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A BACKGROUND TO HIGGS DETECTION*

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ABSTRACT

We demonstrate that, at a high energy hadron collider, the subprocess gluon+ gluon → quark + antiquark + lepton + antilepton is a severe background to the detection of a Higgs boson in the generally favored two W decay channel (when one W decays hadronically, the other leptonically) for Higgs masses up to and exceeding 1 TeV.

It has been anticipated[1] [2] that detection of the Higgs particle in its WW decay mode will be possible at a high energy hadron-hadron collider. The direct background from WW-pair production is substantially smaller than the Higgs production cross section in this mode, given expected resolution in the WW-pair invariant mass, for Higgs masses up to and somewhat beyond 1 TeV. In order to reconstruct this invariant mass at least one W must decay hadronically. If both W's decay hadronically then QCD backgrounds are expected to be severe.[3] Thus, the mode in which one and only one W decays leptonically appears to be preferred. The charged lepton also provides an excellent trigger. In this paper we show, however, that the subprocess $gg \to q\overline{q}' l\overline{l}'$ (denoted by $ggqqll$ hereafter) forms a severe background to this mode at supercollider energies due to the very large gluon-gluon luminosity. We shall see that for all Higgs masses up to and exceeding 1 TeV it will probably be necessary to search for the Higgs in its ZZ-pair decay mode with both Z's decaying leptonically.

We shall consider two contributions to Higgs production. The first arises from gluon-gluon fusion[4] ; the second arises from WW and ZZ fusion (we restrict ourselves to the dominant longitudinal W/Z contribution)[5] [6] [7] . The $ggqqll$ background subprocess has been calculated in a convenient form in ref. 8. This calculation has been checked in the limit of an on-shell W (appropriate here) by comparison to the results of ref. 9 for massless quarks. Backgrounds with the same final state but arising from quark-antiquark collisions have not been included because they are almost certainly unimportant relative to the gluon induced background. (Recall that the gluon-gluon luminosity is larger than the quark-antiquark luminosity at the relevant energies by a factor of approximately 100.[1]) We have also not computed the $gq \to gq' l\overline{l}'$ subprocess background. The resulting final state is in principle distinguishable from that arising through the

Higgs decay. In practice, however, this background could be a problem; although the appropriate luminosity contains only one gluon distribution function, at the subprocess level $gq \to gq' l\overline{l'}$ is larger than $gg \to q\overline{q'} l\overline{l'}$.

In order to fully explore the $q\overline{q'} l\overline{l'}$ channel we have employed Monte Carlo techniques for integrating over the four body final state phase space. In this manner we can easily explore the effects of different cuts upon the magnitude of the Higgs signal relative to the above gluon-gluon induced background. First, it is obvious that one should restrict the invariant mass in the $q\overline{q'}$ and $l\overline{l'}$ channels. It is anticipated[3] that a resolution of

$$\Delta M/M = .05 \tag{1}$$

can be achieved in both the leptonic and hadronic W channels (subject to the usual two-fold ambiguity in determining the neutrino momentum, which we shall ignore). If the width of the Higgs is smaller than 5% of m_H then we shall adopt this same resolution, eqn. (1), for the WW-pair invariant mass. However, for $m_H \geq 300$ GeV, Γ_H is larger than $.05 m_H$. In this latter region we adopt a WW-pair resolution equal to the Higgs decay width. Thus we have

$$\Delta M_{WW} = max\left[.05 m_H, \Gamma_H\right]. \tag{2}$$

Other variables which will be useful are the following-unless otherwise noted they are defined in the overall center of mass frame:

a) the rapidity of the leptonically decaying W, $y_{W_{lep}}$;

b) the rapidity of the hadronically decaying W, $y_{W_{had}}$;

c) the rapidity of the quark, y_q;

d) the rapidity of the antiquark, $y_{\bar{q}}$;

e) the rapidity of the lepton, y_l;

f) the rapidity of the antilepton, $y_{\bar{l}}$;

g) the transverse momentum of the leptonically decaying W, $p^T_{W_{lep}}$;

h) the transverse momentum of the hadronically decaying W, $p^T_{W_{had}}$;

i) the transverse momentum of the quark, p^T_q;

j) the transverse momentum of the antiquark, $p^T_{\bar{q}}$;

k) the transverse momentum of the lepton, p^T_l;

l) the transverse momentum of the antilepton, $p^T_{\bar{l}}$;

m) the acoplanarity angle, Θ_{blq}, defined by the normals to the following two planes–1) the plane defined by $\vec{p}_{W_{lep}}$ and $\vec{p}_{beam}$, 2) the plane defined by $\vec{p}_q$ and $\vec{p}_{\bar{q}}$;

n) the acoplanarity angle, Θ_{lq}, defined by the normals to the following two planes–1) the plane defined by $\vec{p}_l$ and $\vec{p}_{\bar{l}}$, 2) the plane defined by $\vec{p}_q$ and $\vec{p}_{\bar{q}}$;

o) the decay angle of the lepton in the rest-frame of W_{lep} relative to an axis defined by the $\vec{p}_{W_{lep}}$ in the WW-pair center of mass , θ_l;

p) the decay angle of the quark in the rest-frame of W_{had} relative to an axis defined by the $\vec{p}_{W_{had}}$ in the WW-pair center of mass , θ_q;

In order to assess the importance of the *ggqqll* background let us compare it to the signal from Higgs decay using first a series of very minimal cuts. The minimal cuts are defined by:

$$\begin{gathered} |y_q|, |y_{\bar{q}}|, |y_l|, |y_{\bar{l}}| < 4 \\ p_q^T, p_{\bar{q}}^T > 5GeV. \end{gathered} \tag{3}$$

Note that it is necessary to impose some cut on the transverse momenta of the quarks in order to avoid infrared and collinear singularities in the background subprocess. The rapidity cuts in eqn. (3) are designed simply to guarantee that all four particles emerge within detector acceptance. (This was, of course, unnecessary for the neutrino but allows us to treat W^+ and W^- symmetrically.) The full four body phase space will be integrated over subject to the cuts of eqn. (3). We also restrict the $q\overline{q'}$ pair mass, the $l\overline{l'}$ pair mass, and the WW-pair mass according to eqn. (1) and eqn. (2), respectively, with the WW-pair mass centered at a particular value, m_H, and the $q\overline{q'}$ and $l\overline{l'}$ pair masses centered at m_W. We shall plot cross sections for a single lepton channel of given charge and for a single weak doublet, zero mass quark channel including the sum over final colors. Branching ratios are automatically included in our procedure.

The cross sections subject to the cuts (3) for WW/ZZ fusion, gg fusion, and the $ggqqll$ background at $\sqrt{s} = 40$ TeV are plotted in fig. 1 as a function of the Higgs mass. We see that the background dominates the signal even for m_H as large as 1 TeV. Obviously, it is desireable to find additional cuts that will enhance the signal to background ratio. In order to assess which cuts might be useful, we have examined distributions in all the variables mentioned earlier, at two typical Higgs mass values, $m_H = 200$ and 800 GeV.

At 200 GeV gg fusion dominates the Higgs production signal, and so we compare this mechanism in fig. 2 to the $ggqqll$ background. First, we remark that distributions in the rapidities a)-f) exhibit little difference between signal and background and have not been plotted. This is also true of distributions in lepton transverse momenta. The greatest difference between signal and background is found in the distributions with respect to p_q^T and $p_{\bar{q}}^T$, figs. 2a and 2b respectively. From these figures we see that a cut requiring these transverse momenta to be large will considerably enhance the signal. Such a cut keeps the invariants of the $ggqqll$ subprocess well away from the infrared and collinear singular regions. A plot in $p_{W_{had}}^T$ also reveals a related enhancement of the background at low transverse momentum. However, we find that a cut on p_q^T removes this background excess at low $p_{W_{had}}^T$. Distributions with respect to $\cos(\Theta_{blq})$ and $\cos(\Theta_{lq})$[10] reveal no difference between signal and background at this value of m_H, 200 GeV. In contrast the distributions with respect to $\cos(\theta_l)$ and $\cos(\theta_q)$, figs. 2c and 2d respectively, show additional potential for enhancing signal over background by limiting the absolute values of the cosines of these angles to small values.

