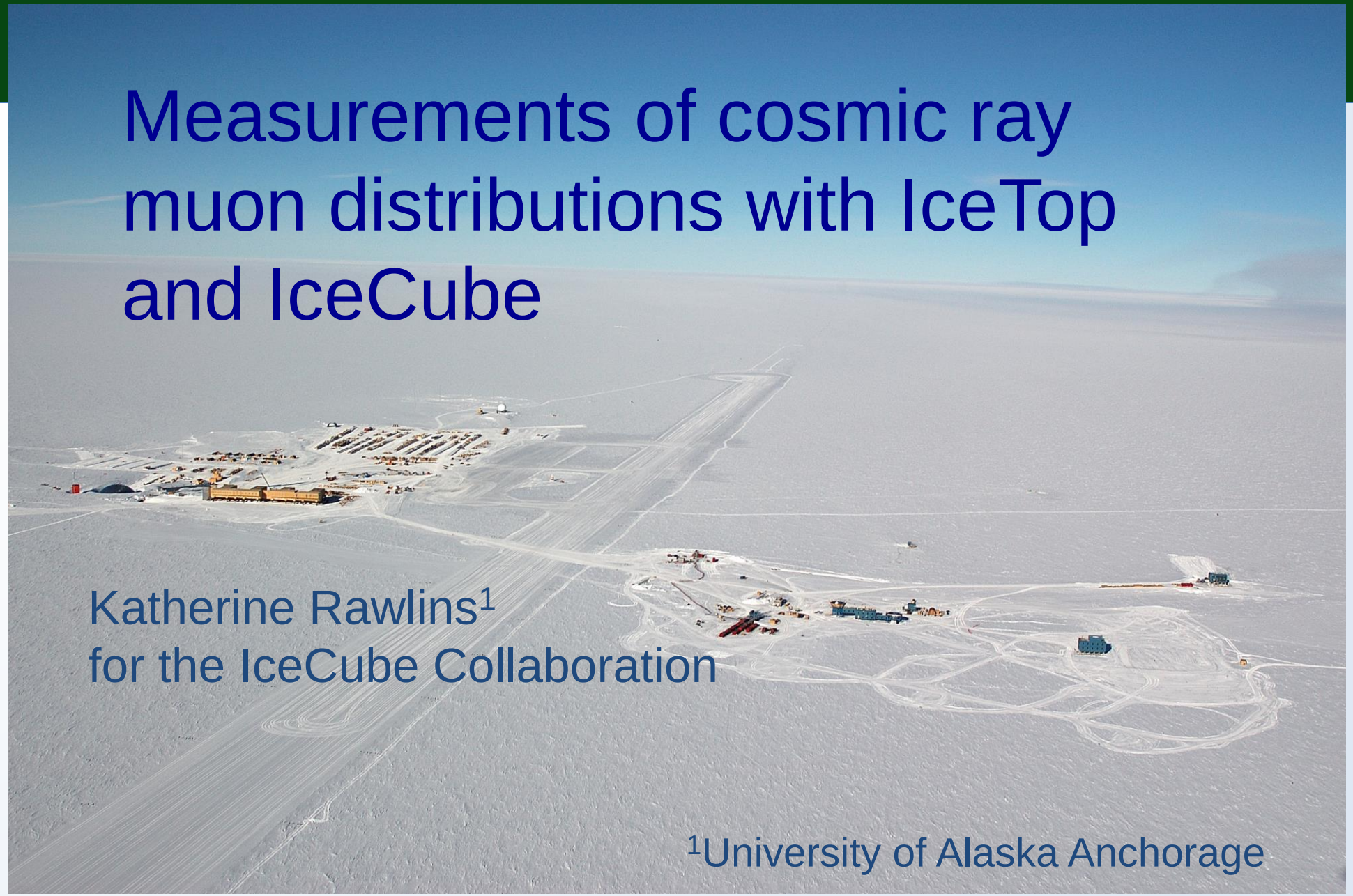
Measurements of cosmic ray muon distributions with IceTop and IceCube



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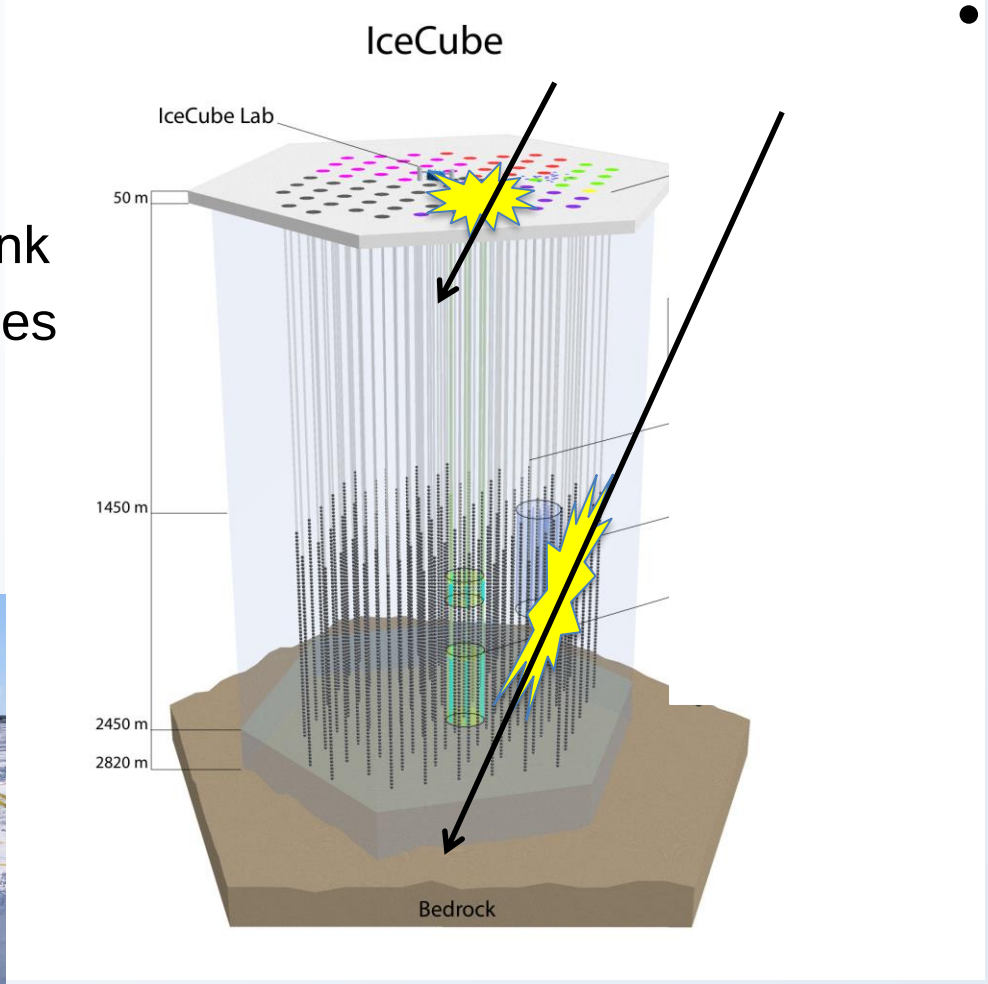
IceCube: components and CR analyses

