# Cosmic-ray Spectrum, Composition, and Anisotropy Measured with IceCube/IceTop

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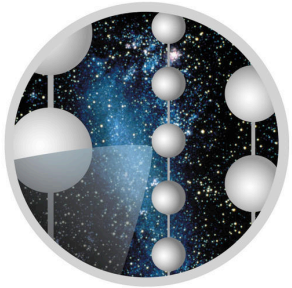



RICAP 2013, Rome – May 22, 2013

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- IceCube and Cosmic-ray Physics
- IceTop-73 Spectrum Analysis
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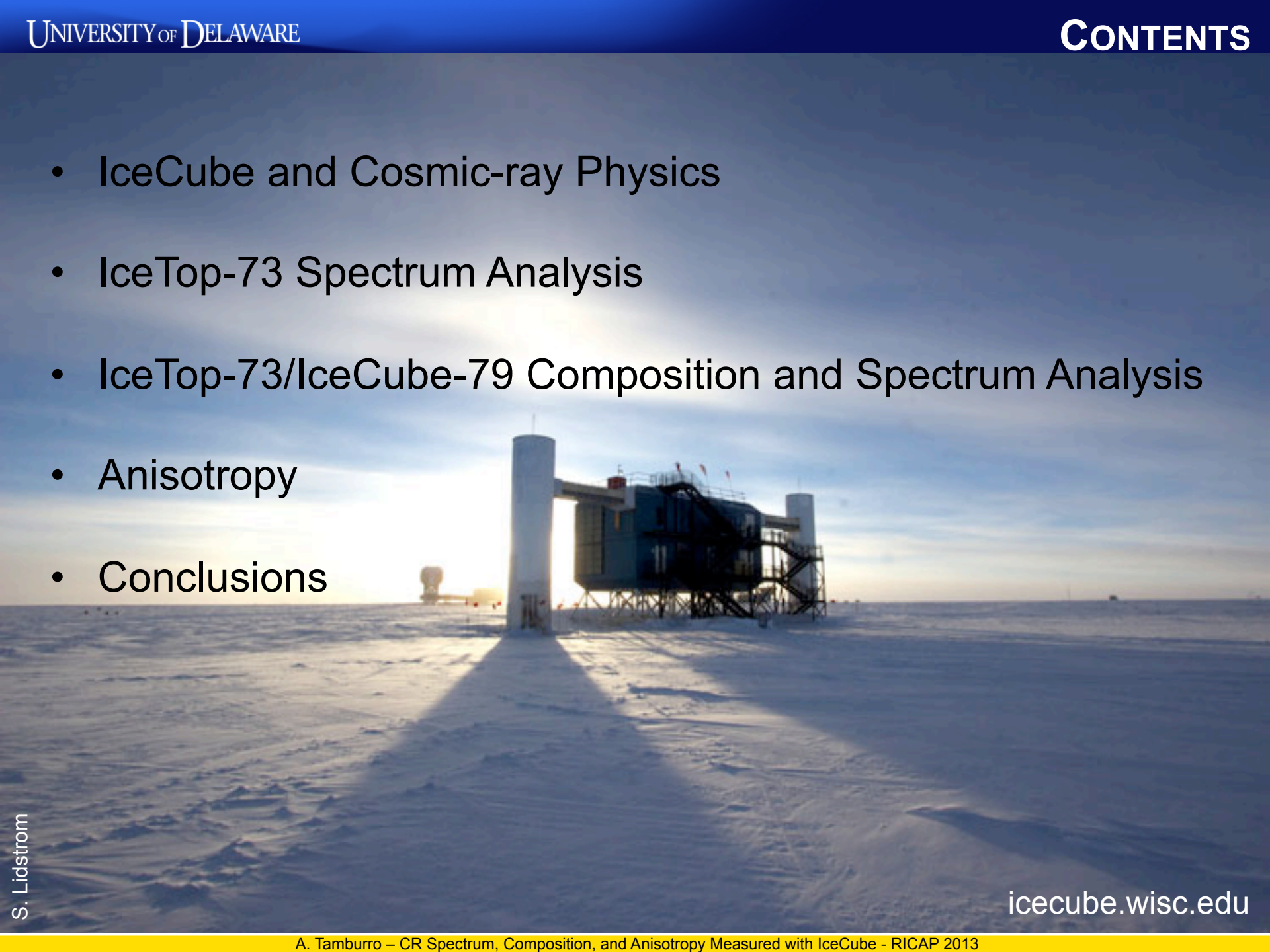
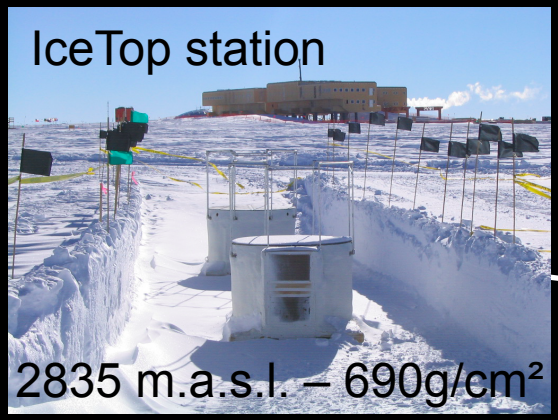


S. Lidstrom

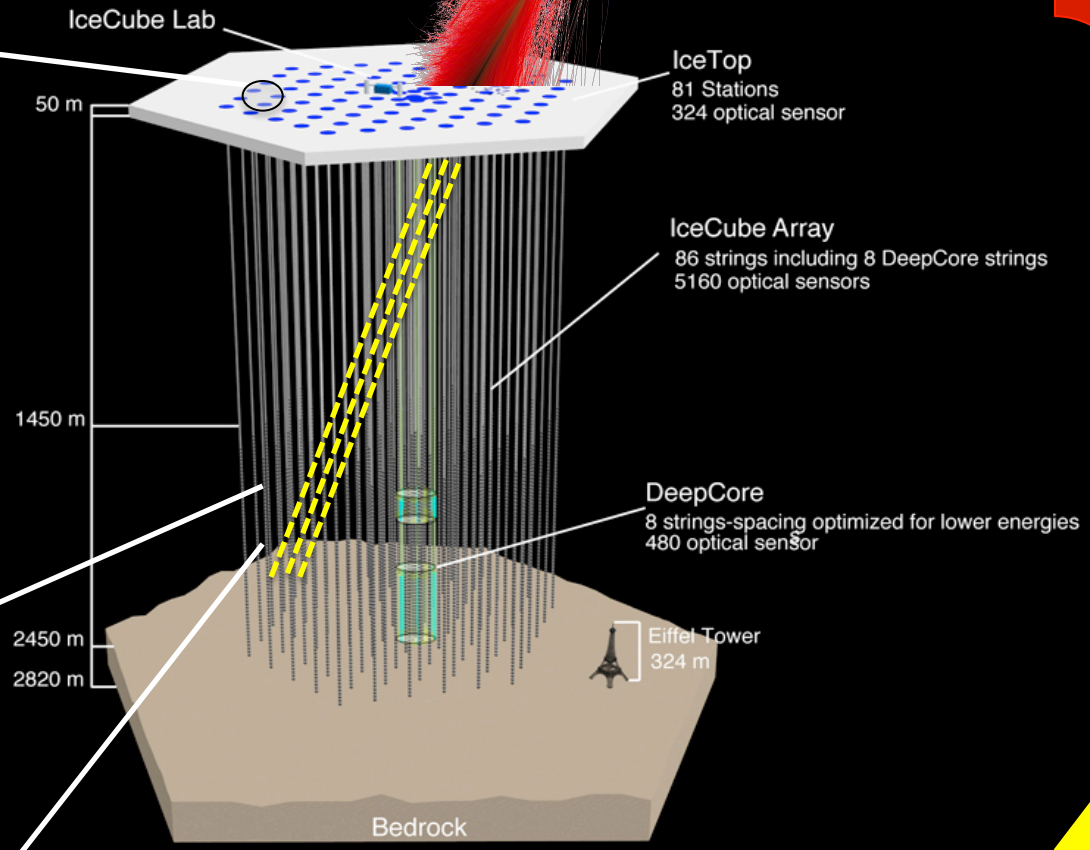
icecube.wisc.edu

# ICECUBE AND COSMIC RAYS




Close to shower max

@ E~3×10$^{16}$ eV or 30 PeV:
Over 2,000 events/yr
(Max E ~ 3 EeV due to km$^2$ size)

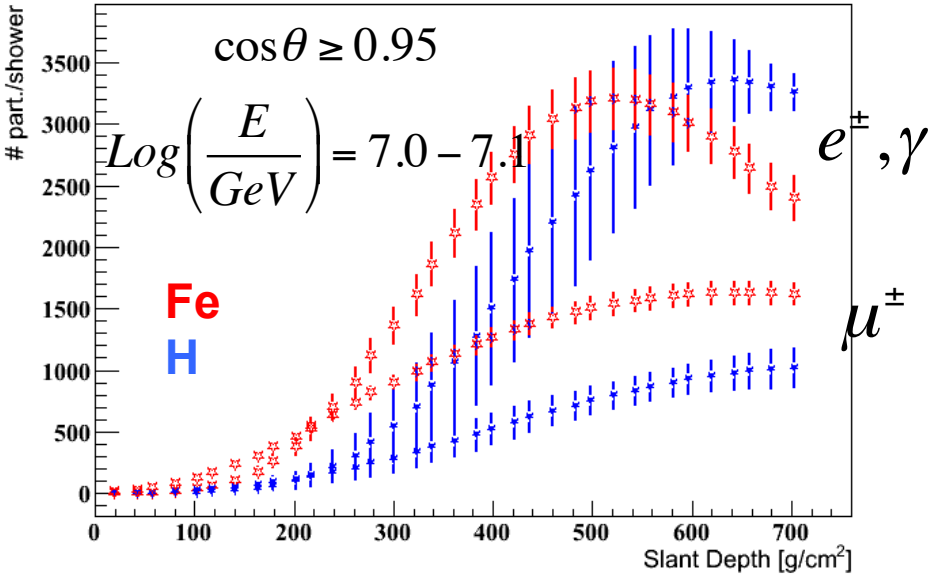


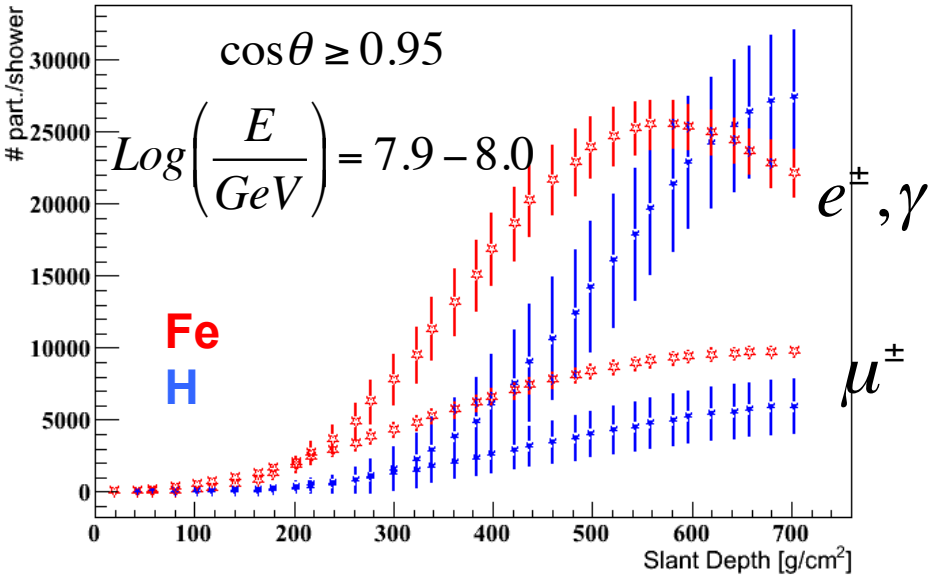


650 coinc. muon bundles/yr
(Max E ~ EeV)

http://icecube.wisc.edu/~atamburro/MOVIES/steamshovel_example.mov

# ICECUBE: A 3D DETECTOR




CR spectrum (PeV – EeV):

- less composition-dependent @ $10^{7.5}$ GeV and above
- precisely measured (low fluctuations at IceTop altitude)

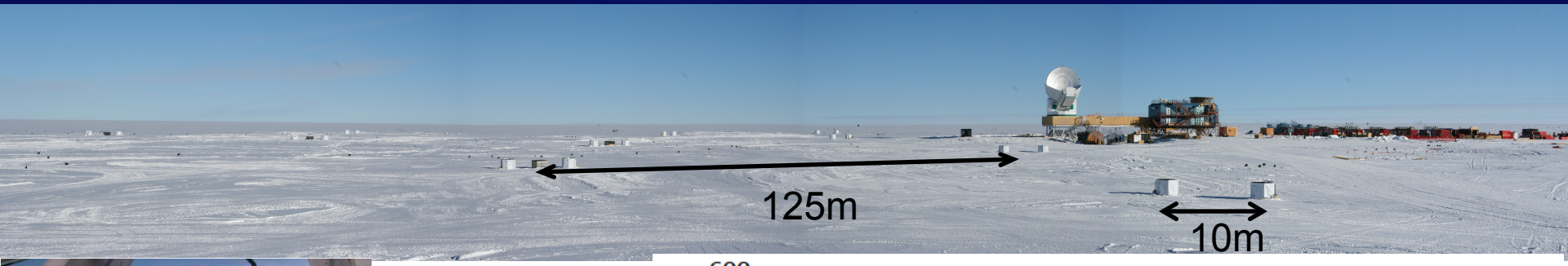
CR composition (PeV – EeV):

- in-ice info allows for studying muon content of showers
- will see transition from galactic to extra-galactic?

