Latest Cosmic Ray Results from IceTop and IceCube

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for the IceCube collaboration

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Outline:

- Introduction to CRs & IceTop/IceCube
- Energy spectrum and composition
- Low energy muons in IceTop
- PeV Gamma ray searches
- PeV Neutron searches
- Summary

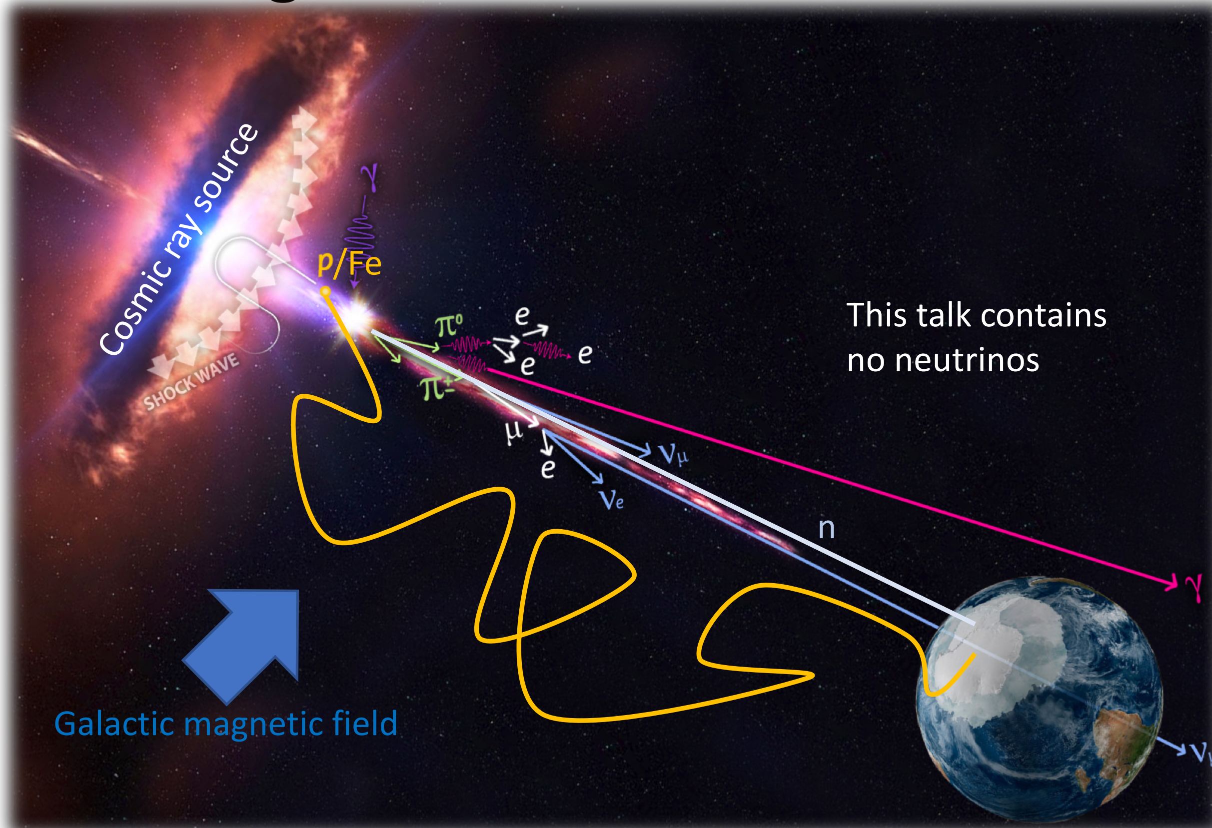
Cosmic Rays Multi-Messenger Search

Goal:

Looking for the origin of galactic comic rays

Explain the structure in the energy spectrum, e.g. knee, second knee, ….

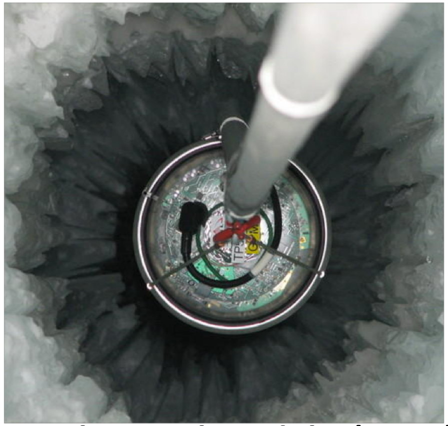
- CR particle deflected (charge dependent)
- High energy γ and neutrons hard to measure



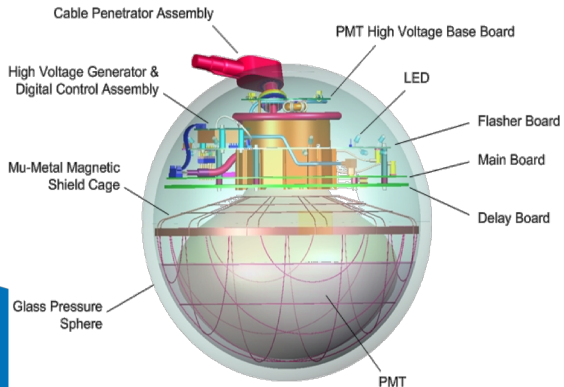
IceCube Observatory

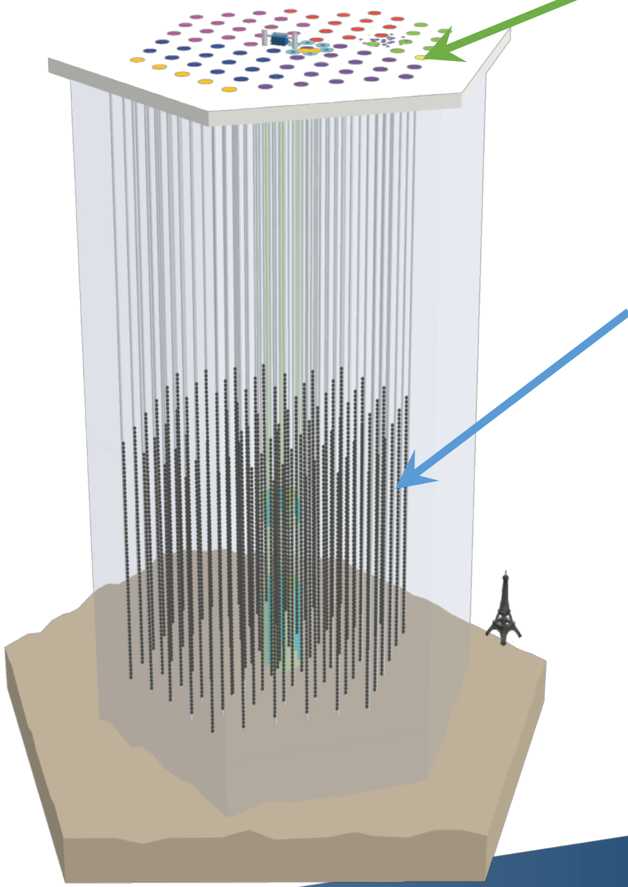
Deployed over 6 seasons:
Completed in 2011

IceCube String



Digital Optical Modules(DOM)





IceTop (Surface Air Shower Array):

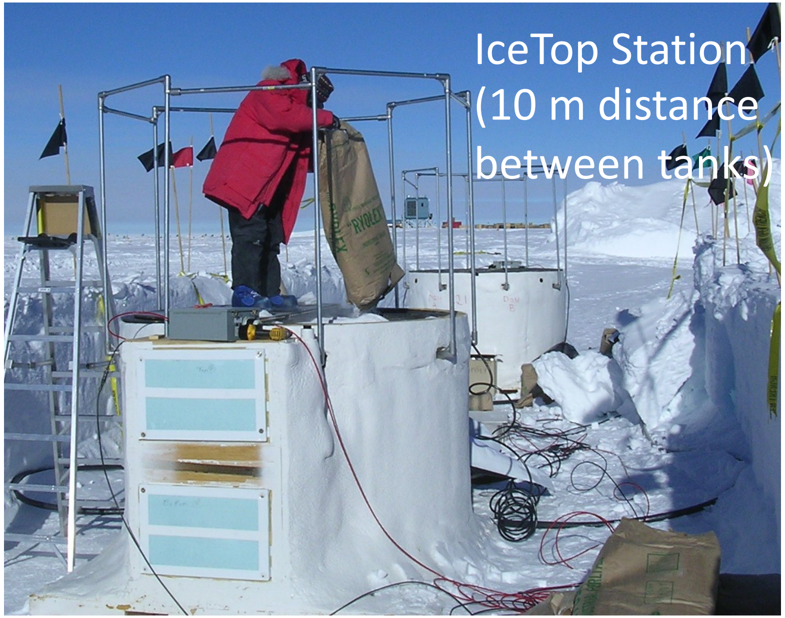
- ~1 km^2 instrumented area
- 81 stations with 2 tanks each
- 2 DOMs per tank→ 324 total DOMs
- Measure electromagnetic and low energy muon components of air shower

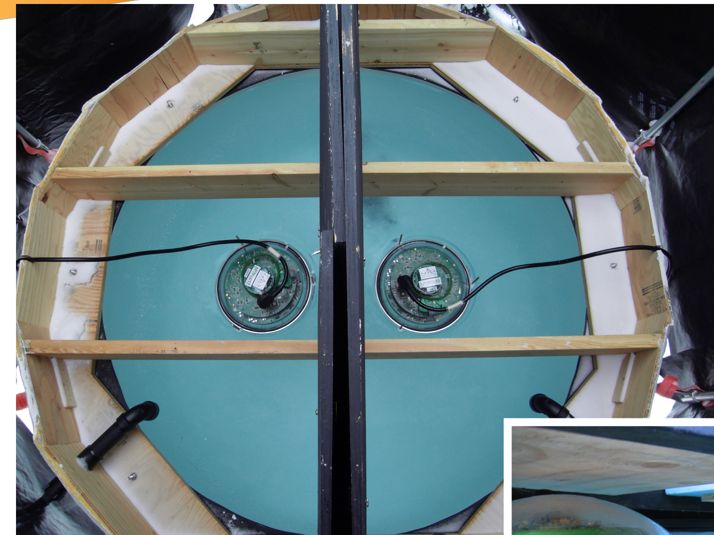
IceCube (In-Ice Array):

- ~1 km^3 instrumented volume
- 86 strings with 60 DOMs each with 17m spacing→5160 total DOMs,
- Depth: 1.45-2.45 km
- Measure high energy muon component of air shower

