QCD Radiative Correction to Zero Recoil Sum Rules for Heavy Flavor Transitions in the Small Velocity Limit.

J.G. Körner\(^1\), K. Melnikov\(^2\) and O. Yakovlev\(^3\)*

Johannes Gutenberg-Universität
Institut für Physik, Staudingerweg 7
D-55099 Mainz, Germany

Abstract

We consider the small velocity sum rules for heavy flavour semileptonic transitions that are used to estimate the zero recoil values of semileptonic heavy flavour form factors. We analyze the complete $O(\alpha_s)$ radiative correction to these sum rules. The corrections are universal and influence all "model-independent" bounds previously derived for semileptonic form factors at zero recoil.

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1. Introduction.

An accurate determination of the Kobayashi-Maskawa matrix element $V_{cb}$ is one of the most important tasks of the heavy quark theory in the physics of heavy hadrons. As is well known there are at least two possibilities for measuring $V_{cb}$: i) to measure inclusive semileptonic decays of heavy hadrons or ii) to extrapolate differential decay distributions of exclusive semileptonic transition to the zero recoil point that gives us $|V_{cb}| f_A$. In the second method precise theoretical predictions for the values of form factor $f_A$ at zero recoil are extremely important for extracting $V_{cb}$ from experiments.

A general approach for obtaining such predictions was suggested by Shifman et al. [1,2]. It is based on recent progress in the analysis of inclusive semileptonic decays of hadrons containing one heavy quark, where the operator product expansion (OPE) method and HQET were applied [3-7]. The leading order result agrees with the free b-quark decay picture. Nonperturbative corrections start to appear only at order $(\Lambda_{QCD} M_Q)^2$ and are determined by the matrix elements of only a few local operators such as the operators of the chromo-magnetic and the kinetic energy [3-7].

The procedure of Shifman et al. [1,2] consists in considering moments of spectral distributions in the small velocity (SV) limit which allows one to obtain corrections to known sum rules as well as new sum rules. A very important result of this approach is that now one has an estimate of the deviation of the value of the exclusive form factor $f_A$ from unity at zero recoil.

The aim of the present note is to analyze the $O(\alpha_S)$ corrections to the SV sum rules. Note that part of these corrections had already been incorporated in the original derivation of the sum rules. We are referring to the vertex renormalization factors $\eta_{A,V}$ which correspond to the finite renormalization of the vertices $\langle \bar{c} \gamma_\mu b \rangle$ and $\langle \bar{c} \gamma_\mu \gamma_5 b \rangle$, respectively. To the best of our knowledge these factors were first introduced in [3]. However, we would like to emphasize that the vertex renormalization factors are not the whole story at the $O(\alpha_S)$ level and extra care is needed to derive correct sum rules with $O(\alpha_S)$ accuracy. The essential point here is that the diagrams with two partons in the intermediate state are also involved.

2. Derivation of SV sum rules.

Let us begin with the forward scattering amplitude:

$$T_{\mu\nu}(qv) = -i \int dx e^{-iqx} < H_b | j_\mu(x)^* j_\nu(0) | H_b > \tag{1}$$

Here $j_\nu$ is the appropriate current and $v$ is the velocity of the heavy hadron $H_b$. The function $T(qv)$ is an analytic function in the $(qv)$- complex plane with the appropriate cuts. The structure of the $T_{\mu\nu}$ cuts is shown in Fig.1. The cut $0 \leq qv \leq M_{H_b} - M_{H_c}$ corresponds to the decay of heavy hadron $H_b \rightarrow H_c + \nu l$ while the lower cut $qv < 0$ and the upper cut $qv > M_{H_b} + M_{H_c}$ represent other (crossed) physical processes. Following Ref.[1] we shall argue latter on that, using duality
concepts, the contributions from the latter "crossed" cuts to the sum rules can be neglected in as much as the theoretical and phenomenological contributions on these cuts can be equated to one another. The imaginary part of the forward scattering amplitude on the "physical cut" $0 \leq qv \leq M_{H_b} - M_{H_c}$ determines the hadronic tensor $W_{\mu\nu} = -\frac{i}{\pi} Im T_{\mu\nu}$ which in turn determines the inclusive decay width of the hadron.

