March 15, 2011

XIV International Workshop on "Neutrino Telescopes"

OPERA

- The OPERA experiment
  - The physics case
  - Detector description
- Experimental results
  - Oscillation physics
    - → First ν_τ candidate event — **Physics Letters B 691 (2010) 138**
    - → $\nu_\mu \leftrightarrow \nu_e$??
  - Non-Oscillation physics
    - → Atmospheric muon charge ratio — **EPJC 67 (2010) 25**
    - → Atmospheric neutrinos??

Summary & Outlook

L Patrizii on behalf of the OPERA Collaboration

INFN - Bologna

The OPERA Collaboration

180 physicists, 33 institutions in 12 countries

Belgium
IIHE Brussels

Croatia
IRB Zagreb

France
LAPP Annecy, IPNL Lyon, IRES Strasbourg

Germany
Hamburg, Münster, Rostock

Israel
Technion Haifa

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

Japan
Aichi, Kobe, Nagoya, Toho, Utsunomiya

Korea
Jinju

Russia
INR Moscow, NPI Moscow, ITEP Moscow, SINP MSU Moscow, JINR Dubna

Switzerland
Bern, Zurich

Tunisia
CNSTN Tunis

Turkey
METU Ankara

http://operaweb.lngs.infn.it

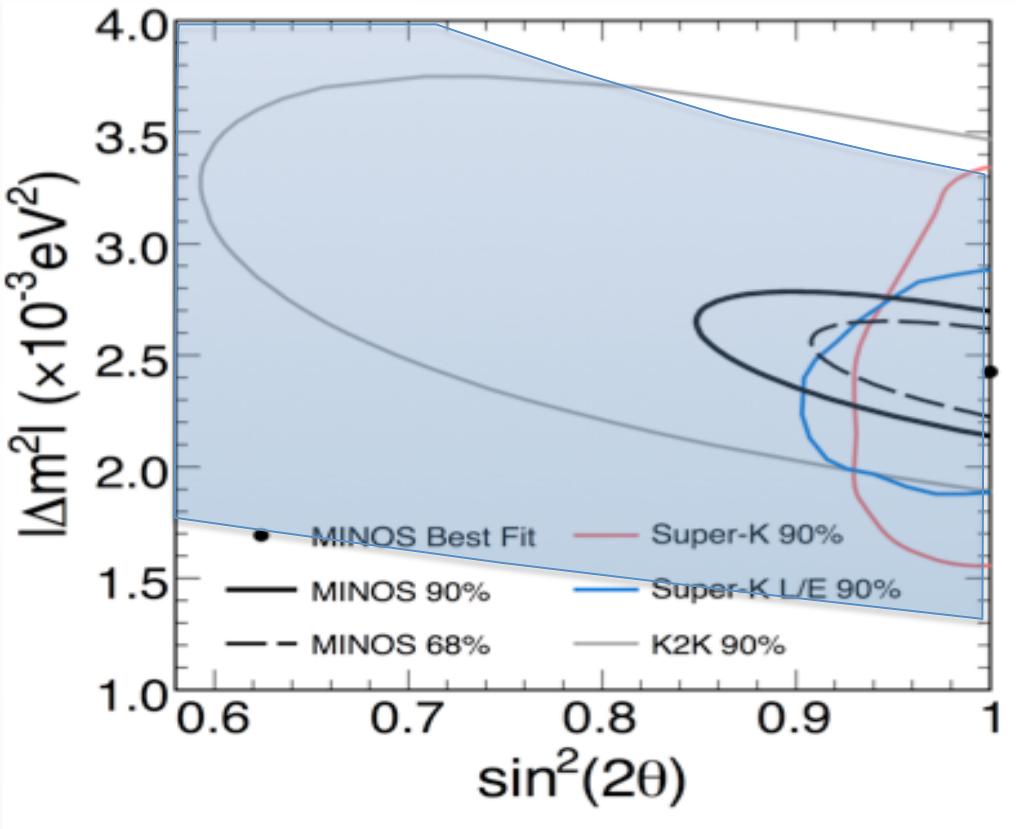
OPERA GOAL

Provide significant evidence for $\nu_\mu \rightarrow \nu_\tau$ oscillation in the region of atmospheric neutrinos by detecting ν_τ appearance in the CNGS ν_μ beam

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2(1.27\Delta m^2_{23} L / E)$$

$$P(\nu_\mu \rightarrow \nu_\tau) = \cos^4 \theta_{13} \sin^2 2\theta_{23} \sin^2(1.27\Delta m^2_{23} L / E)$$

dominant channel



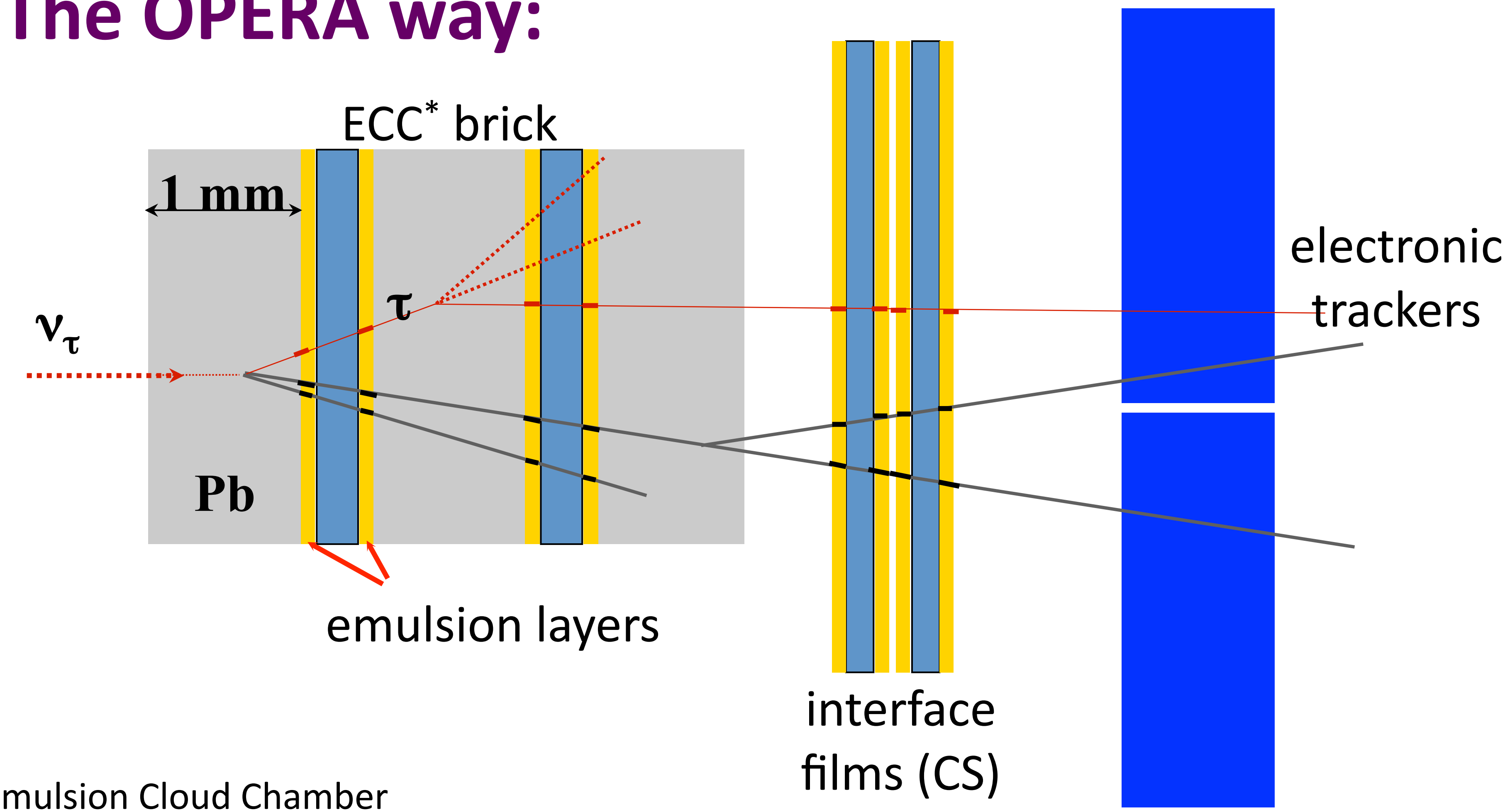
Full mixing and $\Delta m^2_{23} \sim 2.4 \times 10^{-3}$ eV^2

The band indicates the OPERA sensitivity region (90% CL) for the above parameter values for 22.5 x 10^{19} pot

Two conflicting requirements:

- $N_\tau = N_A M_D \int \phi_{\nu_\mu}(E) P_{\nu_\mu \to \nu_\tau}(E, \Delta m^2) \sigma_{\nu_\tau}^{CC}(E) \varepsilon(E) dE$ Large mass ~ *O*(kton)
- signal selection background rejection High granularity ~ 1μm resolution_

The OPERA way:



*Emulsion Cloud Chamber

CNGS neutrino beam

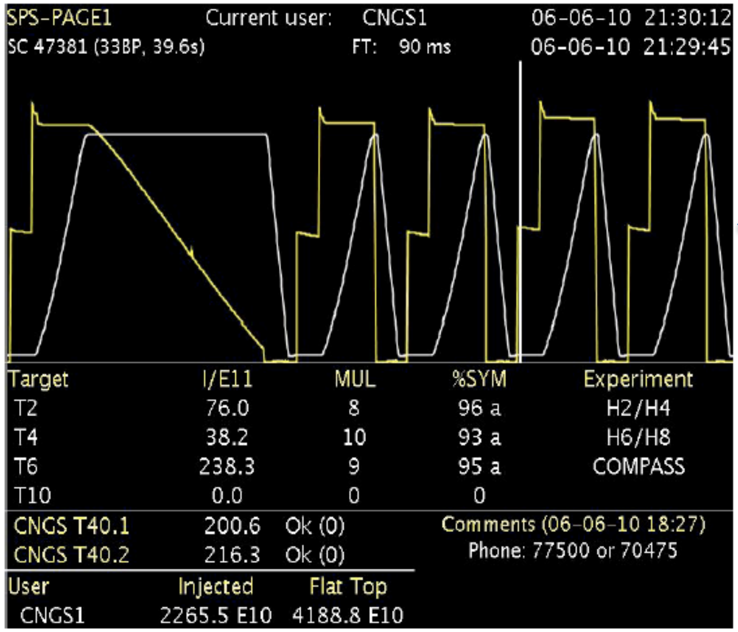
$< E_{\nu_\mu} >$	17.7 GeV
L	730 km
$(\nu_e + \bar{\nu}_e) / \nu_\mu$	0.87 % *
$\nu_\mu / \bar{\nu}_\mu$	2.1 % *
ν_τ prompt	Negligible *

* Interaction rate at LNGS

March 18th: start of 2011 Physics run (dedicated mode)

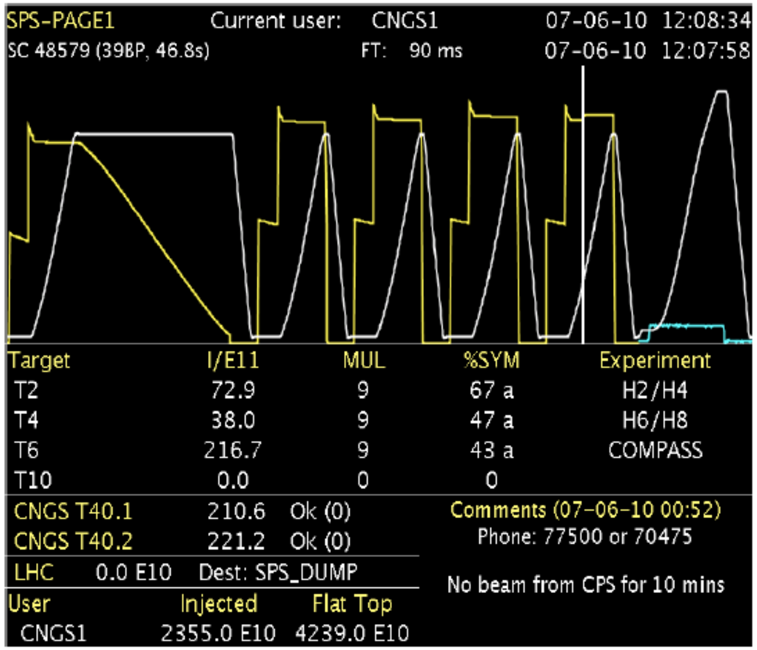
beam commissioning already ongoing

SPS Cycles in 2010

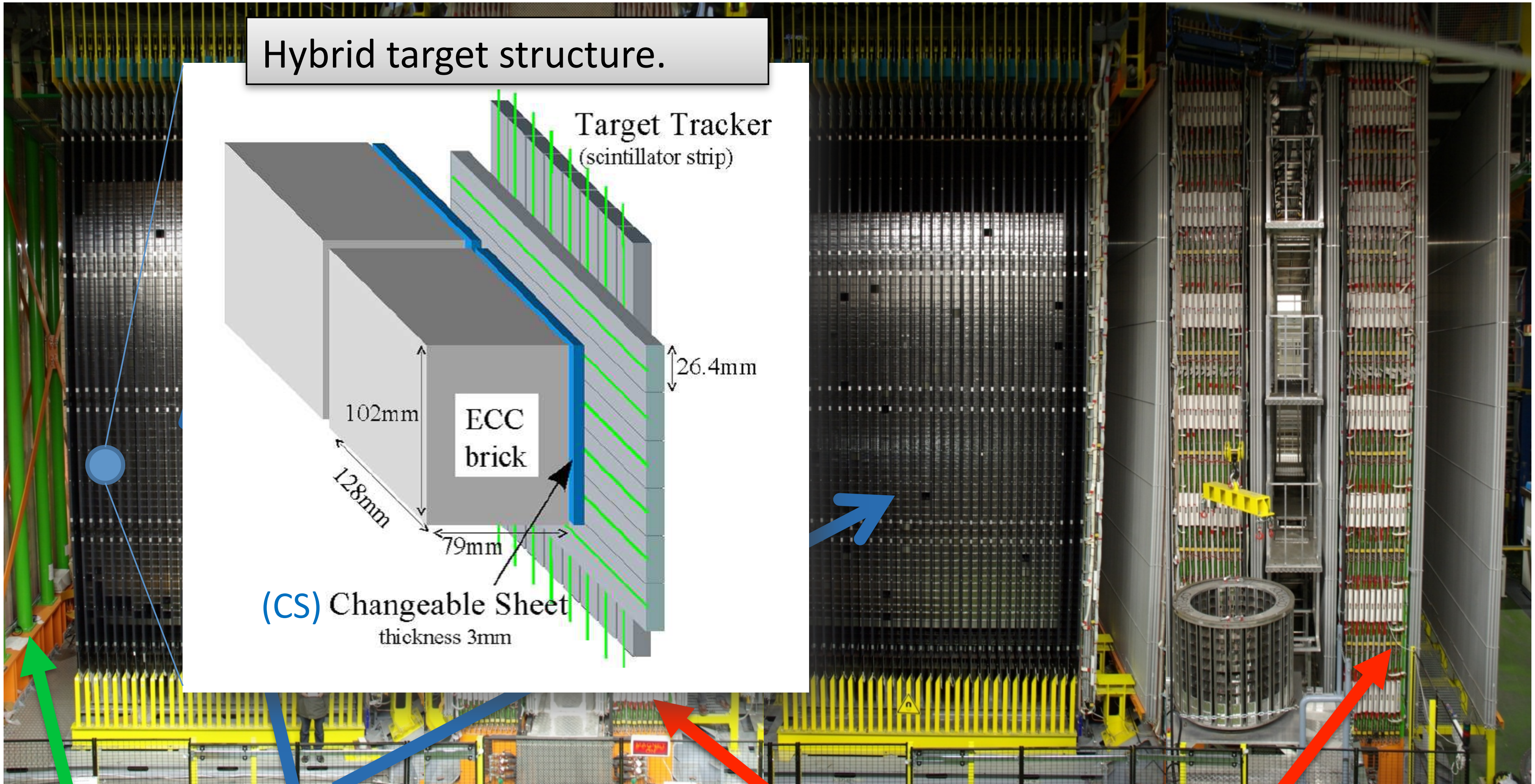


39.6 s
4 CNGS + 1 fixed target expts

46.8 s
4 CNGS + 1 LHC +1 fixed target expts



OPERA detector



VETO

Target Region:
- Target Tracker (Scintillators)
- Lead/Emulsion Bricks (75.000 per SM)

