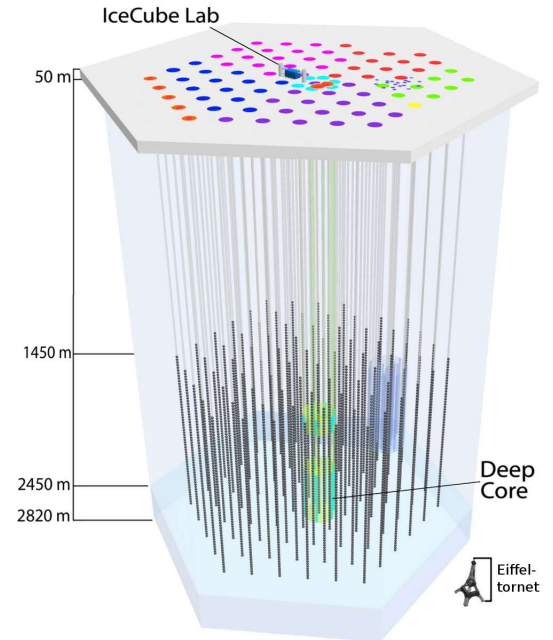
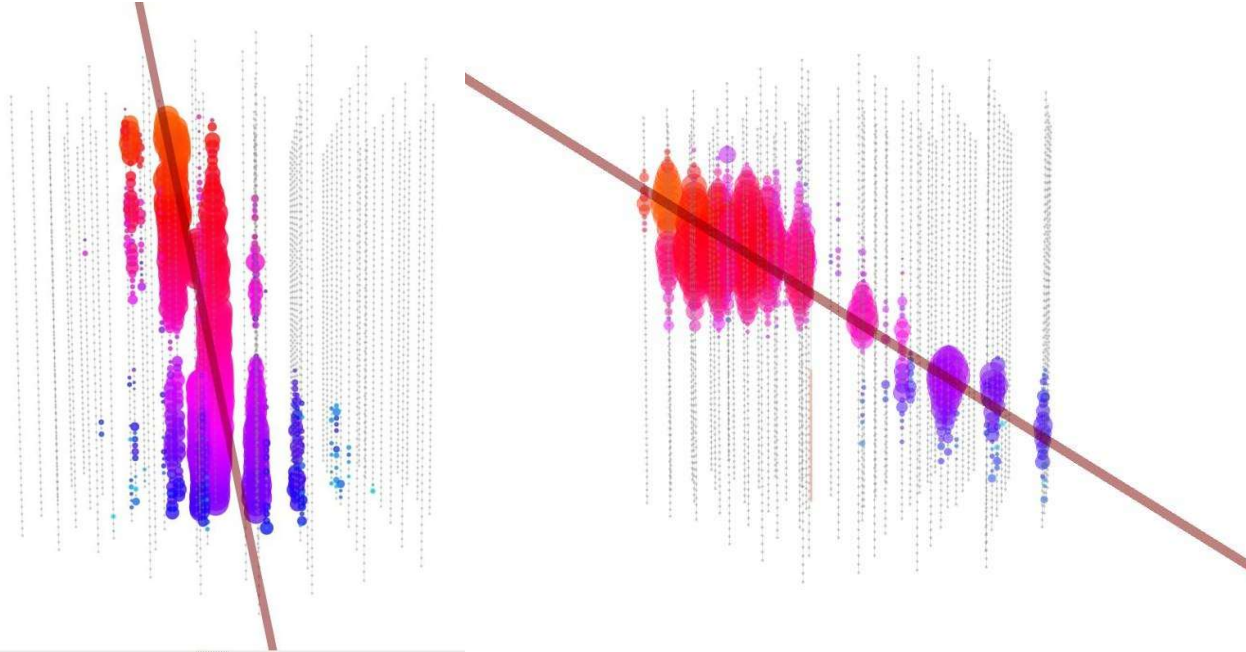


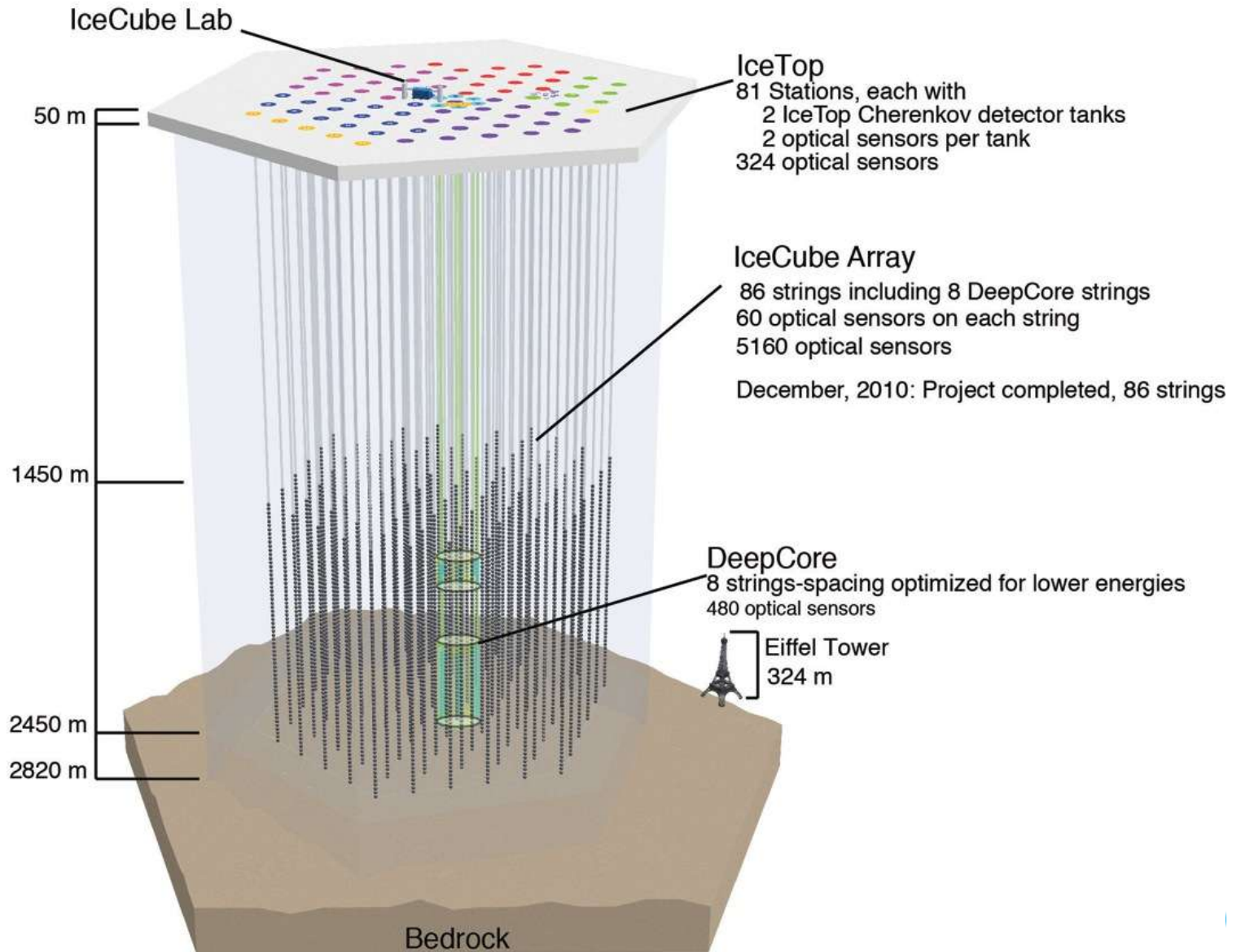
Detecting Prompt Muons with IceCube.



