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A STUDY OF e^+e^- PAIRS IN THE MASS RANGE 11 TO 25 GeV/c^2 AT THE CERN INTERSECTING STORAGE RINGS

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ABSTRACT

A sample of 58 e^+e^- events with an invariant mass greater than 11 GeV/c^2 produced in pp collisions at a centre-of-mass energy of 62.3 GeV is discussed. The cross-sections are presented as a function of the mass and transverse momentum. The electron pairs are produced with a mean transverse momentum of 2.50 ± 0.25 GeV/c.

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A hard scatter between constituent partons in hadronic interactions usually results in a system of two jets at large angles accompanied by two spectator jets [1,2]. The resulting high multiplicity and the variety of diagrams that can contribute make the comparison with theory difficult. Theories about constituent scattering can also be tested in the hadronic production of lepton pairs where one or two of the large angle jets are replaced by two single particles, the leptons. In this less complicated situation, theory can be confronted with experiment in a much more incisive way.

The present letter describes a study of electron pairs produced in proton–proton collisions at the CERN ISR at a centre-of-mass (c.m.) energy, $\sqrt{s}$, of 62.3 GeV. The observation of electrons requires an open geometry which, unlike the study of muons in beam-dump experiments, allows the measurement of charged and neutral particles associated with the electron pair.

The apparatus, shown in fig. 1, consisted of a superconducting solenoid [3] providing a magnetic field of 1.4 T and enclosing a system of 8 cylindrical drift chambers [4]. Four modules of lead-scintillator shower counters were also located inside the magnet. Each module was segmented azimuthally into 8 counters. Each counter was subdivided in depth into a front and a back compartment. The counters were 14 radiation lengths thick and consisted of 16 layers of scintillator interleaved with layers of lead, 4 layers in the front compartment and 12 in the back. The energy deposited in each counter was recorded using photomultipliers at both ends of the front and back compartments. Each module was 1.5 m long, subtended 50° in azimuth and ± 1.1 units of rapidity centred at zero. The detection of electromagnetic showers was completed by two lead-glass (SF 5) modules located outside the magnet in the angular region not covered by the shower counters. A more complete description of the apparatus and calibration methods will be found in refs. [2] and [5]. The r.m.s. energy resolutions, $\Delta E/E$, of the lead glass and shower counters were $(4.3/\sqrt{E} + 2)\%$ and $(16/\sqrt{E})\%$, respectively, with E in GeV. The r.m.s. momentum resolution of the drift-chamber system was $\Delta p_T/p_T = 7\%\ p_T$ (p_T in GeV/c).

The present analysis is restricted to e^+e^- pairs detected in the shower counters only. The invariant mass, m, of the pairs was calculated using the energies as measured in the shower counters and had an r.m.s. resolution of 4% at m = 15 GeV/c^2. The acceptance covered the range $-1.2 < y < +1.2$, where y is the rapidity of the electron pair in the c.m.

The acceptance was calculated using a Monte Carlo program which included apparatus acceptance, resolution effects, and trigger requirements. Events were generated flat in rapidity and with a p_T distribution used by the CFS group [6]:

$$dN/dp_T \propto p_T \{1/[1 + (p_T/p_0)^2]\}^6 , \tag{1}$$

where $p_0 = 2.33 \langle p_T \rangle$.

The decay angular distribution was taken to be $1 + \cos^2\theta^*$. The total acceptance varied from 9% at m = 11 GeV/c^2 to 13% at m = 25 GeV/c^2.

The trigger defined clusters of energy greater than 3.5 GeV in any pair of adjacent shower counters. It then required the presence of at least two such clusters separated by more than 60° in azimuth and with an invariant mass greater than 8.5 GeV/c^2. These thresholds were raised to 4.0 GeV and 10 GeV/c^2, respectively, for about one third of the data presented here. In the analysis these values were raised further to 4.5 GeV and 11 GeV/c, respectively. The data correspond to an integrated luminosity of 1.42×10^{38} cm^{-2} and were collected at an average instantaneous luminosity of 4×10^{31} cm^{-2} s^{-1}.

