A SYSTEMATIC SEARCH FOR LEPTO-HADRONIC SIGNATURES IN VHE BLAZAR SPECTRA

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Abstract

In lepto-hadronic emission models, the high-energy spectral bump observed in blazars may contain contributions from synchrotron self-Compton emission, from proton and muon synchrotron radiation, and from cascades of secondary particles triggered by proton-photon interactions.

For certain ranges of model parameters, combinations of different emission components at very high energies may lead to specific, revelatory signatures in the VHE energy spectrum.

We have developped a lepto-hadronic model and systematically studied its parameter space with respect to applications for (ultra) high-frequency peaked BL Lac objects - (U)HBLs. In this parameter scan, we have searched for characteristic spectral signatures that could be detectable, e.g. with the future Cherenkov Telescope Array.

LEHA - a lepto-hadronic blazar emission code

LEHA is a new code developped by Cerruti et al. [2015] to simulate the stationary emission from BL Lac objects for leptonic, hadronic and mixed scenarios. Relativistic populations of electrons and protons interact inside a plasma blob (of radius R) with a tangled magnetic field (of strength B). The primary particle distributions follow power laws with self-consistent cooling breaks.

In addition to synchrotron emission from primary protons and electrons, and synchrotron self-Compton emission (SSC), the code also treats proton-photon interactions by using the SOPHIA Monte Carlo package (Mücke et al. [2000]). Secondary particles from such interactions trigger pair-synchrotron cascades that are followed for several generations. In addition, the muon synchrotron spectrum is calcuated, as well as Bethe-Heitler pair production and photon-photon pair production.

Physical Constraints

- Leptons and protons are supposed to be co-accelerated and to follow power laws with the same index $n1$, before cooling.
- The maximum proton energy, and the break energy of electron- and proton-spectra, are derived from acceleration and energy loss (radiative and adiabatic cooling) time scales.
- The bulk Doppler factor of the emission region is fixed at $\delta = 30$, a typical value for VHE detected BL Lac objects.
- The minimum size of the emission region is fixed at 10^{14} cm.
- The jet power is estimated for each solution as $L_j \approx 2\pi R^2 c\Gamma^2(u'_B + u'_e + u'_p)$, where the bulk Lorentz factor $\Gamma \approx \delta/2$ in the small-angle approximation, and u'_B, u'_e, u'_p are the comoving energy densities of the magnetic field, electrons and protons, respectively. L_j is not constrained, but can be compared to the Eddington luminosity L_{edd}.

→ We scan B, R and $n1$ and adjust the particle densities, and minimum and maximum lepton energies to the spectral energy distribution (SED).

Solutions for HBLs (PRELIMINARY)

We have modelled two HBLs, PKS 2155-304 (Aharonian et al. [2009]) and Mrk 421 (Abdo et al. [2011]), and found two hadronic scenarios:

1.) **Proton synchrotron** radiation dominates the VHE spectrum, and the whole high-energy bump, for a set of solutions close to the dividing line (black line in Fig. 1) in B-R space between the synchrotron-cooling and adiabatic-cooling dominated regime for protons (blue band). An example SED is shown in Fig. 3. The energy budget can be dominated by the energy of the protons or by the magnetic field, but the best fits are characterized by high jet powers for the sources under consideration (cf. Fig. 2, the range of L_{edd} is indicated by the grey band).

2.) A large parameter space in R-B can be found for solutions where the high-energy bump is composed of a contribution from both **proton synchrotron and muon synchrotron** radiation. The latter dominates the high energy end of the SED. The solutions for the sources studied here are highlighted with the magenta band in Fig. 1,2. An example for an SED is shown in Fig. 4. The energy budget is close to equipartition and the total jet power is generally lower than for the pure proton synchrotron scenario.

An additional component from cascade radiation (cf. Fig. 3,4) can lead to **discernible spectral hardening in the TeV range** (red stars Fig. 1,2).

