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MEASUREMENT OF JET FRAGMENTATION PROPERTIES AT THE CERN $\bar{p}p$ COLLIDER

The UA2 Collaboration

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ABSTRACT

Fragmentation properties of a sample of two-jet events measured by the UA2 detector at the CERN $\bar{p}p$ Collider are described. The energy flow is compared with different model predictions. The charged particle multiplicity in jets is found to exceed extrapolations from lower energy e^+e^- jet data.

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1. INTRODUCTION

The recent unambiguous identification of jets in hadronic collisions [1-4] at the CERN $\bar{p}p$ Collider and at the ISR, has enabled a study of fragmentation properties [5] of these jets. Initial results from the $\bar{p}p$ Collider, based on the 1982 data sample, have been previously published [6-7]. This Letter describes a more detailed study based on the much larger data sample of the 1983 run, which allows for a more significant comparison with e^+e^- data. QCD calculations using as input lower energy structure functions predict that the jets observed in this energy range are a mixture of quark and gluon jets [8]. Therefore by comparing the fragmentation of these jets with quark jets from e^+e^- annihilation one can study differences between quark and gluon jets. According to QCD inspired models [9-10] quarks and gluons are expected to fragment differently because of the larger colour charge of the gluon.

2. APPARATUS

The UA2 detector has been described in detail elsewhere [11-13]. In this analysis the central calorimeter, which has been described briefly in the preceding article [14] and in detail elsewhere [13], is used to measure jet energies, while the vertex detector [12] is used to measure charged particle multiplicities in jets.

The vertex detector is at the centre of the apparatus and consists of a system of cylindrical chambers which measure charged particle trajectories in a region without magnetic field. The vertex detector contains: a) four multi-wire proportional chambers, C_1 to C_4, with wires parallel to the beam axis and cathode strips at ±45° to the wires; b) a scintillation counter hodoscope (VH), made of 24 elements in a barrel-like arrangement, located after chamber C_2; c) two drift chambers with measurement of the charge division on the wires. The vertex detector has full azimuthal coverage over the polar angle range $20° < \theta < 160°$. From the reconstructed tracks the position of the event vertex is determined with a precision of ±1 mm in all directions. Additional tracking is provided in the forward regions ($20° < \theta < 37.5°$ and $142.5° < \theta < 160°$) by the forward-backward drift chambers [12].

3. DATA TAKING AND REDUCTION

The data presented in this Letter were recorded during the 1983 CERN $\bar{p}p$ Collider run. The trigger selection and the data reduction consisted in retaining events with two well-measured jets in the central calorimeter and are described in the preceding article. The integrated luminosity was $\int \mathcal{L} dt = 112\ nb^{-1}$. In order to study events with smaller jet-jet invariant masses a smaller sample of lower threshold data was also used, corresponding to $\int \mathcal{L} dt = 759\ \mu b^{-1}$. The trigger for the low threshold data required that the total transverse energy in the central calorimeter, ΣE_T, be greater than 30 GeV (compared to 40 GeV for the standard sample). The cluster energies were corrected for the loss of energy due to hadrons impinging near the cell boundaries and for other effects such as the calorimeter non-linearity and the cluster algorithm as described in the preceding article [14].

4. CHARGED PARTICLE MULTIPLICITY IN JETS

The charged particle multiplicity in jets was measured using the vertex detector. In order to select a clean sample of two-jet events that were well contained in the central calorimeter the following cuts were applied :

i) the invariant mass of the two highest transverse energy clusters, m_{jj}, exceeds 40 GeV.

ii) the azimuthal separation between the two highest transverse energy clusters, $\Delta\phi^{jj}$, exceeds 150°.

iii) the transverse momentum of the two-jet system, p_T^{jj}, does not exceed 25 GeV.

These cuts retained a sample of ~3×10^4 events.

The analysis is restricted to the transverse plane where the track reconstruction efficiency is highest and where particles not associated with a jet are expected to contribute a uniform azimuthal distribution. Distributions of the azimuthal separation $\Delta\phi$ between all transverse tracks observed in the vertex detector and the energy centroid of the cluster having the highest transverse energy are shown in Fig. 1a for 2 intervals of m_{jj}. There are two peaks at $\Delta\phi \simeq 0$ and $\Delta\phi \simeq \pi$ as expected for two-jet events. The peak at $\Delta\phi \simeq 0$ is narrower than the peak at $\Delta\phi \simeq \pi$ because the finite two-jet transverse momentum [14] implies that the two jets are not exactly back-to-back.

