Inclusive muon measurement: atmospheric muon charge ratio with the OPERA detector

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INFN-LNF

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Atmospheric muon charge ratio

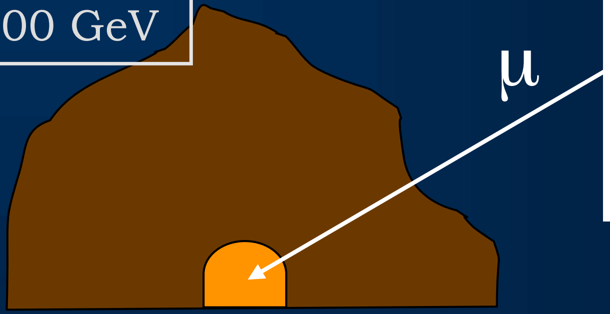
- The atmospheric muon charge ratio $R_\mu \equiv N_{\mu+}/N_{\mu-}$ is being studied and measured since many decades
  - Depends on the chemical composition and energy spectrum of the primary cosmic rays
  - Depends on the hadronic interaction features
  - At high energy, depends on the prompt component
- It provides the possibility to check HE hadronic interaction models (E > TeV) 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)

Atmospheric muon charge ratio

The atmospheric muon charge ratio R_μ mainly depends on:

1) the composition of primary cosmic rays (n/p ratio in the all-nucleon spectrum)
2) the hadronic interactions in atmosphere (π^+/π^- and K^+/K^- ratios)

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



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

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)

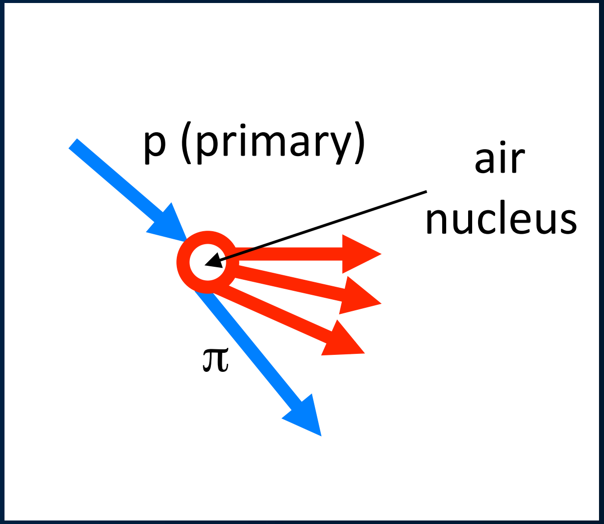
OPERA can measure the atmospheric muon charge ratio in the TeV energy range, where the kaon contribution becomes significant

Analytic predictions

Naïve prediction

- Assume only primary protons with a spectrum $dN/dE = N_0 E^{-(1+\gamma)}$
- Assume only pions and neglect muon decays (HE limit)
- Consider the inclusive cross-section for pions

$$f^{\pm}_{p\pi}(E_\pi,E_p) \equiv \frac{E_\pi}{\sigma^{inel}_{pp}} \frac{d\sigma^{\pm}_{p\to\pi}}{dE_\pi}$$



The pion spectrum is then

$$\pi(E_\pi) = \frac{(const)}{E_\pi}\int_{E_\pi}^{\infty} dE\, E^{-(1+\gamma)} f^{\pm}_{p\pi}(E_\pi,E_p)$$

Assuming Feynman scaling

$$f^{\pm}_{p\pi}(E_\pi,E_p) \equiv \frac{E_\pi}{\sigma^{inel}_{pp}}\frac{d\sigma^{\pm}_{p\to\pi}}{dE_\pi} \xrightarrow[E\to\infty]{} \tilde{f}^{\pm}_{p\pi}(x)$$

Feynman scaling

Analytic predictions

The pion spectum becomes:

$$\pi^{\pm}(E_\pi) = (const) E_\pi^{-(1+\gamma)} Z_{p\pi^{\pm}}$$

$$Z_{p\pi^{\pm}} \equiv \int_0^1 \tilde{f}_{p\pi}^{\pm}(x) x^{\gamma-1} dx$$

Spectrum weighted moments

Finally, the muon charge ratio prediction:

$$R_\mu = \frac{\mu^+(E_\mu)}{\mu^-(E_\mu)} = \frac{\pi^+(E_\pi)}{\pi^-(E_\pi)} = \frac{Z_{p\pi^+}}{Z_{p\pi^-}}$$

Interpretation of the prominent features:

- The result is valid only in the fragmentation region, since in the central region Feynman scaling is strongly violated
- But the steeply falling primary spectrum (γ ~ 1.7) in the SWM suppresses the contribution of the central region in the secondary production → scaling holds (at least for E < 1 TeV);

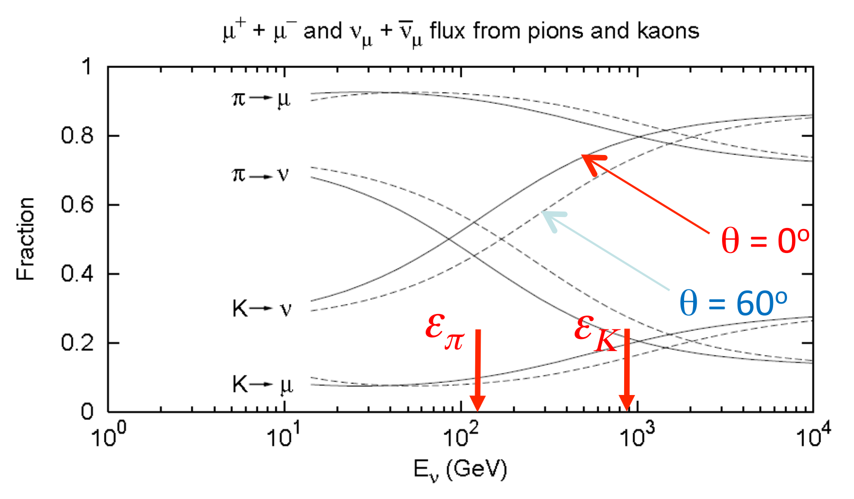
In other words: each pion is likely to have an energy close to the one of the projectile (primary CR proton) and comes from its fragmentation (valence quarks)

→ positive charge

- R_μ does not depend on E_π (or E_μ) nor on the target nature
- R_μ depends on the primary spectrum γ

Kaon contribution

- At higher energy (>100 GeV) the contribution of K becomes important
- In general, the contribution of each component to the muon flux N_{par} = (π, K, charmed, etc.) depends on the relative contribution of decays and interaction probabilities:



$$\boxed{\Phi_\mu = \frac{\Phi_N(\mathrm{E}_\mu)}{1 - Z_{NN}} \sum_{i=1}^{N_{par}} \frac{a_i Z_{Ni}}{1 + b_i \mathrm{E}_\mu / \varepsilon_i(\theta)}}$$

where

$$a_i = a_i(\gamma) = \frac{(1 - r_i^{\gamma+1}) Br(i \to \mu)}{(1 - r_i)(\gamma + 1)}$$

$$b_i = b_i(\gamma) = \frac{(\gamma + 2)(1 - r_i^{\gamma+1})(\lambda_i - \lambda_N)}{(\gamma + 1)(1 - r_i^{\gamma+2})(\lambda_i \log \lambda_i / \lambda_N)}$$

$$r_i = (m_\mu / m_i)^2$$

$\varepsilon_i = \varepsilon_i(\theta)$ is the "critical energy", i.e. the energy above which interactions dominate over decays. Along the vertical (θ = 0°) $\varepsilon_i(0) = m_i c h / \tau_i$ (h = 6.5 km)

ε_π = 115 GeV
ε_K = 850 GeV
$\varepsilon_X > 10^7$ GeV

Kaon contribution to R_μ

For kaons:

$$Z_{pK^+} >> Z_{nK^-} \approx Z_{pK^-}$$

because the reaction

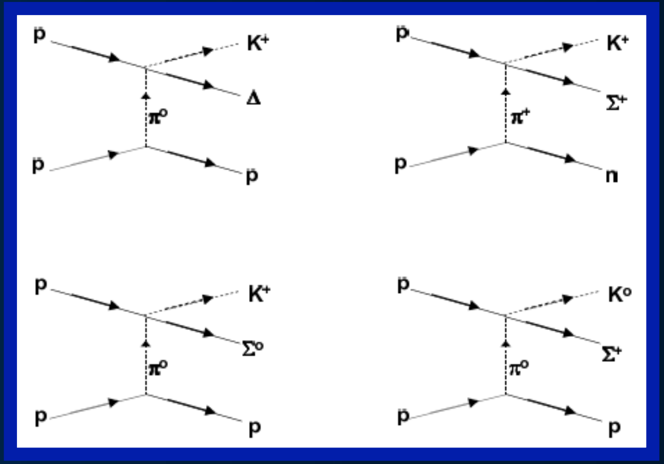
$$pp \rightarrow K^+ \Lambda N + \text{anything}$$

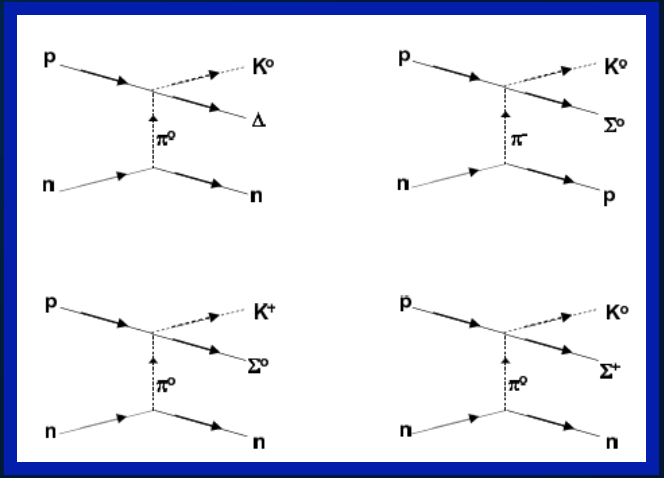
is favoured.

Conservation of strangeness requires production of K^+ and K^0 in association with a Λ or Σ.

On the other hand, the production of $K^-, \overline{K}^0$ requires the creation of an associated baryon and an additional strange meson.

