The study of the longitudinal development of muons in air shower

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Outline

Physical Motivation

☐ Muon production in air shower

- ✓ 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

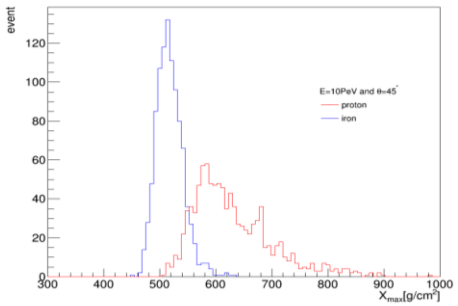
$$p + N(or\ A) \rightarrow p + N(or\ A) + n\pi^{\pm,0} + X$$

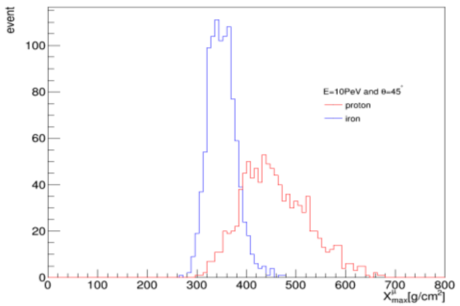
$$\pi^{\pm} \rightarrow \mu^{\pm} + (\overline{v_\mu})$$

- ✓ 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^{μ}_{max} can be used to identify mass compositions of cosmic rays.

Physical Motivation

- Method 1: By tracking the trajectories of the detected muon
  - KASCADE-Grande (reaches up to 10^{18}eV)
- Method 2: By mapping the arrival time of muons far from the core onto muon production distance.
  - Pierre Auger Observatory(reaches up to 10^{20}eV)

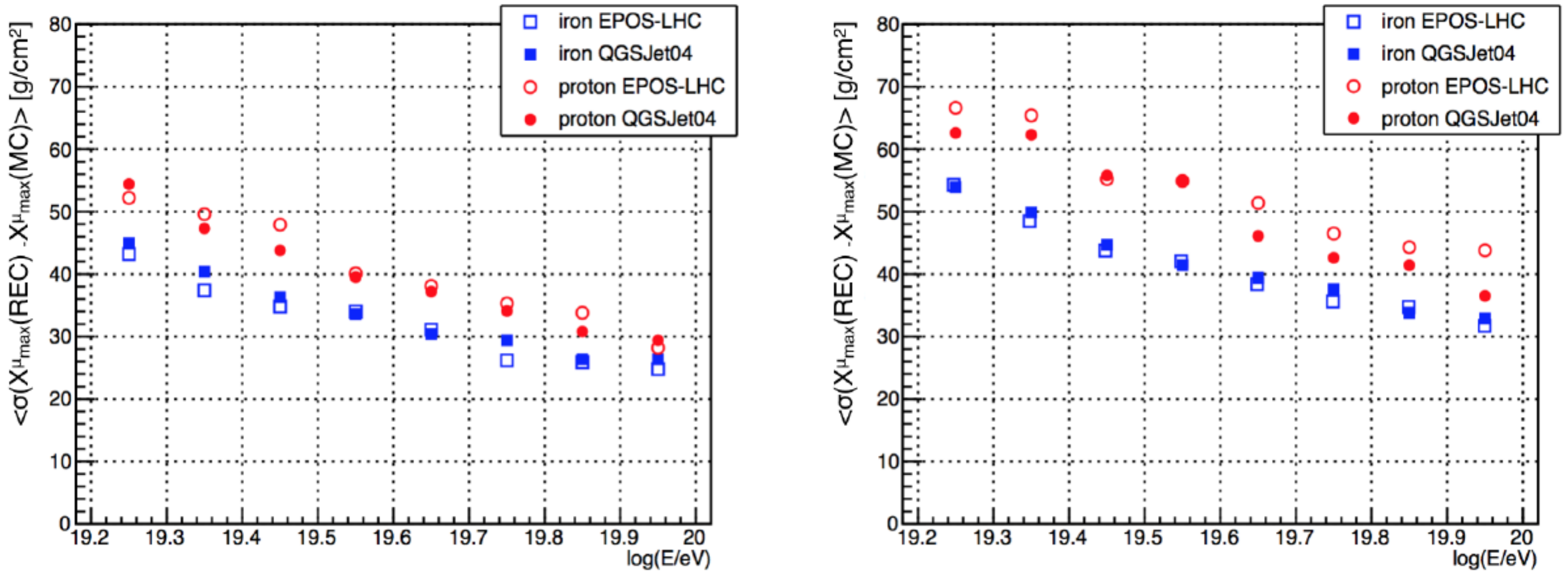
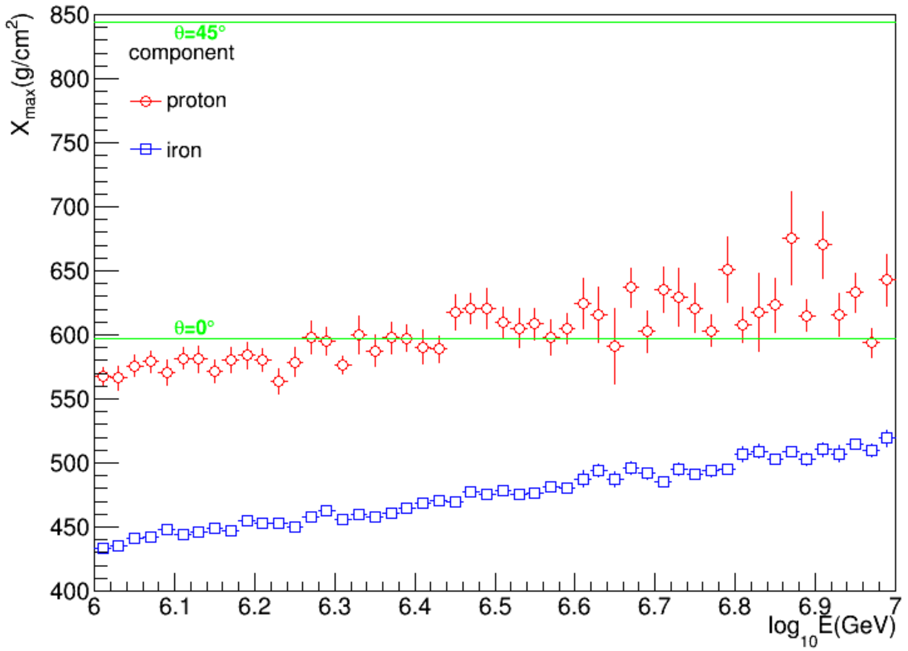


