Physics Beyond the Standard Model with IceCube

Motivation
Main Physics Goals
Detector Design/Construction
Beyond the SM Searches

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Why a km³ ν observatory?

Cosmic Ray Spectrum follows broken power law
Where does the high energy component come from?
1. **Unknown p⁺ accelerators?**
2. Decay of cosmological relics?

Recent AUGER results hint that perhaps the source might be AGN

**Cosmic Ray Flux x E^{2.7}**

- **rp > R_{galaxy}**
- **(E_p > E_{eV})**
- Spectrum hardens at very high energies
- Extragalactic origin
- LHC

Plot from PDG 2007 Fig 24.9

- ~1 event km⁻² yr⁻¹

arXiv:0709.2712v1
Why a km³ ν observatory?

Advantages of neutrinos
1. Point back to source
2. Universe transparent to ν
3. Not GZK suppressed

GZK Suppression
\[ p^+ + \gamma_{\text{CMB}} \rightarrow \Delta \rightarrow p^+ + \pi^0 \]
\[ \rightarrow n + \pi^+ \]

Plot from PDG 2007 Fig 24.10

GZK cutoff
\[ 5 \times 10^{19} \text{ eV} \]
Overview of Physics with IceCube

Point Sources
- cosmic p+ accelerator
- GRB
- Supernovae
- GZK/EHE ν
- Diffuse ν Energy Spectrum
- SUSY WIMPs (Sun and Earth)
- Cosmic Ray Composition
- Cosmic Ray Composition
- Supernovae
IceCube Backgrounds*

Simulated with CORSIKA
(COsmic Ray SImulations for KAskade)

Down-going muons
and muon bundles
(*Cosmic Ray Composition Signal)
IceTop
• Surface array of 80 stations
• 2 ~2.3m$^3$ surface ice tanks per string
• 2 optical modules per tank (high and low gain)

IceCube Design Goal
• 80 Strings, 125 m apart on hexagonal grid
• 60 optical modules per string (~17m spacing)
• Cubic kilometer of instrumented ice

AMANDA
• 19 Strings
• 677 Optical Modules (10-20m spacing)
Simple case of incoming $\nu_\mu$

1. Incoming $\nu$ interacts with N
2. Muons generate Cherenkov light
3. Cherenkov photons detected in DOM
4. Reconstruct $\mu$ from photon arrival times

Simulation - 80 strings
IceCube sensitive to all $\nu$ flavors

Low energy EM and hadronic “cascades” roughly spherical (neglecting dusty ice and LPM effect)

$\nu_e$ : Classic “Double-Bang”

One among several tau signatures: lollipop, inverted lollipop, etc...
DOM
Digital Optical Module

Measures arrival time of photons 2 ATWD
  • Analog Transient Waveform Digitizers
  • 300MHz for 400ns
  • 3 gain channels each (low, medium, high)
  • ping-pong to minimize deadtime

fADC
  • fast Analog to Digital Converter
  • 40MHz for 6.4μs

Local Coincidence triggering
  • Hard Local Coincidence
  • Soft Local Coincidence (isolated hits)

Improvements over AMANDA OMs
  • Digitize waveforms in-ice ⇒ surface
  • Lower noise ~ 400Hz
Drilling Hose Reel for Hot Water Drill

IceTop Tanks
Deployment
The Dust Logger

Designed to map out dust layers
404nm laser as light source
Dusty layers due to volcanic ash
Three Dust Logger runs so far
(strings 21, 50, and 66)
Can measure tilt of dust layers

42k years BP  60k years BP
Photon Propagation Model in Antarctic Ice

Ice properties not uniform: vertical structure due to dust

Optical Ice Properties

- 300nm $\lambda_{sc} \sim (10-40m) \lambda_{abs} \sim (30-120m)$
- 400nm $\lambda_{sc} \sim (10-50m) \lambda_{abs} \sim (50-140m)$
- 500nm $\lambda_{sc} \sim (15-65m) \lambda_{abs} \sim (30-50m)$
- 600nm $\lambda_{sc} \sim (20-80m) \lambda_{abs} \sim 10m$

Maybe up to 250m for deep ice (>2200m)
Exotic $\nu$ oscillations
Violation of Lorentz Invariance (VLI) in $\nu_{\text{atm}}$

Maximum Attainable Velocity (MAV)
states not necessarily flavor eigenstates

$180^\circ$
$90^\circ$

Results Survey
(90% CL on $\delta c/c$)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\delta c/c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMANDA*</td>
<td>$&lt; 5.3 \times 10^{-27}$</td>
</tr>
<tr>
<td>MACRO</td>
<td>$&lt; 25 \times 10^{-27}$</td>
</tr>
<tr>
<td>SuperK+K2K</td>
<td>$&lt; 2.0 \times 10^{-27}$</td>
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</tbody>
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● Battistoni et. al., hep-ex/0503015

Sensitivity Projections
AMANDA (7 yrs) $\delta c/c < 10^{-27}$
IceCube (10 yrs) $\delta c/c < 10^{-28}$

IceCube vs. LHC
New Physics Potential from Cosmic Rays

Cosmic Ray Event Rate
\( \mathcal{L}_{\text{CR}} \sim 10^{-13}\text{cm}^{-2}\text{s}^{-1} \)
\( E > 10^8\text{GeV} \)
\( \Gamma_{\text{NN}} \sim 10^5 \text{ s}^{-1} \)