There is no unique way to define the charged particle multiplicity of jets produced in $\bar{p}p$ collisions because the relative fractions of the particles coming from the jet and coming from the "underlying event" (the part of the event which is due to the spectator parton fragments) are unknown. As a lower limit on the true jet multiplicity one can define the "jet core" multiplicity as the number of charged particles above a flat level corresponding to the value at $\Delta\phi=\pi/2$ (see Fig. 1a):

$$\langle n_{ch}^{jet}\rangle = 1/2\ \{\int_0^\pi [dn/d(\Delta\phi)]\ d(\Delta\phi) - \pi[dn/d(\Delta\phi)]_{\Delta\phi=\pi/2}\} \quad (1)$$

Since the angular coverage of the vertex detector is much larger than that of the central calorimeter, the losses from geometrical acceptance are negligibly small (< 1%).

The data must still be corrected for detector inefficiencies. The transverse track finding efficiency of the vertex detector was measured using the forward-backward spectrometer [12] by comparing tracks reconstructed in each of these detectors. The vertex detector efficiency was measured using "minimum bias" data to be 95±1 %. It was verified that the efficiency was independent of the polar angle θ over the range covered by the forward-backward spectrometers. The measured value of the efficiency is consistent with the value measured at $\theta \sim 90^{\circ}$ for the 1982 data sample using the wedge spectrometer [6]. The fraction of spurious tracks and tracks not coming from the primary vertex, was measured to be 21±1% using the same method. The loss of tracks from the finite two track resolution (~ 5 mm) was estimated from the distributions of the azimuthal separation between neighbouring tracks. The separation was defined as the average transverse separation between tracks at the inner and outer radius of the vertex detector. Plots of the nearest neighbour track separation s were made for different regions of track density. A smooth curve was fitted to the region $s > 12$ mm and the fraction of tracks lost was estimated from the area between the curve and the data in the region $0 < s < 12$ mm. An example of such a fit is shown in Fig. 1b. The effect of this correction varies from ~12% at $\Delta\phi=\pi/2$ to ~ 25% at $\Delta\phi=0$. The data were also corrected for γ conversions and π^0 Dalitz decays (the effect of this correction was 2%).

The corrected jet core multiplicities $\langle n_{ch}^{jet} \rangle$ [see Eq.(1)] are shown as a function of m_{jj} in Fig. 2. The data are consistent within errors with the previously published results from the 1982 data sample [6]. The error bars shown include a common 5% statistical uncertainty in the estimate of the two track resolution loss. The systematic error is estimated to be ~15%. The dominant source of systematic error comes from the uncertainty in the two track resolution correction. The systematic error is mainly an overall scale error and the point to point systematic errors are much smaller. As a check on the correction procedures, the mean multiplicity was calculated for minimum bias events and found to be in good agreement [6] with the value obtained by the UA5 Collaboration [15] in the same pseudo-rapidity interval.

Using the measured angular distributions of charged particles around the jet axis from e^+e^- data [16] the equivalent jet core multiplicity was evaluated for e^+e^- data by making a subtraction corresponding to the flat level at $\Delta\phi=\pi/2$. The results from the TASSO experiment are also shown in Fig. 2. Neither the data from the present experiment, nor the TASSO data, were corrected for strange particle decays. The jet core multiplicity has been defined so that it is sensitive to the nature of the jet but insensitive to its mode of production. In particular differences between the $\bar{p}p$ and e^+e^- results reveal differences between the associated jet samples. The jet core multiplicities represent only a fraction of the true jet multiplicities. For e^+e^- interactions, where the true jet multiplicity is directly measured as half of the total event multiplicity, this fraction is ≃ 65%. Some energy may be lost from the definition of the jet energy which introduces an uncertainty on the measured value of m_{jj}. However the effect of this uncertainty contributes only a 2% systematic error to the measured value of the multiplicity. The result suggests that jets from $\bar{p}p$ collisions in the mass range $40 < m_{jj} < 80$ GeV have higher mean multiplicities than one would expect from extrapolations of e^+e^- data.

