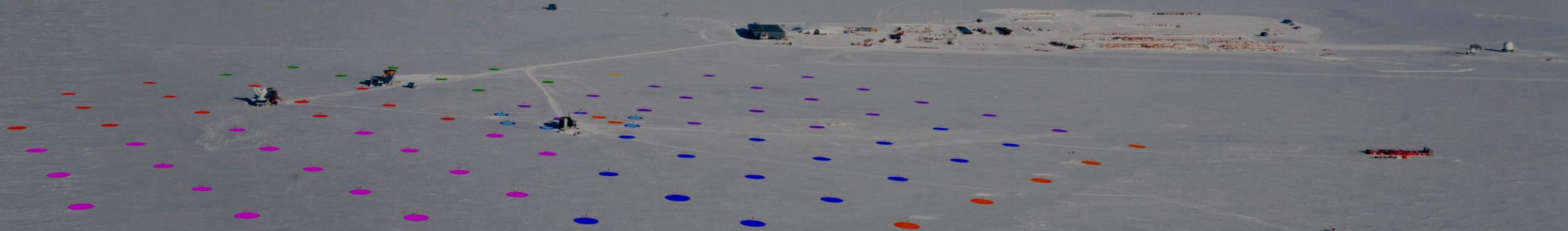




Cosmic Ray Results with IceCube and IceTop

Donghwa Kang for the IceCube Collaboration



- Cosmic-ray energy spectrum and composition
- Low energy muons in IceTop
- Tests of hadronic interaction models
- IceCube-Gen2 surface array

Cosmic Ray Physics

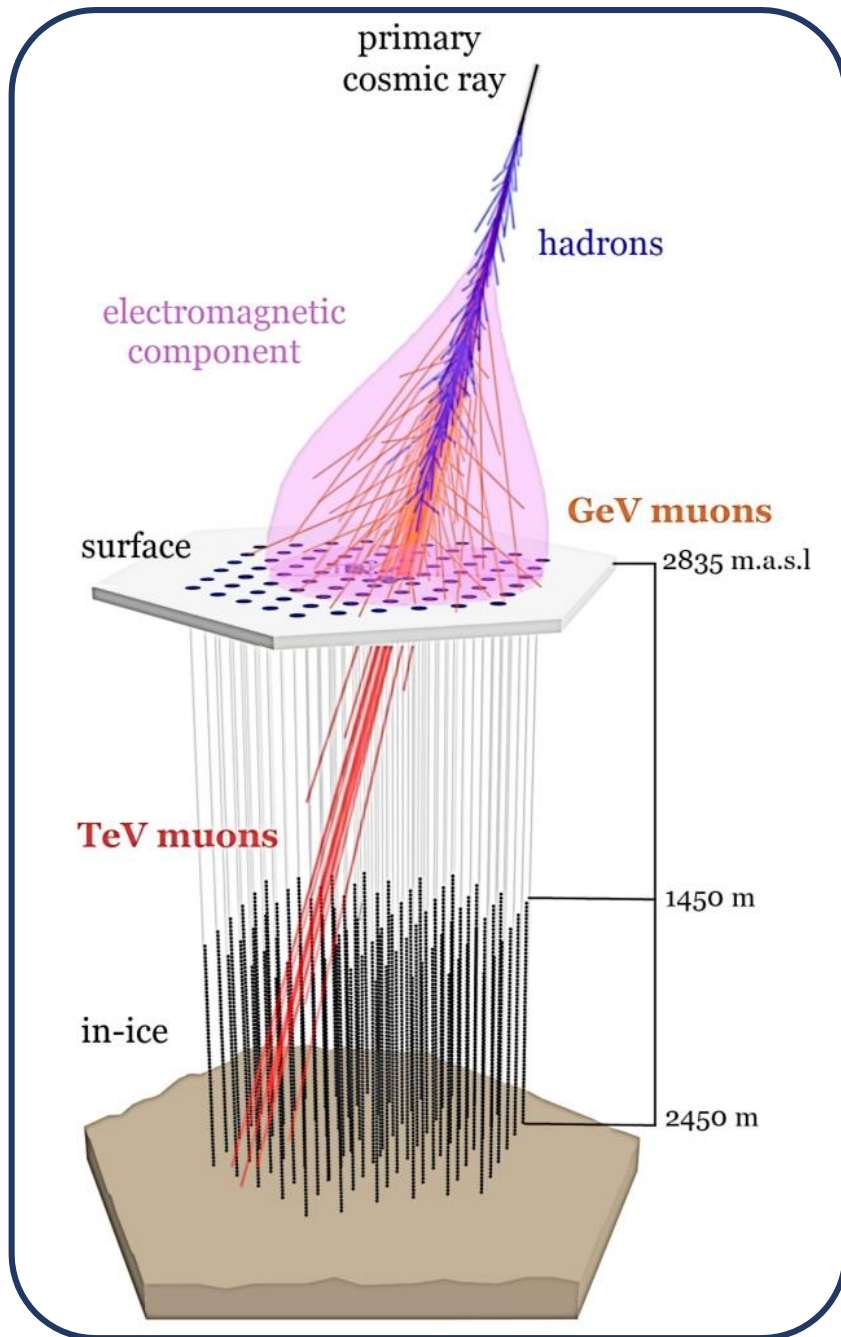
A three-dimensional cosmic ray detector:

IceTop 1 km² surface air shower array

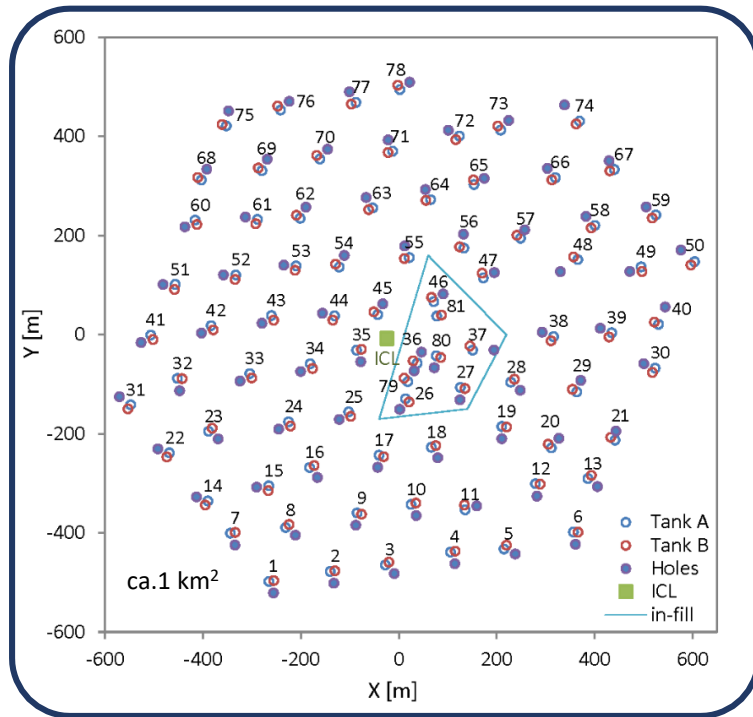
- Cosmic ray energy and direction
- Measure electromagnetic and low energy muon components of air shower
($E_{\mu} \sim 1$ GeV, GeV muons)

