Talk outline

- Introduction
- Neutrino emission from BL Lacs: **flaring states vs. quiescence**
  1. Motivation & Goals
  2. Application to Mrk 421
- Conclusions

(Petropoulou, Coenders & Dimitrakoudis, 2016, APh, 80, 115)
The first discovery of high-energy astrophysical ν from Icecube

**Q:** What is their origin?

**A:** Not known yet.

**Q:** What is needed more?

**A:**
- More statistics
The first discovery of high-energy astrophysical ν from Icecube

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A: Not known yet.

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A:
- More statistics
- Model-independent searches of point sources
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Q: What is their origin?
A: Not known yet.

Q: What is needed more?
A:
- More statistics
- Model-independent searches of point sources
- Theoretical model predictions for particular types of sources.
ν emission during flares and quiescence

Motivation

★ Blazars are variable sources across the electromagnetic spectrum!

Aims

★ How does the ν flux correlate with the photon flux?

★ Comparison between quiescence & flares

★ What is the expected ν event rate from a ~day flare?

★ What is the expected ν event number over the 5yr IceCube livetime?
Mrk 421: an excellent lab for blazar models

Variable source in various energy bands & timescales.

3 data sets used:


2) 13-day flare in 2010; significant X-ray and VHE variability but ~constant GeV flux (Aleksic et al. 2015, A&A, 578)

3) ~7 yr-long Fermi-LAT data

Hovatta, Petropoulou et al. 2015 radio

Fossati et al. 2008

~week

~years
Unprecedented MW coverage & simultaneous obs. for MJD 55265-55277 (data are adopted from Aleksic et al. 2015)

SED modeling

Petropoulou, Coenders & Dimitrakoudis, 2016, APh, 80, 115
Predicted ν emission

Daily all-flavor ν flux spectra

High-energy ν flux vs. photon flux

< 1 PeV neutrino flux is ~ constant

> 1 PeV neutrino flux varies

> 1 PeV neutrino flux is correlated with X-rays and γ-rays

>1 PeV ν - GeV γ-ray correlation will be applied to the long-term Fermi/LAT light curve
Effective areas of the analyses

Up-going events

- Larger statistical sample
- Larger effective volume
- Atm. background not removed
- Poorer energy determination

High-energy starting events (HESE)

- Smaller statistical sample
- Smaller effective volume
- Atm. Background removed
- Accurate energy determination

Neutrino Events in IceCube

- Back grounds
  - Cosmic ray induced atmospheric muons
- Main Signal
  - Neutrino induced muons

Up-going events

$\nu_\mu < 1 \text{PeV}$
Comparison of event rates

<table>
<thead>
<tr>
<th>$E_\nu$ (TeV)</th>
<th>Mrk 421$^a$</th>
<th>Background$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>13-day flare</td>
<td>quiescent</td>
</tr>
<tr>
<td>(55265-55277)</td>
<td>0.023</td>
<td>0.019</td>
</tr>
<tr>
<td>(54850-54983)</td>
<td>0.264</td>
<td>0.282</td>
</tr>
<tr>
<td></td>
<td>0.306</td>
<td>0.288</td>
</tr>
<tr>
<td>$10^3 - 5 \times 10^4$</td>
<td>0.306</td>
<td>0.288</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$\sim 0.57$ evt/yr  $\sim 0.57$ evt/yr  Negligible

✿ Neutrinos (> 100 TeV) expected from the flare: $13 \times 0.57/333 = 0.02$

✿ Neutrinos (> 100 TeV) expected from quiescent period: $120 \times 0.57/333 = 0.2$

✿ Caution needed when associating a $\nu$ event with a flaring blazar lying in the error circle of $\nu$ detection

✿ An accumulation of many similar flares is required for a detection!
The long-term γ-ray activity

The 6.9 yr Fermi light curve (0.1-300 GeV) overlaps with the 5yr IceCube livetime.

