Cosmic-ray results from IceCube/IceTop
<table>
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<tr>
<th>Year</th>
<th>IT</th>
<th>IC</th>
<th>Construction</th>
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<td>2010-11</td>
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Outline

• Primary spectrum with IceTop
• Muons in IceCube
  – Inclusive spectrum
  – Muon bundles
• Anisotropy
• Coincident events – IceTop/deep IceCube
• 81 IceTop staKons
• 2 tanks per staKon
• 2 DOMs per tank (H.G., L.G.)

Installing IceTop tanks (Dec. 2010)
IceTop Array: Triggering & Calibration

**Tank A**
- High Gain @ 5.E6
- Low Gain @ 1.E5

**Tank B**
- High Gain @ 5.E6
- Low Gain @ 1.E5

**Single hits** (1 DOM) or SLC
(muon detection + veto of air showers for in-ice studies)
(1600 Hz)

**Station trigger**
HG-HG or HG-LG coincidence in 1 µs (30 Hz)

**IceTop trigger**
3+ stations in +/- 10 µs (35 Hz)

**Calibration: Vertical Equivalent Muon**

- **DOM 51-61**
- 1 VEM = 118.3 pe
- **Total**
- **Muons**
- **Background**
IceTop Shower Reconstruction – Example from IT-73

\[ \theta = \theta_1.5^\circ, \phi = 33.0^0 \]

\[ E = 2.90 \cdot 10^{17} \text{ eV (H assumption)} \]

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

- \( S_{125} \): signal at \( r = 125\text{m} \)
- \( \beta \): slope at \( r = 125\text{m} \)
- \( \kappa = 0.303 \) fixed
IceTop-73 Data: 326 days live time Jun 2010-May 2011

- Threshold of this analysis
- 5+ Stations \( \cos\theta \geq 0.8 \)
- \( \sim 10 \text{ PeV Proton} \)
- \( \sim 260 \text{ PeV Proton} \)
- 2077 events/yr per bin
- 26 events/yr per bin
- Entries \( 3.731821\times10^7 \)
IceTop-73 Data: Systematics due to snow build up

Events selected by core location

Correction to expected signal is applied at each tank according to its snow depth $z$ during the likelihood minimization

$$S_{\text{expected}} = S_{\text{fit}} e^{-\frac{z \cos \theta}{\lambda}}$$
$E_{\text{primary}}$ for observed $S_{125}$

Proton, $\cos\theta = 0.95$, $\frac{dN}{dE} \sim E^{-2.7}$

$\Delta \log_{10}(S_{125}) = 0.05$

Simulations: CORSIKA - SIBYLL
Distribution of $E_{\text{primary}}$ for each cut in $S_{125}$

Consecutive $\log_{10}(E_{\text{true}})$ distributions for given $\log_{10}(S_{125})$ bins. **Proton** simulation, weighted by $E^{-2.7}$. X axis is $\log_{10}(E_{\text{true}} / \text{GeV})$. 

Mumbai, 12/12/12

Tom Gaisser for the IceCube Collab.
Relation between $S_{125}$ and Primary Energy is mass and zenith dependent.

\[ \log_{10}(E) = p_2 \log_{10}(S_{125})^2 + p_1 \log_{10}(S_{125}) + p_0 \]

Tom Gaisser for the IceCube Collab.

Mumbai, 12/12/12
\[ A_{\text{eff}} = \varepsilon \times 0.521015 \text{ km}^2 \]
Flux

\[ \frac{dN}{d \ln(E)} = \frac{N_{\text{events}} / \text{bin}}{\epsilon A \Delta \Omega T \ln(E_{i+1}/E_i)} \]

All protons:
inferred flux higher near vertical

All iron:
inferred flux suppressed near vertical

Mumbai, 12/12/12
Tom Gaisser for the IceCube Collab.
Use a realistic model of composition


5 nuclear components
3 populations
- Galactic-A (CREAM composition)
- Galactic-B (Hillas)
- Extra-galactic (p or mixed)

Rigidity cutoff for each population

Mumbai, 12/12/12
Tom Gaisser for the IceCube Collab.
Compare Polygonato Model
Estimated systematic uncertainties
Preliminary IceTop spectrum

