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Q^2 Dependence of the Average Squared Transverse Energy of Jets in Deep-Inelastic Muon-Nucleon Scattering with Comparison to QCD

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Abstract

The average transverse energy squared of jets in deep-inelastic muon-nucleon scattering is measured as a function of the momentum transfer squared (Q^2), in the range $3 < Q^2 < 25\ GeV^2$. Perturbative QCD predicts that the average parton transverse energy squared will depend upon the strong coupling constant (α_S). Identifying the transverse energy of the jets with those of the corresponding partons, α_S is found to vary with Q^2 as predicted by QCD.

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In the parton model of deep–inelastic muon–nucleon scattering, a virtual photon interacts with a single quark within the nucleon. The experimental signature in the photon-nucleon center of momentum system (CMS) is a forward jet of particles resulting from the struck quark and a backwards jet coming from the remainder of the nucleon (1+1 topology). Perturbative Quantum Chromodynamic (PQCD) corrections introduce processes with two current partons (2+1 topology) with transverse energy relative to the virtual-photon direction. To first order, the average transverse energy squared of jets is directly proportional to the strong coupling constant (α_S) [1]. We present a measurement of the mean transverse energy squared of jets as a function of the four-momentum transfer squared(Q^2) of the muon scatter. On the assumption that, on average, this is a measure of the parton final state, the data indicate α_S depends on Q^2 as expected in PQCD. These results are related to recent E665 publications of the rates of jet production [2] and the dependence of the mean hadron transverse momentum squared on the total CMS energy squared of the photon–nucleon system (W^2) [3].

Experiment E665 [4] was performed in the NM beamline at Fermilab. The data for this analysis were obtained using a beam of muons with mean energy 490 GeV that struck a 1.15 m long liquid hydrogen or deuterium target. The following kinematic cuts were applied to define the event sample: $Q^2 > 3.0\ GeV^2$, $\nu = E_{beam} - E_{scat} > 40\ GeV$, where E_{beam} and E_{scat} are the incident and scattered muon laboratory-frame energies respectively, $x = Q^2/(2M\nu) > 0.003$, and $y = \nu/E_{beam} < 0.80$, $W^2 = 2M\nu - Q^2 + M^2 > 400\ GeV^2$; M is the mass of the nucleon. The average W^2 is 600 GeV^2 in each Q^2 bin. To reduce the radiative corrections, events with electromagnetic calorimeter energy $E_{cal} > 0.33\nu$, where the energy deposit occurred within 30 cm of the projected position of the incoming beam track, were removed. Charged particles reconstructed in the tracking system and associated with the interaction vertex, as well as neutral particles reconstructed in the electromagnetic calorimeter were used. To select well-reconstructed charged particles, tracks were required to have a χ^2 fit probability greater than 0.001 and fractional momentum error less than 0.05. Neutral particles were reconstructed from isolated calorimeter clusters with energy greater than 5 GeV. Clusters with tracks within 5, 7 and 10 cm in the inner, middle and outer regions of the electromagnetic calorimeter respectively were cut to remove charged-hadron induced showers. The forward spectrometer has negligible acceptance for $x_F < -0.2$ and flat acceptance for $x_F > 0.1$, where $x_F \approx 2P_L/W$ and P_L is the component of the hadron momentum along the virtual-photon direction as determined in the CMS. In contrast to ref. [2], no explicit x_F cut was applied to the particles in this analysis. In order to increase the statistical precision, data from the hydrogen and deuterium targets were combined for a total sample of 12,348 events.

As in our previous studies of jet production rates, we employ the JADE algorithm [5] to define jets. Each event is boosted to the virtual photon-nucleon CMS, and for each pair of particles (i and j) the quantity $y_{ij} = M_{ij}^2/\tilde{w}^2$ is formed, where $M_{ij}^2 = 2E_iE_j(1 - \cos\theta_{ij})$, $E_{i,j}$ are the particle energies, θ_{ij} is the angle between the particles and $\tilde{w}$ is an energy scale taken to be proportional to W. The minimum y_{ij} in the event is compared to a jet resolution parameter, y_{cut}, and if $y_{ij}^{min} < y_{cut}$, the two particles, i and j, are combined by adding their four-momenta. The procedure is repeated until y_{ij}^{min} is larger than y_{cut}, and the resulting combined particles are defined to be jets. We have assumed all charged tracks to be pions and all isolated electromagnetic clusters to be photons. To define the number of jets in the event, $y_{cut} = 0.04$ is used. The 3+1 jet events at this y_{cut} represent $< 1\%$ of the total sample consistent with theoretical predictions. The average uncorrected particle multiplicity of each jet in the [2+1] events is 4.3, with an average corrected CMS momentum per jet of 6 GeV. If one defines a cone about the jet axis containing 90% of the jet energy, in 84% of the events the cones of the two jets are separated[6].

