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$p\bar{p}$ COLLIDER PHYSICS: SUMMARY TALK*

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Abstract

This report briefly summarizes the International Symposium on Physics of Proton-Antiproton Collision, Tsukuba, Japan (March 1985). The table of contents is as follows:

To begin, I would like to express, on behalf of all participants, our thanks for the splendid hospitality and excellent organization for this symposium. In particular I want to thank Dr. K. Kondo of KEK and Dr. Y. Hara of Tsukuba University for their special efforts in making it a great success.

For me, this is a long overdue first visit to Japan. Therefore it is a special pleasure for me to see my friends of many years in their own country. The KEK Laboratory and Tsukuba University here are most impressive to see and bode well for a very productive future in Japanese high energy physics.

In this meeting most of the collider physics news has come from Europe. It is a splendid story. The accomplishments are manifest, not only with the W and Z discoveries, but with much more, as will be described in part in this summary talk. For those of us from Fermilab and for the many Japanese and Italian participants in the CDF effort, the way this meeting can be summarized is simply that we're hungry for some of that data ourselves! In the not-so-distant future we can expect to have it. Indeed, the next step in the U.S. should complement very nicely the European work. The center-of-mass energy will be almost three times higher and the luminosity an order of magnitude higher than most of the running thus far in Europe.

I. QUANTUM CHROMODYNAMICS (QCD)

A. Drell-Yan Production of W and Z

The collider physics in general has verified very well the perturbative-QCD ideas of hard collisions. Probably the most theoretically reliable of these processes is dilepton production.[1,2,3] Here the rates agree to at least 20% with theory. The energy-dependence is satisfactory, and transverse momentum distributions generally agree with theory. In particular the fact that the transverse momentum of W and Z is as large as the theoretical prediction is an important signature of the correctness of the QCD approach. Of course, the large transverse momentum is supposed to be caused by gluon emission in the hard collision. The gluons are indeed seen, and the angular correlations with the dileptons agree with theory.

There was concern in the early data that there seemed to be more jet activity and a higher multiplicity in the events containing the neutral gauge boson Z compared to what is observed in W production. However, as the statistics accumulate in the latest running period this anomaly seems to be going away.[1,2]

B. Inclusive Spectra of Jets

The inclusive spectrum of high p_T jets has been well measured,[4,5] both by UA1 and UA2. Figure 1 shows the UA2 results.[5] The data now is reaching a level of sophistication where the experimentalists believe they can set limits on any short-range anomalous force between quarks and gluons. If there were a quartic point coupling between quarks and/or gluons characterized by a scale Λ, then the results show fairly clearly that a value of below 300 GeV is ruled out, while any value above 470 GeV is clearly not ruled out. A more precise limit may be forthcoming although, with the present state of the theory, it hardly matters.

C. Angular Distributions of Two Jet Final Stages

Here we heard[4] very elegant results from the UA1 collaboration, both in the theoretical approach and the methodology of the analysis. The first point which is important to this analysis is that, within QCD, one may use a "generic parton", with structure function given by

$$F(x) = F_g(x) + \frac{4}{9}(F_q(x) + F_{\bar{q}}(x))$$

If one uses this generic parton distribution, then a universal scattering formula of the Rutherford type can be used for the hard collision cross-section. Of course there are a variety of small corrections to this generic result. But with this approximation one can get a good idea of how the data behave. Upon fixing the overall center of mass energy of the hard collision, one can check the angular distribution of the scattered partons and see whether they follow a Rutherford-like law. Here a nice choice of variable

$$x = \frac{1 + \cos\theta}{1 - \cos\theta}$$

is used. If the Rutherford law is correct, then the distribution in this particular variable should be uniform. Not only does this hold experimentally, but the deviation from uniformity (which is nicely seen now in a linear plot rather than a semi-logarithmic plot) agrees (Fig. 2) with obvious QCD improvements appended to the parton level analysis. These improvements are characterized by a scale parameter of order 200 MeV, which is perfectly reasonable.

One should hasten to add that the experimentalists have not done a full higher order QCD calculation. This needs to be done; however, the scaling violations of parton distributions, along with the running of the coupling constant, should improve the lowest order analysis. Experimentalists can hardly be faulted for putting these in. It is up to theorists to now fill in the remainder.

D. *Dalitz Plot Analysis of Three Jet Final States*

Not only is the two jet final state analysis in very good shape, but the experimentalists have now progressed[4] to an analysis of a very clean 3 jet sample. Here, with appropriate cuts designed to avoid logarithmic collinear singularities, they find the density in the Dalitz plot agrees well with theoretical expectations. This is shown in Figure 3. Furthermore, the ratio of 3-jet to 2-jet cross sections at a given overall invariant mass provides an estimate of the strong coupling constant α_s. The value which was obtained by the lowest order analysis is as follows:

$$\alpha_s \frac{K(3jet)}{K(2jet)} = .186 \pm .036 \pm .031$$

This number is rather large if the K-factors, that is the factors which correct the lowest order calculation, are set to unity. It is considerably larger, I would say by almost 50%, than anticipated by QCD. A similar result is obtained[5] by UA2, although their analysis is somewhat more painful because of the more limited acceptance than possessed by UA1.

At this stage, it seems that the experimentalists are clearly well ahead of the theorists, and that what is needed now are hard calculations to the next order, similar to those which were done in the early days of the 3-jet observations in e^+e^- annihilations. In order to calculate this ratio of K-factors, one will need the production of 4-jet final states in lowest order, along with one loop corrections to amplitudes for production of 3-jet final states. Indeed the theory should go even further, if possible. Before long, 5-jet and 6-jet final states will be seen as well, if not at the SPS, then probably at the Tevatron. Therefore more loops and more complicated final states really ought to be attacked by theory. Certainly, the number of man-years that have gone into theoretical QCD calculations is two orders of magnitude smaller now than the number of man-years that have gone into getting the data. Why not rectify the situation a little? As Quigg described,[6] there is some hope that these calculations can be done. Supersymmetry can be applied in a very pragmatic way to this kind of problem.[7] By generalizing QCD to a supersymmetric QCD containing scalar particles, and just by calculating the amplitudes for producing multiple scalar particle production, the amplitudes for gauge boson production can be extracted via supersymmetry relations.

There is hope that the 2-to-4 calculation can be done reasonably easily analytically. If that turns out to be the case, there may be a future in going on to higher orders. It should be emphasized that this kind of theoretical work is not only interesting for its own sake, i.e., the study of the QCD processes, but that it will also be needed in order to understand backgrounds for any new physics which might be attacked using multijet spectroscopy. An example is heavy quark pair production where both particles decay to 3-jet final states.

Before going on, it should be mentioned that the value of α_s quoted[8] by UA1 at the St. Vincent meeting in Italy was in fact considerably smaller than the one reported here. This was due not to a change in the data or even the experimental analysis, but rather to the theoretical calculations which were used in the comparison. It is perhaps indicative of the fact that what is really needed now is more theory; the quality of the results are now limited by systematic theoretical errors.

E. Interior Structure of Jets

We saw very beautiful data[9] on the inclusive distribution of particles within a jet. The distribution (Fig. 4) agrees quite nicely with what is seen in e^+e^- annihilation. To a rough first approximation, the inclusive distribution in gluon jets looks like the distribution in quark jets. They are compared by using kinematic regions which are quark-jet rich and comparing with kinematic regions which are gluon rich (according to the lowest order QCD expectations). However, it is found (Fig. 5) that for the case of the gluon jets, transverse momenta of hadrons tend to be a little larger than those in quark jets, and that the multiplicity of hadrons in gluon jets is a little larger as well, especially at small values of the scaling variable. Especially interesting is the UA1 study of charge retention, that is, whether the charge of the quark, on average, is found in the hadrons produced in the fragmentation region of the quark. As shown in Table I, there is some evidence that in fact the expected amount of charge is found, in accordance with the anticipated q, $\bar{q}$, or g parentage. The effect is not large and there would be no hope of finding a gluon jet on an event-by-event basis in this way. It would be nice, as a next step, to understand in more detail the composition within the jets, particularly to study lambdas, D^*'s, and so on. In particular, D^*'s were found by UA1 to be copiously produced within jets at small values of the scaling variable. I wonder whether, in fact, this might be a good part of the reason for the excess of multiplicity in gluon jets in that region of the scaling variable.

The UA1 result[10] is 0.6 ± 0.3 charged D^*'s per jet with a cut of greater than 0.1 on the scaling variable. There were other cuts and biases in this sample as well. It is clear that a more extensive analysis needs to be done. We heard a discussion remark by Rubbia of indications from the new data that this large number for D^*'s within jets may decrease. In any case, it seems to me to be important to include this kind of effect in the Monte Carlo simulations to see its impact on other phenomena, especially the more speculative ones like dimuon pair production.

F. Minijets

The UA1 collaboration has made a search[11] for jets within the sample of minimum bias events. This is done by essentially utilizing the same jet finding algorithm as used for the hard collision analysis, but with a lower threshold transverse momentum. When this is done, a sample of jets is found, with a reasonable spectrum (Fig. 6) that joins fairly smoothly onto the larger transverse momentum spectrum determined by the standard analysis. Remarkable is the fact that if one cuts off the jet transverse momentum at around 5 GeV, and integrates the inclusive distribution over all p_T, there is a sizeable contribution of events containing at least one jet, somewhere in excess of 12-15%, to the total cross-section. The sample of minimum bias events which contains the minijets seems to differ sharply in properties (Fig. 7) with the sample which does not. The jet events have mean transverse momenta which do not vary with multiplicity and a multiplicity distribution which is relatively narrow. On the other hand, the events without jets seem to have a transverse momentum which varies somewhat with the overall multiplicity, and which have a multiplicity distribution which is relatively broad. Thus, taken at face value, there seems to be a 2-component picture of the minimum bias events. However, there are many issues which, in my mind, still remain somewhat unclear. In particular, the use of clustering of transverse energy distributions as an algorithm to find jets of transverse momentum as low as 5 GeV proved to be a very ambiguous and controversial procedure at the SPS and

Fermilab fixed target experiments.[12] Therefore, I would like to see more convincing internal evidence that this sample really represents binary hard collisions. One might, for example, look at the fraction of events which contain a second jet in association and see whether this agrees with what one would expect from binary hard collisions. It is a very interesting issue whether the high multiplicity and high transverse energy events are really controlled by hard collision mechanisms as opposed to some sort of thermalization process such as the formation of quark-gluon plasma, which then expands hydrodynamically for several fermis, at which time hadrons are then formed. Another issue is whether the growth in the total cross section is in fact connected to these emergent minijets. I am no expert on this, but would like to know whether this idea is consistent with the rest of the soft physics data such as elastic scattering and single diffraction dissociation cross sections. Certainly the original theoretical logic which was the input for the prediction of the log squared rise of the total cross section had little if anything to do with hard collisions.

But this is a good place to terminate the discussion of hard collision physics and turn to the next section which is, in fact, the physics of soft collisions.

II. SOFT PHYSICS

A. Issues

As we just discussed, a central issue in soft-collision "log s physics" is what causes the rise in the total cross section with energy. As we just mentioned, the original theoretical ideas[13] that led to a log squared rise in the total cross section had to do with the increasing importance of multi-peripheral mechanisms at large impact parameter; thus the importance of absorption occurring at large impact parameters could grow as the energy increased. Multi-peripheral mechanisms do not seem to have much to do, per se, with hard collisions and jets. However, these ideas have evolved considerably down through the years. A later phase of evolution was the Reggeon calculus language of pomeron-pomeron interactions, cuts, triple-pomeron couplings, etc. Here essentially one has a phenomenology considerably more abstract than writing down multi-peripheral diagrams, which can describe a variety of different approaches.[14] But in the Reggeon calculus framework, it again was reasonable that one would get a strong rise in the total cross section with energy. Finally, in more modern times, a great deal of work has been done on the summation of multiple-gluon exchange amplitudes[15] to very high orders of QCD. The results have kinship both with the Reggeon calculus approach and the old multi-peripheral way of looking at things. However, in these diagrammatic calculations, high transverse momenta in loop integrations are important. Therefore, there may be a connection between at least the Reggeon-calculus QCD way of looking at things and the presence of jets as a mechanism for the rise in the total cross section.