This leads to a larger R_μ ratio at high energy

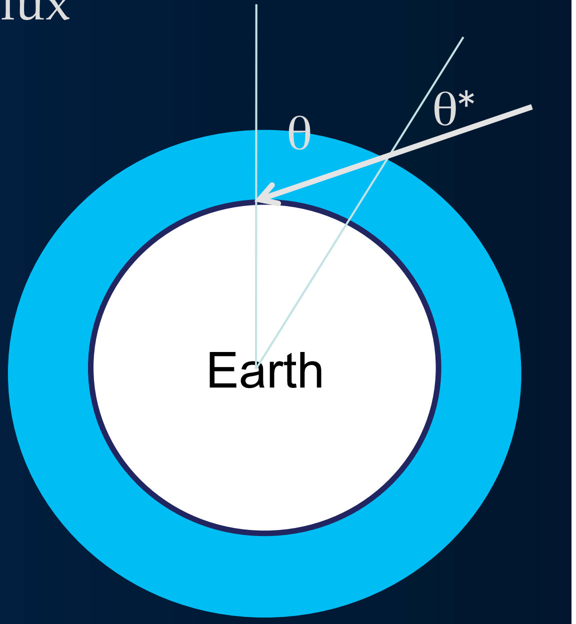




General form for R_μ

- Let us consider again the general form for the muon flux

$$\boxed{\Phi_{\mu^\pm} = \frac{\Phi_N(\mathbf{E}_\mu)}{1-Z_{NN}} \sum_{i=1}^{N_{par}} \frac{a_i Z^\pm_{Ni}}{1+b_i \mathbf{E}_\mu \cos\theta^* / \varepsilon_i(0)}}$$



where we have explicited the $\varepsilon_i(\theta)$ dependence on θ

$$\varepsilon_i(\theta) = \varepsilon_i(0)/\cos\theta^*$$

where θ* is the zenith angle at the production point

- The correct variable to describe the evolution of R_μ is therefore $E_\mu\cos\theta^*$
- The R_μ evolution as a function of $E_\mu\cos\theta^*$ spans over the different sources

$R_\mu = w_\pi R_\mu^\pi + w_K R_\mu^K + w_{charm} R_\mu^{charm} + \ldots$ → POWERFUL HANDLE TO DISCRIMINATE MODELS

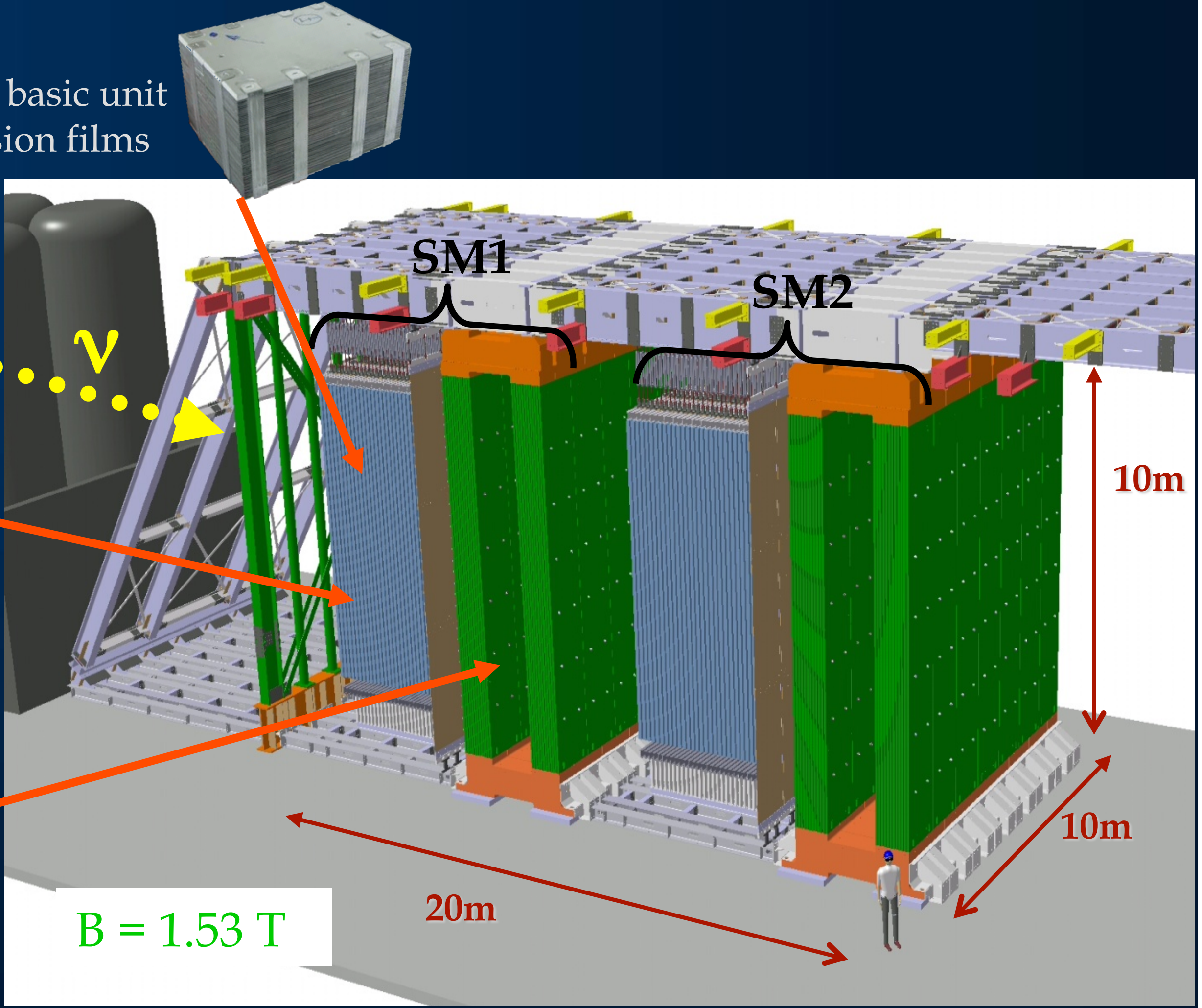
Measuring R_μ as a function of $E_\mu\cos\theta^*$ we can infer the parameters $R_\pi = Z_{N\pi+}/Z_{N\pi-}$ and $R_K = Z_{NK+}/Z_{NK-}$

OPERA: $\langle E_\mu\cos\theta^*\rangle \approx 2000$ GeV → **The (magnetized) experiment with the largest $E_\mu\cos\theta^*$**

R_μ measurements with $E_\mu \cos\theta^* > 1$ TeV

- Utah:
  G. K. Ashley et al., Phys. Rev. D12 (1975) 20
  - Underground at Utah University, flat surface above ~1400 m.w.e., magnetic spectrometer (1.63 T) + spark chambers, six bins with $46° < \theta < 78°$
- Kamiokande-II:
  M. Yamada et al., Phys. Rev. D44 (1991) 617
  - Underground Cherenkov detector at Kamioka ~2700 m.w.e., delayed events on stopping muons, one bin with $0° < \theta < 90°$
- MINOS:
  P. Adamson et al., Phys. Rev. D76 (2007) 052003 + arXiv:0906.3726
  - Underground at Soudan, magnetized steel, flat surface above ~2000 m.w.e., $0° < \theta < 90°$
- LVD:
  N. Agafonova et al., Proc. 31th ICRC, ŁÓDZ 2009
  - Underground at LNGS, average overburden ~3800 m.w.e., scintillators, delayed events on stopping muons, one bin with $\theta < 15°$
- **OPERA:**
  N. Agafonova et al., Eur. Phys. J. C67 (2010) 25
  - Underground magnetic spectrometer (1.53 T) at LNGS, average overburden ~3800 m.w.e., drift tubes + RPC + scintillators, $0° < \theta < 90°$

The OPERA detector



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

Target section:
27 brick walls (75000 bricks)
31 Target Tracker walls (TT)

Neutrino interaction trigger
Brick selection
Calorimetry

Magnetic spectrometer:
22 RPC planes
6 drift tube layers (PT stations)

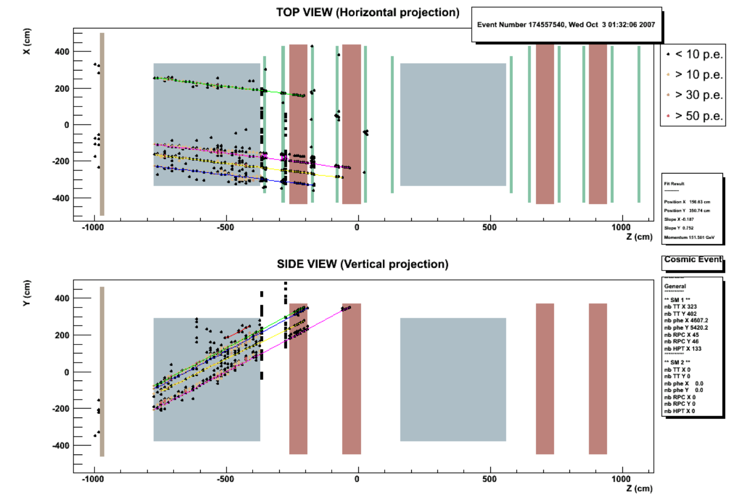
μ ID, charge, momentum

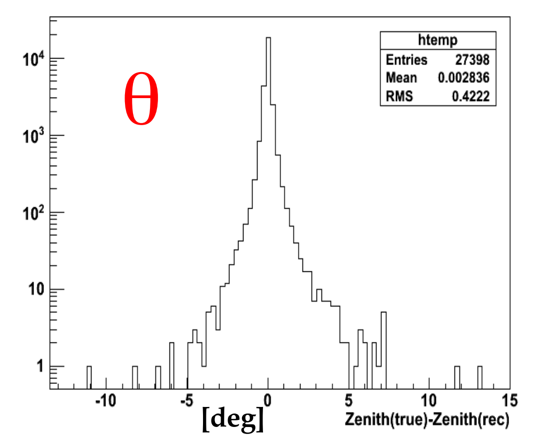
B = 1.53 T

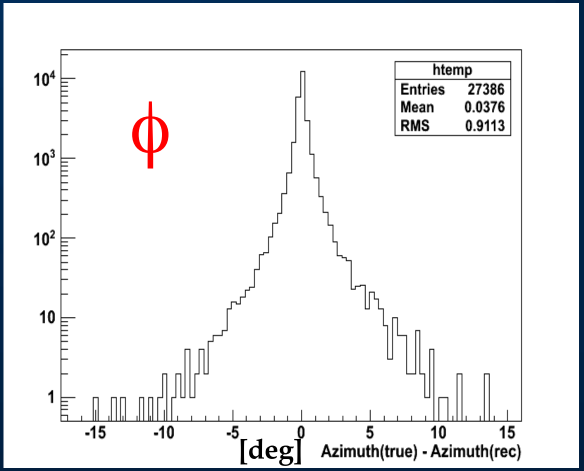
Total target mass = 1.25 ktons

Cosmic event reconstruction performance

- ➢ Multiple muon events well reconstructed



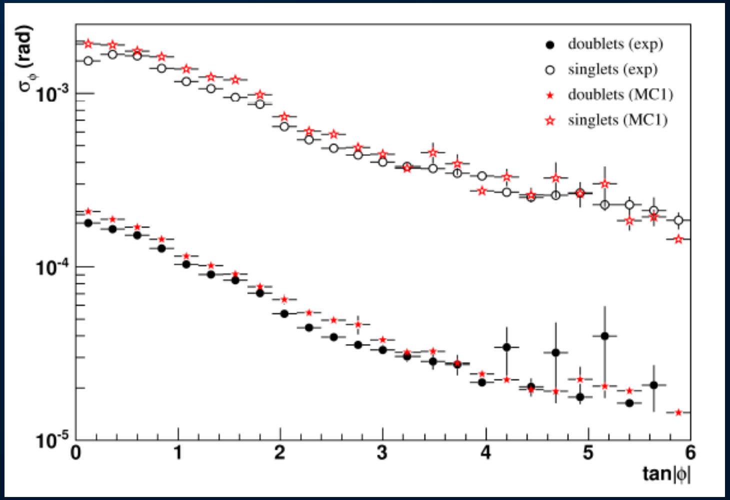




- ➢ Good overall angular resolution

“resolutions” < 1 deg both for zenith and azimuth direction reconstruction

- ➢ High angular resolution in the PT system



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New OPERA data

Major improvements w.r.t. 2010 published analysis (Eur. Phys. J. C67 (2010) 25)

- **Statistics × 3:**
  1454057 μ collected during
  2008-2009-2010 CNGS runs corresponding to 407.1 days of livetime
- Underground R_μ = 1.403 ± 0.008 (stat) + 0.017 – 0.015 (syst)
- Separation of R_μ for single and multiple muons, different at 7.2 σ level

N_μ	**‹A›**	**$\langle E/A \rangle_{primary}$ [TeV]**	**H fraction**	**N_p/N_n**	**R_μ^{unf}**
= 1	3.35 ± 0.09	19.4 ± 0.1	0.667 ± 0.007	4.99 ± 0.05	1.403 ± 0.008
> 1	8.5 ± 0.3	77 ± 1	0.352 ± 0.012	2.09 ± 0.07	1.18 ± 0.03

