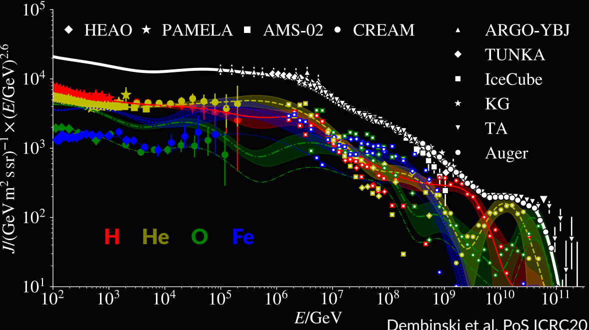
Towards revealing the origin of high-energy cosmic-rays

Agnieszka Leszczyńska for the IceCube@KIT group

Cosmic-ray spectrum from 100 GeV to 100 EeV

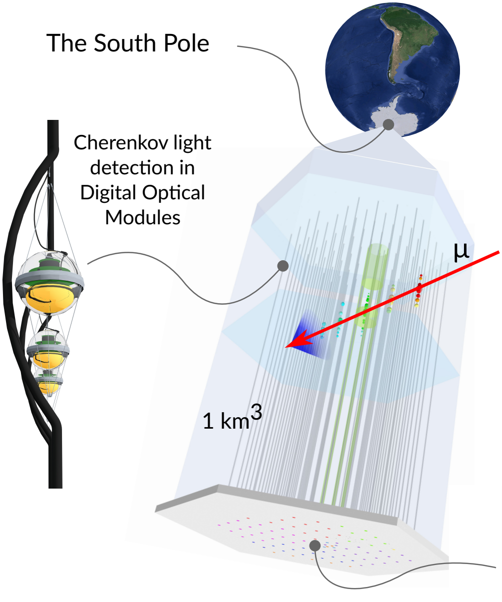


Dembinski et al. PoS ICRC2017

Their origin remains mostly unknown,
specially at the high energies and ultra-high energies

… needs new detection approach …

IceCube Neutrino Observatory

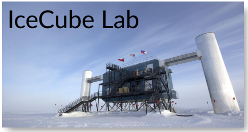


Every year detects around:

10 astrophysical neutrinos

100 thousand atmospheric neutrinos

100 billions atmospheric muons



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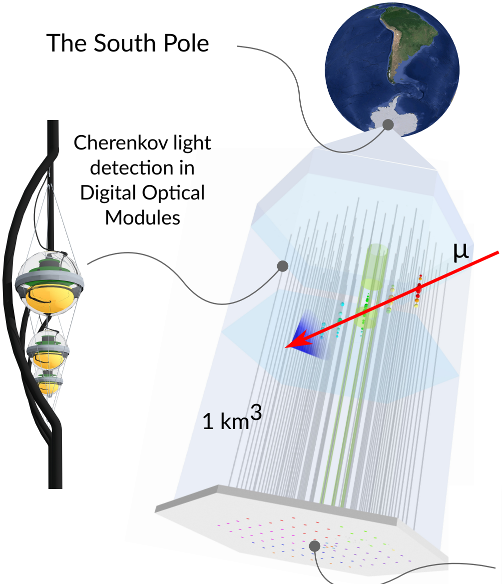
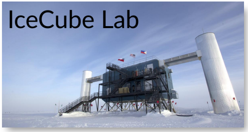
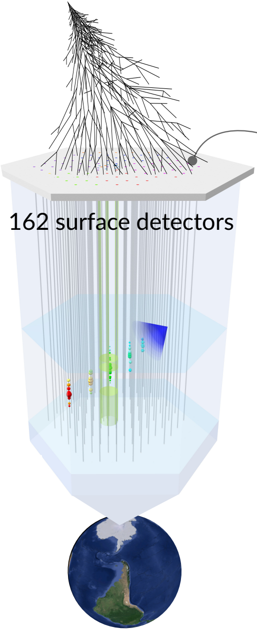