B. Relevant Data

A considerable amount of total and elastic cross-section data was presented[16,17] at this meeting. Some of it is shown in Figs. 8-11. This come not only from the SPS running, but also from the ISR, where pp and $\bar{p}p$ collisions were studied under nearly identical collisions. It is observed that the difference of the pp and $\bar{p}p$ cross section tends toward zero with increasing energy in accordance with standard Regge lore. This is reassuring, since some theorists created other quite peculiar $J = 1$ Regge singularities, as contingency for the opposite situation.

It is also found, in comparing data at the lower energies with the Sp$\bar{p}$S, that geometrical scaling definitely fails. Some evidence for this is the rise in the ratio of the elastic to total cross section (Fig. 10) which should not occur if geometrical scaling were correct. The theoretical structure that survives best with the new data seems to be the "impact picture". Finally, it also seems to be the case that asymptopia is very far away and there is very little expectation that it can ever be reached experimentally. Logarithms pile up slowly with energy. Theorists who use asymptotic formulae to compare with data do so only at very high risk.

C. Structure of the Pomeron

A very interesting subject, in my opinion, is high mass diffraction, especially if one can carry out the scattering process such that the secondary antiproton is tagged via Roman Pot detectors so that one knows that a color-singlet pomeron was exchanged between upper and lower vertex. Then with enough statistics one can search for jets in the high mass system and thereby study the parton structure of the pomeron itself. This has been proposed[18] as an experiment for the Sp$\bar{p}$S by Schlein and others; it is also a prime candidate for studies at the Tevatron with CDF. To my knowledge there is not even much discussion of the parton structure of the pomeron. Does it vary with momentum transfer? Does it vary with incident laboratory energy or the sub-energy of the hard collision? Does it matter, for example, whether the process is single diffraction, as in the experiment described above, or double? The latter could be arranged by simply allowing the upper antiproton vertex to be excited to a relatively high mass state, of order a few GeV or more by relaxing the tagging requirements.

There are various options regarding what the internal structure of the pomeron might be. It could be a single hard gluon plus a soft cloud. It could be a $q\bar{q}$ pair if in fact the pomeron trajectory is something like the f' meson trajectory. Or the pomeron might be basically gluonic. But since it is color singlet, it might be something like a glue-glue bound state, gluonium. This would probably imply almost the same phenomenological consequences as the previous case. It is also possible that the pomeron simply has no hard partons at all, and that it is very soft. If one looks at some of the perturbative calculations of the "impact picture", there are very many gluons exchanged between the upper and lower systems in the diffractive process. It is not obvious that any one of them dominates, but rather they all share the exchanged momentum fairly equally. Another way of saying this might be that the pomeron really does have something to do with strings and there is nothing hard in strings.

I mention all these possibilities only to emphasize that this subject is extremely exploratory and is not in the usual category of highly predictable measurements, using QCD and electroweak theory. Therefore it is not only important but it should be fun.

As to the numbers, one may see[19] from Fig. 12 that the CDF total cross section for single diffraction dissociation into masses of typically 400 GeV is of the order of a millibarn. Of course, these will predominantly not contain jets, but rather contain a system of low p_t hadrons covering a relatively large range in rapidity. However, now and then one ought to get a jet. In order to estimate how often this might be, we can compare the 400 GeV center-of-mass energy of the diffractively produced system and an integrated luminosity of 10^{36} with the SPS experience with a dijet sample of, say, 300,000 dijets containing transverse momenta in excess of 30 GeV. So if we divide now by the ratio of the total diffraction cross section to the total cross section, about 1/60, CDF would still have perhaps of order 10,000 clean dijets in the diffractively produced systems with jet transverse momenta greater than 30 GeV. This should be quite enough to get a first idea of what the lay of the land is.

III. W, Z, AND ELECTROWEAK THEORY

As more data comes in,[2,20,21,22] everything seems to be proceeding according to schedule. It's amazing, in fact, how such a sensational discovery has become almost routine. This can only remain true until something goes wrong. At present, the forward-backward production asymmetry is in very good shape, the values of the masses are in very good shape, and the universality of widths of the leptonic decay channels of the W are in good shape. This is true not only for electrons and muons, but now even for taus, which are convincingly seen.[22]

The precise values of the Z and W masses are a crucially important test of the electroweak theory. But it is a little early to expect measurements precise enough to really examine in a critical way radiative corrections and/or the numbers of neutrinos coupled to Z. A list of the measurements from UA1 and UAII are given in Table II.

We also heard a nice talk[23] by Hioki on the theoretical correlation between the W mass and the Z mass. In particular, if one eliminates the weak mixing angle from the standard model formulae for the W and the Z masses, there is an almost linear correlation as one might expect. Hioki urges measurement along such a line in order to eliminate the uncertainty on the experimental determination of the weak angle and thereby make a sharper test of the standard model. The question arises whether the experimental measurements are similarly correlated. In particular, one might think that calibration uncertainties would affect the W and Z masses in a similar way. The answer to this speculative question is not so clear now. According to the experts, it is evidently not that simple. But is may be that as the analyses reach a higher level of sophistication this pattern might emerge in the future. If so, it is good news for Hioki's approach.

IV. HEAVY QUARK PHYSICS

Heavy quark production at $Sp\bar{p}S$ energies is expected to be quite copious.[24] Not only is the charmed quark cross section expected to be very large (and it seems to be that way in jets!) but also bottom and perhaps even top production. Multilepton production is a good probe of this kind of physics.[25] We heard results[26] on the dimuon samples as seen by UA1. In particular, opposite-sign dimuon production, both "isolated" and "non-isolated", seems to be in agreement with the theoretical expectations based on perturbative QCD for the production of charm and bottom quarks. UA1 quotes a cross-section of two to three microbarns for $b\bar{b}$ production (for transverse momenta greater than 5 GeV and in the central rapidity region, i.e., $y < 2$). Also an Υ signal seems to be emerging (Fig. 13) in the isolated opposite-sign dimuon sample. The cross section for the upsilon is quoted as six-tenths of a nanobarn, with a 40% error. However, other than the Υ signal, the road from theory to observation is quite indirect, so it is a little hard to be completely sure about the significance of the results on open heavy flavor production. The same-sign "non-isolated" dimuons also seem to be understandable (Fig. 14) in terms of expected mechanisms. By "non-isolated" is meant, in a sense more precisely defined by UA1, muons which are produced near or within a neighboring jet. "Isolated" muons are required to not have significant jet activity within a certain angle of the direction of emission. The observed sample of same-sign isolated dimuons are possibly anomalous and will be discussed later.

Another heavy-quark issue that we already mentioned is that of the D^*'s observed within jets at low values of the scaling variable. This seems to be much too big for the theorists to easily explain; they[24] seem not to be able to get (Fig. 15) within a factor of five to ten of the quoted value by UA1.

V. EXTINCT EXOTICA

Many of the low statistics, exotic phenomena seen in the earlier running at the SPS appear to be going away. These include the radiative dilepton decays of Z, none of which have been seen in the 1984 run. This increases the probability that the old events were bremsstrahlung. As far as I'm concerned, good riddance to this phenomenon. It was very hard to interpret in any other way than a statistical fluctuation in the internal bremsstrahlung.

Another phenomenon which does not seem to be confirmed is the peak in the "W-plus-jet" mass spectrum as seen by UA2 in the early data. While that phenomenon probably cannot be strictly ruled out, the trend[27] is certainly towards disappearance. Likewise the 150 GeV bump in the dijet mass spectrum for which there was a hint in the early UA2 data is definitely gone (Fig. 16). Finally, the anomalous jet activity seen by UA1 in association with Z events has not been confirmed by either group. Again, to this phenomenon, good riddance!

VI. EXTANT EXOTICA

A. Monojets

The status of the monojet signal was not discussed by the UA1 experimentalists at this meeting. This extends the trend set in the St. Vincent meeting of experimentalists talking about the theory of monojets, with the theorists talking about the experimental backgrounds. The situation is summarized in a very sketchy way in Fig. 17. While I am a total amateur in this field, it seems to me, by looking at the data presented at St. Vincent, that the new data clearly confirm the presence of a distinct component in the missing transverse momentum spectrum emergent above the estimated mundane background. Also, the slope of the integral spectrum, as function of missing transverse momentum, in the interesting region is similar[27] to the slope of the expected background from Z+jet, where Z decays into neutrinos. The problem is whether or not the observed "monojet" signal really rises significantly above the expected backgrounds from this source and others. *Prima facie* evidence, as cited[28] by Rubbia, is that there is perhaps a factor 5 in the ratio of the integral spectrum signal to background, as estimated from observed W+jet events. But this is hardly the whole story, and various theorists have been suggesting a collection of mechanisms which may reduce this ratio to no more than a factor 2 to 3. This is hardly a time to draw conclusions. Additional analyses of the signal and background sources are called for and more work on this is going on. In addition, it is important to look at the morphology of the jets to see whether there are any distinct differences between the properties of the monojets and of standard QCD jets with the same p_T. I do not understand why such data has not been presented thus far.

B. Top quark

The signal seen in the early data seems to be clearly reproduced[29] by UA1 in the present run. Furthermore, the analyses of backgrounds seem to have been carried out in somewhat more detail than before. The conclusion seems to be sustained that the signal is narrower than background mechanisms, although there is considerable similarity in the shapes of signal and background. Nevertheless, in the corridors I get the feeling that there are some lingering doubts about the effect. The issue is clearly sufficiently important that one wants to be very sure of one's ground. Of course if there is no background present the question of what the mass is is a vital one, especially in Japan. Here there is no new statement by UA1.

C. Possibly Anomalous Same Sign Isolated Dimuons

The data was not presented by the UA1 collaboration. However the properties of the candidate events were presented[30] at St. Vincent, and have been reproduced in Ali's talk.[25] There seems to be an excess, perhaps 4 to 7 in number, of same sign dimuons produced back-to-back, with little if any jet activity nearby in phase space, and with invariant mass in the 10 to 15 GeV range (Fig. 18). There is some suggestion of strange-particle activity in association with these events as well. Since the isolated opposite sign dimuon events (which are not much more numerous) seem to be accounted for by Drell-Yan and upsilon production processes, it is not too easy to see where these same-sign events come from. This includes, according to the UA1 collaboration, any origin based on $b\bar{b}$ mixing. But there are severe cuts nearby and the mass peak may conceivably be related to the presence of these cuts. This bias can be seen rather clearly in the histogram of opposite sign isolated dilepton events in Fig. 13. The influence of these cuts on the data sample is still under study by the UA1 collaboration, and is, I believe, a reason why little was said at this meeting by the collaboration itself. It is clearly not a time to draw any conclusions. But it is also clear that this is an interesting phenomenon which is well worth watching with great care. Again there may be additional theoretical work to be done in the estimation of backgrounds for this phenomenon.

VII. FUTURE DIRECTIONS

A. $Sp\bar{p}S$ and TeV I

In looking at the future for both $Sp\bar{p}S$ and Tevatron I, an obviously vital question is how Tevatron will compare with the $Sp\bar{p}S$. What is really different in the program at higher energy from what has already been seen? In the case of TeV I, its higher energy may allow production of massive systems which are below threshold for $Sp\bar{p}S$. In the case of both facilities a crucial issue is the luminosity available for interesting processes. This means not only machine luminosity but also the energy-dependent hard-collision luminosity associated with the parton beams.

There do exist qualitative distinctions which one can catalog. First of all, the production of W pairs is possible, in principle, to observe only at Tevatron I, although it is a big challenge and backgrounds are sure to be quite difficult. We heard some expressions of pessimism from Quigg, but they were somewhat offset by the optimism of Rubbia. Secondly, if there really is of order one charm pair per high-transverse-momentum gluon jet, perhaps this implies that at sufficiently large transverse momentum there is complete flavor independence in the production of heavy quarks. By appropriately scaling up the p_T threshold for D^* production perhaps it is arguable that there is of order one B^* produced per jet when the transverse momentum is in excess of, let us say, 70 GeV. That would be so sensational that it may indicate this argument is wrong.

