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

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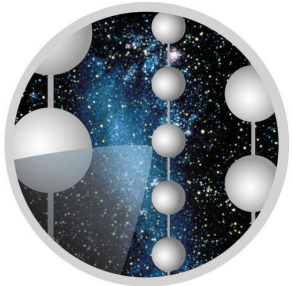
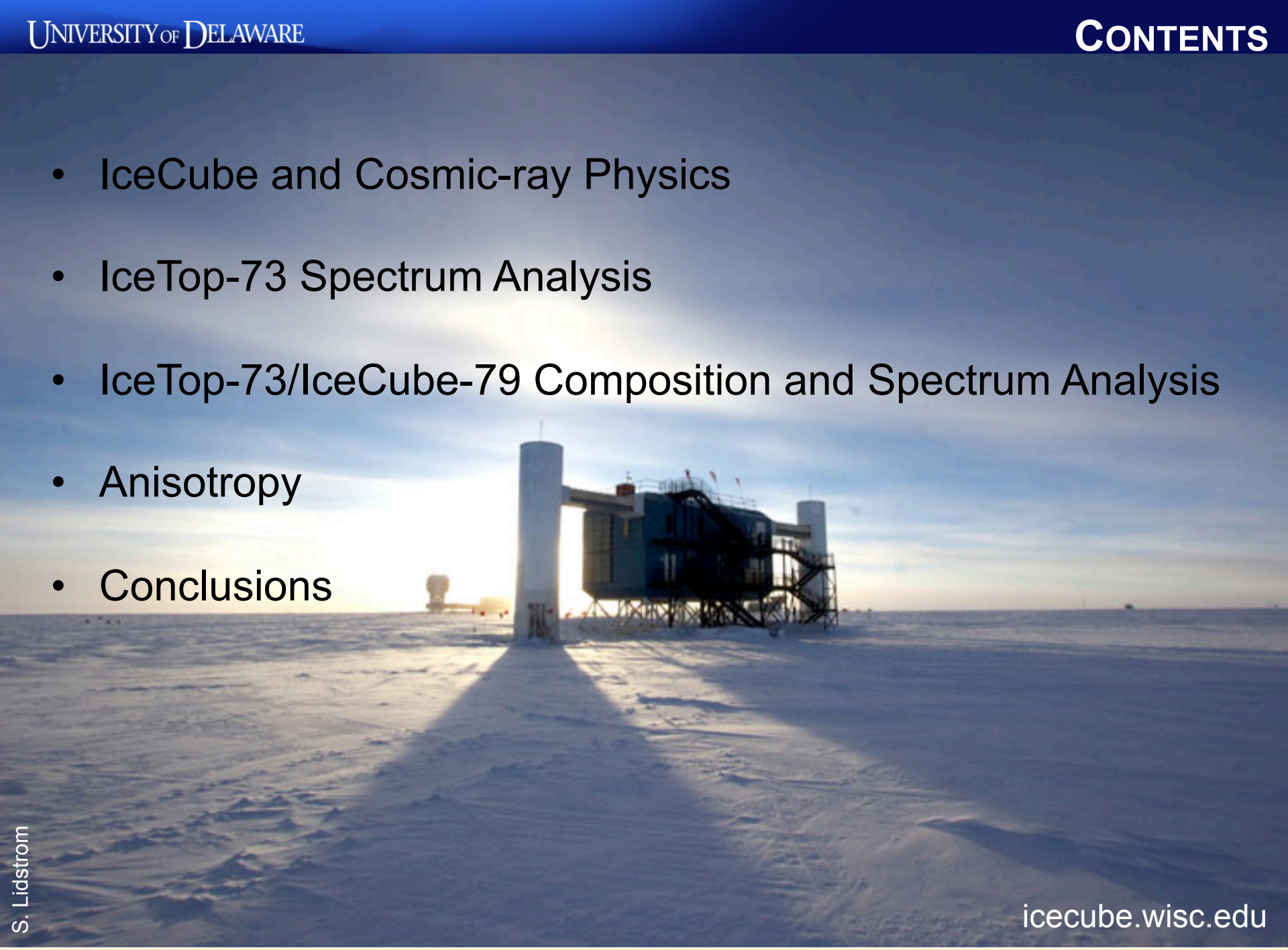


RICAP 2013, Rome – May 22, 2013

CONTENTS

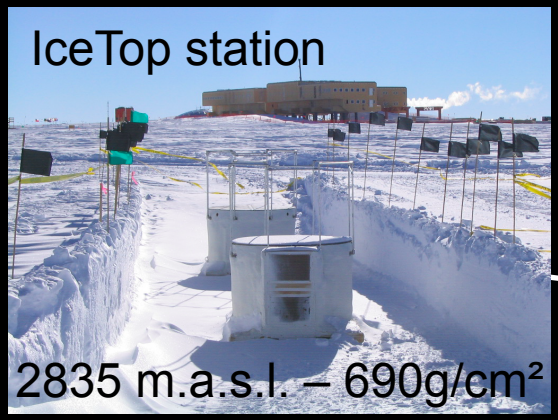
- IceCube and Cosmic-ray Physics
- IceTop-73 Spectrum Analysis
- IceTop-73/IceCube-79 Composition and Spectrum Analysis
- Anisotropy
- Conclusions



S. Lidstrom

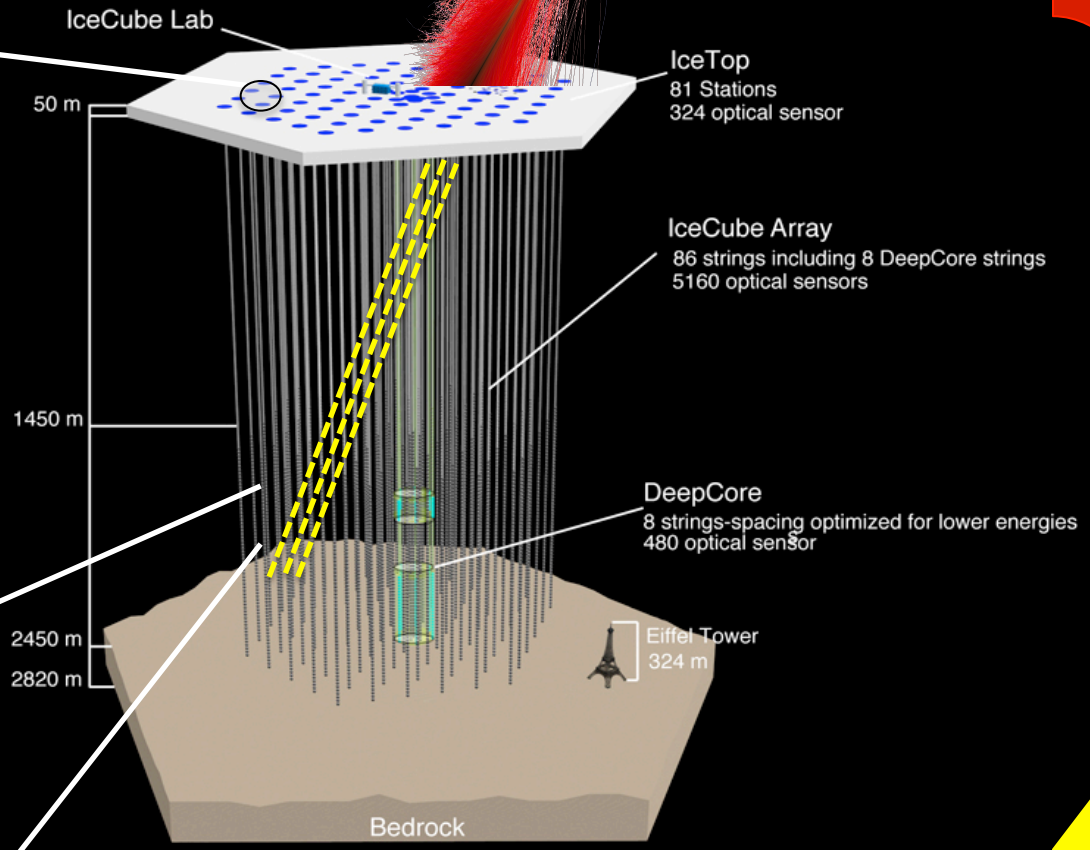
icecube.wisc.edu

ICECUBE AND COSMIC RAYS



Close to shower max

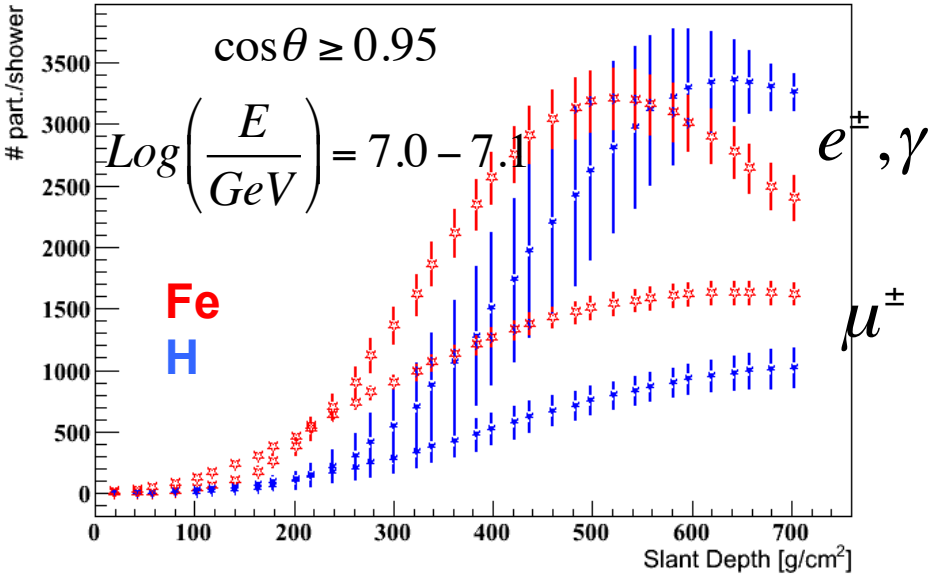
@ E~3×10^{16} eV or 30 PeV:
Over 2,000 events/yr
(Max E ~ 3 EeV due to km^2 size)

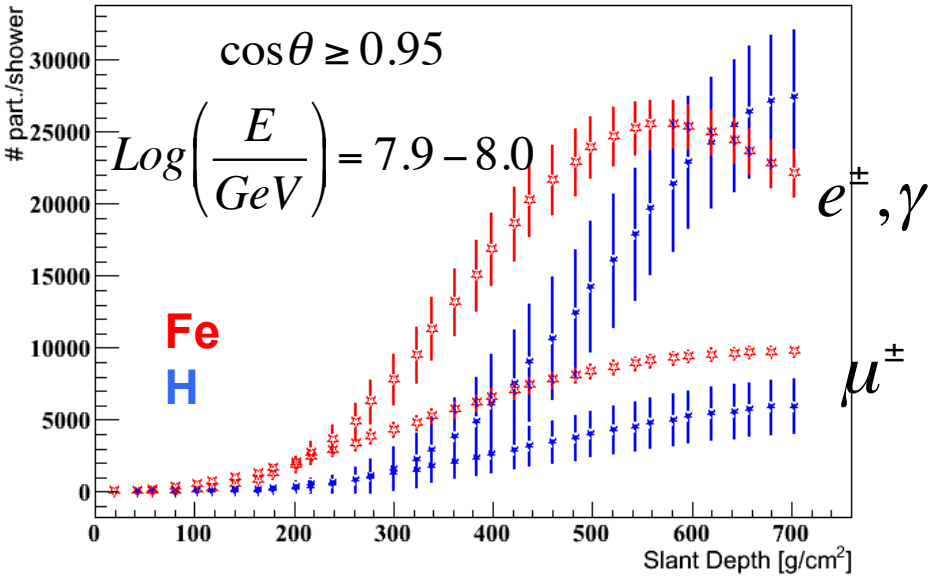


650 coinc. muon bundles/yr
(Max E ~ EeV)

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)

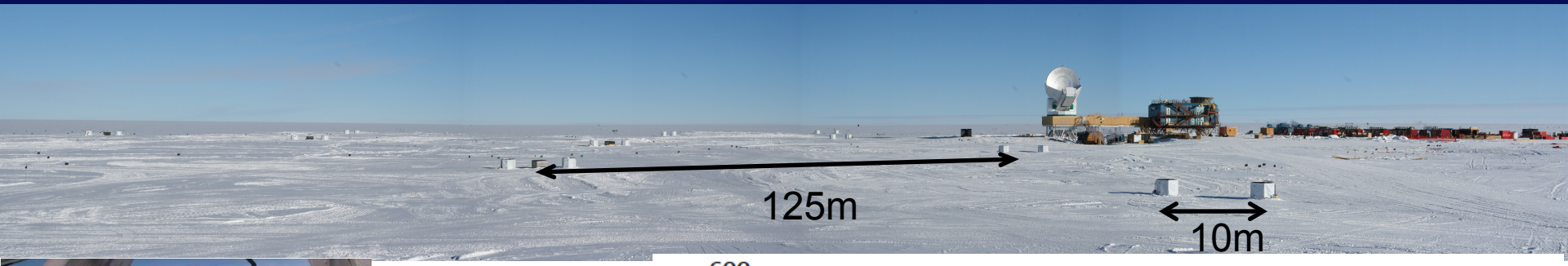
CR composition (PeV – EeV):

- 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):

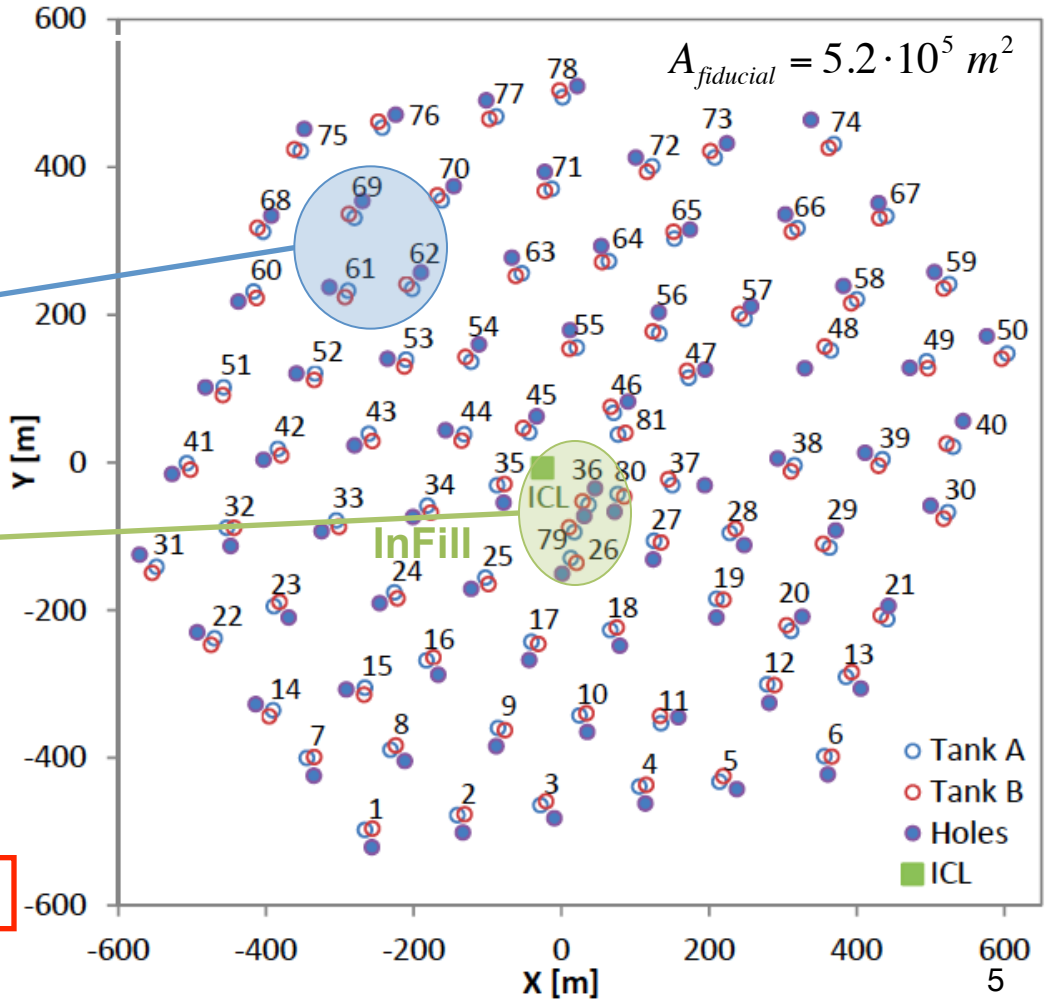
- Large statistics 10^{11} muons/yr –10^{8} showers/yr
- Angular resolution better than 10^{o}

