Astrophysical Neutrinos with the IceCube Detector

Joanna Kiryluk
for the IceCube Collaboration

Stony Brook University
Outline:

- High energy neutrino astronomy: introduction
- IceCube experiment
- Recent results:
  - point sources
  - diffuse fluxes
  - First observation of astrophysical neutrinos (2013)
- Future plans
- Summary and outlook
High Energy Neutrino Astronomy: Motivation

What is the origin of Cosmic Rays with $E$ up to $10^{20}$ eV?

- $\nu$ production:
  \[ p + p \rightarrow \pi + \ldots \rightarrow \nu + \ldots \]
  \[ p + \gamma \rightarrow \Delta \rightarrow \pi + n \rightarrow \nu + \ldots \]

- Fermi acceleration at sources: power law spectrum $E^{-2}$ for $\phi_\nu$

**Supernova Remnants**
Confirmed by Fermi-LAT

**Active Galactic Nuclei**
Initial Pierre Auger Collaboration result, Science 318(2007)938, linking CR and AGN’s, weaken after new data analyzed

J. Kiryluk (SBU), ICHEP2014, 2-9 July 2014
High Energy Neutrino Astronomy: Motivation

What is the origin of Cosmic Rays with E up to $10^{20}$ eV?

Neutrinos as probes of the HE Universe

Low $\nu$ fluxes and small interaction cross section: need for 1 km$^3$ detector- Neutrino Telescopes

J. Kiryluk (SBU), ICHEP2014, 2-9 July 2014
Neutrinos of all flavors interact in or near the detector through charged current (CC) or neutral current (NC) weak interaction:

\[ \nu_\ell \rightarrow \ell \nu_\ell \]

\[ W, Z \]

\[ \text{hadronic shower} \]

**Neutrino interaction identification method:**

*Idea: 1960, M. Markov*

observe the secondaries

- O(km) muon tracks from $\nu_\mu$ CC
  - $1 \text{ TeV} \sim 2.5 \text{ km}, 1 \text{ PeV} \sim 15 \text{ km}$
- O(10 m) e-m and/or hadronic cascades
  - from $\nu_e$ CC, low energy $\nu_\tau$ CC, and $\nu_x$ NC

via Cherenkov radiation detected by a 3D array of optical sensors

J. Kiryluk (SBU), ICHEP2014, 2-9 July 2014
(Very High Energy) Neutrino Telescopes: Locations

Techniques:
- optical detection
- radio/acoustic detection

- Antares
- *Km3net (3 sites)*

Southern Sky

- Lake Baikal

Northern Sky

- Mediterranean

this talk
- IceCube
- HEX
- *PINGU (LE)*
- RICE
- ARA

South Pole Antarctica

Coast of Antarctica

Anita
- Arianna

J. Kiryluk (SBU), ICHEP2014, 2-9 July 2014
The IceCube Detector

Detector configuration:
- IC9 (2006)
- IC22 (2007)
- IC40 (2008)
- IC59 (2009)
- IC79 (2010)
- IC86 (≥2011)
- >99% uptime

Ice properties:
- \( \lambda_{\text{abs}} \approx 110 \text{m} @ 400 \text{nm} \)
- \( \lambda_{\text{sca}} \approx 20 \text{m} @ 400 \text{ nm} \)

J. Kiryluk (SBU), ICHEP2014, 2-9 July 2014
Event Signatures

Neutrino interaction identification method: observe the secondaries (tracks, cascades) via Cherenkov radiation detected by a 3D array of optical sensors.

**μ Tracks:**
- $\nu_\mu + N \rightarrow \mu + X$
- through-going muons
- visible energy resolution $\approx 20\%$
- pointing resolution $<1^\circ$

**Cascades:**
- e-m and hadronic cascades
- $\nu_{e(\tau)} + N \rightarrow e(\tau) + X$
- $\nu_f + N \rightarrow \nu_f + X \quad f = e, \mu, \tau$
- Resolutions, cascades contained in the detector
  - visible energy $< \sim 20\%$
  - angular $\sim 10^\circ-40^\circ$

**Composites** (not yet observed)
- starting tracks
- tau double bangs
- good directional and energy resolution

J. Kiryluk (SBU), ICHEP2014, 2-9 July 2014
Atmospheric $\mu$ Background

Atm. $\mu$ 10$^{11}$/year
Atm. $\nu$ 10$^5$/year

Reconstruct $\mu$ tracks (using max likelihood fits) and identify their origin ($\mu$ vs atm. $\nu$) by their direction

