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# Measurement of $\alpha_s$ in $e^+e^-$ Annihilation at $E_{cm} = 29$ GeV

TPC/Two-Gamma Collaboration

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## Abstract

A measurement of the strong coupling constant $\alpha_s$ using the event-shape variable $y_3$ (the differential two-jet rate) in the reaction $e^+e^- \rightarrow hadrons$ is presented. The analysis is based on data from the $TPC/Two-Gamma$ detector at the $e^+e^-$ storage ring PEP taken between 1984 and 1986 at a center-of-mass energy of $E_{cm} = 29$ GeV. A value of $\alpha_s(29\,\mathrm{GeV}) = 0.160 \pm 0.012$ is obtained, where the error is the quadratic sum of experimental and theoretical uncertainties. The procedure for determining $\alpha_s$ is the same as that used by the ALEPH and TOPAZ experiments, which allows for a consistent comparison of the $\alpha_s$ values obtained at different center-of-mass energies. The observed energy dependence (running) of $\alpha_s$ is found to be in good agreement with the QCD prediction, and is clearly incompatible with a constant value.

## 1. Introduction

Quantum Chromodynamics (QCD) has been well established in recent years as the theory of strong interactions, in which interactions of quarks and gluons (partons) are characterized by the coupling strength $\alpha_s$. Renormalization of ultraviolet divergences in QCD leads to an effective (running) coupling, which is predicted to decrease with an increasing energy scale of the process (asymptotic freedom) [3]. In electron-positron annihilation, $\alpha_s$ can be measured with e.g. distributions of event-shape variables, a recent review of which can be found in [4].

Significant progress in the theoretical predictions of event-shape distributions for the reaction $e^+e^- \rightarrow hadrons$ has been made since the end of the data taking at the PEP and PETRA $e^+e^-$ storage rings in the late 1980's. For example, the QCD prediction for the distribution of the event-shape variable $y_3$ (defined below) using the Durham jet algorithm [5, 6] has become available, and has been used by experiments at LEP and SLC [1, 7, 8] and at TRISTAN [2] to measure the strong coupling constant $\alpha_s$. In particular, the analyses carried out by the ALEPH collaboration [1] at a center-of-mass energy of $E_{cm}$ = 91.2 GeV and by TOPAZ [2] at $E_{cm}$ = 58 GeV use the same analysis technique and similar treatment of systematic uncertainties, allowing for a consistent comparison. In this note, the same analysis is carried out using data from the $TPC/Two-Gamma$ experiment at PEP ($E_{cm}$ = 29 GeV). An attempt is made to identify systematic errors common to all three of the measurements, so as to provide an accurate investigation of the energy dependence of $\alpha_s$.

In order to measure the strong coupling constant one must define an observable sensitive to hard gluon radiation, whose probability density can be computed using perturbative QCD as a function of $\alpha_s$. In this analysis the quantity $y_3$ (or equivalently $L_3 = -\ln y_3$), defined in section 2, is used to provide sensitivity to the three-jet character of an event and hence to the strong coupling of quarks and gluons. The theoretical prediction for the distribution of $L_3$ can be computed to order $O({\alpha_s}^2)$ in perturbative QCD by an appropriate integration of the second order matrix element, done numerically with the program EVENT [9]. In addition, improved predictions valid for the two-jet region (dominated by collinear gluon radiation) have recently become available, where the so-called leading logarithms are summed to all orders, and part of the next-to-leading order solution is computed as well [5]. The QCD prediction used is a combination of the fixed order and leading-log solutions. The measurement of the $L_3$ distribution is discussed in section 3.

Before the QCD prediction can be compared to the measured distribution, it must be modified for (non-perturbative) effects of hadronization. This is done with several Monte Carlo hadronization models, which first generate a system of partons according to perturbative QCD, and then convert these into hadrons by means of a phenomenological mechanism (e.g. cluster, string fragmentation). The theoretical uncertainties in the predicted $L_3$ distribution at hadron level stem both from higher order perturbative corrections as well as non-perturbative effects. The procedures for estimating these uncertainties and the corresponding error in $\alpha_s$, largely following the ALEPH [1] and TOPAZ

[2] analyses, are discussed in section 4. In section 5 the resulting value for $\alpha_s$ from the $TPC/Two-Gamma$ experiment is compared with the measurements from ALEPH and TOPAZ in order to investigate the energy dependence of the strong coupling.

## 2. Event Selection

The data were recorded from 1984-1986 with the $TPC/Two-Gamma$ detector facility [10] at the SLAC $e^+e^-$ collider PEP. The total sample has an integrated luminosity of 66 $pb^{-1}$ at an $e^+e^-$ center-of-mass energy of 29 GeV. The detector, including the central time projection chamber (TPC) for charged particle reconstruction and identification, is described in detail in reference [10]. The measurements presented here are based only on the charged particles, which are reconstructed in the TPC over a solid angle of 87% of $4\pi$ with a momentum resolution of typically $(\Delta p/p)^2 = (0.0015)^2 + (0.0065 \cdot p(GeV/c))^2$.

A detailed description of the data reconstruction and event selection is given in reference [10]. The basic selection criteria are given below, where the $z$-axis is parallel and the $xy$-plane perpendicular to the beam axis. A good charged track is required to satisfy:

- Angle with respect to $xy$-plane, $|\lambda| \leq 60°$
- $p \geq 0.15$ GeV
- Distance of closest approach to event vertex in $xy$-plane $\leq 3$ cm
- Distance of closest approach to event vertex in $z$ direction $\leq 5$ cm
- Track's curvature error, $\Delta c \leq 0.15\, GeV^{-1}$ or $\Delta c/c \leq 0.15$

Using the tracks selected in this way, the total charged energy, $E_{ch}$ (assuming the pion mass), is computed. The sphericity algorithm [11] is used to determine an event axis and its angle with respect to the $xy$-plane $\lambda_{sph}$. Using the above track requirements, multihadronic events are selected which satisfy:

- Number of good tracks $\geq 5$ (suppresses $\tau^+\tau^-$ events)
- $E_{ch} \geq 7.25$ GeV (suppresses two-photon events)
- $\lambda_{sph} \leq 45°$ (insures event well contained in detector)
- $|\sum p_z|/\sum|p| \leq 0.4$ (suppresses two-photon events)
- In at least one hemisphere, at least four non-electron tracks or an invariant mass greater than 2 GeV (suppresses $\tau^+\tau^-$ and Bhabha events)

The procedure yields a sample of 20247 hadronic events. Background levels are estimated to negligible, with 0.4% being $\tau^+\tau^-$ events and 0.5% being two-photon events [12].