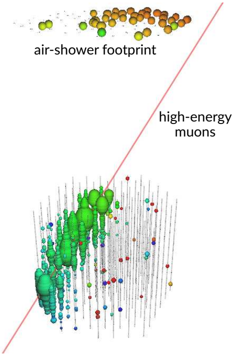


IceTop cosmic-ray detector



Cherenkov tanks filled with ice and read out by PMTs

IceTop reconstructs cosmic-rays of PeV — EeV energy



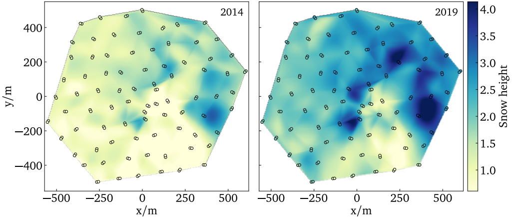
3D cosmic-ray detector

Analysis of **IceCube/IceTop** coincident events:

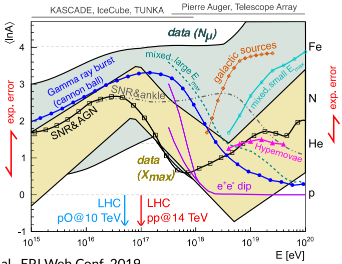
- improves air-shower reconstruction
- enhances cosmic-ray mass determination

Enhancing cosmic-ray detection

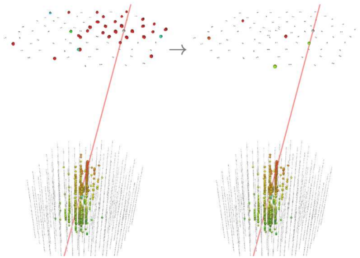
Signals measured by IceTop tanks
get attenuated due to snow coverage



Large uncertainties on elemental composition



Large atmospheric background:
better veto for in-ice searches



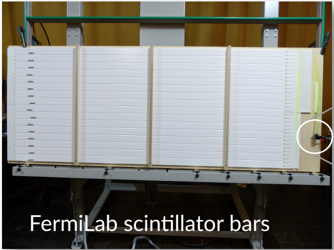
Air-shower—like event   Neutrino—like event

by lowering energy threshold
for cosmic-ray detection

Dembinski et al., EPJ Web Conf. 2019

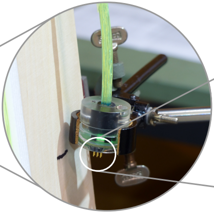
Additional detection channels

Scintillation detector

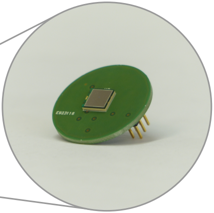


Huber et al. for IceCube-Gen2, PoS ICRC2017

Wavelength-shifting fibres



SiPM readout

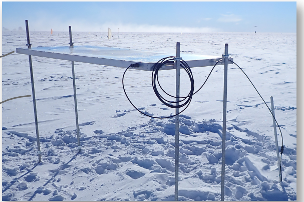


SiPM Calibration:
Marie Oehler, Master Thesis

16 scintillator bars = 1.5 m^2

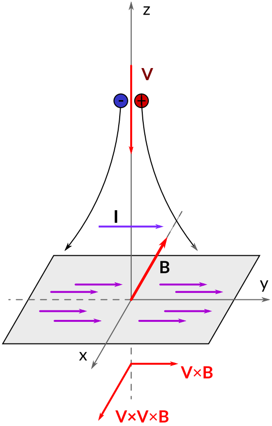
Enclosed in aluminum housing

Elevated on the poles
to avoid snow accumulation



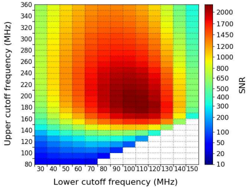
Additional detection channels

Radio antenna



Radio emission from air-showers

Balagopal et al. Eur.Phys.J. C78 (2018)



