UNIVERSITY of DELAWARE

Measuring Low Energy Muons with IceTop

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for the IceCube Collaboration

IceCube

Before We Begin...

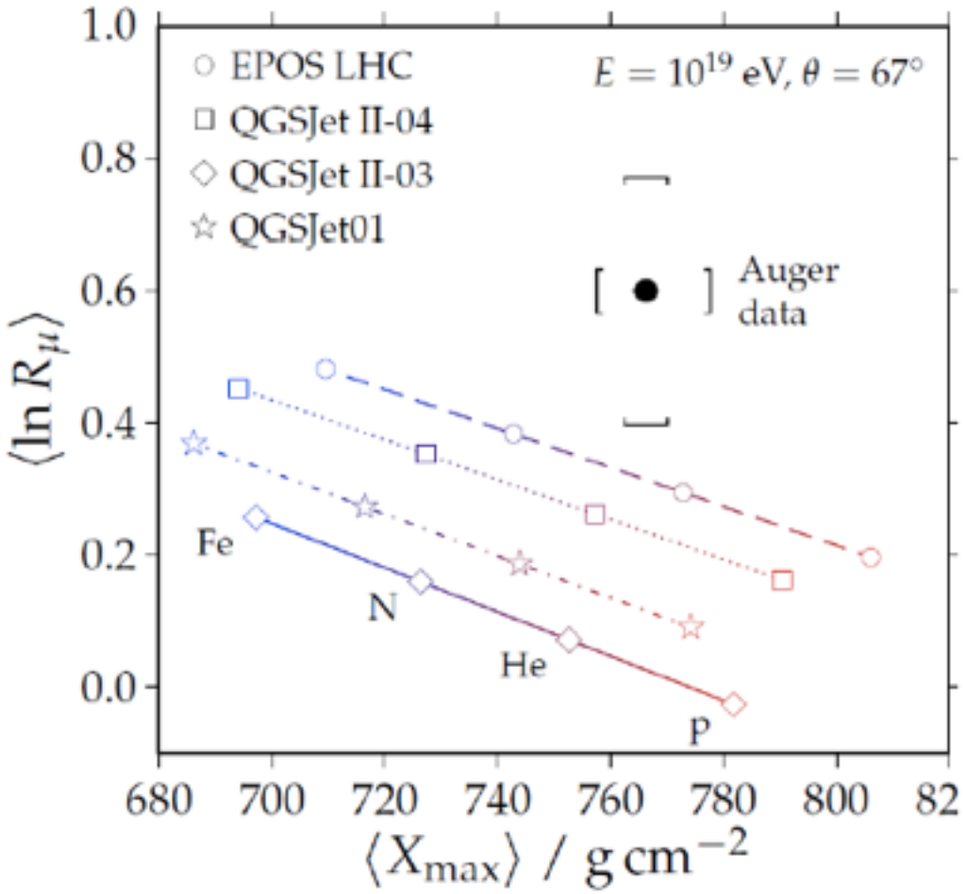
- IceTop detects the low energy muons far away from the shower axis
  (E > 200 MeV, r > 300 m).

- Number of muons is related to the mass of the primary cosmic ray.

- The muon number is expected to scale roughly as a power of the primary energy:

$$N_\mu(r) \propto A \left(\frac{E}{A\epsilon_\pi} \right)^{p_\mu} \qquad p_\mu \sim 0.78$$

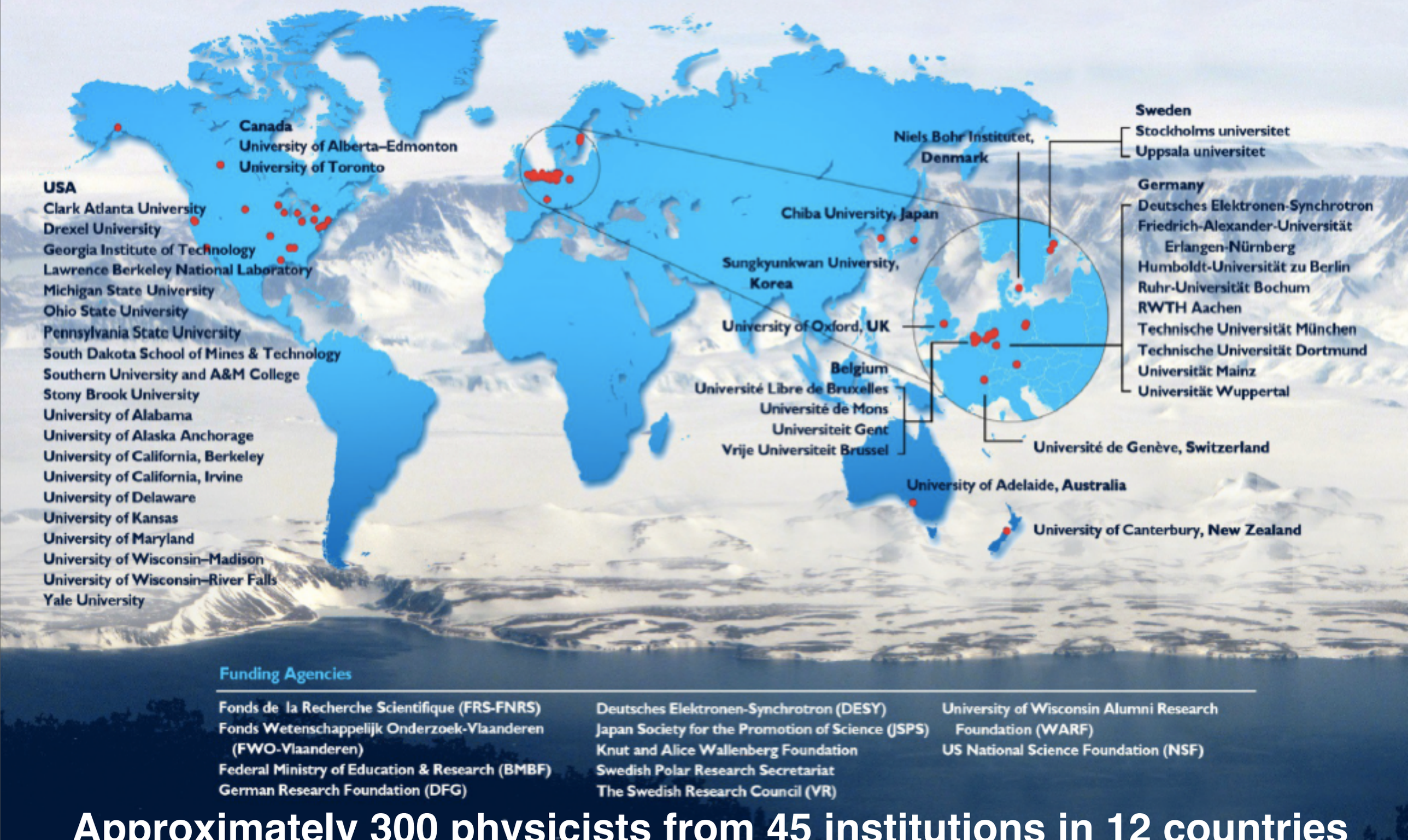
Mass number A, primary energy E,
(0.83 in Akeno)
Parameters are model dependent



Discrepancy with simulations claimed by Pierre Auger coll.
Aab et al. PRD 91, 032003 (2015)

We will look at the energy dependence of the muon density at a fixed reference radius for near-vertical events.

The IceCube Collaboration

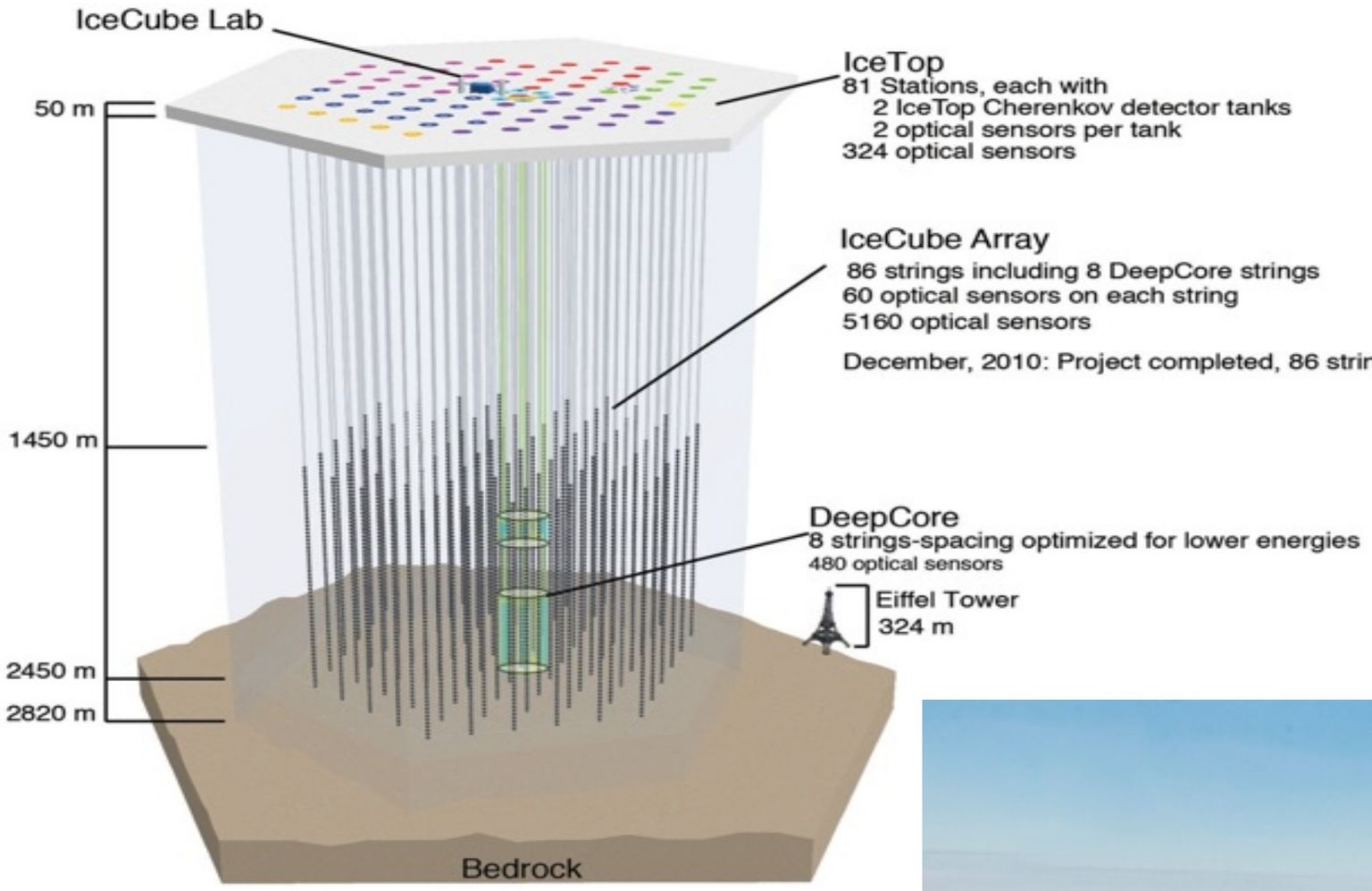


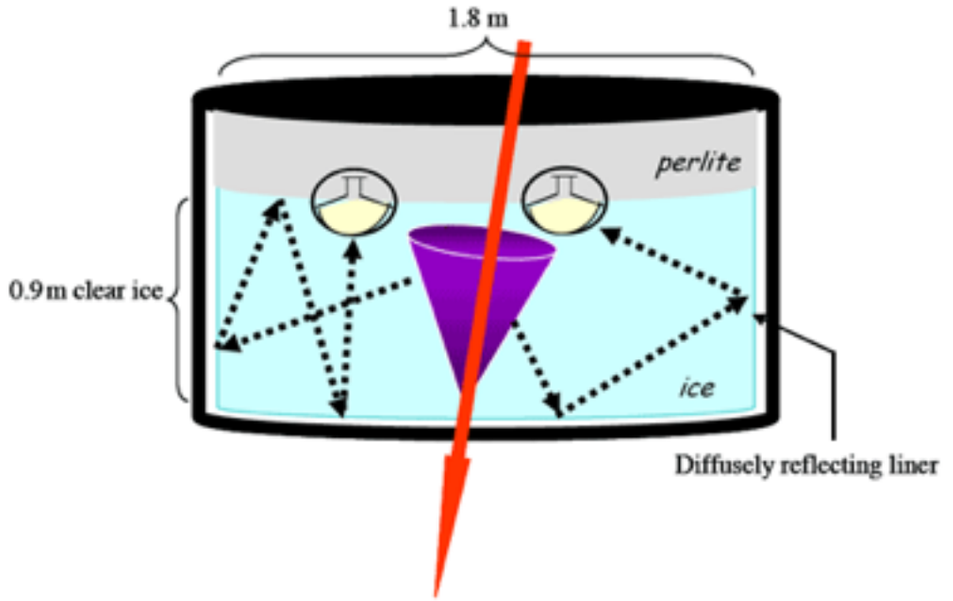
Funding Agencies

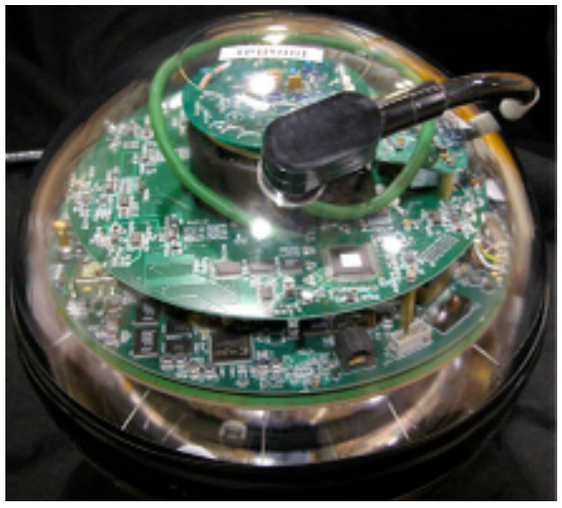
Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

