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Factorial and Cumulant Moments in $e^+e^- \rightarrow$ Hadrons at the Z^0 Resonance*

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ABSTRACT

The ratio of cumulant to factorial moments of the charged-particle multiplicity distribution in hadronic Z^0 decays has been measured in the SLD experiment at SLAC. The data were corrected for effects introduced by the detector. We find that this ratio, as a function of the moment rank q, decreases sharply to a negative minimum at $q \sim 5$, followed by a sequence of quasi-oscillations. We show that the truncation of the tail of the multiplicity distribution due to finite statistics has only a small effect on this result. The observed features are in qualitative agreement with expectations from higher-order perturbative QCD.

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1 Introduction

Multiplicity distributions of particles produced in high energy e^+e^- collisions have been the subject of intense experimental and theoretical investigation. Quantum chromodynamics (QCD) offers natural explanations for such features as KNO-scaling [1, 2]. However, the distributions predicted by lowest order perturbation theory are much wider than those observed experimentally [3]. Efforts have been devoted to include higher-order perturbative corrections [4, 5, 6], which improved the agreement with experiment by reducing the width of the theoretical distribution. One approach toward quantitative comparison of theory and experiment is provided by the study of moments of the multiplicity distribution [4]. The ratio of cumulant to factorial moments, $H_q = K_q/F_q$, has recently been proposed [7] and shown to be a very sensitive measure of details of multiplicity distributions [8].

The factorial moment of rank q, F_q, is defined as

$$F_q \equiv \frac{<n(n-1)...(n-q+1)>}{<n>^q} = \frac{\sum_n n(n-1)...(n-q+1)P(n)}{(\sum_n nP(n))^q}, \tag{1}$$

where $P(n)$ is the probability for production of n particles in a hadronic event, and $<n>$ is the average multiplicity in the event sample. The cumulant moments K_q are related to F_q by [9]

$$F_q = \sum_{m=0}^{q-1} C^m_{q-1} K_{q-m} F_m. \tag{2}$$

Here $C^m_{q-1} = \frac{(q-1)!}{m!(q-m-1)!}$ are the binomial coefficients, and $F_0 = F_1 = K_1 = 1$. Eq. 2 allows one to solve for the K_q. Thus, F_q, K_q, and hence the ratio H_q can be determined from the multiplicity distribution $P(n)$.

Some phenomenological models of particle production have been examined to demonstrate the sensitivity of H_q [8, 9]. For instance, H_q is identically equal to zero for a Poisson distribution (PD), while the negative binomial distribution (NBD) gives rise to $H_q \sim q^{-k}$, where k is the NBD parameter. In perturbative QCD the moments of the parton multiplicity distribution have been calculated [7, 8, 9, 10] up to next-to-next-to leading order, neglecting corrections involving quarks [9, 11]. While the leading double logarithmic approximation (DLA) predicts $H_q \sim q^{-2}$, including the higher order corrections introduces additional features. Next-to-leading corrections give a minimum in H_q for $q \sim 5$, and next-to-next-to-leading corrections predict that this minimum is negative, followed by quasi-oscillatory behavior at larger q. It should be noted that the current theoretical predictions have not taken confinement into account; therefore, detailed quantitative comparisons with experiment are unlikely to be successful [7]. Nevertheless, it is interesting to check if the predicted qualitative features can be observed experimentally in final state particles.

In this paper we present a study of the ratio of cumulant to factorial moments of the charged particle multiplicity distribution in hadronic events from Z^0 decays collected with the SLD experiment at SLAC. The paper is organized as follows. In Section 2 we briefly describe the SLD detector and the track and event selection criteria. Data correction is discussed in Section 3. Section 4 is devoted to the analysis of the ratio of cumulant to factorial moments, followed by a conclusion in Section 5.

