# Unfolding the cosmic ray spectrum using stopping muons in IceCube

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Experimentelle Physik 5b
Fakultät Physik

# Overview

# Motivation

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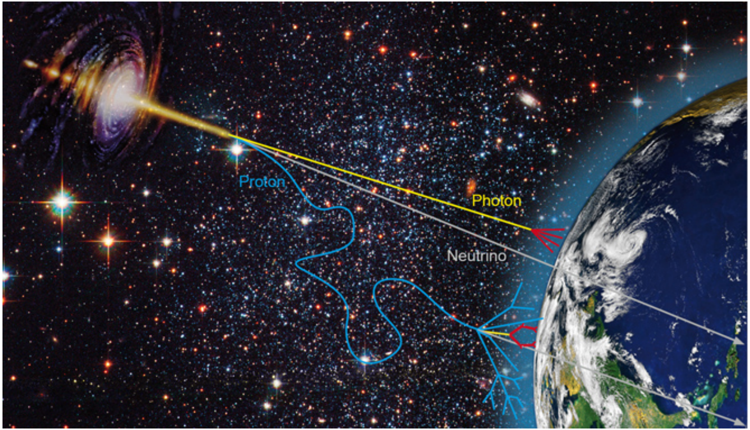
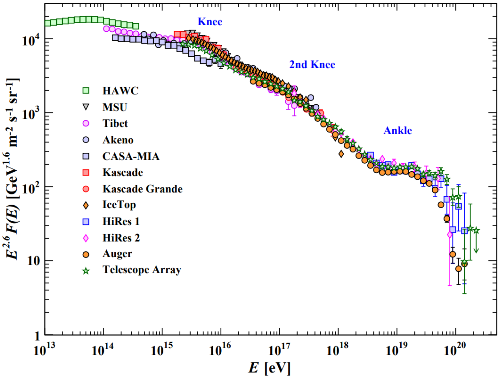



[https://astro.desy.de/theory/multi_messenger_astrophysics/index_eng.html]

# Charged Cosmic Rays

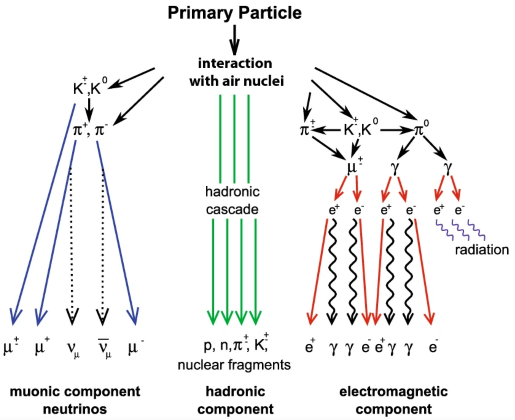
- 85% protons, 12% helium nuclei, 2% leptons, 1% heavier nuclei
- broken power law spectrum
  →"the knee" ≈ 5 PeV
  →"the ankle" ≈ 3 EeV
- for energies exceeding $1 \times 10^{20}$ eV cosmic ray flux drops
  →GZK-cutoff above $5 \times 10^{19}$ eV




C. Patrignani et al. "Review of Particle Physics (RPP)"

# Atmospheric Air Showers

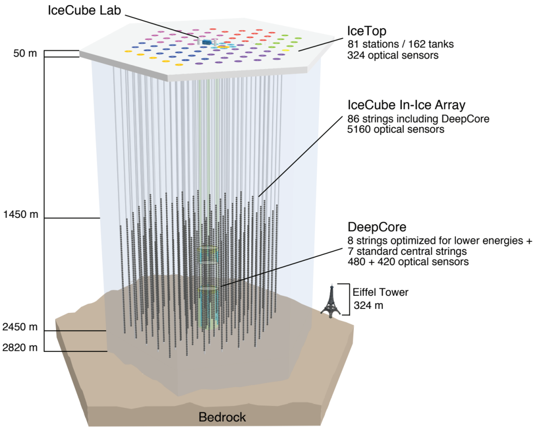
- charged CRs engage in interactions with atmospheric molecules
  →hadronic cascades
  →contain lots of secondary particles
  →secondarys can be detected by ground based telescopes
- muon component: charged pion decay
  $\pi^+ \rightarrow \mu^+ + \nu_\mu$ and $\pi^- \rightarrow \mu^- + \bar{\nu_\mu}$