## 3. Measurement of the $L_3$ distribution

The quantity $y_3$ is defined by means of the following algorithm. For each pair of particles in an event $i$ and $j$, one computes

$$y_{ij} = \frac{2\min(E_i^2, E_j^2)(1 - \cos\theta_{ij})}{E_{vis}^2}\,, \tag{1}$$

where $E_i$ and $E_j$ are the energies of particles $i$ and $j$, $\theta_{ij}$ is their opening angle, and $E_{vis}$ is the total visible energy in the event. (If the algorithm is being applied to events in a Monte Carlo model in which all of the particles are available, or in a theoretical calculation, then $E_{vis}$ is simply the center-of-mass energy $E_{cm}$.) One finds the pair of particles with the smallest $y_{ij}$ and replaces them by a pseudo-particle or *cluster*. The four momentum of the new cluster is given by the sum of the four momenta of particles $i$ and $j$ (the so-called E recombination scheme). This procedure is repeated until three clusters remain. The smallest value of $y_{ij}$ in the three-cluster configuration is then $y_3$. In applying the clustering algorithm with equation (1), the energy of the charged tracks (computed assuming the pion rest mass) is used for the visible energy $E_{vis}$.

The measured distribution for the equivalent variable $L_3 = -\ln y_3$ is corrected for effects of geometrical acceptance, detector efficiency and resolution, decays, secondary interactions and initial state photon radiation by the following procedure. A first set of hadronic events with flavor composition as predicted by the Standard Model was generated using the JETSET Parton-Shower (PS) model [13] including initial state photon radiation. The events were passed through the detector simulation program to produce simulated raw data, which were then processed through the same reconstruction and analysis chain as the real data. A second set of Monte Carlo data without detector simulation was generated, in which all particles with mean lifetimes less than 1 ns were required to decay, the others were treated as stable, and initial state radiation was turned off. These two data sets were used to derive bin-by-bin multiplicative correction factors for the measured quantities. The corrected value $f_i^{corr}$ for bin $i$ is obtained from the measured distribution $f_i^{meas}$ by

$$f_i^{corr} = f_i^{meas} \cdot C_i \tag{2}$$

where the correction factor $C_i$ is

$$C_i = \frac{f_i^{MC\ generator\ only}}{f_i^{MC\ gen.+detector\ sim.}}\,. \tag{3}$$

This procedure corrects the measurements back to a fixed center-of-mass energy (free of initial state radiation) and a well defined final state particle composition that can be compared directly to theoretical predictions. The correction factors, typically in the range $0.8 \leq C \leq 1.4$, are shown for the $L_3$ distribution in Fig. 1. Based on the size of the experimental correction factors it was decided to require $L_3 > 1.6$ in the determination of $\alpha_s$.

Also shown in Fig. 1 are "simplified" correction factors computed with various Monte Carlo generators without a full detector simulation. Instead only charged particles which passed the geometrical cut $|\lambda| < 60°$ and the momentum cut $p > 0.15$ GeV were accepted. The simulated momenta of the tracks were smeared according to a Gaussian resolution function with a width $(\sigma_p/p)^2 = (0.0015)^2 + (0.0065 \cdot p(GeV/c))^2$. From these simulated data sets one obtains simplified corrections:

$$C_i^{simp} = \frac{f_i^{MC\ generator\ only\ (all\ particles)}}{f_i^{MC\ gen. + cuts + p\ smearing(charged\ particles\ only)}} \ . \tag{4}$$

The simplified correction factor for the JETSET simulation, shown in Fig. 1, is in reasonably good agreement with that obtained from the full detector simulation indicating that the detector effects are dominated by the geometrical and momentum cuts. Since this does not require the full detector simulation, the simplified corrections can be easily computed for a variety of models. The relative spread in the simplified factors from model to model is a measure of the systematic uncertainty from generator dependence. In order to propagate the uncertainty in the $L_3$ distribution into an error for $\alpha_s$, alternative versions of the corrected $L_3$ distribution were computed according to the formula,

$$f_i^{alt(MC)} = f_i^{corr} \cdot \frac{C_i^{simp(MC)}}{C_i^{simp(JETSET)}} \tag{5}$$

$$= f_i^{meas} \cdot C_i \cdot \frac{C_i^{simp(MC)}}{C_i^{simp(JETSET)}} \ , \tag{6}$$

where $C_i$ is the correction factor using the full detector simulation according to equation (3), which is based on the JETSET PS model, and $C_i^{simp(MC)}$ is computed with the models HERWIG [15], ARIADNE [16], NLLjet [18], and COJETS [17]. The alternative distributions were then used in the fitting procedure for $\alpha_s$ as described in section 4 below, and the maximum difference between the resulting $\alpha_s$ values was included in the systematic uncertainty. Since the various models include different fragmentation schemes, the resulting error estimate includes the uncertainty arising from the correction for neutral particles, for which one relies on the Monte Carlo model. Fig. 2 shows the corrected $L_3$ distribution compared to the predictions of several hadronization models. The models are quite consistent with the measured distribution.

Additional systematic uncertainties in the measured distribution were investigated by varying all of the track and event selection criteria listed above, redetermining the corrected $L_3$ distribution and repeating the fit procedure for $\alpha_s$. In addition it was checked that the contribution to the correction factors from effects of initial state photon radiation (ISR) are small (less than several percent) in the region of the distribution used to determine $\alpha_s$. This is important when comparing the results of this analysis with that from ALEPH, where the effects of ISR are greatly suppressed, since a systematic error in their correction at $E_{cm} = 29$ GeV would not be common to the result from $E_{cm} = 91.2$ GeV.

## 4. Fitting procedure for $\alpha_s$

The interval of the $L_3$ distribution used for determining $\alpha_s$ was restricted to a region where non-perturbative (hadronization) effects are expected to be small. This was determined by examining the hadron and parton level $L_3$ distributions from a number of parton shower based Monte Carlo models: JETSET PS (with and without an $O(\alpha_s)$ correction for the first gluon emission), HERWIG, ARIADNE and NLLjet. The parameters of these models were tuned using data from the ALEPH experiment at a center-of-mass energy of $E_{cm} = 91.2$ GeV, where they were found to provide a good description of the data [14]. As can be seen in Fig. 2, the models also provide a good description of the $L_3$ distribution at $E_{cm} = 29$ GeV with the same model parameters, with some discrepancies visible for $L_3 > 4$. (Note that high $L_3$ or equivalently low $y_3$ corresponds to a more two-jet like configuration; see equation (1).) This agreement (at least in the three-jet region) allows for a consistent measurement of the energy dependence of $\alpha_s$, without requiring a separate tuning of the model parameters at each energy. This procedure would not be possible with models based on $O(\alpha_s{}^2)$ matrix elements, which have be found to not describe the energy dependence of the experimental data (see e.g. [14]).

Fig. 3 shows the ratio of parton to hadron level $L_3$ distributions from the above mentioned models. The ratios are all close to each other for $L_3 < 2.8$, so that in this range one expects the smallest uncertainty in $\alpha_s$ from hadronization effects. Based on these ratios and taking into consideration the detector correction factors, the range $1.6 < L_3 < 2.8$ was chosen for the determination of $\alpha_s$.

