Istituto Nazionale di Fisica Nucleare

Rencontres de Moriond EW 2012
La Thuile, 3-10 March 2012

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OPERA

On behalf of the OPERA Collaboration

11 countries, 30 institutions, 160 physicists

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
Toho
Kobe
Nagoya
Utsunomiya

Korea
Jinju

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

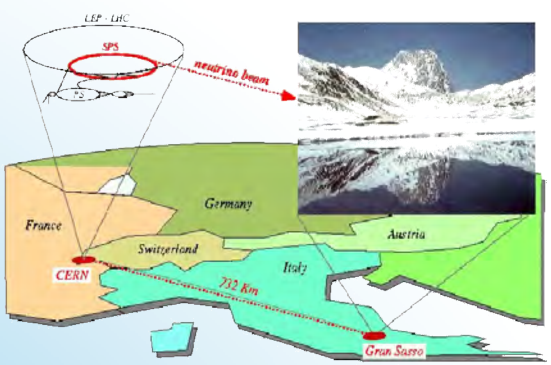
Switzerland
Bern
ETH Zurich

Turkey
METU Ankara

Results from OPERA

- ν oscillation
- ν time-of-flight

Goal: direct detection of $\nu_\mu \rightarrow \nu_\tau$ neutrino oscillation in **appearance** mode



Requirements:

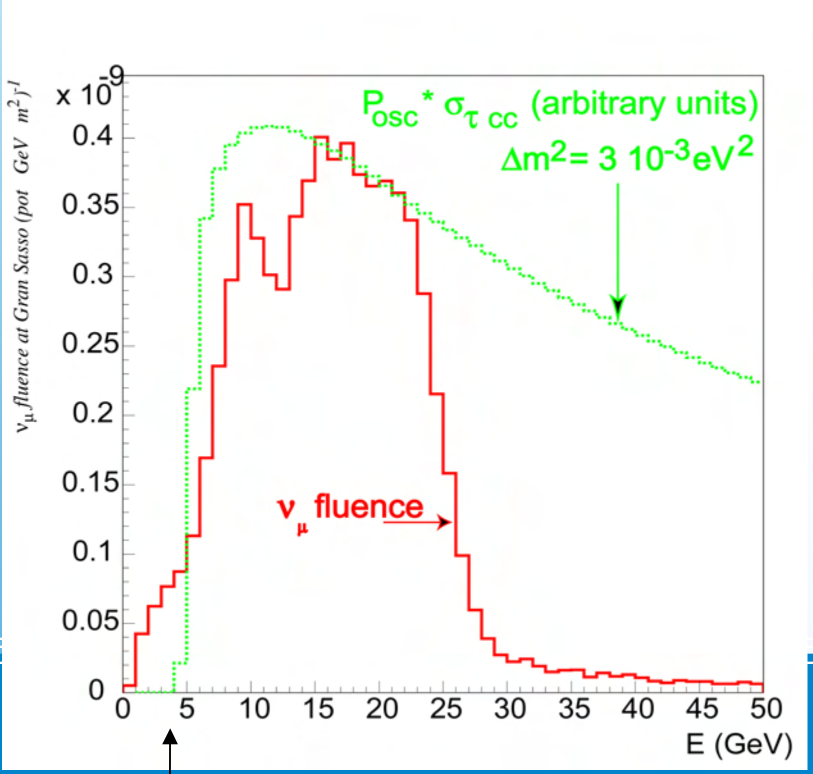
1) long baseline (atmospheric Δm^2)

2) high neutrino energy (τ cross section)

3) high beam intensity (L=730 km) + large mass (1.25 kton)

5) exceptional granularity to detect the short lived τ leptons

– **a major engineering and experimental challenge**:
- CNGS beam: **O(10) more energetic** wrt any other LBL
- Emulsion/electronic hybrid detector: **O(100) more massive** than SBL ancestors (i.e. CHORUS)

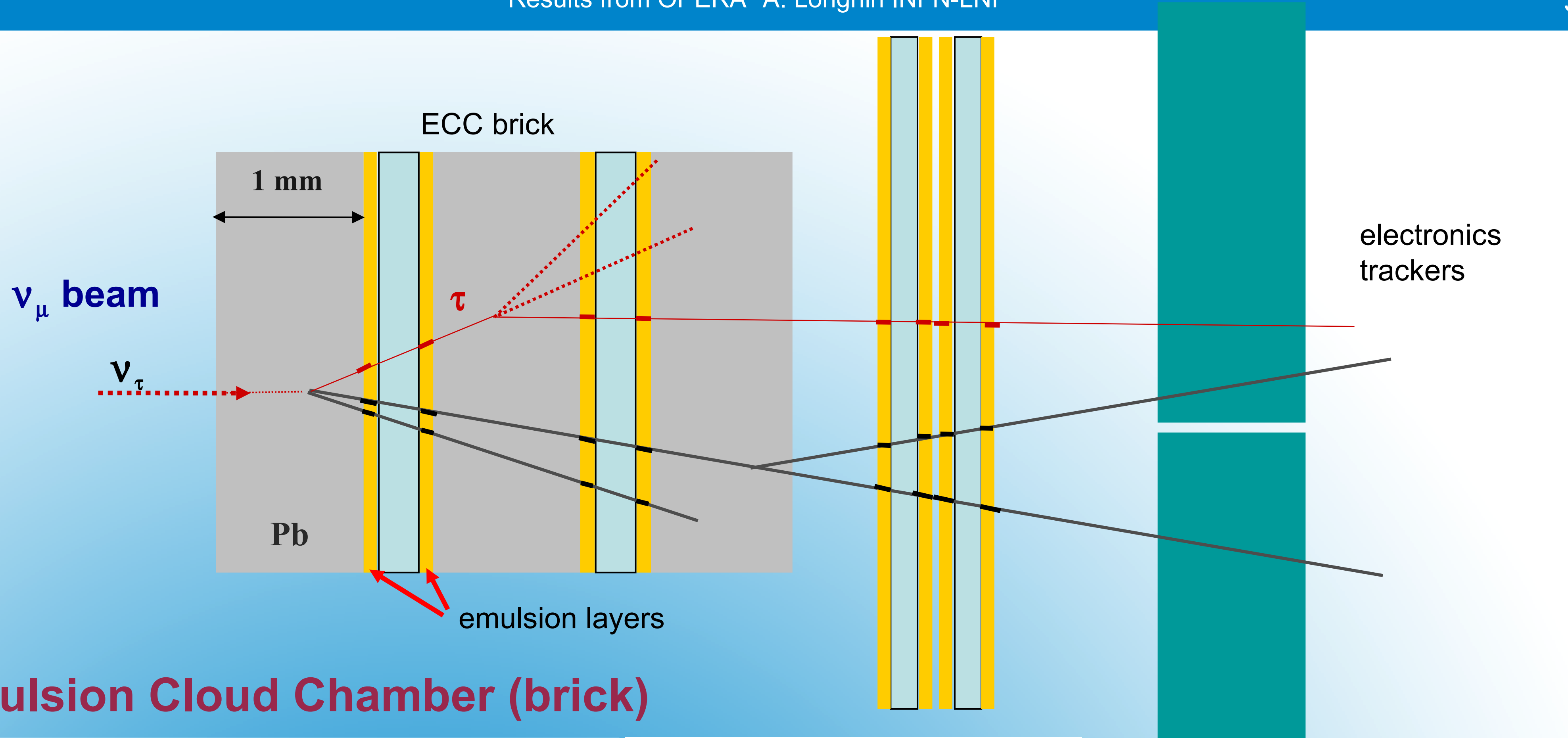


22.5 x 10^{19} pot
23600 ν_μ CC+NC
520 $\bar{\nu}_\mu$ CC+NC
160 $\nu_e + \bar{\nu}_e$ CC
115 ν_τ CC

$$\nu_\mu \longrightarrow \nu_\tau$$

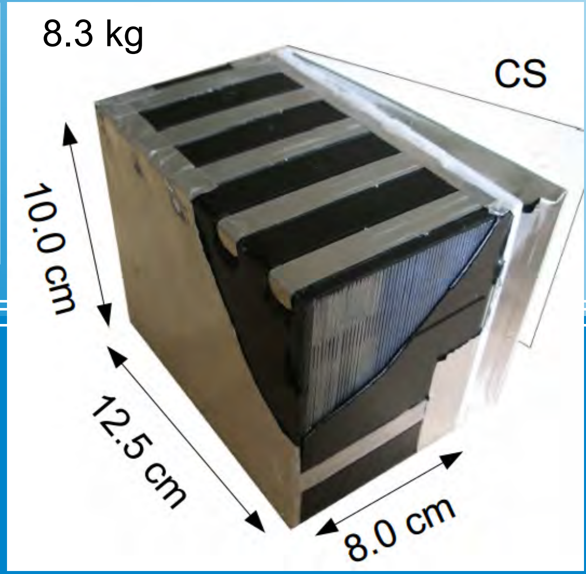
τ threshold ~ 3.5 GeV, slow rise

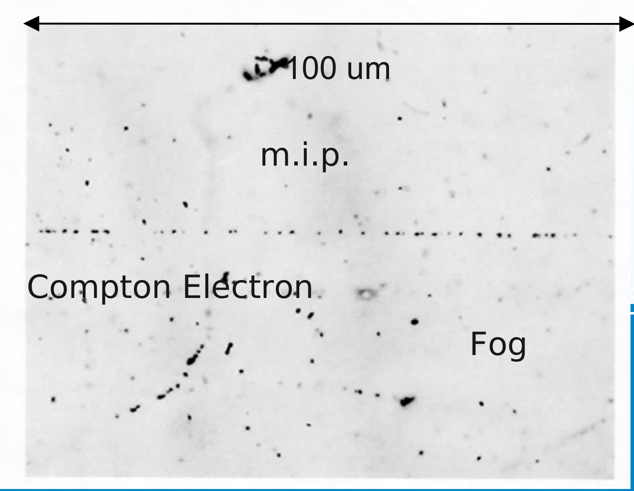
$[(m_\tau+m_p)^2 - m_p^2] /2m_p$



Emulsion Cloud Chamber (brick)

57+56 emulsion films (300um)+lead(1mm) plates
External removable films doublet (CS)
Position: 1 um, slope: 2 mrad at single film
e.m. calorimetry: $\sigma/E = 40\%/\sqrt{E}$
MCS: $\Delta p/p < 0.2$ after 5 X^0 up to 4 GeV

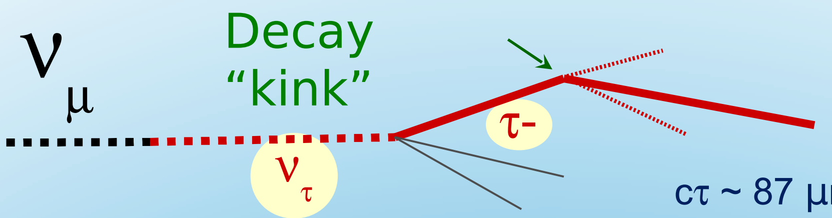




Conceptual design

Separation of ν_τ CC from the dominant ν_μ interactions:

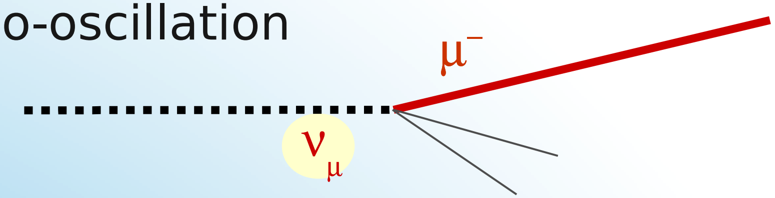
event-by-event identification of the peculiar τ decay topology



$c\tau \sim 87\ \mu m$
$\sim 600\ \mu m$ decay length

35% QE, 65% DIS

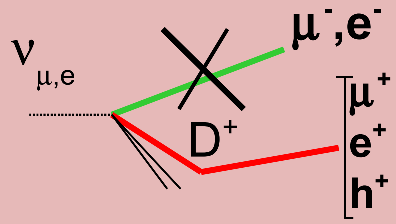
no-oscillation



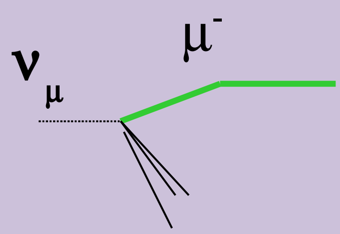
11% QE, 89% DIS

Backgrounds

CC charm production (all decay channels)

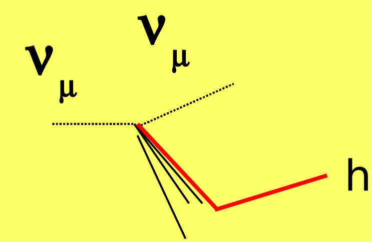


Coulomb large angle scattering of muons in lead
Bck. to $\tau \rightarrow \mu$

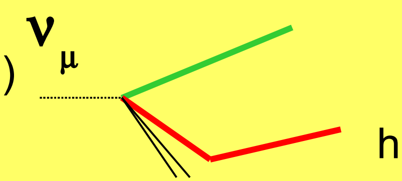


Hadronic interactions

Bck. to $\tau \rightarrow h$



or to $\tau \rightarrow \mu$
(if hadron misid or mismatched with muon)

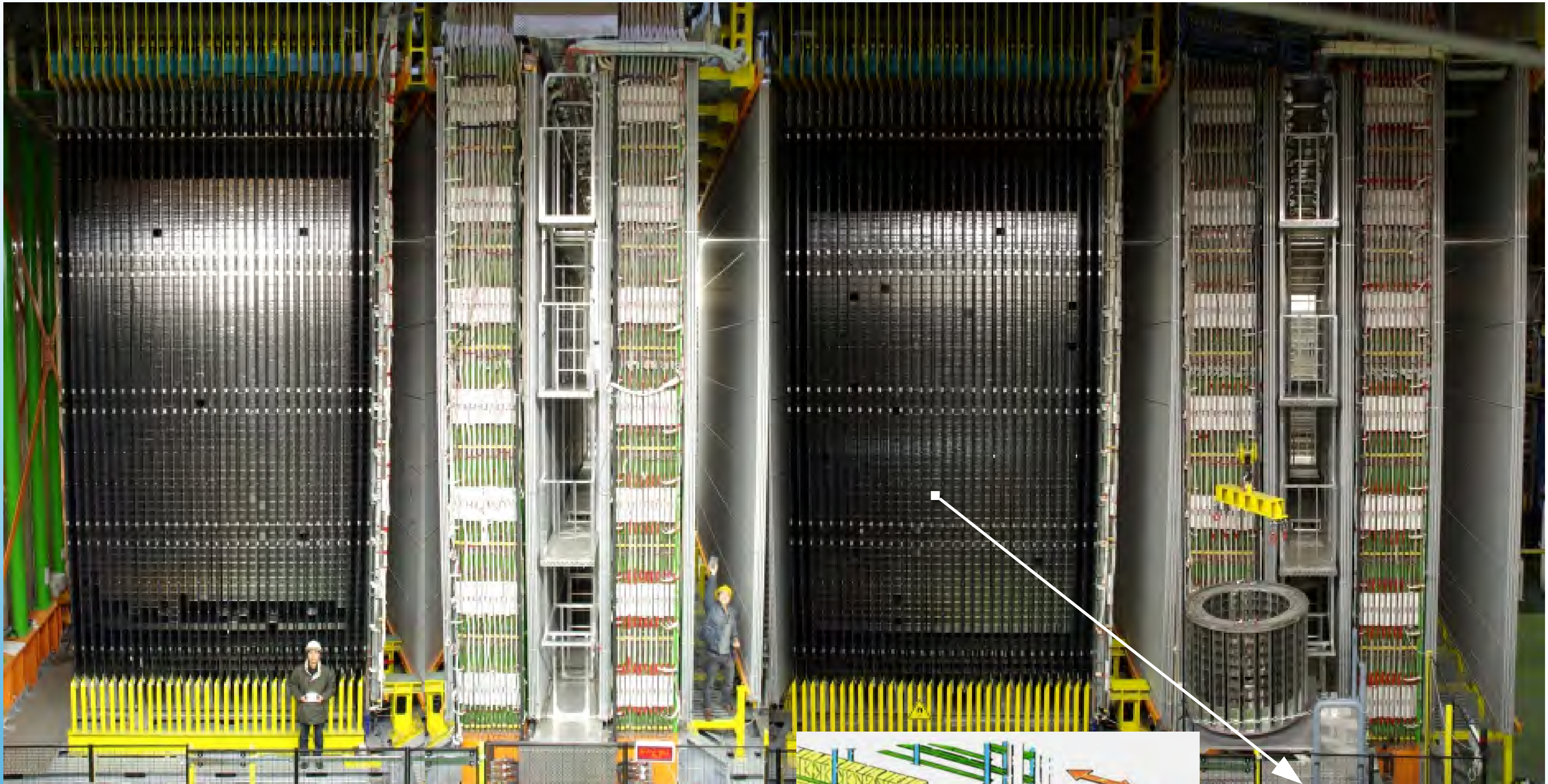


ν_τ detection

$$\nu_\mu \xrightarrow{\text{oscillation}} \nu_\tau + N \rightarrow \tau^- + X$$

Super Module 1

Super Module 2

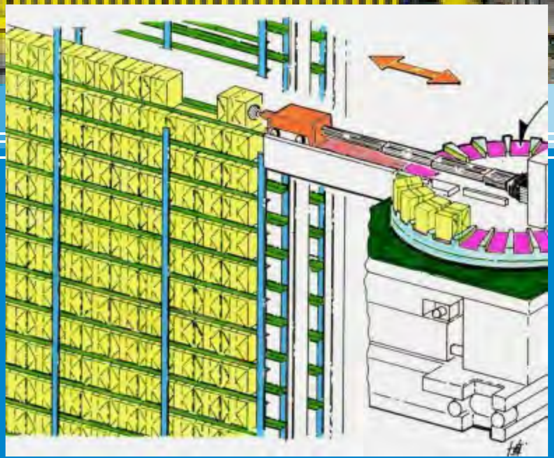


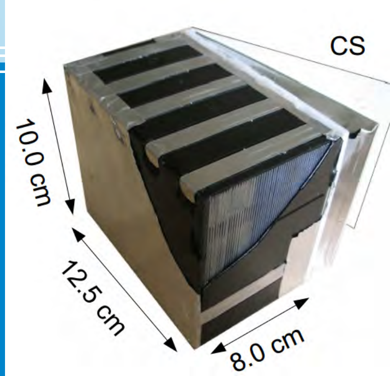
Target area

μ spectrometer

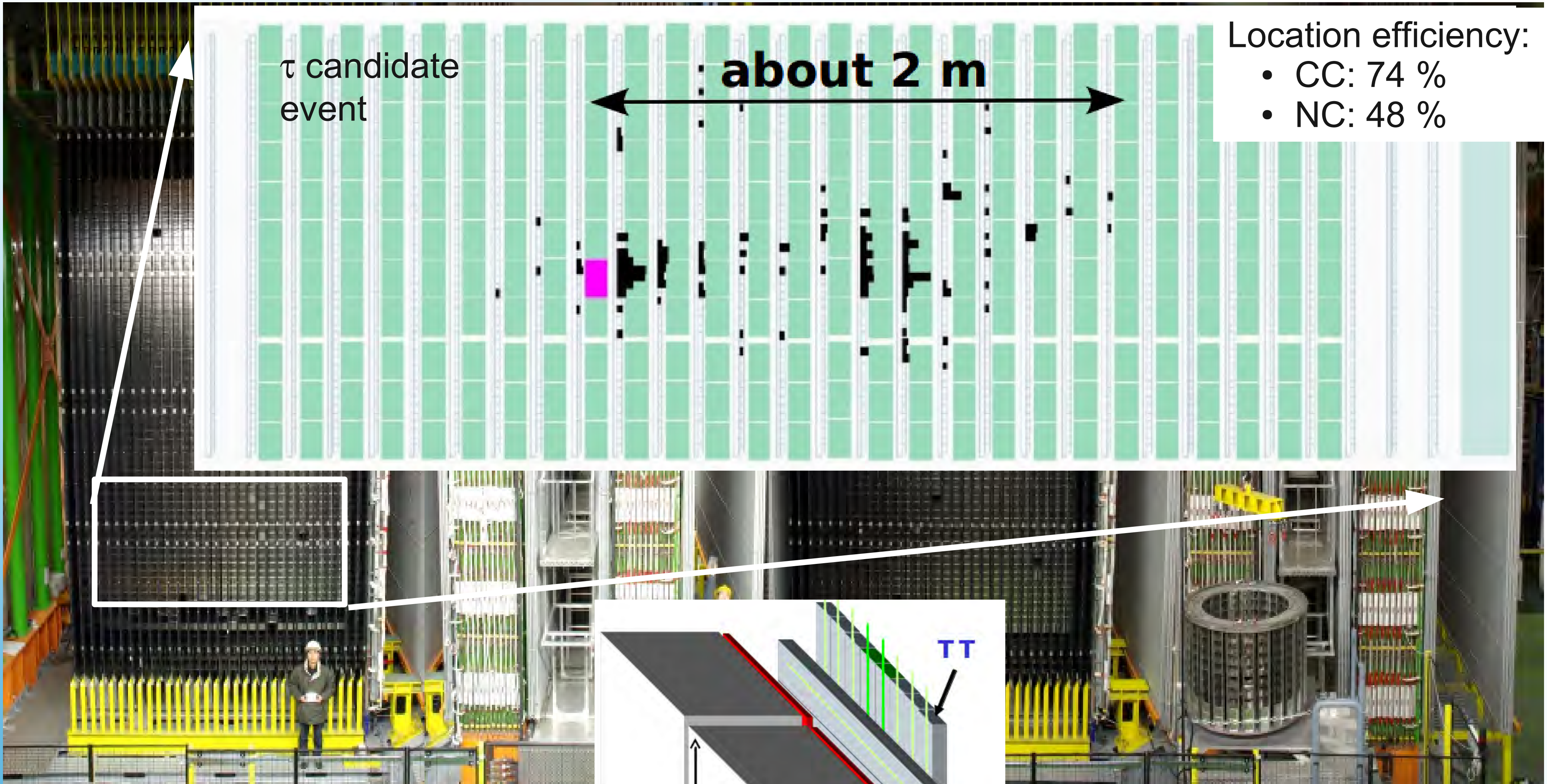
150000 bricks in total. m=1.25 kton

The detector



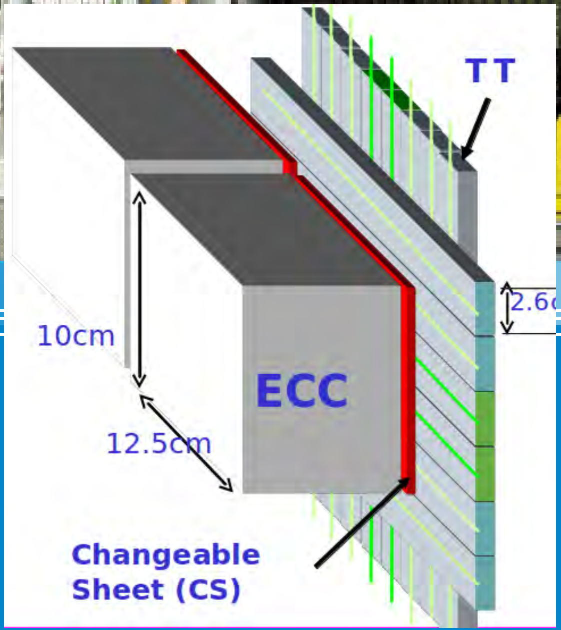


Super Module 1 — Super Module 2

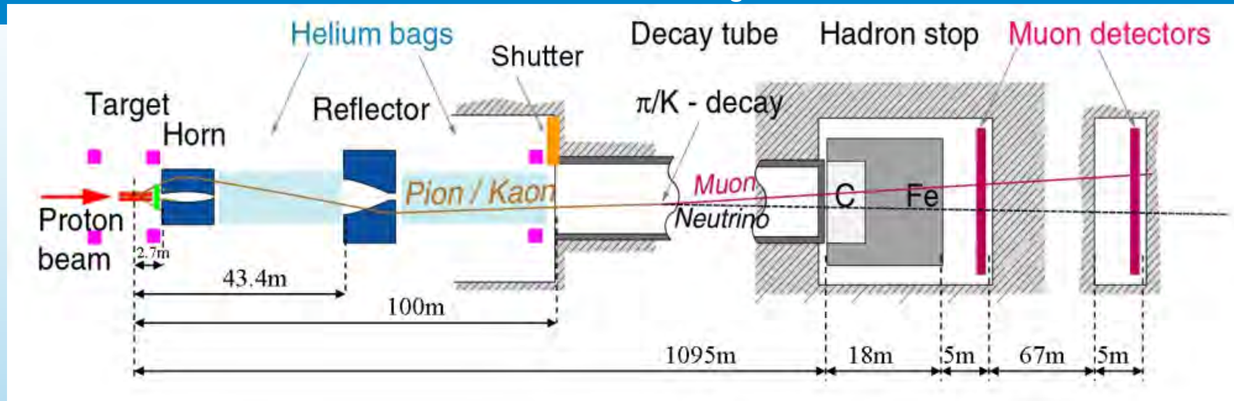


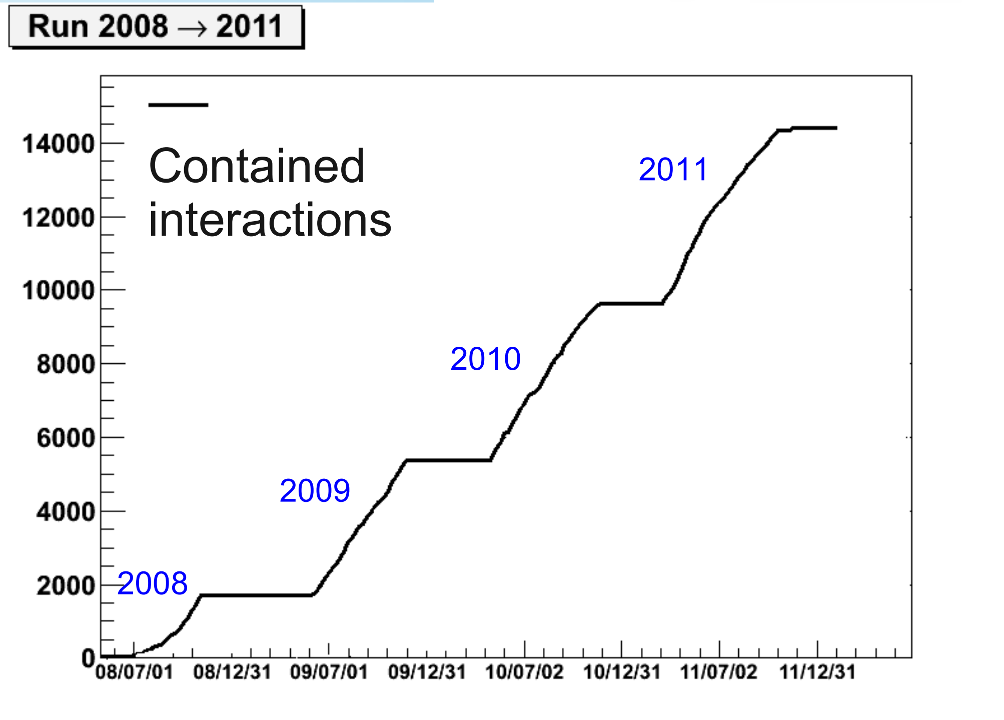
Location efficiency:
- CC: 74 %
- NC: 48 %

Brick finding



Accuracy of predictions:
position:10 mm
slope: 23 mrad





Year	Days	p.o.t. (10^{19})	ν interactions
2008	123	1.78	1698
2009	155	3.52	3693
2010	187	4.04	4248
2011	244	4.84	4762
tot	**709**	**14.18**	**14401**

At the end of 2012 run (from March) we will hopefully be not to far from the design goal (22.5e19)

CNGS beam performance

- 2008-2009 data analysis completed (arXiv:1107.2594v1) Acc. by New Journ. of Phys.
  - 4.8×10^{19} pot, 34% of available sample, 2.6 × more statistics w.r.t. τ candidate publication
  - 2738 fully analysed events (decay search). **No new τ**

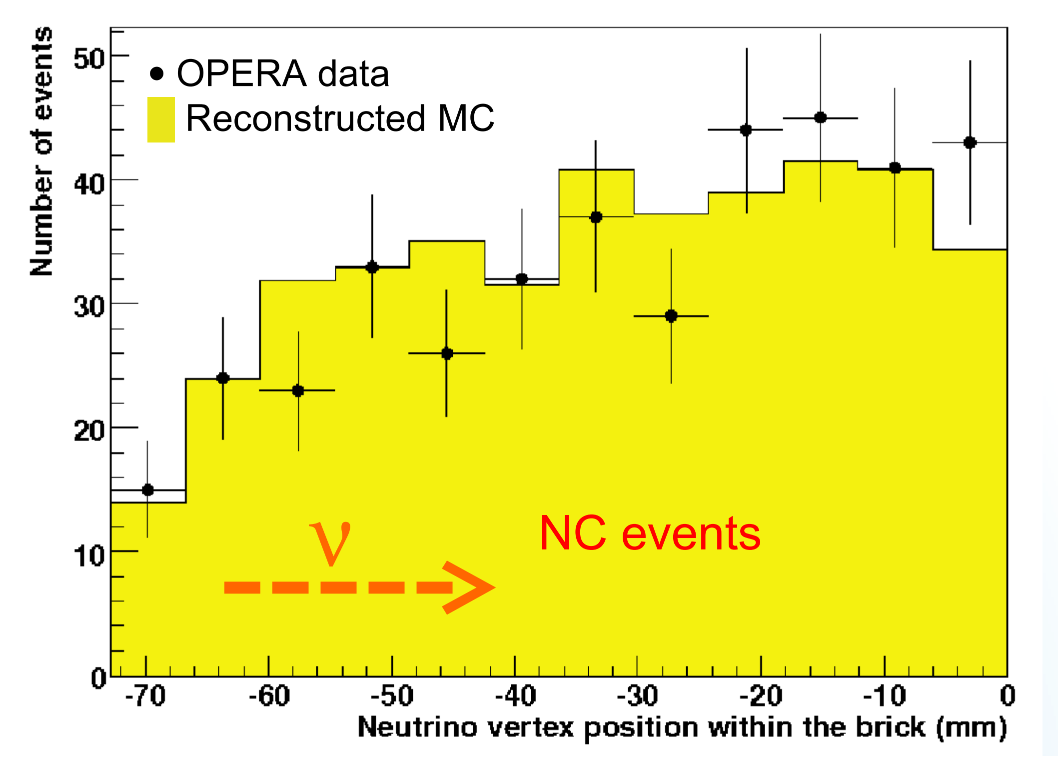
- Analysis improvements

1) Search of highly ionizing tracks in hadronic interactions (↓ bckg for $\tau \rightarrow h$)

2) Follow down of vertex tracks in the emulsion → p-range correlations → increased μ-ID efficiency →
↓ charm background
↓ hadronic bckg from ν_μ^{CC} with μ misID

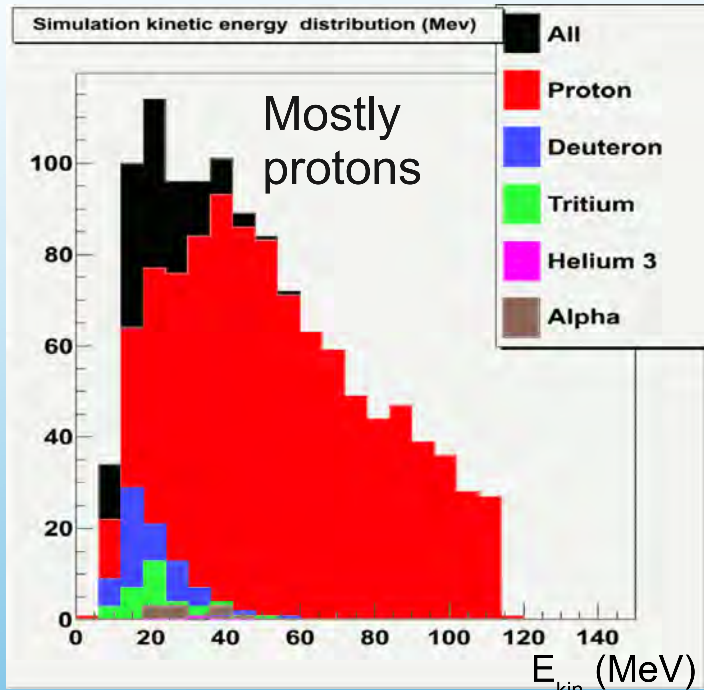
3) Implementation of state-of-the art charm cross section from CHORUS (↑ σ)

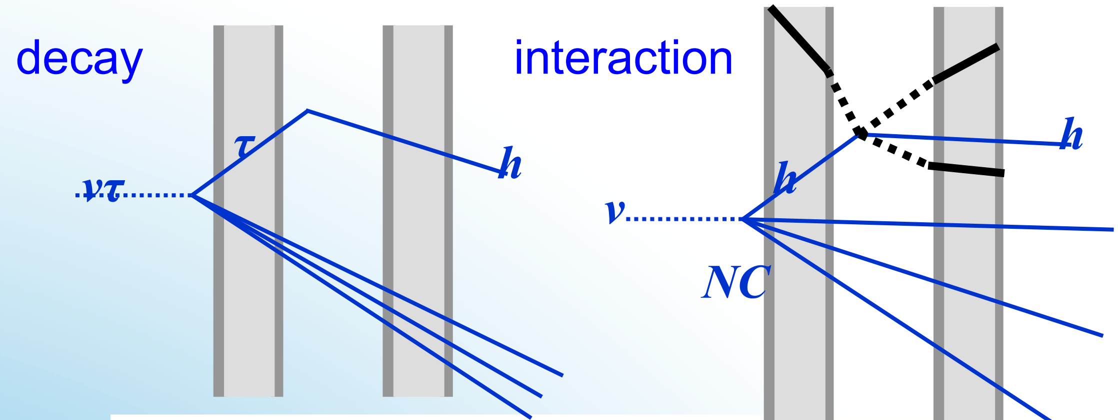
Full simulation chain with reconstruction in the emulsions

