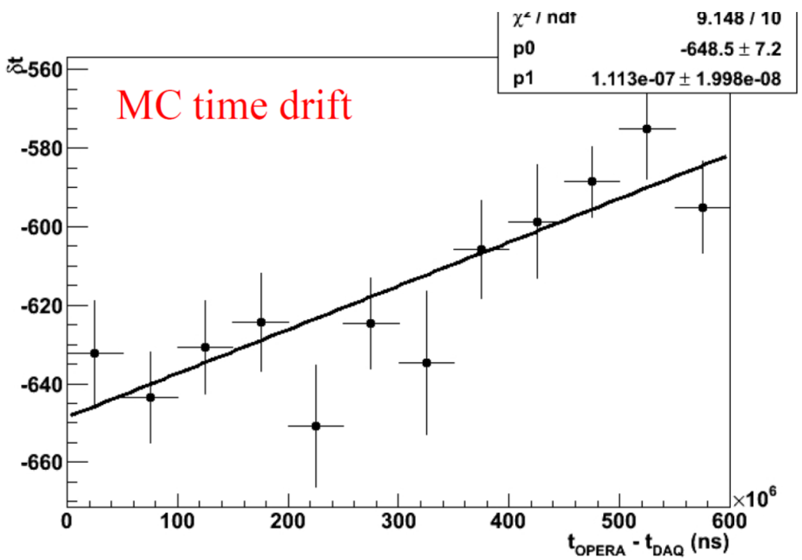
Internal Master Clock frequency:

- Difference w.r.t. nominal frequency Df/f = 1.24×10-7
- Introduce an artificial delay depending on the position of the events within the DAQ cycle

An indipendent Cross Check

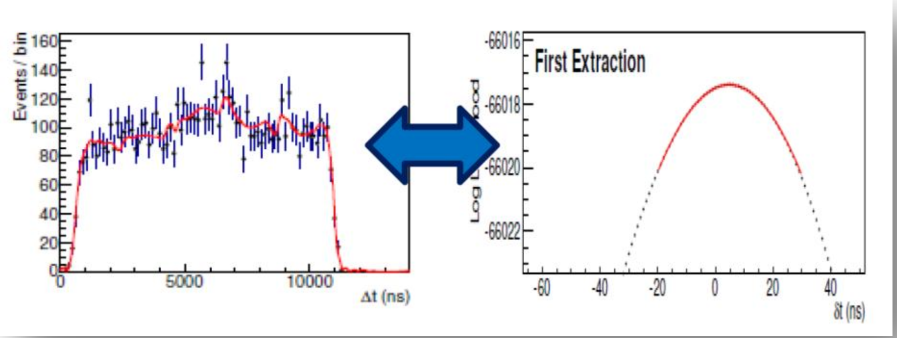
- the two effects were also found using coincident cosmic muon events between OPERA and LVD





Results

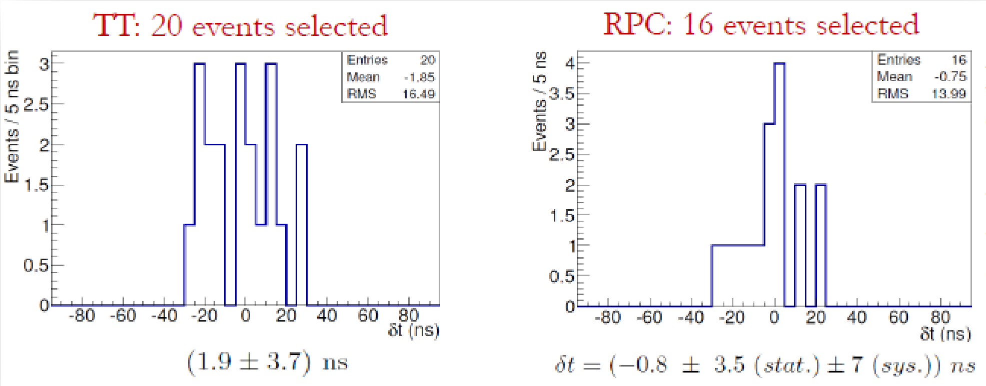
1. For each OPERA event take the BCT waveform of the corresponding extraction: WFD and neutrino time distribution analyzed with a ML approach



$$\delta t = TOF_c - TOF_\nu = \left(6.5 \pm 7.4\ (stat.)^{+9.2}_{-6.8}\ (sys.)\right)\ \text{ns}$$

$$\frac{v-c}{c} = \frac{\delta t}{TOF_c^{'} - \delta t} = (2.7 \pm 3.1\ (\text{stat.})^{+3.8}_{-2.8}\ (\text{sys.})) \times 10^{-6}$$

