Cosmic ray physics with the OPERA Detector

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On behalf the OPERA collaboration

11th ICATPP Conference
October 8th 2009

The OPERA collaboration

Belgium
IIHE Brussels
Bulgaria
Sofia
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, Obninsk
Switzerland
Bern, Zurich
Turkey
METU Ankara

12 countries, 34 institutions and around 200 physicists

Outline

- OPERA experiment
  → neutrino physics and motivations
  → opera detector and LNGS underground lab

- Target Tracker
  → Features and Readout
  → time informations in TT

- Atmospheric neutrinos detection
  → analysis soft and simulation results
  → data analysis

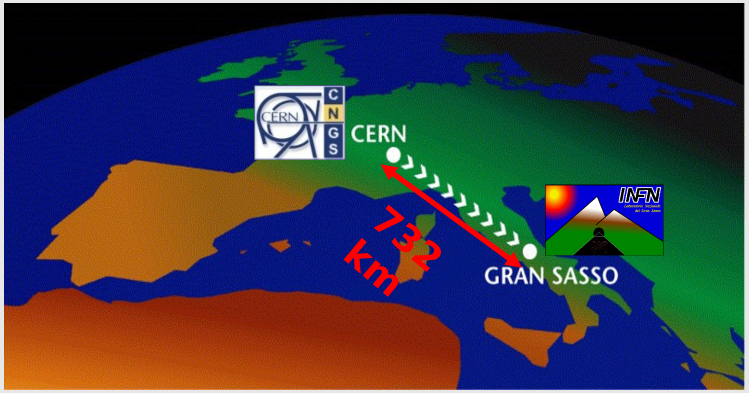
- Others cosmics analysis
  → Charge muons ratio
  → Underground muons spectrum
  → OPERA-LVD coincidence

- Summary

The OPERA experiment

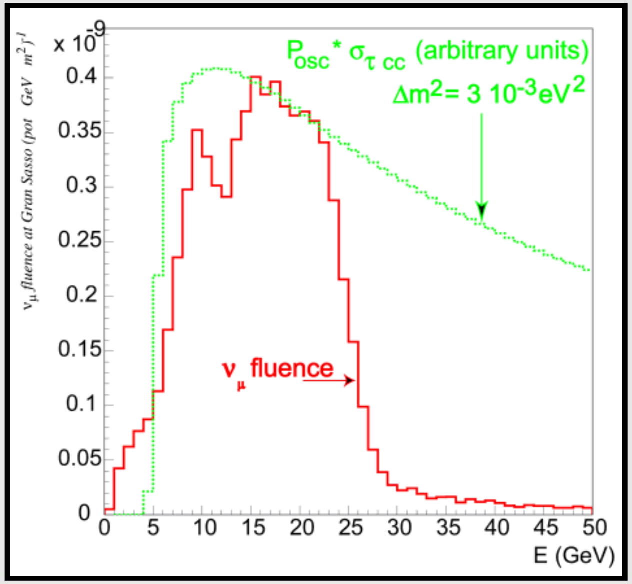
Oscillation Project with Emulsion tRacking Apparatus

OPERA is a long baseline neutrino oscillation experiment aiming at the detection of ν_τ **appearance** in an almost pure ν_μ beam (CNGS)



CNGS beam optimized to maximize the number of ν_τ CC interactions

→ ν_μ flux “off peak” w.r.t the maximum oscillation probability (~1.5 GeV)

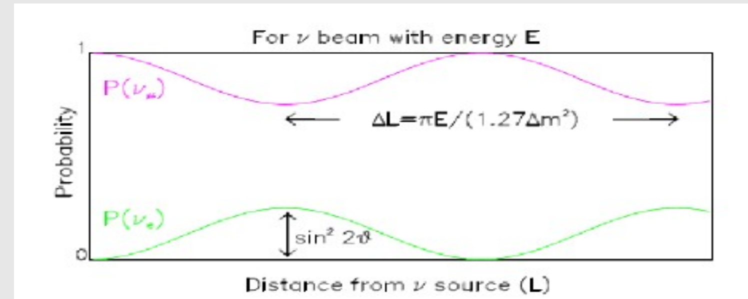


L	**732 km**
$<E_\nu>$	**17 GeV**
$(\nu_e+\bar{\nu}_e)/\nu_\mu$	**0.87%**
$\bar{\nu}_\mu$ / ν_μ	**4.0%**
ν_τ prompt	**negligible**

The OPERA experiment

Neutrinos oscillations :

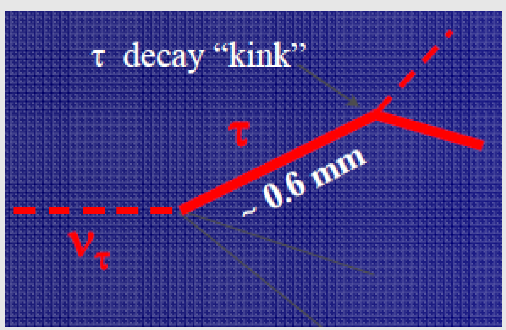
$$P(\nu_e \Rightarrow \nu_\mu) = \sin^2 2\theta \sin^2 \left[\frac{1.27\Delta m^2 (eV^2) L(km)}{E(GeV)} \right]$$



Neutrinos detection :

$$N_\tau = N_A M_D \int \phi_{\nu_\mu}(E) P_{\nu_\mu \to \nu_\tau}(E, \Delta m^2) \sigma_{\nu_\tau}{}^{CC}(E) \varepsilon(E) dE$$

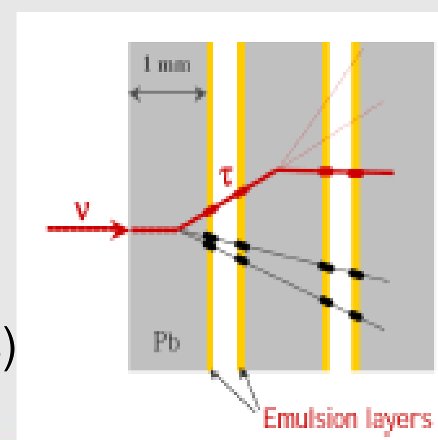
→ Target mass must be O(1kton) for $\Delta m^2 = 10^{-3}$ eV

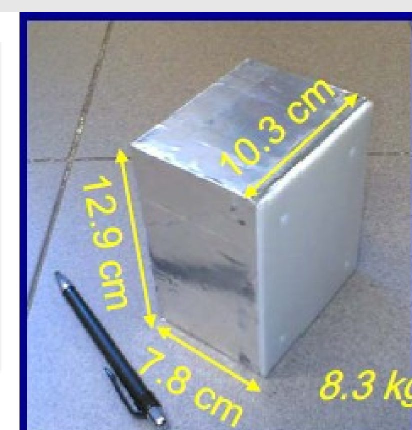


→ Detector resolution must be O(1mm)

→ electronic part : Target Tracker, RPC XPC, HPT
- trigger
- vertex localization

→ passive part : bricks (56 lead sheets + 57 emulsions)
- vertex reconstruction

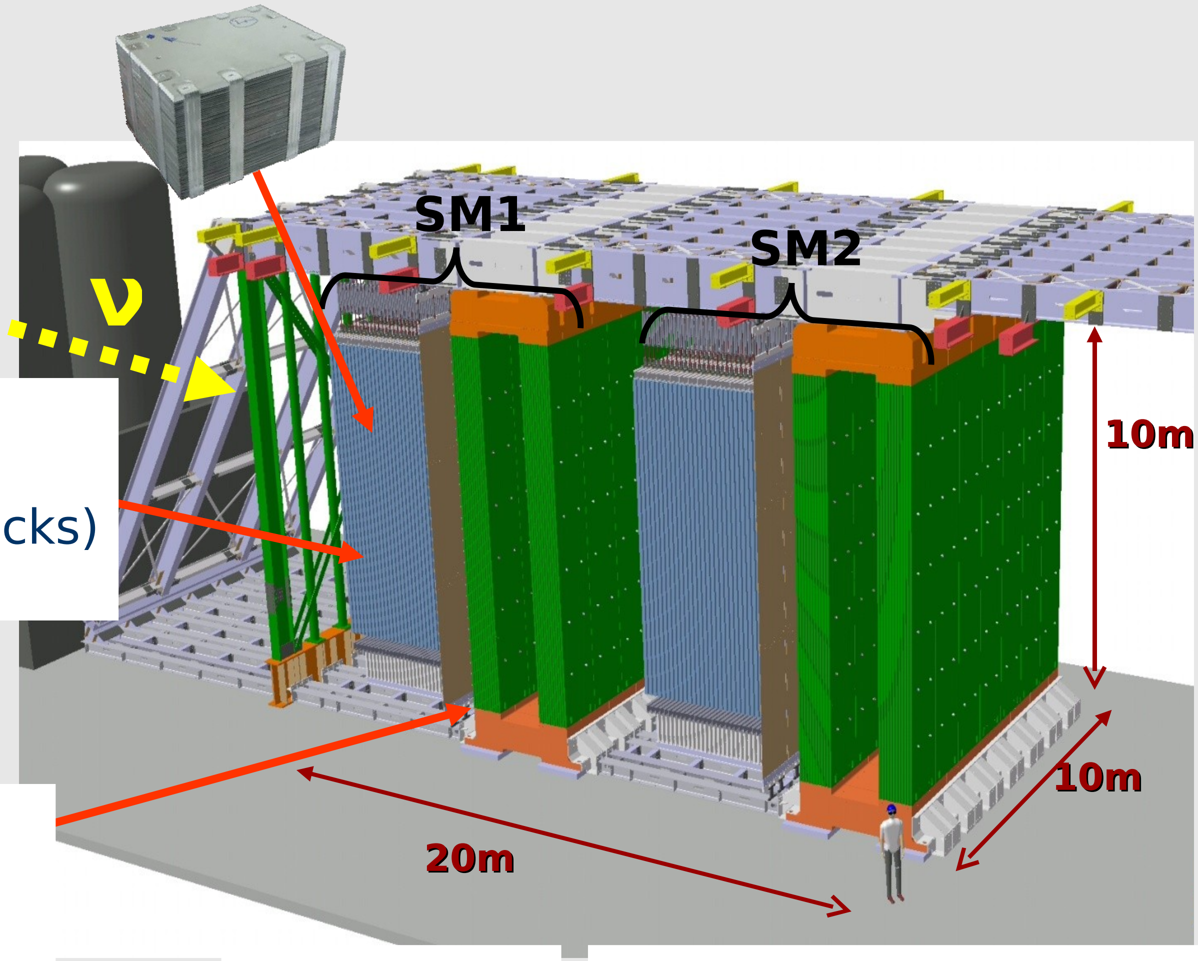




The OPERA Detector

Brick: ECC target basic unit (57 nuclear emulsion films + 56 lead plates, 8.3 kg)

