Cosmic Ray Physics with IceCube and IceTop

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KIT
Karlsruher Institut für Technologie

ICECUBE

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- Low energy muons in IceTop
- Tests of hadronic interaction models
- Anisotropy of cosmic rays
- IceCube-Gen2 surface array enhancement

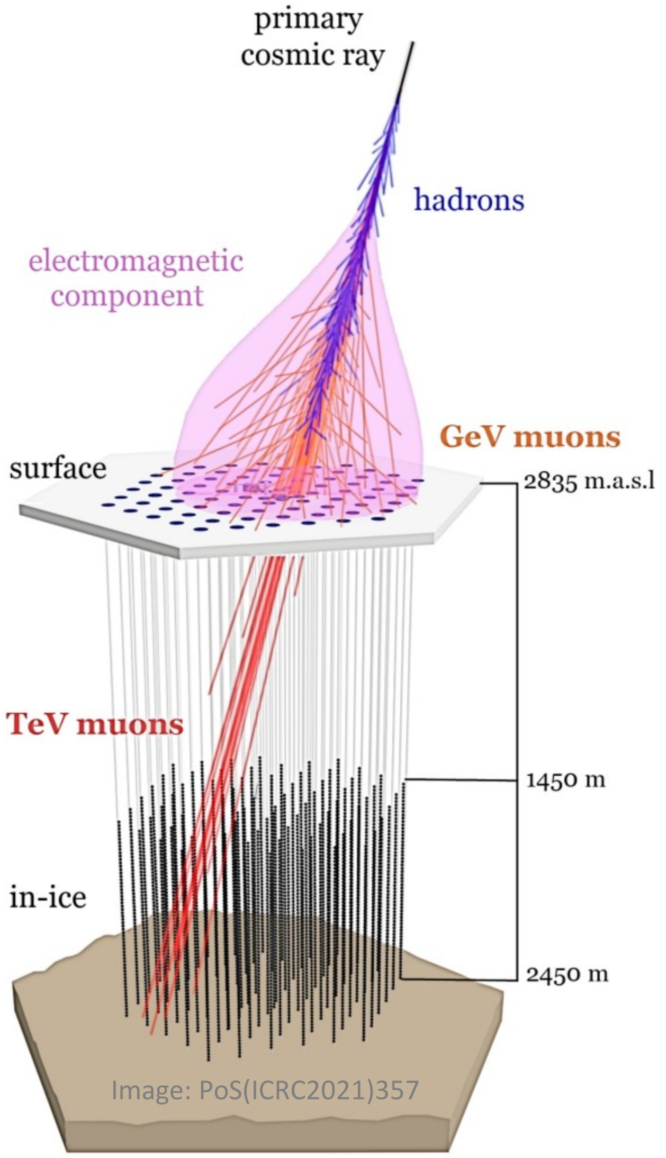
Cosmic Ray Physics

A three-dimensional cosmic ray detector:

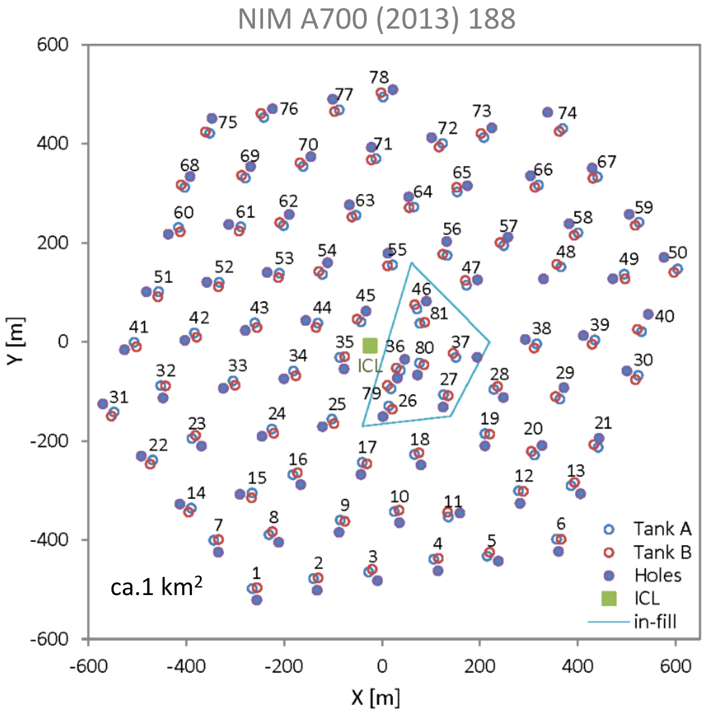
IceTop 1 km^2 surface air shower array
- Cosmic ray energy and direction
- Measure electromagnetic and low energy muon components of air shower ($E_\mu \sim 1$ GeV, GeV muons)

IceCube 1 km^3 in-ice array
- Measure high energy muon component of air shower ($E_\mu > 400$ GeV, TeV muons)
- Bundle reconstruction
- Deposited energy along the track dE/dX

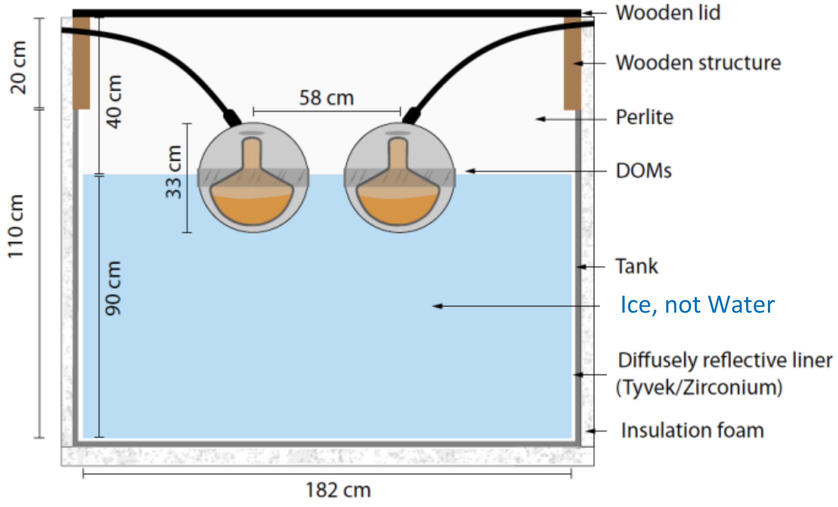
*IceCube Highlights: see J. Aguilar's talk