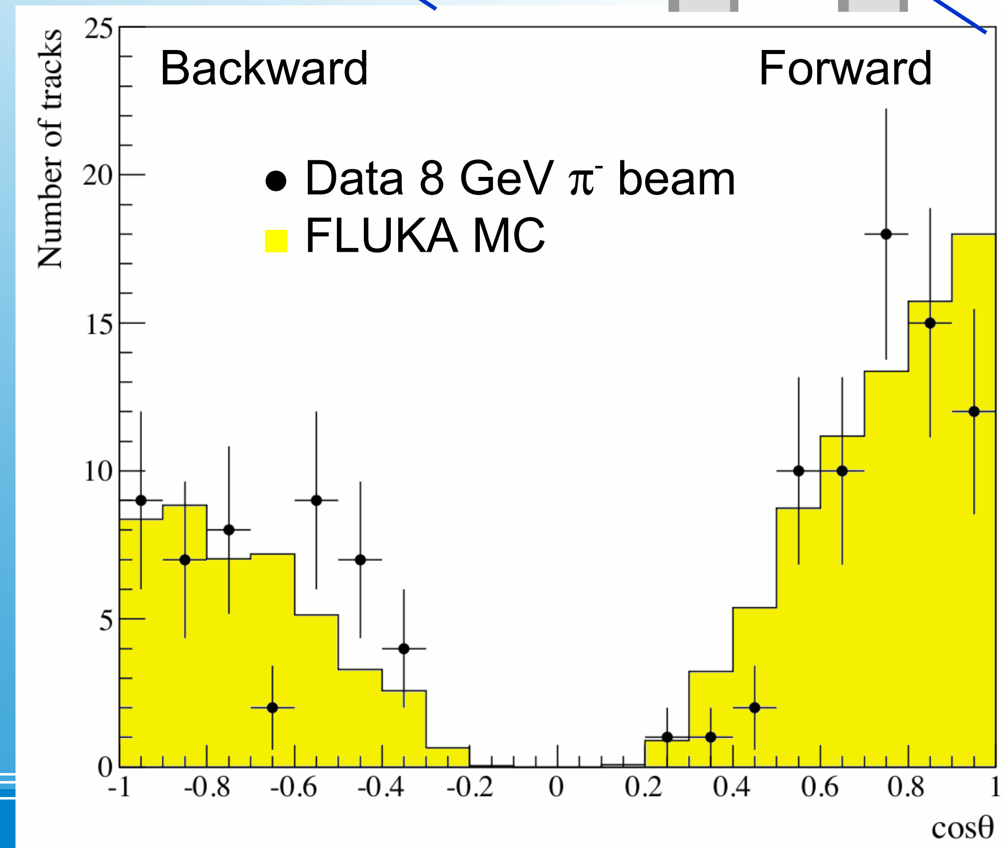


Statistics update and analysis improvements

Highly ionizing tracks tagging







Search for "black" tracks in a large field of view 2.5 x 2.1 mm^2

	data	FLUKA
≥ 1 rec. track	(57 ± 7) %	53 %
F-B asymmetry	(0.75 ± 0.15)	0.71

Probability for a π,K,p to undergo a single prong "kink" with

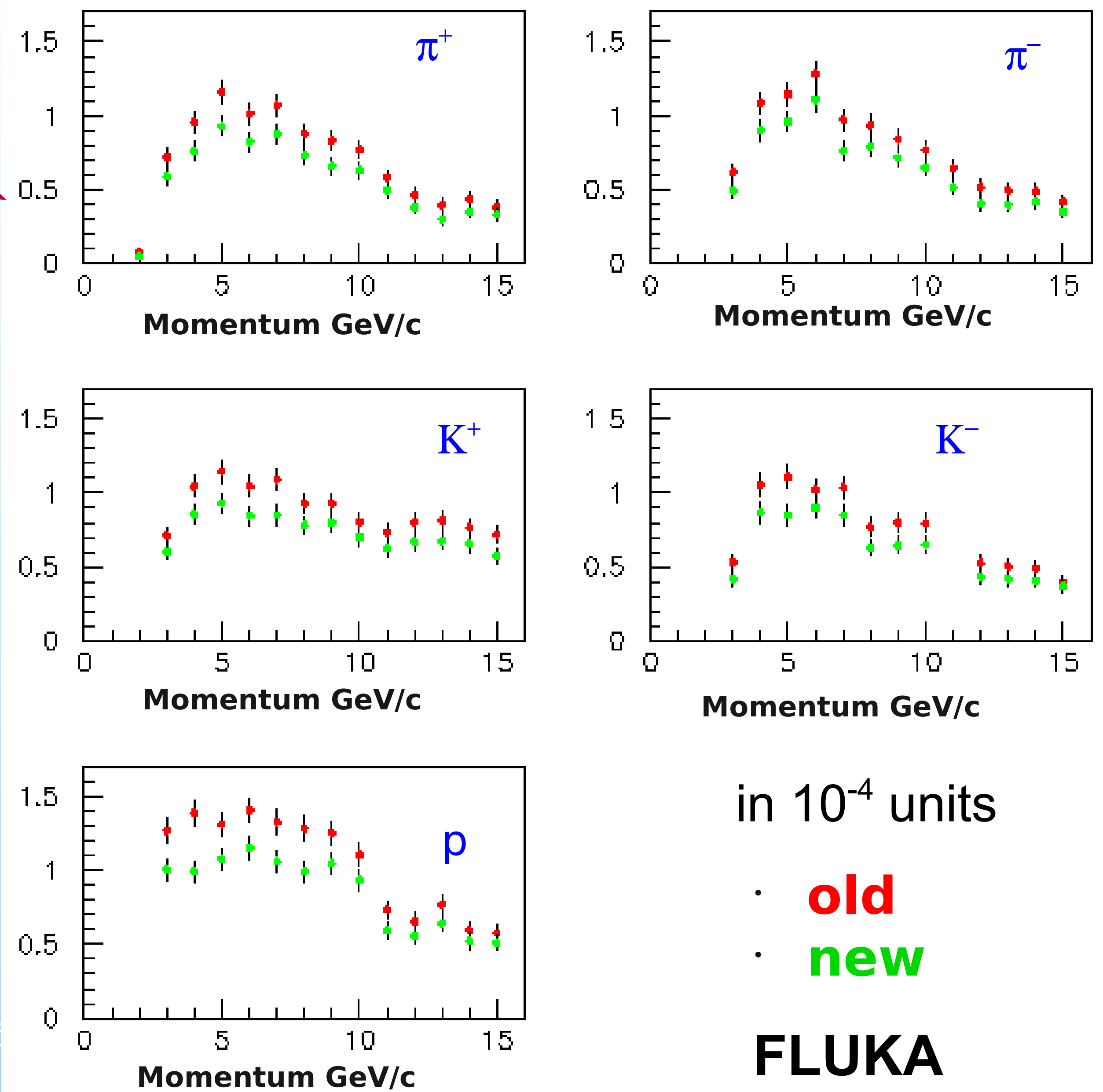
- p > 2 GeV/c
- (p_T > 0.6 GeV/c) or
  (p_T > 0.3 GeV/c + γ)

over 2 mm of lead

1.53×10^{-4} / NC

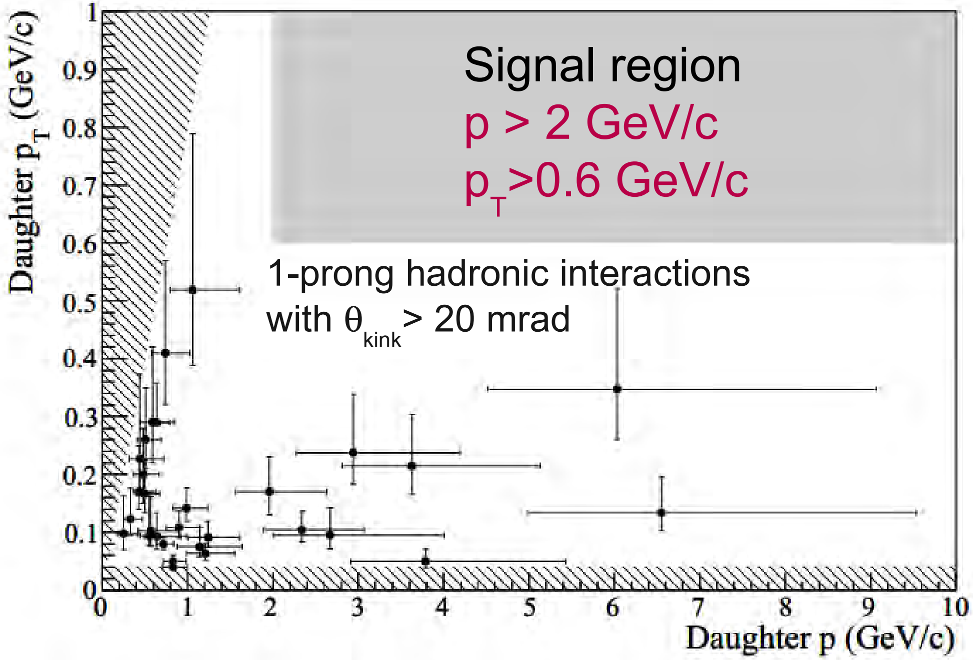
-20% w.r.t. old estimation

Improvements: larger angular acceptance and lower momentum threshold for additional protons and fragments



Hadronic background MC

OPERA neutrino interactions



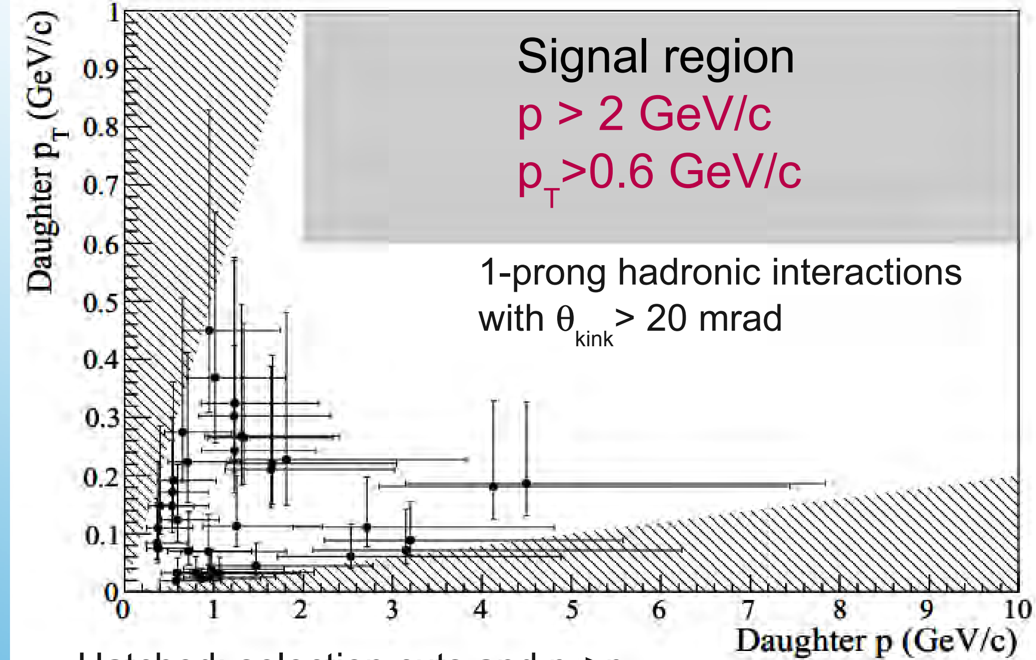
Hadronic track length = 14 m, equivalent to 2300 NC events.

No events in signal region

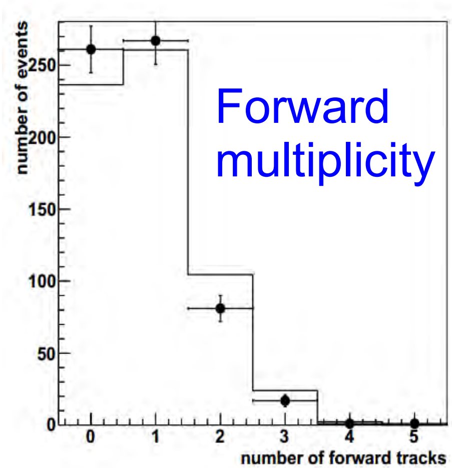
p_T>200 MeV/c:

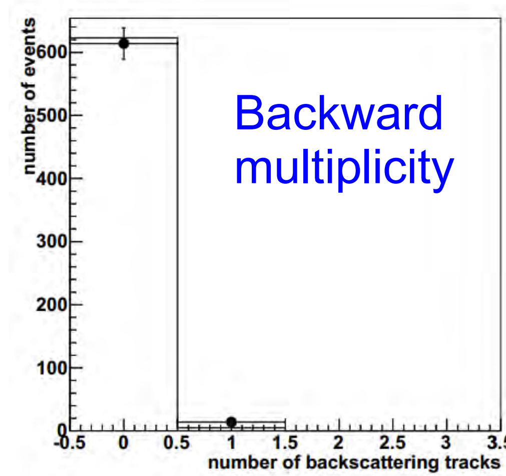
observed 10
expected 10.8

4 GeV π test beam



Hatched: selection cuts and p_T>p





Data driven hadron background constraints

The CHORUS collaboration released an updated analysis based on ~10^3 charged charm events. Numbers were rescaled to OPERA energies $\langle E_\nu \rangle$: 27 → 17 GeV

$\langle E_\nu \rangle$ = 27 GeV $\langle E_\nu \rangle$ = 17 GeV

	CHORUS [%] arXiv:1107.0613 [hep-ex]	@ OPERA [%]	Former value	
$\sigma(\text{charm}) / \sigma(\nu_\mu^{CC})$	5.75 ± 0.32(stat) ± 0.30(sys)	4.46	3.3 ± 0.5	→ +35%
$f(D^+)$	25.3 ± 4.2	21.7 ± 3.6	10 ± 3	→ 2 ×
$f(\Lambda_c)$	19.2 ± 4.2	25.3 ± 5.5	26 ± 8	
$f(D_s)$	11.8 ± 4.7	9.2 ± 3.7	18 ± 5	→ ½ ×

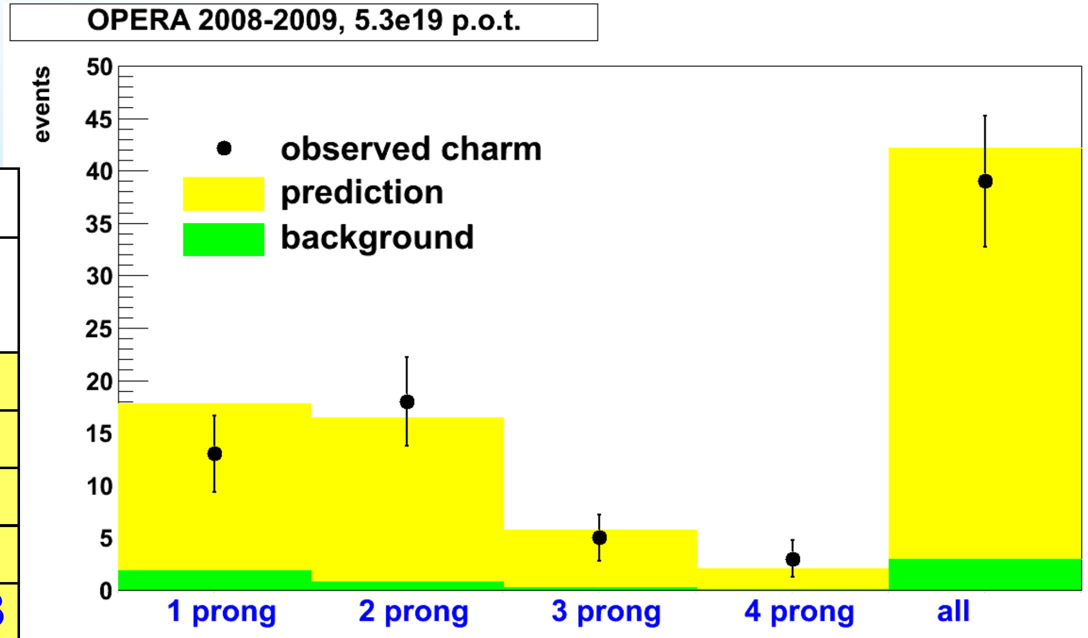
Increase of charm background from × 1.6 to × 2.4 depending on the channel (h-μ)

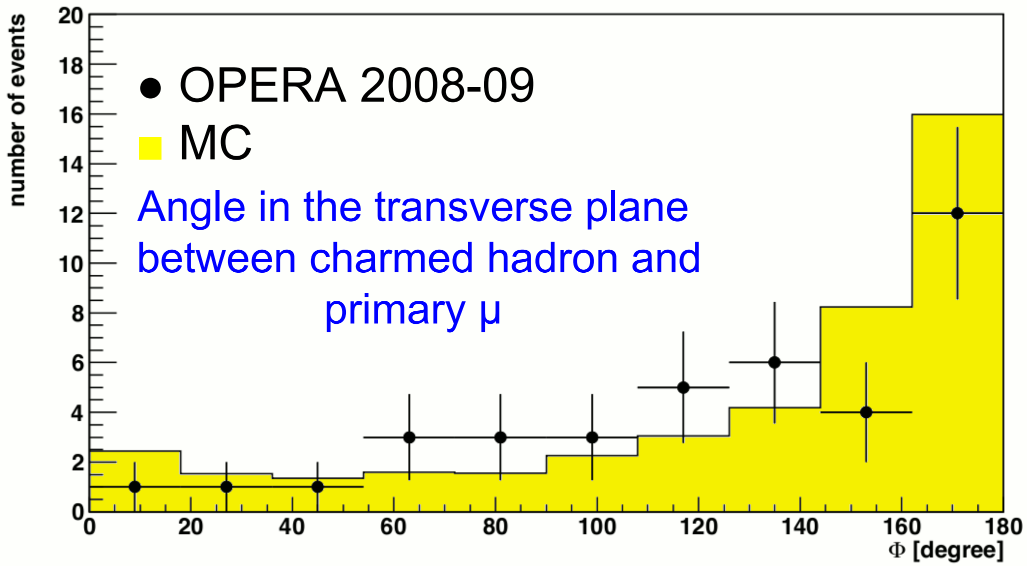
Main contribution from D^+

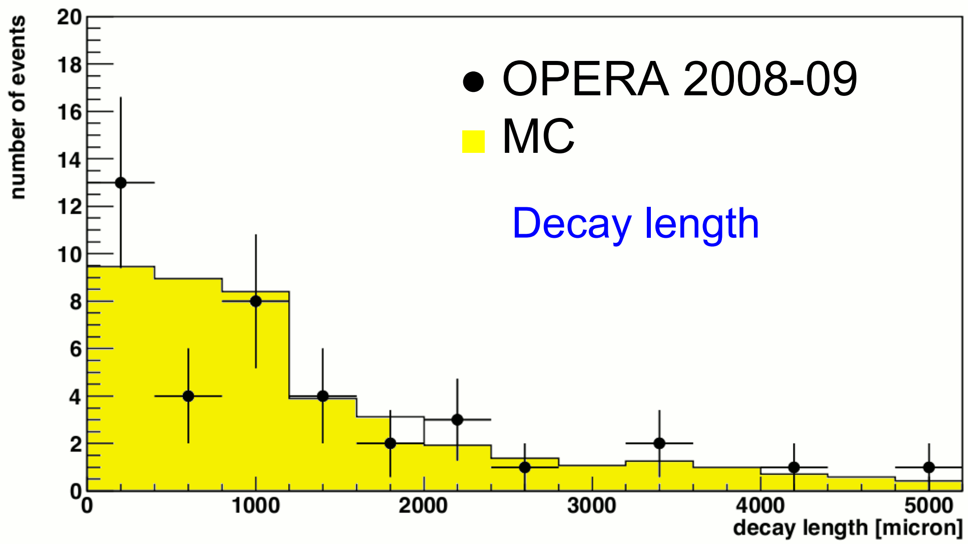
Updated charm prediction

The charm sample offers the opportunity to benchmark the τ efficiency thanks to the similar topologies

prongs	Obs.	Expected		
		Charm	Backgr.	Total
1	**13**	15.9	1.9	**17.8**
2	**18**	15.7	0.8	**16.5**
3	**5**	5.5	0.3	**5.8**
4	**3**	2.0	<0.1	**2.1**
tot	**39**	39.1 ± 7.5	3.0 ± 0.9	**42.2 ± 8.3**



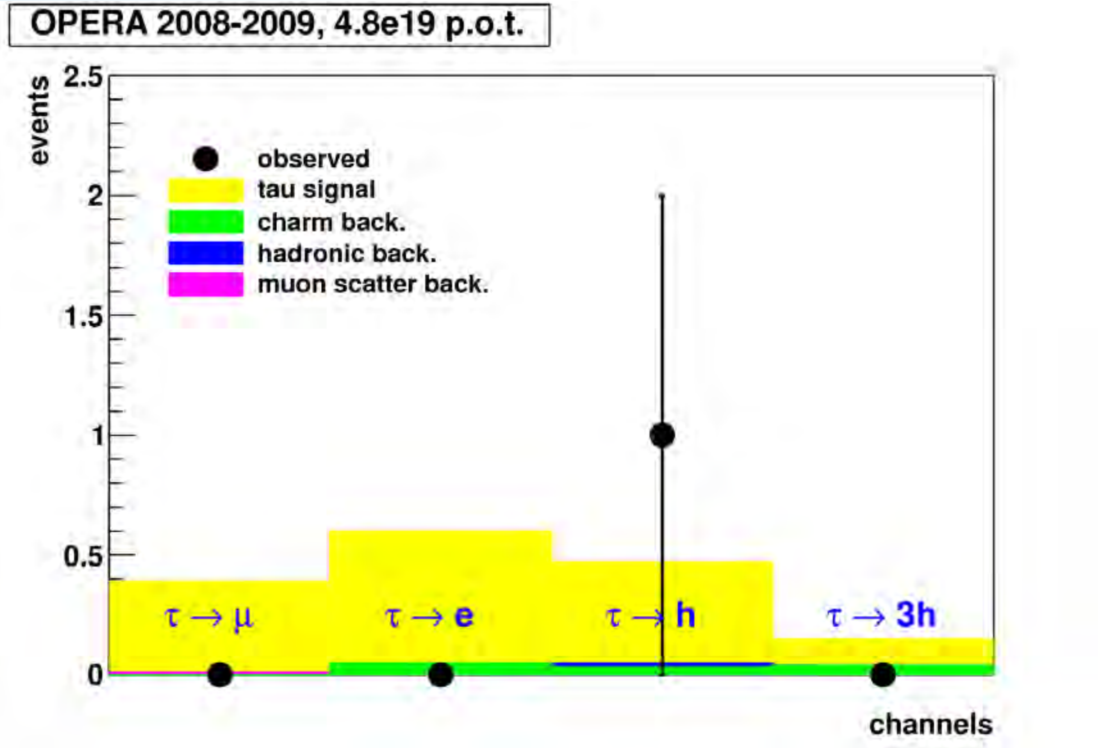




2008-2009 charm sample

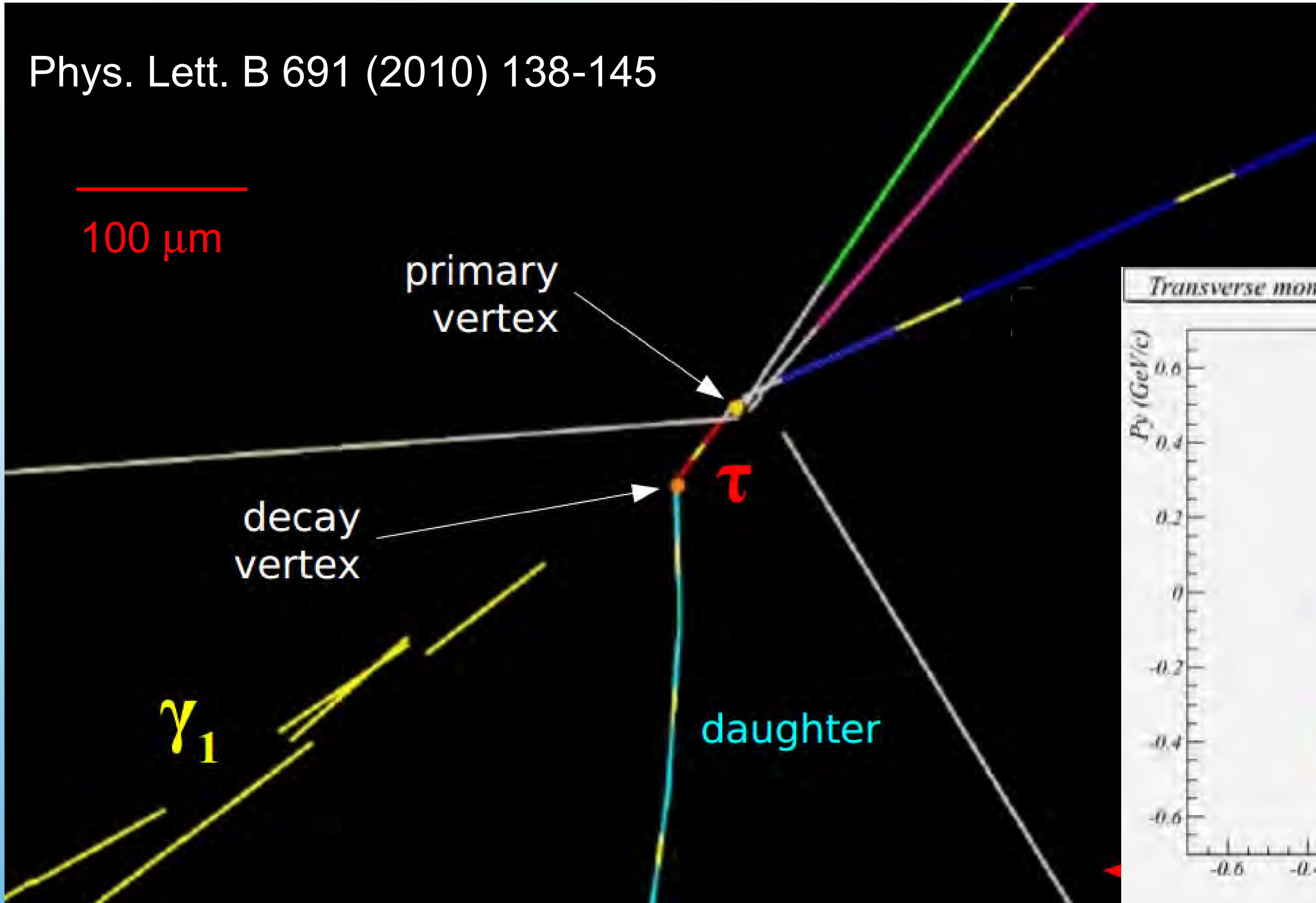
Including all the improvements in the analysis

Decay channel	Expected signal events $\Delta m^2 = 2.5 \times 10^{-3}\ eV^2$	
	22.5 10^{19} p.o.t.	4.8 10^{19} p.o.t. (analysed)
$\tau \to \mu$	1.79	0.39
$\tau \to e$	2.89	0.63
$\tau \to h$	2.25	0.49
$\tau \to 3h$	0.71	0.15
Total	7.63	1.65

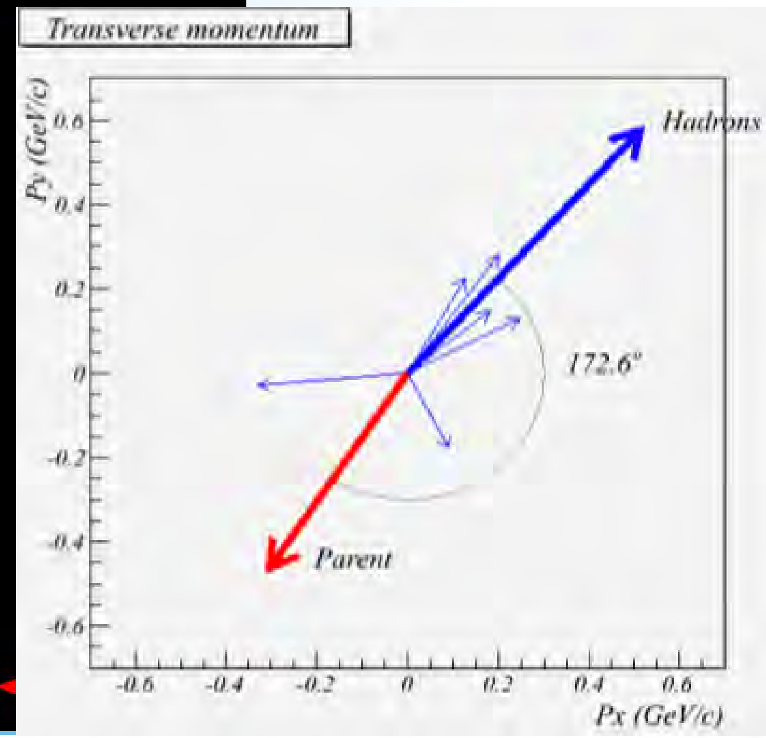


- In the analyzed sample (92% of 08/09 data)
- one ν_τ observed in the $\tau \to h$ channel compatible with the expectation of 1.65
- Expected background in $\tau \to h$: 0.05 ± 0.01 events
- Total background (considering all channels): 0.16 ± 0.03 events
- $\tau \to \mu$ is the cleanest channel

Updated S/B expectations



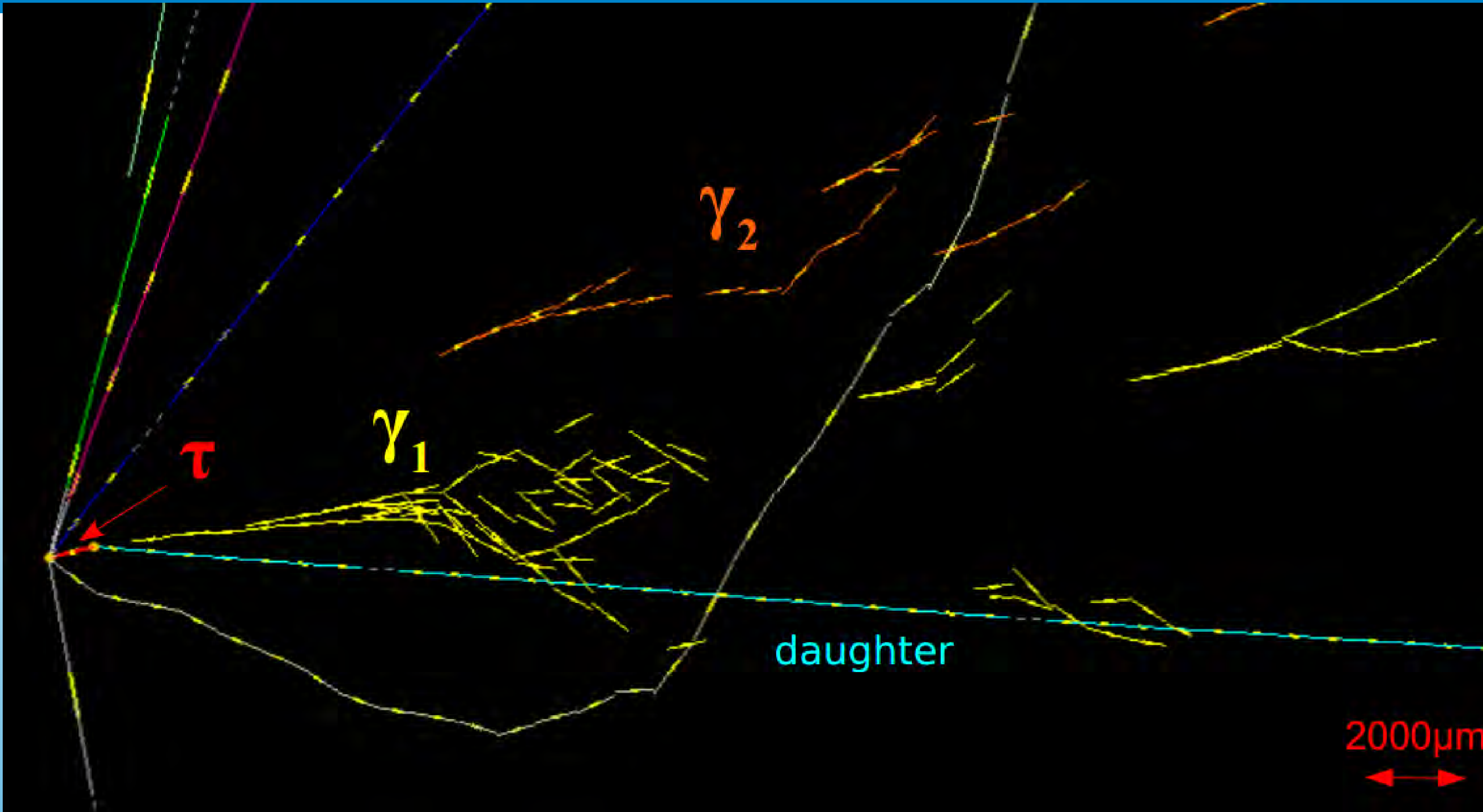
Spring 2010: first ν_τ candidate based on the analysis of 35% of 08/09 statistics.



Used cuts were defined at the time of the experiment proposal (2001) →

Variable	Cut-off	Value
Missing P_T at primary vertex (GeV/c)	<1.0	$0.57^{+0.32}_{-0.17}$
Angle between parent track and primary hadronic shower in the transverse plane (rad)	$> \pi/2$	3.01±0.03
Kink angle (mrad)	>20	41±2
Daughter momentum (GeV/c)	>2	12^{+6}_{-3}
Daughter P_T when γ-ray at the decay vertex (GeV/c)	>0.3	$0.47^{+0.24}_{-0.12}$
Decay length (μm)	<2 lead plates	1335±35

τ candidate



$\tau^- \rightarrow \rho^- + \nu_\tau$ (B.R. ~25%)

$\rho^- \rightarrow \pi^0 + \pi^-$ 640^{+125}_{-80} (stat.)$^{+100}_{-90}$ (sys.) MeV/c^2

$\pi^0 \rightarrow \gamma\gamma$ 120 ± 20(stat.) ± 35(sys.) MeV/c^2

τ candidate

Variable	Cut-off	Value
Missing P_T at primary vertex (GeV/c)	<1.0	$0.57^{+0.32}_{-0.17}$
Angle between parent track and primary hadronic shower in the transverse plane (rad)	$> \pi/2$	3.01±0.03
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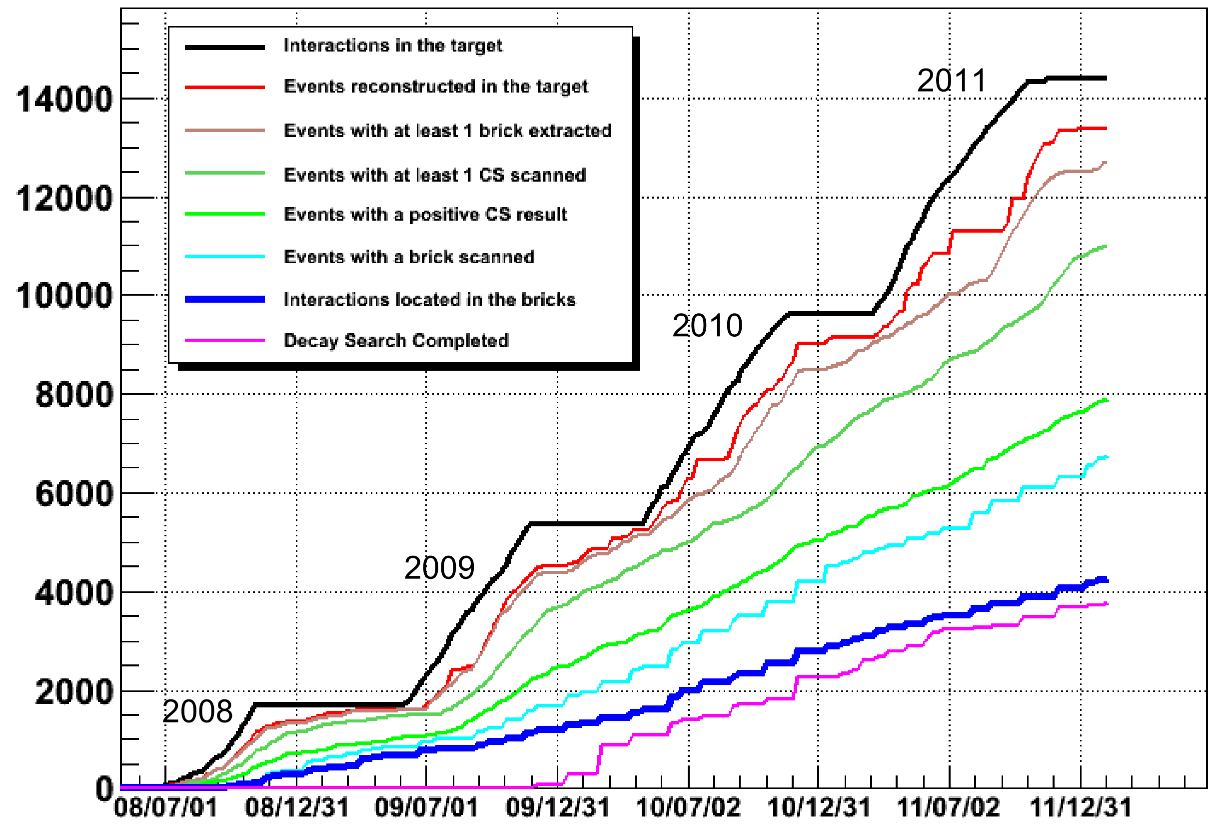
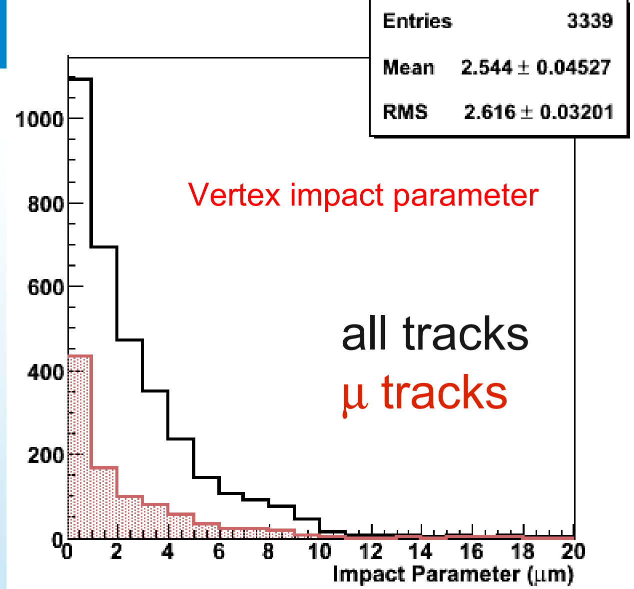
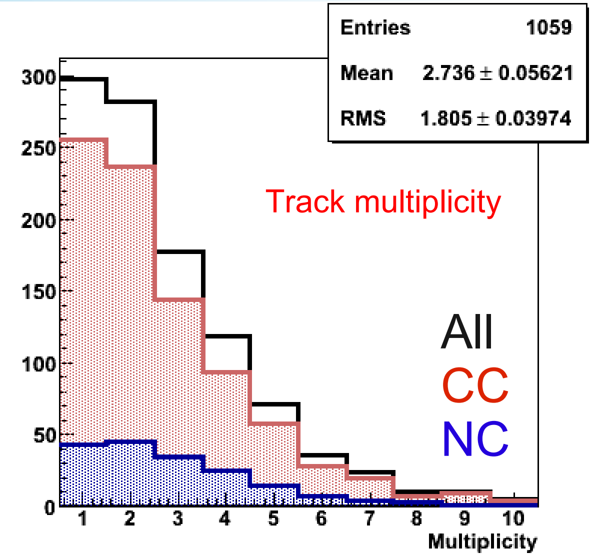
Daughter P_T when γ-ray at the decay vertex (GeV/c)	>0.3	$0.47^{+0.24}_{-0.12}$
Decay length (μm)	<2 lead plates	1335±35

Run 2008 → 2011







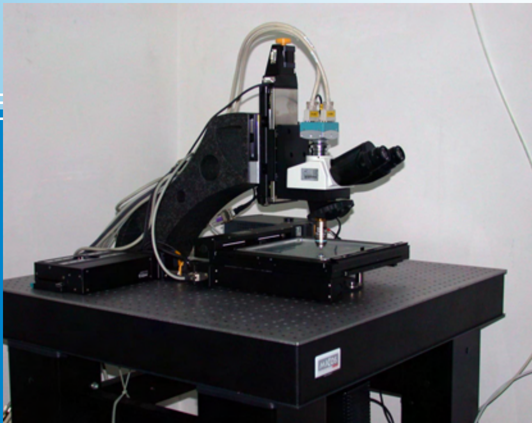
Steady progress: 4268 ν vertices in the emulsions: 55 charm, 24 ν_e

New strategy being followed for 2010/2011 data :

prioritize scanning of τ enriched sample (NC-like or p_μ<15 GeV/c)

Relevant p.o.t. for τ search will scale faster with time wrt the past (inclusive scanning). Detailed report at summer conferences.