Vertex finding, kink topology, kinematics measurements



Target section:
2 « super modules » (SM)
27(28) brick walls (75000 bricks)
31 Target Tracker walls (TT)

Neutrino interaction trigger
Brick selection

Magnetic spectrometer :
22 RPC planes / SM
6 drift tube planes (Precision tracks (PT) stations)

μ ID, charge, momentum

B = 1.53 T

Total target mass ~ 1.25 ktons

The OPERA Detector

1st SuperModule

2nd SM

Veto

Glass RPC,
~100m2

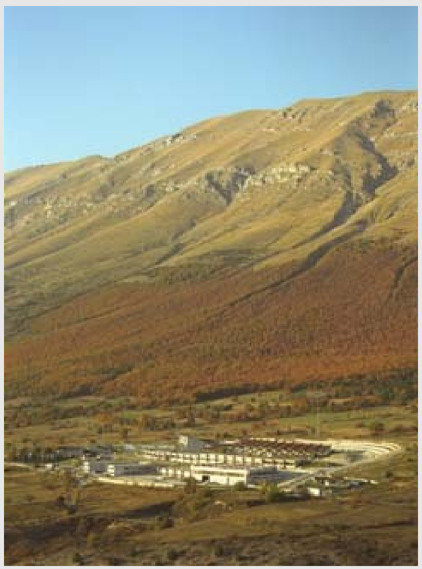
BMS

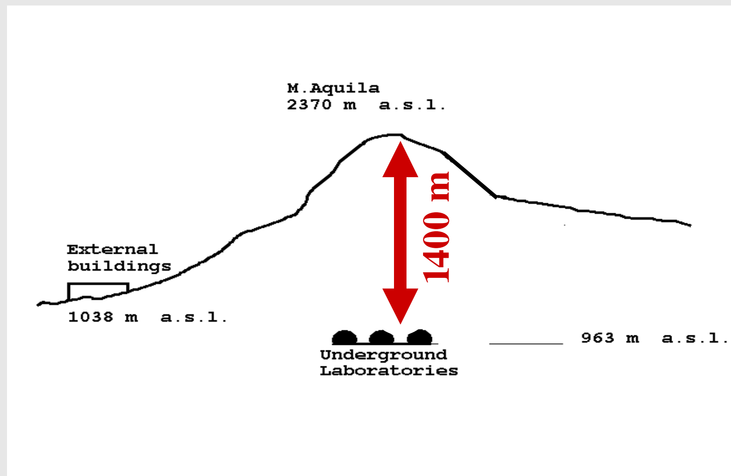
- RPC-XPC, 3050m2
- HPT, 10080 7m tubes
- ~2ktons Fe
- Dipolar magnet 1.55T

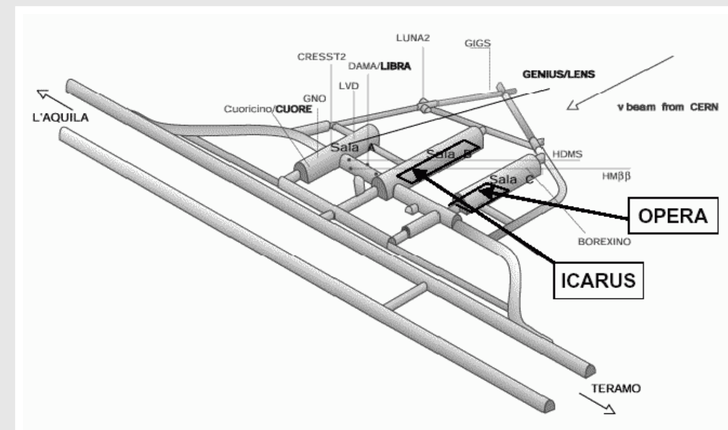
- brick walls (62 walls, 206000 bricks)
- scintillator target tracker (5900m2)

OPERA at LNGS Lab

Gran Sasso National Laboratory (LNGS) : the largest underground lab in the world.







Gran Sasso underground lab : on average 1400 m of rock shielding, cosmic ray flux reduced by a factor 10^6 w.r.t. surface, low radioactivity rock

With OPERA : charge and momentum measurement with the spectrometer at large depth.
"Non oscillations" analyses performed:

- Atmospheric neutrino induced muons
- Atmospheric muon charge ratio
- Neutrino velocity measurement

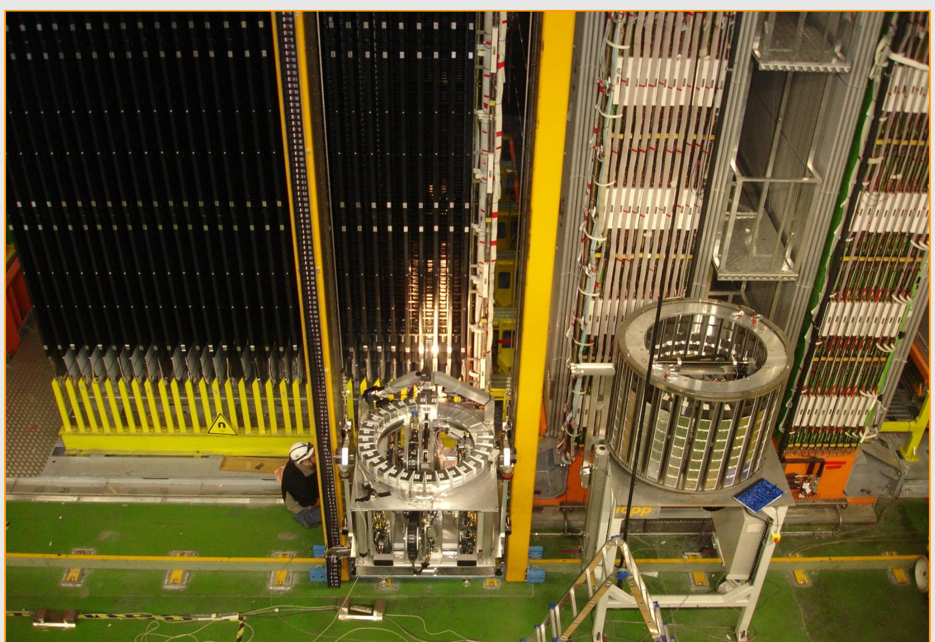
CNGS beam events are identified through a timing coincidence with CERN.

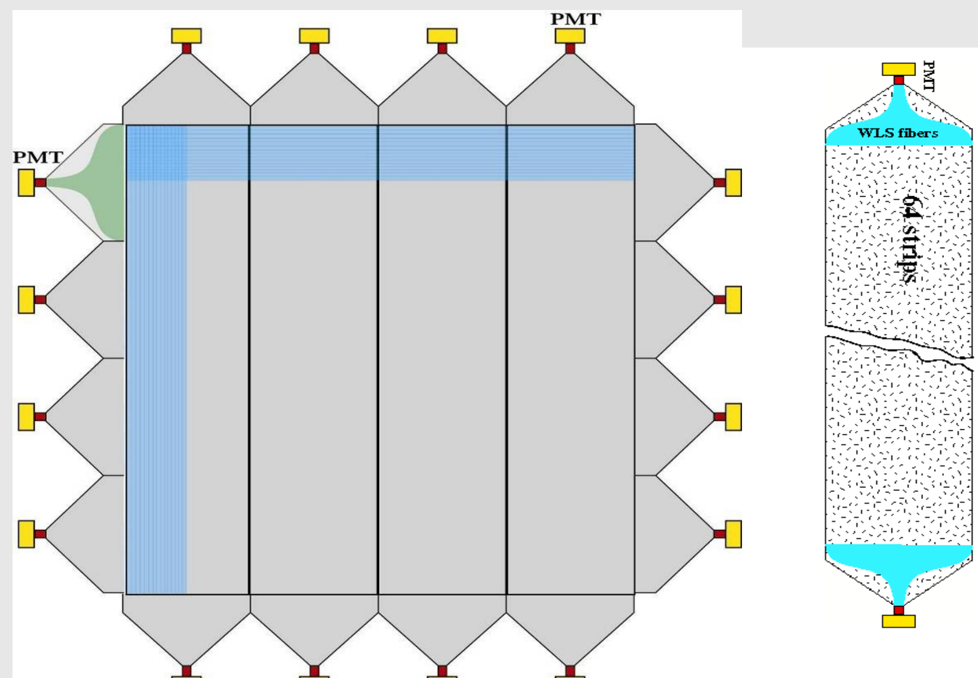
→ possibility to collect cosmic events during the physics run

