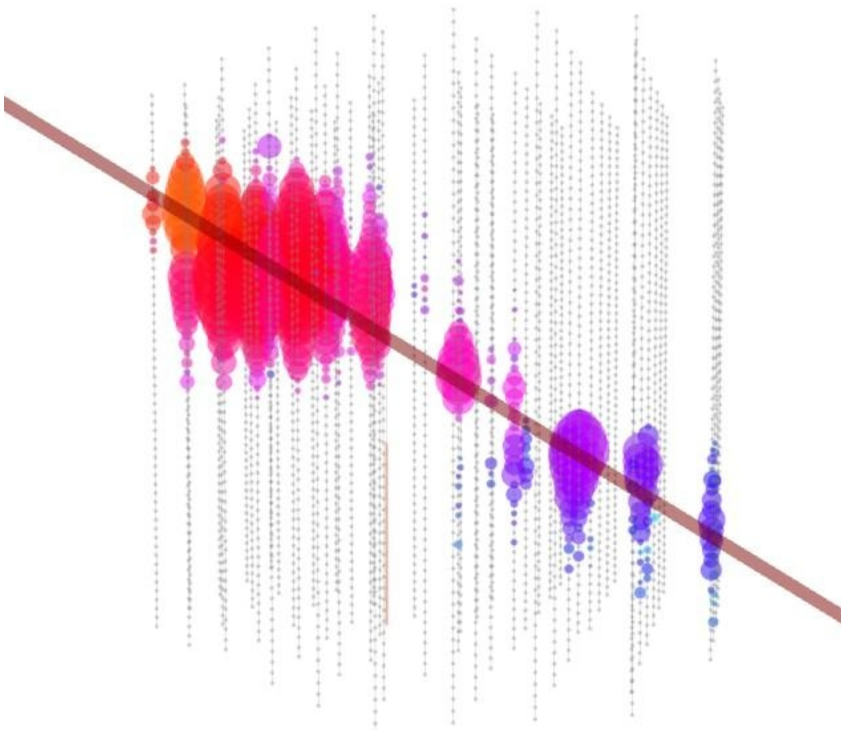
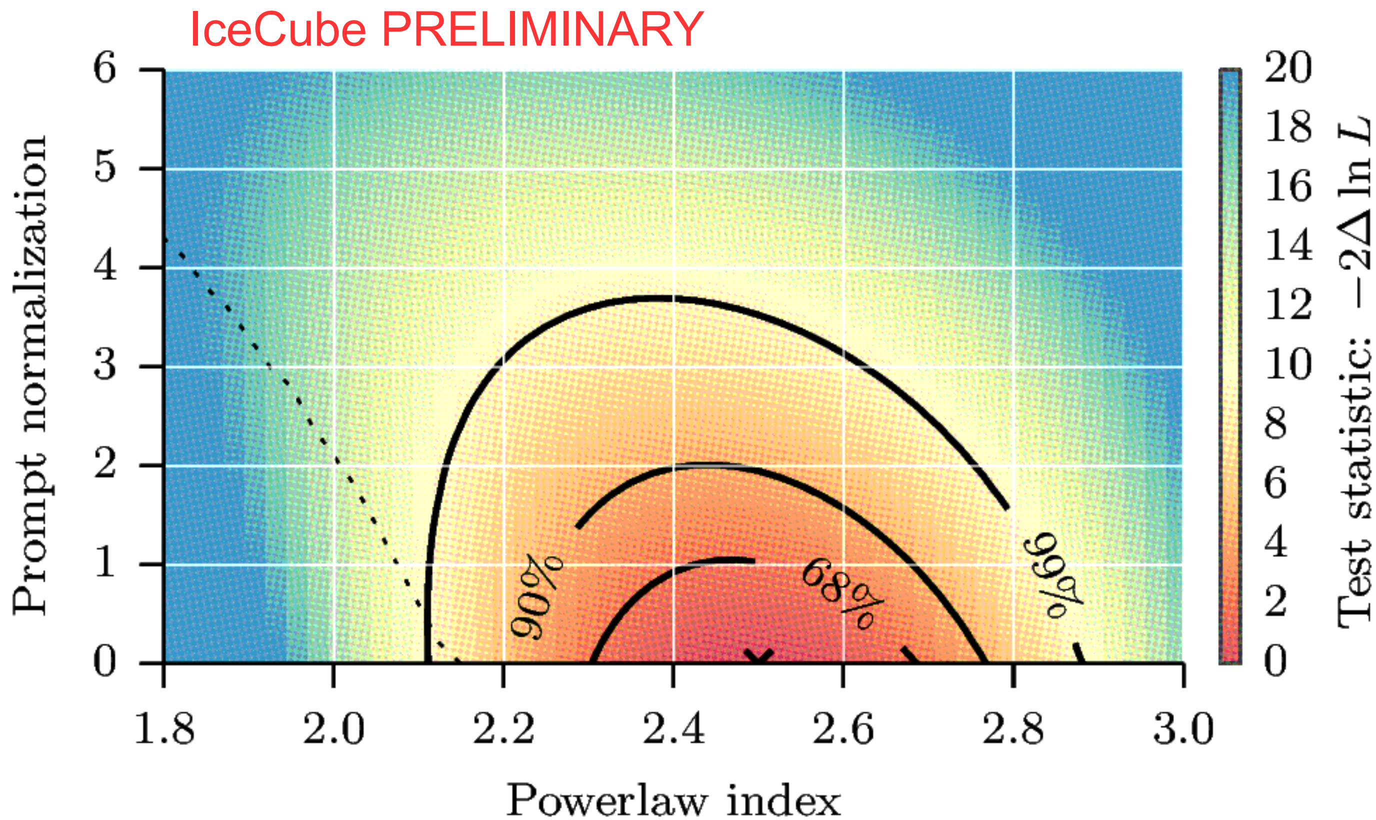
Charm with High Energy Muons in IceCube