In order to determine the transverse energy of the 2+1 jet events, the transverse momentum of each current jet is measured with respect to the virtual photon axis and scaled by the ratio of the jet energy to the total jet momentum. For a 2+1 jet event, the transverse energy ($E_{T\ 2+1}$) is defined as half the sum of the transverse energies of the current jets. This definition reduces effects from intrinsic parton transverse momentum. Based on Monte Carlo studies, contributions to jet transverse energy from fragmentation are small [6]. Finally, we define:

$$\langle \tilde{E}_T^2 \rangle = \frac{\sum_{2+1jet} E_{T\ 2+1}^2}{N_{1+1} + N_{2+1}} \tag{1}$$

where the sum is over events identified as having 2+1 jets in the final state and N_{1+1} and N_{2+1} are the number of 1+1 and 2+1 jet events. The magnitude of the average transverse energy squared will depend on the jet parameter, y_{cut}, which will be considered below.

A GEANT[7]-based Monte Carlo simulation of our detector was used to correct the data distributions for geometrical acceptance, reconstruction efficiency and resolution. The Lund Monte Carlo (LEPTO 5.2 and JETSET 6.3) [8] was used as the physics generator. Data were corrected to the level of hadron production – no correction for fragmentation was applied. Particle decays, secondary strong and electromagnetic interactions as well as a detailed simulation of the detector were included. Electromagnetic radiative corrections were applied using a procedure based on ref. [9]. This Monte Carlo was able to reproduce many aspects of the data, including the uncorrected jet rates. For the acceptance correction, the Jade algorithm was applied to the primary hadrons generated by the Monte Carlo.

The data were corrected bin by bin using the ratio of Monte Carlo before detector simulation and decays, $E_T^{2\,MC\ true}$, to the Monte Carlo with full detector simulation, $E_T^{2\,MC\ reconstructed}$. For both the data and the reconstructed Monte Carlo, the energy scale $\tilde{w} = W/2$ was used, whereas the scale $\tilde{w} = W$ was used for the true Monte Carlo sample. Thus the final results have the scale $\tilde{w} = W$. The sensitivity of the corrected results to the original choice of $\tilde{w}$ in the reconstructed distributions is weak and a 1% uncertainty is assigned to the $\langle E_{T\ 2+1}^2 \rangle$ values from this source. Less than 6% of $\langle E_{T\ 2+1}^2 \rangle$ arises from the low acceptance ($x_F < 0$) region. Based on the level of agreement of the Monte Carlo and data for the hadron multiplicity in this region, a systematic error of 1% is assigned to account for uncertainty in the $x_F < 0$ acceptance. [6]. In the data and the reconstructed Monte Carlo, all jets were identified as current jets. In the true Monte Carlo, the jet with the most negative x_F was identified as the target remnant.

The corrected $\langle E_{T\ 2+1}^2 \rangle$ and $\langle \tilde{E}_T^2 \rangle$ are shown in Figure 1. The statistical uncertainties are shown on the data points. The shaded region indicates the Q^2–dependent systematic uncertainties added in quadrature. These uncertainties are estimated to be $\leq 6\%$ due to the choice of the physics generator used in the Monte Carlo acceptance correction, $\leq 1\%$ due to the model of the efficiency of the detector, $\leq 3\%$ due to the statistical error on the generated Monte Carlo events and $\leq 2\%$ for bin migration. The Q^2–independent systematic uncertainties are estimated to be 4% due to spectrometer calibration.

