Photohadronic modelling of the 2010 gamma-ray flare from Markarian 421

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Motivations

Gamma-ray blazar samples and neutrino correlation studies:

TANAMI BLAZAR SAMPLE + HESE (Krauß et al. 2014 & 2015);
FERMI-LAT (70 months 2FGL catalogue) + HESE (track events) (Brown et al. 2015);
FERMI-LAT (2FHL VHE sources E>50 GeV & 3LAC catalogue E>100 MeV) + HESE (Padovaniet al. 2016); etc...

Possible neutrino sources associated with IceCube events:

TXS 0506+056 and IC-170922A (Aartsen et al. 2018);
3HSP J095507.9+355101 & IceCube200107A (Giommi et al. 2020);
PKS B1424-418 (FSRQ) and HESE IC35 (Kadler et al. 2016).

Hadronic emission as a possible explanation of observed gamma-ray spectral hardening at TeV energies

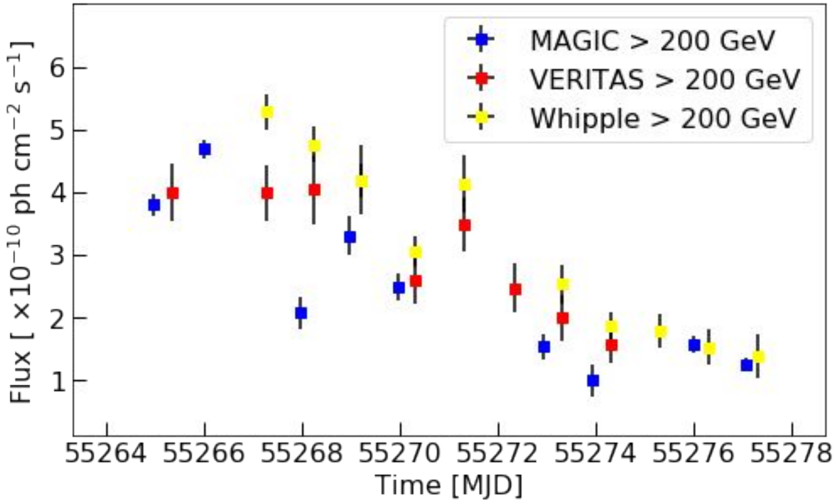
1ES 1101-232 and H 2356-309 (Aharonian et al. 2006);
1ES 0229+200 (Tavecchio et al. 2009);
W Comae, 3C 66A (Böttcher et al. 2013).

Past and ongoing SED modelling for flaring blazars, including orphan TeV flares

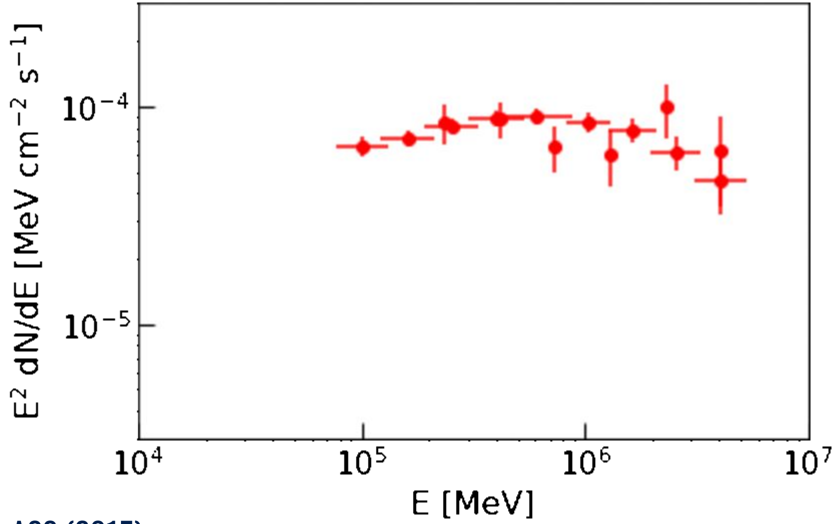
Markarian 501 Mücke &Protheroe (2001); 3C 279 Diltz & Böttcher (2016); TXS 0506+056 by numerous authors, etc...