Target Tracker

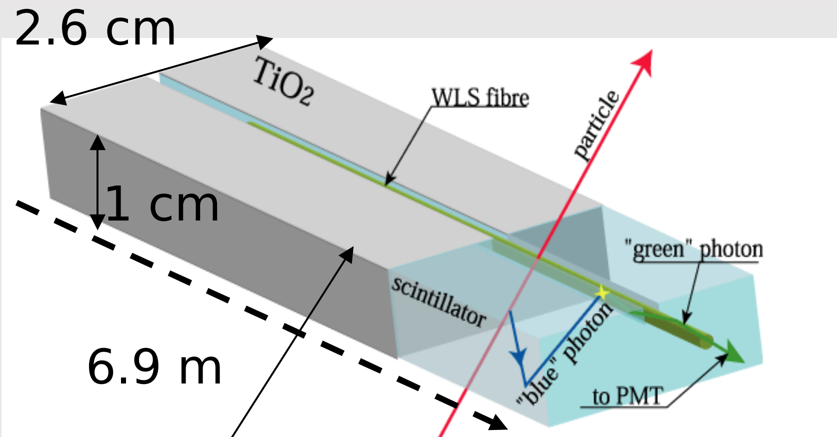
In one SM :
- 31 TT planes

In one TT plane :
- 8 modules of 64 scintillator strips with WLS fibres
- both ends readout via MaPMT + autotriggerable electronics
- event timestamp accuracy : 10ns
- timing corrections applied (propagation times, overall clock chain cabling : see later)

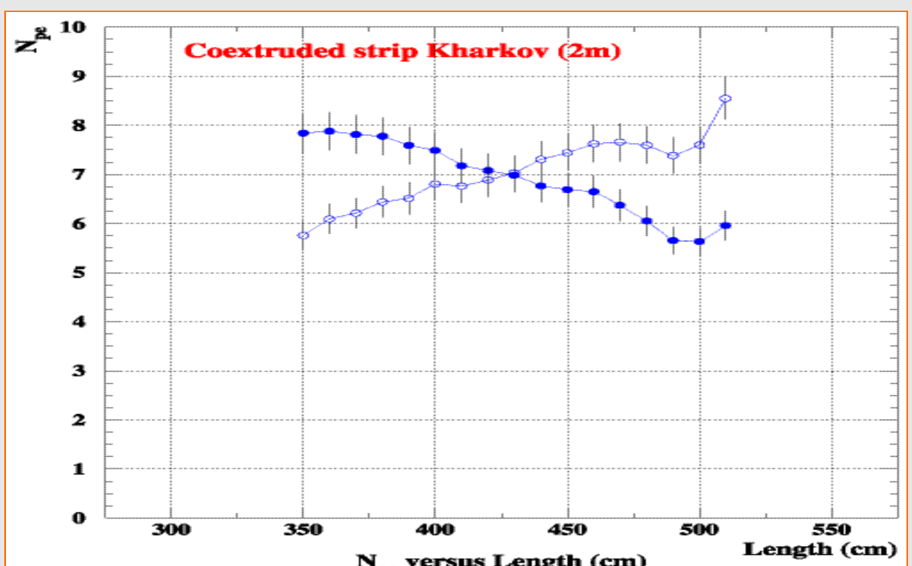


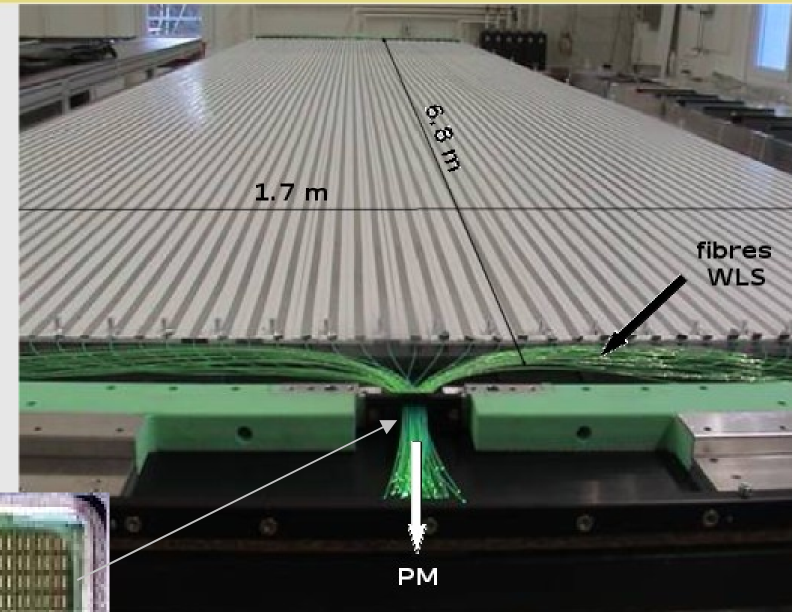


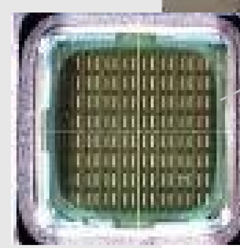
Target Tracker



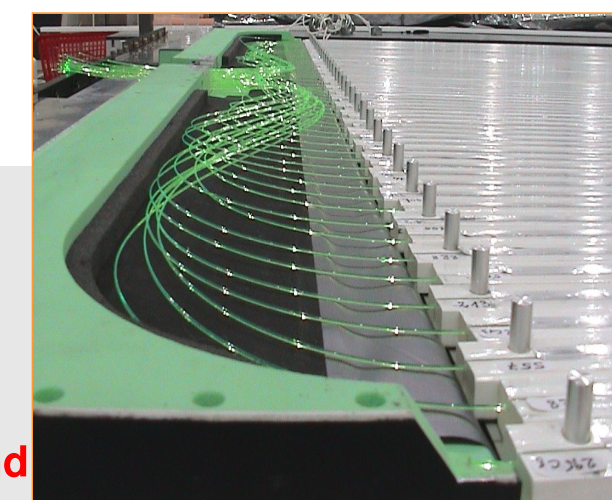
Extruded plastic scintillator strip







One TT module :
64 WLS fibres read
by a multipixel PM



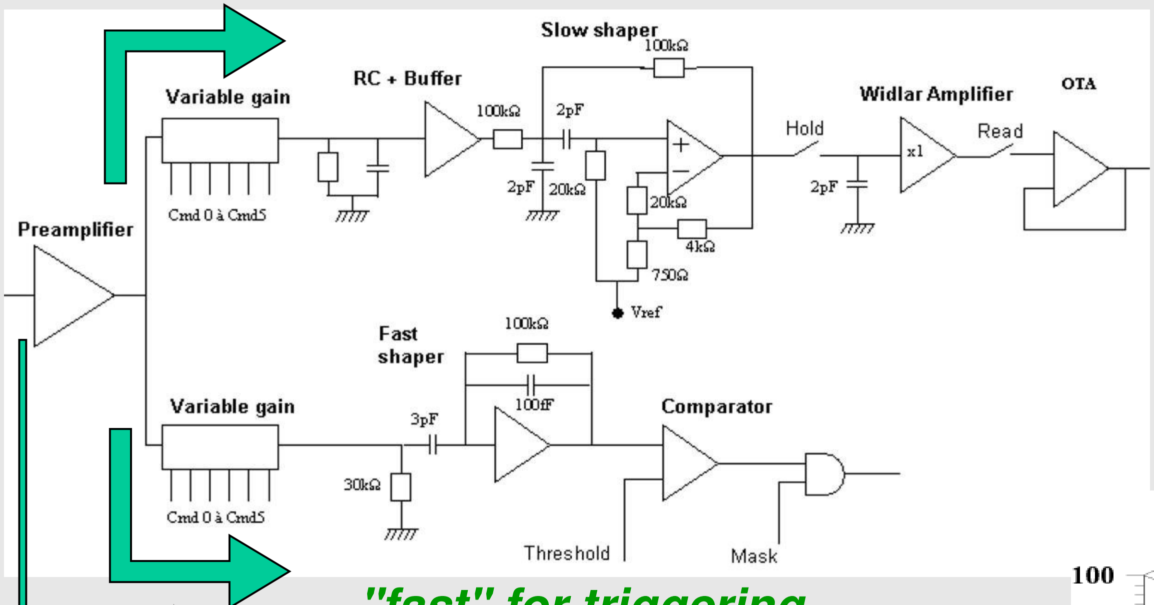
Requirement :

min. 5 p.e. / readout end

TT readout

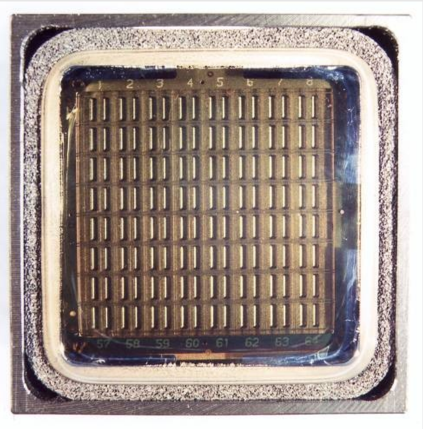
Front-End Chip :

"slow" for charge measurement



"fast" for triggering

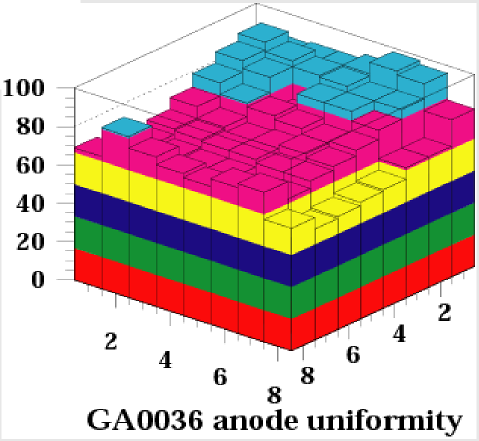
channel to channel
gain adjustment (1:4 range)