Initially, several other event-shape variables such as thrust and heavy jet-mass were also investigated for purposes of determining $\alpha_s$. From the ratios of hadron to parton level distributions it was found, however, that the uncertainty arising from hadronization effects was significantly smaller for the $L_3$ distribution, for which no published measurements were available at PEP/PETRA energies.

In fitting, the parameter $\alpha_s$ is determined by minimizing the quantity

$$\chi^2 = \sum_{i=1}^{n} \frac{(f_i^{corr} - \sum_j P_{ij} f_j^{QCD}(\alpha_s, \mu^2/s))^2}{\sigma_i^2}\ , \tag{7}$$

where $f_i^{corr}$ is the corrected measurement in bin $i$ (as given by equation (2)), $\sigma_i$ is the corresponding statistical error, $f_j^{QCD}(\alpha_s\, \mu^2/s)$ is the QCD parton level prediction for the $L_3$ distribution integrated over bin $j$, and $P_{ij}$ is a matrix of hadronization correction factors based on one of the Monte Carlo hadronization models mentioned above. The hadronization correction matrix $P_{ij}$ gives the probability that an event with $L_3$ in bin $j$ at parton level obtains a $L_3$ value in bin $i$ after hadronization. This is combined with the parton level prediction $f_j^{QCD}(\alpha_s, \mu^2/s)$, where the sum over $j$ in equation (7) covers the entire $L_3$ range, resulting in the hadron level prediction for bin $i$.

The formula for $f_j^{QCD}(\alpha_s, \mu^2/s)$ combines the fixed order $O(\alpha_s{}^2)$ formula with the leading-log solution given in [5]. These must be matched in such a way that the $O(\alpha_s)$ and $O(\alpha_s{}^2)$ parts of the leading-log formula are not counted twice. Two possible schemes, referred to as "$R$-matching" and "ln $R$-matching" were proposed by ALEPH [1], the difference between the two being of order $O(\alpha_s{}^3)$. Fig. 4 shows a fit result using the $R$-matching scheme with the hadronization corrections based on the JETSET PS model. The fit has $\chi^2 = 2.79$ for two degrees of freedom, and the QCD prediction is in reasonably good agreement with the measured distribution even outside the fit range.

Following the convention of ALEPH [1], the nominal $\alpha_s$ value is given as the mean result of the two matching schemes for $\ln(\mu^2/s) = 0$. The maximum difference between this value and values obtained by varying the renormalization scale in the range $-1 < \ln(\mu^2/s) < 1$, using either $R$-matching or $\ln R$-matching, is taken as the systematic uncertainty from the perturbative formula, $f^{QCD}(\alpha_s, \mu^2/s)$. This is illustrated in Fig. 5, where the JETSET PS model has been used for the hadronization correction. The resulting uncertainty of 0.0062 is (conservatively) taken to be symmetric.

Table 1 shows the values obtained using the various models for hadronization corrections for the two matching schemes. The hadronization mechanism in the HERWIG model uses cluster fragmentation, and the rest are based on the Lund string model. All of the models generate a system of partons based on QCD, an approach similar in physical content to the leading-logarithm formula for $f_j^{QCD}(\alpha_s, \mu^2/s)$. Although they are equivalent at the parton level to leading order, they differ in their effective treatment of higher orders, e.g. angular ordering, $O(\alpha_s)$ corrections for the first emitted gluon, definitions of the parton splitting variable, or in the case of NLLjet, explicit inclusion of next-to-leading order terms. The spread in the resulting $\alpha_s$ values reflects therefore not only the uncertainty from the hadronization mechanism but also the theoretical uncertainty of the parton level of the model.

A final value may be obtained by taking the mean of the two extreme results obtained using the various hadronization models, as done in [1]. From Table 1 these are seen to come from HERWIG and NLLjet, the average of which gives $\alpha_s = 0.1596 \pm 0.0033(stat.)$ The uncertainty from the hadronization correction is taken to be half the difference between the two extremes, or 0.0061. This yields the result

$$\begin{aligned} \alpha_s(29\,\text{GeV}) = 0.1596 \;&\pm\; 0.0033\,(\text{statistical}) \\ &\pm\; 0.0074\,(\text{experimental systematic}) \\ &\pm\; 0.0061\,(\text{hadronization model}) \\ &\pm\; 0.0062\,(\text{scale/matching})\,. \end{aligned} \tag{8}$$

For purposes of the investigation of the energy dependence of $\alpha_s$, the result based on hadronization corrections from JETSET PS ($\alpha_s = 0.1574$), rather than the average of NLLjet and HERWIG, will be used in order to have the same analysis technique at each energy.

## 5. Comparison with measurements at different energies

In order to investigate the running of $\alpha_s$, it is a significant advantage to use the same process and same measured quantity at different center-of-mass energies, since many of the systematic errors are common to all energies. This type of approach has been done e.g. by experiments at PETRA in the energy range 8 GeV $< E_{cm} <$ 47 GeV [19, 20, 21] using the thrust distribution and jet rates, and by the Mark II experiment [22] in comparing the $y_3$

| | $R$ matching | $\ln R$ matching | average of $R$ and $\ln R$ matching |
|---|---|---|---|
| Corrected with: | | | |
| JETSET PS | 0.1546 | 0.1607 | 0.1574 |
| HERWIG | 0.1628 | 0.1695 | 0.1657 |
| JETSET PS, no $\mathcal{O}(\alpha_s)$ | 0.1535 | 0.1597 | 0.1562 |
| ARIADNE | 0.1567 | 0.1631 | 0.1595 |
| NLLjet | 0.1504 | 0.1564 | 0.1534 |

Table 1: Fit results for $\alpha_s$ using different hadronization corrections and matching schemes, with the renormalization scale equal to the center-of-mass energy, i.e. $\ln(\mu^2/s) = 0$.

distributions measured at PEP ($E_{cm} = 29$ GeV) and at SLC ($E_{cm} = 91$ GeV). However, the hadronization uncertainties at the lowest energies of the PETRA range are large, and the theoretical predictions with resummed leading logarithms were not employed in the PETRA and Mark II measurements.