A. Haungs et al. "The KASCADE Cosmic-ray Data Centre KCDC: granting open access to astroparticle physics research data"

## The IceCube Detector

- located at geographical South Pole
- instrumented volume: 1 $km^3$
- 5160 digital optical modules (DOMs) at strings at depth between 1.5 km and 2.5 km
- DOMs detect Cherenkov light emited by charged particles entering the ice
- mainly observation of astrophysical neutrinos
- atmospheric muons are background to neutrino observations




The IceCube Collaboration. "The IceCube Neutrino Observatory: Instrumentation and Online Systems"

## Stopping Muons

- atmospheric muons are created in bundles
  →contain hundreds up to thousands of individual muons
- only few muons stop in detector volume
  →stopping muons
  →usually most energetic muon in bundle
  →created early in air shower
- stopping muons carry information about primary particle
- goal: use stopping muons to reconstruct primary flux

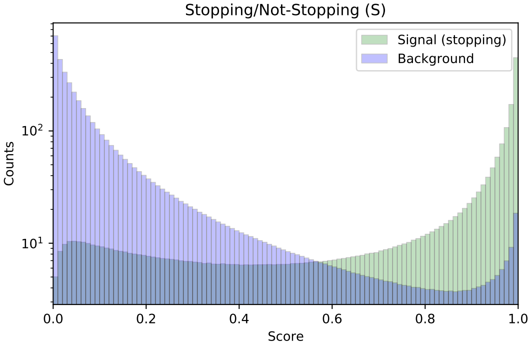
# Event Selection and Reconstruction

## Event Selection and Reconstruction

- using Deep Neural Network to classify muon events as stopping or background
  →reconstructs key parameters (energy, stopping depth, direction)
- start with Level 2 data (basic reconstructed and filtered)
- combine two CORSIKA datasets:
  →11058: 600 GeV - 100 TeV
  →11057: 100 TeV - 100 EeV
  →1291507 events

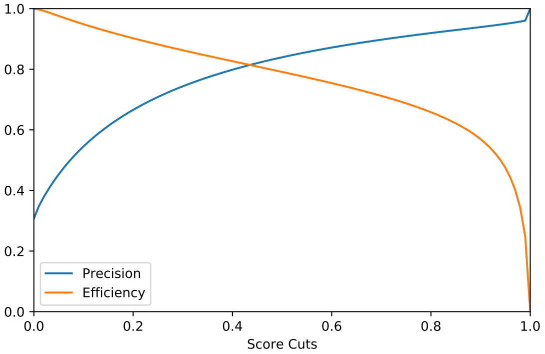
## DNN Scores

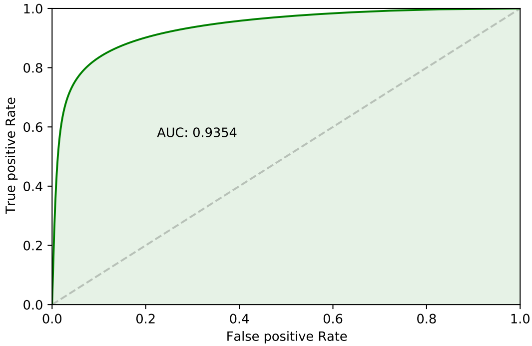
- DNN predicts value between 0 and 1
  →0: most likely background
  →1: most likely stopping event
- visible seperation between signal and background
- upgoing background near value 1: coincident muon events