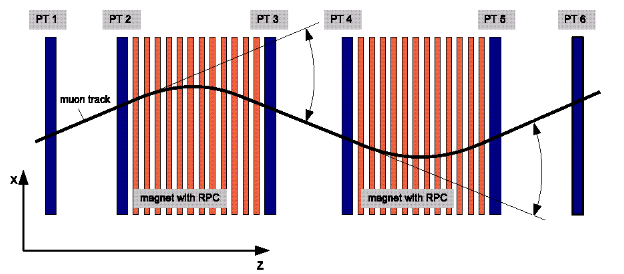
  - Convolution of two effects:
    larger n/p ratio in the all-nucleon spectrum ⊗ different X_F region
- Cosmic events selected outside the CNGS spill window
- Atmospheric neutrino events rejected on the basis of ToF
- Analysis cuts and details in:
  http://www.bo.infn.it/opera/docs/phd_thesis-BO-2011_05_20-mauri.pdf

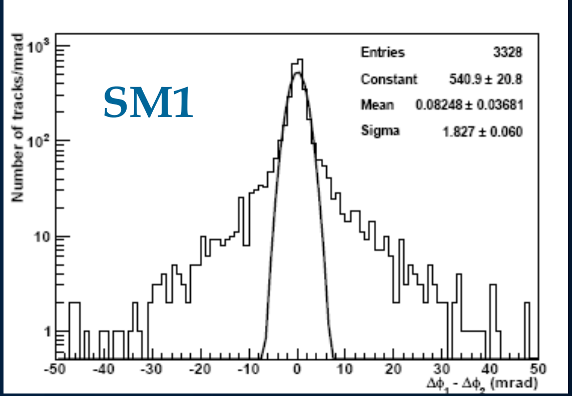
Systematic error estimate

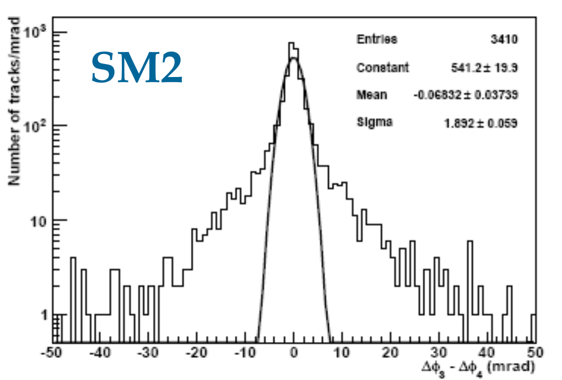
Two main sources for the systematic error

- PT station misalignment: Two-arm test

$\delta(\Delta\phi) = \Delta\phi_1 - \Delta\phi_2 = 0$







- computation of the difference between $\Delta\phi$ angles for tracks crossing both magnet arms in each spectrometer

Propagating the value $\delta(\Delta\phi) = 0.08$ mrad in the R_μ computation

$\delta R_\mu = 0.015$

- Misidentification probability: only from experimental data

- for tracks crossing both magnet arms (subsample of events), computation of the probability of reconstructing opposite charges → we find η_{data}

The difference $\delta\eta = \eta_{data} - \eta_{MC} = 0.007$ is quoted as systematic error on η → propagating in R_μ

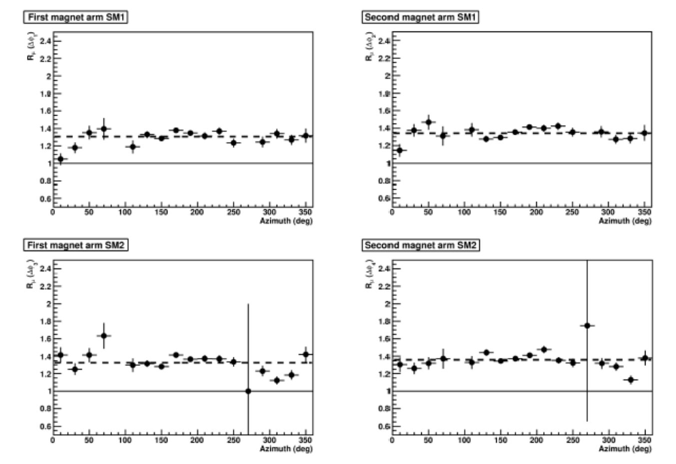
$\delta R_\mu = 0.007$ only positive contribution! ($\eta_{real} \geq \eta_{MC}$)

Consistency checks

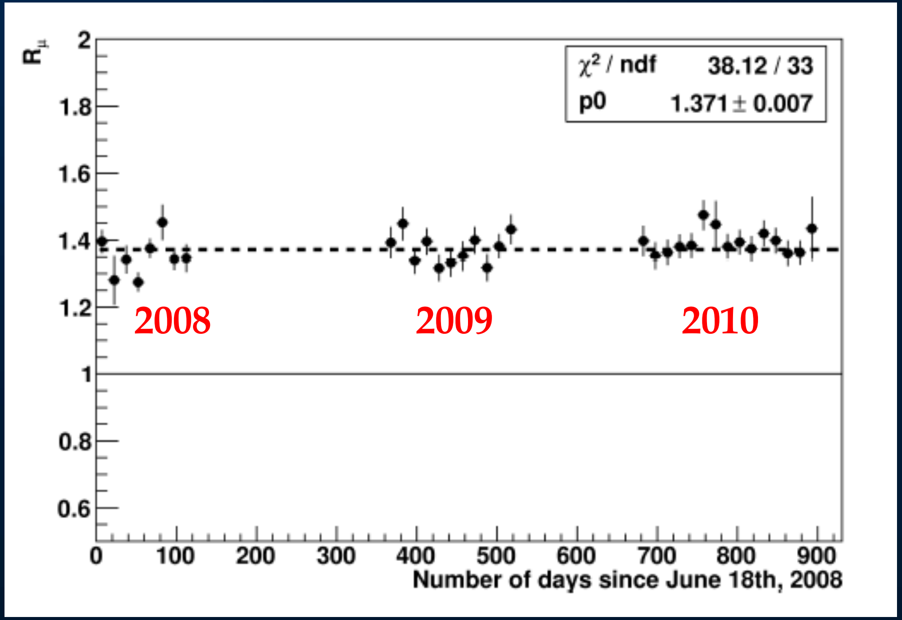
The total systematic uncertainty is $\delta R_{\mu}^{unf}(syst) = ^{+0.017}_{-0.015}$

Consistency checks:

- R_{μ} as a function of the azimuth angle φ (mis-alignment check)



- The 4 R_{μ} values, computed separately for each magnet arm, fluctuate around the average of 0.016, which is within their statistical accuracy (0.018)
- Run with inverted polarity (9+7 days): $R_{\mu}^{inverted} = 1.39 \pm 0.04$
- Run with magnet off (13 days): $R_{\mu}^{off} = 1.02 \pm 0.04$
- Measurement stability as a function of the data taking: R_{μ} remains constant



R_μ as a function of $E_\mu\cos\theta$*

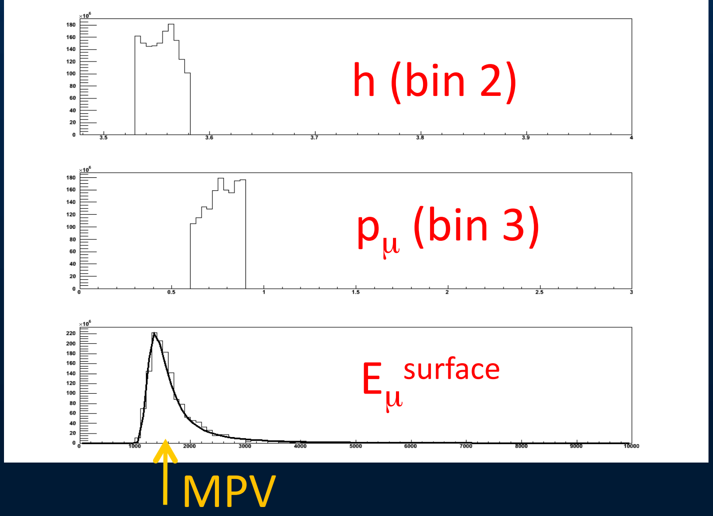
The resolution on E_μ is dominated by fluctuations in the stochastic term β of the energy loss

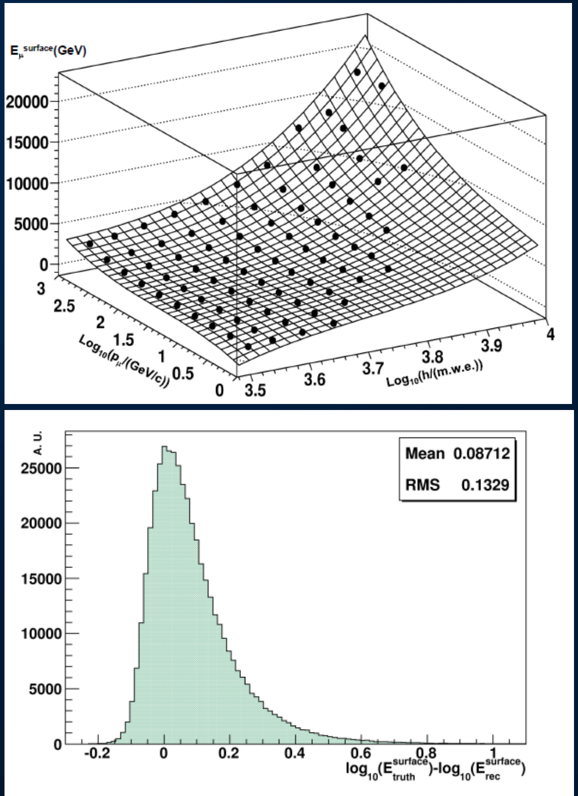
$$E_\mu = (E_\mu + \alpha / \beta)e^{\beta h} - \alpha / \beta$$

$\alpha = \alpha(E)$

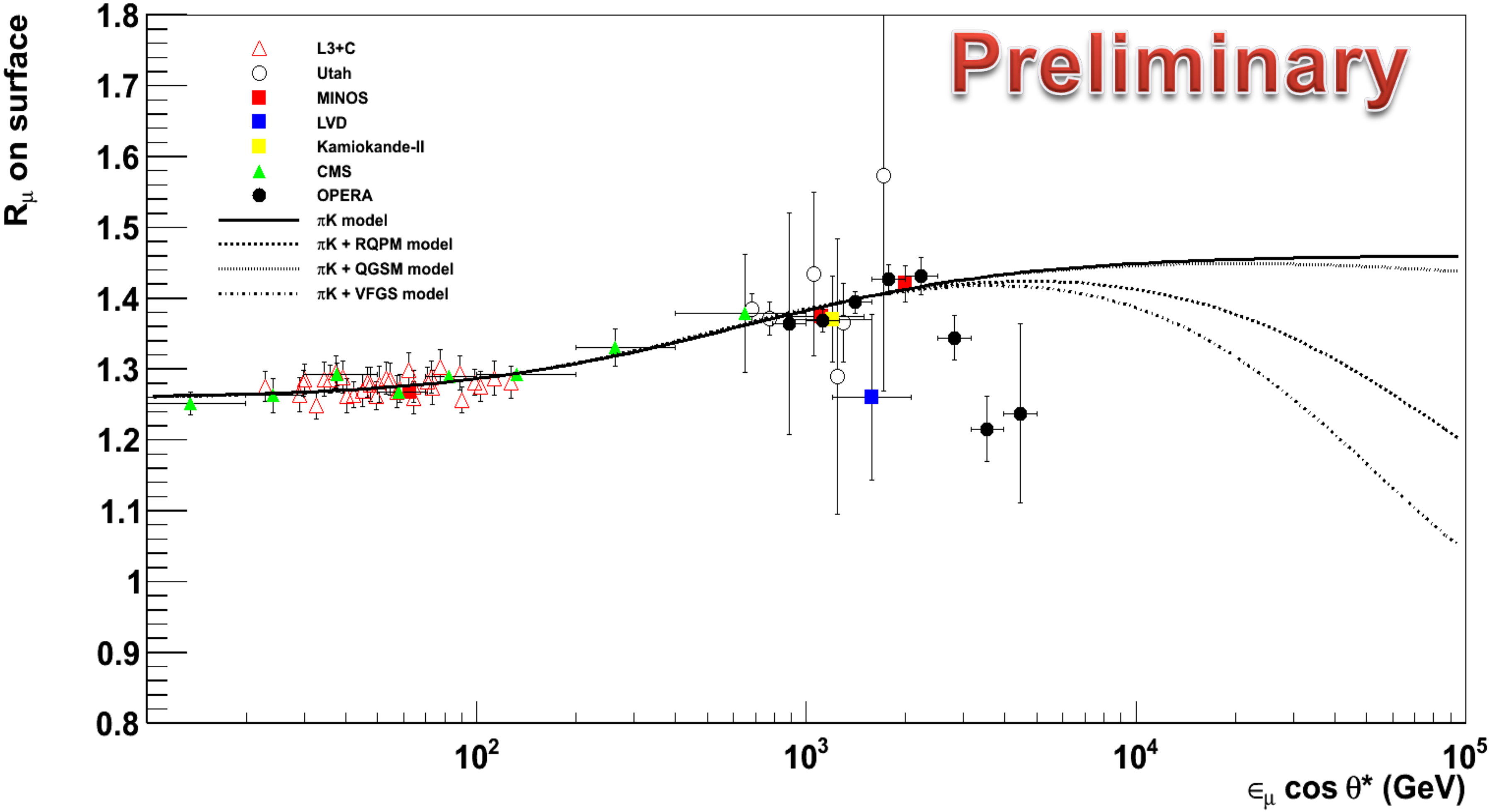
$\beta = \beta(E)$

→Build a table $\langle E_\mu \rangle_{MPV} = f(h, p_\mu)$ using a full MC simulation based on FLUKA: take the MPV of the Landau distribution → better resolution and residuals well centered



