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Black hole mass estimates in quasars

A comparative analysis of high- and low-ionization lines

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ABSTRACT

Context. The inter-line comparison between high- and low-ionization emission lines has yielded a wealth of information on the quasar broad line region (BLR) structure and dynamics, including perhaps the earliest unambiguous evidence in favor of a disk + wind structure in radio-quiet quasars.

Aims. We carried out an analysis of the $\text{CIV}\lambda 1549$ and $\text{H}\beta$ line profiles of 28 Hamburg-ESO high luminosity quasars and of 48 low- z , low luminosity sources in order to test whether the high-ionization line $\text{CIV}\lambda 1549$ width could be correlated with $\text{H}\beta$ and be used as a virial broadening estimator.

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Methods. We analyze intermediate- to high-S/N, moderate resolution optical and NIR spectra covering the redshifted C $\text{IV}\lambda 1549$ and H β over a broad range of luminosity $\log L \sim 44 - 48.5$ [erg s $^{-1}$] and redshift ($0 - 3$), following an approach based on the quasar main sequence.

Results. The present analysis indicates that the line width of C $\text{IV}\lambda 1549$ is not immediately offering a virial broadening estimator equivalent to H β . At the same time a virialized part of the BLR appears to be preserved even at the highest luminosities. We suggest a correction to FWHM(C $\text{IV}\lambda 1549$) for Eddington ratio (using the C $\text{IV}\lambda 1549$ blueshift as a proxy) and luminosity effects that can be applied over more than four dex in luminosity.

Conclusions. Great care should be used in estimating high- L black hole masses M_{BH} from C $\text{IV}\lambda 1549$ line width. However, once corrected FWHM C $\text{IV}\lambda 1549$ are used, a C $\text{IV}\lambda 1549$ -based scaling law can yield unbiased M_{BH} values with respect to the ones based on H β with sample standard deviation ≈ 0.3 dex.

Key words. quasars: general – quasars: emission lines – quasars: supermassive black holes – ISM: jets and outflows – line: profiles

1. Introduction

Type-1 active galactic nuclei (AGN) and quasars show the same broad optical-UV lines almost always accompanied by broad permitted FeII emission (e.g., Vanden Berk et al. 2001). However, even among type-1 sources we face a large diversity in observational manifestations involving line profiles, internal line shifts as well as emission line intensity ratios (e.g., Sulentic et al. 2000a; Bachev et al. 2004; Yip et al. 2004; Kuraszkiewicz et al. 2009; Zamfir et al. 2010; Shen & Ho 2014, and Sulentic & Marziani 2015 for a recent review). Broad line measurements involving H β line width and FeII strength are not randomly distributed but instead define a quasar “main sequence” (MS) (e.g., Boroson & Green 1992; Sulentic et al. 2000a; Shen & Ho 2014). The MS can be traced in an optical plane defined by FeII emission prominence and the Hydrogen H β line width. The FeII strength is parametrized by the intensity ratio involving the FeII blue blend at 4570 Å and broad H β i.e., $R_{\text{FeII}} = I(\text{FeII}\lambda 4570)/I(\text{H}\beta)$, and the Hydrogen H β line width by its FWHM. Along the MS, sources with higher R_{FeII} show narrower broad H β (Population A, $\text{FWHM}(\text{H}\beta) \lesssim 4000 \text{ km s}^{-1}$, Sulentic et al. 2000a). Lower R_{FeII} is associated with sources with broader H β profiles (Pop. B with $\text{FWHM}(\text{H}\beta) \gtrsim 4000 \text{ km s}^{-1}$, Sulentic et al. 2011). A glossary of the MS-related terminology is provided in Appendix A.

Studies of the Balmer lines have played a prominent role for characterizing the MS and the properties of the broad line emitting region (BLR) in low z ($\lesssim 0.8$) quasars with H β providing information for the largest number of sources (e.g., Osterbrock & Shuder 1982; Wills et al. 1985; Sulentic 1989; Zamfir et al. 2010; Hu et al. 2012; Steinhardt & Silverman 2013; Shen 2016, for a variety of observational and statistical approaches). A most important application of the FWHM H β has been its use as a virial broadening estimator (VBE) to derive black hole masses (M_{BH}) from single-epoch observations of large samples of quasars (e.g., McLure & Jarvis 2002; McLure & Dunlop

2004; Vestergaard & Peterson 2006; Assef et al. 2011; Shen 2013; Peterson 2014, and references therein). The underlying assumption is that the H β line width provides the most reliable VBE, which is likely to be the case, even if with some caveats (e.g., Trakhtenbrot & Netzer 2012, see also Shen 2013, Peterson 2014 for reviews).

Balmer lines provide a reliable VBE up to $z \lesssim 2$ (Matsuoka et al. 2013; Karouzos et al. 2015) at cosmic epochs less than a few Gyr. The importance to have a reliable VBE at even earlier cosmic epochs cannot be underemphasized. The entire scenario of early structure formation is affected by inferences from estimates of quasar black hole masses. Overestimates of M_{BH} by lines whose broadening is in excess to the virial one can have implications on the quasar mass function, and at high redshift ($z \gtrsim 6$) when the Universe was less than 1 billion year of age, on the formation and mass spectrum of the seed black holes (Latif & Ferrara 2016) that may have been responsible, along with Pop. III stars, of the reionization of the process at $z \sim 7 - 10$ (e.g., Gallerani et al. 2017, for a review).

Strong and relatively unblended C IV λ 1549 has been the best candidate for a VBE beyond $z \sim 1.5$, where H β is shifted into the IR domain. C IV λ 1549 can be observed up to redshift $z \approx 6$ with optical spectrometers, and in the NIR bands up to redshift $z \approx 7.5$ (Bañados et al. 2018), and beyond. Can C IV λ 1549 be used as an immediate surrogate for H β when H β is invisible or hard to obtain? Before attempting an answer to this question, two considerations are in order.

Firstly, measures of the C IV λ 1549 line profiles remain of uncertain interpretation without a precise determination of the quasar rest frame: an accurate z measurement is not easy to obtain from broad lines, and redshift determinations at $z \gtrsim 1$ from optical survey data suffer systematic biases as large as several hundreds km s $^{-1}$ (Hewett & Wild 2010; Shen et al. 2016). Reliable studies tie C IV measures to a rest frame derived from H β narrow component (+ [O III] λ 4959,5007 whenever applicable Mejía-Restrepo et al. e.g., 2016; for problems in the use of [O III] λ 4959,5007, see Zamanov et al. 2002; Hu et al. 2008).

Secondly, significant C IV λ 1549 blueshifts are observed over a broad range in z and luminosity, from the nearest Seyfert 1 galaxies to the most powerful radio-quiet quasars (Wills et al. 1993; Sulentic et al. 2007; Richards et al. 2011; Coatman et al. 2016; Shen 2016; Bischetti et al. 2017; Bisogni et al. 2017; Vietri 2017; Sulentic et al. 2017). Measures of the C IV λ 1549 profile velocity displacement provide an additional dimension to a 4D “eigenvector 1” (4DE1) space built on parameters that are observationally independent (“orthogonal”) and related to different physical aspects (Sulentic & Marziani 2015). Inclusion of C IV λ 1549 shift as a 4DE1 parameter was motivated by the earlier discovery of internal redshift differences between low- and high-ionization lines (Burbidge & Burbidge 1967; Gaskell 1982; Tytler & Fan 1992; Brotherton et al. 1994b; Corbin & Boroson 1996; Marziani et al. 1996).

The current interpretation of the BLR in quasars sees the broad lines arising in a region that is physically and dynamically composite (e.g., Collin-Souffrin et al. 1988; Elvis 2000; Ferland et al. 2009; Kollatschny & Zetzl 2013; Grier et al. 2013; Du et al. 2016). C IV λ 1549 is a doublet originat-

ing from an ionic species of ionization potential (IP) four times larger than Hydrogen (54 eV vs. 13.6 eV), and is therefore a prototypical high-ionization line (HIL). The line is mainly produced by collisional excitation from the ground state 2S_0 to $^2S_{\frac{1}{2}, \frac{3}{2}}$ at the temperature of photo-ionized BLR gas ($T \sim 10^4$ K, Netzer 1990), in the fully-ionized zone of the line emitting gas. Empirically, the line is relatively strong (rest frame equivalent width $W \sim 10 - 100$ Å depending on the source location on the MS) and only moderately contaminated on the red side (red shelf) by H ϵ λ 1640 and O III λ 1663 plus weak emission from Fe II_{UV} multiplets (Fine et al. 2010). The Balmer line H β assumed to be representative of the low-ionization lines (LILs, from ionic species with IP $\lesssim 20$ eV) is instead enhanced in a partially-ionized zone due to the strong X-ray emission of quasars and to the large column density of the line emitting gas ($N_e \gtrsim 10^{23} \text{ cm}^{-2}$; Kwan & Krolik 1981). Comparison of H β and C IV λ 1549 profiles in the same sources tells us that they provide independent inputs to BLR models — their profiles can be dissimilar and several properties uncorrelated (see, for instance, Fig. C2 of Mejía-Restrepo et al. 2016).

It is possible to interpret H β and C IV λ 1549 profiles as associated with two sub-regions within the BLR (e.g., Baldwin et al. 1996; Hall et al. 2003; Leighly 2004; Snedden & Gaskell 2004; Czerny & Hryniewicz 2011; Plotkin et al. 2015): one emitting predominantly LILs (e.g., Dultzin-Hacyan et al. 1999; Matsuoka et al. 2008), and a second HILs, associated with gas outflows and winds (e.g., Richards et al. 2011; Yong et al. 2018). This view is in accordance with early models of the BLR structure involving a disk and outflow or wind component (Collin-Souffrin et al. 1988; Elvis 2000). Intercomparison of C IV λ 1549 and H β at low z and moderate luminosity provided the most direct observational evidence that this is the case at least for radio-quiet (RQ) quasars (Corbin & Boroson 1996; Sulentic et al. 2007; Wang et al. 2011; Coatman et al. 2016). Modeling involves a disk + wind system (e.g., Proga et al. 2000; Proga & Kallman 2004; Flohic et al. 2012; Sądowski et al. 2014; Vollmer et al. 2018, for different perspectives), although the connection between disk structure and BLR (and hence the H β and C IV λ 1549 emitting regions) is still unclear.

There are additional caveats, as the C IV λ 1549 blueshifts are not universally detected. Their amplitude is a strong function of the location along the MS (Sulentic et al. 2000b, 2007; Sun et al. 2018). Large blueshifts are clearly detected in Population A, with sources accreting at relatively high rate, and reach extreme values for quasars at the high R_{FeII} end along the MS. In Pop. B, the wind component is not dominating the line broadening of C IV λ 1549 at moderate luminosity; on the converse, the C IV λ 1549 and H β line profile intercomparison indicates that the dynamical relevance of the C IV λ 1549 blueshift is small i.e., that the ratio between the centroid at half-maximum $c(\frac{1}{2})$ and the FWHM is $\ll 1$ (Sulentic et al. 2007). Reverberation mapping studies indicate that the velocity field is predominantly Keplerian (Pei et al. 2017 and references therein for the prototypical source NGC 5548, Denney et al. 2010; Grier et al. 2013), and that the C IV λ 1549 emitting region is closer to continuum source than the one of H β (e.g., Peterson & Wandel 2000; Kaspi et al. 2007; Trevese et al. 2014). The issue is complicated by luminosity effects on the C IV λ 1549 shifts that may have gone undetected at low- z . Both Pop. A and B sources at $\log L \gtrsim 47 \text{ erg s}^{-1}$ show large

amplitude blueshifts in C $\text{IV}\lambda 1549$ (Sulentic et al. 2017; Bisogni et al. 2017; Vietri et al. 2018). The present work considers the trends associated with the MS as well as the luminosity effects that may appear second-order in low-luminosity samples to provide corrections to the FWHM of H β and ultimately a scaling law based on C $\text{IV}\lambda 1549$ FWHM and UV continuum luminosity that may be unbiased with respect to H β and with a reasonable scatter.

The occurrence of C $\text{IV}\lambda 1549$ large shifts challenges the suitability of the C $\text{IV}\lambda 1549$ profile broadening as a VBE for M_{BH} estimates (see e.g., Shen 2013, for a review). Results at low-redshift suggest that the C $\text{IV}\lambda 1549$ line is fully unsuitable for part of Pop. A sources (Sulentic et al. 2007). A similar conclusion was reached at $z \approx 2$ on a sample of 15 high-luminosity quasars (Netzer et al. 2007). More recent work tends to confirm that the C $\text{IV}\lambda 1549$ line width is not straightforwardly related to virial broadening (e.g., Mejía-Restrepo et al. 2016). However, the C $\text{IV}\lambda 1549$ line is strong and observable up to $z \approx 6$ with optical spectrometers. It is so highly desirable to have a consistent VBE up to the highest redshifts that various attempts (e.g., Brotherton et al. 2015) have been done at rescaling C $\text{IV}\lambda 1549$ line width estimators to the width of LILs such as H β and Mg $\text{II}\lambda 2800$. Several conflicting claims have been recently made on the valid use of C $\text{IV}\lambda 1549$ width in high- z quasars (e.g., Assef et al. 2011; Shen & Liu 2012; Denney et al. 2012; Karouzos et al. 2015; Coatman et al. 2017; Mejía-Restrepo et al. 2018b).

From the previous outline we infer that a proper approach to testing the suitability of the C $\text{IV}\lambda 1549$ line width as a VBE is to compare C $\text{IV}\lambda 1549$ and H β profiles along the quasar MS, and to extend the luminosity range including intermediate-to-high z ($\gtrsim 1.4$) sources when H β is usually not covered by optical observations. A goal of this paper is to analyse the factors yielding to large discrepancies between the M_{BH} estimates from H β and C $\text{IV}\lambda 1549$, with a focus on the aspect and physical factors affecting the broadening of the two lines.

The quasar sample used in the present paper joins two samples with both H β and C $\text{IV}\lambda 1549$ data, one at low luminosity and z ($\lesssim 0.7$, Sulentic et al. 2007), and one at high luminosity, in the range $1.5 \lesssim z \lesssim 3$ presented and analyzed by Sulentic et al. (2017, hereafter Paper I). The sample provides a wide coverage in luminosity, and Eddington ratio (Sec. 2); H β line coverage for each C $\text{IV}\lambda 1549$ observation; consistent analysis of the line profiles of both C $\text{IV}\lambda 1549$ and H β (Sec. 3). Our approach is intended to overcome some of the sample-dependent difficulties encountered by past studies. Results involve the reduction of the measured C $\text{IV}\lambda 1549$ line width to a VBE (Sec. 4) with a correction factor dependent on both shift amplitude and luminosity. They are discussed in terms of BLR structure (Sec. 5.2), and specifically of the interplay between broadening associated with the outflow (very relevant for C $\text{IV}\lambda 1549$) and with orientation effects (which are dominating for H β). Finally, a new M_{BH} scaling law with line width and luminosity (§5.4) is presented. The new C $\text{IV}\lambda 1549$ scaling law, which considers different corrections for Pop. A and B separately, may provide an unbiased estimator of black hole masses derived from H β over a wide range in luminosity (Sect. 5.5).

2. Sample

2.1. High-luminosity VLT data for Hamburg-ESO quasars

The high- L quasars considered in the present study are 28 sources identified in the HE survey (Wisotzki et al. 2000, hereafter the HE sample), in the redshift range $1.4 \lesssim z \lesssim 3.1$. All satisfy the conditions on the absolute B magnitude $M_B \lesssim -27.5$ and on the bolometric luminosity $\log L \gtrsim 10^{47.5} \text{ erg s}^{-1}$. They are therefore among the most luminous quasars ever discovered in the Universe, and a relatively rare population even at $z \approx 1 - 2$ when luminous quasars were more frequent than at low- z (the luminosity function at $M_B \approx -27.5$ is $\Phi(M_B) \sim 10^{-8} \text{ Mpc}^{-3} \text{ mag}^{-1}$ compared to $\sim 10^{-6} \text{ Mpc}^{-3} \text{ mag}^{-1}$ at $M_B \approx -25$, corresponding to the “knee” of the Boyle et al. 2000 luminosity function).

The C IV λ 1549 data were obtained with the FORS1 spectrograph at VLT and Dolores at TNG; the matching H β observations with the ISAAC spectrometer were analyzed in detail in Sulentic et al. (2006b). The resolution at FWHM of the C IV λ 1549 data is $\lesssim 300 \text{ km s}^{-1}$ and $\lesssim 600 \text{ km s}^{-1}$ for FORS1 and Dolores, respectively; the H β resolution is $\approx 300 \text{ km s}^{-1}$ (Sulentic et al. 2004). Typical S/N values are $\gtrsim 50$.

Resolution and S/N are adequate for a multicomponent nonlinear fitting analysis using the IRAF routine `specfit` (Kriss 1994), involving an accurate deconvolution of H β , [O III] $\lambda\lambda$ 4959,5007, Fe II, He II λ 4686 in the optical, and of C IV λ 1549 and He II λ 1640 in the UV. The C IV λ 1549 and H β data and the immediate results of the `specfit` analysis were reported in Paper I.