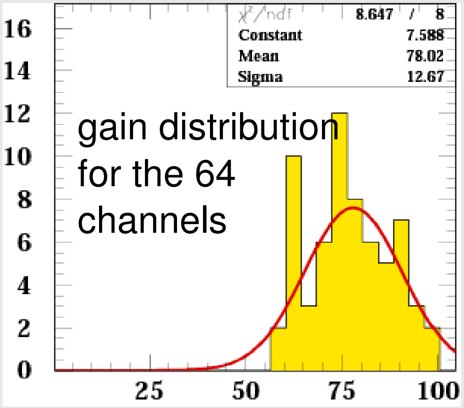


64 # MAPMT

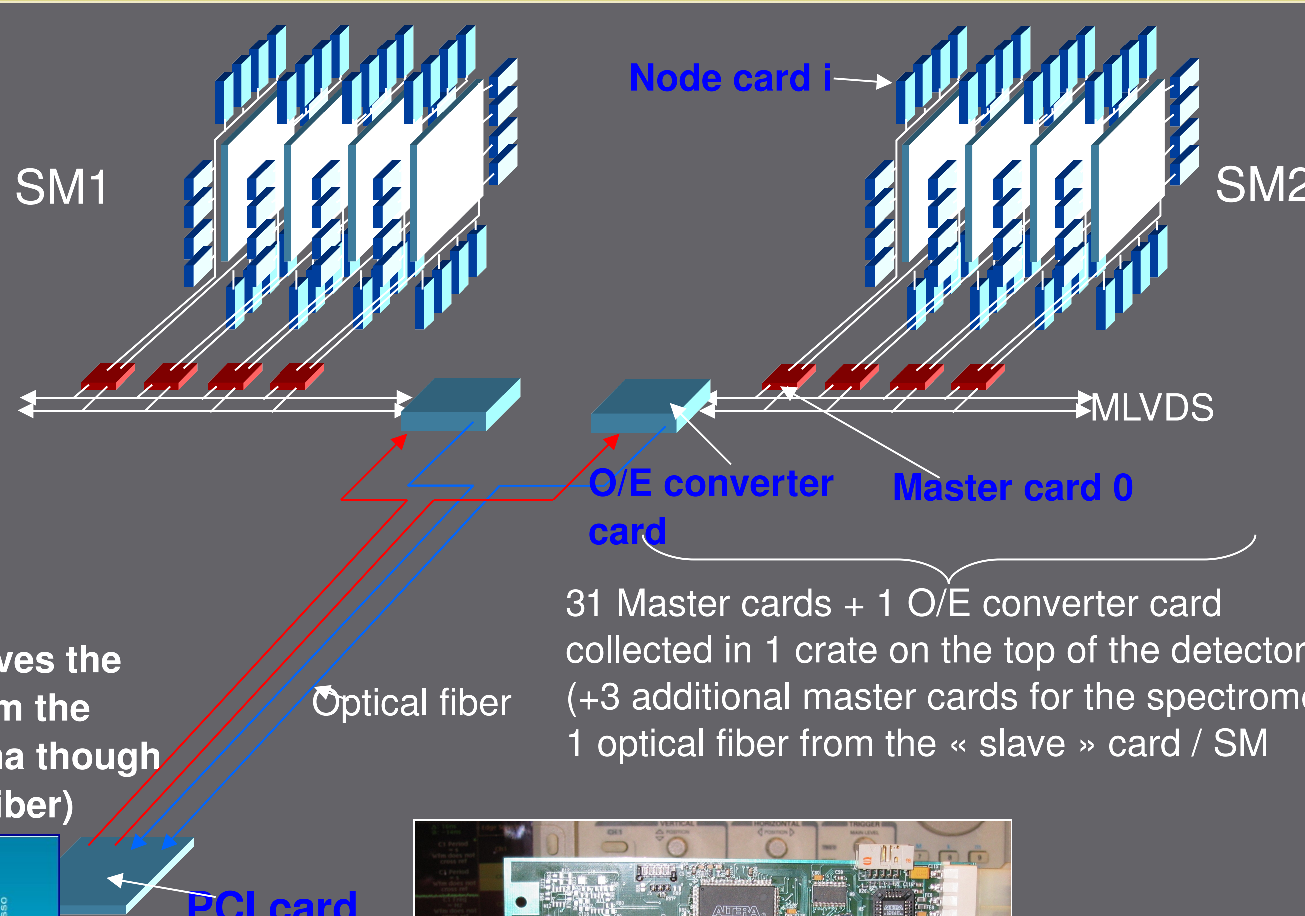
(Hamamatsu)

3x3 cm^2



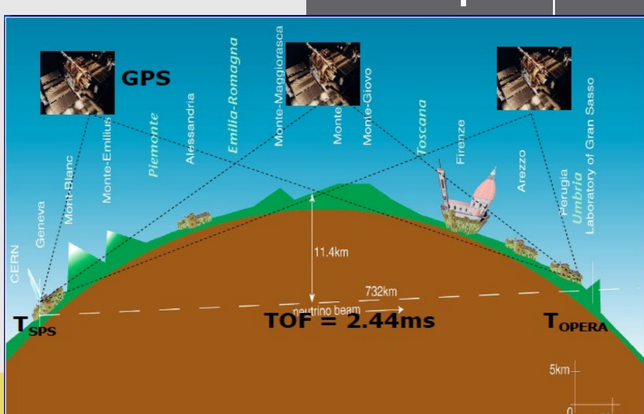


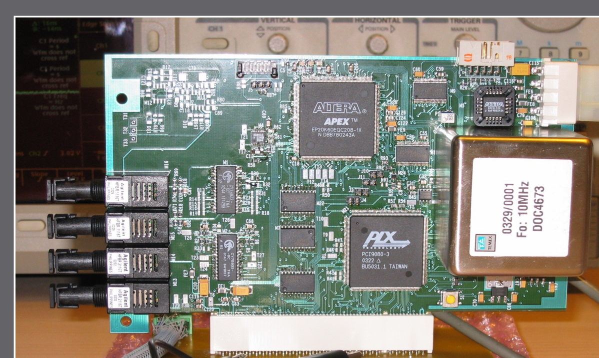
Clock distribution system



31 Master cards + 1 O/E converter card collected in 1 crate on the top of the detector (+3 additional master cards for the spectrometer)
1 optical fiber from the « slave » card / SM

« Slave » clock in Hall C (receives the GPS signal from the Outside antenna though a 8km optical fiber)





Real data sample

For real data :

→ 433.3 days of data taking

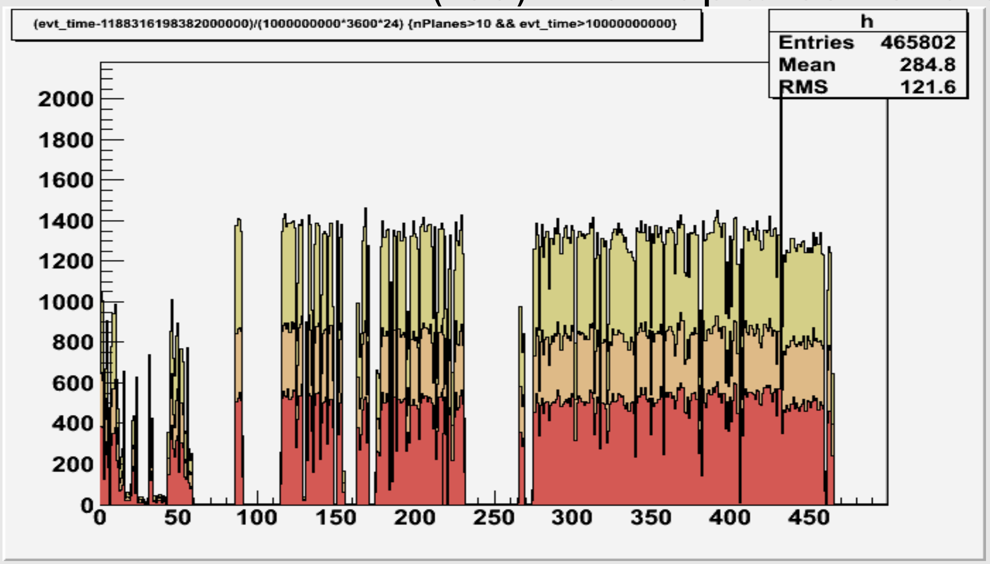
→ correspond to 2008 and 2009 opera runs

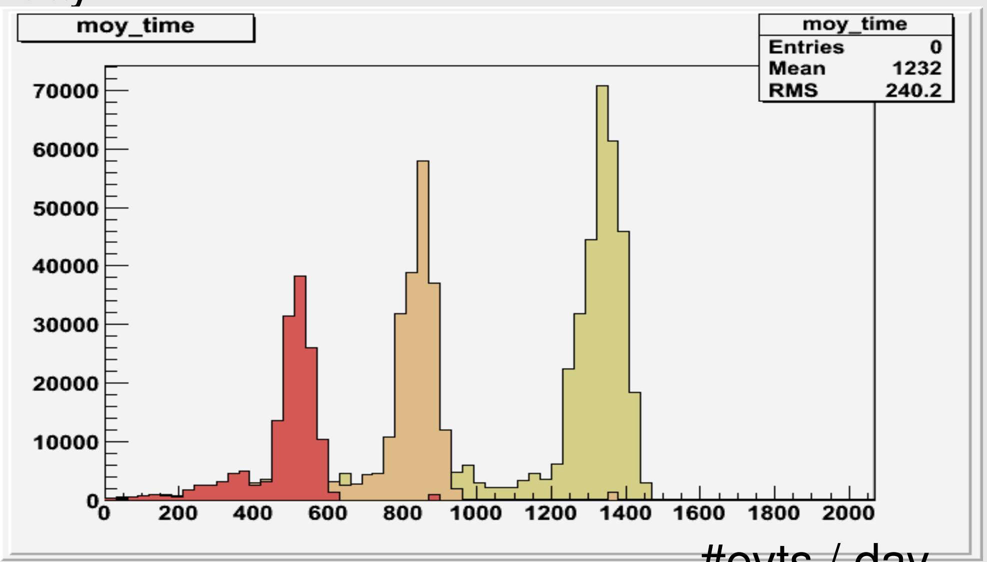
→ quality cut :

- on the mean rate of cosmics events (mean +- 3σ)

  → medium rates :

  - (green) >10 hit planes : 1336 evts/day
  - (orange) >15 hit planes : 841evts/day
  - (red) >20 hit planes : 520 evts/day





