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Measurement of the lepton energy in the decay $\bar{B} \to X \ell \bar{\nu}$ and determination of the Heavy Quark Expansion Parameters*

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Abstract

We measured two moments of the lepton momentum spectrum in $\bar{B} \to X\ell\bar{\nu}$, where $\ell = e$ or μ, for $p_\ell \geq 1.5$ GeV/c. From these we derive the Heavy Quark Expansion (HQE) parameters $\bar{\Lambda}(\overline{\rm MS}) = 0.39 \pm 0.03|_{stat} \pm 0.06|_{sys} \pm 0.12|_{th}$ GeV and $\lambda_1 = -0.25 \pm 0.02|_{stat} \pm 0.05|_{sys} \pm 0.14|_{th}$ GeV^2, through order $1/M_B^3$ in the non-perturbative expansion and $\beta_0\alpha_s^2$ in the perturbative expansion. The theoretical expression needed to extract $|V_{cb}|$ from the measured semileptonic width is evaluated using these HQE parameters. Combined with the world average of the semileptonic width, we find $|V_{cb}| = (40.8 \pm 0.5|_{\Gamma_{sl}} \pm 0.4|_{(\lambda_1,\bar{\Lambda})_{exp}} \pm 0.9|_{th}) \times 10^{-3}$. Finally, the short range b-quark mass m_b^{1S} is evaluated and found to be $4.82 \pm 0.07|_{\exp} \pm 0.11|_{th}$ GeV/c^2.

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I. INTRODUCTION

Experimental data on inclusive B meson semileptonic widths have reached great precision [1]. In order to use these data to determine the Cabibbo-Kobayashi-Maskawa (CKM) parameter $|V_{cb}|$, we need a theoretical evaluation of the hadronic effects for this process. We can make use of theoretical expressions for the differential rate $d\Gamma_{sl}/dE_\ell$ in terms of $|V_{cb}|$. The heavy quark expansion [2–5] is a QCD-based approach that casts perturbative and non-perturbative corrections to the partonic width as power series expansions. An underlying assumption of this approach is quark-hadron duality.

It is important to assess the uncertainty introduced by possible duality violations quantitatively, in order to achieve a full understanding of the theoretical errors and be able to ascertain the true uncertainty on $|V_{cb}|$.

The theoretical expression for the inclusive semileptonic width for $\bar{B} \to X\ell\bar{\nu}$ ($\ell = \mu$ or e) through $\mathcal{O}(1/M_B^3)$ in the non-perturbative expansion and $\beta_0(\frac{\alpha_s}{\pi})^2$ in the perturbative one is given by [4, 6]

$$\begin{aligned}
\Gamma_{sl} \; = \; & \frac{{G_F}^2 |\mathrm{V}_{cb}|^2 {M_B}^5}{192\pi^3}\, 0.3689 \left[1 - 1.54\frac{\alpha_s}{\pi} - 1.43\beta_0 \left(\frac{\alpha_s}{\pi}\right)^2 \right. \\
& -1.648\frac{\bar{\Lambda}}{M_B}\left(1 - 0.87\frac{\alpha_s}{\pi}\right) - 0.946\left(\frac{\bar{\Lambda}}{M_B}\right)^2 - 3.185\frac{\lambda_1}{{M_B}^2} + 0.02\frac{\lambda_2}{{M_B}^2} \\
& -0.298\left(\frac{\bar{\Lambda}}{M_B}\right)^3 - 3.28\frac{\lambda_1\bar{\Lambda}}{{M_B}^3} + 10.47\frac{\lambda_2\bar{\Lambda}}{{M_B}^3} - 6.153\frac{\rho_1}{{M_B}^3} + 7.482\frac{\rho_2}{{M_B}^3} \\
& \left. -7.4\frac{\tau_1}{{M_B}^3} + 1.491\frac{\tau_2}{{M_B}^3} - 10.41\frac{\tau_3}{{M_B}^3} - 7.482\frac{\tau_4}{{M_B}^3} + \mathcal{O}\left(\frac{1}{{M_B}^4}\right)\right]. \qquad (1)
\end{aligned}$$

The parameter λ_1 [2, 3] is related to the average kinetic energy of the b quark inside the B meson:

$$\lambda_1 = \frac{1}{2M_B}\left\langle B(v)|\bar{h_v}(iD)^2 h_v|B(v)\right\rangle . \qquad (2)$$

The parameter λ_2 [2, 3] is the expectation value of the leading operator that breaks the heavy quark spin symmetry. It is formally defined as

$$\lambda_2 = \frac{-1}{2M_B}\left\langle B(v)|\bar{h_v}\frac{g}{2}\cdot\sigma^{\mu\nu}G_{\mu\nu}h_v|B(v)\right\rangle , \qquad (3)$$

where h_v is the heavy quark field, and $|B(v)\rangle$ is the B meson state. It is determined from the $B^\star - B$ mass difference to be 0.128 ± 0.010 GeV^2. $\bar{\Lambda}$ is related to the b-quark pole mass m_b [2, 3] through the expression:

$$m_b = \bar{M}_B - \bar{\Lambda} + \frac{\lambda_1}{2m_b}, \qquad (4)$$

where $\bar{M}_B$ is the spin-averaged $B^{(\star)}$ mass ($\bar{M}_B = 5.313$ GeV$/c^2$). A similar relationship holds between the c-quark mass m_c and the spin-averaged charm meson mass ($\bar{M}_D = 1.975$ GeV$/c^2$).

The shape of the lepton energy spectrum in the decays $\bar{B} \to X\ell\bar{\nu}$ can be used to measure the HQE parameters λ_1 and $\bar{\Lambda}$, through its energy moments, which are also predicted in the

Heavy Quark Expansion. We choose to study truncated moments of the lepton spectrum, with a lepton momentum cut of $p_\ell \geq 1.5$ GeV/c. This choice decreases the sensitivity of our measurement to the secondary leptons from the cascade decays ($b \to c \to s/d\ell\nu$).