Since no charged-particle requirement was included in the trigger, the first step in the data reduction was to require a charged-particle track observed in the drift chambers to point to each of the two clusters. The remaining background was then due to

a) the spatial overlap of a charged hadron with a π^0;
b) electrons and positrons from Dalitz decays of π^0's and photon conversions in the beam pipe (0.02 radiation lengths) and the first layer of the drift chamber (0.025 radiation lengths);
c) charged hadrons which deposited most of their energy in the shower counters after interacting in them.

Candidate electron pairs can be of opposite charge or of same charge. It was assumed that the contribution of background processes to the opposite-charge class is given by the number of events in the same-charge class. This is clearly true for background due to Dalitz decays and conversions. For the charged hadronic background this assumption depends on the absence of charge correlations, which is shown to be valid by the data of Albrow et al. [7].

In order to determine cuts that would eliminate these sources of background while preserving a good electron-detection efficiency, the response of the shower counters to electrons and charged pions was studied in test beams at the CERN Proton Synchrotron. The following cuts were then applied to the data:

i) The track pointing to the energy deposition in the shower counters was required to match it within 0.04 radians in azimuth and 12 cm in the longitudinal dimension of the counters.
ii) The ratio, F, of the energy deposited in the front compartments of the counters contributing to the cluster, to the total energy of the cluster was required to be typically in the range $0.08 < F < 0.45$. The actual values of the cut used had a weak energy dependence.
iii) More than 90% of the energy of the cluster was required to be concentrated in two adjacent shower counters.
iv) The measurements of the energy of the candidate electron as given by the shower counters and of its momentum as given by the drift chambers were required to agree within their uncertainties.
v) Since hadrons which cause background events are expected to be parts of jets, it is likely that other hadrons will emerge near them. Hence further suppression of background events was obtained by requiring that the sum of the momenta of all charged and neutral particles within a cone of 25° half angle centred on the electron candidate be less than 0.75 GeV/c. A study of same-charge events showed that the effect of this cut was to reduce the number of background events by about a factor of 20.

The combined efficiency of cuts (i) to (iv) was estimated to be 90% per electron. The track-finding efficiency of cut (v) is difficult to estimate without a detailed knowledge of the event structure of lepton pairs. It is however expected that this cut will have little effect on electron pairs from the basic Drell-Yan process, as electrons from this process are not produced in close association with hadrons. Without this cut 155 opposite-charge events and 97 same-charge events survive, yielding a net signal of 58 events. With the cut the corresponding numbers are 63 and 5, again yielding a net signal of 58. The most likely value of the efficiency is therefore 100% and this value was used in the subsequent analysis. The lower limit of the efficiency of cut (v) was 60% at the 95% confidence level.

The electron-pairs signal was computed by subtracting the 5 same-charge events from the 63 opposite-charge events. The cross-section $d^2\sigma/dmdy|_{y=0}$ for $11 < m < 25$ GeV/c^2 is shown in fig. 2. The data are in good agreement with other e^+e^- results [8] obtained at the same $\sqrt{s}$.Another experiment [9] measured the dimuon continuum at the ISR in the same mass range and with similar statistics but at a larger mean rapidity. The values of $d^2\sigma/dmdy|_{y=0}$ obtained at Fermilab at $\sqrt{s} = 27.4$ GeV by the CFS Collaboration [6] are also plotted in fig. 2. It can be seen that at the lower $\sqrt{s}$ of the Fermilab experiment the cross-sections are lower than the data presented here by about a factor of 20 at $m = 12$ GeV/c^2 and a factor of 1000 at $m = 20$ GeV/c^2. It is of interest to note that the higher cross-sections at the ISR are compensated by the higher interaction rate in the p-nucleus Fermilab experiment such that the mass spectra of both experiments run out of events at about 20 GeV/c^2.