THE ICETOP ARRAY



~300 TeV showers

~100 TeV showers



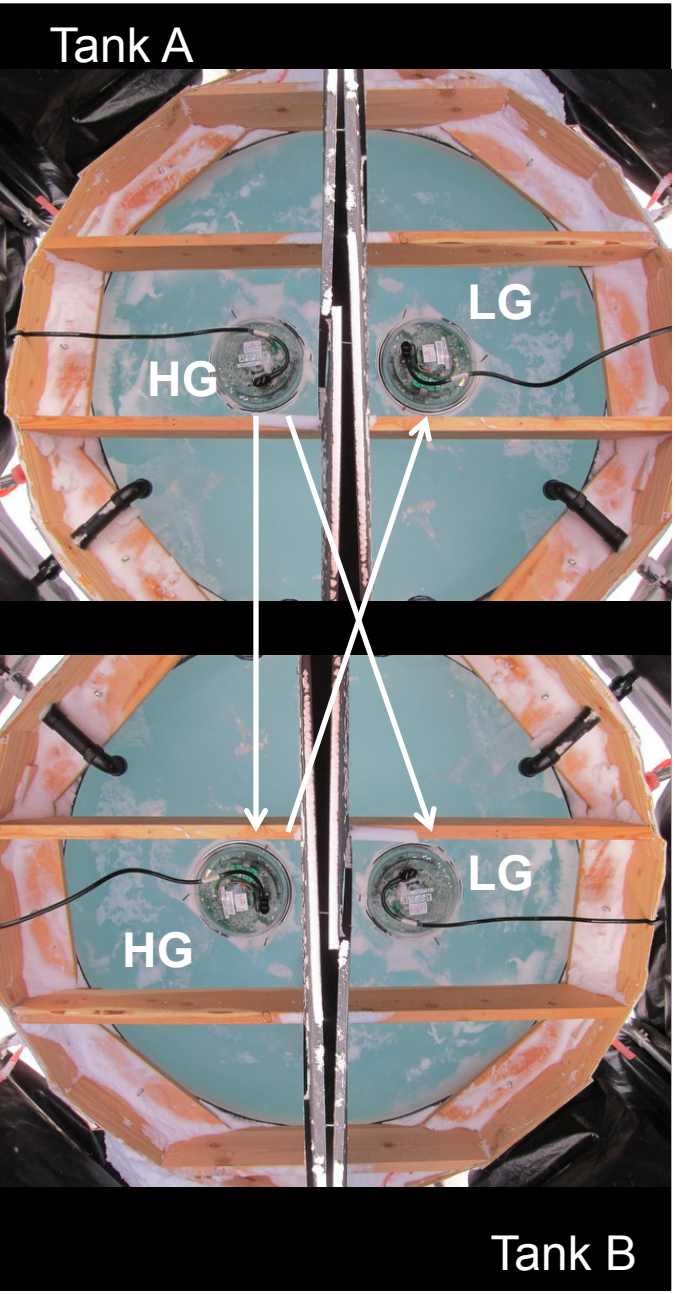
5+ stations
$E \sim PeV - EeV$

Current results

3+ stations
$E > 100\ TeV$

Work in progress

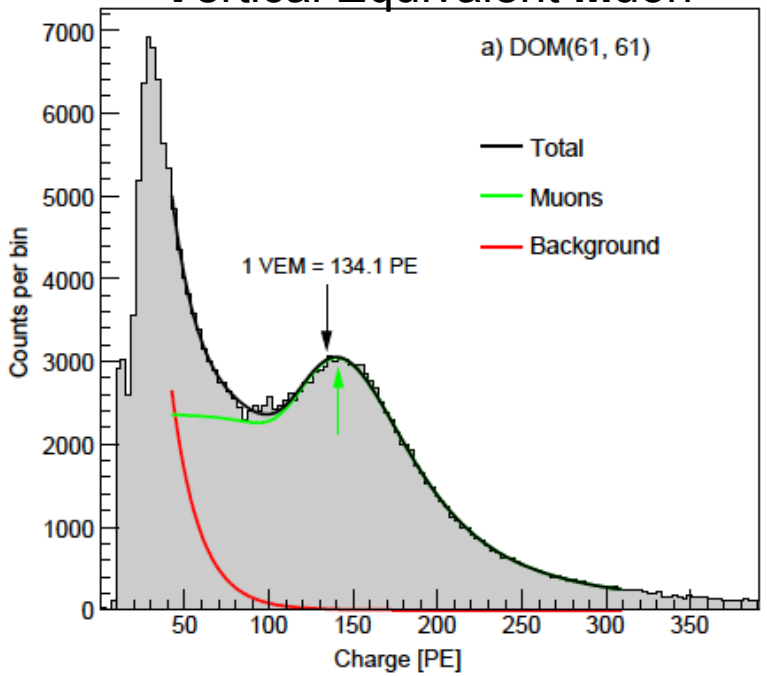
ICETOP ARRAY: OPERATIONS



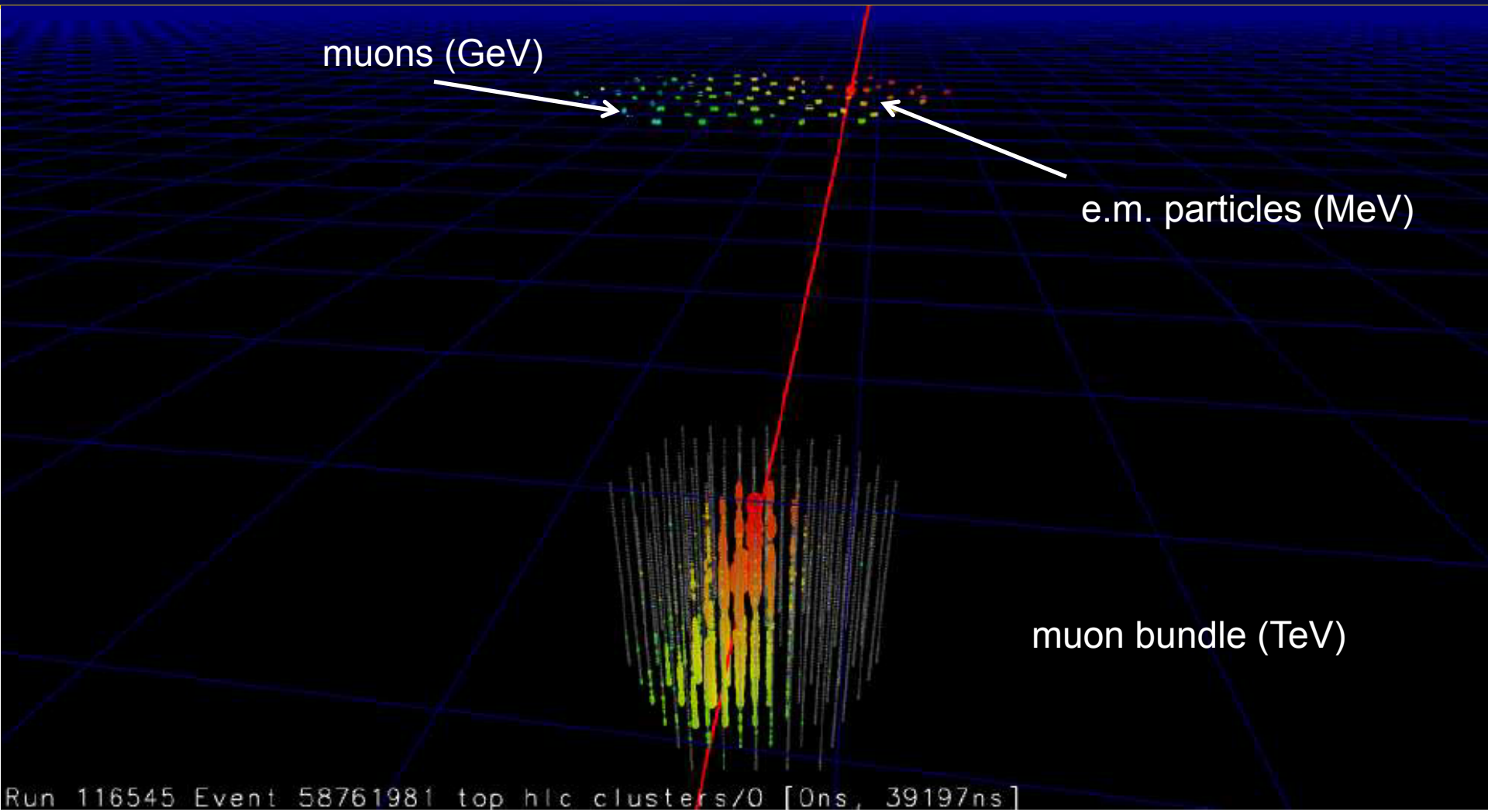
Single hits (1 DOM) or SLC
(muon detection + veto of air showers for in-ice studies)
(**2,000 Hz**)

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

Vertical **E**quivalent **M**uon



COSMIC-RAY COINCIDENT EVENT: AN EXAMPLE



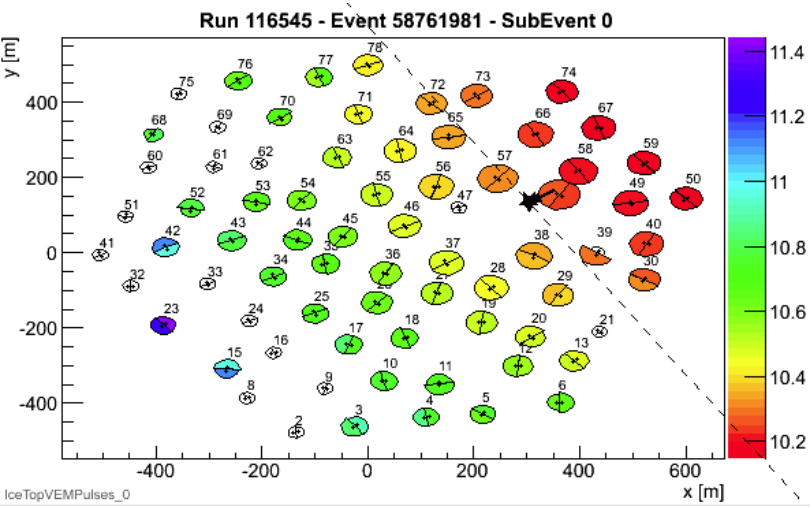
Coincident events:

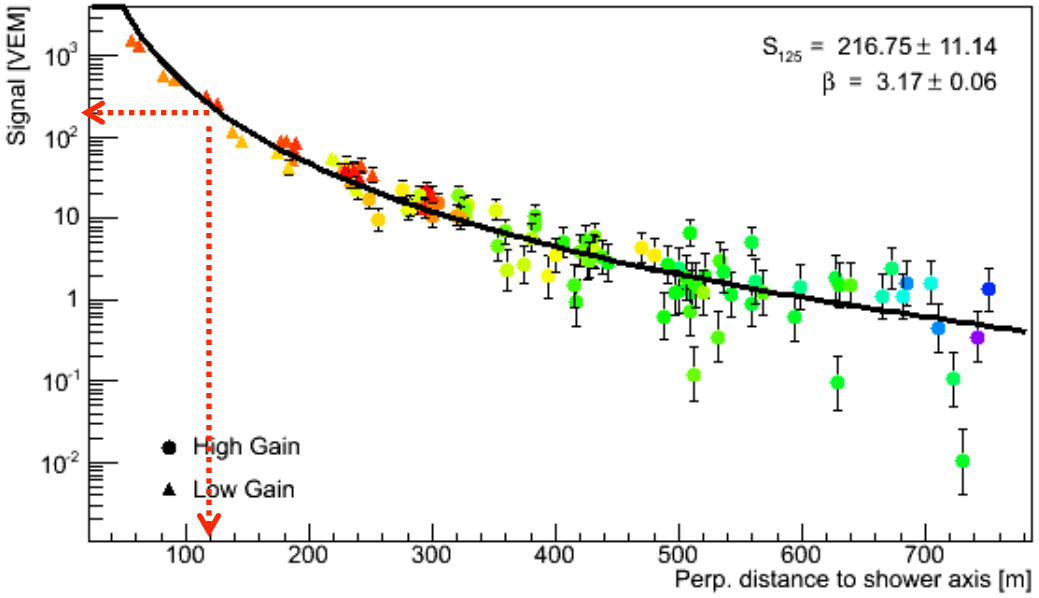
- Shower core contained within IceTop array
- Muon bundle track through in-ice array

