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On the Search for a Heavy Top Quark in the Hadronic Decay Channel at the Fermilab Tevatron.

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Abstract

We explore realistically the search for the Top quark in its hadronic decay mode. By tagging b quark jets and by applying kinematical cuts, and in particular selecting on events with a large sum of jets' transverse momenta, and finally by applying kinematical fit techniques to enhance a top mass signal, we predict that a Top quark with a mass up to 180 GeV can be observed in the hadronic decay mode at the Tevatron by the end of 1994.

1 Introduction

The last elementary fermion to be added to the Standard model with three generations is the Top quark. The Top quark, yet undiscovered, is the partner to the b quark in an SU(2) doublet. Its existence is inferred from measurements of the forward backward asymmetry in $Z \rightarrow b\bar{b}$ at LEP and the absence of flavor-changing neutral currents. Furthermore, the Top quark is needed on theoretical grounds, in order that the Standard Model be anomaly-free.

The Top quark is probably very heavy. It has evaded discovery by e^+e^- accelerators and the current direct search lower mass limit is 91 GeV[1], set by the CDF collaboration at the Tevatron p$\bar{\text{p}}$ collider.

Indirect limits on the Top mass can be estimated by comparing all available data with electroweak calculations which include higher order radiative effects. Precision electro-weak measurements at LEP contributed to obtain [2]: $m_t = 155 \pm 30 GeV$, where the error due to our ignorance of the Higgs mass is substantial (around 20 GeV when m_H is allowed to vary between 50 and 1000 GeV).

For such high Top quark masses the weak decays occur faster than the scale over which strong interactions form bound state mesons. Assuming no deviations from the standard model the Top is expected to decay mainly into a W and a b quark. The different decay modes are governed by the branching ratios of the W. From a search point of view, the branching ratios are divided into lepton-lepton (4/81 or 5%) lepton-jets (24/81 or 30%) and multijets (36/81 or 44%). We do not include lepton channels containing tau leptons in this compilation.

The only working accelerator which has a chance to discover the Top quark is the Fermilab Tevatron, a p$\bar{p}$ collider working at 1.8 TeV center of mass energy. There, the Top quark is produced predominantly in pairs, through gluon-gluon and quark-quark annihilation. The cross section is a steeply function of the Top quark mass [3] varying from 30 pb at 120GeV to 5pb at 190 GeV. The Tevatron is expected to deliver an integrated luminosity of $25pb^{-1}$ in 1993 and $100pb^{-1}$ in 1994, for each of the two experiments CDF and D0.

In the Top search so far, and in most phenomenological papers with emphasis in the Top search in p$\bar{p}$ colliders [4], only the channels in which at least one of the quarks in the created Top pair decays semi-leptonic has been considered. This results mainly from the fact that it is relatively easy to trigger an experiment on a hard lepton. Thus the channel in which both produced Tops decay into hadrons has been neglected.

The use of the 44% ($\frac{2}{3} \times \frac{2}{3}$) of the cross section in the fully hadronic channel and the larger acceptance of the detector for jets is quite tempting. Unfortunately, the QCD production of 6 jets completely overwhelms the signal in this channel (Figure 1). A reduction factor of 100 for the background when requiring a b jet has been estimated in ref. [5].

The measurement of the Top mass in the 6-jet decay mode has an important advantage over measuring the mass in leptonic decays. In leptonic events one neutrino is present for each semi-leptonic decay. This neutrino escapes the detector and it is not measured. In 6-jets Top events the full event is reconstructed.

In this paper we realistically explore the feasibility of Top search in all hadronic (multijets) decay mode. We search for the Top in events which have a six-jet topology and at least one tagged b. A typical detector is simulated to obtain the usual reduction in cross-section through detector effects.

An efficiency for b-tagging of the order of 50% can be reached using a microvertex detector [6] and soft lepton identification. The higher is the momentum of the b quark, the easier is to tag it. A heavy Top quark produces higher P_T b-jets, increasing the b-tagging efficiency for these events.

Tagging b jets has also the advantage of eliminating completely the W + 4 jets background as computed following the lines of ref. [7].

2 Monte Carlo samples

We generated multijet events from Top quark decays through a state of art calculation. This is a Leading Order calculation [8] in α_s which includes both the effects of a finite width of the W particles in the quark decay and those of a non-zero b-quark mass, as well as the complete set of spin correlations in the event.

To generate the QCD background we have used a Monte Carlo program based in the calculations performed in ref. [9]. The cross section is computed at Leading Order in QCD, so tight cuts have to be applied in order to avoid the collinear and infrared singularities and to obtain meaningful results.

The calculation of the matrix elements is exact up to five jets and also for six jets without the processes containing more than three quark pairs. The computation of the matrix elements for 6 jets is very slow and the use of approximations in the Monte

Carlo is imperative. In the approximation developed in ref. [9], special helicity configurations are assumed to be typical for all possible configurations. This assumption is valid provided one considers the shape of the distributions, but the total cross section is overestimated by a factor which depends on the cuts applied. For the current cuts used this factor is equal to 1.2. In this approximation only processes with one or two quark pairs are taken into account.

Another source of theoretical uncertainty is related with the lack of knowledge of the scale and of the structure function of the proton. In this study we have used the average transverse momentum of the jets as the value for the Q^2 and the set MRSB ($\Lambda = 0.2 GeV$) of structure functions. The effect of changing the scale and parton distribution functions has been investigated in ref. [5] and estimated to be of the order of 50%.