CR anisotropy with IceCube/IceTop (10 TeV – 2 PeV, $10^{-3}$ level):

- Large statistics $10^{11}$ muons/yr –$10^{8}$ showers/yr
- Angular resolution better than $10^{o}$

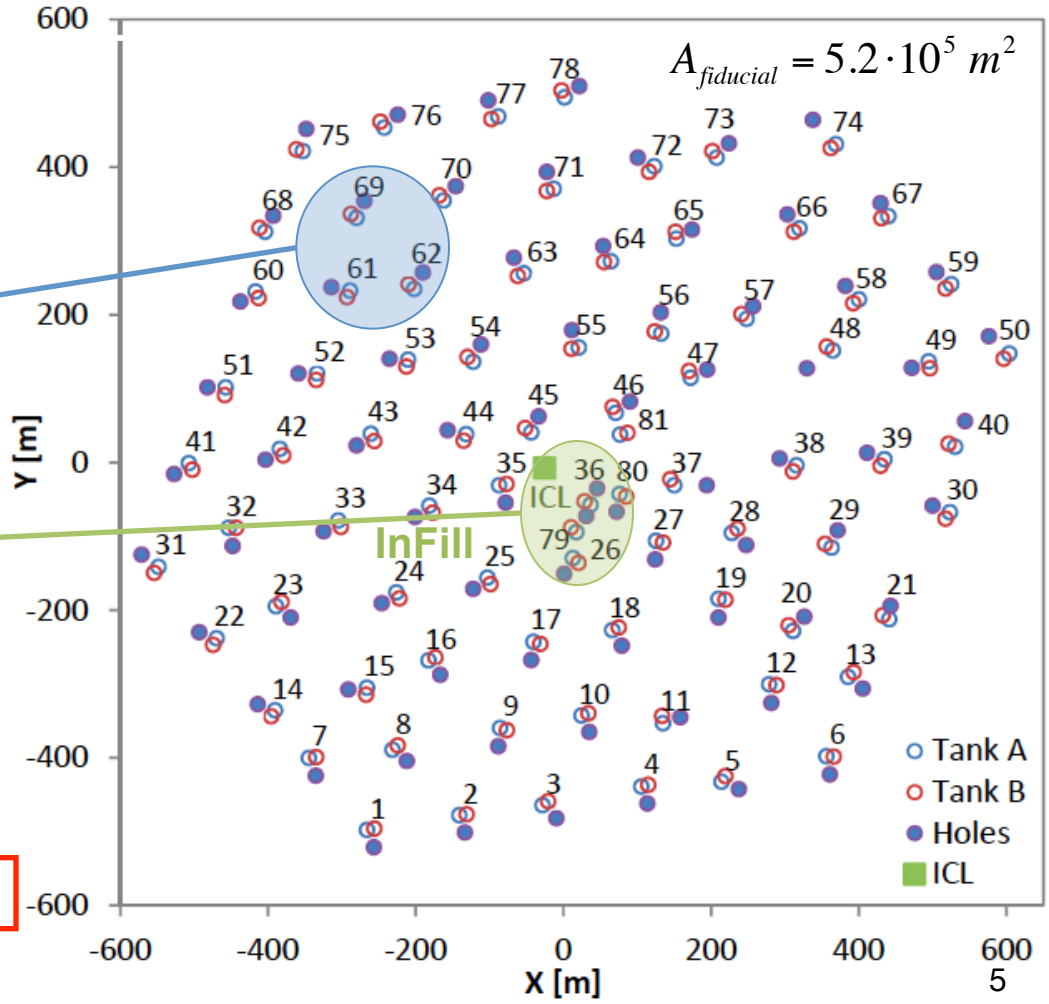
# THE ICETOP ARRAY





~300 TeV showers

~100 TeV showers



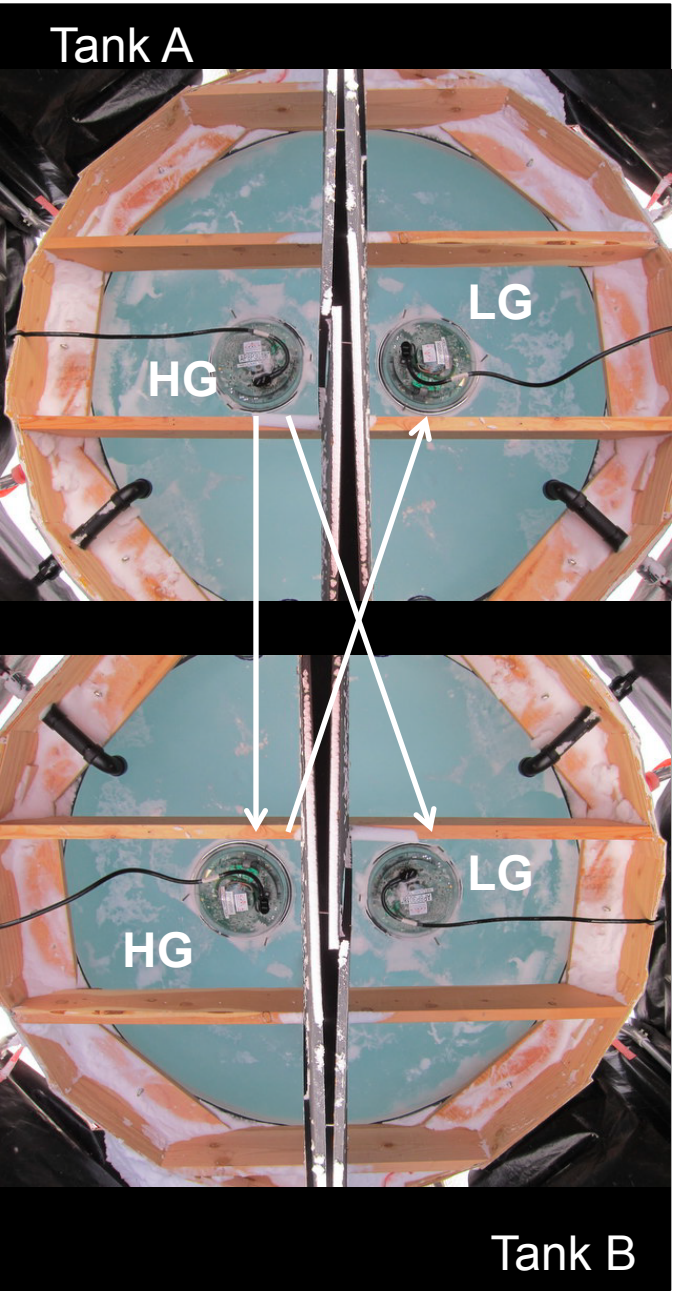

5+ stations
$E \sim PeV - EeV$

**Current results**

3+ stations
$E > 100\ TeV$

**Work in progress**

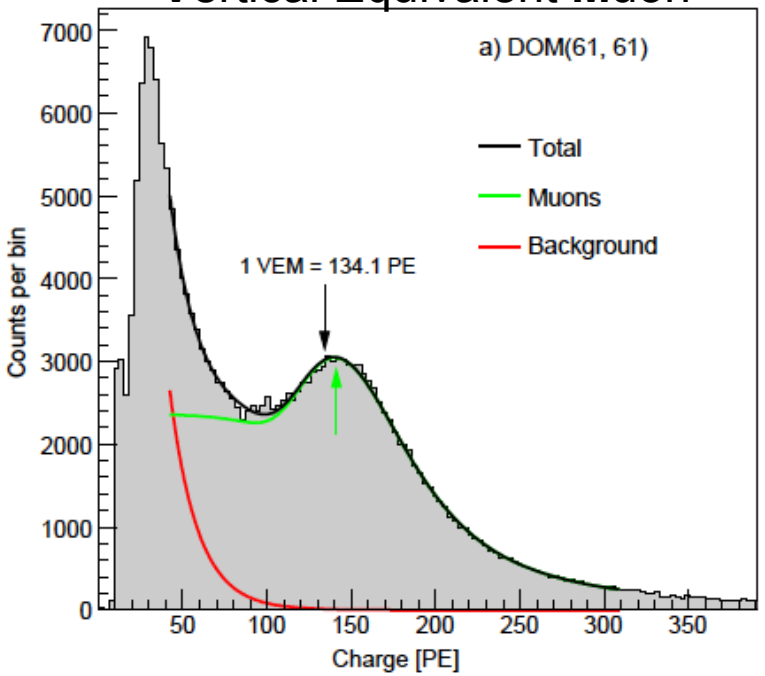
# ICETOP ARRAY: OPERATIONS



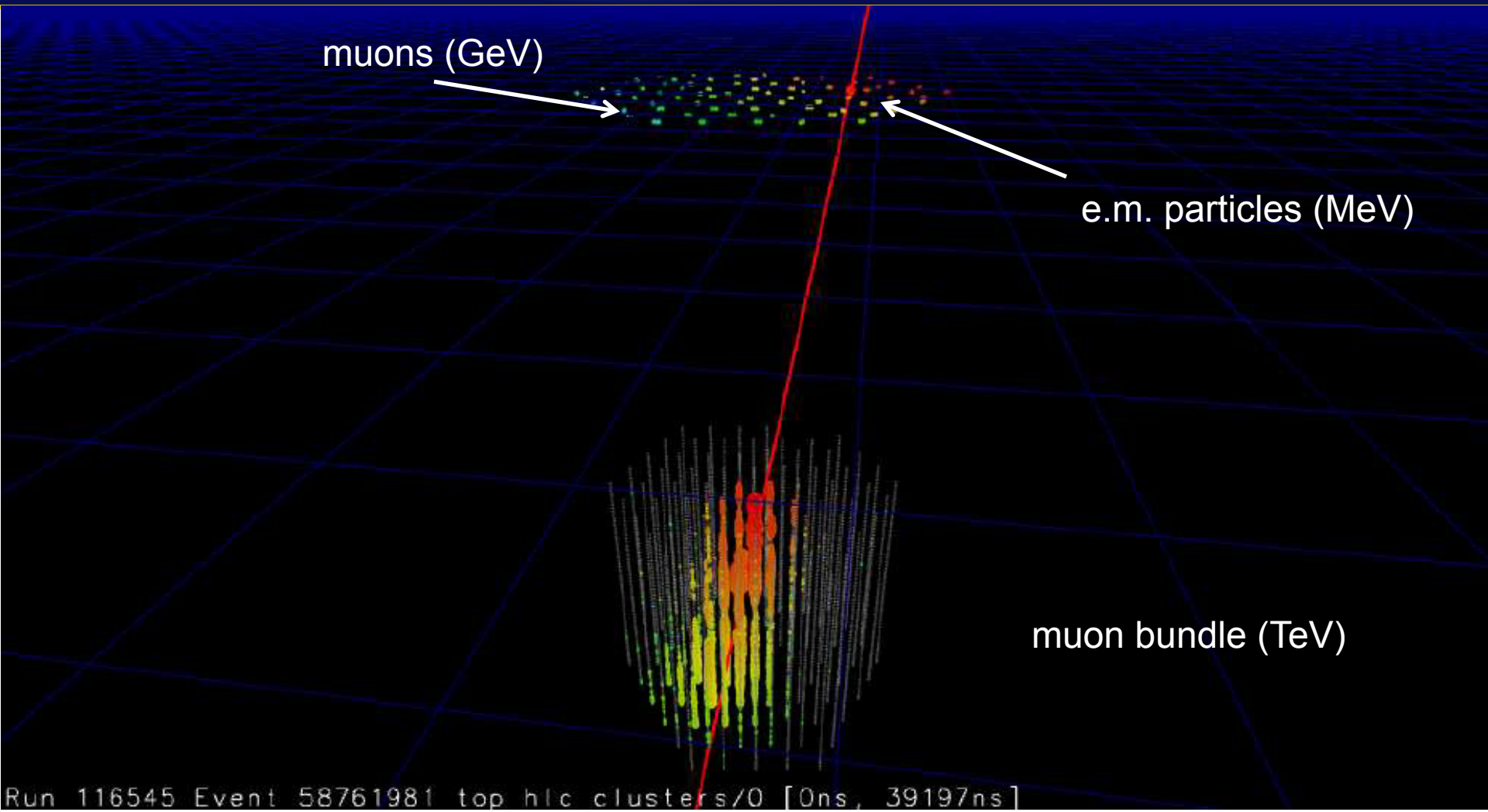

**Single hits** (1 DOM) or SLC
(muon detection + veto of air showers for in-ice studies)
(**2,000 Hz**)

**Station trigger**
HG-HG or HG-LG coincidence in 1 μs (**30 Hz**)
**IceTop trigger**
3+ stations in 6 μs (**20 Hz**)

**V**ertical **E**quivalent **M**uon



# COSMIC-RAY COINCIDENT EVENT: AN EXAMPLE



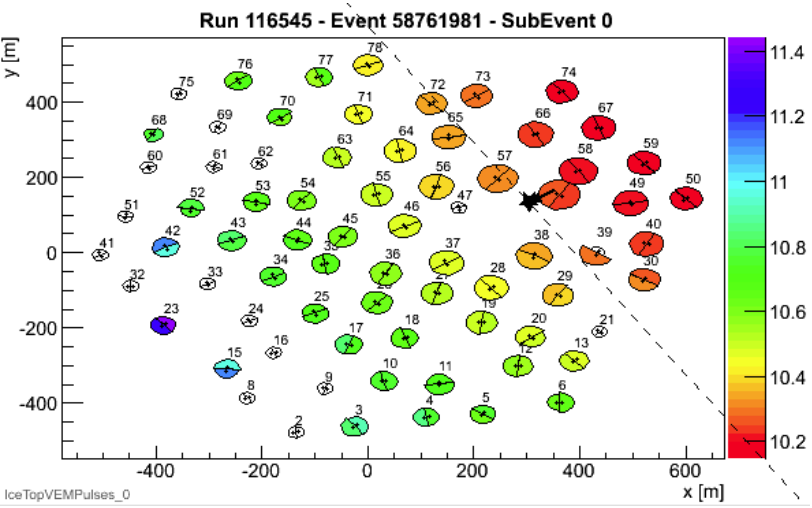

Coincident events:

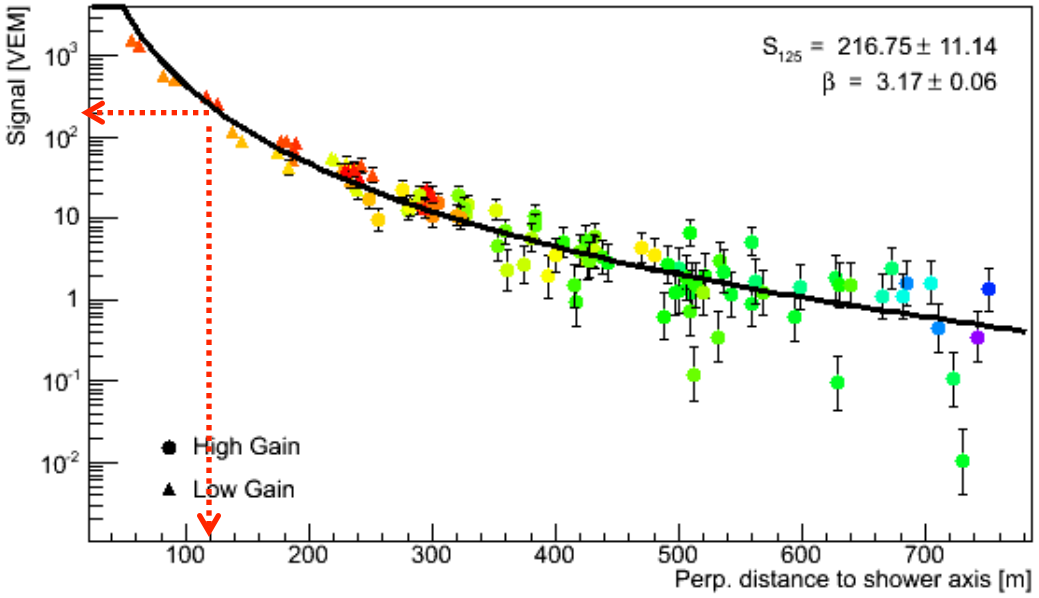
- Shower core contained within IceTop array
- Muon bundle track through in-ice array

