Reconstruction of the muon production longitudinal profiles in extensive air showers

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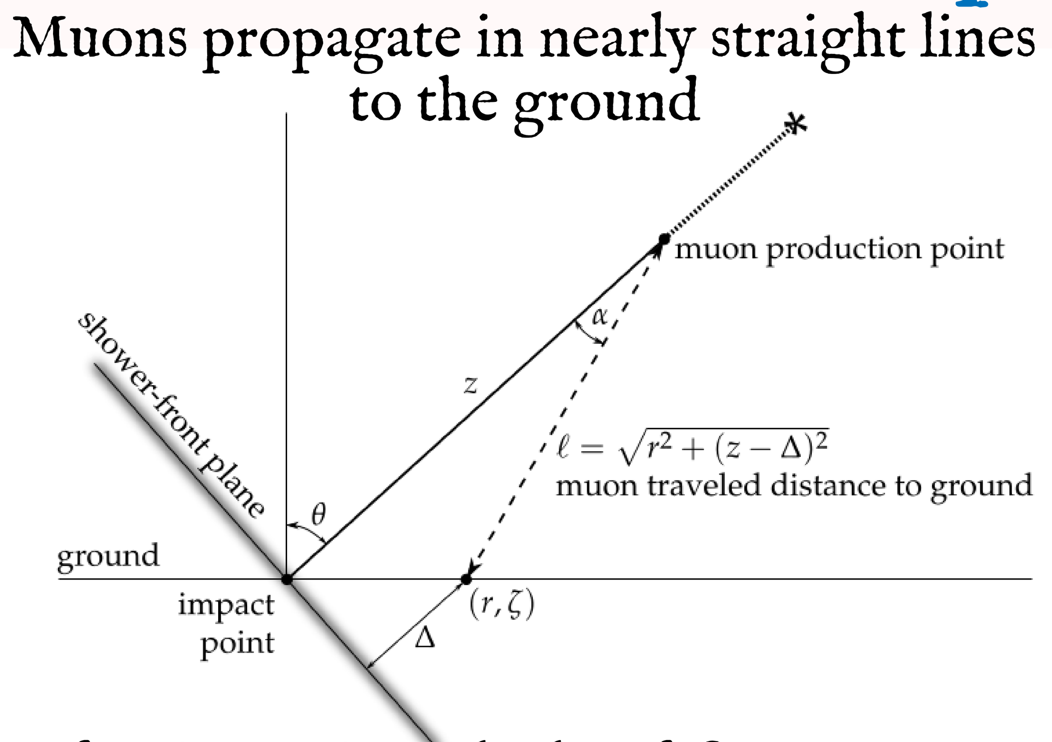
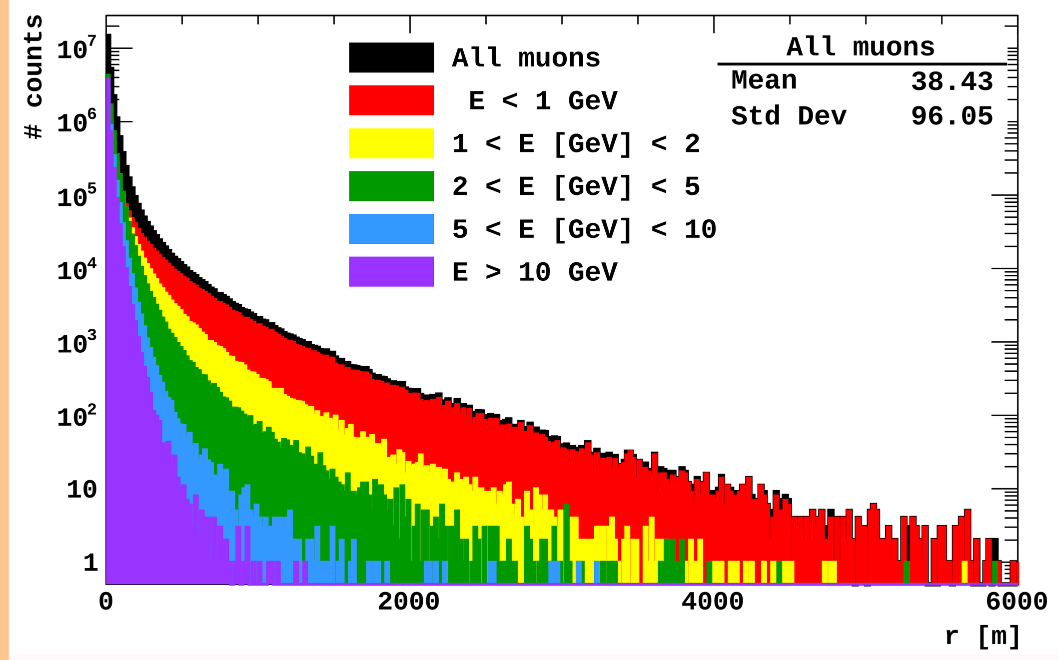
Muon Production Depth