2 Apparatus and Hadronic Event Selection

The e^+e^- annihilation events produced at the Z^0 resonance by the SLAC Linear Collider (SLC) have been recorded using the SLC Large Detector (SLD). A general description of the SLD can be found elsewhere [12]. Charged tracks are measured in the central drift chamber (CDC) and in the vertex detector (VXD) [13]. Momentum measurement is provided by a uniform axial magnetic field of 0.6 T. Particle energies are measured in the Liquid Argon Calorimeter (LAC) [14], which contains both electromagnetic and hadronic sections, and in the Warm Iron Calorimeter [15].

Three triggers were used for hadronic events. The first required a total LAC electromagnetic energy greater than 12 GeV, the second required at least two well-separated tracks in the CDC, and the third required at least 4 GeV in the LAC and one track in the CDC. A selection of hadronic events was then made by two independent methods, one based on the topology of energy depositions in the calorimeters, the other on the number and topology of charged tracks measured in the CDC.

The analysis presented here used the charged tracks measured in the CDC and VXD. A set of cuts was applied to the data to select well-measured tracks and events well-contained within the detector acceptance. The charged tracks were required to have

- a distance of closest approach transverse to the beam axis within 5 cm, and within 10 cm along the axis from the measured interaction point;
- a polar angle, θ, with respect to the beam axis within $|\cos(\theta)| < 0.8$;
- a momentum transverse to the beam axis greater than 0.15 GeV/c.

Events were required to have

- a minimum of five such tracks;
- a thrust axis direction within $|\cos(\theta_T)| < 0.71$;
- a total visible energy E_{vis} of at least 20 GeV, which was calculated from the selected tracks assigned the charged pion mass.

A total of 17,361 events from the 1993 SLC/SLD run survived these cuts and were included in this analysis. The efficiency for selecting hadronic events satisfying the $|\cos(\theta_T)|$ cut was estimated to be above 96%. The background in the selected event sample was estimated to be $0.3 \pm 0.1\%$, dominated by $Z^0 \rightarrow \tau^+\tau^-$ events. Distributions of single particle and event topology observables in the selected events were found to be well described by Monte Carlo models of Z^0 decays [16, 17] combined with a simulation of the SLD.

3 Correction Procedure

We corrected the experimentally observed charged particle multiplicity distribution for the effects introduced by the detector such as geometrical acceptance and resolution, contamination due to γ conversions and particle interactions in the material of the detector, tracking inefficiency, as well as the cuts applied above. In this analysis, the charged multiplicity of an event is defined to include all promptly produced charged particles, as well as those produced in the decay of particles with lifetime $\tau < 3 \cdot 10^{-10}s$. Thus, the charged decay products of K_s^0 and strange baryons are included. The moments were derived from the corrected multiplicity distribution.

Our correction was performed using approximately 146,000 simulated hadronic Z^0 decays generated according to the JETSET 6.3 [16] event generator plus a detailed simulation of SLD. These Monte Carlo (MC) events were reconstructed in the same way as the data. For each such MC event passing the applied cuts, the number of observed tracks n_o, with distribution $N_{obs}^{MC}(n_o)$, was compared with the number of generated tracks n_g, with distribution $N_{gen}^{MC}(n_g)$. This comparison yielded the correction matrix $M(n_g, n_o)$ whose elements are defined as

$$M(n_g, n_o) = \frac{N(n_g, n_o)}{N_{obs}^{MC}(n_o)}, \tag{3}$$

where $N(n_g, n_o)$ stands for the number of MC events with n_g generated tracks when n_o tracks were observed. The observed distribution $N_{obs}^{MC}(n_o)$ is thus related to the generated distribution $N_{gen}^{MC}(n_g)$ by

$$N_{gen}^{MC}(n_g) = \sum_{n_o} M(n_g, n_o) \cdot N_{obs}^{MC}(n_o). \tag{4}$$

The sample employed for constructing the correction matrix had cuts applied, and consequently did not reflect exactly the true multiplicity distribution. In addition, QED initial state radiation results in a small bias to the multiplicity. Both biases were corrected by using a set of factors $C_F(n_g)$, which were calculated from Monte Carlo simulations by comparing the normalized generated multiplicity distribution $P^{fix}(n_g)$, at fixed c.m.s energy in the total sample, to the normalized generated multiplicity distribution $P^{sub}(n_g)$ in the sub-sample, that is, the one which passed the applied cuts,