#evts / day

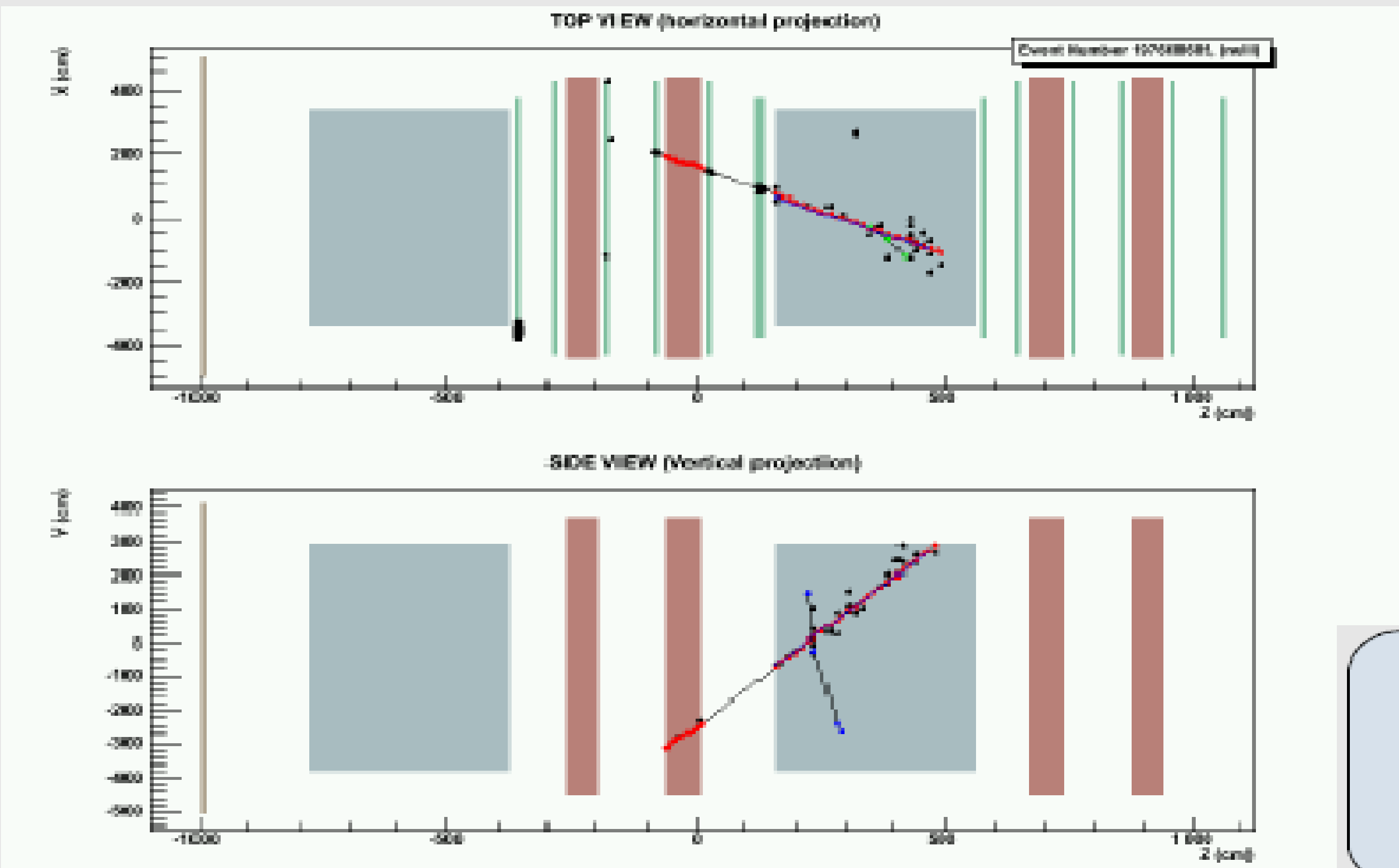
Data/MC comparison

Analysis cut :

→ cut : 0,75 < speed < 1,25 (MACRO value)

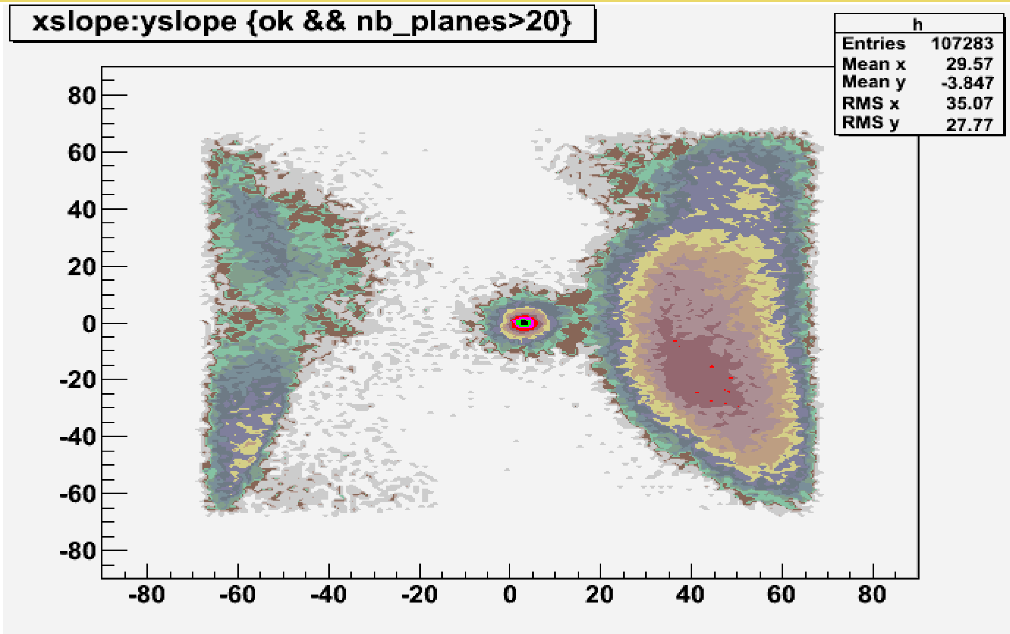
→ ~76% events left ! (but 5,3% of whole stat)

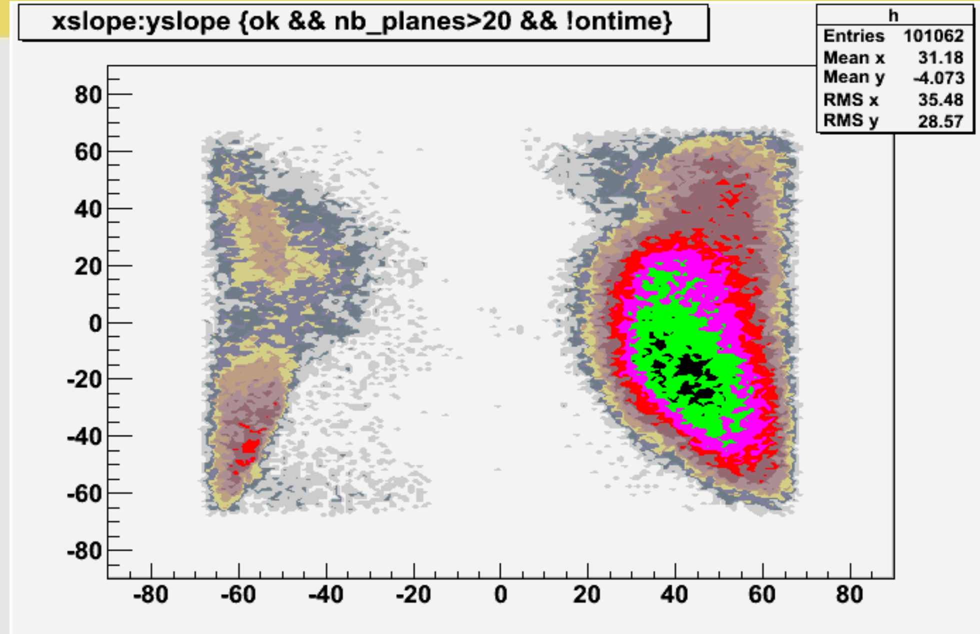
Expected : 11,3 events / observed : 15 events



Event 197668685 :
Wed, 24 Oct 2007 20:35:08 GMT
extraction #428
side view : 1/beta = 1,018
angle = 47,55°
3D length = 4,85 m