Target mass: ~1.25 kton

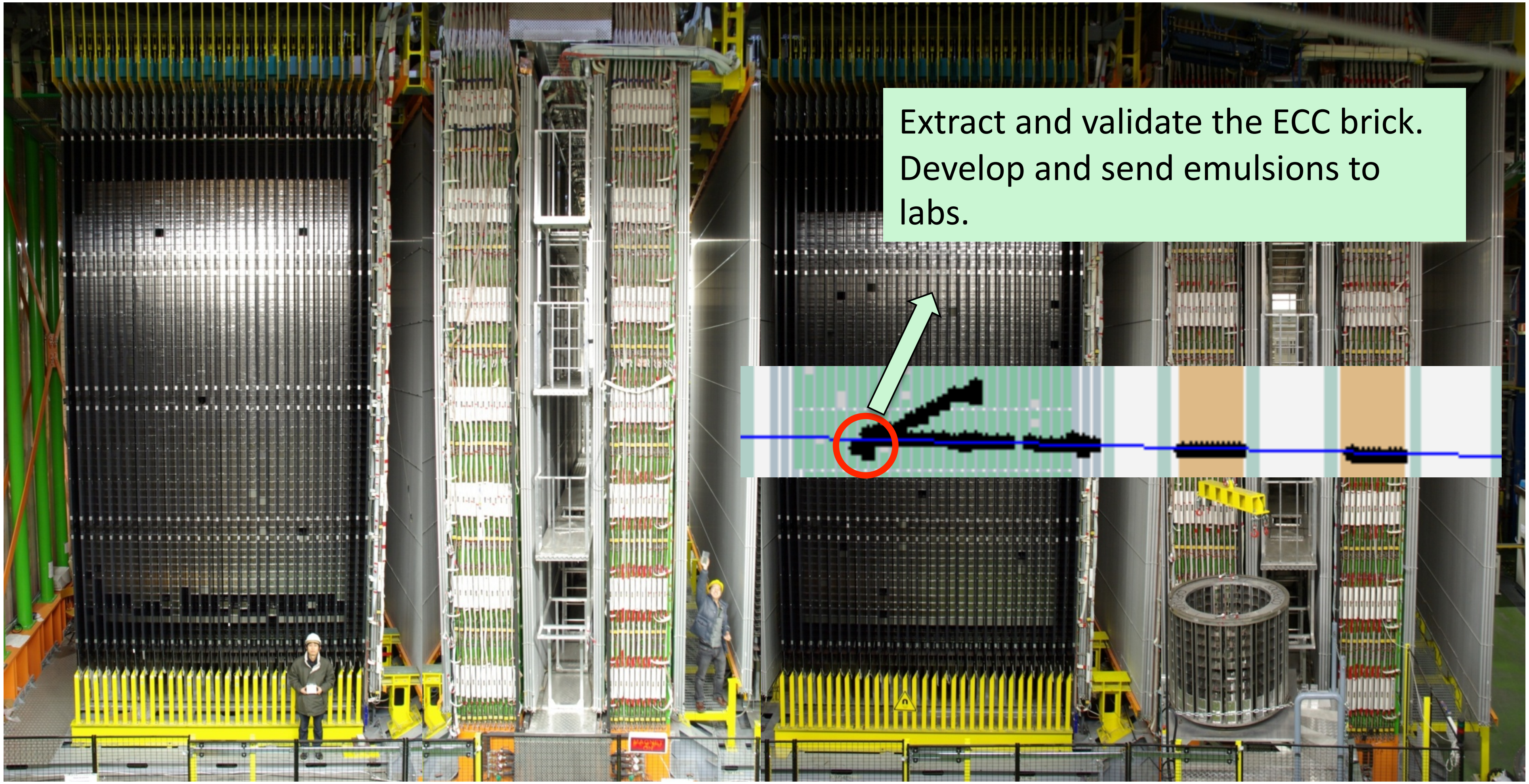
Muon spectrometers

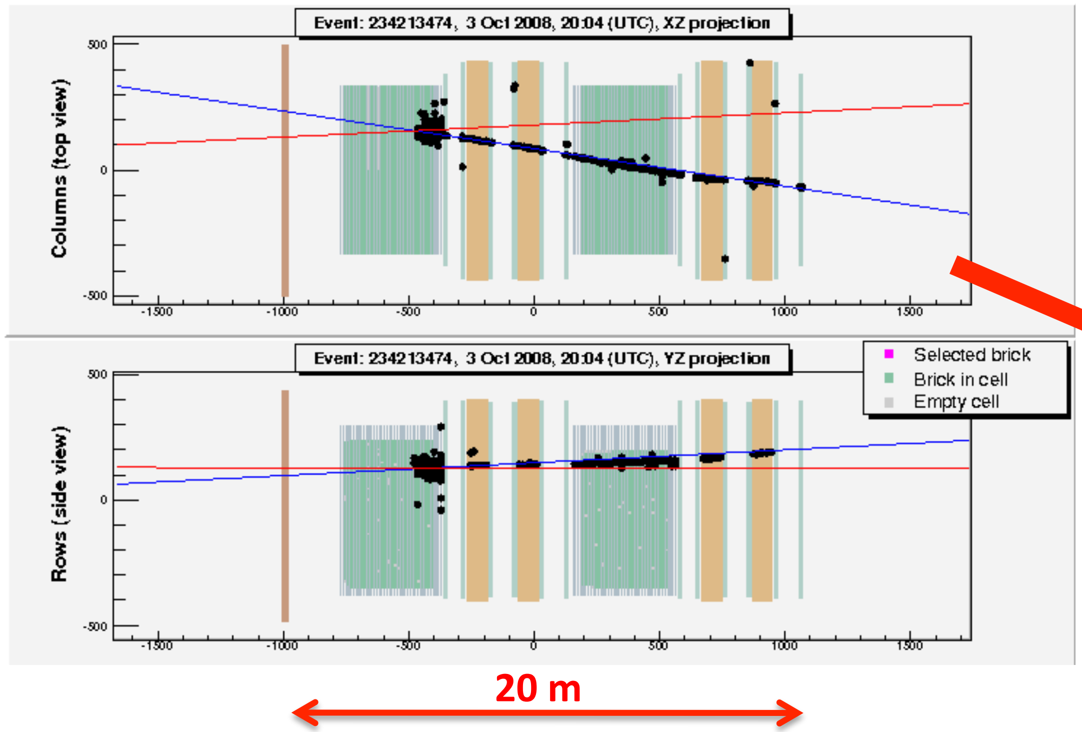
Iron & RPCs

Precision Tracker:

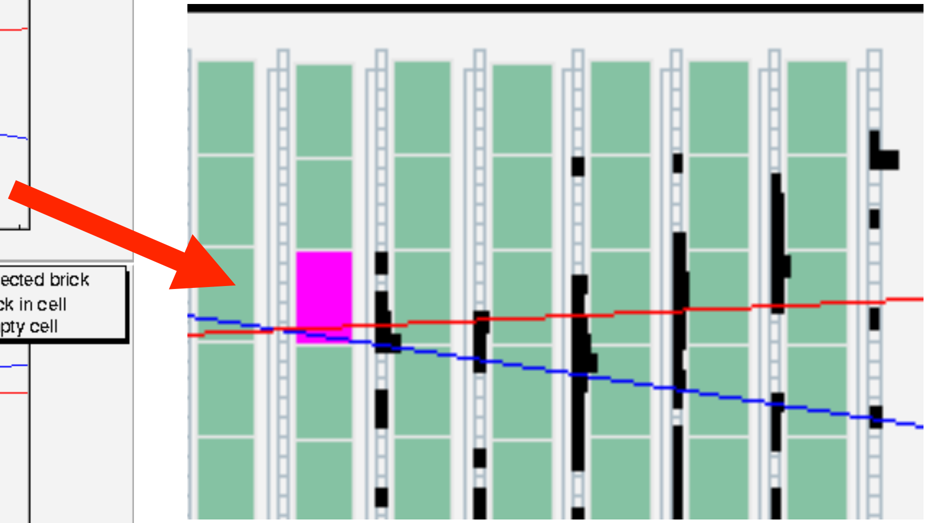
6 planes of drift tubes

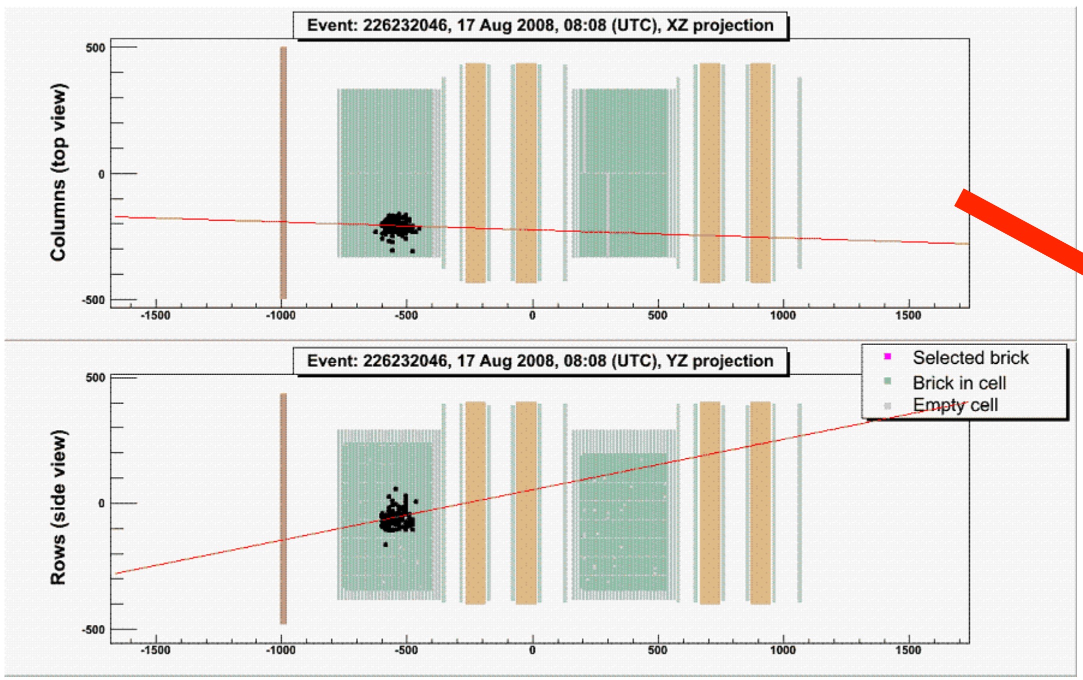
OPERA detector



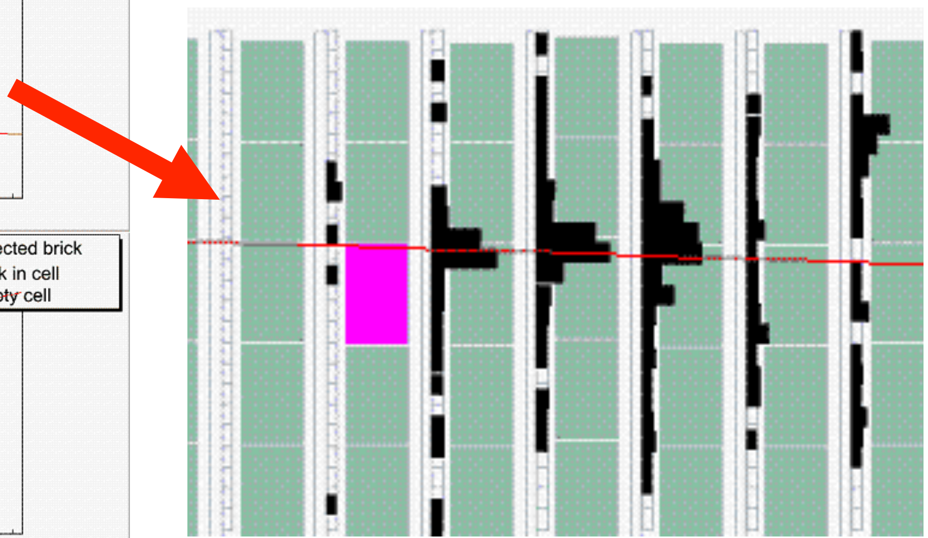


ν_μ CC-like event





ν_μ NC-like event



Expected Performance (Proposal)

Assumptions: Maximal mixing, 22.5×10^{19}p.o.t. (5years @ 4.5×10^{19}p.o.t./year)

τ Decay Channel	B.R. (%)	Signal	Background
$\tau \to \mu$	17.7	2.9	0.17
$\tau \to e$	17.8	3.5	0.17
$\tau \to h$	49.5	3.1	0.24
$\tau \to 3h$	15.0	0.9	0.17
Total		**10.4**	**0.75**

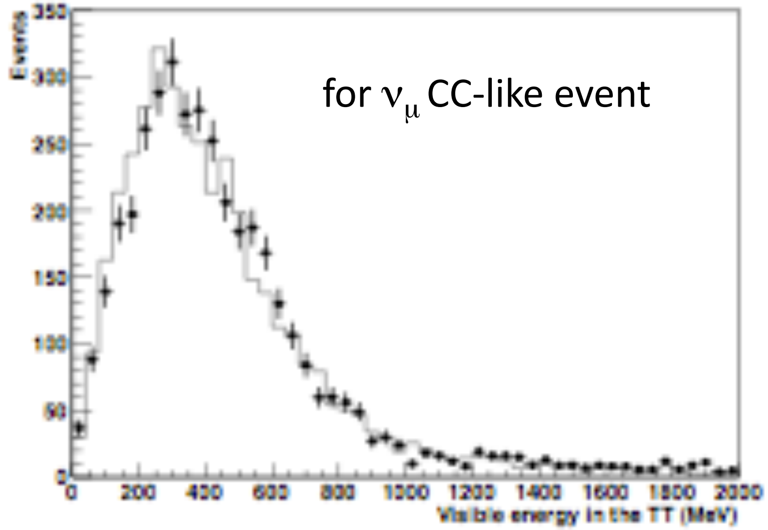
Expected Events:
~ 23600 ν_μ CC+NC interactions
~ 520 $\bar{\nu}_\mu$ interactions
~ 205 $\nu_e + \bar{\nu}_e$ interactions
~ 115 ν_τ CC interactions

For full mixing and $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2 (scales with $(\Delta m^2)^2$).

