Issues for a Bottom Collider Detector at Fermilab*

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Abstract

The possibility of performing a very high statistics dedicated bottom physics experiment in the Tevatron collider at Fermilab is discussed. The issues and opportunities are reviewed and brief comparisons are made to e^+e^- machines and the high rate fixed target approach.

Introduction

In the last couple of years there has been increasing interest by the international physics community to study bottom physics with samples approaching 10^9 $B\bar{B}$ pairs or more. Samples of this size appear to be realistic possibilities for either a new generation of high luminosity electron positron machines or new high energy hadron collider experiments. Sample sizes much beyond this will probably have to wait for an SSC type machine where samples of greater than 10^{11} pairs are discussed.

The physics these experiments address is very broad in scope(ref. [1]). The topics of interest are mixing in both the B_d and B_s systems. The Argus experiment has observed mixing in the B_d system at the 20% level (ref. [2]). This large mixing can substantially increase the size of CP violation in the B system, and therefore a more precise measurement of the mixing is important. The observation of a B_s mass peak and the subsequent study of the decay modes and mixing are very important. It has been pointed out that the relative size of the mixing in B_s and B_d is a test of new quark generations (ref. [3]). Other important information will derive from the study of production mechanisms, rare decays, forbidden decays, and bottom baryons (ref. [4]) (ref. [5]). A thorough study of the charmless decays will be important for understanding the standard model(ref. [6]). Finally, the ultimate goal of these experiments is to reach a *window of sensitivity* where CP nonconserving effects can be tested in the bottom system. Study groups in the future

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will try to determine whether this *window* can be reached for a particular machine and detector design.

This paper addresses the issues that have arisen over the last year regarding a new bottom collider experiment. These questions were raised after two Letters of Intent to build dedicated experiments for intersection region **C** were submitted to the laboratory in March 1987 (ref. [7]) (ref. [8]). The ambitious scope of these experiments suggested that the overall bottom physics program at Fermilab and its goals needed to be discussed with regard to what was wanted and possible for the next generation of high sensitivity bottom experiments. Interest was expressed in pursuing very high rate new fixed target experiments as well (ref. [9]). This workshop brought the interested people together to begin discussions on a very large topic. The main issues relevant to a bottom collider experiment discussed here are:

1) Preamble
2) Bottom Physics Goals
3) Comparisons with e^+e^-
4) Kinematics
5) The detector
6) Conclusions

1. **Preamble**

An important issue is whether building a hadron collider experiment to study bottom physics is unique with respect to other approaches. This comment encompasses several issues. The collider experiment must handle significantly lower rates than a fixed target experiment to collect the same number of bottom events. This is a consequence of the large bottom cross section at the collider, $\sim$ 3000 times larger than at fixed target energies. Furthermore, the ratio of bottom to total cross section is about 1000 times larger at the collider making triggering and the extraction of a bottom signal easier. These two effects make the collider approach more favorable in selecting out many decay modes, rather than focusing on a particular mode since the trigger need not be so restrictive. High rate fixed target experiments probably must run with restrictive triggers. As has been pointed out previously events containing $\psi's$ may provide a clean trigger and sufficient background rejection to signal bottom production (ref. [10]). Alternative approaches to triggering in fixed target experiments are being considered to improve efficiency by including single lepton and multiplicity jump triggers (ref. [11]). However, considerably more experience is needed in this area. It is believed that a collider experiment can fully reconstruct events with high efficiency that contain low multiplicity charged decay modes of bottom. This however has yet to be demonstrated even in simulation. There is a lot of interesting physics in the low multiplicity events (ref. [12]).

The uncertainty in predicting which decay modes give large CP asymmetries suggests that more than one mode should be studied. In particular, an analysis Bjorken suggests and explored further at this workshop by the *Physics Group* (ref. [13]) would imply that $B \to \psi K_s$ and $B \to \pi^+\pi^-$ gives complimentary information. Being sensitive to as many modes as possible would be prudent since this is new ground and the potential for surprise is there.

2. Bottom Physics Goals

The major physics goal is to observe and study CP nonconservation in the neutral and charged bottom system. A CP *window of sensitivity*, which is roughly the number of produced $B\bar{B}$ pairs needed to study CP , is roughly estimated from a combination of cross section assumptions, detector efficiencies and CP asymmetry estimates from calculations in the context of the standard model. Some assumptions are required of course. In order to label the B as particle or antiparticle , the other B in the event must be identified or tagged. The CP asymmetry discussed is the difference in rates for particle and antiparticle into the same final CP eigenstate. The decay mode we use as an example is a CP eigenstate that experimently is all charged and has low multiplicity, $B \to \pi^+\pi^-$. Briefly the factors considered are the:

- branching ratio, about 10^{-4}.
- tagging the other B, 4% – 10%.
- trigger efficiency about 50%.
- vertex separation efficiency, about 50%.
- tracking efficiency, about 95%.
- cracks and Z length of beam, about 50%
- reconstruction efficiency, about 25%.
- geometric acceptance , about 65% of 4π.
- relative production of mesons to baryons is 40%.
- total bottom cross section of about 15 μ barns.

Calculated range 10 – 30 μ barns(ref. [15]).