In order to understand this effect in more detail, the QCD parton shower model of ref. [10] was used to predict the growth of multiplicity with m_{jj} for quark-antiquark ($q\bar{q}$) and gluon-gluon (gg) jets. The model for quark jets has been tuned to agree with e^+e^- data and therefore provides a good model for the extrapolation of e^+e^- data. The model also predicts the relative multiplicities of gluon jets compared to quark jets. The full line represents the prediction of the model for quark jets while the shaded area represents the range of predictions for gluon jets. Gluon jets are expected to have higher multiplicities than quark jets because of the larger colour charge of the gluon [9]. Using the structure functions of ref. [17] which are consistent with the one measured in this experiment [14], one expects that the fraction of gluon jets decreases from ~ 75% to ~ 30% as m_{jj} increases from 40 GeV to 140 GeV. Allowing for this variation in the gluon fraction, the data are in agreement with the expectations of the model.

5. ENERGY FLOW

To measure the transverse energy flow around the jet axis, a clean sample of two-jet events was selected as follows:

i) the two highest transverse energy clusters in the event have transverse energies E_T^1 and E_T^2 exceeding 15 GeV.

ii) The ratio E_T^2/E_T^1 exceeds 1/2.

iii) Their azimuthal separation, $\Delta\phi^{jj}$, exceeds 140°.

To reduce the energy leaking outside the calorimeter acceptance, only clusters having a pseudo-rapidity, $|\eta|$, less than 0.3 (central clusters) are considered in this analysis. The distribution of the azimuthal transverse energy density $dE_T/d\Delta\phi$, integrated over a rapidity interval of ±0.7 units around this central cluster is shown in Fig. 3 for three different intervals of the cluster transverse energy (E_T^j). The peaking in the energy flow is much stronger than in the charged particle flow (note the logarithmic scale in Fig. 3). This means that the particles at wide angles to the jet axis are soft and make only a small contribution to the energy flow. The peak at $\Delta\phi \simeq 0$ is narrower than the peak at $\Delta\phi \simeq \pi$ (not shown in the figure) because of the finite two-jet transverse momentum as for the charged particle flow (see section 4) and because the second jet may partially escape detection in the central calorimeter. For this reason only the region $0<\Delta\phi<\pi/2$ is used in the following analysis. The data are not corrected for the effects of calorimeter granularity and resolution. The main effect arises from the finite cell size ($\Delta\phi\times\Delta\theta$=15°×10°) which tends to smear out the peaks. To compare the data with different fragmentation models, several Monte Carlo calculations were made. All details of the detector response were simulated for samples of events generated according to these models. The Monte Carlo event sample was submitted to the same trigger and analysis procedure as the real data. The corresponding distributions are shown as smooth curves in Fig. 3. The Field-Feynman fragmentation model [18] with a r.m.s. transverse momentum of particles with respect to the jet axis, q_T, set equal to 350 MeV produces jets which are much narrower than the data. The data can be better reproduced by models which include explicitly the effects of gluon bremsstrahlung, such as that used in section 4. The data are bracketed by the predictions for $q\bar{q}$ and gg as expected for a mixture of quark and gluon jets as described by the model of ref. [10].

In order to study the dependence of jet aperture upon energy, the normalised transverse energy flow $1/E_T^j \, dE_T/d\Delta\phi$ is plotted for different slices of E_T^j in Fig. 4. A small but significant shrinking in the width of the jet is observed as its energy increases, although the effect of the jet shrinking is reduced by the effects of the finite calorimeter granularity.

6. CONCLUSIONS

This Letter has presented results on fragmentation properties of jets produced at the CERN $\bar{p}p$ Collider. The charged particle multiplicity has been measured as a function of the two-jet mass and found to exceed extrapolations from lower energy e^+e^- data. This result is in qualitative agreement with the expectations of QCD inspired models which predict that gluon jets should have higher multiplicity than quark jets. The measured transverse energy flow around the jet axis showed that the jets are broader than the expectations of a fragmentation model without gluon radiation. The energy flow data can be explained by models which include gluon bremsstrahlung. In particular the data can be fitted by a mixture of quark and gluon jets according to the model of ref. [10].

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FIGURE CAPTIONS

1. (a) Azimuthal separation $\Delta\phi$ between the energy cluster centroid of the leading jet and all charged transverse tracks, normalised to n, the number of events. The dashed-dotted line represents the level measured in minimum bias events.
(b) Distribution of nearest neighbour transverse track separation s for a local track density of $dn/d\Delta\phi \sim 7$ rad^{-1}.