The quantities that we focus on, originally suggested by Gremm *et al.* [7],[1] are

$$\mathrm{R}_0 = \frac{\int_{1.7}(d\Gamma_{sl}/dE_l)dE_l}{\int_{1.5}(d\Gamma_{sl}/dE_l)dE_l}, \text{ and} \tag{5}$$

$$\mathrm{R}_1 = \frac{\int_{1.5} E_l(d\Gamma_{sl}/dE_l)dE_l}{\int_{1.5}(d\Gamma_{sl}/dE_l)dE_l}. \tag{6}$$

The theoretical expressions for these moments R^{th} [4, 8] are evaluated by integrating over the lepton energy in the decay $b \to c\ell\bar{\nu}$ for the dominant Γ_c component. In addition, the small contribution coming from charmless semileptonic decays $b \to u\ell\bar{\nu}$ is included in the theoretical expression by adding the integral over $d\Gamma_u/dE_\ell$ where the contribution to the moments is scaled by $|V_{ub}/V_{cb}|^2$ [7, 8].

We determine these two moments from the measured lepton spectrum in $\bar{B} \to X\ell\bar{\nu}$ and insert them in the theoretical expressions to determine the two parameters λ_1 and $\bar{\Lambda}$. Previous experimental determinations of $\bar{\Lambda}$ and λ_1 have been obtained by studying the E_γ spectrum in $b \to s\gamma$ [9] and the first moment of the mass M_X of the hadronic system recoiling against the $\ell\nu$ pair in $\bar{B} \to X\ell\bar{\nu}$ decays [10]. We will summarize the present knowledge on these parameters and the implications for $|V_{cb}|$.

In recent years, increasing attention has been focused on "short-range masses," preferred by some authors as they are not affected by renormalon ambiguities [11]. In particular, theoretical determinations of the so-called b-quark mass in the $1S$ renormalization scheme, $m_b^{1\mathrm{S}}$, based on extractions from $\Upsilon(1\mathrm{S})$ resonance data are quoted with impressive theoretical accuracy [12]. Using the formalism developed by C. Bauer and M. Trott [8], we have used semileptonic energy moments to extract $m_b^{1\mathrm{S}}$.

II. EXPERIMENTAL METHOD

The data sample used in this study was collected with the CLEO II detector [13] at the Cornell e^+e^- collider (CESR). It consists of an integrated luminosity of 3.14 fb^{-1} at the $\Upsilon(4\mathrm{S})$ energy, corresponding to a sample of 3.3×10^6 $B\bar{B}$ events. The continuum background is studied with a sample of 1.61 fb^{-1} collected at an energy about 60 MeV below the resonance.

We measure the momentum spectrum of electrons and muons with a minimum momentum requirement of 1.5 GeV/c. This momentum cut serves two purposes. First, it ensures that we can take advantage of good particle identification criteria for both lepton species. Having both lepton species allows us to check crucial systematic effects by examining the μ/e ratio. In addition, in this range the inclusive spectra are dominated by the direct $b \to c\ell\nu$ semileptonic decay, rather than by secondary leptons produced in the decay chain $b \to c \to s\ell\nu$.

Electrons are identified with a likelihood method that includes several discriminating variables, most importantly the ratio E/p of the energy deposited in the electromagnetic calorimeter to the reconstructed momentum, and the specific ionization in the central drift

[1] Our notation is different than what is used in Ref. [7], where R_0 is first introduced as R_2.

chamber. Muon candidates are required to penetrate at least five nuclear interaction lengths of absorber material. We use the central part of the detector ($|\cos\theta| \leq 0.71$ for electrons and $|\cos\theta| \leq 0.61$ for muons).

The overall efficiency is the product of three factors: the reconstruction efficiency, including event selection criteria and acceptance corrections; the tracking efficiency; and the μ or e identification efficiency. The first two factors are close to 1 and estimated from Monte Carlo simulations and checked with data, whereas the lepton identification efficiencies are studied with data: radiative μ-pair events for the μ efficiency and radiative Bhabha electron tracks embedded in hadronic events for the e efficiency. The e identification efficiency is rather constant in our momentum range and equal to $93.8 \pm 2.6\%$. The μ momentum threshold is near our low momentum cut, but the efficiency rises to a plateau of about 95% above 2.0 GeV/c.

Figure 1 shows the raw yields for electrons (top) and muons (bottom) from the $\Upsilon(4S)$ and the scaled continuum background. The scaling factor for the continuum sample is determined by the ratio of integrated luminosities and continuum cross sections and is 1.930 ± 0.013. This scale factor has been determined independently using high statistics samples of tracks with momenta higher than the kinematic limit for B-meson decay products. This control sample has been used to determine the systematic errors in the measurement.

The raw yields include hadrons misidentified as leptons (fakes). This contribution is determined from data as follows. Fake rates are determined from tagged samples: π's from $K^0_S \to \pi^+\pi^-$, K's from $D^{*+} \to D^0\pi^+, D^0 \to K^-\pi^+$, and p's from $\Lambda \to p\pi^-$. Using the measured fake rates and the observed spectrum of hadronic tracks, we compute a fake contribution, which is quite small for both electrons and muons.

Several sources of real leptons must be corrected for. Leptons from J/ψ decays are vetoed by combining a candidate with another lepton of the same type and opposite sign and removing it if their invariant mass is within 3σ of the known J/ψ mass. Corrections are applied for veto inefficiency and for signal leakage into the veto window. Similar procedures are applied to electrons and positrons coming from π^0 Dalitz decays and from γ conversions.