2.2. Low-luminosity C IV λ 1549 and H β data

We considered a Faint Object Spectrograph (FOS) sample from Sulentic et al. (2007) as a complementary sample at low- L and low- z . For the sake of the present paper, we restrict the FOS sample to 29 Pop. A and 19 Pop. B RQ (48 in total) sources covering the C IV λ 1549 blend spectral range and with previous measures for the H β profile and R_{FeII} (Marziani et al. 2003). The list of sources can be obtained by the cross-correlation of the Sulentic et al. (2007) RQ sources (Kellermann’s ratio $\log R_K < 1.8$) and the Marziani et al. (2003) catalog on Vizier. We excluded NGC 4395 and NGC 4253 whose luminosities are $\log L \approx 40.4$ and $41.7 \text{ [erg s}^{-1}\text{]}$ respectively, outlying with respect to the L distribution of the FOS sample. The FOS high-resolution grisms yielded an inverse resolution $\lambda/\delta\lambda \sim 1000$, equivalent to typical resolution of the Marziani et al. (2003)’s data. The S/N is above $\gtrsim 20$ for both the optical and UV low- z data. The FOS sample has a typical bolometric luminosity $\log L \sim 45.2 \text{ [erg s}^{-1}\text{]}$ and a redshift $z \lesssim 0.5$.

2.3. Joint HE+FOS sample

The HE+FOS sample has therefore 76 sources, of which 43 are Pop. A and 33 Pop. B. The distribution of $\log L$ for the 76 sources of the joint sample (derived from the rest-frame luminosity at $1450 \text{ \AA}$, assuming a constant bolometric correction equal to 3.5) uniformly covers the range $44 -$

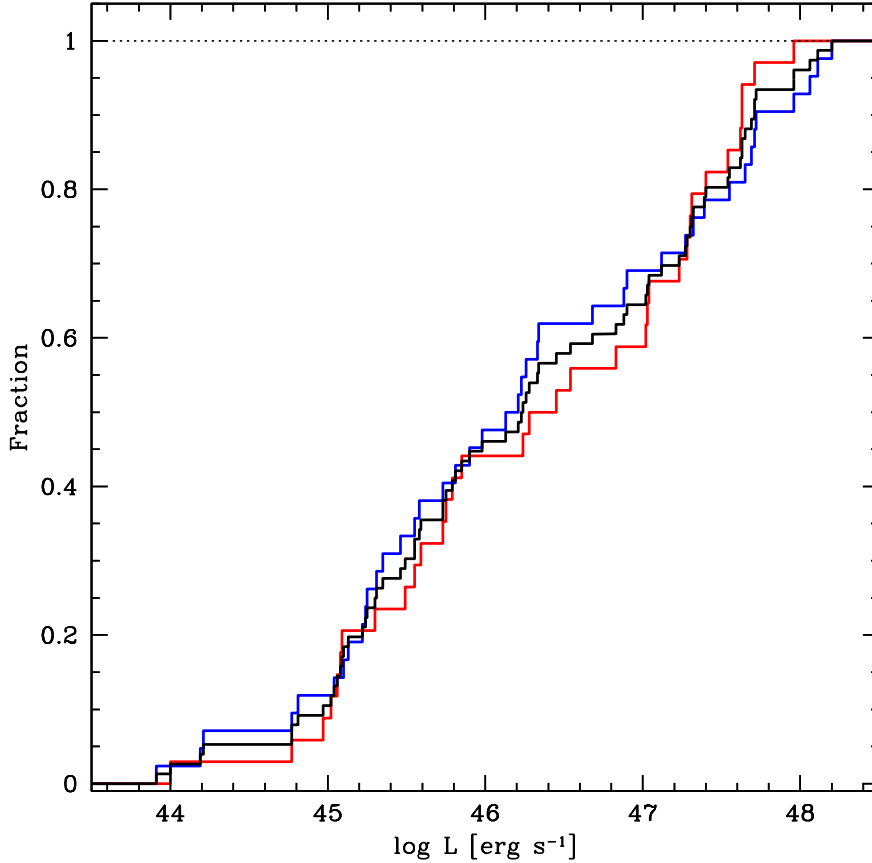


Fig. 1. Cumulative distribution of bolometric luminosity L of the FOS+HE sample (black), Pop. A (blue) and Pop. B (red).

48.5, with similar distributions for Pop. A and B (lower panel of Fig. 1; a K-S test confirms that the two distributions are not significantly different). The Eddington ratio (L/L_{Edd}) covers the range 0.01 – 1 which means complete coverage of L/L_{Edd} range where most sources in optically-selected samples are found.

3. Emission line profile analysis for the FOS+HE sample

3.1. Line modeling and measured parameters

In the following we consider the merit of H β and C ν 11549 as VBEs. Previous work has shown that the H β and MgII λ 2800 profiles are almost equally reliable estimators of the “virial” broadening in samples of moderate-to-high luminosity (e.g., Wang et al. 2009; Trakhtenbrot & Netzer 2012; Shen & Liu 2012; Marziani et al. 2013b, excluding the MgII λ 2800 extreme Population A that is significantly broadened by a blueshifted component, Marziani et al. 2013b). However, the broad H β line full profile is often affected by asymmetries toward the line base and by significant line centroid shifts. Typically, the H β line profiles are characterized by two main asymmetries, differently affecting sources in spectral types along the MS (Appendix A provides the definition of spectral types):

- Pop. A: a blueshifted excess, often modeled with a blueward asymmetric Gaussian component (BLUE) related to the outflows strongly affecting the C $\text{IV}\lambda 1549$ and [O $\text{III}\lambda\lambda 4959, 5007$] line profiles (e.g. Negrete et al. 2018, Paper I, and references therein).
- Pop. B: a redward asymmetry modeled with a broader redshifted (FWHM $\sim 10000 \text{ km s}^{-1}$, $c(\frac{1}{2}) \sim 2000 \text{ km s}^{-1}$) Gaussian. The very broad Gaussian is meant to represent the innermost part of the BLR, providing a simple representation of the radial stratification of the BLR in Pop. B suggested by reverberation mapping (e.g., Snedden & Gaskell 2007). This component (hereafter the very broad component, VBC) has been associated with a physical region of high-ionization virialized and closest to the continuum source (Peterson & Ferland 1986; Brotherton et al. 1994a; Sulentic et al. 2000c; Snedden & Gaskell 2007; Wang & Li 2011). While the properties of the Very Broad Line Region (VBLR) remains debatable, a decomposition of the full H β profile into a symmetric, unshifted H β component (H β_{BC}) and a H β_{VBC} provides an excellent fit to most H β Pop. B profiles (Sulentic et al. 2002; Zamfir et al. 2010).

Figs. 4 and 5 of Paper I show the H β and C $\text{IV}\lambda 1549$ profiles of the HE sample, and their multicomponent interpretation. To extract a symmetric, unshifted component that excluded the blueshifted excess and the VBC, we considered a model of the broad H β and C $\text{IV}\lambda 1549$ line with the following components (see also Appendix A):

- Pop. A H β and C $\text{IV}\lambda 1549$: an unshifted Lorentzian profile (H β_{BC}) + one or more asymmetric Gaussians to model the blueward excess (BLUE).
- Pop. B H β and C $\text{IV}\lambda 1549$: an unshifted Gaussian (H β_{BC}) + a redshifted VBC for H β (H β_{VBC}). In the H β case, there is no evidence of a blueward excess even at the highest luminosity. However, among Pop. B sources of the HE sample, a prominent C $\text{IV}\lambda 1549$ BLUE appears, implying an intensity ratio C $\text{IV}\lambda 1549/\text{H}\beta \gg 1$ in the BLUE component. The C $\text{IV}\lambda 1549$ BLUE is usually fainter in the low-luminosity FOS sample (Paper I).

In the fits, narrow components of both H β (H β_{NC}) and C $\text{IV}\lambda 1549$ (C $\text{IV}\lambda 1549_{\text{NC}}$) were included. In the case of C $\text{IV}\lambda 1549$, separation of the broad and narrow component is subject to significant uncertainty, so that the effect of the C $\text{IV}\lambda 1549_{\text{NC}}$ needs to be carefully considered (see discussion in Sect. 3.2).

The decomposition approach summarized above has a heuristic value, as the various components are not defined on the basis of a physical model, even if the assumptions on line shapes follows from MS trends. The distinction between BC and VBC might be physically motivated (the emitting region associated with the BC is the one emitting most of all Fe II), but the decomposition into two symmetric Gaussians is a crude approximation at best. Full profile measures are added to avoid any exclusive dependence of the results on the profile decomposition. The full profiles of H β and C $\text{IV}\lambda 1549$ are parameterized by the FWHM, an asymmetry index (AI) and centroid at frac-

tional intensity at 1/2 and 1/4 of peak, $c(\frac{1}{2})$ and $c(\frac{1}{4})$. The definition of centroids and A.I. follows Zamfir et al. (2010):

$$c(\frac{i}{4}) = \frac{\lambda_B(\frac{i}{4}) + \lambda_R(\frac{i}{4})}{2\lambda_0} c, \quad i = 1, 2, 3; \quad \frac{i}{4} = 0.9 \quad (1)$$

$$A.I. = \frac{\lambda_B(\frac{1}{4}) + \lambda_R(\frac{1}{4}) - 2\lambda_P}{\lambda_B(\frac{1}{4}) + \lambda_R(\frac{1}{4})} \quad (2)$$

where λ_P is the peak wavelength, and λ_B and λ_R are the wavelengths on the blue and red side of the line at the $i/4$ fractional intensities. The centroids are referred to the quasar rest frame, while the AI is referred to the peak of the line that may be shifted with respect to rest-frame. A proxy to λ_P which will be used in this paper is $\tilde{\lambda}_P \approx \lambda_0(1 + c(0.9)/c)$.

We assume that the symmetric and unshifted H β_{BC} and C IV $\lambda 1549_{\text{BC}}$ are the representative line components of the virialized part of the BLR. It is expedient to define a parameter ξ as follows:

$$\xi_{\text{line}} = \frac{\text{FWHM}_{\text{vir}}}{\text{FWHM}} \quad (3)$$

where the FWHM_{vir} is the FWHM of the “virialized” component, in the following assumed to be H β_{BC} , and the FWHM is the FWHM measured on the full profile (i.e., without correction for asymmetry and shifts). The ξ parameter is a correction factor that can be defined also using components of different lines, for instance C IV $\lambda 1549$ full profile FWHM and H β_{BC} , where H β_{BC} is assumed to be a reference VBE.

3.2. The C IV $\lambda 1549$ narrow component in the HE sample and its role in FWHM C IV $\lambda 1549_{\text{BC}}$ estimates

In only two cases does C IV $\lambda 1549_{\text{NC}}$ contribute to the total C IV $\lambda 1549$ flux of the HE Pop. B sources by more than 10%: HE2202-2557 and HE2355-4621 (Pop. B, Fig. 5 of Paper I). There is no evidence for a strong NC in the HE Pop. A sources except for HE0109-3518 where $I(\text{C IV } \lambda 1549_{\text{NC}}) \leq 0.09$ of the total line flux and whose C IV $\lambda 1549$ profile resembles the ones of low- z sources that are 2-3 dex less luminous (the HE0109-3518 C IV $\lambda 1549$ profile is shown in Fig. 4 of Paper I).

In general, considering H β_{BC} as a reference for Pop. B sources, and comparing FWHM H β_{BC} to FWHM C IV $\lambda 1549$ with and without removing the C IV $\lambda 1549_{\text{NC}}$ (i.e., to FWHM C IV $\lambda 1549_{\text{BC}}$ and FWHM C IV $\lambda 1549_{\text{BC}} + \text{C IV } \lambda 1549_{\text{NC}}$), the C IV $\lambda 1549_{\text{NC}}$ removal improves the agreement with FWHM H β_{BC} in 5 cases out of 6 when C IV $\lambda 1549_{\text{NC}}$ has an appreciable effect on the line width (in the other eight cases there is no effect because C IV $\lambda 1549_{\text{NC}}$ is too weak). The FWHM measured on the C IV $\lambda 1549$ profiles without removing the C IV $\lambda 1549_{\text{NC}}$ (i.e., FWHM C IV $\lambda 1549_{\text{BC}} + \text{C IV } \lambda 1549_{\text{NC}}$) are, on average, $\approx -4\%$ and -11% of the FWHM C IV $\lambda 1549$, for Pop. A and B respectively. There-

fore, (1) subtracting the C IV $\lambda 1549_{\text{NC}}$ improves the agreement between H β and C IV $\lambda 1549$ FWHM; (2) the average effect is too small to affect our inferences concerning on the C IV $\lambda 1549$ line width as a VBE in the HE sample. The C IV $\lambda 1549_{\text{NC}}$ has been always included as an independent component in the line profile fitting of Paper I, following an approach consistently applied for the low- z FOS sample and described by Sulentic et al. (2007).

4. Results

4.1. H β in the HE sample

We considered several different measures of the H β width following empirical corrections derived from previous work on low- z samples:

- substitution of the H β_{BC} extracted through the `specfit` analysis in place of the full H β profile.

In principle, extraction of the H β_{BC} should be the preferred approach, and the FWHM H β_{BC} the preferred VBE. To test the reliability of the FWHM values, we performed Monte-Carlo repetitions of the H β fit for Pop. B sources with the broadest lines (FWHM H $\beta_{\text{BC}} \sim 7000 \text{ km s}^{-1}$, and FWHM H $\beta_{\text{VBC}} \sim 11000 \text{ km s}^{-1}$), under the assumption of $S/N \approx 20$,¹ weak and relatively broad [O III] $\lambda\lambda 4959, 5007$, changing noise pattern and initial values of the fitting. The values of FWHM H β_{BC} and H β_{VBC} were chosen to represent the broadest lines, where FWHM H β_{BC} measures might be affected by a degeneracy in the BC+VBC decomposition. The dispersion of the Monte Carlo FWHM distribution is almost symmetric, and implies typical FWHM H β_{BC} uncertainties $\approx 10\%$ at 1σ confidence level. Therefore, the blending should not be a source of strong bias or of large uncertainties in the H β_{BC} and H β_{VBC} FWHM.² However, we still expect that in the case of very broad profiles, and low S/N or low dispersion, the decomposition of the H β profile into H β_{BC} and H β_{VBC} is subject to large uncertainties difficult to quantify. To retrieve information on the H β_{BC} we introduce several corrections that can be applied to the full H β profile without any multicomponent fitting (which makes the results also model-dependent).

- symmetrization of the full profile: $\text{FWHM}_{\text{symm}} = \text{FWHM} - 2c(\frac{1}{2})$ (symm in Fig. 2). The physical explanation behind the symmetrization approach involves an excess radial velocity on the red side that may be due to gas with a radial infall velocity component, with velocity increasing toward the central black hole (e.g., Wang et al. 2017, and references therein). Generally speaking, redward displacements of line profiles have been explained by invoking a radial infall component plus obscuration (Hu et al. 2008; Ferland et al. 2009);
- Substitution of the FWHM H β_{BC} with the FWHM measured on the full broad profile of H β , corrected according to its spectral type. The spectral types have been assigned following Sulentic et al.

¹ S/N is measured per pixel on the continuum.

² If S/N is relatively high ($\gtrsim 20$) only in some peculiar cases the uncertainty might be significantly larger. For example, if the H β profile is composed for a narrower core and a broader base, the FWHM measure is unstable, and may abruptly change depending on continuum placement.

(2002, for a conceptually equivalent approach see Shen & Ho 2014). The correction are as defined from the analysis of the H β profile in a large SDSS-based sample at $0.4 \lesssim z \lesssim 0.7$ (labeled as `st` in Fig. 2). In practice, this means to correct H β for Pop. B sources by a factor $\xi_{\text{H}\beta} \approx 0.8$ (Marziani et al. 2013a) and extreme population A sources ($R_{\text{FeII}} \geq 1$) by a factor $\xi_{\text{H}\beta} \approx 0.9$. On average, spectral types A1 and A2 show symmetric profiles for which $\xi_{\text{H}\beta} \approx 1$. Recent work confirmed that the effect of a blueshifted excess on the full profile of H β is small at half-maximum, $0.9 \lesssim \xi_{\text{H}\beta} \lesssim 1.0$ (Negrete et al. 2018). We assume $\xi_{\text{H}\beta} = 0.9$ as an average correction. The ratio we derive between BC and full profile FWHM of HE Pop. B H β is $\approx 0.82 \pm 0.09$, consistent with the same ratio estimates at moderate luminosity (Marziani et al. 2013a). The `st` correction can be summarized as follows:

ST	$\xi_{\text{H}\beta}$
A3-A4	0.9
A1-A2	1.0
B1-B1+	0.8

- correction of the width of the full broad H β profile based on the one derived at low z by pairing the observed full broad H β FWHM to the best width estimator from reverberation mapping, following the relation $\text{FWHM}_c \approx 1.14 \text{ FWHM} - 601 - 0.0000217 \text{ FWHM}^2$ derived by Sulentic et al. (2006b, labeled `corr`);

Fig. 2 shows that these corrections all provide similar results if applied to the HE sample FWHM H β . Error bars of Fig. 2 were estimated propagating the uncertainty values reported in Paper I for the full profiles, and the ones derived from `specfit` for the line components (assuming a minimum error of 10%).

The middle panels of Fig. 2 show the ratios of corrected FWHM measures as a function of the FWHM of the full H β profile. The low χ^2_ν indicates that the χ^2_ν associated with the ratios between BC and `symm`, and BC and `st` not significantly different from unity. In the case of BC and `corr` the two measurements are different but only at 1σ confidence level. F tests do not exclude that BC, symmetrization, `st`, and reverberation corrections can be equivalent at a minimum confidence level of 2σ . The bottom panel of Fig. 2 shows the behavior of the full and corrected FWHM versus the “symmetrized” H β FWHM. We consider the symmetrization, as it is relatively easy to apply (once the quasar rest frame is known), and the `st` correction (that does not even require the knowledge of the rest frame) as reference corrections. We remark again that these corrections are relatively minor but still significant: a 20% correction translates into a factor 1.44 correction in M_{BH} . They do not undermine the value of the full line width of H β as a useful VBE (with the caveats discussed in Sec. 5.2), since the H β full line width remains preferable to the uncorrected C $\text{IV}\lambda 1549$ width for most objects.