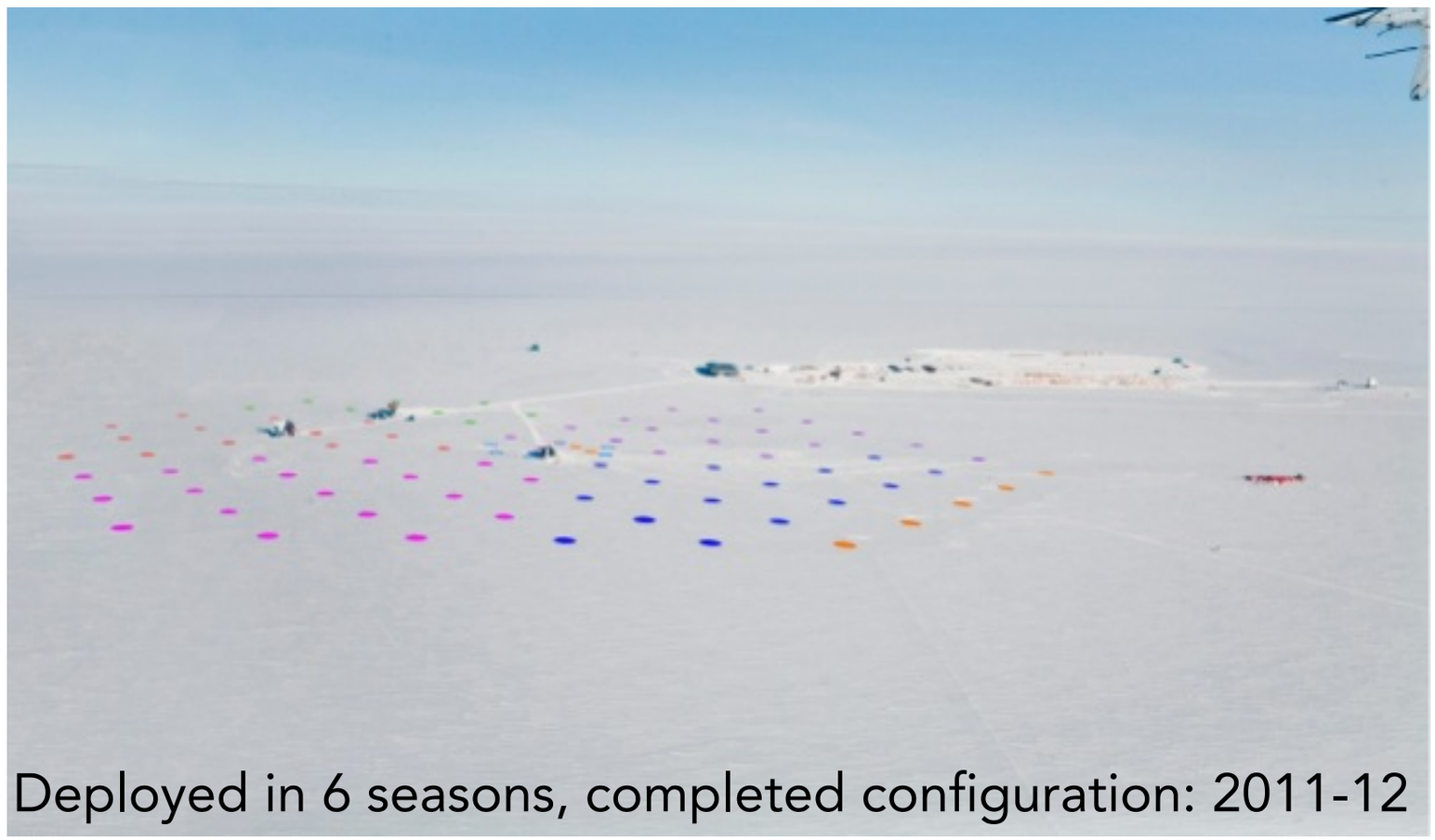
Approximately 300 physicists from 45 institutions in 12 countries

The IceCube Detector



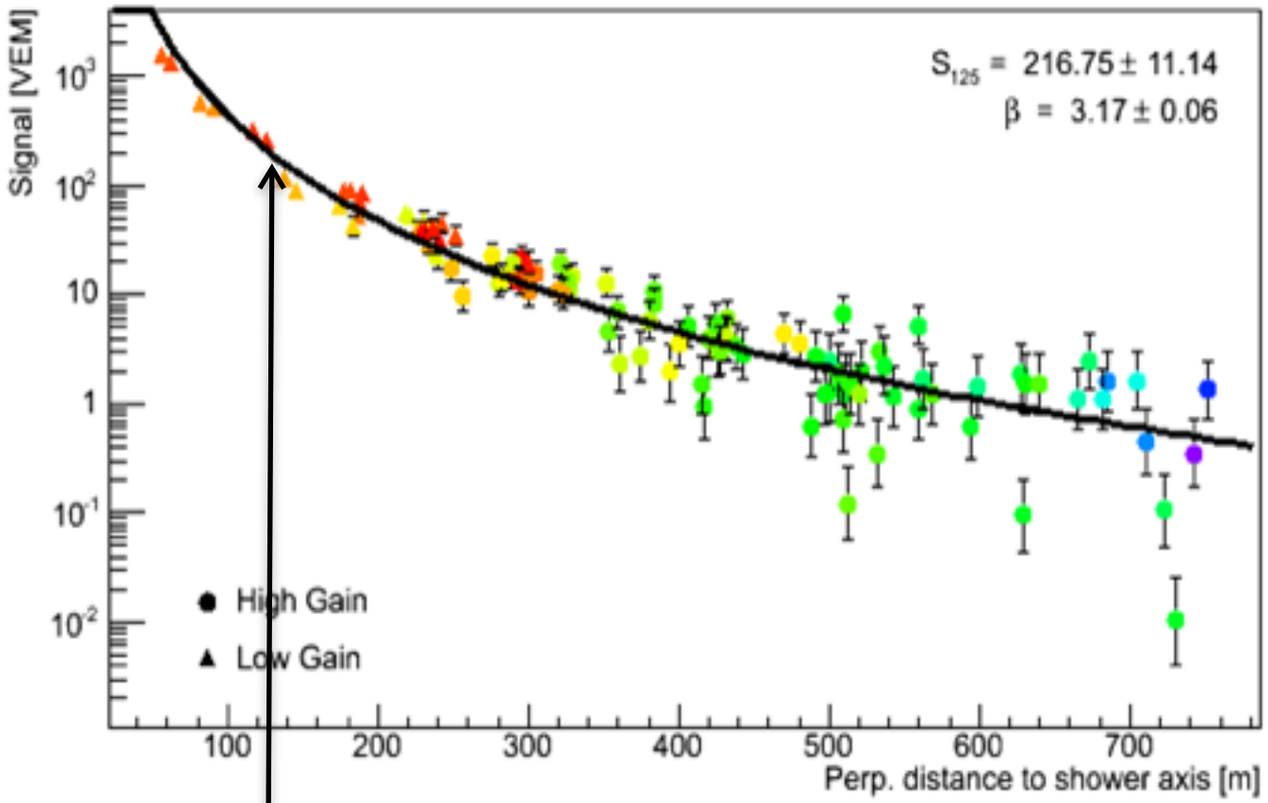






Deployed in 6 seasons, completed configuration: 2011-12

IceTop event
(recap)

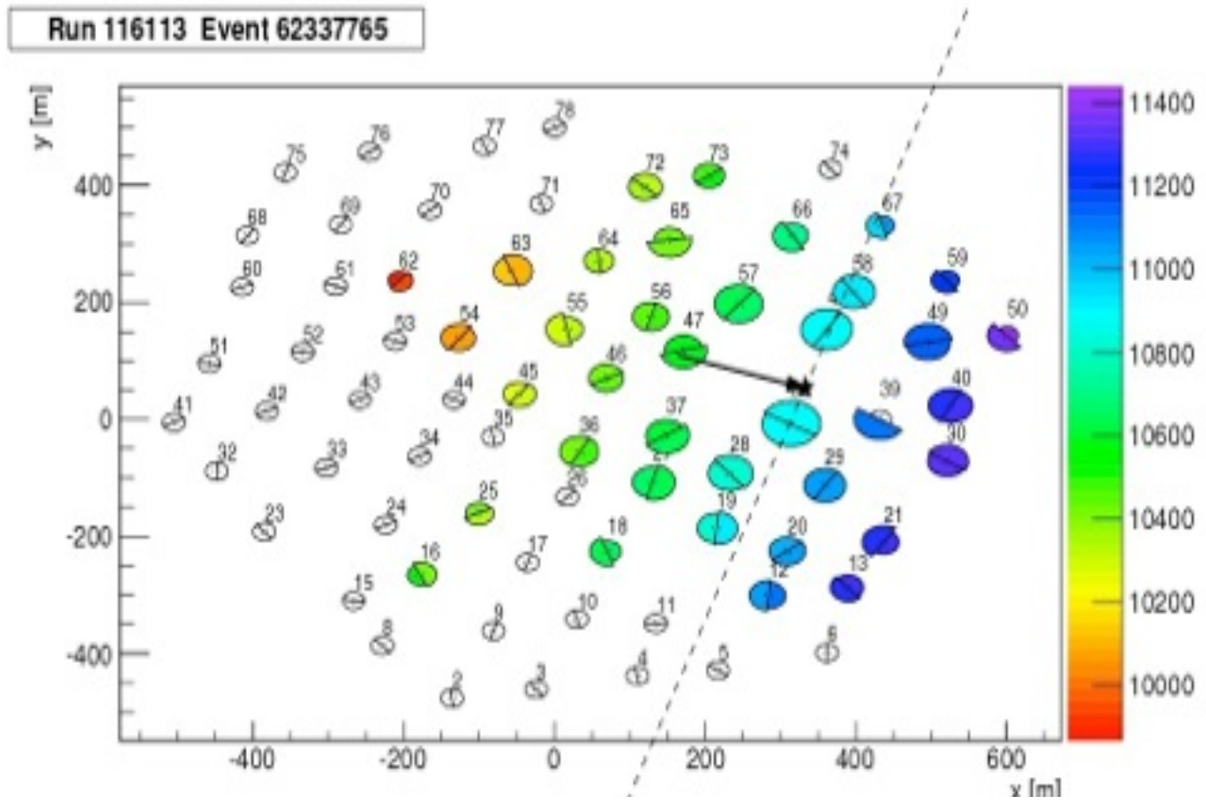


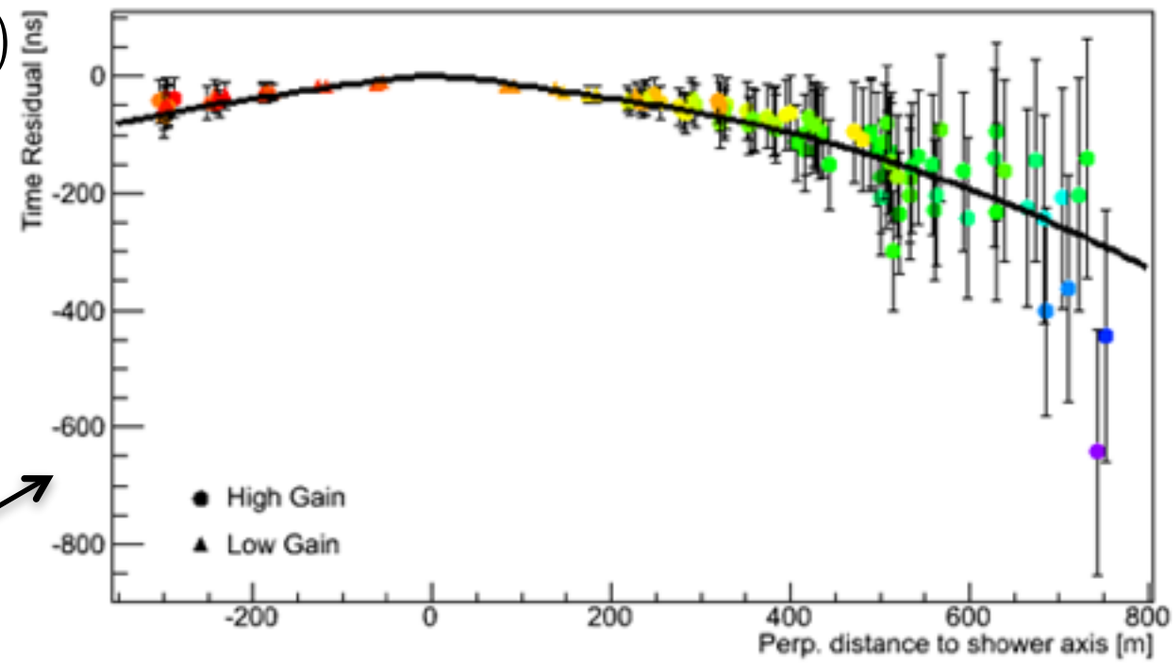
$$S(r) = S_{125} e^{-\frac{d \sec\theta}{\lambda}} \left(\frac{r}{125\,m}\right)^{-\beta - k \log\left(\frac{r}{125\,m}\right)}$$

Attenuation due to snow

$$t(\boldsymbol{x}) = t_0 + \left(\frac{\boldsymbol{x_c} - \boldsymbol{x}}{c}\right) \cdot \boldsymbol{n} + \Delta t(R)$$

$$\Delta t(R) = aR^2 + b\left(\exp\left(-\frac{R^2}{2\sigma^2}\right) - 1\right)$$