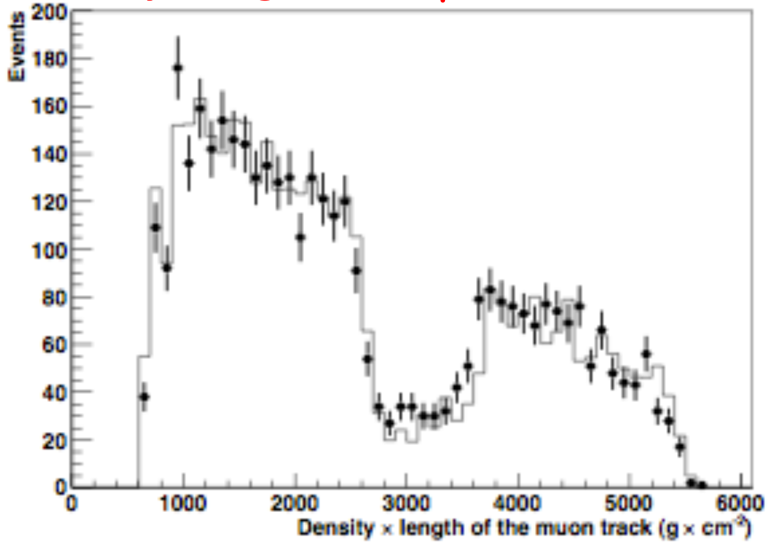
ED performance

arXiv:1102.1882v1 Submitted to NJP

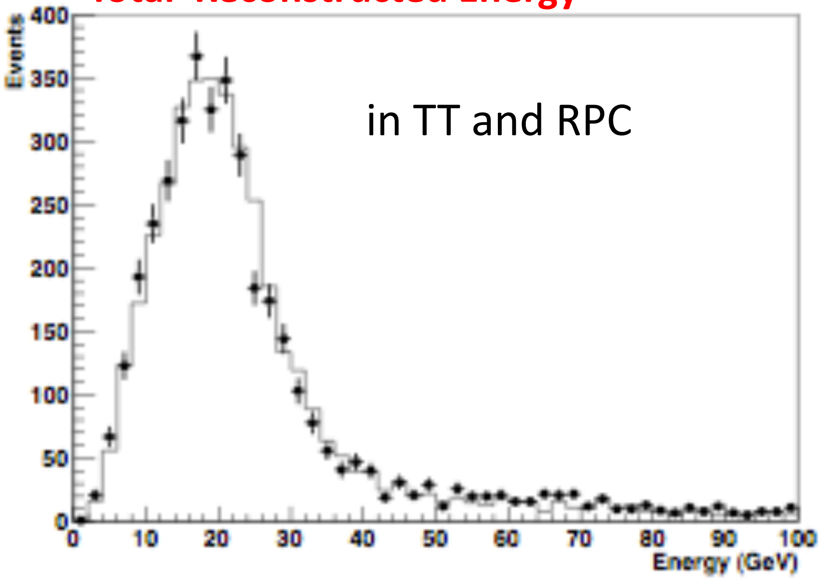
Hadronic energy deposited in TT



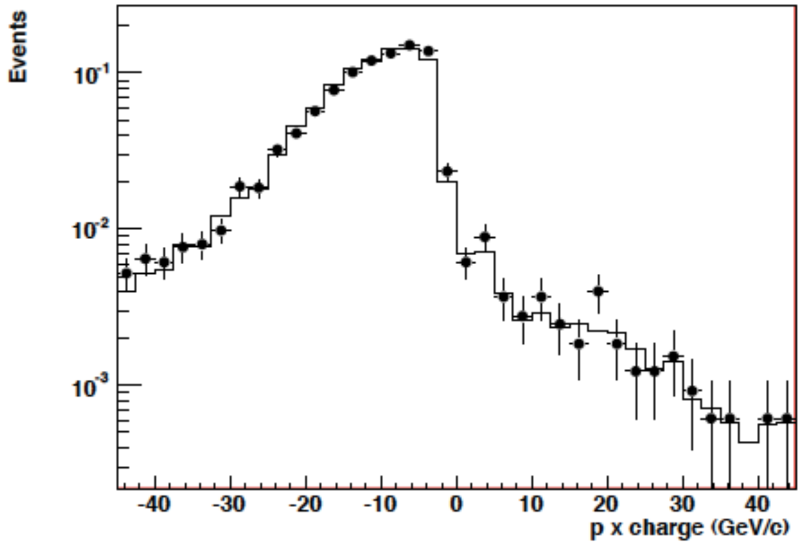
density x length of the μ track



Total Reconstructed Energy

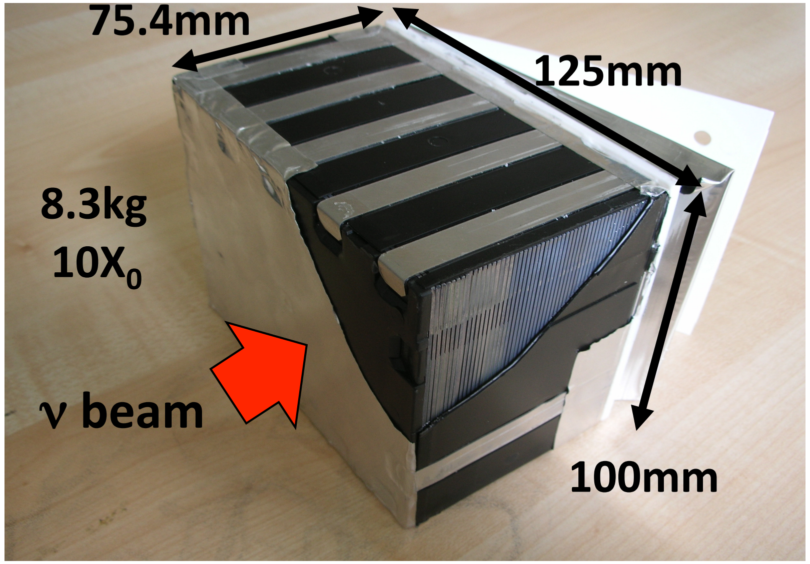


Momentum X charge for muons

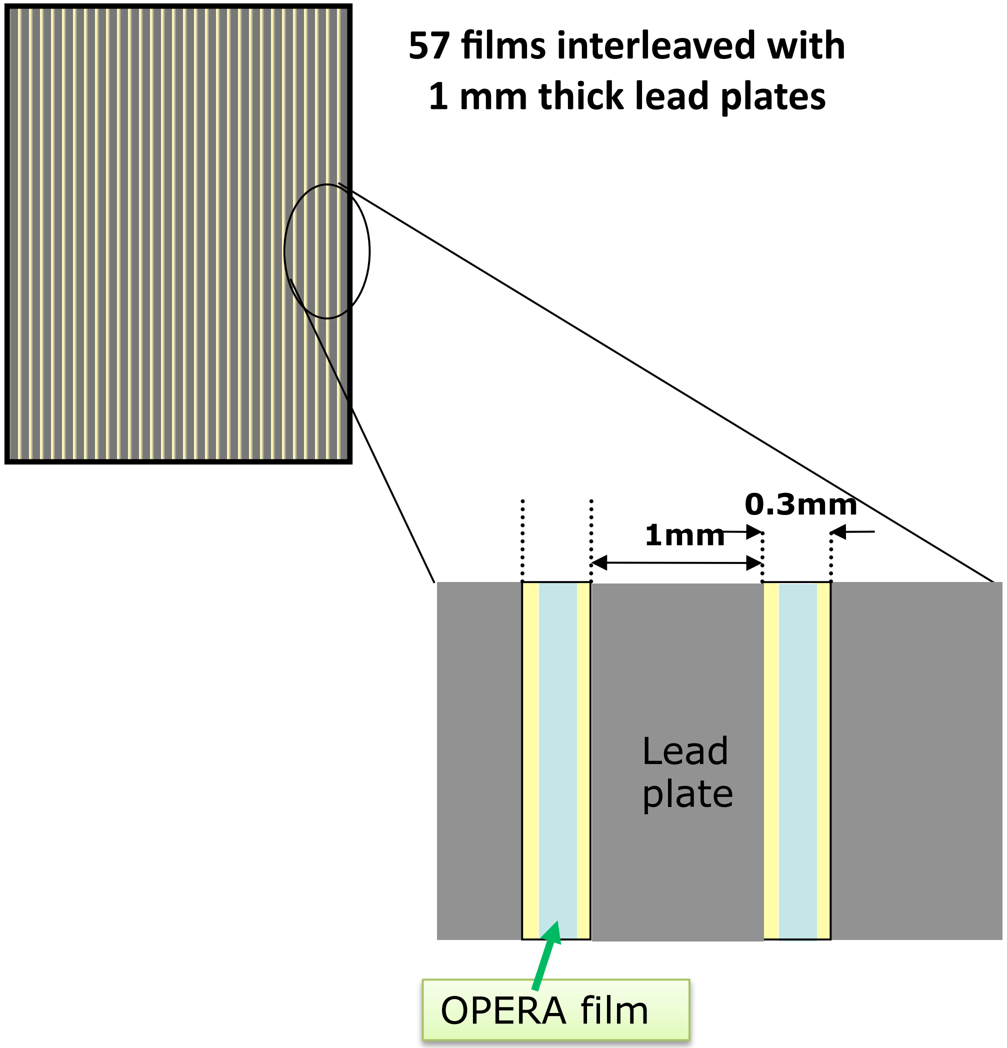


The ECC target brick

The OPERA target consists of about 150,000 bricks.
Total target mass: 1.25 kton



57 films interleaved with 1 mm thick lead plates



2 emulsion layers (44 μm thick) poured on a 205 μm plastic base

Search for $\nu_\mu \rightarrow \nu_\tau$ oscillation: Event selection

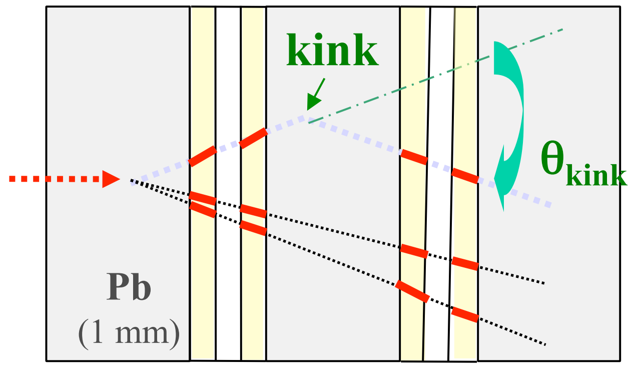
τ selection based on decay topology:

Long decays

$\tau \rightarrow e\nu_\tau\nu_e$

$\tau \rightarrow \mu\nu_\tau\nu_\mu$

$\tau \rightarrow h\nu_\tau$



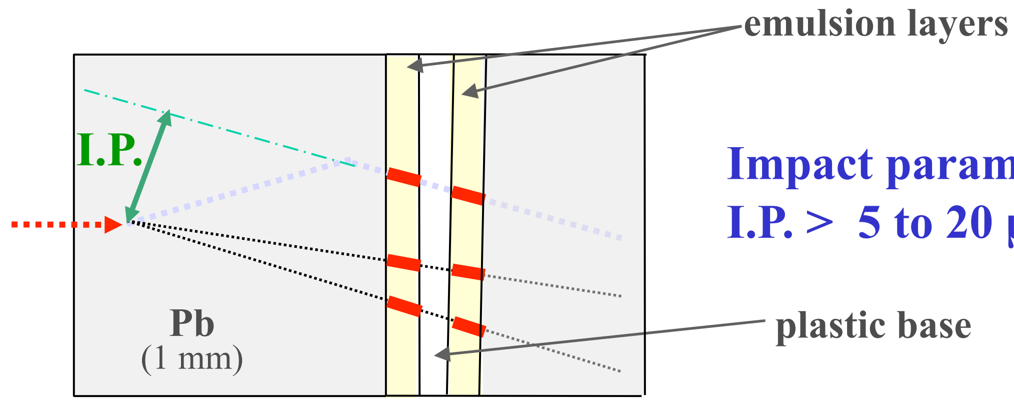
Kink angle

$\theta_{kink} > 20$ mrad

Short decays

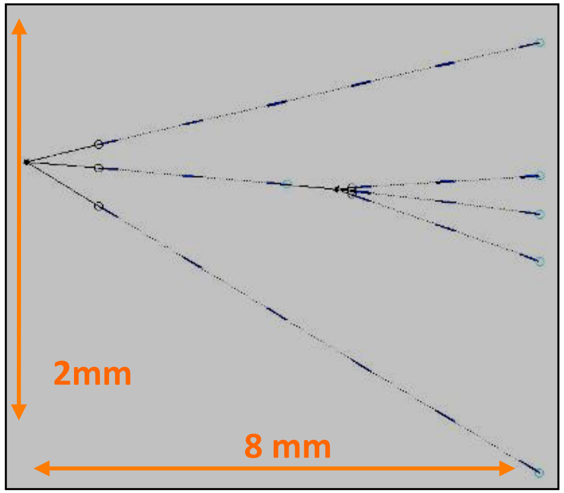
$\tau \rightarrow e\nu_\tau\nu_e$

$\tau \rightarrow \mu\nu_\tau\nu_\mu$



Impact parameter

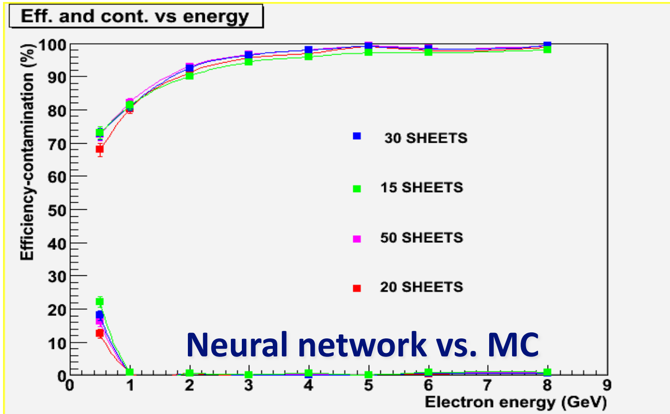
I.P. > 5 to 20 μm

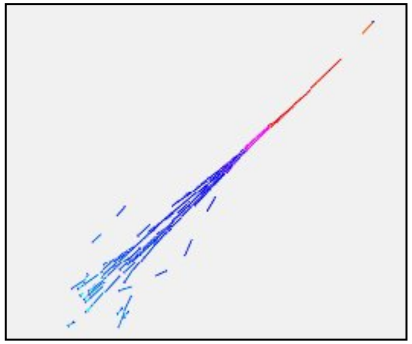


Resolution of a track segment :
σ (angle) = 2 mrad
σ (position) = 0.2 μm

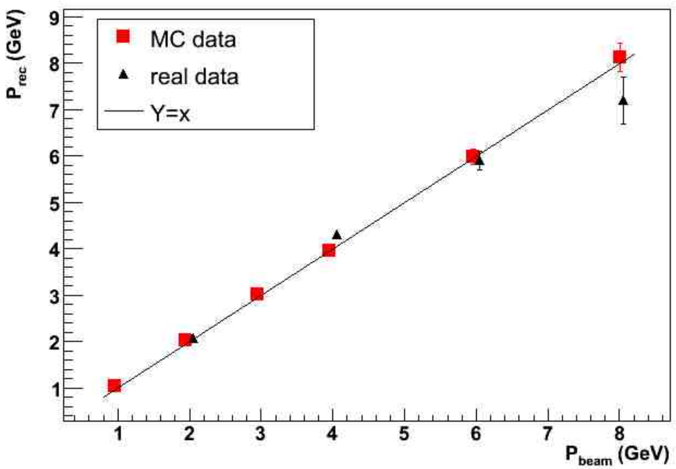
Vertex position resolution ~ 1μm

Electron identification,
e/π separation
e, γ energy





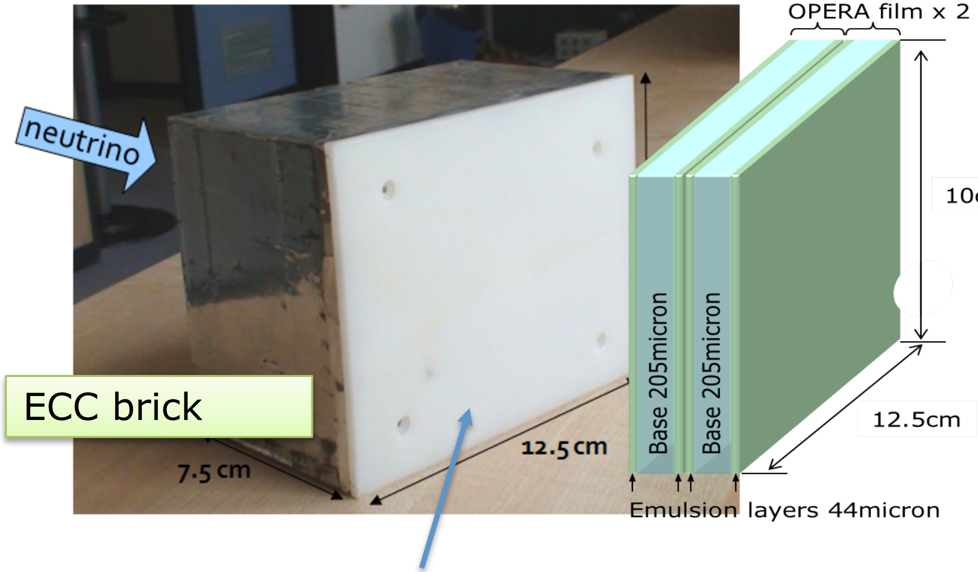
Hadron **momenta** by
Multiple Coulomb Scattering



P_{beam} (GeV)

The Changeable Sheets Doublet
Electronic Detectors - ECC brick interface

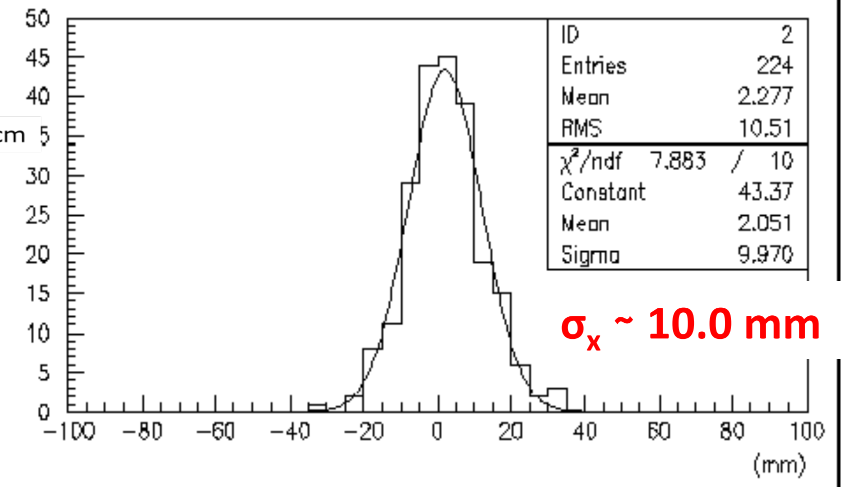
Connecting the ***cm*** world of electronic detectors and the ***μm*** world of emulsions