Same DOMs used for IceCube and IceTop

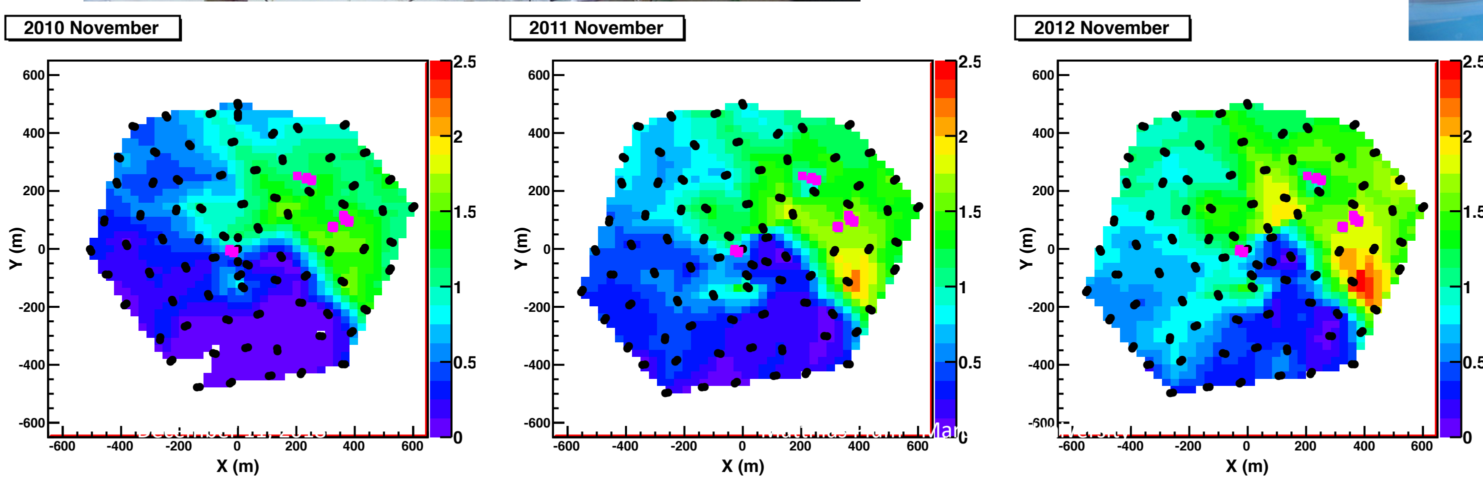
IceTop



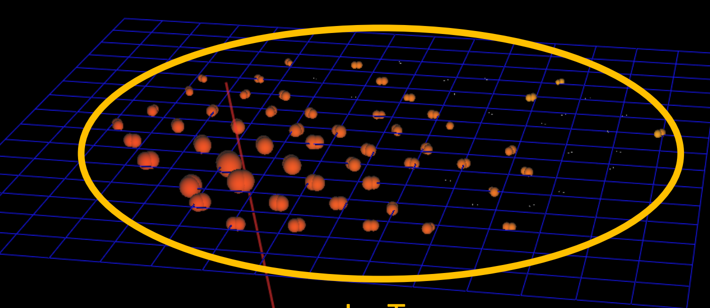


IceTop Tank

- 2 DOMs per tank
- 2.3 m^3 ice



IceTop-Only Reconstruction

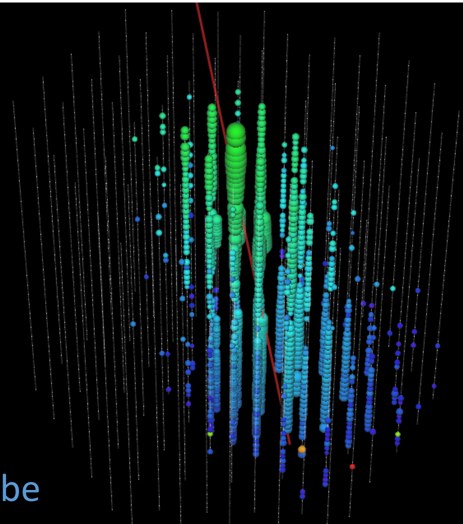


IceTop

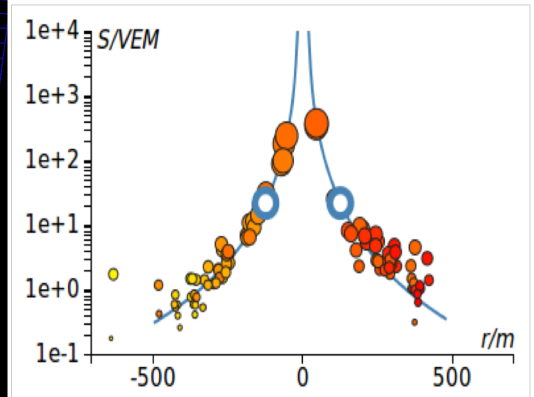
Lateral signal distribution in VEM:

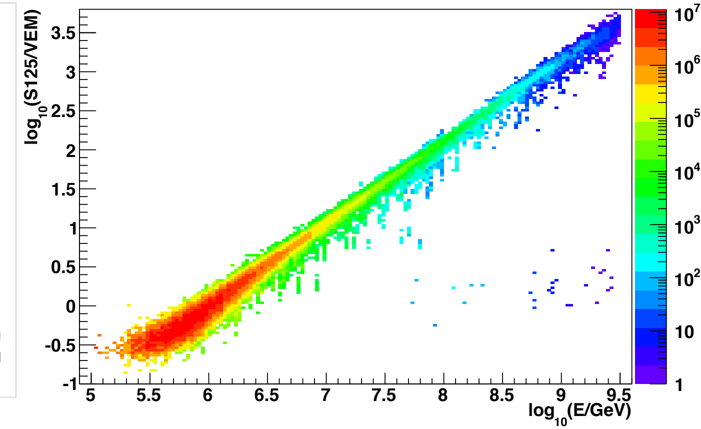
$$S(R) = S(R_0)\left(\frac{R}{R_0}\right)^{-\beta-\kappa\log_{10}\left(\frac{R}{R_0}\right)}$$

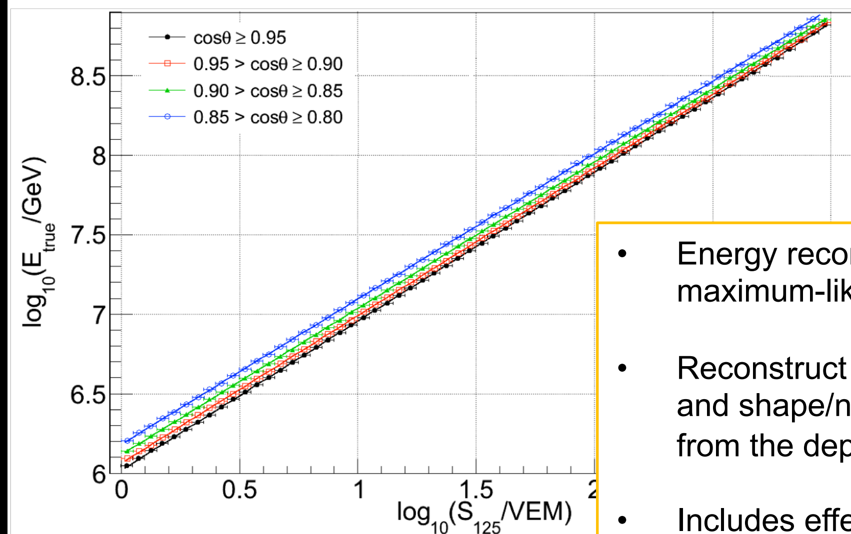
(Double Logarithmic Parabola)



IceCube

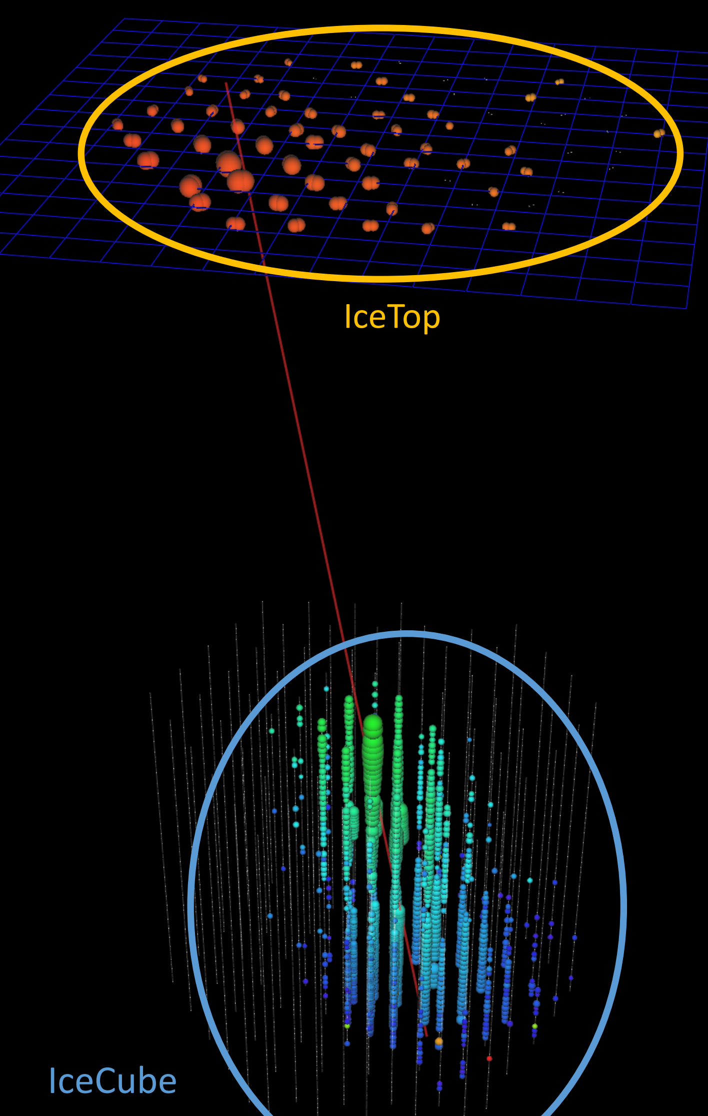


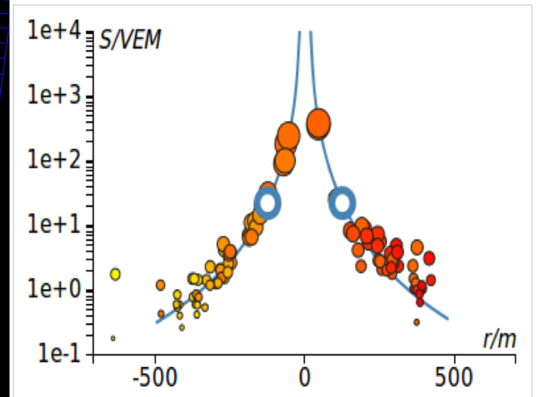


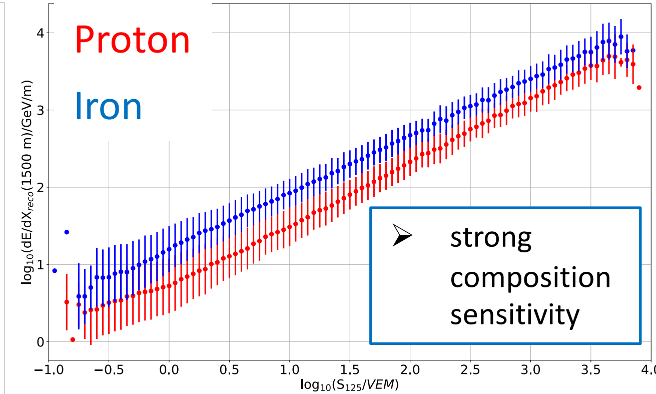


- Energy reconstruction using maximum-likelihood procedure
- Reconstruct core position, direction and shape/normalization of LDF from the deposited charge
- Includes effects snow coverage by assuming an ‘effective attenuation length’ λ (range 2.10 – 2.25m)

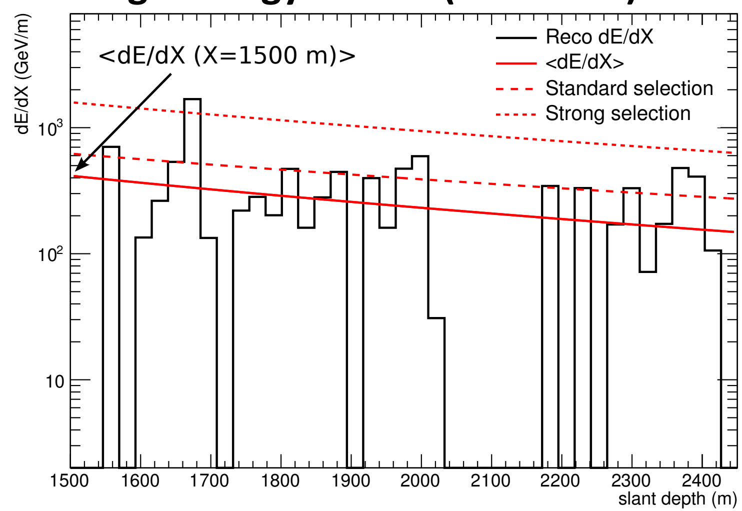
IceCube/IceTop Coincidence Reco.





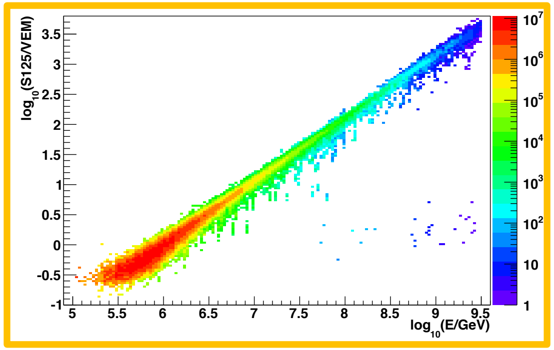


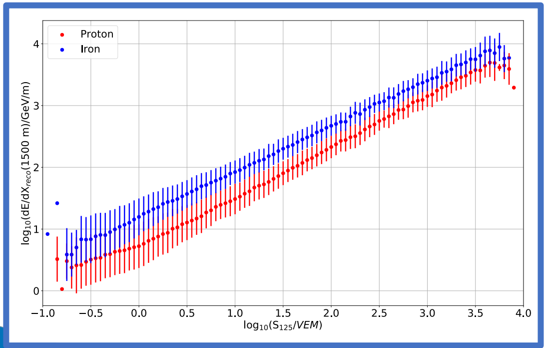
High energy muons (>500 GeV)