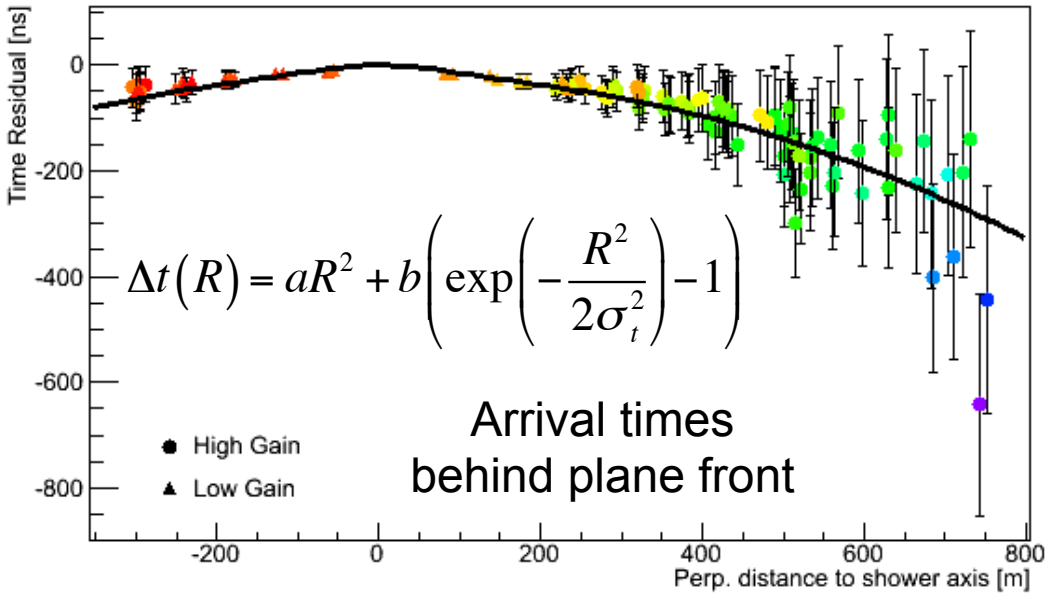
ICETOP SHOWER RECONSTRUCTION

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

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







Arrival times behind plane front

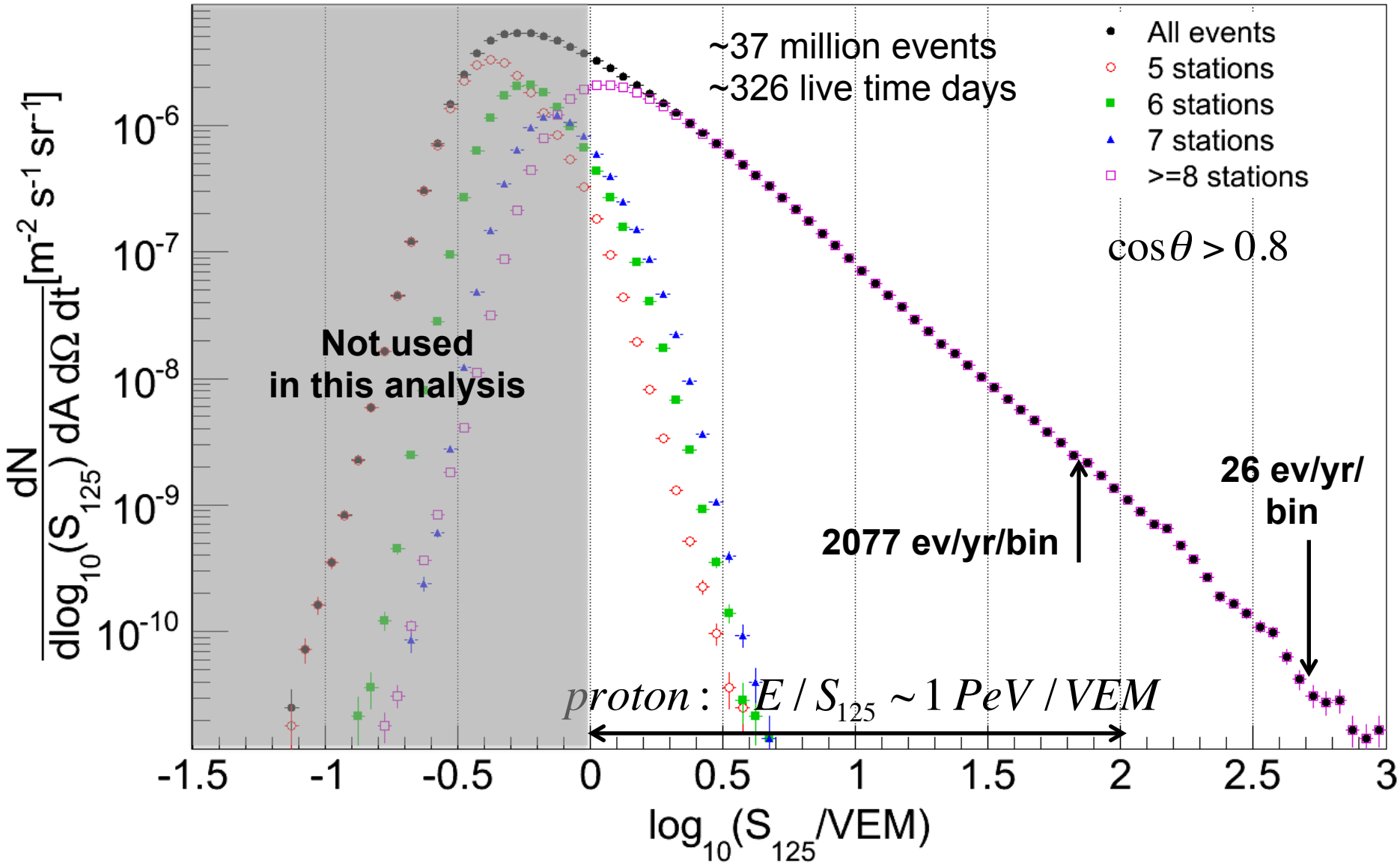
$$S(R) = S_{125}\left(\frac{R}{125m}\right)^{-\beta-\kappa\log(R/125m)}$$

S_{125} "Shower size" at 125m

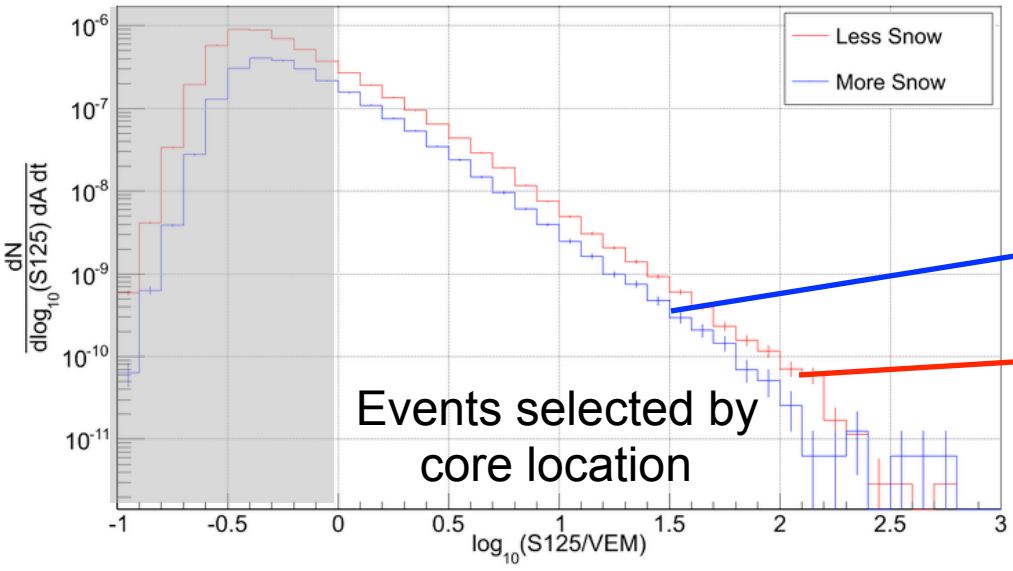
β Slope at 125m

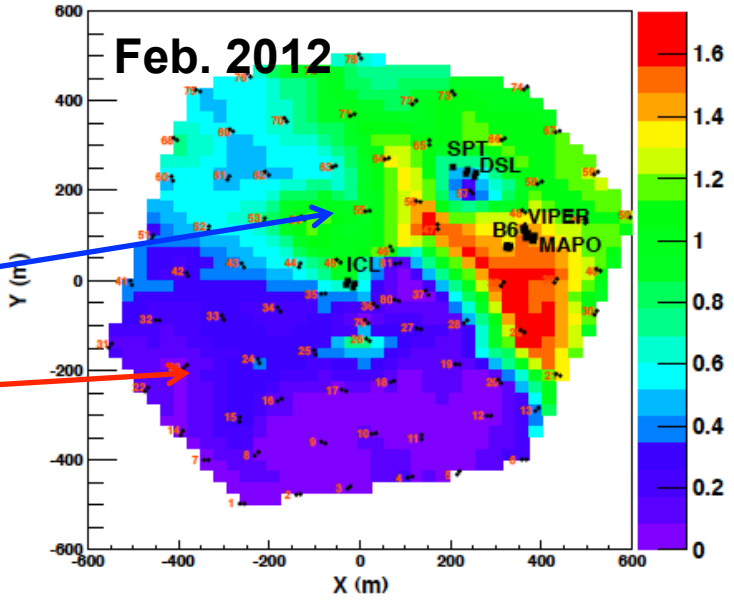
Tank signals are mostly from shower e.m. component.

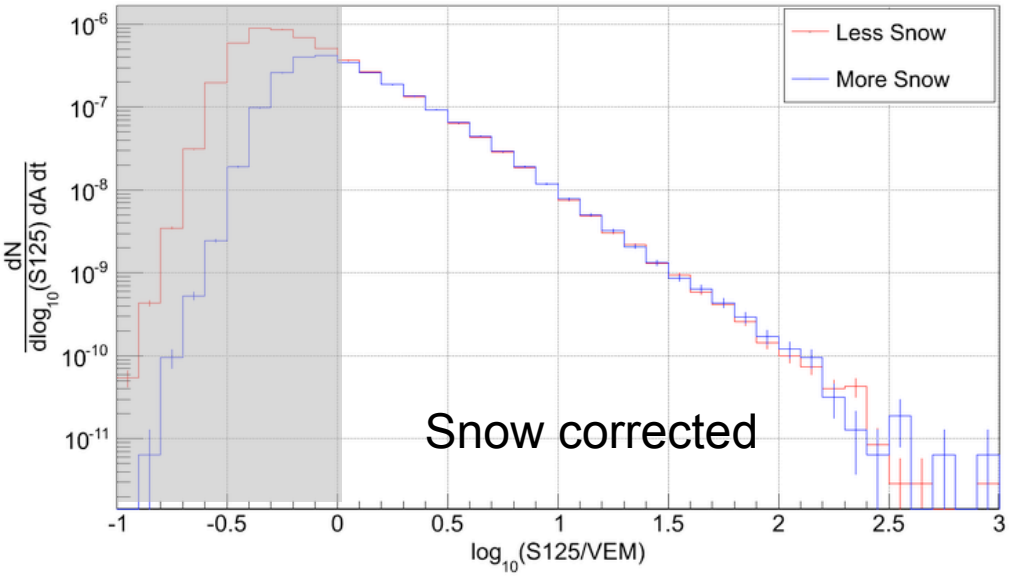
MEASURED ICETOP SHOWER SIZE (IT73)