Usually the generation of events in Matrix Element Monte Carlo's is done by picking at random a configuration in an evenly distributed region of the phase space [10]. Each event is then assigned a weight proportional to the matrix element. Due to the steeply falling distribution of the transverse momentum of the partons, this procedure is very inefficient when trying to get events with equal weight by a weighting rejection algorithm. We have improved this efficiency by applying importance sampling over the inclusive P_T distribution, reducing the spread of the weight distribution, with the approximate function $\frac{exp(-\alpha P_T)}{P_T}$. The value used for the exponent is 0.052, obtained by fitting the transverse momentum spectra of the jets in 6-jets events, generated using a flat phase space, to the above function.

We simulated detector effects in both samples by convoluting the jet energies obtained from the generators with a function that describes the CDF detector jet resolution [11]. In Figure 2, we show the missing transverse energy significance, defined as $S = |\sum \vec{\mathbf{E_t}}|/\sqrt{\sum Et}$, where E_t is the transverse energy of a jet. S is a measure of detector resolution, the larger S is, the worse is the detector jet resolution.

In the subsequent Top analysis we will apply the following cuts: 6 jets, $P_T^{jets} > 10GeV$, $\eta^{jets} > 2.5$ and $\Delta R_{jet-jet} = \sqrt{\Delta\phi^2 + \Delta\eta^2} > 1$, where P_T^{jets} is the jets' transverse momentum, ϕ is the azimuthal angle, and η is the pseudorapidity, defined as $\log(\cot\theta/2)$, θ being the polar angle.

The first three cuts are pretty efficient since for heavy Top quark the jets have high P_T and are very central, but the last one is imposed by the requirement that our sample mimics a realistic jet-clustering algorithm and is less efficient.

3 Kinematical Variables

Intuitively, one expects the decay of a heavy quark to be kinematically different from QCD multijet production. As it is widely known QCD jet cross-sections decrease with jet energies and with larger angular separation between jets, features that one expects from the decay of a heavy object. Therefore we attempt to make use of simple variables which are easy to understand and at the same time fully exploit the properties of a heavy Top quark.

As the P_t of the Top at production is smaller than its mass, the decay products (jets) are expected to project at large angles one from another, causing the event to be spherical in the center of mass of the event. The background is expected to be much less spherical since in most of the cases a larger number of jets can emerge through bremsstrahlung from the main jets in the hard scattering. These jets will mostly lie along the direction of the initial and final partons of the hard interaction or along the plane defined by the hard scattered jets.

One of the simplest ways to characterize the event topology is to calculate the Sphericity tensor in the center of mass of the events. In Figure 3 we plot the Sphericity vs. Aplanarity for Top events and for ordinary QCD events. The Top mass selected is 130 GeV. In the Top mass range between 130 and 190 GeV, the Sphericity and Aplanarity distributions are similar to the one plotted.

From Figure 3 we have chosen the following cuts:

- Sphericity > 0.2

- Aplanarity > 0.05

If the Top quark is very heavy the sum of P_T over all the jets in the event is a very powerful quantity to discriminate it from the background. We show in Figure 4 the differential cross section as a function of $\Sigma_{jets} P_T$ smeared by the jet energy resolution function. The QCD background has a falling logarithmic spectrum with respect to $\Sigma_{jets} P_T$ whilst the for high Top masses it shows a distinctive peaking distribution. We have applied a cut on $\Sigma_{jets} P_T$ of 210 GeV, which reduces substantially the QCD background.

These cuts have an efficiency of 70% for 6 jet Top events for a Top mass of 130 GeV. This efficiency increases for heavier Top. So, although the cross section for Top quark production decreases as a function of mass there is a compensation effect from the increase in efficiency.

4 W Mass and $t\bar{t}$ Constraints

The main experimental problem in this hadronic channel is that the decay products of the Tops are measured as jets. The experimental precision in jet Energy measurements is typically of the order of 10%, not very accurate.

A way to improve the precision of these measurements is to explore properties of the physics process measured, such that the apparently independent jet measurements can be correlated by constraints which arise from the underlying process.

In the particular case of Top decays it is known that the Top should decay through a two body decay, into a W and a b, the W subsequently decaying into two jets. One can think of constraining the 4-momenta of the two jets coming from the W to add to the W mass. This procedure will improve the accuracy of the measurement of the Top mass while removing background. As each Top event has two W's, 4 jets are constrained in this way.

Another important feature of the Top is that its decay width is expected to be small ($O(1)$ GeV), much smaller than the experimental mass resolution, therefore one can implement a further kinematical event constraint, namely that the Top and the Antitop have the same mass. This requirement constrains the remaining two jets of the event. A constraint that the transverse momentum of the Top is the same as the transverse momentum of the Antitop is not applicable, as it is not known how big the transverse momentum of the Top-Antitop system can be.

The formalism commonly used in constraint fits, least squares, needs as input the error matrix of the variables measured. This matrix is usually not available for jets. This problem can be overcome by exploring the properties of jets.

An hadronic jet can be identified by 3 variables (if one assumes the jet to be massless), the jet energy and two angles. Usually calorimeters measure much better the direction of the jet (2 angles) than the energy of the jet. In one particular case, at the CDF detector, jets are measured with an Energy accuracy of $\sim$ 10 % and direction accuracy of 1^o to 2^o degrees [12].

As the direction of the jet axis is measured much better than the jet energy, the error on the jet direction can be neglected. In this case the error matrix for constraints with jets will be diagonal and will have only the error on jet energies.

Using the least squares formalism the kinematical constraint fit of the two jets to form a W can be written as:

$$\chi^2 = \left(\frac{E_u^m - E_u}{\sigma_{E_u}}\right)^2 + \left(\frac{E_d^m - E_d}{\sigma_{E_d}}\right)^2$$

with the constraint:

$$E_u E_d = \frac{M_W^2}{2(1 - cos\theta_{ud})} \equiv K_W$$

where the subscripts 'u' and 'd' refer to the 2 decay jets of the W and superscript 'm' distinguishes between the measured jet energy and the 'true' jet energy (unsuperscripted E). In this expression the mass of the light quarks are neglected w.r.t. their associated jet momenta.

