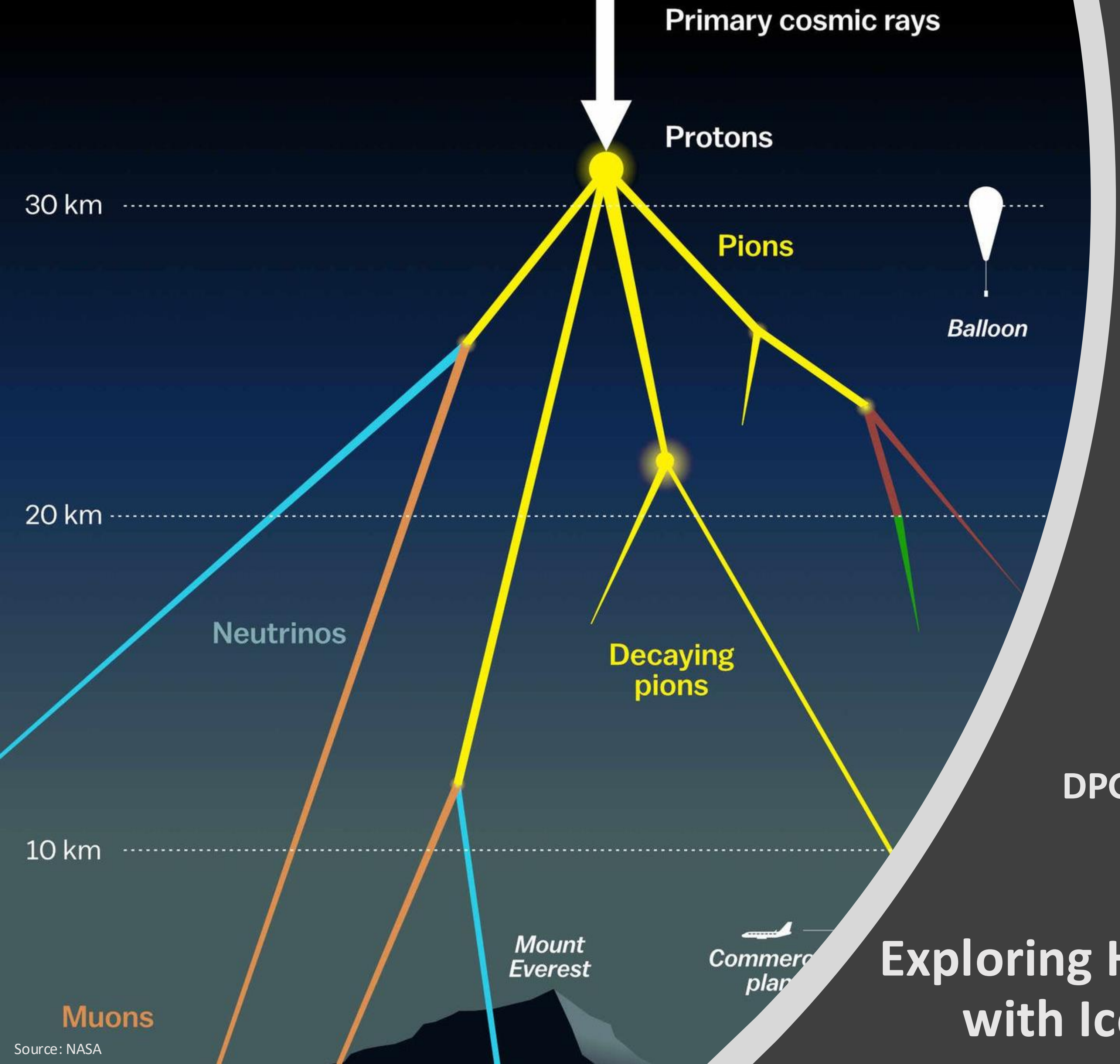


Pascal Gutjahr

DPG Frühjahrstagung in Göttingen | April 4, 2025

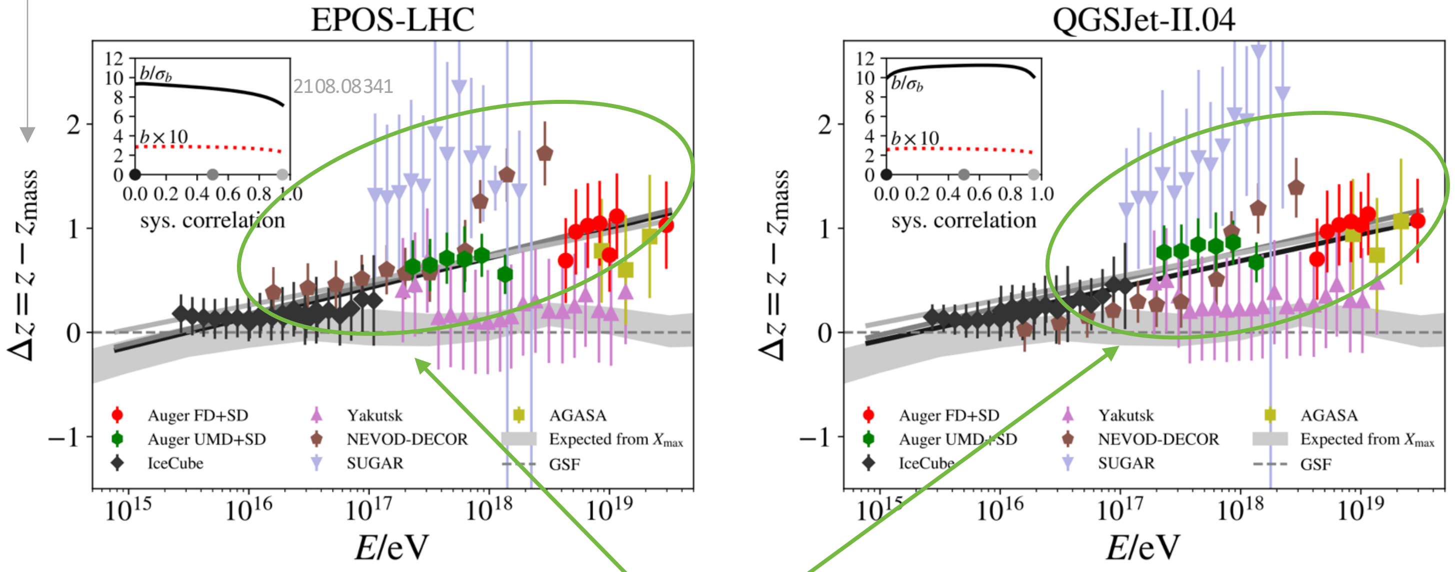
Exploring High-Energy Atmospheric Muons with IceCube: Unfolding the Muon Flux

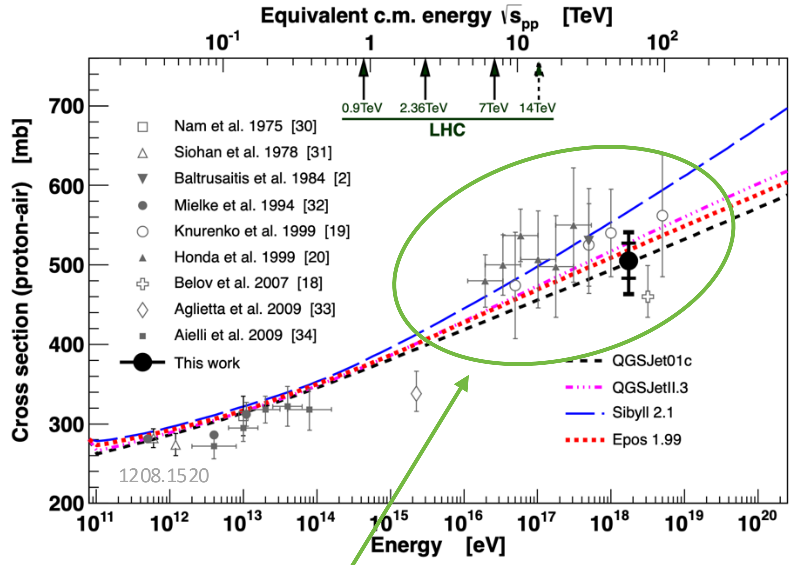
Muon Puzzle & Hadronic Uncertainties

"muon number"

Expected z ("muon number")

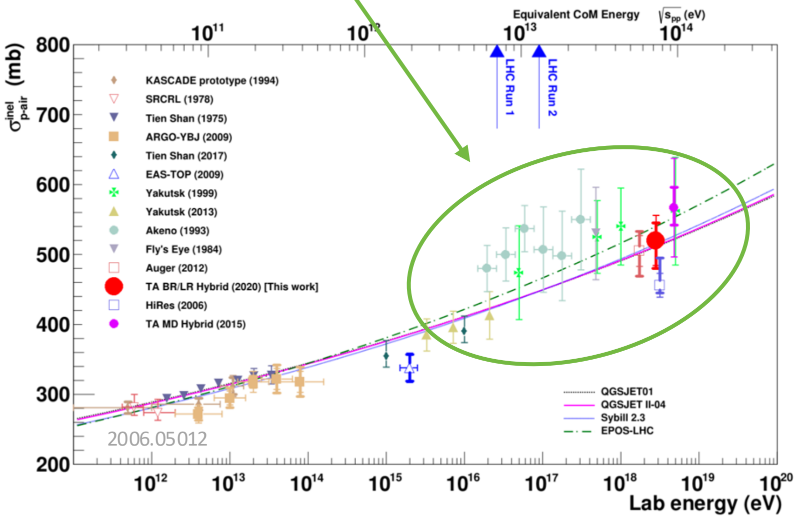
$$z = \frac{\ln\langle N_\mu \rangle - \ln\langle N_\mu \rangle_p}{\ln\langle N_\mu \rangle_{\mathrm{Fe}} - \ln\langle N_\mu \rangle_p}$$





2012

- Uncertainties at E > 10 PeV



2020

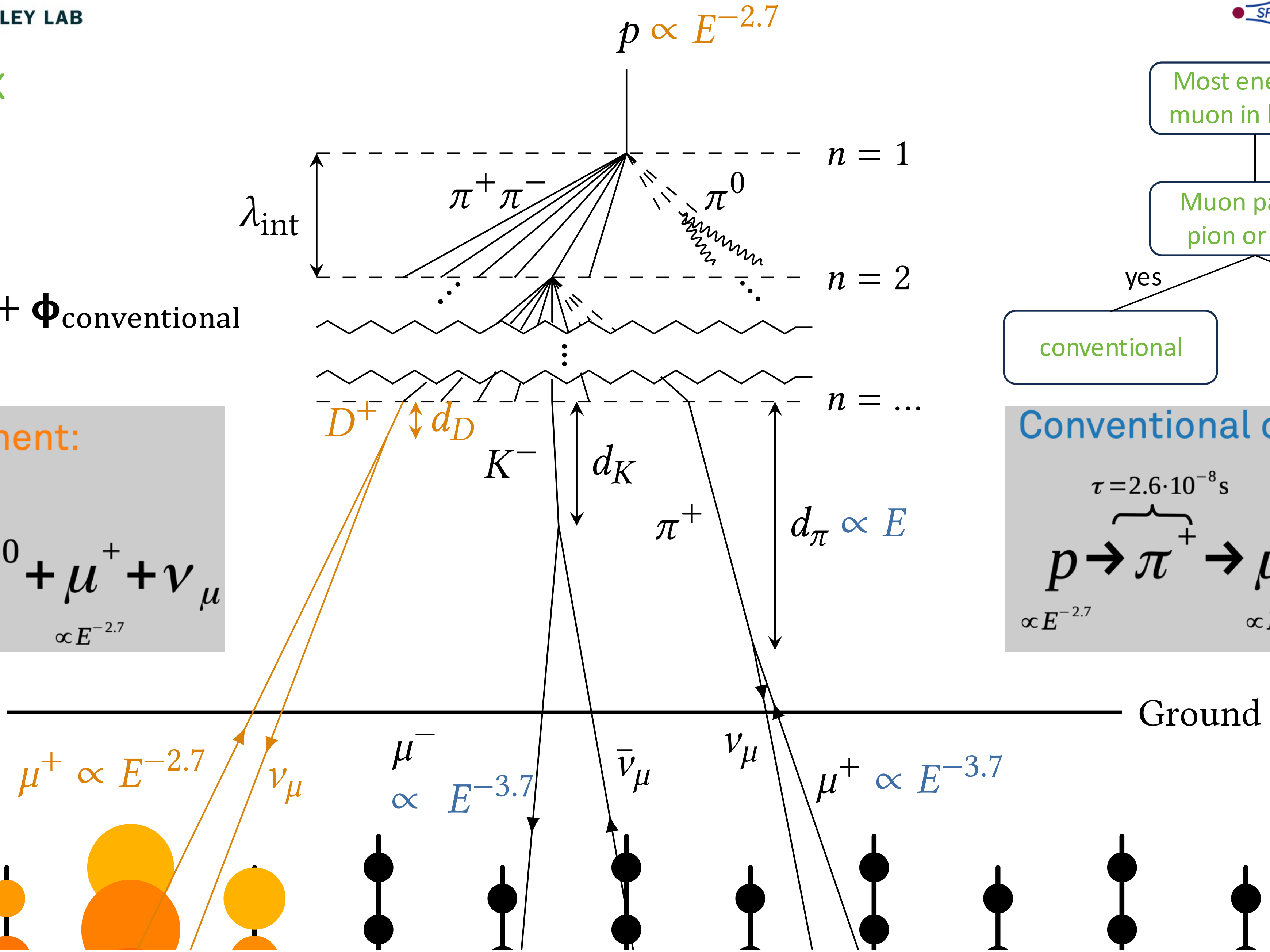
- More muons measured than simulated for E > 40 PeV ~ cms 8 TeV
- Precise pion/kaon ratio measurement needed