IceTop

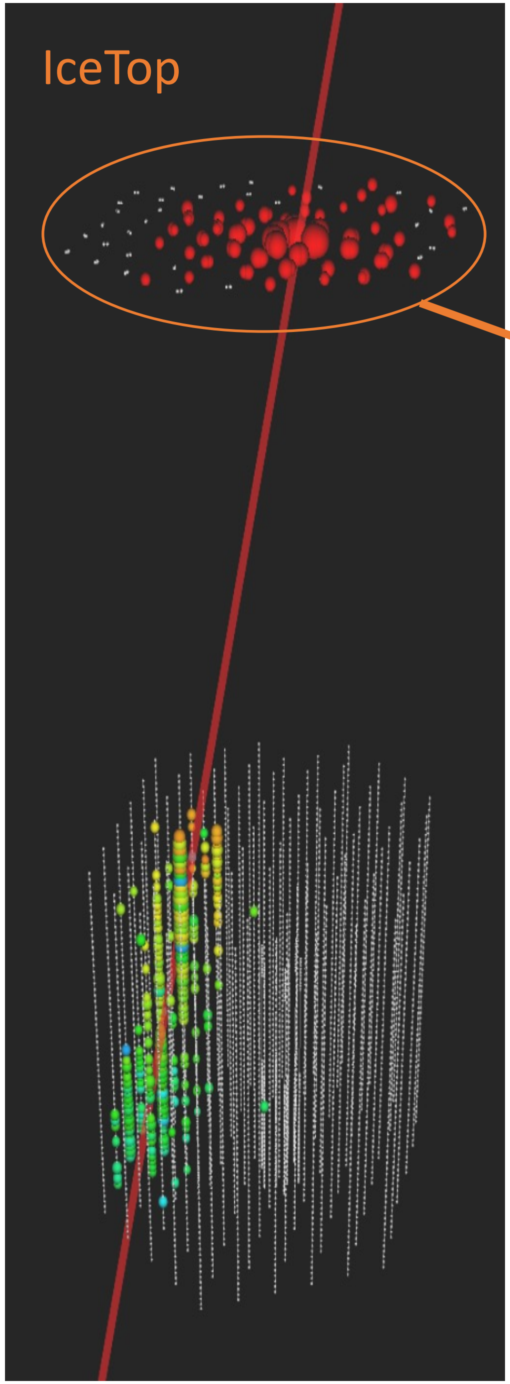


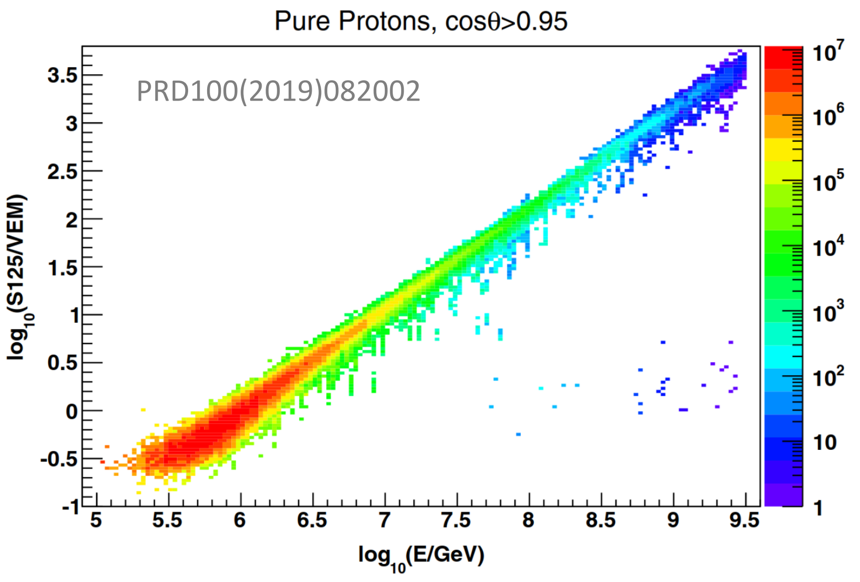
- Cosmic ray energies from 1 PeV to 1000 PeV
- 2835 m a.s.l. 680 g/cm^2
- 81 stations with 2 tanks each (2 DOMs per tank)
- Angular resolution ~ 1°
- Timing resolution 3ns
- Energy resolution 0.1 in $\log_{10}(E/GeV)$

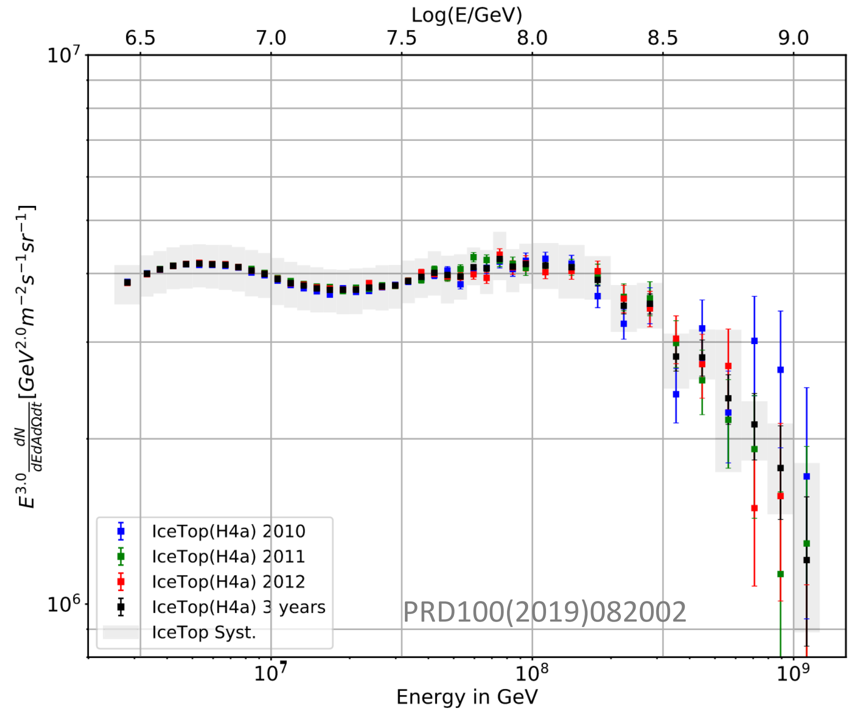


Same DOMs used for IceCube and IceTop

Energy Spectrum (IceTop-alone)







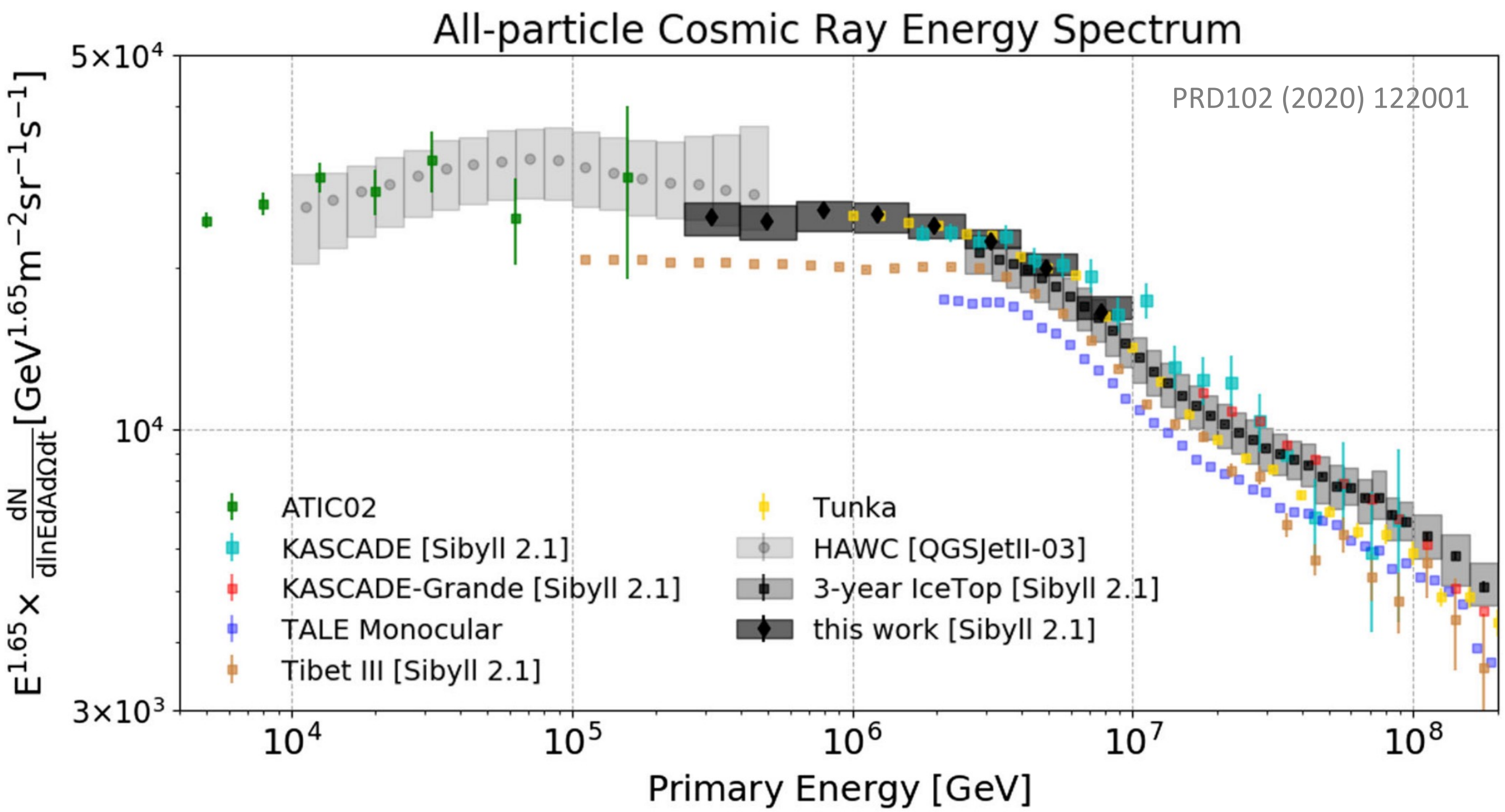
- Lateral Distribution Function (LDF):

$$S(r) = S_{125} \cdot \left(\frac{r}{125\text{m}}\right)^{-\beta-\kappa\cdot\log_{10}(r/125\text{m})}$$

- IceTop energy proxy S_{125} in Vertical Equivalent Muons (VEM)
- Nearly composition independent
- Energy calibration based on MC with Sibyll 2.1 and H4a
- Snow depth taken into account
- Quality cuts and full efficiency

- 3 years of data (May 2010 to June 2013)
- About $5 \cdot 10^7$ selected events
- Dataset divided into individual years shows strong agreement
- Systematic uncertainties ~ 10%

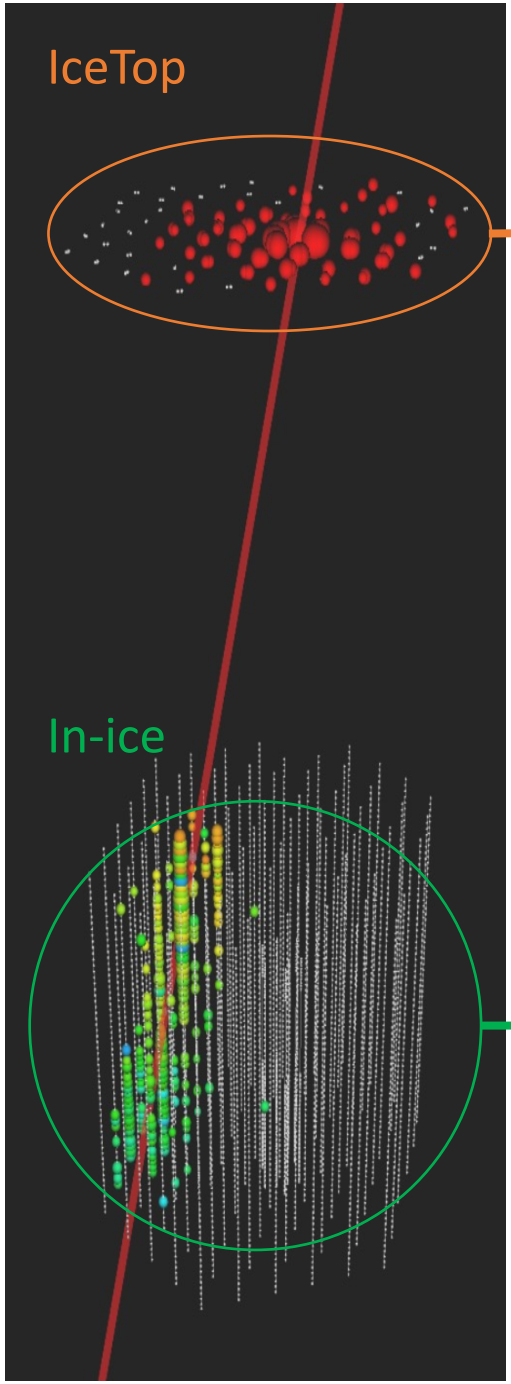
Low Energy Spectrum (IceTop-alone)



