QCD studies in e^+e^- interactions at CLEO

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We use the CLEO detector at the Cornell e^+e^- storage ring, CESR, to study QCD from a wide variety of perspectives. From a study of jet production rates, we compute α_s in the four flavour continuum in agreement with five flavour results from LEP experiments. By comparing the decay rate of $\Upsilon \to \gamma gg$ and $\Upsilon \to ggg$ we explore parton shower distributions and measure α_s in the Υ energy range. Two-photon interactions probe QCD at lower energy scales. The measurement of the two-photon width of the χ_{c2} adds to our understanding of non-perturbative effects in charmonium systems.

1. JET PRODUCTION RATES IN FOUR FLAVOUR CONTINUUM

The QCD parameter α_s defines the strength of the quark-gluon and gluon-gluon coupling, and hence the rate and transverse energy with which gluons will be radiated. We measure the relative 2, 3, and 4 jet rates and compare them to the predictions of QCD extracting a value of α_s. Most measurements of this type have been performed at higher energies, in the five flavour regime[1]. This experiment is performed below the bare-b quark threshold enabling us to test the renormalization group equations which are used to scale α_s with energy across flavour thresholds.

Jets are defined in terms of a jet resolution variable, $y_{ij} = M_{ij}^2/E_{vis}^2$ where M_{ij} is the invariant mass of the i^{th} and j^{th} cluster and E_{vis} is the visible energy in the event. The value of y_{ij} is computed for all cluster pairs in the event. The pair (i,j) with the smallest value of y_{ij} is combined into a single cluster with momentum p_k according to some jet recombination scheme. This process is repeated until the value of y_{ij} exceeds a cut off, y_{cut}, for all remaining pairs of clusters. The number of clusters remaining defines the number of jets, as a function of the cut off, y_{cut}.

In this analysis, we explored many algorithms including the JADE and Durham algorithm in both the energy (E) and momentum (P) scheme and found that the Durham algorithm in the P-scheme was least susceptible to hadronization corrections and variations of y_{cut}. The Durham algorithm in the P-scheme is defined by $\vec{p}_k = \vec{p}_i + \vec{p}_j$, $E_k = |\vec{p}_k|$, and $M_{ij}^2 = 2E_{min}^2(1-\cos\theta_{ij})$, where E_{min} is the minimum of E_i and E_j.

Defining R_3 as the ratio of the three jet cross section σ_3 to the total hadronic cross section σ_T, it is possible to predict its value using a power series expansion in α_s.

$$R_3 = \frac{\sigma_3}{\sigma_T} \quad (1)$$

$$= C_0 \frac{\alpha_s(\mu)}{2\pi} A_3 + C_0 \left(\frac{\alpha_s(\mu)}{2\pi}\right)^2 [A_3\, 2\pi\, b_0 \ln(\frac{\mu^2}{E_{cm}^2}) + B_3] \quad (2)$$

where C_0 relates the total hadronic cross-section to the Born approximation σ_0,

$$\sigma_0 = \sigma_T/(1+\alpha_s/\pi + 1.52(\alpha_s/\pi)^2) \quad (3)$$

$$= \sigma_T C_0 \quad (4)$$

μ is the renormalization scale, $A_3(y_{cut})$ and $B_3(y_{cut}, n_f)$ are parameters determined from QCD[2] for $n_f = 4$ and will be functions of the jet resolution variable, y_{cut}. In a similar way R_4 may be defined as

$$R_4 = \frac{\sigma_4}{\sigma_T} \quad (5)$$

$$= C_0 \left[B_4 \left(\frac{\alpha_s(\mu)}{2\pi}\right)^2\right]. \quad (6)$$

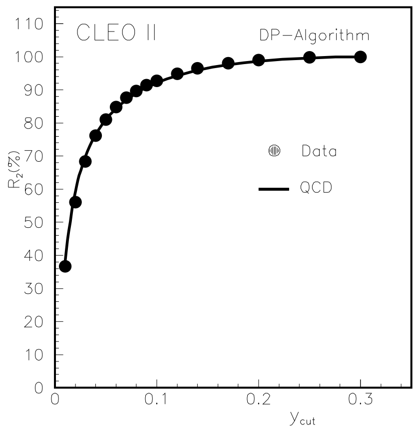

Figure 1. Two jet fraction R2 versus jet resolution variable y_{cut}. The QCD prediction is shown as a solid line.

