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 ($E>1$ TeV) 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), $R_{\mu}$ provides a benchmark for atmospheric $\nu$ flux computations (e.g. background for neutrino telescopes)
Key features of $R_\mu$

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

$$f_{p\pi}^\pm(E_\pi, E_p) \equiv \frac{E_\pi}{\sigma_{pp}^{inel}} \frac{d\sigma_{p\rightarrow \pi}^\pm}{dE_\pi} \left[\frac{E}{E_{\infty}}\right] \sim f_{p\pi}^\pm(x)$$

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 $Z_{ij}$:

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

Spectrum weighted moments (SWM)
Key features of $R_\mu$ (cont’d)

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

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

where:
\[
A = \frac{(Z_{p\pi^+} - Z_{p\pi^-})}{(Z_{p\pi^+} + Z_{p\pi^-})}, \quad B = \frac{(1 - Z_{pp} - Z_{pn})}{(Z_{pp} + Z_{pn})}
\]

\[
\delta_0 = \frac{(p_0 - n_0)}{(p_0 + n_0)} \quad \text{primary proton excess}
\]

Interpretation of the prominent features:
- 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 ($R_\mu > 1$)
- $R_\mu$ does not depend on $E_{\mu}$ (or $E_{\pi}$) nor on the target nature
- $R_\mu$ depends on the primary composition through $\delta_0$
Kaon contribution

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

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

- For kaons:

\[
Z_{pK^+} \gg Z_{nK^-} \approx Z_{pK^-}
\]

because the reaction

\[ p \, \text{Air} \rightarrow K^+ \Lambda \, \text{N} + \text{anything} \]

is favoured (associated production)

\[
\varepsilon_i = \varepsilon_i(\theta) \quad \text{critical energy}
\]

energy above which interactions dominate over decays. Along the vertical (\( \theta = 0^\circ \)):

\[
\varepsilon_\pi = 115 \, \text{GeV}
\]

\[
\varepsilon_K = 850 \, \text{GeV}
\]

\[
\varepsilon_X > 10^7 \, \text{GeV}
\]

\[ \rightarrow \text{This leads to a larger } R_\mu \text{ ratio at high energy} \]
Parameterization of the charge ratio

- Considering the general form for the muon flux

\[
\Phi_{\mu^\pm} = \frac{\Phi_N(E_\mu)}{1 - Z_{NN}} \sum_{i=1}^{N_{par}} \frac{a_i Z_i^{\pm}}{1 + b_i E_\mu \cos \theta^*/\varepsilon_i(0)}
\]

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

\[
\varepsilon_i(\theta) = \varepsilon_i(0) / \cos \theta^*
\]

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

- The \(R_\mu\) evolution as a function of \(E_\mu \cos \theta^*\) spans over the different sources

\[
R_\mu = w_\pi R_\mu^{\pi} + w_K R_\mu^K + w_{\text{charm}} R_\mu^{\text{charm}} + \ldots
\]

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

\(\theta^* \equiv \) zenith angle at the production point

Earth
$R_\mu$ 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 $\sim1400$ m.w.e., magnetic spectrometer (1.63 T) + spark chambers, six bins with $46^\circ < \theta < 78^\circ$

- **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 $\sim2700$ m.w.e., delayed events on stopping muons, one bin with $0^\circ < \theta < 90^\circ$

- **LVD:**
  N. Agafonova et al., Proc. 31th ICRC, ŁÓDZ 2009 + arXiv:1311.6995
  - Underground at LNGS, average overburden $\sim3800$ m.w.e., scintillators, delayed events on stopping muons, one bin with $\theta < 15^\circ$

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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 $0^\circ < \theta < 80^\circ$

CMS provides the measurement of $R_\mu$ in the [5 GeV/c - 1 TeV/c] momentum range: rise in $R_\mu$

$\rightarrow$ 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 $0^\circ < \theta < 90^\circ$

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 $\mu^+$ and $\mu^-$
- Combination of data sets with opposite magnetic field orientations to minimize systematic errors

$R_\mu$ (single $\mu$) = \( 1.266 \pm 0.001 \) (stat.) $^{+0.015}_{-0.014}$ (syst.)