Latest results: Extension to low energies

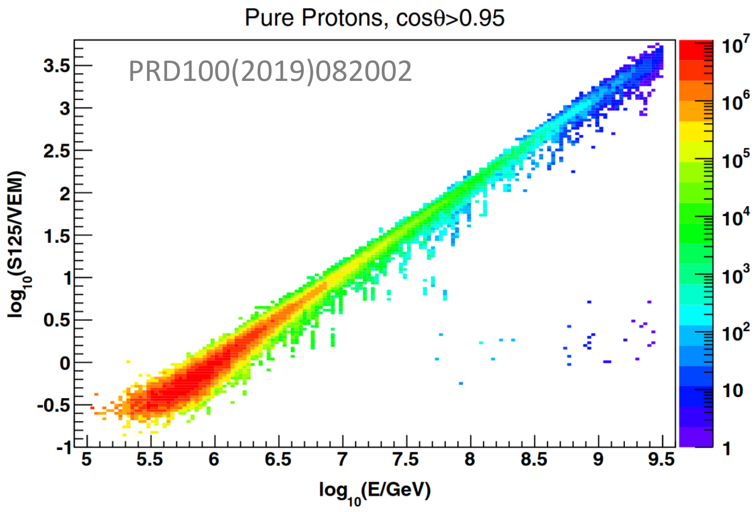
- Lower threshold by using IceTop infill area (250 TeV – 10 PeV)
- LDF fit impracticable → Random Forest (RF) regressions for shower reconstruction
- Connecting to direct measurements, overlap with HAWC
- Overlapping region with 3-year IceTop result → Knee structure visible
- Large systematic uncertainties due to composition, unfolding, atmosphere

Coincident Analysis: Spectrum and Composition



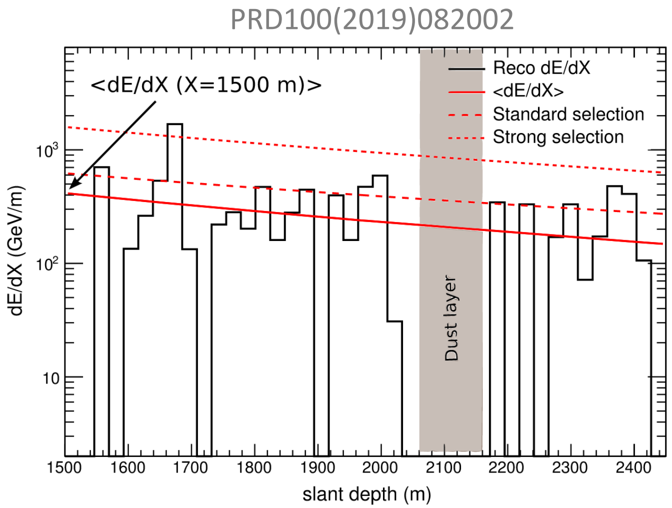
Electromagnetic component of shower:

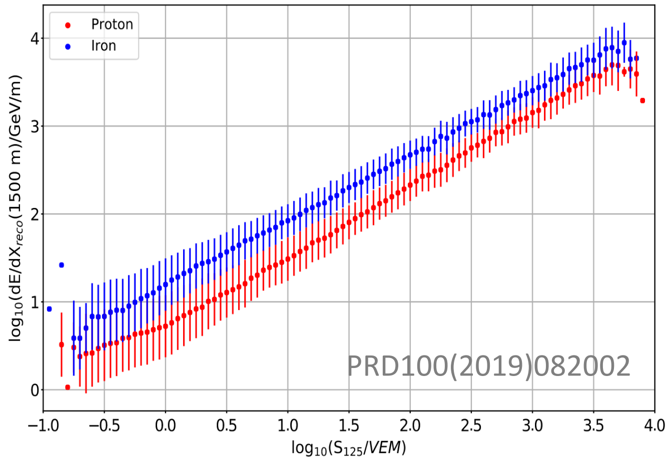
- IceTop energy proxy S_{125}
- Nearly composition independent



High-energy muons (>400 GeV):

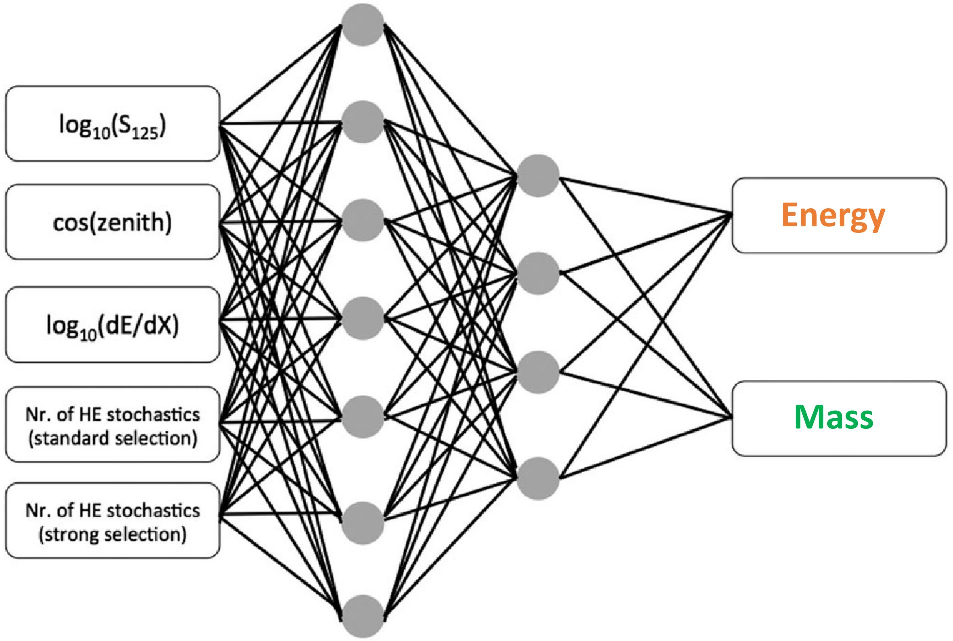
- Mean muon number: $N_{\mu}(E,A) \propto A \cdot (E/A)^{\beta}$, $\beta \sim 0.9$
- Energy loss (dE/dX) at fixed slant depth (X=1500m) in the glacial ice
- Strong composition sensitivity