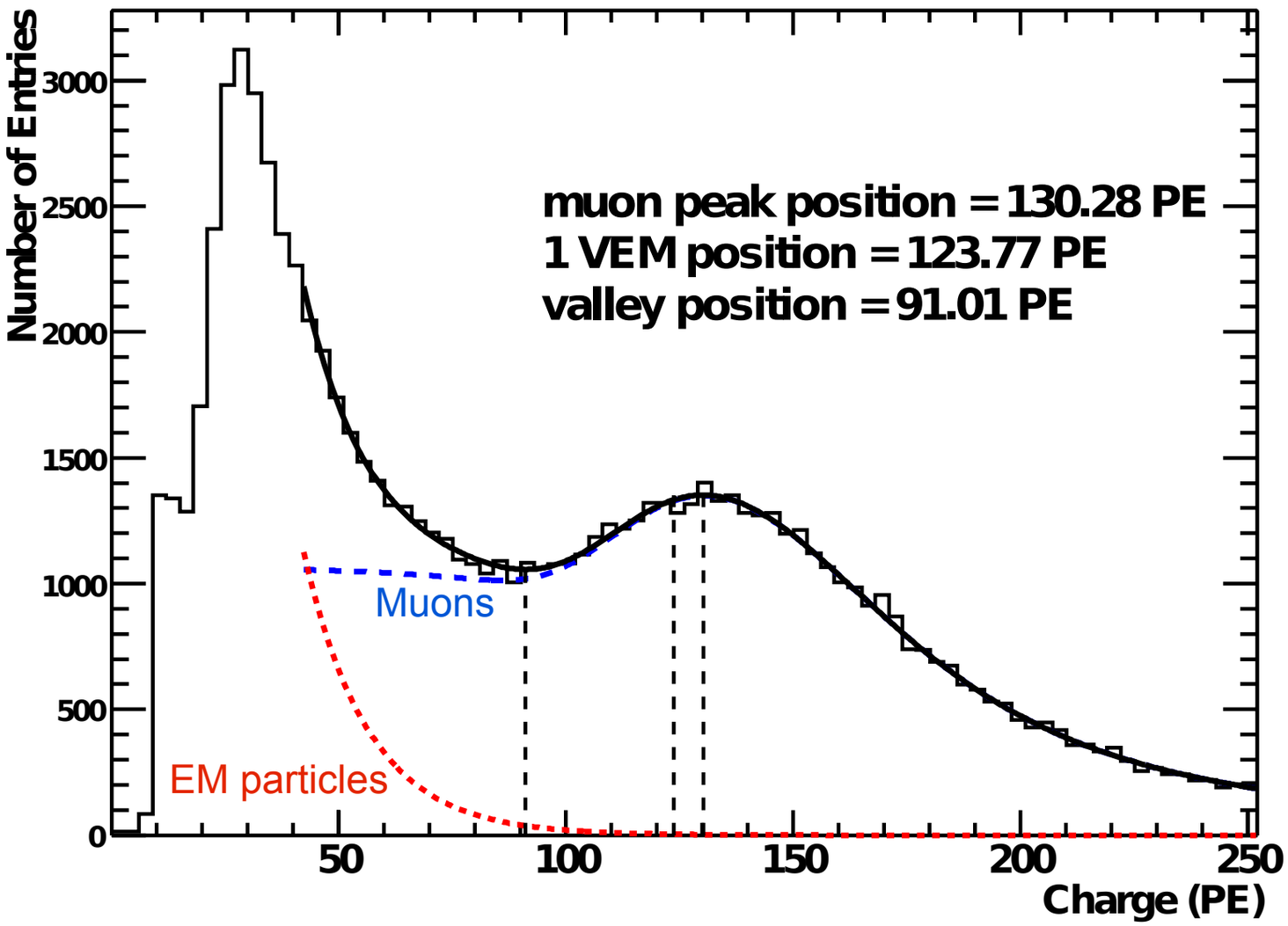




M.G. Aartsen et al., PRD 88 (2013) 042004

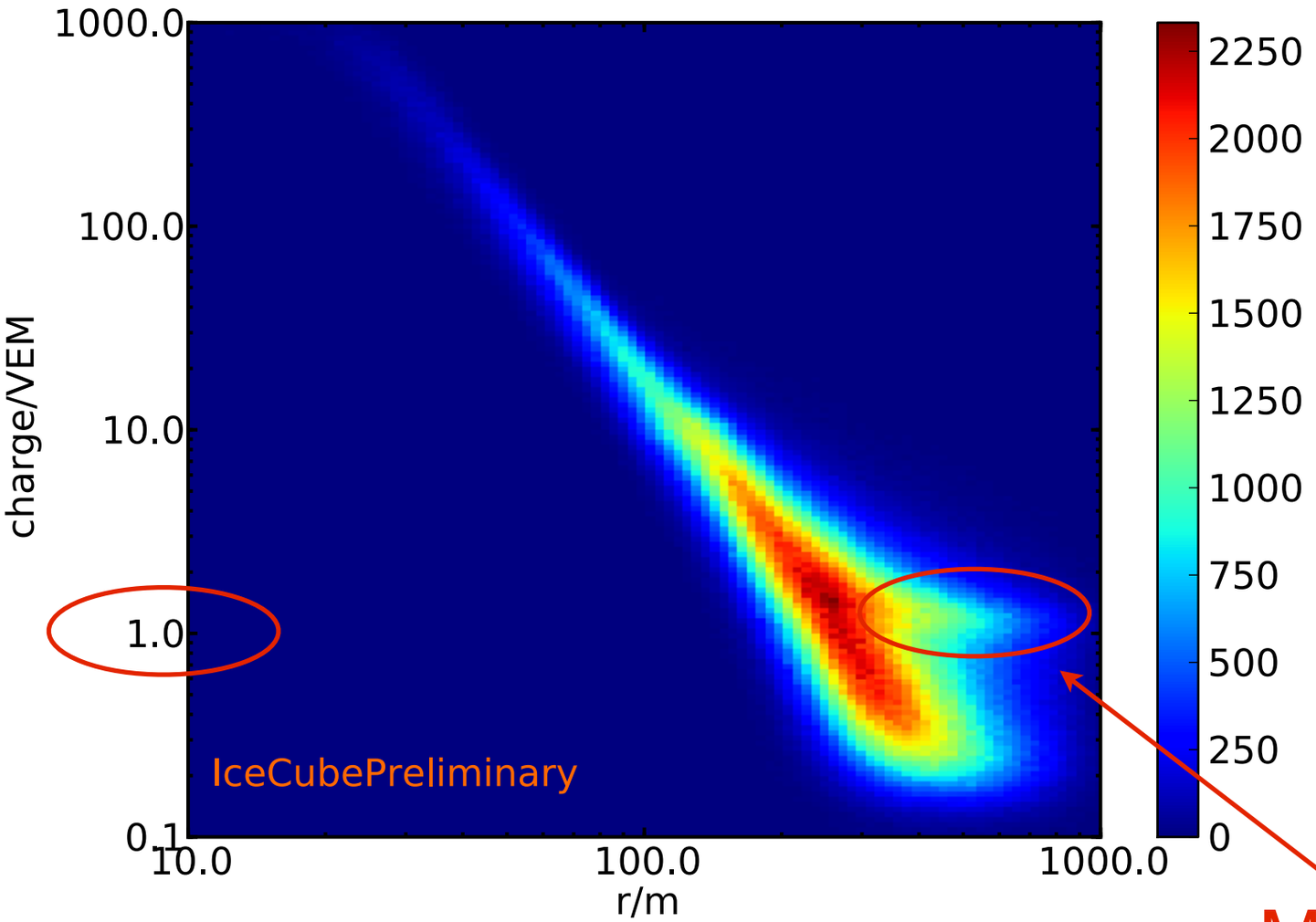
Single-tank Signal Calibration

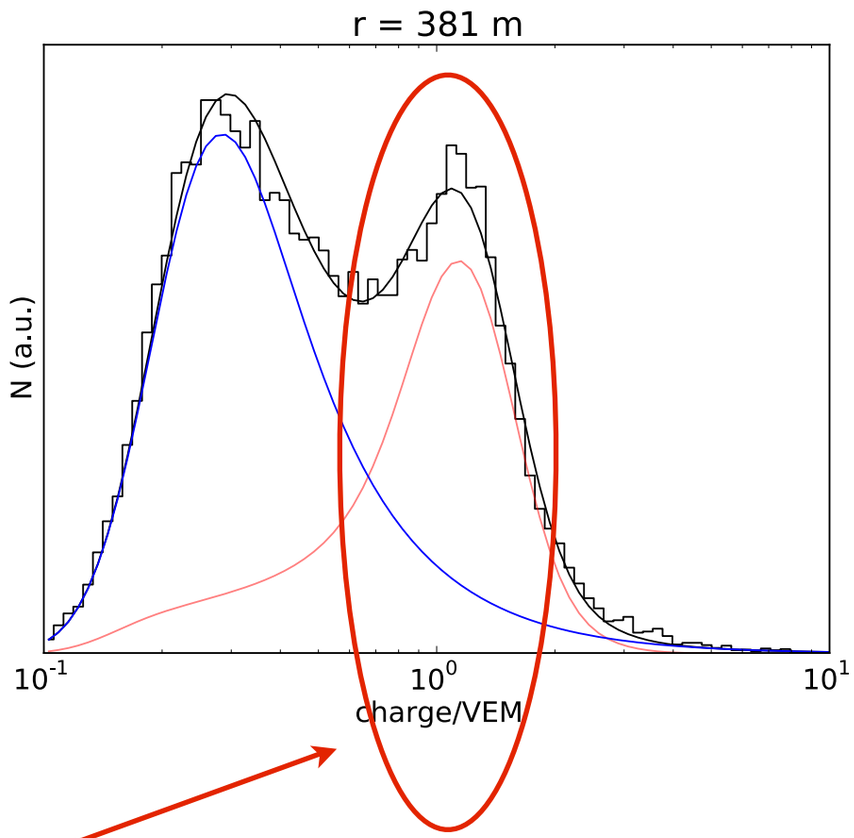
(VEM Calibration)



Example of a VEM calibration histogram for a particular tank, high-gain DOM in tank 61-A.
IceCube Collaboration, ICRC 2011, Beijing

Charge-Distance to Axis Distribution





Muons

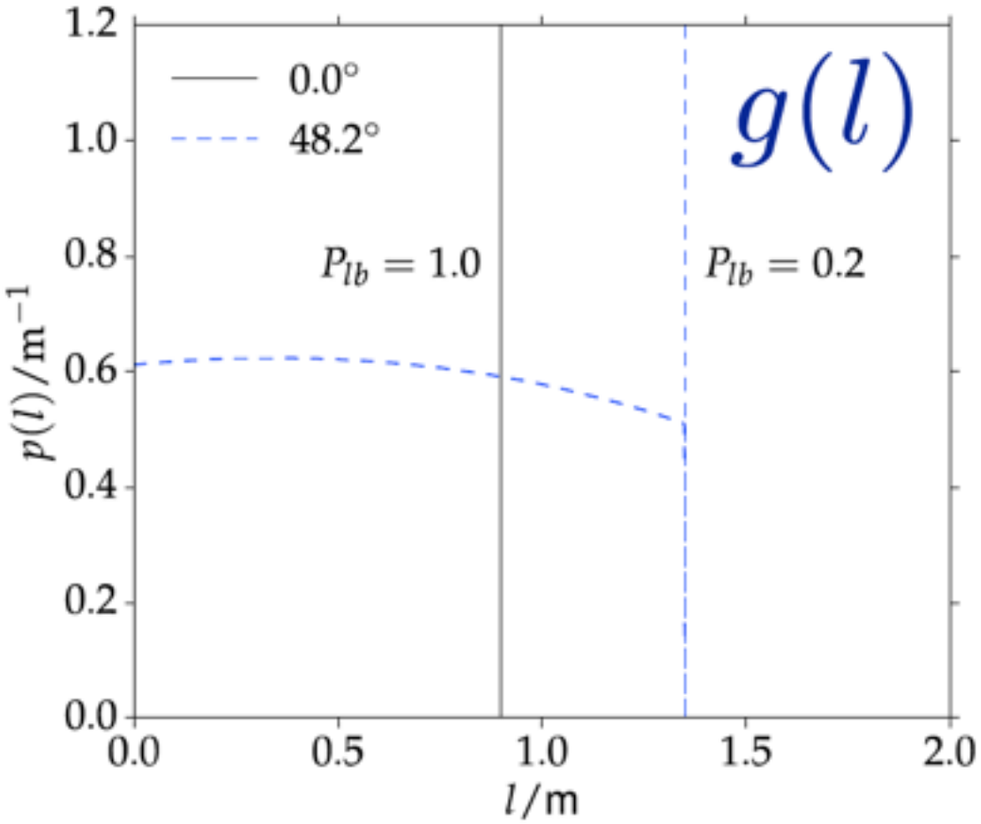
$28^\circ < \theta < 32^\circ$ 10 PeV < E < 12.6 PeV

