Experimental results on the atmospheric muon charge ratio

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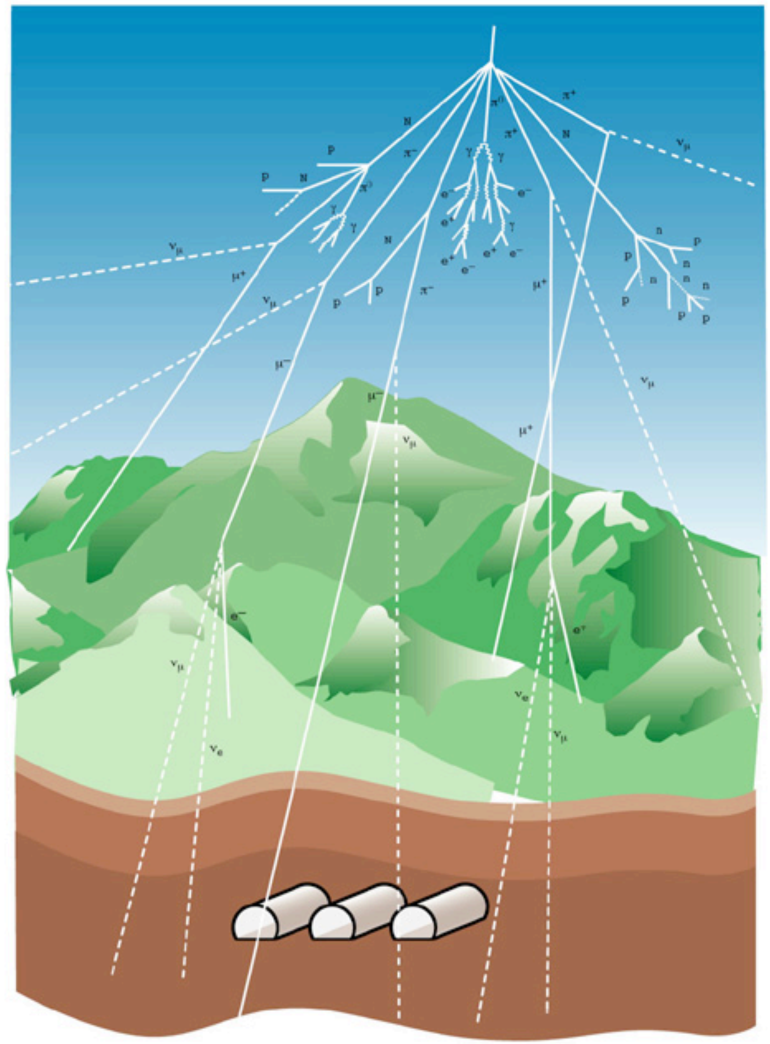
The atmospheric muon charge ratio

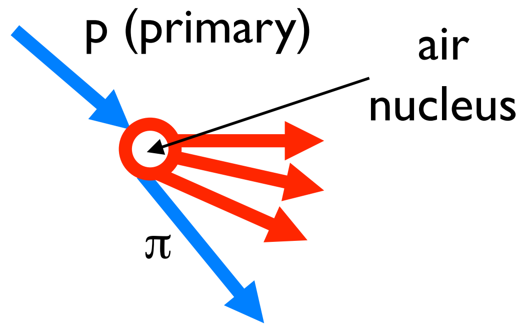
- The atmospheric muon charge ratio $R_\mu \equiv N_{\mu+}/N_{\mu-}$ is being studied and measured since many decades
  - Depends on the **chemical composition** and energy spectrum of the primary cosmic rays
  - Depends on the **hadronic interaction features**
  - At high energy, depends on the **prompt component**
- It provides the possibility to check HE hadronic interaction models (E>1TeV) in the **fragmentation region**, in a phase space complementary to the collider's one
- 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)



Key features of R_μ

Naïf prediction (Gaisser, Cambridge University Press)

- 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



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

Feynman scaling

Assuming Feynman scaling, the muon charge ratio prediction:

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

where Z_{ij}:

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

Spectrum weighted moments (SWM)

Key features of R_μ (cont'd)

Elaborating the minimal model:

• Introducing the neutron component in the primary flux (in heavy nuclei) and considering the isospin symmetries: $Z_{p\pi^+} = Z_{n\pi^-}, \quad Z_{p\pi^-} = Z_{n\pi^+}$

$$R_\mu = \frac{1+\delta_0 AB}{1-\delta_0 AB}$$

where:

$$A = (Z_{p\pi^+} - Z_{p\pi^-})/(Z_{p\pi^+} + Z_{p\pi^-})$$

$$B = (1 - Z_{pp} - Z_{pn})/(Z_{pp} + Z_{pn})$$

$$\delta_0 = (p_0 - n_0)/(p_0 + n_0)$$ primary proton excess

<u>Interpretation of the prominent features</u>:

• The result is valid only in the fragmentation region, enhanced in the SWM

• But the steeply falling primary spectrum ($\gamma \sim 1.7$) in the SWM suppresses the contribution of the central region → scaling holds

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 ($R_\mu > 1$)

Feynman scaling validity →

• <u>R_μ does not depend on E_μ</u> (or E_π) nor on the target nature

• <u>R_μ depends on the primary composition through δ_0</u>

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:

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

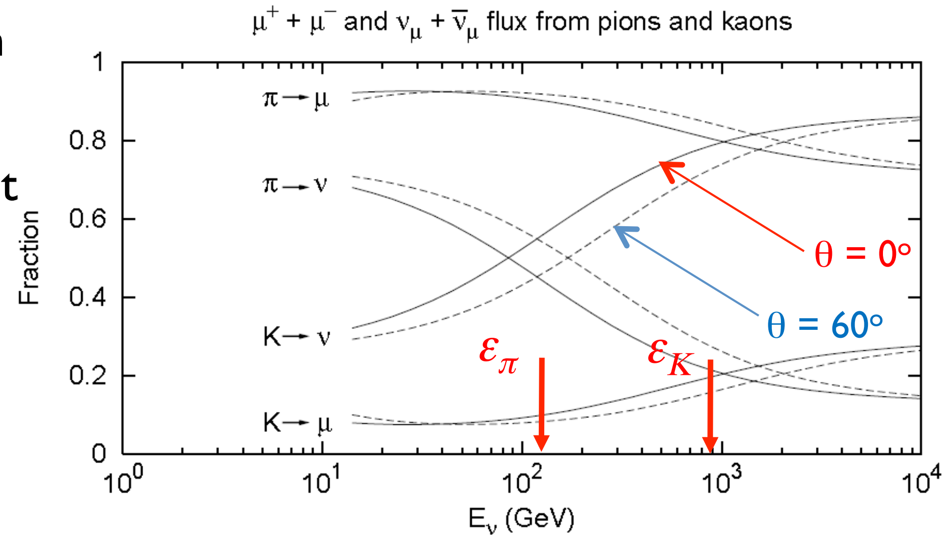
- For kaons:

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

because the reaction

p Air → $K^+ \Lambda$ N + anything

is favoured (***associated production***)



$\varepsilon_i = \varepsilon_i(\theta)$ critical energy energy above which interactions dominate over decays. Along the vertical (θ = 0°):

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

→ This leads to a larger R_μ ratio at high energy

Parameterization of the charge ratio

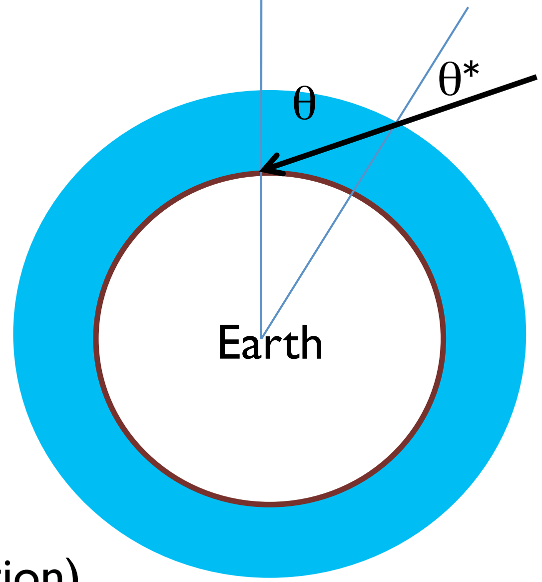
- Considering the general form for the muon flux

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

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

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

$\theta^* \equiv$ zenith angle at the production point



- The correct variable to describe the evolution of R_μ is therefore $E_\mu \cos\theta^*$ (assuming a constant primary composition)

- 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

Analysis of experimental results in terms of $E_\mu \cos\theta^*$

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

Experiments with magnetic field:

- 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 $46° < \theta < 78°$
- CMS: (shallow depth)
  CMS Collaboration, Phys. Lett. B692 (2010) 83
- MINOS:
  P. Adamson et al., Phys. Rev. D76 (2007) 052003 + Phys. Rev. D83 (2011) 032011
- OPERA:
  N. Agafonova et al., Eur. Phys. J. C67 (2010) 25 + Eur. Phys. J. C74 (2014) 2933

Experiments without magnetic field:

- 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 $0° < \theta < 90°$
- LVD:
  N. Agafonova et al., Proc. 31th ICRC, ŁÓDZ 2009 + arXiv:1311.6995
  – Underground at LNGS, average overburden ~3800 m.w.e., scintillators, delayed events on stopping muons, one bin with $\theta < 15°$

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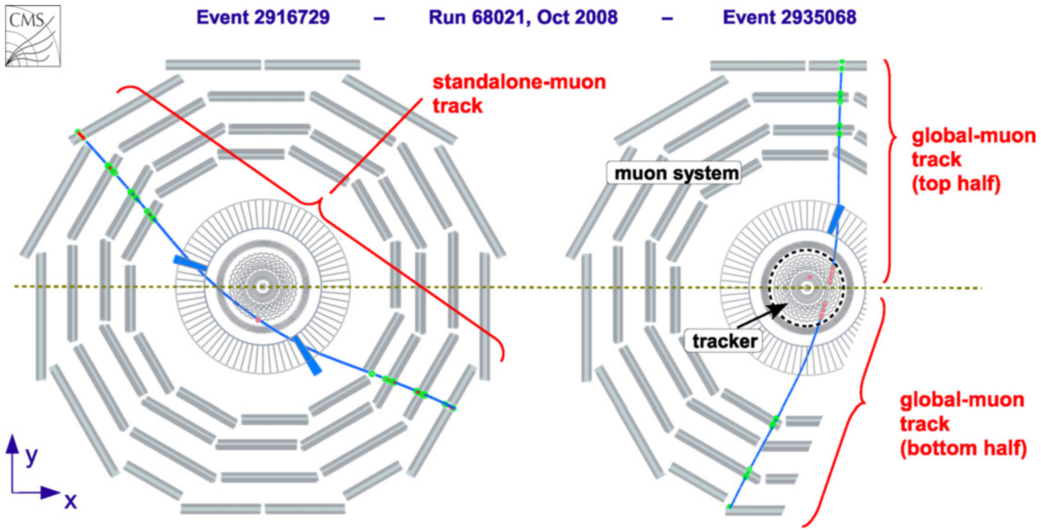
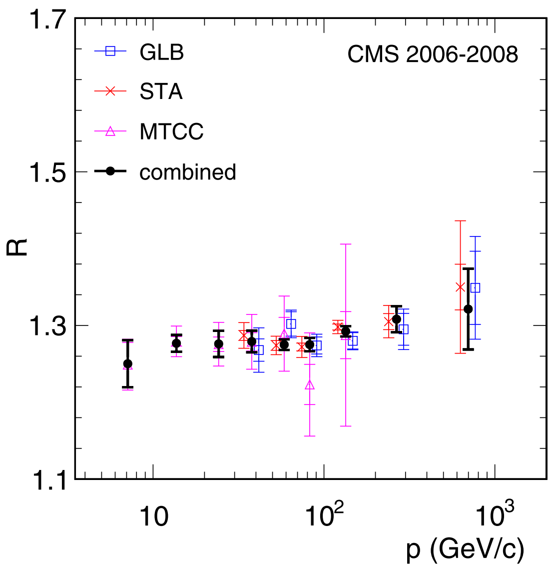
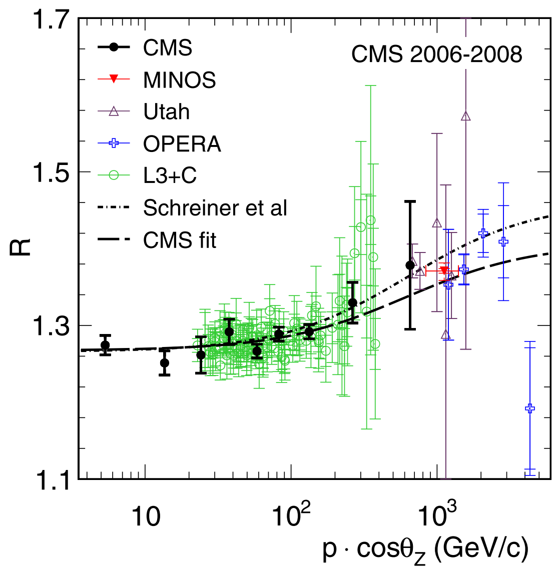
CMS results



- Average vertical overburden ~100 m.w.e.
- Superconducting solenoid (3.8 T)
- Muon tracking with **inner** silicon trackers + **outer** muon chambers (DT + RPC)
- Zenith window $0° < \theta < 80°$

CMS provides the measurement of R_μ in the **[5 GeV/c - 1 TeV/c]** momentum range: rise in R_μ
→ Measurement in the transition region between the pion dominated charge ratio (p < 100 GeV/c) and the pion+kaon charge ratio



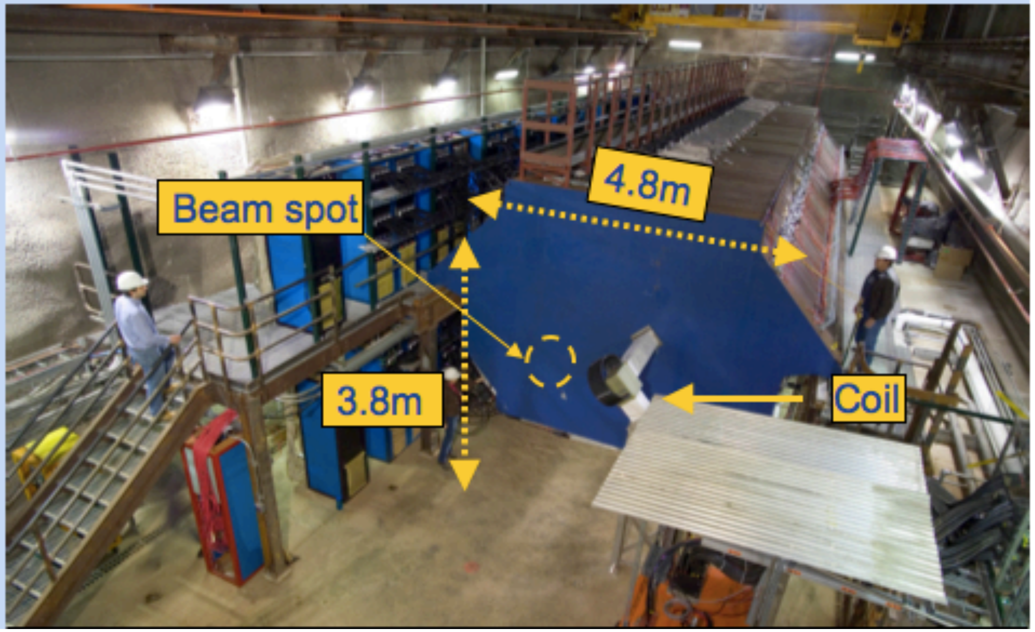


MINOS Near and Far detectors

Identical detectors: magnetized steel (toroidal magnetic field, average ~1.3 T) + scintillators
At FD in Soudan flat overburden profile ~2000 m.w.e., detector angular window 0° < θ < 90°

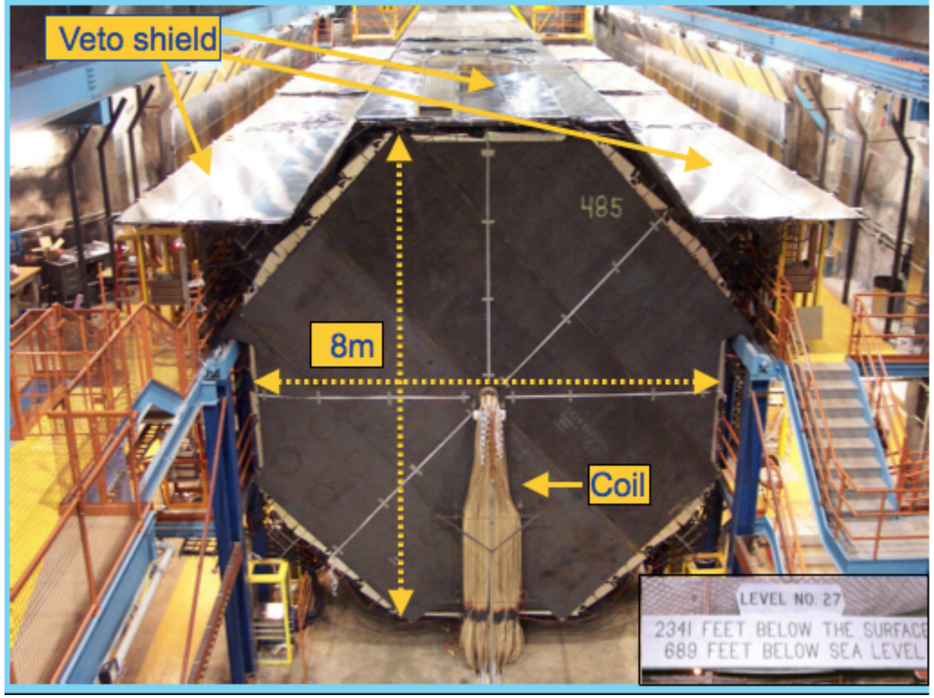
Near Detector

- 980 ton total mass
- Located 1 km downstream of the target at Fermilab
- 100 m depth