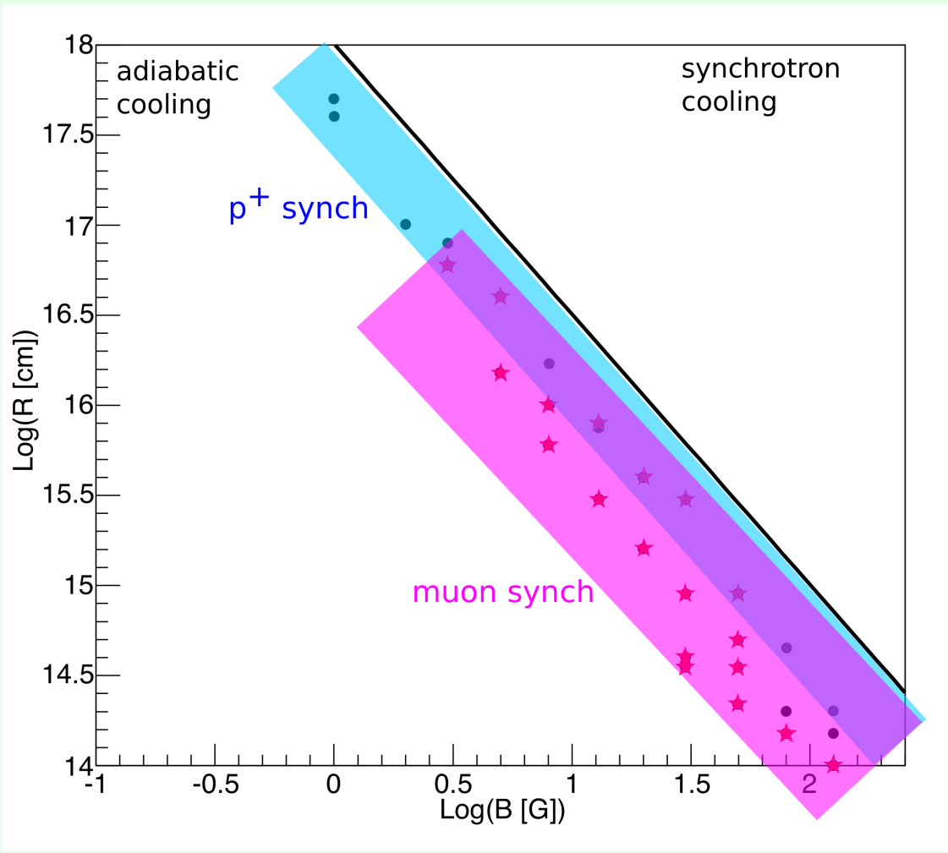

FIG. 1: Source extension vs. magnetic field for HBL models.

