Photohadronic pair injection constrains the FSRQ emitting region: the case of 3C 273

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Abstract

We demonstrate a way to constrain the properties of the γ-ray emitting region in FSRQs, such as its Doppler factor, in scenarios where the γ-ray emission is attributed to proton synchrotron radiation. We show that for low enough Doppler factors the synchrotron emission from secondary pairs produced via photohadronic interactions may violate the observed γ-ray flux, even if the radiation field of the broad line region (BLR) is not taken into account. We apply our method to FSRQ 3C 273 and derive a minimum Doppler factor.

Overview

FSRQs have been studied extensively in the literature as possible PeV neutrino sources. Since purely leptonic models cannot produce neutrinos, leptohadronic models are a necessity in that context. Here we focus on the following scenario:

- the high-energy component of the spectral energy distribution (SED) is explained by proton synchrotron radiation;
- photons produced as a result of photohadronic interactions (photopion production and Bethe-Heitler pair production) emerge typically at very high energies (VHE), i.e. much above the peak of the high-energy hump of the SED;
- these VHE photons, e.g. γ-rays from π^0 decay, are also subjected to intrinsic $\gamma\gamma$ absorption;
- the optical depth of $\gamma\gamma$ absorption ($\tau_{\gamma\gamma}$) is directly related to the optical depth of photopion interactions ($\tau_{p\pi}$), see e.g. [2];
- if $\tau_{\gamma\gamma} \gg 1$, the emission from the initiated EM cascade will affect the high-energy blazar spectrum or may even dominate on the MW emission (e.g. [3]).

Figure 1 shows an illustration of an FSRQ, as modeled in this work. The emission region is taken as a spherical blob with radius R, containing a tangled magnetic field of strength B. Relativistic protons and electrons are assumed to be continuously injected through some acceleration mechanism. The emission region can be inside or outside the BLR region, which will determine the effect of the latter on the MW emission of an FSRQ. Finally, the emission from the blob will appear boosted in the observer's frame due to the relativistic motion of the flow; δ is the respective Doppler factor.