Since $E_d = K_w/E_u$, the minimization of the χ^2 function can be reduced to the condition

$$\frac{\partial \chi^2}{\partial E_u} = 0$$

can be expressed as a quartic equation in E_u:

$$\sigma_{E_d}^2 E_u^4 - \sigma_{E_d}^2 E_u^m E_u^3 + K_W \sigma_{E_u}^2 E_d^m - \sigma_{E_u}^2 K_W^2 = 0$$

which is then solved. The equation has 4 roots, two real and two imaginary. Only one of the roots is real and positive, and it is the physical solution used.

Since we already have asked at least one of the jets to be tagged as a b-jet at most there are 15 possible combinations of the remaining 5 jets to fit into two pair of W's. We choose the best (minimal sum) of the two independent χ^2's. In addition we cut on the sum of the χ^2 of the two W's to be less than 3.5. This cut reduces the efficiency for Top by 25%.

Up to this stage, 4 out of the 6 jets are constrained. There are now 2 W's and 2 b's. There are 2 possibilities for associating the W's to the b's.

The constraint that the Top mass is equal in the two Top systems, $m_t^2 = m_{\bar{t}}^2$ constrain the 2 remaining jets and helps to choose which b to associate with the corresponding W. The constraint reflects into:

$$(E_{W^+} + E_b)^2 - (\vec{P}_{W^+} + \vec{P}_b)^2 = (E_{W^-} + E_{\bar{b}})^2 - (\vec{P}_{W^-} + \vec{P}_{\bar{b}})^2$$

which implies:

$$E_{W^+} E_b - \sqrt{E_{W^+}^2 - m_W^2}\sqrt{E_b^2 - m_b^2} cos\theta_{W^+b} = E_{W^-} E_{\bar{b}} - \sqrt{E_{W^-}^2 - m_W^2}\sqrt{E_{\bar{b}}^2 - m_b^2} cos\theta_{W^-\bar{b}}$$

The χ^2 is now:

$$\chi^2 = \sum_{i=1}^{2} \left(\frac{E^m - E_i}{\sigma_{E_i}} \right)^2$$

This χ^2 is used to decide which b-jet is associated to a particular W. By requiring this χ^2 to be smaller than 6, the total efficiency for Top becomes of the order of 50% and the signal-to-background ratio becomes one.

In 50% of the cases the right combination of jets is chosen to the Top and Antitop by applying these cuts. In an additional 20% of the cases the right Top quark mass is obtained since the b-jet is exchanged with one of the jets coming from its W partner.

The improvement on the Top quark mass measurement after applying these two constraints can be seen in Figure 5. This method improves the mass resolution by a factor of ~ 2, in addition to further rejecting background. For example, In the region of the Top mass peak shown in Figure 5, the signal-to-background ratio is ~ 4.

A recent NLO calculation for Top pair production [13] predicts that in 20% of the Top events, due to the high value of Q^2, the initial state radiation will generate an additional jet with energy higher than 10 GeV. Very little final state bremsstrahlung radiation is expected for such heavy Top quarks. Thus, some Top events are expected to decay into 7 jets. The QCD background reduces for 7 jets although increases the combinatorics for the right assignments.

5 Results and Conclusions.

The search for the Top in the hadronic decay mode can be summarized in three steps:

1. Tagging of b-quark jets

2. Explore kinematical differences between Top events and QCD background. In particular, the sum of the transverse momenta of the jets is a very powerful quantity to select Top events for masses of 130 GeV and beyond. Its discriminating power increases with Top mass.

3. Apply constrained kinematical fits to obtain an invariant mass peak.

In Figure 6 we show the signal to background ratio as a function of the efficiency for Top detection for different Top masses. The efficiency is normalized to the number of events which have 6 jets, and a b-quark tagged. The points in the signal-to-background vs. efficiency plane were obtained by varying the cut on the ΣP_T over the jets, while keeping the Sphericity and Aplanarity cuts fixed at 0.2 and 0.05 respectively. The efficiency of these event shape cuts does not vary significantly with Top mass. The curves plotted are polynomial fits to these points. It is interesting to note that for a given efficiency the signal to noise (background) increased dramatically with the Top mass.

The introduction of the kinematical constraints not only eliminates some background but also improves substantially the measurement of the Top quark mass and makes it less dependent of the relative energy corrections of different parts of the detector. The signal to noise in the 4 bins under the mass peak in Figure 5 is 4:1.

This measurement depends only on the final state and no assumptions have to be made on the value of the Top production cross-section as in the preferred method to obtain the mass from leptonic events (rate counting).

In Figure 7 we summarize our results by plotting the Luminosity needed for the Tevatron to deliver in order to produce a Top mass peak with significance of three standard deviations, requiring b-quark tagging, after applying kinematical cuts and kinematically constraining the events. The lower full curve describes the ideal case, where at least one b-quark is tagged, and the dashed curve describes a more realistic case where only 50% of the Top events are tagged with b-tagging and also that the b-tagging algorithm misidentifies events with no b's 1% of the time. The misidentification rate of 1% of the events decreases the signal-to-noise by a factor of two. From the plot one concludes that if the Tevatron delivers 100 pb^{-1} by the end of 1994, Top masses up to $\sim$ 180 GeV will be accessible.

As the Top mass becomes heavier, its production cross-section decreases and the requirement for more luminosity grows. One can enhance the sensitivity by searching for the Top in all decay modes.

In conclusion, the implementation of kinematical cuts, b-quark tagging and kinematical fits allows the all hadronic decay channel to be added as a valuable contribution to the Top search for heavy Top masses. Furthermore, in the hadronic 6-jet channel, all the decay products of the Top are measured, making this channel the ideal one to extract the Top mass.