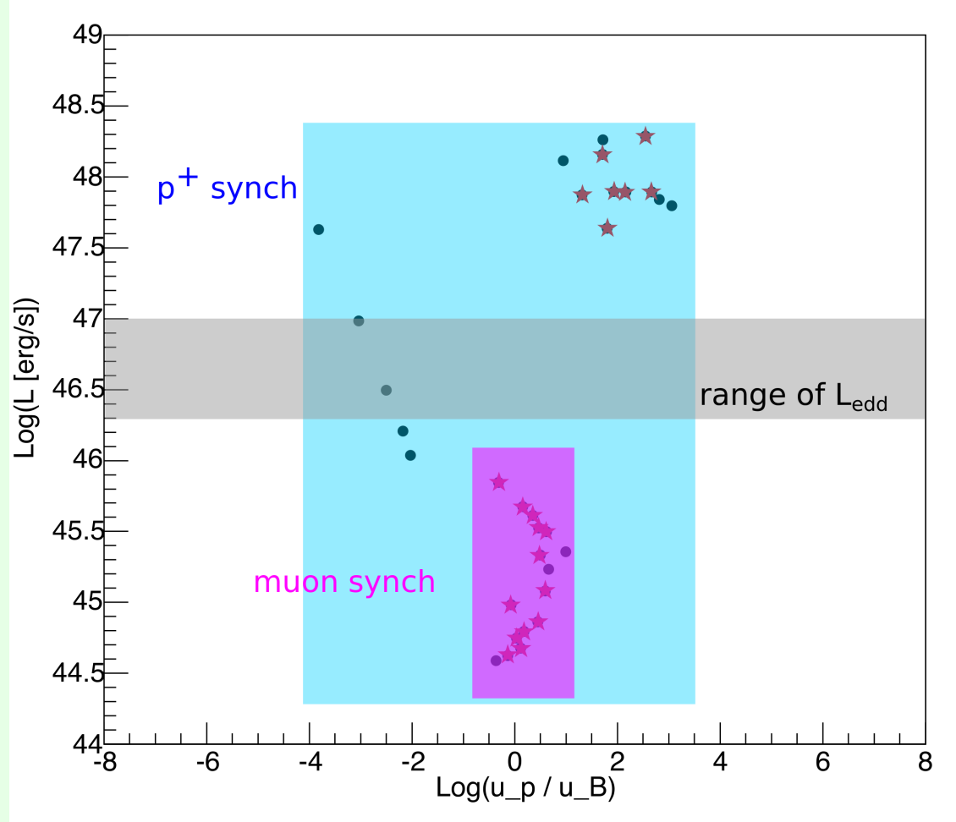

FIG. 2: Jet power vs. equipartition ratio for HBL models.