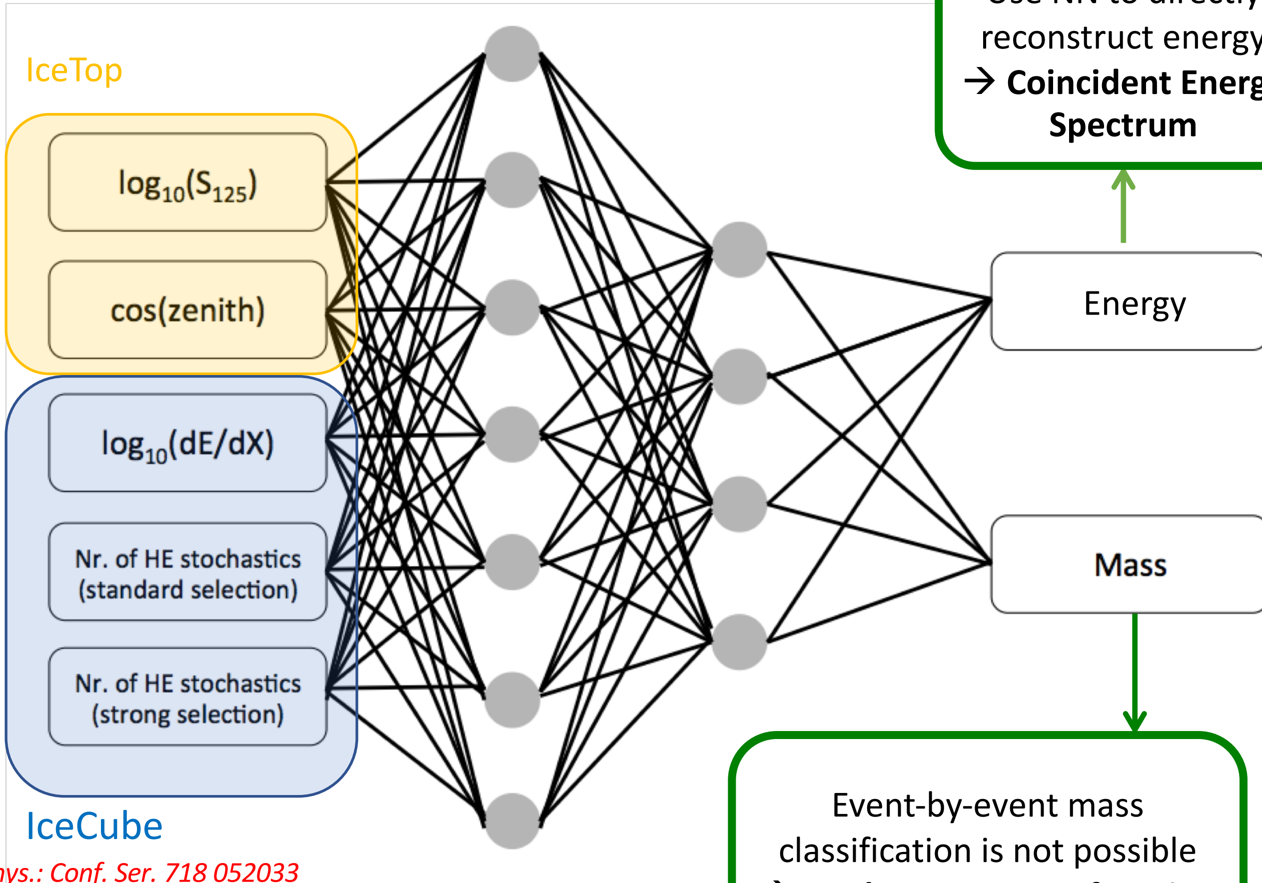


- Energy and mass proxy reconstruction with neural network technique
- Use best available detector simulation including snow coverage

IceTop/IceCube - Neural Network Reconstruction





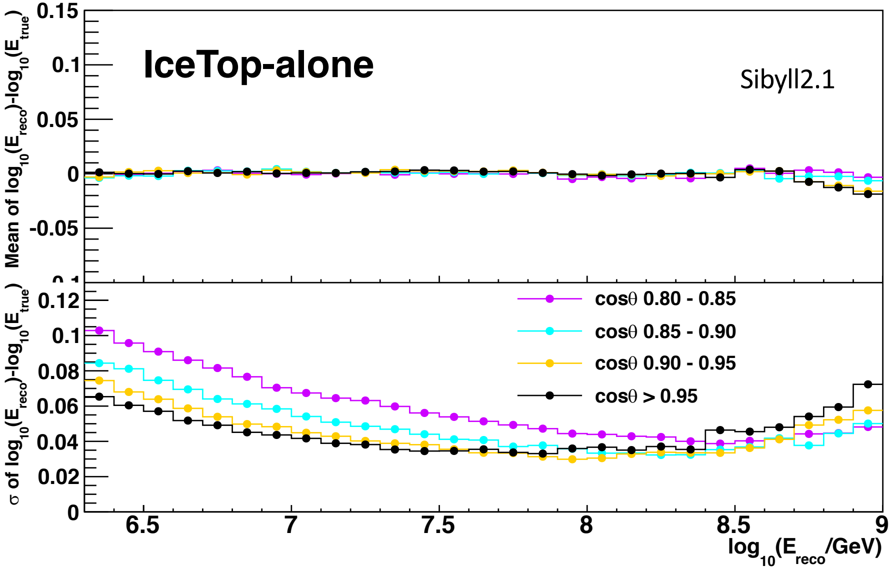


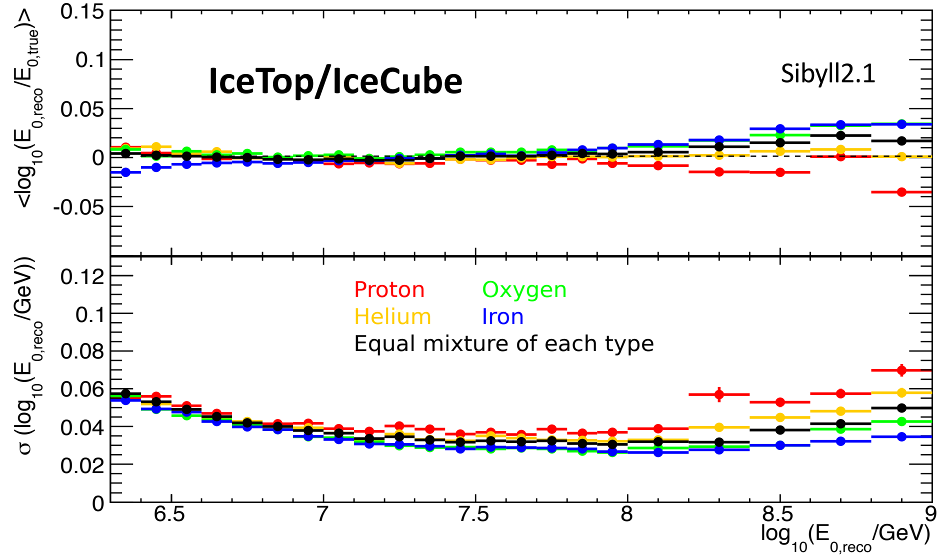
Use NN to directly reconstruct energy
→ **Coincident Energy Spectrum**

Event-by-event mass classification is not possible
→ **Analyze mass as a function of energy on a statistical basis**

J. Phys.: Conf. Ser. 718 052033
Proceedings of ICRC2013(0861)
Astropart.Phys. 42: 15, 2013

Energy Reconstruction & Resolution of Both Analyses



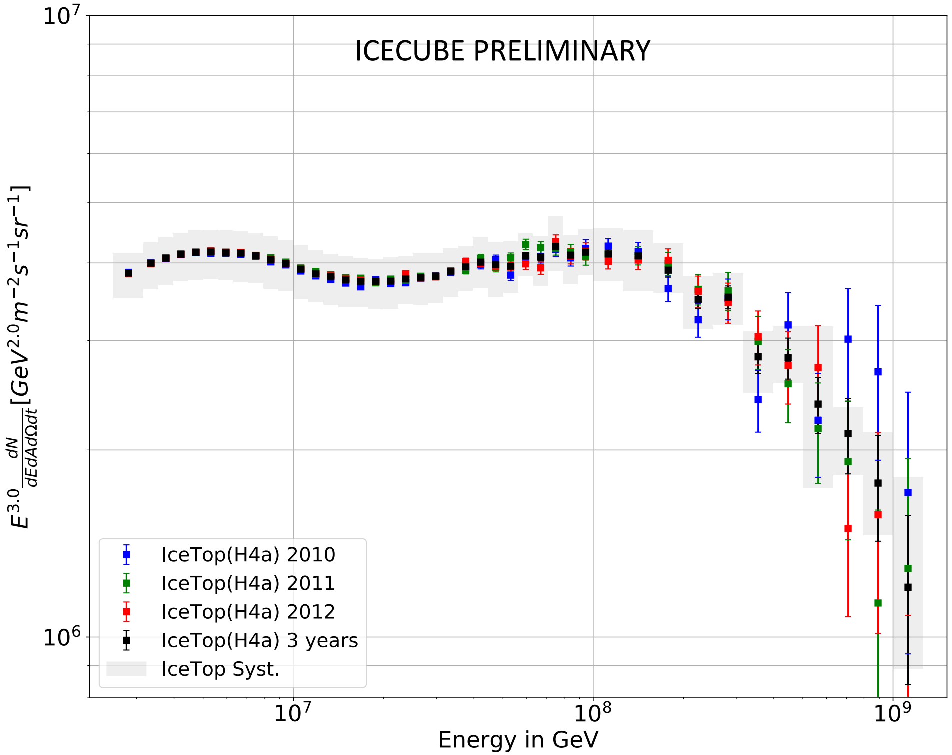


Both analysis method have:

- Similar small energy bias over the whole energy range
- Similar tight resolution

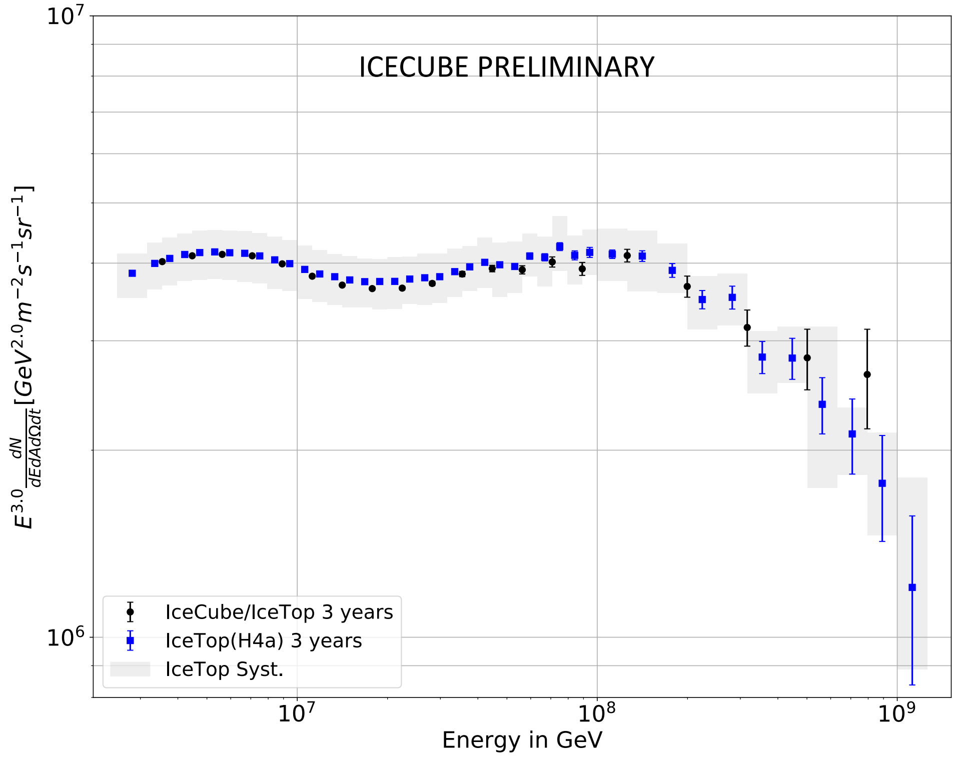
Only small primary composition dependency visible

IceTop Energy Spectrum



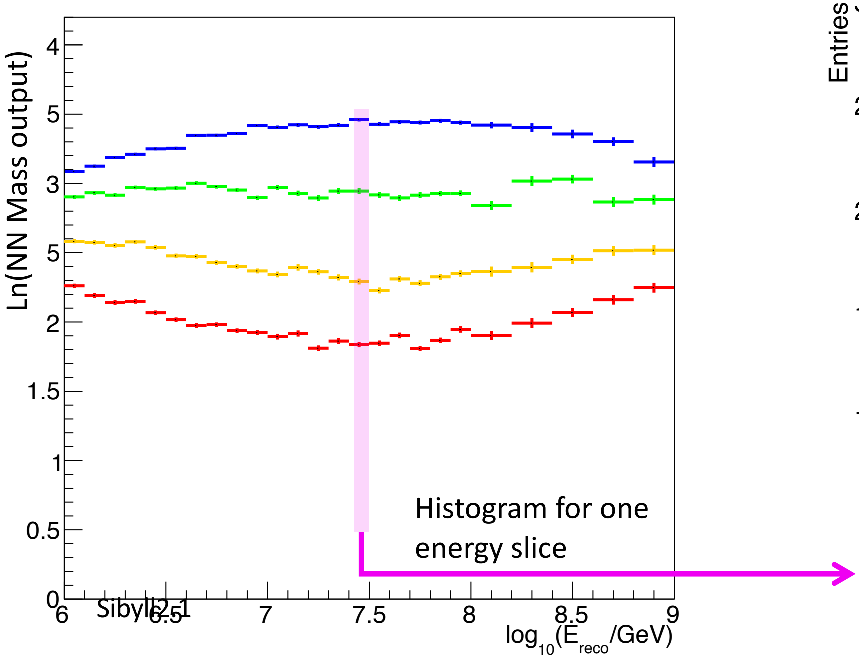
- IceTop Energy Spectrum unfolded using maximum likelihood method. (Composition assumed from H4a model: *T. Gaisser, T. Stanev & S. Tilav: Front. Phys.(Beijing) 8 (2013) 748-758*)
- 3 years of data (May ‘10 – Jun ‘13)
- Standard cuts (*IceCube Collab., M.G. Aartsen et al., PRD 88 (2013) 042004*)
- Data set divided into individual years shows strong agreement