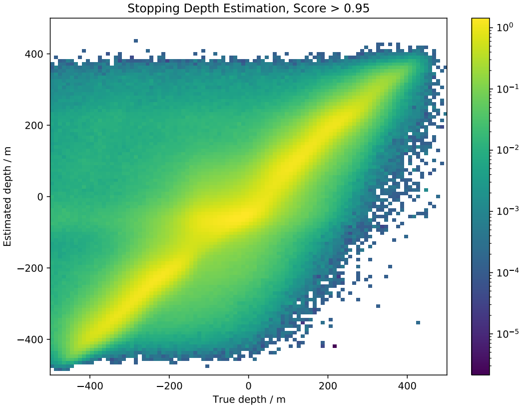
## Precision and Efficiency

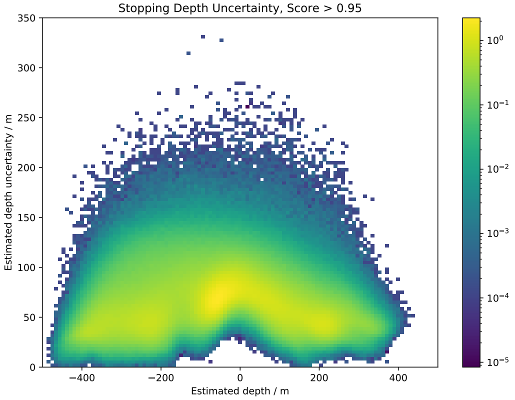
- choose Score Cut at 0.95



# Stopping Depth and Uncertainty for Score Cut at 0.95



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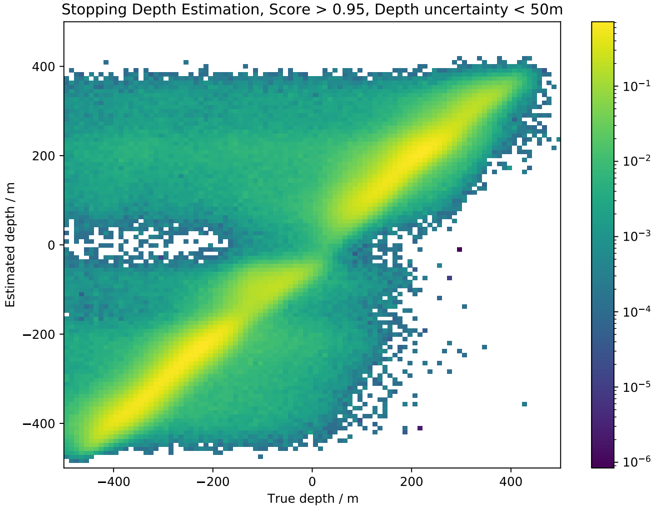
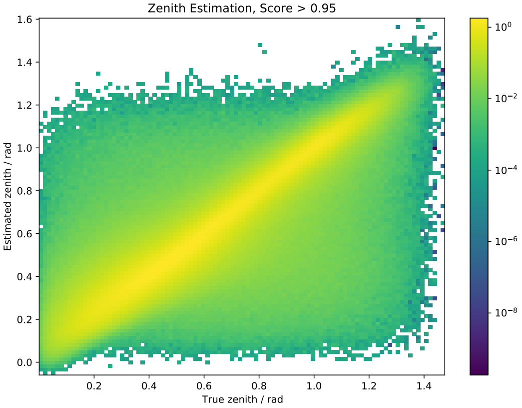
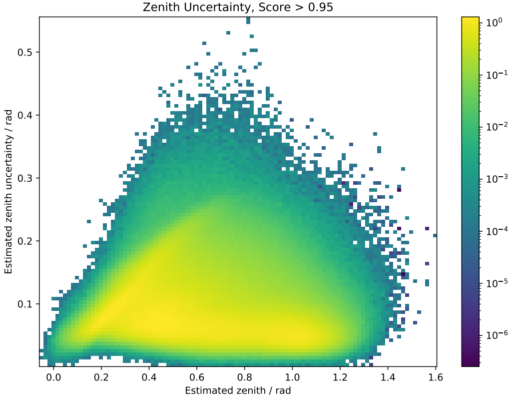