Another feature of the Tevatron which may almost be a qualitative change relative to $Sp\bar{p}S$ is the very large increase in the yield of any new physics such as top pair production[31] or monojets due to the higher incident energy. Furthermore, it may be that multijet spectroscopy will be easier as the overall energy scale goes up and therefore the scale of individual jet momenta go up. The problems of resolution and intrinsic uncertainties in defining the energy of a jet should improve under these circumstances (But QCD backgrounds go up, too!).

But in any case the programs at $Sp\bar{p}S$ and Tevatron will in general be complementary if only because of the differences in the detectors and the style of analysis of the groups. One could not say that they are redundant programs even were they to run at the same energy.

B. Instrumentation and Detectors; Group Theory

Another future direction which we may identify is improved instrumentation. One clear direction already under way is microvertex detection,[32] i.e., trying to find the decay vertices of the charm and bottom hadrons by the use of silicon strip detectors, scintillating fibers, or high precision wire chambers. Another direction[33,34] is improved hermeticity in calorimetry, with fewer cracks and higher resolution, now that it has been seen how successful the calorimetric technique has been. The importance of this hermeticity is, for me as a theorist, downright inspirational. The hermetian detectors are clearly generators of new groups; these must be compact groups only. We may make a classification.

First of all there are the unitary groups. These tend to be very large, say 1,000 physicists, 300 institutions, 50 countries, with group meetings held only in New York, because only the United Nations General Assembly is an appropriate milieu. We all know about that kind of group.

There are also the simplistic groups. These are smaller entities, and utilize smaller detectors of limited scope (perhaps in solid angle) and purpose. An example of a simplistic group would be one which builds a DASP-type spectrometer to look at interiors of jets or to look at processes in the near forward direction. In e^+e^- collisions, this kind of detector is no longer popular. And at the ISR, where there existed small aperture spectrometers, much of the interesting hard collision physics was totally lost. So why should one reintroduce this kind of idea? I think it might be appropriate because the interiors of jets should be very interesting and because there are so many produced. Luminosity is not much of a problem. This is unlike the situation in e^+e^- annihilation and unlike the situation at the ISR, where one didn't know much about jets when the spectrometers were built, and where the rate of jet production was not very large in any case.

Next are orthogonal groups. These are groups which place the axis of the detector orthogonal to the beam axis. We can all agree that this is a stupid thing to do. But if one doesn't go quite to that extreme, but puts the axis of the detector at a small angle to the nominal axis of the beam, and then bring the beam around in an S-curve along the axis of the detector, it is not a stupid thing to do. It then becomes possible to analyze the forward and backward produced systems which emerge downstream of the S-curve bending magnets. This is useful for two reasons. One is that the physics in the forward direction is intrinsically interesting and therefore deserves detailed study. This is very hard to do when a large rapidity interval of forward produced particles tends to go down the beam pipe in conventional detectors. The other reason for this kind of technique is that if one wants to extend the hermeticity idea of full calorimetric coverage to the longitudinal direction as well as to the transverse directions, this is a possible way to do it.[35]

Finally, there are the exceptional groups. This is clearly the correct approach. Just ask any theorist these days; he is likely to be busy with an exceptional group. Exceptional groups also have the advantage that, while large, they cannot become arbitrarily large.

VIII. THE SSC

We have heard already from Quigg[6] about the physics at SSC energies. Here I would like to make only a small commentary on the status and future of the SSC. First of all, the SSC idea has a lot of momentum. The U.S. high energy physics community is fully committed to it. As one can see[36] from Table III of anticipated milestones, a lot is going on. The Department of Energy seems, so far, to be quite responsive to the proposal, with a commitment of about $20M per year of R&D funds in fiscal years 1985 and 1986. Furthermore, the administration, as represented by the President's Science Advisor, has been very strongly supportive of the SSC idea.

It is also clear that the international element will be crucial in shaping the progress of the SSC. This machine, however it is organized, must have a large international element in it, simply because it is so unique scientifically. How this will work out, of course, will depend on the commitments of physics communities in various regions, as well as of the various governmental bodies. This evolution is, in the context of the U.S. and Western Europe, now proceeding via the Versailles summit meetings and their working groups.

I think that everyone should agree that the very possibility of getting support for something like the SSC makes it important that the enterprise be broadly supported on the international front. There is a strong need for constructive action taken on a short time scale in order to move the project along as expeditiously as possible.

VIII. CONCLUDING REMARKS

In conclusion, we may say that the $Sp\bar{p}S$ results are truly impressive. First of all, the W and Z discovery needs no comments here, beyond the statement that theory and experiment agree very well. Secondly, a more quiet, but nevertheless very impressive, result is that the QCD description of hard hadron collisions has not only matched the beautiful results in e^+e^- annihilation but, in my mind, has now in many ways overtaken e^+e^- all the way up to the LEP II energy scale. The level of sophistication of 3-jet phenomenology seems to be similar to that in PETRA/PEP. The real problem now is that theory needs to catch up. Third, there is much to do in soft physics. One needs to understand the total cross section behavior; one needs to better understand the role of jets in minimum bias events, and one needs to understand whether there is, in some fraction of the collisions, any kind of thermalization processes going on leading to production of quark-gluon plasma or something like it. Fourth, the first hints of real heavy-quark physics are being seen in the collider. I think if this subject is going to have a big future it has to go beyond multilepton observations and reconstruct actual charm and bottom hadrons. The future of heavy quark physics, therefore, may rest very heavily on the success of the microvertex detectors now under development. I think this has at present to be regarded as uncertain, simply because the vertices of interest all lie within the beam pipe and the problems of resolution and pattern recognition may be extremely hard. Nevertheless we wish everyone the best of luck.

We can say sayonara to some of the possibly crazy phenomena which were observed in the early lower statistics $Sp\bar{p}S$ running. These include the radiative dilepton decays of the Z^o, the 150 GeV mass peak in the dijet spectrum of UA2, probably the "W-plus-jet" phenomenon seen by UA2, and the anomalous associated jet activity with the Z's as seen by UA1. Finally, the top, the monojets and the same-sign isolated diumuons survive as candidates for new and/or anomalous phenomena. These have not been emphasized in this summary. It seems like the wrong time to do so; more reflection and analysis (if not more statistics!) are called for. We all wait for still more confirmation to be absolutely sure of the reality of these effects.

We can conclude with great assurance that, as a consequence of the great success of the $S\bar{P}PS$ program, Tevatron I should be superb. It is gratifying to see the rapid progress[37,38,39] on the construction of the antiproton source and the CDF detector. To repeat what was said in the beginning, all sides of the CDF collaboration, Japanese, U.S., and Italian, are really hungry.

Finally, I want again to express deep appreciation to our hosts for an excellent meeting.

Table I

Charge retention in quark and gluon jets. What is measured is $\langle Q \rangle = \langle \sum_n z_n^{0.3} Q_n \rangle$. The estimated "priority" of each sample is >70%.

Jet Type	Gluon	Up	Antiup
Observed (%)	-1.6±2.5	+19±3	-24±4
Feynman-Field	0	+23	-23
"Lund"	0	+33	-23

Table II

W and Z Mass/Width Parameters (Preliminary)

UA1: $M_Z = 96.5 \pm 1.2 \pm 2.9$ GeV

$M_W = ?$

$\Gamma_W = ?$

UA2: $M_Z = 92.4 \pm 1.1 \pm 1.4$ GeV

$\Gamma_Z = 2.7^{+2.2}_{-1.6}$ GeV (direct)

$\Gamma_W = 3.3 \pm 1.3$ GeV (from production ratio)

$M_W = 81.5 \pm 1.0 \pm 1.5$ GeV (electron distribution)

$81.2 \pm 0.8 \pm 1.5$ GeV (M_T distribution)

$\sin^2 \theta_W = .227 \pm .004 \pm .009$ (W mass)

$.228 \pm .024$ $(1-M_W^2/M_Z^2)$

$\rho = .998 \pm .033$

Table III

SSC Phase I Program Milestones

Oct 1984	Define Selection Criteria and Technical Information needed for Magnet Selection
Nov 1984	Establish Primary SSC Design Features and SSC Phase I Program Plan Objectives
Apr 1985	*Site Parameters Document
Apr 1985	Review Magnet Development Program
Jul 1985†	*Magnet Design Type Selection
Dec 1985	Preliminary Conceptual Design
Feb 1986	Start Pre-Production Prototype Magnets
Mar 1986	*Conceptual Design Report and Other Documentation
Oct 1986	Magnet Systems Test Begins
Dec 1986	*Site Selection by DOE
Jun 1987	Report on Systems Tests
Aug 1987	Recommended SSC Phase II Management and Procurement Plans Partial Title I Design Report
Oct 1987	*SSC Construction Start (NTP)

*Denote Primary Milestone
†Selection to be made during last quarter of FY85

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Figure Captions

Fig. 1. Inclusive jet spectrum[5] measured by UA2.

Fig. 2. Two-jet angular distribution measured[4] by UA1. The variable x equals $(1+\cos\theta^*)/(1-\cos\theta^*)$.

Fig. 3. Dalitz-plot distributions for 3-jet final states measured[4] by UA1.

Fig. 4. Inclusive distribution of charged hadrons within high transverse-momentum jets, as measured[9] by UA1.

Fig. 5. Estimated ratio of inclusive charged-hadron distributions for gluon and quark induced jets, as measured[9] by UA1.

Fig. 6. "Minijet" spectrum measured[11] by UA1.

Fig. 7. UA1 multiplicity and p_T distributions[11] for minimum-bias events containing (b) and not containing (a) minijets of $E_T > 5$ GeV.

Fig. 8. Total cross-section measurement[16] from UA4.

Fig. 9. Difference of proton-proton and proton-antiproton total cross-sections as measured[16] at the ISR.

Fig. 10. UA4 measurement[16] of ratio of elastic to total cross-section.

Fig. 11. Elastic scattering cross-sections[17] measured at ISR and at $Sp\bar{p}S$ by UA4.

Fig. 12. Estimated mass-spectrum[19] of diffractively dissociated protons at Tevatron energies.

Fig. 13. Isolated opposite-sign dimuon spectrum seen[26] by UA1.

Fig. 14. Spectrum of $\mu^+\mu^-$ plus dijet masses in opposite-sign non-isolated dimuon sample from UA1.[25] The solid curve is a fit from the EUROJET Monte Carlo simulation.

Fig. 15. Observed[10] and estimated[24] spectrum of D^* within jets.

Fig. 16. Dijet mass-spectrum[27] as measured by UA2.

Fig. 17. Sketch (based on data presented by C. Rubbia at the St. Vincent meeting) of integral monojet spectrum, along with a guess of jet + $Z(\rightarrow\nu\nu)$ background extracted[27] from the UA2 discussion.

Fig. 18. Distribution of UA1 same-sign isolated dimuons. The new data (4 events) lie in the shaded region, but the information presented[25] does not allow precise localization.