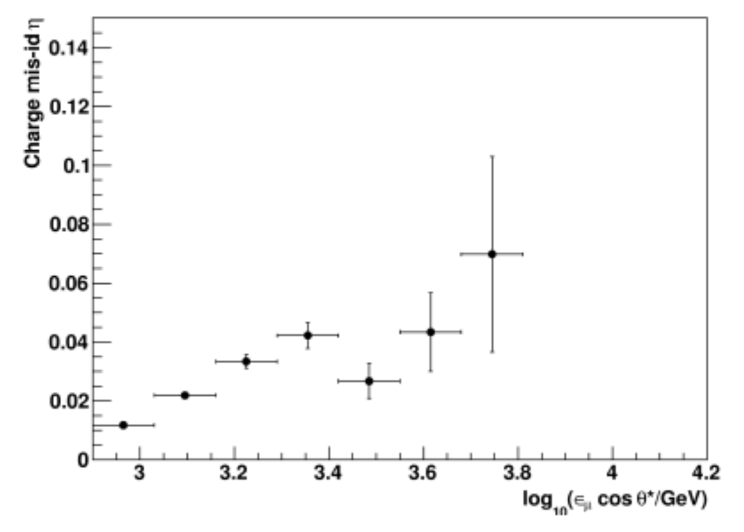


R_μ measurements vs E_μ cosθ*

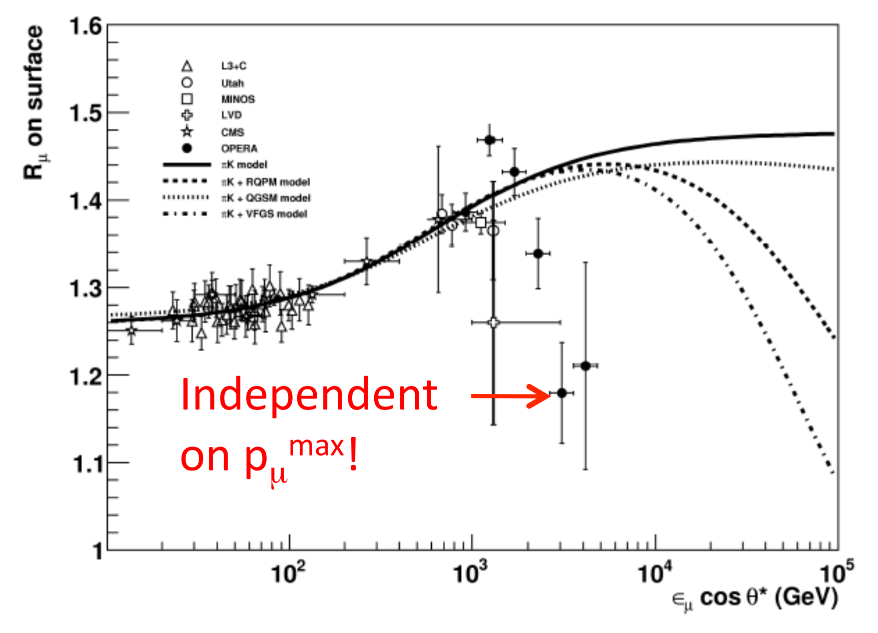


R_μ vs E_μ cosθ*: systematics check

Due to the increased statistics, it is now possible to use only *doublet* data, for which the charge mis-identification can be extracted directly from data (→2-arm test)



only single muons



Independent on p_μ^{max}!

Check two sources of systematics:

- unfolding based on charge misidentification extracted from MC → here extracted from data
- misalignment of the PT system → cut on max μ momentum underground

OPERA measurement result

- There is a clear indication of a smooth transition between the low and high energy regimes as predicted by the π-K model
  - ✓ $R_\mu \approx 1.25$ around 100 GeV → smooth transition to $R_\mu \approx 1.4$ in TeV region

- Sharp drop for $E_\mu \cos\theta^* > 2\text{-}3$ TeV in the OPERA data

- In 2012 we collected one year statistics with inverted magnet polarity, in order to check the alignment systematics
  - ✓ We are analyzing the new data
  - ✓ We plan to publish in the near future the OPERA measurement with the whole statistics (2008-2012)

- If this drop is not explained by any systematic effect we can speculate on its possible physical nature:
  - Sudden change in the n/p ratio in the all-nucleon spectrum?
  - Strong Feynman scaling violation in the forward fragmentation region for π/K mesons?
  - Upraise of a new muon component?

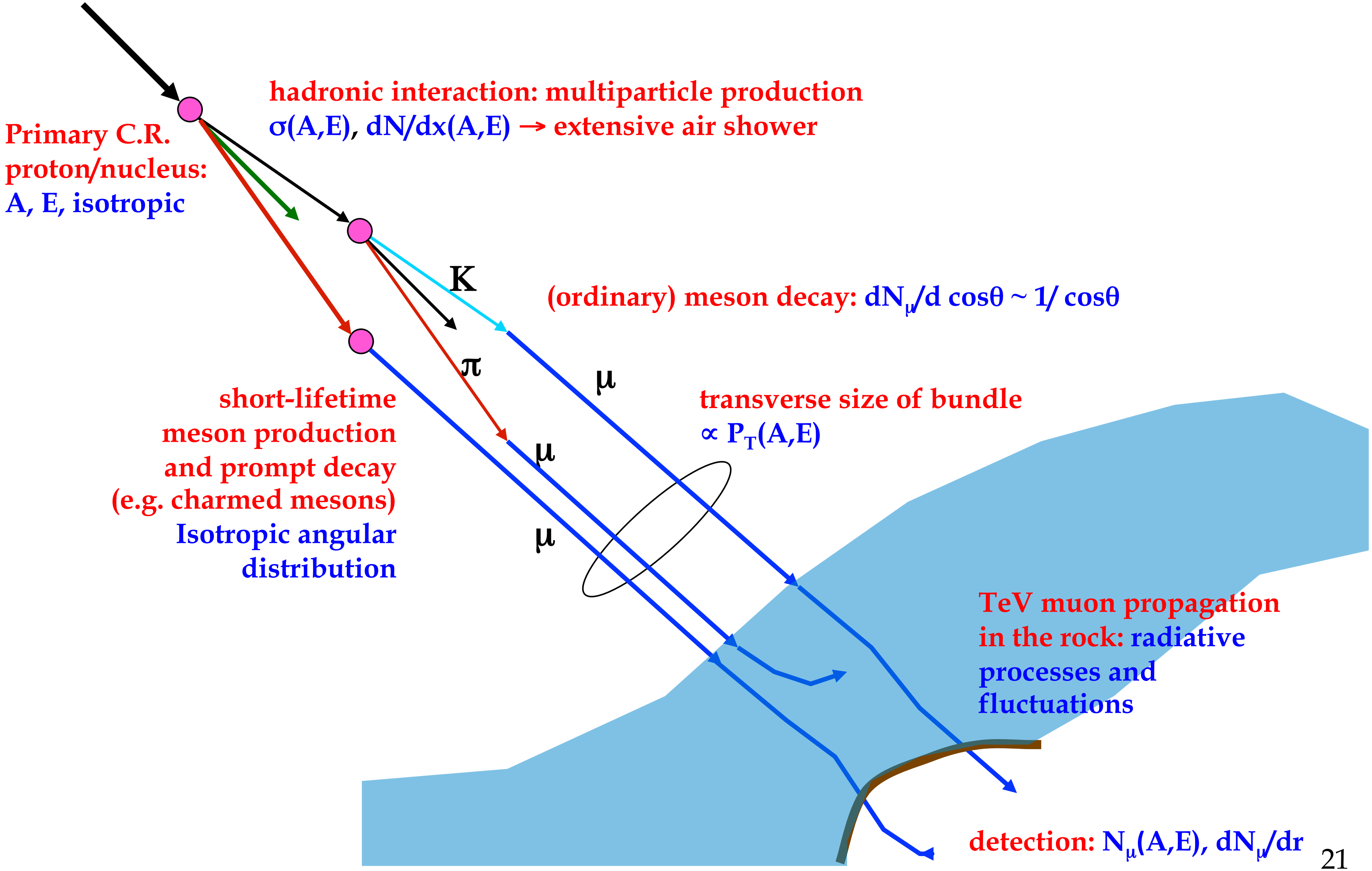
Conclusions

- We reviewed the present knowledge of the atmospheric muon charge ratio for $E_\mu \cos\theta^* > 1$ TeV
- The new OPERA data with a largely increased statistics were presented: OPERA measured the charge ratio in the highest energy region
- Found a strong reduction of the charge ratio for multiple muon events
- The integral value is compatible with expectation from a simple π-K model, as the transition between the pion and the kaon region
- Unexpected behavior in the last HE points of the energy distribution:
  - Further checks mandatory, analysis on going on the 2012 data with inverted magnet polarity
- If the drop will not be explained by still unknown systematic effects, it would be difficult to accommodate the effect within the present knowledge of the primary radiation and of the hadronic interaction features for light mesons in the kinematical region of interest

  [see J. Phys.: Conf. Ser. 375 (2012) 052018]

Spares

The physics of cosmic ray TeV muons



Primary C.R.
proton/nucleus:
A, E, isotropic

hadronic interaction: multiparticle production
$\sigma(A,E)$, $dN/dx(A,E) \rightarrow$ extensive air shower

(ordinary) meson decay: $dN_\mu/d\cos\theta \sim 1/\cos\theta$

short-lifetime
meson production
and prompt decay
(e.g. charmed mesons)
Isotropic angular
distribution

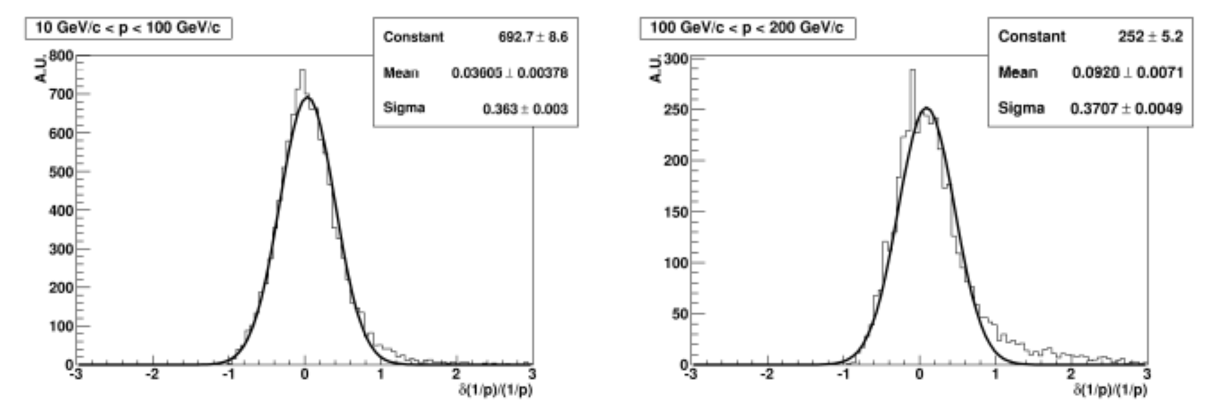
transverse size of bundle
$\propto P_T(A,E)$

