Galactic sources: update information from gamma-rays experiments and implications for IceCube

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based on F. Halzen, A. Kheirandish, VN, arXiv:1609.03072 [astro-ph.HE]
M.C. Gonzalez-Garcia, F. Halzen, VN, arXiv:1310.7194 [astro-ph.HE]

Outline

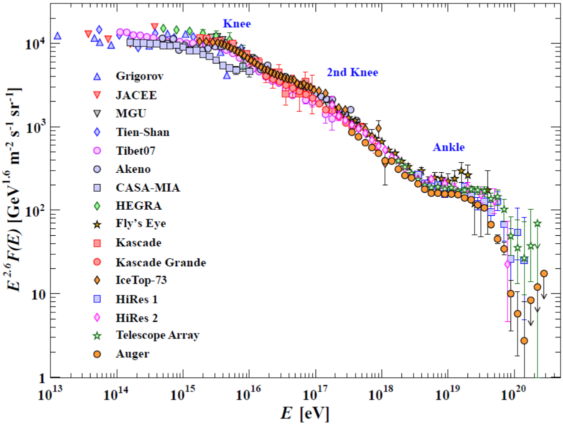
1. Introduction
   - Cosmic-rays
   - Milagro sources
2. High-energy neutrinos
   - IceCube results
   - Predictions for Milagro sources
3. Conclusions

Cosmic-rays and neutrinos

- Cosmic-rays discovered in 1912 by Victor Hess
- Neutrinos are particles that rarely interact with matter and do not feel the magnetic field
  $\Rightarrow$ they can carry information on the physics of accelation of particles and on the most energetic and distant phenomena in the Universe
- They can permit to discriminate unambigously between leptonic and hadronic scenarios
  leptonic: inverse-Compton scattering of low energy photons to high energies by ultra-relativistic electrons
  hadronic: protons and nuclei are accelerated in the source and interact with interstellar material
  $CR + \gamma(p) \rightarrow \pi + X, \qquad \pi^0 \rightarrow \gamma\gamma,\ \pi^- \rightarrow e + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu$
- Neutrinos are "smoking gun" signature of cosmic-rays accelerators
  $\Rightarrow$ identify the origin of cosmic rays

Cosmic-rays spectrum

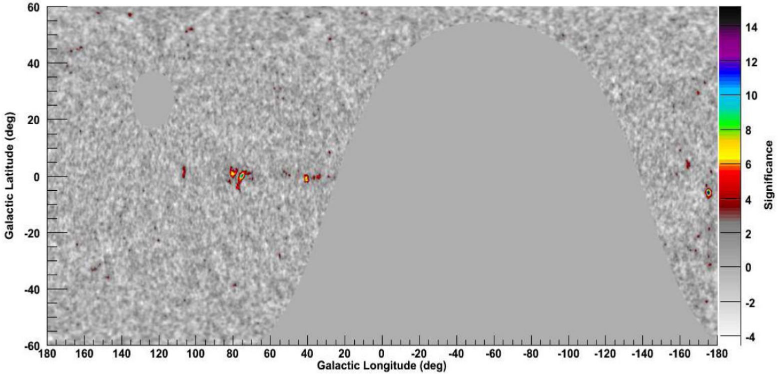
Icetop: 162 Cherenkov detector tanks on top of IceCube
At high energies, protons lose energy interacting with γ_{CMB} (GZK effect)
$\rightarrow \pi^{\pm}$ produce cosmogenic neutrinos



PDG, 2014

Milagro sources

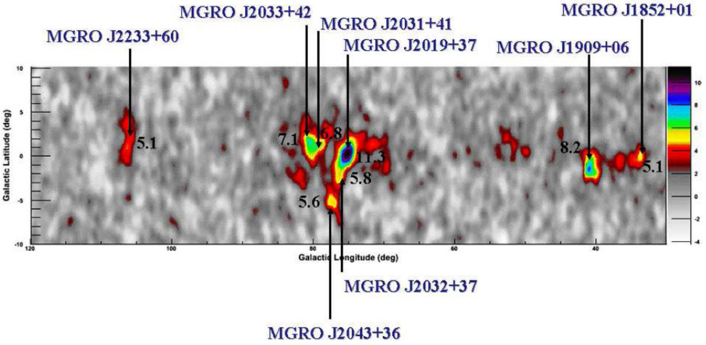
The highest energy survey of the Galactic plane has been performed by Milagro
⇒ bright sources in the nearby Cygnus star-forming region and in the inner part the Galaxy