Fig. 11: The mean of $\sigma(X^{\mu}_{\max}(\text{reconstructed}) - X^{\mu}_{\max}(\text{MC}))$ is shown as a function of energy, for the angular range $\theta = 45^\circ - 55^\circ$ (left) and $\theta = 55^\circ - 65^\circ$ (right).

Introduction to MC simulation data

- **Simulation with CORSIKA (v76400)**
  - EPOS+GHEISHA
  - Zenith angle(θ): fixed 45°
  - Altitude: 4410m ($X = 600g/cm^2$)
  - Energy: 10PeV; 5PeV; 1PeV
  - MUPROD: additional information of muon

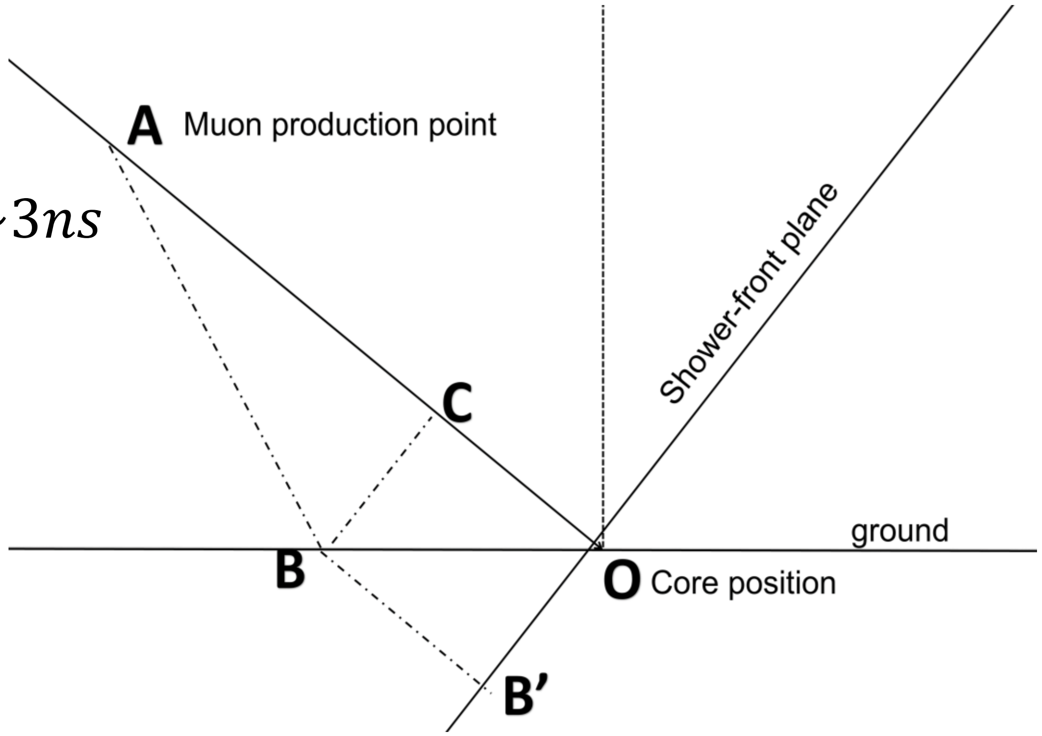


Number of shower	10PeV	5PeV	1PeV
Proton	1000	2000	2000
Iron	1000	2000	2000

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

Reconstruction of Muon Production Depth(MPD)