IceCube 1 km³ 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

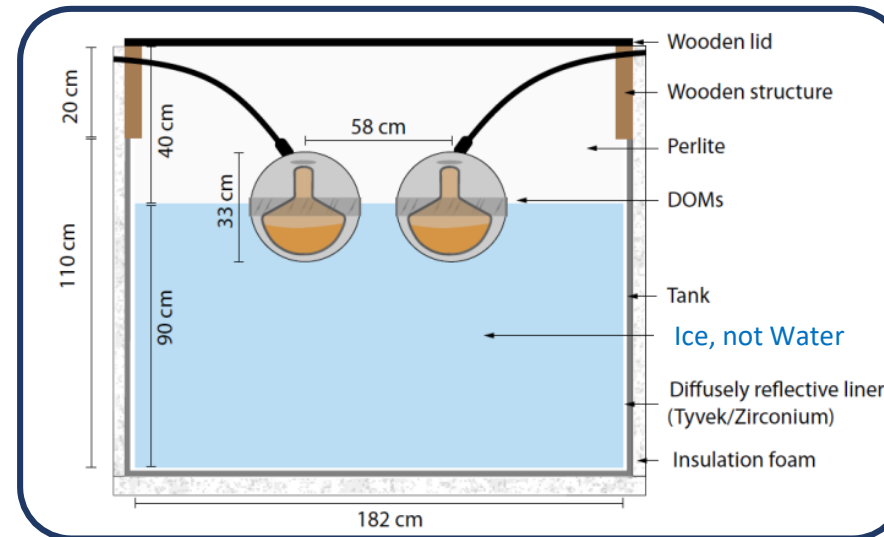


*IceCube overview: see Ignacio Taboada's talk



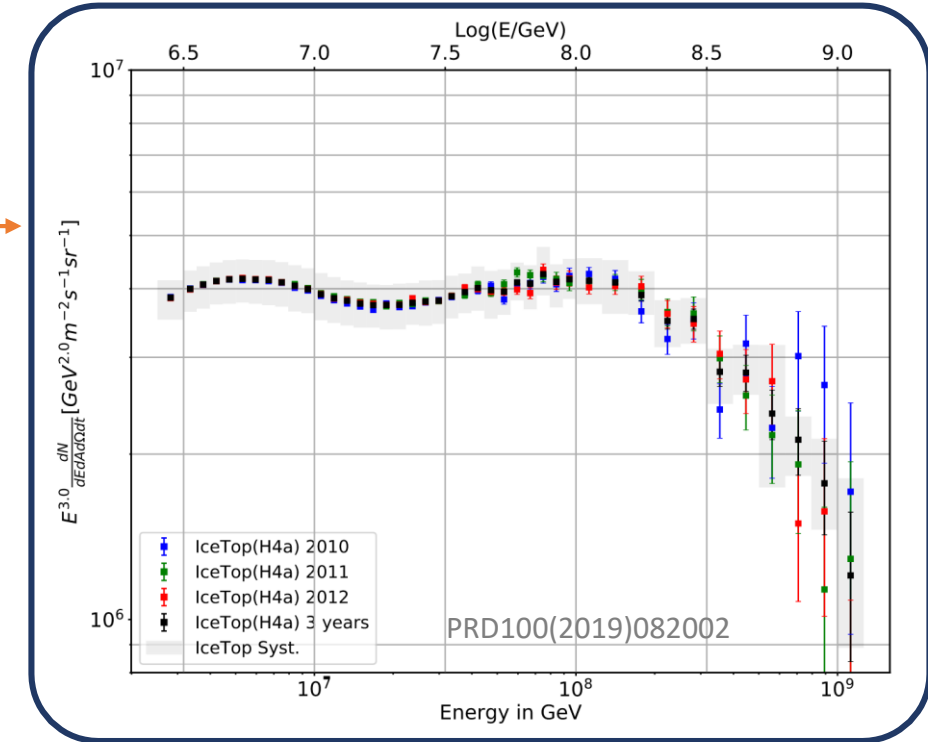
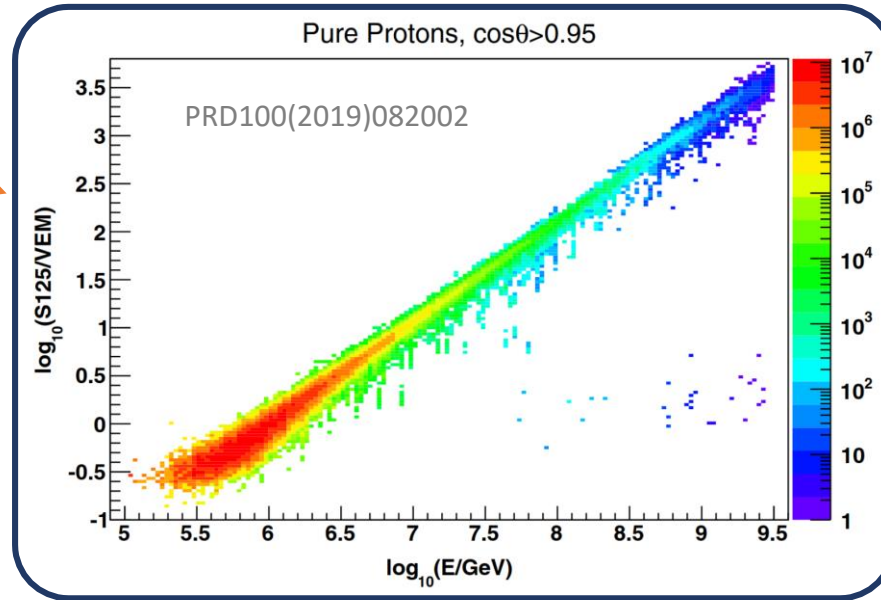
IceTop

- Cosmic ray energies from 1 PeV to 1000 PeV
- 2835 m a.s.l. 680 g/cm²
- 81 stations with 2 tanks each (2 DOMs per tank)
- Angular resolution $\sim 1^\circ$
- Timing resolution 3ns
- Energy resolution 0.1 in $\log_{10}(E/\text{GeV})$



Same DOMs used
for IceCube and
IceTop

Energy Spectrum (IceTop-alone)

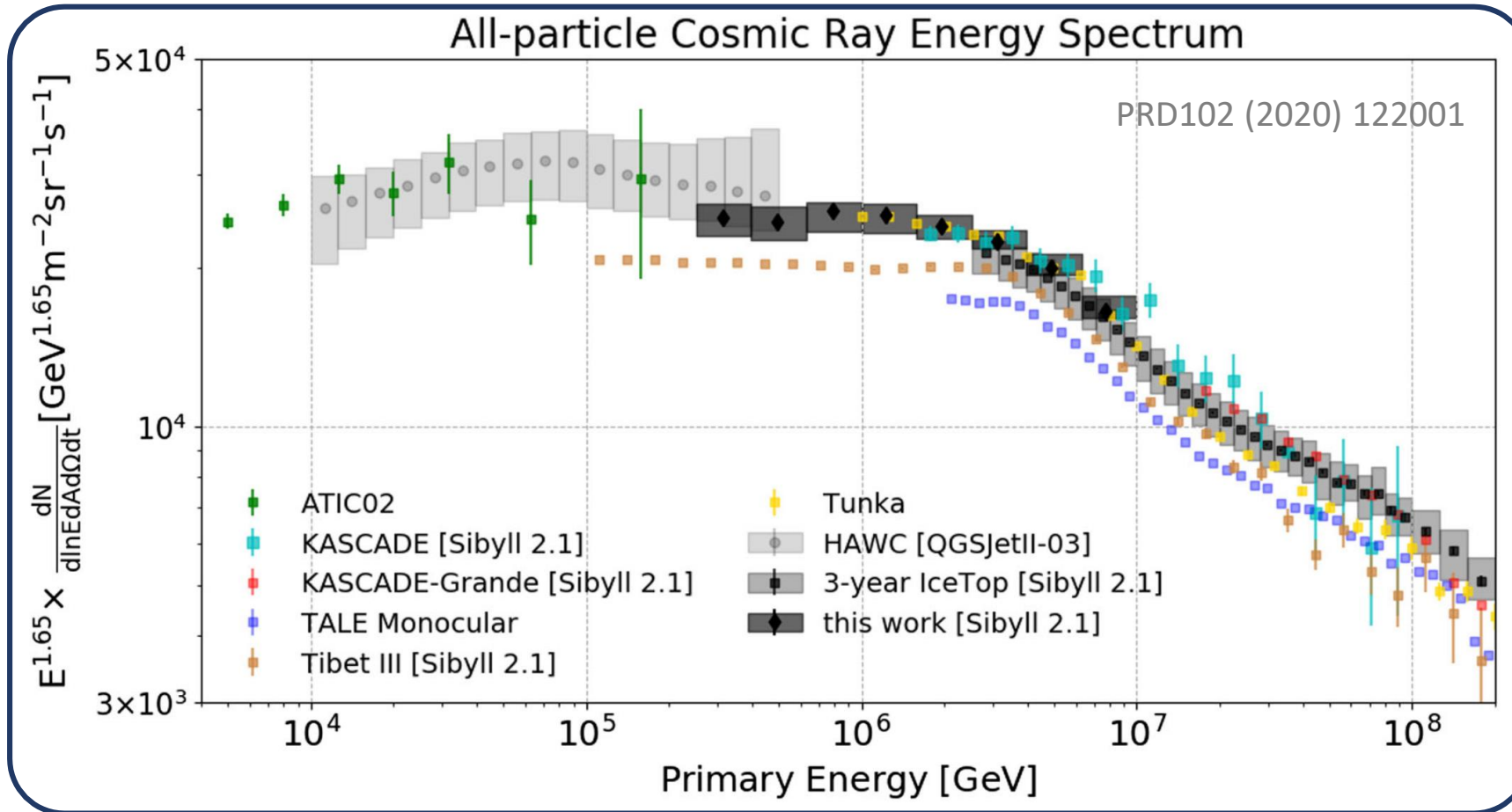


- Lateral Distribution Function (LDF):

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

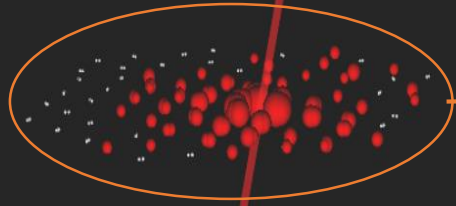
- 3 years of data (May 2010 to June 2013)
- About $5 \cdot 10^7$ selected events
- Dataset divided into individual years shows strong agreement
- Systematic uncertainties $\sim 10\%$