Muon Flux

$$\Phi_{\text{tot}} = \Phi_{\text{prompt}} + \Phi_{\text{conventional}}$$

prompt component:

$$\underset{\propto E^{-2.7}}{p} \rightarrow \overbrace{D^{+}}^{\tau = 1.04\cdot 10^{-12}\,\mathrm{s}} \rightarrow \bar{K}^{0} + \underset{\propto E^{-2.7}}{\mu^{+}} + \nu_{\mu}$$



Most energetic muon in bundle

Muon parent: pion or kaon

yes → conventional

no → prompt

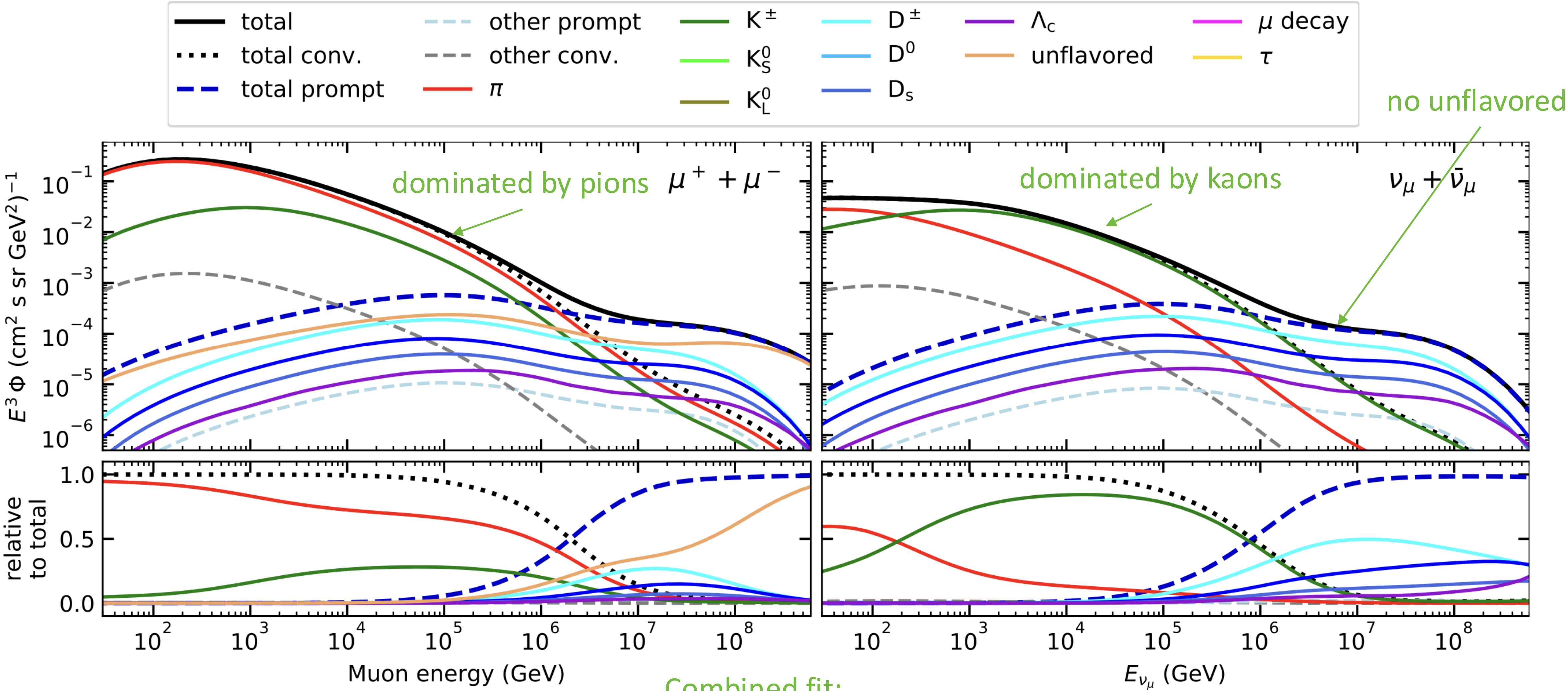
Conventional component:

$$\underset{\propto E^{-2.7}}{p} \rightarrow \overbrace{\pi^{+}}^{\tau = 2.6\cdot 10^{-8}\,\mathrm{s}} \rightarrow \underset{\propto E^{-3.7}}{\mu^{+}} + \nu_{\mu}$$

Credit: Ludwig Neste

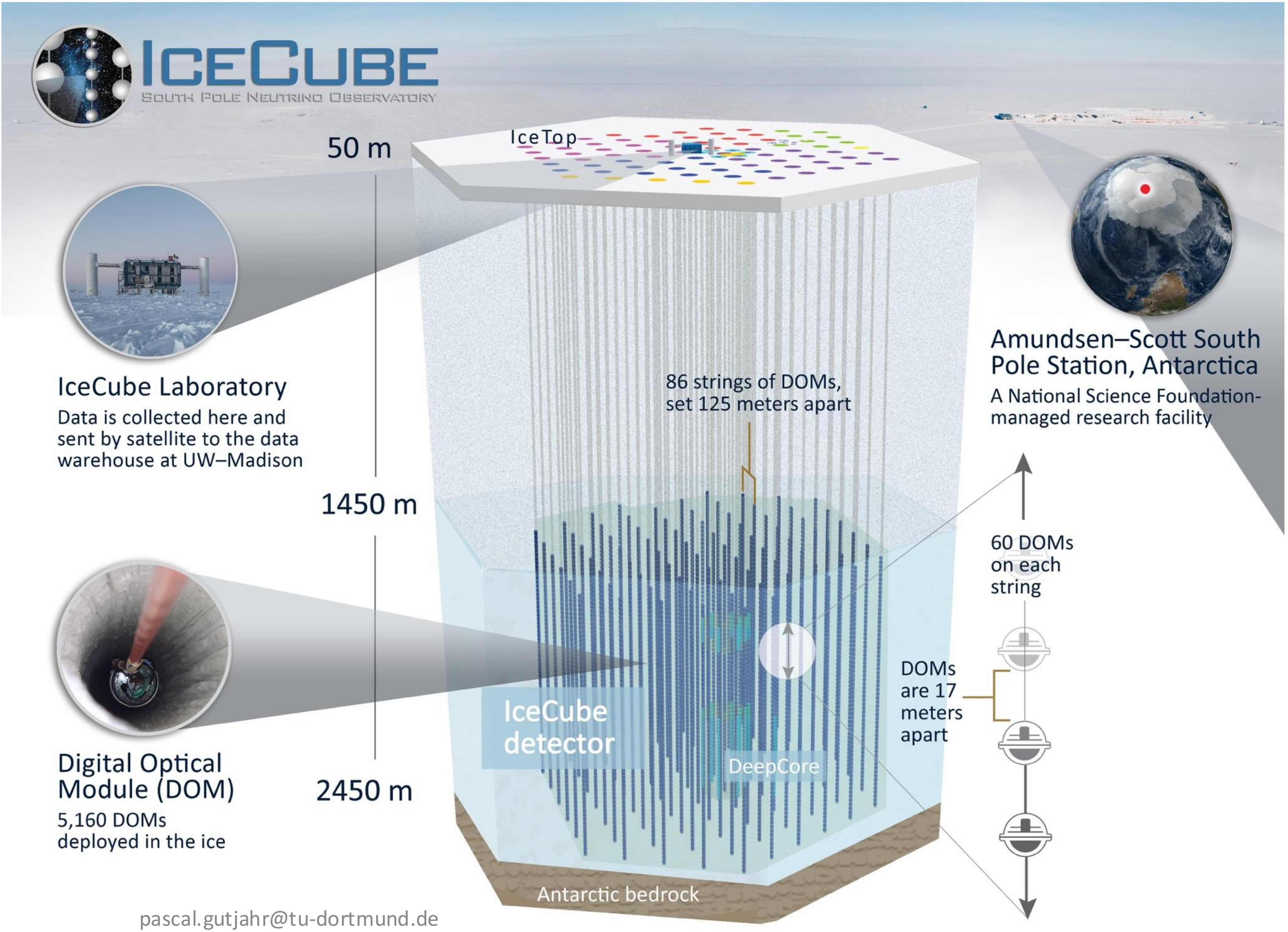
Prompt Atmospheric Muons & Neutrinos

10.1103/PhysRevD.100.103018

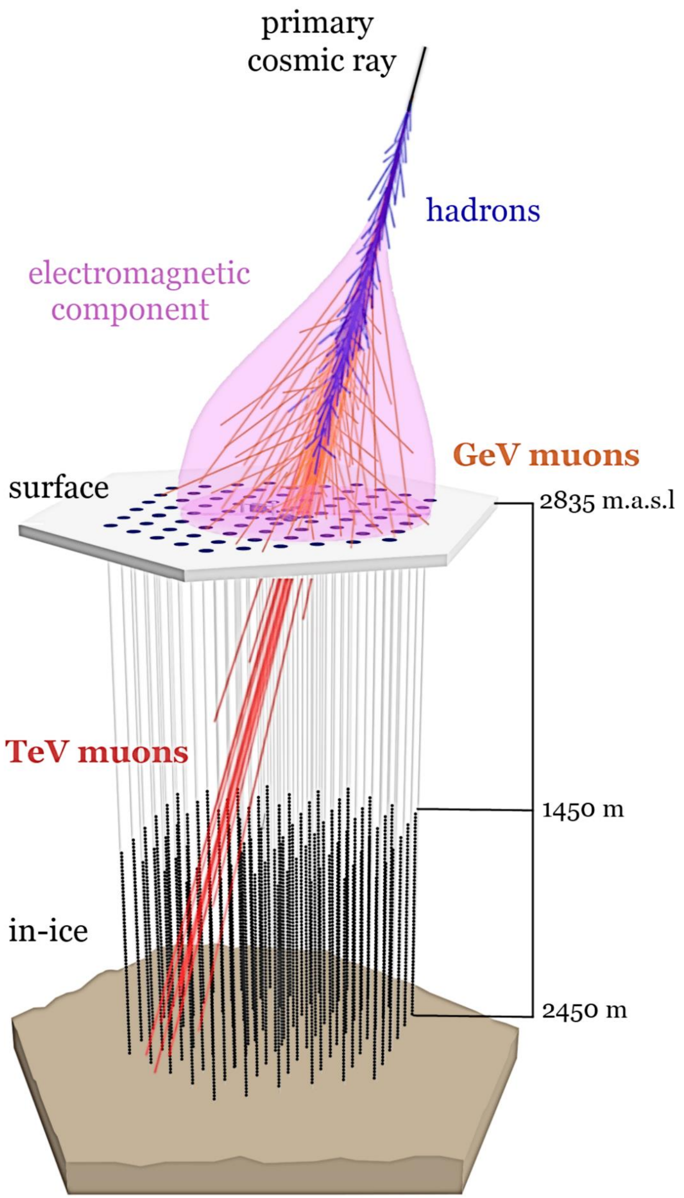


Combined fit:

- handle on pion/kaon ratio
- handle on charmed mesons



icecube.wisc.edu/science/icecube



icecube.wisc.edu/science/research

Overview

Simulation

Dataset
- CORSIKA 77500 Ehist
- SIBYLL 2.3d
- 10 TeV – 100 EeV

Validation
- Tag prompt / conv particles
- MCEq comparisons

Reconstruction

DNN reconstructions
- Muon energies
- Muon direction
- Track geometry

Selection

Level 3
- L2 muon filter
- 500 TeV bundle energy cut at surface
- Add labels

Level 4
- Add DNN reconstructions

Level 5
- Data-MC quality cuts

Analysis

Forward fit

Fit prompt normalization
- Poisson LLH fit

Unfolding

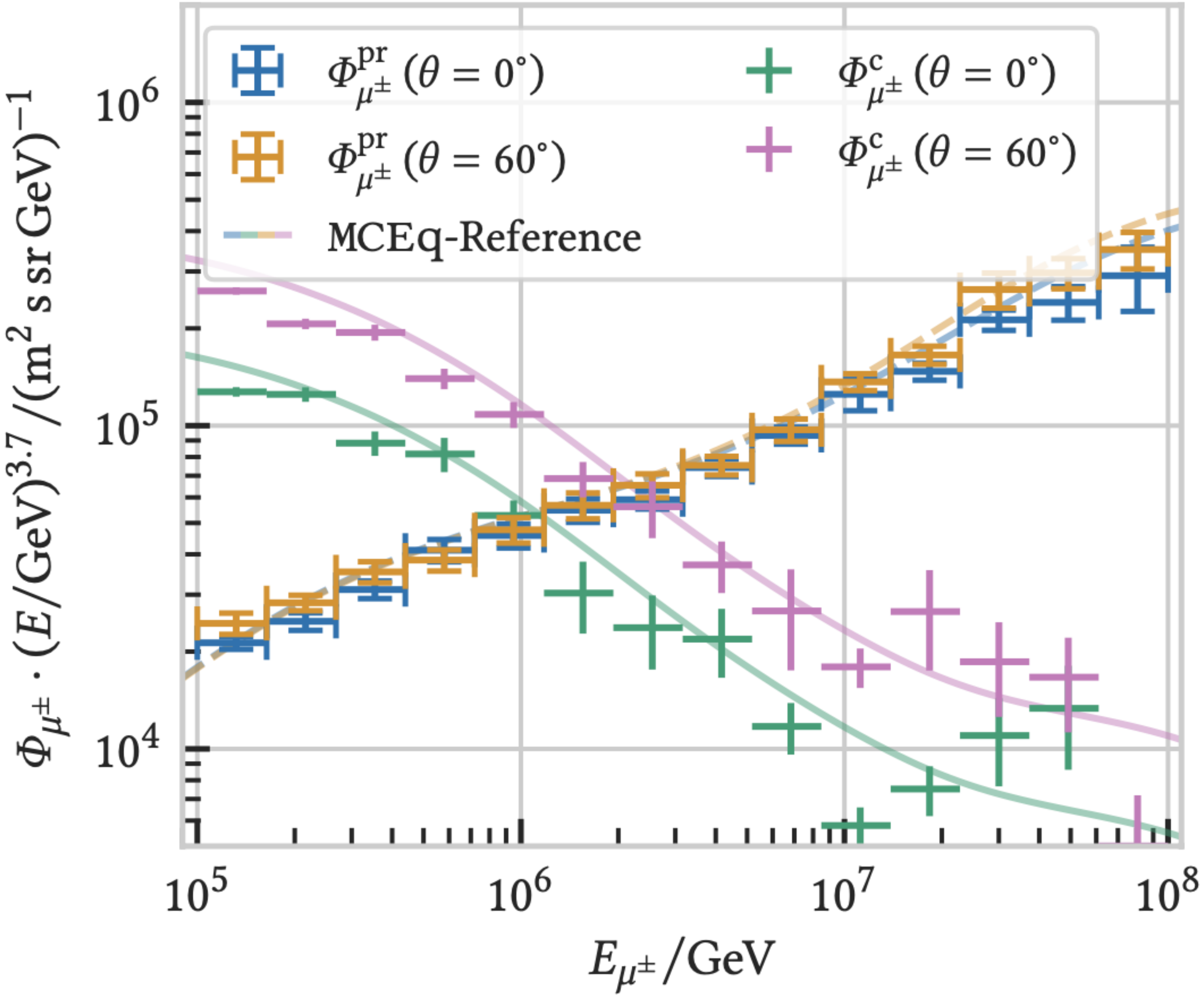
Muon spectrum
- Unfold muon flux

Simulation

tu dortmund university BERKELEY LAB SFB1491 IceCube Neutrino Observatory

CORSIKA 7 vs. MCEq

MCEq: tool to numerically solve the cascade equations that describes the evolution of particle densities as they propagate through a gaseous, dense medium
https://github.com/mceq-project/MCEq



- Good agreement for inclusive flux

Python package developed – PANAMA

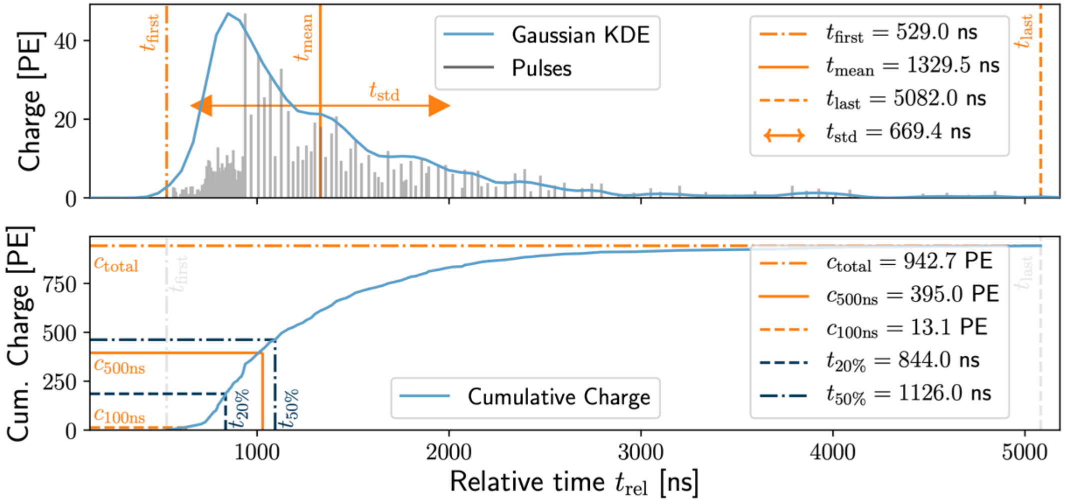
- Execute CORSIKA 7 (multi core)
- Read DAT files → pandas DataFrames
- Parse EHIST option
- Calculate primary weightings

https://github.com/The-Ludwig/PANAMA
https://arxiv.org/pdf/2502.10951

DNN Reconstructions

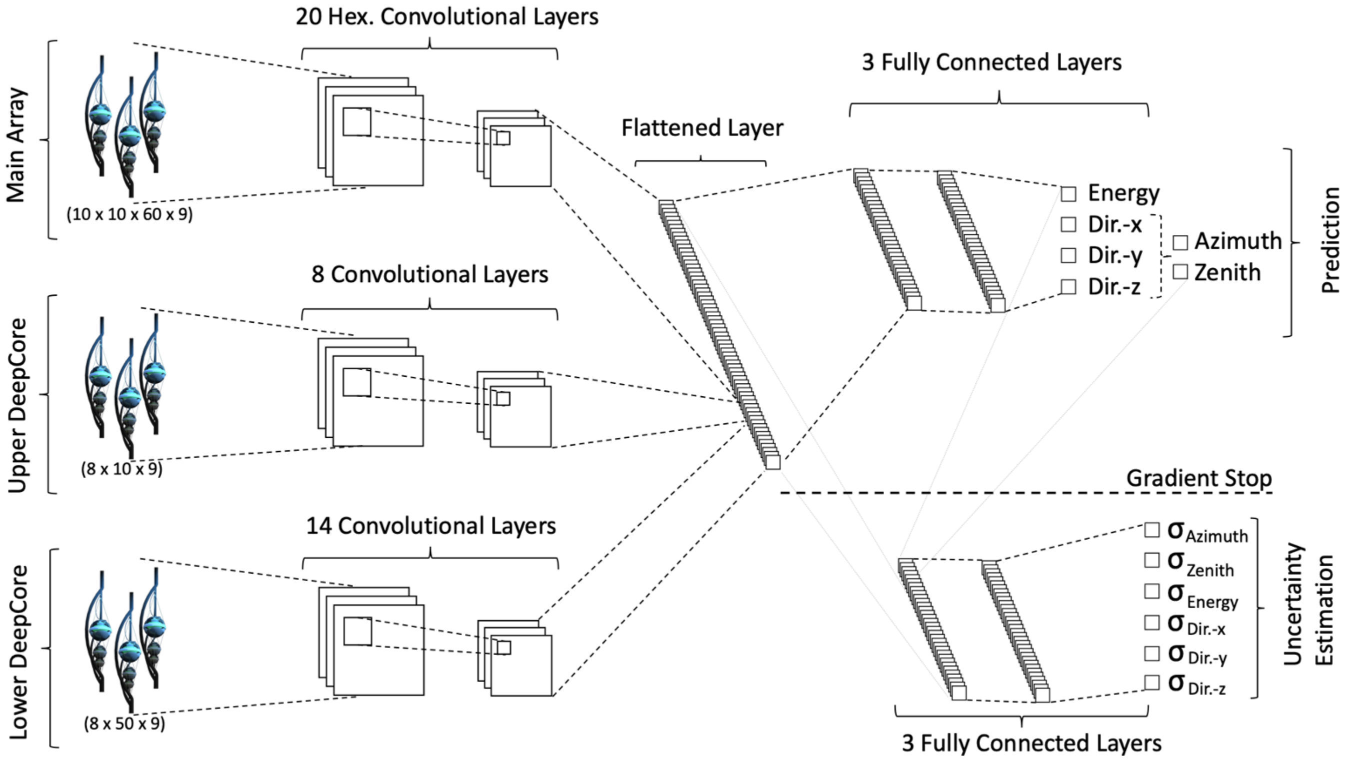
Convolutional Neural Network (CNN)

10.1088/1748-0221/16/07/P07041



Reconstruct:

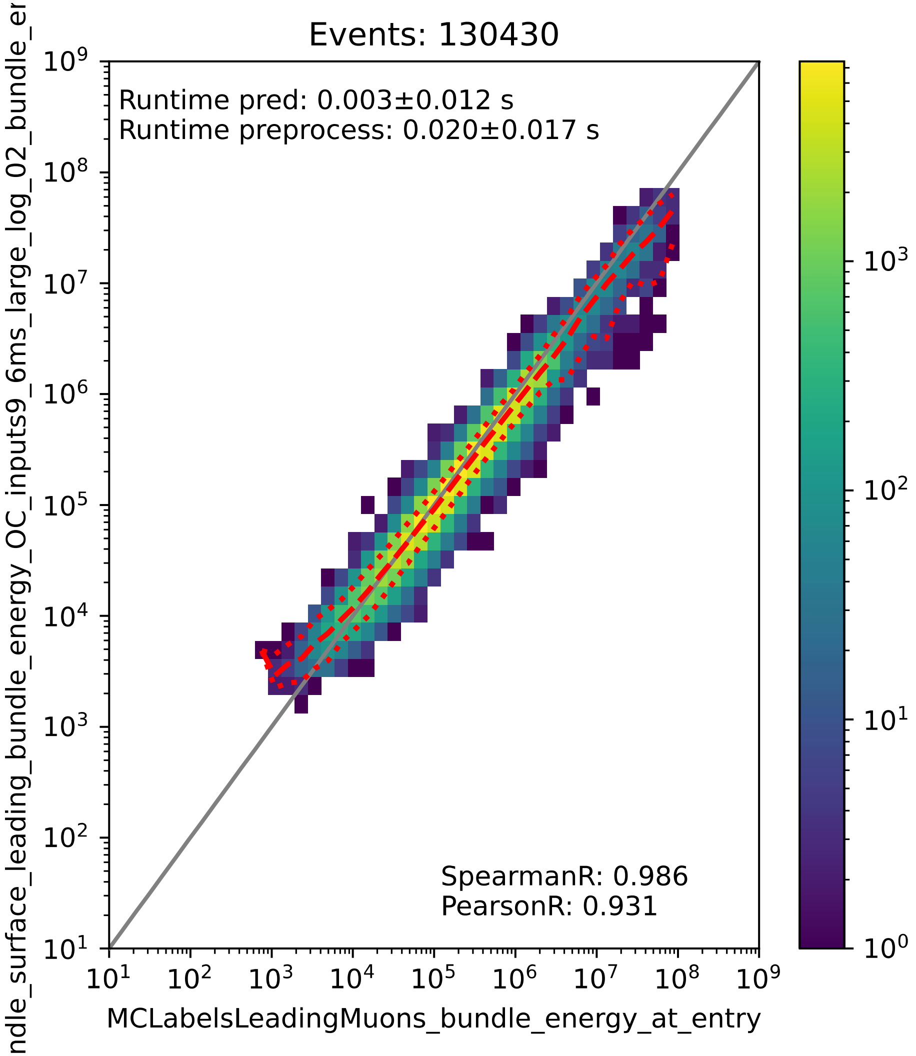
- Energy
  - muon / bundle energy at entry
- Direction
  - zenith / azimuth
- Geometry
  - detector entry / depth

