Comparison of Hadronic Codes for Active Galactic Nuclei

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Introduction

The origin of the γ-ray emission (leptonic vs hadronic) in jetted active galactic nuclei (AGN) has been a long-standing matter of debate. While in leptonic scenarios the γ-ray emission is due to inverse Compton scattering, in hadronic scenarios it is associated with synchrotron emission by protons, and/or secondary leptons produced in proton-photon ($p\gamma$) interactions. Hadronic emission models also predict the production of high-energy neutrinos, which are the smoking gun for acceleration of relativistic hadrons in AGN jets.

The simulation of $p\gamma$ interactions and all associated radiative processes is a complex numerical task, and different approaches to the problem have been adopted in the literature. So far, no systematic comparison between the different codes has been performed, preventing a clear understanding of the underlying uncertainties in the numerical simulations. To fill this gap, we have undertaken the first comprehensive comparison of hadronic radiative transfer codes for jetted AGN.

Codes

We perform a systematic comparison of four hadronic radiative transfer codes (in alphabetical order): AM3 [1], ATHEνA [2, 3], Böttcher et al. [4], and PARIS [5]. The properties of each numerical code are reported below.

	AM3	ATHEνA	Böttcher	PARIS
Steady state	✓	✓	✓	✓
Time dependent	✓	✓	✗	✗
Linear EM cascades	✓	✓	✓	✓
Non-linear EM cascades	✓	✓	✗	✗
Meson synchrotron cooling	✗	✓	✗	✓
Muon synchrotron radiation	✗	✗	✗	✓

Production Rates of Photo-Hadronic Interactions

We compute proton-photon interactions between relativistic protons with a power-law energy distribution of index $\alpha_p = 1.9$ and exponential cut-off at $\gamma_{p,\mathrm{cut}} = 10^8$, and low-energy photons. For the latter, we consider two cases.

Case I: fixed power-law radiation field. The target photons are described by a power-law energy distribution with index $\alpha_\gamma = 2.0$, extending from $\epsilon_{\min} = 10^{-6}\ m_e c^2$ to $\epsilon_{\max} = 0.1\ m_e c^2$.