2. Mean charged "jet core" multiplicities n_{ch}^{jet} (see text for definition) as a function of $\sqrt{s_{e^+e^-}}$ for e^+e^- data and of the invariant two-jet mass m_{jj} for $\bar{p}p$. The solid curve is the prediction of the model of ref. [10] for quark jets and the shaded area represents the predictions for gluon jets. The uncertainty in the prediction arises from the range of parameters for which the quark jets fit the e^+e^- data.

3. Distribution of the azimuthal transverse energy density $dE_T/d\Delta\phi$ where $\Delta\phi$ is measured with respect to the centroid of the central cluster ($|\eta|<0.3$) for three ranges of E_T^j.
(a) $20 < E_T^j < 30$ GeV.
(b) $30 < E_T^j < 40$ GeV.
(c) $40 < E_T^j < 50$ GeV.
The dotted curve represents the predictions of the Field-Feynman fragmentation model[18]. The dashed (solid) curve represents the predictions of the model of ref. [10] for quark (gluon) jets (see text for details).

4. Distribution of the normalized transverse energy density $1/E_T^1\ dE_T/d\Delta\phi$ for two intervals of the highest cluster transverse energy E_T^1.

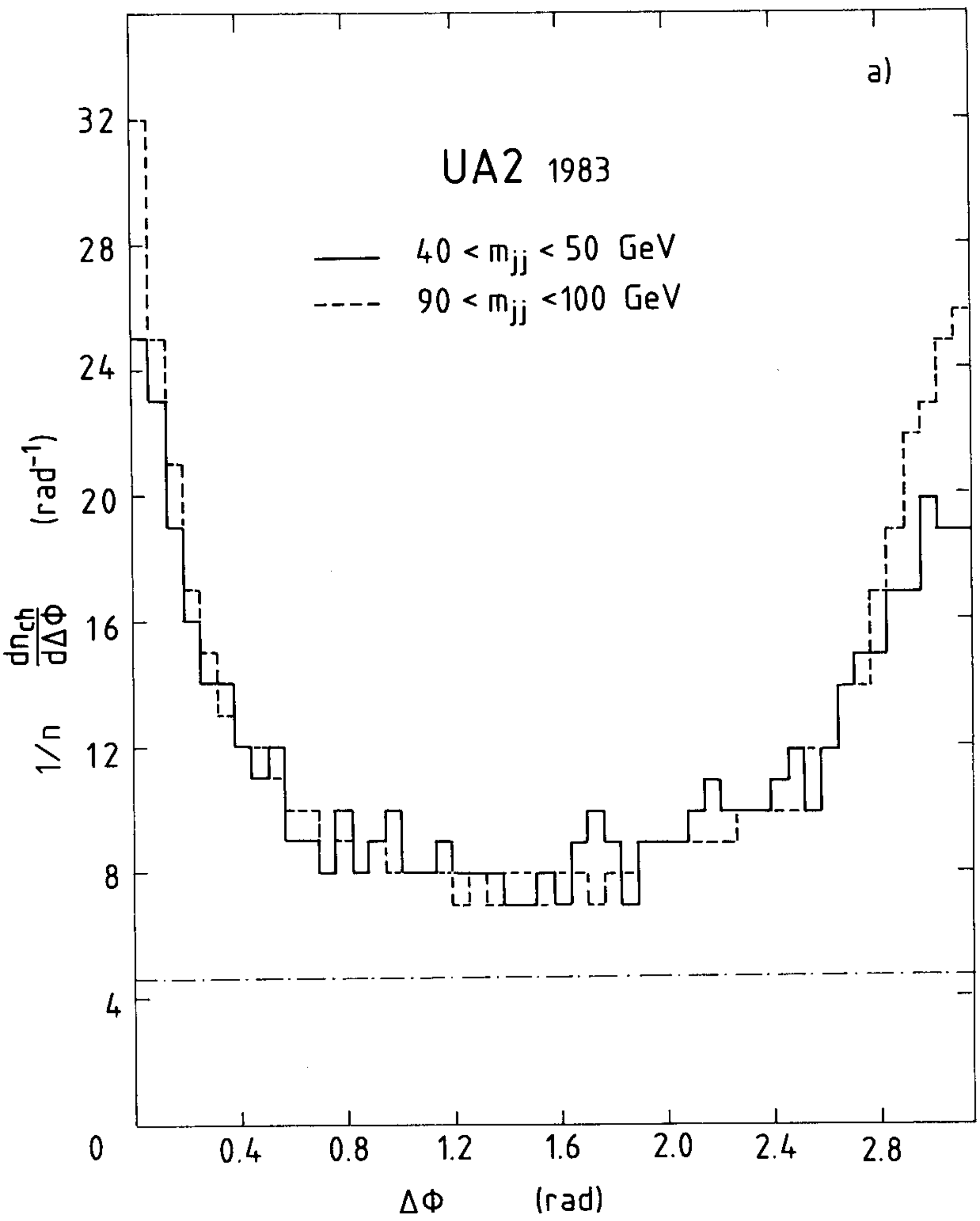

a)
UA2 1983
40 < m_{jj} < 50 GeV
90 < m_{jj} <100 GeV
32
28
24
20
16
12
8
4
0
$1/n \frac{dn_{ch}}{d\Delta\Phi}$ (rad^{-1})
0.4
0.8
1.2
1.6
2.0
2.4
2.8
ΔΦ (rad)