It should be emphasized that the primary goal of this analysis is not to provide the most precise measurement of $\alpha_s$ but rather to investigate its energy dependence. In order to do this an attempt has been made by the $TPC/Two-Gamma$, ALEPH and TOPAZ collaborations to use a similar analysis technique, so that as many of the systematic errors as possible are common to all energies. The comparison of this analysis at $E_{cm} = 29$ GeV with the $\alpha_s$ measurements by TOPAZ at $E_{cm} = 58$ GeV and ALEPH at $E_{cm} = 91.2$ GeV takes advantage of the following common points:

- All analyses use the same event-shape variable, $L_3 = -\ln y_3$, with the same theoretical prediction, i.e. the mean of $R$-matching and $\ln R$-matching with a renormalization scale equal to the the center-of-mass energy, i.e. $\ln(\mu^2/s) = 0$.
- Several models were used by each experiment for the hadronization corrections, and the discrepancies in the results given by the various models were used to estimate the systematic uncertainty. The conventions adopted in doing so differ slightly, since the hadronization corrections are significantly higher for lower energy. All experiments provide $\alpha_s$ values, however, using hadronization corrections based on the JETSET PS model with QCD and hadronization parameters from reference [14].
- The measurements were all made with charged particles detected by time projection chambers with similar solid angle and momentum coverage, with dimensions that roughly scale with energy. The corrections for detector effects were all based on the JETSET PS model.

Fig. 6 shows the $\alpha_s$ values obtained from this analysis and from ALEPH [1] and TOPAZ [2] as a function of the renormalization scale, for the two matching schemes, $R$ and $\ln R$. The associated uncertainty is slightly smaller for ALEPH, since the smaller $\alpha_s$ value at higher $E_{cm}$ leads to a reduced influence of higher order terms in the $L_3$ distribution. Because of the larger non-perturbative effects at $E_{cm} = 29$ GeV, it was necessary to restrict the fit range to $1.6 < L_3 < 2.8$, whereas the TOPAZ used $1.2 < L_3 < 4.4$ and ALEPH used $1.6 < L_3 < 4.0$. Although this leads in principle to a different dependence on the renormalization scale, the results from Fig. 6 indicate that this effect is not large. To a good approximation in the energy range between 29 and 91.2 GeV, the error from missing higher order terms corresponds to a constant shift in the QCD scale parameter $\Lambda$. The somewhat larger dependence on matching and scale shown by the TOPAZ experiment is related to the larger fit range used [23].

The values of $\alpha_s$ from this analysis and from the TOPAZ and ALEPH analyses, obtained from the mean of $R$ and $\ln R$ matching schemes, with $\ln(\mu^2/s) = 0$, and using hadronization corrections based on the JETSET PS model, are shown in Fig. 7. The theoretical uncertainties from the renormalization scale and matching scheme are not shown on the plot, since to a good approximation they are common for all energies. That is, the scale and matching errors correspond approximately to a common shift for all experiments in the QCD scale parameter $\Lambda$, and the uncorrelated part of the uncertainty is small compared to e.g. the hadronization error. The total error bars shown in Fig. 7 are the quadratic sum of the statistical, experimental systematic, and hadronization errors. Using the errors defined in this way, and neglecting possible correlations, the QCD scale parameter $\Lambda_{\overline{MS}}$ was fit to a value of 350 MeV, with $\chi^2 = 0.68$ for two degrees of freedom. (One should be cautioned against using the value of $\Lambda_{\overline{MS}}$ obtained in this way as an absolute measurement; the purpose of this study is to observe the energy dependence of $\alpha_s$.) For an $\alpha_s$ independent of energy, one obtains $\alpha_s = 0.130$ and $\chi^2 = 15.0$ for two d.o.f.

It should be noted that the interpretation of the $\chi^2$ in terms of probabilities is not, strictly speaking, possible here and $\chi^2$ should be treated as a qualitative measure of goodness-of-fit. First, the systematic errors have been estimated using necessarily arbitrary (and conservative) conventions, which do not correspond to errors of one standard deviation. In addition, the hadronization and detector related systematic uncertainties are correlated to a certain extent, since the corresponding corrections were based on the same Monte Carlo model. It is plausible that these facts lead to the very small $\chi^2$ value for the QCD prediction. Similarly, the $\chi^2$ value for the constant $\alpha_s$ would presumably be larger if the correlations were correctly taken into account. The correlations from hadronization and detector corrections are difficult to estimate, however, and the errors are treated here as uncorrelated. It is nevertheless evident that the results are in good agreement with QCD and are incompatible with a constant value.

## 6. Conclusions

The distribution of the event-shape variable $L_3 = -\ln y_3$ has been used to determine the strong coupling constant $\alpha_s$ at a center-of-mass energy of 29 GeV. Although the result is not as accurate as similar measurements at higher energies, the main result of the present analysis is the observation of the energy dependence of $\alpha_s$. This was made possible by coordinating the analysis efforts of three experiments at different center-of-mass energies — 29, 58 and 91.2 GeV — so that some of the common systematic errors could be identified and removed. The three measurements constitute the clearest observation to date of the running of $\alpha_s$ based on a single physical process. A natural extension of this study will arise with the advent of the LEP II accelerator, which will allow measurements of $\alpha_s$ using the same technique at energies up to 170 GeV.


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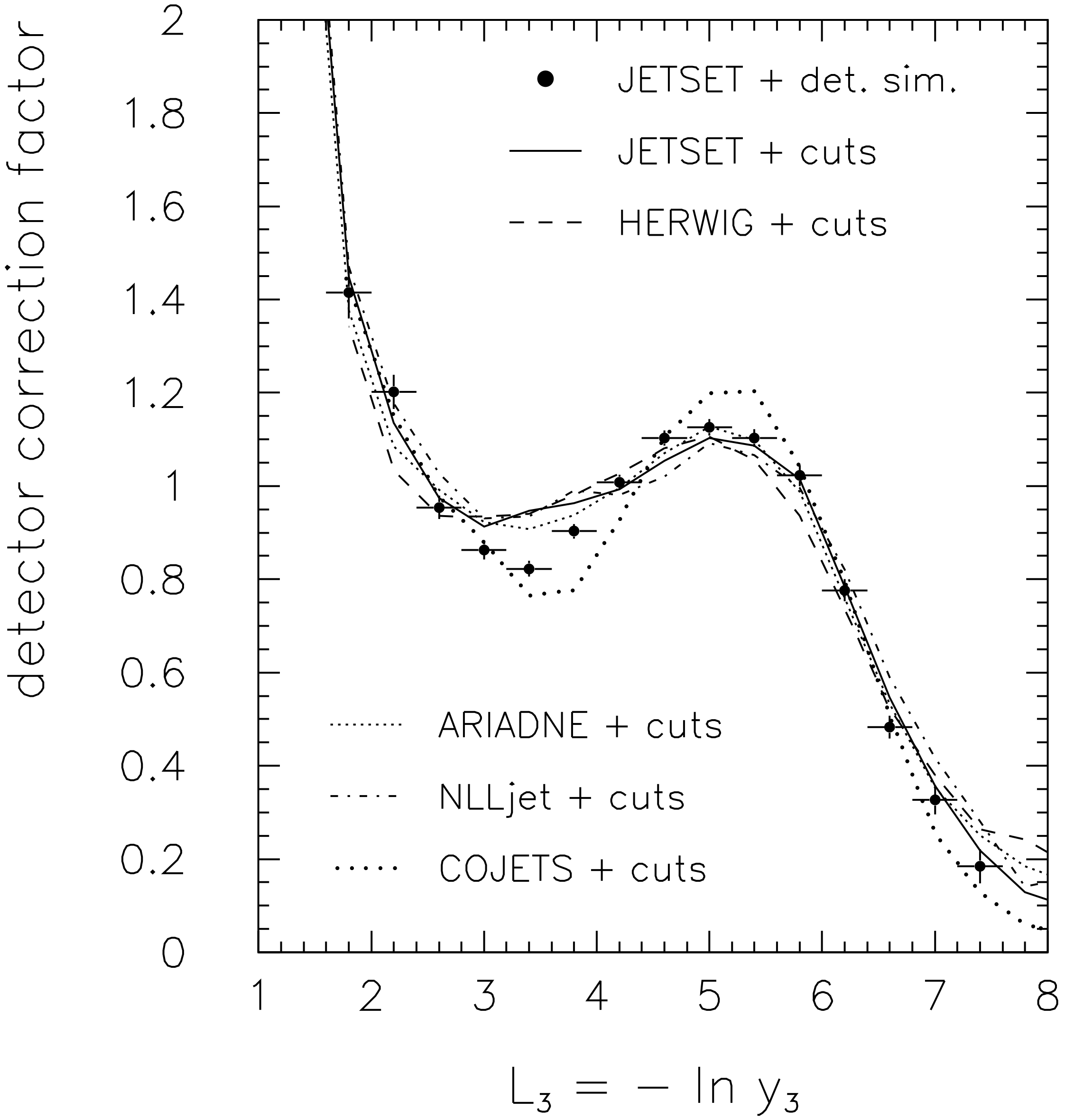


