Potential of TeV muons at the FPF for Astroparticle Physics

Physics with Muons at the FPF

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TeV muons in astroparticle physics experiments

- most common particles in underground experiments
  - muons from cosmic ray air showers
  - muons from ν_μ interactions
- muon production from hadron decay $\rightarrow$ overlap to QCD studies
- deep inelastic scattering in neutrino interactions $\rightarrow$ overlap to PDF studies

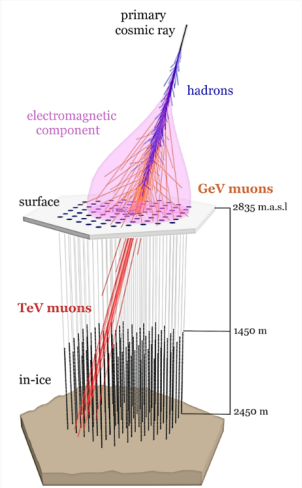

Figure 1: Cosmic ray air shower in IceCube. D. Soldin, ISVHECRI 2022 [arXiv:2208.01911]

TeV muon propagation and energy loss

- muons loose energy stochastically via
  - ionization
  - e^+e^- pair production
  - bremsstrahlung
  - photonuclear interaction
- $\langle -dE/dX \rangle \approx a + bE$
- large losses predominantly due to bremsstrahlung and photonuclear interaction

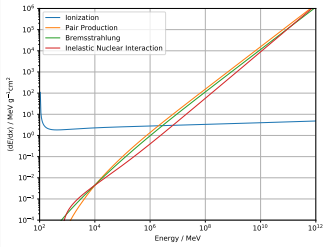

Figure 2: Average energy loss of muons in ice.

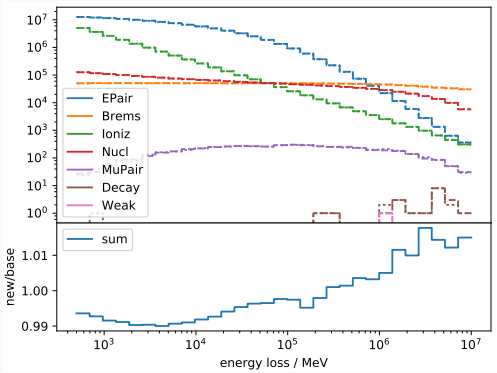

Figure 3: Secondary particle distribution from 10 TeV muons. Soedingrekso, Sandrock & Rhode, ICRC 2019 [arXiv:1910.07050]

Theoretical uncertainty of cross-section parametrizations

- For surface muon spectrum $dN/dE = N_0 E^{-\gamma}$, spectrum at depth h is given by

$$\frac{dN}{dE} = N_0 \exp(-\gamma bh) \left\{ E + \frac{a}{b}[1 - \exp(-bh)] \right\}^{-\gamma}$$

  $\rightarrow$ precise knowledge of cross-sections necessary
- Ionization, pair production, and bremsstrahlung are known quite precisely with sub-percent accuracy
- Photonuclear interaction has largest uncertainties of $\sim 10\%$ $\rightarrow$ uncertainty of a few percent on total energy loss

Photonuclear interaction

- dominated by inelastic scattering at low values of $Q^2 \rightarrow$ non-perturbative QCD
- various parametrizations used, based either on Regge theory or on vector meson dominance
- extrapolation from low-Q^2 measurements at eN, eA, μN, μA facilities (HERA, NMC, E665, ...)
- at low Q^2, shadowing is substantial and depends on the nucleus

Existing muon cross-section measurements at accelerators

- muon energy range up to about 200 GeV
- accuracy in the region of several percent, dependent on relative size of energy loss
- measurements targeting muon cross-sections
  - Kopp et al. "A Measurement of Energy Loss Distributions of Energetic Muons in Iron" *Z. Phys. C* 28 (1985) 171.
  - Baumgart et al. "Interactions of 200 GeV muons in an electromagnetic streamer tube calorimeter" *Nucl. Instr. Meth. Phys. Res. A* 258 (1987) 51
  - Berger et al. "A measurement of the energy loss spectrum of 150 GeV muons in iron" *Z. Phys. C* 73 (1997) 455
  - Amaral et al. "A precise measurement of 180 GeV muon energy losses in iron" *Eur. Phys. J. C* 20 (2001) 487
- Alexa et al. "A measurement of the photonuclear interactions of 180 GeV muons in iron" *Eur. Phys. J. C* 28 (2003) 497

Existing muon cross-section measurements using cosmic rays

- energy range up to about 10 TeV muon energy
- energy-dependent accuracy, typically $\sim$ 5–10%, worse at higher energies
- Measurements targeting muon cross sections
  - Stamm et al. "Electromagnetic Interactions of Cosmic-Ray Muons in Iron." *Il Nuovo Cimento* 51A (1979) 242.
  - Mitsui et al. "Electromagnetic Interactions of Cosmic-Ray Muons up to 10 TeV (Pair Productions and Bremsstrahlung)" *Il Nuovo Cimento* 73A (1983) 235.
  - Sakumoto et al. "Measurement of TeV muon energy loss in iron." *Phys. Rev. D* 45 (1992) 3042.
- Measurements targeting photonuclear cross section
  - Borog et al. "Energy dependence of the nuclear interaction cross-section of cosmic muons in the range 0.3–3 TeV". *Proc. 13th ICCR Denver* 3 (1973) 1982.
  - Okada et al. "Inelastic scattering of cosmic ray muons on iron nuclei and the virtual photon shadowing" *Fortschr. Phys.* 32 (1984) 135.
  - Korolkova et al. "Study of Inelastic Muon Scattering with 100-ton Artyomovsk Scintillation Detector" *Proc. 20th ICRC Moscow* 6 (1987) 182.
  - Bakatanov et al. "Cross section of the photonuclear interaction at photon energies from 0.9 to 10 TeV" *JETP Letters* 48 (1988) 129.
  - Vereshkov et al. "Total Cross Section for Photon-Nucleon Interaction in the Energy Range $\sqrt{s} = 40$–250 GeV" *Phys. At. Nucl.* 66 (2003) 565.

Possible measurements at the FPF

- existing more precise measurements at energies up to a few 100 GeV
- existing measurements of muon cross-sections at TeV energies with limited accuracy
- Possibilities at FPF
  - validate parametrizations of electromagnetic processes at higher energies and with better accuracy
  - measure photonuclear interactions of TeV muons
- possible measurement strategies
  - measurement of discrete energy losses in finely-grained detectors such as FASER
  - measurement of integral energy loss during propagation from muon production to the detectors of the FPF

Thank you for your attention!