Optimised frequency band

Elevated to avoid snow accumulation

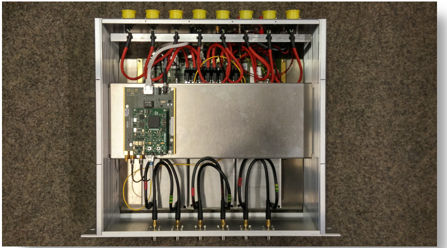
Renschler et al. J. Phys.: Conf. Ser. 2019

Roxanne Turcotte-Tardif, Hrvoje Dujmovic

Hardware R&D

RadioTAXI DAQ to sample and digitize scintillation and radio signals

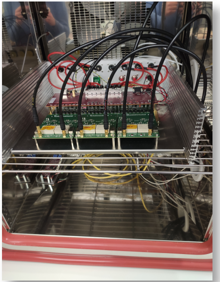
Hybrid DAQ



Peter Steinmüller, Master Thesis — Max Renschler, PhD Thesis — Noah Goehlke, Bachelor Thesis

- **charge** integration of scintillator waveform and **timestamp** sent to TAXI
- scintillators trigger radio antennas via FPGA, full radio waveform sent to ICL

Low-temperature test



Anja Schmidt, Bachelor Thesis

Single components tested and calibrated

Institute for Data Processing and Electronics (**IPE**) & DESY.

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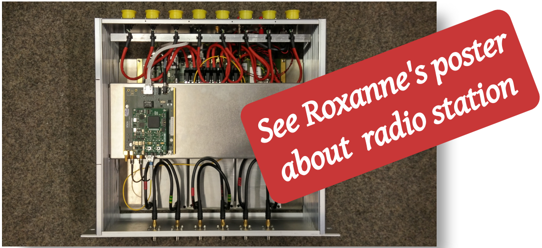
Hybrid DAQ



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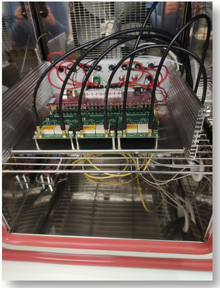


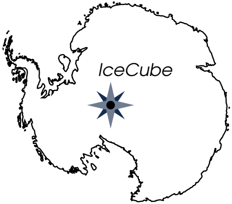
Anja Schmidt, Bachelor Thesis

Single components tested and calibrated

Institute for Data Processing and Electronics (**IPE**) & DESY.


`...all my bags are packed
I'm ready to go...'

Our activities at the South Pole



Thomas Huber KIT

14 scintillation detector of 2 types

Max Renschler KIT

2 radio antennas + new DAQ

Marie Oehler, Frank Schröder KIT

8 scintillation detectors
+ 3 radio antennas + new DAQ

2021-2022

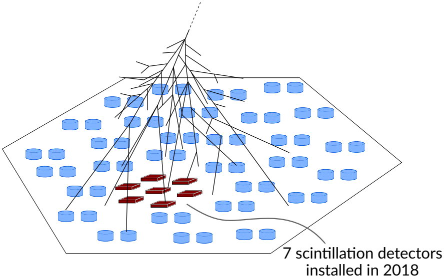
Further deployment of surface enhancement