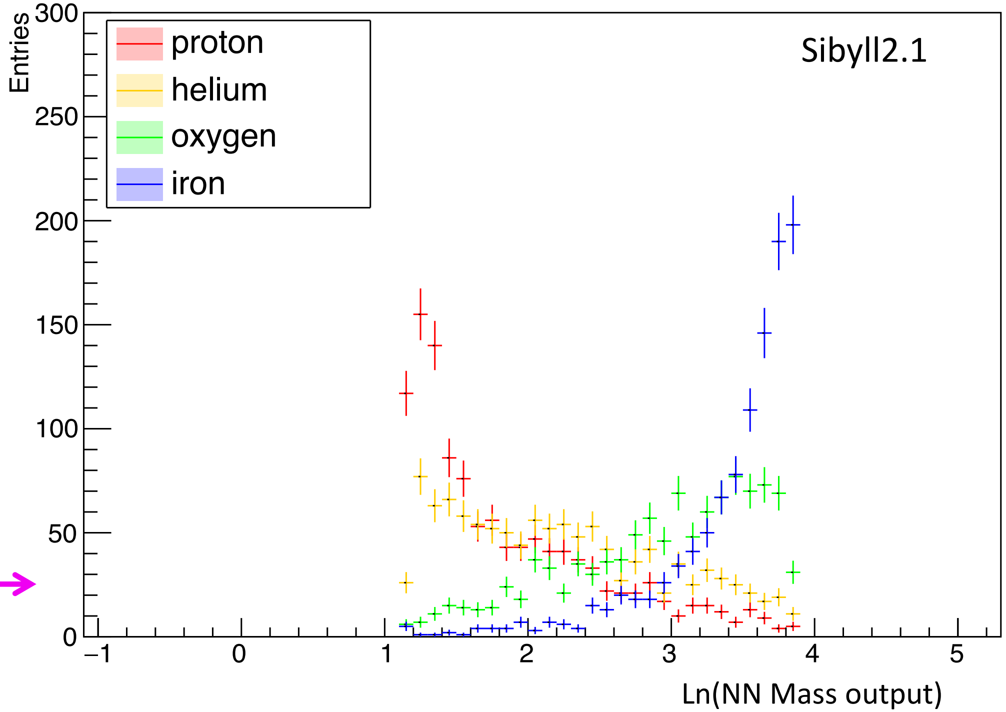
IceTop/IceCube Energy Spectrum



- 3 years of data (May '10 – Jun '13)
- Standard cuts (*IceCube Collab., M.G. Aartsen et al., PRD 88 (2013) 042004*)
- Due to geometric constraints, energy bin size of coincidence analysis reduced
- Strong agreement between both analysis technique

Mass Reconstruction





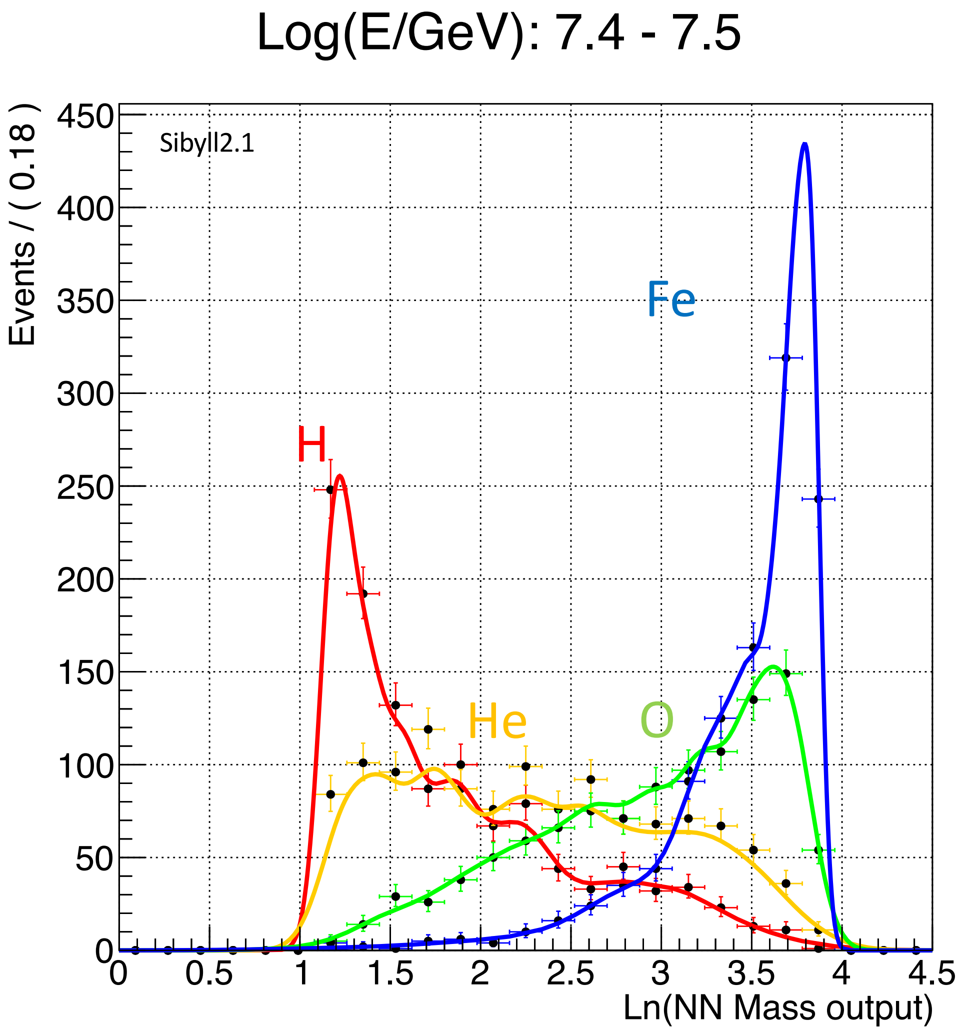
- Mass types reconstruction needs an extra step
  - ➢ Event-by-event classification not possible

Analyze mass as a function of energy on statistical bases

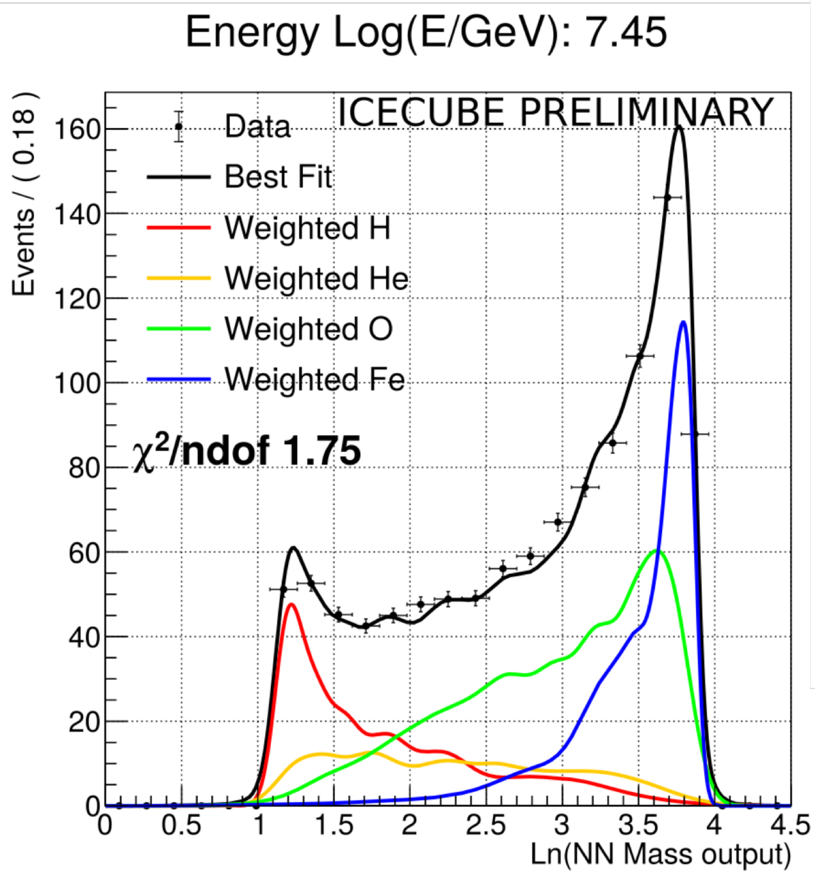
KDE templates

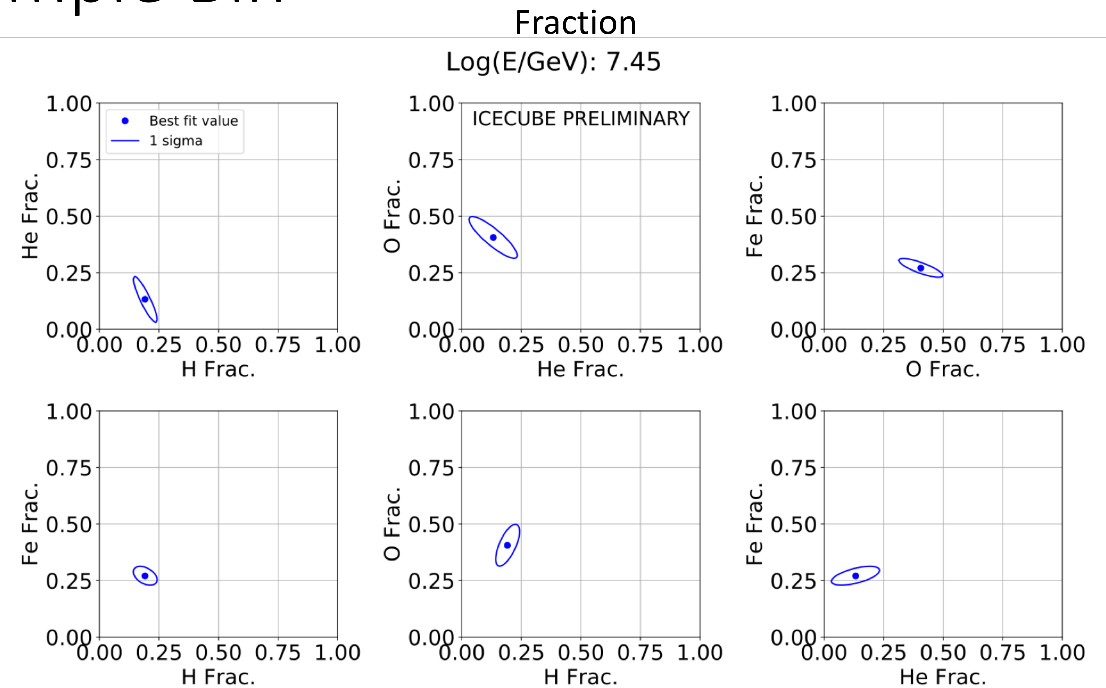
- Monte Carlo data converted into template 'probability density functions' (PDFs) for each primary in each energy bin
- Used adaptive Gaussian kernel width to preserve characteristic features of neural net output
- PDFs used in extended Likelihood data analysis
- Superposition model of weighted primary group PDFs fitted to data result:

$$f(x;\theta) = \sum_{i=1}^{m} \theta_i f_i(x),$$



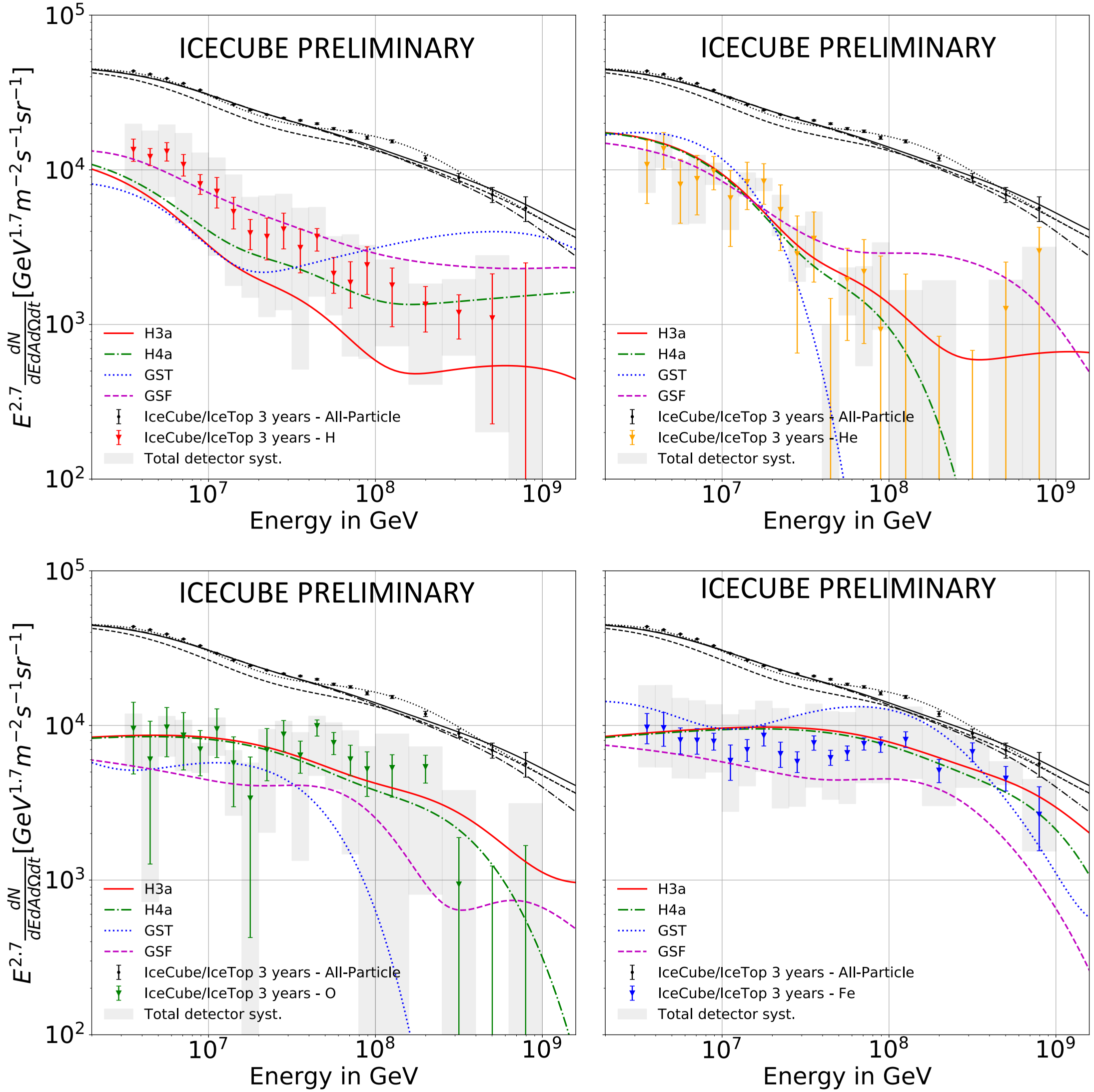
Application to Data – Example Bin





- Weights correspond to a mass fraction
- Strong correlation between neighboring primary groups