Muons propagate in nearly straight lines to the ground



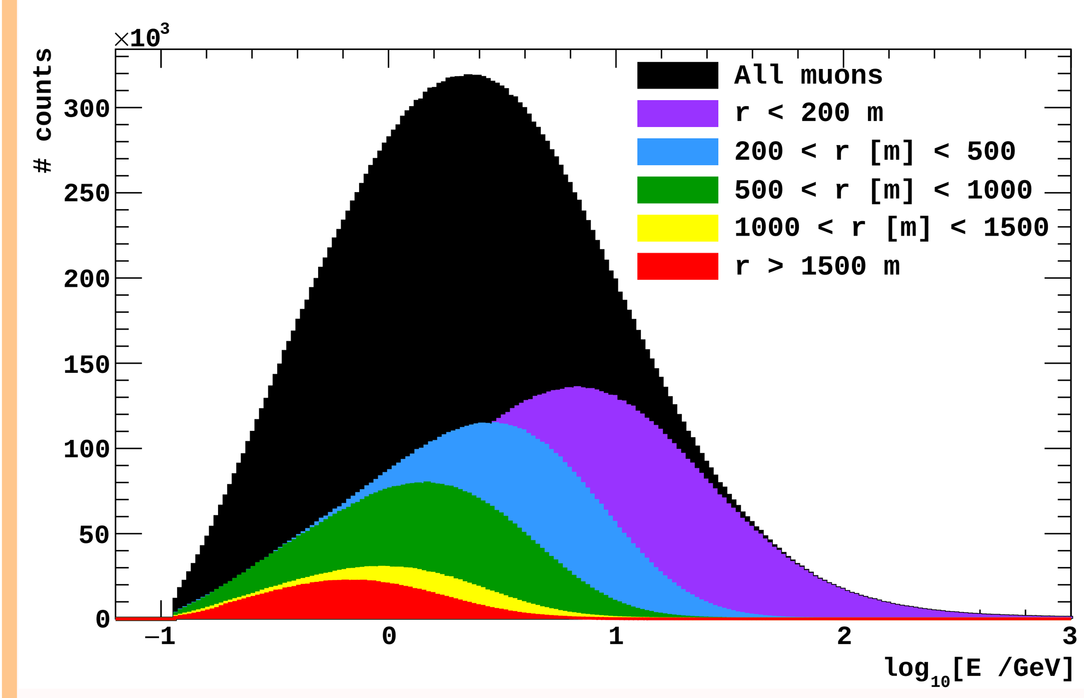
Production point calculated from geometric relation between μ arrival time and position

