The study of the longitude development of muons in air shower

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Introduction

Muon introduction

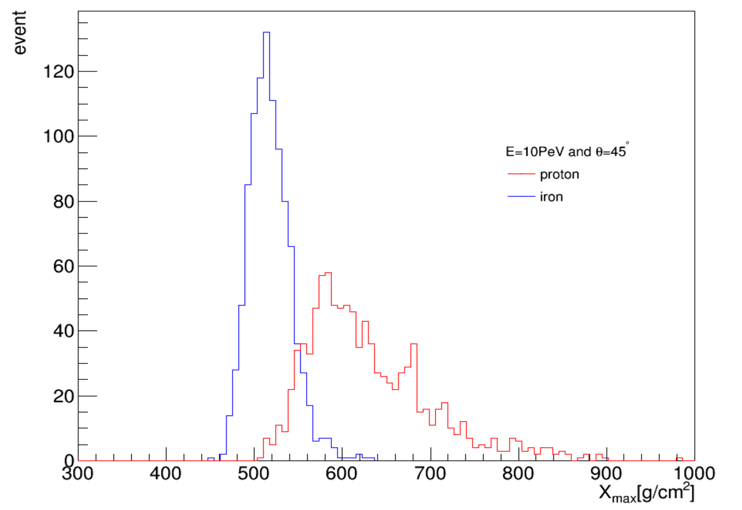
1. The main contributors to the muon component in air showers are charged pions $(\pi^+, \pi^-)$and kaons (K^+, K^-, K_L^0), but also charmed particles, such as $D^\pm, D^0$,J/ψ and others

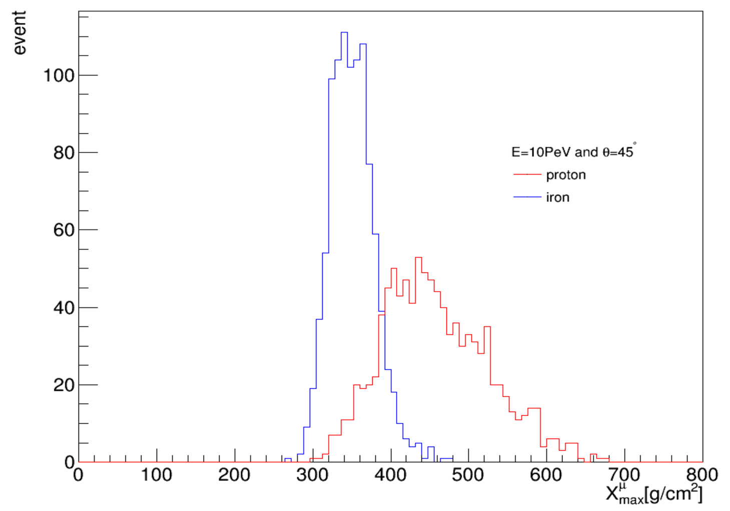
$$p + N(or\ A) \rightarrow p + N(or\ A) + n\pi^{\pm,0} + X$$
$$\pi^\pm \rightarrow \mu^\pm + (\overline{\nu_\mu})$$

2. Longitude development of muons preserves the information of primary particles and plays an important role in the study of composition identification with energy 10^{15} eV-10^{16} eV.

Purpose to study Muon

- Measure the cosmic ray energy spectrum and mass composition around knee region
- Helps to study the hadronic interaction model
- Provide insight on whether new physics phenomena take place





X_{max}: the air depth of the shower maximum development

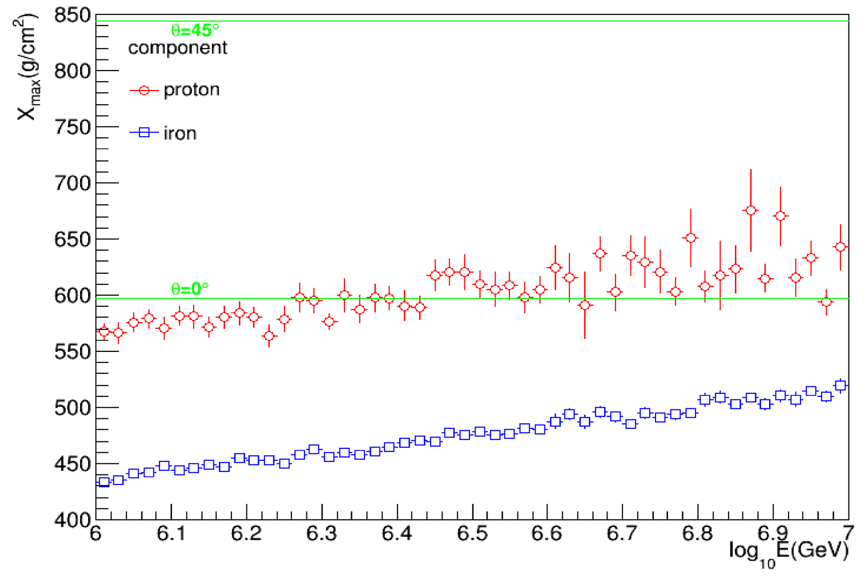
X^μ_{max}: the maximum of the longitudinal profile of the muon production rate