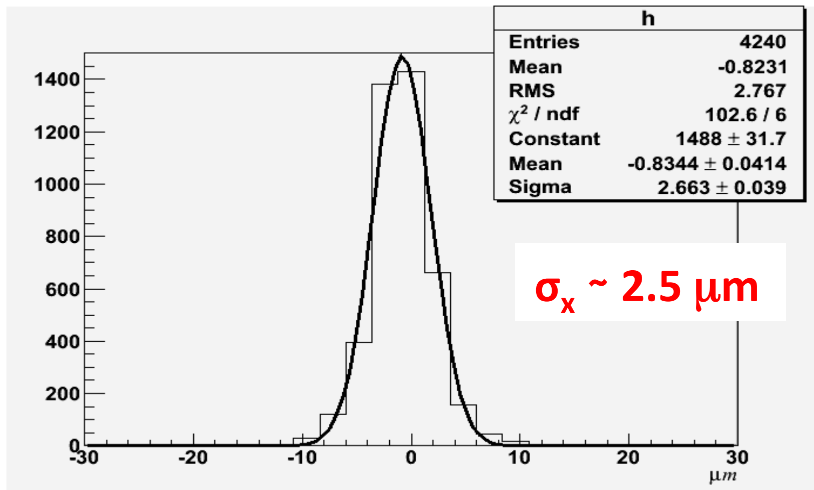
Interface **films** (CS)

Detachable box containing 2 films.
- Validation of the brick prediction by the ED.
- Replaceable in case prediction is wrong (brick reinsertion)

Position accuracy of the electronic predictions



CS doublet alignment by Compton electrons



ECC brick Scan & Analysis Load

Japan : EU = 50:50

EU : 10 labs

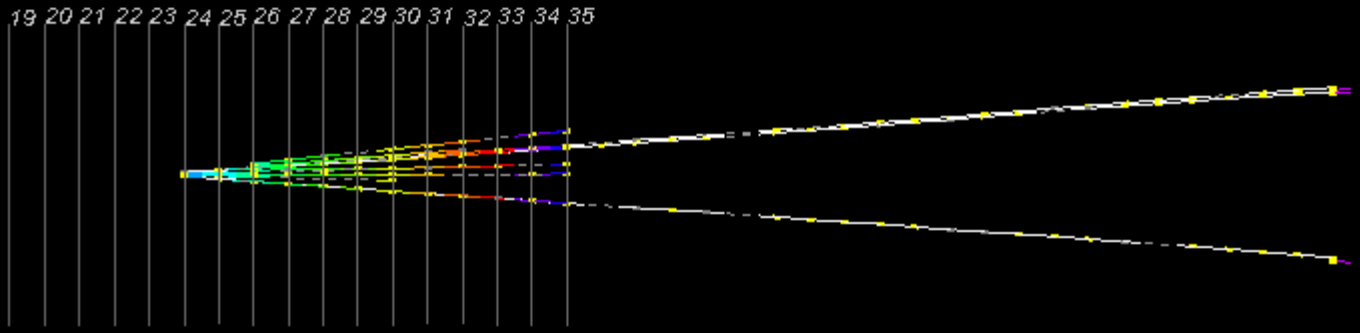
Changeable Sheets Scan & Analysis Load

JAPAN : LNGS = 50:50

Event analysis in ECC brick

(Animation)

Event reconstruction



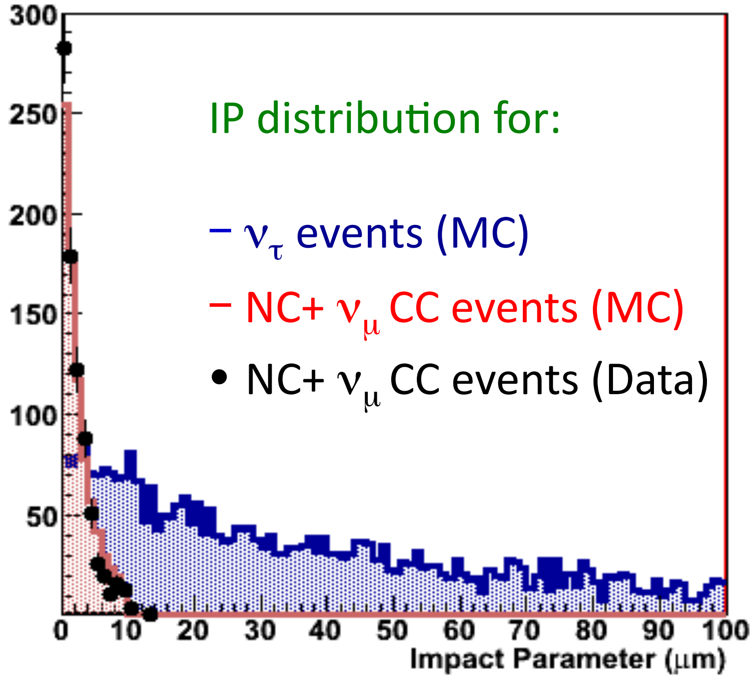
5 mm

Emulsion gives 3D vector data, with a few micron precision of the vertex accuracy.

The frames correspond to scanning area. Yellow short lines are measured tracks. Other colored lines are interpolation or extrapolation.

ECC performance

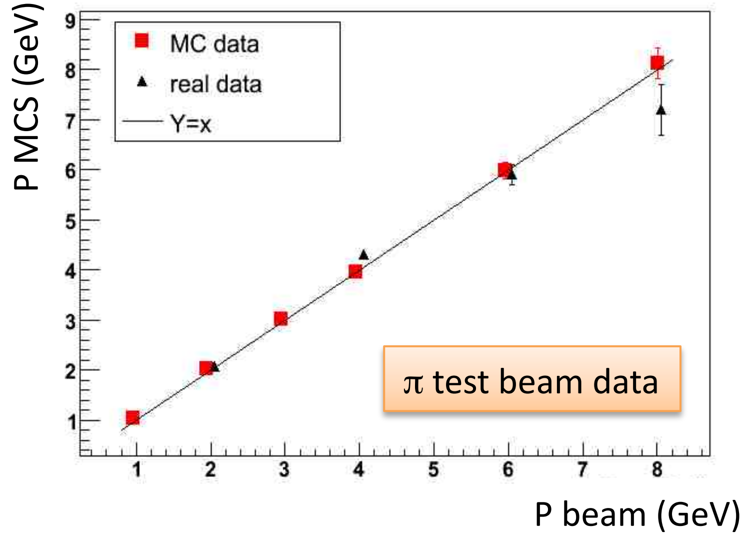
Impact parameter measurements



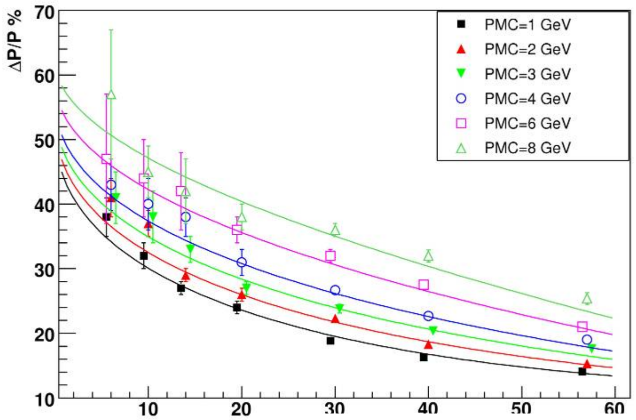
The detection of decay topologies is triggered by the observation of a track with a large IP wrt the primary vertex, in addition to kink detection.

Momentum measurement by MCS

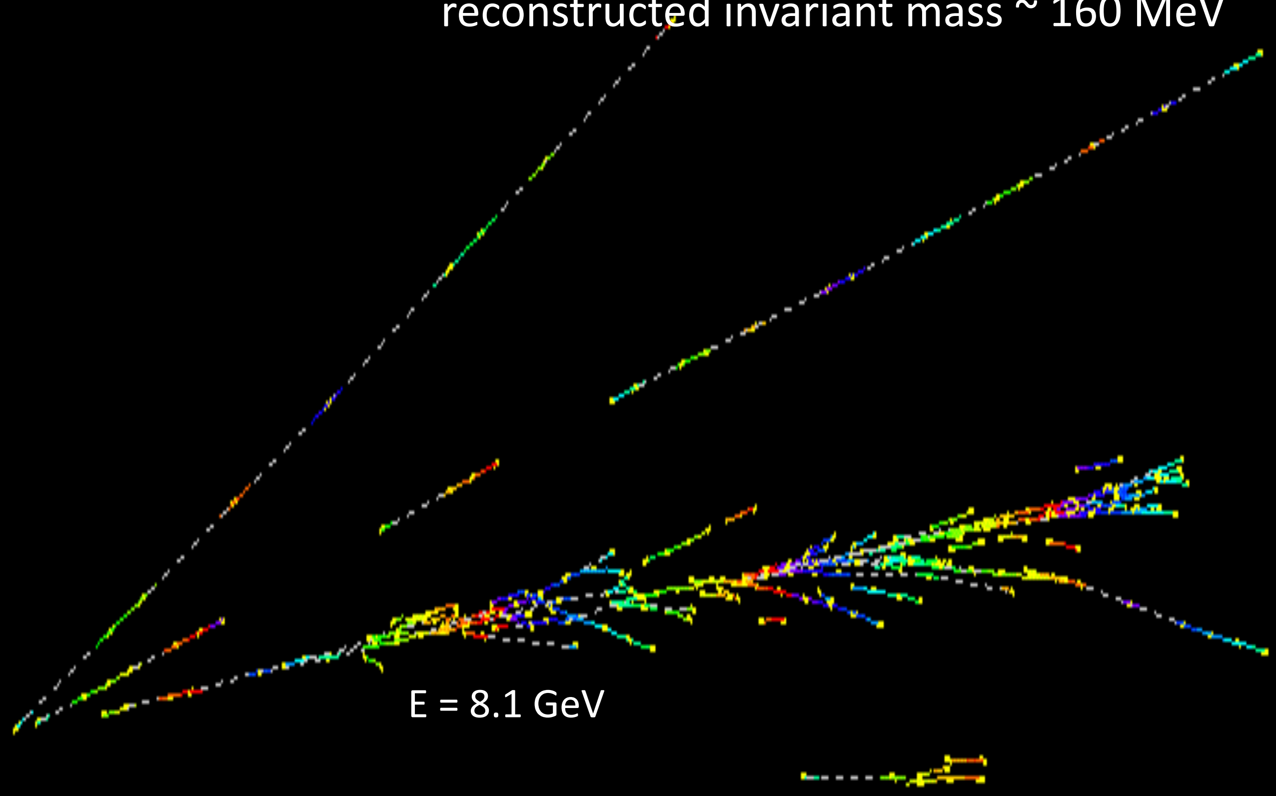
Linearity of momentum center



Resolution

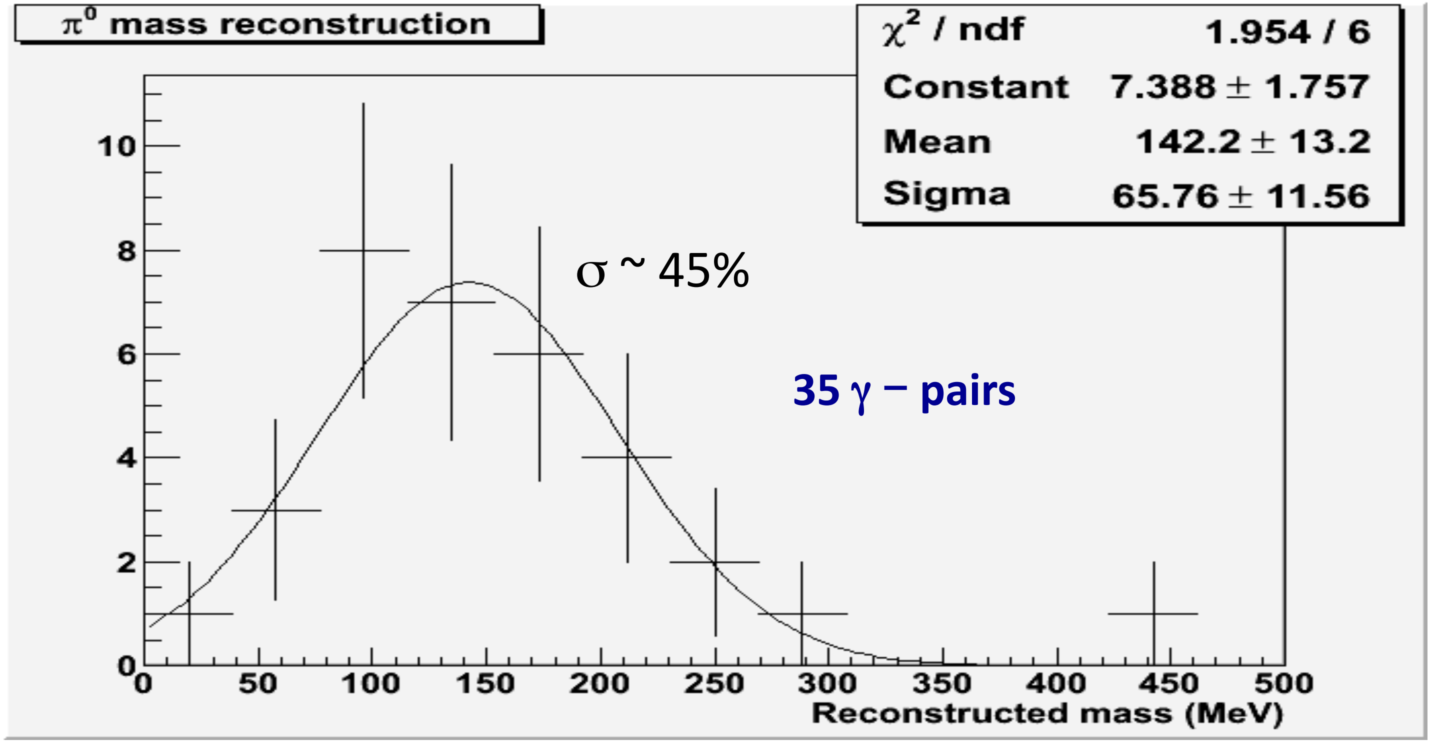


ECC bricks : standalone detectors
***e* , γ detection and π^0 mass reconstruction**