We would like about 1000 events of this mode so that CP asymmetries of 10% or greater can be studied. The predicted range is $5-30\%$ (ref. [17]). The tagging mode assumed is $B \to D^*e\nu$ or $B \to De\nu$ for a total of about 4% tagging assuming 20% of all charm can be reconstructed (ref. [16]). In the ideal CP analysis, it is assumed all the decay products of both bottom particles in the event are fully reconstructed. If the tagging criteria can be relaxed to indicate that there are two vertices (a B

and D vertex) and that the lepton comes from the B vertex, as distinct from a charm or the beam collision point, the tagging efficiency may be increased over full reconstruction. Any remaining improvement in the tagging efficiency will come from trying to extract information from the nonleptonic decay modes of bottom. Triggering on these events has not been studied. Eventually the mistagged events will have to be studied very carefully. Detailed simulation work that studies the optimization of tagging is very important since this is an area where many events can be gained or lost. The 50% trigger efficiency is a challenge and ambitious but has not been simulated at the level where it can be thought of as a realistic estimate yet. The reconstruction efficiency should be high once the event has been accepted by the trigger and the vertex cut is applied. The design peak luminosity of the Tevatron is $10^{30} cm^{-2} sec^{-1}$, leading to an average of about 1/2 of that, giving 7.5 $B\bar{B}$'s produced per second or about 10^8 per running year. The upgrade luminosity is estimated to improve the luminosity by a factor of 50, or giving about 10^{10} produced $B\bar{B}$'s per running year. A sample of 1000 $B \rightarrow \pi^+\pi^-$ can be studied in one year of running assuming a 10% tag of the other bottom particle in the event. This does not include effects due to backgrounds and assumes that a 3 σ measuremnt on a 10% CP asymmetry is a reasonable analysis goal. Therefore *the CP window of sensitivity is* 10^9 *to* 10^{11} produced $B\bar{B}$'s. Running over several years will help insure against undue optimism in these estimates. The main comments at this point are:

-The need for an upgraded Tevatron is absolutely clear. A factor of 10 improvement is minimal and the full factor of 50 over the present design luminosity is preferrable.

Can the experiment be built that produces the above performance characteristics?

3. Comparison with e^+e^-

Anyone thinking about a new B physics experiment at a hadron machine must look carefully at the e^+e^- options. The vast majority of the information about the bottom system has come from e^+e^- colliders and there is much activity in this area. The physics and future machines are discussed by a contribution to this workshop by D. Macfarlane. The e^+e^- environment is very clean, the ratio of B meson to continuum production is about 1/4, compared to about 5×10^{-4} at the collider. Furthermore, on the $\Upsilon(4s)$ resonance, all charged tracks come from the bottom meson since there is not enough energy to produce extra pions. At the Tevatron, an average of 80 charged tracks are produced per collision in the bottom events. The cross section at the $\Upsilon(4s)$ is about 1 nb or $\sim$ 20,000 times less than at the Tevatron collider. This is partially offset by the fact that the luminosity of present day machines like $CESR$ are running close to $10^{32} cm^{-2} sec^{-1}$. The luminosity achieved in the Tevatron at this point is about $10^{29} cm^{-2} sec^{-1}$ and the design is $10^{30} cm^{-2} sec^{-1}$. A proposed upgrade to the Tevatron might reach $5 \times 10^{31} cm^{-2} sec^{-1}$, which would be competitive with the luminosity achieved in e^+e^- machines.

However, there are two physics reasons why the $\Upsilon(4s)$ is not the ideal place to do CP studies. As pointed out by Sanda and Bigi(ref. [17]), a *clean* test of the standard model comes from studying the CP eigenstates of the neutral B system. Since the $\Upsilon(4s)$ is a well defined CP state, to discover CP nonconservation on the $\Upsilon(4s)$ requires essentially a few golden events. This is quite different from the Tevatron or in the continuum where *asymmetries* are measured and a few events observed does not constitute violation of CP . As stated in this reference the CP rate on the $\Upsilon(4s)$ is proportional to a mixing factor, times the *square* of an imaginary term which contains amplitude information, times the products of the individual transition rates of the two bottom particles in the event. Off the $\Upsilon(4s)$, the imaginary term is raised to the power one. This means a 10% CP asymmetry off the $\Upsilon(4s)$ enters effectively as 1% on the $\Upsilon(4s)$. This is a large penalty for running on the $\Upsilon(4s)$. Secondly, it can be shown (ref. [17]) the event does not conserve CP unless the two B 's have the same CP parity. The requirement that both B's must come from a CP eigenstate means that the small rates of these states enters as a product in the overall CP violating rate. A list of factors that contribute to the overall CP rate on the $\Upsilon(4s)$ are:

- 10^{-4} branching ratio for one B decay
- 10^{-4} for the other B decay
- about 0.5 for the same CP parity requirement
- .01 – .35 for the CP asymmtry term
- 0.6 for the mixing term
- 0.1 for the experimental detection efficiency

The probability of one CP violating event is about 10^{-10} to 3×10^{-12}. A luminosity of 10^{32} cm^{-2} sec^{-1} produces 10^6 $B\bar{B}$ pairs per 10^7 second running period. Present day e^+e^- machines cannot reach CP violation in neutral decays. The most ambitious of the new machines is the low energy linear collider approach, proposed by U. Amaldi and G.Coignet (ref. [18]) and by D. Cline (ref. [19]). Here luminosities of $10^{34} cm^{-2} sec^{-1}$ may be achievable. Other ambitious approaches have been put forward from SIN, KEK, and $SLAC$ (ref. [20]),(ref. [21]), (ref. [22]). Even so, this is still short of providing a clean test of the standard model which is afforded by the neutral bottom system. The area of CP violation accessible to these new machines is charged bottom decay, where final state interactions cause the CP nonconserving decays. Of course surprises can be expected.