# Zenith and Uncertainty for Score Cut at 0.95



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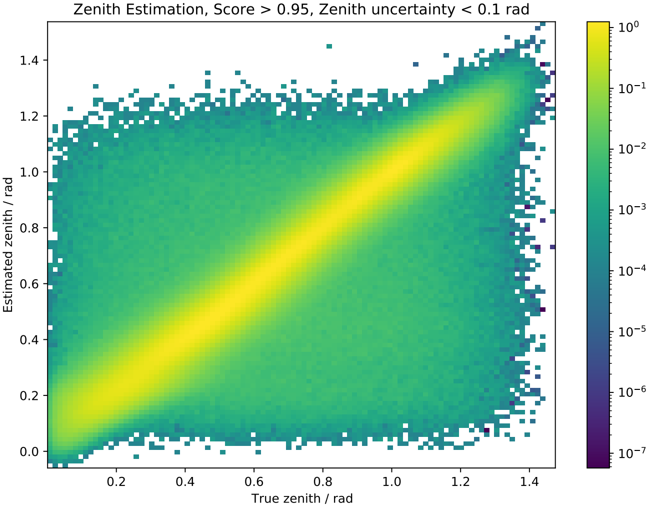
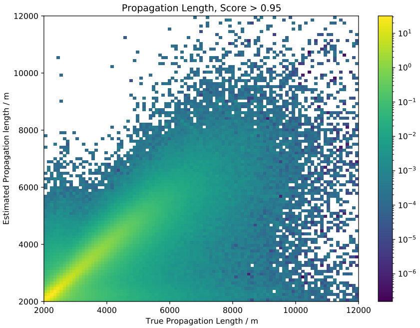


## Propagation Length for Score Cut at 0.95

- propagation length depends on two observables: zenith angle and stopping depth

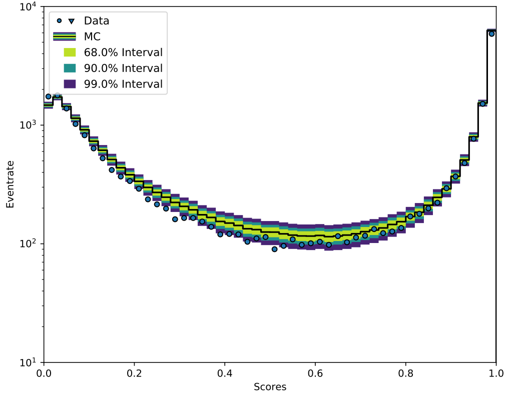
$$r = \sqrt{\left(R_{\mathrm{E}}^2 - \left(R_{\mathrm{E}} - z_{\mathrm{stop}}\right)^2\right) \sin{\Theta_{\mathrm{Z}}}^2 + R_{\mathrm{E}}^2 \cos{\Theta_{\mathrm{Z}}}^2} - \left(R_{\mathrm{E}} - z_{\mathrm{stop}}\right) \cos \Theta_{\mathrm{Z}}$$