Hans-Peter Bretz
DESY Zeuthen

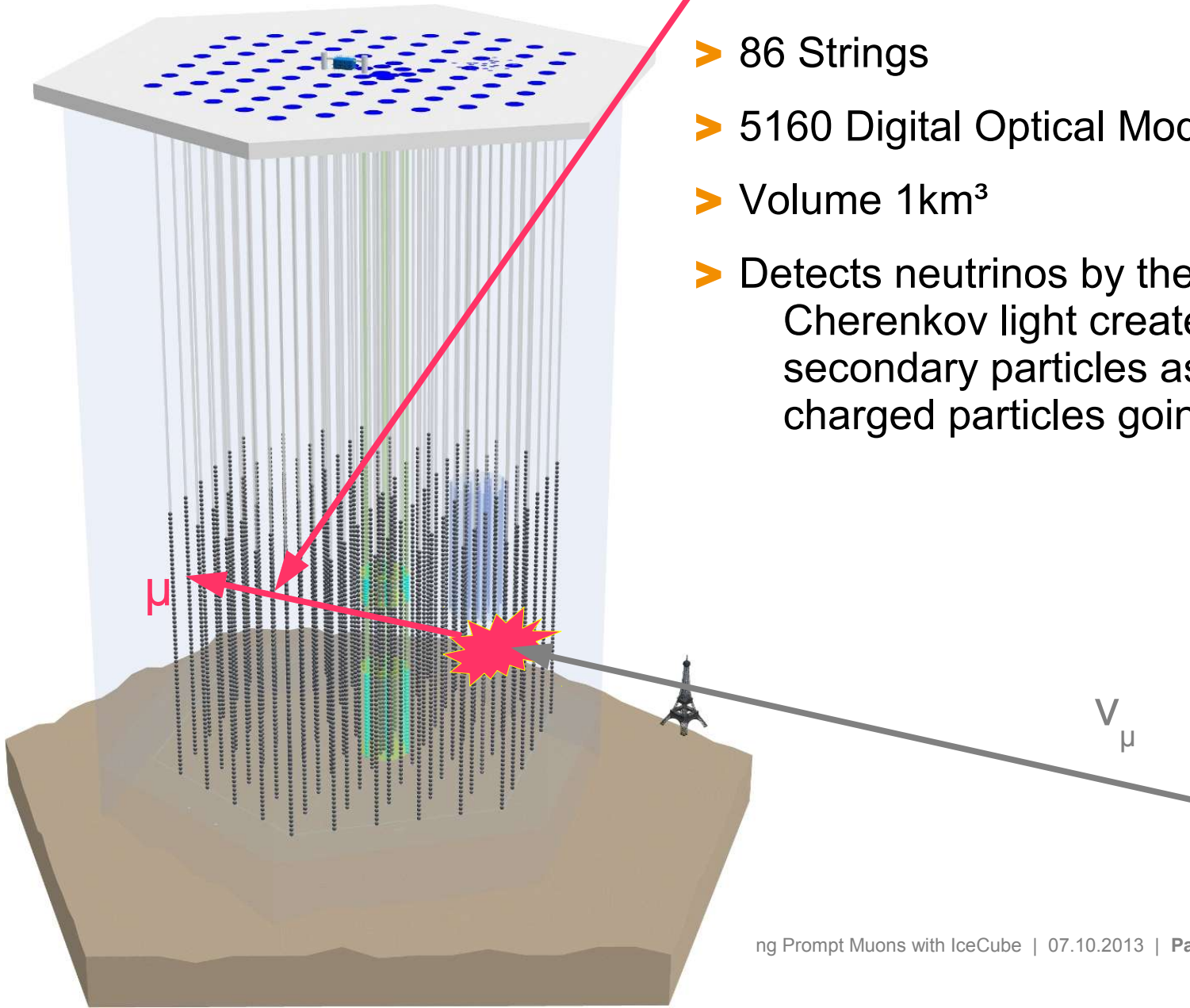
Detecting Prompt Muons with IceCube
Schule für Astroteilchenphysik 2013,
7.10.2013

IceCube Neutrino Telescope



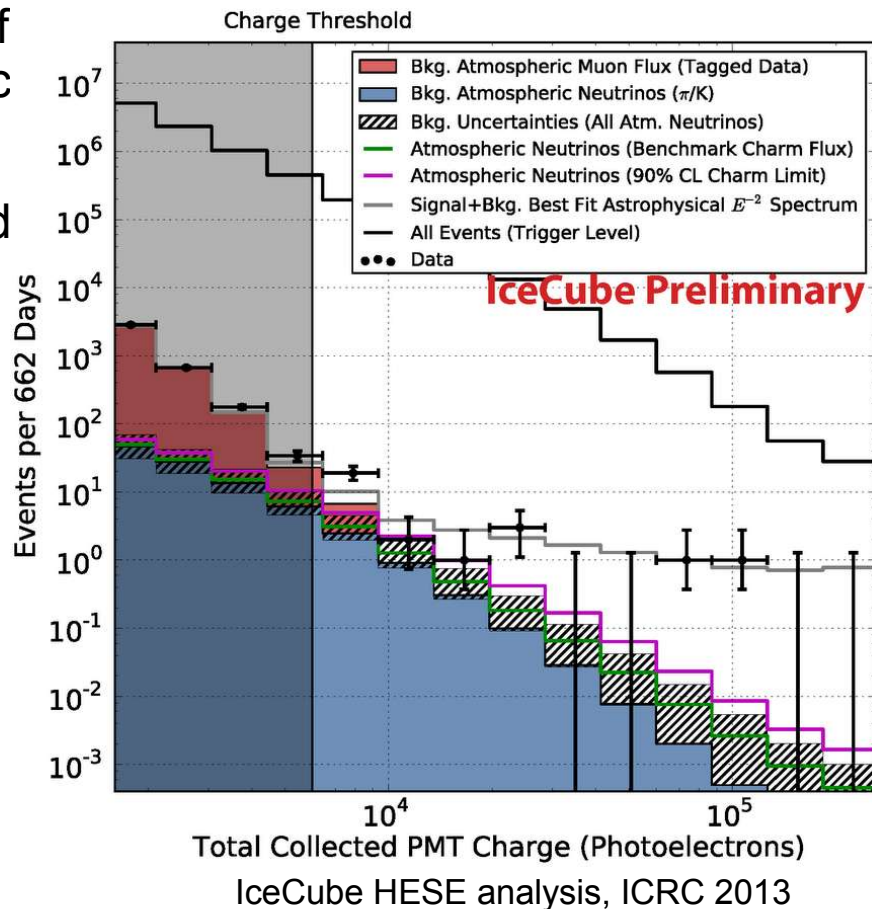
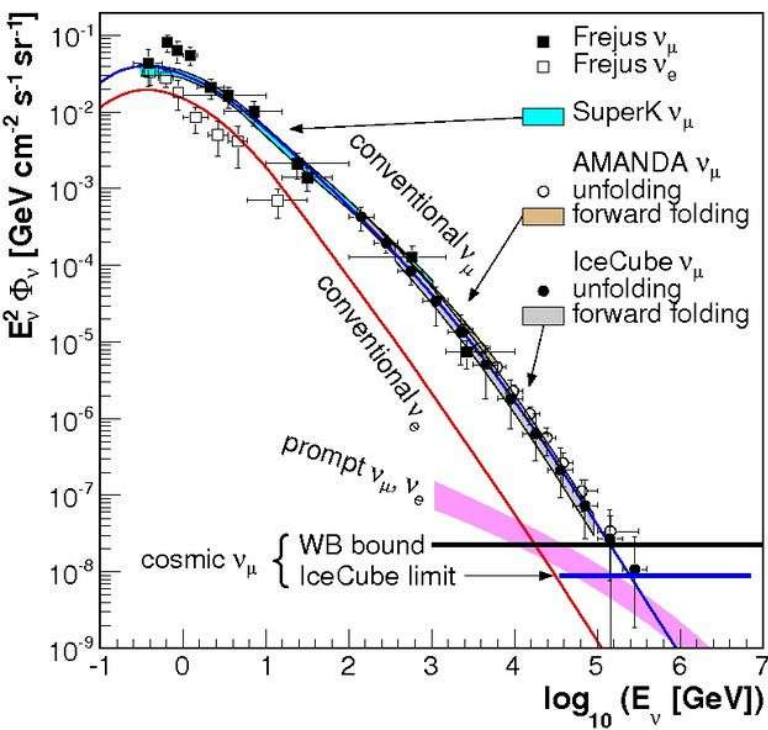
IceCube Neutrino Telescope

- 86 Strings
- 5160 Digital Optical Modules
- Volume 1km³
- Detects neutrinos by the Cherenkov light created by their secondary particles as well as charged particles going through