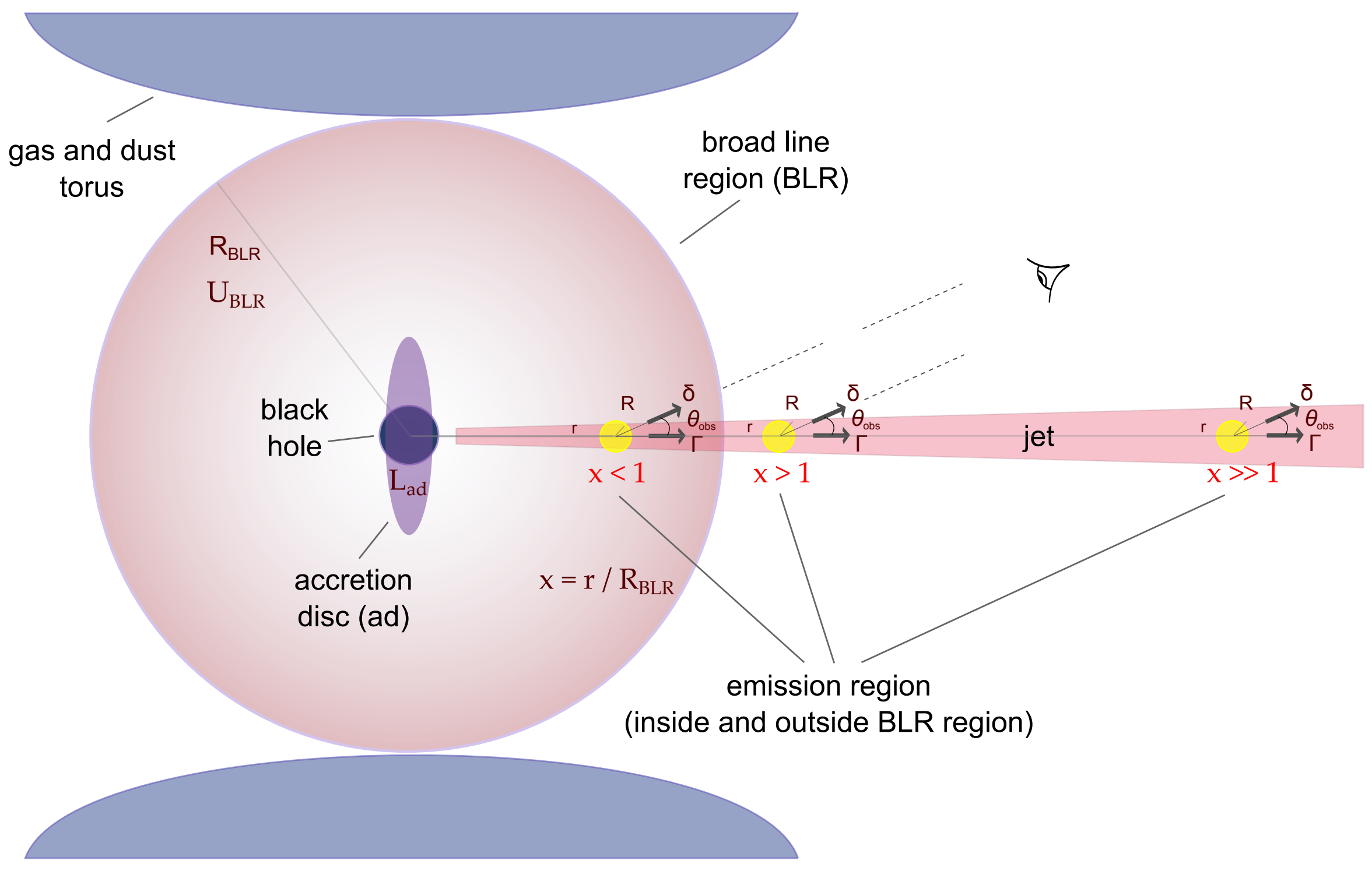
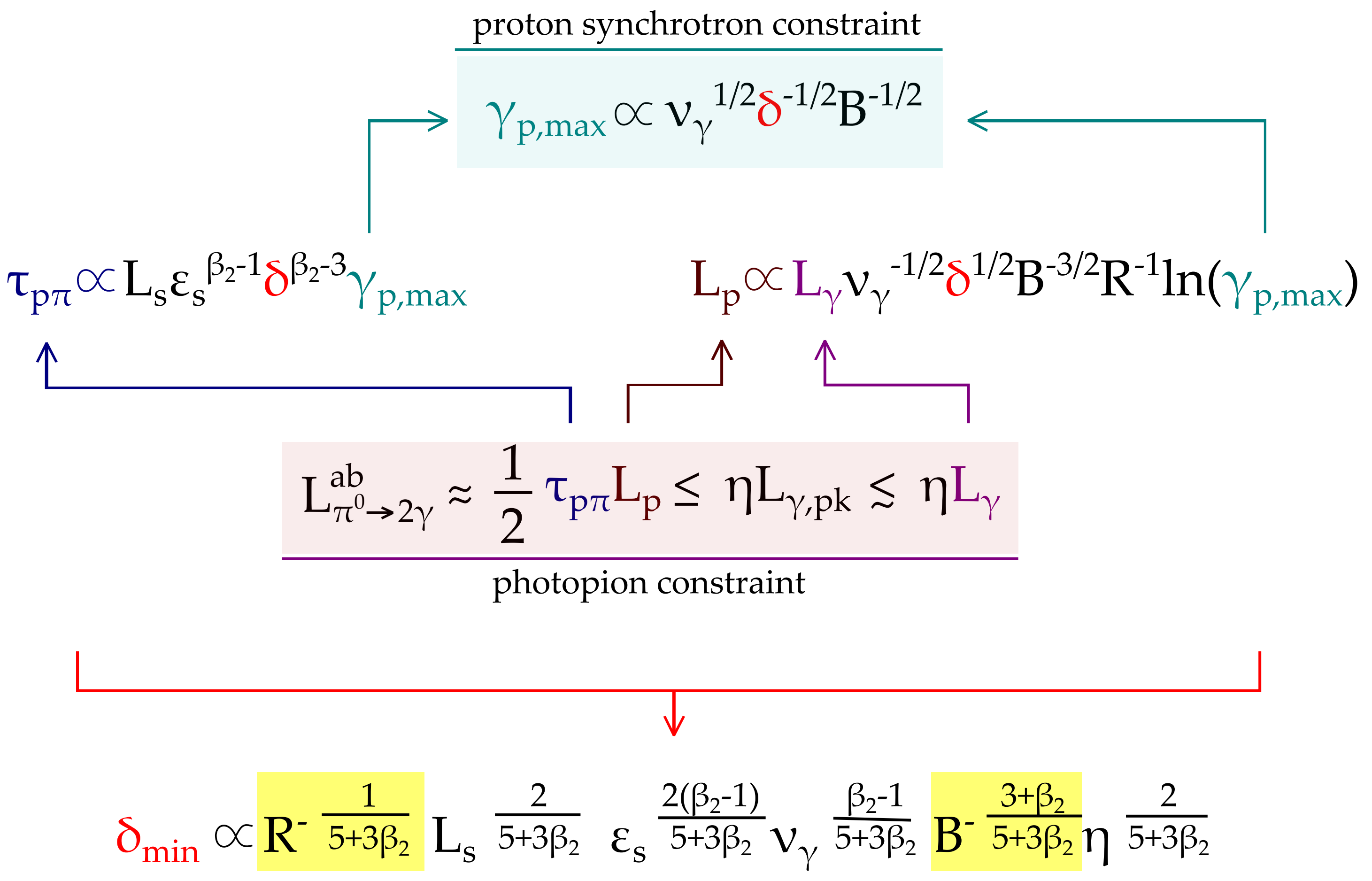