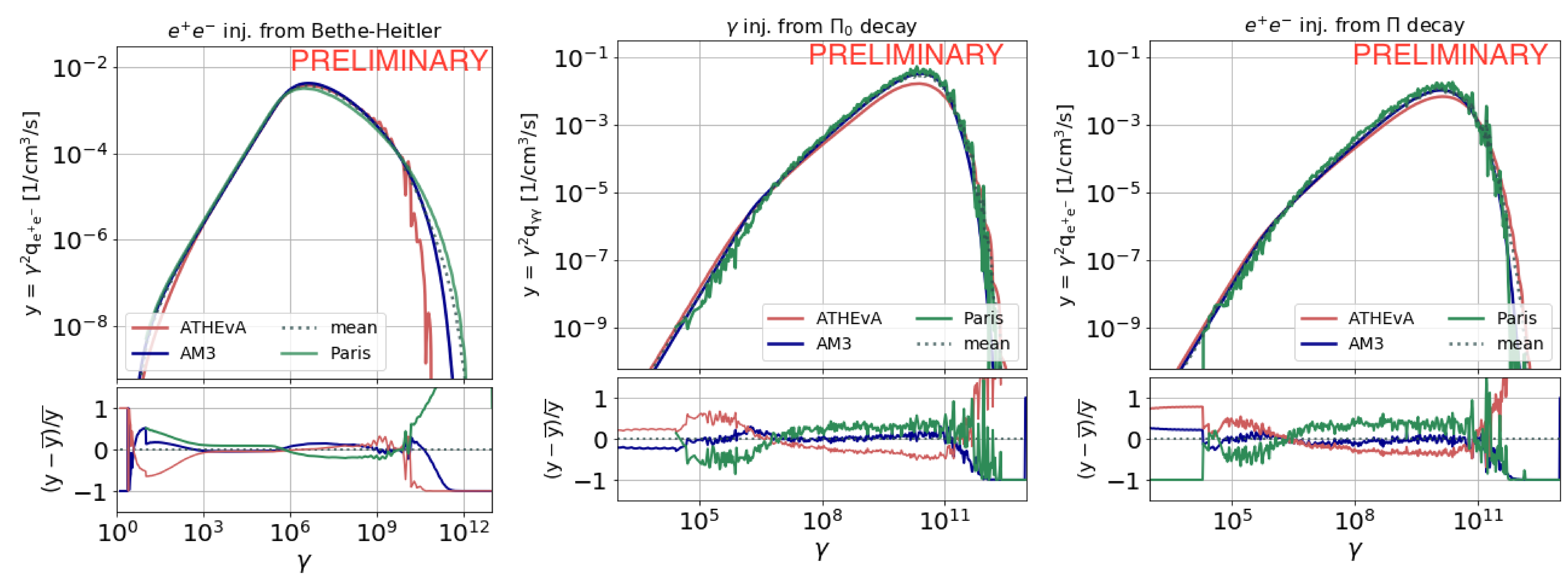

Figure 1: Injection rates of Bethe-Heitler $e^\pm$ (left), photo-meson $e^\pm$ (middle), and γ-rays (right). Bottom panels show the relative difference of the numerical solutions.

Case II: proton-synchrotron radiation field. The target photons are produced by synchrotron radiation of a power-law $e^\pm$ distribution with index $\alpha_e = 1.9$ and exponential cut-off at $\gamma_{e,\mathrm{cut}} = 10^3$. The parameters of the emitting region are $\delta = 30$, $B = 10$ G, $R = 10^{15}$ cm.