At 800 GeV WW/ZZ fusion dominates the signal. Distributions with respect to the rapidity of W_{had} and W_{lep} reveal only minor differences between signal and background, and are not plotted. In fig. 3a we plot the distribution of signal and backgound with respect to $y_{\bar{q}}$. Clearly a cut requiring $|y_{\bar{q}}| < 2$ is desireable. This also applies to y_q. In fig. 3b we plot distributions with respect to $p_{\bar{q}}^T$. As in the case of the lower mass Higgs a cut requiring large $p_{\bar{q}}^T$ will considerably enhance the signal relative to the background. As at $m_H = 200$ GeV these same statements also apply to p_q^T. Distributions with respect to the lepton and antilepton transverse momenta also exhibit background enhancement at low $p_{l,\bar{l}}^T$. However, we have found that a cut requiring large quark and antiquark p^T's is sufficient to remove this enhancement. This later statement applies as well to $p_{W_{had}}^T$ and $p_{W_{lep}}^T$. Distributions with respect to the two acoplanarity angles show little difference between signal and background at small angles where both cross sections are largest. More interesting are the distributions with respect to $\cos(\theta_l)$ and $\cos(\theta_q)$, figs. 3c and 3d, which demonstrate that a restriction requiring θ_l and θ_q to be near 90 or 270 degrees will substantially enhance the signal relative to background. One expects the signal to be peaked in the variables θ_q and θ_l near 90 or 270 degrees since the distributions of longitudinally polarized W's (dominant in H decay) exhibit such behavior, while those of transversely polarized W's do not.

A systematic search for the optimal experimental cuts at each Higgs mass is beyond the scope of this paper. However, from the preceeding discussion it is clear that similar phase space restrictions can be employed at both low and high m_H values to reduce the importance of the background. After considerable experimentation we adopted the following restrictions on the final state phase space as being illustrative of the possibilities. These restrictions greatly increase the signal/background ratio while leaving adequate cross section at an integrated luminosity of $L = 10^{40}/cm^2$. These 'standard cuts' are:

$$\begin{aligned} |y_q|, |y_{\bar{q}}| &< 2 \\ |y_l|, |y_{\bar{l}}| &< 4 \\ p_q^T &> .3m_H . \\ p_{\bar{q}}^T &> .1m_H \\ |\cos(\theta_l)| &< .2 \end{aligned} \qquad (4)$$

As before we impose the mass resolution constraints of eqns. (1), (2). The resulting cross sections are plotted in fig. 4. We see that the background is no longer larger than the signal cross section throughout the *entire* region, $m_H < 1$ TeV. In fact, above $m_H = 800$ GeV the Higgs production cross section from

WW/ZZ fusion is slightly above the background. It is interesting to reexamine the distributions in all the variables a)-p) after imposing the restrictions (4). At $m_H = 200$ GeV we confine ourselves to noting that, while there are several additional restrictions in the variables a)-p) that could be imposed which would somewhat increase the signal to background ratio, none are adequate to overcome the $1/50$ ratio of fig. 4 at this value of Higgs mass. At $m_H = 800$ GeV, where the signal is marginally above background for the standard cuts, (4), small improvements could make a big difference to the observability of the Higgs. The largest differences between signal and background distributions appear in the variables $p_{\bar{q}}^T$ and $\cos(\theta_l)$ plotted in fig. 5a and 5b. From fig. 5a we see that a restriction to $p_{\bar{q}}^T > 160$ GeV would essentially eliminate the background entirely at a sacrifice of (roughly) a factor of 10 in the Higgs cross section. Even including a sum over two quark modes (the resolution in the t-b decay channel is expected to be poor, so this mode has not been included), two lepton modes and a factor of two for allowing either the W^+ or the W^- to decay leptonically (for a total factor of eight), we are clearly left with too few events at $L = 10^{40}/cm^2$. Similar remarks apply to the $\cos(\theta_q)$ distribution of fig. 5b. Restricting to $|\cos(\theta_q)| < .2$ would leave no background but would result in a decrease of the Higgs cross section by a factor of twenty.

It is our hope that a more refined treatment may lead to better signal/background ratios than we have been able to achieve in this first examination. If a $1:1$ signal/background ratio is the best that can be achieved with reasonable cross section, and this only at high m_H values where Γ_H is large, then we are forced to conclude that detection of the Higgs in its WW decay mode will be very difficult. When Γ_H is large the absolute cross section of the background must be computable with substantial certainty. In our calculation we have ignored Kfactors and other higher order corrections, and have only employed one set of gluon distribution functions (EHLQ, $N_{set} = 2^{[1]}$). Accurate knowledge of these ingredients is required before detection of an event excess would be possible. Of course, all these remarks apply equally to the ZZ decay mode of the Higgs when one Z decays hadronically and the other leptonically. The $ggqqll$ background is of very similar size while the branching ratio for Higgs decay to the ZZ channel is somewhat smaller than for decay to the WW channel.

Fortunately, detection of the Higgs in its ZZ decay channel should still prove feasible by focusing on the mode in which both Z's decay leptonically. The effective branching ratio for the Higgs to decay to two Z's and for both Z's to decay leptonically is

$$\frac{\Gamma(H \to ZZ)}{\Gamma(H \to all)} \left[\frac{\Gamma(Z \to e^+e^- or \mu^+\mu^-)}{\Gamma(Z \to all)}\right]^2 \approx 1.2\ 10^{-3}. \tag{5}$$

Let us employ the Higgs cross sections computed by EHLQ[1] at $\sqrt{s} = 40TeV$ (which include only rapidity cuts, $|y_Z| < 2.5$) of

$$\sigma \approx \begin{cases} 50pb & m_H = 200GeV \\ 1pb & m_H = 800GeV \end{cases} . \tag{6}$$

We then see that, while there will be several hundred events in the double leptonic ZZ decay mode for m_H values in the region of 200 GeV, there will be at most tens of events for m_H values around .8 to 1 TeV at $L = 10^{40}/cm^2$. Therefore, the search for the Higgs may be possible over the *full* mass range only at the above maximal luminosity.

An additional implication of our results concerns the WW- and ZZ- pair production processes. These are, as remarked earlier, smaller than the Higgs cross section after restricting the WW-pair or ZZ-pair mass to a given resolution interval about m_H.[1] In contrast the $ggqqll$ background to any given channel in which one vector boson decays hadronically and the other leptonically, when subjected to the same resolution, is larger. Thus we anticipate that the $ggqqll$ subprocess will prove an awesome background to vector boson pair production in the above hadronic/leptonic decay channel. Even the associated production of a W and a Z will be subject to this background when the Z decays hadronically (assuming that the charge of a two jet pair cannot be determined). This subject will be more thoroughly explored in a future work.

We thus conclude that detection of the Higgs at a hadron collider in any mode other than its ZZ-pair decay channel with both Z's decaying leptonically, will be far more difficult than heretofore anticipated. In addition observation of the standard WW-pair and ZZ-pair cross sections in any hadronic decay mode may prove impossible.

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9. J. F. Gunion, P. Kalyniak, M. Soldate, and P. Galison, *Phys. Rev. Lett.* 54(1985)1226, and SLAC-PUB-3604.
10. This variable is not quite the same as that considered by M.J.Duncan, G.L.Kane, and W.W.Repko, PRINT-85-0448(Michigan). However, we have examined distributions in their variable and agree with their result.

FIGURE CAPTIONS

1. The integrated cross section subject to the minimal cuts of eqn. (3) as a function of the Higgs mass m_H. The figure legend explains the various curves.

2. Normalized distributions in four sensitive variables for both gg fusion Higgs production and the *ggqqll* subprocess, with the minimal cuts of eqn. (3). We plot:

   a) the distribution in p_q^T;

   b) the distribution in $p_{\bar{q}}^T$;

   c) the distribution in $|\cos(\theta_l)|$;

   d) the distribution in $|\cos(\theta_q)|$.

   The distributions plotted are normalized dN/N distributions. The integral of any curve over the full plot must be 1. The fraction of events in any bin can thus be determined by taking ordinate times bin width.

3. Selected normalized (see explanation in fig. 2 caption) distributions for WW/ZZ fusion production of the Higgs, compared to the ggqqll background. The minimal cuts of eqn. (3) are applied. We plot:

   a) the distribution in $|y_q|$;

   b) the distribution in $p_{\bar{q}}^T$;

   c) the distribution in $|\cos(\theta_l)|$;

   d) the distribution in $|\cos(\theta_q)|$.

4. The integrated cross section subject to the standard cuts of eqn. (4) as a function of the Higgs mass m_H. The figure legend explains the three curves.

5. The two normalized distributions showing the greatest difference between signal and background after restricting final state phase space by the standard cuts of eqn. (4). We plot:

   a) the distribution in $p^T_{\bar{q}}$;

   b) the distribution in $|\cos(\theta_q)|$.