Fig. 1: An illustration of the source region and of the physical objects affecting it.

Derivation of $\delta_{\min}$ for $r \gg R_{\rm BLR}$

While proton synchrotron radiation accounts for most of the high energy part of the SED, the highest energy data point in Figure 3 can best be explained by the photohadronic component. Being more susceptible to changes in the initial conditions, which are mostly regulated by the free parameter δ, that data point can help constrain δ. In Figure 2 we present, in brief, the analytical derivation of a minimum value for δ, with the spectral shape approximated as a broken power law.



proton synchrotron constraint

$$\gamma_{p,\max} \propto \nu_\gamma^{1/2}\delta^{-1/2}B^{-1/2}$$

$$\tau_{p\pi} \propto L_s \varepsilon_s^{\beta_2-1}\delta^{\beta_2-3}\gamma_{p,\max} \qquad L_p \propto L_\gamma \nu_\gamma^{-1/2}\delta^{1/2}B^{-3/2}R^{-1}\ln(\gamma_{p,\max})$$

$$L^{ab}_{\pi^0\rightarrow 2\gamma} \approx \frac{1}{2}\tau_{p\pi}L_p \leq \eta L_{\gamma,pk} \lesssim \eta L_\gamma$$

photopion constraint

$$\delta_{\min} \propto R^{-\frac{1}{5+3\beta_2}} L_s^{\frac{2}{5+3\beta_2}} \varepsilon_s^{\frac{2(\beta_2-1)}{5+3\beta_2}} \nu_\gamma^{\frac{\beta_2-1}{5+3\beta_2}} B^{-\frac{3+\beta_2}{5+3\beta_2}} \eta^{\frac{2}{5+3\beta_2}}$$

Fig. 2: Schematic overview of the factors governing δ_{min}, through an analytical approach.

Most of the parameters that $\delta_{\min}$ depends on are constrained by observations. However, R and B are free parameters.

Effect of δ on the SED: the case of 3C 273

The limiting case $r \gg R_{\rm BLR}$

Having derived $\delta_{\min}$ analytically, we proceeded to fit the SED of 3C 273 numerically, using a variation of the code first presented in [1].

