Status of the OPERA experiment

On behalf of the OPERA Collaboration
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Hot Topics in Neutrino Oscillations
Università Roma Tre
Dipartimento di Fisica e Sezione INFN
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The OPERA Collaboration
160 physicists, 30 institutions, 11 countries

Belgium
IIHE-ULB Brussels

Croatia
IRB Zagreb

France
LAPP Annecy
IPNL Lyon
IPHC Strasbourg

Germany
Hamburg

Israel
Technion Haifa

Italy
LNGS Assergi
Bari
Bologna
LNF Frascati
L'Aquila
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

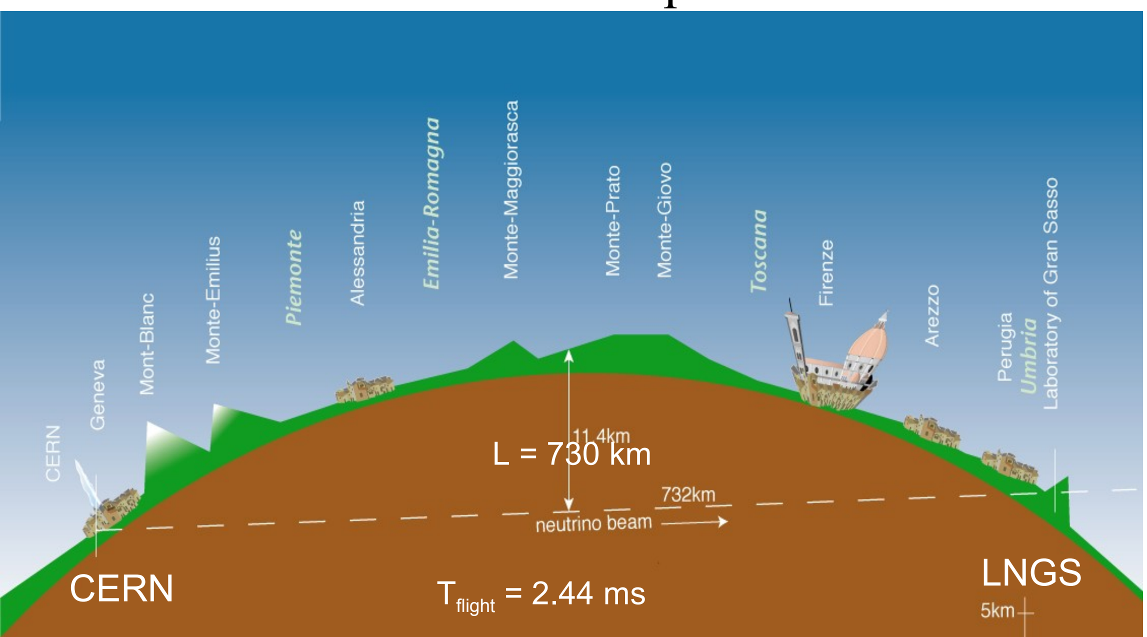
http://operaweb.lngs.infn.it/scientists/?lang=en

OPERA: first direct detection of neutrino oscillations in appearance mode in the $\nu_\mu \rightarrow \nu_\tau$ channel

following the Super- Kamiokande discovery of oscillations with atmospheric neutrinos and the confirmation obtained with accelerator beams.

OPERA main features:

1) long baseline, 2) high neutrino energy, 3) ≅ Kton detector mass, 5) **detect short lived taus** produced in tau neutrino interactions

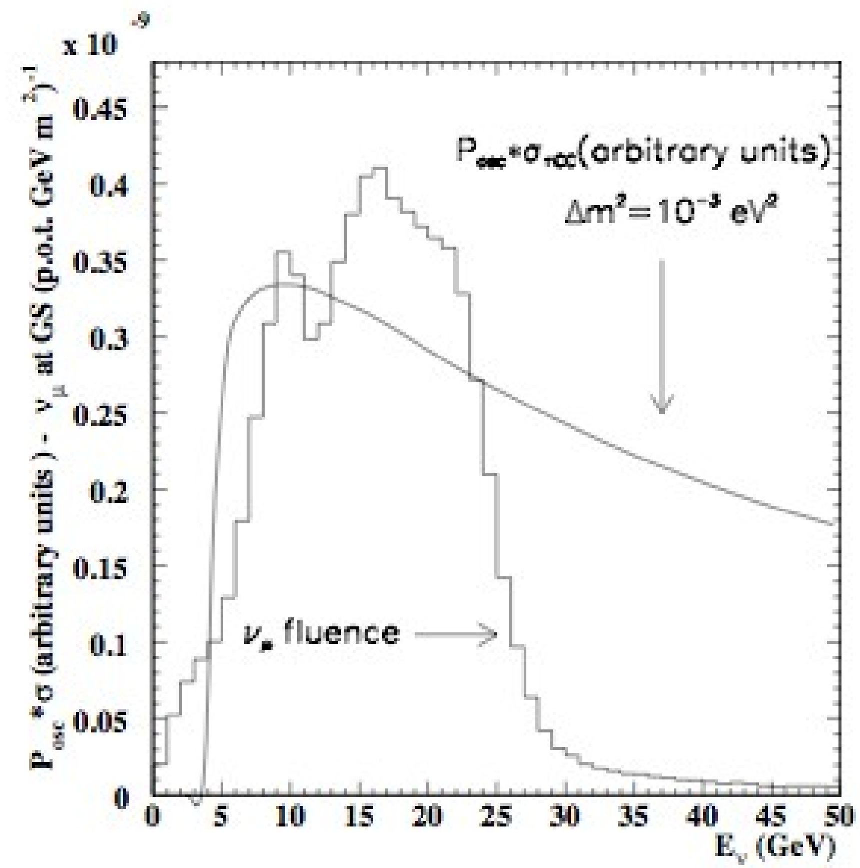


Expected neutrino interactions for 22.5x10[19] pot:

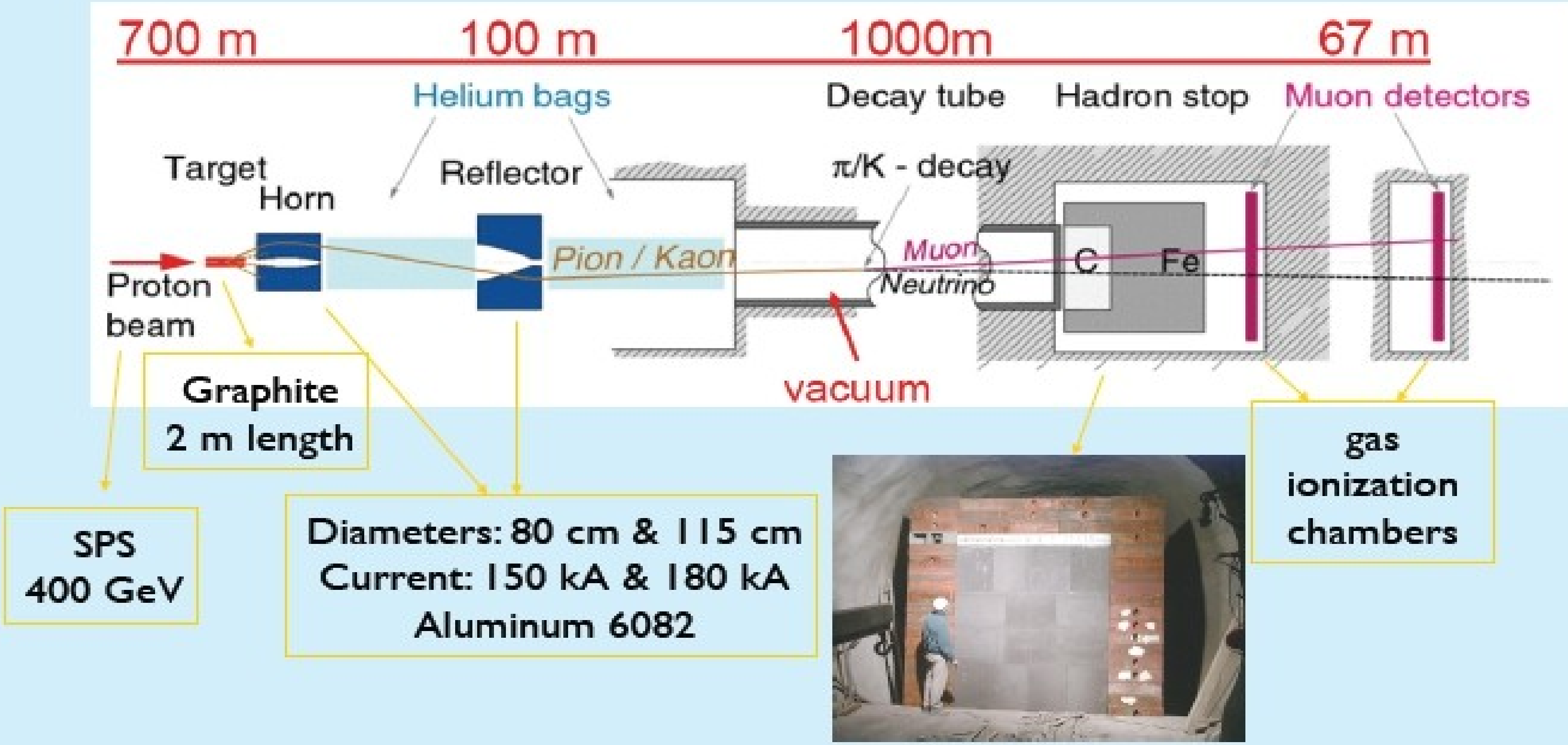
~ 23600 ν_μ CC + NC

~ 160 $\nu_e + \nu_e$ CC

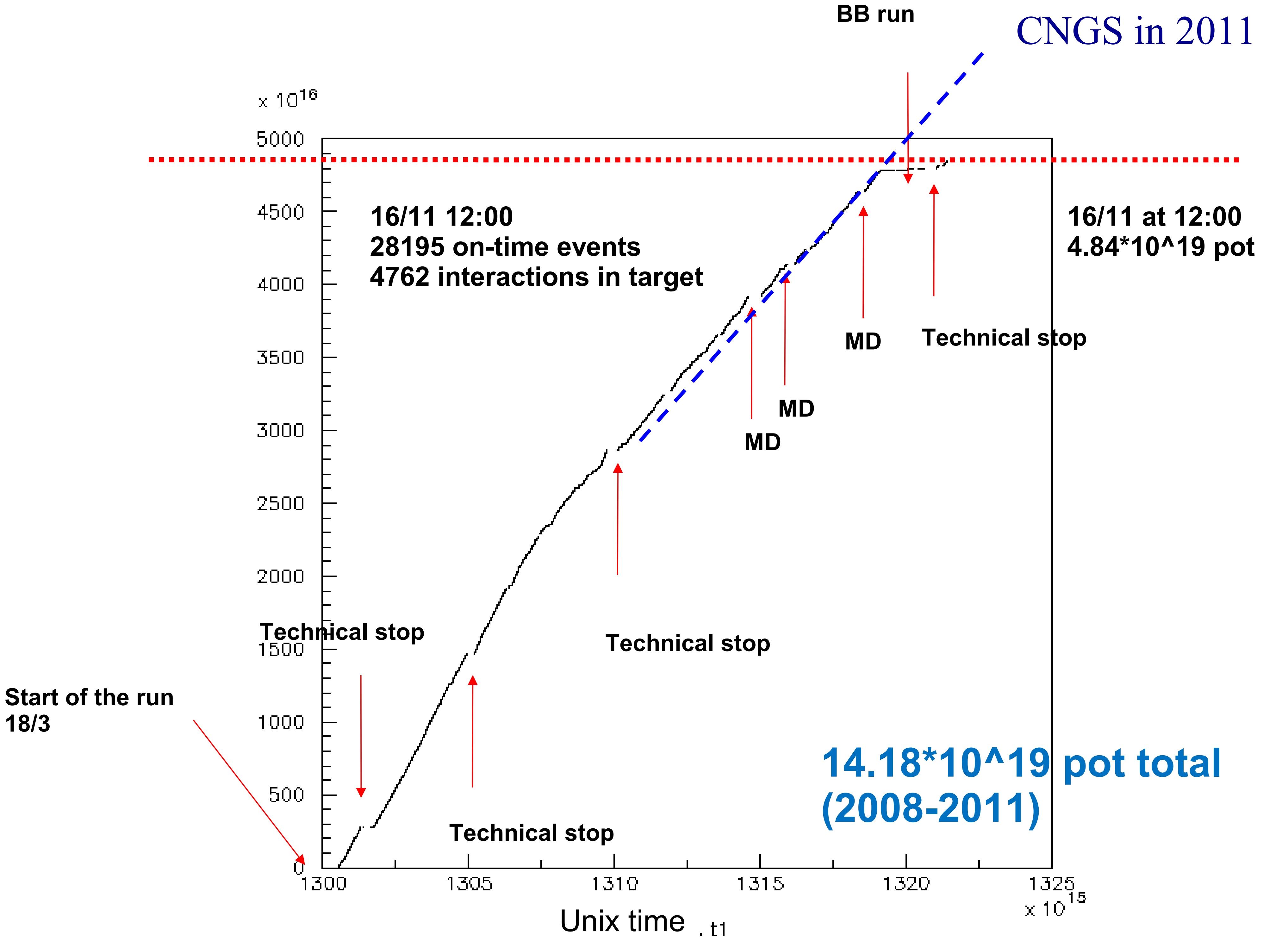
~ 115 ν_τ CC ($\Delta m^2 = 2.5 \times 10^{-3}$ eV^2)



CNGS neutrino beam

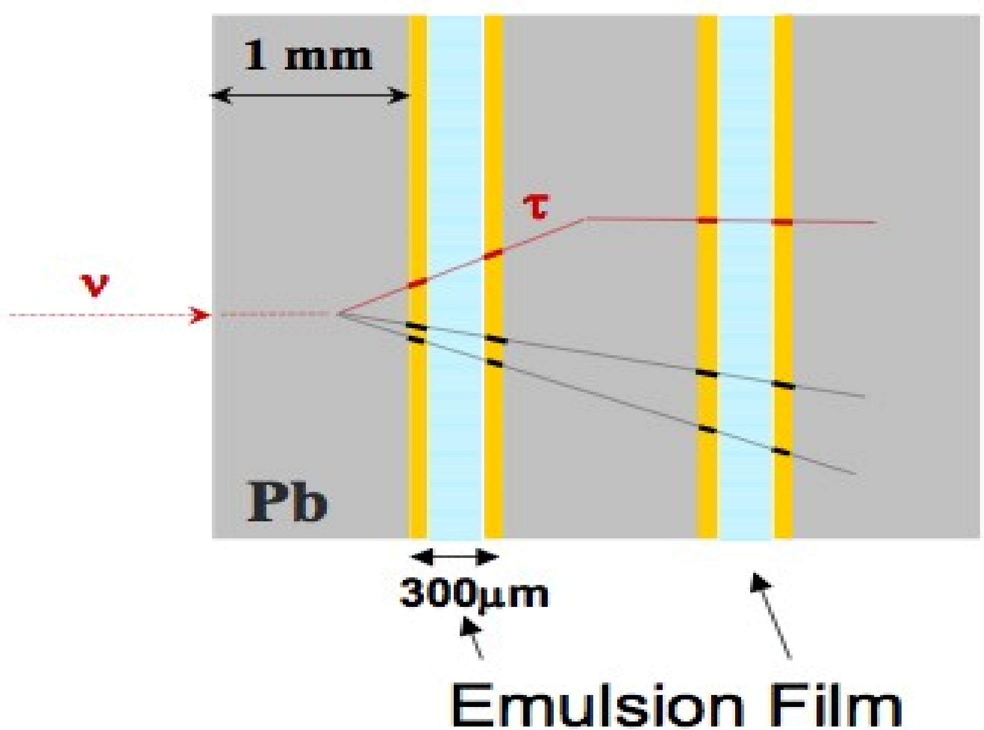


Year	POT (10^19)	Notes
2006	0.076	Commissioning
2007	0.082	Commissioning
2008	1.78	Physics run
2009	3.52	Physics run
2010	4.04	Physics run
2011	4.84	Physics run

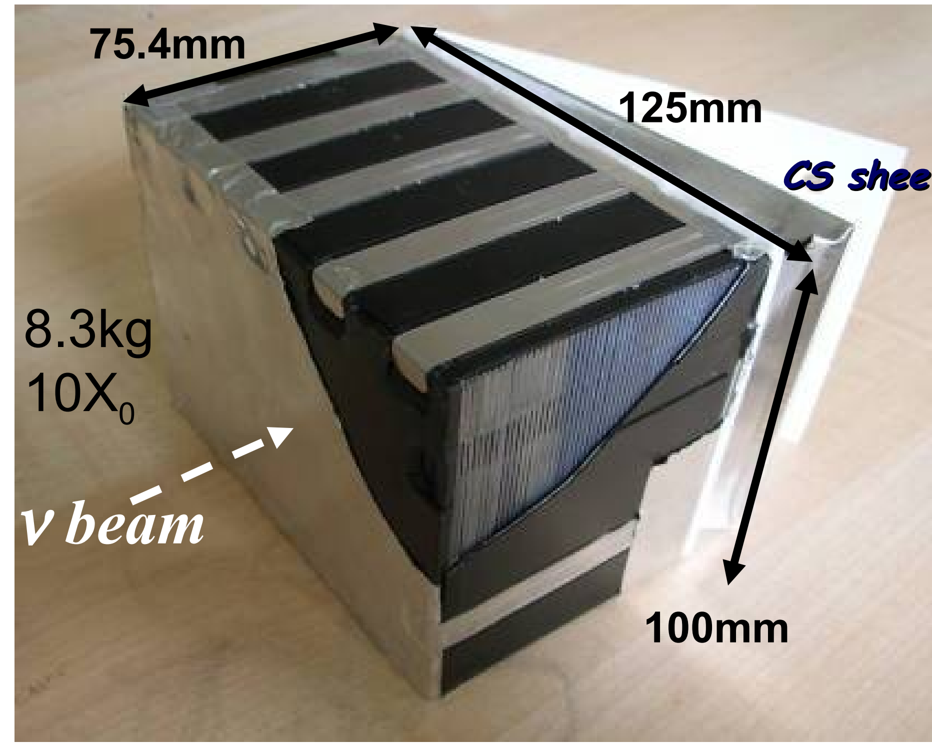

CNGS in 2011
BB run
x 10^16
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
1300
1305
1310
1315
1320
1325
x 10^15
Unix time . t1
16/11 12:00
28195 on-time events
4762 interactions in target
16/11 at 12:00
4.84*10^19 pot
MD
MD
MD
Technical stop
Technical stop
Technical stop
Technical stop
Start of the run
18/3
14.18*10^19 pot total
(2008-2011)

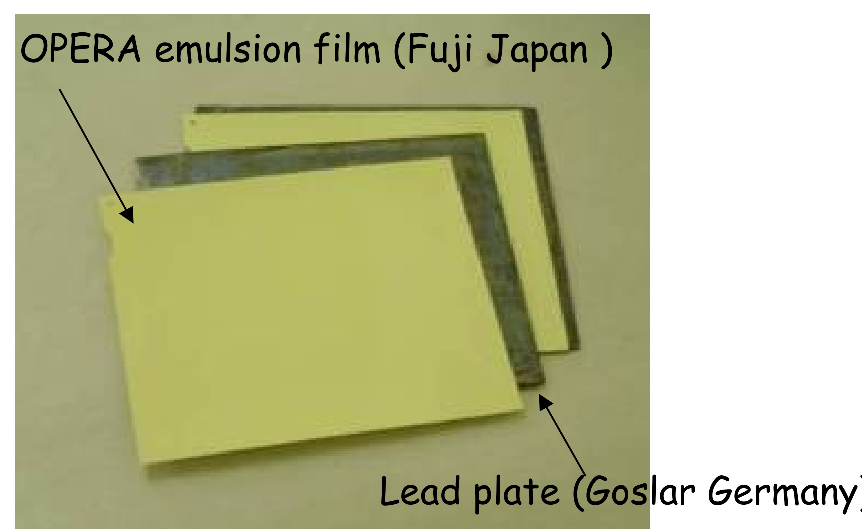
Detecting τ leptons with ECC detectors

The heart of the experiment:
THE ECC TARGET BRICKS



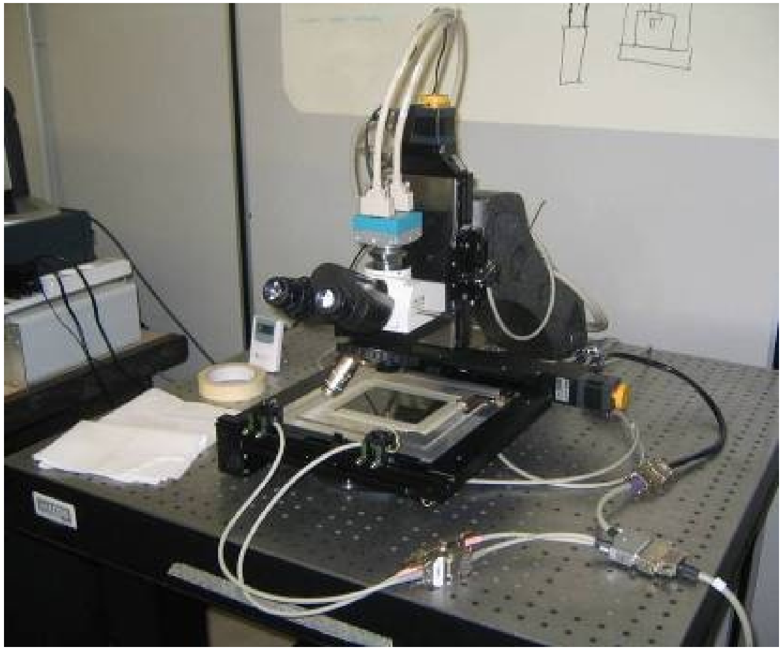
Stack of
57 OPERA films,
56 lead plates (10 X_0)