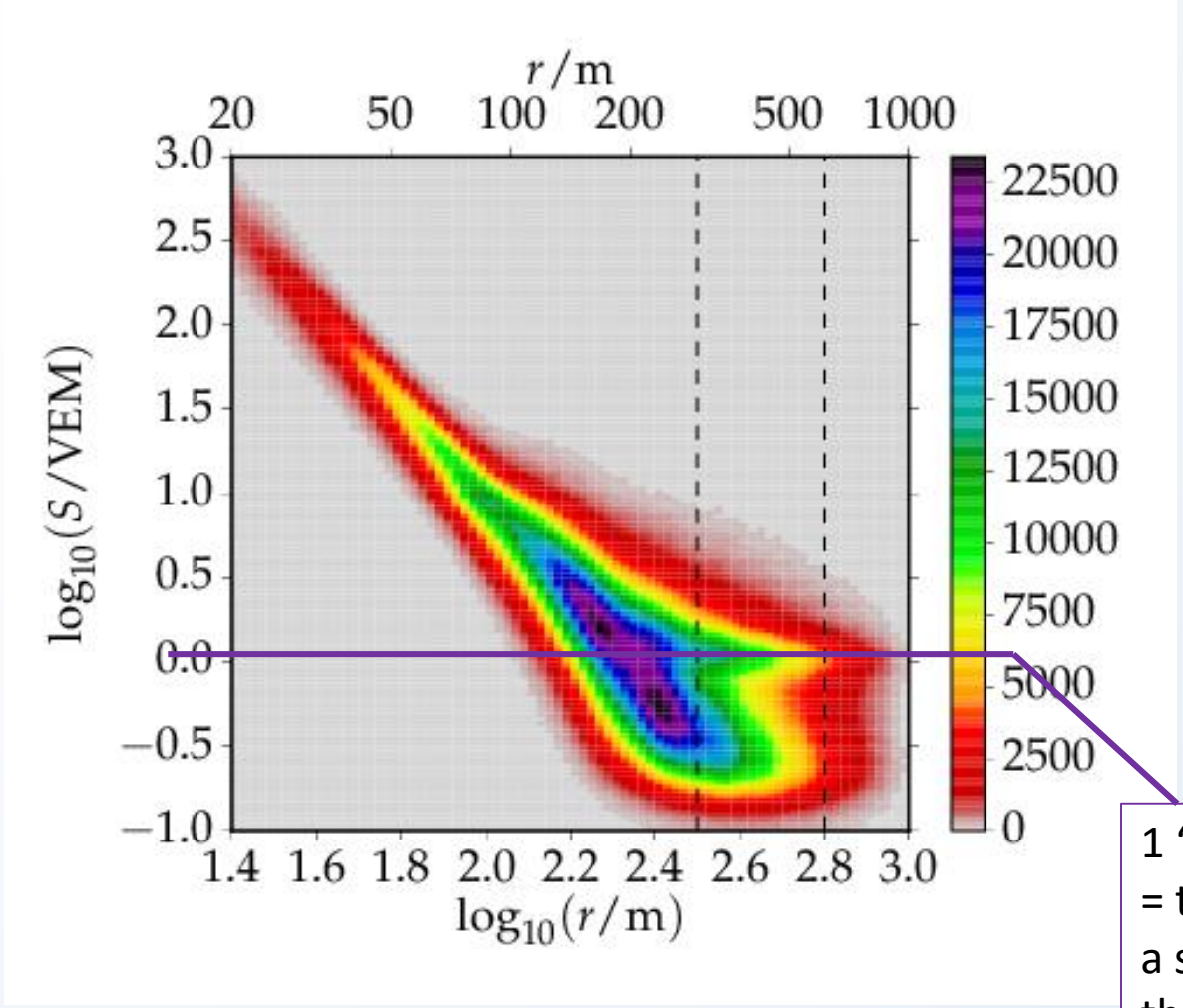
- IceTop
  - 81 “stations” of two frozen water tanks
  - Two DOM’s in each tank
  - Sensitive to EM particles and GeV muons



- “In-Ice” detector
  - 86 strings of DOM’s
  - Deployed 1450-2450 meters depth
  - Sensitive to TeV muons

Part 1: IceTop (GeV) muons

Anatomy of IceTop signal distributions:

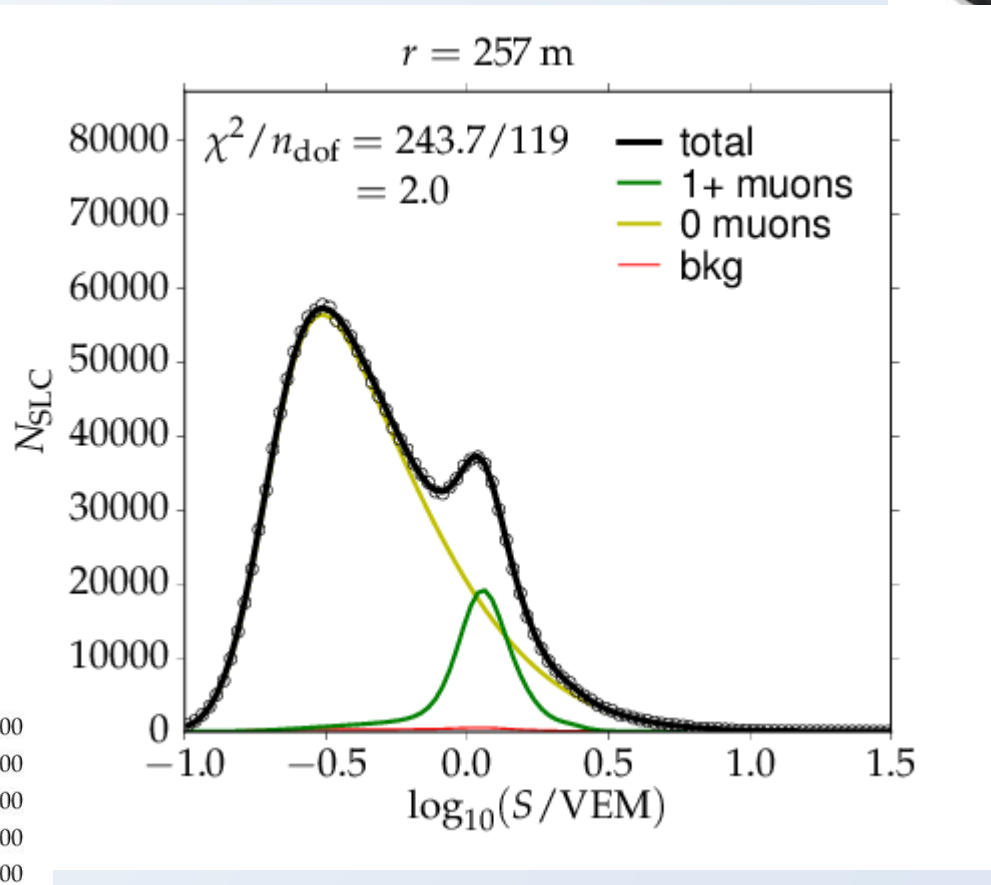


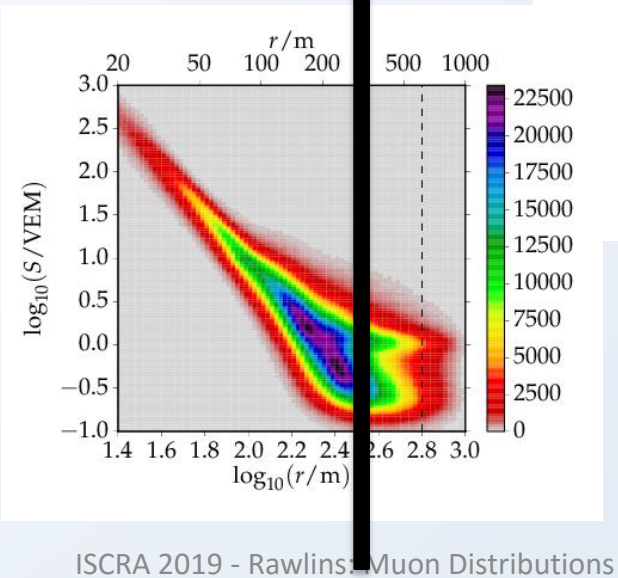
- EM signals dominate near the core of the shower.
- At larger distances, the EM component weakens, and signals from single muons become visible

1 “VEM” = “Vertical Equivalent Muon” = the amount of charge deposited by a single muon going straight down through a tank.

Fitting the EM component and muon component:

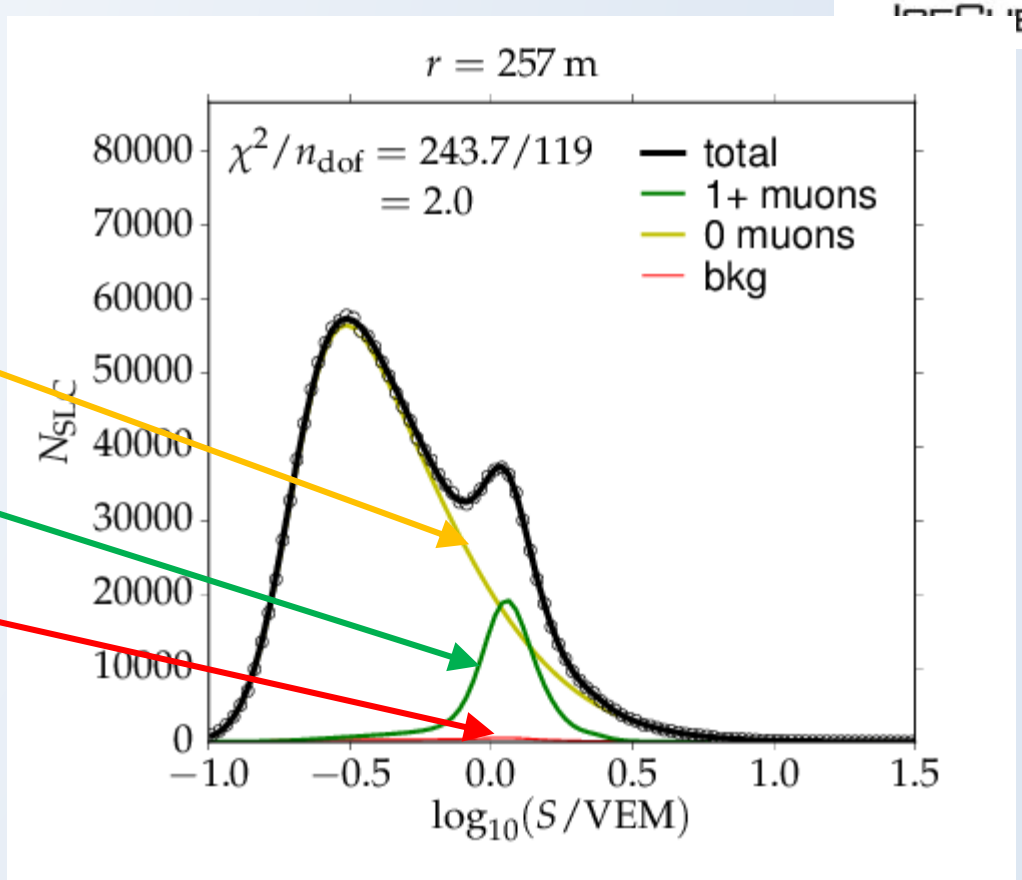
- Look at the distribution of charges within a “slice” at a particular radius
  - The signal is still dominated by EM particles
  - A “lump” from the muon contribution can be distinguished, at about 1 VEM