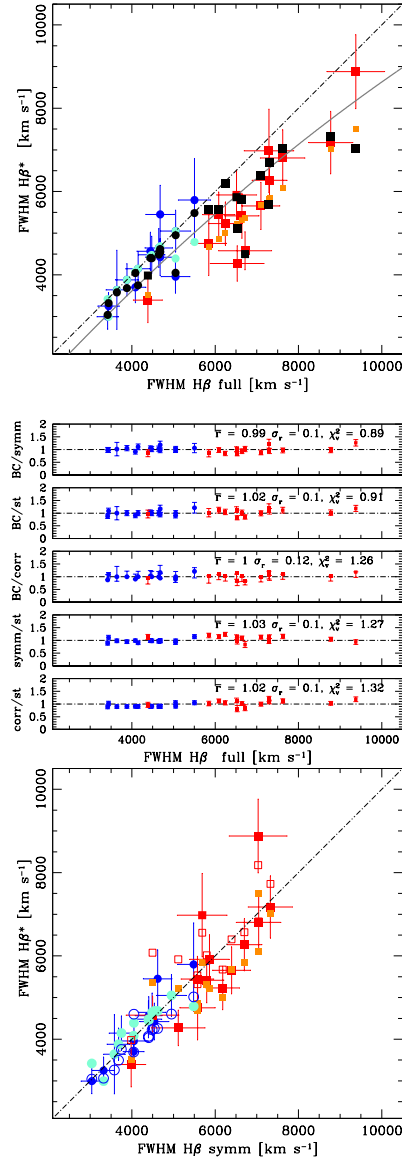


Fig. 2. Virial broadening estimators based on H β , with several corrections applied to the HE sample. Top square panel: FWHM H β_{BC} (blue (Pop. A) and red (Pop. B)) with error bars, symmetrized FWHM H β (symm, black), and FWHM H β corrected according to spectral type (st, aquamarine and dark orange for Pop. A and B respectively) versus FWHM of the full H β profile. The grey line traces the correction (corr) following the relation of Sulentic et al. (2006b) reported in §4. Middle panels: ratios of FWHM after various corrections vs. full profile FWHM. First panel from top: BC/symm, BC/st, BC/corr, symm/st, corr/st. Average values, standard deviation and normalized χ^2_{ν} are reported in the upper right corner of the panels. Bottom square panel: BC, spectral type st and reverberation corrected (corr, open symbols) FWHM values vs. symmetrized FWHM.

4.2. C IV λ 1549 in the full HE+FOS sample

The results on the HE C IV λ 1549 profiles do not bode well for the use of C IV λ 1549 FWHM as a VBE, as also found by Sulentic et al. (2007) and other workers (Sect. 5.1 for a brief critical review). The presence of very large blueshifts in both Pop. A and B makes the situation even more critical than at low L . Fig. 3 (top panel) shows that there is no obvious relation between the FWHM of C IV λ 1549 and the FWHM of H β if FOS+HE data are considered together.

For the Pop. A sources in the HE+FOS sample, C IV λ 1549 is broader than H β save in two cases in the HE sample, and FWHM(C IV λ 1549) shows a broad range of values for similar FWHM H β

i.e., FWHM(C IV $\lambda 1549$) is almost degenerate with respect to H β . The C IV $\lambda 1549$ line FWHM values are so much larger than the ones of H β to make it possible that the M_{BH} derived from FWHM C IV $\lambda 1549$ might be higher by even more than one order of magnitude. Formally, the Pearson's correlation coefficient $r \approx 0.52$ is highly significant for a sample of $n = 43$, with significance at an $\approx 4.5\sigma$ confidence level. A weighted least square fits yields $\text{FWHM}(\text{C IV } \lambda 1549) = (1.822 \pm 0.204) \text{FWHM}(\text{H}\beta) + (-624 \pm 677) \text{ km s}^{-1}$, with a significant scatter, $\text{rms} \approx 1959 \text{ km s}^{-1}$. Unfortunately it is not possible to apply a simple C IV $\lambda 1549$ symmetrization as done for H β : subtracting $2 \cdot c(\frac{1}{2})$ to FWHM C IV $\lambda 1549$ leads to corrections that are unrealistically large.

If we combine the Pop. B FOS and HE samples, FWHM C IV $\lambda 1549$ and H β become loosely correlated (the Pearson's correlation coefficient is ≈ 0.4 , significant at $P \approx 98\%$ for a sample of 33 objects). A weighted least-square fit yields $\text{FWHM}(\text{C IV } \lambda 1549) \approx (0.764 \pm 0.165) \text{FWHM}(\text{H}\beta) + (810 \pm 1030) \text{ km s}^{-1}$, and $\text{rms} \approx 1090 \text{ km s}^{-1}$, with a significant deviation from the 1:1 relation. In the case of Pop. B sources, the trend implies $\text{FWHM C IV } \lambda 1549 \sim \text{FWHM H}\beta$, and even a *slightly narrower* FWHM C IV $\lambda 1549$ with respect to H β .

The large scatter induced by using uncorrected C IV $\lambda 1549$ line FWHM may have contributed to the statement that line width does not contribute much to M_{BH} determinations (Croom 2011).

4.3. Practical usability of C IV $\lambda 1549_{\text{BC}}$

The fitting procedure scaled the H β profile to model the red side of C IV $\lambda 1549$ so that the FWHM C IV $\lambda 1549_{\text{BC}}$ estimate is not independent from FWHM H β_{BC} . The FWHM values of the two BCs are in agreement because of this enforced condition.

The C IV $\lambda 1549_{\text{BC}}$ extraction is very sensitive to the assumed rest frame, and also requires that the C IV $\lambda 1549$ line is cleaned from contaminant such as Fe II (weak) and He II $\lambda 1640$ (moderate, but flat topped and gently merging with the C IV $\lambda 1549$ red wing; Marziani et al. 2010; Fine et al. 2010; Sun et al. 2018). Without performing a line profile decomposition, one can consider the width of the red side with respect to rest frame as the half-width half maximum (HWHM) of the virial component. Again this requires (1) an accurate redshift that can be set, in the context of high z quasars, either by using the H β narrow component or by the [O II] $\lambda 3727$ doublet (Eracleous & Halpern 2004; Hu et al. 2008), and (2) the decomposition from He II $\lambda 1640$ emission blended on the C IV $\lambda 1549$ red side. If [O II] $\lambda 3727$ is covered, then Mg II $\lambda 2800$ is also likely to be covered. As mentioned in Sect. 3, the Mg II $\lambda 2800$ line width is a reliable VBE for the wide-majority of type-1 AGN. The same is not true for C IV $\lambda 1549$. For spectra where C IV $\lambda 1549$ is conveniently placed at $z \gtrsim 1.45$, the [O II] $\lambda 3727$ line is shifted beyond $9000 \text{ \AA}$, a domain where intense sky emission makes it difficult to analyze a relatively faint narrow line. The extraction of C IV $\lambda 1549_{\text{BC}}$ is therefore not a viable solution if single-epoch C IV $\lambda 1549$ observations are available without the support of at least a narrow LIL that may set a reliable rest frame. This is unlikely to occur on the same optical spectra. An alternative strategy for M_{BH} estimation using C IV $\lambda 1549$ FWHM should consider the origin of the C IV $\lambda 1549$ non-virial broadening.

4.4. Reducing C_{IV}λ1549 to a VBE estimator consistent with Hβ

The main results of Paper I suggest a strong dependence of the C_{IV}λ1549 blueshift on L/L_{Edd} , especially above a threshold value $L/L_{\text{Edd}} \approx 0.2 \pm 0.1$ (Sulentic et al. 2014, and references therein). A correlation between Eddington ratio and the FWHM(C_{IV}λ1549) to FWHM(Hβ) ratio (i.e., $1/\xi_{\text{CIV}}$, c.f., Saito et al. 2016) is detected at a high significance level (Pearson’s correlation coefficient $r \approx 0.55$) joining all FOS RQ sources of Sulentic et al. (2007, Fig. 4). In this context, L/L_{Edd} was computed from the M_{BH} scaling law of Vestergaard & Peterson (2006), using the FWHM of Hβ and $\lambda L_{\lambda}(5100)$. A bisector best fit with SLOPES (Feigelson & Babu 1992a) yields

$$\log \frac{1}{\xi_{\text{CIV}}} \approx (0.426 \pm 0.043) \frac{L}{L_{\text{Edd}}} + (0.401 \pm 0.035). \quad (4)$$

An L/L_{Edd} – dependent correction is in principle a valid approach. However, it is not obvious how to calculate L/L_{Edd} from UV spectra without resorting to Hβ observations. In addition FWHM Hβ is strongly affected by orientation and yields biased values of L/L_{Edd} (Sect. 5.2.1). Both FWHM(Hβ_{BC})/FWHM(C_{IV}λ1549) and $c(\frac{1}{2})$ are both correlated with Eddington ratio. Consistently, the C_{IV}λ1549 blueshift is correlated with FWHM C_{IV}λ1549 (Paper I, Coatman et al. 2016), and accounts for the broadening excess in the C_{IV}λ1549 FWHM. Measures of the C_{IV}λ1549 blueshift or the FWHM(Hβ_{BC})/FWHM(C_{IV}λ1549) can be used as proxies for L/L_{Edd} . At the same time, Paper I reveals a weaker correlation with L , which is expected in the case of a radiation driven wind. If the correction factor is $\xi_{\text{CIV}} = \text{FWHM}(\text{H}\beta_{\text{BC}})/\text{FWHM}(\text{CIV}\lambda 1549)$, then it should include a term in the form $1/\zeta(L, L/L_{\text{Edd}})$.

4.5. Calibrating empirical corrections on FWHM C_{IV}λ1549

Coatman et al. (2017) introduced a non-parametric measure of the C_{IV}λ1549 blueshift associated with the wavelength that splits the line flux in equal parts on its blue and red side (flux bisector). The flux bisector is strongly correlated with $c(\frac{1}{2})$ and $c(\frac{1}{4})$, and $c(\frac{1}{2})$ and $c(\frac{1}{4})$ are correlated among themselves in the FOS+HE sample (Pearson’s $r \approx 0.95$): $c(\frac{1}{2}) = (0.773 \pm 0.307)c(\frac{1}{4}) - (58 \pm 65) \text{ km s}^{-1}$. The bisector correlation is stronger with $c(\frac{1}{4})$ (Pearson’s correlation coefficient $r \approx 0.98$), with flux bisector $\sim (0.98 \pm 0.04)c(\frac{1}{4}) + (220 \pm 110) \text{ km s}^{-1}$ (Fig. 5). The lower panel of Fig. 5 shows a few objects with difference between $c(\frac{1}{4})$ and flux bisector $\gtrsim 20\%$; these sources are either with small shifts (within the measurement uncertainties; shaded area of Fig. 5), or sources strongly affected by broad absorptions, for which a measure of blueshift is tricky regardless of the method employed. Therefore it is possible to apply Eq. 4 of Coatman et al. (2017) substituting the $c(\frac{1}{4})$ to the flux-bisector blueshift measurements:

$$\xi_{\text{CIV},0} = \frac{1}{a \left(-\frac{c(\frac{1}{4})}{1000} \right) + b} \quad (5)$$

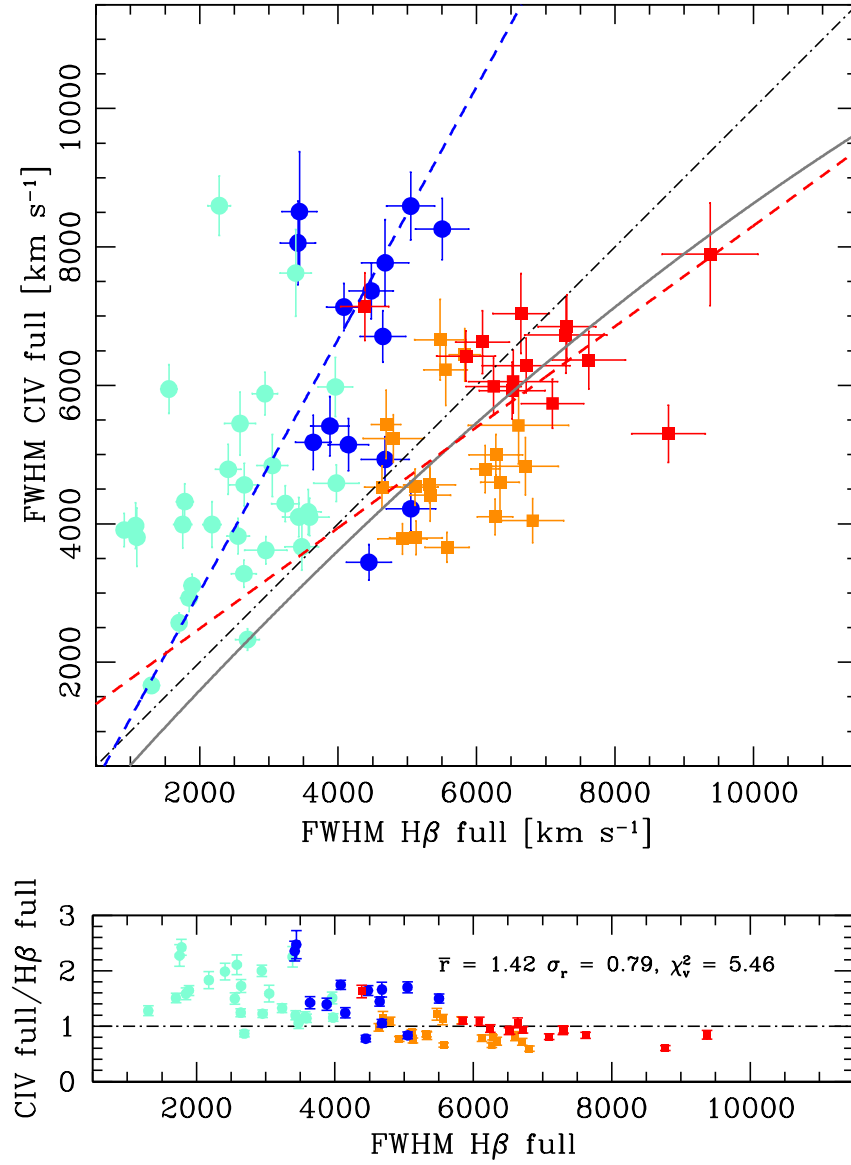


Fig. 3. Top panel: FWHM(C $\text{IV}\lambda 1549$) vs FWHM(H β) (full profiles) for the FOS+HE sample. Data points are color-coded according to sample and population. HE Pop. A: blue circles ($\bullet$), HE Pop. B: red squares ($\blacksquare$), FOS Pop. A: aquamarine circles ($\bullet$), FOS Pop. B: golden squares ($\blacksquare$). Best fitting lsq lines (dashed) are shown in the blue for all Pop. A and red for all Pop. B. The black dot dashed line is the equality line. The continuous grey line is the expected FWHM following the correction of Sulentic et al. (2006b, corr). Lower panel: ratio between FWHM C $\text{IV}\lambda 1549$ and FWHM H β as a function of FWHM (H β).

with $a = 0.41 \pm 0.02$ and $b \approx 0.62 \pm 0.04$ (the minus sign is because Coatman et al. (2017) assumed blueshifts to be positive), to correct the FWHM C $\text{IV}\lambda 1549$ of the FOS+HE sample. The resulting trend is shown in Fig. 6. The Eq. 4 of Coatman et al. (2017) undercorrects both Pop. A and B sources at low L (the FOS sample) and provides a slight overcorrection for the HE sources.

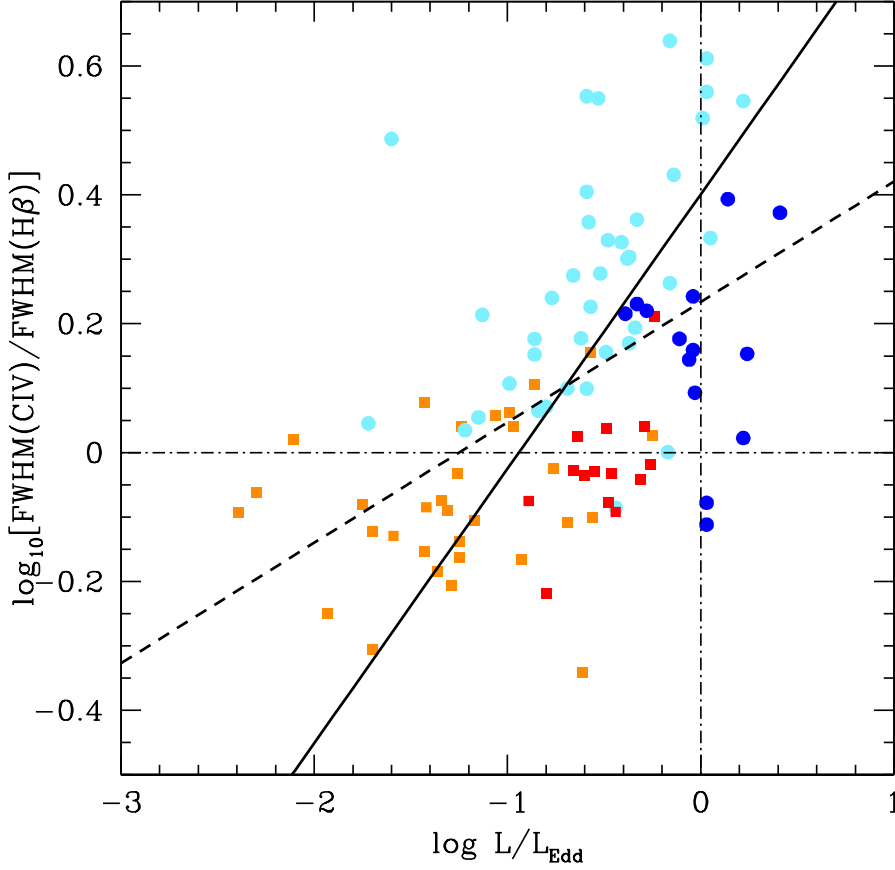


Fig. 4. Relation between the logarithm of the FWHM ratio of C $\text{IV}\lambda 1549$ to H β and the logarithm of the Eddington ratio L/L_{Edd} . The vertical dot-dashed line traces the Eddington limit. The colors and shape of symbols are as in Fig. 3. The dashed line is an unweighted least squares fit, the filled line was obtained with the bisector method (Feigelson & Babu 1992b).