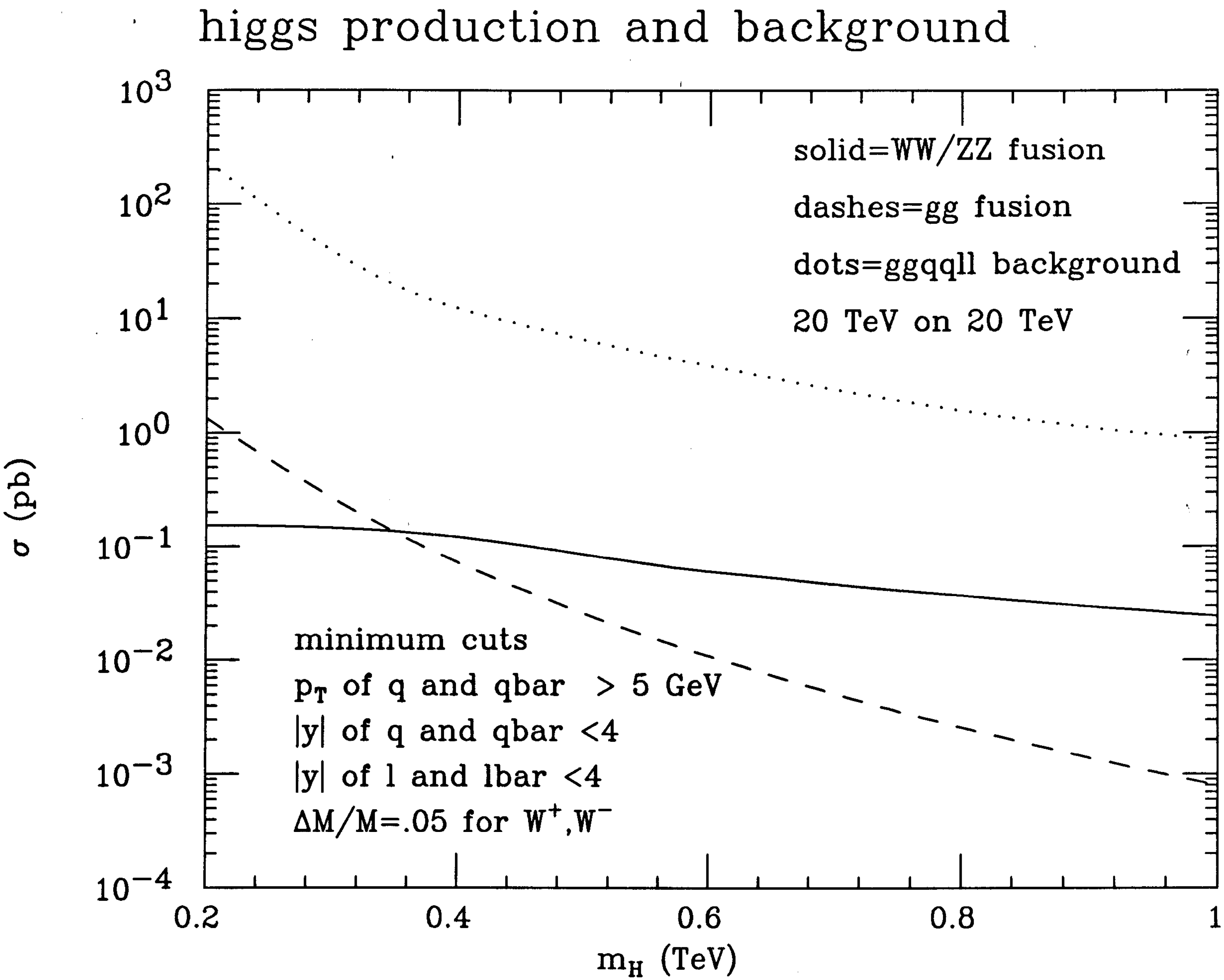

higgs production and background
solid=WW/ZZ fusion
dashes=gg fusion
dots=ggqqll background
20 TeV on 20 TeV
minimum cuts
p_T of q and qbar > 5 GeV
|y| of q and qbar <4
|y| of l and lbar <4
ΔM/M=.05 for W^+,W^-
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
σ (pb)
0.2
0.4
0.6
0.8
1
m_H (TeV)

FIGURE 1

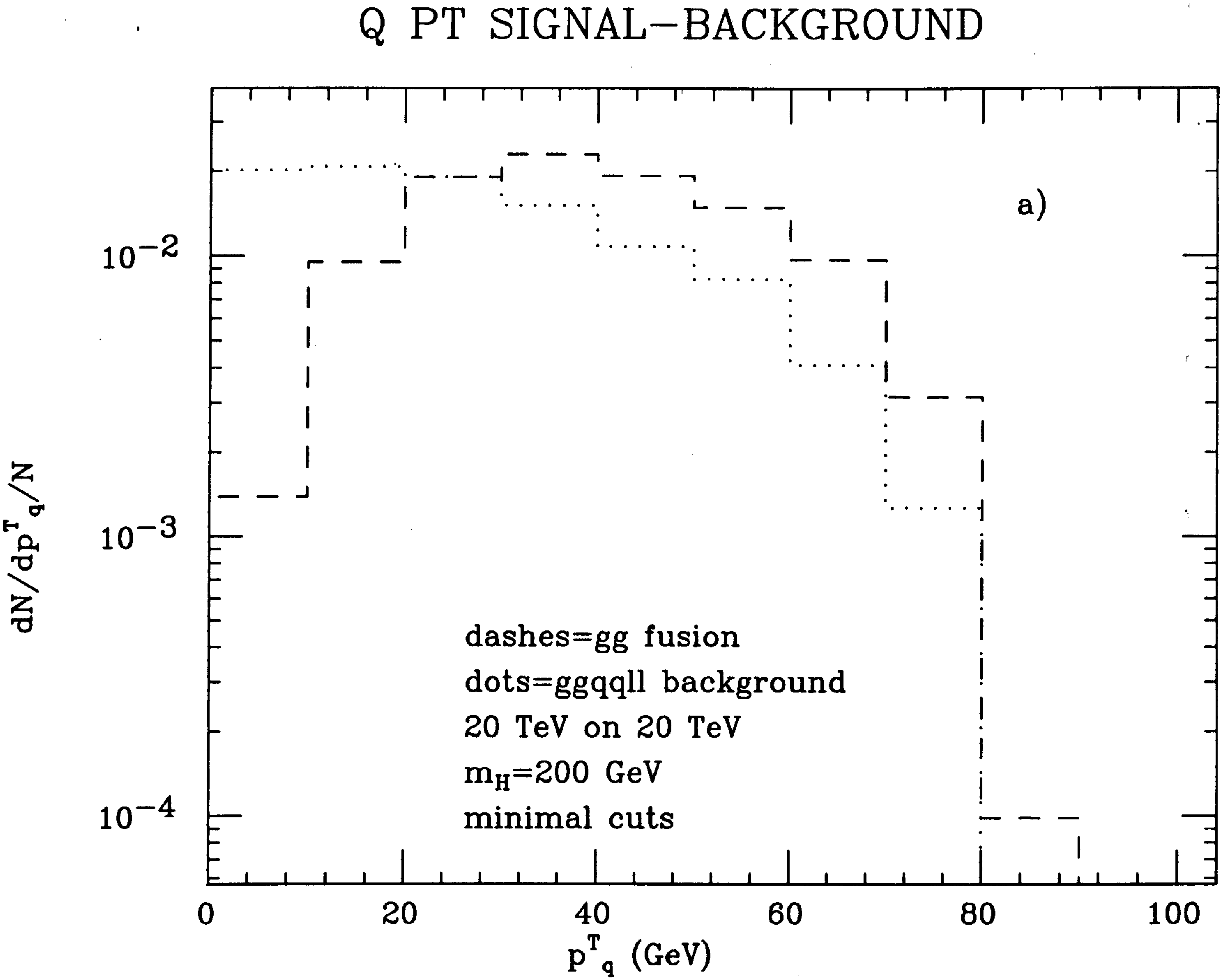

Q PT SIGNAL−BACKGROUND
a)
10^{-2}
10^{-3}
10^{-4}
dashes=gg fusion
dots=ggqqll background
20 TeV on 20 TeV
m_H=200 GeV
minimal cuts
0
20
40
60
80
100
$p^T{}_q$ (GeV)
$dN/dp^T{}_q/N$