J. Kiryluk (SBU), ICHEP2014, 2-9 July 2014
IceCube 59-string Data

Hit Modules: 610
Zenith: 91.2°
Azimuth: 274.1°
Angular Unc.: 0.2°
Muon Energy: 83 TeV
Neutrino Energy: > 100 TeV

Run 114305  Event 10091078  [Ops 14000ns]  Color = hit times
Moon shadow observed in cosmic ray muons

Data: 59-strings (2009-2010)

Important verification of angular resolution and absolute pointing

- Moon shadow seen with $\sim 14\sigma$ (deficit of $\sim 8700$ events)
- Systematic pointing error less than $0.1^\circ$
- Angular resolution $0.7^\circ$

J. Kiryluk (SBU), ICHEP2014, 2-9 July 2014
Point Source Neutrino Search (ν\textsubscript{μ})

Search for excess of astrophysical ν from a common direction over the background of atmospheric ν (Northern Sky) or μ (Southern Sky)

Signal: Astrophysical neutrinos clustering in space
Background: Isotropic atmospheric neutrinos

Maximize the likelihood function:

$$L(n_s, \gamma) = \prod_{i=1}^{N} \left( \frac{n_s}{N} S_i(\gamma) + (1 - \frac{n_s}{N}) B_i \right)$$

Braun et al., arXiv:0801.1604

Test statistic:

$$\lambda = \log \left( \frac{L(\hat{n}_s, \hat{n}_s)}{L(n_s = 0)} \right)$$

Obtain p-value by comparing test statistic for real data to random trials from scrambled data

Fit for:
- n\textsubscript{s}, # of signal events
- γ, neutrino spectral index

Repeat: at every point in the sky
Point Source Neutrino Search $\nu_\mu$

40-, 59-, 79- and 86- strings (4 years) data combined

Submitted to ApJ

The significance map

Example: Hottest spot in the Northern sky
Ra=29.25, Dec=10.75
- Not significant
- 22.6% of trials have significance $\geq$ hottest spot

... a mostly uniform structure ...

J. Kiryluk (SBU), ICHEP2014, 2-9 July 2014
Search for Diffuse Neutrino Fluxes

*Diffuse flux* = effective sum from all (unresolved) extraterrestrial sources (e.g. AGNs) Possibility to observe diffuse signal even if flux from an individual source is too small to be detected by point source techniques.

- Search for excess of astrophysical neutrinos with a harder spectrum than background atmospheric neutrinos using energy and direction (self-veto)

  *See next talk: T. Gaisser*

- Advantage over point source search: can detect weaker fluxes

- Sensitive to all three flavors of neutrinos assumption: $\nu_e : \nu_\mu : \nu_\tau \equiv 1:1:1$ at Earth

- IceCube does not distinguish between $\nu$ and $\bar{\nu}$ exception: $\nu_e$ and $\bar{\nu}_e$ at the Glashow resonance

- Disadvantage: high background solution: containment cut / veto technique

J. Kiryluk (SBU), ICHEP2014, 2-9 July 2014
Atmospheric Neutrinos: $\nu_\mu$ and $\nu_e$

Conventional neutrino flux

$\pi, K \rightarrow \mu + \nu_\mu \rightarrow e + \nu_e + \nu_\mu$

atmospheric $\nu_\mu$ spectrum (IC40);
first measurement in the energy range 80 GeV – 6 TeV

atmospheric $\nu_e$ spectrum, measured in IC79 (Deep Core);
first measurement in the energy range 200 GeV – 10 TeV

Prompt neutrino flux

decays of D,B mesons

predicted prompt atmospheric $\nu$-fluxes from charmed meson decays, Enberg et al


- not yet measured, IceCube limit:
  $\Phi_{\text{prompt}} (E_\nu) \leq 3.8 \times \Phi_{\text{ERS08+H3a}} (E_\nu)$
  
  Phys. Rev. D89 (2014) 062007 ($\nu_\mu$ IC59)

See next talk: T. Gaisser

Atmospheric Neutrinos: $\nu_\mu$ and $\nu_e$


assumption: 1:1:1 flavor ratio, 1:1 neutrino:anti-neutrino

Astrophysical neutrinos

Waxman-Bahcall Bound (all flavor)