SNOW BUILD-UP SYSTEMATICS



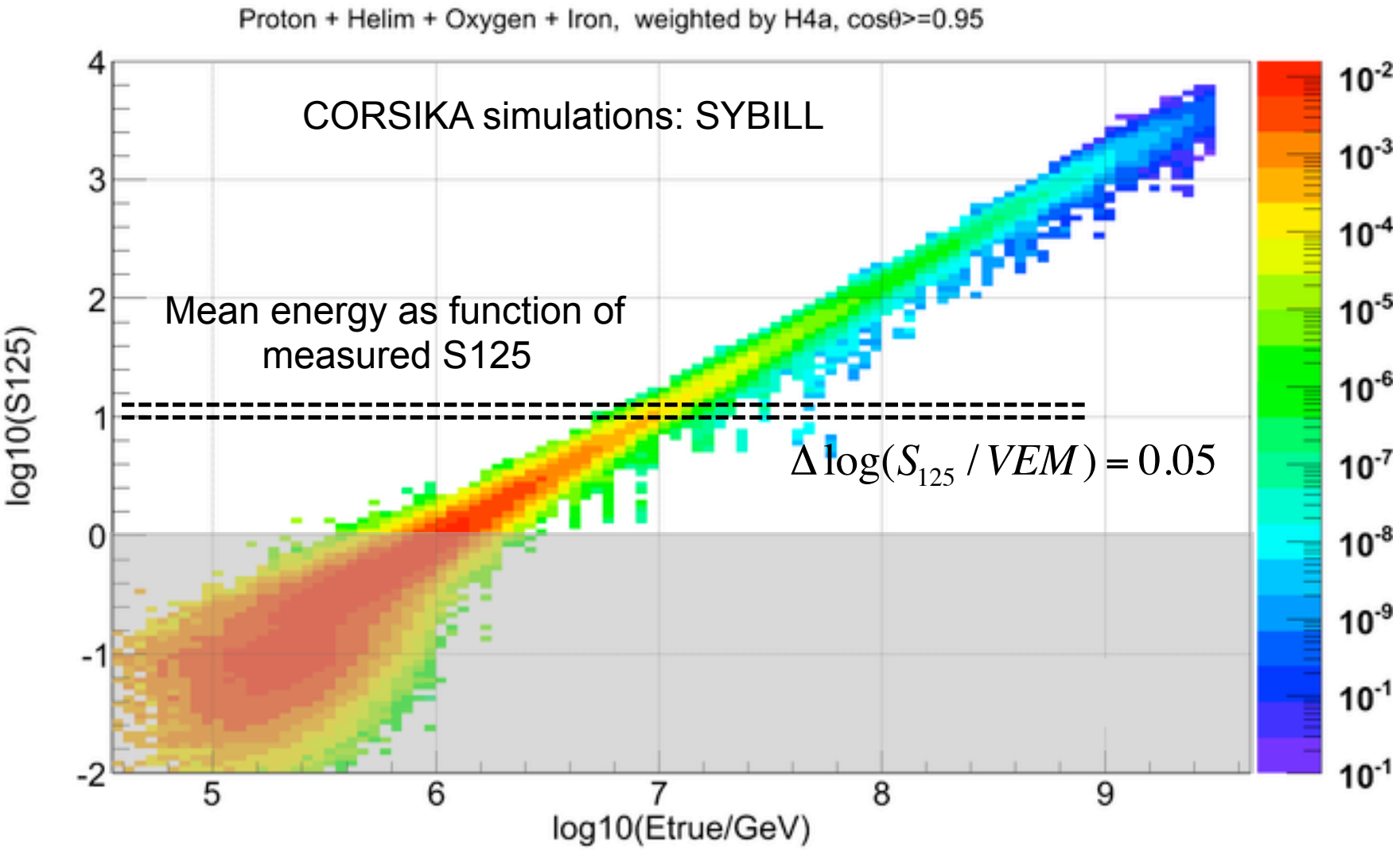




$$S_{corr} = S_{meas.} e^{\frac{z\cos\theta}{\lambda}}$$

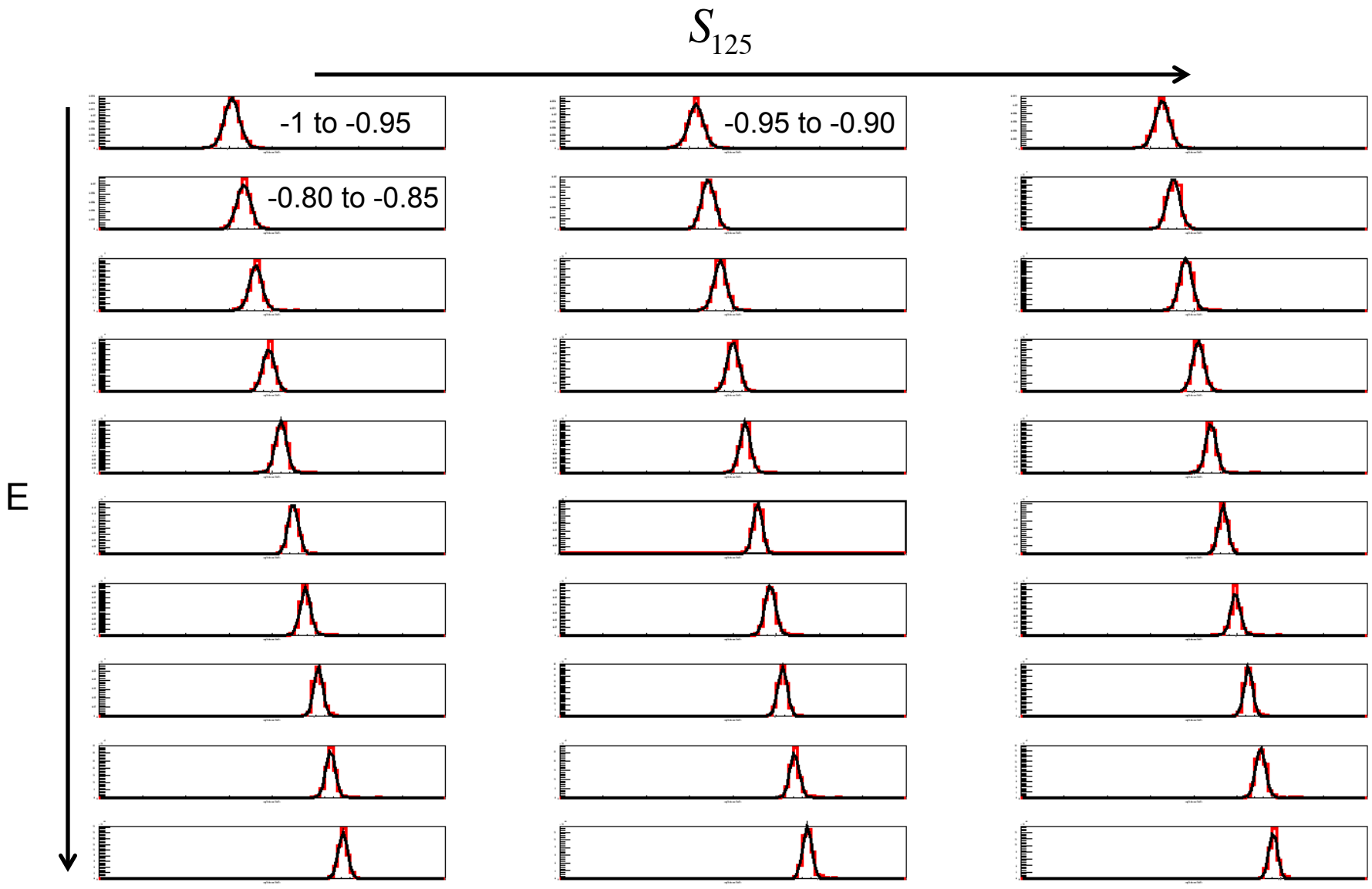
FROM MEASURED S125 TO ESTIMATED $E_{PRIMARY}$

Need to assume reasonable composition to derive energy spectrum

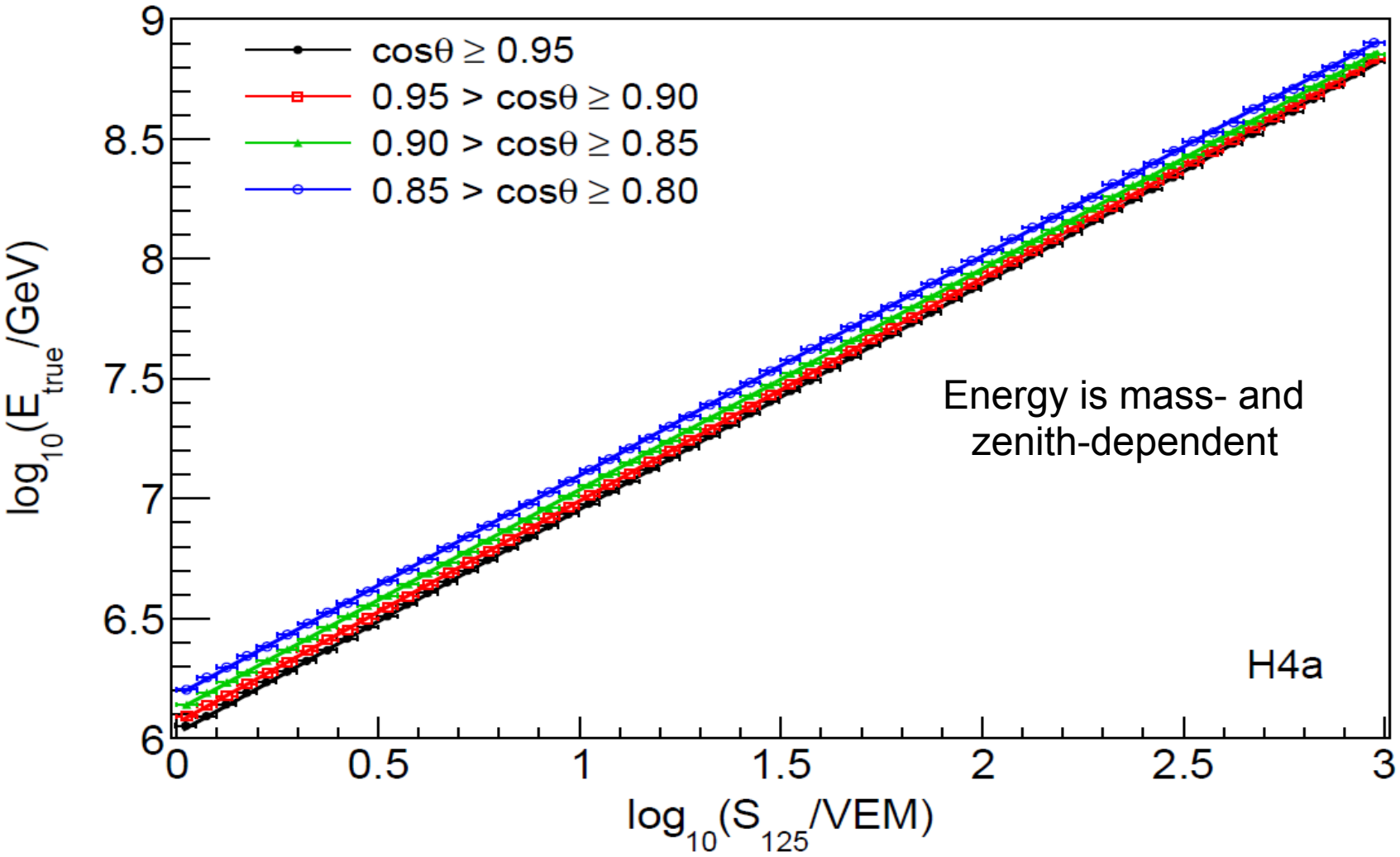


H4a: Gaisser, Astropart. Phys. 35 (2012) 801

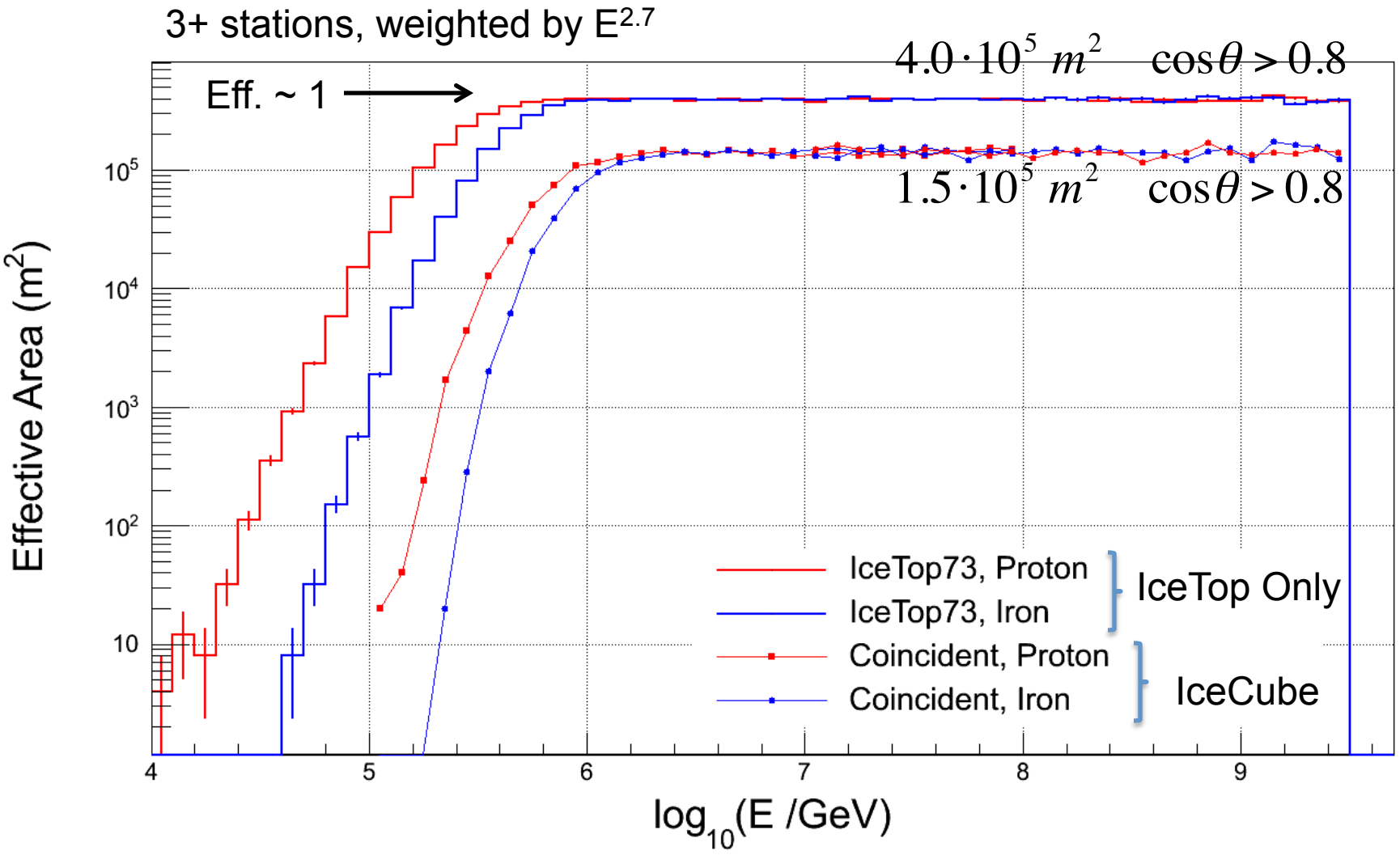
ENERGY ESTIMATOR: <$E_{PRIMARY}$> FOR GIVEN S125



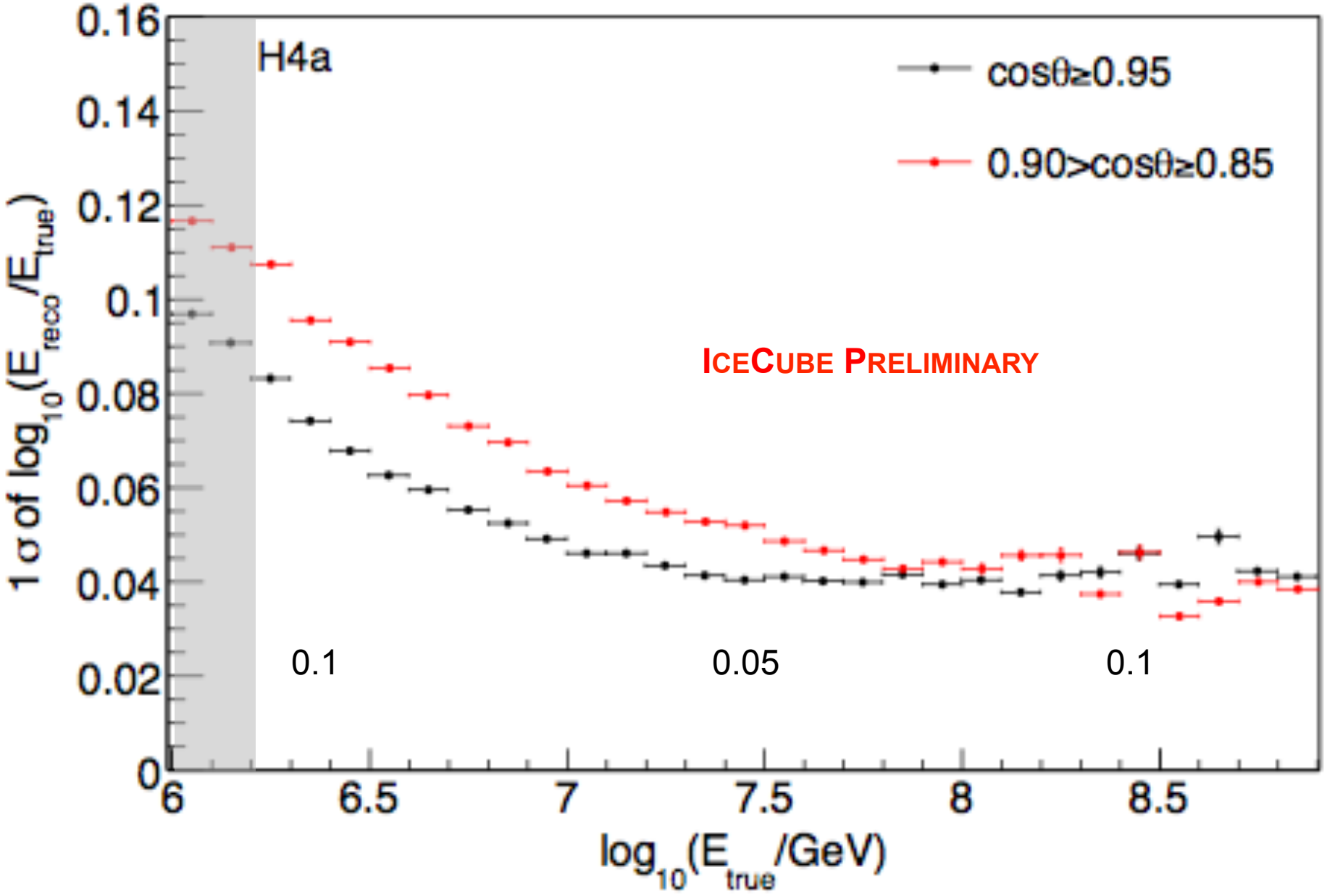
S125 → $E_{PRIMARY}$ RELATIONSHIP



EFFECTIVE AREA (IT73/IC79)