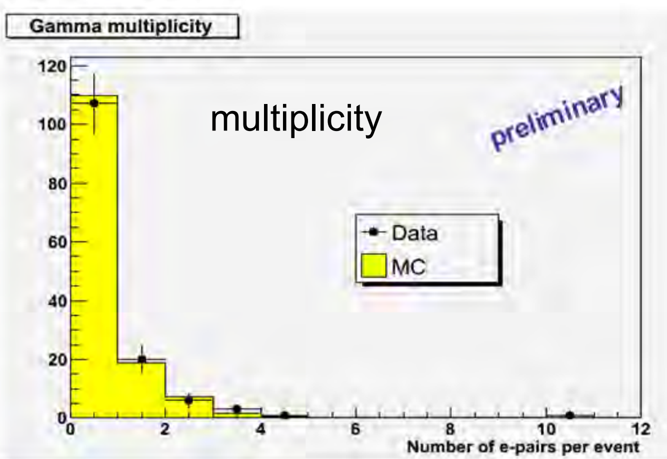
Scanning progress

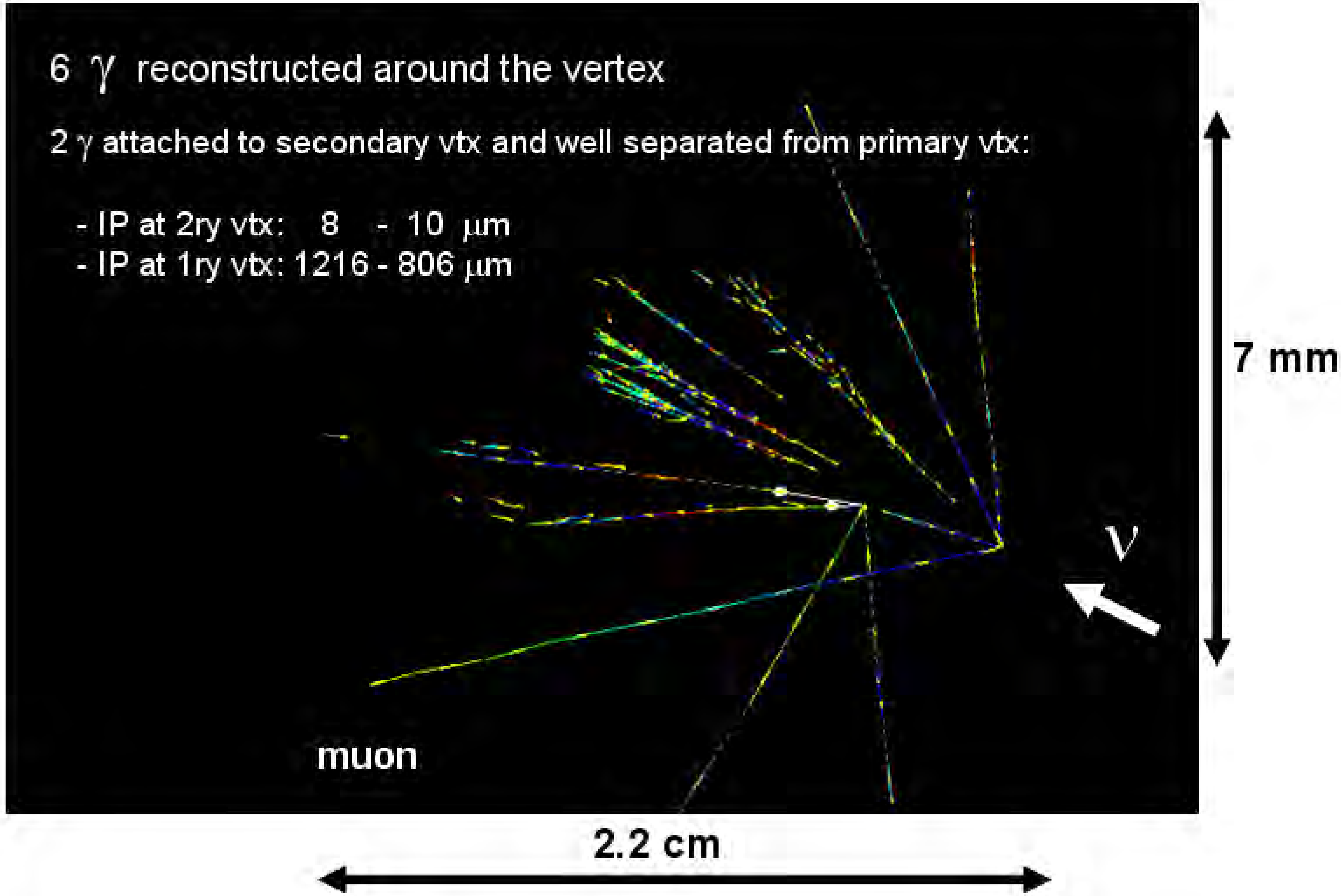


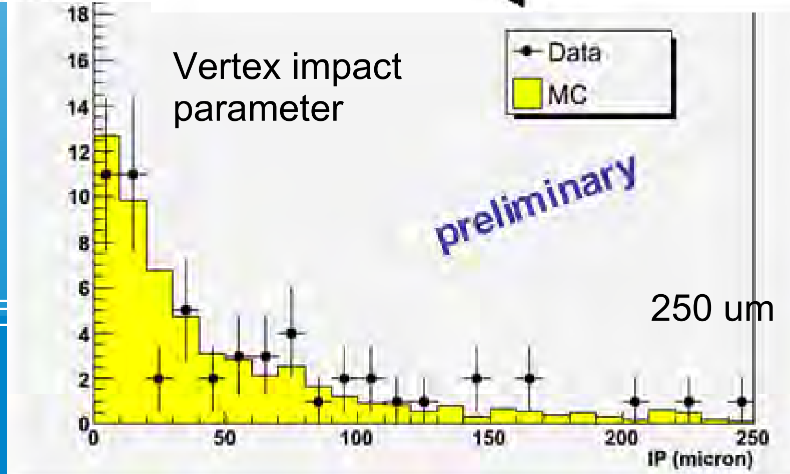
One of the scanning microscopes

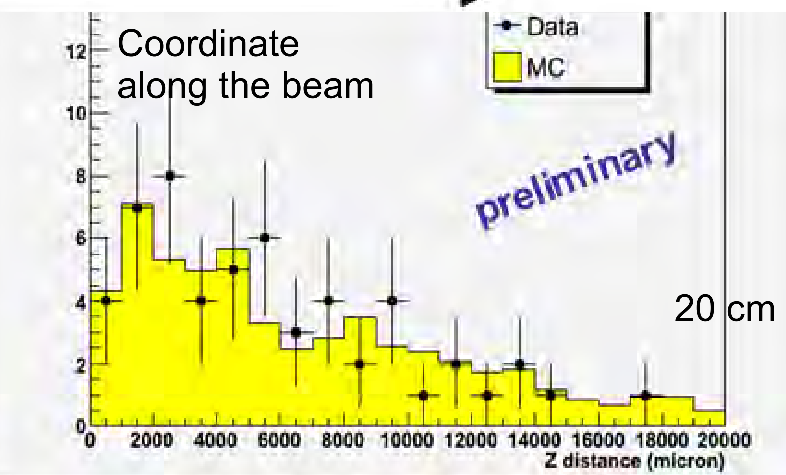
Scan of 20 plates × 1 cm^2 downstream of ν vertex

good description by MC









Reconstruction of γ

Currently 24 ν_e events as the by-product of ν_τ search

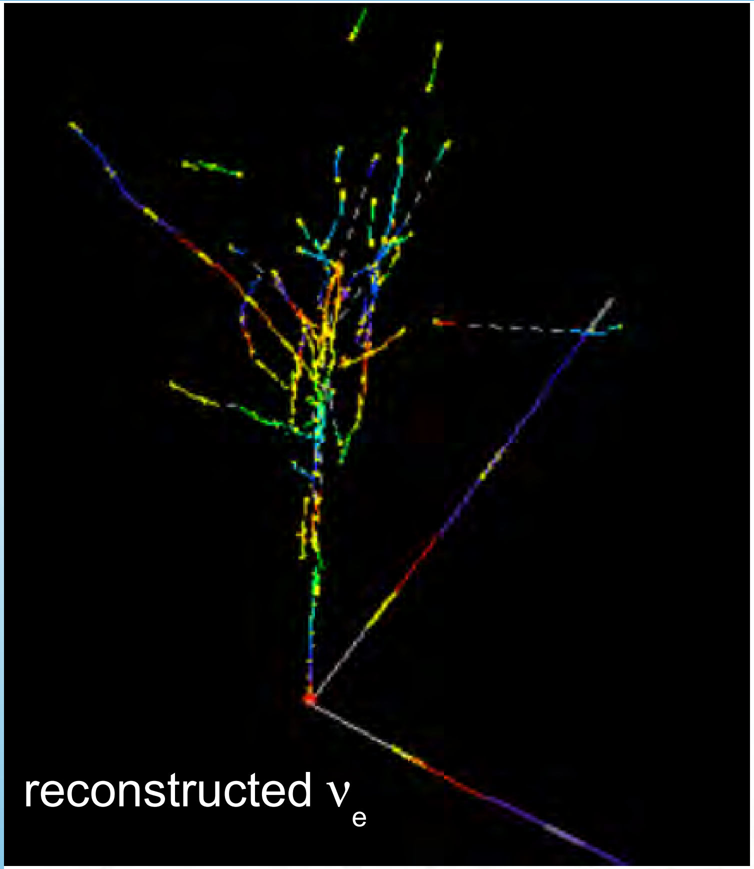
- A dedicated strategy using shower signature in the CS doublet is being pursued to increase efficiency.

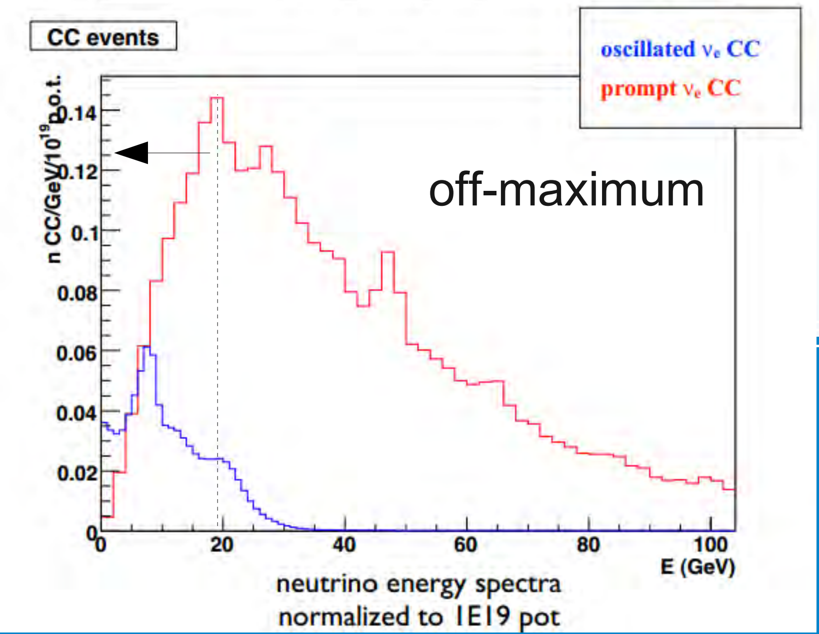
In progress:

- efficiency evaluation with complete simulation framework (well advanced)
- energy reconstruction tuning
- backgrounds: prompt ν_e and γ conversions

E < 20 GeV	2008-2009 preliminary	22.5e19 estimation
ν_e (prompt)	2.8	13.1
$(\tau \rightarrow e)$ + NCπ^0	1.6	7.5
$\sin^2 2\theta_{13} = 0.11$	1.2	5.6

- Plans for publication of 2008-09 sample in 2012





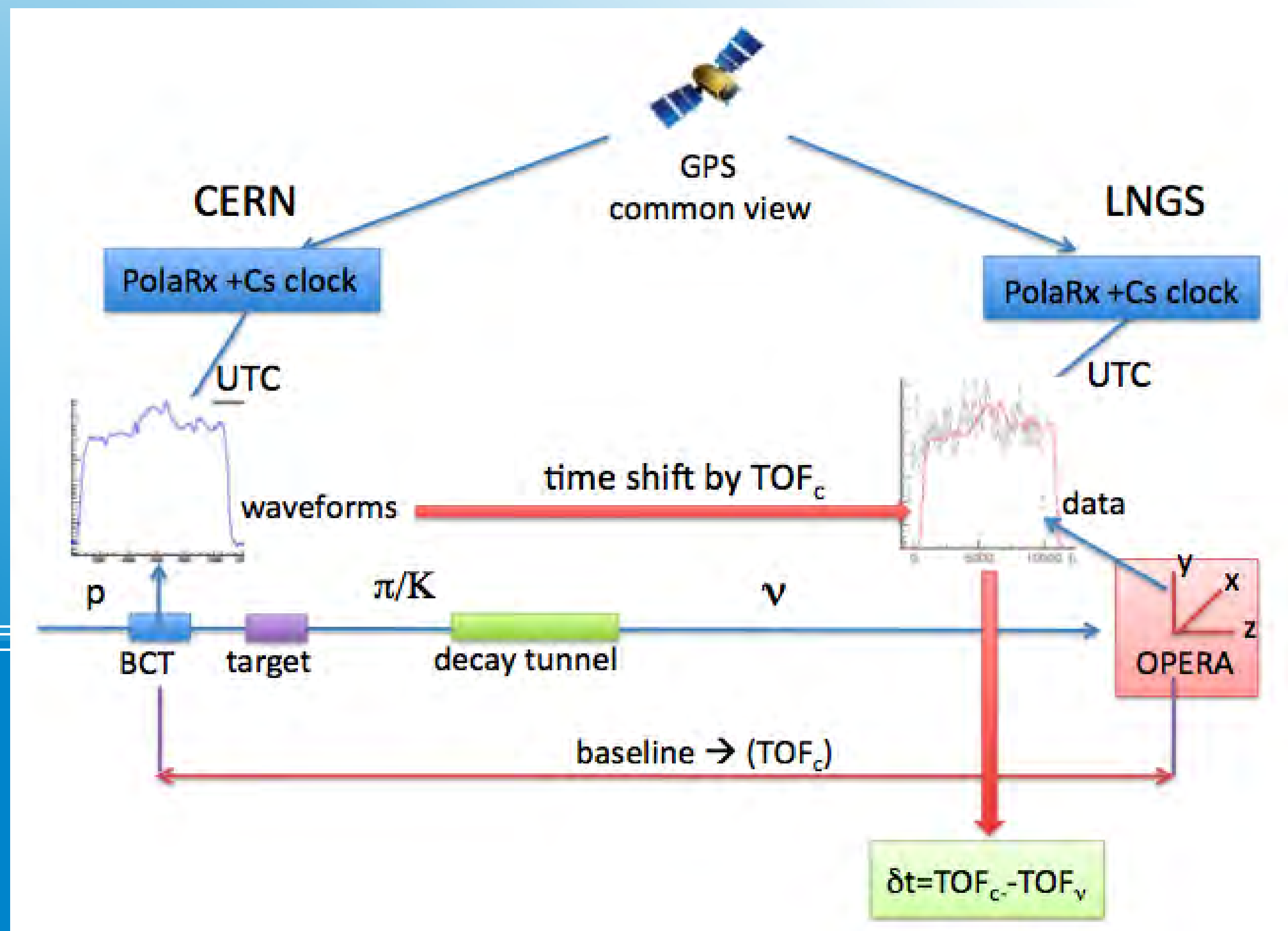
ν_e sample

- Basic ingredients*:

* will omit plenty of details and cross checks arXiv:1109.4897

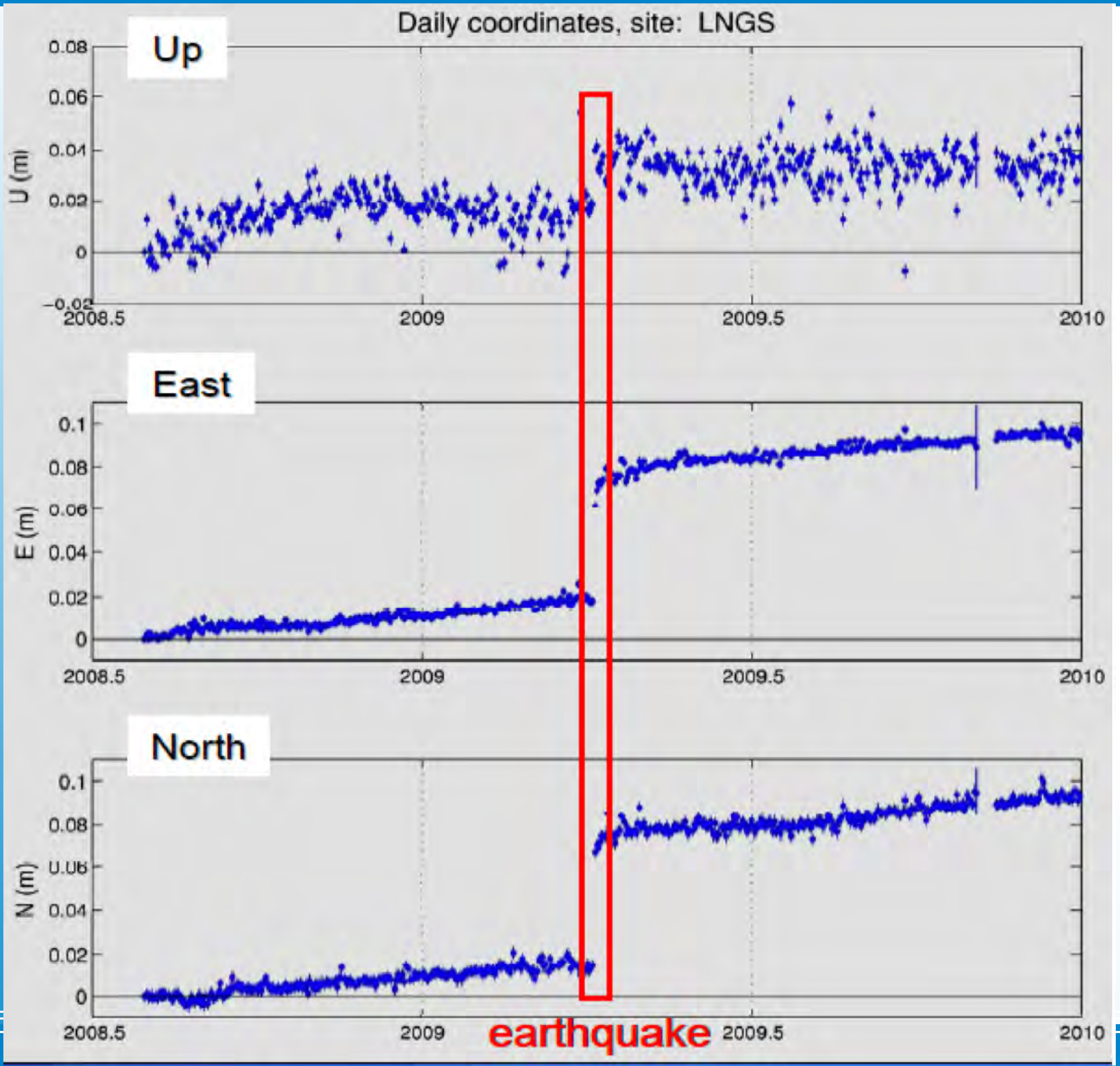
  - CNGS-OPERA synchronization at ~1ns (GPS common view mode)
  - Calibrations of the timing chains at CERN and OPERA
  - ν time distribution at CERN through proton waveforms with BCT
  - High ν energy - high statistics (~ 15k events) or beam with fine time structure
  - Geodesy: L= **731278.0 ± 0.2 m** (error dominated by extrapolation to underground)

ν-TOF



Long and short time scale phenomena visible:

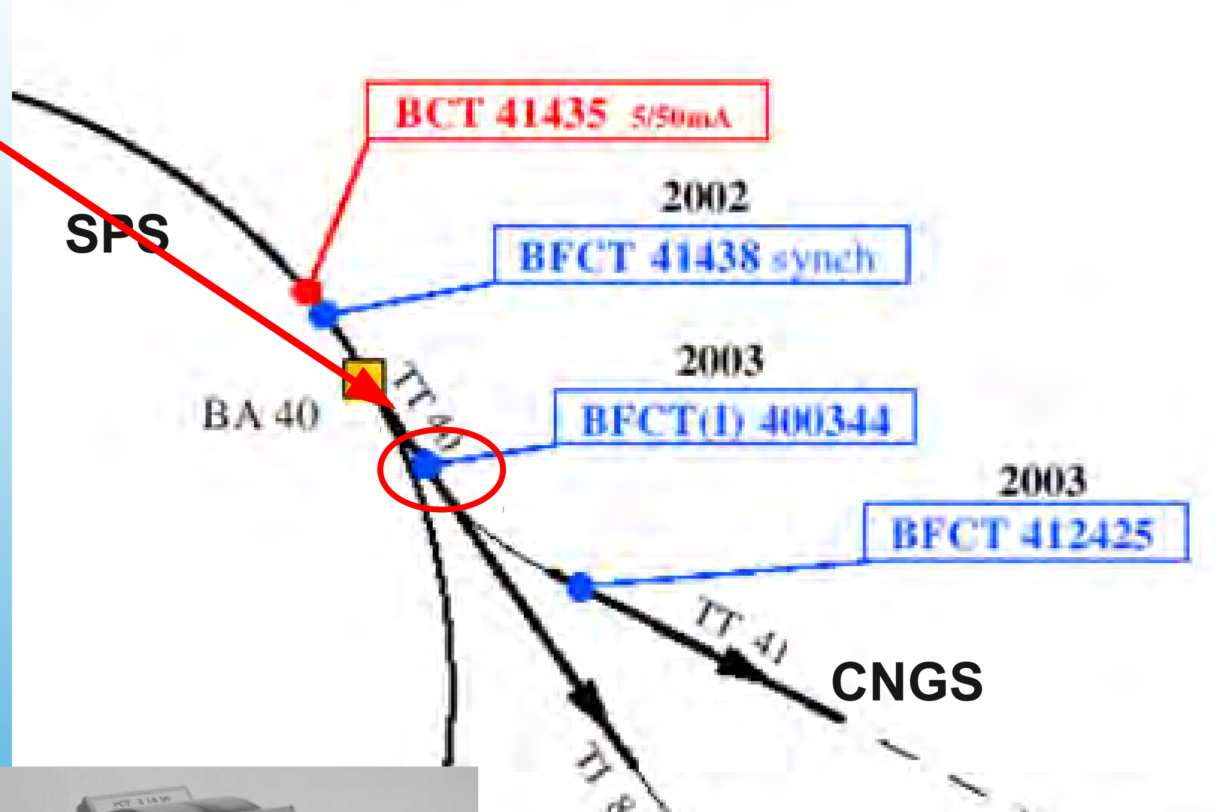
→ continental drift
→ 2009 L'Aquila earthquake



LNGS position monitoring

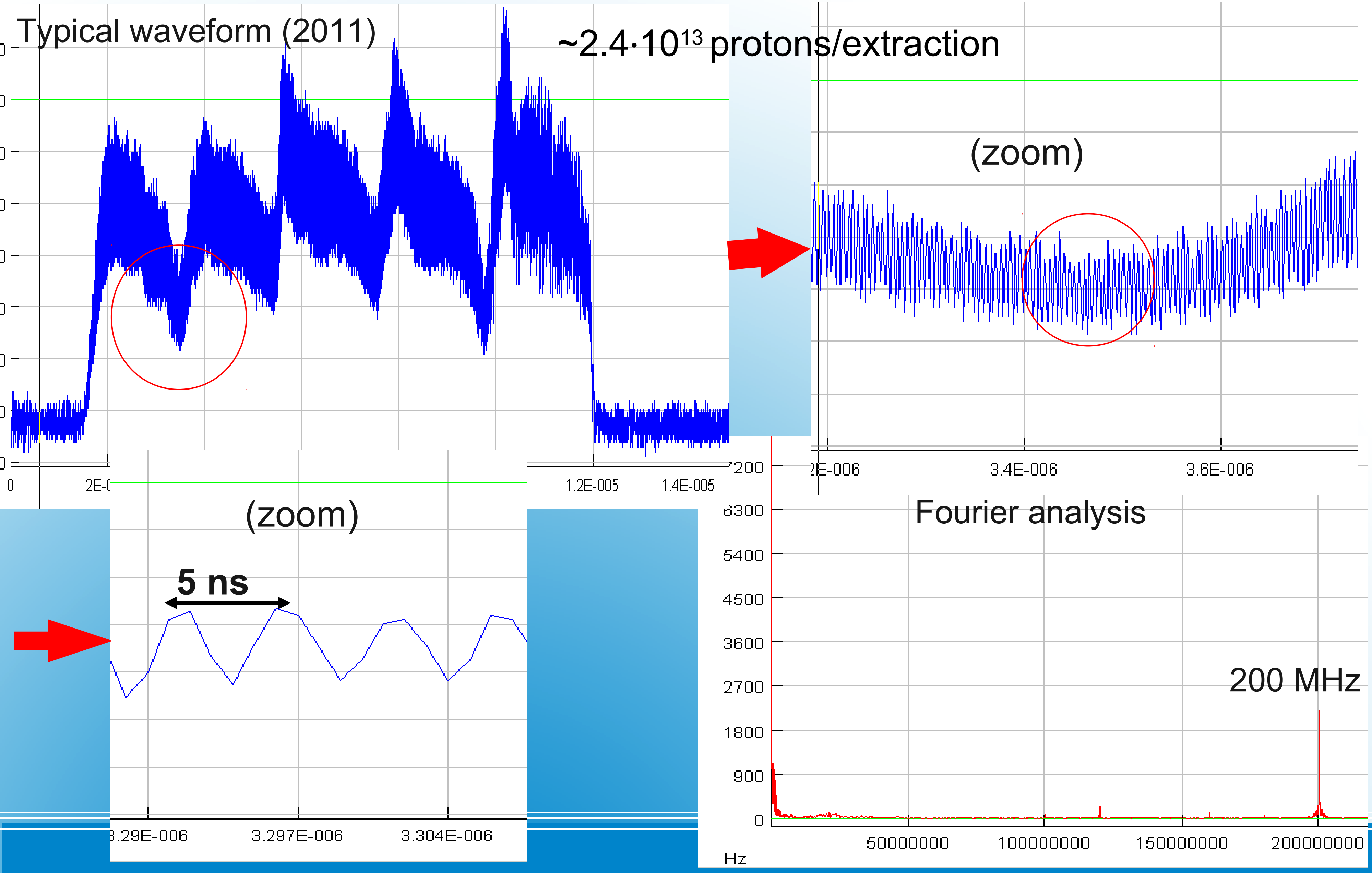
Fast Beam Current Transformer
("BCT", id 400344)
400 MHz bandwidth

- Proton pulse digitized by a 1GS/s waveform digitizer ("WFD", Acqiris DP110)
- WFD triggered by a replica of the kicker signal
- Waveforms are UTC time-stamped and stored in CNGS database for offline analysis

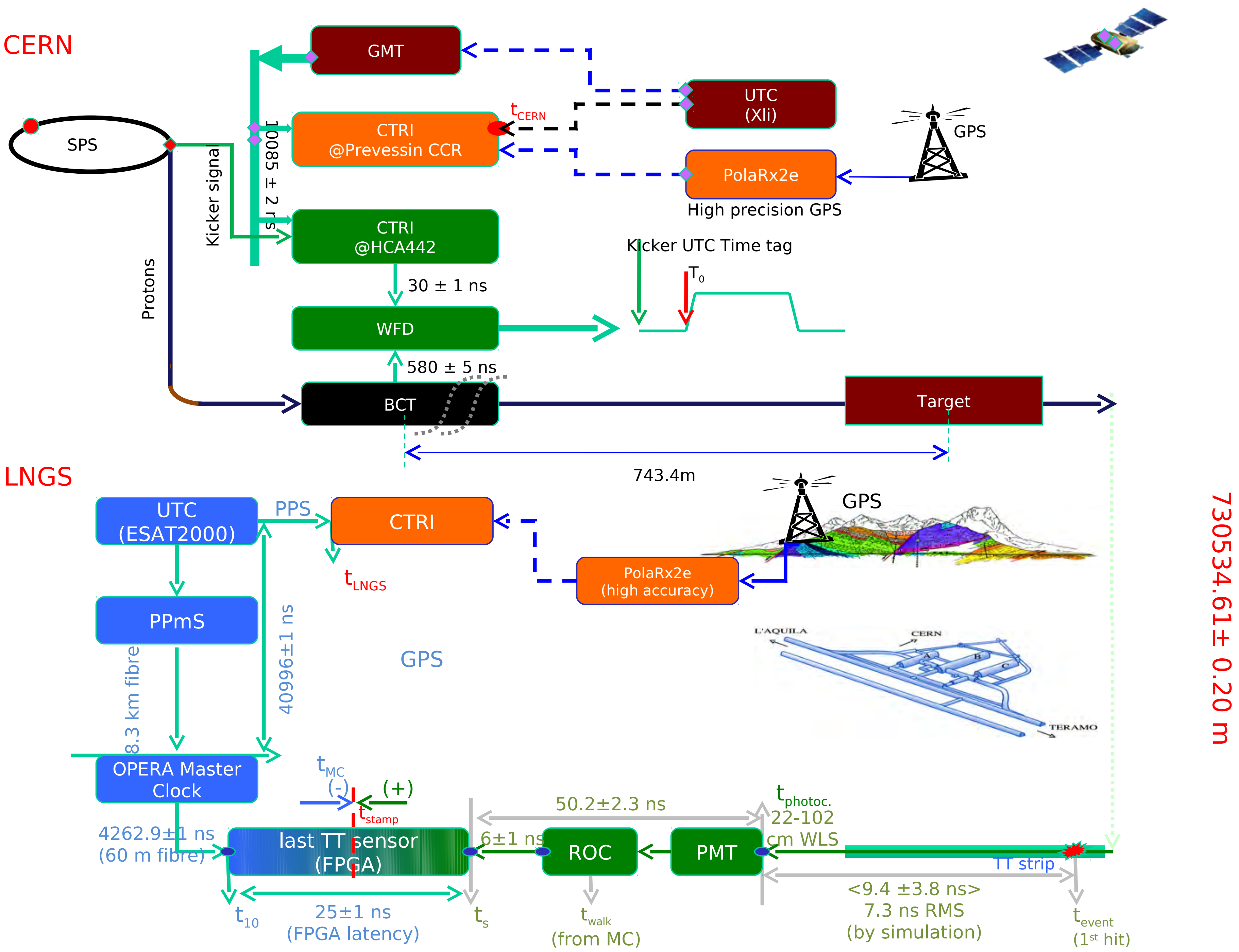



2010 calibration with Cs clock

Accurate p timing

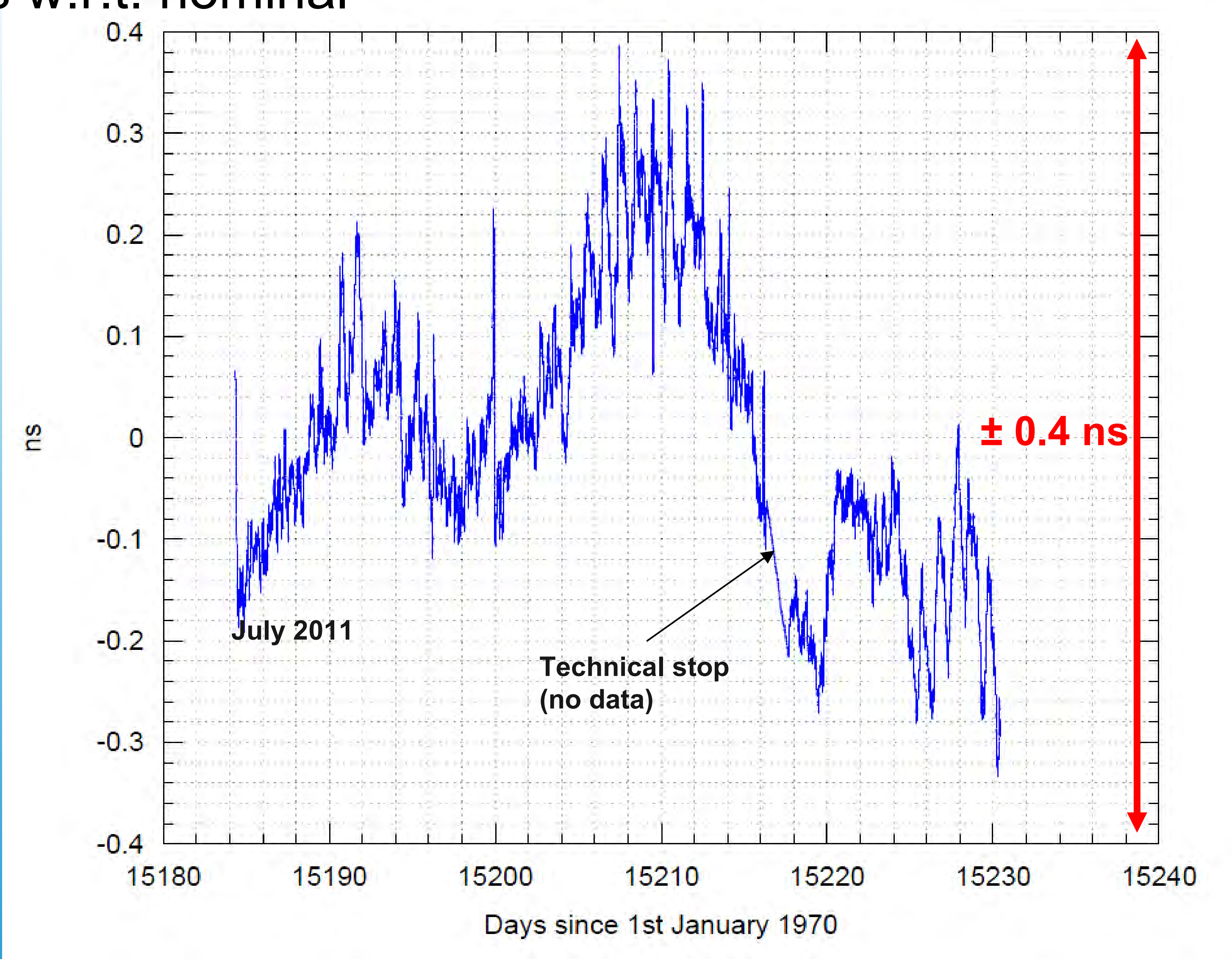


Single proton wave-form example



CERN
GMT
UTC (Xli)
SPS
CTRI @Prevessin CCR
t_{CERN}
PolaRx2e
High precision GPS
GPS
Kicker signal
10085 ± 2 ns
CTRI @HCA442
Protons
30 ± 1 ns
Kicker UTC Time tag
T_0
WFD
580 ± 5 ns
BCT
Target
743.4m
LNGS
UTC (ESAT2000)
PPS
CTRI
t_{LNGS}
GPS
PolaRx2e (high accuracy)
PPmS
8.3 km fibre
40996±1 ns
GPS
L'AQUILA
CERN
TERAMO
730534.61± 0.20 m
OPERA Master Clock
t_{MC}
(-)
(+)
t_{stamp}
4262.9±1 ns (60 m fibre)
last TT sensor (FPGA)
50.2±2.3 ns
$t_{photoc.}$
22-102 cm WLS
6±1 ns
ROC
PMT
TT strip
t_{10}
25±1 ns (FPGA latency)
t_s
t_{walk} (from MC)
<9.4 ±3.8 ns>
7.3 ns RMS
(by simulation)
t_{event} (1st hit)