In the Drell-Yan model [10] the quantity $m^3\, d^2\sigma/dmdy|_{y=0}$ or alternatively $s\, d^2\sigma/d\sqrt{\tau}dy|_{y=0}$ is expected to be a function of $\tau\,(= m^2/s)$ only rather than a function of m and s separately. Scaling violations would invalidate this prediction but they have been shown [11] to be less than 10% in the τ and $\sqrt{s}$ range covered by this experiment. The validity of this scaling prediction is demonstrated in fig. 3, where the scaled cross-sections from this experiment and from CFS are seen to agree to better than a factor of 2 in spite of the large differences observed in $d^2\sigma/dmdy|_{y=0}$. As discussed above, the requirement of little energy in the vicinity of the electron candidates could result in an underestimate of the cross-sections.

In order to determine the mean transverse momentum, $\langle p_T \rangle$, of the electron pairs the value of $\langle p_T \rangle$ used in the Monte Carlo was varied until the output p_T distribution best represented the data. In this way $\langle p_T \rangle$ was found to be 2.50 ± 0.25 GeV/c. The acceptance-corrected p_T distribution is shown in fig. 4 together with the form (1) with $\langle p_T \rangle = 2.5$ GeV/c and normalized to the same number of events. The acceptance weighted average of the data yields $\langle p_T \rangle = 2.60 \pm 0.25$ GeV/c.

Values of $\langle p_T \rangle$ obtained in this experiment and at various [6,9,12] $\sqrt{s}$ for $\sqrt{\tau} \sim 0.22$ are plotted in fig. 5 as a function of $\sqrt{s}$. The linear increase with $\sqrt{s}$, as observed in several other compilations [13], is evident. The increase of $\langle p_T \rangle$ with $\sqrt{s}$ is understood, within the framework of QCD, to arise from diagrams other than the simple quark–antiquark annihilation of the Drell-Yan model. Quark–gluon Compton scattering and quark–antiquark annihilation into a virtual photon and a gluon are two such examples. Further evidence for such processes will be discussed in the following letter. A linear fit to the data shown in fig. 5 yields $\langle p_T \rangle = (0.391 + 0.0285\sqrt{s})$ GeV/c. Extrapolating this fit to $\sqrt{s} = 540$ GeV, the mean transverse momentum of lepton pairs at the CERN $p\bar{p}$ Collider at $\sqrt{\tau} = 0.22$ is expected to be (16 ± 2) GeV/c. The values of $\langle p_T \rangle$ reported [14] for the W and Z^0 ($\sqrt{\tau} = 0.15$ and 0.17, respectively) are considerably smaller than this extrapolation. These bosons are expected to be produced by the same mechanisms. Full QCD calculations will have to explain the $\langle p_T \rangle$ for W and Z bosons as well as the $\langle p_T \rangle$ for lepton pairs at lower $\sqrt{s}$ and lower mass.

In conclusion, the cross-sections for the production of e^+e^- pairs in the mass range 11 to 25 GeV/c^2 have been measured at $\sqrt{s} = 62.3$ GeV. The data are consistent with the scaling hypothesis when compared with lower $\sqrt{s}$ data. The mean transverse momentum of the pairs is found to be 2.50 ± 0.25 GeV/c. The large values of the transverse momentum observed indicate contributions from higher order diagrams than the Drell-Yan mechanism.

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For the UA2 results, see the talk of J. Schacher at the 4th Proton–Antiproton Collider Workshop, Bern, March 1984.

Figure captions

Fig. 1 The apparatus viewed along the beam axis.

Fig. 2 The cross-section $d^2\sigma/dmdy|_{y=0}$ obtained in this experiment at $\sqrt{s} = 62.3$ GeV and at $\sqrt{s} = 27.4$ GeV by the CFS Collaboration.

Fig. 3 The scaling quantity $s\, d^2\sigma/d\sqrt{\tau}dy|_{y=0}$ obtained in this experiment at $\sqrt{s} = 62.3$ GeV and at $\sqrt{27.4}$ GeV by the CFS Collaboration.

Fig. 4 The acceptance corrected distribution of the transverse momentum of electron pairs with masses greater than 11 GeV/c^2. A fit to the data, discussed in the text, is also shown.

Fig. 5 The mean transverse momentum of lepton pairs produced in pp collisions plotted as a function of $\sqrt{s}$.