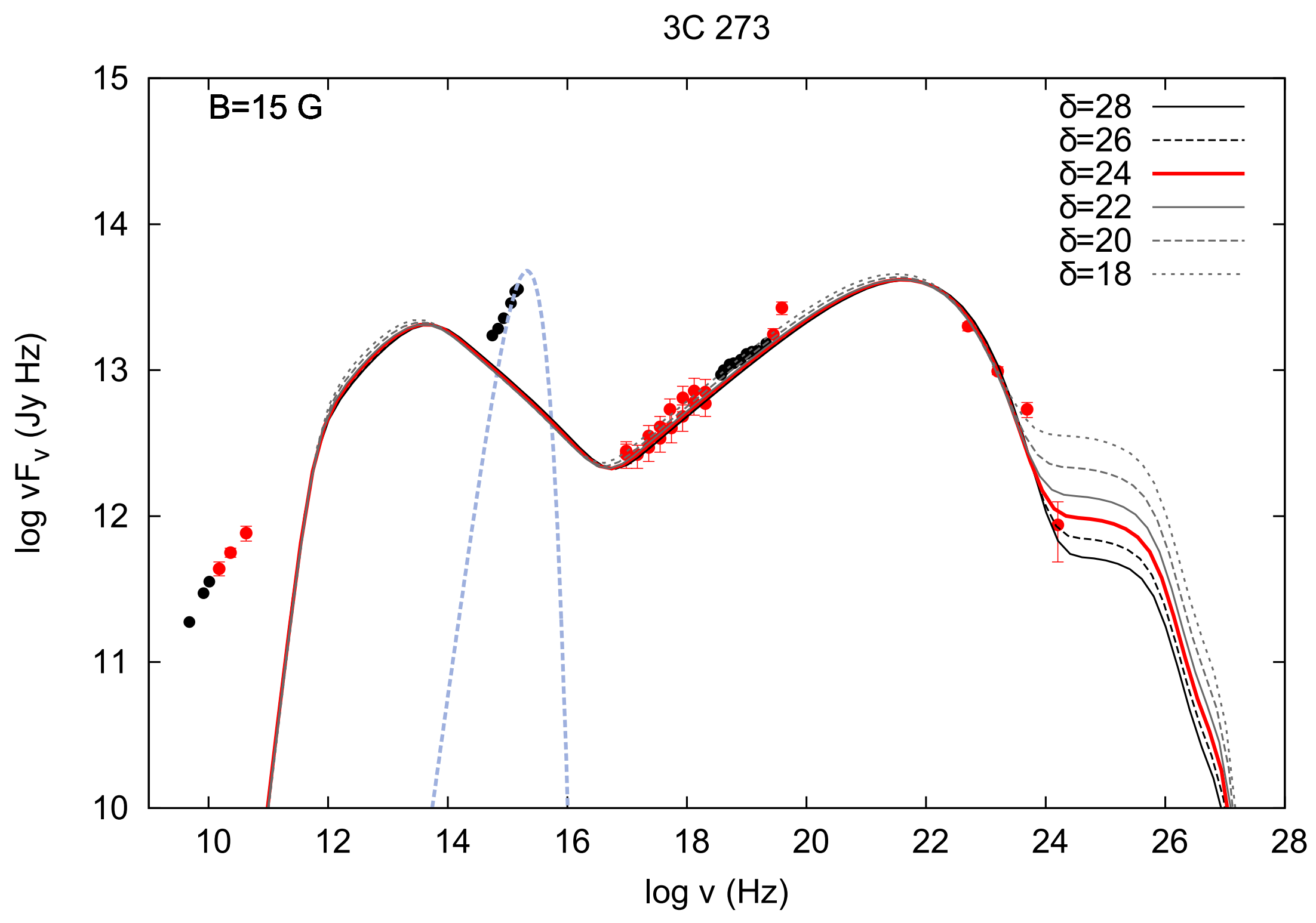


Fig. 3: Leptohadronic fits of 3C 273 for $B = 15$G and various values of δ.The red curve represents the lower limit for δ for which there can be a fit. The emission from the disk (blue dashed line) is approximated with a black-body at temperature $T = 3 \times 10^4$K. Note that this the most conservative scenario; in the limit $r \gg R_{\rm BLR}$, the BLR photons are not targets for photohadronic interactions.