Summary of Patrick Berghaus' Results



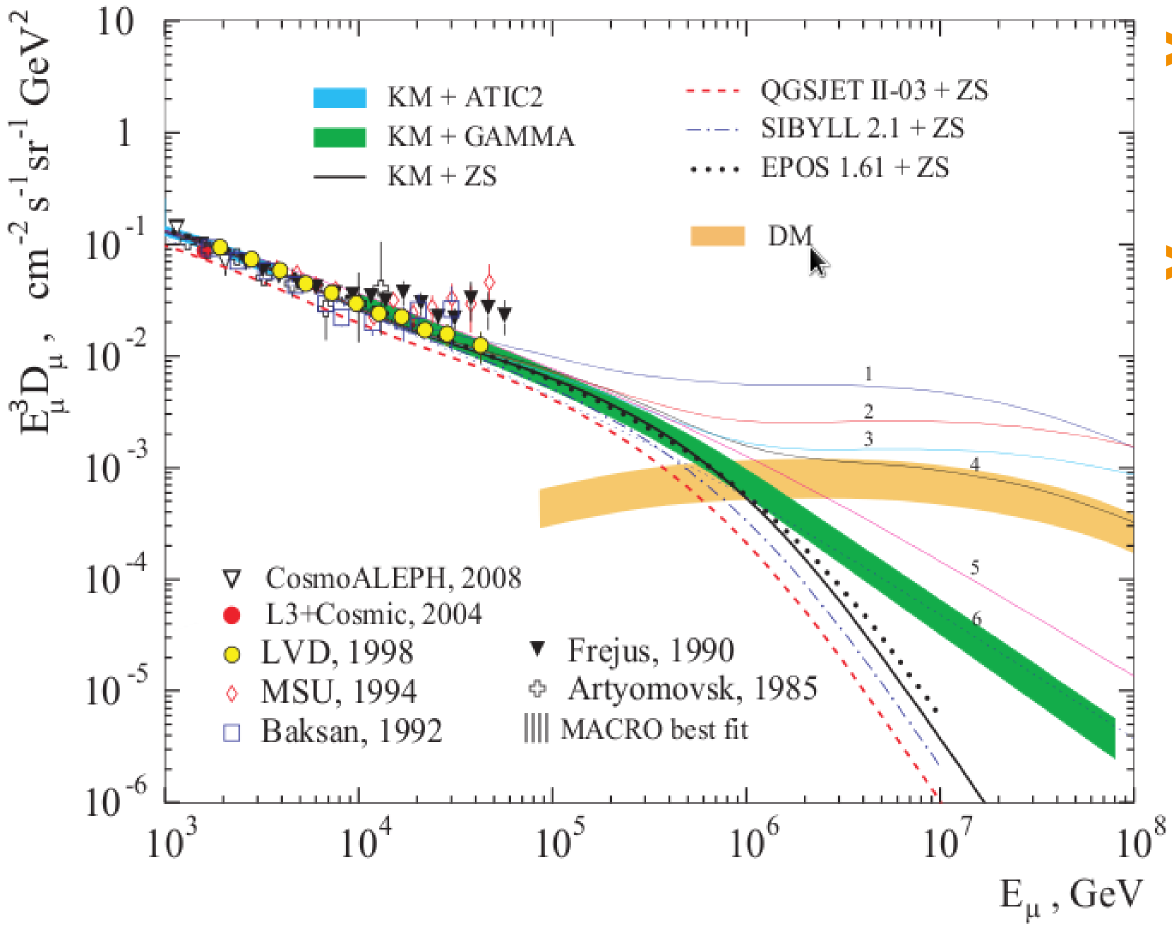
Hans-Peter Bretz, Patrick Berghaus
MANTS Meeting
Geneva, September 20, 2014

Charmed Leptons in IceCube Neutrino Analyses



- Prompt Neutrinos background at higher energies
- Best fit is zero charm component, upper limit of ~1.36 times prediction of Enberg model
- Higher charm component would favor harder astrophysical spectrum

Muon Spectrum

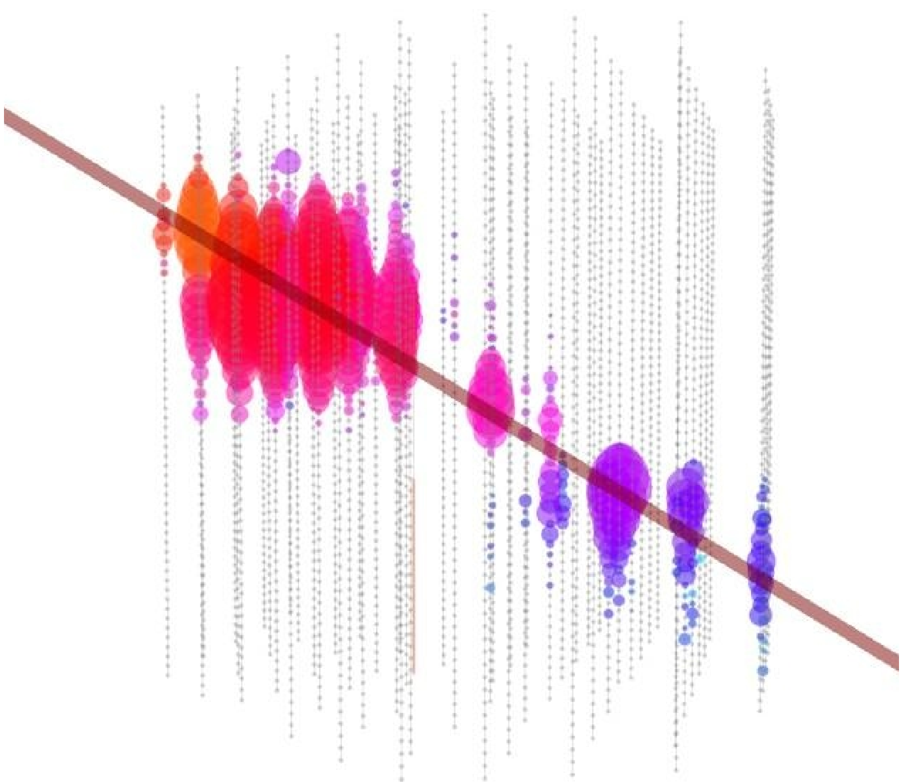


- Muon energy spectrum currently measured up to ~100 TeV
- Dipole Model (Enberg et al.) model used as benchmark in IceCube

1-4: different calculations for prompt flux
5-6: conventional flux for different primary cosmic ray flux models around knee

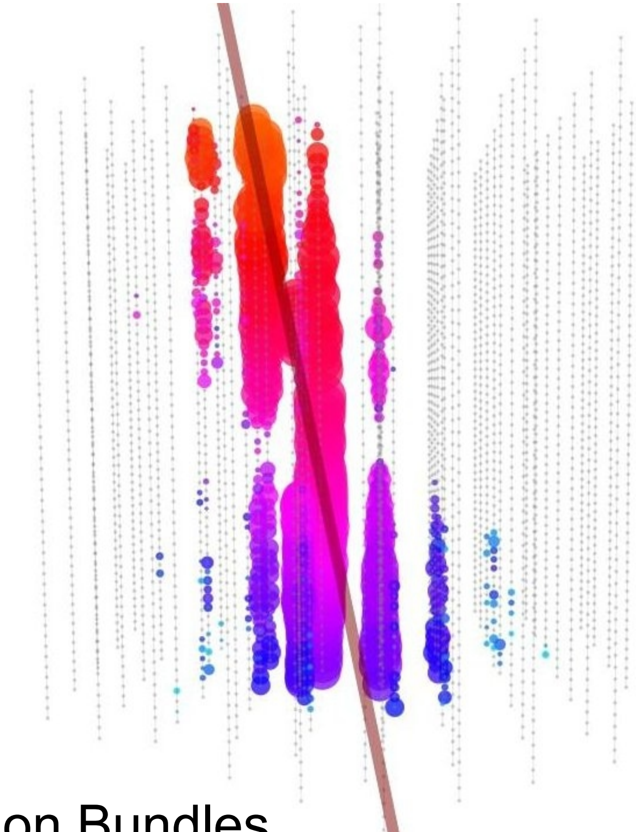
Sinegovsky et al. arXiv:0906.3791
Enberg et al. arXiv:0806.0418