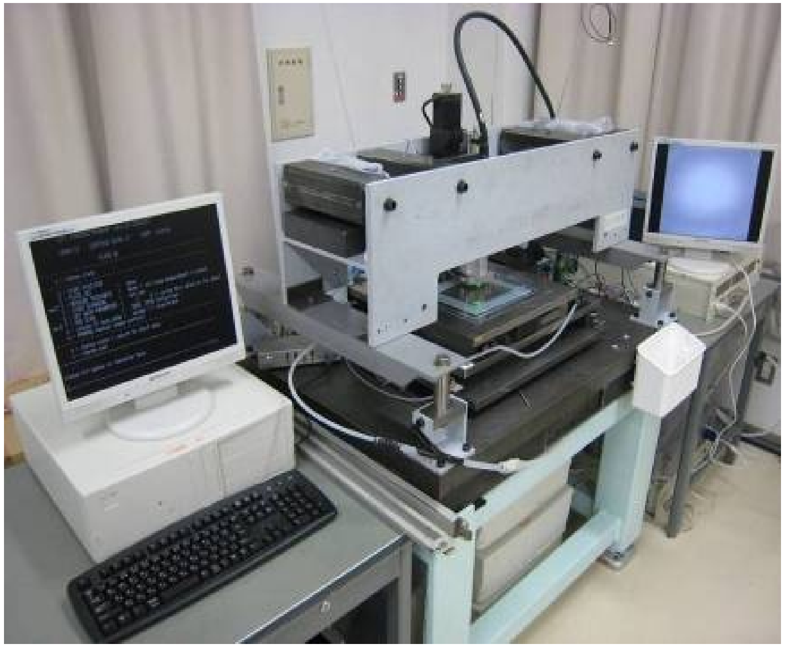
Emulsion film scanning

EU: ESS (European Scanning System)



- Scanning speed/system: 20cm^2/h
- Customized commercial optics and mechanics
- Asynchronous DAQ software

Japan: SUTS (Super Ultra Track Selector)



- Scanning speed/system: 75cm^2/h
- High speed CCD camera (3 kHz), Piezo-controlled objective lens
- FPGA Hard-coded algorithms

Similar performances

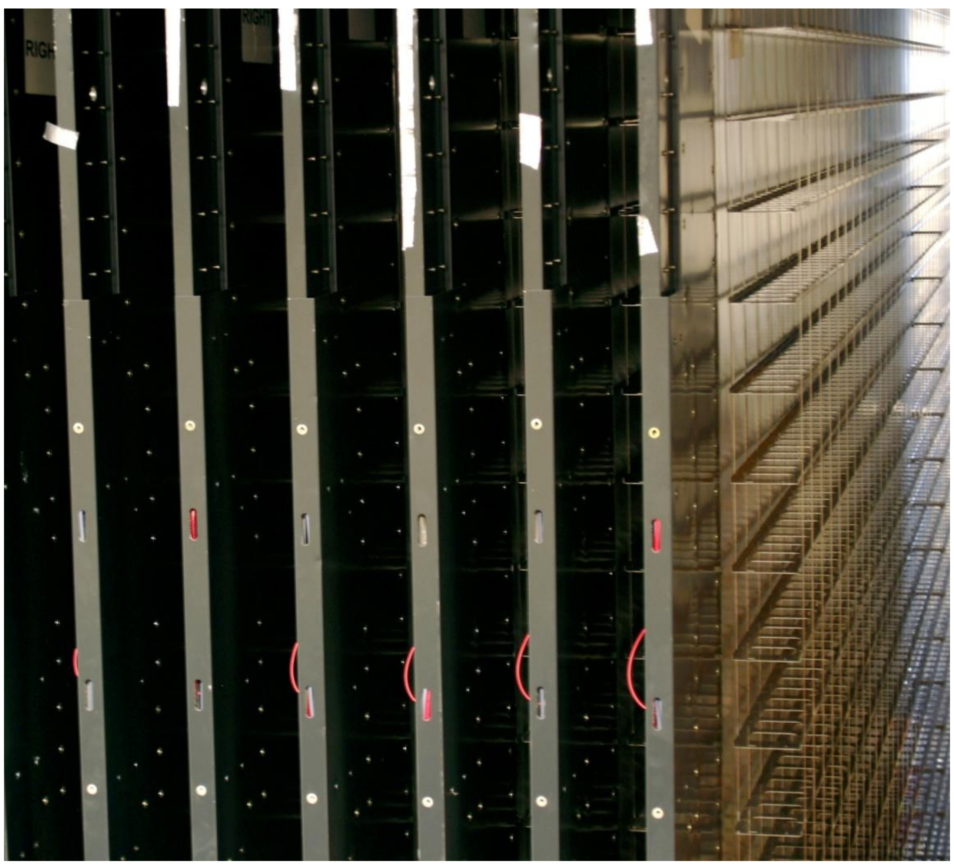
- ~ 0.3 micron spatial resolution
- ~ 2 mrad angular resolution

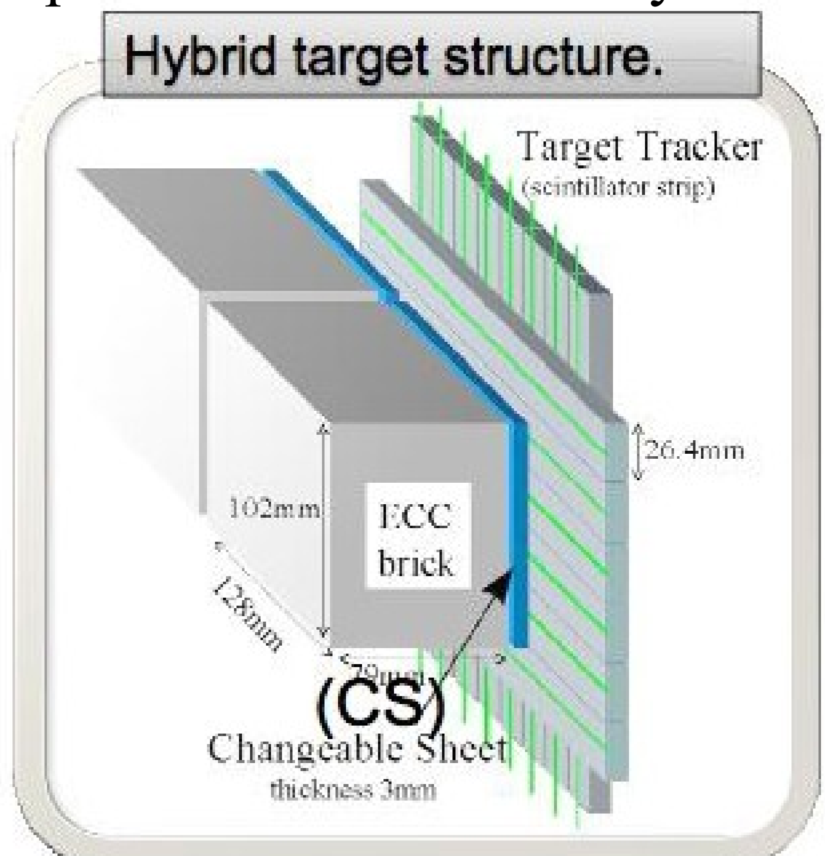
The target region of the OPERA detector

The OPERA detector is hybrid: *bricks* are organized in *walls* interleaved with scintillating strips

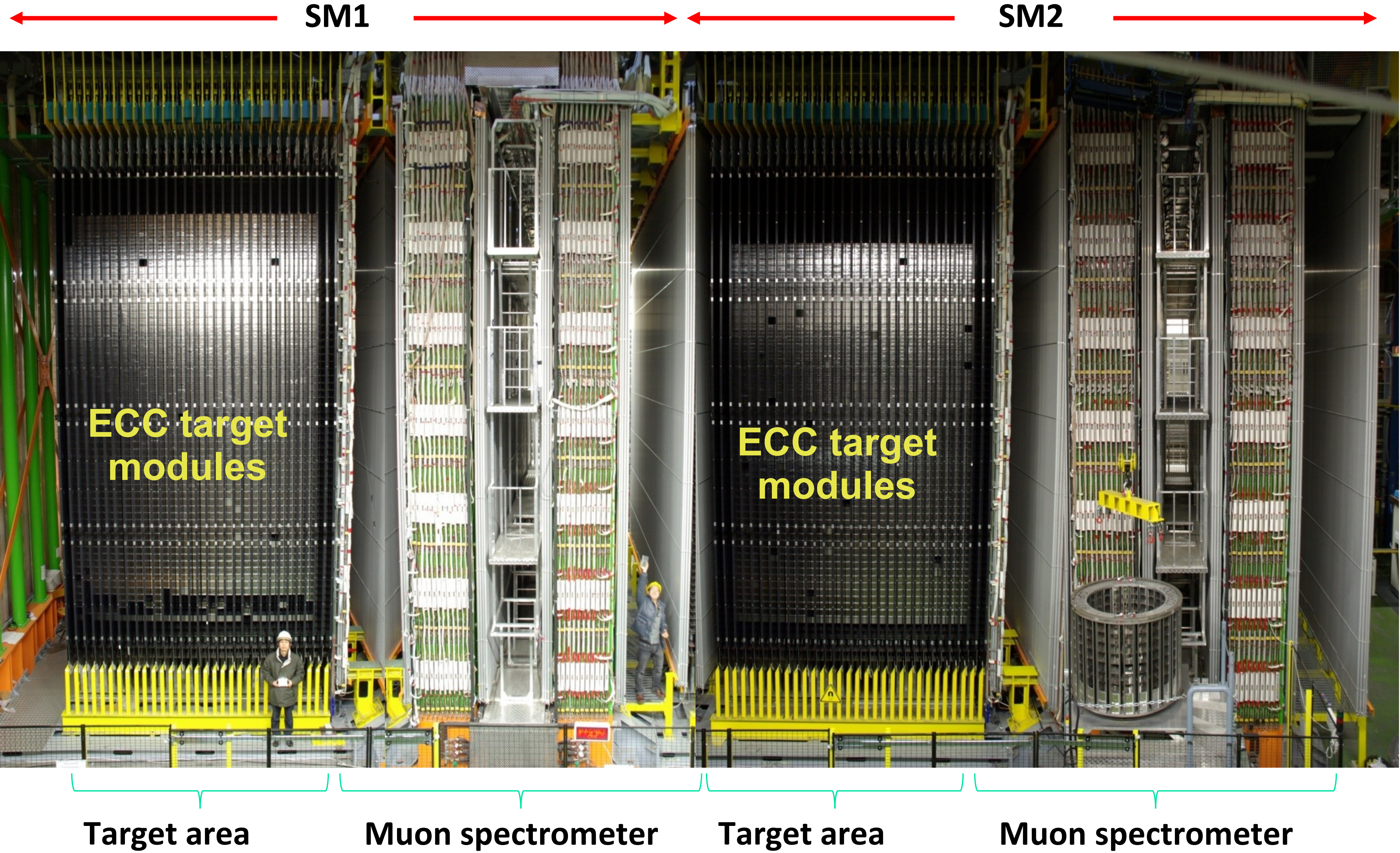
Electronic detectors:

- Provide timing information on neutrino events
- Preselect the neutrino interaction point with ≅cm accuracy





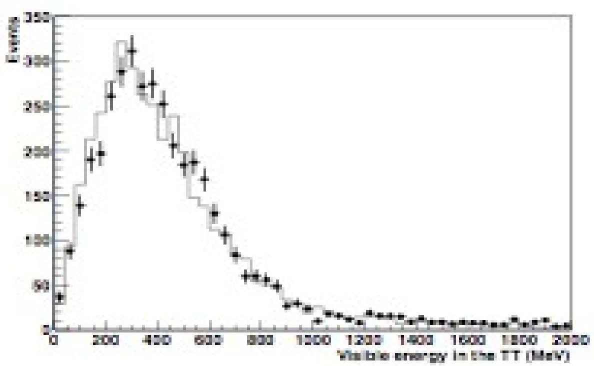
The OPERA detector



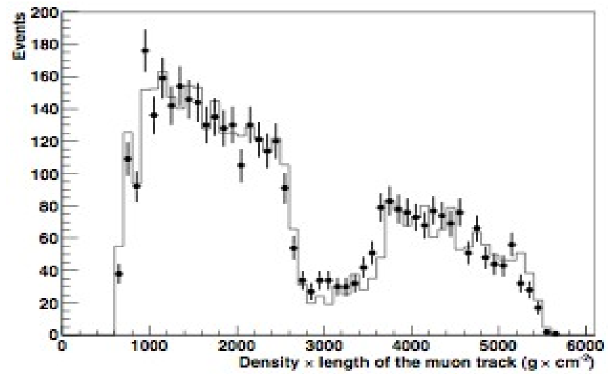
Data/MC comparison

The electronic detectors simulation has been compared with the available data, showing a good agreement (*New J.Phys. 13 (2011) 053051*).

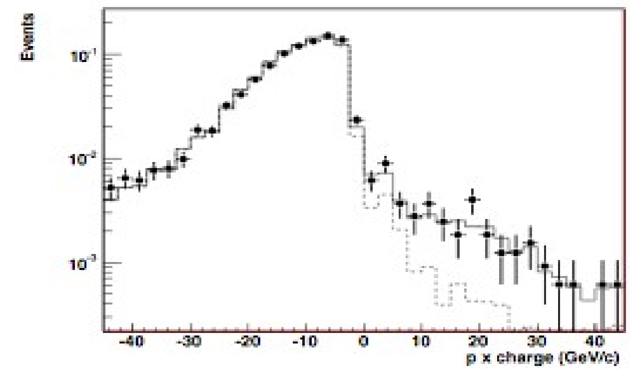
Hadronic energy deposited in TT



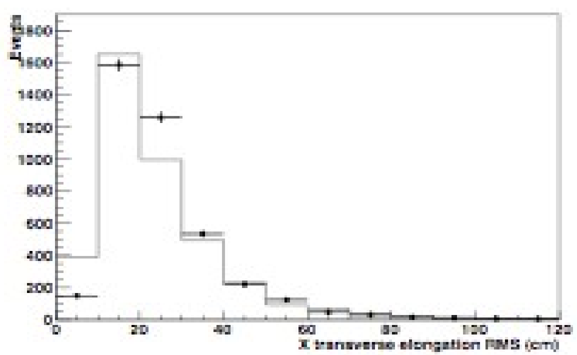
density x length of the muon track



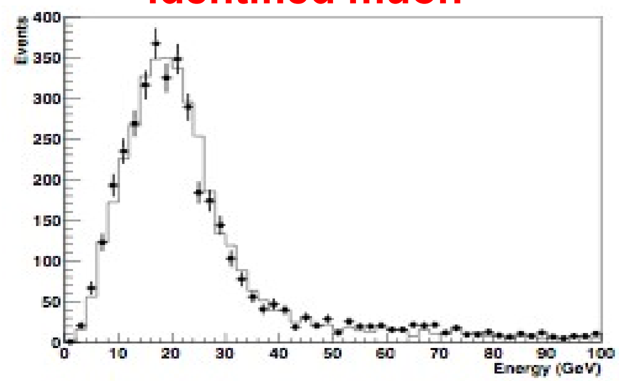
Momentum X charge for muons



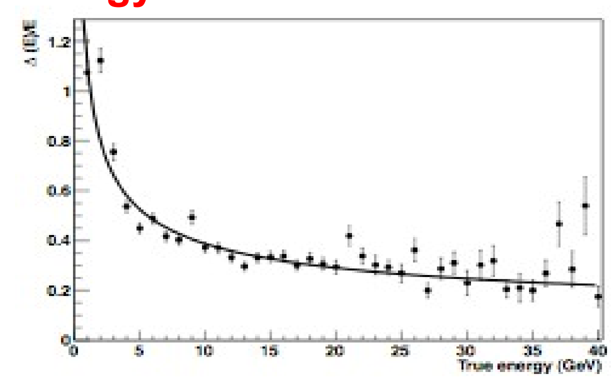
Tranverse profile of hadronic showers



Total reconstructed energy in events with at least one identified muon



Energy resolution

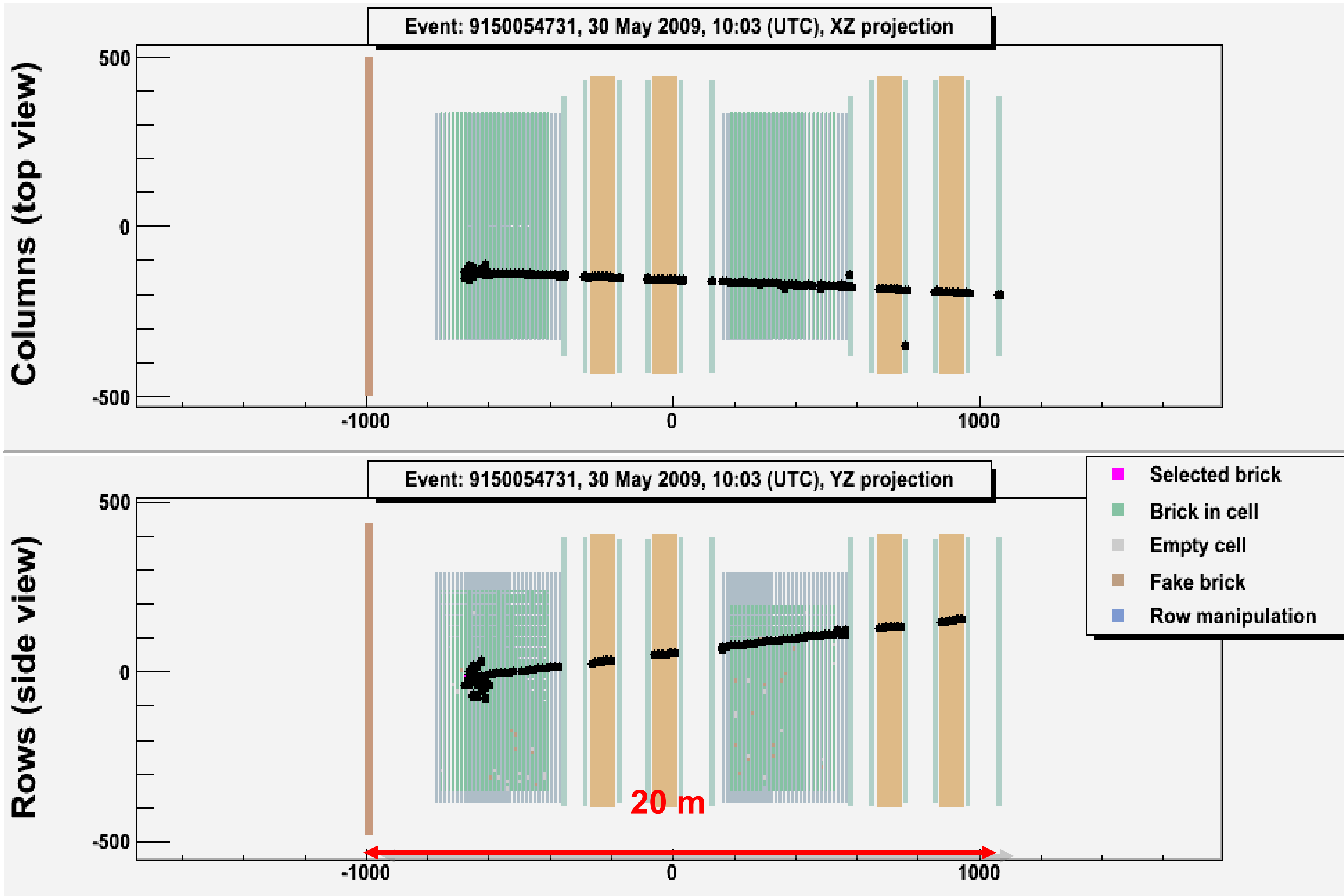


	μ+/μ-
Data	(3.92±0.37)%
MC	(3.63±0.13)%

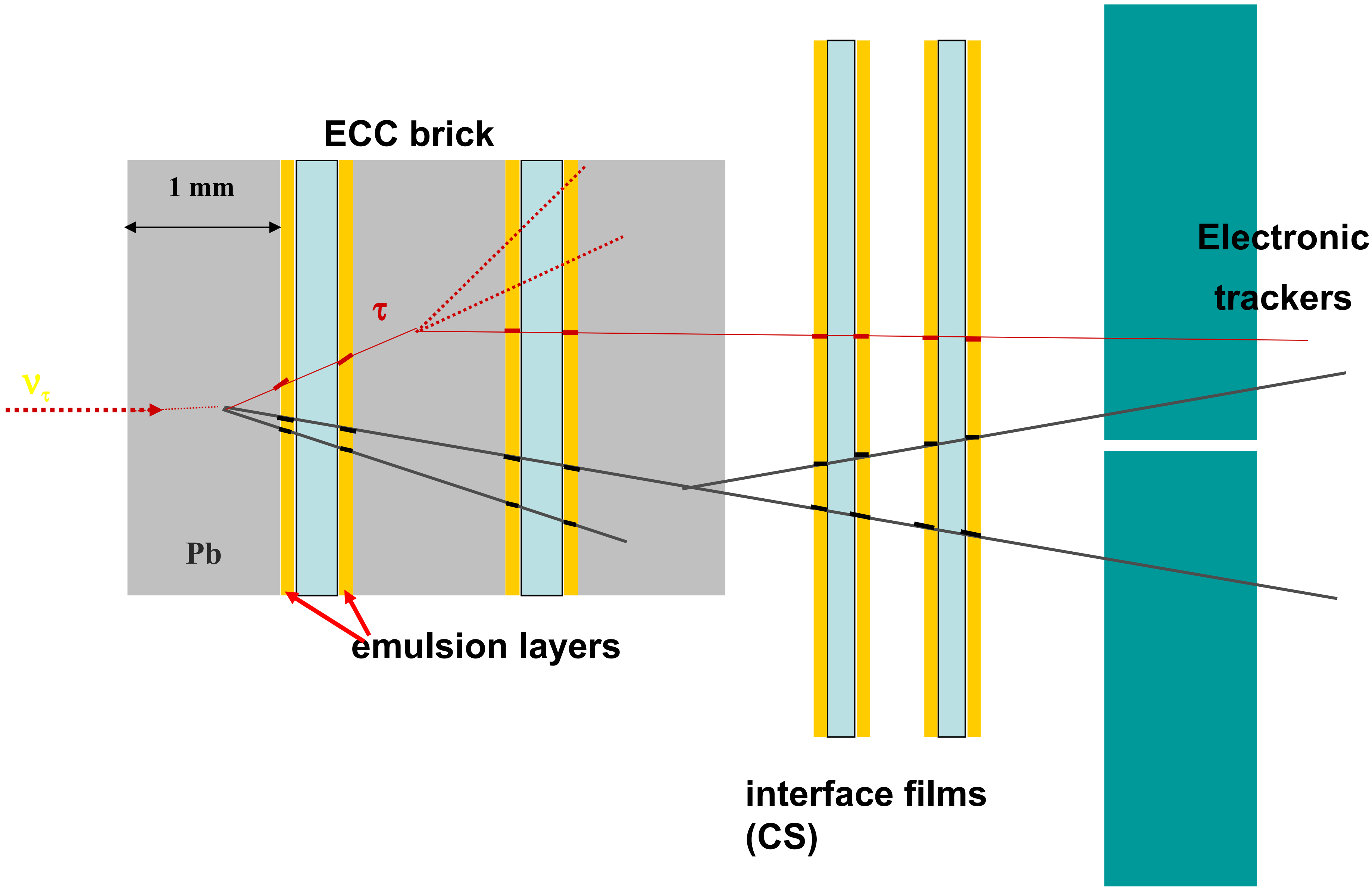
	NC/CC
Data	0.228±0.008
MC	0.257±0.031

ν event reconstruction

Neutrino event reconstruction in tho phases:
1)Electronic detector reconstruction