$$C_F(n_g) = \frac{P^{fix}(n_g)}{P^{sub}(n_g)}. \tag{5}$$

The correction matrix M and correction factors C_F were applied to the experimentally observed multiplicity distribution $N^{exp}_{obs}(n_o)$ to yield the corrected multiplicity distribution, $N^{exp}_{cor}(n)$:

$$N^{exp}_{cor}(n) = C_F(n) \cdot \sum_{n_o} M(n, n_o) \cdot N^{exp}_{obs}(n_o). \tag{6}$$

4 Analysis

The corrected normalized charged particle multiplicity distribution is shown in Fig. 1. Because of charge conservation the corrected charged multiplicity of an event is always even-valued while observed multiplicities can be odd-valued. Since the selection criteria required at least 5 observed tracks per event, the entries for n=2 and 4 were not derived from data but taken instead from the JETSET 6.3 model. The experimental uncertainties contain the statistical and systematic errors added in quadrature. Also shown in Fig. 1 is a best fit to the negative binomial distribution (NBD)

$$P_n(\langle n\rangle, k) = \frac{k(k+1)...(k+n-1)}{n!} \left(\frac{\langle n\rangle}{\langle n\rangle + k}\right)^n \left(\frac{k}{\langle n\rangle + k}\right)^k, \tag{7}$$

where $\langle n\rangle$ and k are free parameters, with fitted values $k = 24.86 \pm 0.93$, $\langle n\rangle = 20.64 \pm 0.10$, and $\chi^2/NDF = 22.86/24$.

The corrected normalized multiplicity distribution $P(n)$ was employed to calculate the moments. The factorial moments F_q, cumulant moments K_q, and their ratio H_q were calculated up to rank $q = 17$ according to Eqs. 1 and 2, and the resulting H_q are shown in Fiq. 2. The errors shown correspond to statistical and systematic errors added in quadrature, which will be described below. It can be seen that H_q falls rapidly at the lower ranks and reaches a negative minimum at $q \sim 5$. For increasing q, H_q exhibits a quasi-oscillatory behavior as shown in the window with enlarged scale. These observed qualitative features are in good agreement with the predictions from higher-order perturbative QCD as described in Sect. 1, and are clearly inconsistent with the leading double logarithmic approximation (DLA) which predicts H_q monotonically decreasing to zero as $H_q \sim q^{-2}$. An analysis [18] of existing LEP data yielded similar conclusions.

Statistical effects on the results were studied from a set of Monte Carlo samples of the same statistical size as the data. We notice that for ranks greater than $q \sim 7$ the phase of the oscillations is sensitive to the sample size. However, the dominant qualitative features of the data, namely the steep decrease at small q, the first negative minimum near $q = 5$, and the existence of quasi-oscillatory behavior at larger q, are not found to be dependent on the size of the data set. The dispersion of these Monte Carlo sample sets was taken as the statistical error on each point.

We have examined the following contributions to the experimental systematic uncertainties. In each case the entire correction and analysis process described above was repeated in order to test the influence of a systematic effect on the final results.

- Tracking inefficiency. Knowledge of the dependence of the tracking efficiency on multiplicity is important for this study. The matrix $M(n_g, n_o)$ calculated from Monte Carlo events, as described in Sect. 3, includes a simulation of this efficiency. From the fact that the MC overestimated the track multiplicity by 3.4% on average, we deduced that the discrepancy between the detector tracking efficiency and its simulation in terms of average multiplicity was $(2.4 \pm 1.7)\%$. This additional inefficiency of 2.4% was applied to the simulated efficiency, and its uncertainty of 1.7% was included in the systematic error for the final results.