Figure 1: Correction factors for the $L_3$ distribution using the full detector simulation (points) and using only geometrical and momentum cuts with momentum smearing (curves).

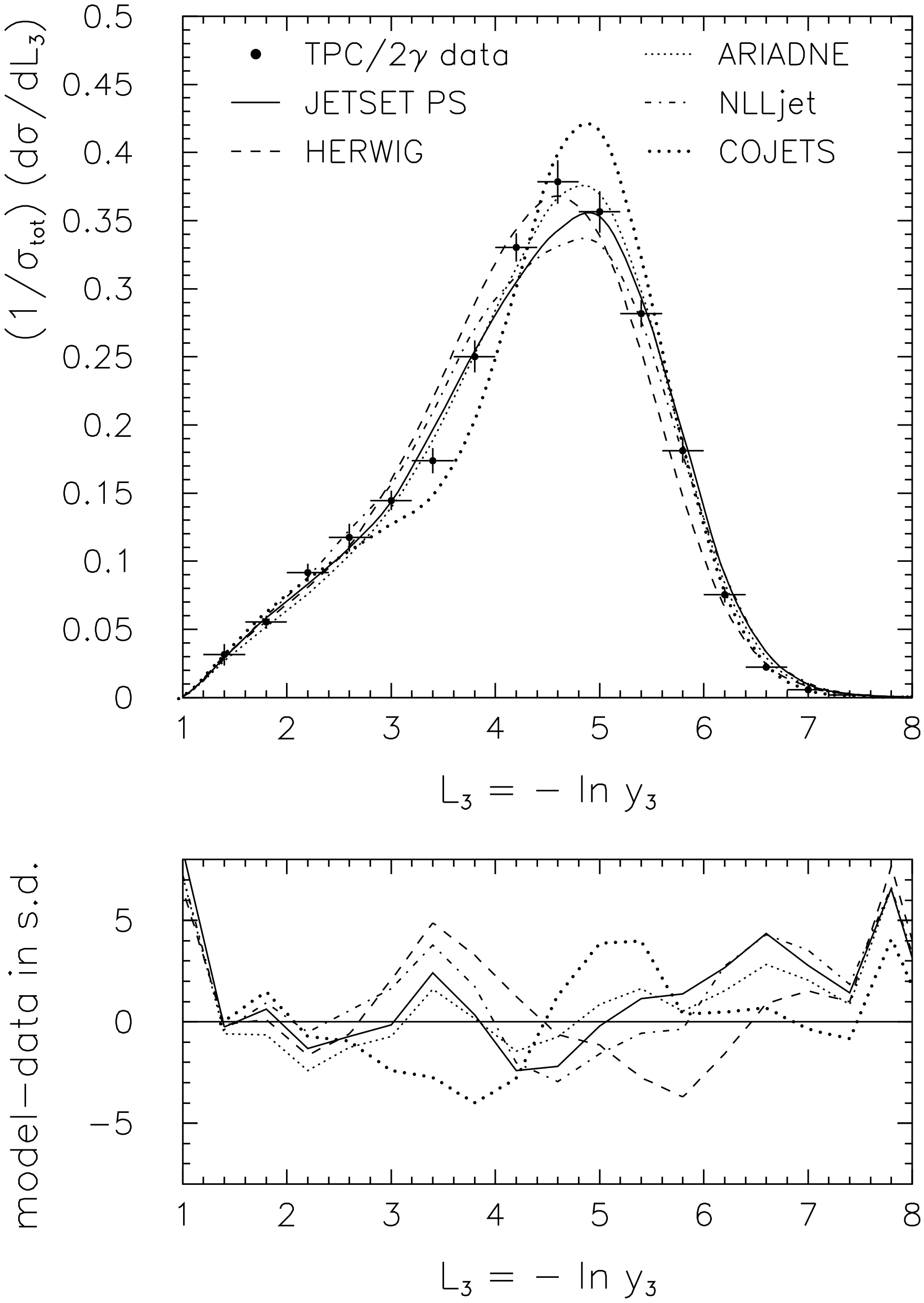


Figure 2: Measured $L_3$ distribution (points) shown with the predictions of several hadron production models. Below: The difference between model prediction and experimental result measured in standard deviations (quadratic sum of systematic and statistical errors).