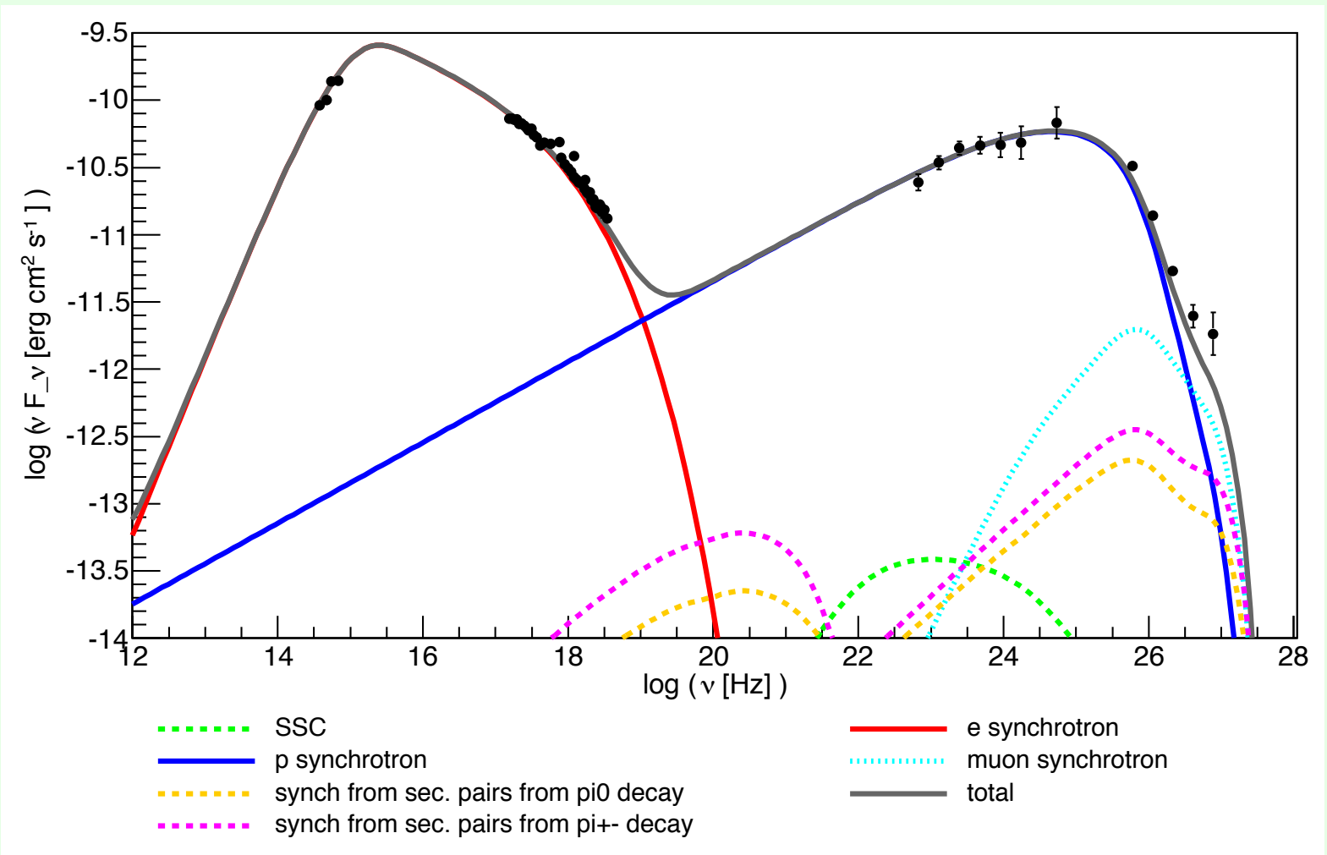

FIG. 3: Proton synchrotron dominated model for PKS 2155-304.