A. Abdo PhD thesis; Milagro ApJL: A. Abdo, arXiv:0705.0707, A. Abdo, arXiv:0904.1018; Milagro: A. Abdo, arXiv:1202.0846, A.J. Smith, arXiv:1001.3695;

Milagro sources

MGRO J1908+06, MGRO 2019+37, and MGRO J2031+41;
MGRO J2043+36 (C1) and MGRO J2032+37 (C2): Candidate sources;
MGRO J1852: below threshold;



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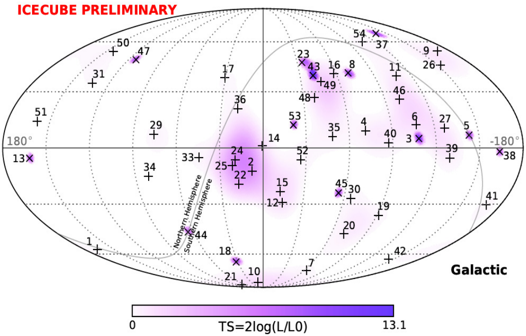
Milagro: A. Abdo, arXiv:1202.0846, A.J. Smith, arXiv:1001.3695;

Four years of IceCube data: astrophysical neutrinos



M.G.Aartsen, 1510.05223 [astro-ph.HE]

54 events: 39 cascades events, 14 track events, 1 event excluded in the analysis (bkg)
Skymap of the test statistic value (L: maximized likelihood; L_0: likelihood under the null hypothesis). Best-fit locations of individual events: vertical crosses (showers) and angled crosses (muon tracks).

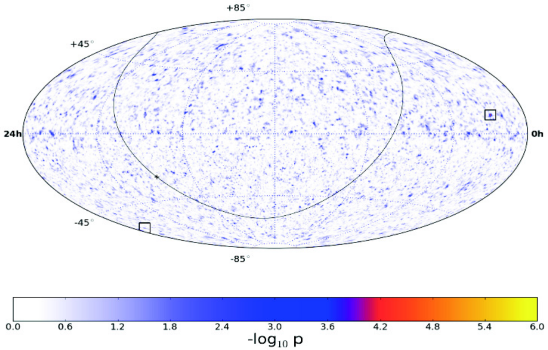
MGRO J1908+096 plausible astronomical counterpart of event 33

P. Padovani and E. Resconi, 1406.0376 [astro-ph.HE]

IceCube point source searches

IC40+59+79+86-I:

- MGRO J2019+37 and MGRO J1908+06: $\hat{n}_S = 0$ (best-fit number of signal events). No $p-$value reported.
- six Milagro sources: $p-$value: 2%



Aarsten, et. al, arXiv: 1406.6757 [astro-ph.HE]

HAWC results and neutrino flux

The HAWC experiment has confirmed only four of the six sources:
MGRO J1908+06, MGRO J1852+01, MGRO J2031+41, and MGRO J2019+37

A.U. Abeysekara et al., arXiv:1509.05401 [astro-ph.HE]; A. Sandoval, talk at Gamma2016

Considering the following parametrization of the gamma-ray flux:

$$\frac{dN_\gamma(E_\gamma)}{dE_\gamma} = k_\gamma \left(\frac{E_\gamma}{\mathrm{TeV}}\right)^{-\alpha_\gamma} \exp\left(-\sqrt{\frac{E_\gamma}{E_{cut,\gamma}}}\right) ,$$

the neutrino flux at the Earth after oscillations can be described by

$$\frac{dN_{\nu_\mu+\bar{\nu}_\mu}(E_\nu)}{dE_\nu} = k_\nu \left(\frac{E_\nu}{\mathrm{TeV}}\right)^{-\alpha_\nu} \exp\left(-\sqrt{\frac{E_\nu}{E_{cut,\nu}}}\right) ,$$

with

$$k_\nu = (0.694 - 0.16\alpha_\gamma)k_\gamma, \quad \alpha_\nu = \alpha_\gamma, \quad E_{cut,\nu} = 0.59 E_{cut,\gamma} .$$