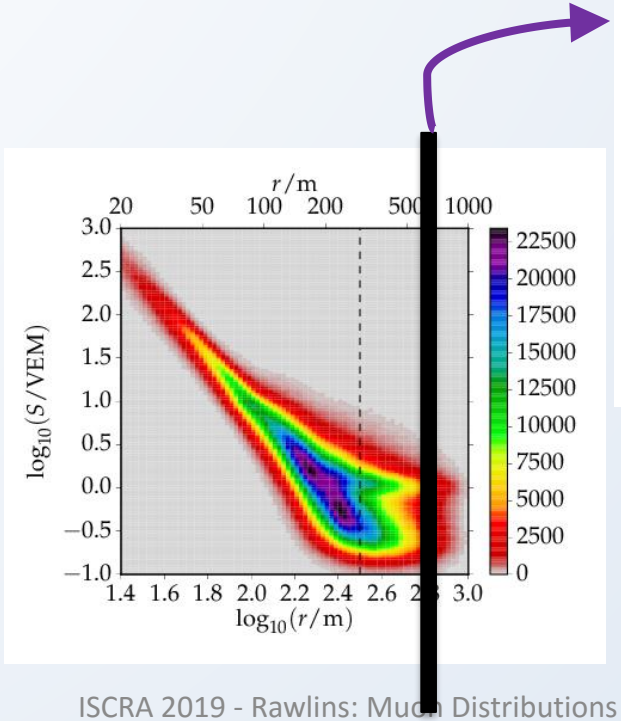
Fitting the EM component and muon component:

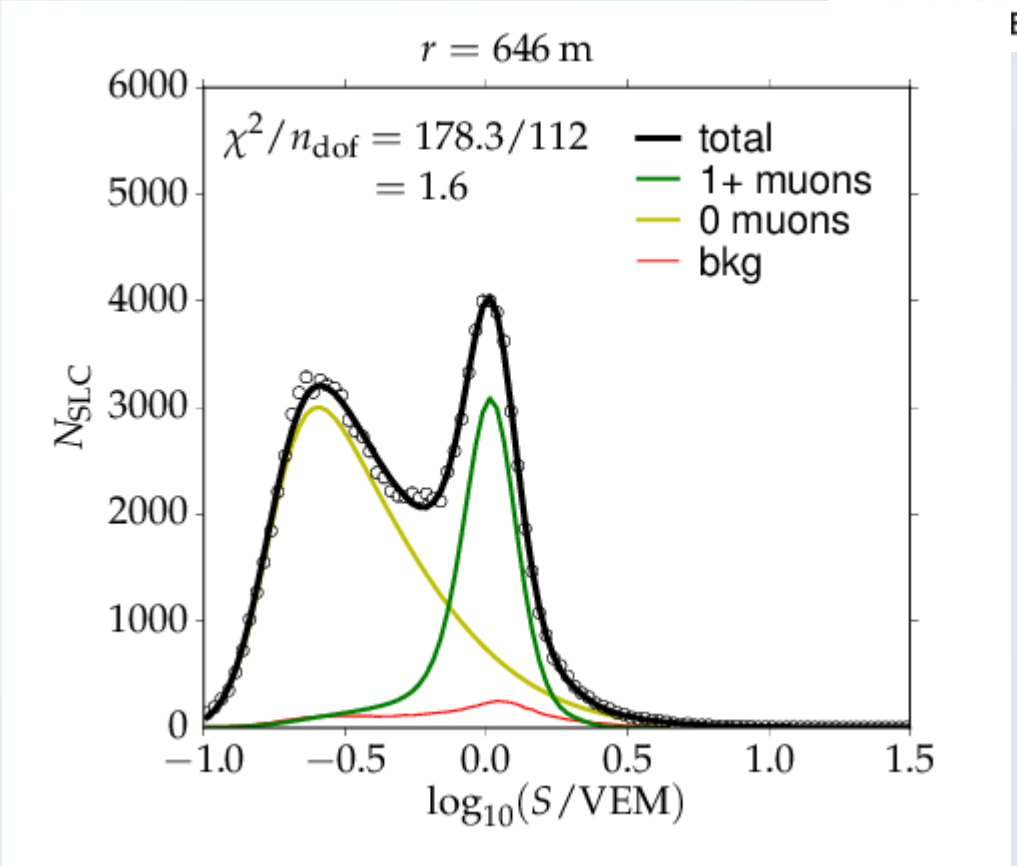
- Fit the overall distribution to three contributions:
  - An EM component (power law + threshold behavior)
  - A muon component (single VEM's, modulated by geometry
  - Background from accidental coincidence hits
- The average number of muons <N> is one of the results of the fit



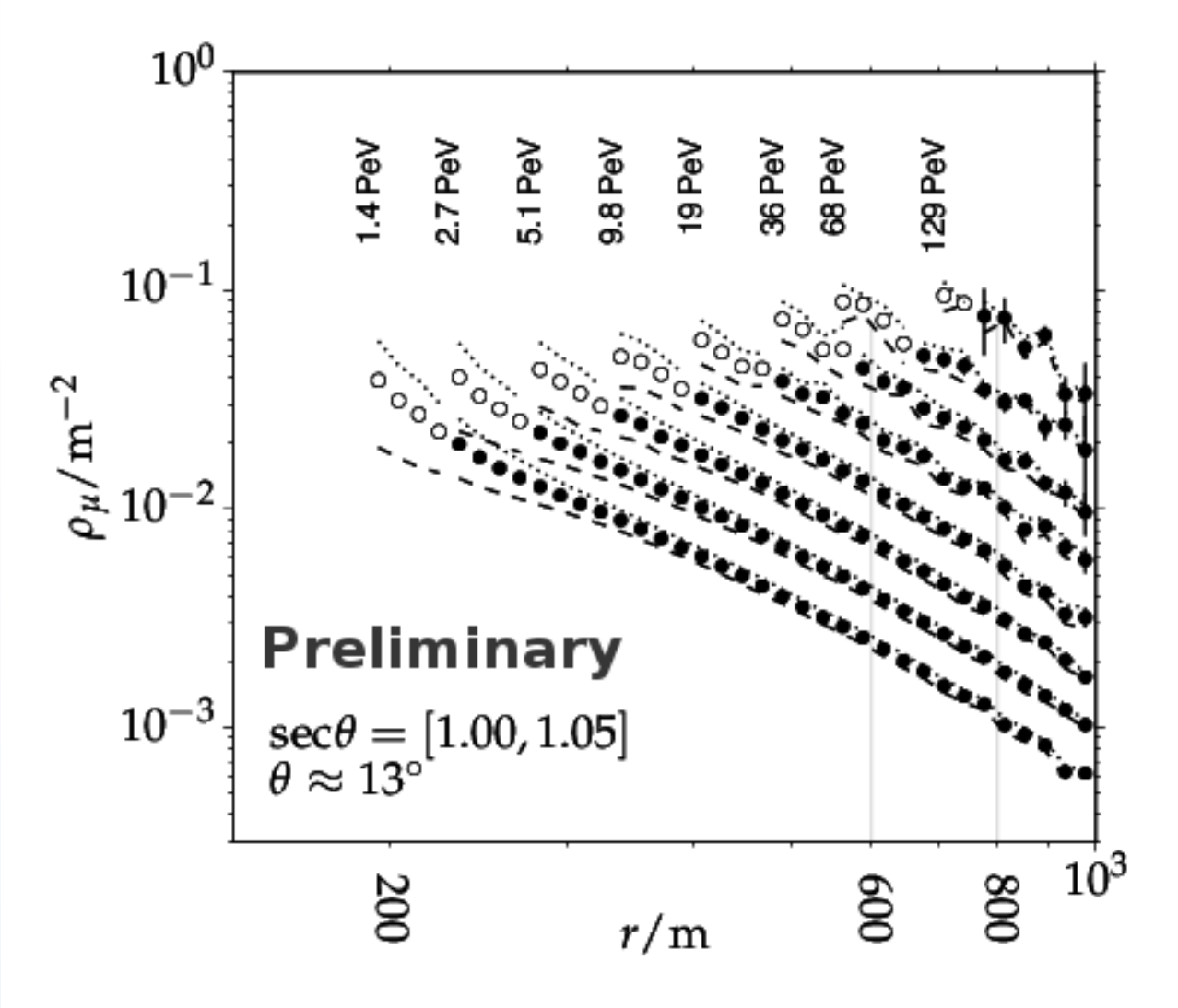
Larger distances:

- The muon “thumb” becomes more pronounced





Assemble many of these measurements:

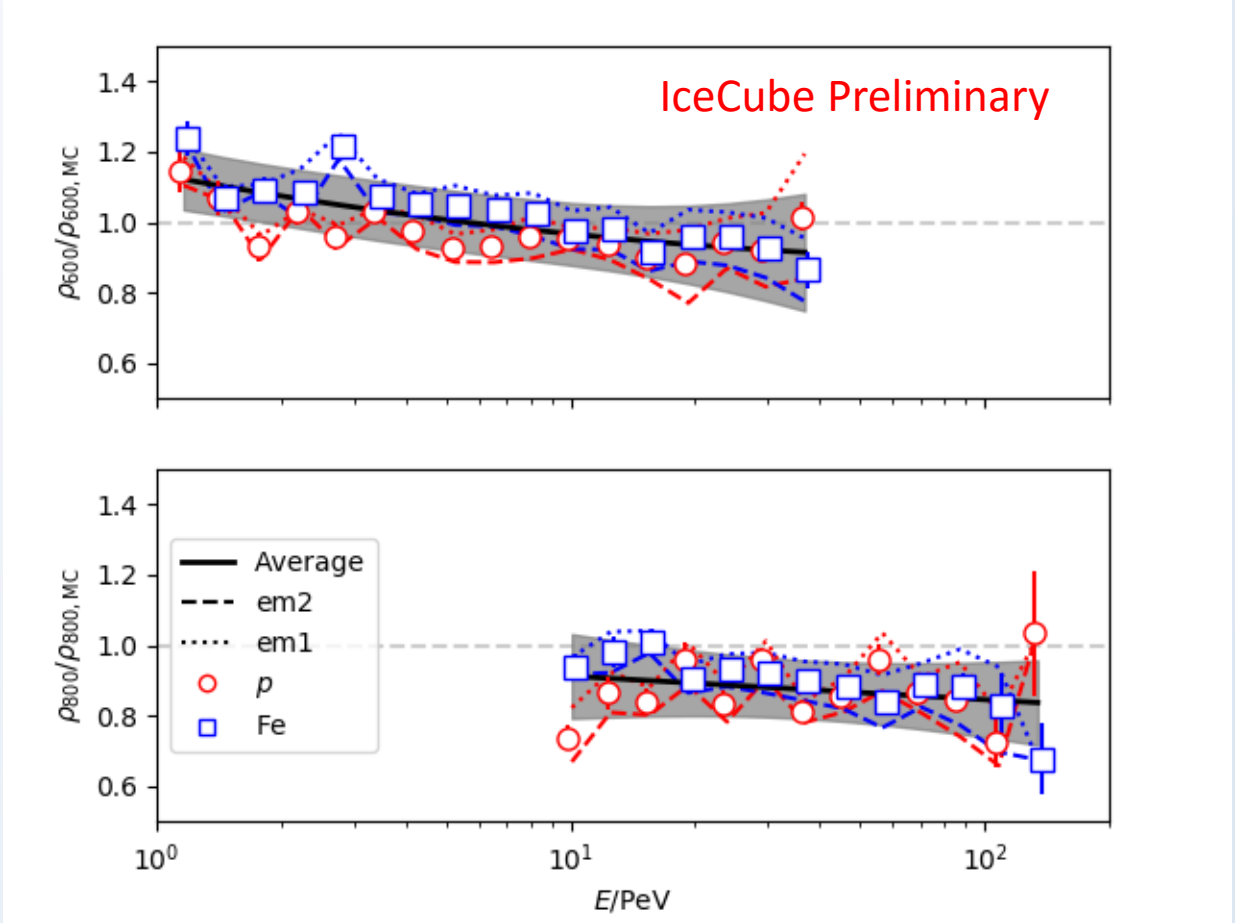


- Different distances…
- Different energies…

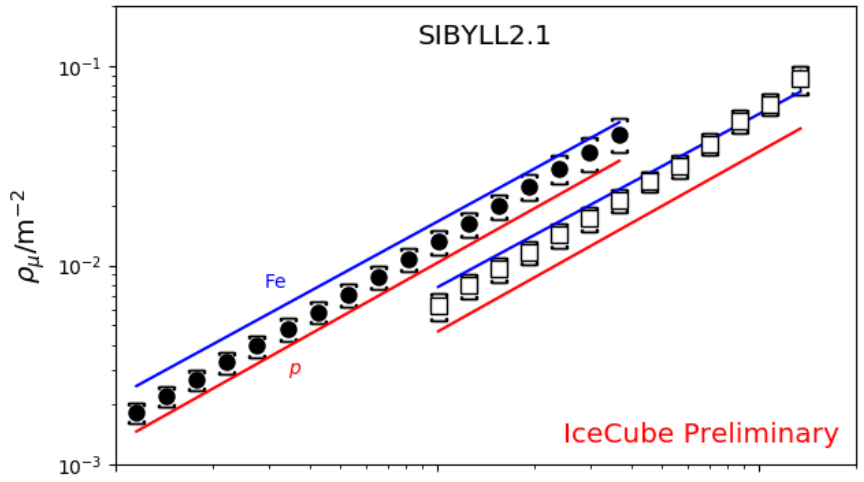
- Find the muon density ρ_μ at two reference distances: 600m and 800m

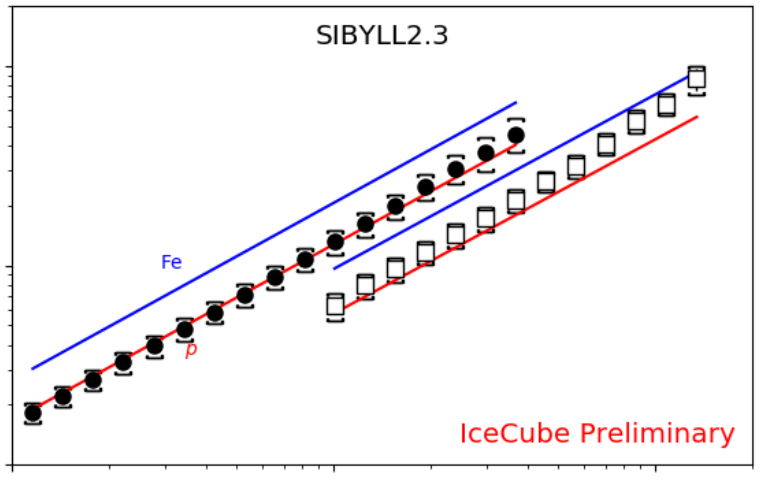
Apply a correction factor

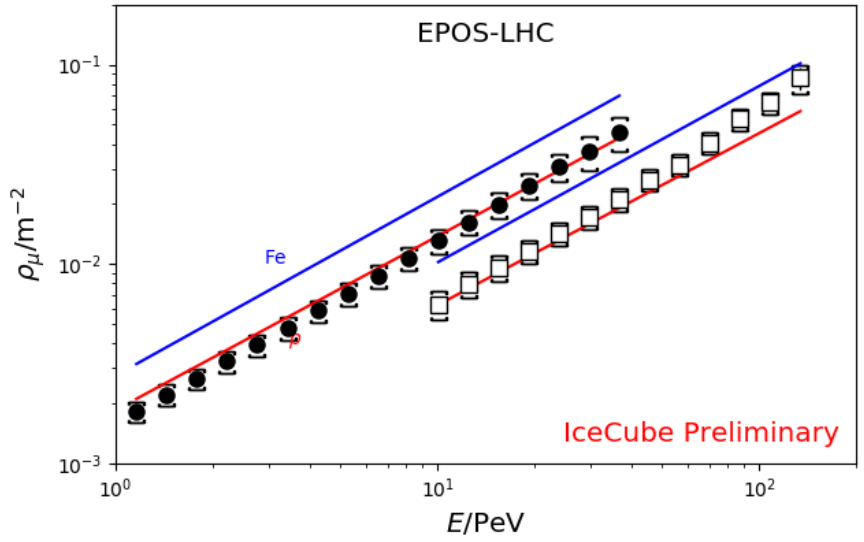
- Can do this for both MC and data
- In MC, we can also extract the *true* ρ_μ, which is a little different due to various systematic effects