X^μ_{max} can be used to identify mass compositions of cosmic rays.

Air shower simulation

- **Simulation with CORSIKA (v76400)**
  - EPOS-LHC,QGSJETII-04
  - Zenith angle(θ): fixed 45°
  - Altitude: 4410m ($X = 600g/cm^2$)
  - Energy: 10PeV; 5PeV; 1PeV

Number of shower	10PeV	5PeV	1PeV
Proton	1000	2000	2000
Iron	1000	2000	2000



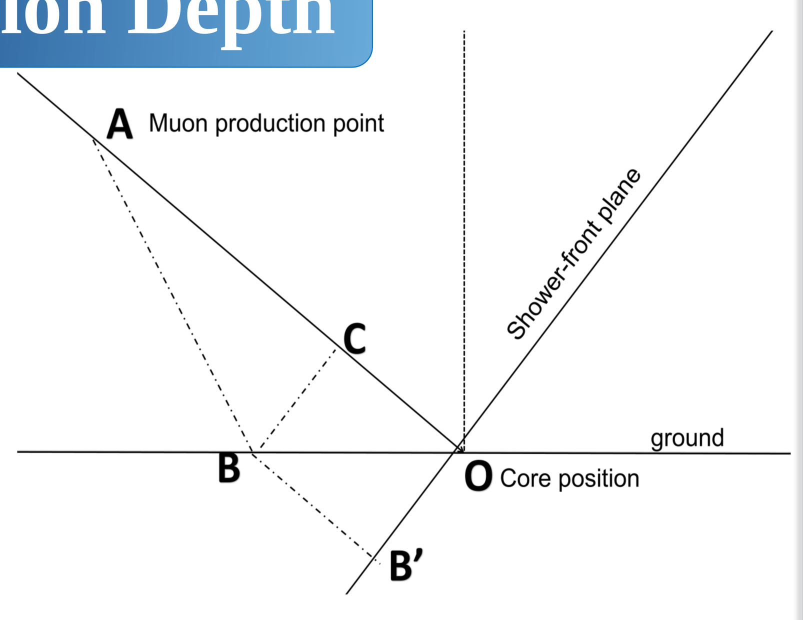
Y axis shows X_{max}, X axis shows $\log_{10}(E)$; green lines are air depth on ground with θ=0° and θ=45°

In order to ensure the shower full development, the zenith angle is selected as 45°

Reconstruction of Muon Production Depth

- Correction by the path traveled by the parent mesons :t_π~3ns
- Considering geometric delay as :t_g (geometric delay)
- $\overline{AB} = \sqrt{\overline{BC}^2 + (\overline{AO} - \overline{BB'})^2}$
- $\overline{AB} = \overline{AC} + c \times t_g$

$$\overline{AO} = \frac{1}{2}\left(\frac{\overline{BC}^2}{c\times(t_g)} - c \times (t_g)\right) - c \times t_\pi$$



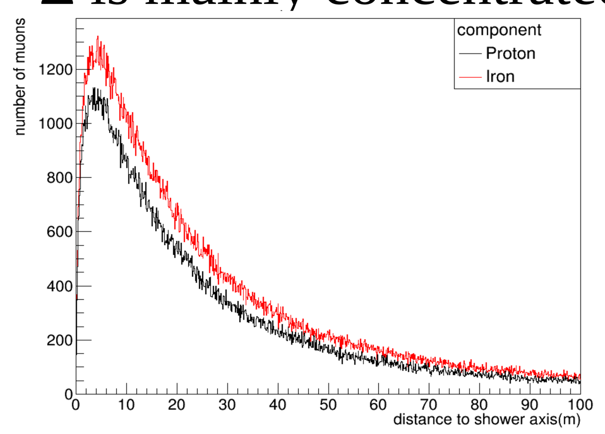
$\overline{AB}$: muon track $\overline{AO}$: *shower axis*