S. Kelner, F.A. Aharonian, V. Bugayov, arXiv:astro-ph/0606058

A. Kappes, J. Hinton, C. Stegmann, F.A. Aharonian, arXiv:astro-ph/0607286

Events

Number of events detected by IceCube from a source at zenith angle θ_Z:

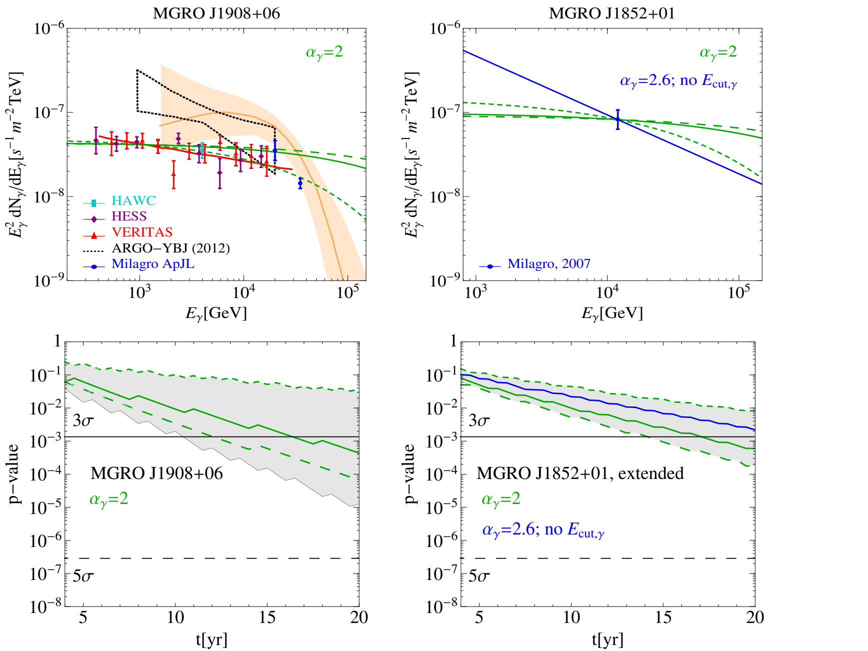
$$N_{ev} = t \int_{E_\nu^{\rm th}} dE_\nu \, \frac{dN_\nu(E_\nu)}{dE_\nu} \times A_\nu^{\rm eff}(E_\nu, \theta_Z)\,,$$

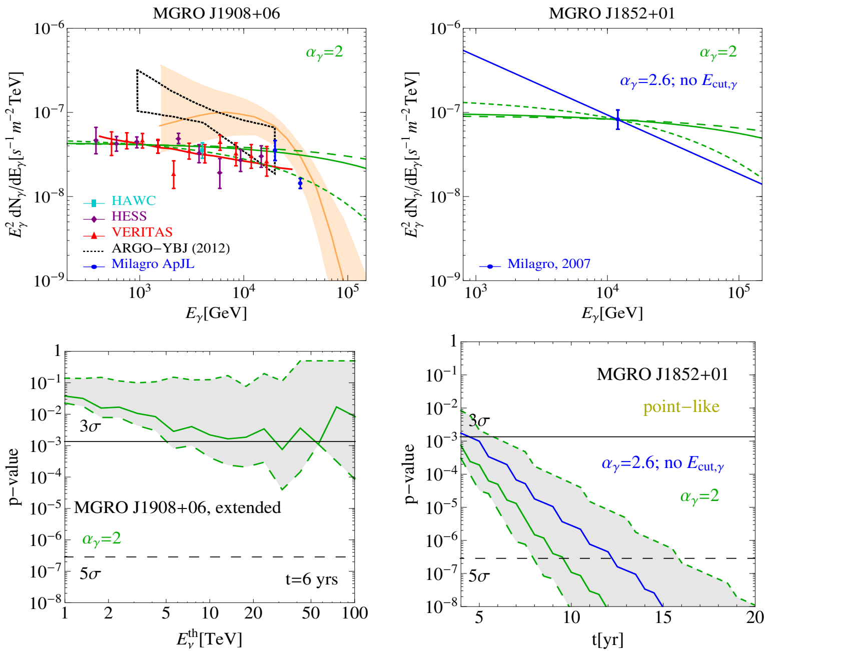
Angular opening and normalization for the flux considered in the analysis:

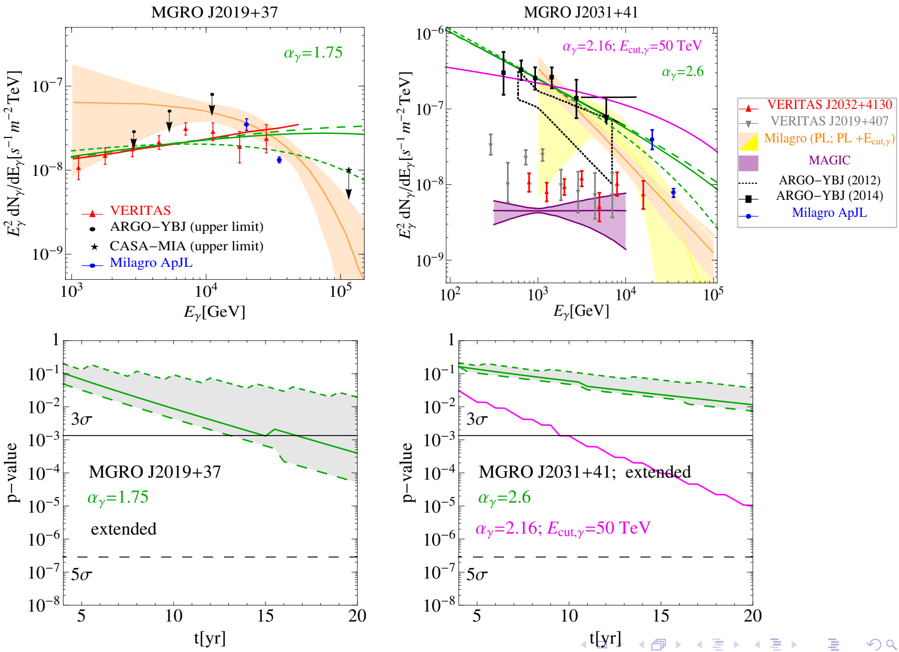
Source	$\sigma_{\rm eff}$(point-like; extended)	Flux
MGRO J1908+06	0.64°; 0.72°	HESS
MGRO J1852+01	0.64°; 1.63°	Milagro
MGRO J2031+41	$-$; 1.91°	ARGO-YBJ (+Fermi-LAT)
MGRO J2019+37	0.64°; 0.73°	VERITAS

$\sigma_{\rm eff} \equiv \sqrt{\sigma_{\rm ext}^2 + \sigma_{\rm IC}^2}$; $\sigma_{\rm ext}$ is the extension of the source, $\sigma_{\rm IC} \equiv 1.6\ \Delta\xi_{\rm IC}$, with $\Delta\xi_{\rm IC} = 0.4^\circ$, is the IceCube angular resolution.
Assuming gaussianity, $\simeq 72\%$ of source flux is contained within this angular bin.