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

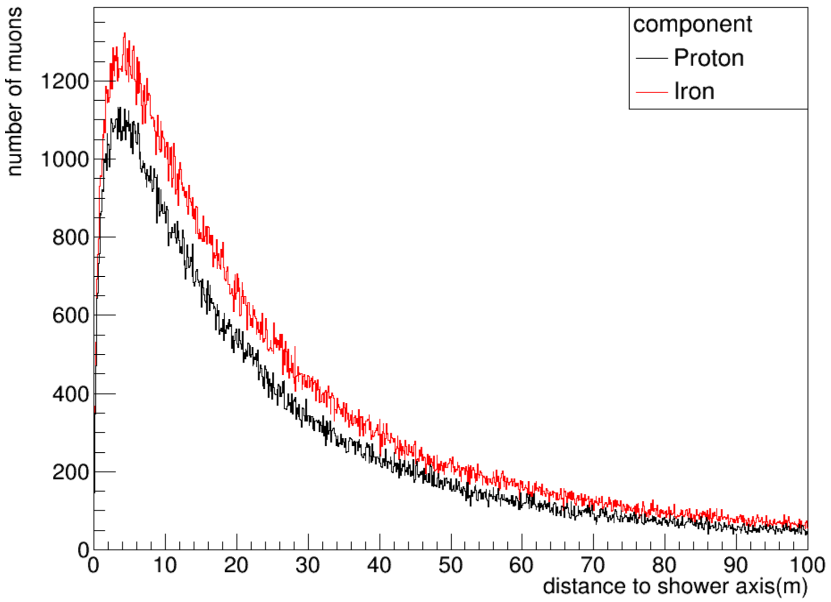


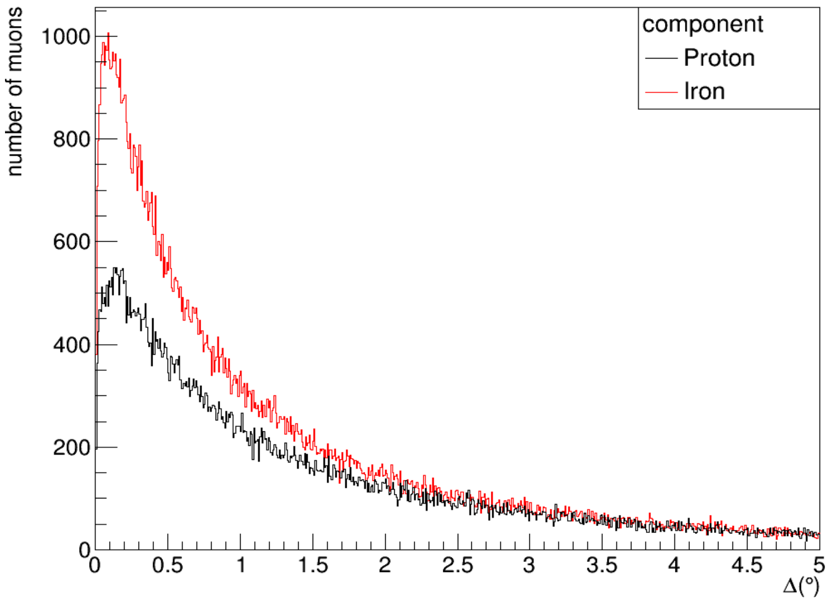
$$\overline{AO} = \frac{1}{2}\left(\frac{\overline{BC}^2}{c\times(t_g)} - c \times (t_g)\right) - c \times t_\pi$$

- The muons are produced on the shower axis
- Muons travel in straight lines

Reconstruction of Muon Production Depth(MPD)