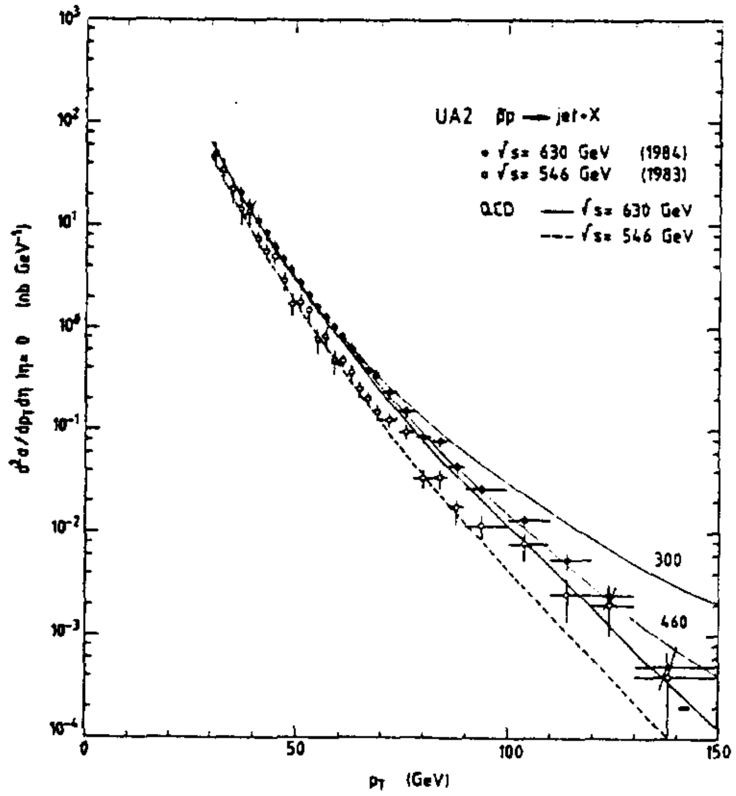


Figure 1

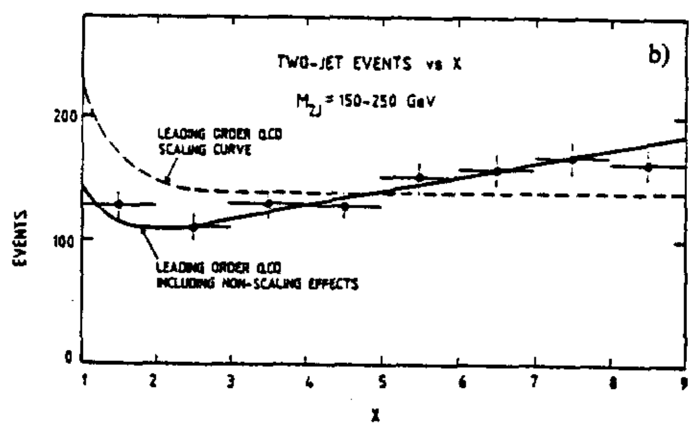


Figure 2

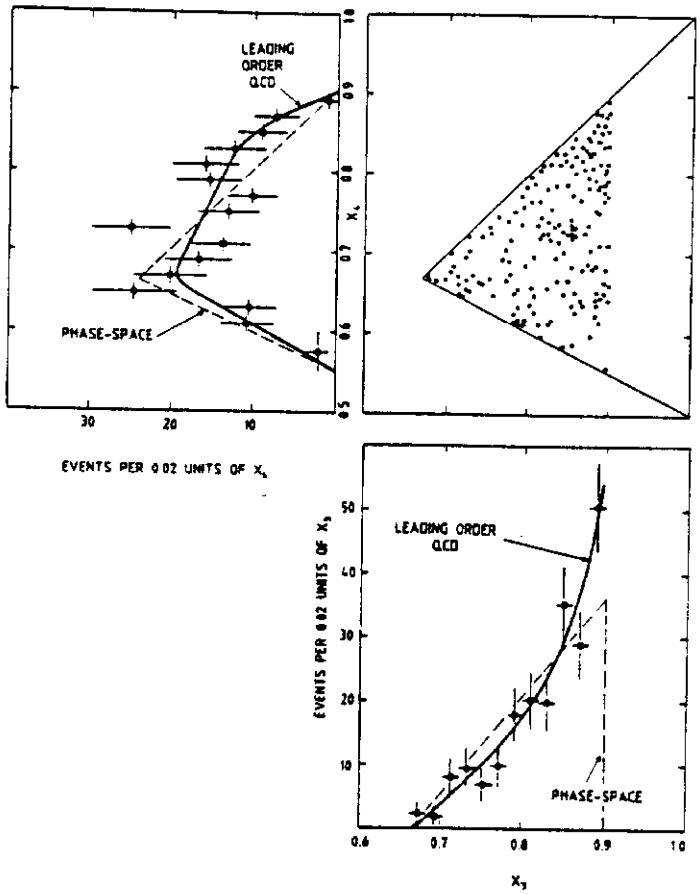

LEADING ORDER QCD
PHASE-SPACE
EVENTS PER 0.02 UNITS OF X_1
EVENTS PER 0.02 UNITS OF X_3
LEADING ORDER QCD
PHASE-SPACE

Figure 3

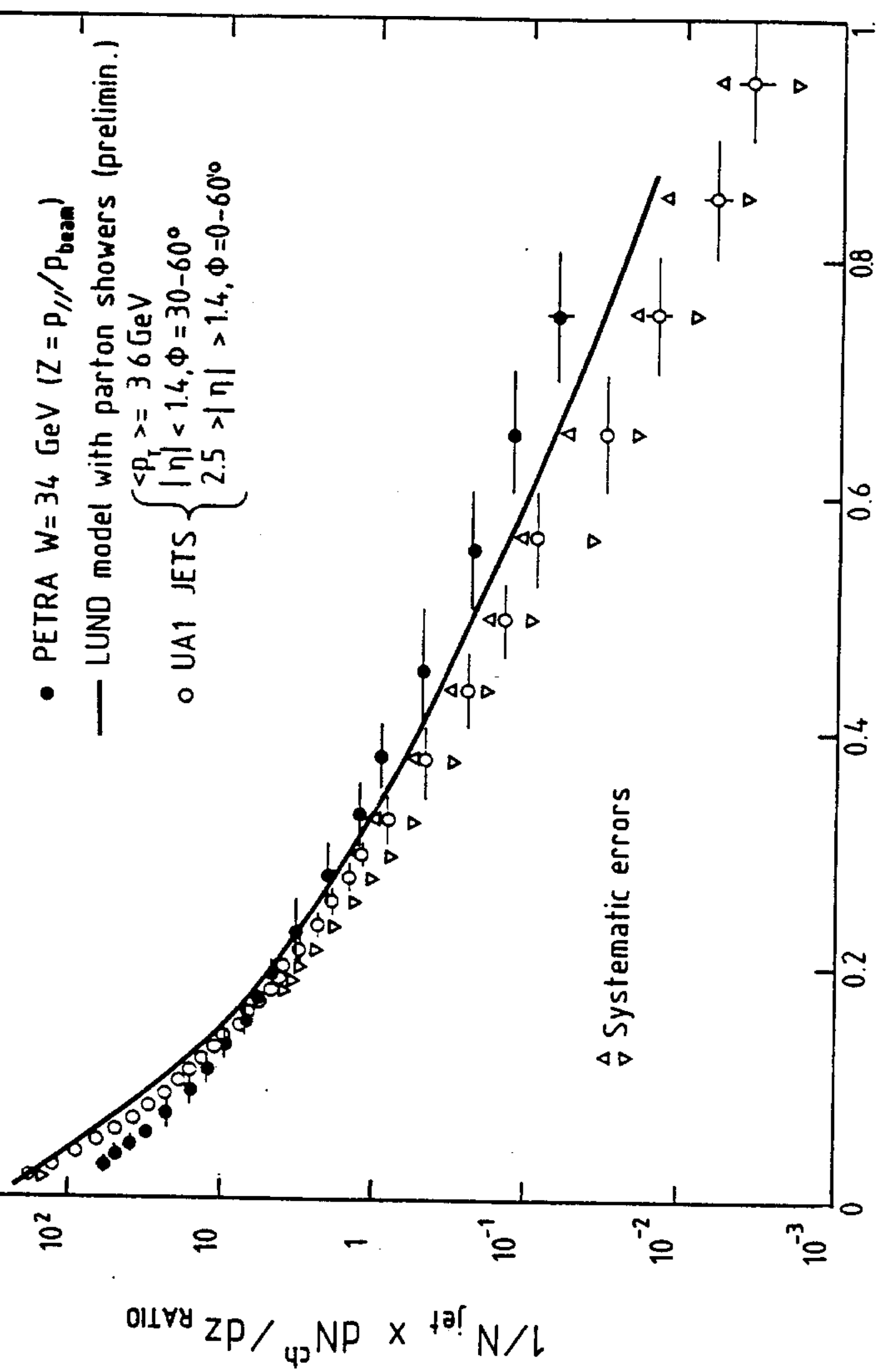
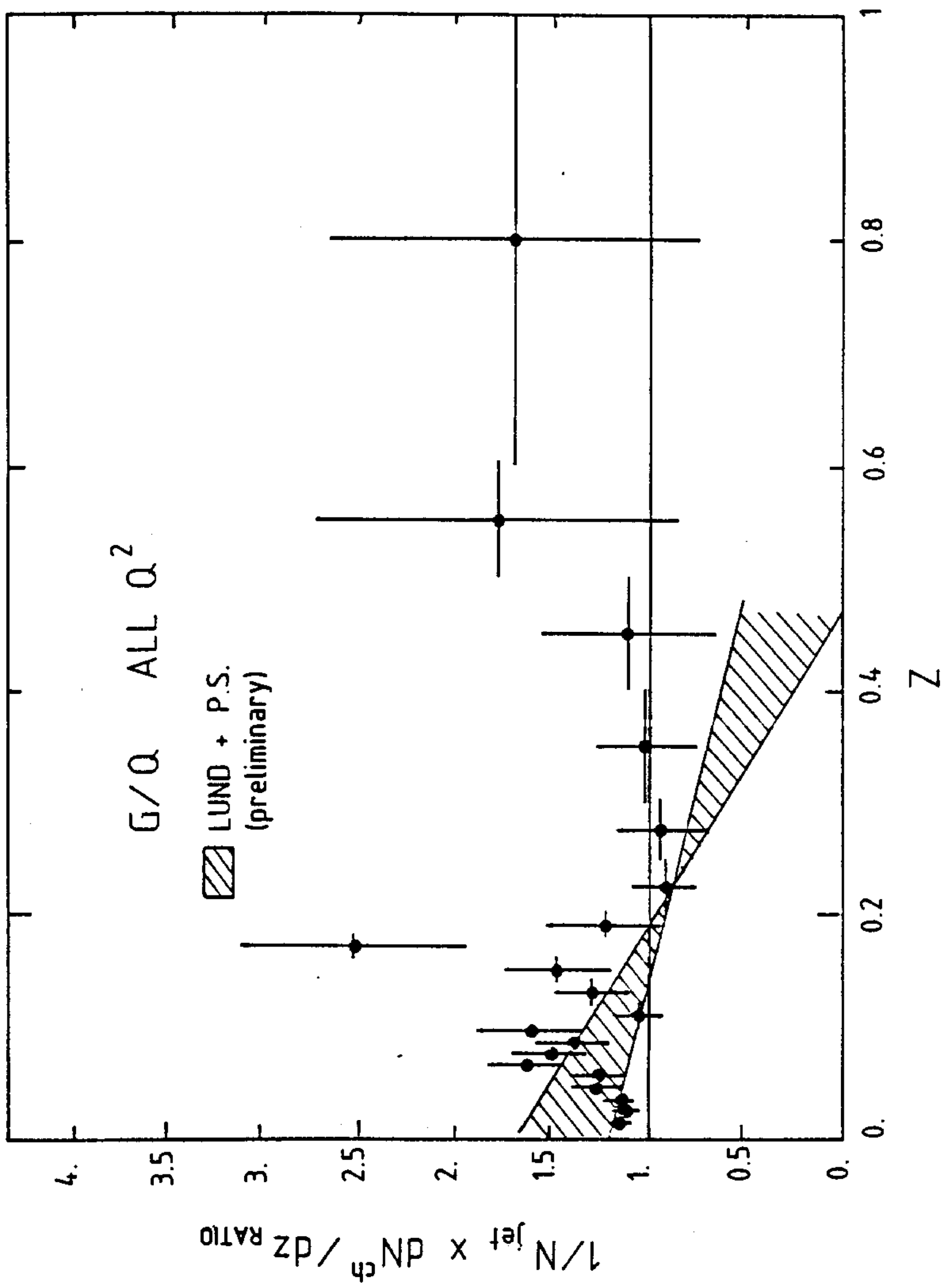
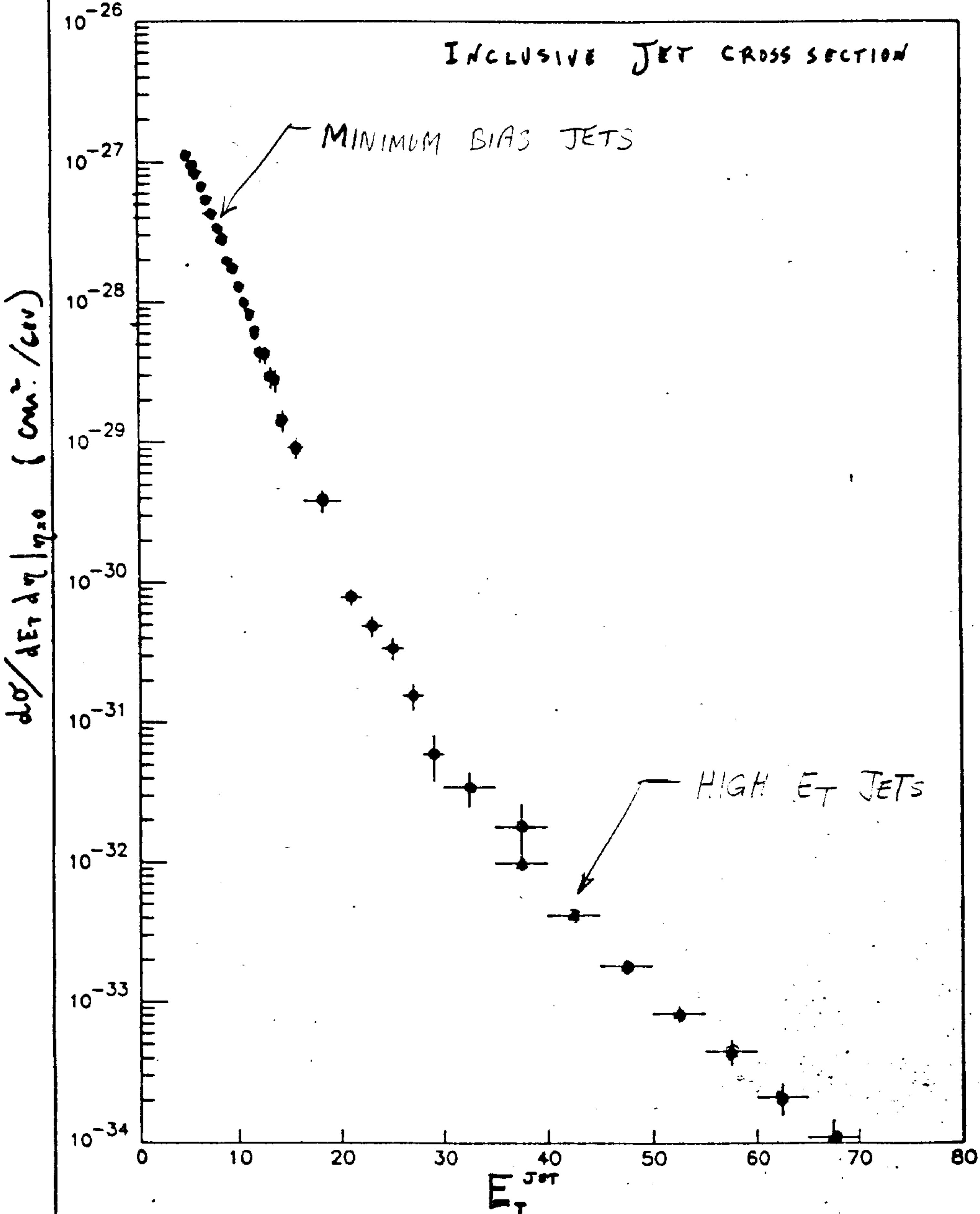