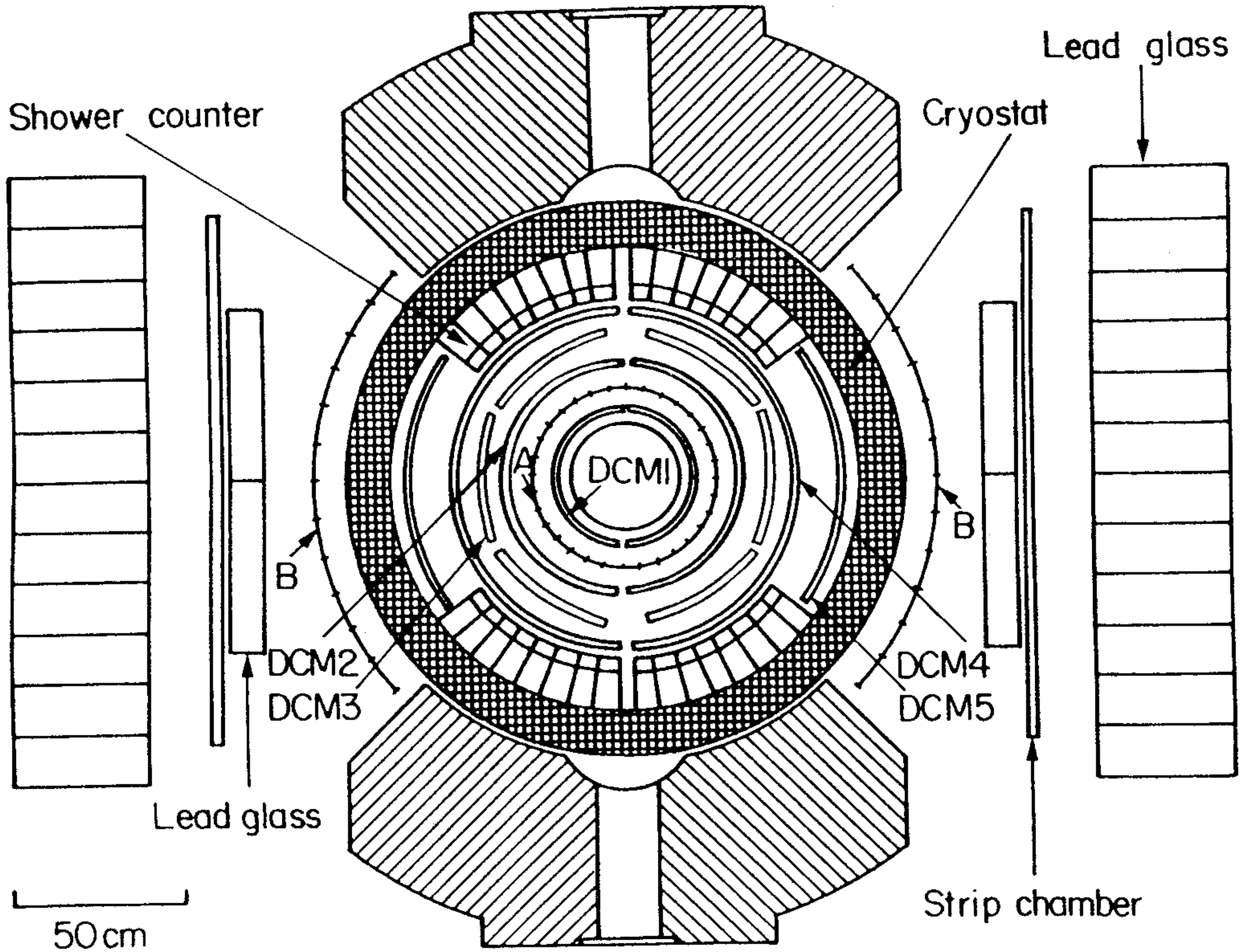