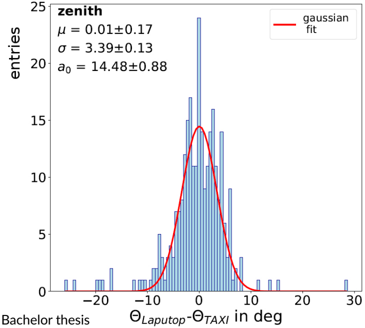
Prototype-station data

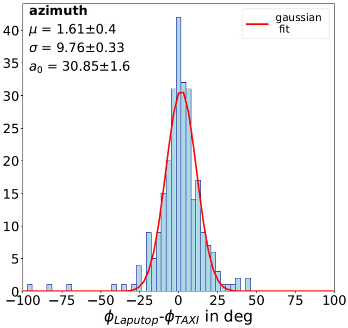
Time-coincident events with IceTop

where IceTop-reconstructed core is inside scintillator station

Full IceTop reconstruction & plane-front+COG for scintillators







F. Ellwanger, Bachelor thesis

Kauer et al. PoS ICRC2019

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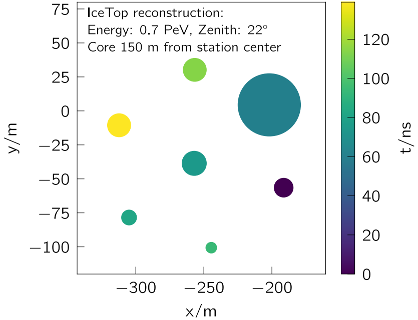
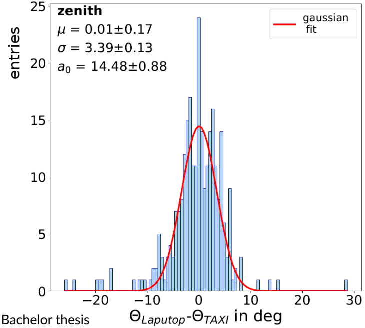
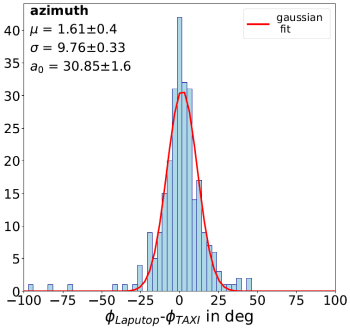
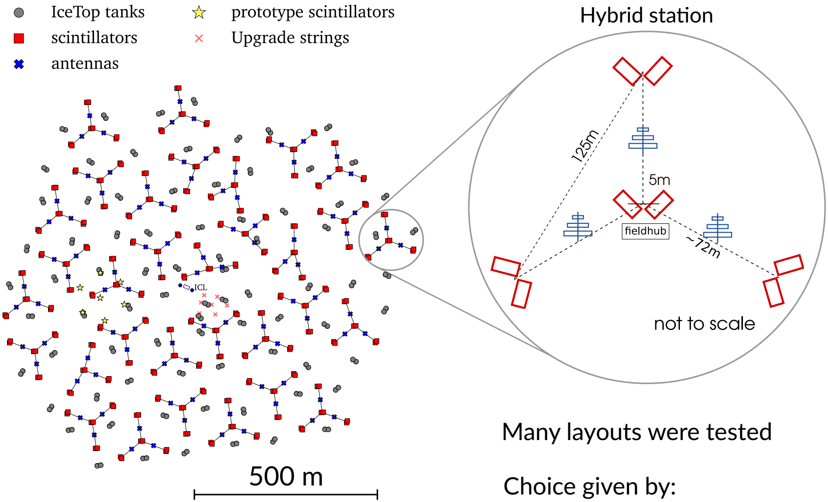






F. Ellwanger, Bachelor thesis
Kauer et al. PoS ICRC2019

Hybrid surface array



Many layouts were tested

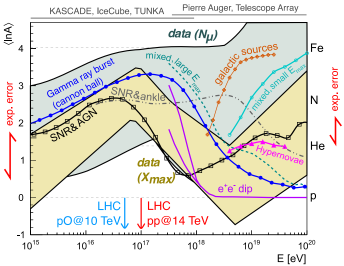
32 × 8 scintillation detectors

32 × 3 radio antennas

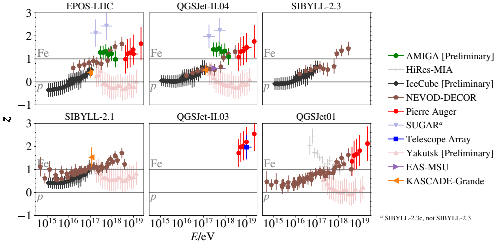
Choice given by:
optimal trenching length
without increasing threshold