Finally, we want to express our gratitude to W.Giele and J.Huth for useful discussions.

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Figure Captions

Fig. 1 $t\bar{t} \rightarrow 6jets$ cross section for different Top Quark masses. Also shown the QCD prediction for 6 jets production (solid) and the QCD prediction for 6 jets production with at least one b quark (dashed).

Fig. 2 Missing ET distribution as an indication of the assumed detector performance in the simulation.

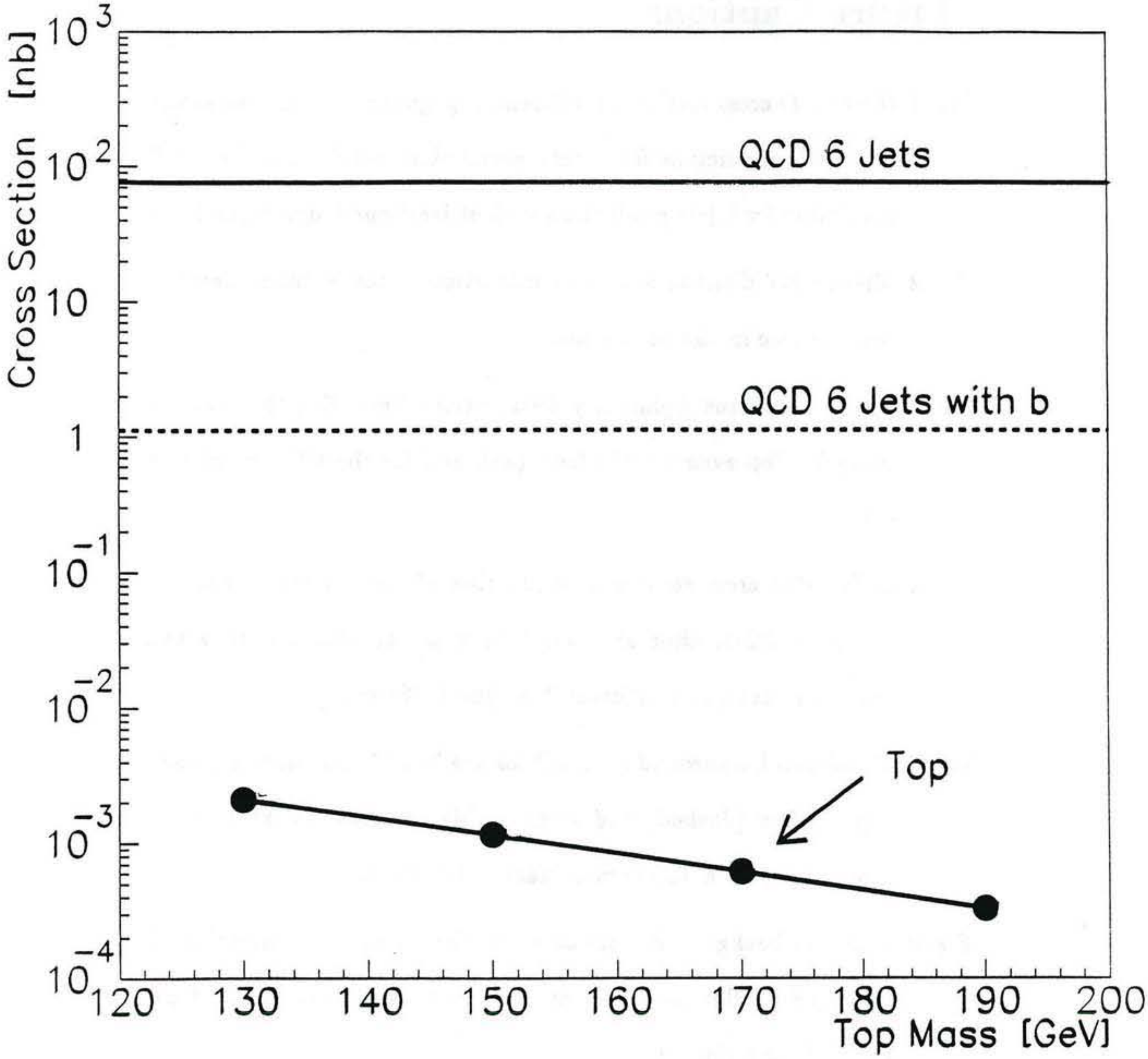
Fig. 3 Sphericity versus Aplanarity distributions (including the previous cuts) for Top events (130 GeV (a)), and for the QCD prediction (b).

Fig. 4 Differential cross section as a function of ΣP_T of the jets in the event for QCD, after applying b-tagging and the sphericity and aplanarity cuts, and different Top Quark Masses.

Fig. 5 Signal and background (dotted) for the Top Quark Mass measurement before (dashed) and after (solid) applying the kinematical constraints, for a Top Quark Mass of 130 GeV.

Fig. 6 Signal to background ratio as a function of the Top detection efficiency for following values of the Top mass: 130 GeV, 150 GeV, 170 GeV and 190 GeV.

Fig. 7 Luminosity required for getting a three sigma signal to background ratio as a function of the Top Mass, both assuming a perfect b-tagging and a more realistic 50% efficiency and 1% fake rate.



