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New Phenomena and New Physics

Intermediate Mass Dimuon Events

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Abstract: We report the observation of 67 dimuon events at the CERN $p\bar{p}$ collider with the UA1 detector. The events will be interpreted in terms of the Drell-Yan mechanism, J/Ψ and Υ decays and heavy flavour production.

1. Introduction

The muonic decay of the Z^0 particle is reported in this conference [1]. As dimuon events have the advantage of little background contamination, the search for events with two muons has been extended to the region of lower masses, with the following p_t cuts on the muon:

$$p_t\ (1) > 3\ \mathrm{GeV/c}$$
$$p_t\ (2) > 3\ \mathrm{GeV/c}$$
$$p_t\ (1) + p_t\ (2) > 10\ \mathrm{GeV/c}$$

The results of the 1983 run will be published soon [2]. This contribution is based on the data of the 1983 and 1984 collider runs.
There are several expected sources of medium mass dimuons:
The Drell-Yan mechanism [3]

$$p\bar{p} \to \gamma^* \to \mu^+\mu^-$$

produces unlike sign dimuons with a steeply falling mass spectrum. The J/Ψ and Υ resonances decay into unlike sign muon pairs with branching ratios of 7.5% and 3% respectively. Because of our p_t cuts the J/Ψ can only be observed if it is produced with large p_t. In all these processes the muons are expected to be isolated.

Another source of dimuons is the associated production of heavy quark pairs via strong interactions of quarks and gluons. The heavy quarks can then decay semileptonically into muons:

(1)

$$p\bar{p} \to b\bar{b}$$
$$b \to \mu^-\ c\ \nu$$
$$\bar{b} \to \mu^+\ \bar{c}\ \nu$$

(similarly with c quarks). This process gives rise to unlike sign muon pairs. In bb production the muons can also come from the second generation decay of the c quark, e.g.:

(2)

$$p\bar{p} \to b\bar{b}$$
$$b \to \mu^-\ c\ \nu$$
$$c \to \mu^+\ s\ \nu$$

(3)

$$p\bar{p} \to b\bar{b}$$
$$b \to \mu^-\ c\ \nu$$
$$b \to c\ d\ \bar{u}$$
$$c \to \mu^-\ s\ \nu$$

Process (2) gives unlike sign muon pairs, whereas process (3) produces like sign dimuons. Because of our 3 GeV/c p_t cut we expect that the strongest contribution comes from $b\bar{b}$ pairs rather than $c\bar{c}$ production (about 10%). This is due to the harder fragmentation of the b-quark ($z \approx 0.8$) and the V-A decay. By the same token the second generation decays (2),(3) are surpressed. We therefore expect mostly unlike sign muon pairs. It should be mentioned, that an additional contribution to like sign pairs might come from B^0-$\bar{B}^0$ mixing.

Muons produced in heavy flavour decays are accompanied by hadrons from the fragmentation of the heavy quark and the products of its semileptonic decay. The muons are therefore expected not to be isolated.

Heavy quarks can also be produced by the decay of Intermediate Vector Bosons, e.g.:

(4)

$$Z^0 \rightarrow b\bar{b}$$
$$b \rightarrow \mu^- c \nu$$
$$\bar{b} \rightarrow \mu^+ \bar{c} \nu$$

(5)

$$W^+ \rightarrow t\, b$$
$$b \rightarrow \mu^+ c \nu$$
$$t \rightarrow \mu^+ b \nu$$

There we expect events with high transverse energy jets. Process (4) will lead to unlike sign pairs, process (5) to like sign pairs, which are not isolated.[1]

2. Detection and Identification of Muons, Jets and Neutrinos.

2.1 Muon Detection

The UA1 detector has been described in detail elsewhere [4]. In brief a muon coming from the interaction point has to traverse the central detector (CD) where its momentum is measured in a 0.7 T dipole field. The accuracy of the muon momentum measurement in the CD is $\Delta p/p = 0.005p$ (GeV/c). It then has to pass the electromagnetic calorimeter, the hadron calorimeter and additional iron shielding. This are more than 9 interaction lengths of material. Finally the muon is detected in the muon chambers which surround the central calorimeters, covering 75% of the solid angle.

The muon detector consists of two chambers seperated by 60 cm. Each chamber consists of two double layers of drift tubes, and both projections of a track can

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[1] However the muon from the top decay tends to be isolated, because of the high mass of the top

be measured seperately.[2] The chambers achieve an average spatial resolution of 300 μm. The muon detector has a trigger capability. The muon trigger checks if the hit pattern in the drift tubes is compatable with a track comming from the vertex. This selects events with a track in the muon chambers pointing to the vertex within a cone of ±150 mrad.

2.2 Jet Identification

Jets are defined by the standard UA1 jet algorithm [5] applied to energy vectors from calorimeter cells. A correction is applied to the measured energy and momentum of a jet (about 25 %) as a function of pseudorapidity, azimuth and transverse energy on the basis of test beam data and Monte Carlo studies.

2.3 Neutrino Identification

The presence of neutrinos is signalled by an apparent transvers energy imbalance when the calorimeter measurement of missing transverse energy is combined with the muon transverse momenta measurements. For relatively low muon momenta (p_t < 10 GeV/c), where the momentum errors of the tracks are small, the accuracy of the missing transverse energy is $0.7 \sqrt{\Sigma E_t}$, where ΣE_t is the scalar sum of the transverse energy (in GeV) deposited in each calorimeter cell.

3. Event Selection

During the 1983 and 1984 data taking periods we recorded an integrated luminosity of 378 nb^{-1} Events were triggered in both years using the muon trigger which required a track in the muon chambers pointing to the vertex as described in section 2. The first stage of event selection was an inclusive search for high p_t muons. In 1983 this was done using an off-line fast filter program which selected muon candidates with p_t > 3 GeV/c. In 1984, 168E on-line processors were used to select muon candidates. A selection program which applied stricter CD track quality and CD/muon chamber matching requirements was used to select muon events. This resulted in about 70000 events from 1983 and 1984. A dimuon selection was made from these events requiring:

$$p_t\,(1) > 3\ \mathrm{GeV/c}$$
$$p_t\,(2) > 3\ \mathrm{GeV/c}$$

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[2] With exception of the bottom chambers. There are drift tubes only in one projection, the other is measured by time division.

$$p_t(1) + p_t(2) > 10 \text{ GeV/c}$$

251 candidates were selected.