$E^2 \Phi_{WB} \approx 3.4 \times 10^{-8}$ GeV/cm$^2$sr s
Astrophysical All Flavor Neutrinos: Contained Cascades

Data: 40-strings (2008-2009)
High Energy $E_{\text{reco}} > 100$ TeV

IceCube, Phys. Rev. D 89 (2014) 102001

Observed 3 events (energies 140 TeV – 220 TeV)

2.7σ excess over atm. $\mu$ and at. $\nu$

$E_\nu^2 \cdot \Phi_{\text{astro}} (E_\nu) = 5 \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$

$E_\nu^2 \cdot \Phi_{\text{astro}} (E_\nu) = (2 - 14) \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$

all flavor

at 90% CL

J. Kiryluk (SBU), ICHEP2014, 2-9 July 2014
IC79+IC86 analysis of *Extremely High Energy* filter data (2010-2012) to search for cosmogenic or GZK all-flavor neutrinos (PeV-EeV)

\[ p + \gamma_{\text{CMB}} \rightarrow \Delta \rightarrow \pi + n \rightarrow \nu + ... \]

\[ E_p > 6 \times 10^{19} \text{eV} \]

Two cascade like PeV events, found in an analysis dedicated to a search for bright events
Evidence for High Energy Extraterrestrial Neutrinos

IceCube Collab., Science 22 Vol. 342 no. 6161

IC79+IC86 analysis of “Starting Events” (2010-2012, 662 days) to search for all-flavor neutrinos (starting tracks + contained cascades)

We report on results of an all-sky search for high-energy neutrino events interacting within the IceCube neutrino detector conducted between May 2010 and May 2012. The search follows up on the previous detection of two PeV neutrino events, with improved sensitivity and extended energy coverage down to approximately 30 TeV. Twenty-six additional events were observed, substantially more than expected from atmospheric backgrounds. Combined, both searches reject a purely atmospheric origin for the twenty-eight events at the 4σ level. These twenty-eight events, which include the highest energy neutrinos ever observed, have flavors, directions, and energies inconsistent with those expected from the atmospheric muon and neutrino backgrounds. These properties are, however, consistent with generic predictions for an additional component of extraterrestrial origin.
High Energy Starting Events ("HESE")

Data: 79- and 86-strings (2010-2013, 988 days)

*Accepted by Phys. Rev. Lett.; arXiv:1405.5303*

- Select high charge ($Q_{\text{tot}}>6000$ p.e.) events with vertices well contained in the detector volume
- No flavor tagging, combination of neutrino induced muons and cascades
- Use of the "veto" technique to reject bg and veto tagging to estimate remaining bg from exp data

Reject incoming muons when "early charge" in veto region

J. Kiryluk (SBU), ICHEP2014, 2-9 July 2014
High Energy Starting Events ("HESE")

Data: 79- and 86-strings (2010-2013, 988 days)


Observed 37 events (28 cascade-like, 9 track-like) in $30 \ TeV < E_\nu < 3 \ PeV$, Expected $8.4 \pm 4.2$ number of background $\mu$ and $6.6^{+5.9}_{-1.6}$ atm. $\nu$ events.

J. Kiryluk (SBU), ICHEP2014, 2-9 July 2014
High Energy Starting Events ("HESE")

Data: 79- and 86-strings (2010-2013, 988 days)


J. Kiryluk (SBU), ICHEP2014, 2-9 July 2014
High Energy Starting Events ("HESE")

Data: 79- and 86-strings (2010-2013, 988 days)


J. Kiryluk (SBU), ICHEP2014, 2-9 July 2014
High Energy Starting Events ("HESE")

Data: 79- and 86-strings (2010-2013, 988 days)


\[ E^2 \Phi = \left( 0.95 \pm 0.30 \right) \times 10^{-8} \text{[GeV}^{-1}\text{sr}^{-1}\text{cm}^{-2}] \] (per \( \nu \) flavor)

60 TeV \( \leq E_\nu \leq 3 \text{PeV} \) fit energy range

Background only hypothesis disfavored at 5.7\( \sigma \)
High Energy Starting Events (“HESE”)

Data: 79- and 86-strings (2010-2013, 988 days)


ν interacts in the Earth (Earth absorption)
interaction cross section increases with energy
High Energy Starting Events ("HESE")

Data: 79- and 86-strings (2010-2013, 988 days)


atm. ν self-veto

Earth absorption
High Energy Starting Events ("HESE")

Data: 79- and 86-strings (2010-2013, 988 days)