- Statistical fluctuations in the correction matrix. The correction matrix $M(n_g, n_o)$ was constructed from a Monte Carlo sample with finite statistics. A smoothed version of the matrix was found by parametrization, and the difference compared with that calculated from the original matrix was conservatively taken as a systematic error.

- Model dependence. Since the selection criteria required at least 5 observed charged tracks per event, the values for $n = 2$ and $n = 4$ were not derived from the data but were taken instead from the expectation of JETSET 6.3. The difference with the case when these entries are not included in the calculation is included in the systematic error.
- Hadronic event and track selection. The criteria for selecting well-measured tracks and events well-contained within the detector were varied over a wide range to check their effects on the final results. Any significant sensitivity to the selection cuts was included in the systematic error.

Of the above sources of systematic error, the tracking inefficiency is the dominant one. These contributions were added in quadrature to give the overall systematic uncertainty, which was found to be small compared with statistical errors. Our results for H_q, including both statistical and systematic errors are listed in Table 1.

It was recently argued [19] that the truncation of the tail of the multiplicity distribution due to finite sample size could lead to quasi-oscillations in H_q which are similar to those observed in the data. We investigated this by observing the effect on H_q due to truncation of the tail of the NBD which is the best fit to our observed multiplicity distribution. When the NBD was truncated at multiplicity values equal to or larger than the truncation of the experimental data, the observed distortions of H_q were found to be negligiblly small. Similar results were obtained with a best fit PD replacing the NBD. As evident from Fig. 2, the H_q resulting from a truncated NBD is inconsistent with the experimental data.

5 Conclusion

We have studied the ratio of cumulant to factorial moments of the charged-particle multiplicity distribution in hadronic Z^0 decays. We find that this ratio, as a function of the moment rank q, decreases sharply to a negative minimum at $q \sim 5$, followed by a sequence of quasi-oscillations. The observed qualitative features are in good agreement with the predictions from higher-order perturbative QCD calculations. The effect from the truncation of the tail of the multiplicity distribution due to finite statistics was found to be small. The DLA parameterization of the multiplicity distribution, based on leading order QCD, and the phenomenological NBD distribution, are clearly inconsistent with our data.