The leading order PQCD prediction for the parton mean transverse energy squared, $\langle \tilde{\mathcal{E}}_T^2 \rangle$ was originally calculated in ref. [1]. Applying the JADE jet algorithm at the parton level restricts the 2+1 parton event sample to the region where the invariant mass squared of the pairs of final state partons is greater than $y_{cut}W^2$ [10]. As a result, the expression for $\langle \tilde{\mathcal{E}}_T^2 \rangle$ becomes dependent on the jet resolution parameter y_{cut}:

$$
\begin{aligned}
\langle \bar{\mathcal{E}}_T^2 \rangle &= \frac{1}{\sigma_{DIS}} \int_{m_{ij} > y_{cut} W^2} \mathcal{E}_T^2 d\sigma_{2+1}(x, Q^2, y_{cut}) \\
&= \frac{\alpha_S(Q^2)}{2\pi} \frac{Q^2 x}{F_2(x, Q^2)} \frac{1 - y + y^2/2}{1 - y + y^2/2(1 + R_{QCD})} \\
& \left\{ \int_{(1-x)y_{cut}+x}^{1-2(1-x)y_{cut}} \frac{d\eta}{\eta^2} [F_2(\eta, Q^2) p_q^T(x, \eta, y_{cut}) + (\sum_i e_i^2) \eta G(\eta, Q^2) p_G^T(x, \eta, y_{cut})] \right. \\
& + \frac{1 - y}{1 - y + y^2/2} \int_{(1-x)y_{cut}+x}^{1-2(1-x)y_{cut}} \frac{d\eta}{\eta^2} [F_2(\eta, Q^2) p_q^L(x, \eta, y_{cut}) \\
& \left. + (\sum_i e_i^2) x G(\eta, Q^2) p_G^L(x, \eta, y_{cut})] \right\}. \qquad (2)
\end{aligned}
$$

σ_{DIS} and σ_{2+1} are the cross sections for deep-inelastic scattering and 2+1 jet production, respectively. F_2, G, and R_{QCD} represent the structure function, the gluon distribution, and the ratio of the longitudinal to transverse cross sections. Processes involving gluons and quarks in the initial state ($\gamma^* G \to q\bar{q}$ and $\gamma^* q_i \to q_i G$) are indicated by the subscripts G and q. e_i is the charge of quark type i. T and L denote the transverse and longitudinal contributions. Defining $v = (1 - x)y_{cut}/(1 - \eta)$ and $z = x/\eta$, the weighting functions, p, are given by:

$$
\begin{aligned}
p_q^L(z, v) &= \frac{4}{9}(1 - z)(1 - 6v^2 + 4v^3), \\
p_G^L(z, v) &= \frac{2}{3}(1 - z)^2(1 - 6v^2 + 4v^3), \\
p_q^T(z, v) &= \frac{(1 - 2v)}{9z}[7 + 2z + 2v(1 - v)(1 + 2z - 6z^2)] - p_q^L(z, v), \\
p_G^T(z, v) &= \frac{1 - z}{3z}(1 - 2v)[1 - v(1 - v)(1 - 6z + 6z^2)] - p_G^L(z, v). \qquad (3)
\end{aligned}
$$

Eq. 2 is valid if higher order corrections are small, which will be assumed in the subsequent discussion.

On the assumption that, on average, the observed jets represent the partons, $\langle \bar{\mathcal{E}}_T^2 \rangle$ can be compared to $\langle \bar{E}_T^2 \rangle$ constructed from the data according to Eq. 1. In Fig. 1b, curves show the theoretical expectation from directly evaluating Eq. 2 at the average x of the data in each Q^2 bin, weighting according to the beam phase-space, applying the kinematic limits of the data analysis, and using $y_{cut} = 0.04$. Curves are calculated using both a running ($\Lambda^{4\ flavors}_{DIS\ NLO} = 350MeV$) and a constant α_S. The data favor the former. Figure 2 compares the y_{cut} dependence of the corrected $\langle \tilde{E}_T^2 \rangle$ with the theoretical prediction at the parton level, for $3 < Q^2 < 25\ GeV^2$. The theoretical prediction agrees with the behavior of the data for $y_{cut} \geq 0.03$, indicating that effects from fragmentation and higher order corrections are small. Eq. 2 can be recast to permit a direct evaluation of α_S from the measured $\langle \tilde{E}_T^2 \rangle$.