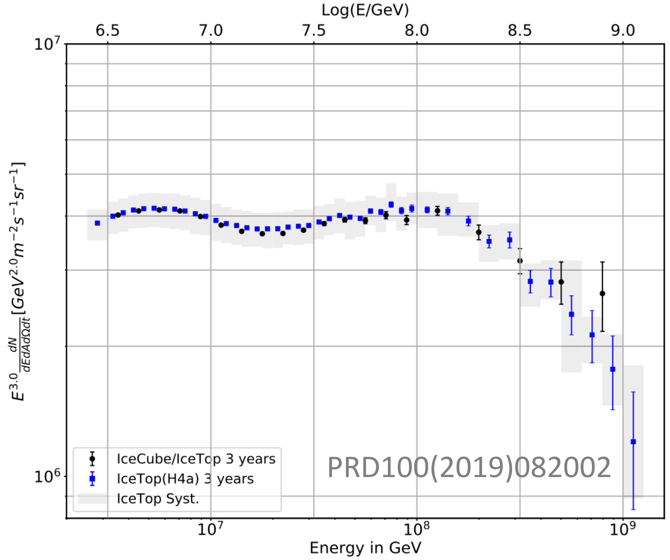


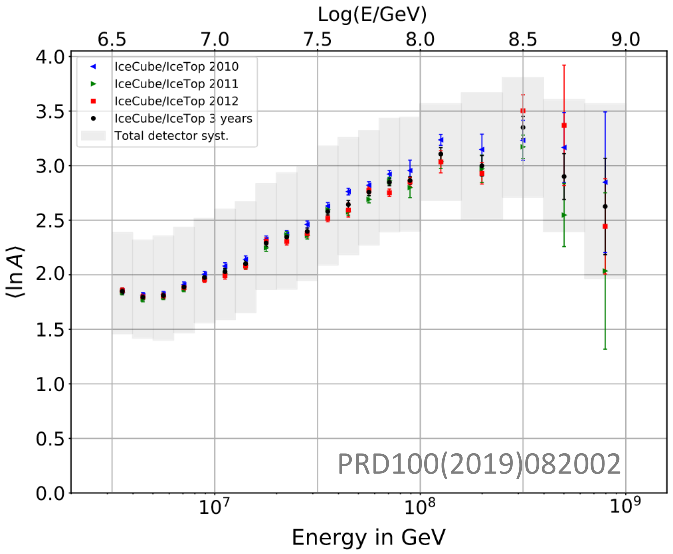
Spectrum and Composition

Use Neural Network to directly reconstruct energy → Coincident energy spectrum



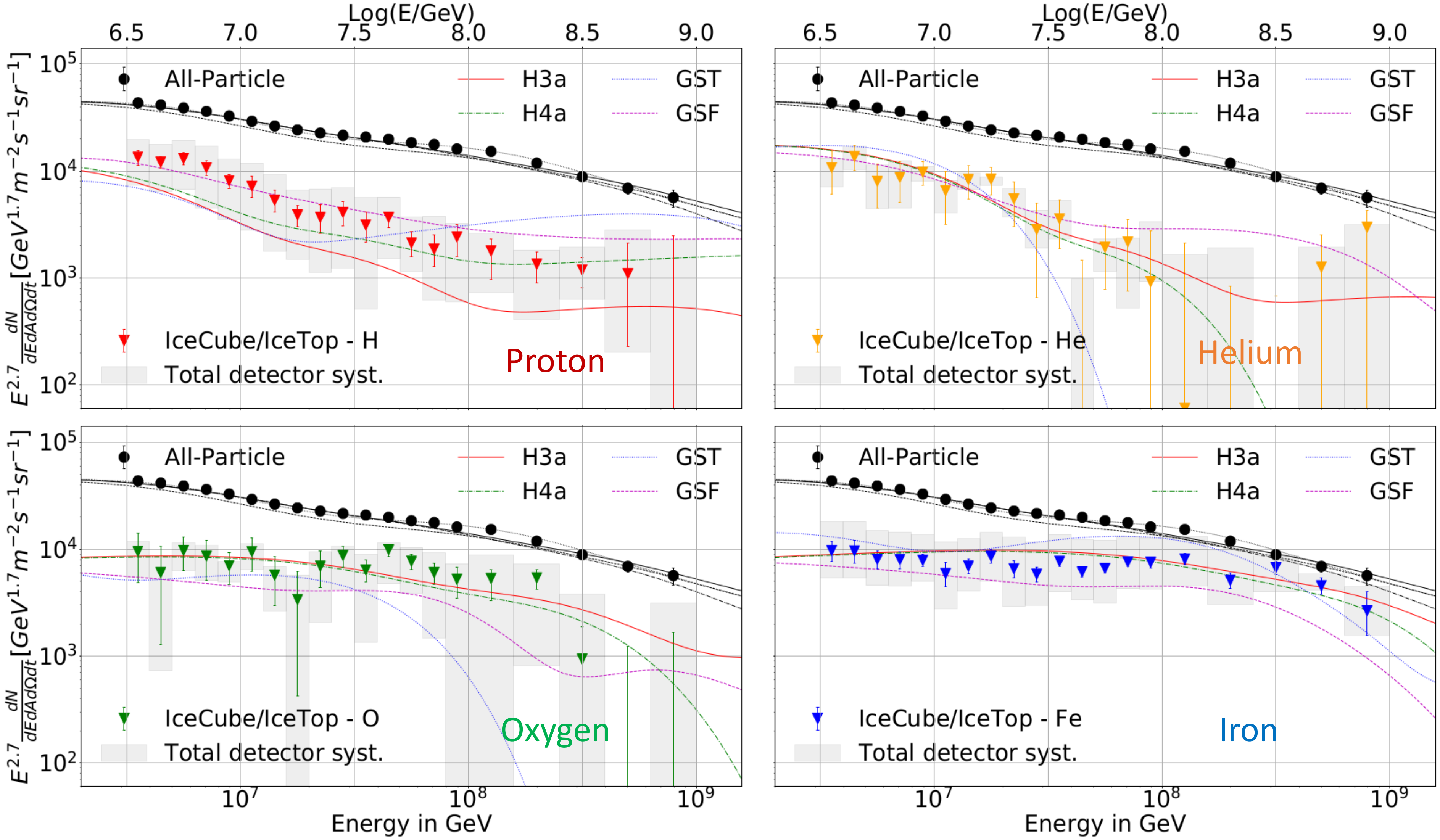
Event by event mass classification is not possible → Analyze mass as a function of energy on a statistical basis





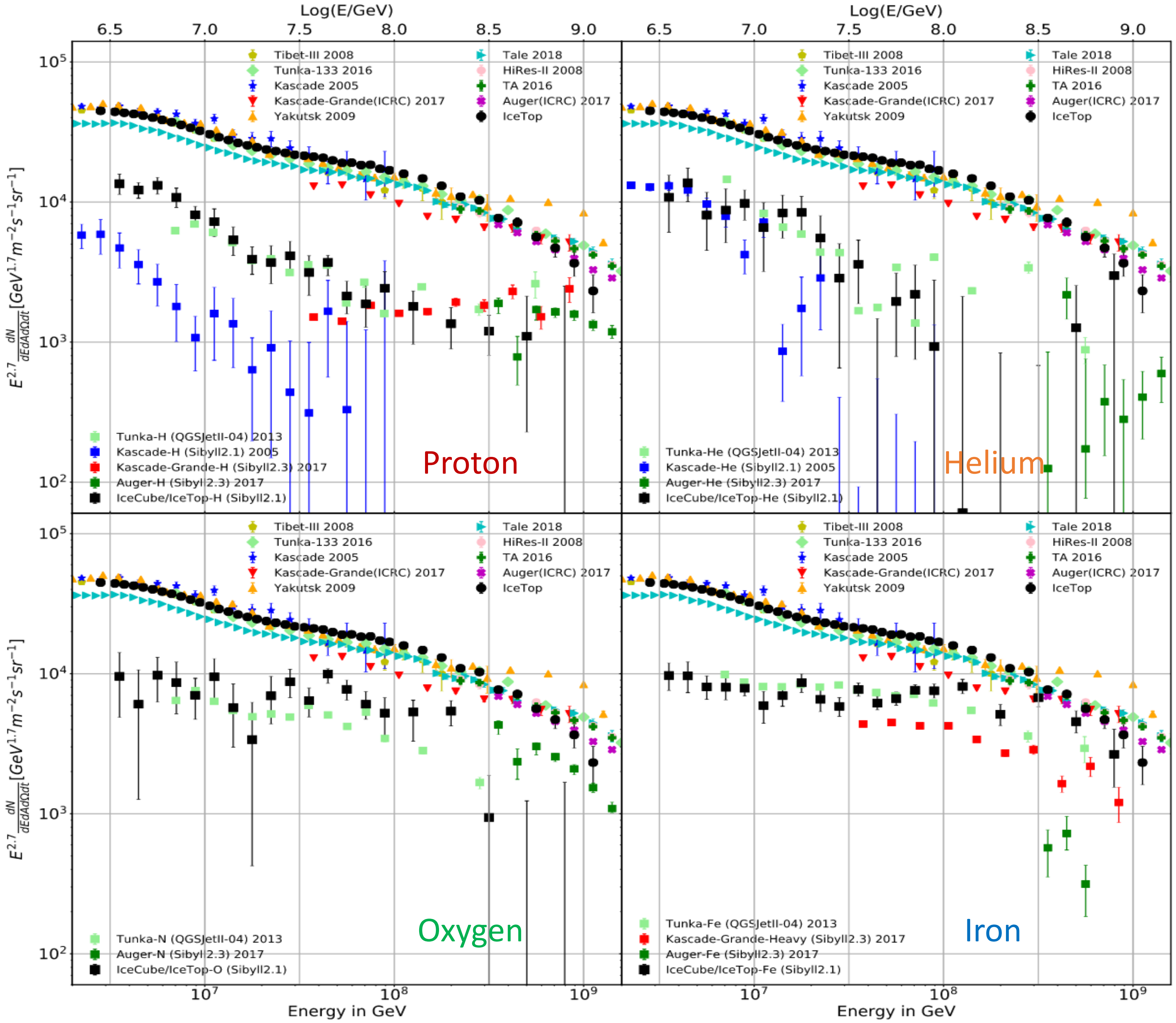
- Same dataset as IceTop-alone analysis
- Agreement with IceTop-alone spectrum
- Coincidence requirement gives composition analysis fewer events and smaller energy range than IceTop-alone analysis

- Mean log mass <lnA> derived from the individual fractions which best fit the NN mass output
- Combined systematic uncertainties of the IceTop and in-ice detectors for coincident analysis:
  - Energy scale ~ 3%
  - In-ice light yield ~ 10%
  - Snow accumulation ~ ±2m



- Each of the four individual fractions from the NN mass output is translated into an individual spectrum
- Composition becomes heavier with increasing energy up to 10^8 GeV
- Agreement with models within statistical and systematic uncertainty

PRD100(2019)082002



- Comparison of the all-particle and composition spectra of the four elemental groups H, He, O, and Fe based on Sibyll 2.1