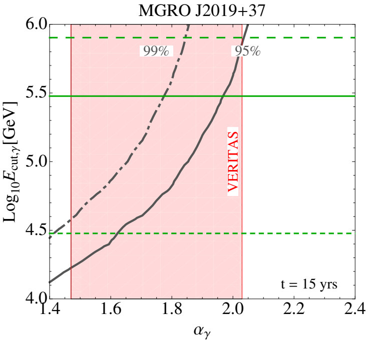
D. Alexandreas et al., Nucl.Instrum.Meth. A328 (1993)


MGRO J1908+06
MGRO J1852+01
α_γ=2
α_γ=2.6; no $E_{cut,\gamma}$
$E_\gamma^2\, dN_\gamma/dE_\gamma [s^{-1}\, m^{-2}\, \mathrm{TeV}]$
E_γ[GeV]
HAWC
HESS
VERITAS
ARGO−YBJ (2012)
Milagro ApJL
Milagro, 2007
p−value
t[yr]
3σ
5σ
MGRO J1908+06
MGRO J1852+01, extended


MGRO J1908+06
MGRO J1852+01
α_γ=2
α_γ=2.6; no $E_{cut,\gamma}$
E_γ^2 dN$_\gamma$/dE$_\gamma$[s^{-1} m^{-2}TeV]
E_γ[GeV]
HAWC
HESS
VERITAS
ARGO−YBJ (2012)
Milagro ApJL
Milagro, 2007
p−value
3σ
5σ
MGRO J1908+06, extended
t=6 yrs
E_ν^{th}[TeV]
MGRO J1852+01
point−like
t[yr]


MGRO J2019+37
α_γ=1.75
VERITAS
ARGO−YBJ (upper limit)
CASA−MIA (upper limit)
Milagro ApJL
$E_\gamma^2\, dN_\gamma/dE_\gamma [s^{-1} m^{-2}$ TeV]
E_γ[GeV]
MGRO J2031+41
α_γ=2.16; $E_{cut,\gamma}$=50 TeV
α_γ=2.6
VERITAS J2032+4130
VERITAS J2019+407
Milagro (PL; PL +$E_{cut,\gamma}$)
MAGIC
ARGO−YBJ (2012)
ARGO−YBJ (2014)
Milagro ApJL
p−value
3σ
5σ
MGRO J2019+37
α_γ=1.75
extended
t[yr]
MGRO J2031+41; extended
α_γ=2.6
α_γ=2.16; $E_{cut,\gamma}$=50 TeV
t[yr]

Confidence level limits



Future IceCube data can independently constrain values of α_γ and $E_{\mathrm{cut},\gamma}$ and probe the presence of a low-energy cut-off.

Conclusions

- If the gamma rays are hadronic in origin
  $\Rightarrow$ observation of an accompanying neutrino flux is likely over the lifetime of IceCube

- We have used updated information from air-Cherenkov and air-shower array experiments;

  Prospects for observing these sources: entangled with discrepancies in the detailed fluxes/morphologies measured by different experiments (difference in angular resolution; range of energies).

  The uncertainty of the nature of these sources
  $\Rightarrow$ difficult to understand the observed spectrum and the production mechanism; HAWC will help resolve these discrepancies

Thank you!

"Don't panic (and carry a towel)",
The Hitchhiker's Guide to the Galaxy, Douglas Adams

BACKUP SLIDES

Cosmic acceleretors and neutrinos

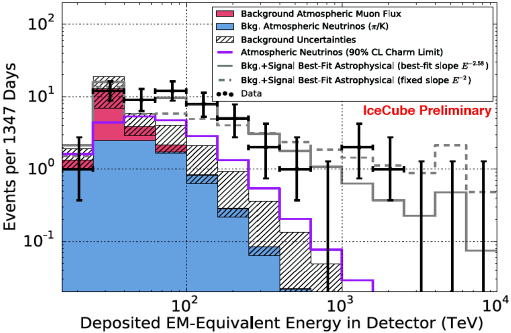
There are different possible sources of cosmic rays, among which:

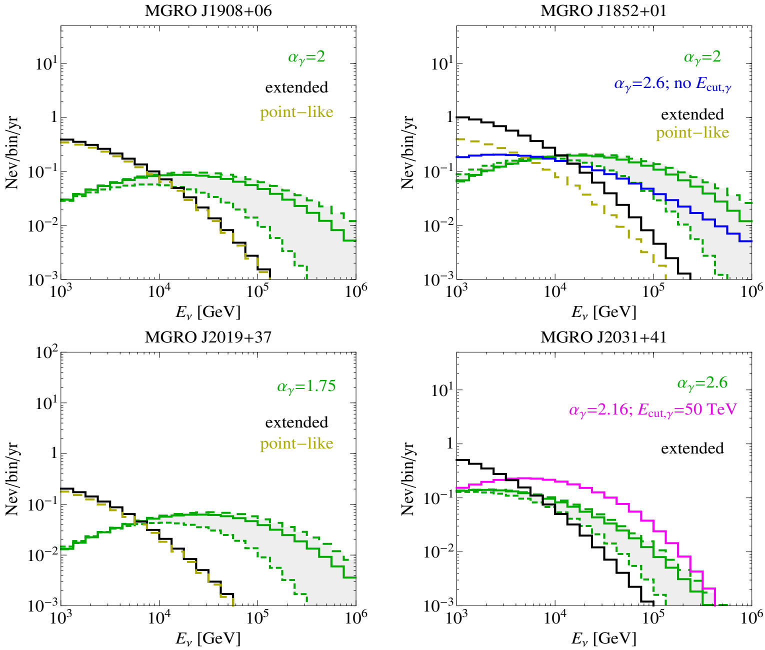
- Supernova remnant: considered the major source of galactic cosmic rays
  first suggested by Walter Baade and Fritz Zwicky in 1934
  in 2013 the Fermi satellite has revealed γs from π^0 decay for SNR IC443 and W44
  $\rightarrow$ evidence for SNR as sources of cosmic-rays *M. Ackermann et al., 1302.3307 [astro-ph.HE]*
- Gamma ray bursts
- Active Galactic Nuclei

Calculation of neutrinos aspected at IceCube from specific *galactic* sources of high-energy neutrinos
$\Rightarrow$ Milagro sources *M.C. Gonzalez-Garcia, F. Halzen, V. Niro, arXiv:1310.7194 [astro-ph.HE]; F. Halzen, A. Kheirandish, VN, arXiv:1609.03072 [astro-ph.HE]*

$\Rightarrow$ Neutrinos from RX J1713.7-3946, Vela Junior, Milagro sources, Fermi Bubble
F. Vissani, F. Aharonian, arXiv: 1112.3911 [astro-ph.HE], F. Vissani, F. Aharonian, N. Sahakyan, arXiv: 1101.4842 [astro-ph.HE]

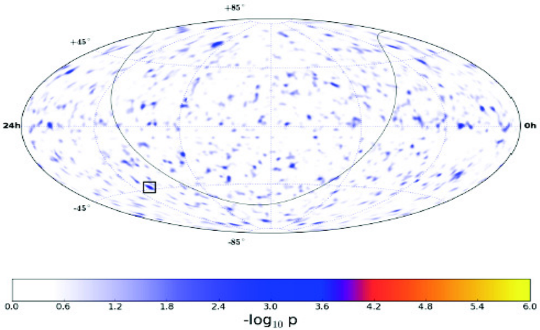
Energy spectrum




MGRO J1908+06
α_γ=2
extended
point−like
MGRO J1852+01
α_γ=2
α_γ=2.6; no $E_{\mathrm{cut},\gamma}$
extended
point−like
MGRO J2019+37
α_γ=1.75
extended
point−like
MGRO J2031+41
α_γ=2.6
α_γ=2.16; $E_{\mathrm{cut},\gamma}$=50 TeV
extended
Nev/bin/yr
E_ν [GeV]

IceCube searches

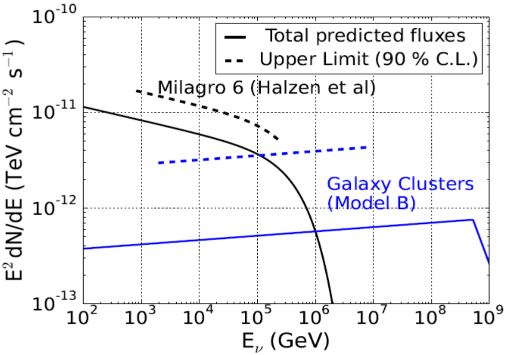
All-Sky Scans for Extended Sources (one degree extension)



Aarsten, et. al, arXiv: 1406.6757 [astro-ph.HE]

IceCube point source searches

IC40+59+79+86-I:
When the six Milagro sources are considered together: $\hat{n}_S = 51.4$, $\hat{\gamma} = 3.95$, $p-$value: 2%.
Constraint: $\Phi^{90\%}_{\nu_\mu+\bar{\nu}_\mu} = 1.98$ model flux considered.