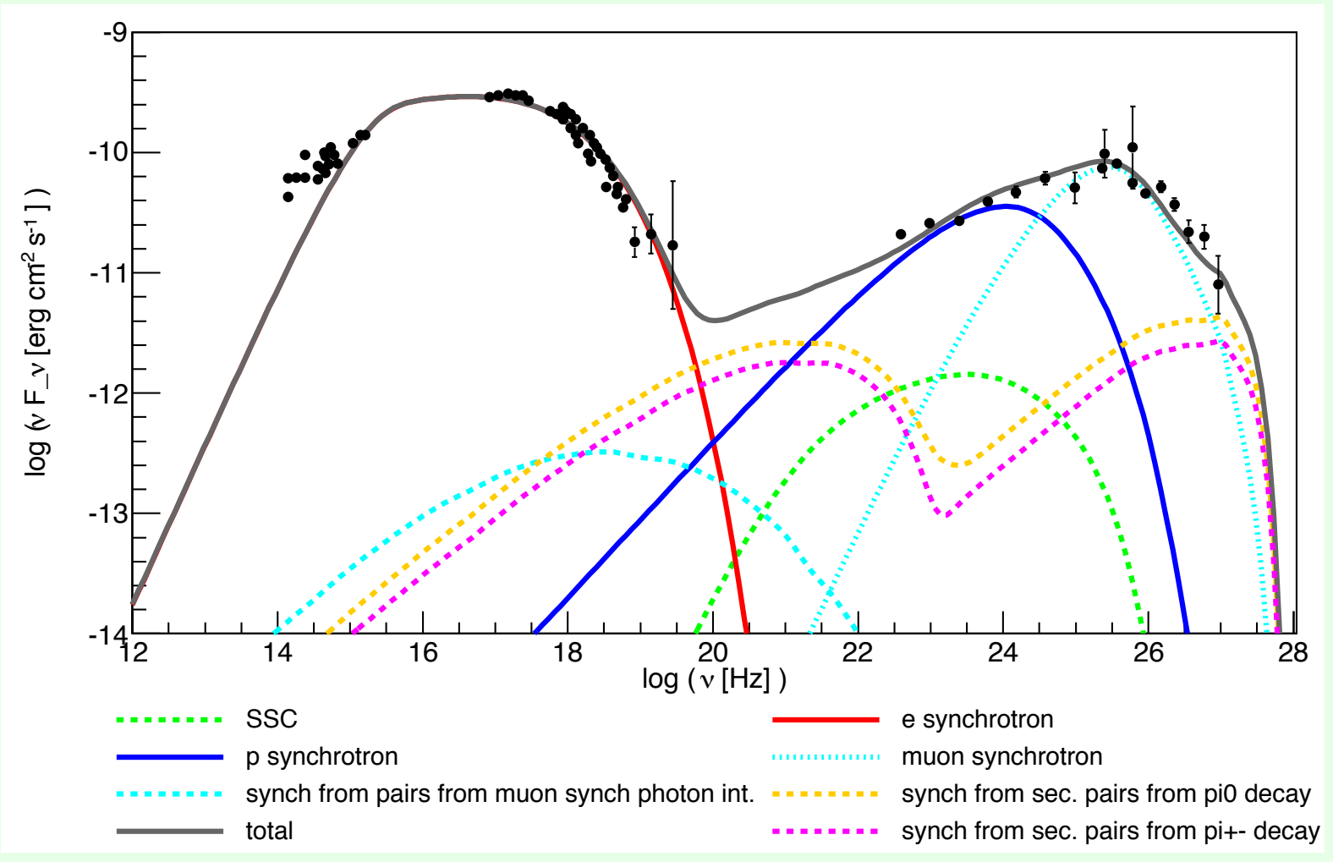

FIG. 4: Muon synchrotron dominated model for Mrk 421.

Solutions for UHBLs (Cerruti et al. [2015])

Good representations of the spectral energy distributions of five UHBLs were found for two distinct regions in B-R parameter space:

1.) **Proton synchrotron** radiation dominates the high-energy spectral bump for a large set of solutions around the dividing line between different cooling regimes in B-R space (blue band in Fig. 5). For these models, as in the three examples shown in Fig. 7, contributions from cascade emission and SSC are negligible. The energy budget is largely dominated by the energy density of the magnetic field (cf. Fig. 6) and the jet power decreases approximately as $1/B$.

2.) A combination of both **SSC and proton-induced cascade emission** dominates the high-energy spectral bump for a second set of solutions that can be found in a more compact region in B-R space for smaller values of B (red band in Fig. 5). For these models, proton synchrotron emission occurs at intermediate energies and is very weak compared to the emission from SSC and cascades. Three examples are shown in Fig. 8. The energy budget is dominated by the kinetic energy of the relativistic protons (cf. Fig. 6).

In both scenarios, contribution from muon synchrotron emission is small and there is no spectral feature in the TeV range from cascades.