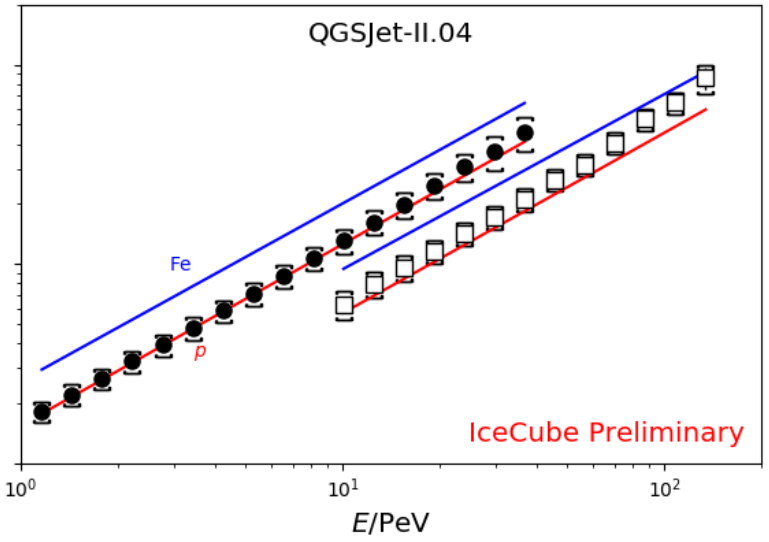


Results: Measured muon density

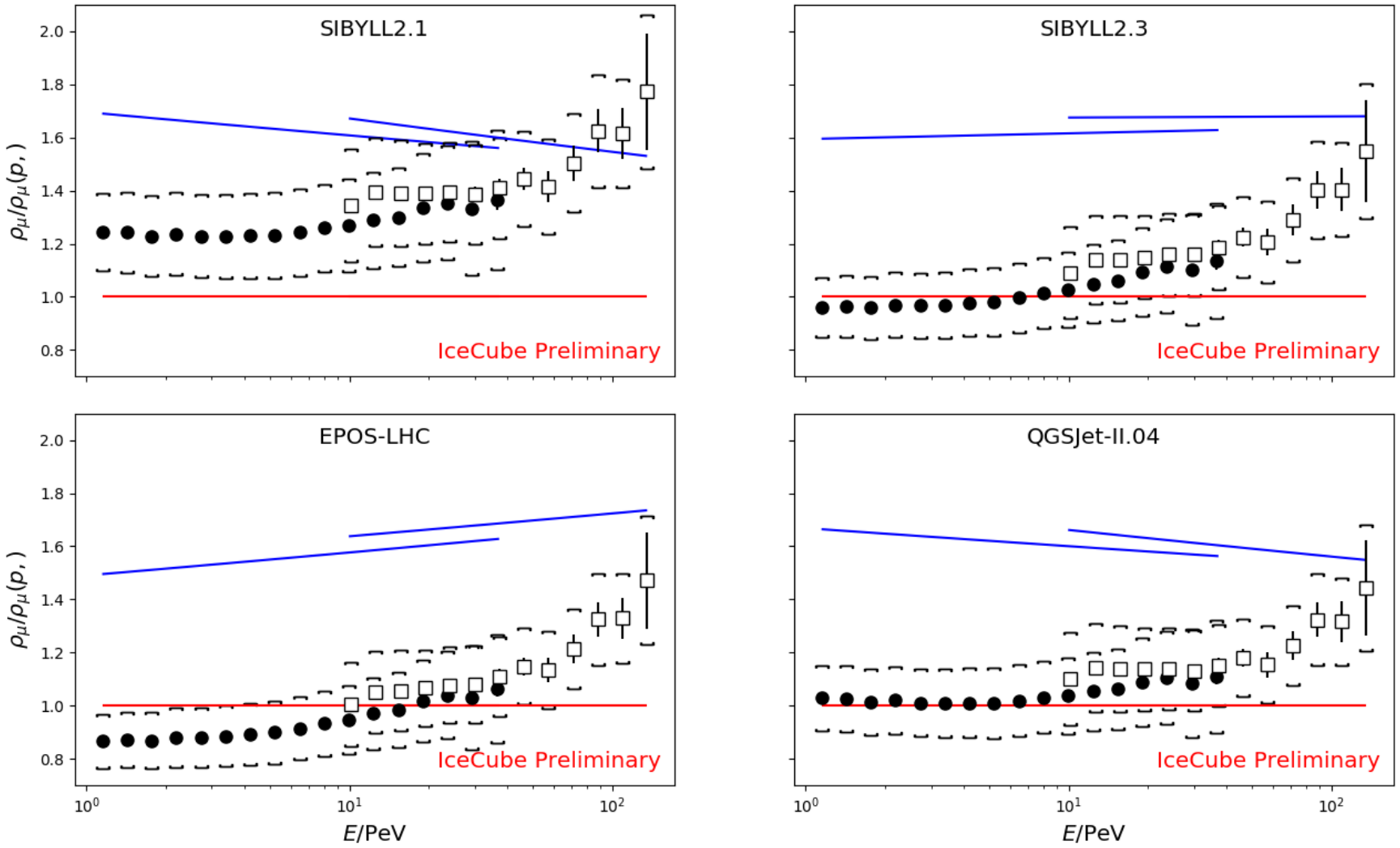




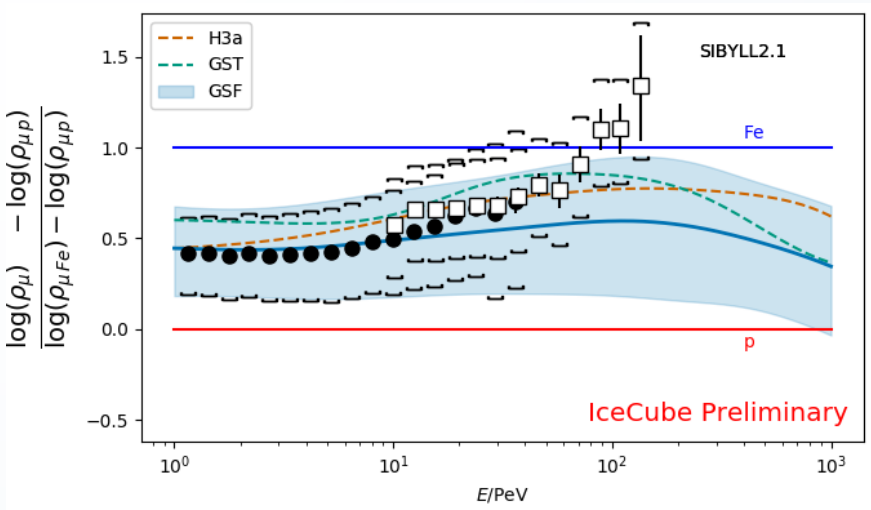


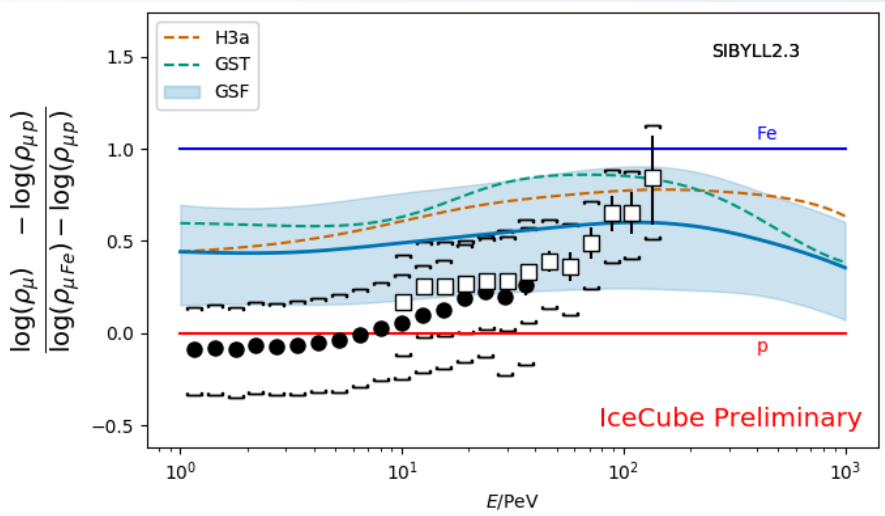


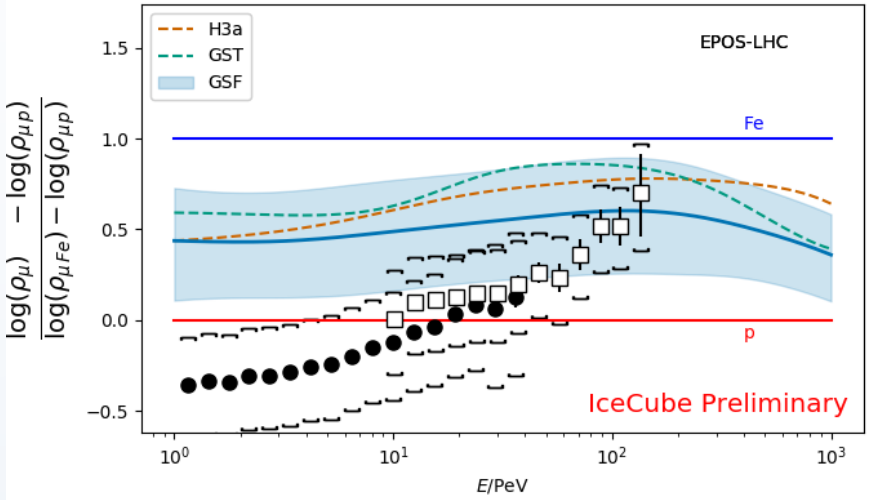