High Energy Starting Events ("HESE")

Data: 79- and 86-strings (2010-2013, 988 days)

High Energy Starting Events (“HESE”)

Data: 79- and 86-strings (2010-2013, 988 days)


J. Kiryluk (SBU), ICHEP2014, 2-9 July 2014
High Energy Starting Events ("HESE")

Data: 79- and 86-strings (2010-2013, 988 days)

High Energy Starting Events (“HESE”)

Data: 79- and 86-strings (2010-2013, 988 days)


J. Kiryluk (SBU), ICHEP2014, 2-9 July 2014
High Energy Starting Events ("HESE")

Data: 79- and 86-strings (2010-2013, 988 days)


J. Kiryluk (SBU), ICHEP2014, 2-9 July 2014
High Energy Starting Events ("HESE")

Data: 79- and 86-strings (2010-2013, 988 days)

High Energy Starting Events ("HESE")

Data: 79- and 86-strings (2010-2013, 988 days)


\[ E_{\text{up}} > 240 \text{ TeV} \]

atm. $\nu$ self-veto

Earth absorption

J. Kiryluk (SBU), ICHEP2014, 2-9 July 2014
High Energy Starting Events ("HESE")

Data: 79- and 86-strings (2010-2013, 988 days)


J. Kiryluk (SBU), ICHEP2014, 2-9 July 2014
High Energy Starting Events ("HESE")

Data: 79- and 86-strings (2010-2013, 988 days)


J. Kiryluk (SBU), ICHEP2014, 2-9 July 2014
High Energy Starting Events ("HESE")

Data: 79- and 86-strings (2010-2013, 988 days)

High Energy Starting Events ("HESE")

- spectrum unfolded true neutrino energy, simultaneously fitting for backgrounds ($E > 60$ TeV)
- assumption: 1:1:1 flavor ratio, 1:1 neutrino:anti-neutrino


$E^{-\gamma}$  
Shape consistent with $E^{-2}$ (+cut-off?)
Alternative explanation: softer spectrum  $\gamma = -2.3 \pm 0.3$

J. Kiryluk (SBU), ICHEP2014, 2-9 July 2014
High Energy Starting Events ("HESE")

Data: 79- and 86-strings (2010-2013, 988 days)

No evidence of (significant) spatial clustering

J. Kiryluk (SBU), ICHEP2014, 2-9 July 2014
High Energy Starting Events ("HESE")

Data: 79- and 86-strings (2010-2013, 988 days)

Correlation with potential sources?

Northern source list: p-value = 28%
Southern source list: p-value = 8%

Correlation with Galactic plane?

Best fit width +/- 7.5 degrees : p-value = 2.8%
Fixed width +/- 2.5 degrees : p-value = 24%

No evidence of (significant) correlation

J. Kiryluk (SBU), ICHEP2014, 2-9 July 2014

Diffuse Flux of Muon Neutrinos: Tracks


Data: 79+86-strings (2010-2012): PRELIMINARY

Best-fit results:

\[ E^2 \cdot \Phi_{\text{astro}}(E_{\nu}) = 1.0 \times 10^{-8} \text{GeVcm}^{-2}\text{s}^{-1}\text{sr}^{-1} \]

\[ E^2 \cdot \Phi_{\text{astro}}(E_{\nu}) = (0.7 - 1.4) \times 10^{-8} \text{GeVcm}^{-2}\text{s}^{-1}\text{sr}^{-1} \quad 1\sigma \text{ range} \]

Background only hypothesis disfavored at 3.9\(\sigma\)

J. Kiryluk (SBU), ICHEP2014, 2-9 July 2014
The IceCube $\nu_\mu$ flux is at the same level as the HESE (starting event) flux (per flavor): strong indication for an all flavor flux with its implications.