Cross Section [nb]
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
QCD 6 Jets
QCD 6 Jets with b
Top
120
130
140
150
160
170
180
190
200
Top Mass [GeV]

Fig 1

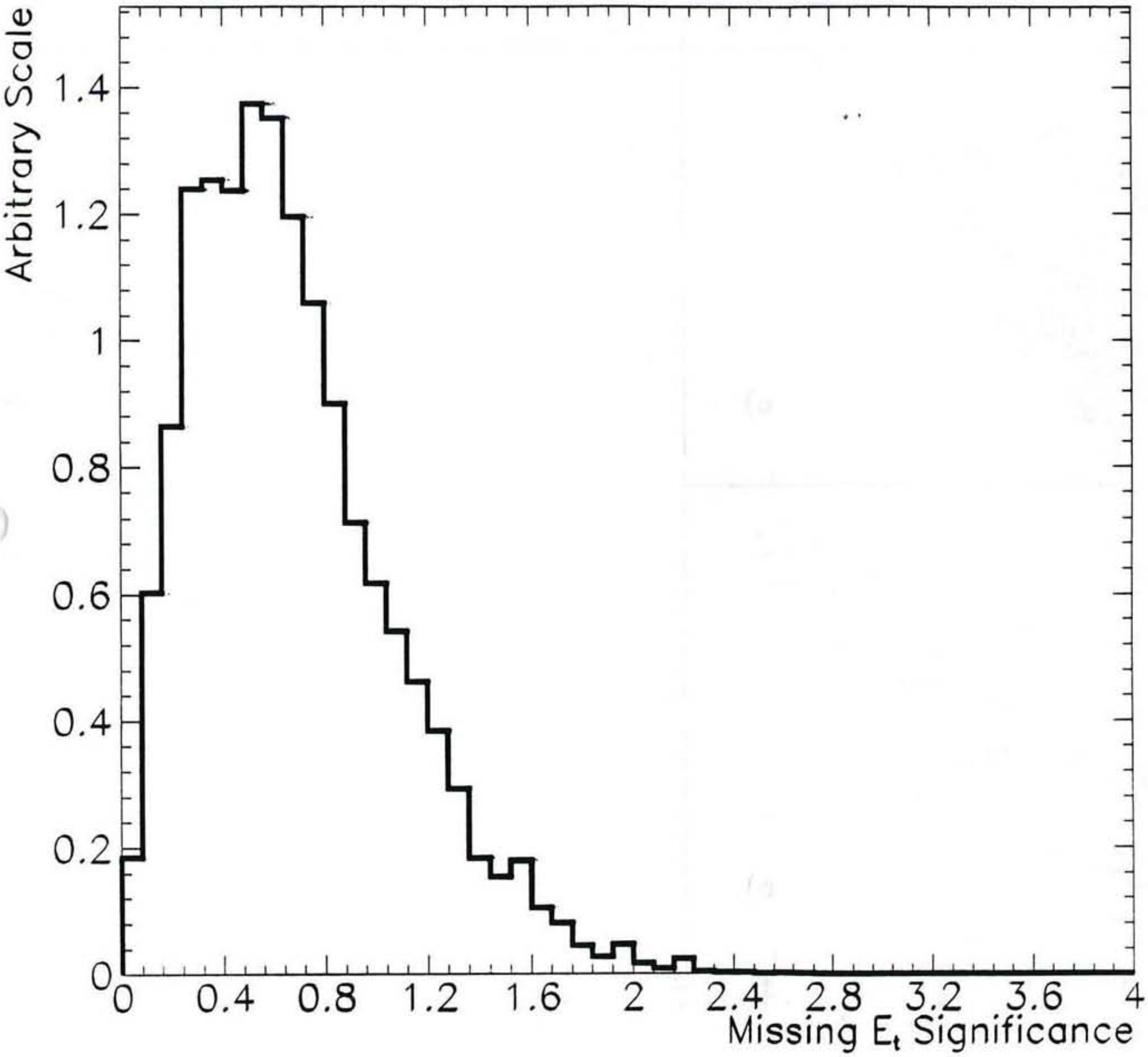

Arbitrary Scale
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.4
0.8
1.2
1.6
2
2.4
2.8
3.2
3.6
4
Missing E_t Significance