2) emulsion analysis



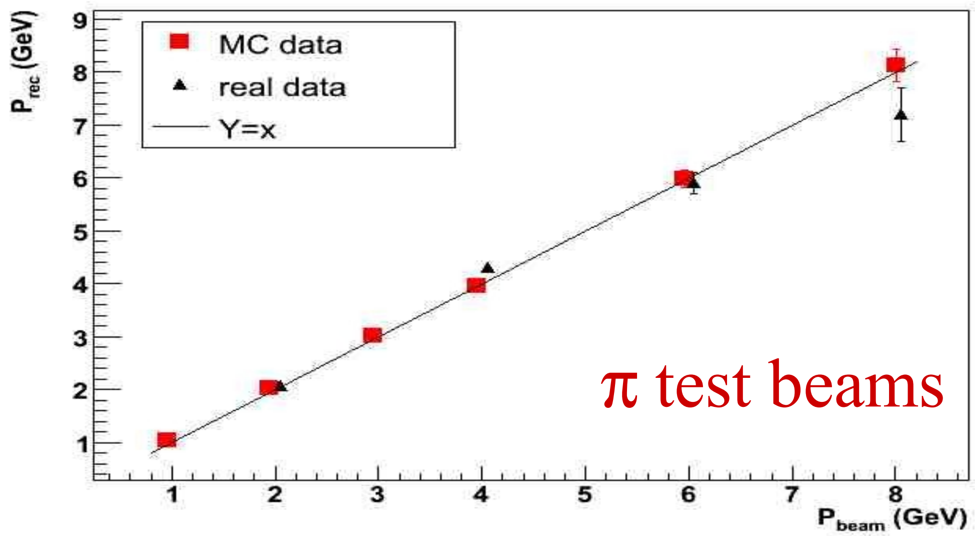
Kinematical measurements in ν event analysis

Important to achieve large signal/background ratio

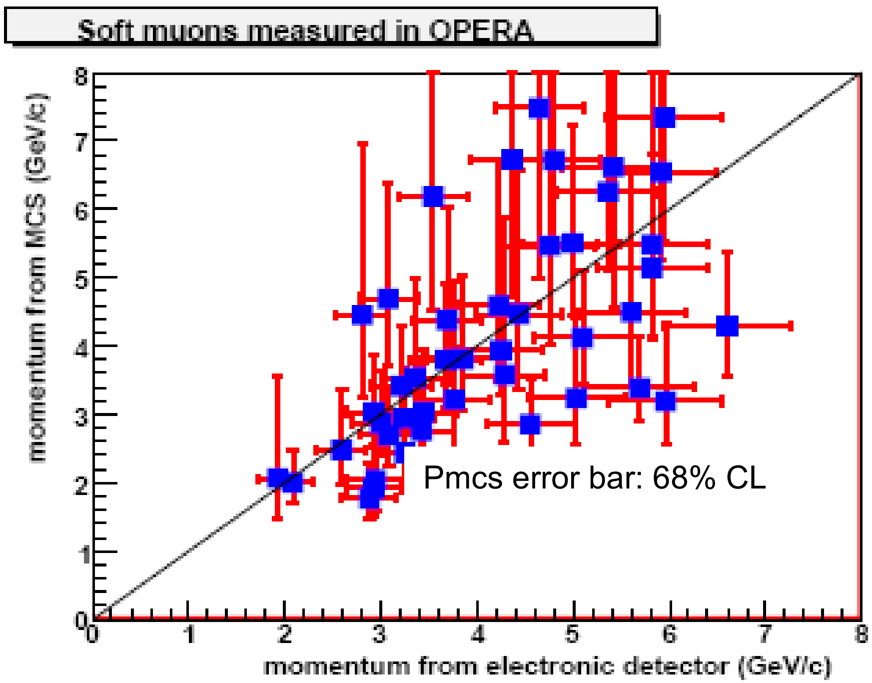
The use of a succession of lead plates as ν target allows:

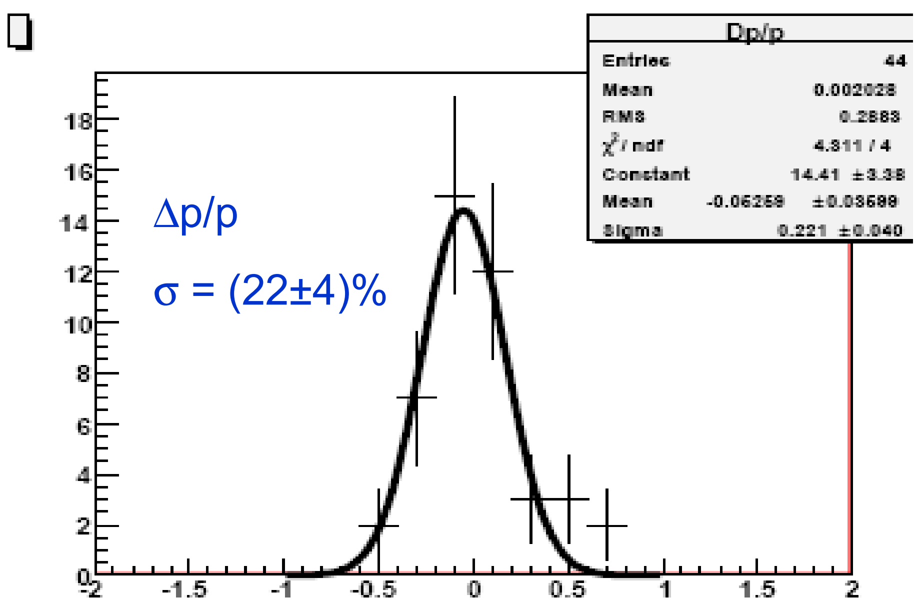
- e/γ identification and e/m shower calorimetry
- momemtum measurement for charged particles

Momentum measurement by Multiple Coulomb Scattering

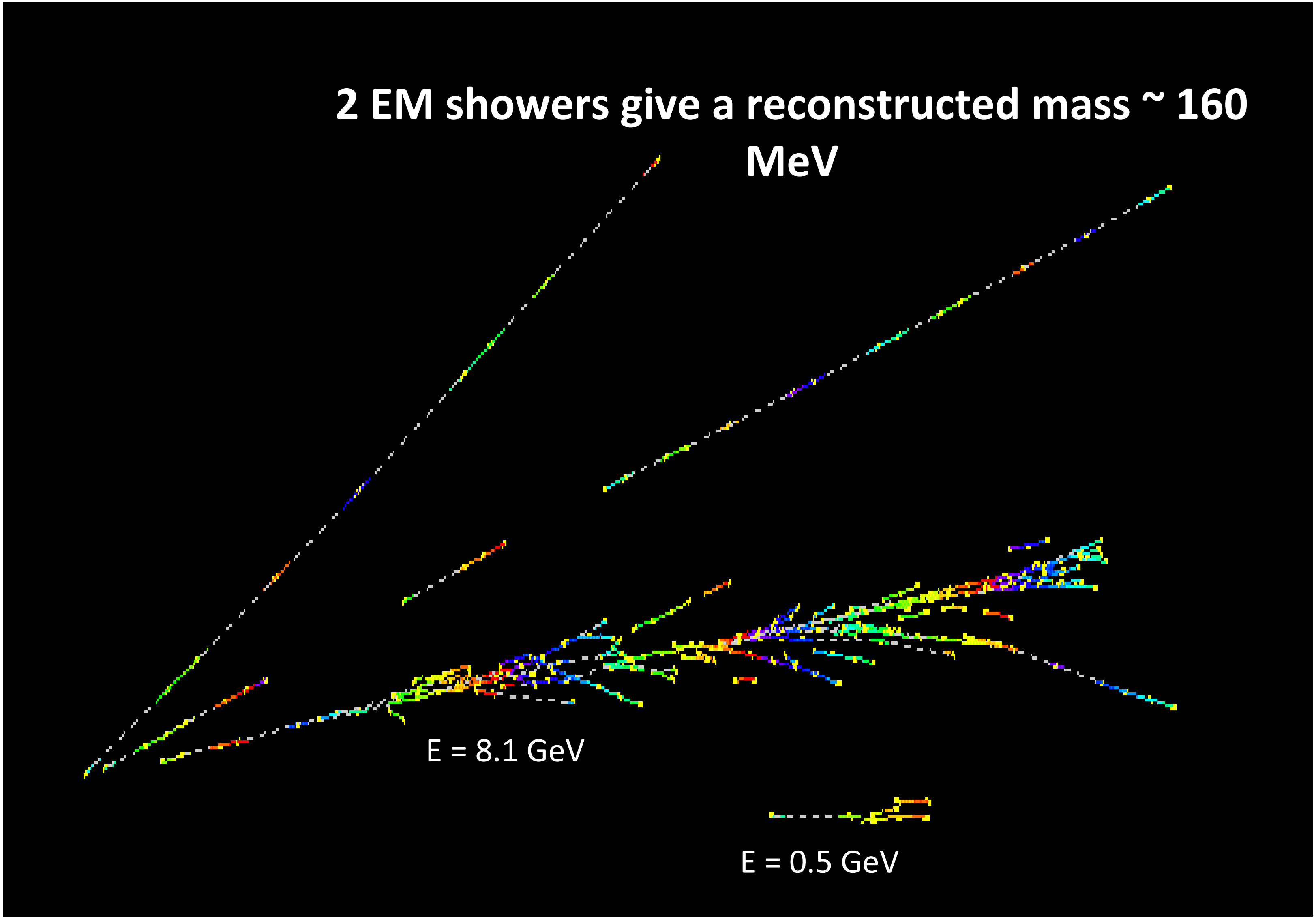


Comparison with muon spectrometer measurements





γ detection and π^0 mass reconstruction

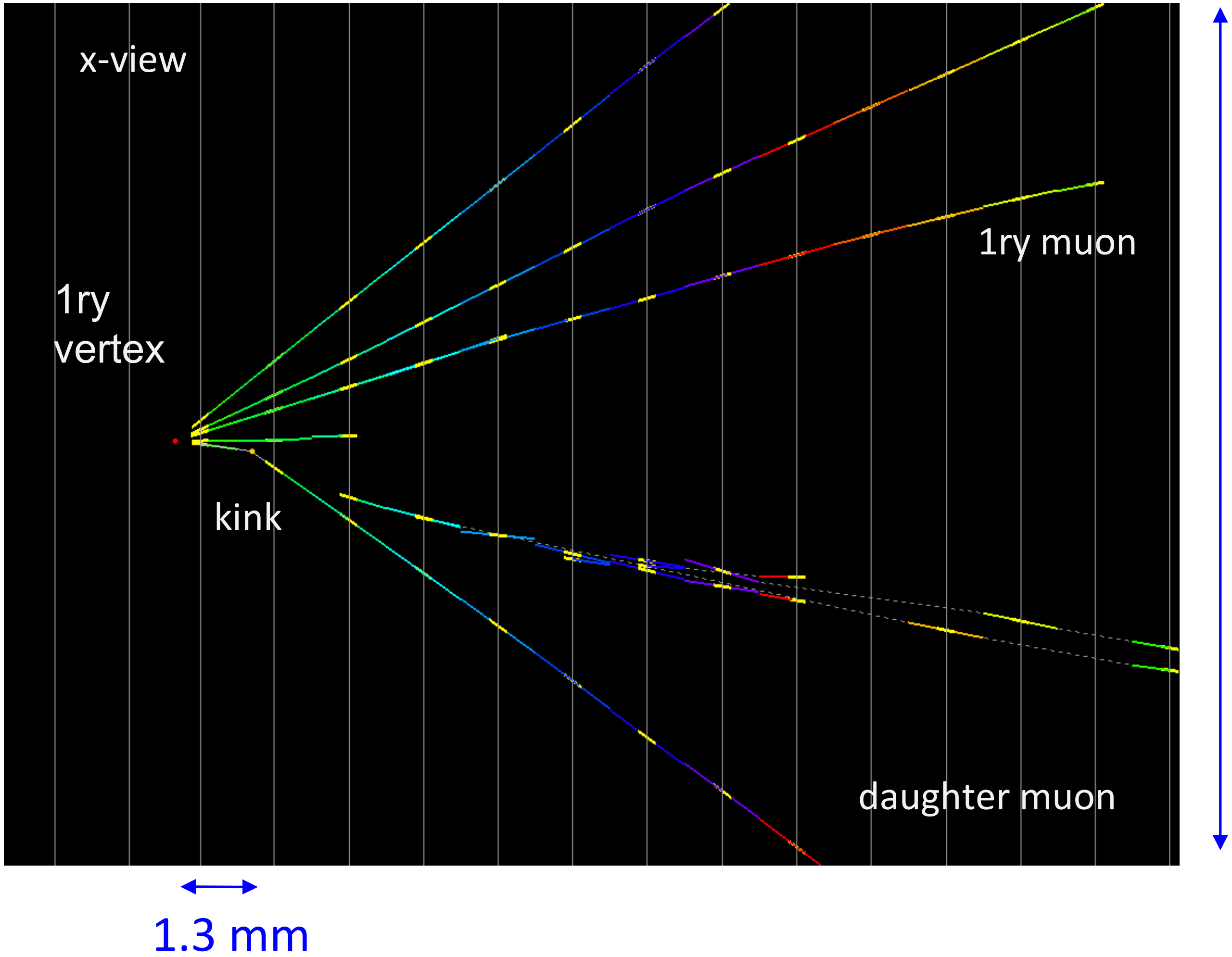


EM shower energy measured by shower shape analysis and Multiple Coulomb Scattering method

Detection of charmed particle produced in ν_μ CC interactions

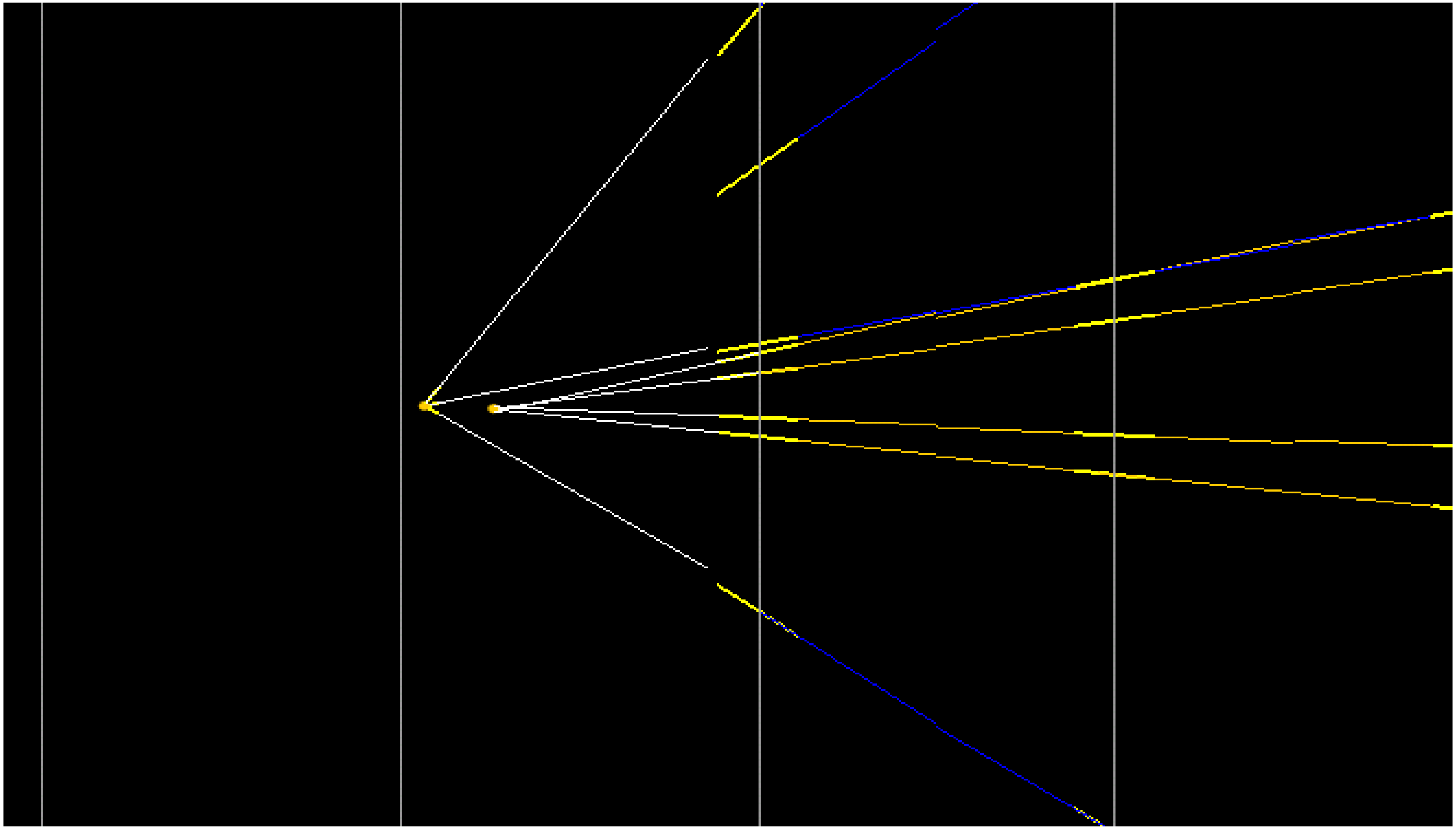
Charmed particles production in neutrino events in OPERA as a control sample for tau decay detection efficiency

Charm candidate event (dimuon)



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 candidate event (4-prong)