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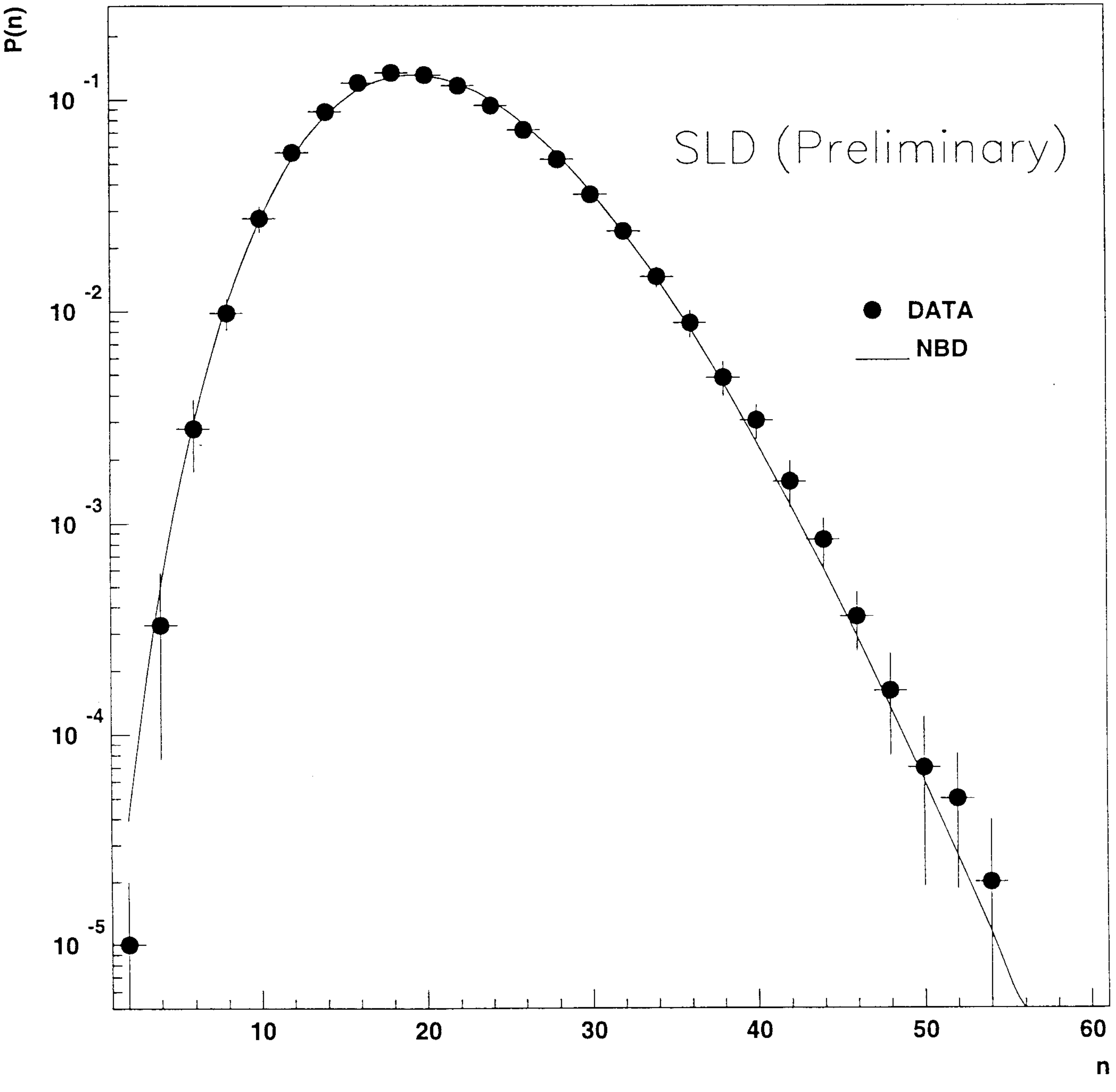
Table 1: Ratio of cumulant to factorial moments, H_q. Statistical and systematic errors are listed separately.

q	H_q	stat. error	sys. error
2	4.024E-02	7.894E-04	2.131E-04
3	5.300E-03	2.900E-04	6.904E-05
4	3.049E-04	1.997E-04	4.800E-05
5	-4.609E-04	9.446E-05	1.931E-05
6	-3.161E-04	2.884E-05	1.389E-06
7	-9.620E-05	1.767E-05	5.094E-06
8	3.533E-05	1.592E-05	7.949E-06
9	8.508E-05	4.973E-06	4.517E-06
10	5.786E-05	4.670E-06	2.408E-06
11	-1.032E-05	9.252E-06	6.954E-06
12	-6.320E-05	9.154E-06	5.063E-06
13	-5.634E-05	4.188E-06	2.400E-06
14	1.129E-05	7.091E-06	9.744E-06
15	8.977E-05	1.205E-05	9.508E-06
16	9.961E-05	1.059E-05	2.906E-06
17	-1.960E-05	5.760E-06	2.357E-05

Figure captions

Figure 1. The corrected charged particle multiplicity distribution with a fit to the negative binomial distribution (NBD). The error bars correspond to statistical and systematic errors added in quadrature.

Figure 2. Ratio of cumulant to factorial moments, H_q, as a function of the moment rank q. The error bars correspond to statistical and systematic errors added in quadrature. Also shown are the results from the truncated Poisson and negative binomial distributions.