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

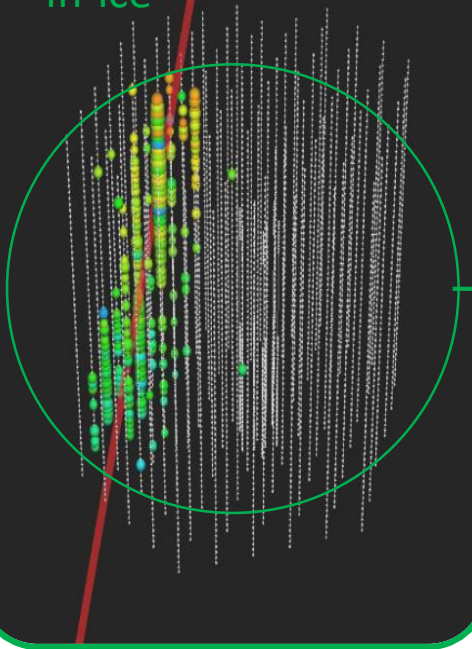
IceTop



Electromagnetic component of shower:

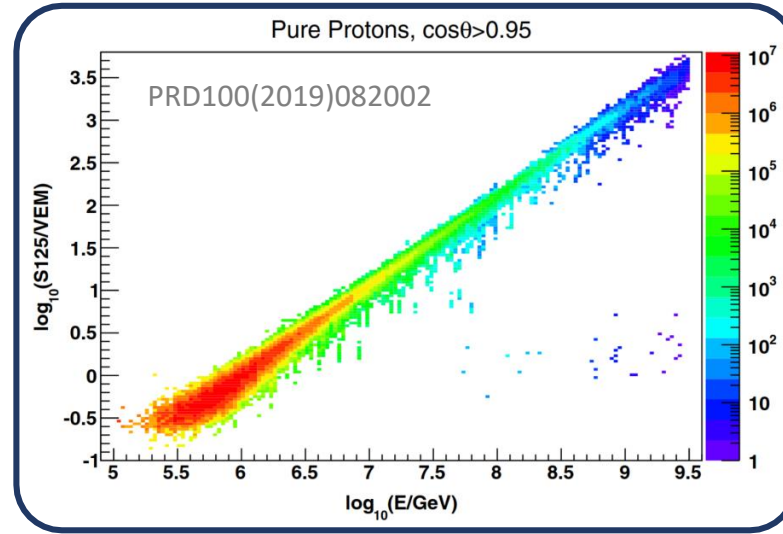
- IceTop energy proxy S_{125}
- Nearly composition independent

In-ice

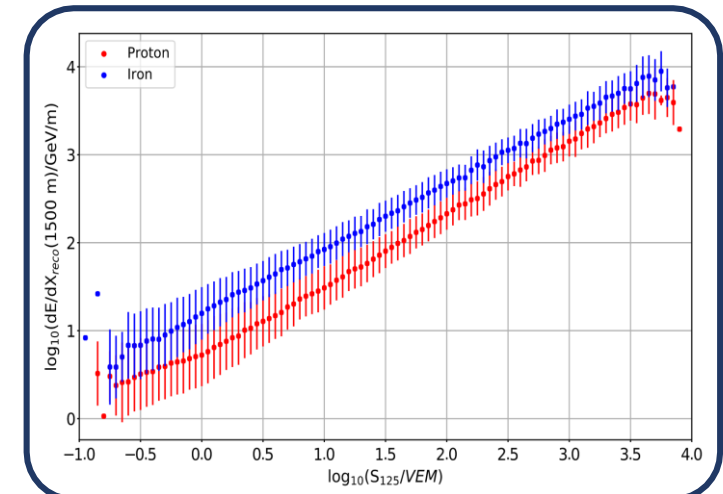
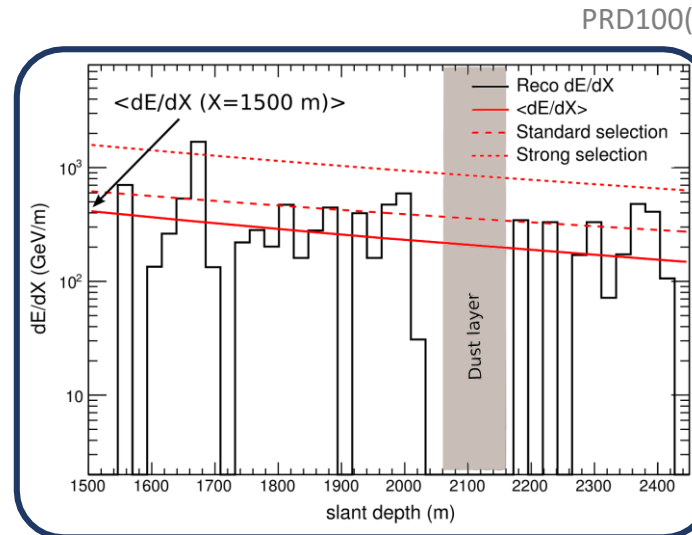


High-energy muons (>400 GeV):

- 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 ($X=1500\text{m}$) in the glacial ice
- Strong composition sensitivity

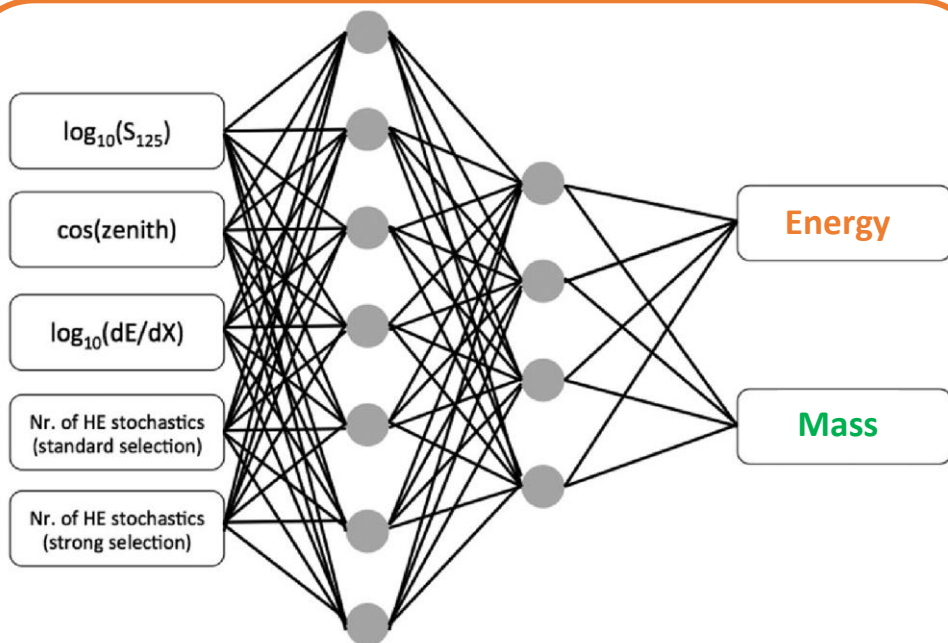


Coincident Analysis: Spectrum and Composition

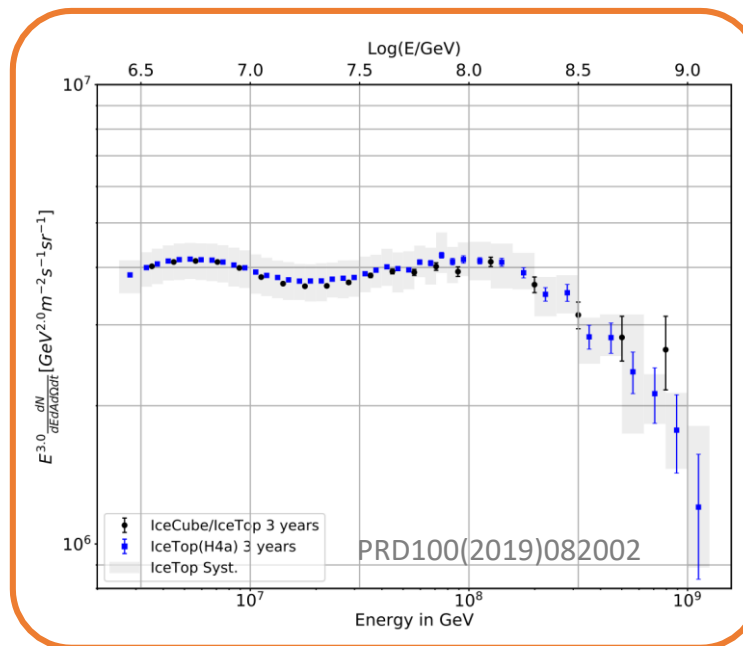


Spectrum and Composition

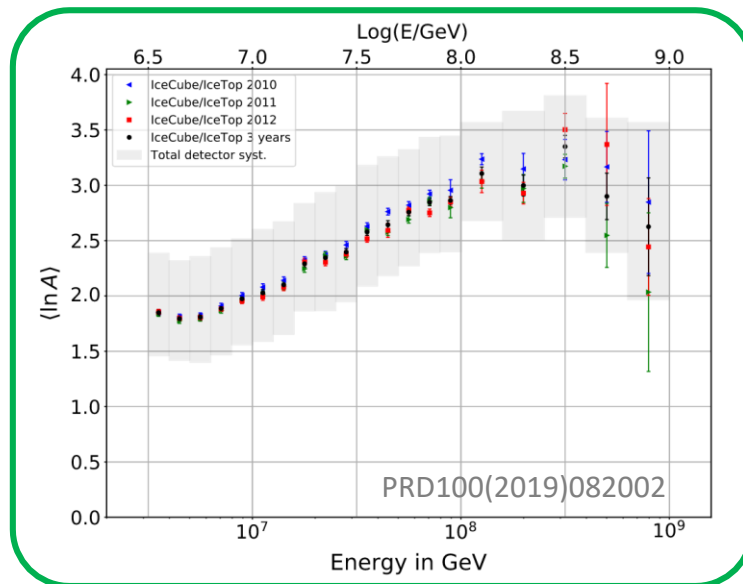
Use Neural Network to directly reconstruct energy → Coincident energy spectrum