Detector Response to Single Muons

Signal probability distribution:

$$p(S|1,\theta) = \int g(l)K(S|l)dl$$

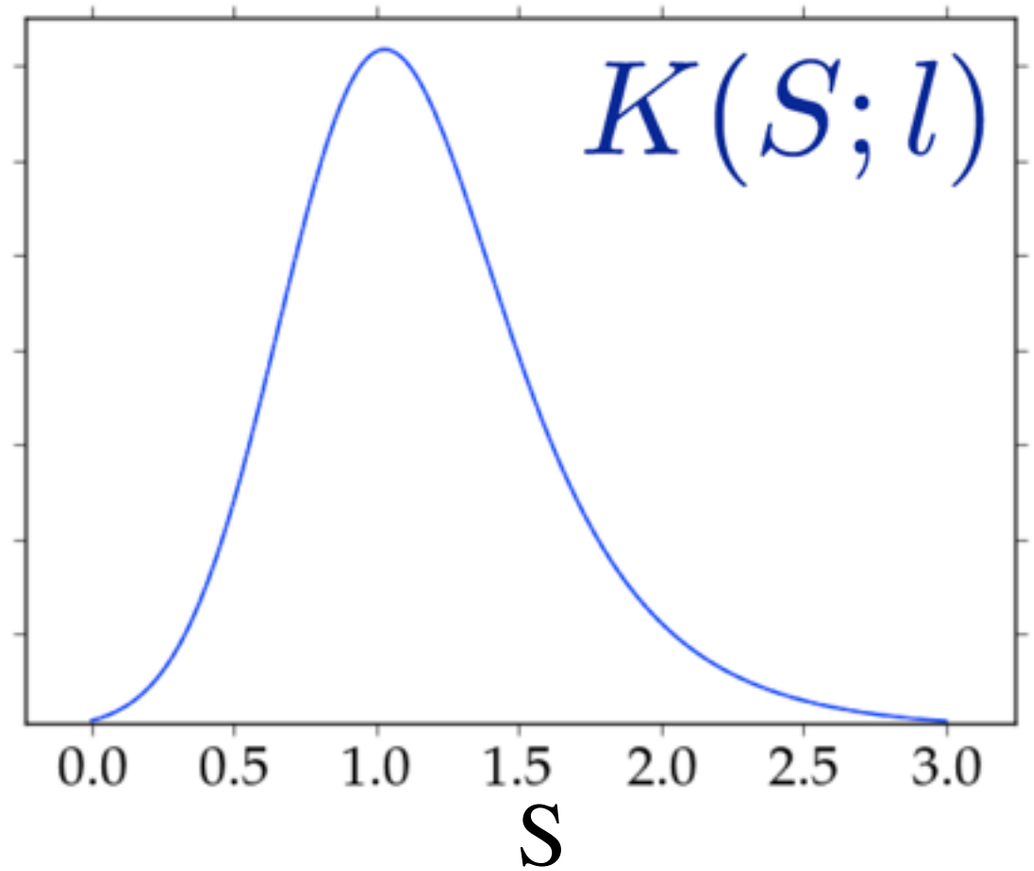
Track length distribution



B. Kegl, D. Veberic, Auger note (2009)
http://arxiv.org/abs/1502.03347

Detector response

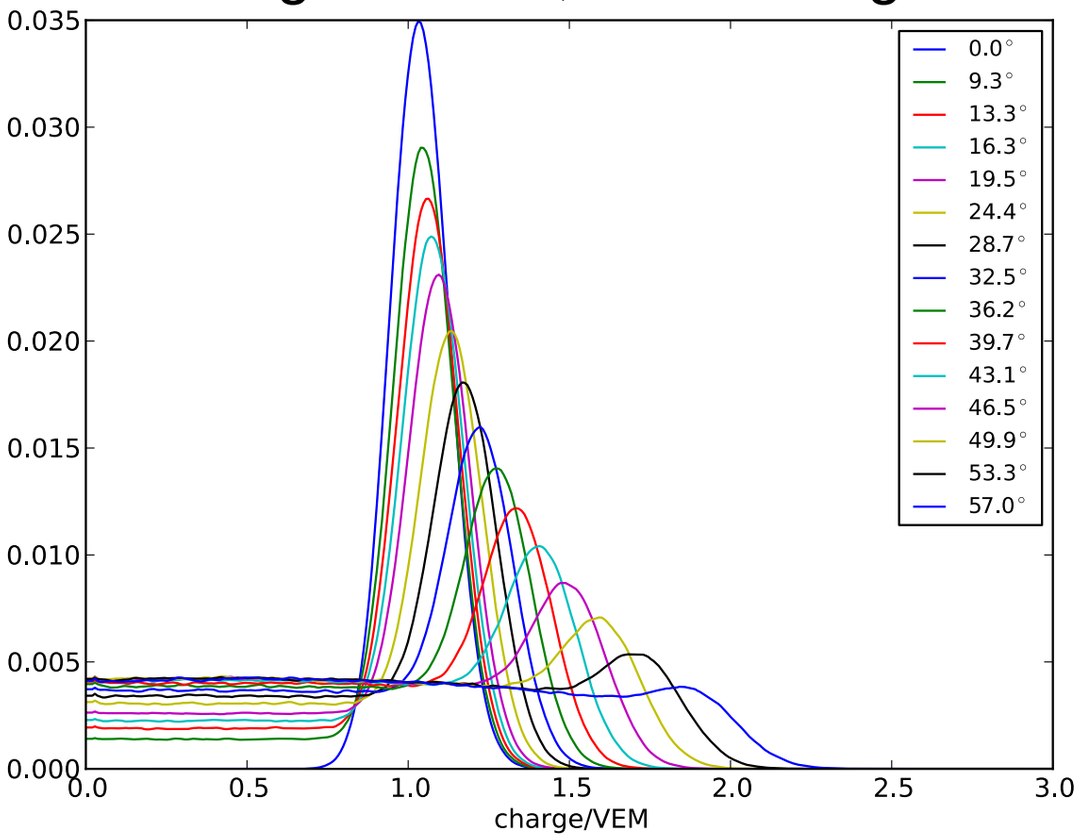
$$K(S|\mu,\sigma,\lambda) = \frac{\lambda}{2}\exp\left(\frac{\lambda}{2}(2\mu+\lambda\sigma^2-2S)\right) \times \mathrm{erfc}\left(\frac{\mu+\lambda\sigma^2-S}{\sqrt{2}\sigma}\right)$$



1 VEM = 90 cm

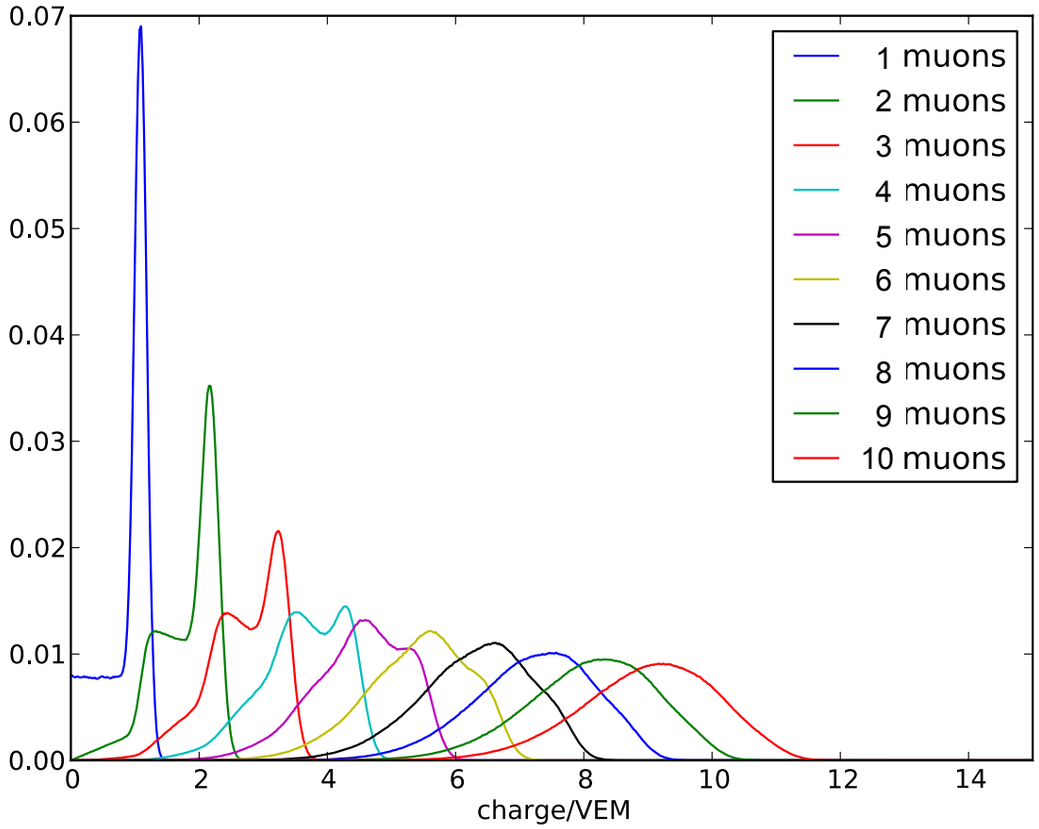
Response to Multiple Muons

Single muons, various angles



Response to single muons obtained from Geant4 simulations of IceTop detectors

Few muons, fixed angle (~10º)



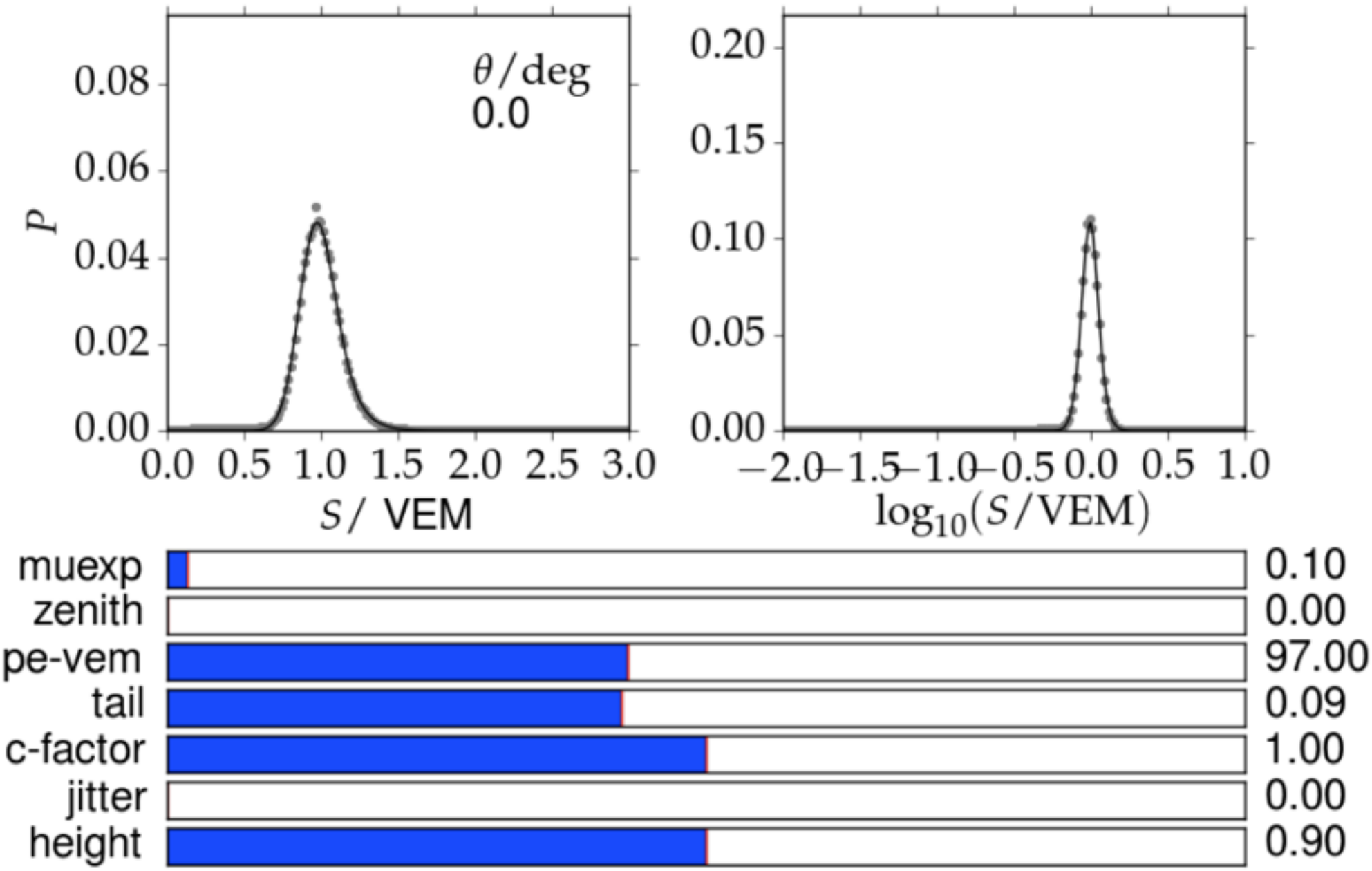
The response to n muons is the n-th order autoconvolution of the single-muon response

$$p(q|N_\mu,\theta) = \sum_n \frac{p^n e^{-\langle N_\mu \rangle}}{n!} p(q|n,\theta)$$