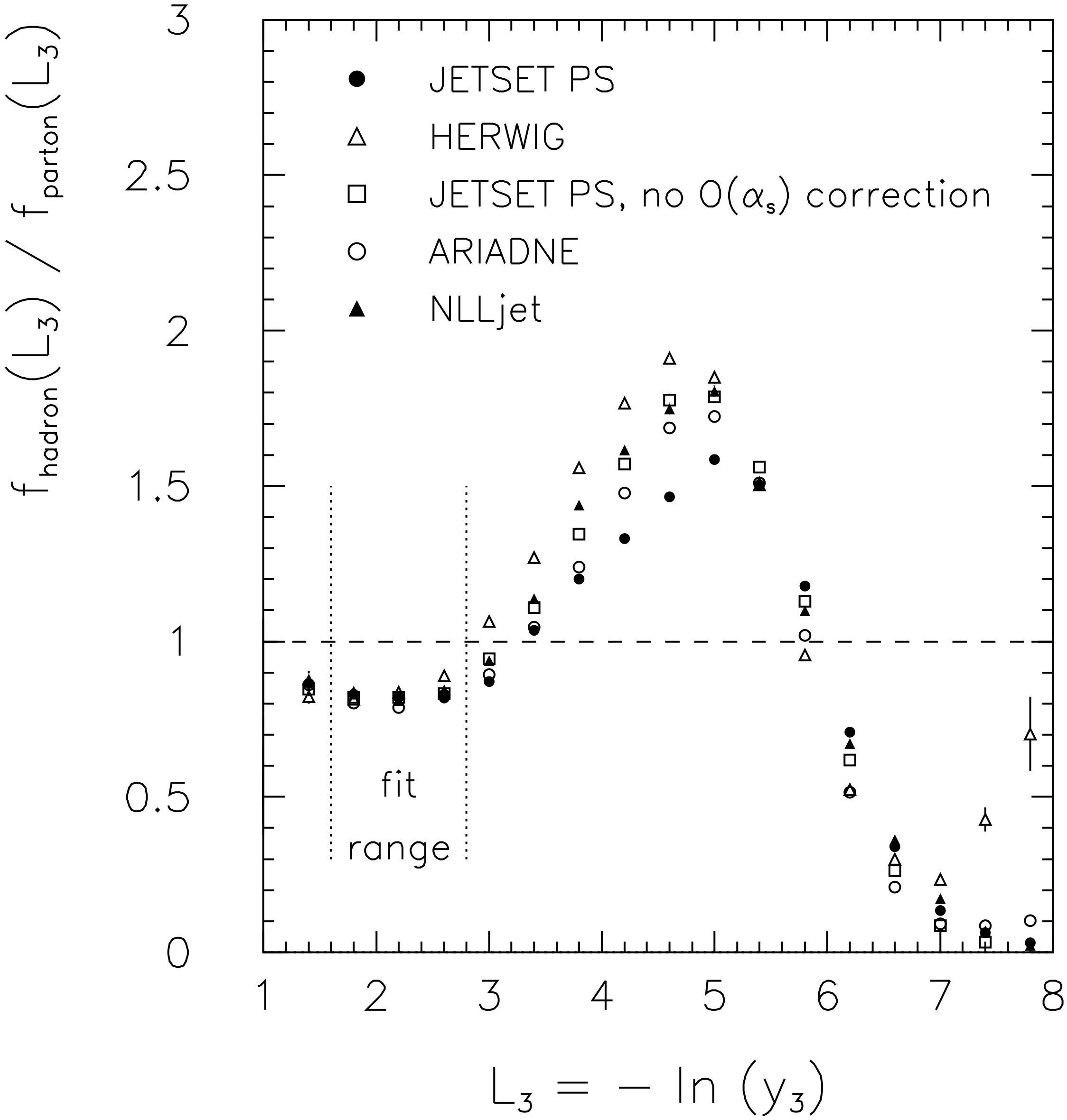


Figure 3: Ratio of hadron level to parton level $L_3$ distributions for several QCD based hadron-production models. The fit range for determining $\alpha_s$ was chosen such that these ratios were close to each other (and close to one) for all the models considered.

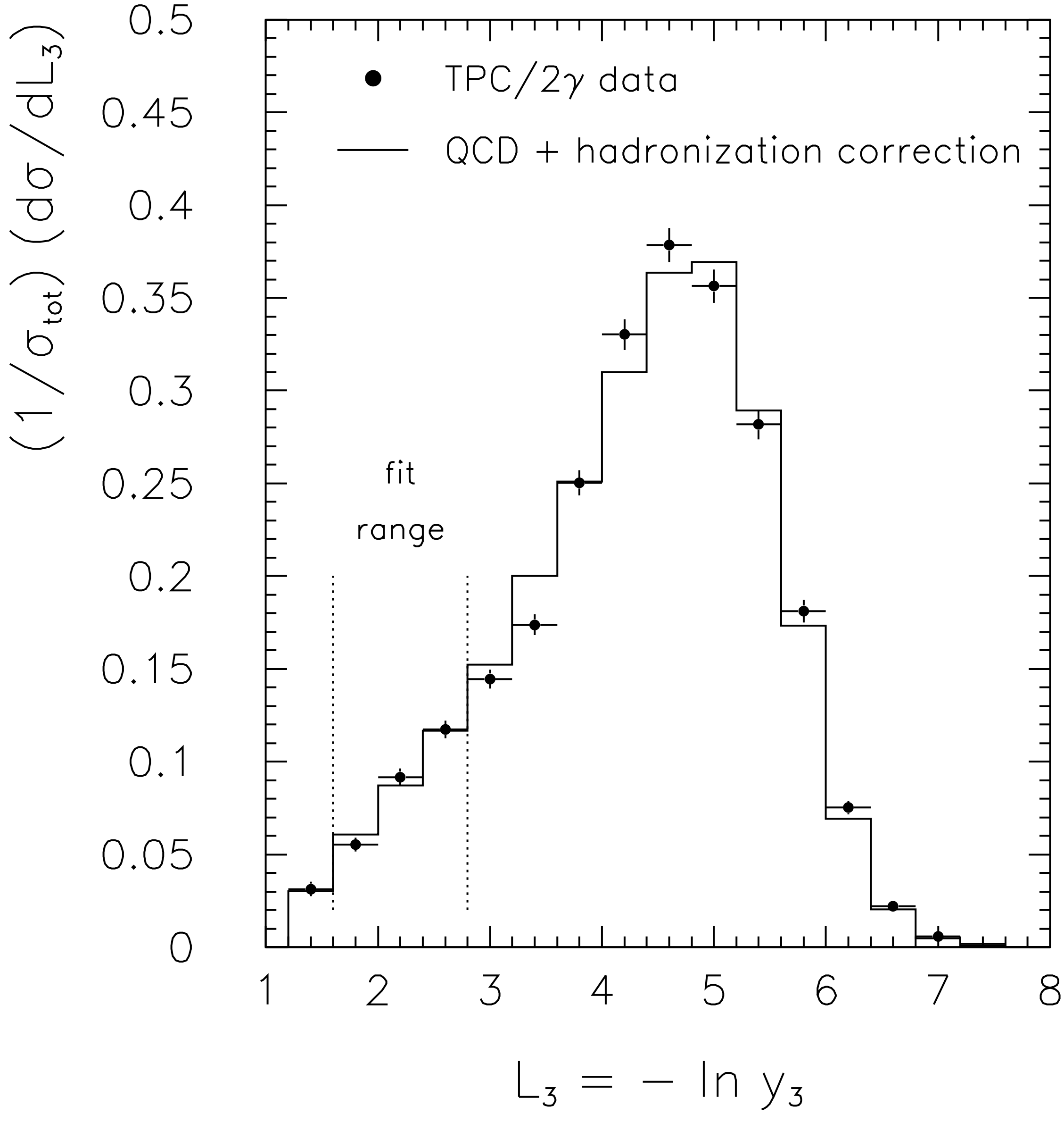


Figure 4: Measured $L_3$ distribution with fit result. The vertical dotted lines show the fit range between $1.6 < L_3 < 2.8$. The hadronization corrections here are taken from the JETSET PS model, and the QCD prediction uses the $R$ matching scheme and a renormalization scale equal to the center-of-mass energy.