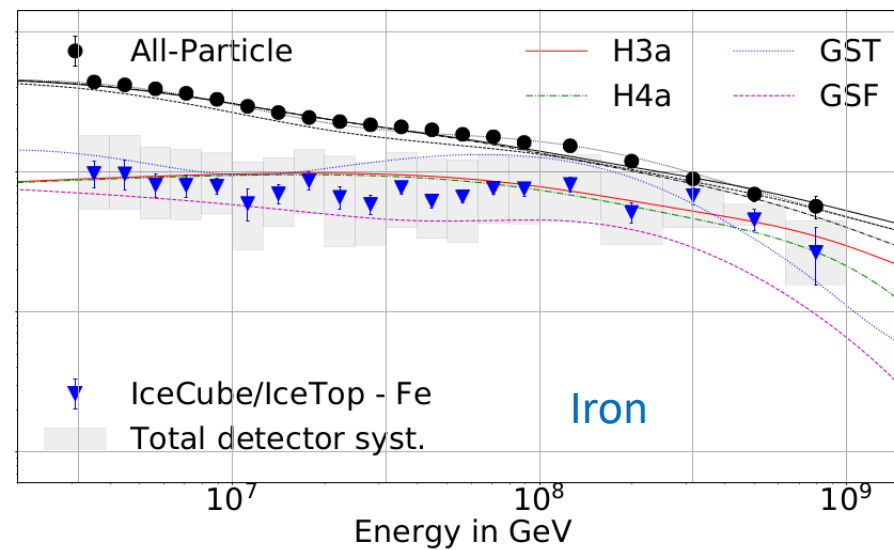
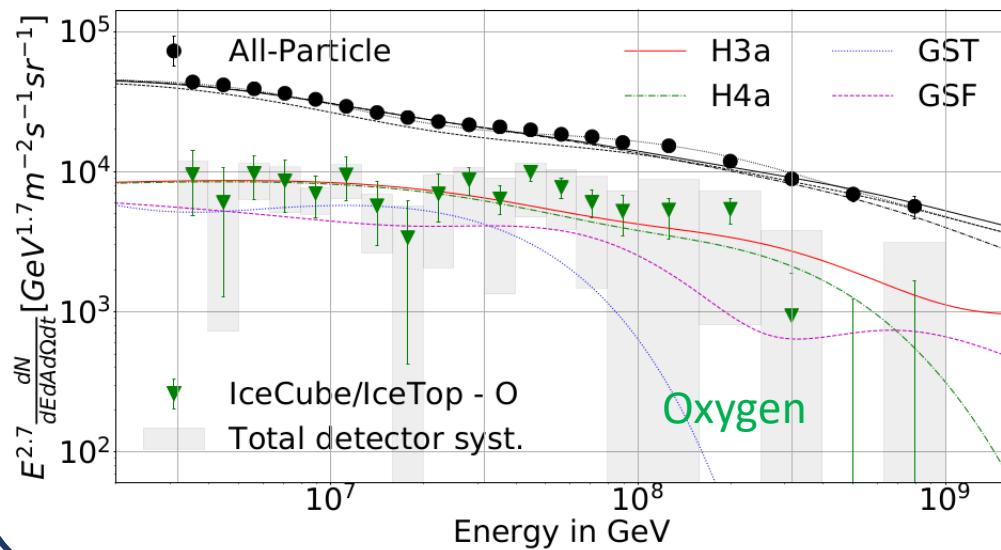
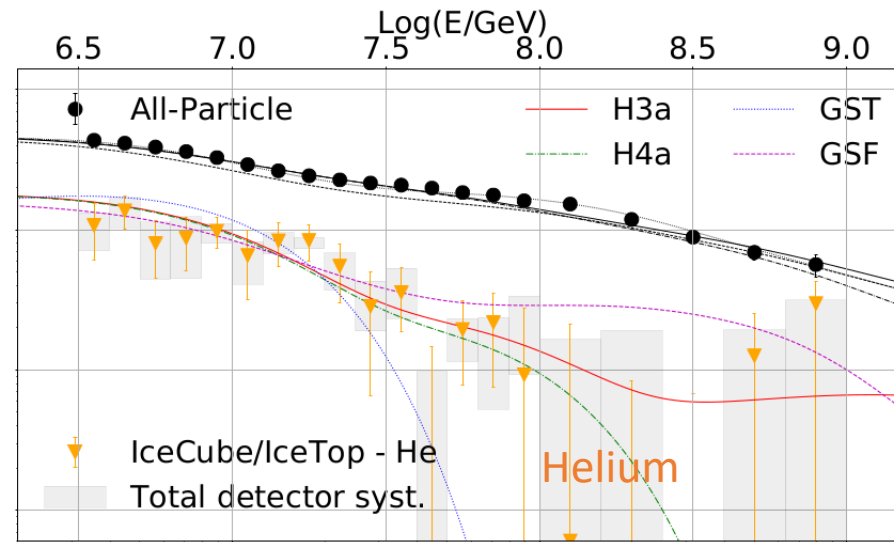
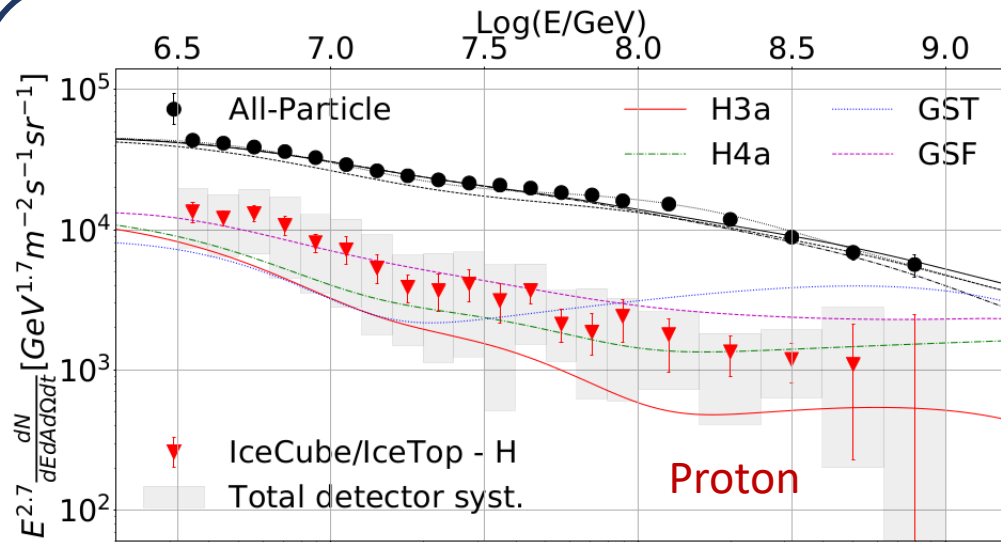
Event by event mass classification is not possible → Analyze mass as a function of energy on a statistical basis



