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Bose-Einstein Correlations in Deep Inelastic Scattering at HERA

H1 Collaboration

Abstract

Two-particle correlations in invariant mass are studied separately for like-sign and unlike-sign charged particles. The like-sign correlations exhibit the familiar enhancement at low invariant masses possibly related to the dimensions of the hadronic source. The data are compared to QCD models without Bose-Einstein correlations, where the hadronization is performed with the string-fragmentation model. The Monte Carlo generators are used in order to construct reference samples, where the Bose Einstein correlations are absent, but all detector related effects are properly accounted for. The observed correlations can be described with parametrisations quite similar to those obtained in previous analyses of μp -inelastic scattering and e^+e^- - annihilation. The data were taken with the H1 detector in the running period of 1994.

1 Introduction

Bose-Einstein (BE) correlations have been analyzed in high energy physics for many years in order to study the space-time evolution of particle production (see e.g. [1, 2, 3, 4, 5, 6] for reviews). The BE effect shows up as an enhancement in the production rate of identical bosons with similar momenta.

In the traditional interpretation of this effect particles are assumed to be emitted from a set of sources distributed in space-time with a distribution $\rho(x)$. If the particles are identical bosons, then it is necessary to impose Bose symmetry on the production amplitude. This leads to an interference term in the amplitude-squared which is observable only if the sources are incoherent. If two identical pions with four-momenta p_1 and p_2 are observed in their rest-frame, then the enhancement due to the interference over the rate without interference is

$$R(T) = 1 + \lambda \mid \tilde{\rho}(T) \mid^2 \tag{1}$$

where $\tilde{\rho}$ is the Fourier transform of $\rho(x)$ and λ is a measure of the incoherence of the source: $\lambda = 1$ for complete incoherence and $\lambda = 0$ for complete coherence. T^2 is related to the invariant mass M of the pion pair by

$$T^2 = -(p_1 - p_2)^2 = M^2 - 4m_\pi^2 \ . \tag{2}$$

Early models assumed e. g. a sphere of emitters with a Gaussian density

$$\rho(x) = \rho(0) \exp(-\frac{x^2}{2r^2}) \ . \tag{3}$$

The width r is interpreted as the size of the production area. Such a source results in an enhancement

$$R(T^2) = 1 + \lambda \exp(-r^2 T^2) \ . \tag{4}$$

As most other experiments we will use this parametrization too in the comparison to our data.

2 Event and track selection

The present study is based on a sample of positron proton collider events collected in 1994 with the H1 detector at HERA, where 27.6 GeV positrons collide with 820 GeV protons. Low Q^2 deep inelastic scattering events are selected via the detection of the scattered positron with $E_e \geq 10$ GeV and $157° \leq \theta_e \leq 173°$, where the polar angle θ is measured with respect to the proton beam direction. The invariant mass squared of the final hadronic system W^2 has to exceed 3000 GeV^2. The energy deposited in the calorimeter in the forward (proton beam) direction within the polar angle $4.4^0 < \theta < 15^0$ has to be larger than 0.5 GeV, to remove diffractive ("rapidity gap") events[9]. Rapidity gap events are excluded. Charged tracks are required to have a fit to the primary vertex, a transverse momentum $p_T > 0.15$ GeV/c and a polar angle θ satisfying $22° < \theta < 150°$. The measured track has to start at a radial distance from the beam line of less than 50 cm. All charged particles are assumed to be pions. At least four tracks are required in an event. A total of 44500 events passed these cuts.

Our data are compared to, and corrected with, two DIS Monte Carlo (MC) models: the MEPS model (an option of the LEPTO generator [10]) incorporates the QCD matrix elements

(ME), with additional soft emissions generated by adding leading log parton showers (PS). In the CDM model [11, 12] the showering starts from a chain of independently radiating color dipoles (CD) formed by emitted gluons. Both models use the Lund string fragmentation, without BE correlation, for hadronization. The generated MC events are tracked through the detector and processed through the same reconstruction program as the data.