Aarsten, et. al, arXiv: 1406.6757 [astro-ph.HE]

Confidence level

Following standard techniques we define C.L. as

$$C.L. = \frac{P_{(s+b)}}{1 - P_b} \,.$$

where $P_{(s+b)}$ and P_b are the p-values for the signal plus bkg and bkg only hypothesis of the data. The denominator avoid penalizing models to which one has little or no sensitivity. *T. Junk, arXiv:hep-ex/9902006*

If $C.L. \leq \alpha$, a specific source is excluded with $(1-\alpha)$ confidence level.

For the statistical significance of discovery, we use the total number of expected signal and bkg events and we compute the bkg-only p-value: *ATL-PHYS-PUB-2011-011, CMS-NOTE-2011-005*

$$p_{\rm value} = \frac{1}{2}\left[1 - {\rm erf}\left(\sqrt{q_0^{obs}/2}\right)\right] \,,$$

where q_0^{obs} is defined as

$$q_0^{obs} \equiv -2 \ln \mathcal{L}_{b,D} = 2\left(Y_b - N_D + N_D \ln\left(\frac{N_D}{Y_b}\right)\right) \,,$$

with N_D is the estimated experimental data –generated as the median of a large sample of event numbers that are Poisson distributed around the expectation of signal plus bkg– and Y_b is the theoretical expectation for the bkg.

Source	Type	σ_{ext} (ACT)	σ_{ext} (EAS)
MGRO J1908+06	UNID		
$\hookrightarrow$ ARGO-YBJ			$0.49^\circ \pm 0.22^\circ$
$\hookrightarrow$ HESS J1908+063		$0.34^\circ\ ^{+0.04}_{-0.03}$	
$\hookrightarrow$ VERITAS		$0.44^\circ \pm 0.02^\circ$	
MGRO J1852+01	UNID		Milagro: $3^\circ \times 3^\circ$ search region
MGRO J2031+41	UNID		
$\hookrightarrow$ ARGO J2031+4157			$1.8^\circ \pm 0.5^\circ$
MGRO J2019+37	PWN		Milagro: 0.7°
$\hookrightarrow$ VER J2019+368		$\sim 0.35^\circ$	

Source	$E_\gamma^{\rm norm}$; dN_γ^{12}/dE_γ at $E_\gamma^{\rm norm}$; α_γ (ACT or EAS)
MGRO J1908+06	
↪ HESS J1908+063	1 TeV; $4.14 \pm 0.32_{stat} \pm 0.83_{sys}$; $2.10 \pm 0.07_{stat} \pm 0.2_{sys}$
↪ VERITAS	1 TeV; $4.23 \pm 0.41_{stat} \pm 0.85_{sys}$; $2.20 \pm 0.10_{stat} \pm 0.20_{sys}$
MGRO J1852+01	
↪ Milagro	12 TeV; $(5.7 \pm 1.5_{stat} \pm 1.9_{sys}) \times 10^{-2}$; 2.6
MGRO J2031+41	
↪ ARGO J2031+4157	w/o Fermi-LAT:
	1 TeV; $(2.5 \pm 0.4) \times 10$; 2.6 ± 0.3
	w Fermi-LAT:
	0.1 TeV; $(3.5 \pm 0.3) \times 10^3$; 2.16 ± 0.04
MGRO J2019+37	
↪ VER J2019+368	5 TeV; $(8.1 \pm 0.7_{stat} \pm 1.6_{sys}) \times 10^{-2}$; $1.75 \pm 0.08_{stat} \pm 0.2_{sys}$

Confidence level limits