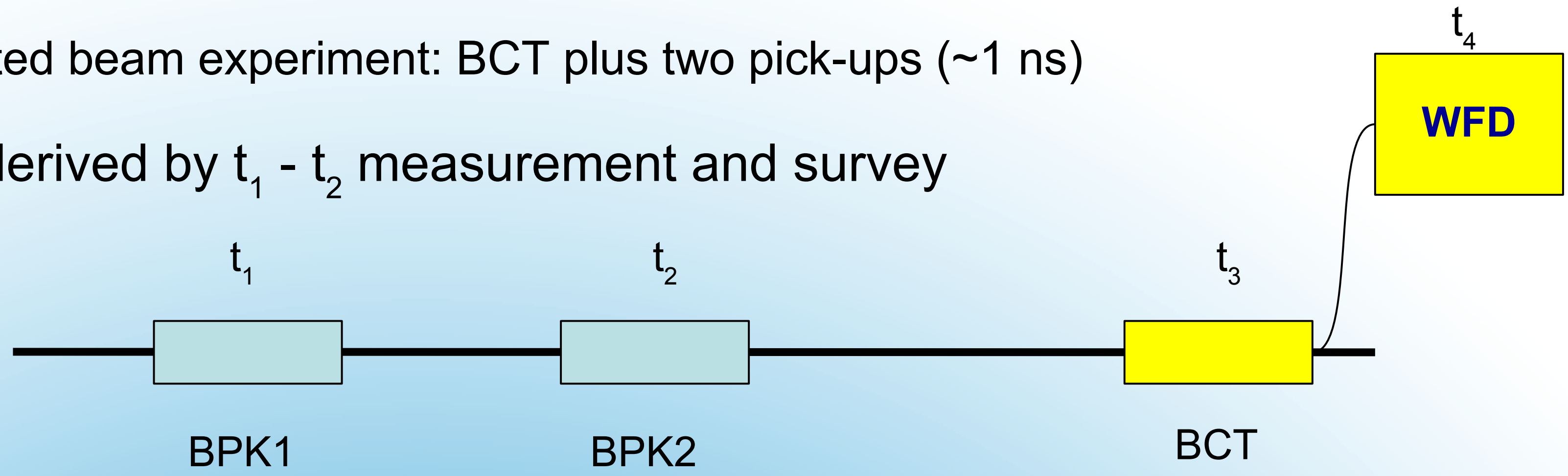
variations w.r.t. nominal



Continuous two-way measurement of UTC delay at CERN

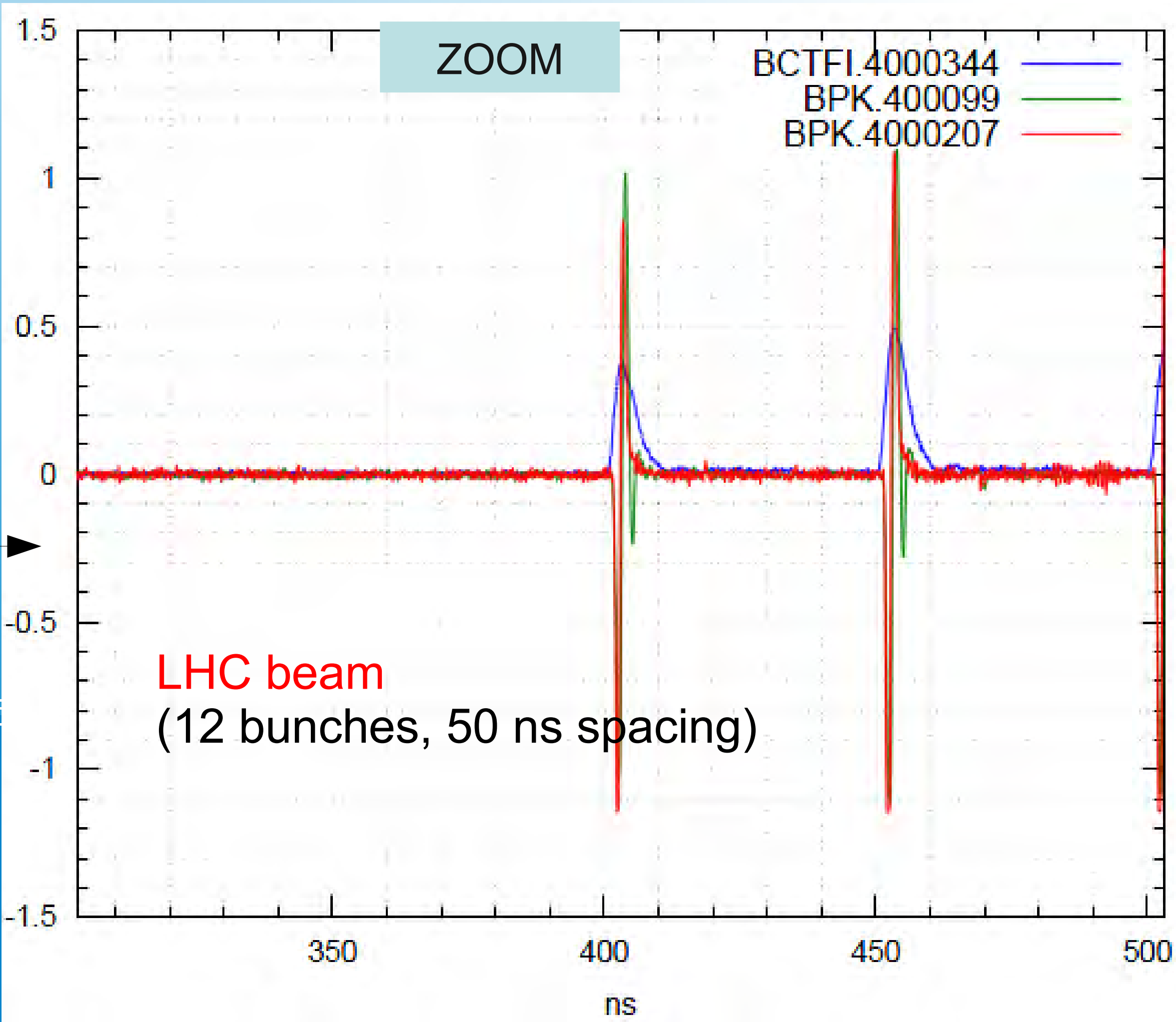
Dedicated beam experiment: BCT plus two pick-ups (~1 ns)

t_3 : derived by t_1 - t_2 measurement and survey



$\Delta t_{BCT} = t_4 - t_3 = (580 \pm 5)$ ns

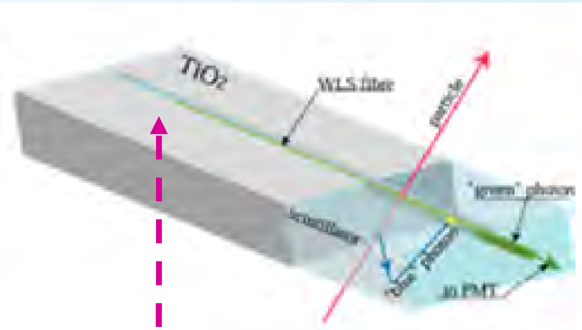
result: signals comparison after Δt_{BCT} compensation

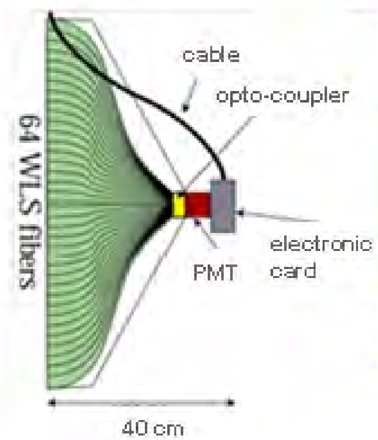


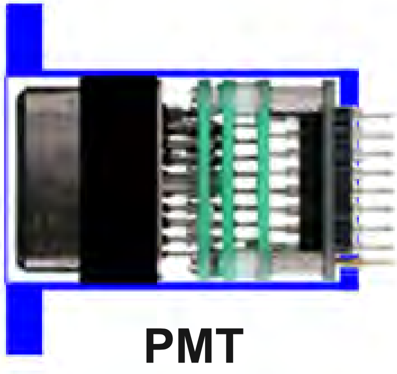
BCT calibration

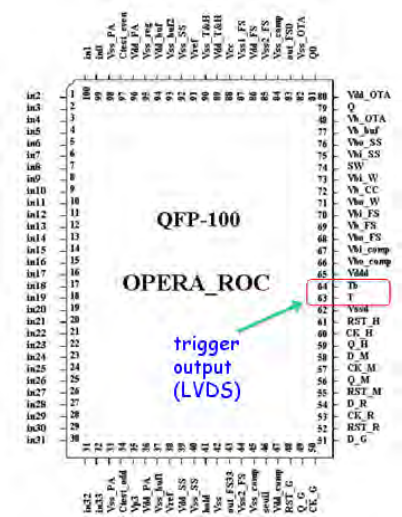
signal →

Scintillator + WLS fibers | PMT | analog Front End chip (ROC) | FPGA









FPGA

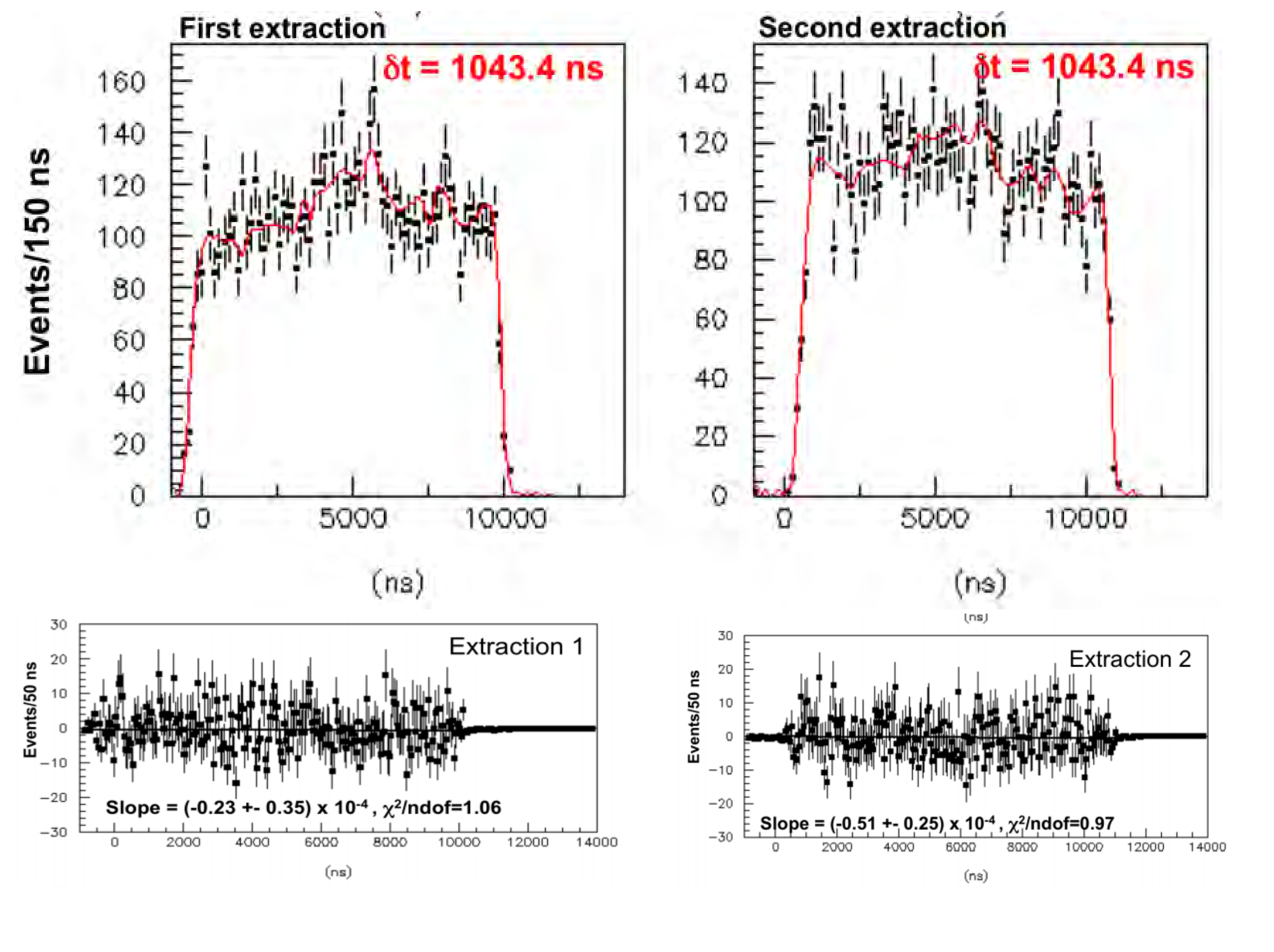
picosecond UV laser excitation:

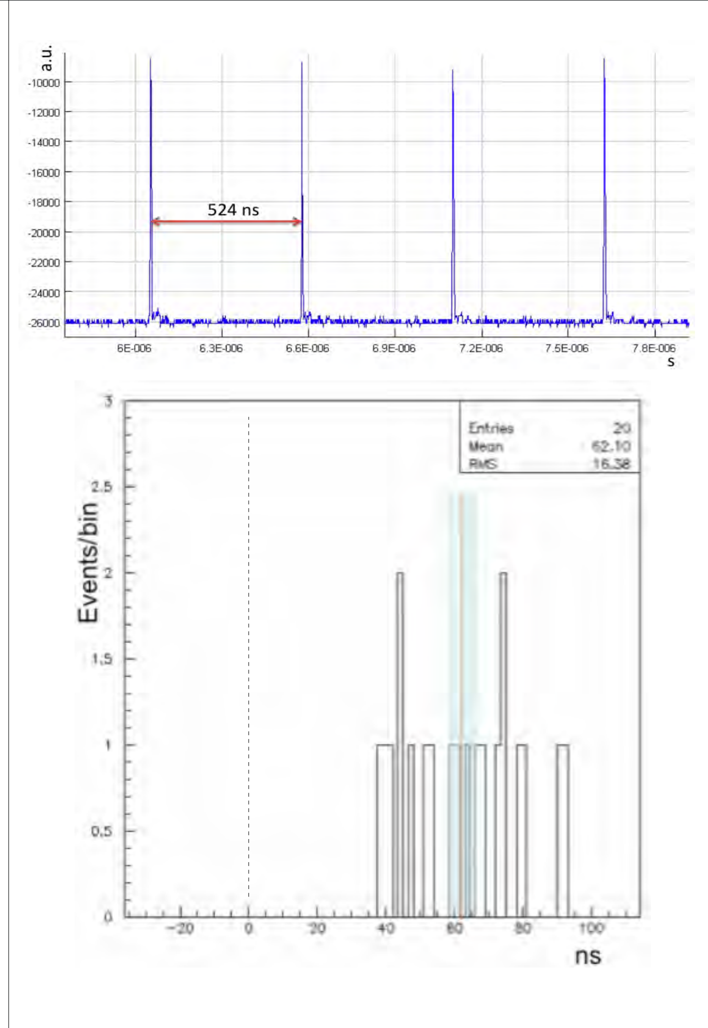
→ delay from photo-cathode to FPGA input: (50.2 ± 2.3) ns

→ average event time response: (59.6 ± 3.8 (sys.)) ns

including event position, pulse height dependence, ROC time-walk, DAQ quantization effects with simulations

TT time response measurement





Standard beam (two 10.5 us wide bunches), 3 years.

57.8 ± 7.8 (stat.) ns $^{+8.3}_{-5.9}$(sys.) unbinned LL with average PDFs

54.5 ± 5.0 (stat.) ns $^{+9.6}_{-7.2}$(sys.) unbinned LL with event-by-event PDFs

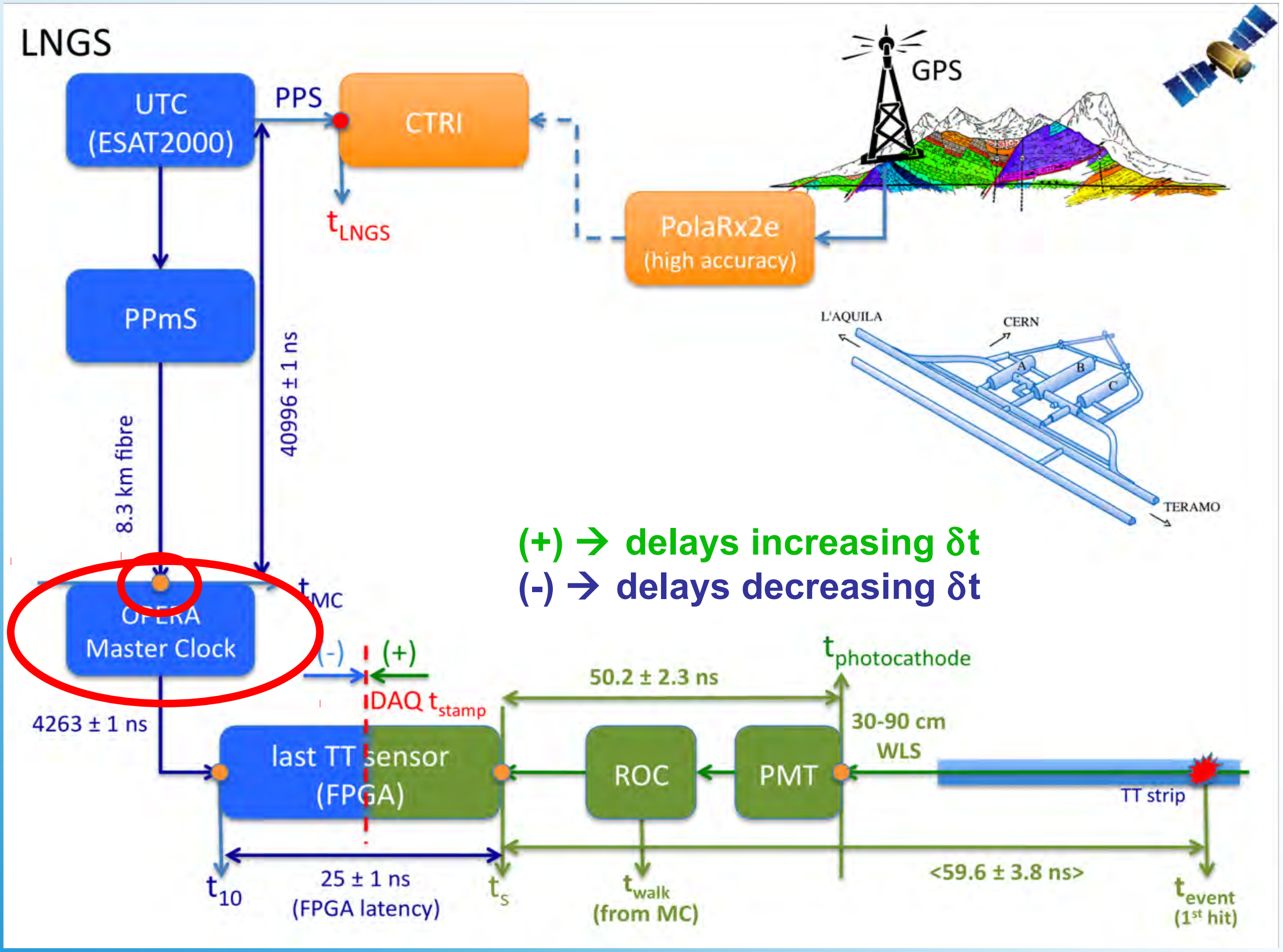
Bunched beam, 2 weeks in Nov 2011 (confirms robustness of statistical treatment): **62.1 ± 3.7 ns**

(Old) results after applying all corrections

Official statement (23/2/2012)

"The OPERA Collaboration, by continuing its campaign of verifications on the neutrino velocity measurement, has identified two issues that could significantly affect the reported result. The first one is linked to the oscillator used to produce the events time-stamps in between the GPS synchronizations. The second point is related to the connection of the optical fiber bringing the external GPS signal to the OPERA master Clock.

These two issues can modify the neutrino time of flight in opposite directions. While continuing our investigations, in order to unambiguously quantify the effect on the observed result, the Collaboration is looking forward to performing a new measurement of the neutrino velocity as soon as a new bunched beam will be available in 2012. An extensive report on the above mentioned verifications and results will be shortly made available to the scientific committees and agencies."



Recent findings

Oscillation:

- 1 ν_τ candidate, with an expectation of 1.65 signal and 0.05 ± 0.01 background events.
- The analyzed sample (2008-2009) corresponds to ~ 21% of the overall nominal statistics of which 63 % has been collected so far (14.1e19 pot).
- The 2012 run will hopefully bring us close to nominal statistics (22.5e19 pot with 7.6 τ expected)
- Improvement in the analysis and (data driven) background control achieved and being pursued further.
- Constant progress in scanned events statistics: a really demanding task!
- Update at summer conferences foreseen with signal expectation significatly > 1.
- ν_e appearance results in 2012 on 2008/2009 sample.

Summary

$\nu-$TOF:

- A very powerful experimental setup and analysis method has been used (only partially reported)
- BUT, two issues that could significantly affect the reported TOF anomaly have been identified recently
- A new bunched beam run in 2012 requested to provide a clarified picture.

Summary

THANK YOU for your attention!

Back-up slides

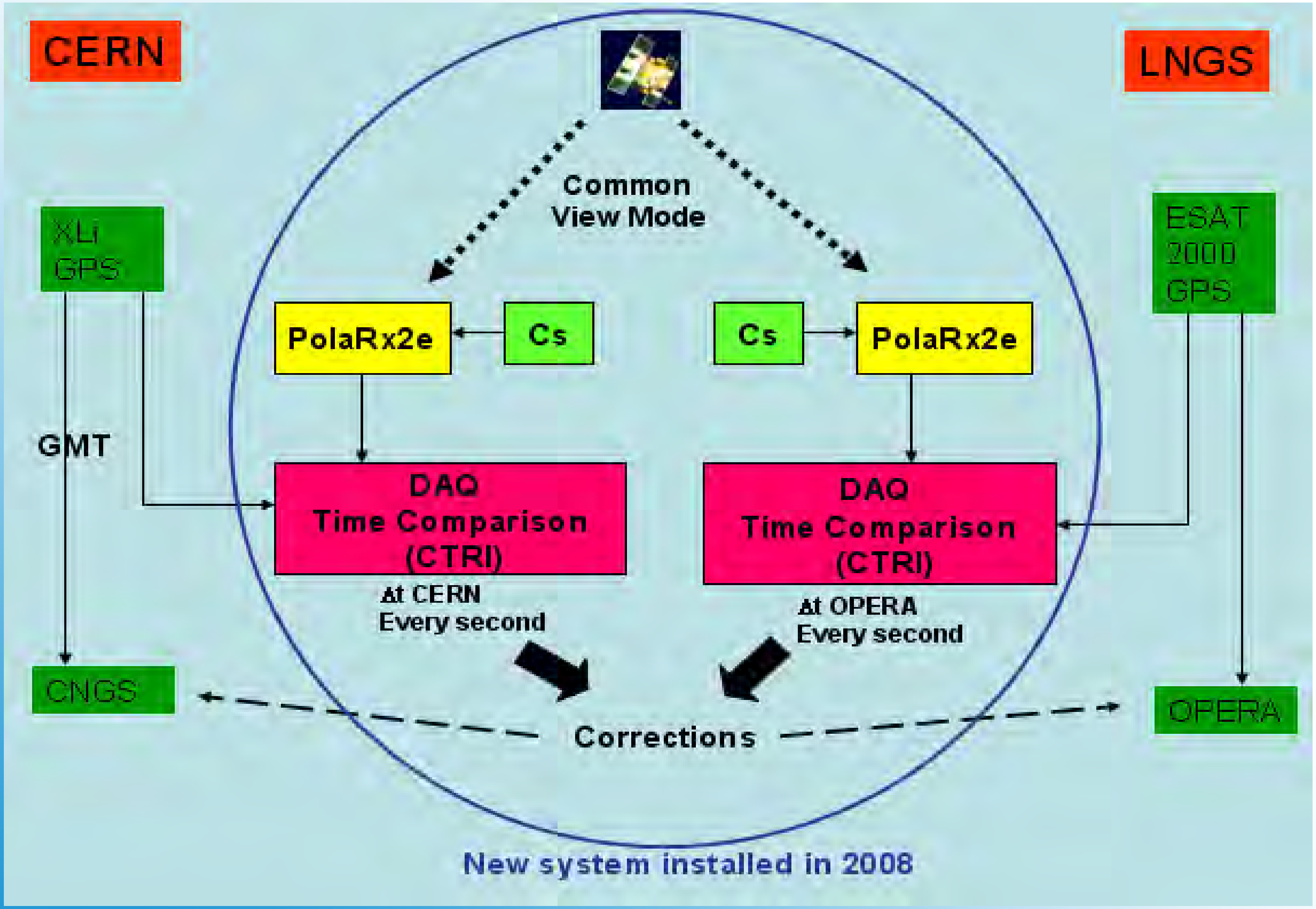
Standard GPS receivers have ~100 ns accuracy:

- XLi (CERN)
- ESAT 2000 (LNGS)

2008: installation of a twin high accuracy system calibrated by METAS (Swiss metrology institute)

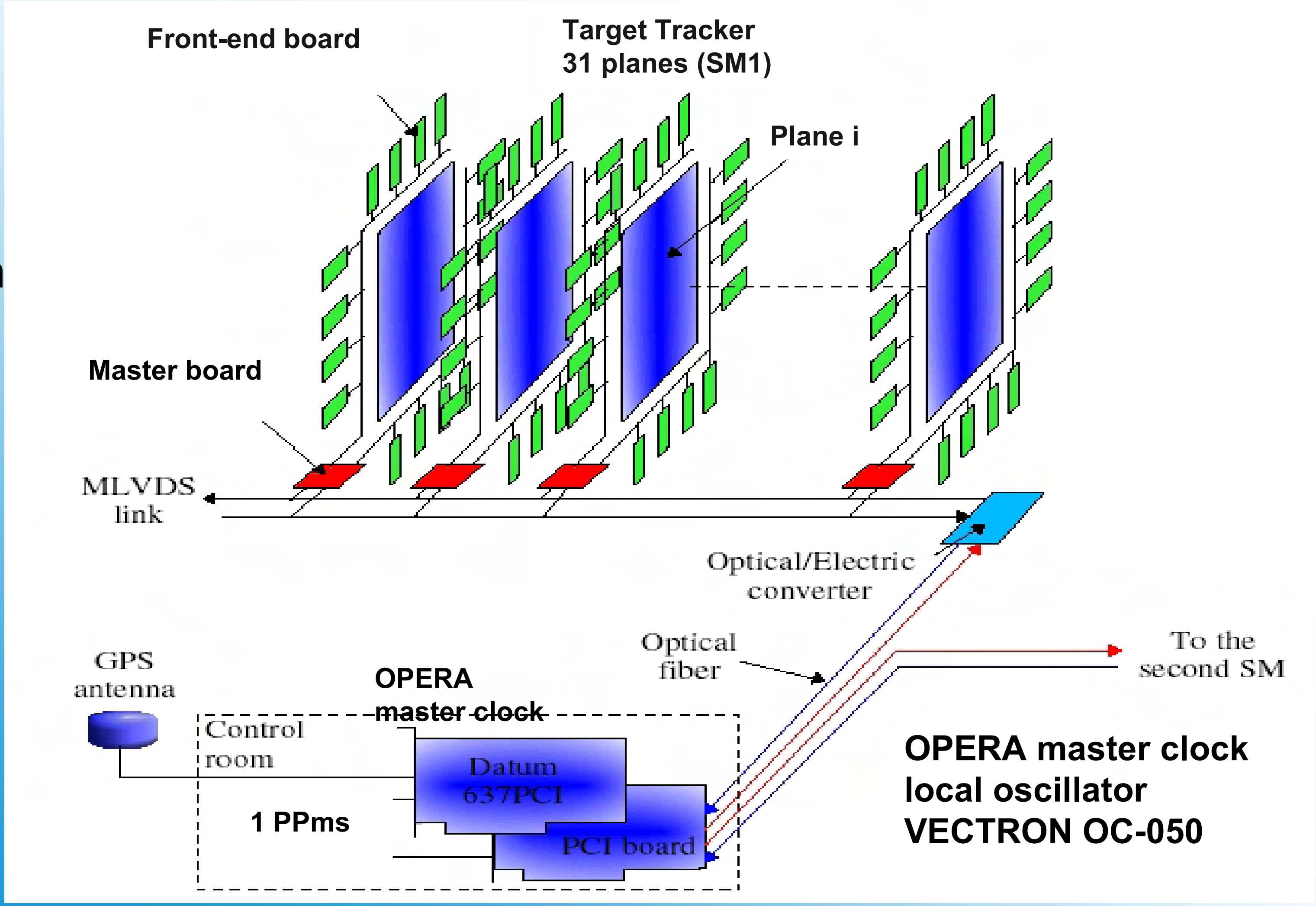
- PolaRx2e GPS receiver
- Cs-clock

at CERN and LNGS



CNGS OPERA synchronization

- 1200 asynchronous FE-nodes
- Gigabit ethernet network
- “trigger-less” system
- for each FE node mezzanine card: CPU (embedded Linux), memory, FPGA, clock receiver
- 10 ns UTC event time stamp granularity



OPERA read-out system and clock distribution

LNGS

Rome La Sapienza
Geodesy group

Dedicated measurements:
July-Sept. 2010

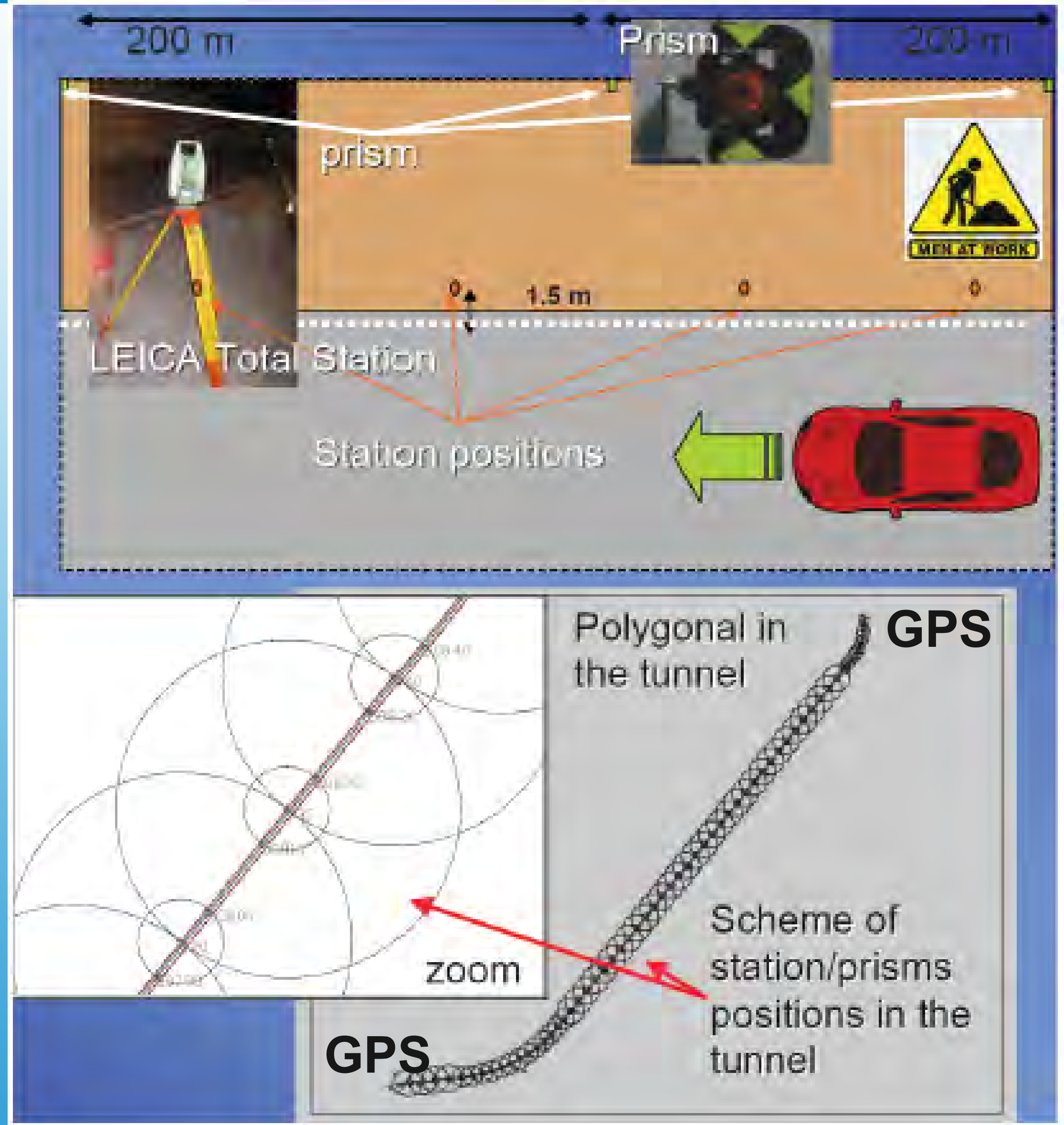
2 new GPS benchmarks on each side of the 10 km highway tunnel