The higher energy e^+e^- colliders like LEP and SLC have the benefit of a boosted bottom meson allowing the possibility of vertex detection, a reasonably low multiplicity event, and very powerful detectors. However, they will not produce enough events to address CP violation in the neutral B system. Even at 10^7 Z^0's produced per year this is less $B\bar{B}$'s than $CESR$ produces now. These experiments will be able to study mixing in both the B_d and B_s systems simultaneously since they are above threshold, unlike experiments running on the $\Upsilon(4s)$.

In the near future e^+e^- machines will continue to dominate the bottom physics scene. *The niche available for high luminosity hadron machines is clearly CP violation studies.*

4. Kinematics

The kinematics of bottom production in a hadron collider are in many ways startling at first observation. At the Tevatron, with each beam at 1 *Tev* in energy, the bottom meson P_t spectrum is very soft, averaging about 4.4 Gev/c. This can be compared to the value at the SSC(20 on 20 Tev), where it is about 6 Gev/c, quite similar. The reason is that the large cross section, about 15 μbarns, comes from gluon fusion, which has a pole around a P_t equal to the mass of the heavy quark being produced.(ref [23]). The other constraining factor is the rapidity distribution of the tracks from the bottom particles. About 85% of the tracks are contained within ± 4 units of rapidity at the Tevatron, about 25% within ± 2 units, yet only a few percent are contained between 2 to 4 units of rapidity. This is because the low P_t of the bottom meson relative to its mass causes the bottom tracks to spread over typically a couple of units of rapidity. Hence it is critical to cover *large* solid angle to pick up all the tracks from the bottom meson since the goal is to fully reconstruct the decays. At the SSC, most tracks are contained within ± 6 units and this is because the increased particle production is pushed to higher values of rapidity as the energy of the collision is increased. The η spectrum of bottom tracks and the bottom meson P_t spectrum are shown, see fig. 1 and fig. 2. An important difference between high energy hadron colliders and either lower energy fixed target experiments or e^+e^- colliders is the large multiplicity per event in the hadron collider. The charged track multiplicity per event averages about 80 tracks and has large fluctuations. The distribution is shown in fig. 3.

The average P_t of the lepton from the bottom meson is about 1.6 Gev/c and the momentum averages 8.3 Gev/c. The spectra are shown in fig. 4 and fig. 5. This is a major problem for any hadron collider detector trying to capture the largest part of the cross section. The experimental techniques for identifying very low P_t electrons at hadron colliders such as the Tevatron or CERN do not exist.

A feature of the Tevatron is its very long luminous region along the beam direction. Typically this is a Gaussian distribution of sigma about $35cm$. This makes the experimental design of the vertex detector difficult if full acceptance is desired.

Another important feature of the kinematics involves the path length l distribution of the B mesons from the collision point. As is well known, the separation significance of the bottom meson vertex from the beam collision point is nearly constant once the decaying particle velocity approaches $\beta \sim 1$. The forward bottom particles, though more boosted, are not separated with any greater significance than softer more centrally produced mesons. Assuming a simple detector geometry, Figures 6 and 7 show the significance of separation in two η slices where the vertex error includes the beam size (40μ), multiple scattering contributions to the track error and effects of opening angles. The average value is about 5 for all B events and if one B meson is required to have two significant impact parameters $\delta/\sigma > 3$, then the average $l/\Delta l$ is about 10. The object is to make Δl as small as possible, and the situation should improve by reducing the beam size using tracks in the event to determine the collision point more precisely. Figure 8 shows the average bottom path length, which is about 770μ for $\eta < 1$ and figure 9 shows the bottom charm separation for $\eta < 1$. The latter averages around 650μ and is important in determining how often the charm particle can be cleanly separated from the bottom vertex. As stated earlier some tagging techniques rely on seeing the separted vertex of the charm from the bottom and primary vertices.

Shown for completeness is the K momentum spectrum versus rapidity in figure 10. Techniques for finding K 's in the central region may well be different from finding kaons in the forward region.

5. Detector

This section describes briefly some issues regarding the components of the detector and the required performance. This detector has a roughly 1 *meter* radius magnet for tracking, calorimetry for electron identification, particle identification for kaons and no hadron calorimetry since missing E_t is unimportant. It should cover 90^0 to 2^0 in theta.