The evaluation of the integral at each x and Q^2 used the Morfin-Tung "B2-DIS" parton distribution [11] which agree with the experimental structure functions in the kinematic region of this analysis. It was found that if xG and F_2 were varied simultaneously by 10%, then a 7%, Q^2-independent systematic variation in the normalization of α_S was observed. A 5% Q^2–independent uncertainty was assigned for assuming $y_{cut}^{theory} = y_{cut}^{data}$. Partial calculations of the higher order contributions indicate that $O(\alpha_S)$ corrections are expected to be small, but Q^2 dependent [12, 13]. The data, shown in Fig. 3a, decrease from 0.33 to 0.22 over the range 3 to 25 GeV^2, consistent with the PQCD predictions. The data are shown in Fig 3b. in comparison with a recent summary [14] of α_S as measured in a variety of experiments.

In conclusion, we have presented measurements of the mean transverse energy squared of 2+1 jet events in deep–inelastic muon–nucleon scattering. The Q^2 dependence of the data is consistent with the running of the strong coupling constant expected from PQCD. If higher order corrections are small and the assumption that the jets represent the partons is justified, then this represents a self–contained measurement of the variation of the strong coupling constant with Q^2 from a single process in a single data set.

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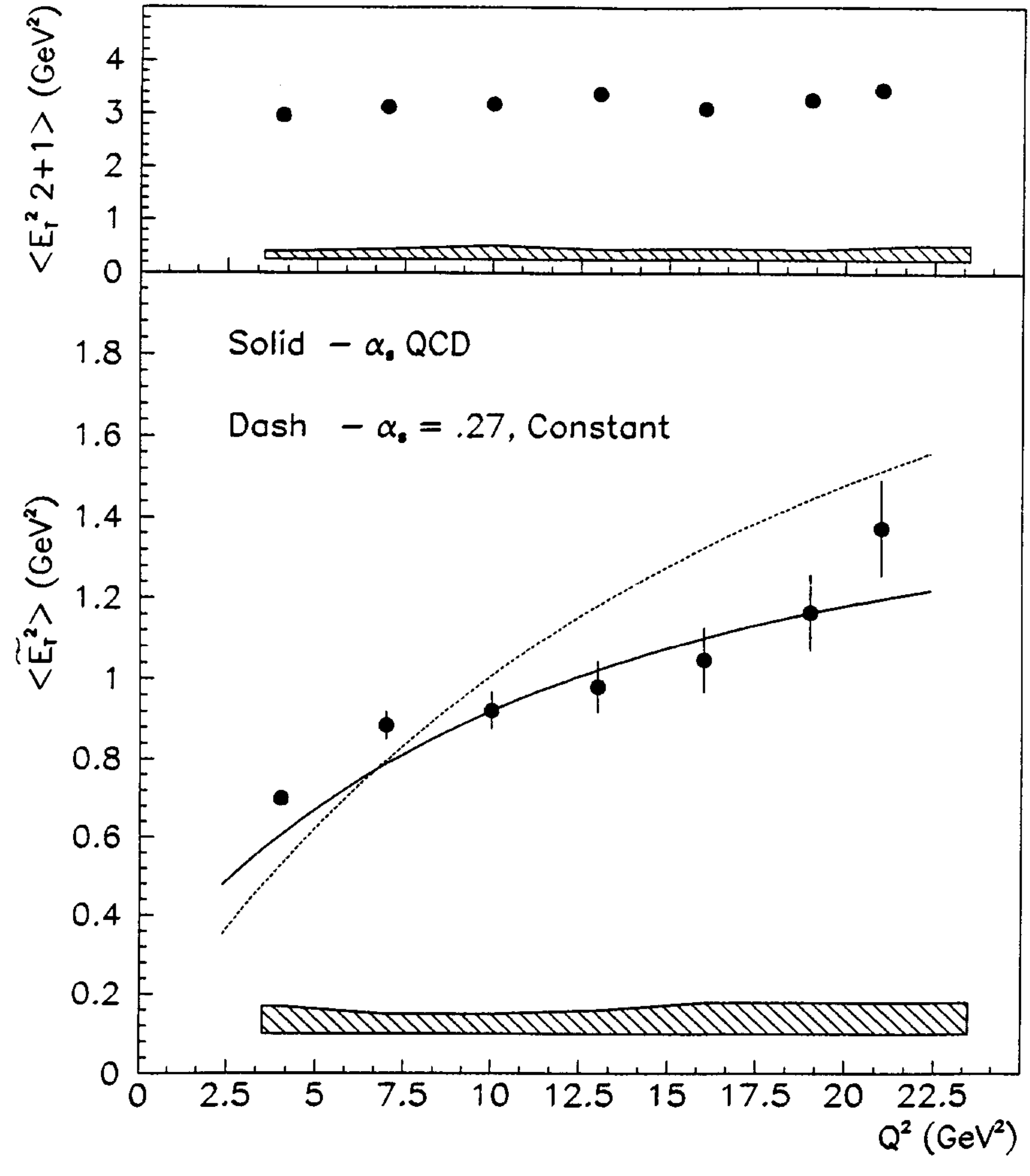