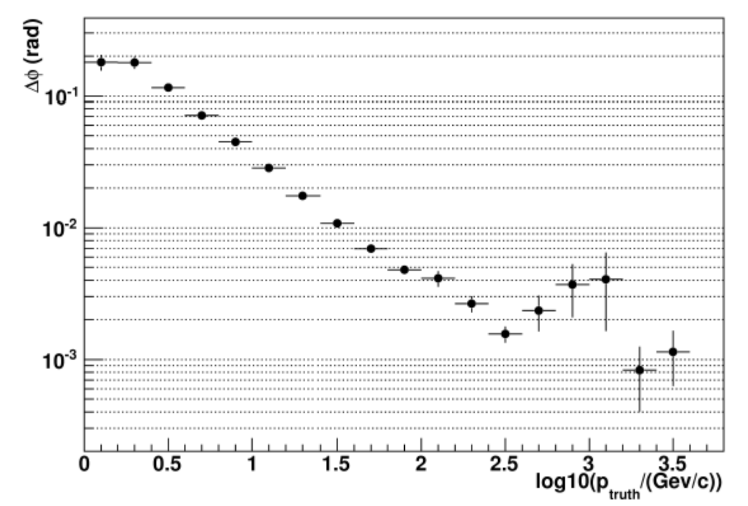
TeV muon propagation
in the rock: radiative
processes and
fluctuations

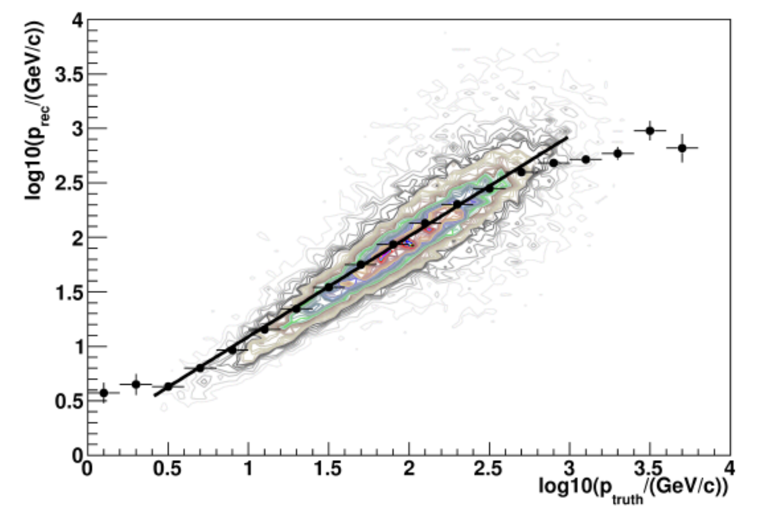
detection: $N_\mu(A,E)$, dN_μ/dr

Momentum reconstruction performance

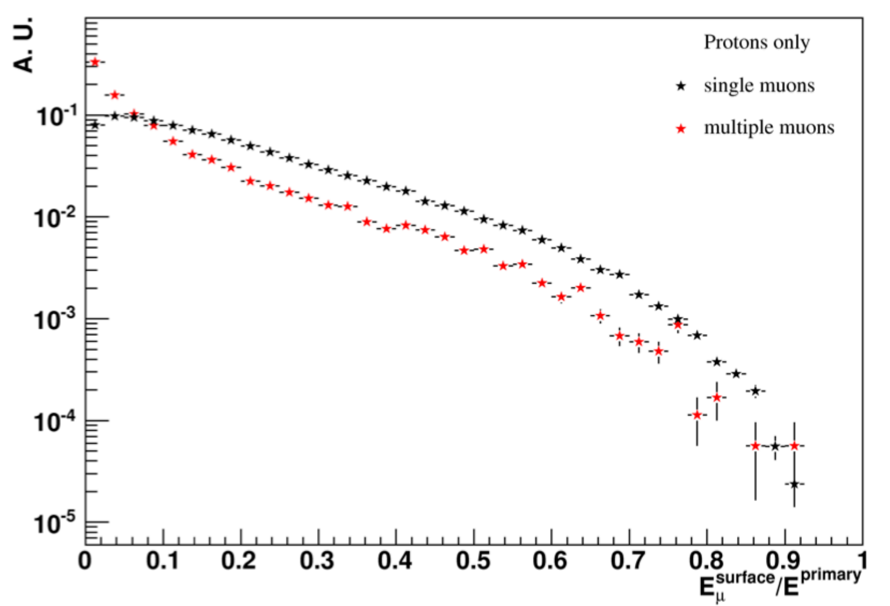
Momentum resolution





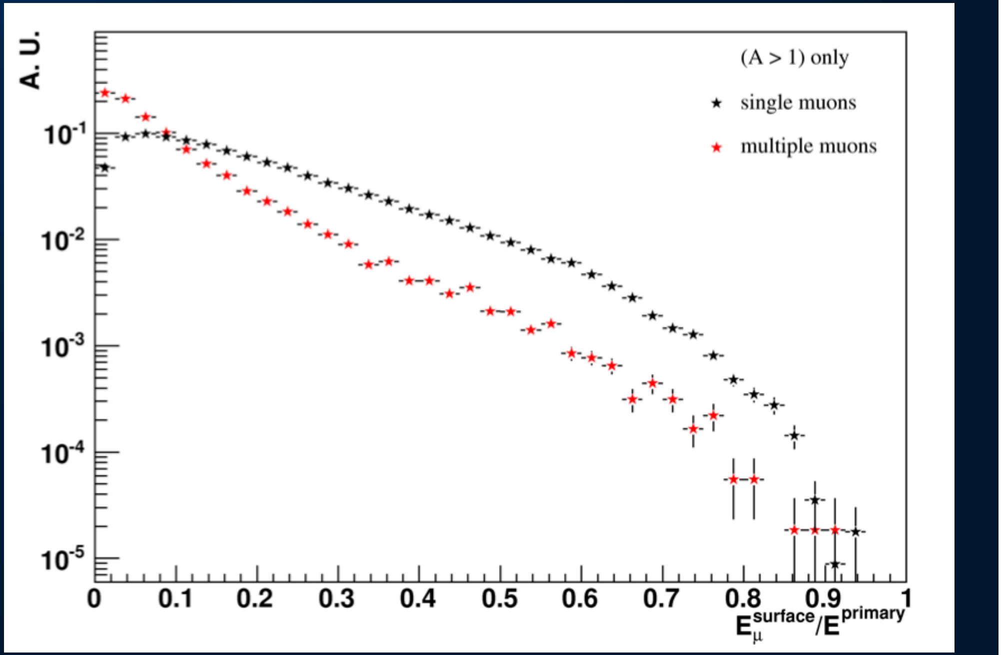


Fraction of primary energy taken by μ



$E_\mu^{surface} / E^{primary}$

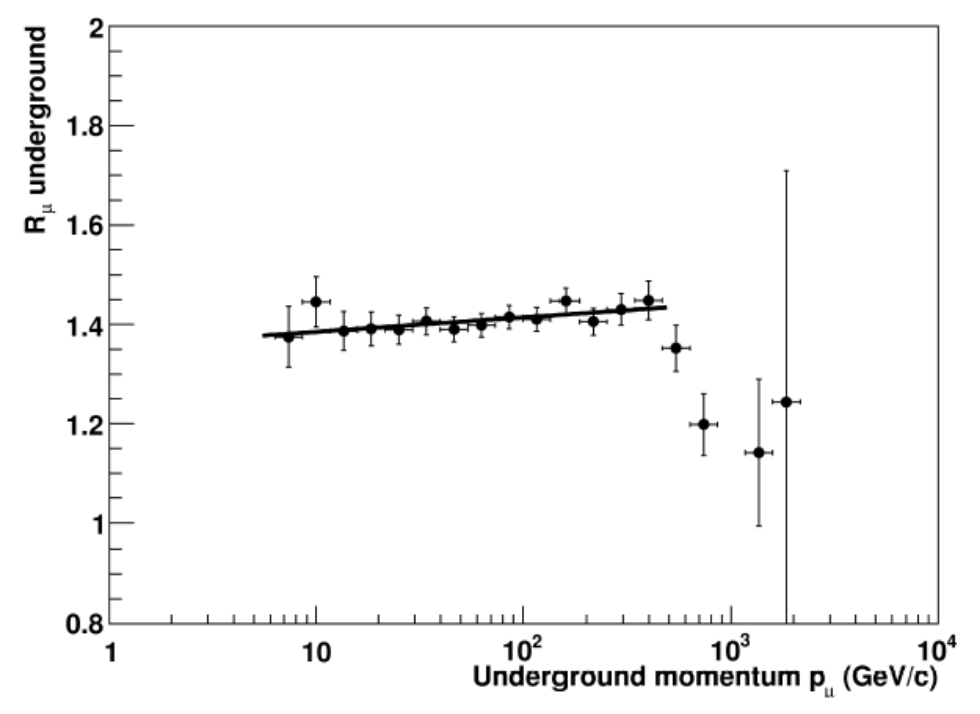
Different distributions for single and for multiple muons



R_μ as a function of p_μ

R_μ for single muons was computed in bins of p_μ (underground momentum) and unfolded (bin migrations taken into account with the Bayes method)

Evolution with p_μ is compatible with a constant



Linear fit in the range (5,500) GeV/c

$R_\mu = a_0 + a_1 \log_{10} p_\mu$

→ $a_0 = 1.36 \pm 0.03$

→ $a_1 = 0.029 \pm 0.018$

$R_\mu = c_0$

→ $c_0 = 1.409 \pm 0.008$

$\Delta\chi^2$/dof = 2.48/1 (~1.6 σ)
(compatible with a constant)

Maximum detectable momentum

Consider the magnetic field bending and the total deflection spoiling (detector + MCS)

$$\Delta\phi_B = \frac{0.3Bd}{p} \qquad \sigma_{\Delta\phi} = \sqrt{\sigma^2_{\phi_1} + \sigma^2_{\phi_2} + \left(\frac{0.0136}{p}\right)^2 \frac{d}{X_0}}$$

Requiring $\Delta\phi_B/\sigma_{\Delta\phi} > 1$ we obtain (for $\phi=0$):

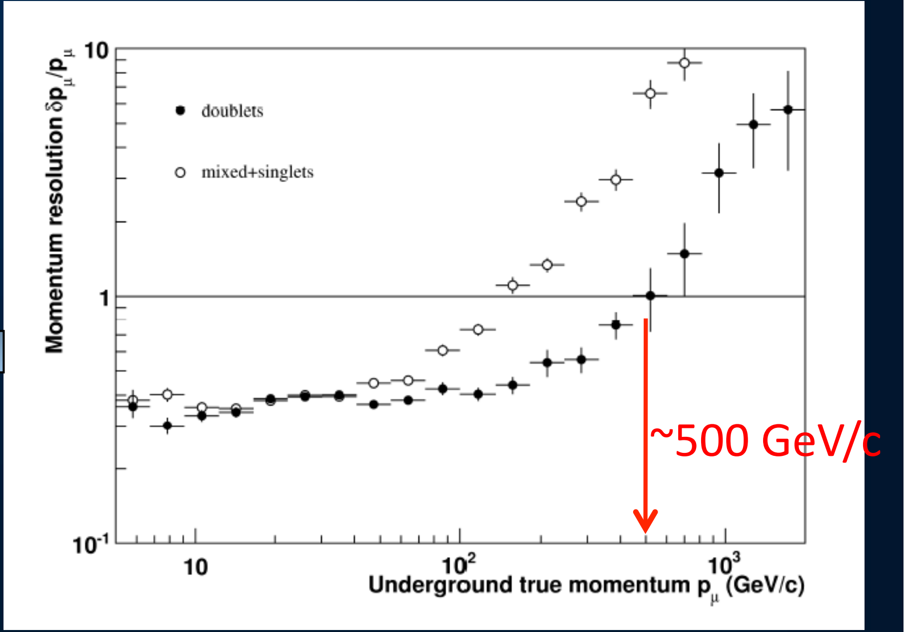
p_{max}(doublets) = 1.25 TeV/c

p_{max} (singlets) = 150 GeV/c

p_{max} (mixed) = 260 GeV/c

Exact computation at all angles (MC)