Composition Energy Spectrum



- Nominal results derived from Sibyll2.1
- Agreement with models within statistical and systematic uncertainty

Models (as discussed in [*Astroparticle Physics 35 (2012) 801–806*])

H3a [T. Gaisser, T. Stanev & S. Tilav: *Front. Phys.(Beijing) 8 (2013) 748-758*]

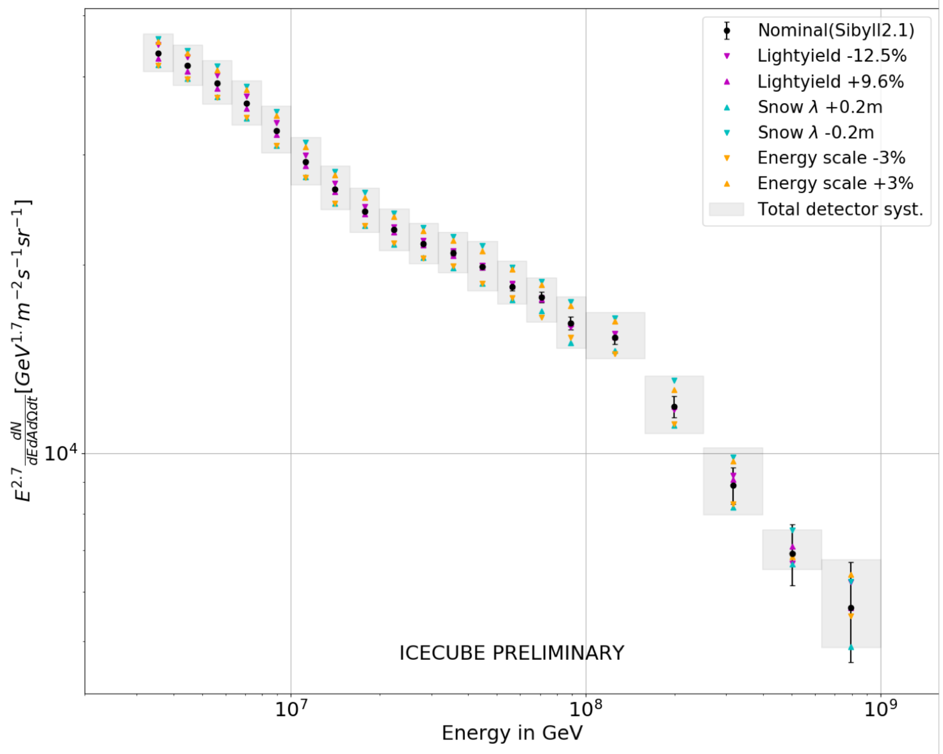
H4a [T. Gaisser, T. Stanev & S. Tilav: *Front. Phys.(Beijing) 8 (2013) 748-758*]

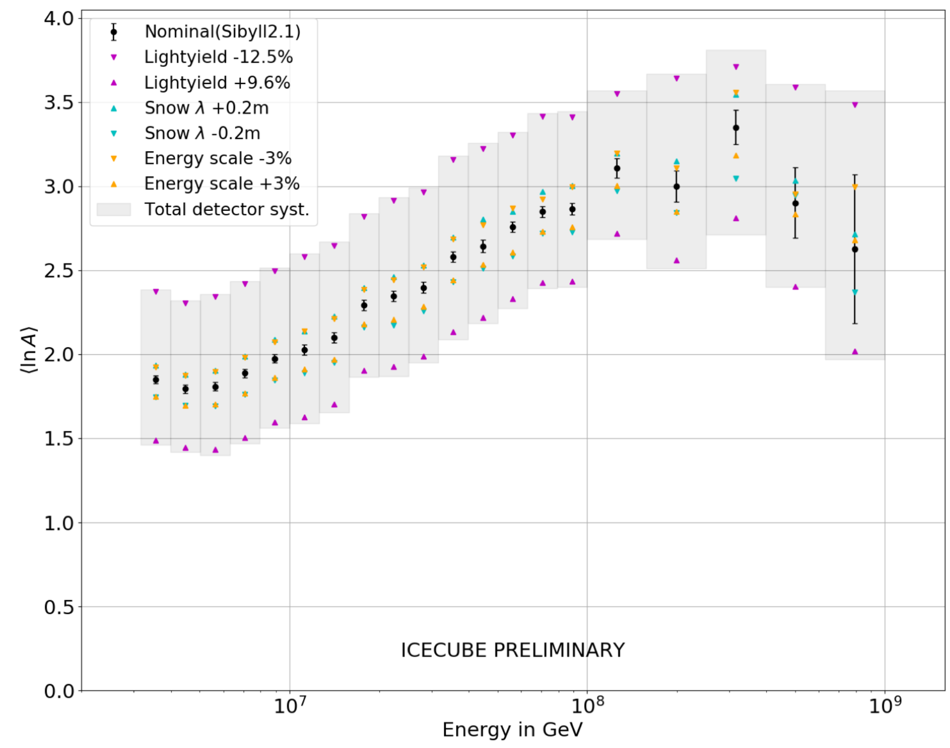
Fits:

GST [T. **G**aisser, T. **S**tanev & S. **T**ilav: *Front. Phys.(Beijing) 8 (2013) 748-758*]

GSF (**G**lobal **S**pline **F**it) [H. Dembinski, R. Engel, A. Fedynitch, T. Gaisser, F. Riehn, T. Stanev: *PoS(ICRC2017)533*]

Detector Systematic Uncertainty

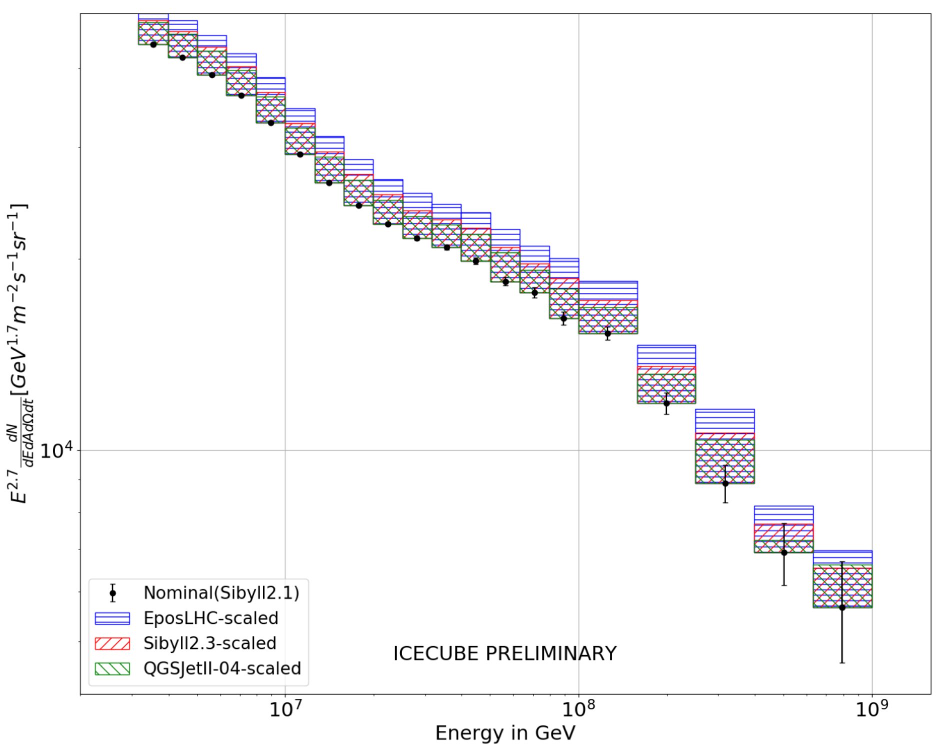


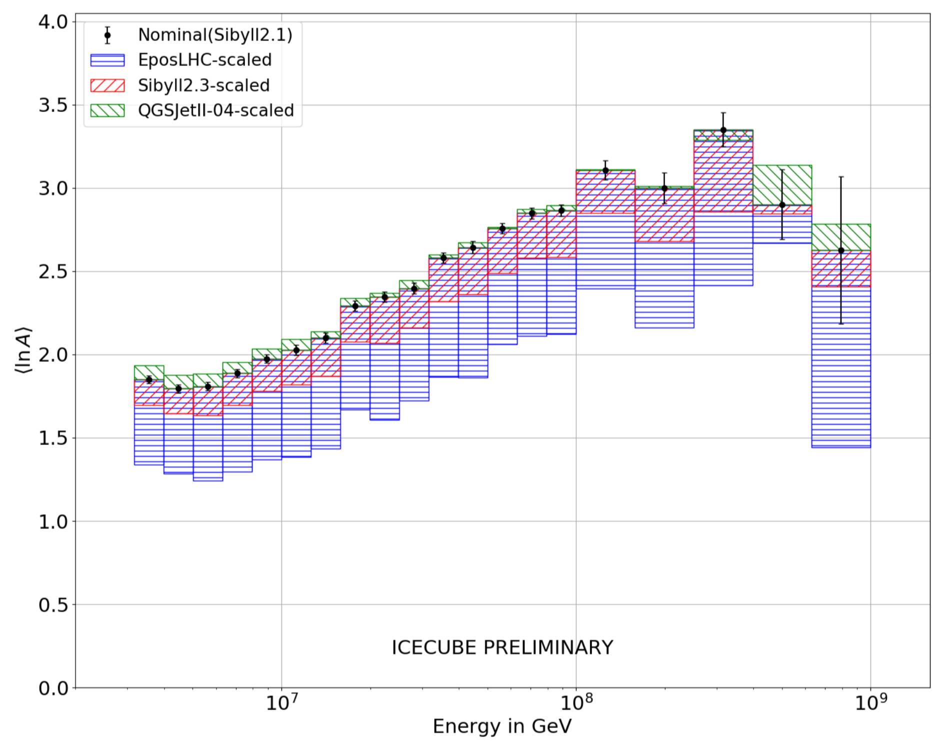


Systematic offsets on flux and <ln(A)> due to:

- Snow (±0.2 m)
- Light yield (-12.5% , +9.6%)
- Energy scale (±3%)