Fig. 1a

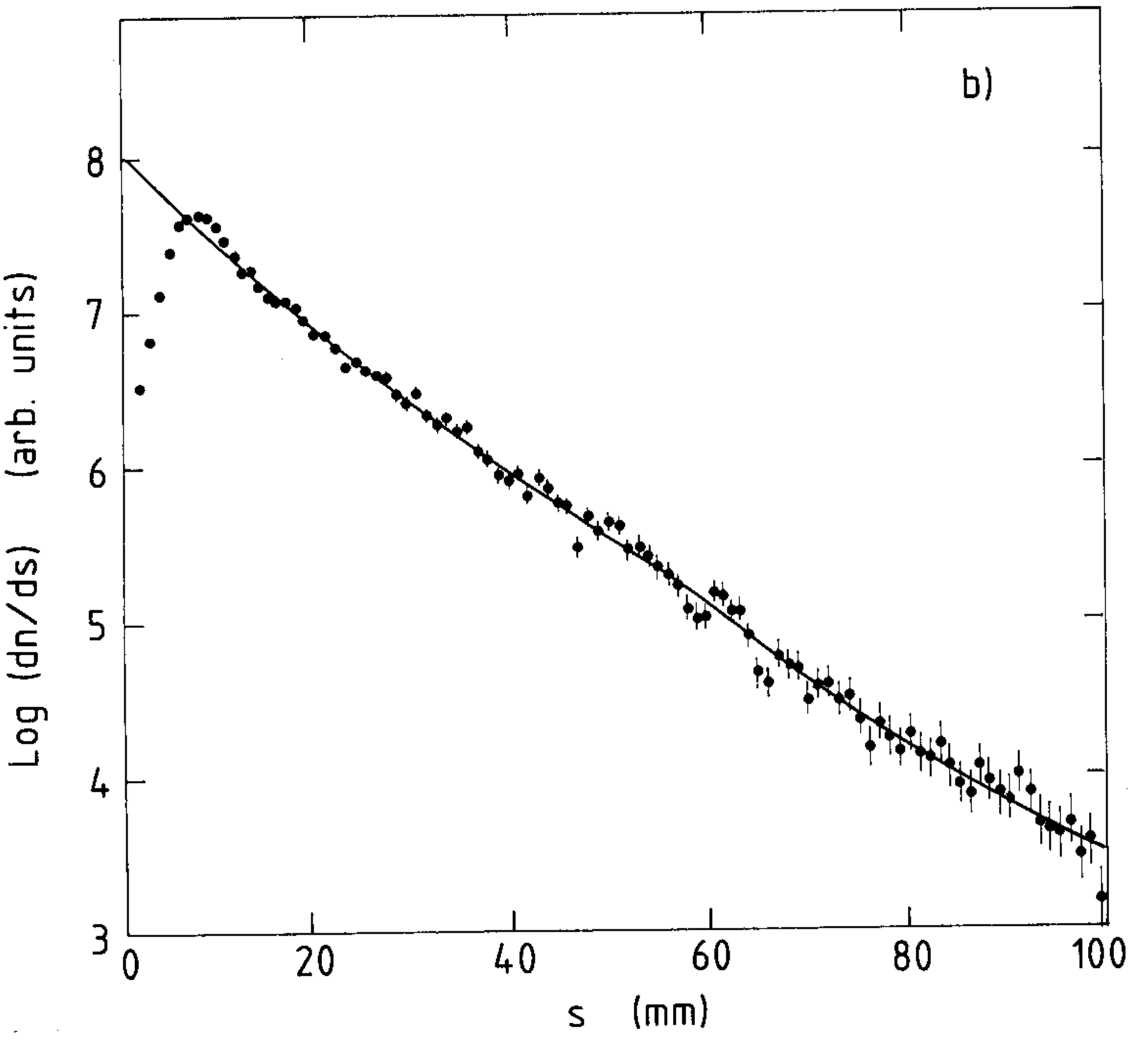