Muons @ Production



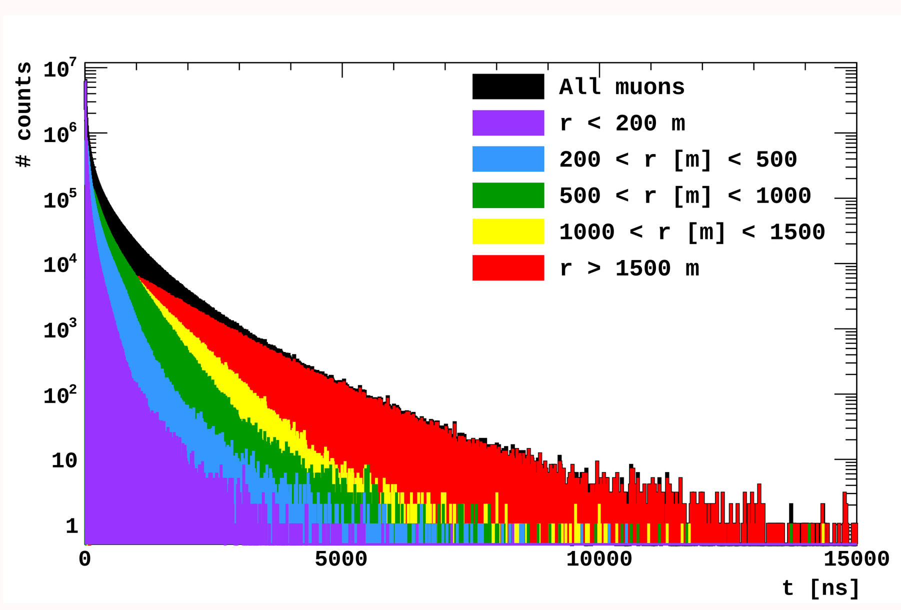
Most muons produced within few tens of meters from the shower axis