Finally, we subtract leptons coming from ψ' decays or the secondary decays $b \to c \to s\ell\nu$ and $B \to \tau \to \ell\nu\bar{\nu}$ using Monte Carlo studies. Figures 2 and 3 show the individual estimated background contributions to our sample. Note that all of the backgrounds are small compared to the signal.

Our goal is a precise determination of the shape of the lepton momentum spectrum, so corrections for the distortion introduced by electroweak radiative effects are important. We use the prescription developed by D. Atwood and W. Marciano [14]. This procedure incorporates leading-log and short-distance loop corrections, and sums soft-virtual and real-photon corrections to all orders. It does not incorporate hard-photon bremsstrahlung, which mainly modifies the low energy portion of the electron spectrum, and is not used in our analysis. An independent method of studying QED radiative corrections in semileptonic decays, based on the simulation package PHOTOS [15], has been used to obtain an independent assessment of the corrections. The difference between the two methods is used to obtain the systematic error of this correction.

Finally, we use a Monte Carlo sample of signal events to derive an unfolding matrix to boost the spectra into the B-meson rest frame (B mesons typically have a momentum of ≈ 300 MeV/c in the laboratory frame). Figure 4 shows the resulting electron and muon spectra.

Our first goal is to extract the truncated moments R_0 and R_1 defined in Eqs. 5 and 6.

Using the measured spectra, we evaluate the relevant integrals and obtain the results shown in Table I, where the first error is statistical and the second is systematic in each quoted number.

	R_0^{exp}	R_1^{exp}
$e^{\pm}$	$0.6184 \pm 0.0016 \pm 0.0017$	$1.7817 \pm 0.0008 \pm 0.0010$
$\mu^{\pm}$	$0.6189 \pm 0.0023 \pm 0.0020$	$1.7802 \pm 0.0011 \pm 0.0011$
Combined	$0.6187 \pm 0.0014 \pm 0.0016$	$1.7810 \pm 0.0007 \pm 0.0009$

TABLE I: Measured truncated lepton moments for $e^{\pm}$ and $\mu^{\pm}$, and for the sum.

The dominant uncertainty for both lepton species is related to particle identification efficiency. As the moments are ratios of measured quantities, the effects of several uncertainties, which are nearly independent of the of the energy, cancel out. The overall systematic uncertainties are 0.28% for R_0^{exp} and 0.06% for R_1^{exp} for the $e^{\pm}$ sample, and 0.32% and 0.06% for the $\mu^{\pm}$ sample. These are comparable to the statistical uncertainties. Since the two moments are extracted from the same spectra, we must use the covariance matrix $V_{\alpha\beta}$ to extract the HQE parameters. Table II shows this covariance matrix for electrons and muons.

	$V_{\alpha\beta}$
Electrons	$\begin{pmatrix} 2.4 \cdot 10^{-06} & 1.1 \cdot 10^{-06} \\ 1.1 \cdot 10^{-06} & 6.7 \cdot 10^{-07} \end{pmatrix}$
Muons	$\begin{pmatrix} 5.2 \cdot 10^{-06} & 2.2 \cdot 10^{-06} \\ 2.2 \cdot 10^{-06} & 1.3 \cdot 10^{-06} \end{pmatrix}$
Combined	$\begin{pmatrix} 1.9 \cdot 10^{-06} & 8.4 \cdot 10^{-07} \\ 8.4 \cdot 10^{-07} & 5.0 \cdot 10^{-07} \end{pmatrix}$

TABLE II: Covariance matrices for the statistical errors on R_0^{exp} and R_1^{exp} moments.

III. DETERMINATION OF THE HQE PARAMETERS $\bar{\Lambda}$ AND λ_1

We can determine $\bar{\Lambda}$ and λ_1 using the published expressions for the moments R_0 and R_1 in terms of the HQE parameters [7, 8]. We use the terms describing the integral over the $b \to q\ell\bar{\nu}$ processes. These theoretical expressions include terms accounting for electroweak radiative effects and unfolding from the laboratory to the rest frame. We do not include these terms because our data are corrected for these effects. The theoretical expressions include terms through order $1/M_B^3$ in the non-perturbative expansion [2–4]. These introduce 6 additional form factors, denoted as ρ_1, ρ_2, τ_1, τ_2, τ_3, and τ_4. From dimensional arguments, they are expected to be of the order Λ_{QCD}^3 and thus they are generally assumed to be $\leq (0.5)^3$ GeV^3. In addition, ρ_1 is expected to be positive from the vacuum-saturation approximation [16]. Furthermore, as Gremm and Kapustin have noted [4], the B^*-B and $D^* - D$ mass splittings impose the constraint

$$\rho_2 - \tau_2 - \tau_4 = \frac{\kappa(m_c) M_B^2 \Delta M_B (M_D + \bar{\Lambda}) - M_D^2 \Delta M_D (m_B + \bar{\Lambda})}{M_B + \bar{\Lambda} - \kappa(m_c) \cdot (M_D + \bar{\Lambda})}, \tag{7}$$

where $\kappa(m_c) \equiv [\alpha_s(m_c)/\alpha_s(m_b)]^{(3/\beta_0)}$ and $\Delta M_{B,D}$ represents the vector-pseudoscalar meson splitting in the charm and beauty sectors.

The values of the HQE parameters and their experimental uncertainties are obtained by calculating the χ^2 from the measured moments R_0^{exp} and R_1^{exp} and the covariance matrix $\mathrm{V}_{\alpha\beta}$:

$$\chi^2 = \sum_{\alpha=0}^{\alpha=1} \sum_{\beta=0}^{\beta=1} (\mathrm{R}_\alpha^{exp} - \mathrm{R}_\alpha^{th}) \ \mathrm{V}_{\alpha\beta}^{-1} \ (\mathrm{R}_\beta^{exp} - \mathrm{R}_\beta^{th}). \tag{8}$$

In Fig. 5 we show the $\Delta\chi^2 = 1$ contours for electrons and muons corresponding to the quoted experimental uncertainties.