Muons in IceCube



High Energy Muon

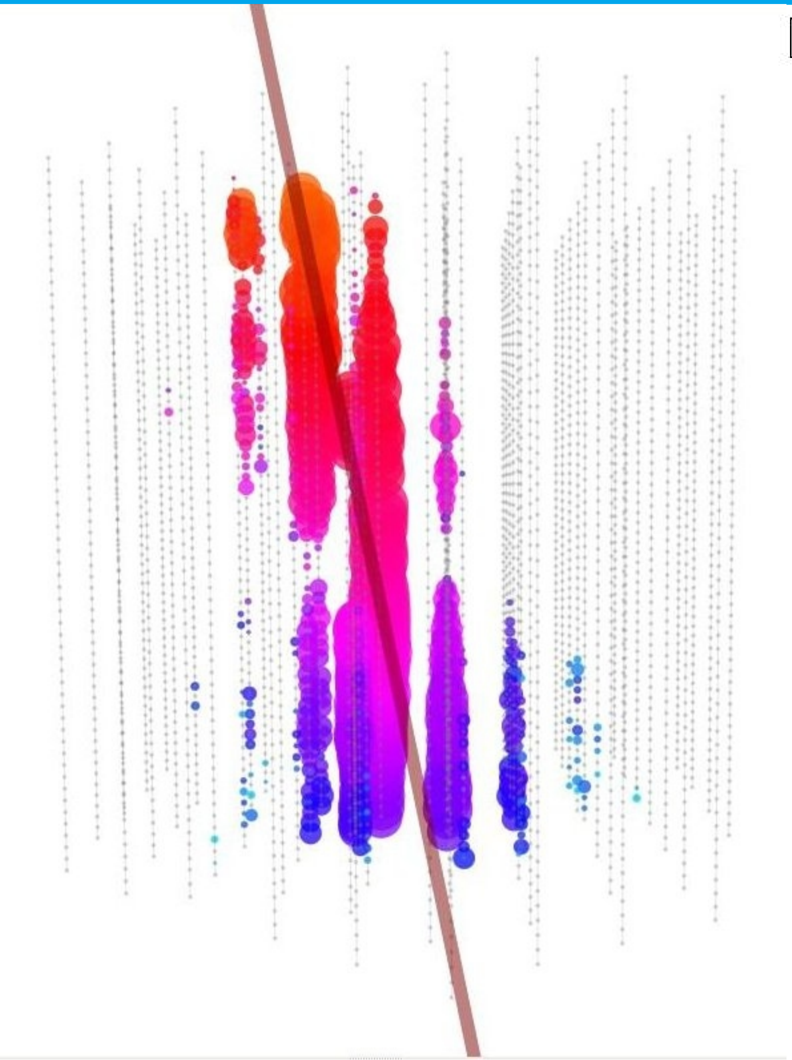
- Mostly from high energy protons
- Need to distinguish high energy muons from bundles for single muon spectrum