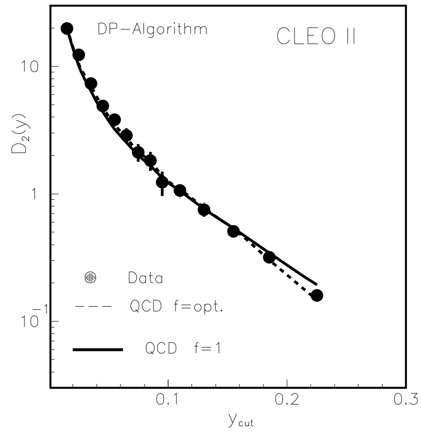

Figure 2. Differential two jet fraction D2 versus jet resolution variable y_{cut}. QCD predictions are shown with $\mu = E_{cm}$ (solid line) and μ optimised (dashed line).

The 2-jet fraction is defined as all events not recognized as 3 or 4-jet events,

$$R_2 = 1 - R_3 - R_4. \tag{7}$$

The strong coupling constant can be defined in terms of $\Lambda_{\overline{MS}}$ as

$$\alpha_s(\mu) = \frac{1}{b_0 \ln(z^2)} \left(1 - \frac{b_1}{b_0} \frac{\ln\left(\ln\left(z^2\right)\right)}{\ln\left(z^2\right)}\right) \tag{8}$$

where

$$b_0 = \frac{33 - 2n_f}{12\pi}, \tag{9}$$

$$b_1 = \frac{153 - 19n_f}{24\pi^2}, \tag{10}$$

n_f is the number of active flavours, taken to be 4, and

$$z = \frac{\mu}{\Lambda_{\overline{MS}}}. \tag{11}$$

Figure 1 shows the fraction of events which are classified as 2-jet events, as a function of the jet resolution variable, y_{cut}, while Figure 2 shows the differential 2-jet distribution where the data points are statistically uncorrelated.

The differential 2-jet distribution is defined by

$$D_2(y - \Delta y/2) = \frac{R_2(y) - R_2(y - \Delta y)}{\Delta y}. \tag{12}$$

The data is corrected to account for detector effects using the detector simulation package GEANT, and the effects of hadronization using the parton shower Monte Carlo PS, and LUND fragmentation model in JETSET. Parton shower generation in the Monte Carlo is calculated to all orders in α_s, but only Born level diagrams are considered. In both Monte Carlo and data, all charged particles are treated as pions and all neutral clusters as photons.

If QCD were solved to all orders it would be independent of renormalization scale. Since this is not the case, it is important to choose a meaningful renormalization scale, μ. We have tried two approaches. The first fixes $\mu = fE_{cm}$ at $f = 1$, and varies $\Lambda_{\overline{MS}}$ in order to fit the $D_2(y_{cut})$ distribution over the range $0.05 < y_{cut} < 0.2$. The second approach varies both μ and $\Lambda_{\overline{MS}}$ in the fit to $D_2(y_{cut})$. In figure 2 this is shown as the dashed line with f optimised. In evaluting α_s, we choose the renormalization scale where $\Lambda_{\overline{MS}}$ is the average of the two fit values. The uncertainty due to renormalization scale is given by half the difference of the two fit values of $\Lambda_{\overline{MS}}$.

From this fit, a value of

$$\alpha_s(10.53\,\mathrm{GeV}) = 0.164 \pm 0.004 \pm 0.014 \tag{13}$$

is obtained. Extrapolating to M_Z gives

$$\alpha_s(M_Z) = 0.113 \pm 0.002 \pm 0.006 \qquad (14)$$

to be compared to the LEP result from jet rate analyses[1] of

$$\alpha_s(M_Z) = 0.120 \pm 0.006. \qquad (15)$$

The uncertainties in the determination of α_s are statistical fluctuations in the number of hadronic events as well as from the detector simulation procedure (± 0.004). Additional uncertainty comes from the y_{cut} fit range (± 0.002), the hadronization model (± 0.003), parton virtuality (± 0.007), and uncertainty in the choice of renormalization scale (± 0.012).

2. $\Upsilon \rightarrow \gamma gg$

We have measured the direct photon spectrum from the decay $\Upsilon(1S) \rightarrow \gamma gg$ and compared its rate to the rate of the dominant three gluon decay $\Upsilon(1S) \rightarrow ggg$. The direct photon spectrum and the ratio of these decay widths

$$R_\gamma = \frac{\Gamma(\Upsilon(1\mathrm{S}) \rightarrow \gamma gg)}{\Gamma(\Upsilon(1\mathrm{S}) \rightarrow ggg)} = \mathcal{O}(\frac{\alpha}{\alpha_s}) \qquad (16)$$

can be predicted in perturbative QCD.

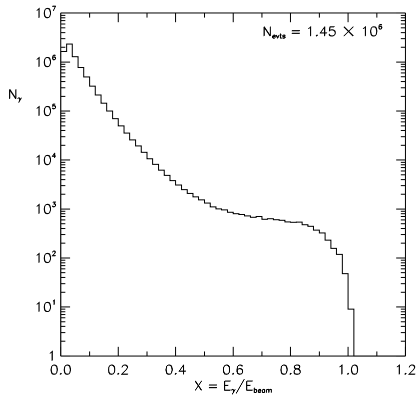

Figure 3. Inclusive photon spectrum from running at the Υ(1S) energy, in terms of the scaled photon energy.