Latest published results

\[ \nu F_{\nu} \text{ [erg/cm}^2\text{s]} \]

\[ 10^{-10} \]

\[ 10^{-9} \]

\[ 10^{-8} \]

\[ 01/'09 01/'10 01/'11 01/'12 01/'13 01/'14 01/'15 \]

0.1-300 GeV  Quiescence  13d flare  Flaring

\[ N_{\nu}(t)|_{E_{\nu}>1\text{PeV}} \]

\[ 0 \]

\[ 1 \]

\[ 2 \]

\[ 3 \]

\[ 4 \]

\[ 5 \]

95%

90%

prediction for <1PeV

\[ t \text{ [MJD - 55348]} \]
Major GeV flares

<table>
<thead>
<tr>
<th>No.</th>
<th>T (days)</th>
<th>$\nu_\mu + \bar{\nu}_\mu$</th>
<th>$P_{N_{\nu} \geq 1}(%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flares 1a+1b</td>
<td>105</td>
<td>$0.61 \pm 0.16$</td>
<td>$46 \pm 8$</td>
</tr>
<tr>
<td>Flare 2</td>
<td>70</td>
<td>$0.32 \pm 0.07$</td>
<td>$27 \pm 5$</td>
</tr>
<tr>
<td>Flare 3</td>
<td>98</td>
<td>$0.26 \pm 0.05$</td>
<td>$23 \pm 4$</td>
</tr>
<tr>
<td>Flares 4a+4b</td>
<td>112</td>
<td>$0.26 \pm 0.05$</td>
<td>$23 \pm 4$</td>
</tr>
<tr>
<td>$\Sigma$ Flares</td>
<td>385</td>
<td>$1.46 \pm 0.32$</td>
<td>$77 \pm 7$</td>
</tr>
</tbody>
</table>

Without GeV major flares

<table>
<thead>
<tr>
<th>Season</th>
<th>T (days)</th>
<th>$\nu_\mu + \bar{\nu}_\mu$</th>
<th>$P_{N_{\nu} \geq 1}(%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>06/2010-05/2011</td>
<td>364</td>
<td>$0.43 \pm 0.06$</td>
<td>$34 \pm 4$</td>
</tr>
<tr>
<td>06/2011-05/2012</td>
<td>364</td>
<td>$0.38 \pm 0.05$</td>
<td>$32 \pm 3$</td>
</tr>
<tr>
<td>06/2012-05/2013</td>
<td>371</td>
<td>$0.71 \pm 0.11$</td>
<td>$51 \pm 5$</td>
</tr>
<tr>
<td>06/2013-05/2014</td>
<td>364</td>
<td>$0.70 \pm 0.11$</td>
<td>$50 \pm 5$</td>
</tr>
<tr>
<td>06/2014-05/2015</td>
<td>350</td>
<td>$0.47 \pm 0.06$</td>
<td>$38 \pm 4$</td>
</tr>
<tr>
<td>$\Sigma$ w/o Flares</td>
<td>1834a</td>
<td>$2.73 \pm 0.38$</td>
<td>$94 \pm 2$</td>
</tr>
<tr>
<td>$\Sigma$ w Flares</td>
<td>1834</td>
<td>$3.59 \pm 0.60$</td>
<td>$97 \pm 2$</td>
</tr>
</tbody>
</table>

* Similar probability for detecting at least 1 neutrino from the 2012 flare alone and the whole IC Season 3
* Still <50%
Constraining the model

**Q:** What means a neutrino non-detection of Mrk 421?

**A:** Correlation between >1PeV ν and GeV γ-rays differs in major flares

OR

Much lower power is carried by CR in blazar jets

>100 TeV ν flux (normalized to 4e-10 erg/s/cm²)

vs. T (yr) needed for IceCube ν detection at 90% (95%) CL

Upper limits on CR power given a non-detection (at 90%, 95% CL) of muon Ν (> 100 TeV) from Mrk 421 in X years.

<table>
<thead>
<tr>
<th>X (yr)</th>
<th>90%</th>
<th>95%</th>
<th>90%</th>
<th>95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>0.71</td>
<td>0.9</td>
<td>6.2 x 10^{47}</td>
<td>7.8 x 10^{47}</td>
</tr>
<tr>
<td>8</td>
<td>0.53</td>
<td>0.68</td>
<td>4.6 x 10^{47}</td>
<td>5.9 x 10^{47}</td>
</tr>
<tr>
<td>10</td>
<td>0.43</td>
<td>0.54</td>
<td>3.7 x 10^{47}</td>
<td>4.7 x 10^{47}</td>
</tr>
<tr>
<td>20</td>
<td>0.21</td>
<td>0.27</td>
<td>1.8 x 10^{47}</td>
<td>2.3 x 10^{47}</td>
</tr>
</tbody>
</table>
What about FSRQ flares?

No physical model for the flare of PKS B1424-418


3C 279 then...

And now... minute-timescale Fermi-LAT flare

Difficult to explain the flare with hadronic cascades!