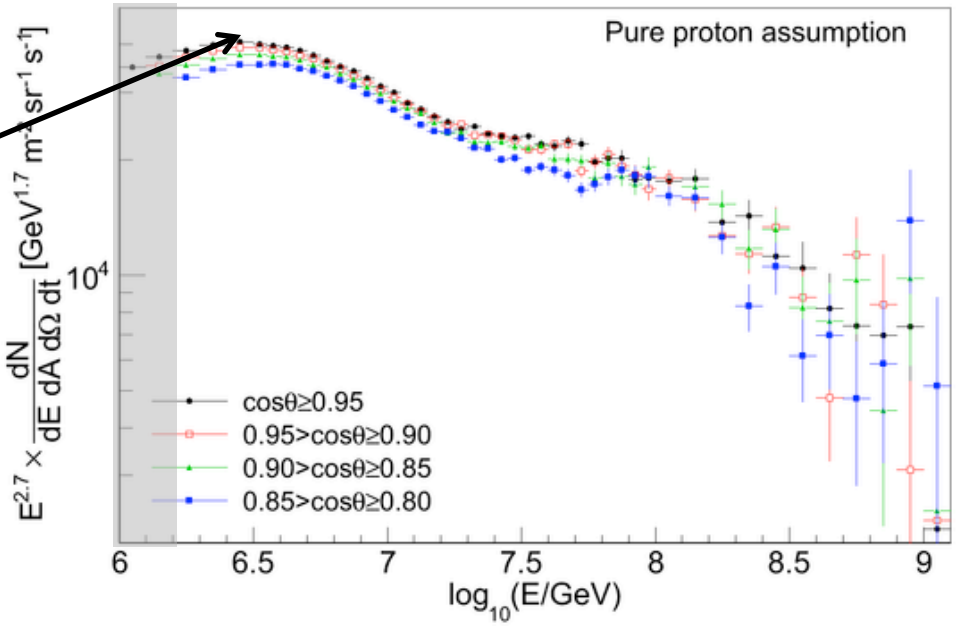


ENERGY RESOLUTION

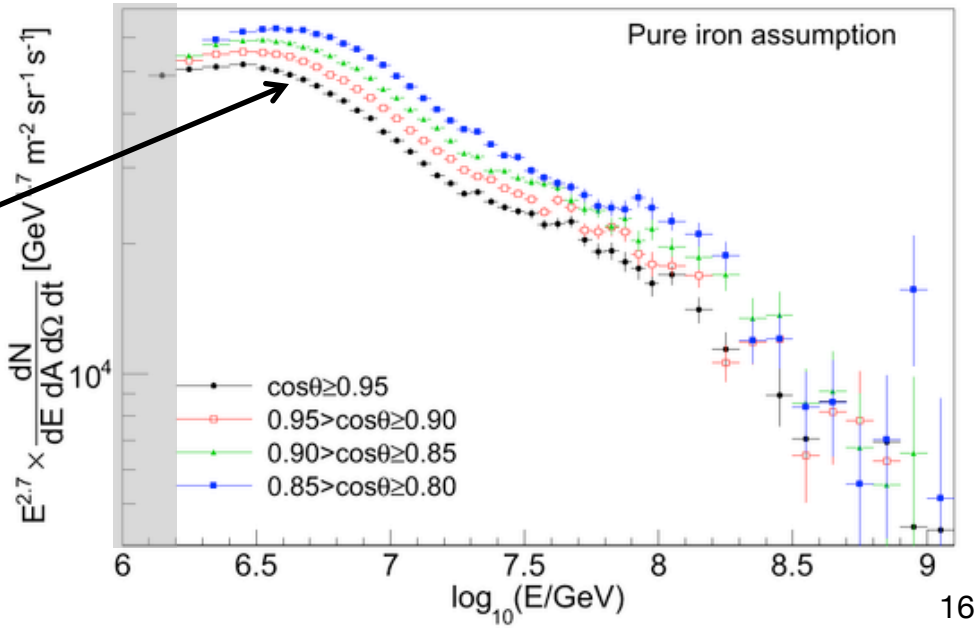


FLUX FOR 2 EXTREME ASSUMPTIONS

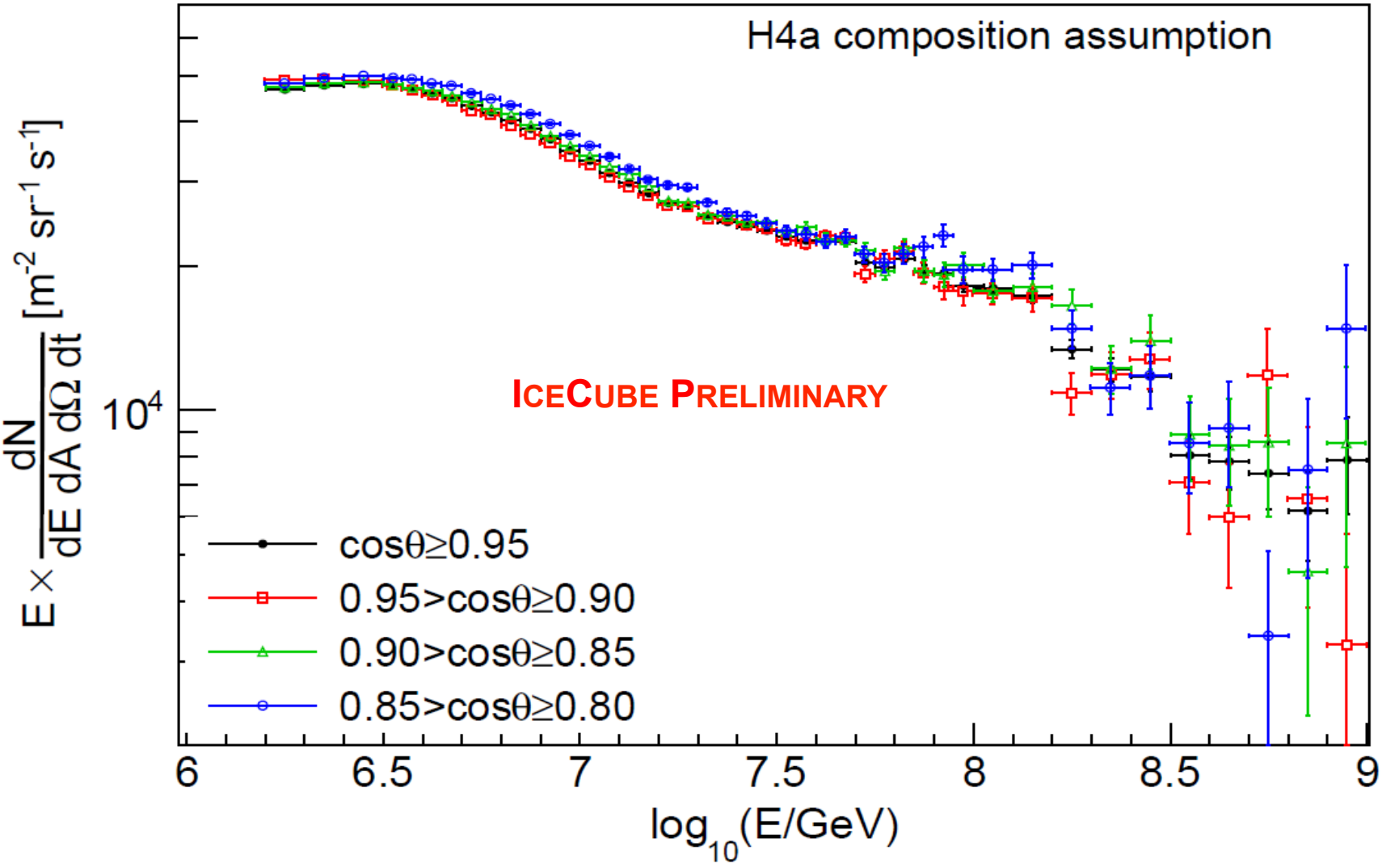
Inferred proton flux is **higher** near the vertical