- 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

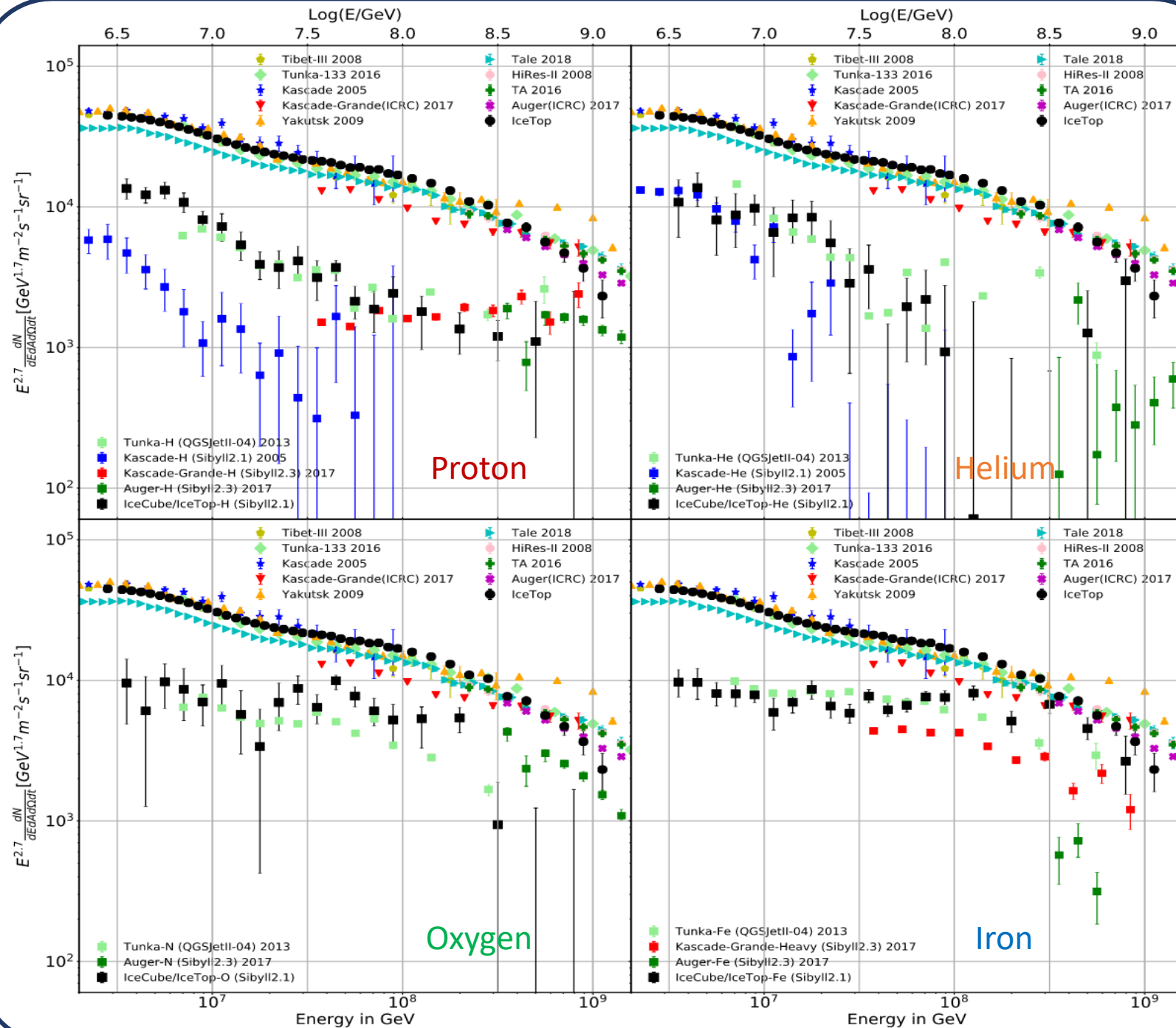


- Mean log mass $\langle \ln A \rangle$ derived from the individual fractions which best fit the NN mass output
- Combined systematic uncertainties of the IceTop and in-ice detectors for coincident analysis:
 - Energy scale $\sim 3\%$
 - In-ice light yield $\sim 10\%$
 - Snow accumulation $\sim \pm 2\text{m}$



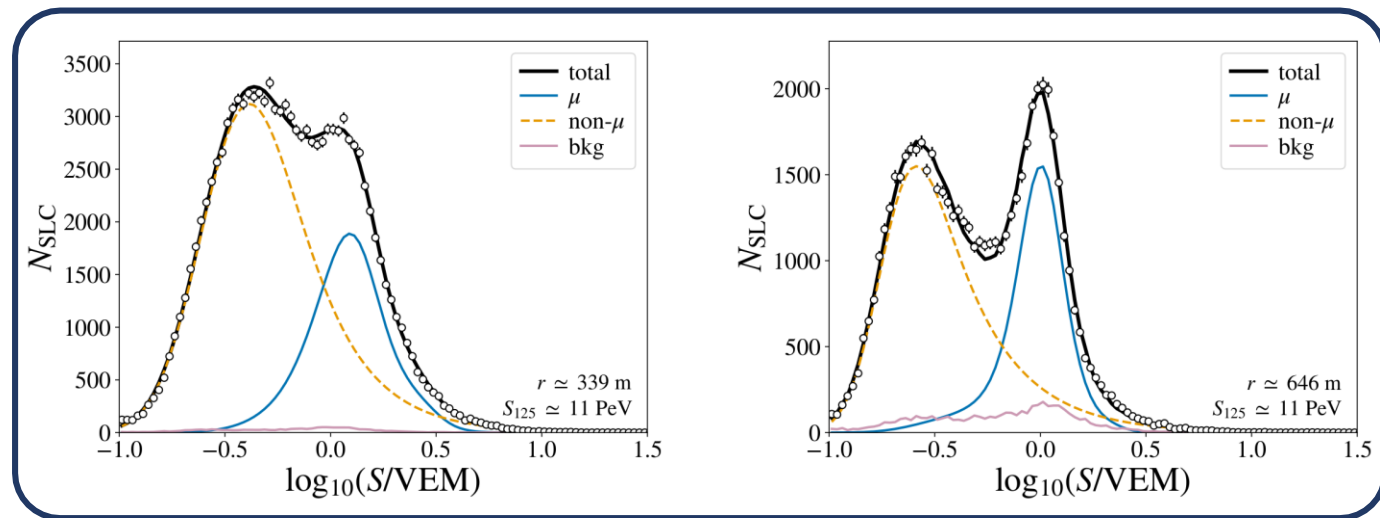
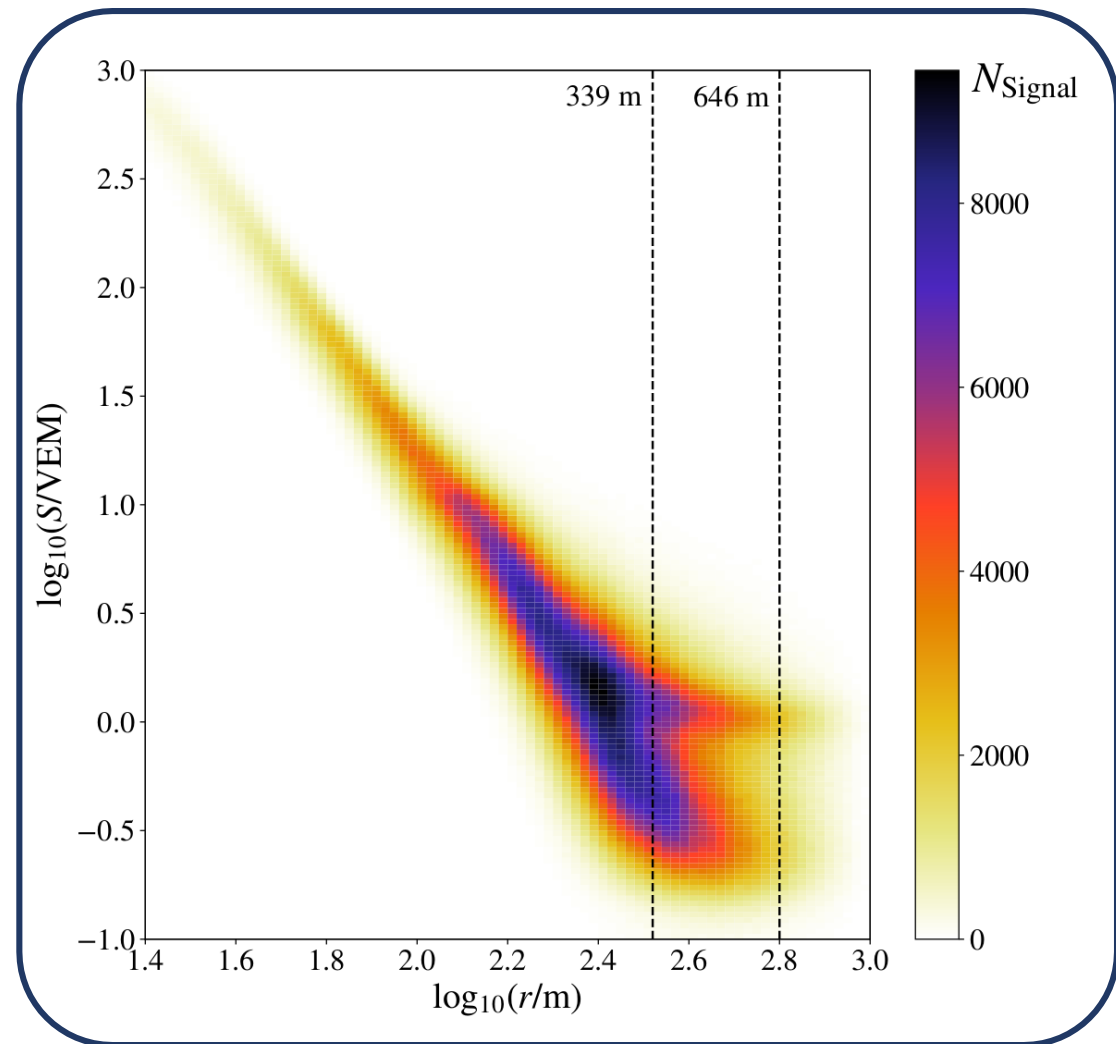
- Each of the four individual fractions from the NN mass output is translated into an individual spectrum
- Composition becomes heavier with increasing energy up to 10^8 GeV
- Agreement with models within statistical and systematic uncertainty