The theoretical uncertainties on the HQE parameters are determined by varying, with flat distributions, the input parameters within their respective errors: $|\frac{V_{ub}}{V_{cb}}| = 0.09 \pm 0.02$, $\alpha_s = 0.22 \pm 0.027$, $\lambda_2 = 0.128 \pm 0.010$ GeV^2, $\rho_1 = \frac{1}{2}(0.5)^3 \pm \frac{1}{2}(0.5)^3$ GeV^3, $\rho_2 = 0 \pm (0.5)^3$ GeV^3, $\tau_i = 0.0 \pm (0.5)^3$ GeV^3. The contour that contains 68% of the events is shown in Fig. 6. This procedure for evaluating the theoretical uncertainty from the unknown expansion parameters that enter at order $1/M_B^3$ is similar to that used by Gremm and Kapustin [4] and Bauer and Trott [8], but different from the procedure used in our analysis of hadronic mass moments [10]. The dominant theoretical uncertainty is related to the $1/M_B^3$ terms in the non-perturbative expansion discussed before.

The measured λ_1 and $\bar{\Lambda}$ are given in Table III.

	$\lambda_1(\mathrm{GeV}^2)$	$\bar{\Lambda}(\mathrm{GeV})$
Electrons	$-0.28 \pm 0.03\vert_{stat} \pm 0.06\vert_{syst} \pm 0.14\vert_{th}$	$0.41 \pm 0.04\vert_{stat} \pm 0.06\vert_{syst} \pm 0.12\vert_{th}$
Muons	$-0.22 \pm 0.04\vert_{stat} \pm 0.07\vert_{syst} \pm 0.14\vert_{th}$	$0.36 \pm 0.06\vert_{stat} \pm 0.08\vert_{syst} \pm 0.12\vert_{th}$
Combined	$-0.25 \pm 0.02\vert_{stat} \pm 0.05\vert_{syst} \pm 0.14\vert_{th}$	$0.39 \pm 0.03\vert_{stat} \pm 0.06\vert_{syst} \pm 0.12\vert_{th}$

TABLE III: Measured λ_1 and $\bar{\Lambda}$ values, including statistical, systematic, and theoretical errors.

A previous CLEO measurement used the first moment of the hadronic recoil mass [10] and the first photon energy moment from the $b \to s\gamma$ process [9]. Figure 7 shows a comparison of our results with the previously published ones. We overlay the ellipse from the electron spectrum measurements extracted using $|\frac{V_{ub}}{V_{cb}}| = 0.07$ for consistency with their assumptions. The agreement is good, although the theoretical uncertainties do not warrant a very precise comparison.

Using the expression of the full semileptonic decay width given in Eq. 1, we can extract $|\mathrm{V}_{cb}|$. We use $\Gamma_{sl}^{exp} = (0.43 \pm 0.01)\times 10^{-10}$MeV [17]. Assuming the validity of quark-hadron duality,

$$|\mathrm{V}_{cb}| = (40.8 \pm 0.5|_{\Gamma_{sl}} \pm 0.4|_{\lambda_1,\bar{\Lambda}} \pm 0.9|_{th}) \times 10^{-3}, \tag{9}$$

where the first uncertainty is from the experimental value of the semileptonic width, the second uncertainty is from the HQE parameters (λ_1 and $\bar{\Lambda}$) and the third uncertainty is the theoretical uncertainty obtained as described above.

Finally, we use the formalism of Ref. [8] to extract the short range mass of the b-quark $m_b^{1\mathrm{S}}$, defined as $m_b^{1S} \equiv \bar{M}_B - \bar{\Lambda}^{1S}(\mathrm{GeV})$. Table IV summarizes the measurement of these parameters for electrons, muons and the sum. The theoretical uncertainty is extracted using the method described above. Our result is in good agreement with a previous estimate of m_b^{1S} [12] derived from $\Upsilon(1S)$ data, $m_b^{1\mathrm{S}}= 4.69 \pm 0.03$ GeV$/c^2$.

	$\bar{\Lambda}^{1S}$(GeV)	m_b^{1S}(GeV/c^2)
Electrons	$0.52 \pm 0.04\|_{stat} \pm 0.06\|_{syst} \pm 0.11\|_{th}$	$4.79 \pm 0.07\|_{exp} \pm 0.11\|_{th}$
Muons	$0.46 \pm 0.05\|_{stat} \pm 0.08\|_{syst} \pm 0.11\|_{th}$	$4.85 \pm 0.09\|_{exp} \pm 0.11\|_{th}$
Combined	$0.49 \pm 0.03\|_{stat} \pm 0.06\|_{syst} \pm 0.11\|_{th}$	$4.82 \pm 0.07\|_{exp} \pm 0.11\|_{th}$

TABLE IV: The measured $\bar{\Lambda}^{1S}$ and m_b^{1S}. The quoted errors reflect statistical, systematic and theoretical uncertainties, respectively.

IV. CONCLUSION

We have measured the moments R_0 and R_1 of the lepton energy in $\bar{B} \to X\ell\bar{\nu}$ decays and obtained the HQE parameters $\bar{\Lambda} = 0.39 \pm 0.03|_{stat} \pm 0.06|_{syst} \pm 0.12|_{th}$ GeV and $\lambda_1 = -0.25 \pm 0.02|_{stat} \pm 0.05|_{syst} \pm 0.14|_{th}$ GeV^2. These results imply that $m_b^{pole} = 4.90 \pm 0.08|_{exp} \pm 0.13|_{th}$ GeV/c^2. The short range mass m_b^{1S} is found to be $4.82 \pm 0.07|_{exp} \pm 0.11|_{th}$ GeV/c^2. Finally, we obtain $|V_{cb}| = (40.8 \pm 0.5|_{\Gamma_{sl}} \pm 0.4|_{\lambda_1,\bar{\Lambda}} \pm 0.9|_{th}) \times 10^{-3}$.