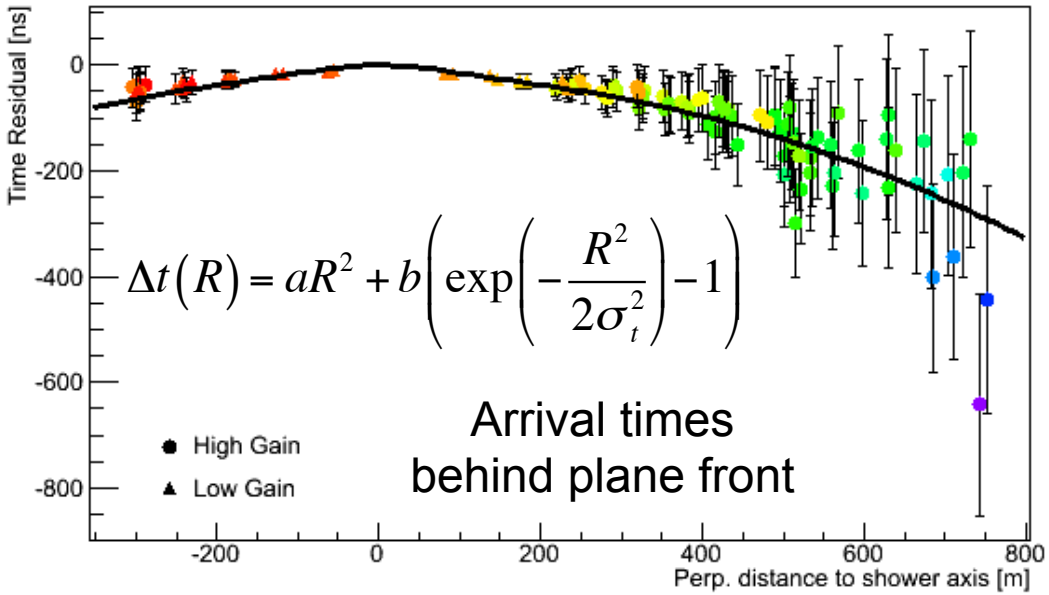
# ICETOP SHOWER RECONSTRUCTION

$\theta = 11.5^{o}, \phi = 33.0^{0}$

$E = 2.90 \cdot 10^{17}\ eV\ (H\ assumption)$




Arrival times behind plane front

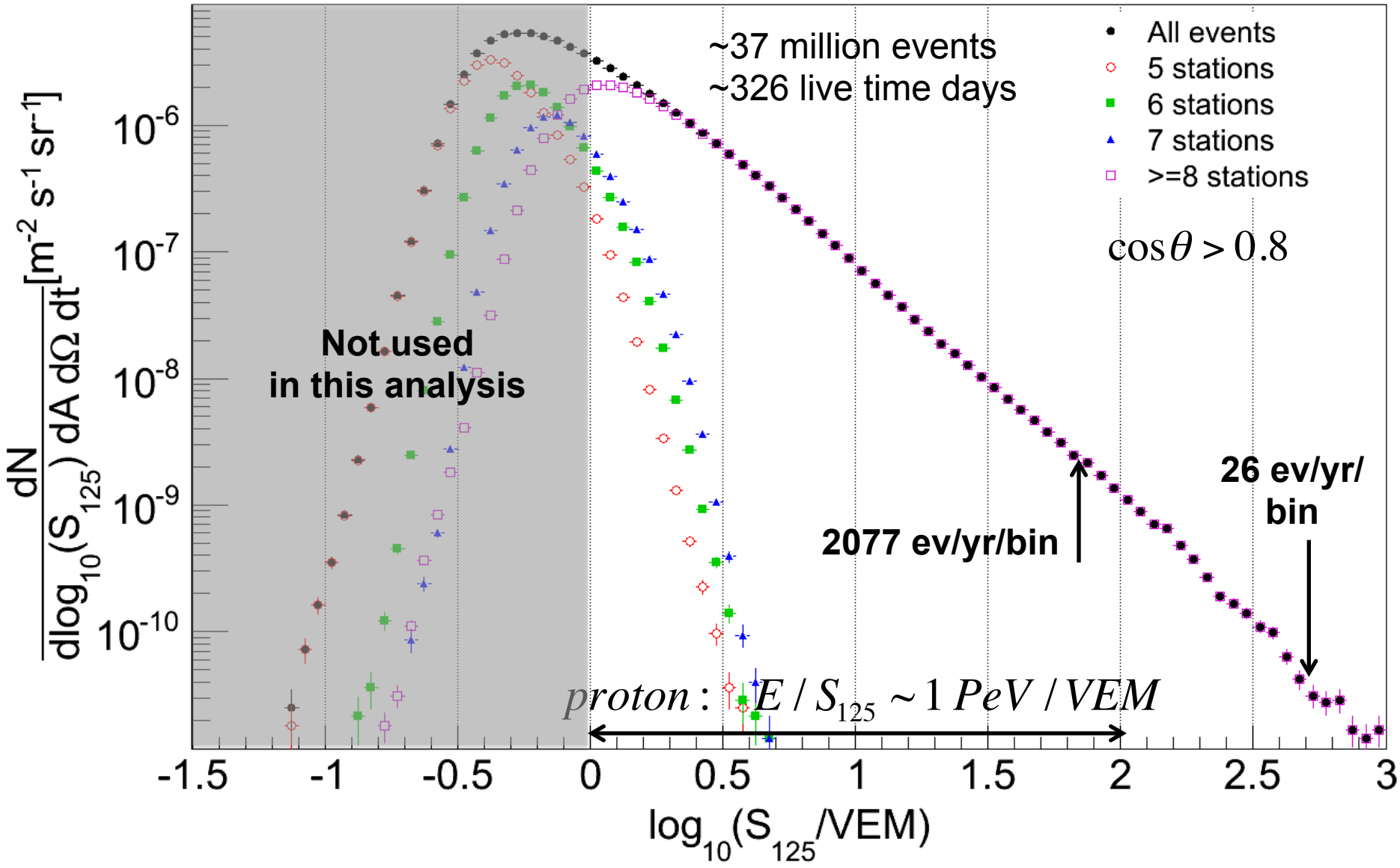
$$S(R) = S_{125}\left(\frac{R}{125m}\right)^{-\beta-\kappa\log(R/125m)}$$

$S_{125}$ "Shower size" at 125m

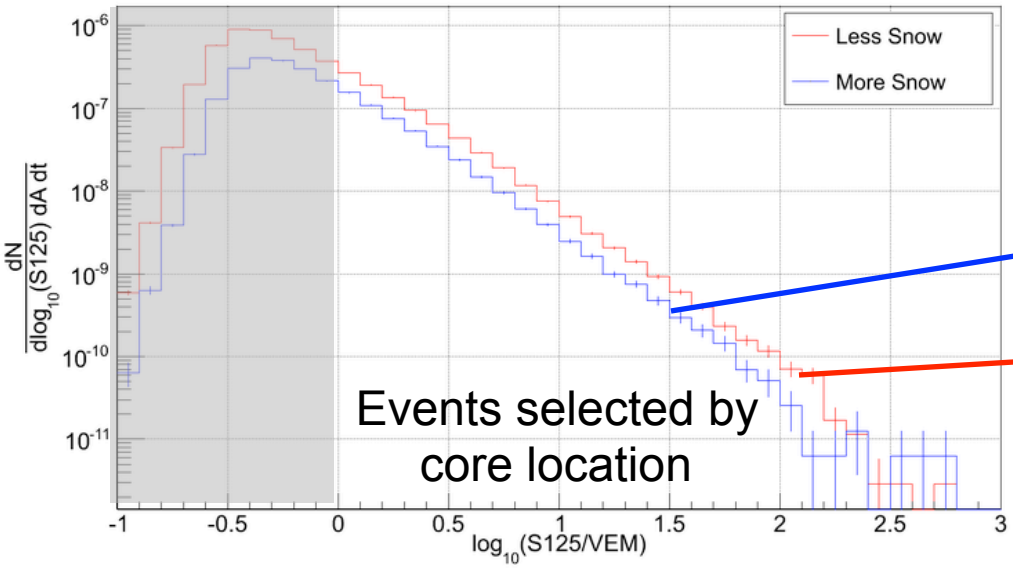
$\beta$ Slope at 125m

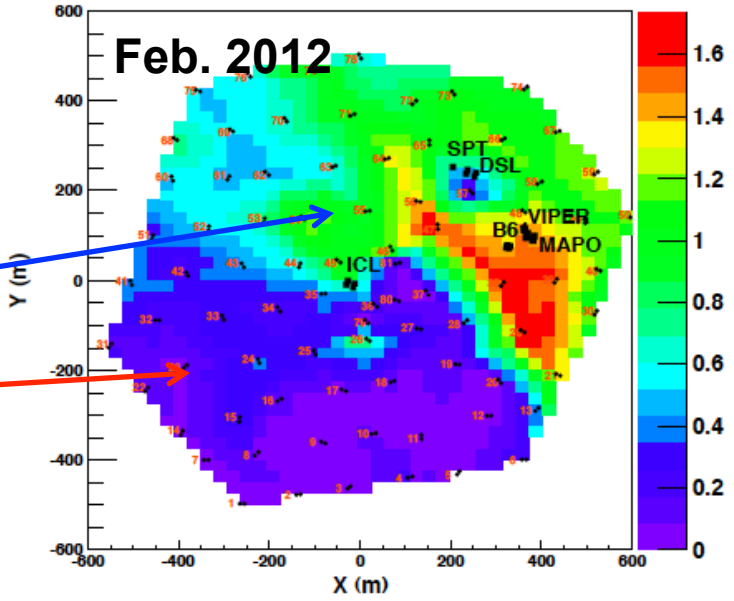
Tank signals are mostly from shower e.m. component.

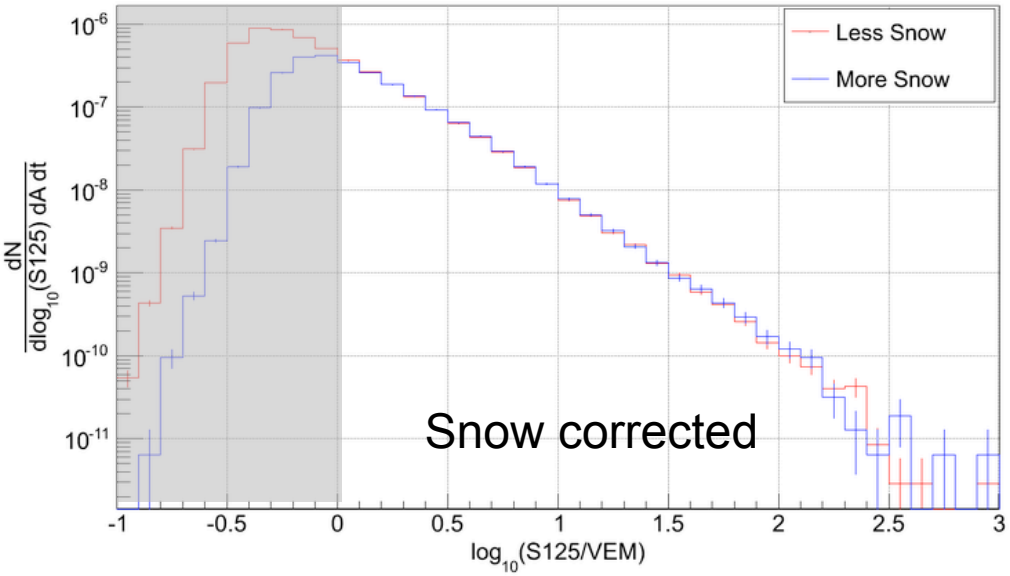
# MEASURED ICETOP SHOWER SIZE (IT73)



# SNOW BUILD-UP SYSTEMATICS



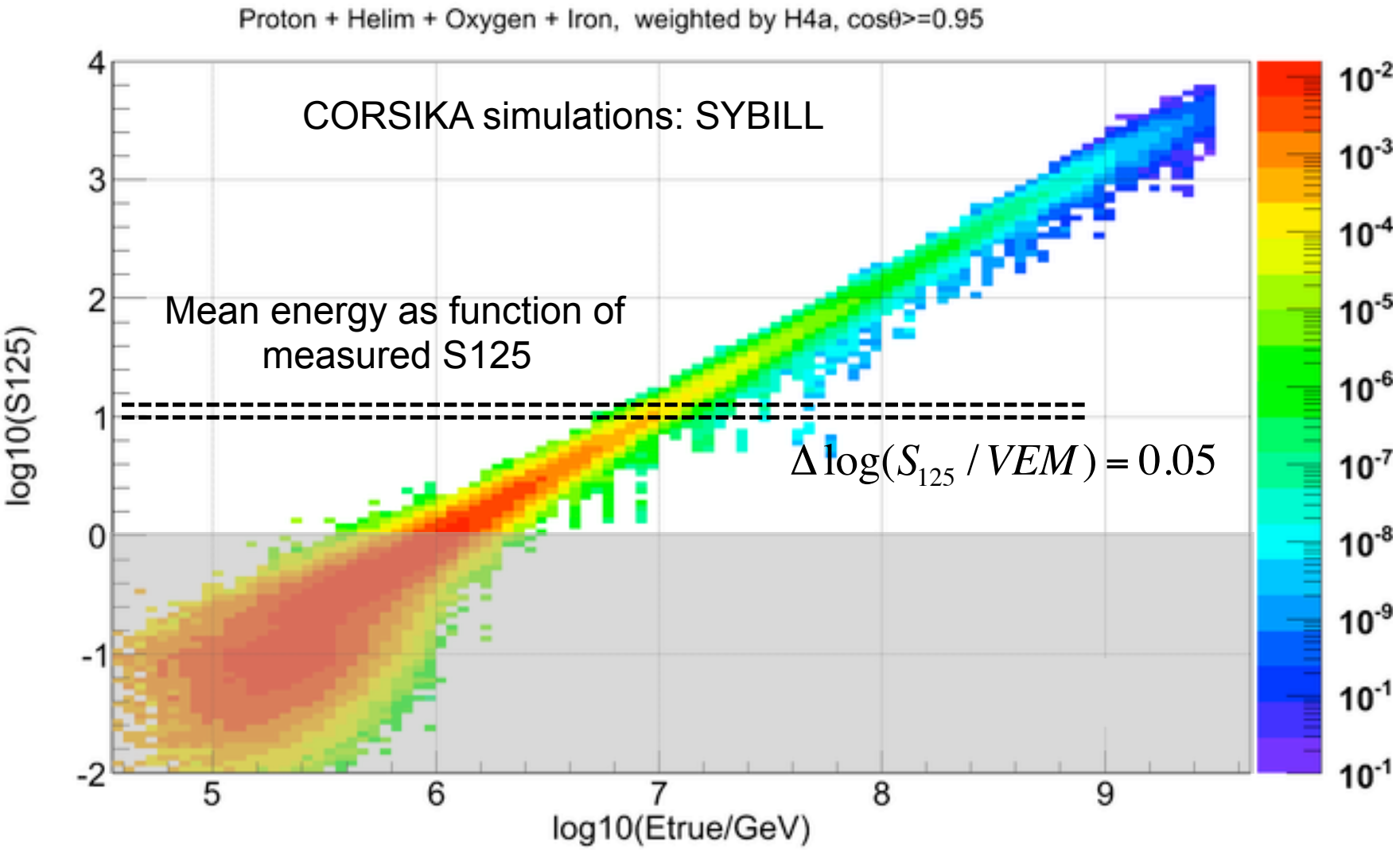




$$S_{corr} = S_{meas.} e^{\frac{z\cos\theta}{\lambda}}$$

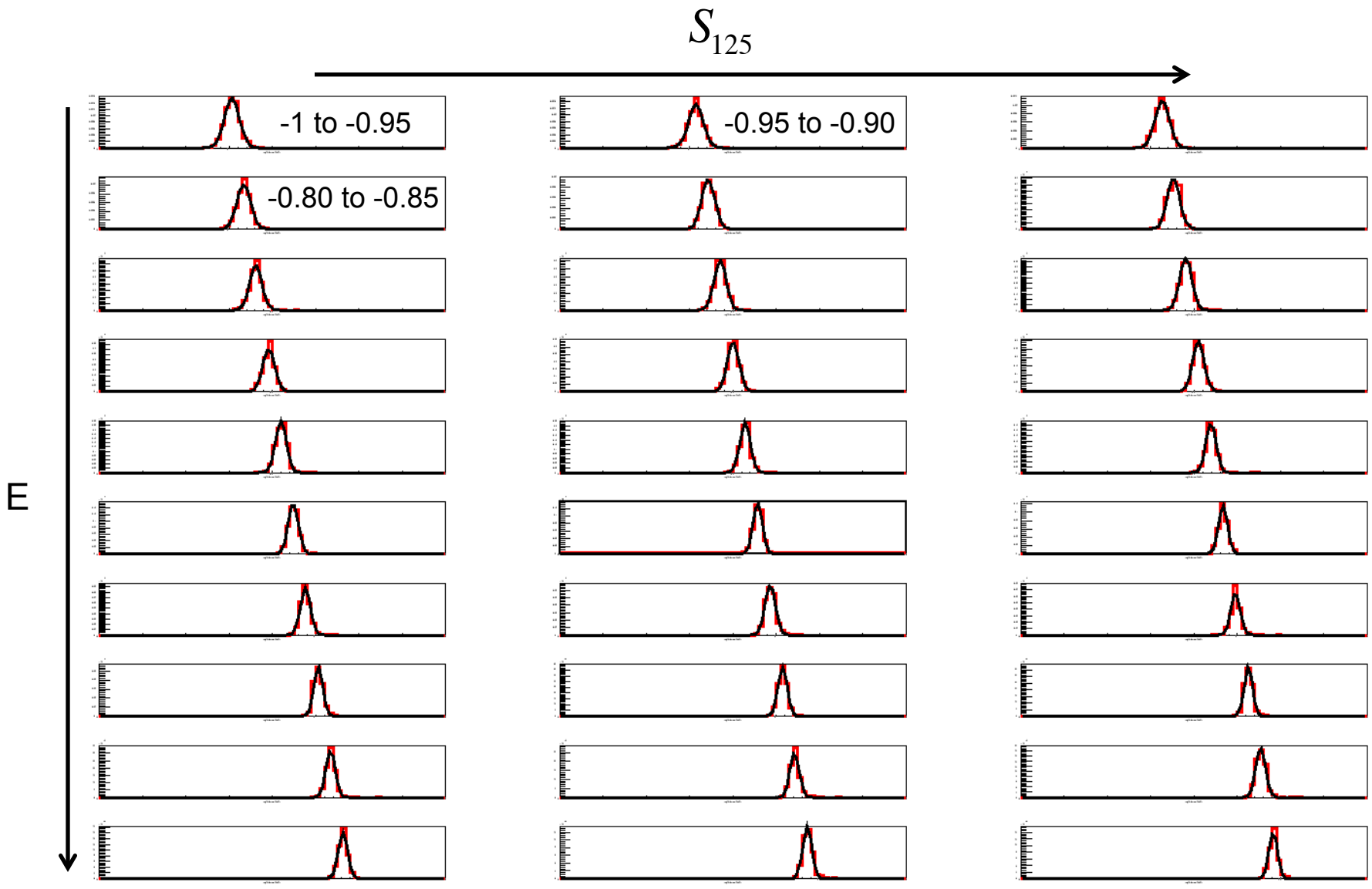
# FROM MEASURED S125 TO ESTIMATED $E_{PRIMARY}$