3 Technical aspects of the analysis

In order to measure the correlation function (4) we have to normalize the two-particle like-sign inclusive density $\rho_2(M)$ with a reference sample (background) that contains no Bose-Einstein correlations and form the ratio :

$$R(M) = \frac{\rho_2(M)}{\rho_2^{\mathrm{ref}}(M)} \ . \tag{5}$$

For this reference distribution we use either the two particle unlike-sign inclusive distribution $\rho_2^U(M)$ or we create uncorrelated pairs by mixing tracks from different events, denoted by $\rho_1 \otimes \rho_1(M)$. These two techniques are commonly used in different experiments [16, 14, 17, 18]. In the event-mixing technique, the event sample is divided into four classes according to the invariant mass of the final hadronic system W and only candidates in the same class are mixed. To reduce distortion in the mass spectra of the mixed sample, the second event is rotated such that positron tracks have the same direction in the r-ϕ plane.

It is worthwhile to note that the two reference samples are not equivalent as was demonstrated by DELPHI in [14]. There, λ and r were derived for the two methods, and inserted in the JETSET 7.3 generator with the BE option switched on. The generated events were then compared to the data. JETSET, with the parameters derived from the event mixing method described the data nicely, whereas the events generated with the parameters from the unlike reference sample failed (Figs. 10a and b in [14]).

Correlations not due to Bose-Einstein effects are estimated using the MC models without Bose-Einstein correlations. To obtain the final result, we take the double ratio by dividing the correlation function (5) from the data by the one obtained from reconstructed MC events

$$R'(M) = \frac{R^{\mathrm{data}}(M)}{R^{\mathrm{MC}}(M)} \tag{6}$$

This procedure also corrects for the geometrical acceptance and kinematical cuts, and resonance decays if the unlike-sign reference sample is used. The correlation functions thus obtained were then fitted with the "Goldhaber parametrization" [3] equation (4).

4 Results and discussion

Fig. 1 shows $\rho_2(M)$, the inclusive two-particle density and $\rho_1 \otimes \rho_1(M)$, the uncorrelated reference obtained from event mixing. The upper one (a) is for like-sign pairs and the lower one (b) for unlike-sign pairs. The shape of the function $\rho_1 \otimes \rho_1(M)$ is identical for the like-sign and the unlike-sign combinations because they are determined from the single-particle distributions which are identical for positive and negative particles. Figure 2 shows the same distributions as Fig. 1 for Monte Carlo events (CDM), after reconstruction. For further analysis, the first bin in figs. 1 and 2 was excluded because their content is strongly affected by reconstruction bias, especially in the like-sign sample. That range is therefore not shown in figs. 3 and 4.

Figures 3a, 3b and 3c show the ratio $R(M)$ for both data and the CDM-model. The unlike-sign inclusive density, $\rho_2^{\mathrm{U}}(M)$ normalized to the reference $\rho_1 \otimes \rho_1^{\mathrm{U}}(M)$ from event-mixing displayed in Fig. 3a is used as a check of the Monte Carlo. The fragmentation models overestimate the amount of ρ production, as previously observed in ref.[15, 16, 14, 17]; otherwise good agreement between data and MC is observed.

Fig. 3b shows the ratio $R(M)$ for like-sign pairs where the reference sample is obtained from event mixing ($\rho_2^{\mathrm{L}}(M)$ over $\rho_1 \otimes \rho_1^{\mathrm{L}}(M)$). The experimental values of $R(M)$ are considerably higher than those of the MC for M smaller than 0.6 GeV/c^2. This is usually attributed to the Bose-Einstein interference. The Monte Carlo also predicts a rise of $R(M)$ towards threshold. These correlations are mainly caused by mixing tracks of events with a different jet topology which generates a shift towards larger masses and a depletion of the $\rho_1 \otimes \rho_1(M)$ distribution at small masses. This can be seen from Fig. 2a. These residual (non-BE) correlations should be nearly absent for events with no typical jet structure, as discussed in [14, 17]. The rotation of the event axis mentioned in section 3 removes this problem only partially.

From this discussion and the agreement of data and Monte Carlo demonstrated in Fig. 3a, it becomes apparent that the double ratio of equation (6) should be used to fit the BE enhancement of equation (4). Fig. 3c shows the ratio of like-sign $\rho_2^{\mathrm{L}}(M)$ over unlike-sign $\rho_2^{\mathrm{U}}(M)$ two-particle densities. Clear K_s^0 and ρ^0 signals at 0.5 and 0.77 GeV, respectively, are visible in both figures 3a and 3c.