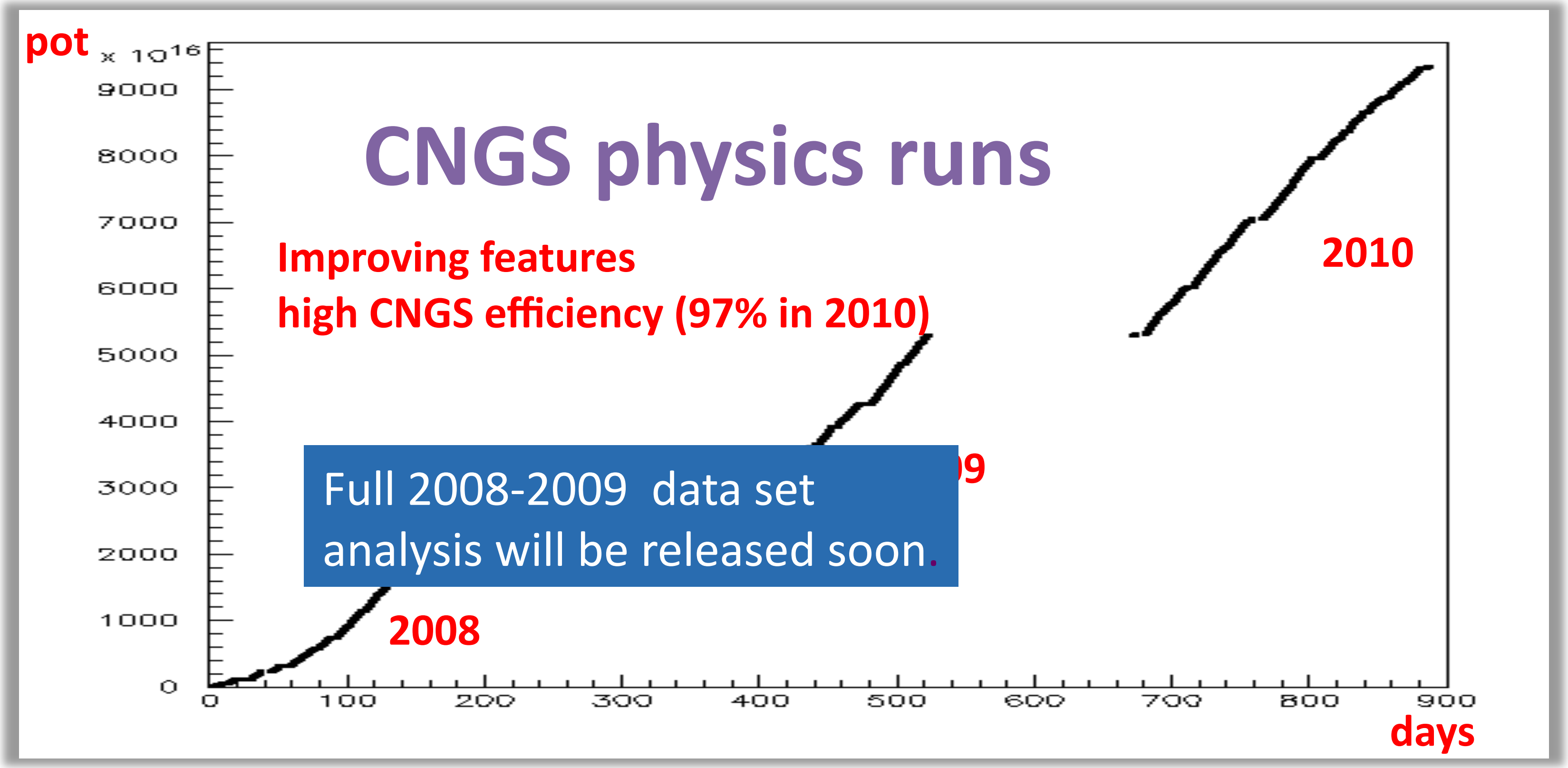


EM shower energy measured by shower shape analysis and Multiple Scattering method

π^0 mass resolution (real data)



mass resolution: ~45%



year	beam days	protons on target	SPS eff.	events in the bricks
2008	123	1.78×10^{19}	61%	1698
2009	155	3.52×10^{19}	70%	3693
2010	187	4.04×10^{19}	81%	4248
TOTAL	465	**9.34×10^{19}**	<71%>	**9639**

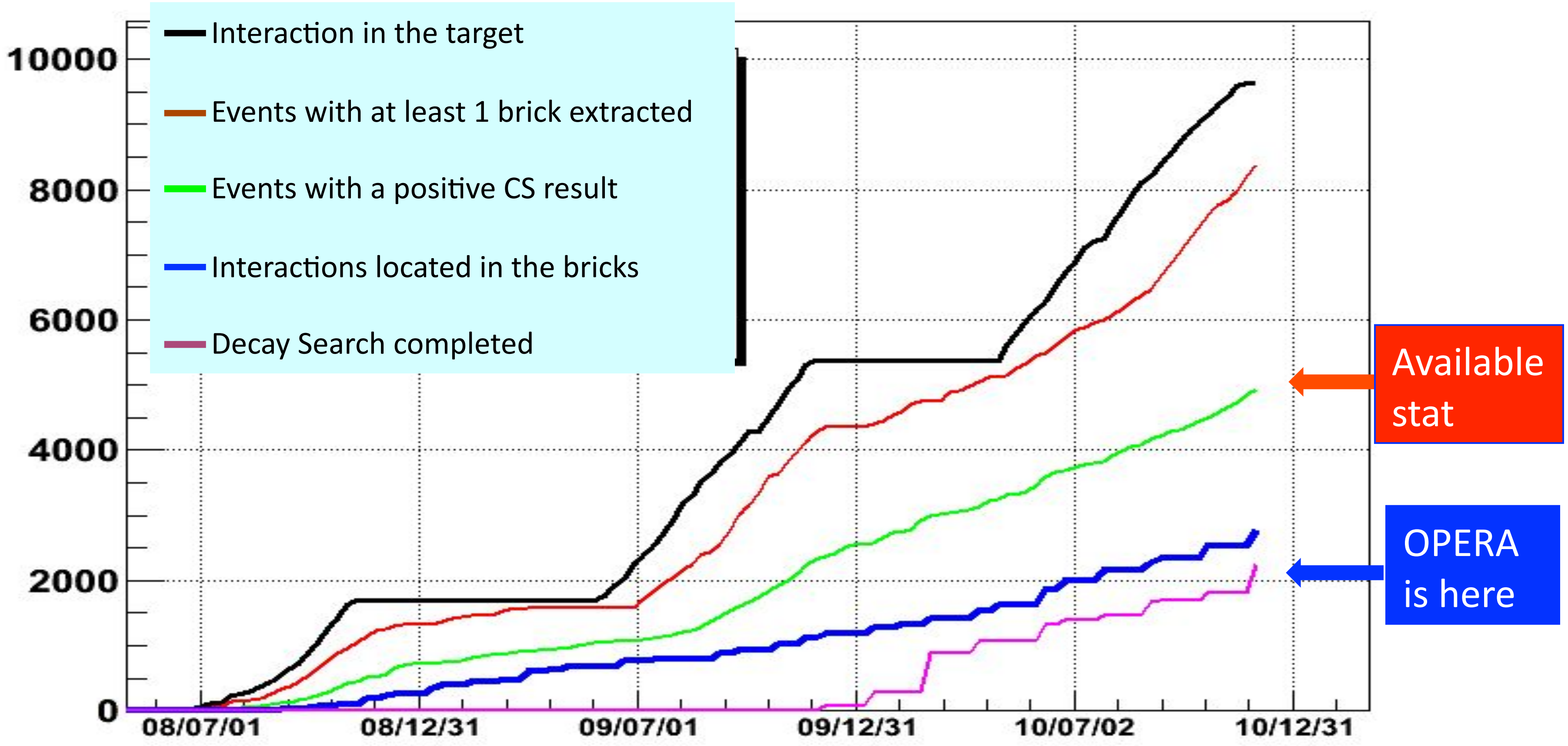
2.1 nominal CNGS years

NB. In what follows results refer to data released in physics publications **1088 (187 NC)**
1.85×10^{19} p.o.t. , 35% of 2008-'09 statistics, 20% of the total)

With that limited statistics, for $\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV^2 and full mixing OPERA expected ~ 0.5 ν_τ events

Event statistics (2008-2010 runs)

Global efficiency 0-μ : ~ 42%
Brick tagging efficiency * 1-μ : ~ 64% <extracted brick per event> 1.45
vertex location efficiency all : ~ 60%

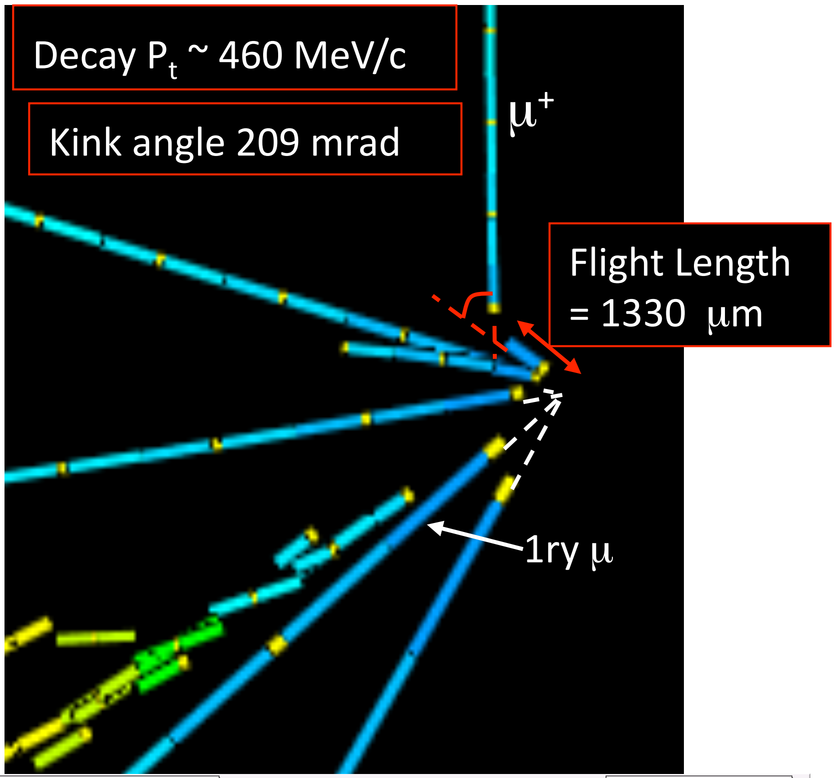


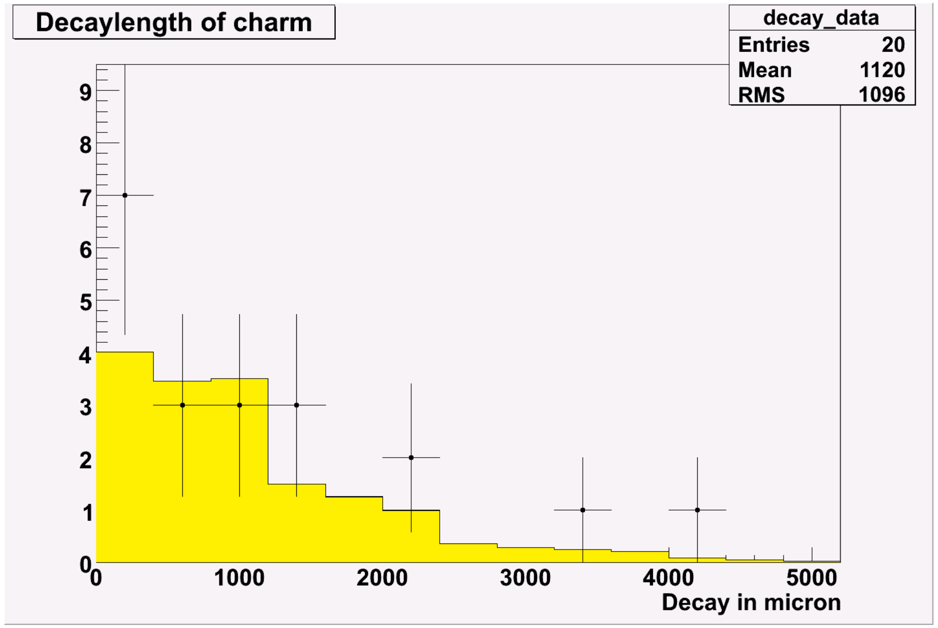
Charm candidate events

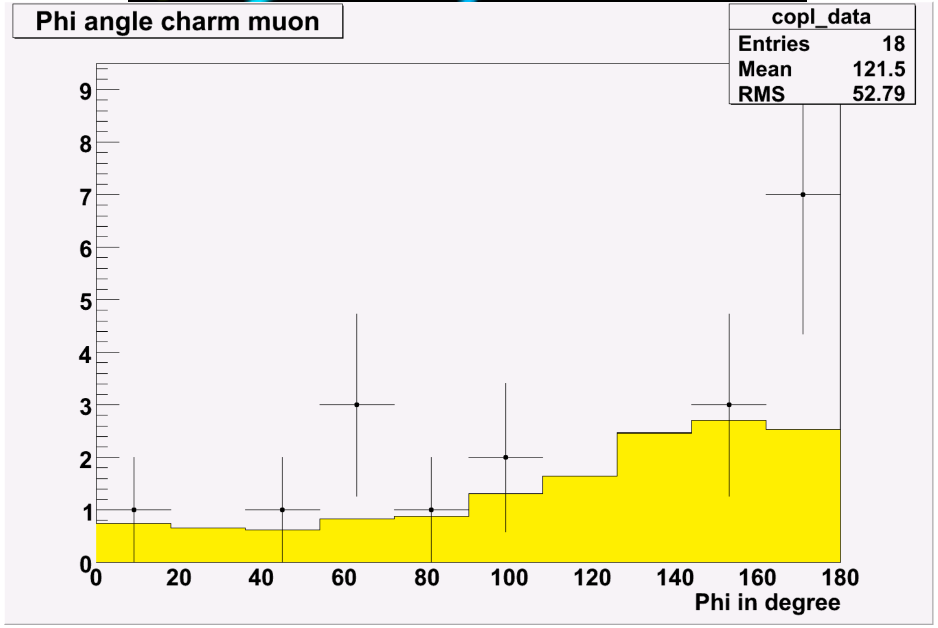
- τ detection efficiency test-

- 20 charm events selected
  (3 events with 1-prong kink topology)
- Expected: 16.0 ± 2.9
  (0.80 ± 0.22 with kink)
- ~ 2 BG events expected

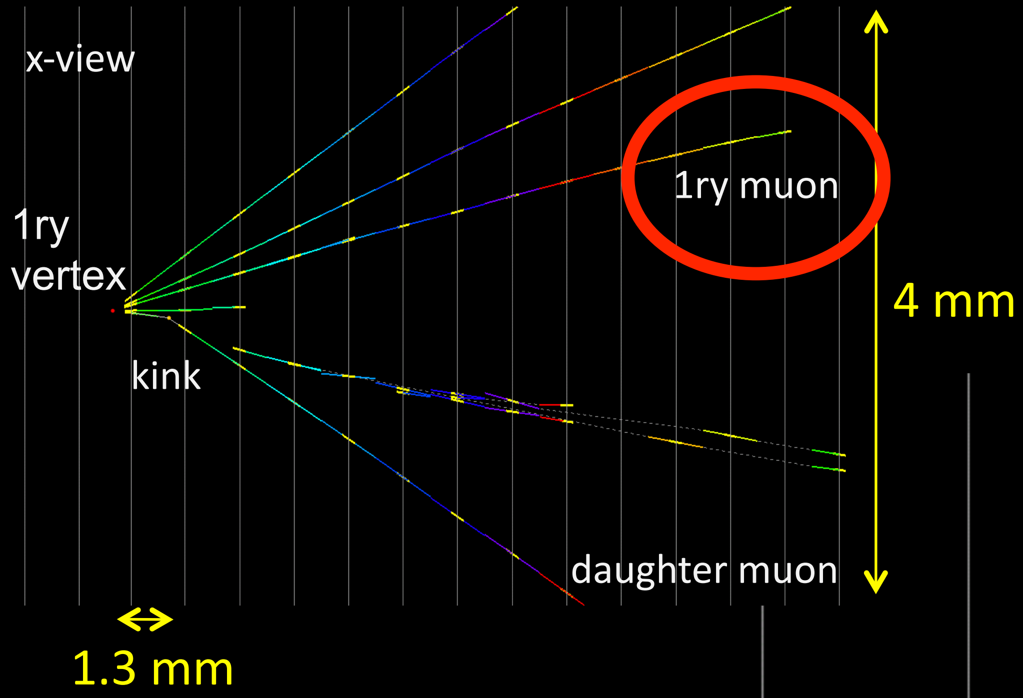
Charm event



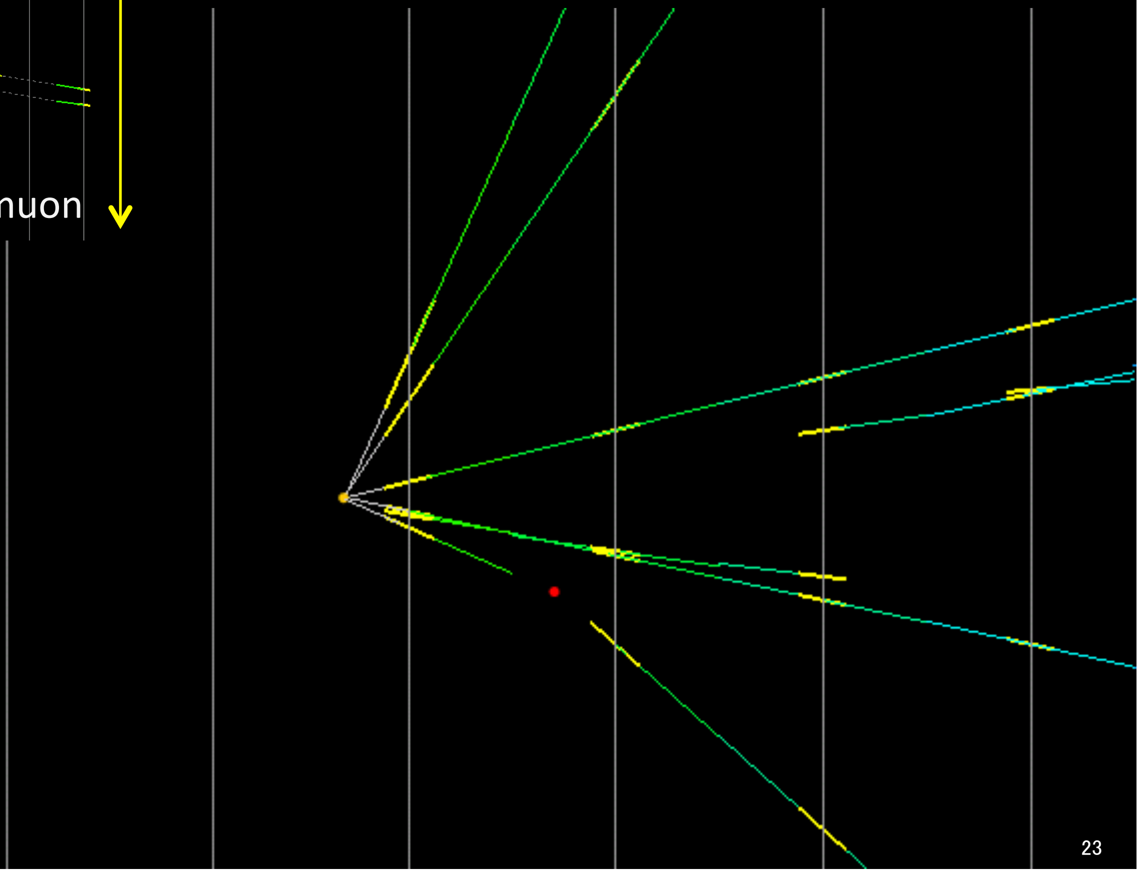




Charm candidate event (dimuon)