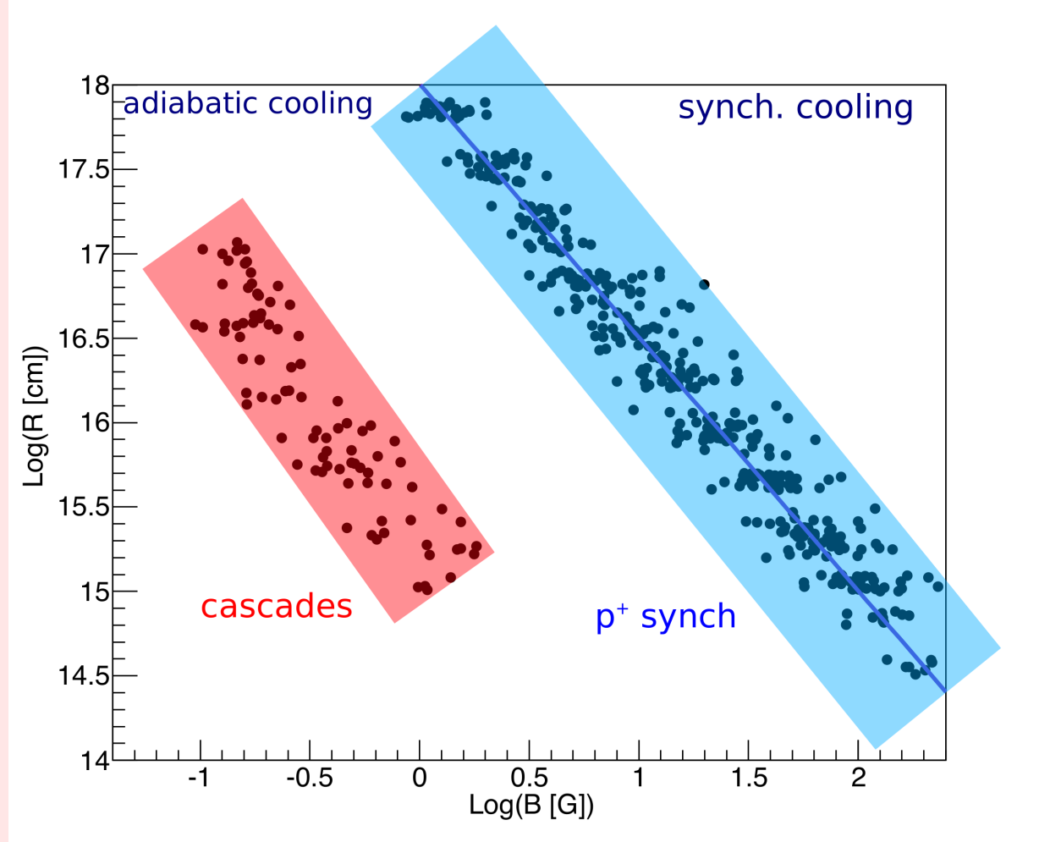

FIG. 5: Source extension vs. magnetic field for UHBL models.

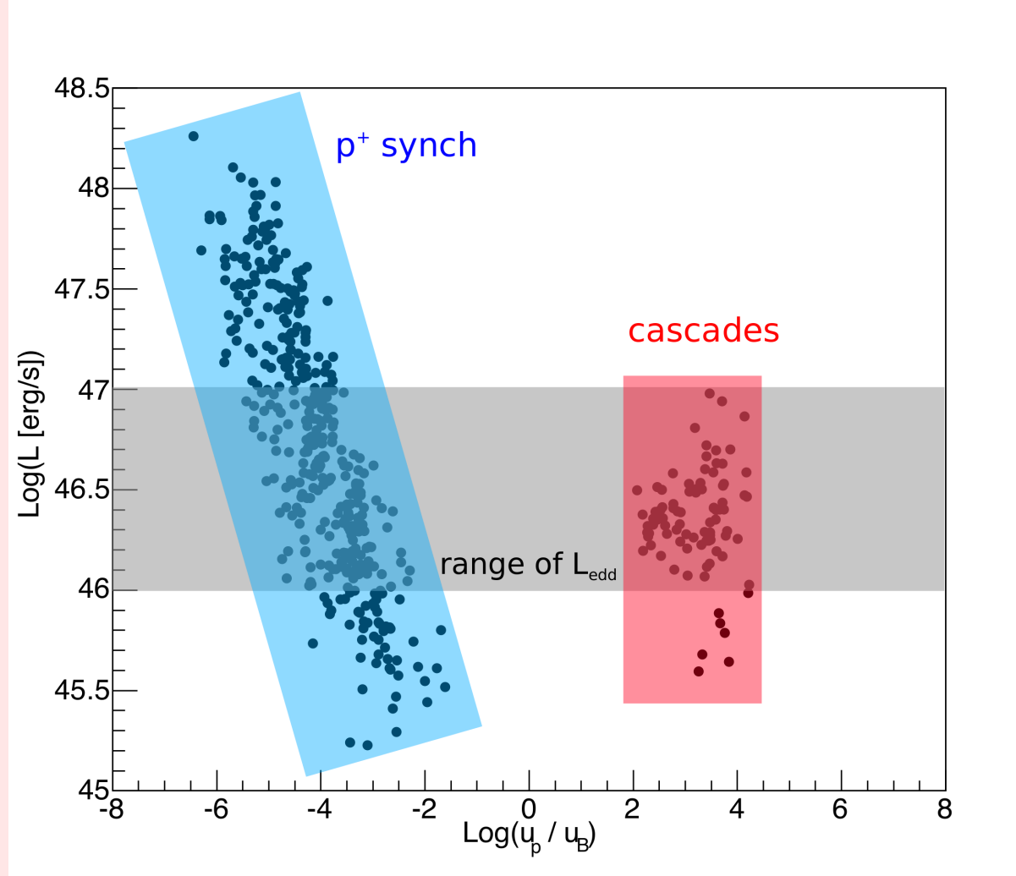

FIG. 6: Jet power vs. equipartition ratio for UHBL models.