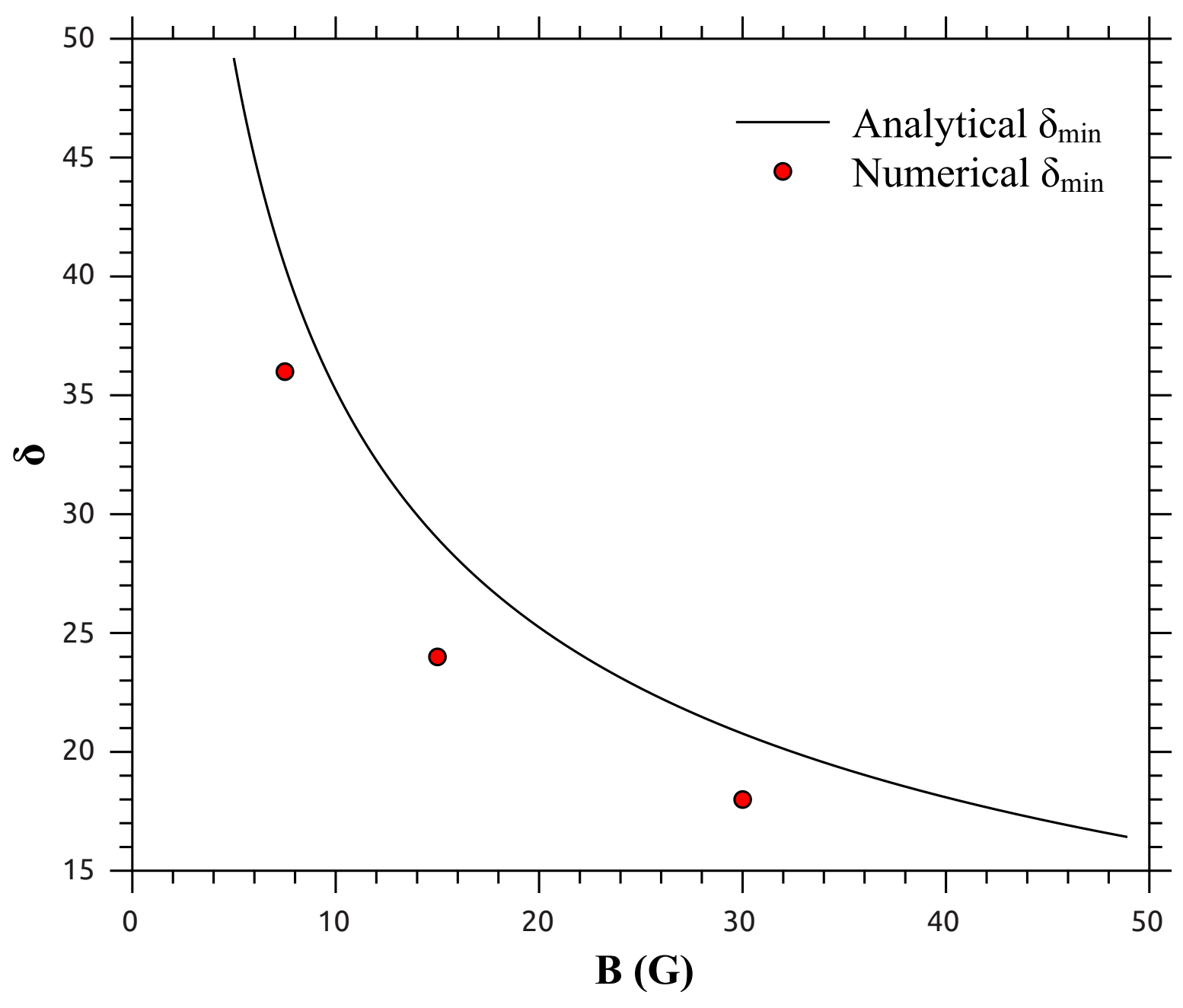


Fig. 4: Minimum Doppler factor $\delta_{\min}$ as a function of the magnetic field strength for $R = 3 \times 10^{16}$ cm. The solid line is the analytical prediction, while the points are the values derived numerically.For $\delta < \delta_{\min}$ the cascade emission deforms the proton synchrotron spectrum. We used parameter values relevant to 3C 273.

The general case

We express the BLR energy density as measured in the comoving frame as a function of $x \equiv r/R_{\rm BLR}$, where r is the distance of the emitting region along the jet. Following [5] and [4], we may write:

$$u'_{\rm BLR} = \frac{0.4\xi_{\rm BLR}\Gamma^2 L_{\rm d}}{3\pi c R^2_{\rm BLR}}\lambda(x), \qquad \lambda(x) = \frac{1}{1+x^4}.$$

This parametrization of the problem allows, therefore, for solutions within or outside the BLR and is a generalization of the approach presented in the analytical section. Figure 5 shows the minimum distance x for each value of δ, down to δ_{min} for each of two values of B. It is interesting to note that x quickly becomes very weakly dependent on the value of δ.