Enhancing cosmic-ray detection. **Bigger scale**

Dembinski et al., EPJ Web Conf. 2019

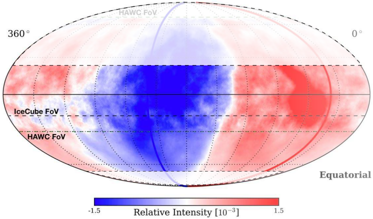


Cosmic-ray origin



Tests of hadronic interaction models in CORSIKA

HAWC and IceCube Collaborations, ApJ 871 (2019)

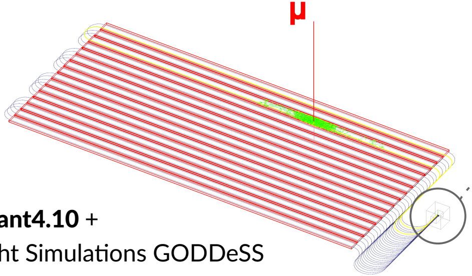


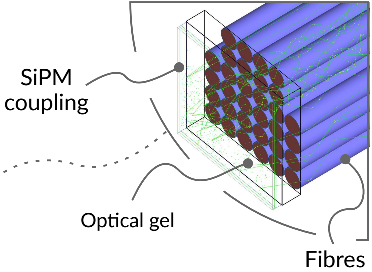
Mass-dependent anisotropy

X-Ray:NASA/CXC/UMass/D. Wang et al.

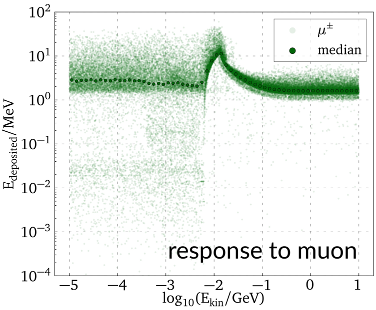
Search for PeV photons from Galactic Center

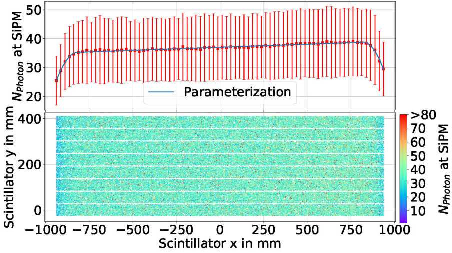
Simulations for scintillation detectors





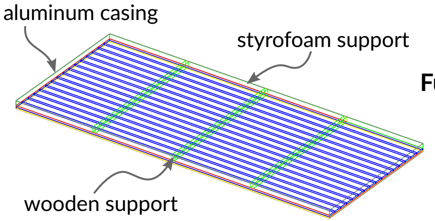
Geant4.10 +
Light Simulations GODDeSS





Parametrisation of detector response

Simulations for scintillation detectors

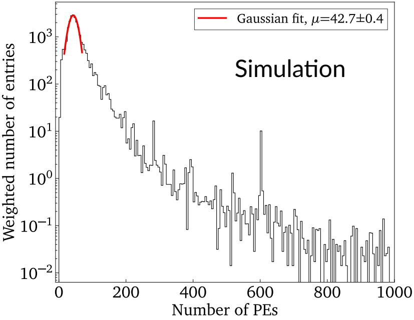


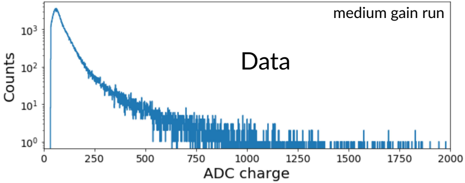
Full array simulations with simplified geometry