Fig 2

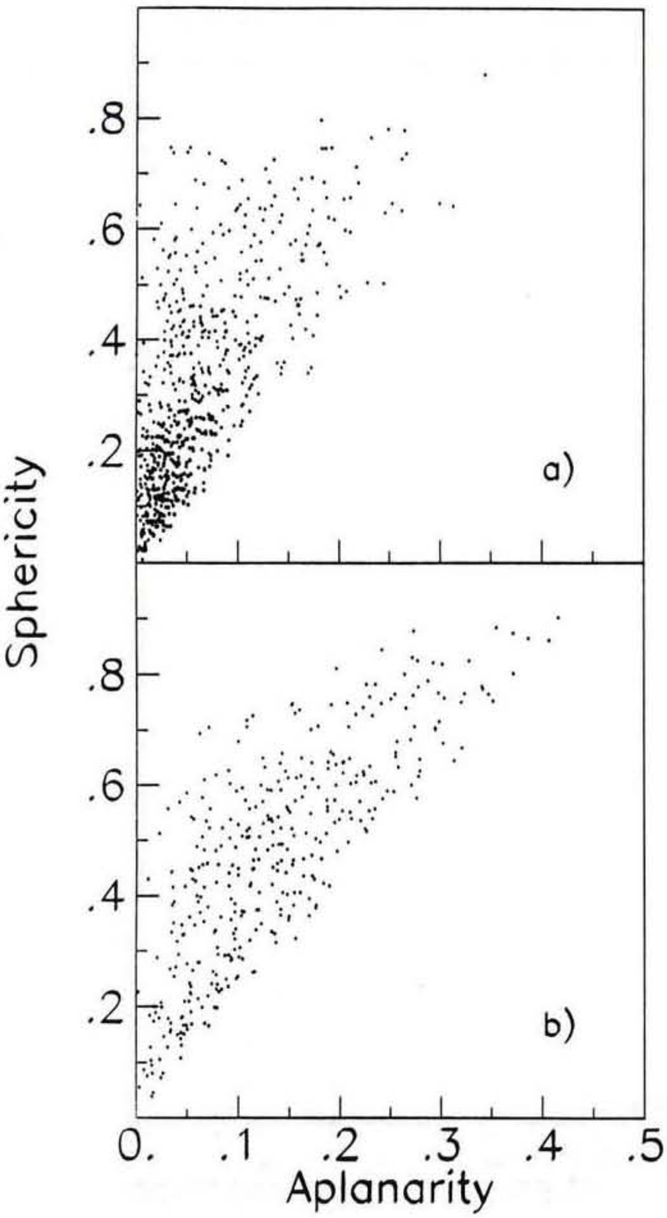
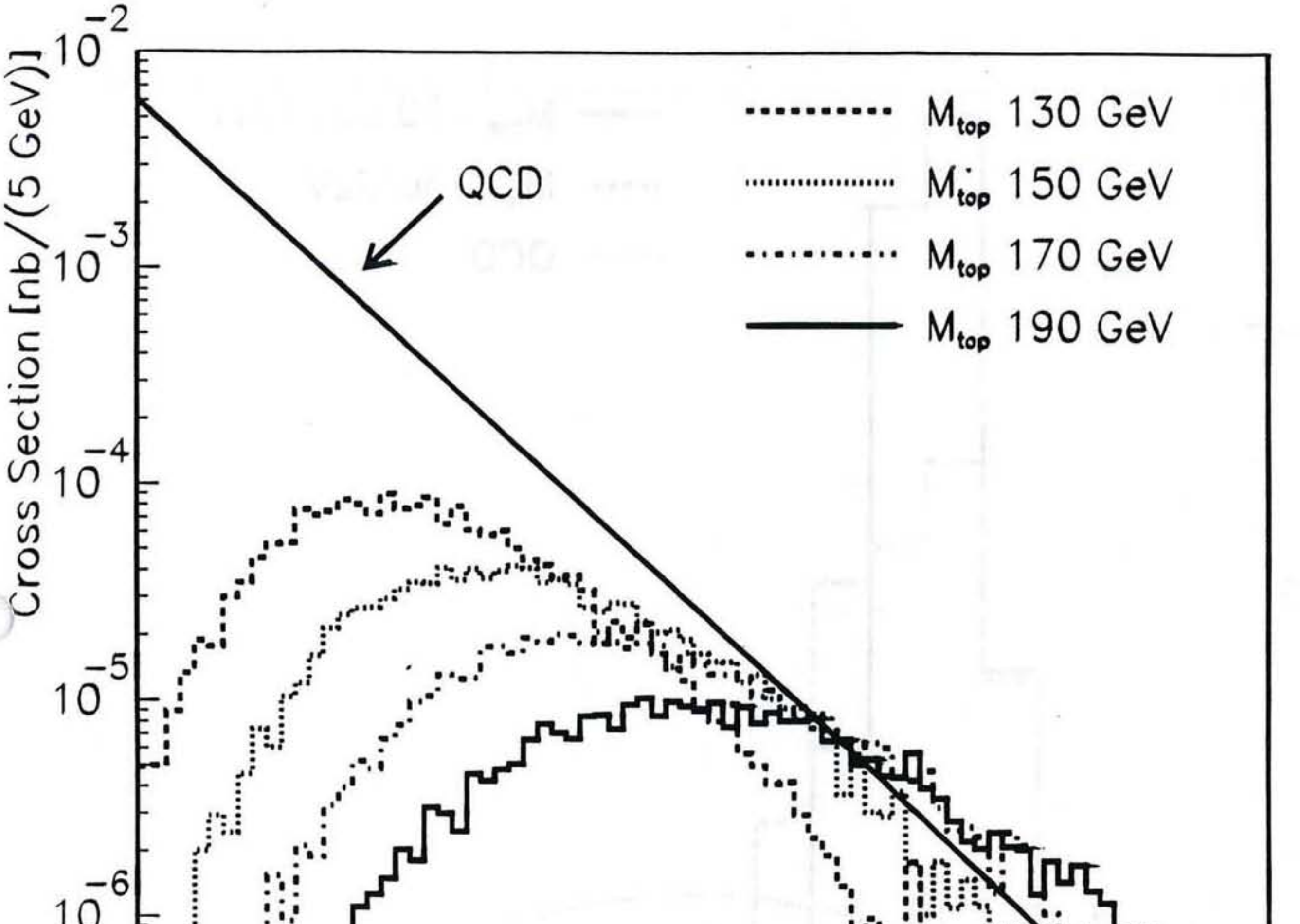


Fig. 3



Cross Section [nb/(5 GeV)]
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
150
250
350
450
550
SumEt [GeV]
QCD
M_{top} 130 GeV
M_{top} 150 GeV
M_{top} 170 GeV
M_{top} 190 GeV