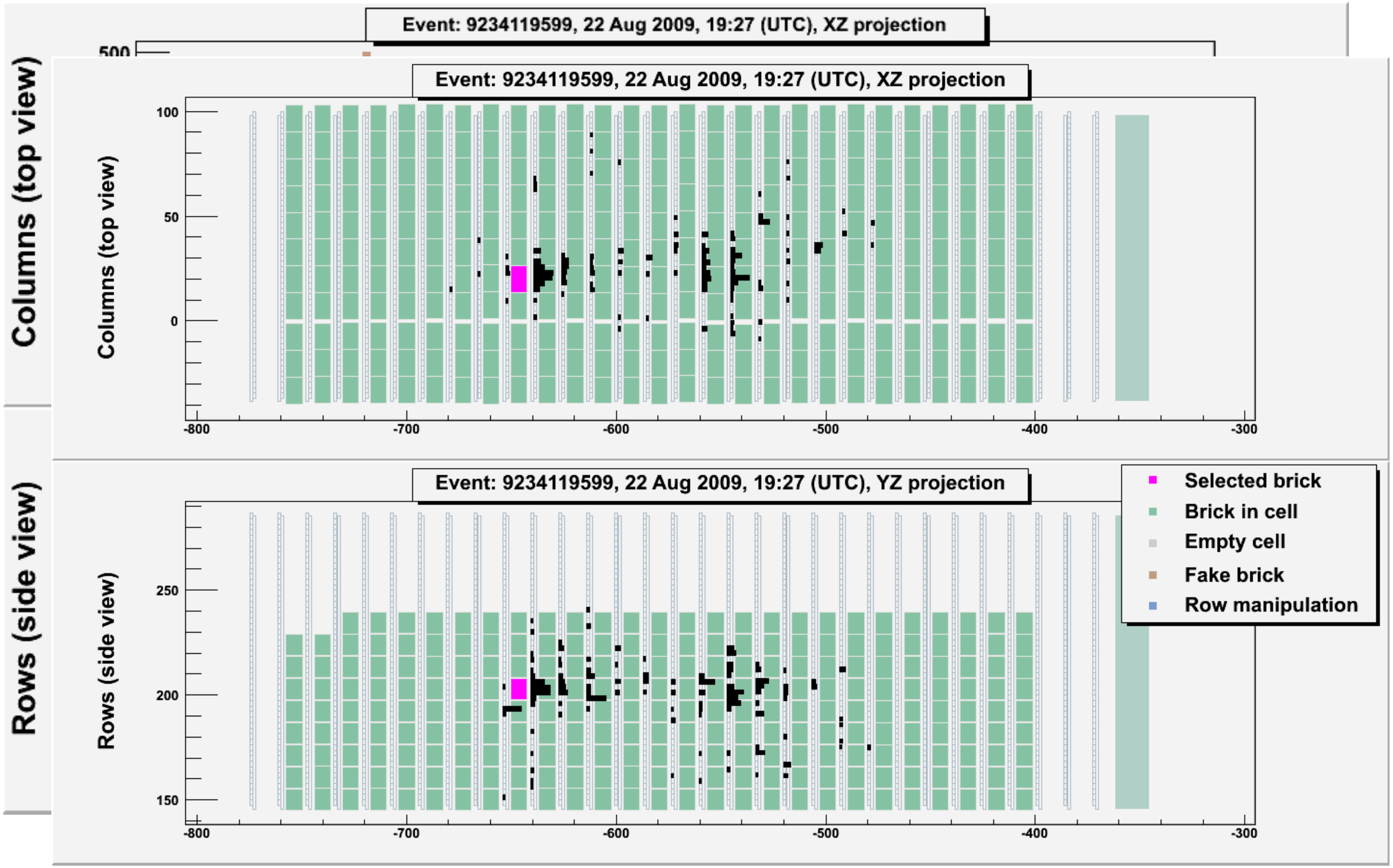


flight length: 1330 microns
kink angle: 209 mrad
IP of daughter: 262 microns
daughter muon: 2.2 GeV/c
decay Pt: 0.46 GeV/c



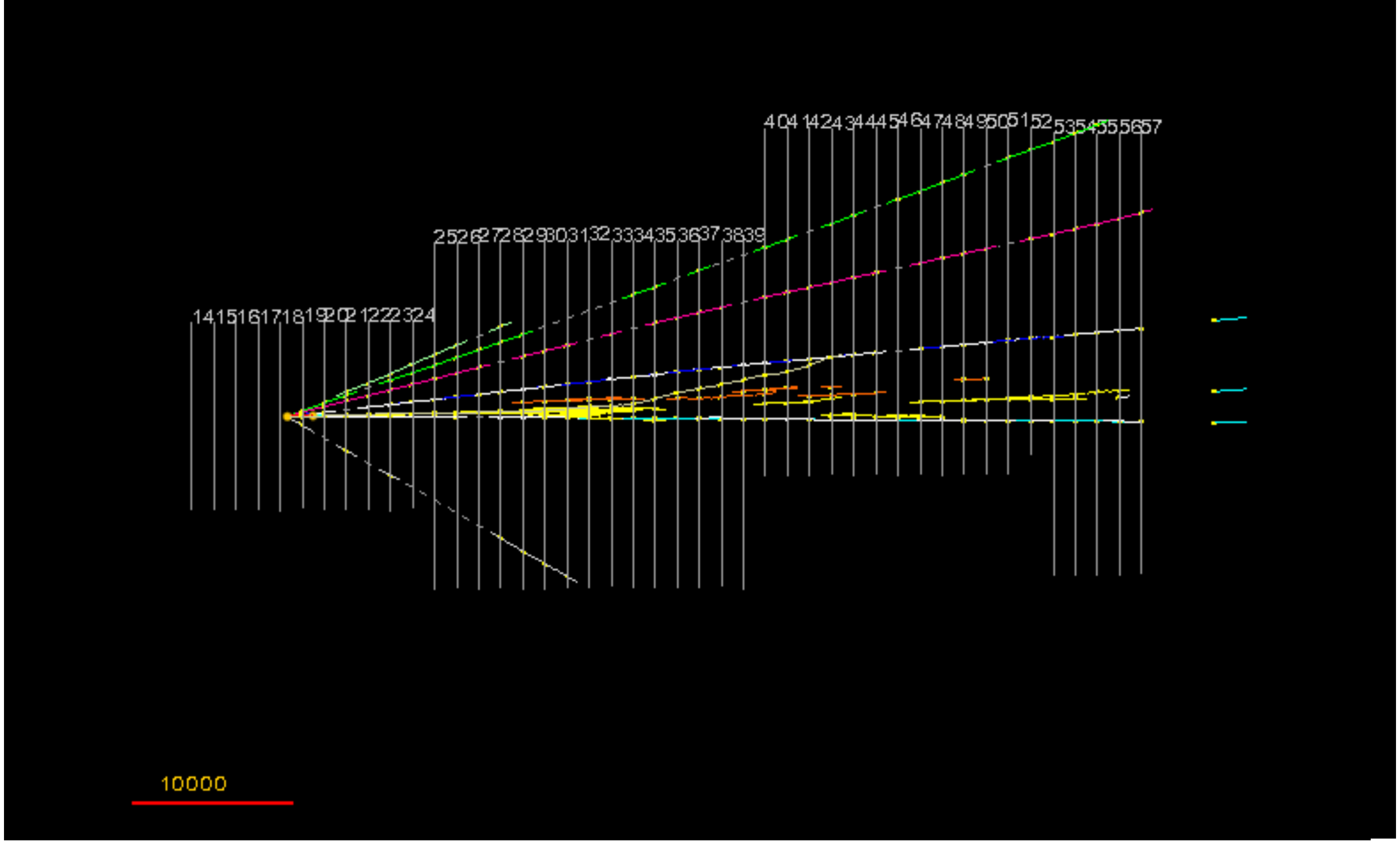
The first ν_τ candidate event

Phys. Lett. B 691 (2010) 138

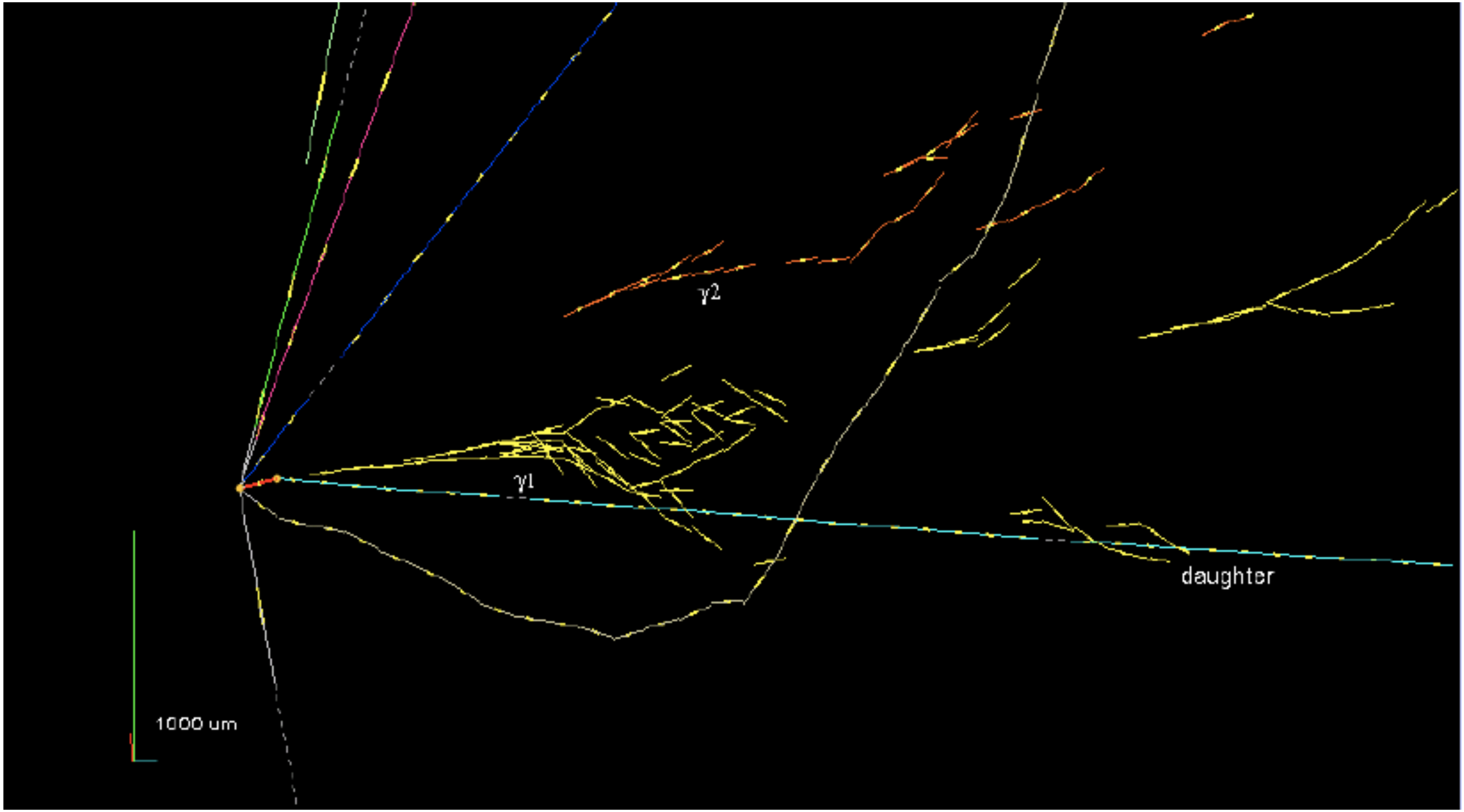


FROM CS TO VERTEX LOCATION

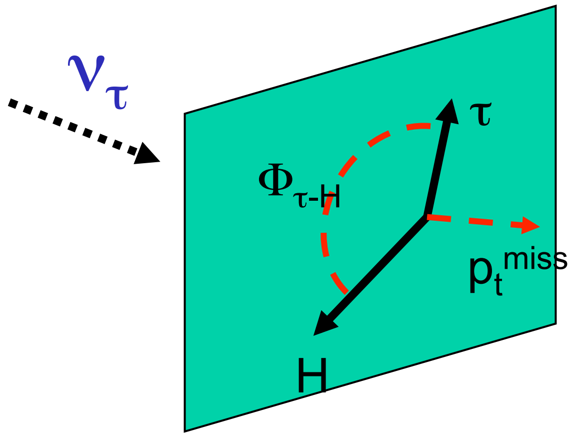
Large area scanning
Full reconstruction of vertices and showers

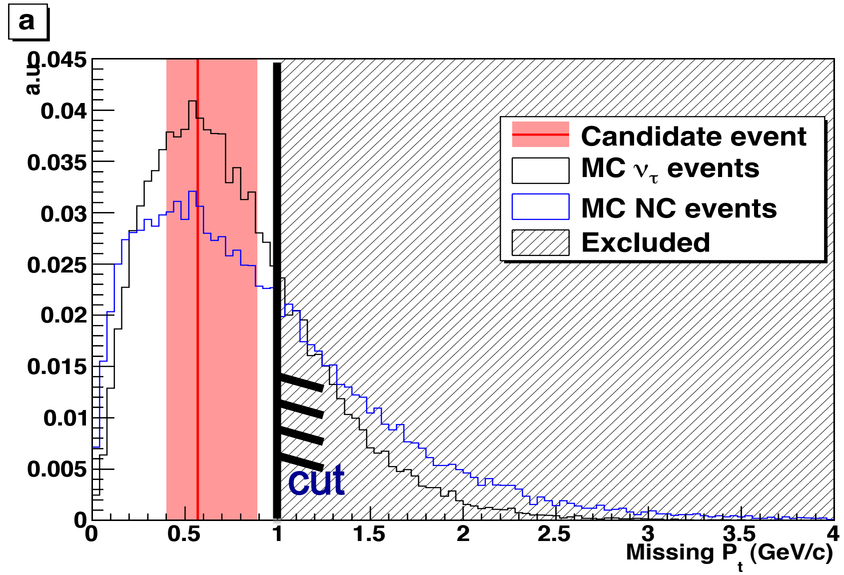


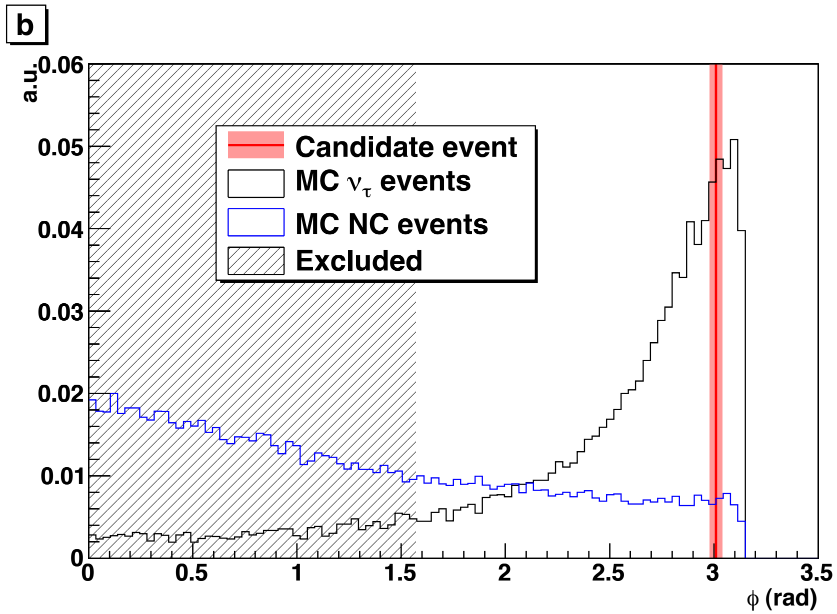
Reconstructed ν_τ Candidate in Emulsions