Before discussing the calculation of the $O(\alpha_s)$ corrections we would like to mention that there exist two different approaches for deriving SV sum rules. One was proposed by Chay, Georgi and Grinstein (CGG approach) [4] and the other by Shifman et. al. (BSVU approach) [1]. Both approaches are based on the duality idea (global and local) but use a somewhat different language. We shall discuss them in turn.

The basis of the CGG approach is connected with the possibility to perform an analytic continuation of the forward scattering amplitude to the whole complex $(qv)$-plane and to connect the integral over the physical cut with the integral over a "large-radius" circle in the complex plane where the OPE is justified. This can be thought of as a formal statement of the assumed duality. A representative integration path $C_1$ is shown in Fig.1.

Integrating over the physical cut and equating moments of theoretical spectral functions with their phenomenological counterparts we obtain the sum rule:

$$\int_{phys.cut} d\bar{\epsilon} \bar{\epsilon}^n W_{phen}(\bar{\epsilon}) = \int d\bar{\epsilon} \bar{\epsilon}^n W_{QCD}(\bar{\epsilon}), \quad (2)$$

where $\bar{\epsilon} = qv - M_{H_b} - M_{H_c}$. The integrand on the r.h.s of these sum rules includes nonperturbative $\frac{1}{m_Q}$ power corrections as well as radiative QCD corrections which can be systematically incorporated by using standard OPE calculations.

In the second (BSVU) approach [1] one writes down a dispersion relation representation for the forward scattering amplitude

$$T(\epsilon) = \frac{1}{\pi} \int_{phys.cut} d\bar{\epsilon} \frac{Im T(\bar{\epsilon})}{\epsilon - \bar{\epsilon}}, \quad (3)$$

and expands the integrand in powers of $\frac{1}{\epsilon}$, where, in the rest frame of the initial hadron, $\epsilon = m_b - m_c - q_0$. Such an expansion is justified only for $\epsilon$-values $\epsilon >> \Lambda_{QCD}$ and $\epsilon << 2m_c$. However, in general there are excited states with large invariant mass ($\approx m_c, (m_b - m_c)$) whose contributions are not suppressed (the perturbative analogue is surely "hard" gluon emission). This means that one cannot expand the integrand of Eq.(3) in terms of powers of $\frac{1}{\epsilon}$. It is then inevitable to split the region of integration in the dispersion integral at some scale $\mu >> \Lambda_{QCD}$ and $\mu << 2m_c$. Rewriting Eq.(3) as

$$\int_{0}^{M_{H_b} - M_{H_c}} d\bar{\epsilon} \frac{W(\bar{\epsilon})}{\epsilon - \bar{\epsilon}} = \int_{0}^{\mu} d\bar{\epsilon} \frac{W(\bar{\epsilon})}{\epsilon - \bar{\epsilon}} + \int_{\mu}^{M_{H_b} - M_{H_c}} d\bar{\epsilon} \frac{W(\bar{\epsilon})}{\epsilon - \bar{\epsilon}}, \quad (4)$$

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and assuming $\epsilon >> \mu$, we can expand the first term on the r.h.s. in terms of powers of $\frac{1}{\epsilon}$ while the second term on the r.h.s. (which reflects the contribution of excited states) does not generally have a Laurent expansion for $\epsilon << \mu$. However, at this point one can invoke local duality to evaluate the second term in the r.h.s. In some sense this piece of the theoretical spectral function has to incorporate all radiative corrections coming from the hard region. In other words we apply duality to equate the integral over the region $[\mu, M_{H_b} - M_{H_c}]$ on the partonic side to the sum over excited states (with energy $E > \mu$). Thus we assume that duality is valid up to the scale $\mu << m_c$. Then doing an expansion in $\epsilon$ we obtain the result:

$$\int_0^\mu d\bar{\epsilon}(\bar{\epsilon})^n W^{\text{Phen.}}(\bar{\epsilon}) = \int_0^\mu d\bar{\epsilon}(\bar{\epsilon})^n W^{\text{QCD}}(\bar{\epsilon}).$$

(5)

We want to emphasize that $\mu$ is the scale where the excited states come into play. In this sense the $\mu$ scale is quite similar to the energy of the continuum threshold in the usual QCD/SVZ sum rules. It is well known that a particular choice for the onset of the continuum contributions affects the final result of the QCD/SVZ sum rules analysis and typically results in 20-30 percent uncertainties. This shows that some care is also needed to estimate the size of this uncertainty in the analysis of the SV sum rules.