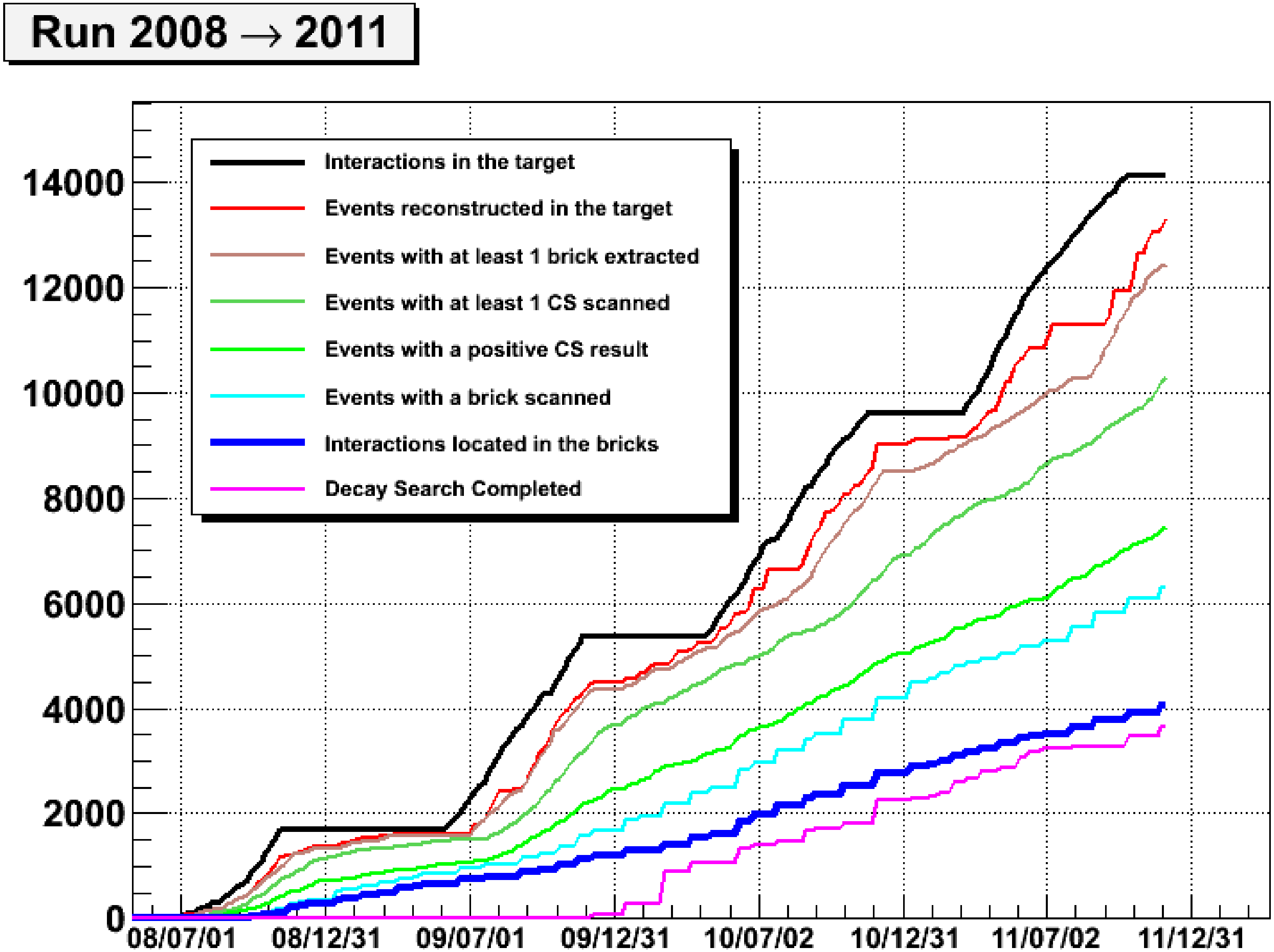


Flight lenght: 313.1 microns

ϕ : 173.2^0

minimum invariant mass: 1.7 GeV

Present statistics: 2008÷2011 physics runs

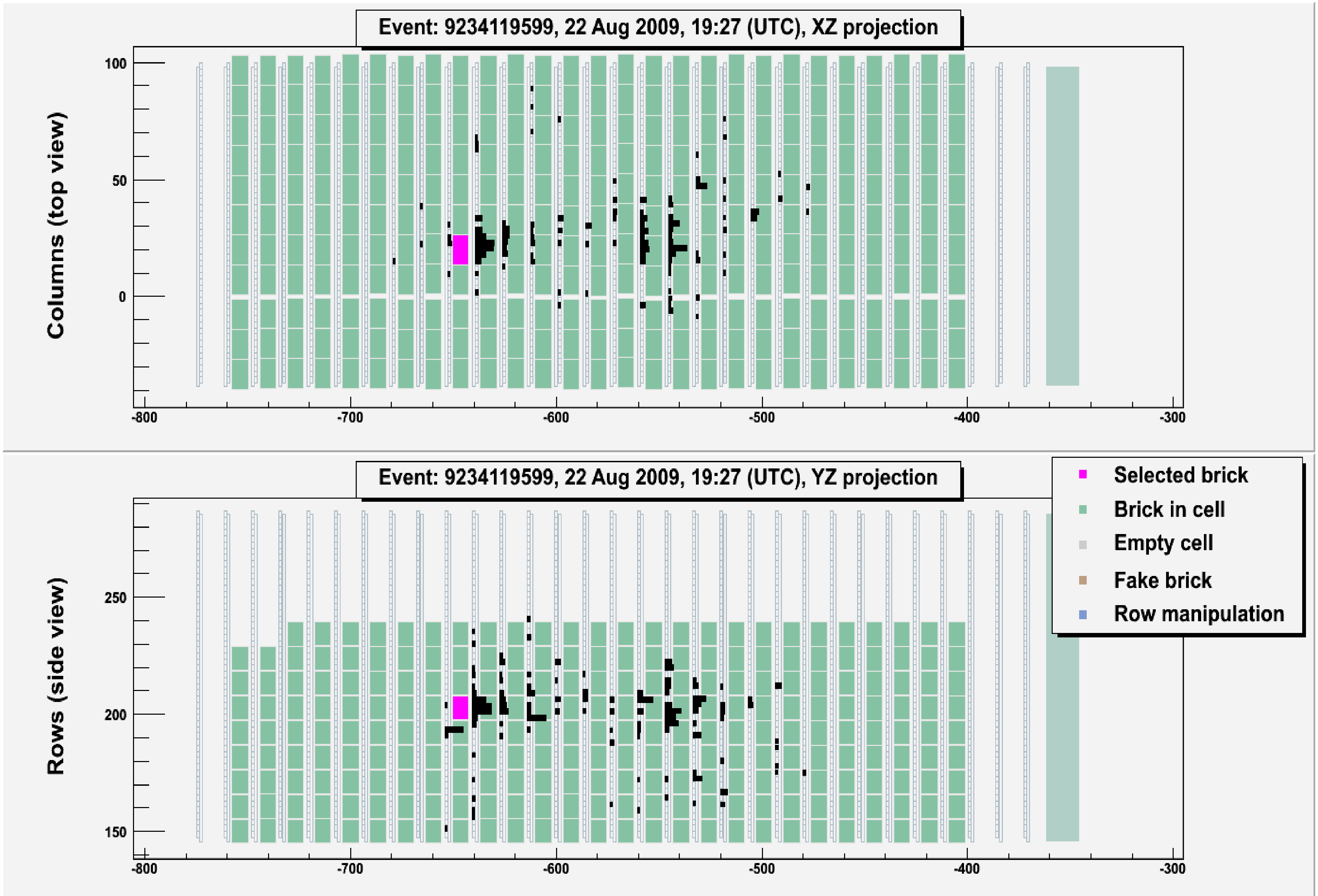


Located interactions: 4056

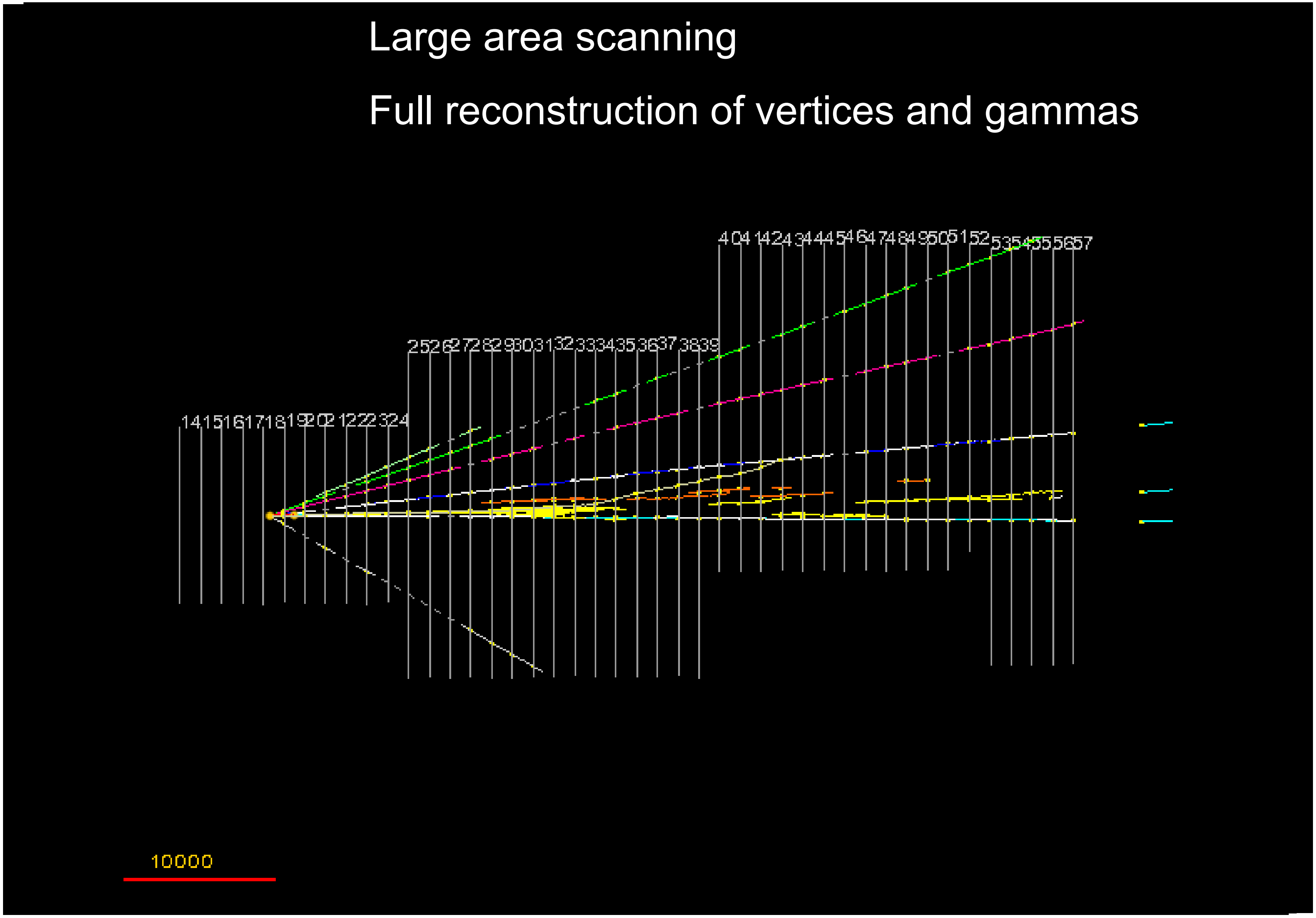
Decay searched events: 3662

The first signal event

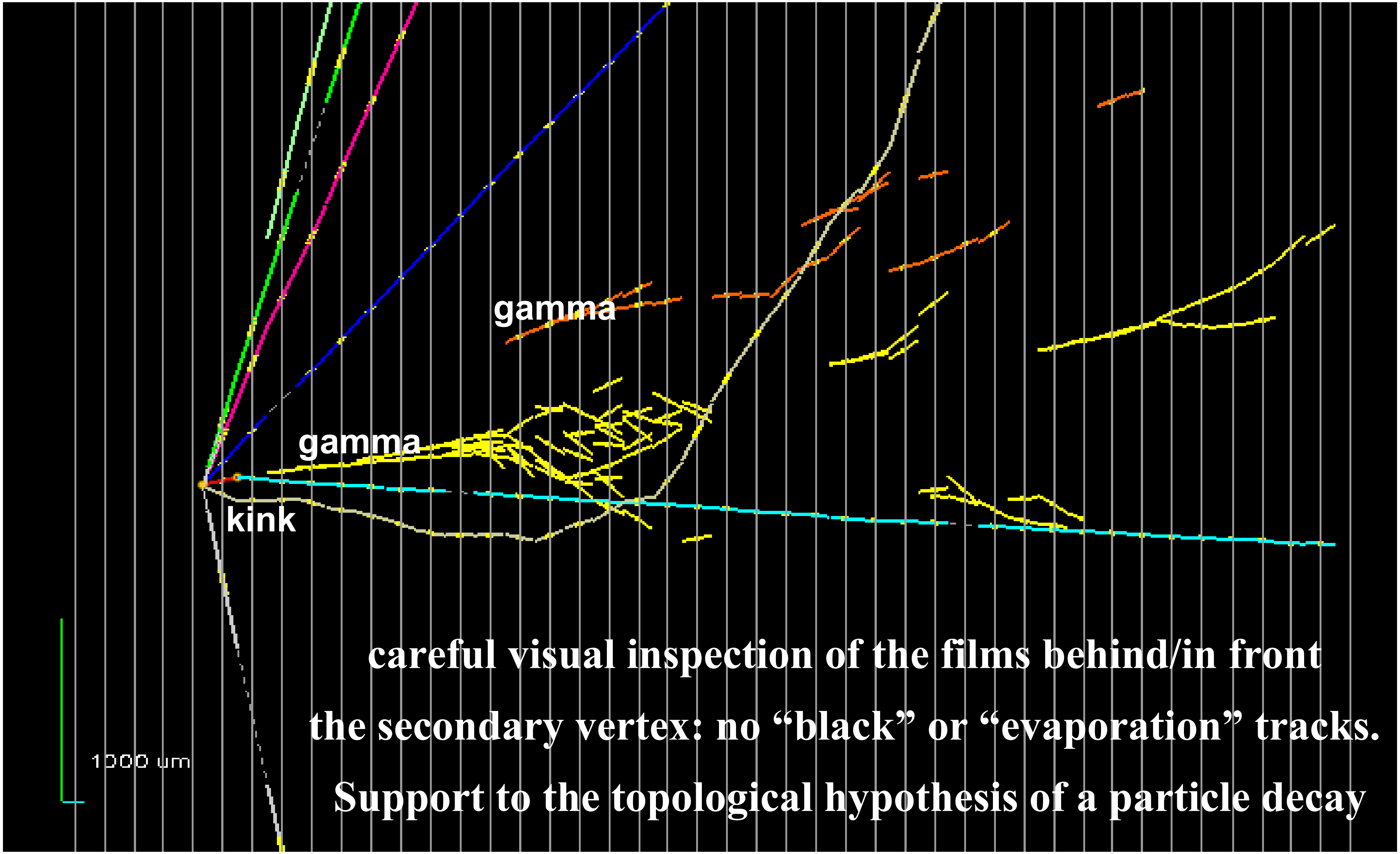
Muonless event 9234119599, taken on 22 August 2009, 19:27 (UTC)



From CS to vertex location

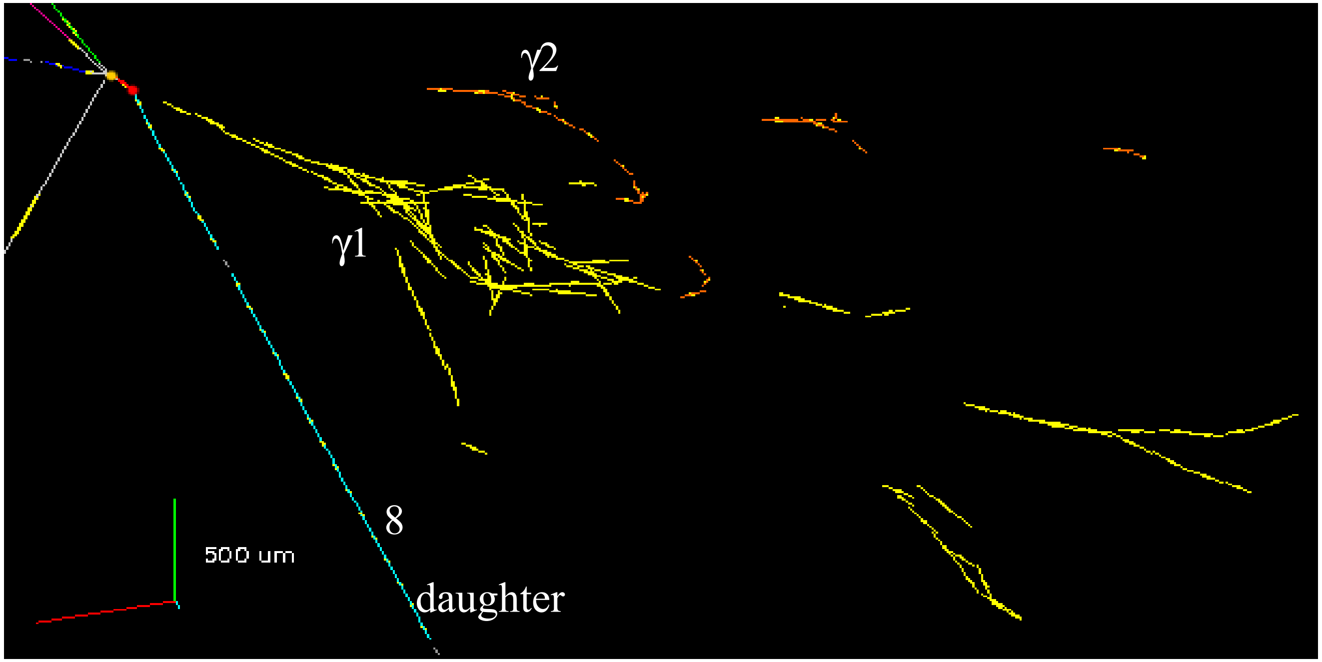


Event reconstruction (I)



careful visual inspection of the films behind/in front the secondary vertex: no “black” or “evaporation” tracks. Support to the topological hypothesis of a particle decay

γ detection



- length available for γ detection downstream of the vertices: 6.5 X_0

- 2 gammas detected, both assumed to come from secondary vertex after impact parameter analysis

	Energy (GeV)
1st γ	5.6 ± 1.0 ± 1.7
2nd γ	1.2 ± 0.4 ± 0.4

Kinematical and topological variables

The kinematical variables are computed averaging the two sets of track parameter measurements

VARIABLE	AVERAGE
kink (mrad)	**41 ± 2**
decay length (μm)	**1335 ± 35**
P daughter (GeV/c)	**12^{+6}_{-3}**
Pt daughter (MeV/c)	**470^{+230}_{-120}**
missing Pt (MeV/c)	**570^{+320}_{-170}**
ϕ (deg)	**173 ± 2**

Uncertainty on Pt due to the gamma attachment choice is smaller than 50 MeV

Topological and kinematical analysis

OPERA analysis flow (as defined in the experiment proposal) applied to this candidate event:

- kink occurring within 2 lead plates downstream of the primary vertex
- kink angle larger than 20 mrad
- daughter momentum higher than 2 GeV/c
- decay Pt higher than 600 MeV/c, 300 MeV/c if ≥ 1 gamma pointing to the decay vertex
- missing Pt at primary vertex lower than 1 GeV/c
- azimuth angle between the resulting hadron momentum direction and the parent track direction larger than $\pi/2$ rad

Event interpretation and invariant mass analysis

- This event passes all cuts, with the presence of at least 1 gamma pointing to the secondary vertex
- This event is a ν_τ candidate with the $\tau \rightarrow$ 1-prong hadron decay mode.
- The invariant mass of the two detected gammas is consistent with the π^0 mass value (see below).
- The invariant mass of the (daughter+γ+γ) system is compatible with that of the ρ (770). The ρ appears in about 25% of the τ decays: $\tau \rightarrow \rho\ (\pi^- \pi^0)\ \nu_\tau$.

(γ+γ) mass	(γ+γ+daughter) mass
120 ± 20 ± 35 MeV	$640\ ^{+125}_{-80}\ ^{+100}_{-90}$ MeV

Background sources

- 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 reinteractions ~ 10^{-5}/CC

Statistical significance

(from Phys.Lett.B691:138-145,2010)

1 ν_τ candidate in the 1 prong decay channel observed.

Given the statistics mentioned in the paper above, the background expectation was:

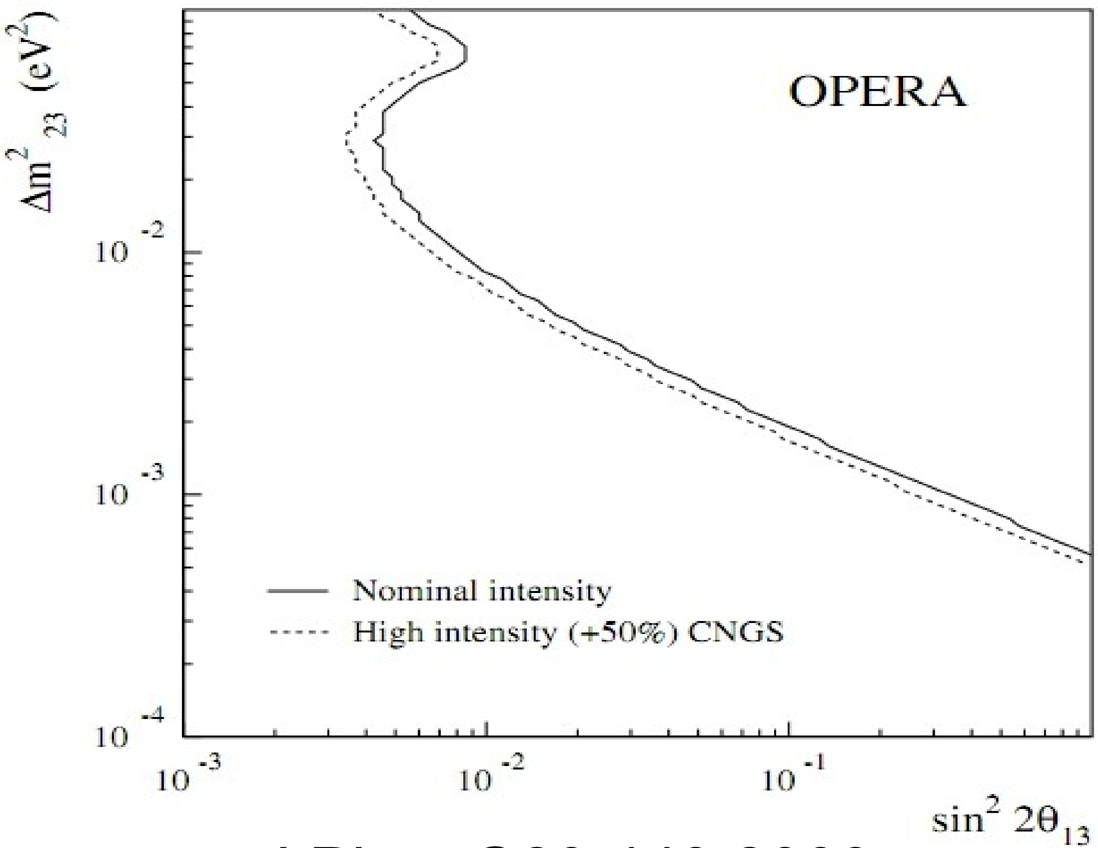
Considering all decay channels: 0.045 ± 0.020 (syst) BG events
Considering only $\tau \rightarrow 1$prong channel: 0.018 ± 0.007 (syst) BG events

The probability to observe at least 1 BG event is (all decay channels) 4.5%.
The probability to observe at least 1 BG event is (only t $\rightarrow$ 1prong) 1.8%.