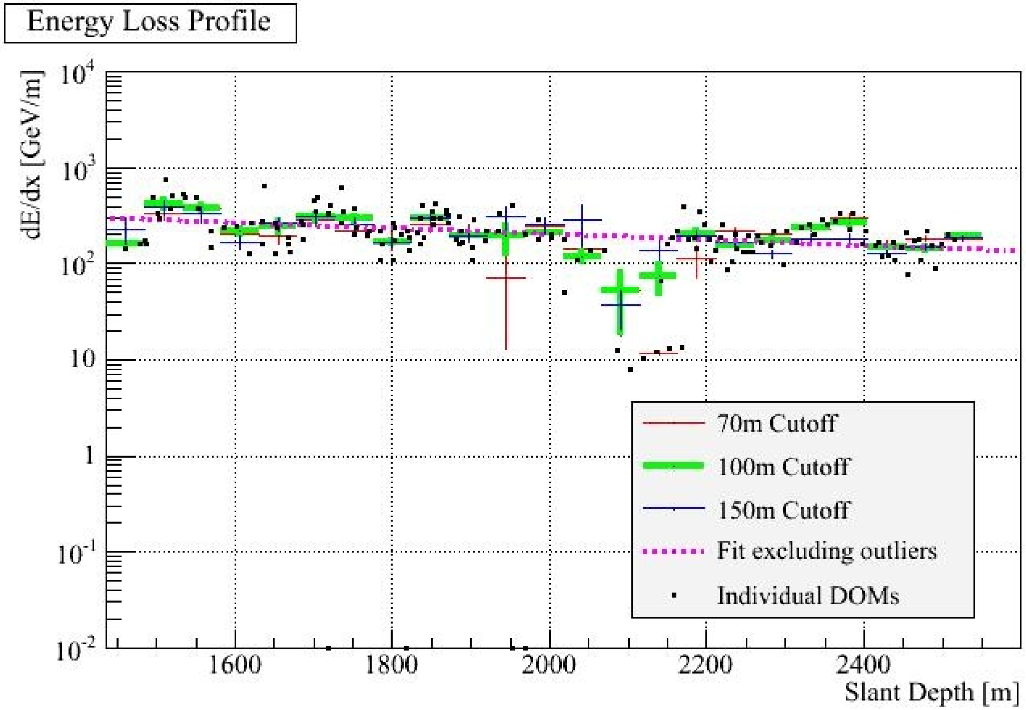


Muon Bundles

- Accounts for majority of bright muon events

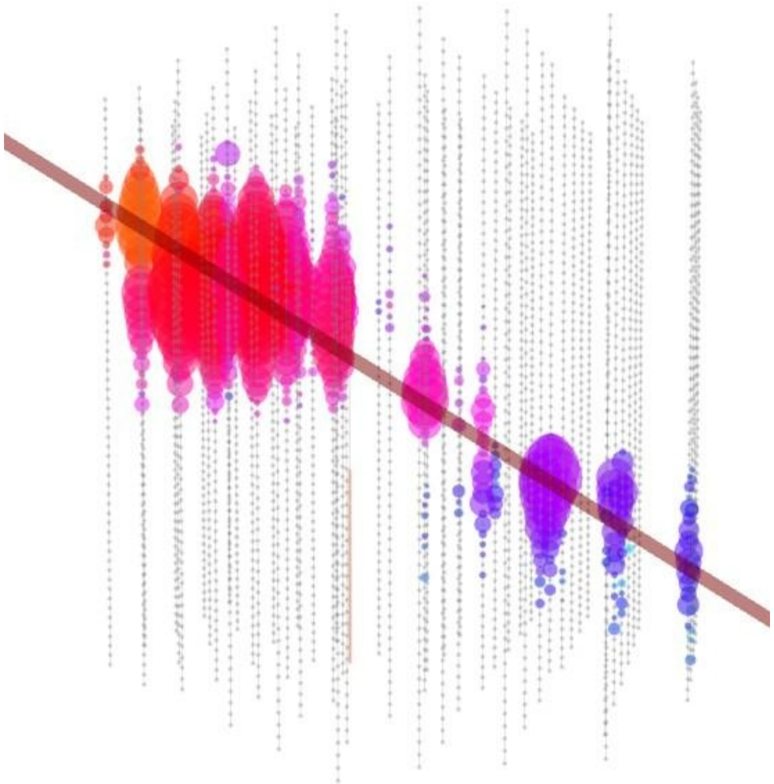
Muon Bundles in IceCube

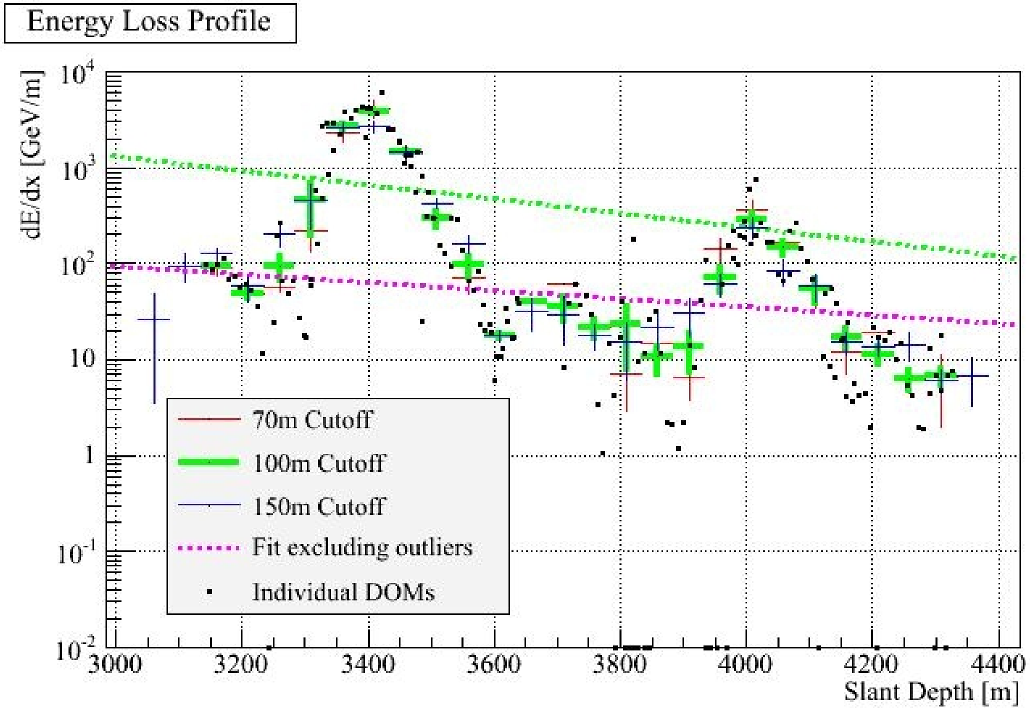




- Smooth energy loss profile

High Energy Muons in IceCube

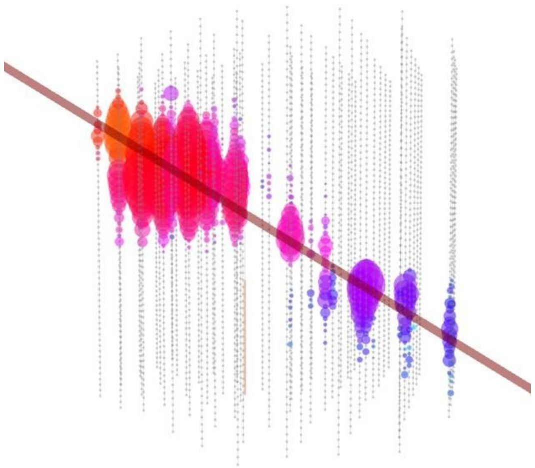




- Big stochastic losses
- Energy loss peaks can be used to distinguish high energy muons from muon bundles

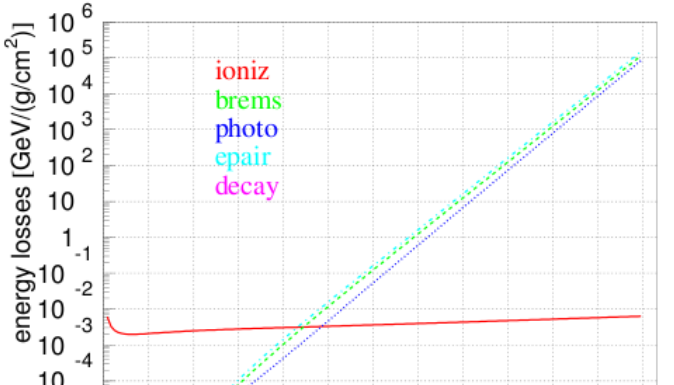
High Energy Muon Analysis - Structure

- Stochastic losses
- Energy reconstruction and muon bundle supression
- Prompt component and all sky spectrum