**Need to assume reasonable composition to derive energy spectrum**

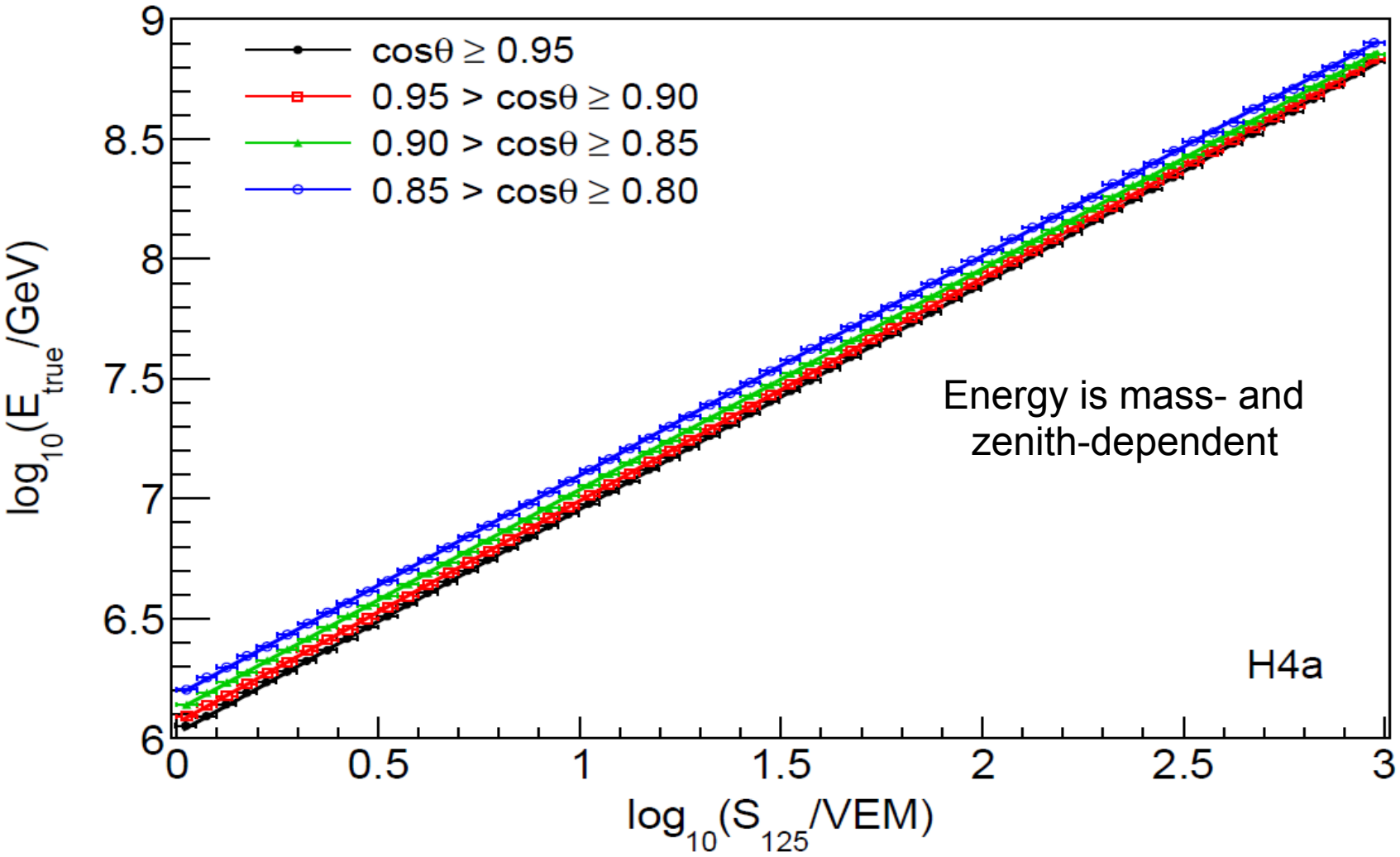



H4a: Gaisser, Astropart. Phys. 35 (2012) 801

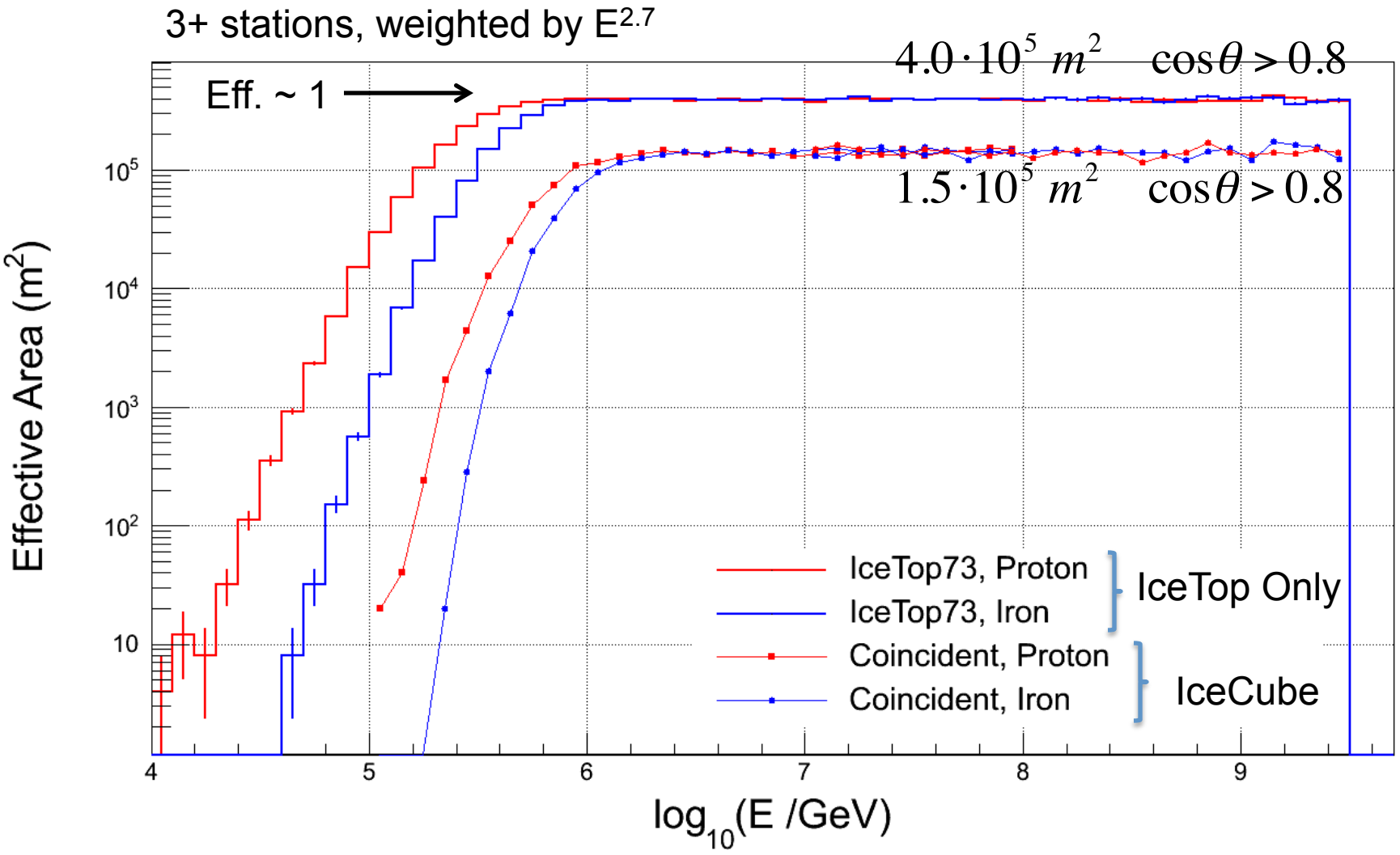
# ENERGY ESTIMATOR: <$E_{PRIMARY}$> FOR GIVEN S125