PETRA W= 34 GeV (Z = p///p_beam)
LUND model with parton showers (prelimin.)
UA1 JETS
<p_T >= 36 GeV
|η| < 1.4, Φ = 30-60°
2.5 >|η| > 1.4, Φ=0-60°
Systematic errors
Z
1/N_jet x dN^ch / dz RATIO
10^2
10
1
10^-1
10^-2
10^-3
0
0.2
0.4
0.6
0.8
1

Figure 4



G/Q ALL Q²
LUND + P.S.
(preliminary)
1/N jet x dN ch / dz RATIO
Z
0.
0.2
0.4
0.6
0.8
1
0.
0.5
1.
1.5
2.
2.5
3.
3.5
4.

Figure 5



INCLUSIVE JET CROSS SECTION
MINIMUM BIAS JETS
HIGH E_T JETS
$d\sigma/dE_T\,d\eta|_{\eta=0}$ (cm² / GeV)
E_T^{JET}
10^-26
10^-27
10^-28
10^-29
10^-30
10^-31
10^-32
10^-33
10^-34
0
10
20
30
40
50
60
70
80

Figure 6

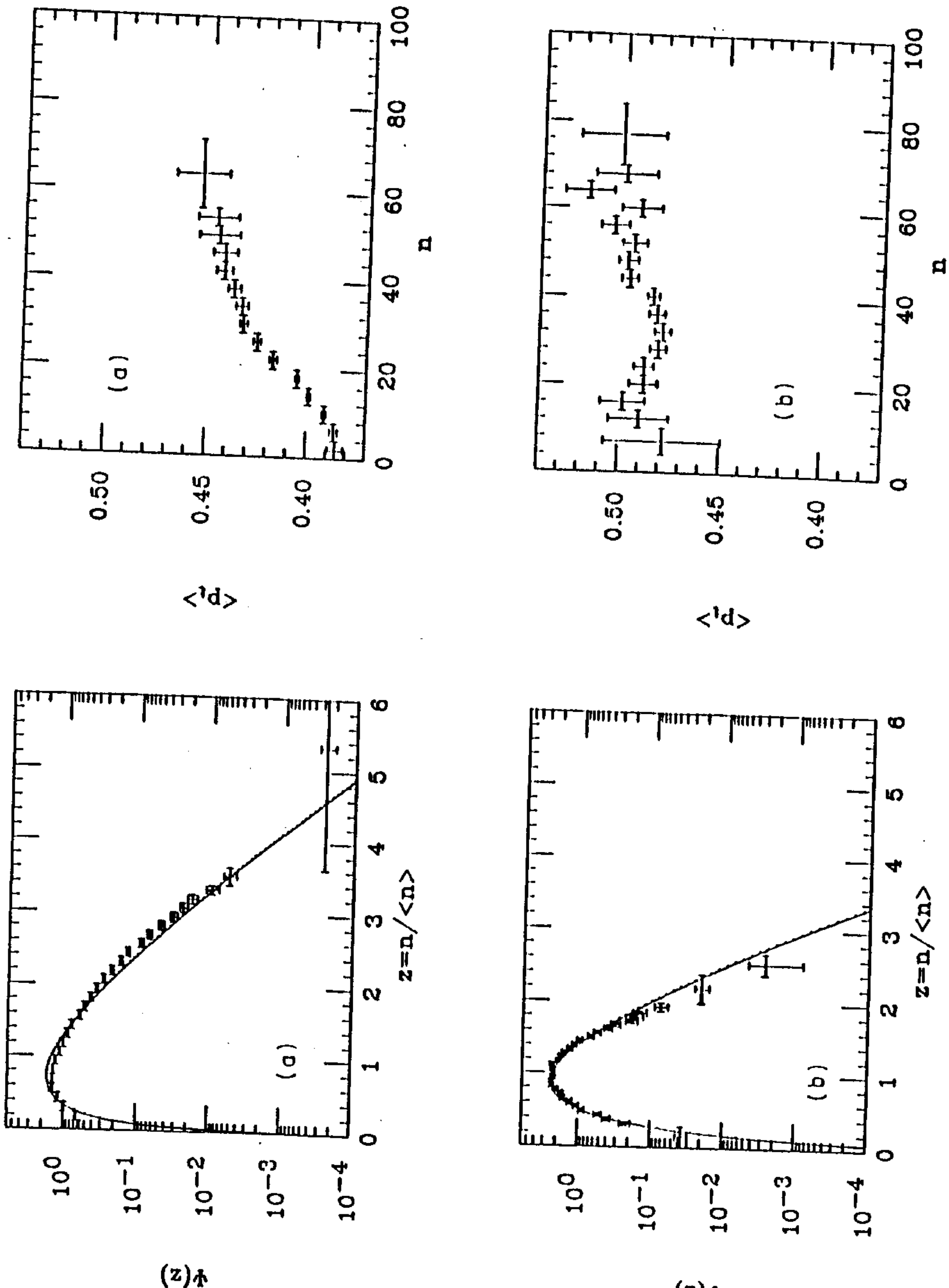


Figure 7

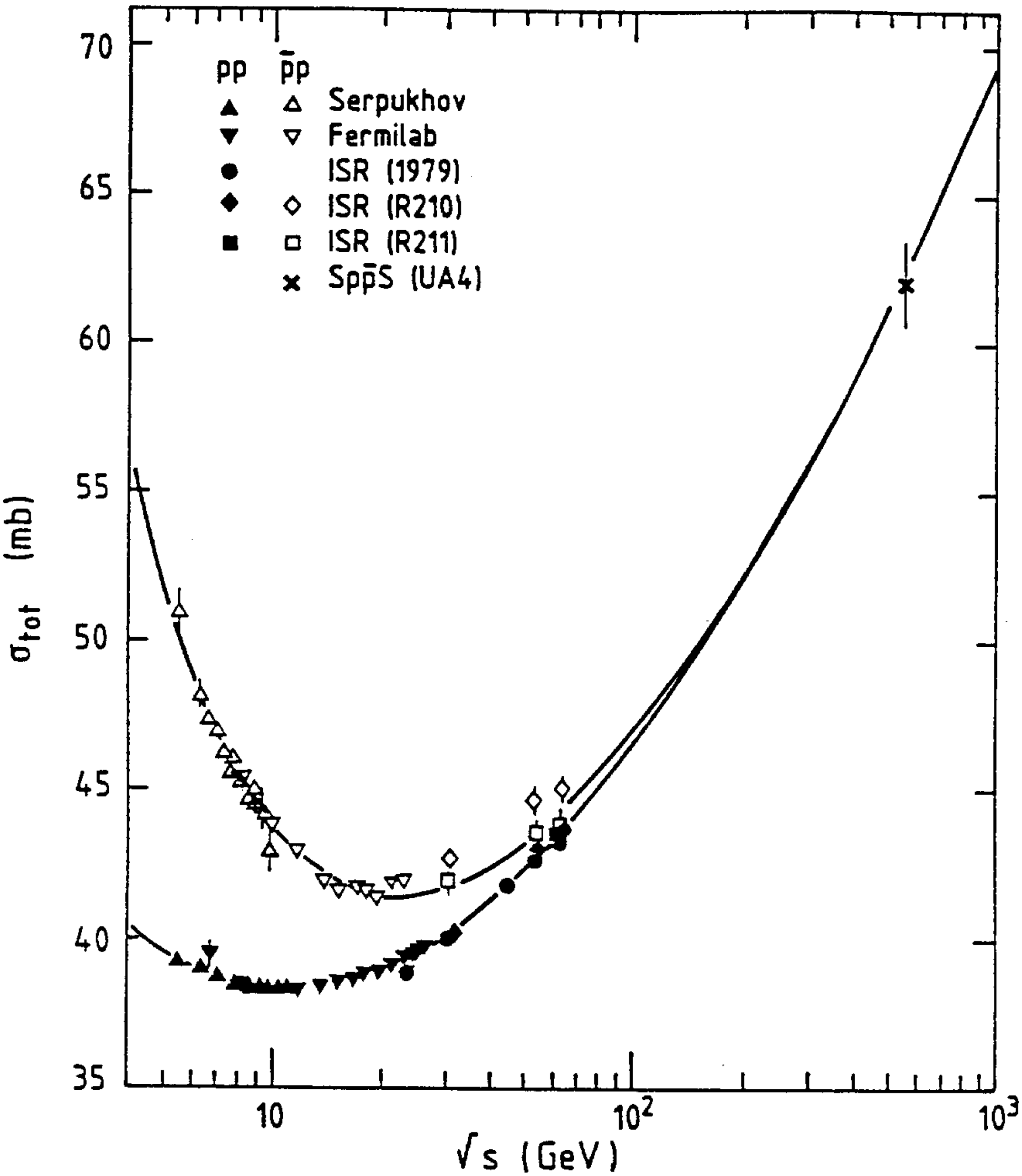
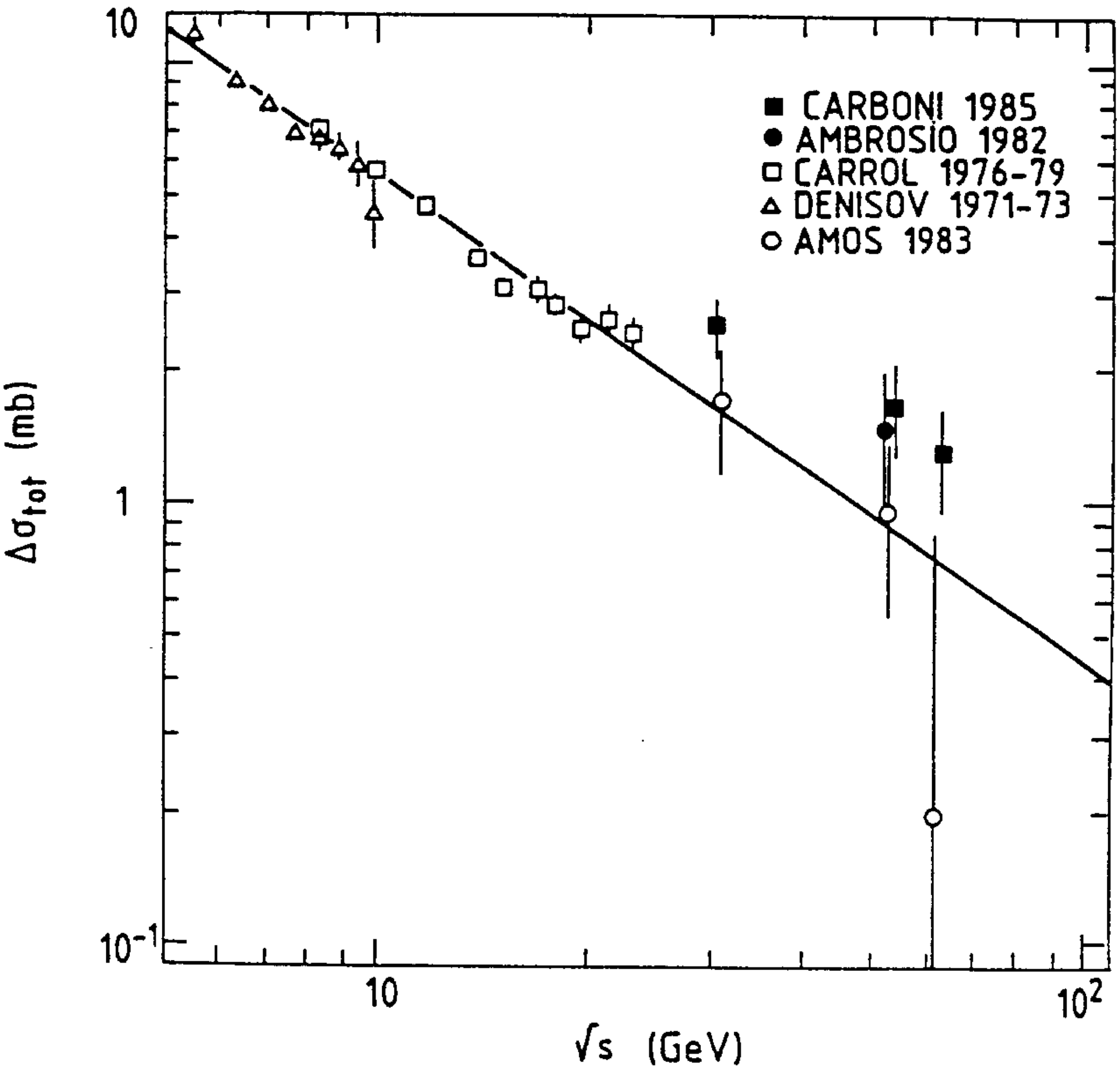

pp
p̄p
Serpukhov
Fermilab
ISR (1979)
ISR (R210)
ISR (R211)
Sp̄p̄S (UA4)
70
65
60
55
50
45
40
35
σ_{tot} (mb)
10
10^2
10^3
$\sqrt{s}$ (GeV)

Figure 8



CARBONI 1985
AMBROSIO 1982
CARROL 1976-79
DENISOV 1971-73
AMOS 1983
10
1
10⁻¹
10
10²
Δσ_tot (mb)
√s (GeV)

Figure 9

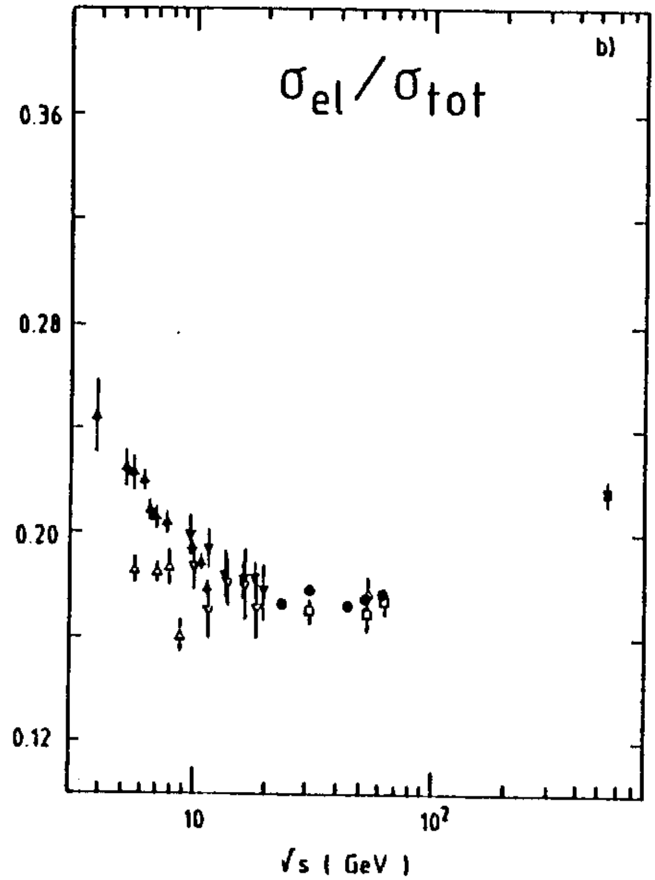
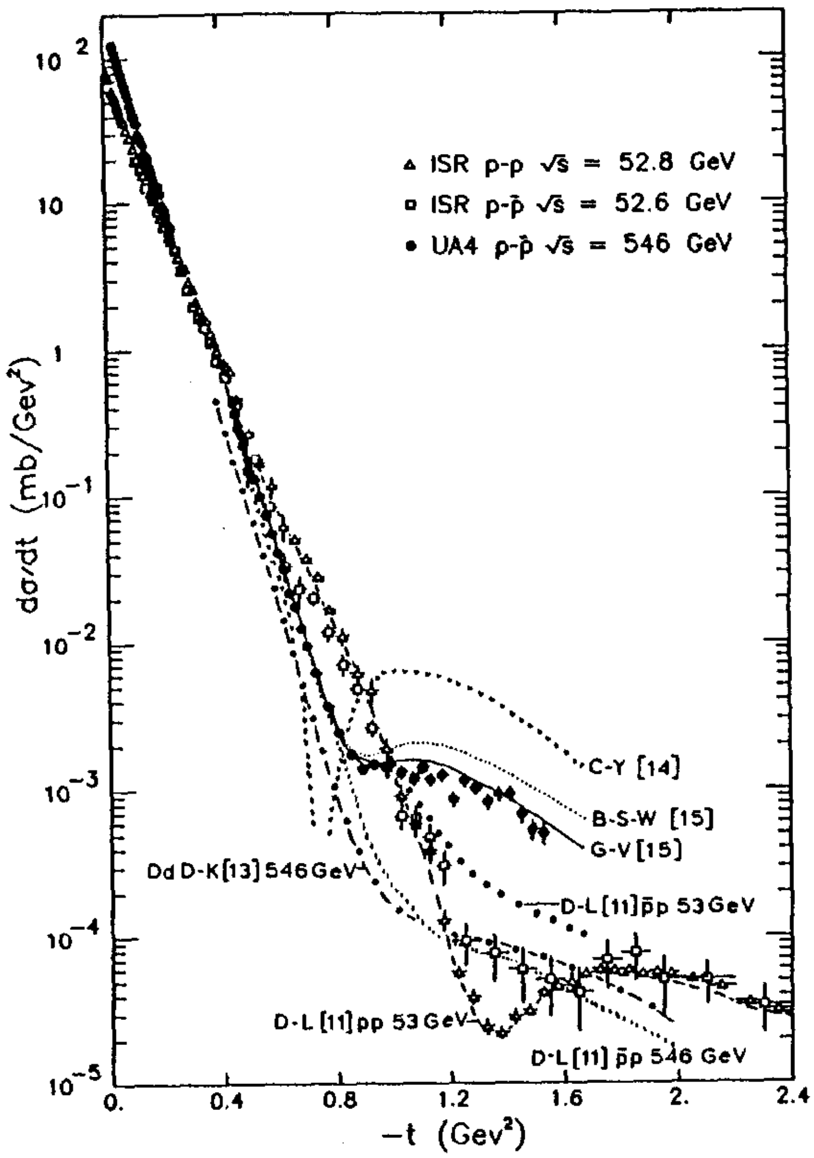
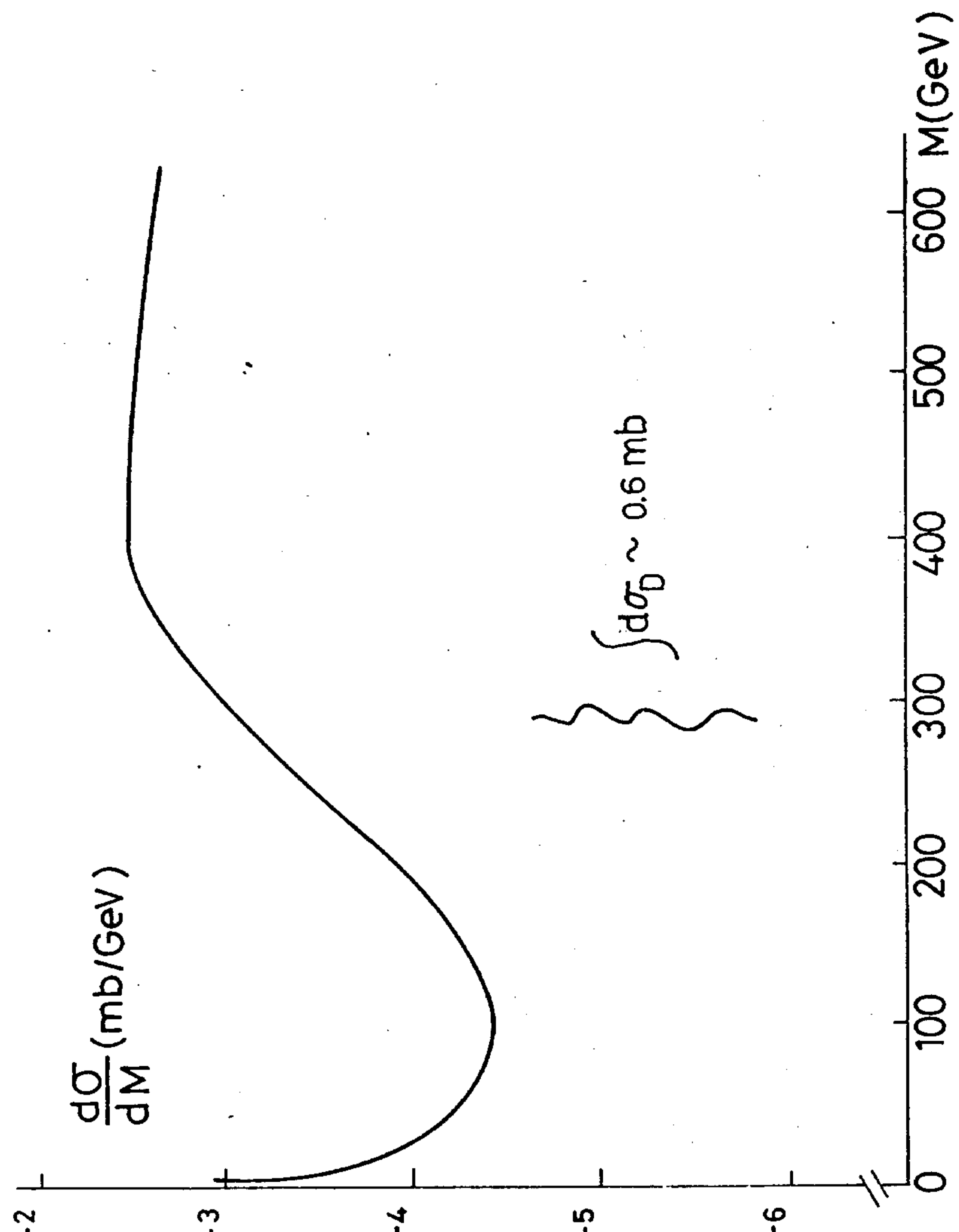