The correction of Coatman et al. (2017) does not yield FWHM (C $\text{IV}\lambda 1549$) in agreement with the observed values of FWHM(H β). This does not necessarily mean that the FWHM(C $\text{IV}\lambda 1549$) values are incorrect, as FWHM(H β) is likely more strongly affected by orientation effects than FWHM(C $\text{IV}\lambda 1549$) (see the discussion in Sect. 5.2).

A correction dependent on luminosity reduces the systematic differences between the various samples in the present work but it has to be separately defined for Pop. A and B (Fig. 7). The following expression:

$$\xi_{\text{CIV},1} = \frac{1}{b(a - \log \lambda L_{\lambda}(1450)) \cdot \left(\left| \frac{c(\frac{1}{2})}{1000} \right| \right) + c} \quad (6)$$

provides a suitable fitting law, with a , b , c different for Pop. A and B. Here we consider the $c(\frac{1}{2})$ because of its immediate connection with the FWHM, and because it is highly correlated with $c(\frac{1}{4})$ (Sec. 5.5). Eq. 6 is empirical: it entails a term proportional to shift and one to the product of $\log L_{1450}$ and shift. Multivariate, nonlinear lsq results for Eq. 6 are reported in the first rows of Table 1. For

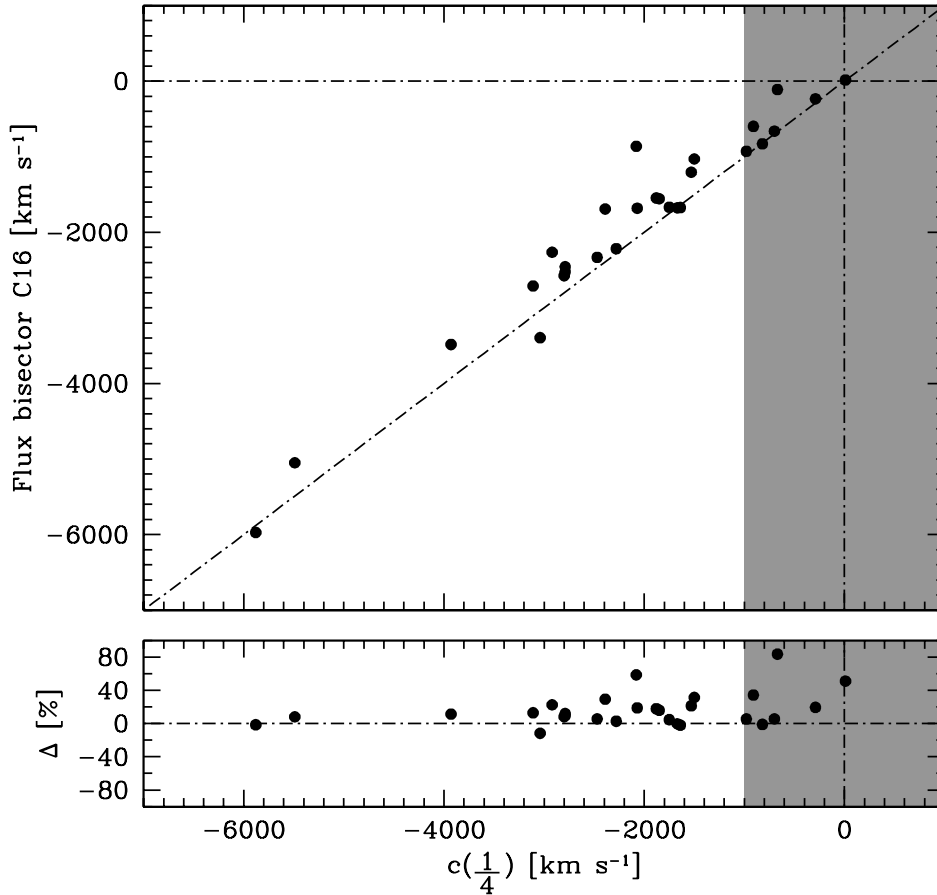


Fig. 5. Top panel: bisector flux estimator of Coatman et al. (2017) vs $c(\frac{1}{4})$, in km s^{-1} . The dot-dashed line is the equality line. Bottom panel: Percentage residuals. The shaded areas indicate the average error of measurement at a 2σ confidence level computed from Table 4 of Paper I.

Pop. A the correction is rather similar to the one of Coatman et al. (2017), and is driven by the large blueshifts observed at high L/L_{Edd} . The luminosity-dependent factor accounts for low-luminosity sources that are not present in Coatman et al. (2017) sample. The use of the absolute value operator provides an improvement with respect to the case in which blueshifts are left negative. There are only three objects for which $c(\frac{1}{2})$ is positive. The improvement is understandable if one consider any C IV λ 1549 shift as affecting the difference between the FWHM of C IV λ 1549 and H β . An A(+) sample was defined from the Pop. A sample minus three objects with positive $c(\frac{1}{2})$, i.e., all A(+) sample sources show blueshifts. No significant improvement was found with respect to Eq. 6.

The correction for Pop. B is less well defined, considering the uncertainty in a , and the low value of b (Table 1). The corrections for Pop. B still offer an improvement because they remove a significant bias (as evident by comparing Fig. 3 and Fig. 7). In practice, for Pop. B, at low L the ξ_{CIV} could be considered constant to a zero-order approximation, with $\xi_{\text{CIV}} \sim 1$. In other words, when the velocity field is predominantly virial, and no prominent blueshifted component affects the line width, C IV λ 1549 may be somewhat broader than H β as expected for the stratification revealed by reverberation mapping of lines from different ionic species (Peterson & Wandel 1999, 2000). The

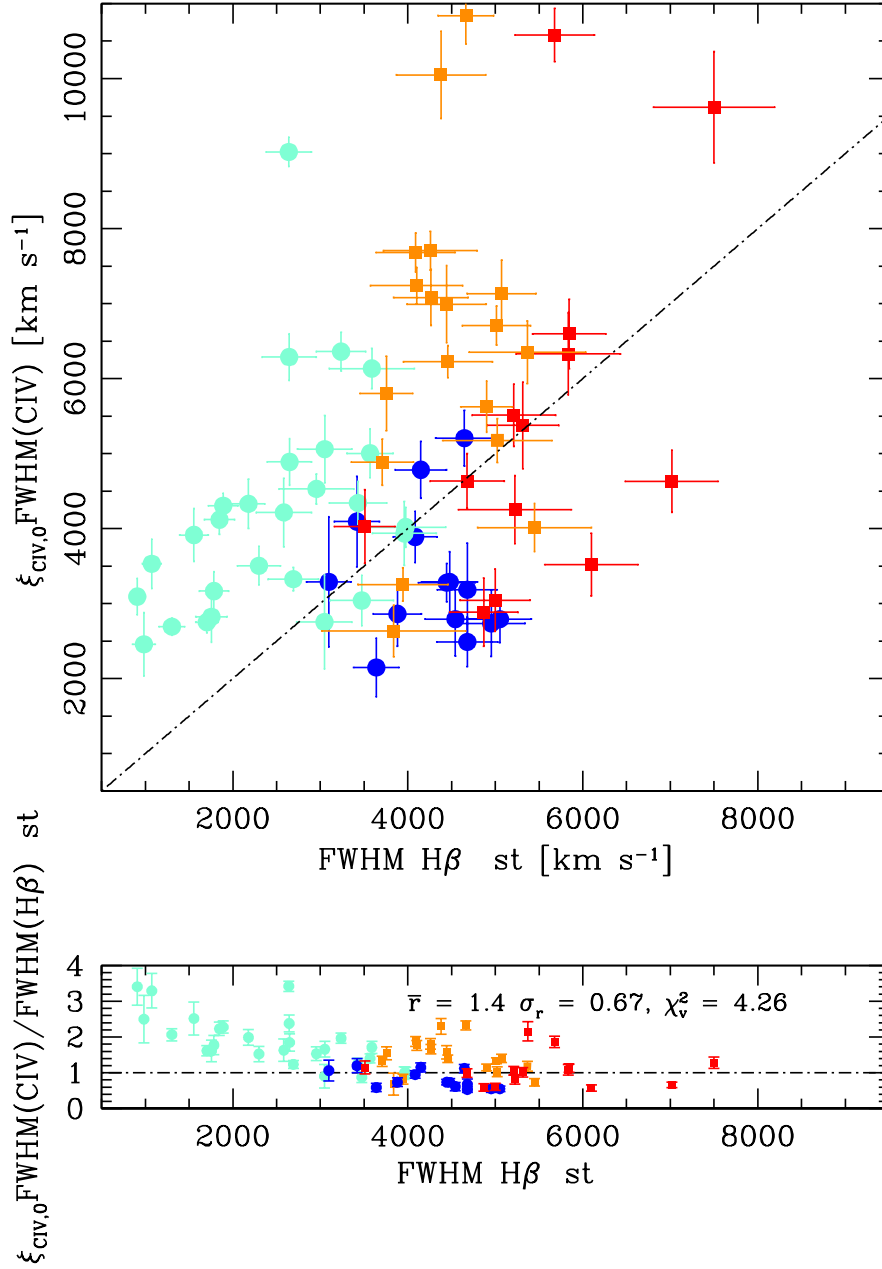


Fig. 6. Top panel: $\text{FWHM}(\text{CIV}\lambda 1549)$ C16 i.e., corrected following Coatman et al. (2016) vs $\text{FWHM}(\text{H}\beta) \text{ st}$ for the FOS+HE sample. Meaning of symbols is the same as for Fig. 3. The black dot dashed line is the equality line. The bottom panel shows the residuals. Average ratio, dispersion and χ^2_v refer to all sources.

fit is consistent with ξ_{CIV} depending on shift but only weakly on luminosity. The Pop. B correction is so ill-defined that larger samples are needed for a better determination of its coefficients.

Slightly different fitting laws

$$\xi_{\text{CIV},2} = \frac{1}{a + b \log \lambda L_{\lambda}(1450) + c \frac{c(\frac{1}{2})}{1000}} \quad (7)$$

which considers a linear combination $\log \lambda L_{\lambda}(1450)$ and shift, and

$$\xi_{\text{CIV},3} = \frac{1}{a - b \log \lambda L_{\lambda}(1450) \cdot \frac{c(\frac{1}{2})}{1000}} \quad (8)$$

which assume a dependence from the product $\log \lambda L_{\lambda}(1450)$ and shift, provide consistent results, with fitting parameters, their 1σ confidence level associated uncertainty, and rms residuals of ξ_{CIV} reported in Table 1. The fitting relations yield a lower residual scatter in ξ_{CIV} than assuming no luminosity dependence. For instance, using Eq. 7 we obtain a scatter in $\xi_{\text{CIV},2}$ that is a factor 1.86 lower than if Eq. 5 is used. We also considered the A.I. in place of $c(\frac{1}{2})$ in Eq. 6 (without the absolute value operator; bottom rows of Table 1). The A.I. has a non-negligible advantage to be independent from the choice of the rest frame. The A.I. is correlated with both $c(\frac{1}{4})$ and $c(\frac{1}{2})$, and shows higher correlation with $c(\frac{1}{4})$ (Pearson's $r \approx 0.66$). However, the scatter in $\xi_{\text{CIV,A.I.}}$ is unfortunately large, and would imply a scatter ≈ 1.5 higher in M_{BH} estimates than in the case Eq. 6 is considered for Pop. A.

If Pop. A and B are considered together, the final scatter in ξ_{CIV} is close for the different fitting function (Eq. 6 yields a slightly better result) but much higher than if Pop. A and B are kept separated. It is therefore necessary to distinguish between Pop. A and B as the intrinsic structure of their BLR may be different (e.g., Goad & Korista 2014; Wang et al. 2014b). In Pop. B, at low L/L_{Edd} , the lines are mainly broadened following a virial velocity field (Peterson & Wandel 2000). The relative prominence of the blueshifted to the virialized component (ratio BLUE over BC), a consequence of the low L/L_{Edd} for Pop. B sources. Both properties are expected to contribute to the overall consistency between H β and C $\text{IV}\lambda 1549$ profiles in Pop. B sources. At any rate, ξ_{CIV} should always be $\lesssim 1$, with $\xi_{\text{CIV}} \approx 1$ for Pop. B at low- L , and $\xi_{\text{CIV}} \ll 1$ in case of very large shifts, as in Pop. A at high- L .

It is possible, in most cases, to distinguishing between Pop. A and B from the UV spectrum emission blend, making the correction applicable at least to a fraction of all quasars in large samples. Several criteria were laid out by Negrete et al. (2014): (1) broad line width; (2) evidence of a prominent red wing indicative of a VBC; (3) prominence of C $\text{III}\lambda 1909$. Population B sources show a C $\text{IV}\lambda 1549$ red wing and strong C $\text{III}\lambda 1909$ in the 1900 Å. Extreme Population A (xA) sources are easy to recognize; they show strong Al $\text{III}\lambda 1860$ in 1900 Å blend and low $W(\text{CIV}\lambda 1549)$. A prototypical composite spectrum of xA sources is shown by Martínez-Aldama et al. (2018). However, some intermediate cases along the MS (i.e., spectral type A1) may be easier to misclassify. Also, with only the UV spectral range available the redshift estimate may be subject to large errors.

Table 1. Fits of ξ_{CIV}

Sample	$a \pm \delta a$		$b \pm \delta b$		$c \pm \delta c$		rms $_{\xi}$	d.o.f.
$\xi_{\text{CIV},1} \approx 1/(b * (a - x) * y + c)$								
A	-0.3093	0.1581	0.3434	0.0881	1.0763	0.0949	0.198	40
B	3.9224	14.1170	0.0206	0.0568	0.9845	0.0602	0.187	30
A+B	-0.1805	0.2603	0.1978	0.0584	1.0117	0.0641	0.227	73
$\xi_{\text{CIV},1} \approx 1/(b * (a - x) * y + c)$								
A	-0.4161	0.3325	-0.1825	0.0693	1.3245	0.0919	0.222	40
B	28.967	496.591	-0.0030	0.0486	1.0182	0.0449	0.187	30
A+B	-0.1346	0.4991	-0.1202	0.0467	1.1508	0.0510	0.238	73
$\xi_{\text{CIV},2} \approx 1/(a + b * x + c * y)$								
A	0.356	0.160	-0.3480	0.0580	-0.351	0.0814	0.199	40
B	1.080	0.126	0.0223	0.0416	-0.0764	0.0515	0.186	30
A+B	0.7605	0.125	-0.1460	0.0452	-0.2204	0.0532	0.237	73
$\xi_{\text{CIV},3} \approx 1/(a - b * x * y)$								
A	1.3036	0.0884	0.1408	0.0481	...		0.222	41
B	1.0343	0.0436	-0.0463	0.0255	...		0.187	31
A+B	1.1470	0.0488	-0.1116	0.0288	...		0.237	74
$\xi_{\text{CIV,A.I.}} \approx 1/(b * (a - x) * z + c)$								
A	-1.7004	0.5528	-1.0575	0.4703	1.5515	0.1183	0.240	40
B	-2.346	0.3153	0.7571	0.3026	1.1057	0.0413	0.184	30
A+B	5.147	21.138	-0.1121	0.3292	1.2474	0.0501	0.257	73

Notes. $x = \log \lambda L_{\lambda}(1450) - 48$, $y = c(\frac{1}{2})/1000$, $z = \text{A.I.}$

Negrete et al. (2014) provide a helpful recipe; however, their recipe applied to three of their 8 sources allowed for a precision $\sim 100 \text{ km s}^{-1}$ in the rest frame, but the remaining 5 had an uncertainty on average $\gtrsim 500 \text{ km s}^{-1}$.

5. Discussion

Recently, the problems outlined in earlier works by Sulentic et al. (2007) and Netzer et al. (2007) have been ascribed to a “bias” in the C IV λ 1549 M_{BH} estimates (Denney et al. 2016). The C IV λ 1549 M_{BH} bias is dependent on the location in the 4DE1 quasar MS: Fig. 2 and 3 clearly show the different behavior for Pop. A and B. By the same token, an L/L_{Edd} – dependent correction is in principle a valid approach, as L/L_{Edd} is probably one of the main drivers of the MS (Boroson & Green 1992; Sulentic et al. 2000a; Sun & Shen 2015). Unfortunately, several recent works still ignore 4DE1-related effects (or, in other words, MS trends). For instance, scaling laws derived from the pairing of the virial products for *all* sources with reverberation mapping data should be viewed with care (as shown by the reverberation mapping results of Du et al. 2018).