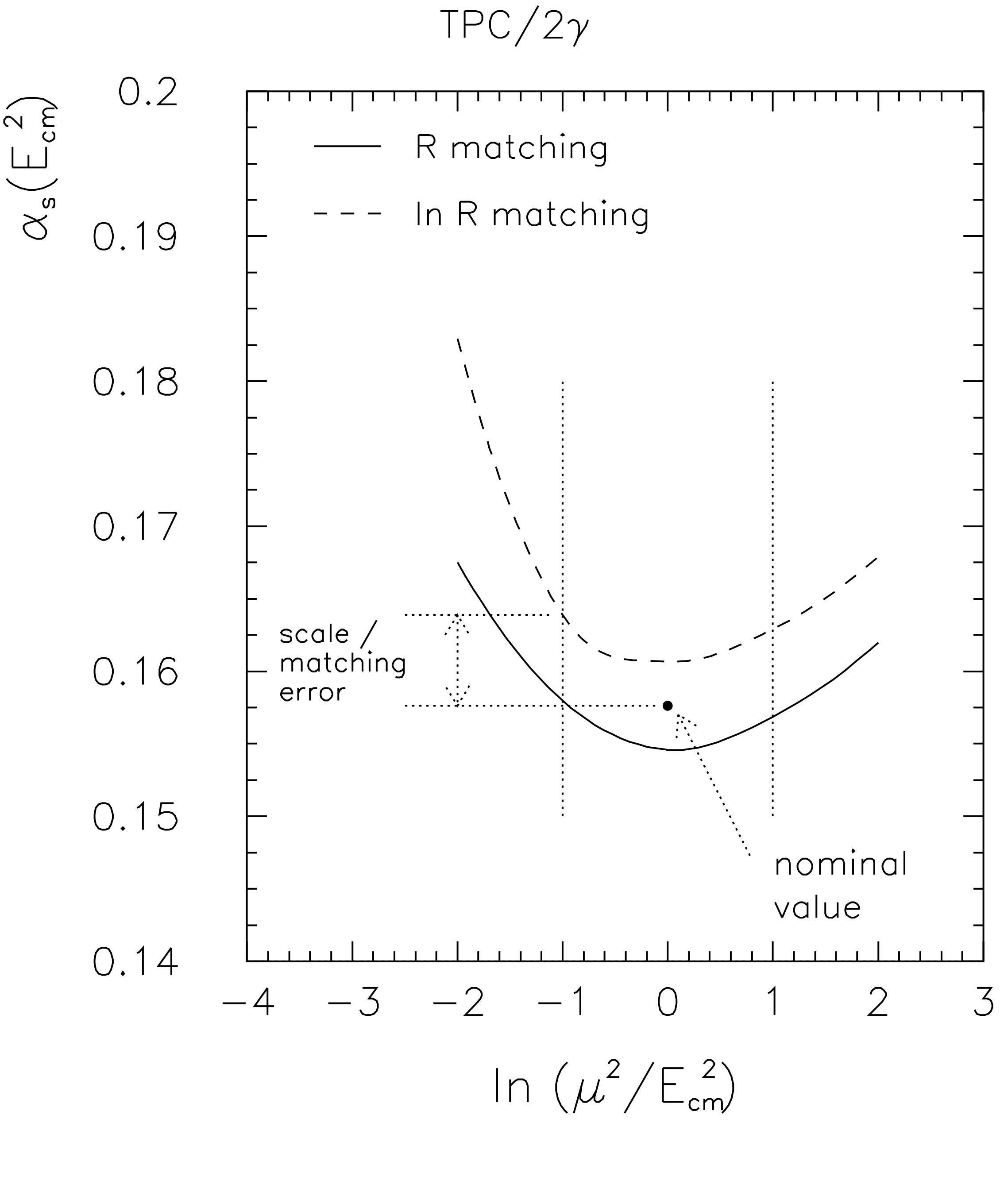


Figure 5: Measured values of $\alpha_s(E_{cm}^2)$ as a function of the logarithm of the renormalization scale $\ln(\mu^2/E_{cm}^2)$ using both the $R$ and $\ln R$ matching schemes. The nominal value is take as the mean of the $R$ and $\ln R$ results at $\ln(\mu^2/E_{cm}^2) = 0$. The systematic uncertainty attributed to the matching and the renormalization scale is taken to be the largest distance between the nominal value and any determined value in the range $-1 < \ln(\mu^2/E_{cm}^2) < 1$.