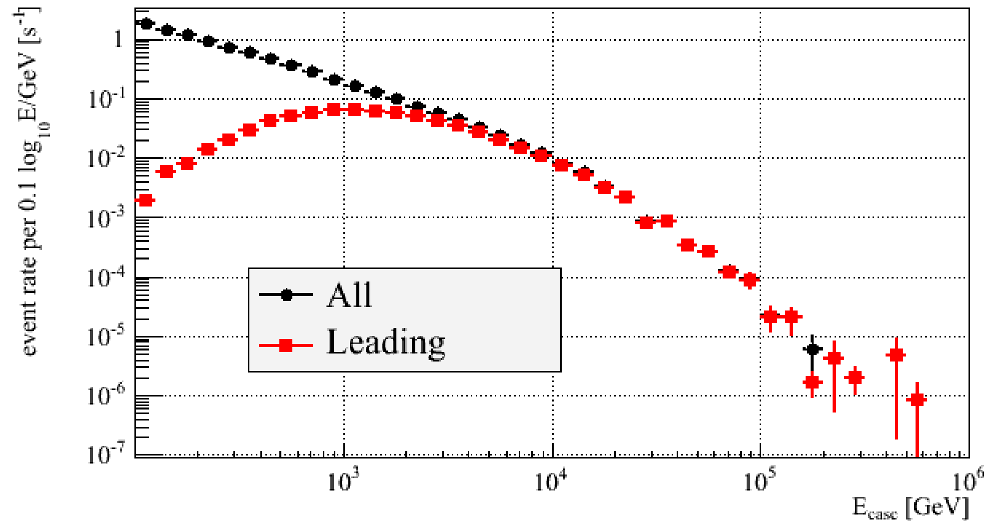
→ dE/dX → Energy Spectrum

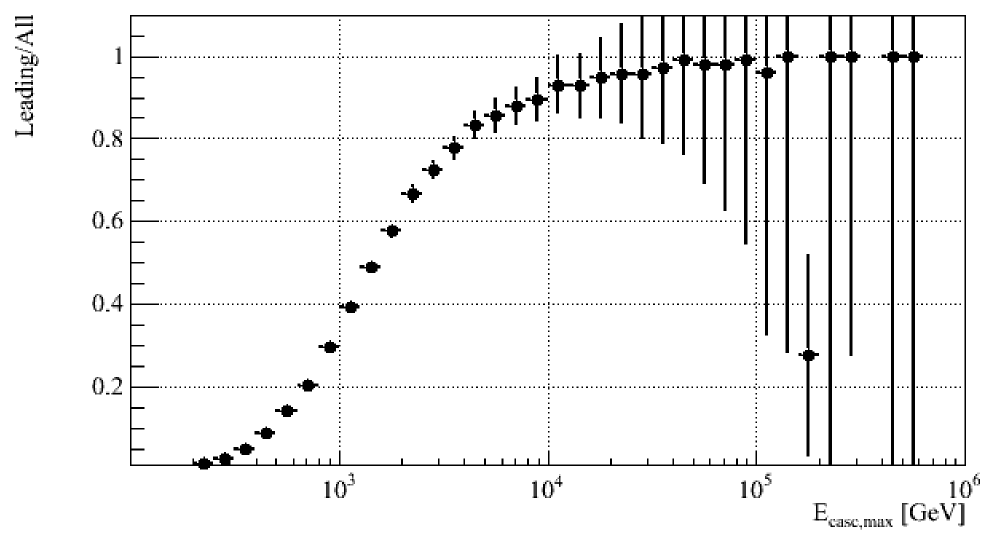
Stochastic Energy Losses of HE Muons



$$dE/dX = a + bE$$

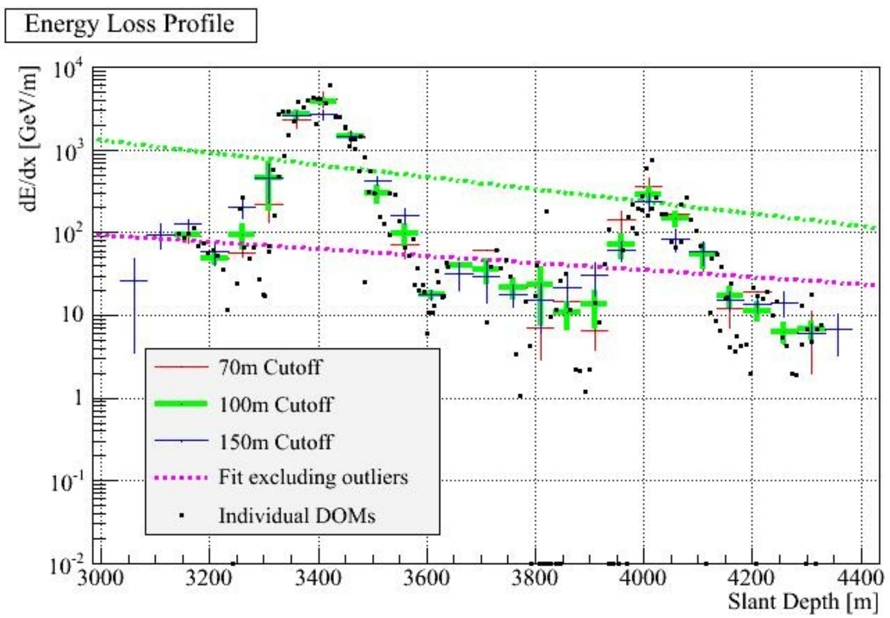
arXiv:hep-ph/0407075



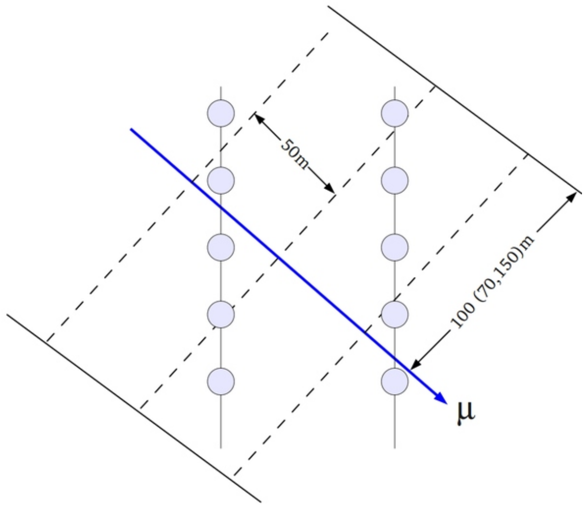


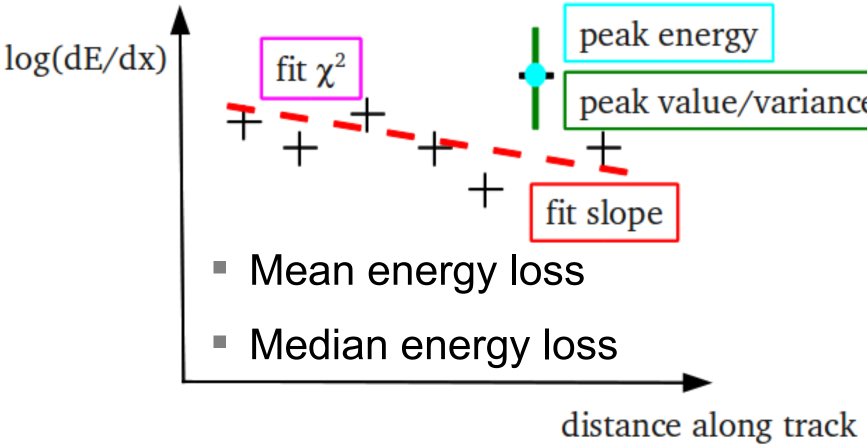
- Energy loss in single (leading) cascades
- Cascade energy proportional to muon energy