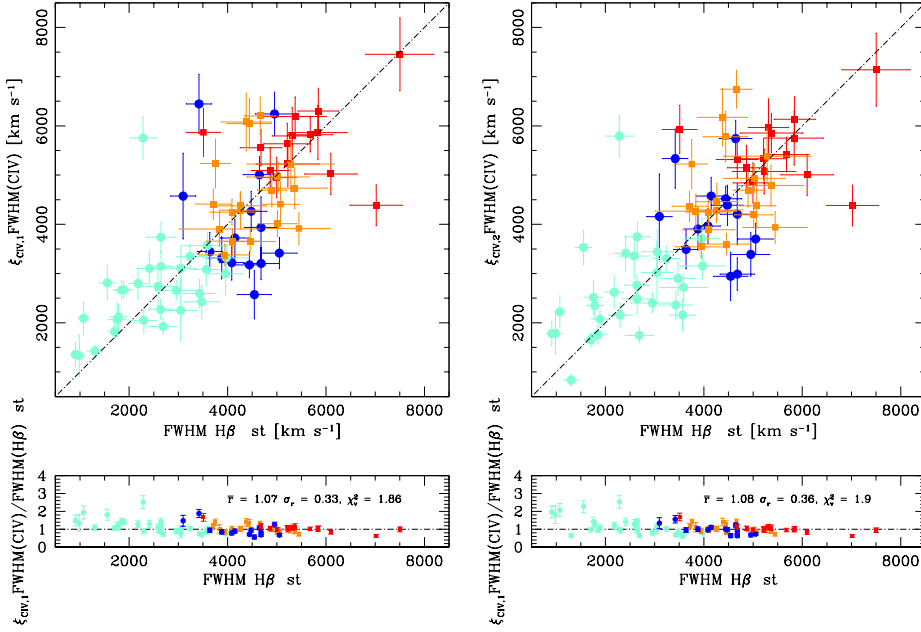


Fig. 7. Top left panel: $\xi_{\text{Civ1}} \text{FWHM}(\text{Civ}\lambda 1549)$ i.e., $\text{FWHM}(\text{Civ}\lambda 1549)$ after correction for blueshift and luminosity dependence following Eq. 6 vs $\text{FWHM}(\text{H}\beta)$ cm for the FOS+HE sample. The black dot dashed line is the equality line, meaning of color code is the same as in Fig. 3. Top right: same, but with ξ_{Civ2} computed from Eq. 7.

5.1. C $\nu\lambda$ 1549 and H β as M_{BH} estimators: input from recent works

Attempts at using the C $\nu\lambda$ 1549 as a VBE have been renewed in the last few years, not last because C $\nu\lambda$ 1549 can be observed in the optical and NIR spectral ranges over which high-redshift quasars have been discovered and are expected to be discovered in the near future. The large C $\nu\lambda$ 1549 blueshifts indicate that part of the BLR gas is under dynamical conditions that are far from a virialized equilibrium. At high Eddington ratio ionized gas may escape from the galactic bulge, and even be dispersed into the intergalactic medium, as predicted by numerical simulations (e.g., Debuhr et al. 2012), and at high luminosity ($\log L \gtrsim 47$ [erg s $^{-1}$]) might have a significant feedback effect on the host galaxy (Marziani et al. 2016).

A firm premise is that the disagreement between H β and C $\nu\lambda$ 1549 mass estimates is not a matter of S/N (Denney et al. 2013). The C $\nu\lambda$ 1549 line width suffers of systematic effects which emerge more dramatically at high S/N i.e., when it is possible to appreciate the complexity of the C $\nu\lambda$ 1549 profile. Given this basic result, recent literature can be tentatively grouped into three main strands: (1) low- z studies, involving FOS and Cosmic Origin Spectrograph (COS) spectra to cover C $\nu\lambda$ 1549; (2) high- z studies, where the prevalence of large C $\nu\lambda$ 1549 shifts is high; (3) studies attempting to correct the C $\nu\lambda$ 1549 FWHM and reduce it to an equivalent of H β , some of them employing results that are directly connected to the MS contextualization of quasar properties.

Low- z studies A large systematic analysis of the C $\nu\lambda$ 1549 profiles paired to H β emission was carried out using HST/FOS (in part used for the present work) and optical observations (Sulentic et al.

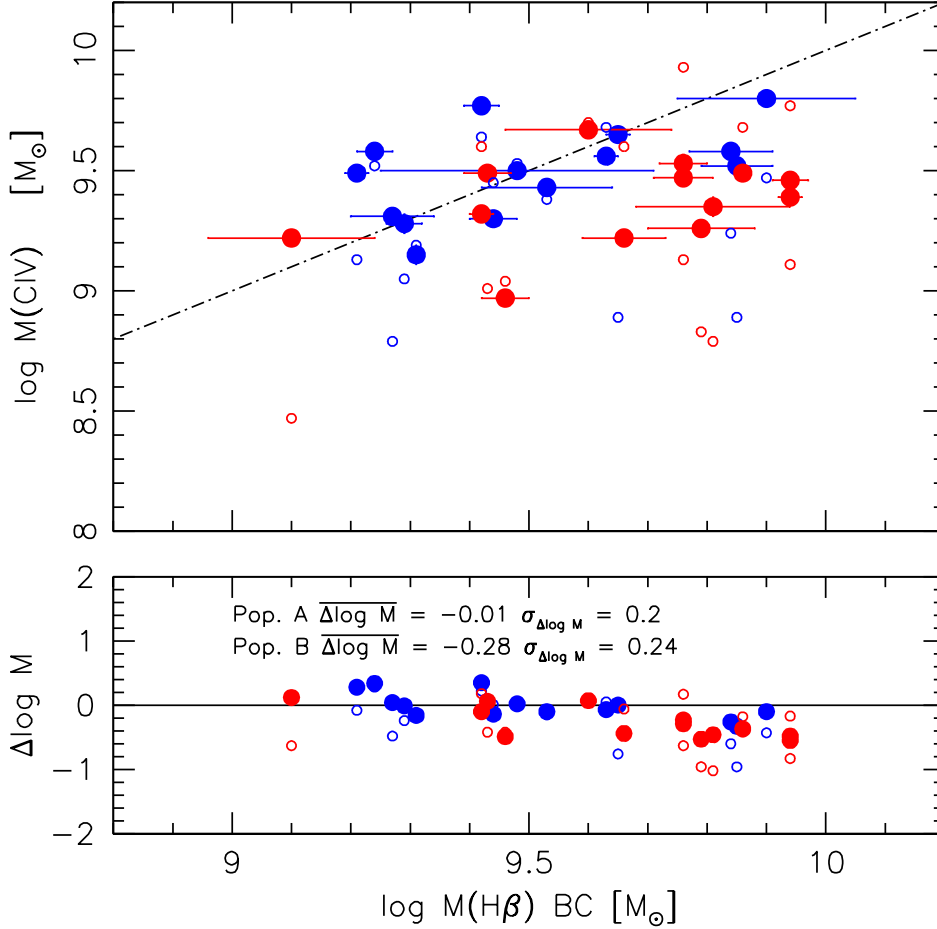


Fig. 8. Black hole mass computed from the fiducial relation of Vestergaard & Peterson (2006) based on FWHM H β vs. the one computed from the C $\nu\lambda 1549$ FWHM following Park et al. (2013), for Pop. A (blue) and B (red) HE sources. M_{BH} values obtained from the Vestergaard & Peterson (2006) C $\nu\lambda 1549$ scaling law after the correction suggested by Brotherton et al. (2015, small dots) are shown by small open circles. The lower panel shows residuals as a function of M_{BH} . The average and the scatter reported for Pop. A and B refer to the Park et al. (2013) scaling laws.

2007). The results of this study emphasized the role of the C $\nu\lambda 1549$ line width in the M_{BH} estimates. The Fig. 6 of Sulentic et al. (2007) clearly shows the importance of placing sources in an E1 context: estimates of the masses could be easily overestimated by a factor $\lesssim 100$ for extreme Pop. A sources such as I Zw 1, while for Pop. B C $\nu\lambda 1549$ and H β M_{BH} estimates appeared more consistent albeit with a large scatter. The line width (let it be the FWHM or the velocity dispersion σ) remains a major factor in C $\nu\lambda 1549$ vs H β M_{BH} determinations since broadening enters squared in the scaling laws (Kelly & Bechtold 2007). Similar warnings on using C $\nu\lambda 1549$ FWHM were issued by Netzer et al. (2007). Low- z samples are less affected by the Eddington ratio bias that is cutting low-Eddington ratio sources at a given M_{BH} for a fixed flux limit (Sulentic et al. 2014). Therefore, it may not be surprising to find studies based on excellent spectra that find an overall consistency between H β and C $\nu\lambda 1549$ M_{BH} estimates. Intrinsic scatter is probably high if full line width without any correction are used: Tilton & Shull (2013) find ≈ 0.5 dex from COS observations of low- z quasars. Denney et al. (2013) claim to be able to reduce the disagreement between

H β and C IV $\lambda 1549$ derived M_{BH} to ≈ 0.24 dex by using the velocity dispersion of the C IV $\lambda 1549$ line. Since the C IV $\lambda 1549$ profile in the Denney et al. (2013) sample almost never shows large blueshifts which may be associated to a velocity shear in outflowing gas, these results appear consistent with the Pop. B properties of the FOS sample.

High- z studies generally concur that the C IV $\lambda 1549$ FWHM is poorly correlated with the Balmer line FWHM. Shen & Liu (2012) describe the scatter between C IV $\lambda 1549$ and H β FWHM as due to an irreducible part (≈ 0.12 dex), and a part that correlates with the blueshift of the C IV $\lambda 1549$ centroid relative to that of H β . They propose scaling laws in which the virial assumption is abandoned i.e., with the exponent of the line FWHM significantly different from 2. For C IV $\lambda 1549$, this means to correct for the overbroadening associated with the non-virial component. The scaling law introduced by Park et al. (2013) is consistent with the Shen & Liu (2012) approach and implies $M_{\text{BH}} \propto \text{FWHM}^{0.5}$ i.e., a FWHM dependence that is very different from the one expected from a virial law ($M_{\text{BH}} \propto \text{FWHM}^2$). As shown in Fig. 8, the scaling law suggested by Park et al. (2013) applied to the HE sample properly corrects for the overbroadening of Pop. A sources, but overcorrects the width of Pop. B, yielding a large deviation from the H β -derived M_{BH} values (on average ≈ 0.28 dex).

Studies exploiting MS trends The results reported in §4 and in Paper I indicate that any solution seeking to bring C IV $\lambda 1549$ M_{BH} estimates in agreement with the ones from H β cannot exclude the strong L/L_{Edd} dependence of the C IV $\lambda 1549$ blueshift that is in turn affecting the C IV $\lambda 1549$ FWHM (Fig. 4). The discussion in Sect. 3 and in Sect. 4.5 identifies the C IV $\lambda 1549$ blueshift as an expedient L/L_{Edd} proxy. Any parameterization of the blueshifted amplitude such as $c(\frac{1}{2})$, the flux bisector of Coatman et al. (2016) or the ratio $\text{FWHM}(\text{C IV } \lambda 1549)/\text{FWHM}(\text{H}\beta)$ is taking into account the MS trends in C IV $\lambda 1549$ properties, due to the L/L_{Edd} and C IV $\lambda 1549$ blueshift correlation. Another L/L_{Edd} proxy may involve the Si IV $\lambda 1397/\text{C IV } \lambda 1549$ peak ratio: at low Si IV $\lambda 1397/\text{C IV } \lambda 1549$ the M_{BH} is underestimated with respect to H β , at high Si IV $\lambda 1397/\text{C IV } \lambda 1549$ the mass is overestimated (Brotherton et al. 2015). Since the ratio Si IV $\lambda 1397/\text{C IV } \lambda 1549$ is a known 4DE1 correlate (Wills et al. 1993; Bachev et al. 2004), these results confirm that FWHM C IV $\lambda 1549$ leads to overestimate M_{BH} for Pop. A (as Pop. A outflows produce blue shifted emission that significantly broadens the line (Fig. 3; cf. Denney et al. 2012). In our sample, however, applying the correction suggested by Brotherton et al. (2015), $\delta \log M \approx -1.23 \log \frac{1400}{\text{CIV}} - 0.91$ to the masses derived from the Park et al. (2013) would move the M_{BH} of Pop. B further down, leading to a further increase of the overcorrection, and also destroying the agreement for Pop. A sources: on top of the $\propto \text{FWHM}^{0.5}$ law, the additional correction is $\delta \log M \approx -0.91$ if $\frac{1400}{\text{CIV}} \sim 1$, as for extreme Pop. A. The correction is lower but still negative for most Pop. B sources where $\frac{1400}{\text{CIV}} \sim 0.3$, exacerbating the disagreement between the H β and C IV $\lambda 1549$ derived masses. A better consistency is achieved if the correction of Brotherton et al. (2015) is applied to the Vestergaard & Peterson (2006) scaling law for C IV $\lambda 1549$. In this case (shown in Fig. 8 by small open circles) the correction for Pop. A still

imply non-negligible systematic residuals $\delta \log M = \log M_{\text{BH}}(\text{H}\beta_{\text{BC}}) - \log M_{\text{BH}}(\text{C IV}\lambda 1549) \approx 0.23$. The average residual is higher for Pop. B M_{BH} , with $\delta \log M \approx 0.27$, and scatter ≈ 0.39 dex.

Assef et al. (2011) used a sample of ≈ 10 quasars with optical spectra covering C IV λ 1549 and near-IR spectra covering H β or H α and show that M_{BH} estimates can be made consistent. The approach of Assef et al. (2011) may be also understood as a correction related to the MS. Assef et al. (2011) suggest that much of the dispersion in their virial mass is caused by the poor correlation between λL_{λ} at 5100 Å and at 1350 Å rather than between their line widths. Their Figs. 14 and 15 shows that the FWHM C IV λ 1549 over H β ratio depends on the flux ratio at 1350 Å and 5100 Å, which is an MS correlate (Laor et al. 1997; Shang et al. 2011). The Assef et al. 2011 sample of gravitationally-lensed quasars might have lowered the Eddington ratio bias described by Sulentic et al. (2014), leading to a preferential selection of Pop. B quasars, and better agreement between H β and C IV λ 1549 line width.

5.2. A virialized component

A systematic increase in line width in the HE sample is expected if the line broadening is predominantly virial: Fig. 5 of Paper I shows that there are no FWHM H β $\lesssim 3000$ km s $^{-1}$ at $\log L \gtrsim 47$ [erg s $^{-1}$]. Fig. 9 shows that a similar increase in FWHM as a function of luminosity is occurring in the FOS+HE sample for both H β and C IV λ 1549. The FWHM ratio between C IV λ 1549 and H β does not instead appear strongly influenced by L , suggesting the interpretation that the broadening of both lines – even if the C IV λ 1549 centroid measurements are significantly affected by an outflowing component – may be mostly related to the gravitational effects of the supermassive black hole (as further discussed below). As mentioned, Balmer lines provide a VBE up $z \gtrsim 2$, and the results of (Paper I) extended this finding to the highest luminosities. For C IV λ 1549, Fig. 9 and the correlation $\text{FWHM} - c(\frac{1}{2})$ justify the assumption of a virial broadening component coexisting with a non virial one (Wang et al. 2011).

5.2.1. Orientation effects on H β

A large part of the C IV λ 1549 – H β scatter is expected to be due to orientation effects. The issue of orientation effects remains open for RQ sources, and orientation effects are most-likely strongly affecting the FWHM of H β (Mejía-Restrepo et al. 2018b), even if it remains hard to distinguish them from other physical factors (such as M_{BH} and L/L_{Edd}). A clue is given by the 4DE1 predictions at extreme orientations: objects observed near the disk rotation axis (i.e., nearly pole-on) have the smallest FWHM H β , the strongest Fe II and Ca II intensities (Dultzin-Hacyan et al. 1999), the largest soft X excess, and the largest C IV λ 1549 blue shifts/asymmetries. These predictions are motivated by the physical scenarios involving an accretion disk - wind system. From a pole-on orientation we should see the smallest Doppler broadening of virially dominated H β emitting clouds, and the strongest intensity of Fe II and other LILs if they are emitted from clouds in the outer part of the disk (Martínez-Aldama et al. 2015). We should also observe the largest contribution of the soft X

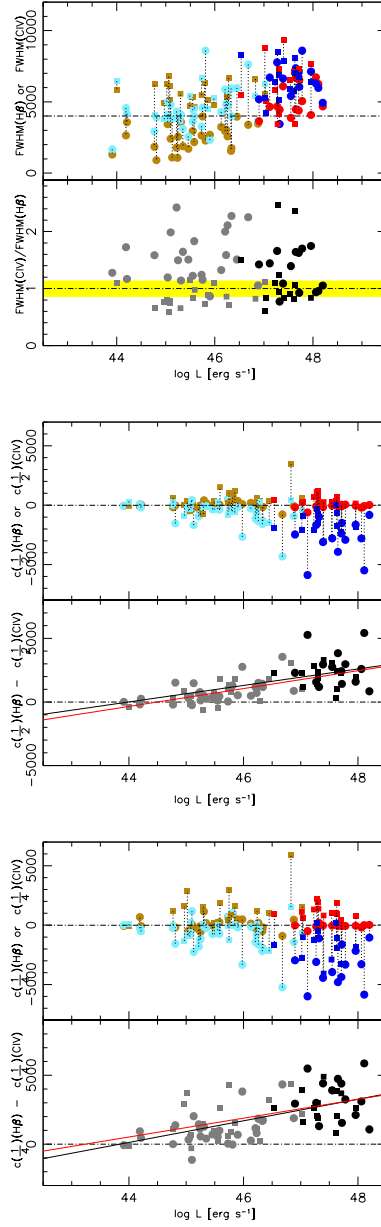


Fig. 9. H β and C $\text{IV}\lambda 1549$ profile parameter comparison as a function of luminosity. Top panels: behavior of FWHM C $\text{IV}\lambda 1549$ and H β (upper half) and of the ratio FWHM(C $\text{IV}\lambda 1549$)/FWHM(H β) as a function of L (lower half), for FOS (golden and pale blue) and HE sample (red and blue). The yellow band identifies the region where FWHM(C $\text{IV}\lambda 1549$)/FWHM(H β)=1 within the errors. Middle panels: $c(\frac{1}{2})$ of H β and C $\text{IV}\lambda 1549$ (upper half), and difference $\delta(\frac{1}{2})$ as a function of L (lower half). Square symbols indicate Pop. B, circles Pop. A. Lines trace an unweighted lsq fit for the Pop. A (black) and for Pop. B (red) sources. Bottom panels: same for $c(\frac{1}{4})$ and $\delta(\frac{1}{4})$. The vertical dotted lines join H β and C $\text{IV}\lambda 1549$ parameters for the same object (e.g., they are not error bars).

excess if it is related to disk emission (Wang et al. 1996; Boller et al. 1996; Wang et al. 2014a). And finally, if a wind is associated with an optically thick disk, and its dynamics is dominated by radiation pressure, HILs such as C $\text{IV}\lambda 1549$ emitted in the wind would show the largest blue shifts (if the receding part of the flow is shielded from view). The case of I Zw 1 provided a prototypical case in which a flattened LIL emitting systems and a radial outflow could be seen at small inclination (e.g., Marziani et al. 1996; Leighly 2004).