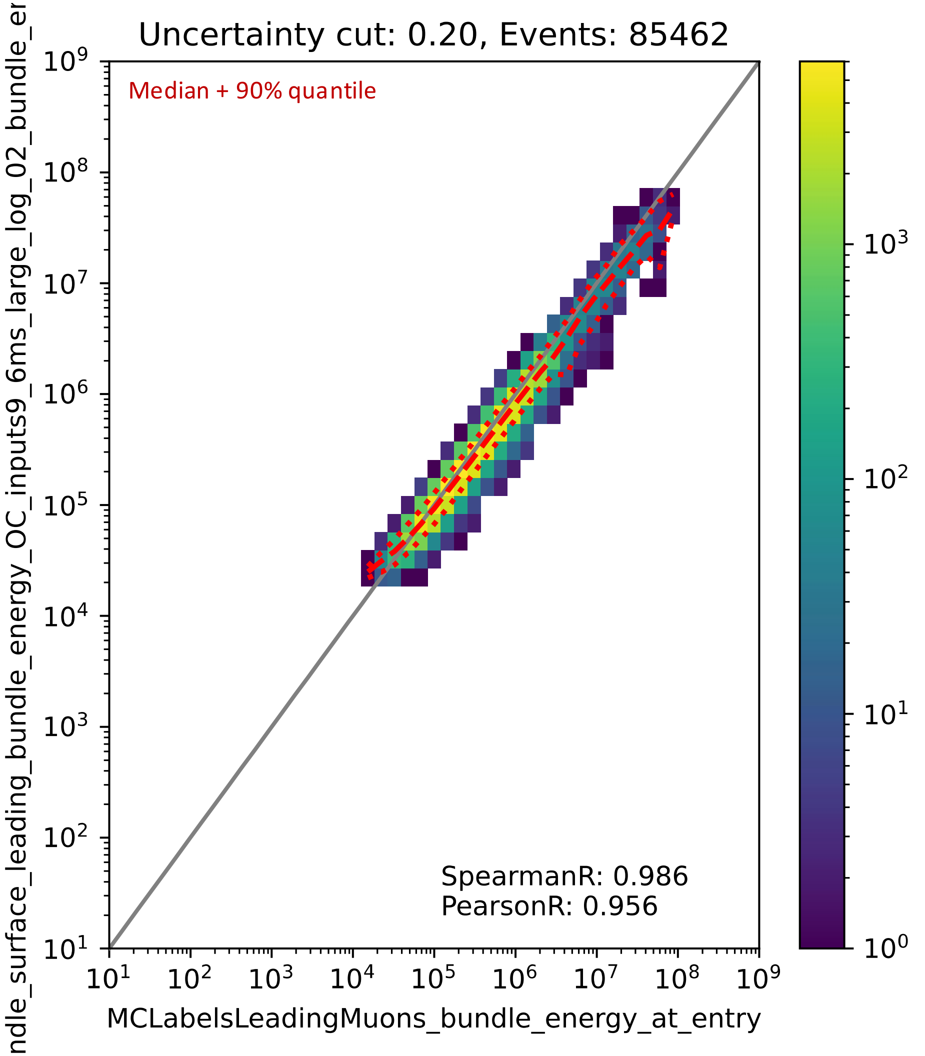


2101.11589

Bundle energy at entry – 6 µs cleaned pulses

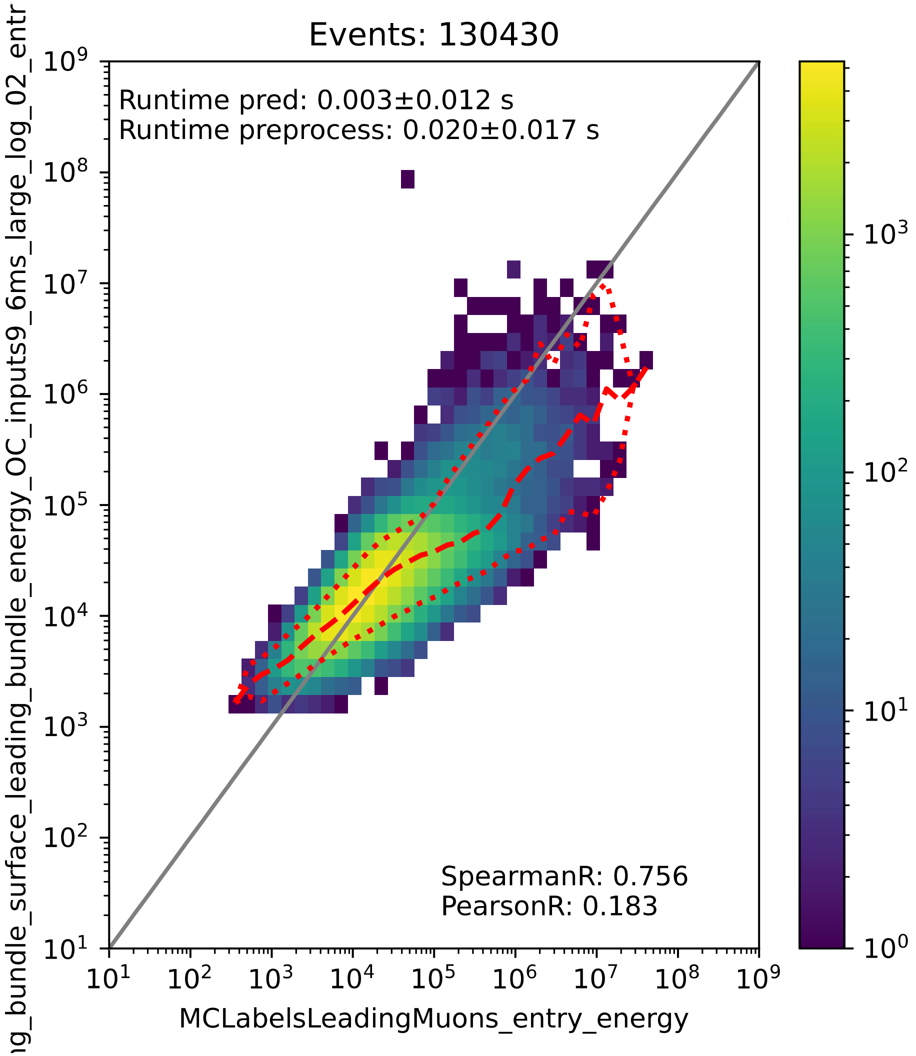
Prediction

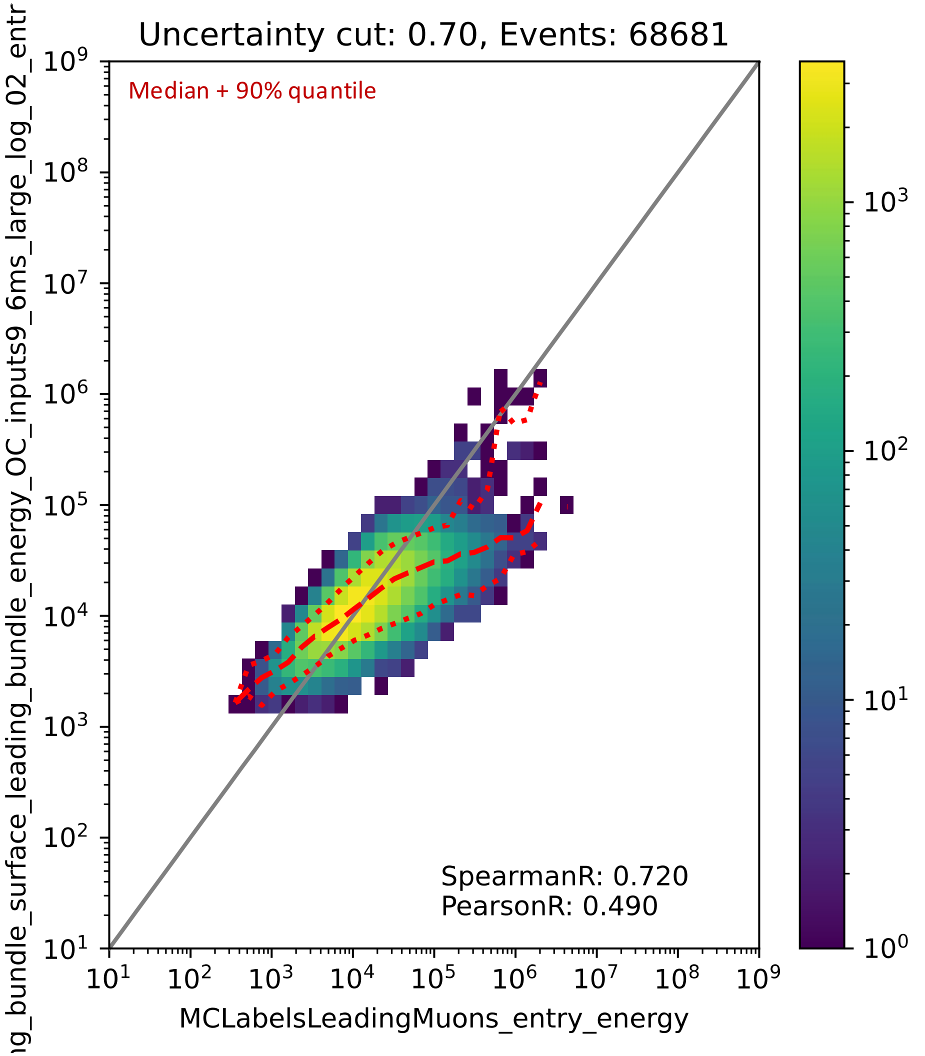




True

Leading muon energy at entry – 6 µs cleaned pulses





Prediction

True

Unfolding

Unfolding in a Nutshell

measured proxy · detector response · background · true energy distribution

$$g(y) = \int_{E_0}^{E_1} A(E_\mu, y) f(E_\mu)\,\mathrm{d}E_\mu + b(y)$$

1. discretized form: $\underbrace{\vec{g} = A\vec{f}}_{\text{folding}} \leftrightarrow \underbrace{\vec{f} = A^{-1}\vec{g}}_{\text{unfolding}}$

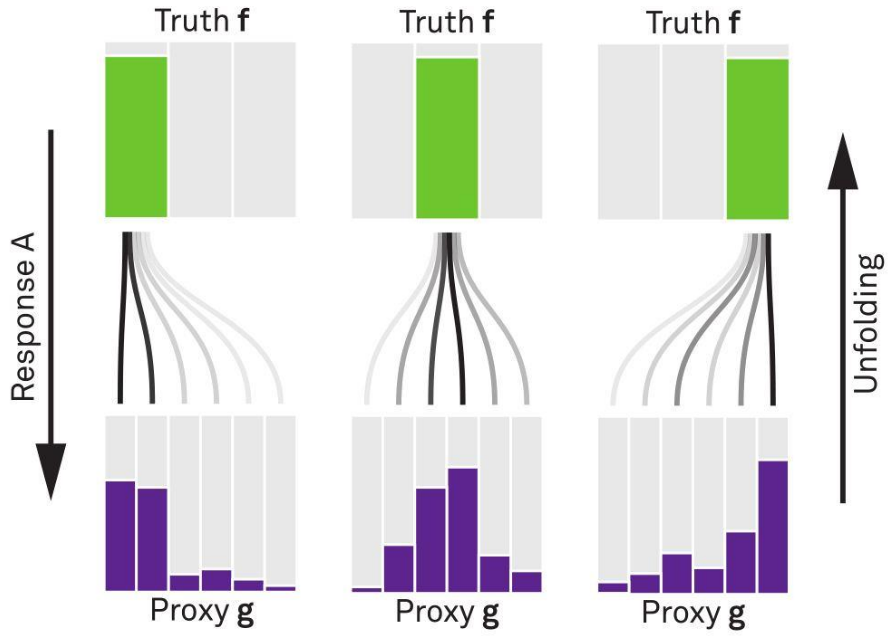
2. maximum likelihod method:

$$\mathcal{L}(\vec{g}|\vec{f}) = \prod_{j=1}^{M} \frac{\lambda_j^{g_j}}{g_j!} \exp(-\lambda_j)$$
$$= \prod_{j=1}^{M} \frac{(A\vec{f})_j^{g_j}}{g_j!} \exp(-(A\vec{f})_j)$$

3. Thikonov regularization:

$$t(\vec{f}) = -\frac{1}{2}(C\vec{f})^T (\tau 1)^{-1} (C\vec{f})$$

4. maximize $\log(\mathcal{L}(\vec{g}|\vec{f})) + t(\vec{f})$
with respect to $\vec{f}$ using
Markov Chain Monte Carlo (MCMC)
or Minuit