These events were scanned on a computer graphics display facility. 91 events were identified as cosmic rays, 74 events as leakage of a hadronic shower, 7 were 'kinks' (K-decays), 9 events were Z^0 canditates, 3 events have ambiguous matching between CD tracks and tracks in the muon chambers and are not considered here, leaving 67 dimuon candidates.

4. Background

We have considered a number of possible backgrounds to the muon sample. High p_t charged hadrons can fake muons either by penetrating the calorimeters and the additional iron shielding without interaction, or by leakage of the hadronic shower. As the particles have to traverse more than 9 interaction lengths, the probability to pass without interaction is extremely low. This probability has been measured in a test beam and is less than 10^{-4}, after requiring a good matching between CD and muon chamber.
The dominant background is due to pion and kaon decays. The probability for a pion (kaon) to decay in flight before reaching the calorimeter is $0.02/p_t$ $(0.11/p_t)$, where p_t is in GeV/c. Assuming that pions (kaons) constitude 50% (25%) of all charged particles the probability to fake a muon by decay is about $0.04/p_t$ per hadron.

The background of the dimuon sample due to pion and kaon decays has been studied extensively. This was done using an inclusive muon sample of $p_t > 3$ GeV/c. We looked for high p_t tracks and simulated their decay assuming them to be hadrons. We then applied the same cuts as for the dimuon sample. Scaling to an integrated luminosity of 378 nb^{-1} the background to the dimuon sample is estimated as 4.1 events. The background is shown in figure 1 integrated over different regions in the plot of p_t (fast muon) versus p_t (slow muon).
The background for events with isolated muons is much lower. For events with both muons isolated we expect a background of less than one event.

5. Classification and Interpretation of Events

In this section the events are classified in terms of isolation, like sign or unlike sign muons and dimuon masses. The isolation is an important tool to distingush between Drell-Yan process (Υ and J/Ψ as well) and heavy flavour decay. We classify muons as isolated if the sum of the transverse energy (ΣE_T) in a cone of $\Delta R < 0.7$ is less than 4 GeV. ΔR is defined as:

$$\Delta R^2 = \Delta\eta^2 + \Delta\Phi^2$$

η : pseudorapidity

ϕ : azimuth in radians

This criterion was deduced from minimum bias events in which a ΔR cone was randomly distributed. Summing the E_t and unfolding the Landau distribution of the energy loss of the muon we got the distribution shown in Fig. 2 b) (dashed line).

Using this isolation criterion we found 25 (7) unlike (like) sign events with both muons isolated and 27 (8) events with at least one muon not isolated.
The isolated unlike sign events are interpreted as Drell-Yan process, J/Ψ or Υ decays. The not isolated dimuons will be discussed as heavy flavour decays.
We see also 7 events with like sign isolated muons which do not fit in these categories. These events are not discussed here [11].

5.1 Drell-Yan Candidates

Drell-Yan events should be characterized by two unlike sign muons that are isolated. Twentyfive events fullfill these criteria. If we exclude events with dimuon masses in the J/Ψ and Υ region (2.5 - 3.5 GeV/c² and 9 - 11 GeV/c²) 13 events remain. The events with masses below 10 GeV/c² have to be produced with a large p_t to satisfy our cuts. We observe 5 such events.
7 events have masses larger than 11 GeV/c². We used the ISAJET Monte Carlo [6] to calculate the acceptance of our apparatus for Drell-Yan muons. Assuming that all 7 events are from Drell-Yan production, we find the total Drell-Yan Cross section for masses larger than 11 GeV/c²:

$$\sigma^{dy}\ (M > 11\ \mathrm{GeV/c^2}) = 0.23 \pm 0.09\ \mathrm{nb}$$

if the scaling function $F(\tau) = m^3\, d^2\sigma/dmdy\ (y=0)$ is compared to the extrapolation of low energy data [7] it fits reasonably well (Fig. 3). However we remind the reader that the sample may be contamined by dimuons from heavy flavour production, and no correction has been applied.

5.2 J/Ψ Candidates

J/Ψ candidates are identified on the basis of the dimuon mass. 5 events were cluster near 3.1 GeV/c² and are interpreted as J/Ψ decays (Fig. 4). Due to the p_t cuts applied in the selection, such events are only observed if the J/Ψ is produced at very large p_t . Since the p_t distribution is not known very well, it is not possible to calculate an acceptance corrected cross section for J/Ψ production.

5.3 Υ Production

Eight events with unlike sign isolated muons are compatible with masses of the Ψ states. Because of our cuts the acceptance changes rapidly in the mass region from 9 to 11 GeV/c². Hence our acceptance is very sensitive to the p_t distri-

bution of the Υ. The same is true for the Drell-Yan background in this region. In order to improve our acceptance we reselected isolated events with masses larger than 6 GeV/c², dropping the $p_t(1) + p_t(2) > 10$ GeV/c cut. Up to now this has been done for 1984 data only, for 1983 the work is in progress.
We found 20 additional events, 8 of these events are Υ candidates. The mass spectrum of these events is shown in Fig. 6. Included is our prediction for the Drell-Yan background using the ISAJET Monte Carlo. If we use the Drell-Yan acceptance from ISAJET for the Υ, we can calculate the cross section for Υ decaying to $\mu^+\mu^-$[3]:

$$\sigma\ (p\bar{p} \rightarrow \Upsilon\ X \rightarrow \mu^+\mu^-\ ) = 0.57 \pm 0.23\ \text{nb}$$

The scaling function $d\sigma/dy$ $(y=0)$ is in good agreement with the theoretical prediction of Barger et al. [8].

5.4 Heavy Flavour Candidates

Muons coming from the decay of heavy flavours are expected to be not isolated. The dimuon sample contains 35 events where at least one muon is not isolated according to our criteria. One event is excluded, as it is a J/Ψ candidate. 8 of these events have like sign muon pairs. The ΣE_t distribution for these events is shown in Fig. 2. Also show is the distribution for ΣE_t obtained from the EUROJET Monte Carlo [9] From this the probability of one muon to be isolated is 0.3 per muon. If the we assume that the probability for both muons to be isolated is 0.3^2 ,we expect 3 events from heavy flavour decays contaminating the Drell-Yan sample.
In 27 events the muons are in differnt hemispheres, in 7 events both muons are in the same hemisphere, coming most likely from the first and second generation decay.
The degree of B^0-$\bar{B}^0$ mixing can in principle be measured using the ratio of the numbers of like sign to unlike sign events. We observe a ratio of:

$$R = 0.3 \pm 0.1$$

This value lies within the boundaries of the Monte Carlo prediction [9]

$$R = 0.24 - 0.47$$

0.24 : no B^0-$\bar{B}^0$ mixing
0.47 : full B^0-$\bar{B}^0$ mixing

However, because of the large statistical error no statement about the degree of mixing can be made.