◆ Muon production vertex



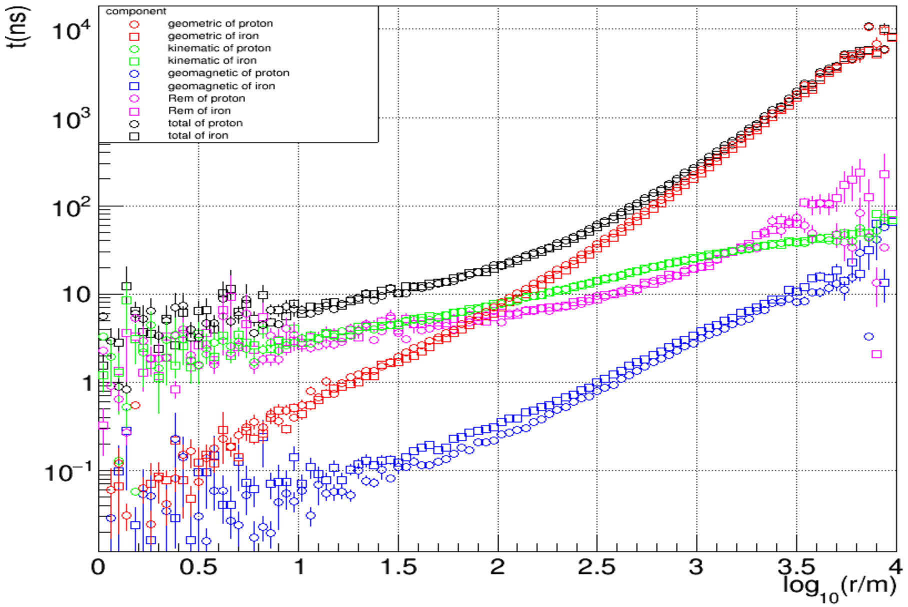


✓ **Approximation I: The muons are produced on the shower axis**

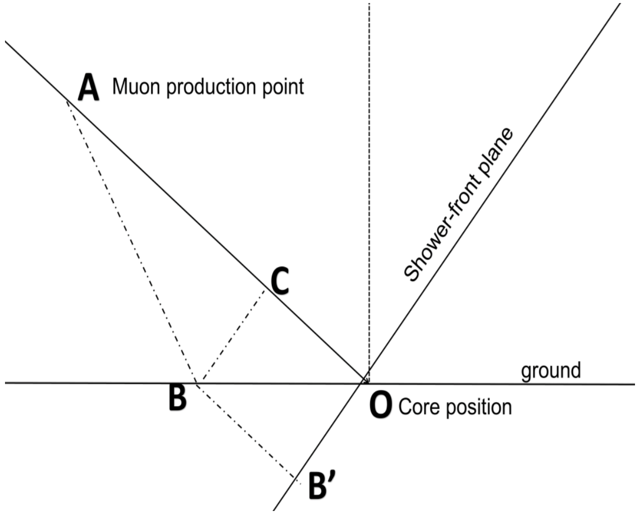
* production point of most muons is confined to a cylinder with a radius of 10m

⋆ Δ is mainly concentrated within 0.2°.

Muon propagation



- 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



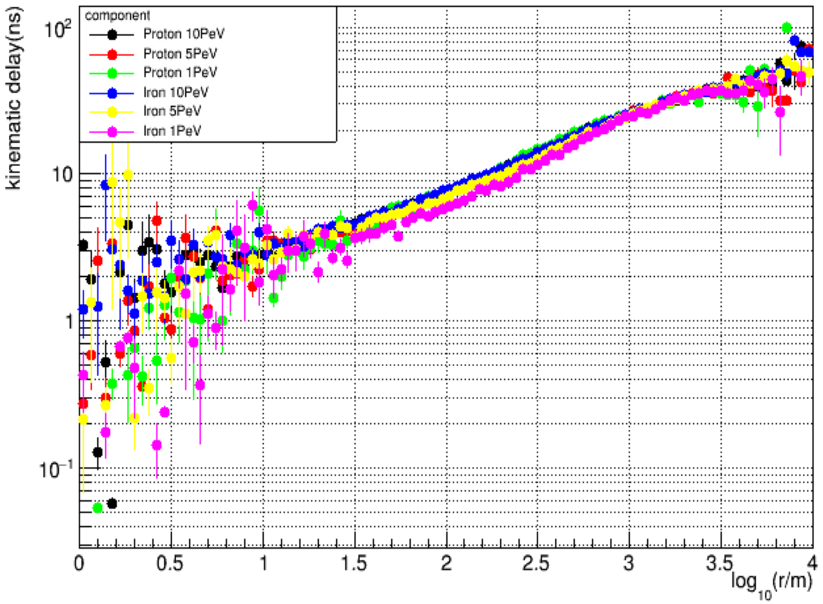
✓ Approximation II: Muons travel in straight lines