a case study: Markarian 421

Mrk 421: prominent blazar (BL Lac)
RA=66.114°, Dec = 38.209°, z=0.031
near bright gamma-ray source (TeV),
highly active, constant monitoring (MWL campaign 2010)



2010 Flaring activity:
14-days in March 2010 (MJD 55264–55277)
remarkable flux variability at the VHE band (E > 100 GeV)



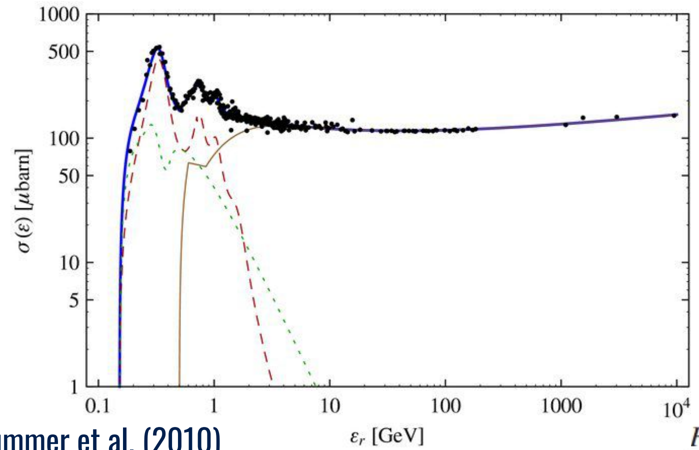
Aleksić et al., A&A 578, A22 (2015)

Modelling → Output

Let's assume:

One-zone leptonic model (electron-synchrotron + SSC)

+ Hadronic (pγ → Δ^+-resonance approx)



Hümmer et al. (2010)

σ_{peak}~500 μbarn, which is 5×10^{-28}cm^2, being this the dominant decay channel (~5x the direct channel)

$$p\gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p\pi^0 & (2/3) \\ n\pi^+ & (1/3) \end{cases}$$

Fermi:

$$\frac{dN}{d\epsilon_\gamma} = N_{PL}\epsilon_\gamma^{-\kappa}$$

PH contribution:

$$F_\gamma(E_\gamma) = A_\gamma \Phi_{input}(\epsilon_\gamma)\left(\frac{E_\gamma}{TeV}\right)^{-\alpha+3} e^{-\tau_{\gamma\gamma}(E_\gamma, z)}$$

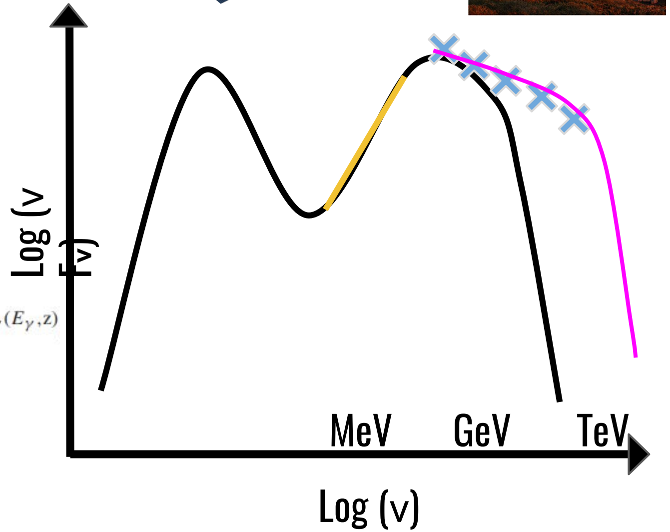
Neutrinos:

$$\frac{dN_\nu}{dE_\nu} = A_\nu E_\nu^{-2}$$

Model output: PH contribution

Fermi

IACTs



Akaike Information Criterion

Akaike (1974)