Far Detector

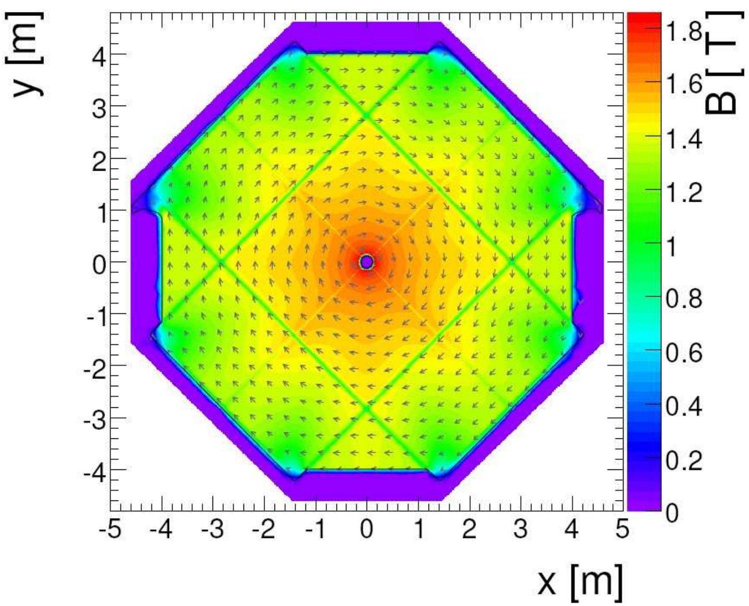
- 5.4 kton, 2 supermodules
- Located 735 km away in Soudan mine, MN
- 714 m depth
- Veto shield enables atmospheric neutrino studies

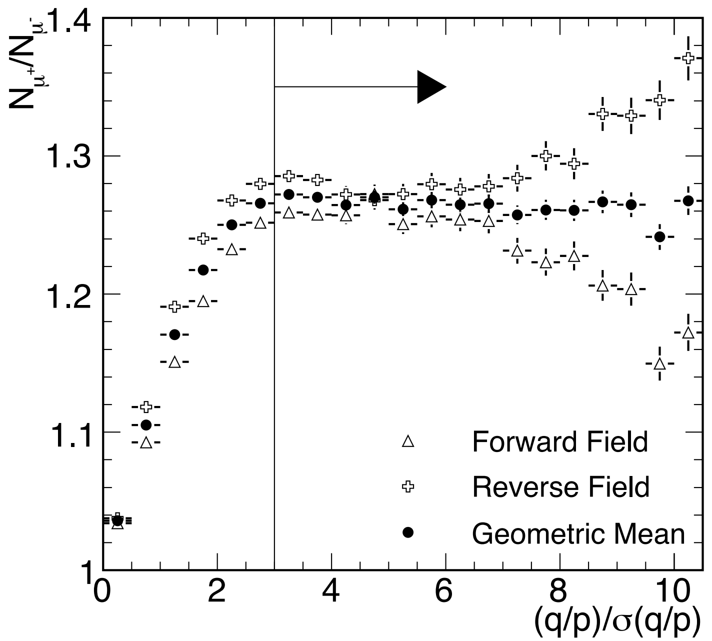


MINOS results

Measurements by two functionally identical detectors, one at shallow depth, one deep underground

- Toroidal magnetic field: different acceptance for μ^+ and μ^-
  - Combination of data sets with opposite magnetic field orientations to minimize systematic errors



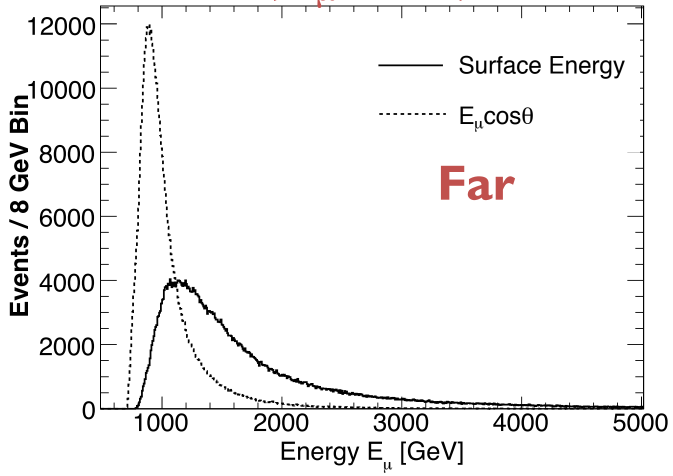


Near [R_μ (single μ) = 1.266 ± 0.001(stat.) $^{+0.015}_{-0.014}$ (syst.)

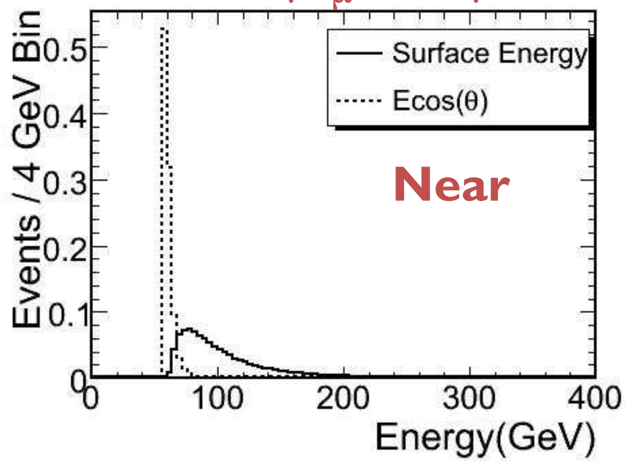
Far [R_μ (single μ) = 1.374 ± 0.004 (stat.) $^{+0.012}_{-0.010}$ (syst.)
R_μ (multiple μ) = 1.080 ± 0.004 (stat.) (C. Castromonte et al., Proc. 33rd ICRC, 2013)