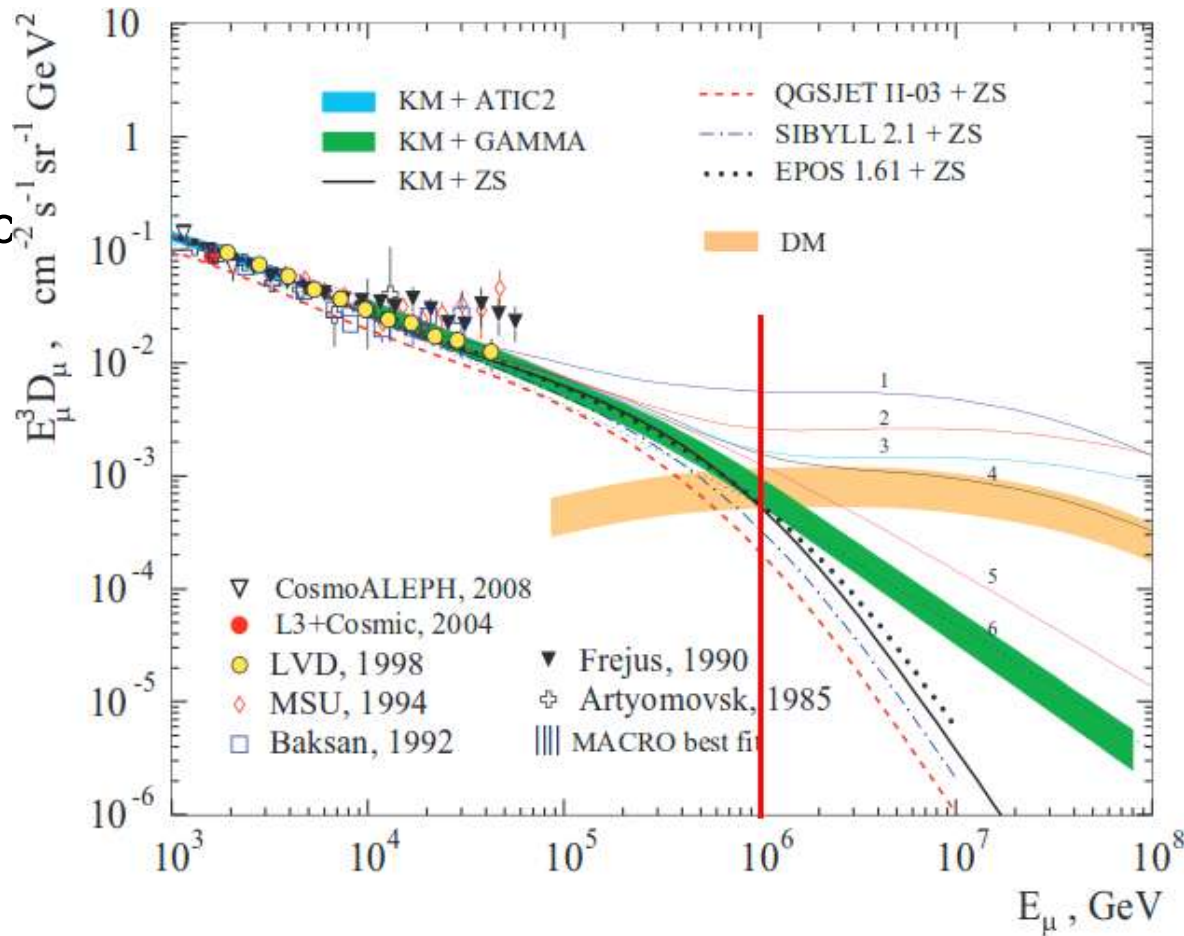
Prompt Muons in IceCube Analyses

- Diffuse neutrino searches look for flux of neutrinos from galactic and extragalactic sources
- Atmospheric neutrinos main background
- Astrophysical flux expected to dominate at high energies
- Prompt flux is background for high energies



Atmospheric Muons

- Muons from cosmic ray induced air showers
- Allow to investigate cosmic ray flux and nucleon flux
- High uncertainty in model predictions
- Aim to extend range to 1PeV

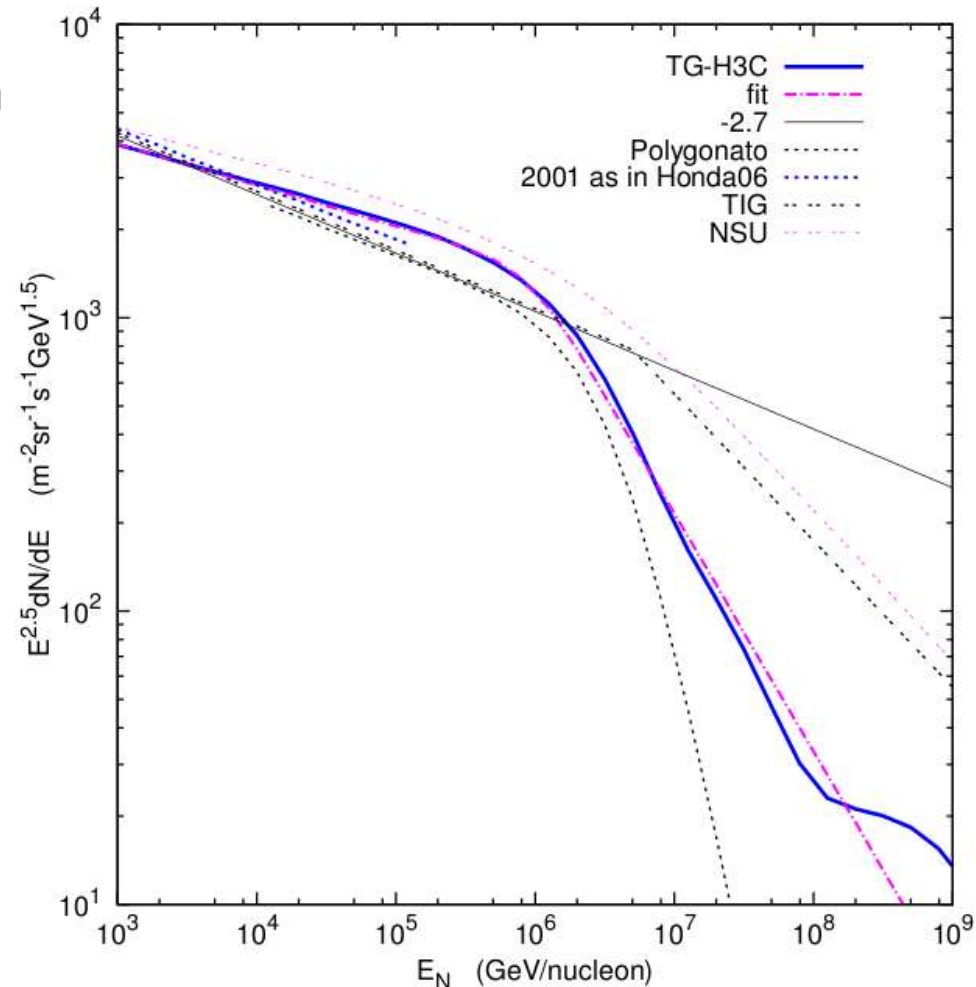


Sinegovsky et al. arXiv:0906.3791



Prompt Muons

- Conventional muons from pions and kaons which can re-interact in the atmosphere before decaying
- Additional prompt flux from charmed mesons that decay before the first interaction
- Harder spectrum for prompt muons
- Muon flux depends on nucleon flux, correct shape of knee is important