These results are consistent with previous measurements, and thus we have no evidence for quark-hadron duality violations. A quantitative assessment of these unknown errors will be possible only when the $1/M_B^3$ uncertainties are known more precisely.

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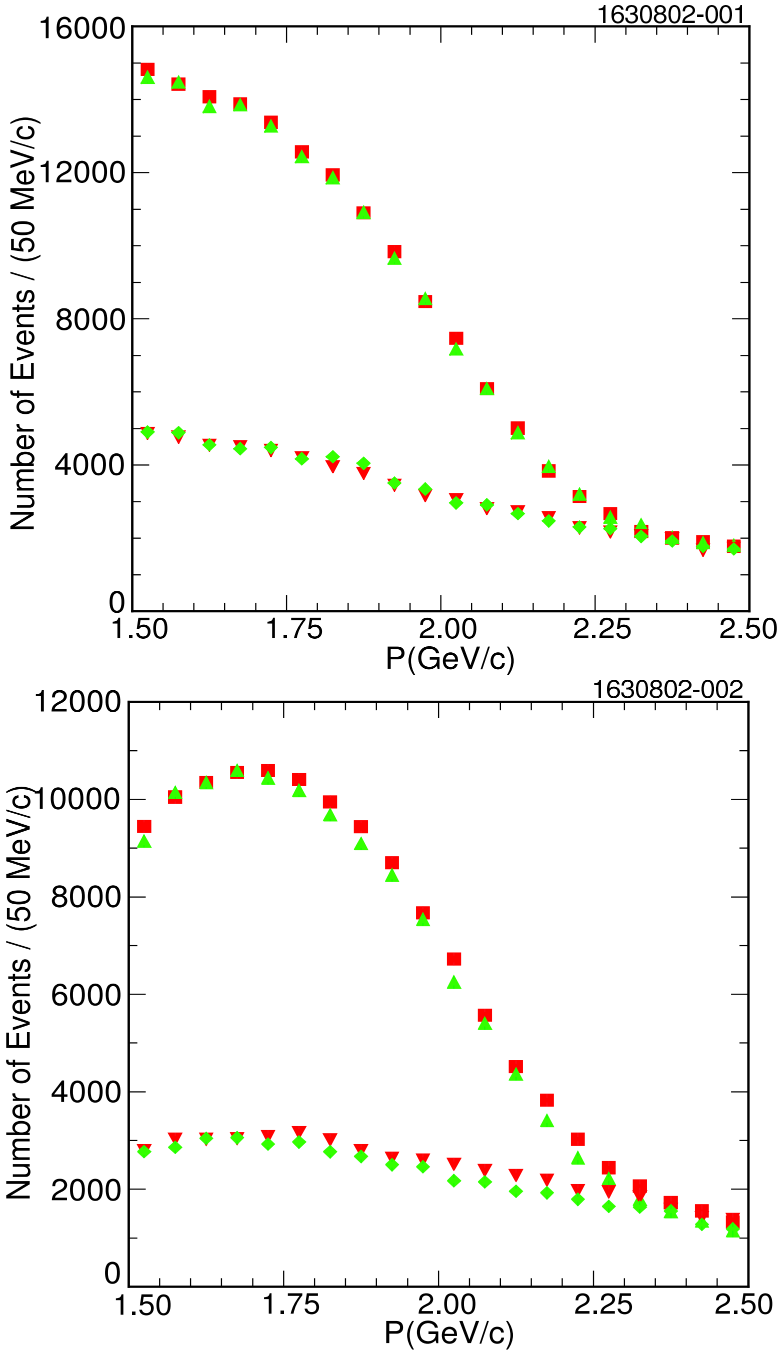

FIG. 1: Raw electron (top) and muon (bottom) spectra from $\Upsilon(4S)$ ($\blacksquare$ and $\triangle$) and scaled continuum ($\diamond$ and ∇) data. Positive (red) and negative (green) leptons are shown separately.