Petropoulou, Nalewajko, Hayashida, in prep.
Petropoulou & Murase, in prep.
Hadronic SED modeling is a powerful tool for neutrino calculations!

Accumulation of many week-duration flares necessary for the detection of at least 1 neutrino from Mrk 421

Neutrino flux >1 PeV correlates with X-ray and γ-ray fluxes

Major flares (long duration & large flux increase) have a significant impact on the # ν over time

Utilizing the >1 PeV ν / GeV γ-ray correlation and Fermi/LAT light curve of Mrk 421 we expect: ~3.6 ν with flares and ~2.7 ν without flares included. These exceed the threshold value for detection of at least 1 neutrino at 95% CL and 90% CL respectively

No high-energy ν detection would suggest that the correlation does not hold during major flares or/and set upper limits on the CR power of the blazar.

Thank you!
Back-up Slides
Successful hadronic fits to all 13 days.

Small changes (~2-3) of the parameter values.

Calculation of daily $\nu$ spectra.
Radiative processes in a nutshell

Photon density + source size

\[ \varepsilon^2 \Phi(\varepsilon) \]

\[ 0.01 \text{ GeV}^2/E_{\gamma} \ldots 0.05 E_{p,\text{max}} \]

\[ \Delta\text{-resonance} \]

\[ \sigma \sim 0.5 \text{ mb} \sim 5\times10^{-29} \text{ cm}^{-2} \]

\[ E \cdot E \sim 0.16 \text{ GeV}^2 \]

\[ \varepsilon \]

\[ \varepsilon_r [\text{GeV}] \]
A zoo of candidate sources

- AGN jets
  - e.g. Guetta et al. 2002, Torres et al. 2005
  - e.g. Kachelriess & Ostapchenko 2014

- GRBs

- Supernovae/Hypernovae
  - e.g. Murase et al. 2011, Zirakashvili & Ptuskin 2015

- microquasars
  - e.g. Metzger et al. 2015

- Star-forming galaxies
  - e.g. Tamborra et al. 2014, Loeb & Waxman 2006

- γ-ray novae

(Review by Ahlers et al 2015)
ν production processes

Jets as ν sources

AGN

GRBs

PHOTOHADRONIC INTERACTIONS

CR reservoirs as ν sources

Galaxy groups/clusters

Star forming galaxies

INELASTIC pp COLLISIONS

\( \varepsilon^2 \Phi(\varepsilon) \)

Photon density + source size

\( s_v \neq s_p \)

0.01 GeV\(^2/E_y \) ... 0.05 \( E_{p,\text{max}} \)

\( \varepsilon \)

\( \varepsilon^2 \Phi(\varepsilon) \)

Gas density + source size

\( s_v = s_p \)

0.05 \( E_{p,\text{min}} \) ... 0.05 \( E_{p,\text{max}} \)

\( \varepsilon \)
Introduction: $\nu$ production processes

Jets as $\nu$ sources

AGN

GRBs

CR reservoirs as $\nu$ sources

Galaxy groups/clusters

Star forming galaxies

PHOTOHADRONIC INTERACTIONS

INELASTIC pp COLLISIONS

$\sigma_{py} \sim 0.5 \text{ mb} \sim 5 \times 10^{-29} \text{ cm}^{-2}$

$E_p E_\gamma \sim 0.16 \text{ GeV}^2$

$\Delta$-resonance

$\sigma_{pp} \sim 30 \text{ mb} \sim \text{const}$
Pion, muon & kaon decay is modeled using results of MC code SOPHIA (Muecke et al. 2000).

Synchrotron cooling of the above is also included.
BL Lacs as counterparts of IceCube neutrinos

* Catalogs used:
  - TeVCat (VHE detected)
  - 1WHSP (~1000 VHE candidates)
  - 1FHL (>10 GeV)
* Cuts applied to the sample of 35 events:
  - $E > 60\,\text{TeV}$
  - median angular error < 20 deg
* “Energetic” criterion

* Catalogs used:
  - 3LAC (>100 MeV)
  - 2WHSP (~1700 VHE candidates)
  - 2FHL (>50 GeV)
* Cuts applied to the sample of 51 events:
  - $E > 60\,\text{TeV}$
  - median angular error < 20 deg
* “Energetic” criterion
BL Lacs as counterparts of IceCube neutrinos
BL Lacs as counterparts of IceCube neutrinos