FIGURE 2a

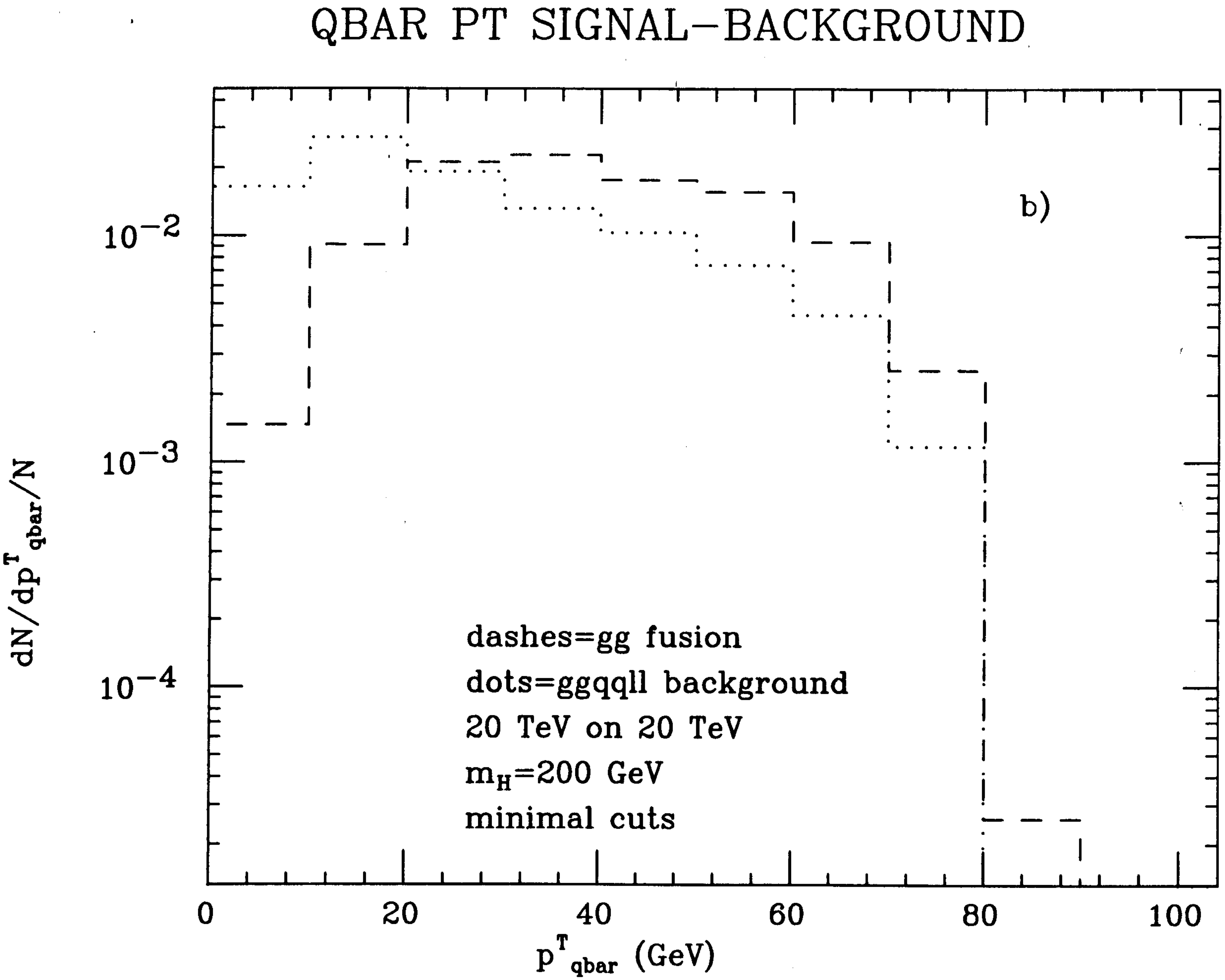

QBAR PT SIGNAL−BACKGROUND
b)
10^{-2}
10^{-3}
10^{-4}
$dN/dp^{T}_{qbar}/N$
dashes=gg fusion
dots=ggqqll background
20 TeV on 20 TeV
m_H=200 GeV
minimal cuts
0
20
40
60
80
100
p^{T}_{qbar} (GeV)

FIGURE 2b

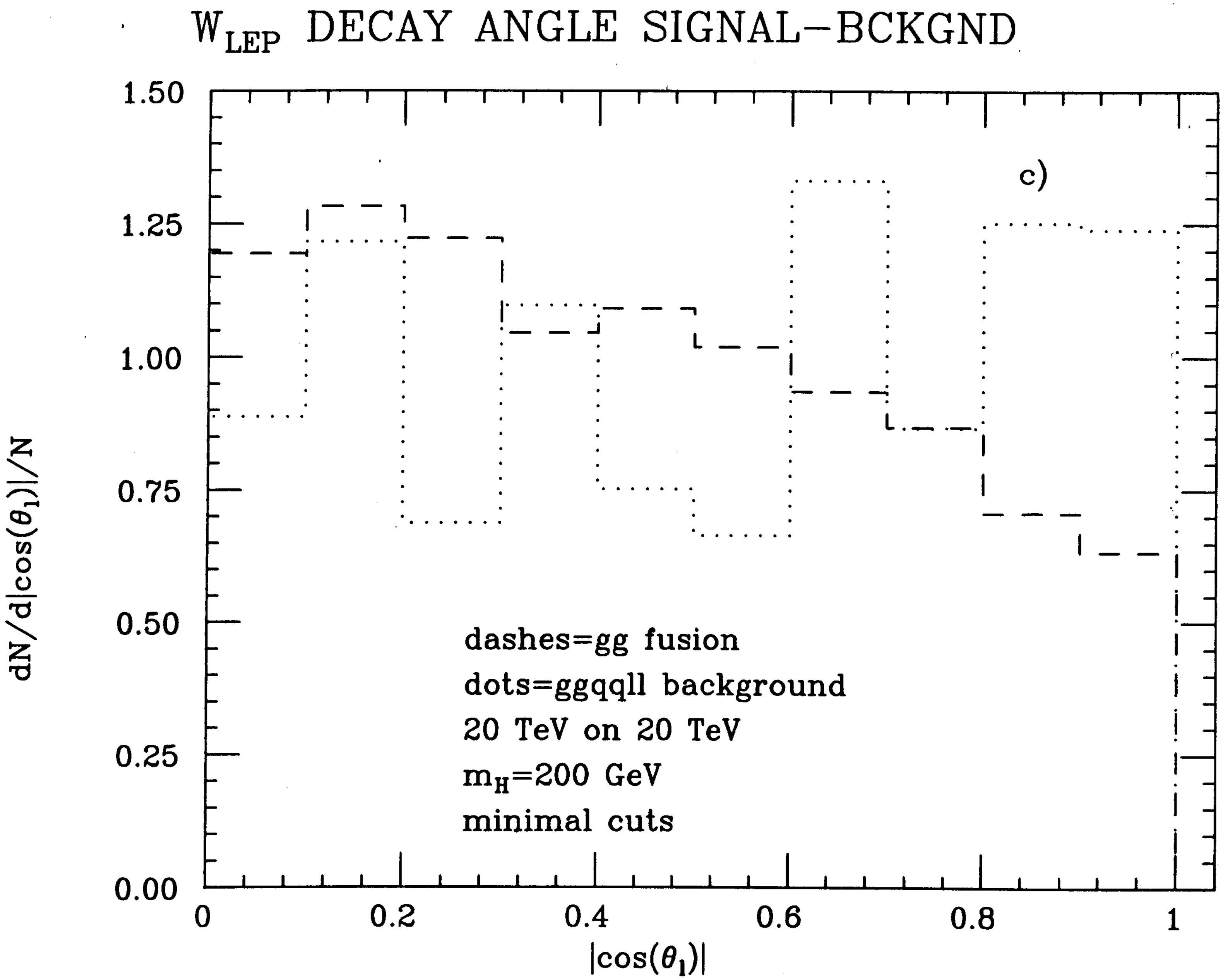

W_{LEP} DECAY ANGLE SIGNAL–BCKGND
c)
dashes=gg fusion
dots=ggqqll background
20 TeV on 20 TeV
m_H=200 GeV
minimal cuts
$dN/d|\cos(\theta_l)|/N$
0.00
0.25
0.50
0.75
1.00
1.25
1.50
0
0.2
0.4
0.6
0.8
1
$|\cos(\theta_l)|$