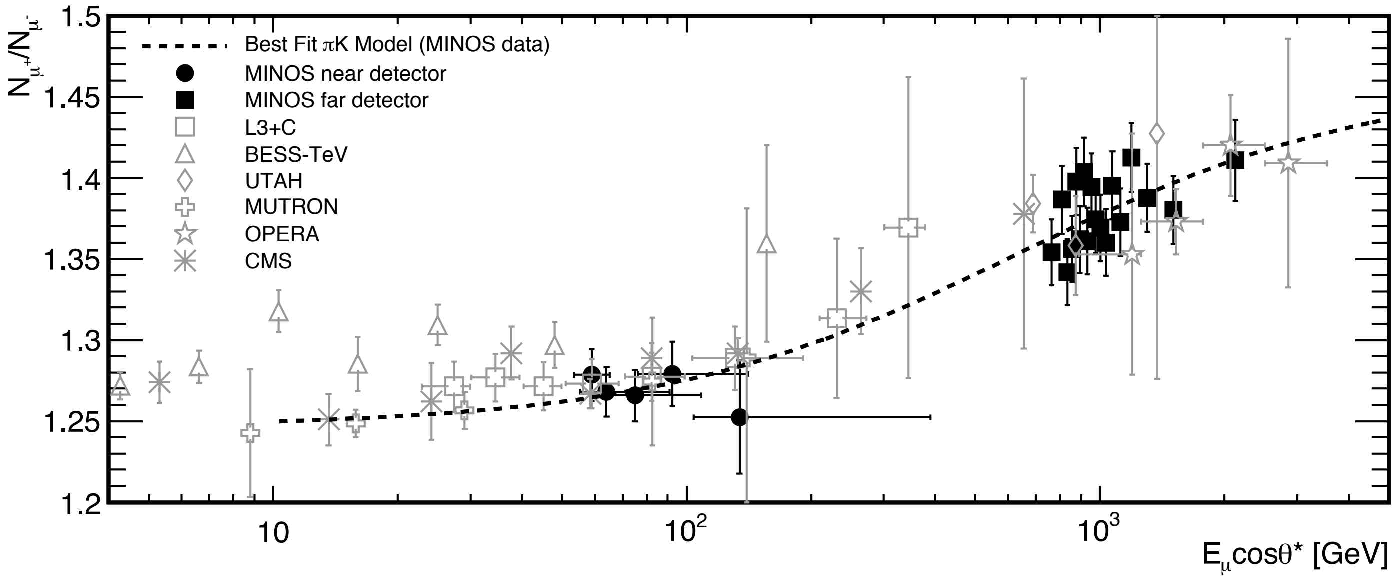
MINOS results

MINOS Far $\langle E_\mu \cos\theta^* \rangle \approx 1$ TeV



MINOS Near $\langle E_\mu \cos\theta^* \rangle \sim O(100)$ GeV

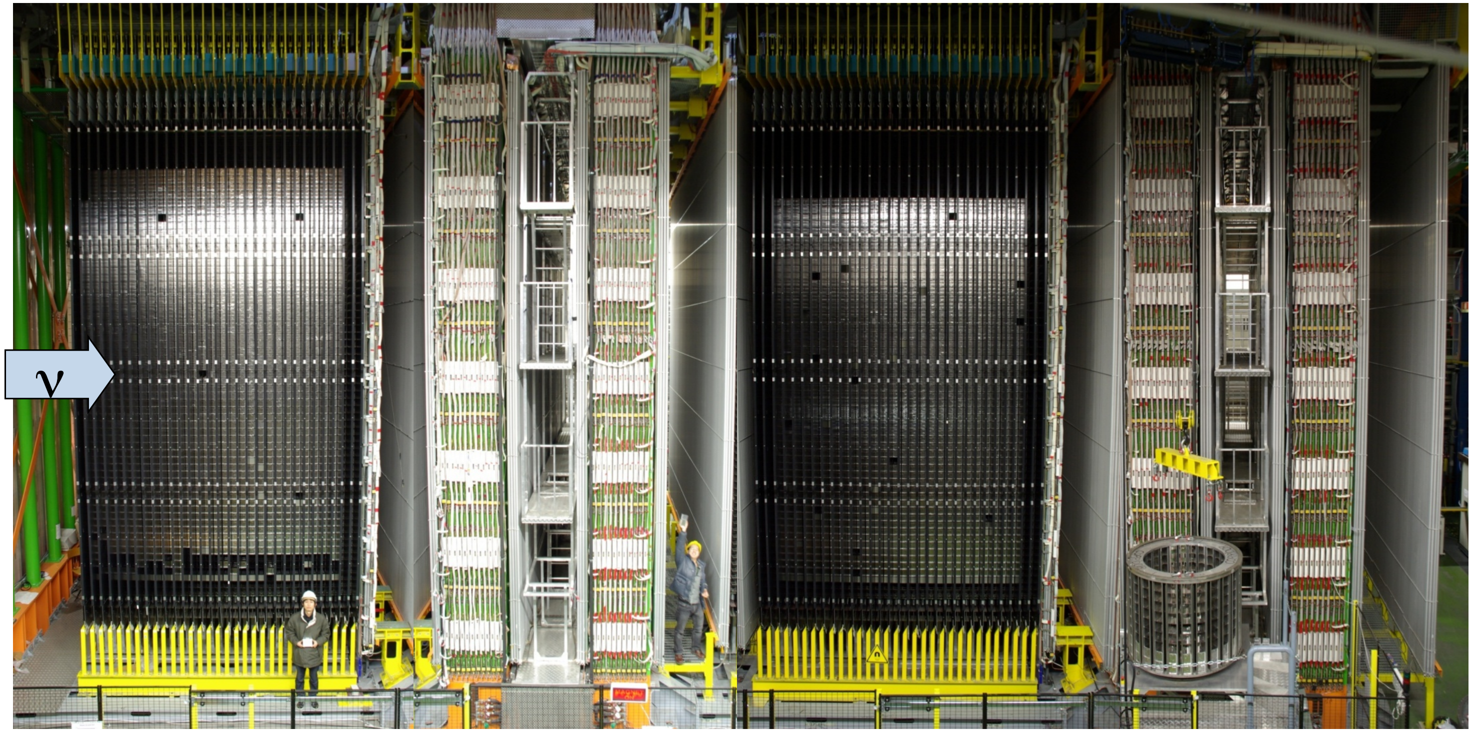




OPERA detector

Target + magnetic spectrometer (1.53 T) at LNGS, average overburden ~3800 m.w.e., drift tubes + RPC + scintillators, detector angular window 0° < θ < 90°

SM 1 SM 2



Target
bricks walls + Target Tracker

Spectrometer
RPC + drift tubes

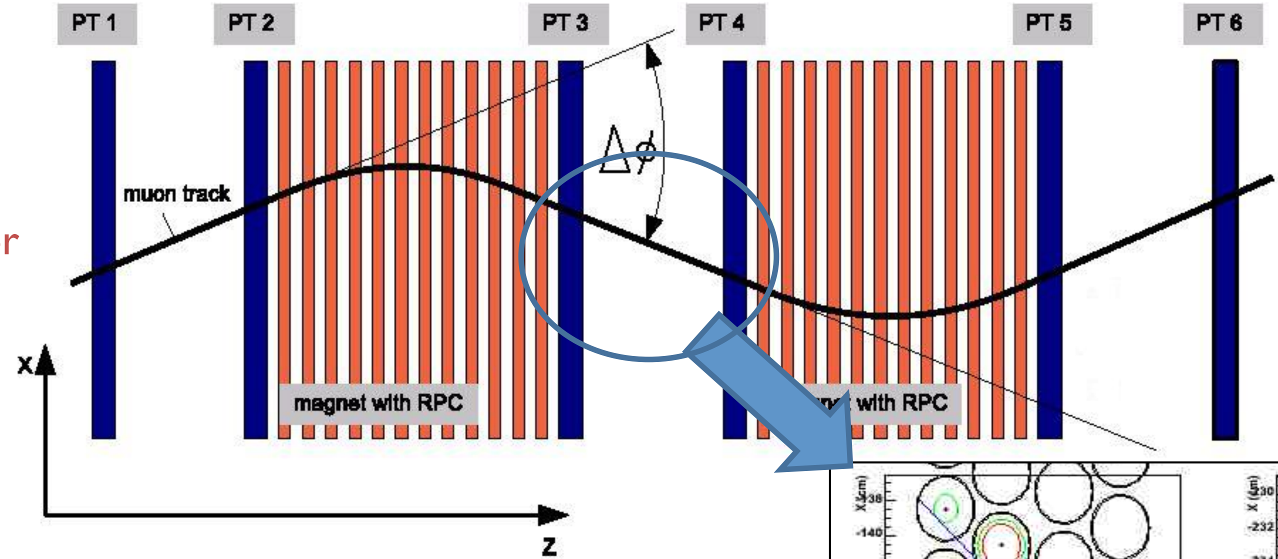
Target
bricks walls + Target Tracker

Spectrometer
RPC + drift tubes

OPERA: $\langle E_\mu \cos\theta^* \rangle \approx 2$ TeV → **The (magnetized) experiment with the largest $E_\mu \cos\theta^*$**

Charge and momentum reconstruction

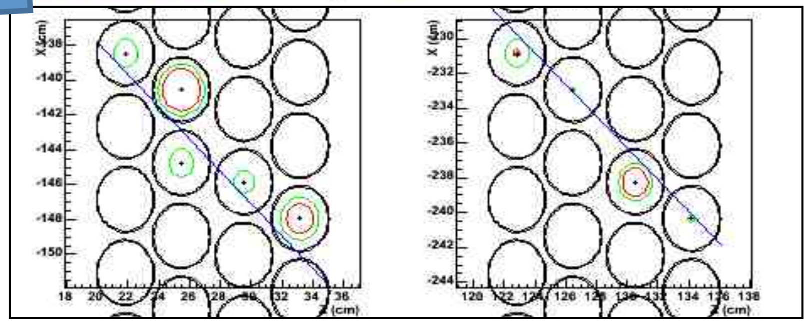
Top view of the OPERA detector



Δφ ≡ bending angle

charge-symmetric detector:
same acceptance for μ^+ and μ^-

- Charge and momentum information provided by the bending angle $\Delta\phi_k = \phi_i - \phi_j$ (k=1,...,4, for the 4 arms)