Remember that, when calculating QCD radiative correction to the Wilson coefficients, we have to introduce yet another scale which divides the region of integration into a perturbative and a nonperturbative region. In order to distinguish these scales we shall denote latter scale as $\mu_{\text{OPe}}$ whereas we denote the duality scale discussed above by $\mu_D$. From perturbative QCD we roughly expect $\mu_{\text{OPe}} \geq 300 \text{MeV}$ whereas we take $\mu_D \sim 1 \text{GeV}$ for the duality scale. By definition the sum rules (2)-(5) cannot depend on the scale $\mu_{\text{OPe}}$. Also the SV sum rules do not depend on $\mu_D$ to leading order in $\alpha_S$ and to any arbitrary order in $\frac{1}{m_Q}$ because the spectral functions originate entirely from the resonance region. The leading order spectral function (leading in $\alpha_S$) consists of a $\delta(\epsilon)$ function and $\delta$-function derivatives. Note though that, in the next to leading order in $\alpha_S$, the spectral function starts to depend on $\mu_D$ explicitly.

Thus it is impossible to derive realistic "model-independent" bounds for the form factors: the choice of "switching on" the $\mu_D$—dependence is intrinsically model dependent. It is worth mentioning that the same problem appears in the CGG approach and is, technically, connected with the possibility to choose different integration contours in the $(q^4)$-plane, each contour $C_2$ being defined by the point where it leaves the physical cut - this is the aforementioned $\mu_D$ ambiguity (see Fig.1) in a different guise.

It is important to realize that the dependence on $\mu_D$ appears only at next to leading order in $\alpha_S$, and not at leading order as in the usual QCD/SVZ sum rules. To estimate the size of this ambiguity and thereby to understand the accuracy of the SV sum rules we have to compute QCD radiative corrections to the SV sum
rules at arbitrary values of the scale $\mu_D$.

3. Results for structure functions.
In this section we present the result of calculating QCD radiative corrections to those spectral functions that are needed for the zero velocity sum rules. The hadronic tensor $W_{\mu\nu}$ can be expanded in terms of 14 structure functions (see [4,6,8]):

$$W_{\mu\nu} = -g_{\mu\nu}W_1 + v_\mu v_\nu W_2 - i\epsilon_{\mu\nu\alpha\beta}v^\alpha q^\beta W_3 + q_\mu q_\nu W_4 + (q_\mu v_\nu + q_\nu v_\mu)W_5$$

$$-q_s[-g_{\mu\nu}W_6 + v_\mu v_\nu W_7 - i\epsilon_{\mu\nu\alpha\beta}v^\alpha q^\beta W_8 + q_\mu q_\nu W_9 + (q_\mu v_\nu + q_\nu v_\mu)W_{10}]$$

$$(s_\mu v_\nu + s_\nu v_\mu)W_{11} + (s_\mu q_\nu + s_\nu q_\mu)W_{12} + i\epsilon_{\mu\nu\alpha\beta}s^\alpha q^\beta W_{13} + i\epsilon_{\mu\nu\alpha\beta}q^\alpha s^\beta W_{14}$$

where $v$ is the velocity and $s$ is the spin of the initial hadron.

As a next step one defines diagonal helicity structure functions $W_L$ (longitudinal), $W_{TL,R}$ (transverse left,right), and $W_0$ (time-component or scalar) by contracting the hadronic tensor $W_{\mu\nu}$ with the appropriate polarization vectors $n_\nu \lambda n_\nu^* \lambda$ ($\lambda = 0, +, -, t$). (see Ref.[8] for details ).

At zero recoil one finds:

$$W_L = W_1$$

$$W_0 = -W_1 + W_2 + (qv)^2 W_4 + 2(qv)W_5$$

$$W_{TL,R} = W_1 \pm \hat{n}sW_{TS},$$

where

$$W_{TS} = (W_{13} + qvW_{14})$$

and $\hat{n}$ defines the quantization axis of the off-shell $W$-boson.