The vertex detector is the heart of this experiment. Without excellent vertex detection B mesons will never be reconstructed in a hadron collider because of the huge combinatoric background. There exists no design for the vertex detector with full coverage. Work is in progress to evaluate different designs (ref. [24]). The vertex confusion arising from the many tracks in the event suggests that $3D$ information is necessary. In order to reduce multiple scattering, double sided silicon detectors are needed. As a design criteria to aim for, 20 μ is assumed the maximum tolerable uncertainty for a track impact parameter in the $x-y$ plane. This is based on the experience of E-691 at Fermilab. Another interesting point is the fact that multiple coulomb scattering in the collider geometry depends linearly on the P_t of the track and the radial distance of the first measurement layer from the beamline. This implies that getting as close to the beam is critically important in order to minimize scattering of the softer tracks. Collider experiments require that the first vertex detector plane be located about 1 *cm* from the beamline.

The magnetic geometry is of course very important since tracking over 4π is desired. After this workshop a large dipole was prefered , but the toroid or quadrupole still may reappear. The magnetic tracking must provide good pattern recognition and extrapolate with high precision into the silicon vertex detector. The mass resolution needed for separating out B_d and B_s and rejecting combinatoric background is about 25 Mev/c. Gas tracking is needed to minimize the contribution of multiple scattering to the mass resolution. A further challenge is the need for good Z resolution for mass reconstruction and pattern recognition. One interesting point not appreciated by many 'colliding beam experimentalists' is that tracking densities in the collider are much less than those already handled in the fixed target programs at CERN and Fermilab.

Triggering presents a major challenge because the leptons are extremely soft in P_t . There will be a great deal of work in this area because in a hadron collider the trigger defines the overall number of $B\bar{B}$'s that can be analysed.

6. Conclusions

The bottom physics that can be studied at a hadron collider is broad in scope and potentially very exciting. The ultimate goal is to study CP nonconservation in the neutral and charged bottom system, which may be the *niche* for an experiment at a high energy hadron collider.

Present day e^+e^- machines, operating with record luminosities, cannot in general produce enough bottom events to address CP in the B system. Machines presently being discussed need to improve the luminosity by orders of magnitude. The technical developments will require considerable time. The fixed target experiments using hadron beams must learn to trigger and record data at rates above 10^7 interactions per second. The experience of several experiments presently running will determine which approach will be best for high rate bottom physics.

At Fermilab, people have begun to study the design issues of a bottom collider detector. The final design will most likely be ambitious and novel. A great deal of work is necessary before one can demonstrate that it is possible to build such a device and accumulate a sample of 10^9 bottom events. Though challenging, the technical goals do not seem out of reach. It is felt that a bottom physics experiment seeking 10^9 $B\bar{B}$'s or more is possible using the Tevatron collider and this would fall inside the CP *window of sensitivity.*

Finally, the experience gained from running a dedicated bottom physics collider experiment combined with the high rate techniques being developed for the fixed target program should help solve many of the problems associated with an SSC B spectrometer design. The options available for pursuing bottom physics in the next decade are very diverse and exciting indeed.

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7 $l/\Delta l$ $1 < \eta < 2$
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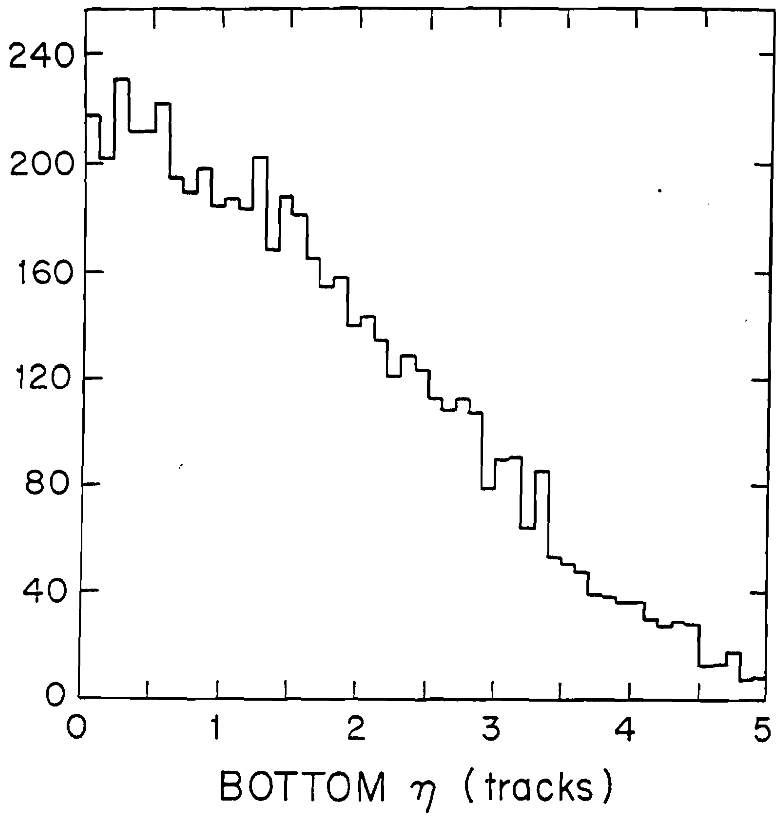
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40
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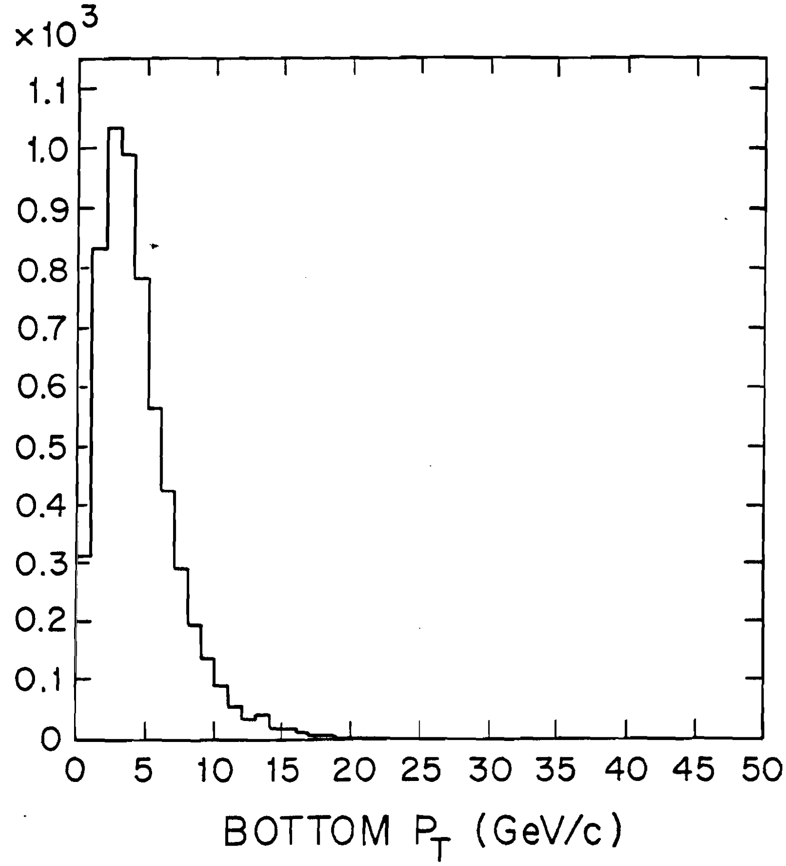
1
2
3
4
5
BOTTOM η (tracks)