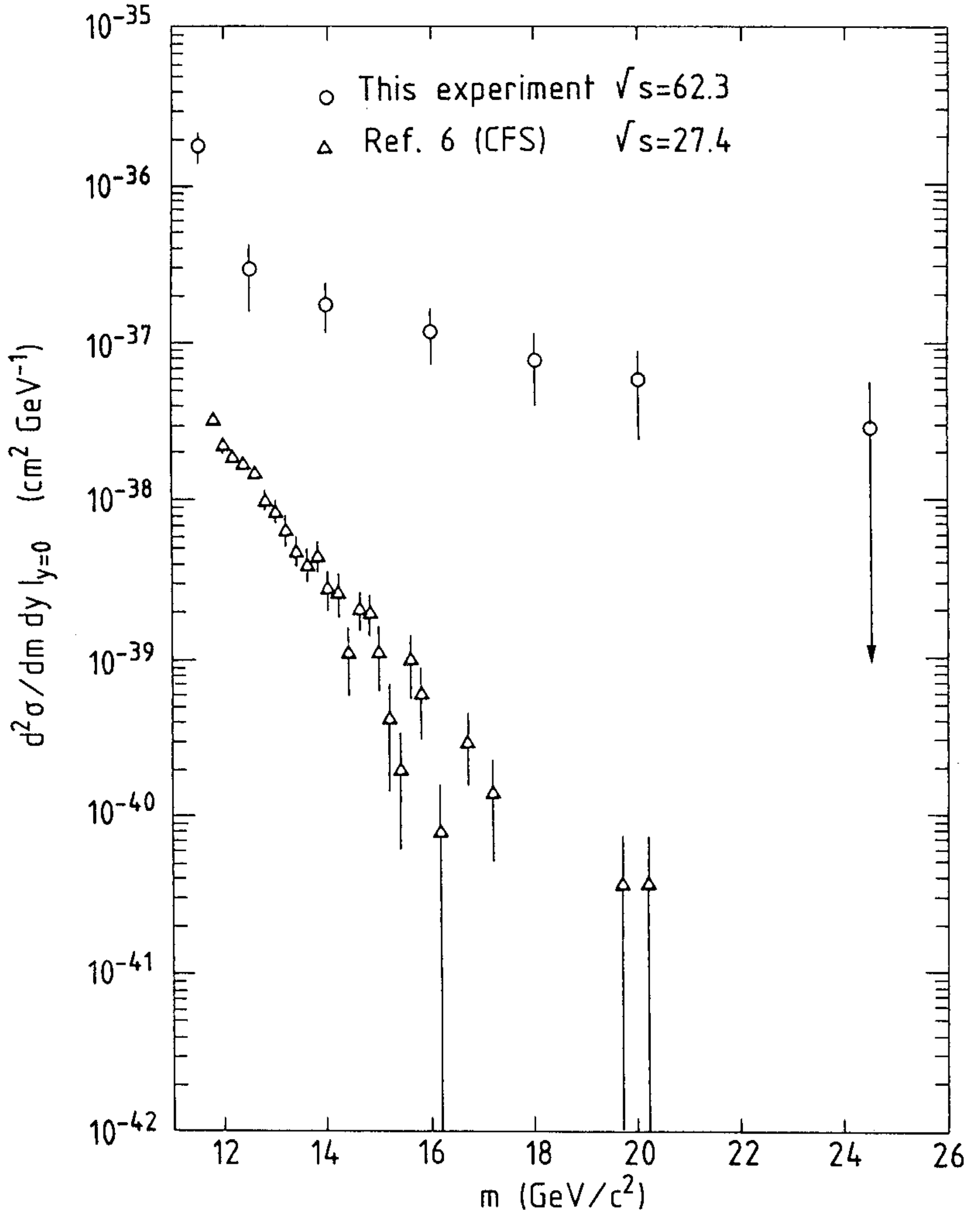