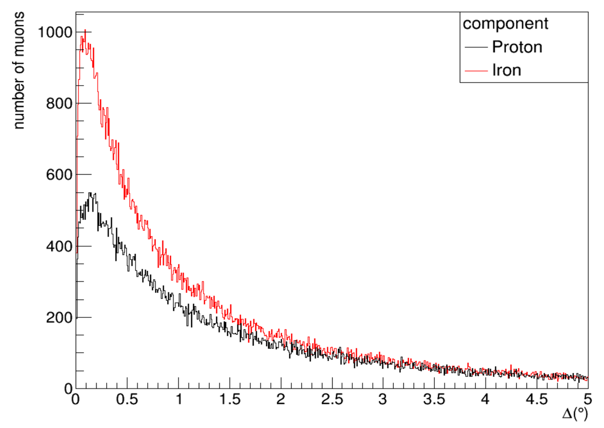
Muon propagation

- **Approximation I: The muons are produced on the shower axis**

* production point of most muons is confined to a cylinder with a radius of 10m

* Δ is mainly concentrated within 0.2°.





(Left) distributions of the perpendicular distance from the production point of muons to the shower axis

(Right):the difference of the direction of the muon between the production and incidence at the ground.

- **Approximation II: Muons travel in straight lines at the speed of light c**

* $t_B + t_{Rem} < t_{total}$ × 10% when r>400m

* t_g is the dominated when r>400m

r:distance from muon position on ground to core on SFP

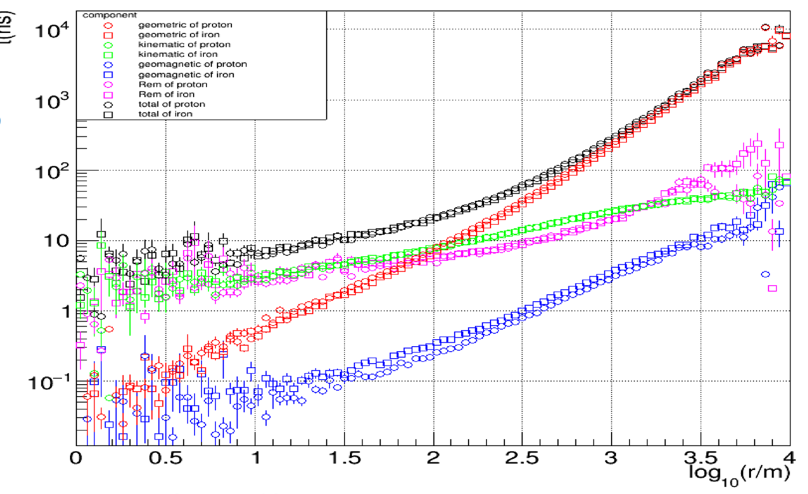
t_{total}: total time delay

t_g: geometric delay

t_ϵ: kinematic delay

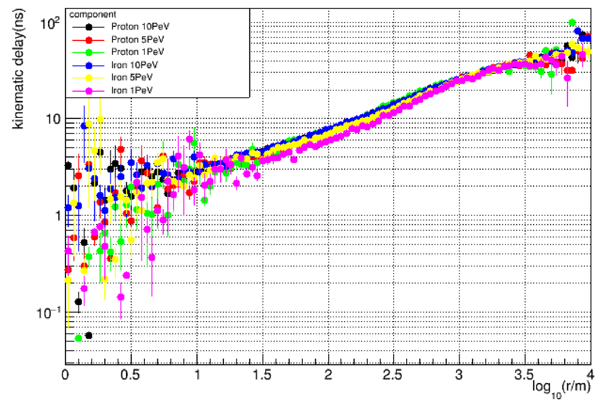
t_B: geomagnetic delay

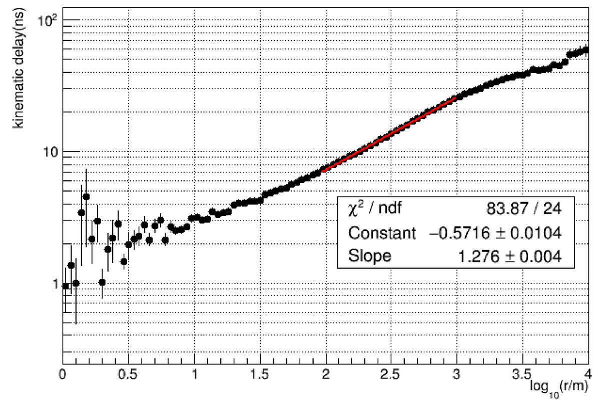
t_{Rem}:multiple scattering



Average time delay for different contribution to the total delay