$R_\mu$ (single $\mu$) = \( 1.374 \pm 0.004 \) (stat.) $^{+0.012}_{-0.010}$ (syst.)

$R_\mu$ (multiple $\mu$) = \( 1.080 \pm 0.004 \) (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

![Graph showing MINOS results]

- Surface Energy
- $E_\mu \cos \theta$

Far

- Events / 8 GeV Bin

Near

- Events / 4 GeV Bin

Figure 6: Distribution of $E$ and $E_{\text{surface}} \cos \theta$ for MINOS data muons in the Far Detector, after cuts (GeV).

Figure 7: Distribution of $E$ and $E_{\text{surface}} \cos \theta$ for MINOS muons in the Near Detector, after cuts (GeV).

We have used Equation 14 and the measured muon charge ratio to study $r_\pi$ and $r_K$. We have done chi-squared fits in $E_{\text{surface}} \mu \cos \theta^*$ to the MINOS data.
OPERA detector

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

\[ \langle E_\mu \cos \theta^* \rangle \approx 2 \text{ TeV} \]

The (magnetized) experiment with the largest $E_\mu \cos \theta^*$
Charge and momentum reconstruction

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

- Combination of the two data sets with opposite magnet polarities → disposing of the misalignment systematics ($\sim 0.1$ mrad)

$\Delta \phi \equiv$ bending angle

charge-symmetric detector: same acceptance for $\mu^+$ and $\mu^-$

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

Top view of the OPERA detector
Systematic uncertainty on $R_\mu$

Two main sources of systematic uncertainties:

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

→ **Charge misidentification** $\eta$ from experimental data
  - Estimate $\delta \eta = \eta_{\text{data}} - \eta_{\text{MC}}$ for a subsample of events crossing both arms of a spectrometer: computation of the probability $p$ of reconstructing opposite charges

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

Total systematic uncertainty for multiple $\mu$: $\delta R_\mu^{\text{unf}(\text{syst})} = +0.015, -0.013$
Results: underground muon charge ratio

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

$R_\mu$ computed separately for single and multiple muon events

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

| $N_\mu$ | $\langle A \rangle$ | $\langle E/A \rangle_{\text{primary}}$ [TeV] | H fraction | $N_p/N_n$ | $R_\mu^\text{unf}$ |
|--------|---------------------|-------------------------|------------|----------|-----------------|
| = 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 $R_\mu$ for multiple muon events

convolution of two effects:

larger n/p ratio in the all-nucleon spectrum $\otimes$ 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

n/p ratio in primary cosmic rays

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

Multiple muon sample:
  smaller $x_F$, towards the central region
$R_\mu$ as a function of $p_\mu$

- $R_\mu$ (single muons)
- Evolution with $p_\mu$ is compatible both with a constant and with a logarithmic energy increase, with a $2.4\sigma$ preference for the latter

\[
R_\mu = a_0 + a_1 \log_{10} p_\mu
\]
\[
\Rightarrow a_0 = 1.322 \pm 0.023
\]
\[
\Rightarrow a_1 = 0.030 \pm 0.012
\]
\[
(\chi^2/\text{dof} = 14.99/16)
\]

\[
R_\mu = c_0
\]
\[
\Rightarrow c_0 = 1.377 \pm 0.006
\]
\[
(\chi^2/\text{dof} = 20.86/17)
\]

\[
\Delta\chi^2/\text{dof} = 5.87/1 (~2.4 \text{ sigma})
\]
$R_\mu$ as a function of $E_\mu \cos \theta^*$

| Bin | $E_\mu \cos \theta^*$ (GeV) | $(E_\mu \cos \theta^*)_{MPV}$ (GeV) | $\langle \theta \rangle$ (deg) | $R_\mu$ | $\delta R_\mu$(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            |

- **Fit with the function**

$$
\phi_{\mu \pm} \propto \frac{a_\pi f_\pi^\pm}{1 + b_\pi \varepsilon_\mu \cos \theta / \varepsilon_\pi} + R_{K\pi} \frac{a_K f_K^\pm}{1 + b_K \varepsilon_\mu \cos \theta / \varepsilon_K}
$$