Is a test used to compare and select a model from a set of models. Seeks the preferred model based on:

$$AIC_s = -2ln(L_s) + 2k_{f\,s}$$

1) goodness of the fit:

How close it is to the true values
L_s = Likelihhod of a model s

2) simplicity of the model:

k_{fs} = Number of free parameters

AIC Difference

$$\Delta AIC_{p,q} = AIC_p - AIC_q$$

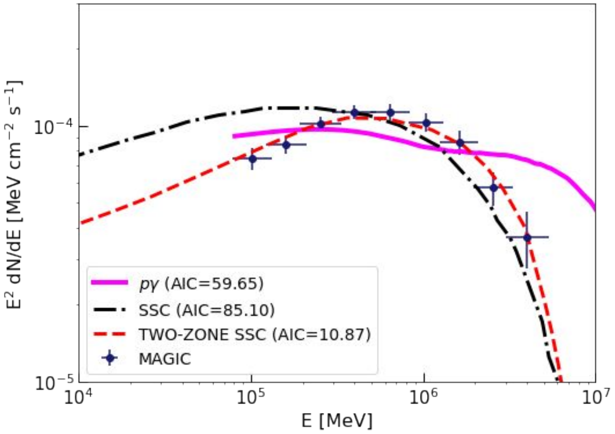
pγ vs one-zone SSC (Aleksić et al., 2015)
pγ vs two-zone SSC (Aleksić et al., 2015)

As a rule of thumb: Any model comparison with an AIC difference >2 represents a substantial worse fitting for the highest value.

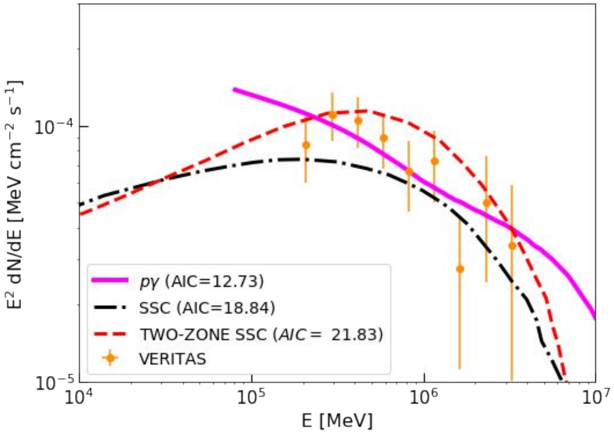
Δ_i	Level of Empirical Support of Model i
0-2	Substantial
4-7	Considerably less
> 10	Essentially none.

Burnham and Anderson (2002).