In a more modern perspective, there are several indications that the low-ionization BLR is a flattened system (Mejía-Restrepo et al. 2017, 2018a; Negrete et al. 2017; Negrete et al. 2018). We see the clearest evidence at the MS extrema: extreme Pop. B sources radiating at very-low L/L_{Edd} frequently show LIL profiles consistent with a geometrically thin accretion disk profiles (e.g., Chen & Halpern 1989; Strateva et al. 2003; Storchi-Bergmann et al. 2017), which may be hidden in the majority of Pop. B sources (Bon et al. 2007, 2009). A highly flattened LIL-BLR is also suggested in blazars, which are also Pop. B low-radiators (Decarli et al. 2011), by comparing the virial product to mass estimates obtained from the correlation between M_{BH} the host galaxy luminosity. At the other end of the MS, extreme Pop. A quasars show deviations from virial luminosity estimates consistent with the effect of orientation on the line width, if the emitting region is highly flattened (Negrete et al. 2018). A flattened low-ionization BLR is also suggested by comparing the virial product to mass estimates obtained from accretion disk fits to the SED (Mejía-Restrepo et al. 2017, 2018a).

The effect of orientation on the FWHM and on M_{BH} and L/L_{Edd} estimates can be computed by assuming that we are observing randomly-oriented samples of quasars whose line emission arises from a flattened structure – possibly the accretion disk itself. The probability of viewing the structure with an isotropic velocity broadening δv_{iso} at an angle θ between line-of-sight and the symmetry axis of a flattened structure is $P(\theta) = \sin(\theta)$. The radial velocity spread (in the following we use the FWHM as a measure, $\delta v_{\text{obs}} = \text{FWHM}$) can be written as

$$\frac{\text{FWHM}^2}{4} = \delta v_{\text{iso}}^2 + \delta v_{\text{K}}^2 \sin^2 \theta, \quad (9)$$

which implies that

$$\frac{M_{\text{BH,obs}}}{M_{\text{BH,K}}} = \frac{\delta v_{\text{obs}}^2}{\delta v_{\text{K}}^2} = 4 \cdot (\kappa^2 + \sin^2 \theta), \quad (10)$$

where $\kappa = \delta v_{\text{iso}}/\delta v_{\text{K}}$. From Eq. 9 one can estimate the ratio δv_{obs} intrinsic velocity δv_{K} either by computing a most probable value of θ or by deconvolving the observed velocity distribution from $P(\theta)$. The calculations are described in Appendix B. The average ratio is $\langle \frac{M_{\text{BH,obs}}}{M_{\text{BH,K}}} \rangle \approx 1.1$ if $\kappa = 0.1$. If the FWHM of the H β line is used, the M_{BH} suffers of a small bias, if the LIL emitting region is highly flattened. If $\kappa = 0.5$ (a “fat” emitting region), then the bias is much larger $\langle \frac{M_{\text{BH,obs}}}{M_{\text{BH,K}}} \rangle \approx 2.1$. The M_{BH} dispersion in the case of $\kappa = 0.1$ was estimated for large samples (10^6 replications) with θ distributed according to $P(\theta)$ (Appendix C), and was found to be $\sigma_{M_{\text{BH}}} \approx 0.33$ dex. Therefore, even if $P(\theta)$ strongly disfavor cases with $\theta \rightarrow 0$, the viewing angle can account for a large fraction of the dispersion in the M_{BH} scaling laws with line width and luminosity.

5.3. A wind component

The interpretation of the C IV $\lambda 1549$ profile (and H β profile differences) rests on the main results of Paper I: the C IV $\lambda 1549$ shifts are dependent on L/L_{Edd} and, to a lesser extent on L ; the C IV $\lambda 1549$ broadening is due to a blueshifted component whose strength with respect to a virialized component increases with L/L_{Edd} and L .

At $\frac{1}{4}$ and $\frac{1}{2}$ fractional intensity the difference in the line centroid radial velocity of H β and C IV $\lambda 1549$ i.e. $c(\frac{1}{2})(\text{H}\beta) - c(\frac{1}{2})(\text{C IV } \lambda 1549)$ and $c(\frac{1}{4})(\text{H}\beta) - c(\frac{1}{4})(\text{C IV } \lambda 1549)$ are almost always positive, and can reach 7000 km s^{-1} and 4000 km s^{-1} in the HE sample and FOS respectively mainly because of the large C IV $\lambda 1549$ blueshifts (Fig. 9). A luminosity dependence of $\delta(\frac{1}{2}) = c(\frac{1}{2})(\text{H}\beta) - c(\frac{1}{2})(\text{C IV } \lambda 1549)$ and $\delta(\frac{1}{4}) = c(\frac{1}{4})(\text{H}\beta) - c(\frac{1}{4})(\text{C IV } \lambda 1549)$ is illustrated in Fig. 9. The centroid separations are correlated with L , with a similar slope at both $\frac{1}{2}$ and $\frac{1}{4}$ fractional intensity (Fig. 9): for $c(\frac{1}{2})$ of Pop. A,

$$\delta(\frac{1}{2}) \approx (648 \pm 121) \log L - (28530 \pm 5600) \text{ km s}^{-1}, \quad (11)$$

in the range $44 \lesssim \log L \lesssim 48.5$.

The trends of Fig. 9 suggest that the C IV $\lambda 1549$ broadening is however affected by M_{BH} , as both the H β and C IV $\lambda 1549$ widths steadily increase with luminosity, and their ratio shows no strong dependence on luminosity. This may be the case if the outflow velocity is a factor k of the virial velocity ($k = \sqrt{2}$ would correspond to the escape velocity). The correlation between shift and FWHM of Paper I indicates that we are seeing an outflow component “emerging” on the blue side of the BC. If we assume that line emission arises from a flattened structure with velocity dispersion v_{iso} (i.e., as in Eq. 9), and that the outflowing component from the accretion disk contributes to an additional broadening term proportional to $\cos \theta$ (the projection along the line of sight of the outflow velocity), then the observed C IV $\lambda 1549$ broadening can be written as

$$\text{FWHM}_{\text{CIV}}^2 = 4(\delta v_{\text{iso}}^2 + \delta v_{\text{K}}^2 \sin^2 \theta) + \mathfrak{J}^2 \delta v_{\text{K}}^2 \mathcal{M} \frac{L}{L_{\text{Edd}}} \cos^2 \theta, \quad (12)$$

where $\mathfrak{J}$ is a proportionality constant, and $\mathcal{M}$ the force multiplier. It follows that the total broadening can easily exceed δv_{K} for a typical viewing angle $\theta = \pi/6$, provided that the factor $Q = \mathfrak{J}^2 \mathcal{M} \frac{L}{L_{\text{Edd}}}$ is larger than 1. The factors $\mathfrak{J}$ and $\mathcal{M}$ depend on physical properties (density, ionization level) and should be calculated in a real physical model linking ionization condition and dynamics. The factor Q encloses the dependence of wind properties on radiation forces, opacity, etc. (Stevens & Kallman 1990) along with the dependence on ionization. For example, in the case of optically thick gas being accelerated by the full absorption of the ionizing continuum, the force multiplier is $\mathcal{M} = \frac{\alpha}{\sigma_{\text{T}} N_{\text{c}}} \approx 7.5$ for column density $N_{\text{c}} = 10^{23} \text{ cm}^{-2}$, and $\alpha = 0.5$ (α is the fraction between the ionizing and bolometric luminosity, Netzer & Marziani 2010). If $L/L_{\text{Edd}} \rightarrow 1$, and $\mathfrak{J} \sim 1$,

implying $Q \sim O(10)$, the FWHM_{CIV} can exceed by up to a factor of several the virial broadening, as indeed observed in the most extreme radiators from the comparison between C $\text{IV}\lambda 1549$ and H β .

Eqs. 9 and 12 account for the consistent increase in broadening of C $\text{IV}\lambda 1549$ and H β (Fig. 9). In the context of the present sample covering a wide range in luminosity, L can be considered a proxy for the increase in M_{BH} ($L \propto M_{\text{BH}}$, with a scatter set by the L/L_{Edd} distribution) and therefore in Keplerian velocity. The top and middle panels of Fig. 9 show a consistent increase of the centroid, and of the centroid difference $\delta(\frac{1}{2})$ and $\delta(\frac{1}{4})$ with L . This result motivated the introduction of a luminosity-dependent correction to the line width. The centroid difference can be written as:

$$\delta(\frac{i}{4}) \sim \frac{1}{2} \delta v_K(\frac{i}{4}) \cos \theta \left(-\mathfrak{I} \left(\mathcal{M} \frac{L}{L_{\text{Edd}}} \right)^{\frac{1}{2}} + f \right), i = 1, 2, \quad (13)$$

with $f \equiv 0$ for Pop. A, and f defined by the infall velocity $v_{\text{inf}} = f \delta v_K$ as a fraction of the radial free-fall velocity for Pop. B. Eq. 13 and 12 imply that $\text{FWHM}_{\text{CIV}}^2 = \text{FWHM}_{\text{H}\beta}^2 + 4\delta^2(\frac{1}{2})$, if $f = 0$.

If we ascribe the redward displacement of the H β wing in Pop. B sources to gravitational and transverse redshift (e.g., Corbin 1990; Bon et al. 2015),

$$\begin{aligned} \delta(\frac{i}{4}) &= \frac{1}{2} \left(-\delta v_K(\frac{i}{4}) \mathfrak{I} \left(\mathcal{M} \frac{L}{L_{\text{Edd}}} \right)^{\frac{1}{2}} \cos \theta + \frac{3}{2} c z_g(\frac{i}{4}) \right) \\ &= \frac{1}{2} \delta v_K(\frac{i}{4}) \left(-\mathfrak{I} \left(\mathcal{M} \frac{L}{L_{\text{Edd}}} \right)^{\frac{1}{2}} \cos \theta + \frac{3}{2} \frac{\delta v_K(\frac{i}{4})}{c} \right) \end{aligned} \quad (14)$$

where $c z_g \sim c G M_{\text{BH}} / c^2 r$ is the $c(\frac{1}{2})$ or $c(\frac{1}{4})$ of H β , which usually can be 0 (Pop. A) or ≥ 0 (Pop. B), and where we have used the weak field approximation for the gravitational redshift.

Eqs. 13 and 15 account for the steady increase of the centroid difference δ with luminosity. The H β centroid displacement in Pop. B may be associated with free fall or gravitational redshift. The amplitude of blueshift depends on luminosity in Pop. A. The point is that both H β redward displacement and blueshift of C $\text{IV}\lambda 1549$ (and hence their differences) are proportional to the δv_K and hence to the M_{BH} .

The ξ_{CIV} factor can be written as:

$$\begin{aligned} \xi_{\text{CIV}} &= \left(\frac{\delta v_{\text{iso}}^2 + \delta v_K^2 \sin^2 \theta}{4(\delta v_{\text{iso}}^2 + \delta v_K^2 \sin^2 \theta) + \mathfrak{I}^2 \delta v_K^2 \mathcal{M} \frac{L}{L_{\text{Edd}}} \cos^2 \theta} \right)^{\frac{1}{2}} \\ &= \left(\frac{1}{1 + \frac{Q \cos^2 \theta}{4(\kappa^2 + \sin^2 \theta)}} \right)^{\frac{1}{2}} \end{aligned} \quad (15)$$

The ξ_{CIV} behavior as a function of the viewing angle θ is described in of Fig. 10. Fig. 10 shows the dependence in case of a flat $\kappa = 0.1$ (black) or fat $\kappa = 0.5$ (red) for four values of

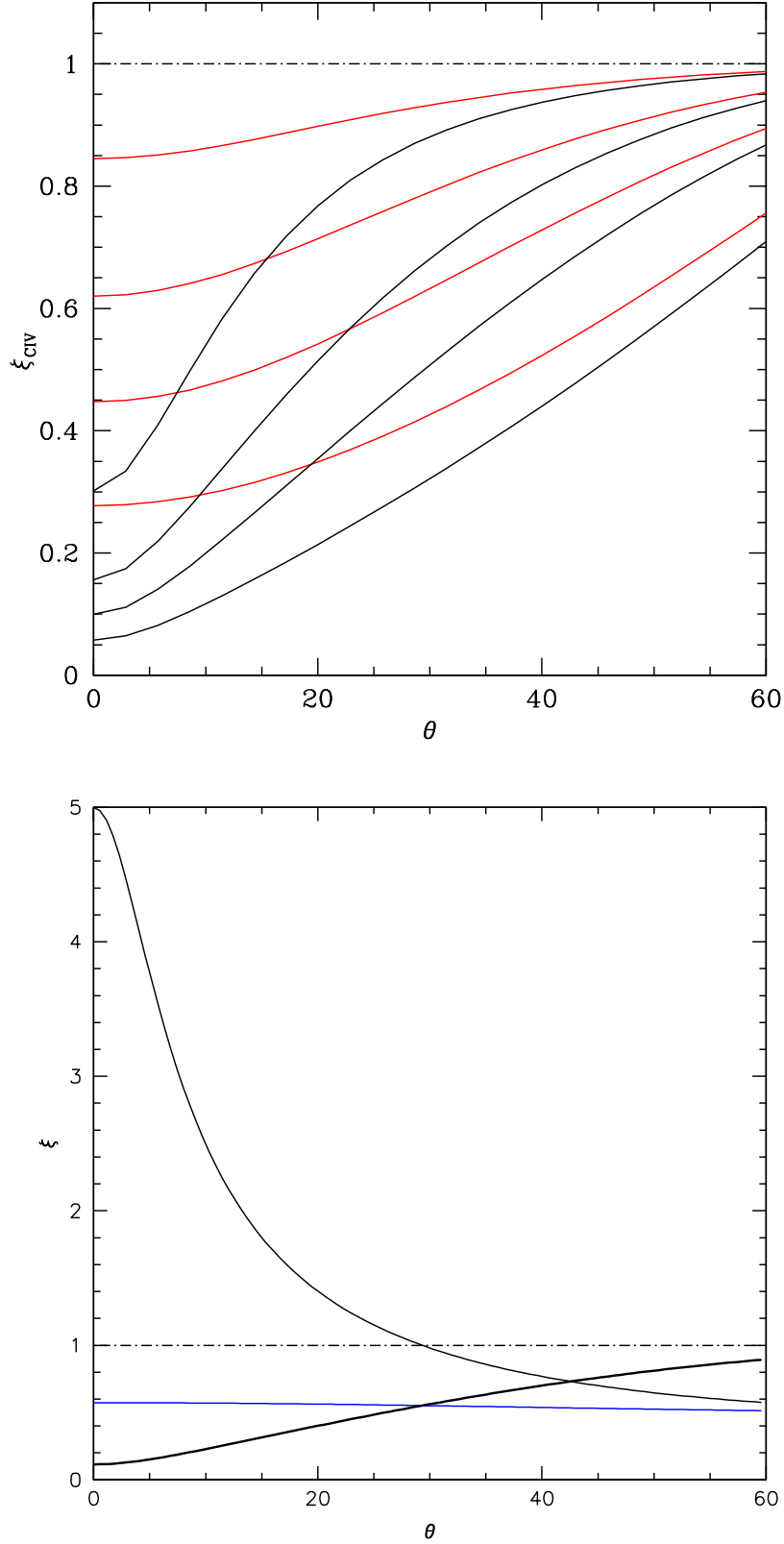


Fig. 10. Top: parameter ξ_{CIV} behavior as a function of viewing angle as a function of θ for a “thin” emitting region with $\kappa = 0.1$, for different Q values (0.4, 1.6, 4.0, 12.0; black lines). Red line: ξ_{CIV} behavior for a thick emitting region $\kappa = 0.5$, for the same Q values. Bottom: same as above for $\kappa = 0.1$, with $Q = 12$. The thin lines are the ξ values for H β (black) and C ν 1549 (blue). See text for more details. The thick line is their ratio (also shown in the top panel).