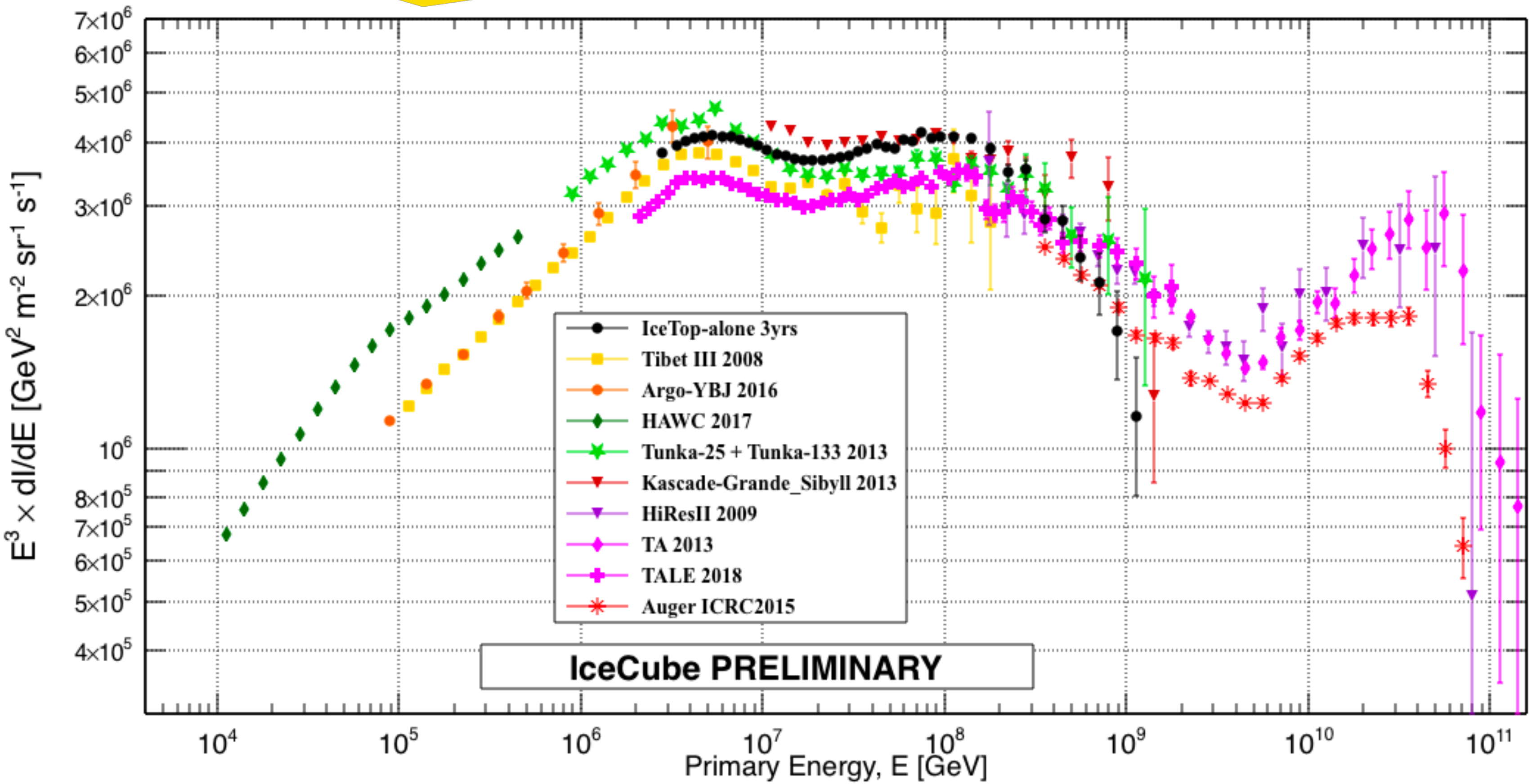
Hadronic Systematic Uncertainty





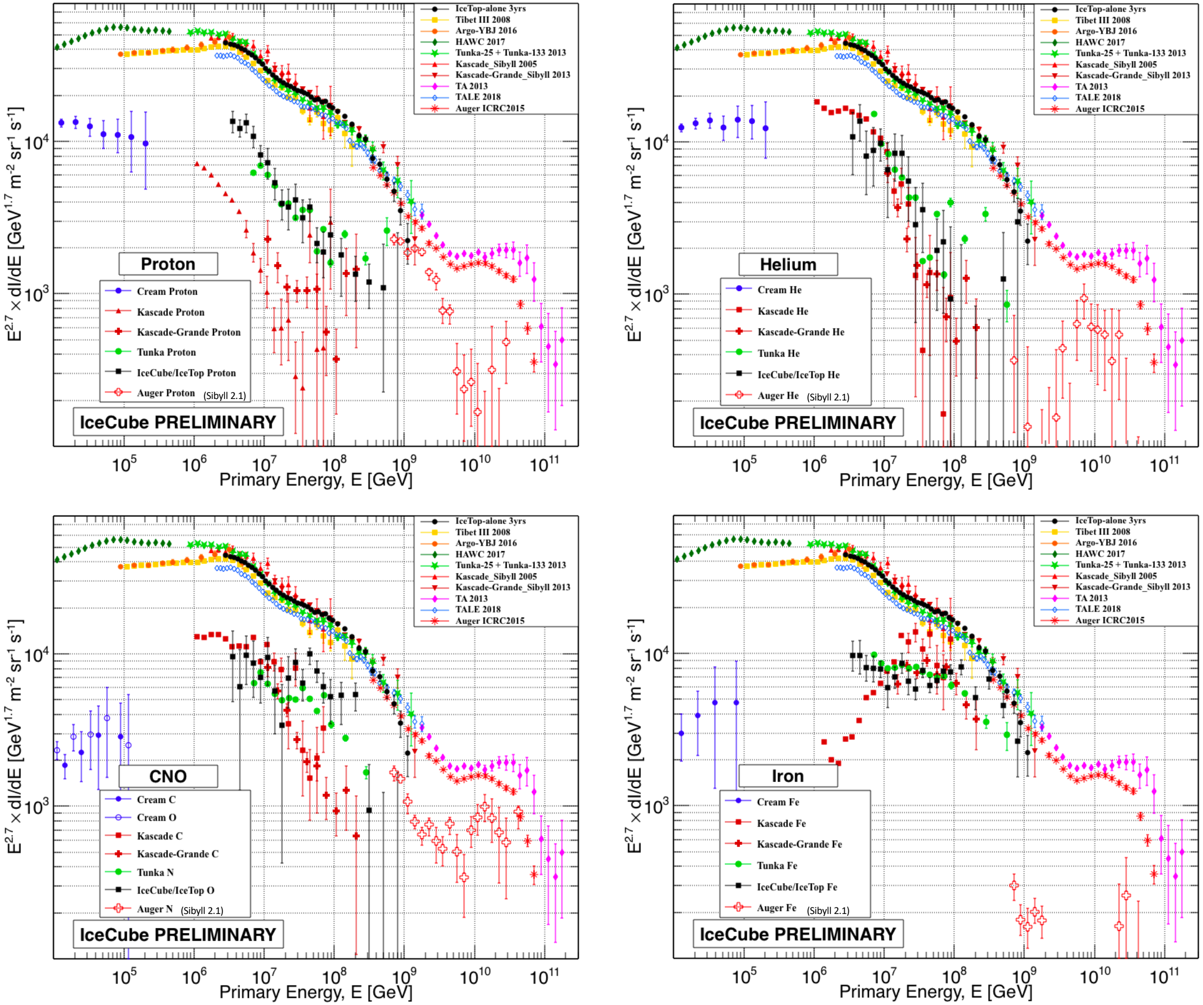
Scaling data according to differences in detector response due to interaction models result in uncertainty region in the flux and the <ln(A)>

Comparison with other Experiments



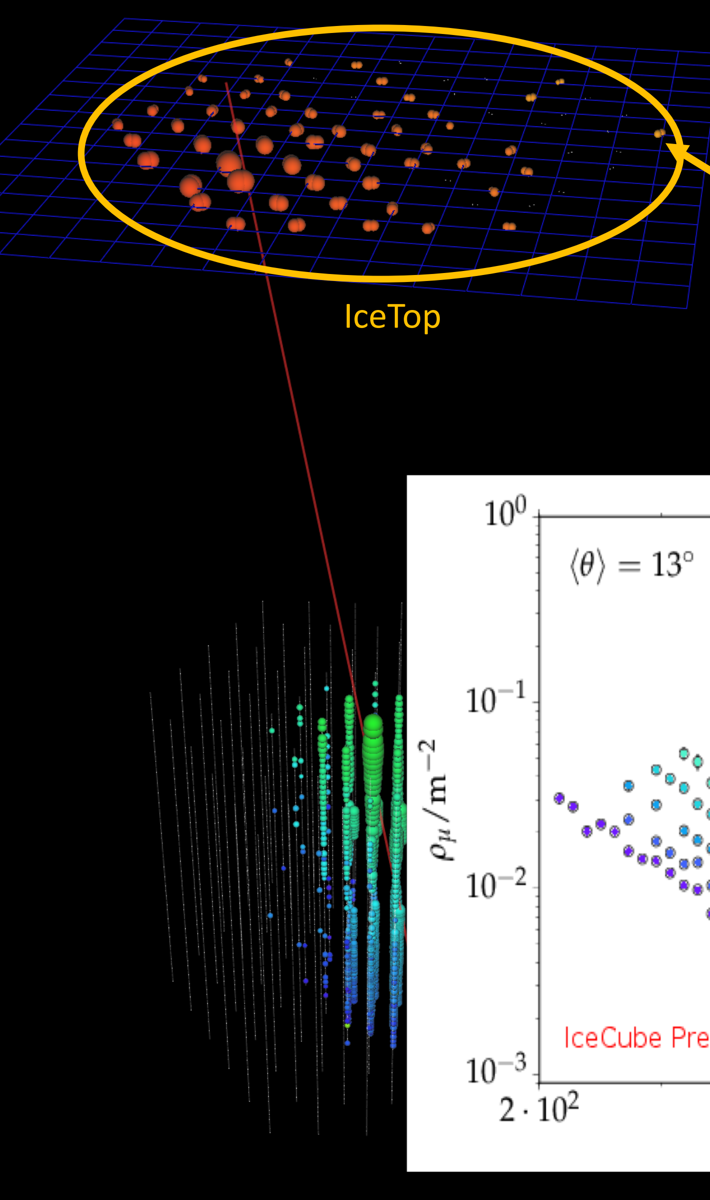
Overall good agreement of with results from other experiments

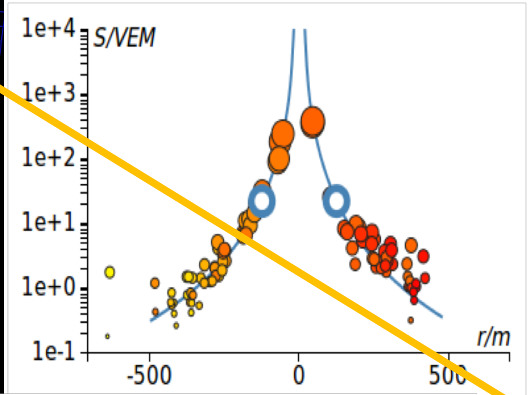
Comparison with other Experiments

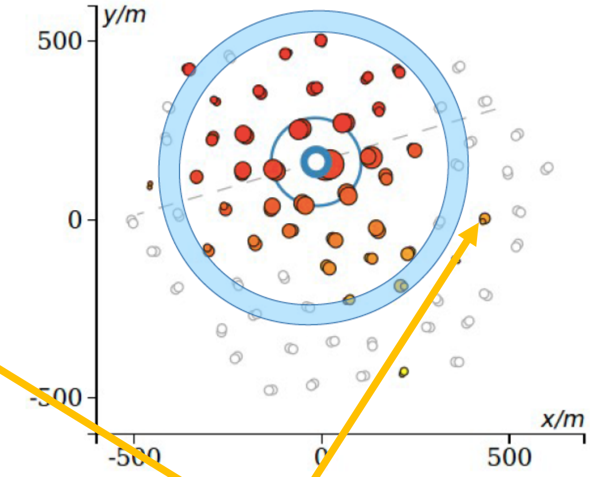


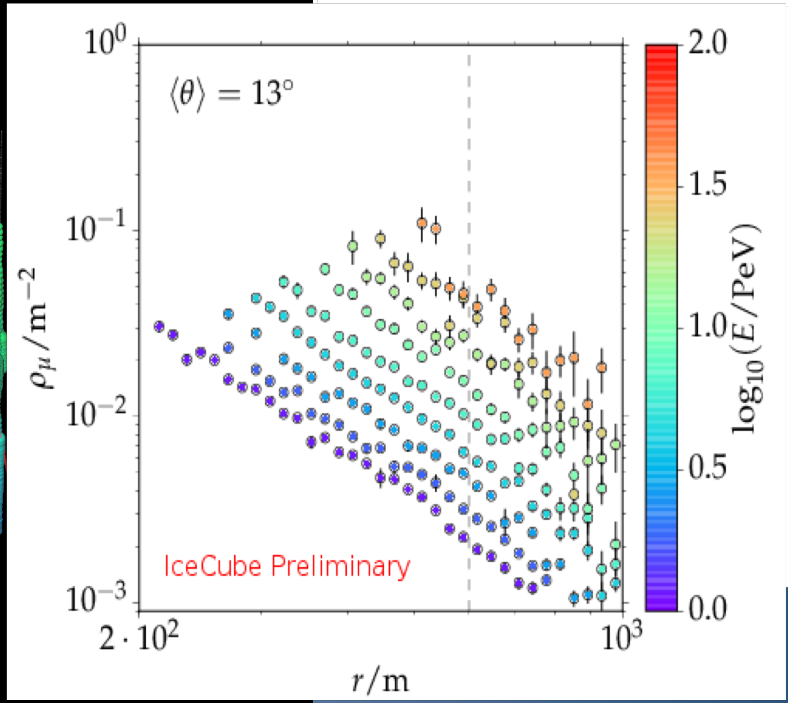
- Composition seems to get heavier with increasing energy up to 10^8 GeV
- Overall good agreement with the composition results from most other experiments