➢ 0.15 mrad angular resolution for $\phi = 0$ (improve for $\phi > 0$)

➢ Combination of the two data sets with opposite magnet polarities
→ disposing of the misalignment systematics (~0.1 mrad)

Systematic uncertainty on R_μ

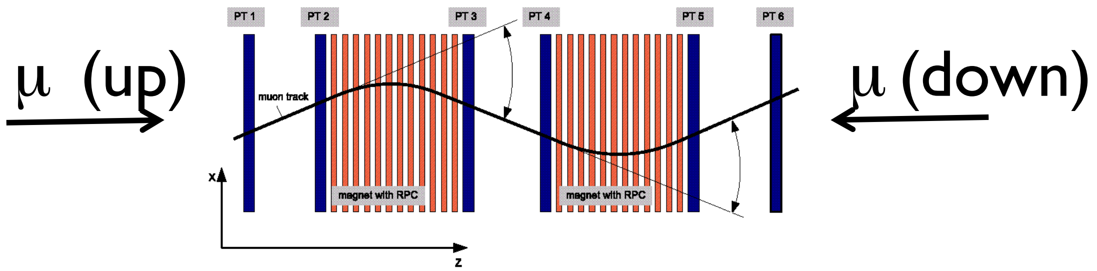
Two main sources of systematic uncertainties:

→ <u>Misalignment</u>: combination procedure

- Estimate of the residual systematic uncertainty related to the combination procedure: difference between the charge ratio R_μ for muons coming from opposite directions: $\delta R_\mu = |R_\mu\,(up) - R_\mu\,(down)|$

→ <u>Charge misidentification</u> η from experimental data

- Estimate $\delta\eta = \eta_{data} - \eta_{MC}$ <u>for a subsample of events</u> crossing both arms of a spectrometer: computation of the probability p of reconstructing opposite charges



Total systematic uncertainty for single μ: $\delta R_\mu^{unf}(syst) = +0.007, -0.001$

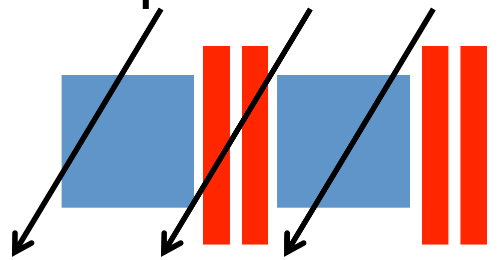
Total systematic uncertainty for multiple μ: $\delta R_\mu^{unf}(syst) = +0.015, -0.013$

Results: underground muon charge ratio

Full OPERA data set (2008-2012): combining data taken with opposite magnet polarities

R_μ computed separately for single and multiple muon events

- Multiple muons: compute R_μ when the 3D multiplicity is > 1, independently on the number of measured charges in the event



primary features extracted from a full MC

Full OPERA data (5-year statistics)

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	**1.377 ± 0.006**
> 1	8.5 ± 0.3	77 ± 1	0.352 ± 0.012	2.09 ± 0.07	**1.098 ± 0.023**

"dilution" of R_μ for multiple muon events

convolution of two effects:

larger n/p ratio in the all-nucleon spectrum ⊗ different x_F region

Charge ratio of multiple muon events

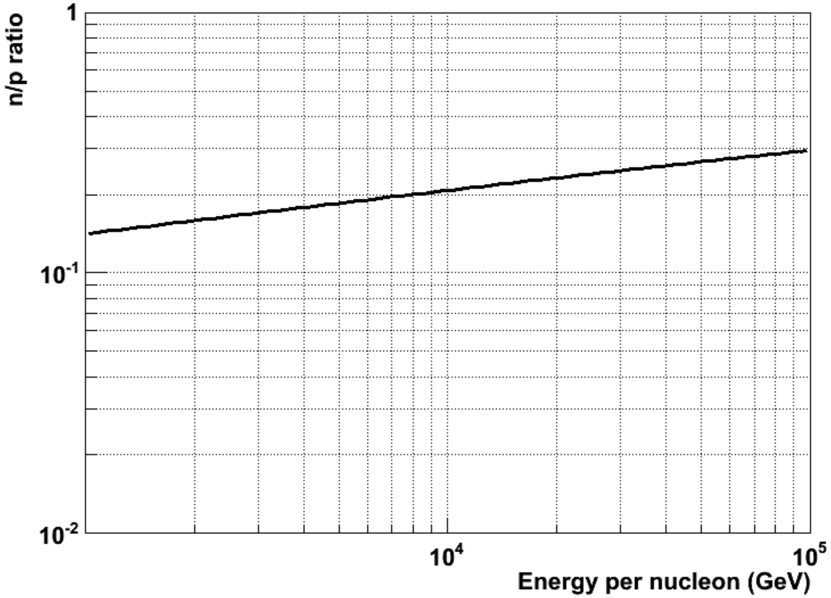
- The smaller value of the charge ratio of multiple muons is due to the convolution of two effects:

larger n/p ratio in the all-nucleon spectrum ⊗ different x_F region

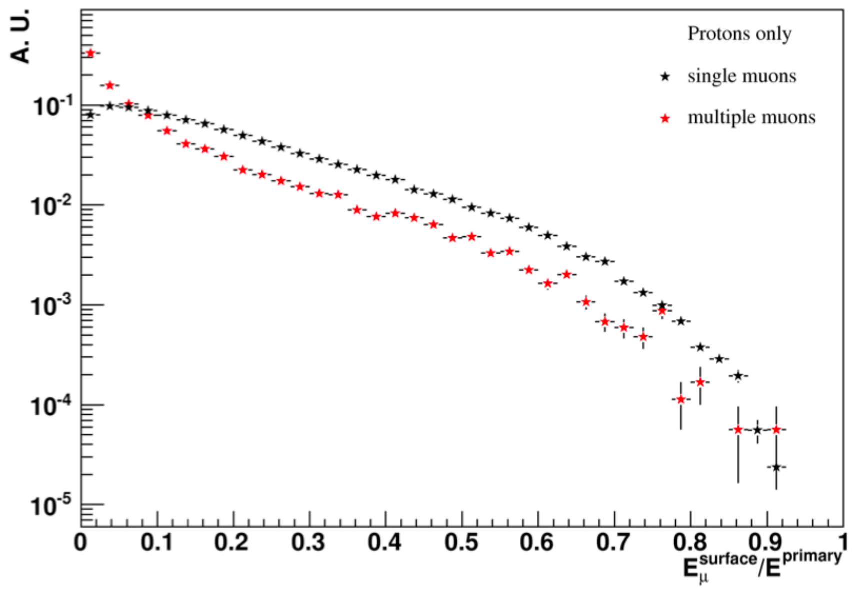
Multiple muon sample:
higher E/nucleon, higher average A