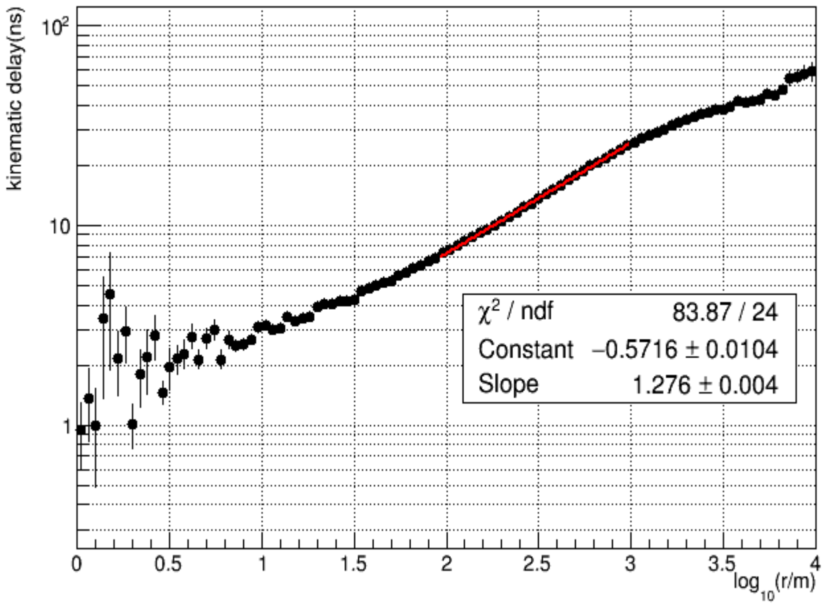
* $t_B + t_{Rem} < t_{total} \times 10\%$ when r>400m

* t_g is the dominated when r>400m

Reconstruction of Muon Production Depth(MPD)

◆ Muon propagation





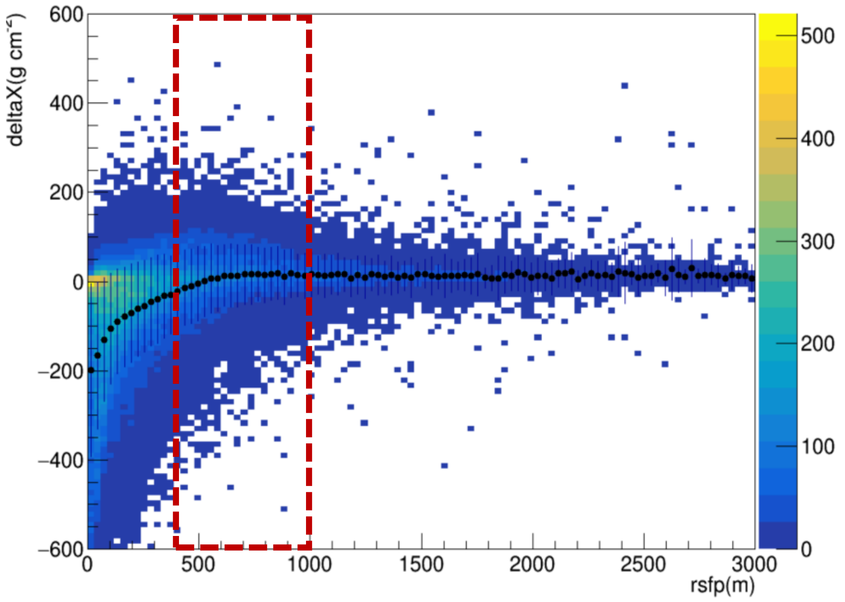
kinematic time delay distributions for showers with different compositions and energies can be fitted with an exponential function:

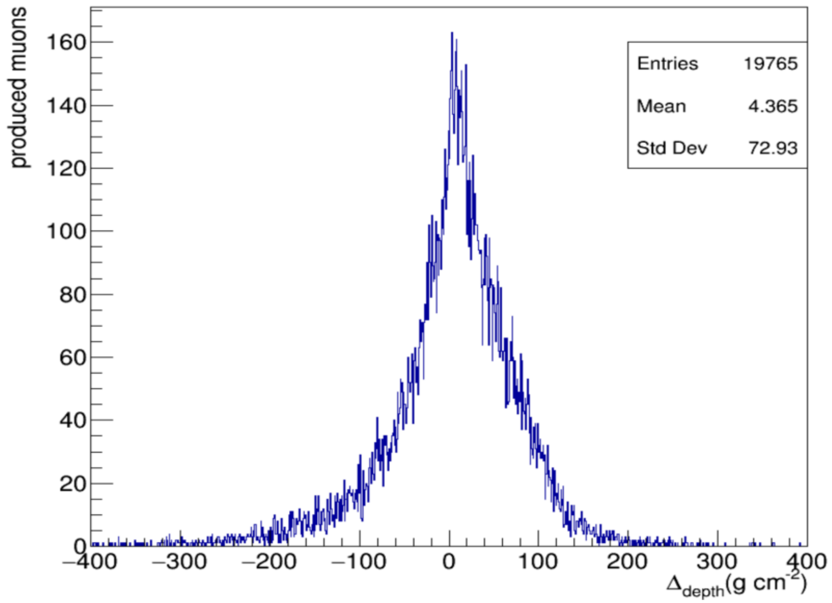
$$t_\epsilon = \exp(-0.57 + 1.276 \times log_{10}(r))$$