The observation of 1 ν_τ canditate event corresponds to a significance of 2.01 σ if we consider all dacay channels, 2.36 σ for the 1prong decay channel.

ν_e event detection

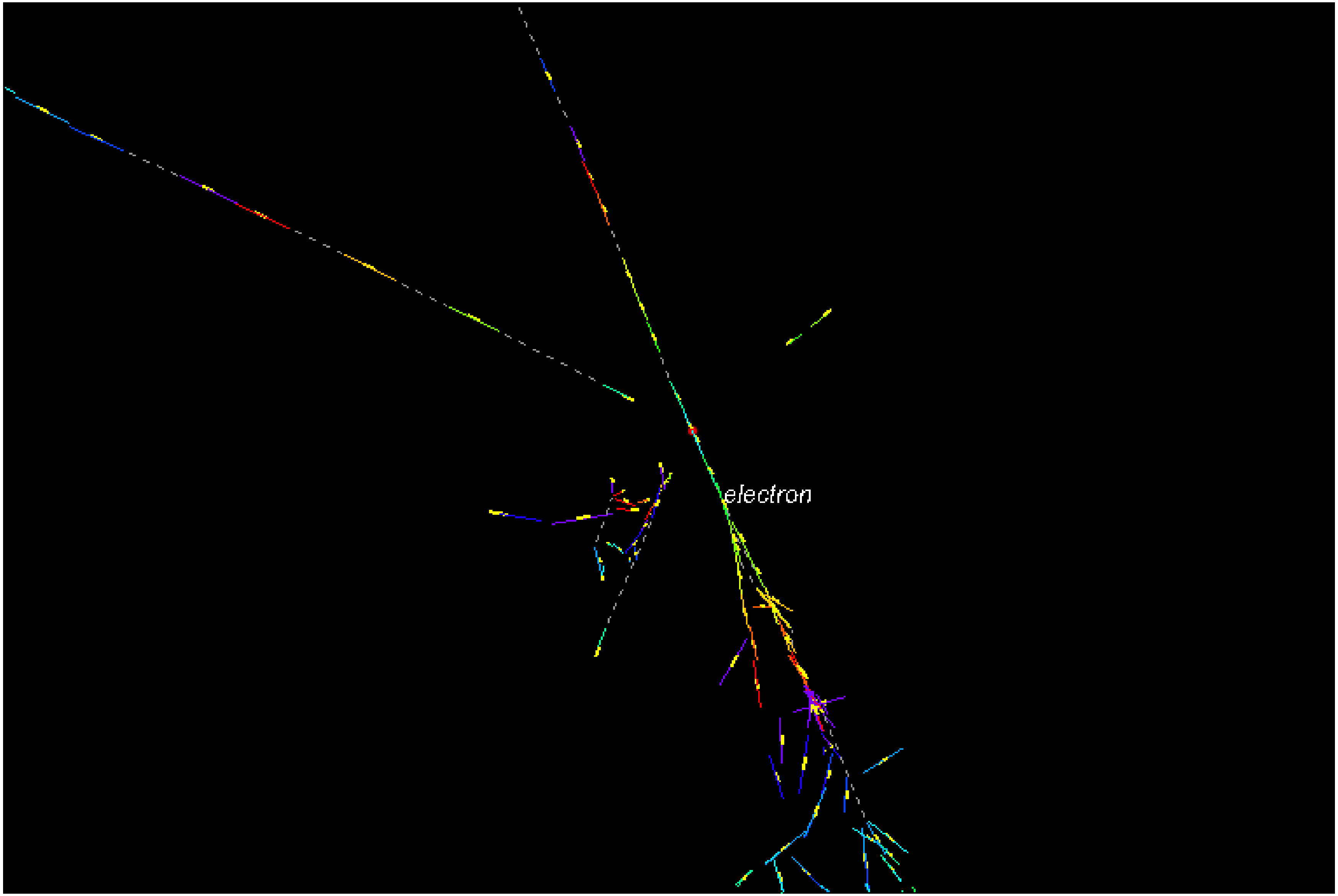
- ECC detector allows the identification of ν_e events
- Additional physics subject: study $\nu_\mu \rightarrow \nu_e$ oscillations
- Background from ν_e prompt: $\cong$ 0.9% of CC events
  (further reduced by energy measurement)



J.Phys.G29:443,2003

New evaluation of OPERA sensitivity in progress

ν_e event detection



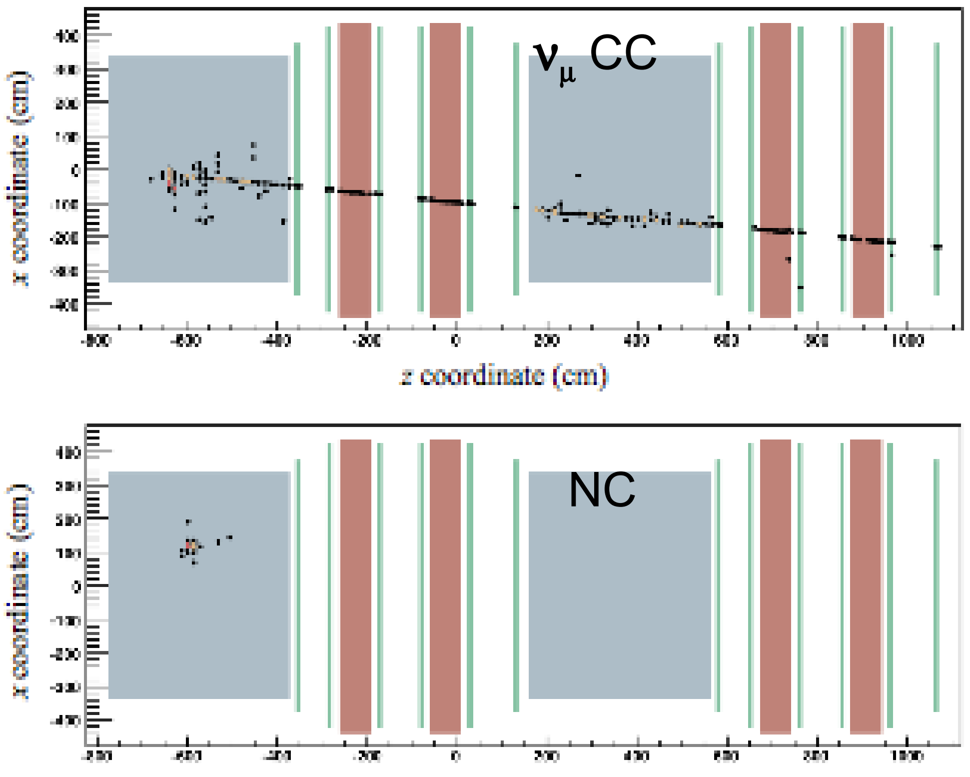
21 ν_e event candidates detected so far

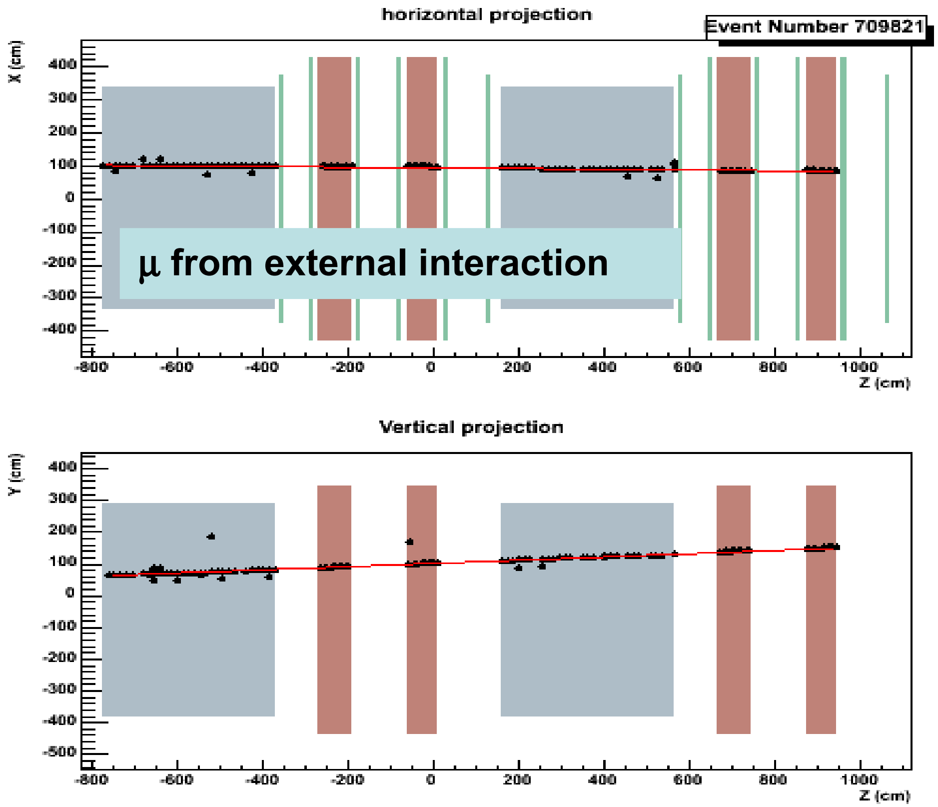
Principle of the neutrino velocity measurement

Definition of neutrino velocity:
ratio of precisely measured baseline and time of flight

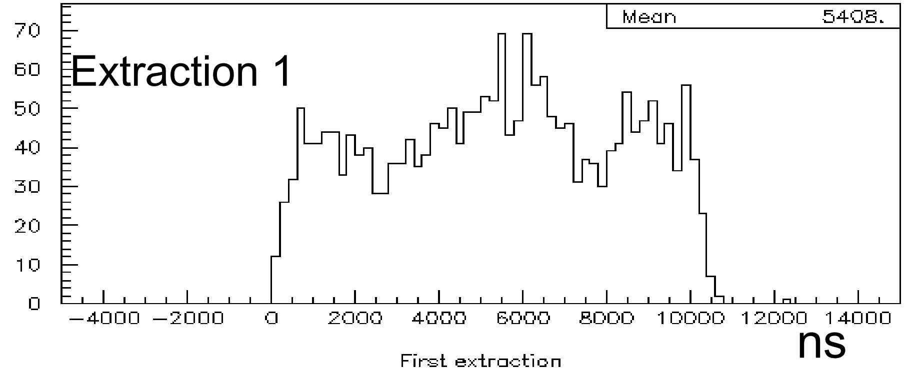
Time of flight measurement:

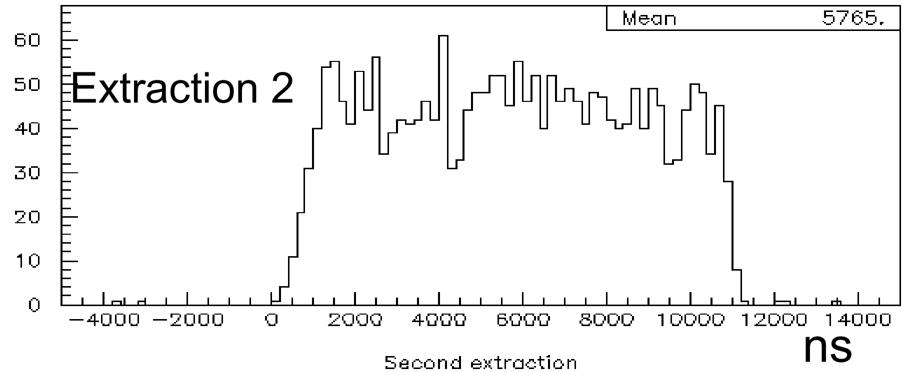
- tagging of neutrino production time
- tagging of neutrino interaction time by a far detector
- accurate determination of the baseline (geodesy)
- expected small effects: long baseline required
- blind analysis





Measurement of the neutrino event time distribution

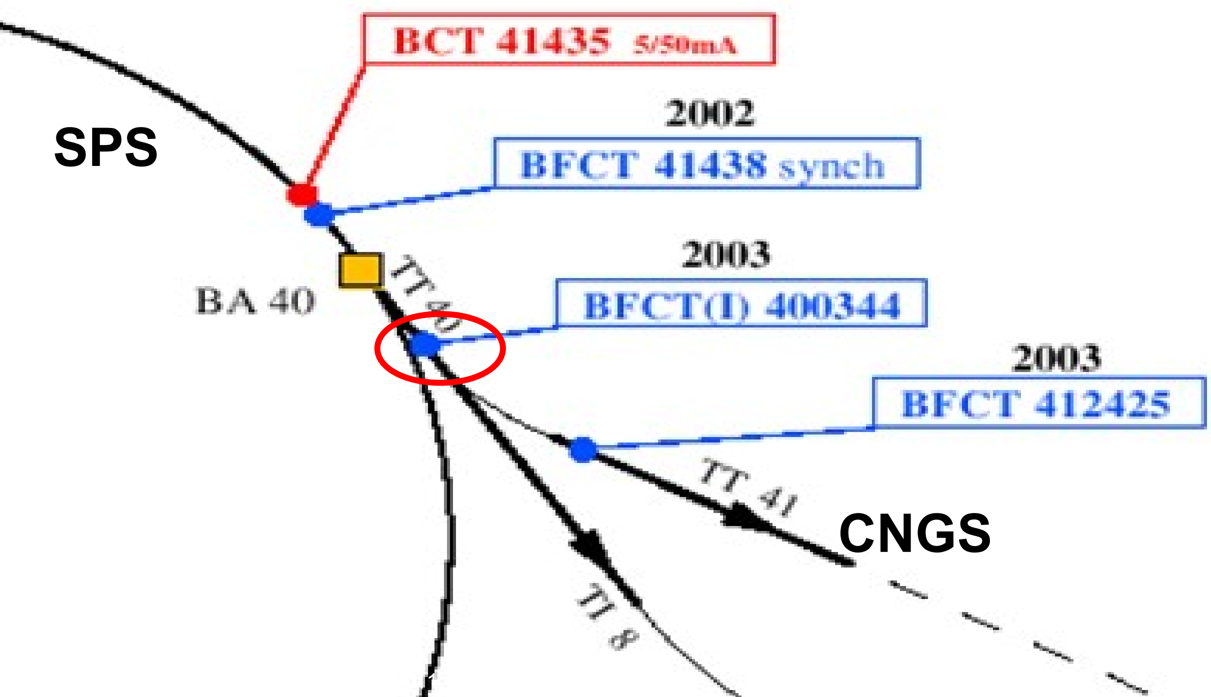




Typical neutrino event time distributions in 2008 w.r.t kicker magnet trigger pulse:

1) not flat
2) different for 1st and 2nd extraction

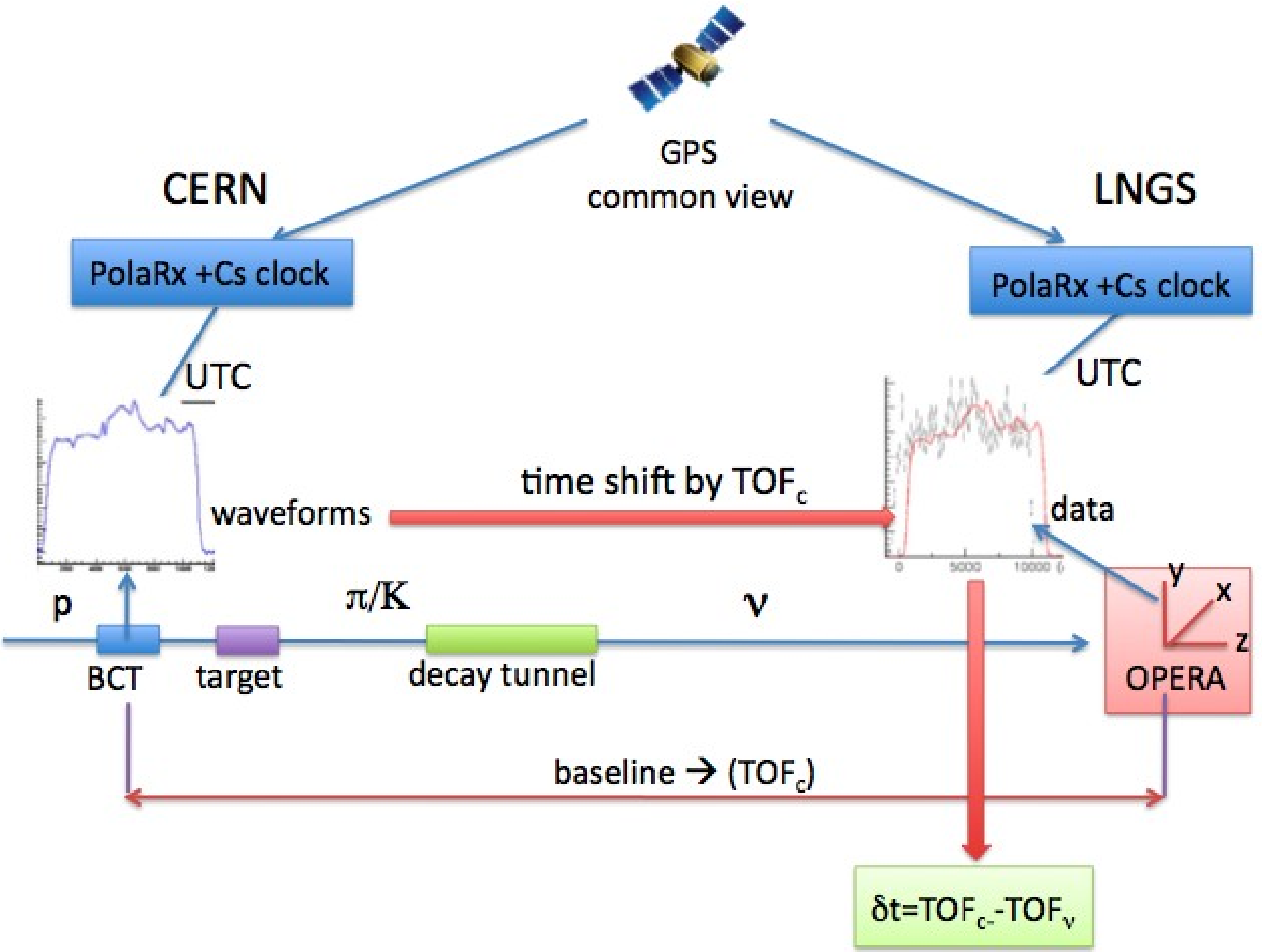
Proton timing by Beam Current Transformer



Proton pulse digitization:

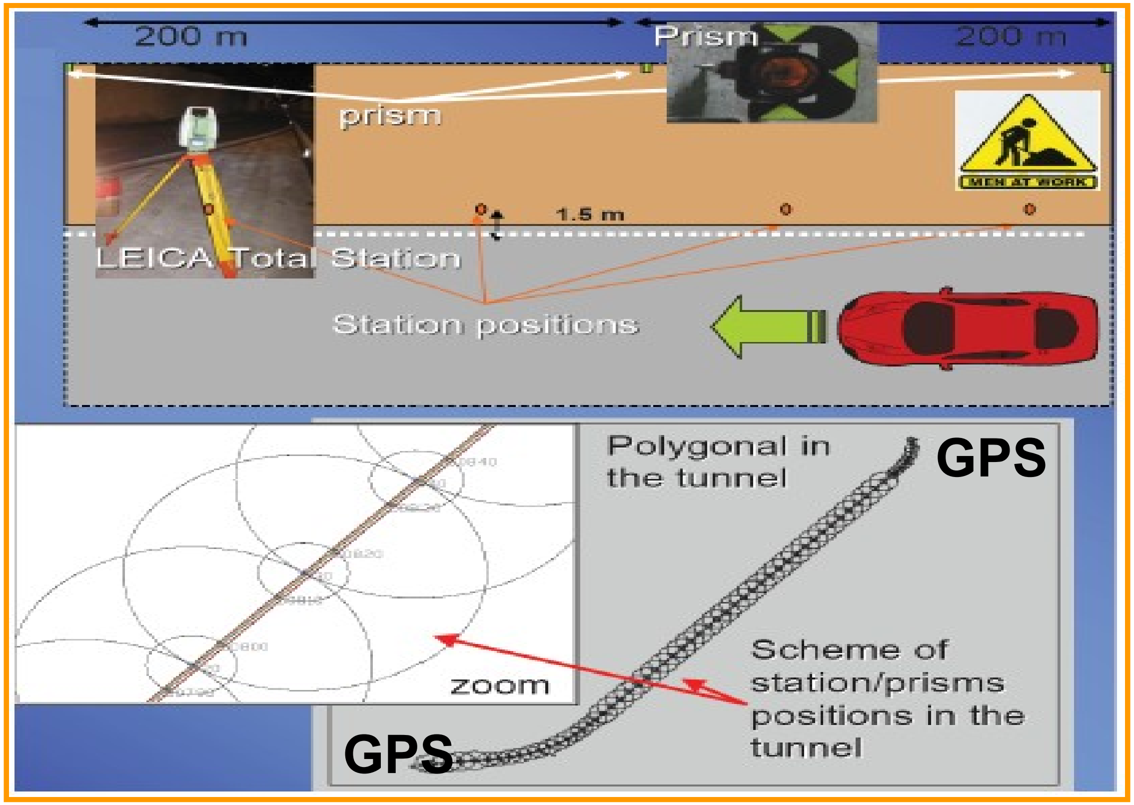
- Acqiris DP110 1GS/s waveform digitizer (WFD)
- WFD triggered by a replica of the kicker signal
- Waveforms UTC-stamped and stored in CNGS database for offline analysis

Summary of the principle for the TOF measurement



Measure $\delta t = TOF_c - TOF_\nu$

Geodesy at LNGS and CERN



Dedicated measurements at LNGS (Rome Sapienza Geodesy group)

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

GPS measurements ported underground to OPERA

CERN –LNGS measurements (different Periods) combined in the ETRF2000 European Global system, accounting for earth dynamics.