Results: Expressed relative to ρ_μ for protons

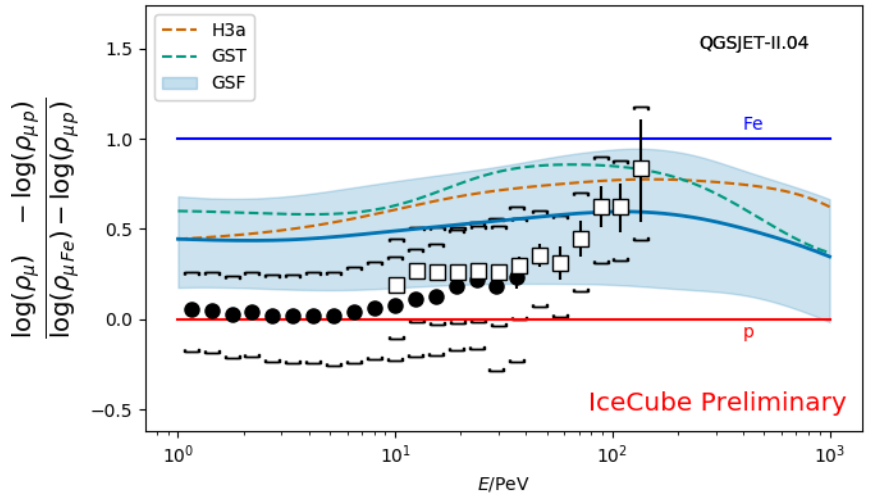


Compared to various composition models







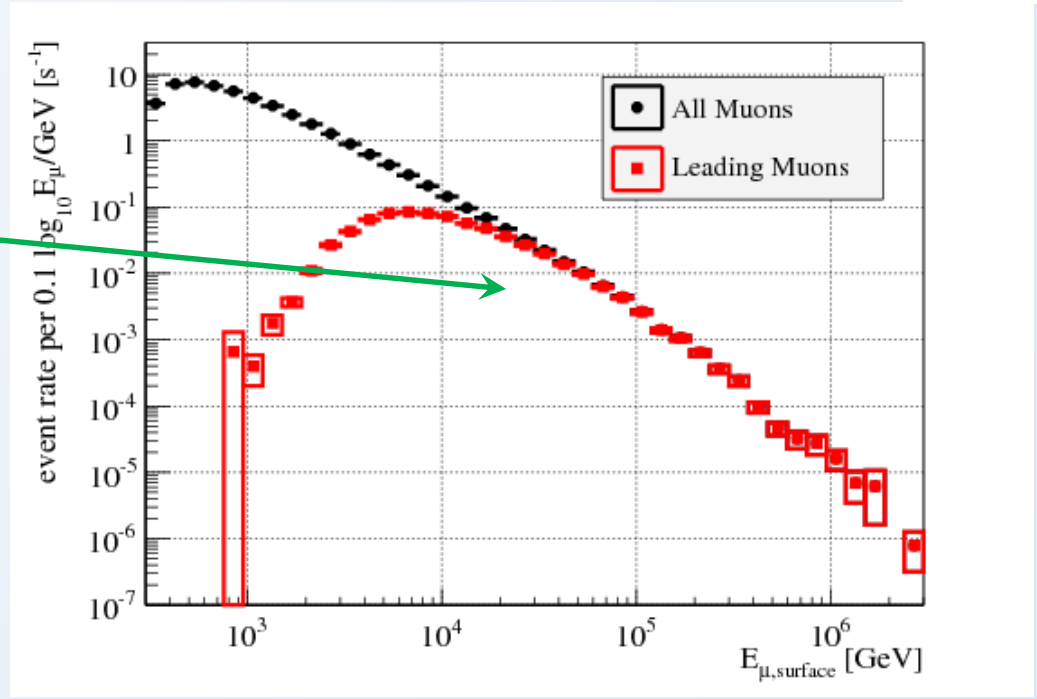


- Is the data "bracketed" by protons and iron?
- Does the data match composition models?