The double ratio of data and Monte Carlo for signal and reference sample (Fig. 3b and Fig. 3c), i.e. the quantity $R'(M) = R^{\mathrm{data}}(M)/R^{\mathrm{MC}}(M)$ is shown in Fig. 4b and Fig. 4a, respectively. The fit of the "Goldhaber parametrization" (4) is superimposed. In Fig. 4a the region around the ρ^0 is excluded.

The results (Table 1) for the two different reference samples are slightly different, as already observed in other experiments [13, 14, 17, 18, 20, 21]. These differences are ascribed [22, 2] to correlations imposed by the decays of other long lived resonances as e. g. ω, η, η', non-resonant $\pi\pi-$interaction and Coulomb effects. The results obtained from the double ratios using the CDM and MEPS models agree with each other, when the event-mixed tracks are used as reference sample.

In Table 1 we also compare the H1 results with those from other experiments. The errors quoted are purely statistical. Bearing in mind that some experiments have used additional procedures to correct for the purity of the pion sample, and/or the Coulomb interaction, which has not been done yet for this analysis, our preliminary results are broadly consistent with results from $\ell N-$scattering at lower energies and from e^+e^--annihilation. At this moment we do not want to address the question of interference of directly produced pions and pions from resonance decays, as was done by E665 [19].

Table 1. Results from this analysis (preliminary) and other experiments (compiled in [5]):

EXPERIMENT		Reference sample: unlike-sign $\rho_2^{\mathrm{U}}(M)$ r(fm)	λ	event-mixed $\rho_1 \otimes \rho_1(M)$ r(fm)	λ
H1 (CDM)	ep	0.73±0.04	0.48±0.03	0.53±0.04	0.27±0.02
H1 (MEPS)	ep	0.64±0.05	0.31±0.03	0.57±0.05	0.27±0.03
EMC [18]	μp	0.84±0.03	1.08±0.10	0.46±0.03	0.73±0.06
E665 [19]	μp			0.39±0.02	0.35±0.02
νN [21]	νN	0.80±0.04	0.61±0.04	0.64±0.04	0.46±0.03
DELPHI [13, 14]	e^+e^-	0.83±0.03	0.31±0.02	0.47±0.03	0.24±0.02
ALEPH [17]	e^+e^-	0.80±0.04	0.62±0.04	0.50±0.02	0.40±0.02
OPAL [20]	e^+e^-	0.93±0.02	0.86±0.03		
MARK 2 [23]	e^+e^-	0.84±0.06	0.50±0.07		
TASSO [24]	e^+e^-	0.80±0.06	0.35±0.07		

5 Conclusion

The Bose-Einstein interference effect has been studied in the invariant mass distributions for pairs of like-sign particles relative to two different reference samples. Two deep inelastic scattering Monte Carlo models that use the Lund string model for hadronization, but without the Bose-Einstein effect, were used to study the additional correlations that might affect the determination of the pion source parameters. The interference effect can be extracted by dividing these residual correlations out. A clear enhancement of the correlations towards small invariant masses is observed. These are attributed to the Bose-Einstein effect. They are fit to the Goldhaber parametrization and the source radius r and the parameter λ are extracted. The fit results are broadly consistent with those of other experiments.