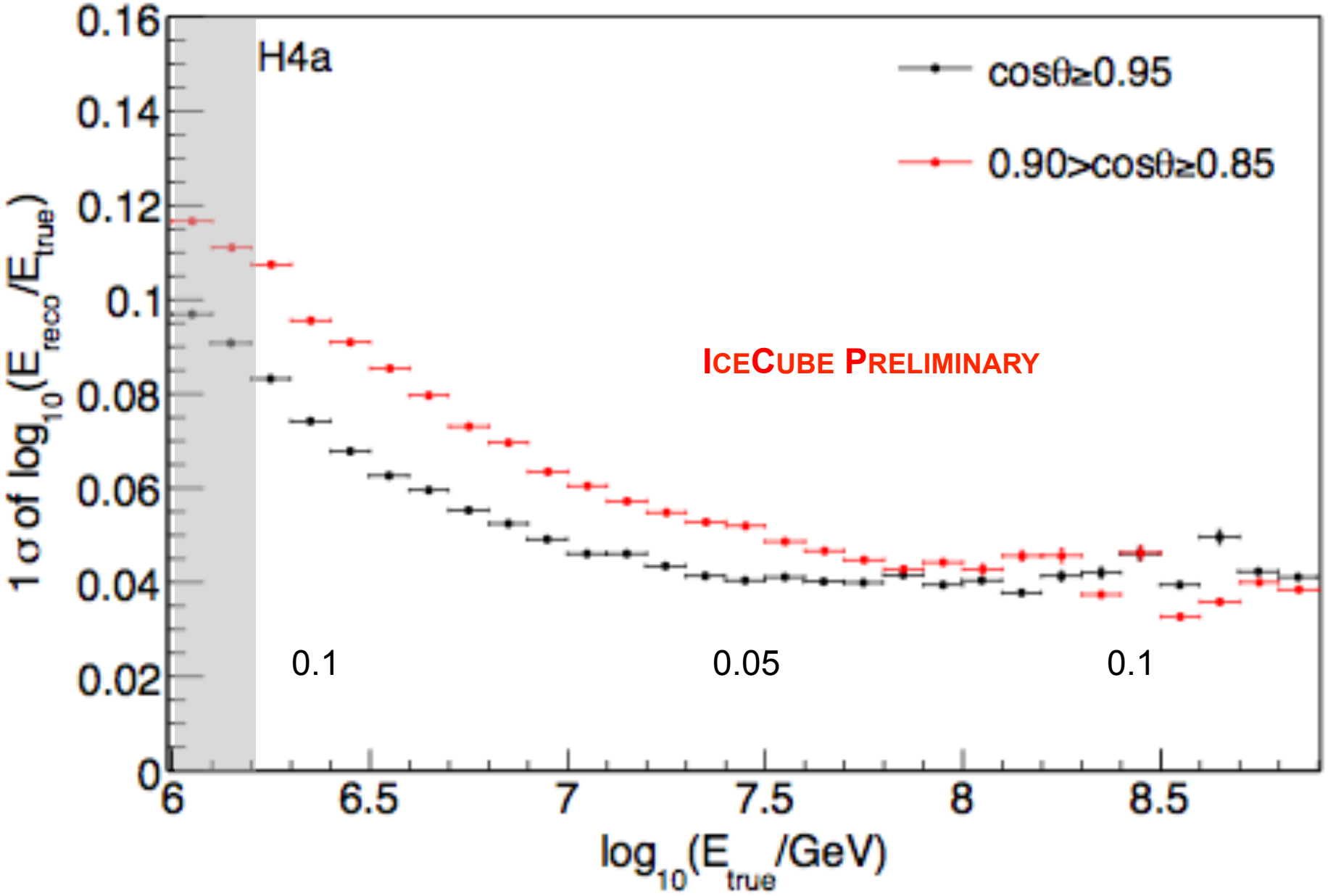
# S125 → $E_{PRIMARY}$ RELATIONSHIP



# EFFECTIVE AREA (IT73/IC79)

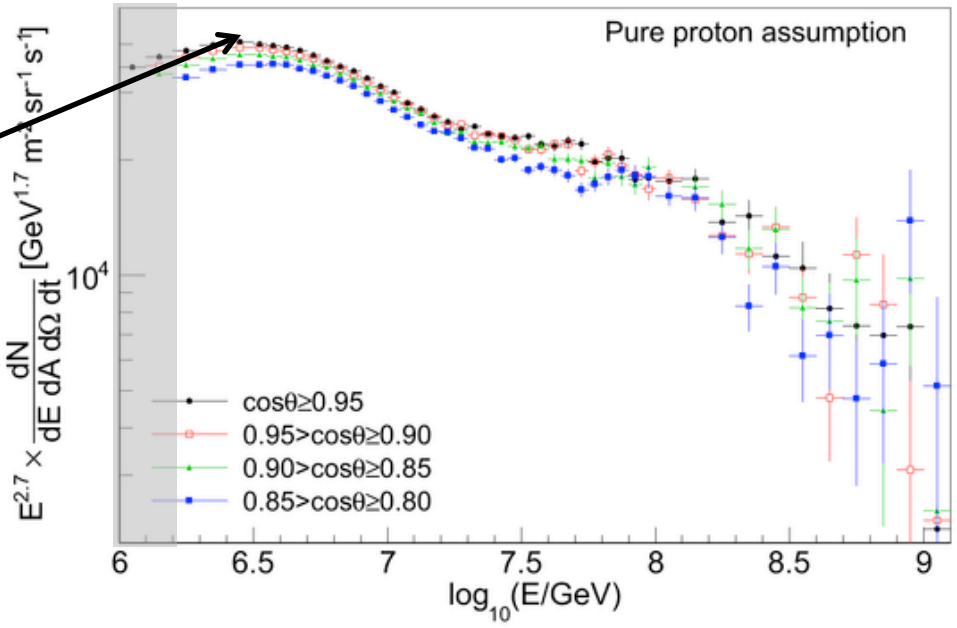


# ENERGY RESOLUTION

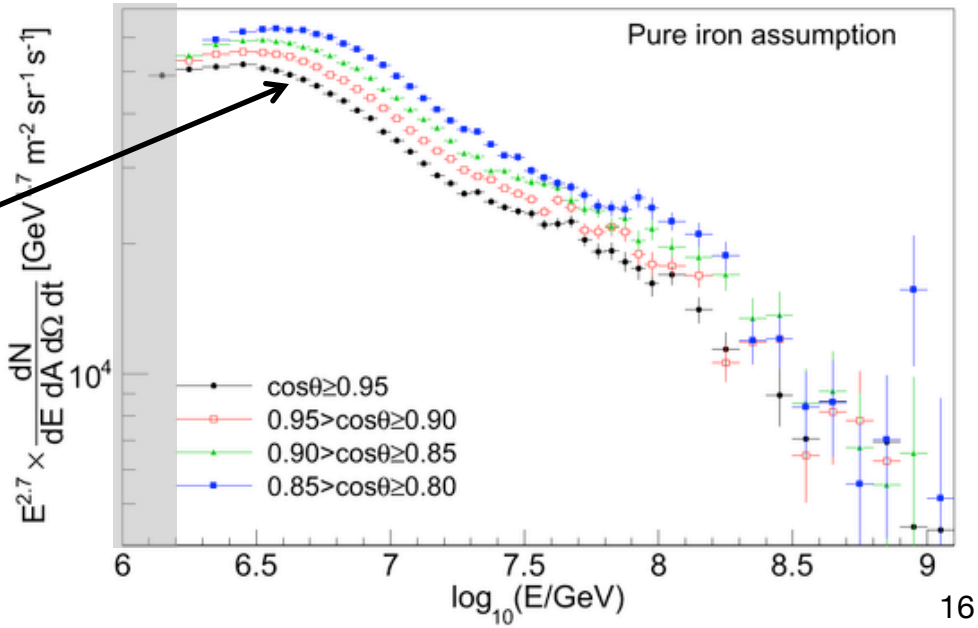


# FLUX FOR 2 EXTREME ASSUMPTIONS

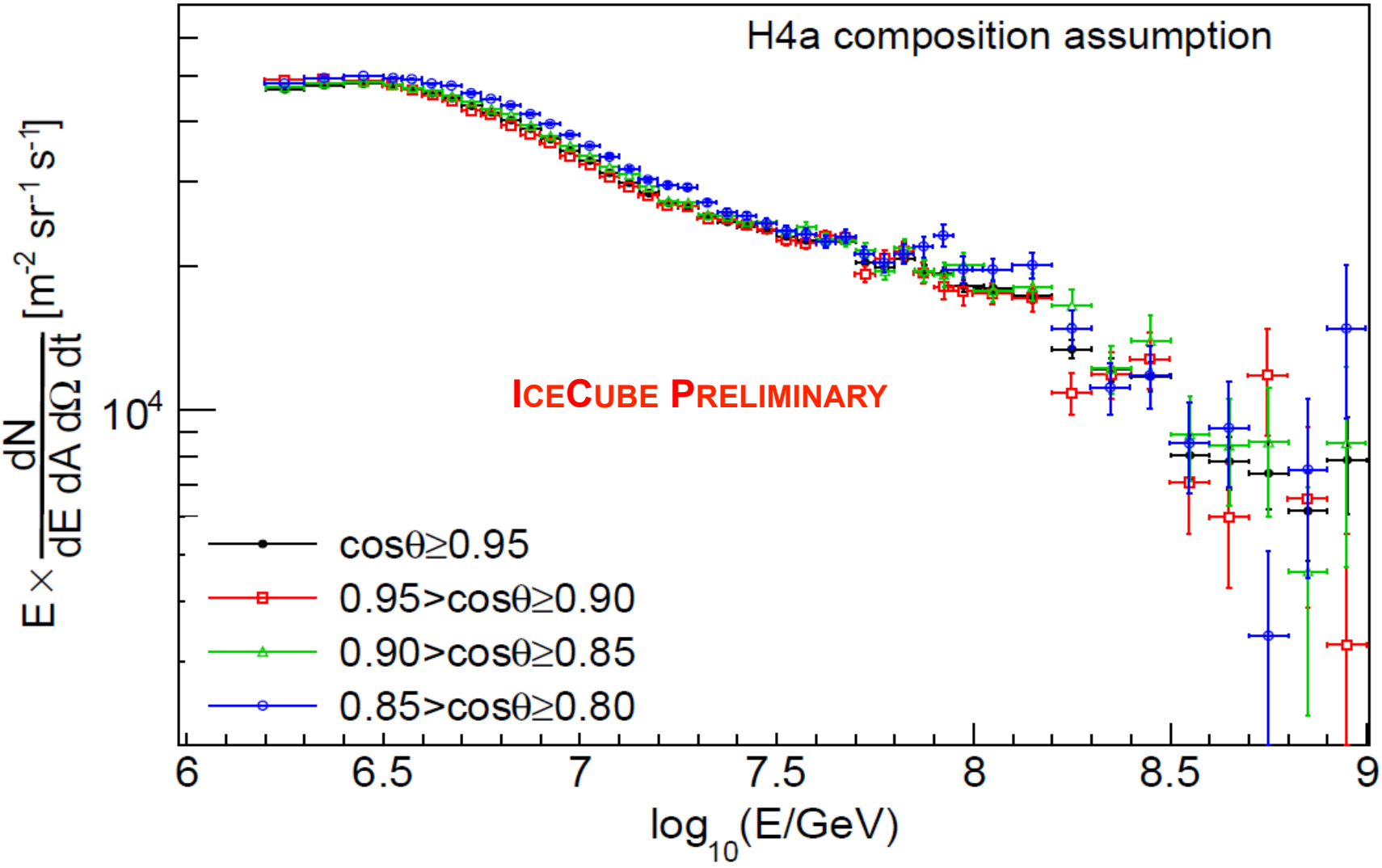
Inferred proton flux is **higher** near the vertical




Inferred iron flux is **suppressed** near the vertical

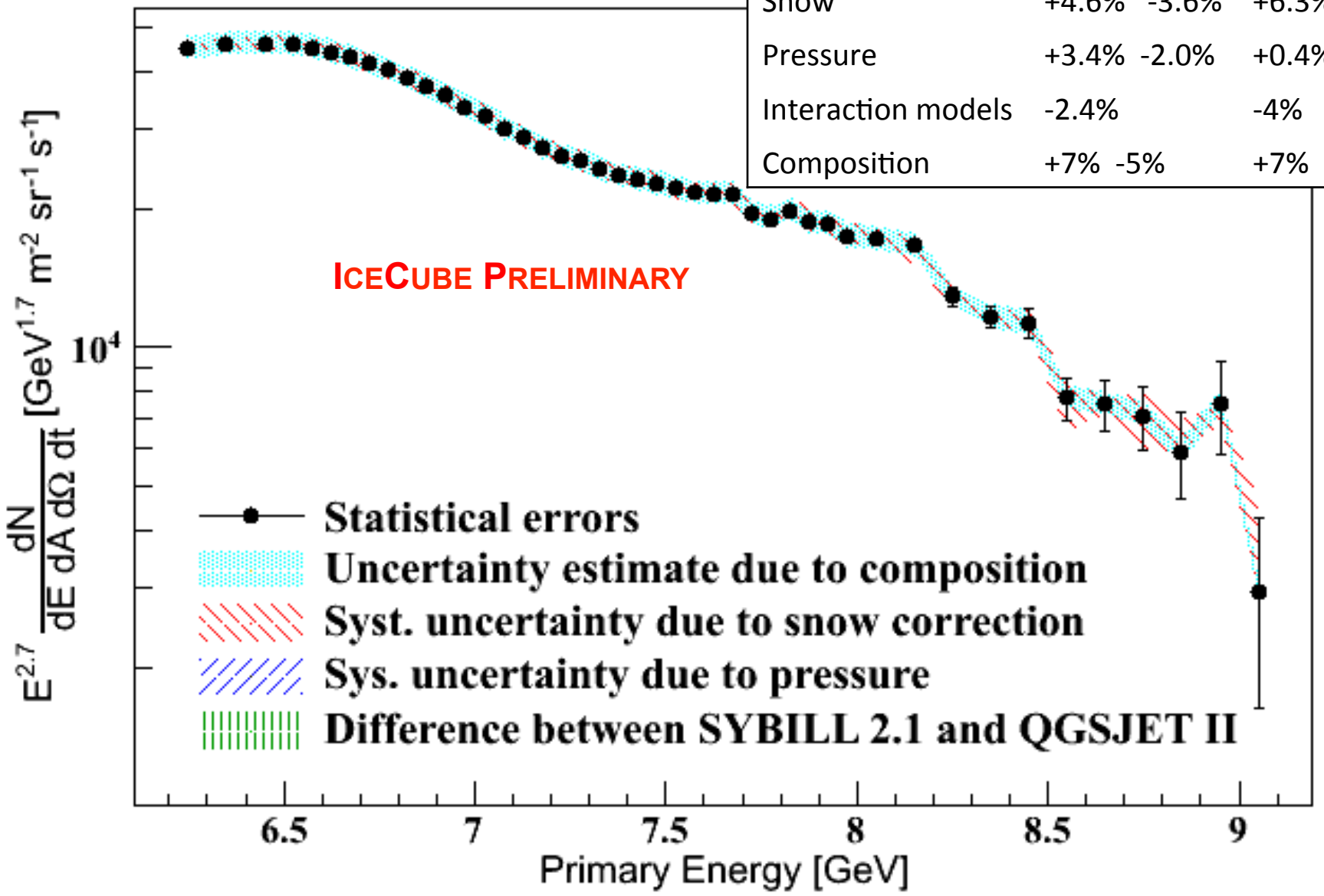


# COSMIC-RAY SPECTRUM WITH H4A ASSUMPTION



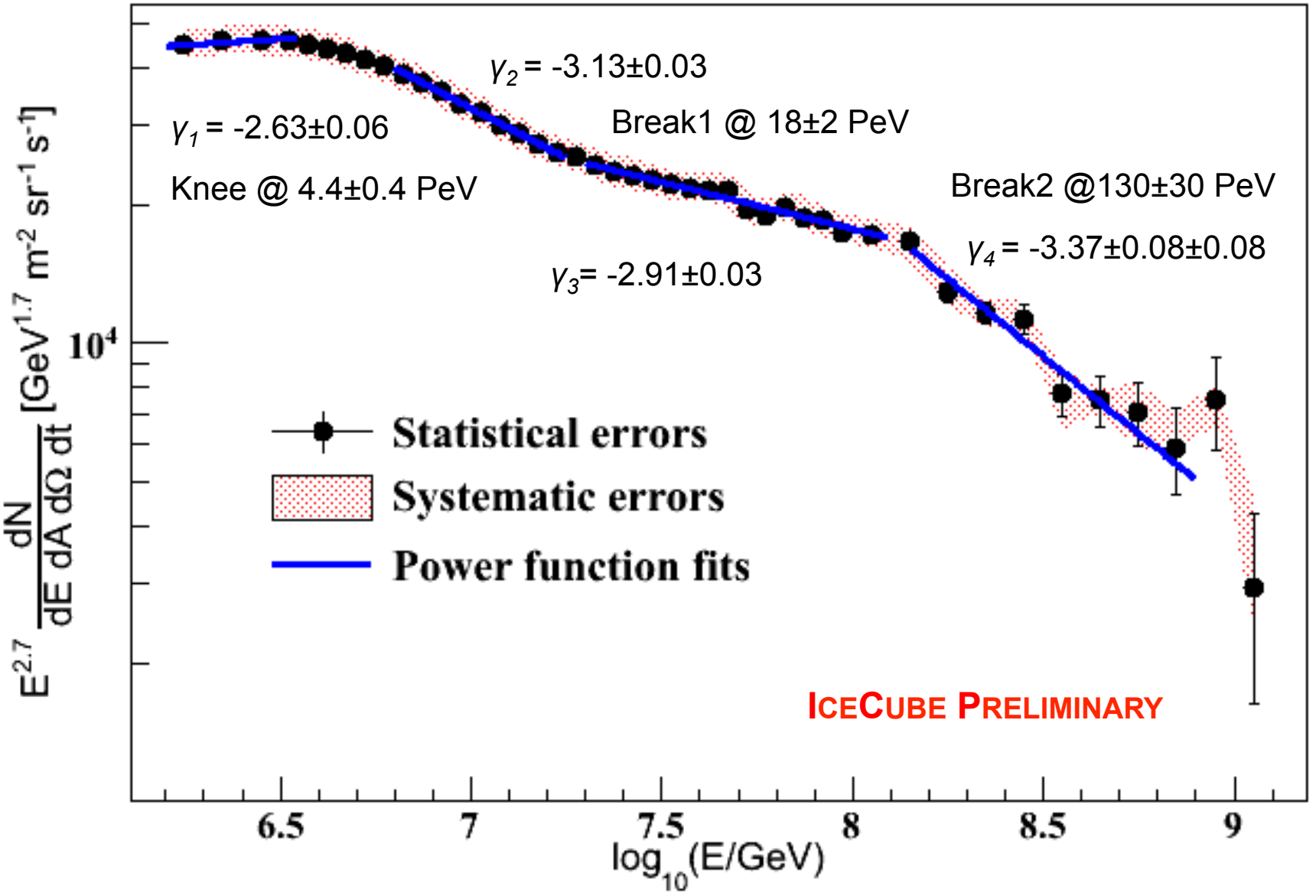
# SYSTEMATICS

| | 3 PeV | 30 PeV |
|---|---|---|
| Snow | +4.6% -3.6% | +6.3% -4.9% |
| Pressure | +3.4% -2.0% | +0.4% -1.0% |
| Interaction models | -2.4% | -4% |
| Composition | +7% -5% | +7% -5% |