- Fixing $R_{K\pi} = 0.127$ (weighted average of experimental values, Grashorn et al.):
  - $f_{\pi^+} = 0.5512 \pm 0.0014$
  - $f_{K^+} = 0.705 \pm 0.014$
\( R_\mu \) as a function of \( E_\mu \cos \theta^* \) and \( \delta_0 \)

Taking into account an explicit dependence on \( \delta_0 = (p - n)/(p + n) \):

\[
R_\mu = \left[ \frac{f_{\pi^+}}{1 + B_\pi E_\mu \cos \theta^*/\epsilon_\pi} + \frac{1}{2} \left( 1 + \alpha_K \beta \delta_0 \frac{A_K/A_\pi}{1 + B_K E_\mu \cos \theta^*/\epsilon_K} \right) \right] 
\times \left[ \frac{1 - f_{\pi^+}}{1 + B_\pi E_\mu \cos \theta^*/\epsilon_\pi} + \frac{(Z_{NK-}/Z_{NK}) A_K/A_\pi}{1 + B_K E_\mu \cos \theta^*/\epsilon_K} \right]^{-1}
\]

\( \delta_0 \) depends on \( E_{\text{primary/nucleon}} \approx 10 \ E_\mu \) (not on \( E_\mu \cos \theta^* \! \) )

→ Different dependencies:
  fit in 2-dimensions (\( E_\mu, \cos \theta^* \) )
  20 bins: 5 energy bins \( \times \) 4 angular bins

Fixed parameters (see table)
Inferred parameters: \( Z_{pK^+} \) and \( \delta_0 \)

Parameter & Value & Ref. \\
\hline
\text{Parameters depending on hadronic interactions} & & \\
\hline
Z_{p\pi^+} & 0.046 & [2] \\
Z_{p\pi^-} & 0.033 & [2] \\
Z_{pK^-} & 0.0028 & [2] \\
\beta & 0.909 & [22] \\
\text{Parameters depending on primary spectral index} & & \\
A_\pi & 0.675 Z_{N\pi} & [7] \\
A_K & 0.246 Z_{NK} & [7] \\
B_\pi & 1.061 & [7] \\
B_K & 1.126 & [7] \\
\text{Parameters depending on primary composition} & & \\
b & -0.035 & [2] \\
\text{Critical energies} & & \\
\epsilon_\pi & 115 \text{ GeV} & [22] \\
\epsilon_K & 850 \text{ GeV} & [22] \\
\hline
$R_\mu$ as a function of $E_\mu$

Fit result:  
\begin{align*}
\delta_0 (E_N \approx 20 \text{ TeV/n}) &= 0.61 \pm 0.02 \\
Z_{pK^+} &= 0.0086 \pm 0.0004
\end{align*}

Projecting the fit result on the average OPERA zenith $\langle \cos \theta^* \rangle \approx 0.7$:

$R_\mu$ as a function of the surface muon energy

![Graph showing $R_\mu$ as a function of $E_\mu$.]
Conclusions

• The measurement of the atmospheric muon charge ratio $R_\mu$ provides relevant information for both particle- and astrophysics

• $R_\mu$ was measured in a wide energy range, from $O(1 \text{ GeV})$ up to $O(10 \text{ TeV})$

• The results of CMS, MINOS and OPERA show a rise of $R_\mu$ 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
  ➢ $R_\mu$ for single muons compatible with the expectation from a simple $\pi$-K model
  ➢ No significant contribution of the prompt component up to $E_\mu \cos \theta^* \sim 10 \text{ TeV}$
  ➢ Extracted relevant parameters on the primary composition ($\delta_0$) and the associated kaon production in the forward fragmentation region ($Z_{pK^+}$ moment)
  ➢ Validity of Feynman scaling in the fragmentation region up to $E_\mu \sim 20 \text{ TeV}$, corresponding to primary energy/nucleon $E_N \sim 200 \text{ TeV}$
Dependencies of $R_\mu$

- $R_\mu$ exhibits a zenith dependence if:
  
  a) Muon contributions from different sources with different $R_\mu$
  
  b) At least one source has a zenith dependence (e.g. $\pi$ and $K$ due their relatively long lifetimes)

- In the past several authors applied corrections to convert inclined to vertical $R_\mu$ measurements

- This procedure has a limit: it assumes no other sources apart from $\pi$ 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

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