but including *reflective coating* and

elements important for energy loss

Minimum Ionising Particle

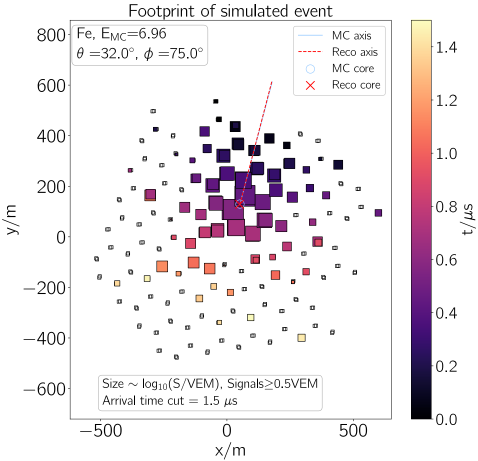




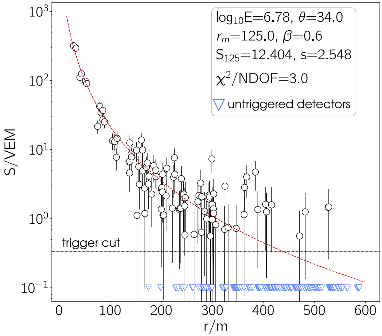
Comparison of simulated low-energy showers and free-running detector data

Signal and time distribution

CORSIKA @ KIT air-shower simulations + GEANT4 array response



Time - parabolic curvature



$$S(r) = S_{\mathrm{ref}} \left(\frac{r}{R_{\mathrm{ref}}} \right)^{-\beta - \kappa \log\left(\frac{r}{R_{\mathrm{ref}}}\right)}$$

energy estimator

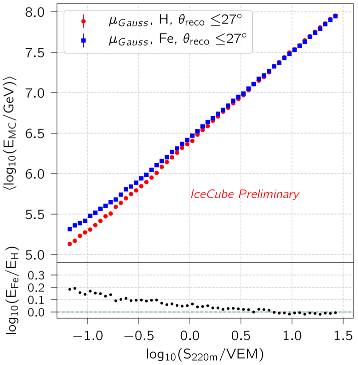
sensitive to primary mass

Air-shower reconstruction

Reconstruction procedure:

1. Plane front and COG seeds
2. **Iterative nLLH minimisation:**
- lateral distribution fit
- time delay wrt shower-front plane
- LLH includes parametrisation of spread of air-shower distributions *(signal and time uncertainty)*
3. Post-selection: *containment, parameters within physical boundaries*
4. Estimation of cosmic-ray energy

Energy estimation

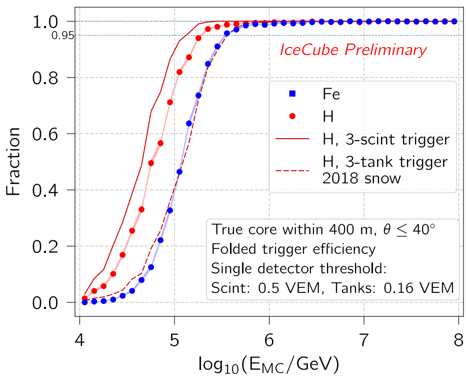


Leszczyńska et al. for IceCube, PoS ICRC2019

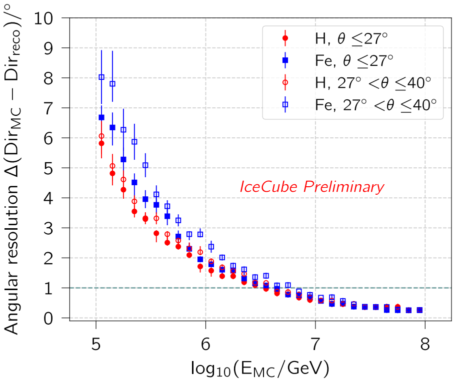
Cosmic-ray energy estimator = signal at R_{ref} = 220 m from shower axis

Capabilities of air-shower reconstruction

Reconstruction efficiency



Direction resolution

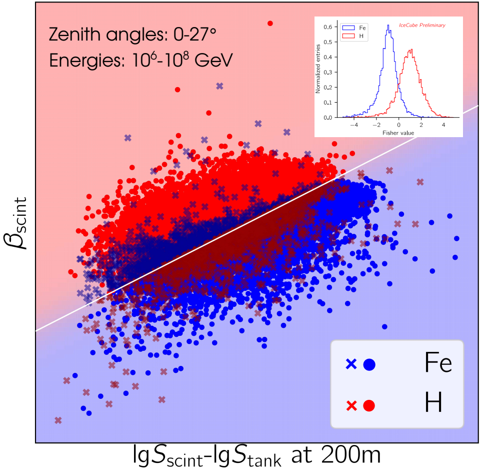


The scintillator array is fully efficient at a few hundreds of TeV for H/Fe primaries