GPS measurements ported underground to OPERA

CERN survey group

CERN measurements
(taken in different periods) combined in the ETRF2000 European Global system, accounting for earth dynamics

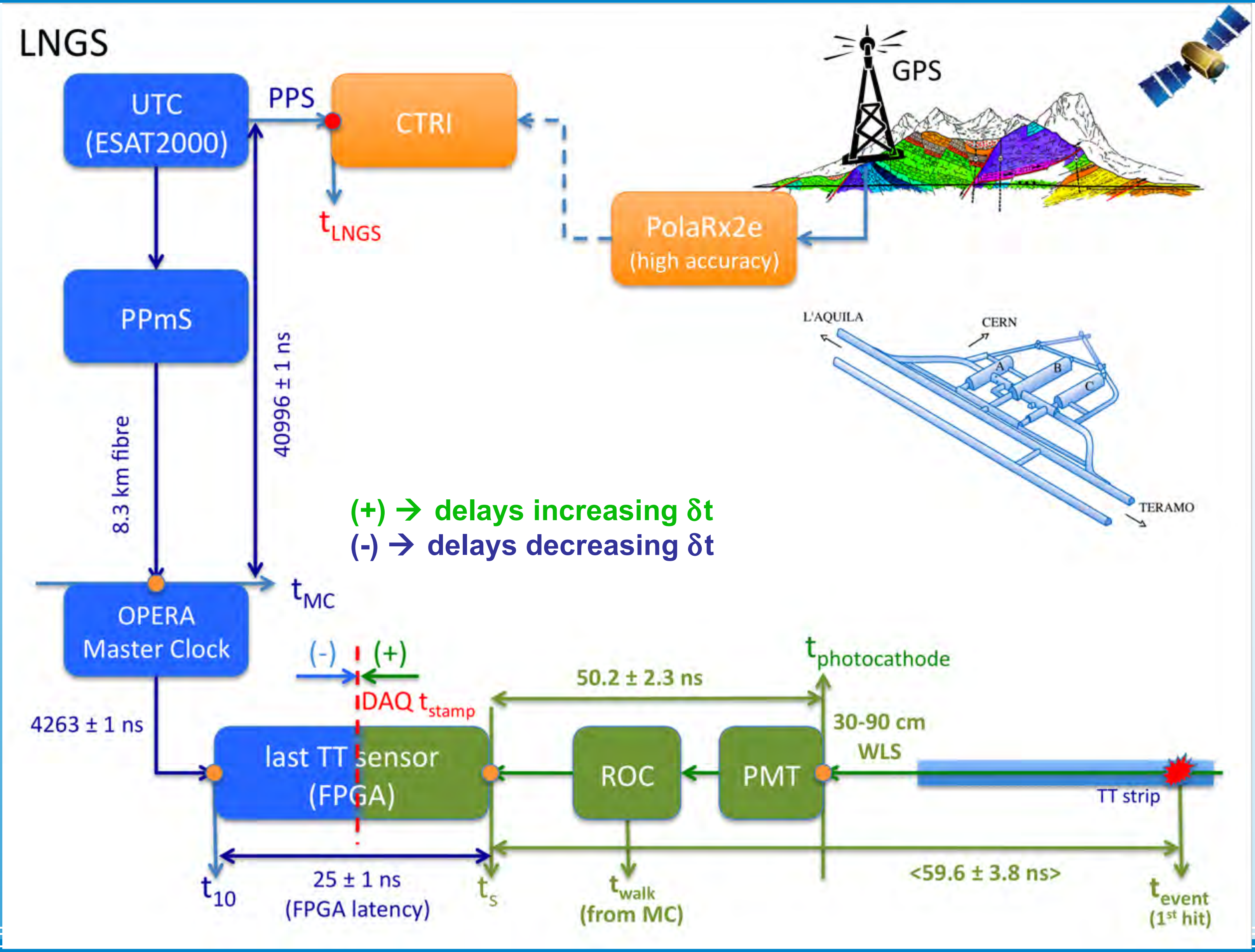
Cross-check in June 2011:
simultaneous CERN-LNGS measurement of GPS benchmarks



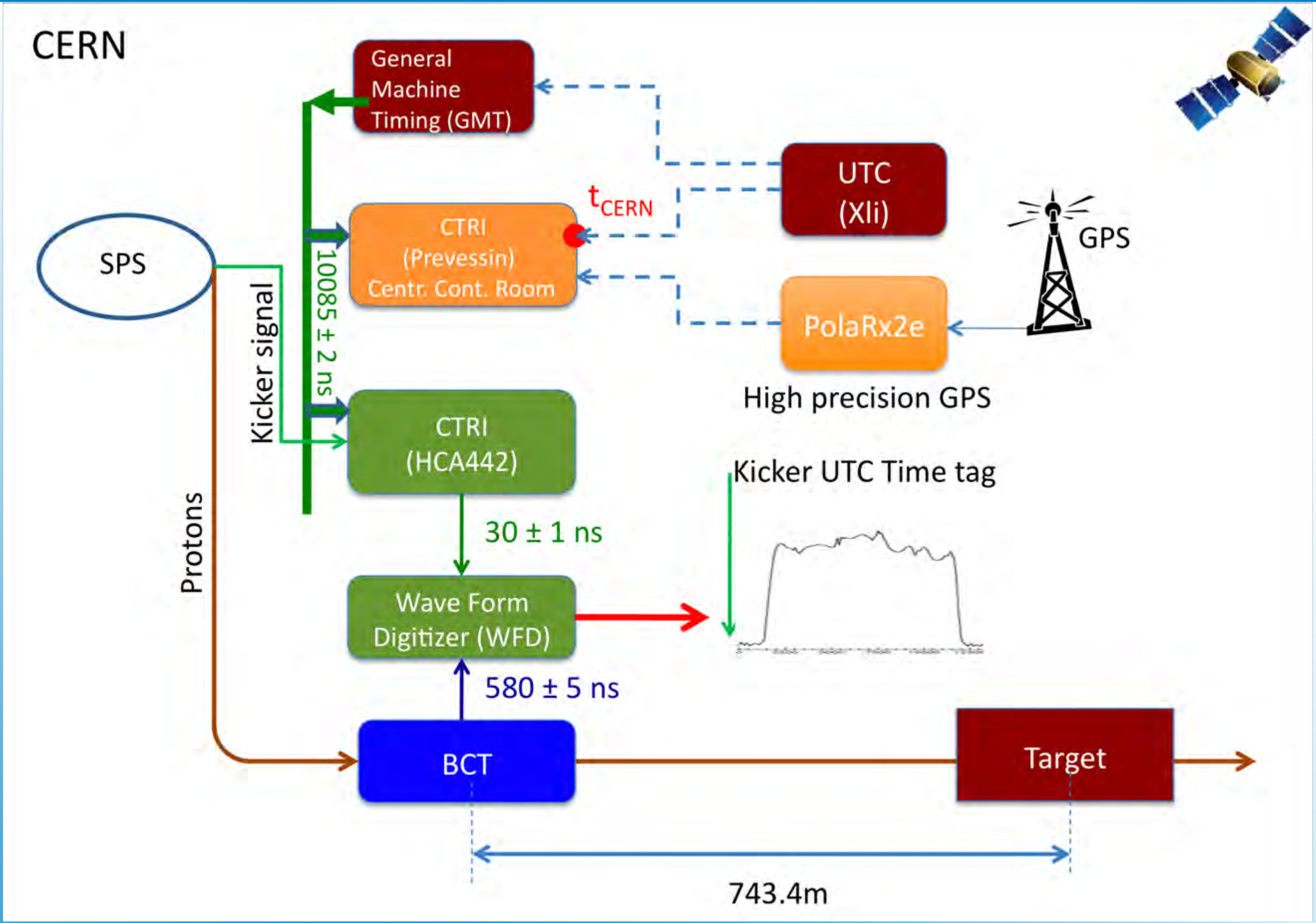
Geodesy

Distance (BCT - OPERA reference frame) =

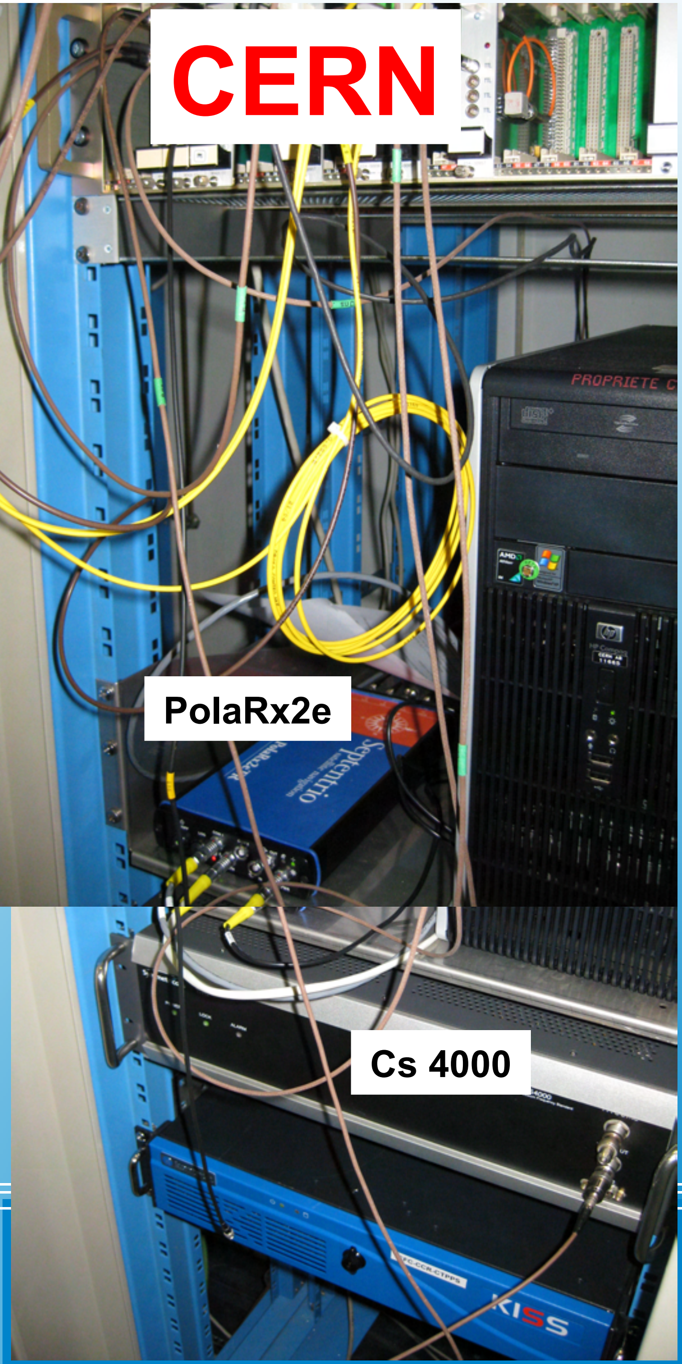
(731278.0 ± 0.2) m



Delay calibrations: LNGS side

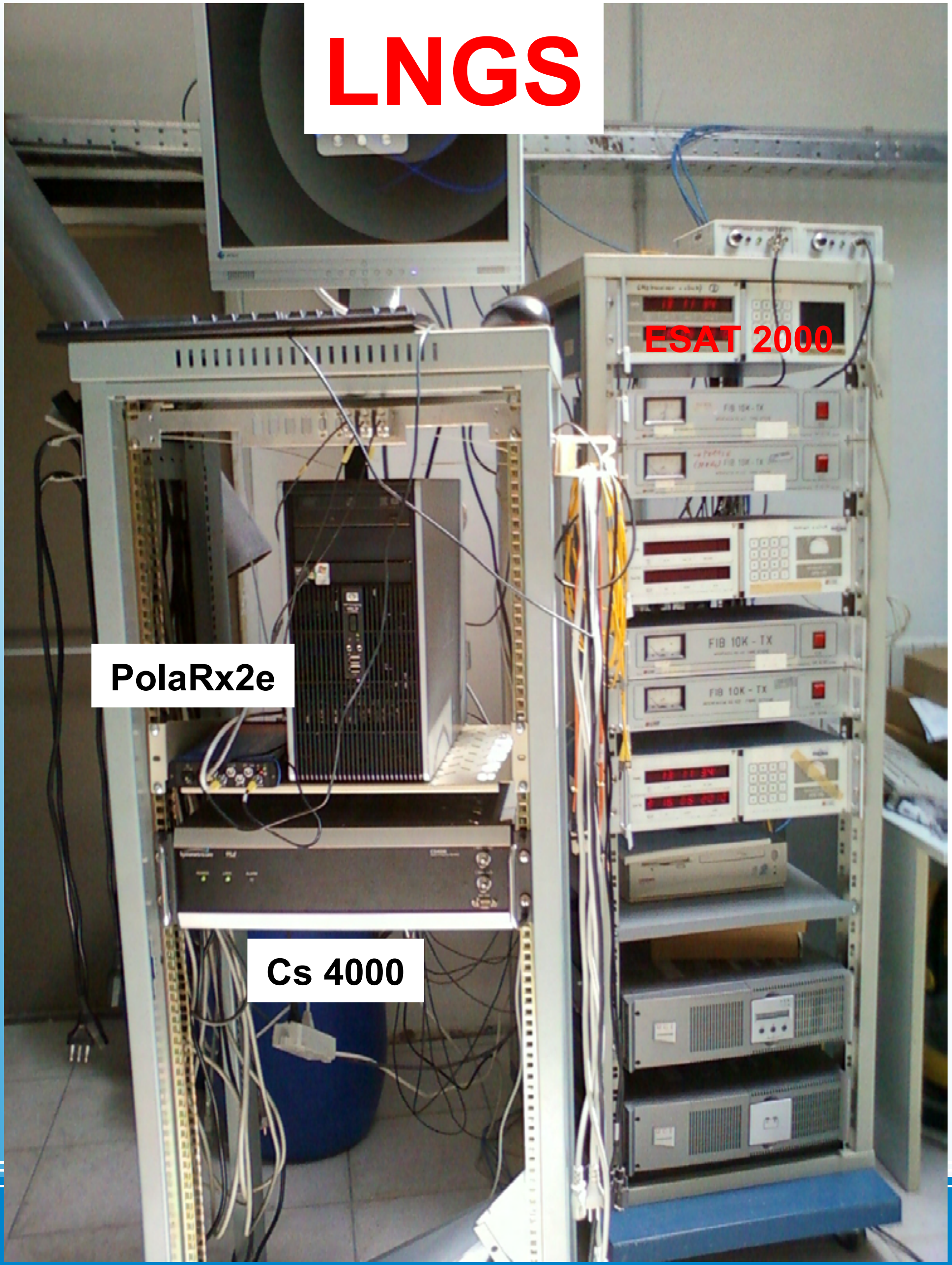


Delay calibrations: CERN side



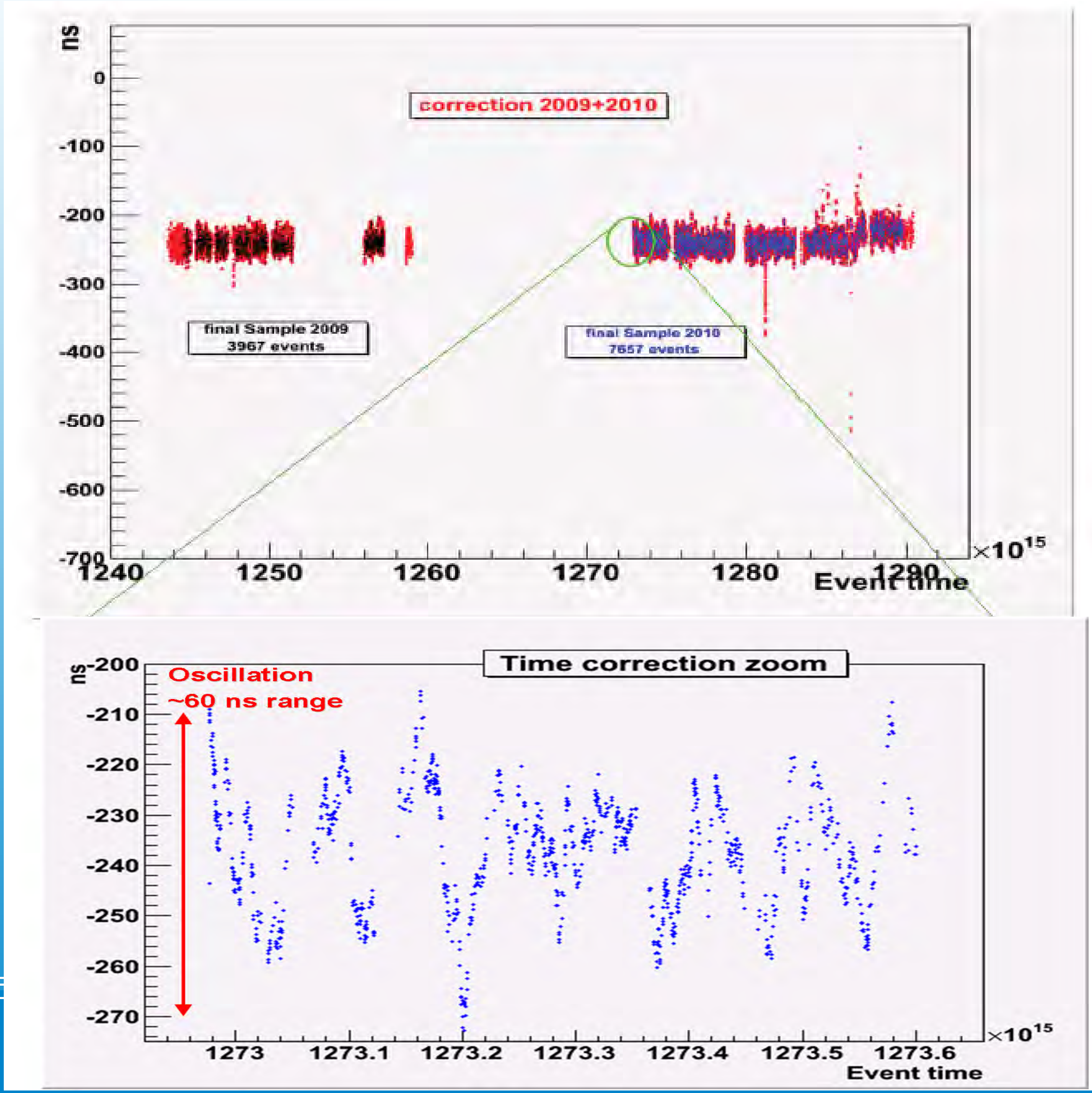
PolaRx2e :
GPS receiver for time-transfer applications:

- frequency reference from Cs clock (Cs-4000)
- internal time tagging of 1PPS with respect to individual satellite observations
- off-line common-view analysis in CGGTTS format
- use ionosphere-free code (P3)

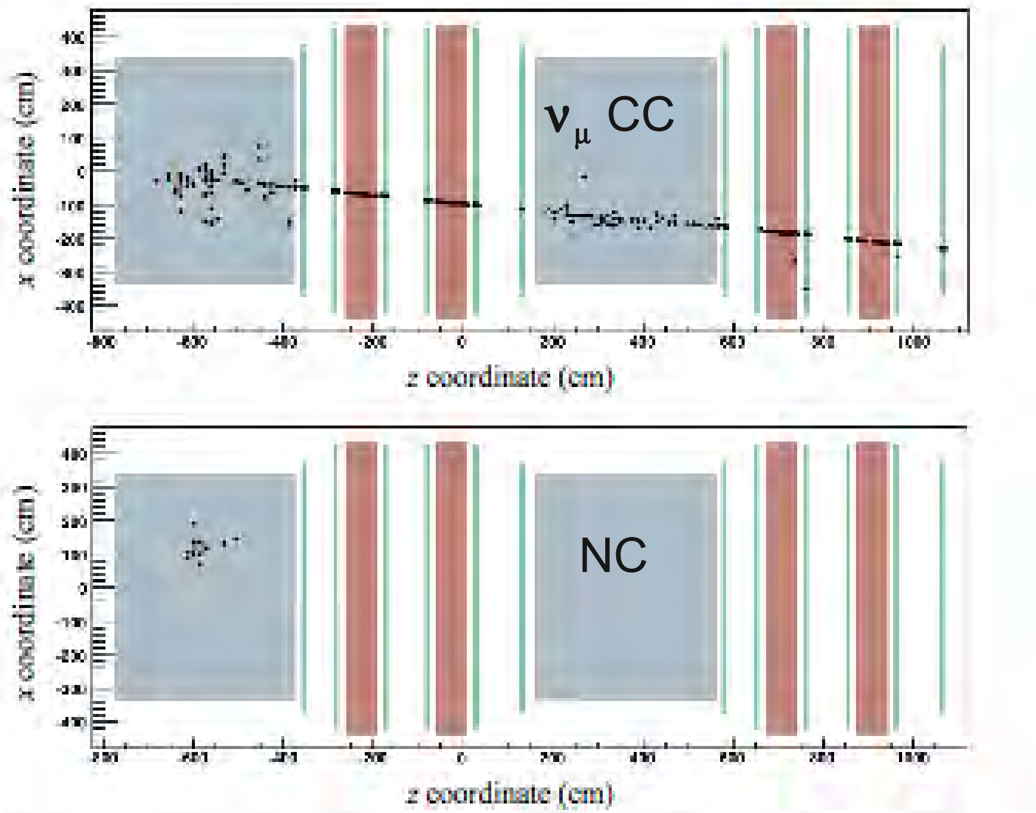


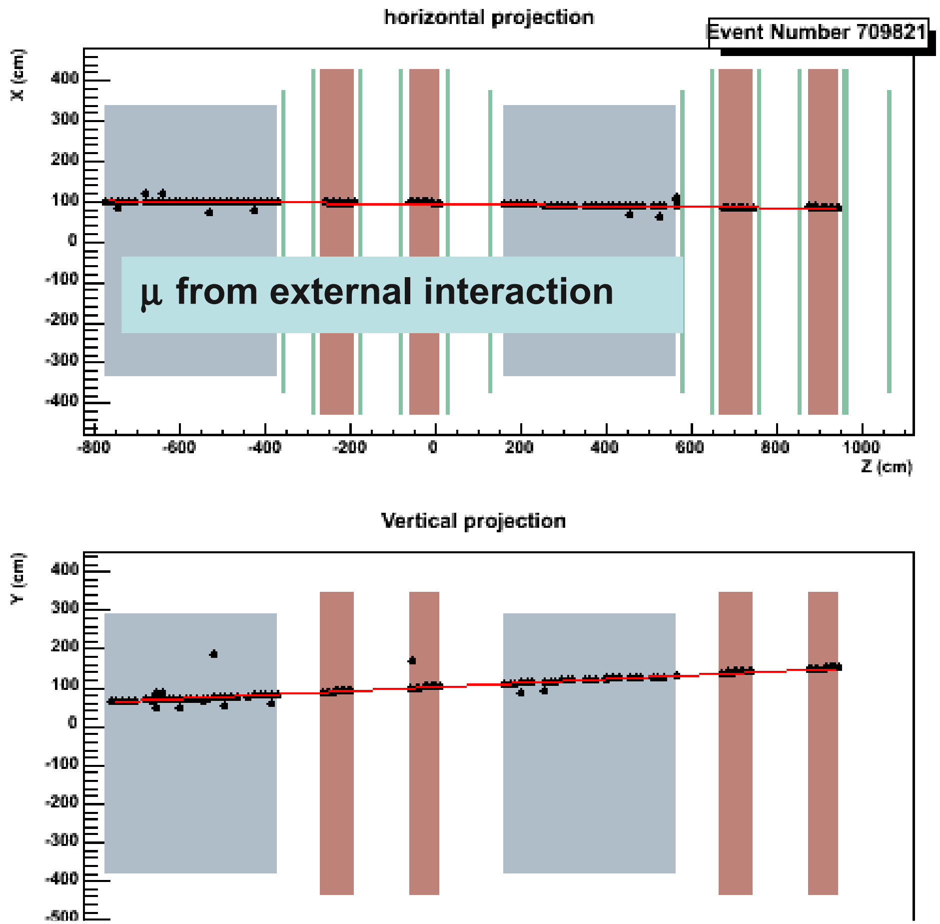
Twin synchronization devices

Event-by-event correction
From the GPS common view mode operations



Result: TOF timelink correction





First TT hit used as "stop"
and translated in time to a common reference point (assuming c)
Internal/External: 7235/7988 events with 2009-2010-2011 CNGS runs (~10^{20} pot)
External events timing checked with full simulation → 2 ns systematic uncertainty

Internal and external events

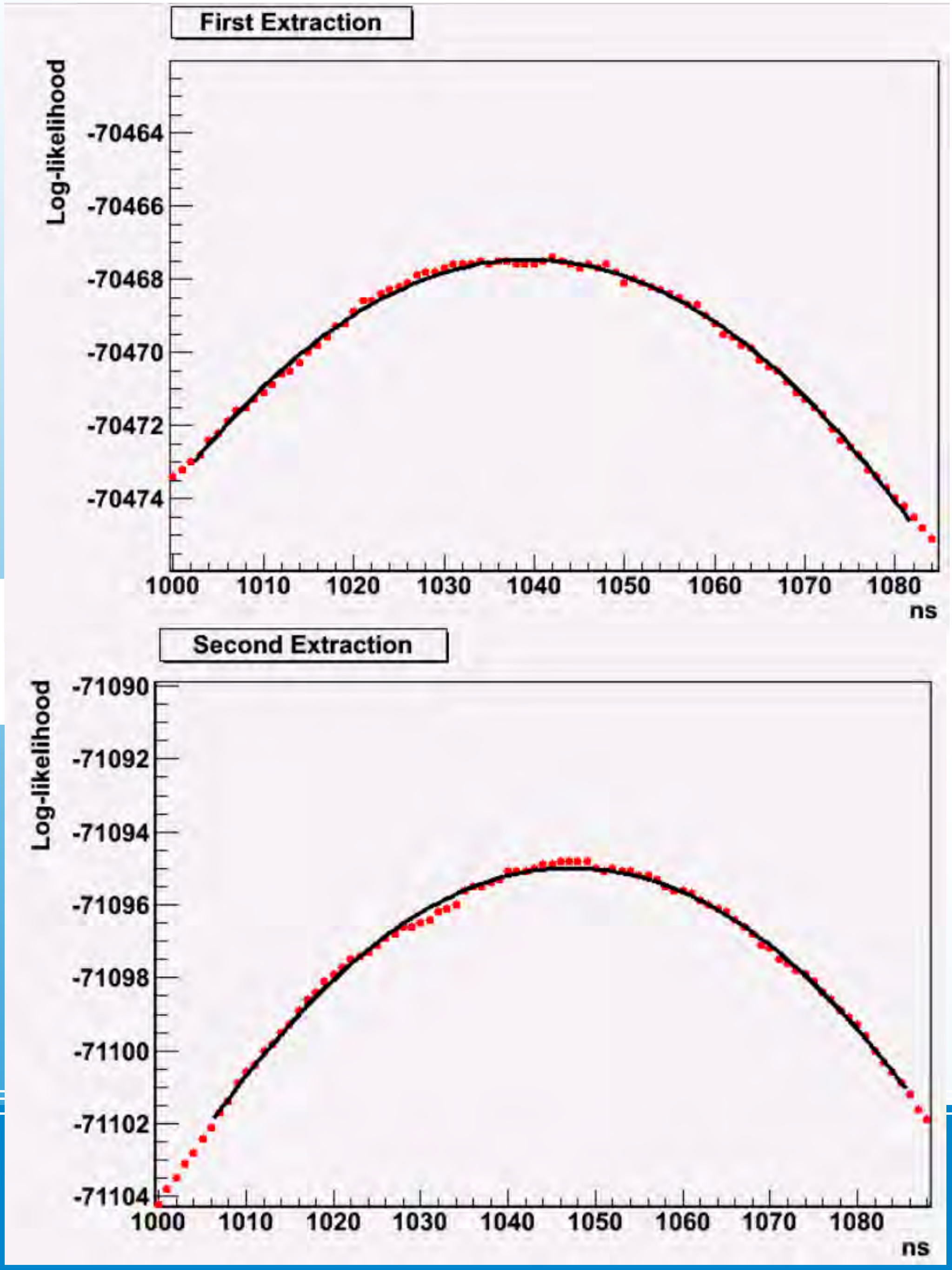
$\delta t = TOF_c - TOF_\nu$

positive (negative) δt →
ν arrives earlier (later) than light

Unbinned Log-Likelihood maximised over δt:

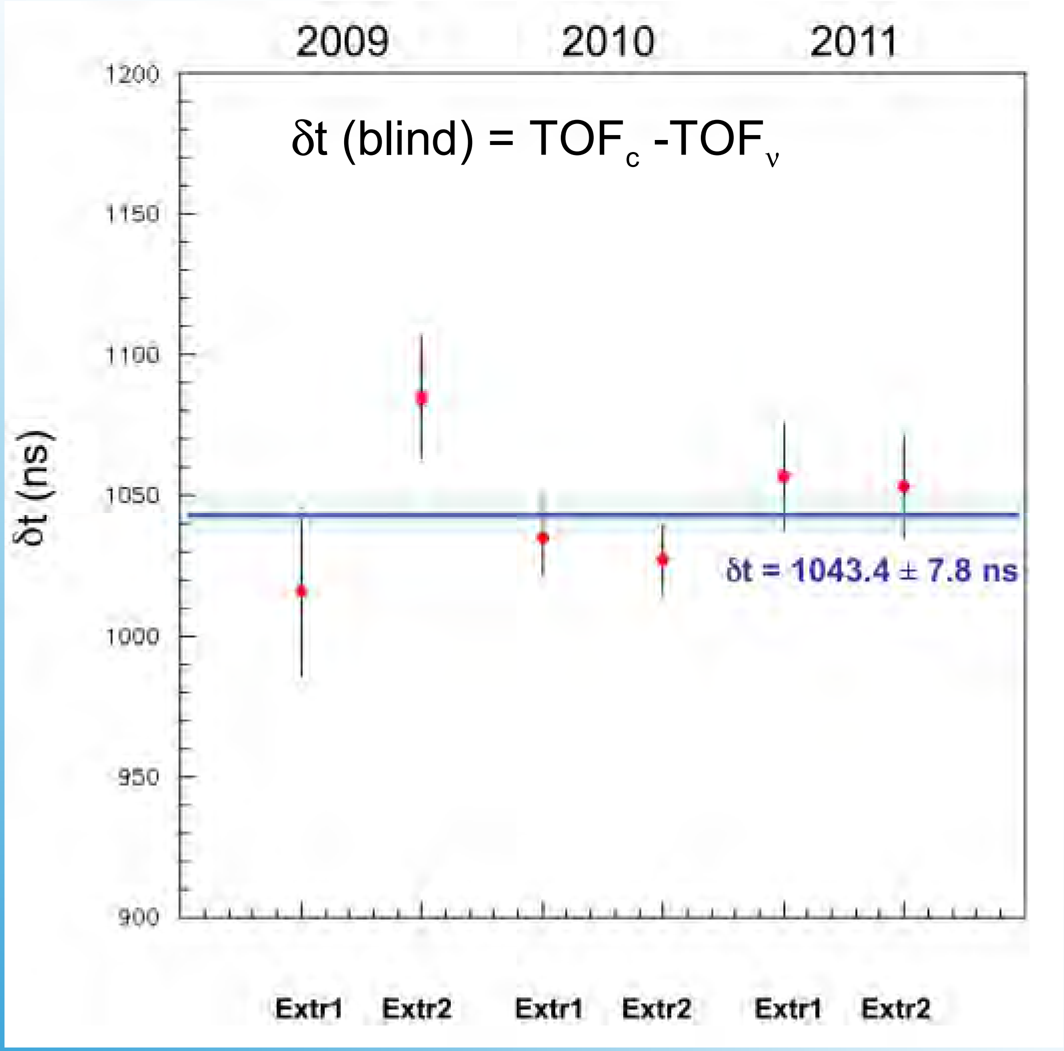
$$L_k(\delta t_k) = \prod_j w_k(t_j + \delta t_k)$$ k=1,2 extractions

Statistical error evaluated from log likelihood curves



Analysis method

1) Coherence among
CNGS runs/extractions



2) No hint for day-night

|day-night| = 16.4 ± 15.8 ns

3) or seasonal effects:
|(spring+fall) - summer|: 15.6 ± 15.0 ns

4) Internal vs external events:

All: 1043.4 ± 7.8 ns
Internal: 1045.1 ± 11.3 ns

Cross-checks

Timing and baseline corrections

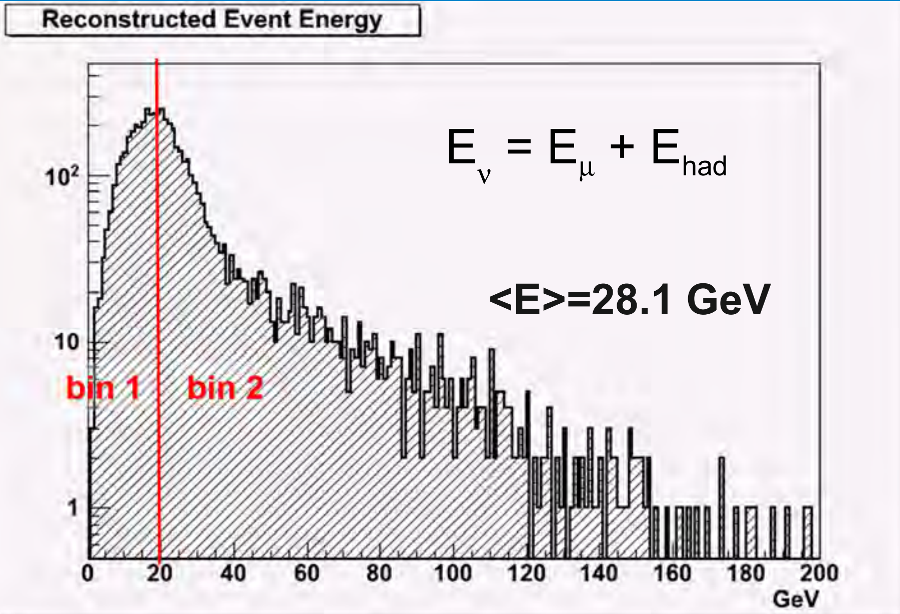
	Blind analysis (ns) 2006	Final analysis (ns) 2011	Correction (ns)
Baseline	2440079.6	2439280.9	
Earth rotation		2.2	
Correction baseline			-796.5
CNGS delays:			
UTC calibration	10092.2	10085.0	
Correction UTC			-7.2
WFD	0	30	
Correction WFD			30
BCT	0	-580	
Correction BCT			-580
OPERA Delays:			
TT response	0	59.6	
FPGA	0	-24.5	
DAQ clock	-4245.2	-4262.9	
Correction OPERA			17.4
GPS Corrections:			
Synchronisation	-353	0	
Time-link	0	-2.3	
Correction GPS			350.7
Total correction			**-985.6**