Fig. 1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1.0
0.9
0.8
0.7
0.6
0.5
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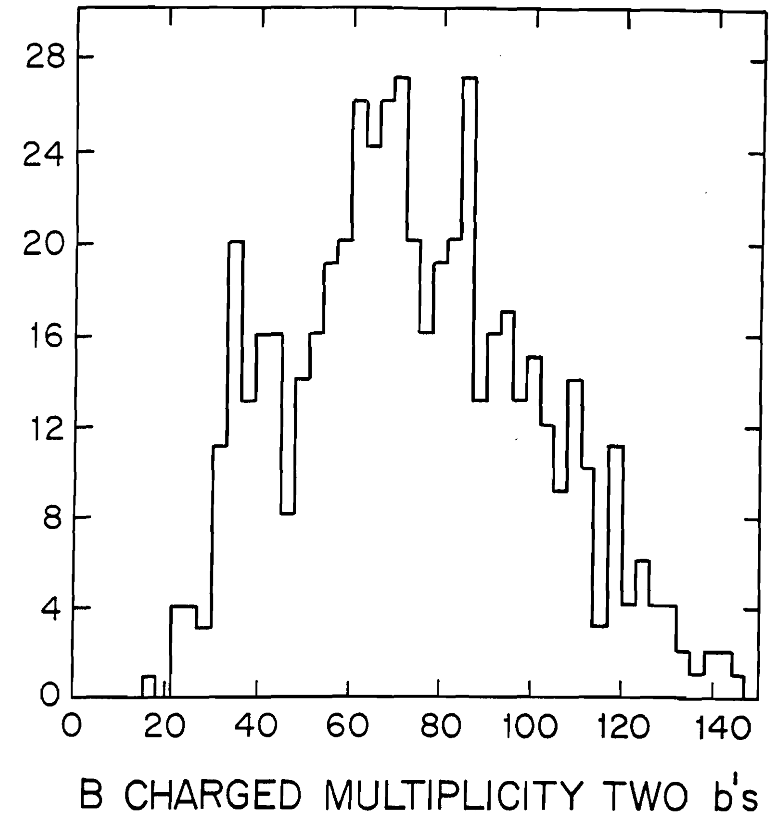
0.3
0.2
0.1
0
0 5 10 15 20 25 30 35 40 45 50
BOTTOM P_T (GeV/c)