Data Analysis

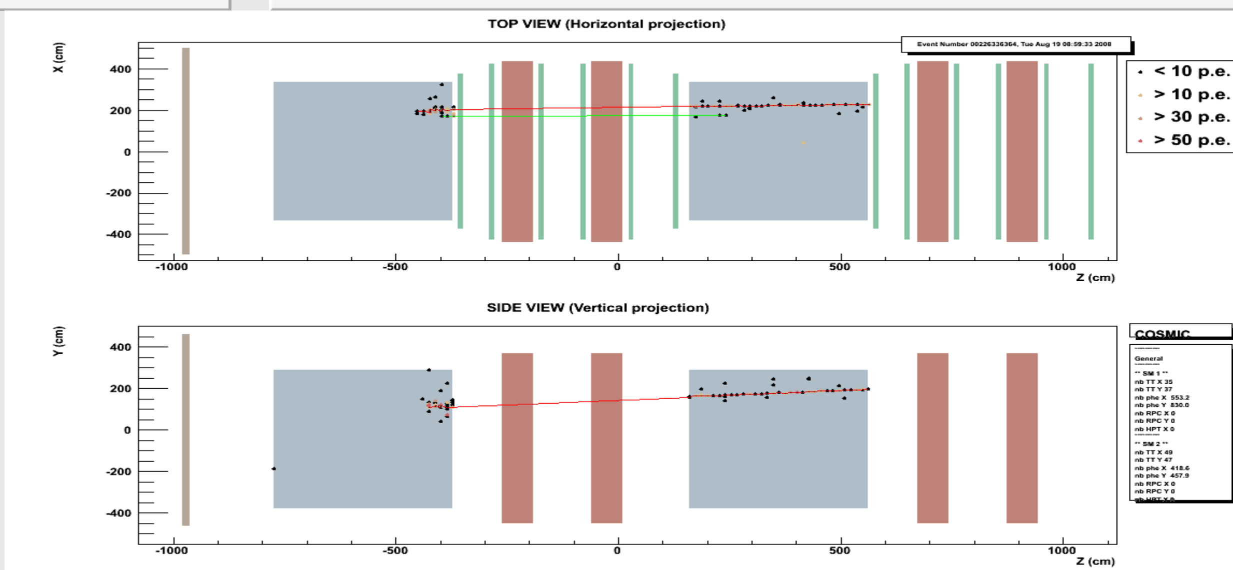




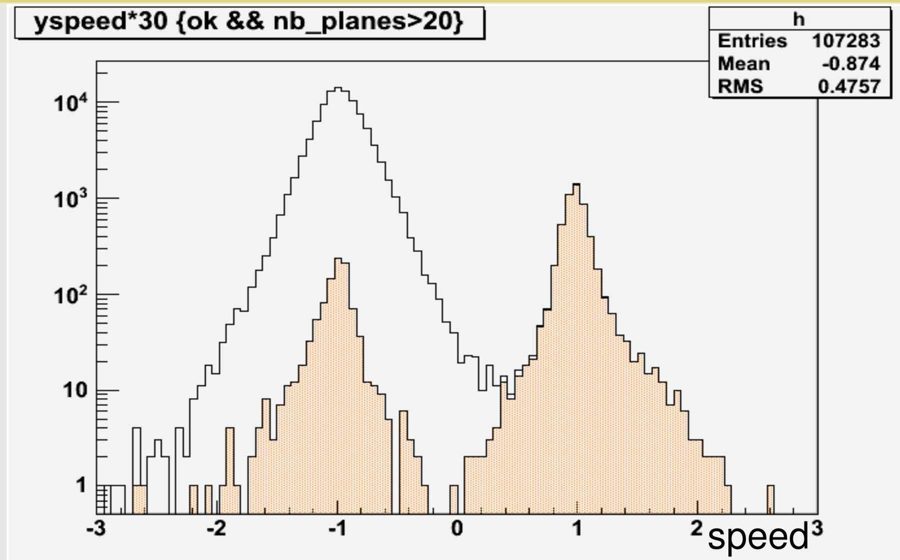
Beam events :

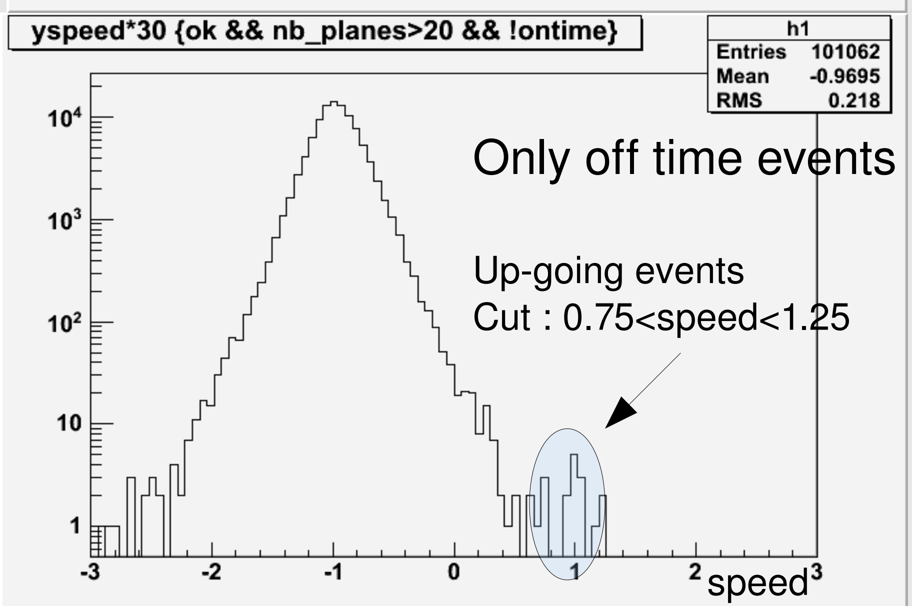
→ low X angle

→ low Y angle



Data Analysis

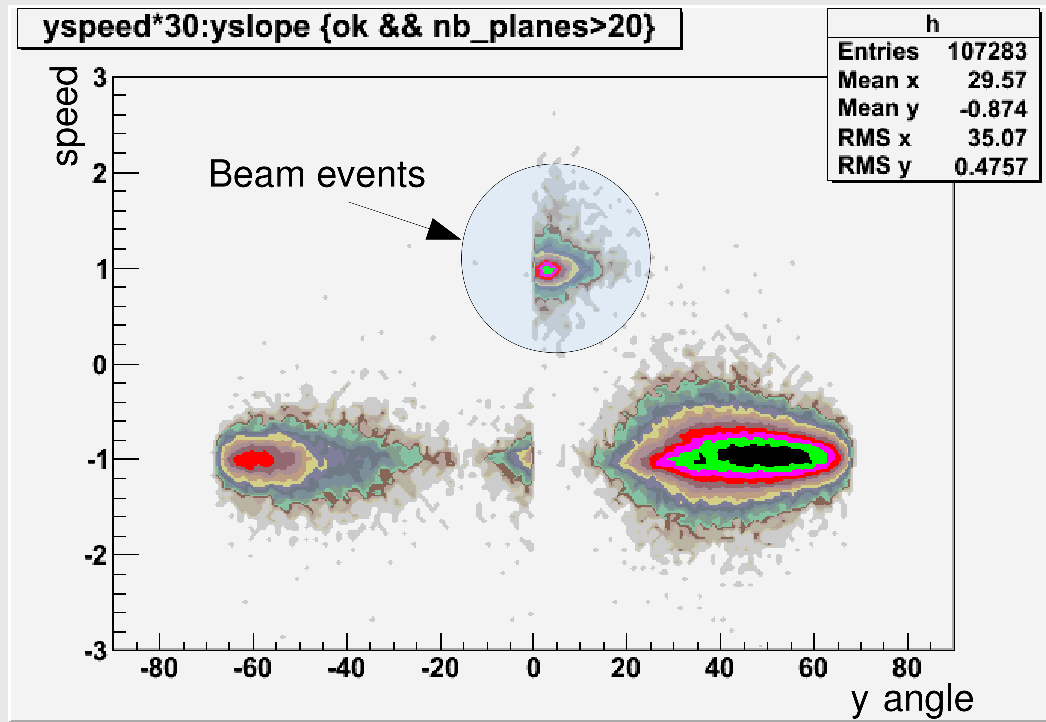




« speed » plots convention :

→ -1 peak : down-going particles

→ +1 peak : up-going particles

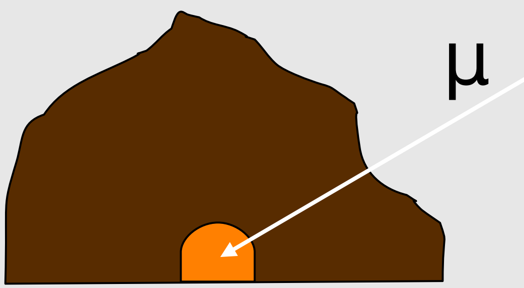


Speed function as angle for side view

Charge muons ratio

The atmospheric muon charge ratio $R_\mu = N\mu_+/N\mu_-$ mainly depends on:

1) the composition of primary cosmic rays (proton over neutron fraction)
2) the hadronic interactions in atmosphere (π^+/π^- and K^+/K^- ratios)



Underground experiments measure the charge ratio in a high energy region: muons are energy-selected with the overburden

$<E_\mu>$ underground: ~270 GeV
$<E_\mu>$ surface cut-off: ~1500 GeV

About 1): OPERA can provide R_μ separately for single muons and multiple muon bundles, testing the hypothesis of “dilution” of charge excess in neutron-enriched primaries.

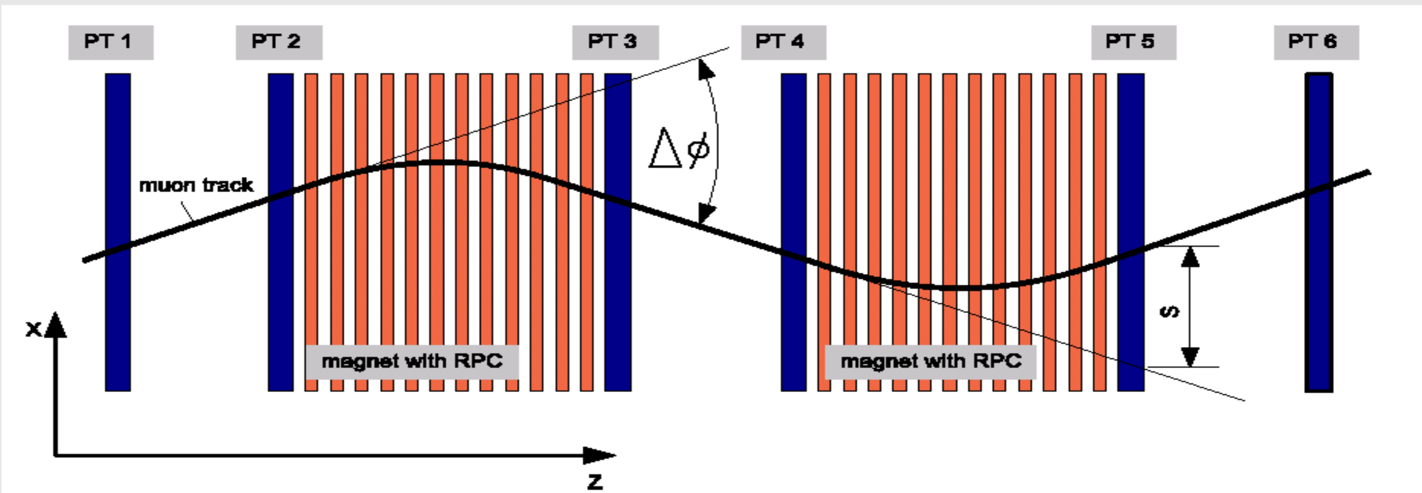
About 2): The underground charge ratio measurement gives useful information on K production in the TeV fragmentation region, where there are no data from accelerators

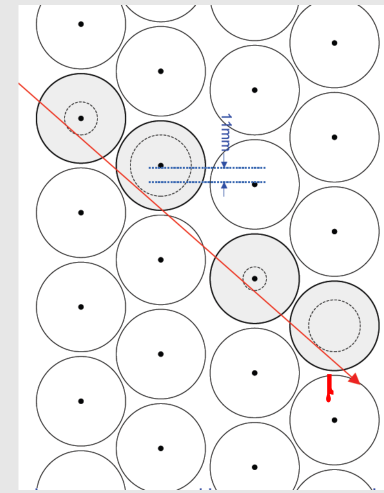
This measure can provide constraints on theoretical hadronic models, in particular for fluxes of atmospheric TeV ν‘s (dominated by K production).