We can form a μ-μ-jet-jet system from the jets associated to the muons. If both muons are associated to the same jet, the largest jet opposite is used as the second jet. If there is no jet around the muon in $\Delta R < 1.0$ a jet is formed by adding the energy vectors of all calorimeter cells around the muon in $\Delta R <$

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[3] A production ratio of $\Upsilon : \Upsilon' : \Upsilon'' = 1 : 0.3 : 0.15$ was assumed [10]

0.7. The mass of the μ-μ-jet-jet system is shown in Fig. 8. Superposed is the prediction from the EUROJET Monte Carlo for QCD production. The curve is in reasonable agreement with the data for low masses, but we observe an excess of events in the region above 80 GeV/c² . This might be due to Intermediate Vector Bosons decaying to heavy quarks. By comparision of our data with the predictions of the EUROJET Monte Carlo (including our acceptance due to cuts and geometry) we obtain a cross section for $b\bar{b}$ production:

$$\sigma\ (p\bar{p} - b\bar{b}) = 2.3 \pm 0.4 \pm 0.4\ \mu b$$
$$\text{for } p_t(b) > 5\ \text{GeV/c}$$
$$\text{and } |\eta| < 2.0$$

6. Conclusions

In the data from the 1983 and 1984 runs, corresponding to an integrated luminosity of 378 nb^{-1} , we observe 67 intermediate mass dimuon events. We interpret 5 events as J/Ψ decays. 8 are ϒ candidates. In order to be more sensitive for the ϒ we relaxed our cuts and got 8 additional candidates. We give a cross section for ϒ decaying in muons:

$$\sigma(p\bar{p} \rightarrow \Upsilon X \rightarrow \mu^- \mu^+) = 0.57 \pm 0.23\ \text{nb}$$

13 unlike sign, isolated events can be explained as Drell-Yan candidates. Using 7 events with a mass larger than 11 GeV/c² we calculate a cross section:

$$\sigma^{dy}(M^{\mu\mu} > 11\ \text{GeV/c}^2) = 0.23 \pm 0.09\ \text{nb}$$

But it is possible that these events contain some coming from heavy flavour decays. We observe 34 events which are interpreted as heavy flavour decays. This corresponds to a cross section of:

$$\sigma(p\bar{p} \rightarrow b\bar{b}) = 2.3 \pm 0.4 \pm 0.4\ \mu b$$
$$p_t(b) > 5\ \text{GeV/c}$$
$$|\eta| < 2.0$$

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References

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[2] UA1 Collaboration, G. Arnison et al.: 'Intermediate Mass Dimuon Events at the CERN $p\bar{p}$ Collider at $\sqrt{}$=540 GeV', to be published in Phys. Letters B.

[3] See for example:
S. Pakvasa et al., Phys. Rev. D20 (1979) 2862
Z. Kunszt and E. Pietarinen, Nucl. Phys. B164 (1980) 45

[4] M. Barrao Luque et al., Nucl. Instrum. Methods 176 (1980) 75
M. Calvetti et al., Nucl. Instrum. Methods 176 (1980) 255
M. Calvetti et al., IEEE Trans. Nucl. Sci. NS-30 (1983) 71
M. Corden et al., Phys. Scr. 25 (1982) 5 and 11
K. Eggert et al., Nucl. Instrum. Methods 176 (1980) 217
The the muon detection is also described in [1]

[5] UA1 Collaboration, G. Arnison et al., Phys. Lett. 132B (1983) 214.

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[8] R.J.N. Phillips, in Proc. of the XX International Conference on High Energy Physics, Madison, 1980 (AIP Conf. Proc. 68, 1981)

[9] These calculations were made using the EUROJET Monte Carlo program which contains all first order (α_s^2) and second order (α_s^3) QCD processes [see B. Van Eijk, UA1 Technical Note UA1/TN/84-93 (1984), unpublished, and A. Ali, E. Pietarinen and B. Van Eijk, to be published]. The heavy quark is fragmented using the parametrization of C. Peterson et al., Phys. Rev. D27 (1983) 105, and V-A matrix elements.

[10] J.K. Yoh et al. Phys. Rev. Lett. 41 (1978) 684.

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Figure Captions

1. p_t of the slow muon versus p_t of the fast muon.
Also shown is the estimated number of background events integrated over different regions of the plot.

2. Transverse energy in a ΔR cone of 0.7 around the muon (ΣE_t).

   a. ΣE_t of the slow muon versus ΣE_t of the fast muon

   b. ΣE_t of both muons. The curves show the expected distributions for heavy flavour decays (solid line) and for a randomly orientated cone in minimum bias events (dashed line).

3. P_t of the dimuon versus the mass of the dimuon for isolated unlike sign events (p_{t1} + p_{t2} > 10 GeV/c). The small figure shows the mass spectrum of these events.