FIGURE 2c

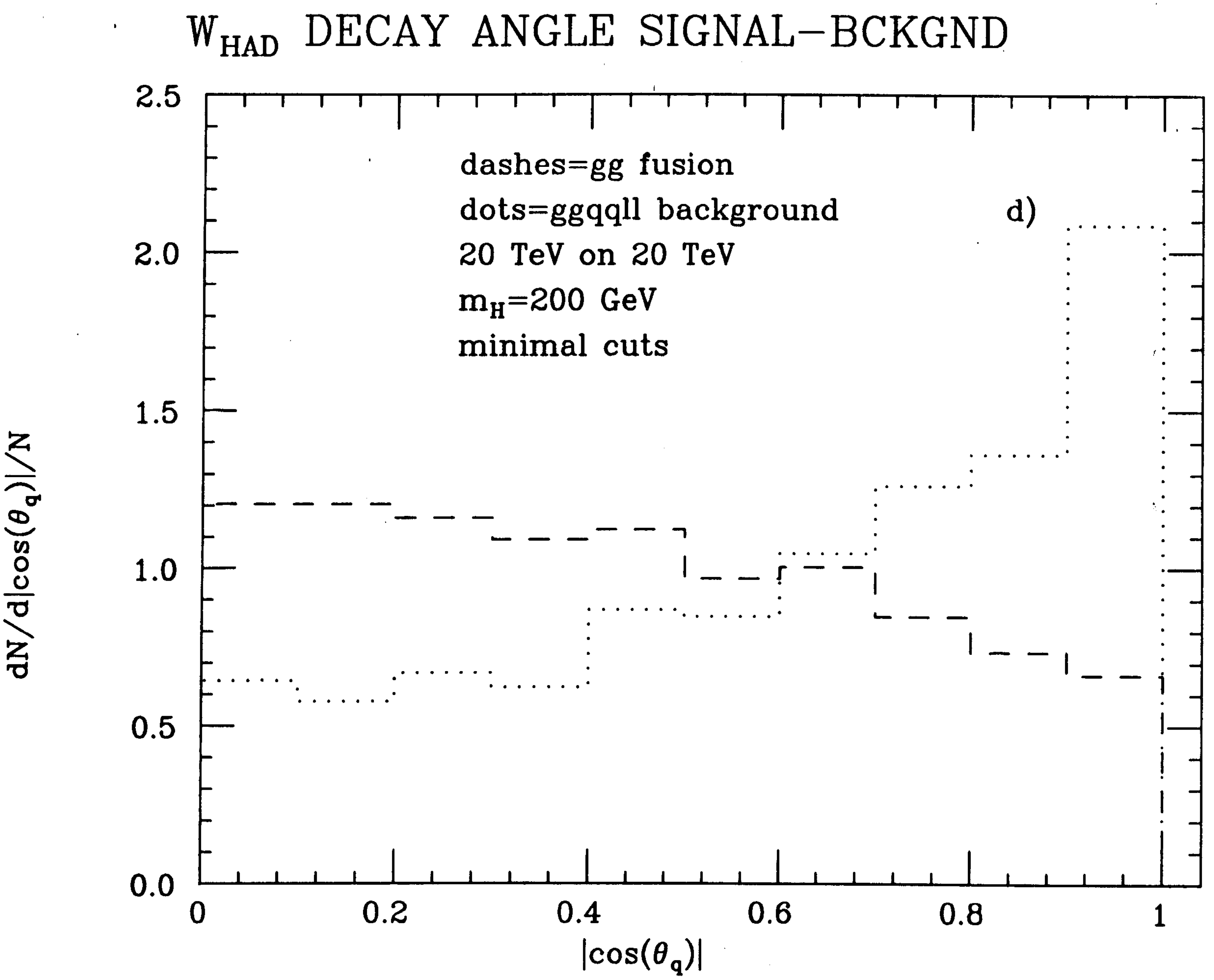
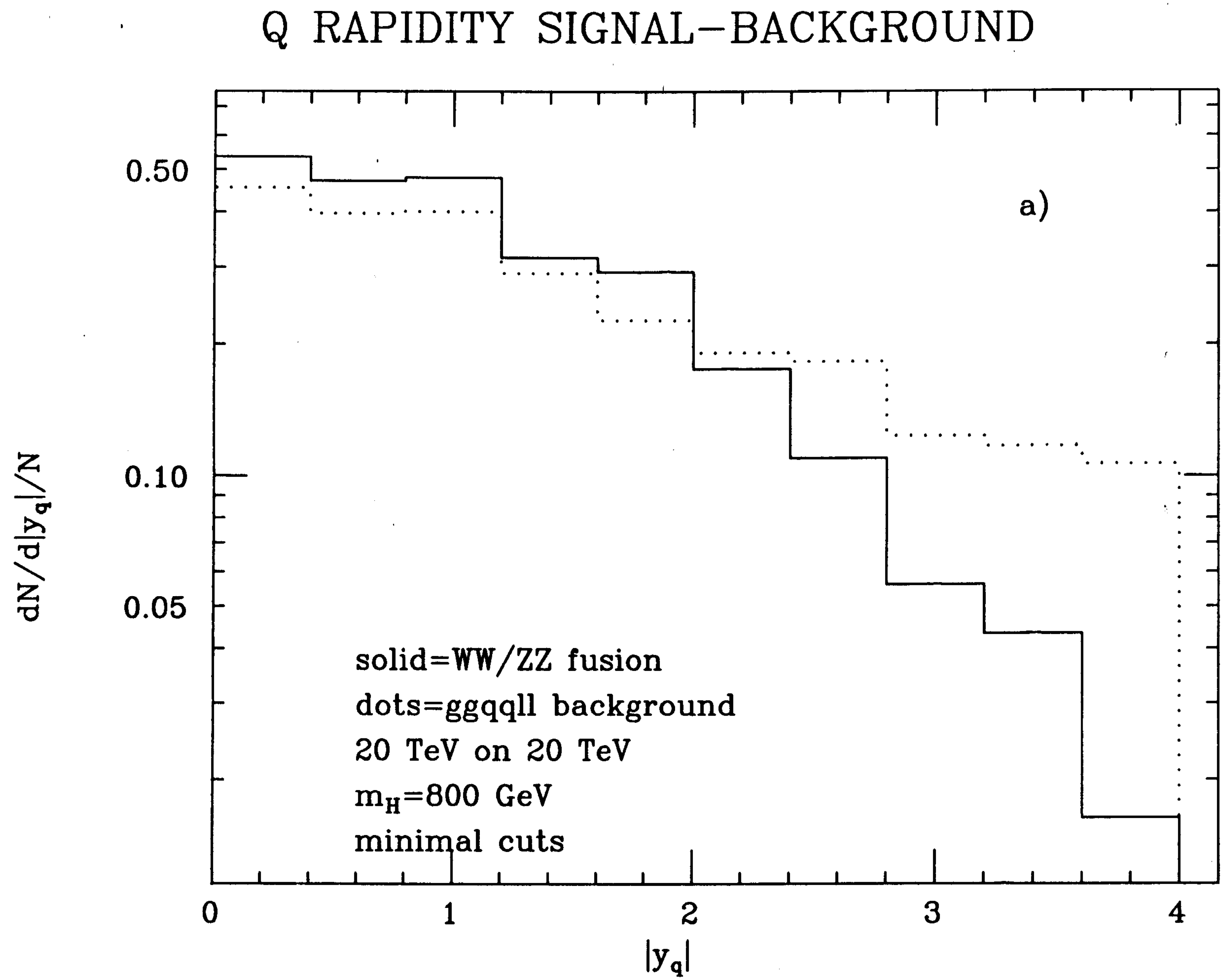

W_{HAD} DECAY ANGLE SIGNAL−BCKGND
dashes=gg fusion
dots=ggqqll background
20 TeV on 20 TeV
m_H=200 GeV
minimal cuts
d)
$dN/d|\cos(\theta_q)|/N$
0.0
0.5
1.0
1.5
2.0
2.5
0
0.2
0.4
0.6
0.8
1
$|\cos(\theta_q)|$