OPERA can measure the atmospheric muon charge ratio in the TeV energy range, where the kaon contribution becomes significant.

Charge muons ratio

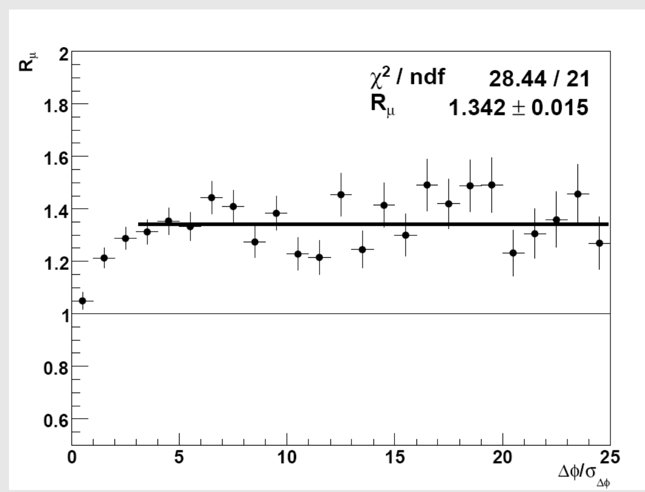
→ Analysis based on the deflection angle Δφ in the spectrometers

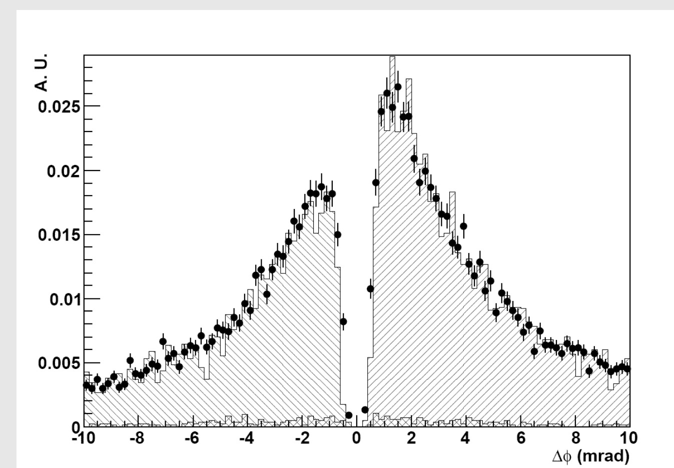




→ <u>Main analysis cuts :</u>

- At least 1 reconstructed angle Δφ
- “Clean” PT events
- “Good” deflection angles





→ Good deflections means Δφ larger than the experimental resolution

Exp. data
MC data

Charge muons ratio

→ Progressive reduction (expressed as events/day, absoulute normalization)

	Exp. data [events/day]	Monte Carlo [events/day]
Acceptance	992 (100%)	1219 (100%)
Clean PT	515 (51.9%)	951 (78.0%)
Deflection	391 (39.4%)	700 (57.4%)
Single μ	379 (38.2%)	666 (54.6%)
Multiple μ	12 (1.2%)	34 (2.8%)

→ Total number of events after cuts = 44370

→ Using Monte Carlo, we evaluated the charge misidentification η, i.e. The fraction of tracks with wrong charge reconstruction. After cuts, η = (4.12 ± 0.14)%

→ η value used to unfold :

$$R_\mu^{unf} = \frac{\eta - (1-\eta) R_\mu^{meas}}{\eta R_\mu^{meas} - (1-\eta)}$$

→ the result, for single and multiple muon event separately, is:

M_μ	$\langle A \rangle$	$\langle E/A \rangle_{primary}$	H fraction	N_p/N_n	R_μ^{unf}
=1	3.35±0.09	(19.4±0.1) TeV	0.667±0.007	4.99±0.05	1.389±0.015
>1	8.5±0.3	(77±1) TeV	0.352±0.012	2.09±0.07	1.24±0.07

Syst. Err. on R_μ^{unf} :

+0.009
-0.006

Indication at 2.1σ level of $R_\mu(M_\mu=1) \neq R_\mu(M_\mu>1)$

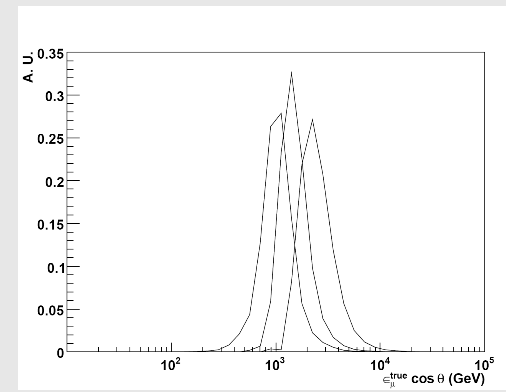
Charge muons ratio

Final data sample divided in three bins of $E_\mu \cos\theta$ (resolution dominated by the stochastic term in the energy loss)

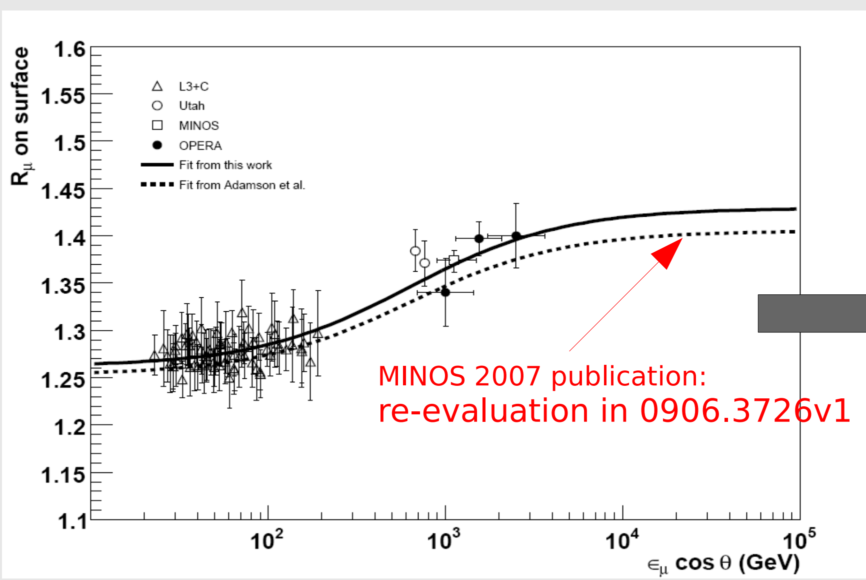
→ Compute and unfold the charge ratio in each bin

→ Fit with the function
$$\phi_{\mu^\pm} \propto \frac{a_\pi f_{\pi^\pm}}{1 + b_\pi \mathcal{E}_\mu \cos\theta / \epsilon_\pi} + R_{K\pi} \frac{a_K f_{K^\pm}}{1 + b_K \mathcal{E}_\mu \cos\theta / \epsilon_K}$$
keeping the meson charge ratios as free parameters