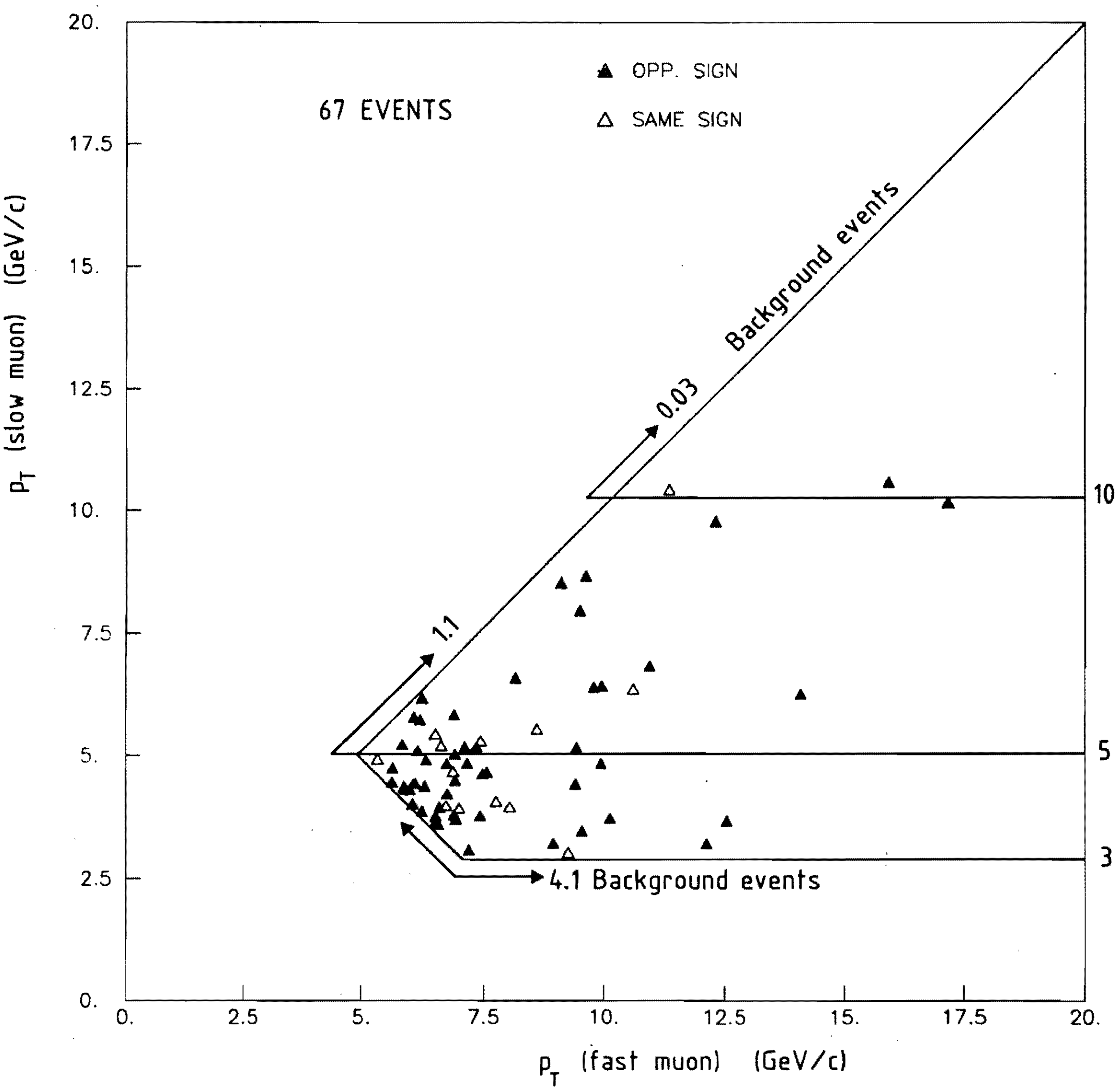
4. The scaling function for the Drell-Yan process:
$F(\tau)=m^3 d^2\sigma/dmdy$ (y=0) $\tau=m/\sqrt{s}$ [7]
Our data point includes both the 1983 ($\sqrt{s}$=540 GeV) and 1984 ($\sqrt{s}$=630 GeV) data.

5. Mass distribution of the 5 J/Ψ candidates

6. Mass distribution of isolated unlike sign dimuons.
p_t>3 GeV/c and $M^{\mu\mu}$ > 6 GeV/c² (1984 only)
The solid line shows the expected background from the Drell-Yan process including the acceptance.

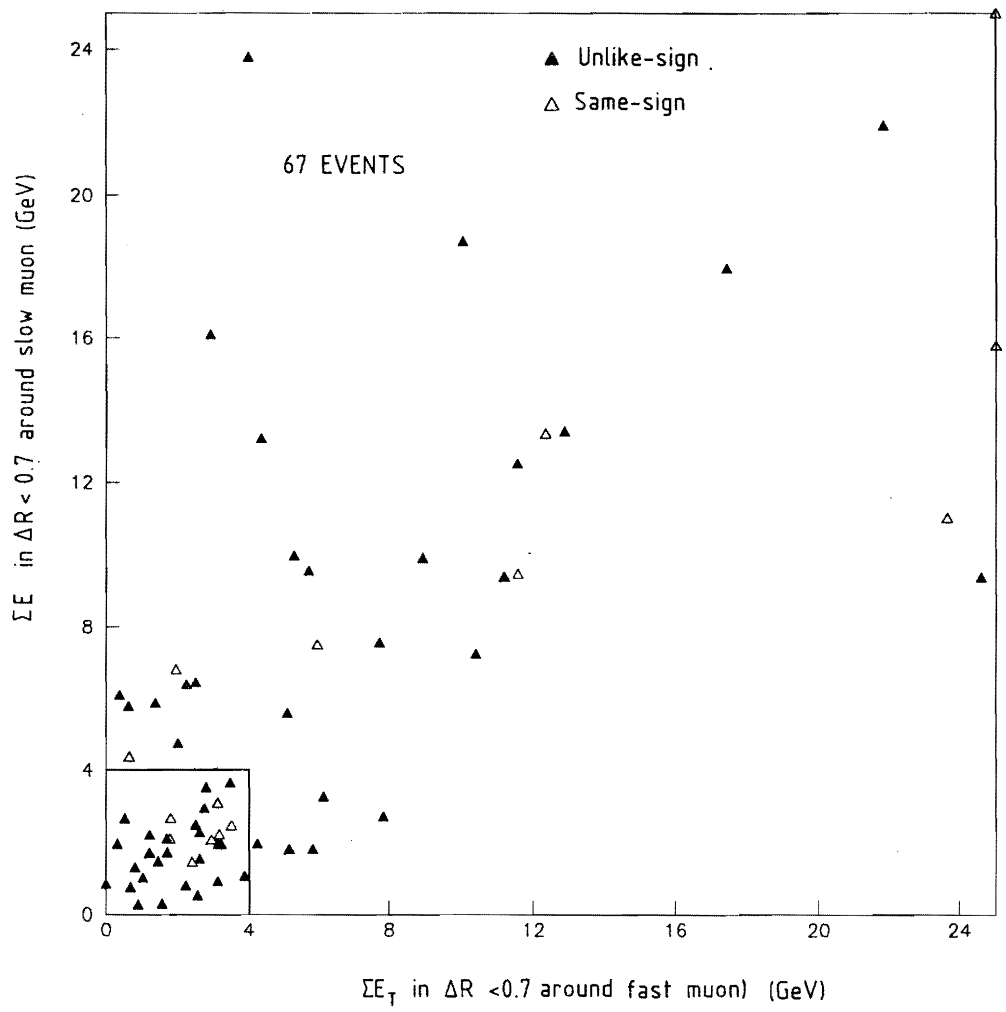
7. Υ cross section calculated from gluon fusion [8]