Multiple muon sample:
smaller x_F, towards the central region

n/p ratio in primary cosmic rays

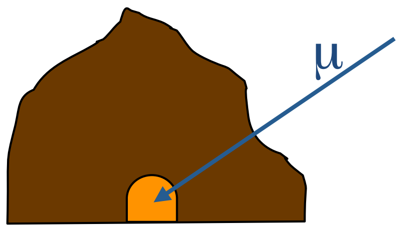


Feynman x: $x_F \cong E_{secondary}/E_{primary}$

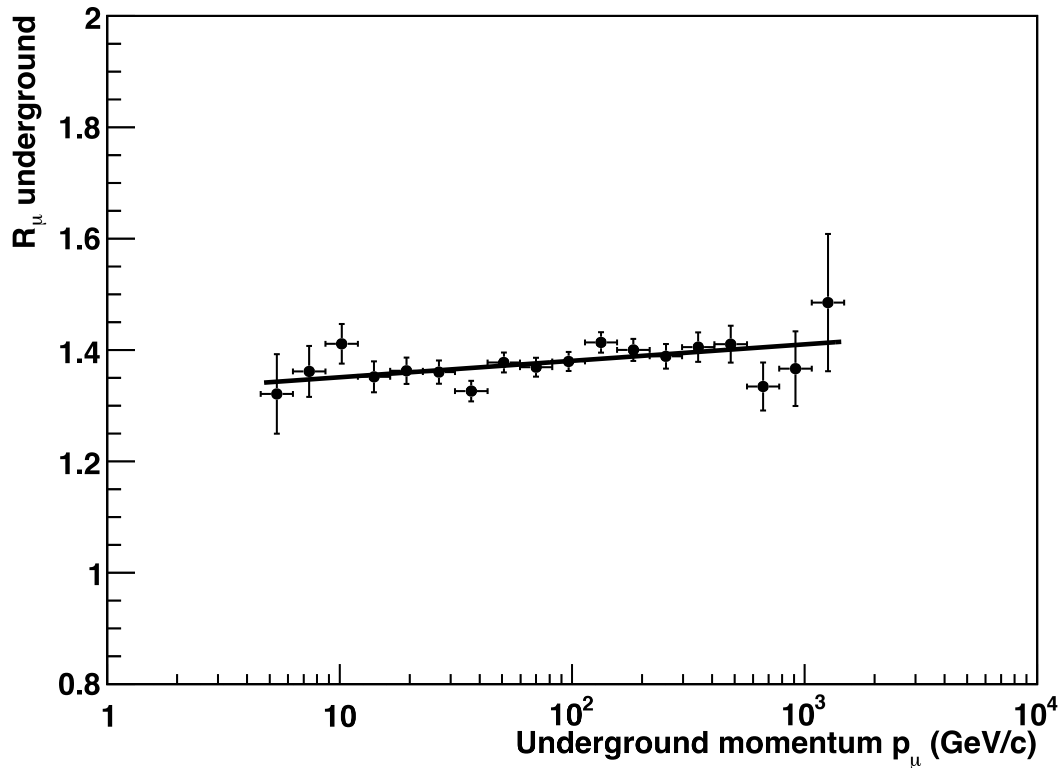


R_μ as a function of p_μ

- R_μ (**single muons**)
- Evolution with p_μ is compatible both with a constant and with a logarithmic energy increase, with a 2.4σ preference for the latter



underground



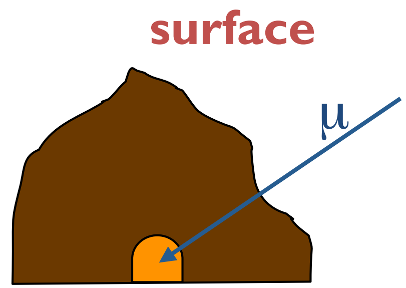
$R_\mu = a_0 + a_1 \log_{10} p_\mu$
→ $a_0 = 1.322 \pm 0.023$
→ $a_1 = 0.030 \pm 0.012$
(χ^2/dof = 14.99/16)

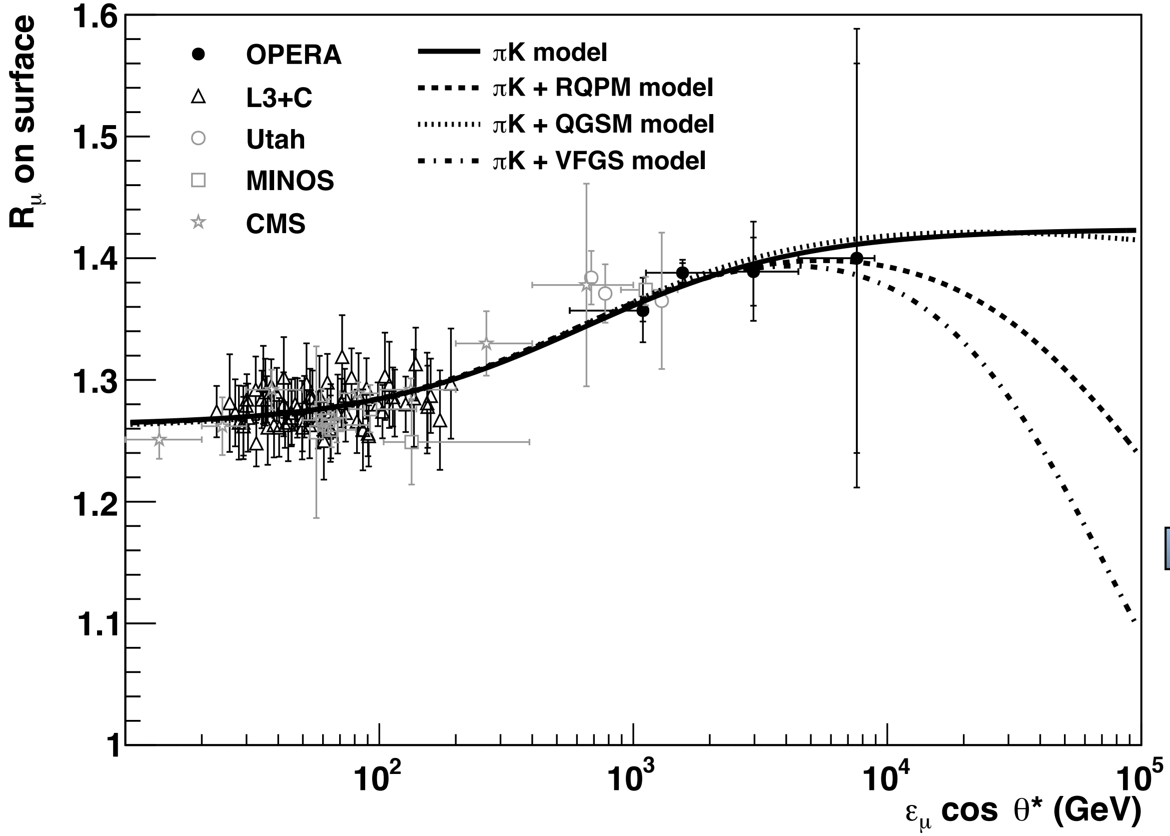
$R_\mu = c_0$
→ $c_0 = 1.377 \pm 0.006$
(χ^2/dof = 20.86/17)

$\Delta\chi^2$/dof = 5.87/1 (~2.4 sigma)

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

Bin	$\mathcal{E}_\mu \cos\theta^*$ (GeV)	$(\mathcal{E}_\mu \cos\theta^*)_{MPV}$ (GeV)	$\langle\theta\rangle$ (deg)	R_μ	$\delta R_\mu(stat.)$	$\delta R_\mu(syst.)$ %
1	562 - 1122	1091	47.5	1.357	0.009	1.8
2	1122 - 2239	1563	42.8	1.388	0.008	0.1
3	2239 - 4467	2972	46.9	1.389	0.028	2.1
4	4467 - 8913	7586	60.0	1.40	0.16	7.1





only single muons

- Fit with the function

$$\phi_{\mu^\pm} \propto \frac{a_\pi f_{\pi^\pm}}{1 + b_\pi \mathcal{E}_\mu \cos\theta/\epsilon_\pi} + R_{K\pi} \frac{a_K f_{K^\pm}}{1 + b_K \mathcal{E}_\mu \cos\theta/\epsilon_K}$$

Fixing $R_{K\pi}$ = 0.127 (weighted average of experimental values, Grashorn et al.):
$f_{\pi+}$ = 0.5512 ± 0.0014
f_{K+} = 0.705 ± 0.014

R_μ as a function of $E_\mu \cos\theta^*$ and δ_0

Taking into account an explicit dependence on δ_0 = (p - n)/(p + n):

(Gaisser, Astropart. Phys. 35 (2012) 801)

$$R_\mu = \left[\frac{f_{\pi^+}}{1+B_\pi \mathscr{E}_\mu \cos\theta^*/\varepsilon_\pi} + \frac{\frac{1}{2}(1+\alpha_K \beta \delta_0) A_K/A_\pi}{1+B_K^+ \mathscr{E}_\mu \cos\theta^*/\varepsilon_K}\right] \times \left[\frac{1-f_{\pi^+}}{1+B_\pi \mathscr{E}_\mu \cos\theta^*/\varepsilon_\pi} + \frac{(Z_{NK^-}/Z_{NK}) A_K/A_\pi}{1+B_K \mathscr{E}_\mu \cos\theta^*/\varepsilon_K}\right]^{-1}$$

δ_0 depends on $E_{primary}$/nucleon ≈ 10 E_μ (not on $E_\mu \cos\theta^*$!)