Figure 10



ISR p-p √s = 52.8 GeV
ISR p-p̄ √s = 52.6 GeV
UA4 p-p̄ √s = 546 GeV
dσ/dt (mb/GeV²)
-t (GeV²)
C-Y [14]
B-S-W [15]
G-V [15]
Dd D-K [13] 546 GeV
D-L [11] p̄p 53 GeV
D-L [11] pp 53 GeV
D-L [11] p̄p 546 GeV

Figure 11



$\frac{d\sigma}{dM}$ (mb/GeV)
$\int d\sigma_D \sim 0.6$ mb
M(GeV)
0
100
200
300
400
500
600
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}

Figure 12

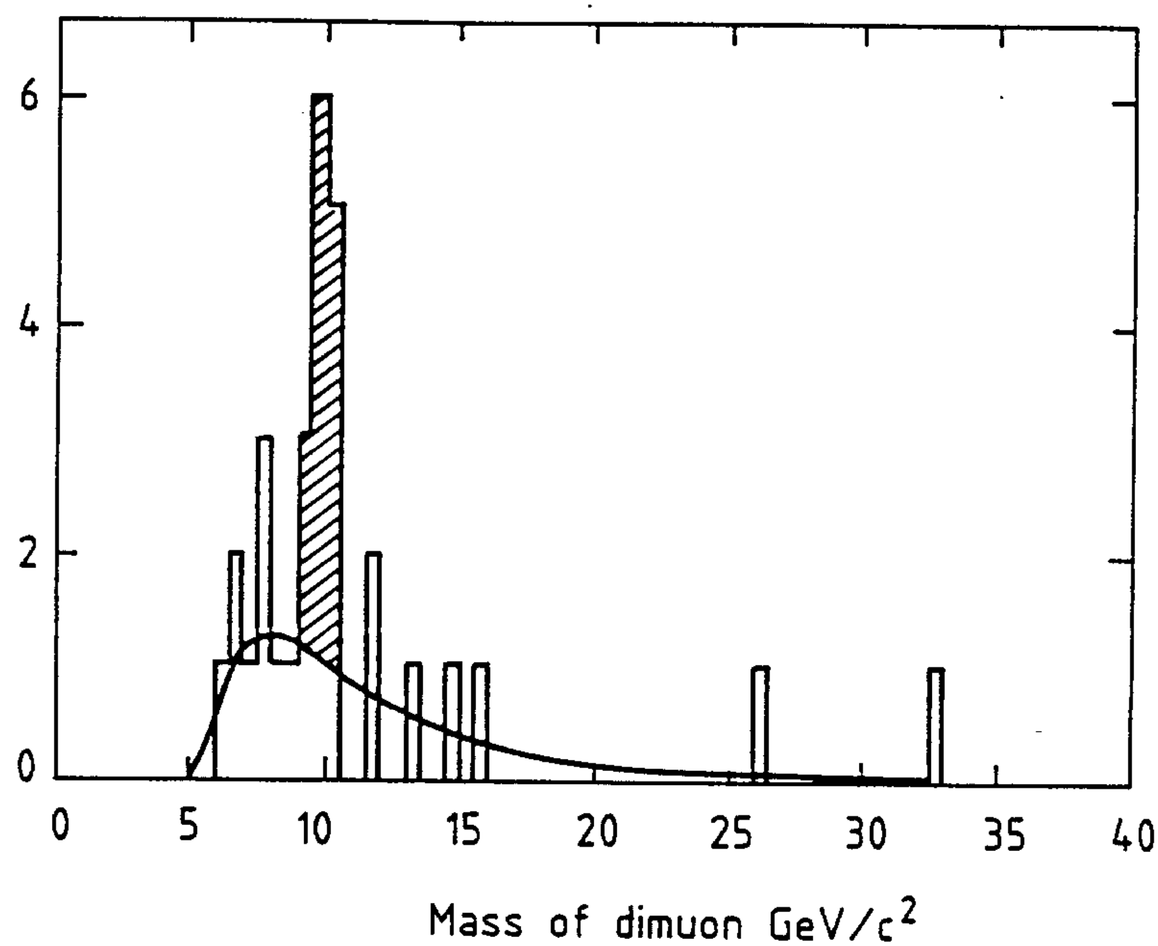
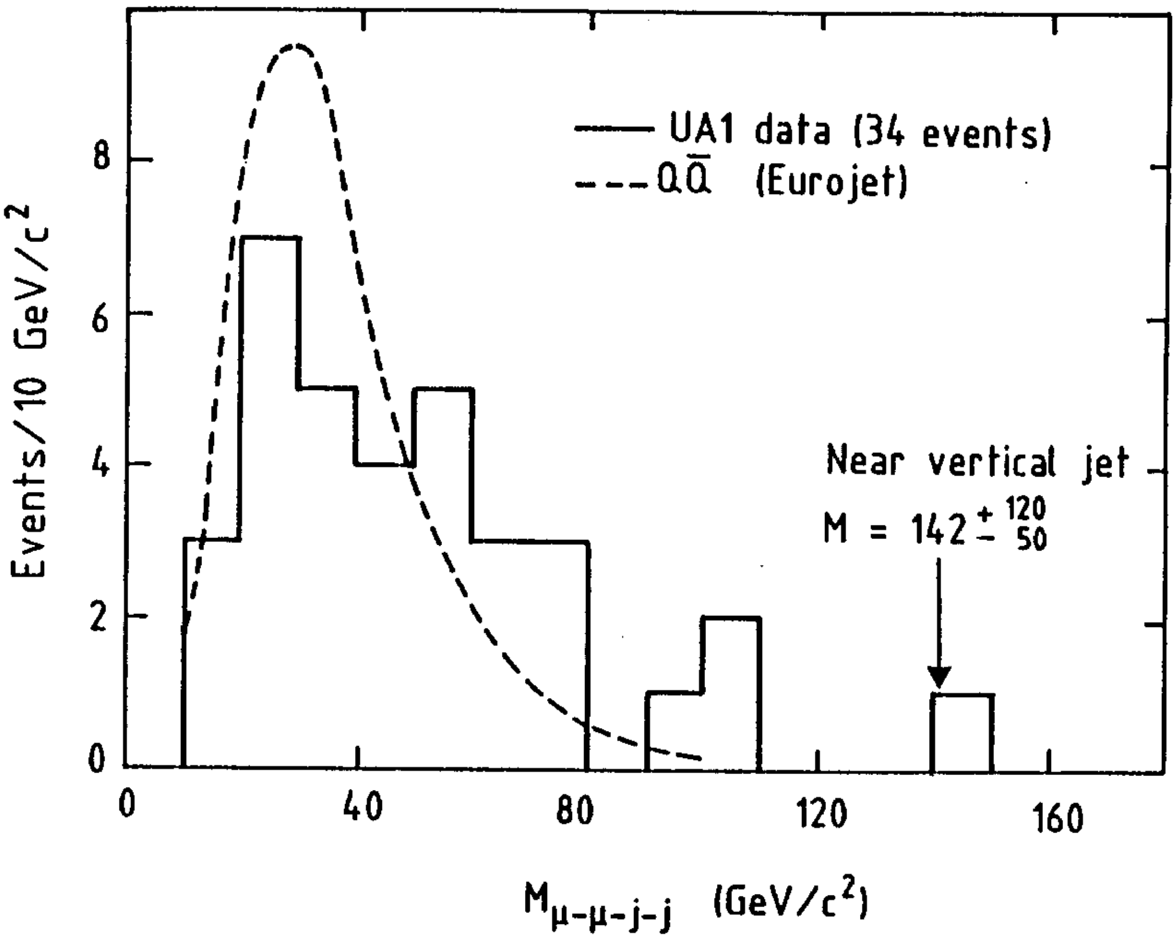


Figure 13



Events/10 GeV/c^2
8
6
4
2
0
0
40
80
120
160
UA1 data (34 events)
$Q\bar{Q}$ (Eurojet)
Near vertical jet
$M = 142^{+120}_{-50}$
$M_{\mu-\mu-j-j}$ (GeV/c^2)

Figure 14

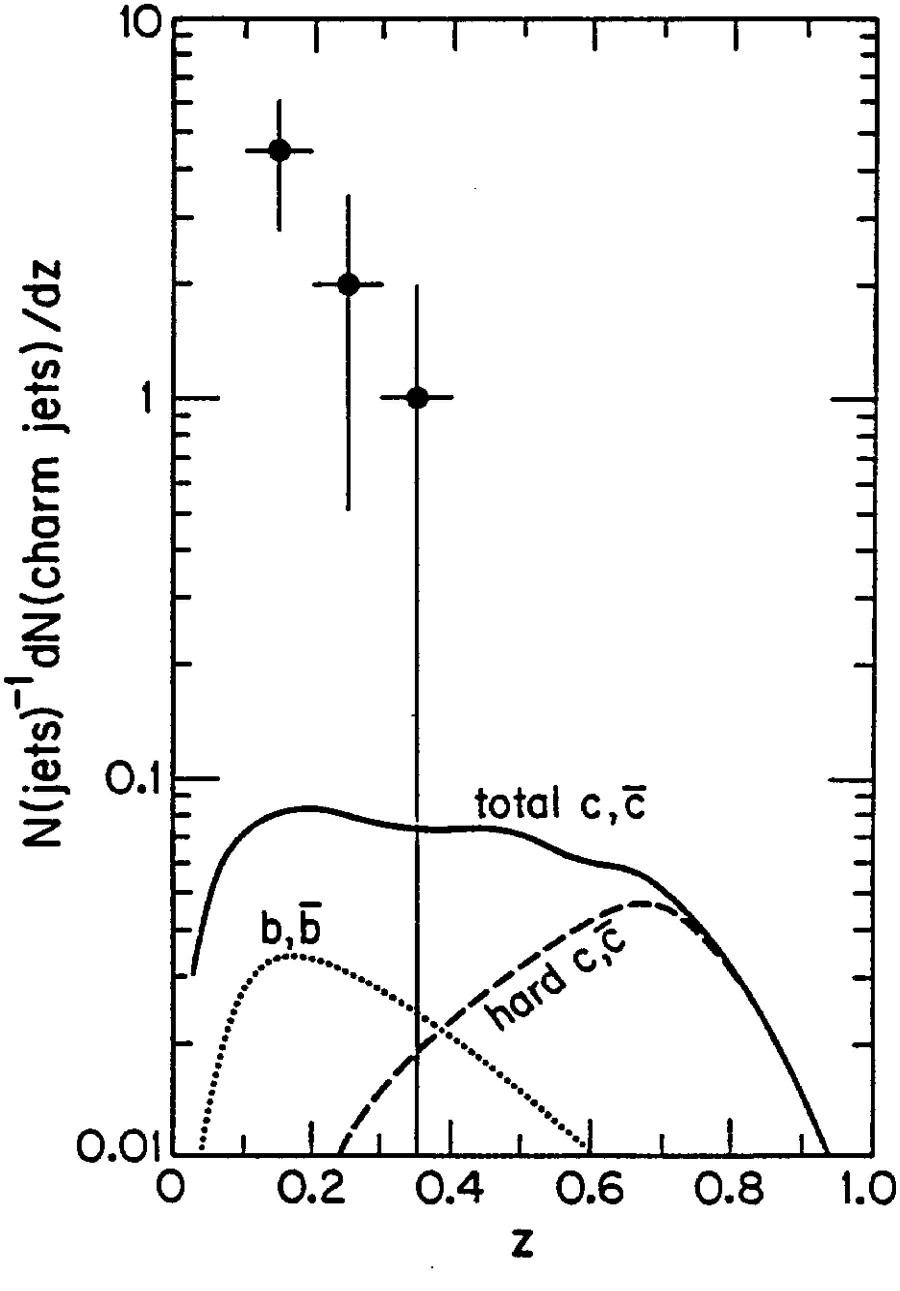

10
1
0.1
0.01
N(jets)$^{-1}$ dN(charm jets)/dz
total c,$\bar{c}$
b,$\bar{b}$
hard c,$\bar{c}$
0
0.2
0.4
0.6
0.8
1.0
z