Cross-check: simultaneous CERN-LNGS measurement of GPS benchmarks (2011)

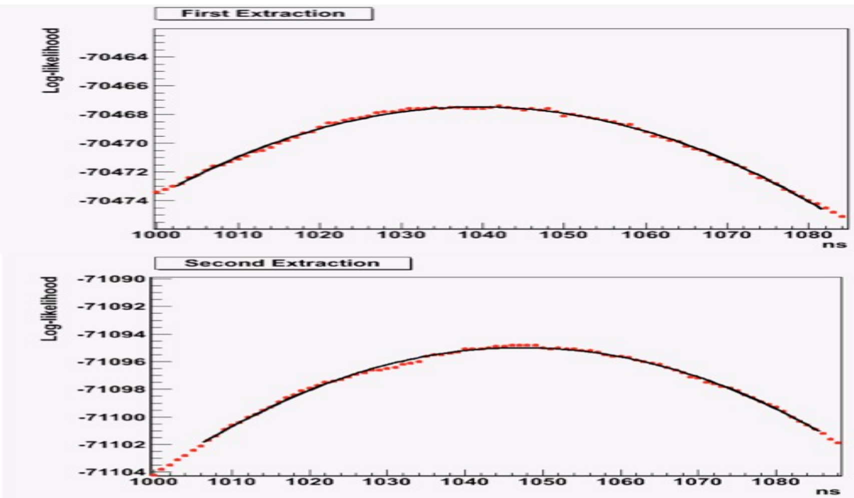
Resulting distance (BCT – OPERA reference frame)

(731278.0 ± 0.2) m

Analysis method

For each neutrino event in OPERA → proton extraction waveform

Sum up and normalise: → PDF w(t) → separate likelihood for each extraction



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

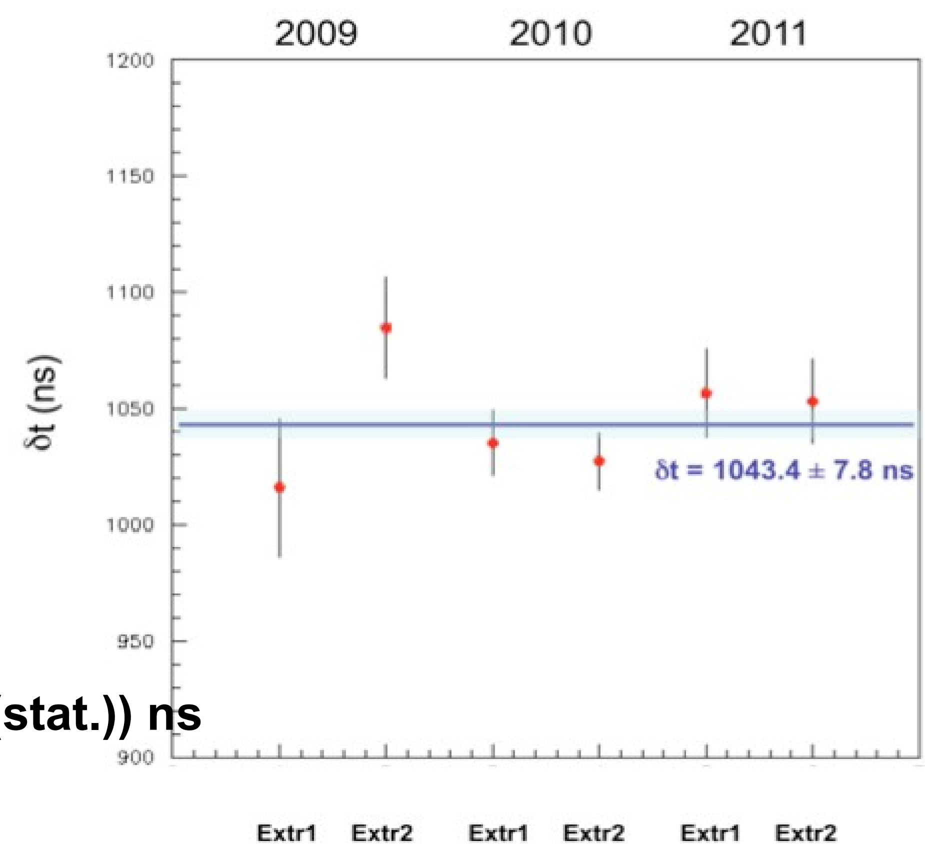
Maximised versus δt:

1) Coherence among CNGS runs/extractions

2) No hint for *e.g.* day-night or seasonal effects:

|d-n|: (16.4 ± 15.8) ns

|(spring+fall) – summer|: (15.6 ± 15.0) ns



All events: δt (blind) = $TOF_c - TOF_\nu$ = **(1043.4 ± 7.8 (stat.)) ns**

Internal events only: (1045.1 ± 11.3 (stat.)) ns

Opening the box

timing and baseline corrections

	Blind 2006	Final analysis	Correction (ns)
Baseline (ns)	2440079.6	2439280.9	
Earth rotation (ns)		2.2	
Correction baseline			-796.5
CNGS DELAYS :			
UTC calibration (ns)	10092.2	10085	
Correction UTC			-7.2
WFD (ns)	0	30	
Correction WFD			30
BCT (ns)	0	-580	
Correction BCT			-580
OPERA DELAYS :			
TT response (ns)	0	59.6	
FPGA (ns)	0	-24.5	
DAQ clock (ns)	-4245.2	-4262.9	
Correction TT+FPGA+DAQ			17.4
GPS syncronization (ns)	-353	0	
Time-link (ns)	0	-2.3	
Correction GPS			350.7
Total			**-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**	

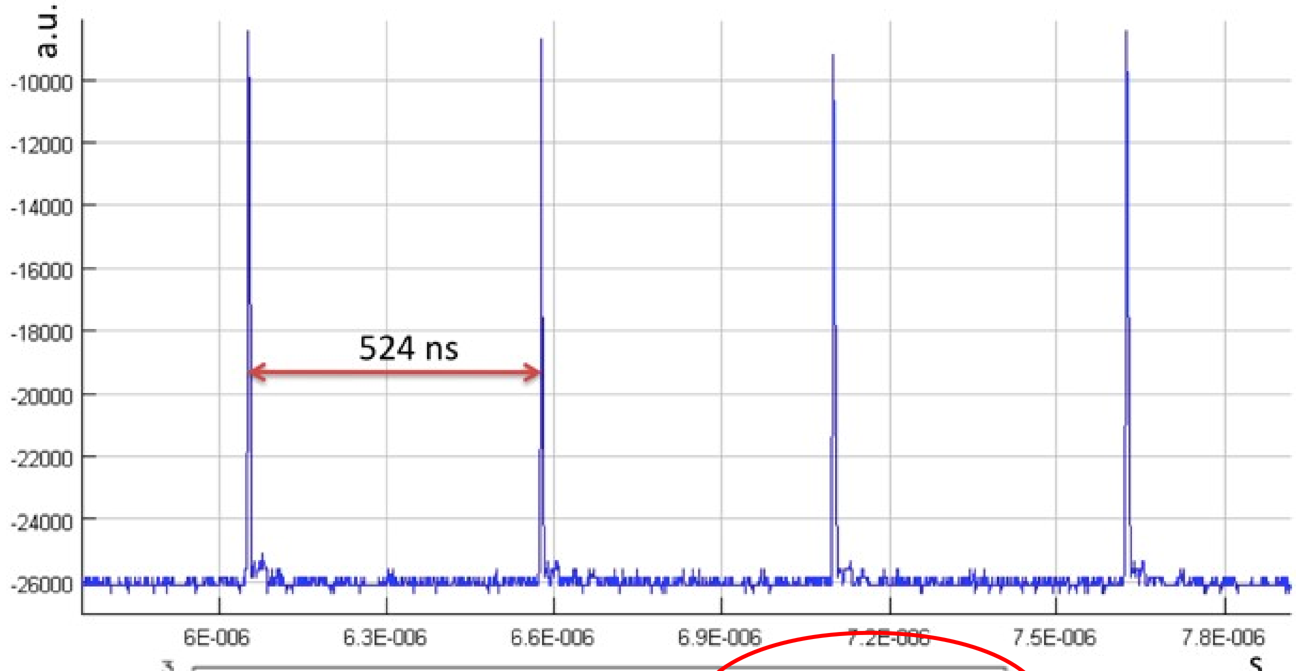
$\delta t = TOF_c - TOF_\nu =$

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

$(v-c)/c = \delta t/(TOF_c - \delta t) = (2.37 \pm 0.32\ (\text{stat.})\ ^{+0.34}_{-0.24}(\text{sys.})) \times 10^{-5}$

(730085 m used as neutrino baseline from parent mesons average decay point)

Short-bunch wide-spacing neutrino beam

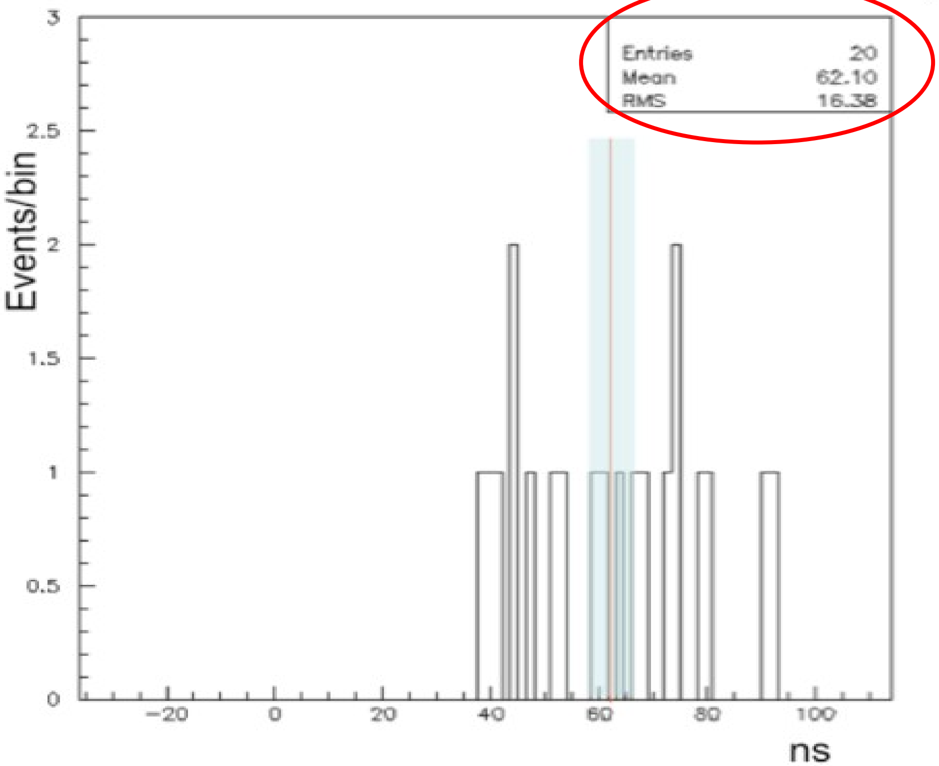


$4x10^{16}$ pot accumulated

Proton bunch-length 3ns

35 beam-related events

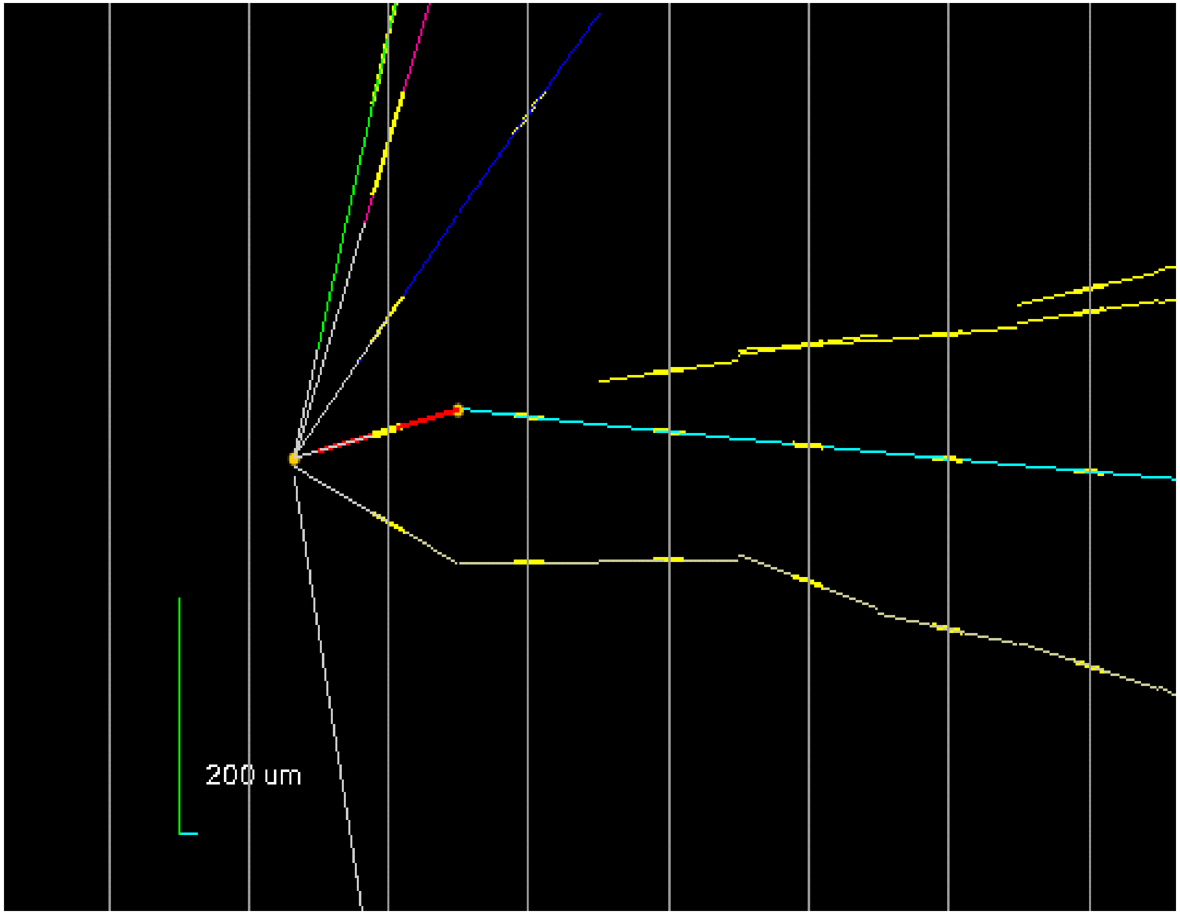
20 events selected



$\delta t = (62.1 \pm 3.7$ (stat.))

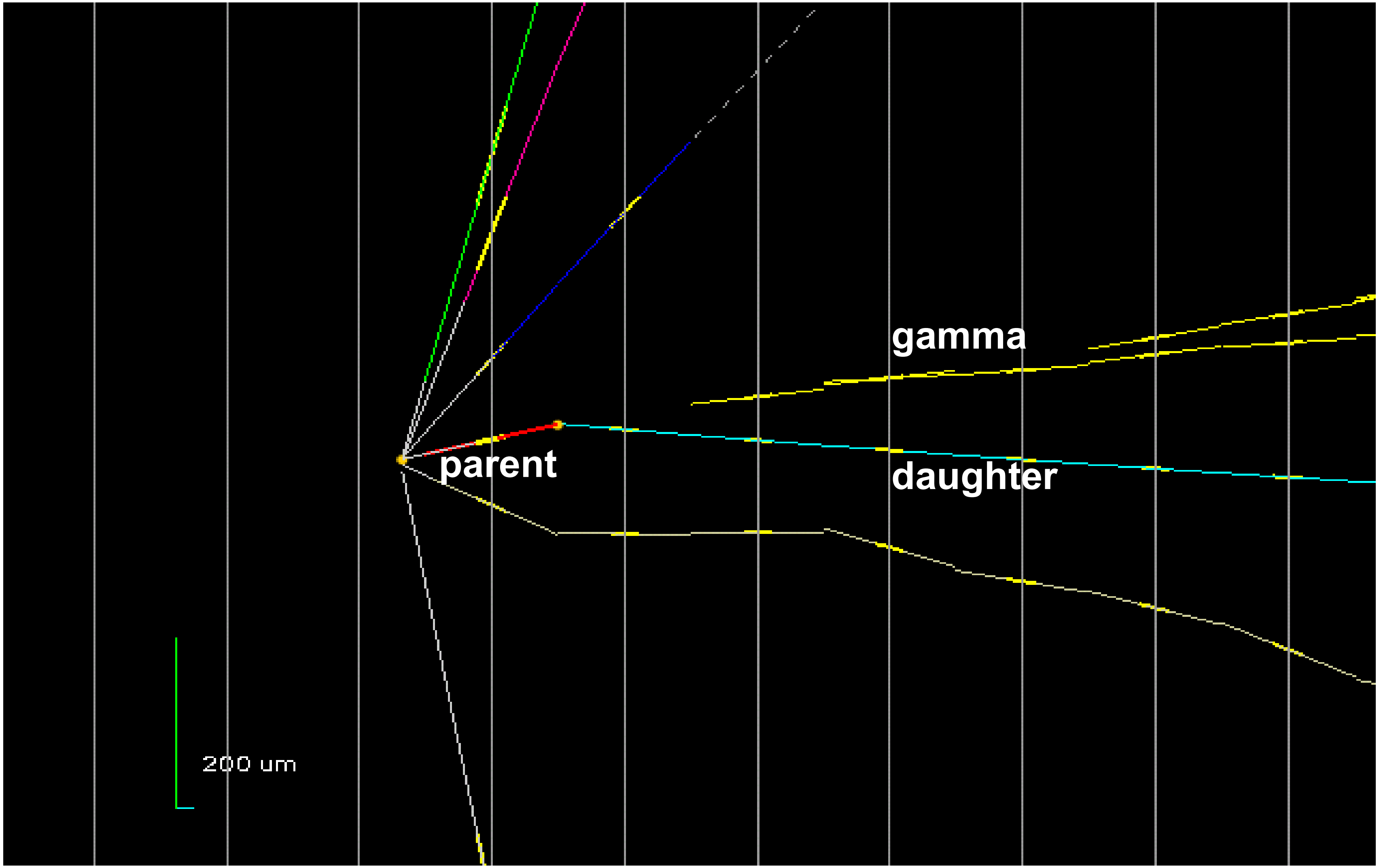
The systematic uncertainties are equal or smaller than those affecting the result with the nominal CNGS beam

These result excludes biases affecting the PDF based analysis

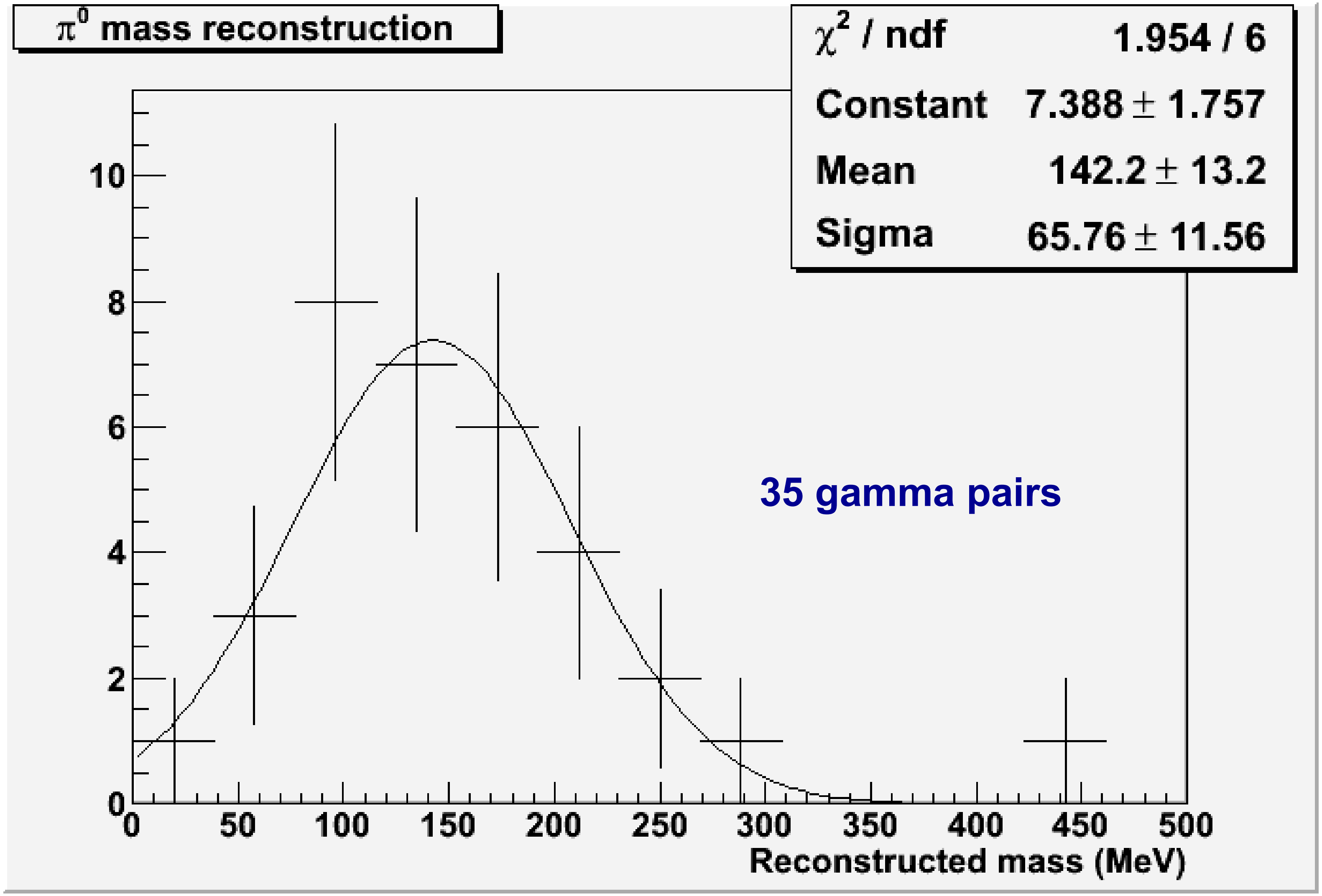


Thank you for your attention!