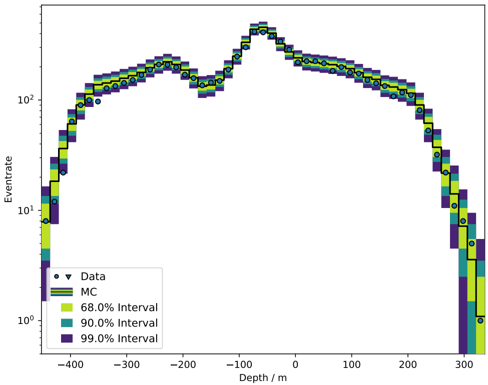


# Data-MC-Agreement

## Data-MC-Agreement

- Score cut at 0.95
- 130 s of data from 08/28/2015



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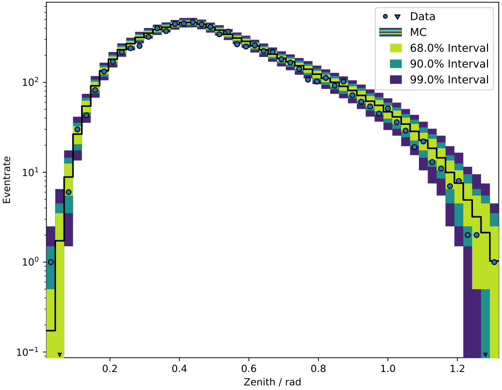
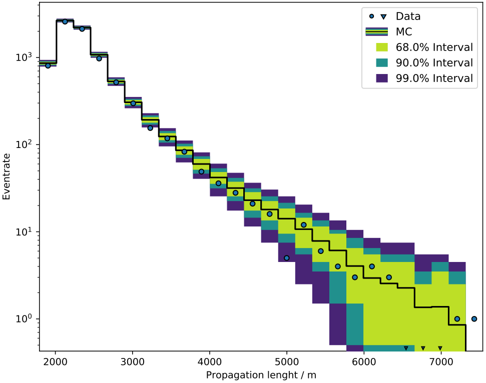


# Unfolding Primary Spectrum

## Unfolding

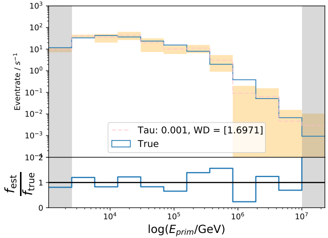
- not all events in true spectrum are represented in oservable spectrum
- also, observable spectrum contains events not related to true physical events of interest
- measured observables related to true spectrum via detector response:

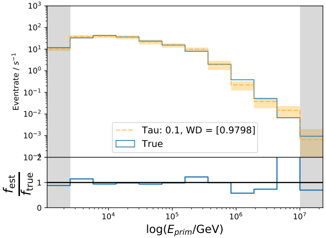
$$\vec{g} = A \cdot \vec{f} + \vec{b}$$

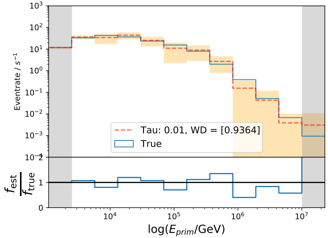
- instead of directly inverting: minimize negative log-likelihood
- approach still yields oscillation solutions
  →Tikhonov regularisation $\tau(f)$

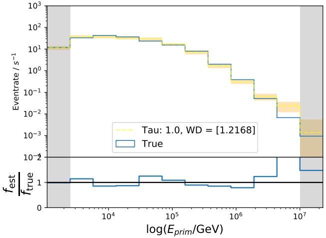
$$-l(\vec{g}|\vec{f}) = \sum_{\mathrm{i}} (A \cdot f)_{\mathrm{i}} - g_{\mathrm{i}} \ln((A \cdot f)_{\mathrm{i}}) + \tau(f)$$