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

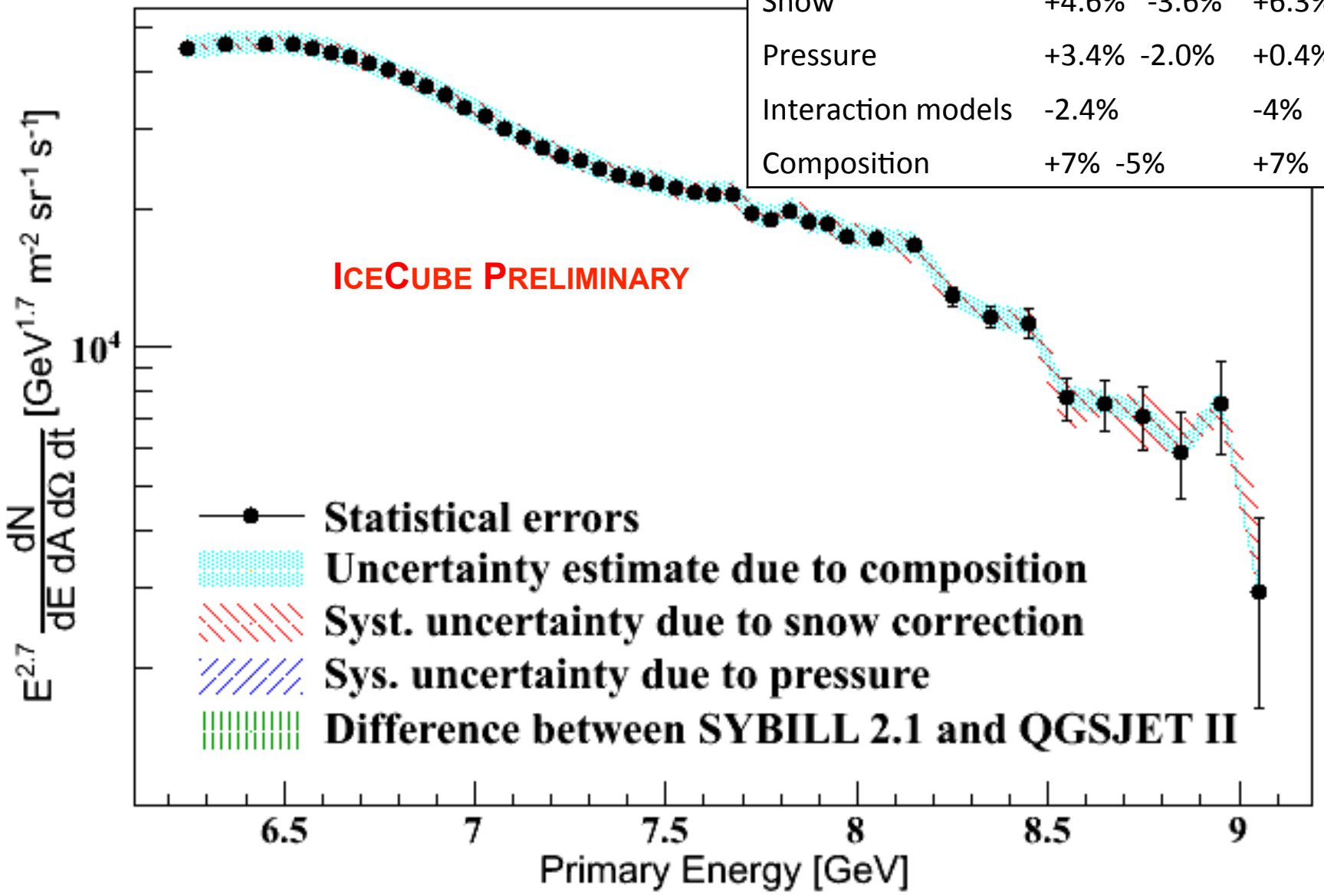


COSMIC-RAY SPECTRUM WITH H4A ASSUMPTION



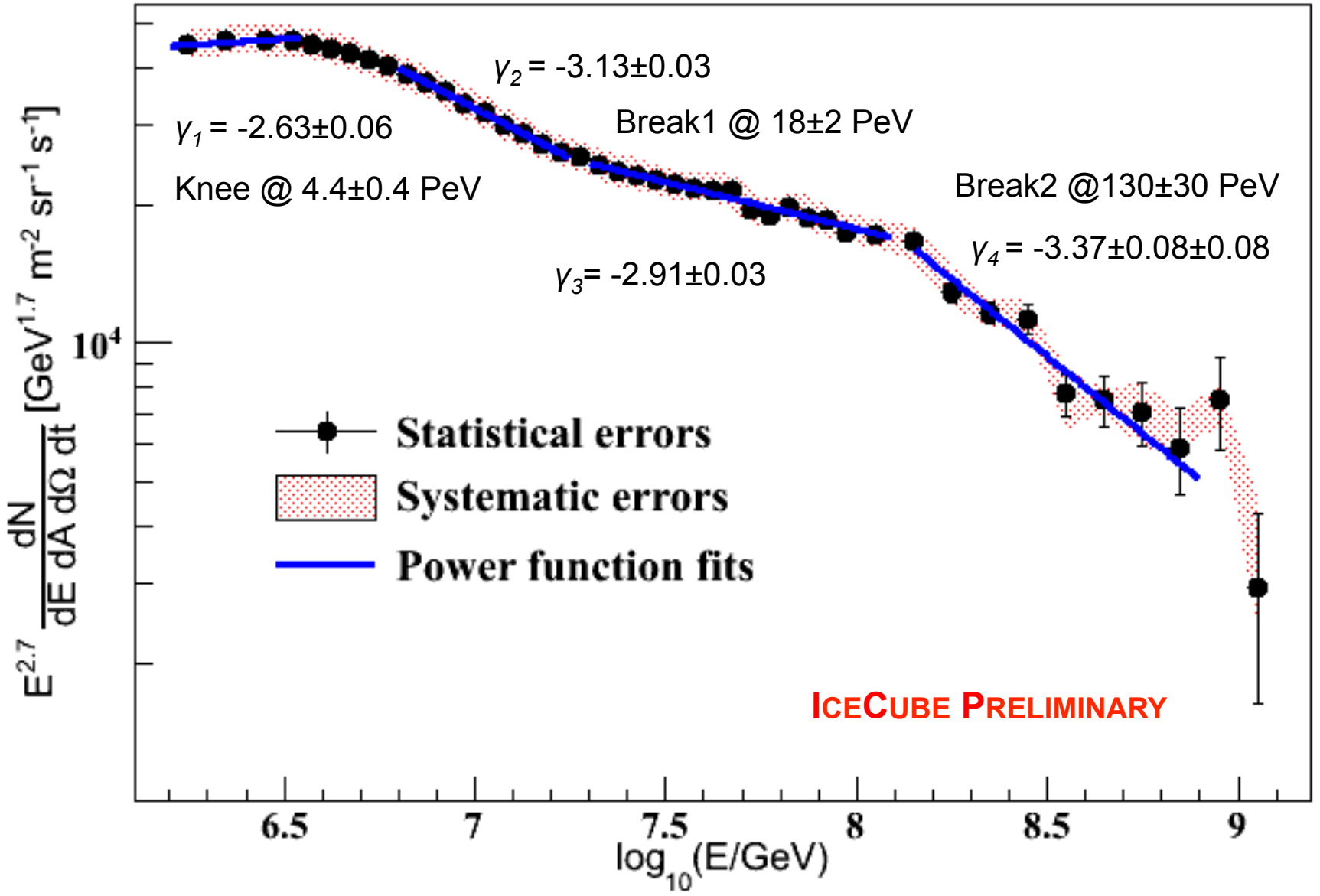
SYSTEMATICS

	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%

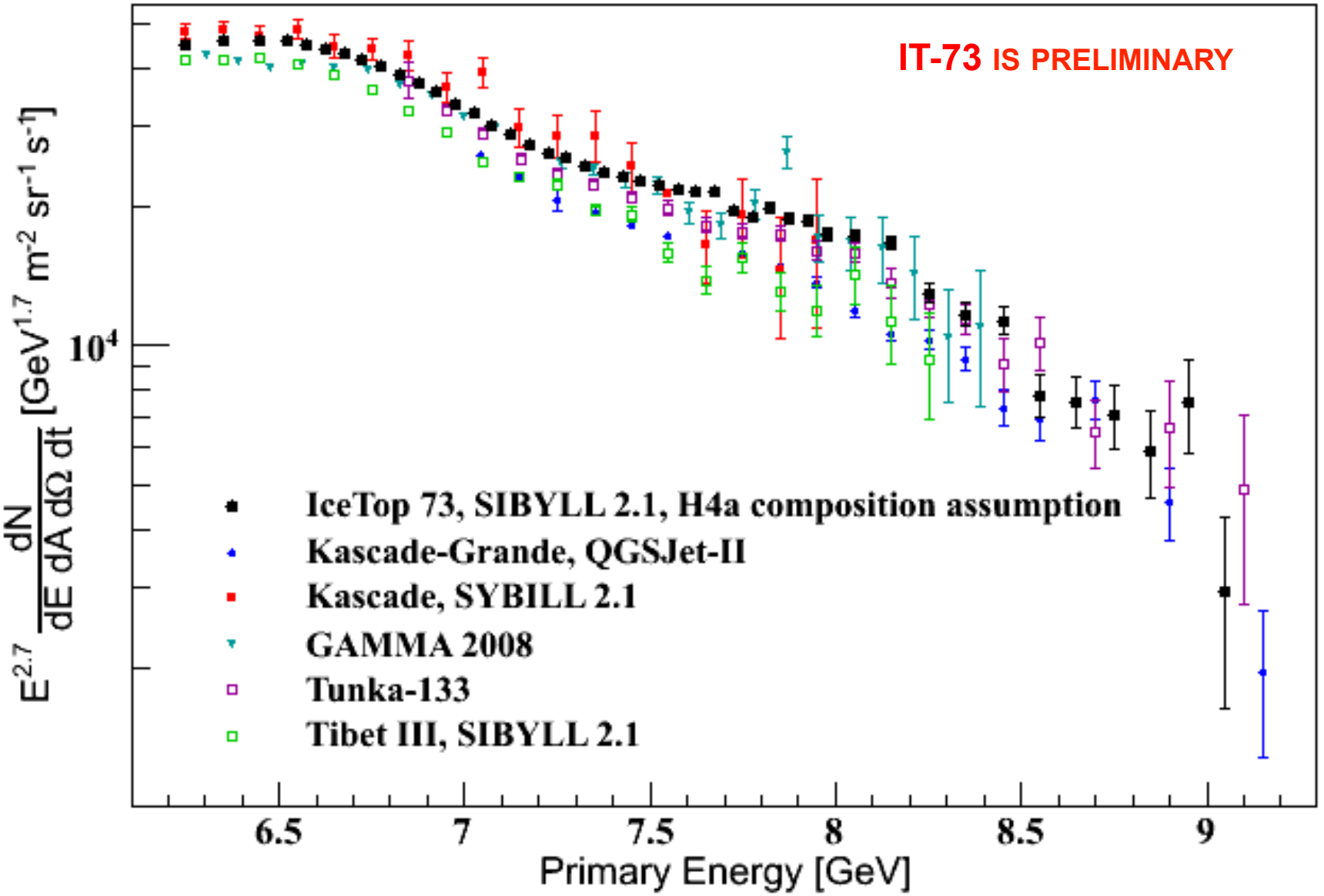


COSMIC-RAY SPECTRUM AND FEATURES

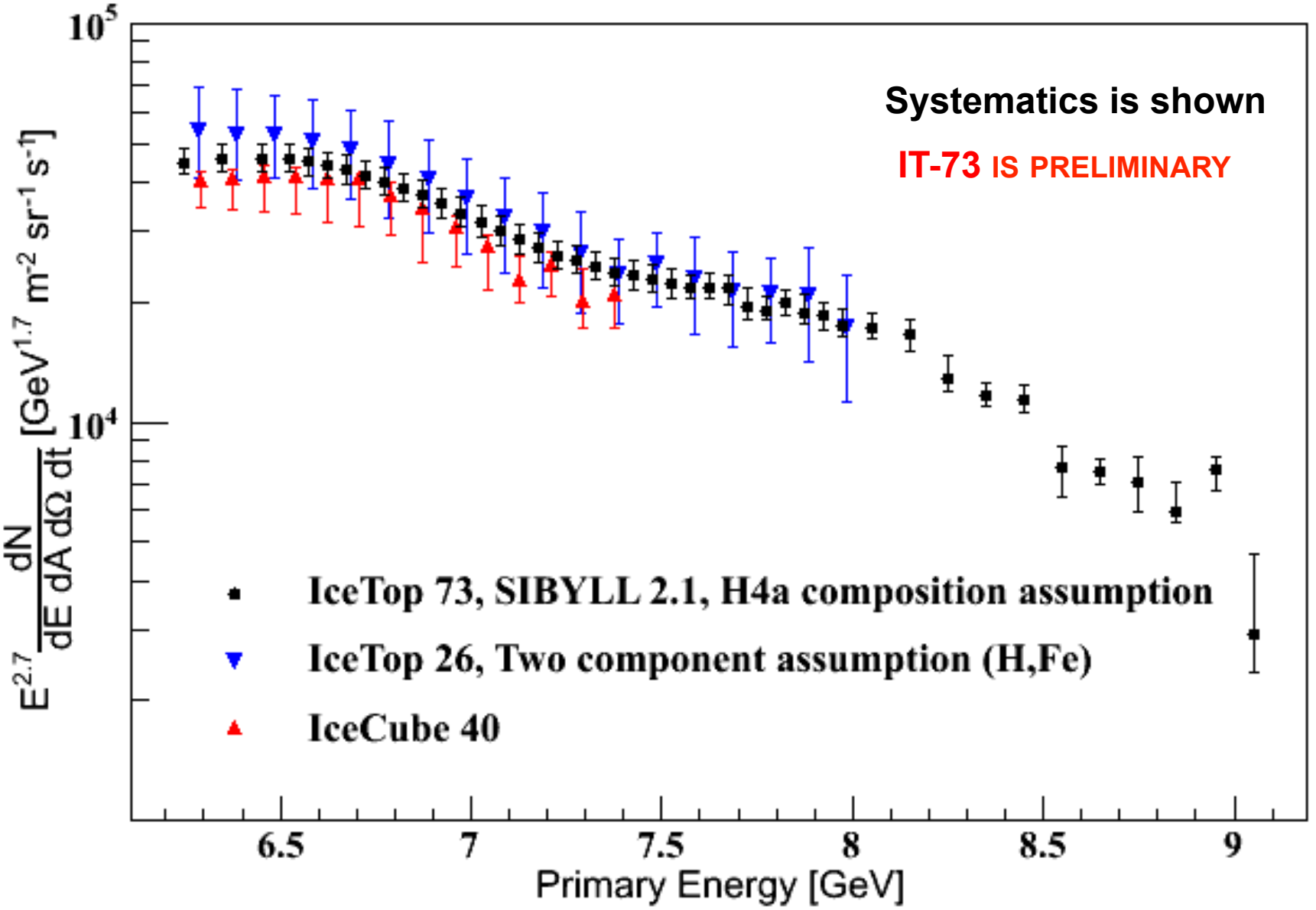
Energy "break" measured where a change in power law slope is observed



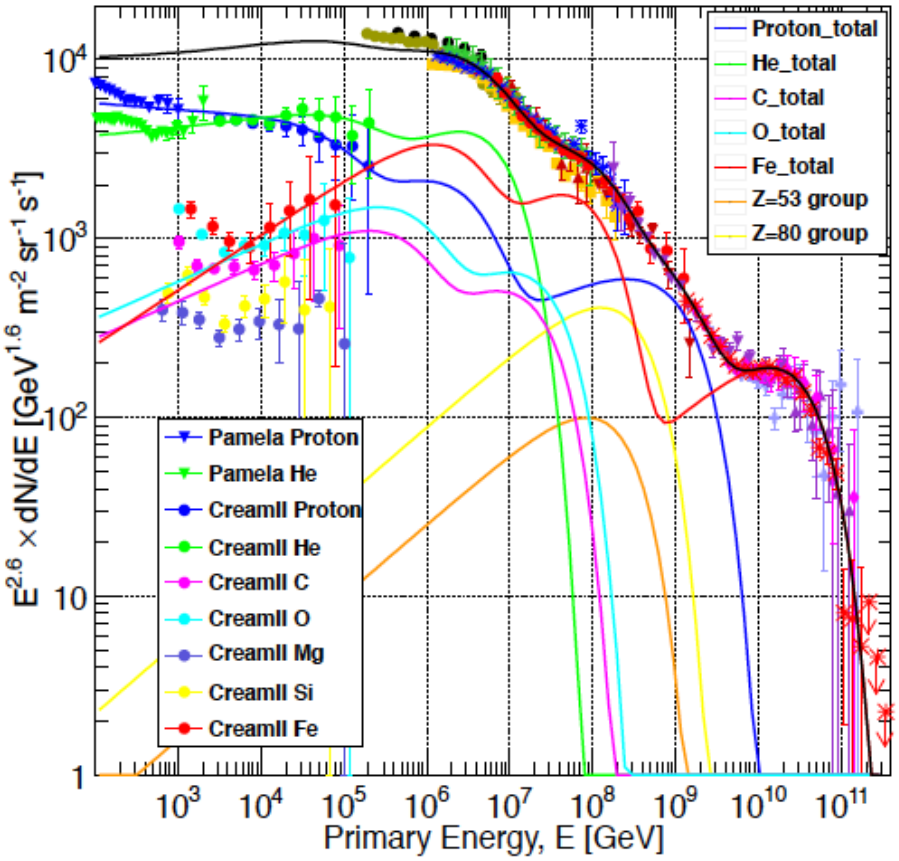
ICETOP AND OTHER RECENT MEASUREMENTS

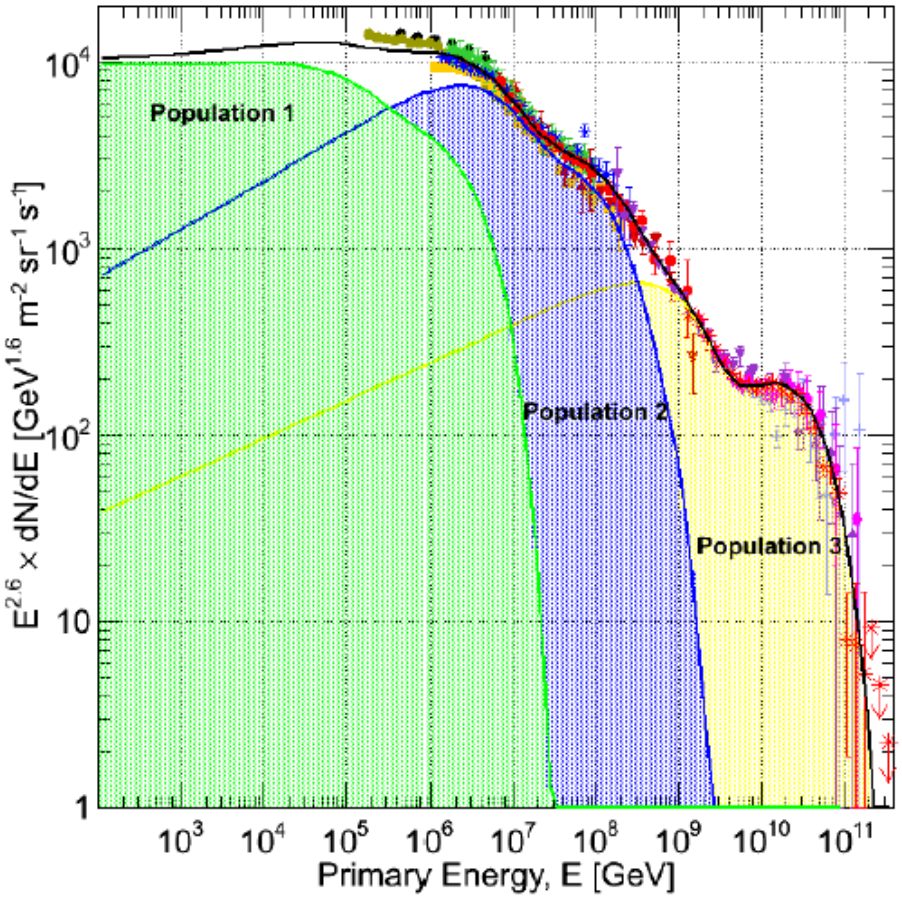


ICETOP DURING THE YEARS



BREAKS IN GLOBAL FIT TO CR DATA





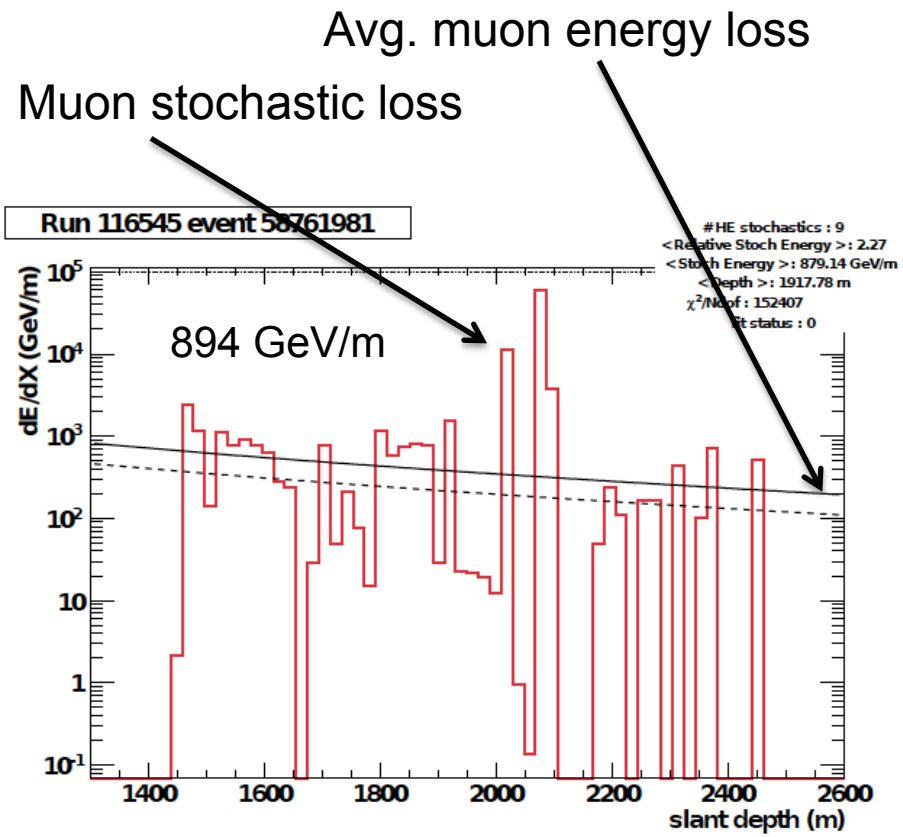
Including composition measurements when fitting Fe cutoffs identifies finer spectral structures corresponding to different populations of sources

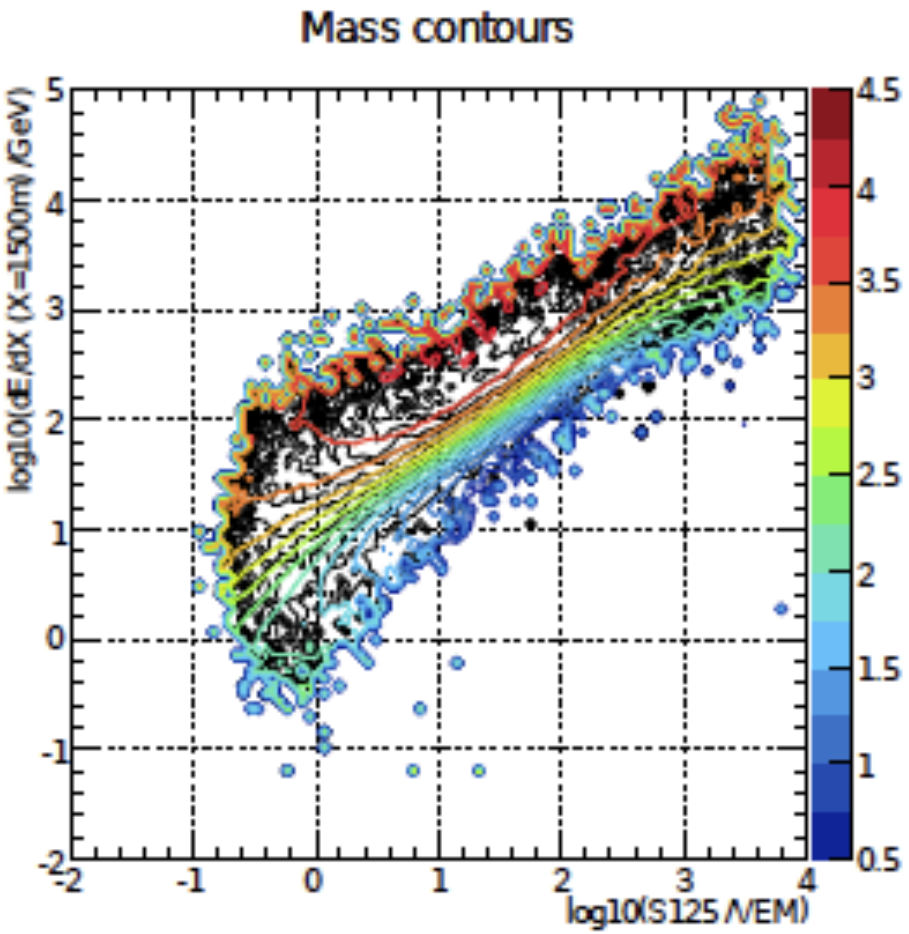
Will IceCube see a transition from galactic to extra-galactic CRs?