→ Different dependencies:

fit in 2-dimensions (E_μ, $\cos\theta^*$)

20 bins: 5 energy bins × 4 angular bins

Fixed parameters (see table) →

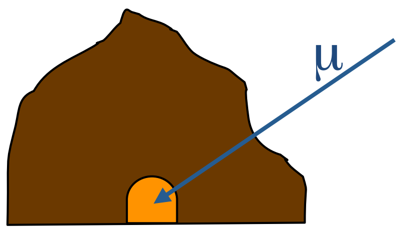
Inferred parameters: Z_{pK+} and δ_0

Parameter	Value	Ref.
Parameters depending on hadronic interactions		
$Z_{p\pi^+}$	0.046	[2]
$Z_{p\pi^-}$	0.033	[2]
Z_{pK^-}	0.0028	[2]
β	0.909	[22]
Parameters depending on primary spectral index		
A_π	0.675 $Z_{N\pi}$	[7]
A_K	0.246 Z_{NK}	[7]
B_π	1.061	[7]
B_K	1.126	[7]
Parameters depending on primary composition		
b	-0.035	[2]
Critical energies		
ε_π	115 GeV	[22]
ε_K	850 GeV	[22]

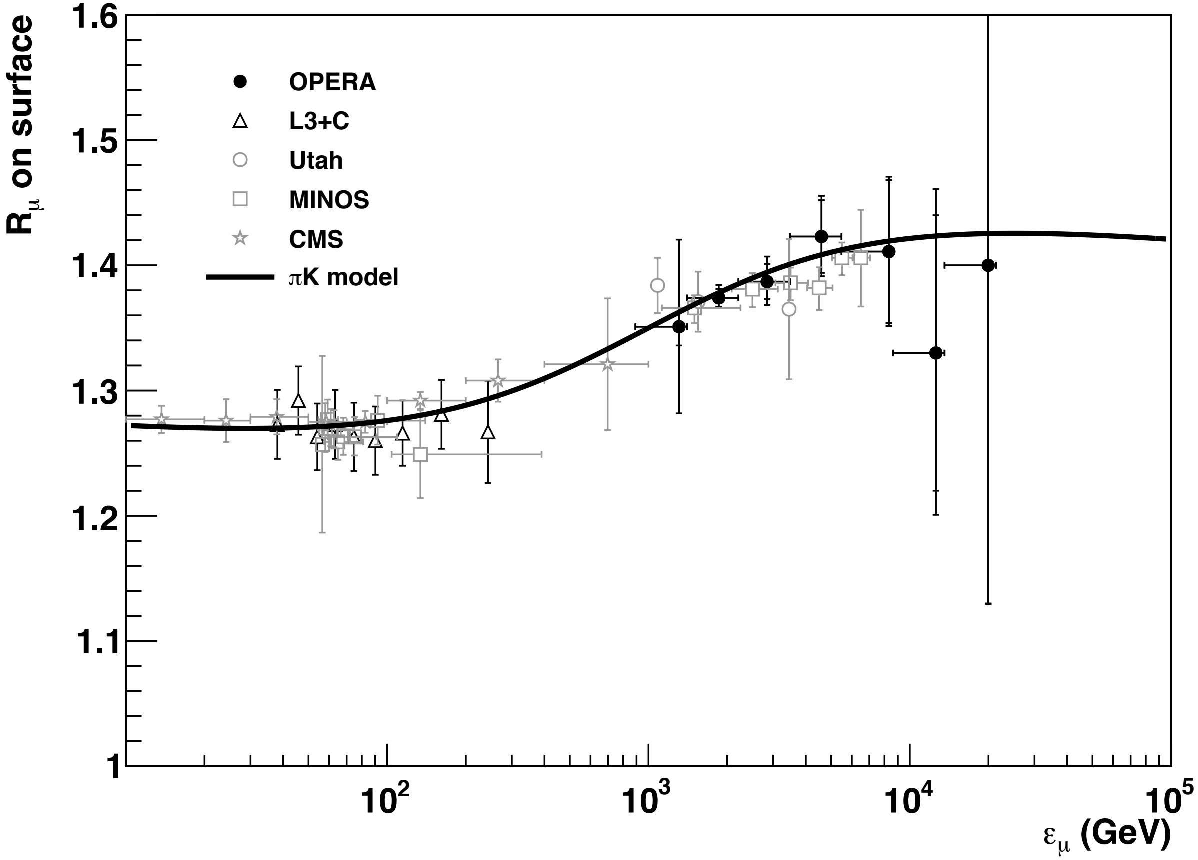
R_μ as a function of E_μ

Fit result:

δ_0 ($E_N \approx$ 20 TeV/n)= 0.61 ± 0.02
Z_{pK+} = 0.0086 ± 0.0004



Projecting the fit result on the average OPERA zenith <cos θ^*> ≅ 0.7:
R_μ as a function of the surface muon energy



only single muons

Conclusions

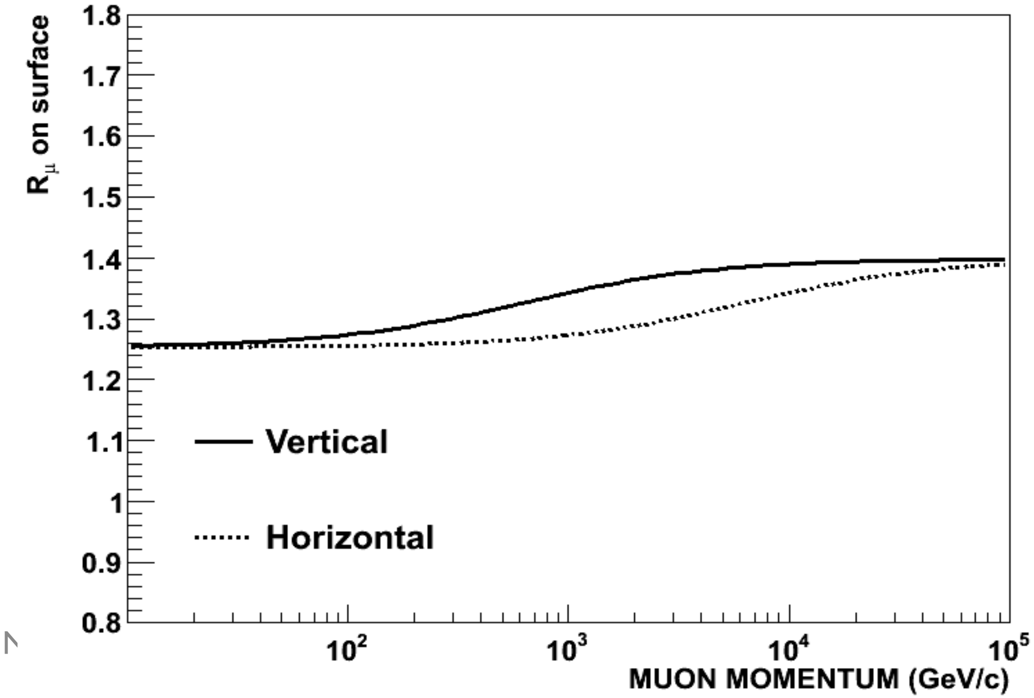
- The measurement of the atmospheric muon charge ratio R_μ provides relevant information for both particle- and astrophysics
- R_μ was measured in a wide energy range, from O(1 GeV) up to O(10 TeV)
- The results of CMS, MINOS and OPERA show a rise of R_μ vs $E_\mu \cos\theta^*$
  → increasing kaon contribution
- The OPERA measurement in the highest energy region:
  - Found a strong reduction of the charge ratio for multiple muon events
  - R_μ for single muons compatible with the expectation from a simple π-K model
  - No significant contribution of the prompt component up to $E_\mu \cos\theta^* \sim 10$ TeV
  - Extracted relevant parameters on the primary composition (δ_0) and the associated kaon production in the forward fragmentation region (Z_{pK+} moment)
  - Validity of Feynman scaling in the fragmentation region up to $E_\mu \sim 20$ TeV, corresponding to primary energy/nucleon $E_N \sim 200$ TeV

Spares

Dependencies of R_μ

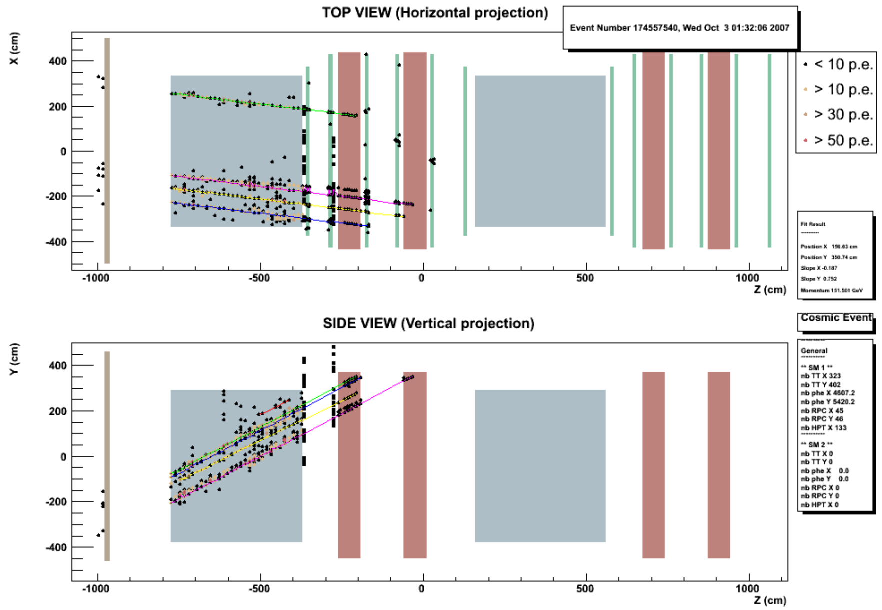
- R_μ exhibits a zenith dependence if:
  a) Muon contributions from different sources with different R_μ
  b) At least one source has a zenith dependence (e.g. π and K due their relatively long lifetimes)
- In the past several authors applied corrections to convert inclined to vertical R_μ measurements
- This procedure has a limit: it assumes no other sources apart from π and K and it assumes $Z_{p\pi}$ and Z_{pK} are known