The IceCube astrophysical $\nu$ flux is at the same level as the Waxman-Bahcall upper bound: coincidence or “physics” (indication for extra-Galactic $\nu$ sources)?
IceCube Upgrade: High Energy Extension (HEX) in addition to PINGU Low Energy extension (see talk by K. Clark /July 4)

Initial simulation of geometries

IC86 (current detector)
string spacing: ~125m

Angular resolution: 0.5°
Effective area: 1.6km²

IC86+96 strings
string spacing: ~240m

0.4°
5.0 km²

IC86+2x60 strings
string spacing: ~240m

0.4°
6.5 km²

J. Kiryluk (SBU), ICHEP2014, 2-9 July 2014
Background rejection:
- reject most of atm. $\mu$ and atm. $\nu$

An extended surface array:
- increase the angular veto coverage

Flux: $47.4 \times 10^{-8} \ E^{-2.3}$

-~75% increase in rate >100TeV

Surface array to 5 km
Summary and Outlook

Atmospheric neutrinos:
- Atmospheric conventional TeV neutrino flux measurements, prompt neutrino limits
  100,000’s $\nu$ on the books

Astrophysical neutrinos:
- First observation of astrophysical high energy (PeV) neutrinos
  - Diffuse flux (79+86 strings):
    - “Starting events” (3y): $E^2 \Phi_{\text{astro}} = (0.95 \pm 0.30) \times 10^{-8} \text{[GeV s}^{-1}\text{sr}^{-1}\text{cm}^{-2}]$
    - Muon neutrinos (2y): $E^2 \cdot \Phi_{\text{astro}} = 1.0^{+0.4}_{-0.3} \times 10^{-8} \text{[GeV cm}^{-2}\text{s}^{-1}\text{sr}^{-1}]$
  - Cascade channel (2y): unblinded, results release soon
  - No evidence of significant spacial clustering found. Extra-Galactic neutrinos?

IceCube continues to gain in sensitivity
- Continuous data taking with full detector, improved analysis techniques

Proposal for a next generation HEX detector (in addition to PINGU LE extension)
- Increased in-ice volume, enhanced surface veto (astrophysical $\nu$ point sources)

Era of km$^3$ neutrino astronomy has begun – Stay tuned!
The IceCube Collaboration

250 people, 43 institutions, 12 countries

Funding Agencies

<table>
<thead>
<tr>
<th>Funding Agency</th>
<th>Funding Agency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fonds de la Recherche Scientifique (FRS-FNRS)</td>
<td>Deutsches Elektronen-Synchrotron (DESY)</td>
</tr>
<tr>
<td>Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)</td>
<td>Japan Society for the Promotion of Science (JSPS)</td>
</tr>
<tr>
<td>Federal Ministry of Education &amp; Research (BMBF)</td>
<td>Knut and Alice Wallenberg Foundation</td>
</tr>
<tr>
<td>German Research Foundation (DFG)</td>
<td>Swedish Polar Research Secretariat</td>
</tr>
<tr>
<td></td>
<td>The Swedish Research Council (VR)</td>
</tr>
<tr>
<td></td>
<td>University of Wisconsin Alumni Research Foundation (WARF)</td>
</tr>
<tr>
<td></td>
<td>US National Science Foundation (NSF)</td>
</tr>
</tbody>
</table>

http://icecube.wisc.edu
Backup
Digital Optical Module (DOM)

DOM+Main Board - a complete DAQ system

- internal digitization (waveform digitizers) and time stamping the photonic output signals from the PMT
- wide dynamic range: from single p.e. to thousands p.e.
- performs PMT gain and time calibration
- power consumption 3W, deadtime < 1%, dark noise rate < 400 Hz

Triggering and Filtering

- Local coincidence communication between DOMs
- Triggering on surface
- Physics filtering (simple reconstruction algorithms) on data sent to the North via satellite

Example, InIce DAQ

Online Data Filtering
Satellite transfer
Data Warehousing

J. Kiryluk (SBU), ICHEP2014, 2-9 July 2014
Ice Properties: scattering and absorption

The South Pole ice is:

- very clear and tilted
- well understood/modelled
- an excellent medium for particle detection!


J. Kiryluk (SBU), ICHEP2014, 2-9 July 2014
Cascades - resolutions

Diffuse Flux of Muon Neutrinos

Data: 59-strings (2009-2010)

Best-fit results:

\[ E_\nu \cdot \Phi_{\text{astro}} (E_\nu) = 0.25^{+0.70}_{-0.20} \times 10^{-8} \text{GeVcm}^{-2}\text{s}^{-1}\text{sr}^{-1} \]

prompt flux \[ N_p [\text{ERS08+H3a}] = 0.00^{+2.41}_{-0.00} \]

Upper limits 90%CL

\[ E_\nu^2 \cdot \Phi_{\text{astro}} (E_\nu) \leq 1.44 \times 10^{-8} \text{GeVcm}^{-2}\text{s}^{-1}\text{sr}^{-1} \]

\[ \Phi_{\text{prompt}} (E_\nu) \leq 3.8 \times \Phi_{\text{ERS08+H3a}} (E_\nu) \]

\[ 35 \text{ TeV} \leq E_\nu \leq 36 \text{ PeV} \]

\[ 3 \text{ TeV} \leq E_\nu \leq 0.36 \text{ PeV} \]