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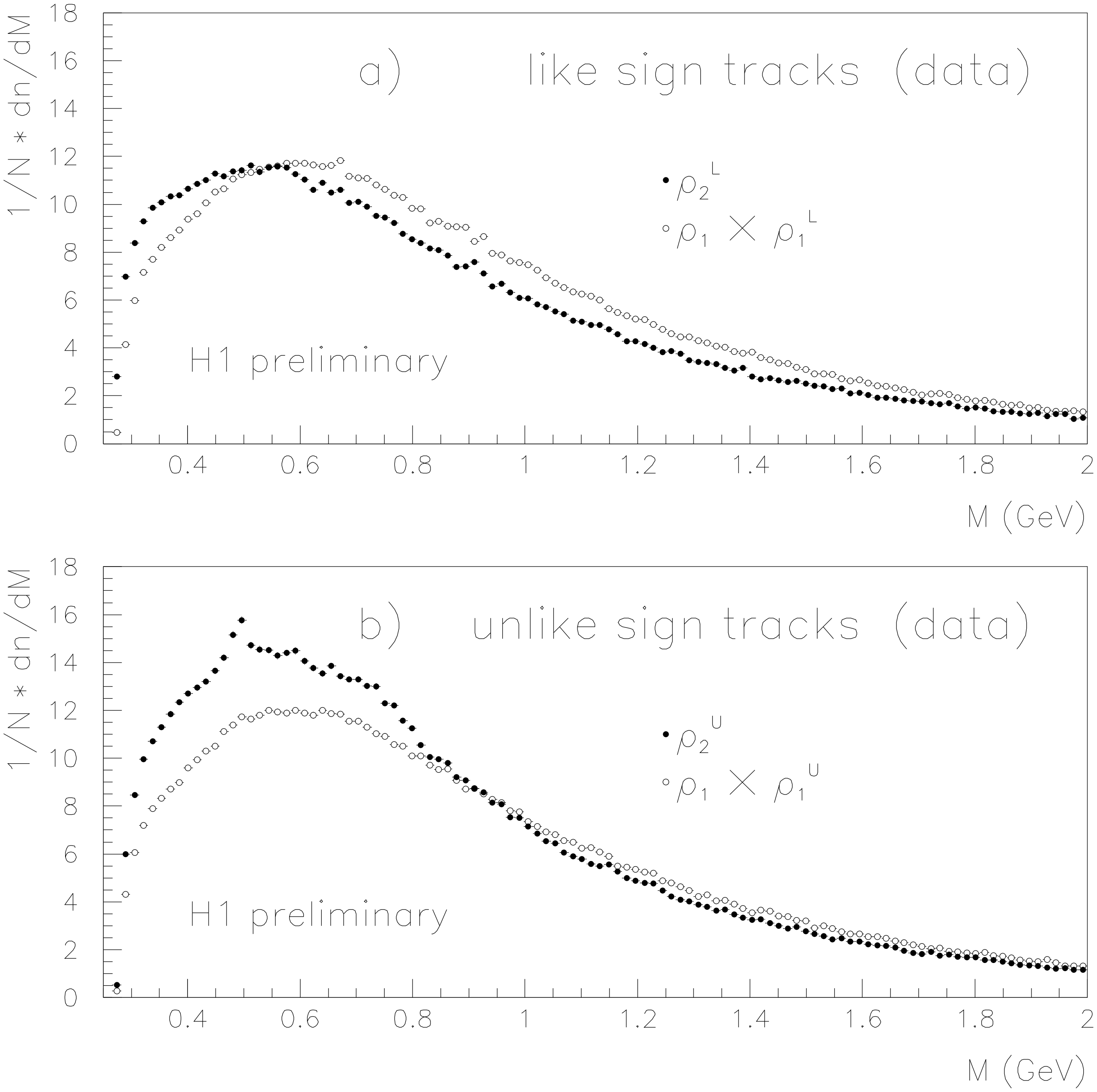

Figure 1: The invariant mass distribution of pairs of tracks, normalized to the number of events N.
In a) the full dots denote the two particle inclusive spectrum for like-sign pairs ($\rho_2^{\rm L}(M)$). The open circles represent the distribution obtained from event mixing $\rho_1 \otimes \rho_1(M)$.
In b) the same is shown for unlike-sign pairs: full dots $\rho_2^{\rm U}(M)$ and open circles $\rho_1 \otimes \rho_1(M)$.