8. Mass distribution for the μ-μ-jet-jet system. The solid line shows the distribution for QCD-processes, calculated using the EUROJET Monte Carlo [9]



20.
17.5
15.
12.5
10.
7.5
5.
2.5
0.
0.
2.5
5.
7.5
10.
12.5
15.
17.5
20.
67 EVENTS
OPP. SIGN
SAME SIGN
Background events
0.03
1.1
4.1 Background events
10
5
3
p_T (slow muon) (GeV/c)
p_T (fast muon) (GeV/c)

fig.1


▲ Unlike-sign
△ Same-sign
67 EVENTS
ΣE in ΔR < 0.7 around slow muon (GeV)
ΣE_T in ΔR <0.7 around fast muon) (GeV)

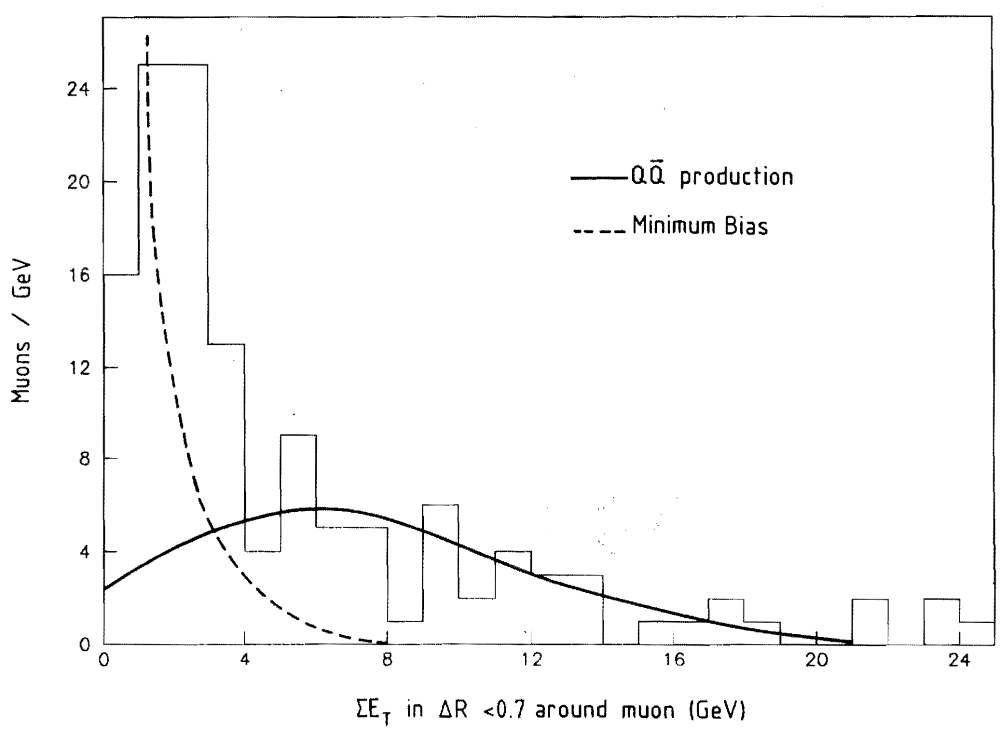

QQ̄ production
Minimum Bias
Muons / GeV
ΣE_T in ΔR <0.7 around muon (GeV)