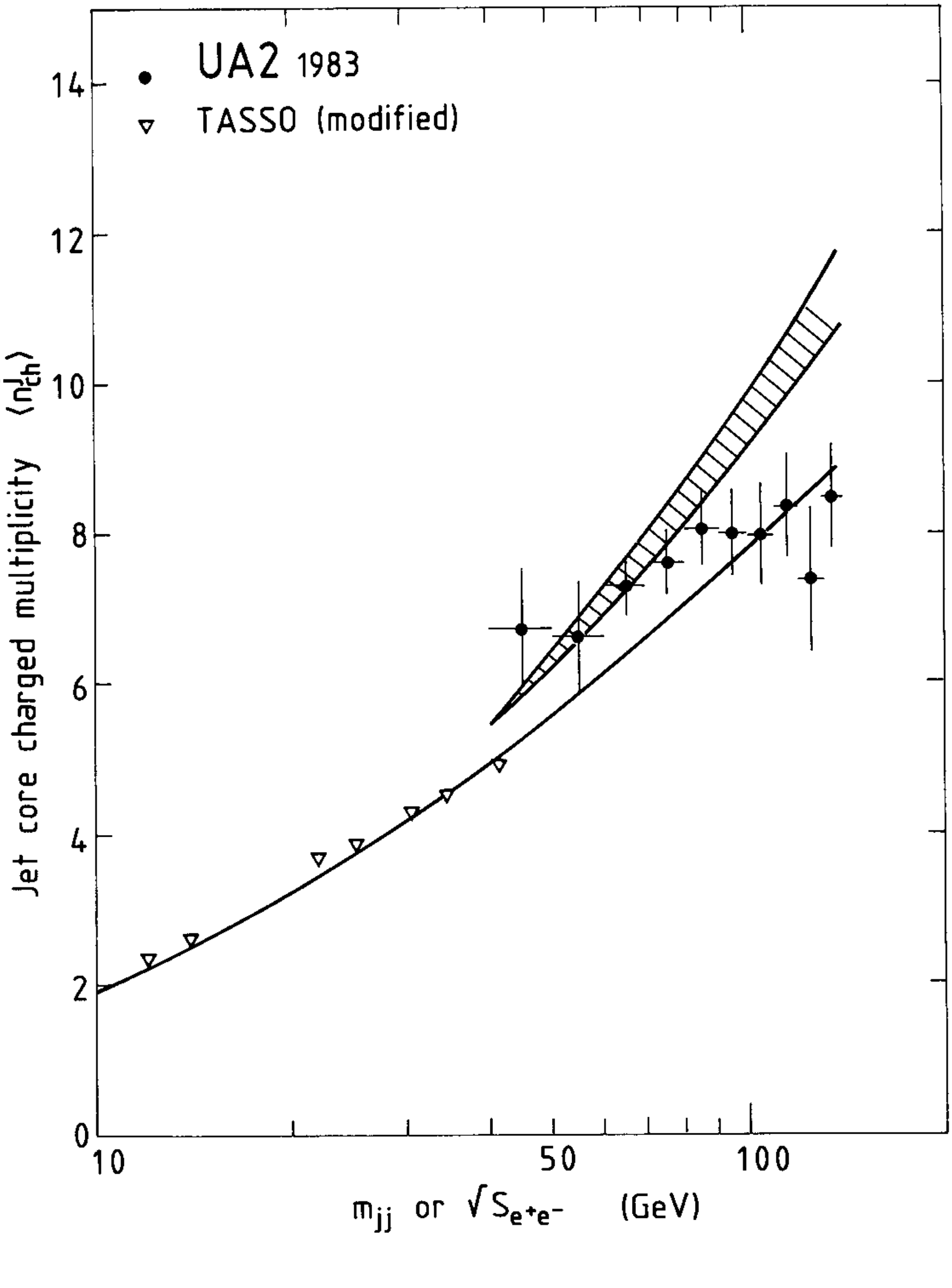