Fig. 4

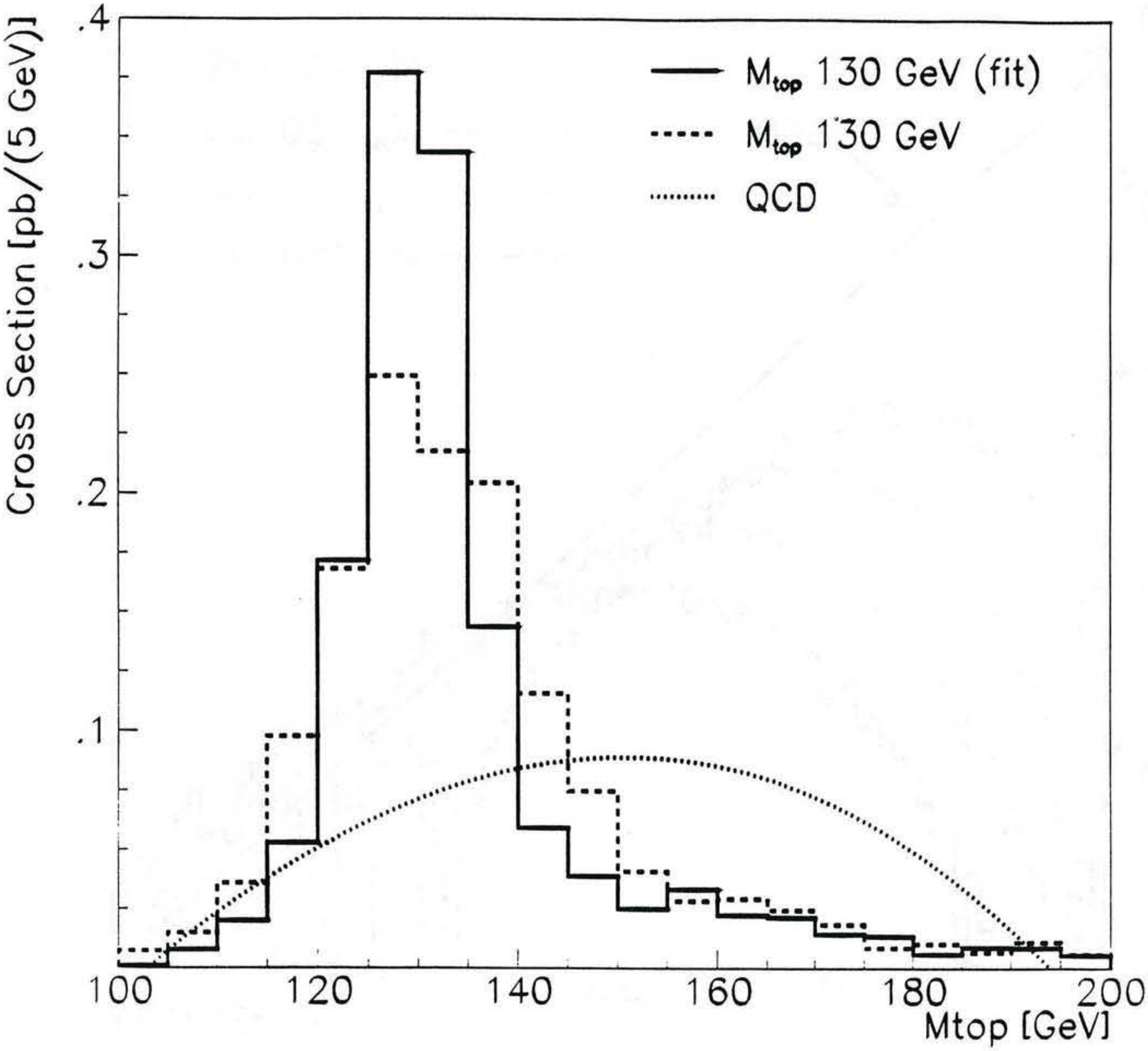

Cross Section [pb/(5 GeV)]
.4
.3
.2
.1
M_{top} 130 GeV (fit)
M_{top} 130 GeV
QCD
100
120
140
160
180
200
Mtop [GeV]

