Search for PeV Gamma-Ray Point Sources with IceCube

Zach Griffith and Hershal Pandya

The IceCube Collaboration

ICRC2017

19 July 2017

Busan, South Korea
Motivation

IceCube is the most sensitive southern hemisphere experiment to PeV gamma rays

IceCube can test whether the spectra of known TeV sources extend up to PeV energies without a cut-off
Motivation

Observation of PeV Gamma-rays can indicate galactic origin of some of the IceCube neutrinos.

primary process $\rightarrow \pi^0 (+\pi^\pm) + \ldots \rightarrow \gamma_{\text{UHE}} (+\nu_{\text{UHE}}) + \ldots$
Gamma Hadron Discrimination

- Gamma-ray air showers have ~10 times fewer muons, less local fluctuations, and younger shower age compared to cosmic-ray showers

- IceTop measures:
  ‣ Shower energy
  ‣ Shower core and direction
  ‣ Peripheral GeV muons
  ‣ Lateral distributions of energy and timing

- IceCube measures:
  ‣ Thoroughgoing (>300 GeV) muons from shower core
IceTop Gamma/Hadron Discrimination

**Gamma Ray Simulation**

Log(Tank Charge / VEM)

Log(Lateral Distance from Shower Axis / m)

**Cosmic Ray Data**

Log(Tank Charge / VEM)

Log(Lateral Distance from Shower Axis / m)

\[ LLHR = \log_{10} \left( \frac{L(\{Q_i R_i\} \mid H'_\gamma)}{L(\{Q_i R_i\} \mid H_{CR})} \right); i = 1 \text{ to } 162 \text{ IT Tanks} \]

Random Forest Classifier

- Features
  - IceCube Charge
  - IceTop LLHRatio
  - $\log_{10}(S_{125})$ (IceTop energy proxy)
  - $\sin(\text{Declination})$
  - IceCube Containment

- Train 2 classifiers:
  - 1\textsuperscript{st} with gamma simulation weighted to $E^{-2.0}$
  - 2\textsuperscript{nd} with gamma simulation weighted to $E^{-2.7}$

- Point source selection takes events with random forest score $>0.7$ in either classifier
All-Sky Scan

- Implemented with 5 years of full detector data
- Test over entire sky using standard unbinned likelihood method
  ‣ with energy weights
  ‣ fitting to spectral index
- Significance of hottest spot determined by background trial comparison
- hottest spot post-trial p-value: 77%

South Pole Projection

Hottest Spot

- $\delta = -63.5^\circ$  $\quad \alpha = 28.5^\circ$
- $\gamma = 3.21$  $\quad n_s = 11.22$
- Flux: $1.75 \times 10^{-19}$ GeV$^{-1}$cm$^{-2}$s$^{-1}$
Point Source Sensitivity

- Sensitivity:
  ‣ 90% C.L. upper limit
- Discovery Potential:
  ‣ 5σ detection 50% of the time

- H.E.S.S. sources shown assume optimistic scenario:
  ‣ no break in the fitted power law at TeV energies
  ‣ no absorption

Flux at 1 PeV [cm$^{-2}$s$^{-1}$TeV$^{-1}$]

Unexplored Sky  H.E.S.S. Gal. Plane Survey

Declination (°)
# H.E.S.S. Sources

<table>
<thead>
<tr>
<th>Source</th>
<th>pre-trial p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>HESS J1356-645</td>
<td>&gt;0.50</td>
</tr>
<tr>
<td>HESS J1507-622</td>
<td>0.28</td>
</tr>
<tr>
<td>SNR G292.2-00.5</td>
<td>0.39</td>
</tr>
<tr>
<td>Kookaburra (Rabbit)</td>
<td>0.35</td>
</tr>
<tr>
<td>HESS J1458-608</td>
<td>0.20</td>
</tr>
<tr>
<td>HESS J1427-608</td>
<td>0.11</td>
</tr>
<tr>
<td>Kookaburra (PWN)</td>
<td>&gt;0.50</td>
</tr>
<tr>
<td>SNR 6318.2+00.1</td>
<td>&gt;0.50</td>
</tr>
<tr>
<td>MSH 15-52</td>
<td>0.47</td>
</tr>
<tr>
<td>HESS J1018-589 B</td>
<td>0.09</td>
</tr>
<tr>
<td>HESS J1018-589 A</td>
<td>0.12</td>
</tr>
<tr>
<td>HESS J1503-582</td>
<td>0.24</td>
</tr>
<tr>
<td>HESS J1026-582</td>
<td>0.04</td>
</tr>
<tr>
<td>Westerlund 2</td>
<td>0.07</td>
</tr>
<tr>
<td>SNR G327.1-01.1</td>
<td>&gt;0.50</td>
</tr>
</tbody>
</table>