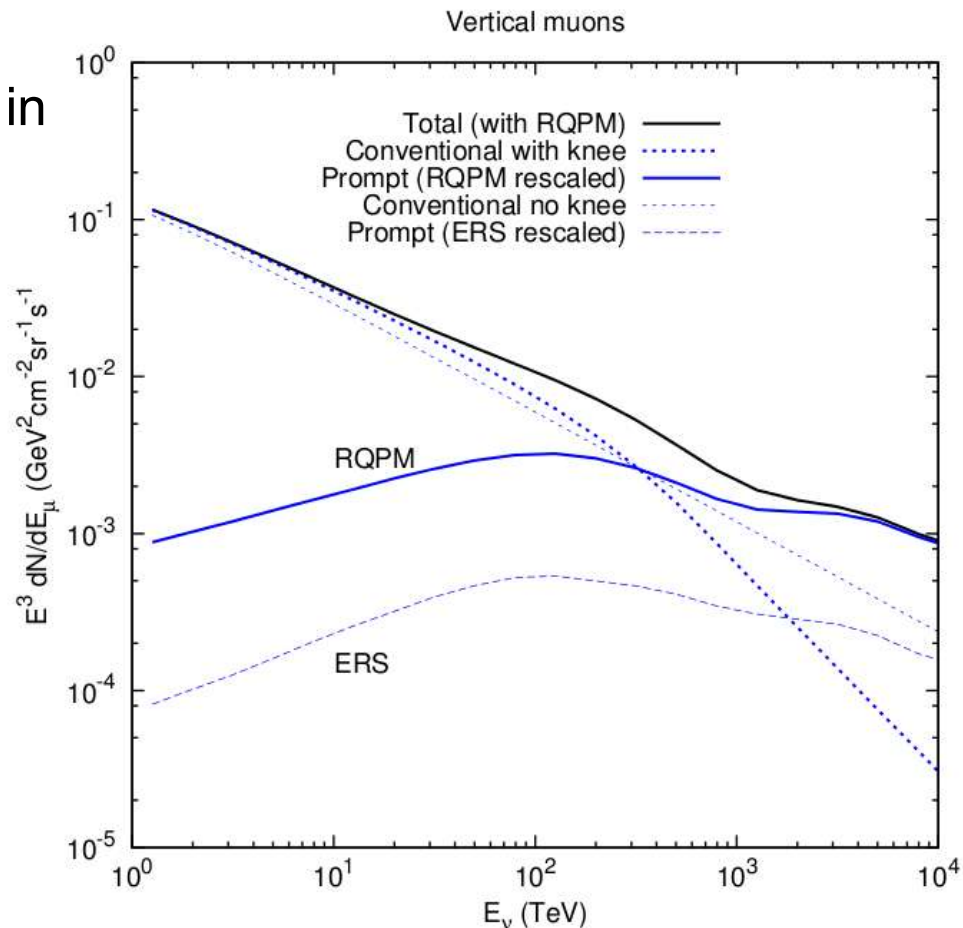


Tom Gaisser: arXiv:1303.1431



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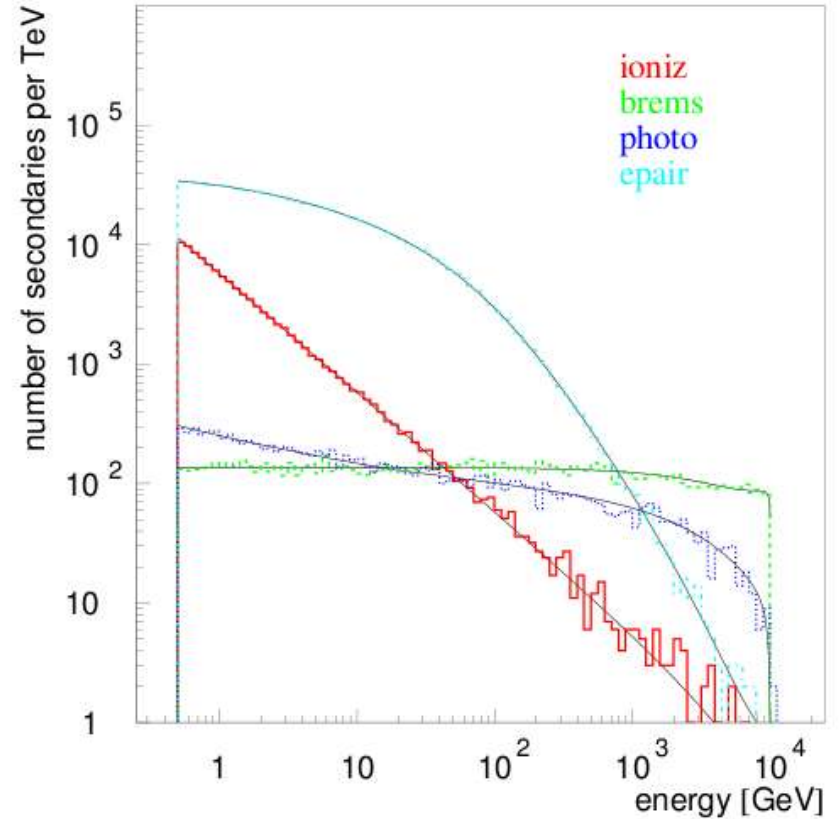
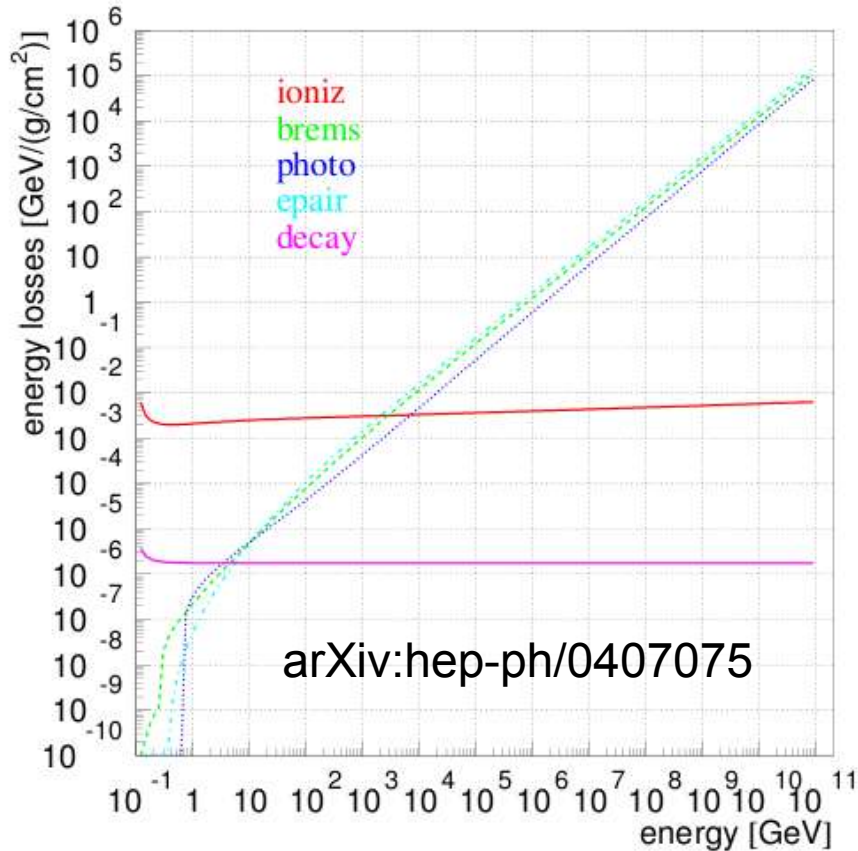