FIGURE 2d



Q RAPIDITY SIGNAL-BACKGROUND

FIGURE 3a

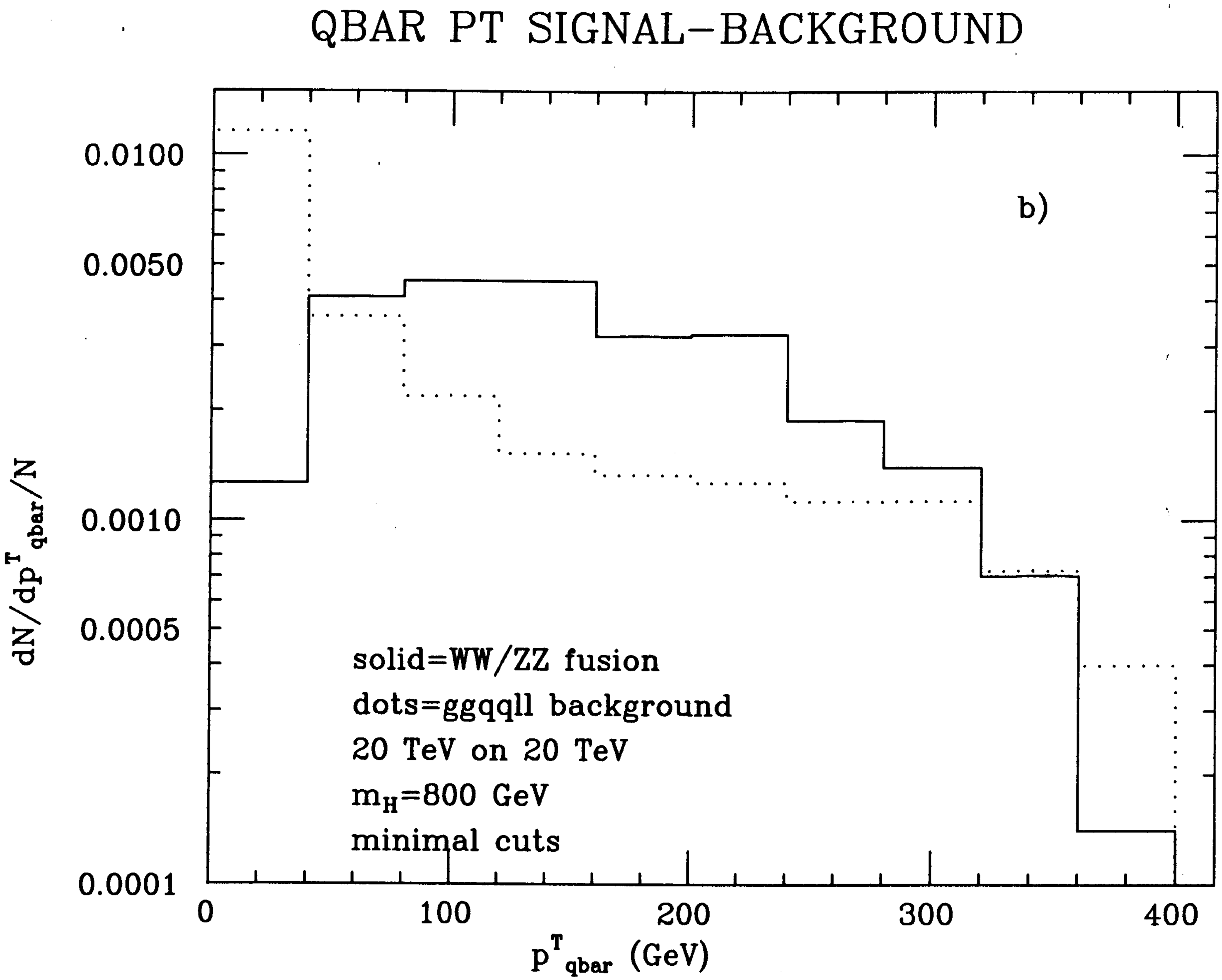

QBAR PT SIGNAL-BACKGROUND
b)
0.0100
0.0050
0.0010
0.0005
0.0001
$dN/dp^T_{qbar}/N$
0
100
200
300
400
p^T_{qbar} (GeV)
solid=WW/ZZ fusion
dots=ggqqll background
20 TeV on 20 TeV
m_H=800 GeV
minimal cuts

FIGURE 3b

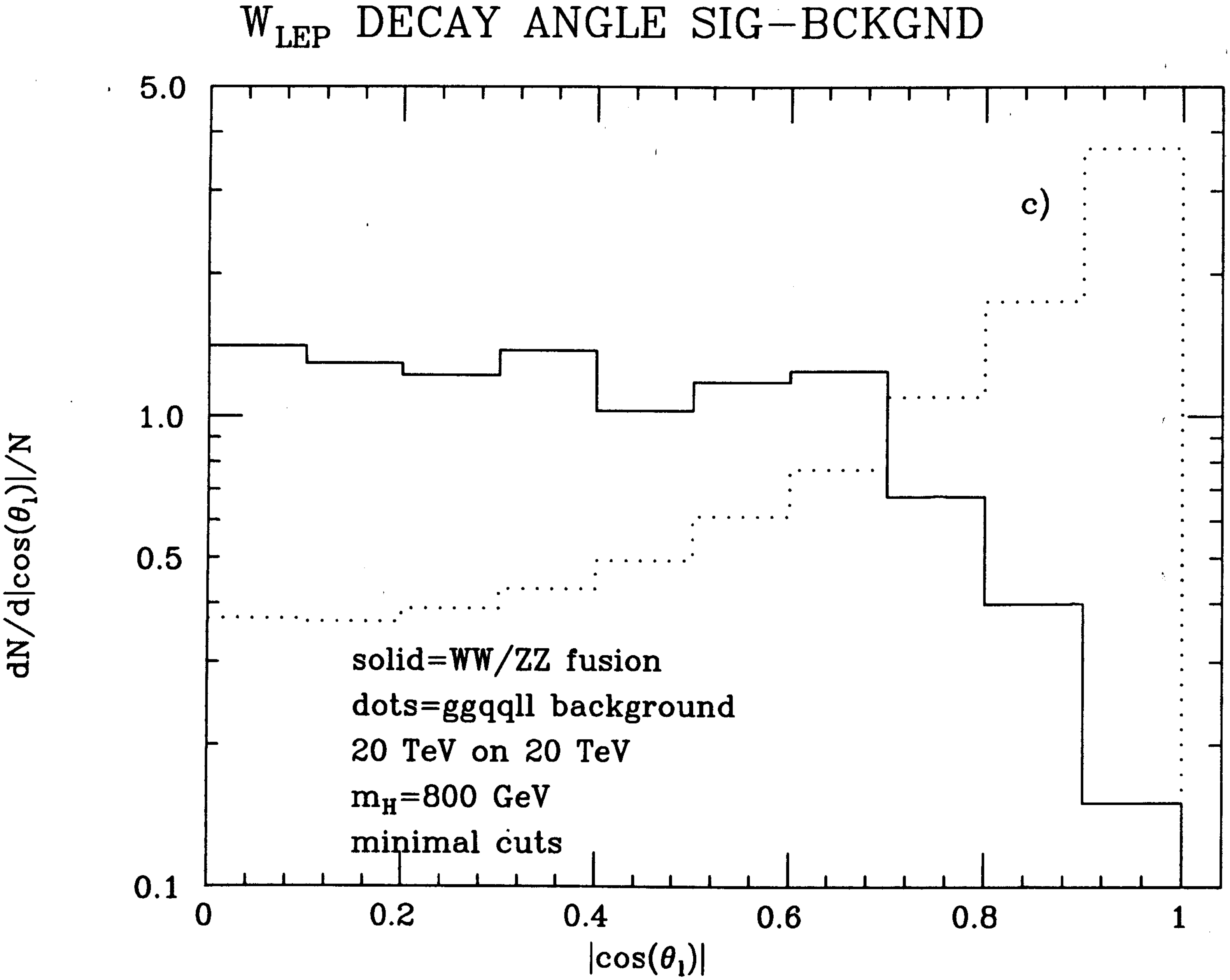

W_{LEP} DECAY ANGLE SIG−BCKGND
5.0
1.0
0.5
0.1
c)
dN/d|cos(θ_l)|/N
0
0.2
0.4
0.6
0.8
1
|cos(θ_l)|
solid=WW/ZZ fusion
dots=ggqqll background
20 TeV on 20 TeV
m_H=800 GeV
minimal cuts