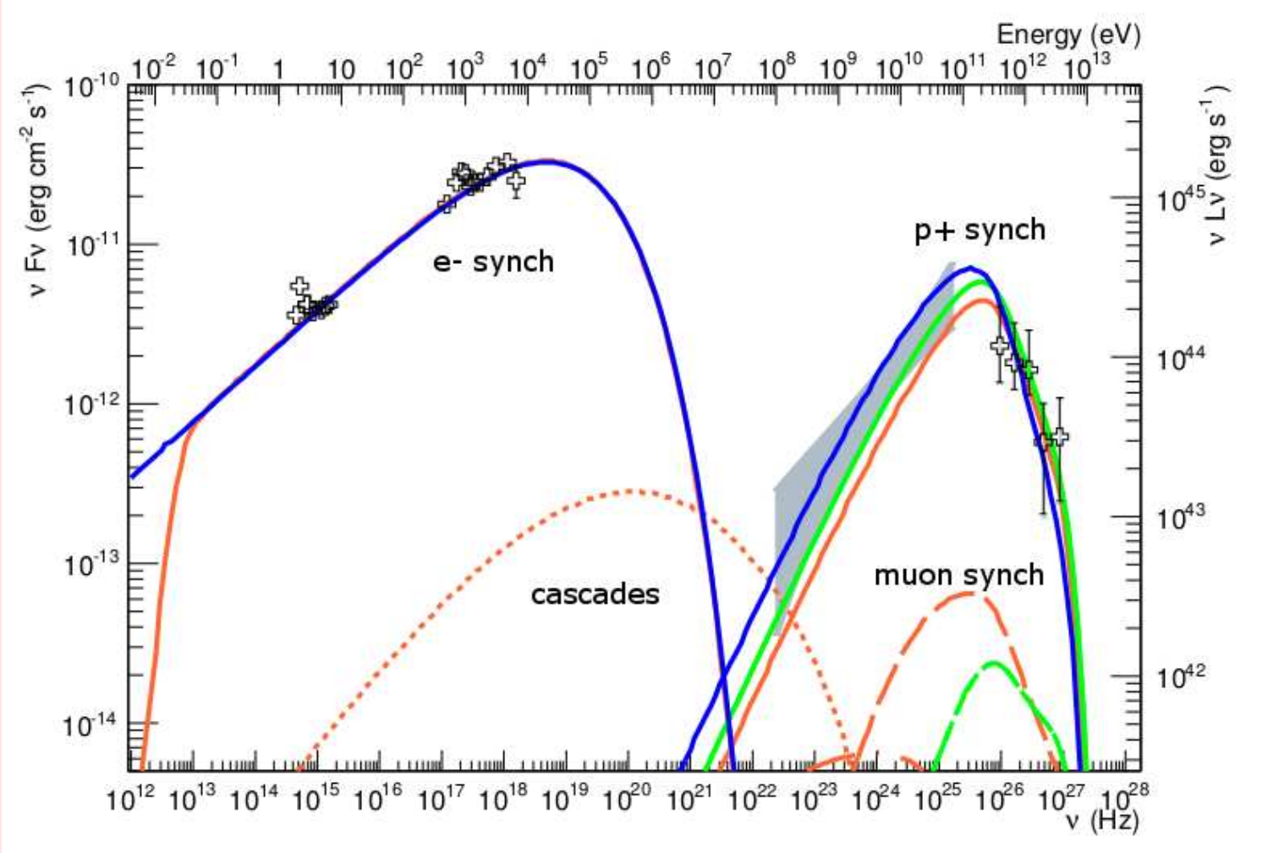

FIG. 7: Proton synchrotron model for RGB J0710+591.