Next we calculate the zero recoil $O(\alpha_s)$ contributions to the helicity structure functions $W_0$, $W_L$ and $W_{TS}$. The generic graphs which contribute to the $O(\alpha_s)$ correction are shown in Fig.2. There are in principal several possibilities to cut the graphs in Fig.2. The difference is the number of partons in the intermediate state. The cuts with one parton in the intermediate state reproduce the vertex renormalization $\eta_{A,V}$ factors which were discussed earlier. The two-parton cuts give rise to the absorptive contributions in the range $0 \leq qv \leq m_b - m_c$. We mention that the infrared singularities cancel in the sum of the two-parton intermediate state contributions in the soft gluon limit $qv \to m_b - m_c$. This is in accord with the observation that the virtual corrections have no infrared singularity at the zero recoil point [3,10].

We first consider the correlator of two axial vector currents $j_\mu = \bar{c}\gamma_\mu \gamma_5 b$ and obtain the following zero recoil contributions:

$$W_{L}^{AA}(t) = \eta_\lambda^2 W_{L}^{Born}(t) + \frac{\alpha_s C_F}{2\pi} \frac{5t^2 + 10tx + 3x^2 + 2x + 3(t + 2x)t}{6(t + x)^3 m_b},$$

(10)
where $t = \frac{m_b - m_c - q^2}{m_b} \quad \text{and} \quad x = \frac{m_c}{m_b}$. The vertex renormalization factor in Eq.(12) reads [3]:

$$\eta_A = 1 - \frac{\alpha_s}{\pi} \left( \frac{1}{1-x} \log(x) + \frac{8}{3} \right)$$

and, for the corresponding vector current case,

$$\eta_V = 1 - \frac{\alpha_s}{\pi} \left( \frac{1}{1-x} \log(x) + 2 \right).$$

The $O(\alpha_s^0)$ Born contributions (which are state-dependent) include both the zeroth order result and the effects of non-perturbative corrections and can be found elsewhere [1,2,6-9]. Concerning the vector current case the structure functions (10)-(12) are the same except for a sign change in the fourth term of the first brackets (2x-term) in all formulas (10-12).

4. QCD Radiative corrections to SV sum rules.

Next let us discuss the $O(\alpha_s)$ corrections to the SV sum rules. As concerns sum rule applications the three helicity structure functions $W_L^{AA}, W_{TS}^{AA}$ and $W_0^{VV}$ are the most important. These are the structure functions that have nonvanishing contributions at zero recoil from the quasi-elastic contributions $B \to D, D^*$ and $\Lambda_b \to \Lambda_c$ and $\Omega_b \to \Omega_c, \Omega_c^*$. We want to discuss how these sum rules are modified when $O(\alpha_s)$ radiative corrections are taken into account.

For the "time-component" helicity structure function $W_0^{VV}$ we obtain

$$(\int_0^{\mu_{OPE}} + \int_{\mu_{OPE}}^{\mu_D}) W_0^{VV} (t) dt = \eta_V + \frac{\alpha_s C_F}{2\pi} (J_1(\mu_D) - J_1(\mu_{OPE})) + n/\text{pert}(\mu_{OPE}) \tag{15}$$

where $J_1$ is defined in the Appendix. The last term in Eq.(15) is a symbolic notation for the non-perturbative parameterization of the contribution from the soft region: $[0, \mu_{OPE}]$. Since we are mainly interested in how previously derived sum rules change when the new $O(\alpha_s)$ corrections are included the last term in Eq.(15) will not be written out explicitly in the following since these contributions have been investigated in previous papers (see Refs[1,2,8,9]). On the other hand, $\int_0^{\mu_D} W_0^{VV} dx$ is connected with the sum rule for the vector form factors, e.g. in the $\Lambda_b$ case (for form factor definitions see e.g. [8]):

$$\left| \sum_{i=1}^{3} f_i^V \right|^2 \leq \int_0^{\mu_D} W_V^{(0)} dx \tag{16}$$
Let us just for illustrative purposes assume $\mu_{\text{OPE}} \to 0$ and $\mu_D = m_b - m_c$ that corresponds to integration over whole physical cut. We then obtain:

$$|\Sigma f_V|^2 \leq \eta_V + \frac{\alpha_s C_F}{8\pi} \cdot (\log(x)(5x^2 + 2x - 1) - (x^4 + x^3 - x - 1)).$$