- **Approximation III: $t_g = t_{total} - t_\epsilon$**





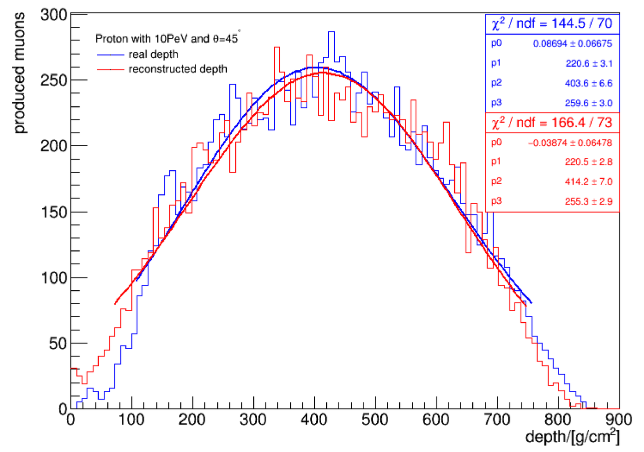
kinematic time delay distributions for showers with different compositions and energies can be fitted with an exponential function:

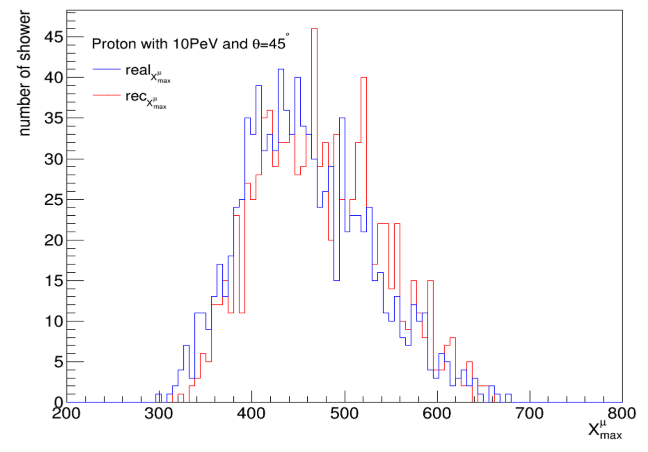
$$t_\epsilon = \exp(-0.57 + 1.276 \times log_{10}(r))$$

Features of the muon profiles

Fit the longitudinal profile of the muon

Profile meet: ①10 ns time resolution is considered ②400m<r<1000m ③Muon energy>1GeV





(Left): distributions of muon real production depth(blue) and muon reconstructed production depth(red) of a sower initiated by a proton with E=$10^{16}eV$ and θ=45°

(Right): distributions of real X^μ_{max} and reconstructed X^μ_{max} for 1000 showers initiated by protons with E=10^{16} eV and θ=45°

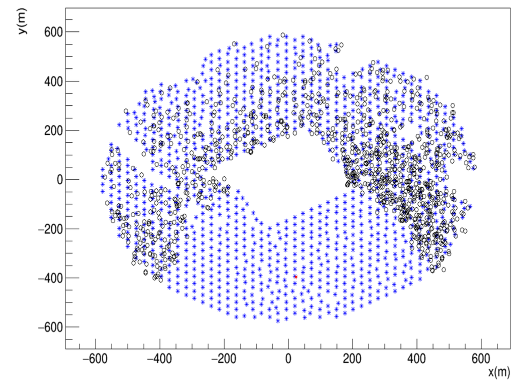
Fit formula: $\frac{dN}{dX} = (1 + \frac{R}{L}(X - X^\mu_{max}))^{R^{-2}} exp^{-\frac{X - X^\mu_{max}}{LR}}$

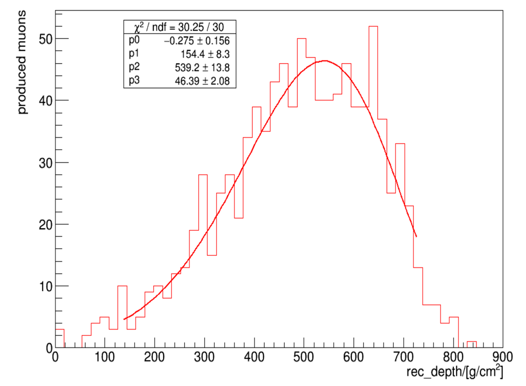
✓ **The reconstructed X^μ_{max} is close to the real X^μ_{max}**