Figure 15

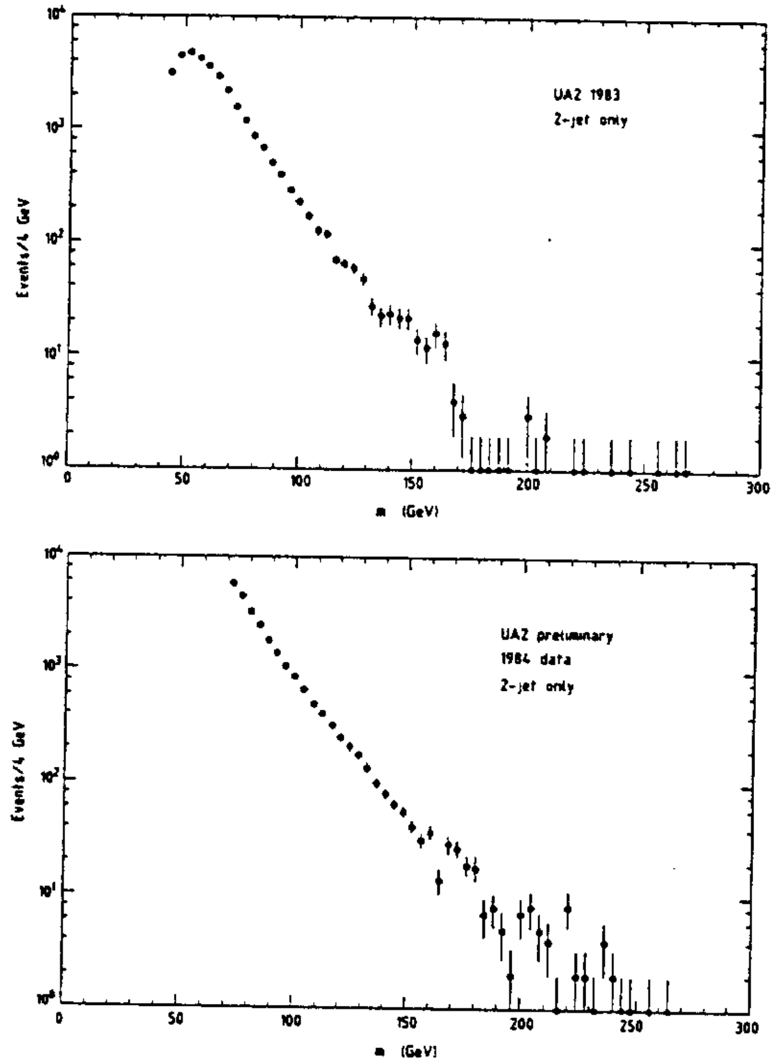

UA2 1983
2-jet only
Events/4 GeV
m (GeV)
UA2 preliminary
1984 data
2-jet only
Events/4 GeV
m (GeV)

Figure 16

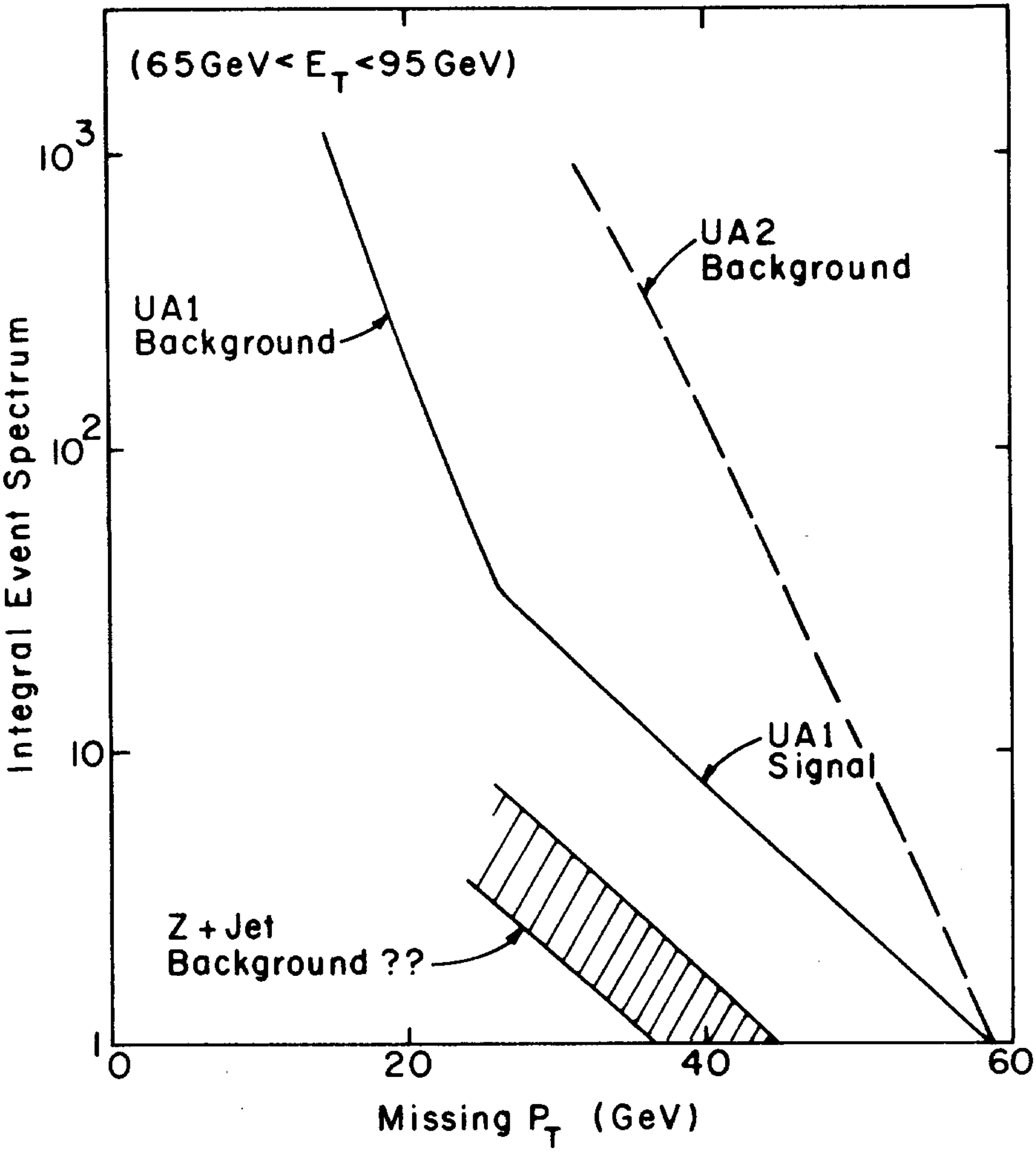


Figure 17

71917

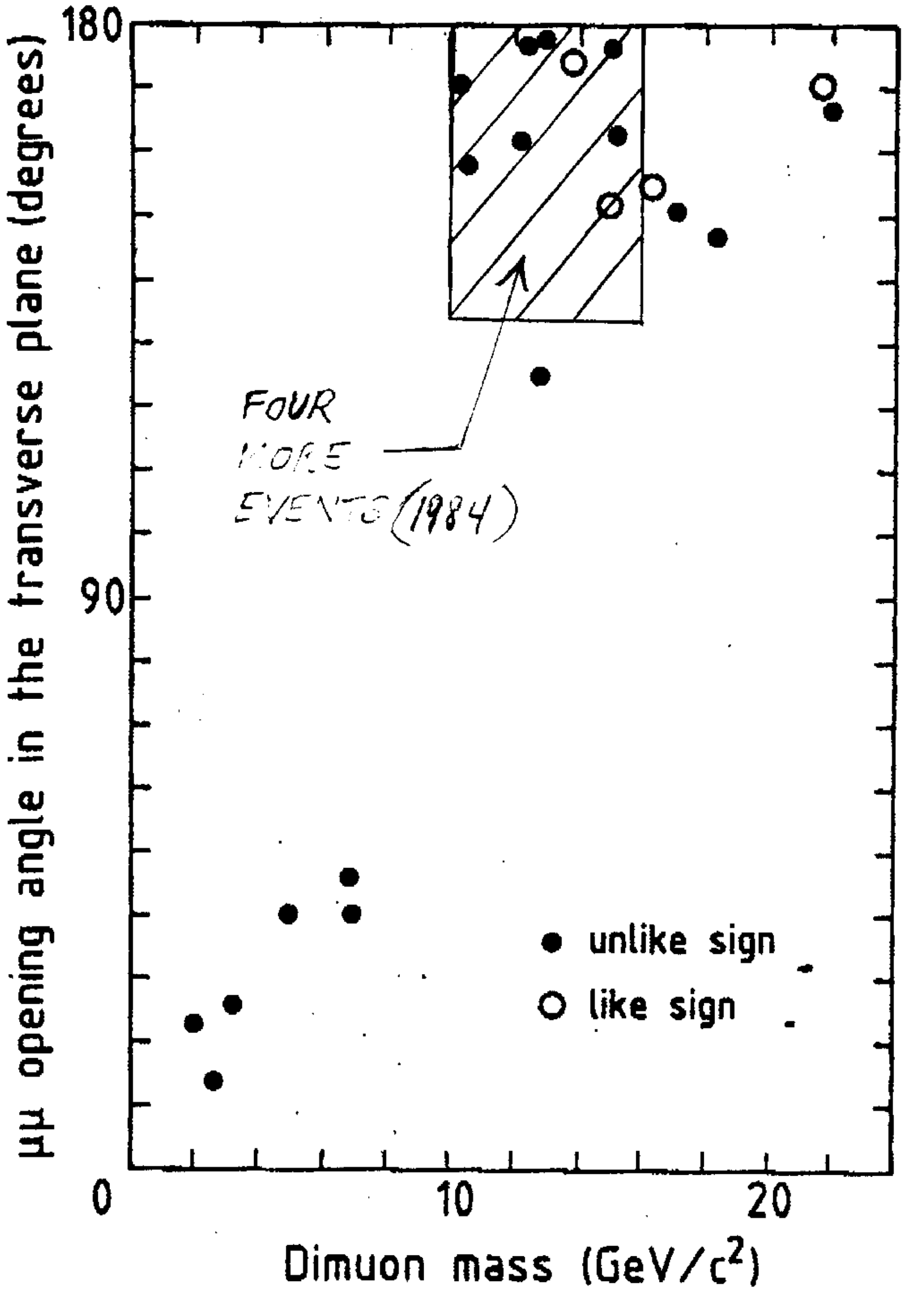

180
90
0
10
20
μμ opening angle in the transverse plane (degrees)
Dimuon mass (GeV/c²)
FOUR MORE EVENTS (1984)
unlike sign
like sign

Figure 18