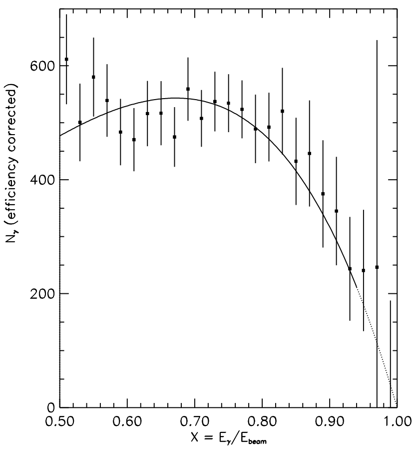

Figure 4. Background-subtracted efficiency-corrected direct photon spectrum in terms of the scaled photon energy. The smooth curve is a fit to the model of Ref. 3.

In order to obtain the direct photon spectrum from the overwhelming inclusive photon spectrum, it is necessary to subtract several components. The non-resonant component can be removed by subtracting the off-resonance spectrum scaled by beam energy and integrated luminosity. The resonant contribution to the inclusive photon spectrum is primarily from decays of π^0, ω, and η mesons. By reconstructing the mesons, and using the Monte Carlo to measure the reconstruction efficiency, we are able to subtract these secondary photons leaving only the direct photon spectrum. The inclusive and direct photon spectra are shown in Figures 3 and 4 in terms of the scaled photon energy, $x = E_\gamma/E_{beam}$.

The direct photon spectrum is corrected for detection efficiency based on our Monte Carlo simulations of the γgg decay. This efficiency is about 90% and is nearly independent of the photon energy except near the beam energy where perturbative modeling of the two gluon system is poor. The resulting background-subtracted efficiency-corrected direct photon spectrum is fit to the Field[3] model in the region $0.5 < x < 0.94$. We integrate this function over the full range to obtain the total number of direct photons in $\Upsilon(1S)$ decay.

The three gluon decays are obtained by subtracting the virtual photon and γgg decays of the Υ, as well as all non-resonant hadronic events from all hadronic decays, leaving $(9.82 \pm 0.01) \times 10^5$ three gluon events. These results give the ratio of partial decay widths as

$$R_\gamma = (2.69 \pm 0.07 \pm 0.16) \times 10^{-2}. \quad (17)$$

Treating R_γ as a power series expansion[4] in α_s and using the same renormalization scale treatment as the jet-rate analysis to derive α_s yields a value of

$$\alpha_s(M_\Upsilon) = 0.164 \pm 0.003 \pm 0.008 \pm 0.013 \quad (18)$$
$$\alpha_s(M_Z) = 0.111 \pm 0.001 \pm 0.003 \pm 0.005 \quad (19)$$

which compares very well with the jet-rate result.

3. Two-photon width of the χ_{c2}

In lowest order QCD

$$\frac{\Gamma(\chi_{c2} \to \gamma\gamma)}{\Gamma(\chi_{c2} \to gg)} = \frac{8}{9}\frac{\alpha^2}{\alpha_s^2}. \quad (20)$$

It has been customary in perturbative QCD analyses to treat the two gluon decay width of the χ_{c2} as being equal to the hadronic decay width. However, the annihilation of P-wave $q\bar{q} \to gg$ is suppressed by a factor of v^2 by the angular momentum barrier. Gluon bremsstrahlung allows the $q\bar{q} \to g(gg)$ to annihilate in an S-wave which is not suppressed by the angular momentum barrier, competing with 2-gluon decay[5]. We cannot yet calculate this soft gluon bremsstrahlung perturbatively, but it should be equal to the hadronic decay width of the χ_{c1} because χ_{c1} can decay via $g(gg)$ only, and the rate is independent of the angular momentum value J.

$$\Gamma(\chi_{c2} \to g(gg)) = \Gamma(\chi_{c1} \to hadrons) \quad (21)$$

where

$$\Gamma(\chi_{cJ} \to hadrons) = \Gamma_{\text{total}} - \Gamma(\chi_{cJ} \to \gamma\psi). \quad (22)$$

Using these expressions, and a new measurement of the two-photon width of the χ_{c2},[6] we have been able to improve our comparison with lowest order QCD.

In this analysis we observe the χ_{c2} in it decay $\chi_{c2} \to \gamma\psi \to \gamma l^+ l^-$ with $l^\pm = e$ or μ. Our excellent mass resolution for the ψ ($\sigma_M = 12$ MeV/c^2) makes for very low background, as can be seen in the Figures 5 and 6 showing the reconstructed di-lepton mass and the $\chi_{c2} - \psi$ mass difference. Remaining backgrounds are estimated by taking events from the ψ mass sidebands and creating a mass difference plot, shown as a dashed line in figure 6.