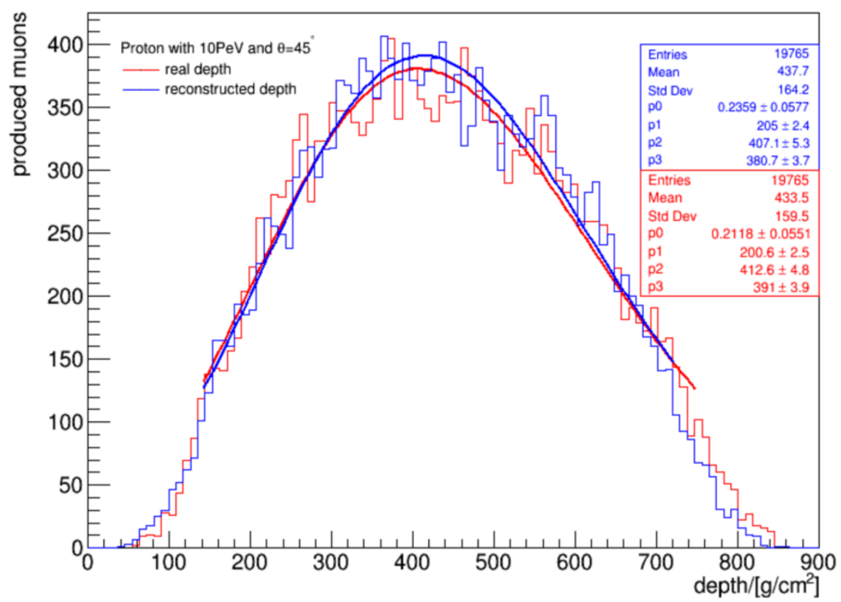
✓ **Approximation III: $t_g = t_{total} - t_\epsilon$**

◆ **Fit the longitudinal profile of the muon**(Proton with energy 10PeV)

Sampling criteria: ① 400m<r<1000m ② Muon energy>1GeV





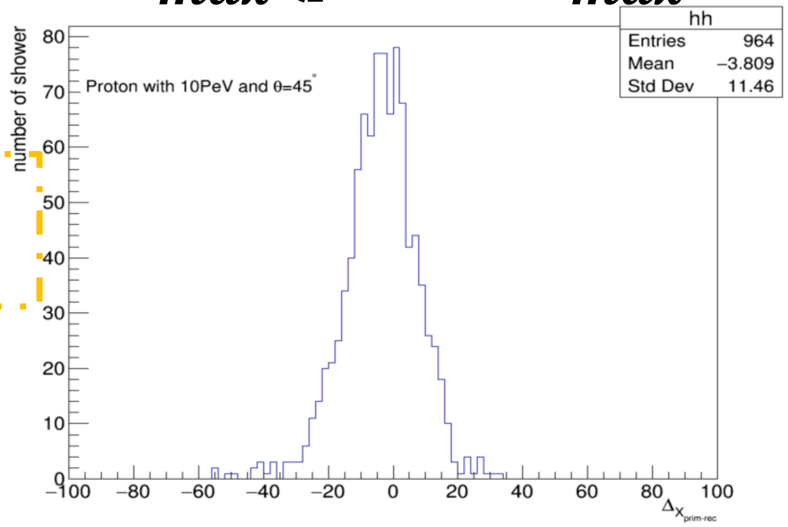


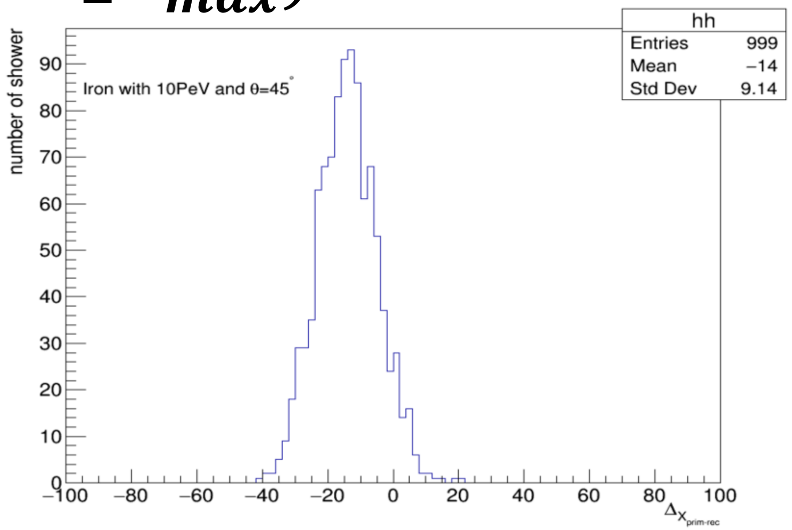
$$Fit\ formula: \frac{dN}{dX} = N_{max}\left(1 + \frac{R}{L}\left(X - X^{\mu}_{max}\right)\right)^{R^{-2}} exp^{-\frac{X - X^{\mu}_{max}}{LR}}$$