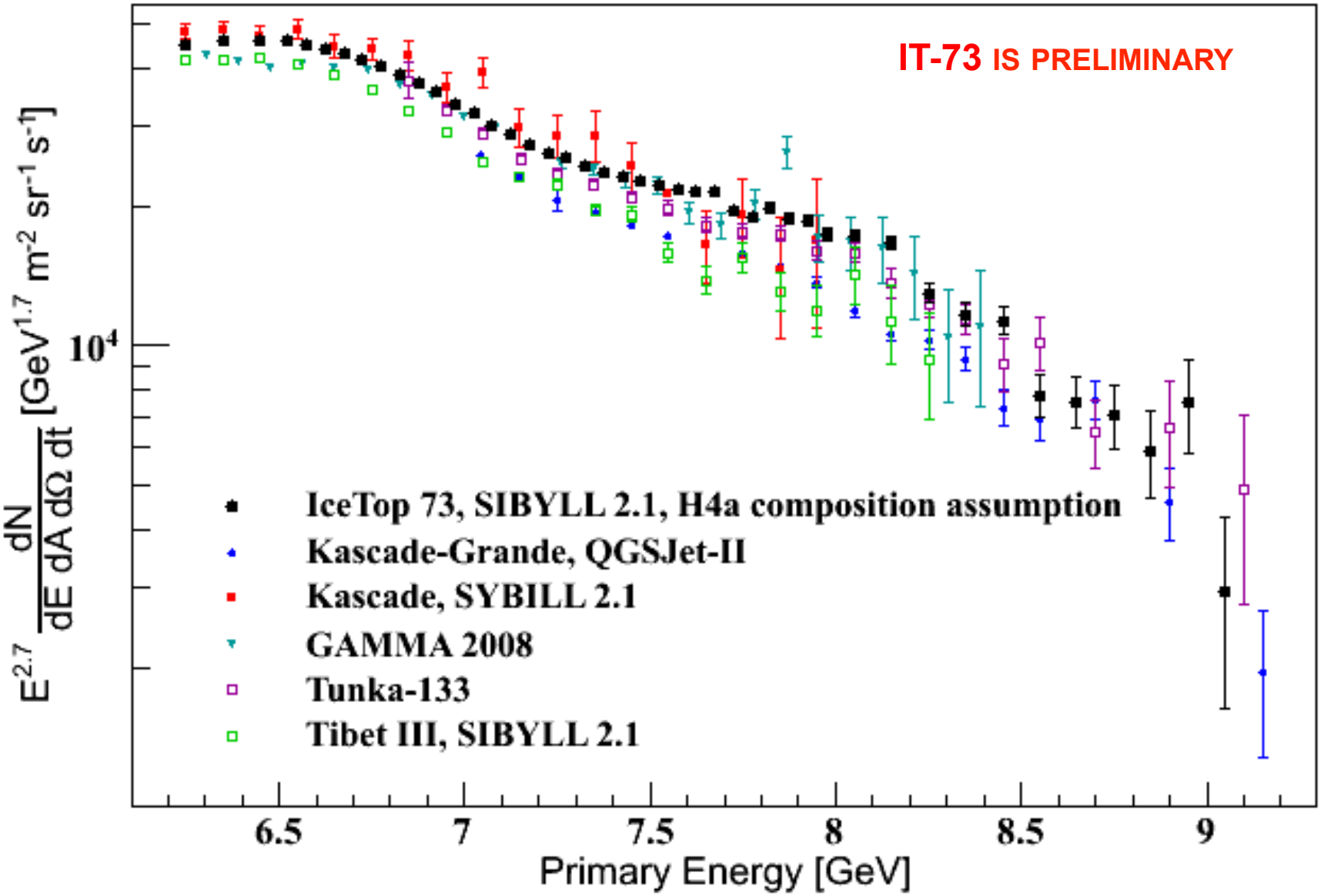


# COSMIC-RAY SPECTRUM AND FEATURES

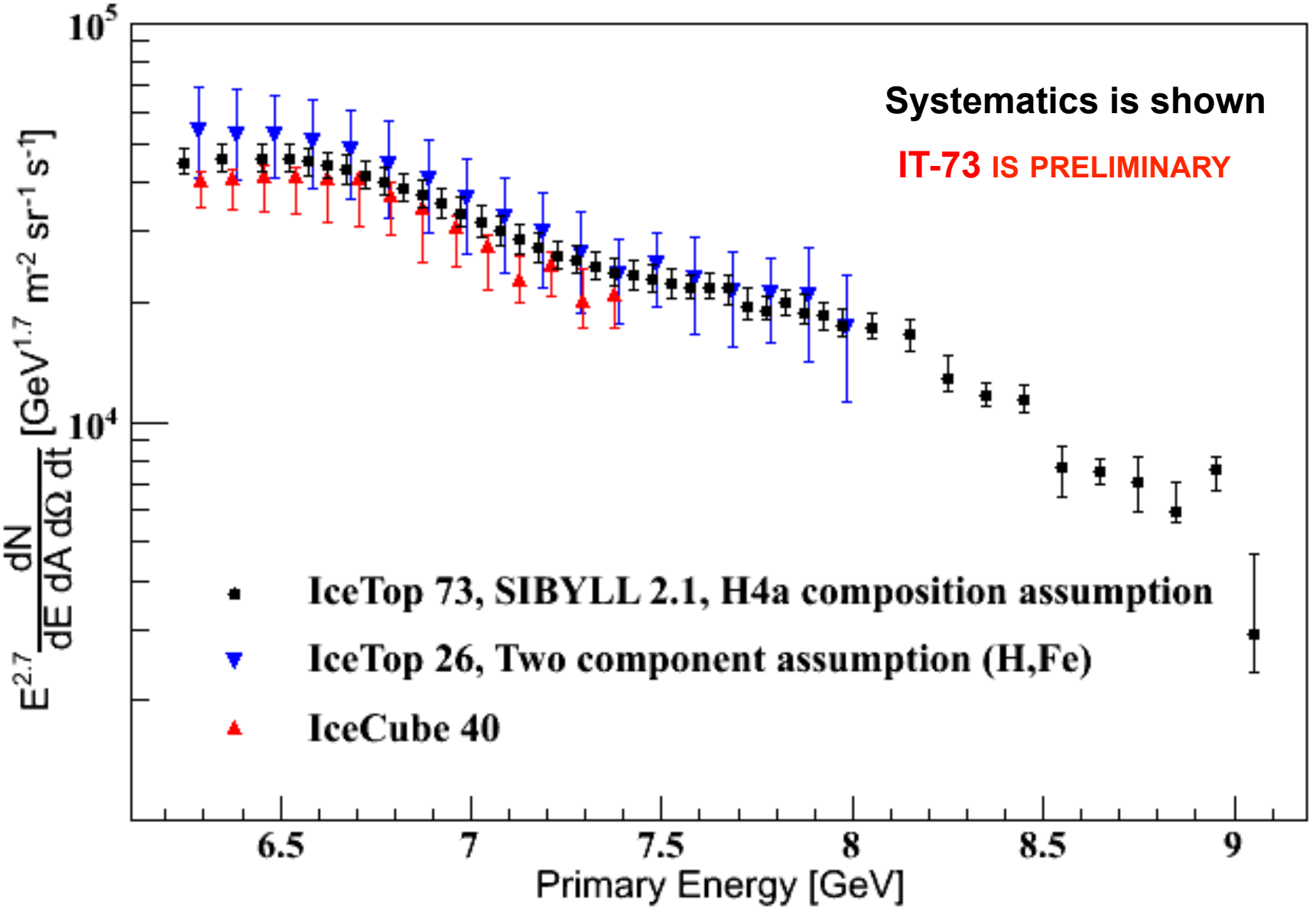
Energy "break" measured where a change in power law slope is observed



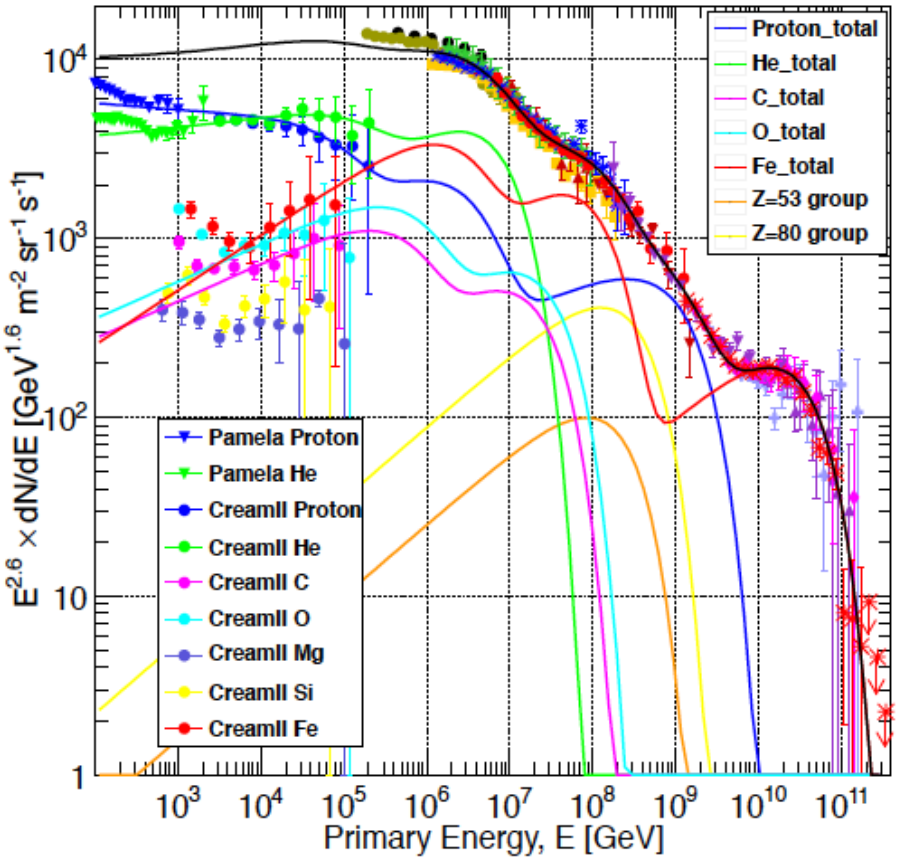
# ICETOP AND OTHER RECENT MEASUREMENTS

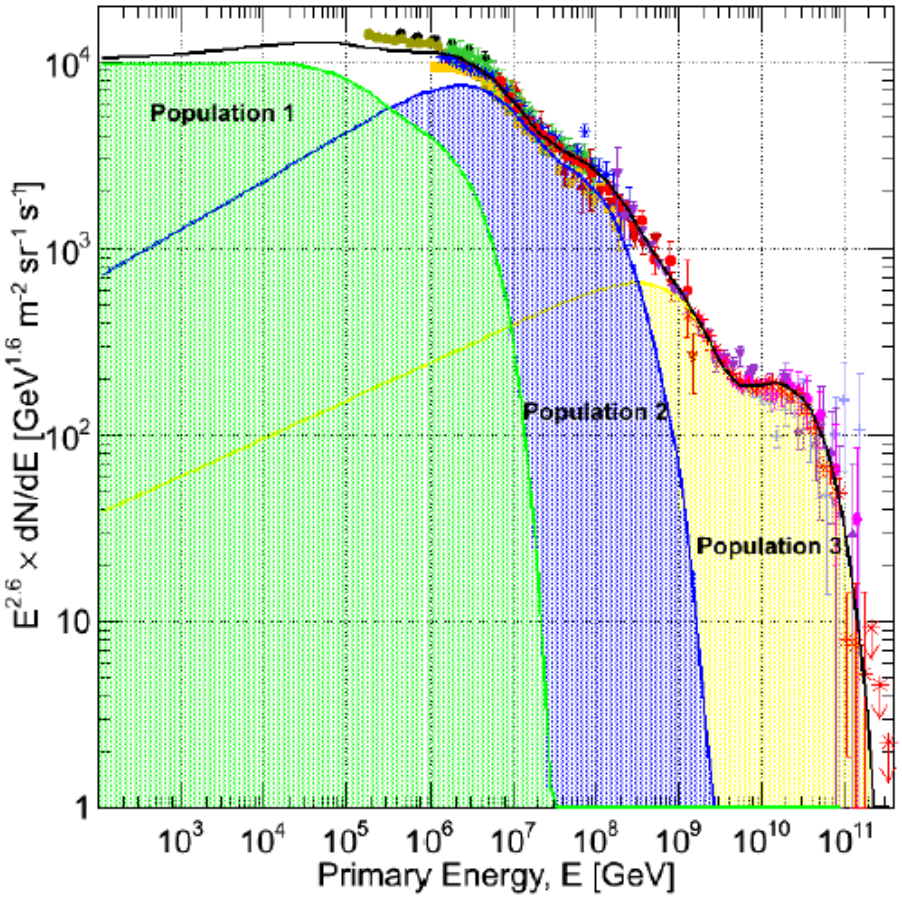


# ICETOP DURING THE YEARS



# BREAKS IN GLOBAL FIT TO CR DATA



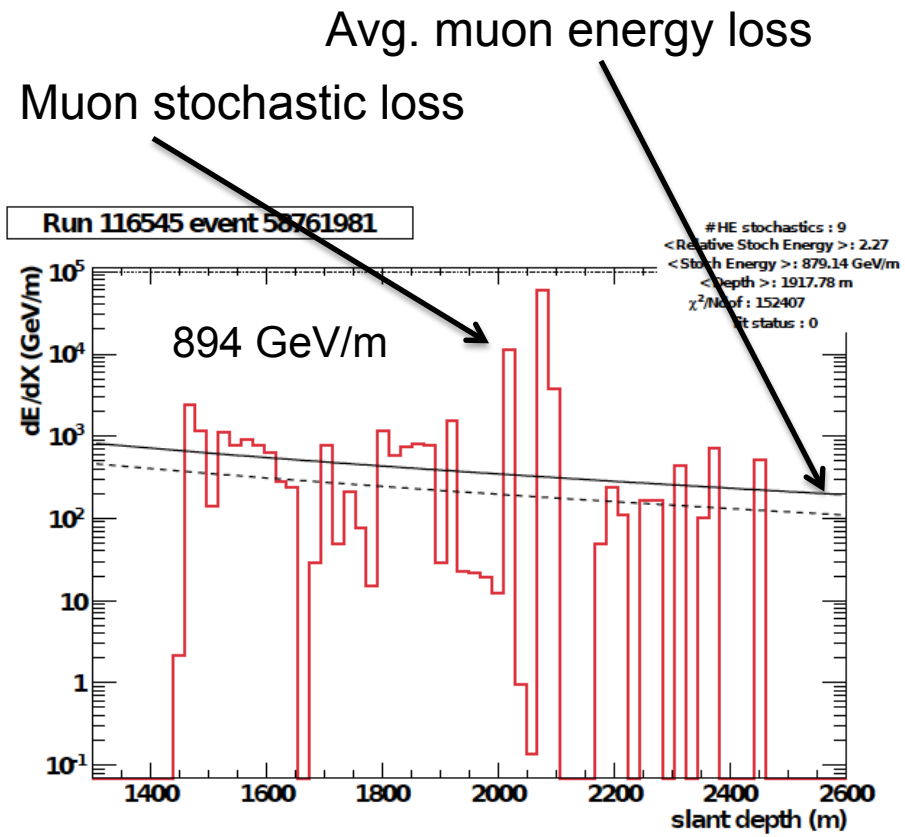

Including composition measurements when fitting Fe cutoffs identifies finer spectral structures corresponding to different populations of sources

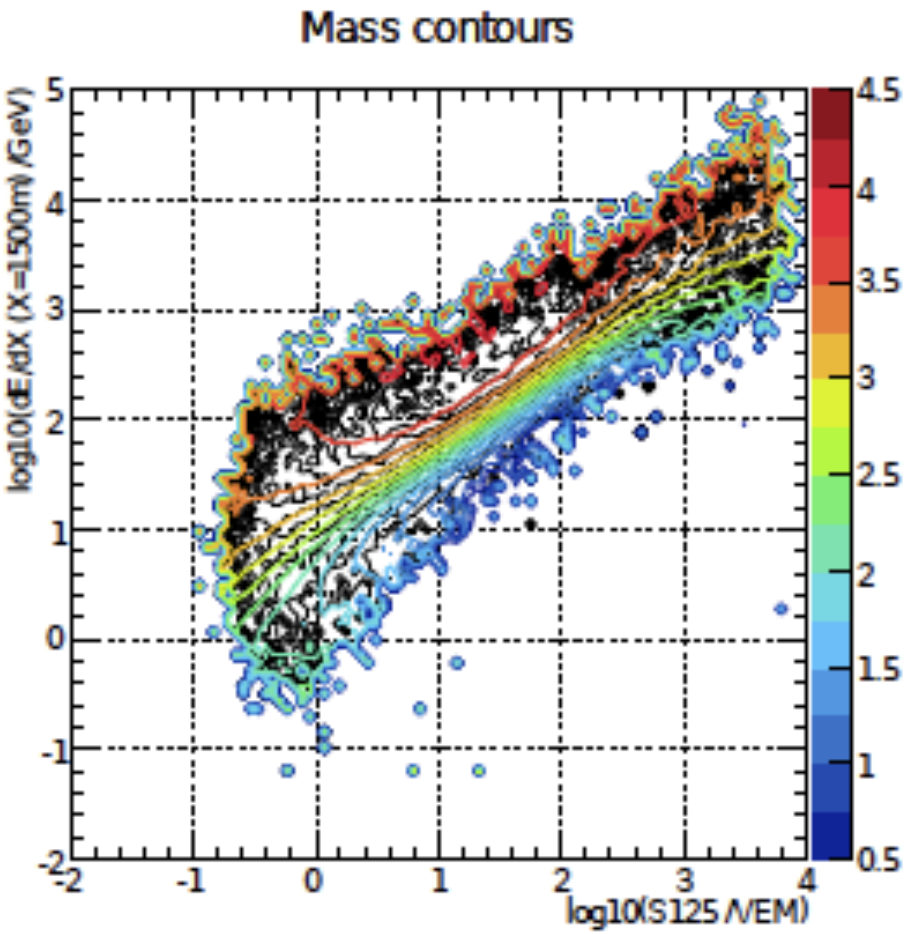
**Will IceCube see a transition from galactic to extra-galactic CRs?**