Part II: In-ice (TeV) muons

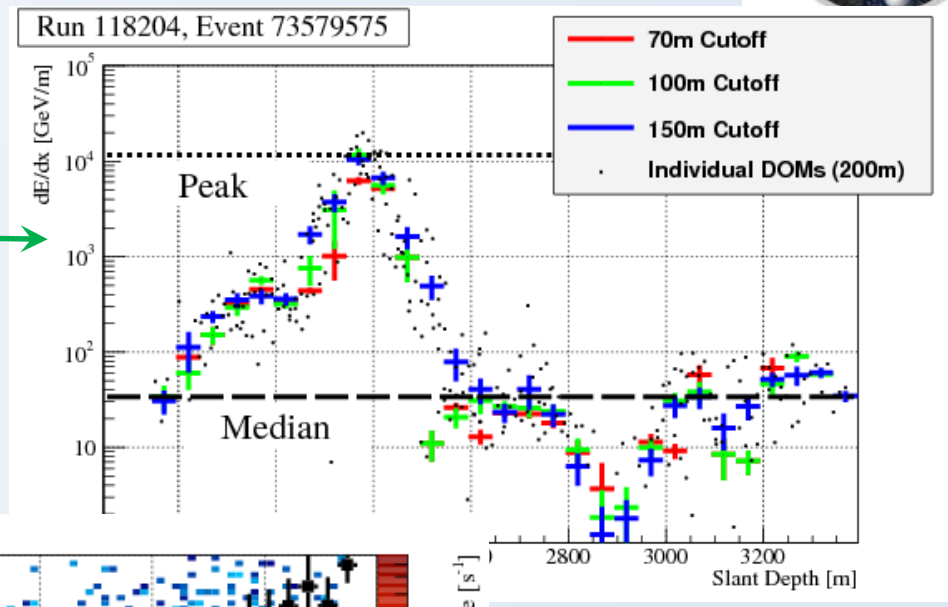
Looking at In-Ice HE muons

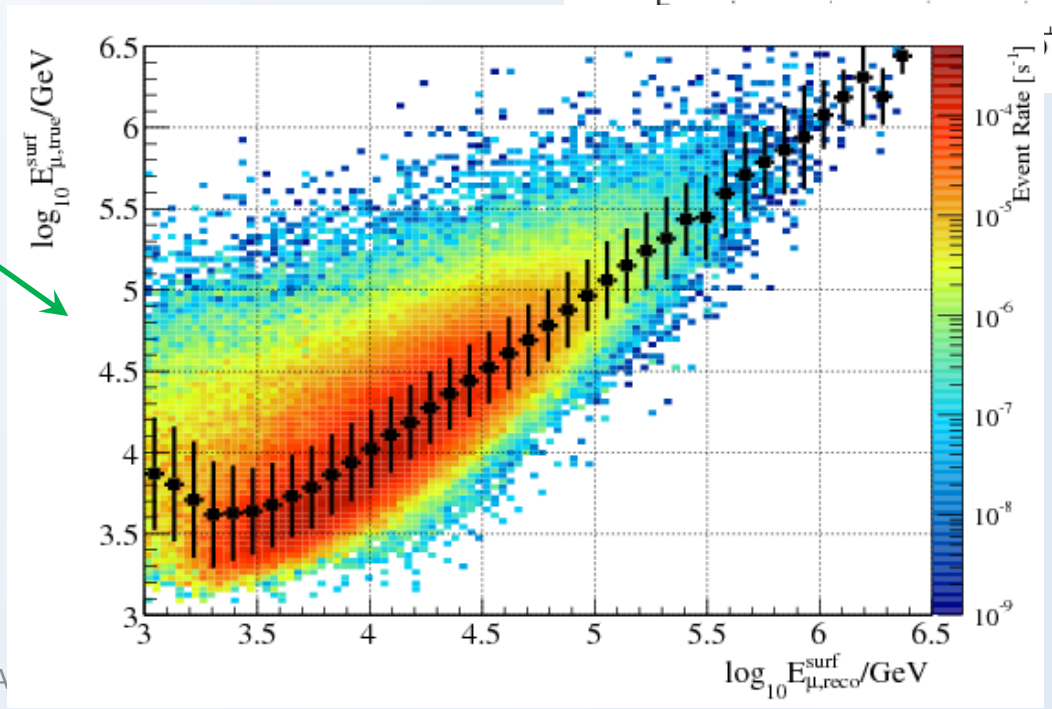
- Look at large events only (>1000 PE's)
  - If you see a high enough (>30TeV) energy in muons, it'd have come from the *leading* muon in the bundle
  - This'll be closely related to the energy of the CR primary



Looking at In-Ice HE muons

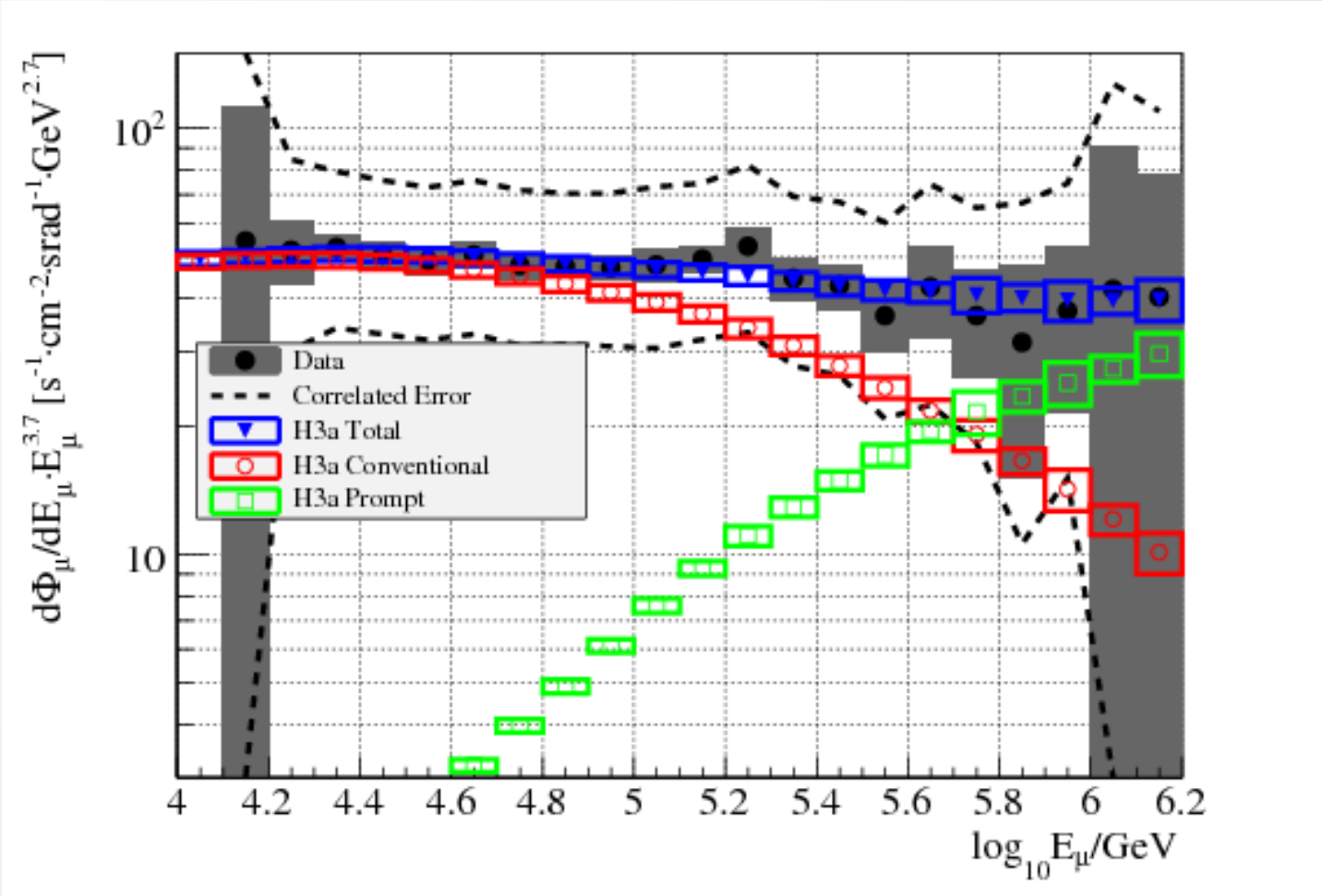
- Look for single large stochastic loss (high “peak to median” ratio) to identify these muons, and estimate their energy…





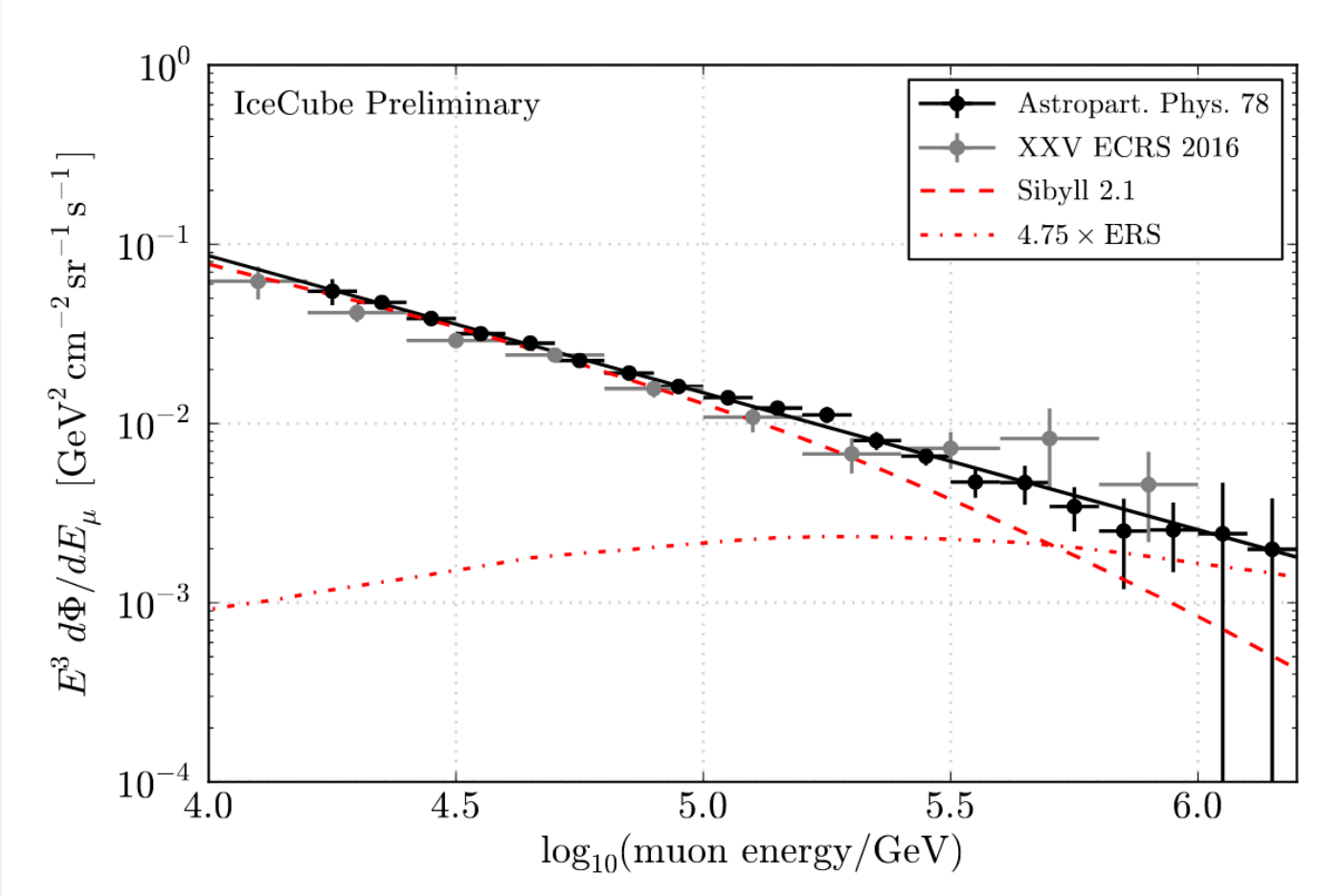
…and use this to derive a spectrum:

- Note that one must include some prompt component…



Invoking machine learning

- A similar analysis, but using a machine learning approach, yields a similar conclusion



Conclusions

- Using IceTop to measure ρ_μ of GeV muons:
  - The data is (mostly) bracketed by p and Fe for SIBYLL2.1 and QGSJET-04, but not by SIBYLL2.3 or EPOS-LHC
  - For all models, there are discrepancies between the ρ_μ data and various composition models… if it matches in one energy range, it tends to not match at another.