$\delta p_\mu/p_\mu = 1$



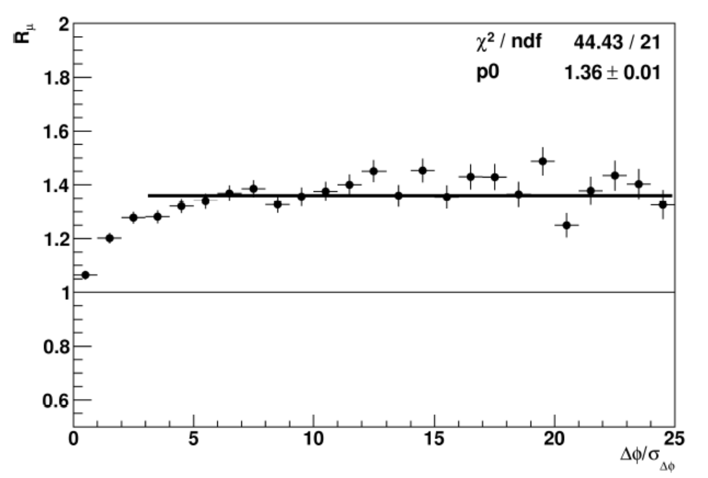
Quality cuts

Deflection Cut: Cut on bending angle information below the PT resolution

We choose the cut: $\Delta\phi/\sigma_{\Delta\phi} > 3$

R_μ saturates above 3σ; as expected, for lower number of σ, $R_\mu \rightarrow 1$ (charge misidentification ~50%, total randomization of charge reconstruction)

We also require Δφ < 100 mrad, to reject isolated secondary particles produced at large angles by high energy muons

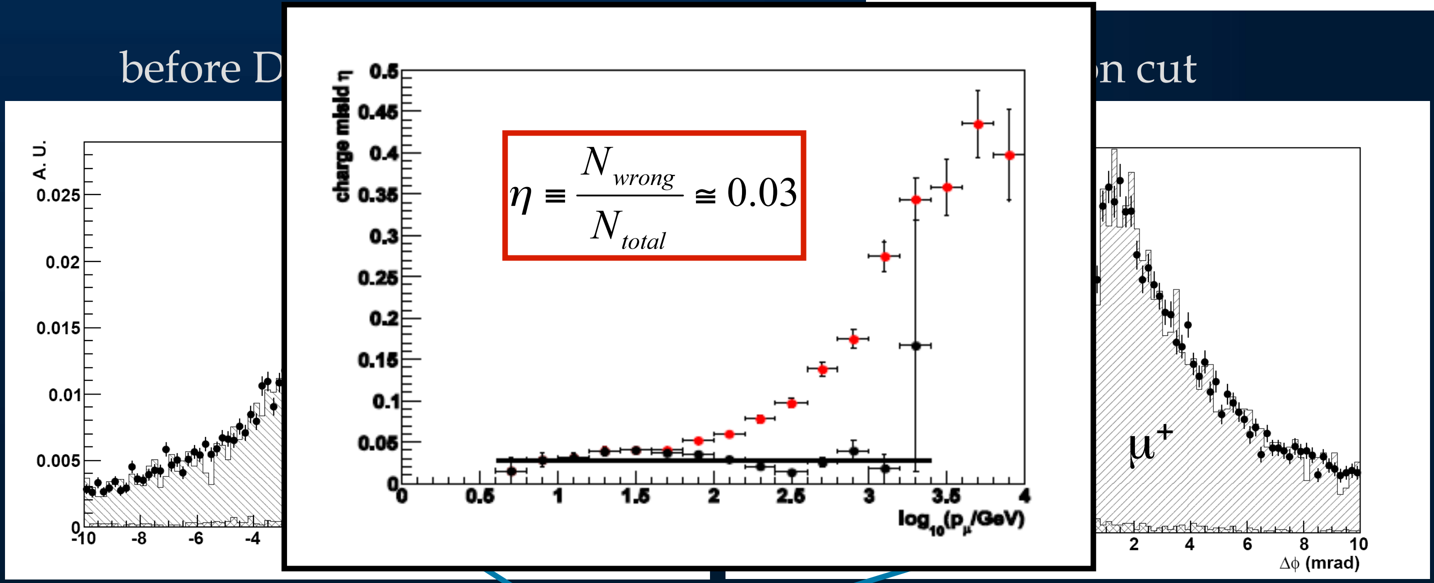


before D … n cut

Exp. data ●

MC data ▨

MC distributions are split in the 2 regions μ^+_{true} and μ^-_{true}



$$\eta \equiv \frac{N_{wrong}}{N_{total}} \cong 0.03$$

misidentification probability

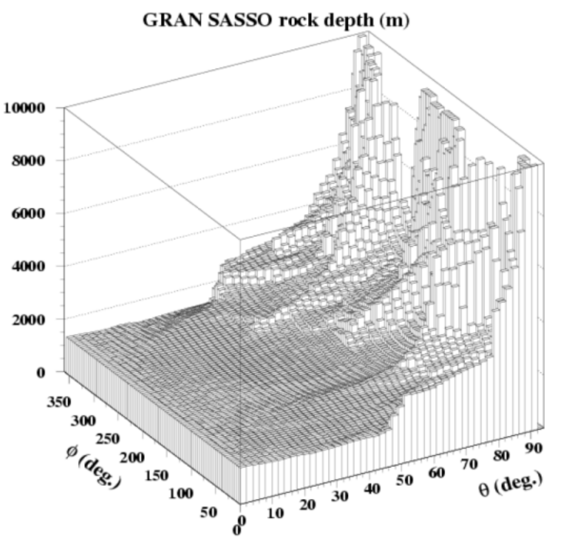
Phenomenological background

Taking into account the contribution of kaons and pions to the muon flux, a simplified model of the atmospheric muon charge ratio (Gaisser) is given

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

where E_μ is the muon energy in atmosphere, θ is the zenith angle, $\gamma \sim 2.7$ is the primary cosmic ray spectral index, $a_{\pi/K}$ and $b_{\pi/K}$ are known kinematical factors, $\varepsilon_{\pi/K}$ are π/K critical energies

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 magnetized experiment with the largest $\langle E_\mu\cos\theta\rangle$

- UTAH (1975): $\langle E_\mu\cos\theta\rangle \sim 500$ GeV
- MINOS (2007): $\langle E_\mu\cos\theta\rangle \sim 1000$ GeV
- OPERA (2009): $\langle E_\mu\cos\theta\rangle \sim 2000$ GeV

The $E_\mu \cos\theta$ regions

SOUDAN

LNGS

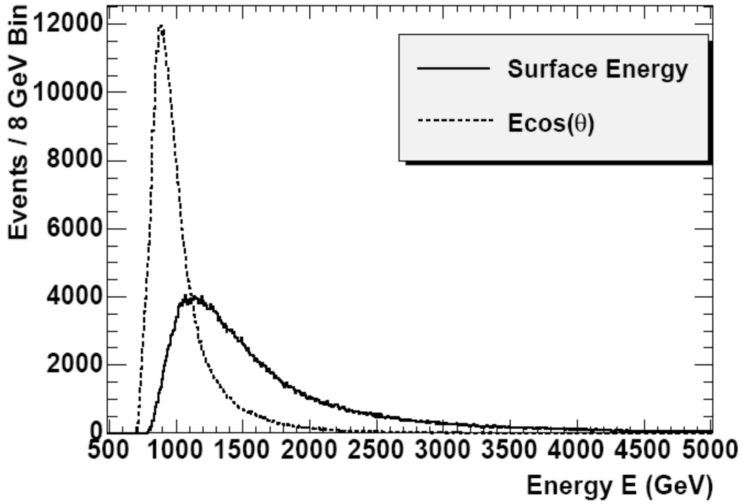
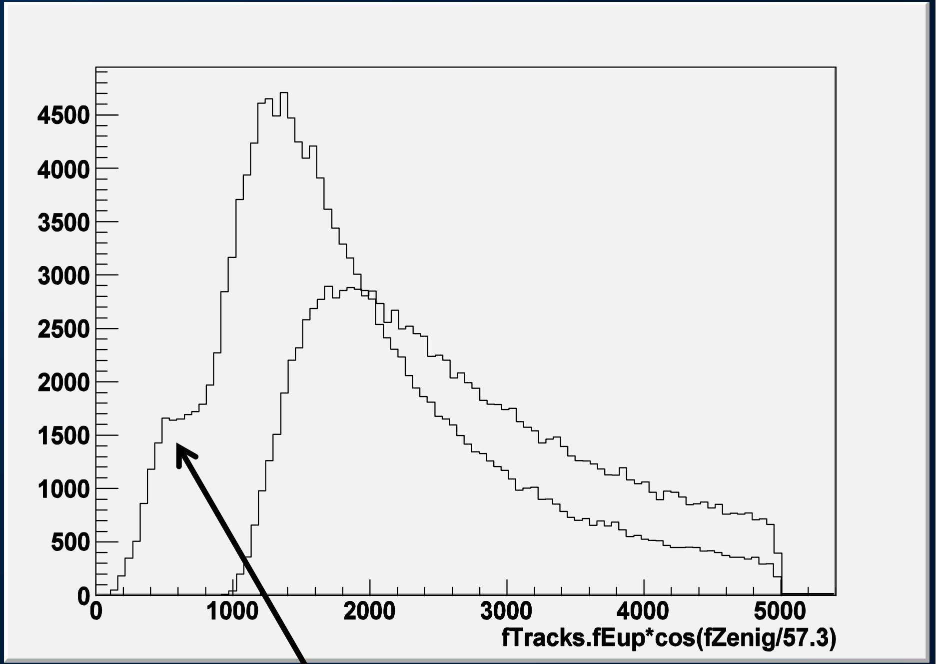


Figure 1: Distribution of E and $E_\mu^{surface}\cos\theta$ for MINOS data muons in the far detector, after cuts.