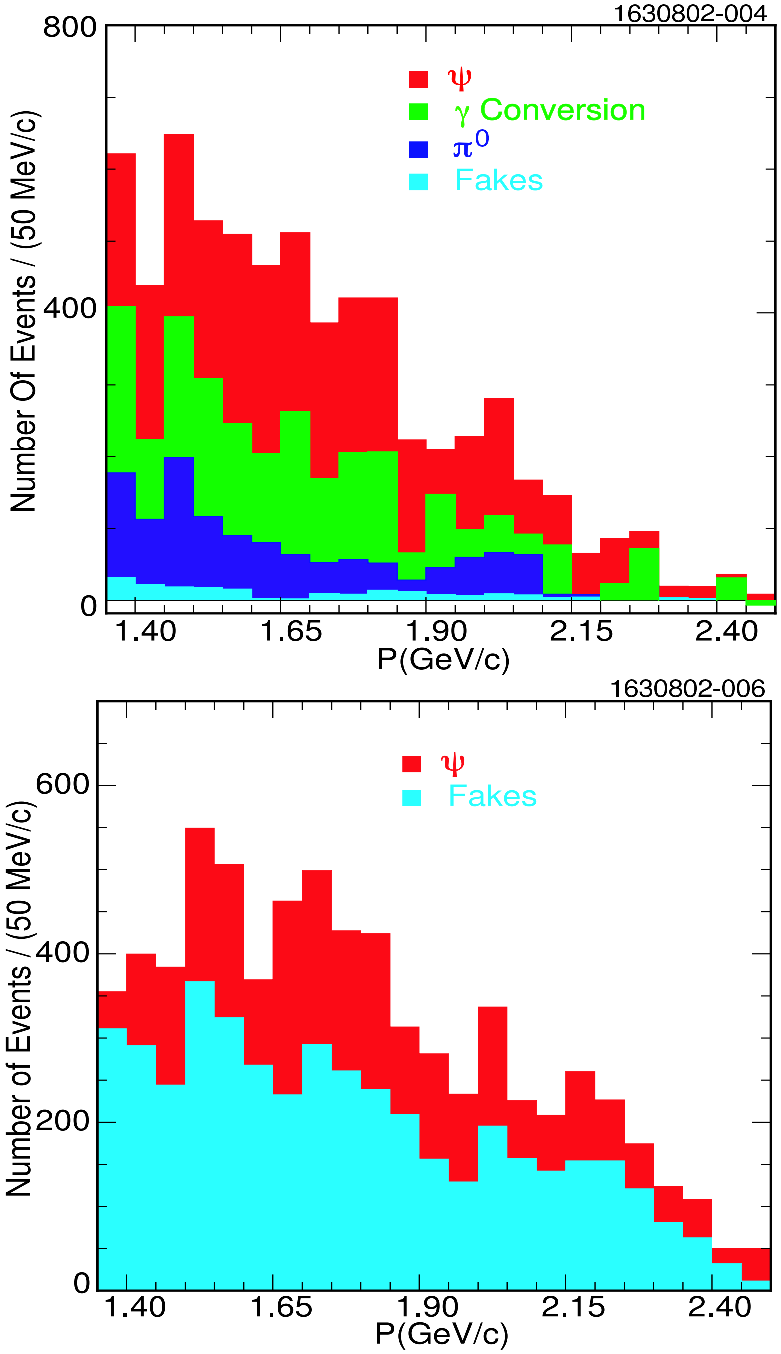

FIG. 2: Contributions to the electron (top) and muon (bottom) spectra from background processes that were estimated with data.

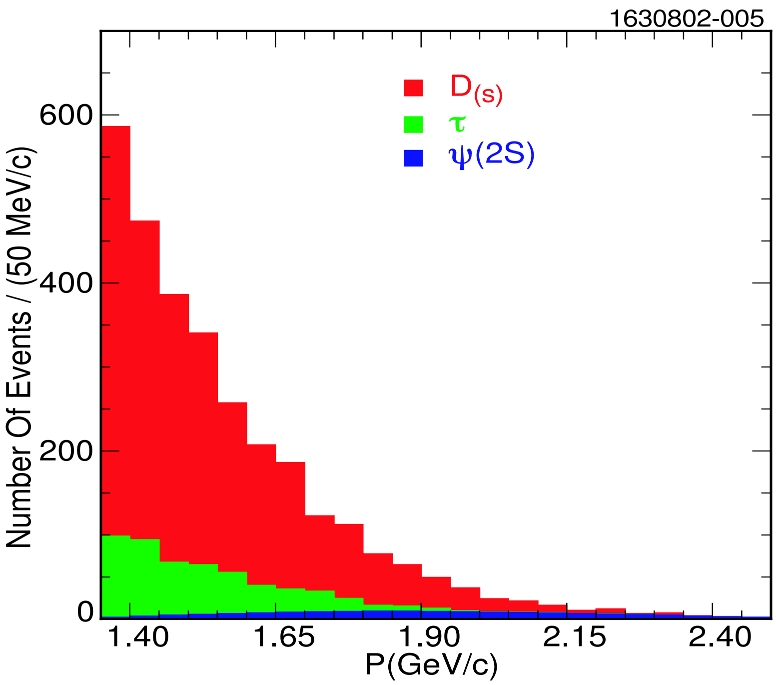

FIG. 3: Contributions to the electron spectrum from background sources that were modeled with Monte Carlo.

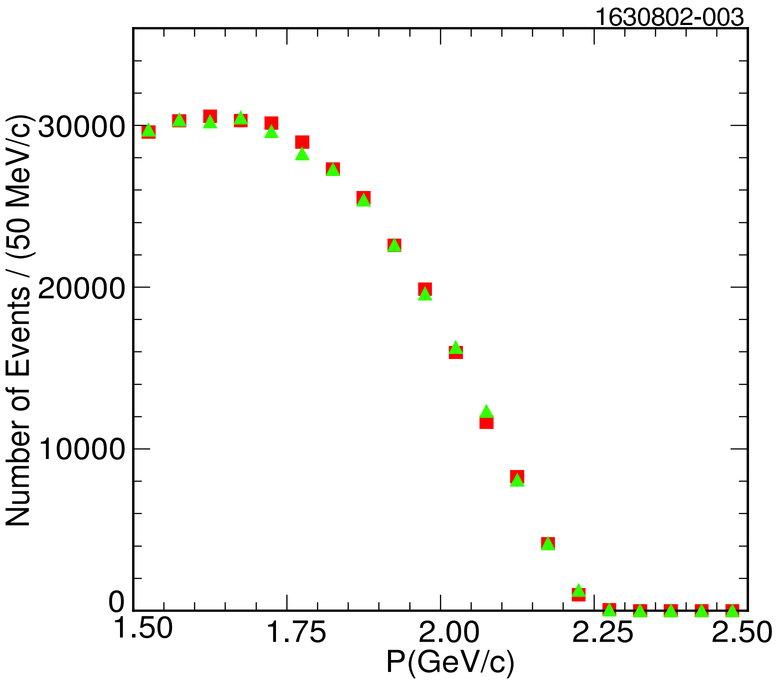

FIG. 4: Corrected electron (green △) and muon (red ■) momentum spectra in the B-meson rest frame.