fig.2

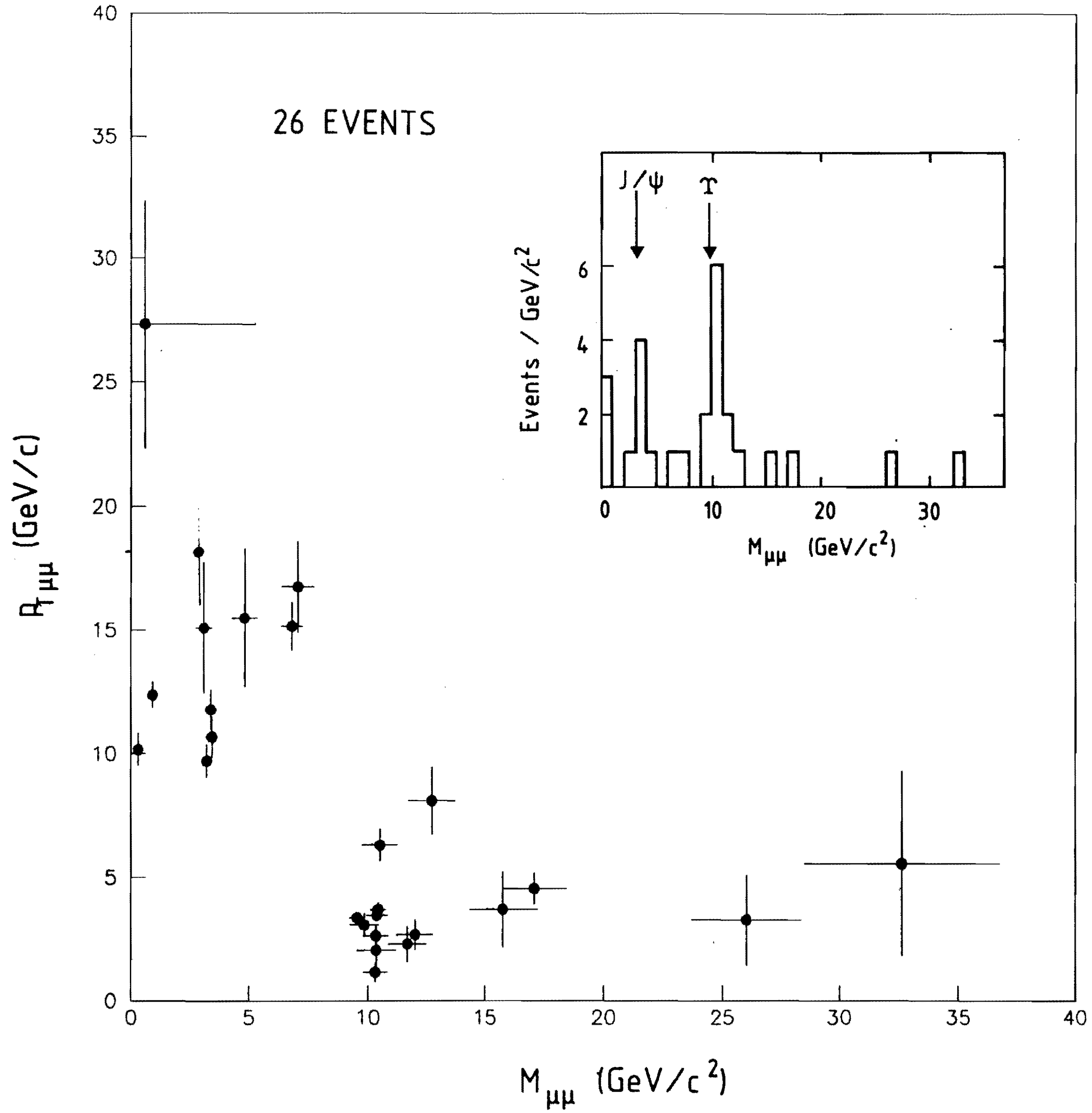


fig.3

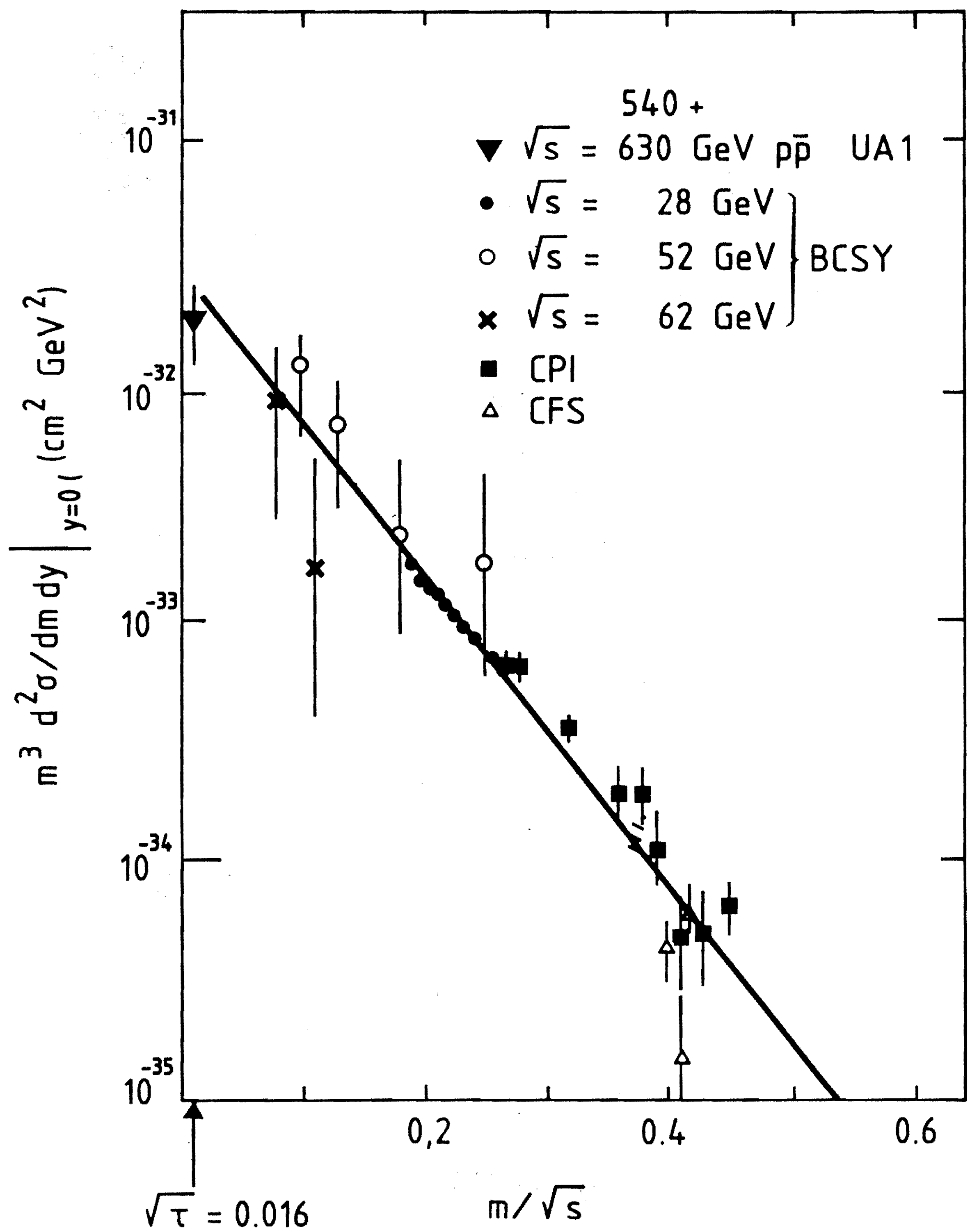

540 +
▼ √s = 630 GeV pp̄ UA1
• √s = 28 GeV
○ √s = 52 GeV
× √s = 62 GeV
BCSY
■ CPI
△ CFS
10^-31
10^-32
10^-33
10^-34
10^-35
m^3 d^2σ/dm dy |y=0 (cm^2 GeV^2)
0,2
0.4
0.6
√τ = 0.016
m/√s