Expected number of muons

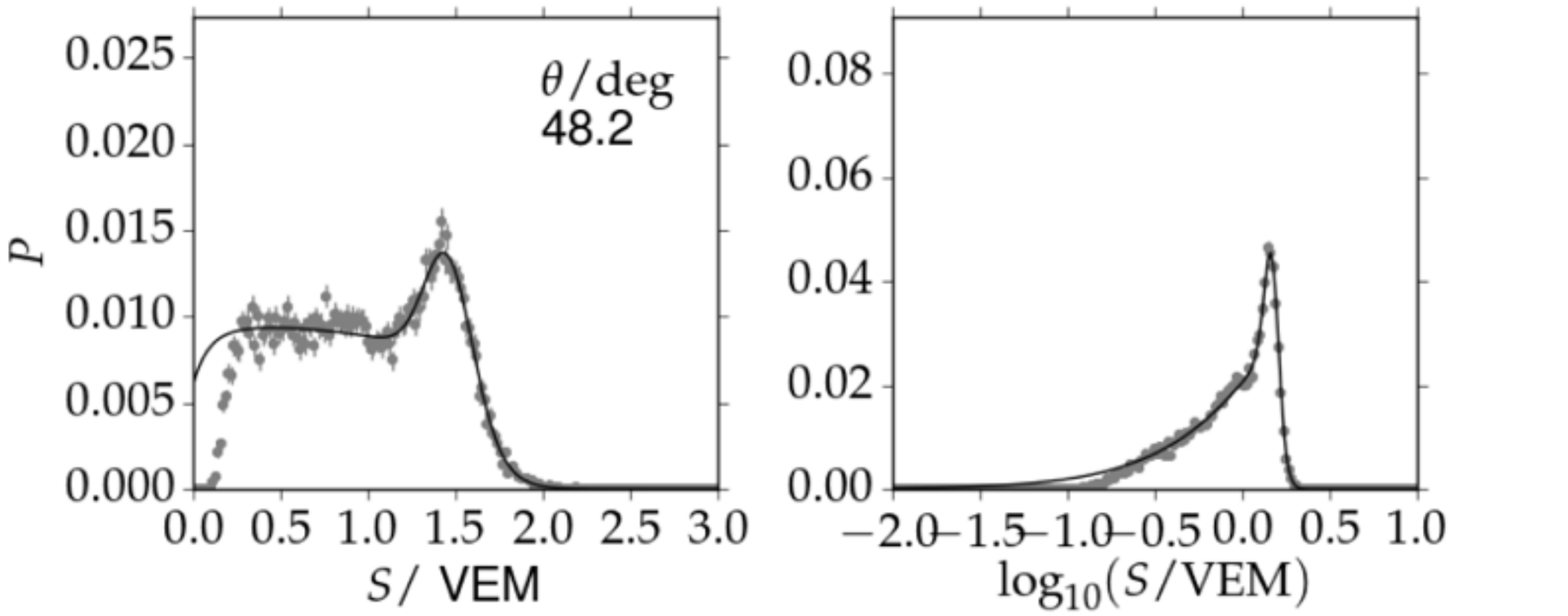
response to a number of muons

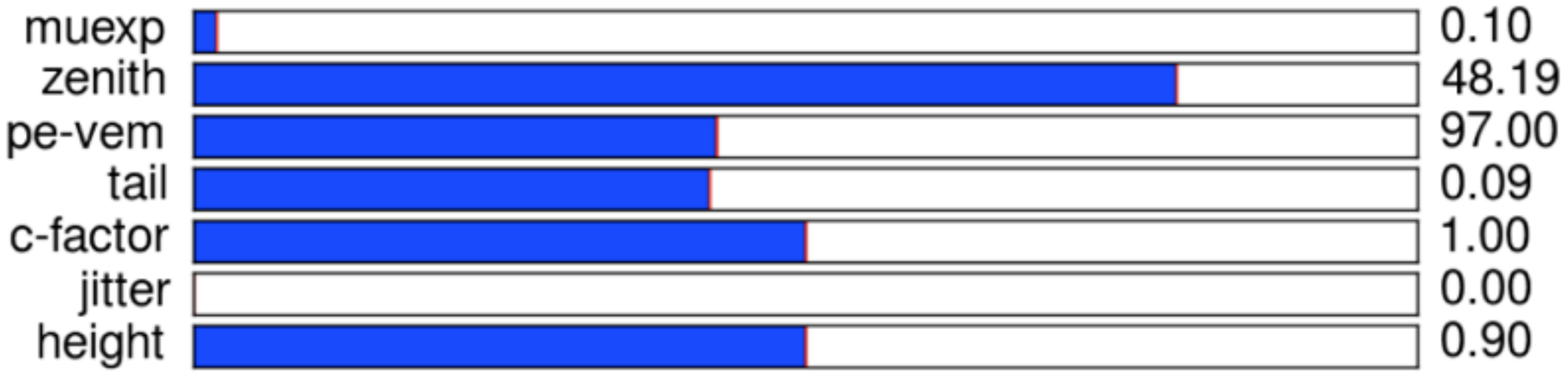
Comparison to Geant4



Data points: Tank response simulated with Geant4

Comparison to Geant4

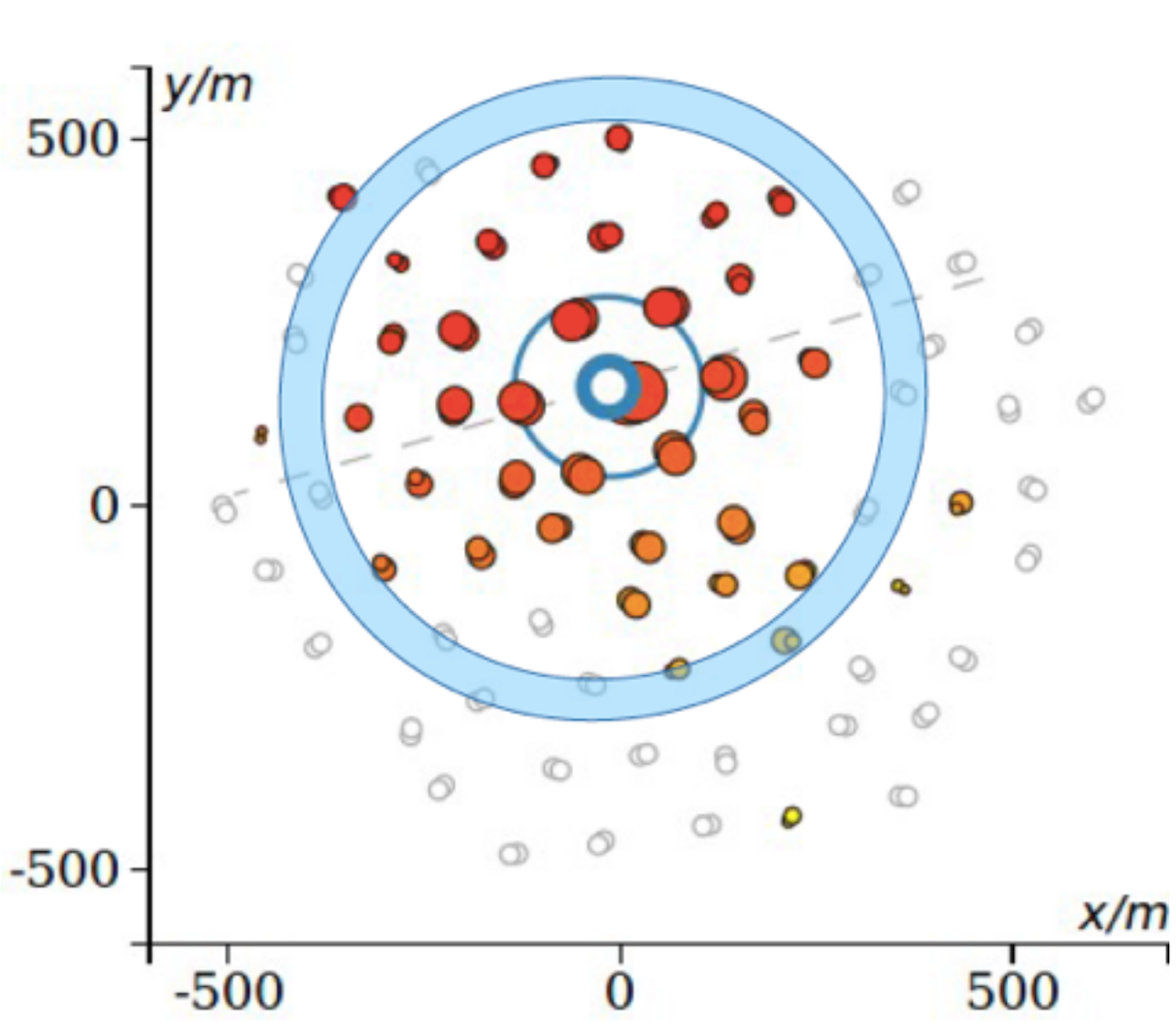


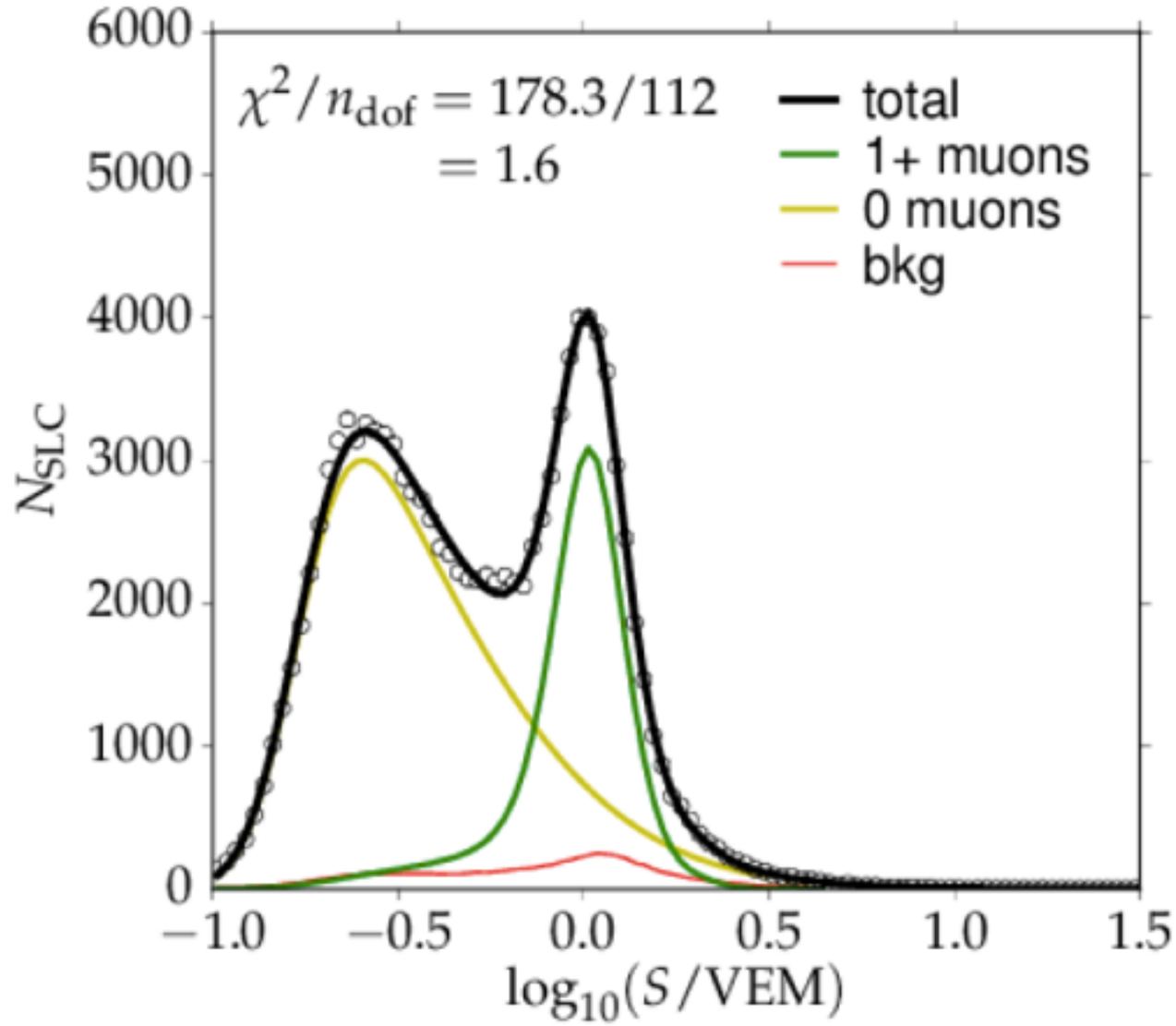


Data points: Tank response simulated with Geant4

Getting the Muon Density

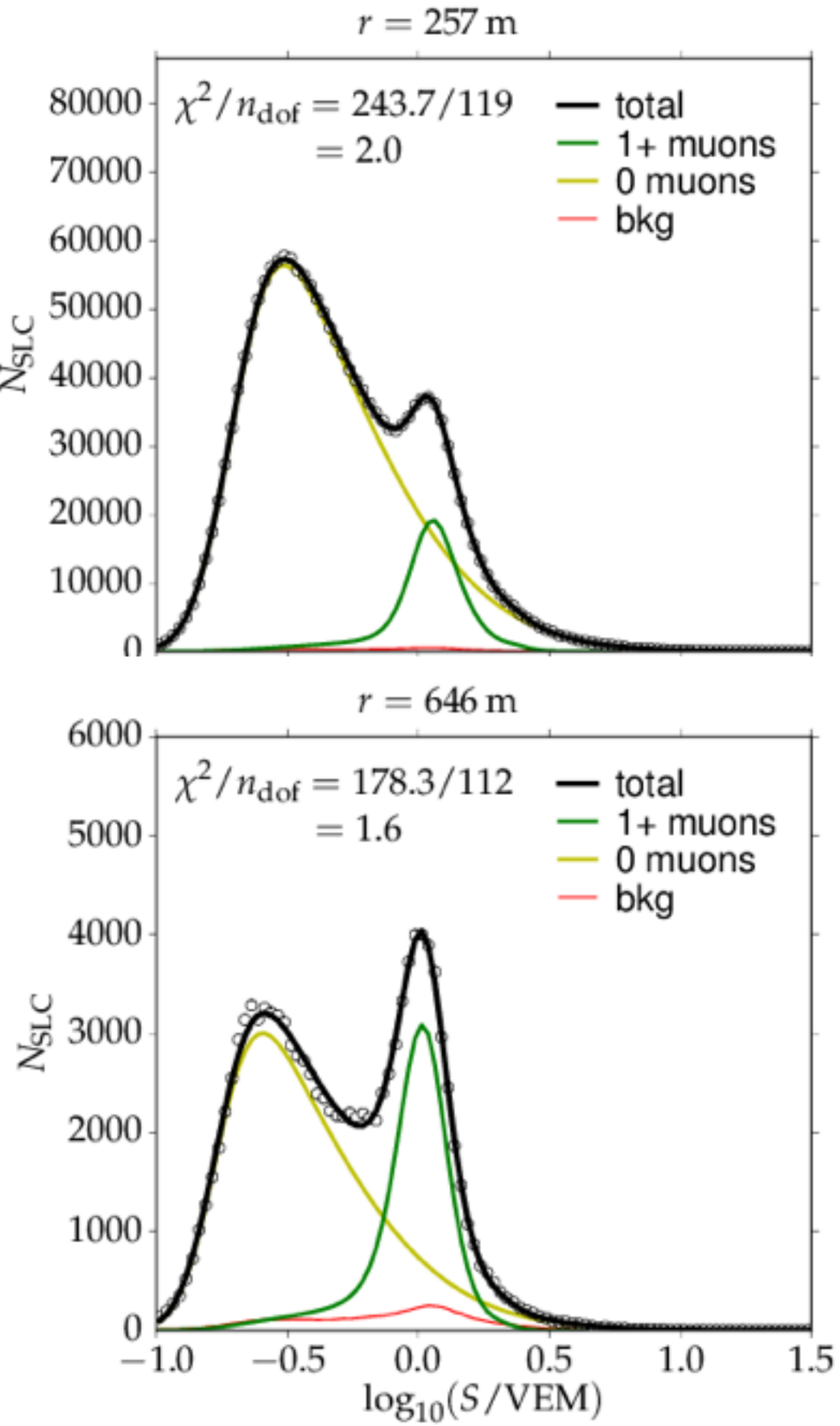
$$\rho_\mu \approx \frac{N_{\text{tanks with muons}}}{N_{\text{all tanks}}} \frac{1}{A_{\text{tank}}}$$