Data-Derived Differential Deposition Reconstruction (DDDDR)



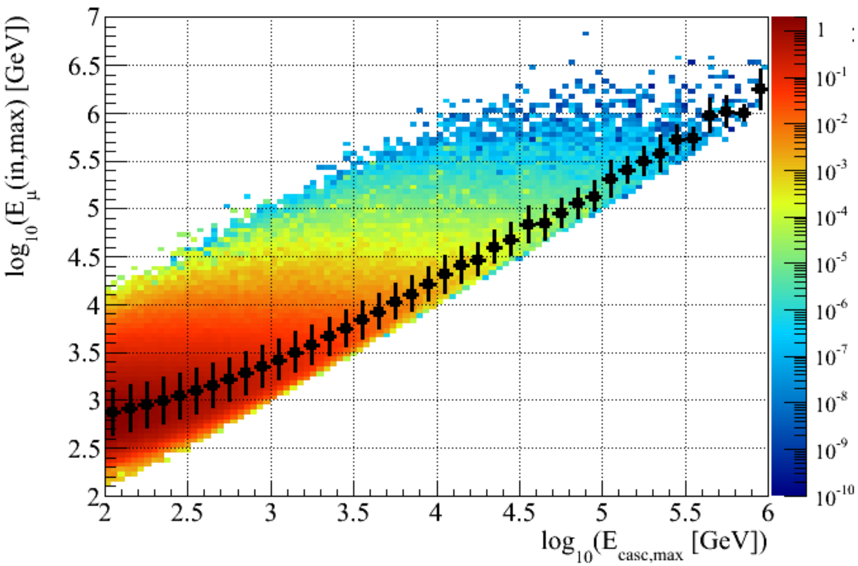
- Differential energy loss estimated from charge measured along the track
- Peak energy over median energy main identifier for stochastic losses
- Cascade energy to estimate muon surface energy