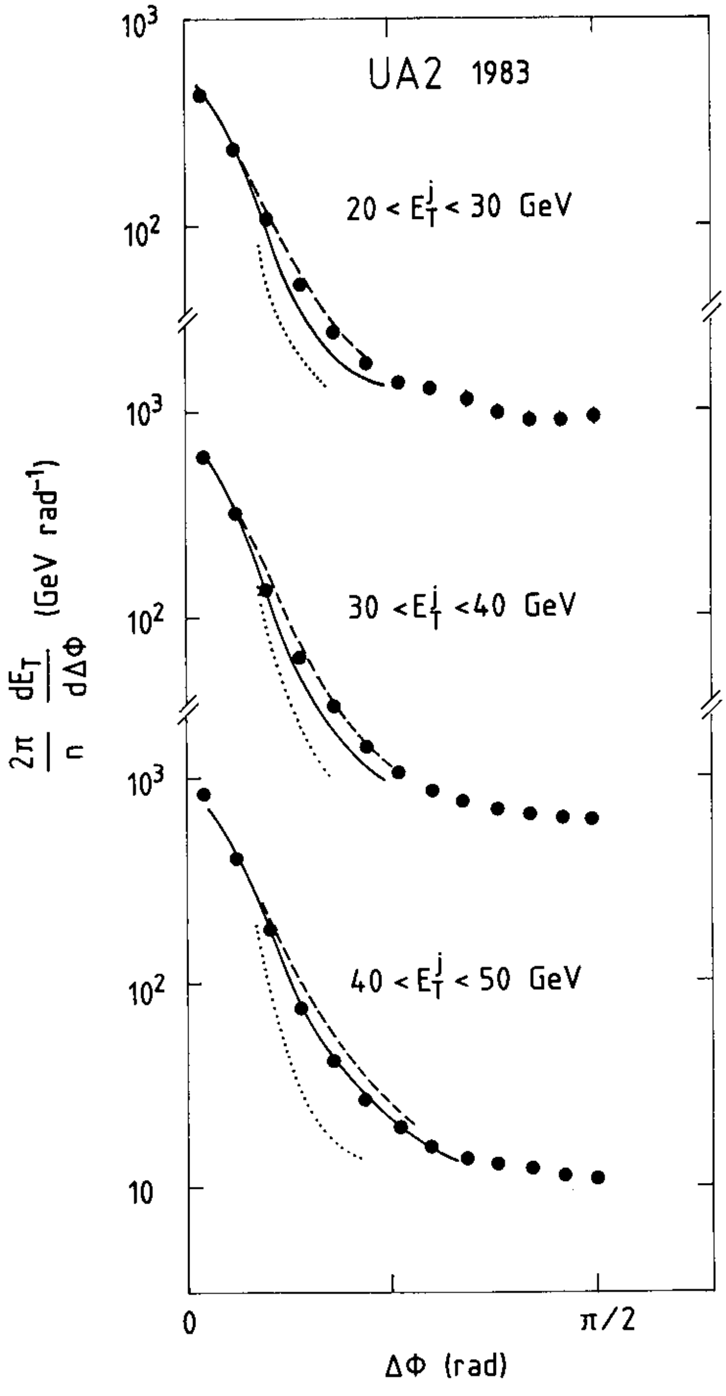