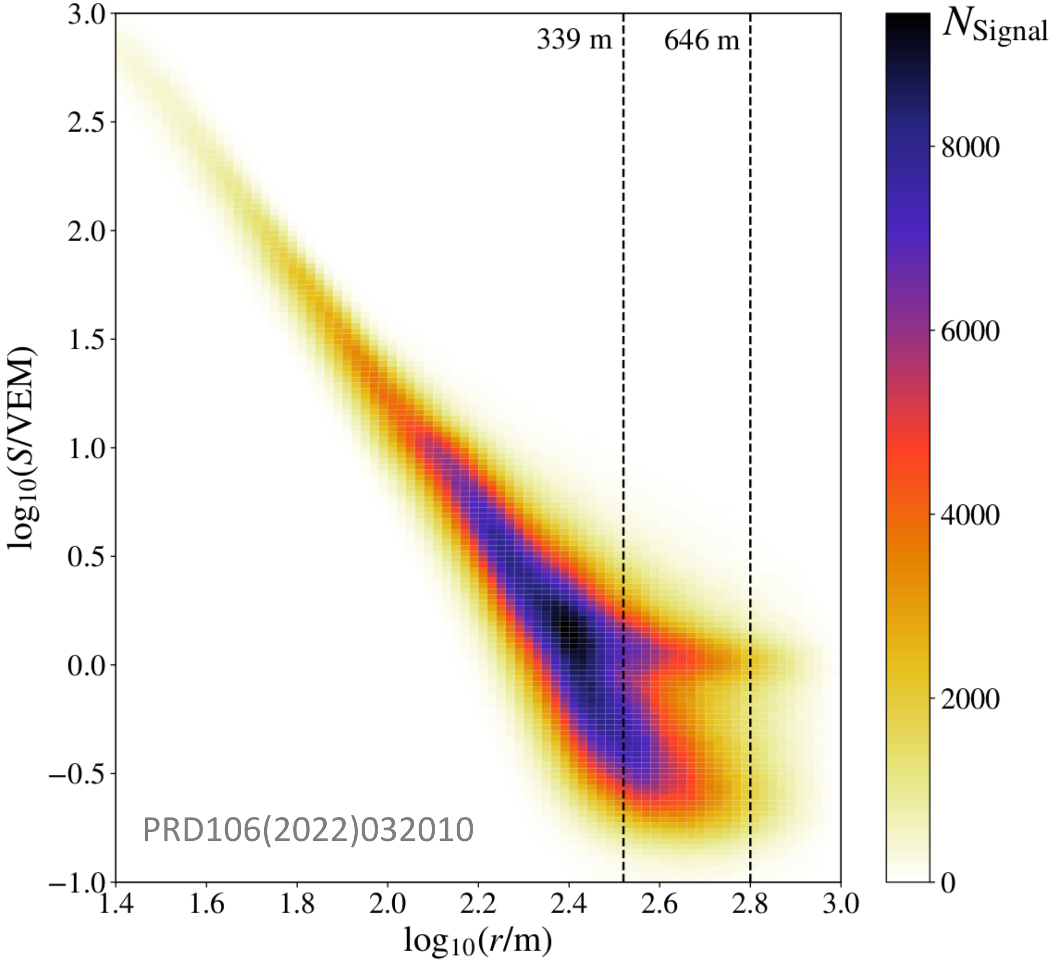
- Individual elemental fluxes across a wider range in energy than any previous experiment

- The knee energy increasing as mass increases

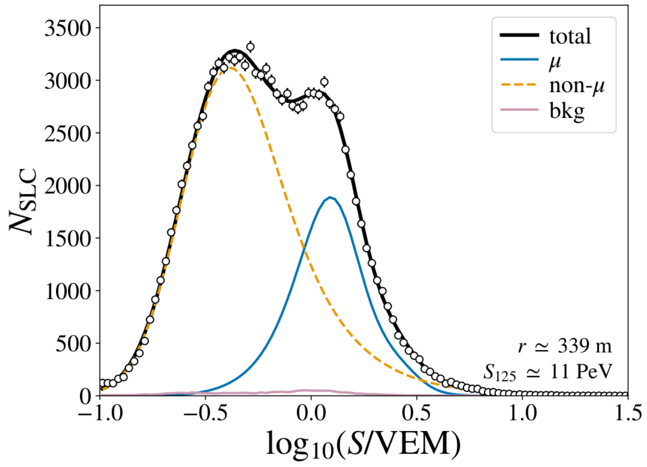
- Differences in how different experiments handle the intermediate elements may lead to systematic differences in flux measurements