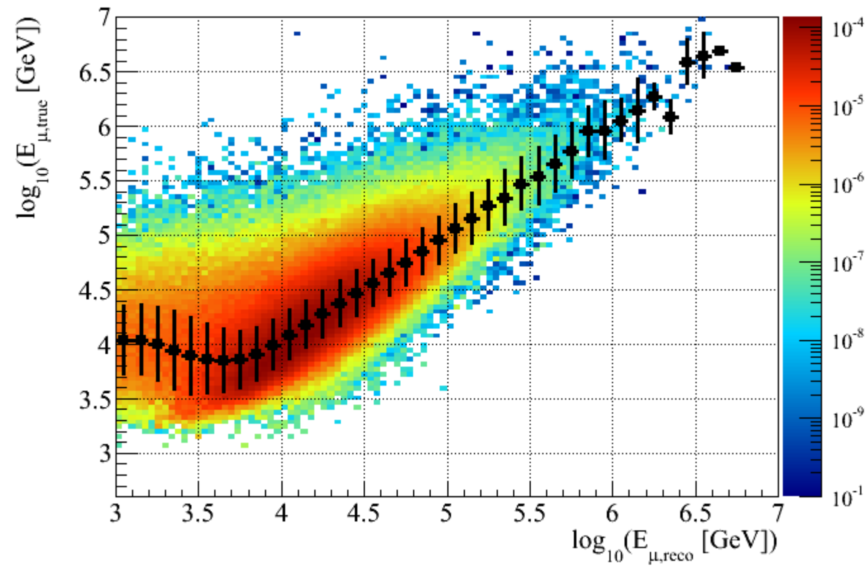


Energy Reconstruction

Leading cascade energy vs muon energy



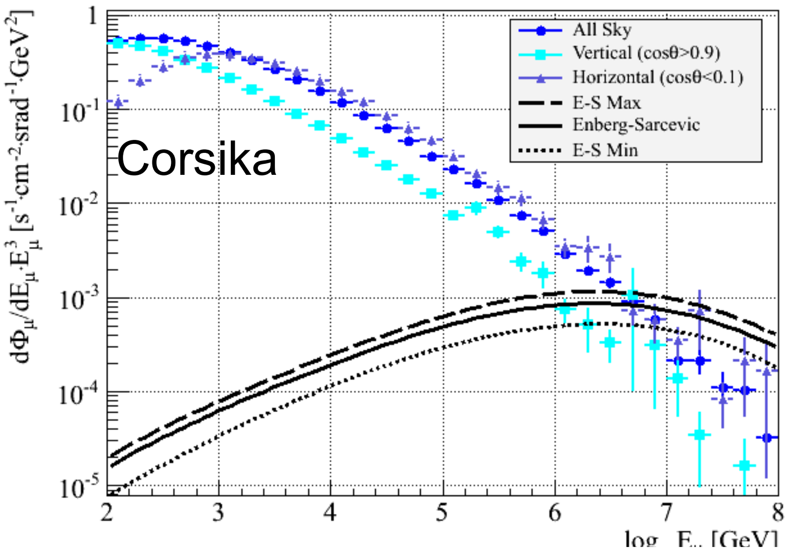
Reconstructed vs true surface energy

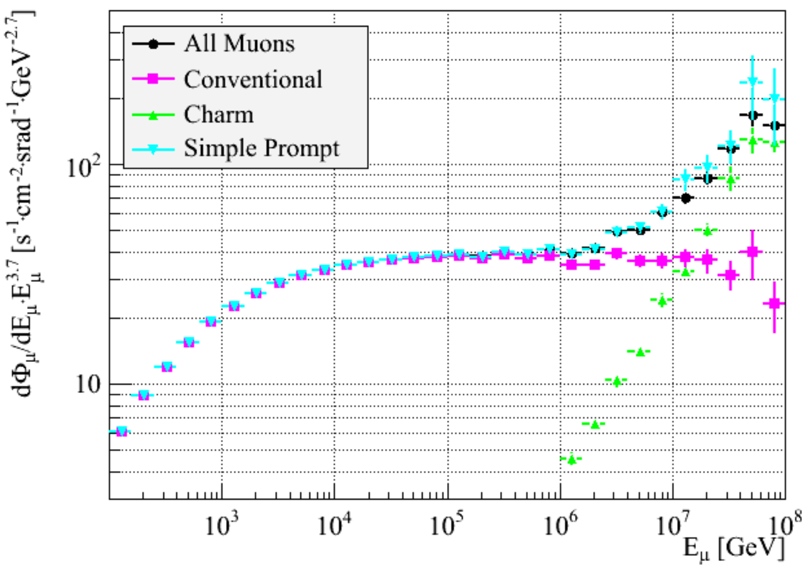


> Cascade energy proportional to muon energy in detector

> Calculate surface energy from slant depth in detector

Muon Spectrum with Prompt



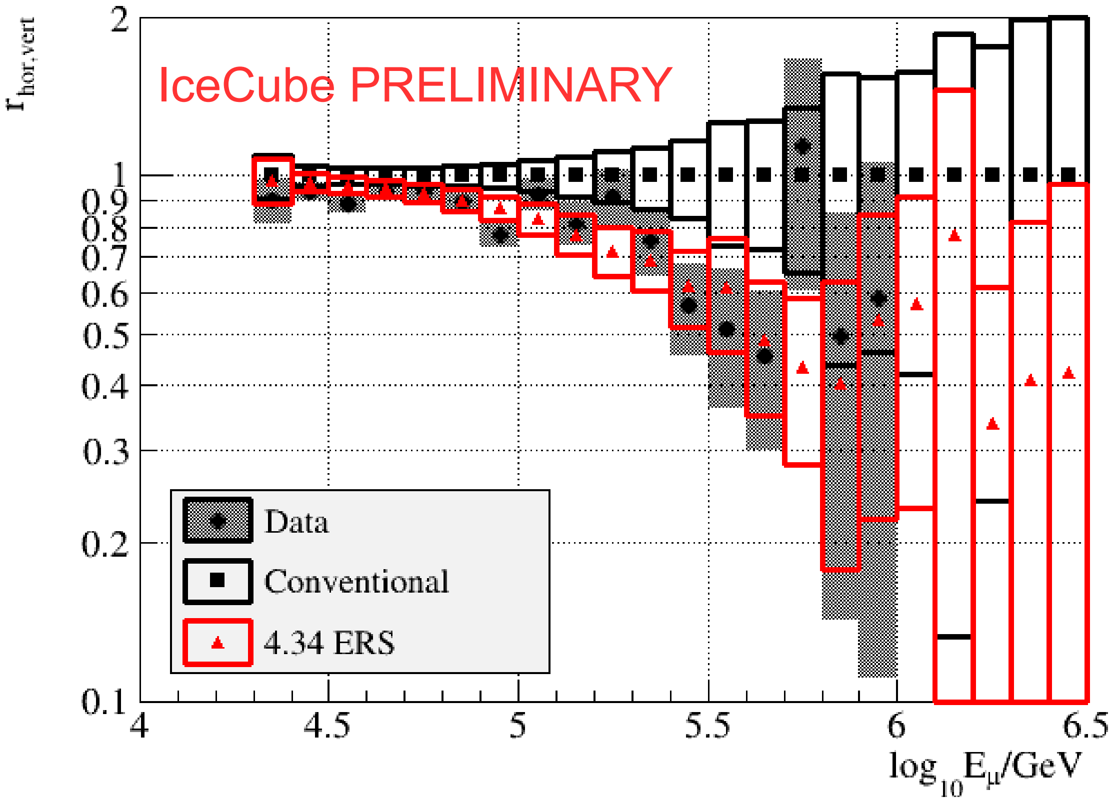


- Muon flux consists of
  - Conventional muons (zenith dependent)
  - Isotropic prompt muons from charmed decays with $\gamma_{prompt} = \gamma_{conv} + 1$
- Approximate prompt flux from conventional flux[1]

$$\Phi_{\mu,prompt}(E_\mu, \theta_{zen}) = \Phi_{\mu,conv}(E_\mu, \theta_{zen}) \cdot \frac{E_\mu}{E_{1/2} \cdot cos\theta_{zen}}$$

- $E_{1/2}$ energy where prompt equal to conventional flux
- X^2 fit to determine $E_{1/2}$ for different primary cosmic ray models
- [1] Illana et al., arXiv:1010.5084

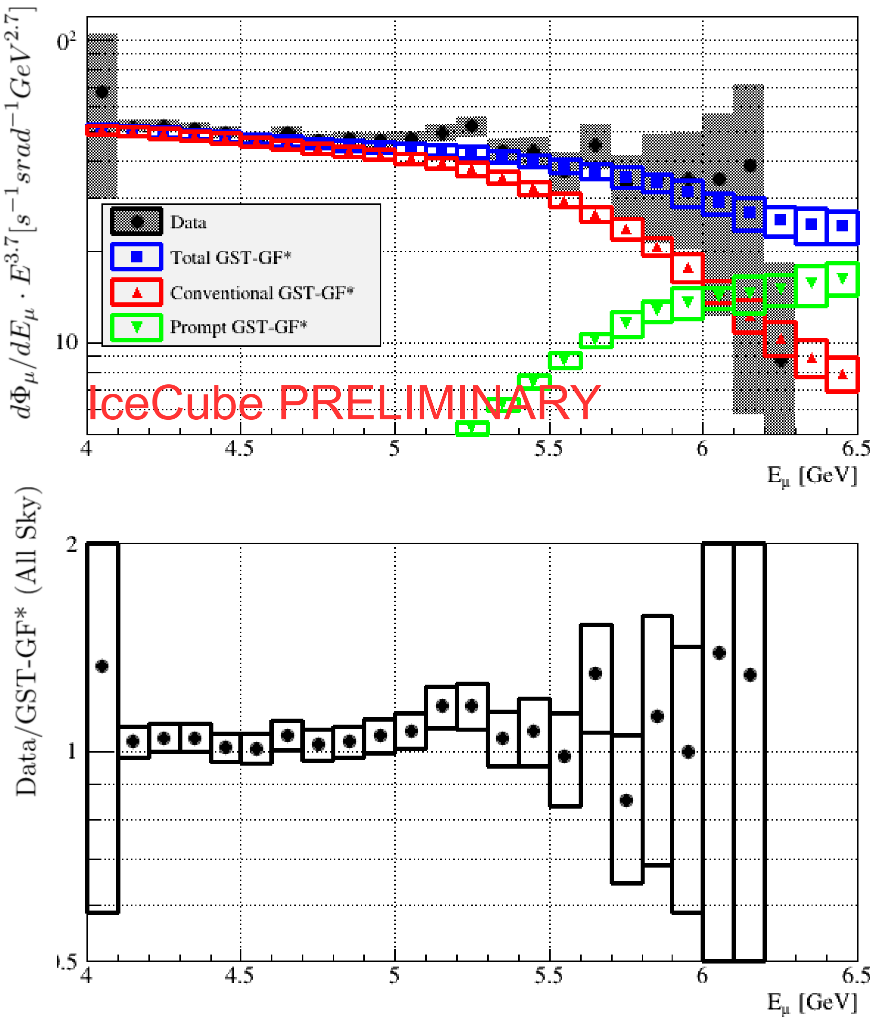
Angular Distribution Fit



$$r_{hor,vert} = \frac{N_{data,hor}/N_{MC,hor}}{N_{data,vert}/N_{MC,vert}}$$

- Angular distribution almost independent of primary cosmic ray flux
- Prompt isotropic, conventional zenith dependent
- Use ratio of horizontal to vertical flux
- Simulation only conventional
- Ratio of 1 means no prompt