Direction resolution is a few degrees below PeV and better than 1° for air showers of higher energies

First approach to combined analysis

2 separate scintillator & tank reconstructions



Two parameters for linear discriminant analysis:

- slope β from scintillator-signal distribution (LDF)
- ratio of two LDFs at 200 m

$$\text{Figure of merit} = \frac{|\mu_H - \mu_{Fe}|}{\sqrt{\sigma_H^2 + \sigma_{Fe}^2}}$$

Figure of merit ~ 1.3
for 2 decades in energy

Promising result for further investigation of CR composition

Steps towards multi-array reconstruction

Great computer hardware is only a doorstop without great software.
C. King

Combining all detection channels can **boost** cosmic-ray measurements

Every detector has specific response to air-shower particles

To obtain real combined analysis ALL details need to be merged

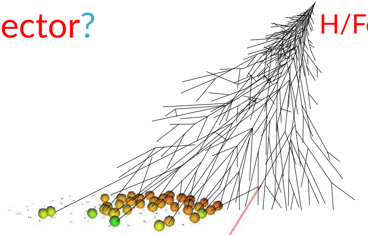
New flexible software base to perfom multi-component reconstruction

combined LLH calculations to obtain best fit parameters

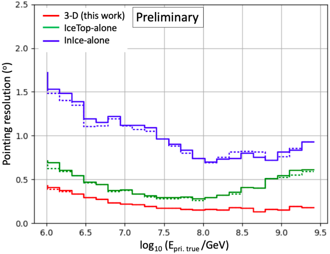
How to use IceCube + IceTop as

3D cosmic-ray detector?

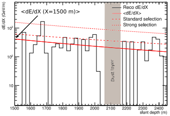
H/Fe?



Implementing reconstruction
in new framework



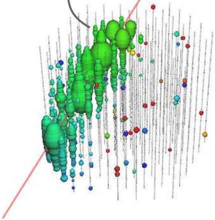
Improved direction reconstruction
and larger solid angle



more detailed
analysis?

Exploring possible
parameters for
improved analysis

muons



How to use IceCube + IceTop as

3D cosmic-ray detector?

Implementing reconstruction
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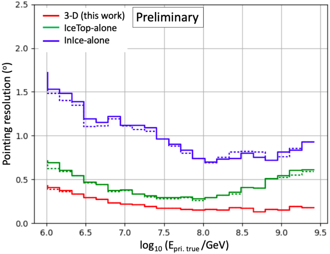

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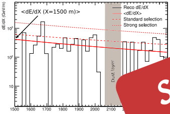
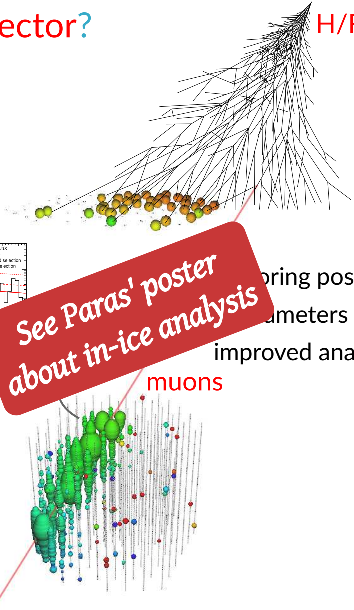


more detail...
analysis?



See Paras' poster
about in-ice analysis

...oring possible
...ameters for
improved analysis


IceCube Observatory showed great potential
to explore high-energy universe...
...by looking in all directions
we can reveal even more!

Summary

- IceCube surface array is under enhancement
- Intensive prototype development and detector production at KIT
- 3 seasons of successful deployment and measurements
- Simulations and reconstruction for scintillator array
- Development of multi-array reconstruction and analysis