Tom Gaisser: arXiv:1303.1431

ERS-model, Enberg et al, arXiv:0806.0418



Muon Energy Losses



- For high energies, proportional energy loss becomes dominant

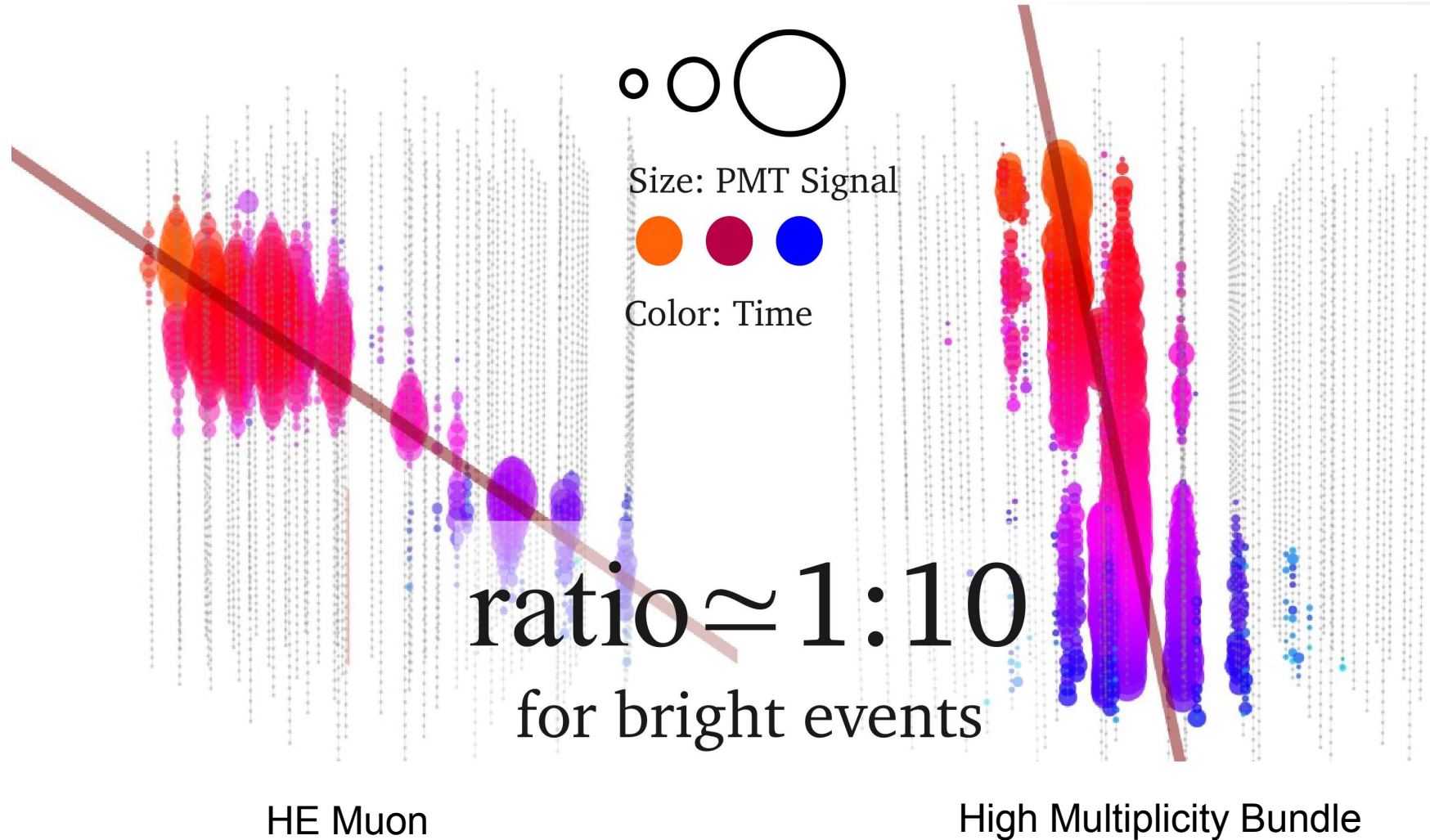
$$dE/dX = a + bE$$

$$a = 0.268 \text{ GeV/mwe}$$

$$b = 0.470 \cdot 10^{-3} \text{ mwe}^{-1}$$

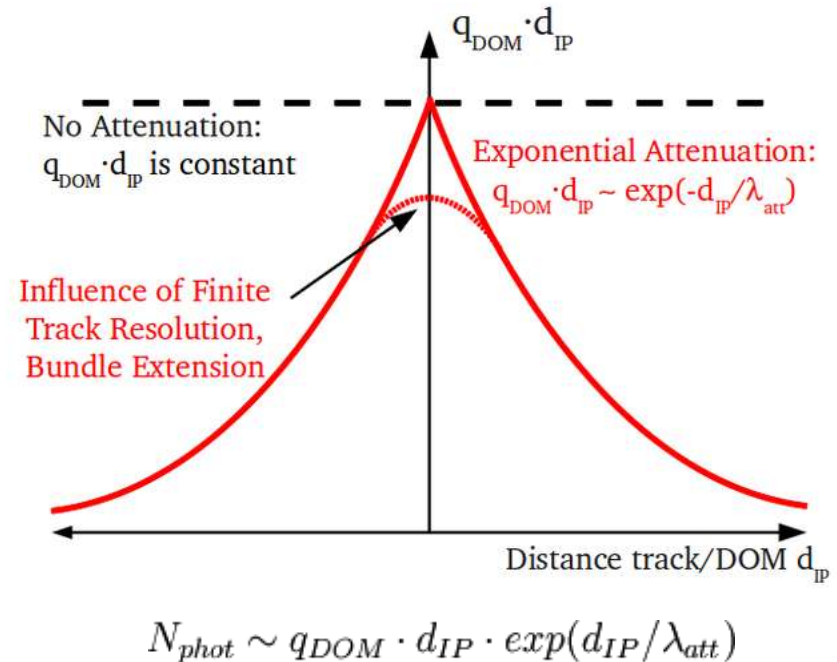


Muon Event types in IceCube

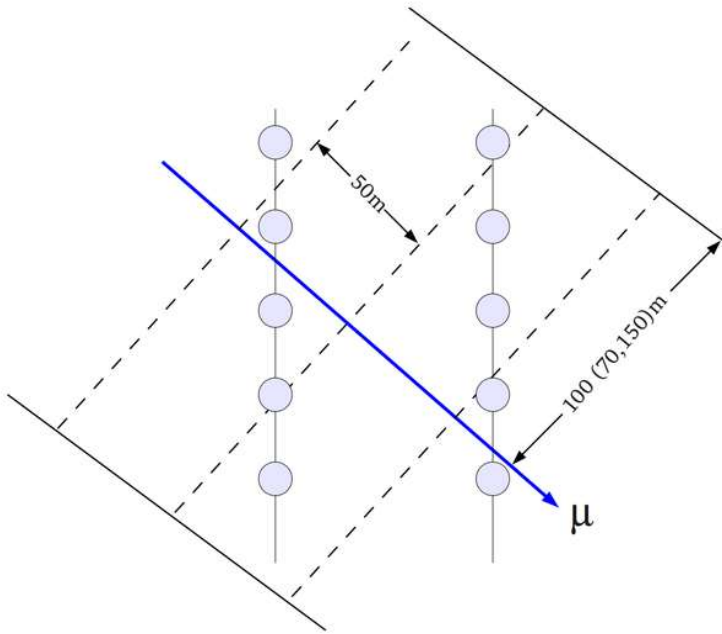


Energy Estimators for Muons/Muon Bundles

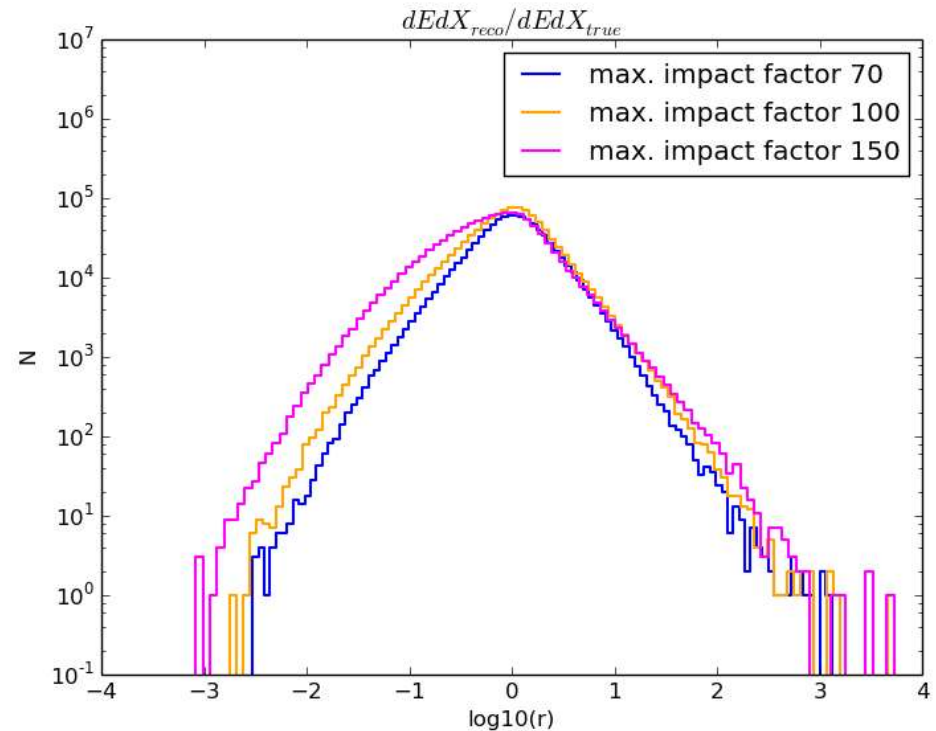
- MuEx, Millipede (detailed multi-dimensional likelihood reconstruction)
- DDDDR
 - Data-Derived Differential Deposition Reconstruction
 - Independent of ice model simulation
 - Conservative energy estimator
 - Derive light attenuation length in ice from fit to data