Results of the Combined Fit



Model	Prompt (ERS)	p-value
GST-GF*	2.04	0.282
Poly-Gonato	7.49	0.149
H3a	8.32	0.075
ZS	7.82	0.014

IceCube PRELIMINARY

- Best fit with prompt above neutrino analysis limits
- Some primary cosmic ray flux models favor high prompt contribution

GST-GF* (Gaisser et al.) arXiv:1303.3565

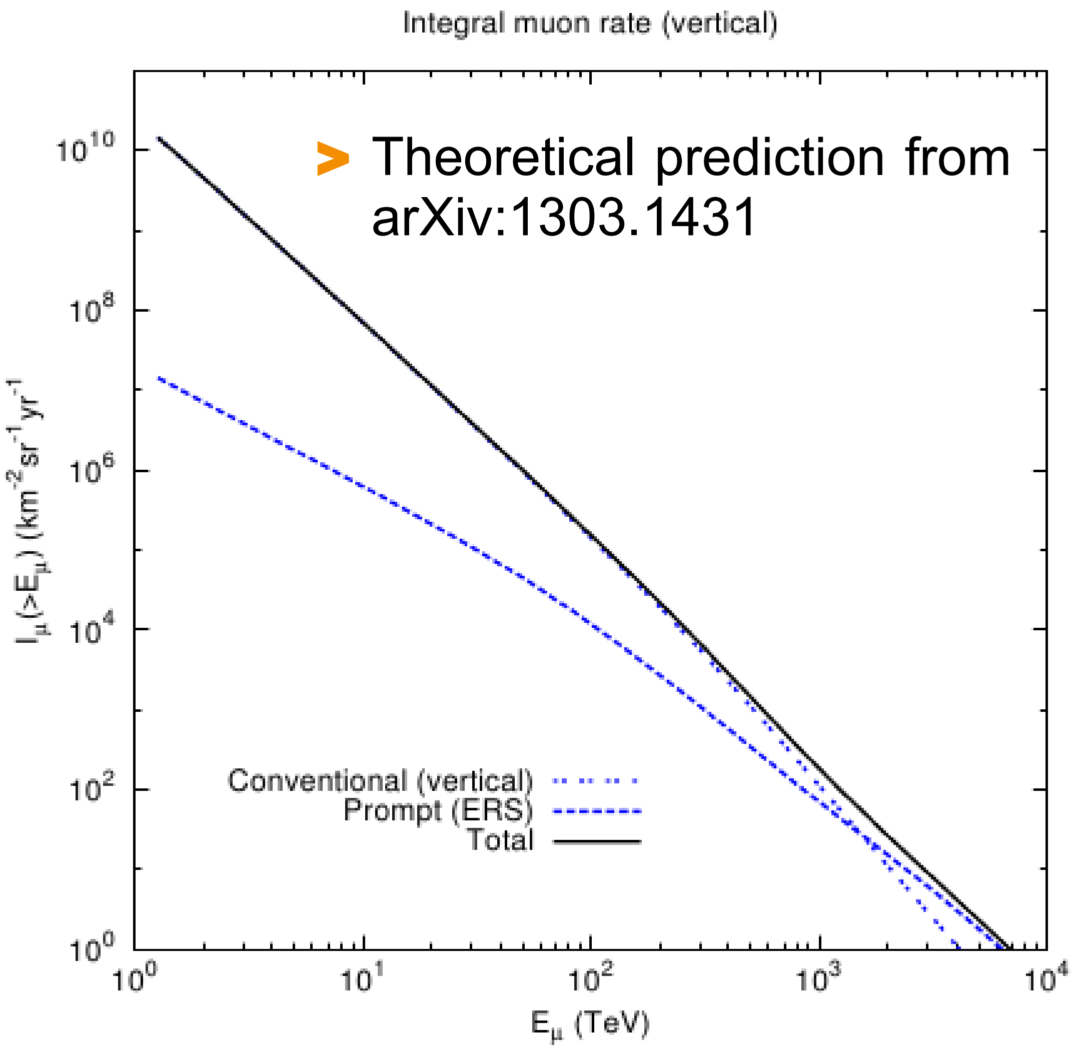
Conclusion

- High energy muons can be distinguished from muon bundles by identifying stochastic energy losses
- Depending on primary cosmic ray model, prompt flux higher than in neutrino analyses is favored, zero prompt is disfavored, but..
- Detector systematics have to be studied further
- Analysis soon to be done on additional four years of data
- Result not published yet due to systematic uncertainties

Similar study from water would be welcome!

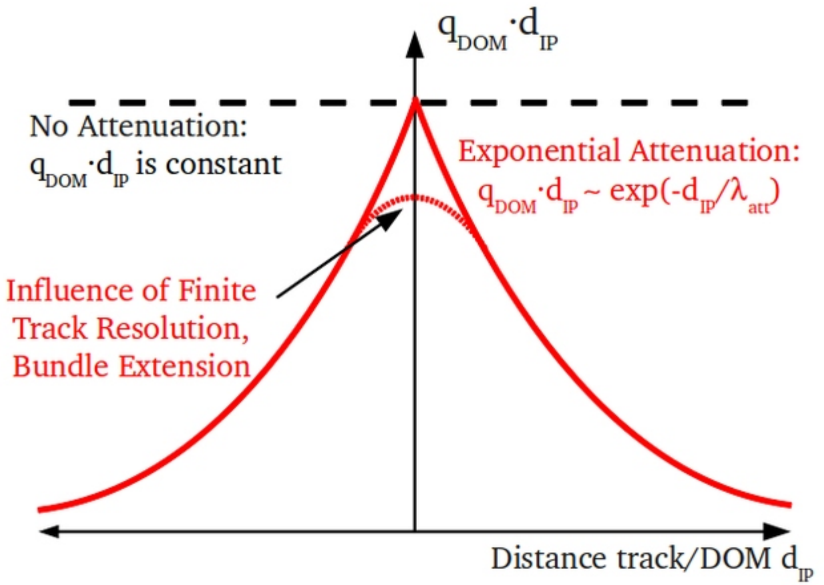
Vertical Muon Rate for a km^3 detector per year

- Theoretical prediction from arXiv:1303.1431



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



$$N_{phot} \sim q_{DOM} \cdot d_{IP} \cdot exp(d_{IP}/\lambda_{att})$$