PRD100(2019)082002



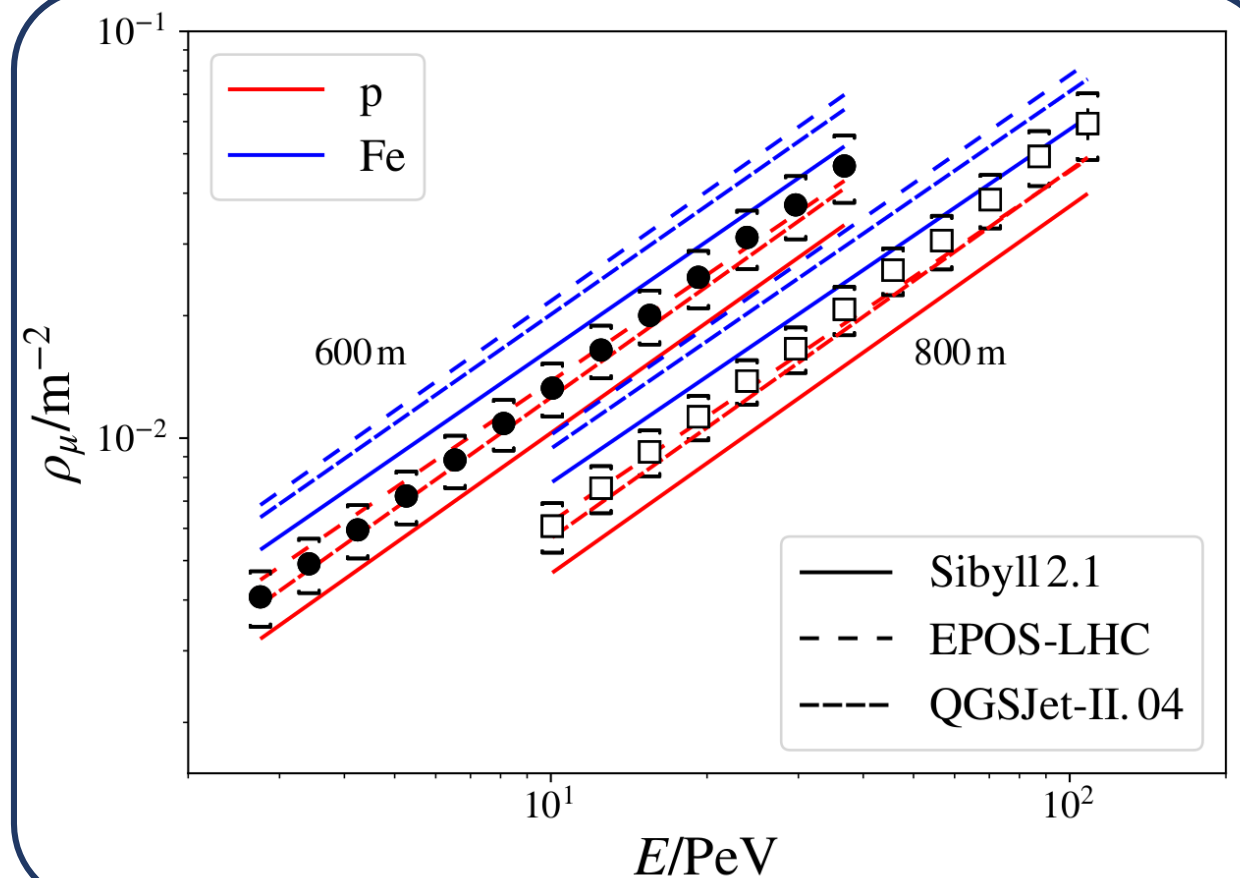
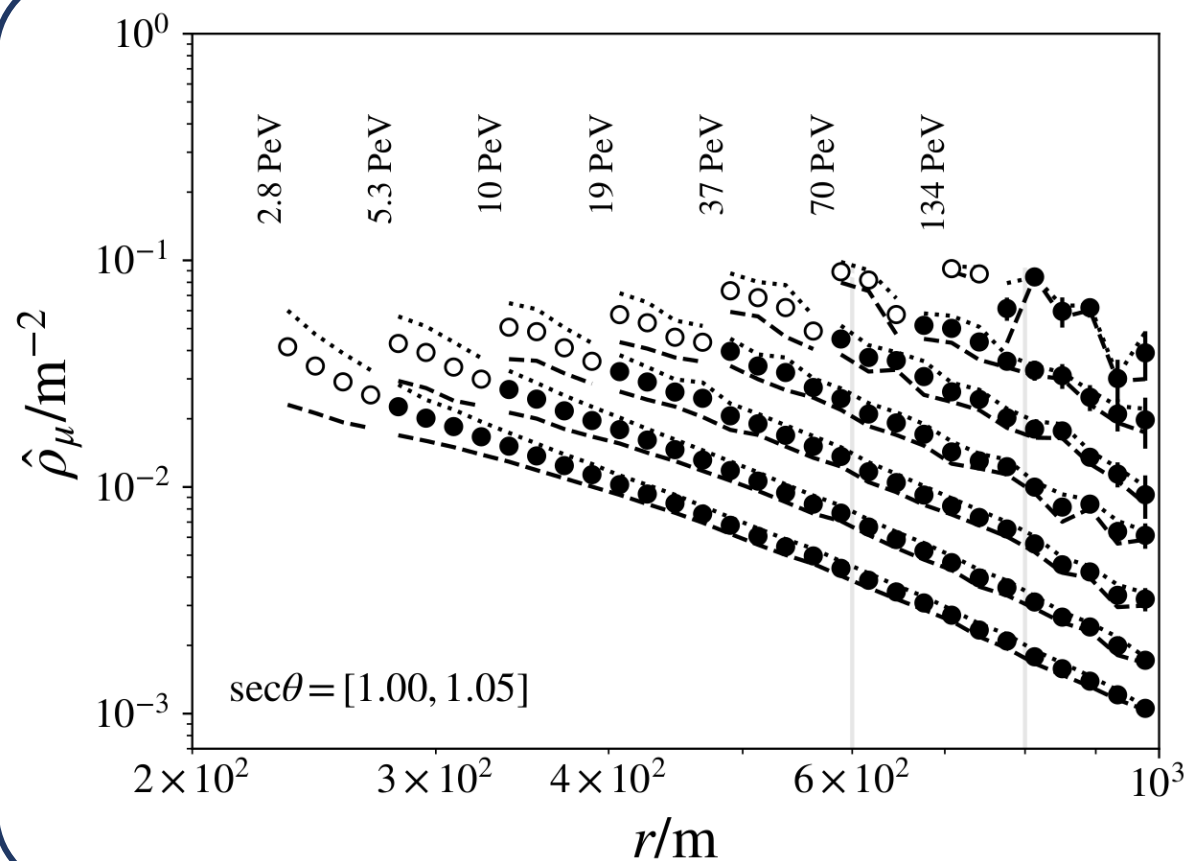
- Comparison of the all-particle and composition spectra of the four elemental groups H, He, O, and Fe based on Sibyll 2.1
- Individual elemental fluxes across a wider range in energy than any previous experiment
- The knee energy increasing as mass increases
- Differences in how different experiments handle the intermediate elements may lead to some systematic differences in flux measurements

GeV Muon Density in IceTop



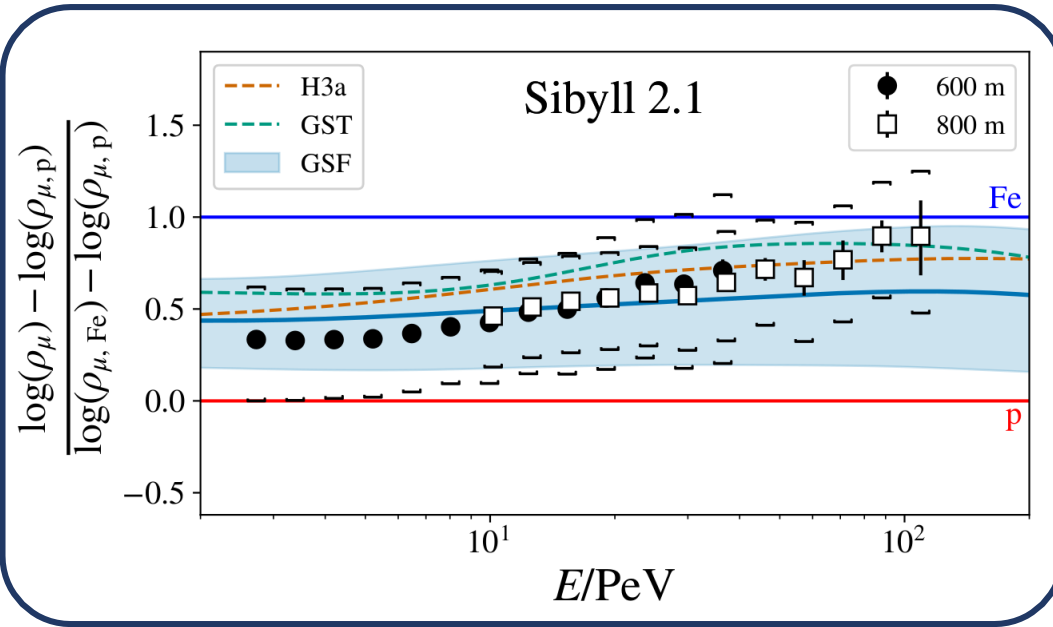
- Muon peak at 1 VEM
- EM signal contribution usually smaller, smooth distribution
- Muon peak more pronounced at large distances from shower core
- Binned in energy, zenith, lateral distances
- Derive muon density $\rho_{\mu}(r)$ by counting muons per tank