P(n)
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10 -3
10 -4
10 -5
SLD (Preliminary)
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NBD
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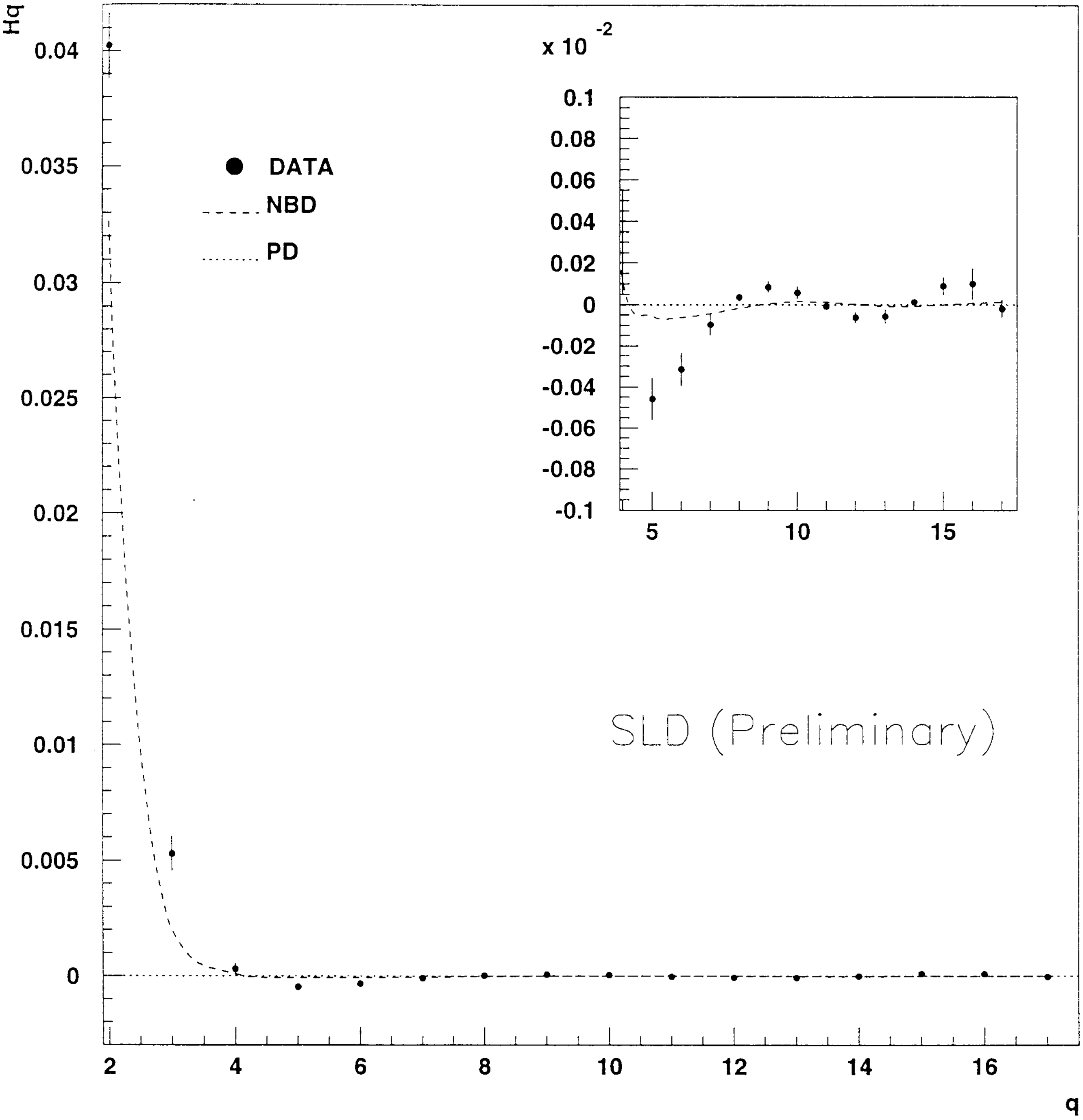
n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DATA
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0.08
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SLD (Preliminary)
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