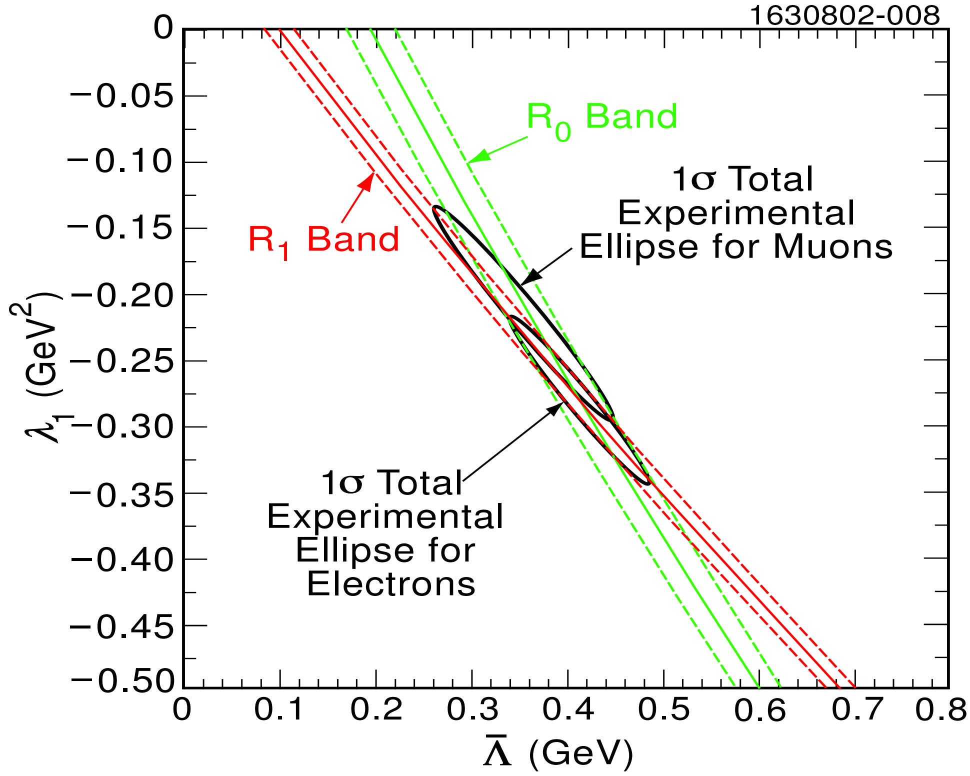

FIG. 5: Constraints on the HQE parameters λ_1 and $\bar{\Lambda}$ from our measurements of the moments R_0 and R_1. The contours represent $\Delta\chi^2 = 1$ for the combined statistical and systematic errors on the measured values. The parameters λ_1 and $\bar{\Lambda}$ are computed in the $\overline{MS}$ scheme to order $1/M_B^3$ and $\beta_0\alpha_s^2$.

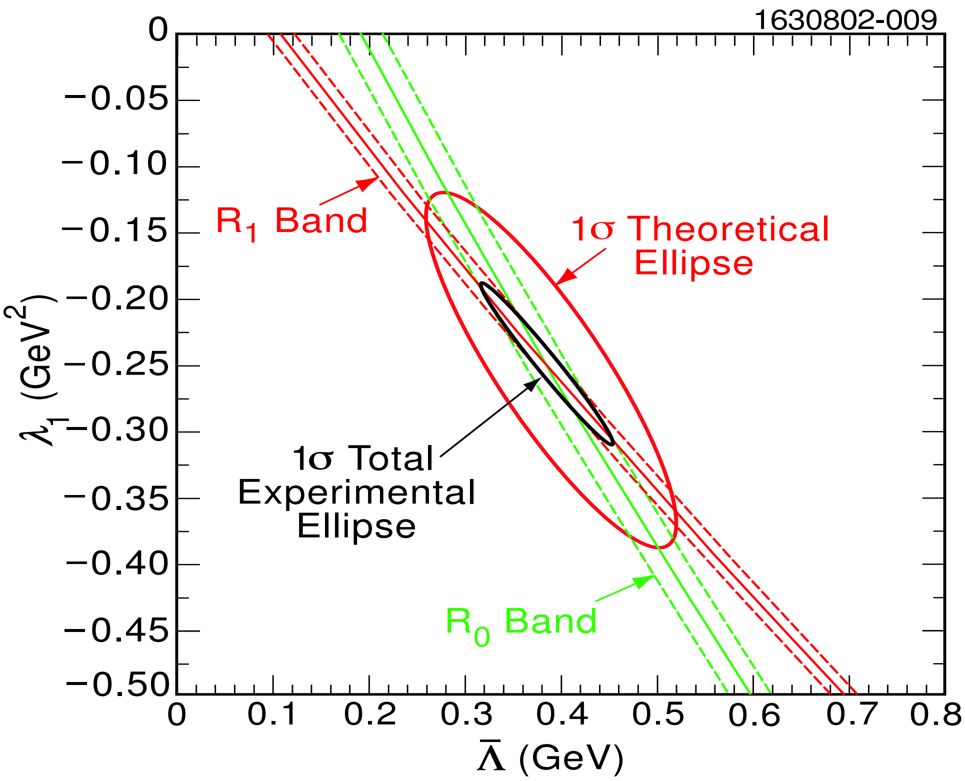

FIG. 6: The constraints from our combined electron and muon R_0 and R_1 moments, with $\Delta\chi^2 = 1$ contours for total experimental and theoretical uncertainties. The parameters λ_1 and $\bar{\Lambda}$ are computed in the $\overline{MS}$ scheme to order $1/M_B^3$ and $\beta_0\alpha_s^2$.