- Using IceCube to measure dE/dX of TeV muons:
  - The muon energy spectrum is inconsistent with a flux containing no prompt component
  - Assuming H4a, Φ_{prompt} = 4.75 x ERS
  - …but the contribution from the prompt component is highly dependent on systematic effect with uncertainties

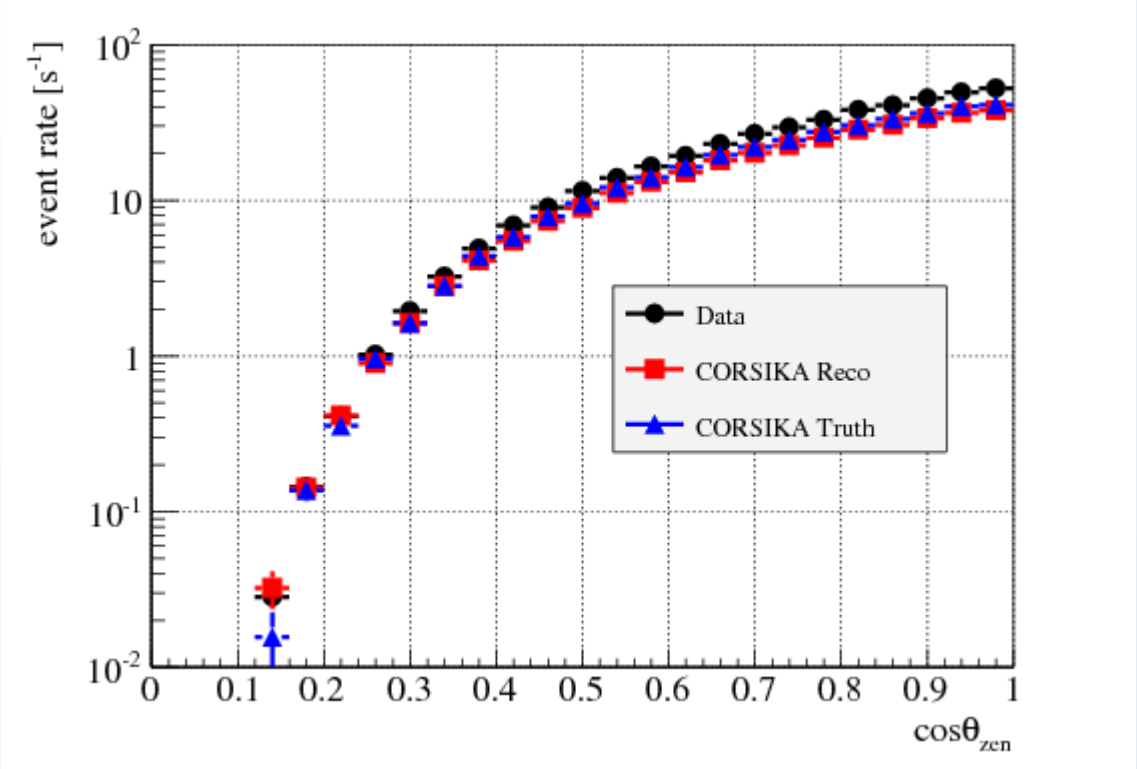
Thank you for your attention!

(Backup slides…)

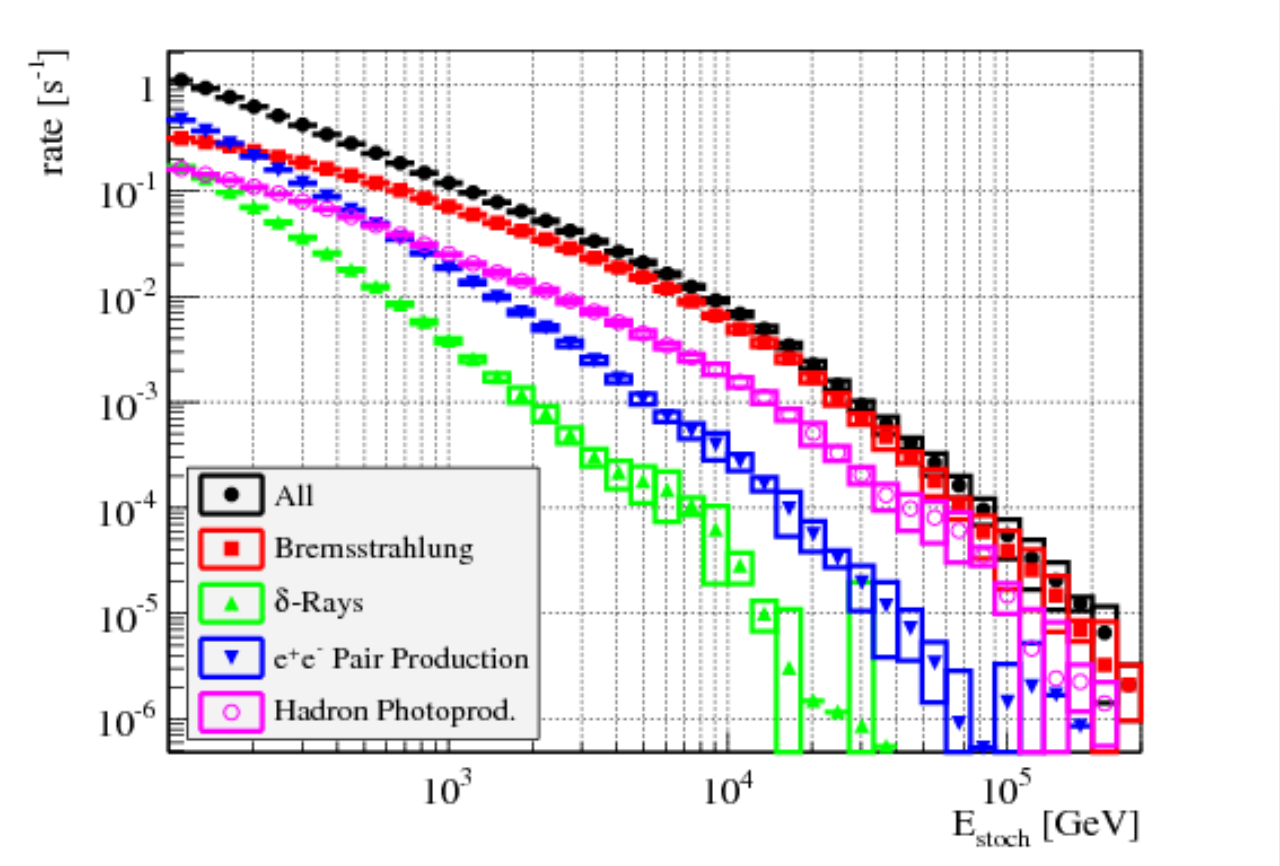
ERS fluxes

CR Model	Best Fit (ERS)	χ^2/dof	1σ Interval (90% CL)	Pull ($\Delta\gamma$)	$\sigma(\Phi_{\text{Prompt}} > 0)$
GST-Global Fit [13]	2.14	7.96/9	1.27 - 3.35 (0.77 - 4.30)	0.01	2.64
H3a [13]	4.75	9.09/9	3.17 - 7.16 (2.33 - 9.34)	-0.03	3.97
Zats.-Sok. [35]	6.23	13.98/9	4.55 - 8.70 (3.59 - 10.68)	-0.23	5.24
PG Constant $\Delta\gamma$ [33]	0.94	9.07/9	0.36 - 1.63 (< 2.15)	0.03	1.52
PG Rigidity [33]	6.97	5.86/9	4.73 - 10.61 (3.53 - 13.83)	-0.06	4.35

Discrepancies, visible in zenith angle



Sources of energy loss in the ice



Expected energy losses (according to simulations), for a E-2.7 power law of primary cosmic rays