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A deep learning based reconstruction of high-energy muons in IceCube

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13. September 2023

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Introduction: prompt muons

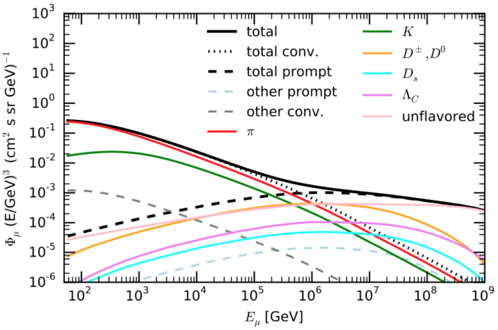
- Atmospheric muons divided into a prompt and a conventional component
- Conventional component:

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu}), \tag{1}$$

$$K^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu}) \tag{2}$$

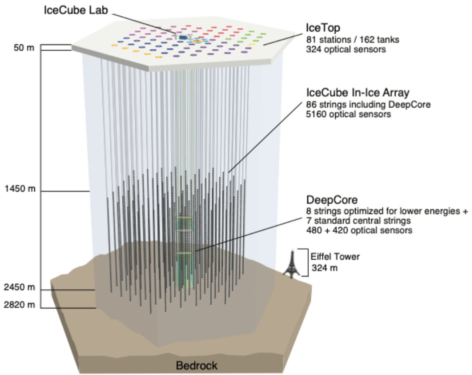
- Lifetime: $\tau_{\pi} \approx 2.6 * 10^{-8}$s, $\tau_{K} \approx 1.2 * 10^{-8}$s
- Prompt component: originate from particles with a significantly shorter lifetime like the D-meson ($\tau_{D} \approx 10^{-12}$s) and unflavored mesons
- Short lifetime →decay before interaction
- Main differences to conventional muons
  - Isotropic angular distribution
  - Energy spectrum: prompt component becomes dominant for high energies

Introduction: Prompt muons



- Main differences to conventional muons [3]
  - Isotropic angular distribution
  - Energy spectrum: prompt component becomes dominant for high energies

Introduction: IceCube Neutrino Observatory

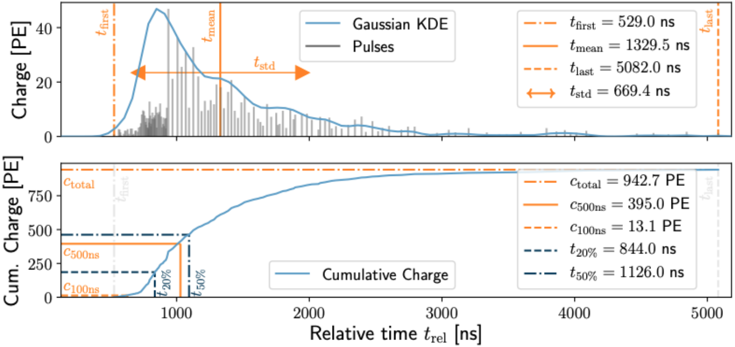


- Kilometer-scale cherenkov detector [1]
- Designed to detect neutrinos, atmospheric muons are background
- 3000 Hz event rate →fast runtime needed

Introduction

- Detecting the prompt component of the atmospheric muon flux requires efficient energy reconstruction
- Focus on the leading muon: most energetic muon in a bundle
- Two important values to reconstruct:
  - Bundle energy at detector entry
  - Energy of the leading muon at detector entry
- Neural networks: Good results in similar tasks

Introduction: Input features

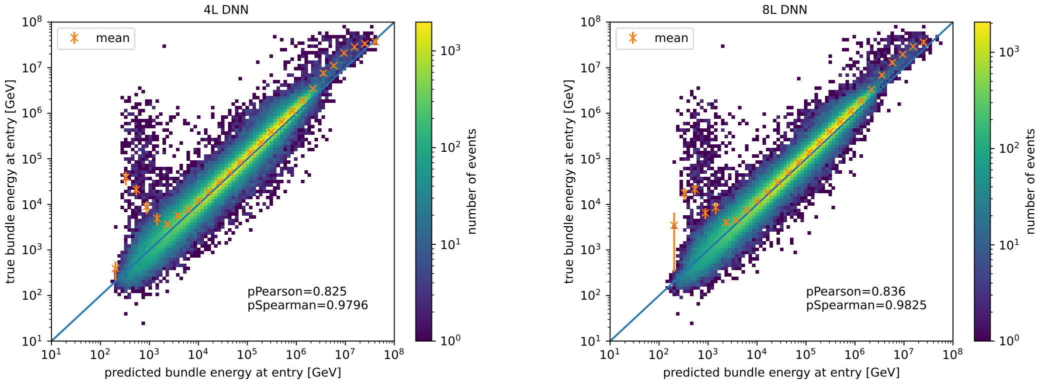


- DNN input features: pulse series summarized by nine features [2]
- Only three used to minimize runtime
  - c_{total}
  - t_{first}
  - t_{std}