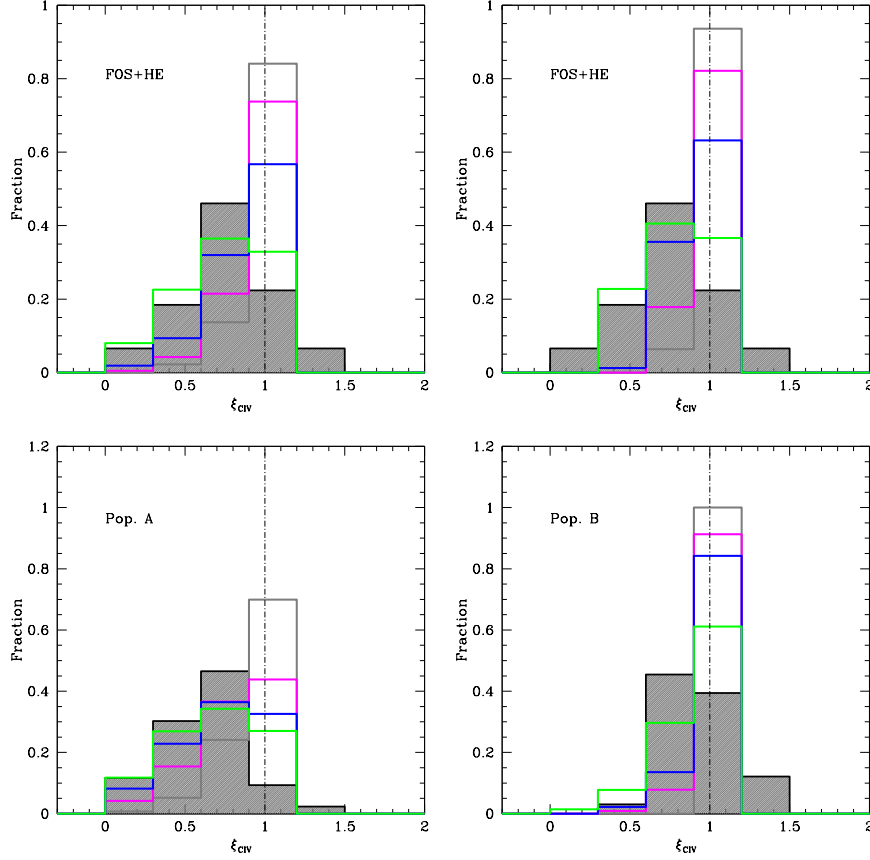


Fig. 11. Top left: Observed distribution of ξ_{CIV} for the full FOS+HE sample (shaded histogram), and distribution of ξ_{CIV} for $Q=0.4$ (grey), 0.8 (magenta), 2.0 (blue), 7.8 (green), assuming $\kappa = 0.1$, for randomly-oriented synthetic samples. Top right: same as in top left panel, for $\kappa = 0.5$. Bottom left: distribution of ξ_{CIV} restricted to Pop. A sources for $Q=1.0$ (grey), 2.0 (magenta), 4.0 (blue), 12.0 (green), for $\kappa = 0.1$. Bottom right: same for Pop. B sources, with $Q=0$ (grey), 0.2 (magenta), 0.4 (blue), 1.6 (green), for $\kappa = 0.1$. See text for more details.

Q . The bottom panel of Fig. 10 shows the behaviour of the ratios $\tilde{\xi}_{\text{H}\beta} = 1/[4(\kappa^2 + \sin^2 \theta)]^{1/2}$ and $\tilde{\xi}_{\text{CIV}} = 1/(4\kappa^2 + 4\sin^2 \theta + Q\cos^2 \theta)^{1/2}$. The $\tilde{\xi}$ are the ratios between the δv_K and the observed FWHM. At low θ , the FWHM(H β) underestimates the δv_K by a large factor, while the overestimation of δv_K by the FWHM(C ν 11549) is almost independent of θ and a factor ≈ 2 .

The panels of Fig. 11 compare the observed distribution of $\xi_{\text{CIV},1}$ (shaded histogram) with the prediction of synthetic samples randomly oriented, at different Q . We are not seeking a fit of the observed distribution especially around $\xi_{\text{CIV}} \approx 1$ because of the many biases affecting our sample and of the problem raised by $\xi_{\text{CIV}} > 1$ (see below), but a qualitative consistency in the distribution of $\xi_{\text{CIV}} < 1$.

If we focus the analysis of Fig. 11 mainly on large shifts, the presence of low ξ_{CIV} values and their higher frequency favors a highly flattened low-ionization BLR, as well as high Q for the full sample. A fat $\kappa = 0.5$ BLR is unable to reproduce the largest shift amplitudes. The scatter in ξ_{CIV} linear values at $Q \gtrsim 2$ is ≈ 0.2 , implying a dispersion in the M_{BH} of ≈ 0.15 dex. If we separate Pop. A and B, more extreme values of $Q \gtrsim 2$ are required to fit the large shift distribution in Pop. A, with $Q \sim 10$. The distribution of ξ_{CIV} for Pop. B is more peaked around $\xi_{\text{CIV}} \approx 1$, and the ξ_{CIV} distribution can be qualitatively accounted for if $Q \lesssim 2$.

The ξ_{CIV} observed distribution includes values > 1 . These values are not possible following our model: the $\text{FWHM}(\text{CIV}\lambda 1549)$ should be always in excess or comparable to $\text{FWHM}(\text{H}\beta_{\text{BC}})$. In the case $Q \gg 1$, the C IV λ 1549 line is broadened by an outflowing component; if $Q \rightarrow 0$, $\xi_{\text{CIV}} \lesssim 1$. In the latter case, the excess broadening may come from the smaller emissivity-weighted distance expected for C IV λ 1549 in a virial velocity field. The existence of cases with $\text{FWHM C IV}\lambda 1549 < \text{FWHM H}\beta$ was already noted by Mejía-Restrepo et al. (2018b), so it is not unique to the FOS+HE sample. The bottom right panel of Fig. 11 shows that such cases are relatively frequent among Pop. B. Inspection of the HE spectra in Paper I reveals that the C IV λ 1549 profile is significantly affected by semi-broad absorptions such as the ones often found in mini-BAL quasars (Vestergaard 2003; Sulentic et al. 2006a). Since mini-BALs cluster around the line core, it is most likely that these Population B sources would satisfy the condition $\text{FWHM C IV}\lambda 1549 \gtrsim \text{FWHM H}\beta$ if the effect of the absorptions could be removed.

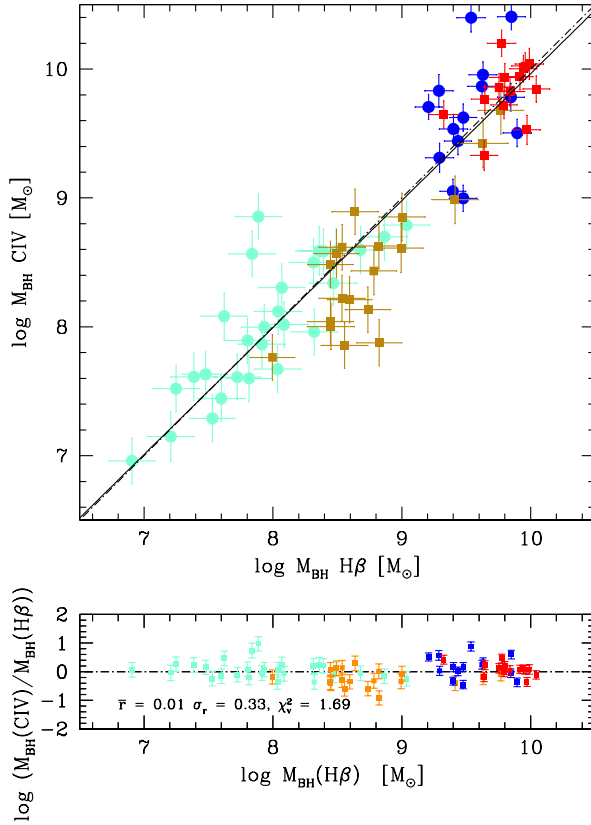


Fig. 12. M_{BH} computed from the fiducial relation of Vestergaard & Peterson (2006) based on $\text{FWHM H}\beta$ vs. the one computed from the C IV λ 1549 FWHM corrected following Eq. 6. Error bars include luminosity uncertainties estimated by the scatter in L derived from the UV and the visual spectral ranges along with errors on FWHM propagated quadratically. The lower panel shows the residuals for the three cases. Meaning of color code is the same as in the previous Figures.

5.4. M_{BH} scaling laws dependent on L/L_{Edd} and L

The goal is to obtain an M_{BH} estimator based on C IV λ 1549 that is consistent with the scaling law derived for H β . In this context, a second-order dependence on luminosity of FWHM C IV λ 1549 cannot be ignored especially if samples encompass a broad range in luminosity. This will be the case in deep, forthcoming surveys. Considering the corrections to FWHM C IV λ 1549 of §4, the M_{BH} scaling law is derived in the form $\log M_{\text{BH}} = \alpha \cdot \log L + 2 \cdot \log \text{FWHM} + \gamma$ by minimizing the scatter and any systematic deviation of M_{BH} estimated from C IV λ 1549 with respect to the H β -derived masses: the unweighted least square fit of Fig. 12 yields

$$M_{\text{BH}}(\text{CIV}) \approx (0.99 \pm 0.04)M_{\text{BH}}(\text{H}\beta) + (0.11 \pm 0.39). \quad (16)$$

The C IV λ 1549 scaling law takes the form:

$$\log M_{\text{BH},1} \text{ CIV} \approx (0.64^{+0.045}_{-0.025}) \log L_{1450} + 2 \log (\xi_{\text{CIV},1} \text{FWHM}(\text{CIV})) + (0.525^{+0.22}_{-0.18}) \quad (17)$$

for the FWHM correction using Eq. 6. Applying Eq. 7, the scaling law does not change appreciably, and uncertainties in the coefficients are only slightly different.

$$\log M_{\text{BH},2} \text{ CIV} \approx (0.63^{+0.045}_{-0.035}) \log L_{1450} + 2 \log (\xi_{\text{CIV},2} \text{FWHM}(\text{CIV})) + (0.525^{+0.275}_{-0.19}) \quad (18)$$

The scaling law parameter uncertainties have been estimated following the standard approach in Bevington & Robinson (2003, p. 210ff), with the constrain that unbiased consistency between M_{BH} from H β and C IV λ 1549 (Eq. 16) is satisfied within the 1σ uncertainties. The rms scatter is $\sigma \approx 0.33$ for the Eq. 6 and to $\sigma \approx 0.35$ for Eq. 7. Assuming a single correction for both Pop. A and B significantly worsens the fit quality, and no scaling law is reported.

An application of the bisector fitting technique using SLOPES (Feigelson & Babu 1992a) yields :

$$\log M_{\text{BH},1} \text{ CIV} \approx (0.5925^{+0.0275}_{-0.030}) \log L_{1450} + 2 \log (\xi_{\text{CIV},1} \text{FWHM}(\text{CIV})) + (0.62 \pm 0.32) \quad (19)$$

$$\log M_{\text{BH},2} \text{ CIV} \approx (0.572^{+0.0285}_{-0.032}) \log L_{1450} + 2 \log (\xi_{\text{CIV},2} \text{FWHM}(\text{CIV})) + (0.64 \pm 0.35) \quad (20)$$

The Vestergaard & Peterson (2006) H β scaling laws suffer from a significant scatter (see the discussion in their paper) that can be explained on the basis of the scatter induced by orientation (0.33 dex at 1σ) according to the results of Appendix B. The C $\nu\lambda$ 1549 and H β relation should be considered equivalent. The luminosity exponent (≈ 0.64) is in agreement with previous observations (Peterson et al. 2005). It is slightly above the exponent of the C $\nu\lambda$ 1549 radius dependence on luminosity found in more recent reverberation mapping studies ($\approx 0.52 - 0.55$ Kaspi et al. 2007; Lira et al. 2017, 2018).

Fig. 12 suggests the presence of a well-behaved distribution with a few outlying points. It is possible to reduce the scatter to $\sigma \approx 0.25$ applying a σ clipping algorithm (i.e., eliminating all sources deviating more than $\pm 2\sigma$), with no significant change in the best fitting parameters. This selective procedure is however unwarranted: as shown in Appendix C, outlying points are expected right because of the possible occurrence of low-probability viewing angles. The residual rms can be largely accounted for by orientation effects if Q is small, and by the combination of orientation effects and outflow prominence if Q is much larger than 1 (Appendix C).

5.5. Application to a large sample with H β and C $\nu\lambda$ 1549 data

The Coatman et al. (2017) data provides a different sample for the testing of the scaling law of Eq. 17. The flux bisector can be converted into $c(\frac{1}{4})$ (Sect. 4.5). An application of Eq. 17 to Pop. A and B (applying the luminosity-dependent separation as in Paper I) is yielding agreement with the expectation of an unbiased M_{BH} estimator with respect to the H β M_{BH} estimates using the scaling law of Vestergaard & Peterson (2006): the slope of an unweighted lsq fit is $\approx 0.958 \pm 0.065$ (using SLOPES, Feigelson & Babu 1992a, Fig. 13).

6. Conclusion

The present investigation was focused on the C $\nu\lambda$ 1549 relations to H β over a broad range of luminosity ($\log L \sim 43 - 48$, including very high luminosities $\log L \gtrsim 47$) in the Eigenvector 1 context, with the goal of testing the C $\nu\lambda$ 1549 suitability as virial broadening estimators when low-ionization lines observations are not available. The Eigenvector 1 context means that the quasar main sequence is considered to properly interpret first-order Eddington ratio effects and luminosity effects that appear to be second order in low- z samples.

The main conclusions reached in this paper are as follows:

1. Within the limits of our sample size, and of our UV spectral coverage, it does not appear that the C $\nu\lambda$ 1549 FWHM can be used as a reliable virial broadening estimator without significant

corrections. There is a large scatter between FWHM measurements on H β and C λ 1549 that seems to defy the definition of a meaningful trend.

2. The C λ 1549_{NC} removal improves the agreement between C λ 1549 and H β measures in the HE sample, but C λ 1549_{NC} is not a major factor hampering the definition of a C λ 1549 VBE consistent with H β .
3. Corrections to FWHM C λ 1549 and C λ 1549-based M_{BH} estimates that vary systematically along the 4DE1 sequence and are strongly dependent on Eddington ratio are promising and should be further explored.
4. Following the results of Paper I, we define a correction to the FWHM(C λ 1549) based on the full-profile C λ 1549 $c(\frac{1}{2})$ (a proxy for L/L_{Edd}) and on the luminosity at 1450 Å. Given the intrinsic differences between Pop. A and B, and their “threshold” separation dependent on a critical L/L_{Edd} , two different correction laws were considered for the two populations. We remark that the correction for Pop. B as derived from the FOS+HE sample is highly uncertain.
5. The M_{BH} scaling law (Eq. 17) associated with the corrected FWHM(C λ 1549) following Eq. 6, as explained in Sect. 5.4, allows for the preservation of the virial dependence on line broadening. Its practical usefulness rests on the ability to distinguish Pop. A and B quasars. This can be achieved in a large fraction of quasars following the guideline set forth by Negrete et al. (2014).
6. We constructed a toy model that helped the interpretation of the scatter. Orientation effects induce scatter $\approx 0.3\text{--}0.4$ dex in mass estimates that account for a large fraction of the dispersion in the landmark scaling law of Vestergaard & Peterson (2006). A physical model of the disk + wind system might allow to recover the viewing angle θ for individual quasars.

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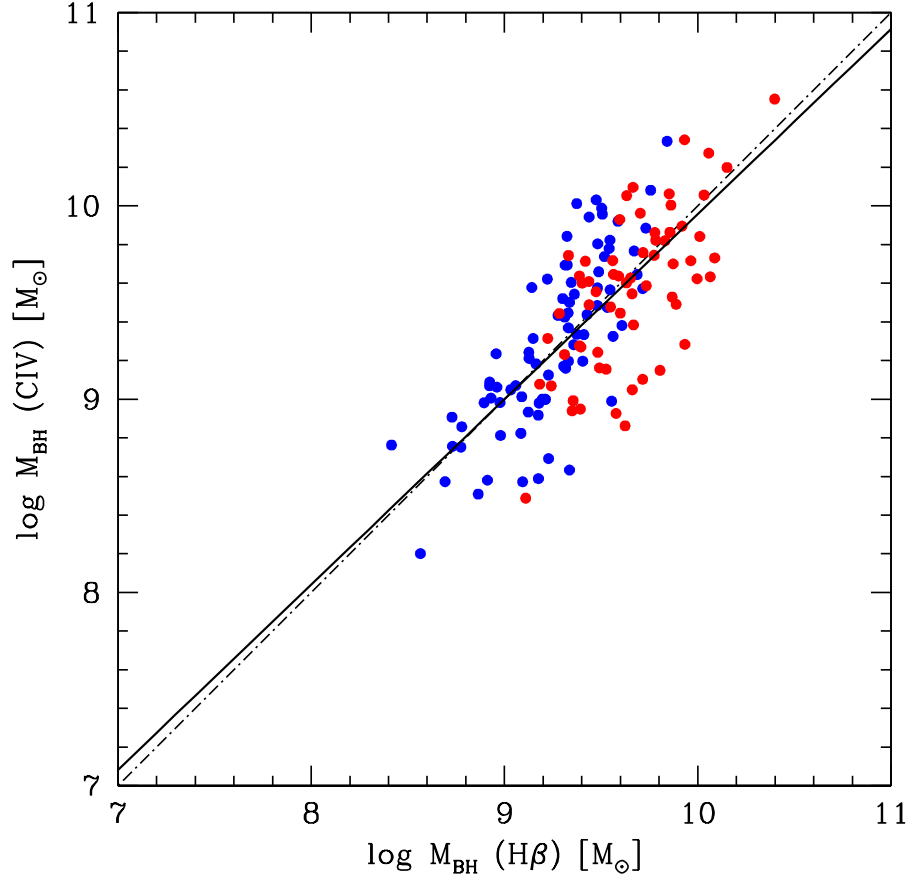


Fig. 13. Estimates of M_{BH} using corrected C $\text{IV}\lambda 1549$ FWHM as a VBE versus M_{BH} computed from H β FWHM using the scaling-law of Vestergaard & Peterson (2006). The luminosity and FWHM data from Coatman et al. (2017) with Pop. A (blue) and B sources kept separated (see Sect. 5.5 for more details), and with M_{BH} computed according to Eq. 17. The dot-dashed line traces the 1:1 relation between M_{BH} from C $\text{IV}\lambda 1549$ and H β ; the black line is an unweighted lsq fit for the A+B M_{BH} estimates.