Figure 1. Average transverse energy squared vs. Q^2 with $y_{cut} = 0.04$: a) for the 2+1 jet sample, b) normalised to all events ($\langle \tilde{E}_T^2 \rangle$). The dotted curve is the calculation of $< \tilde{E}_T^2 >$ using a running α_S, the dashed curve uses a fixed α_S.

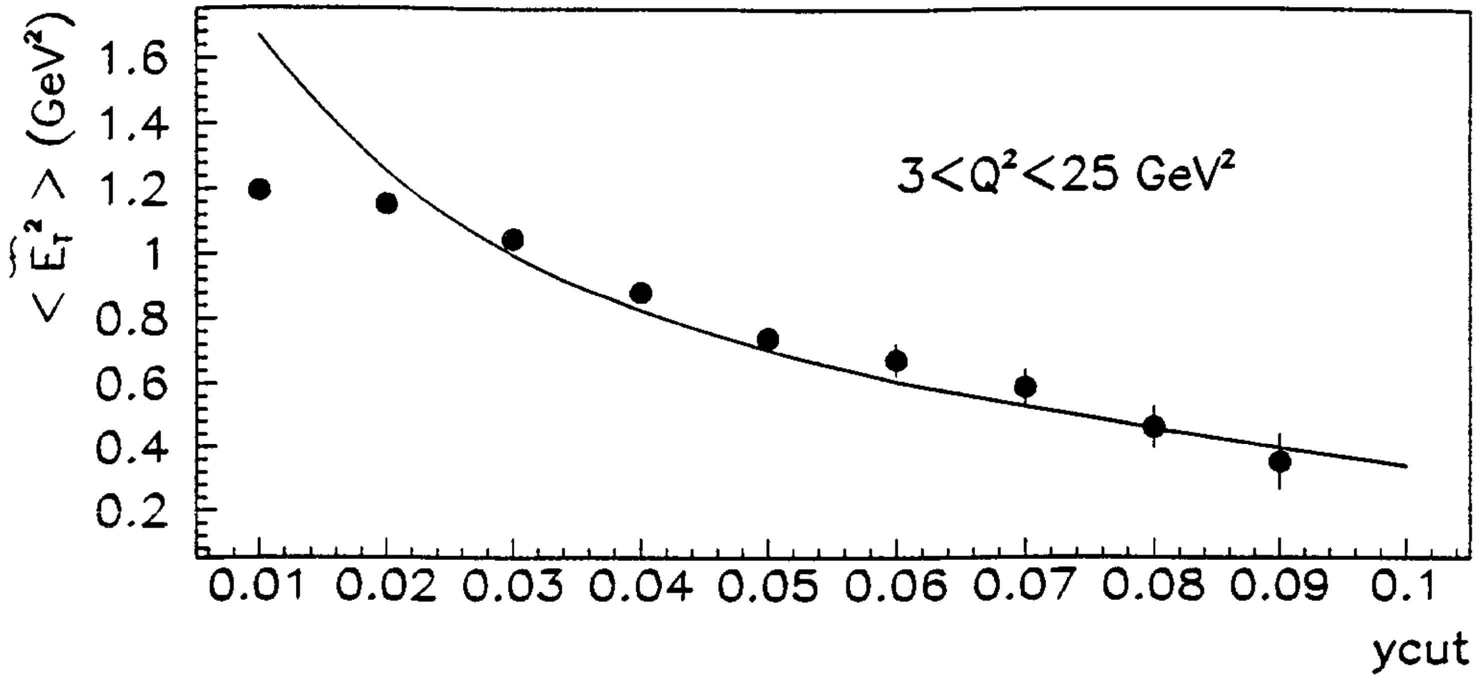

Figure 2. The y_{cut} dependence of $\langle \tilde{E}_T^2 \rangle$ for all Q^2. The curve shows the theoretically predicted dependence at the parton level.