GeV Muon Density in IceTop

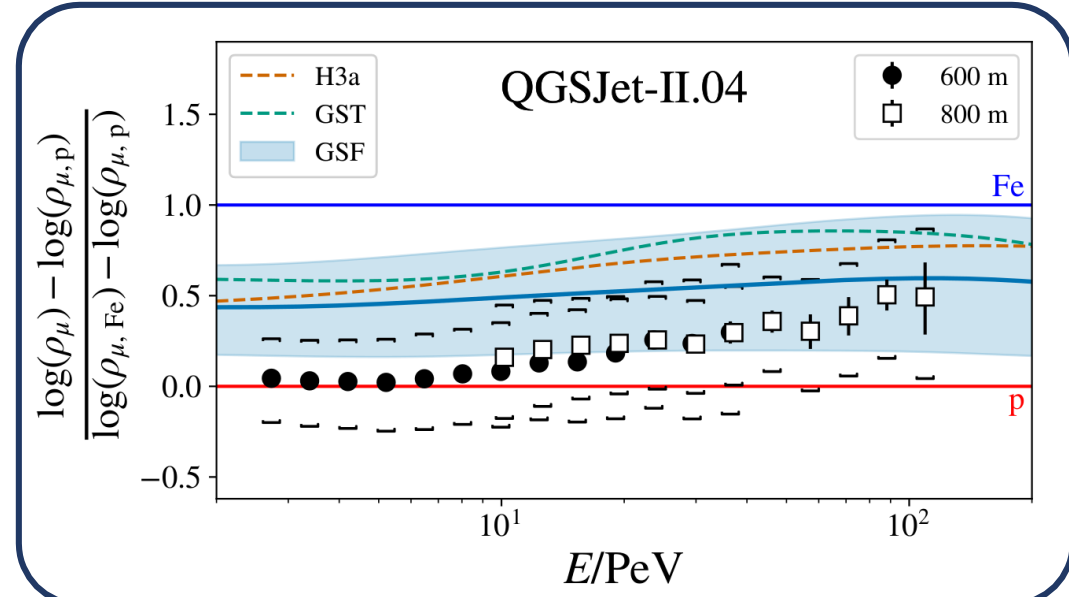
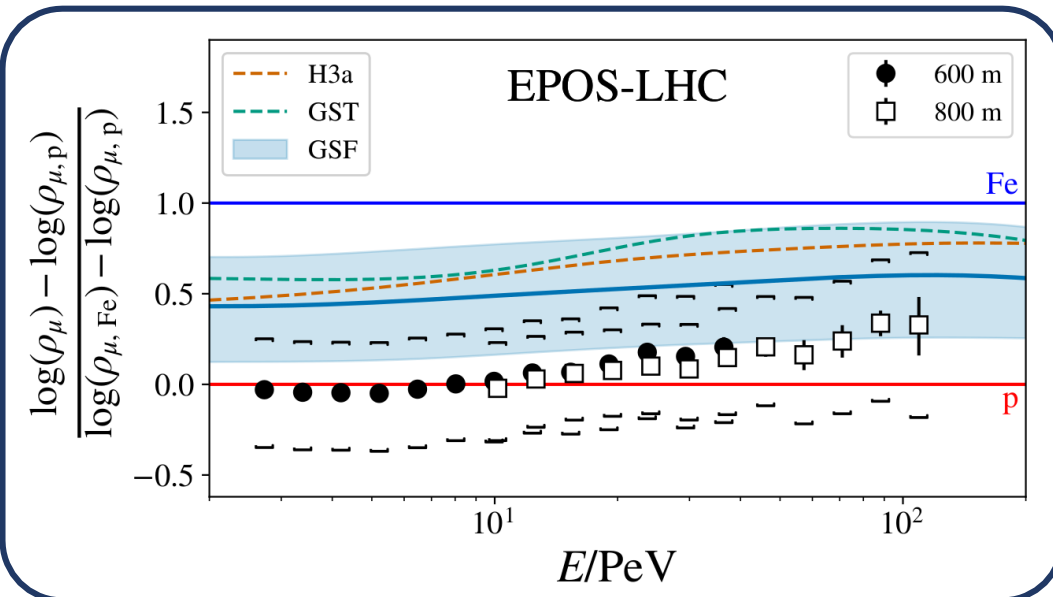


- Measured muon density at 600 m (2.5 – 40 PeV) and 800 m (9 – 120 PeV) reference distances
- Comparisons with different model predictions

GeV Muon Density for Different Models

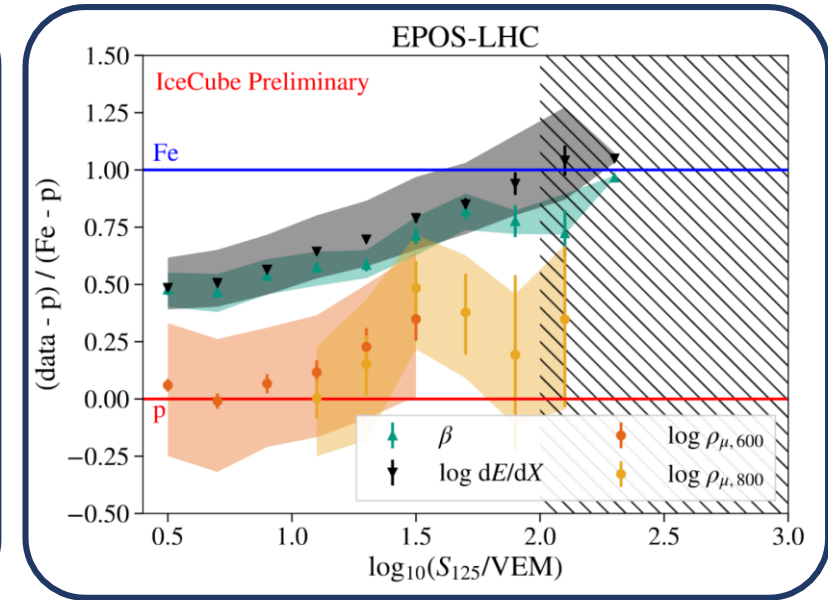
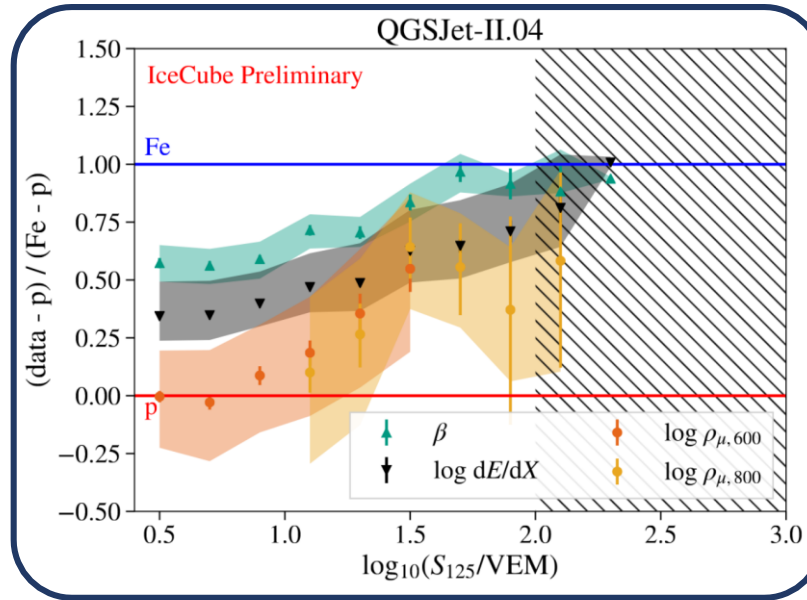
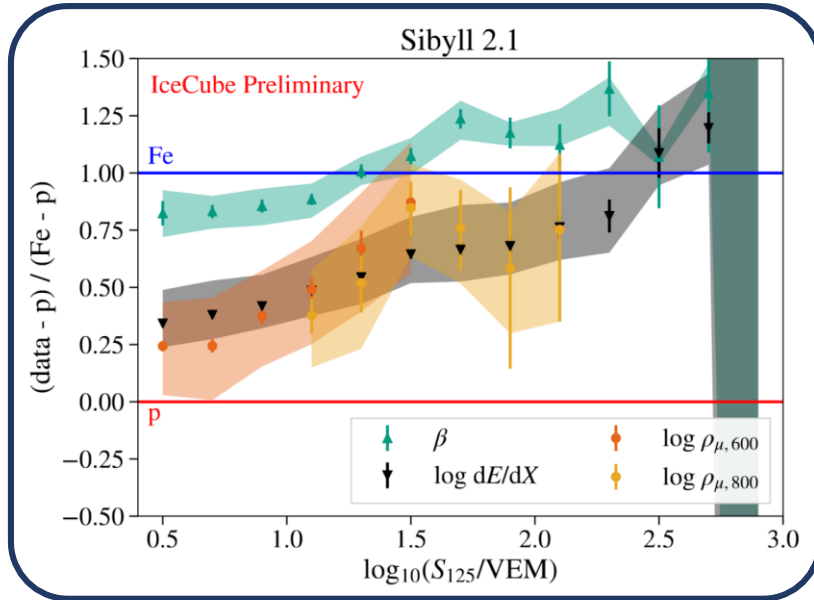