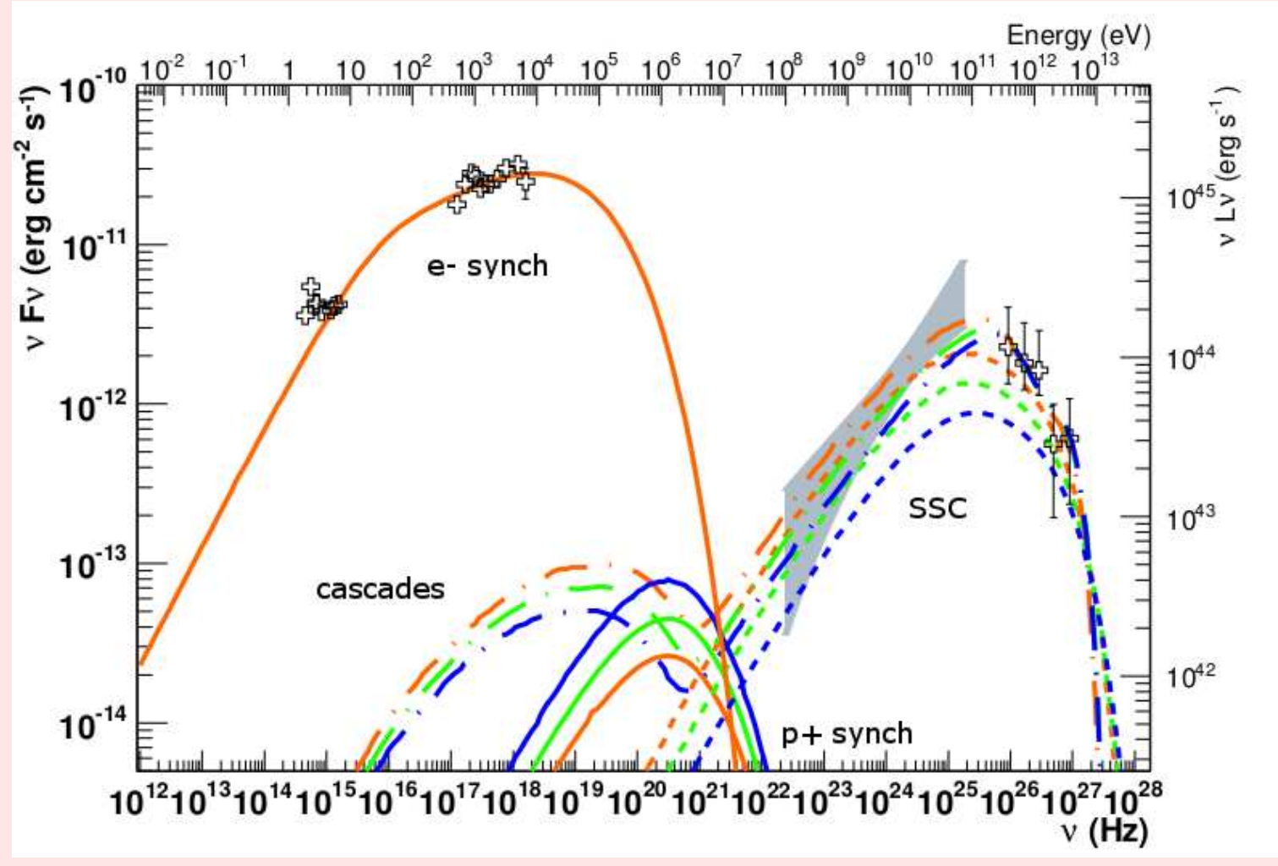

FIG. 8: "Lepto-hadronic" model for RGB J0710+591.

Conclusions & Outlook

(Lepto-)hadronic modelling of UHBLs and HBLs leads to distinct solutions for both BL Lac subclasses. In both cases, the high-energy bump can be represented with proton synchrotron emission. HBLs allow for a second set of solutions where muon synchrotron emission dominates the VHE spectrum, while the high-energy bump in UHBLs can be alternatively modelled with a combination of SSC and cascade emission.

Solutions with **sub-Eddington jet powers** can be found for all the sources we have studied so far (5 UHBLs and 2 prominent HBLs), providing an acceptable energy budget for the (lepto-)hadronic alternative to leptonic models (cf e.g. Ghisellini et al. [2014]).

Characteristic **spectral hardening in the VHE spectrum** is only observed for the HBLs we have studied, and only for a subset of the proposed solutions where the proton population is sufficiently dense, such that the contribution from proton-induced cascades becomes significant at the highest energies. This subset includes several solutions with sub-Eddington jet powers.

The detectability of such spectral features with the future Cherenkov Telescope Array has been demonstrated for one example (Zech et al. [2013]). A more systematic evaluation is now being undertaken to estimate the range of expected signatures and the required observation times for a set of selected HBLs.

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