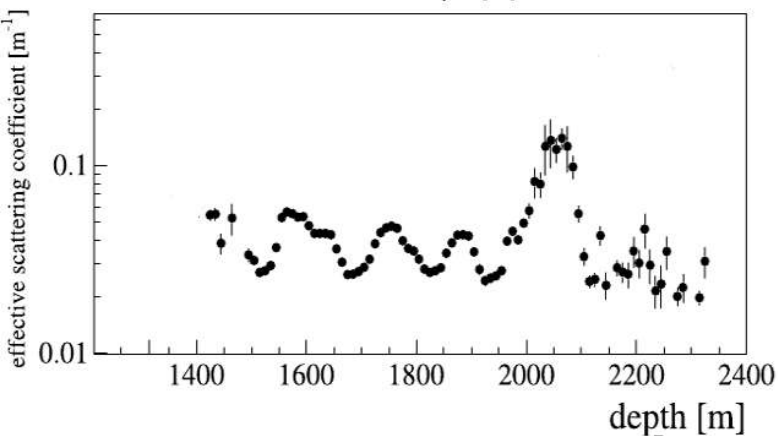
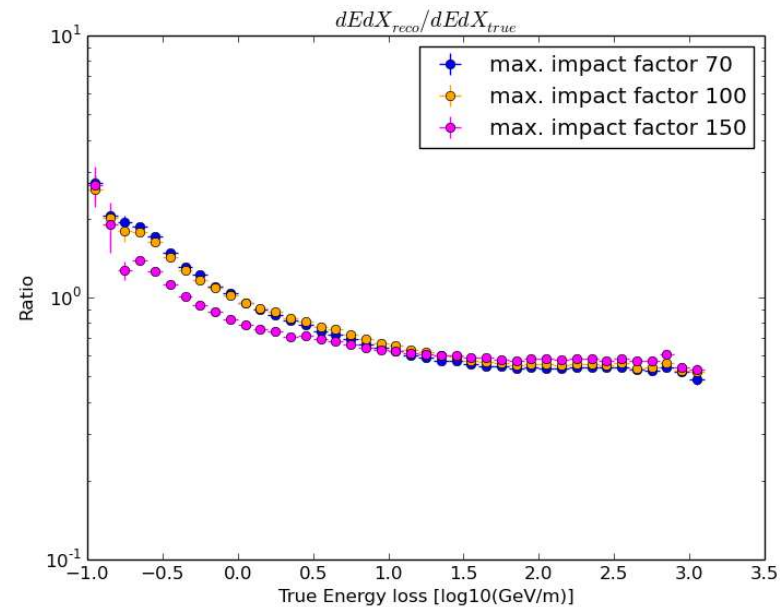
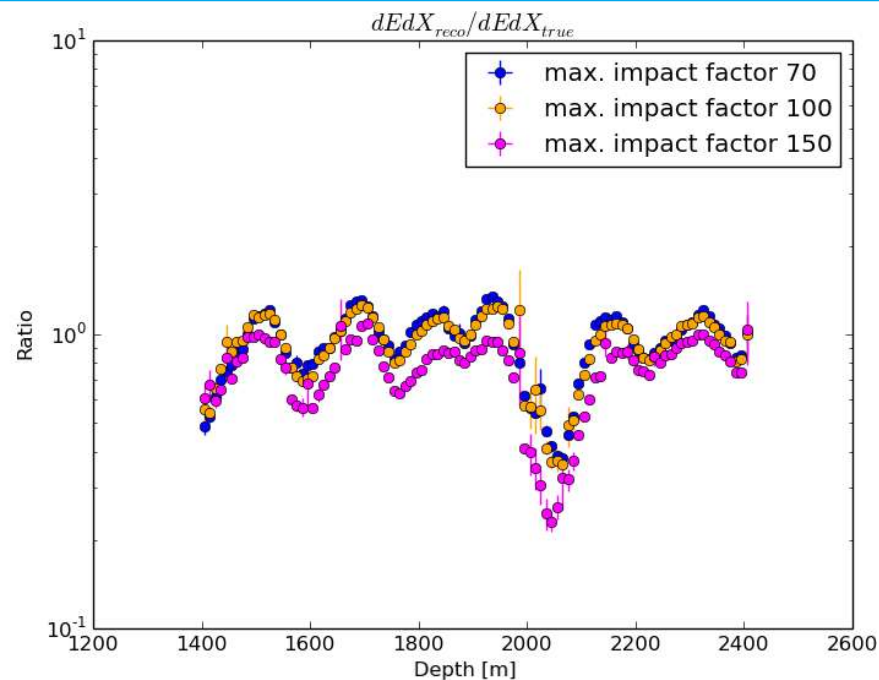
True Energy Loss vs. DDDDR



- Construction of energy loss parameter
- Energy loss for each individual DOM with max impact factor of 100 (70, 150)m
- Average over bins of 50m



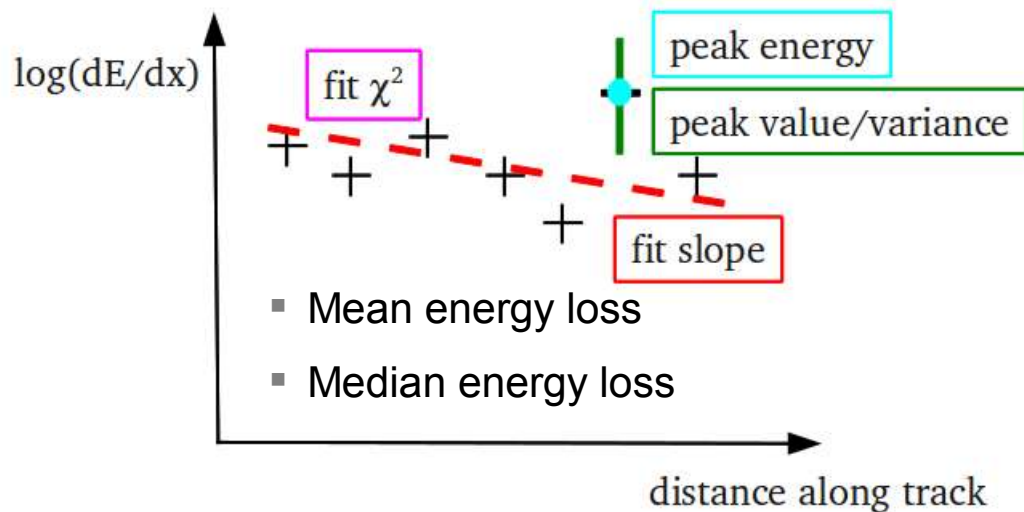
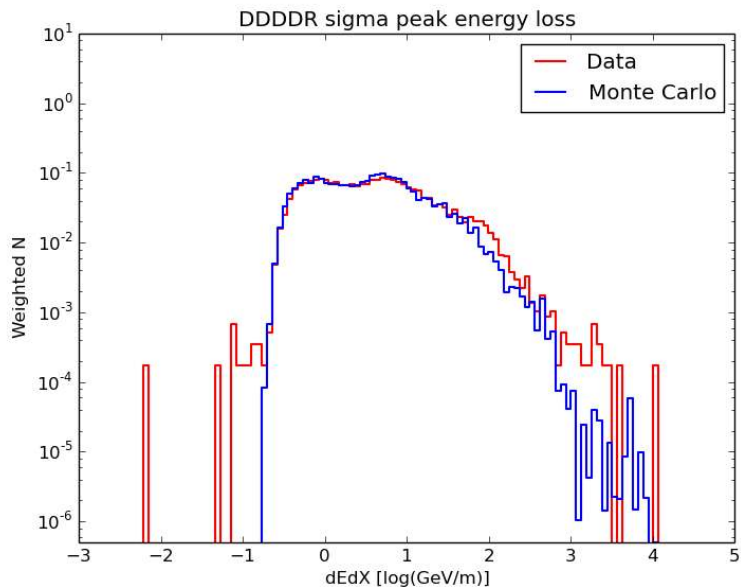
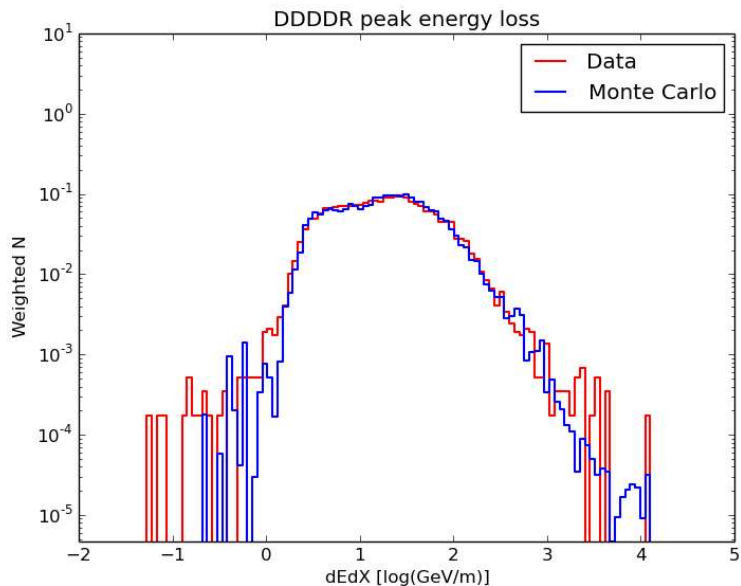
Reconstructed Energy Loss over True Energy Loss