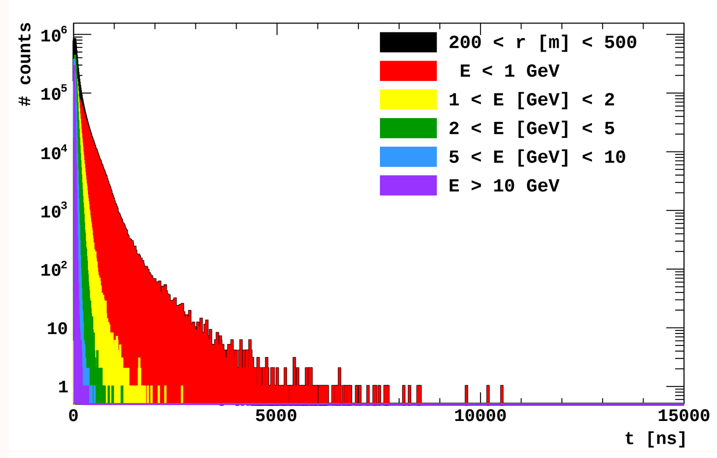
Muon energy spectra

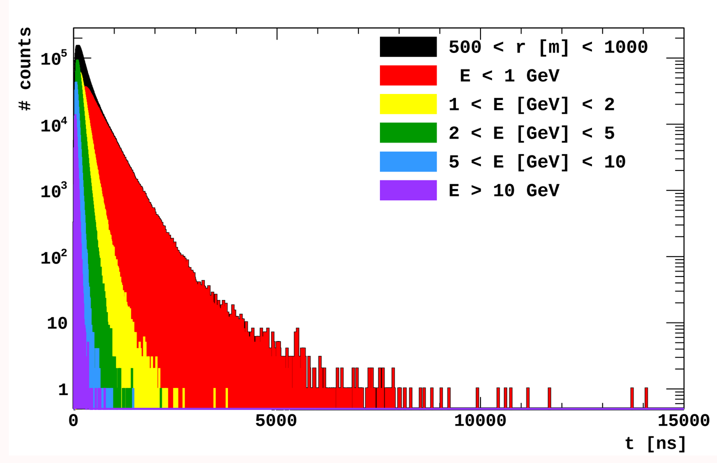


More energetic muons are predominant close to the shower core

Arrival time



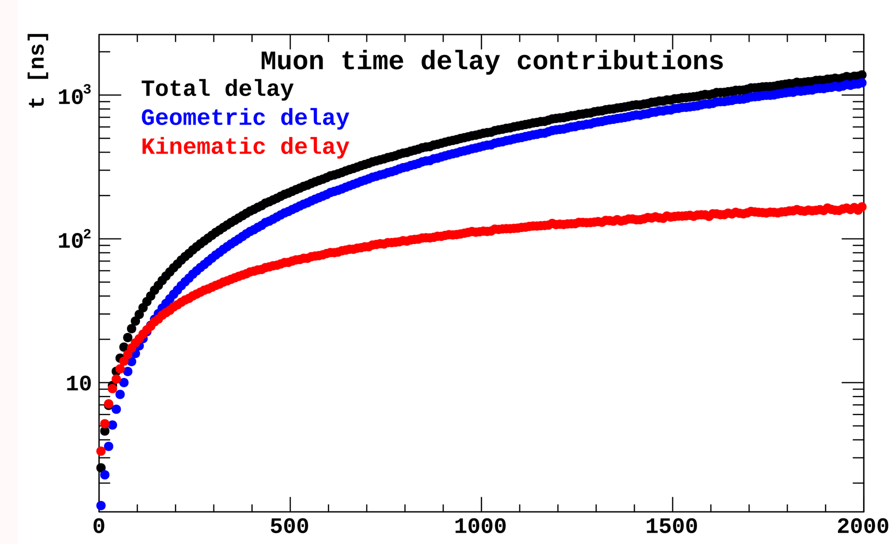




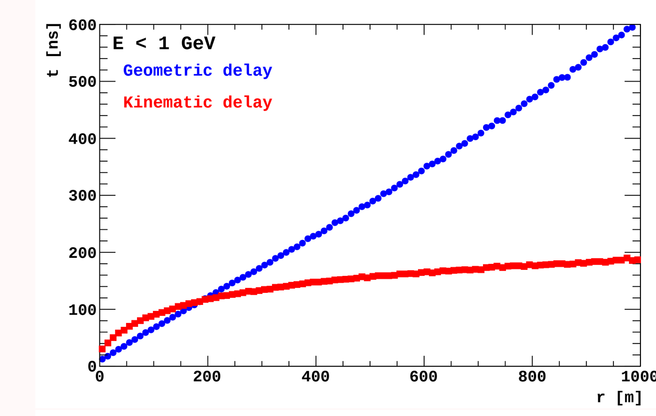
Arrival time distributions broaden with distance from the shower core

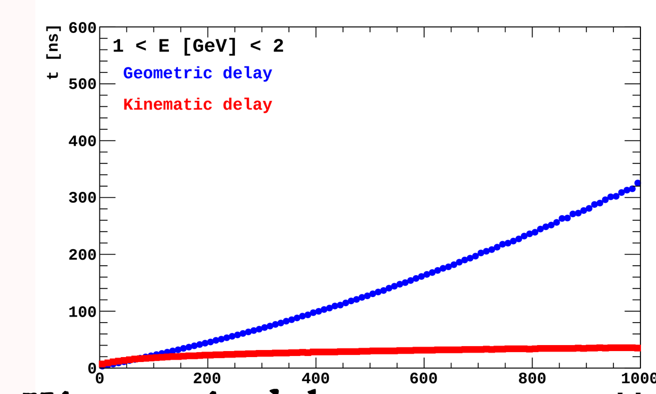
Time delay contributions

$t = t_g + t_\epsilon + t_B + t_{MS} + \ldots$



Geometric and kinematic delays are the dominant contributions to the total delay





Kinematic delay:

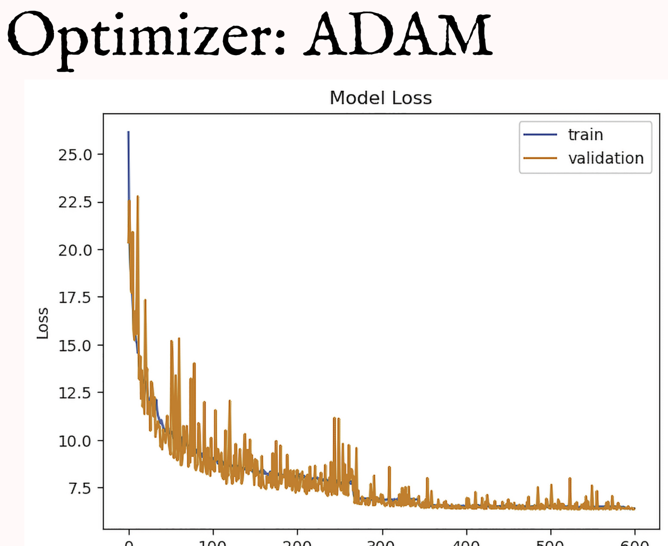
- Dominant close to the core
- Higher for low-energy muons