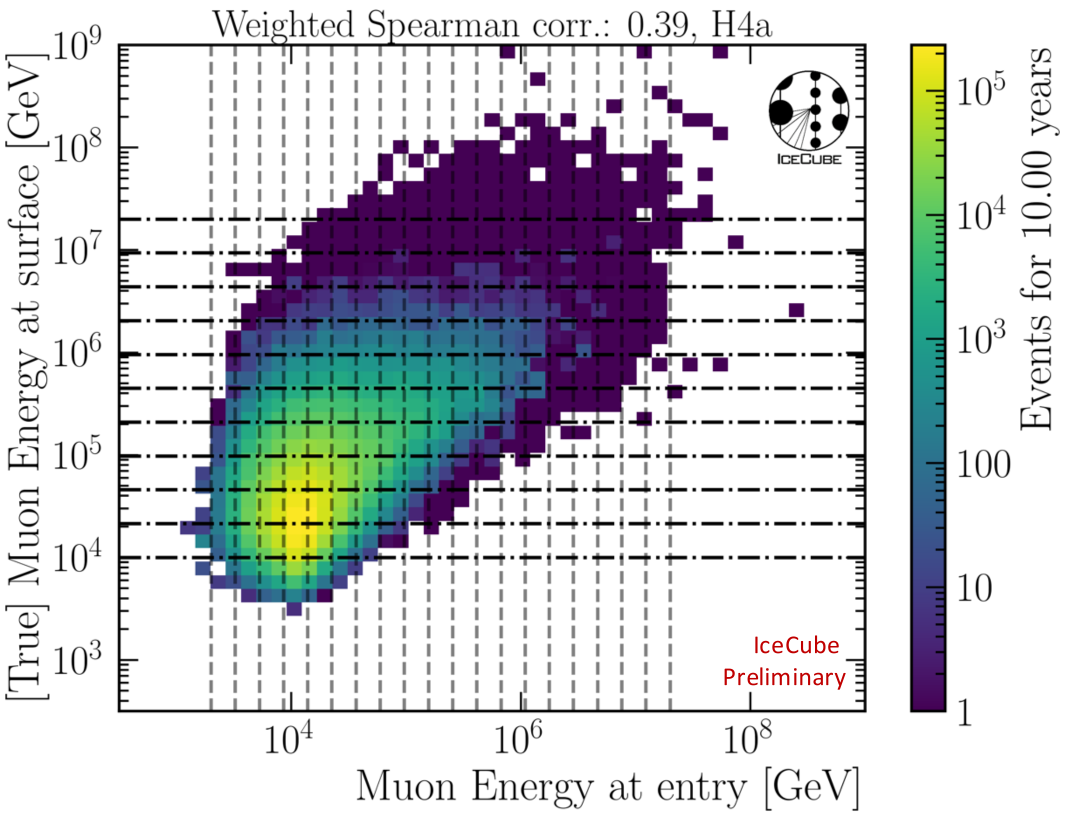


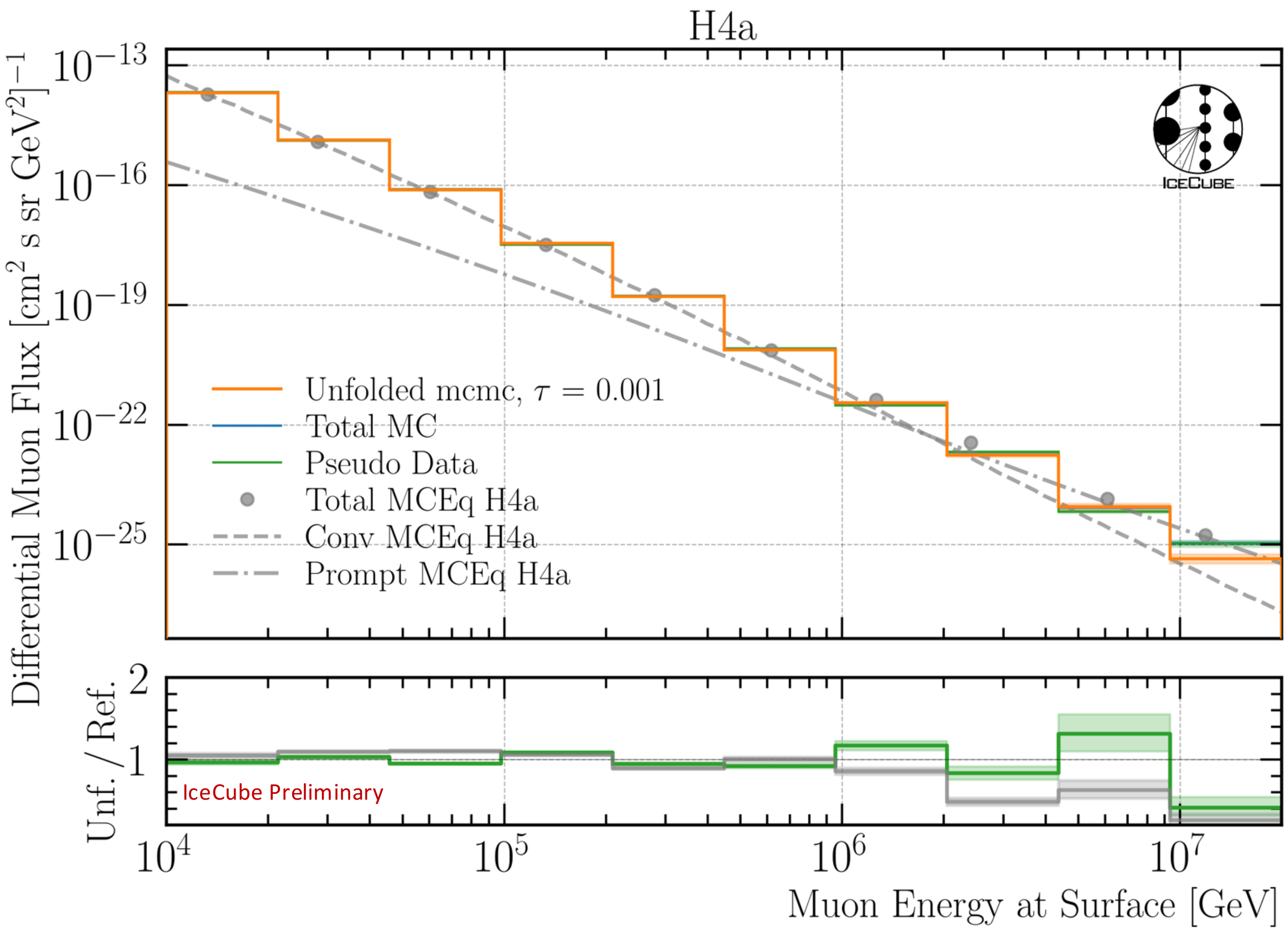
Credit: T. Hoinka

GitHub **funfolding**
by M. Börner

Unfolded Muon Flux at Surface

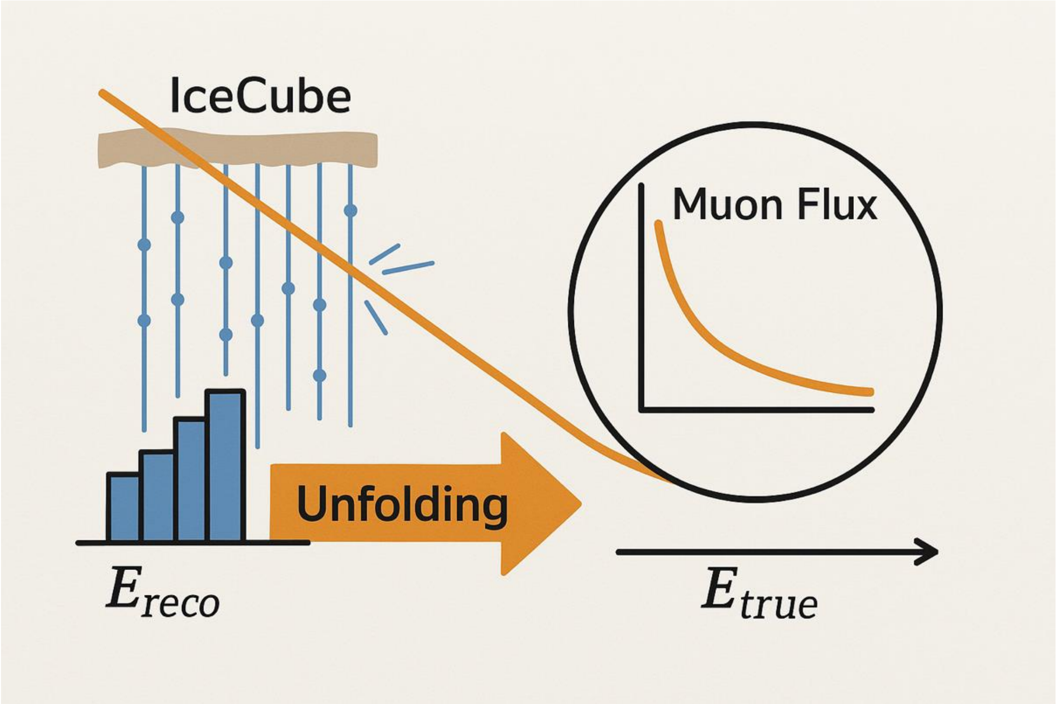
MC only





Conclusion & Outlook

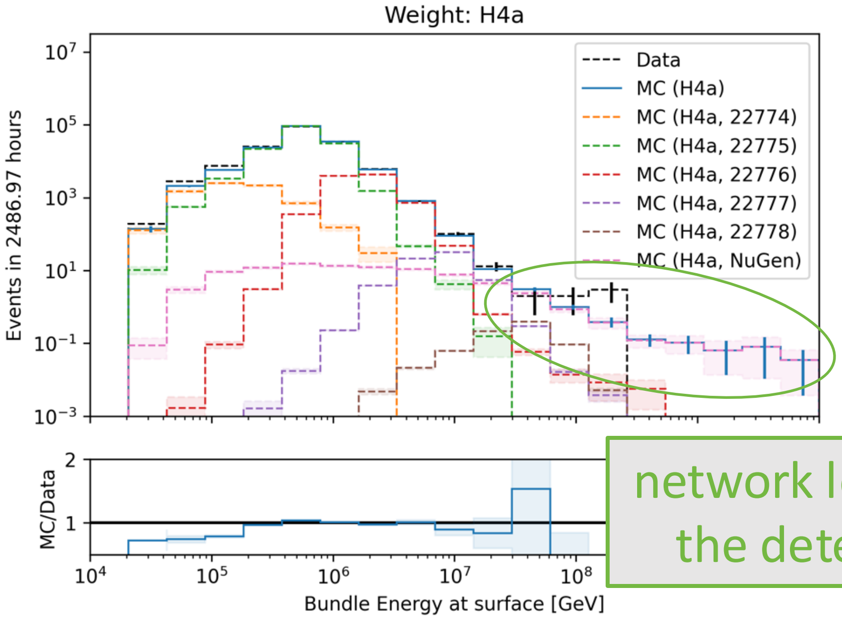
- New CORSIKA simulations with parent information
  - Tag prompt and conventional muons
  - Validation: agreement with MCEq
  - arXiv: 2502.10951
  - github.com/The-Ludwig/PANAMA
- New DNN reconstructions
  - Energy, direction, detector geometries
- Unfolding of muon flux at surface works
  - Fine-tune regularization strength
- Unblind IceCube data until ICRC



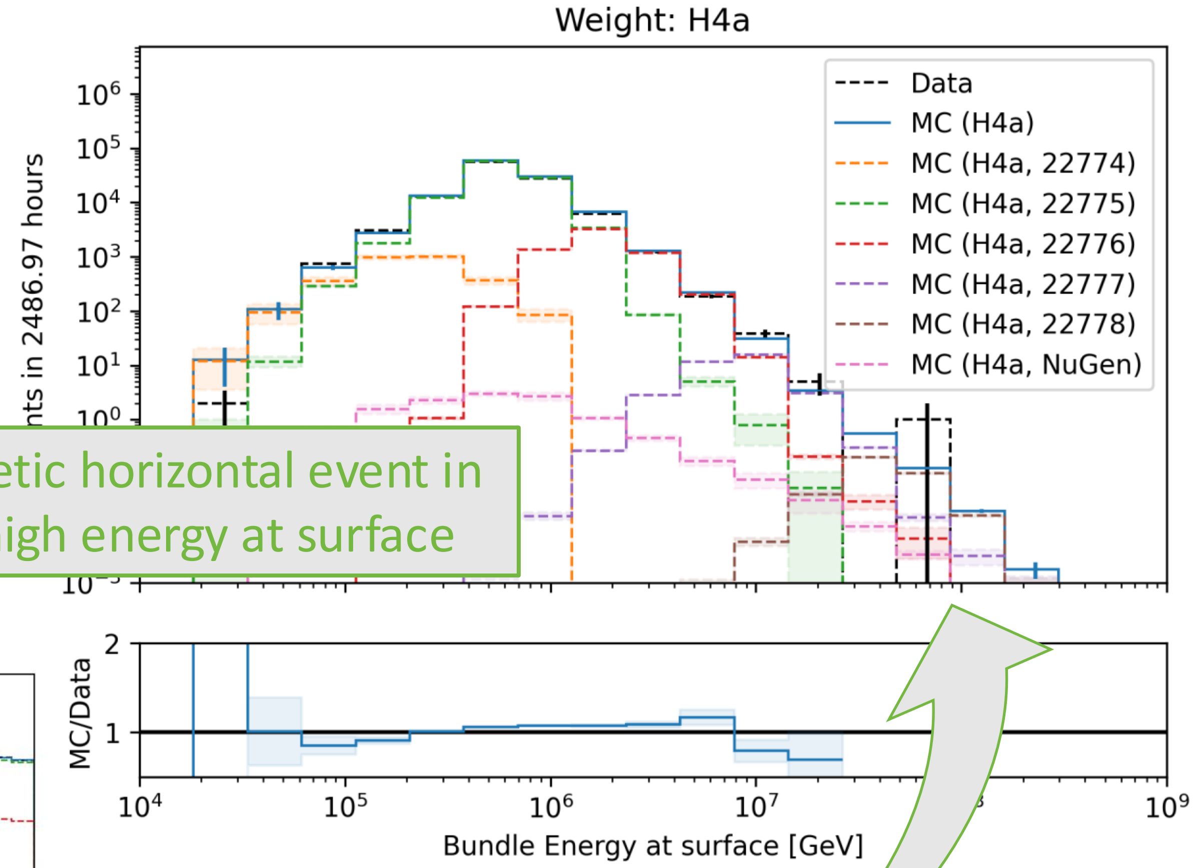
How ChatGPT illustrates the unfolding of the atmospheric muon flux with IceCube.