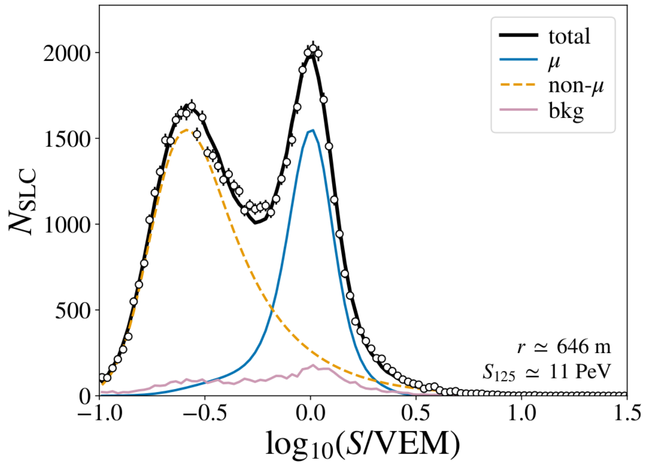
PRD100(2019)082002

GeV Muon Density in IceTop



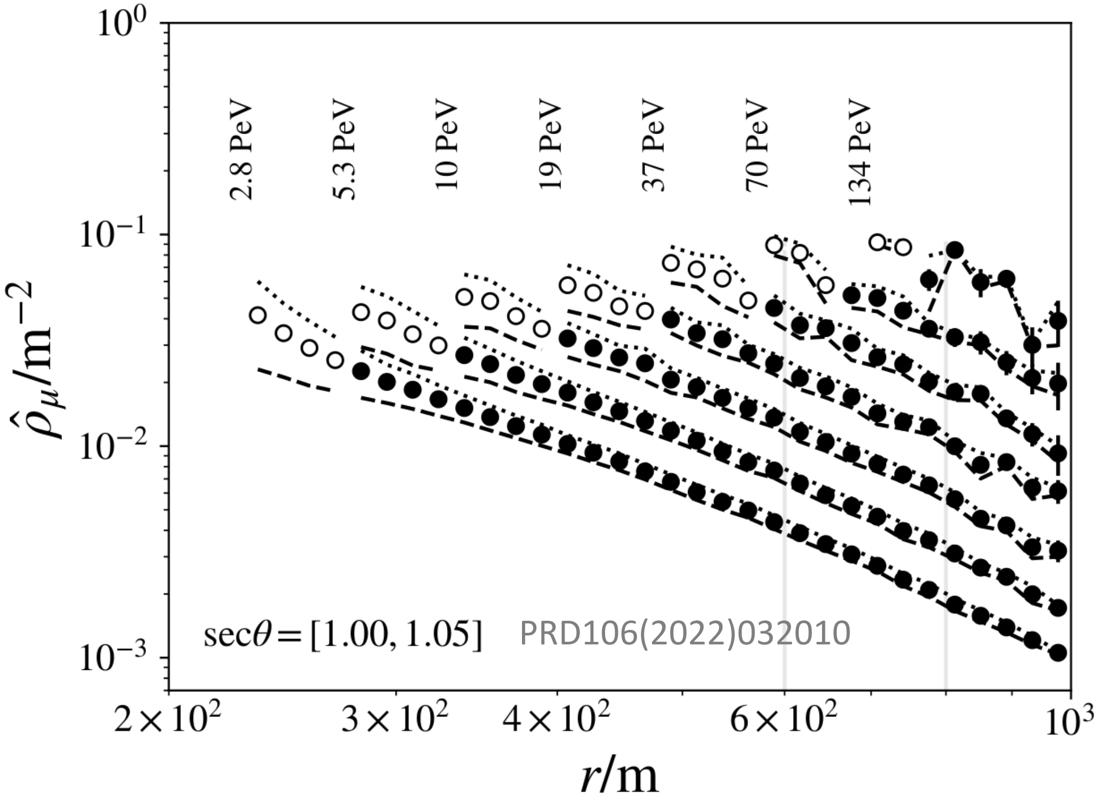
PRD106(2022)032010

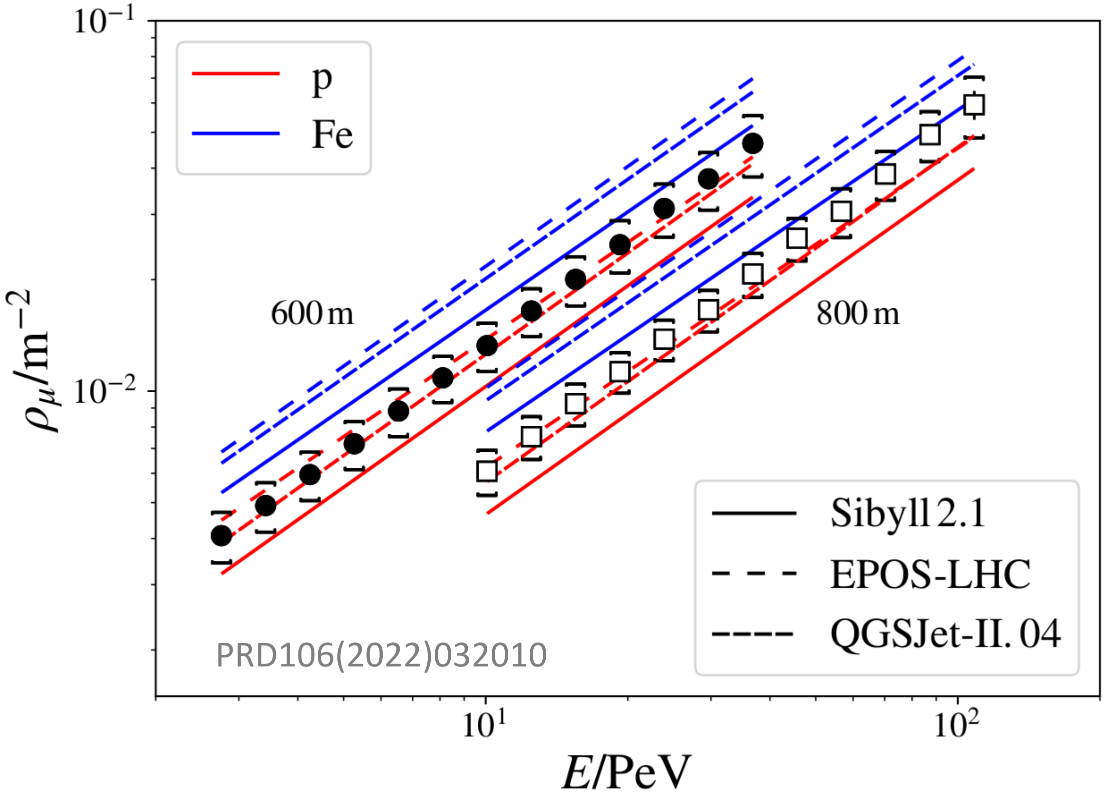




- Muon peak at 1 VEM
- EM signal contribution usually smaller, smooth distribution
- Muon peak more pronounced at large distances from shower core
- Binned in energy, zenith, lateral distances
- Derive muon density $\rho_\mu(r)$ by counting muons per tank

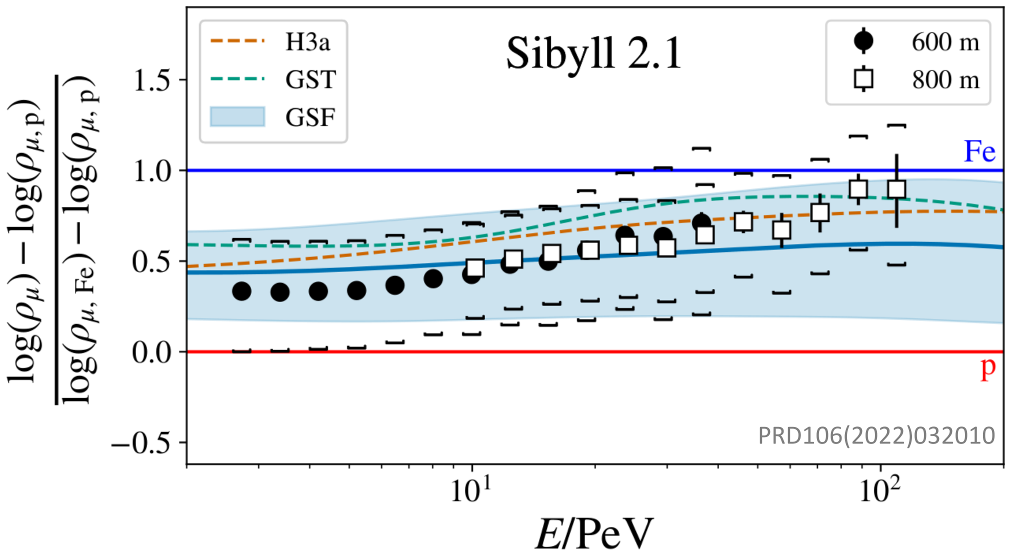
GeV Muon Density in IceTop



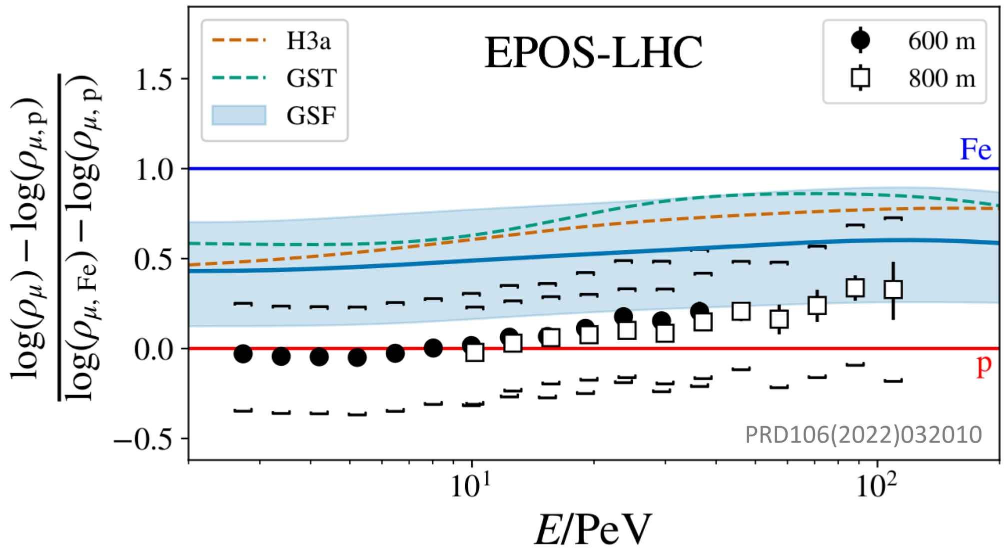


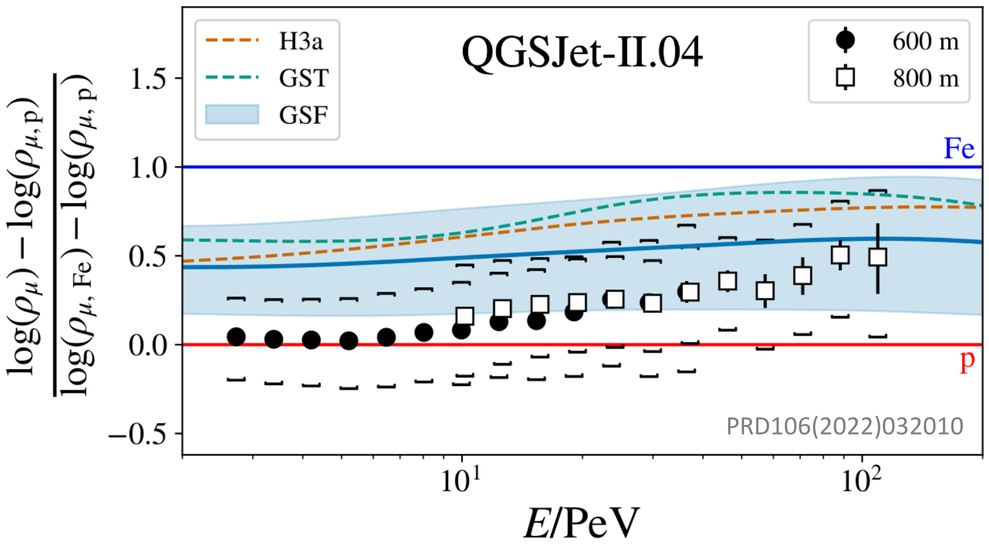
- Measured muon density at 600 m (2.5 – 40 PeV) and 800 m (9 – 120 PeV) reference distances
- Comparisons with different model predictions

GeV Muon Density for Different Models

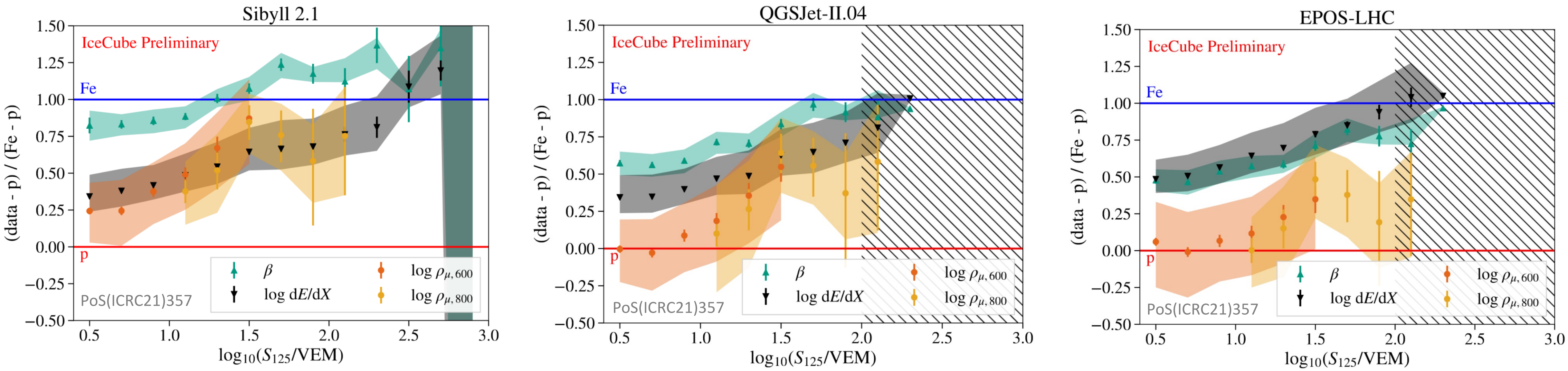


- Results in terms of z-value: $z = \dfrac{\log\rho_\mu - \log\rho_{\mu,p}}{\log\rho_{\mu,Fe} - \log\rho_{\mu,p}}$
- Hadronic interaction models:
  Sibyll 2.1(pre-LHC), QGSJet-II.04 and EPOS-LHC (post-LHC)
- Flux composition models: H3a, GST, GSF
- Good agreement for Sibyll 2.1
- Post-LHC models expect more muons → light mass composition