- Ice in reconstruction is modeled with layers of different attenuation length
- Energy loss in dust peaks is underestimated
- Ratio vs. True energy loss

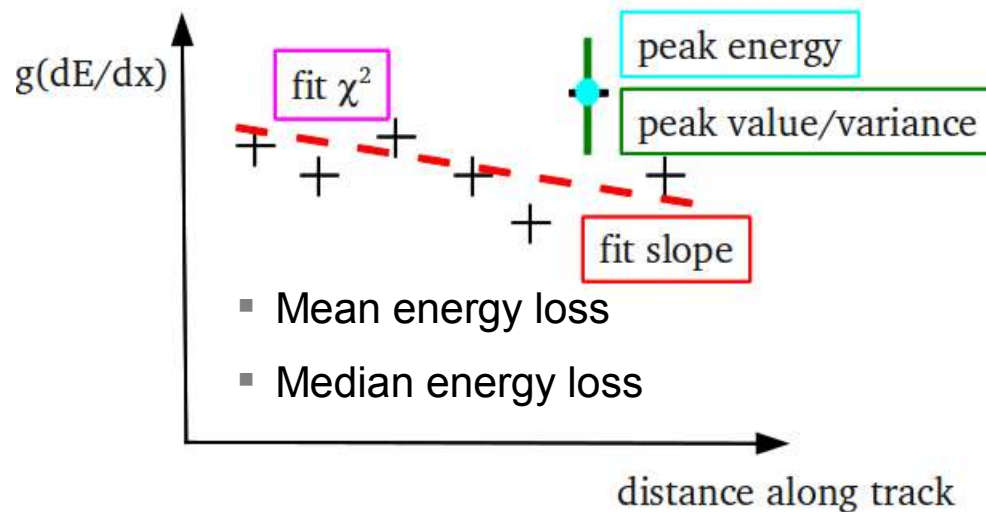
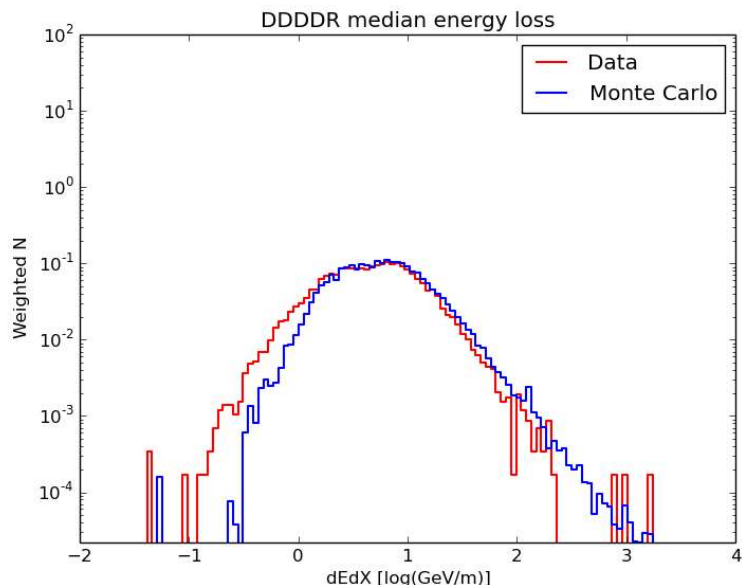
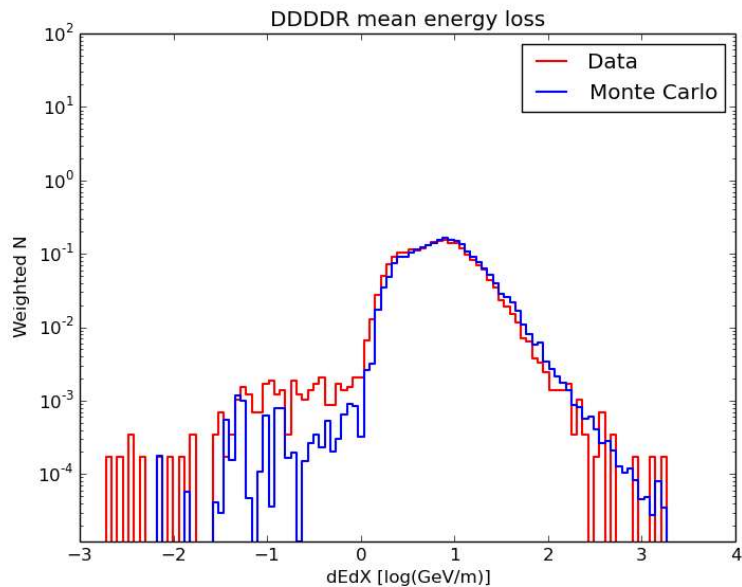


Monte Carlo Data Comparison



- Differential energy loss reconstruction parameters can be used to separate muon bundles from single muons
- Example comparisons for high energy sample