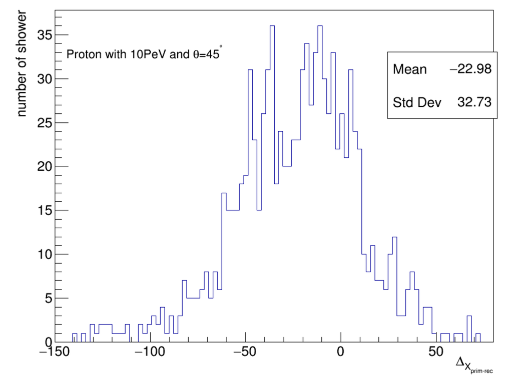
Consider the sampling of MD

* The configuration of muon detectors of LHAASO used [3]

Sampling criteria: ① 10 ns time resolution ② r>400m ③ Muon energy>1GeV ④ MD array



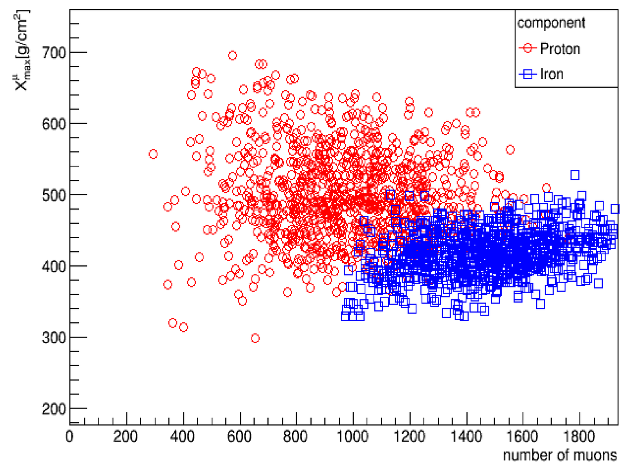


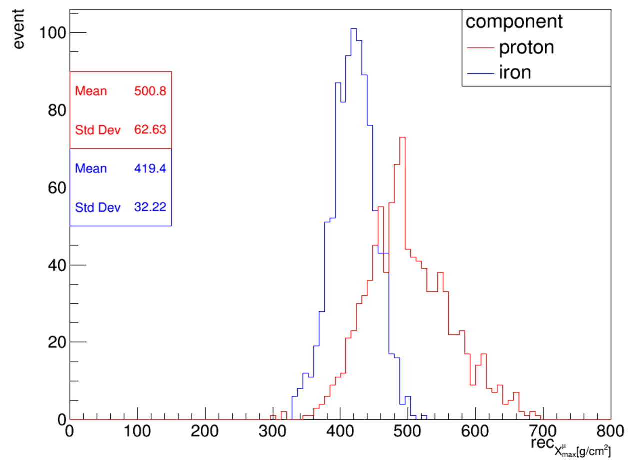


(Left)Distribution of muons on muon detectors(black); muon detectors distribution(blue);core position(red)

(Center) Distribution of muon reconstructed production depth of a shower initiated by proton with E=10^{16} eV and θ=45°

(Right):Distribution of real X^μ_{max} - reconstructed $X^\mu_{max}$for 1000 showers initiated by protons with E=10^{16} eV and θ=45°





(Left):Y axis: $rec_{X^\mu_{max}}$; X axis: number of muons; showers initiated by protons and irons with E=10^{16} eV and θ=45°

(Right):Distributions of $rec_{X^\mu_{max}}$ of showers initiated by protons and irons with E=10^{16} eV and θ=45°

Summary

- ✓ X^μ_{max} can be reconstructed with resolution $32g/cm^2$ by muon detectors(like LHAASO)
- ✓ X^μ_{max} can be used to identify mass compositions of cosmic rays
- ✓ Correlation between numbers of muon and X^μ_{max} is weak

Reference: 1 A. Aabet al.(Pierre Auger), Phys. Rev. D90, 012012 (2014), [Addendum: Phys.Rev.D 90,039904 (2014), Erratum: Phys.Rev.D 92, 019903 (2015)], arXiv:1407.5919 [hep-ex] 2 L. Collica (Pierre Auger), Eur. Phys. J. Plus131, 301 (2016), arXiv:1609.02498 [astro-ph.HE] 3 Z. Caoet al., Nature594, 33 (2021). 4 K. Nakamuraet al.(Particle Data Group), J, Phys. G37, 075021 (2010)