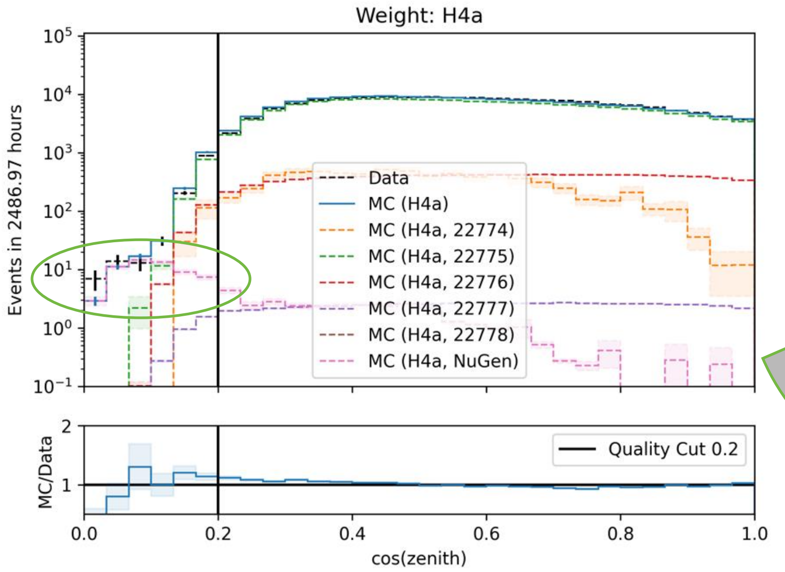
Backup

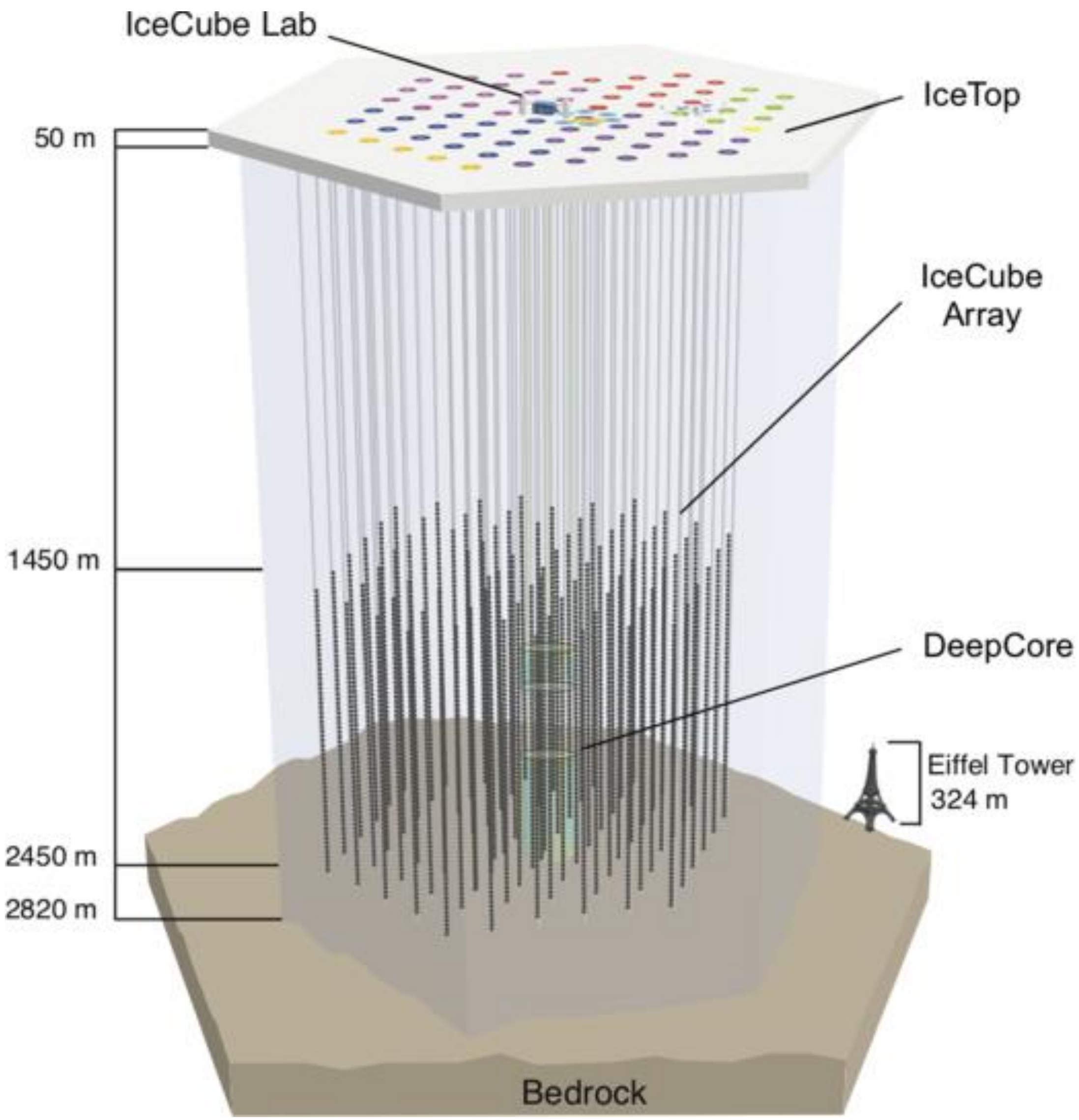
Level5: quality cuts → removes neutrinos



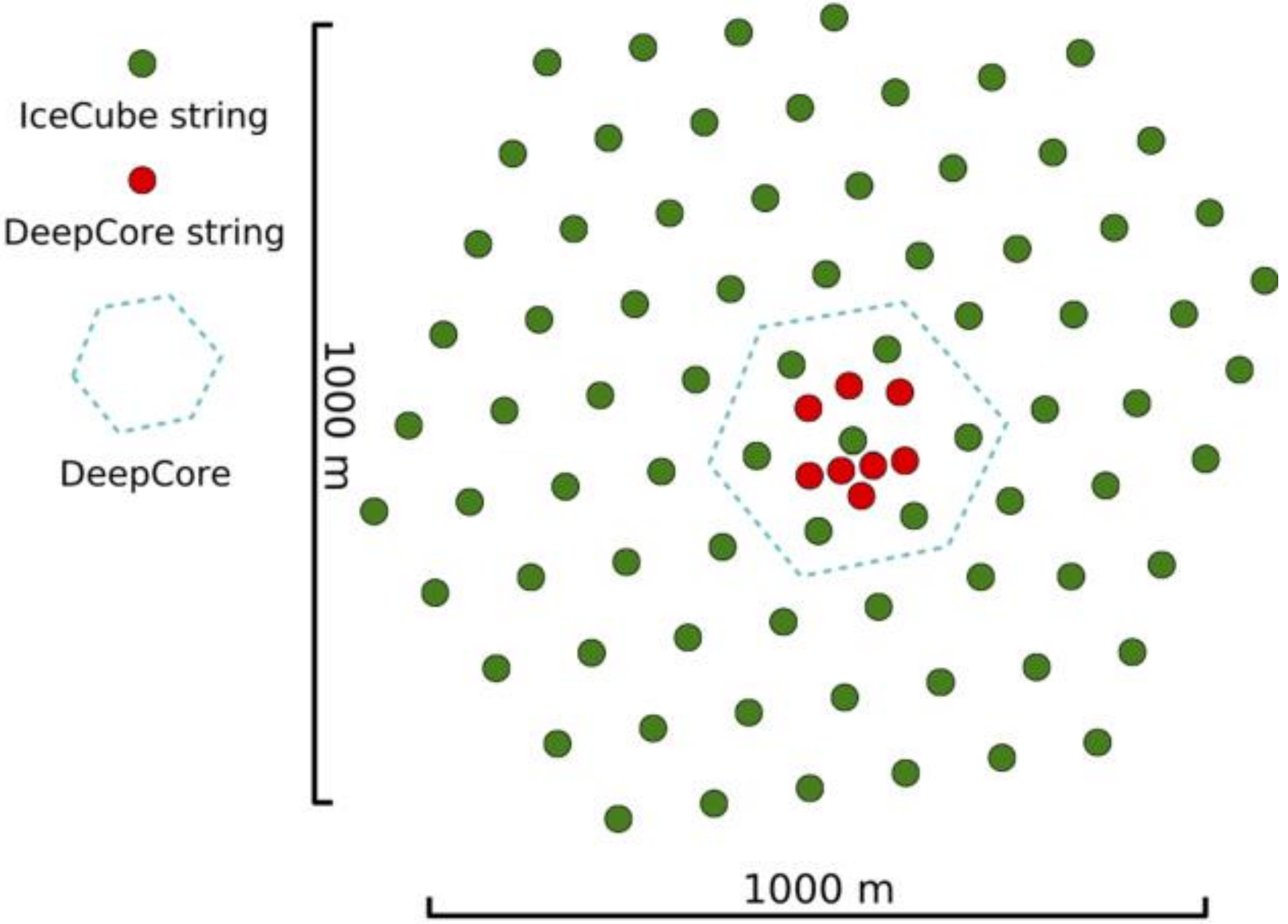
network learns: a high-energetic horizontal event in the detector needs a very high energy at surface







1806.05696v1



Analysis Goals

1) Measure prompt component of the atmospheric muon flux
2) Unfold a muon energy spectrum

Idea:

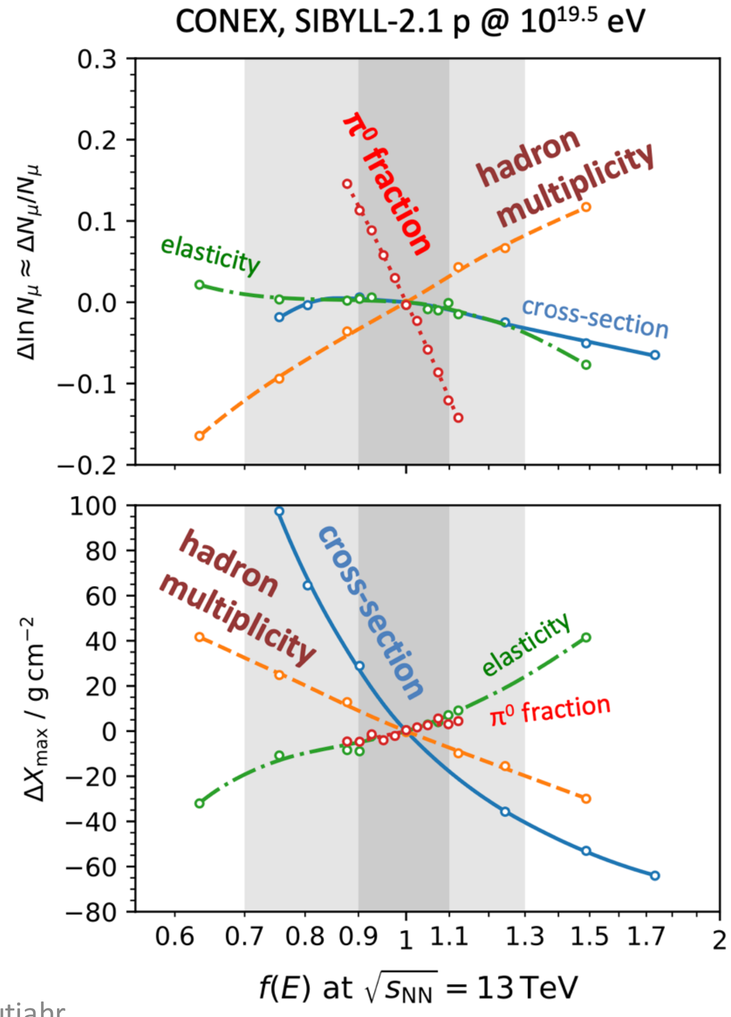
- New CORSIKA simulations with extended history
- Tag muons by parent → prompt or conventional
- Scale amount of prompt particles
  - Scaling saves time and resources instead of doing multiple simulations with different interaction models
  - Perform forward fit of the prompt normalization

Future:

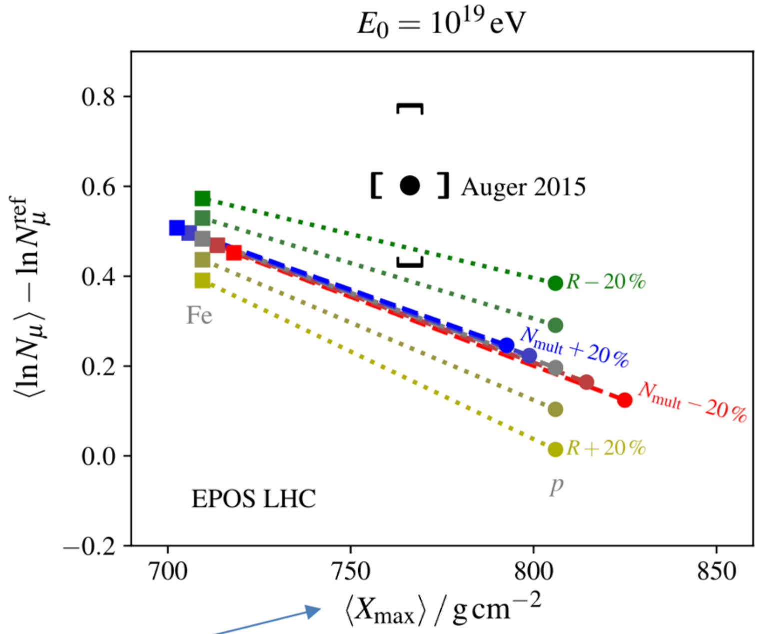
- Measure prompt neutrinos
- Combined muon and neutrino fit → pion/kaon ratio