fig.4

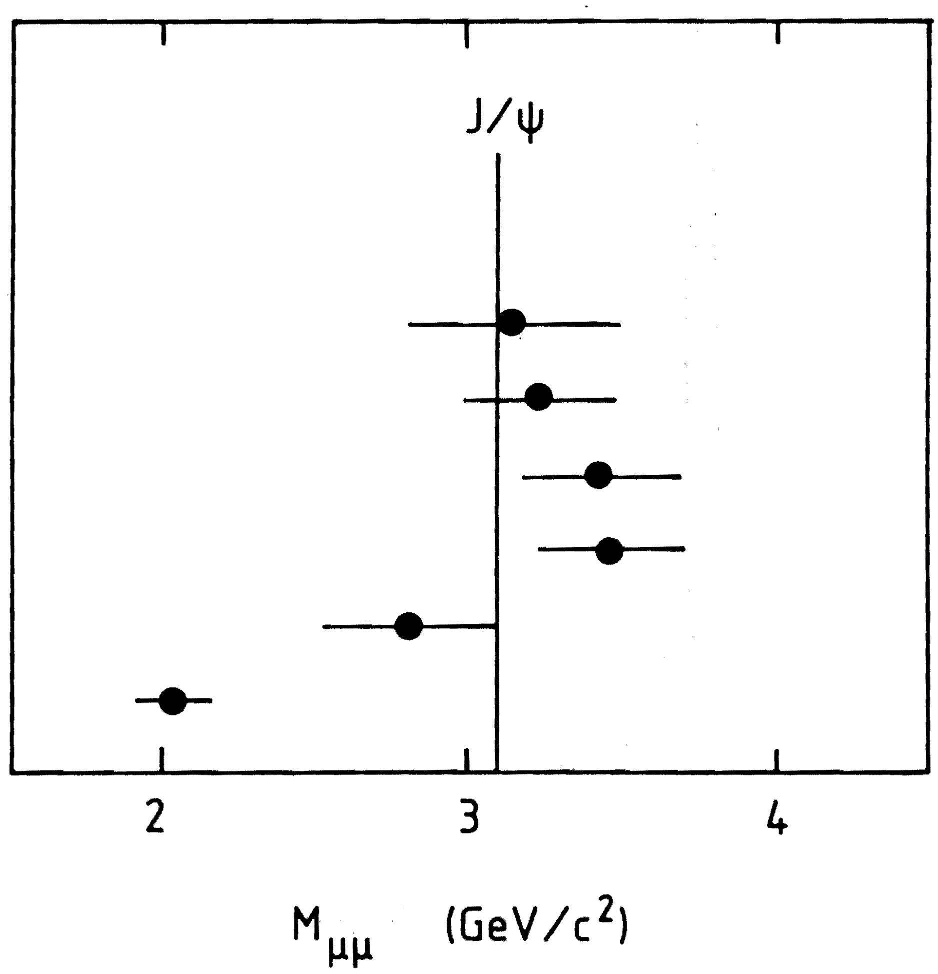


fig. 5

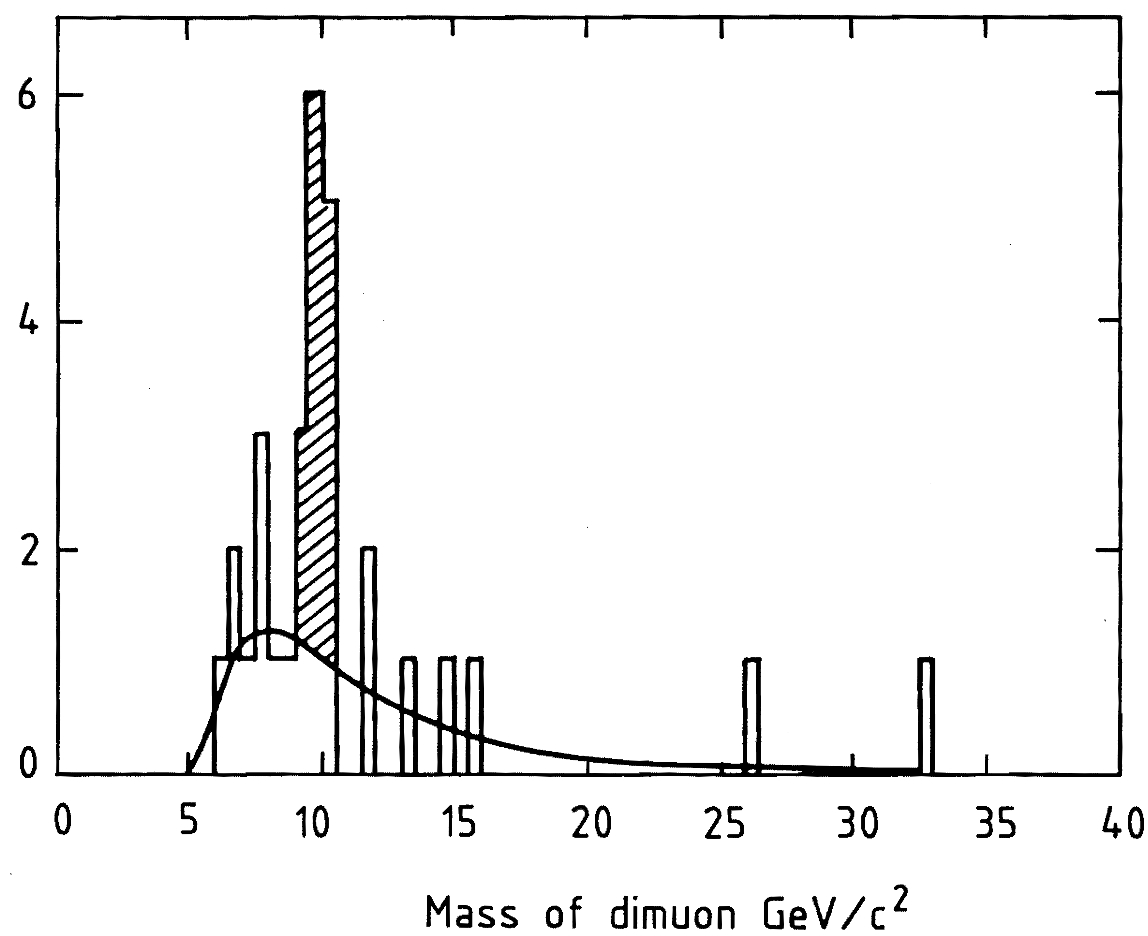
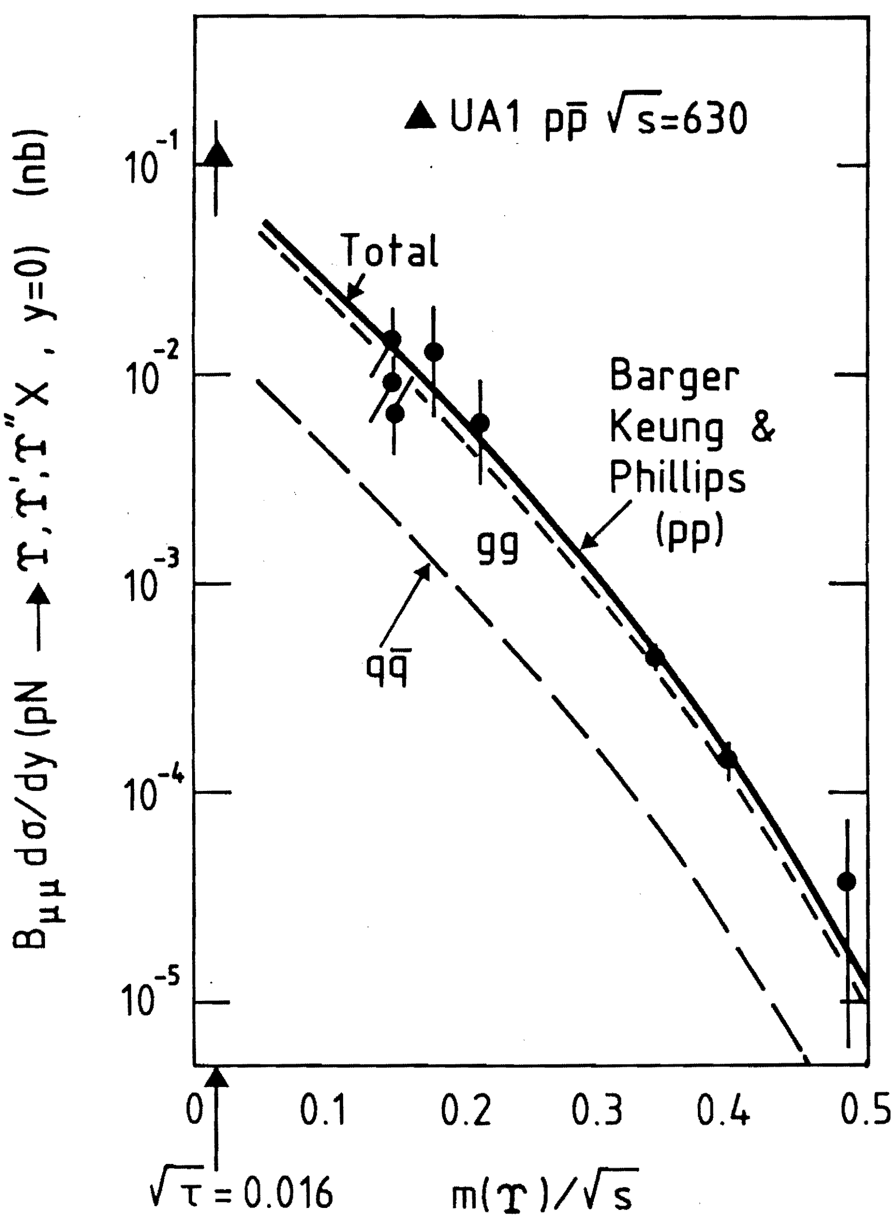