(17)

But integrating over resonance region $\mu_D \ll m_c$ and assuming $\mu_{\text{OPE}} \to 0$ we have

$$|\sum_{i=1}^{3} f^i_V|^2 \leq \eta_V + \frac{\alpha_s C_F}{4\pi}(x-1)^2 \frac{m^2}{m^2} + n/\text{pert}(0).$$

(18)

Now let us consider the SV sum rules more carefully and estimate their dependence on the duality scale $\mu_D$ and $\mu_{\text{OPE}}$. The basic function $J_1(\mu)$ is shown in the Fig.3. Let us emphasize that $J_1$ is small in the infrared region and hence our result for perturbative correction is not sensitive to $\mu_{\text{OPE}}$. Thus we may set $\mu_{\text{OPE}} = 0$ and forget about the $\mu_{\text{OPE}}$-dependence of operators with higher dimensions and use the known expressions for the $\eta_{V,A}$ factors [3].

In order to make reliable estimates we have to decide on the value of $\mu_D$. In principle using the CGG approach we may choose any $\mu_D$ in the interval $[\mu_{\text{OPE}}, m_b - m_c]$ based on various assumptions about the applicability of duality. Conventionally one takes $\mu_D \simeq 1 \sim 3$ GeV in QCD sum rule applications. We see from Fig.3 that the result for the QCD radiative corrections to leading operator does have a substantial dependence on $\mu_D$ in the region 1-3 GeV. The size of the effect varies from 0.5 % at $\mu_D = 1$GeV to 3. % at $\mu_D = 3$GeV, here we have used $\alpha_s = 0.3$, $m_b = 4.8$Gev, $m_c = 1.5$GeV for definiteness.

A similar situation occurs for all the other sum rules considered in the literature before. For instance, taking the external current to be axial and projecting on the longitudinal helicity function for $B \to D^*$, the radiative corrections considered here change the original inequality $|f_A|^2 \leq |\eta_A|^2 + n/\text{pert}$ derived in Refs. [1,2] to

$$|f_A|^2 \leq \eta_A + \frac{\alpha_s C_F}{2\pi} \cdot (J_2(\mu_D) - J_2(\mu_{\text{OPE}})) + n/\text{pert}(\mu_{\text{OPE}})$$

(19)

with $J_2$ from the Appendix. In the case $\mu_{\text{OPE}} \to 0$ and $\mu_D \ll m_c$ we obtain

$$|f_A|^2 \leq \eta_A + \frac{\alpha_s C_F}{4\pi}(x^2 + \frac{2}{3}x + 1) \frac{\mu^2}{m^2} + n/\text{pert}(0).$$

(20)

This result changes the prediction for the bound $f_A < 0.94$ obtained in Ref.[2]. The bound is pushed upward by 0.5% and 2. % for $\mu_D = 1$ and 3 GeV, respectively.

Note that the authors of Refs. [1,2] have used one single scale $\mu = \mu_D = \mu_{\text{OPE}}$ implicitly including considered effects to nonperturbative operators. But if this is the case one has to estimate and include the $\mu$-dependence of the nonperturbative matrix elements. This is important at $O(\alpha_s)$ accuracy since the $\mu$-dependent part of
these operators turns out to be of the order $\alpha_S(\frac{\mu}{m_c})^2 \approx \alpha_S$ at $\mu \approx m_c$. A simple way to avoid this problem is to take $\mu \ll m_c$ as it has been done in Ref.[1,2]. However, strictly speaking, this choice for the value of $\mu$ is not quite harmless as one applies duality concept up to an extremely small scale $\mu \ll m_c$ where local duality can break down (see for example Ref.[11]). Moreover, if we use the commonly accepted numerical values for $\Lambda_{QCD}$ and $m_c$ then the reliability of the strong inequality is doubtful:

$$\Lambda_{QCD} \ll \mu \ll m_c \tag{21}$$

On the other hand a numerical analysis of our formulas shows that the typical size of radiative corrections to the small velocity sum rules is of the order of 1% at $\mu = m_c$. We can regard this as an estimate of the theoretical uncertainty within the SV sum rule calculations. Phenomenologically this results in a 1 − 2% increase of the relevant bounds on the zero recoil form factors.