Leptonic γ-ray emission

Hadronic γ-ray emission

\[ Y_{\nu\gamma} = \frac{L_{\nu}^{(\text{all})}}{L_{>10\text{GeV}}} \]

\( \approx 1 \)

\( \ll 1 \)
Neutrino emission from all BL Lacs

Monte-Carlo simulation for blazar population (Giommi & Padovani 2012, 2013, 2015):
- Radio luminosity function & evolution
- Distribution of synchrotron peak frequency
- Redshift
- Distribution of Doppler factor
- $\gamma$-ray constraints

$$E_{\nu}F_{\nu}(E_{\nu}) = \int_{x_{\text{min}}}^{\infty} dx \frac{F_{\gamma}(> 10 \text{ GeV})}{x^{-s}e^{-x}} \left( \frac{E_{\nu}}{E_{\nu,p}} \right)^{-s+1} \exp \left( -\frac{E_{\nu}}{E_{\nu,p}} \right)$$

$$E_{\nu,p}(\delta, z, \nu_{\text{peak}}^{S}) \approx \frac{17.5 \text{ PeV}}{(1 + z)^2} \left( \frac{\delta}{10} \right)^2 \left( \frac{\nu_{\text{peak}}^{S}}{10^{16} \text{ Hz}} \right)^{-1}$$
### Predicted # of events

<table>
<thead>
<tr>
<th>Y=0.8, Eγ=200GeV, ΔΓ=0.5</th>
<th>With Glashow resonance</th>
<th>Without Glashow resonance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7 (2-10 PeV)</td>
<td>4.6 (2-10 PeV)</td>
</tr>
<tr>
<td></td>
<td>9-10 (2-100PeV)</td>
<td>6.6-7.6 (2-100 PeV)</td>
</tr>
<tr>
<td>Y=0.8, Eγ=100GeV, ΔΓ=1.0</td>
<td>~6 (2-10 PeV)</td>
<td>4 (2-10 PeV)</td>
</tr>
<tr>
<td></td>
<td>~8-9 (2-100PeV)</td>
<td>6-7 (2-100PeV)</td>
</tr>
<tr>
<td>Y=0.3, Eγ=200GeV, ΔΓ=0.5</td>
<td>2.6 (2-10 PeV)</td>
<td>1.7 (2-10 PeV)</td>
</tr>
<tr>
<td></td>
<td>~4 (2-100PeV)</td>
<td>~3 (2-100PeV)</td>
</tr>
</tbody>
</table>

6.6 is the 3σ upper limit for 0 events (Gehrels 1985)

Using the effective areas from IceCube (2013) in the range 2-10 PeV and extrapolating for the energy range 10-100 PeV.
Extragalactic backgrounds

- Another source population? (e.g. starburst galaxies: Lacki et al. 2014; Stecker 2007)
- Another physical process? (e.g. pp collisions; Mannheim 1995, Ahlers et al. 2012)

- Contribution from individual BL Lacs? (e.g. Mrk 421)
- Galactic contribution? (e.g. PWN)
Neutrino emission from all BL Lacs

Top left: Redshift distribution of ~0.5% of BL Lacs that make 95% of the NBG at 1 PeV.

Bottom right: Results from individual simulations showing the scatter in Monte Carlo simulations.

An “outlier” in the Monte Carlo simulation (a single bright source) mimics the neutrino emission from a point source!
Calculation of muon neutrino number

\[ N_\nu = T \int_{E_{\nu, \text{min}}}^{E_{\nu, \text{max}}} dE_\nu \int_{\Delta \Omega(E_\nu)} d\Omega \ A_{\text{eff}}(E_\nu, \vec{x}) \sum_i \frac{\partial^2 F_{\nu,i}}{\partial \Omega \partial E_\nu} \]

1) Atmospheric background
2) Diffuse Astrophysical Flux
3) Point source flux
Calculation of uncertainties

\[ N_\nu \equiv \dot{N}_\nu T = \frac{\dot{N}_\nu^q}{F_\nu^q} \int_T dt F_\nu(t) = \dot{N}_\nu^q \int_T dt \left( \frac{F_\gamma(t)}{F_\gamma^q} \right)^A \]

\[ \sigma_{n_\nu}^2 = f_{\dot{N}_\nu}^2 + f_{F_{\gamma,i}}^2 + f_{F_\gamma^q}^2 + f_A^2 \]

Stacked contributions of various sources of uncertainty to the total one