Systematic uncertainties

Systematic uncertainties	**ns**	**Error distribution**
Baseline (20 cm)	0.67	Gaussian
Decay point	0.2	Exponential (1 side)
Interaction point	2.0	Flat (1 side)
UTC delay	2.0	Gaussian
LNGS fibres	1.0	Gaussian
DAQ clock transmission	1.0	Gaussian
FPGA calibration	1.0	Gaussian
FWD trigger delay	1.0	Gaussian
CNGS-OPERA GPS synchronisation	1.7	Gaussian
MC simulation for TT timing	3.0	Gaussian
TT time response	2.3	Gaussian
BCT calibration	5.0	Gaussian
Total systematic uncertainty	**-5.9, +8.3**	

$$\delta t = TOF_c - TOF_\nu = (1043.4 - 985.6)\ \text{ns} = (57.8 \pm 7.8\ (\text{stat.})^{+8.3}_{-5.9}(\text{sys.}))\ \text{ns}$$

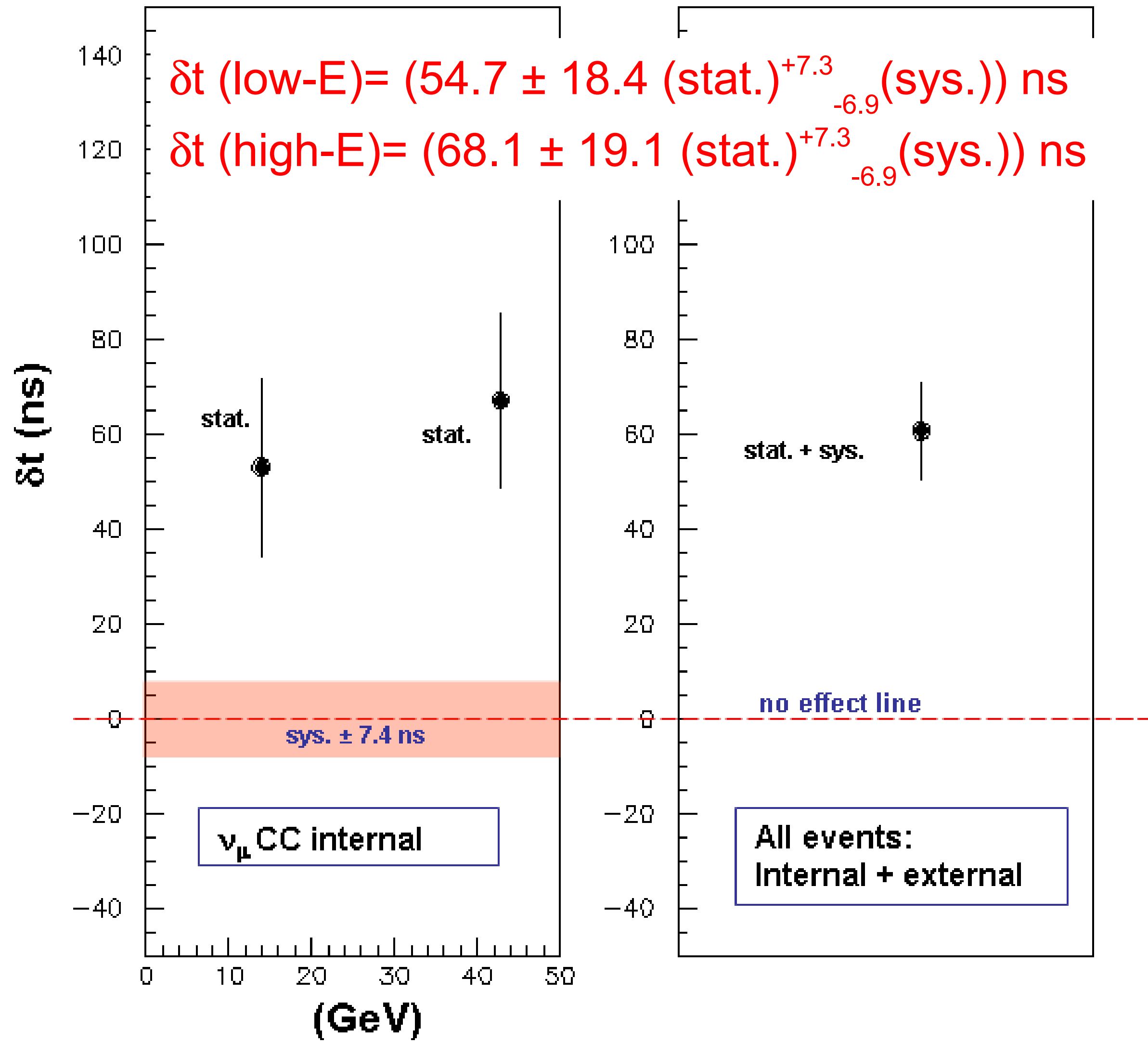
Opening the box: result



Only internal muon-neutrino CC events used (5199 events)

$\delta t = (61.1 \pm 13.2\ (\text{stat.})^{+7.3}_{-6.9}(\text{sys.}))$ ns

No indication for energy dependence within the present sensitivity in the explored energy domain



Energy dependence

$\delta t = (62.1 \pm 3.7)$ ns

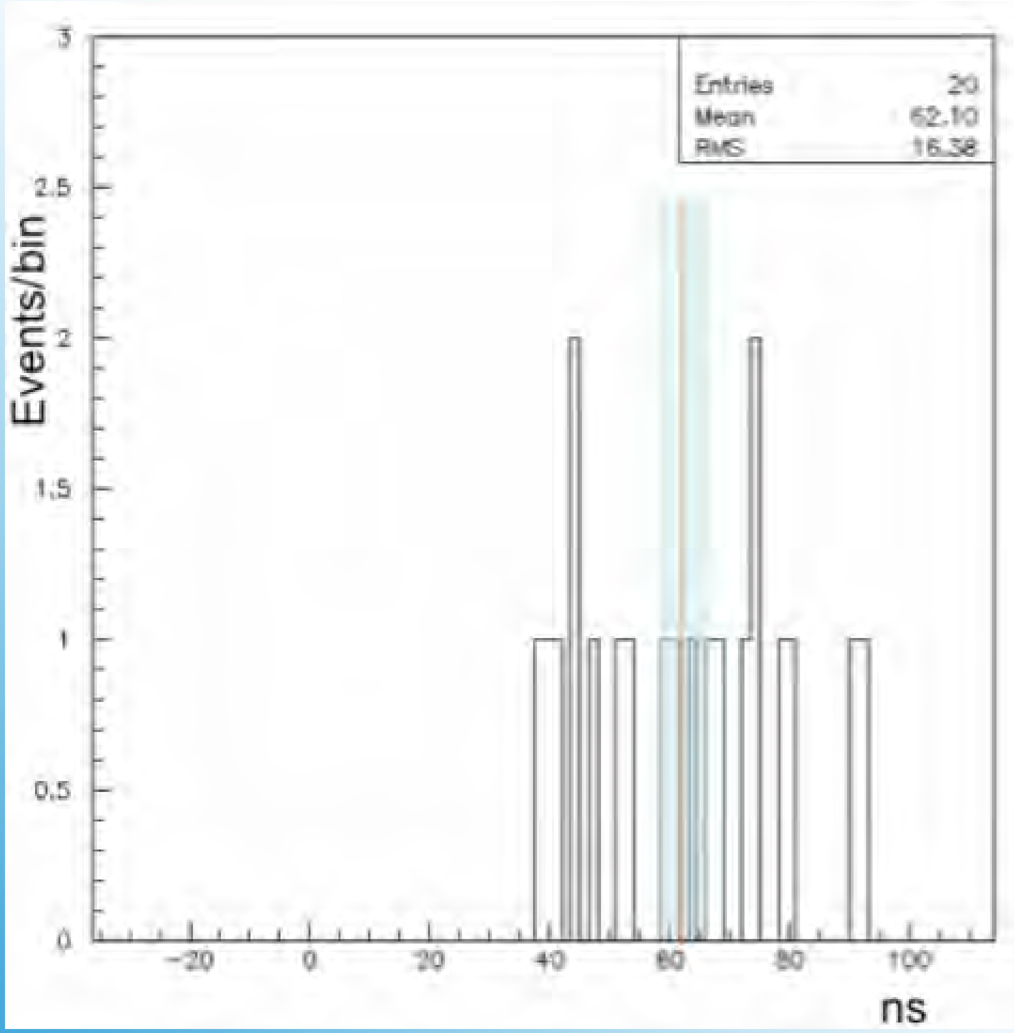
with original beam timing : 57.8 ± 7.8 ns

Main contributions to the RMS (16.4 ns):

- TT response (7.3 ns)
- DAQ time granularity (10 ns full width)
- ± 25 ns flat jitter

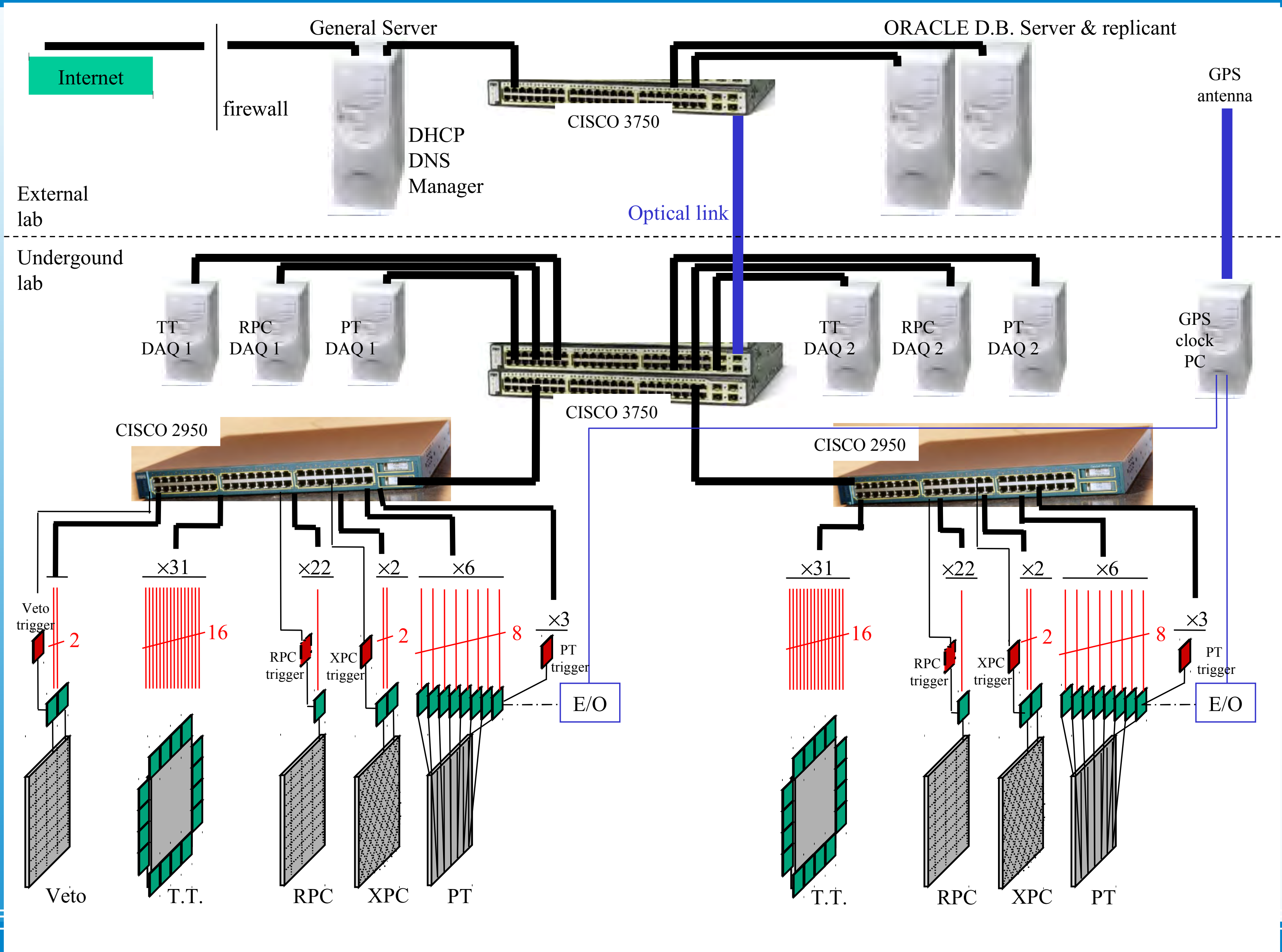
– The dominant ± 25 ns term is related to the tagging of the GPS signal by the 20 MHz OPERA master clock (RMS = 50 ns/$\sqrt{12}$ = 14.4 ns).

The statistical accuracy on the average δt is already as small as 3.7 ns with only 20 events (collected in 15 days).



Bunched-beam result

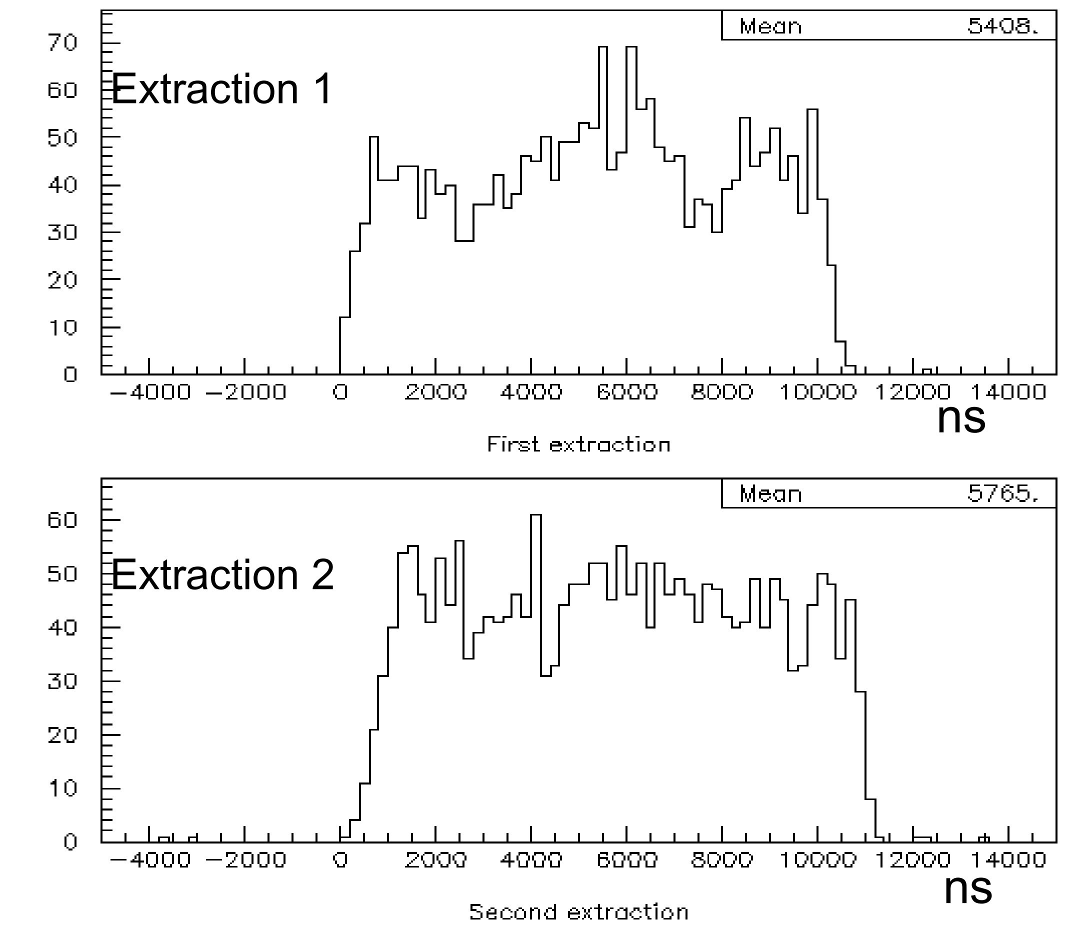
- Trigger-less
- 1200 asynchronous FE nodes
- Gigabit ethernet network



OPERA read-out scheme

Typical neutrino event time distributions w.r.t kicker magnet trigger pulse =>

- Not flat
- Different timing for the two extractions



→ Need to measure precisely the proton spills

From selection to the velocity measurement

- FNAL experiment (Phys. Rev. Lett. 43 (1979) 1361)

  ν_μ (E_ν > 30 GeV) short baseline experiment.

  $|v-c|/c \leq 4 \cdot 10^{-5}$ (comparison of ν_μ and μ velocities).

- Supernova SN1987A (e.g. Phys. Lett. B 201 (1988) 353)

  electron (anti) ν, E ~ 10 MeV, 168.000 light years baseline.

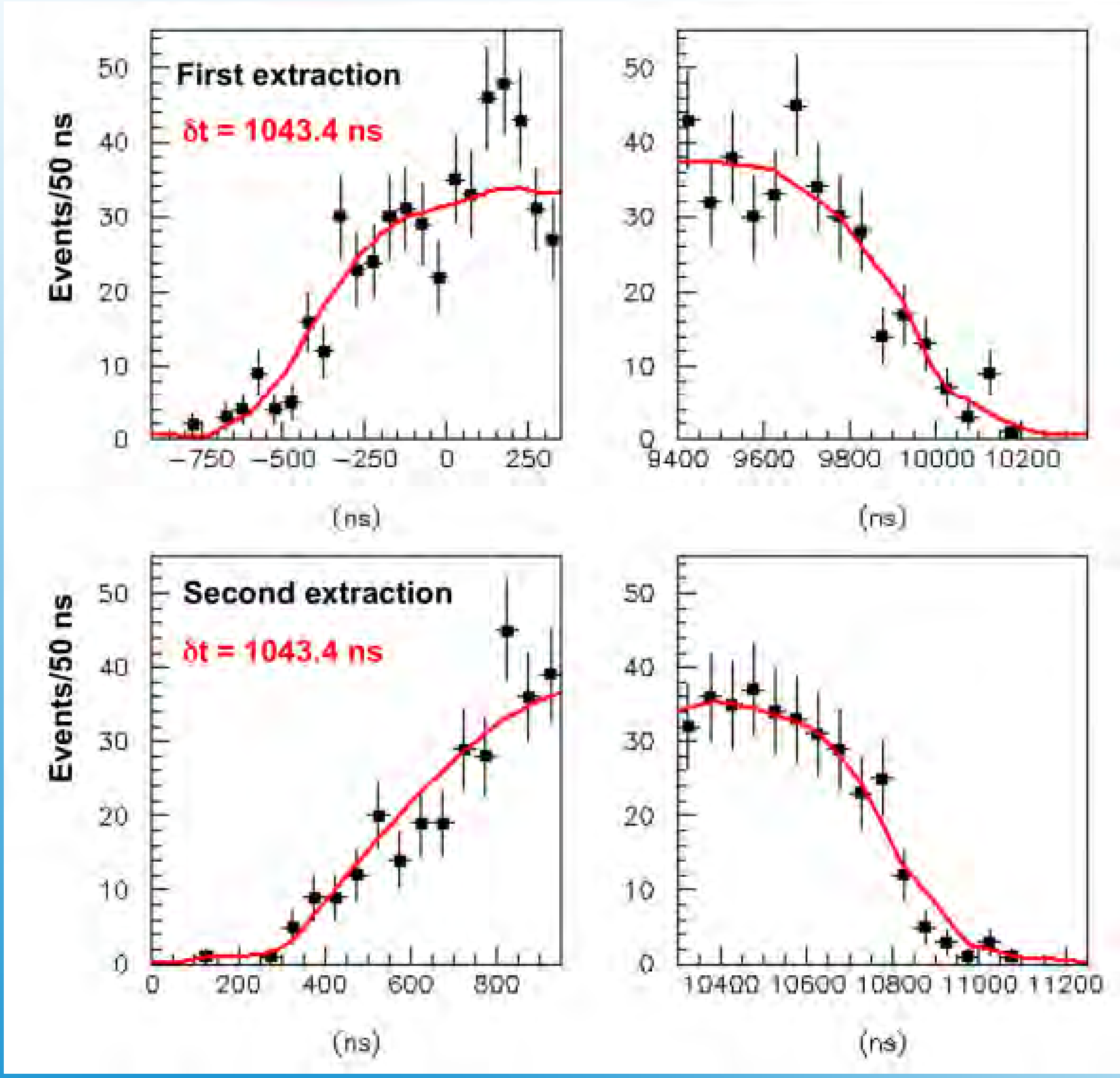
  $|v-c|/c \leq 2 \cdot 10^{-9}$ (ν and light arrival time).

- MINOS (Phys. Rev. D 76 072005 2007)

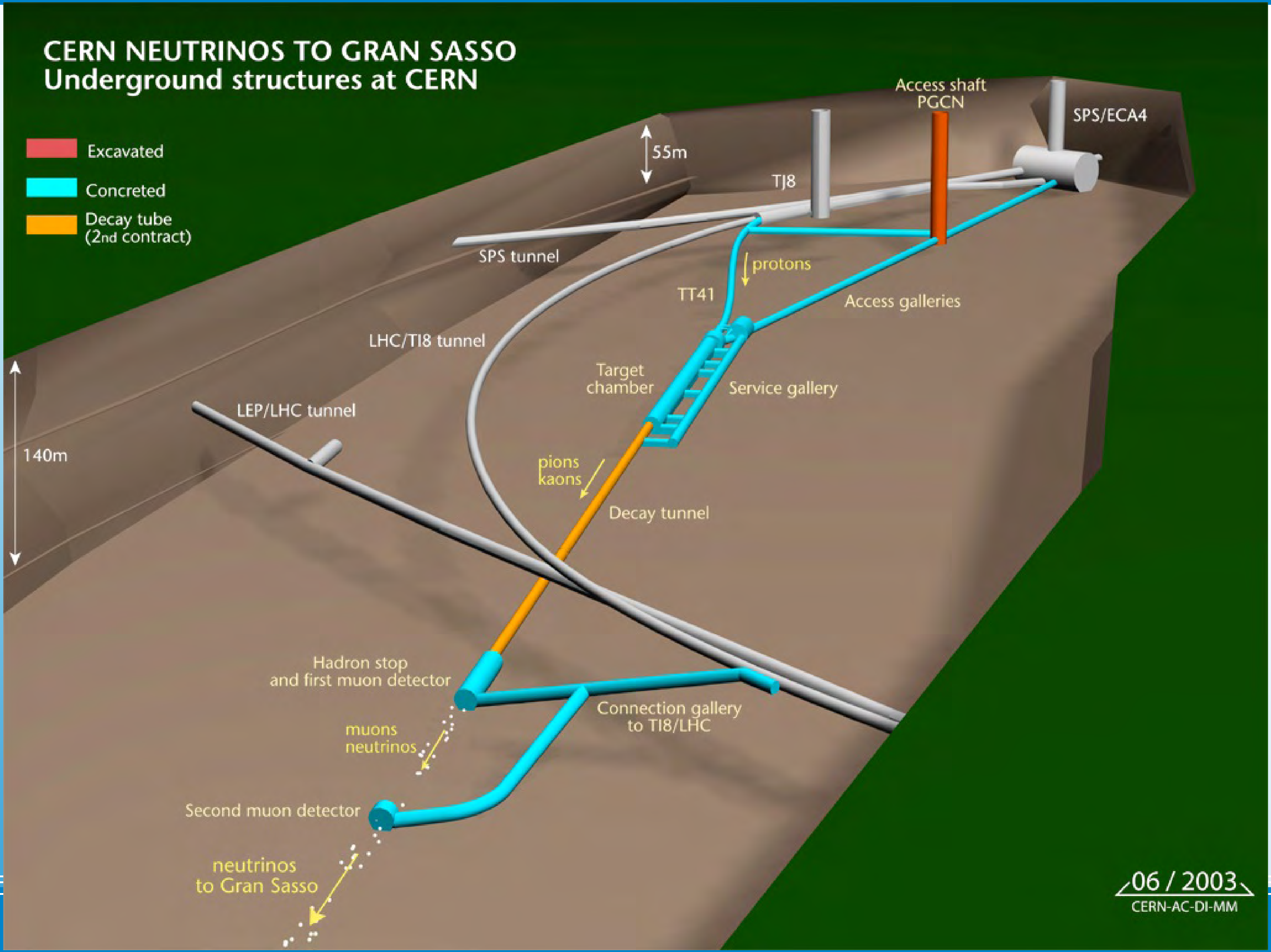
  ν_μ , E_ν ~ 3 GeV with a tail above 100 GeV. 730 km baseline.

  $(v-c)/c = (5.1 \pm 2.9)\ 10^{-5}$,1.8 σ, (ν_μ at near and far site)

Previous ν–velocity measurements



Edge regions


CERN NEUTRINOS TO GRAN SASSO
Underground structures at CERN
Excavated
Concreted
Decay tube
(2nd contract)
55m
Access shaft
PGCN
SPS/ECA4
TJ8
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

CNGS

CERN-LNGS measurements (different periods) combined in the ETRF2000 European Global system, accounting for earth dynamics (collaboration with CERN survey group)

LNGS benchmarks
In ETRF2000

Benchmark	X (m)	Y (m)	Z (m)
GPS1	4579518.745	1108193.650	4285874.215
GPS2	4579537.618	1108238.881	4285843.959
GPS3	4585824.371	1102829.275	4280651.125
GPS4	4585839.629	1102751.612	4280651.236

Cross-check done in June 2011: simultaneous CERN-LNGS measurement of GPS benchmarks

Distance (BCT - OPERA reference frame) = (731278.0 ± 0.2) m

Combination with CERN geodesy

$$L(\delta t) = \prod_j w_j(t_j + \delta t)$$

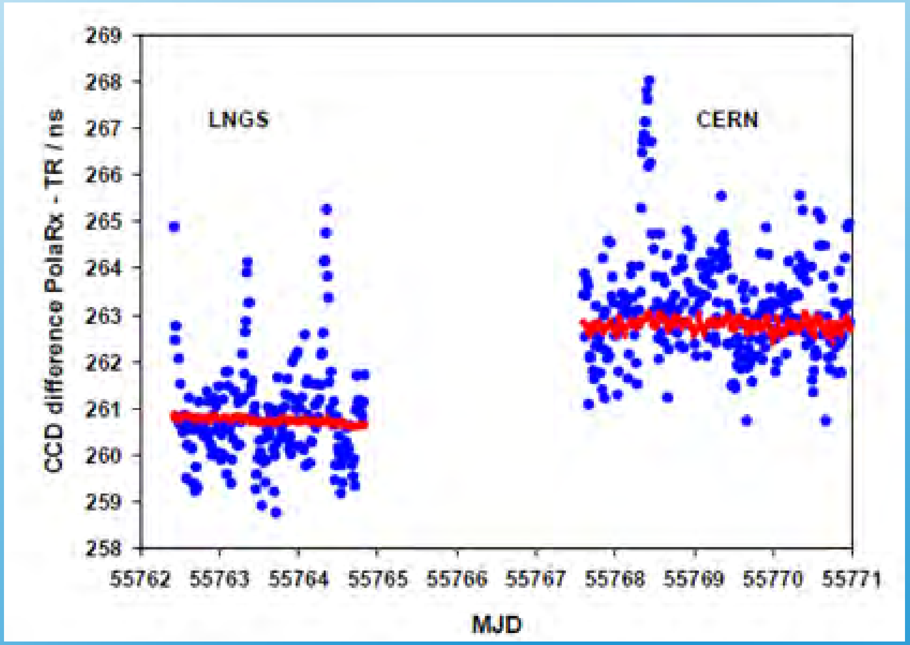
$$\delta t = (54.5 \pm 5.0\ (\text{stat.})\ ^{+9.6}_{-7.2}\ (\text{sys.}))\ \text{ns}$$

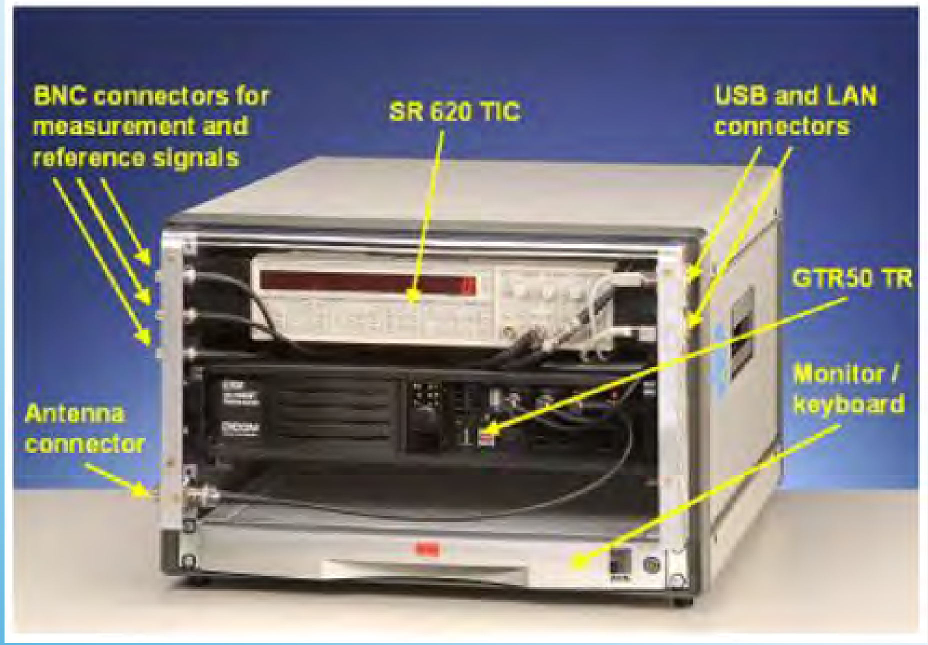
Event-by-event PDFs

Independent twin-system calibration by the Physikalisch-Technische Bundesanstalt

High accuracy/stability portable time-transfer setup @ CERN and LNGS

GTR50 GPS receiver, thermalised, external Cs frequency source, embedded Time Interval Counter





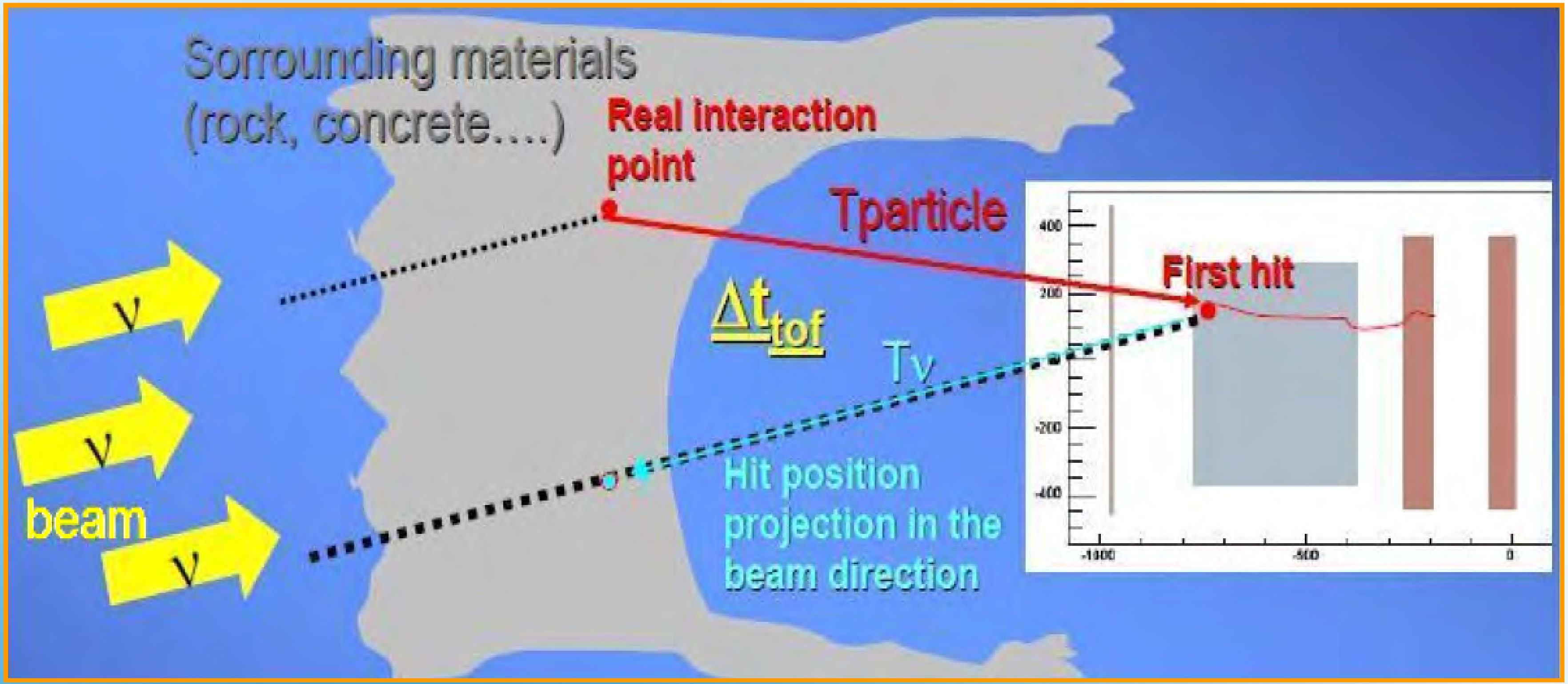
Correction to the time-link:

$t_{CERN} - t_{OPERA} = (2.3 \pm 0.9)$ ns

CERN-OPERA intercalibration cross check

Item	Result	Method
CERN UTC distribution (GMT)	10085 ± 2 ns	• Portable Cs • Two-ways
WFD trigger	30 ± 1 ns	Scope
BTC delay	580 ± 5 ns	• Portable Cs • Dedicated beam experiment
LNGS UTC distribution (fibers)	40996 ± 1 ns	• Two-ways • Portable Cs
OPERA master clock distribution	4262.9 ± 1 ns	• Two-ways • Portable Cs
FPGA latency, quantization curve	24.5 ± 1 ns	Scope vs DAQ delay scan (0.5 ns steps)
Target Tracker delay (Photocathode to FPGA)	50.2 ± 2.3 ns	UV picosecond laser
Target Tracker response (Scintillator-Photocathode, trigger time-walk, quantisation)	9.4 ± 3 ns	UV laser, time walk and photon arrival time parametrizations, full detector simulation
CERN-LNGS intercalibration	2.3 ± 1.7 ns	• METAS PolaRx calibration • PTB direct measurement