Tests of Hadronic Interaction Models



Tests with composition-sensitive observables:

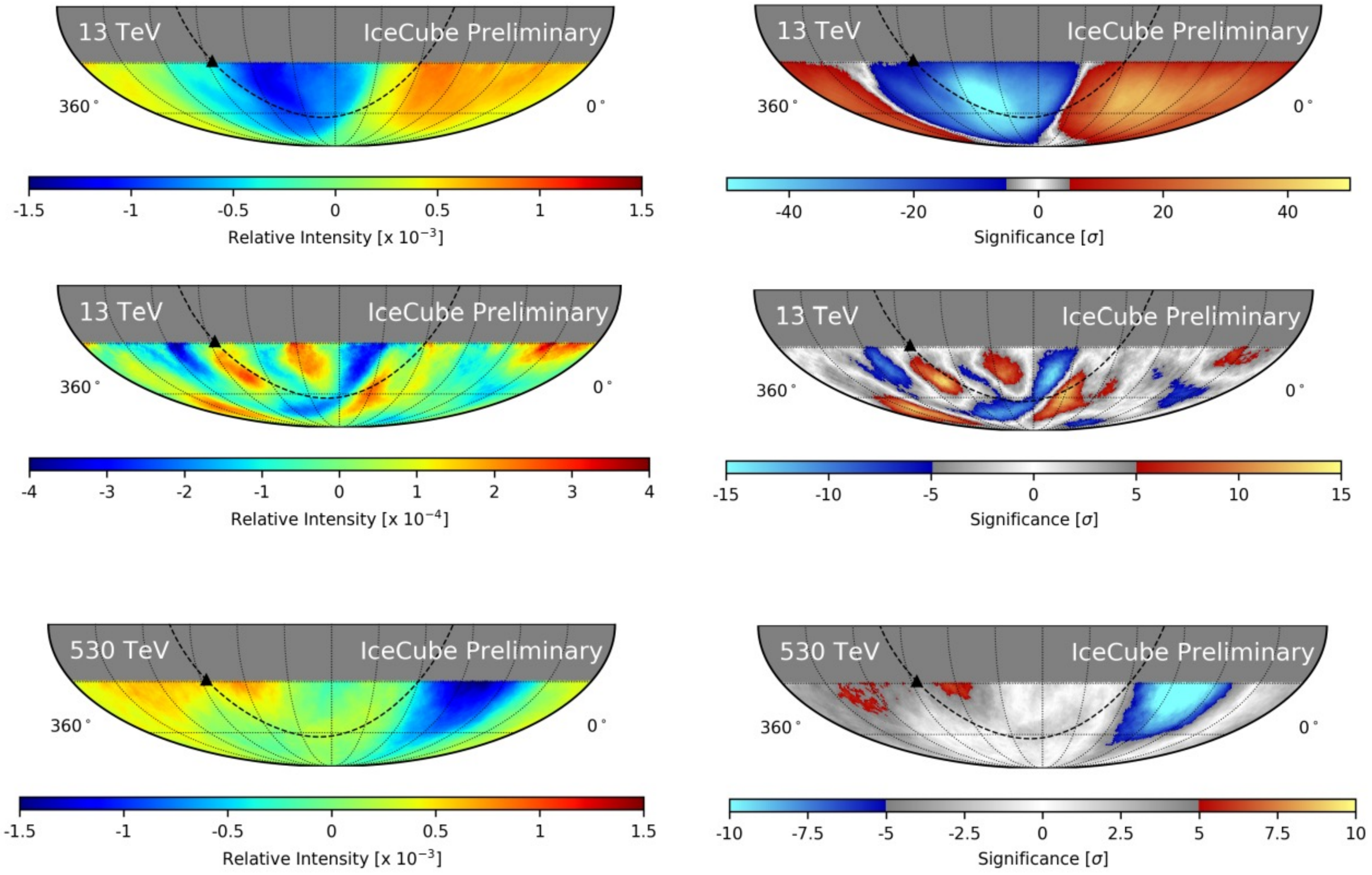
- GeV muon densities at shower core distances of 600 and 800 m
- Energy deposit in-ice of TeV muons (dE/dX)
- Slope of lateral distribution

All mass sensitive parameters compared to prediction of three different hadronic interaction models

- All three models show no consistency for all parameters
- TeV muons and GeV muons are not consistent in post-LHC models
- Inconsistencies between models
- No obvious muon puzzle below about 100 PeV