FIGURE 3c

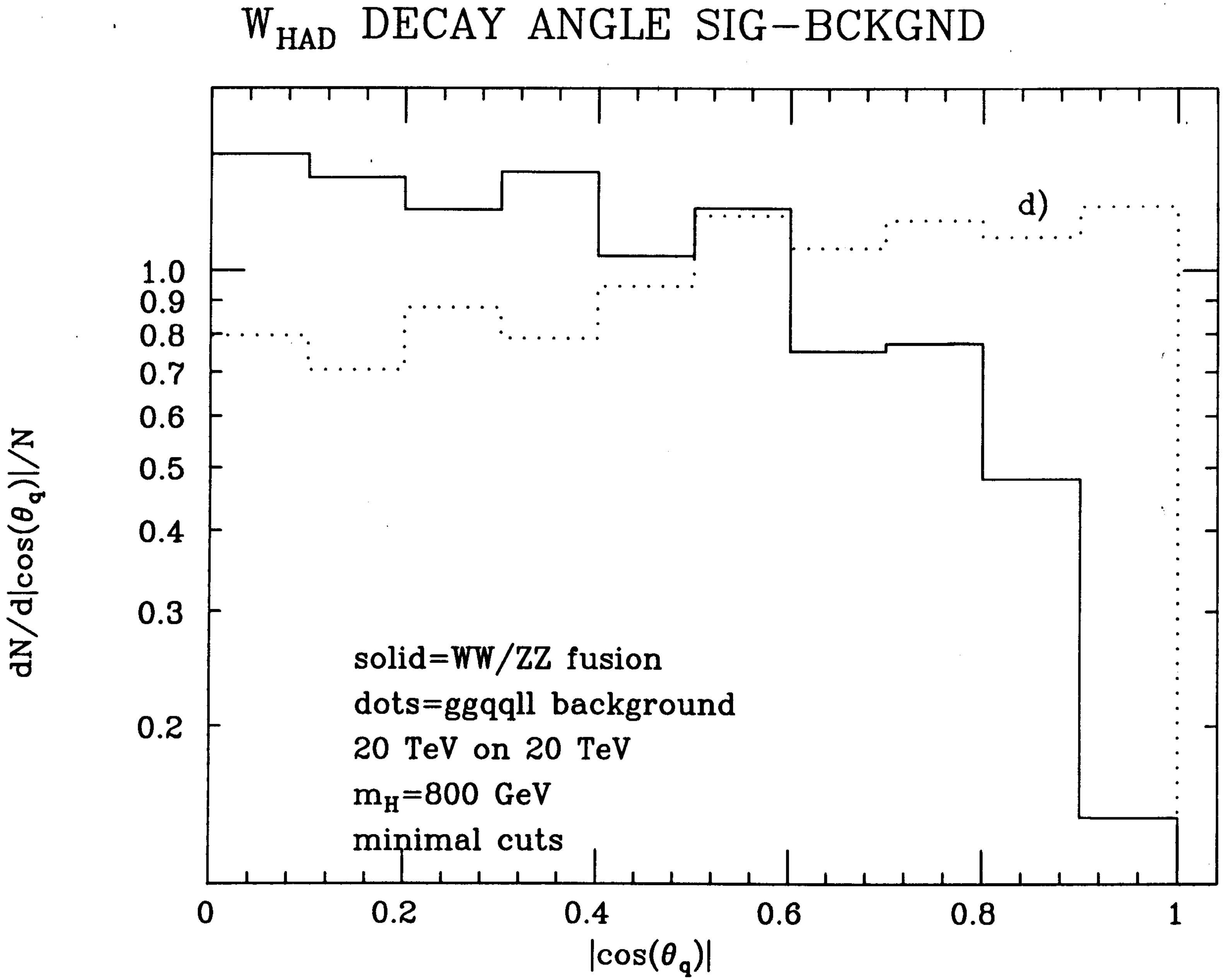

W_{HAD} DECAY ANGLE SIG−BCKGND
d)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
$dN/d|\cos(\theta_q)|/N$
solid=WW/ZZ fusion
dots=ggqqll background
20 TeV on 20 TeV
m_H=800 GeV
minimal cuts
0
0.2
0.4
0.6
0.8
1
$|\cos(\theta_q)|$

FIGURE 3d

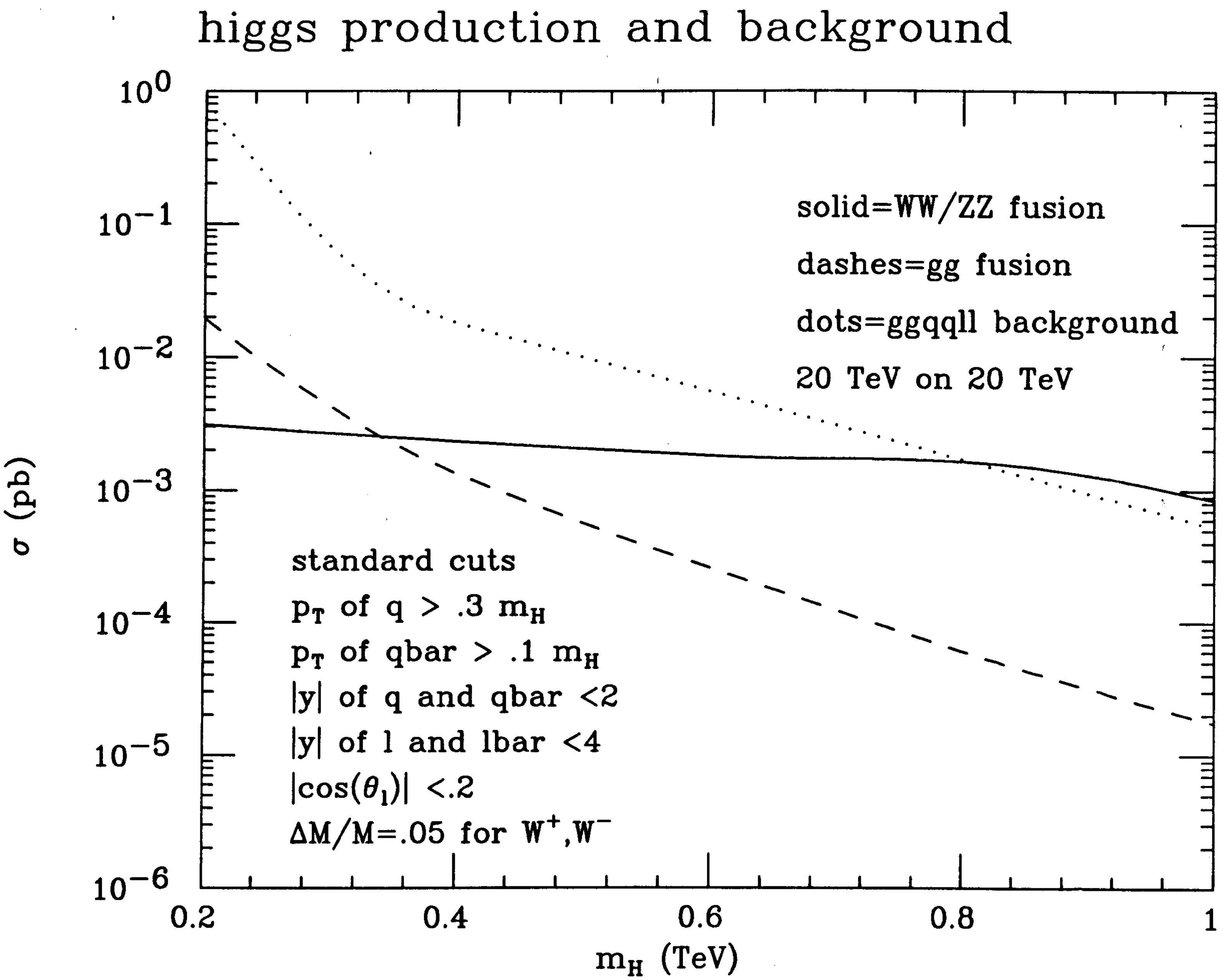

higgs production and background
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
σ (pb)
0.2
0.4
0.6
0.8
1
m_H (TeV)
solid=WW/ZZ fusion
dashes=gg fusion
dots=ggqqll background
20 TeV on 20 TeV
standard cuts
p_T of q > .3 m_H
p_T of qbar > .1 m_H
|y| of q and qbar <2
|y| of l and lbar <4
$|\cos(\theta_l)|$ <.2
$\Delta M/M$=.05 for W^+,W^-