J. Kiryluk (SBU), ICHEP2014, 2-9 July 2014
Data: 59-strings (2009-2010)
High Energy - astrophysical cascades

A. Schoenwald et al (IceCube), ICRC2013 paper 0662

- After final selections: 8 events found (4 bg expected), no excess

Flux upper limit 90% CL

\[ E^2 \Phi_{90\%} = 1.7 \times 10^{-8} \text{ GeV s}^{-1} \text{ sr}^{-1} \text{ cm}^{-2} \]

43 TeV < \( \nu \) < 6 PeV

(per \( \nu \) flavor)
High Energy Starting Events ("HESE")

Throughgoing muon

- Total detector
- Veto region

Q/pe vs Time/μs

Veto region

Q/pe vs Time/μs

T_{250} = time at which Q = 250 pe

Contained cascade

- Total detector
- Veto region – barely contained cascade
- Veto region – well contained cascade

Q/pe vs Time/μs

Veto region

Q/pe vs Time/μs

T_{250} = time at which Q = 250 pe
High Energy Starting Events ("HESE")

Data: 79- and 86-strings (2010-2013, 988 days)


J. Kiryluk (SBU), ICHEP2014, 2-9 July 2014
High Energy Starting Events ("HESE")

Data: 79- and 86-strings (2010-2013, 988 days)


Likelihood fit results

Note: LLh fit results are for $E_{\text{vis}} > 60$ TeV

J. Kiryluk (SBU), ICHEP2014, 2-9 July 2014
High Energy Starting Events ("HESE")

Data: 79- and 86-strings (2010-2013, 988 days)


<table>
<thead>
<tr>
<th>60 TeV &lt; ( E_{\text{dep}} &lt; 3 ) PeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muons</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>Tot. Events</td>
</tr>
<tr>
<td>Up</td>
</tr>
<tr>
<td>Down</td>
</tr>
<tr>
<td>Track</td>
</tr>
<tr>
<td>Shower</td>
</tr>
<tr>
<td>Fraction Up</td>
</tr>
<tr>
<td>Fraction Down</td>
</tr>
<tr>
<td>Fraction Tracks</td>
</tr>
<tr>
<td>Fraction Showers</td>
</tr>
</tbody>
</table>

Note: Llh fit results are for \( E_{\text{vis}} > 60 \) TeV

J. Kiryluk (SBU), ICHEP2014, 2-9 July 2014
High Energy Starting Events ("HESE")

Data: 79- and 86-strings (2010-2013, 988 days)

<table>
<thead>
<tr>
<th>E_{dep} &lt; 60 TeV</th>
<th>Muons</th>
<th>π/K atm. ν</th>
<th>Prompt atm. ν</th>
<th>E^{-2} (best-fit)</th>
<th>Sum (central)</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tot. Events</td>
<td>8.0</td>
<td>4.2</td>
<td>&lt; 3.7</td>
<td>2.2</td>
<td>14.4</td>
<td>16</td>
</tr>
<tr>
<td>Up</td>
<td>0</td>
<td>2.5</td>
<td>&lt; 2.3</td>
<td>1.2</td>
<td>3.7</td>
<td>4</td>
</tr>
<tr>
<td>Down</td>
<td>8.0</td>
<td>1.7</td>
<td>&lt; 1.4</td>
<td>1.1</td>
<td>10.7</td>
<td>12</td>
</tr>
<tr>
<td>Track</td>
<td>\sim 7.2</td>
<td>2.9</td>
<td>&lt; 0.7</td>
<td>0.4</td>
<td>10.5</td>
<td>4</td>
</tr>
<tr>
<td>Shower</td>
<td>\sim 0.8</td>
<td>1.4</td>
<td>&lt; 3.0</td>
<td>1.8</td>
<td>4.0</td>
<td>12</td>
</tr>
<tr>
<td>Fraction Up</td>
<td>0%</td>
<td>60%</td>
<td>63%</td>
<td>51%</td>
<td>26%</td>
<td>25%</td>
</tr>
<tr>
<td>Fraction Down</td>
<td>100%</td>
<td>40%</td>
<td>37%</td>
<td>49%</td>
<td>74%</td>
<td>75%</td>
</tr>
<tr>
<td>Fraction Tracks</td>
<td>&gt; 90%</td>
<td>68%</td>
<td>19%</td>
<td>19%</td>
<td>72%</td>
<td>25%</td>
</tr>
<tr>
<td>Fraction Showers</td>
<td>&lt; 10%</td>
<td>32%</td>
<td>81%</td>
<td>81%</td>
<td>28%</td>
<td>75%</td>
</tr>
</tbody>
</table>