- Results in terms of z-value: $z = \frac{\log \rho_\mu - \log \rho_{\mu,p}}{\log \rho_{\mu,Fe} - \log \rho_{\mu,p}}$
- Hadronic interaction models: Sibyll 2.1(pre-LHC), QGSJet-II.04 and EPOS-LHC (post-LHC)
- Flux composition models: H3a, GST, GSF
- Good agreement for Sibyll 2.1
- Post-LHC models expect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



Tests of Hadronic Interaction Models

PoS(ICRC21)357



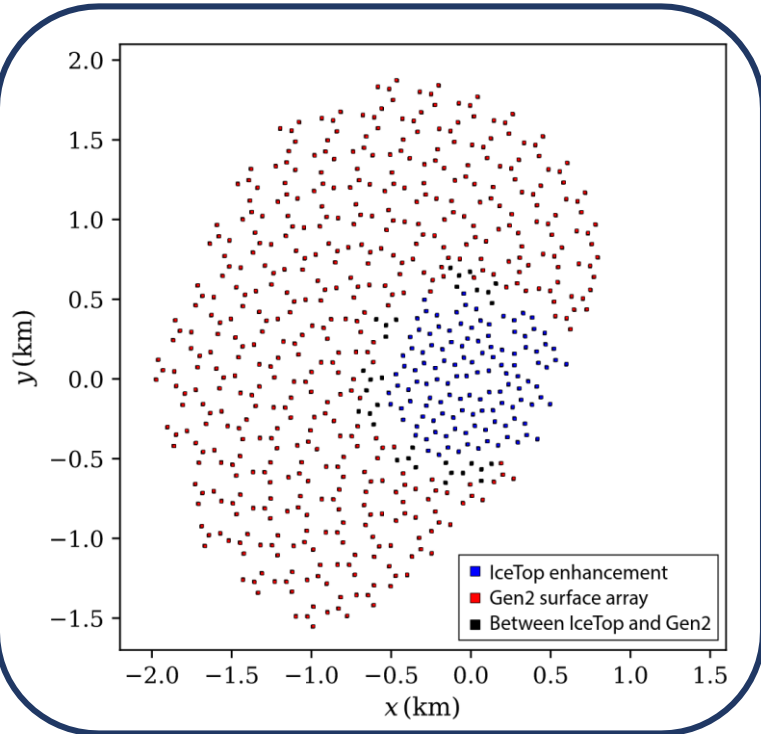
Tests with composition-sensitive observables:

- 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

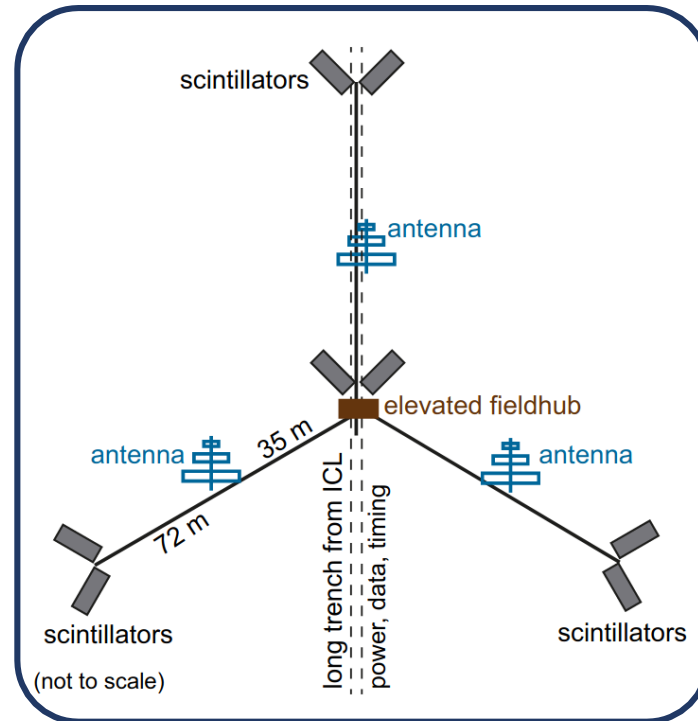
All mass sensitive parameters compared to prediction of three different hadronic interaction models

- 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

IceTop: Hybrid Surface Detector Enhancement



PoS(ICRC2021)407



4 pairs of scintillation detectors + 3 antennas



Complete prototype station since 2020



Science goals:

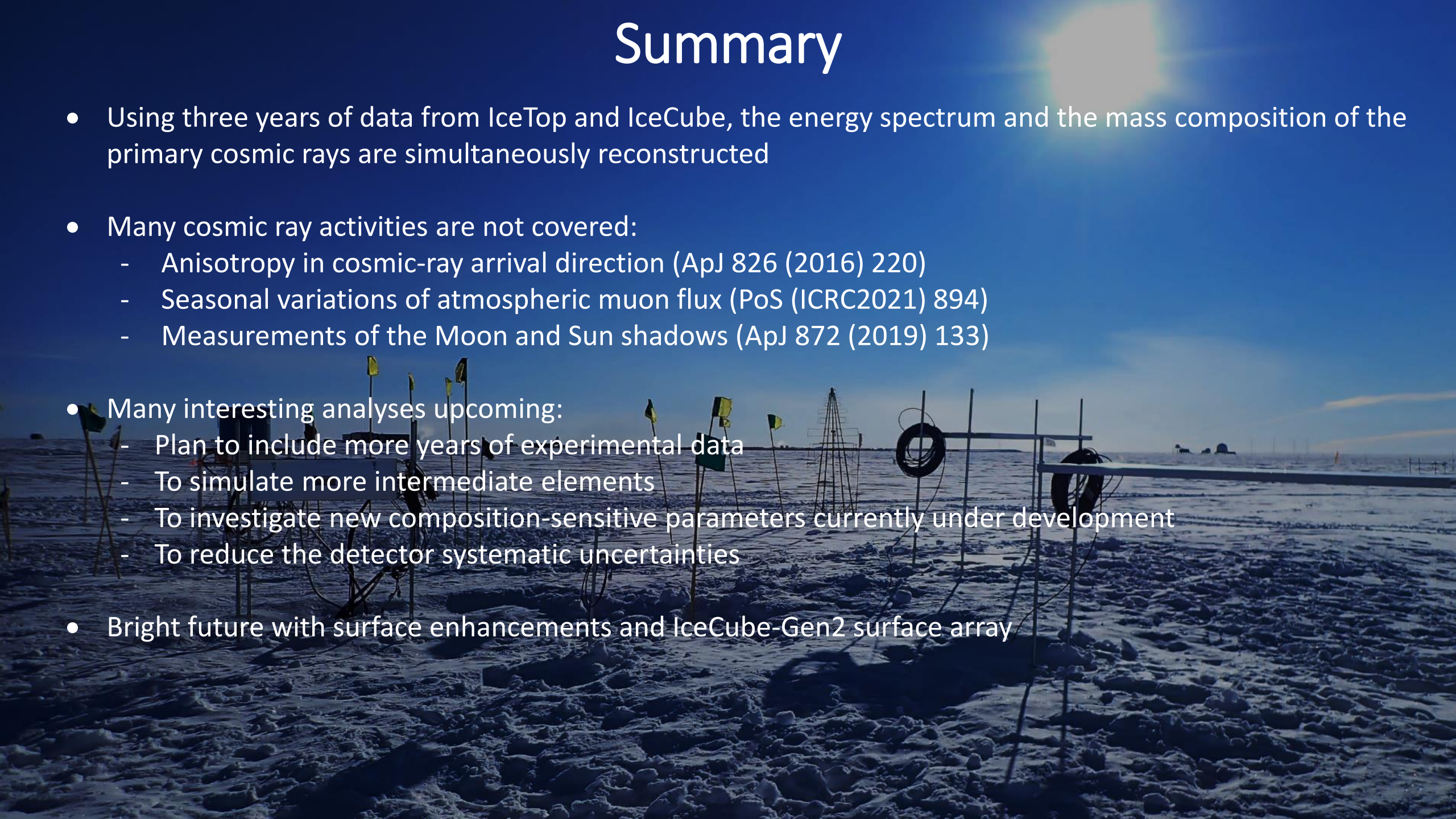
- Improve systematics due to snow coverage
- Improve cosmic ray veto for neutrino detection
- Improve mass composition measurements
- Composition dependent anisotropy studies
- Improve PeV gamma ray search
- Validate hadronic interaction models

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:
 - Anisotropy in cosmic-ray arrival direction (ApJ 826 (2016) 220)
 - Seasonal variations of atmospheric muon flux (PoS (ICRC2021) 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
 - To reduce the detector systematic uncertainties
- Bright future with surface enhancements and IceCube-Gen2 surface array



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