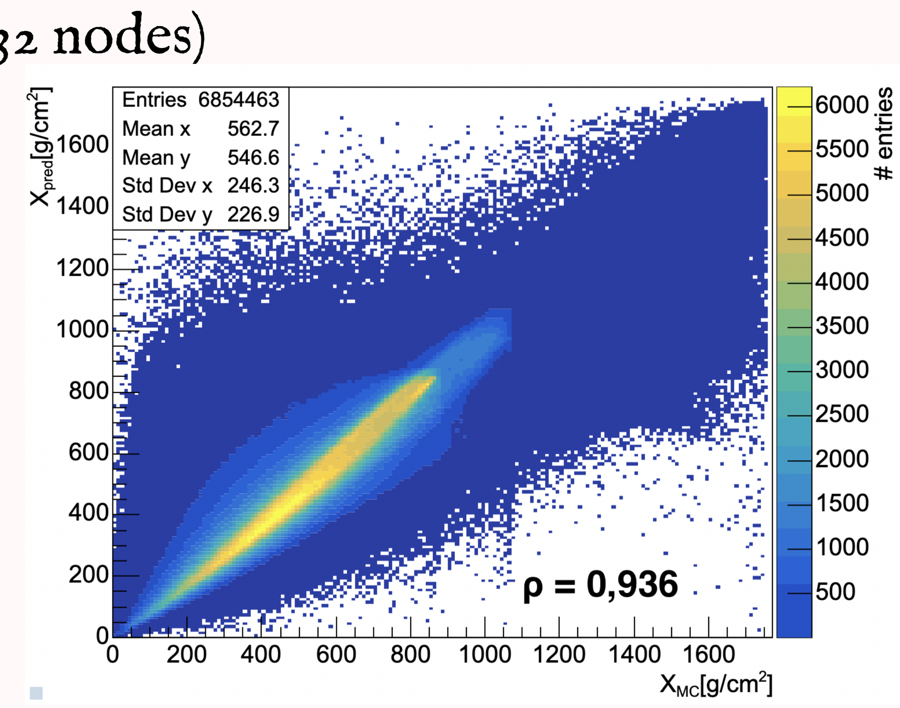
Estimating the kinematic delay using DNNs

- Input features:
  - Zenith angle sec $(\boldsymbol{\theta})$
  - Azimuth angle cos $(\boldsymbol{\zeta})$
  - Core distance r
  - Muon arrival time t
  - Reaches detectors at 2.3 m depth? Flag $= \{0, 1\}$
  - Loss function: $\mathbf{L} = \left(\frac{z_{pred} - z_{MC}}{z_{MC} + 1}\right)^2 + [(1 - \boldsymbol{\rho}) + \gamma_3]\,\mathbf{c}$
- Output: Muon production distance z
  - $X^\mu = \int_z^\infty \rho(z')\,dz'$