Gaisser, Stanev, Tilav, 2013
(See Stanev's talk)

# ADDING IN-ICE INFORMATION

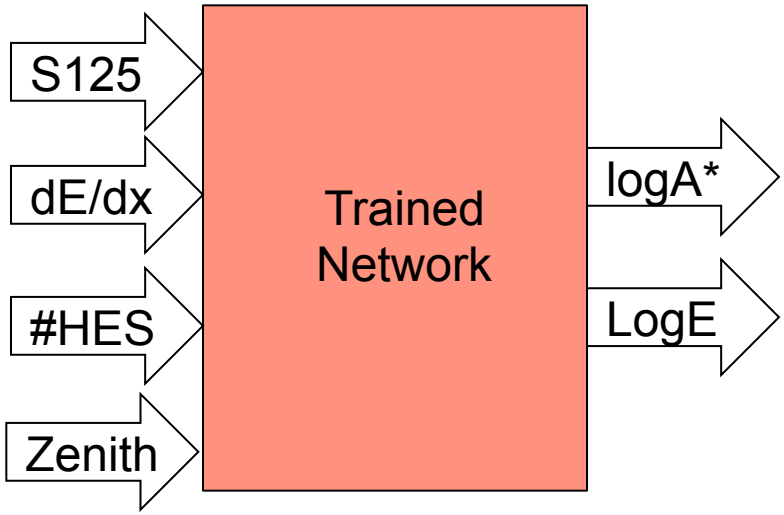
Larger S125:
Higher energy/Deeper Xmax
Larger dE/dx:
More muons/Heavier primary



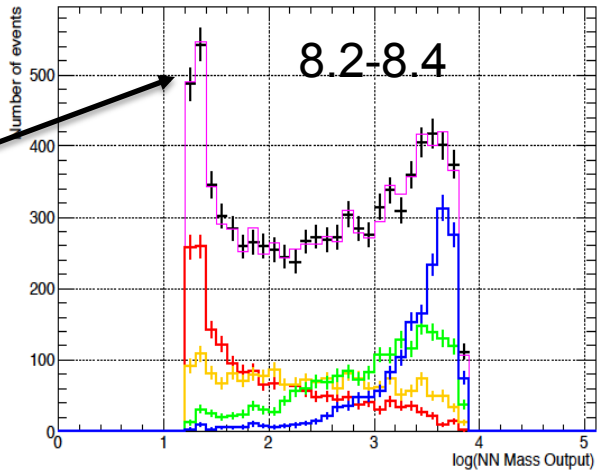



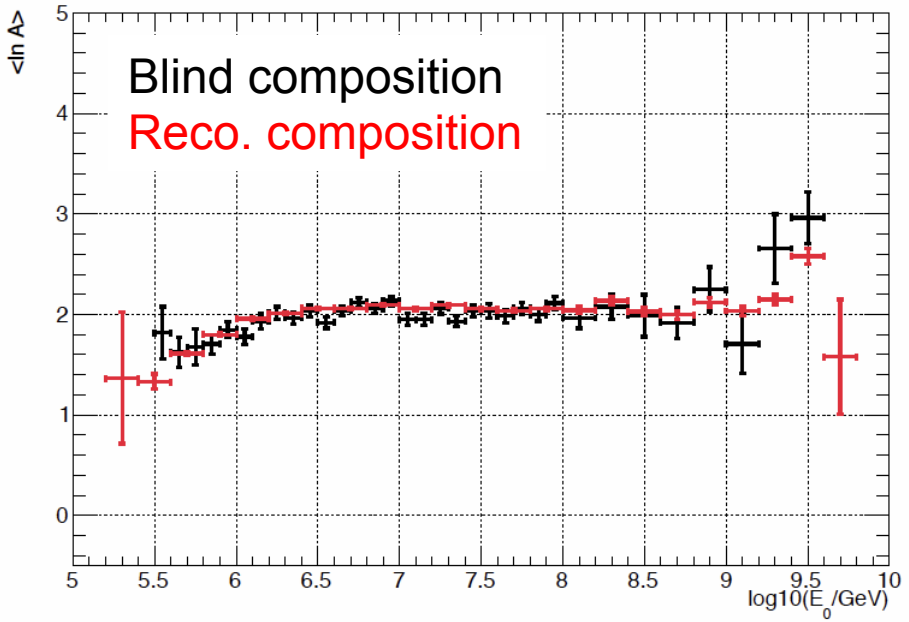
# COINCIDENT EVENT ANALYSIS (IT73/IC79)

## Neural Network Approach

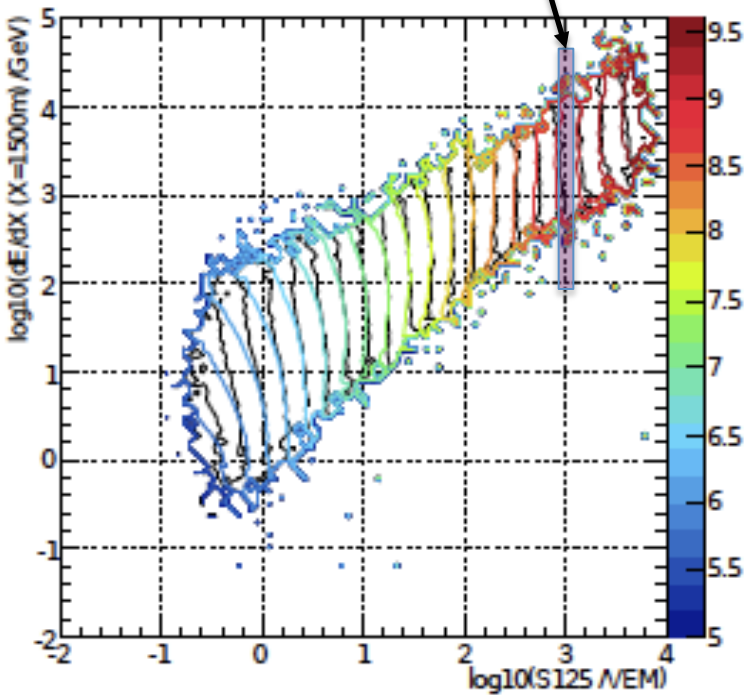



Template fitting




Energy contours



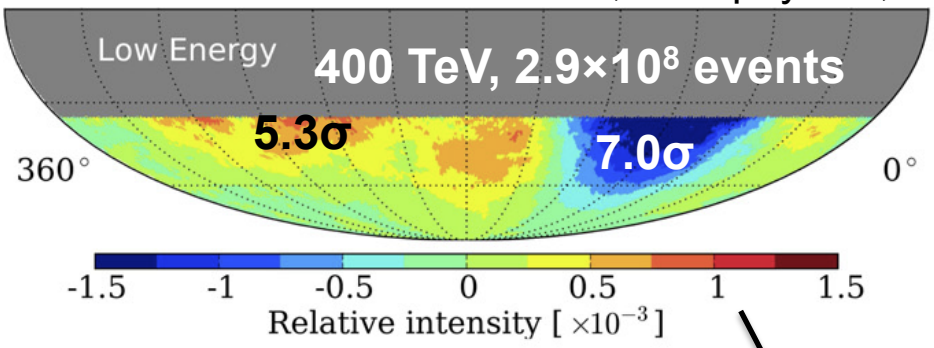
# COSMIC-RAY MASS COMPOSITION

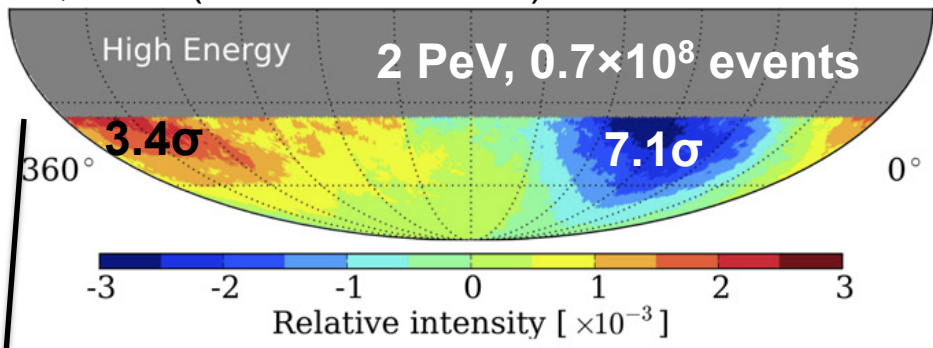
Results not formally approved in time to be shown here

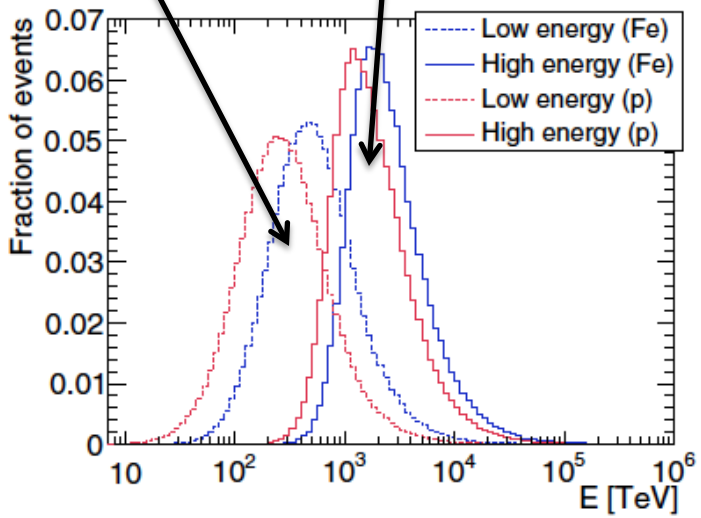
- We observe same trend observed with IC40 data up to 10**8 GeV
- Systematics studies on-going
- **We can discriminate different masses**
- **We can reach 1 EeV**
- Full year results will be available at ICRC

# ICETOP MEASUREMENT OF ANISOTROPY

IceCube Coll., Astrophys. J., 765, 55, 2013 (See Desiati's talk)



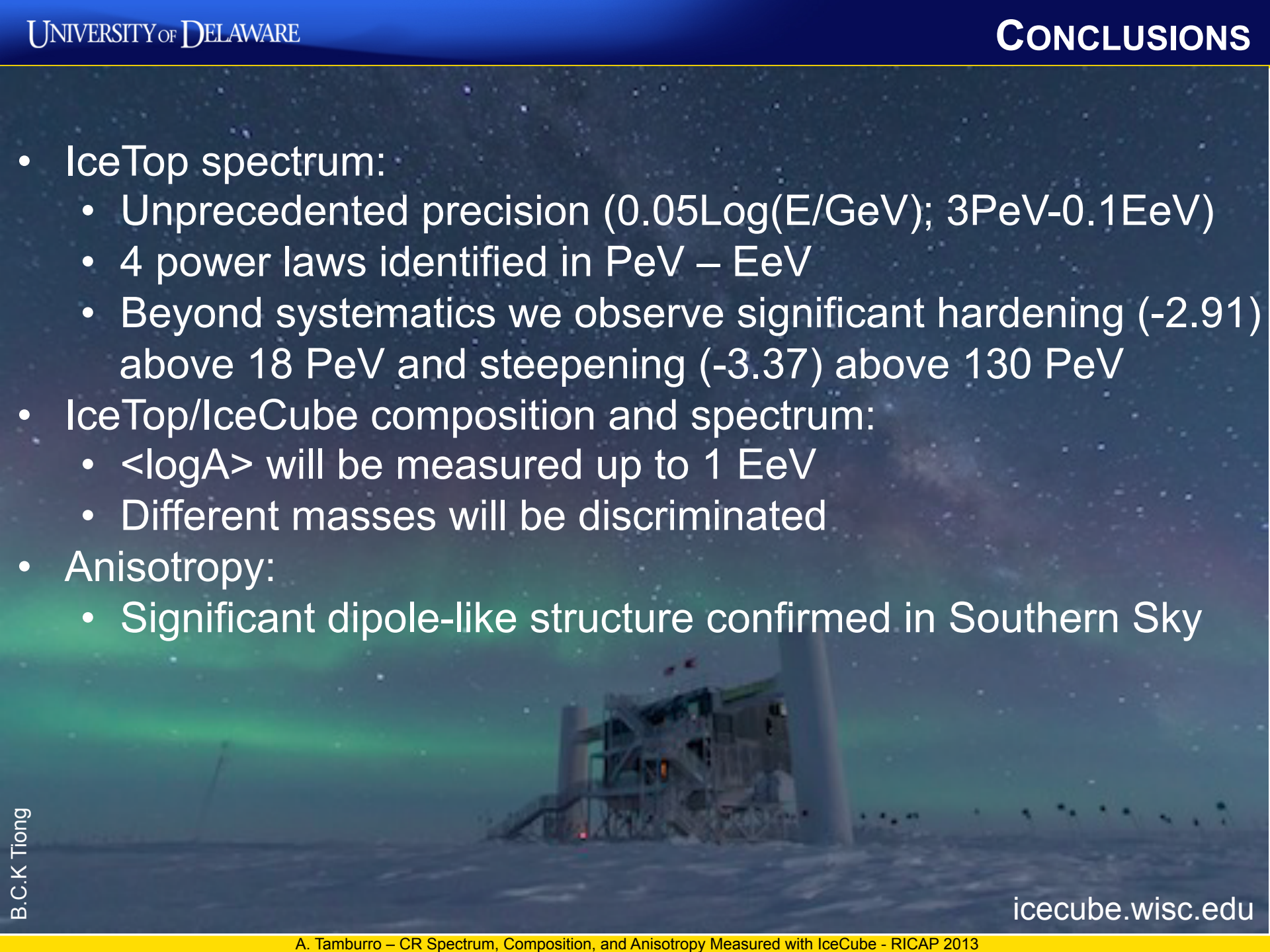




Smoothing 20deg

IceTop confirms a "dipole-like" large scale anisotropy, inconsistent with CG effect

# CONCLUSIONS

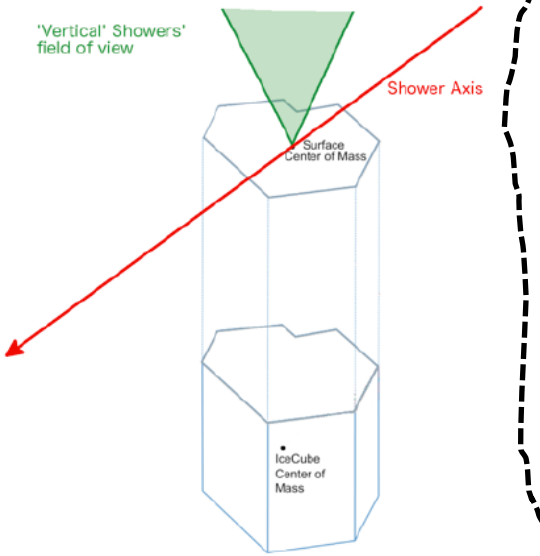
- IceTop spectrum:
  - Unprecedented precision (0.05Log(E/GeV); 3PeV-0.1EeV)
  - 4 power laws identified in PeV – EeV
  - Beyond systematics we observe significant hardening (-2.91) above 18 PeV and steepening (-3.37) above 130 PeV
- IceTop/IceCube composition and spectrum:
  - <logA> will be measured up to 1 EeV
  - Different masses will be discriminated
- Anisotropy:
  - Significant dipole-like structure confirmed in Southern Sky