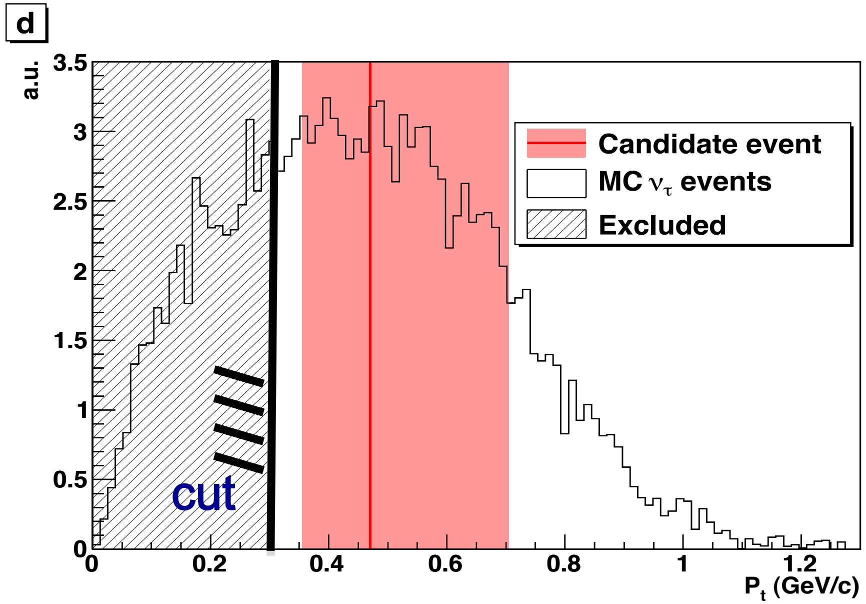


Kinematical analysis

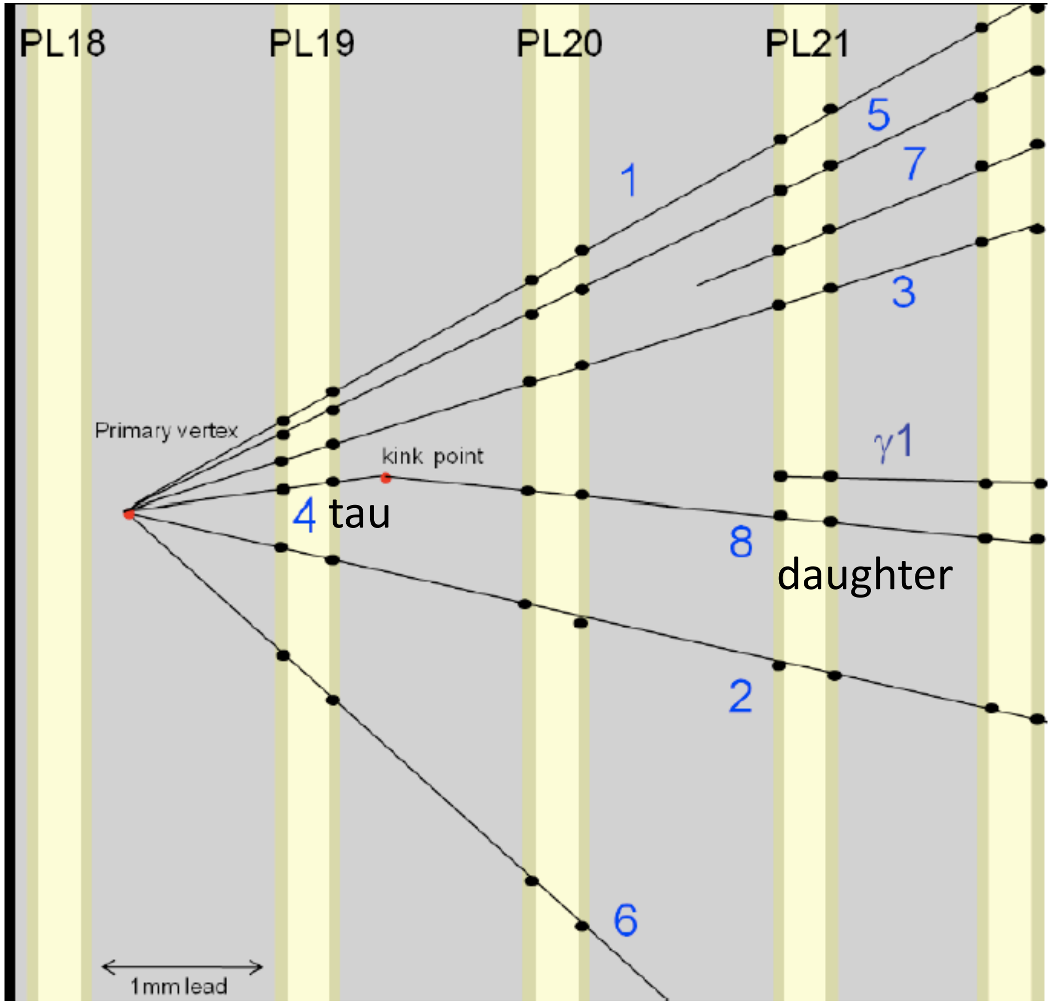








Kinematical variables



VARIABLE	Measured	Selection criteria
Kink (mrad)	**41 ± 2**	**>20**
Decay length (μm)	**1335 ± 35**	**Within 2 plates**
P daughter (GeV/c)	**12^{+6}_{-3}**	**>2**
Pt daughter (MeV/c)	**470^{+240}_{-120}**	**>300 (γ attached)**
Missing Pt (MeV/c)	**570^{+320}_{-170}**	**<1000**
φ (deg)	**173 ± 2**	**>90**

Nature of the event

- Event passes all selection cuts → candidate to $\tau \rightarrow$ 1-prong hadron decay.
- 2 γ invariant mass consistent with π^o mass = 120 ± 20 ± 35 *MeV*
- $\pi^- \ \gamma \ \gamma$ system invariant mass compatible with ρ (770) mass = $640\ ^{+125}_{-80}\ ^{+100}_{-90}$ *MeV*

Likely decay mode: $\tau^- \rightarrow \rho\ (\rightarrow \pi^- \pi^0)\ \nu_\tau$

B.R. $[\tau^- \rightarrow \rho\ (\pi^- \pi^0)\ \nu_\tau] \approx 25\%$

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

Main backgrounds:

- Decay of charmed particles produced in ν_μ interactions (CC & NC) ~ 10^{-5}/CC
- Hadronic interactions (CC & NC) ~ 10^{-5}/CC

ν_τ candidate event energy

From the scanning, we know that all the charged hadrons and electromagnetic particles attached to the primary vertex have been measured.

P_{miss} at primary vertex **$0.57^{+0.32}_{-0.17}$** GeV/c
→ event kinematics almost closed (no neutral particle missing at the primary)

Sum of the modulus of the momenta at the primary vertex **$24.3^{+6.1}_{-3.2}$** GeV/c

Total hadronic momentum at the primary vertex ~ **5.5** GeV/c
(not including that of the parent assumed to the a τ)

Statistical Considerations

Background expectation in 1-prong hadron τ decay channel

0.011 events (hadron re-interactions)
0.007 events (charm)
assume conservative 50% error on each component
0.018 ± 0.007 (syst.) events 1-prong hadron

Background expectation all decay modes:
1-prong hadron, 3-prongs + 1-prong μ + 1-prong *e :*
0.045 ± 0.020 (syst.) events considering all decay modes

Probability to observe 1 event due to bck fluctuation in 1-prong channel: 1.8%

Statistical significance on the measure of a first ν_τ candidate event: of 2.36 σ

Considering all decay modes, the background fluctuation probability is 4.5% and the significance is 2.01 σ.

$\nu_\mu \leftrightarrow \nu_e$??

OPERA: good *e*_ID capability
well suited for $\boldsymbol{\nu_\mu \leftrightarrow \nu_e}$ searches

- Main backgrounds:
  - ν_e beam contamination (largest contribution)
  - π^0 identified as electrons produced in ν_μ^{NC} or ν_μ^{CC} with the muon not identified
  - $\tau \rightarrow e$ from $\nu_\mu \rightarrow \nu_\tau$ oscillations

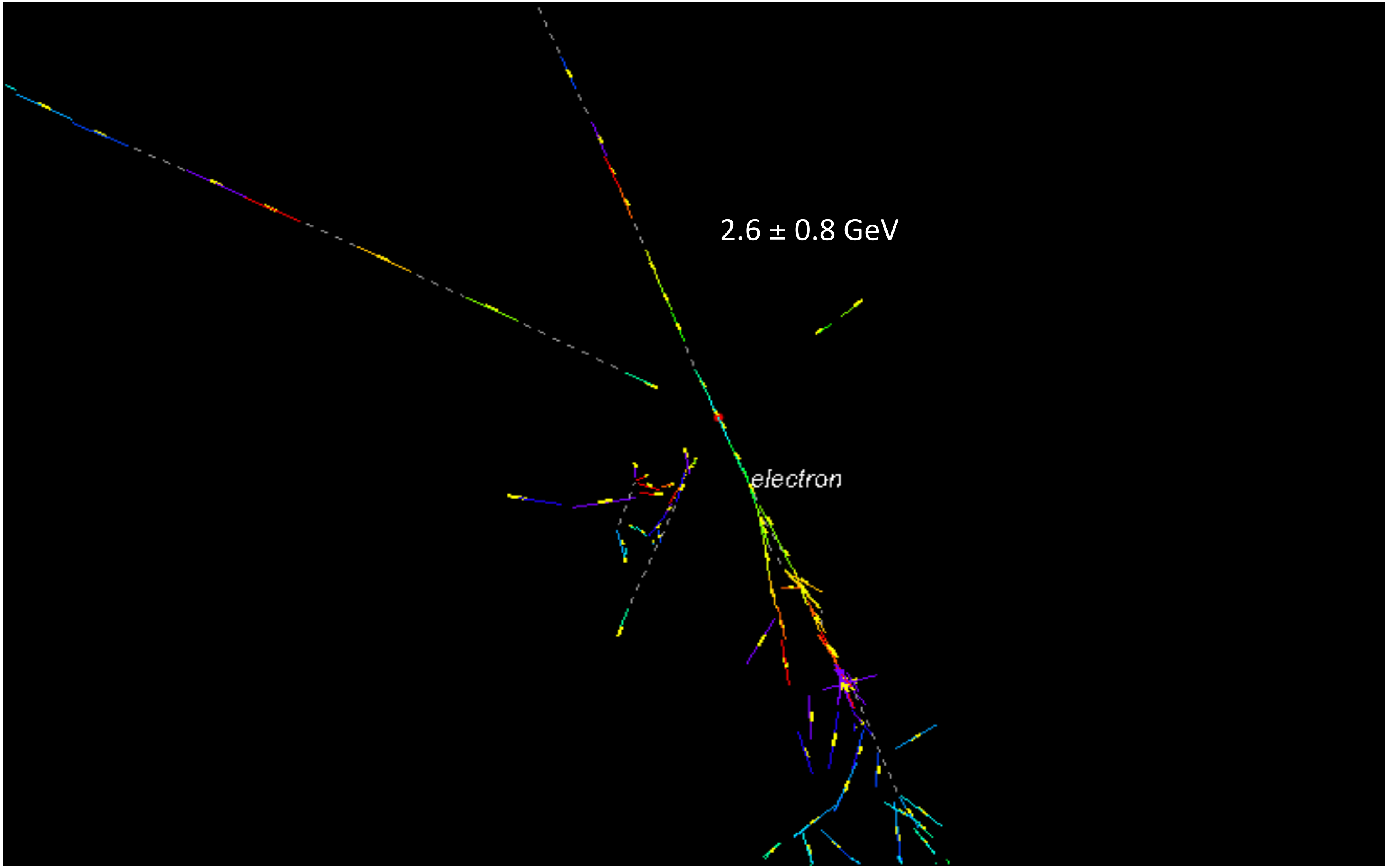
The game is to seek for an excess of low energy ν_e charged-current events

θ_{13}	signal	$\tau \rightarrow e$	ν_μCC	ν_μNC	ν_eCC beam
9°	6.7	3.2	0.7	3.7	13
8°	5.3	3.2	0.7	3.7	13
7°	4.2	3.3	0.7	3.7	13
5°	2.2	3.3	0.7	3.7	13
Efficiency	0.31	0.032	0.34×10^{-4}	7.0×10^{-4}	0.082

Expected signal and background
1.3 kt target
2×10^{20} p.o.t.
$\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV^2 $\sin^2 2\theta_{23} = 1$

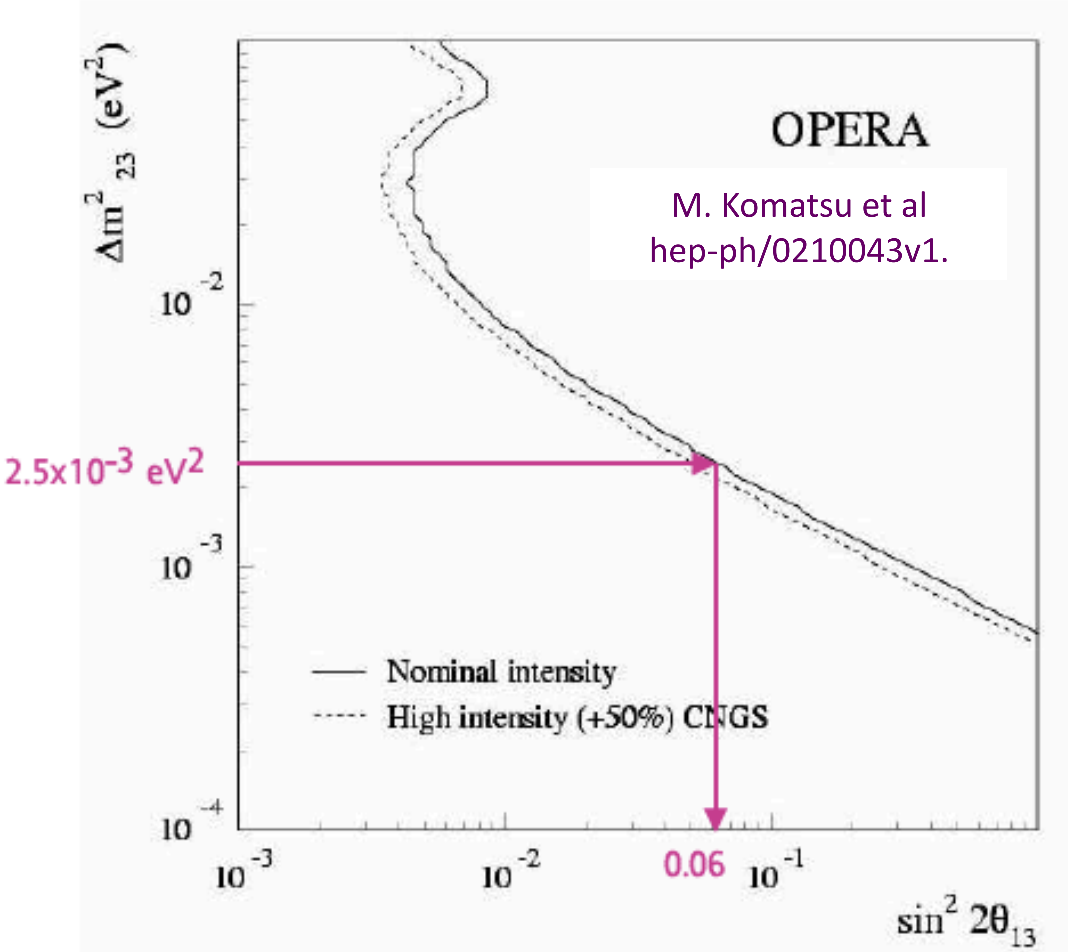
M. Komatsu, et al.arXiv:hep-ph/0210043v1.