Lead glass
Shower counter
Cryostat
DCMI
A
B
B
DCM2
DCM3
DCM4
DCM5
Lead glass
Strip chamber
50cm

Fig. 1



This experiment √s=62.3
Ref. 6 (CFS) √s=27.4
10^-35
10^-36
10^-37
10^-38
10^-39
10^-40
10^-41
10^-42
d²σ/dm dy |y=0 (cm² GeV⁻¹)
12
14
16
18
20
22
24
26
m (GeV/c²)

Fig. 2

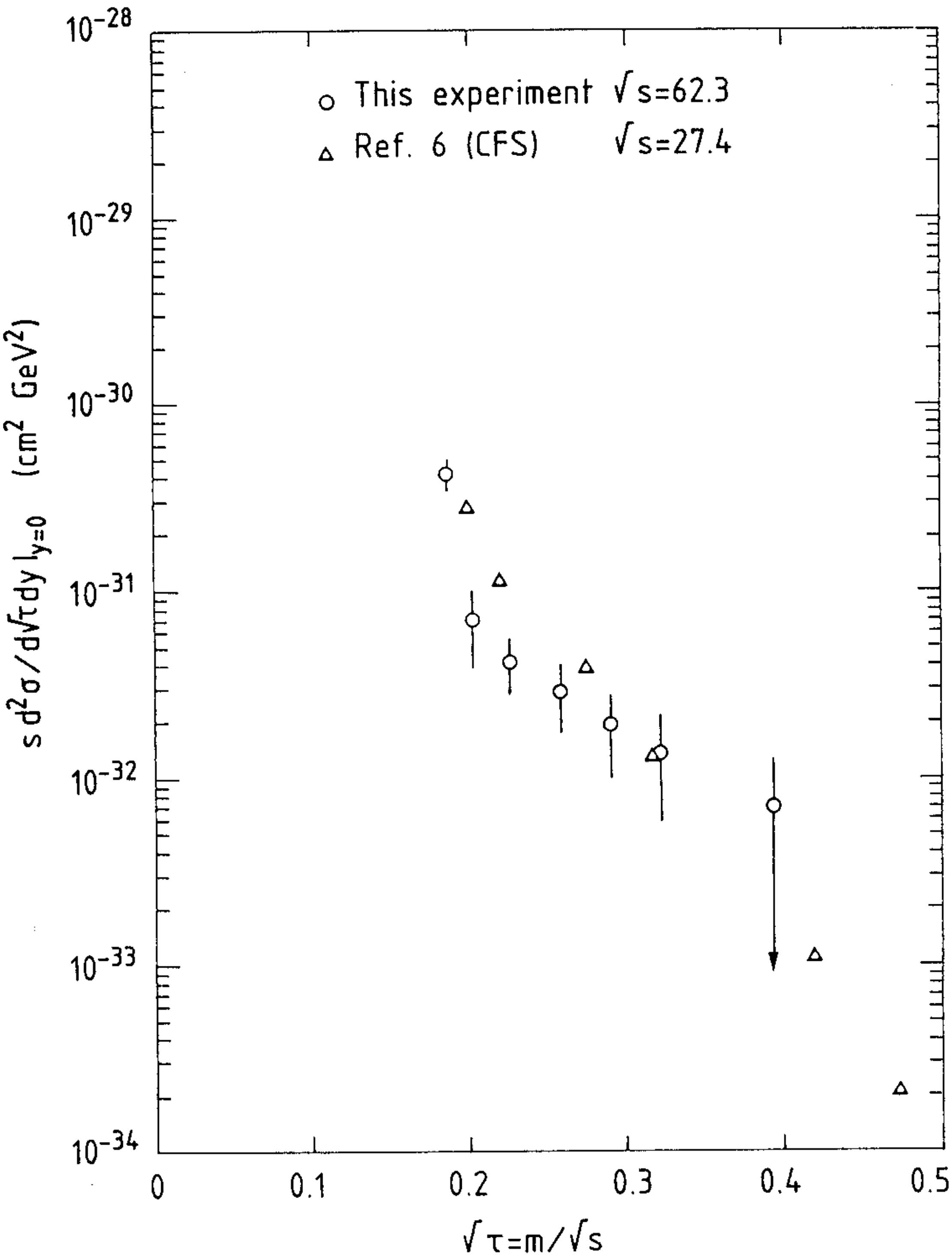
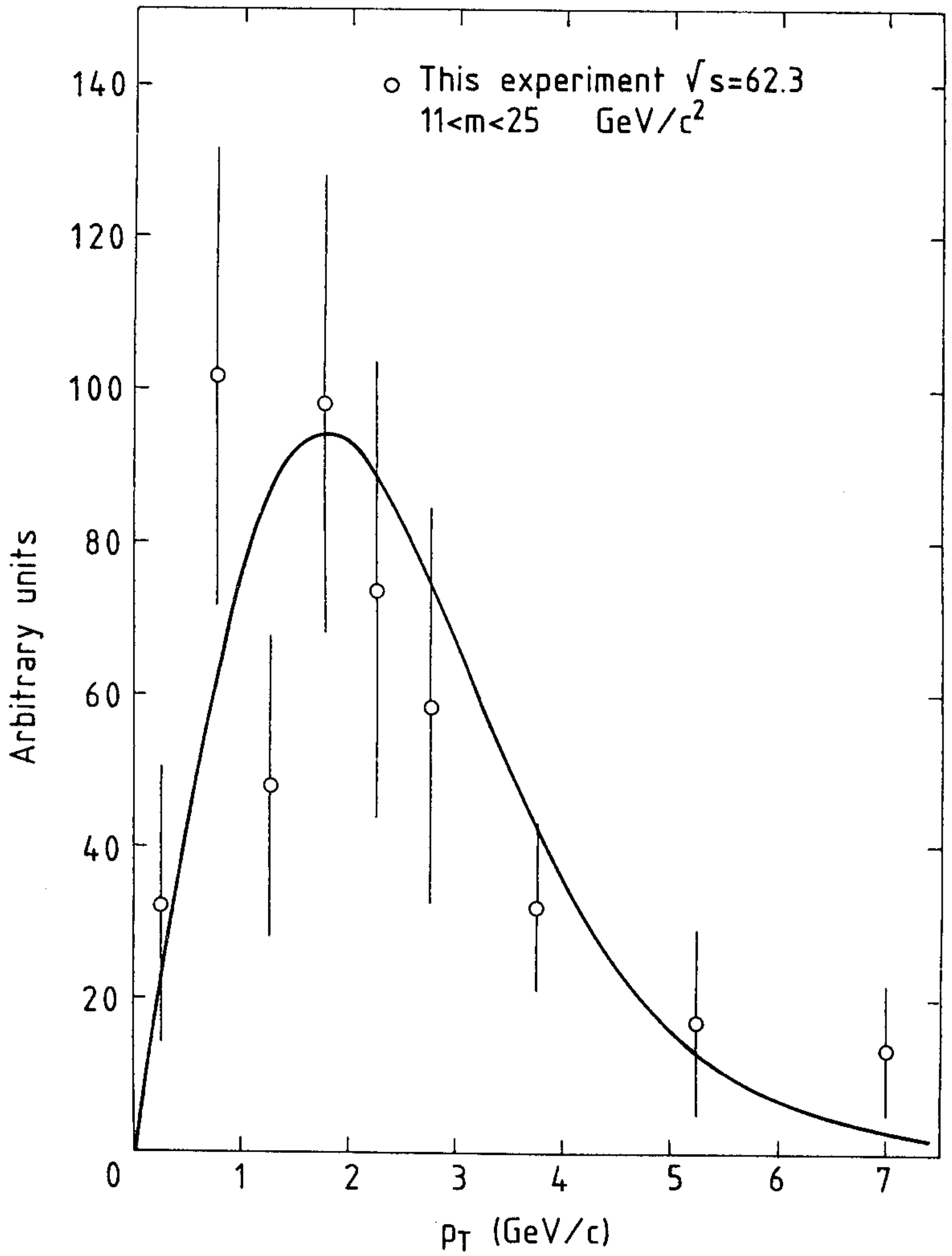
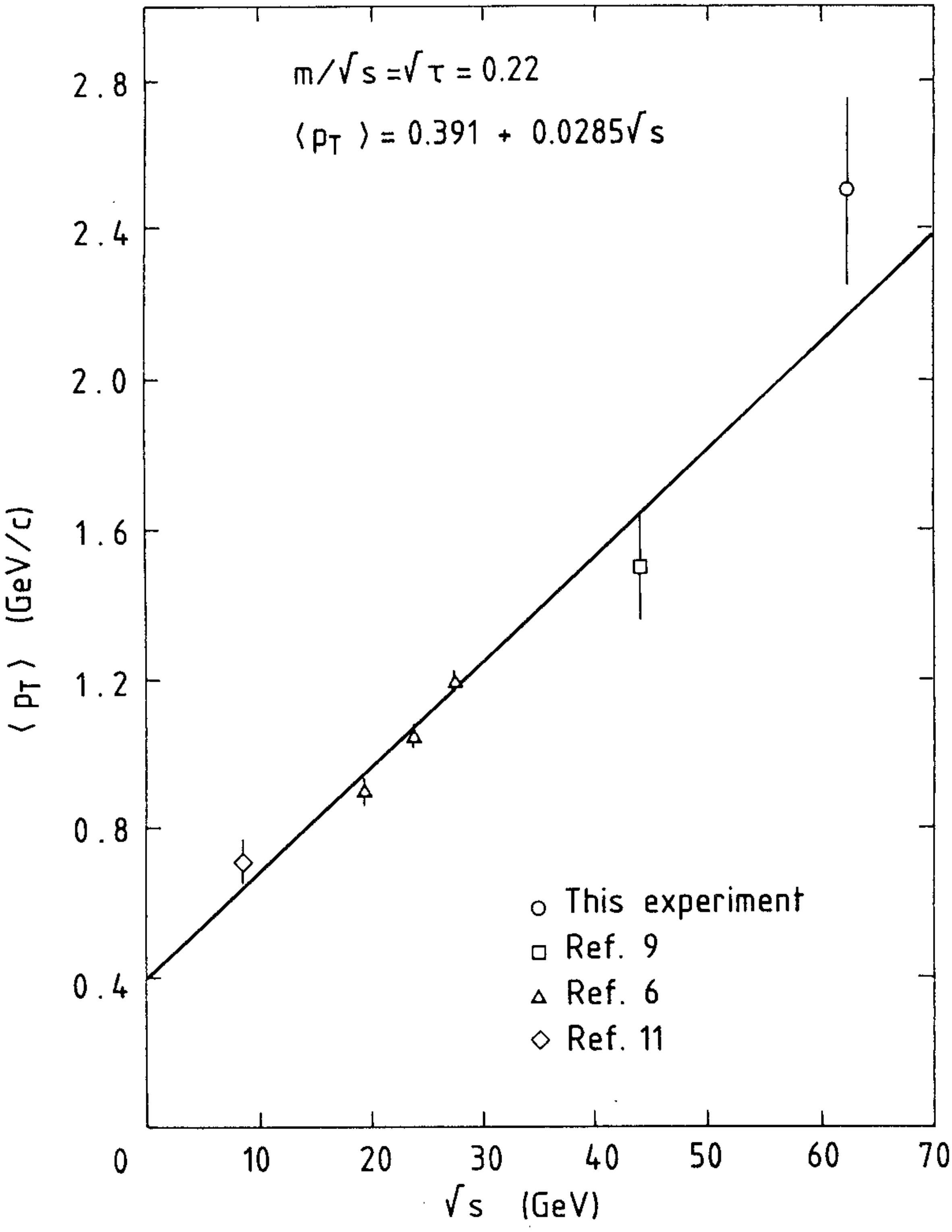

This experiment √s=62.3
Ref. 6 (CFS) √s=27.4
s d²σ/d√τ dy |y=0 (cm² GeV²)
√τ=m/√s
10⁻²⁸
10⁻²⁹
10⁻³⁰
10⁻³¹
10⁻³²
10⁻³³
10⁻³⁴
0
0.1
0.2
0.3
0.4
0.5

Fig. 3



o This experiment √s=62.3
11<m<25 GeV/c²
Arbitrary units
0
20
40
60
80
100
120
140
1
2
3
4
5
6
7
p_T (GeV/c)

Fig. 4



m/√s = √τ = 0.22
⟨pT⟩ = 0.391 + 0.0285√s
2.8
2.4
2.0
1.6
1.2
0.8
0.4
⟨pT⟩ (GeV/c)
0
10
20
30
40
50
60
70
√s (GeV)
This experiment
Ref. 9
Ref. 6
Ref. 11

Fig. 5