Fig. 2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20
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40
60
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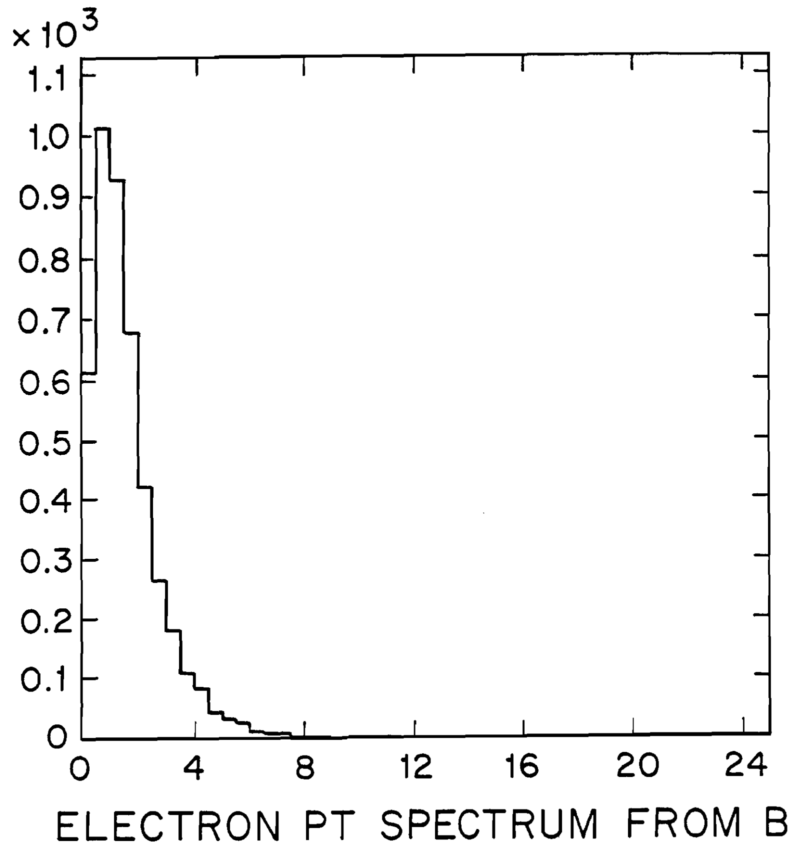
120
140
B CHARGED MULTIPLICITY TWO b's

Fig. 3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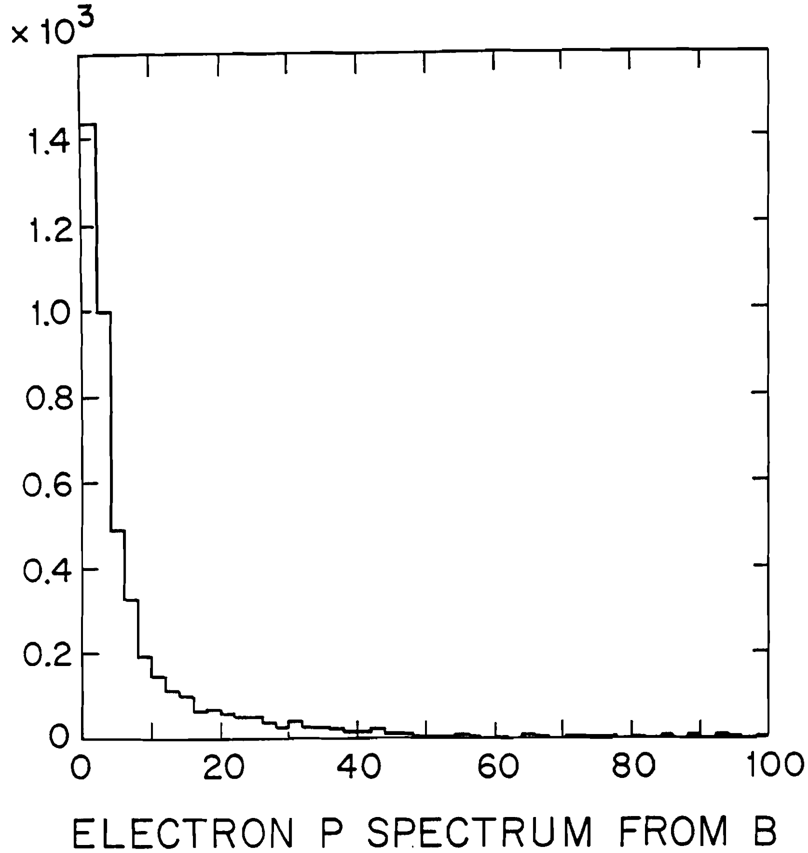
4
8
12
16
20
24
ELECTRON PT SPECTRUM FROM B

Fig. 4



× 10^3
1.4
1.2
1.0
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0
0
20
40
60
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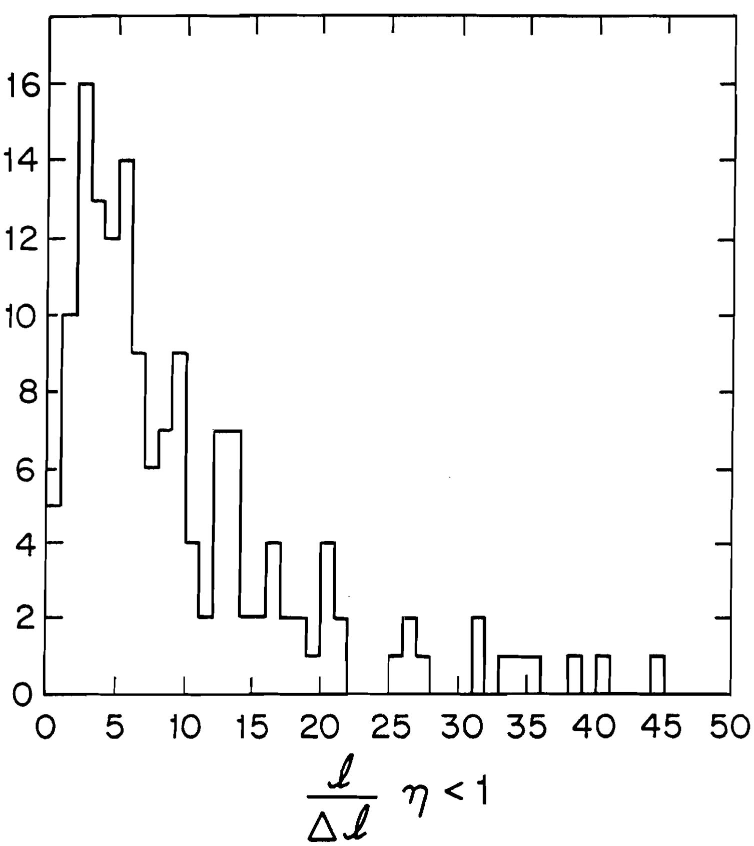
100
ELECTRON P SPECTRUM FROM B