13 ν_e candidate events observed



OPERA sensitivity to θ_{13}

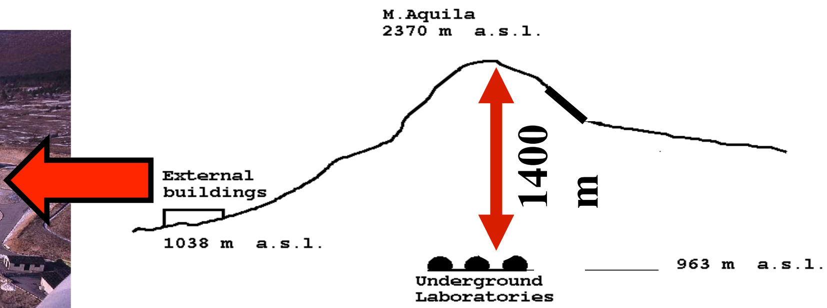
By fitting simultaneously the E_e, missing p_T and E_{vis} distributions we got the sensitivity at 90% C.L.



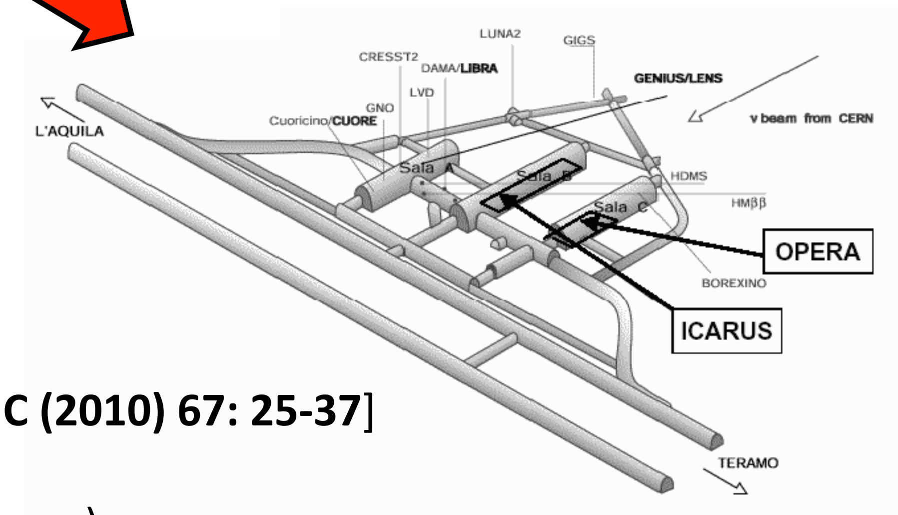
Full mixing, 5 years run
nominal CNGS intensity

OPERA: 1.8 kt target

OPERA as a Cosmic Ray Detector



Gran Sasso underground lab: 1400 m of rock (3800 m.w.e) shielding, cosmic ray flux reduced by a factor 10^6 w.r.t. surface, very reduced environmental radioactivity.



OPERA :

- deep underground
- charge and momentum reconstruction
- timing capabilities (~10 ns).

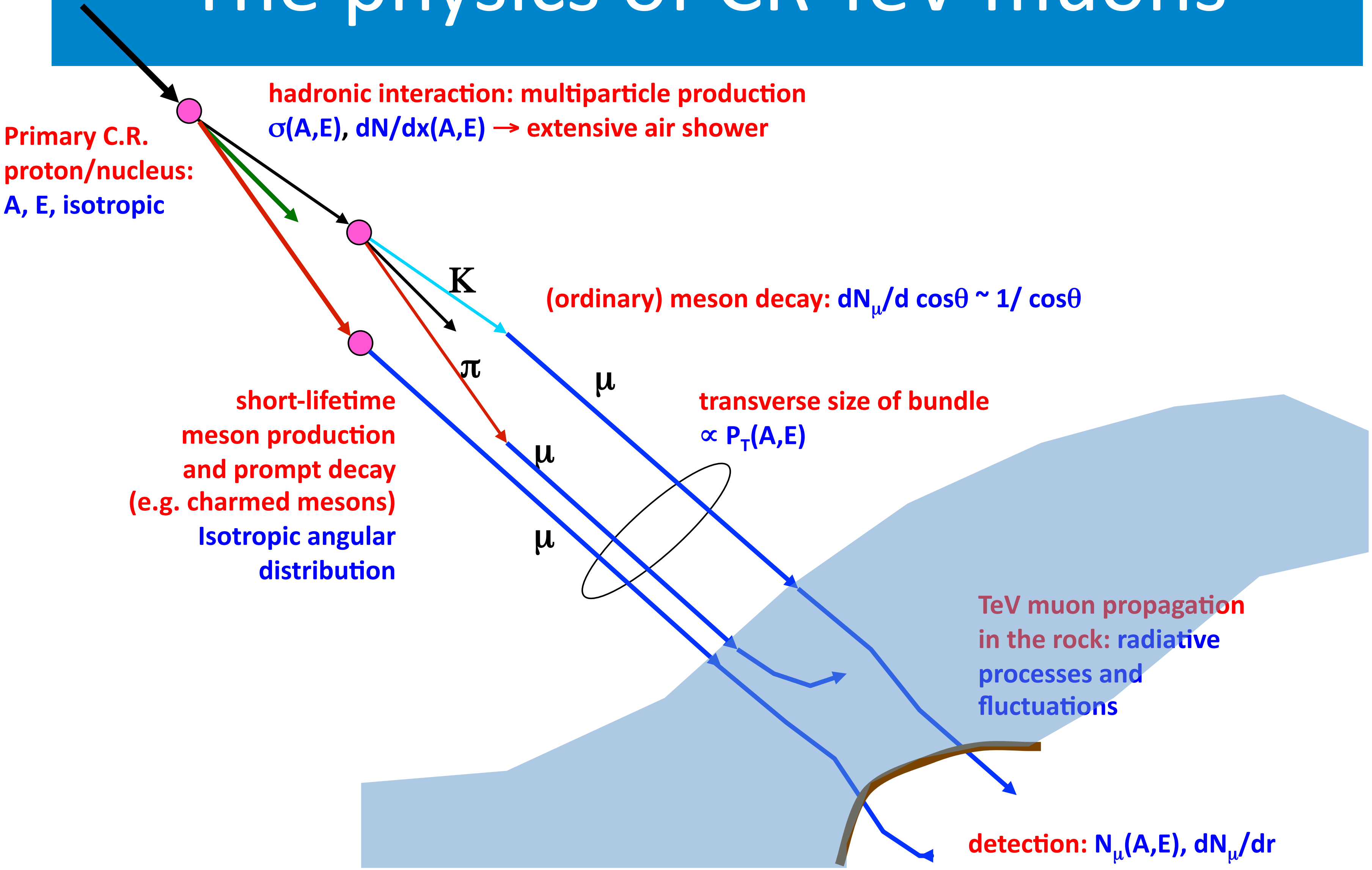
➢**Atmospheric muon charge ratio [Eur. Phys. J. C (2010) 67: 25-37**]

➢Atmospheric neutrino induced muons (in progress)

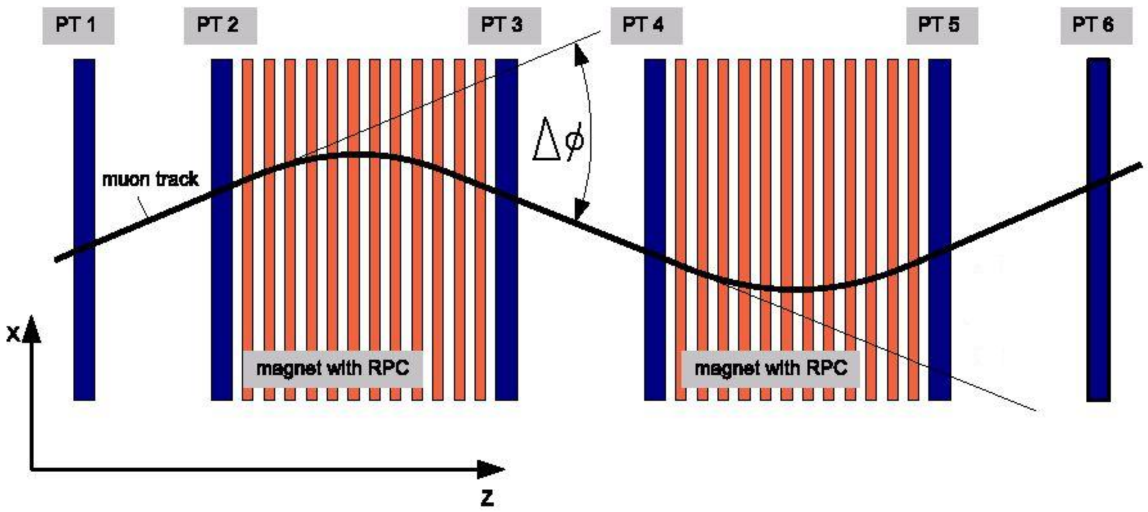
Atmospheric muon charge ratio

- The atmospheric muon charge ratio $R_\mu \equiv N_{\mu+}/N_{\mu-}$
  - Depends on the chemical composition and energy spectrum of the primary cosmic rays
  - Depends on the hadronic interaction features
  - At high energy, depends on the prompt component
- Possibility to check HE hadronic interaction models (E>1TeV) in the fragmentation region, where no data exist
- Since atmospheric muons are kinematically related to atmospheric neutrinos (same sources), R_μ provides a benchmark for atmospheric ν flux computations (e.g. background for neutrino telescopes)

The physics of CR TeV muons



Momentum & Charge reconstruction

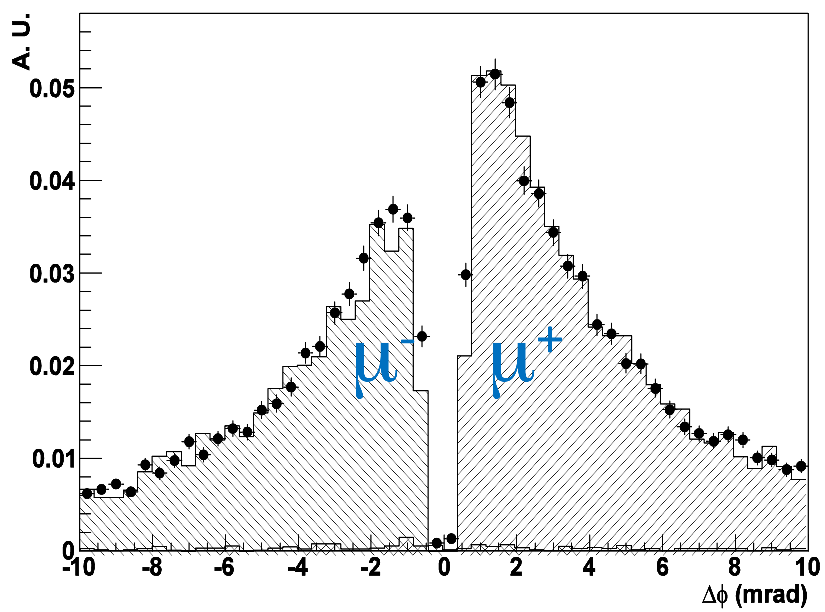


- In each side of the magnet arm we can reconstruct an independent angle ϕ_j, j=1,...,6.
- Charge is reconstructed according to the $\Delta\phi$ sign

Results based on data recorded during the 2008 CNGS Physics Run: 403069 cosmic ray muons, corresponding to 113.4 days of livetime, were analyzed.

Two main analysis cuts were applied:

1) Clean PT cut: removes events with a large number of PT hits.
2) Deflection cut: rejects events with a $\Delta\phi$ smaller or compatible with the experimental resolution.

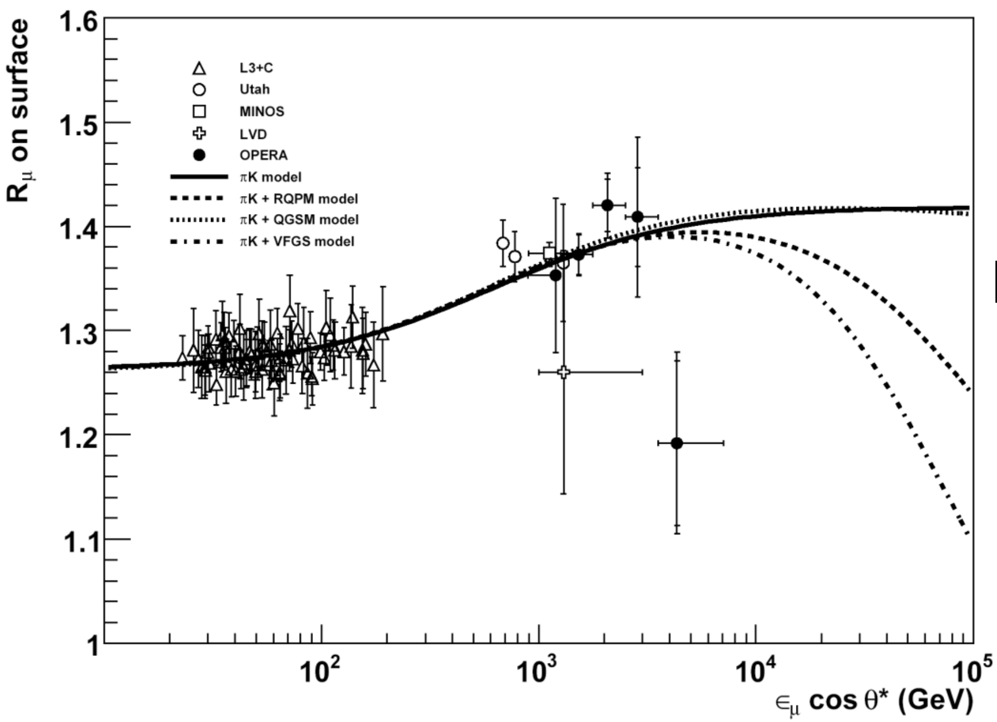


R_μ computed separately for single and multiple muon events

– check of the hypothesis of "dilution" of R_μ when proton-Air and neutron-Air interactions change their relative contributions

N_μ	‹A›	$\langle E/A \rangle_{primary}$ [TeV]	H fraction	N_p/N_n	R_μ^{unf} (2008)
= 1	3.35 ± 0.09	19.4 ± 0.1	0.667 ± 0.007	4.99 ± 0.05	1.377 ± 0.014
> 1	8.5 ± 0.3	77 ± 1	0.352 ± 0.012	2.09 ± 0.07	1.23 ± 0.06

Different at 2.4σ level: first indication of a "dilution" effect



$$R_\pi = Z_{N\pi^+}/Z_{N\pi^-} = 1.229 \pm 0.001$$

$$R_K = Z_{NK^+}/Z_{NK^-} = 2.12 \pm 0.03$$

Summary

OPERA is performing as expected

- **Data analysis promising : - 1 ν_τ candidate event detected (2.36 σ significance; 0.5 expected))**
  - **charm candidate events as expecte**
  - **ν_e candidate events detected**
- **Suffering some delay from poor CNGS initial performances : collected statistics**

in 2008-2010 ~ 2.1 years @ nominal intensity

- **"Other Products" : Muon Charge Ratio,....**

Outlook

- **CNGS "scheduled" running for 2011 and 2012**
- **2011 (starting March 18th) : 6 extra weeks in dedicated mode**

  ⟹ if CNGS and OPERA eff. as in 2010 ~ 1.2 nominal years

- **By end of 2012 : ~ 20 E^{19} POT collected i.e. ~ 90 % of the proposal statistics.**

Then **OPERA will keep its word...**