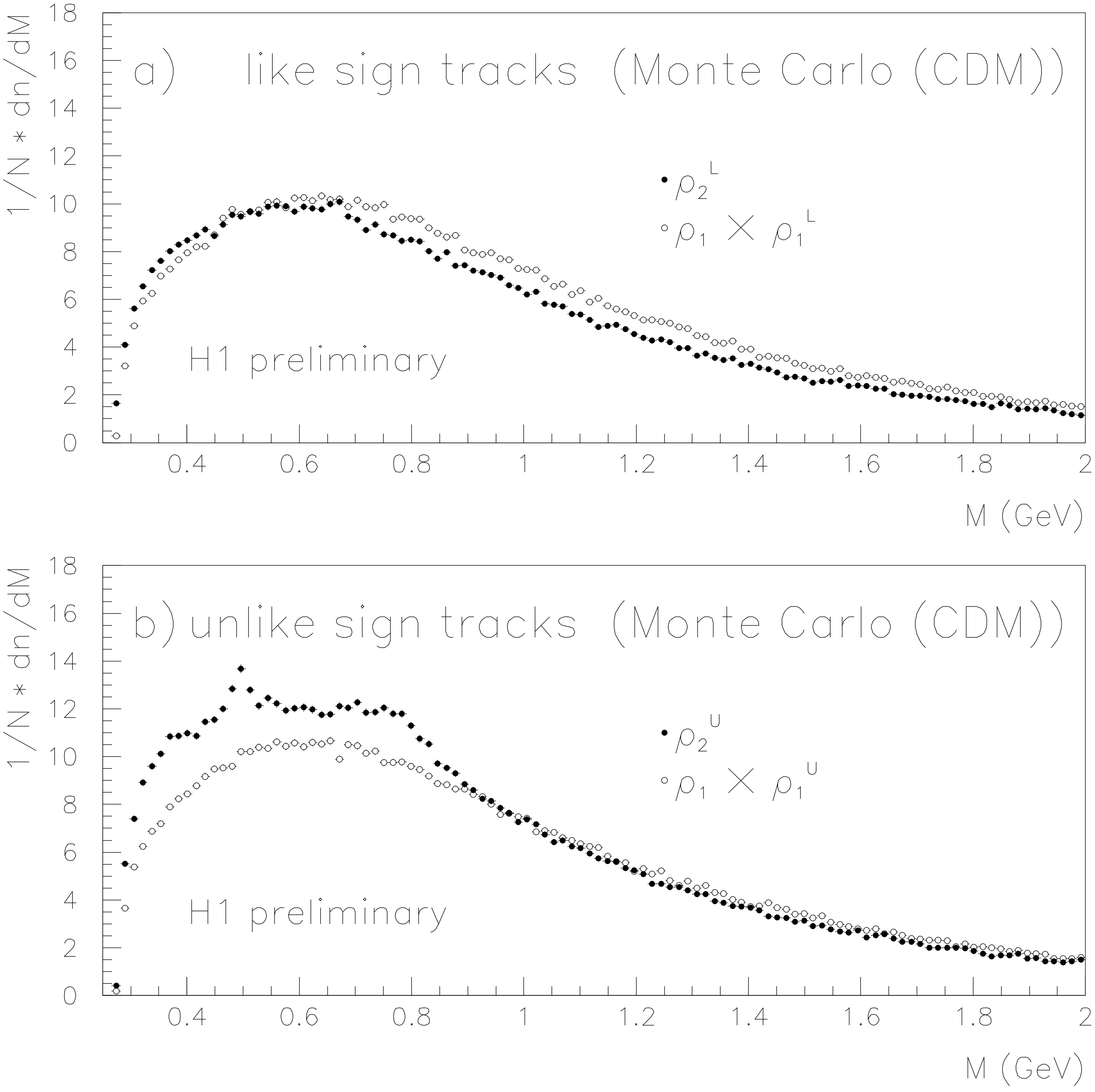

Figure 2: The same as Fig. 1 for Monte Carlo events.