- 15 total in FOV with no evidence of a cutoff at TeV energies
- Hottest individual H.E.S.S. source: H.E.S.S. J1026-582
  - post-trial p-value of hottest source: 45%
- Stacked likelihood test also performed with catalog
  - stacking test p-value: 5%
- Unidentified source with confirmed counterpart at GeV energies by Fermi (Guo et al. 2016)
- Well fit to $E^{-2}$ over 4 orders of magnitude (GeV-TeV) with no cut-off, unique among known TeV sources
- IceCube limit is first at PeV energies
IceCube High Energy Starting Event (HESE) Neutrinos

- Pure sample of neutrino events with strong astrophysical evidence

- Using 4-year sample, where 11 total events have a reconstructed direction within $1\sigma$ of FOV

- Event types:
  
  » Cascades: good energy resolution, poor angular resolution

  » Tracks: poor energy resolution, good angular resolution
IceCube High Energy Starting Event (HESE) Neutrinos

- Cascades
  - Broad spans in declination require convolution of detector acceptance - use template method
  - Spectral index fixed at 4-yr best fit of HESE data: $E^{-2.58}$
  - p-value > 49%

- Tracks
  - Vertical location of track limits right ascension only scrambling
  - For <5° zenith, scramble in right ascension and declination
  - p-value > 71%
Conclusion

- 5 years of IceCube data were analyzed
- 471,461 total candidates in final event sample
- No significant excess found in any point source search
  ‣ All-sky scan
  ‣ H.E.S.S. sources correlation
  ‣ HESE sample correlation
- Limits set most stringent yet to PeV gamma rays
Thank you!
Backup Slides
Comparison to Prior Analysis

- IC40 Analysis:
  - IceCube used as veto
  - No point sources were found
  - Upper limit on the diffuse gamma-ray flux from the Galactic Plane in the energy range 1.2 - 6.0 PeV

- Current Analysis Details:
  - 5 years of IC86 data
  - Energy range of ~1 PeV - 100 PeV
  - Random forest for event selection
  - Cleaned and optimized In-Ice charge
  - Composition sensitive IceTop LLH ratio
IceCube Charge

- The IC-40 analysis required 0 HLC hits in IceCube.
- This analysis uses the total charge in IceCube as a separating feature, a sum of:

  - **Charge in HLC hits**
    - Keep pulses with $3.5 \mu s < t_{\text{pulse}} - t_{\text{ITtrigger}} < 11.5 \mu s$ for events with no IceCube trigger
    - Clean with SeededRT for events with IceCube trigger

  - **Charge in SLC hits**
    - within 130 meters of reconstructed track
    - Top 16 DOMs
    - 1.8 $\mu s$ time window
    - Starting Time = $(4.8 \mu s + \text{depth}/c)/\cos(\text{Zenith})$
Random Forest Classifier

- Implemented using scikit-learn
- Data used for background
  - 10% of each year dedicated as burn sample for training
- Gamma simulation used for signal
  - 80% used for training, remaining 20% kept for final sensitivity
- 5-fold cross-validation used for hyper-parameter optimization
- Overtraining tested with KS test and validation curves of training and testing samples

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>min_samples_split</td>
<td>2</td>
</tr>
<tr>
<td>min_samples_leaf</td>
<td>1</td>
</tr>
<tr>
<td>min_weight_fraction_leaf</td>
<td>0</td>
</tr>
<tr>
<td>max_leaf_nodes</td>
<td>None</td>
</tr>
<tr>
<td>max_depth</td>
<td>8</td>
</tr>
<tr>
<td>n_estimators</td>
<td>1000</td>
</tr>
</tbody>
</table>