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

ADDING IN-ICE INFORMATION

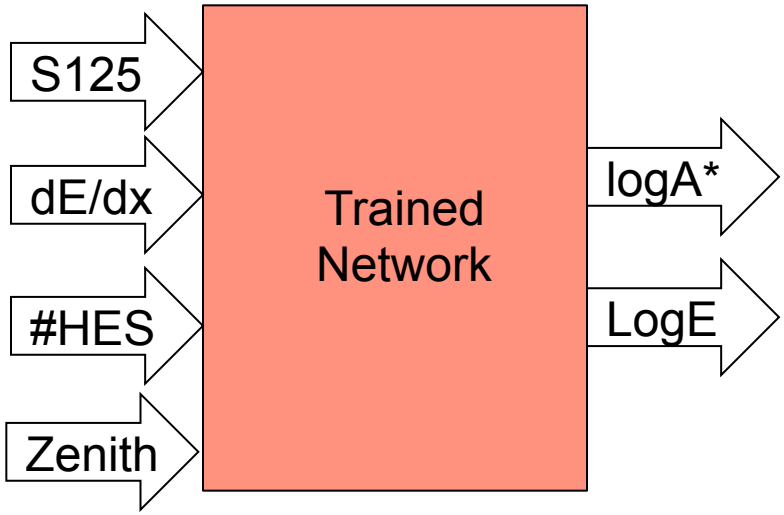
Larger S125:
Higher energy/Deeper Xmax
Larger dE/dx:
More muons/Heavier primary



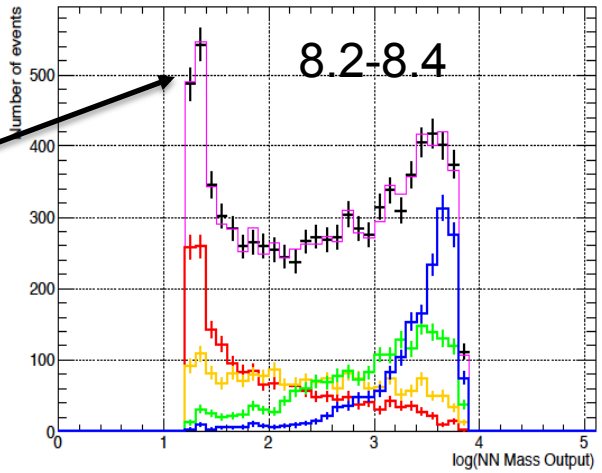


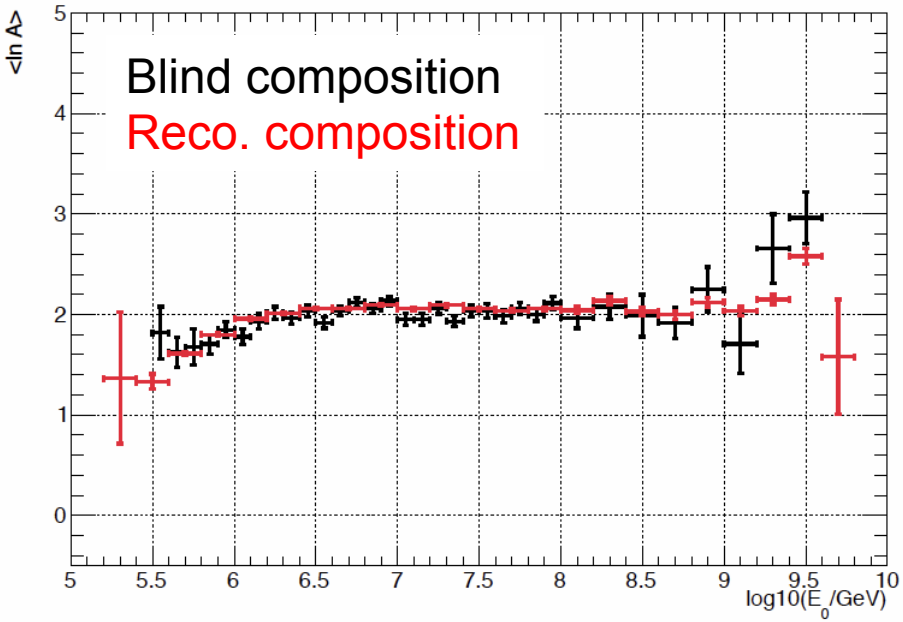
COINCIDENT EVENT ANALYSIS (IT73/IC79)

Neural Network Approach

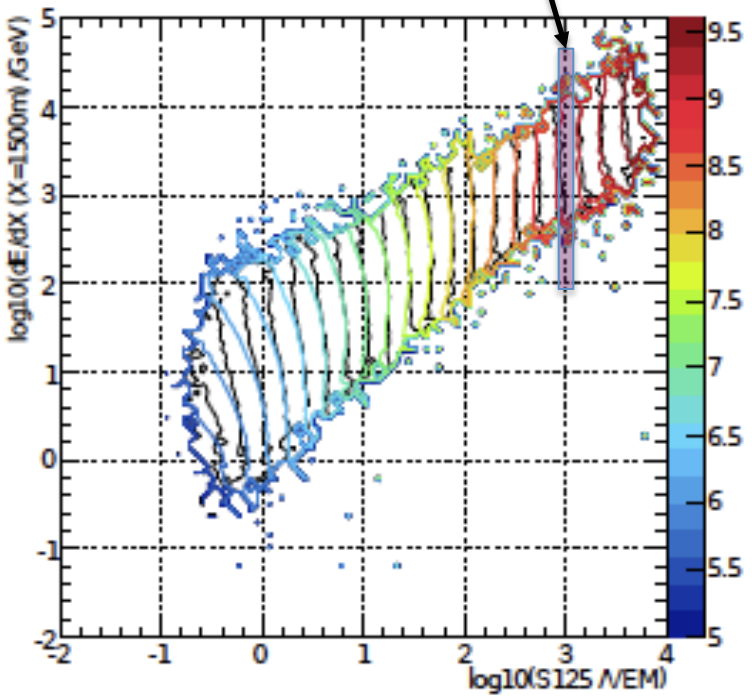


Template fitting





Energy contours



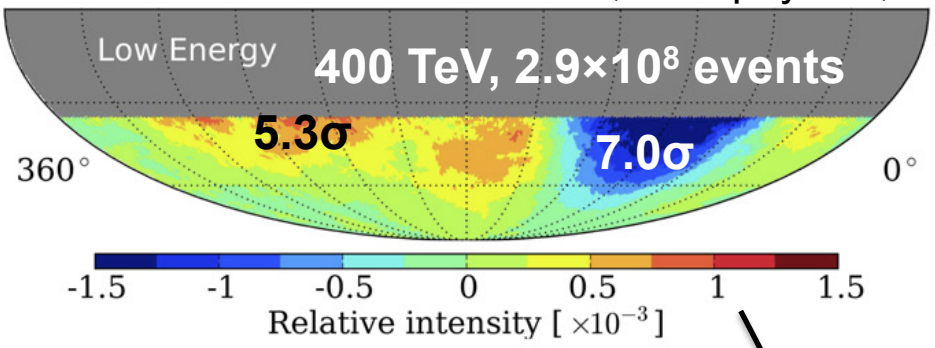
COSMIC-RAY MASS COMPOSITION

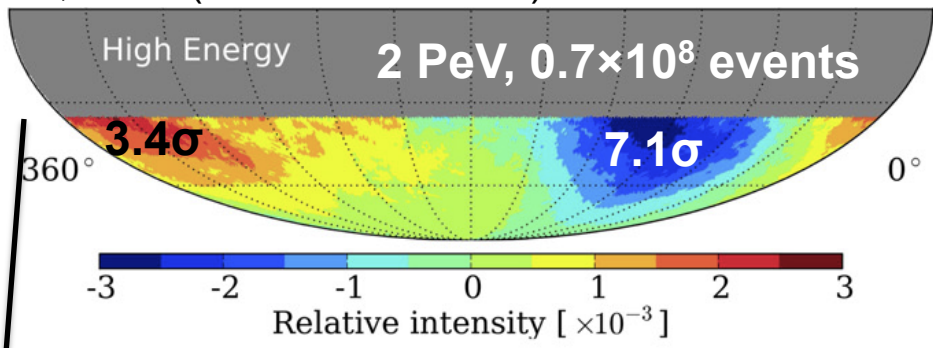
Results not formally approved in time to be shown here

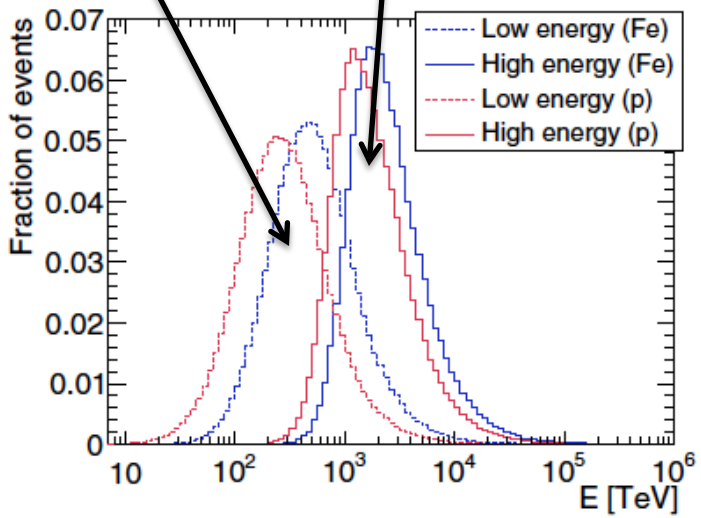
- We observe same trend observed with IC40 data up to 10**8 GeV
- Systematics studies on-going
- **We can discriminate different masses**
- **We can reach 1 EeV**
- Full year results will be available at ICRC

ICETOP MEASUREMENT OF ANISOTROPY

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





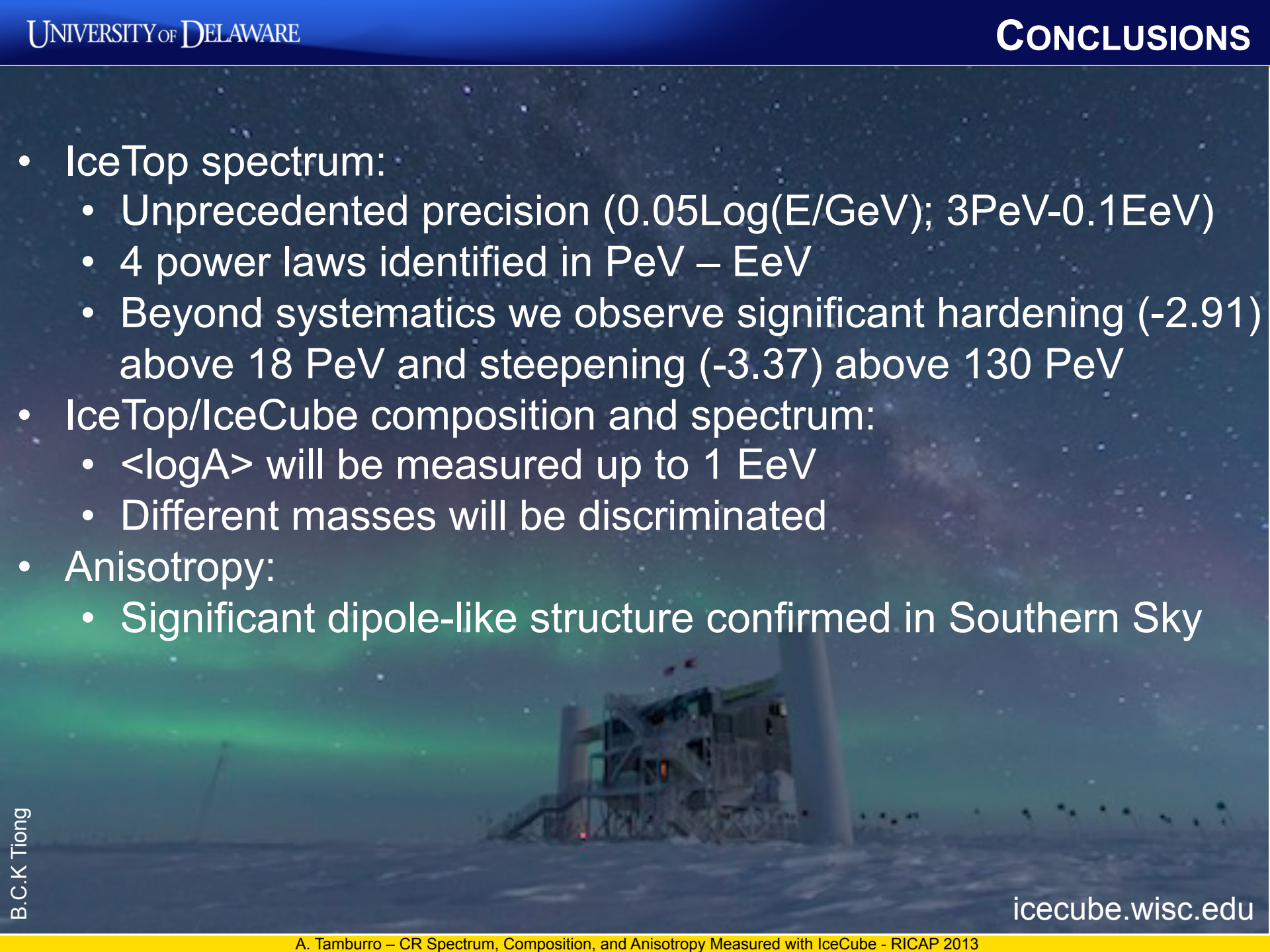


Smoothing 20deg

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

CONCLUSIONS

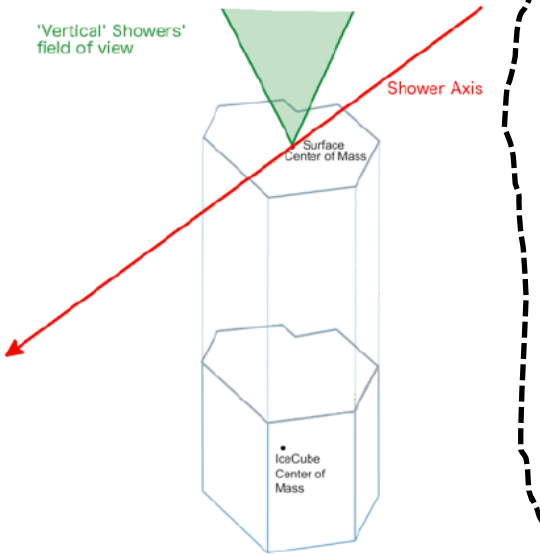
- IceTop spectrum:
  - Unprecedented precision (0.05Log(E/GeV); 3PeV-0.1EeV)
  - 4 power laws identified in PeV – EeV
  - Beyond systematics we observe significant hardening (-2.91) above 18 PeV and steepening (-3.37) above 130 PeV
- IceTop/IceCube composition and spectrum:
  - <logA> will be measured 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