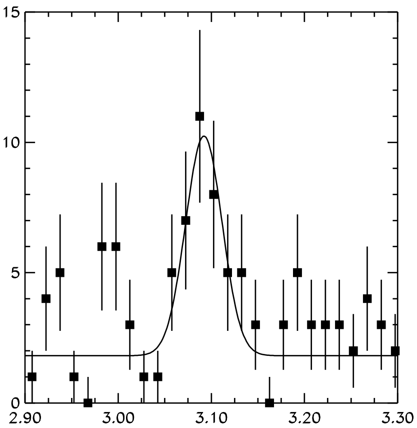

Figure 5. Mass of lepton pairs in χ_{c2} candidate events. The solid line is a fit to a constant background plus a gaussian function.

The observed excess of 25.4 ± 6.9 events above background translates into a production cross section of

$$\sigma(e^+e^- \to e^+e^-\chi_{c2}) = 5.5 \pm 1.6 \pm 1.3\,\text{pb}. \quad (23)$$

We use a two-photon Monte Carlo to extract the two-photon width by scaling the MC production cross section to equal the observed production cross section. The MC uses a ψ form factor, and assumes only helicity-2 states contribute to the cross section. This yields

$$\Gamma(\chi_{c2} \to \gamma\gamma) = 1.08 \pm 0.30 \pm 0.26\,\text{keV} \quad (24)$$

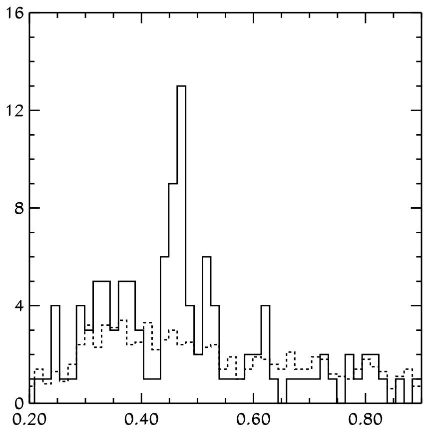

Figure 6. Mass difference between $l^+l^-\gamma$ effective mass and l^+l^- mass. The excess at 0.459 GeV is the signal of χ_{c2} production.

to be compared to the theoretical prediction of

$$\Gamma(\chi_{c2} \to \gamma\gamma)_{theory} = 0.82 \pm 0.23 \pm 0.30\,\mathrm{keV} \quad (25)$$

obtained using the Particle Data Group values for the two-gluon width calculation and a value of $\alpha_s(m_c) = 0.25$. Analysis of the complete CLEO data set will help us compare our result with the other statistically significant result of E760[7],

$$\Gamma(\chi_{c2} \to \gamma\gamma) = 0.321 \pm 0.078\,\mathrm{keV}\,(\mathrm{E760}). \quad (26)$$

4. Conclusions

CLEO has measured jet production rates in the 4-flavour regime. The shape of the relative jet rate distribution agrees with the predictions of perturbative QCD. The value of α_s measured in the CLEO jet rate analysis,

$$\alpha_s(10.53\,\mathrm{GeV}) = 0.164 \pm 0.004 \pm 0.014, \quad (27)$$

agrees with the CLEO measurement of α_s from $\Upsilon(1S) \to \gamma gg$,

$$\alpha_s(9.46\,\mathrm{GeV}) = 0.164 \pm 0.003 \pm 0.015. \quad (28)$$

The CLEO jet rate result, extrapolated up to M_Z,

$$\alpha_s(M_Z) = 0.113 \pm 0.006\ (\mathrm{CLEO\ Jet\ rates}) \quad (29)$$

also agrees with previous measurements of the same process at higher energies and 5-flavours[1],

$$\alpha_s(M_Z) = 0.120 \pm 0.006\ (\mathrm{LEP\ Jet\ rates}). \quad (30)$$

This measurement shows the validity of renormalization group equations in the scaling of QCD with energy across flavour boundaries.

CLEO has measured the relative branching ratios of Υ(1S) to γgg versus ggg. This is the most precise measurement of

$$R_\gamma = \frac{\Gamma(\Upsilon(1S) \to \gamma gg)}{\Gamma(\Upsilon(1S) \to ggg)} \quad (31)$$

$$= (2.69 \pm 0.007 \pm 0.016) \times 10^{-2}. \quad (32)$$

CLEO has measured the two-photon width of the χ_{c2},

$$\Gamma_{\gamma\gamma}(\chi_{c2}) = 1.08 \pm 0.30 \pm 0.26\,\mathrm{keV} \quad (33)$$

which tests both the perturbative and non-perturbative aspects of QCD.

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