Syst. Errors added in quadrature
Compare to other IceCube spectra
Comparison with other measurements
Muons in IceCube

• 2.5 kHz of TeV muons
  – High statistics allows anisotropy measurements
  – Precision studies of seasonal variations
• $\mu$ – bundles from high-energy cosmic rays
  – From all directions
  – In coincidence with showers in IceTop
  – Measure $\mu$ with separation $> 200$ m from bundle
• Inclusive $\mu$ spectrum to PeV
  – Measure stochastic losses to obtain $dN_{\mu}/dE_{\mu}$
Burst spectrum \rightarrow \mu \text{ spectrum}

1.07(\pm 60\%) \text{ PeV surface energy (MC-simulation estimate based on cascade energy, slant depth)}

300 \text{ TeV Cascade, 60}^\circ \text{ Track (depth: 3400m)}

Energy Deposition along Track

Patrick Berghaus: ISVHECRI-2012
μ spectrum compared expectation


μ spectrum depends on E/nucleon

50% offset at low energy

Need to consider prompt component in PeV range

Analysis in progress
μ bundles & primary spectrum/composition

Differential Energy Loss Reconstruction:
Smooth Distribution
Gradual Slope (Range-Out)

See Patrick Berghaus ISVHECRI-2012: analysis in progress

Upper
($\lambda_{\text{abs}} \sim 100\text{m}$)

Dust Layer
($\lambda_{\text{abs}} \sim 50\text{m}$)

Lower
($\lambda_{\text{abs}} \sim 200\text{m}$)
Laterally separated $\mu$

Detection of parallel tracks coincident with CR muon bundle
Background estimate using off-time data

L. Gerhard and S. Klein, ICRC 2011
cosmic ray anisotropy

Tibet-III
Amenomori et al., ICRC 2011

IceCube-59

Milagro + IceCube TeV Cosmic Ray Data (10° Smoothing)

relative intensity
large scale anisotropy
statistical significance

small scale anisotropy

2 hr = 30˚
4 hr = 60˚
360˚
0˚

1 TeV
20 TeV

equatorial coordinates

Abdo et al., PRL, 101, 221101, 2008
Amenomori et al., ICRC 2011
cosmic ray anisotropy

relative intensity  
equatorial coordinates

IceCube-59

$\Delta N/N \times 10^{-3}$

20 TeV

400 TeV

Santander et al., arXiv:1205.3969

be Collaboration
Anisotropy with IceTop

Low Energy ~ 400 TeV

High Energy ~ 2 PeV

http://arxiv.org/abs/1210.5278
Muon rates map stratosphere

- Variations of temperature cause atmosphere to expand and contract
- Muon production from meson decay increases and decreases
- Main effect comes from stratosphere
- Both seasonal effects and sudden changes can be studied
- Potential sensitivity to production of heavy hadrons (kaons, charm)
K70 is a measure of muon bundle size in IceCube (analogous to S125 on the surface).
IceTop-40/IceCube-40 Spectrum & Composition 1-30 PeV


systematics
Concluding comments

• IceTop spectrum
  – Preliminary result with IT-73 based on 0.5 km² sr yr
  – Can add one km² sr yr with data since May, 2011

• Muon spectrum to PeV in progress
  – Potential to determine level of charm needed for search for UHE ν of astrophysical origin

• Muon bundles from 0 – 80° (with and without coincidences)
  – will expand reach of composition measurements
  – Coincident event analysis with full year of IT-73, IC-79 is in progress
Extras
Spectra for 5 assumptions
Comparison of several measurements

Data, statistical errors only

Shifted

Model
Tibet Sibyll HD
K-Grande
HEGRA
CasaMia
Kascade-2005
Tunka
IT-73

Allparticle model 2
Tibet Sibyll HD (1.05*E)
K-Grande-2 (1.05*E)
HEGRA (0.9*E)
CasaMia (1.2*E)
Kascade-2005 (0.95*E)
Tunka
IT-73

$E^2 \frac{dN}{dE} (m^{-2} sr^{-1} s^{-1} GeV^{-5})$

$E$ (GeV)