Fig. 5



16
14
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8
6
4
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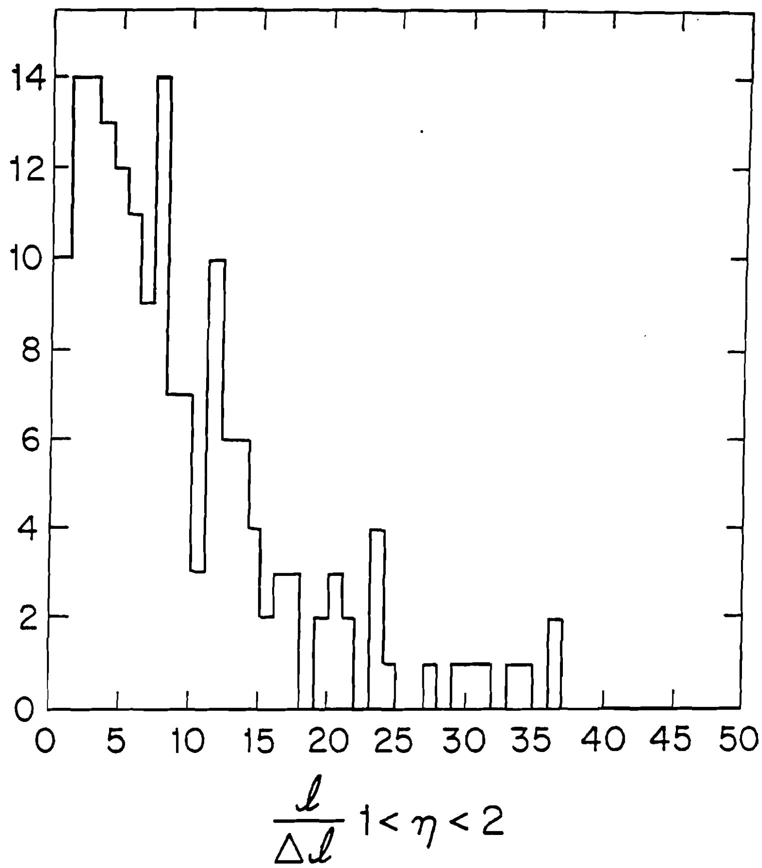
15
20
25
30
35
40
45
50
$\frac{\ell}{\Delta \ell}$ $\eta < 1$