fig.6



▲ UA1 pp̄ √s=630
Total
Barger
Keung &
Phillips
(pp)
gg
qq̄
$B_{\mu\mu}\, d\sigma/dy\, (pN \longrightarrow \Upsilon, \Upsilon', \Upsilon'' X\ ,\ y=0)$ (nb)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
0.1
0.2
0.3
0.4
0.5
$\sqrt{\tau} = 0.016$
$m(\Upsilon)/\sqrt{s}$

fig. 7

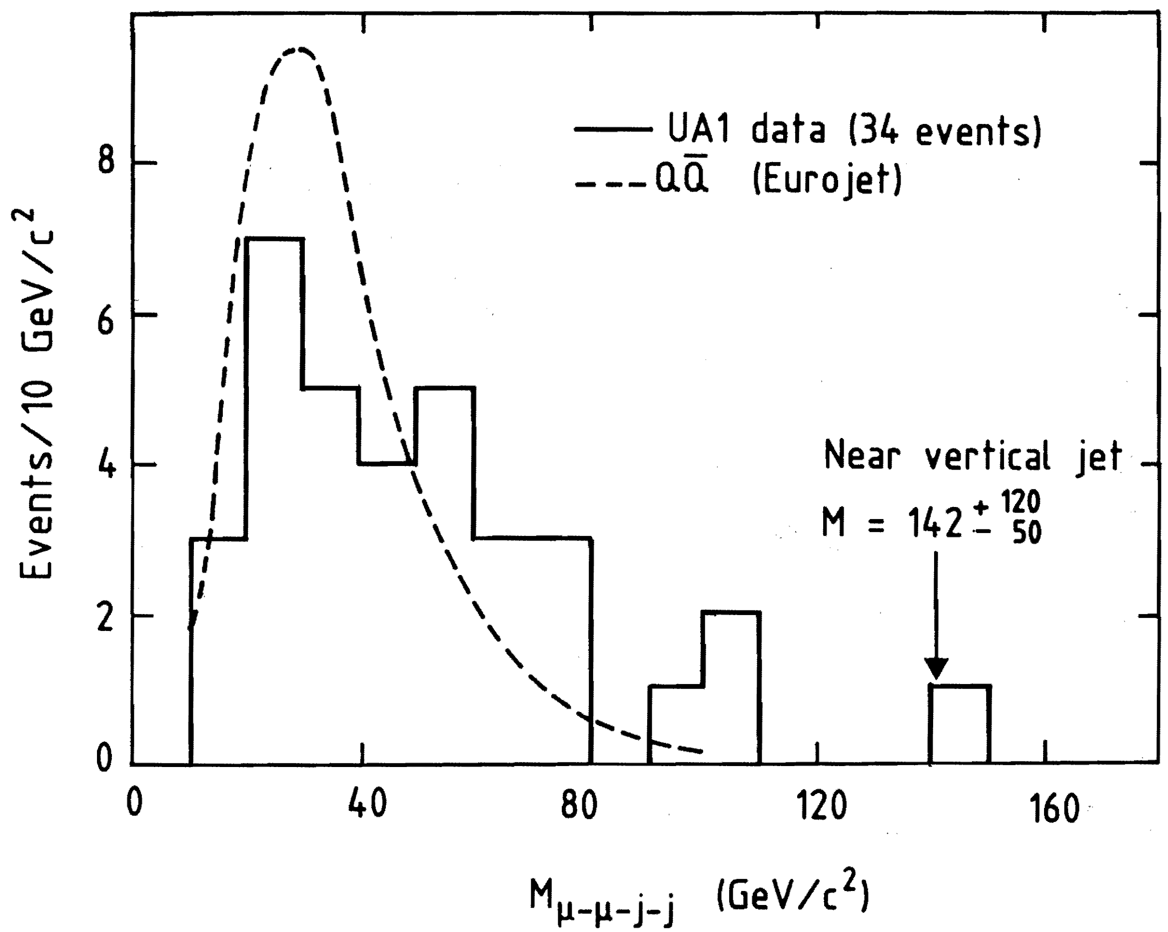

UA1 data (34 events)
QQ̄ (Eurojet)
Near vertical jet
M = 142 +120 −50
Events/10 GeV/c²
M_{μ-μ-j-j} (GeV/c²)
0
2
4
6
8
0
40
80
120
160

Fig.8