Event reconstruction (II)

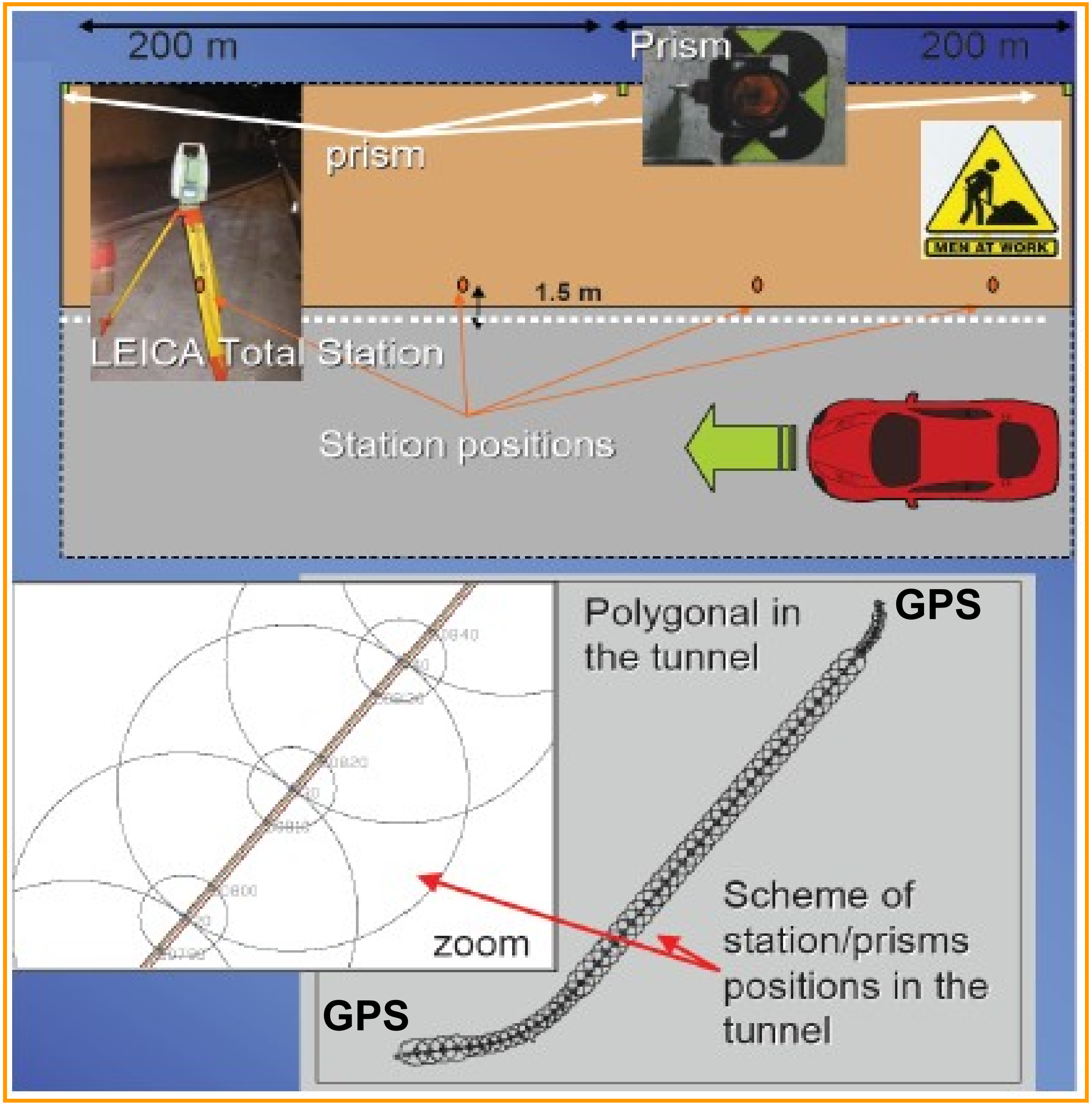


π^0 mass resolution (data)



1 σ mass resolution: ~ 45%

Geodesy at LNGS



Dedicated measurements at LNGS: July-Sept. 2010 (Rome Sapienza Geodesy group)

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

GPS measurements ported underground to OPERA

Combination with CERN geodesy

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

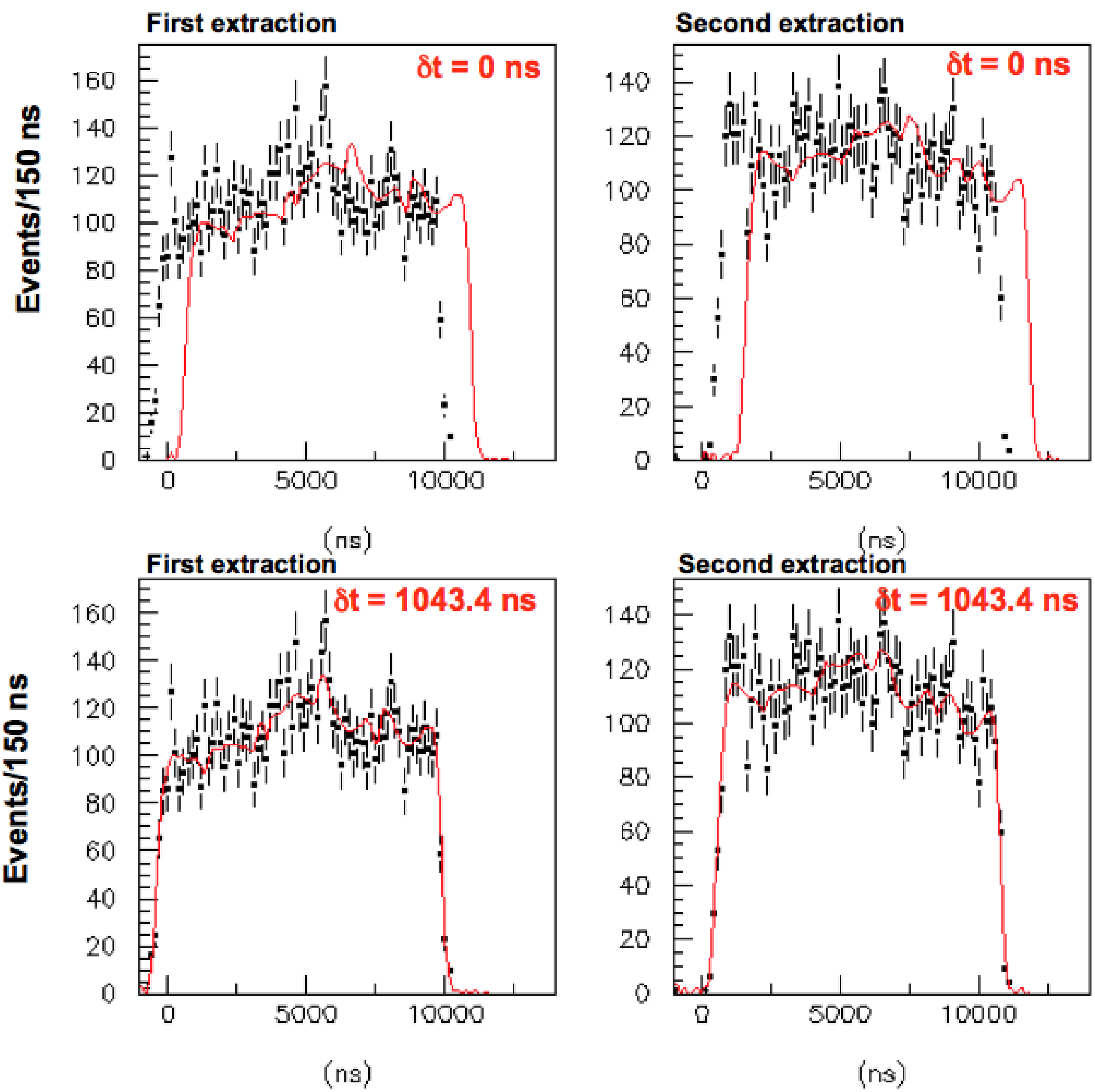
Cross-check: simultaneous CERN-LNGS measurement of GPS benchmarks,

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

Resulting distance (BCT – OPERA reference frame)

(731278.0 ± 0.2) m

Data vs PDF: before and after likelihood result



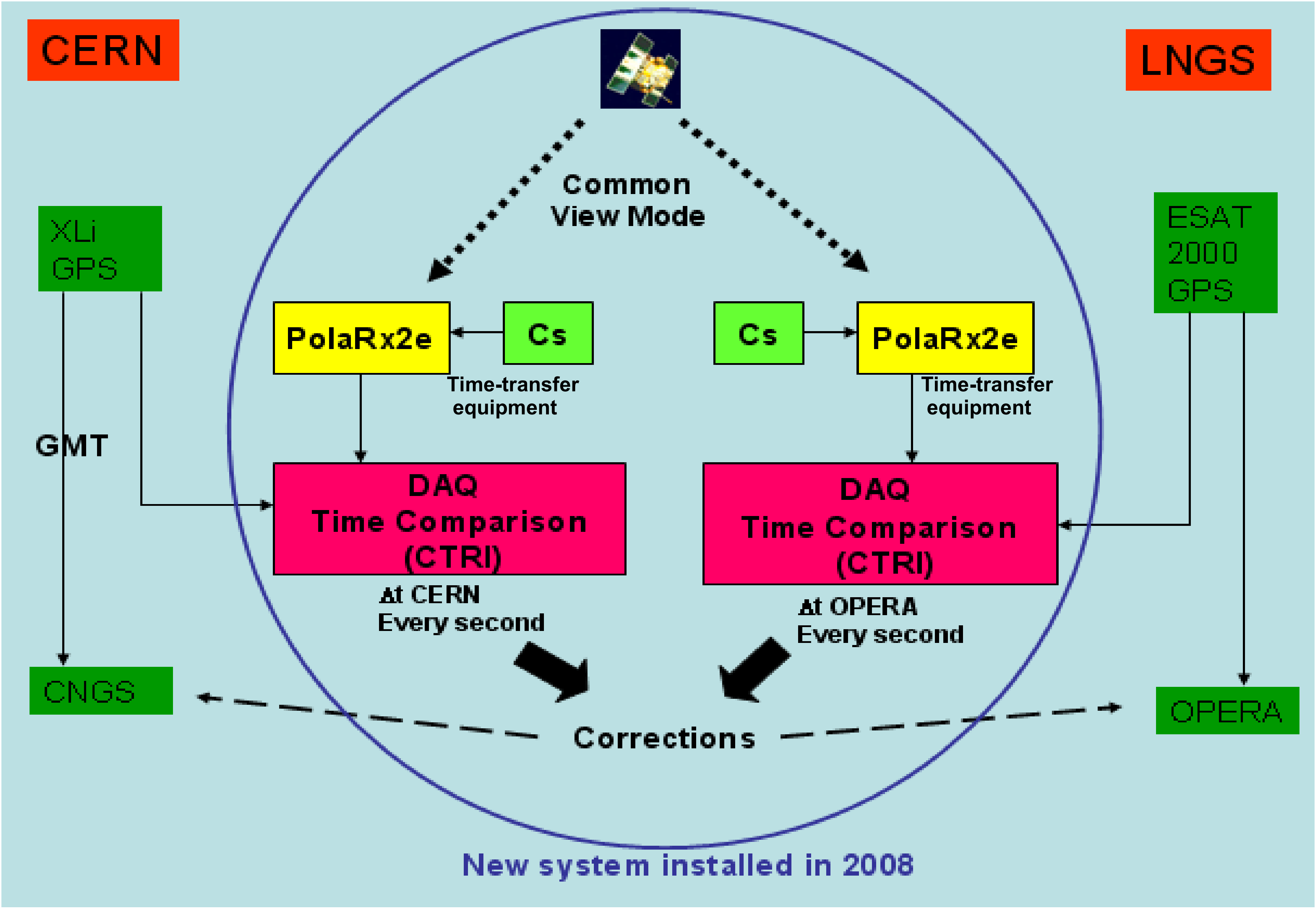
(BLIND) $\delta t = TOF_c - TOF_\nu =$

(1043.4 ± 7.8) ns (stat)

χ^2 / ndof :

first extraction: 1.1
second extraction: 1.0

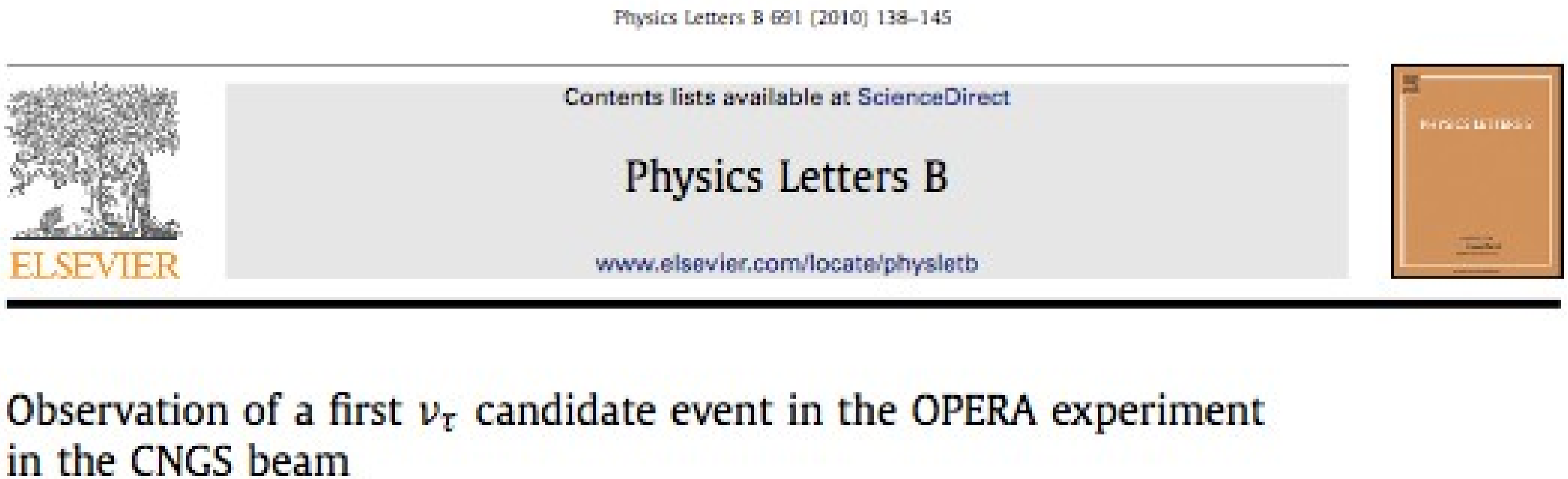
CNGS-OPERA synchronization



Features of event tracks

TRACK NUMBER	PID	Probability	LAB 1			LAB 2		
			tan Θ_X	tan Θ_Y	P (GeV/c)	tan Θ_X	tan Θ_Y	P (GeV/c)
1	HADRON range in Pb/emul=4.1/1.2 cm	Prob(μ)≈10^{-3}	0.177	0.368	0.77 [0.66,0.93]	0.175	0.357	0.80 [0.65,1.05]
2	PROTON	range, scattering and dE/dx	-0.646	-0.001	0.60 [0.55,0.65]	-0.653	0.001	
3	HADRON	interaction seen	0.105	0.113	2.16 [1.80,2.69]	0.110	0.113	1.71 [1.42,2.15]
4 (PARENT)			-0.023	0.026		-0.030	0.018	
5	HADRON: range in Pb/emul=9.5/2.8 cm	Prob(μ)≈10^{-3}	0.165	0.275	1.33 [1.13,1.61]	0.149	0.259	1.23 [0.98,1.64]
6	HADRON: range in Pb/emul=1.6/0.5 cm	Prob(μ)≈10^{-3}				0.334	-0.584	0.36 [0.27,0.54]
7	From a prompt neutral particle		0.430	0.419	0.34 [0.22,0.69]	0.445	0.419	0.58 [0.39,1.16]
8	HADRON	[illegible]		[illegible]				

Event statistics (as reported in Physics Letters B 691 (2010) 138–145 paper)


Physics Letters B 691 (2010) 138–145

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ELSEVIER

Observation of a first ν_τ candidate event in the OPERA experiment in the CNGS beam

Events with search of decay topologies completed: 1088

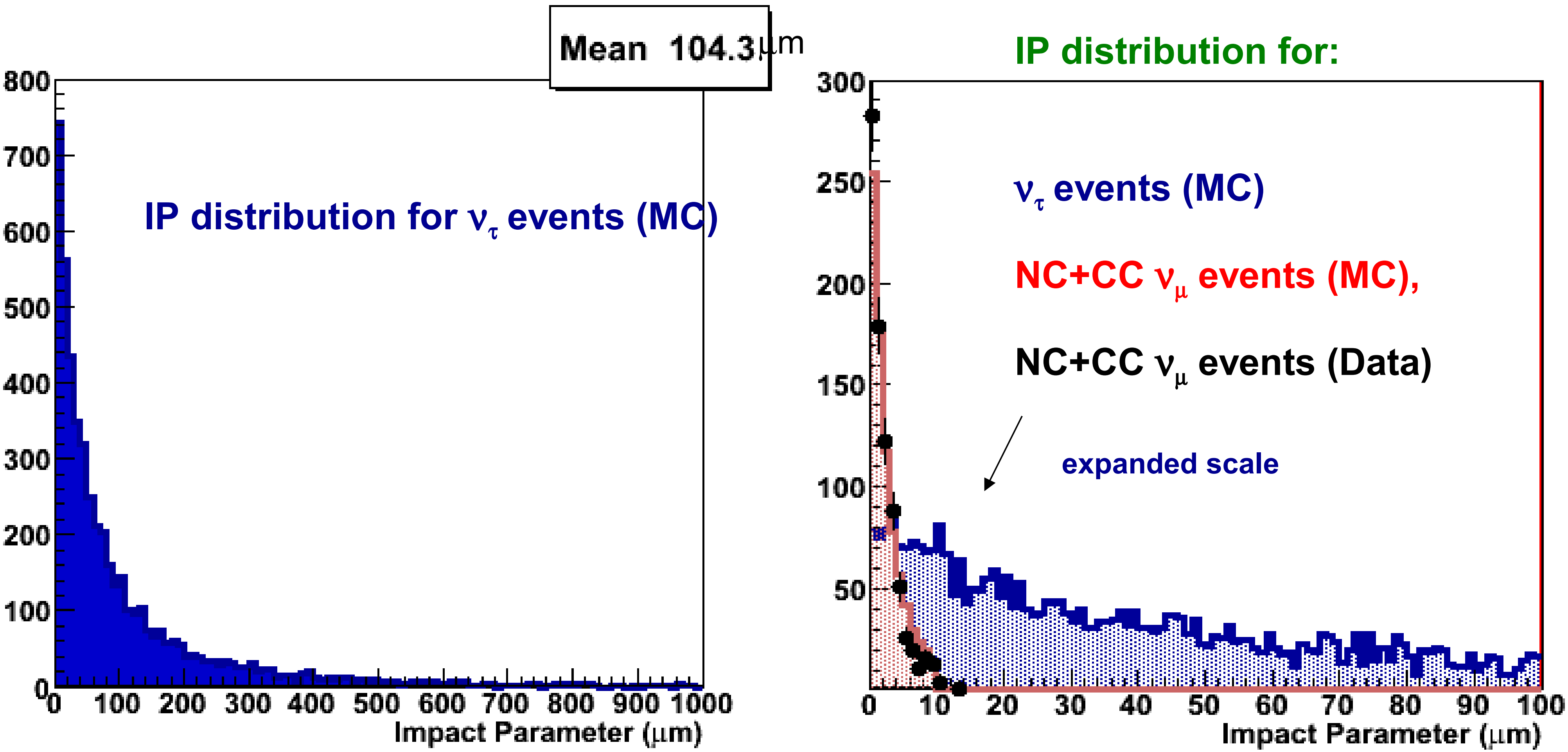
(current number is ≅1700)

This is about 35% of the total 2008-2009 run statistics, corresponding to 1.85×10^{19} pot

With the above statistics, and for $\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV^2 and full mixing,