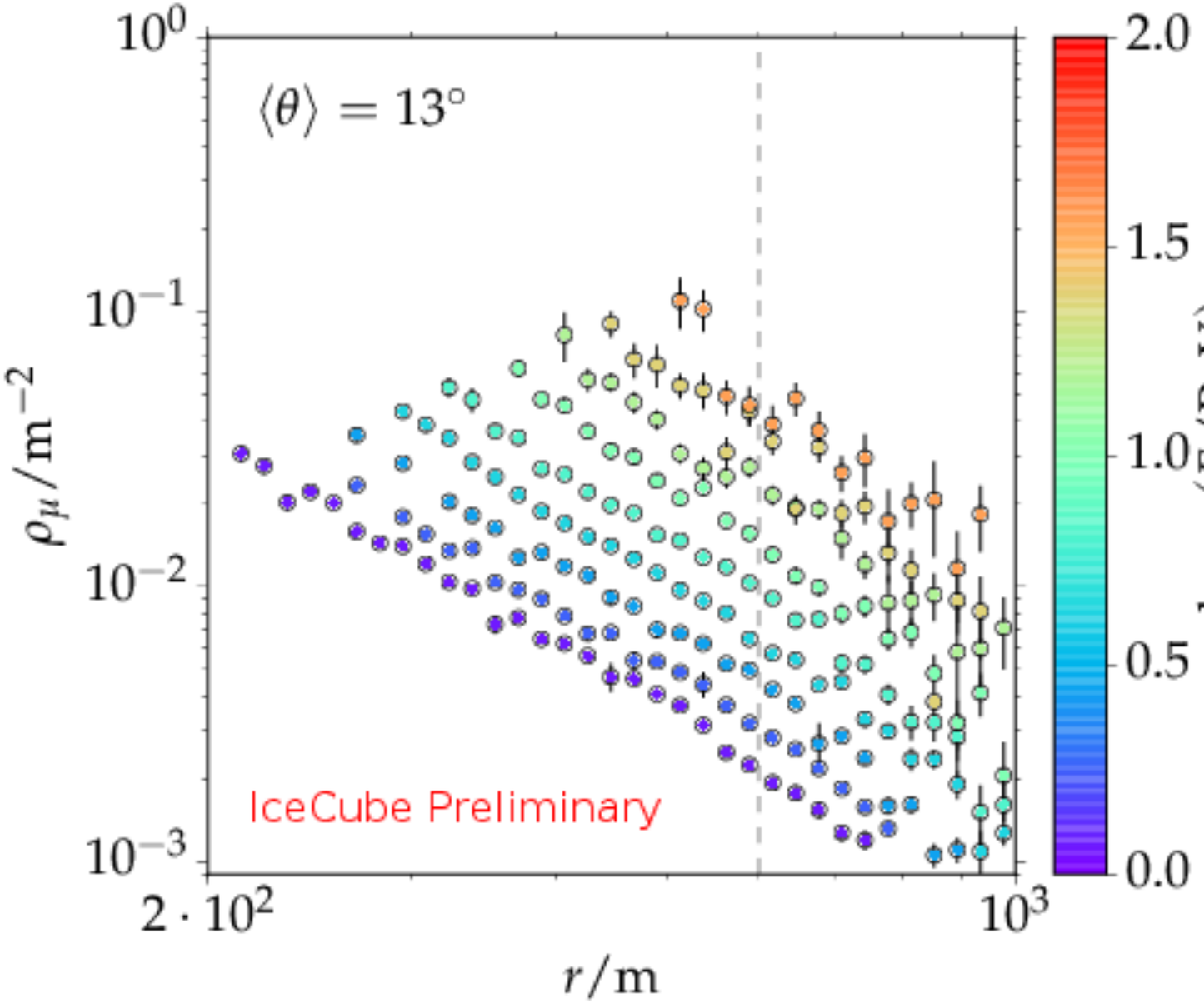


$$p_{\mu\, hit} = \frac{N_{\mu \geq 1}}{N_{tanks}} = 1 - e^{-\langle N_\mu \rangle}$$

Determination in Radial Bins

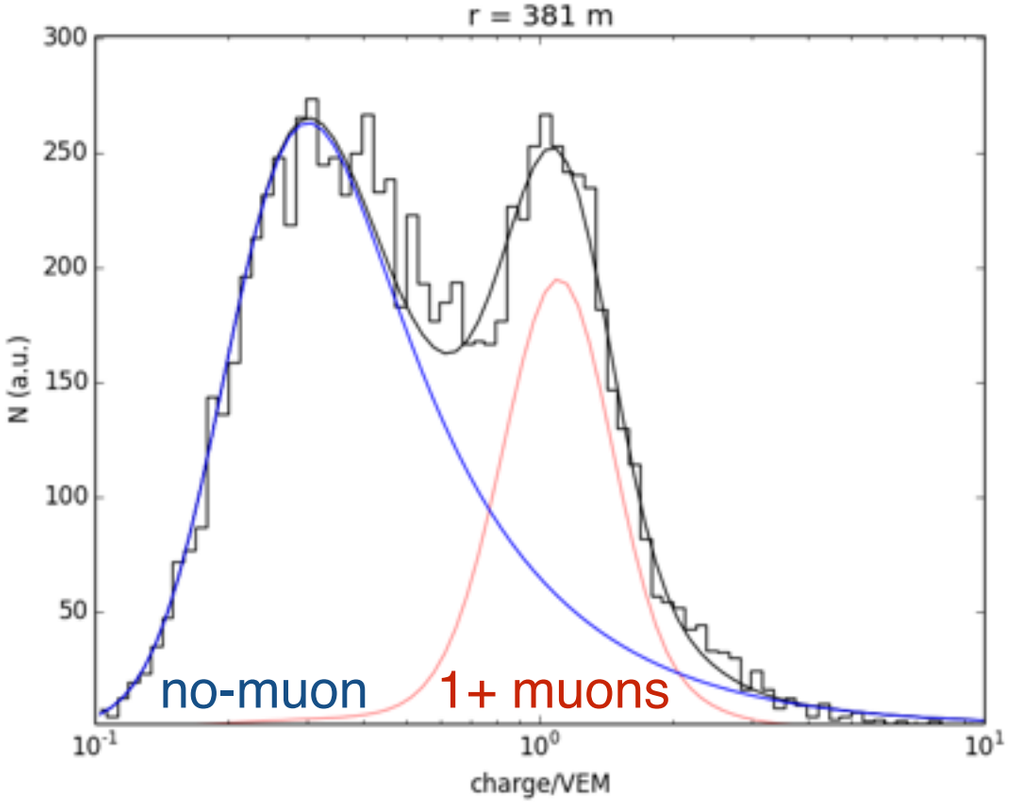


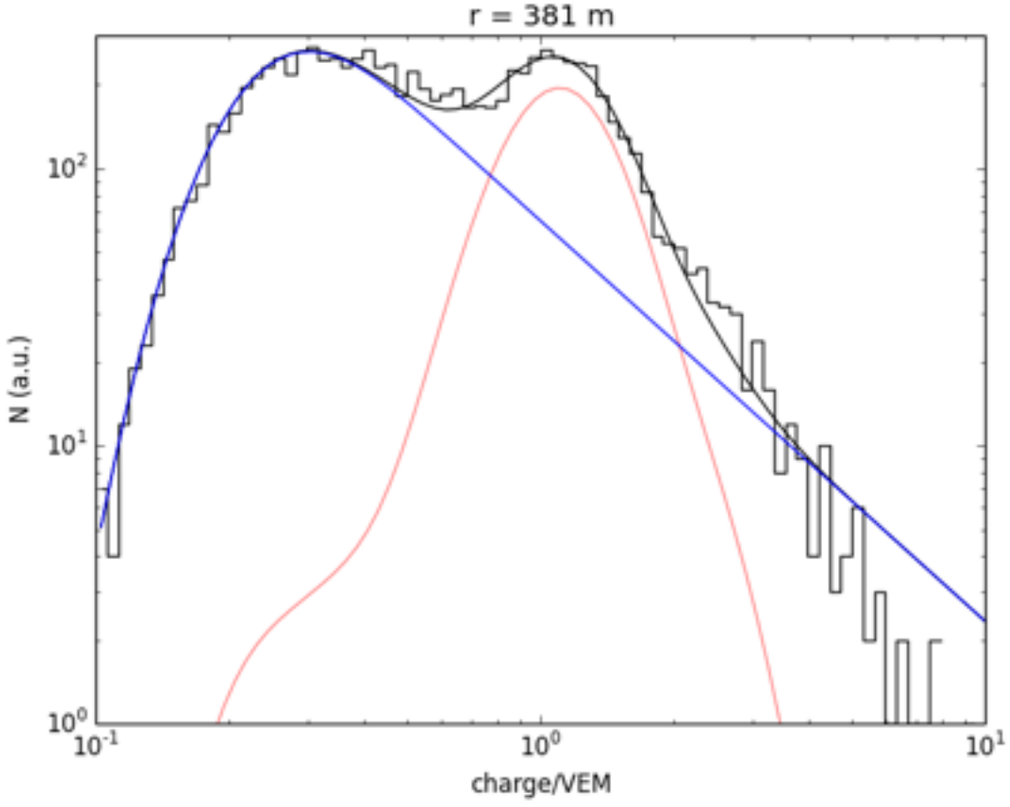
- Standard quality cuts
  (IceCube Collab., M.G. Aartsen et al., PRD 88 (2013) 042004)
- Zenith angle θ < 40°
- Shower size S125 > 1 VEM (~ 1 PeV)
- One month of data (June 2011)



Some Systematic Effects

Energy Uncertainty	11%
Shape of no-muon distribution	~20% (?)
Snow (other than through Energy)	~3%





(old plots to illustrate the point)