From: [MINOS Collaboration], in ICRC '07 proceedings (arXiv: 0706.0538v1); also in arXiv:0906.3726v1

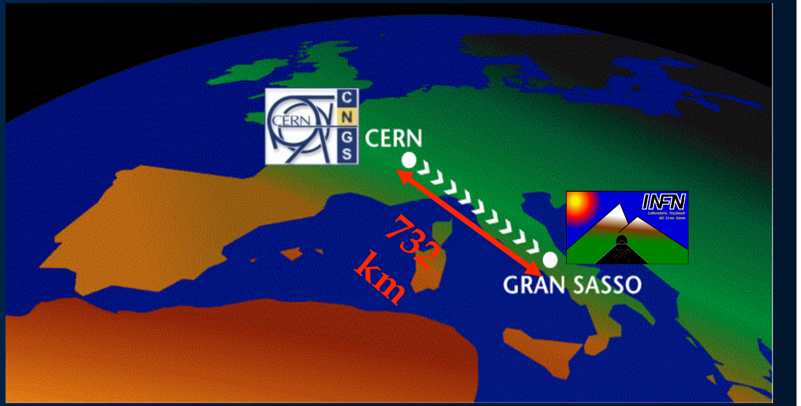


"Teramo Valley"

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)

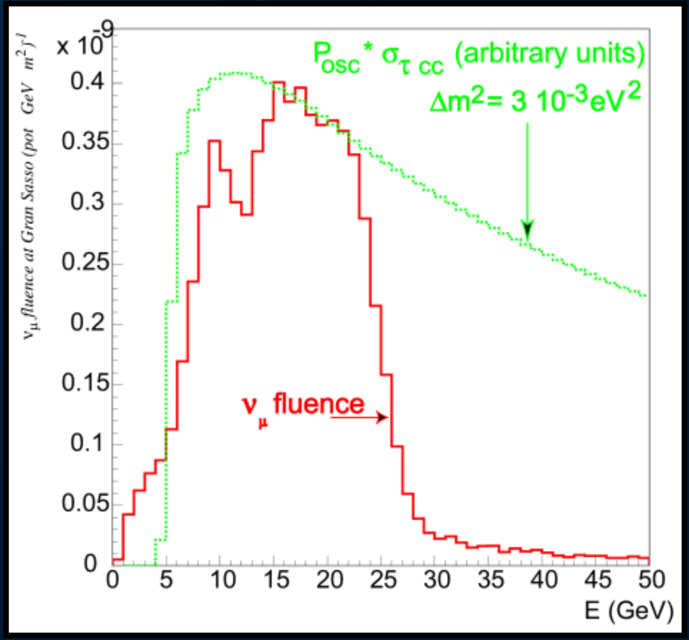


CNGS beam optimized to maximize the number of ν_τ CC interactions: taking into account the ν_τ CC cross section and the τ production threshold

→ 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%**
$\bar{\nu}_\mu / \nu_\mu$	**2.1%**
ν_τ prompt	**negligible**

(ν_μ CC)



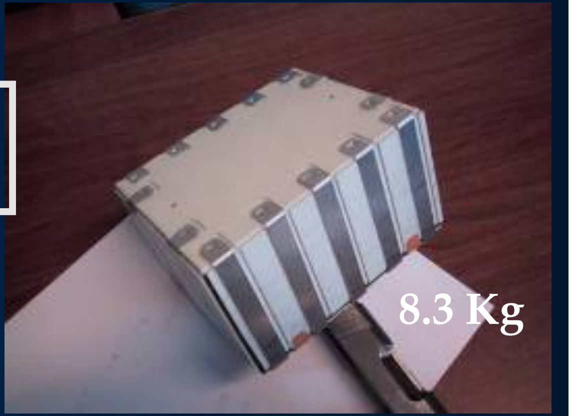
Emulsion Cloud Chamber

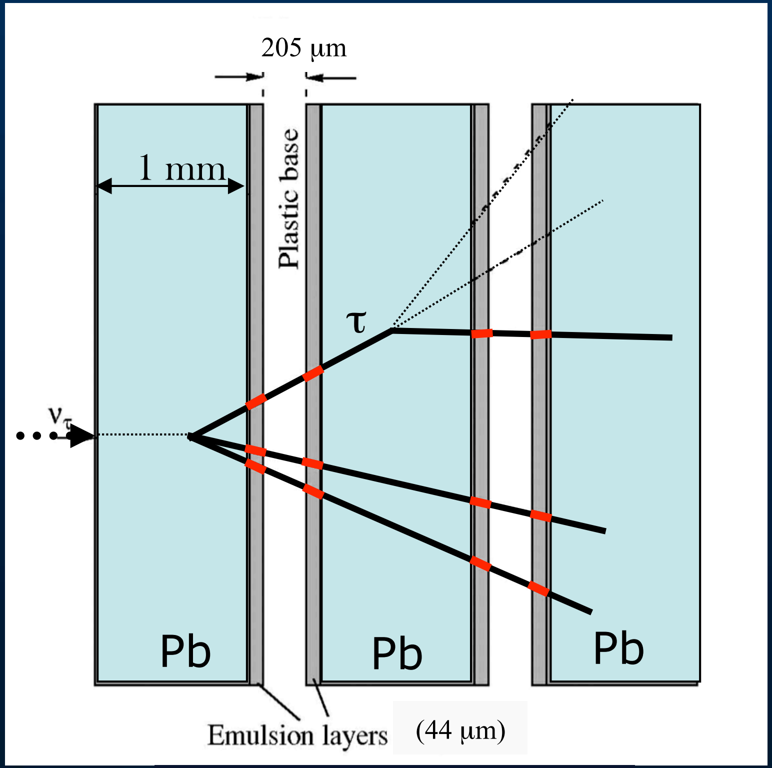
ECC = sequence of emulsion-lead layers

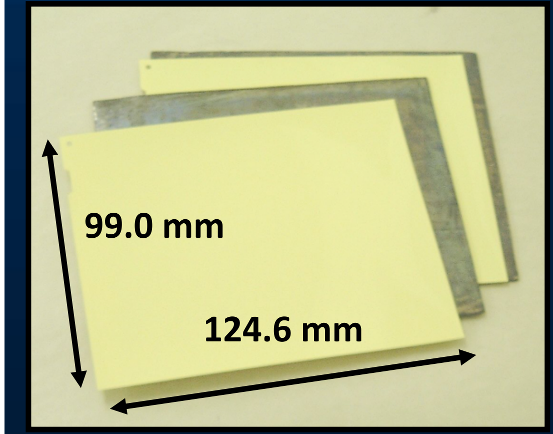
→ High resolution and large mass in a modular way

The brick is the target basic component

- 57 nuclear emulsion films interleaved with 1 mm thick lead plates







Emulsion resolution:

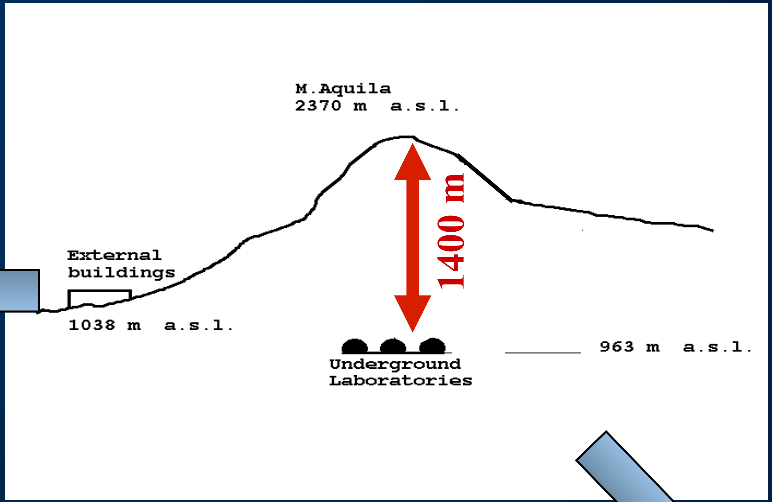
δx = 1 μm

δθ = 2 mrad

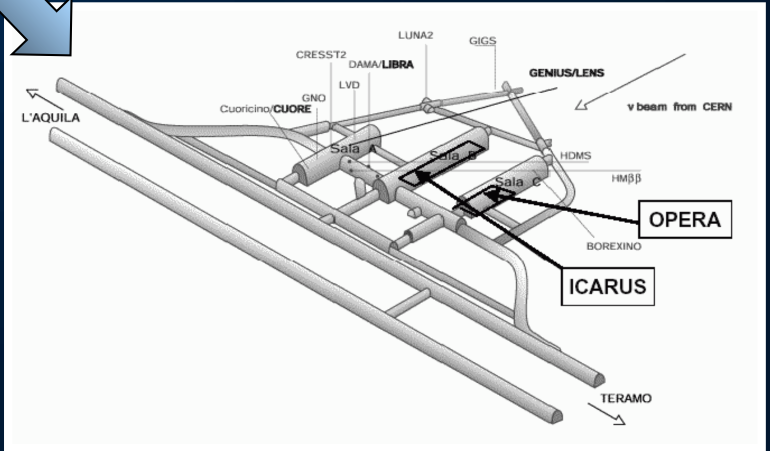
~150000 bricks (1.25 ktons)

Cosmic ray studies with OPERA

CNGS beam events are identified through a timing coincidence with CERN
→ possibility to collect cosmic events during the physics run



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



OPERA vs. previous and current underground experiments: charge and momentum measurement with the spectrometer at large depth and excellent timing capabilities (~10 ns)

Monte Carlo simulation

Two Monte Carlo simulations for different purposes:

1) a fast tool for the cross-check with experimental data, for the validation of the analysis software and for unfolding

→ a parameterized generator (MC1) with a primary chemical composition based on the MACRO fit model [Phys. Rev. D56 (1997) 1418]

Approximate but fast

$$\boxed{\frac{Rate_{DATA}}{Rate_{MC1}} = (96.3 \pm 0.3)\%}$$

2) a reliable tool for surface muon energy estimation and a link between underground variables and primary cosmic ray parameters

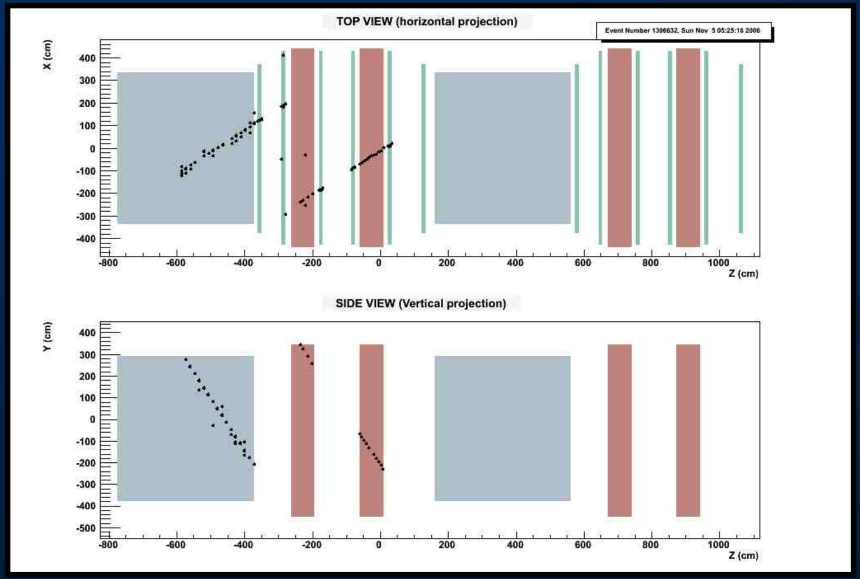
→ a FLUKA-based full Monte Carlo simulation (MC2) with primary composition model from Astropart. Phys. 19 (2003) 193

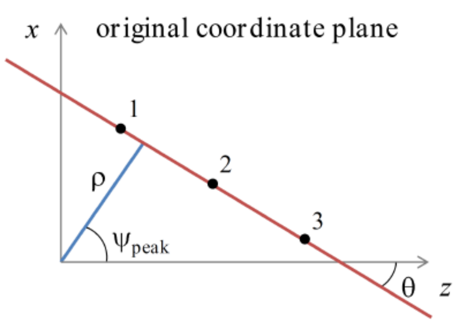
Reliable but slow

Event reconstruction: Pattern recognition

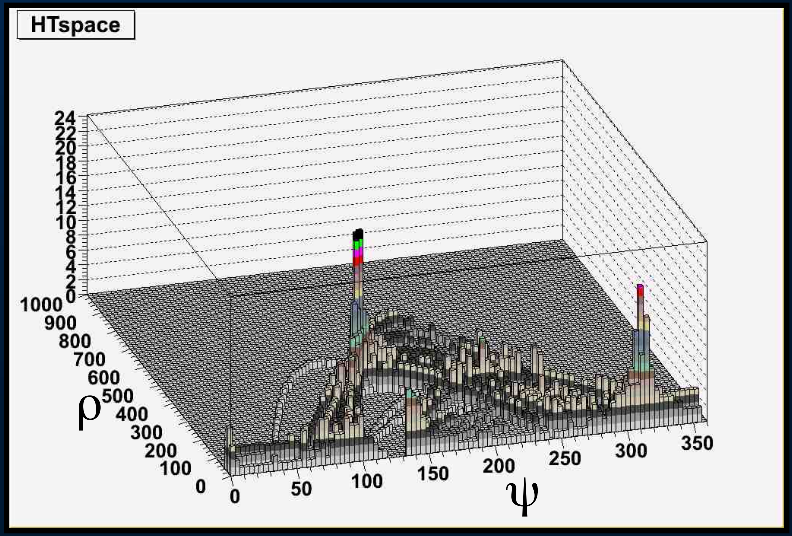
Dedicated pattern recognition for cosmic events (≡ outside CNGS spill window): takes into account event topology and multiple events (μ bundles):