Note: Llh fit results are for E_{vis} > 60 TeV

J. Kiryluk (SBU), ICHEP2014, 2-9 July 2014
High Energy Starting Events ("HESE")

Data: 79- and 86-strings (2010-2013, 988 days)

<table>
<thead>
<tr>
<th>all events</th>
<th>Muons</th>
<th>(\pi/K) atm. (\nu)</th>
<th>Prompt atm. (\nu)</th>
<th>(E^{-2}) (best-fit)</th>
<th>Sum (central)</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tot. Events</td>
<td>8.4 ± 4.2</td>
<td>6.6^{+2.2}_{-1.6}</td>
<td>&lt; 9.0 (90% CL)</td>
<td>23.8</td>
<td>38.8</td>
<td>37 (36)</td>
</tr>
<tr>
<td>Up</td>
<td>0</td>
<td>4.0</td>
<td>&lt; 5.8</td>
<td>8.2</td>
<td>12.2</td>
<td>9</td>
</tr>
<tr>
<td>Down</td>
<td>8.4</td>
<td>2.6</td>
<td>&lt; 3.2</td>
<td>15.6</td>
<td>26.6</td>
<td>27</td>
</tr>
<tr>
<td>Track</td>
<td>\sim 7.6</td>
<td>4.5</td>
<td>&lt; 1.7</td>
<td>4.5</td>
<td>16.7</td>
<td>8</td>
</tr>
<tr>
<td>Shower</td>
<td>\sim 0.8</td>
<td>2.1</td>
<td>&lt; 7.3</td>
<td>19.3</td>
<td>22.2</td>
<td>28</td>
</tr>
<tr>
<td>Fraction Up</td>
<td>0%</td>
<td>61%</td>
<td>65%</td>
<td>34%</td>
<td>31%</td>
<td>25%</td>
</tr>
<tr>
<td>Fraction Down</td>
<td>100%</td>
<td>39%</td>
<td>35%</td>
<td>66%</td>
<td>69%</td>
<td>75%</td>
</tr>
<tr>
<td>Fraction Tracks</td>
<td>&gt; 90%</td>
<td>69%</td>
<td>19%</td>
<td>19%</td>
<td>43%</td>
<td>24%</td>
</tr>
<tr>
<td>Fraction Showers</td>
<td>&lt; 10%</td>
<td>31%</td>
<td>81%</td>
<td>81%</td>
<td>57%</td>
<td>76%</td>
</tr>
</tbody>
</table>