Features of the muon profiles

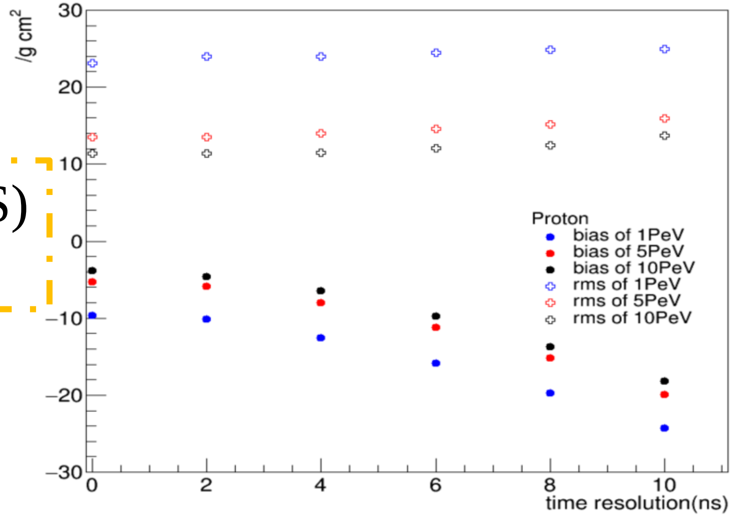
◆ **Distribution of $\Delta X^{\mu}_{max}(prim\_X^{\mu}_{max} - rec\_X^{\mu}_{max})$**

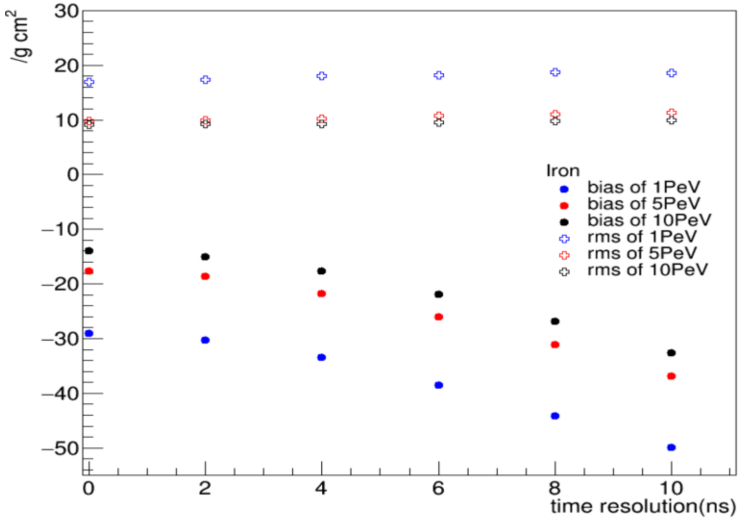
Distribution of ΔX^{μ}_{max} of Proton and Iron