- ➢ hybrid strategy:
  global method (Hough Transform) + local method (pivot points)

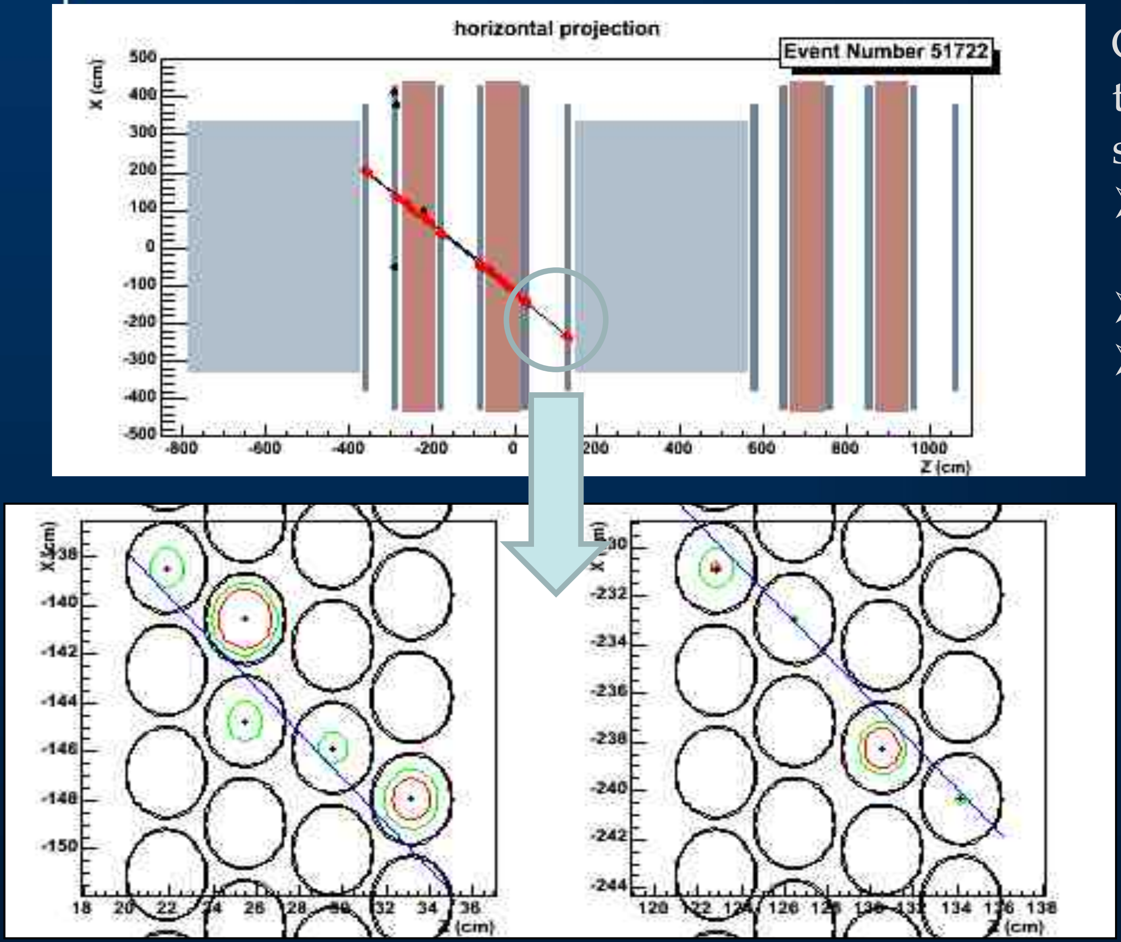




Real double muon event



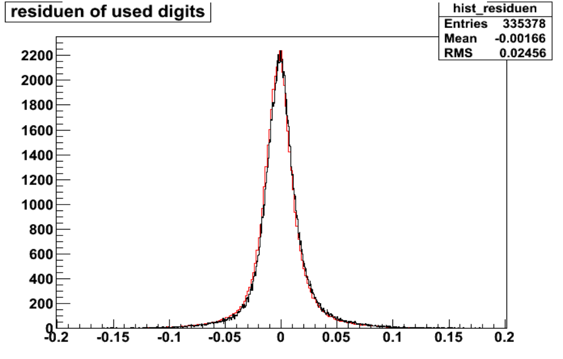
PT track reconstruction



Global tracks are used to "guide" track finding and fitting in the PT system:

- Find the line tangent to the drift circles with the best χ^2
- 250 μm position resolution
- 0.15 (1) mrad angular resolution for doublets (singlets) for $\phi = 0$ (improve for $\phi > 0$)

Residuals ~250 μm



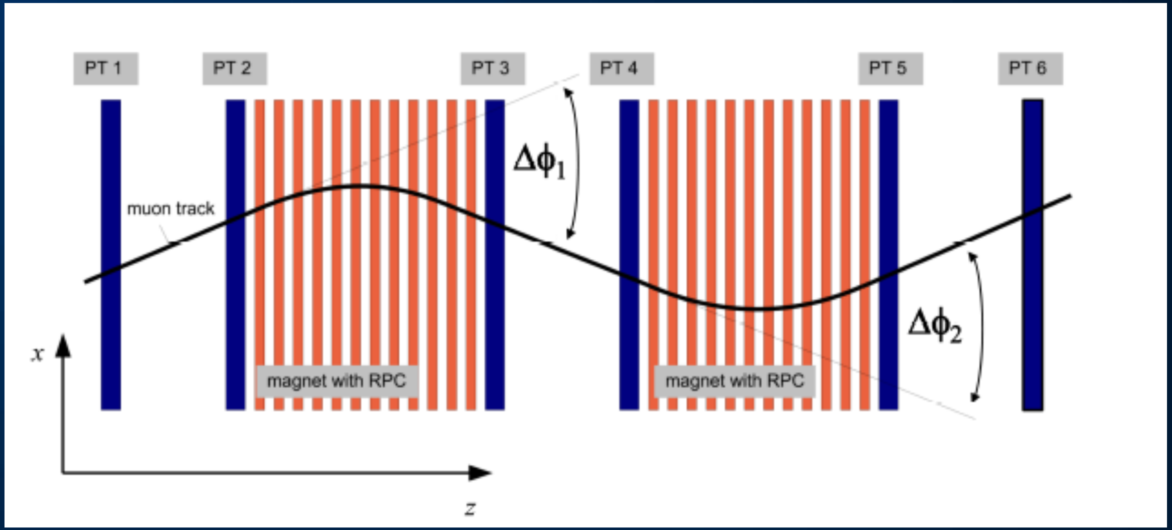
Track reconstructed in 1 PT station (in a pair) ≡ singlet

Track reconstructed in 2 PT station (in a pair) ≡ doublet

Charge and momentum reconstruction

The charge and momentum reconstruction is performed for tracks crossing at least one magnet arm using the bending angle information Δϕ

Top view of the OPERA detector



- In each side of the magnet arm we can reconstruct an independent angle ϕ_j, j=1,...,6.
- Each ϕ_j can be reconstructed with one station (*singlets*) or two stations (*doublets*)
- We compute $\Delta\phi_k = \phi_i - \phi_j$, k=1,...,4, angle differences between adjacent station-pairs
  - 55% of Δϕ's comes from doublets
  - 9% from singlets
  - 36% are mixed

$$p_k = \frac{l(dE/dx)}{1-\exp[\Delta\phi(dE/dx)/e\overline{B}]}\sqrt{1+\frac{s_{yz}^2}{1+s_{xz}^2}}$$

$\overline{B} \equiv Bd/l =$ effective magnetic field

Data reduction

A set of progressive cuts applied in order to isolate a clean data sample:

a) at least one reconstructed $\Delta\phi$ angle (*acceptance cut*)

b) Remove events with large number of PT hits (*clean PT cut*)

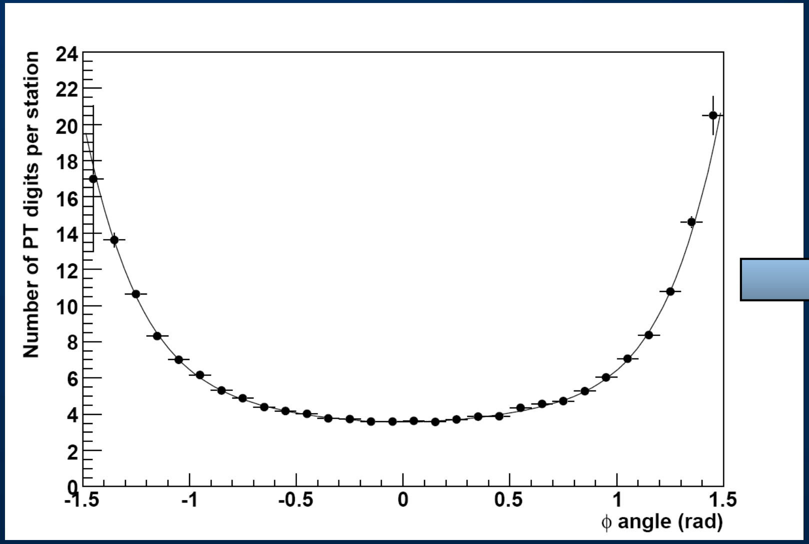
c) Remove events with bending smaller than the experimental resolution (*deflection cut*)

c’) Remove events with very large bending (effective for $p_\mu < 5$ GeV/c)

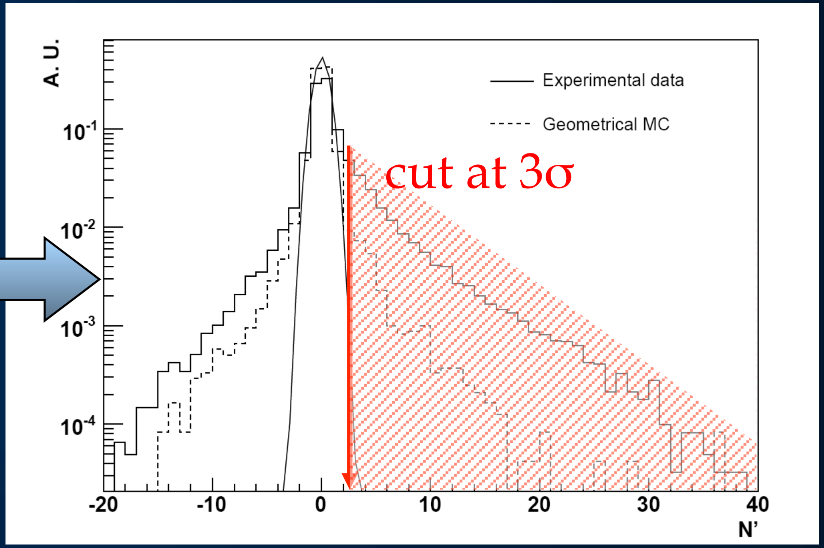
Quality cuts

Clean PT Cut: number of digits allowed from geometrical considerations:

$$N_{data}(\text{re-scaled}) = N_{data} - N_{MC}(\text{geometrical})(\phi)$$



Geometrical MC dependence on the ϕ angle



Re-scaled distribution of the experimental number of PT digits

The cut is chosen at 3σ of the gaussian fit on MC data.

We verified by visual inspection that events removed by this cut have many PT digits fired due to interactions, showers, δ-rays