Note: LH fit results are for \(E_{\text{vis}} > 60\) TeV

J. Kiryluk (SBU), ICHEP2014, 2-9 July 2014
<table>
<thead>
<tr>
<th>Category</th>
<th>Source</th>
<th>RA (°)</th>
<th>Dec (°)</th>
<th>$n_s$</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNR</td>
<td>TYCHO</td>
<td>6.36</td>
<td>64.18</td>
<td>0.0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Cas A</td>
<td>350.55</td>
<td>58.82</td>
<td>0.0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>IC443</td>
<td>04.18</td>
<td>22.53</td>
<td>0.0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>W51C</td>
<td>290.75</td>
<td>14.19</td>
<td>0.7</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>W44</td>
<td>284.04</td>
<td>1.38</td>
<td>2.5</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>W28</td>
<td>270.43</td>
<td>-23.34</td>
<td>4.3</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>RX J1713.7-3048</td>
<td>268.25</td>
<td>-30.75</td>
<td>0.0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>RX J0852.0-4629</td>
<td>132.00</td>
<td>-46.37</td>
<td>0.0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>RCVW 86</td>
<td>220.68</td>
<td>-62.48</td>
<td>0.3</td>
<td>0.41</td>
</tr>
<tr>
<td>XB/mqso</td>
<td>LSI 303</td>
<td>40.13</td>
<td>61.23</td>
<td>0.0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Cyg X-3</td>
<td>308.10</td>
<td>41.23</td>
<td>0.8</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>Cyg X-1</td>
<td>290.59</td>
<td>35.20</td>
<td>1.0</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>HESS J0632-057</td>
<td>98.24</td>
<td>5.81</td>
<td>0.0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>SS433</td>
<td>287.96</td>
<td>4.96</td>
<td>1.5</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>LS 5039</td>
<td>278.56</td>
<td>-14.83</td>
<td>4.0</td>
<td>0.002</td>
</tr>
<tr>
<td></td>
<td>GX 339.4</td>
<td>255.7</td>
<td>-48.70</td>
<td>0.0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Cir X-1</td>
<td>230.17</td>
<td>-57.17</td>
<td>0.0</td>
<td>-</td>
</tr>
<tr>
<td>Star Form</td>
<td>Cyg OB2</td>
<td>308.10</td>
<td>41.23</td>
<td>0.8</td>
<td>0.05</td>
</tr>
<tr>
<td>Region</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pulsar/PWN</td>
<td>MGRO J19019+37</td>
<td>305.32</td>
<td>36.83</td>
<td>0.9</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>Crab Nebula</td>
<td>83.63</td>
<td>22.01</td>
<td>0.0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Geminga</td>
<td>98.48</td>
<td>17.77</td>
<td>0.0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>HESS J1912+101</td>
<td>288.21</td>
<td>10.15</td>
<td>0.8</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>Vela X</td>
<td>128.75</td>
<td>-45.6</td>
<td>0.0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>HESS J1632-478</td>
<td>248.04</td>
<td>-47.82</td>
<td>0.0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>HESS J1616-508</td>
<td>243.78</td>
<td>-51.40</td>
<td>0.0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>HESS J1033-575</td>
<td>155.83</td>
<td>-57.76</td>
<td>0.2</td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td>MSH 15-52</td>
<td>298.53</td>
<td>-50.16</td>
<td>0.6</td>
<td>0.48</td>
</tr>
<tr>
<td></td>
<td>HESS J1303-631</td>
<td>195.74</td>
<td>-63.52</td>
<td>0.8</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>PSR B1959-63</td>
<td>195.74</td>
<td>-63.52</td>
<td>0.8</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>HESS J1356-645</td>
<td>209.00</td>
<td>-64.5</td>
<td>0.5</td>
<td>0.35</td>
</tr>
<tr>
<td>Galactic</td>
<td>Sgr A*</td>
<td>266.42</td>
<td>-29.01</td>
<td>3.1</td>
<td>0.04</td>
</tr>
<tr>
<td>Center</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Not</td>
<td>MGRO J19019-06</td>
<td>286.90</td>
<td>6.27</td>
<td>1.3</td>
<td>0.03</td>
</tr>
<tr>
<td>Identified</td>
<td>HESS J1834-087</td>
<td>278.09</td>
<td>-8.76</td>
<td>4.7</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>HESS J1741-309</td>
<td>265.35</td>
<td>-30.2</td>
<td>2.5</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>HESS J1503-582</td>
<td>228.46</td>
<td>-58.74</td>
<td>0.2</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>HESS J1507-622</td>
<td>225.72</td>
<td>-62.34</td>
<td>0.1</td>
<td>0.47</td>
</tr>
</tbody>
</table>

**SUPPL. TABLE II.** Catalog of 36 galactic sources, grouped according to their classification as supernova remnants (SNR), X-ray binaries or microquasars (XB/mqso), pulsar wind nebulae (PWN), star formation regions, and unidentified sources. The post-trials p-values for the entire catalog in the northern and southern hemispheres were 28% and 8%, respectively. For each source, the pre-trials p-value was estimated by repeating the source catalog search with the data randomized in right ascension. The fraction of test statistic (TS) values from all individual sources that were greater than or equal to the observed TS determined the pre-trials p-value. The best-fit # of signal events ($n_s$) is the result of the likelihood fit at each individual source. When $n_s = 0$, no p-value is reported. Since many sources are spatially close together relative to the angular resolution, adjacent sources often receive similar fit results. For sources separated by less than 1°, their positions are averaged and they are treated as one source.

**SUPPL. TABLE III.** Catalog of 42 extragalactic sources, grouped according to their classification as BL Lac objects, Radio galaxies, Flat Spectrum Radio Quasars (FSRQ), Starburst galaxies, and Seyfert galaxies. A description of the information in the table can be found in Suppl. Tab. III.