Motivation

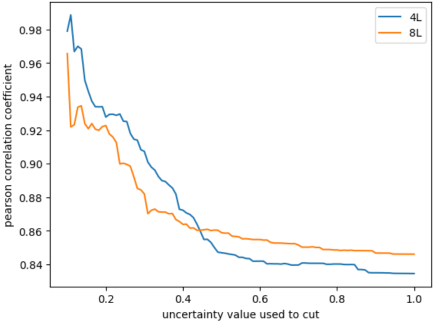
- Muon puzzle: Unexplained difference between measurement and simulation of muon number
- Likely reason: Hadronic interactions
- Improving knowledge of hadronic interactions

Bundle energy



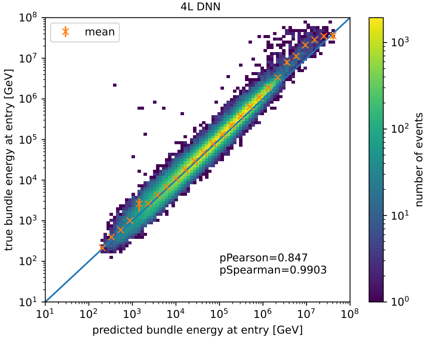
- Some significant smearing for lower energies
- Bigger network doesn't seem to be visibly better, except for slight improvements in correlation
- Bias towards underestimation for higher energies

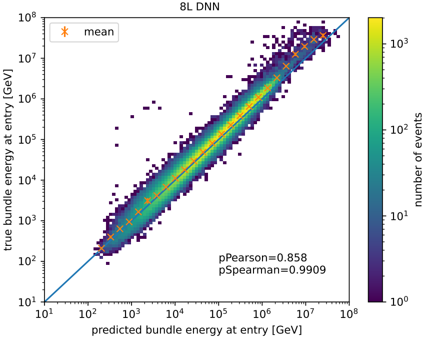
Bundle energy quality cut



- Uncertainty estimated by separate subnetwork
- Improve reconstruction by cutting for low uncertainty
- Value to cut depends on application: How much data loss is affordable?
- Correlation coefficient can be used as an indication

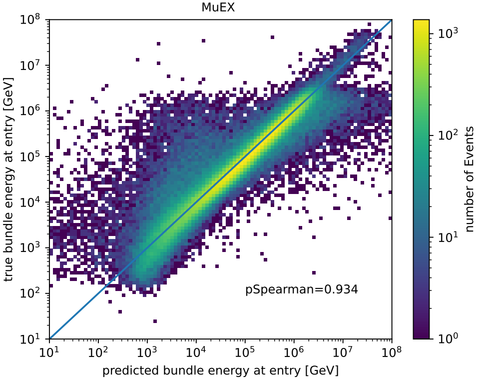
Bundle energy quality cut

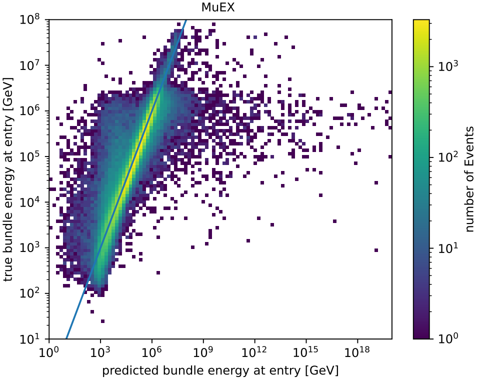




- Fixed uncertainty cut for both networks σ = **0.5**
- Events remainig: **84.9 %** (4L) and **87.1 %**
- Smearing on low energies almost completely eliminated, bias still present
- Better linear correlation
- Limited amount of statistic → Bigger cuts hard to evaluate