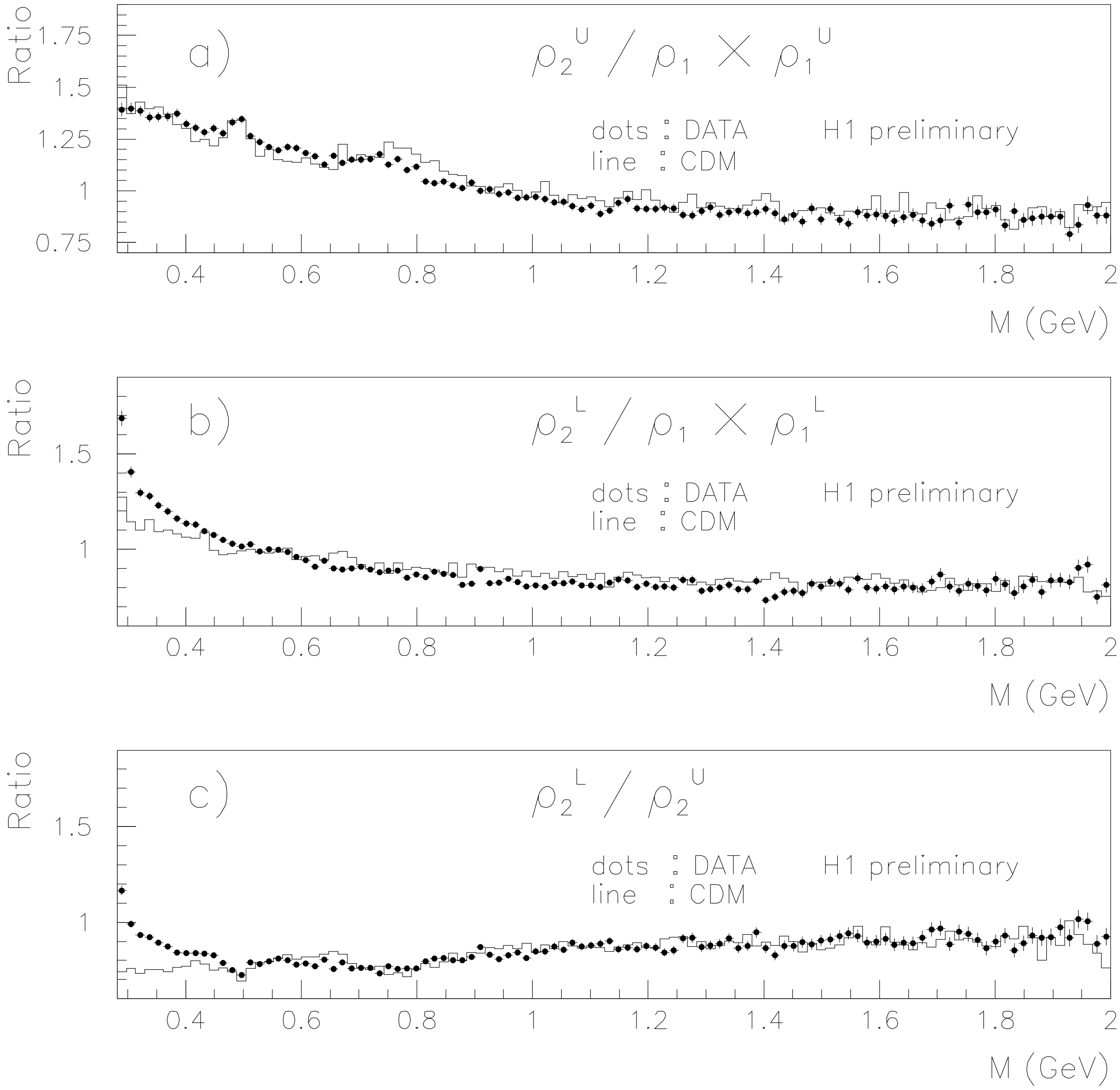

Figure 3: The ratio $R(M) = \rho_2(M)/\rho_2^{\mathrm{ref}}(M)$ for three combinations:
a) (+-) pairs normalized with event mixing: $\rho_2^{\mathrm{U}}(M)/\rho_1 \otimes \rho_1(M)$.
b) the like-sign density normalized by event mixing: $\rho_2^{\mathrm{L}}(M)/\rho_1 \otimes \rho_1(M)$.
c) the like-sign density normalized by the unlike-sign density: $\rho_2^{\mathrm{L}}(M)/\rho_2^{\mathrm{U}}(M)$.
The full dots represent the data, the histograms represent the CDM Monte Carlo. The difference between Monte Carlo and data in b) and c) is attributed to the Bose-Einstein correlation.