2. 2011 BB: for each OPERA event take the “centroid” of the corresponding BCT WF (unambiguous association) ; Results from both TT and RPC sub-detectors : cross-check of systematics related to detector calibrations (but DAQ in common)

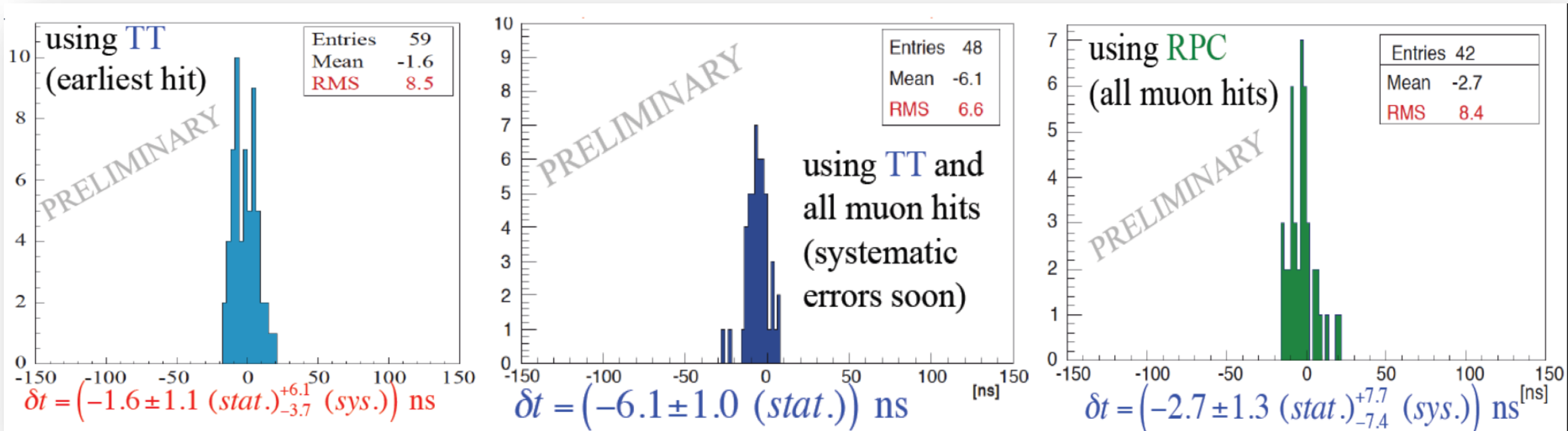


Results

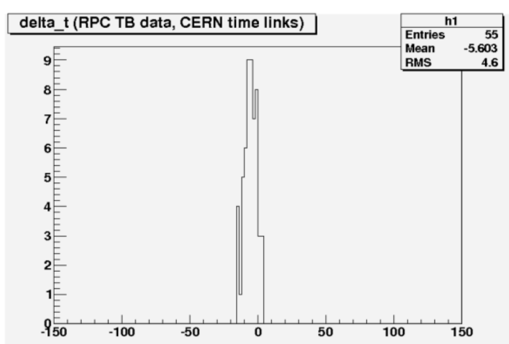
3. 2012 BB

New calibrations:

- CERN: Time delay related to BCT: (583.7±1) ns
- CERN & LNGS: White Rabbit system for continuous time delay monitoring
- OPERA: Master Clock equipped with a TDC to improve the GPS signal latching



4. Indipendent timing system: used in parallel exploting "Timing Boards" installed on RPC detectors



Result:

$$\delta t = (-5.6 \pm 0.6(stat)^{+6.5}_{-5.1}(syst))ns$$

Dominant systematic error on the streamer formation time (5 ns)