→ Charge asymmetry (~0.5%) in muon propagation not (yet) considered



True values of $E_\mu \cos\theta$ (from Monte Carlo) in the three bins

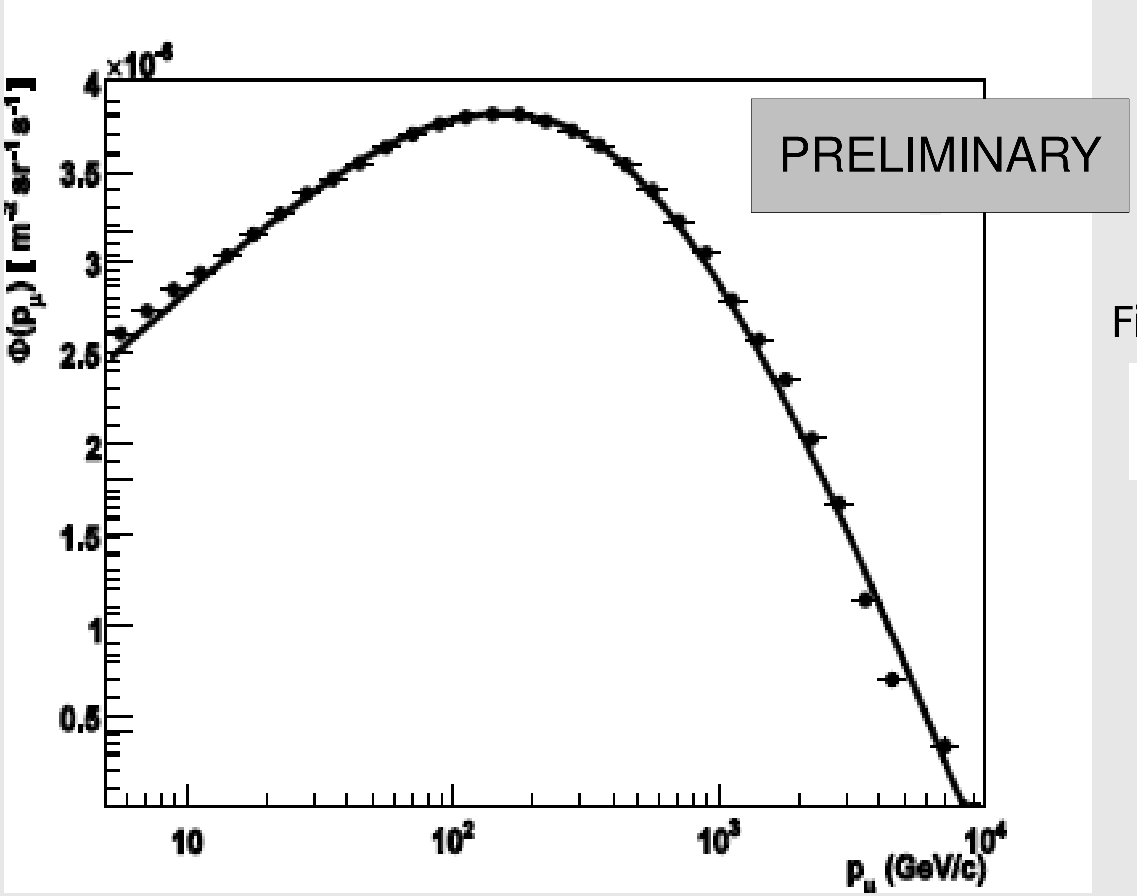


Fixing $R_{K\pi}$ = 0.149 (Gaisser):
$R_\pi = Z_{N\pi+}/Z_{N\pi-} = 1.226 \pm 0.001$
$R_K = Z_{NK+}/Z_{NK-} = 2.19 \pm 0.03$

Fixing R_π = 1.226:
$R_{K\pi} = 0.11 \pm 0.10$
$R_K = 2.73 \pm 0.04$

Underground muon spectrum

Underground muon spectrum directly related to the primary cosmic ray index :



Unfolded muon Spectrum
- method: Bayes
- software: RooUnfold

Fit with the function, α and β fixed, γ free :

$$\Phi(E_\mu) = const[E_\mu + \alpha/\beta(1 - e^{-\beta h})]^{-(\gamma+1)}$$

$$\gamma = 2.82 \pm 0.02$$

OPERA-LVD Coincicences

→ Study of high pT phenomena

→ Large muon separation is the convolution of muon production height and meson transverse momentum:

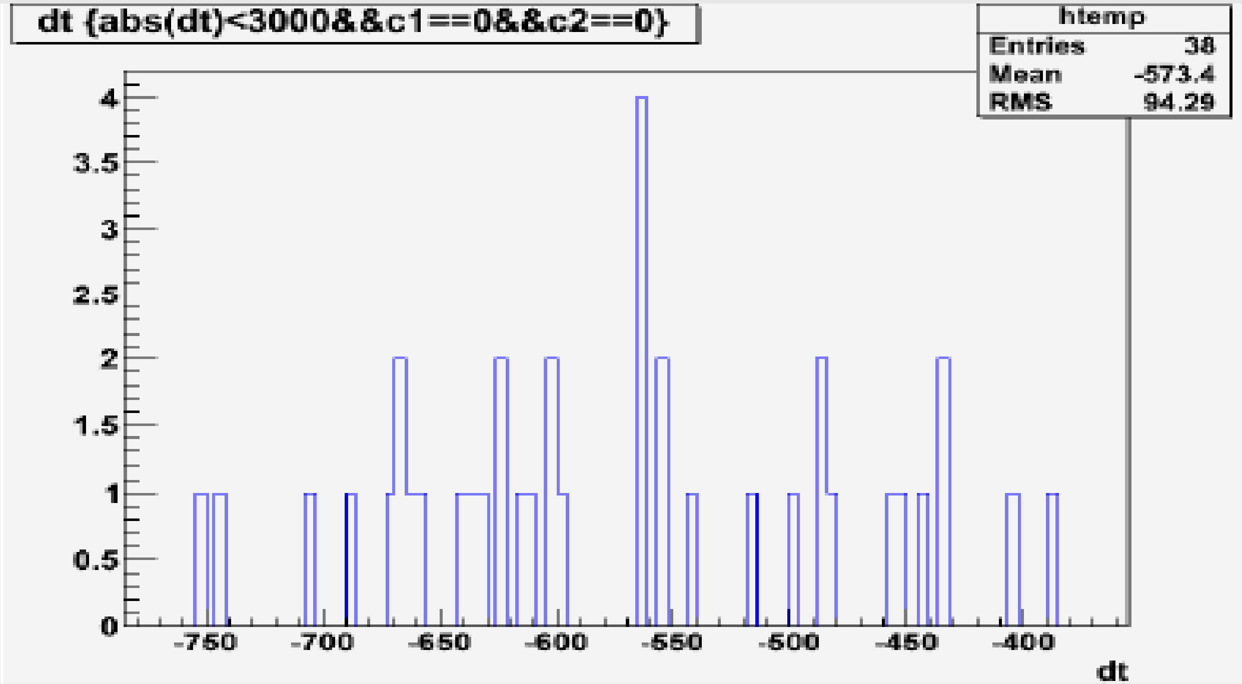
$$r \sim \frac{P_t}{x_F^{\pi,K} E_0} H_{prod} \propto \frac{P_t}{x_F^{\pi,K} E_0} \left(\log \sigma_{n-Air}^{inel} + const. \right)$$

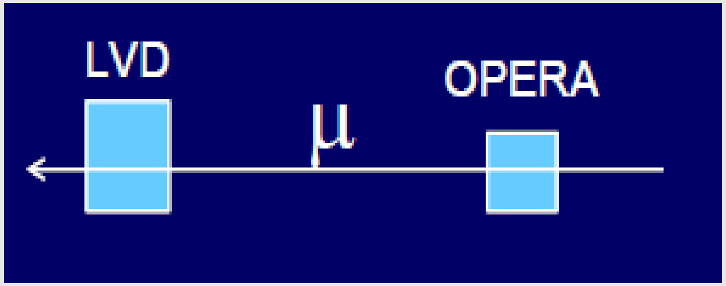
→ Roughly double the MACRO linear extension:
– MACRO ~70m
– OPERA → T600 ~90m
– OPERA → LVD ~170m

→ At this distances/pT (> 2 GeV/c) we get inside pQCD → predictions not strictly related to forward modeling

→ Possibility to study also beam events (cross-check for timing and search for large angle di-muon events)

OPERA-LVD Coincicences





38 events peaked at -573.4 ns!

→ Explanation (confirmed by visual inspection) : all events coming from the "Teramo valley" sticking OPERA first and LVD after

→ Distance measured by ToF: 573ns × 0.3m/ns = 172m (Expectations : dmin÷dmax=170m÷176m → Δtmin÷Δtmax= -587ns÷-567ns)

Conclusions

The OPERA experiment, running at Gran Sasso, was used as a cosmic ray detector.

Four experimental results presented:

→ Atmospheric ν's. 15 observed events vs 11 expected: physics potential limited by acceptance.
→ Cosmic ray charge ratio. Data provided at the largest $E\mu\cos\theta$ values.
→ Underground muon spectrum. Experimental data with the primary cosmic ray γ index.
→ OPERA-LVD coincidences. Technique proven, new results with the forthcoming data.

Charge muons ratio

Simplified model of the atmospheric muon charge ratio (Gaisser)

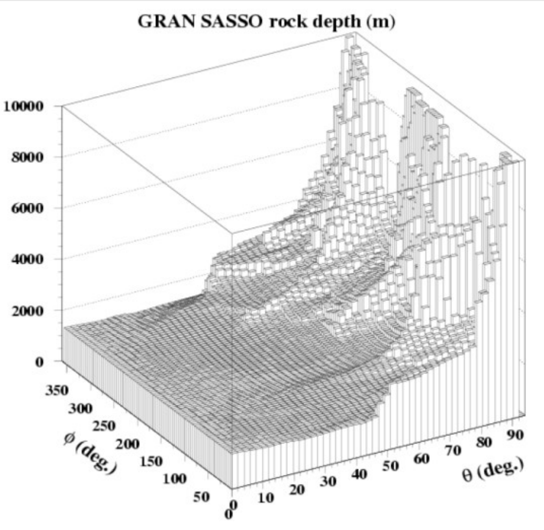
$$\phi_{\mu^\pm} = \frac{\phi_0 \mathcal{E}_\mu^{-\gamma}}{1 - Z_{NN}} \left\{ \frac{a_\pi Z_{N\pi^\pm}}{1 + b_\pi \mathcal{E}_\mu \cos\theta/\epsilon_\pi} + \frac{a_K Z_{NK^\pm}}{1 + b_K \mathcal{E}_\mu \cos\theta/\epsilon_K} \right\}$$

where $\mathbf{E_\mu}$ is the muon energy in atmosphere, θ is the zenith angle, γ ~ 2.7 is the primary cosmic ray spectral index, $a_{\pi/K}$ and $b_{\pi/K}$ are known kinematical factors, $\epsilon_{\pi/K}$ are π/*K* critical energies. The spectrum weighted moments are defined:

$$Z_{ij} \equiv \int_0^1 \frac{1}{\sigma_{ij}} \frac{d\sigma_{ij}}{dx_{lab}} (x_{lab})^{\gamma-1} dx_{lab}$$

Where σ_{ij} are the inclusive cross sections and $x_{lab} \sim x_{Feynman}$

Measuring R_μ as a function of $E_\mu \cos\theta$ we can infer the parameters $R_\pi = Z_{N\pi+}/Z_{N\pi-}$ and $R_K = Z_{NK+}/Z_{NK}$



OPERA is the underground experiment with the largest $E_\mu \cos\theta$:
- UTAH (1975): $\langle E_\mu \cos\theta \rangle \approx 500$ GeV
- MINOS (2007): $\langle E \cos\theta \rangle \approx 1000$ GeV
- OPERA (2009): $\langle E_\mu \cos\theta \rangle \approx 2000$ GeV