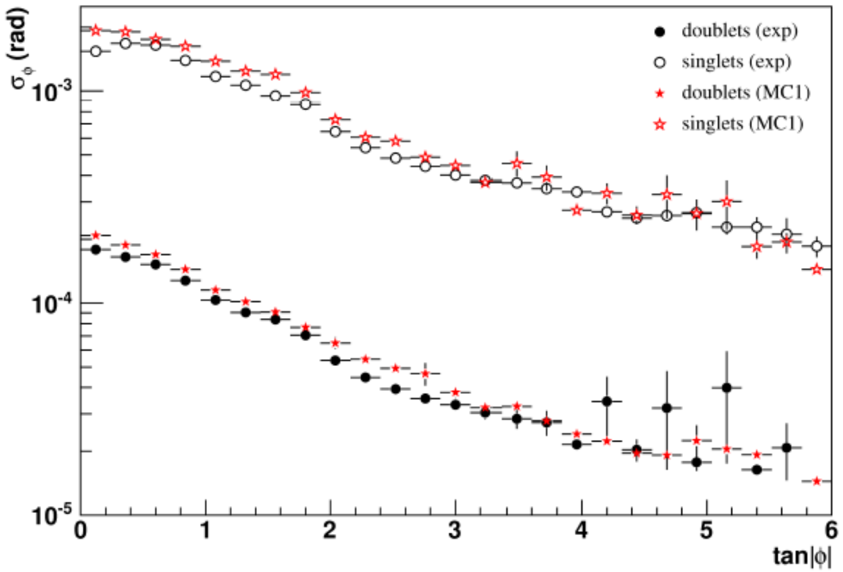
- The projection on the vertical via $E_\mu \cos\theta$ is safer → capability to explore new (isotropic) components and to derive $Z_{p\pi}$ and Z_{pK} from data



Cosmic event reconstruction in OPERA

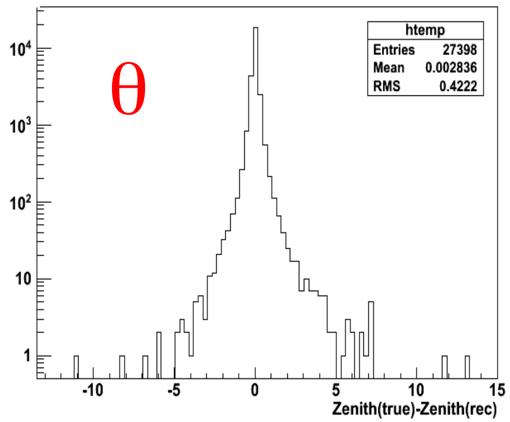
- Multiple muon events well reconstructed

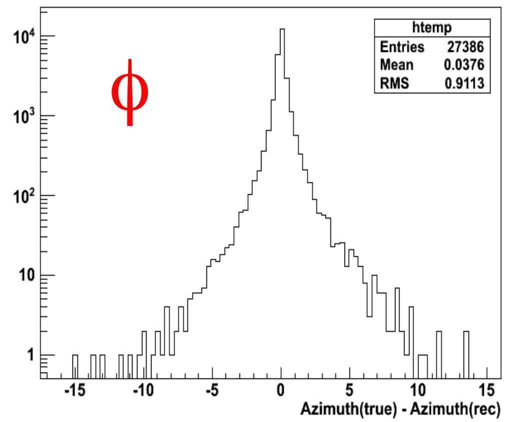




- High angular resolution in the PT system

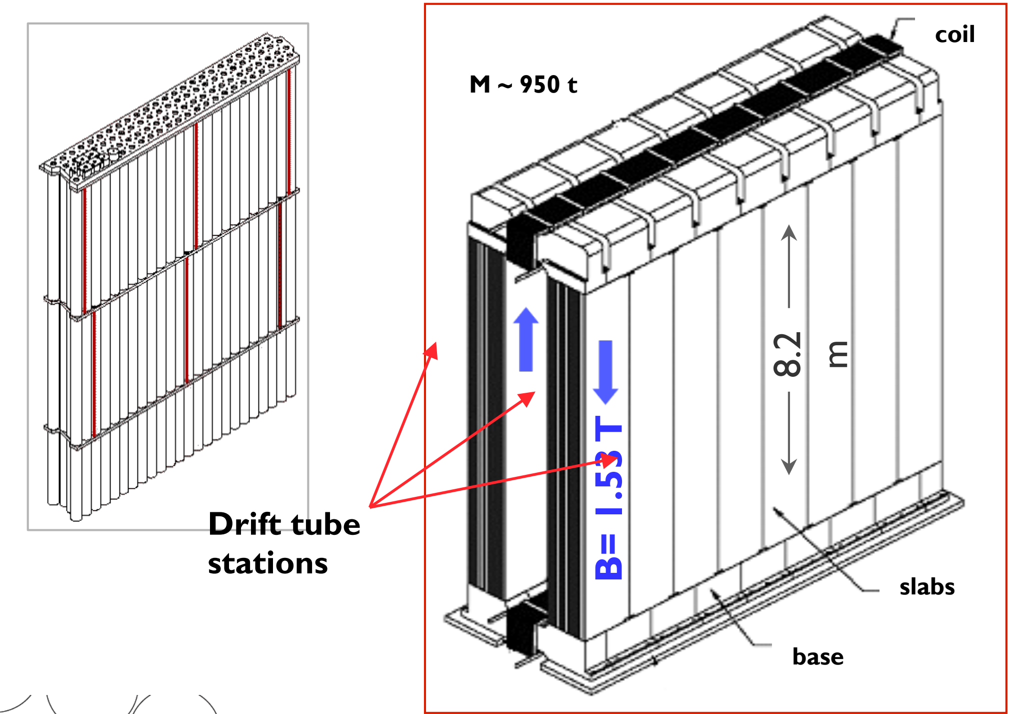
- Good overall angular resolution
"resolutions" < 1 deg both for zenith and azimuth direction reconstruction

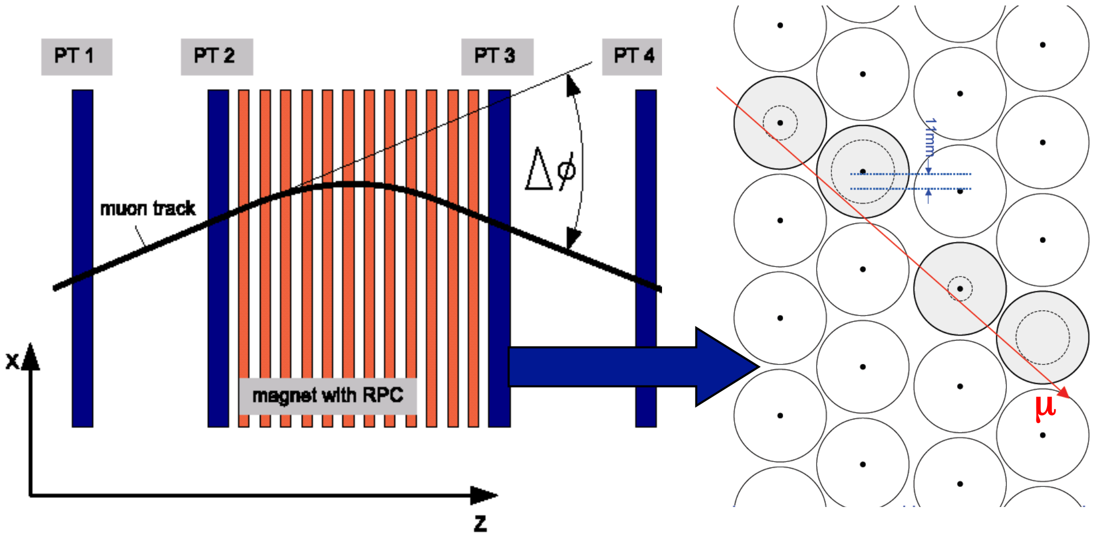




PT system in the spectrometer

6 PT stations for each spectrometer: 2 upstream of the first magnet arm, 2 in the middle, 2 downstream of the second magnet arm





Top view of the OPERA spectrometer