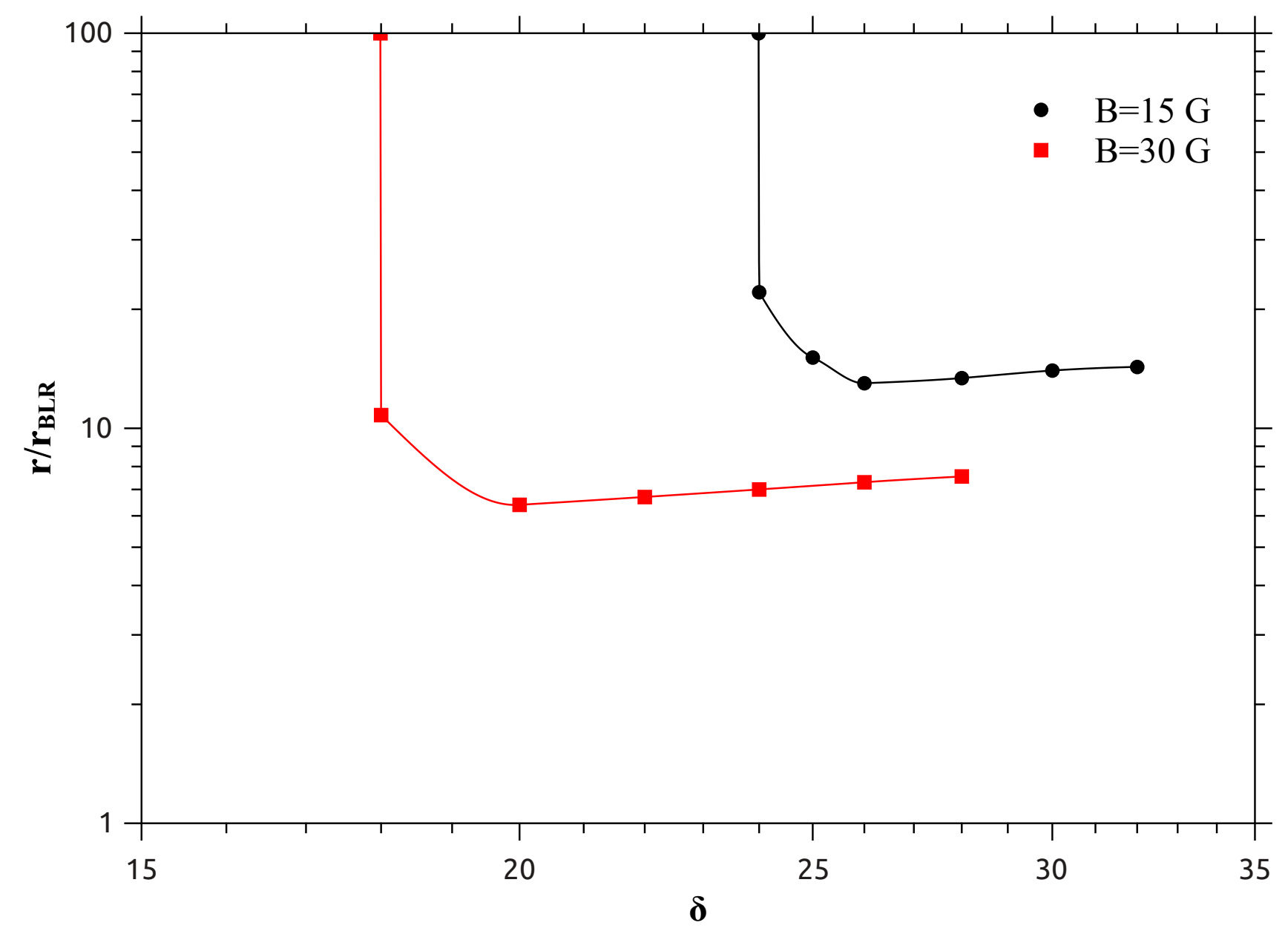


Fig. 5: Minimum distance of the emitting region along the jet (normalized to $R_{\rm BLR}$) as a function of the Doppler factor for two values of the magnetic field strength.

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