B.C.K Tiong

icecube.wisc.edu

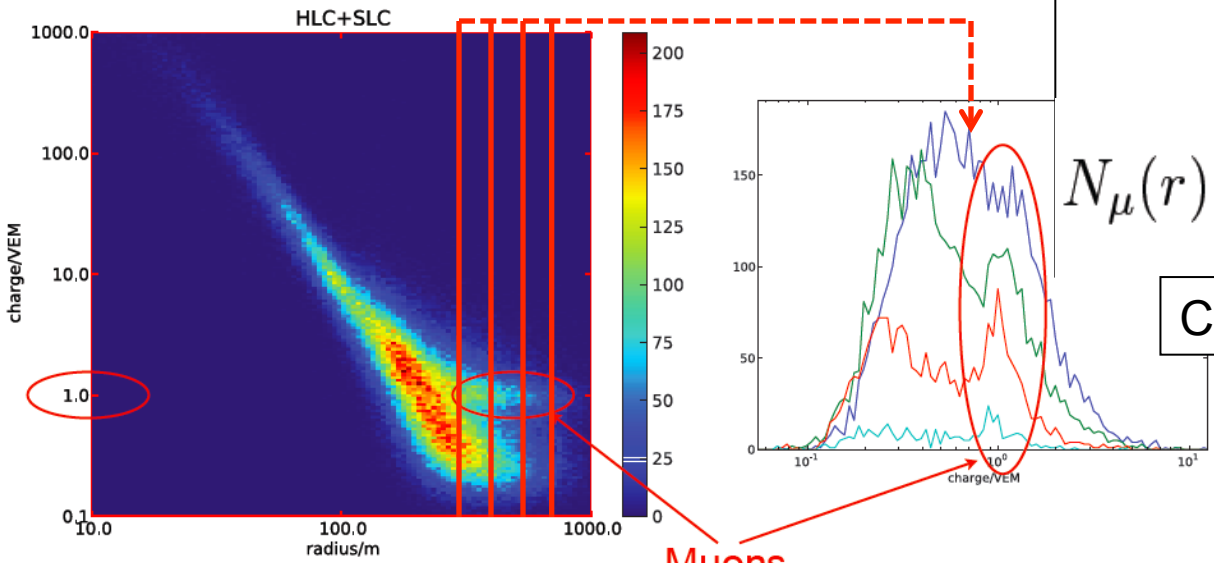
# COSMIC RAYS IN ICECUBE: AN OUTLOOK




On-axis
+100% exposure (<60°)


Off-axis (<60°)
poorer reco., SLC-dominated

Increase sensitivity to muon content of showers
Reach out for GC

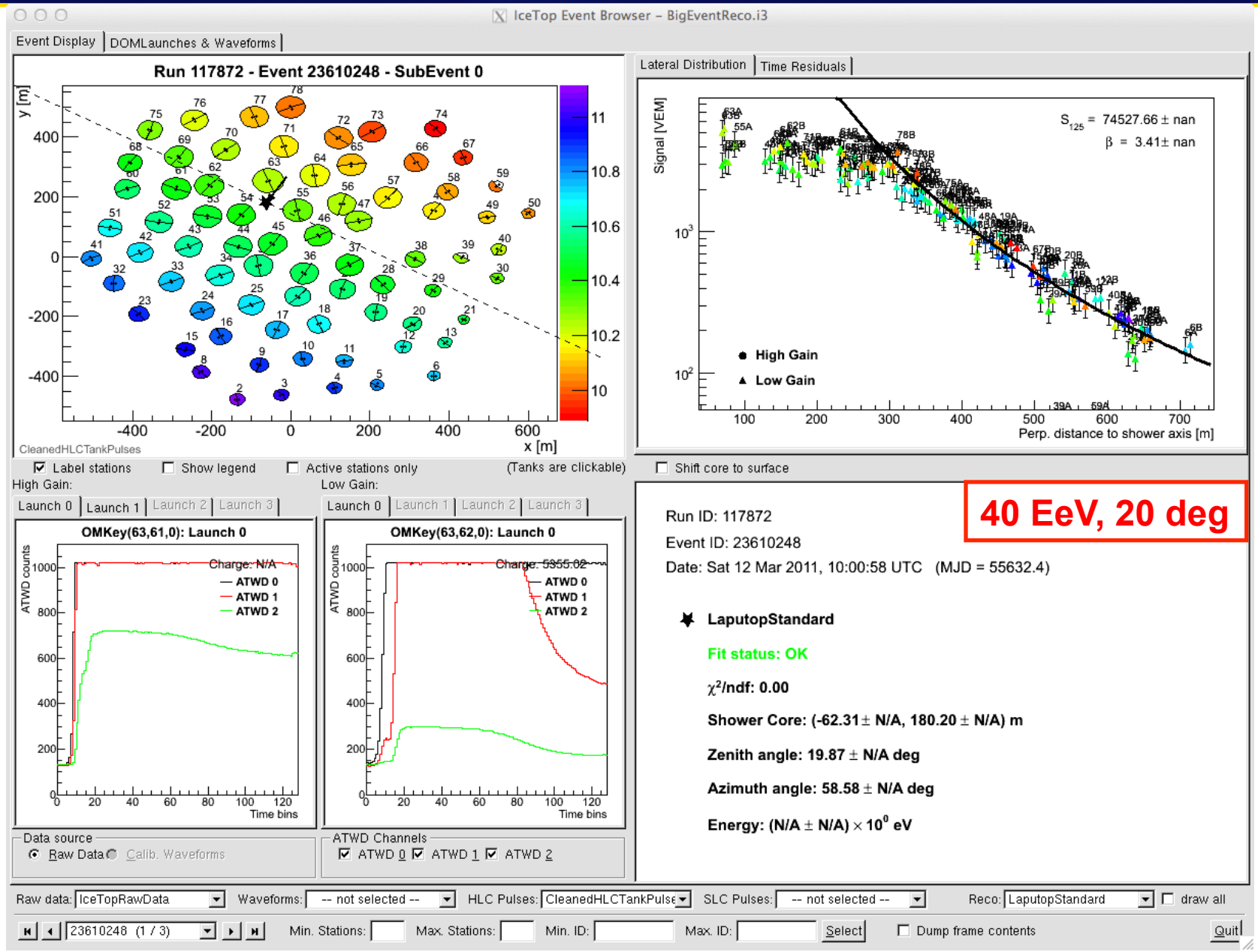



Muon LDF

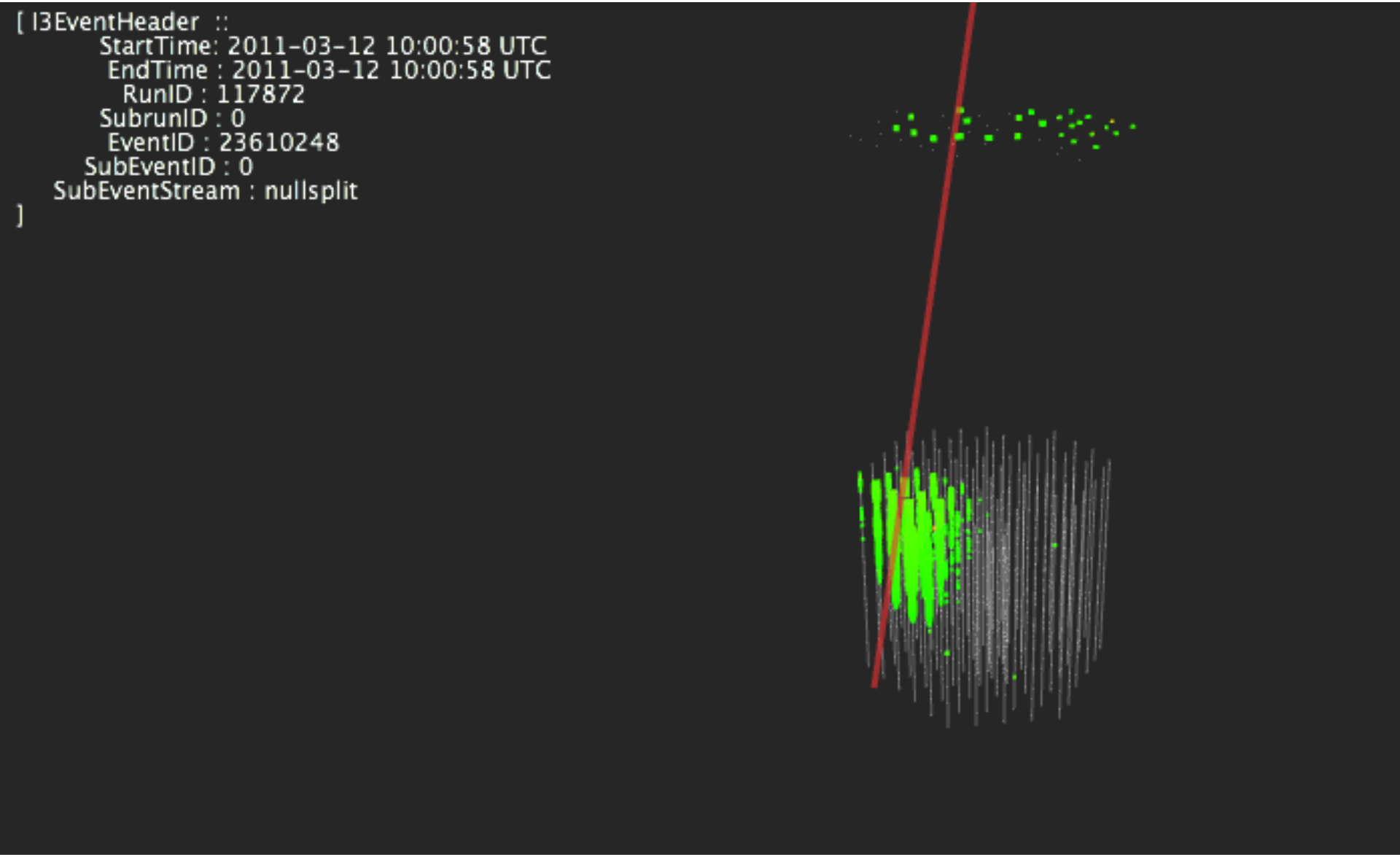
$$N_\mu(r) = A\, r^{-0.75} \left(1 + \frac{r}{320\text{m}}\right)^{-\gamma}$$

Compare with Greisen prediction

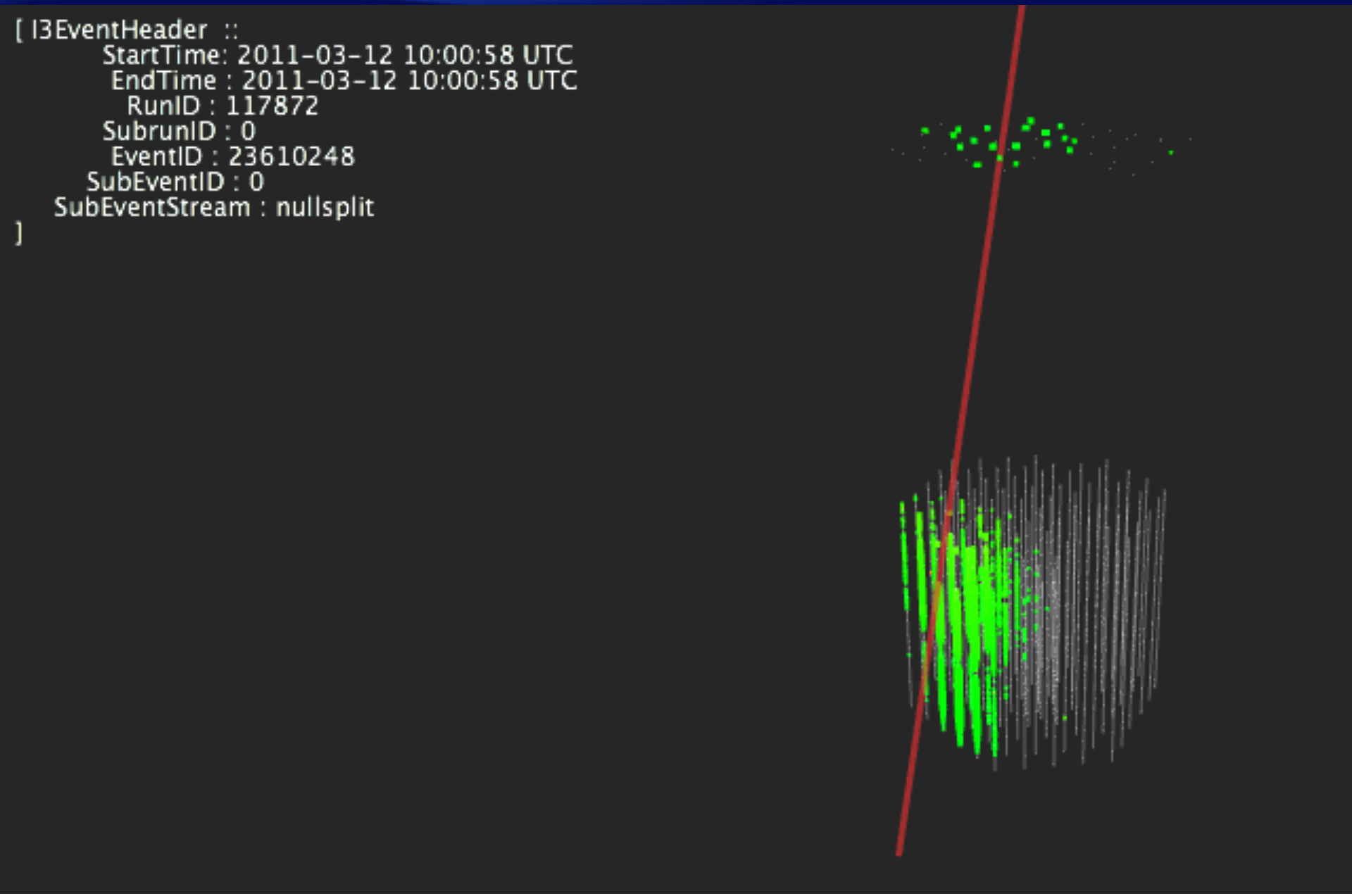
# AN EEV EVENT


IceTop Event Browser – BigEventReco.i3
Event Display
DOMLaunches & Waveforms
Run 117872 - Event 23610248 - SubEvent 0
y [m]
x [m]
CleanedHLCTankPulses
Label stations
Show legend
Active stations only
(Tanks are clickable)
Lateral Distribution
Time Residuals
Signal [VEM]
$S_{125}$ = 74527.66 ± nan
β = 3.41± nan
High Gain
Low Gain
Perp. distance to shower axis [m]
Shift core to surface
High Gain:
Low Gain:
Launch 0
Launch 1
Launch 2
Launch 3
OMKey(63,61,0): Launch 0
OMKey(63,62,0): Launch 0
ATWD counts
Time bins
Charge: N/A
Charge: 5355.02
ATWD 0
ATWD 1
ATWD 2
Data source
Raw Data
Calib. Waveforms
ATWD Channels
ATWD 0
ATWD 1
ATWD 2
40 EeV, 20 deg
Run ID: 117872
Event ID: 23610248
Date: Sat 12 Mar 2011, 10:00:58 UTC (MJD = 55632.4)
LaputopStandard
Fit status: OK
χ²/ndf: 0.00
Shower Core: (-62.31± N/A, 180.20 ± N/A) m
Zenith angle: 19.87 ± N/A deg
Azimuth angle: 58.58 ± N/A deg
Energy: (N/A ± N/A) × 10⁰ eV
Raw data: IceTopRawData
Waveforms: -- not selected --
HLC Pulses: CleanedHLCTankPulse
SLC Pulses: -- not selected --
Reco: LaputopStandard
draw all
23610248 (1 / 3)
Min. Stations:
Max. Stations:
Min. ID:
Max. ID:
Select
Dump frame contents
Quit

# AN EEV EVENT


[ I3EventHeader ::
StartTime: 2011-03-12 10:00:58 UTC
EndTime : 2011-03-12 10:00:58 UTC
RunID : 117872
SubrunID : 0
EventID : 23610248
SubEventID : 0
SubEventStream : nullsplit
]

# AN EEV EVENT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