Fig. 1b



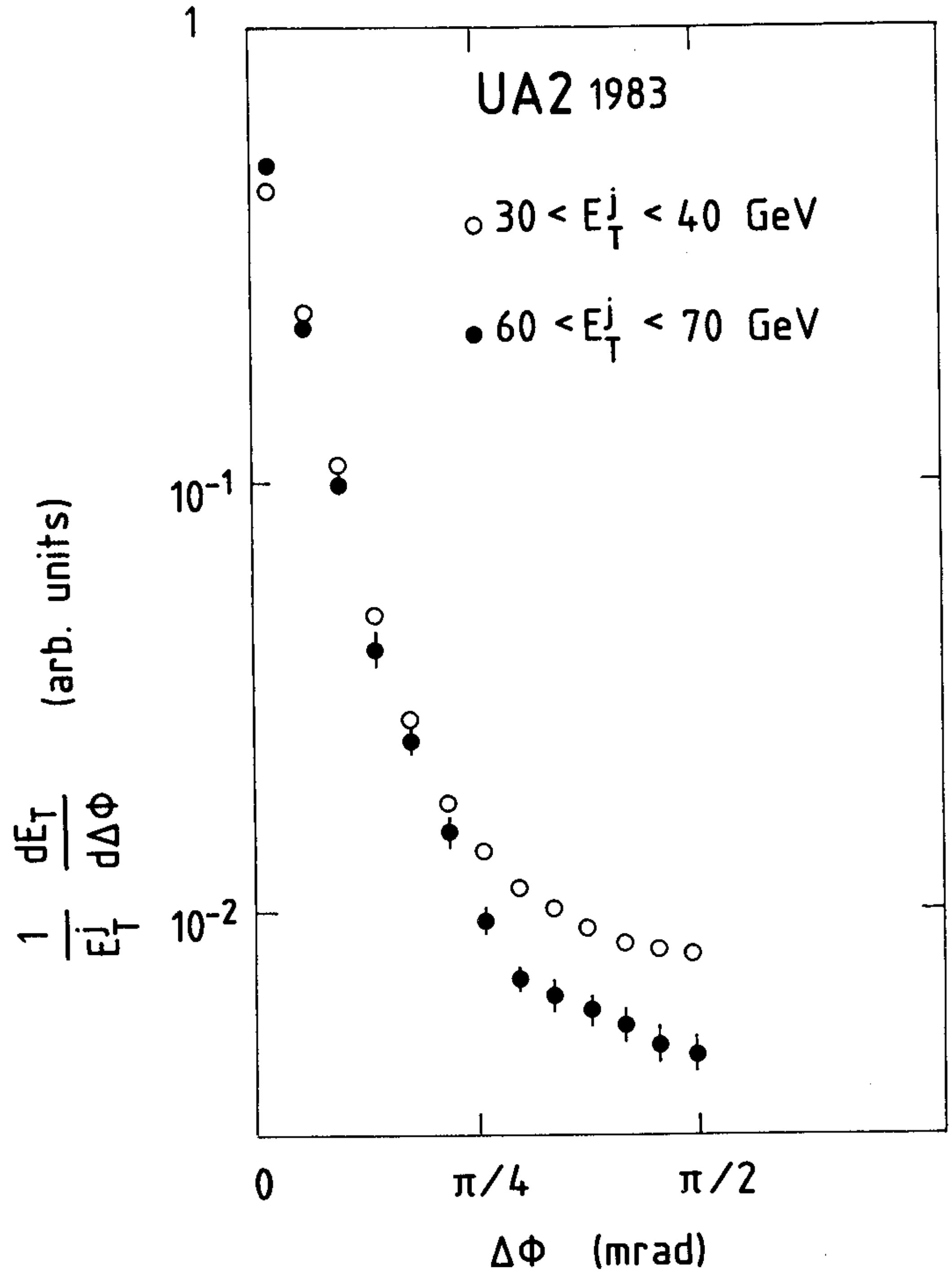
UA2 1983
TASSO (modified)
Jet core charged multiplicity ⟨n^j_{ch}⟩
0
2
4
6
8
10
12
14
10
50
100
m_{jj} or $\sqrt{S_{e^+e^-}}$ (GeV)

Fig. 2



UA2 1983
$20 < E_T^j < 30$ GeV
$30 < E_T^j < 40$ GeV
$40 < E_T^j < 50$ GeV
10^3
10^2
10
$\frac{2\pi}{n} \frac{dE_T}{d\Delta\Phi}$ (GeV rad^{-1})
0
$\pi/2$
$\Delta\Phi$ (rad)

Fig. 3



1
UA2 1983
○ 30 < E_T^j < 40 GeV
● 60 < E_T^j < 70 GeV
10^{-1}
10^{-2}
$\frac{1}{E_T^j} \frac{dE_T}{d\Delta\Phi}$ (arb. units)
0
π/4
π/2
ΔΦ (mrad)

Fig. 4