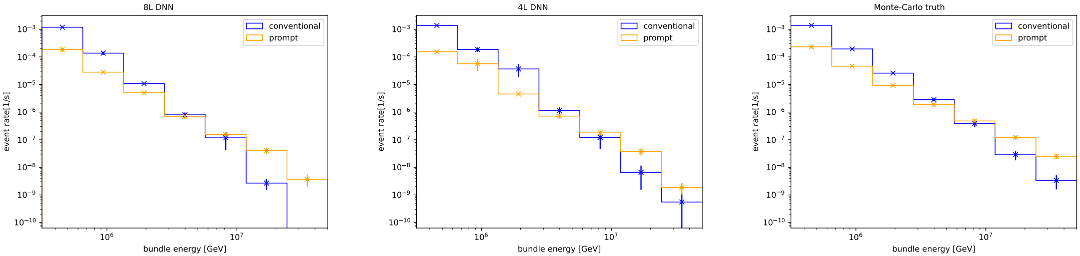
Comparison to non DNN based reconstruction





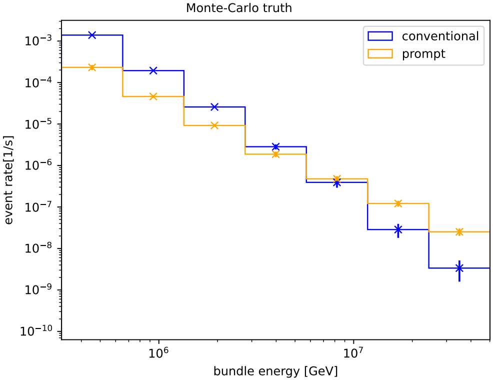
- Considerably stronger overall smearing than for the DNN
- Extreme overestimation for high energies (up to 10^{27} GeV)
- Non DNN based approach shows significantly worse reconstruction especially in the important high energy region

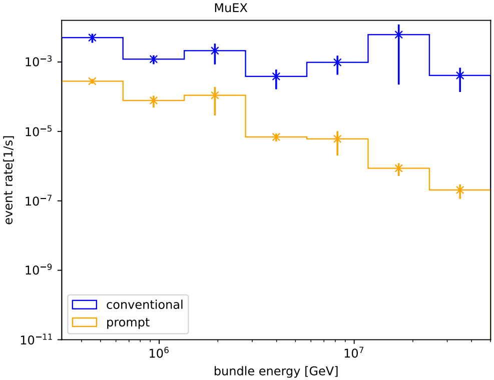
Resulting energy spectrum for high bundle energies: DNN



- All plots weighted using GaisserH3a
- Both DNNs generally show a good reconstruction of the high energy spectrum. the systematic underestimation leads to a slightly lower event rate in the highest energy bins

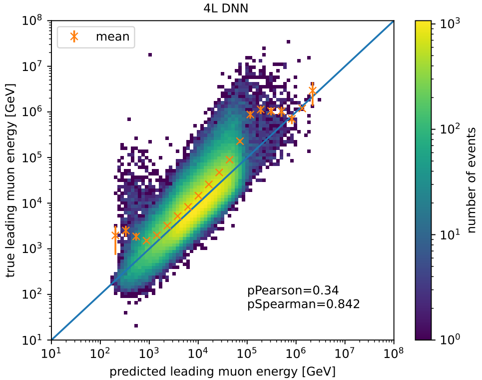
Resulting energy spectrum for high bundle energies: MuEX

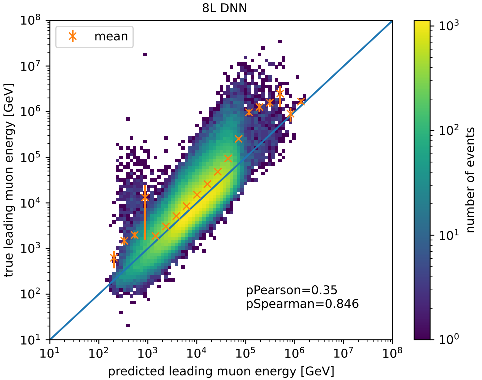




- Unrealistically high event rate for very high energies
- The MuEX Fit does not even see the prompt component as dominant for high energies. →strong overestimation makes it unusable for the purpose of this analysis