# Eventrates for different regularisation parameters



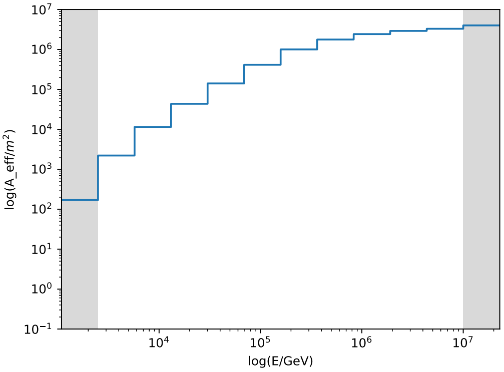



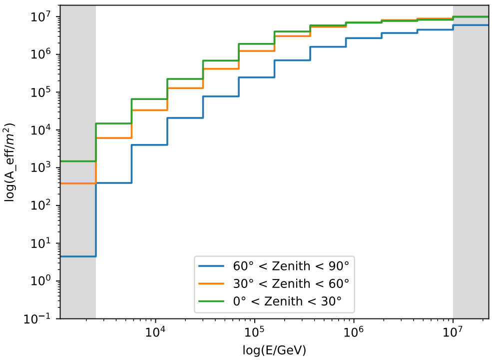



## Effective Area

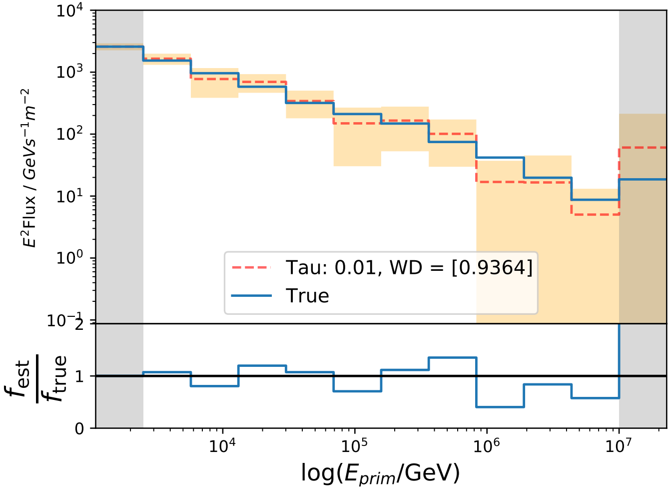
- to calculate flux: effective area has to be considered
- accounts the efficiency of detector
- rescaling detector area with fraction of selected to generated events
- in this work: calculate generation probability
  → how many particles are generated per energy, area and solid angle
- to estimate effective area: invert generation probability and histogram

# Effective Area



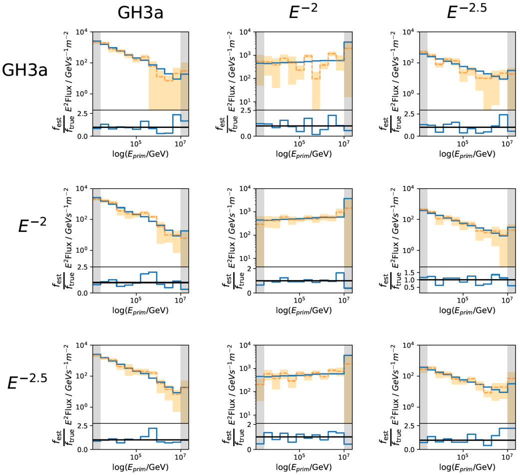



## Unfolded Cosmic Ray Flux



# Testing Unfolding with different spectra

- show that unfolded spectrum is independent of assumed training spectrum
- choose different training spectra for response matrix
- do unfolding with diffierent combinations of training and test spectra



# Outlook

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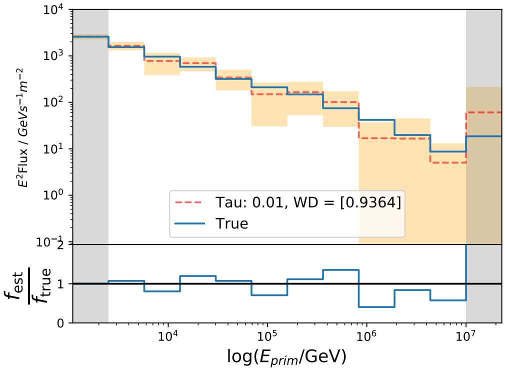
- still need of fixing the MC-labeling for coincident muon events
- more bootstrapping iterations
- unfolding dependent on zenith angle
- due to high statistics choose higher binning
- test on burnsample



# Thank you!