The Hadronic Code Comparison Project: First Results

Matteo Cerruti, Michael Kreter, Maria Petropoulou, *Annika Rudolph
Markus Böttcher, Stavros Dimitrakoudis, Shan Gao, Susumu Inoue, Apostolos Mastichiadis, Kohta Murase, Foteini Oikonomou, Xavier Rodrigues, Gabriel Schmid, Andreas Zech

02.12.2019, TeVPA Conference (Sydney)
Lepto-Hadronic modeling of Blazars

Blazar SED either:

(A) purely leptonic
electron synchrotron, self-compton, external inverse compton

(B) from both hadronic and leptonic processes
electron and proton synchrotron, cascade emission

Neutrino emission only in lepto-hadronic scenario possible!

Modeling BL Lac object 3C66A

Red: Leptonic scenario
Green: Lepto-hadronic scenario
Hadronic models in the light of TXS

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

Aartsen et al 2018
Hadronic models in the light of TXS

Keivani et al. 2018

Xue et al. 2019

Gao et al. 2018

Aartsen et al. 2018

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

How robust are those predictions?
What are the effects of underlying assumptions in the different models?
What and how to compare?

**Physical processes entering the models:**
- Leptonic: Synchrotron, synchrotron self-absorption, Inverse Compton, photo-pair production
- Hadronic: Synchrotron, Inverse Compton, Bethe-Heitler pair production, photo-meson processes

**Quantities used in the comparison:**
- Observed spectra (photons and neutrinos)
- Injection rates in the source
  (- source spectra of primaries like protons and electrons)

**Cases that will be compared:**
1. Leptonic: steady state and time-dependent
2. Hadronic: steady state and time-dependent, non-linear hadronic cascades
The Codes (I)

**ATHEvA**

- Time-dependent code solving a series of coupled PDEs
- Photopion interactions from SOPHIA
  Photopair interactions Protheroe & Johnson
  Leptonic and hadronic feedback channels
- Applied eg. to GRBs and several AGNs (TXS)

**Paris**
Cerruti et al 2015

- Steady-state solver
- Photopion interactions from SOPHIA
  Bethe-Heitler from Kelner & Aharonian
  Iterative computation of pair cascades
- Applied eg. to EHBLs and TXS

12/02/19
The Codes (II)

**AM3**
Gao et al 2016

- Time-dependent code solving a series of coupled PDEs
- Photohadronic following Hümmer et al Pair-annihilation Vurm & Poutanen
  Leptonic and hadronic feedback channels
- Applied eg. to PKS 1424-418 and TXS

**Boettcher**
Boettcher et al 2013

- Steady-state solver
- Photopion interactions and Bethe-Heitler from Kelner & Aharonian (2008, based on SOPHIA)
- Applied eg. Fermi Blazars
Leptonic solutions: SSC cases

A simple case: Low magnetic field (0.1 G) no pair-annihilation, simple electron power-law

Slightly more complicated: Higher Lorentz factor of electrons -> pair-annihilation effects

Observed spectrum

Deviation with respect to mean

PRELIMINARY
Leptonic solutions: SSC cases

A simple case: Low magnetic field (0.1 G) no pair-annihilation, simple electron power-law

Paris Code: geometrical factor of \( \frac{3}{4} \) in target photons for IC Component

When corrected for this: good agreement!

Slightly more complicated: Higher Lorentz factor of electrons -> pair-annihilation effects
AM3: Higher IC Component -> Higher pair production rate
Paris: 1. ¾ factor from IC component
2. Aharonian (83) formula instead of Coppi & Blandford (90)
   Resulting in factor ½
-> when correcting for both, good agreement!

Main conclusion: If one uses the γγ absorption rate from CB90 and the Aharonian+83 rate for pair production, one underestimates the production rate by a factor of ~2
AM3: Higher IC Component -> Higher pair production rate

Paris: 1. $\frac{3}{4}$ factor from IC component
2. Aharonian (83) formula instead of Coppi & Blandford (90)
   Resulting in factor $\frac{1}{2}$
-> when correcting for both, good agreement!

Main conclusion: If one uses the $\gamma\gamma$ absorption rate from CB90 and the Aharonian+83 rate for pair production, one underestimates the production rate by a factor of $\sim 2$

Monte-Carlo simulations confirm Aharonian formula!
A first lepto-hadronic scenario

Proton Synchrotron Case

Parameters:
- Large magnetic field (10 G)
- Large baryonic loading
- Simple power-law for both electrons and protons ($s = 2.9$)
- No pair-annihilation -> study photo-hadronic processes in detail

Good agreement on leptonic and hadronic synchrotron peaks!
A first lepto-hadronic scenario

**Observed SED**

- Proton synchrotron
- Electron synchrotron

**Bethe-Heitler pair injection**

**Photo-hadronic processes**

Injection rates in the source

**Pion-decay photon injection**

---

12/02/19

The Hadronic Code Comparison Project- Annika Rudolph, TeVPA 2019
A first lepto-hadronic scenario

Observed SED

Predicted neutrino fluxes

12/02/19

The Hadronic Code Comparison Project - Annika Rudolph, TeVPA 2019
Summary and future perspectives

Done:
• Successful comparison of leptonic scenarios, differences in pair-production rates understood and resolved
• Started comparison on lepto-hadronic scenarios. Good agreement for proton synchrotron, solved issues on Bethe-Heitler production. Discrepancies in energy spectra/rates of photo-meson secondaries. Why?

On the agenda:
• Compton catastrophe comparison
• Compare photo-meson module of codes using a black-body target photon field -> cleaner case
• Compare more realistic lepto-hadronic scenario
MC comparison for pair-annihilation

- $\omega_1$: frequency of soft target photon
- $\omega_2$: frequency of incident HE photon
- $\epsilon$: energy of created electron/positron

Comparison to Aharonian+ (83)

For $\omega_1$ approx. 1, the Aharonian formula shows different behavior at low electron/positron energies, is ok at higher energies.

Good agreement for cases with incident photons in VHE/UHE range which are relevant in relativistic jets.