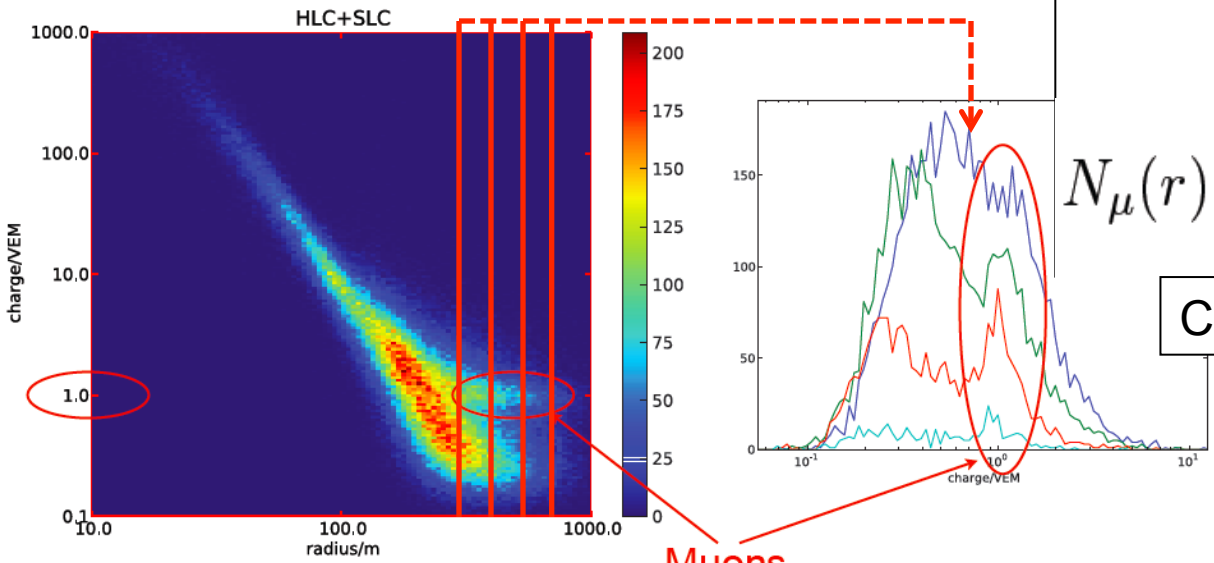
COSMIC RAYS IN ICECUBE: AN OUTLOOK



On-axis
+100% exposure (<60°)

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

Increase sensitivity to muon content of showers
Reach out for GC

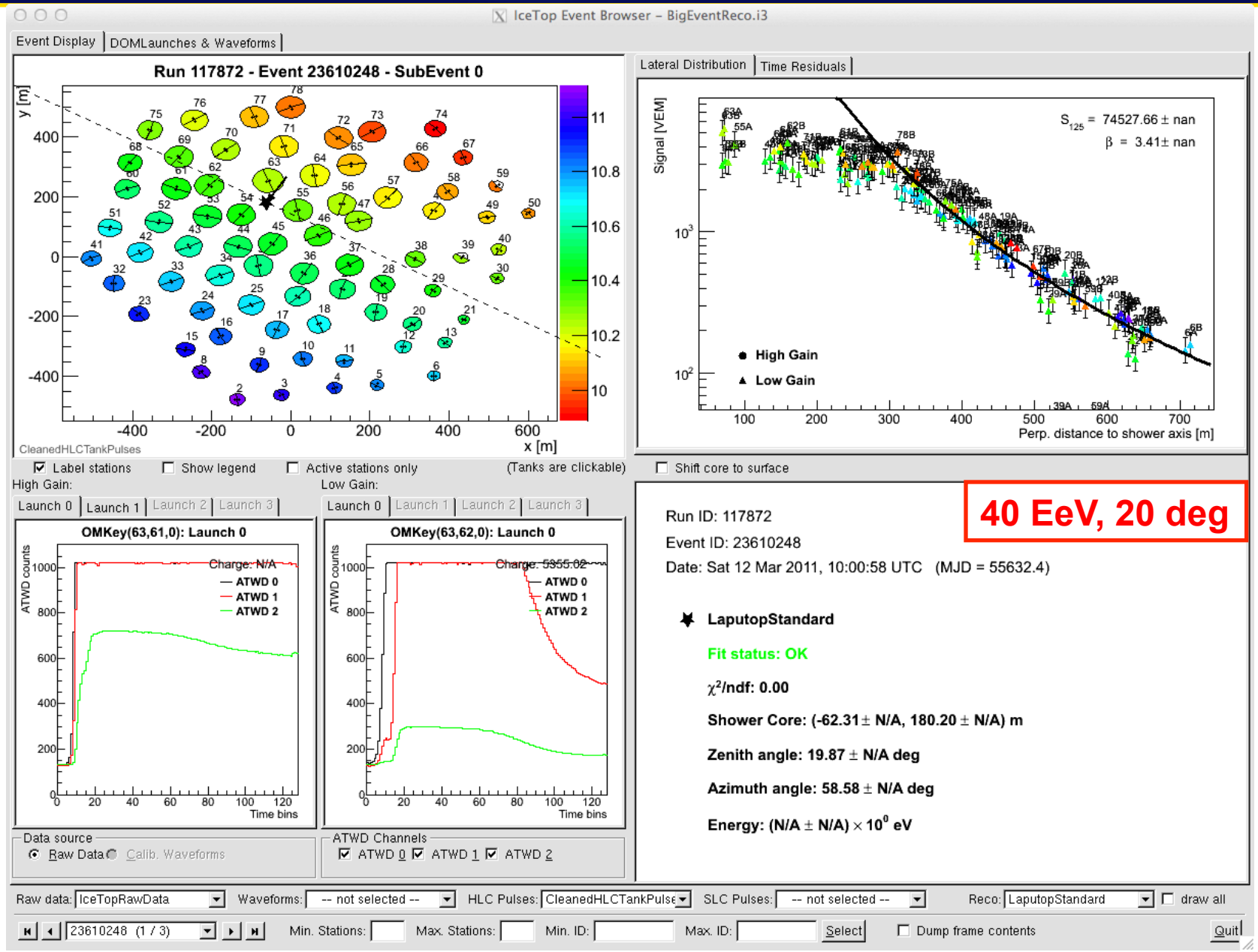


Muon LDF

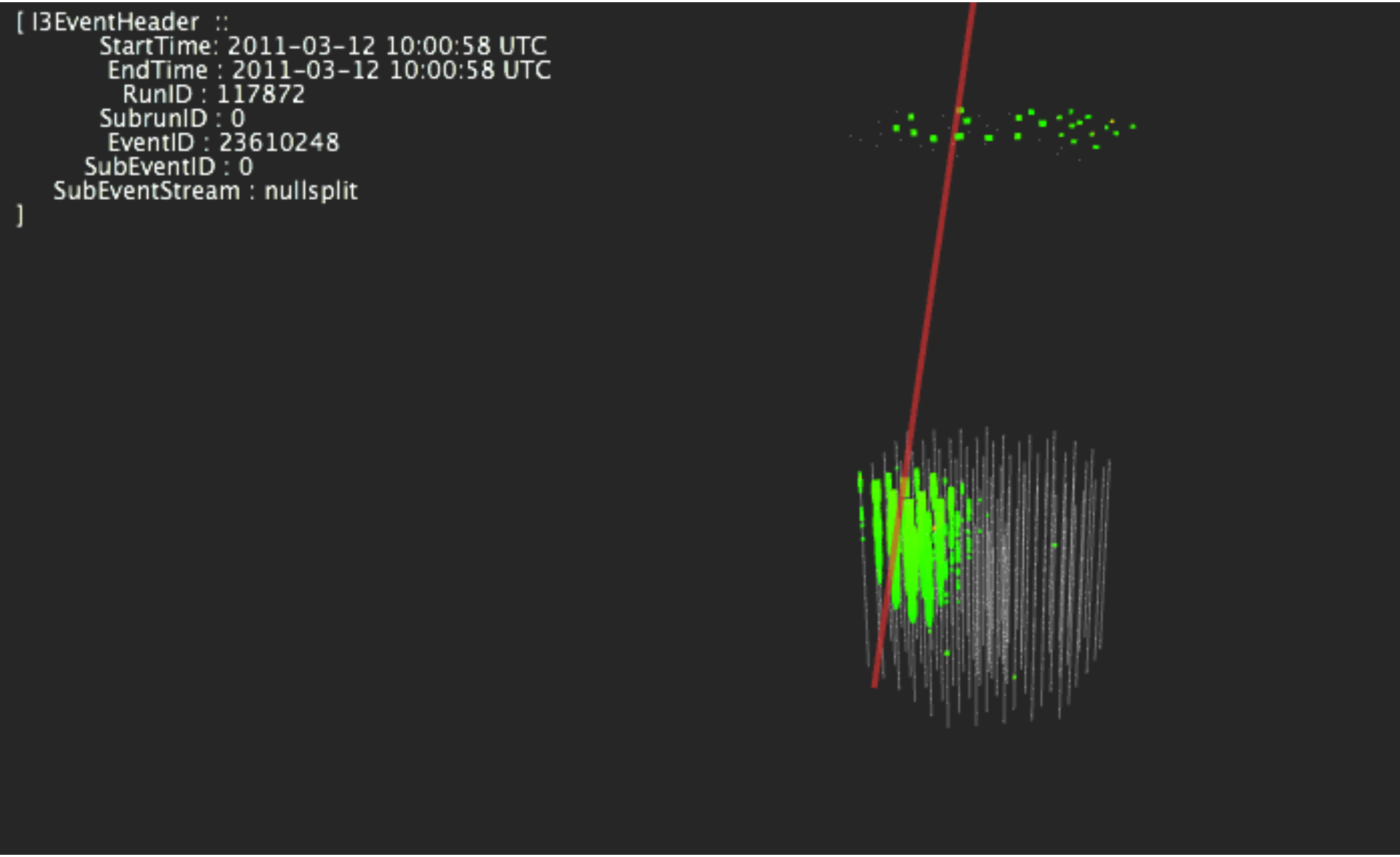
$$N_\mu(r) = A\, r^{-0.75} \left(1 + \frac{r}{320\text{m}}\right)^{-\gamma}$$

Compare with Greisen prediction

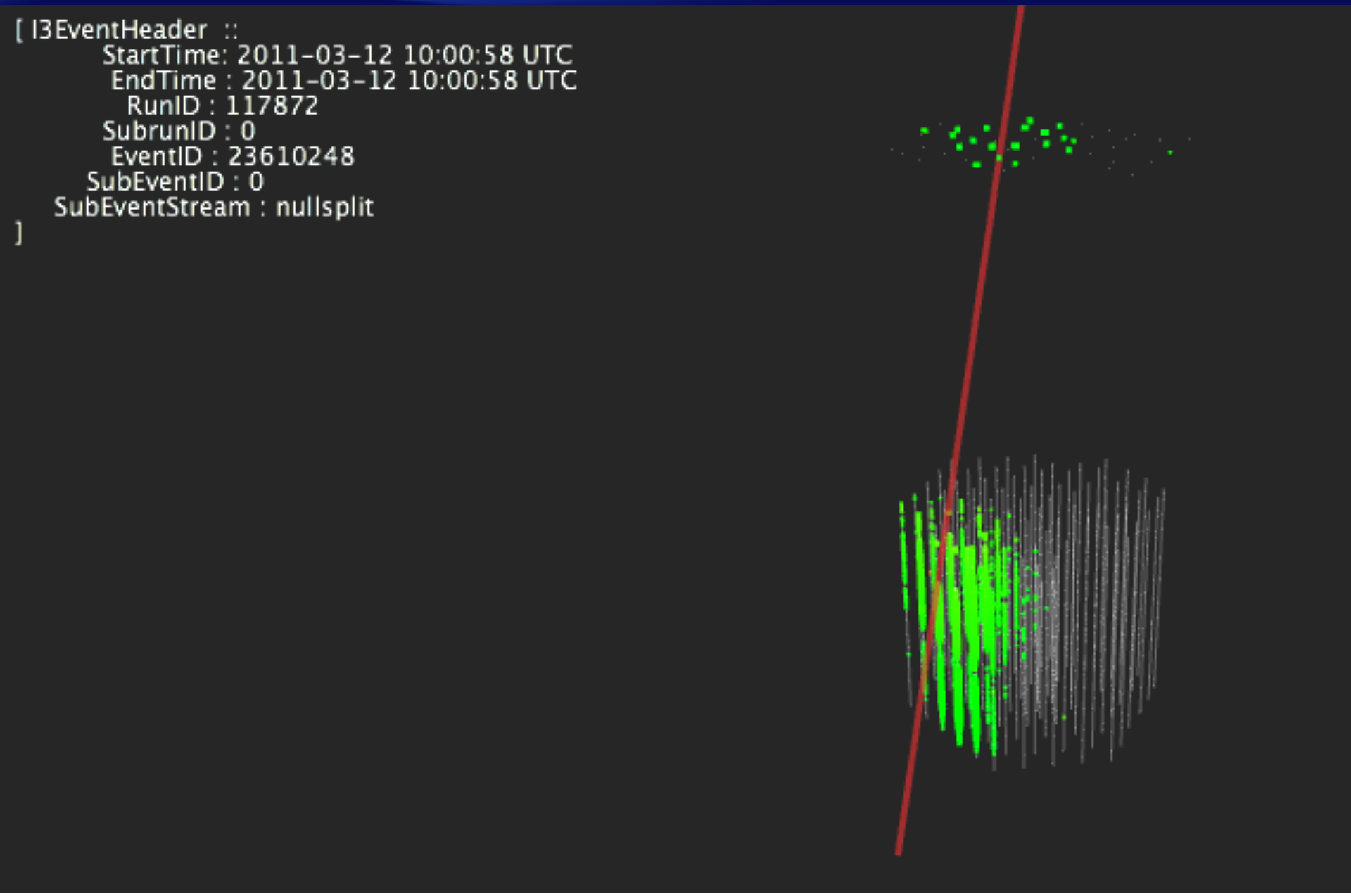
AN EEV EVENT


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
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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