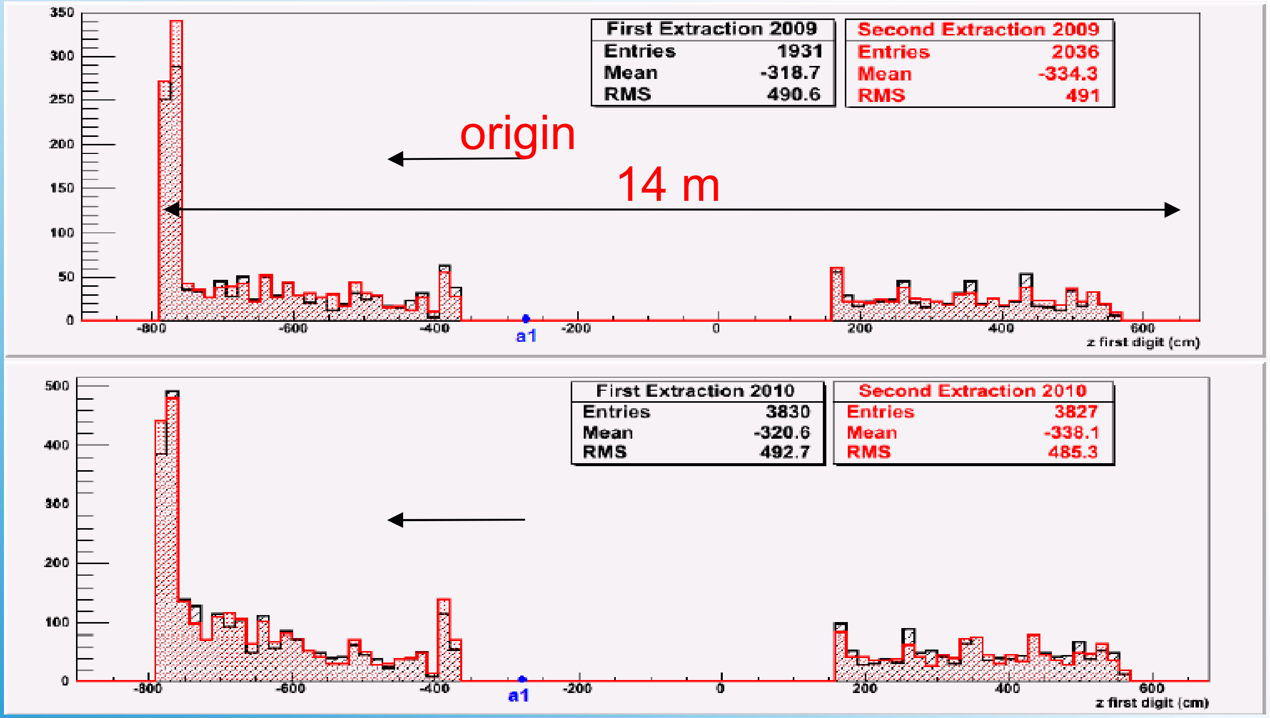
Delay calibrations summary



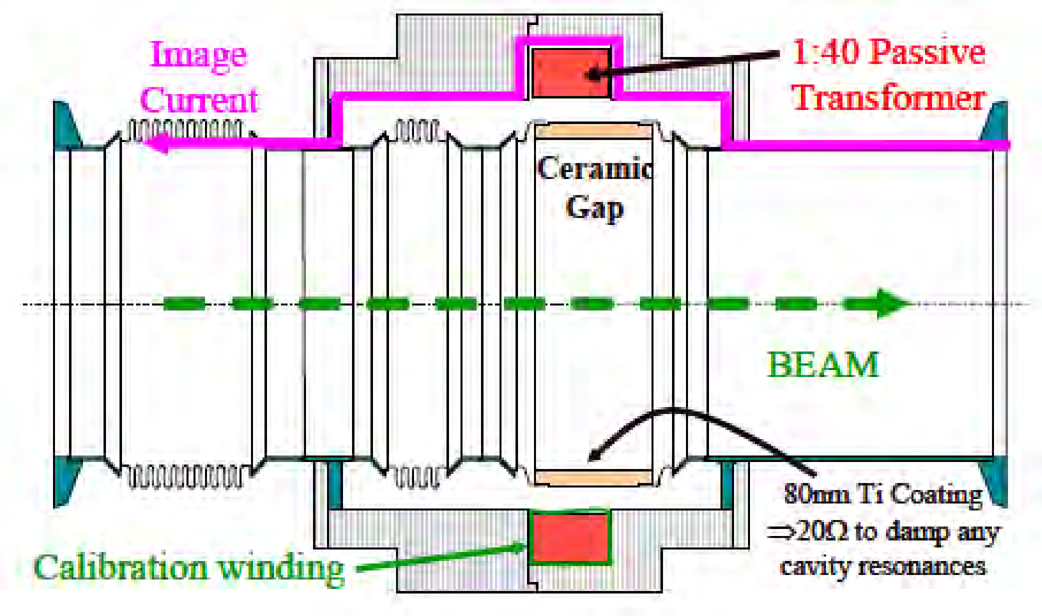
External events

Correction due to the earliest hit position

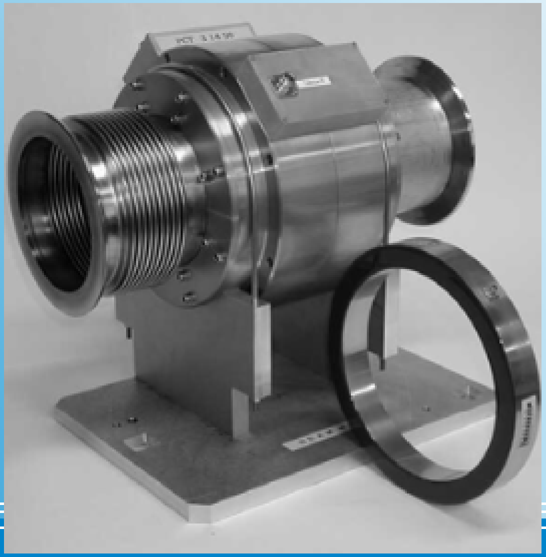
Average correction: 140 cm (4.7 ns)



Z correction



Raw BCT signal used, no integration
<1% linearity
Large bandwidth 400 MHz
Low droop <0.1%/µs



Fast beam current transformer

GPS common view mode

GPS standard operation

resolves (x, y, z, t) with ≥ 4 satellite observations

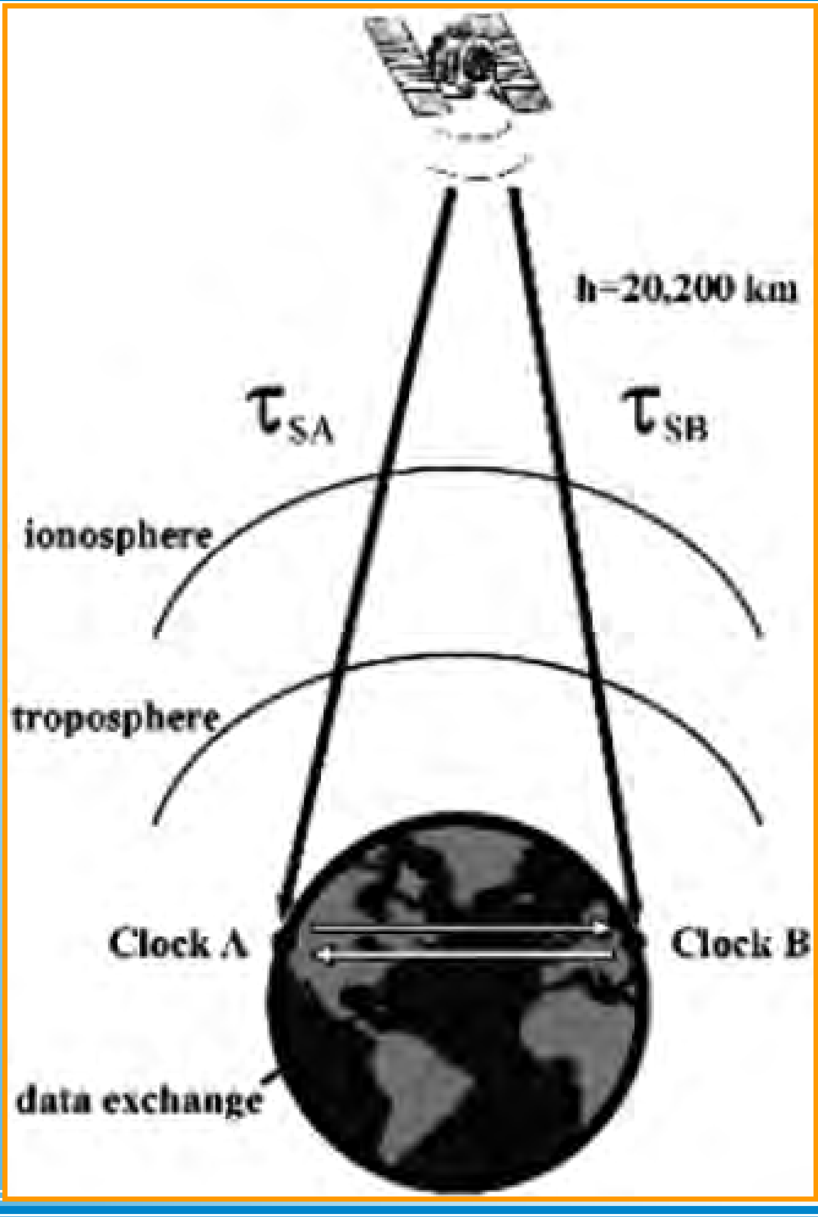
GPS "common-view" mode

same satellite visible from two sites

Knowing (x, y, z) of the sites from former dedicated measurements → determine time differences of local clocks w.r.t. the satellite, by off-line data exchange

Advantage: 730 km << 20000 km (satellite height) → similar paths in ionosphere → error cancellation

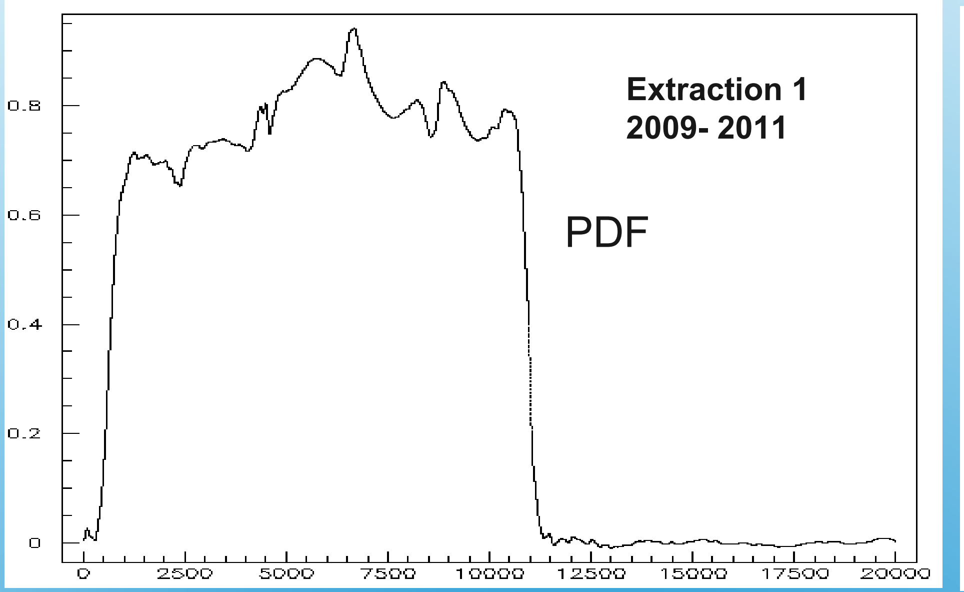
Standard technique for high accuracy t-transfer
Permanent time link (~1 ns) between reference points at CERN and OPERA

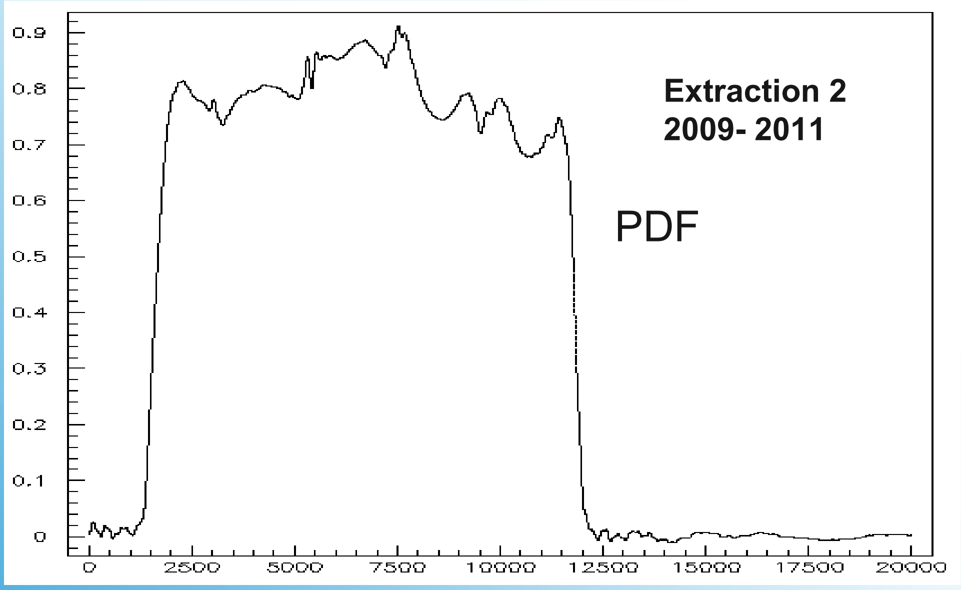


- Each event is associated to its proton spill waveform
- The "parent" proton is unknown within the 10.5 μs extraction time

→ normalize each waveform and sum:

Average Probability Density Function (PDF) of the predicted t-distribution of ν events





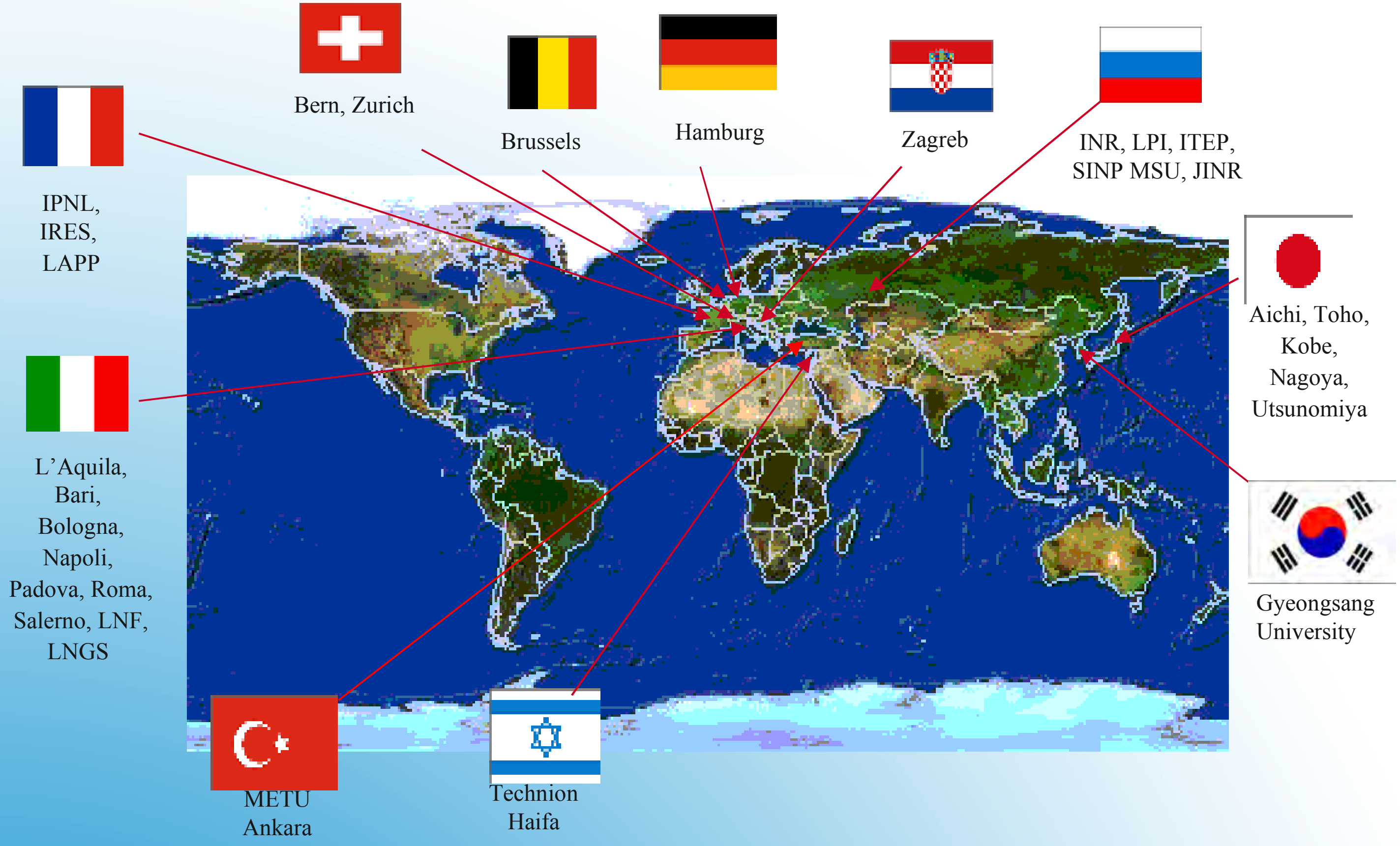
Another approach:

→ normalize each waveform and use a different PDF for each ν event

Neutrino event-time PDF

OPERA Coll.

- 11 countries
- 30 institutions
- 160 physicists



Collaborators

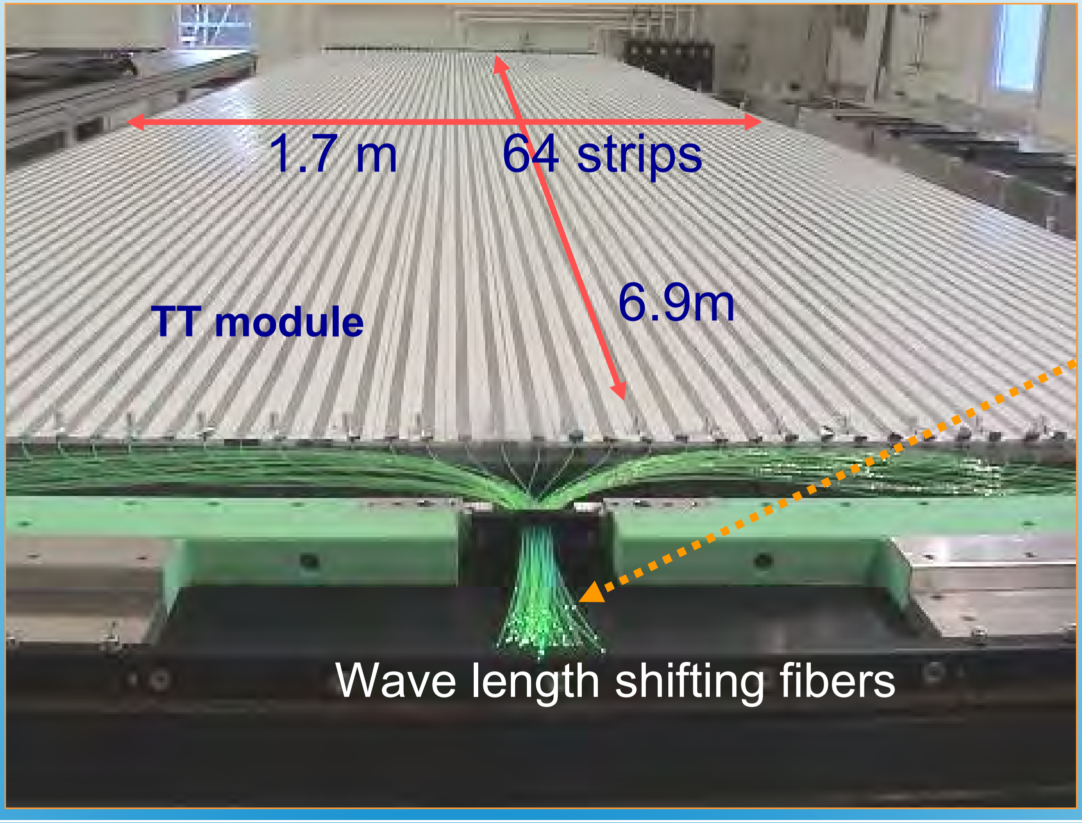
- CERN groups: CNGS beam, survey, timing and PS
- Geodesy group of the Università Sapienza of Rome
- Swiss Institute of Metrology (METAS)
- German Institute of Metrology (PTB)

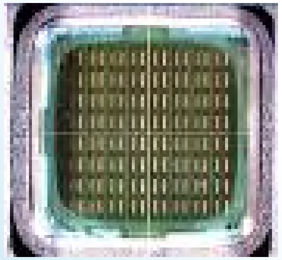
http://arxiv.org/pdf/1109.4897v2

OPERA and collaborating groups

Tasks: location of the ECC containing the ν interactions and event timing

- extruded plastic scintillator strips (2.6 cm width)
- light collections with wave length shifting fibers (WLS)
- fibers read-out at either side with multi-anode 64 pixels PMTs (H7546)



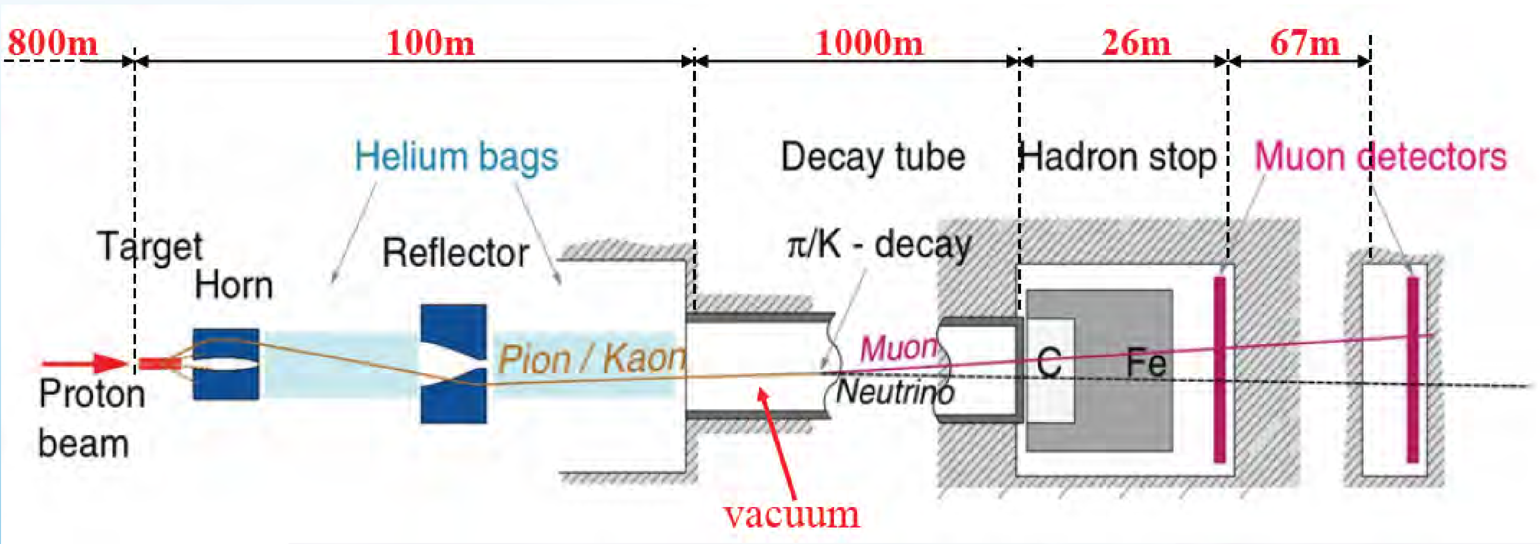


H7546
photomultiplier

one front-end DAQ board per side

The target tracker

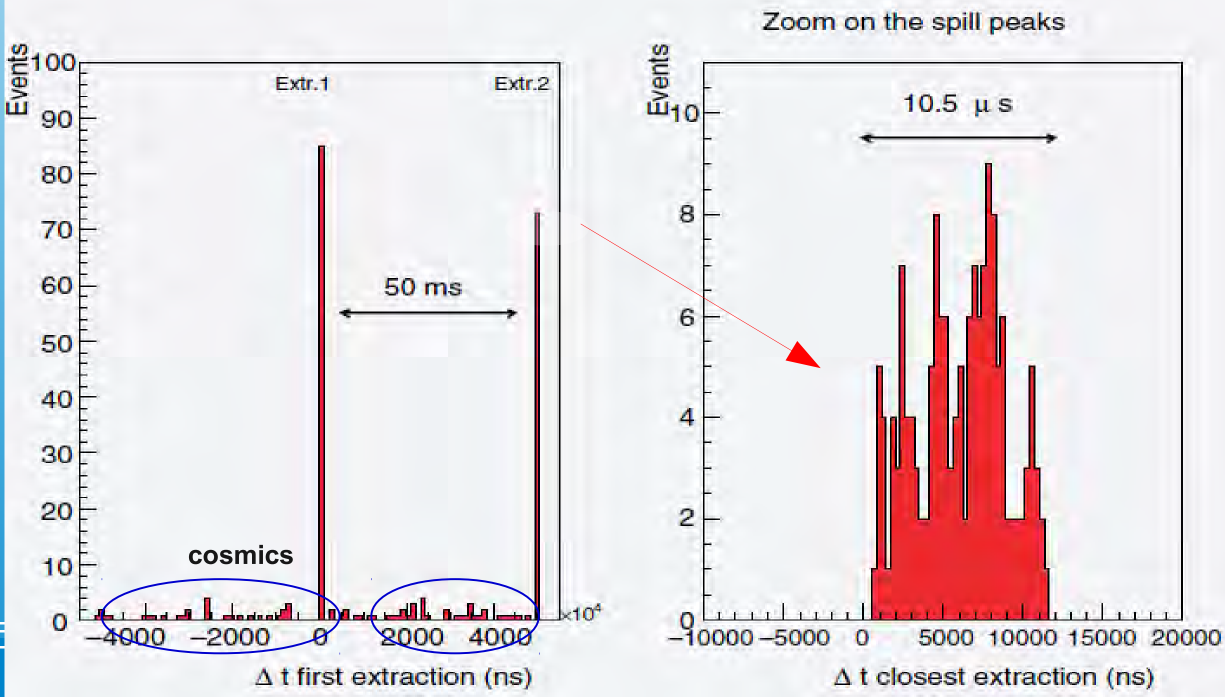
- SPS p: 400 GeV/c
- 6 s cycle
- ~ pure ν_μ
- $<E_\nu>$ = 17 GeV traveling through the Earth's crust



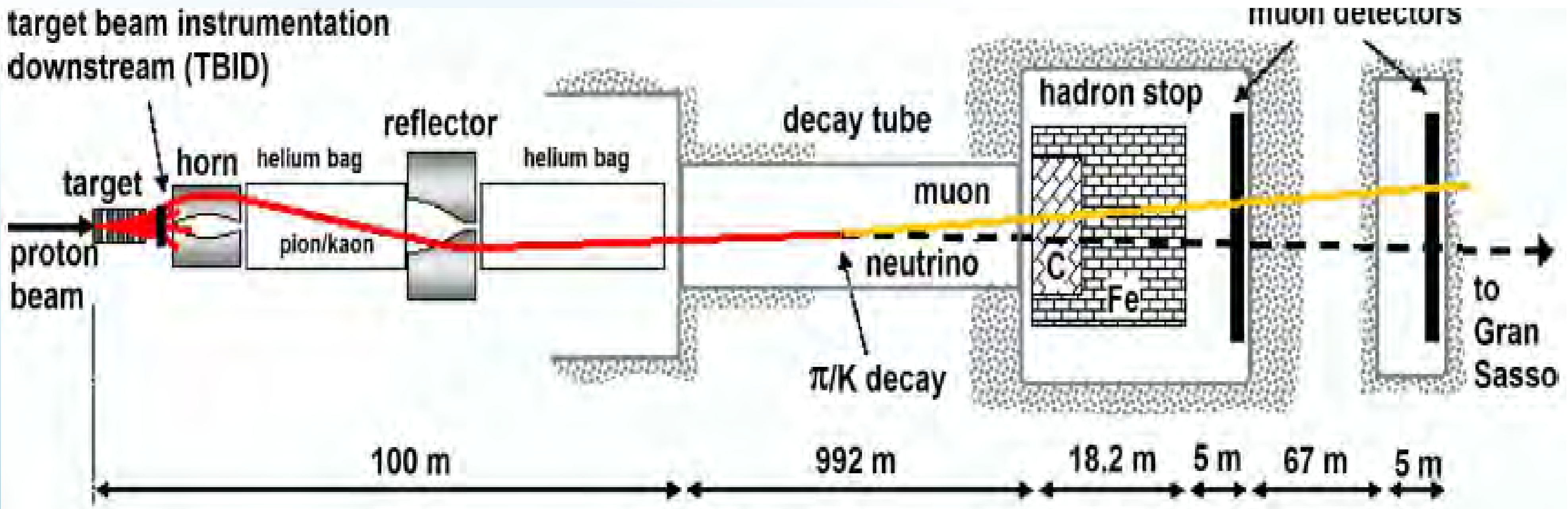
- Two 10.5 μs extractions (by kicker magnet) separated by 50 ms

$2.4 \cdot 10^{13}$ protons/extraction

Negligible cosmic-ray background: $O(10^{-4})$



The CNGS neutrino beam



- ν production point is not known but:
  - accurate UTC time-stamp of protons
  - relativistic parent mesons

TOF_c = assuming *c* from BCT to OPERA (2439280.9 ns)

TOF_{true} = accounting for speed of mesons down to decay point

$$\Delta t = \frac{z}{\beta c} - \frac{z}{c} = \frac{z}{c}\left(\frac{1}{\beta} - 1\right) \approx \frac{z}{c}\frac{1}{2\gamma^2}$$

$\langle\Delta t\rangle = TOF_{true} - TOF_c$ = 14 ps full FLUKA simulation

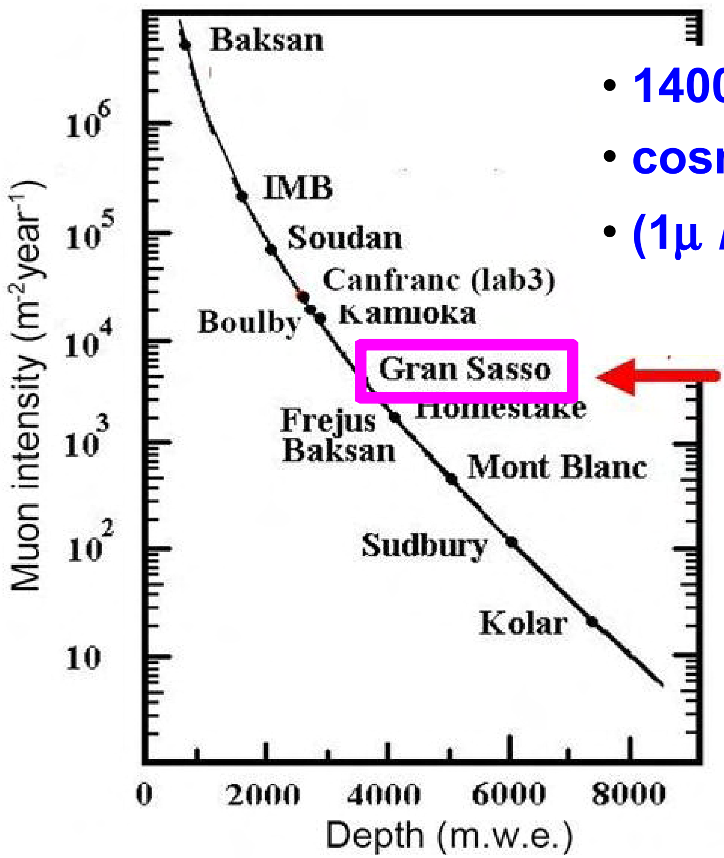
Neutrino production point

Laboratori Nazionali del Gran Sasso (the largest underground lab)

- ν phys. ($\beta\beta0\nu$ solar-ν, atm.-ν, LB ν-osc.)