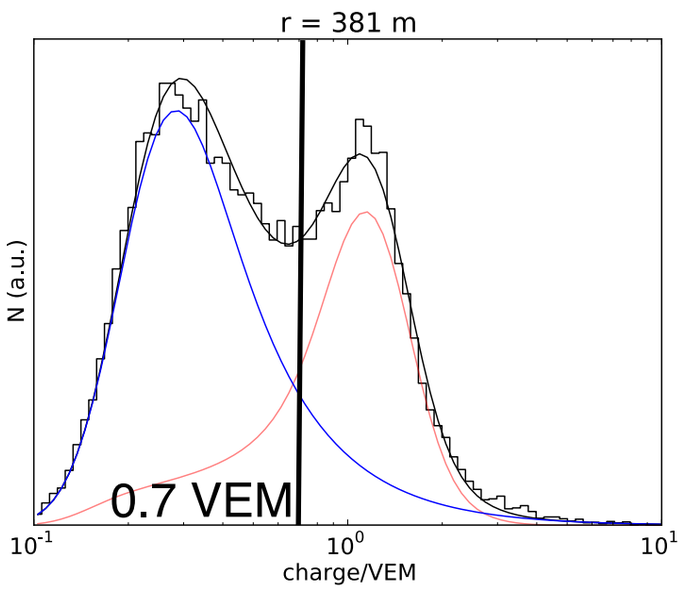
Some Systematic Effects

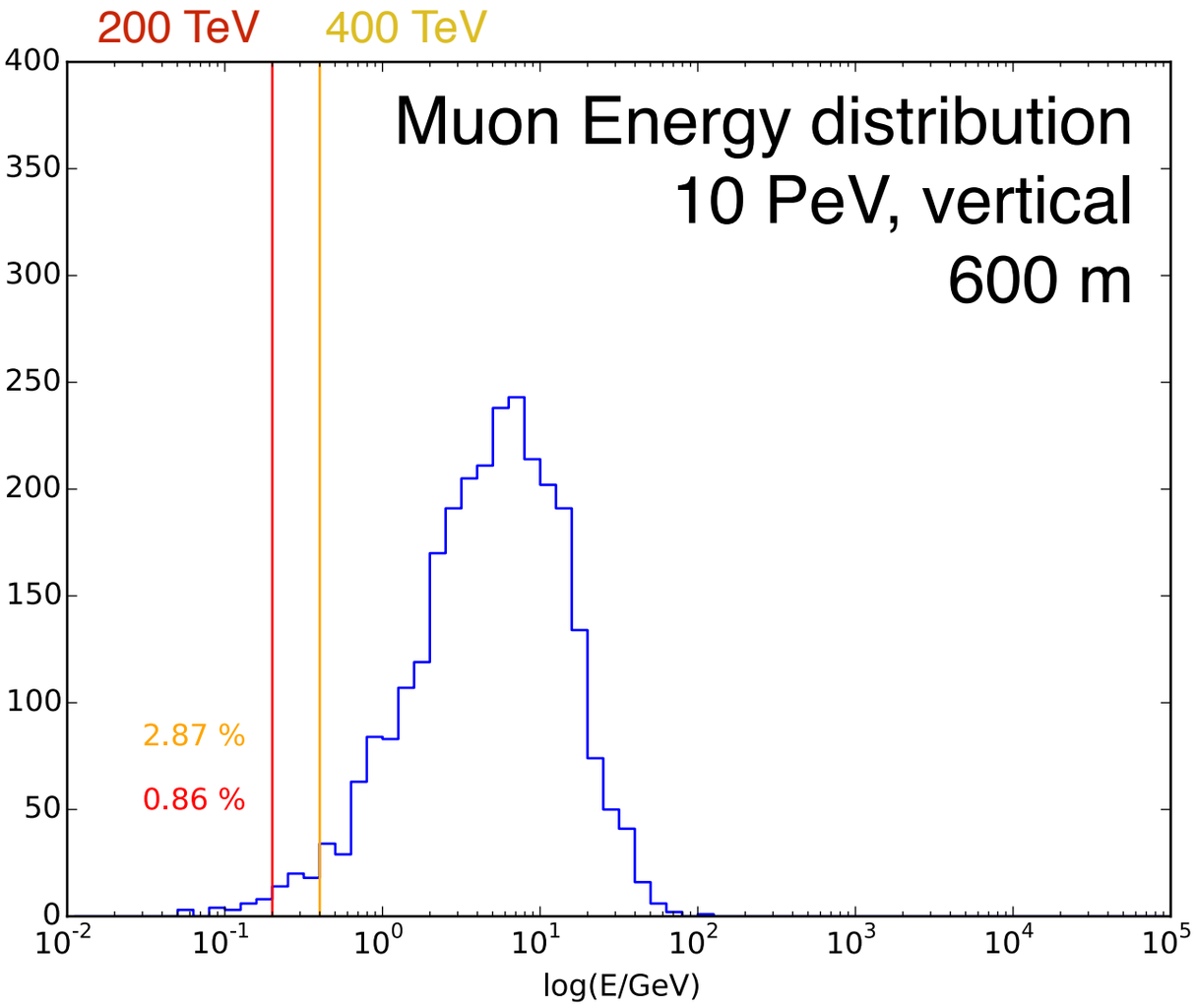
Energy Uncertainty	11%
Shape of no-muon distribution	~20% (?)
Snow (other than through Energy)	~3%

1 VEM ~ 180 MeV

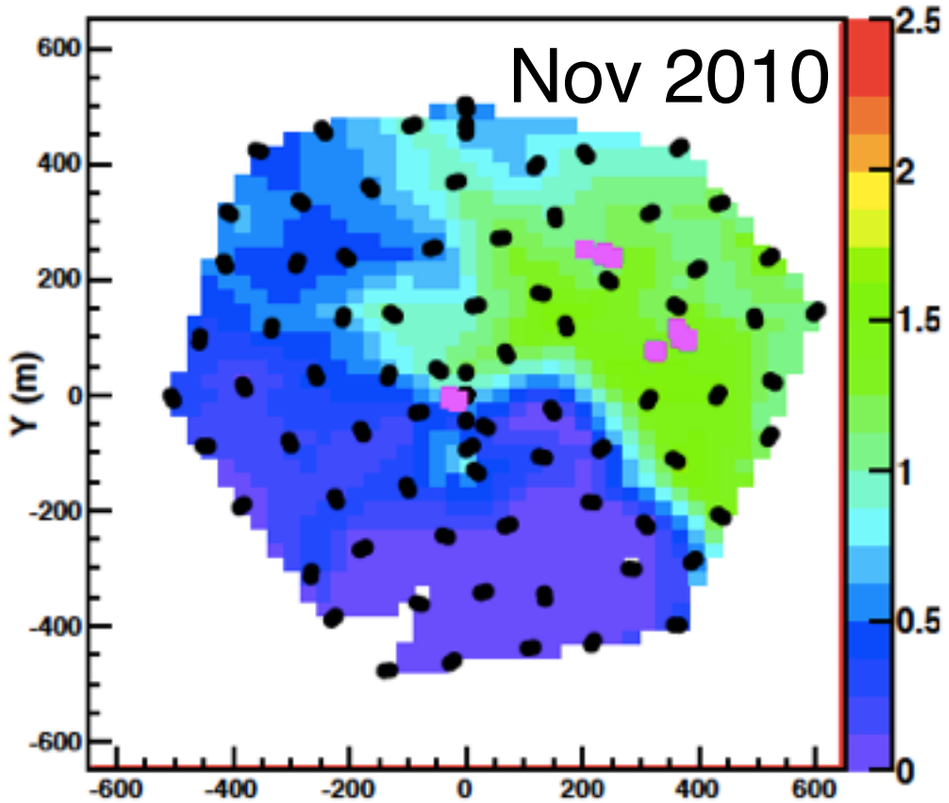
MIP through 2 m of snow
0.34 to 0.40 g/cm^3

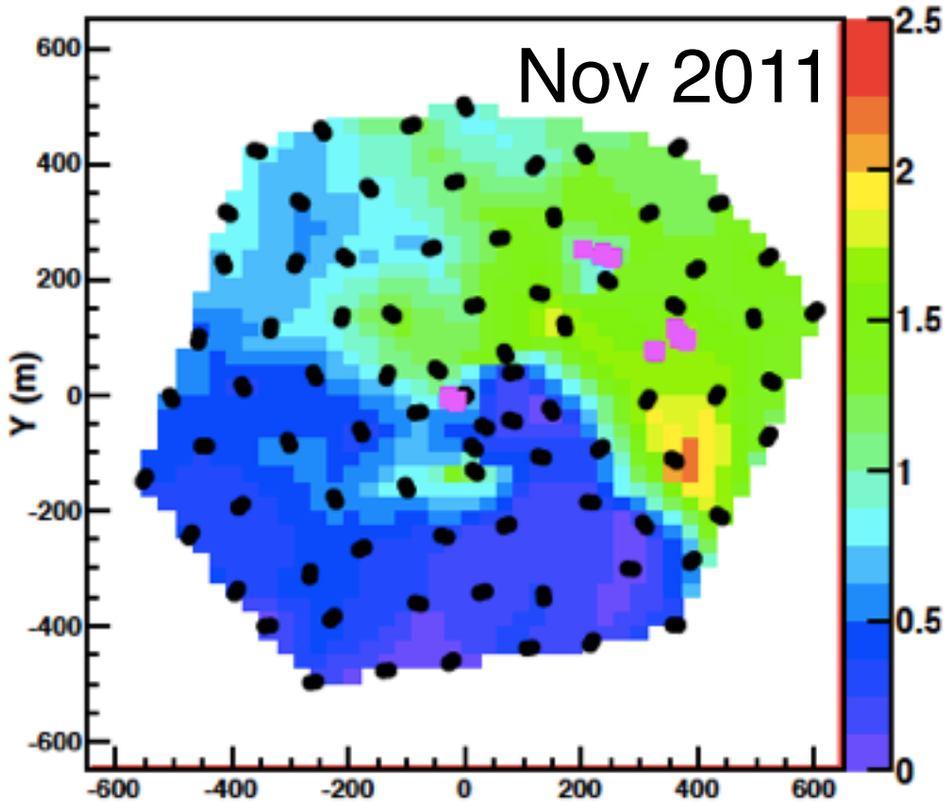
~80 MeV

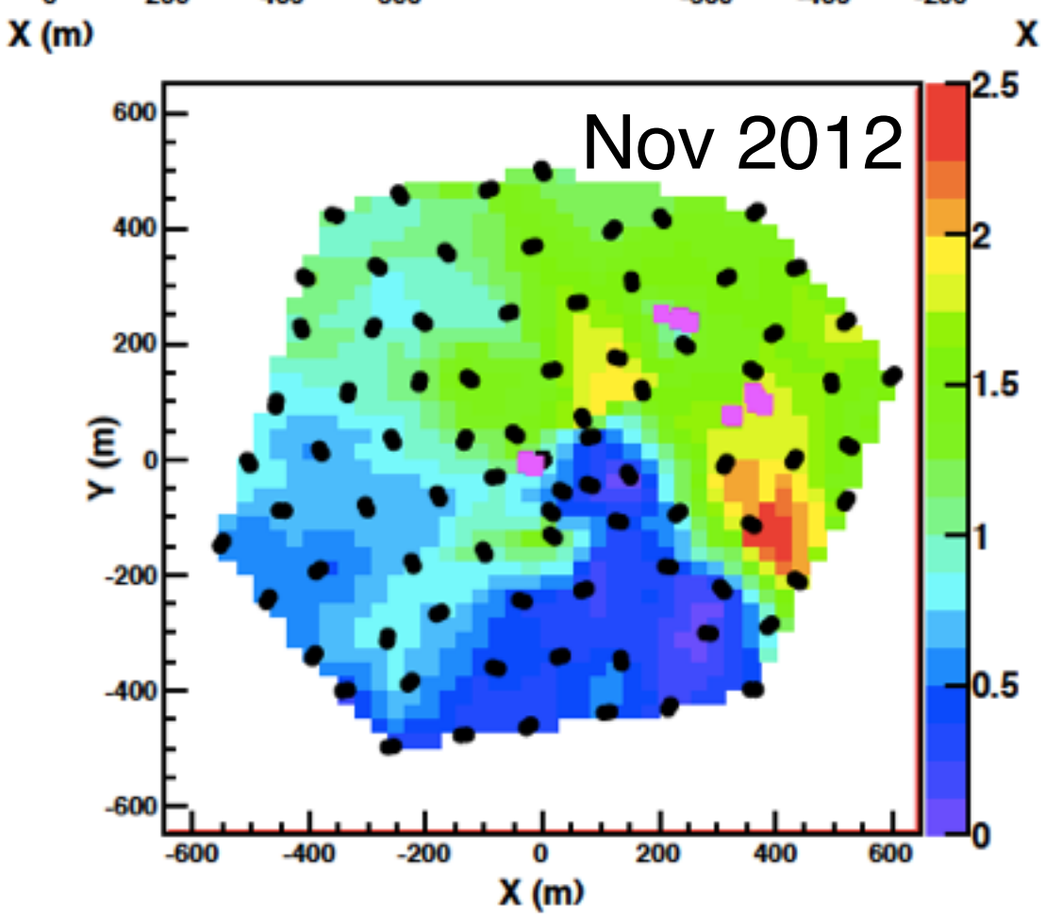




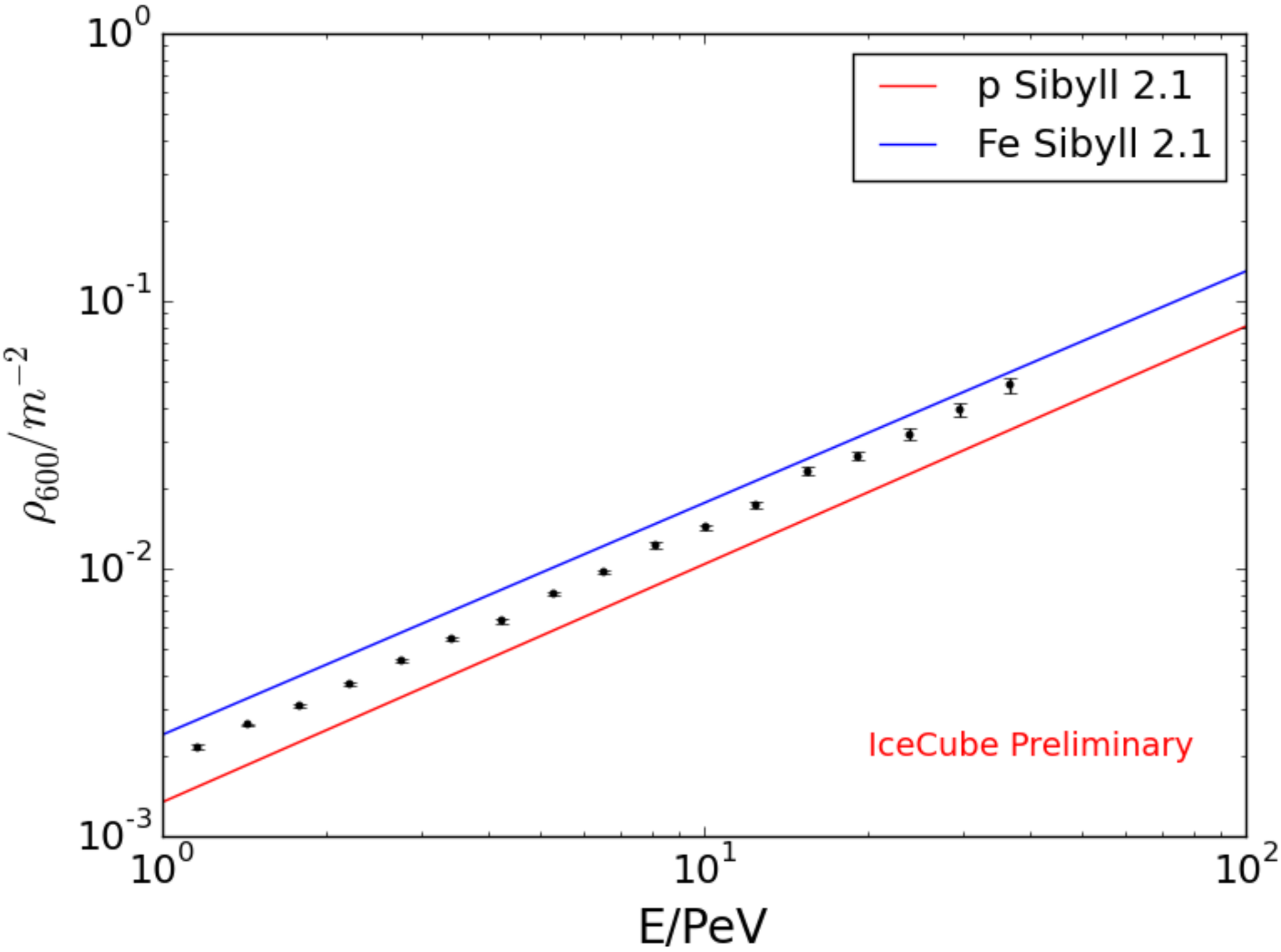
Snow Heights







Muon Number Vs Energy



IceCube collaboration, ISVHECRI 204, arxiv:1501.03415

Abu-Zayyad et al. [HiRes-MIA~Collaboration] Phys. Rev. Lett. **84**, 4276 (2000)