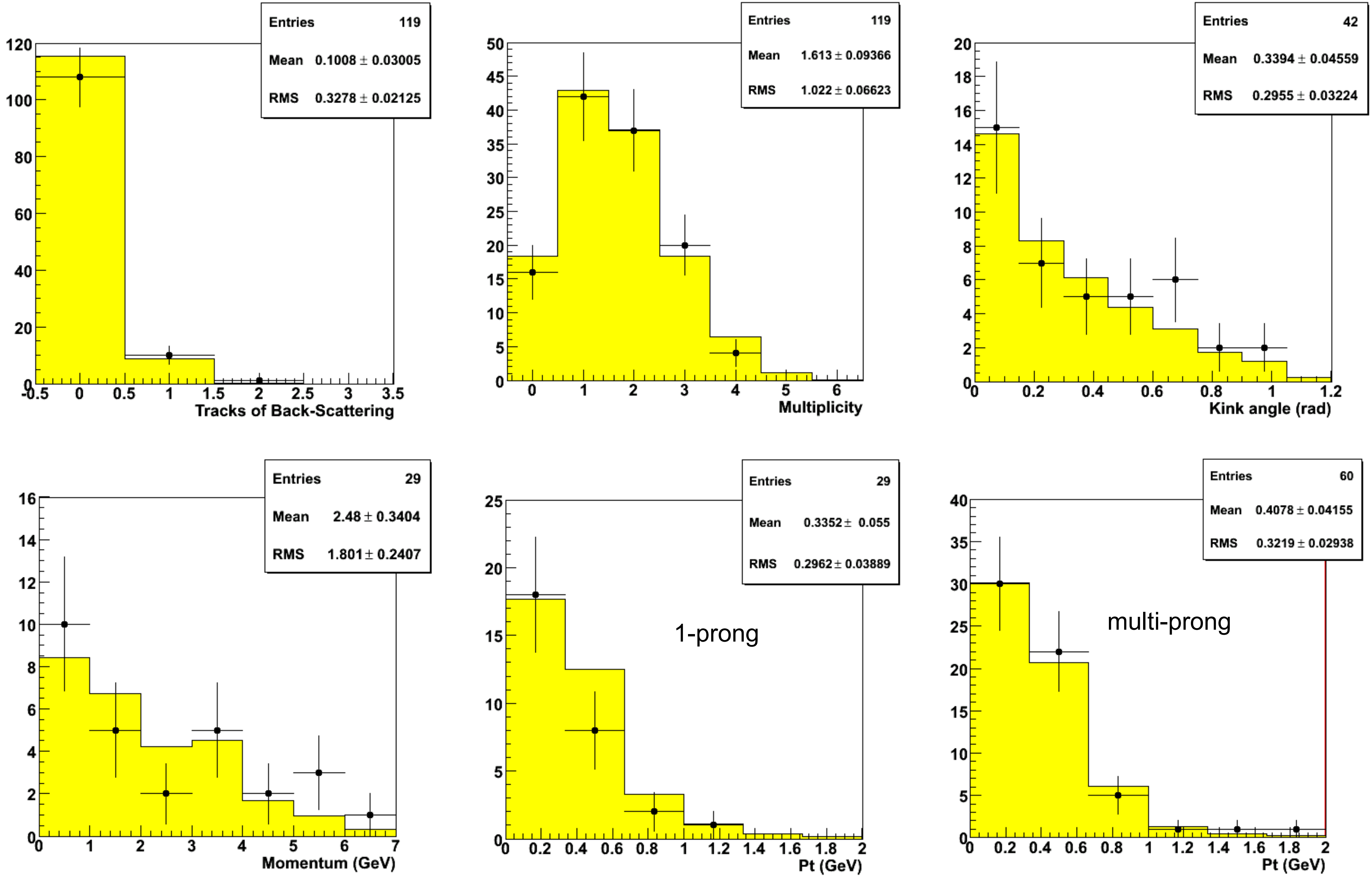
OPERA expects: ~ 0.5 ν_τ events

Impact parameter measurement

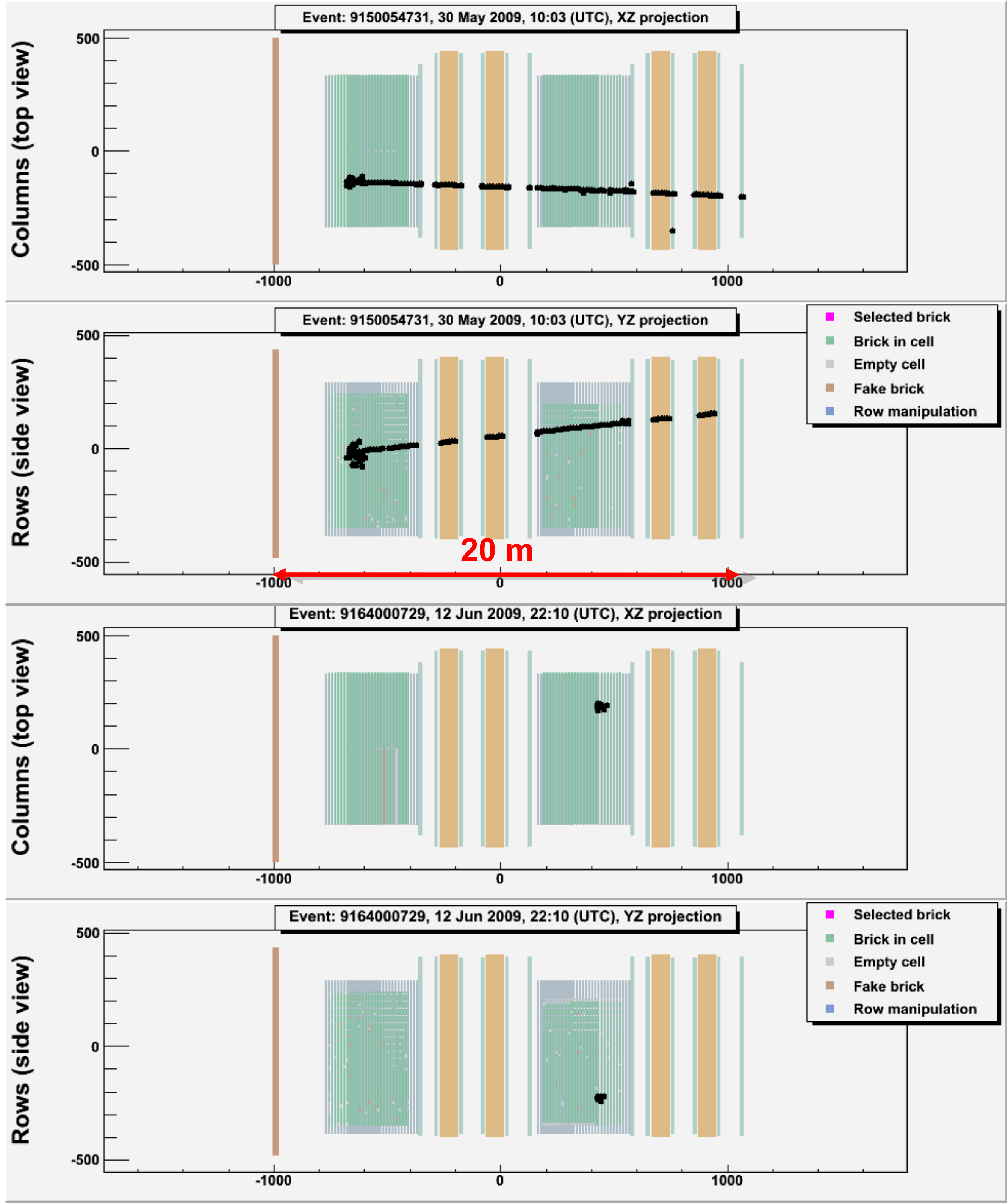


DATA/MC comparison: good agreement in normalization and shape

(pion test-beam exposure)

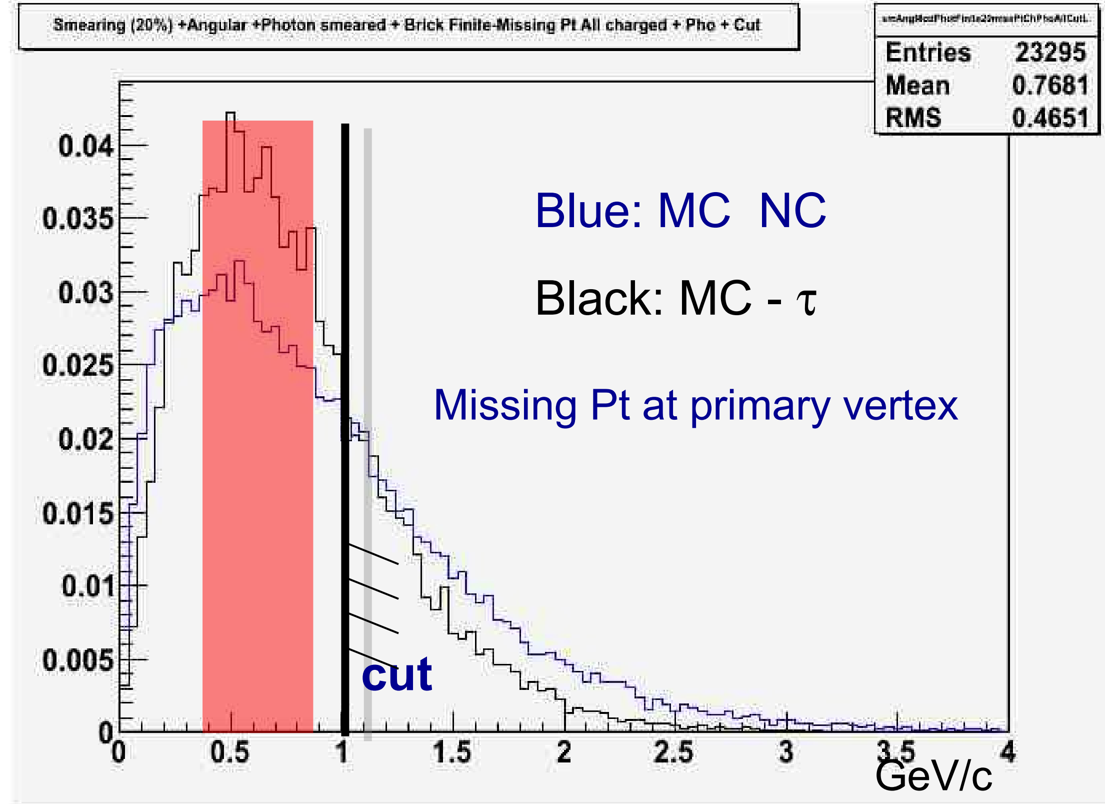


Typical ν_μCC-like and NC-like events

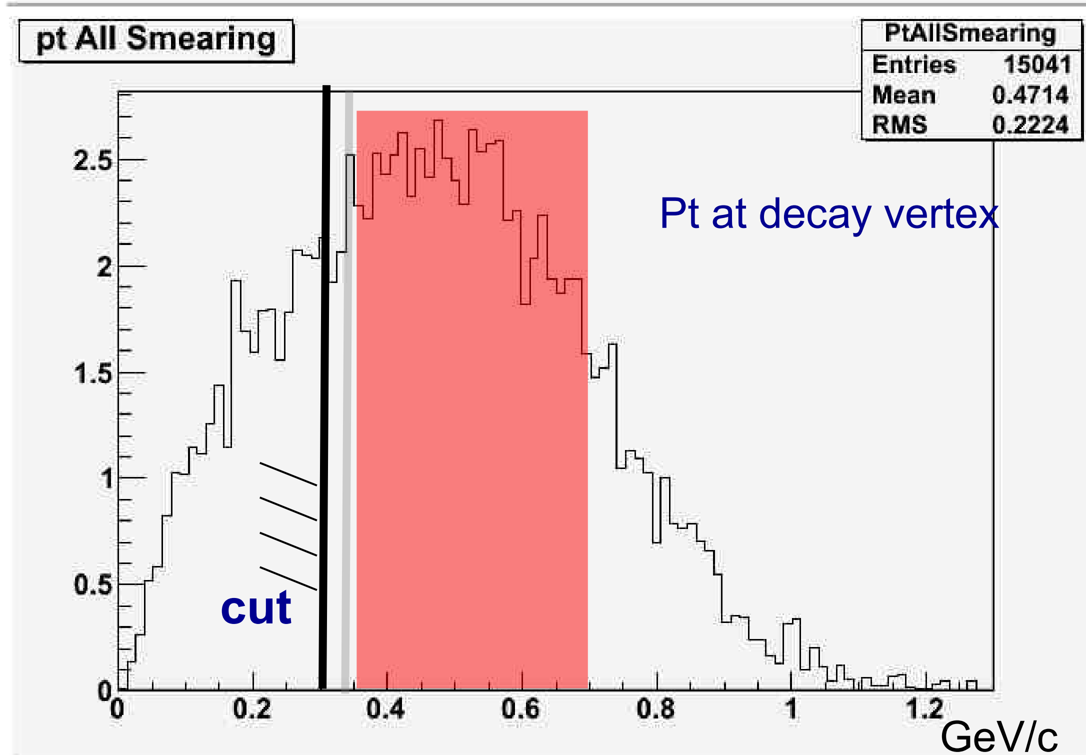


Kinematical cuts to be passed

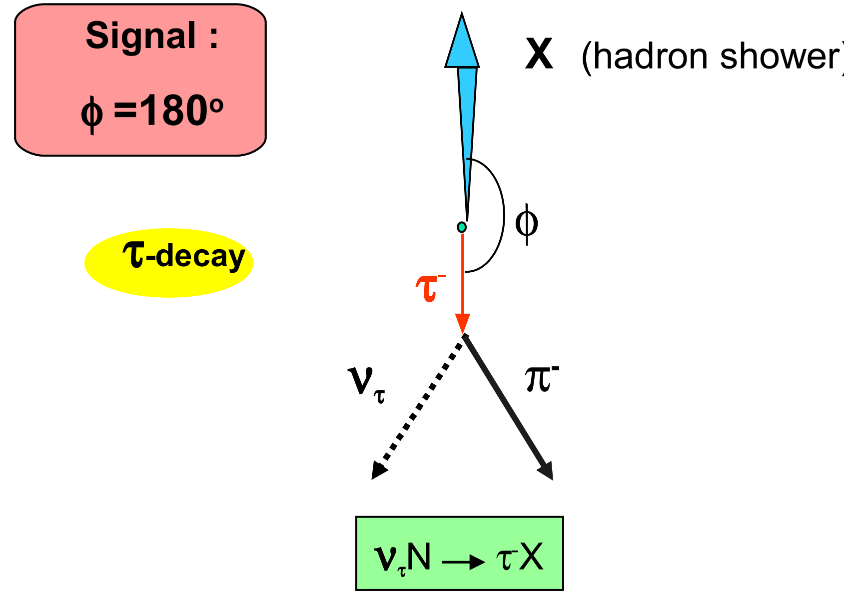
Reject NC events with larger missing Pt (neutrino) →

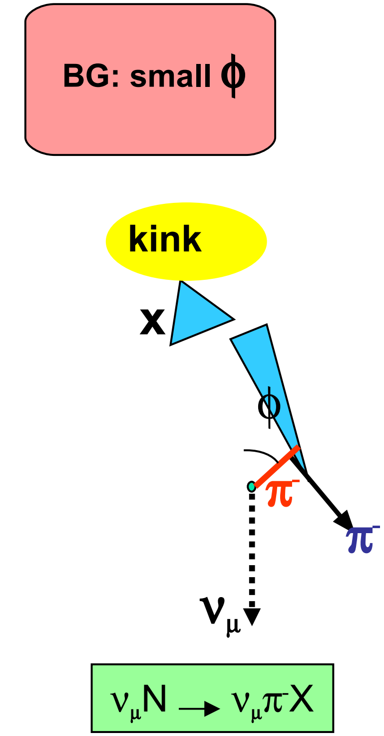


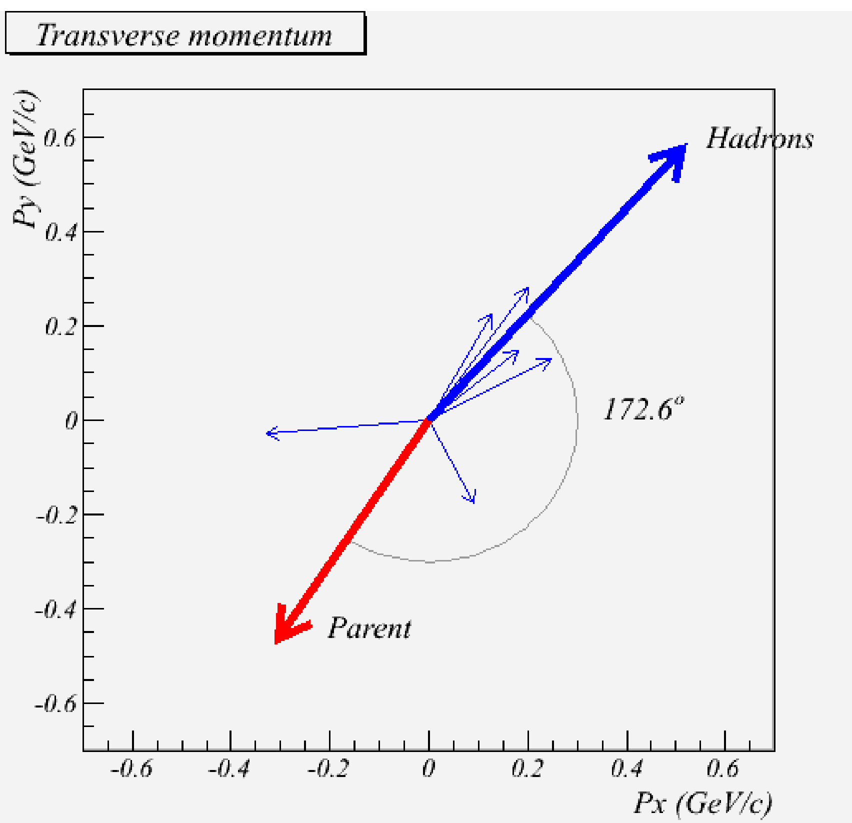
Reject hadron interactions →

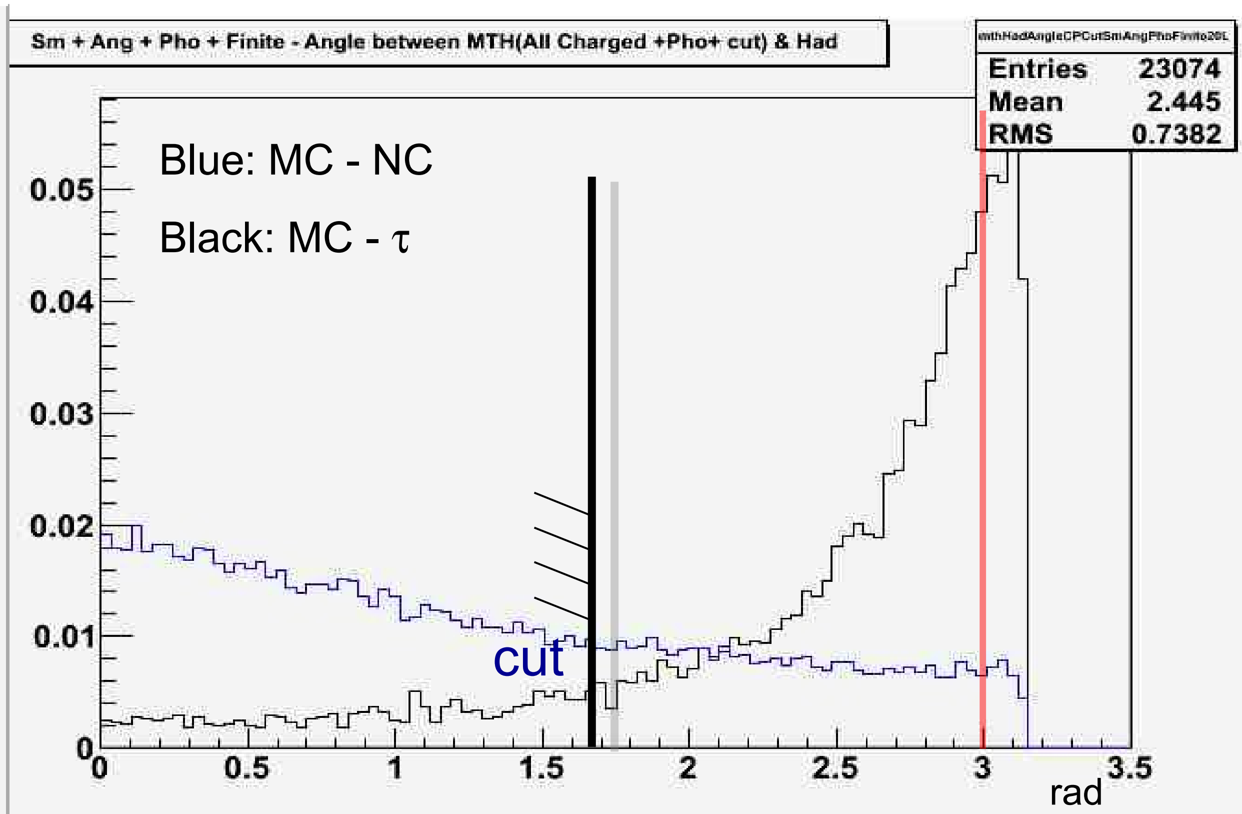


Azimuthal angle between the resulting hadron momentum direction and the parent track direction





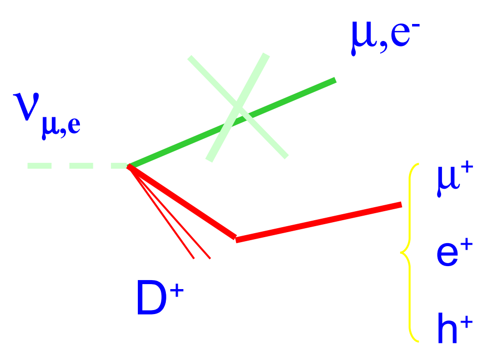




Charm background

Charmed particles have similar

decay topologies to the τ



- charm production in CC events represents a background source to all tau decay channels
- for the 1-prong hadronic channel 0.007±0.004 (syst) background events are expected for the analyzed statistics
- further charm BG reduction is under evaluation by implementing the systematic follow-down of low energy tracks in the bricks and the inspection of their end-range, as done for the "interesting" event. For the latter we have 98-99% muon ID efficiency.
- this background is suppressed by identifying the primary lepton with ~ 95% muon ID

Charm search: 20 candidate events selected by the kinematical cuts,

Expected: (16.0 ± 2.9) + ~2 BG events