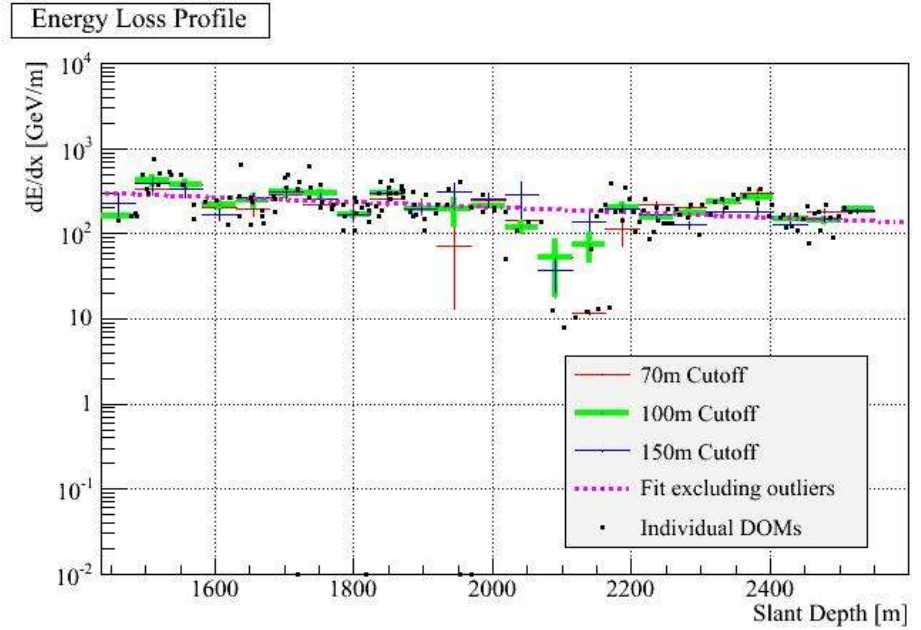
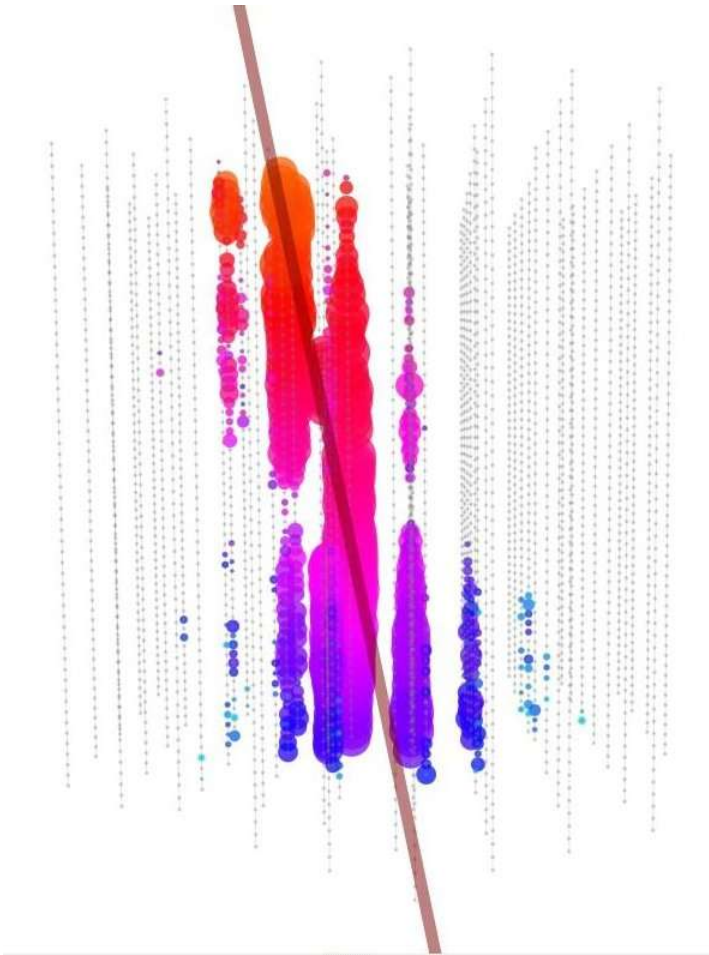
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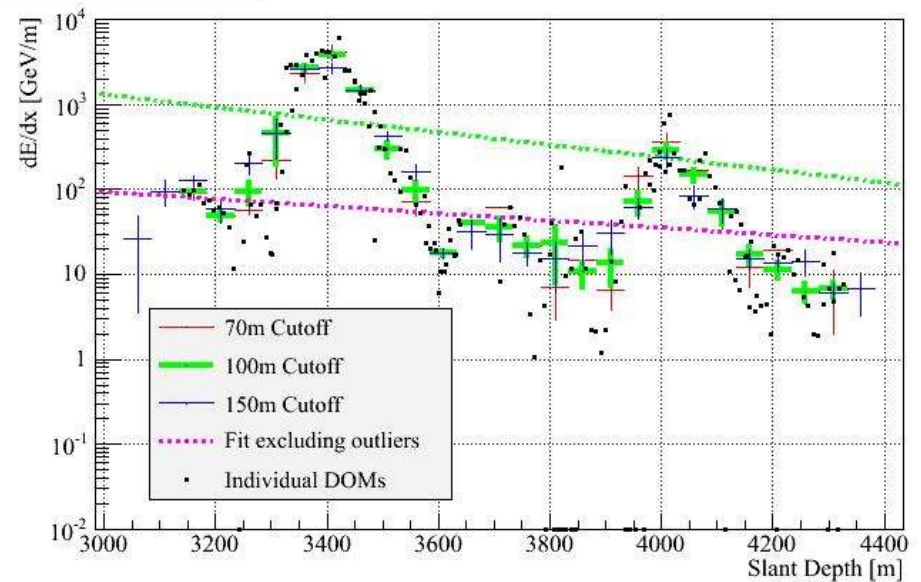
Muon Bundle



- Smooth energy loss profile
- Gradual slope

High Energy Muon

Energy Loss Profile



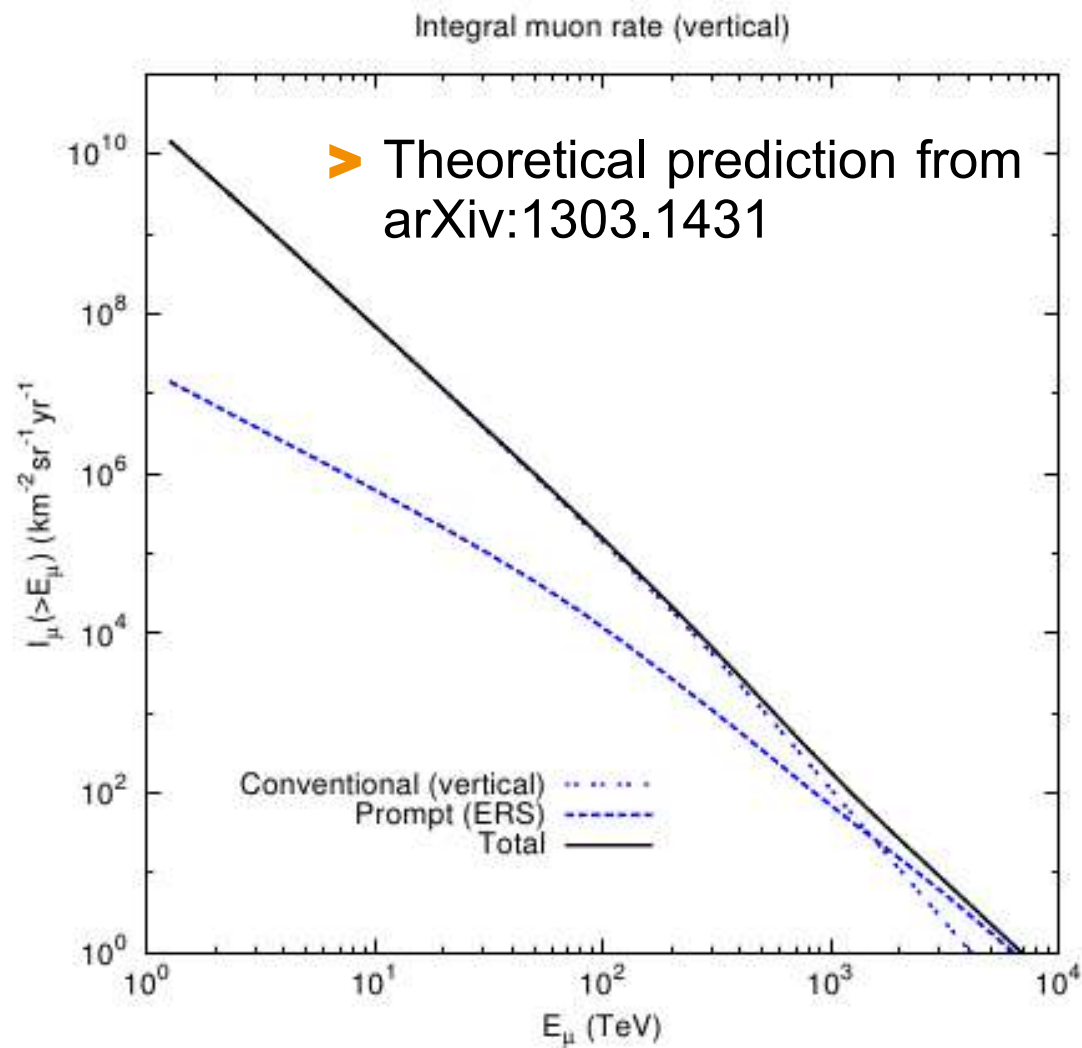
- Big stochastic losses
- Energy loss peaks can be used to distinguish high energy muons from muon bundles

Conclusion

- Prompt muon flux has not been measured so far
- Presented a method to separate high energy muons from high multiplicity muon bundles
- Biggest challenge are systematics
 - Detector
 - Cosmic ray spectrum



Vertical Muon Rate for a km³ detector



Peak Energy and Peak Sigma