DNN performance

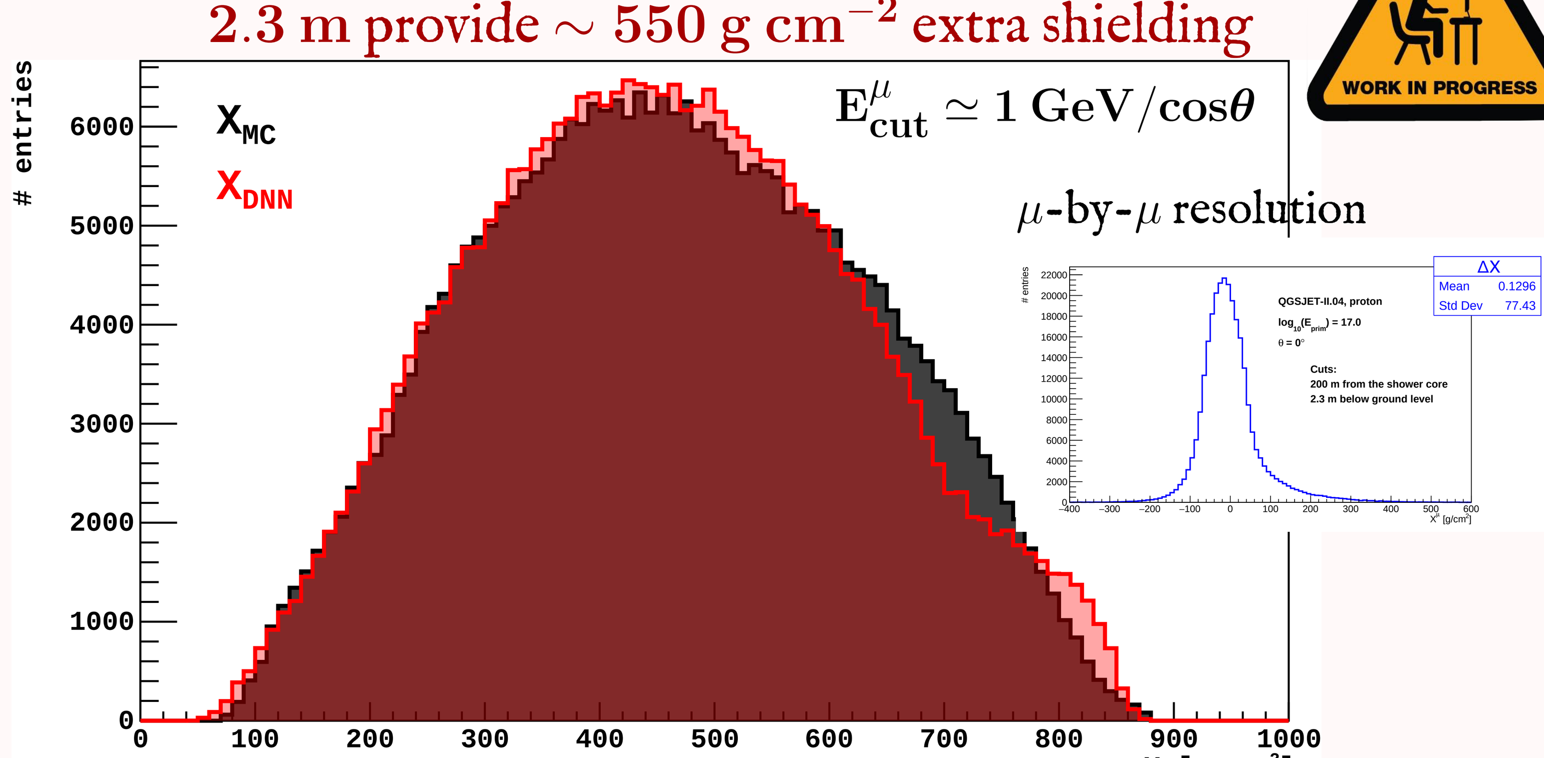
- Fully Connected Neural Network
  - 6 hidden layers
    - pyramid scheme (1024 ⟶ 32 nodes)
  - Activation function: ReLU
  - Optimizer: ADAM





Results - MPD @ 2.3m depth

2.3 m provide $\sim 550\ \mathrm{g\,cm^{-2}}$ extra shielding



10^{17} eV proton initiated shower, zenith angle $\theta = 0°$

Summary and Conclusions

- We are working on an extension of the method proposed in [1, 2] for:
  - $\theta < 60°$
  - $r > 200$ m
  - $E > 10^{17}$eV
- Kinematic delay estimation is the largest source of systematic uncertainties
- Our kinematic delay parametrization obtained from fully connected NN
  - For muons reaching the ground and at 2.3 m depth
  - μ-by-μ reconstruction @ 2.3 m:
    - $\langle \Delta X \rangle < 10\ \mathrm{g\,cm^{-2}}$, $\sigma(\Delta X) \sim 80\ \mathrm{g\,cm^{-2}}$

Buried detectors improve the MPD reconstruction due to the removal of the electromagnetic contamination and low-energy muon component

References:

[1] L. Cazon, R. A. Vazquez, A. A. Watson and E. Zas, Astropart. Phys. 21 (2004), 71-86

[2] L. Cazon, R. A. Vazquez and E. Zas, Astropart. Phys. 23 (2005), 393-409

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