HM$\beta\beta$, MACRO, GNO, BOREXINO, OPERA, ICARUS, CUORICINO, COBRA, CUORE, GERDA

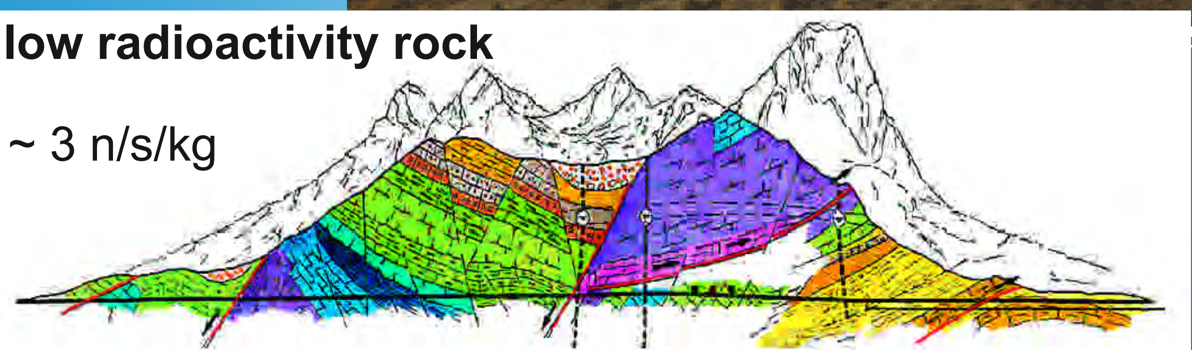
- DM - CRESST, DAMA, LIBRA, HDMS, GENIUS-TF, XENON, WARP
- Particle & nuclear astrophysics - EASTOP, LVD, LUNA, VIP
- Gravitational waves - LISA / Geophys., seismology - ERMES, UNDERSEIS, TELLUS, GIGS. Biology - ZOO, CRYO-STEM



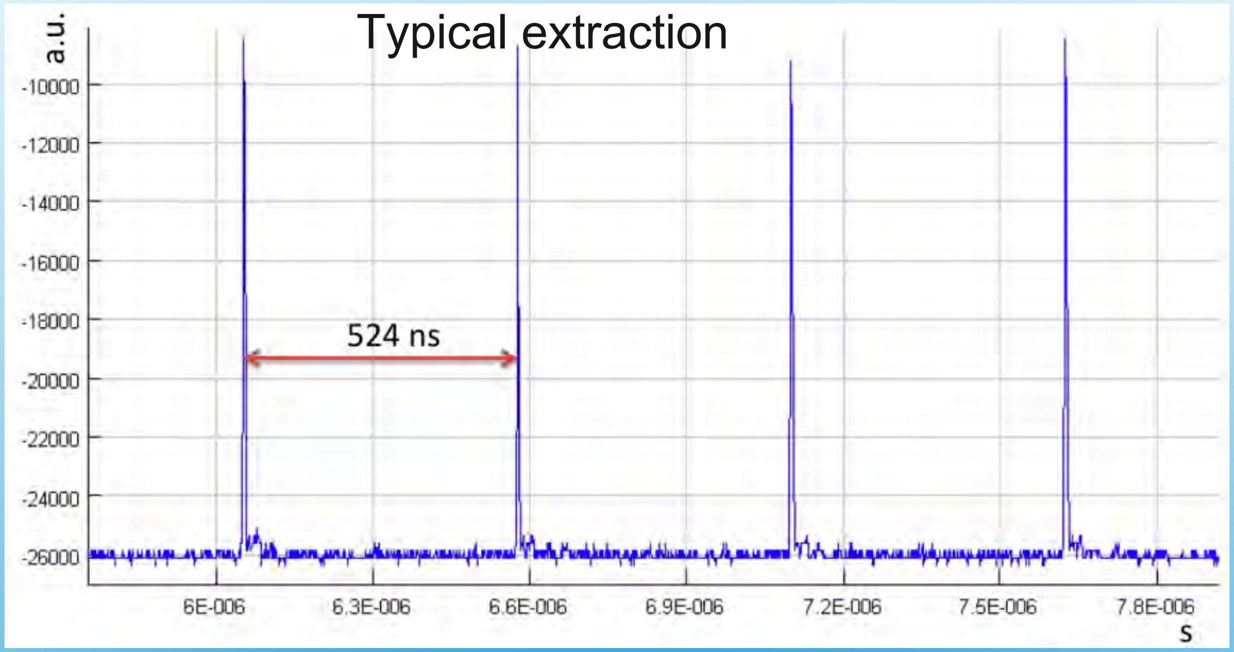
- 1400 m rock overburden
- cosmic μ reduction ~ 10^6
- (1μ /m^2/h)

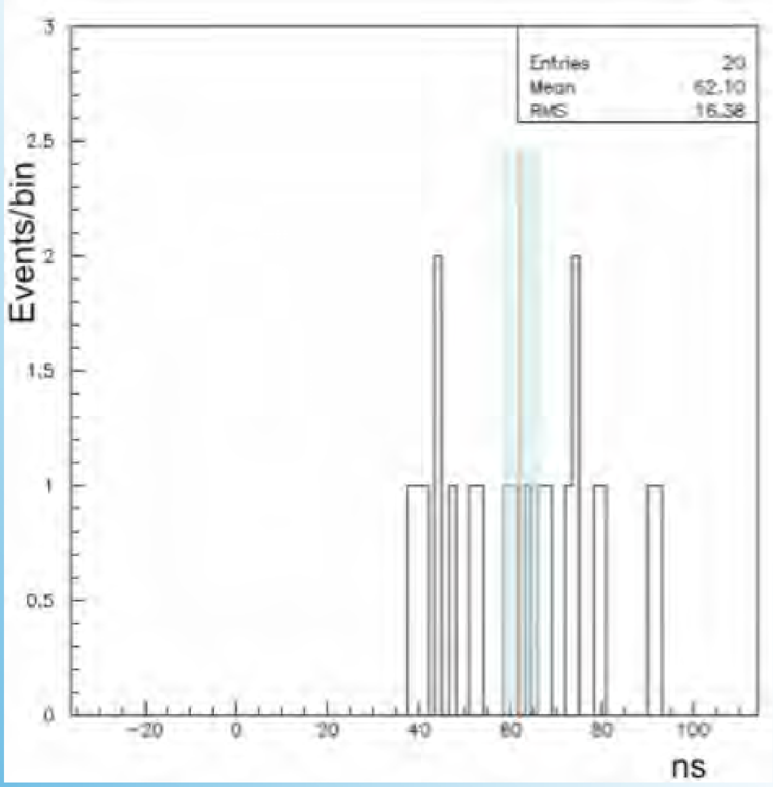
low radioactivity rock

~ 3 n/s/kg



November 2011, bunched beam:
The robustness of statistical treatment is confirmed and anomaly persists (62.1 ± 3.7) ns



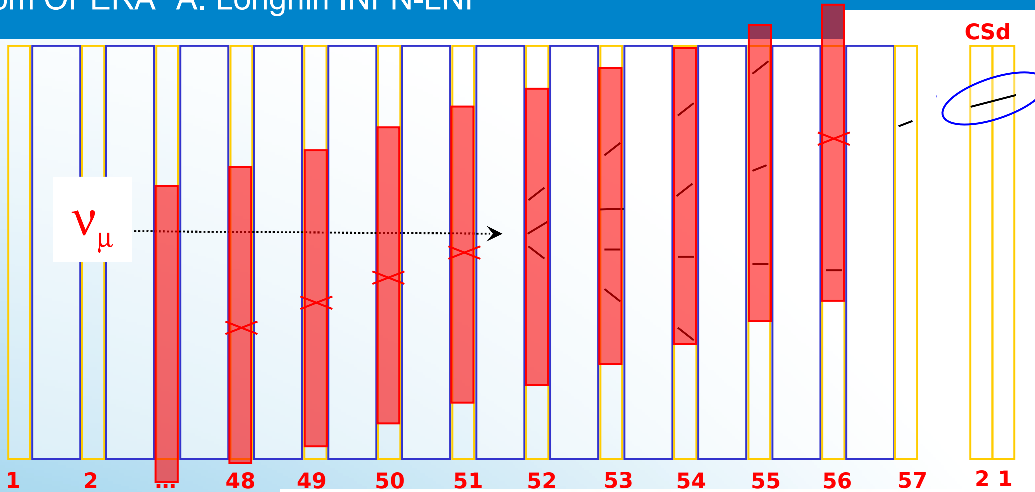


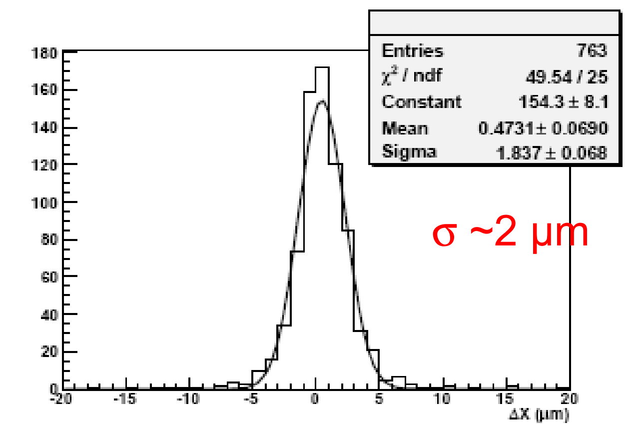
October 22 to November 6, 2011

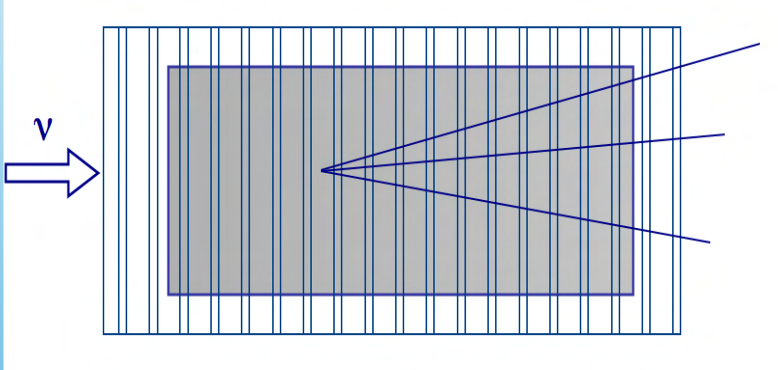
Analysis with a "bunched-beam"

Track follow-up film by film:

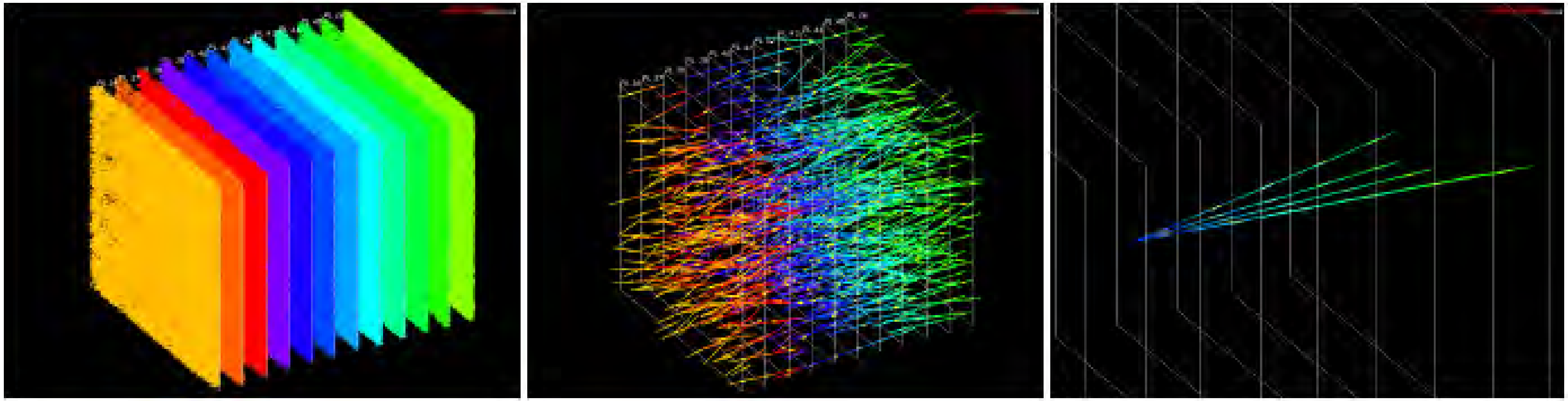
- alignment using cosmic ray tracks
- definition of the stopping point





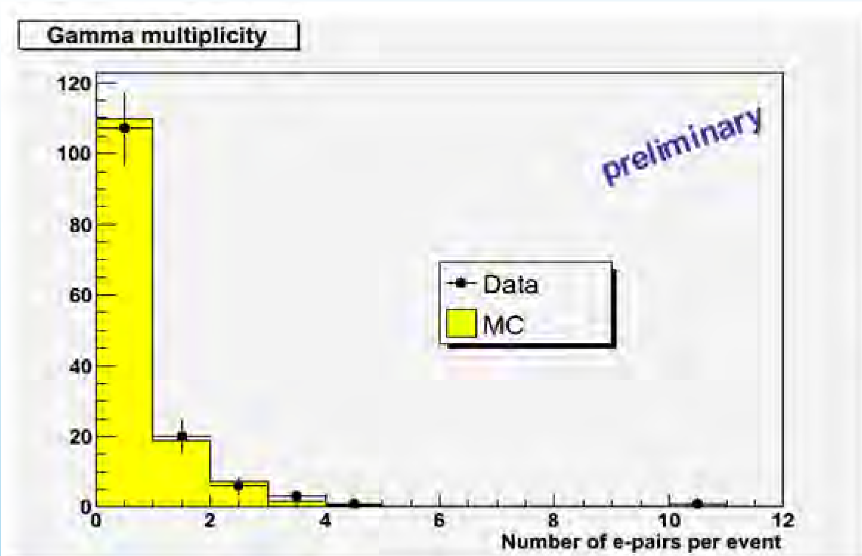


Volume scanning (~2 cm³) around the stopping point



JINST 4 (2009) P06020

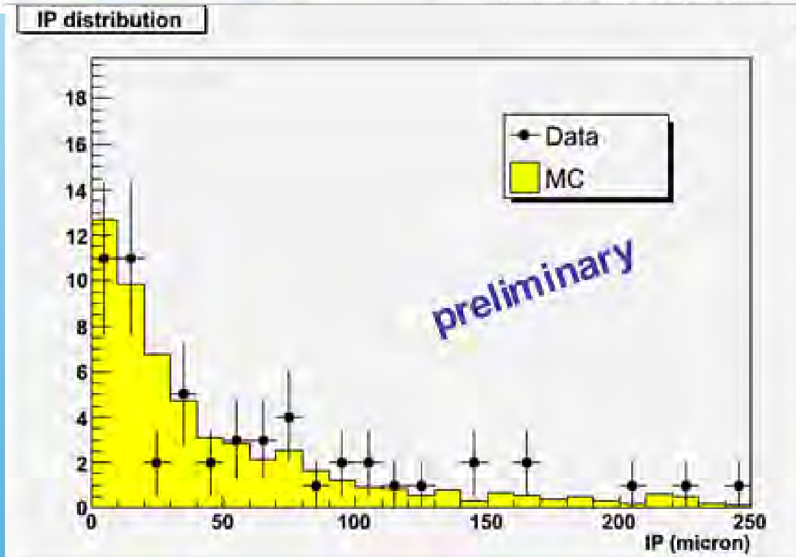
Vertex finding

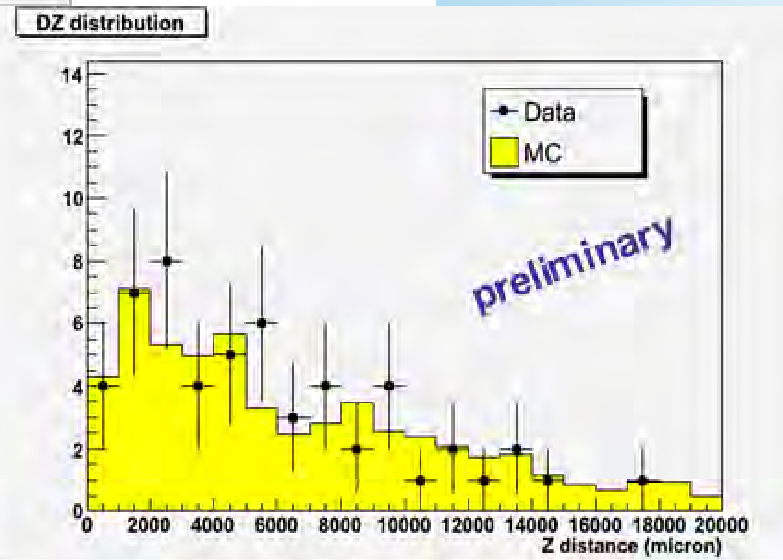


Comparison data/MC for the Gamma multiplicity in ν_μ CC+NC events

Volume scan of 20 plates $\times$ 1 cm^2 downstream of ν vertex

good description





γ conversions: data/MC

Decay channel	Number of background events for:							
	22.5×10^{19} p.o.t.				Analysed sample			
	Charm	Hadr.	Muon	Total	Charm	Hadr.	Muon	Total
t → μ	0.025	0.00	0.07	0.09 ± 0.04	0.00	0.00	0.02	0.02 ± 0.01
t → *e*	0.22			0.22 ± 0.05	0.05			0.05 ± 0.01
t → *h*	0.14	0.11		0.24 ± 0.06	0.03	0.02		0.05 ± 0.01
t → 3*h*	0.18			0.18 ± 0.04	0.04			0.04 ± 0.01
Total	0.55	0.11	0.07	0.73 ± 0.15	0.12	0.02	0.02	0.16 ± 0.03

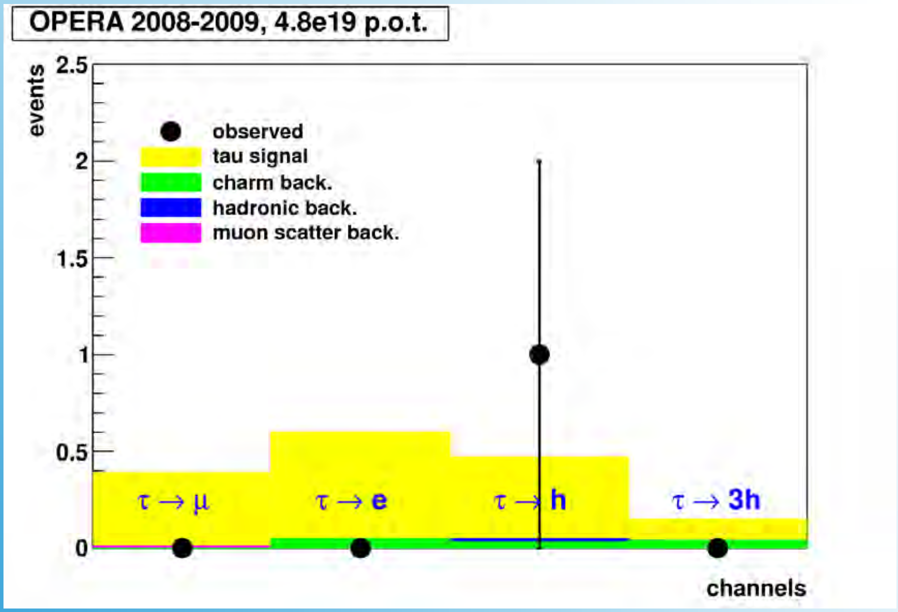
$\tau \rightarrow \mu$ is very clean

Expected background in $t \rightarrow h$: 0.05 ± 0.01

Probability of a background fluctuation up to at least one event is 5%

Total background: 0.16 ± 0.03

Probability background fluctuation 15%

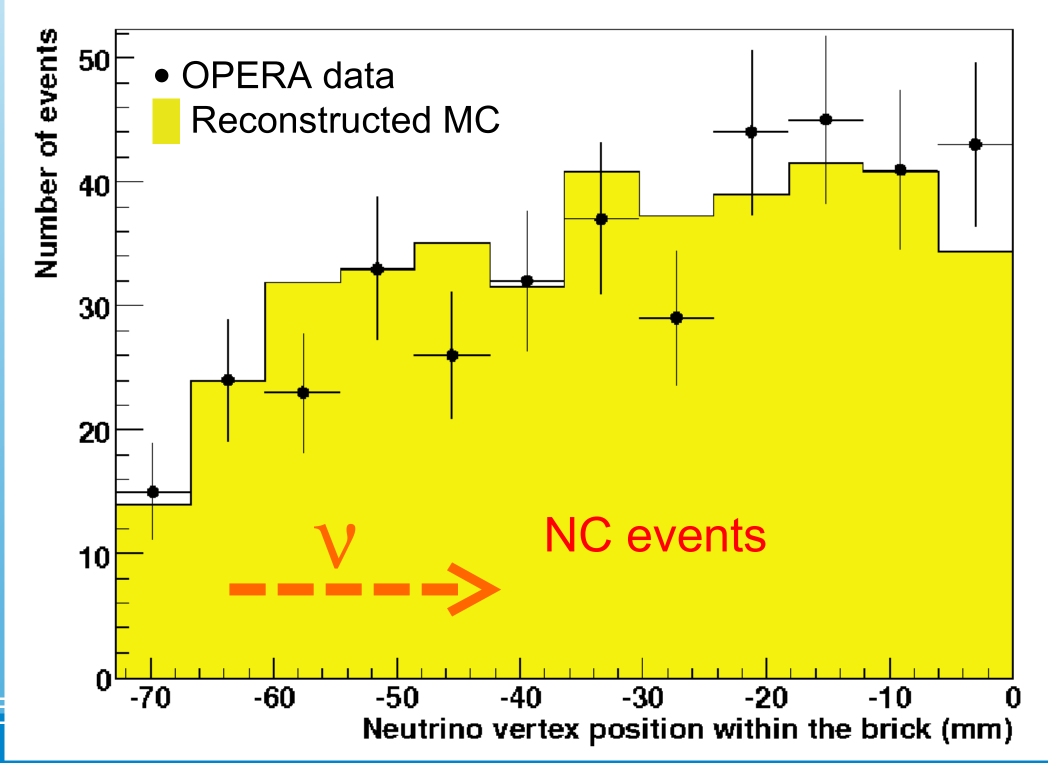


Summary of backgrounds

	0 mu	1 mu	All
Triggered (CNGS on-time)			31576
predicted by the target tracker	1503	3752	5255
located in dead material	54	245	299
located in the ECC	519	2280	2799
decay search performed	494	2244	2738

85% are events induced by neutrino interaction outside OPERA target

→ 92% of the expected sample that could be decay searched (2978±75)



Location efficiency:

- CC: 74 %
- NC: 48 %

Full simulation chain including newly developed off-line emulsion reconstruction software

2008-2009 sample

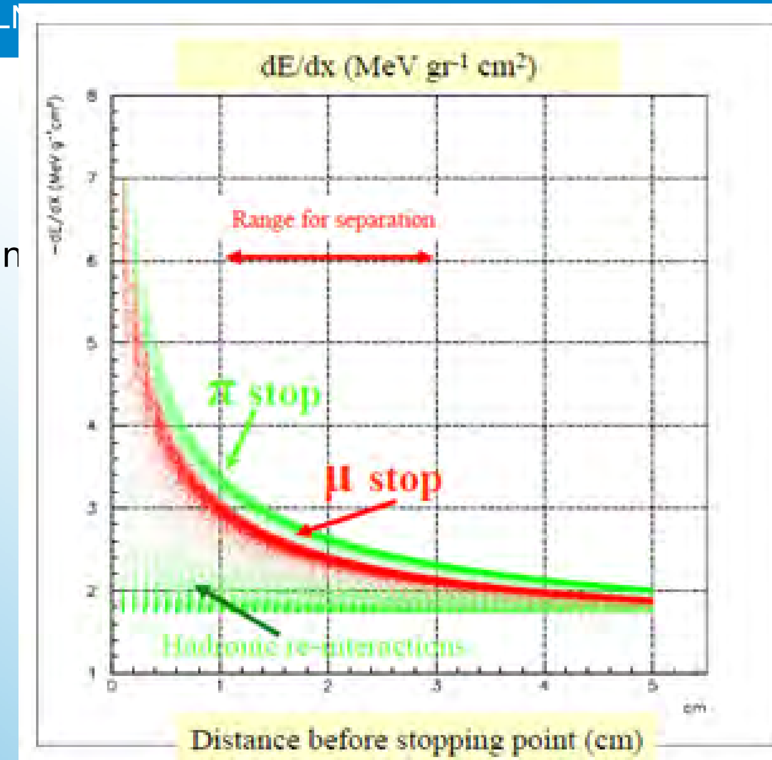
Tracks classification:

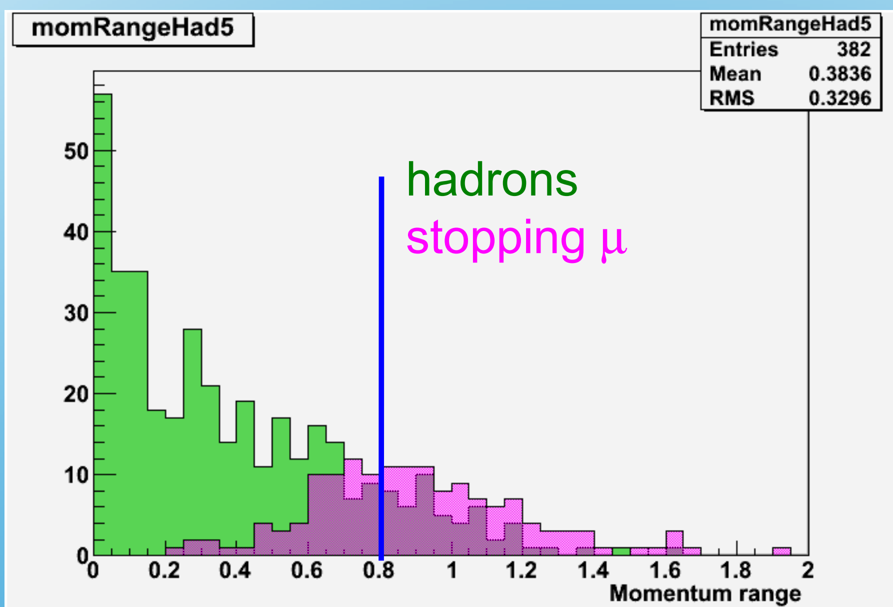
- visible interaction in the brick
- dE/dx at end point (π/μ separation)
- Momentum/range correlation

L = track length
Rlead = μ range in
p = momentum measured in the emulsion

Discriminating variable

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

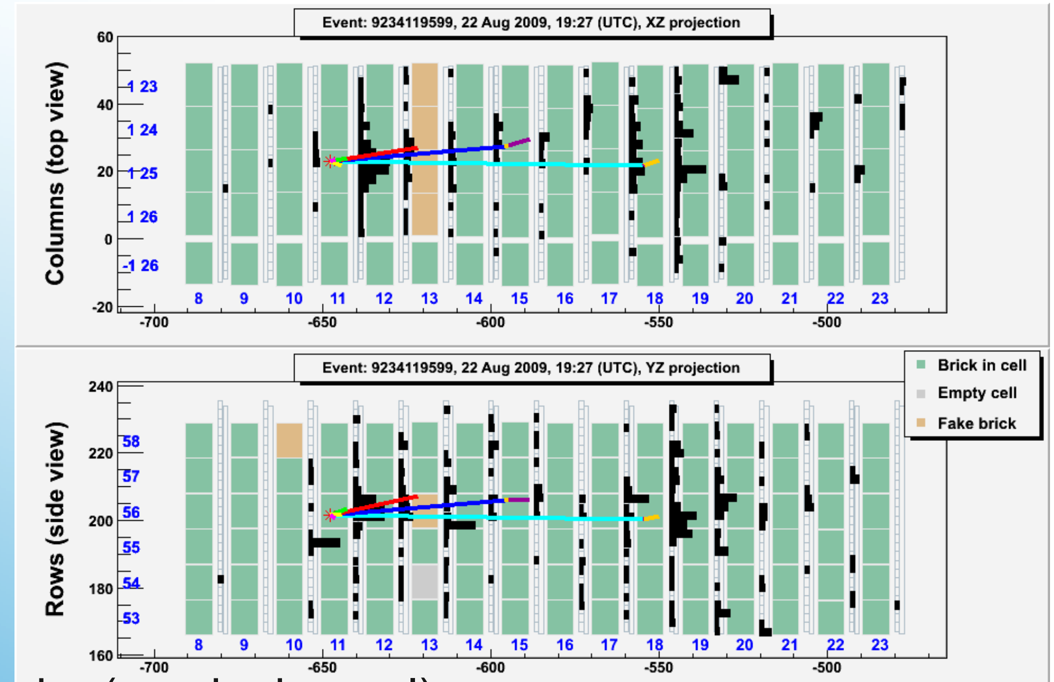




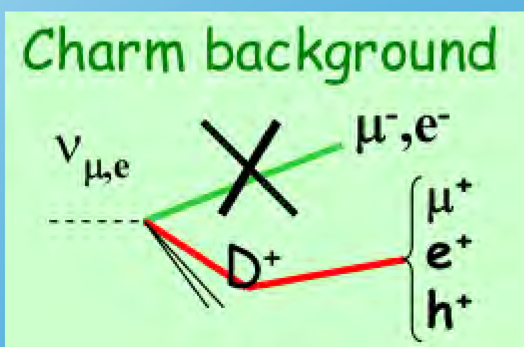
- 34% reduction of μ mis-ID in charm events (3.28%)
- 2 orders of magnitude reduction for the hadronic background to $\tau \to \mu$ due to μ mismatch in CC and NC events

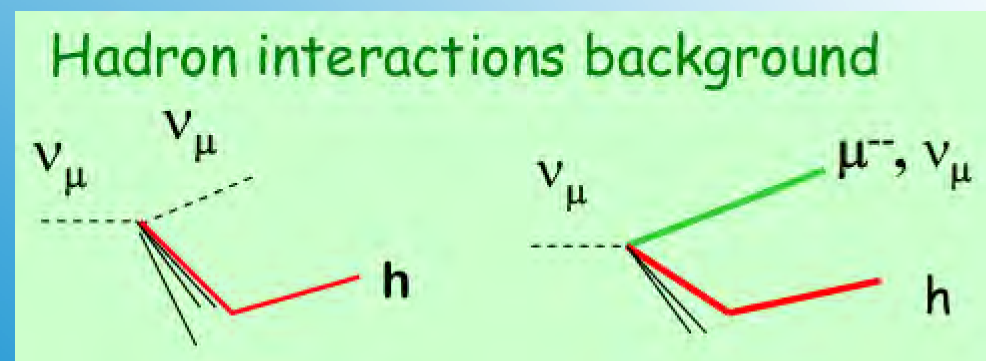
Track Follow Down

- For the first ν_τ candidate we followed down all the tracks to search for possible muon not identified by the electronic detectors

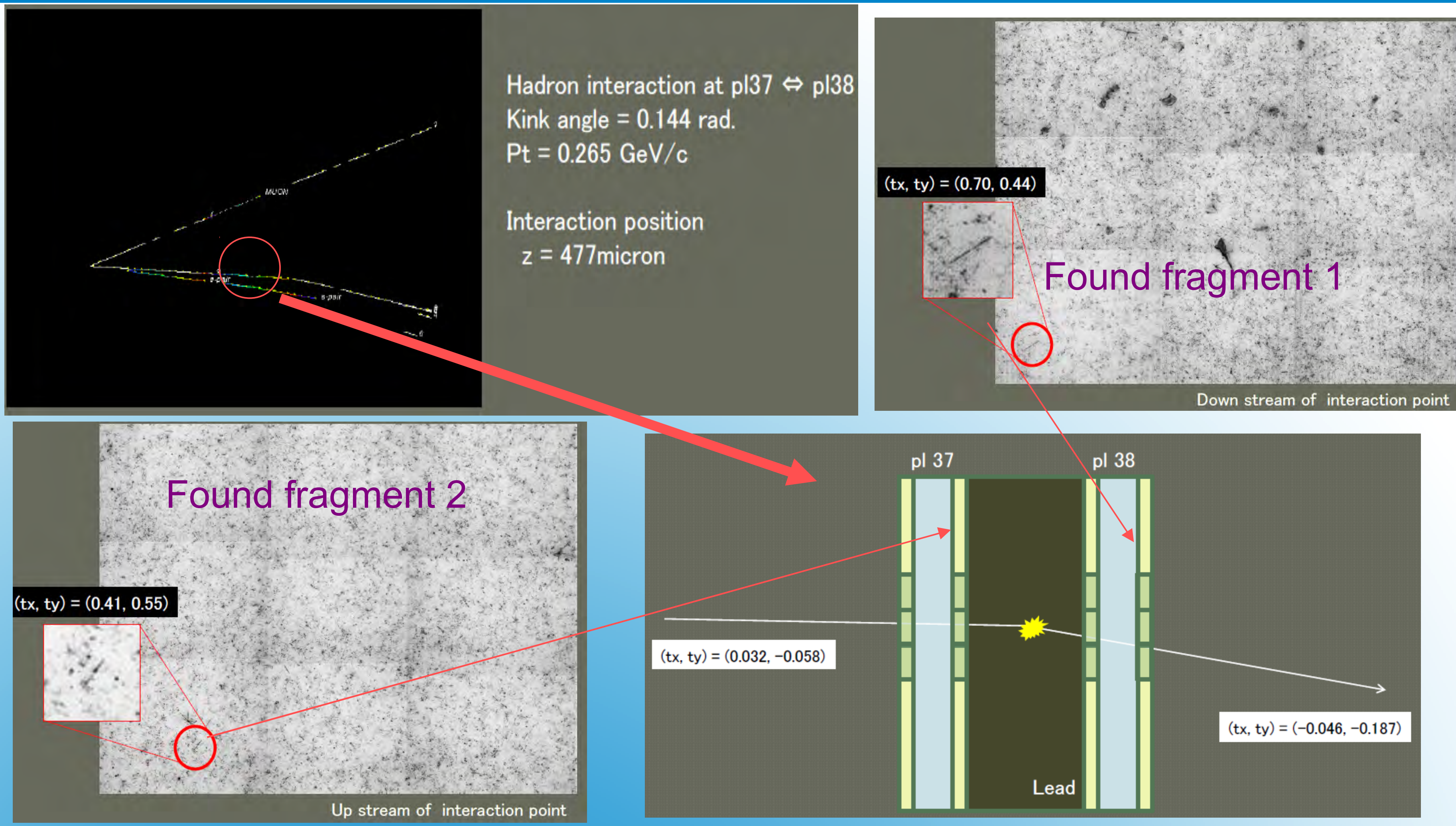


We can suppress backgrounds due to
- Charm
- Hadron interactions in ν_μ CC with misidentified μ ($\tau \rightarrow h$ channel)
- Hadron interactions in ν_μ CC and NC ($\tau \rightarrow \mu$ channel)





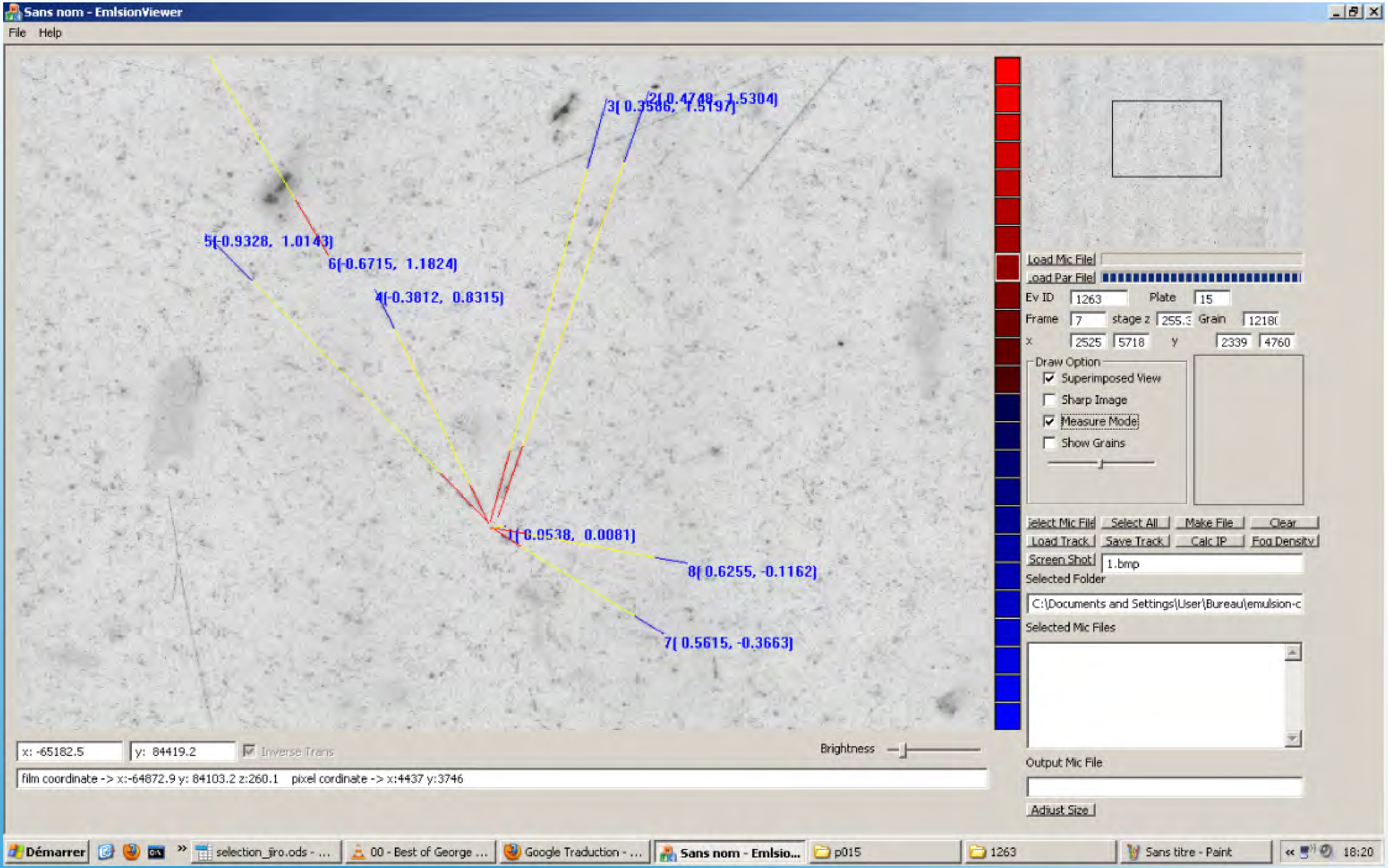
Track Follow Down



Intra-nuclear interactions and nuclear evaporation → p and nuclear fragments emission

High-efficiency tagging to reduce the hadronic background

Tagging of highly ionizing particles in hadron interactions


Sans nom - EmlsionViewer
File Help
2[0.4748, 1.5304]
3[0.3586, 1.5197]
5[-0.9328, 1.0143]
6[-0.6715, 1.1824]
4[-0.3812, 0.8315]
1[0.0538, 0.0081]
8[0.6255, -0.1162]
7[0.5615, -0.3663]
x: -65182.5
y: 84419.2
Inverse Trans
Brightness
film coordinate -> x:-64872.9 y: 84103.2 z:260.1 pixel cordinate -> x:4437 y:3746
Load Mic File
Load Par File
Ev ID 1263
Plate 15
Frame 7
stage z 255.3
Grain 12180
x 2525 5718
y 2339 4760
Draw Option
Superimposed View
Sharp Image
Measure Mode
Show Grains
Select Mic File
Select All
Make File
Clear
Load Track
Save Track
Calc IP
Fog Density
Screen Shot
1.bmp
Selected Folder
C:\Documents and Settings\User\Bureau\emulsion-c
Selected Mic Files
Output Mic File
Adjust Size
Démarrer
selection_jiro.ods - ...
00 - Best of George ...
Google Traduction - ...
Sans nom - Emlsio...
p015
1263
Sans titre - Paint
18:20