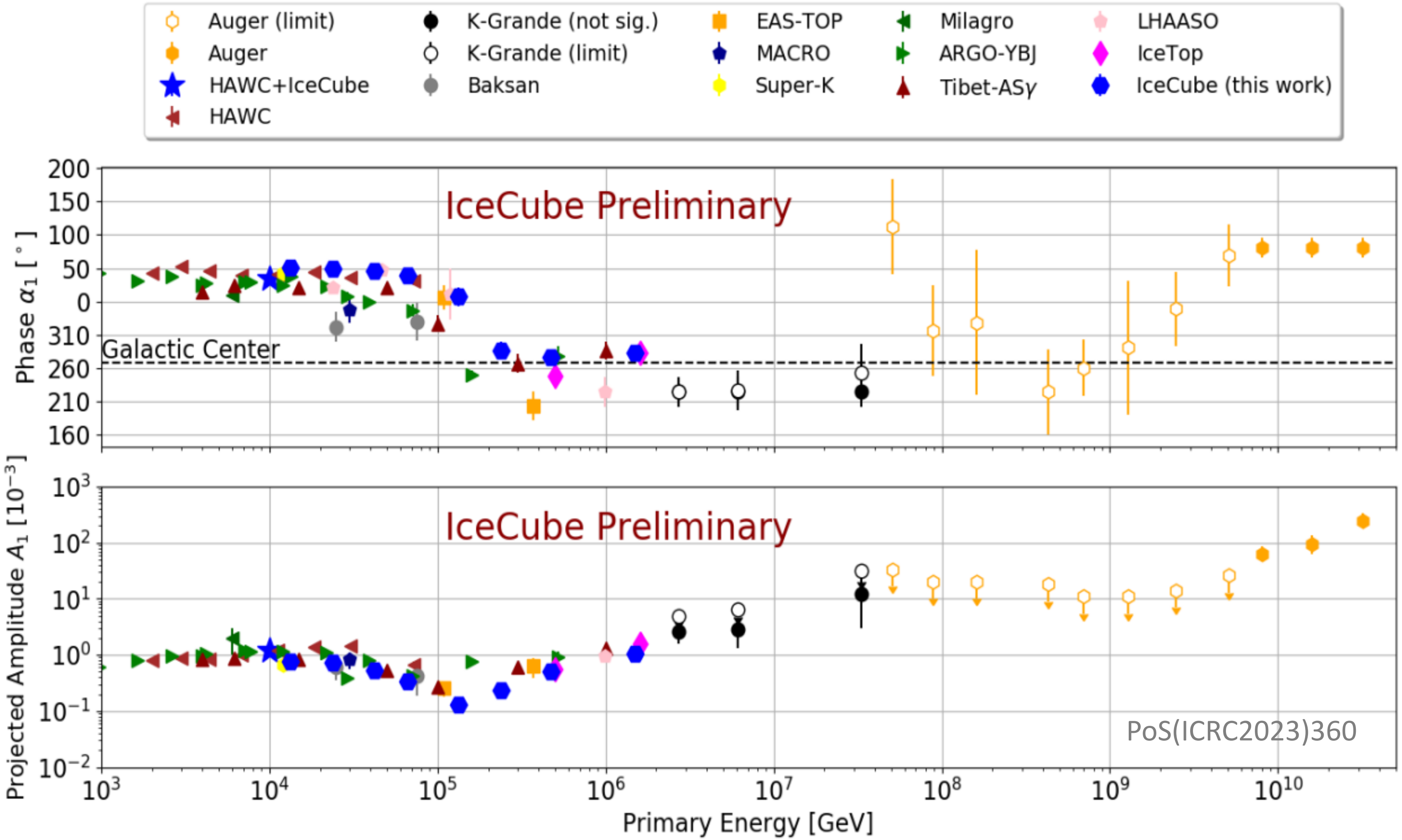
IceCube Cosmic Ray Anisotropy

PoS(ICRC2023)360



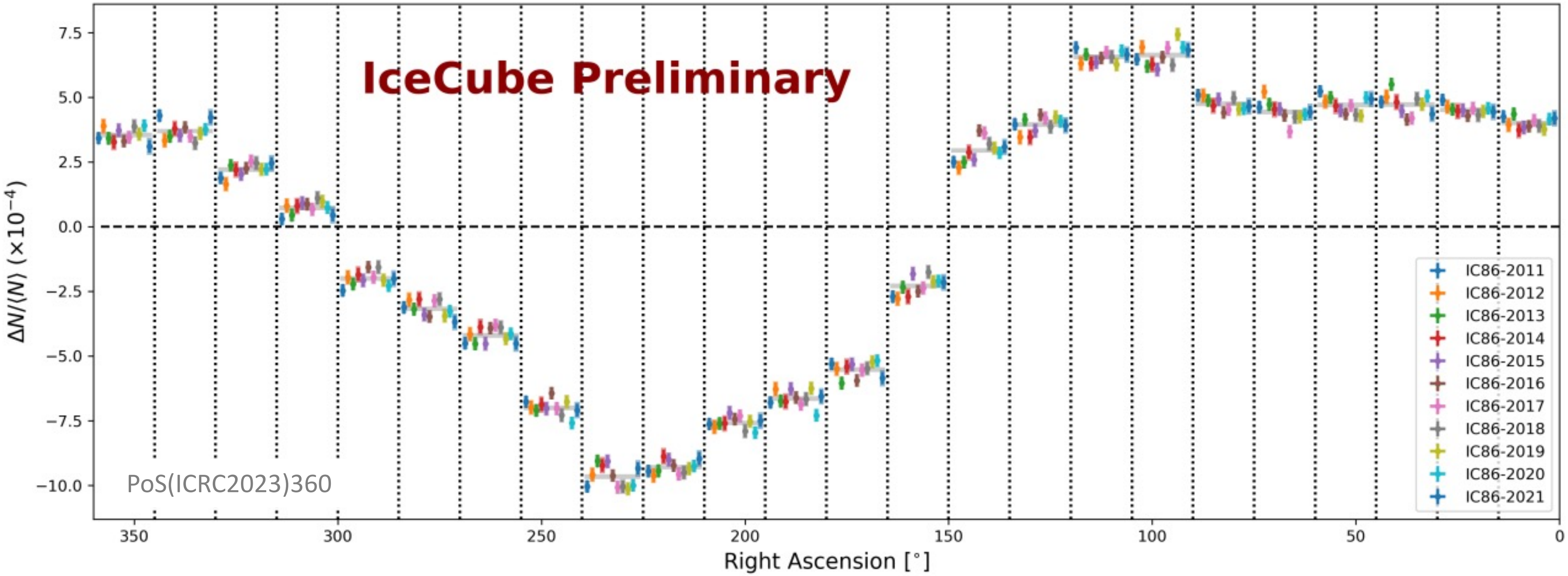
- Improved statistics: Eleven years of data (~ 700 billion events)
- Improved MC simulation and better handling of year-to-year processing → reduce systematic uncertainties significantly
- Relative intensity and significance maps → Observed cosmic-ray anisotropy of the order of 10^{-3}
- Residual anisotropy by subtracting the best-fit dipole and quadrupole components
- Topological change between 10 TeV and 1 PeV is consistent with previous measurements

IceCube Cosmic Ray Anisotropy



- The dipole component's amplitude decreases from 10 TeV to slightly above 100 TeV, reaching a minimum of about 2×10^{-4}, and increases again at higher energy
- Consistent with the observation of all other ground-based experiments
- The phase flips from an RA of about 50° to about 260° at around 100 TeV

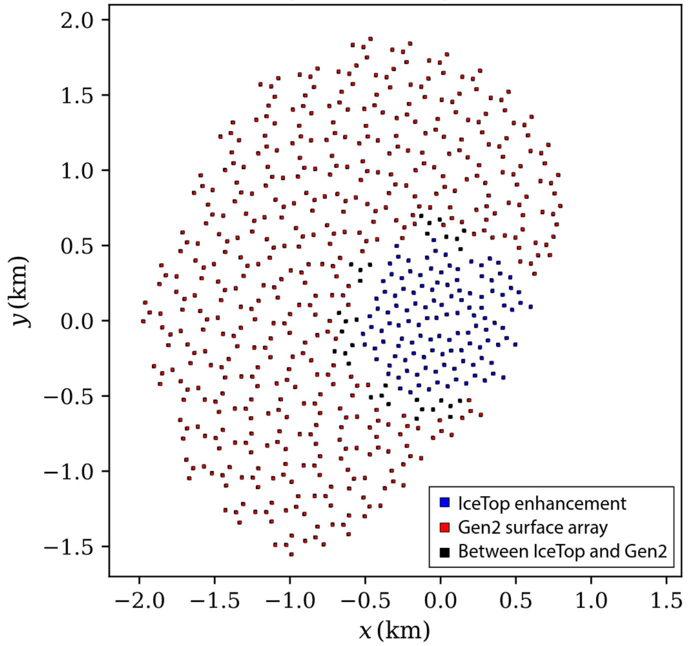
Anisotropy Stability Over Time

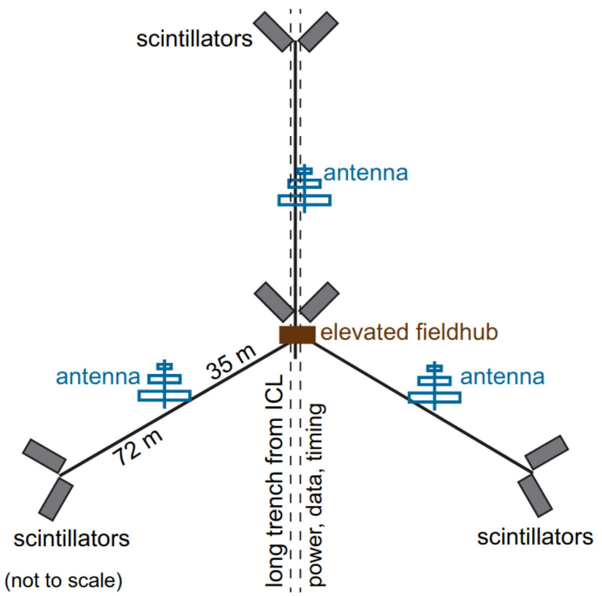


- Relative intensity as a function of RA for each calendar year
- Both statistical (error bars) and systematic (shaded boxes) uncertainties are included, calculated independently using the anti-sidereal frame for each year
- The gray band in each bin indicates the average value for all years
- Each year is compatible with the 11-year data within about 2σ

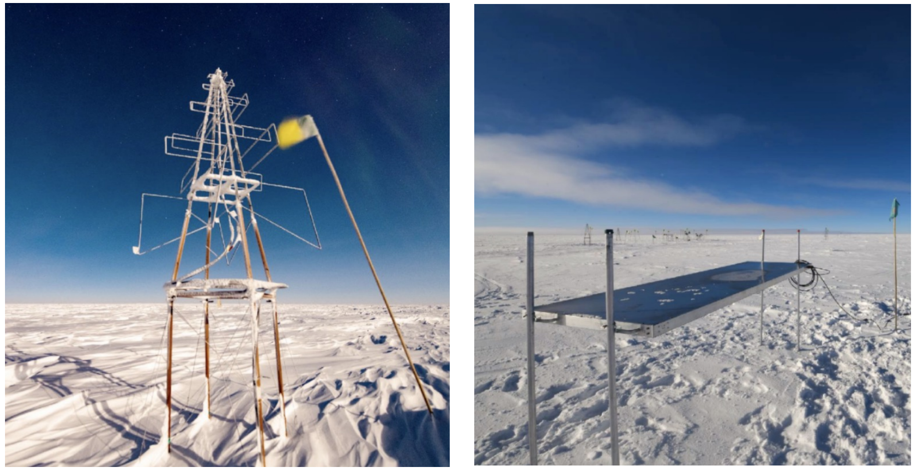
IceTop: Hybrid Surface Detector Enhancement

PoS(ICRC2021)407





4 pairs of scintillation detectors
+ 3 antennas



Complete prototype station since 2020

Science goals:

- Improve systematics due to snow coverage
- Improve cosmic ray veto for neutrino detection
- Improve mass composition measurements
- Composition dependent anisotropy studies
- Improve PeV gamma ray search
- Validate hadronic interaction models

A multi-detector IceTop enhancement by adding to IceTop Cherenkov tanks:

- Scintillation detector panels
- Radio antennas
- Cherenkov light telescopes (IceAct)

Summary

- Using three years of data from IceTop and IceCube, the energy spectrum and the mass composition of the primary cosmic rays are simultaneously reconstructed

- Many cosmic ray activities are not covered:
  - Seasonal variations of atmospheric muon flux (PoS(ICRC2019)894)
  - Measurements of the Moon and Sun shadows (ApJ 872 (2019) 133)

- Many interesting analyses upcoming:
  - Plan to include more years of experimental data
  - To simulate more intermediate elements
  - To investigate new composition-sensitive parameters currently under development (PoS(ICRC21)312)
  - To reduce the detector systematic uncertainties

- Bright future with surface enhancements and IceCube-Gen2 surface array

THE ICECUBE COLLABORATION

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Vrije Universiteit Brussel

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