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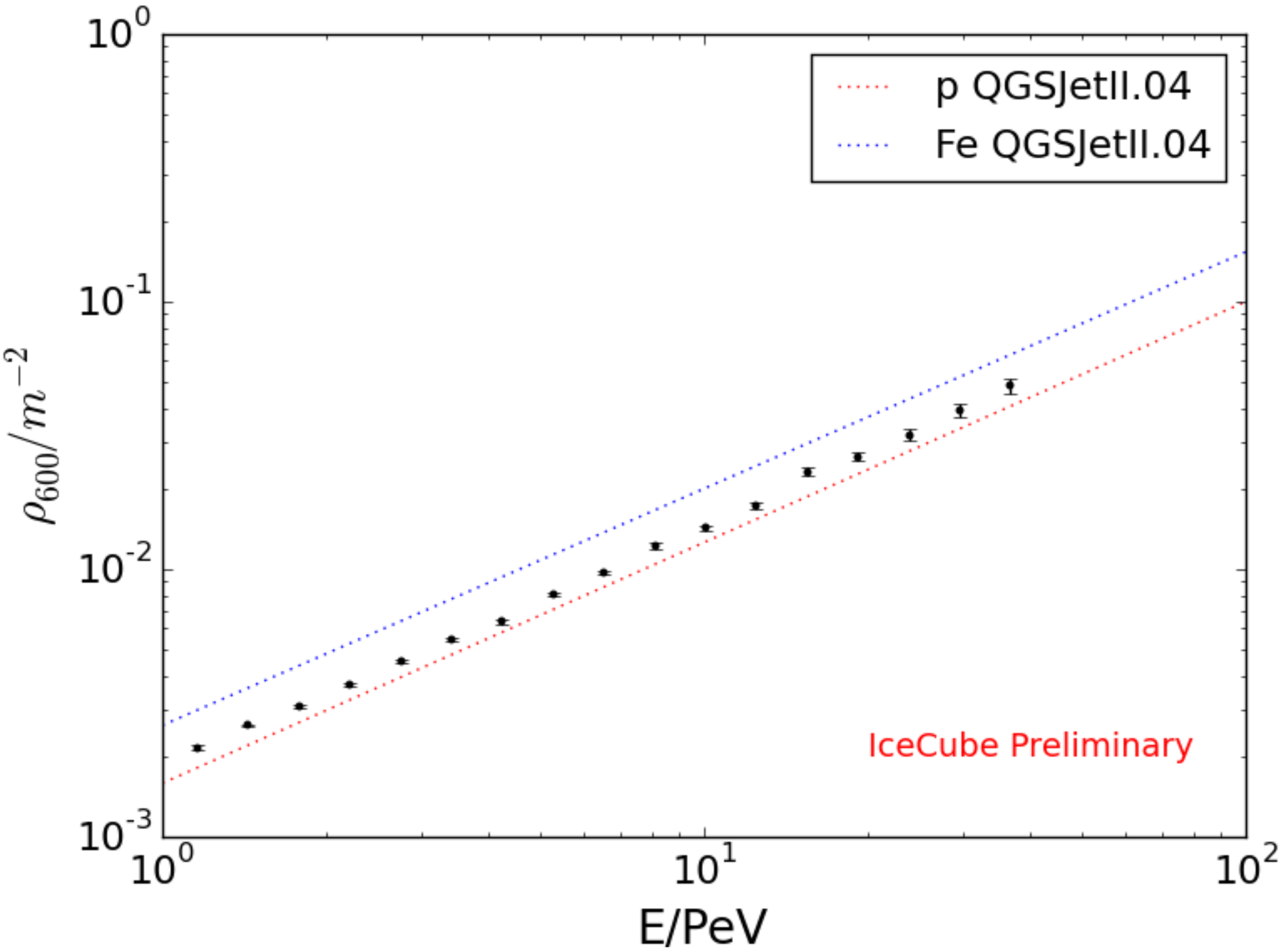

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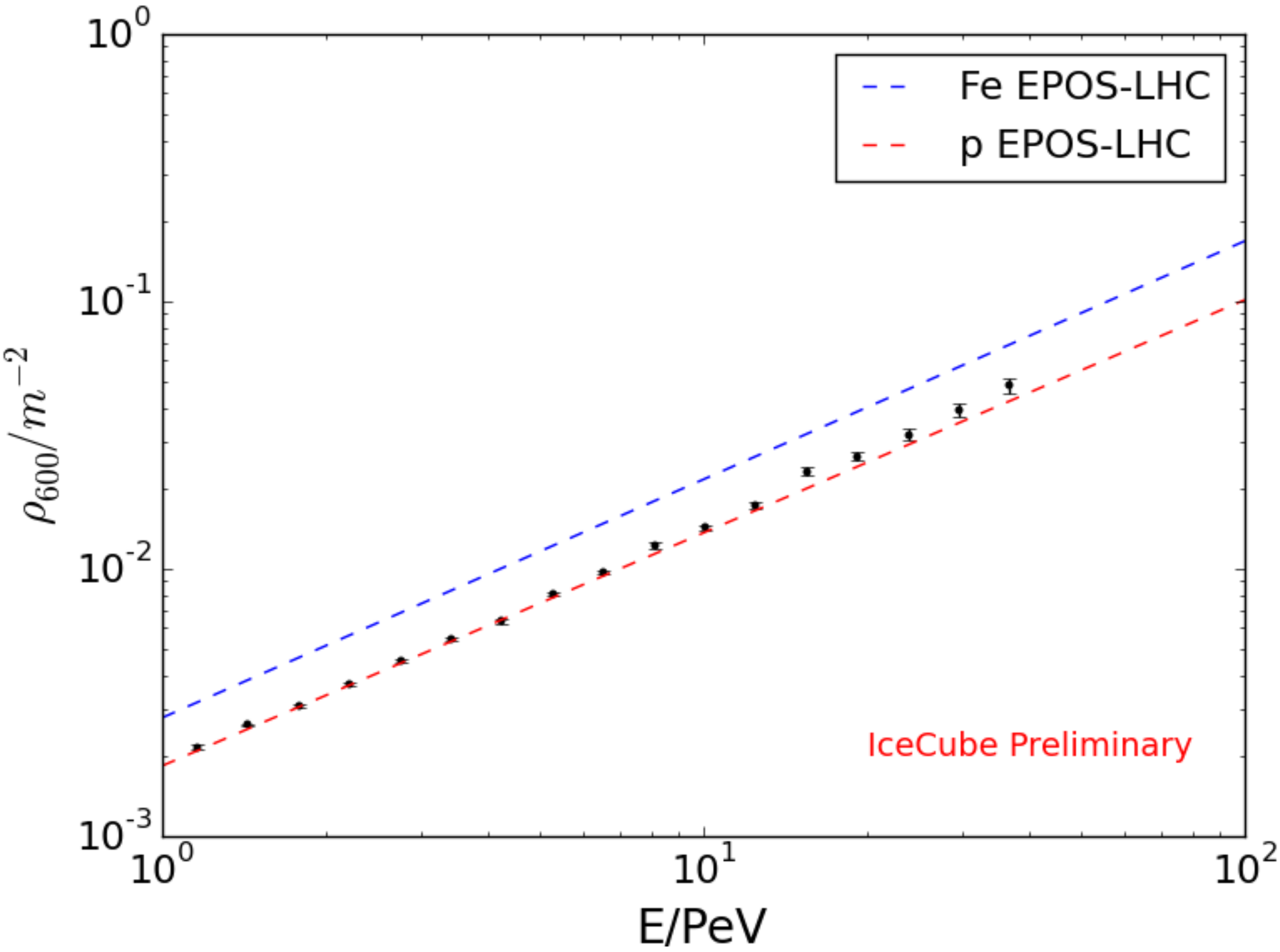

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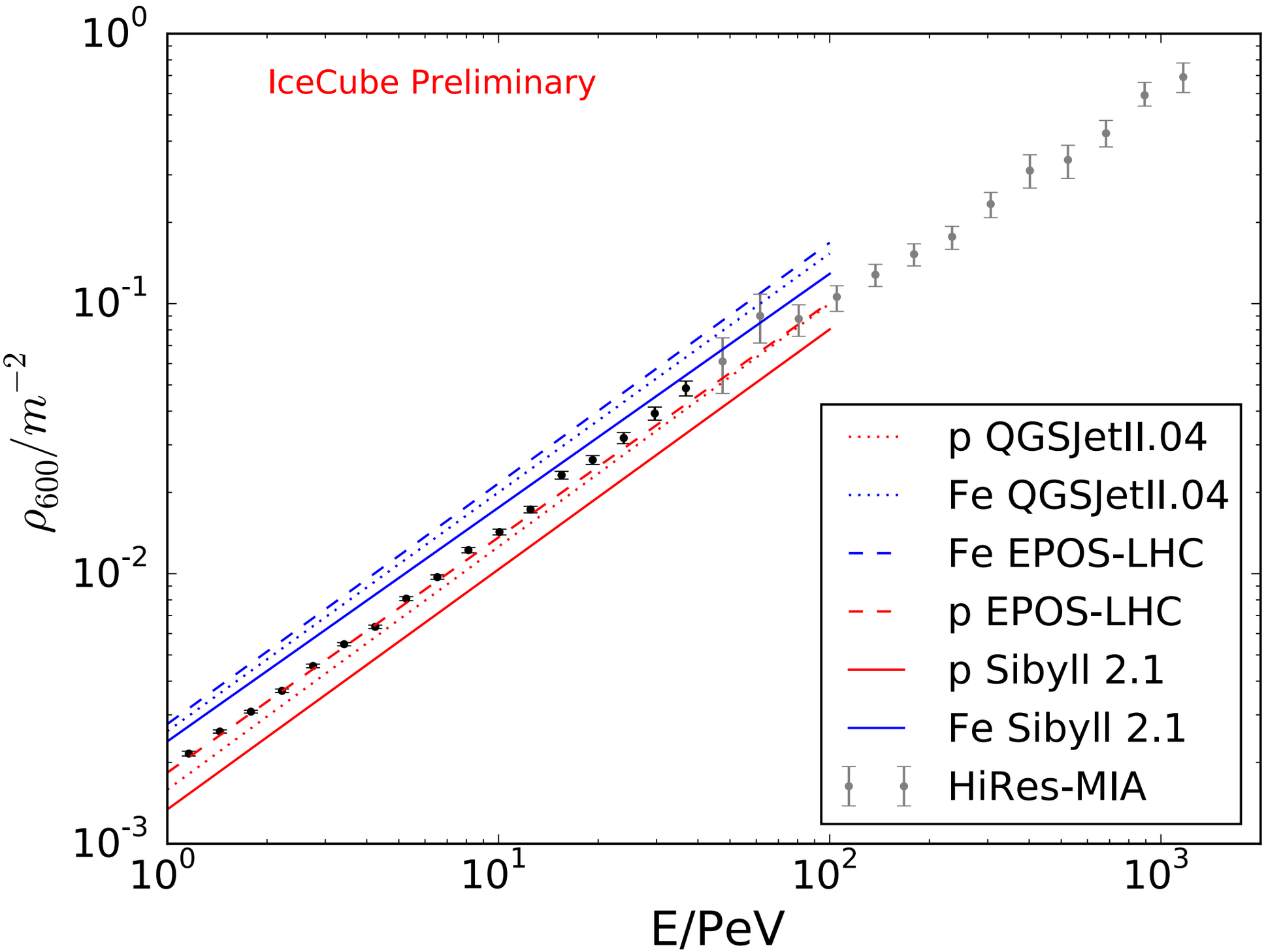

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Conclusion

- With IceTop we can measure the average number of muons at large distances from the shower axis. We used 600 m at this time.
  - High-resolution measurement of muon density from 250 m to 1000 m
  - No air shower simulation input (except conversion $S_{125} \leftrightarrow$ energy)
- We draw no conclusion regarding primary composition.
  - ρ_μ(600m) in vertical events bracketed by p/Fe showers simulated with CORSIKA + Sibyll-2.1/EPOS-LHC/QGSJetII.04 + Fluka
- (Dis)Agreement with IceCube/IceTop combined analysis can point to hadronic model effects, but a self-consistent analysis remains to be done.
- Systematic uncertainties under study:
  - EM contribution. A change in parametrization can alter the result.
  - Snow can introduce small effects in threshold.
  - Checks with air shower simulations.