Appendix A: The MS / 4DE1 formalism: a glossary

In the optical plane of the quasar main sequence, spectral types are isolated following Sulentic et al. (2002). Fig. A.1 provides a sketch with the spectral types identification in the optical plane of the MS. Here we provide a glossary of the MS-related terms and acronyms employed in the paper, along the order of the quasar main sequence. A more thorough description can be found in Sulentic et al. (2011) and Marziani et al. (2018). The rationale for two type-1 quasar populations (A and B) was originally given by Sulentic et al. (2000a).

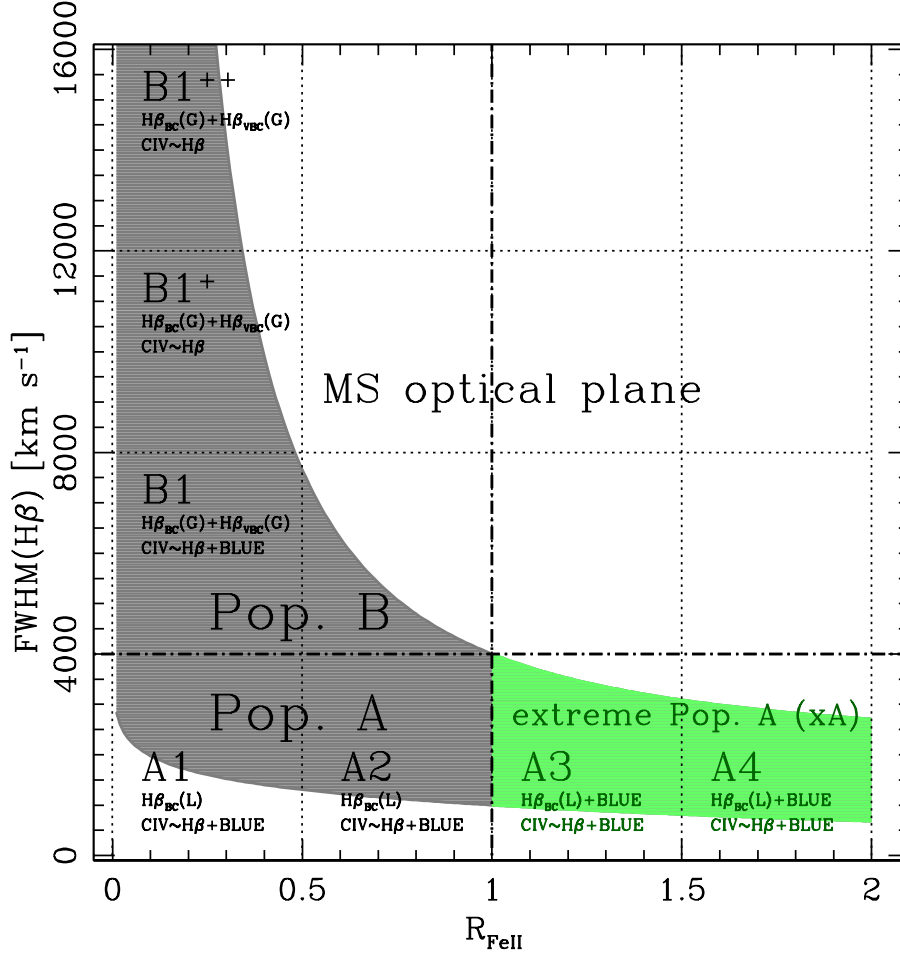


Fig. A.1. Schematic representation of the optical plane of the quasar MS, with the subdivisions identifying spectral types along the sequence. The main components that are blended in the H β and C IV λ 1549 profile are listed in each spectral bin. The shaded area shows the approximate occupation of low- z quasars sample in the plane.

ST	Definition
Population B: $\text{FWHM}(\text{H}\beta) \geq 4000 \text{ km s}^{-1}$. Virial-dominated with redward-asymmetric profiles in H β and Mg II λ 2800. Also described a disk-dominated (Richards et al. 2011).	
B1++	$12000 \text{ km s}^{-1} \leq \text{FWHM}(\text{H}\beta) < 16000 \text{ km s}^{-1}$, $R_{\text{FeII}} < 0.5$
B1+	$8000 \text{ km s}^{-1} \leq \text{FWHM}(\text{H}\beta) < 12000 \text{ km s}^{-1}$, $R_{\text{FeII}} < 0.5$
B1	$4000 \text{ km s}^{-1} \leq \text{FWHM}(\text{H}\beta) < 8000 \text{ km s}^{-1}$, $R_{\text{FeII}} < 0.5$
Population A: $\text{FWHM}(\text{H}\beta) \leq 4000 \text{ km s}^{-1}$. Sources frequently show C IV λ 1549 blueshifts, and H β Lorentzian-like profiles (Du et al. 2016). Includes a range of FeII emission.	
A1	$\text{FWHM}(\text{H}\beta) < 4000 \text{ km s}^{-1}$; $R_{\text{FeII}} < 0.5$
A2	$\text{FWHM}(\text{H}\beta) < 4000 \text{ km s}^{-1}$; $0.5 \leq R_{\text{FeII}} < 1$
A3 [xA]	$\text{FWHM}(\text{H}\beta) < 4000 \text{ km s}^{-1}$; $1 \leq R_{\text{FeII}} < 1.5$
A4 [xA]	$\text{FWHM}(\text{H}\beta) < 4000 \text{ km s}^{-1}$; $1.5 \leq R_{\text{FeII}} < 2$

Spectral types A3 and A4 are also indicated as extreme Population A, with $R_{\text{FeII}} \gtrsim 1$. They are the highest radiators per unit mass and possibly super-Eddington accretors (Wang et al. 2014a).

The 4D Eigenvector-1 formalism was introduced to limit the set of MS-correlated parameters to the four ones that are most relevant for the MS physical interpretation. In addition to FWHM H β , R_{FeII} , and $c(\frac{1}{2})$ C IV $\lambda 1549$, the soft X-ray photon index Γ_{soft} is also considered (Sulentic et al. 2000b). The four parameters were meant to represent the velocity dispersion of the LIL-emitting part of the BLR, the physical condition within the LIL-BLR (R_{FeII}), the dynamical condition of the HIL emitting gas, and the accretion state of the black hole. $\Gamma_{\text{soft}} > 2$ implies a soft X-ray excess that is exclusive of Population A (Wang et al. 1996; Boller et al. 1996; Shen & Ho 2014; Bensch et al. 2015).

Line components assumed in the decomposition along the MS are defined as follows (see also the sketch of Fig. A.1).

Line component	Definition
Low-ionization lines (LILs): H I H β	
H β_{VBC}	Gaussian FWHM $\sim 10000 \text{ km s}^{-1}$, redshifted by $1 - 2000 \text{ km s}^{-1}$ (defining property of Pop. B; absent in Pop. A)
H β_{BC}	Lorentzian, FWHM $\sim 1 - 4000 \text{ km s}^{-1}$ (Pop. A); Gaussian FWHM H $\beta \gtrsim 4000 \text{ km s}^{-1}$ (Pop. B)
H β BLUE	Asymmetric Gaussian which models an excess of emission on the blue side of H β ; usually weak save in ST A3 and A4
H β	Sum of H β_{BC} , H β_{VBC} , and BLUE (when applicable); full broad H β profile
H β_{NC}	H β narrow component
High-ionization lines (HILs): C IV $\lambda 1549$	
C IV $\lambda 1549_{\text{VBC}}$	Gaussian FWHM $\sim 10000 \text{ km s}^{-1}$, redshifted by $1 - 2000 \text{ km s}^{-1}$
C IV $\lambda 1549_{\text{BC}}$	Lorentzian, if FWHM(H β) $\leq 4000 \text{ km s}^{-1}$ (Pop. A); Gaussian FWHM $\gtrsim 4000 \text{ km s}^{-1}$ (Pop. B)
C IV $\lambda 1549$ BLUE	Asymmetric Gaussian which models an excess of emission on the blue side of C IV $\lambda 1549$; detected in most quasar and most prominent in spectral types A3 and A4
C IV $\lambda 1549$	Sum of C IV $\lambda 1549_{\text{BC}}$, C IV $\lambda 1549_{\text{VBC}}$, and C IV $\lambda 1549$ BLUE; full broad C IV $\lambda 1549$ profile
C IV $\lambda 1549_{\text{NC}}$	C IV $\lambda 1549$ narrow component, prominent in Pop. B at low- z ; almost absent in most Pop. A sources

BLUE becomes detectable as a blueward excess in the H β profile mainly in A3 and A4 (more infrequently in A2). For C IV $\lambda 1549$, BLUE increases in prominence along the sequence from B1 $^{++}$, to A4. In B1 $^{++}$ and B1 $^{+}$ is weak and often undetectable, while in A3 and A4 it may dominate C IV $\lambda 1549$ emission.

Appendix B: Effect of orientation on H β M_{BH} estimates

From the inversion of Eq. 9, we obtain an expression for the viewing angle $\theta = \arcsin \sqrt{x^2/4 - \kappa^2}$, where $x = v_{\text{obs}}/\delta v_K$ and $\kappa = \delta v_{\text{iso}}/\delta v_K$. The probability to observe v_{obs} for a given δv_K is then

$$P(x) = \sqrt{x^2/4 - \kappa^2} \frac{d\theta}{dx} = \frac{x/4}{\sqrt{\kappa^2 - x^2/4 + 1}} \quad (\text{B.1})$$

The black hole mass is $\propto x^2$. Therefore the average effect can be written as

$$\langle \frac{M_{\text{BH,obs}}}{M_{\text{BH,K}}} \rangle = \int_{x(v_{\text{iso}})}^{x(\text{edge})} x^2 P(x) dx / \int_{x(v_{\text{iso}})}^{x(\text{edge})} P(x) dx \quad (\text{B.2})$$

The integrals of Eq. B.2 can be computed analytically:

$$\int x^2 P(x) dx = \left(-\frac{4}{3} \sqrt{4\kappa^2 - x^2 + 4}\right) - \frac{4}{3} \kappa^2 \sqrt{4\kappa^2 - x^2 + 4} - \frac{1}{6} (x^2 \sqrt{4\kappa^2 - x^2 + 4}) \quad (\text{B.3})$$

$$\int P(x) dx = -\sqrt{1 + \kappa^2 - x^2/4} \quad (\text{B.4})$$

Note that the integration limits in x (which correspond to $\theta = 0$ and $\theta = 45$) are different for $\kappa = 0.1$ and 0.5 . For $\kappa = 0.1$, $x_{\text{iso}} = 0.2$ and $x_{\text{edge}} \approx 1.43$. In the latter case, $\theta = 0$ corresponds to $x_{\text{min}} = 1$ and $\theta = 45$ to $x_{\text{edge}} \approx 1.73$: M_{BH} will be always overestimated, for every possible θ value larger than 0.

If we consider the Eddington ratio, we obtain:

$$\int P(x)/x^2 dx = -\arctan h \left(\frac{\sqrt{\kappa^2 + 1}}{\sqrt{\kappa^2 - x^2/4 + 1}} \right) / 4 \sqrt{\kappa^2 + 1} \quad (\text{B.5})$$

Eq. B.5 implies a significant effect on L/L_{Edd} for both $\kappa = 0.1$ and $\kappa = 0.5$. In the first case, the L/L_{Edd} will be overestimated by a factor ≈ 1.8 . In the second case, the L/L_{Edd} will be underestimated by a factor ≈ 2 , due to the systematic overestimation in M_{BH} .

Appendix C: Origin of scatter in scaling laws

We considered synthetic samples of ~ 10000 objects obtained from random variates with distribution $P(\theta) \propto \sin \theta$ ($0 \leq \theta \leq \pi/4$), and “true” M_{BH} uniformly distributed in the range $10^7 M_{\odot} \leq M_{\text{BH}} \leq 10^9 M_{\odot}$. The dependence on orientation of the H β FWHM is assumed to follow Eq. 9, with $\kappa = 0.1$. The effect of orientation on FWHM is such that, in a randomly oriented synthetic sample, the M_{BH} estimated from H β deviates from the true M_{BH} as in Fig. C.1 (top panel). The dispersion is ≈ 0.35 , which is comparable to the uncertainty in the scaling-law M_{BH} estimate following Vestergaard & Peterson (2006, ≈ 0.5 at 1σ confidence level).

The estimates of M_{BH} C $\nu\lambda 1549$ show a significant scatter if plotted against M_{BH} H β (Fig. 12). The origin of the scatter is in part related to orientation, in part to the outflow component. The second panel from top of Fig. C.1 shows the M_{BH} C $\nu\lambda 1549$ vs H β for a synthetic sample to which no correction has been applied. FWHM of C $\nu\lambda 1549$ and H β are expected to be related to the Keplerian velocity by Eqs. 12 and 10, respectively. The distribution of L/L_{Edd} has been assumed Gaussian, peaking at $\log L/L_{\text{Edd}} = -0.3$, and $\sigma \approx 0.5$. Typical values of ξ_{CIV} and Q are appropriate for Pop. A sources. There is a strong bias (0.5 dex) and a standard deviation of the mass ratios of ≈ 0.6 dex. In some rare instances (a combination of face-on orientation and large outflow velocity) the ratio between M_{BH} from H β and C $\nu\lambda 1549$ can reach a factor $\sim 10^2$, as actually found by Sulentic et al. (2007).

The third and fourth panels from top shows the same configuration, but after applying a correction factor ξ_{CIV} in the form $1/\xi(L, L/L_{\text{Edd}})$

$= 1/(1 + kL^a(L/L_{\text{Edd}})^b)$, with $a \approx 0.1$, $b \approx 1$ and no dependence on orientation, intended to mimic the correction actually applied to the data in Sect. 4. The orientation effect is changing the C $\nu\lambda 1549$ FWHM following Eq. 12, and therefore displacing the M_{BH} from the true mass also after correcting the FWHM. Note that the outlying blue points are due to H β underestimates of the mass by more than 0.33 dex because of low values of the viewing angle θ . On the converse, the relatively high value of Q in the simulation produces a significant fraction of M_{BH} C $\nu\lambda 1549$ with are overestimating the M_{BH} by more than 0.33 dex (red points). The dispersion is however reduced with respect to the case with no correction, with an rms ≈ 0.3 . The bottom panel is a realization of the synthetic sample for a number of sources $\lesssim 100$, comparable to the size of the FOS+HE sample, and Gaussian distribution of L/L_{Edd} as for case shown and correction in the second panel from top.

In all of these cases save the one of the second panel from top the dispersion remains ~ 0.3 , comparable to the one measured for the scaling laws of Eq. 17 and Eq. 18. It is interesting to note that, in the framework of the toy model, if $Q = 0$ the orientation-induced scatter is the same for H β and C $\nu\lambda 1549$; if $Q \approx 4$, C $\nu\lambda 1549$ becomes an almost perfect VBE, with all the scatter being due to H β , in a plot M_{BH} C $\nu\lambda 1549$ vs M_{BH} H β . This results may be consistent with no strong dependence on orientation of the C $\nu\lambda 1549$ line shift in RL quasars (Runnoe et al. 2014).³

³ However, it is not clear whether the results of Runnoe et al. (2014) are applicable to radio quiet quasars: RL sources show no strong evidence of large blueshifts (Sulentic et al. 2007; Richards et al. 2011) as the disk outflow properties may be strongly affected by the powerful radio ejecta (e.g. Punsly 2010; Punsly & Zhang 2011; Sulentic et al. 2015, and references therein).

A uniform distribution of Q between 0 and 1.6, a situation more appropriate for Pop. B, was also considered. Results are similar with smaller dispersion and biases.

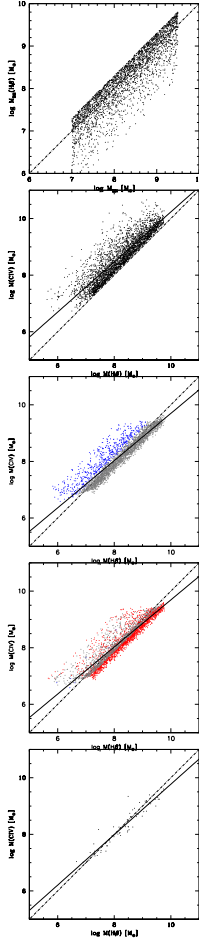


Fig. C.1. Top panel: M_{BH} with effect of orientation via Eq. 10 vs “true” M_{BH} , for a synthetic sample of 10000 sources. Second from top: M_{BH} C $\nu\lambda 1549$ vs M_{BH} H β estimated for an Eddington ratio distribution as described in the text and no correction. Third from top: The FWHM M_{BH} C $\nu\lambda 1549$ has been corrected because of outflow broadening using a correction factor ξ . The blue dots identify the M_{BH} H β estimates that are under 0.33 dex the true M_{BH} ; the red ones are for overestimates by more than 0.33 dex. The grey dots represent mass estimates within -0.33 and $+0.33$ dex from the true value. Fourth from top: same, with color coding referring to C $\nu\lambda 1549$ M_{BH} . Bottom: a synthetic sample with $n \lesssim 80$ sources, as in the FOS+HE sample. See text for more details. In all panels, the dot-dashed line is the equality line; the filled line traces an unweighted least square fit.

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