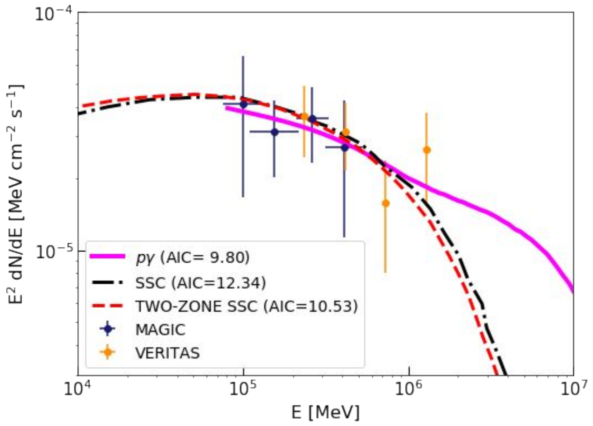
MJD 55266



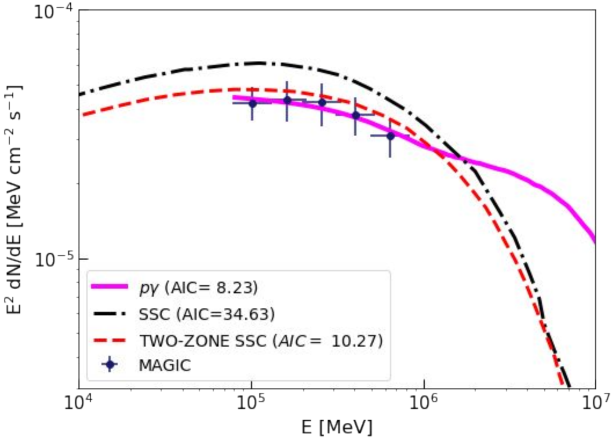
MJD 55267



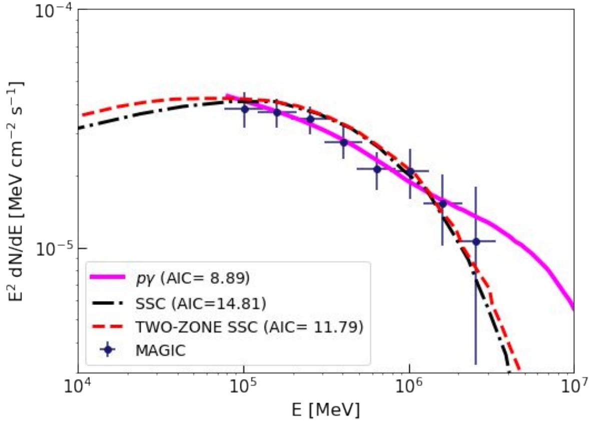
MJD 55274



MJD 55276



MJD 55277



Likelihood is assessed using a χ^2 statistic.

Number of free parameters:
pγ = 4
one-zone SSC=5
two-zone SSC=4

Rosales et al., MNRAS, Volume 501, 2198 (2021)

Results

Time MJD	A_γ	α	Preferred Model	$\Delta\mathrm{AIC}_{\mathrm{SSC},\,p\gamma}$	$\Delta\mathrm{AIC}_{\text{two zone, SSC},\,p\gamma}$
55266	5.02 ± 2.74	3.12 ± 0.07	two-zone SSC	25.45	-48.78
55267	27.24 ± 12.79	3.41 ± 0.09	$p\gamma$	6.11	9.10
55274	0.19 ± 0.01	2.31 ± 0.03	inconclusive	2.54	0.73
55276	0.10 ± 0.02	2.17 ± 0.03	$p\gamma$	26.40	2.04
55277	0.18 ± 0.02	2.32 ± 0.03	$p\gamma$	5.92	2.90

- In most of cases the pγ model was favoured as a better fit description, and always with a respect to the one-zone leptonic model from Aleksic et al. (2015)
- The high frequency of the seed photons considered lowers the energy threshold for the protons: 40 GeV < E_p < 2.45 TeV (comoving reference frame)
- Above TeV energies is where the models differ the most, this can be tested further with the upcoming CTA.
- Neutrinos Expected? For IC-59, during the 14 days we calculated an upper limit of N_{events} < 0.14

Conclusions & Outlook

- Results show the potential of pγ contributions within a lepto-hadronic origin of VHE gamma-rays and neutrinos

Advantages:	Caveats:
Proton energy required for pγ interactions Balance: goodness of the fit & simplicity	Extension to lower energies? Data in the MeV energy range would enable a better description

- A hadronic component could be dominant at VHE, followed by a dominant SSC leptonic component. If the proton injection occurs randomly, there is no preferred time for hadronic dominance during the flare.

- To explore the neutrino/gamma-ray connection in the upcoming years, the next generation of gamma-ray and neutrino observatories, such as CTA, SWGO, AMEGO, IceCube-Gen2, Trinity, will play a crucial role.

- Future gamma-ray observations above tens of TeV (CTA) and below 100 MeV in energy (AMEGO) will be crucial to test and discriminate between models.

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