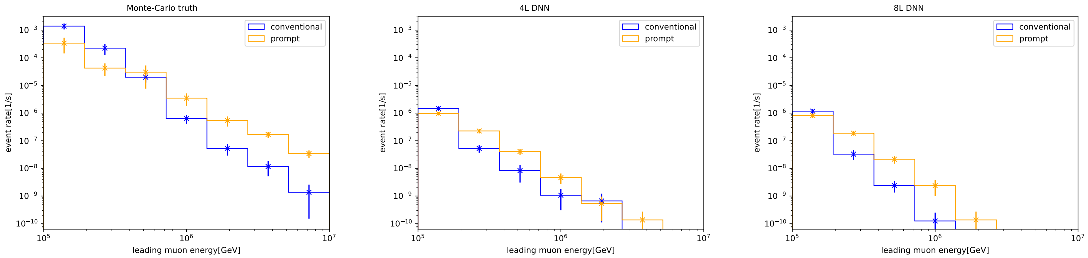
Energy of the leading muon





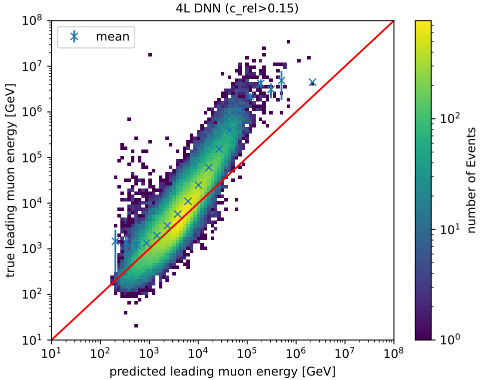
- As expected: Results much worse compared to bundle energy (especially linear correlation)
- Generally higher spread
- Strong underestimation in high energy region
- Reconstructed energy rarely above **100** TeV (only **8.9 %** of events above **100** TeV were predicted above **100** TeV)

Leading muon energy spectrum



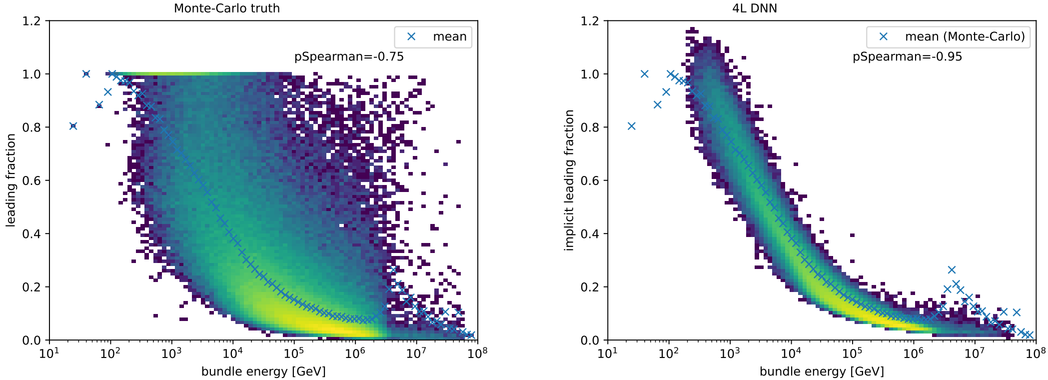
- Prompt sensitivity is better in this label, as seen in Monte-Carlo
- Event rate at least three orders of magnitude too low for both DNNs
- Spectrum much steeper than it should be
- Strong underestimation in the highest energy bins as seen in correlation plots previously

Leading muon energy reconstruction: leading fraction



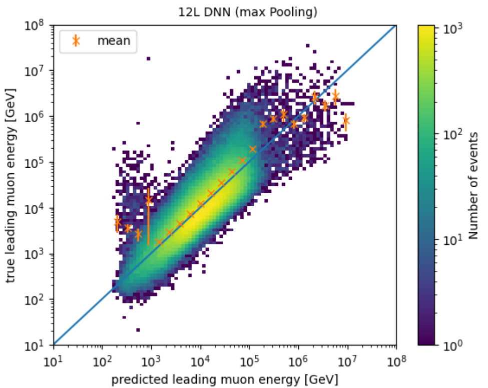
- Assumption: if the network is actually able to predict, how dominant the leading muon is within the bundle, this should be easier to reconstruct for higher leading fractions
- Cut for events with more dominant leading muons $E_{lead}/E_{bundle} > 0.15$
- Resulting energy reconstruction is significantly worse for higher energies