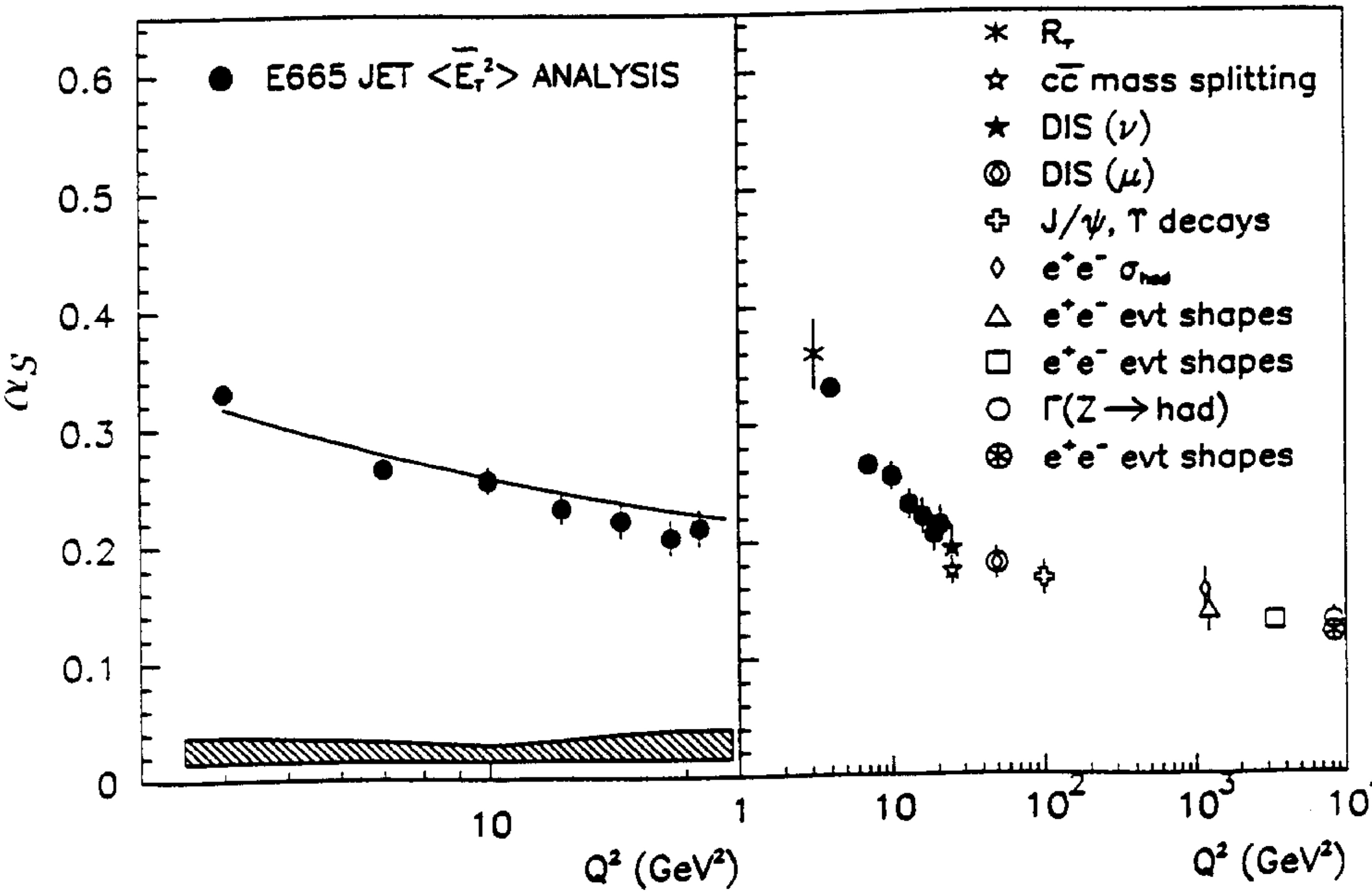

Figure 3a) $\alpha_S(Q^2)$. The points are the data; the error bars are statistical only. Q^2-dependent uncertainties are shown by the striped region. The solid curve shows a PQCD prediction for the data. 3b) The data points, $\alpha_S(Q^2)$, compared with α_S from other experiments[14].