Possible Solutions

R. Ulrich, R. Engel, M. Unger, PRD 83 (2011) 054026



S. Baur, HD, M. Perlin, T. Pierog, R. Ulrich, K. Werner, arXiv:1902.09265



$$R = \frac{E_{\pi^0}}{E_{\text{other hadrons}}}$$

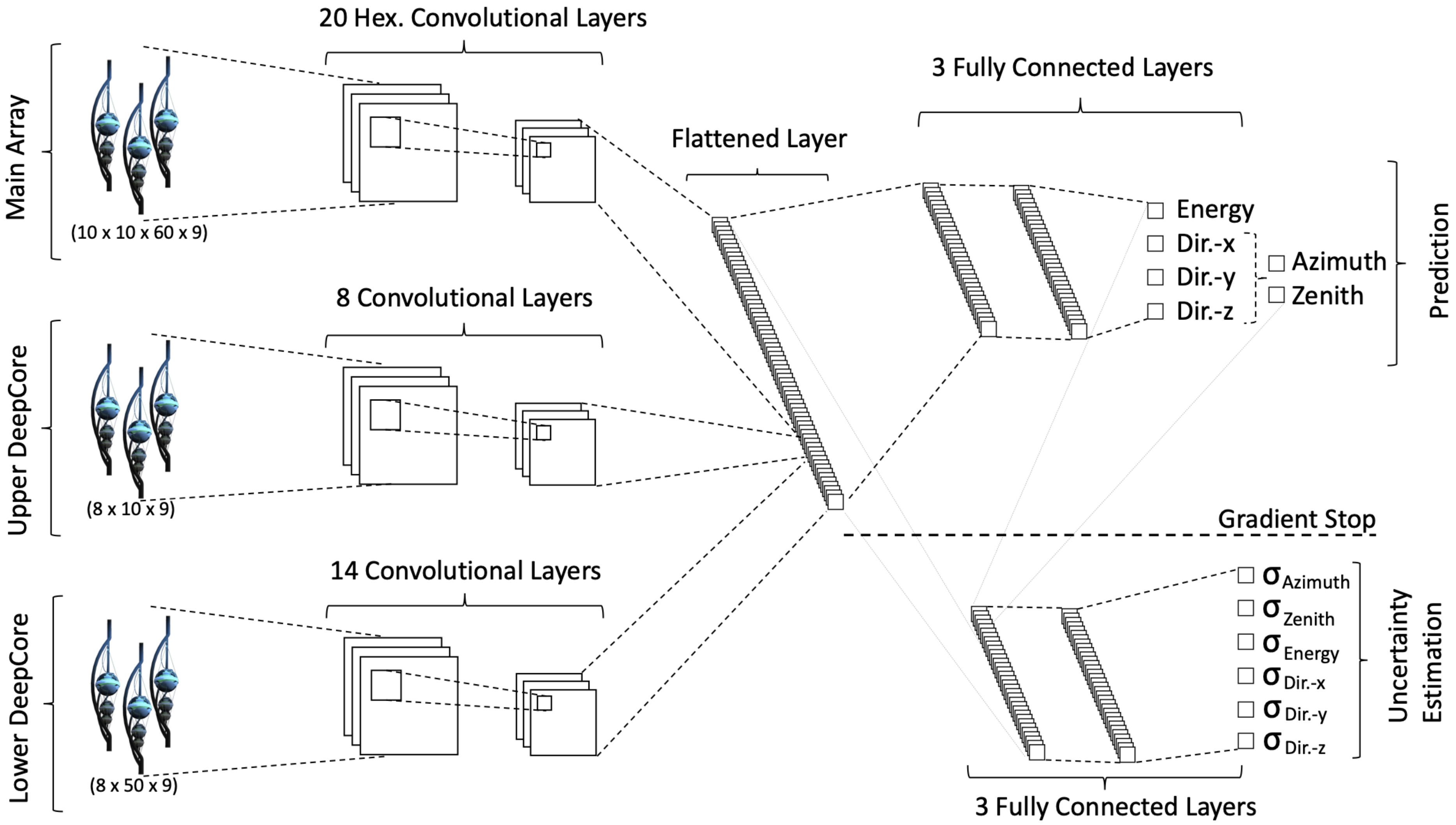
- Only changes to R can solve muon puzzle
- Small changes have large effect, R needs to be known to about 5 %

Hans Dembinski

Convolutional Neural Network (CNN)

Machine learning approach:

- fast
- identifying spatial patterns
- better event reconstruction and classification



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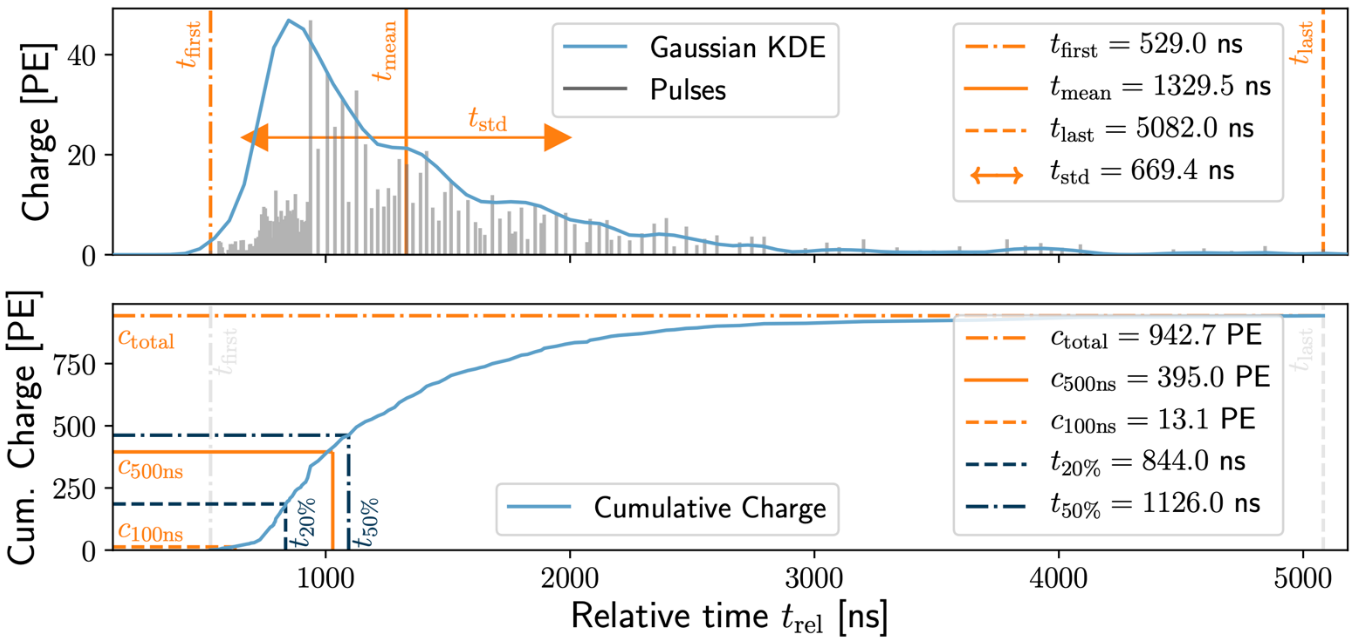
Input data per DOM

10.1088/1748-0221/16/07/P07041



3 inputs

- c_{total}: Total charge
  - Sum of charge
- t_{first}: Relative time of first pulse
  - Relative to total time offset, calculated as the charge weighted mean time of all pulses
- t_{std}: Standard deviation of first pulse
  - Charge weighted standard deviation of pulse times relative to total time offset

9 inputs

- t_{last}: Relative time of last pulse
  - Relative to total time offset, calculated as the charge weighted mean time of all pulses
- $t_{20\%}$: Relative time of 20% charge
  - Relative to total time offset, calculated as the charge weighted mean time of all pulses
- $t_{50\%}$: Relative time of 50% charge
  - Relative to total time offset, calculated as the charge weighted mean time of all pulses
- t_{mean}: Mean time
  - Charge weighted mean time of all pulses relative to total time offset
- c_{500ns}: Charge at 500ns
  - Sum of charge after 500ns
- c_{100ns}: Charge at 100ns
  - Sum of charge after 100ns

Input pulses

- SplitInIceDSTPulses
- SplitInIceDSTPulsesTWCleaning6000ns
- (DNN framework performs an internal cleaning)

Training datasets

- 20904
- 21962
- 22020
- 22187

Reconstructed properties

Energy

- ❑ entry_energy: Leading muon energy at the detector entry
- ❑ bundle_energy_at_entry: Muon bundle energy at the detector entry
- ❑ muon_energy_first_mctree: Leading muon energy at surface
- ❑ bundle_energy_in_mctree: Muon bundle energy at surface

Network 1

Network 0: Muon bundle energy at surface (fast pre-cut)

Track geometry

- ❑ Length: Propagation length of muon in the ice
- ❑ LengthInDetector: Propagation length of muon in the detector
- ❑ center_pos_x: Closest x position of muon to center of the detector
- ❑ center_pos_y: Closest y position of muon to center of the detector
- ❑ center_pos_z: Closest z position of muon to center of the detector
- ❑ center_pos_t: Time of closest approach to the center of the detector
- ❑ entry_pos_x: x position of muon at the detector entry
- ❑ entry_pos_y: y position of muon at the detector entry
- ❑ entry_pos_z: z position of muon at the detector entry
- ❑ entry_pos_t: Time of muon at the detector entry

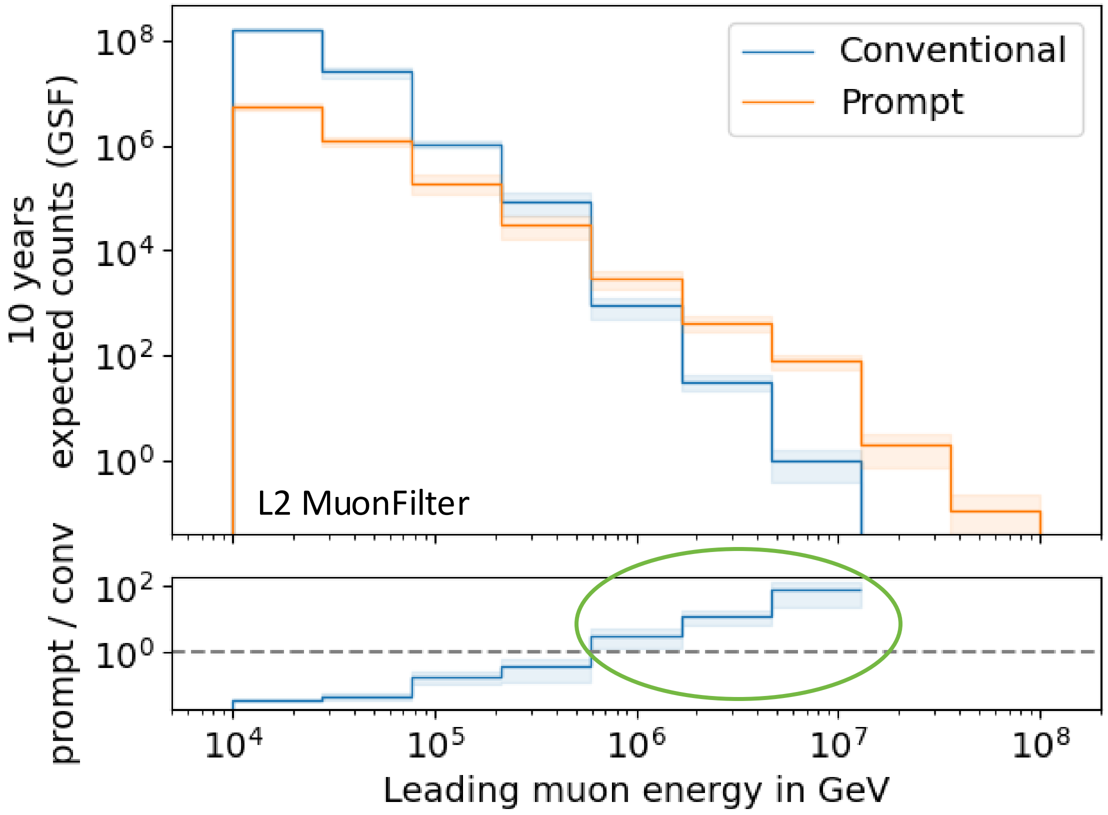
Network 2

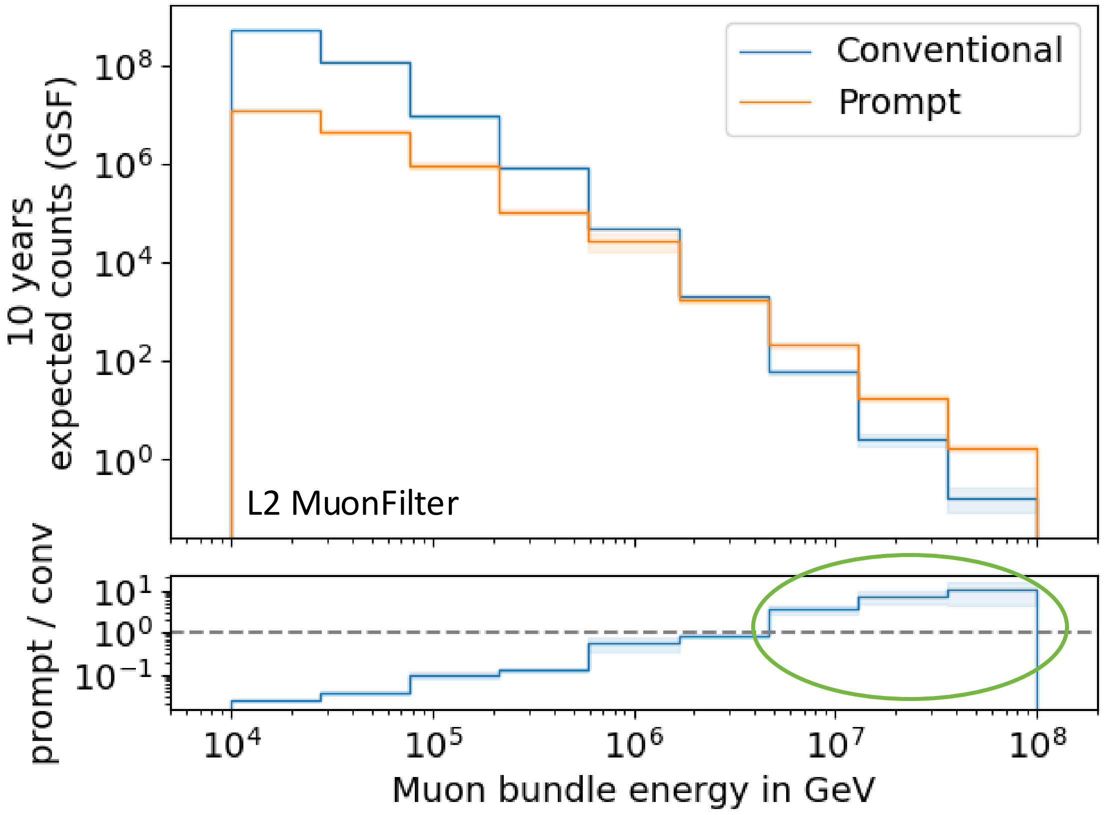
Direction

- ❑ zenith: Zenith angle of muon
- ❑ azimuth: Azimuth angle of muon

Network 3

Expected Muons For 10 Years: Leading vs. Bundle Energy (GSF)