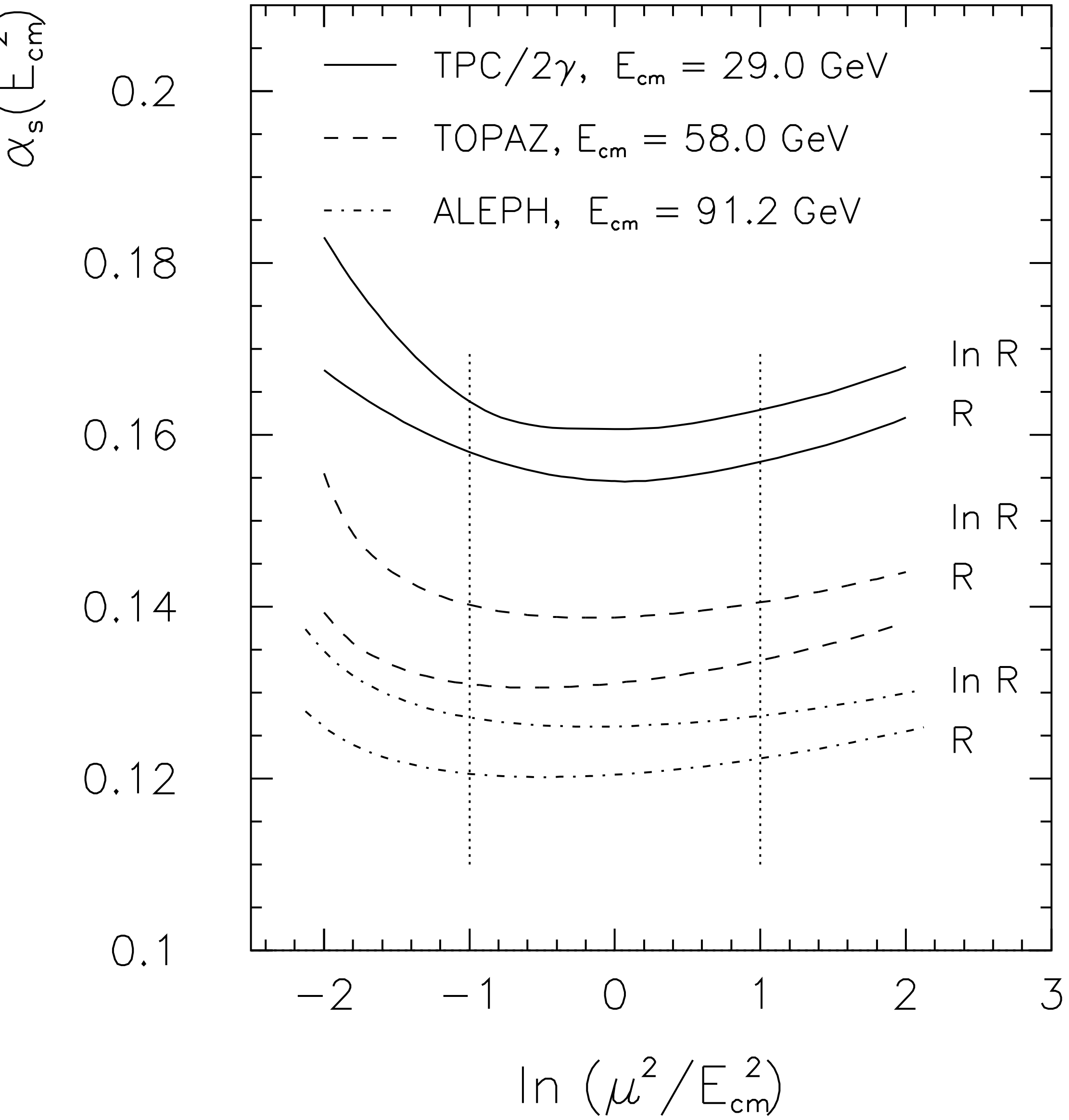


Figure 6: Measured values of $\alpha_s(E_{cm}^2)$ from this analysis ($E_{cm} = 29$ GeV), TOPAZ ($E_{cm} =$ 58 GeV) and from ALEPH ($E_{cm} = 91.2$ GeV) using the $R$ and $\ln R$ matching schemes, as a function of the renormalization scale $\ln(\mu^2/E_{cm}^2)$. The vertical dotted lines indicate the variation of the renormalization scale considered in estimating the systemamtic error.

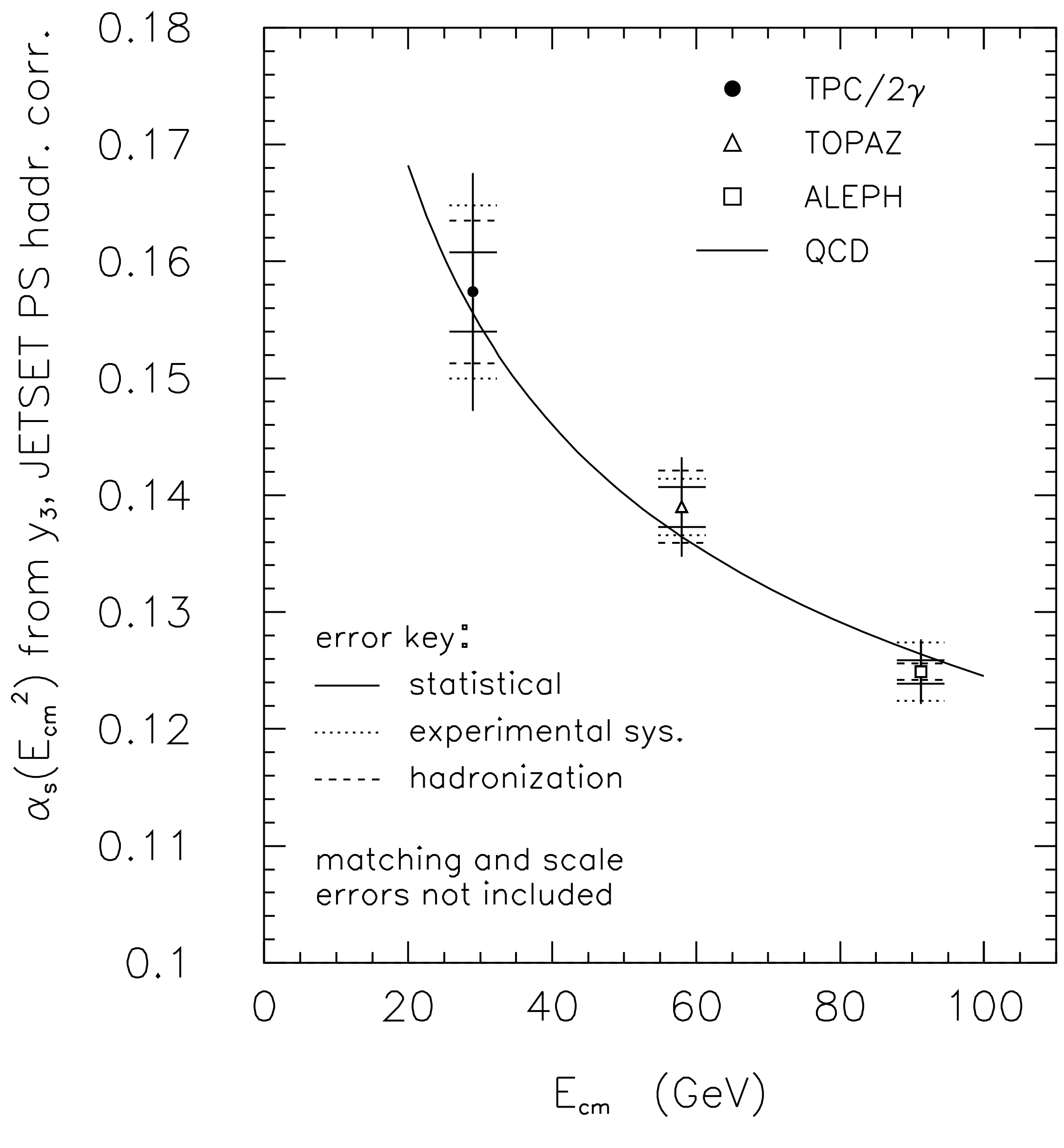


Figure 7: Values of $\alpha_s(E_{cm}^2)$ as a function of center-of-mass energy from this analysis ($E_{cm}$ = 29 GeV), TOPAZ ($E_{cm}$ = 58 GeV) and from ALEPH ($E_{cm}$ = 91.2 GeV) along with the prediction of QCD. The total error bars are the quadratic sum of the statistical, experimental systematic, and hadronization uncertainties. The matching and scale errors are not shown, since to a good approximation this is common to all experiments and corresponds to a shift in the QCD scale parameter $\Lambda$.