Muon Density Measurement







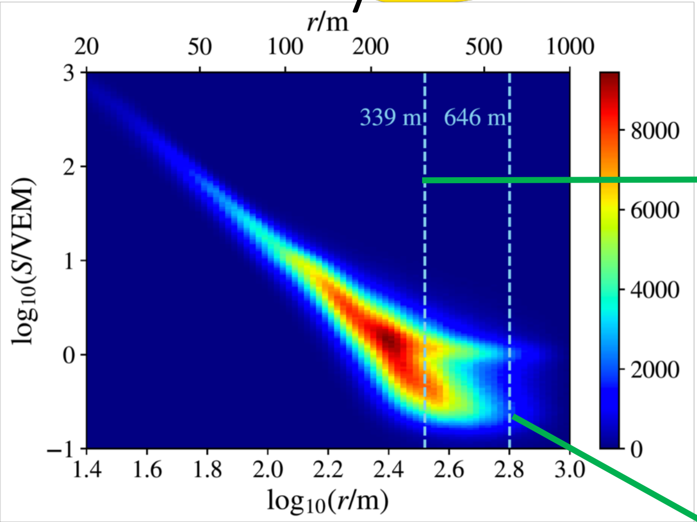


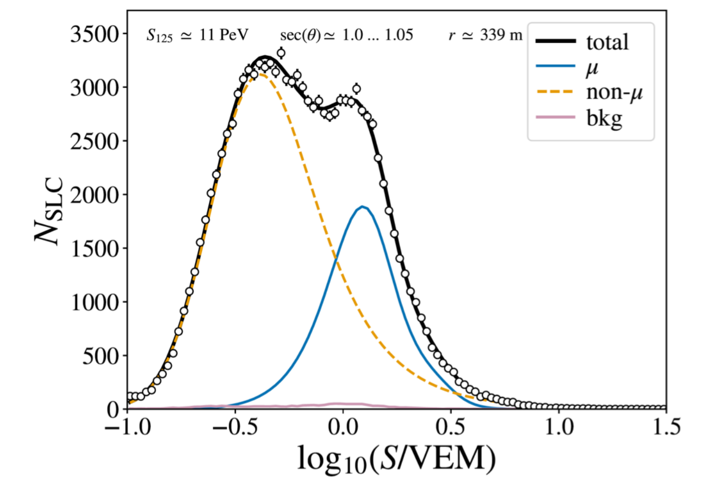
Low Energy Muons (>1GeV) at IceTop

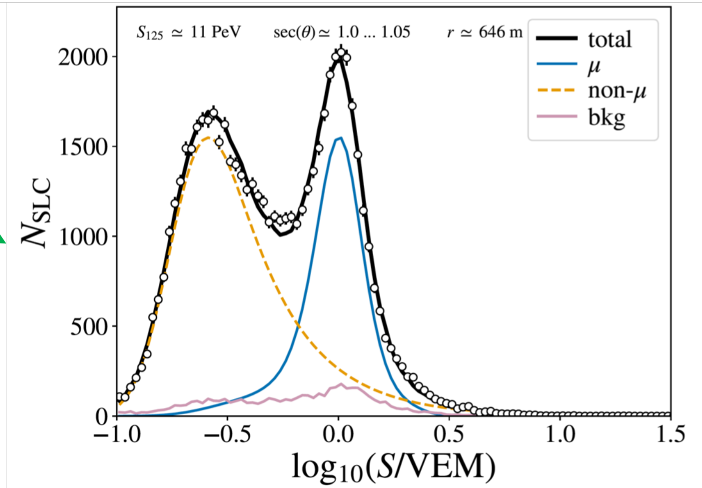
At large lateral distance where EM component is no longer dominant, IceTop can directly count the number of low-energy muons, which provides clues about the hadronic interaction models.

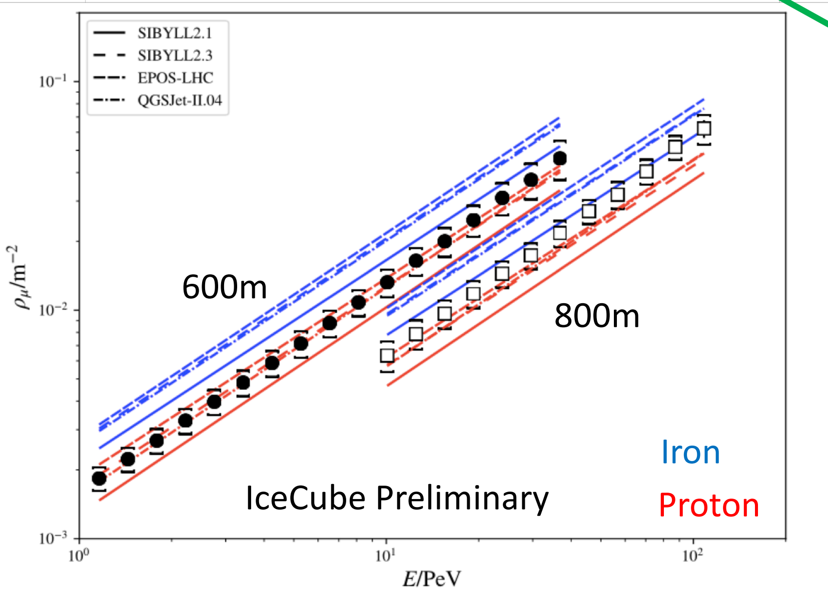
EPJ Web Conf. 99 (2015) 06002 arXiv:1501.03415
EPJ Web Conf. 145 (2017) 01003

Muon Density Measurement



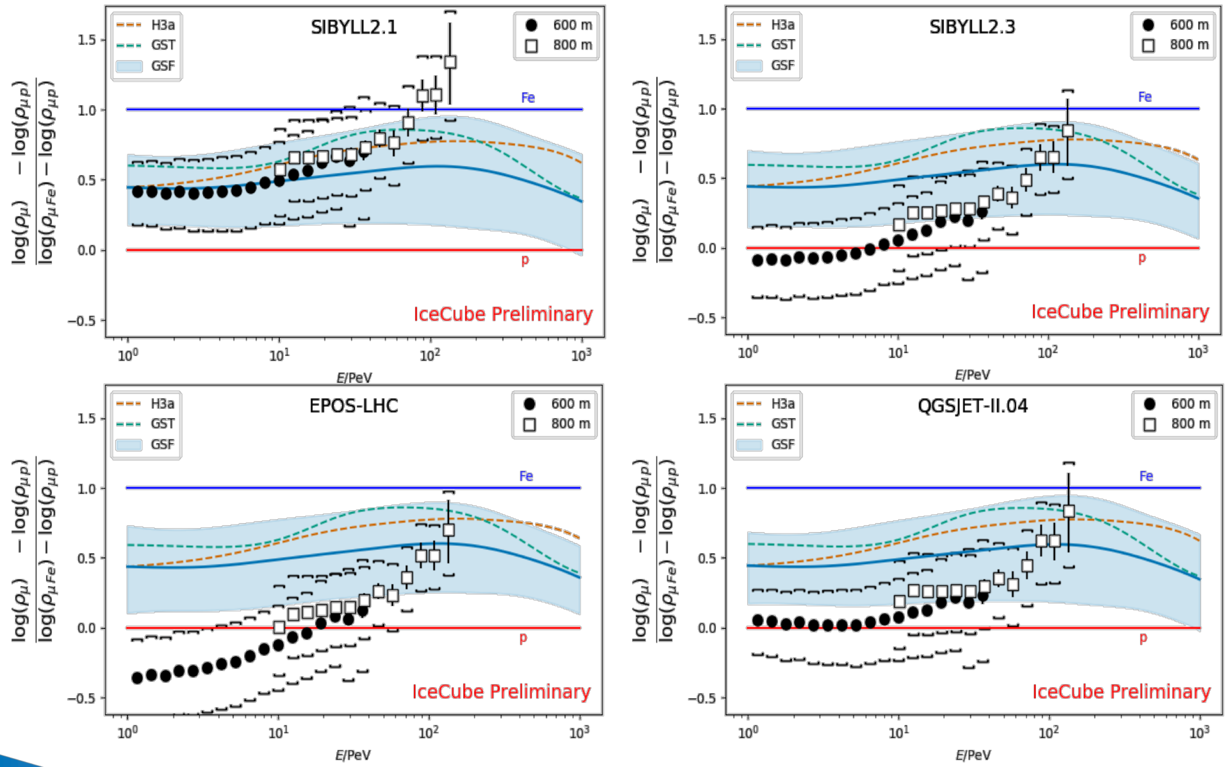






- Charge distribution shows clear single muon peak at large distances to shower core

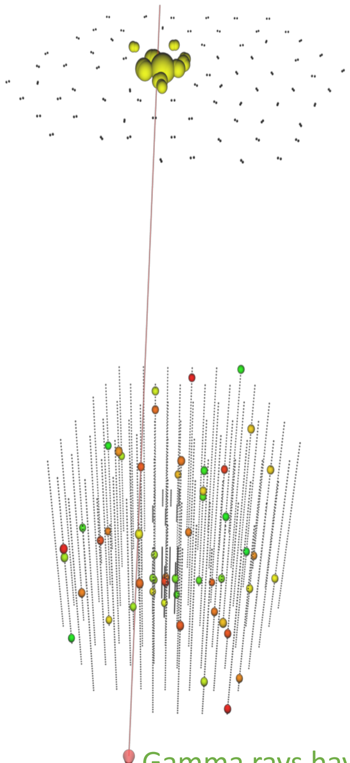
Comparing low energy muons with CR Flux Models



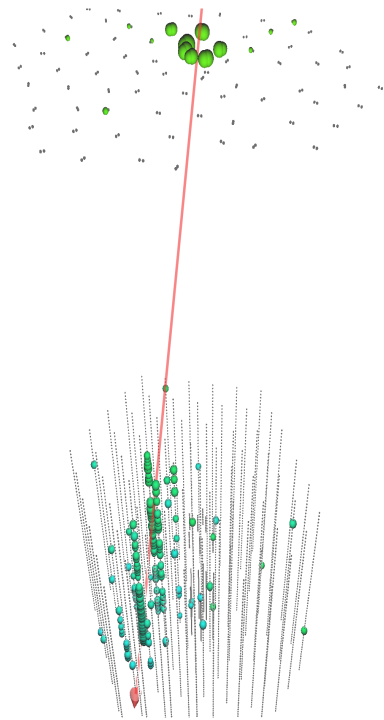
- Muon density is very sensitive to the primary mass composition
- Possible test internal consistency of the hadronic interaction model

PeV Gamma Ray Search

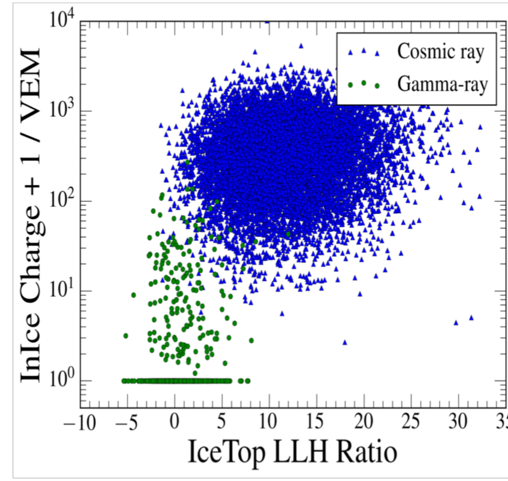
Gamma-ray like shower

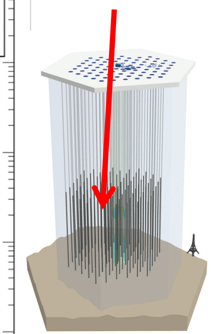


Charged Cosmic ray shower

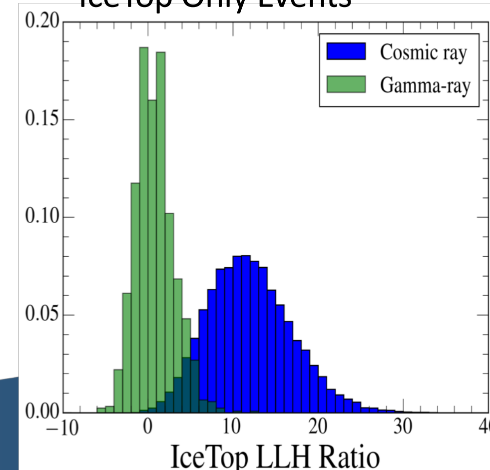


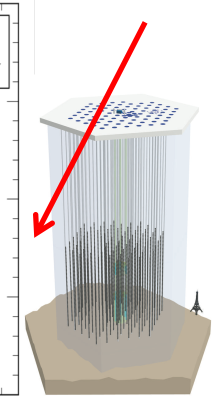
IceTop-IceCube Coincident Events





IceTop Only Events





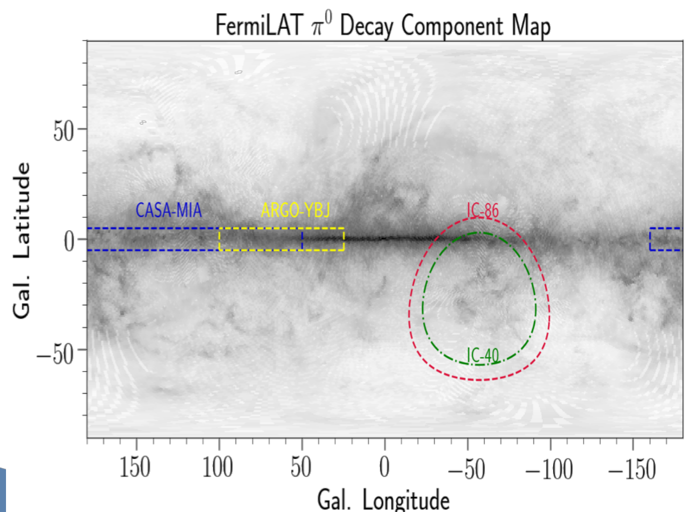
Gamma rays have fewer muons, fewer fluctuations and interact deeper in the atmosphere than hadrons: discrimination using LLH Ratio