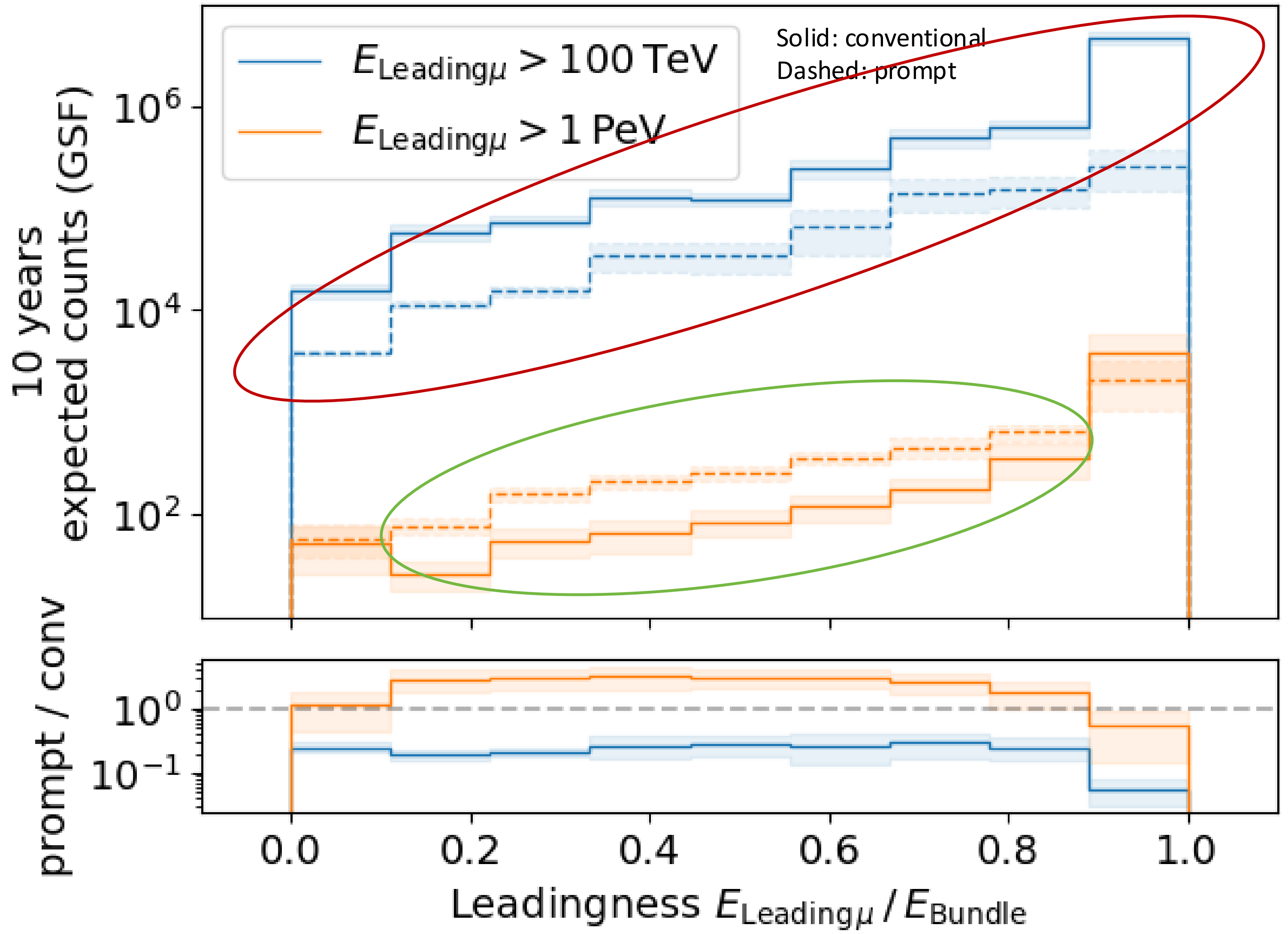




- Both leading and bundle energy are sensitive to detect prompt
- Leading muon energy is more sensitive

Leading Muon Energy Fraction

- ➢ Prompt dominates for energies > 1 PeV
- ➢ Leading energy sweet spot: 0.1 – 0.9



Leading Muon Contribution

Patrick Berghaus

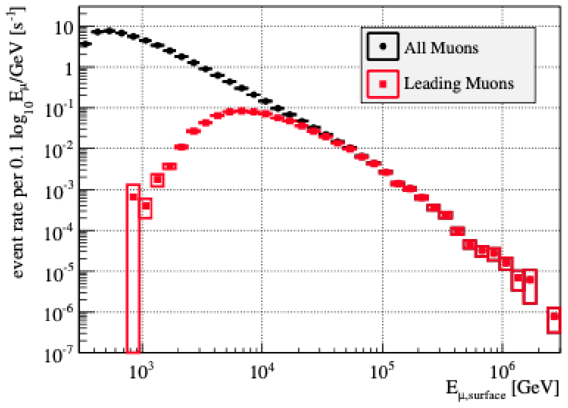
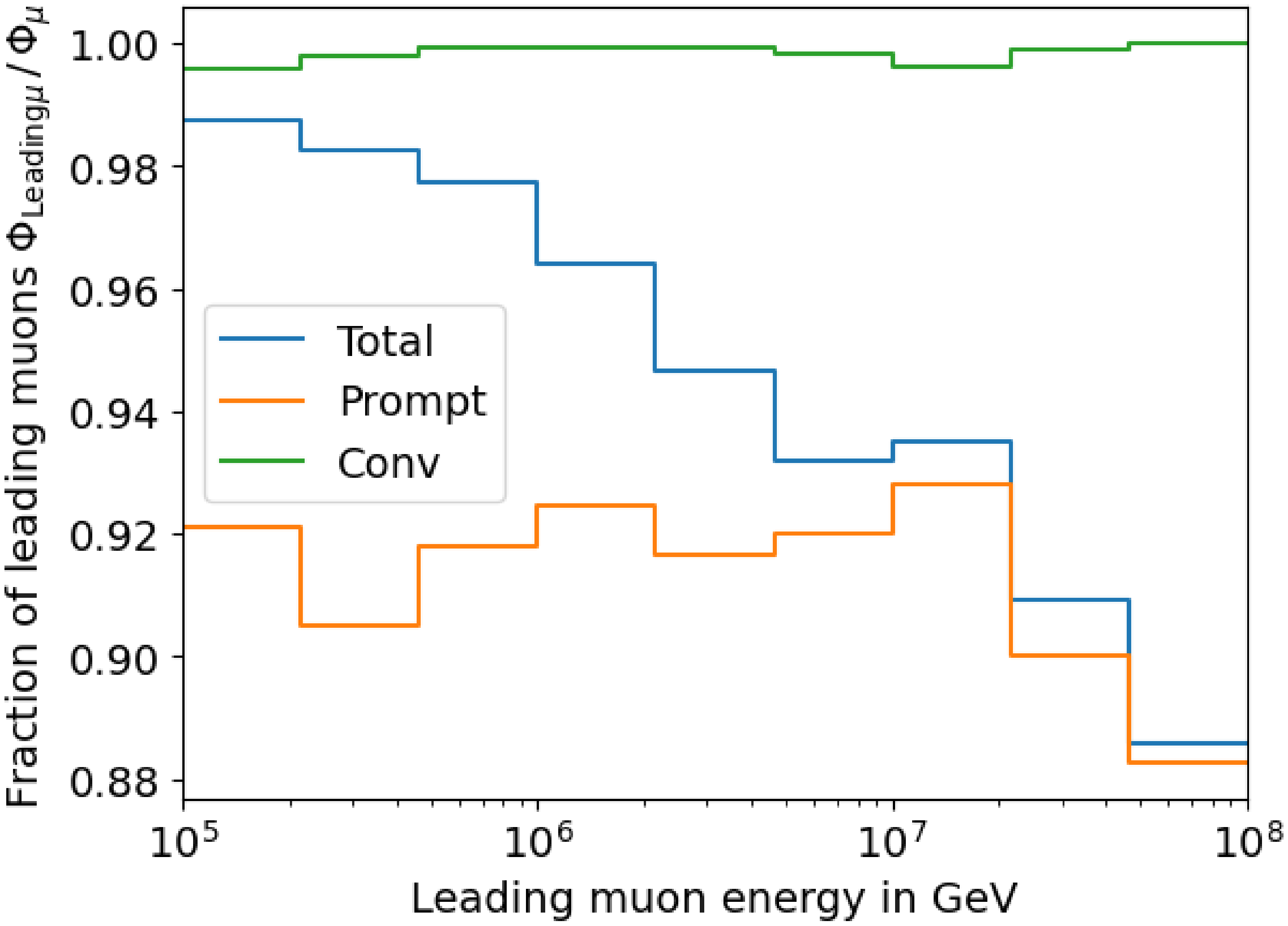


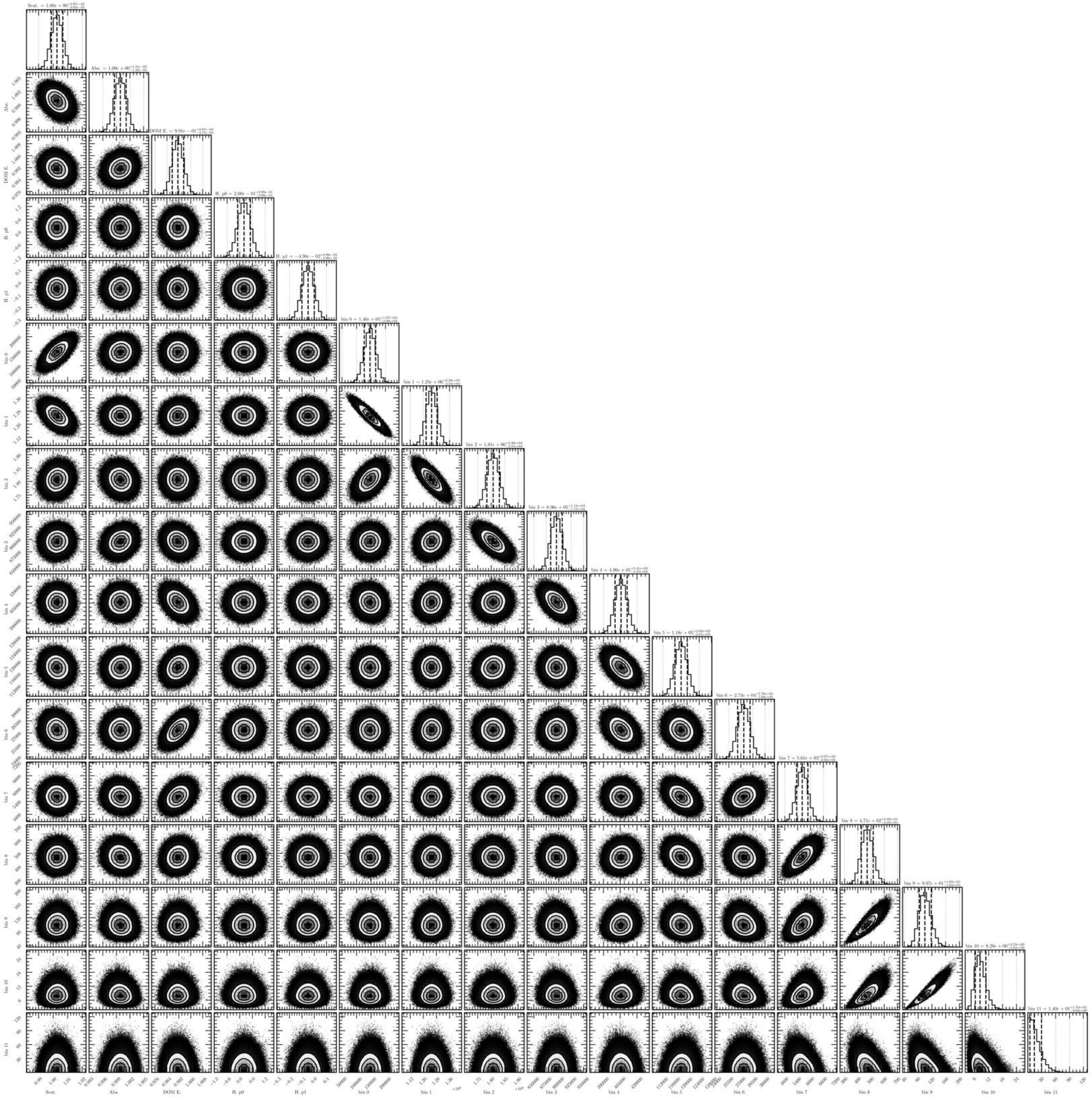
Figure 10: Surface energy distribution for all and most energetic ("leading") muons in simulated events with a total of more than 1,000 registered photo-electrons in IceCube.



- Muons with energies between 100 TeV and 50 PeV dominate the bundle by more than 90%
- In average conventional muons are more dominant than prompt
- But: at high energies, there are more prompt than conventional events

➢ High leading energy fraction does not lead to more sensitivity to detect prompt

Tau = 0.001



Unfolded Muon Flux at Surface