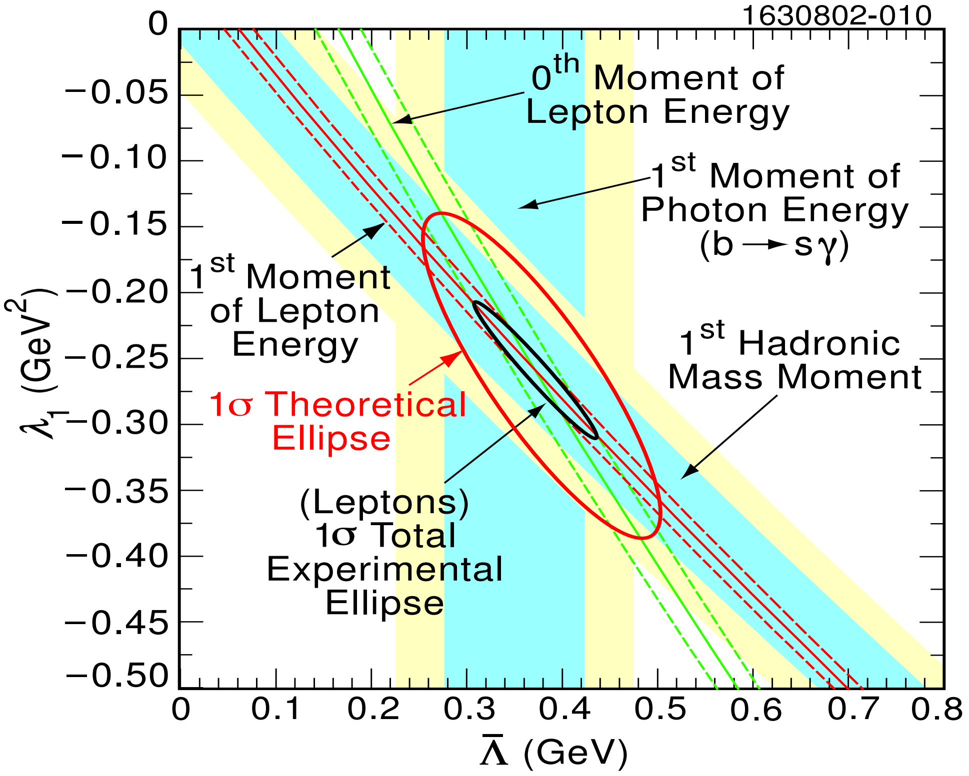

FIG. 7: Constraints from the $\bar{B} \to X_c \ell \bar{\nu}$ hadronic mass moment and $b \to s\gamma$ E_γ moment [10] compared with the combined electron and muon R_0 and R_1 constraints. The parameters λ_1 and $\bar{\Lambda}$ are computed in the $\overline{MS}$ scheme to order $1/M_B^3$ and $\beta_0 \alpha_s^2$.

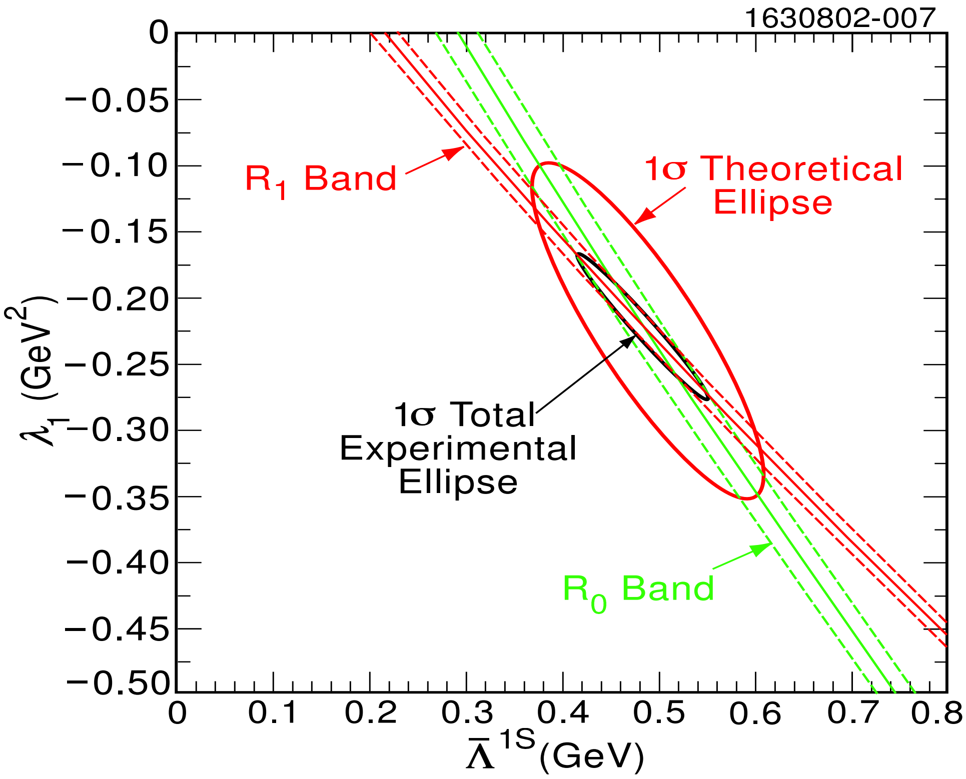

FIG. 8: The combined electron and muon R_0 and R_1 constraints, with $\Delta\chi^2 = 1$ contours for total experimental and theoretical uncertainties in the plane of λ_1 and $\bar{\Lambda}^{1S}$, according to the scheme of Ref. [8] to order $1/M_B^3$.