Applying SV sum rules techniques one can also obtain inequalities for the matrix elements of non-perturbative operators. For example for the $\Lambda_b$-case discussed in Ref.[8] the following inequality was obtained:

$$\mu_s^2 + \frac{\mu_{\pi}^2}{3} \leq 0 \tag{22}$$

Here $\mu_s^2$ stands for the expectation value of the heavy quark kinetic energy operator while $\mu_s^2$ parameterizes the $\frac{1}{m_b}$ correction for the axial vector current matrix element between $\Lambda_b$ states.

Using our previous results the inequality (21) gets changed to

$$\mu_s^2 + \frac{\mu_s^2}{3} - \frac{\alpha_s C_F}{2 \pi} m_b^2 \frac{2}{3} \left( J_3(\mu_D) - J_3(\mu_{OPE}) \right) \leq 0 \tag{23}$$

when the $O(\alpha_S)$ radiative corrections are included. The function $J_3$ is defined in the Appendix. Again at $\mu_{OPE} \to 0$ and $\mu_D \ll m_c$ we obtain

$$\mu_s^2 + \frac{\mu_s^2}{3} + \frac{\alpha_s C_F}{4 \pi} \left( 1 + \frac{2}{3} x - \frac{1}{3} x^2 \right) m_b^2 \frac{\mu_D^2}{m_c^2} \leq 0. \tag{24}$$

All terms in the last equation can be of the same order of magnitude in principle ($\mu_s^2 \approx 0.5 GeV$, last term in Eq.(24) is about $0.8(\frac{m_b}{m_c})^2$) and there are no a priori reason to discriminate between them. But then the values for $\mu_s^2$ and $\mu_{\pi}^2$ are not connected directly what is the major advantage when the radiative corrections are neglected.

5. Conclusion

To conclude, we have analysed the $O(\alpha_s)$ radiative corrections to zero recoil sum rules for semileptonic heavy hadrons form factors. Our results are universal and
shift all previously derived model-independent bounds on zero recoil form factors by 1-2 percents with obvious consequences for the extraction of $V_{cb}$ from experiment.

6. Acknowledgments When this work was completed the extended version of Ref.[1] appeared where similar questions were discussed. The results obtained in Ref.[1] are in agreement with our results. We would like to thank A.Vainshtein for clarifying conversations on the subject.

7. Appendix

In this appendix we collect our results for the $O(\alpha_s)$ QCD corrections to the leading order term in the SV sum rules. These corrections arise from the two parton intermediate states.

The QCD radiative correction to the zeroth moment of the $W_0^{VV}$ helicity structure function ($J_1(\mu) = \int_0^\mu W_0^{VV}(t)dt$) in the vector current correlator is

$$J_1(\mu) = \frac{1}{4(y+x)^2}(-2(yx + \log\left(\frac{y+x}{x}\right)(y+x)^2(5x^2 + 2x - 1) - y^2(17x^2 + 2x - 1) - 3y^4 - 12y^3x)$$

with $y = \mu/m_b$ and $x = \frac{m_c}{m_b}$. For the $W_L^{AA}$ helicity structure function the correction to zeroth moment is given by:

$$J_2(\mu) = \frac{1}{12(y+x)^2}(-2(yx + \log\left(\frac{y+x}{x}\right)(y+x)^2(7x^2 - 2x - 3) - y^2(27x^2 - 2x - 3) - 5y^4 - 20y^3x).$$

Finally for the transverse structure function $W_{TS}^{AA}$ one has

$$J_3(\mu) = \frac{1}{12(y+x)^2}(-2(yx + \log\left(\frac{y+x}{x}\right)(y+x)^2(x^2 + 2x + 3) - y^2(5x^2 + 2x + 3) - y^4 - 4y^3x).$$

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Figure captions

**Fig.1** The structure of the forward scattering cuts in the \( qv \) complex plane. \( C_1 \) and \( C_2 \) are representative integration paths.

**Fig.2** The generic graphs which contribute to the \( O(\alpha_S) \) correction.

**Fig.3** Dependence of \( J_1(\mu) \) (upper), \( J_2(\mu) \) and \( -J_3(\mu) \) (lower on r.h.s.) on \( \mu \) at \( m_b = 4.8 GeV, m_c = 1.5 GeV \).