FIGURE 4

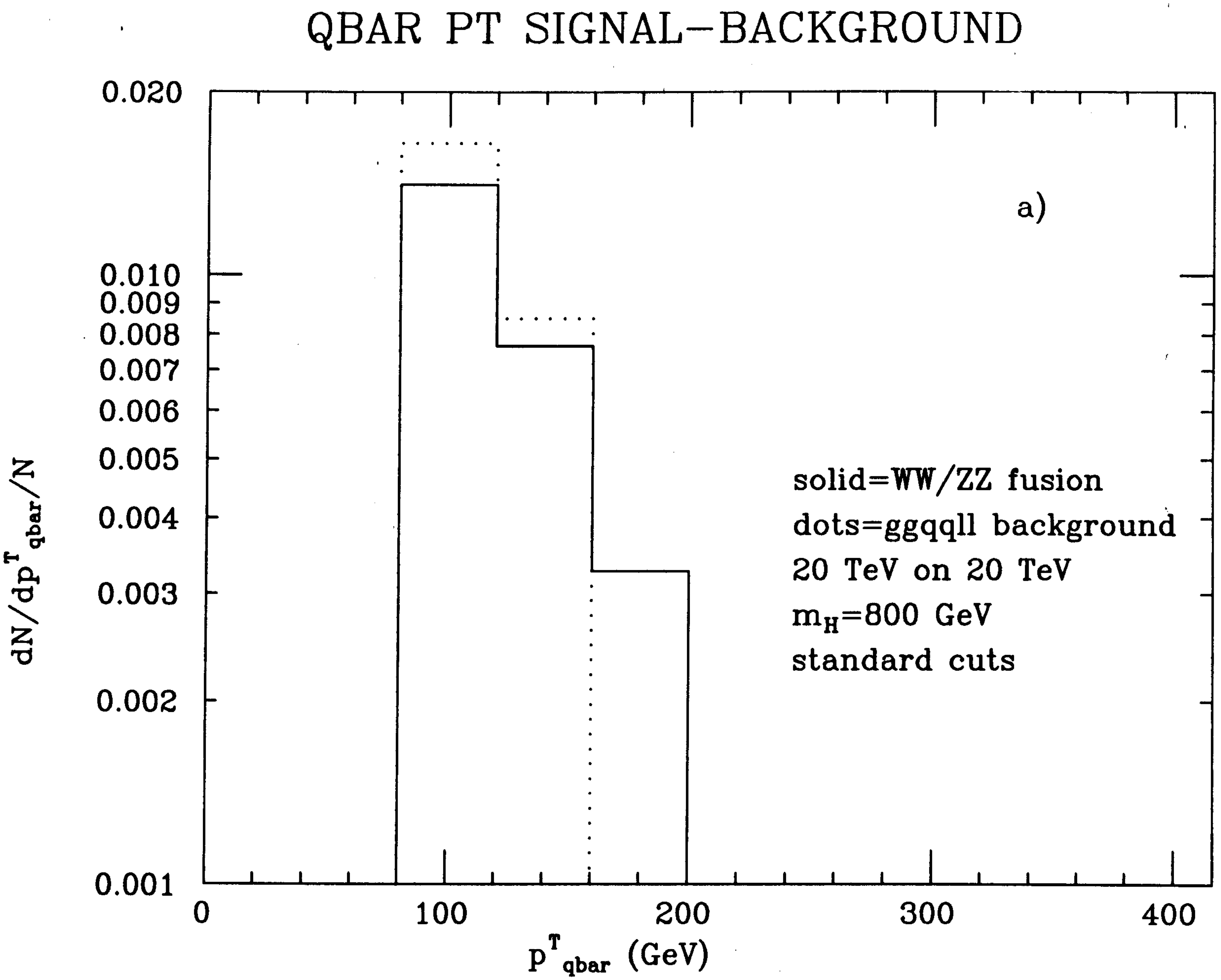
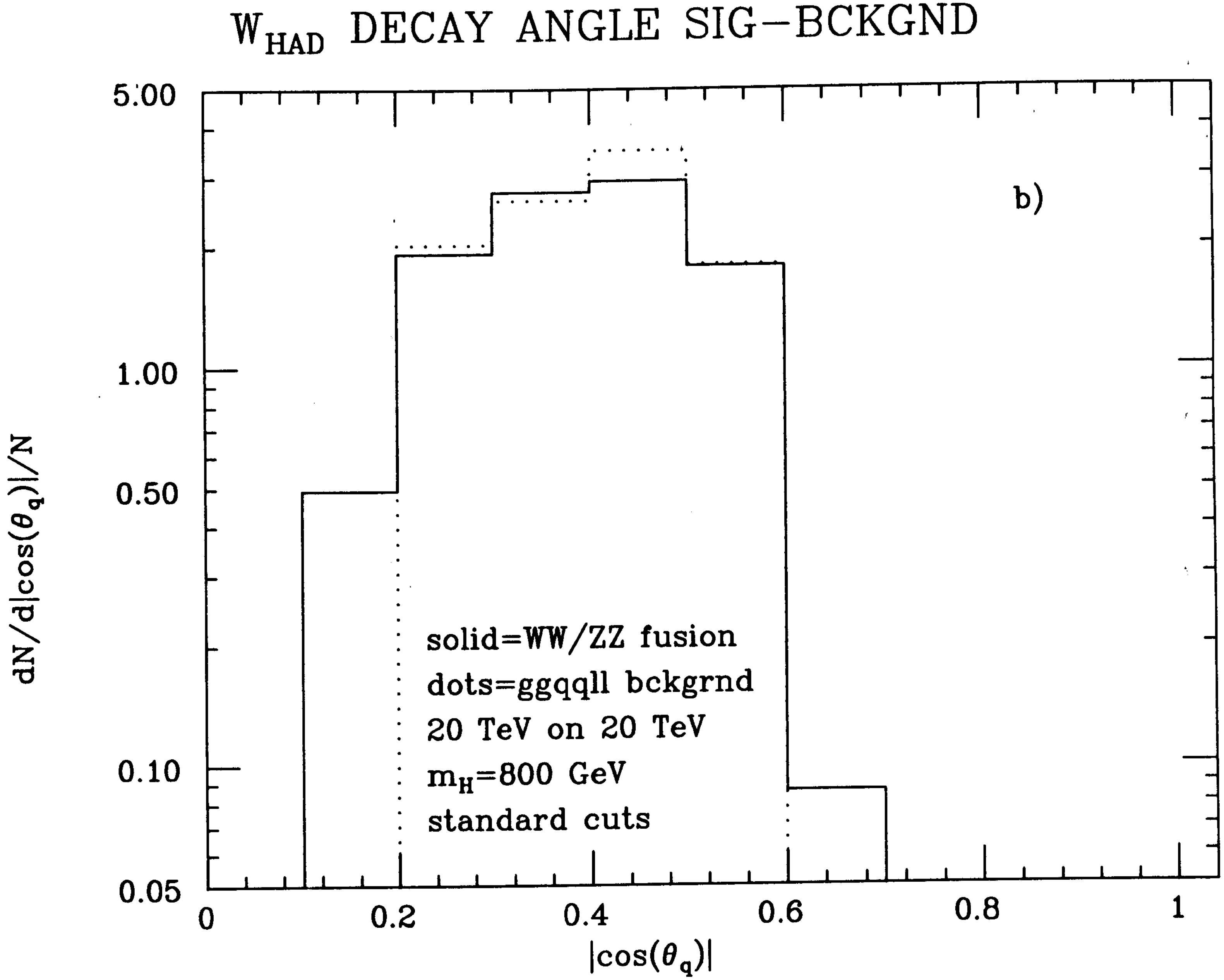

QBAR PT SIGNAL-BACKGROUND
0.020
0.010
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
dN/dp^T_qbar/N
a)
solid=WW/ZZ fusion
dots=ggqqll background
20 TeV on 20 TeV
m_H=800 GeV
standard cuts
0
100
200
300
400
p^T_qbar (GeV)

FIGURE 5a



W_{HAD} DECAY ANGLE SIG−BCKGND
b)
solid=WW/ZZ fusion
dots=ggqqll bckgrnd
20 TeV on 20 TeV
m_H=800 GeV
standard cuts
5.00
1.00
0.50
0.10
0.05
0
0.2
0.4
0.6
0.8
1
$dN/d|\cos(\theta_q)|/N$
$|\cos(\theta_q)|$

FIGURE 5b

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(T/E)

ADDENDUM

A BACKGROUND TO HIGGS DETECTION*

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Note Added:

After completion of our work, we learned of closely related work by W. J. Stirling, R. Kleiss and S. D. Ellis, CERN–TH–4209/85. It uses similar techniques, but focuses on W–pair production.

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