LHC Event Rate
\( \mathcal{L} \sim 10^{34}\text{cm}^{-2}\text{s}^{-1} \)
\( \sqrt{s} = 14\text{TeV} \)
\( \Gamma_{\text{pp}} \sim 10^9 \text{ s}^{-1} \)

1 event km\(^{-2}\) hr\(^{-1}\)
\( \sqrt{s_{\text{p-p}}} > 14\text{TeV} \)

1 event km\(^{-2}\) yr\(^{-1}\)
\( \sqrt{s_{\text{p-p}}} > 140\text{TeV} \)
How they are produced?
1. UHE CR produce SUSY particles
2. SUSY particles cascade to NLSP
3. Meta-stable NLSP travels to IceCube

stau ($\tilde{\tau}$) will look very similar to a muon in IceCube

M. Ahlers, J.I. Illana, M. Masip, D. Meloni
SUSY in Cosmic Rays

Signature
- Two nearly parallel $\mu$-like tracks near the horizon separated by more than 100m
- Above the horizon dominated by SM $\mu^+\mu^-$ background

Other stau sources via $\nu$-N
- Cosmic HE (unknown diffuse flux)
- Atmospheric prompt charm decay

SM $\mu^+\mu^-$ background $\theta<80^\circ$
No background $\theta>80^\circ$
Signal $80^\circ<\theta<90^\circ \phi(1\text{ yr}^{-1})$

M. Ahlers, J.I. Illana, M. Masip, D. Meloni

I.F.M. Albuquerque, G. Burdman, Z. Chacko

S. Ando, J. F. Beacom, S. Profumo, D. Rainwater

6-0.1 yr$^{-1}$ @ WB limit
20-1 yr$^{-1}$ @ MPR limit

<1 yr$^{-1}$ & dominates over cosmic $\nu$
Heavy Exotics with IceCube
Monopoles, Q-balls, Nuclearites, Preons, etc...

Light (m<10^{12}\text{GeV}) & Relativistic (\beta>0.5)
Basic E&M
Cherenkov Radiation
\delta_e ("knock-on") production

Heavy (m\sim 10^{16}\text{GeV}) & Slow (10^{-4}<\beta<10^{-2})
Nucleon catalyzed decay
Magnetic Monopole : \sigma_{MP} \sim \sigma_{QCD}
SUSY Q-ball : \sigma_{SENS} \gg \sigma_{QCD}

Heavy (m<10^{16}\text{GeV}) & Large (R\sim \text{Å})
DeRujula-Glashow Mechanism
plasma shock wave emits blackbody radiation
Monopole Acceleration

Only “light” Monopoles expected to be relativistic
Heavy (\(M_{\text{MP}} \sim 10^{16}\) GeV) can’t be accelerated to relativistic speeds by known sources
Relativistic Monopole Photon Production

Cherenkov Radiation

\[
\frac{d^2 n}{d\lambda dx} = (n g)^2 \frac{2\pi \alpha}{\lambda^2} \left(1 - \frac{1}{n^2 \beta^2}\right)
\]

\(\delta_e\) ("knock-on") electrons ionization electrons above the Cherenkov threshold

Quantum corrections and Monopole structure play a small role at these speeds

~10^4 x bare \(\mu\)
Monopoles on IceCube - $\beta > 0.8$
Monopoles on IceCube - $\beta \sim 0.6$
't Hooft-Polyakov SU(5) GUT Monopoles

Rubakov-Callan Mech.
Catalyzed Nucleon Decay
- $\sigma_{\text{cat}} \sim \sigma_{\text{QCD}} F(\beta)$

Decay Modes
- $p, n \rightarrow e^+\pi$ (90%)
- $p, n \rightarrow \mu^+\kappa$ (10%)

Model as a series of 1GeV
EM showers ($\sim 4 \times 10^4 \gamma$)

Assume only proton
decay of H in H$_2$O

\[ \sigma_{\text{cat}} = \sigma_0 \beta^{-1} \]

\[ \sigma_{\text{cat}} = \sigma_0 \beta^{-2} \]

“bare” $\mu$

Vary mean
free path in
simulation (0.1m-10m)

Relativistic events
only a few $\mu$s long

Work in progress for IceCube
MC (signal and background)
Trigger/Filtering estimates for 2008

A. Pohl - AMANDA simulation
Monopoles at ICRC 2007
(International Cosmic Ray Conference - Merida, Mexico)

Relativistic Monopoles

A. Pohl (Uppsala University)
113 days AMANDA 2001
D. Hardtke (U.C. Berkeley) for IceCube

Slow Monopoles

H. Wissing (Aachen University)
154 days AMANDA 2000
Brian Christy (UMD), A. Olivas (UMD), and
D. Hardtke (U.C. Berkeley) for IceCube
Conclusion

IceCube currently the largest neutrino observatory
25 IceCube strings + 19 AMANDA + 26 stations on surface
• $\nu$: Point Sources, Diffuse flux, Exotic $\nu_{\text{atm}}$ Oscillations
• Cosmic Ray Composition
• Supernovae Detection
• Gamma Ray Bursts
• WIMPs (Dark Matter)
• Monopoles, Q-balls, etc..
• SUSY sleptons w/ N-N and $\nu$-N
• TeV Gravity in cosmogenic $\nu$-N

String Deployment Plan
• 07-08 - 14 strings (36 IceCube strings)
• 08-09 - 14 strings (50 IceCube strings)
• 09-10 - 14 strings (64 IceCube strings)
• 10-11 - 11+ strings (75+ IceCube strings)

Deployment season has begun
23rd string deployed Dec. 8th
24th string deployed Dec. 13th
25th string deployed Dec. 15th