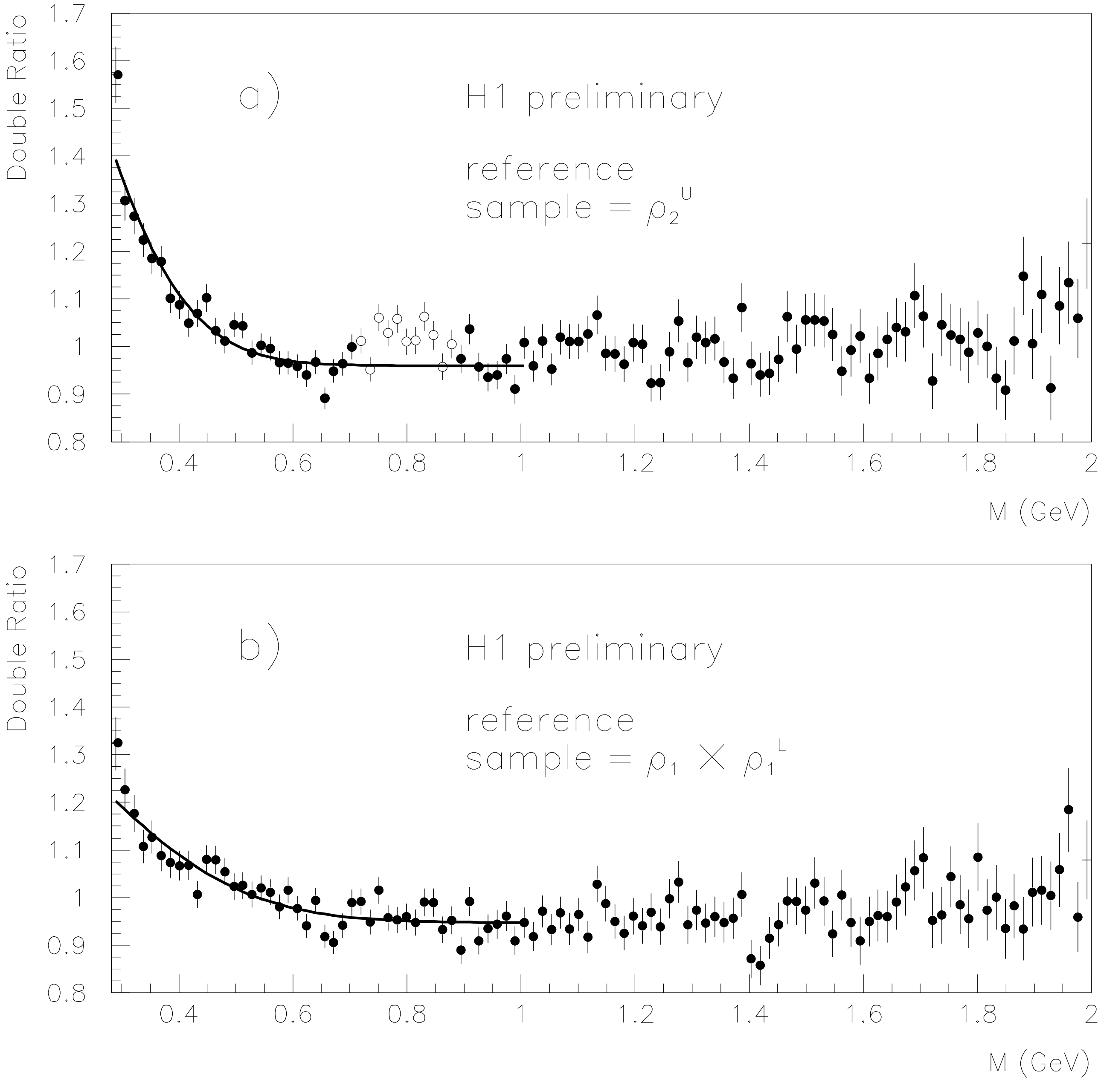

Figure 4: The double ratio $R'(M) = R^{\mathrm{data}}(M)/R^{\mathrm{MC}}(M)$ for two different reference samples.
a) unlike-sign pairs, cf. Fig. 3c.
b) event mixing, cf. Fig. 3b.
The curve is a fit to eqn. (4) in the range from 0.3 - 1. GeV. In a) the region of the ρ is excluded from the fit (open circles).