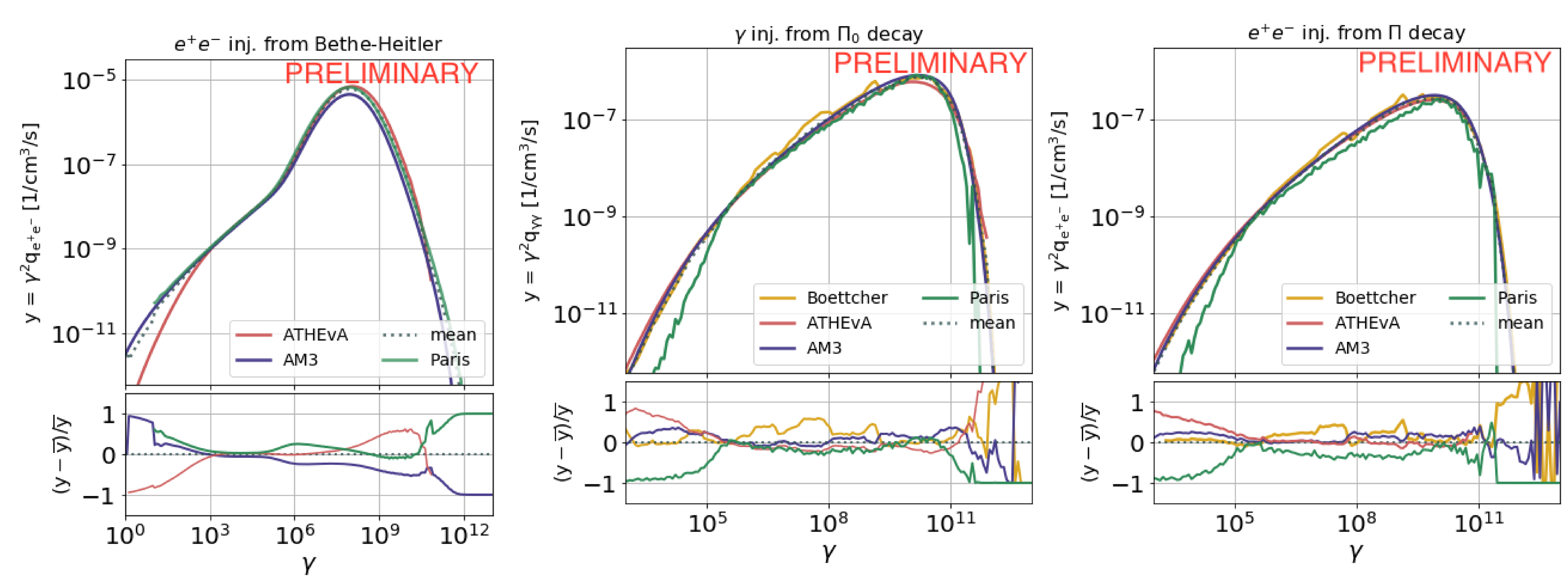

Figure 2: Same as in Figure 1.

Neutrino Energy Spectra

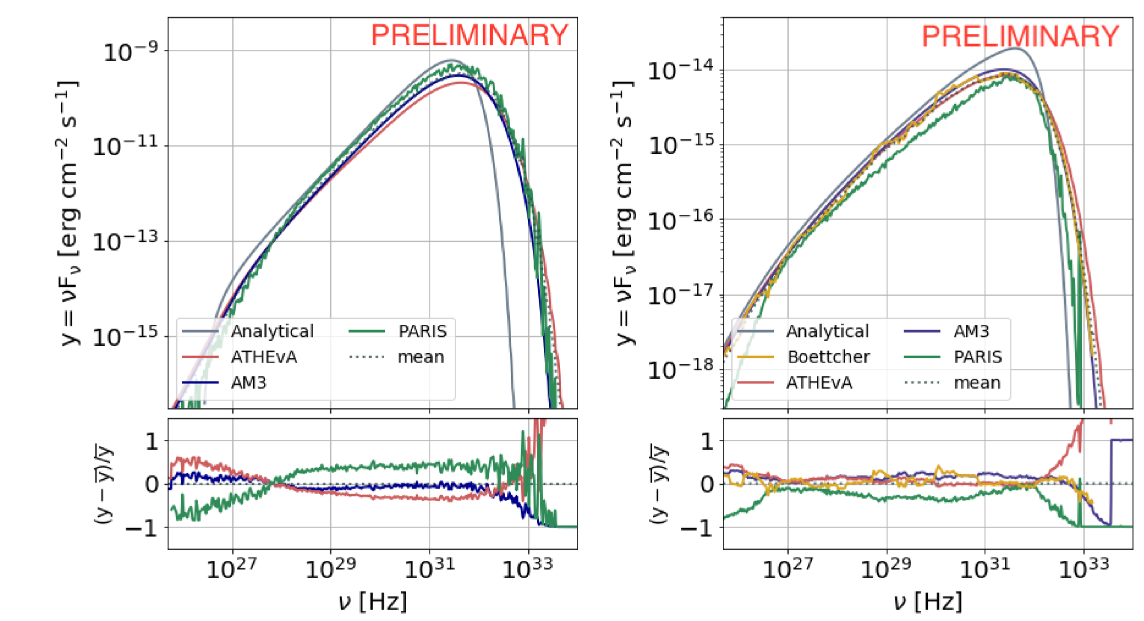

Figure 3: Neutrino spectra simulated by the four hadronic codes for Case I (left) and II (right). We also show approximate semi-analytic results, following [6].

Next Steps & Conclusions

As **next steps**, we plan to:

- perform more comparisons, probing different parts of the parameter phase space (e.g., high-opacity, and proton-cooling regime).
- test the codes for leptonic scenarios (e.g., synchrotron self-Compton and external Compton).
- perform comparison of codes in application to the multi-messenger 2017 dataset of TXS 506+056.
- prepare a dedicated publication with the results from the code comparison for the modeling of AGN emission. All output files will be made publicly available (online material).

In conclusion, the spread among the numerical simulations should be considered as a systematic uncertainty of numerical calculations for AGN multi-messenger emissions.

References

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