Use to build random forest tree classifier

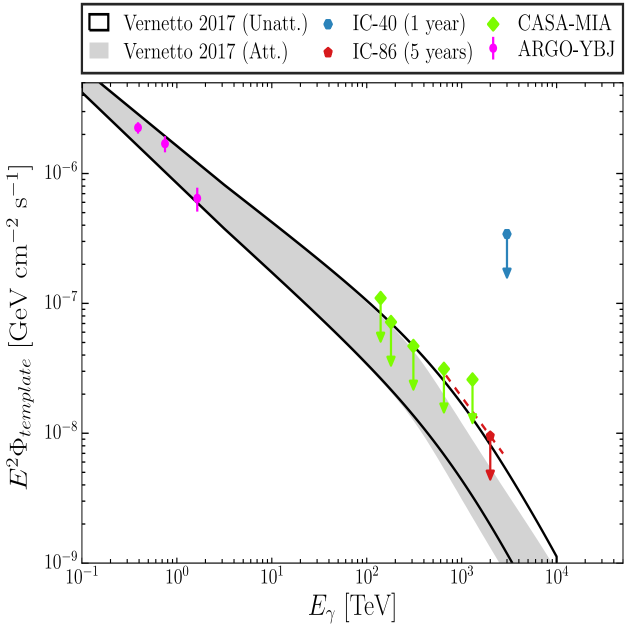
PeV Gamma Ray Search

- 5 years of IceCube data analyzed
- ~500k events in final sample
- No significant evidence found to exclude the null hypothesis in
  - All Sky Scan
  - H.E.S.S. Correlation Study
  - HESE Correlation Study

Analysis field of view



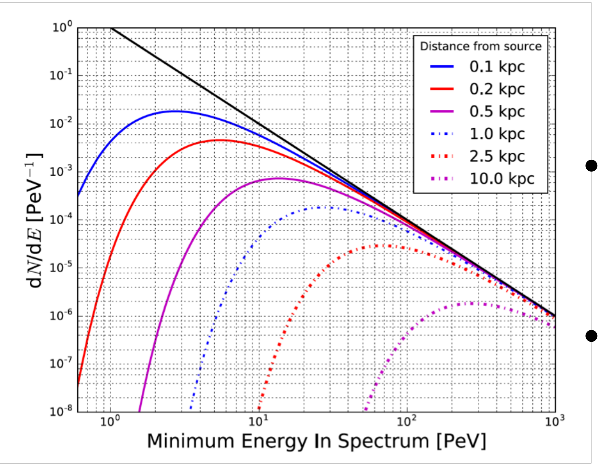
Scaled Angular-integrated Flux



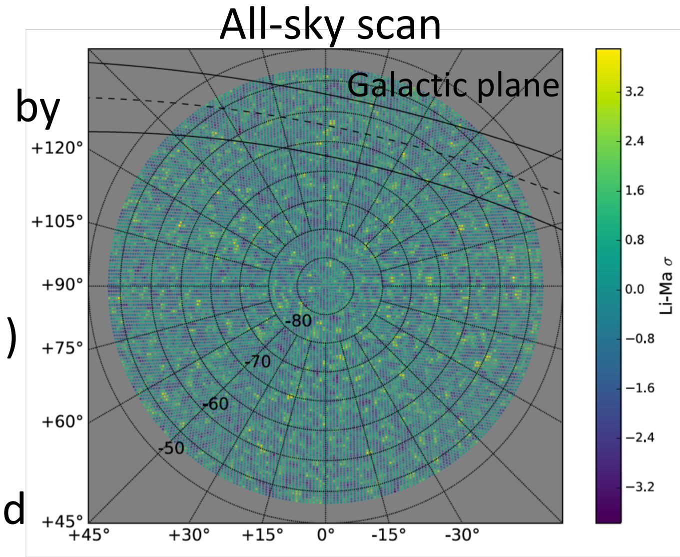
- Sensitivity of the analysis is calculated to place an upper limit on the flux.

PoS(ICRC2017)705
PoS(ICRC2017)715

PeV Neutron Search



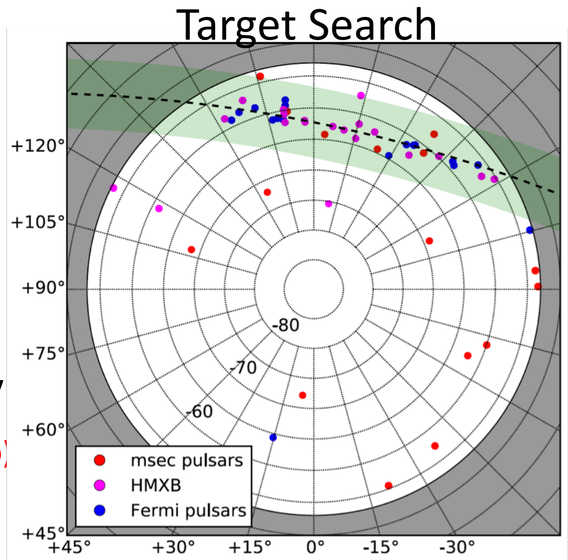
- PeV neutrons can be produced by interaction of charged CRs
- Only nearby sources should be detectable (R ~ 10 kpc (E/PeV))
- Target (E> 100 PeV) and all-sky (E> 10 PeV) searches performed

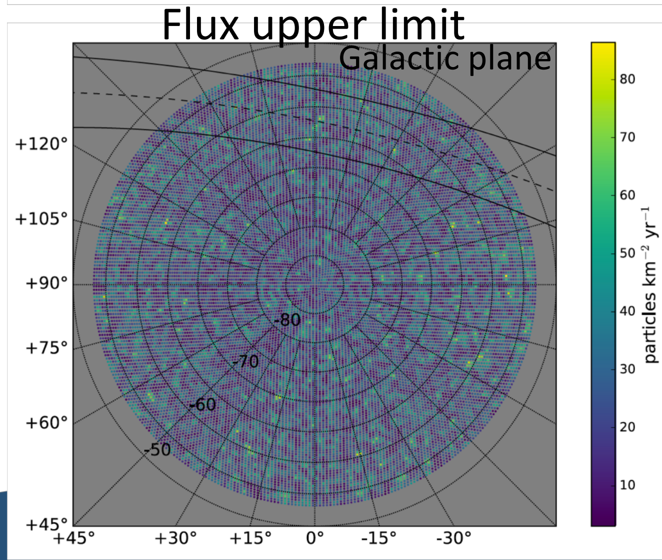


In 4 years of data (2010-2014)

- No significant correlation is found with known nearby galactic objects
- Upper limit on the flux calculated 10 PeV < E < 1 EeV

Astrophysical Journal, 830:129 (12pp)





Summary & Outlook

- IceTop+IceCube are versatile cosmic ray detector
- Determine the all-particle cosmic ray flux with two different analysis methods
- Determine the flux of cosmic rays for four mass groups (with representative masses H, He, O, Fe) (publication soon)
- Study the low energy muon content of air showers providing hints to guide interaction model development (publication soon)
- Search for gamma-rays with energy above 1 PeV (publication soon)
- Search for neutrons with energy above 10 PeV (published)

Backup

Superposition Model of Mass Composition PDFs

Total PDF for all nuclear mass cosmic rays is given by
(our model only use 4 typical components (H,He,O,Fe))

$$f(x;\theta) = \sum_{i=1}^{m} \theta_i f_i(x),$$

Due to the constraint, one fraction parameter can be substituted

$$\theta_m, \text{ by } 1 - \sum_{i=1}^{m-1} \theta_i$$

With Extended LogLikelihood:

$$\log L(\nu,\theta) = -\nu + \sum_{i=1}^{n} \log\left(\sum_{j=1}^{m} \nu\theta_j f_j(x_i)\right)$$

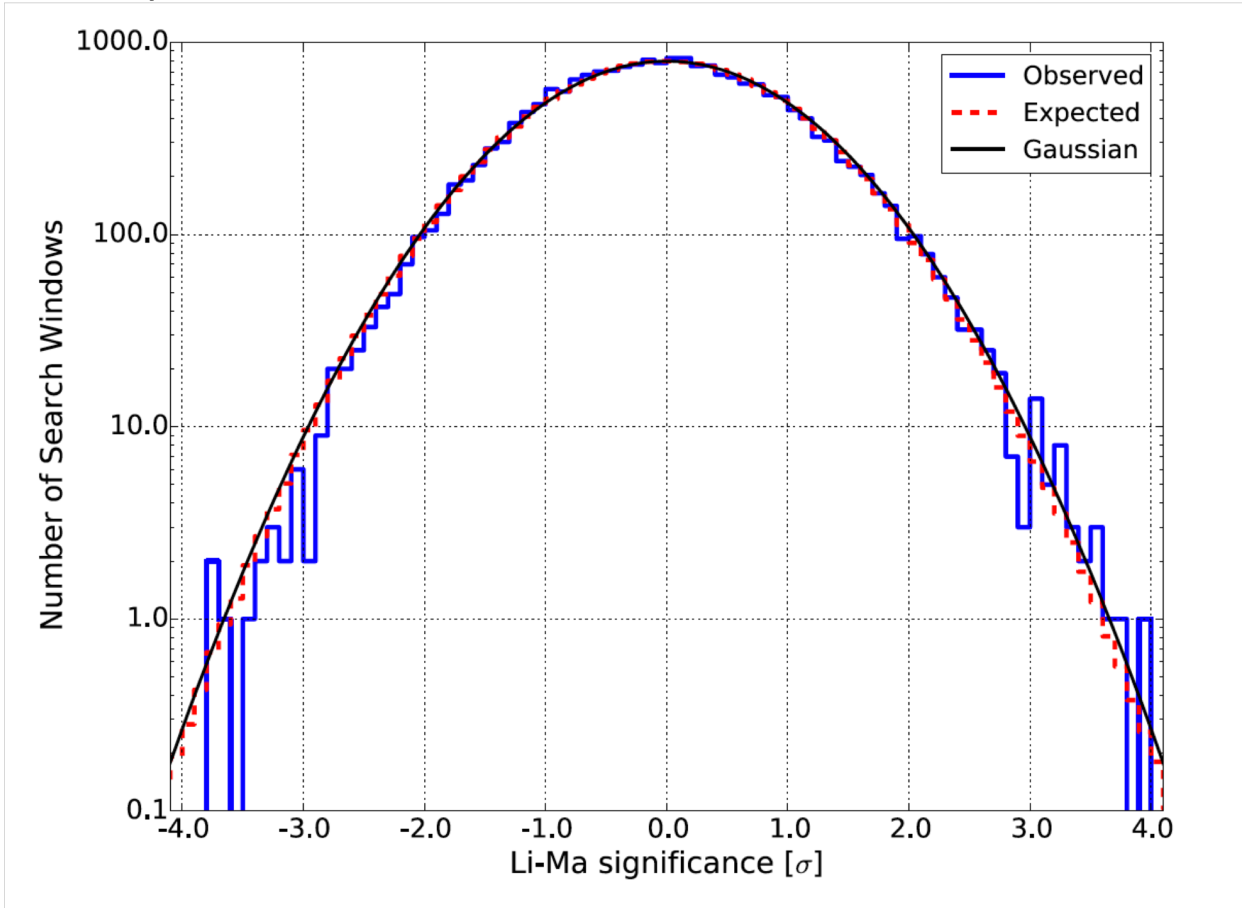
- Poisson fluctuations included
- Advantage of extended LL is to have a more symmetrical fit problem (easier fitting and error calculation)
  - 4 free fit parameter

- By using $\mu_i = \theta_i \nu$ follows

$$\log L(\mu) = -\sum_{j=1}^{m} \mu_j + \sum_{i=1}^{n} \log\left(\sum_{j=1}^{m} \mu_j f_j(x_i)\right)$$

Fit result gives now the number of events per mass species, which we need for the energy spectrum

Neutron All-Sky



Neutron Target Search

- msec pulsars [Manchester et al. 2005]:
  - http://www.atnf.csiro.au/research/pulsar/psrcat/
  - 17 objects with P < 10 msec
  - median distance ~ 1.9 kpc —> Ec ~ 220 PeV
- ɣ pulsars [Abdo et al. 2013]: confirmed high energy photons
  - http://fermi.gsfc.nasa.gov/ssc/data/access/lat/2nd_PSR_catalog
  - 16 objects
  - median distance ~ 2.7 kpc —> Ec ~ 320 PeV
- HMXB [Liu et al. 2007]: compact object + massive star
  - http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/442/1135
  - 20 objects
  - median distance ~ 4.2 kpc —> Ec ~ 480 PeV