Fig. 6



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12
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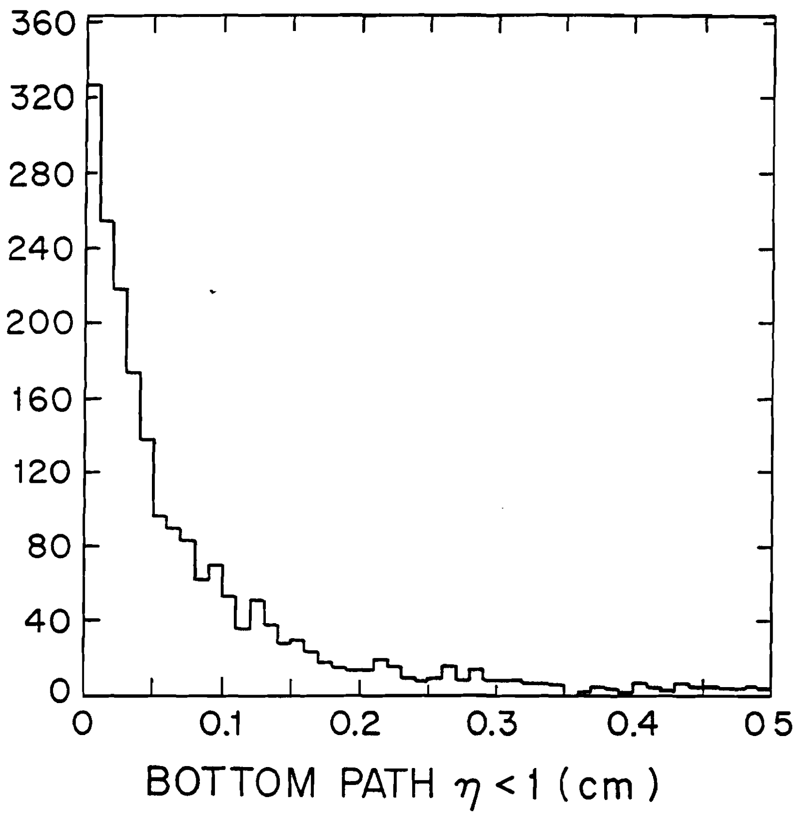
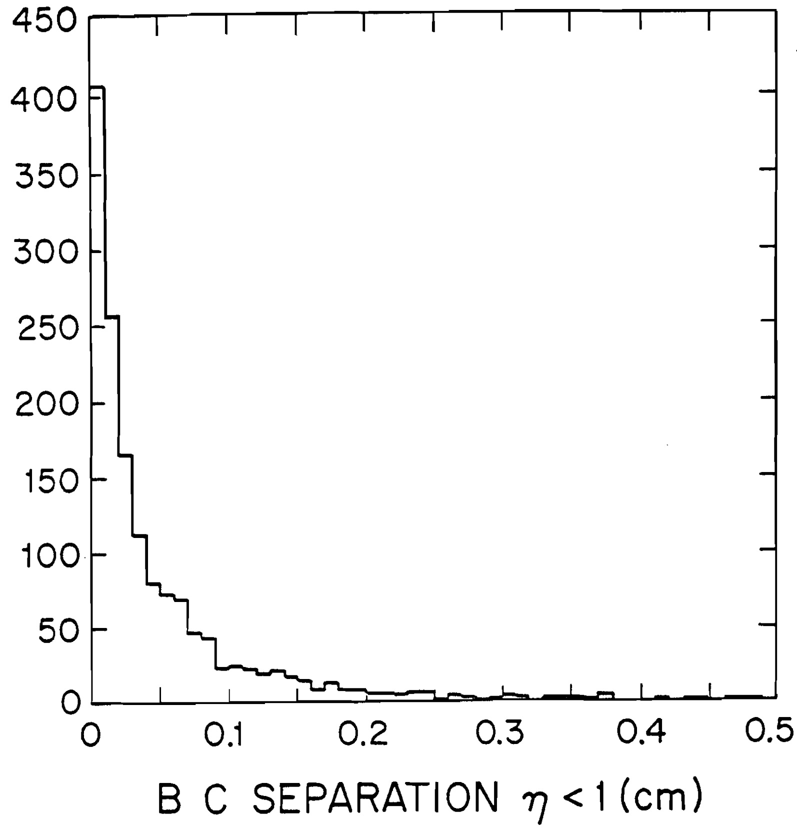
Fig. 7



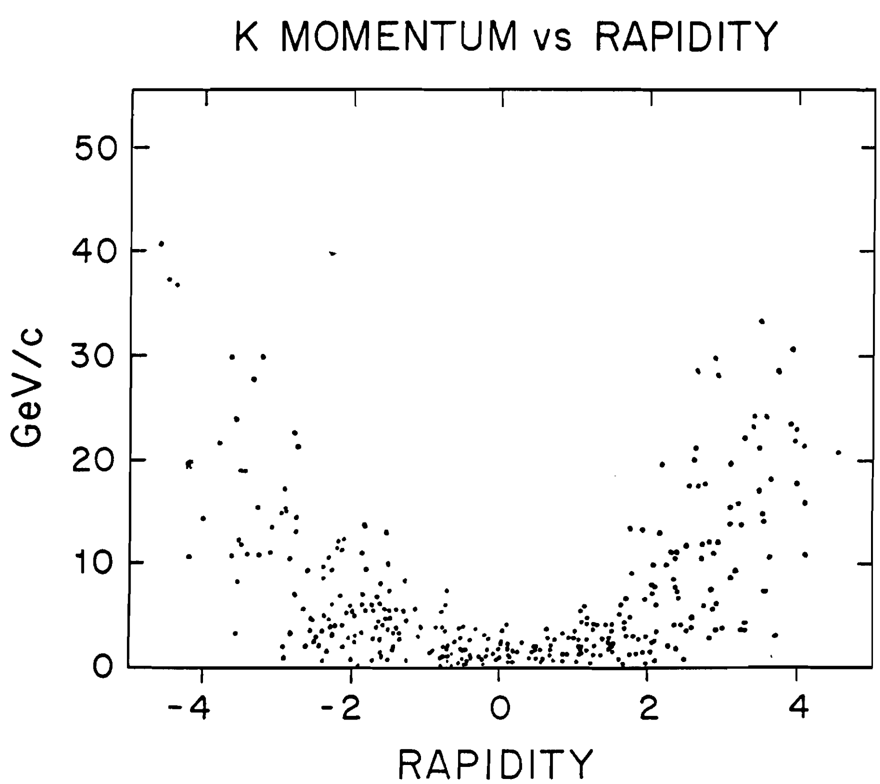
360
320
280
240
200
160
120
80
40
0
0 0.1 0.2 0.3 0.4 0.5
BOTTOM PATH $\eta < 1$ (cm)

Fig. 8



450
400
350
300
250
200
150
100
50
0
0
0.1
0.2
0.3
0.4
0.5
B C SEPARATION $\eta < 1$ (cm)

Fig. 9



K MOMENTUM vs RAPIDITY
50
40
30
20
10
0
GeV/c
-4
-2
0
2
4
RAPIDITY

Fig. 10