Correlation of Bias(RMS) and time resolution

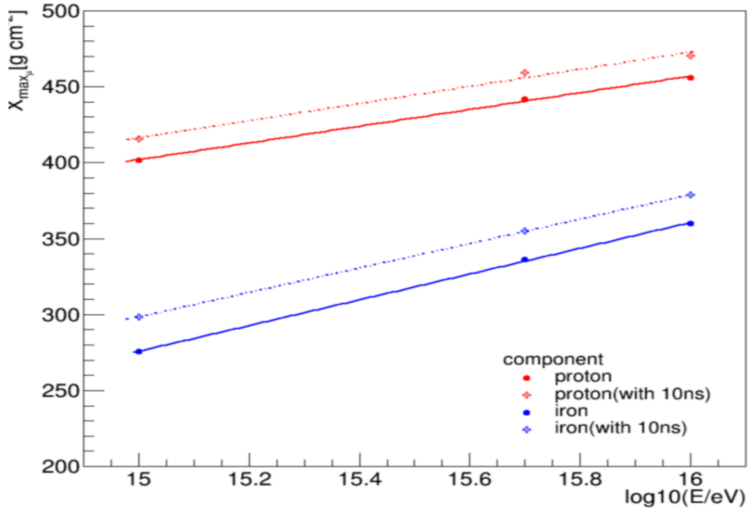


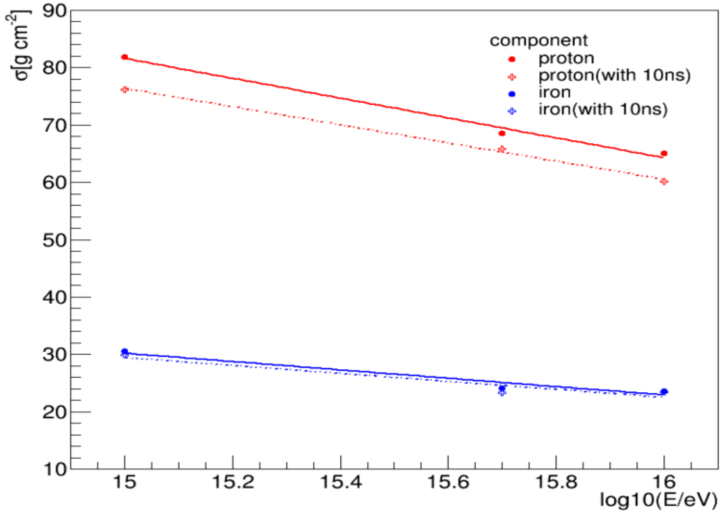


* As the time resolution increases, the bias is increasing and the rms is almost constant

Features of the muon profiles

◆ Distribution of X_{max}^{μ} of different component





Proton(Iron)	1PeV	5PeV	10PeV
0	401.6(275.6)	442(336)	456(360)
2ns	400.5(277.1)	444.8(336.9)	457.4(361)
4ns	403.1(280.2)	447(340)	457.4(363.8)
6ns	407.2(285.4)	450.2(344.2)	462.4(367.9)
8ns	410.4(291.5)	454.3(349.3)	466.8(372.9)
10ns	415.5(298.5)	459.2(355.1)	470.5(378.7)

* Measure lnA by learning the longitudinal development of muons
* Identify mass compositions of cosmic rays.

Summary

Summary

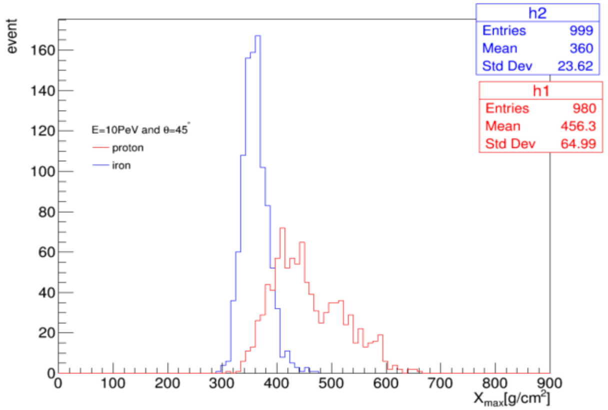
- The longitude development in the air shower and X_{max}^{μ} can be reconstructed according the geometry effect.
- The reconstructed resolution of X_{max}^{μ} is almost constant by different time resolution,
- X_{max}^{μ}can be used to identify mass compositions of cosmic rays.
- Measure lnA by learning the longitudinal development of muons

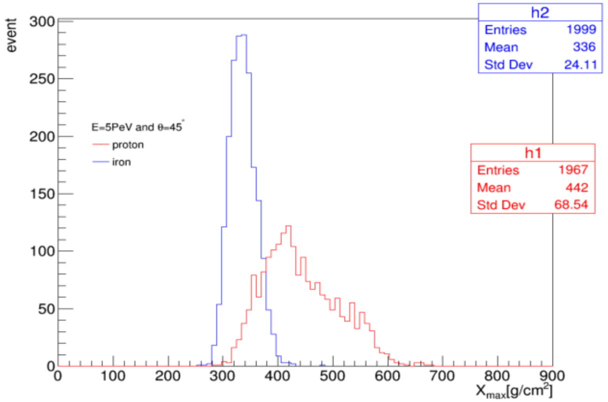
THANK YOU

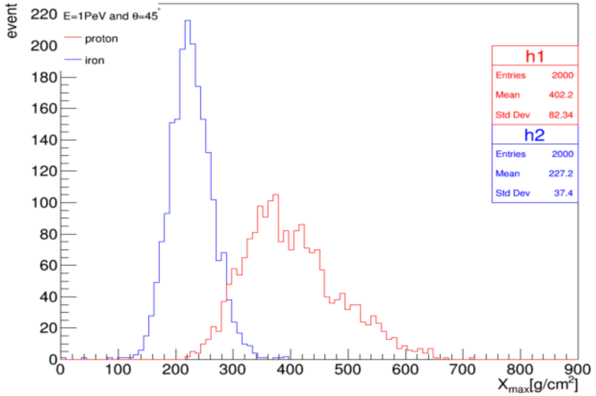
不加时间分辨率

Back Up

0ns时间分辨率







2ns时间分辨率