Fig. 5

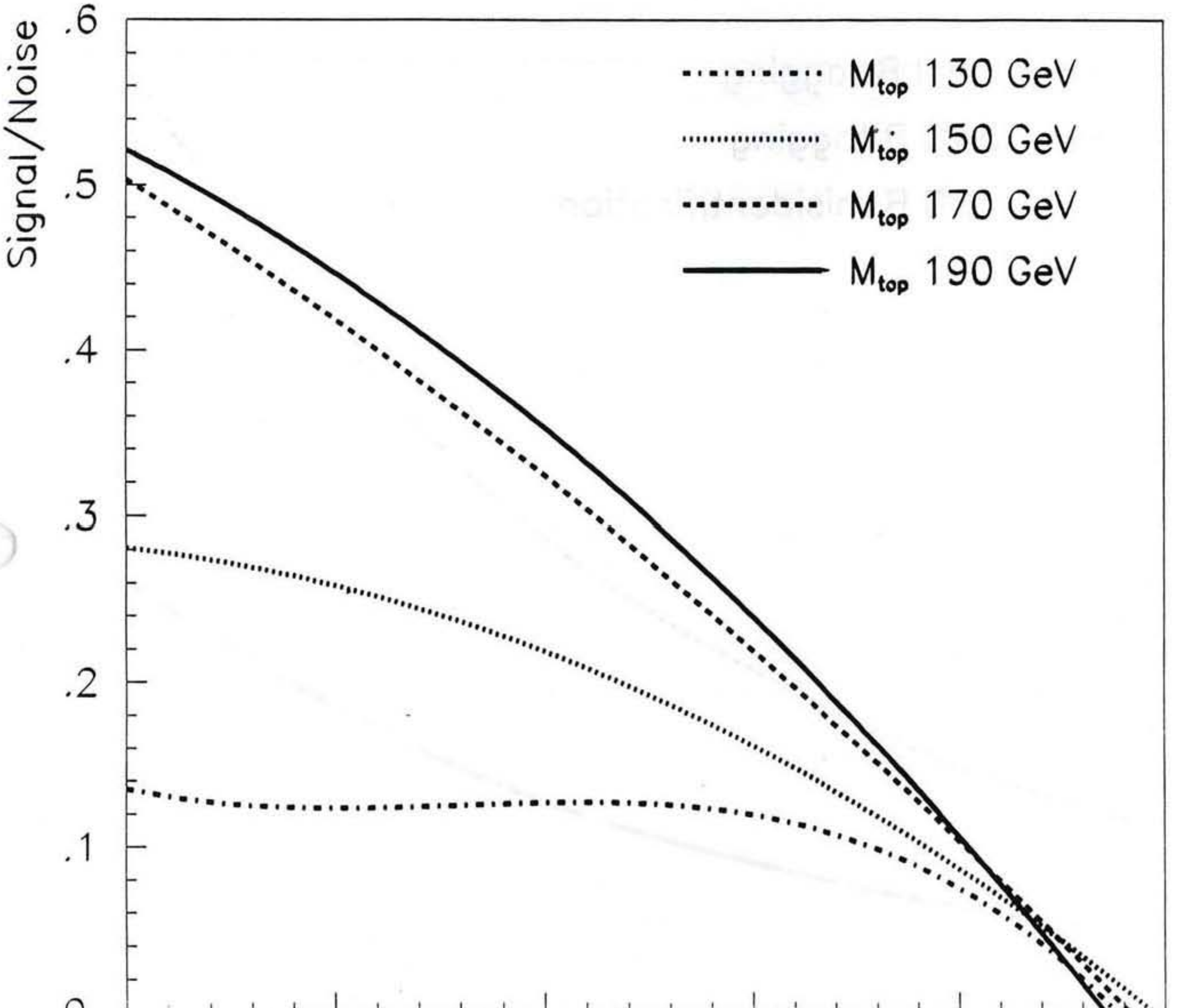

Signal/Noise
.6
.5
.4
.3
.2
.1
0
M top 130 GeV
M top 150 GeV
M top 170 GeV
M top 190 GeV
.4
.5
.6
.7
.8
.9
Efficiency

Fig. 6

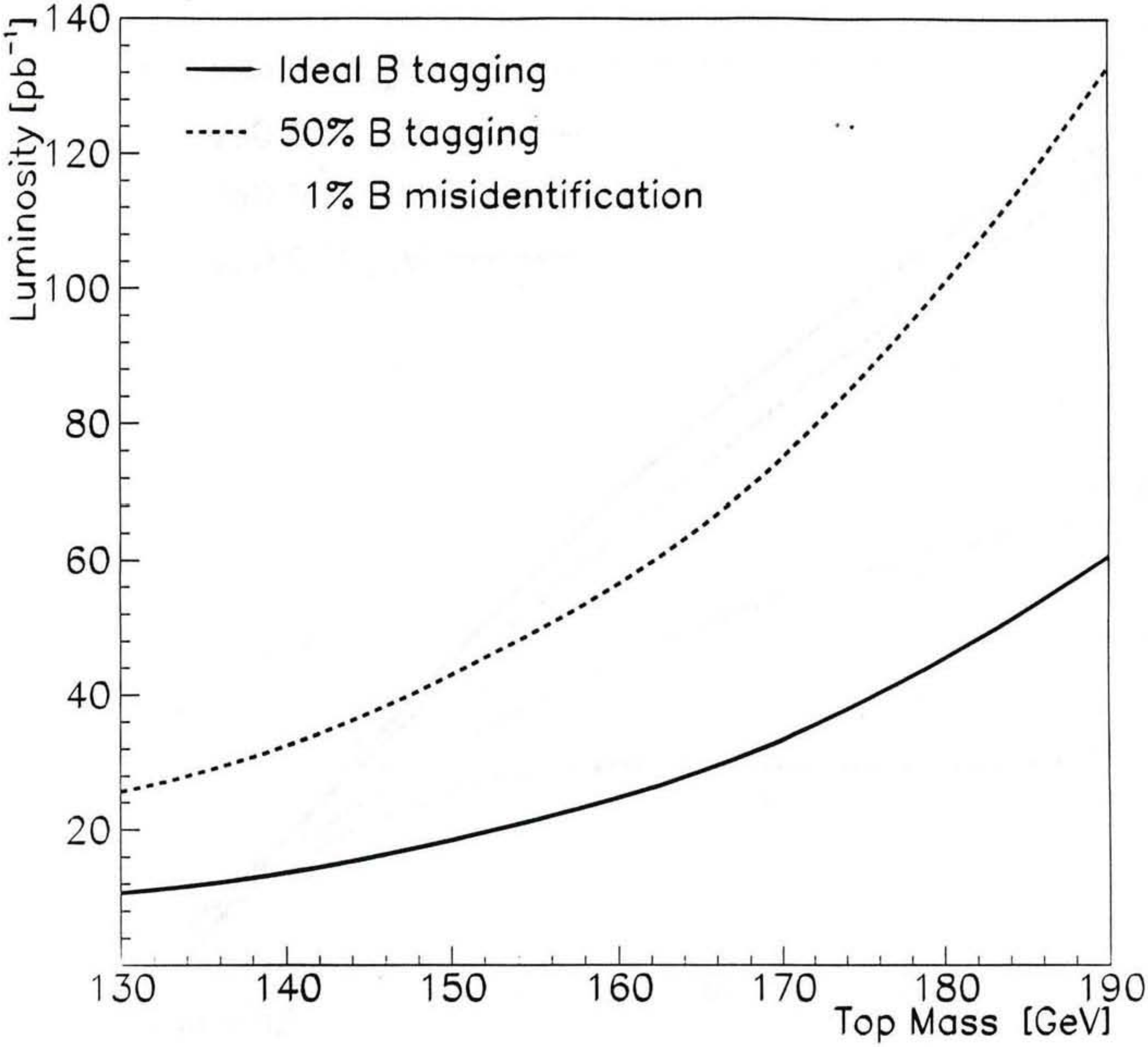

Luminosity [pb^{-1}]
140
120
100
80
60
40
20
Ideal B tagging
50% B tagging
1% B misidentification
130
140
150
160
170
180
190
Top Mass [GeV]

Fig. 7