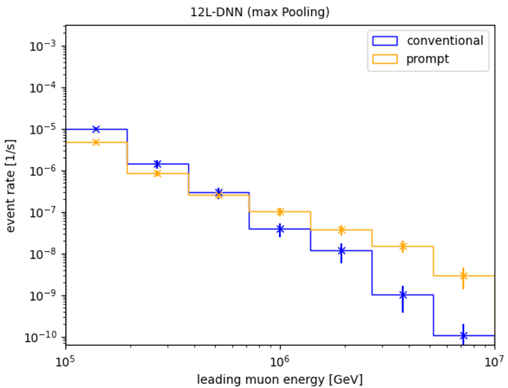
Correlation of bundle energy and leading fraction



- Reconstructed leading fraction shows very strong correlation to bundle energy
- Spearman correlation coefficient: $\rho_{MC} = -0.75$, $\rho_{DNN} = -0.95$
- Prediction as energy based mean instead of actual prediction of the leading fraction
- Automatically assuming a low leading fraction for high energies explains the underestimation

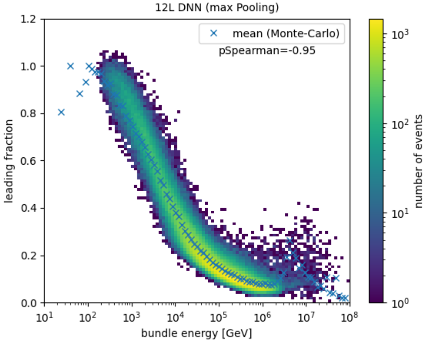
Optimization: Leading muon energy





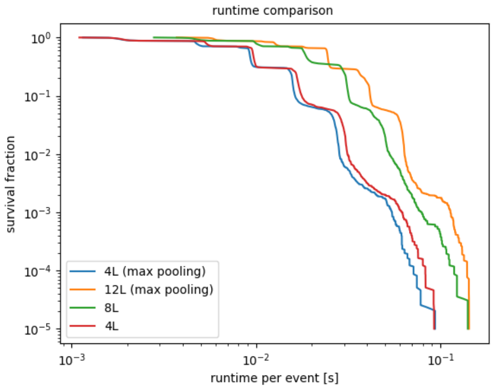
- To improve the leading moun reconstruction, further changes can be made
- Increasing number of convolutional layers and number of filters, max instead of average pooling
- Use independently calculated leading fraction
- Better coverage of the high energy region: 22.3 % compared to 8.9 %
- Leads to better spectrum and prompt sensitivity

Optimization: Leading muon energy



- Underlying problem remains the same
- Event rate still underestimated →bundle energy better alternative
- Potential limited unless leading fraction is separated from bundle energy
- Not easily achieved by increasing network size

Runtime comparison



- Median:
  - median(t_{4L}) = 0.0096 s
  - median(t_{8L}) = 0.0185 s
  - median(t_{12L}) = 0.0247 s
- Median(t_{8L}/t_{4L} = 1.88) →small DNN almost twice as fast
- Faster in **99, 9%** of cases

Summary

- Good reconstruction for the bundle energy
- DNNs outperform non DNN based alternative
- Leading muon energy is not correctly learned
- Bigger DNN provides no significant performance improvement in relation to runtime increase

Outlook

- Improve leading muon energy prediction
- Can this be properly trained or are the underlying physics just not there?
- Evaluate event multiplicity reconstruction
- Simulate and try to train on stochasticity
- Single label reconstruction

Bibliography

[1] M.G. Aartsen u. a. „The IceCube Neutrino Observatory: instrumentation and online systems“. In: Journal of Instrumentation 12.03 (März 2017), P03012–P03012. DOI: 10.1088/1748-0221/12/03/p03012. URL: https://doi.org/10.1088%2F1748-0221%2F12%2F03%2Fp03012.

[2] R. Abbasi u. a. „A convolutional neural network based cascade reconstruction for the IceCube Neutrino Observatory“. In: Journal of Instrumentation 16.07 (Juli 2021), P07041. DOI: 10.1088/1748-0221/16/07/p07041. URL: https://doi.org/10.1088%2F1748-0221%2F16%2F07%2Fp07041.

[3] Anatoli Fedynitch u. a. Calculation of conventional and prompt lepton fluxes at very high energy. 2015. arXiv: 1503.00544 [hep-ph].